Lecture #3: Feedback Processes & Impact on Galaxy Formation and Evolution

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M82

(Smith, Gallagher, & Westmoquette '05)

Types of Feedback

- Mechanical:
  - Mechanical energy / momentum from starbursts and/or AGN
  - Affect thermal and chemical properties of galaxies over entire galaxy mass spectrum
- Radiative:
  - Heating (e.g., Compton-heated winds in AGN)
  - Ionization (e.g, ionization cones, proximity effect in QSOs)
  - Destruction of molecules (H_2, PAH), grains (sublimation), …
  - Particularly important in dwarf galaxies at high redshifts

Plan

- Basic physics of mechanical feedback
- A few nearby examples
- Statistics on winds at $z < 0.5$
- High–z winds
- Impact on galaxy formation and evolution
- Open issues: Theoretical & observational

Relevant Reviews

- Veilleux, Cecil, Bland–Hawthorn 2005, ARAA, 43, 769-826 (galactic winds)
- Ferrara 2004, astro-ph/0406554 (high-z)

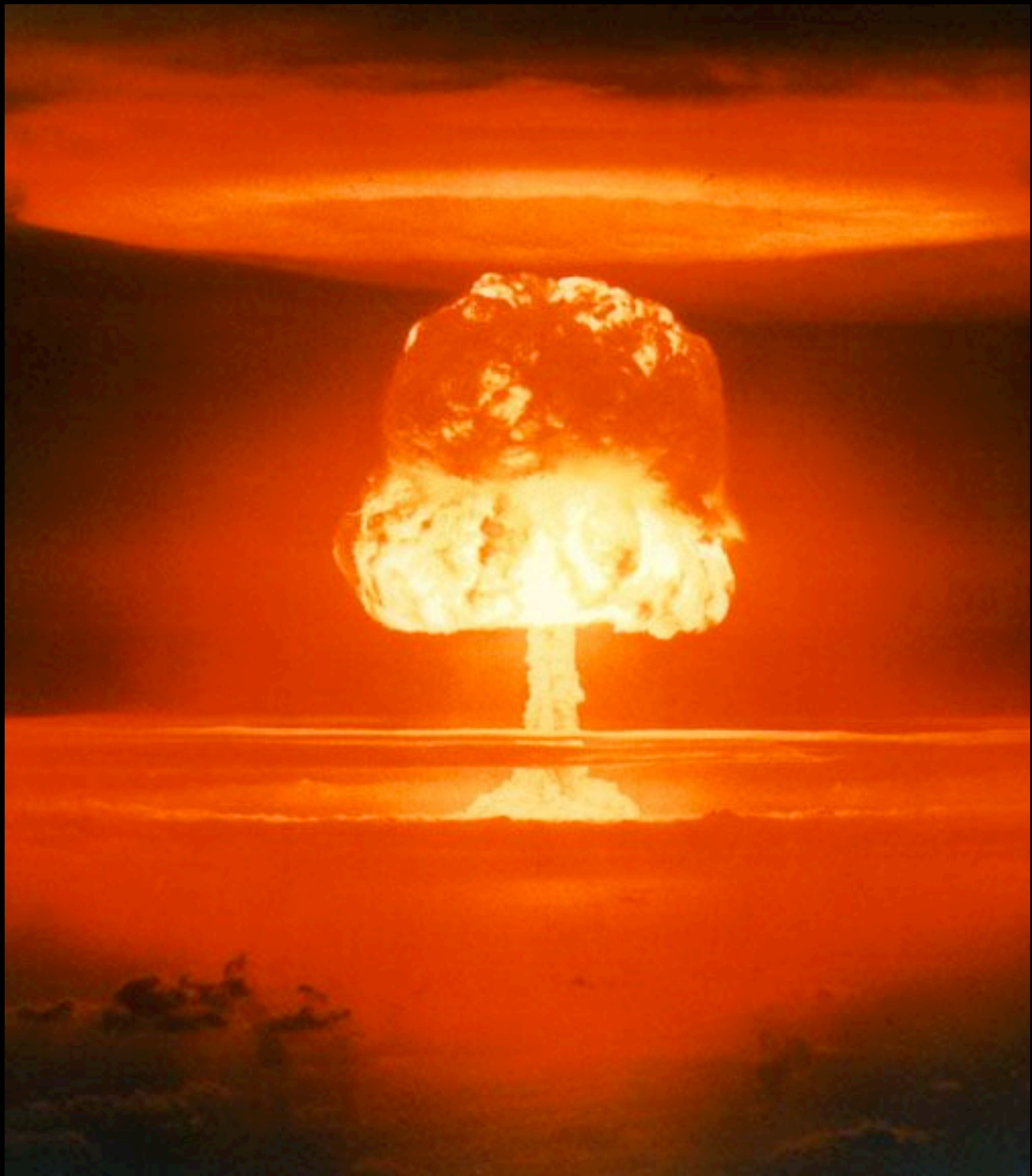
Sources of Energy

- Starburst winds:
  - **Mechanical energy / momentum from stellar (OB, WR) winds**
  - **Mechanical energy / momentum from supernovae (SNe)**

Scales with *SFR*

- AGN winds:
  - **Radiation pressure**
  - **Radiative heating → Compton-heated wind (U > 10-25)**
  - **Magnetic fields in accretion disks → (loosely) collimated jets in (radio-quiet) radio-loud AGN**

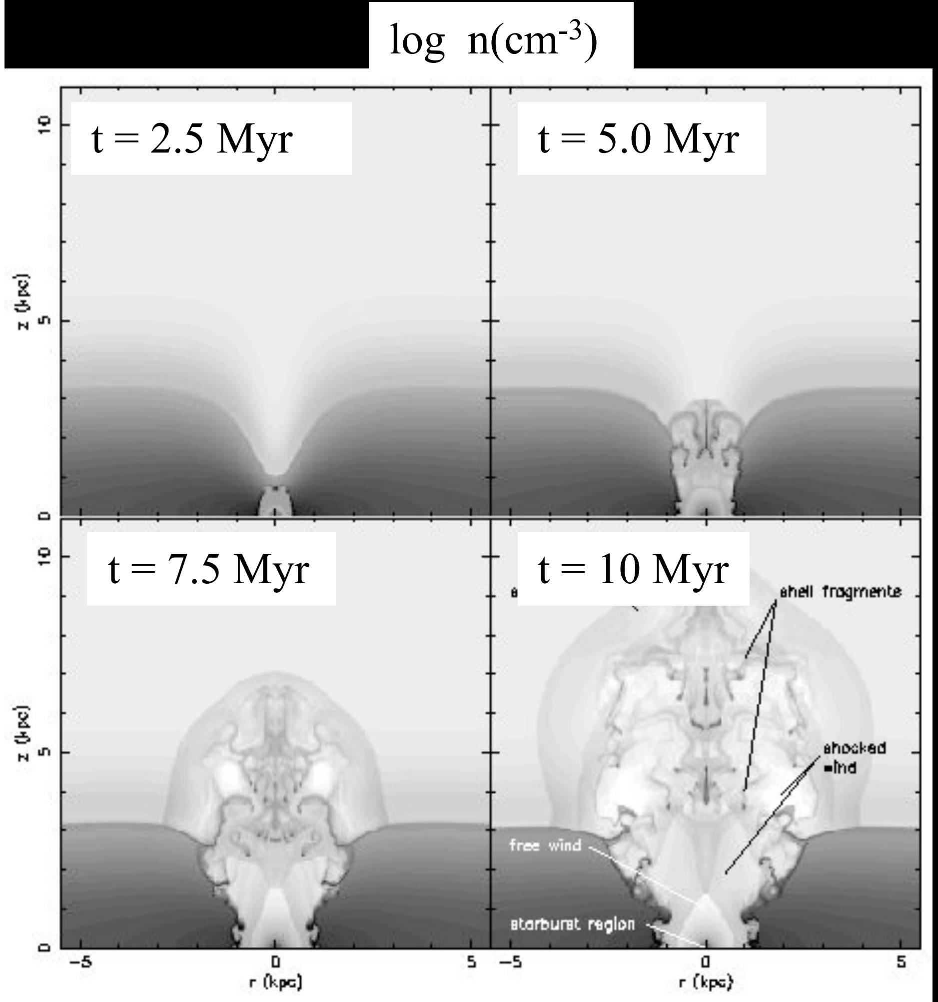
Scales with *L*(AGN) or *dM/dt (SMBH)*



Explosions in Galaxies!

- Blowout vortex in a stratified atmosphere

Galactic Winds: Basic Physics



(Strickland & Stevens 2000)

- $T(\text{hot gas}) \sim \dot{E} / \dot{M} \sim 10^8\ \xi\ \Lambda^{-1}$ [K]

  ξ = thermalization efficiency < 1

  $\Lambda = M_{total}/M_{ejecta}$ = mass-loading term > 1

- $V(\text{bubble}) \sim 100\ (\xi\ dE/dt_{42})^{0.2}\ n_0^{-0.2}\ \ t_7^{-0.4}$ = expansion speed of adiabatic bubble

  n_0 = nucleon density [cm^{-3}]

  dE/dt_{42} = rate of deposition of mechanical energy [10^{42} erg s^{-1}]

  t_7 = age of bubble [10^7 yrs]

- $V(\text{wind}) \sim 3000\ \xi^{0.5}\ \Lambda^{-0.5}$ = terminal velocity

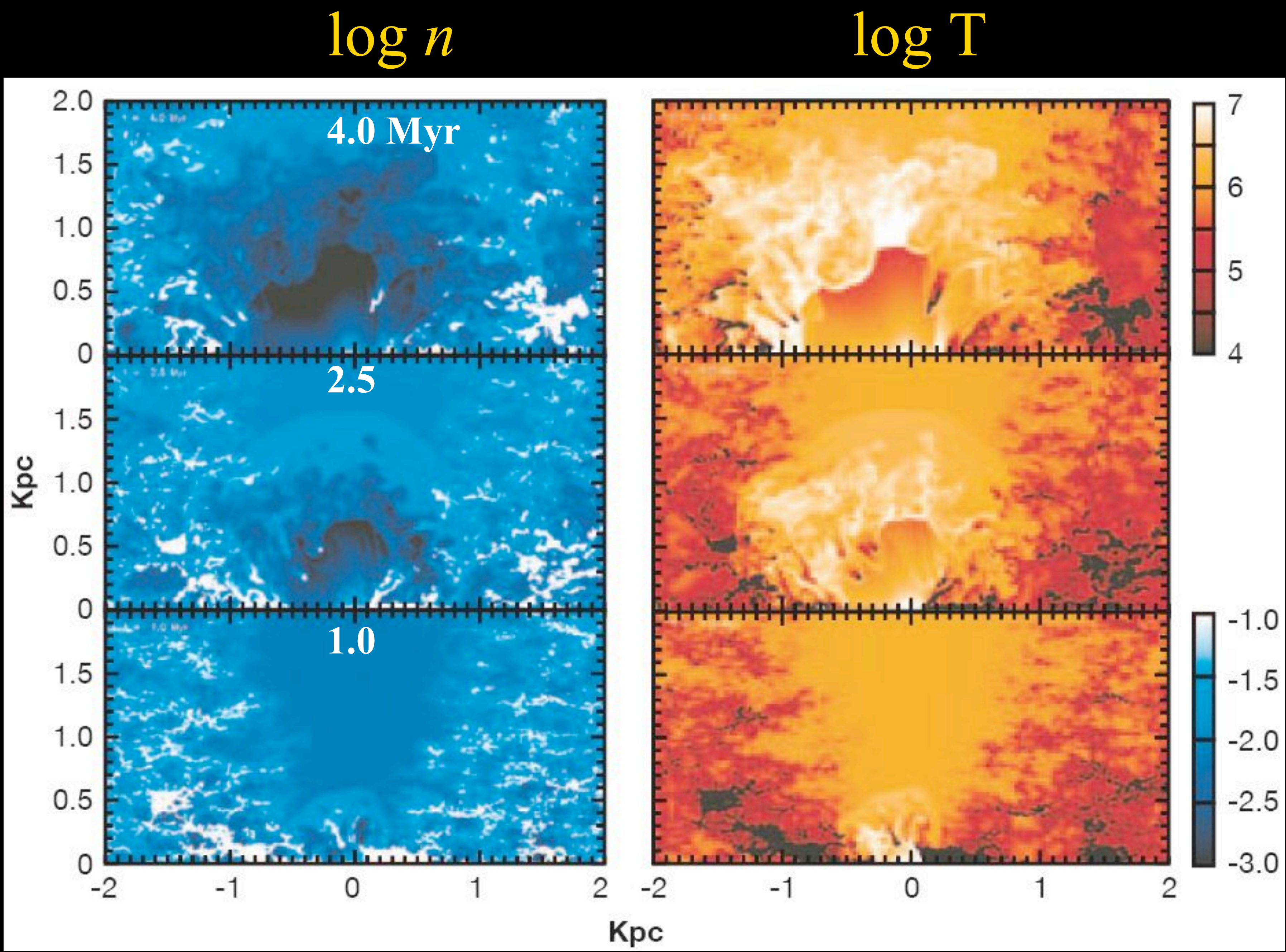
- V(cloud) = terminal velocity of cloud accelerated by wind ram pressure $\sim 600\ dp/dt_{34}^{\ 0.5}\ \Omega_w^{\ -0.5}\ r_{0,kpc}^{\ -0.5}\ N_{cloud,21}^{\ -0.5}$

  $N_{cloud,21}$ = column density of cloud [10^{21}cm^{-2}]

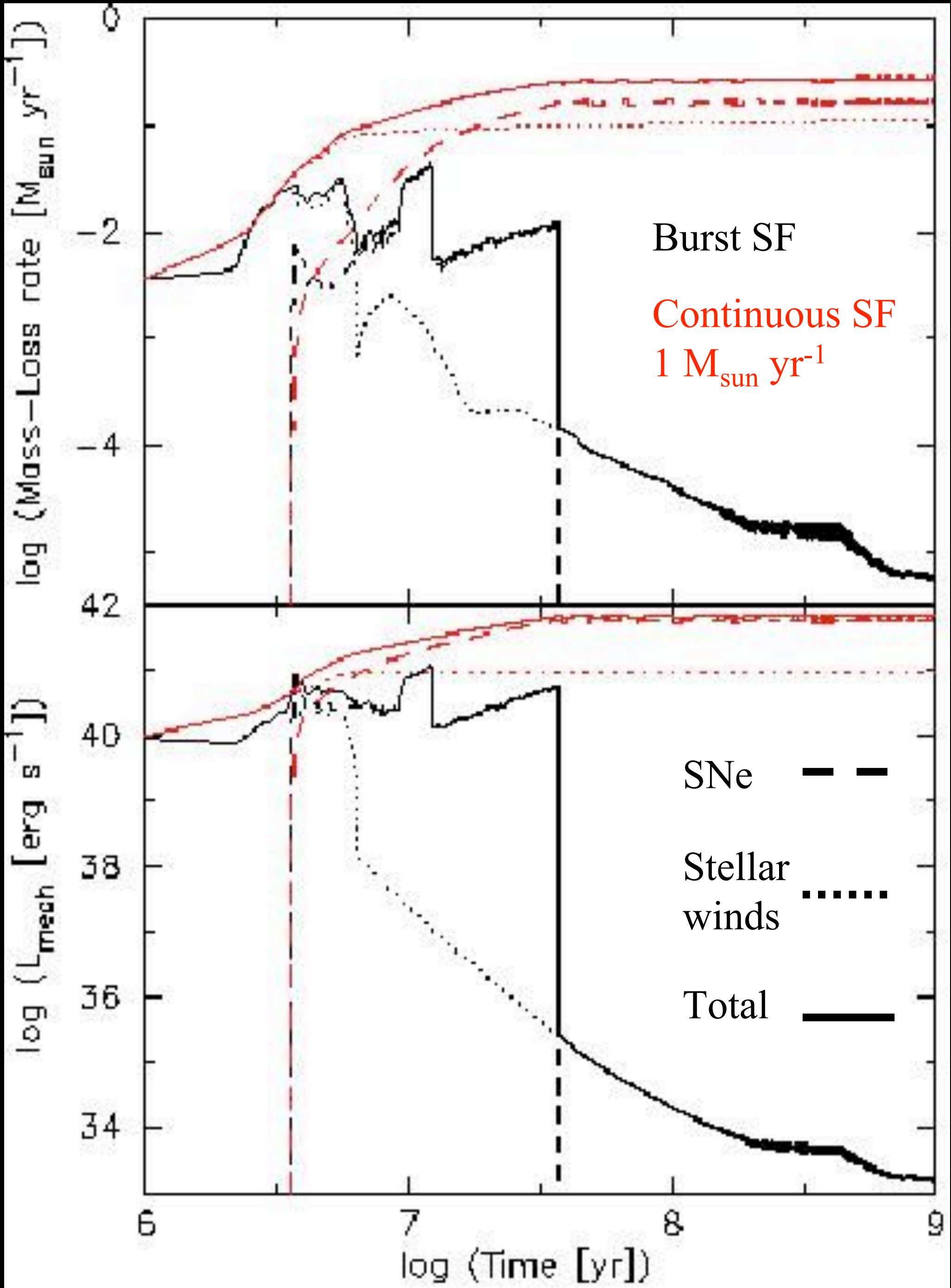
  r_0 = initial radius [kpc]

  dp/dt_{34} = wind momentum flux [10^{34} dynes]

  Ω_w = solid angle of wind [sr]



(Cooper, Bicknell, & Sutherland 2007)

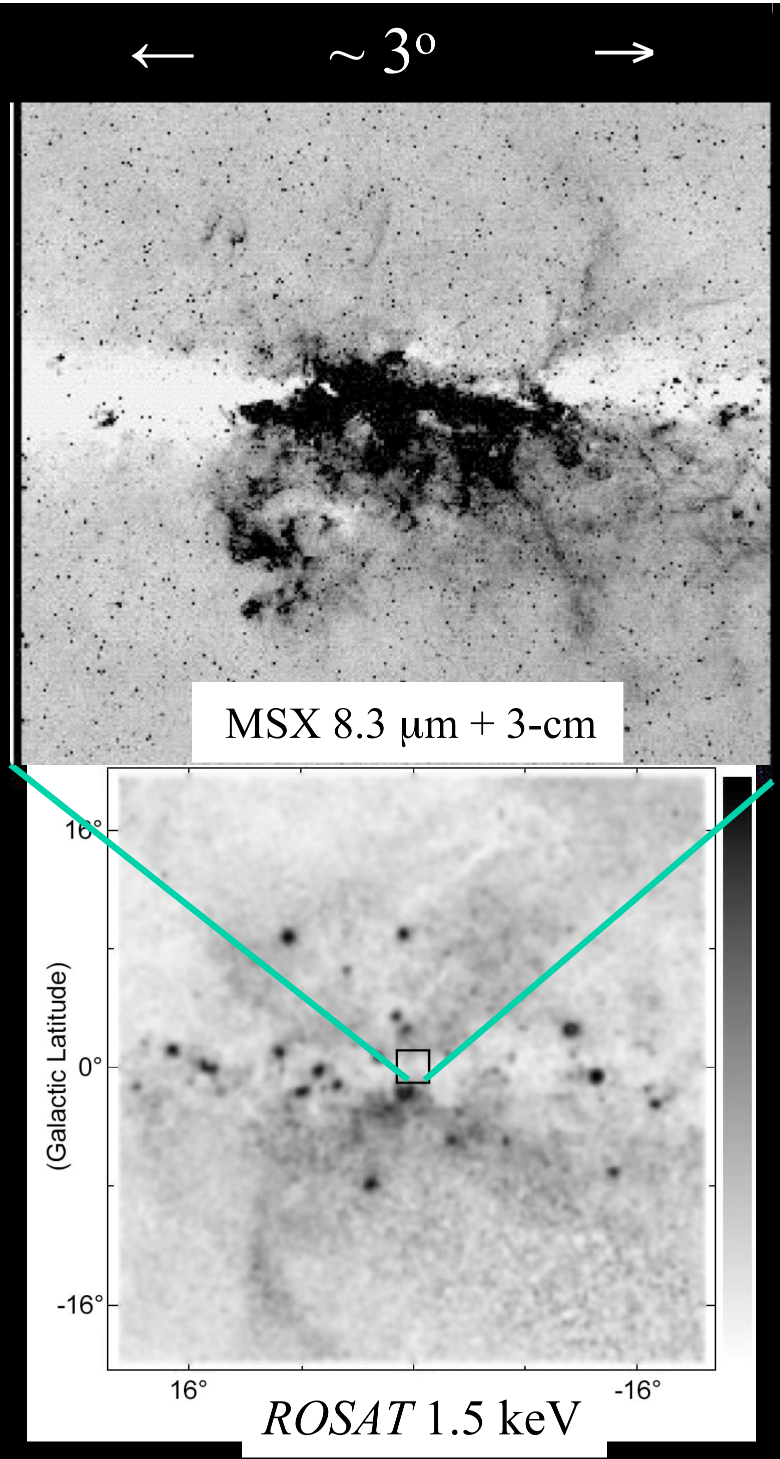


Mass and Energy Injection Rates

For instantaneous starbursts:

- 0 – 6 x 10^6 yrs:
  Winds from OB and WR stars dominate
- After 6 x10^6 yrs:
  Core-collapse Type II SNe dominate until ~ 40 Myr

(Starburst99: Leitherer et al. 1999)



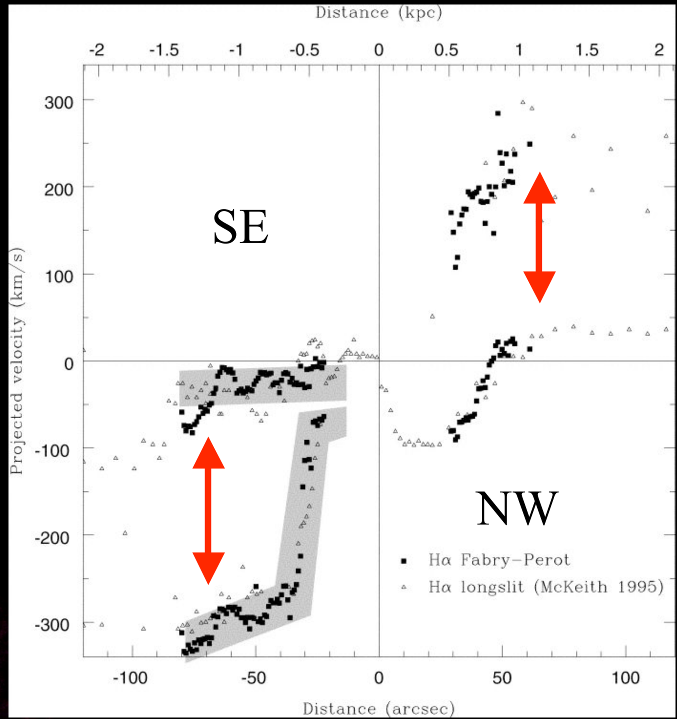
Galactic Wind in the Milky Way

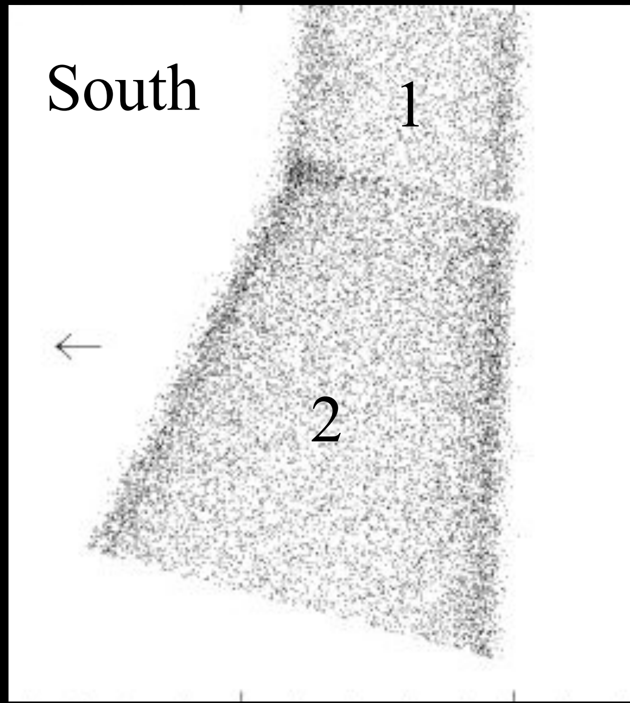
- **Dusty Bipolar Wind (~ 350 pc)**
  - **Warm dust / Galactic Center Lobe** ***(Sofue & Handa 1984)***
  - **Energy Requirement:**
    $M(H_2) \sim$ few x 10^6 M_{sun}
    V ~ 150 km s^{-1} ⇒ KE ~ 10^{55} ergs
  - **Dynamical timescale: ~ 1 – 2 Myr**
- **X-rays:**
  - **ROSAT 1.5 keV map of inner 45°**
  - **Diffuse 6.7 keV Kα emission from He-like Fe XXV** ***(Hyodo+06)***

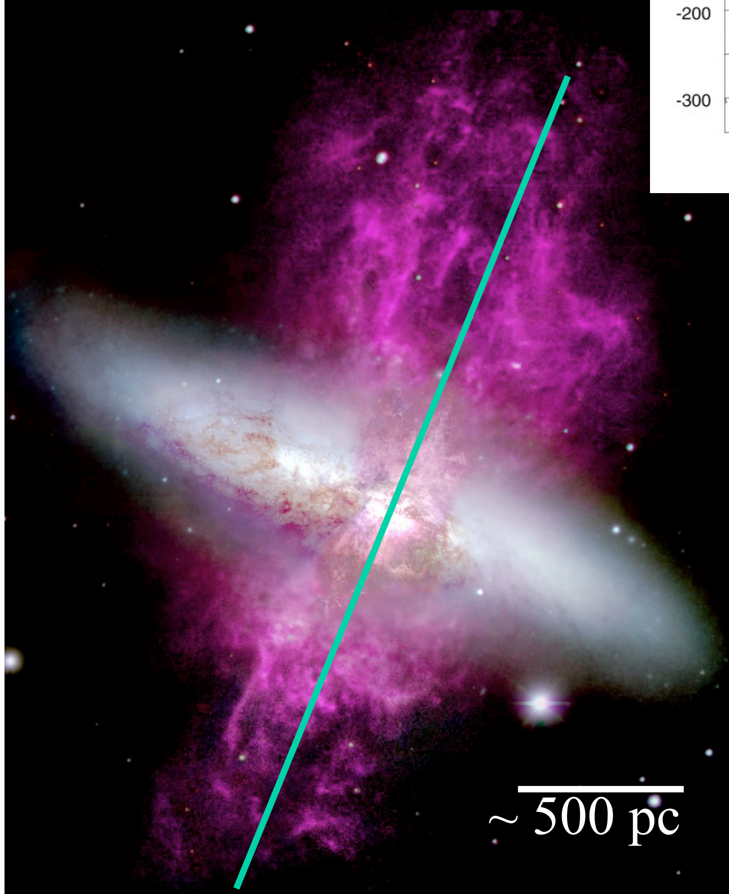
(Bland-Hawthorn & Cohen 2003)

M82

(e.g., Shopbell & Bland-Hawthorn 1998)

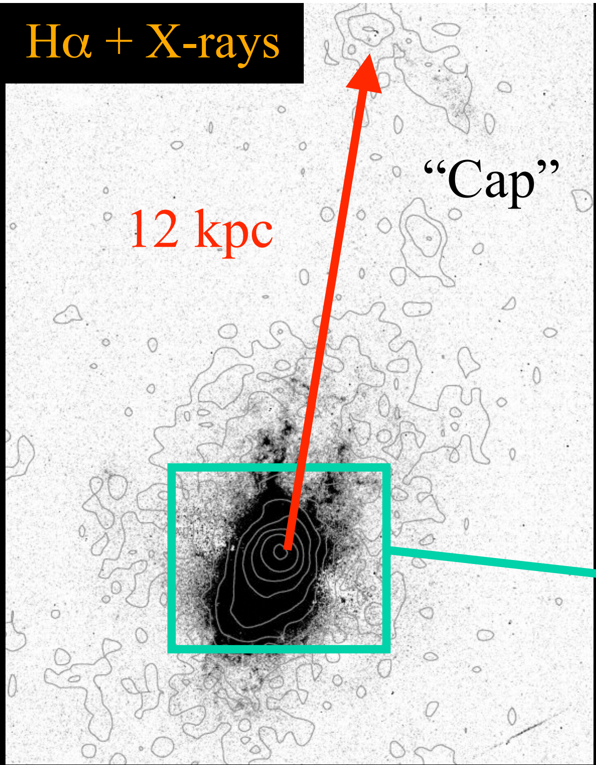


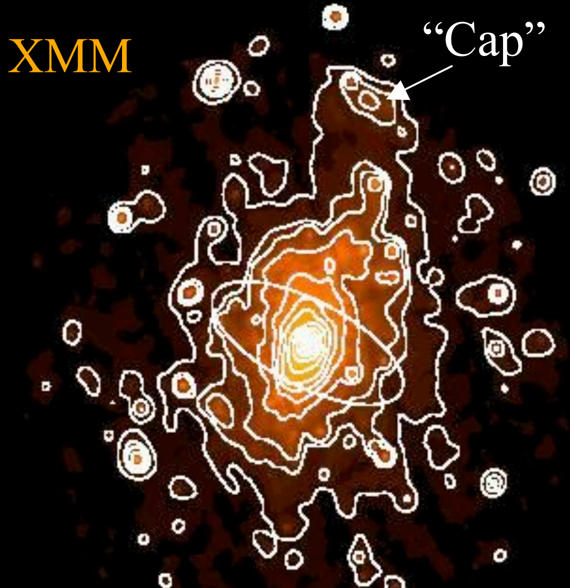




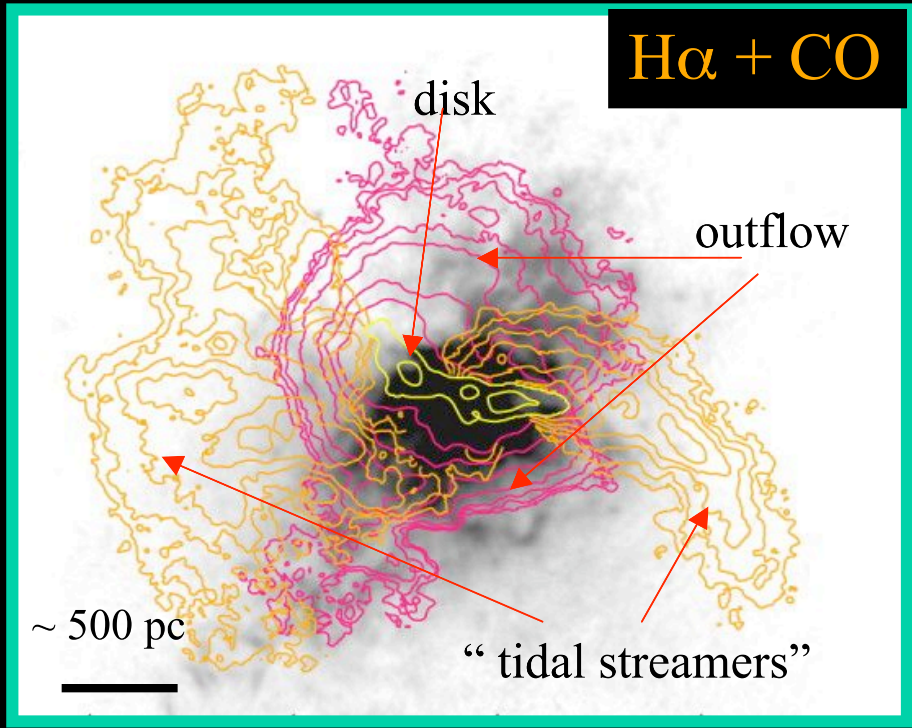
- **Pair of inclined cones: $\Theta_1 = 5^0$ and $\Theta_2 = 25^o$ (tilted 5^0 and 15^0 w/r to spin axis of galaxy)**
- **V(filaments) ~ 525 – 655 km s^{-1} (deprojected)**
- **M(filaments) ~ 5.8 x 10^6 M_{Sun}**
- **KE(filaments) ~ 2.1 x 10^{55} ergs (~ 1% of total mechanical energy input from starburst)**

M 82 – The Multiwavelength Picture





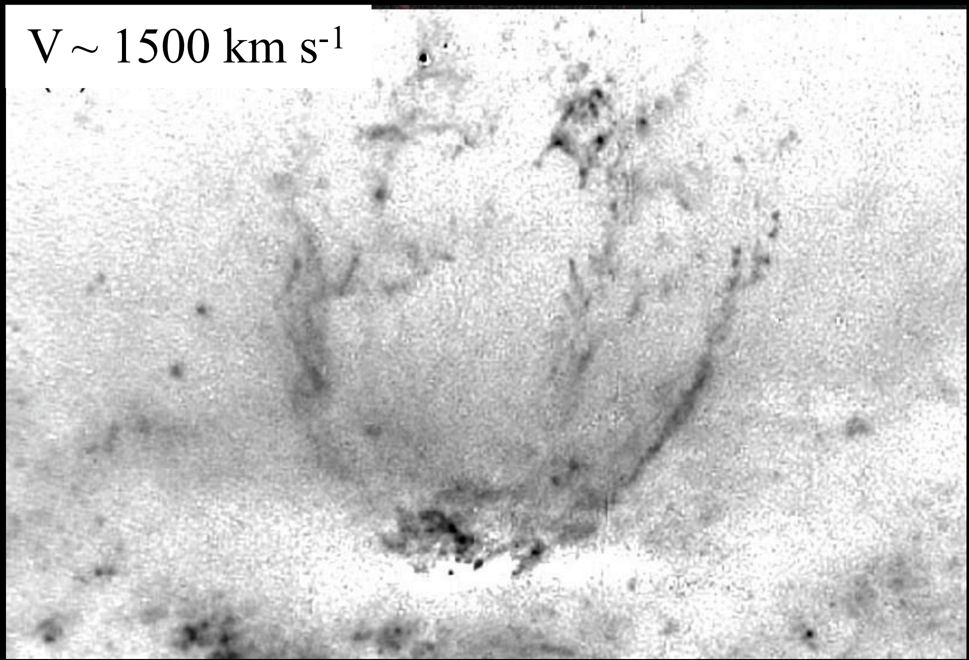
(Strickland+97; Devine & Bally 1999; Lehnert+99; Griffiths+00; Stevens+03)



(Walter, Weiß, & Scoville 2002)

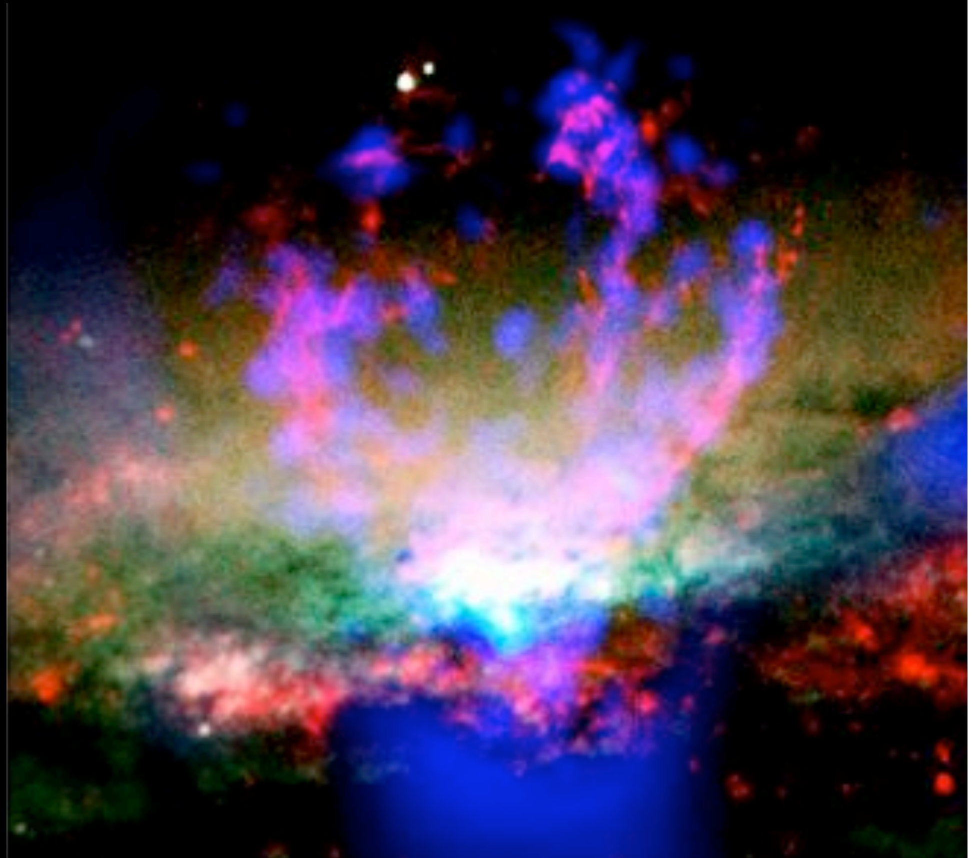
- **Ionized Component: Warm (50 – 200 km s^{-1} blueshifted) and hot ionized gas extends out to ~12 kpc from the nucleus → escape?**
- **Molecular (CO) outflow:**
  $\langle V_{outflow} \rangle$ ~ 100 km s^{-1} (V_{max} ~ 230 km s^{-1})
  Θ ~ 55^o M ~ 3 x 10^8 M_{sun} KE ~ 3 x 10^{55} ergs

Starburst-driven Superbubble in NGC 3079



1 kpc: ————

HST Hα + [N II]

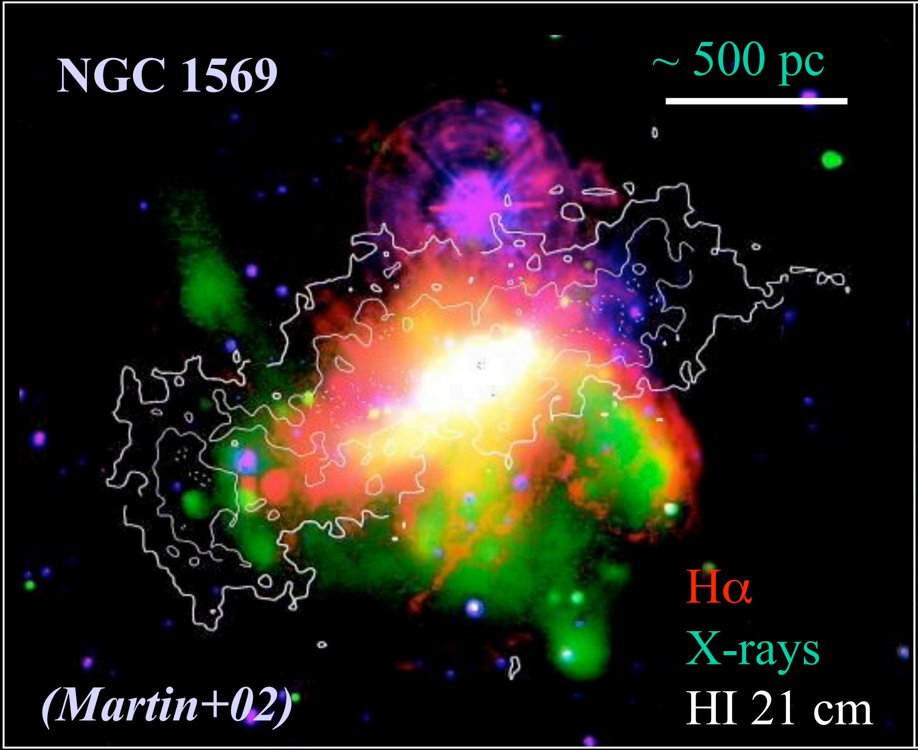


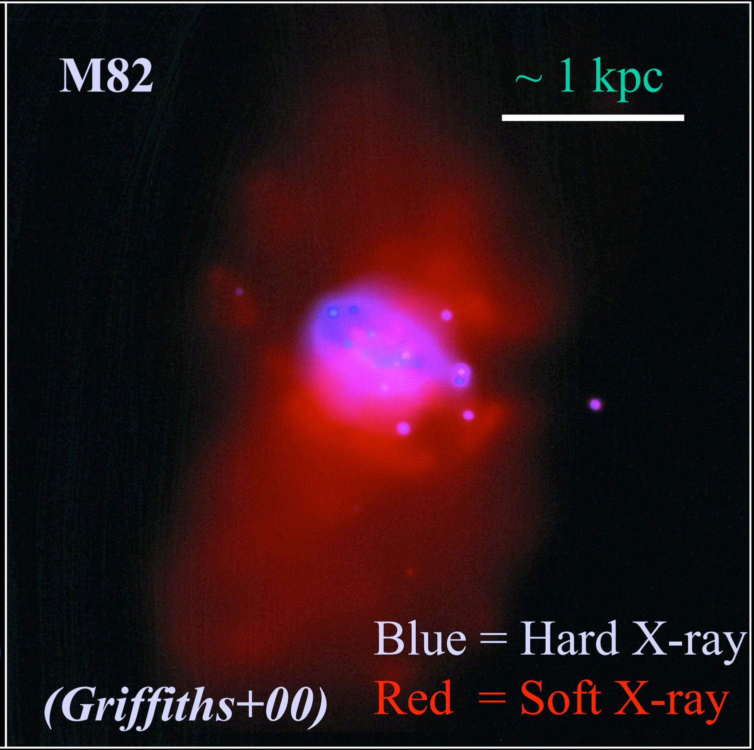
HST + *CXO*

(SV et al. 1994; Cecil et al. 2001; Cecil, Bland-Hawthorn, & SV 2002)

Chemical Enrichment of ISM / IGM

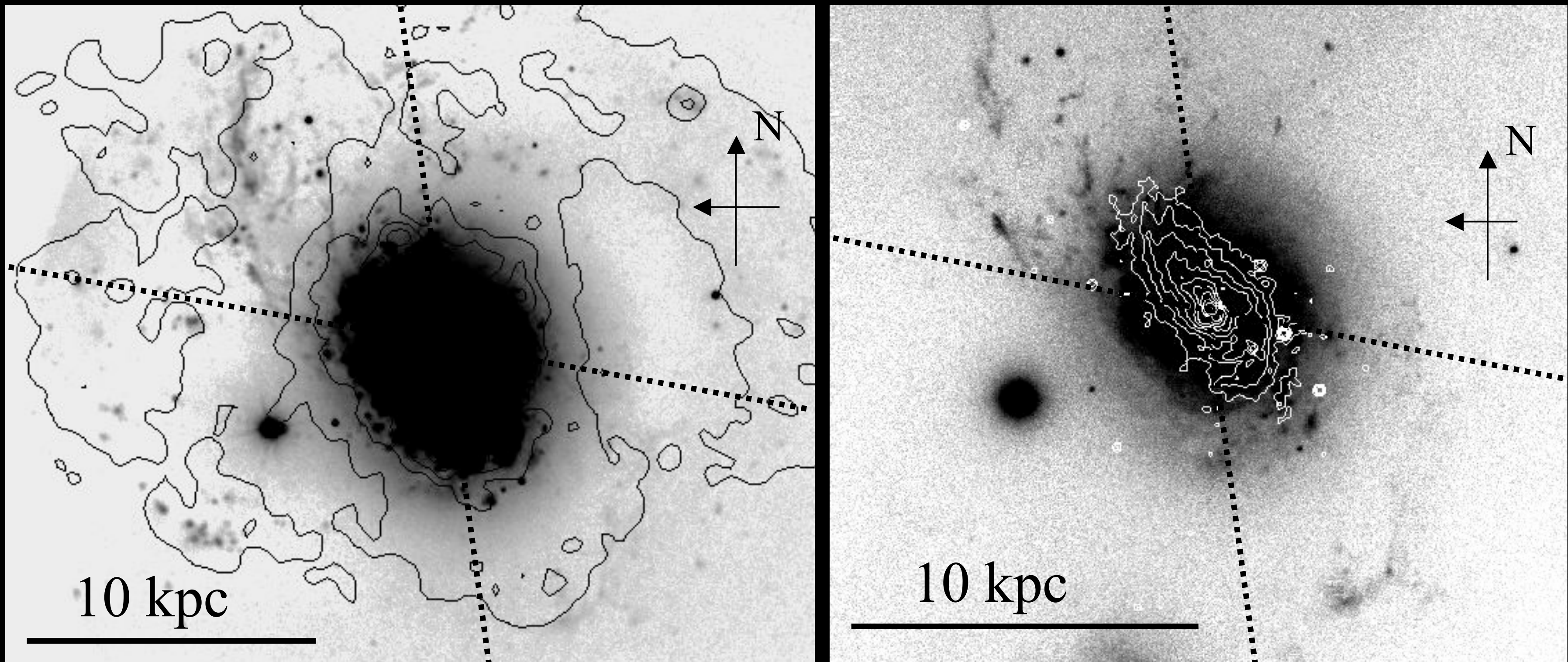
- **Chemically-enriched wind fluid has been directly observed in X-rays in M82, possibly NGC 1569, and almost certainly MW**
  - **α-elements / Fe ~ 2 – 4 x (solar ratio) [NGC 1569]; ≥ 1 x (solar) [M 82]**
  - **Most of the metals expelled by SNe II may escape from these galaxies [assuming no halo drag]**





“Zone of Influence” of AGN–driven Winds

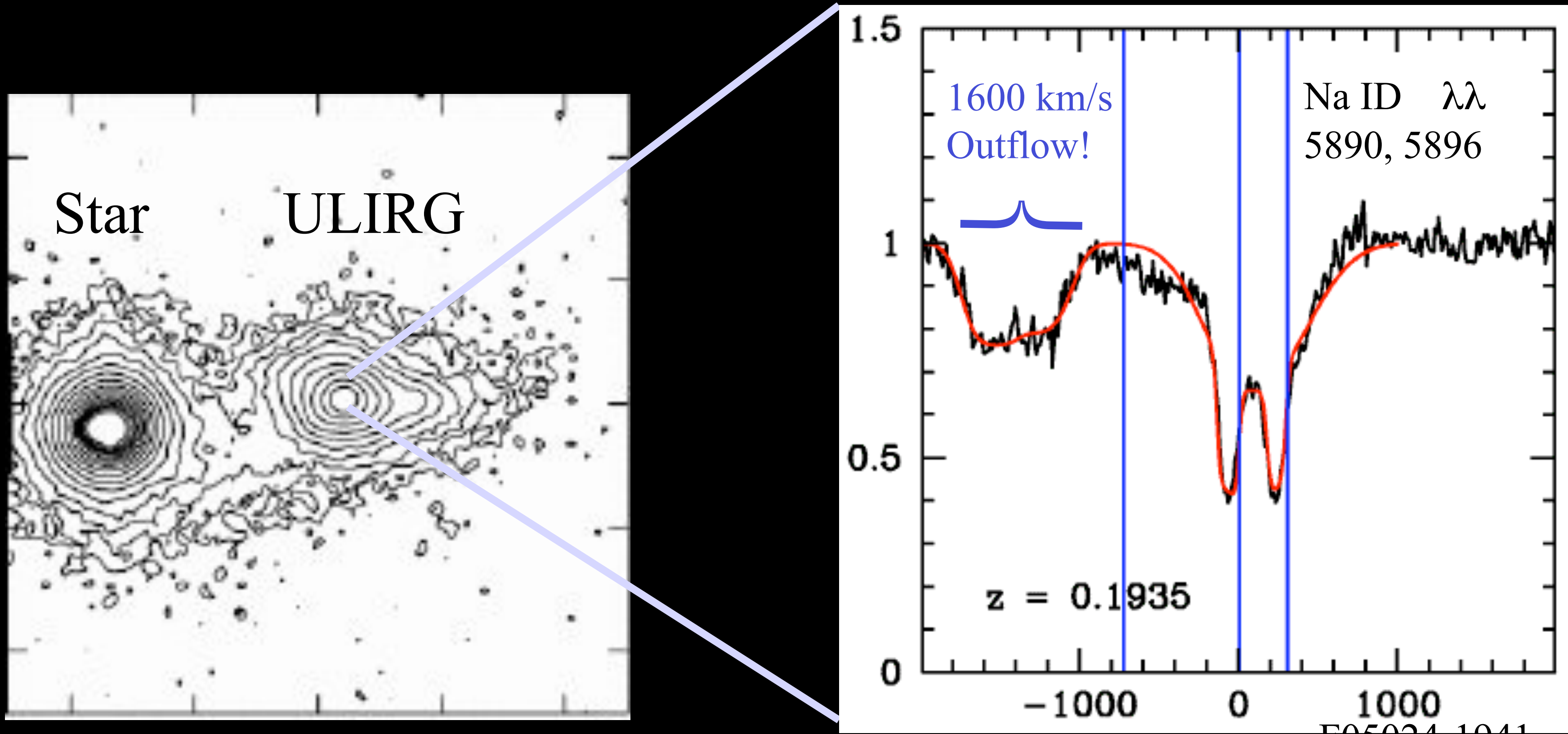
NGC 1068 log(Hα) + HI 21-cm log([O III]) + X-rays



(Optical: *SV et al. 2003;* HI: *Brinks 2003*; X-ray: *Young, Wilson, & Shopbell 2001)*

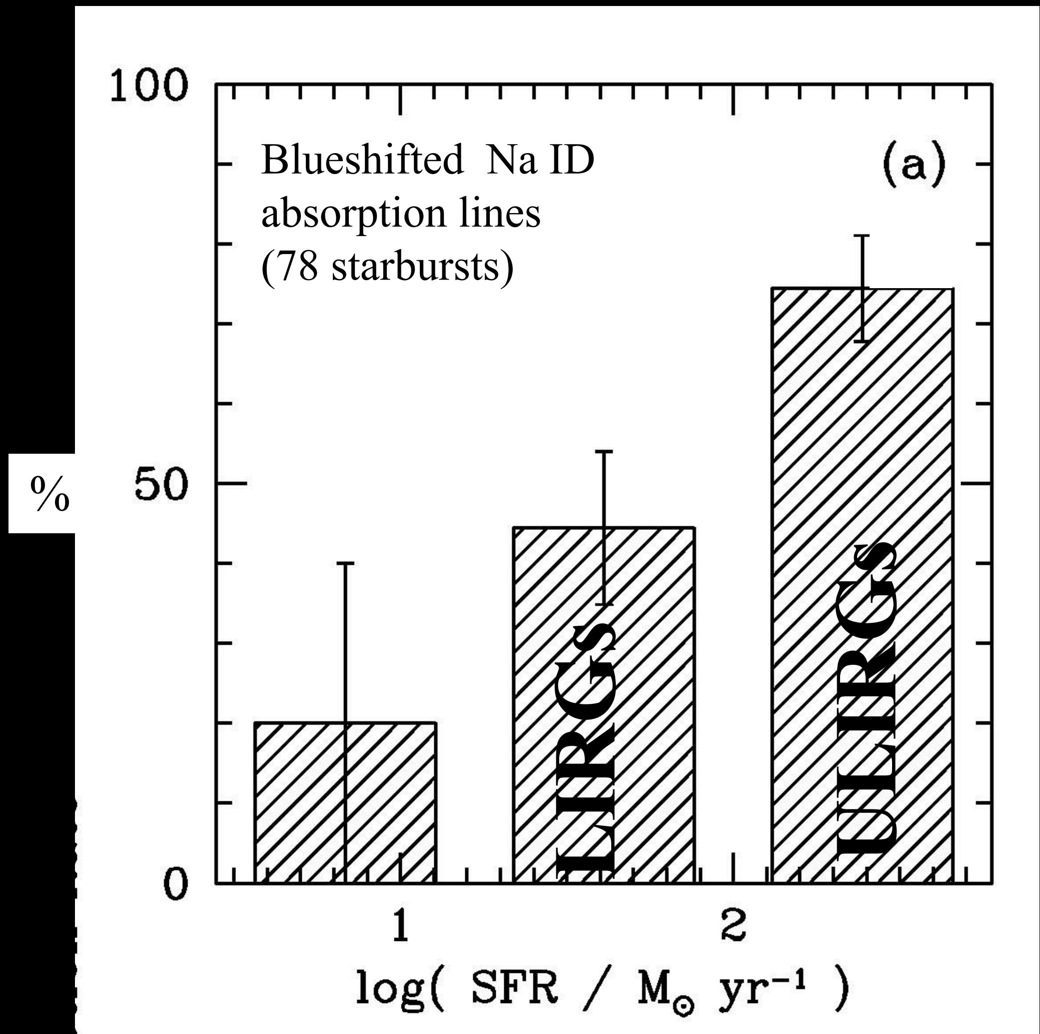
- AGN-driven winds clear out path for ionizing radiation
  → “ionization cones” on large scale

Statistics on Galactic Winds @ $z = 0 - 0.5$

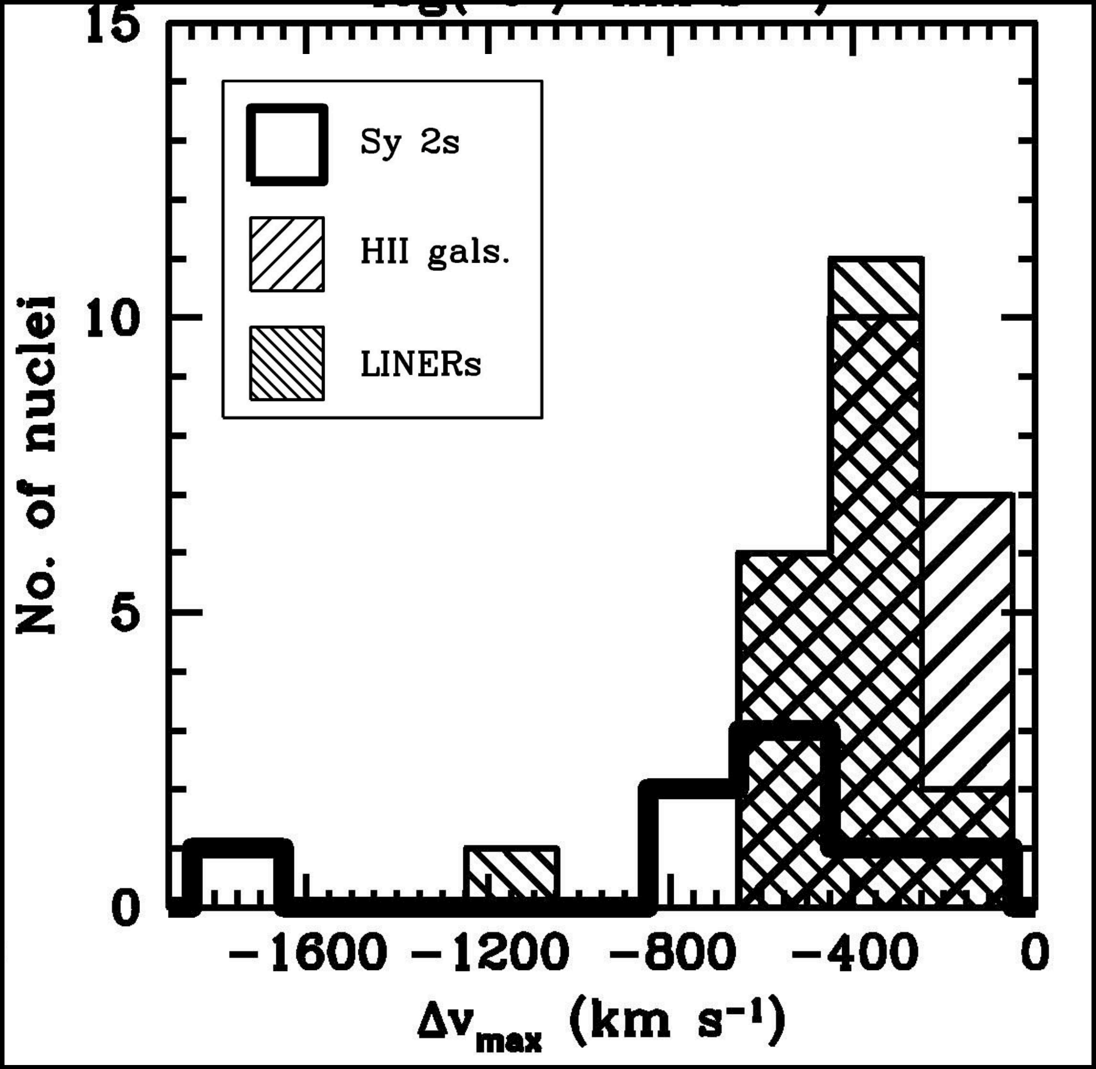


Rupke, SV, & Sanders (2002, 2005abc); Rupke & SV (2005)

Wind Detection Rate in Local Starbursts



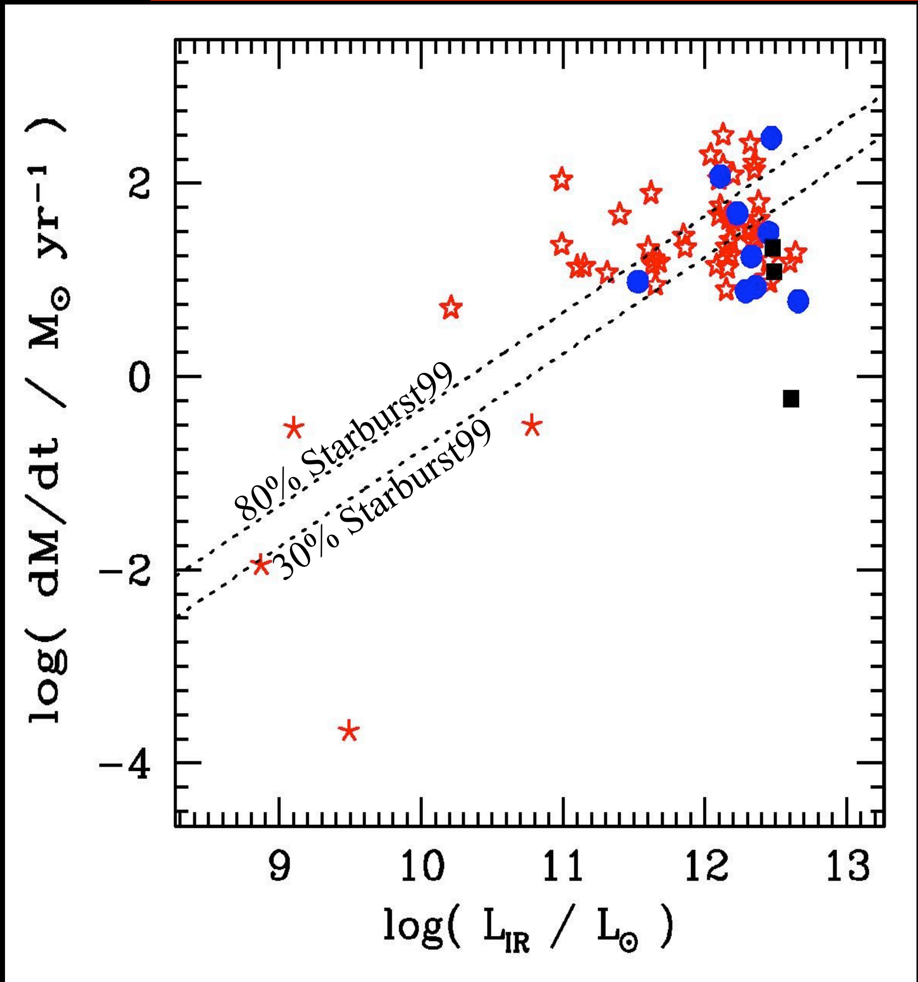
Outflow Velocities of Neutral Gas

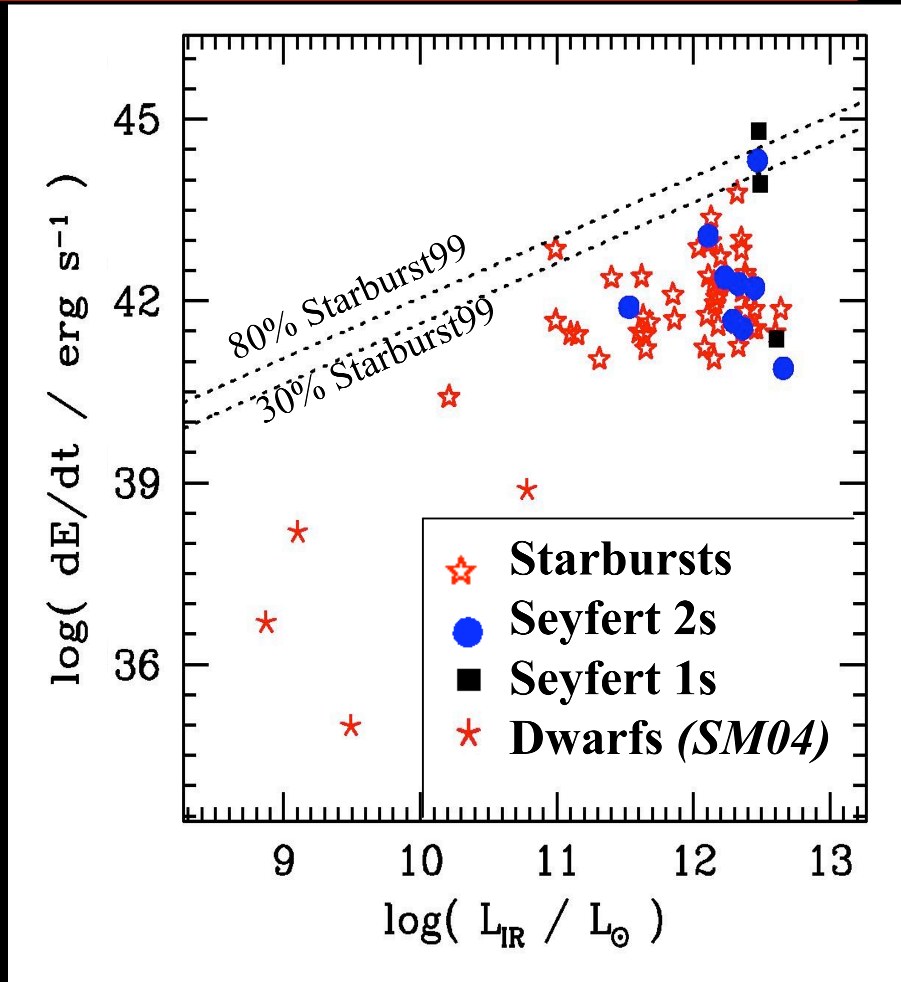


f_{esc} ~ 5–20%
(if no halo drag)
→ **IGM polluter !**

Winds have a profound effect on the hosts

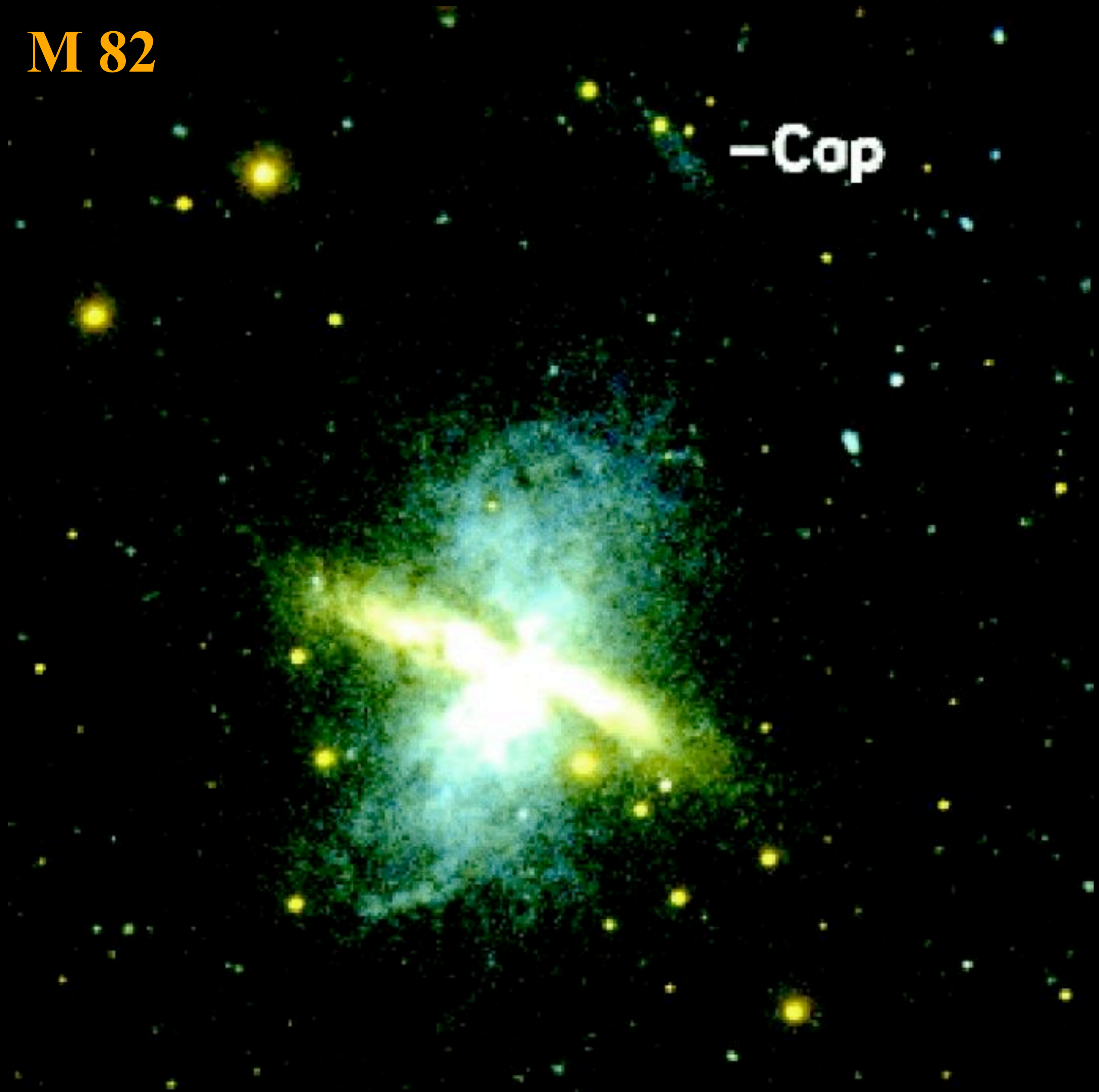
$M_{wind} = 10^{8} - 10^{10}\ M_{sun}$ $E_{wind} = 10^{56} - 10^{59}$ ergs





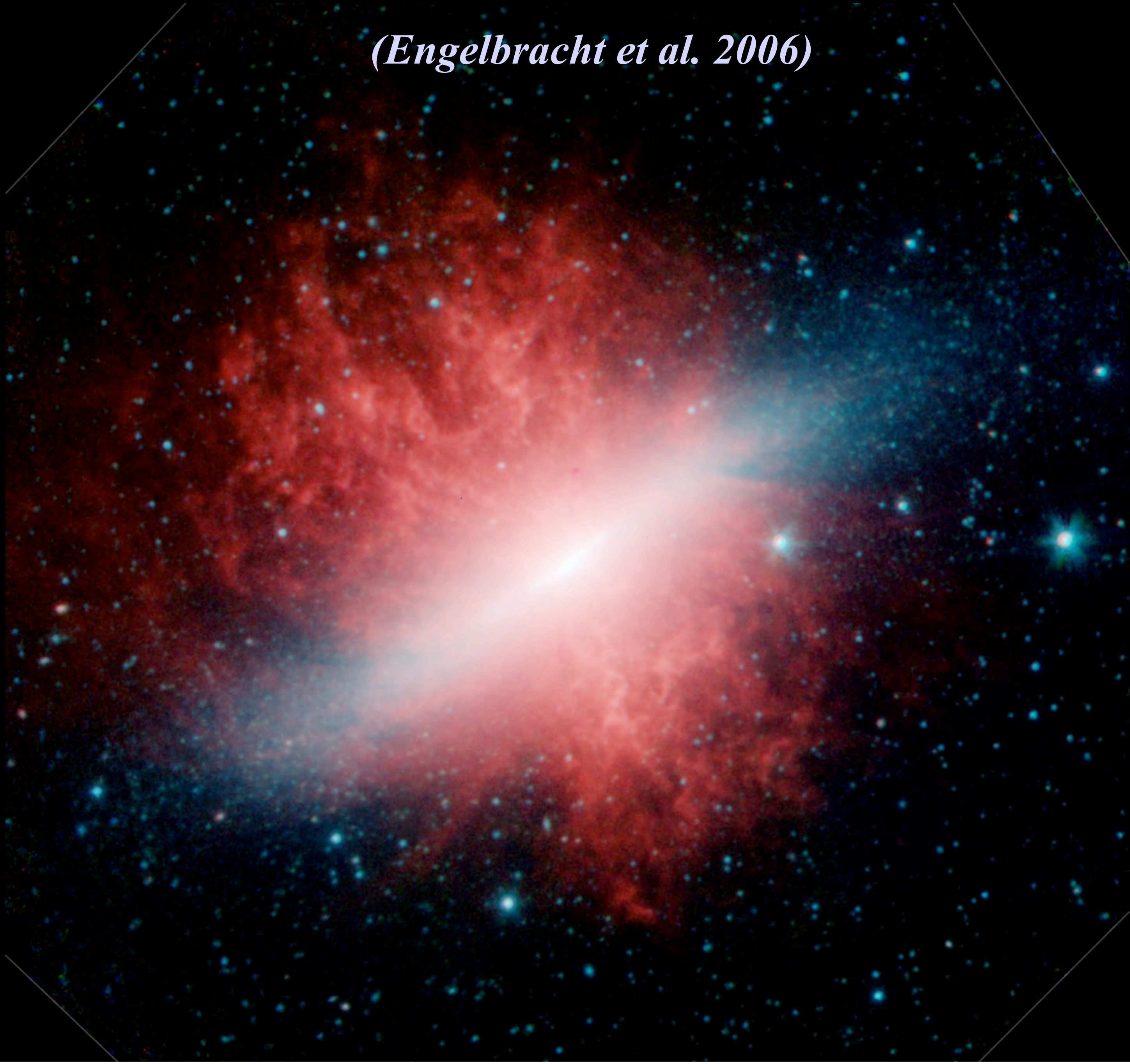
Dust Outflow: GALEX

(Hoopes et al. 2005)



Dust Outflow: **SST IRAC**

(Engelbracht et al. 2006)



Dust Outflow

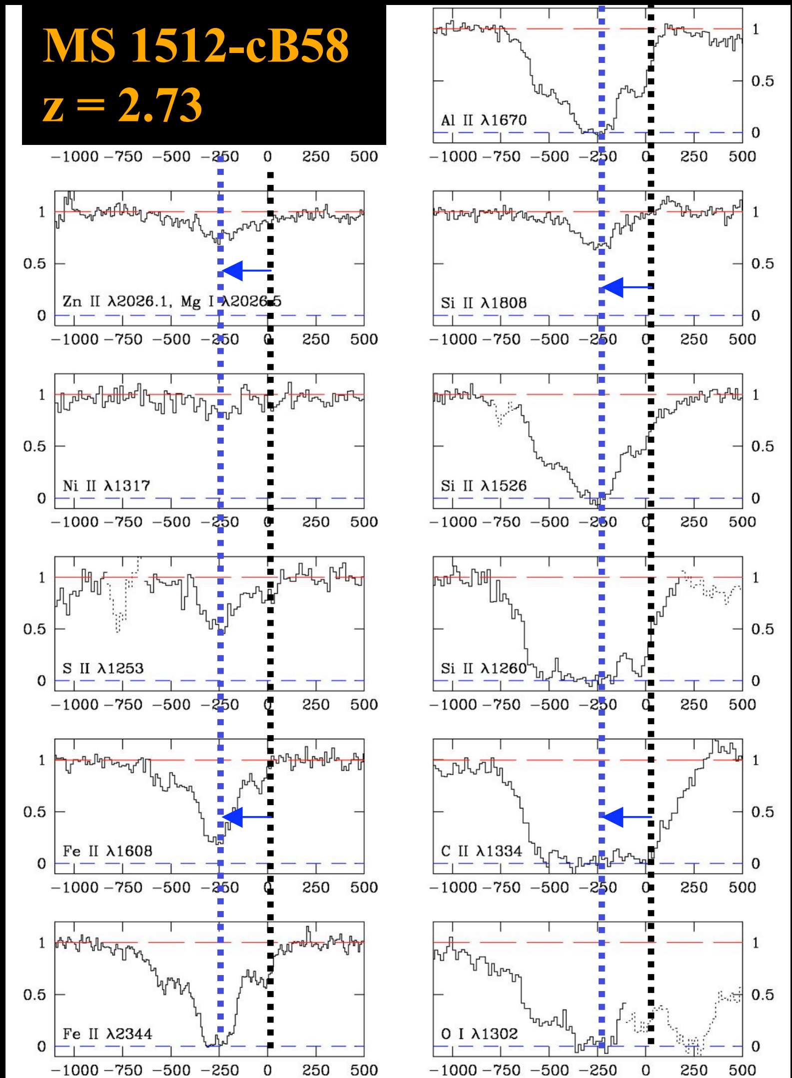
- **Importance:** $dM/dt_{dust} \sim 1\%\ dM/dt_{neutral}$?
- **Implications:** intergalactic dust? *(e.g., Coma ICM; Stickel+98)*

Summary

- SFR > few M_{sun} yr^{-1} or SFR/ πR_{25}^2 > 0.001 M_{sun} yr^{-1} kpc^{-2}
- Most radio-loud AGN and > 1/3 radio-quiet AGN

- $\Omega_{wind}/4\pi \sim 0.1 - 0.5$
- $R_{outflow}$ = few – 50^+ kpc (optical, X-ray, UV absorption line systems)
- $V_{outflow}$ = 25 – 10^{3+} km s^{-1} (= function of SFR, T_{gas})
- $dM/dt_{outflow} = \beta$ SFR where $\beta \sim 0.01 - 5$
  (entrainment efficiency β "saturates" at the highest SFR)
- $dM/dt_{outflow} \geq dM/dt$ (accretion on SMBH)
- $dM/dt_{dust} \sim 1\%\ dM/dt_{neutral}$?
- $f_{esc} \sim 5 - 20\%$? (= function of T_{gas}; halo drag?)
- $E_{outflow} = 10^{53} - 10^{59}$ ergs
  ~ (10% - 50%) x (total KE returned to ISM by starburst)
- Jet mechanical luminosity $Q \sim 0.1\ L_{Edd}$
- Energy stored in radio lobes: ~ $10^{58} - 10^{61}$ ergs

Winds in Distant Galaxies



- **Galactic winds have been observed in several (most?) z ~ 2 – 5 galaxies**
  - **SFR ~ 10 – 100s M_{sun} yr^{-1}**
  - **$\langle v_{wind} \rangle$ ~ 300 km s^{-1}**
  - **Zone of Influence: ~ 500 kpc???**

    (along paths of least resistance?)

Galactic Winds:
The 'Miracle Cure' to Cosmology's Ailments!?

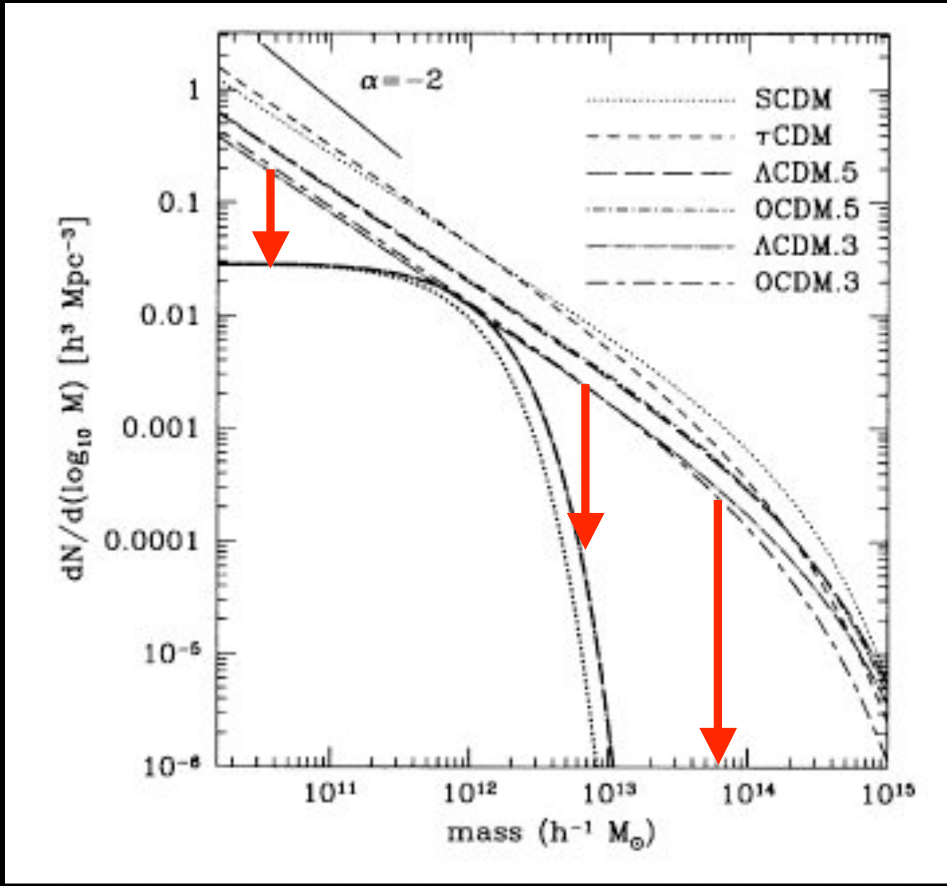
- **Explain "baryon deficit":**
  - **Ω(stars) / Ω(baryons) < 0.10**

Galactic Winds:
The 'Miracle Cure' to Cosmology's Ailments!?

- **Remove material with low specific angular momentum early on**
  → help enlarge gas disks in CDM simulations ***(e.g., Steinmetz & Navarro 1999; Bullock et al. 2001; Binney, Gerhard, & Silk 2001)***

Galactic Winds:
The 'Miracle Cure' to Cosmology's Ailments!?

- **Suppress number of *visible* dwarf galaxies (starbursts)**
- **Avoid "cooling catastrophe" at high redshift that would result in the overproduction of massive luminous galaxies (QSOs + RGs)**



Needed:
Few x 10^{49} ergs per solar mass formed

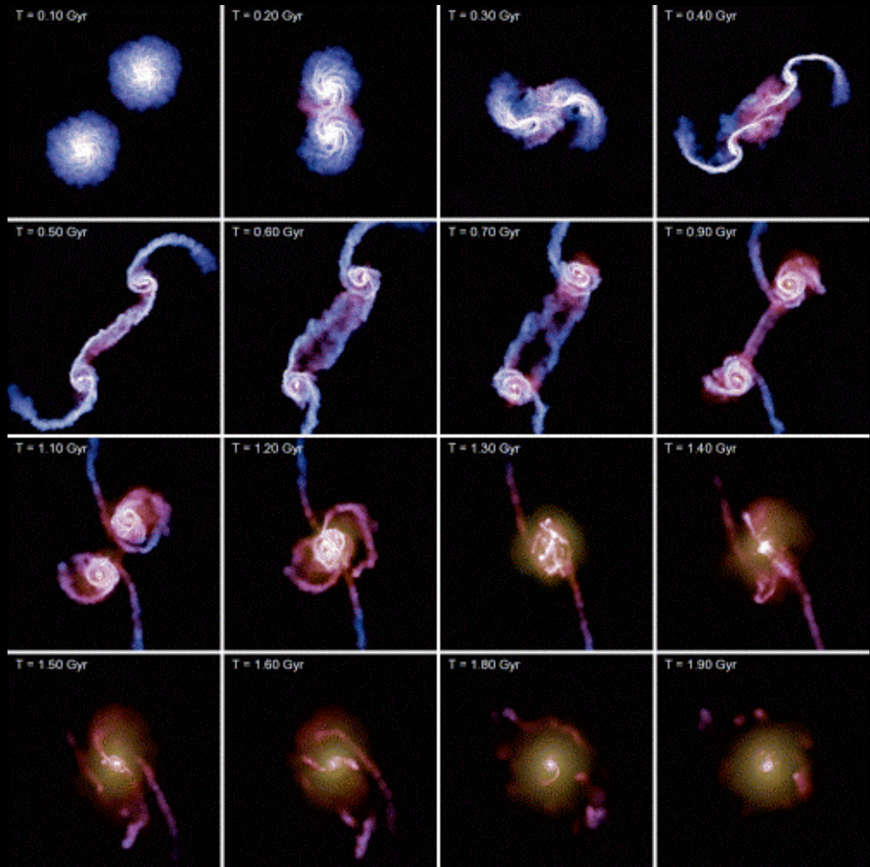
Observed:
$Q \sim 0.1\, L_{Edd}$

(Somerville & Primack 1999)

Galactic Winds:
The 'Miracle Cure' to Cosmology's Ailments!?

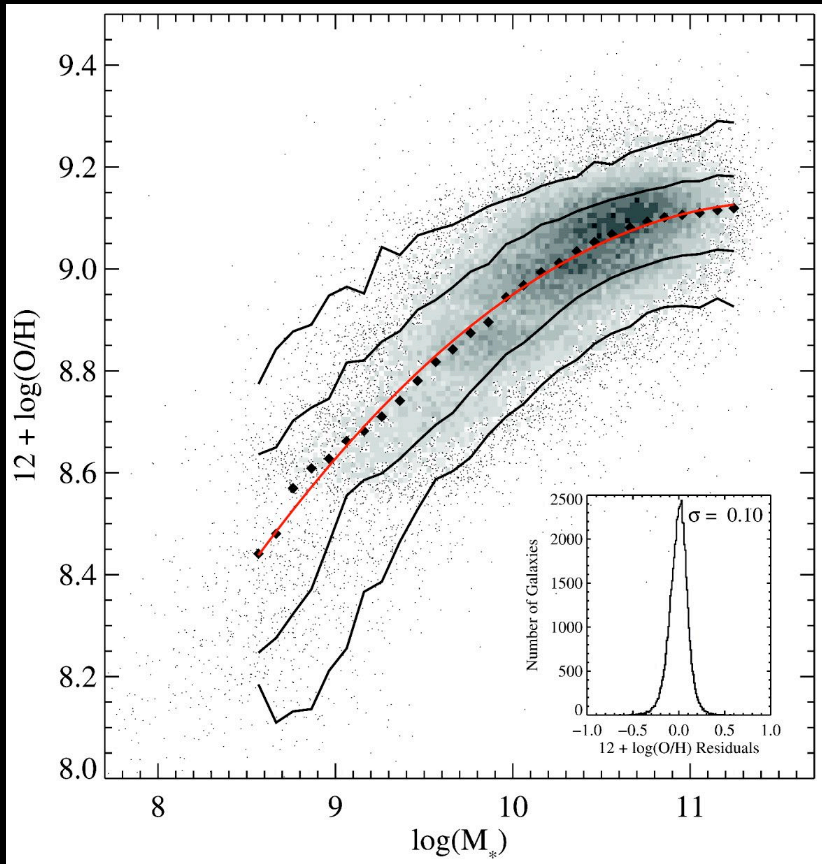
SMBH – spheroid connection:

$M(SMBH) \sim 0.001\ M(bulge)^{1.0} \sim 1.3 \times 10^8\ M_{sun}\ (\sigma_e/200\ \mathrm{km\ s^{-1}})^{4.0}$



Galactic Winds: The ‘Miracle Cure’ to Cosmology’s Ailments!?

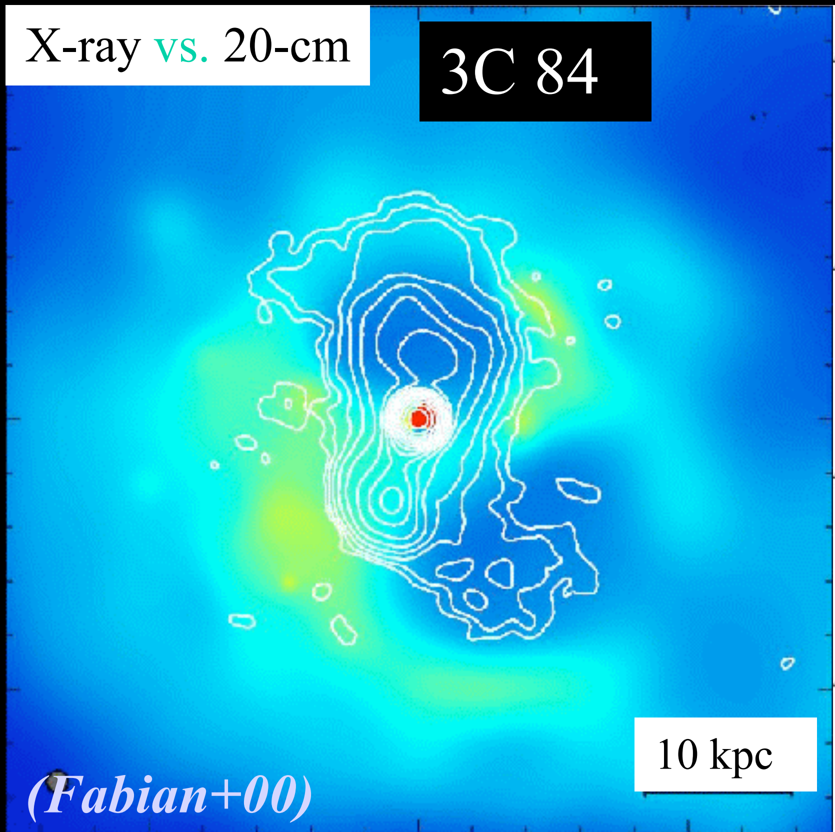
- **Explain mass-metallicity relation of galaxies from selective loss of metal-enriched gas from smaller galaxies (shallower potentials)**

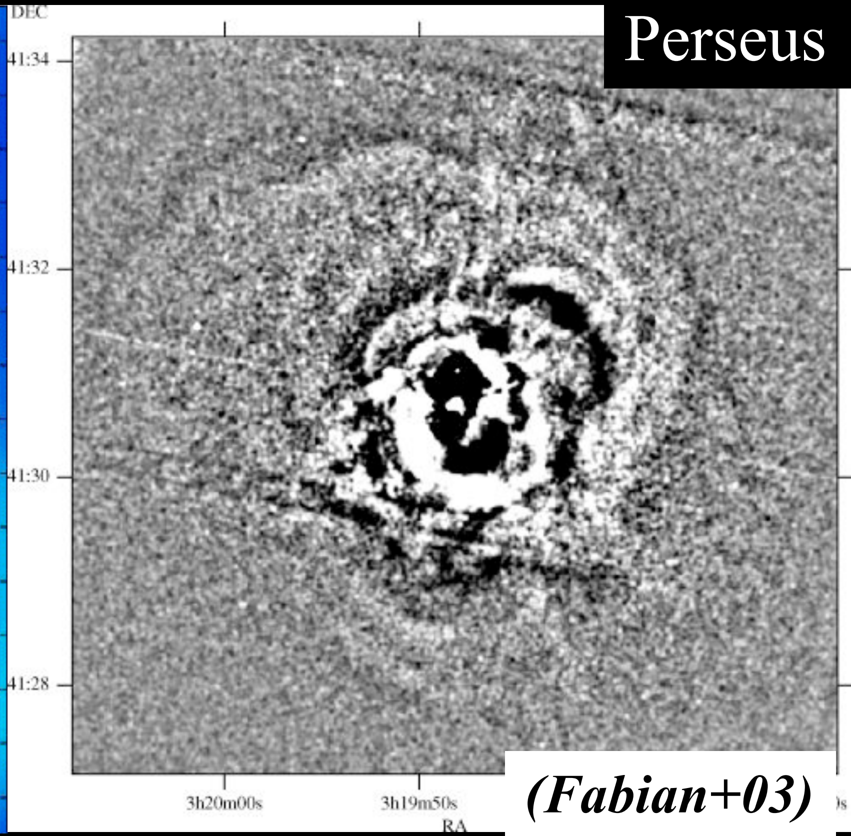


(e.g., Tremonti+04)

Galactic Winds:
The ‘Miracle Cure’ to Cosmology’s Ailments!?

- **Enrich & “pre-heat” ICM**
- **Enrich IGM without disturbing Lyα forest significantly**
- **Inhibit cooling flows in galaxy clusters with active cD galaxies**





Theoretical Challenges

(see SV, Cecil, & Bland-Hawthorn 2005, ARAA)

- Modeling the energy source
- Modeling the host ISM
- Coupling the radiation field to the gas

Observational Challenges

(SV, Cecil, & Bland-Hawthorn 2005, ARAA)

- **Hot wind fluid (Z; mass loading)**
- **Entrained molecular gas & dust** ***(SST)***
- **Zone of influence & escape efficiency**
- **Thermalization efficiency**
- **Wind/ISM interface & magnetic fields**
- **Positive feedback** ***(e.g., M82: Matsushita et al. 2004)***
- **Galactic winds in the distant universe**

Challenges: Thesis Topics?!

- Modeling the energy source
- Modeling the host ISM
- Coupling the radiation field to the gas

- Hot wind fluid (Z; mass loading)
- Entrained molecular gas & dust *(SST)*
- Zone of influence & escape efficiency
- Thermalization efficiency
- Wind/ISM interface & magnetic fields
- Positive feedback *(e.g., M82: Matsushita et al. 2004)*
- Galactic winds in the distant universe