Feedback and the halos of star-forming galaxies

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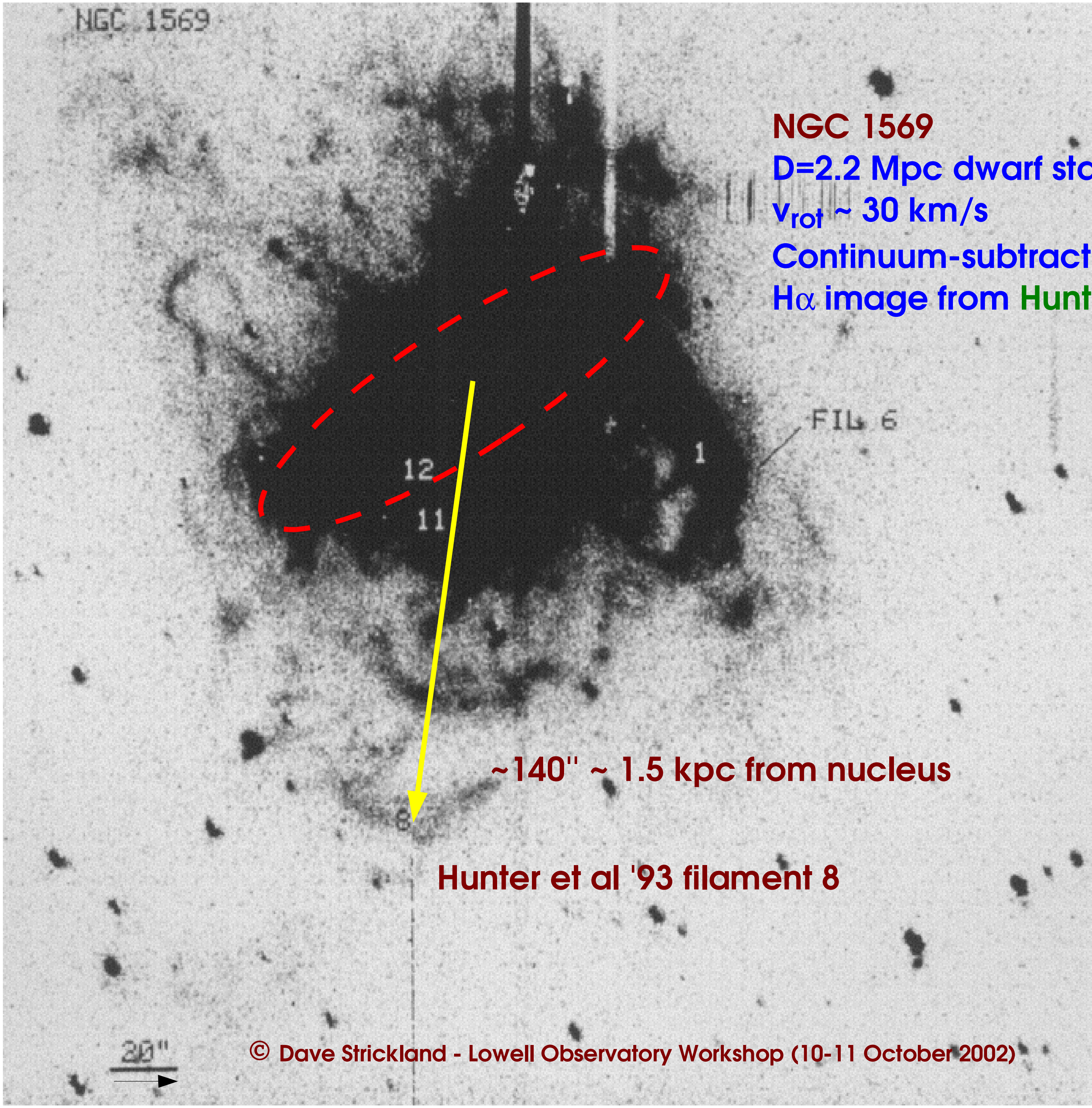
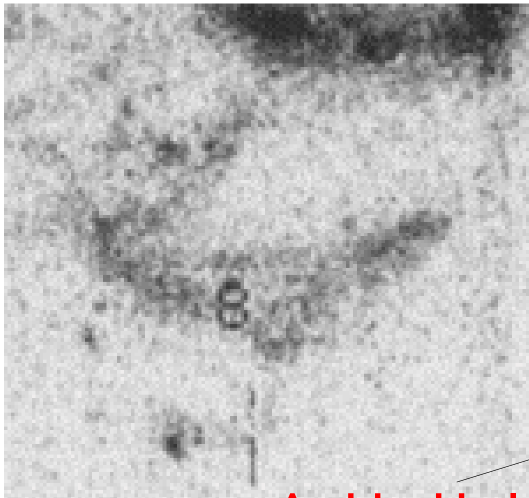


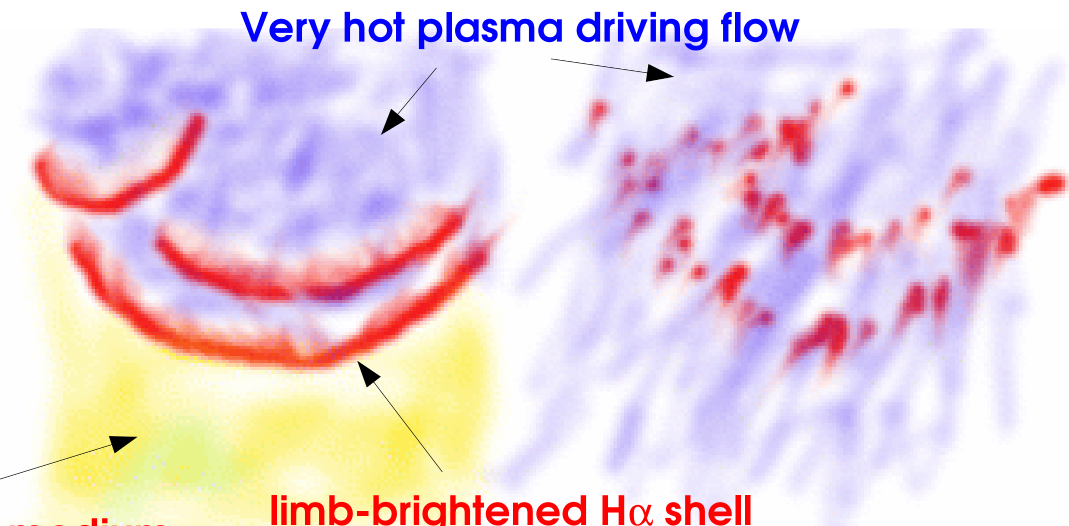
NGC 1569
D=2.2 Mpc dwarf starburst
v_{rot} ~ 30 km/s
Continuum-subtracted
Hα image from Hunter et al 1993.

~140" ~ 1.5 kpc from nucleus

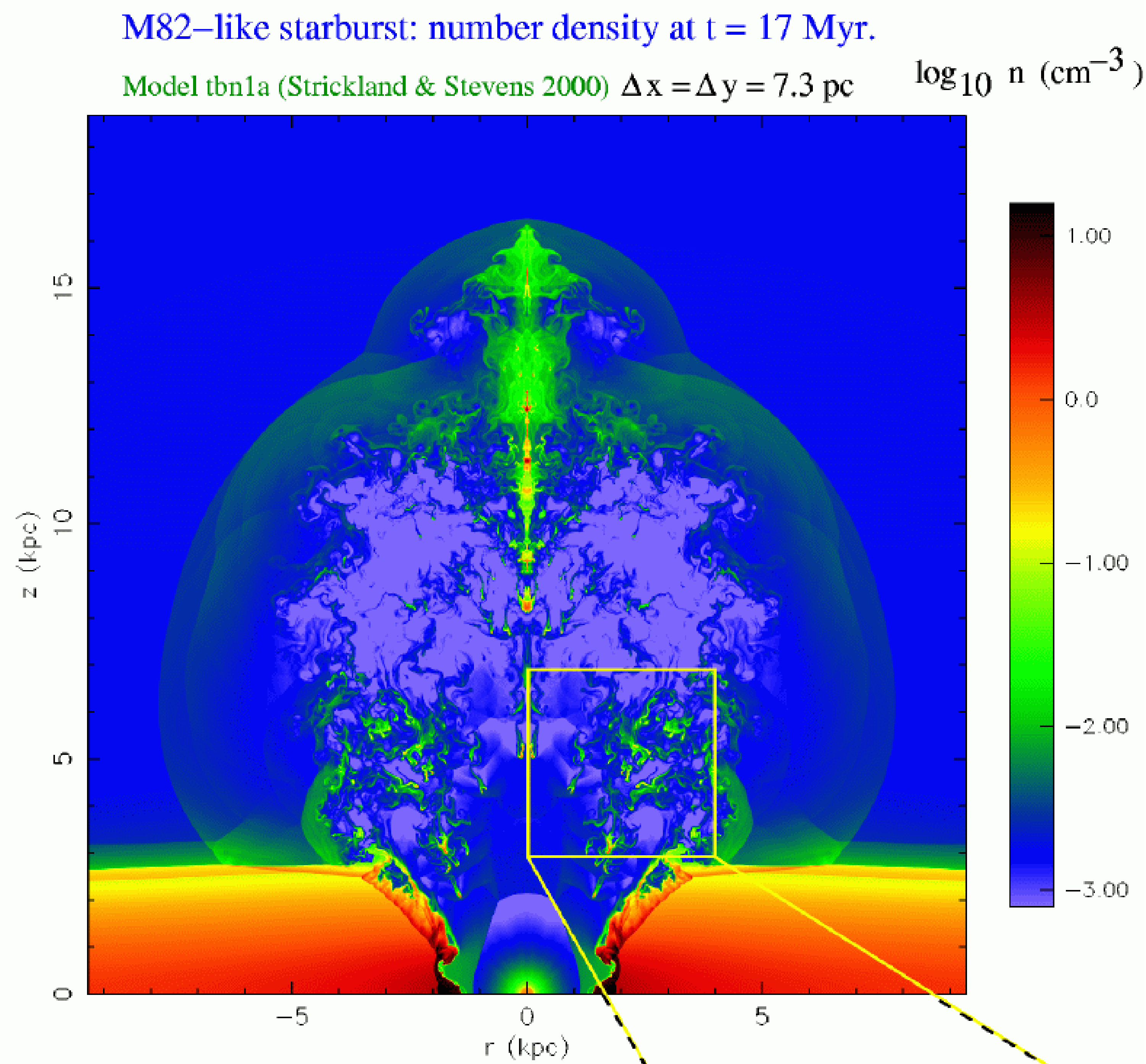
Hunter et al '93 filament 8

Ha shells and filaments -- fragmentation 101





- A shell comprised of swept-up **disk** gas should fragment, due to RT instabilities, upon breaking out of the disk.
- IF filament 8 is a coherent shell, then its failure to fragment implies EITHER:
  - The density gradient from disk to halo is very shallow (log dr/log dz > -2), or equivalently...
  - the shell hasn't broken out of the gas layer, even ~1 kpc above the plane.
- OR
  - The Ha shell is swept-up halo gas, created post-break out (implies rhalo high enough that forward shock is radiative).
- BOTH imply significant amounts of gas pre-exist at a few kpc about the plane.


M82–like starburst: number density at t = 17 Myr.
Model tbn1a (Strickland & Stevens 2000) Δx = Δy = 7.3 pc
log10 n (cm−3)
1.00
0.0
−1.00
−2.00
−3.00
z (kpc)
0
5
10
15
r (kpc)
−5
0
5

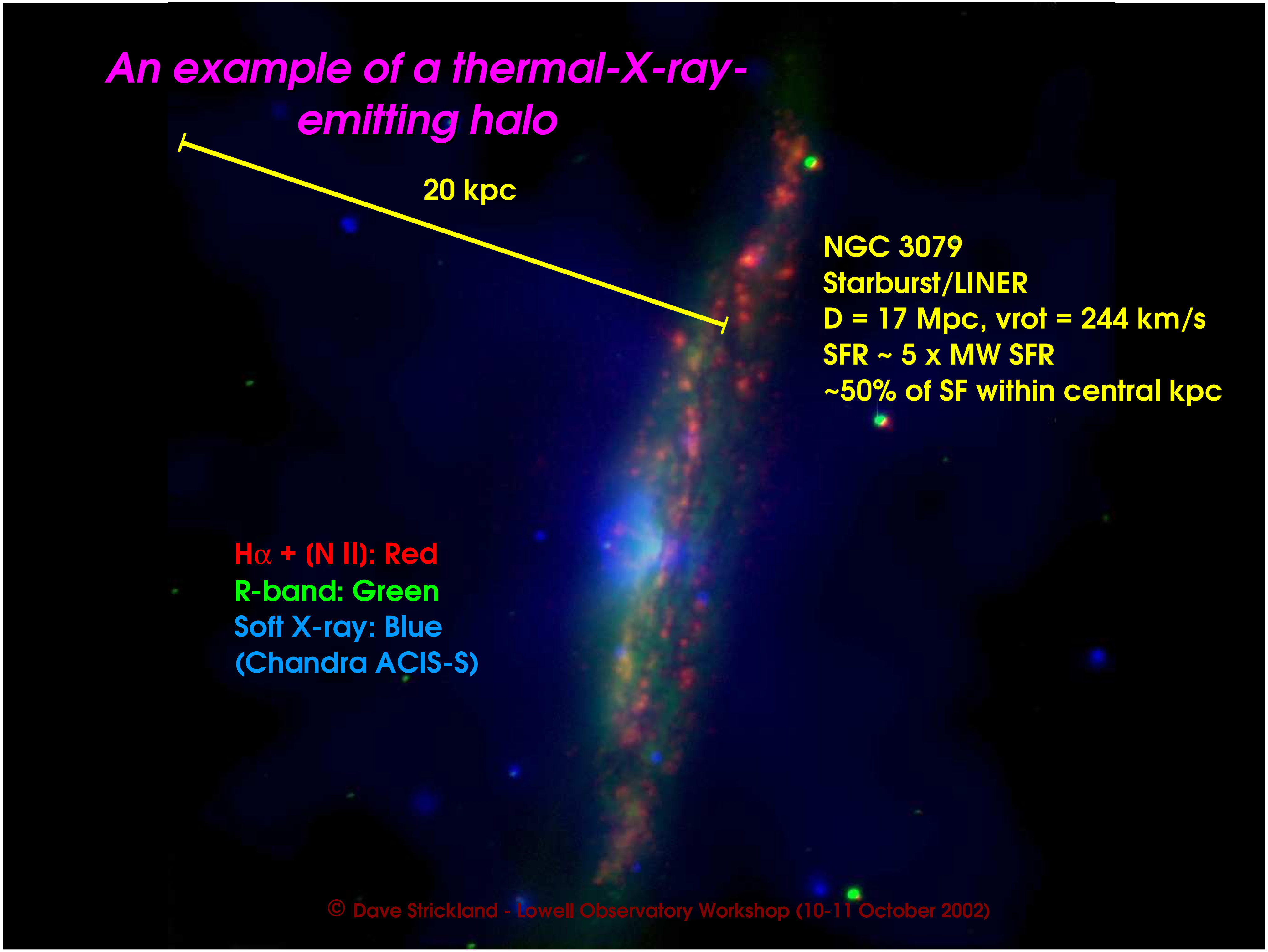
High z gas - so what?

- The IGM, even at redshift~3, contains metals. How do they get out of galaxies?
- Consider a spherical galaxy in vacuum: Can a SN-driven wind escape?
  - $v_{gas} \sim 3000\ \varepsilon^{0.5}$ km/s, where ε (~0.1-0.3?) is the thermalization efficiency.
- --> Its not gravity that stops SN-driven winds - its the gas distribution in the galaxy and/or in its halo (see theoretical studies by, e.g. Babul, De Young & Heckman, Suchkov, Silich etc...).
- Unfortunately...
  - Analytical or numerical theories of disk break out are largely uncalibrated.
  - Its hard work to study the gas structure of the halos of spiral and dwarf galaxies.

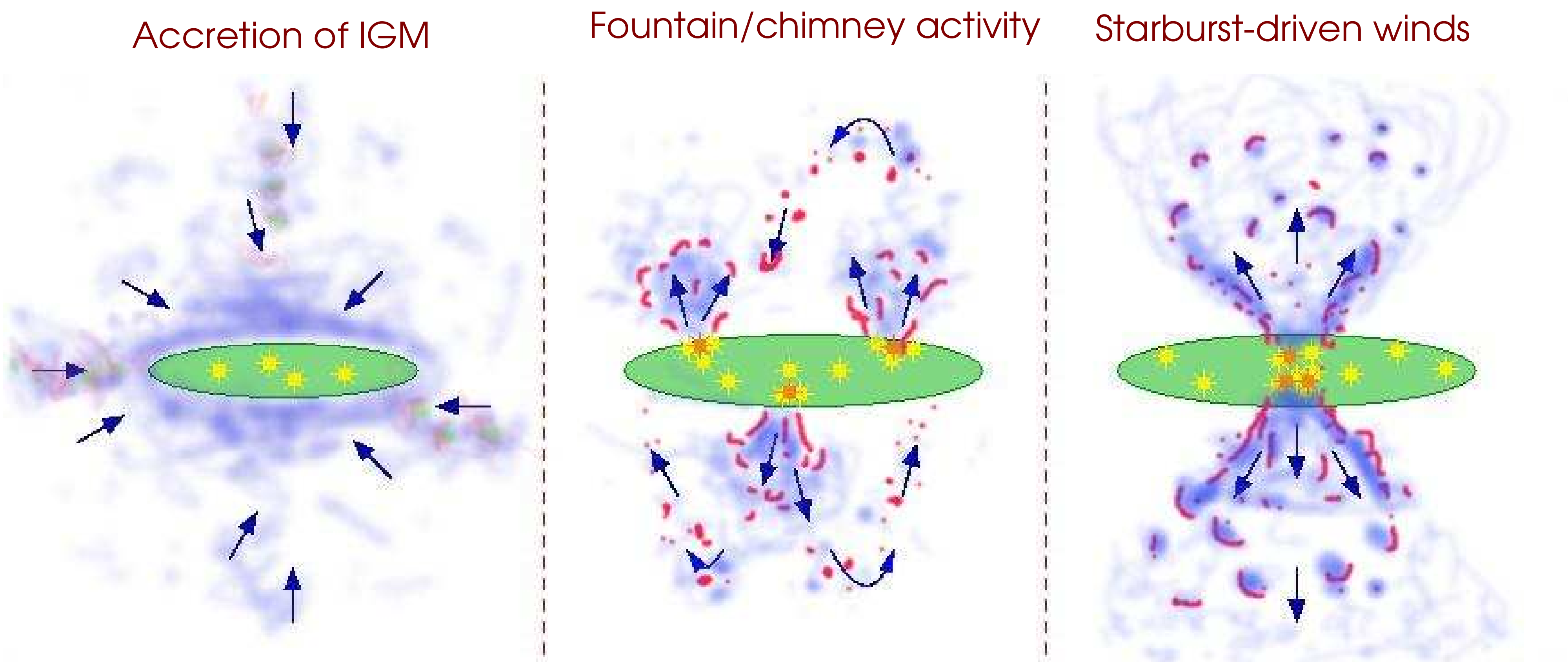
What this talk is about...

- An empirical look at the properties hot gas in the halos of SFing disk galaxies.
  - X-ray-emitting gas is almost certainly a result of SN feedback (almost...)
  - Big disks brighter than dwarfs. Its also easier to find edge-on ones...
- Use these results to test the very basic tenets of superbubble/superwind theory.
  - Critical break-out luminosity (Mac Low & McCray 1988)
  - That the efficacy of winds is a strongly decreasing function of galaxy mass (basic physical intuition, but particularly Mac Low & Ferrara 1999; Ferrara & Tolstoy 2000).

An example of a thermal-X-ray-emitting halo



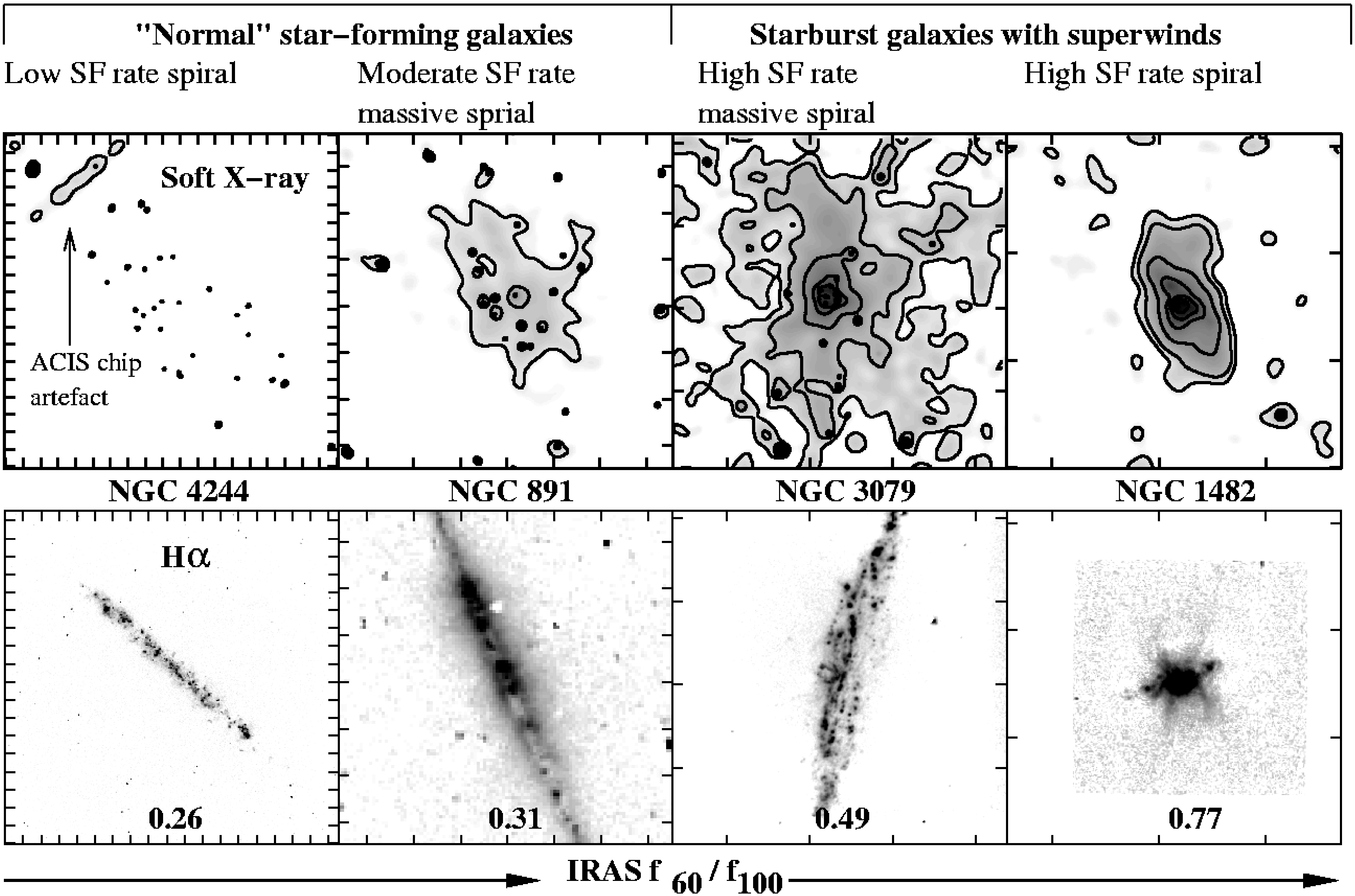
Creating hot gas halos around SFing galaxies



Driven by supernovae - stellar 'feedback' on galactic/IG scales

- Product of SAM/SPH cosmological models...
- ... feedback treatment of dubious quallity.
- Observational evidence?

- Direct kinematic evidence for winds, wide variety of convincing obs. evidence for aspects of fountain model
- Conceptual basis well explored theoretically/numerically.
- Quantitative understanding - driving and effect - lacking.



From Strickland et al 2002 (IAU 212 proceedings), on astro-ph/0207177

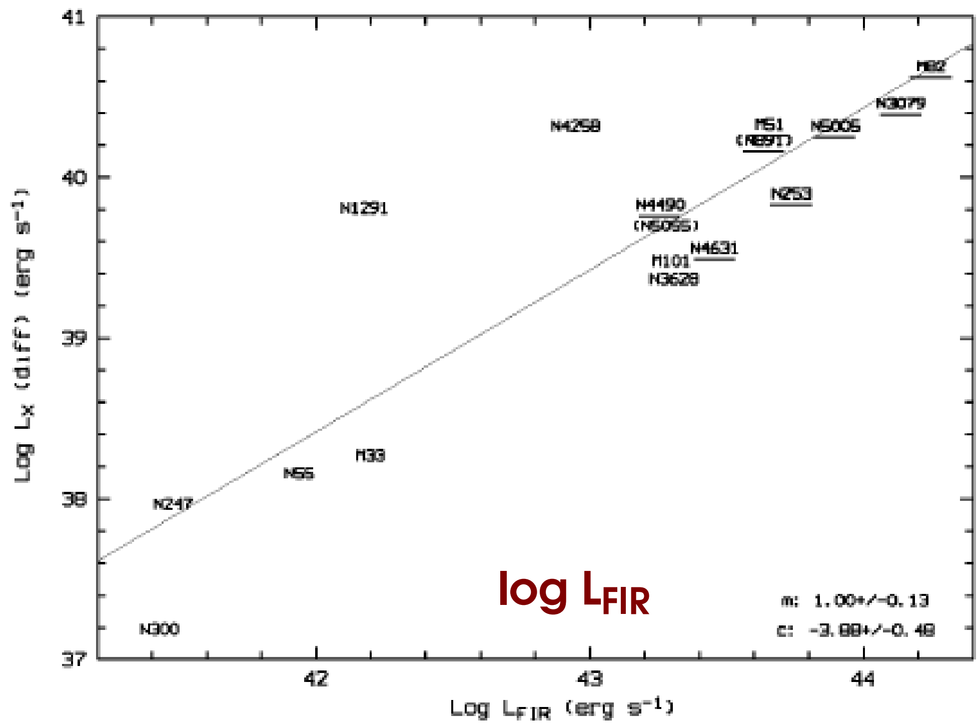
1. **Distinguish between the accretion and feedback models.**
2. **Test fundamental aspects of the theories:**
   E.g. "Feedback" - critical energy required to "break out" of a disk (Mac Low)
   E.g. winds only effective in low mass M < 10^9 Msun galaxies (Ferrara).

Tests of these models...

- **Accretion:** Lx the same, irrespective of presence/absence of stellar feedback (Toft et al 2002, Sommer-Larsen, private comm.)!!!
  - **T_X ~ 0.2 (vrot/230 km/s) keV** if gas heated to halo virial temperature
  - Predicted **Lx ~ 1e40 (vrot/230 km/s)^5** erg/s --> (as X-ray luminous as starbursts!)
  - Diffuse X-ray emission peaks nears disk, Σ_X ~ exp(-z/H).
- **SN feedback:** X-ray properties should correlate with SF rate, SF rate/unit disk area.
  - X-ray temperature not correlated with v_{rot}. Can be greater than halo virial temperature.
    - X-ray emission from freely-expanding SN ejecta --> adiabatic cooling.
    - X-ray emission from fountains or superwind cloud interactions --> no simple predictions
  - Diffuse X-ray surface brightness Σ_X:
    - X-ray emission from freely expanding SN ejecta --> power law Σ_X.
    - Fountains --> pseudo-exponential Σ_X. Wind/cloud interaction --> no predictions as yet?

Pre-existing observational studies of hot gas in the halos of SFing galaxies

log L_X diffuse



(from Read & Ponman 2001, using ROSAT PSPC)

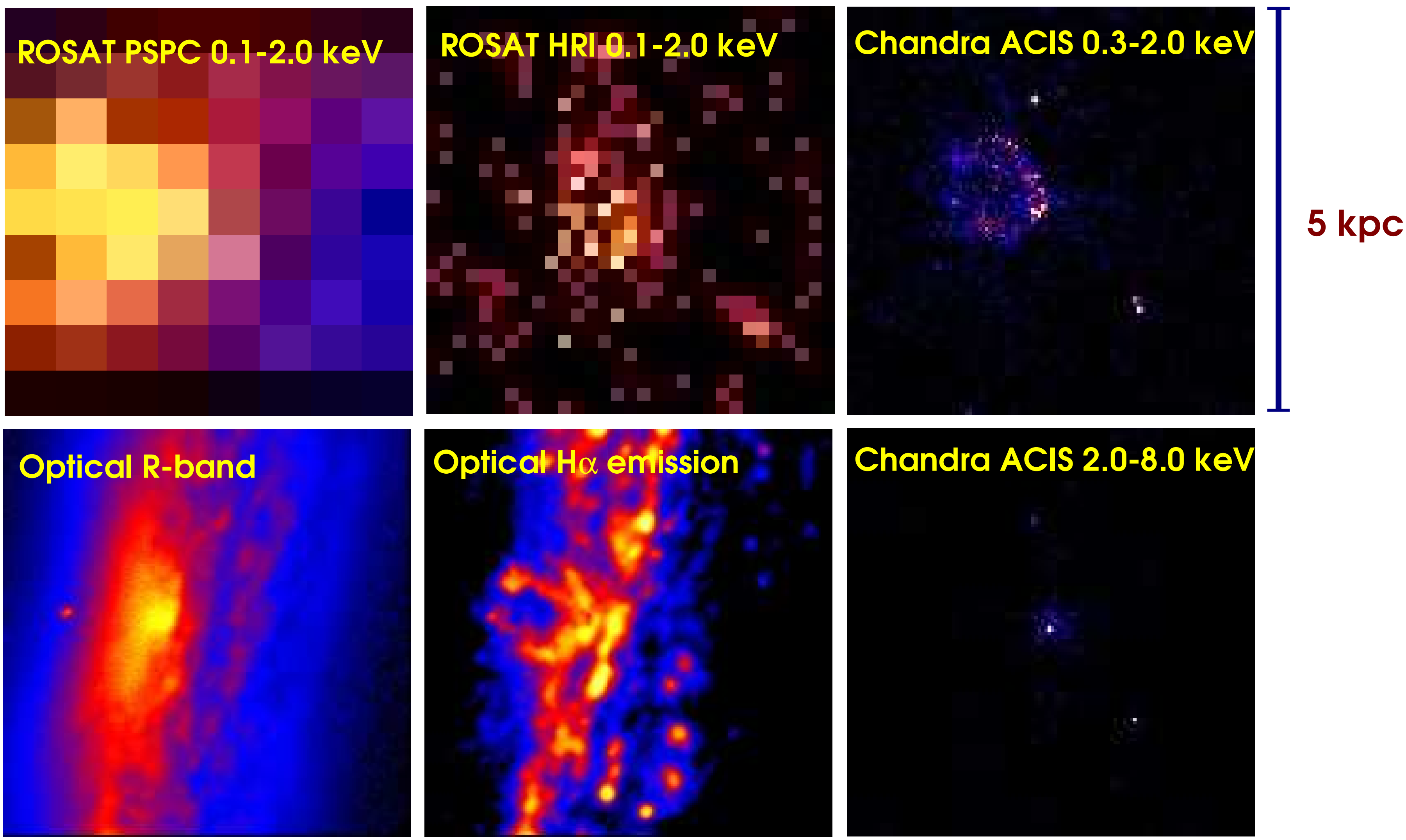
- Einstein - can obtain total X-ray flux and correlate with L_B, L_{FIR} etc (e.g. Fabbiano & co-workers, Shapely et al 2001).
- ROSAT PSPC - first order point source removal - total L_X diffuse vs L_{FIR} (RPS'97, Read & Ponman 2001).
- BUT: Little or no good information on exact shape of surface brightness distribution, spatial variations in spectral properties, correlations with SF intensity etc etc.

Old and new views of NGC 3079

PSPC FWHM ~30"
resolution ~ 2500 pc

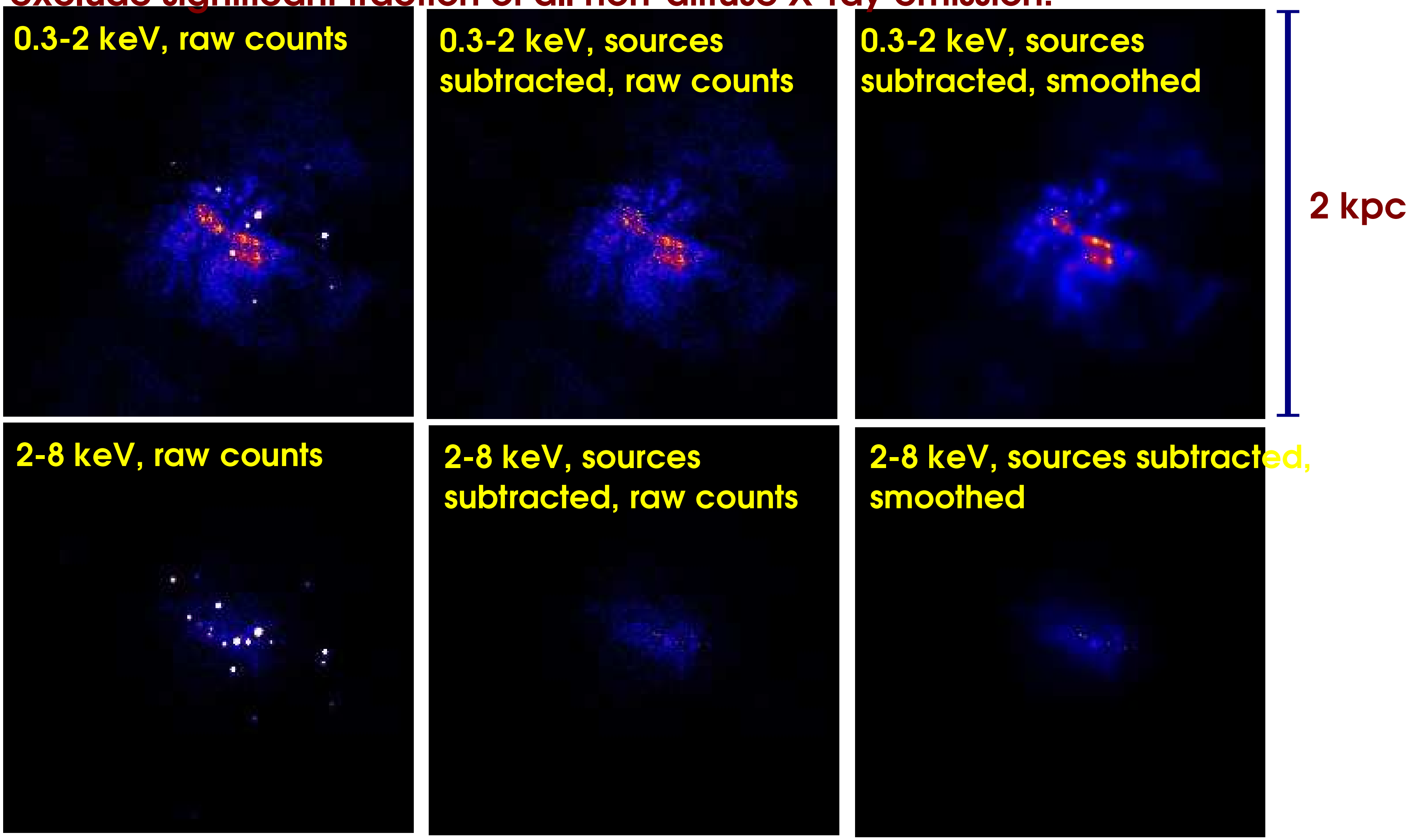
HRI FWHM ~5"
resolution ~ 415 pc

ACIS FWHM ~0.8"
resolution ~ 66 pc



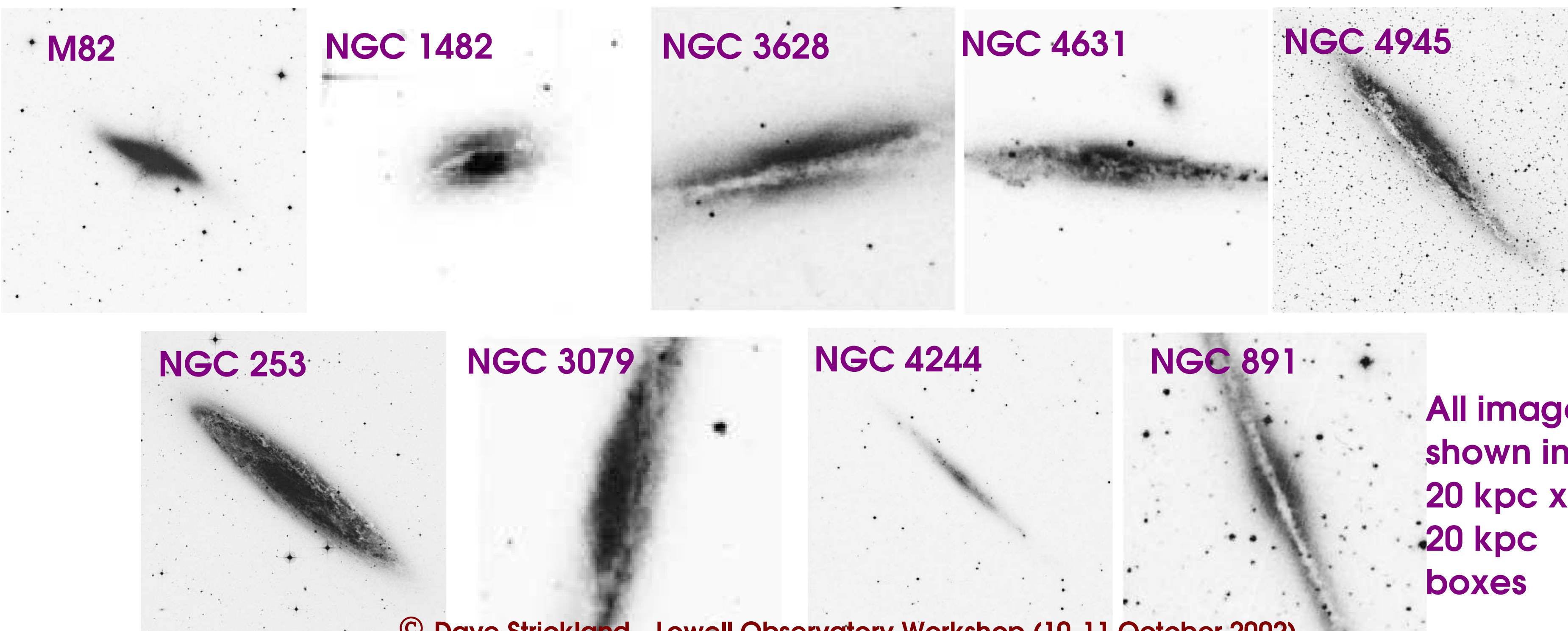
Robust point source removal

Identify sources down to ~10 photons per source -- e.g. central 2 kpc of M82
Brightest point sources typically dominate total point source emission --> can exclude significant fraction of all non-diffuse X-ray emission.



The Chandra edge-on SFing disk galaxies sample

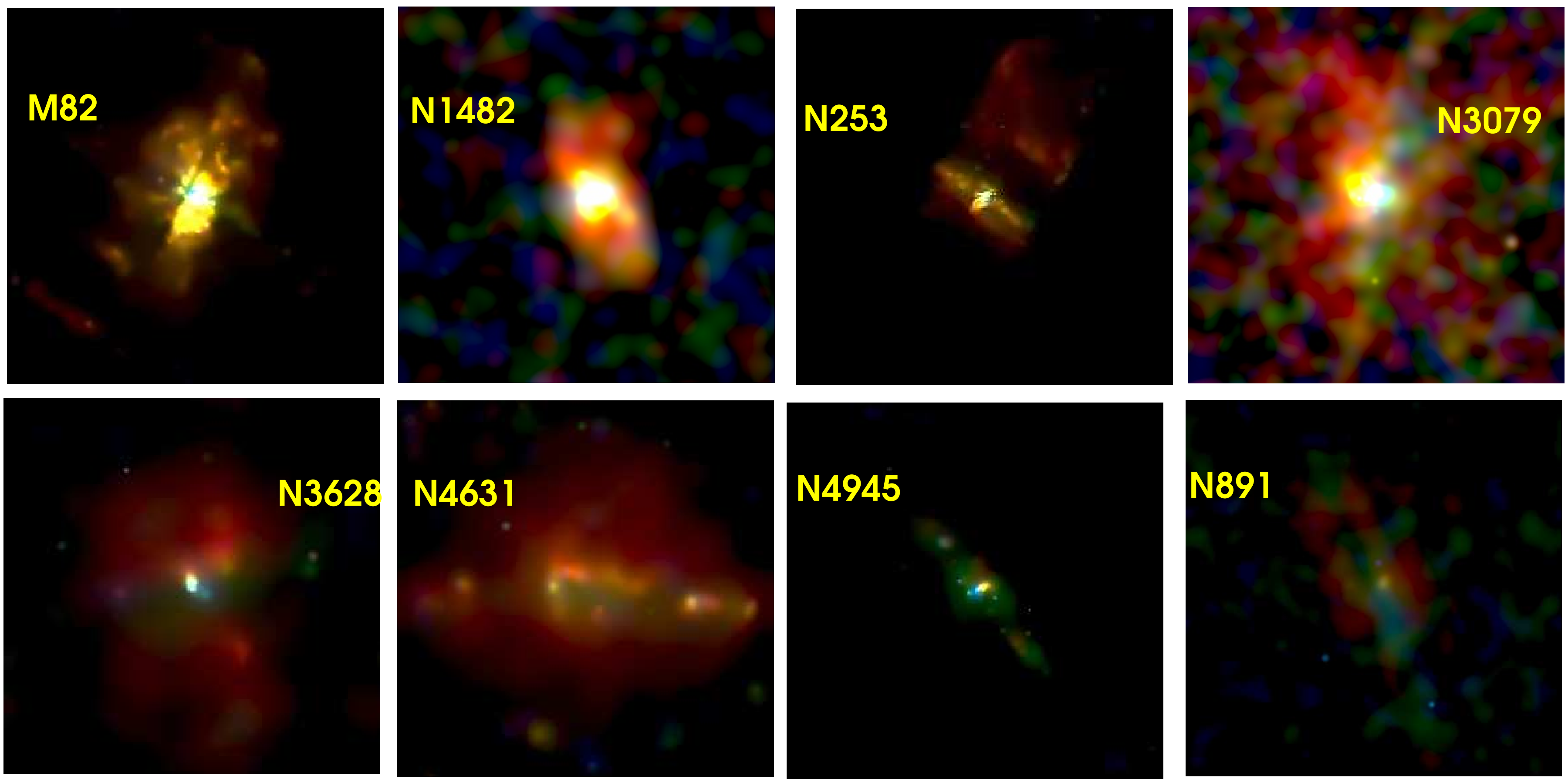
- 7 IR-luminous nuclear starburst galaxies ($L_{bol} \sim L_*$), typically v_{rot} ~200 km/s, but a few lower mass systems (v_{rot} ~100 -- 150 km/s). Distances between 2 to 20 Mpc.
  - IR-bright (IRAS f_{60} > 30 Jy), IR-warm (f_{60}/f_{100} > 0.4), high inclination (a/b > 2) galaxies with low foreground Galactic N_H.
- Supplemented with the only(!) 3 edge-on "normal" spirals observed by Chandra: NGC 891, NGC 4244 & NGC 6503.
- 12 data sets on 10 galaxies, 6 datasets are from the archive



All images shown in 20 kpc x 20 kpc boxes

Results from a Chandra ACIS survey of 10 nearby, edge-on SFing disk galaxies

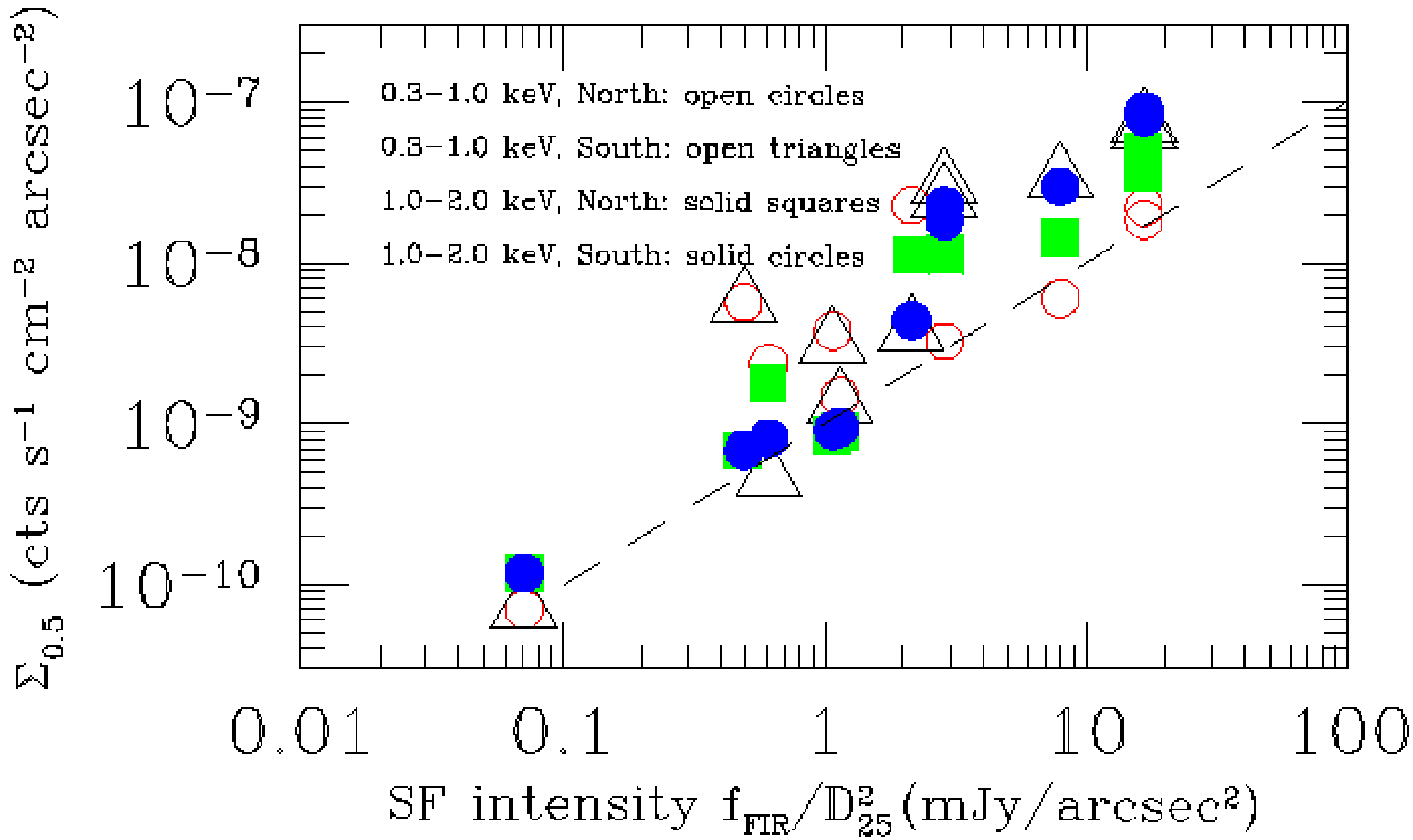
Diffuse emission only --- all point sources removed.
Red = 0.3-1.0 keV emission, Green = 1.0-2.0 keV emission, Blue = 2.0-8.0 keV emission.
20 kpc x 20 kpc boxes, centered on the nucleus,
identical sqrt intensity scale applied to all images.
(from Strickland et al 2002 in prep)



Halo diffuse X-ray: SN or accretion?

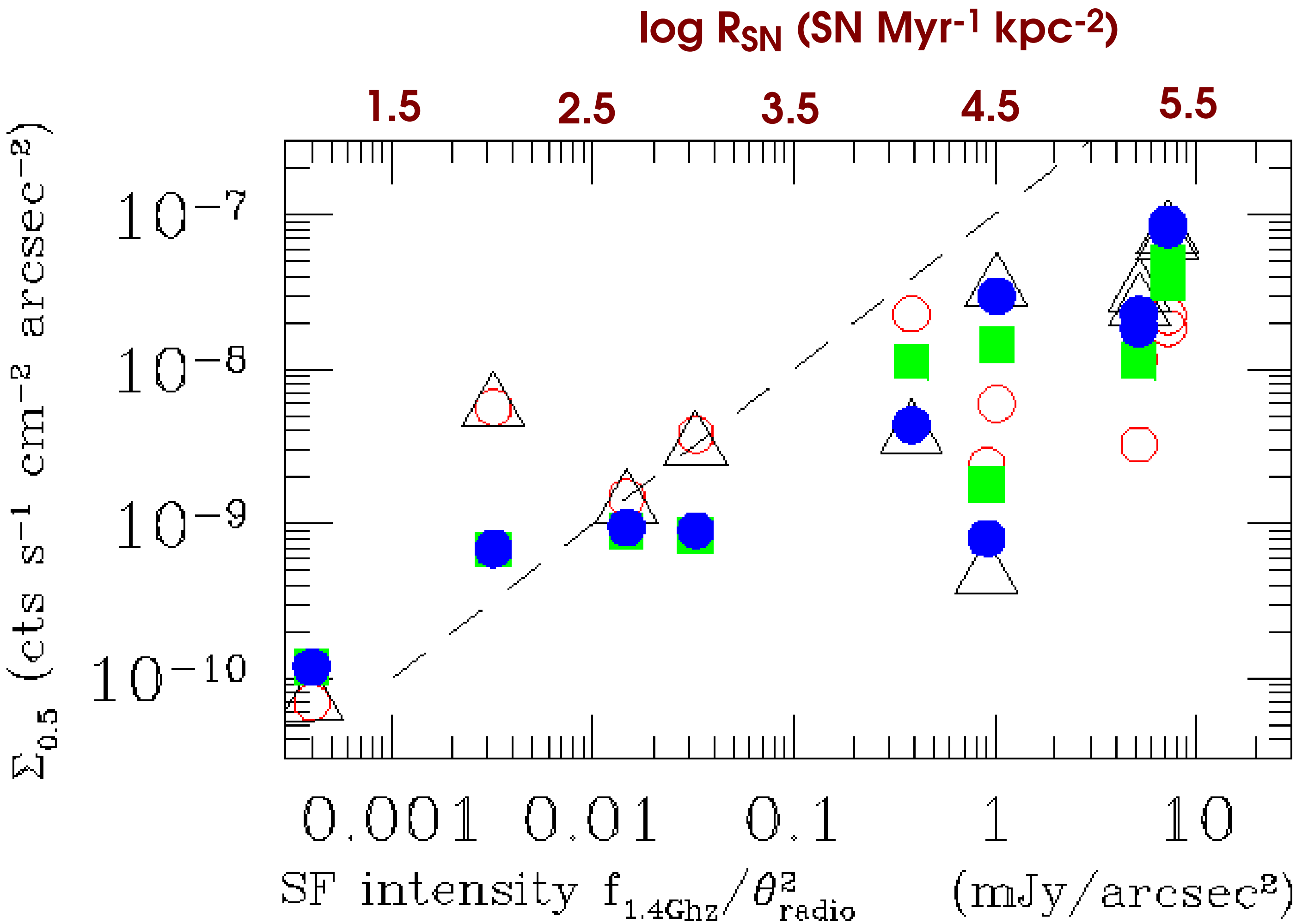
minor-axis X-ray half-light surface brightness

4 points per galaxy to account for both boths, two independent energy bands



FIR emission from dust heated by massive stars
D25 is optical size, so not well matched to region of SF

Halo diffuse X-ray: SN or accretion?

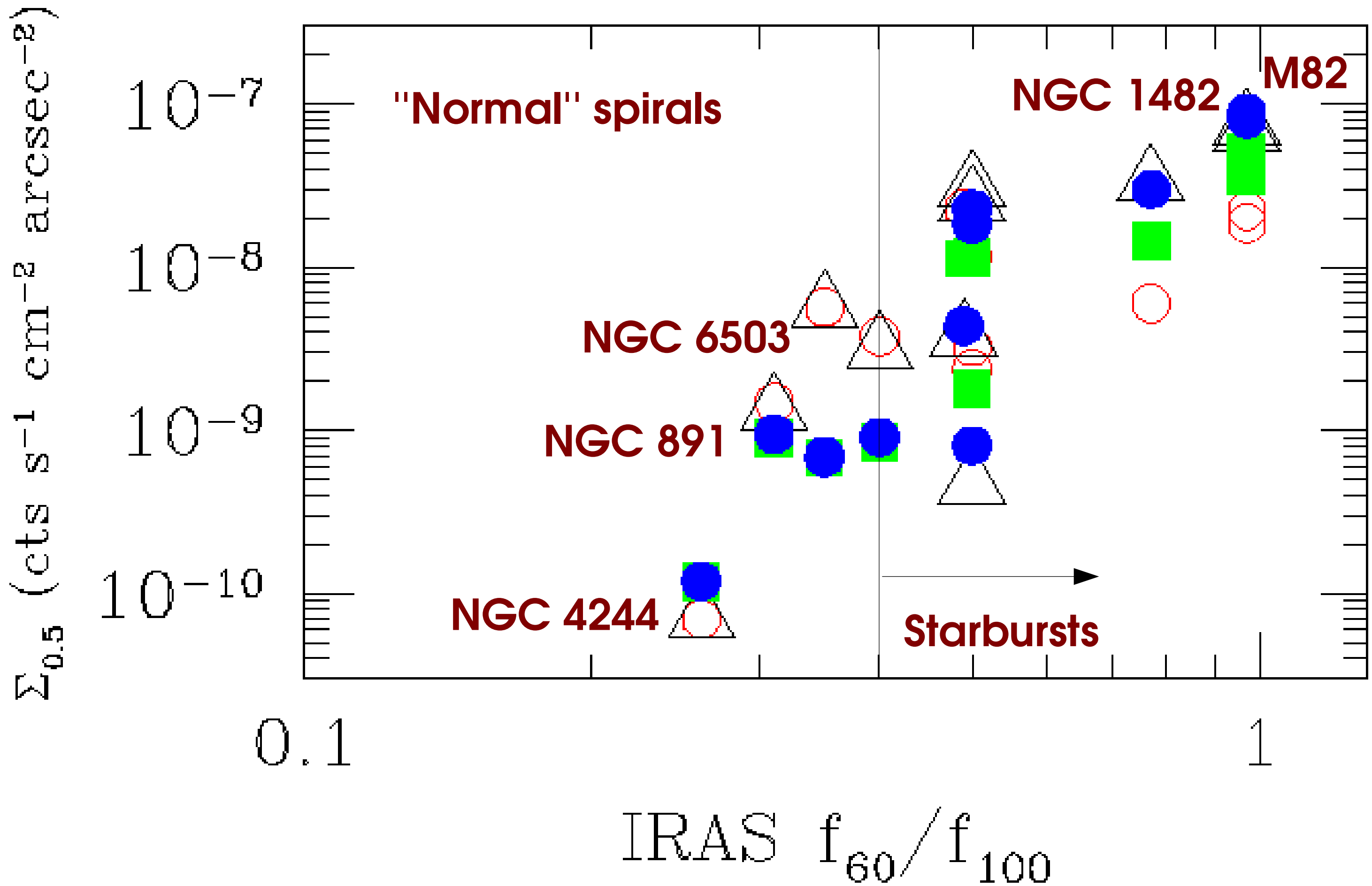


NVSS 1.4 Ghz radio fluxes and sizes

(nonthermal radio emission from cosmic rays produced by SNe)

Halo diffuse X-ray: SN or accretion?

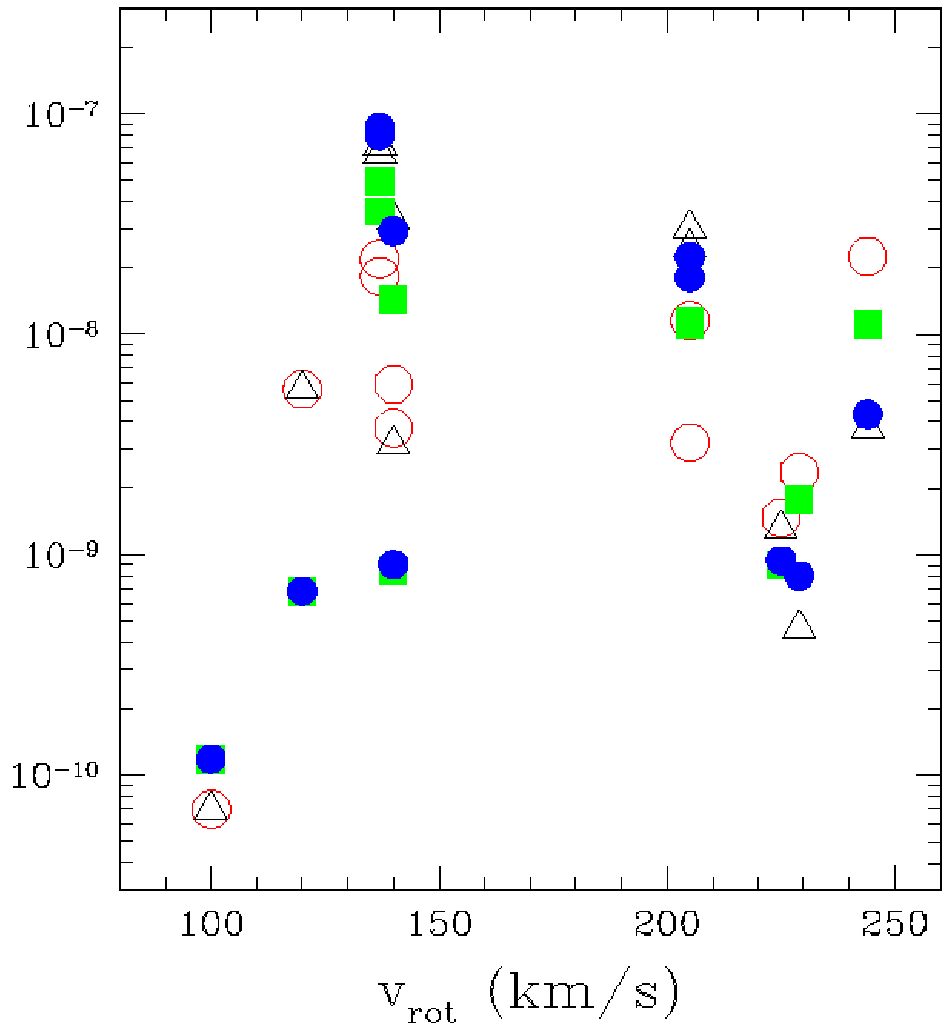
$f_{60}/f_{100} \sim 0.32\ (U_{ISRF}\ (\mathrm{eV\ cm^{-3}}))^{1/3}$



IRAS 60 to 100 μm ratio a function of dust temperature,
itself a function of the IS FUV radiation energy density -> hence SF/volume

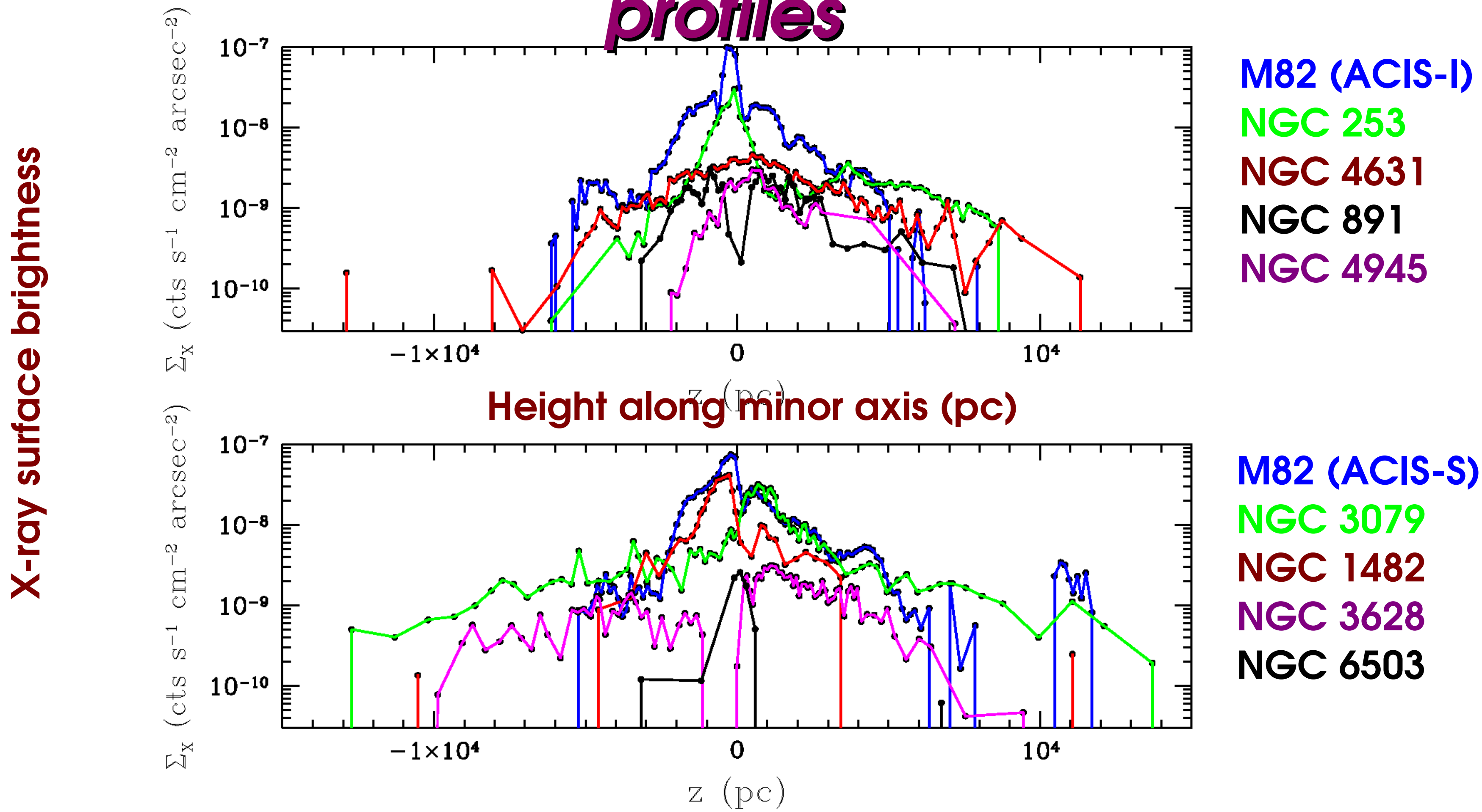
Halo diffuse X-ray: SN or accretion?

Σ_X
X-ray
surface
brightness



No correlation between v_{rot} and diffuse Σ_X apparent,
nor trend for L_X to increase as v_{rot}^5.

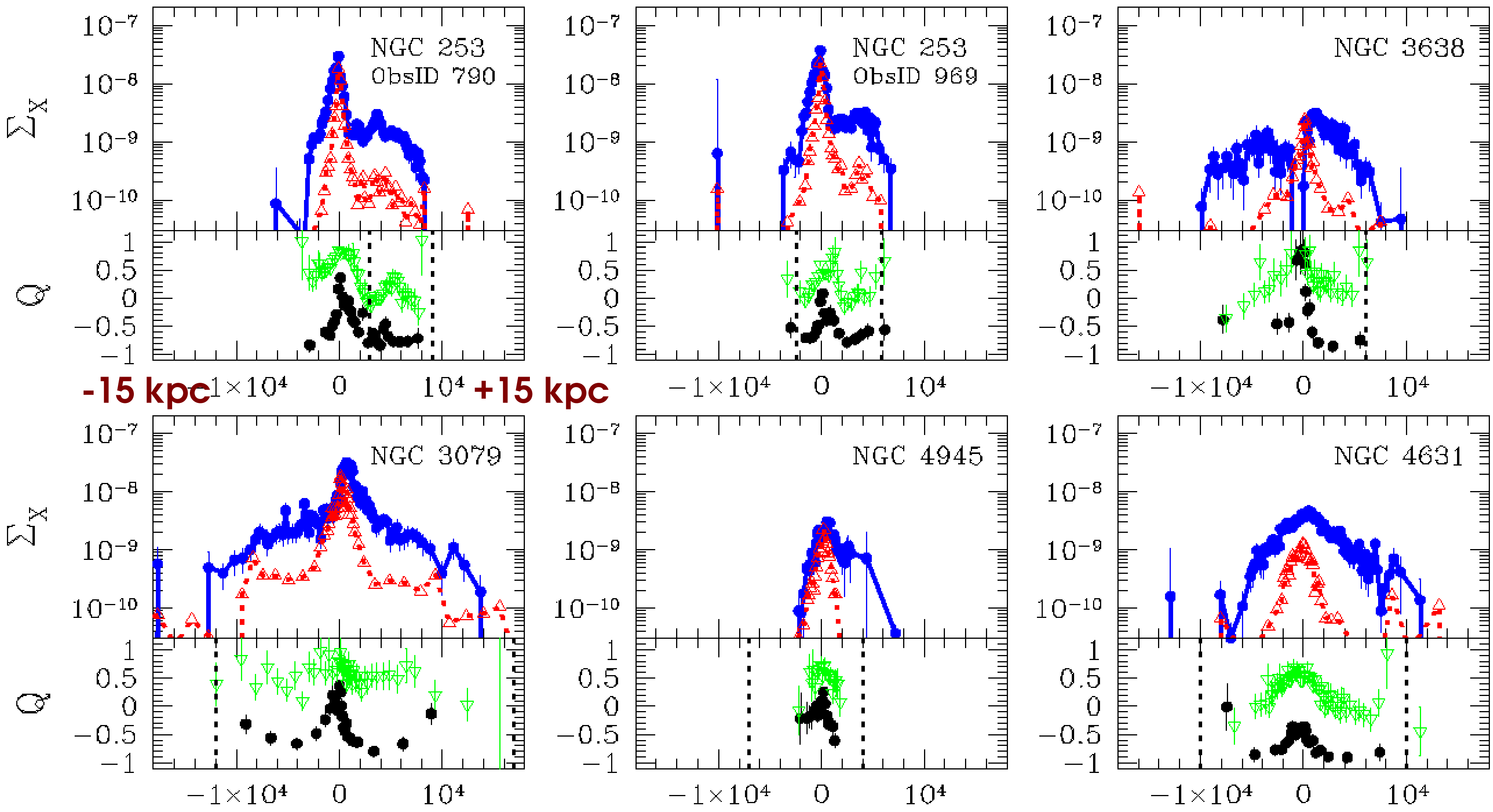
Exponential X-ray surface brightness profiles



- 1. Minor axis surface brightness semi-exponential, scale-heights typically 2-- 4 kpc.
- 2. Gaussian profile can not be excluded. Can exclude power law $\Sigma_X(z)$..
- 3. X-ray emission spectrally uniform for |z|>2 kpc. Wind interaction with thick disk?
- 4. 2 & 3 rule out X-ray emission as being from volume-filling (mass-loaded) wind fluid.

Σ_X minor axis diffuse X-ray surface brightness cts s^{-1} cm^{-2} $arcsec^{-2}$

blue: 0.3-1.0 keV band, red: 1.0-2.0 keV band.



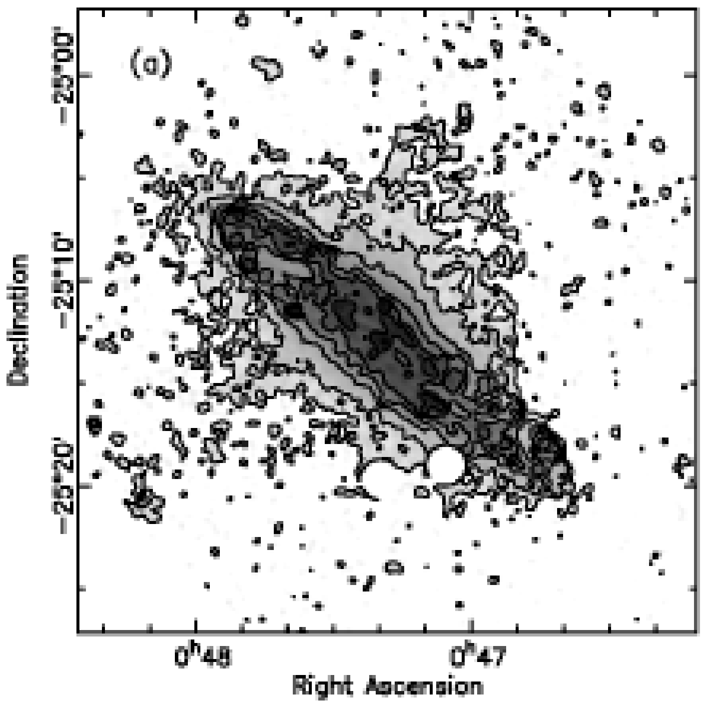
Q: spectral hardness ratio (+ve hot or absorbed, -ve cool or unabsorbed)

green uses 0.3-0.6 vs 0.6-1.0 keV bands, black uses 0.3-1.0 vs 1.0-2.0 keV bands

X-ray AND Hα emission: a clue to the origin of the emission...

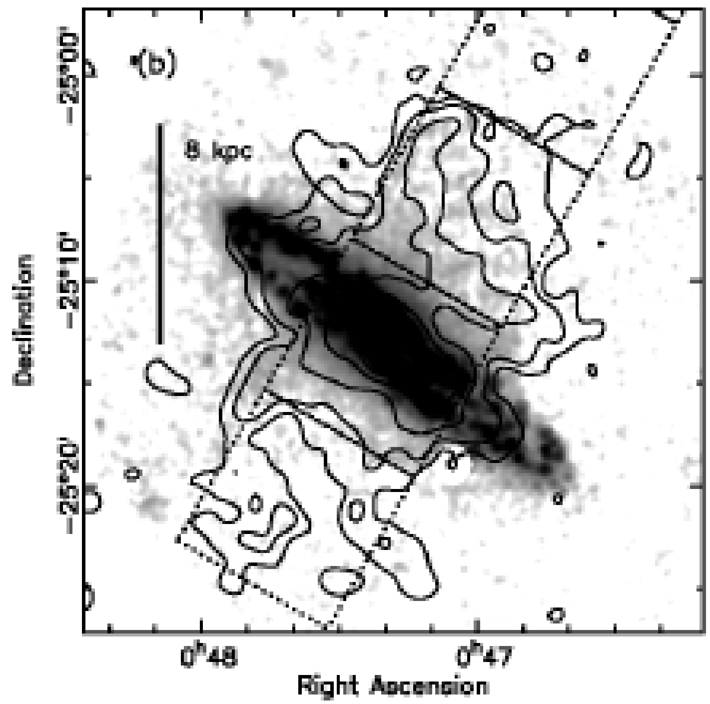
Northern halo Hα.

$f_{H\alpha}$ ~ 5.4e-13 erg/s/cm².



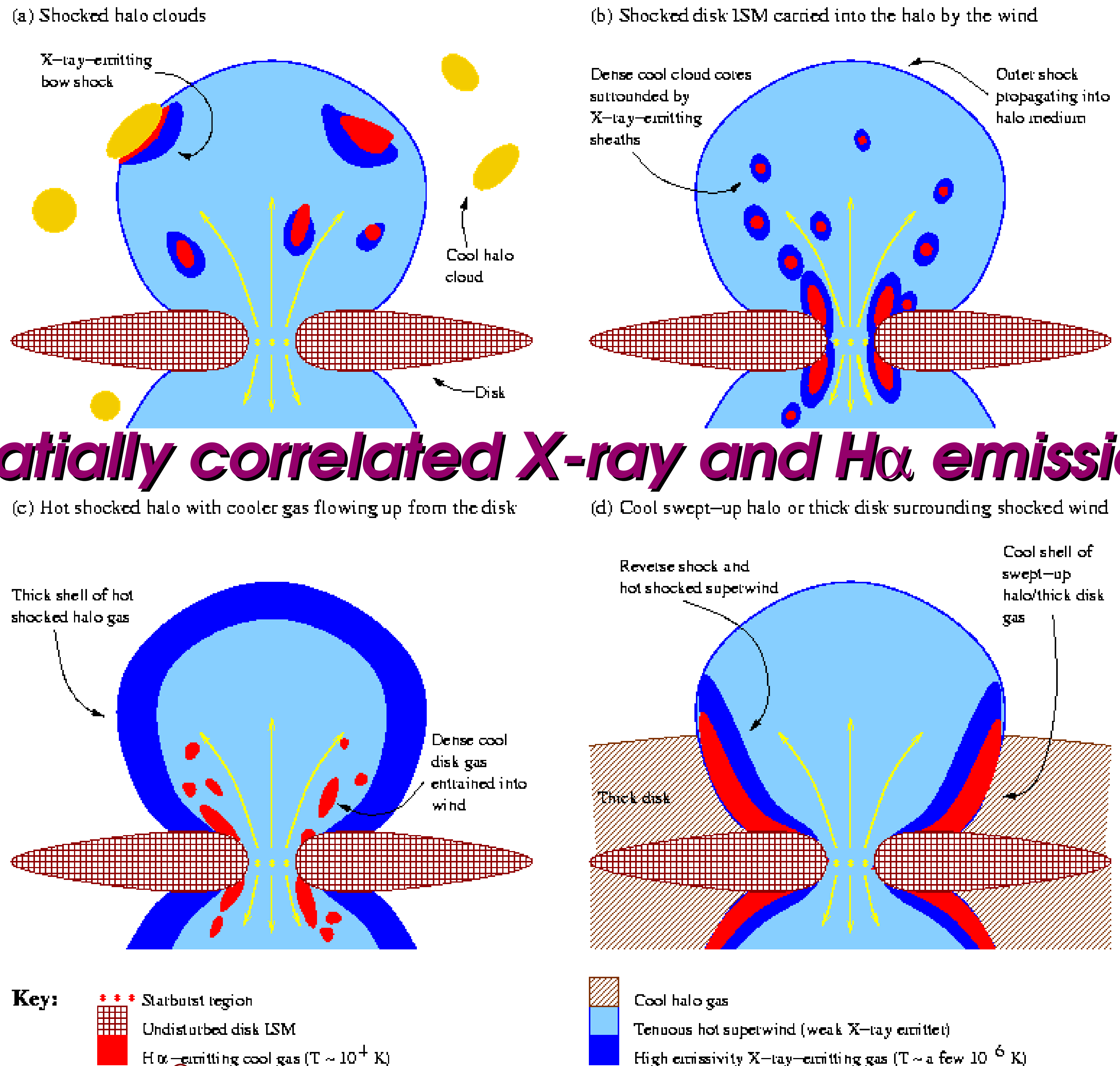
Northern halo: X-ray 0.3-2.0 keV.

f_X ~ 5.0e-13 erg/s/cm².

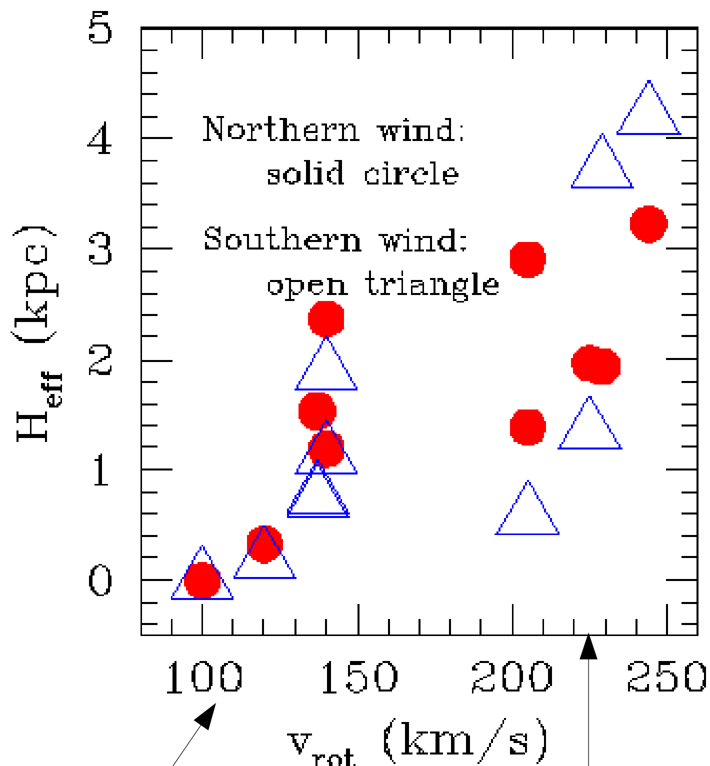


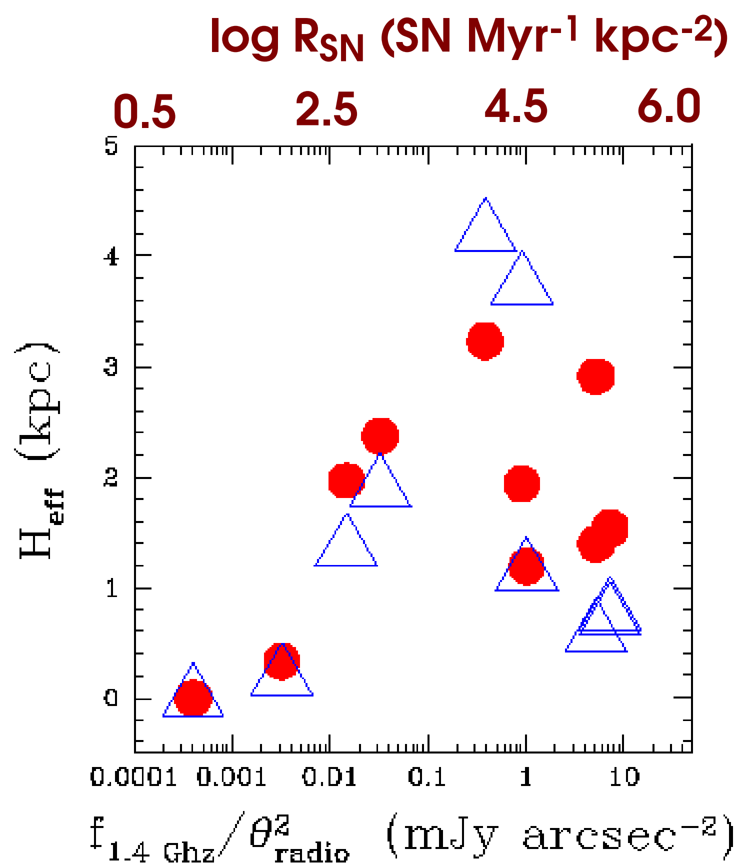
(From Strickland, Heckman, Hoopes, Weaver & Dahlem 2002, ApJ vol something or other.

Spatially correlated X-ray and Hα emission



Outflows: galaxy mass and SF intensity





M_{gal} ~ 10^{10} Msun

M_{gal} ~ 10^{11} Msun

Disk break out: Standard theory based on Mac Low & McCray (1988) requires $R_{SN} > 200\ \varepsilon^{-1}\ P_{4.5}^{1.5}\ n_0^{-0.5}$, where ε is thermalization efficiency (ε<1 (~0.1 for N891?)).
We observe halo diffuse X-ray and Hα emission when R_{SN} > 300.

Summary (last slide but 1...)

- Brightness of extra-planar diffuse X-ray emission correlates well with various independent measures of SF intensity (SF per unit disk area), and NOT with galaxy rotational velocity, or AGN luminosity. Exponential with surface brightness scale heights of
  - Thus: Halo activity is feedback related, with a SF intensity threshold (?) as low as ~300 SN kpc^{-2} Myr^{-1} (based on NGC 891). Starbursts have SN/unit areas up to ~3 dex greater than this.
  - What is the origin of the $5x10^6$ K and 10^4 K halo gas? --> earlier/current fountain activity, occasionally lit-up by a superwind running into it...
  - Caveats: We need more X-ray data on edge-on normal spirals of varying degrees of SF activity.
  - Break-out in disk galaxies close to what, maybe easier, than theory predicts.
  - Quite massive galaxies show 20+ kpc scale, high velocity outflows.
  - Is the paradigm of winds being more effective in dwarfs than spirals completely upside-down?

Yeah yeah, but what about the outer regions of dwarf galaxies?

- Analytical theory and simulation:
  - Its worth taking the (previously untested anyway) theoretical orthodoxy of wind and bubble break-out and quenching in massive galaxies with a bit of salt, until its been tested anyway....
  - If the numerical cosmologists get the ISM structure in very big galaxies wrong then how well are they treating the (poorly-resolved) dwarfs?
- The whole point of the talk is to (hopefully) motivate you to...
  - ...think about halos and the vertical dimension as an outer region worth studying...
  - ...tell the feedback theorists what the ISM and halo gas in dwarfs is like.
- ***QUESTIONS FOR YOU TO ANSWER:***
  - eDIG in dwarf galaxies? NGC 1569 is all very pretty but....
  - Would a dwarf even have any real halo medium?
  - Why are the kinematics of the optical filaments & shells in dwarf galaxies so quiescent, in comparison to the classic $L_{FIR} \sim L_{\star}$ starbursts?