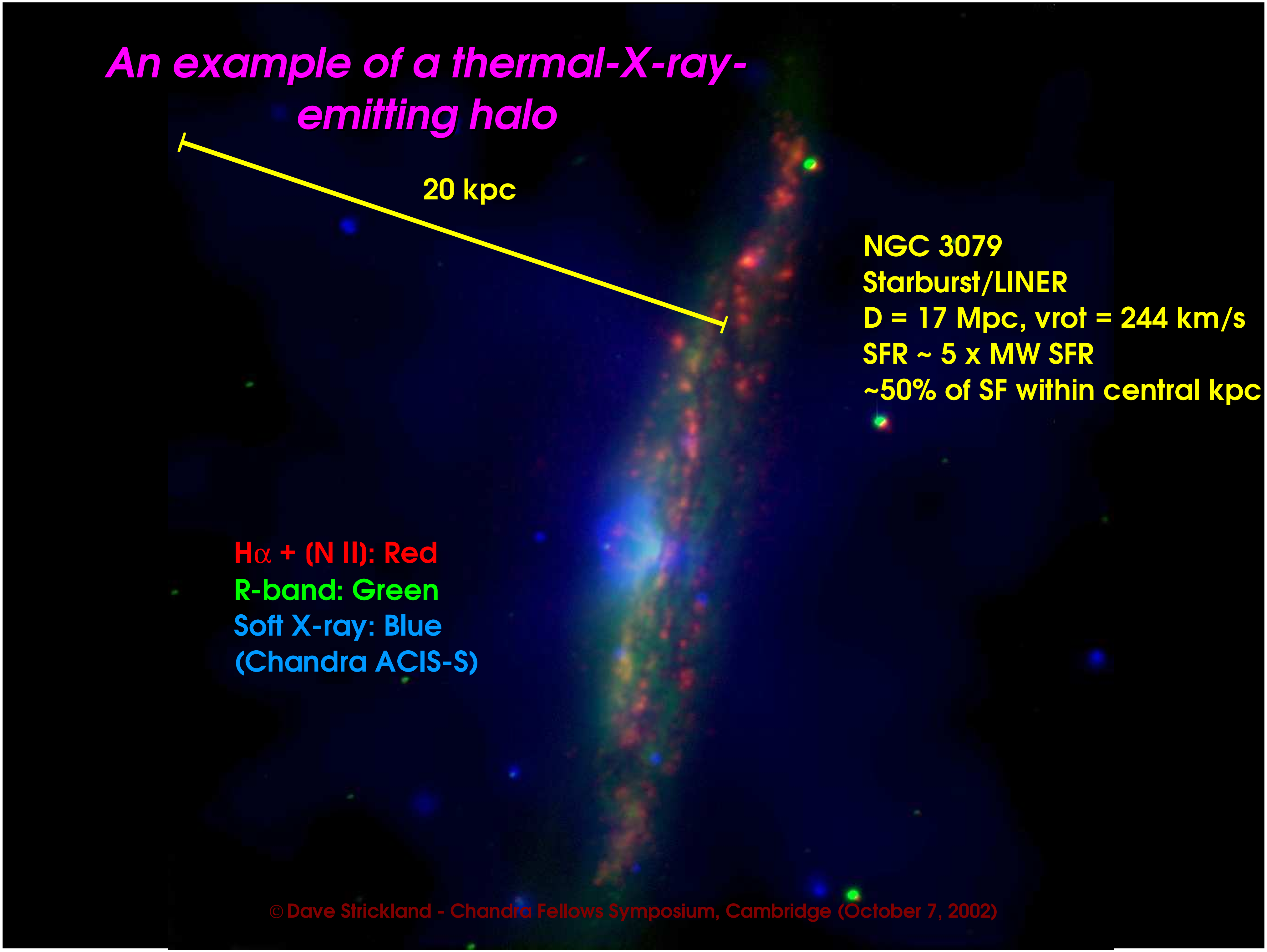
Hot gas in the halos of star-forming disk galaxies

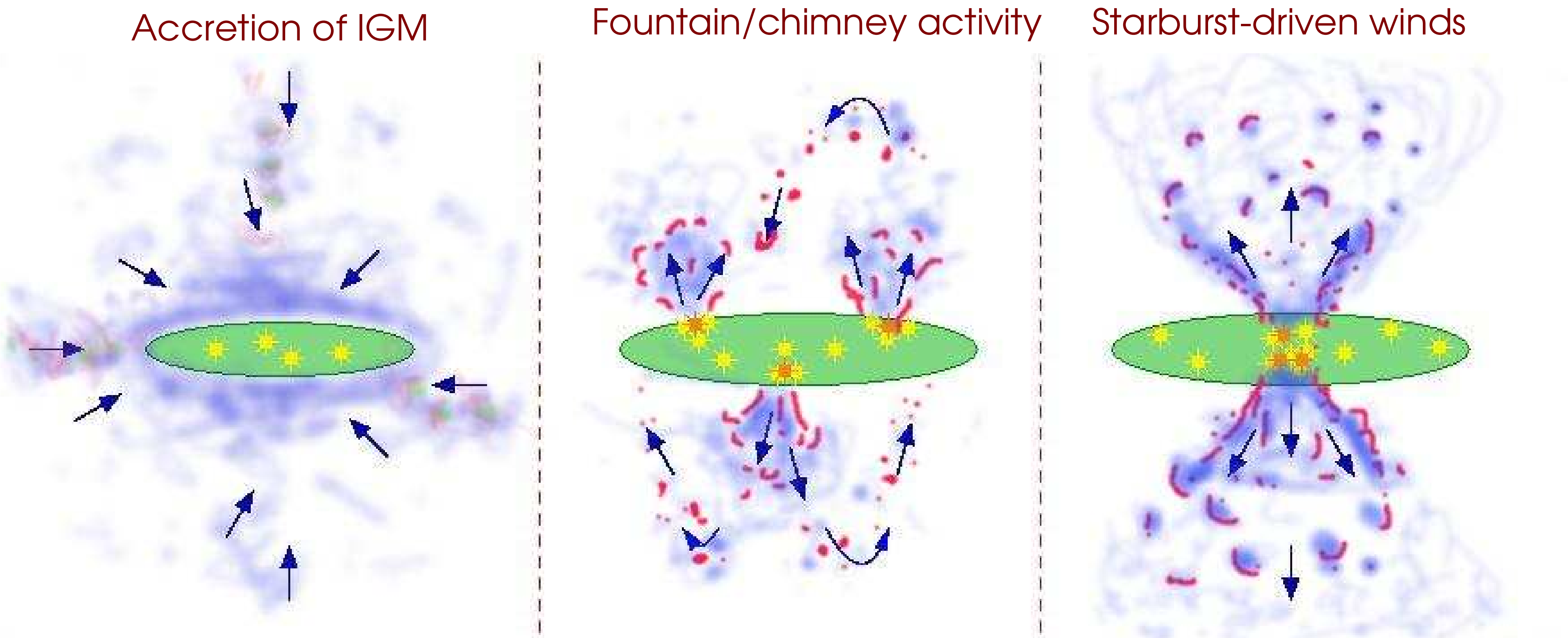
Dave Strickland[1,2],
Tim Heckman[2], Ed Colbert[2],
Charles Hoopes[2] and Kim Weaver[2,3]

(1) Chandra Fellow
(2) Johns Hopkins University
(3) NASA/GSFC

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



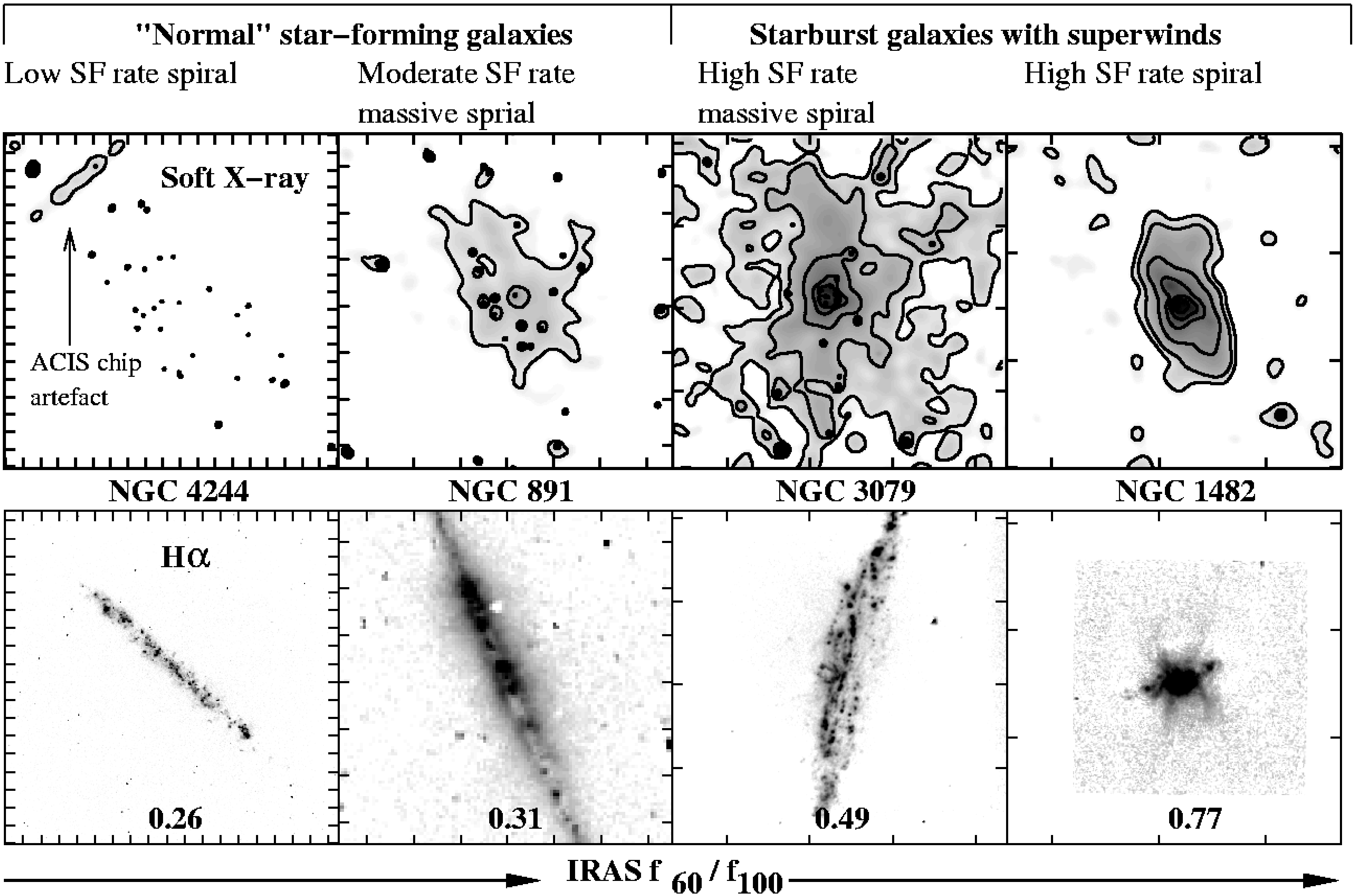
Creating hot gas halos around SFing galaxies



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

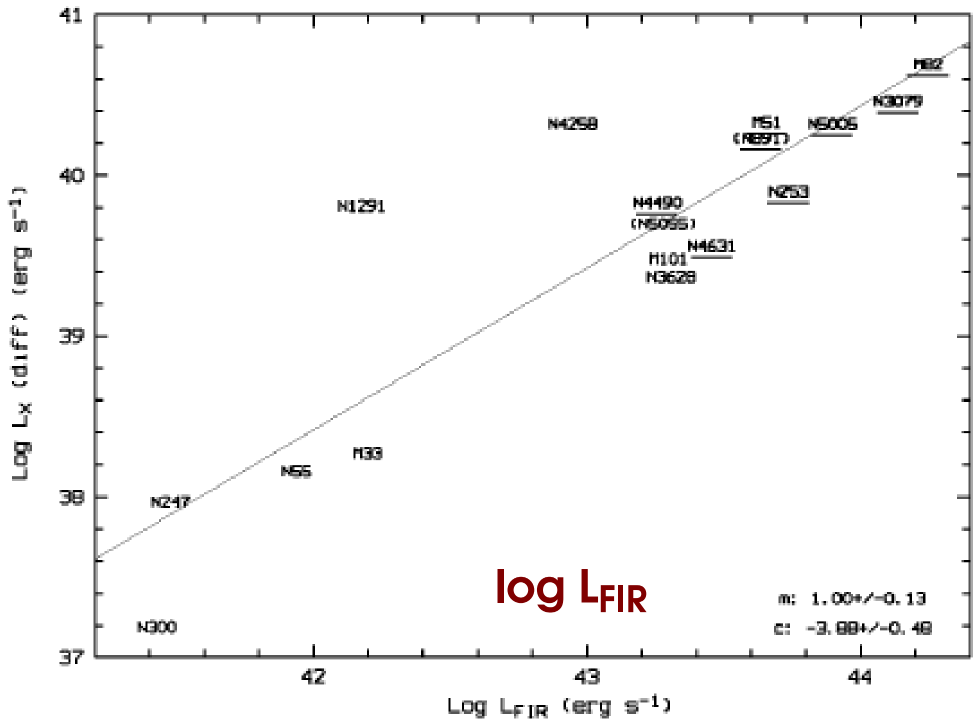
1. Distinguish between the accretion and feedback models.
2. Test fundamental aspects of the theories:
   E.g. "Feedback" - critical energy required to "break out" of a disk (Mac Low)
   E.g. winds only effective in low mass M < 10^9 Msun galaxies (Ferrara).

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, $\Sigma_X \sim \exp(-z/H)$.
- **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 --> ?

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

log L_X diffuse



(from Read & Ponman 2001, using ROSAT PSPC)

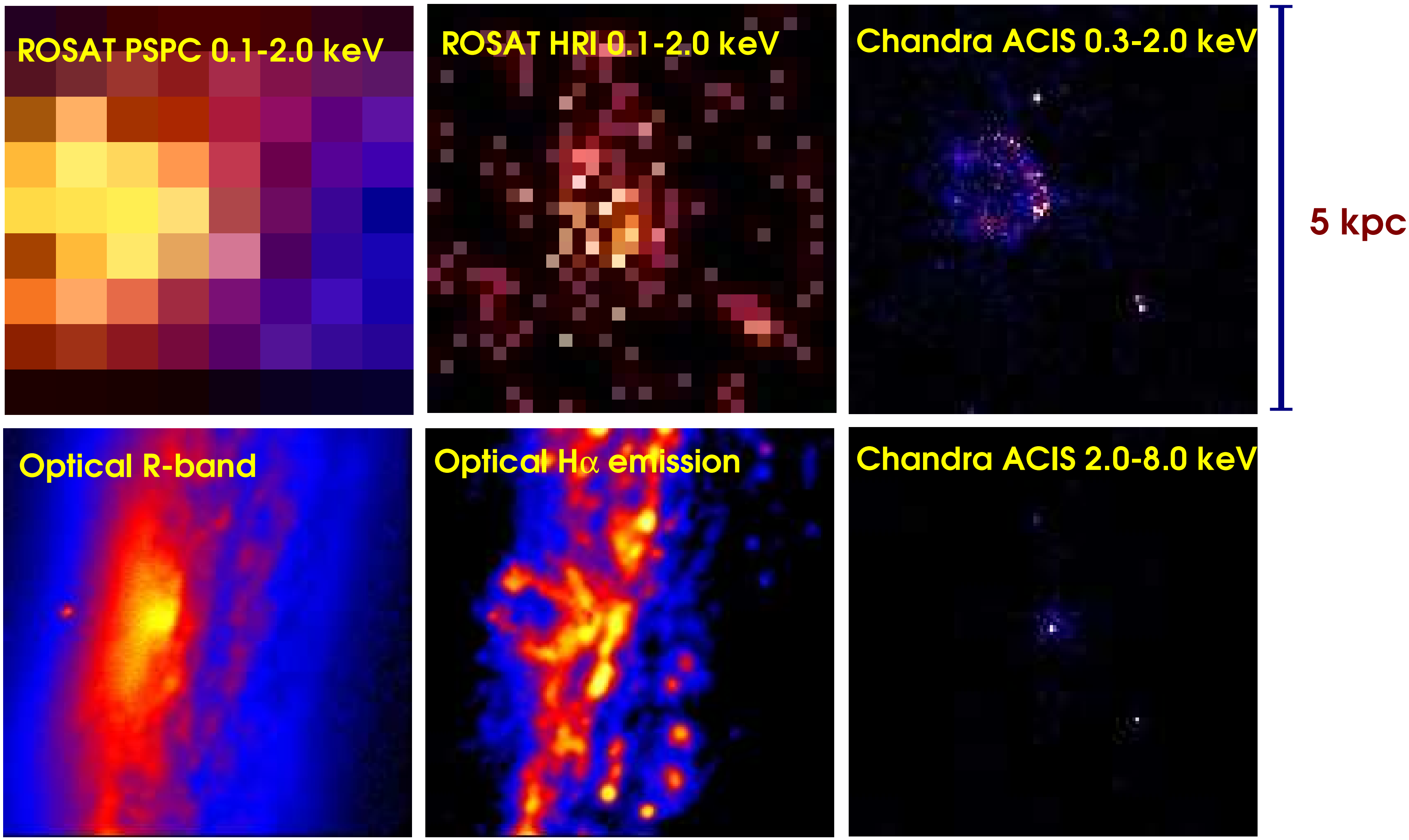
- Einstein - can obtain total X-ray flux and correlate with L_B, L_{FIR} etc (e.g. Fabbiano & co-workers, Shapely et al 2001).
- ROSAT PSPC - first order point source removal - total L_X diffuse vs L_{FIR} (RPS'97, Read & Ponman 2001).
- BUT: Little or no good information on exact shape of surface brightness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

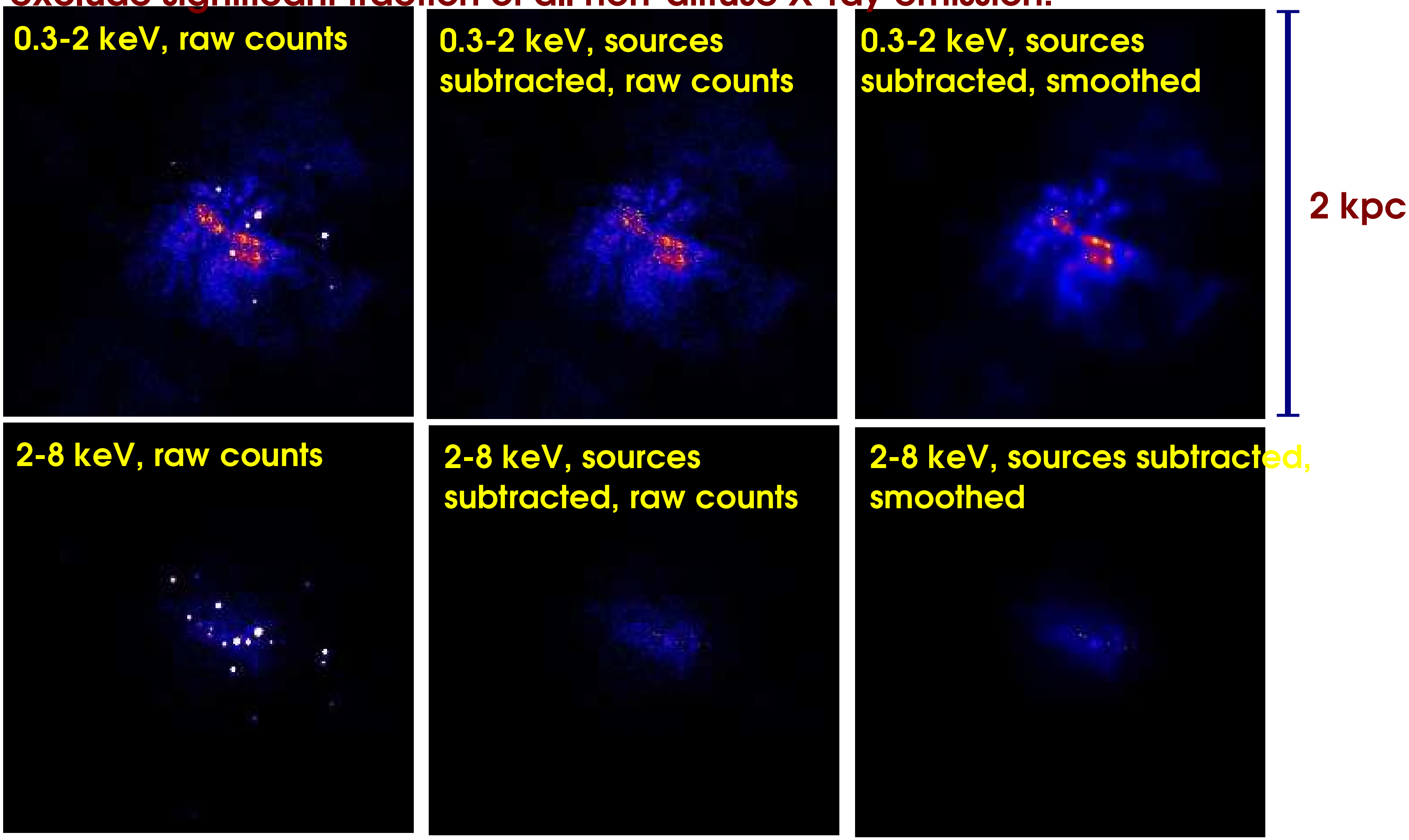
HRI FWHM ~5"
resolution ~ 415 pc

ACIS FWHM ~0.8"
resolution ~ 66 pc



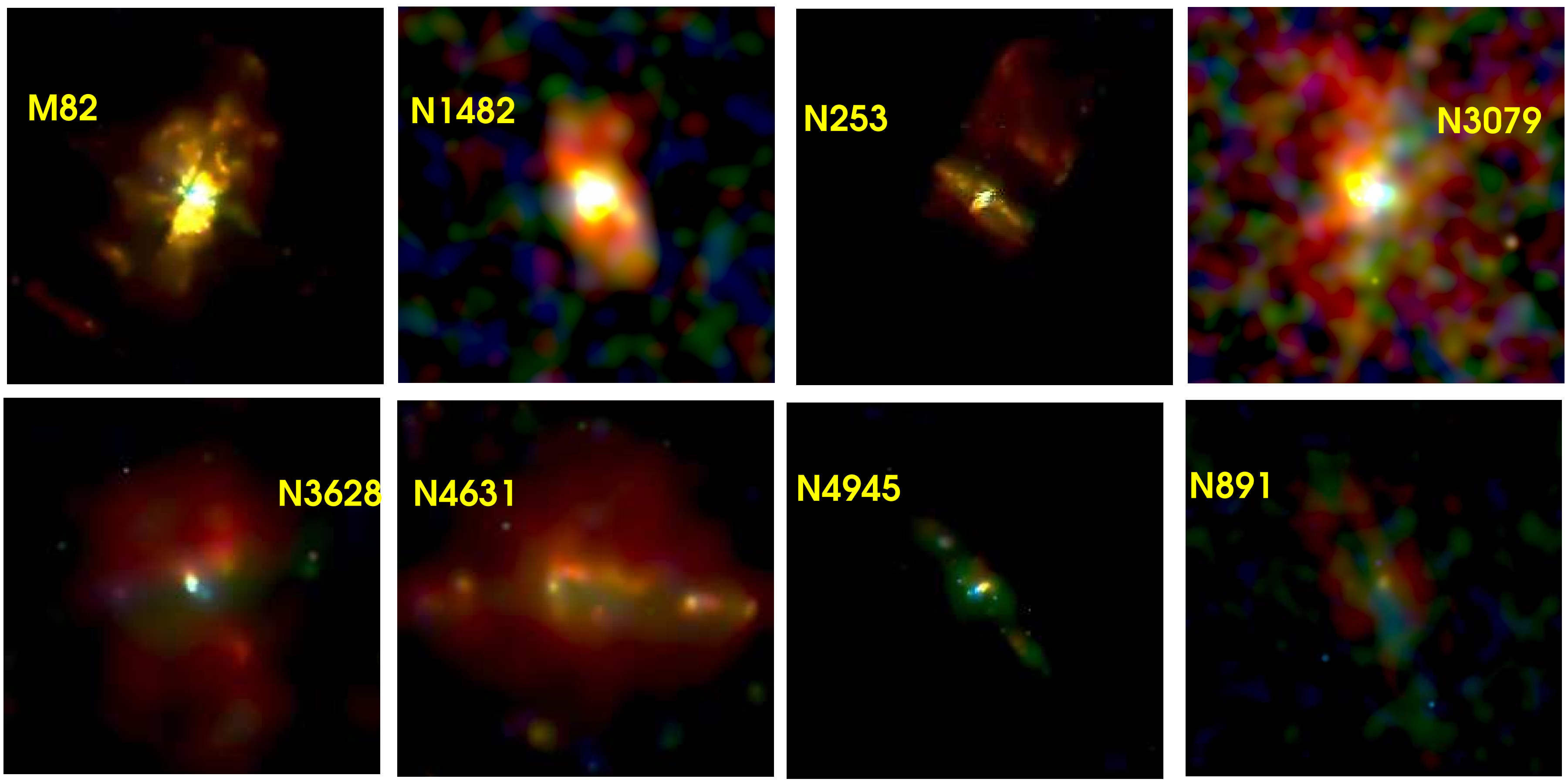
Robust point source removal

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.

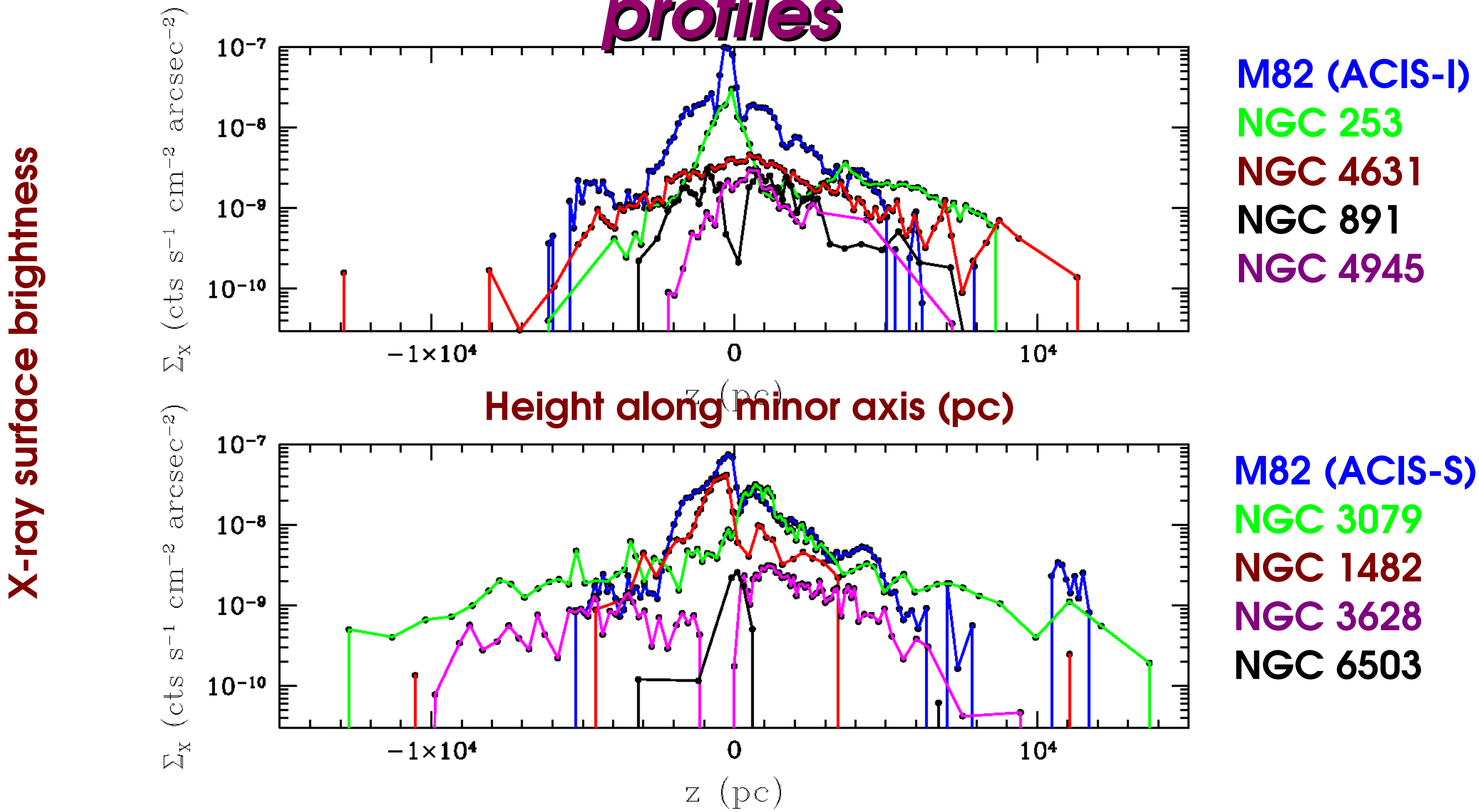


Results from a Chandra ACIS survey of 10 nearby, edge-on SFing disk galaxies

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)



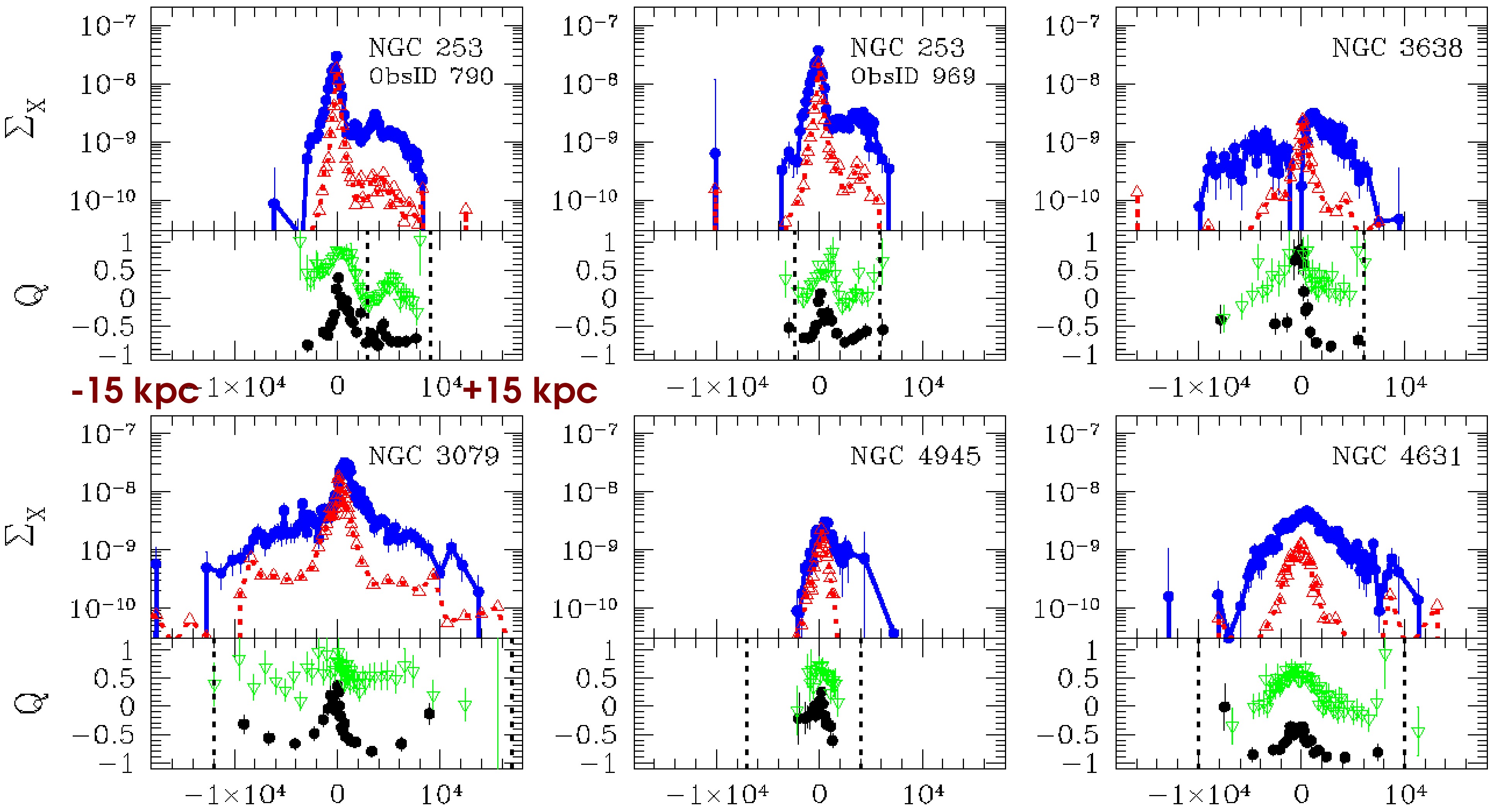
Exponential X-ray surface brightness profiles



- 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} $arcsec^{-2}$

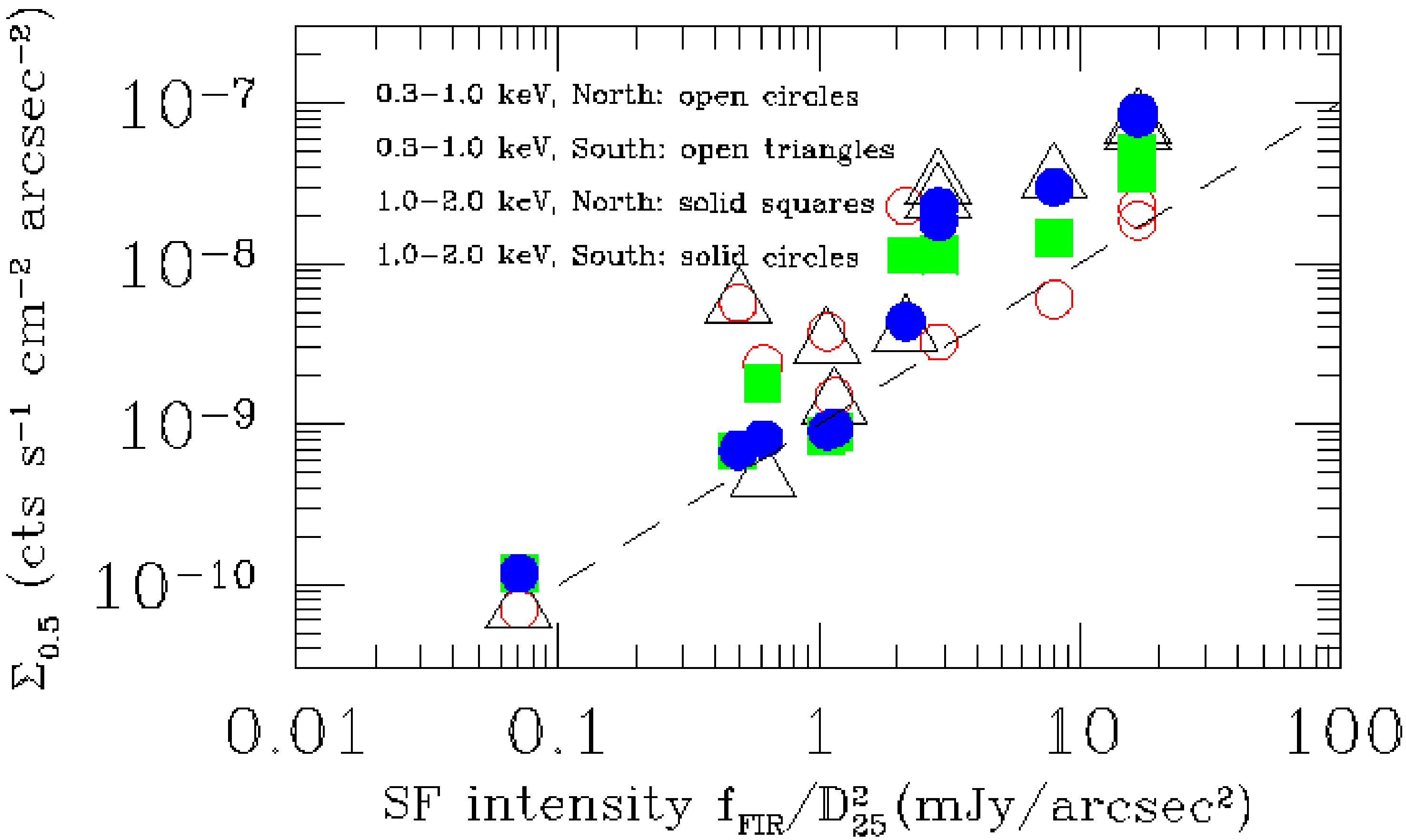
blue: 0.3-1.0 keV band, red: 1.0-2.0 keV band.



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

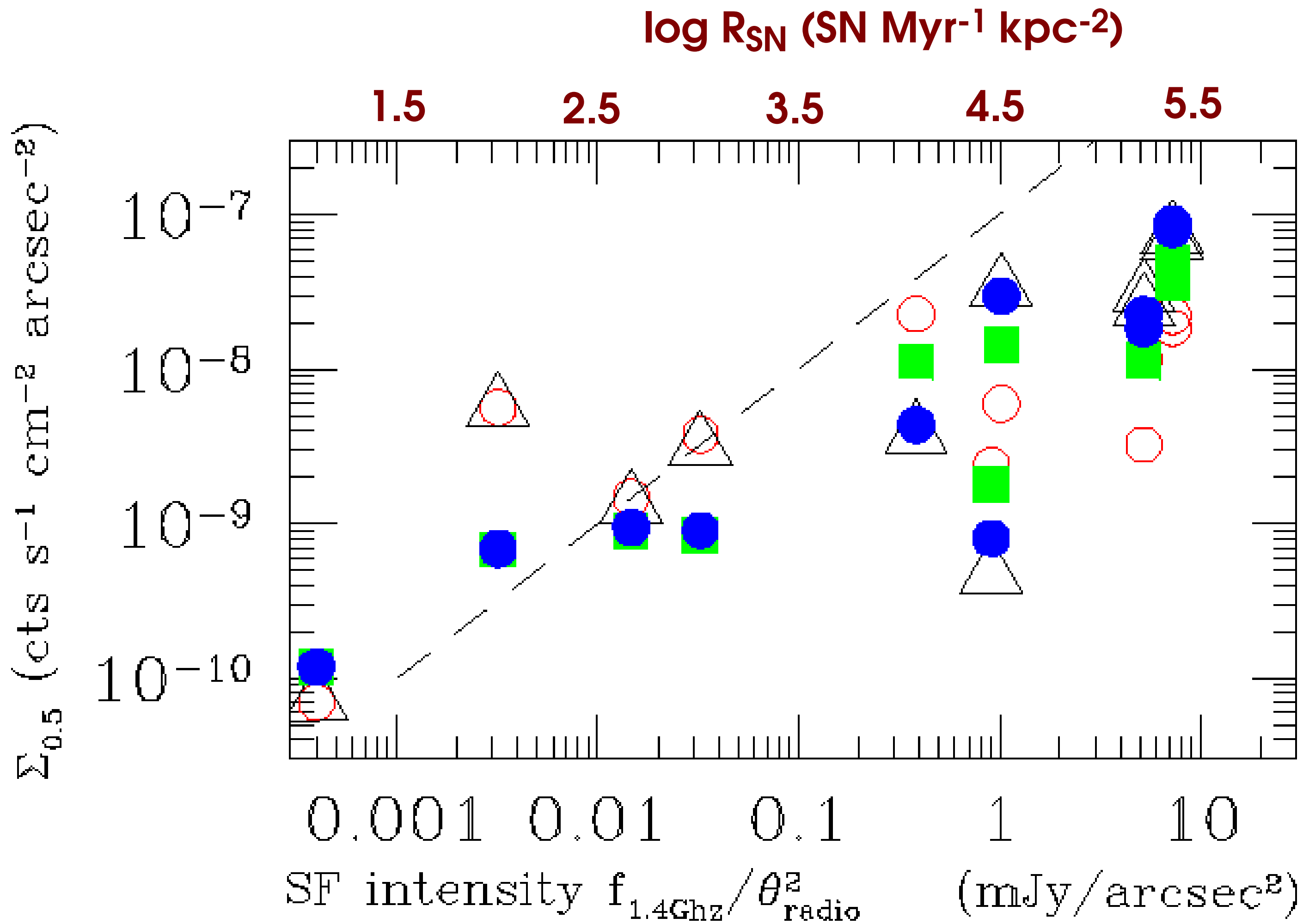
green uses 0.3-0.6 vs 0.6-1.0 keV bands, black uses 0.3-1.0 vs 1.0-2.0 keV bands

Halo diffuse X-ray: SN or accretion?



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?

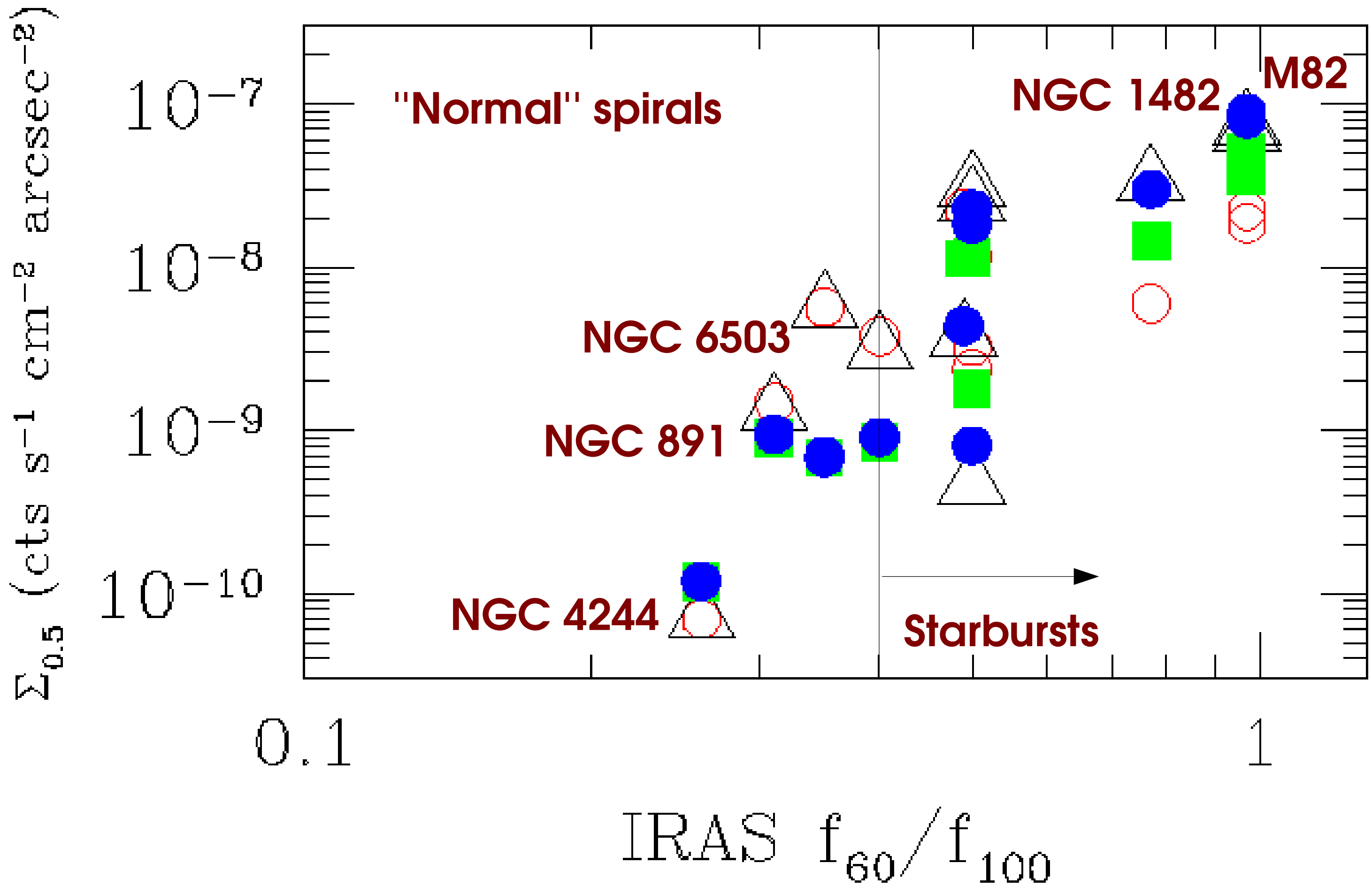


NVSS 1.4 Ghz radio fluxes and sizes

(nonthermal radio emission from cosmic rays produced by SNe)

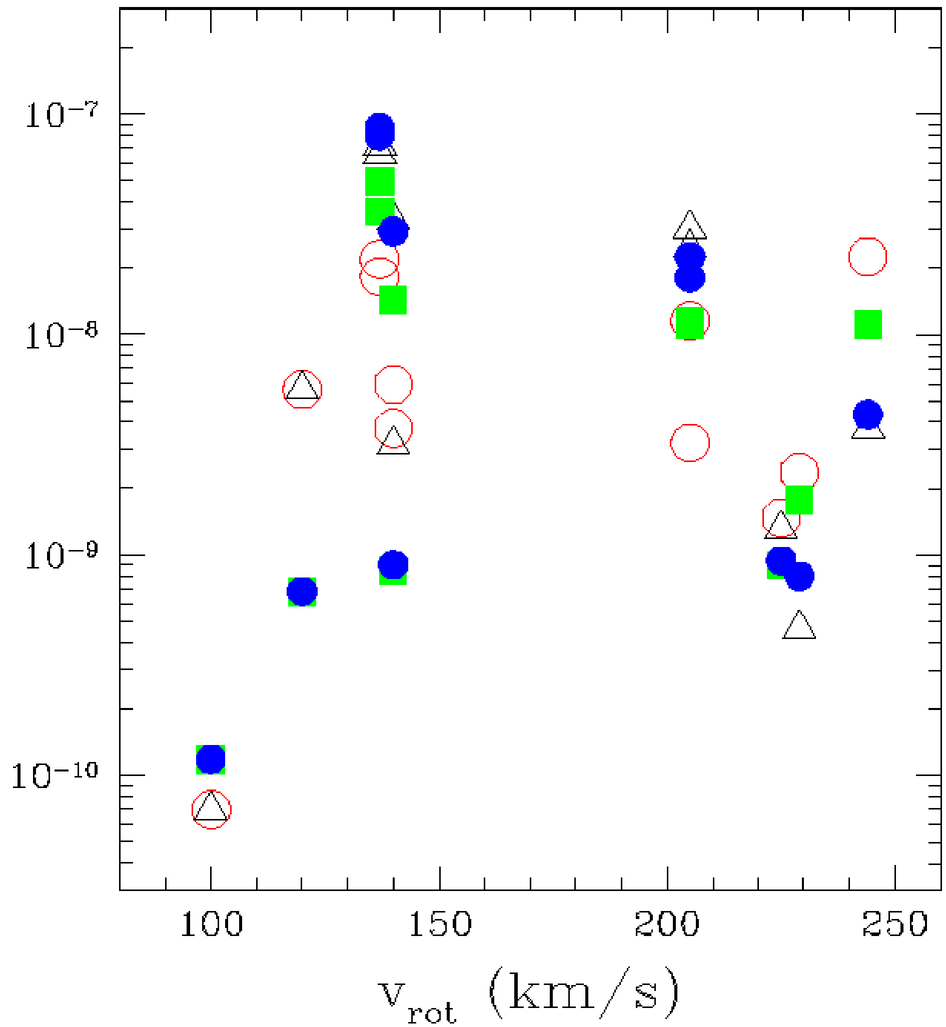
Halo diffuse X-ray: SN or accretion?

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



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

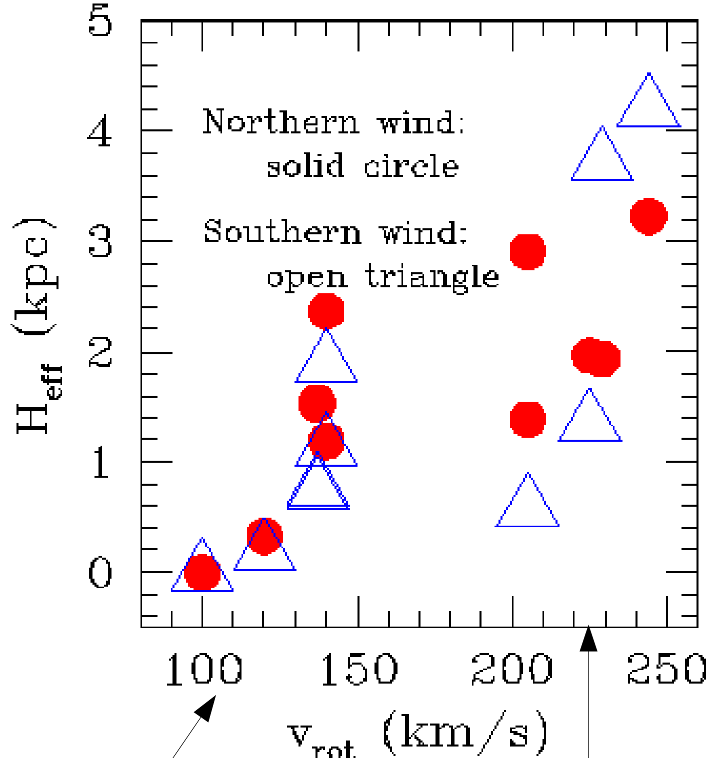
Halo diffuse X-ray: SN or accretion?

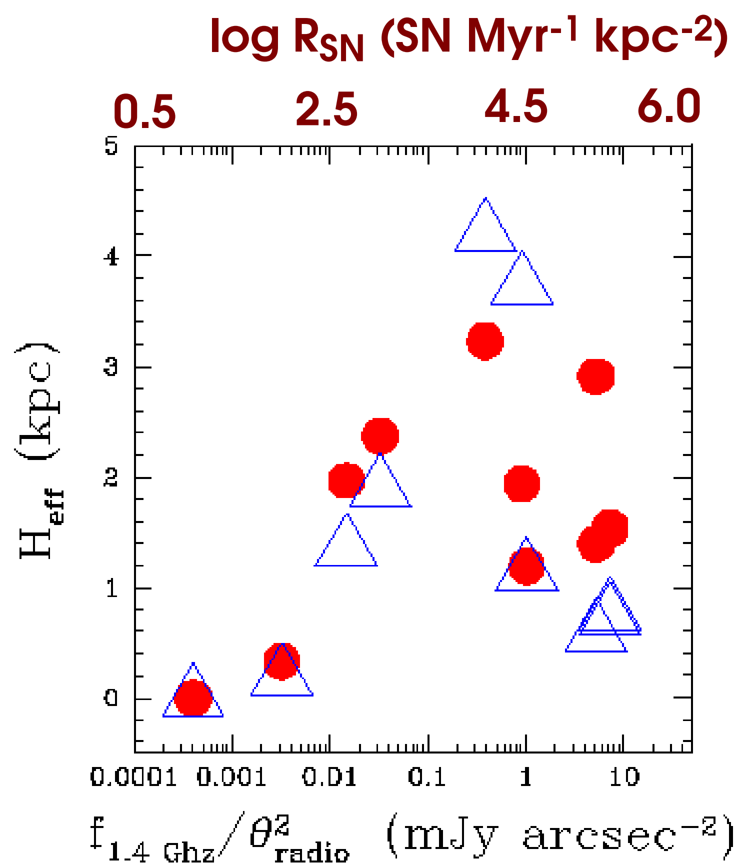


Σ_X
X-ray
surface
brightness

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

Outflows: galaxy mass and SF intensity





$M_{gal} \sim 10^{10}$ Msun

$M_{gal} \sim 10^{11}$ Msun

Disk break out: Standard theory based on Mac Low & McCray (1988) requires $R_{SN}\ \varepsilon > 200$, where ε is thermalization efficiency ($\varepsilon<1$).

We observe halo diffuse X-ray and Hα emission when $R_{SN} > 300$.

Summary

- Brightness of extra-planar diffuse X-ray emission correlates well with various independent measures of SF intensity (SF per unit disk area)
- Does not correlate with galaxy rotational velocity, or AGN luminosity (LLAGN-driven winds a whole separate talk...).
- NGC 891 only "normal" (non-starburst) spiral with diffuse halo X-ray emission, but X-ray properties very similar to superwinds --> fountains and winds not distinct phenomena?
- Spectral data (not shown) consistent with these conclusions.
- 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.
- Caveat: We need more data on edge-on normal spirals of varying degrees of SF activity.
- Quite massive galaxies show 20+ kpc scale, high v outflows. Don't believe uncalibrated, untested theories that claim that only low mass galaxies drive winds!