X-raying Galaxies: A Chandra Legacy

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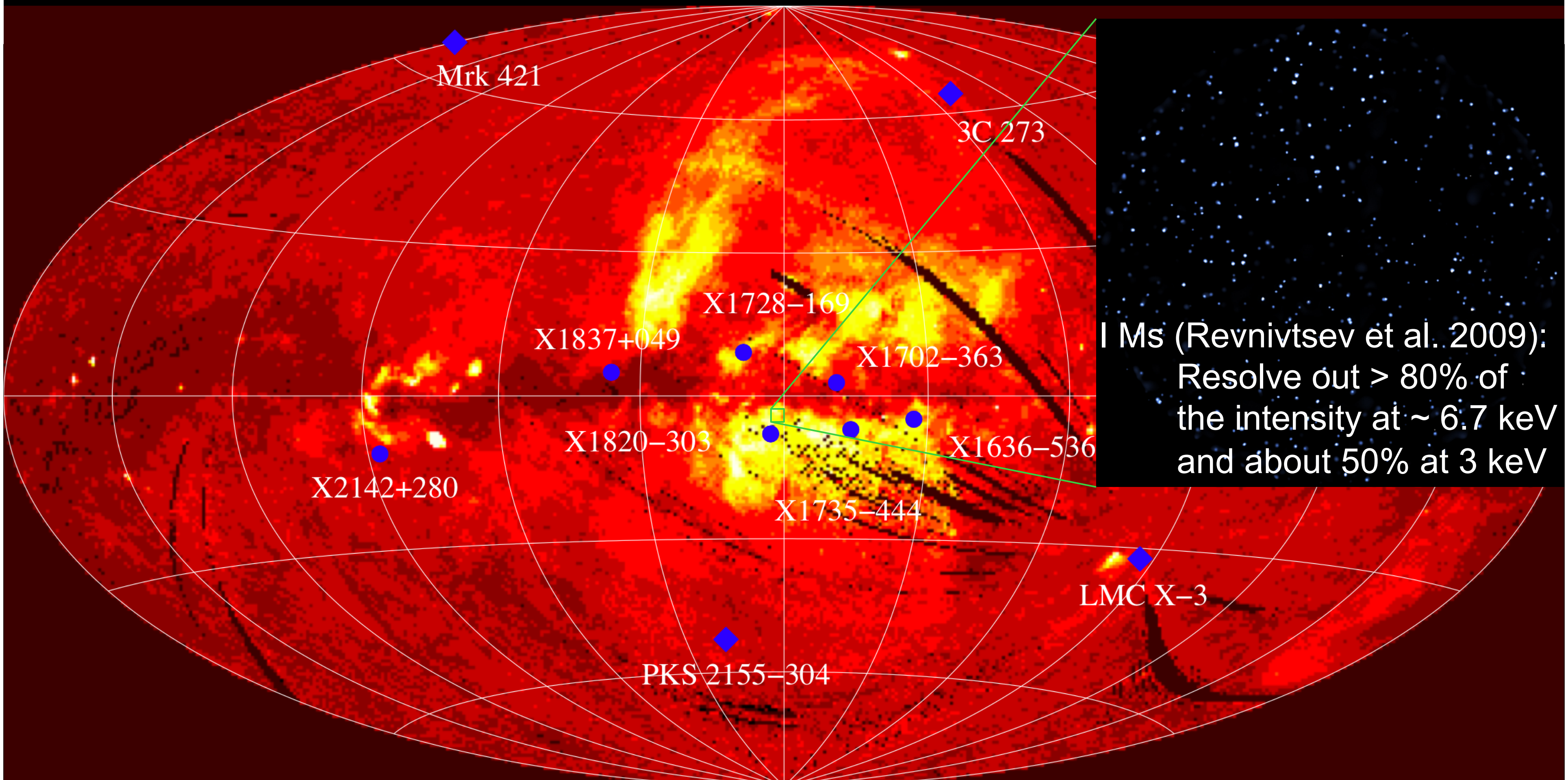
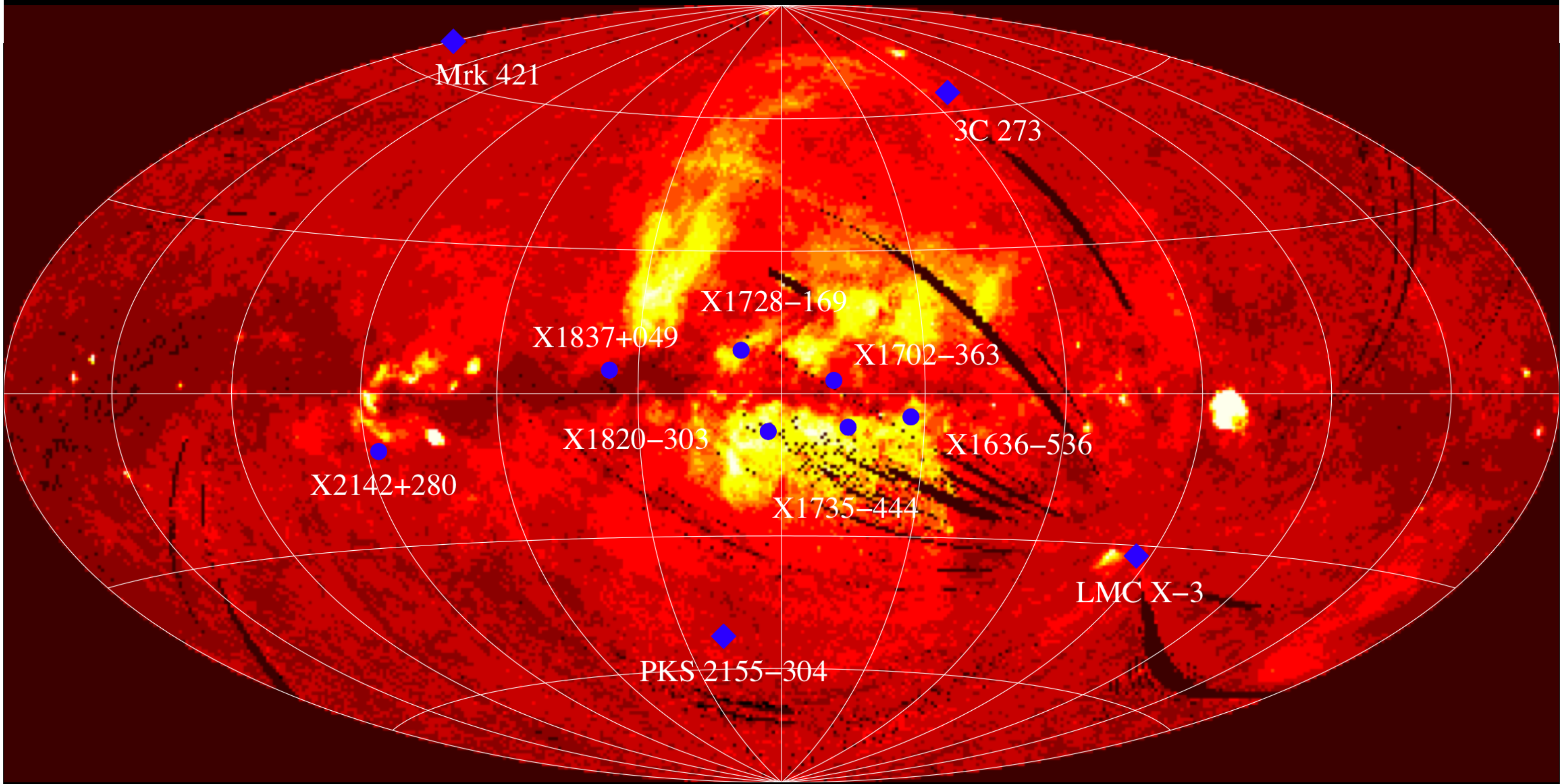
Chandra ACIS observation of M83;
Soria & Wu (2002)



ROSAT all-sky survey
in the $\frac{3}{4}$-keV band

X-ray absorption line spectroscopy: adding depth into the map

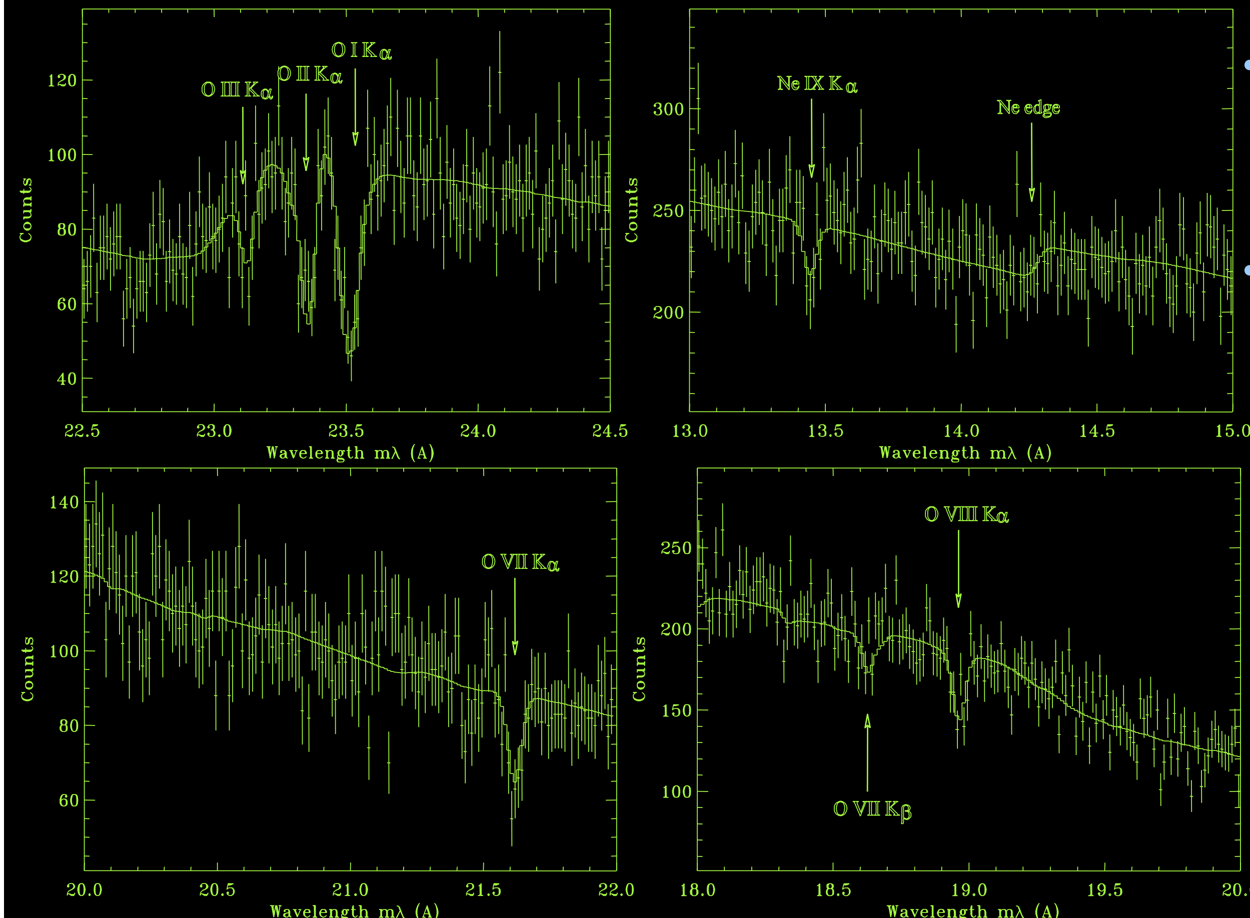


◆ AGN
● X-ray binary

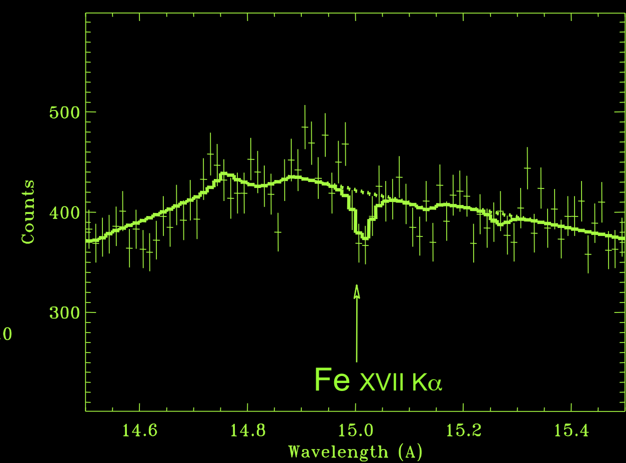
Futamoto et al. 2004, Wang et al. 05, Yao & Wang 05/06, Yao et al. 06/07/08

ROSAT all-sky survey in the $\frac{3}{4}$-keV band

X-ray absorption line spectroscopy is powerful !

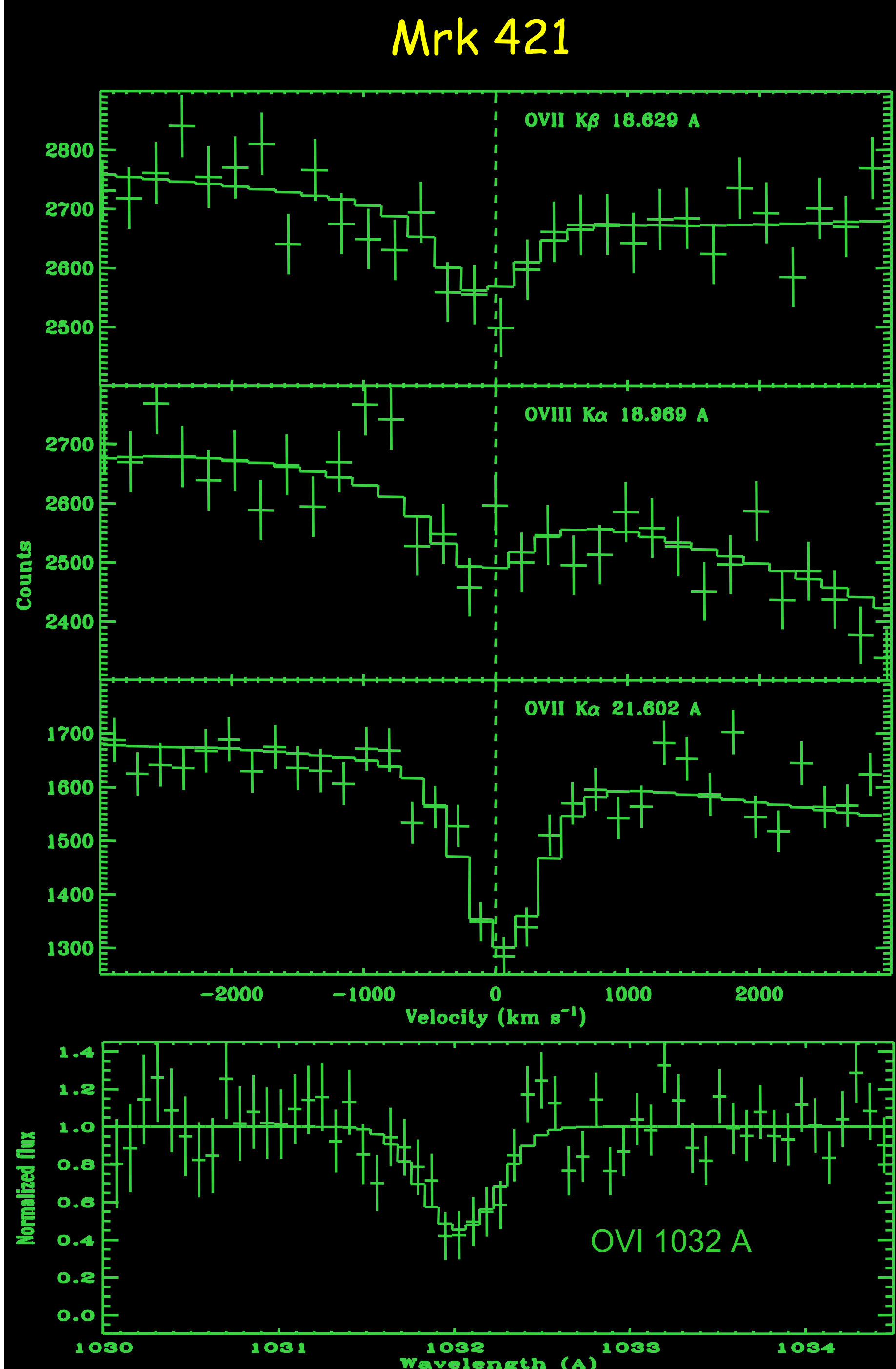


- Tracing all K transitions of metals → all three phases of the ISM.
- Not affected by photo-electric absorption→ unbiased measurements of the global ISM.



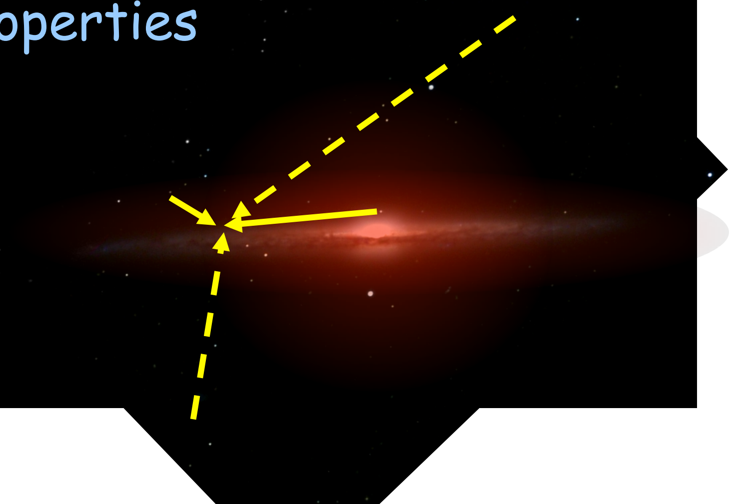
LETG+HETG spectrum of LMXB 1820-303

Yao & Wang 2006, Yao et al. 2006, Futamoto et al 2004

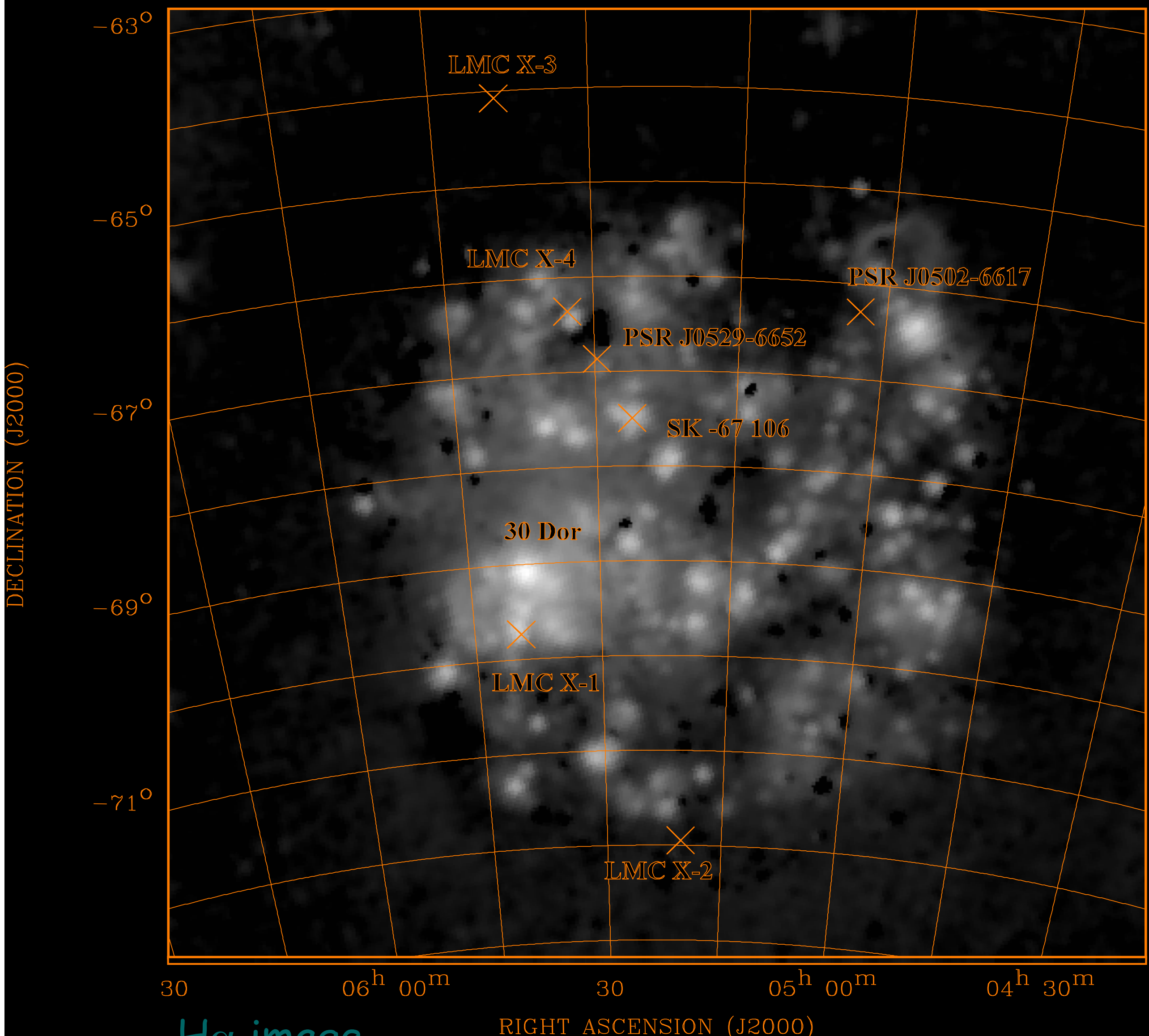


Spectroscopic diagnostics

- One line (e.g., OVII Kα) → velocity centroid and EW → constraints on the column density, assuming b and T
- Two lines of different ionization states (OVII and OVIII Kα) → T
- Two lines of the same state (Kα and Kβ) → b
- Lines from different species → abundance f_a
- Joint-fit of absorption and emission data --> pathlength and density
- Multiple sightlines --> differential hot gas properties



LMC X-3 as a distance marker

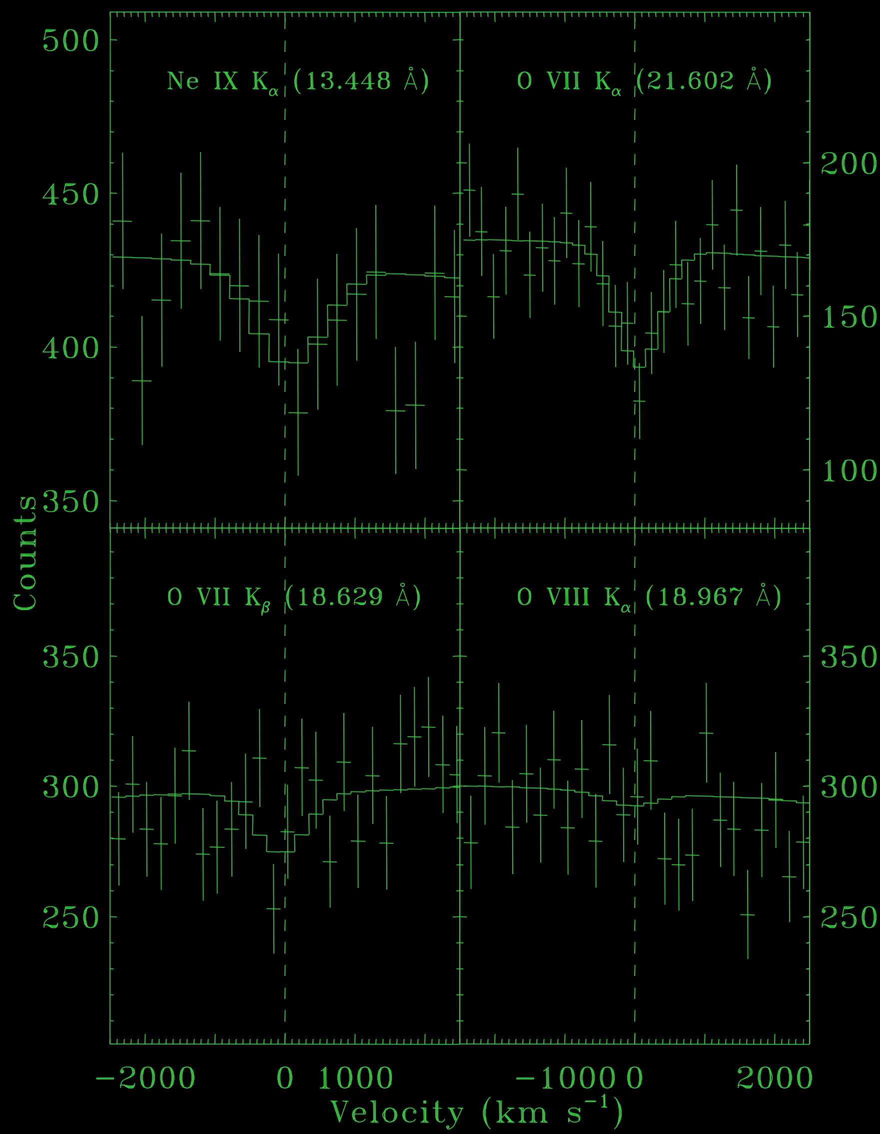


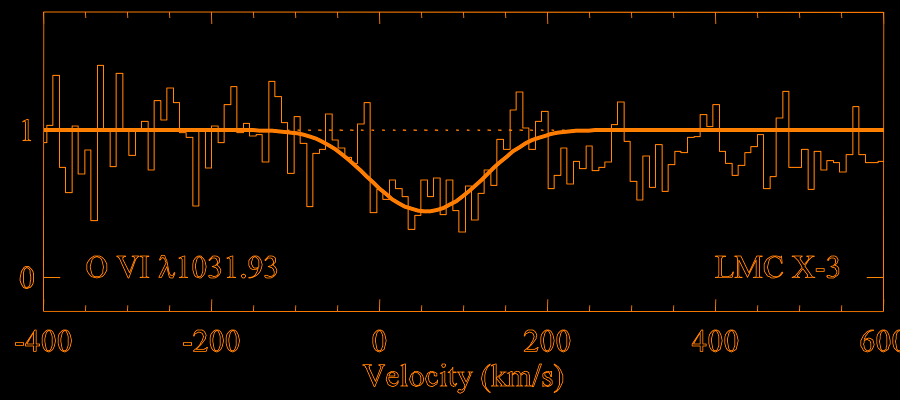
Hα image

- BH X-ray binary undergoing Roche lobe accretion
- 50 kpc away
- V_s = +310 km/s
- Away from the LMC main body

Wang et al. 2005

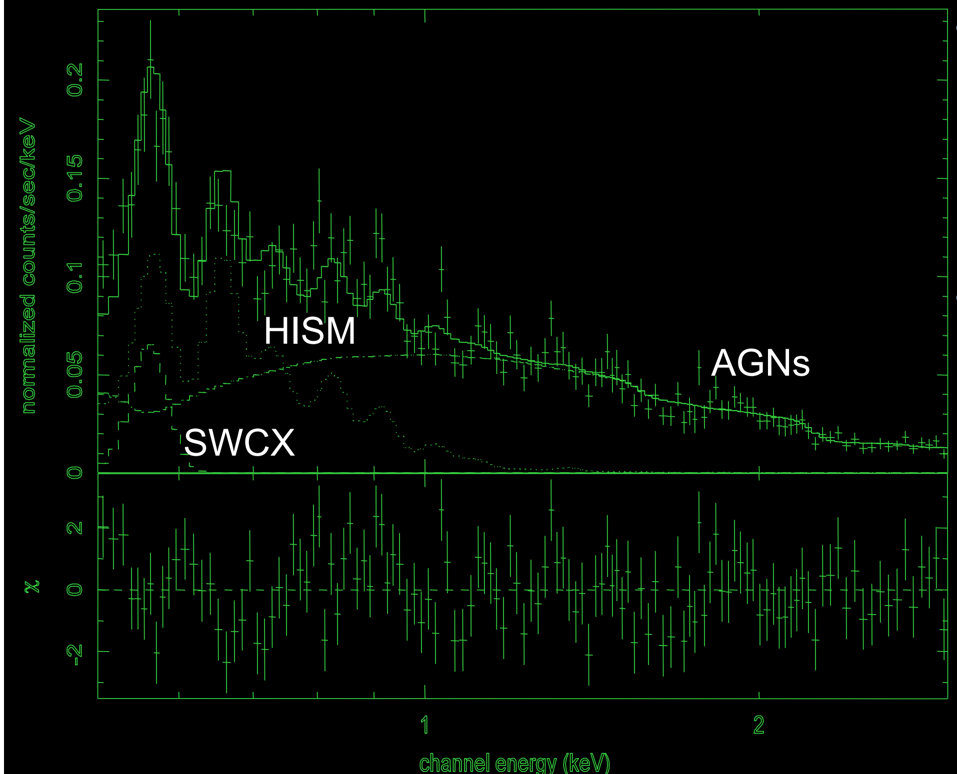
LMC X-3: absorption lines





- The line centroids of the OVI and OVII lines are consistent with the Galactic origin.
- N_O~1.9 x 10^{16} atoms/cm^2, similar to those seen in AGN spectra!
- T ~ 1.3 x 10^6 K
- b ~ 79 km/s

Joint-fit to the Suzaku XIS diffuse emission spectrum



100 ks Suzaku observations of LMC X-3 off-fields

(Yao, Wang, et al. 2008)

- Single temperature fit → T= 2.4×10^6 K, significantly higher than that inferred from the X-ray absorption lines.
- Joint-fit to the absorption and emission data gives
  - $n_e = (3.6\times10^{-3}\ K)\ e^{-|z|/2.8\ kpc}$;
  - $T = (2.4\times10^{6}\ K)\ e^{-|z|/1.4\ kpc}$

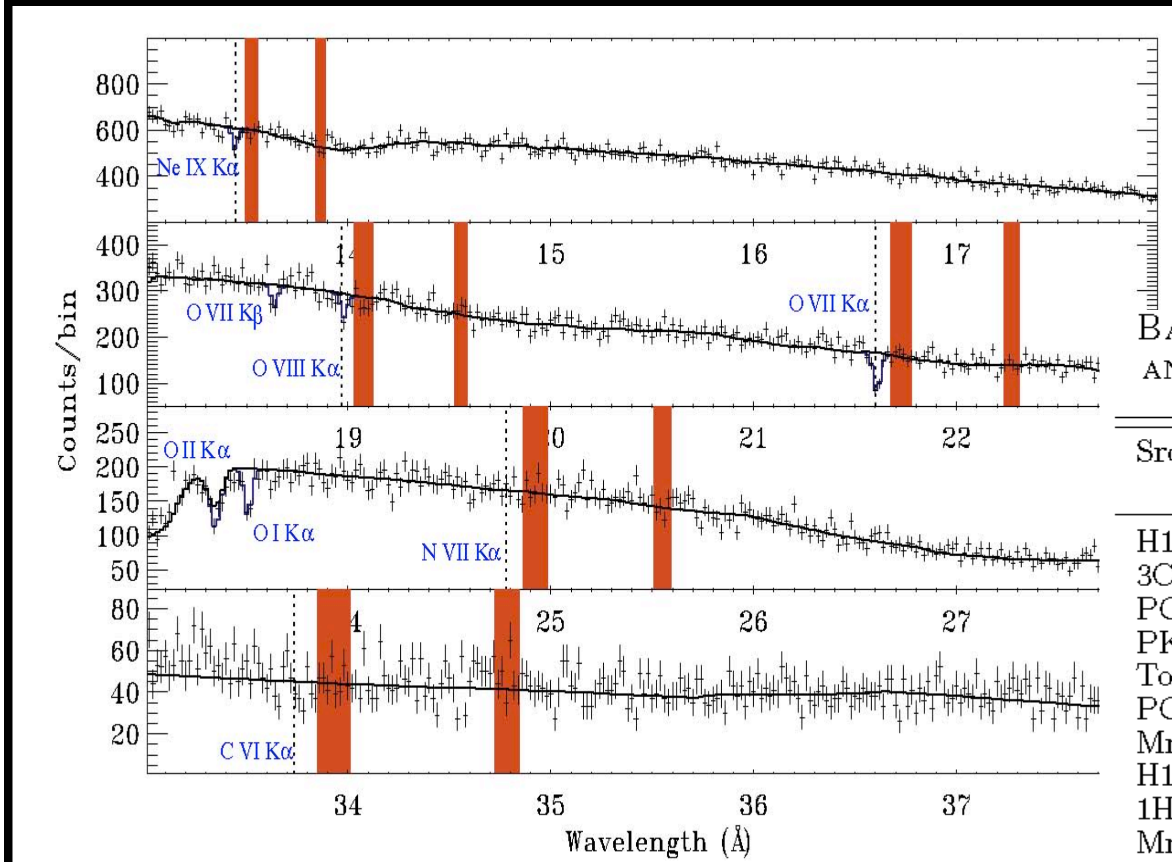
  → $P/k \sim 1.1\times10^{4}\ cm^{-3}$ K, assuming filling factor =1.

  → This thick hot disk can explain all the OVI absorption, except for ~10% of high-*v* OVI emission.

Galactic global hot gas properties

- Thermal property:
  - mean T ~ $10^{6.3}$ K toward the inner region
  - ~ $10^{6.1}$ K at solar neighborhood
- Velocity dispersion from ~200 km/s to 80 km/s
- Abundance ratios ~ solar
- Structure:
  - A thick Galactic disk with a scale height of ~ 2 kpc,
    ~ the values of OVI absorbers and free electrons
  - Enhanced hot gas around the Galactic bulge
  - No evidence for a large-scale (r ~ 10^2 kpc) X-ray-emitting/absorbing halo with an upper limit of N_H~1 x10^{19} cm^{-2}.

No evidence for X-ray line absorption by hot gas in intervening groups of galaxies



- Sightline: 3C 273
- Total exposure: 530 ks
- Selected galaxies: < 500 kpc projected distance.

BACKGROUND AGNS, *Chandra* OBSERVATIONS, AND THE NUMBER OF INTERVENING GALAXIES

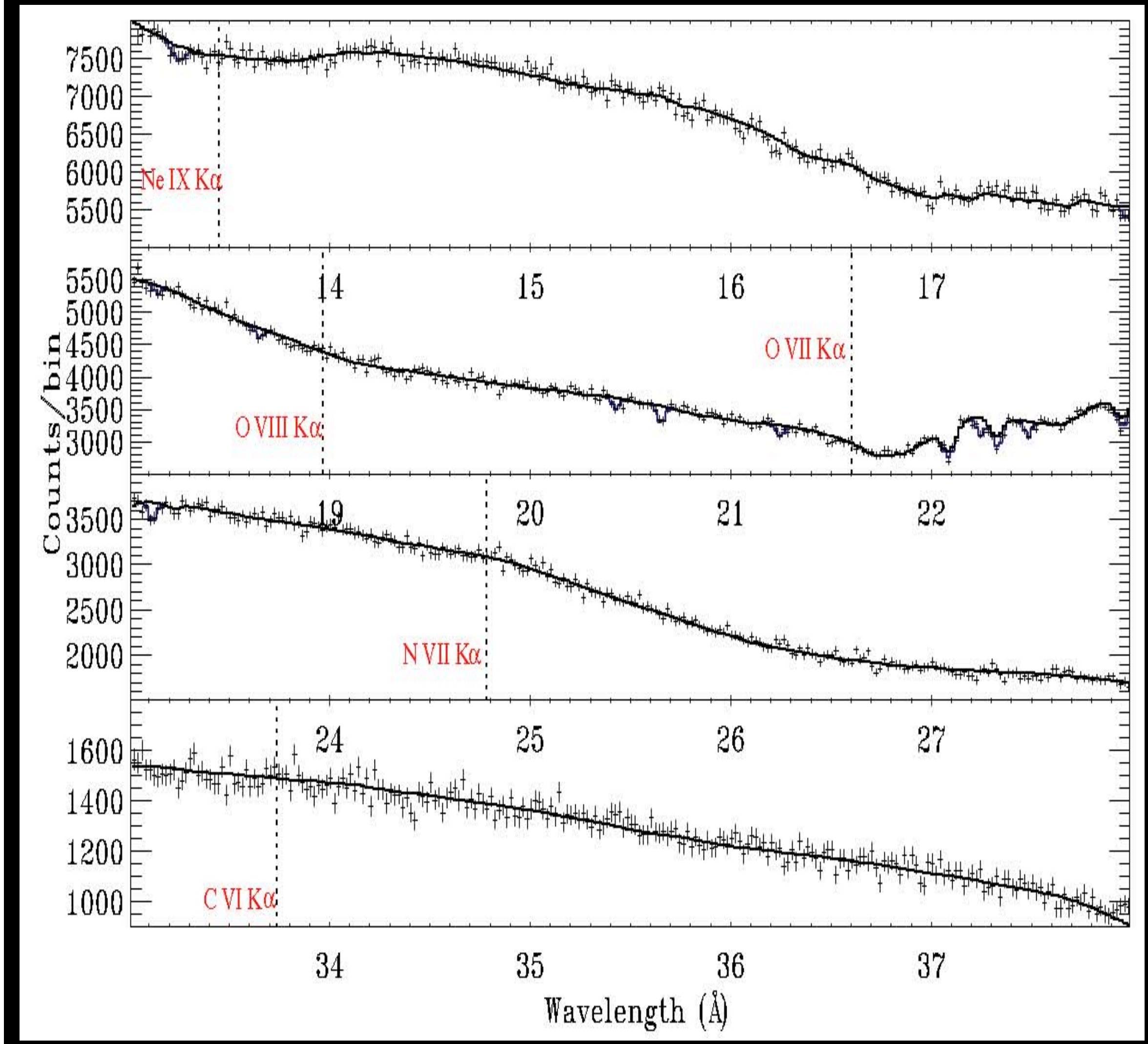
Src. Name	z_{AGN}	No. of Obs.	Exp. (ks)	No. of[a] gal.
H1821+643	0.297	5	600	7(5)
3C 273	0.158	17	530	47(44)
PG 1116+215	0.176	1	89	12(11)
PKS 2155-304	0.117	46	1075	14(13)
Ton S180	0.062	1	80	3(3)
PG 1211+143	0.081	3	141	46(45)
Mrk 766	0.013	1	90	13(12)
H1426+428	0.129	3	184	3(3)
1H 0414+009	0.287	2	88	4(2)
Mrk 509	0.034	1	59	1(1)
IC 4329a	0.016	1	60	3(3)
Fairall 9	0.047	1	80	1(1)
Sub total:		82	3076	154(143)

Blue lines: Galactic absorption

Vertical red bars: expected group absorption line positions

Yao, Y., DW, et al. (2009)

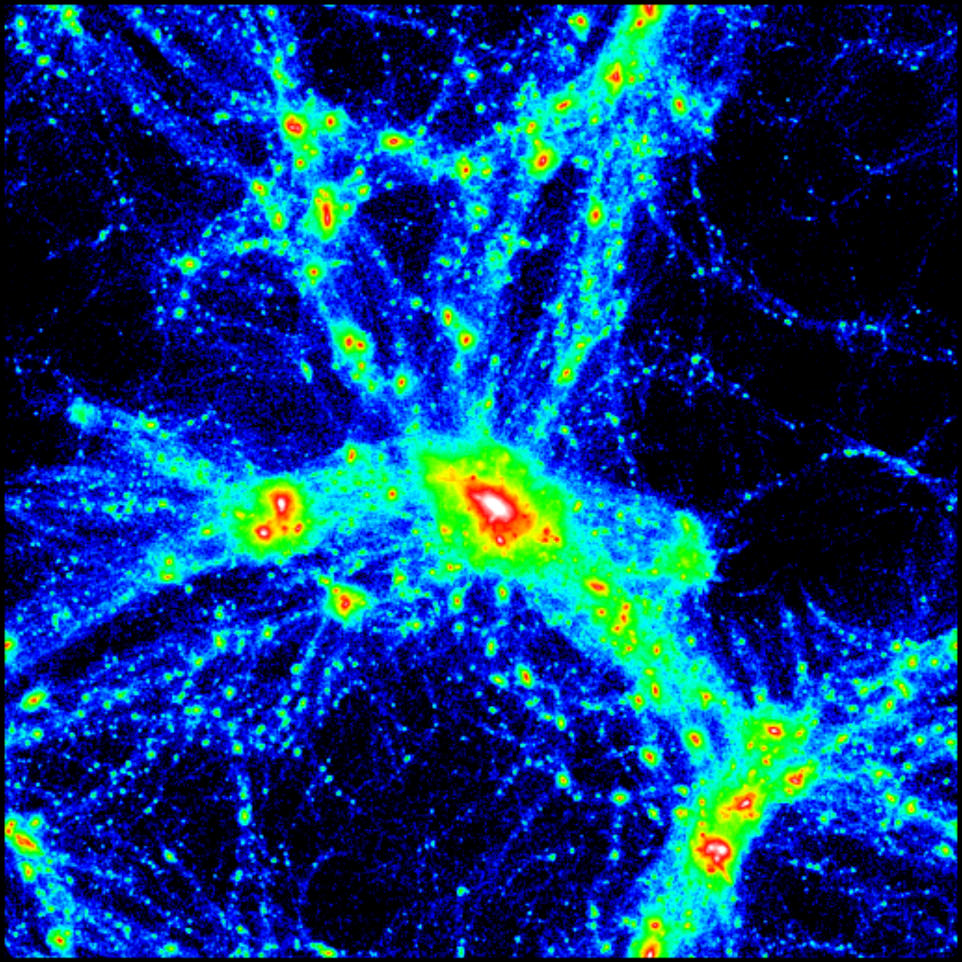
Stacking of absorption line spectra according to intervening galaxy/group redshifts



With an effective exposure: ~ 10 Ms, no absorption is detected!

- N(OVII) < 10^{15} cm^{-2}, or < 1/10 of the column density observed around the Milky Way.
- Groups typically contain little gas at T~$10^{5.5}$-$10^{6.5}$ K, unless the Oxygen abundance is < 1/10 solar.
- Is the WHIM a hype?

Galaxy formation and evolution context

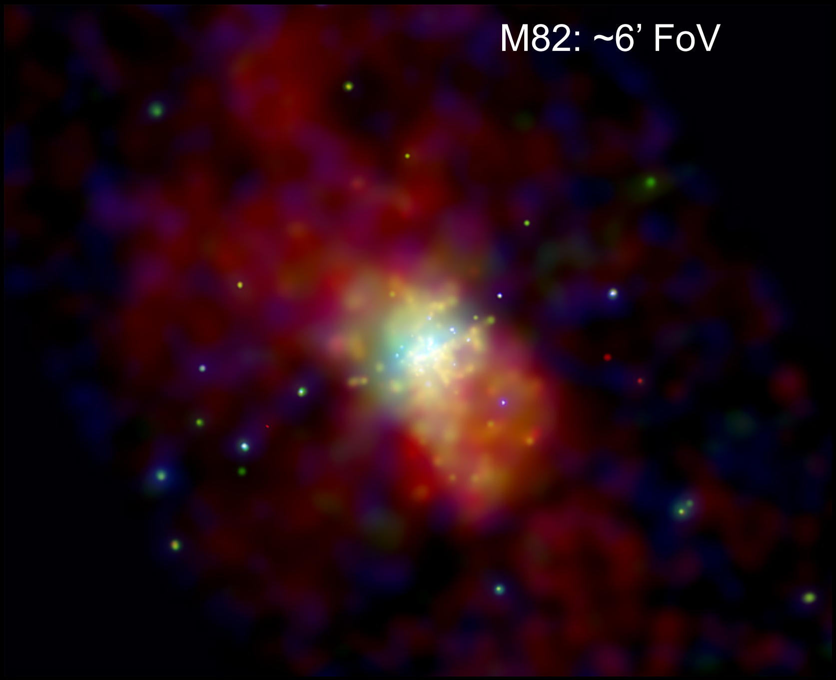


- Stars and the ISM accounts for 1/3-1/2 of the baryon expected from the gravitational mass of a galaxy.
- Where is this missing baryon matter?
  - In a hot gaseous galactic halo?
  - Or having been pushed away?

  Both are related to the galactic energy feedback.
- Without the feedback, we have the "overcooling" problem: Too much condensation to be consistent with observations (e.g., Navarro & Steinmetz 1997).

Understand the Galactic feedback is essential to the study of the galaxy formation and evolution!

Feedback from starburst galaxies



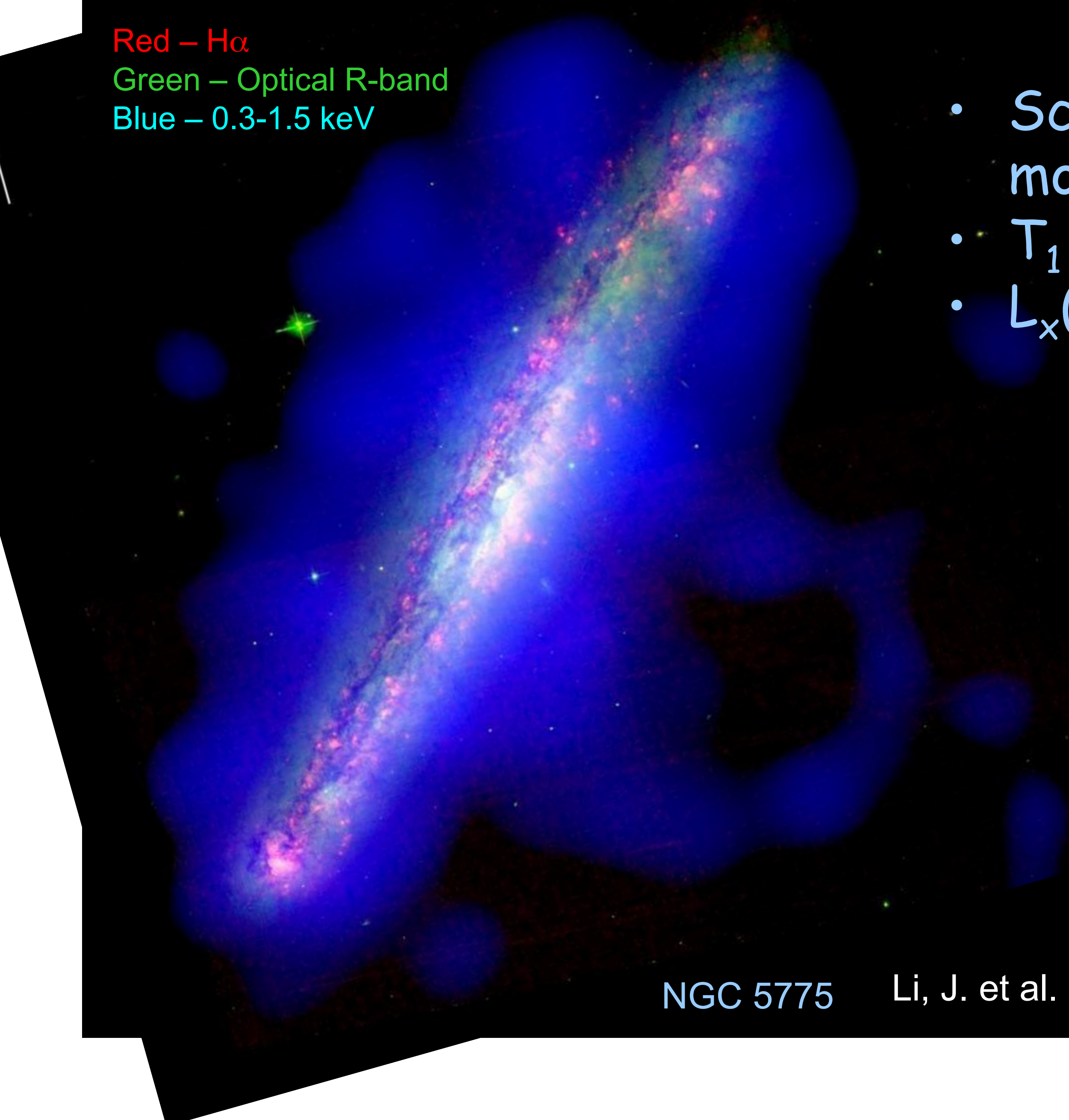
X-ray composite image from Chandra

Composite of optical (HST), infrared (Spitzer), and X-ray (Chandra) images

- Soft X-ray arises primarily from the interplay between a superwind and entrained cool gas clouds.
- Comparison between the data and simulations shows the superwind has T ~ 3-8 $\times 10^7$ K and a mass rate of ~ 2 $M_{\odot}$/yr.
- Bulk of the starburst mechanical energy escapes from the galaxy → strong effect on the galactic environment!

D. Strickland et al. (2006, 2009)

Feedback from disk-wide star formation

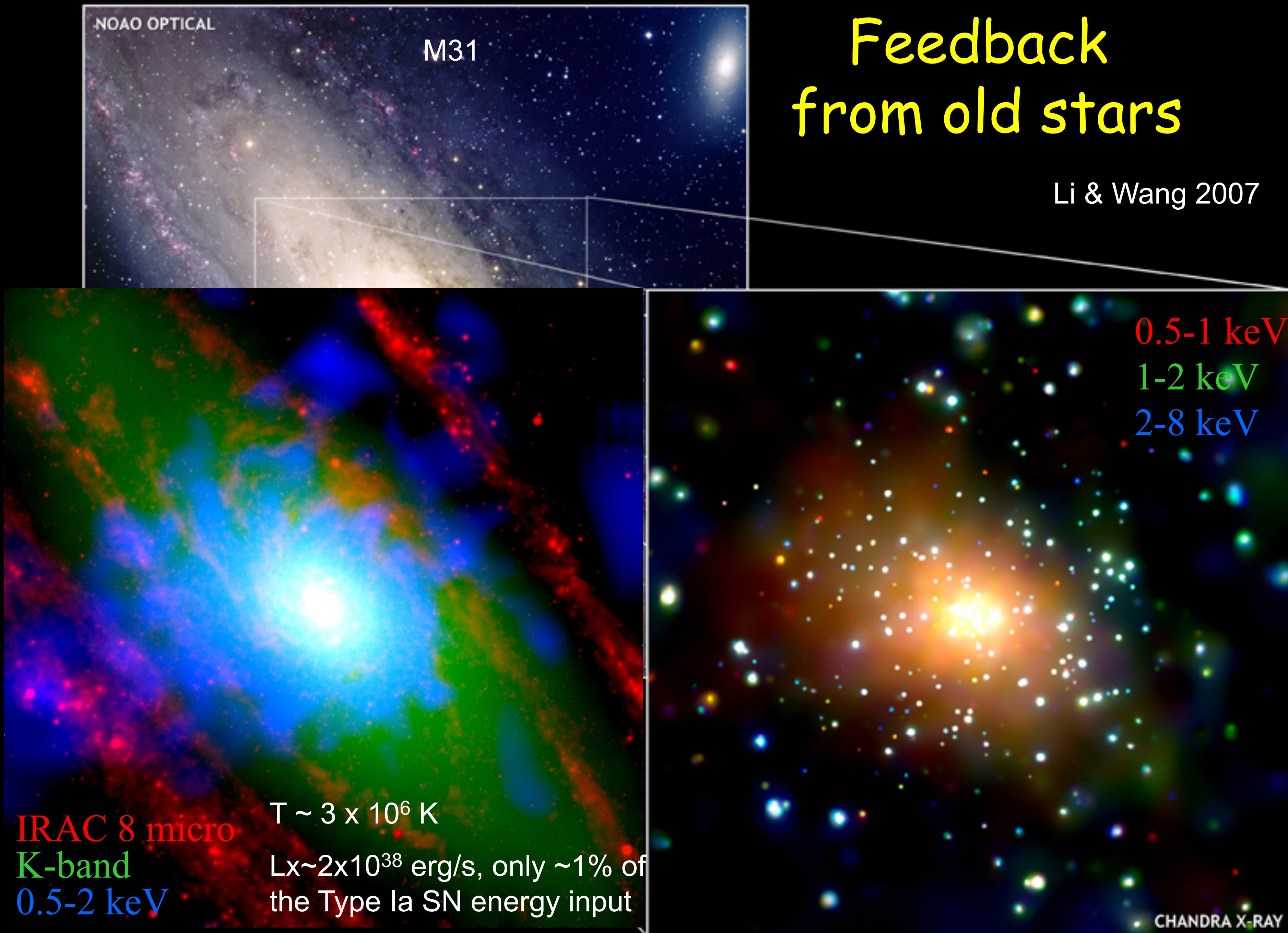


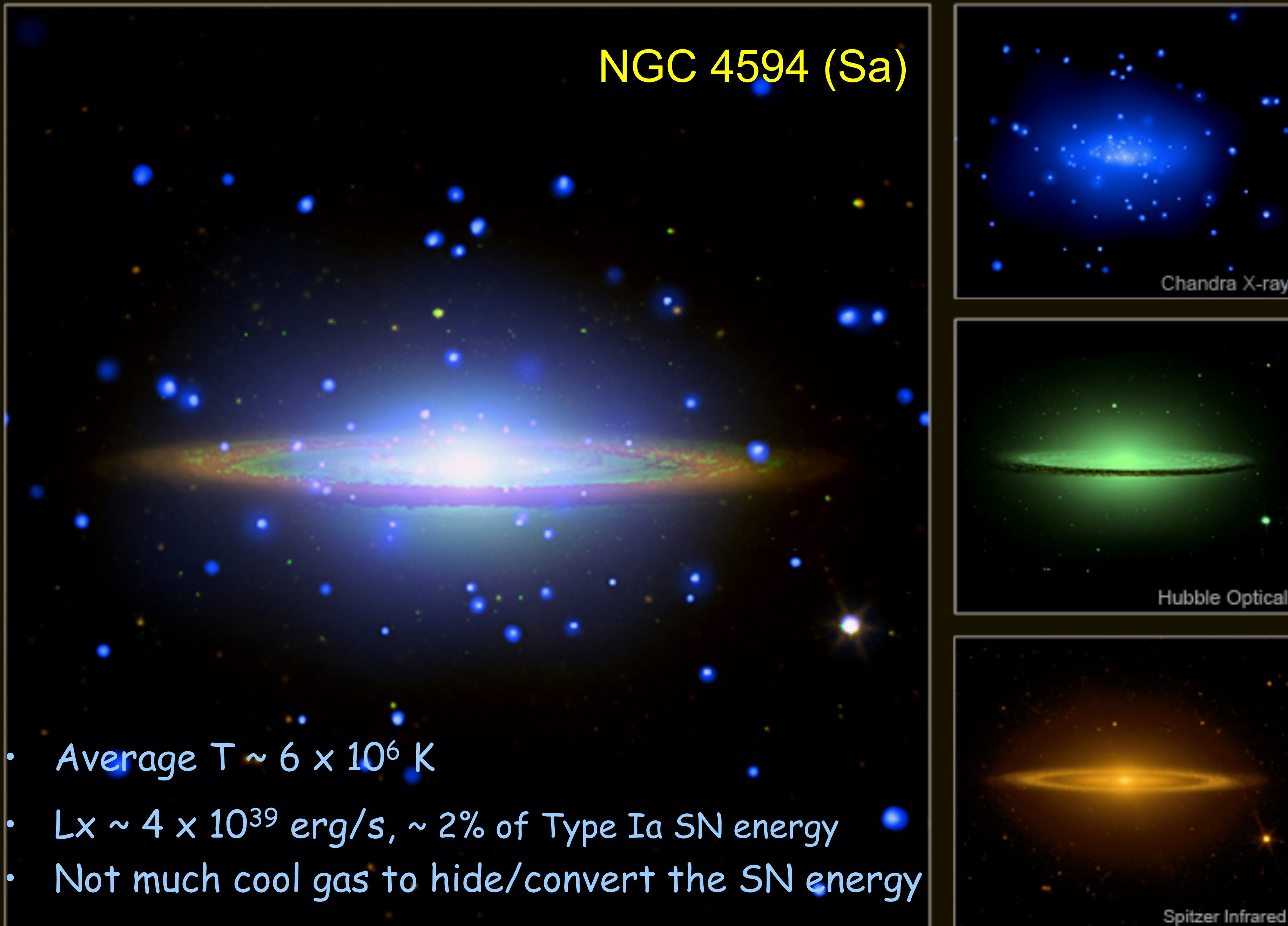
- Scale height ~ 2 kpc + more distant blubs.
- $T_1 \sim 10^{6.3}$ K, $T_2 > 10^{7.1}$ K
- L_x(diffuse) ~ 4×10^{39} erg/s

NGC 5775 Li, J. et al. (2008)

Feedback from old stars

Li & Wang 2007

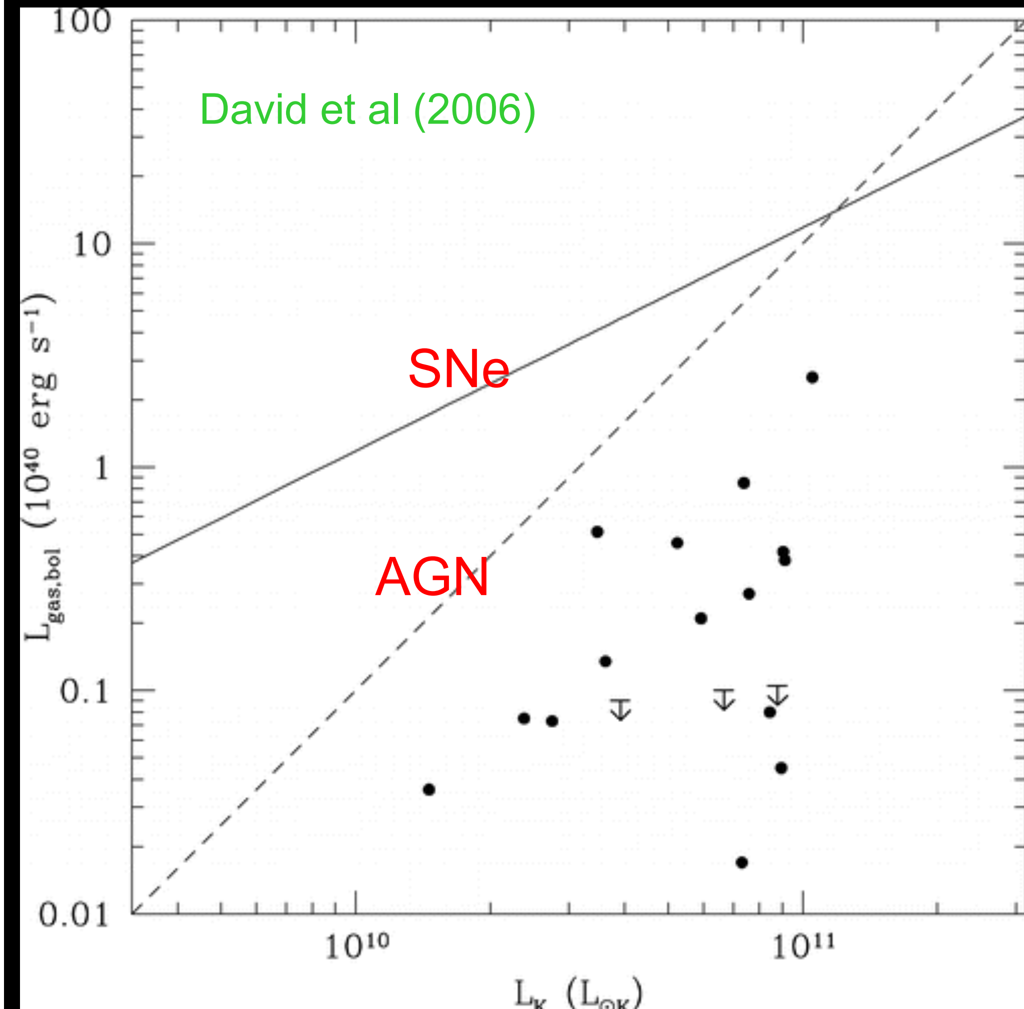




- Average T ~ 6 x 10^6 K
- Lx ~ 4 x 10^{39} erg/s, ~ 2% of Type Ia SN energy
- Not much cool gas to hide/convert the SN energy

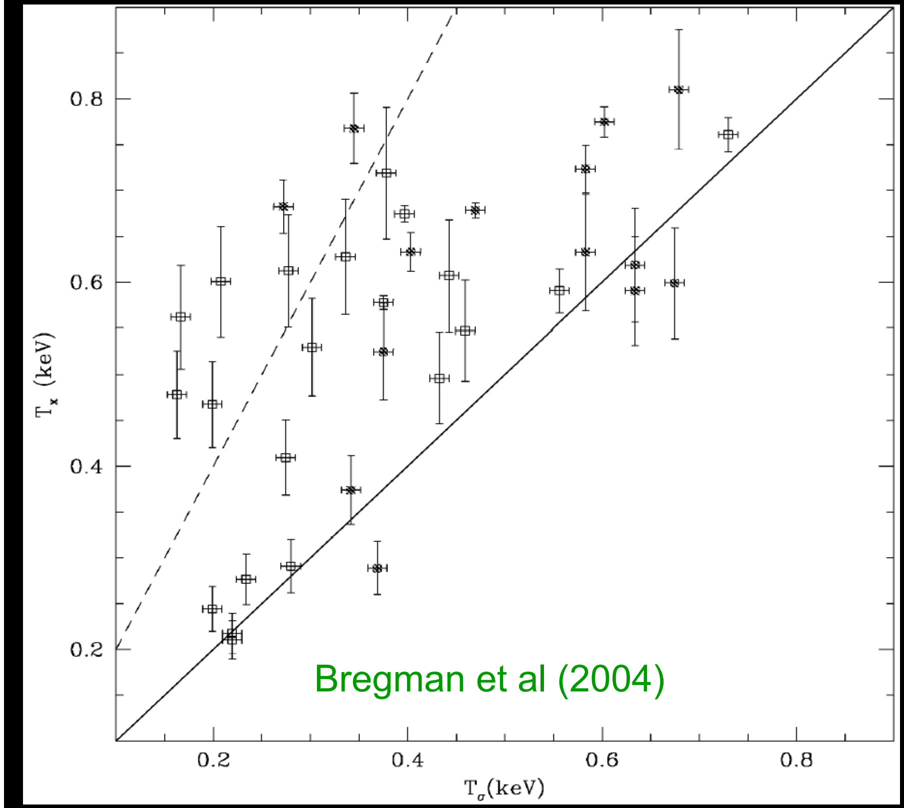
Li et al. 2007

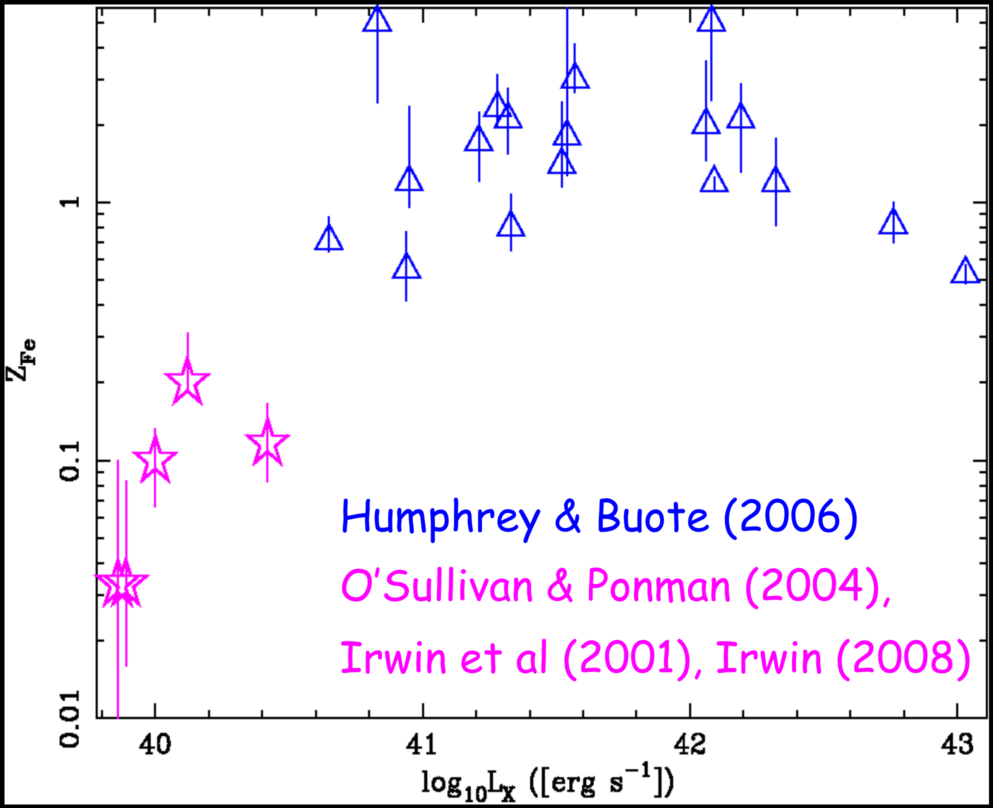
The missing energy and large L_X/L_K dispersion problems of low-mass ellipticals



- Energy input from Ia SNe: ~ 0.2 $/10^{10}L_{\odot B}/100$yr + velocity dispersion among stars.
- Observed L_X has a large dispersion, but is < 10% of the energy inputs.
- Mass loss from evolved stars: ~ 0.2 $M_\odot/10^{10}L_{\odot B}$/yr.
- Specific temperature: kT ~ 1-2 kev.
- Fe abundance ~Z_*+5($M_{SN,Fe}$/ 0.7$M_\odot$).

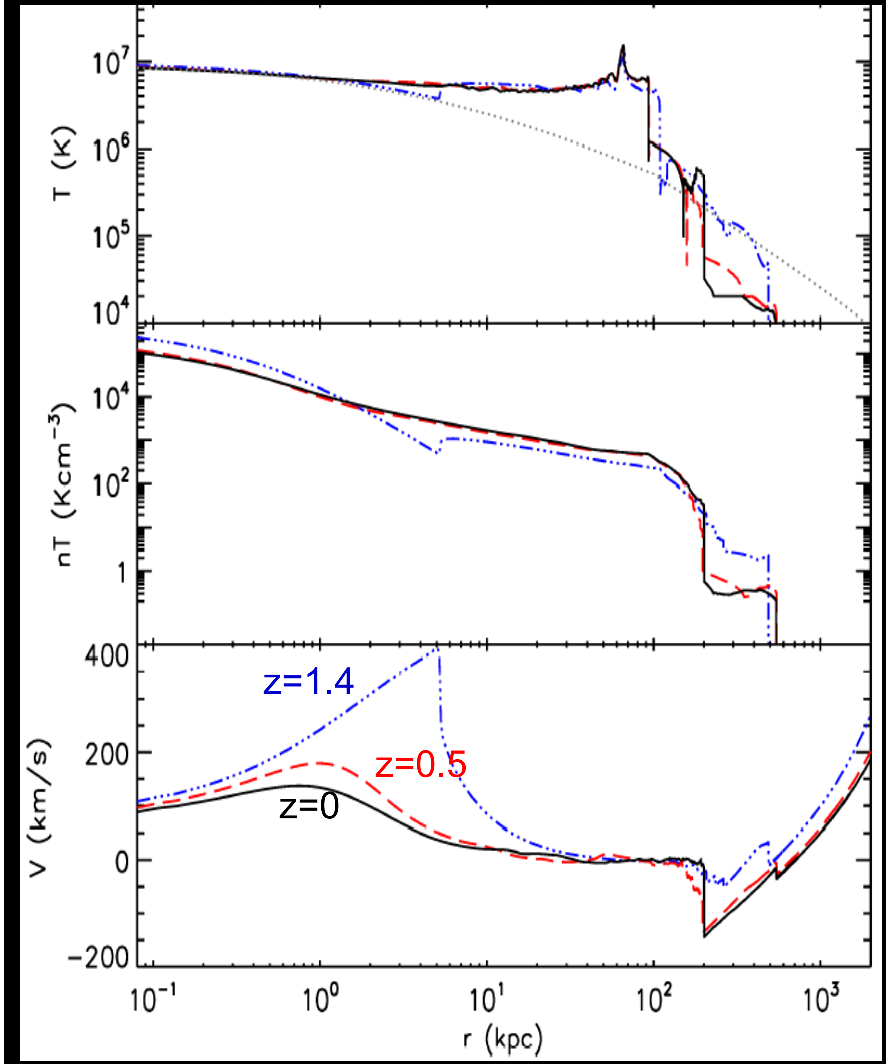
Observations of stellar feedback





- Both gas temperature and Fe abundance are less than the expected.

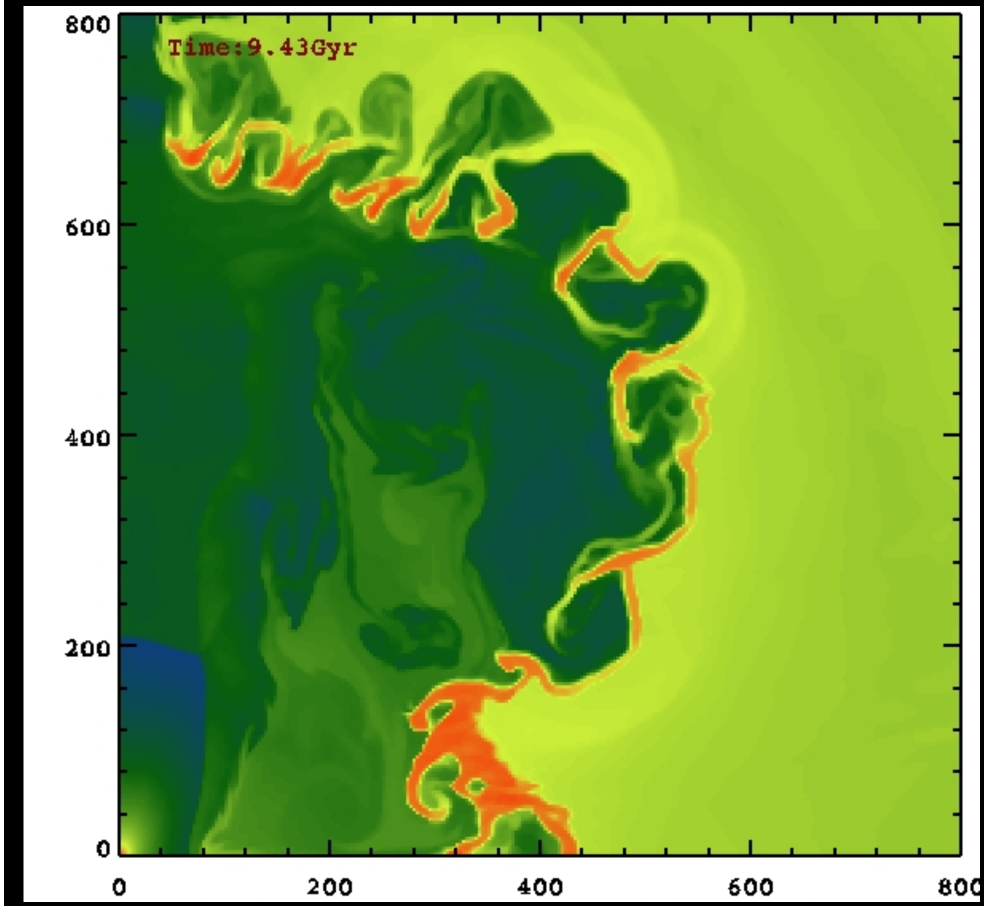
Feedback and galaxy formation: 1-D simulations



Tang, Wang, et al 2009, see also Kim, Wise, & Abel 2009

- Evolution of both dark and baryon matters (with the final total mass of 10^{12} $M_\odot$).
- Initial spheroid formation (5×10^{10} $M_\odot$) → starburst → shock-heating and expanding of surrounding gas.
- Later Type Ia SNe → wind/outflow, maintaining a low-density, high-T gas halo and preventing a cooling flow.
- Outflow can be long-lasting → higher Lx and more extended profile.
- The dependence on the feedback strength, galaxy mass, and environment → L_X/L_B dispersion.

2-D simulations of the feedback: bulge wind

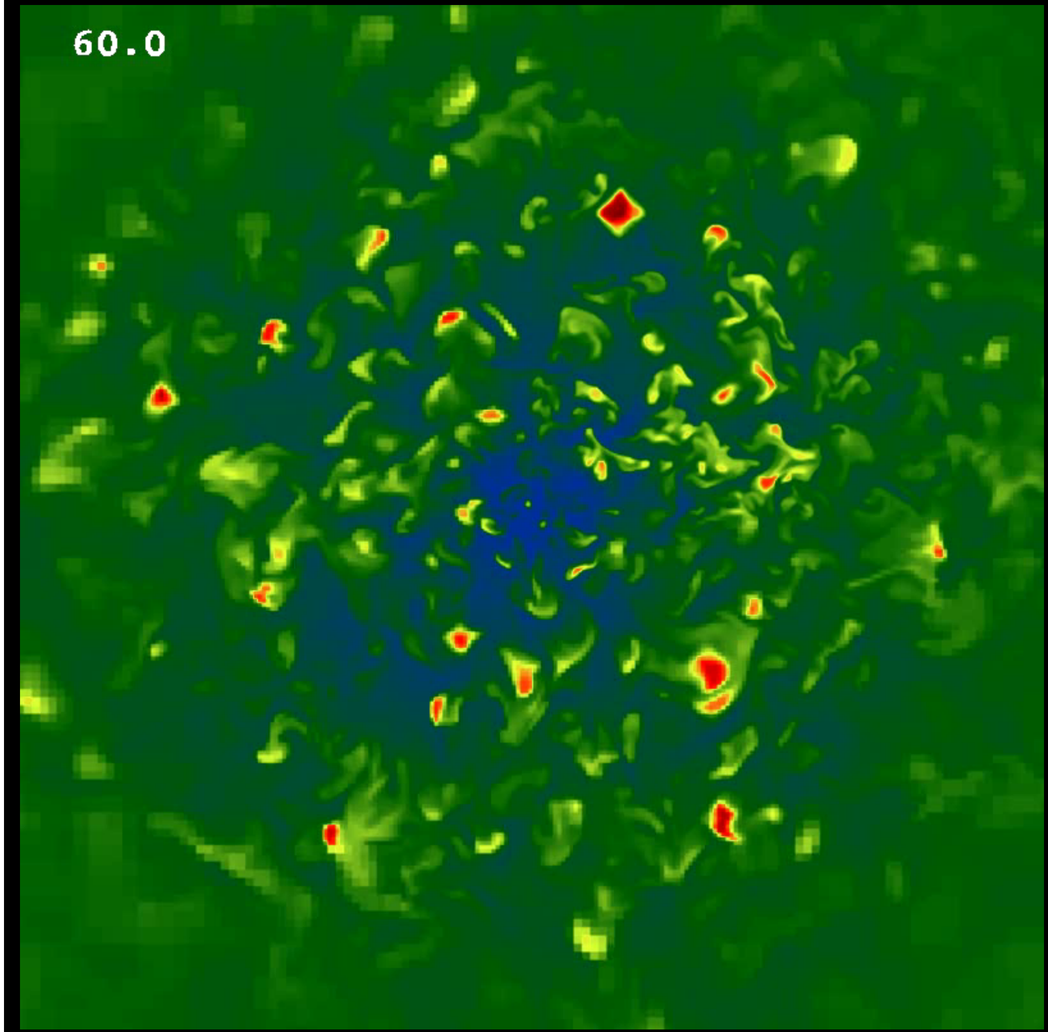


Setup: an ellipsoid bulge (q=0.6), a disk, and an NFW halo

- Qualitatively consistent with the 1-D results
- Instabilities at the contact discontinuities → formation of HVCs?

Tang & Wang (2009)

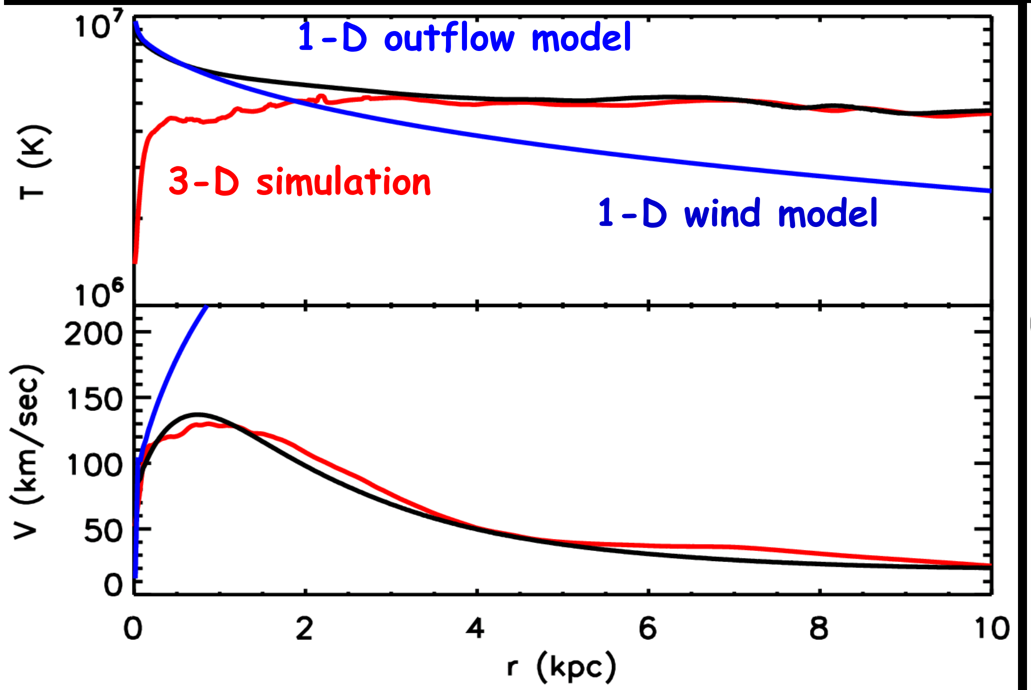
Subsonic Outflow: 3-D Simulations

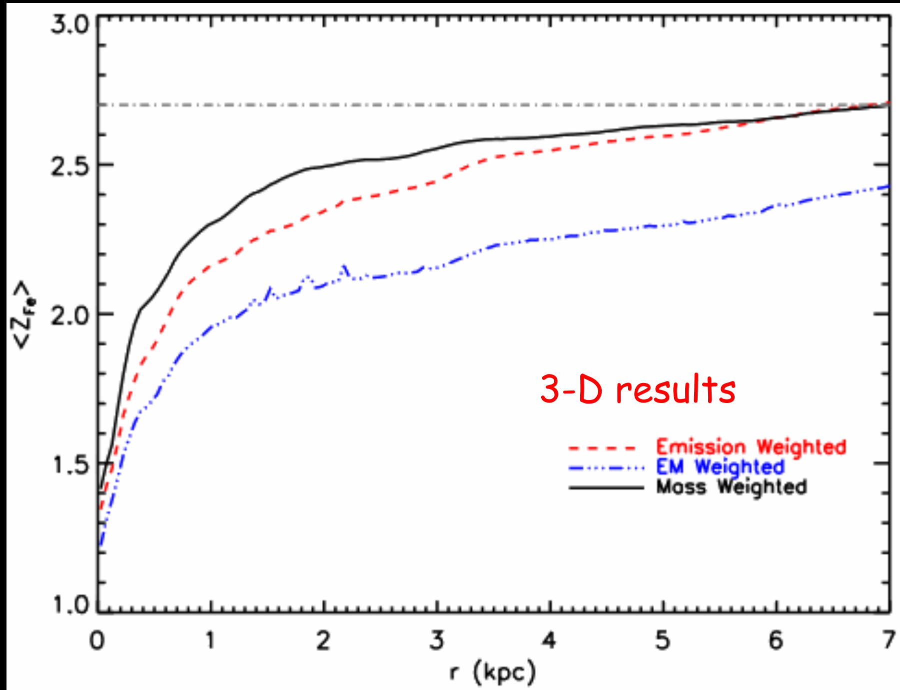


Fe abundance map (Tang & Wang in prep)

- Adaptive mesh refinement → ~2 pc spatial resolution
- Sporadic SNe in both time and space
- Continuous and smooth mass injection, following stellar light
- Broad temperature and density distributions → Low X-ray measured temperature and metal abundance if modeled with a 1- or 2-T plasma
- Fe ejecta moves much faster than stellar mass-loss materials.

3-D Subsonic Outflow Simulations: Results





Positive temperature gradient, mimicking a "cooling flow"!

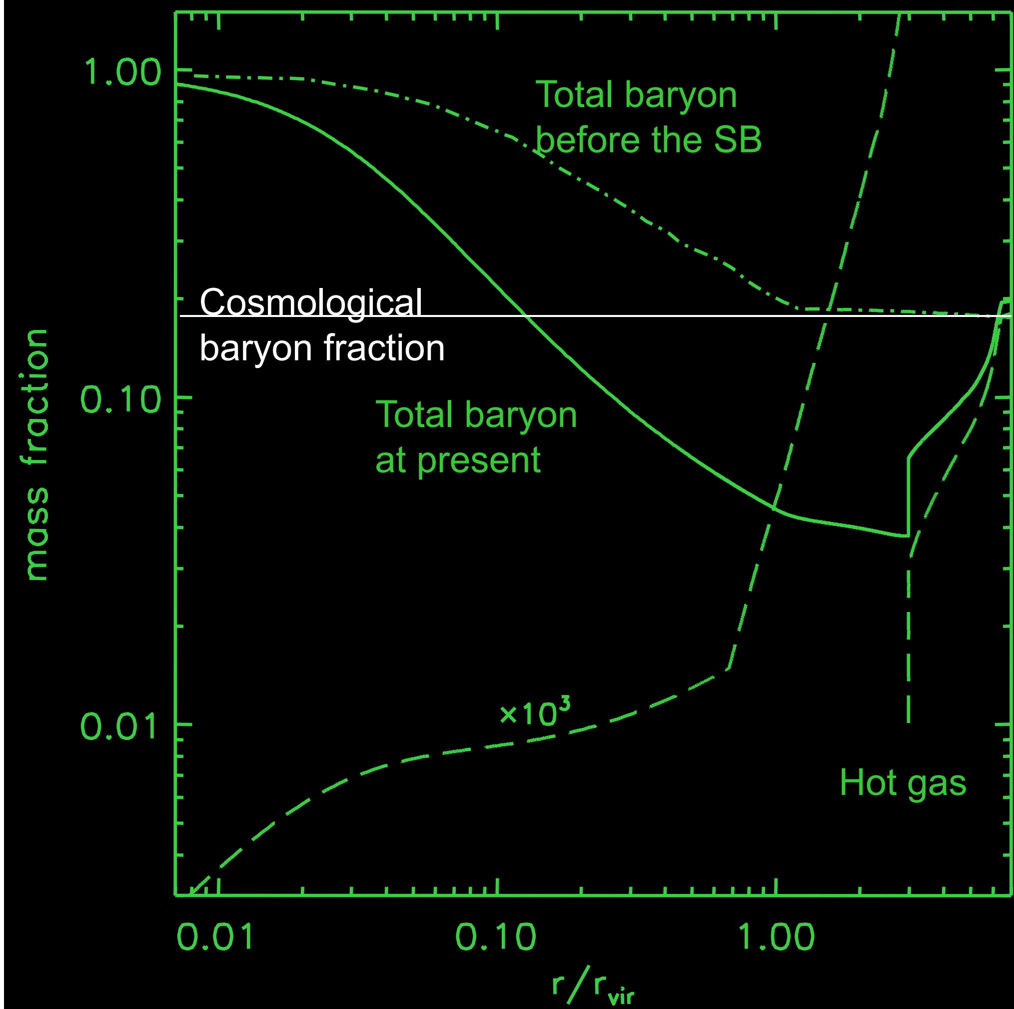
Positive Fe abundance gradient, as observed in central regions of ellipticals

Summary

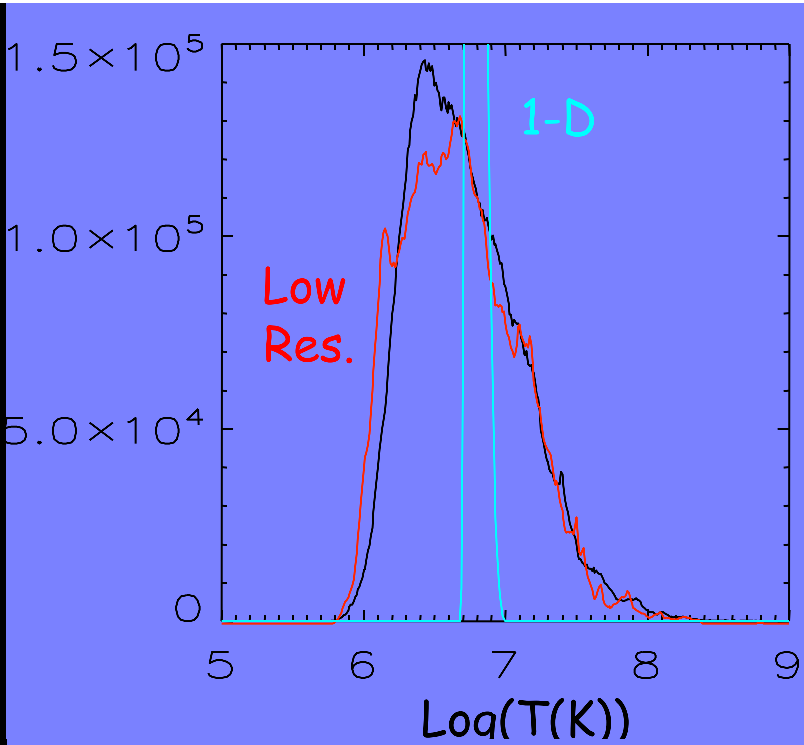
- At least two components of diffuse hot gas:
  - Disk – typically driven by massive stars
  - Bulge – heated primarily by Type-Ia SNe
- Characteristic extent ~ a few kpc, except for starburst galaxies.
- Temperature ~ a few 10^6 K. but also evidence for a poorly constrained T >~ 10^7 K component.
- Stellar feedback can play a key role in galaxy evolution:
  - Initial burst leads to the heating and expansion of gas beyond the virial radius.
  - Ongoing feedback can keep this circum-galactic medium from cooling and maintain a hot gas outflow.

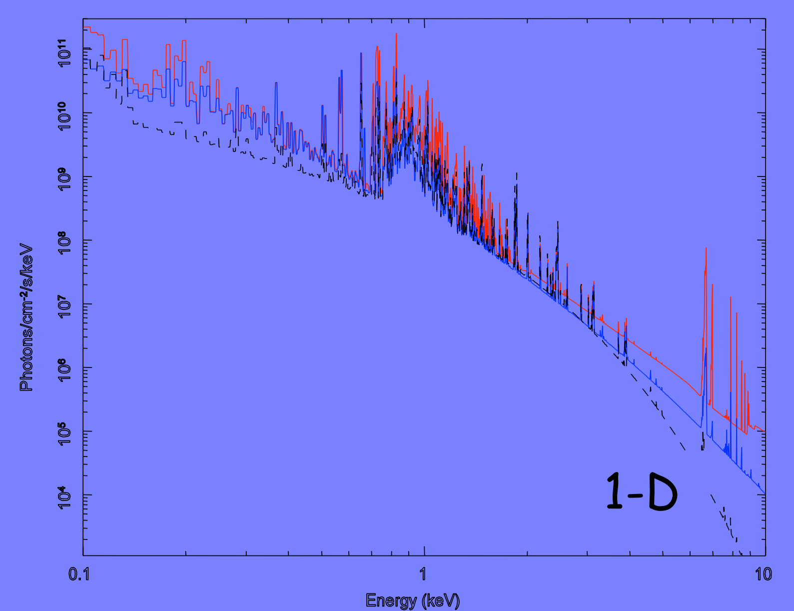
    → explaining the missing galactic feedback, the baryon deficit around galaxies, and the passive evolution of stellar spheroids.
- 3-D structures significantly affect X-ray measurements (Lx, T, intensity profile, and Fe abundance).

Galaxies such as the MW evolve in hot bubbles of baryon deficit!



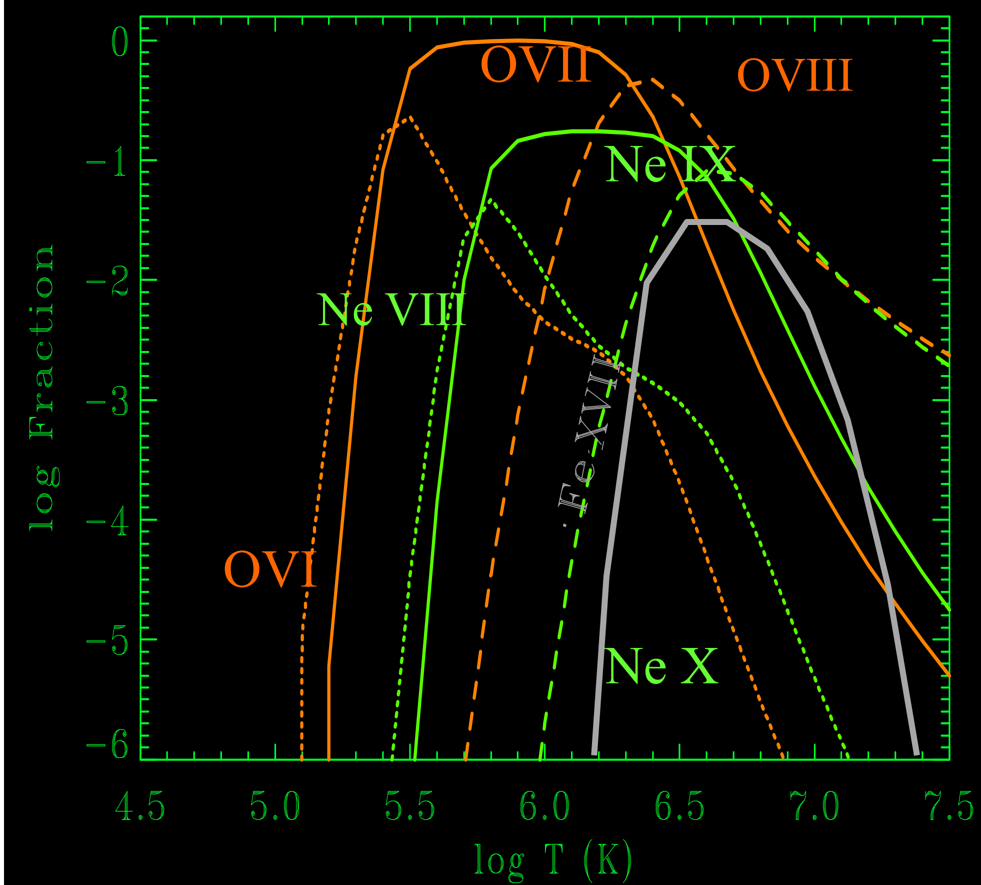
- Explains the lack of large-scale X-ray halos.
- Bulge wind drives away the present stellar feedback.





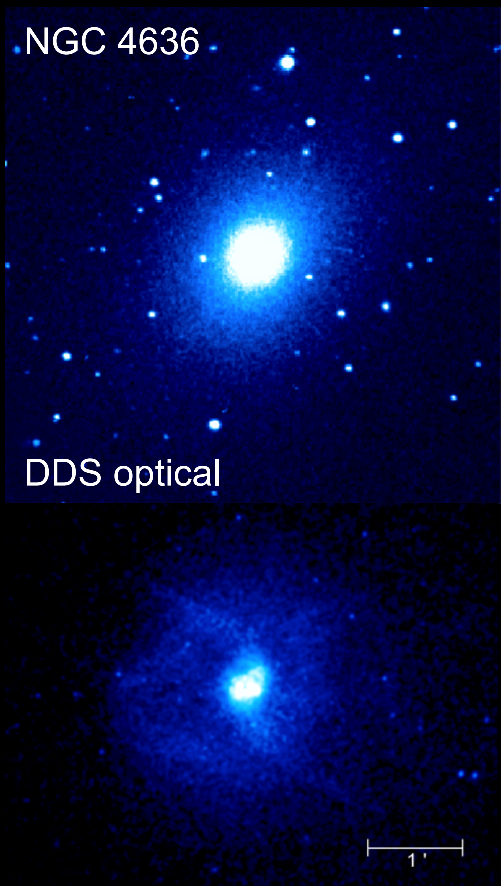
3-D Effects

- Large dispersion →
  - enhanced emission at both low and high temperatures
  - Overall luminosity increase by a factor of ~ 3.
  - Low metallicity if modeled with a 1-T plasma.
- Consistent with the 1-D radial density and temperature distributions, except for the center region.

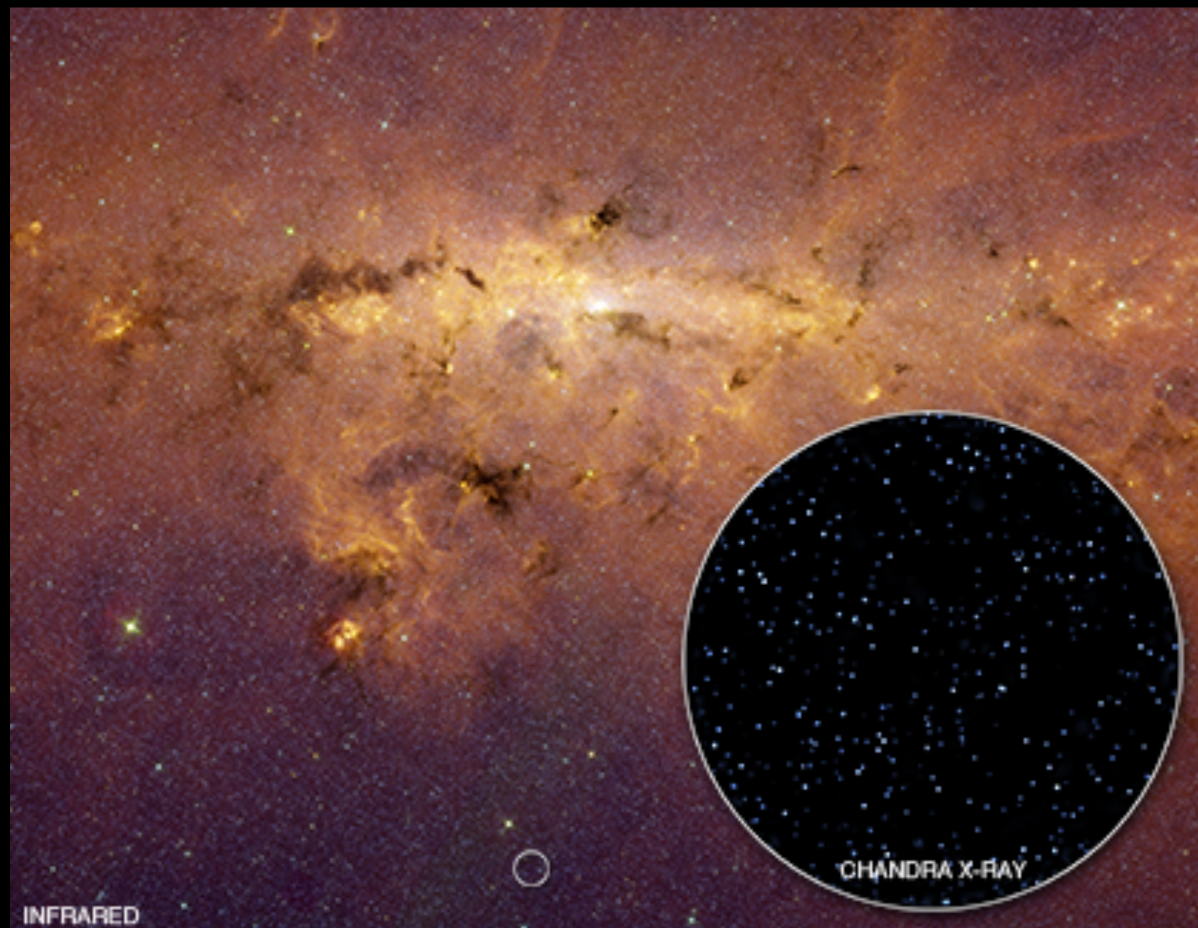


Assuming solar abundances and CIE

Galactic bulge and elliptical galaxies



Chandra X-ray



C. Jones et al. (2001)

M.Revnivtsev et al. (2009)

Conclusions

- Diffuse hot gas is strongly concentrated toward galactic disks/bulges (< 20 kpc) due to the feedback.
- But the bulk of the feedback is not detected and is probably propagated into very hot (~10^7 K) halos.
- The feedback from a galactic bulge likely plays a key role in galaxy evolution:
  - Initial burst led to the heating and expansion of gas beyond the virial radius
  - Ongoing feedback keeps the gas from forming a cooling flow and starves SMBHs
  - Mass-loaded outflows account for diffuse X-ray emission from galactic bulges.

Galaxies like ours reside in hot bubbles!

No overcooling or missing energy problem!