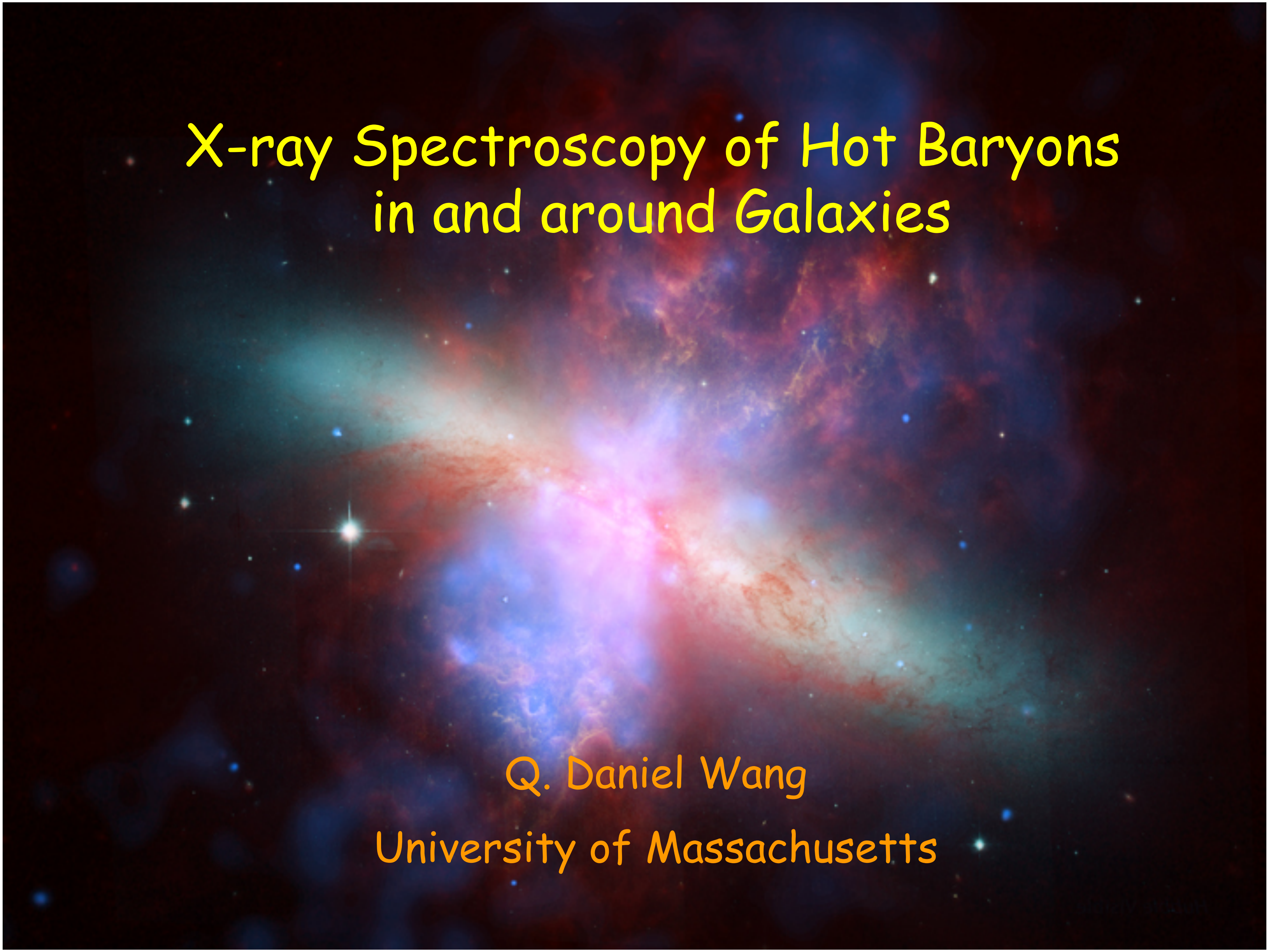
X-ray Spectroscopy of Hot Baryons in and around Galaxies



Q. Daniel Wang

University of Massachusetts

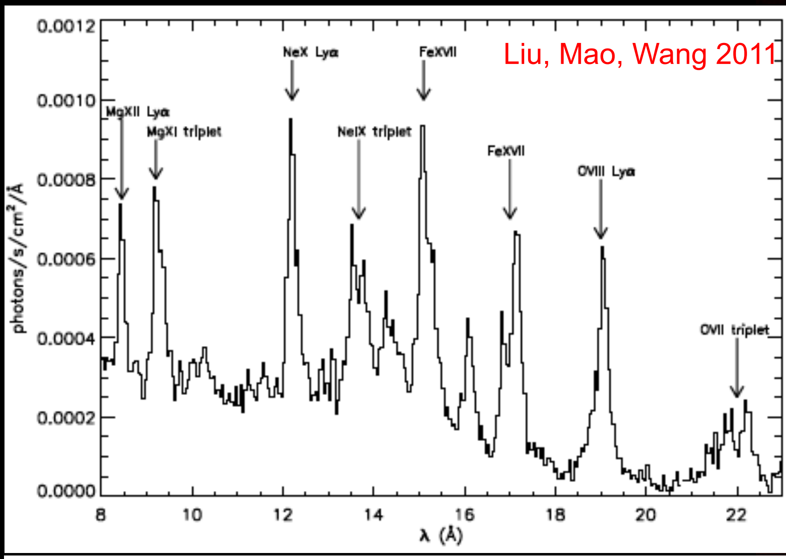
Why Hot Plasma?

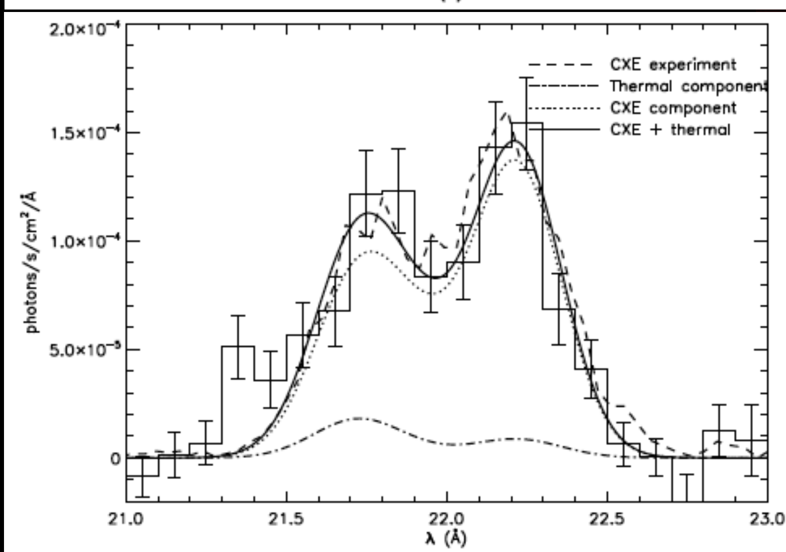
- Cold ISM+Stars account for <1/3 of the baryon expected from the gravitational mass of a galaxy.
- Much of this missing baryon matter is believed to be in diffuse hot plasma around galaxies.
- The hot plasma is thus a gas reservoir of galaxies, as well as a feedback depository.

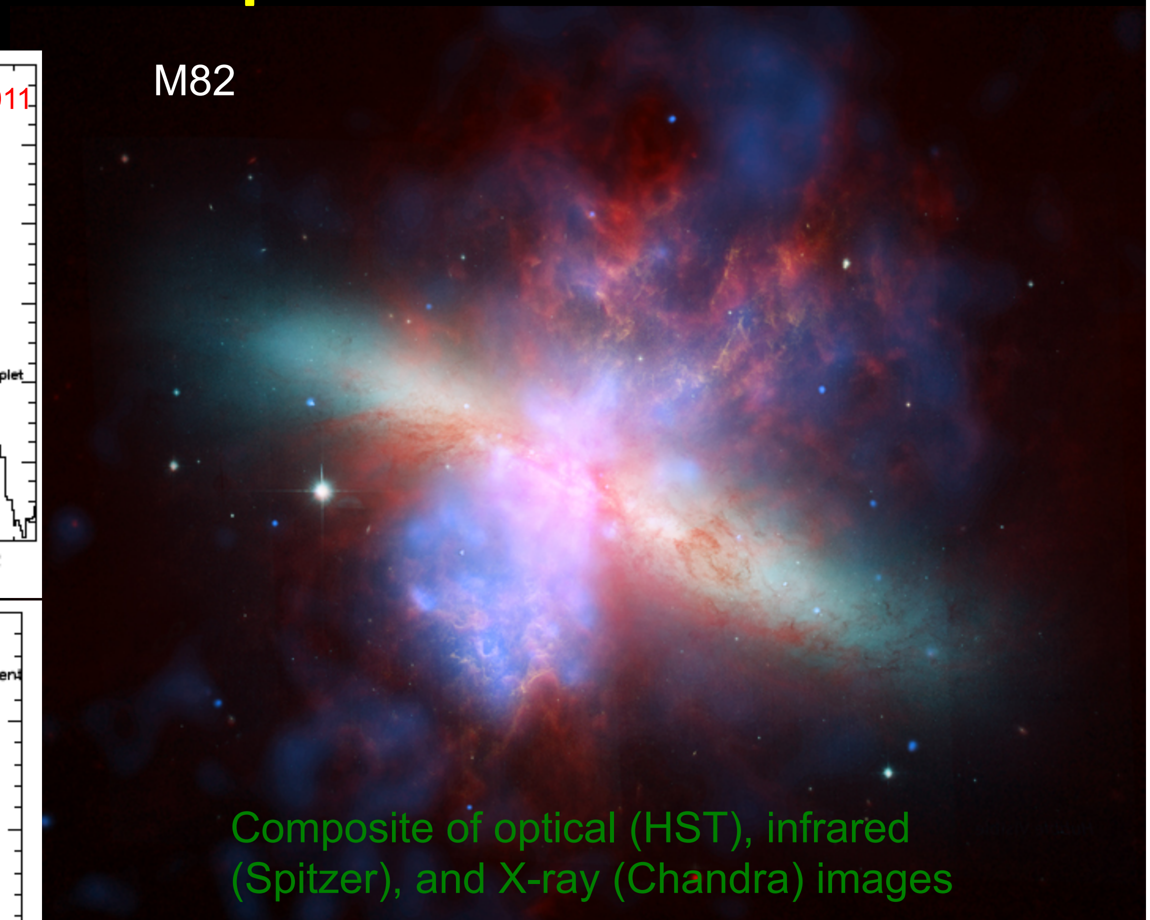
Questions:

1. What are the spatial, thermal, chemical, and kinetic properties of the hot plasma?
2. How does the plasma interact with other phases of the ISM?

Does diffuse soft X-ray emission trace hot plasma?



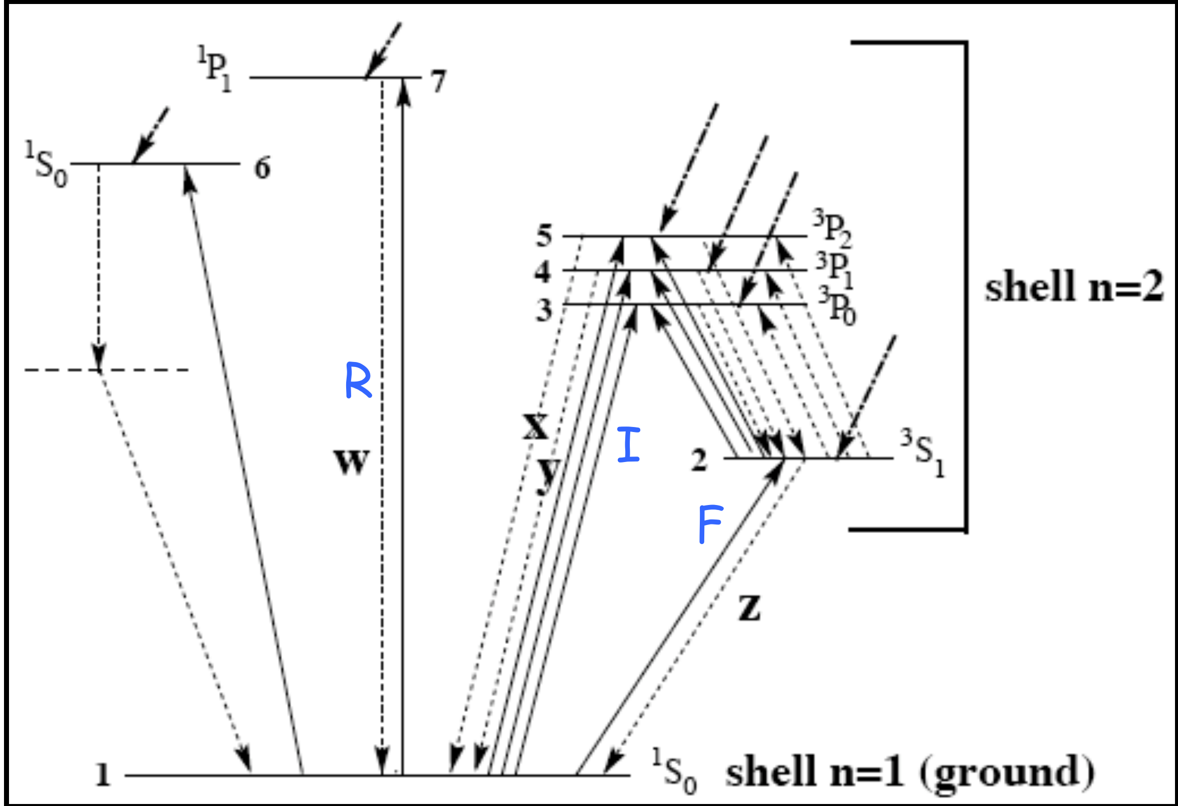




Composite of optical (HST), infrared (Spitzer), and X-ray (Chandra) images

The most likely cause of the high f/r ratio is the charge exchange, which has a cross-section of ~10^{-15} cm^{-2}

X-ray spectroscopy: He-like ions

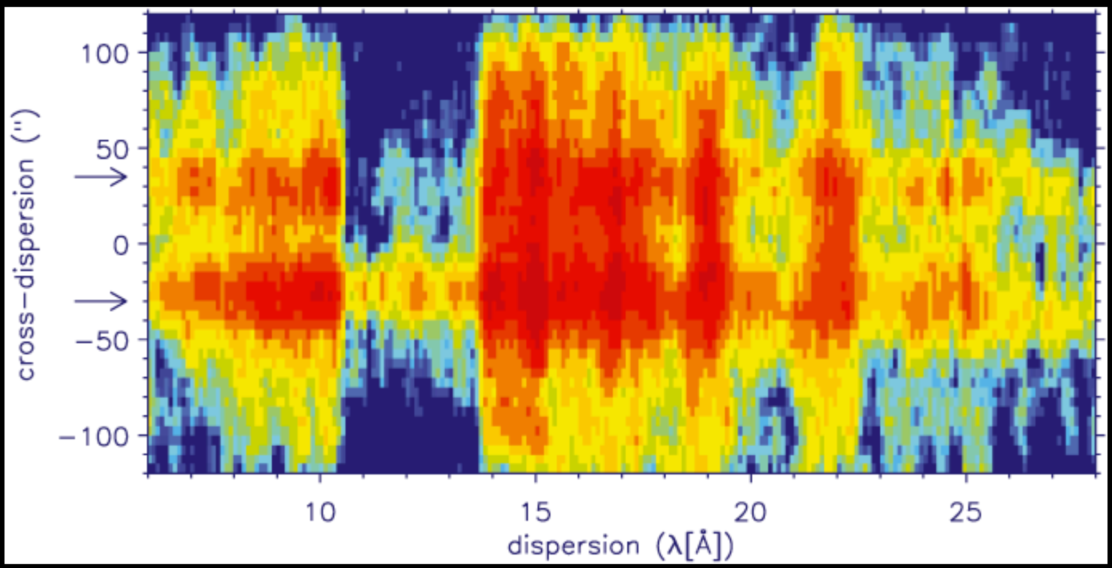


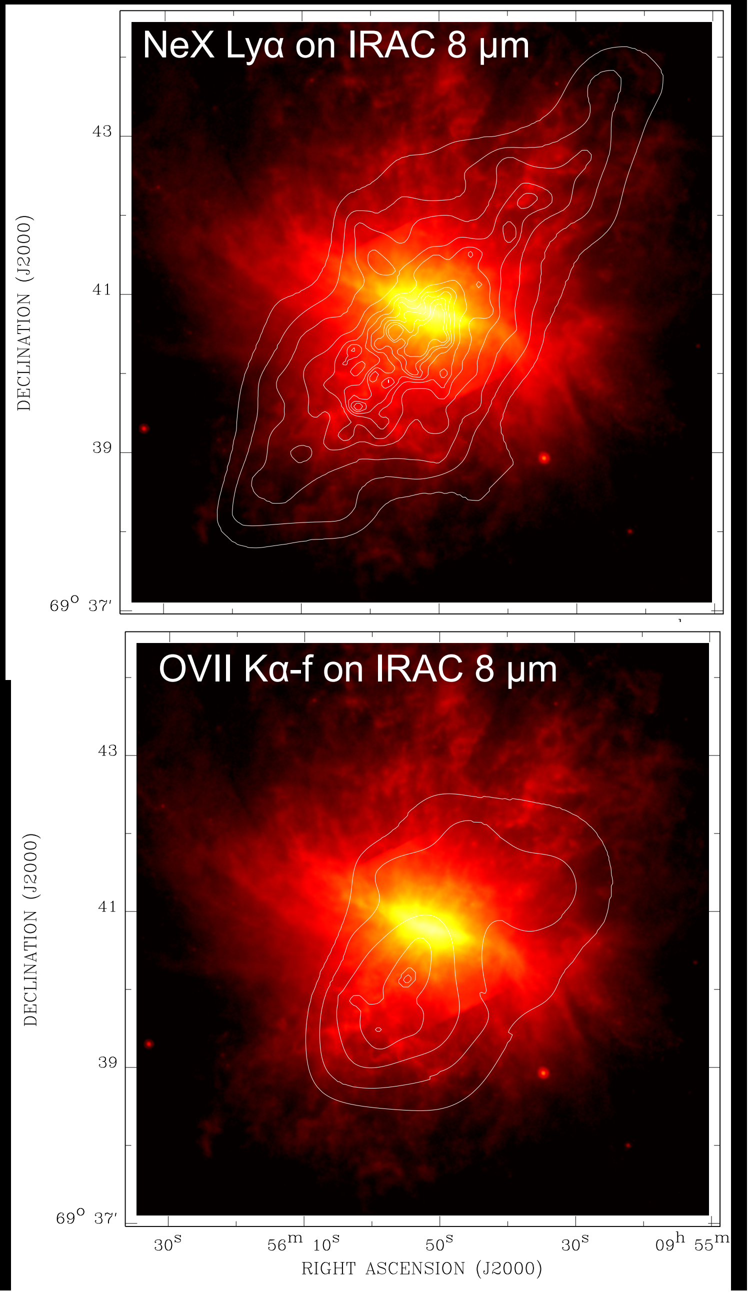
Simplified Grotrian diagram Porquet & Dubau (2000)

- **R (or W):** Resonance line (allowed)
  $1s2p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$
  electronic dipole transition
- **I (or x+y):** Intercombination line
  $1s2p\ ^3P_1 \rightarrow 1s^2\ ^1S_0$ (y)
  $1s2p\ ^3P_2 \rightarrow 1s^2\ ^1S_0$ (x)
  Triple or quadruplet
- **F (or z):** Forbidden line
  $1s2s\ ^3S_1 \rightarrow 1s^2\ ^1S_0$
  relativistic magnetic dipole transition (A_{ji} very low)

The most likely cause of the high f/r ratio is the charge exchange, which has a cross-section of ~10^{-15} cm^{-2}

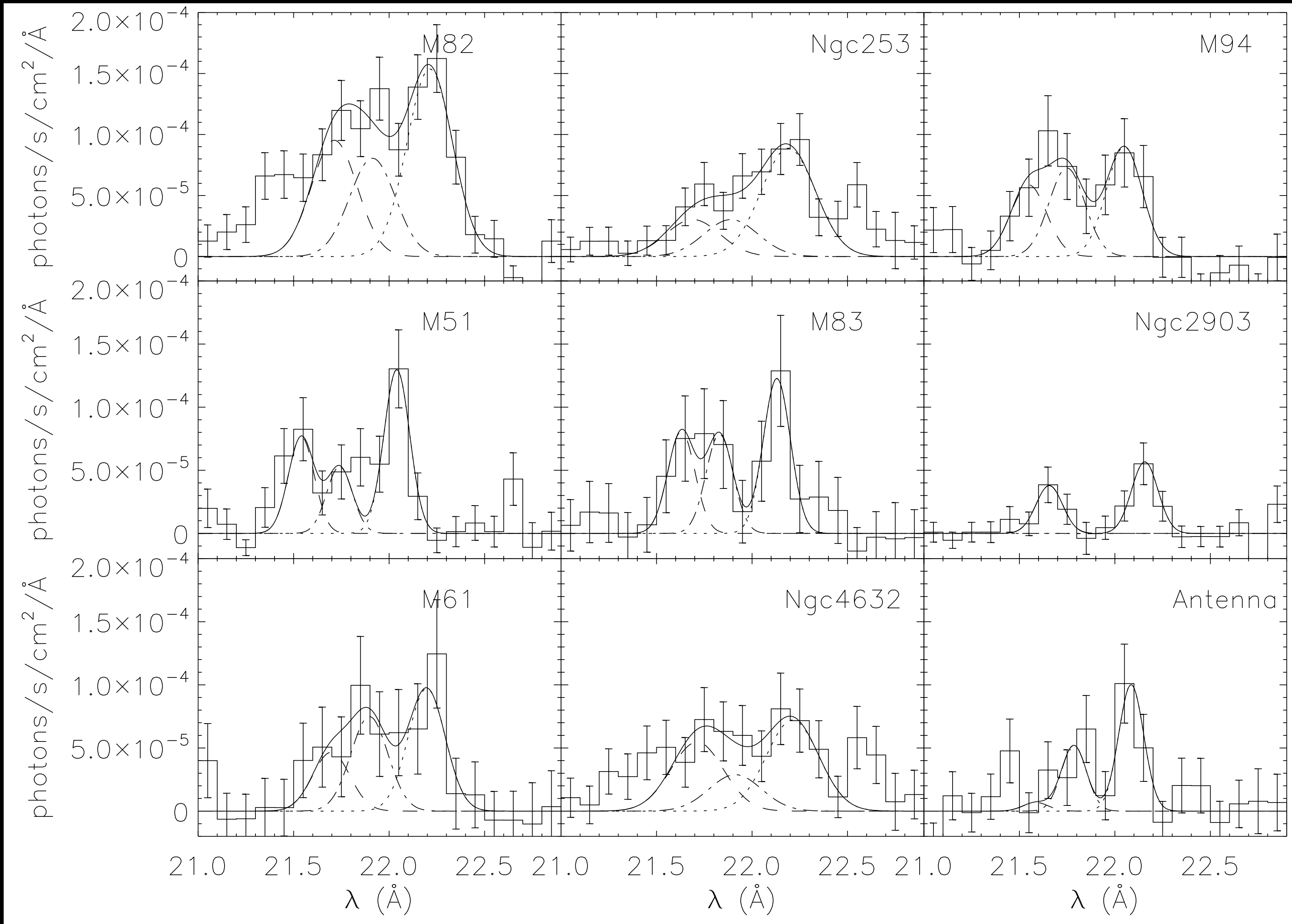
Spatially-resolved X-ray spectroscopy



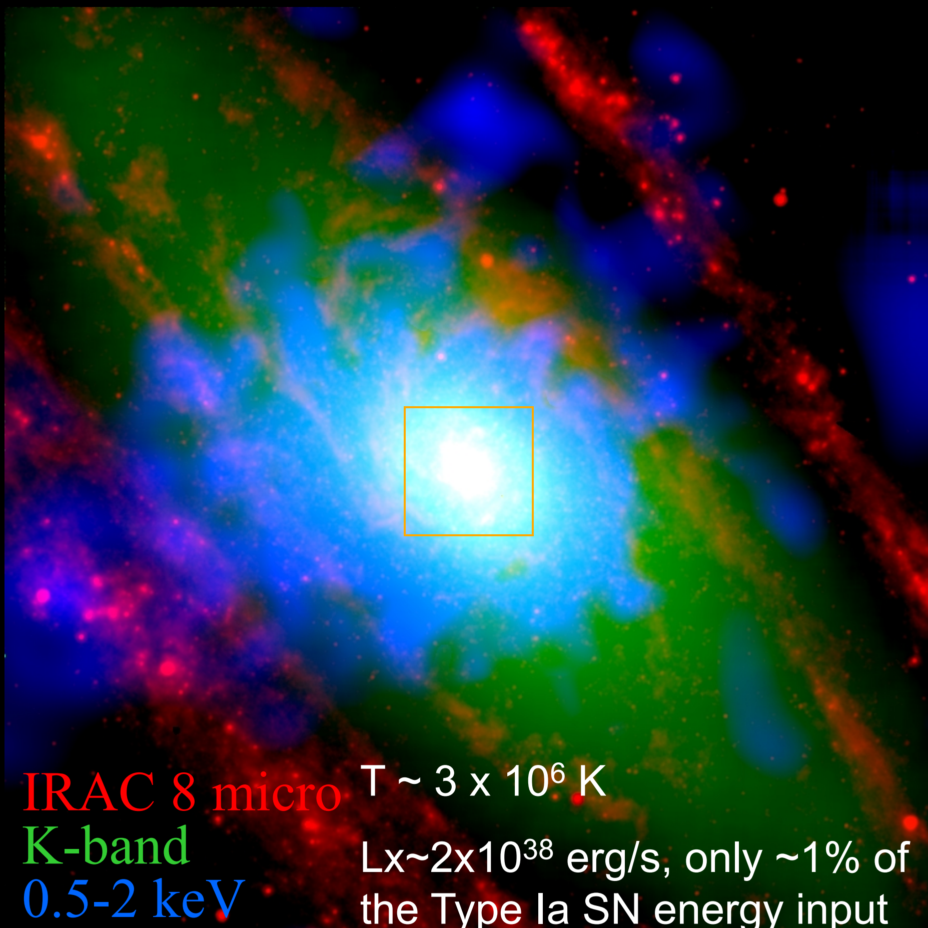


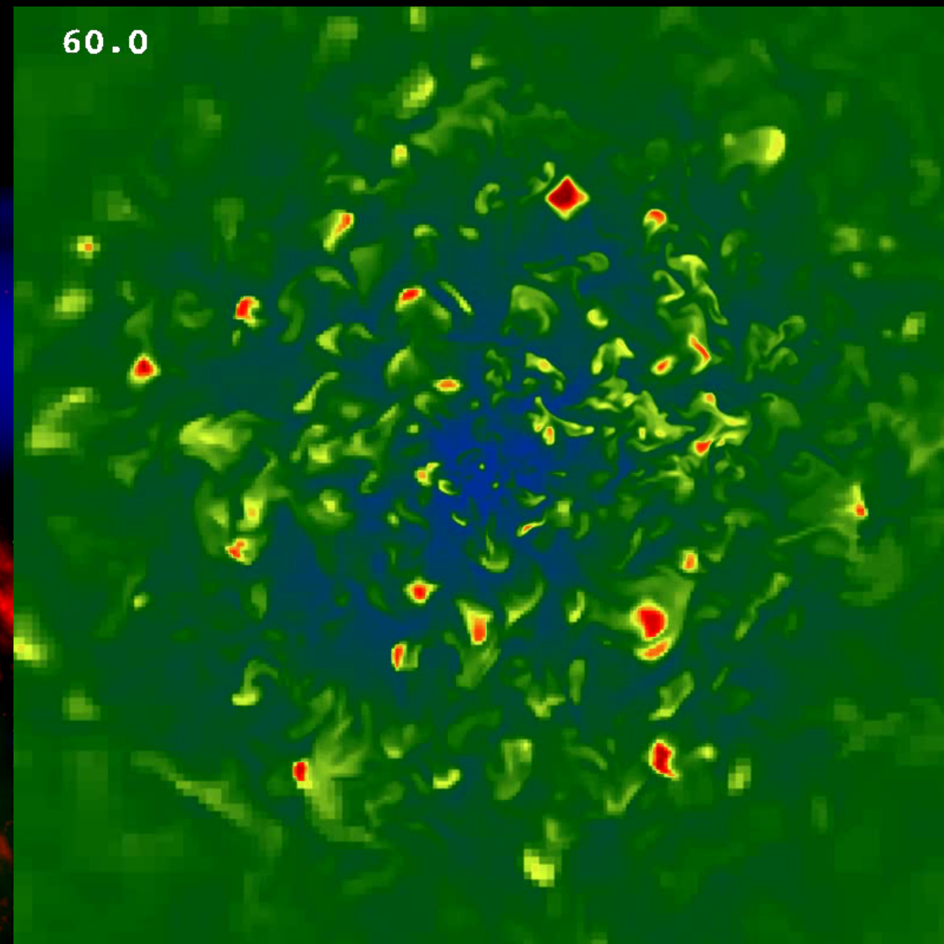
One may also measure the velocity using two observations with opposite dispersion directions

OVII Ka Triplets of Nearby Galaxies



Diffuse hot gas in the bulge of M31

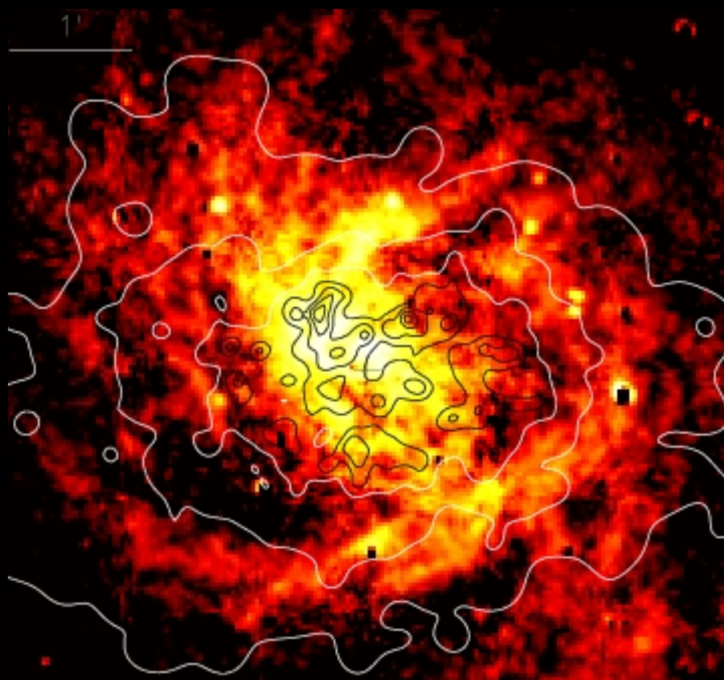


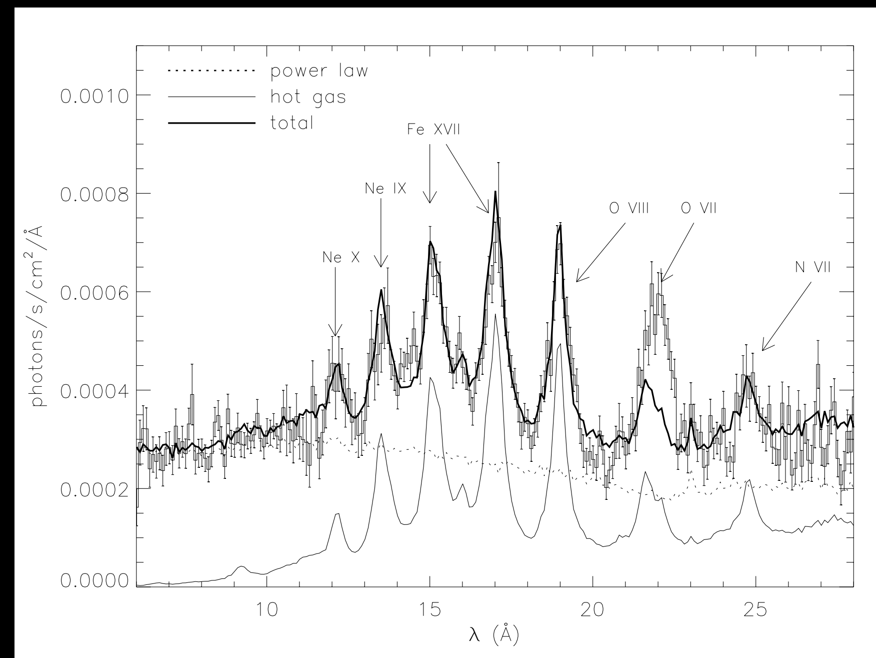


Li & Wang 2007

Tang, Wang, MacLow, & Joung 2009

XMM-Newton RGS spectrum



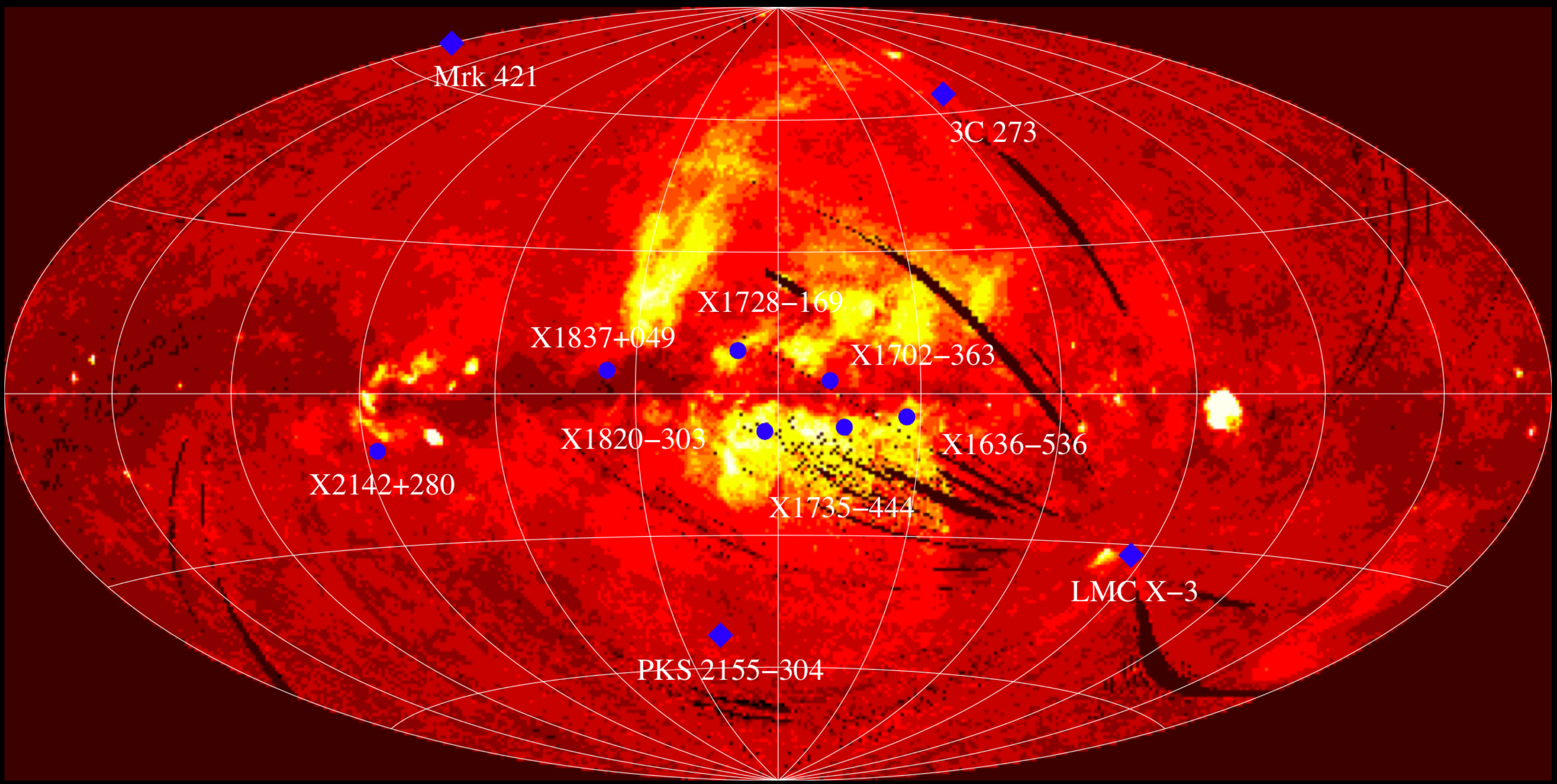


Liu, Wang, Li, & Peterson 2010

Strong deviation of the OVII Ka triplet from the model: the forbidden line at 21.80 Å is much stronger than the resonance line at 21.60 Å.

Much of the soft X-ray emission from galaxies seems to trace the interplay between hot plasma with cold gas!

X-ray Absorption Line Spectroscopy

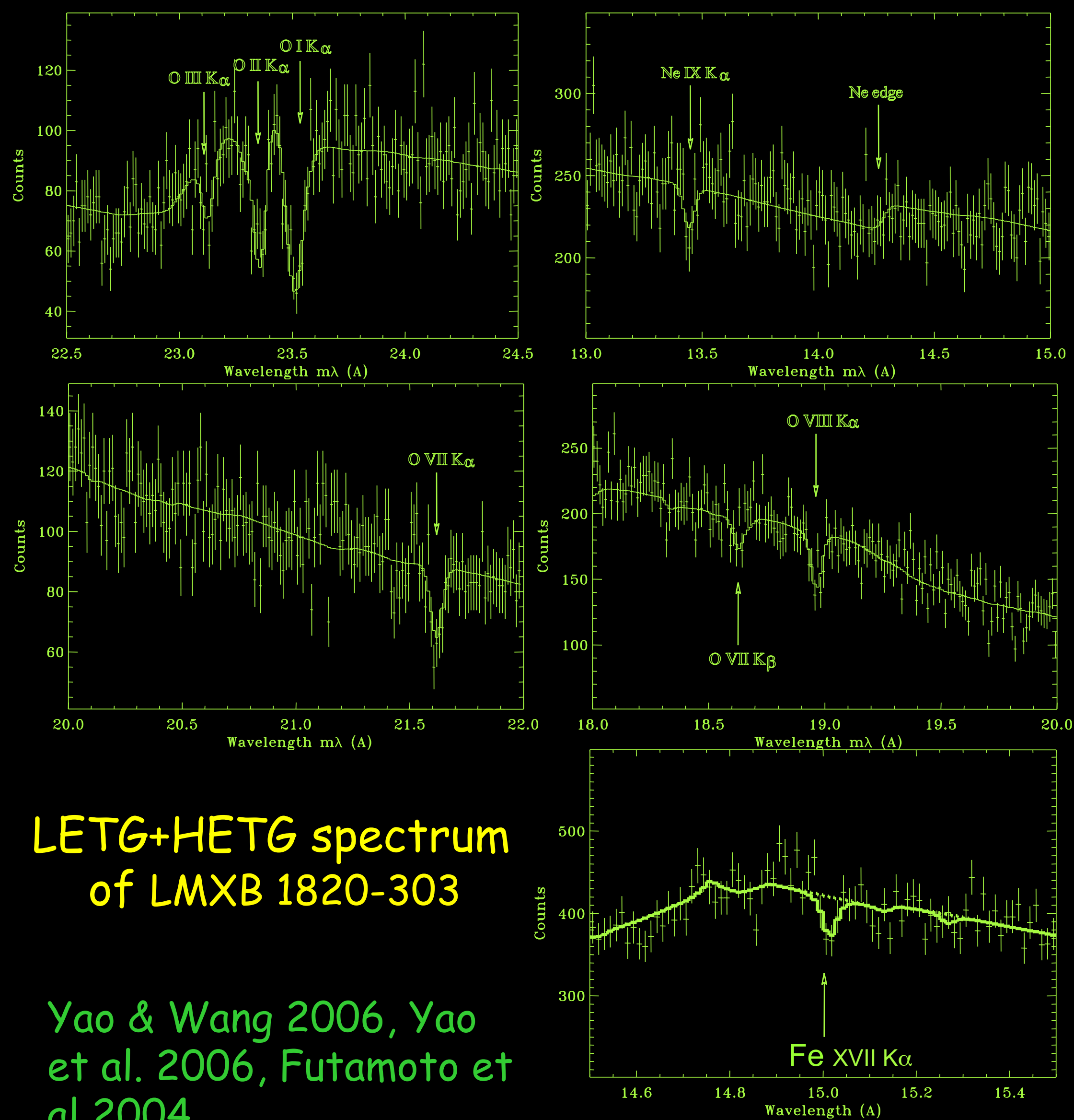


◆ AGN
● X-ray binary

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

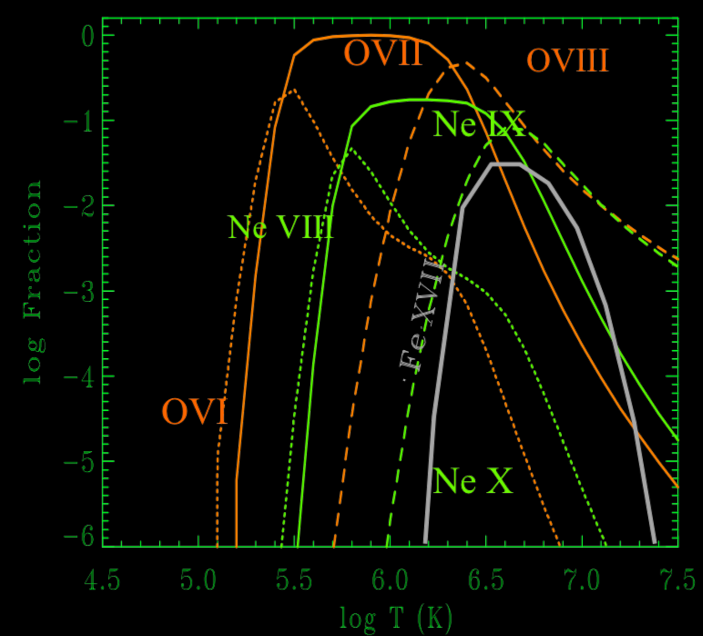
X-ray absorption line spectroscopy is powerful!



LETG+HETG spectrum of LMXB 1820-303

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

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



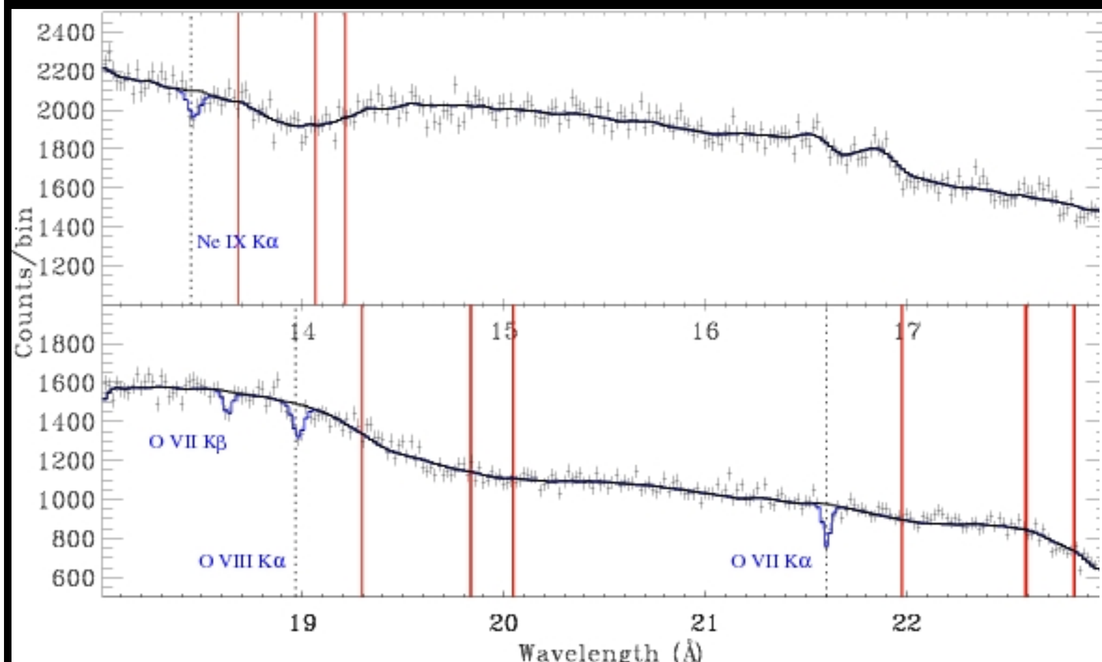
Galactic global hot plasma properties

- 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
  - 95% upper limit: N_{OVII}~ 3 x10^{15} cm^{-2} for r > 10 kpc
    ~ 1 x10^{15} cm^{-2} for r > 50 kpc

No evidence for a large-scale X-ray-emitting/absorbing halo!

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

- Sightline: PKS 2115-304
- Total exposure: 1 Ms
- Selected galaxies: < 500 kpc projected distance.



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

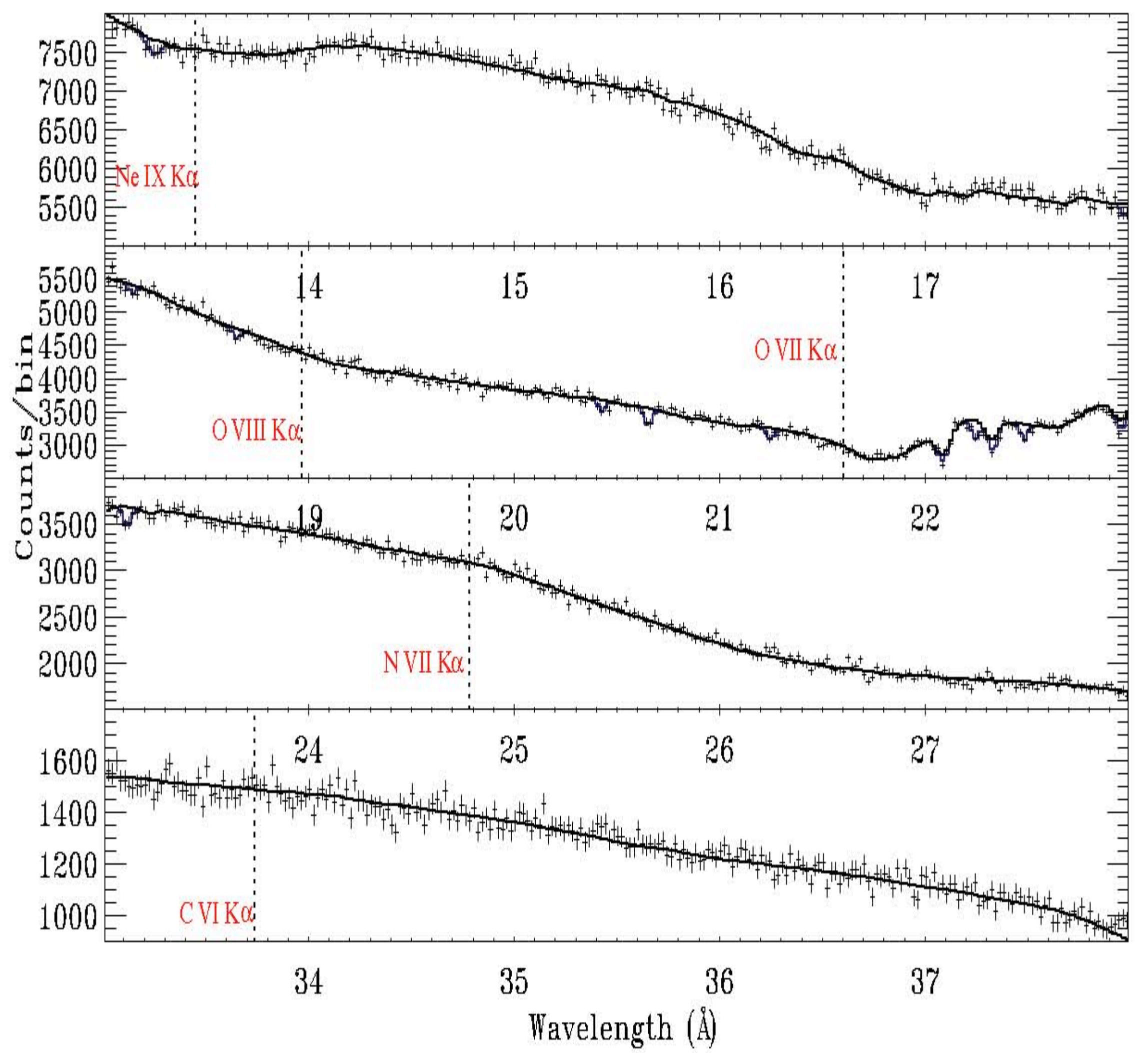
Src. Name	$z_{\rm AGN}$	No. of Obs.	Exp. (ks)	No. of[a] gal.
H1821+643	0.297	5	600	7(5)
3C 273	0.158	17	530	47(44)
PG 1116+215	0.176	1	89	12(11)
PKS 2155-304	0.117	46	1075	14(13)
Ton S180	0.062	1	80	3(3)
PG 1211+143	0.081	3	141	46(45)
Mrk 766	0.013	1	90	13(12)
H1426+428	0.129	3	184	3(3)
1H 0414+009	0.287	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, QDW, Tripp, et al. (2010)

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

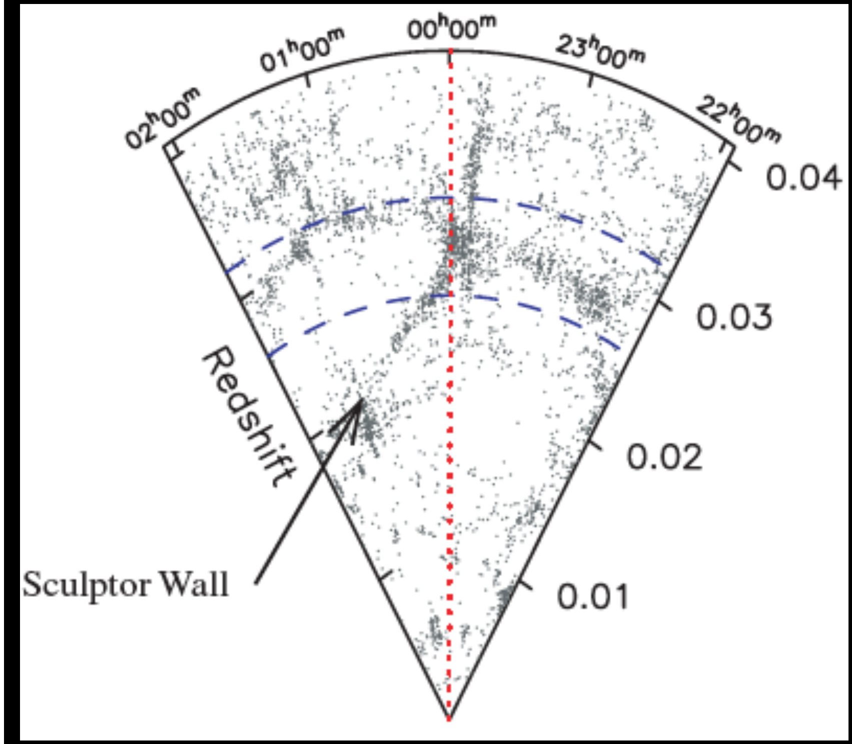


With an effective exposure: ~ 10 Ms, no absorption is detected!

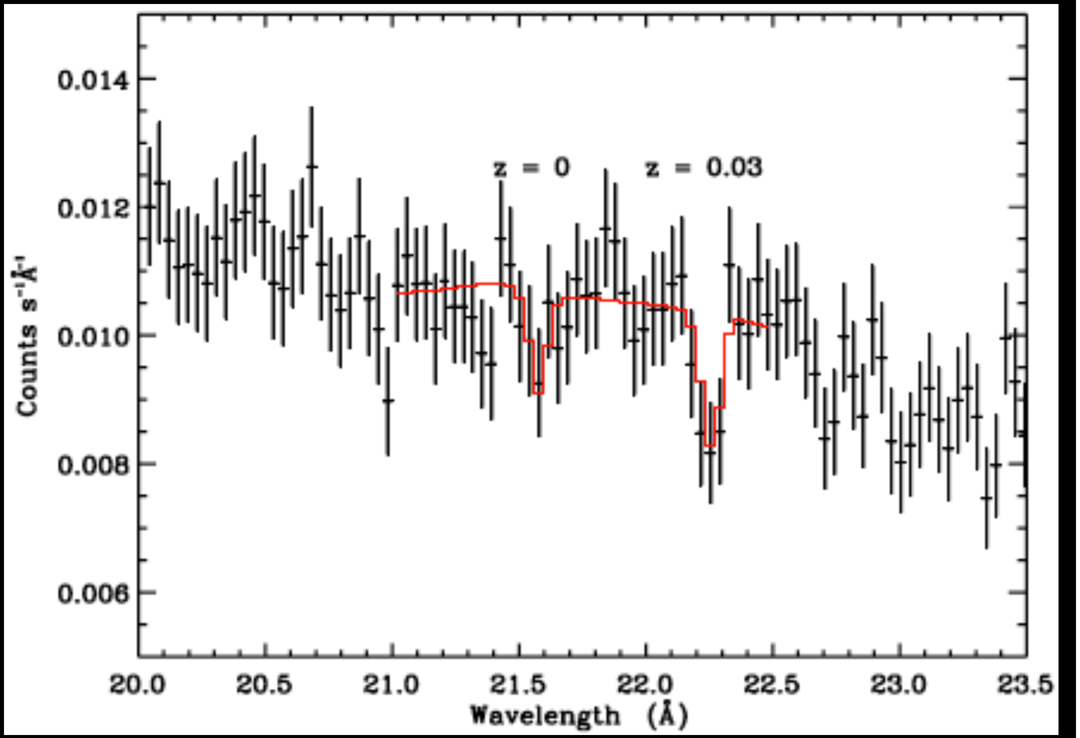
- N_{OVII} < 10^{15} cm^{-2}, or < 1/10 of the column density observed around the Milky Way.
- Groups typically contain little gas at T~$10^{5.3}$-$10^{6.3}$ K, unless the Oxygen abundance is << 1/10 solar.

OVII Kα line associated with the Sculptor Wall

Toward H 2356-309



N(OVII) ~ 2 x 10^{16} cm^{-2}



Chandra Grating Data

Buote et al. 2009; Fang et al. 2010

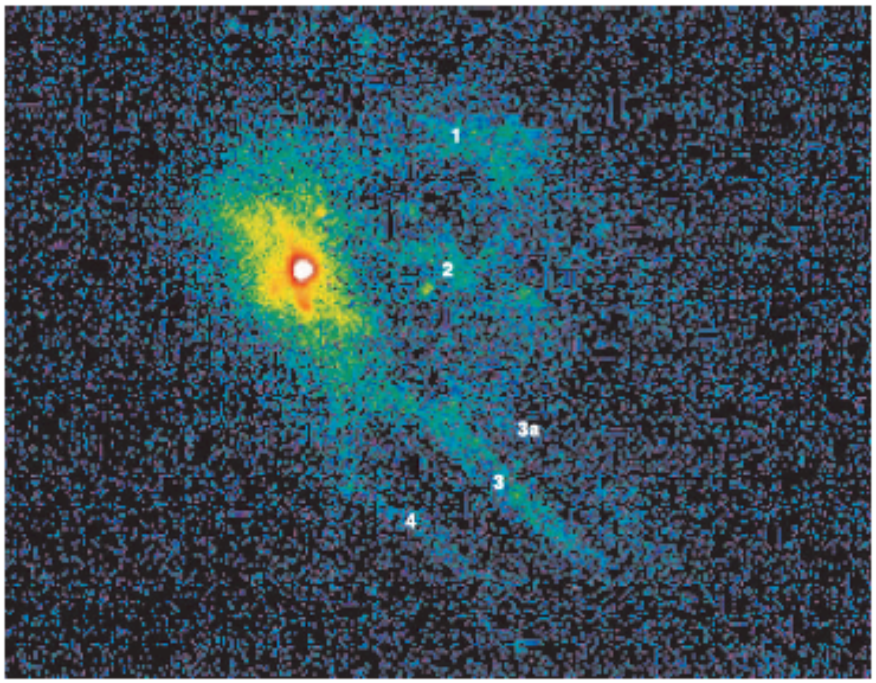
Summary

1. A substantial fraction of the diffuse soft X-ray emission may arise from charge exchange.
2. We now have the first characterization of the spatial, thermal, chemical, and kinetic properties of the global hot ISM in the Milky Way, based on X-ray absorption line spectroscopy.
3. Bulk of the mass, energy, and metals from the galactic feedback is likely gone with outflows in stellar spheroids, as well as in starburst galaxies.
4. The missing baryon matter is apparently not in the immediate vicinity of galaxies.

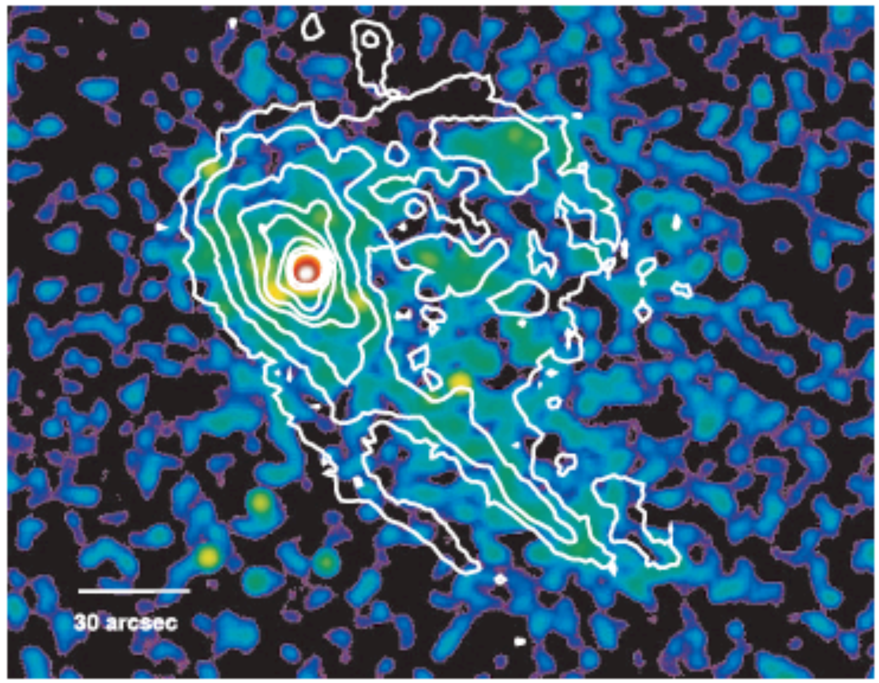
CX may also be important in many other circumstances

(Lallement 2004)

NGC 4438 in the Virgo Cluster



Ha+[NII] image (Kenney et al. 1995).



Chandra 0.3-2 keV image, Machacek et al. 2004