Limits on Hot Galactic Halo Gas from X-ray Absorption Lines

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Eight Years of Science with Chandra
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Hot gas (~10^6 K) in and around the Milky Way

- Local hot bubble (Snowden et al. 1998)
  - L: ~100 pc;
  - NH: ~10^{18} cm^{-2}
- Hot Galactic disk (e.g., Savage et al. 2003)
  - L: ~2 kpc;
  - NH: ~10^{19} cm^{-2}
- Galactic halo (e.g., Sembach et al. 2003)
  - L: ~20-250 kpc
  - NH: ????????
- Intergalactic medium in the Local group
  - L: ~ 1 Mpc
  - NH: ????????

Theoretical basis: large-scale hot gaseous halo

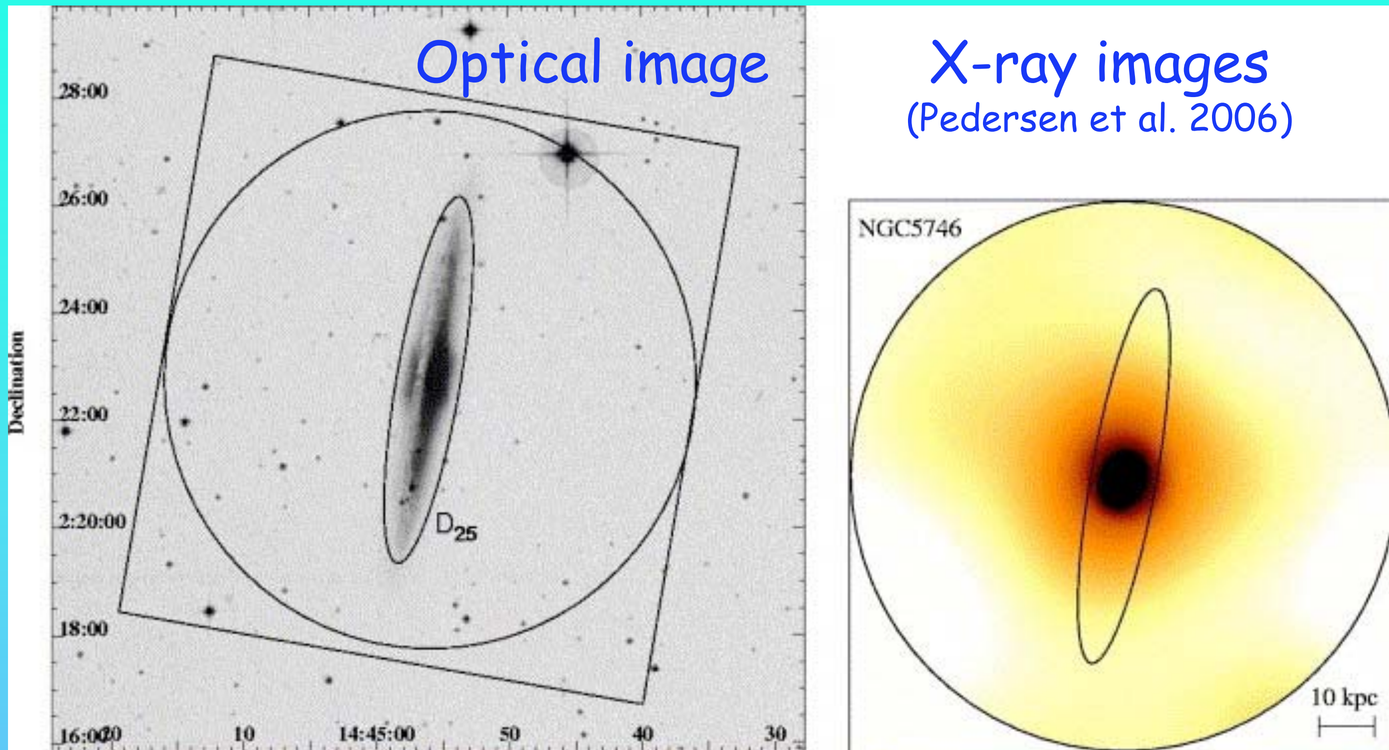
The "missing" baryon problem

Cosmic microwave background (CMB) measurement suggests the baryon mass fraction (baryon mass/total mass) to be ~0.15 (Spergel et al. 2007). However, in individual galaxies, the measured value is < 0.1 (e.g., McGaugh 2007) !!!

- For the Milky Way
  - M_{virial} ~8x 10^{11} $M_{\odot}$ (Klypin, Zhao, & Somerville 2002)
  - For a universal baryon fraction f ~ 0.15, the baryon mass of the MK is expected to be ~1.2x10^{11} $M_{\odot}$
  - The total baryon mass found: 6x10^{10} $M_{\odot}$ (Dehnen & Binney 1991)

Half of baryons is missing, which is supposed to be in the large-scale Galactic halo at temperatures ~10^6 K, according to the theories and simulations for the disk galaxy formation (NFW 1995; Toft et al. 2002; Maller & Bullock 2004).

Large-scale halo gas: emission study

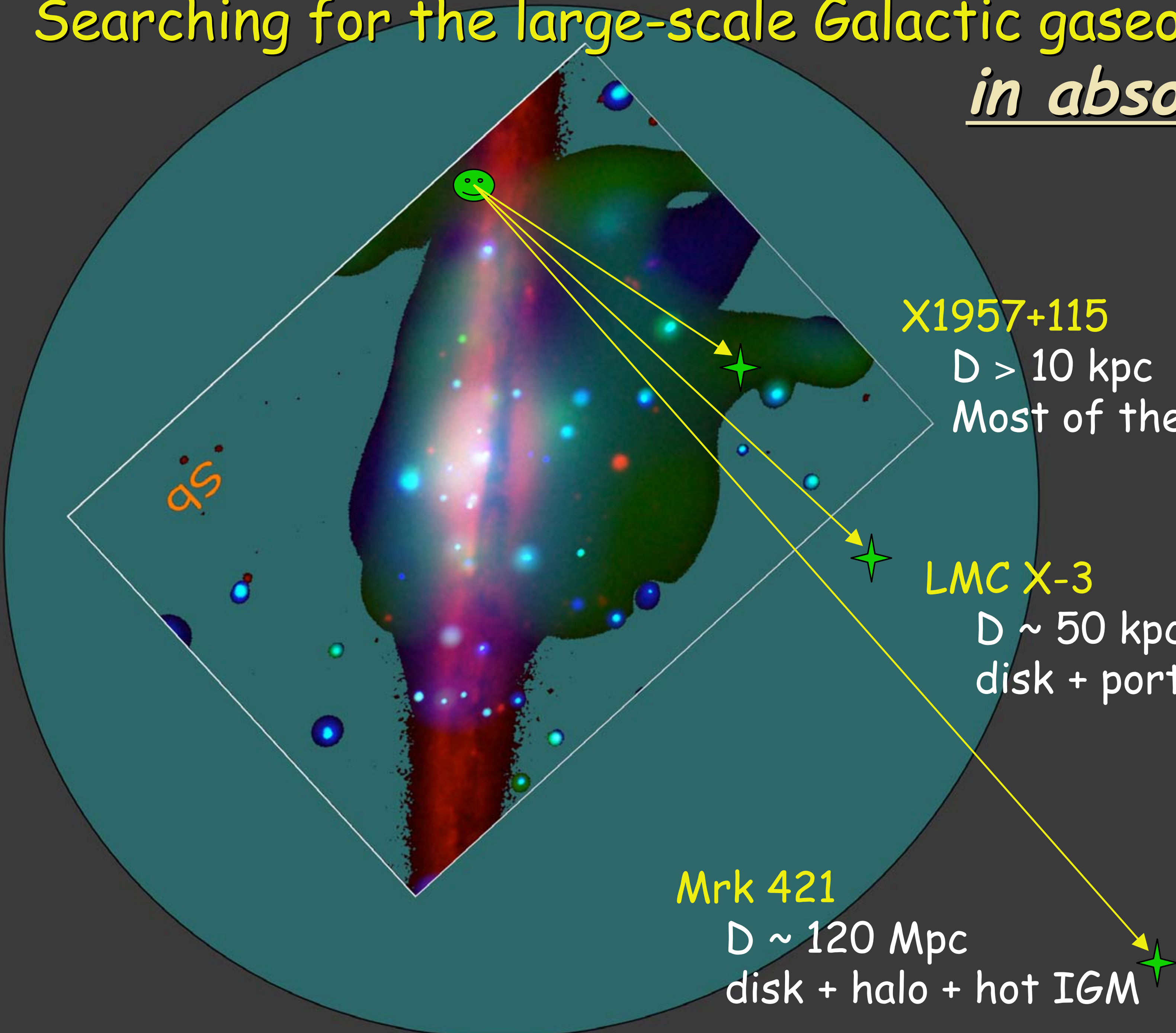


<u>The first and the only claimed detection!</u>

However, reanalysis of the same data did not confirm the detection! The previous detection could be confused by the un-removed point sources (Wang 2007)!

<u>X-ray emission should be very weak (low density and metallicity)!</u>

Searching for the large-scale Galactic gaseous halo ***in absorption***



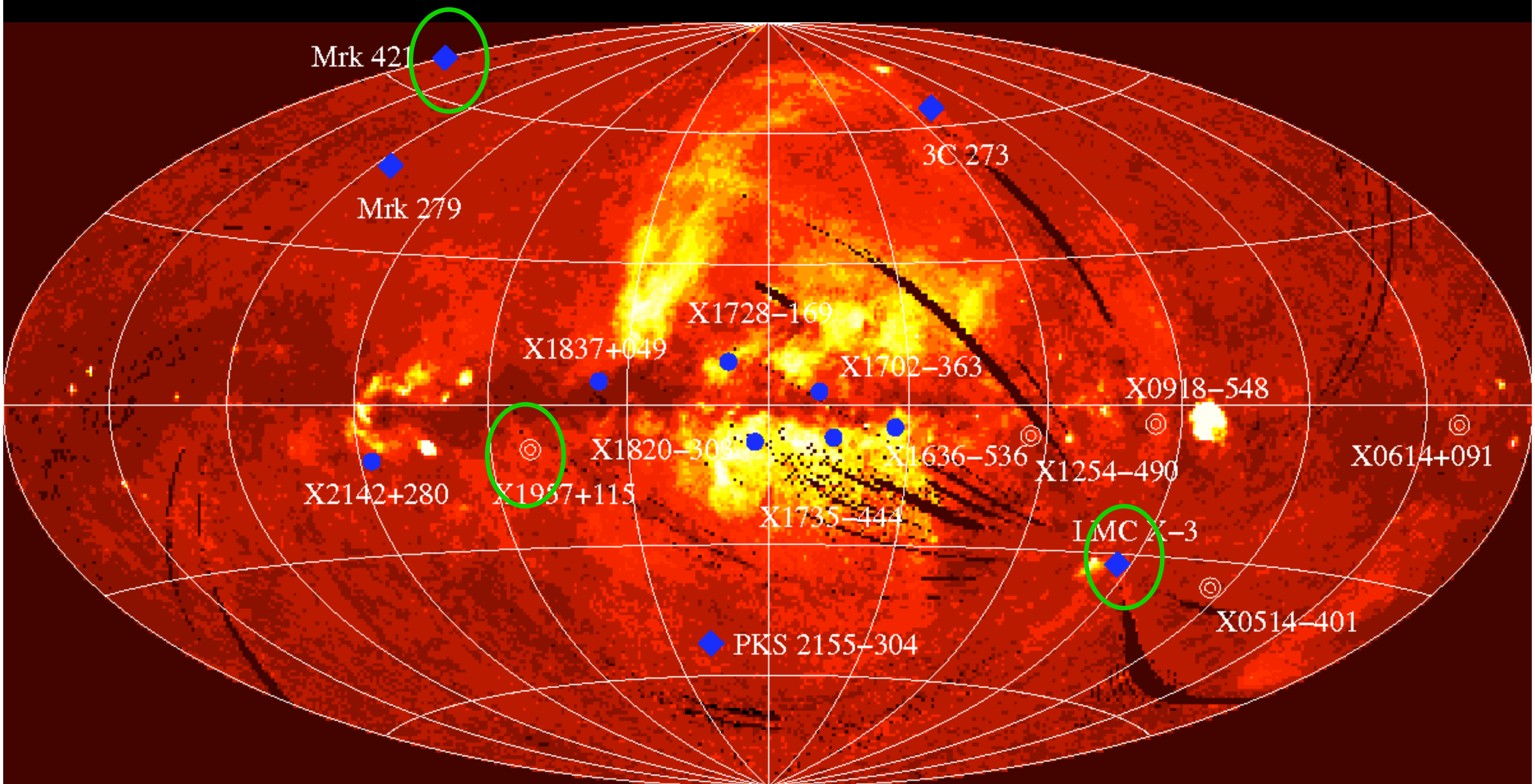
X1957+115
D > 10 kpc
Most of the disk

LMC X-3
D ~ 50 kpc
disk + portion halo

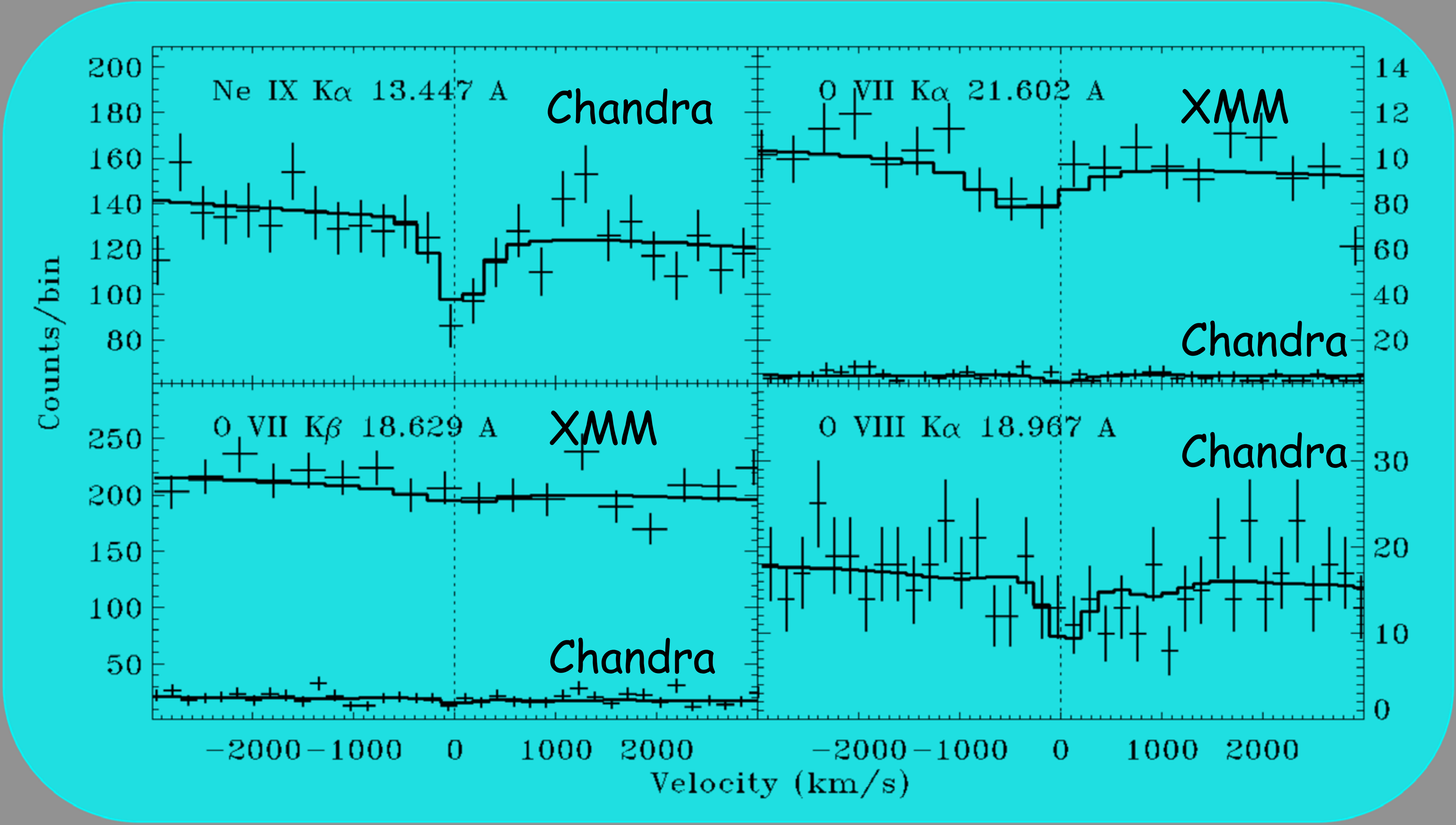
Mrk 421
D ~ 120 Mpc
disk + halo + hot IGM

Searching for the large-scale Galactic gaseous halo

--- targets



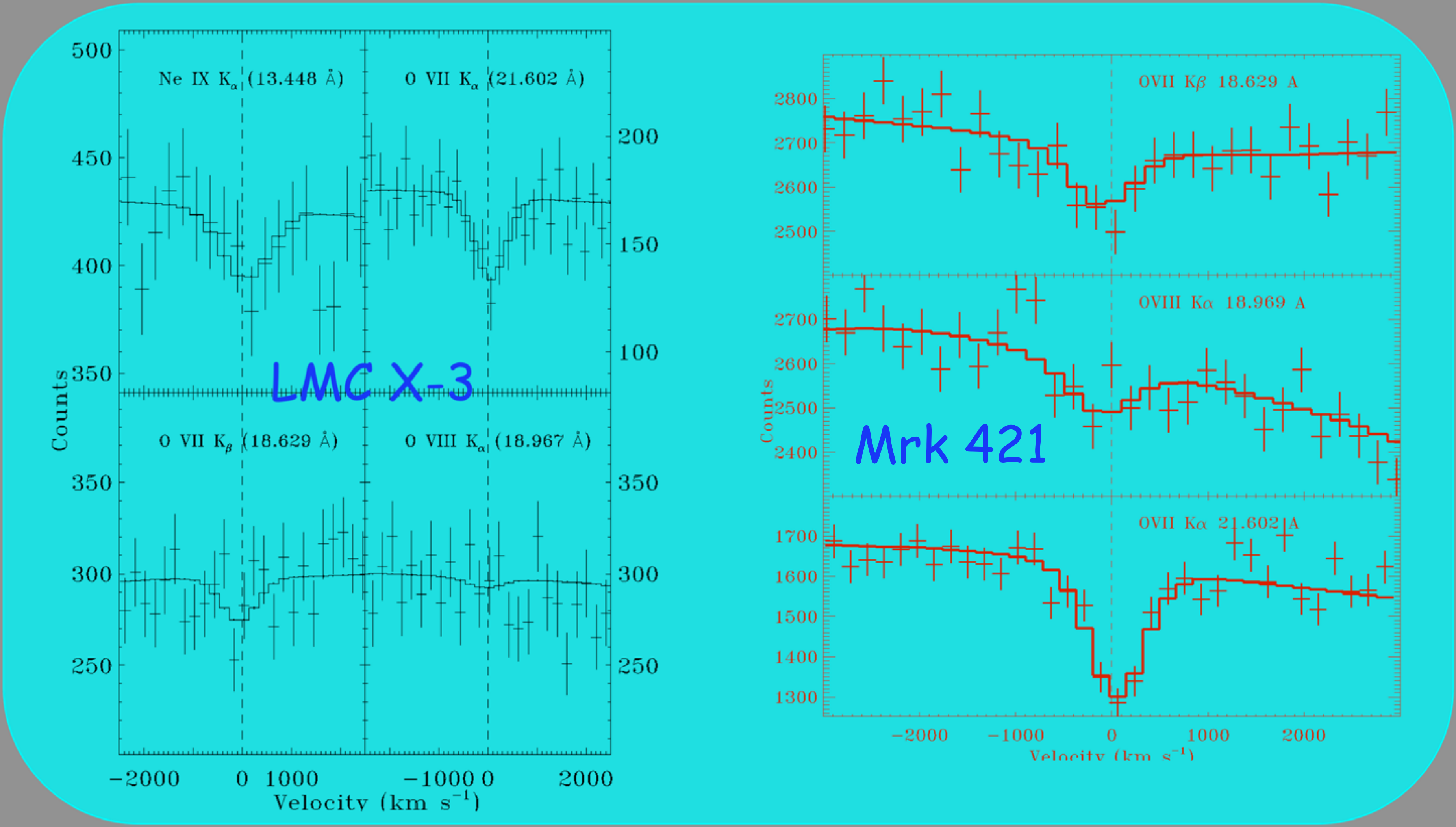
The Galactic source: 4U 1957+11 (V1408 Aql)



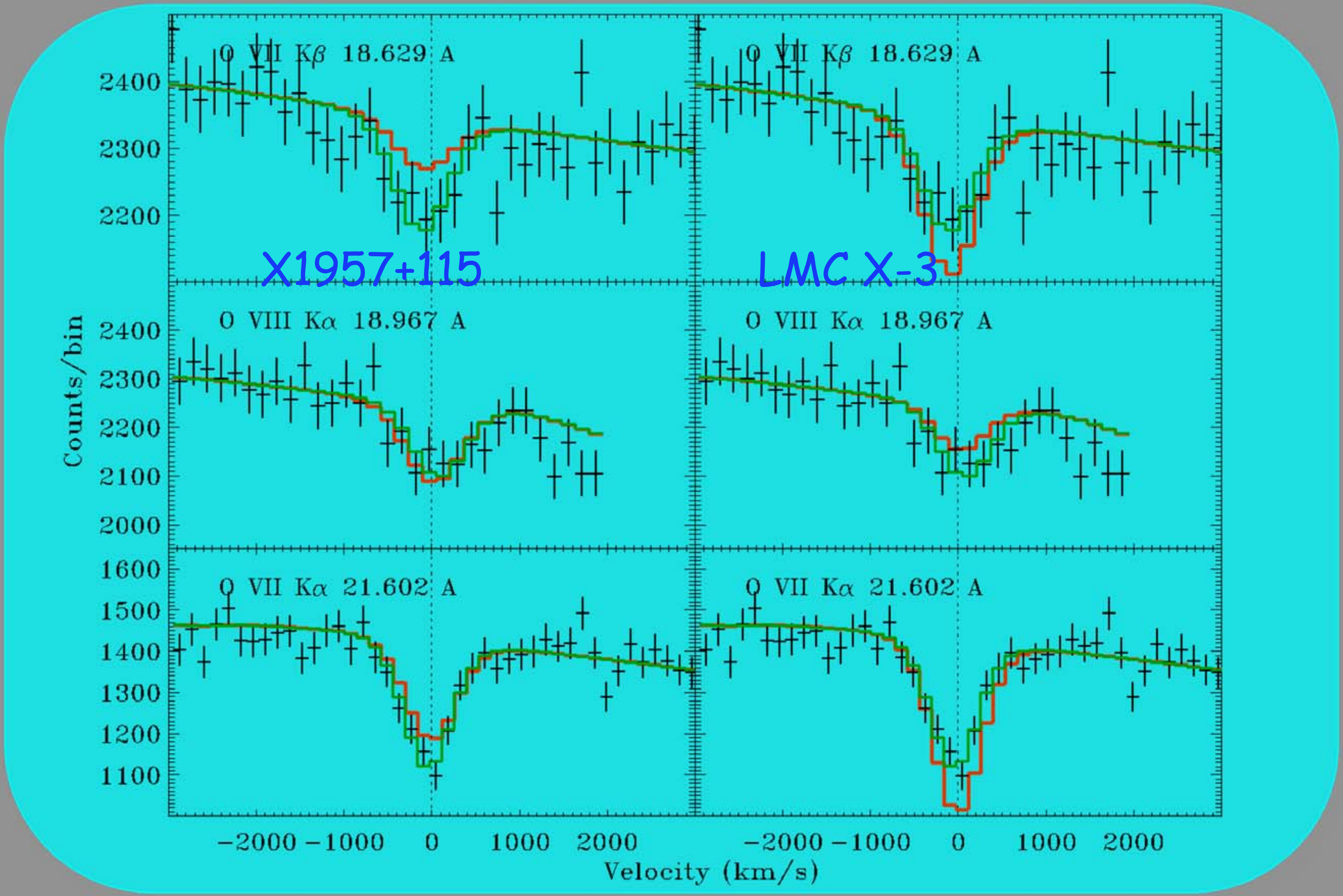
Temperature: 1.8×10^6 K (Yao et al. 2007)

Column density: $N_{OVII} \sim 7 \times 10^{15}$ cm^{-2}, $N_H \sim 1.4 \times 10^{19}$ cm^{-2}

Extragalactic sources



The differential study: direct comparison



No absorption contribution from the gas beyond X1957 and LMC!

Results: some upper limits

Differential analysis of 4U 1957 and Mrk 421 sightlines

1) No ***metal*** (O and Ne) absorption beyond 4U 1957

2) $N_{OVII} < 5\times10^{15}$ cm^{-2} (95% confidence) or equivalent to $N_H < 9.1/A_O \times10^{18}$ cm^{-2} (A_O: gas metallicity in solar unit)

<u>Assumption:</u> disk gas and halo gas have same properties

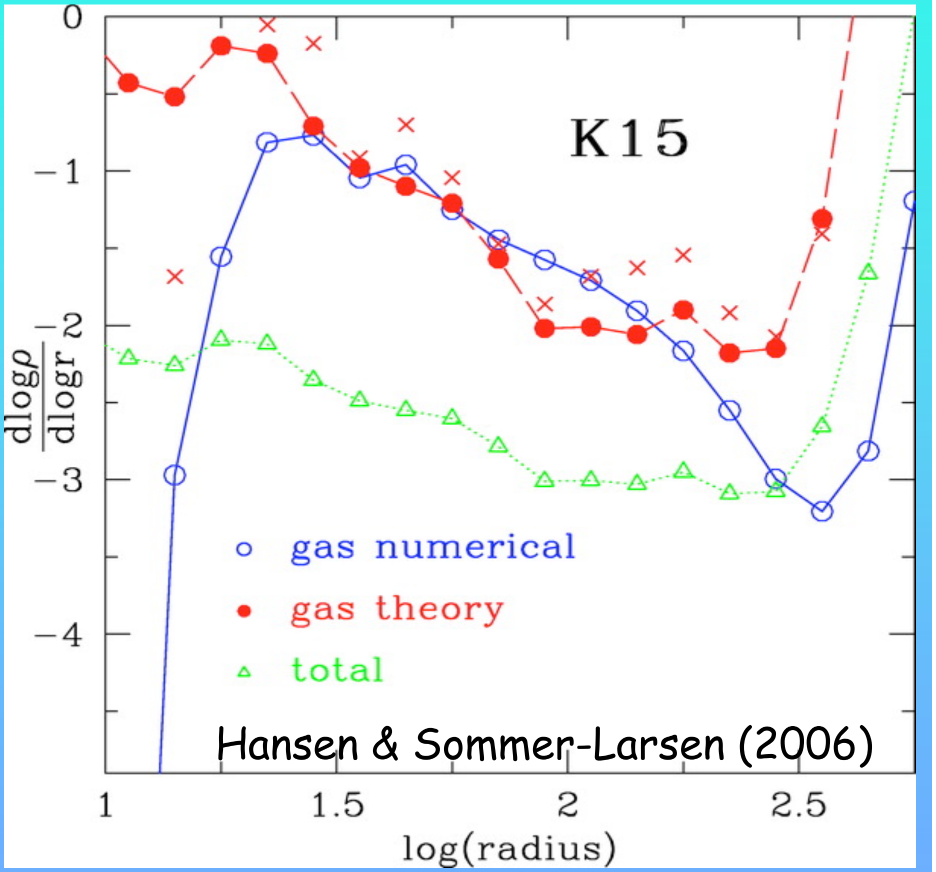
- Log(T): 6.23(6.21, 6.32)
- V_b: 70(50, 172) km/s

Results confront theories (1)

Power-law density distribution in halo: $\rho(r)= \rho_0(r/r_0)^{\alpha(r)}$
(Hansen & Sommer-Larsen 2006)

$N_H < 9.1/A_O \times 10^{18}$ cm^{-2} $\Rightarrow$
$M_{halo} < 2.2\times10^9\ M_\odot$ for $A_O = 1$
$< 6.0\times10^{10}\ M_\odot$ for $A_O = 0.037$

In contrast:
Baryon missing in the WM:
$\sim 6\times10^{10}\ M_\odot$



Results confront theories (2)

A more flat density distribution derived the fragmentation cooling (Maller & Bullock 2004)

$N_H < 9.1/A_O \times 10^{18}\ \mathrm{cm}^{-2} \Rightarrow$

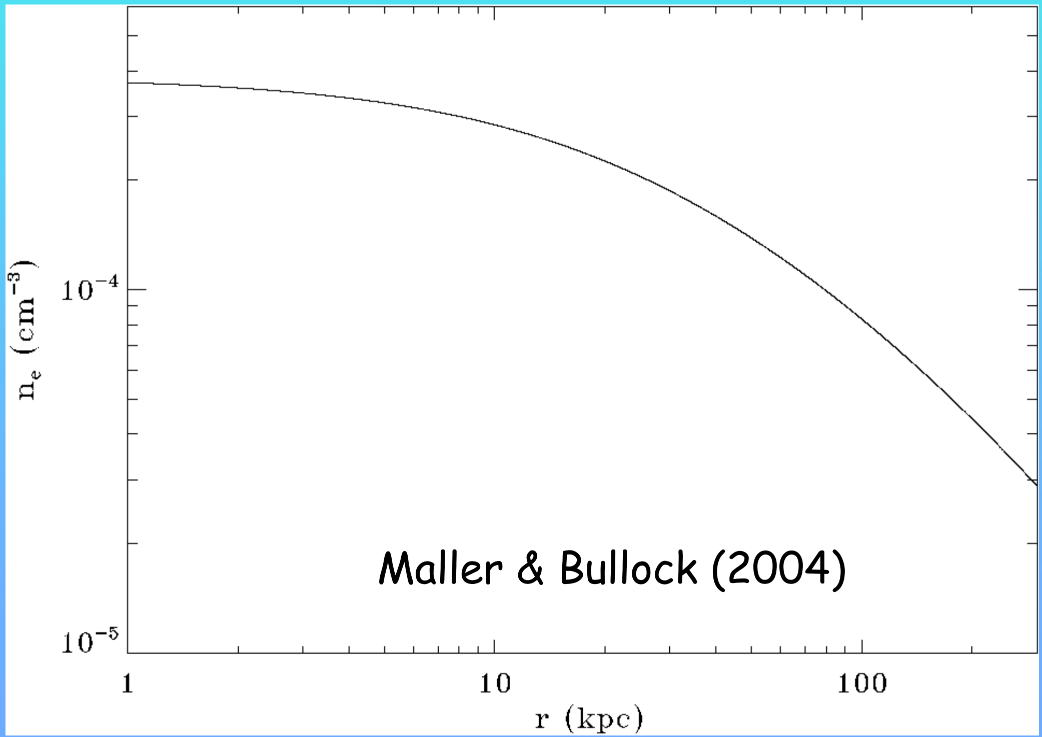
$M_{halo} < 1.2\times10^{10}\ M_\odot$ for $A_O = 1$

$< 6.0\times10^{10}\ M_\odot$ for $A_O = 0.2$

In contrast:

Baryon missing in the WM:

$\sim 6\times10^{10}\ M_\odot$



Summary:

For the Milky Way:

- ✓ NO metal line absorption produced in the hot gaseous halo at > 10 kpc.

- ✓ The halo contains <20% simulated baryon mass.
- ✓ Or, if indeed about 6×10^{10} $M_{\odot}$ distributed in the large-scale halo, the gas metallicity should be < 20%!!

Absorption lines (2)

<u>Nature of lines:</u> intrinsic vs. ISM

- LMXB: no stellar wind
- Disk wind: possible
  - P: 9.33 hr, M_x: < 16 $M_\odot$
  - $\Rightarrow$ binary separation: $\leq$ 6 $R_\odot$
  - Fx (0.5-10 keV): 1.3×10^{-9} erg/cm^2/s

    $\Rightarrow$ L: $1.19D^2_{10kpc}\times10^{37}$ erg/s

    $\Rightarrow$ ionization para. $\log(L_x/nr^2)$ < 3 to have NeIX

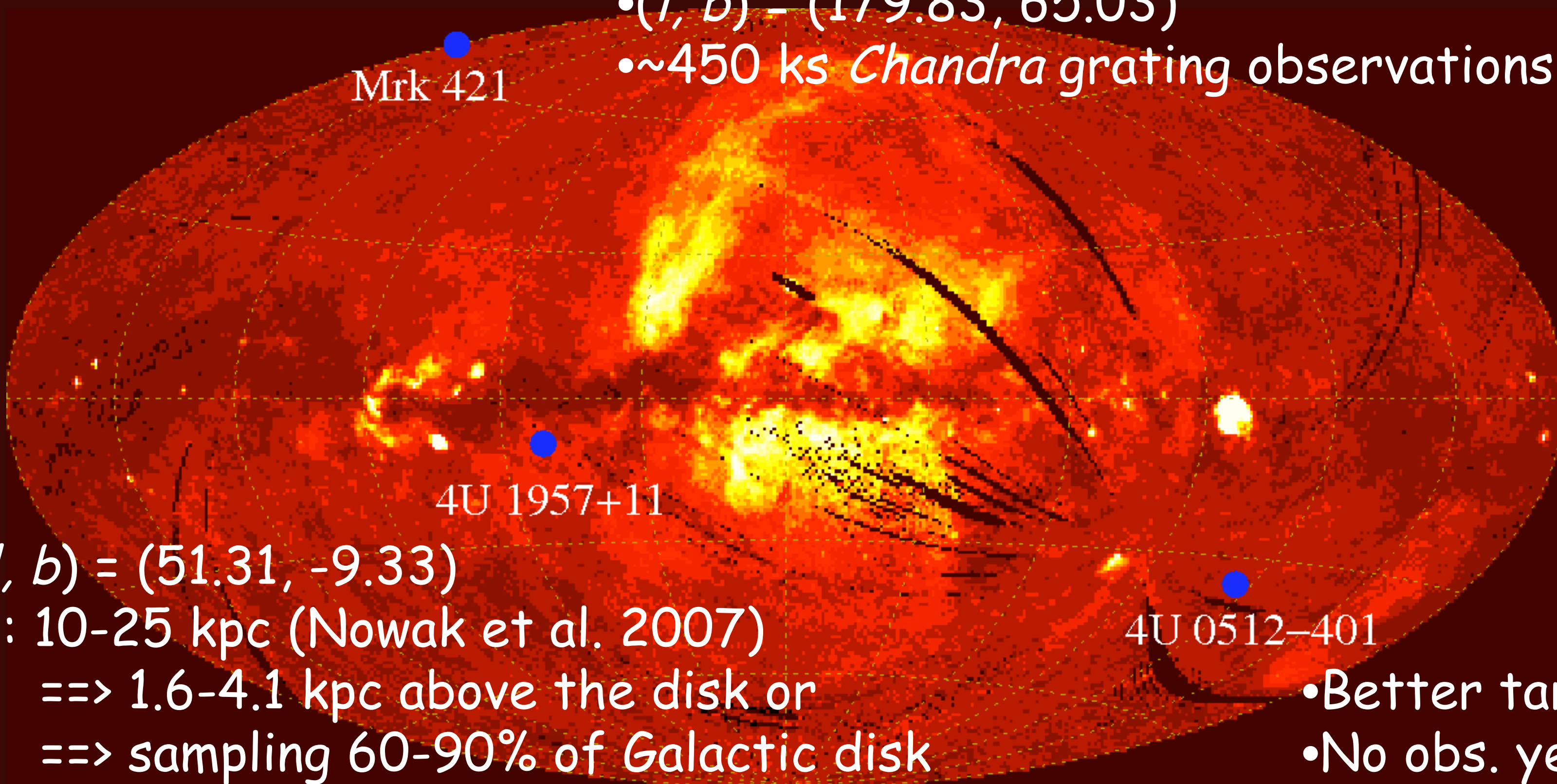
    $\Rightarrow$ R_w > 18 $R_\odot$ ----> not inflow
  - Escape velocity of the system:

    v > 200 sqrt($10M_\odot$/Rw) km/s

    All lines are consistent with **<u>no</u>** velocity shift ---> not outflow
- ISM origin is more likely!

Chandra targets

•(*l*, *b*) = (179.83, 65.03)
•~450 ks *Chandra* grating observations

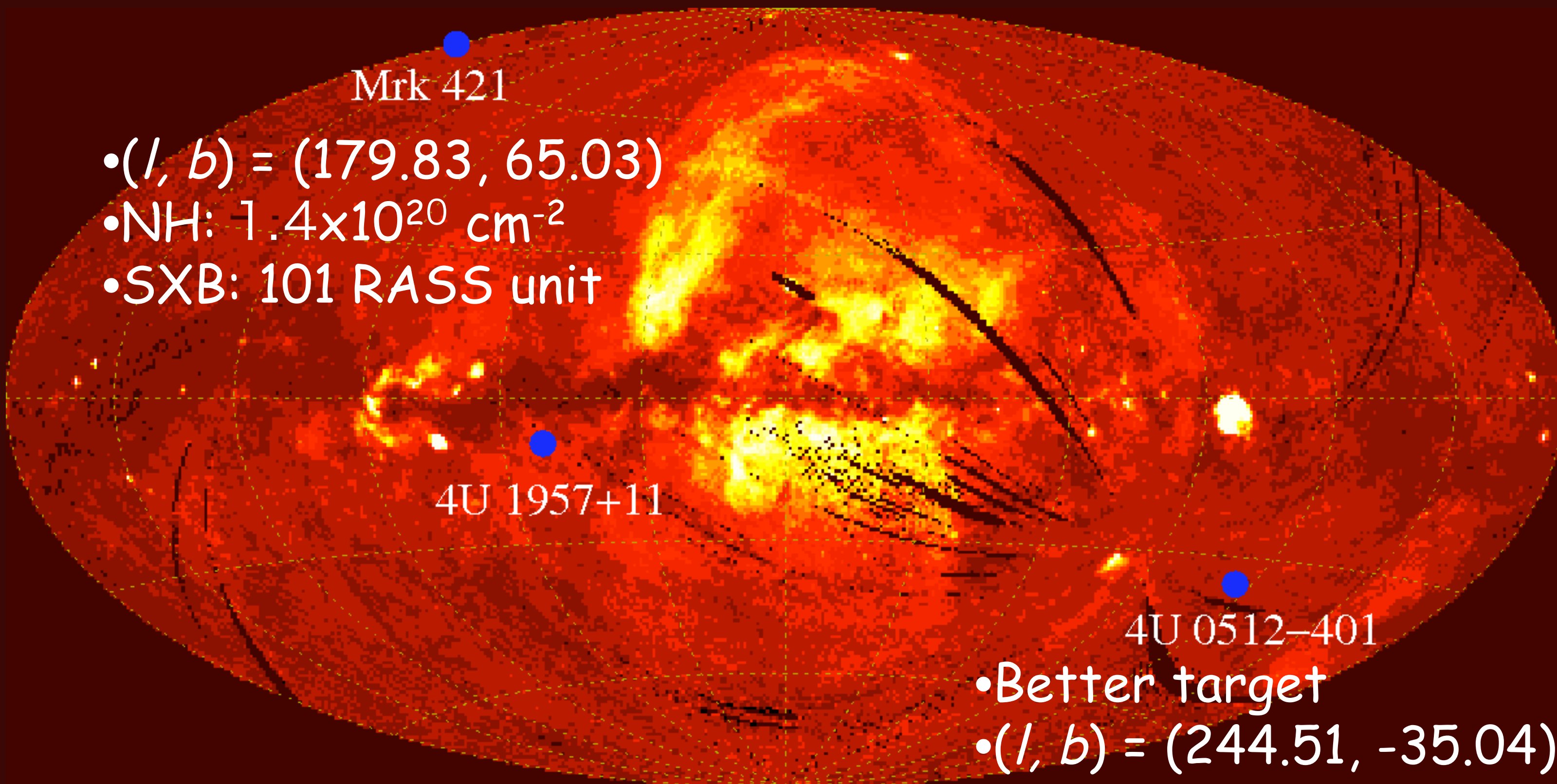


•(*l*, *b*) = (51.31, -9.33)
•D: 10-25 kpc (Nowak et al. 2007)
==> 1.6-4.1 kpc above the disk or
==> sampling 60-90% of Galactic disk
•67 ks HETG GTO and 45 K *XMM-Newton*

•Better target
•No obs. yet

RASS 3/4 keV SXB map (Snowden et al. 1997)

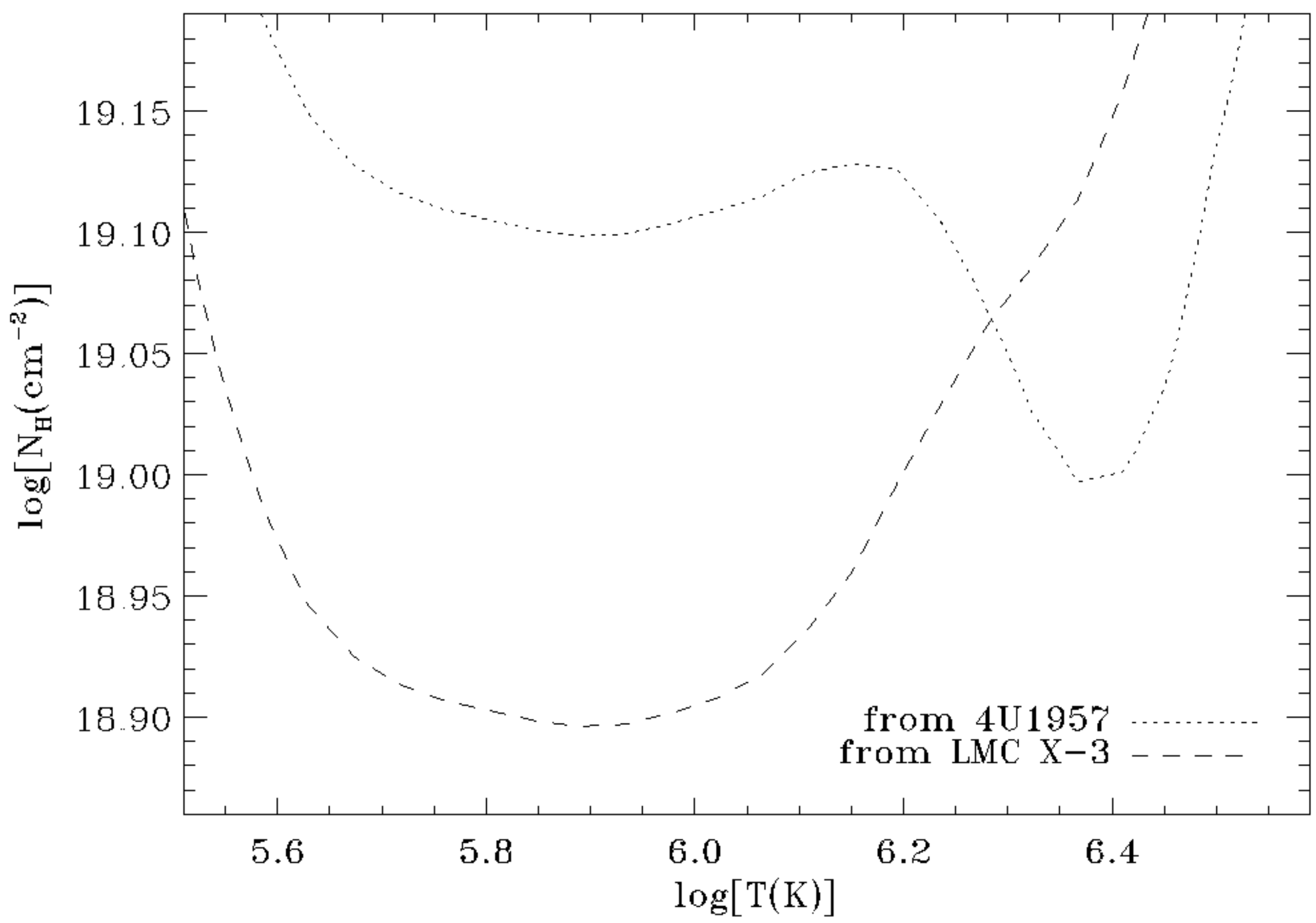
A better Chandra target



- (l, b) = (179.83, 65.03)
- NH: 1.4×10^{20} cm^{-2}
- SXB: 101 RASS unit

- Better target
- (l, b) = (244.51, -35.04)
- D: 11 kpc (NGC 1851)
  ==> sample >95% disk gas
- NH: 3.5×10^{20} cm^{-2}
- SXB: 116 RASS unit

Results: some upper limits (2)



Theoretical basis: large-scale hot gaseous halo

- Theories and simulations for disk galaxy formation and evolution (e.g., NFW 1995; Toft et al. 2002)
- Gas in-fall --> gas heated (~10^6 K)--> cool --> fuel of galaxy formation
  - For massive (≥10^{11} $M_{\odot}$) spirals, cooling is inefficient --> long standing large-scale (>20 kpc) hot gaseous halo
  - Mass of the hot halo is comparable to that of stars and cool gas in the galaxy
- For the Milky Way
  - M_{virial} ~8x 10^{11} $M_{\odot}$ (Klypin, Zhao, & Somerville 2002)
  - For a universal baryon fraction f ~ 0.15, the baryon mass of the MK is ~1.2×10^{11} $M_{\odot}$
  - The total baryon mass found: 6×10^{10} $M_{\odot}$ (Dehnen & Binney 1991)
  - Half of baryons are missing, which is supposed to be in the large-scale hot gaseous halo (Maller & Bullock 2004)!!