The Interstellar Medium: XII
The Hot Ionized Medium

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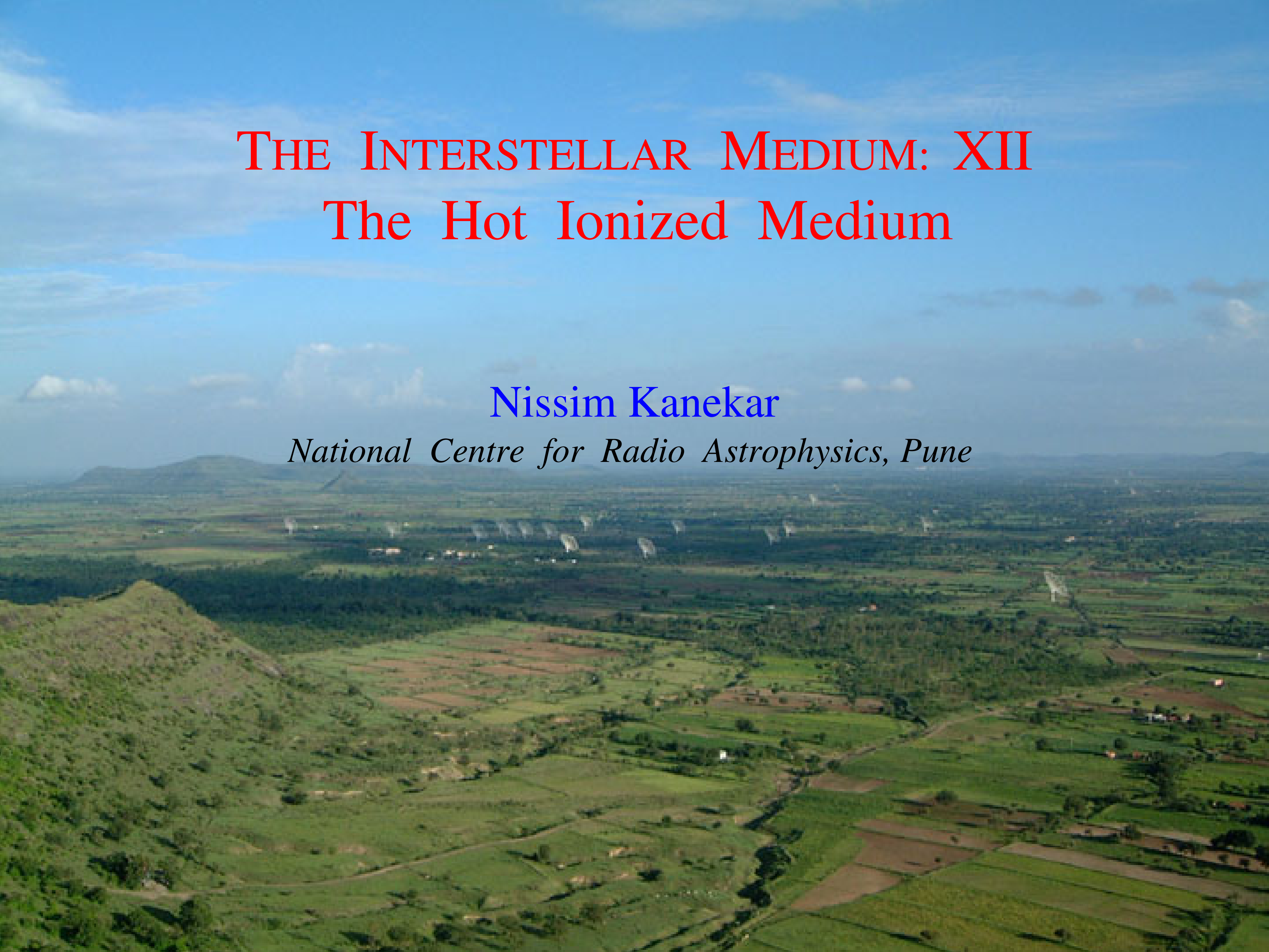


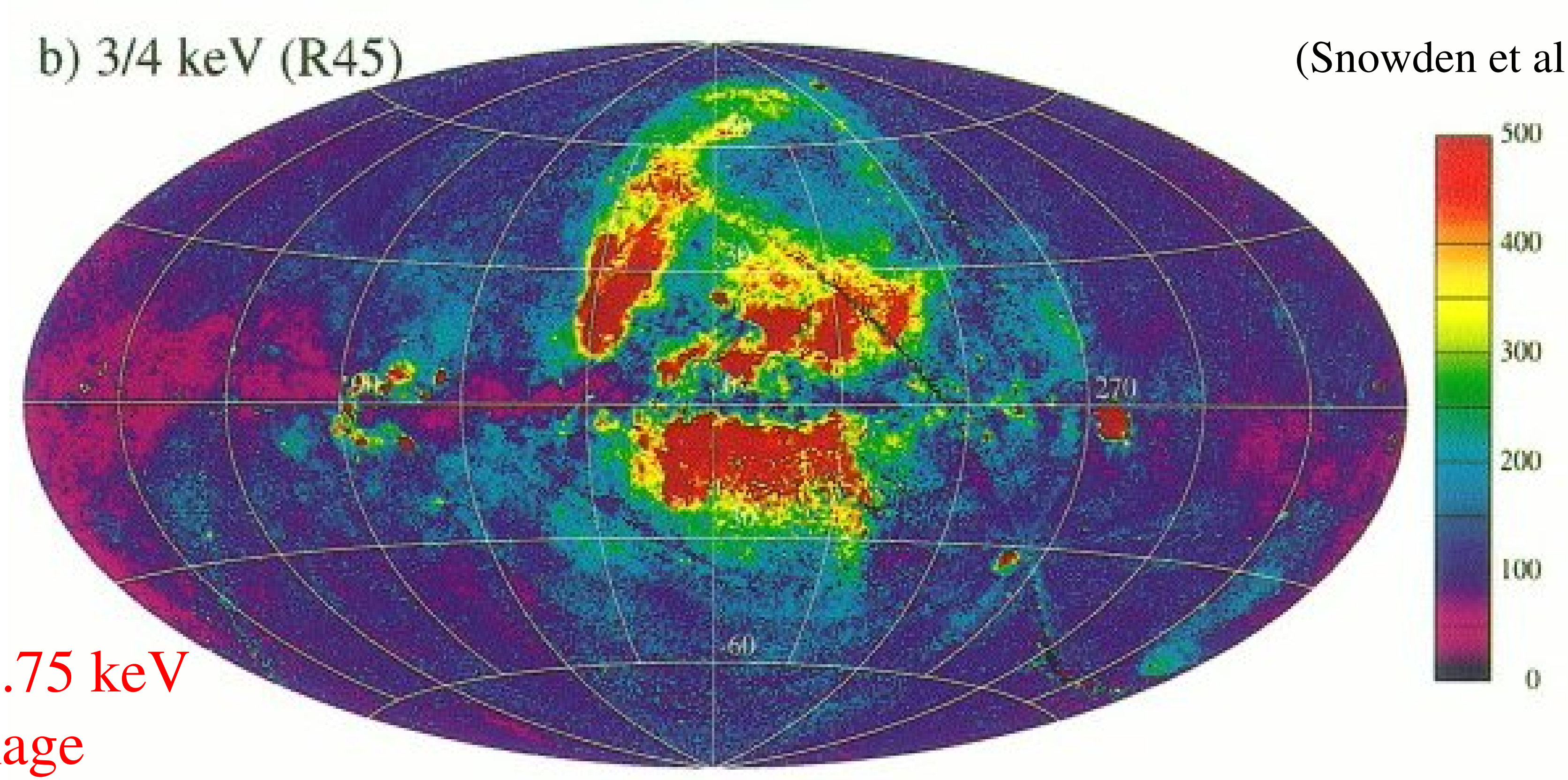
Outline

- Background.
- The hot ionized medium: Structure and probes.
- O VI absorption studies.
- X-ray emission studies.
- Physical condition in the HIM.

Background

- Warm Ionized Medium: T ~ 8000 K; $n \sim 0.03$ cm^{-3}; Mass ~ 10^9 $M_\odot$.
- Pulsar dispersion: Group velocity in a plasma is lower at lower frequencies: High frequency signals arrive earlier. DM = $\int n_e.ds$.
- Typical DM ~ 30 pc cm^{-3} at 1 kpc distance ⇨ $n_0 = 0.03$ cm^{-3} !
- For a uniform plasma: Scale height ~ 1830 pc; $n_0 = 0.014$ cm^{-3}.
- Determine the Galactic distribution of free electrons via DM (++).
- Hα emission studies: $I_{H\alpha} = (h\nu_{H\alpha}/4\pi) \times \alpha_{H\alpha} \times EM$; $EM = \int n_e^2\, ds$.
- EM (Plane) ~ (9 – 23) cm^{-6} pc ⇨ $n_e^2 \sim (4.5 - 11.5) \times 10^{-3}$ cm^{-6}.
- Compare DM and EM ⇨ Low WIM filling factor, f ~ 0.05 – 0.2.
- Ionization by O stars ⇨ UV photons must travel large distances!
  ⇨ Requires HI "holes" for propagation ⇨ Clumpy WIM & WNM !

THE HOT IONIZED MEDIUM



(Snowden et al. 1997)

ROSAT 0.75 keV
all-sky image

- Predicted by Lyman Spitzer in 1956: HI clouds far above the plane would be over-pressured, and would rapidly expand to the low background density ⇨ Hot gas for pressure support! (Spitzer 1956)

- Spitzer: T ~ 10^6 K; $n_e \sim 5 \times 10^{-4}$ cm^{-3}; scale height ~ 7.5 kpc.

- Balloon-based X-ray emission; *Copernicus* OVI UV absorption!

(Bowyer 1968; Rogerson et al. 1973)

The Hot Ionized Medium

- Highly ionized gas, e.g. C IV, N V, O VI, S VI. Fills the Galactic halo. Temperature ~ $3 \times 10^5 - 3 \times 10^6$ K. Density ~ 0.001 – 0.003 cm^{-3}.

- Not enough UV photons for photo-ionization and heating ⇨ Collisional ionization and heating by supernova shocks and fast stellar winds. Cooling by radiative losses and free-free emission.

- Collisional ionization equilibrium (CIE), with collisional ionization balancing radiative recombination. Rate coefficients from laboratory measurements, numerical work ⇨ Numerical CIE or NEI studies.

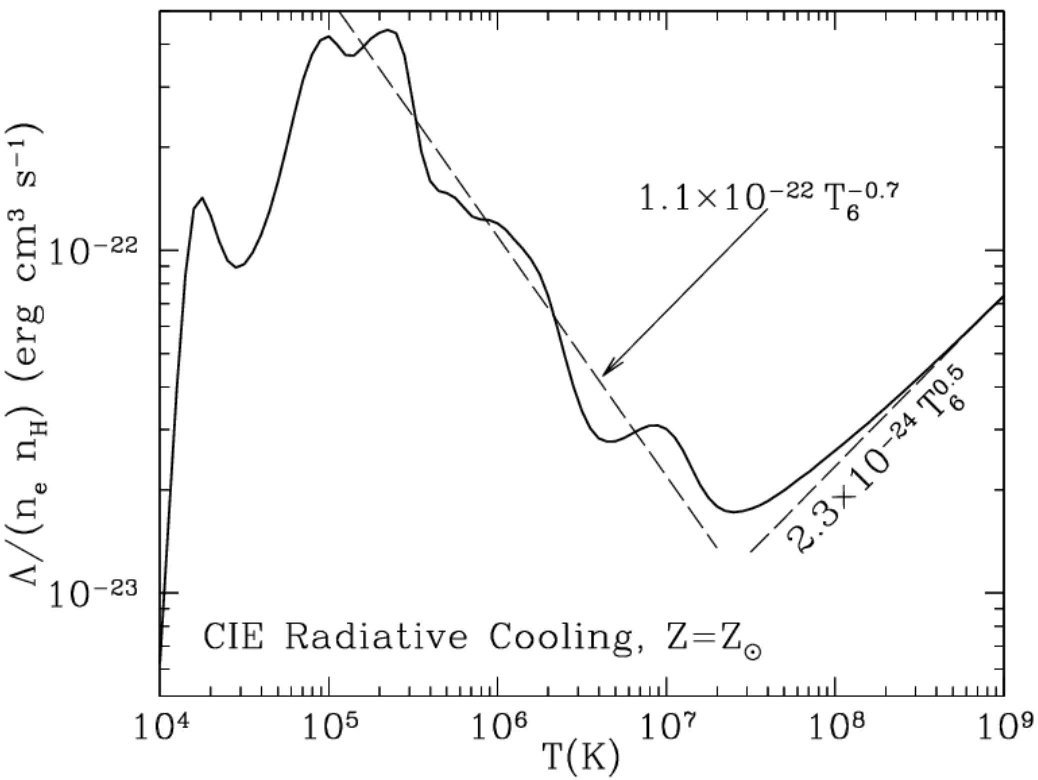
  (Dopita & Sutherland; Dere et al.)

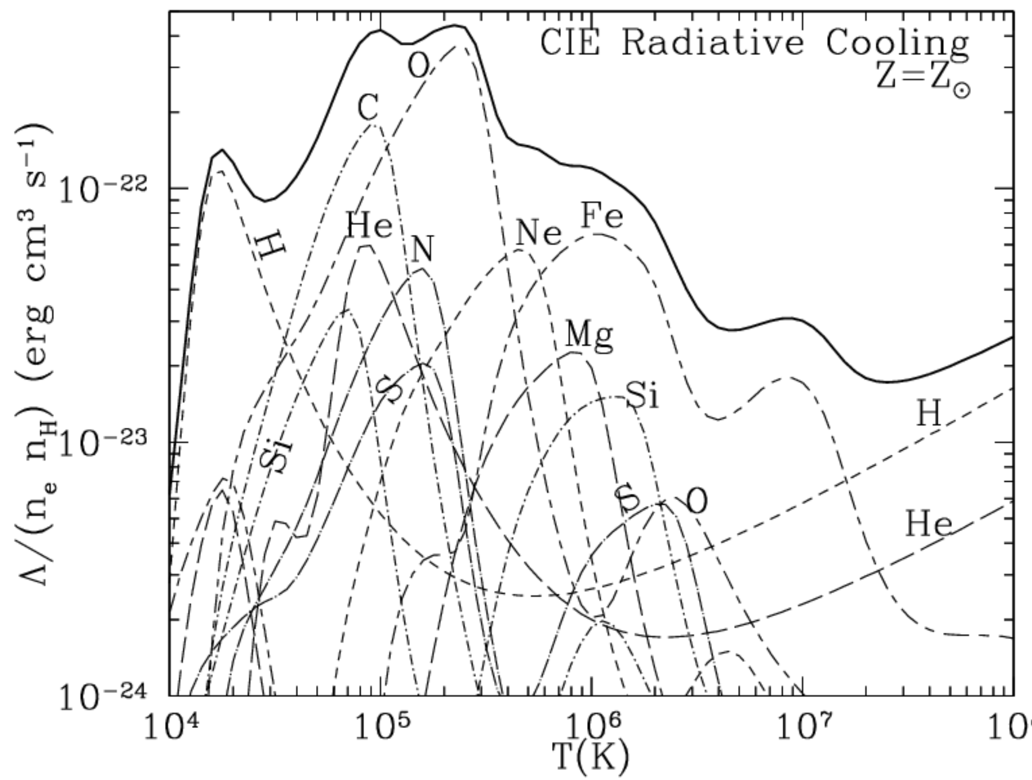
- Density always lower than the critical density, but large number of cooling species, many transitions ⇨ Numerical cooling rates.

  (e.g. "Chianti"; Dere et al. 2009)

- Probes: (1) X-ray continuum emission; line emission/absorption.
  (2) Far-UV O VI, C IV, N V absorption against stars/quasars.

The Hot Ionized Medium: CIE and Cooling

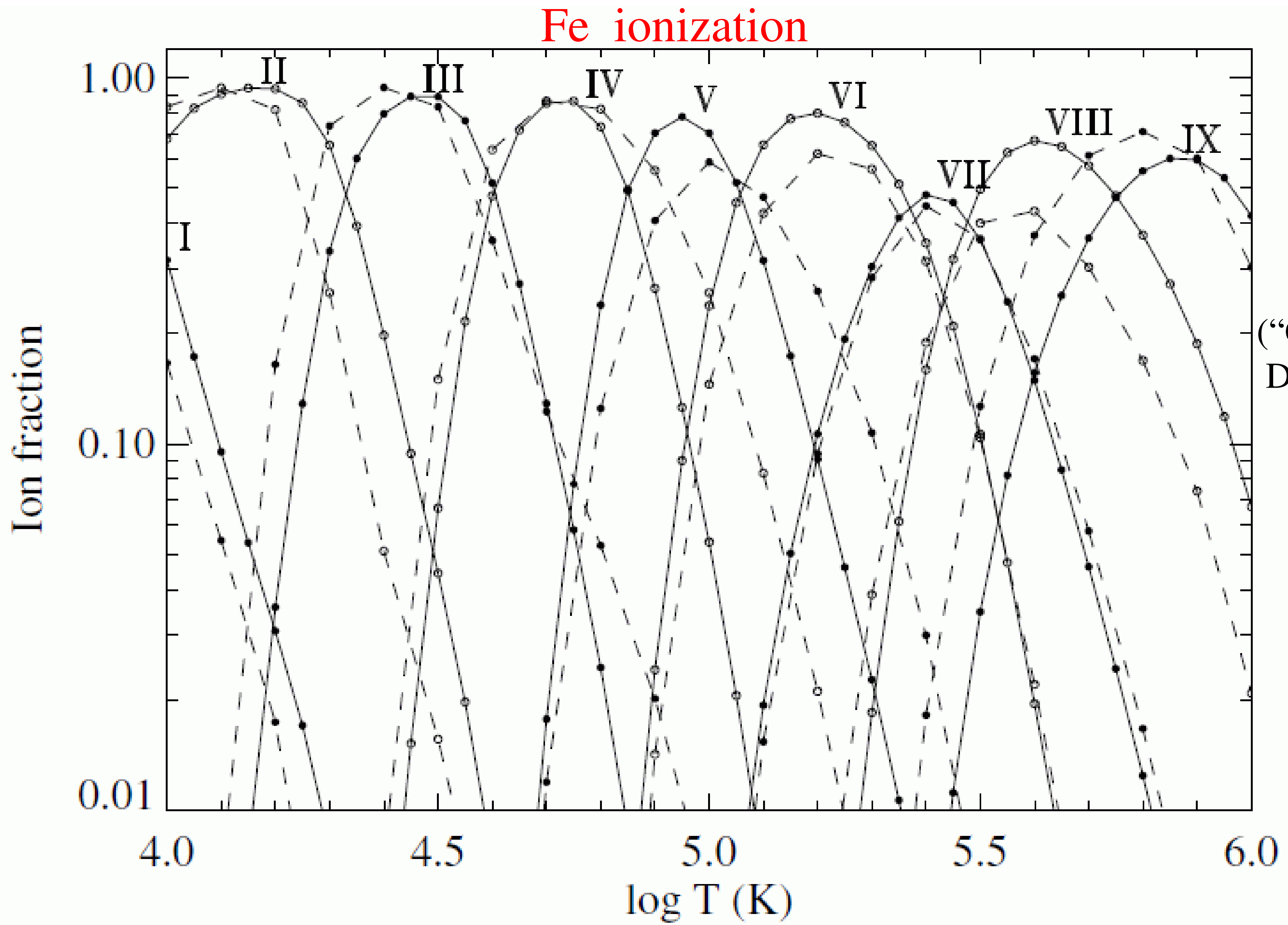




(Draine 2011; Dere et al. 2009)

- Cooling via metal lines at $T \leqslant 10^7$ K, by free-free emission at $T > 10^7$ K.
- Large number of cooling species, many transitions! Many rate coefficients still unknown or inaccurate.
- Low density ⇨ Long cooling times ($> 10^7$ years at $T >\sim 10^6$ K!).

THE HOT IONIZED MEDIUM: CIE AND COOLING



("Chianti": Dere et al. 2009)

- Ionization state depends critically on the gas temperature!

Crucially, again, many rate coefficients still unknown or inaccurate.

The Hot Ionized Medium: X-Ray Emission

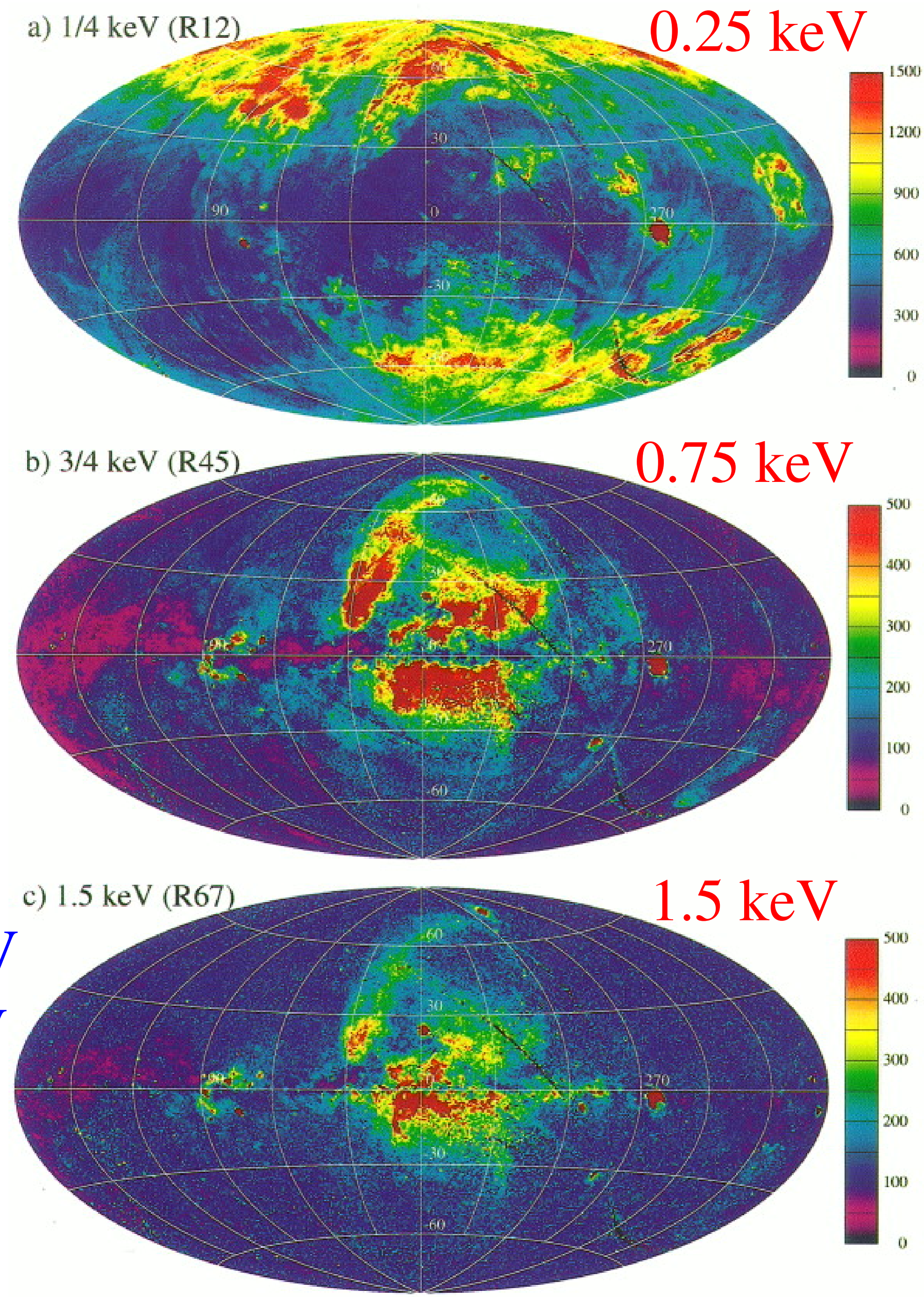
- Higher energy emission from higher temperature gas:
  0.25 keV: $T \sim 10^6$ K.
  0.75 keV: $T \sim 3 \times 10^6$ K.
  1.5 keV: $T \sim 6 \times 10^6$ K.

- Strongest emission at 0.25 keV!

- But absorption from cool gas ⇨ Energy-dependent mean free path.

- Mean free path ~ 100 pc at 0.25 keV
  ~ 1 kpc at 0.75 keV
  ~ 4 kpc at 1.5 keV

⇨ 0.25 keV emission from Local Bubble and Galactic Halo!



(Snowden et al. 1997)

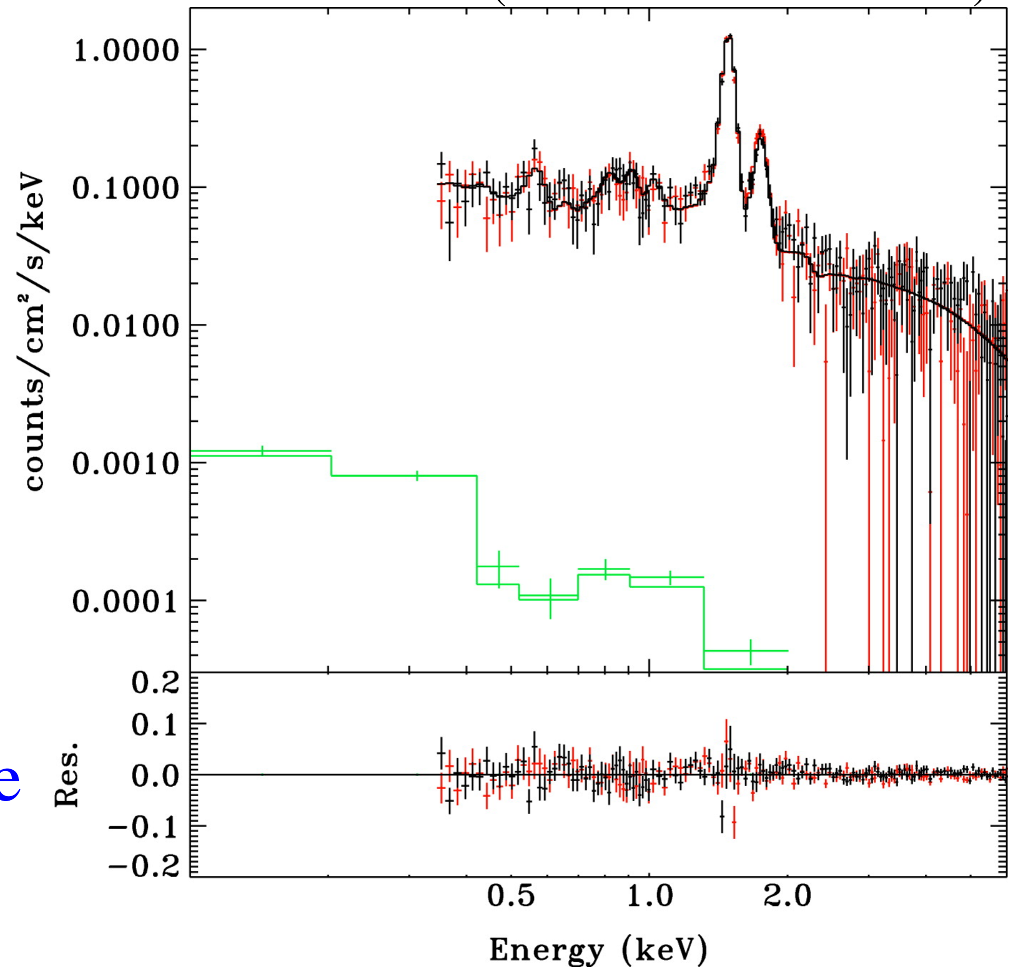
The Hot Ionized Medium: X-Ray Emission

- XMM-Newton spectrum of Local Bubble ⇨ OVII 0.56 keV emission!
  ⇨ $T \sim 1.1 \times 10^6$ K.
  (Kuntz & Snowden 2008)

- < 20% of 0.75 & 1.5 keV emission from the Local Bubble.

- Ratio of 0.75 keV to 1.5 keV emission above the Galactic Centre
  ⇨ $T \sim 4 \times 10^6$ K, $n_e \sim 0.003$ cm^{-3}.
  Scale height ~ 2 kpc.
  Pressure ~ 30,000 cm^{-3} K !!!
  (Snowden et al. 1997)

(Kuntz & Snowden 2008)

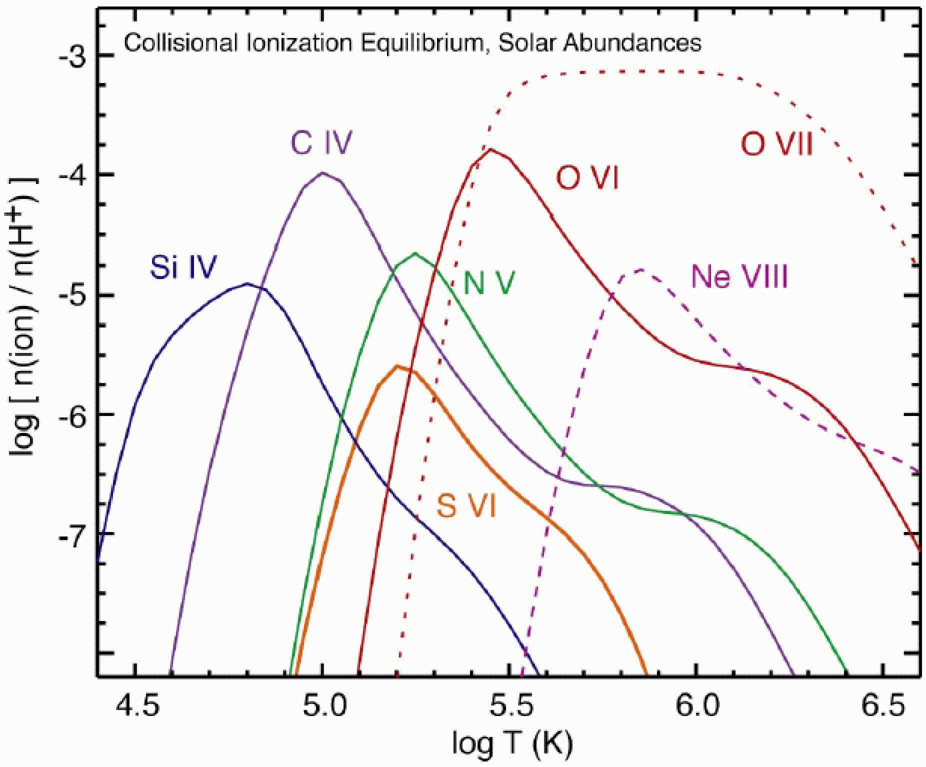


- Absorption shadow in the 0.25 keV emission detected from the 3 kpc molecular cloud ⇨ > 50% likely from the Galactic bulge.

The Hot Ionized Medium: Far-UV Absorption

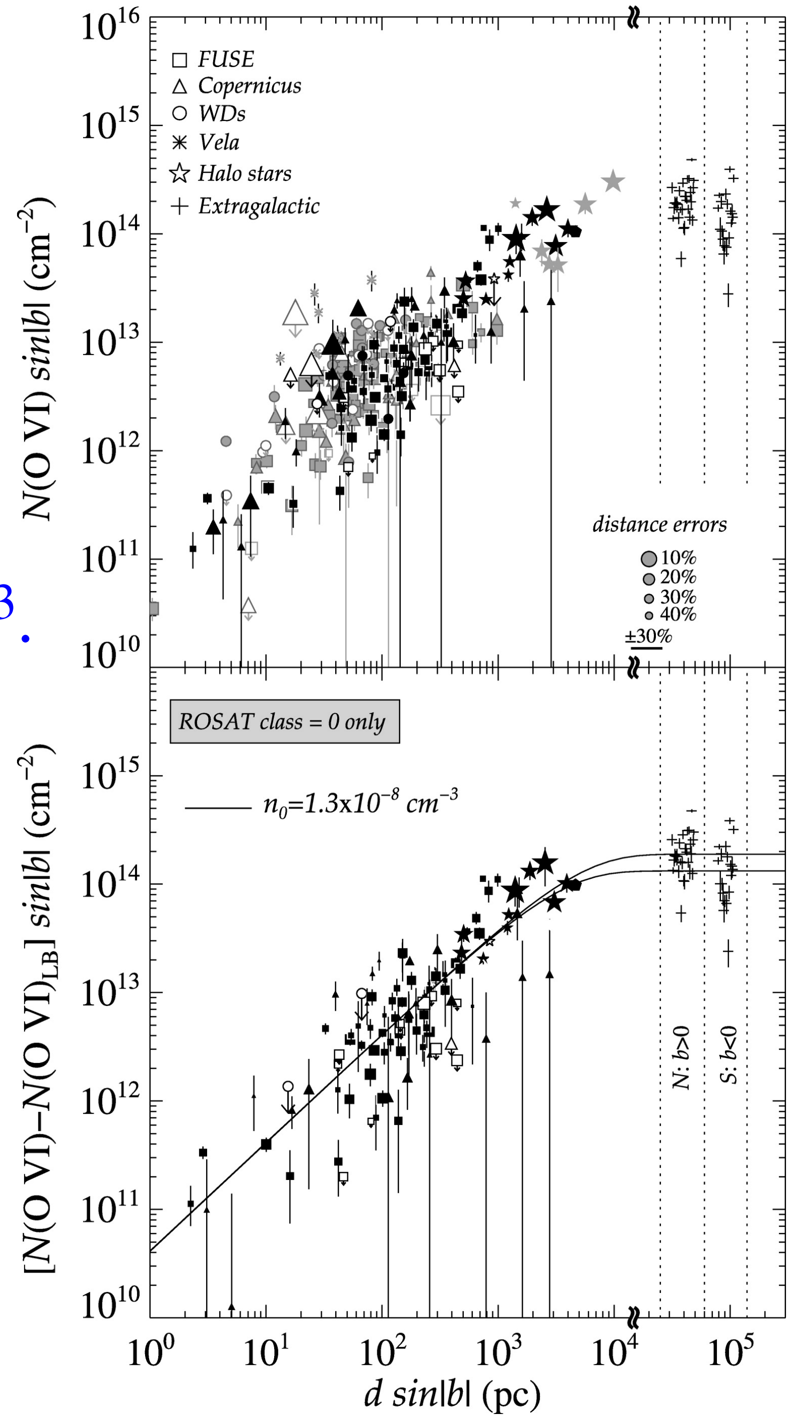
- Can be studied using lines of species with high ionization potential. Ionization potential > 100 eV ⇨ Definitely from the HIM!
- Strong OVI doublet at λ1032/λ1038 ; Ionization potential ~ 113 eV! Best tracer of collisionally ionized gas, T ~ 3 × 10^5 K.
- OVI absorption detected in all directions in the Galaxy. Line widths ~ 15 km/s ⇨ T ~ 3 – 4 × 10^5 K.
- Huge improvements with *FUSE*!
- Fractional abundances in different ionization states ⇨ Gas temperature, density.

(e.g. Savage et al. 2005)



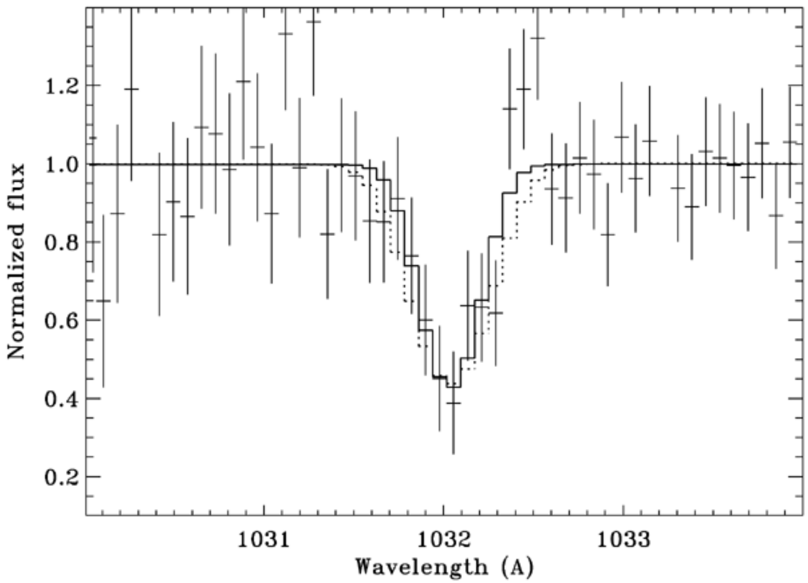
THE SCALE HEIGHT OF OVI ABSORPTION

- *FUSE* OVI survey of 148 stars!
- Subtract Local Bubble contribution and fit exponential function for the scale height
  ⇨ H ~ 4.6 kpc (North)
  H ~ 3.2 kpc (South).
  Mid-plane OVI density ~ 1.3×10^{-8} cm^{-3}.
  (Bowen et al. 2008)
- For [O/H] ~ 5×10^{-4} & 20% of O in OVI
  ⇨ $n \sim 1.3 \times 10^{-4}$ cm^{-3}.
  But unknown filling factor, 20 – 70 % ?
- Similar scale heights in other species:
  H ~ 5.1 kpc (SiIV)
  H ~ 4.4 kpc (CIV)
  H ~ 3.3 kpc (NV)
  (Savage et al. 2005)

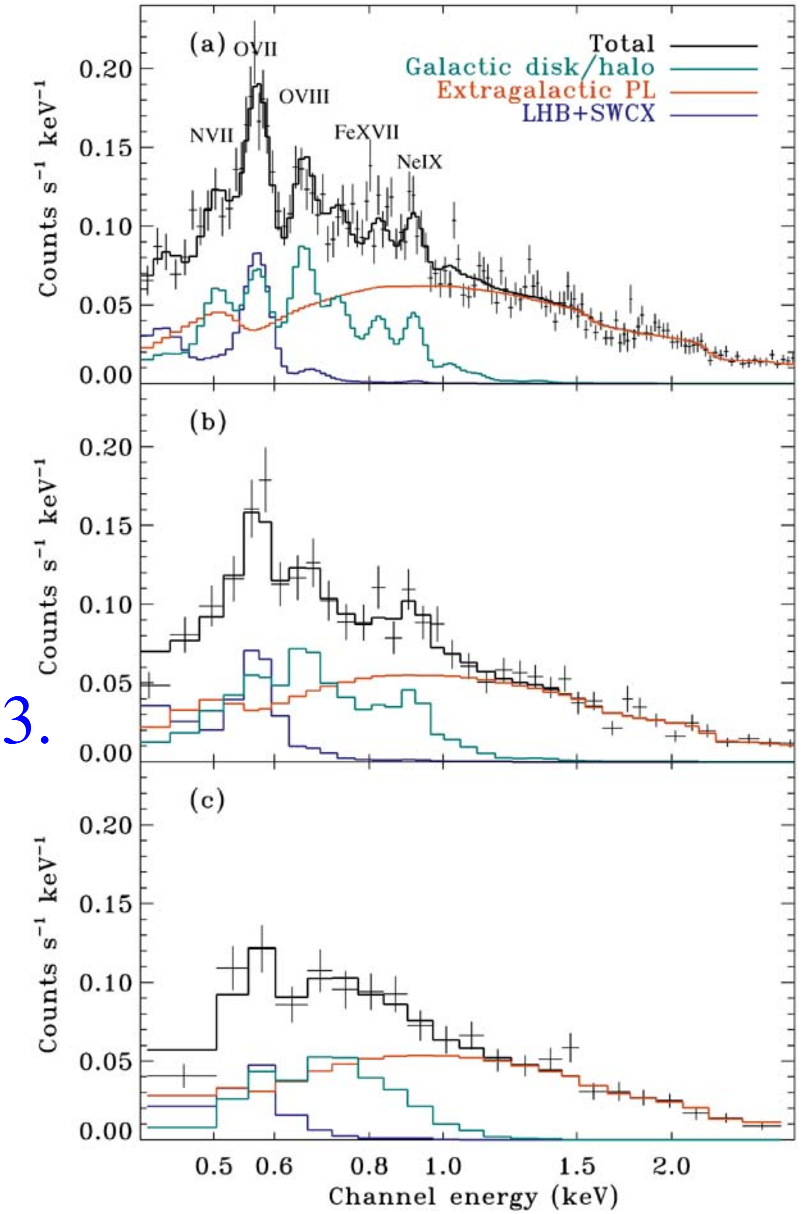


(Bowen et al. 2008)

LMC X-3: X-Ray Emission and OVI Absorption



(Wang et al. 2005)



(Yao et al. 2009)

- *Chandra* OVII 0.56 keV and *FUSE* OVI λ1032/λ1038 absorption towards LMC X-3. (Wang et al. 2005)
- *Suzaku* detection of OVII 0.56 keV, OVIII 0.65 keV and NeIX 0.91 keV emission, close to LMC X-3. (Yao et al. 2009)
- Joint fit, assuming CIE:
  ⇨ $T \sim 3 \times 10^6$ K
  $n \sim 1.4 \times 10^{-3}$ cm^{-3}
  H ~ 2.8 kpc.

(Yao et al. 2009)