Lyα Radiative Transfer and The Wouthuysen-Field Effect

in the Milky Way Galaxy

(WF effect = Coupling of Lyα scattering with the 21 cm transition)

Kwang-il Seon
Korea Astronomy & Space Science Institute (KASI)
University of Science & Technology (UST)
Korea

Chang-Goo Kim
Princeton University
USA

SFDE17, August 10th (Thursday)

Seon et al. (2017, in preparation)

What determines the spin temperature?

- The 21 cm spin temperature of H atom is important because it is a tracer of the gas temperature.
- The spin temperature is mainly determined by two mechanisms.

(1) Direct Radiative Transitions by the background radiation field (Cosmic Microwave Background + Galactic Synchrotron)

$$T_R = 2.73 \text{ K or } 3.77 \text{ K}$$

(2) Collisional Transitions by collision with other hydrogens and electrons

$$\text{gas kinetic temperature} = T_K$$

$$\boxed{T_s = \frac{T_R + y_c T_K}{1 + y_c}}$$

Collisional Effect on Spin Temperature

$$T_s = \frac{T_R + y_c T_K}{1 + y_c}$$
$$y_c \approx \frac{n}{4.18 \times 10^{-4}\ \mathrm{cm}^{-3}} \frac{1}{T_K}$$

- High density, low temperature medium (CNM)

$$T_s \approx T_K \quad (y_c \gg 1)$$

- Low density, high temperature medium (WNM, IGM)

$$T_s \ll T_K \quad (y_c \ll 1)$$

Collisions is not be significant (Field 1958; Liszt 2001).

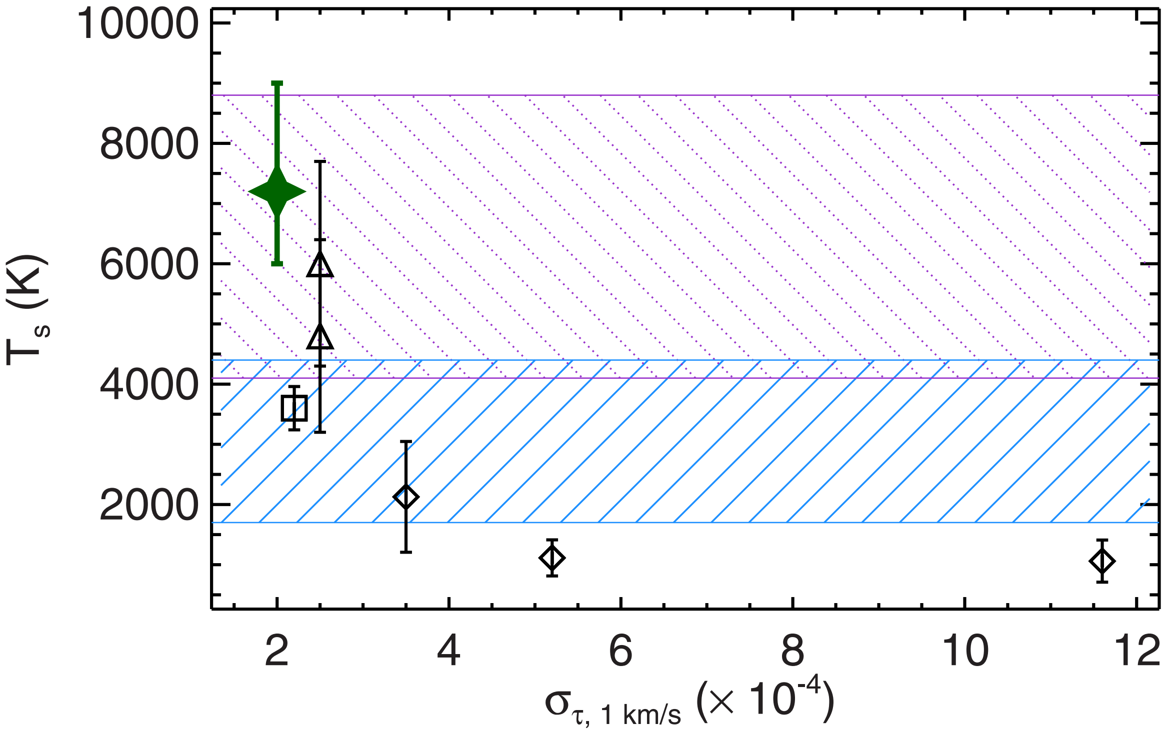
The very low density hydrogen gas at outer regions of disk galaxies might be invisible in H I emission line.

But,

- In halo gas of a nearby spiral galaxy NGC 3067 toward the 3C 232 sight line, it was found that

  spin temperature ~ kinetic temperature.
  (Keeney et al. 2005)

- The WNM component has a spin temperature of ~ 7200 K (Murray et al. 2014).



Other mechanism?

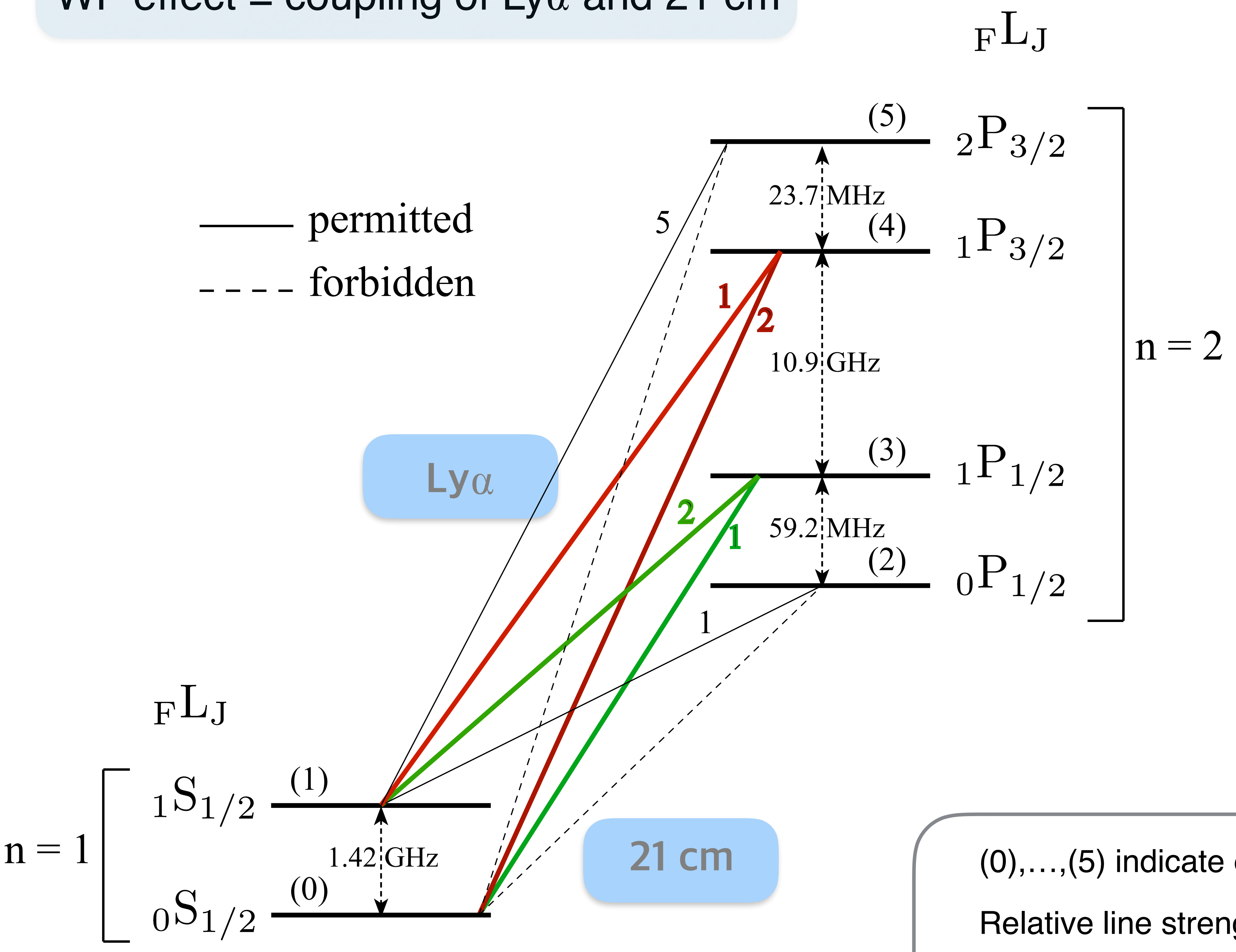
- There should be other processes to excite the hyperfine states of the ground level.
- **Wouthuysen-Field effect** **(Wouthuysen 1952; Field 1958, 1959)**

  Lyα pumping on the 21 cm spin temperature

  The Lyα photons couple the 21 cm spin temperature to the gas kinetic temperature.

Hyperfine Structures of Hydrogen Atom

WF effect = coupling of Lyα and 21 cm



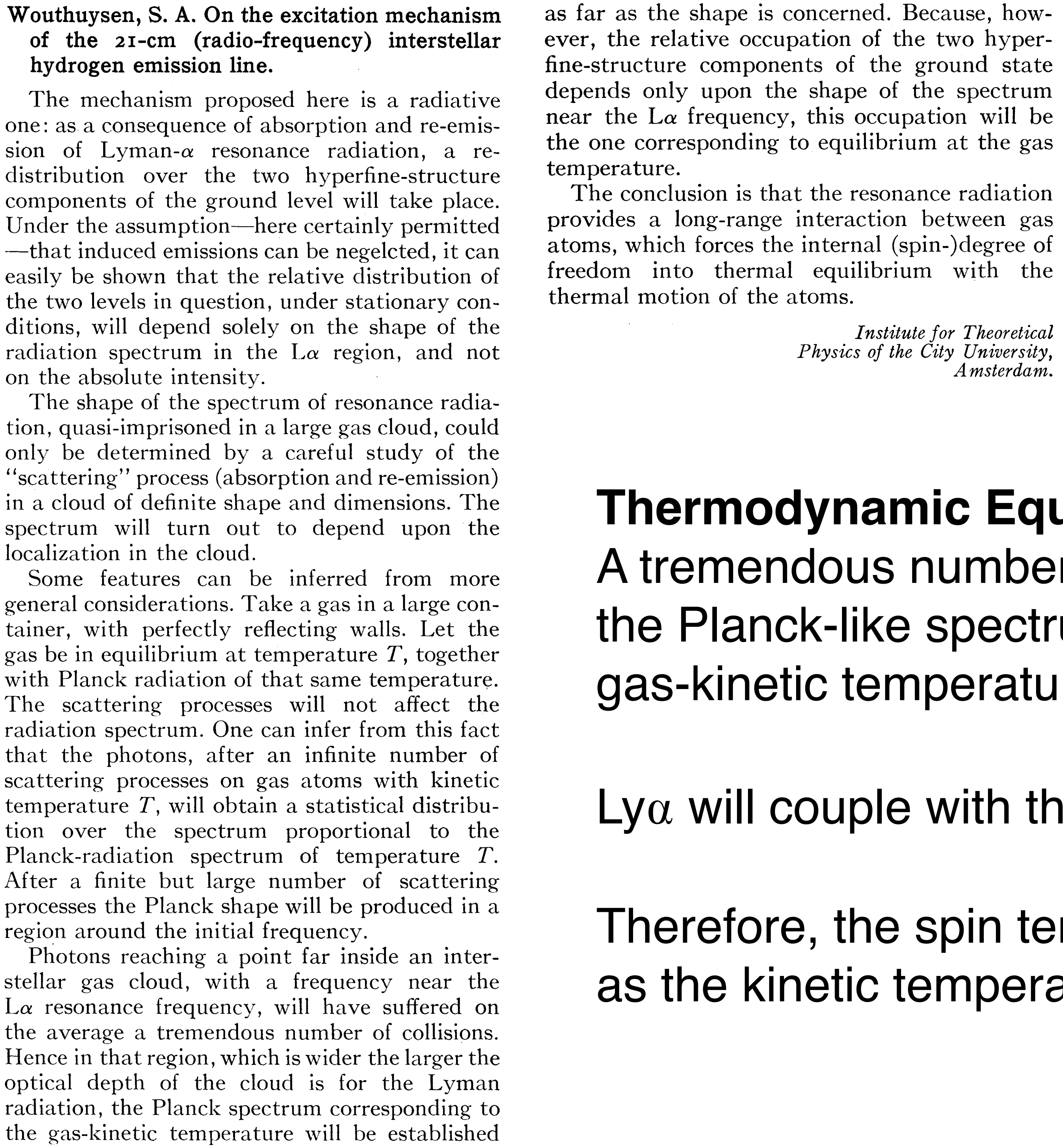
(0),…,(5) indicate energy levels.

Relative line strengths are

$$S_{51} : S_{41} : S_{40} : S_{31} : S_{30} : S_{21} = 5 : 1 : 2 : 2 : 1 : 1$$
$$S_{50} = S_{20} = 0$$

Wouthuysen-Field Effect

- Wouthuysen (1952)



Wouthuysen, S. A. On the excitation mechanism of the 21-cm (radio-frequency) interstellar hydrogen emission line.

The mechanism proposed here is a radiative one: as a consequence of absorption and re-emission of Lyman-α resonance radiation, a redistribution over the two hyperfine-structure components of the ground level will take place. Under the assumption—here certainly permitted—that induced emissions can be negelcted, it can easily be shown that the relative distribution of the two levels in question, under stationary conditions, will depend solely on the shape of the radiation spectrum in the Lα region, and not on the absolute intensity.

The shape of the spectrum of resonance radiation, quasi-imprisoned in a large gas cloud, could only be determined by a careful study of the "scattering" process (absorption and re-emission) in a cloud of definite shape and dimensions. The spectrum will turn out to depend upon the localization in the cloud.

Some features can be inferred from more general considerations. Take a gas in a large container, with perfectly reflecting walls. Let the gas be in equilibrium at temperature T, together with Planck radiation of that same temperature. The scattering processes will not affect the radiation spectrum. One can infer from this fact that the photons, after an infinite number of scattering processes on gas atoms with kinetic temperature T, will obtain a statistical distribution over the spectrum proportional to the Planck-radiation spectrum of temperature T. After a finite but large number of scattering processes the Planck shape will be produced in a region around the initial frequency.

Photons reaching a point far inside an interstellar gas cloud, with a frequency near the Lα resonance frequency, will have suffered on the average a tremendous number of collisions. Hence in that region, which is wider the larger the optical depth of the cloud is for the Lyman radiation, the Planck spectrum corresponding to the gas-kinetic temperature will be established as far as the shape is concerned. Because, however, the relative occupation of the two hyperfine-structure components of the ground state depends only upon the shape of the spectrum near the Lα frequency, this occupation will be the one corresponding to equilibrium at the gas temperature.

The conclusion is that the resonance radiation provides a long-range interaction between gas atoms, which forces the internal (spin-)degree of freedom into thermal equilibrium with the thermal motion of the atoms.

Institute for Theoretical
Physics of the City University,
Amsterdam.

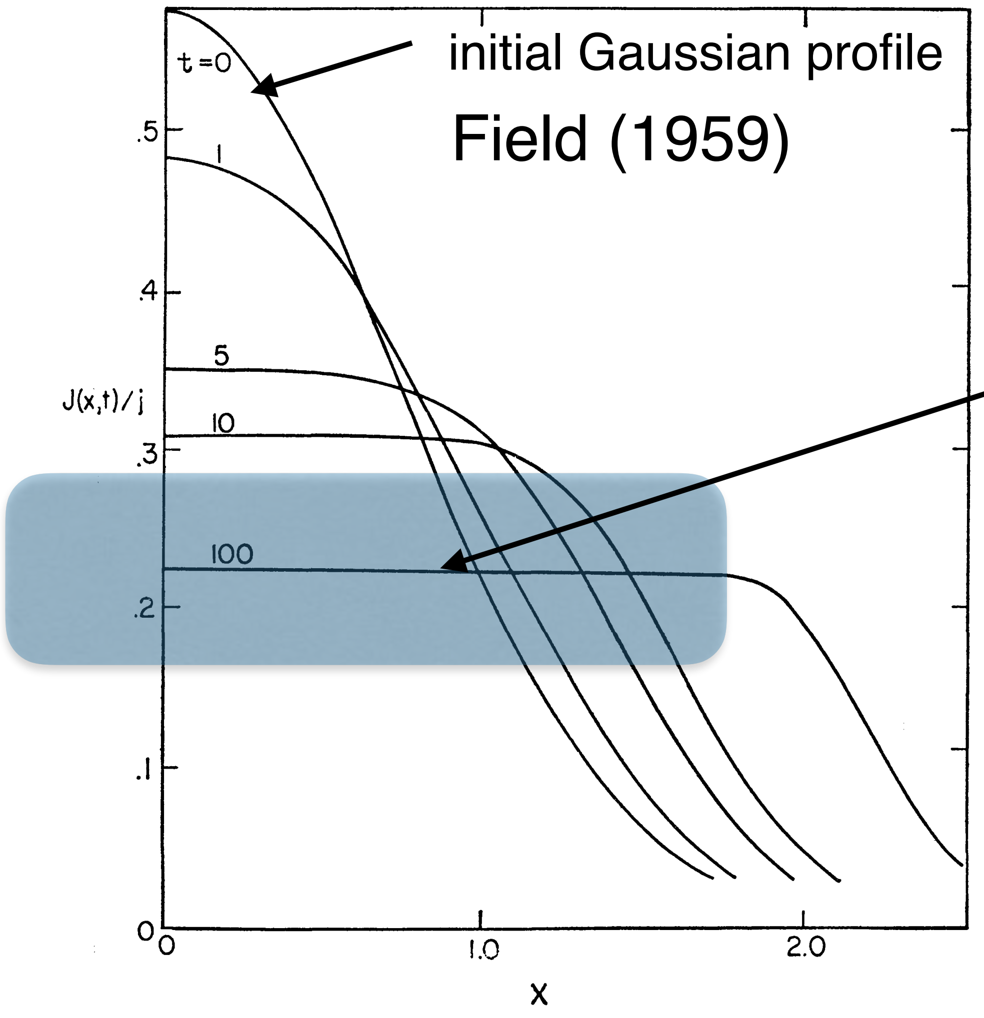
Thermodynamic Equilibrium:
A tremendous number of scattering will establish the Planck-like spectrum corresponding to the gas-kinetic temperature.

Lyα will couple with the hyperfine state of H atom.

Therefore, the spin temperature will be the same as the kinetic temperature of H gas.

Recoil Effect (momentum transfer between H and Lyα)

Field (1959) : The Lyα profile has a profile of Boltzmann distribution by recoil effect, after a huge amount of scattering.



Without recoil:

The spectral Profile becomes flat at the line center when the photons undergoes a large number of resonance scattering.

$$J(x \sim 0, t \to \infty) = \text{constant}$$

With recoil:

Recoil of the scattering atom changes the slope of the Lyα central profile after an infinite number of scattering.

$$J(x \sim 0, t \to \infty) \propto e^{-h\nu/k_B T_\alpha}$$

with $T_\alpha = T_K$

Equation for spin temperature

- Rate equation for the population of the hyperfine states 0 and 1:

$$n_0\left(P_{01}^R+P_{01}^c+P_{01}^\alpha\right)=n_1\left(P_{10}^R+P_{10}^c+P_{10}^\alpha\right)$$

in steady-state

$P_{01}^R,\ P_{10}^R$ = transition rate (per sec) caused by radio (21 cm) background

$P_{01}^c,\ P_{10}^c$ = transition rate by collision

$P_{01}^\alpha,\ P_{10}^\alpha$ = transition rate by Lyα scattering

Assuming that

$$J(\nu)\propto\exp\left[-\frac{h(\nu-\nu_0)}{k_BT_\alpha}\right]$$

at the line center of Lyα

$$y_c\equiv\frac{T_*}{T_K}\frac{P_{10}^c}{A_{10}}$$

We obtain

$$T_s=\frac{T_R+y_cT_K+y_\alpha T_\alpha}{1+y_c+y_\alpha}$$

$$y_\alpha\equiv\frac{T_*}{T_K}\frac{P_{10}^\alpha}{A_{10}}$$

$$T_*=\frac{h\nu_{10}}{k_B}=0.0681\ ^\circ\mathrm{K}$$

Questions:

- **spectral shape:** How many scattering (how large optical depth) is required to obtain the Boltzmann-distribution-like spectral shape with the kinetic temperature?

  Some studies have claimed that the number of scattering required to guarantee the Boltzmann function is too huge to be achieved in most astrophysical systems.

- **y_α:** Are the Lyα production rate and the number of scattering large enough to make T_s equal to T_K?

Monte-Carlo Simulation

- Monte Carlo simulation algorithm for Lyα RT has been well developed in the high-redshift Lyα community.
- However, no one has tried to predict the spectral shape within the medium.
- Lucy (1999)'s method is used to calculate the spectral profiles in the medium.

$$J_\nu \Delta\nu = \frac{c}{4\pi}\frac{1}{\Delta V}\sum_i \epsilon_* \frac{\delta t_i}{\Delta t} \quad \rightarrow \boxed{J_\nu = \frac{1}{4\pi \Delta V \Delta\nu}\frac{L_*}{N_*}\sum_i \delta l_i}$$

- Number of scattering is obtained as follows:

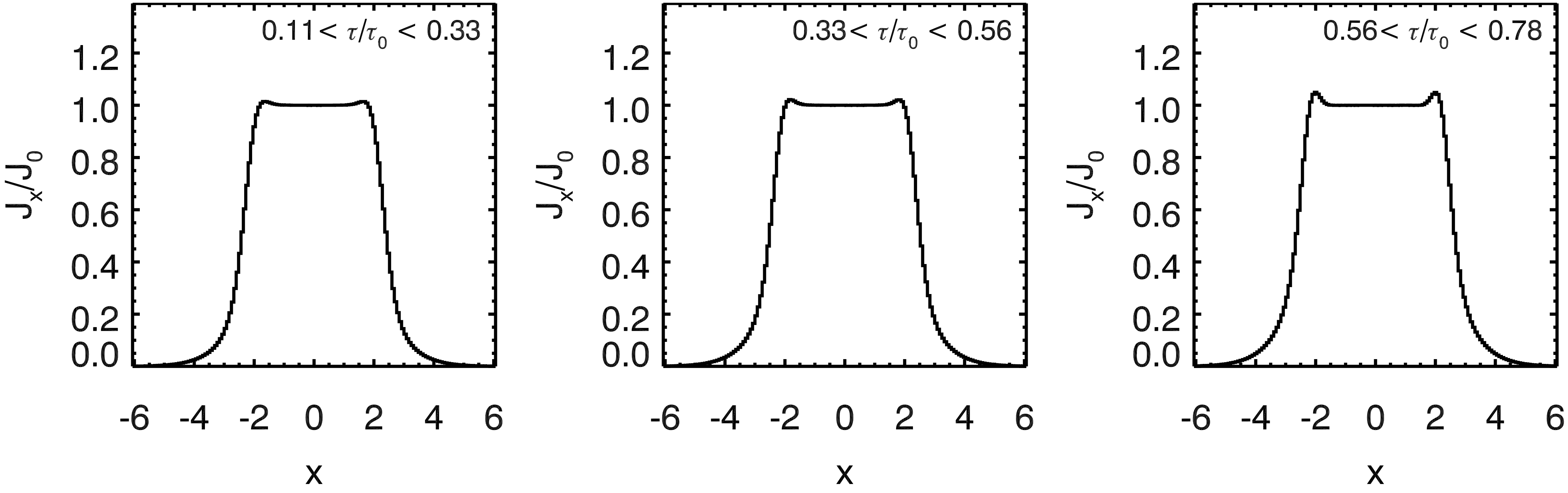
$$\begin{aligned} P_\alpha &= \frac{L_* \Delta t / h\nu_\alpha}{N_{\rm packet}} \frac{1}{n_H \Delta V_k \Delta t} N_k^{\rm scatt} \\ &= \frac{L_* / h\nu_\alpha}{N_{\rm packet}} \frac{1}{n_H \Delta V_k} N_k^{\rm scatt} \end{aligned}$$

Without recoil effect

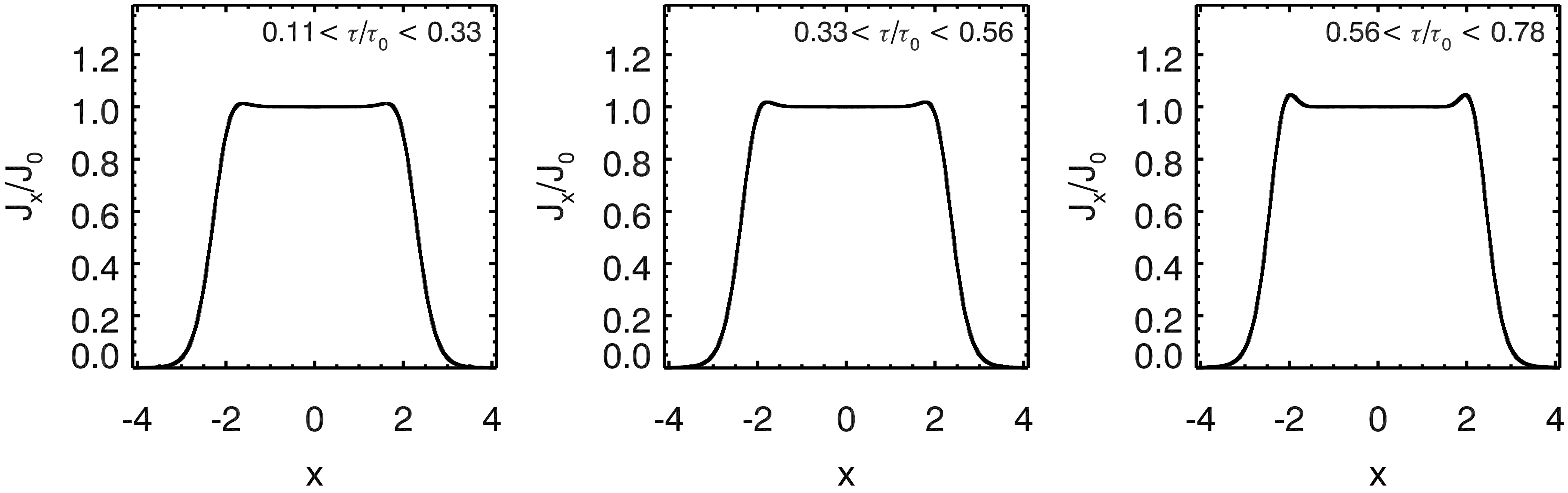
Infinite Slab

$J_x = \text{constant}$

$T = 10\ \text{K},\ \tau_0 = 10^2$



$T = 10^4\ \text{K},\ \tau_0 = 10^2$

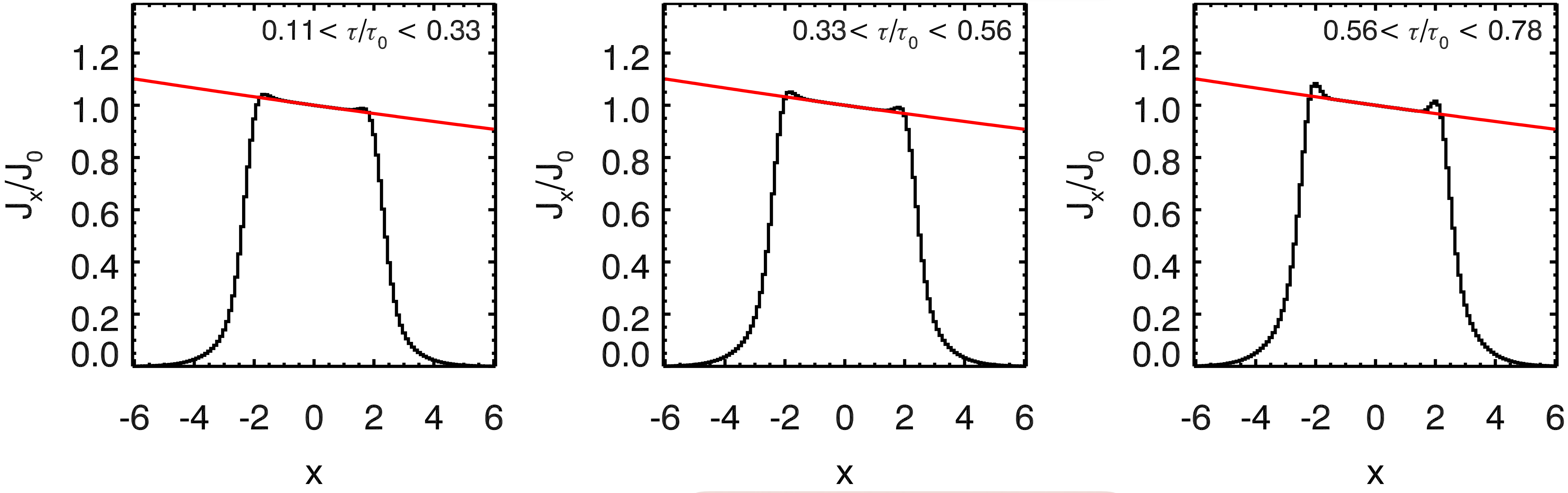


With recoil effect

Infinite Slab

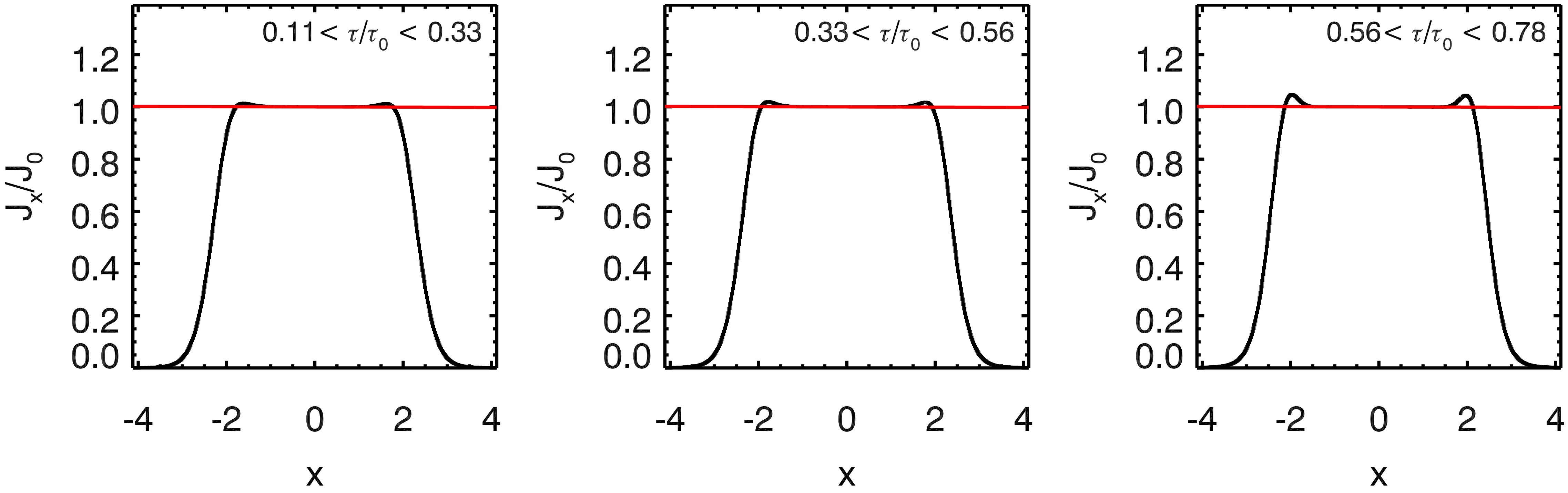
$T = 10\ \mathrm{K},\ \tau_0 = 10^2$

$$J_x = J_0 \exp\left(-\frac{h\Delta\nu_D}{k_\mathrm{B}T_\mathrm{K}}x\right)$$



$T = 10^4\ \mathrm{K},\ \tau_0 = 10^2$

$$J_x = \text{constant?}$$

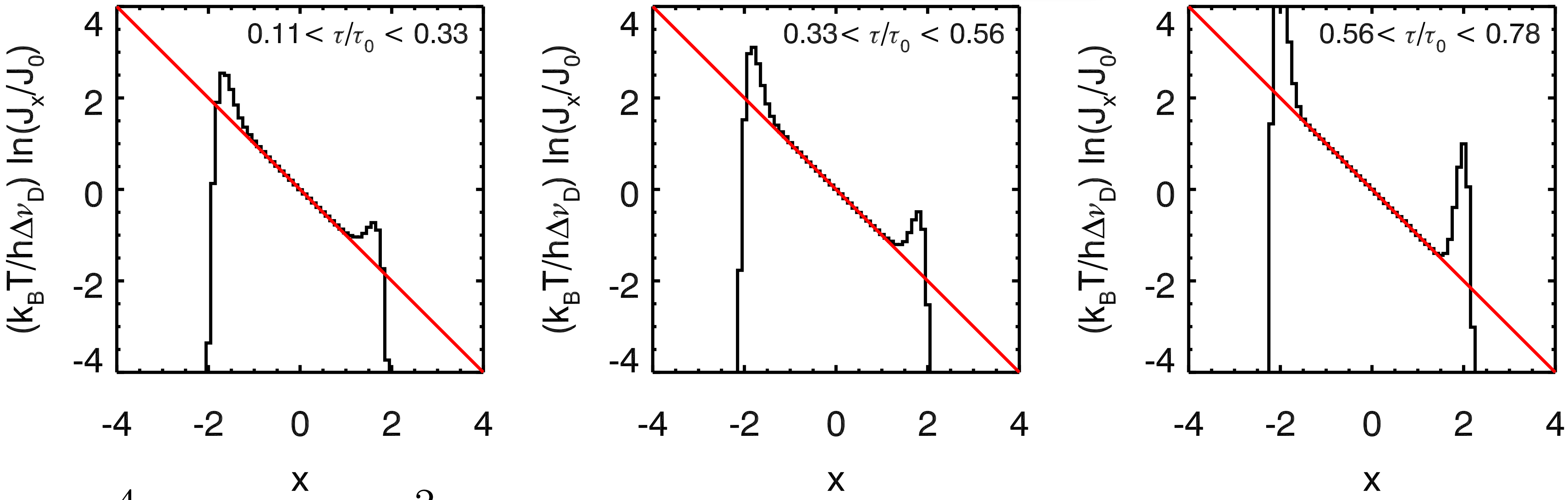


With recoil effect

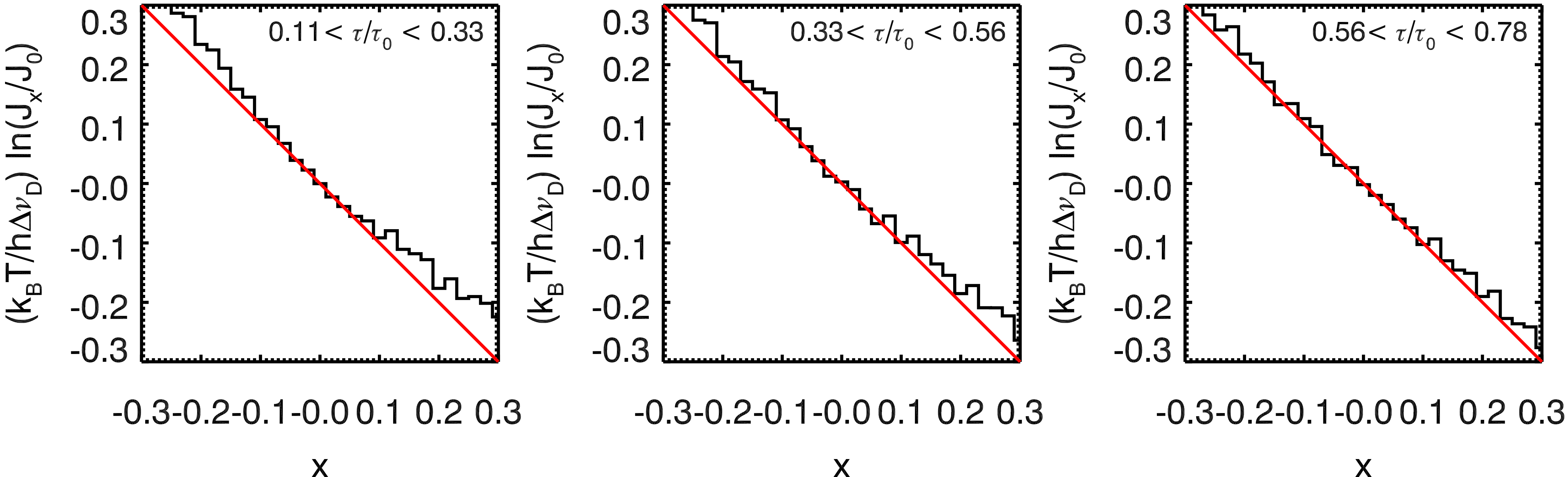
$$\ln\left(\frac{J_x}{J_0}\right) = -\frac{h\Delta\nu_D}{k_{\rm B}T_{\rm K}}x$$

Infinite Slab

$T = 10\ \mathrm{K},\ \tau_0 = 10^2$



$T = 10^4\ \mathrm{K},\ \tau_0 = 10^2$



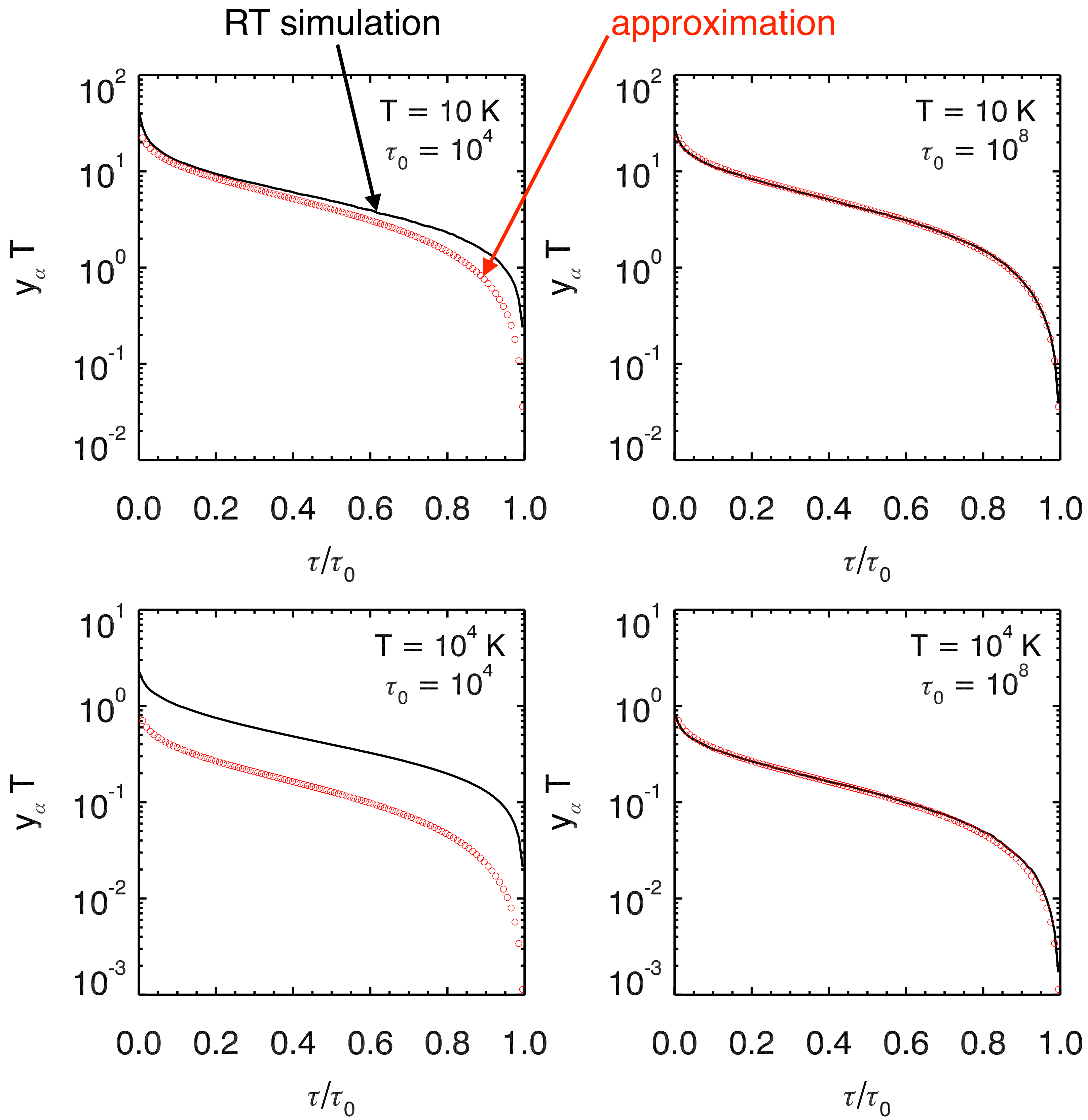
- **spectral shape?**

  Yes, Boltzmann-distribution is easily established even an optical depth as low as 100.

  In most astrophysical situations, the Boltzmann-distribution can be guaranteed.

How Significant is the Lyα scattering?: No Dust

Slab geometry



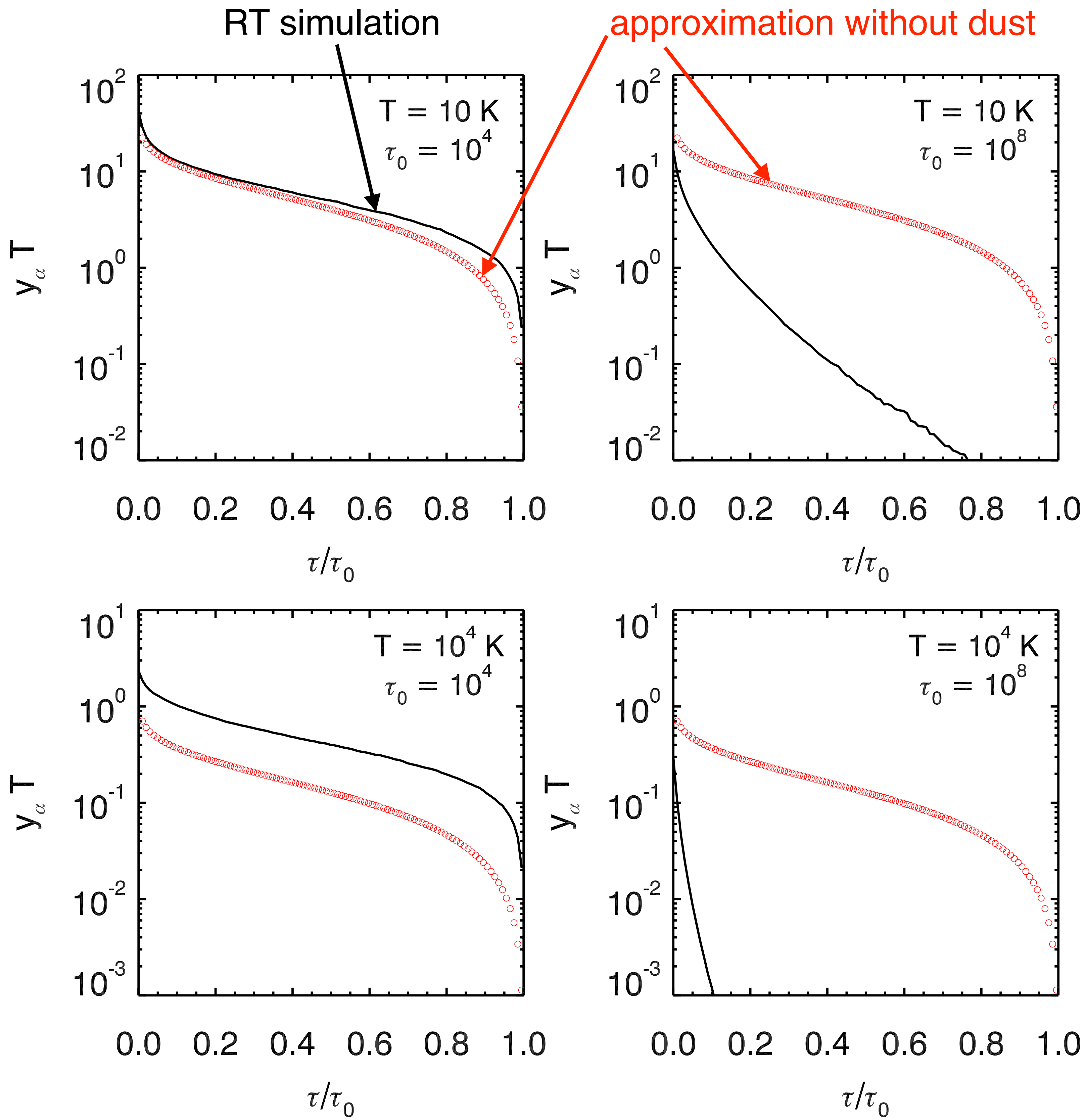
Analytic Approximation

$$J_x(x=0) = -\frac{\sqrt{6}}{8\pi^2}\ln\left[\tan\left(\frac{\pi}{4}\frac{\tau}{\tau_0}\right)\right]$$

$$\approx -\frac{\sqrt{6}}{8\pi}\ln\left(\frac{\pi}{4}\frac{\tau}{\tau_0}\right) \quad \text{as} \quad \frac{\tau}{\tau_0} \ll 1$$

How Significant is the Lyα scattering?: Dust Effect

Slab geometry



RT simulation

approximation without dust

The WNM of our Galaxy : Source

- **Number of Lyα photons** (Vacca et al. 1996)

  Production rate of ionizing photons from 429 O- and early-B stars within 2.5 kpc of the Sun

  $$\Psi_{\mathrm{Lyc}} = 3.7 \times 10^7 \ \mathrm{photons\ cm^{-2}\ s^{-1}}$$

  Lyman-alpha production rate

  (Lyα photons per recombination = 0.68)

  $$\begin{aligned}\Psi_{\mathrm{Ly}\alpha} &= 0.68 \times \Psi_{\mathrm{Lyc}} \\ &= 2.5 \times 10^7 \ \mathrm{photons\ cm^{-2}\ s^{-1}}\end{aligned}$$

- **Spatial distribution of OB stars** (Ferriere 1998)

  $$N_{\mathrm{Ly}\alpha}(z) \propto \exp\left(-\frac{1}{2}\left|\frac{z}{81\ \mathrm{pc}}\right|^2\right)$$

Two Phases ISM Model

- **<u>Two phases (Cold Neutral Medium + Warm Neutral Medium)</u>**

  (Ferriere 1998)

CNM: $\langle \rho_c(z) \rangle = (0.340\ \mathrm{cm}^{-3}) \left\{ 0.859 \exp\left[-\left(\frac{z}{H_1} \right)^2 \right] + 0.047 \exp\left[-\left(\frac{z}{H_2} \right)^2 \right] + 0.094 \exp\left[-\frac{|z|}{H_3} \right] \right\}$

WNM: $\langle \rho_w(z) \rangle = (0.226\ \mathrm{cm}^{-3}) \left\{ 0.456 \exp\left[-\left(\frac{z}{H_1} \right)^2 \right] + 0.403 \exp\left[-\left(\frac{z}{H_2} \right)^2 \right] + 0.141 \exp\left[-\frac{|z|}{H_3} \right] \right\}$

density contrast: $\frac{\rho_c}{\rho_w} = 100$

filling fraction of CNM: $f = 0.01$

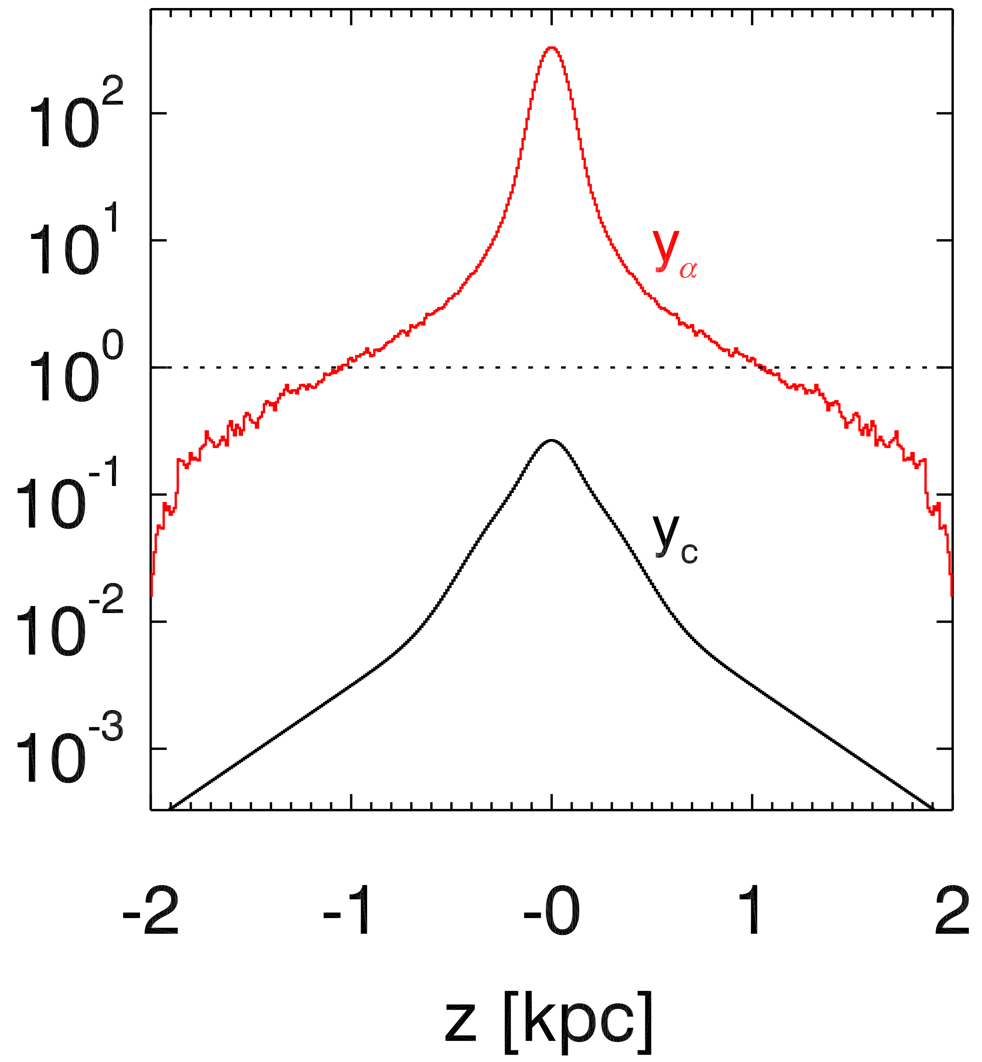
temperatures: $T_c = 80K$

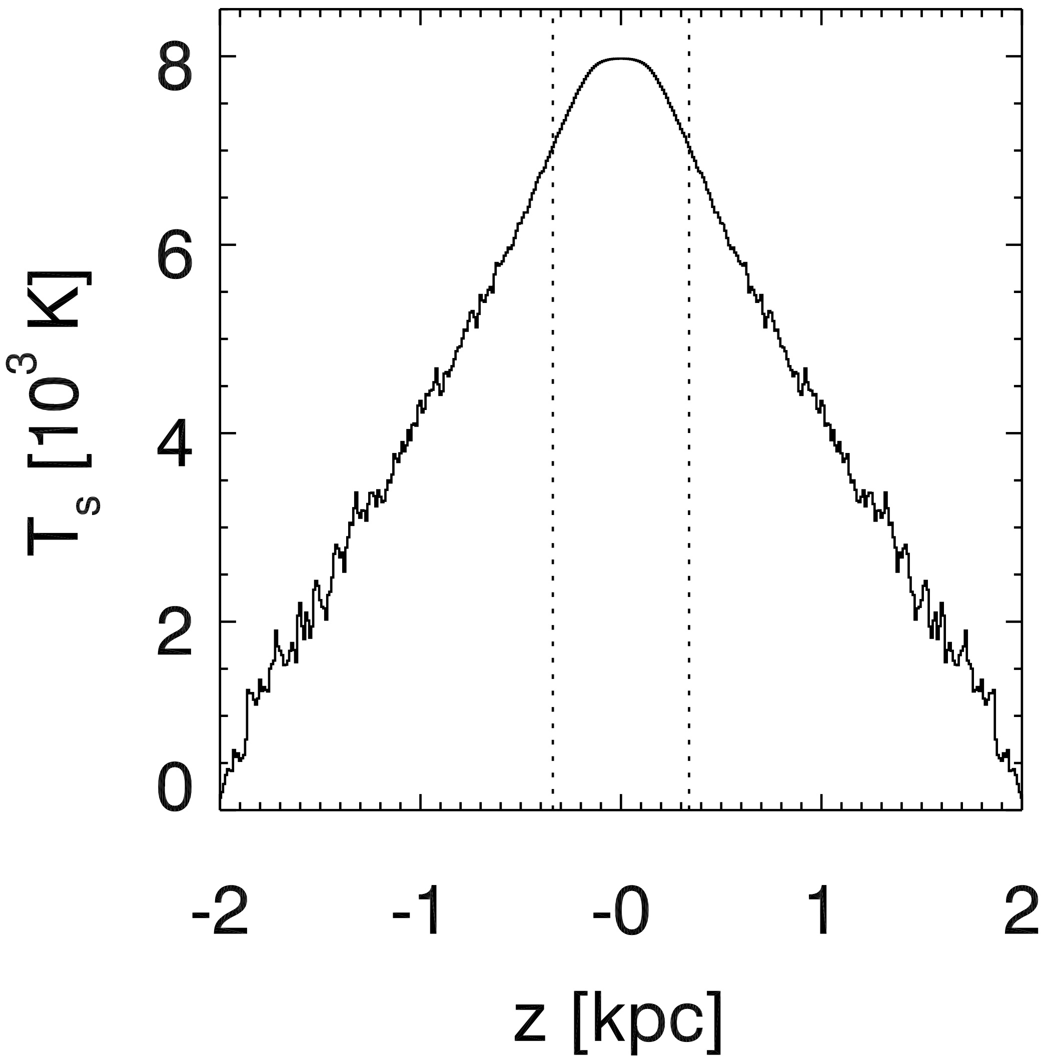
$T_w = 8000K$

- **<u>Milky Way Dust-to-Gas ratio ~ 100 by mass</u>**

Results: Two-phase Medium

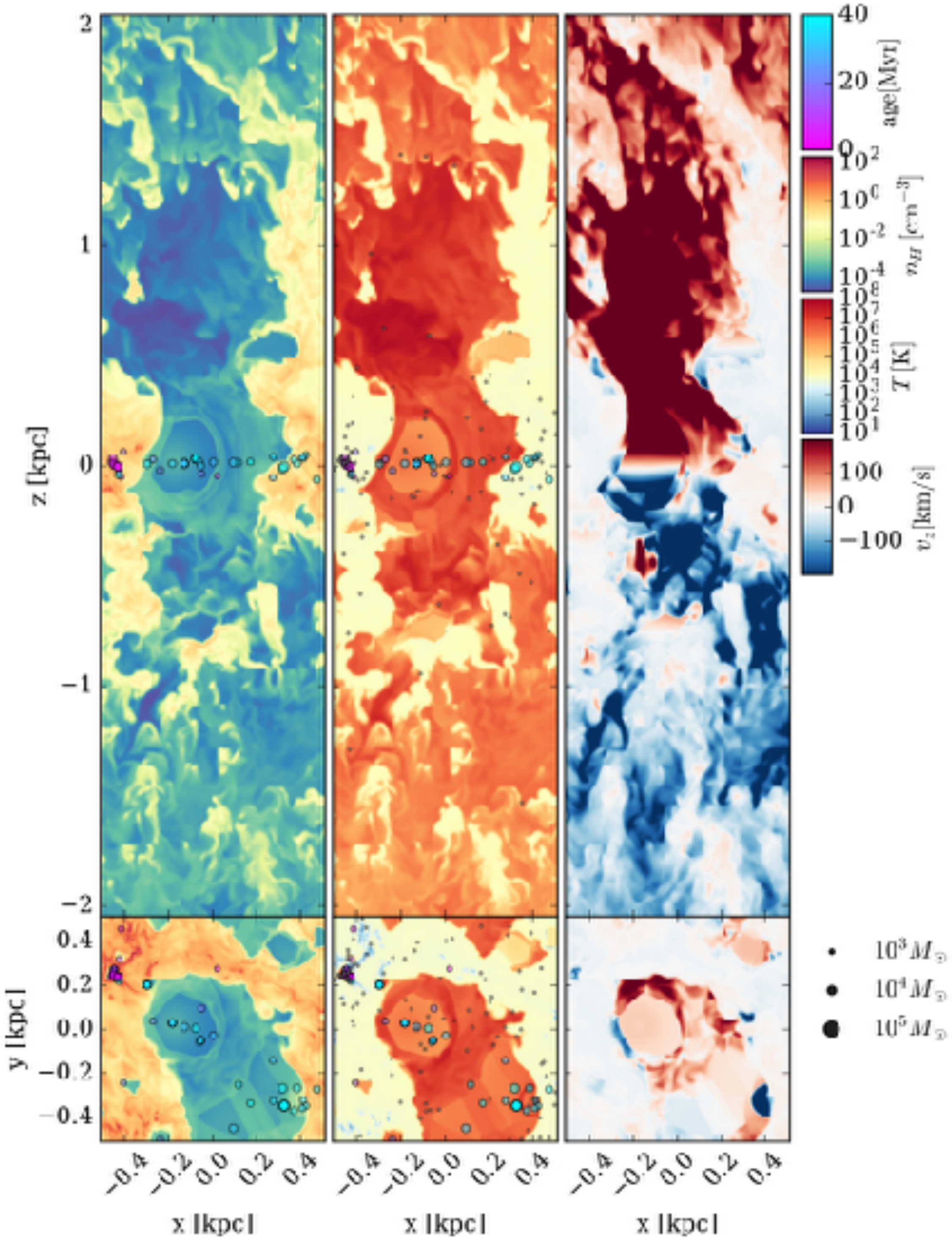
- **Spin temperature is higher than 7000 K up to 350 pc above the plane.**





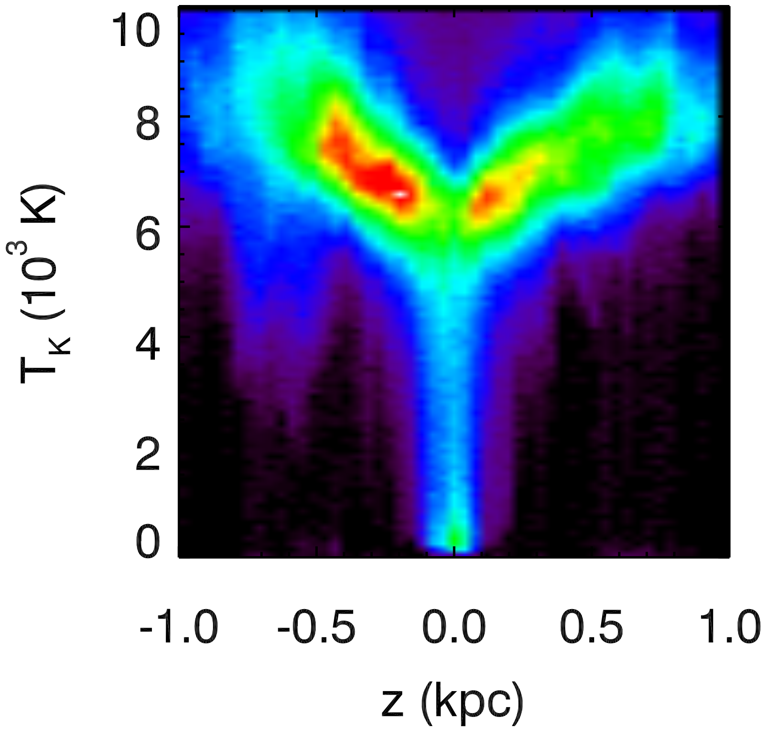
TIGRESS Model

TIGRESS = Three-phase Interstellar medium in Galaxies Resolving Evolution with Star formation and Supernova feedback (Kim et al. 2017; ApJ, submitted)

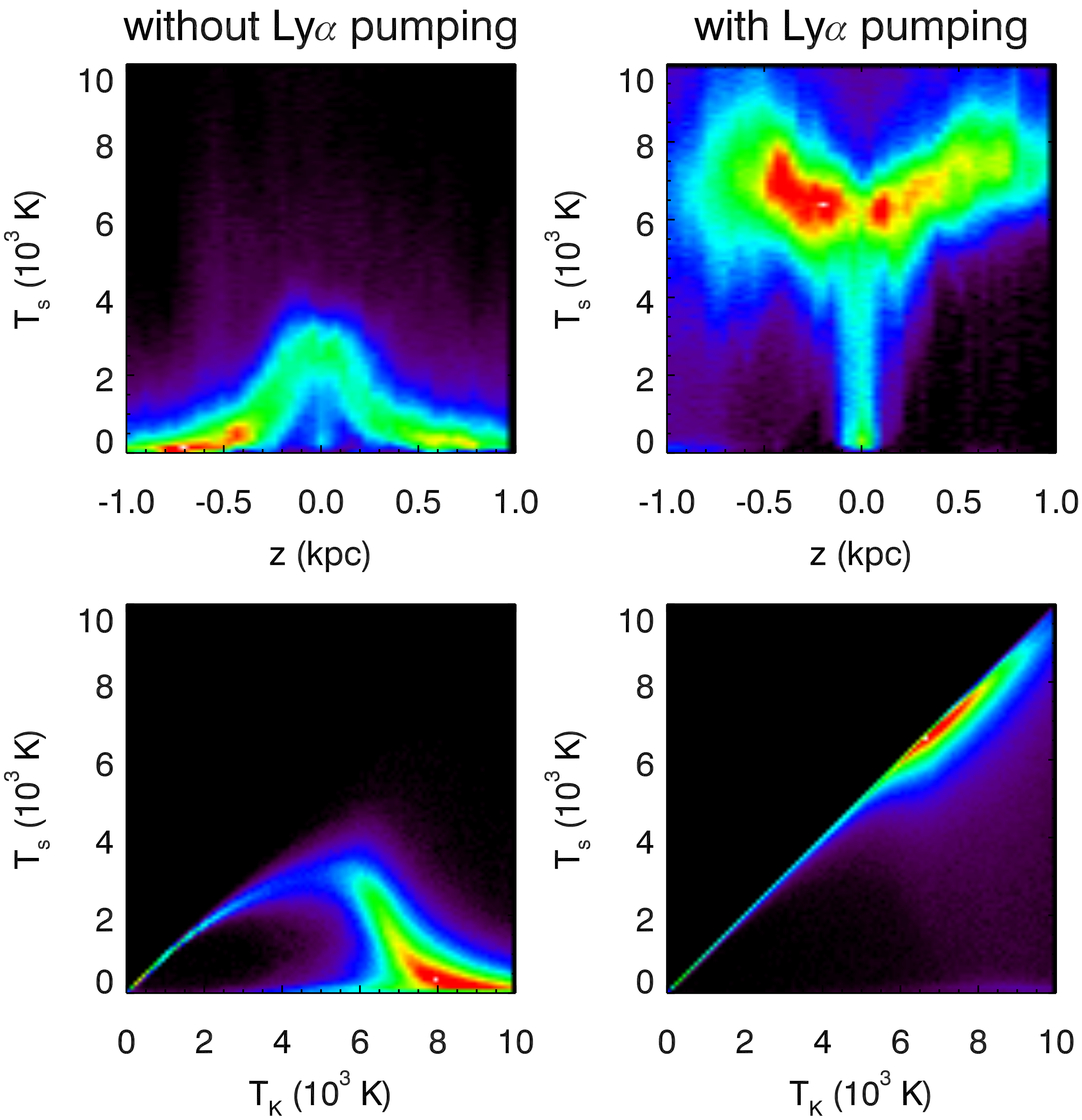


Kinetic & Spin Temperatures

Kinetic Temp.



Spin Temp.


without Lyα pumping

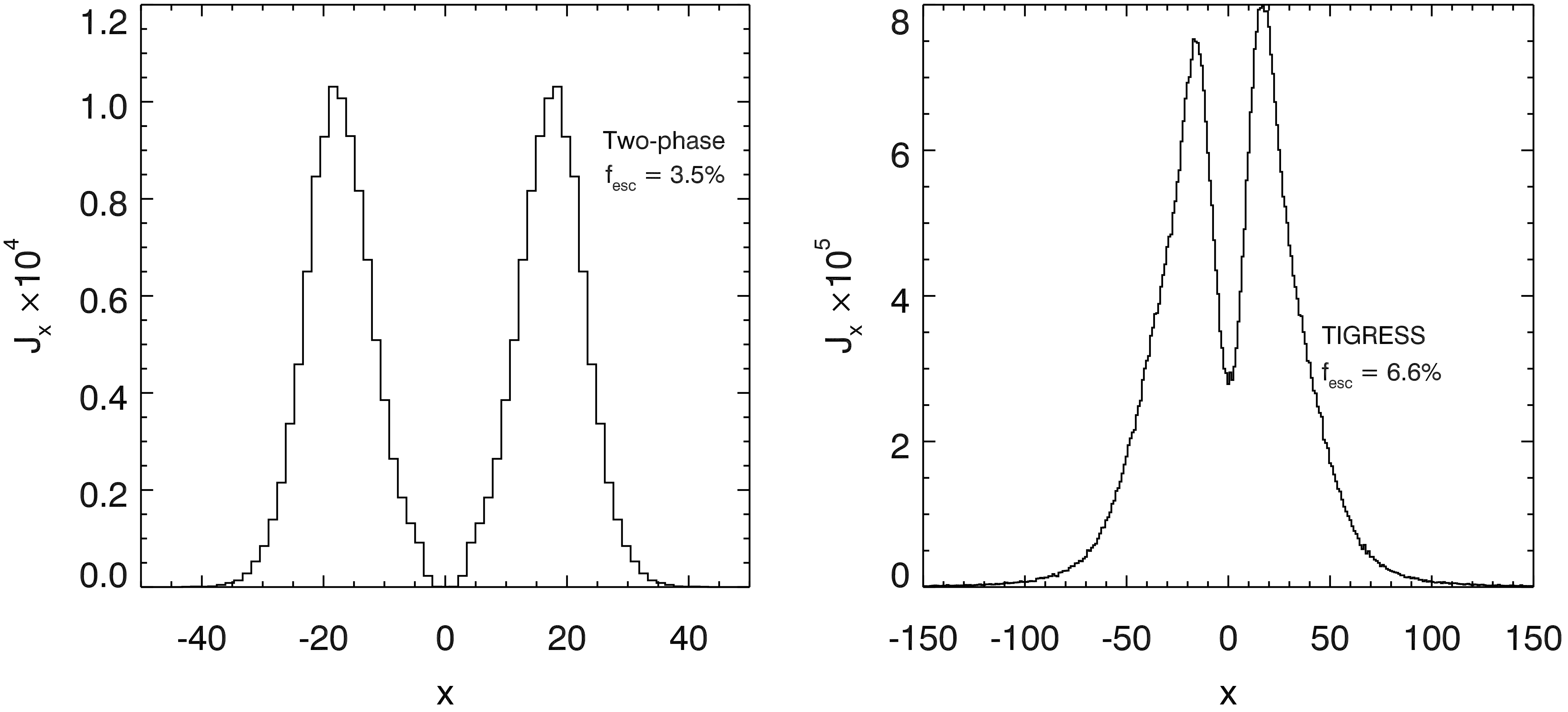
with Lyα pumping

- **y_α?**

  Yes, the Lyα production rate and the number of scattering are large enough to make T_s equal to T_K in the WNM.

Escape Fraction of Lyα

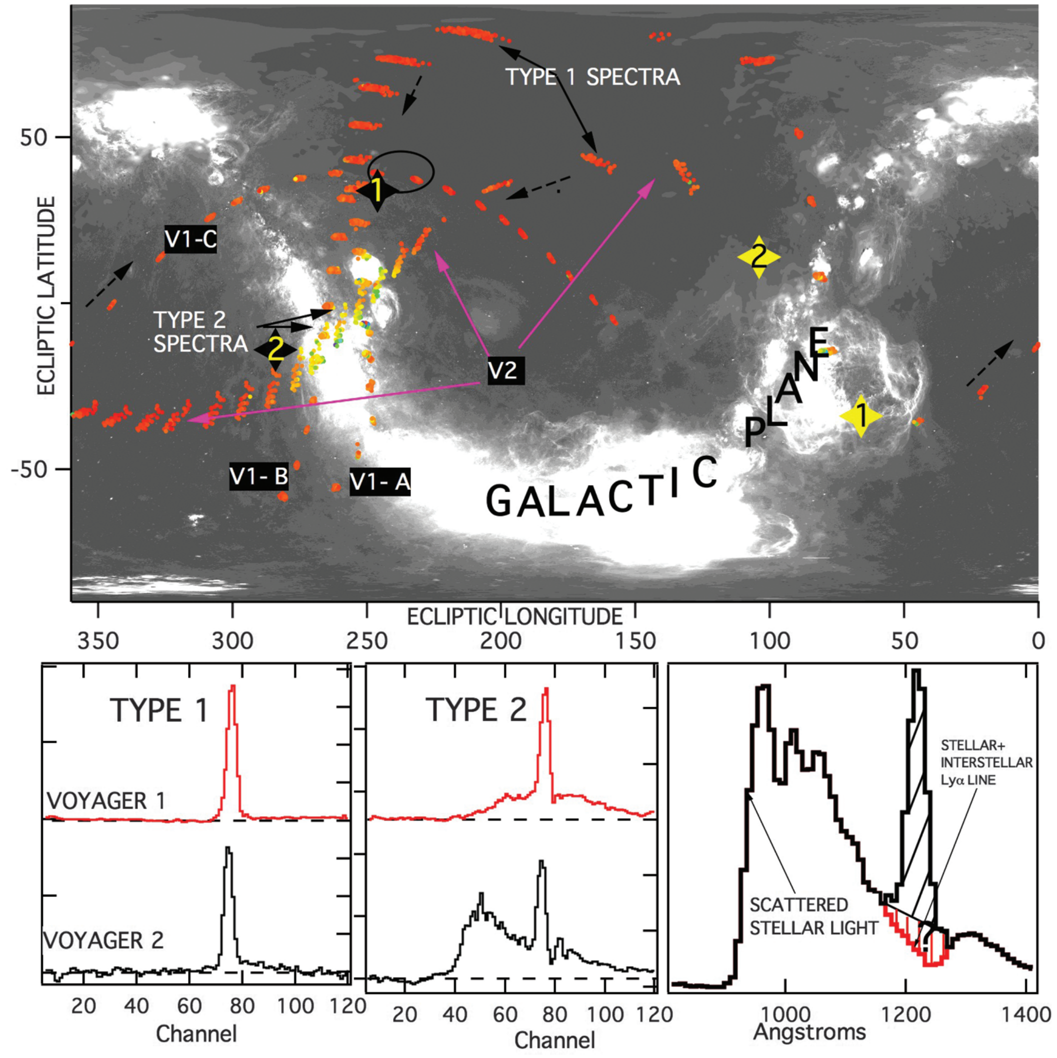
Escape fraction ~ a few %

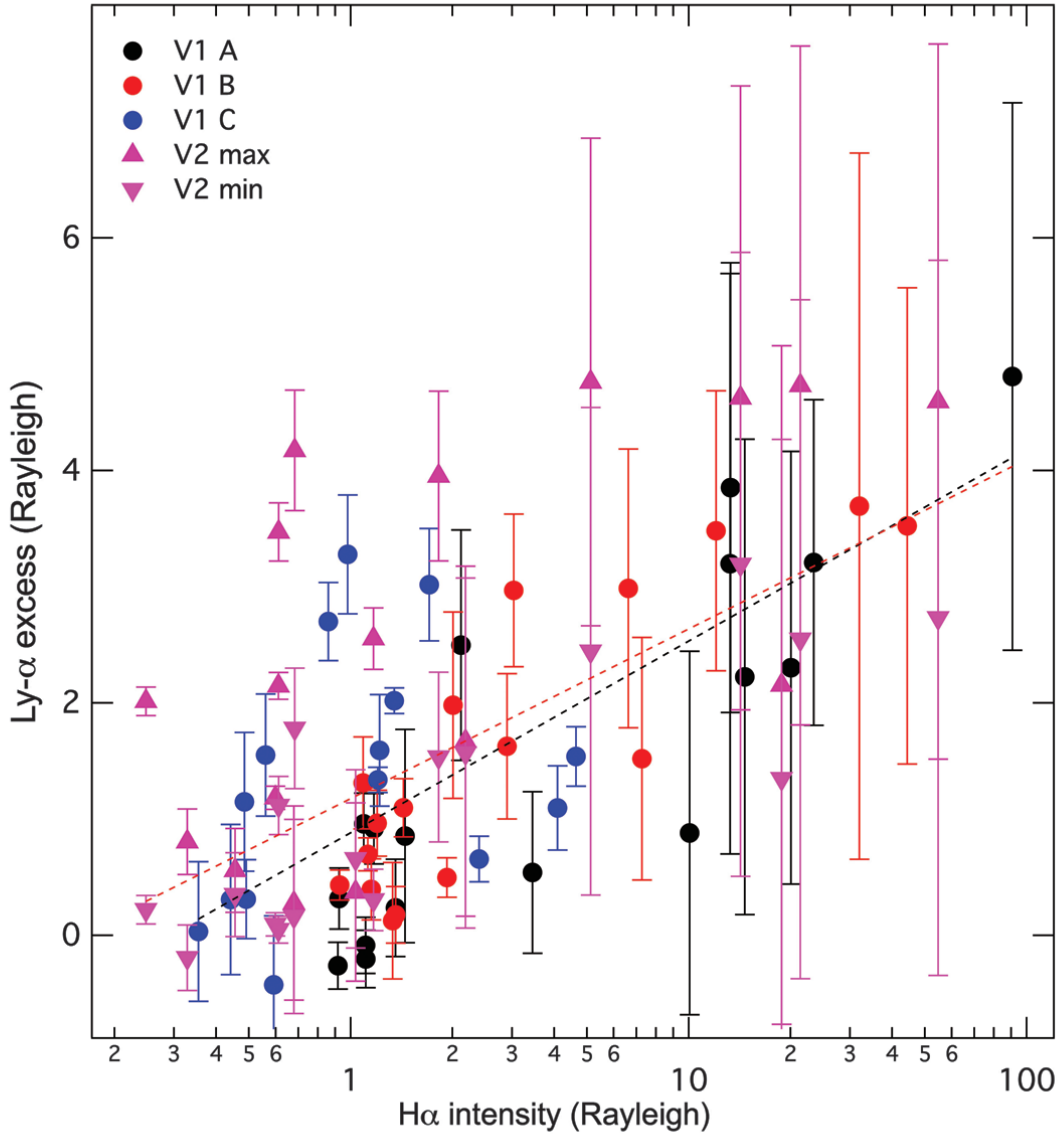


Observations: Lyα from the Milky Way

- Voyager measurements (Lallement et al. 2011)
  - first detection of Lyα from our Galaxy
  - the heliospheric contribution removed
  - **Escape fraction = Lyα/(1.61 x Hα) ~ 3%**

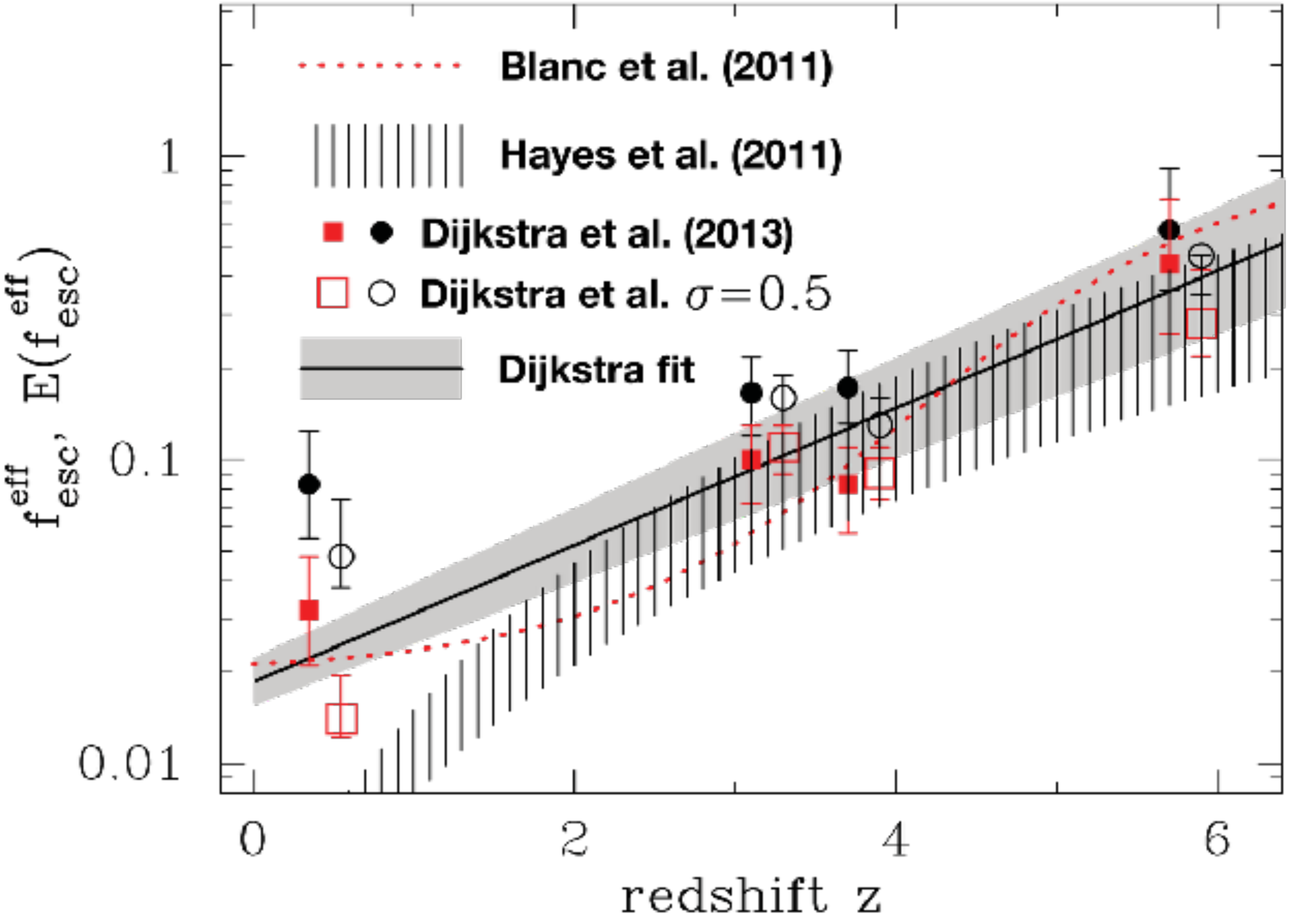
    (Intrinsic ratio of Lyα/Hα ~ 1.61)





Observations: Lyα from external galaxies

- Escape fraction in local Universe ~ a few percent.



Summary

- The WF effect is important not only in the IGM at the reionization epoch but also in the WNM.
  - Lyα spectral profile approaches to a Boltzmann function with the gas kinetic temperature, even at an optical depth as low as 100.
  - Lyα radiation field is strong enough to thermalize the 21 cm hyperfine spin temperature in the WNM to the gas kinetic temperature.
- The escape fraction of Lyα is found to be a few percent, which is consistent with the Lyα observations of our Galaxy and external galaxies in local universe.