Physics 224
The Interstellar Medium

Lecture #14

What are “ISM Phases”?

Characteristic states of gas in a galaxy:
defined by ionization, chemical, density, temperature state

Possibly the result of some sort of equilibrium:
pressure, chemical, thermal, etc

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pressure, chemical, thermal, etc

Questions:

- What are the dominant processes that set these phases and how do they change from galaxy to galaxy?
- To what degree is the idea of “phases” an accurate representation of the ISM?

Phases in the Milky Way

Name	T (K)	Ionization	frac of volume	density (cm^{-3})	P ~ nT (cm^{-3} K)
hot ionized medium	10^6	H^+	0.5(?)	0.004	4000
ionized gas (HII & WIM)	10^4	H^+	0.1	$0.2-10^4$	$2000 - 10^8$
warm neutral medium	5000	H^0	0.4	0.6	3000
cold neutral medium	100	H^0	0.01	30	3000
diffuse molecular	50	H_2	0.001	100	5000
dense molecular	10-50	H_2	10^{-4}	10^3-10^6	$10^5 - 10^7$

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Pressure equilibrium

interaction rate

$$\Gamma \quad \text{heating rate per volume} \quad \sim \boxed{n_H\, X_H}\,\boxed{n_{coll}\, v_{coll}\, \sigma}\,\boxed{Y(E)}$$

density of whatever
is being ionized
X_H = abundance
relative to H

energy yield
per interaction

* Integrate this over the
distribution of collider
energies

Heating:

- Cosmic Ray Ionization
- Photoionization of H & He
- Photoionization of metals
- Photoelectric effect from dust
- Shocks, turbulent dissipation, MHD phenomena

Common theme:
interaction rate is set by
external radiation field
or cosmic ray flux so…

$$\Gamma \sim n_H\, \zeta\, E$$

interaction rate

Γ heating rate per volume $\sim \boxed{n_H X_H}\boxed{n_{coll}\ v_{coll}\ \sigma}\boxed{Y(E)}$

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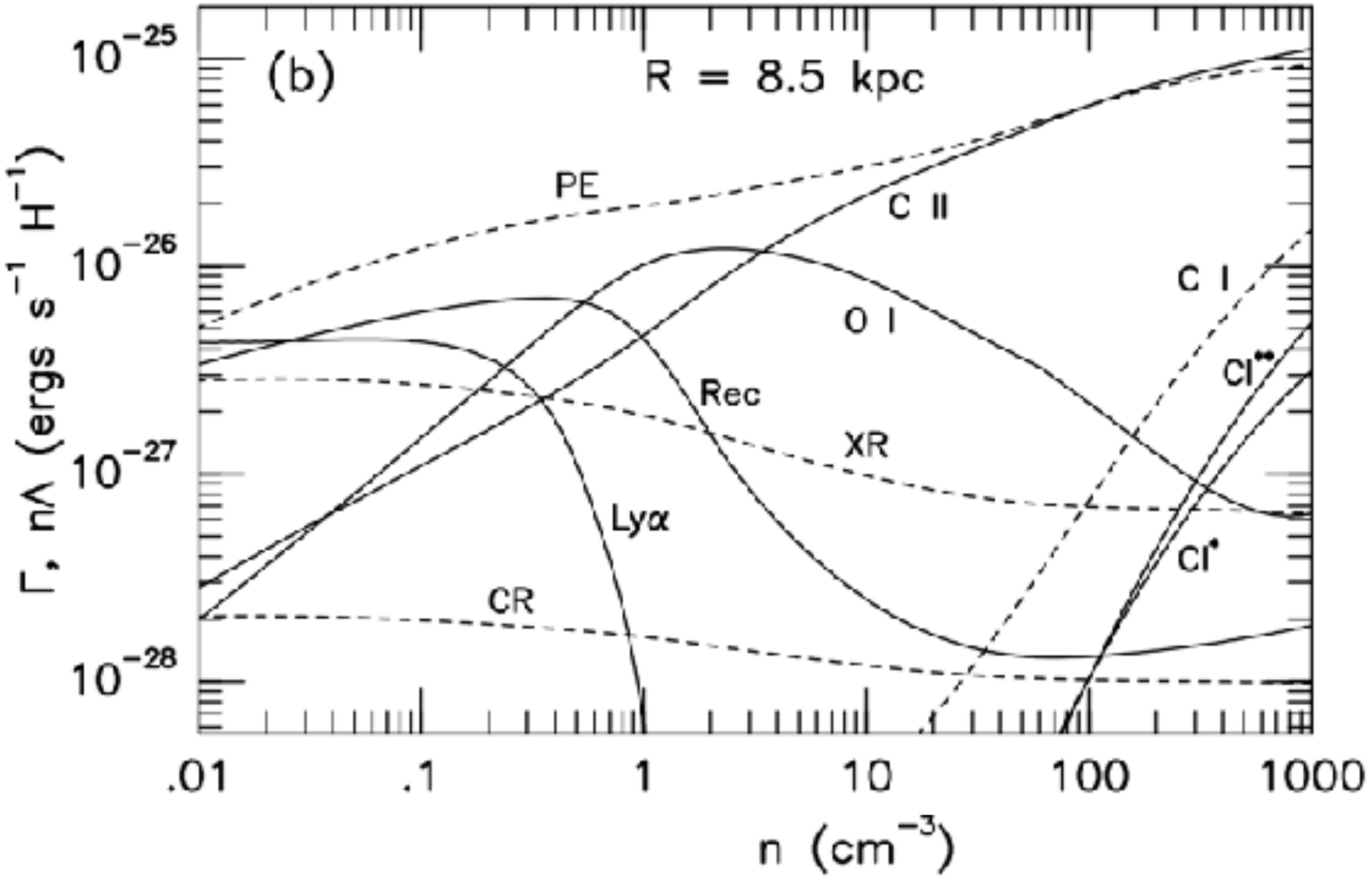
Wolfire et al. 2003



Λ cooling rate per volume $\sim n_C \, n_X \, k_{10} \, E_{10}$

In the case where $n_c \gg n_{crit}$, i.e. every collision leads to radiative transition.

where n_c = collider density
n_X = collisionally excited species density
k_{10} = collisional rate coefficient
E_{10} = energy difference of levels

Cooling:

- Collisionally excited fine structure lines
- Lyman α at $T>10^4$ K
- recombination of e- and grains

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Recall “collision strength” Ω_{ul}

$$k_{u\ell} = \frac{h^2}{(2\pi m_e)^{3/2}} \frac{1}{(kT)^{3/2}} \frac{\Omega_{u\ell}}{g_u}$$

separates gas temperature from atomic properties

Cooling:

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In the case where $n_c >> n_{crit}$, i.e. every collision leads to radiative transition.

note that different colliders have different k values

Important point:
cooling rate ~ n^2

$\Lambda \sim n^2 \, \lambda(T)$ const

function of gas temperature

quantum mechanics

Cooling:

- Collisionally excited fine structure lines
- Lyman α at $T>10^4$ K
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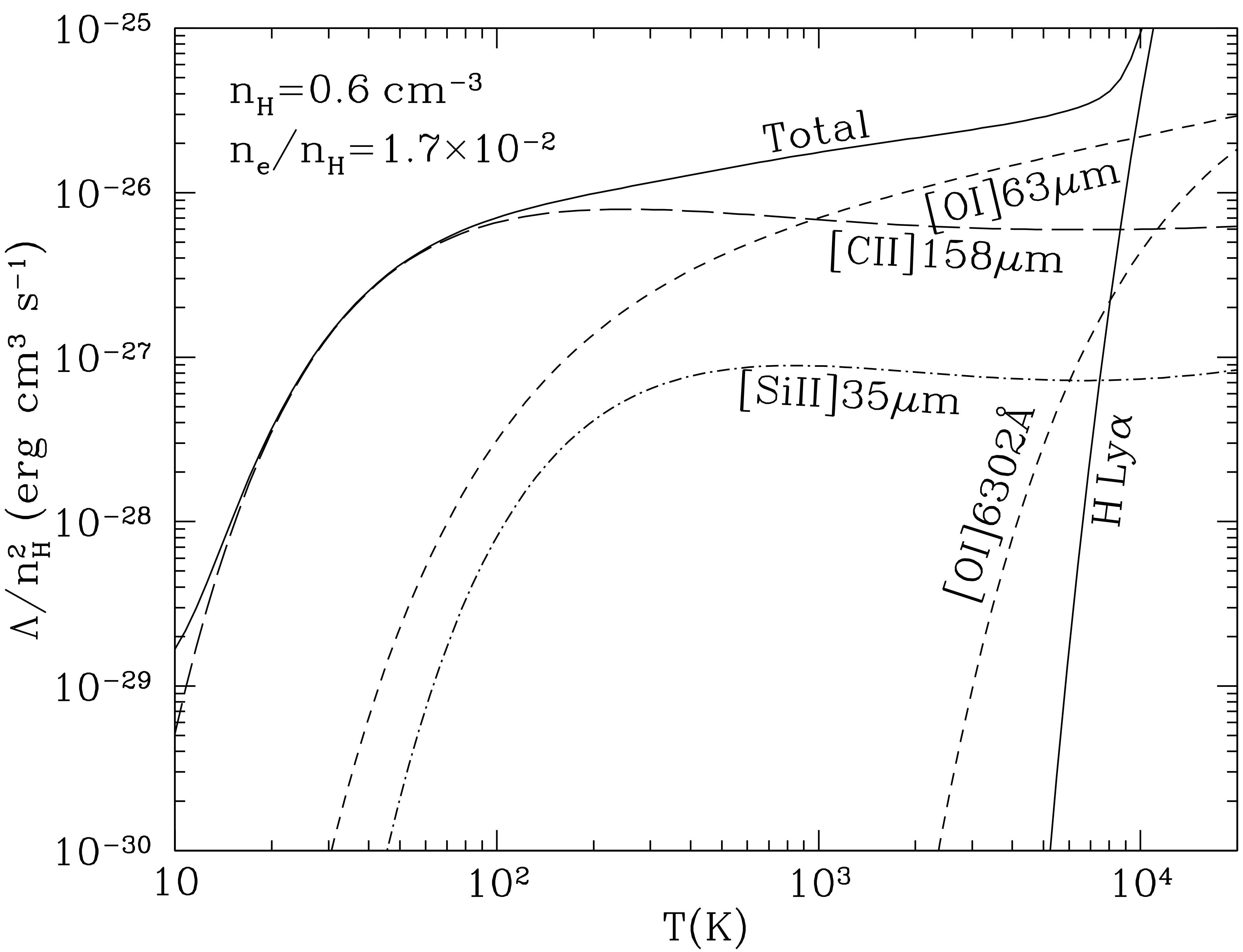
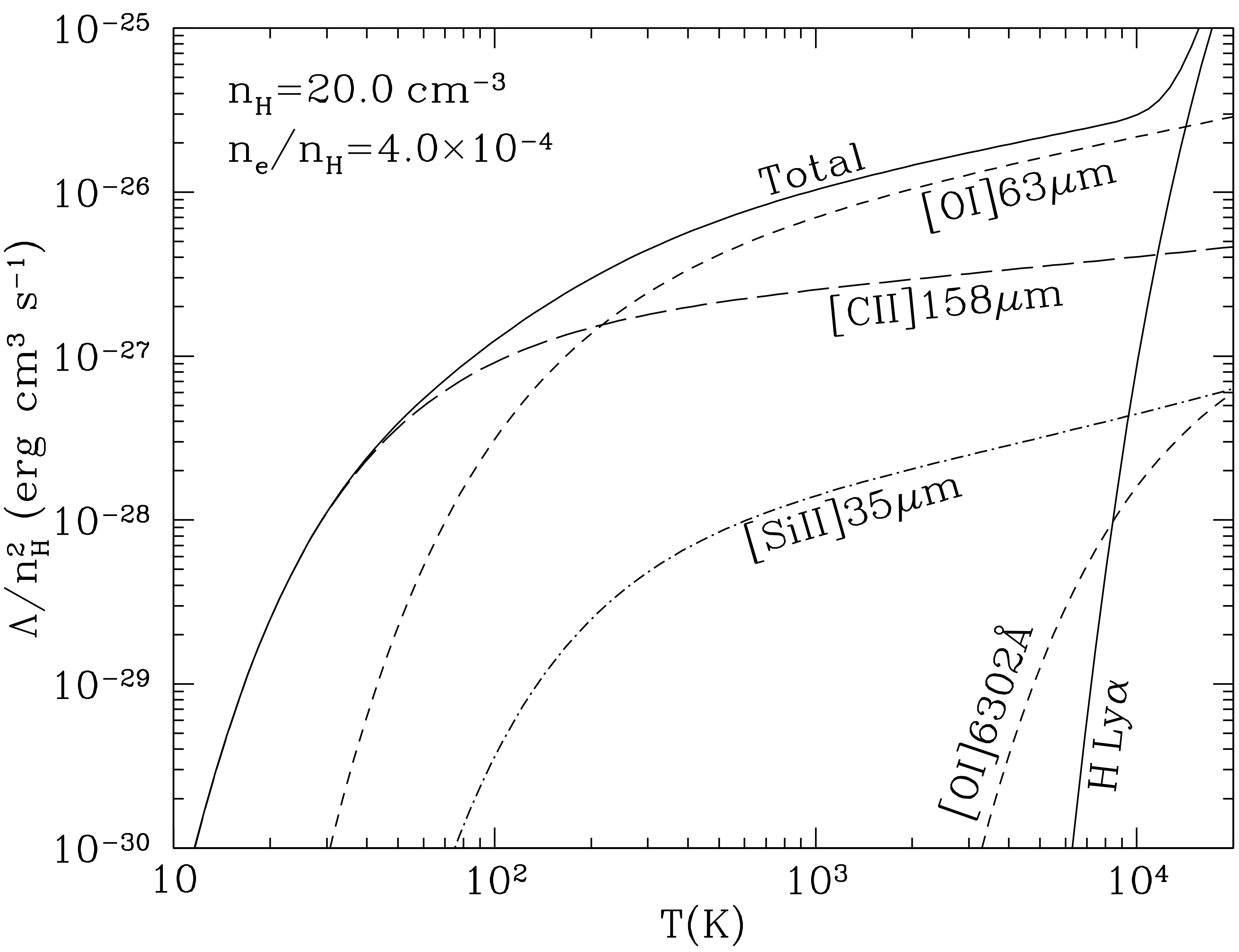

$n_H = 0.6\ \mathrm{cm^{-3}}$
$n_e/n_H = 1.7 \times 10^{-2}$
Total
[OI]63μm
[CII]158μm
[SiII]35μm
[OI]6302Å
H Lyα
Λ/n_H^2 (erg cm^3 s^{-1})
T(K)
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10
10^2
10^3
10^4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n_e/n_H=4.0×10^{-4}
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10
10^2
10^3
10^4

Phases in Pressure Equilibrium

net heating
or cooling

$L(n,T) = \Gamma - \Lambda$

$L > 0$ heating
$L = 0$ equilibrium
$L < 0$ cooling

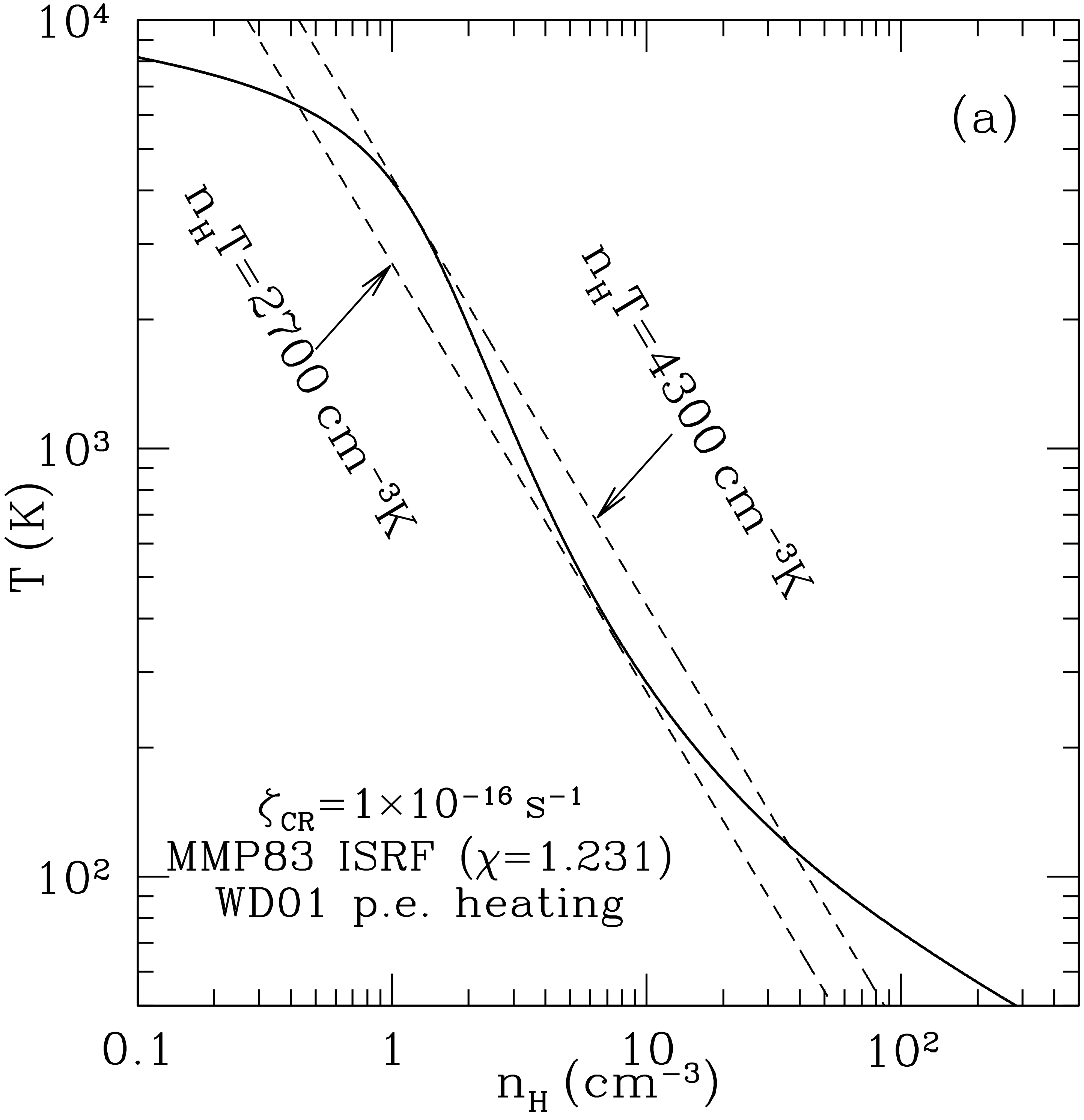
Recall:

$\Gamma \sim n\,\zeta$ ← insensitive to T

$\Lambda \sim n^2\,\lambda(T)$ const ← sensitive to T

Find combination of n and T were $L(n,T) = 0$

Phases in Pressure Equilibrium

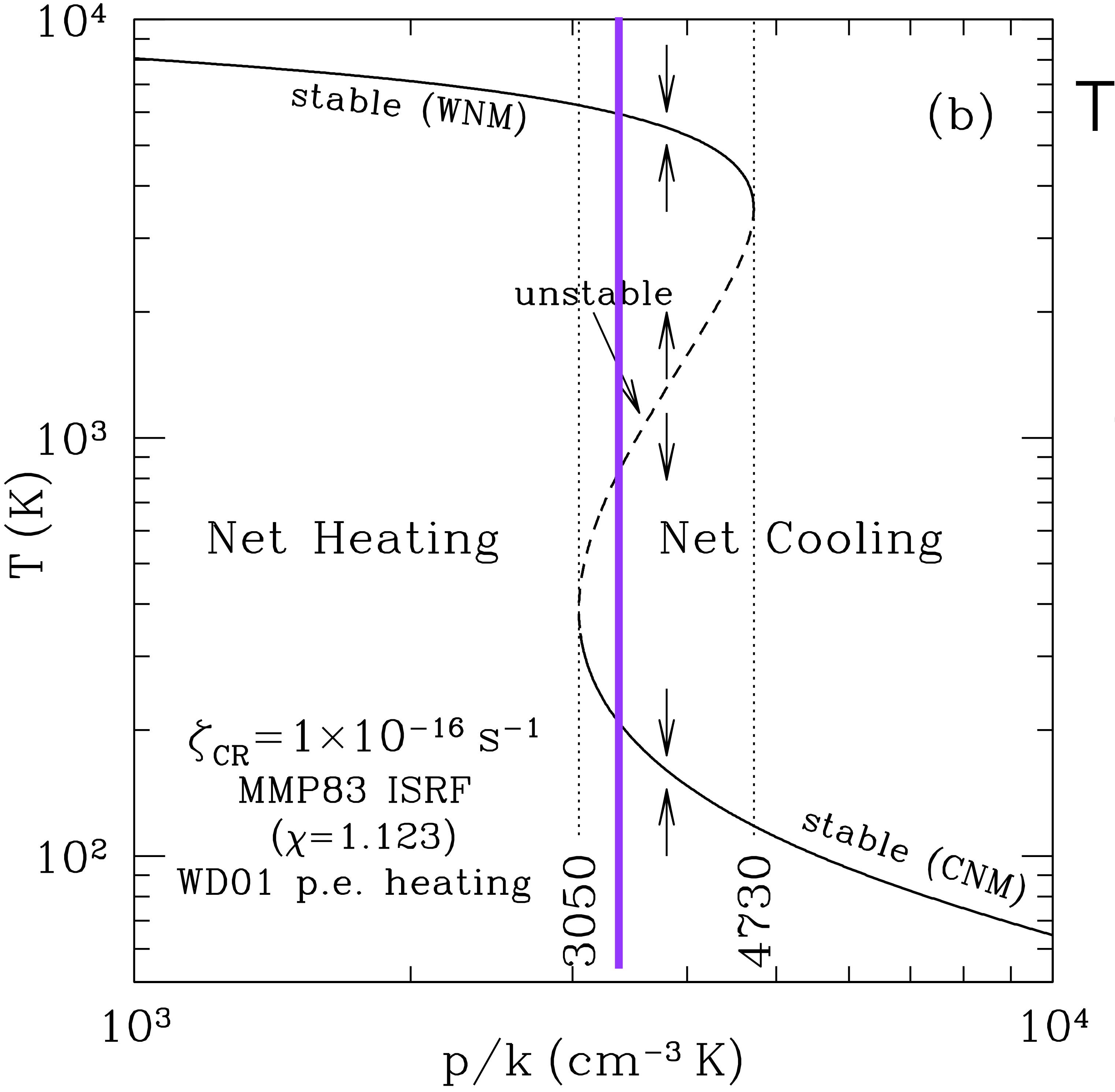


Solid line is L(n,T) = 0 heating/cooling equilibrium

Details include:
solving self-consistently
for ionization state of gas,
electron density,
dust grain charge

Range of pressures where there are multiple n,T combos with L=0

Phases in Pressure Equilibrium



Three points at fixed $P = nkT$ where $L=0$.

$T \sim 10^3 - 10^4$ branch = WNM

$T \sim 10^1 - 10^2$ branch = CNM

Phases in Pressure Equilibrium

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Recall:

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Perturb the fluid away from equilibrium (i.e L=0)
at a fixed pressure, instability results if:

$$\left(\frac{\partial L}{\partial T}\right)_P < 0$$

If this is true, making the gas colder makes
L < 0 which results in more cooling.

Phases in Pressure Equilibrium

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Perturb the fluid away from equilibrium (i.e L=0)
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$$\left(\frac{\partial L}{\partial T}\right)_P = \left(\frac{\partial L}{\partial T}\right)_n + \frac{n_0}{T_0}\left(\frac{\partial L}{\partial n}\right)_T < 0$$

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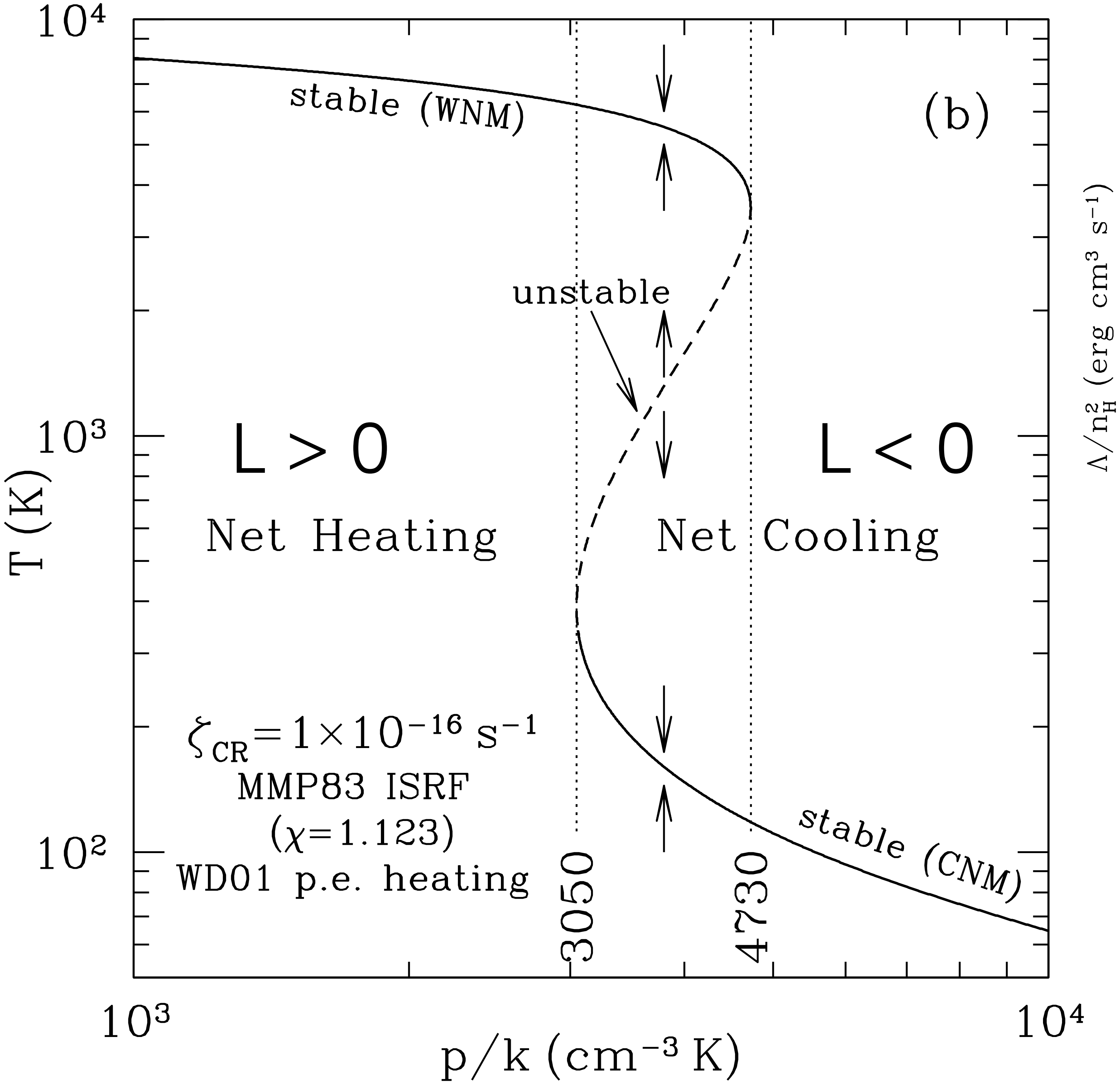
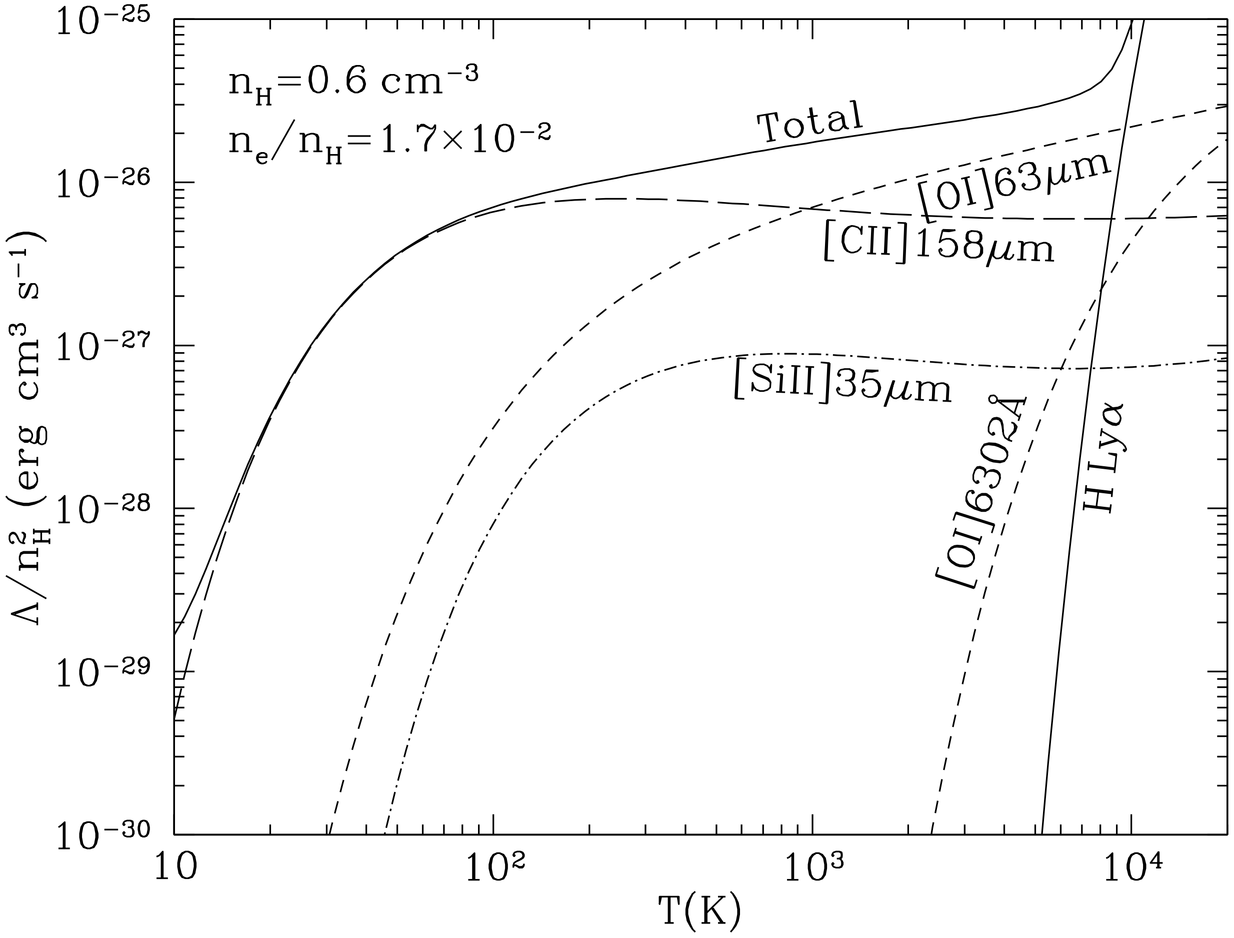
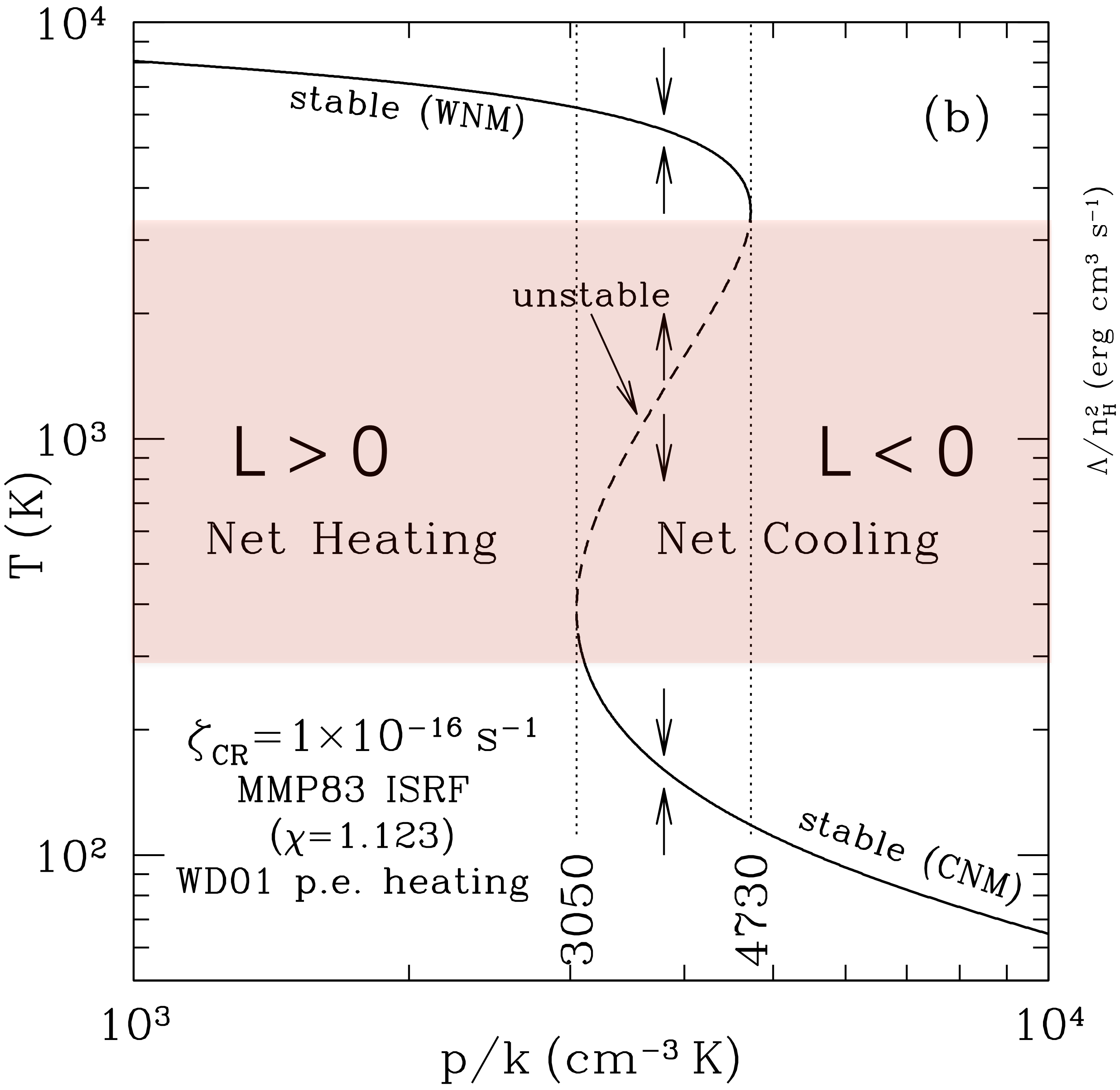
$$\frac{\partial \ln \lambda}{\partial \ln T} < 1$$

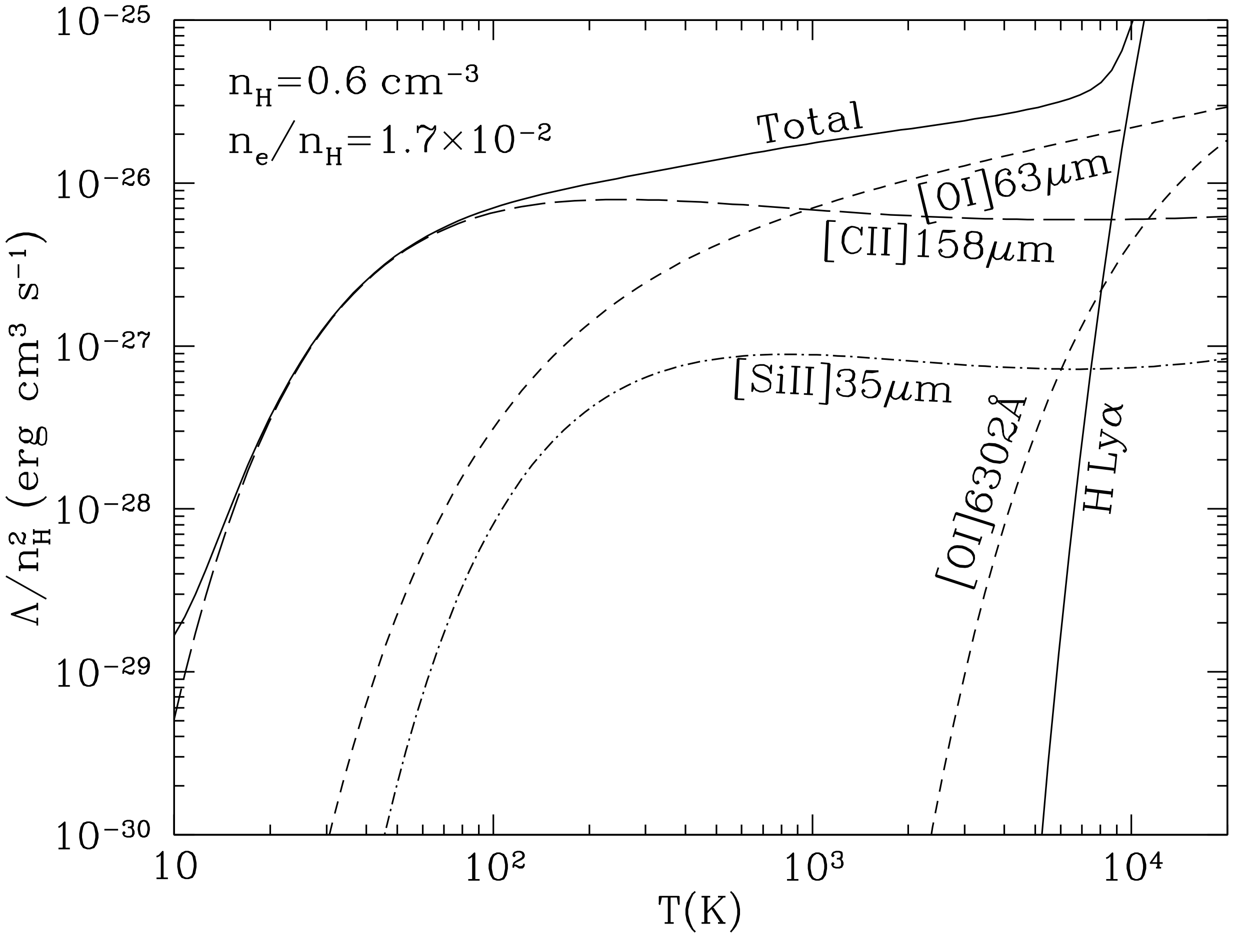
Phases in Pressure Equilibrium



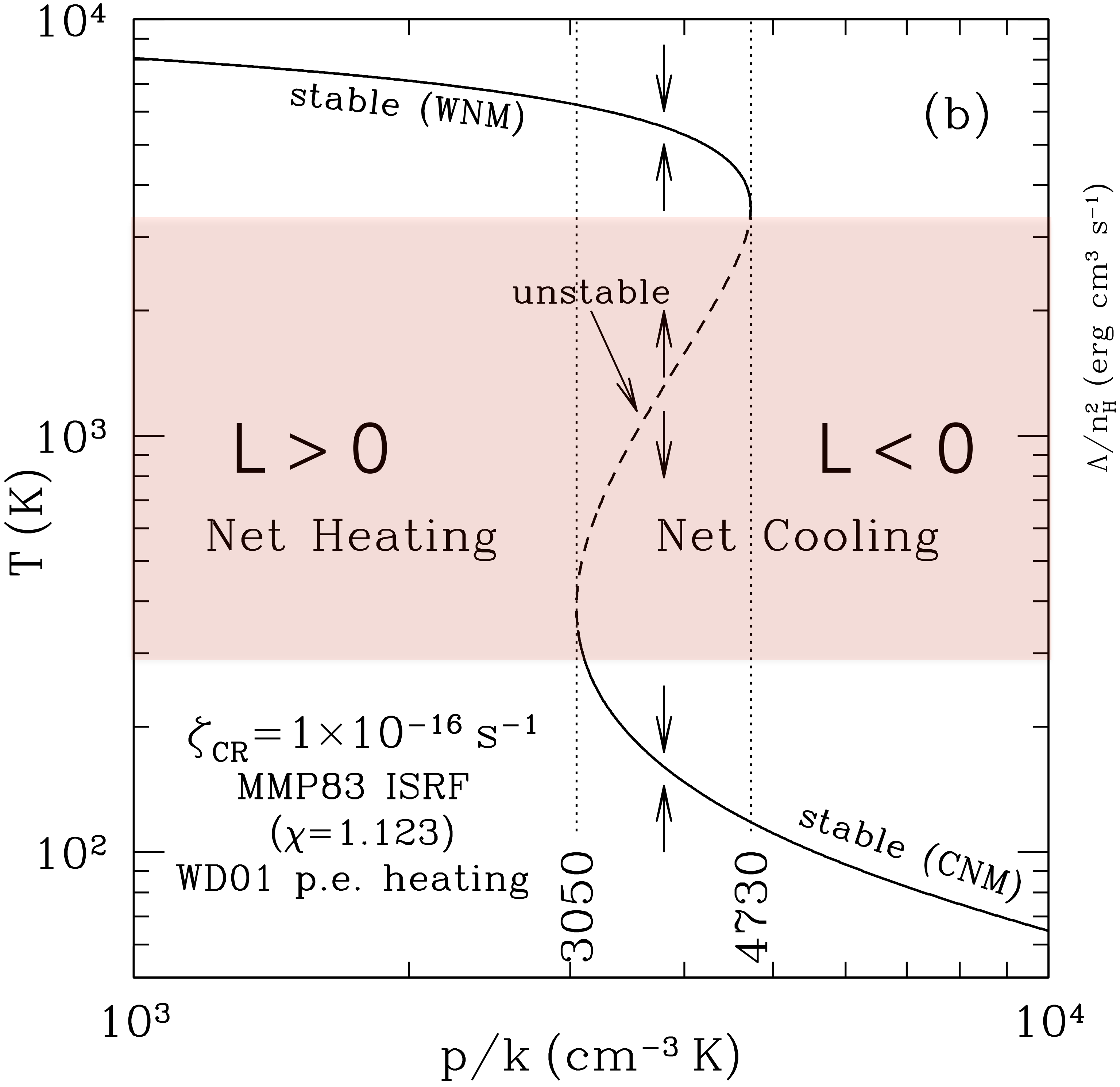


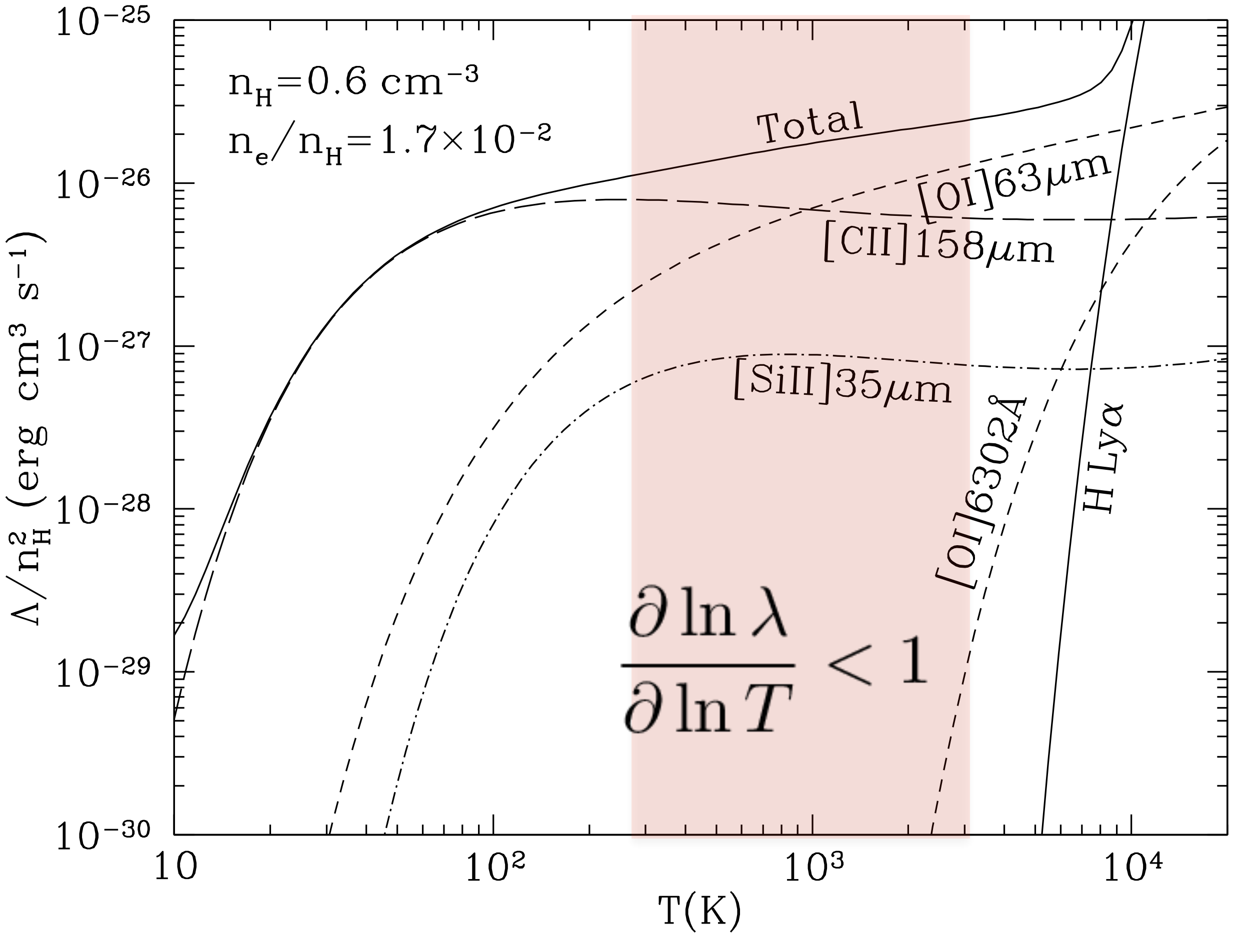
Phases in Pressure Equilibrium



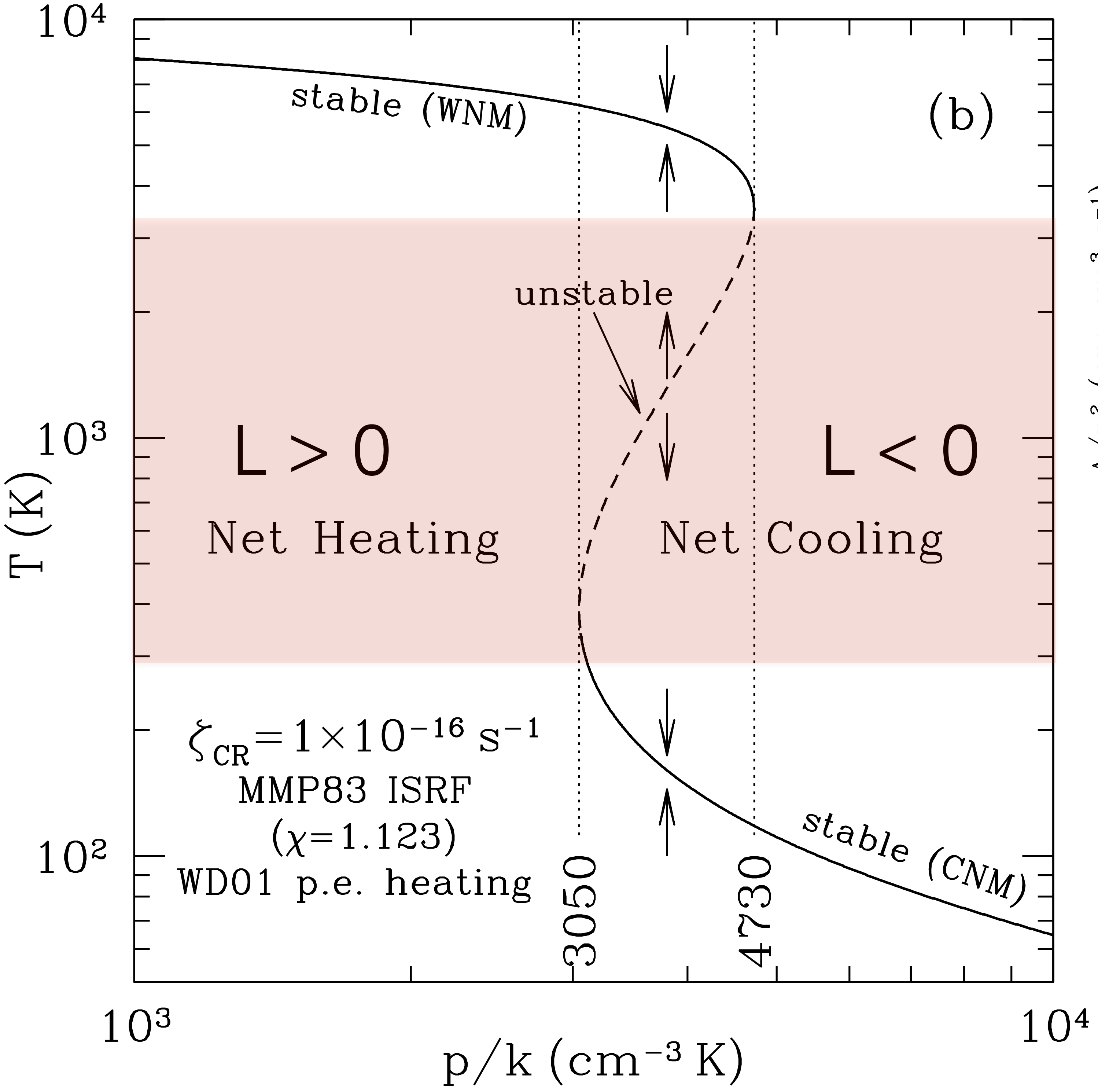


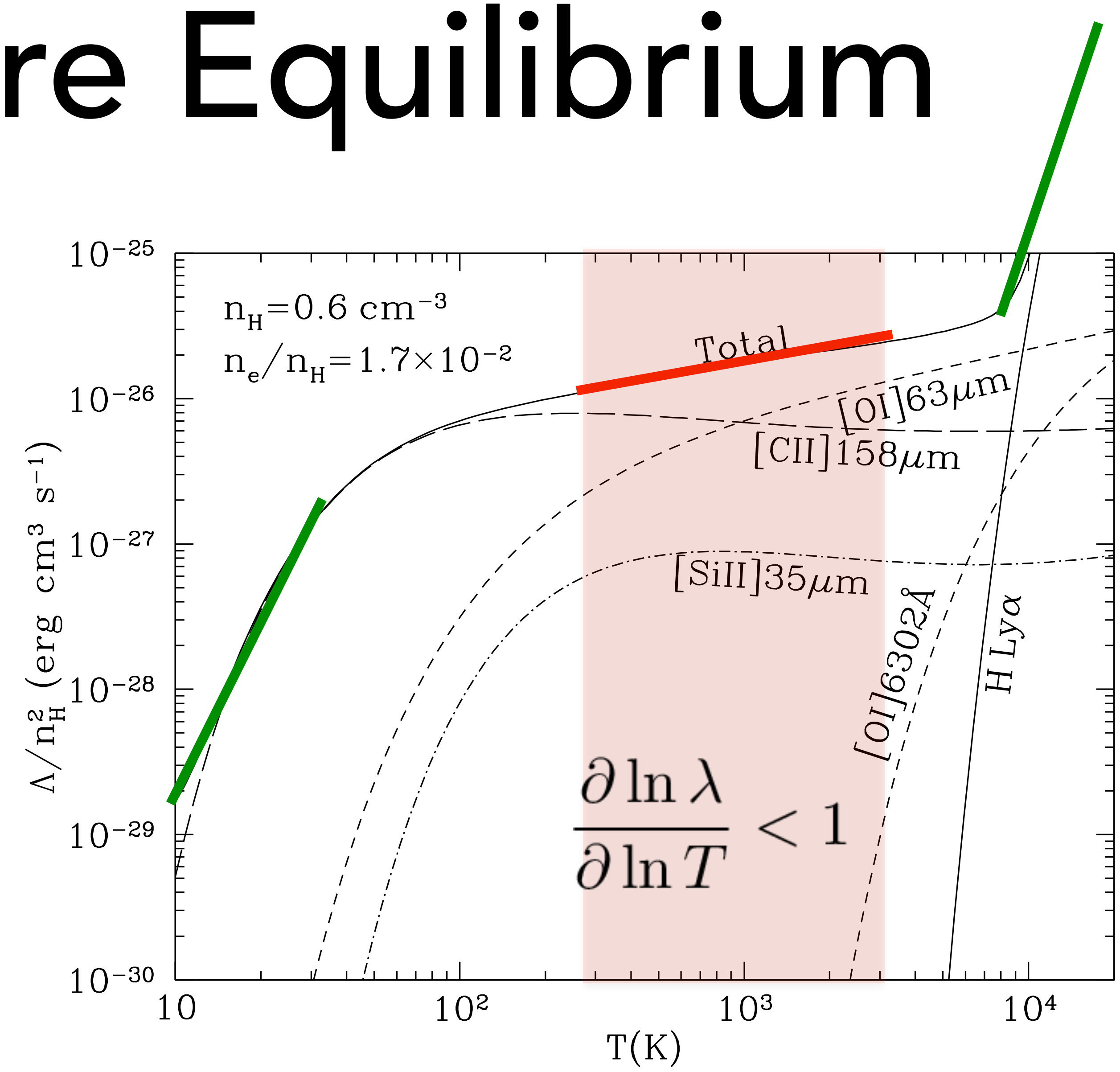
Phases in Pressure Equilibrium





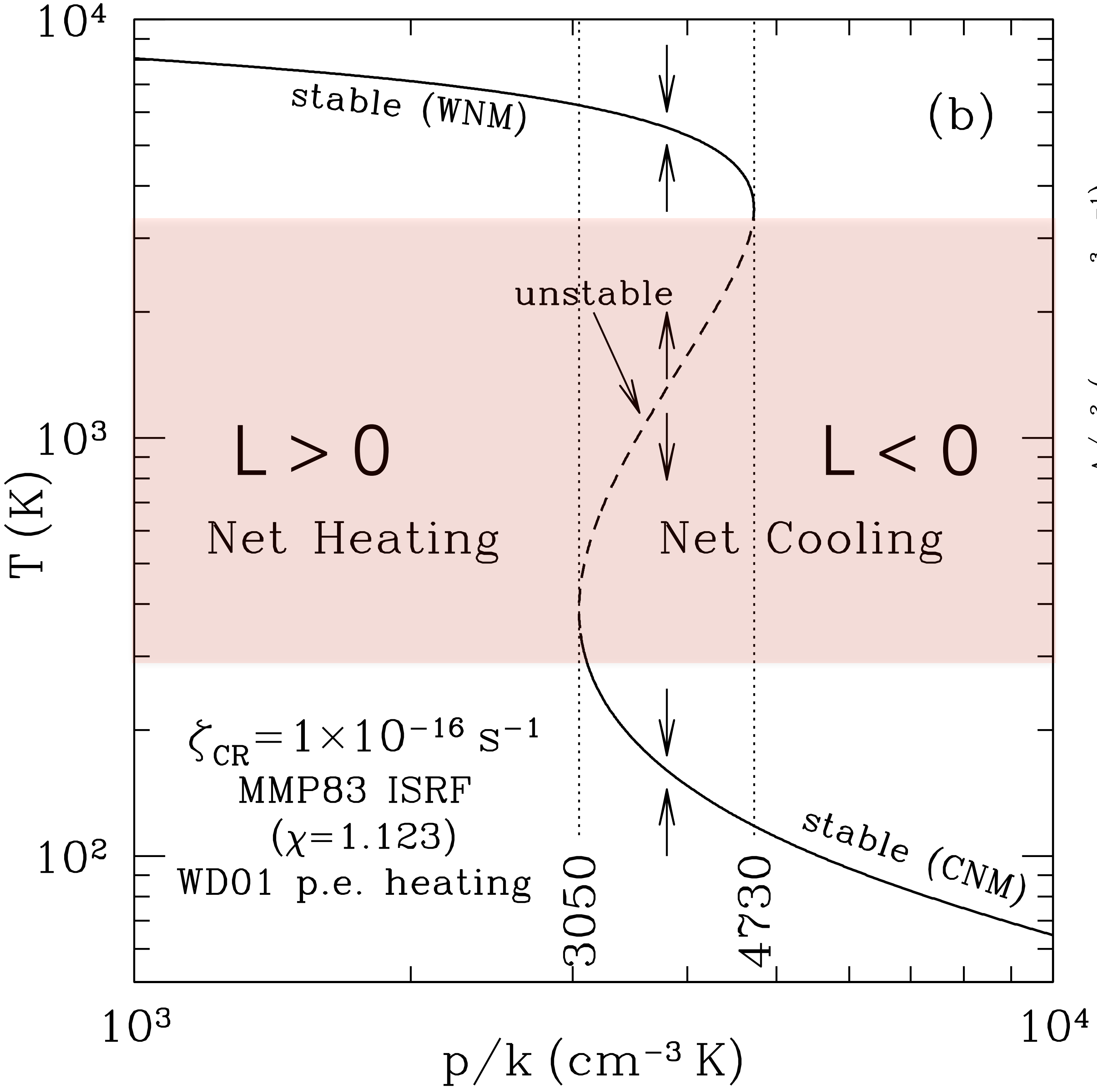
Phases in Pressure Equilibrium

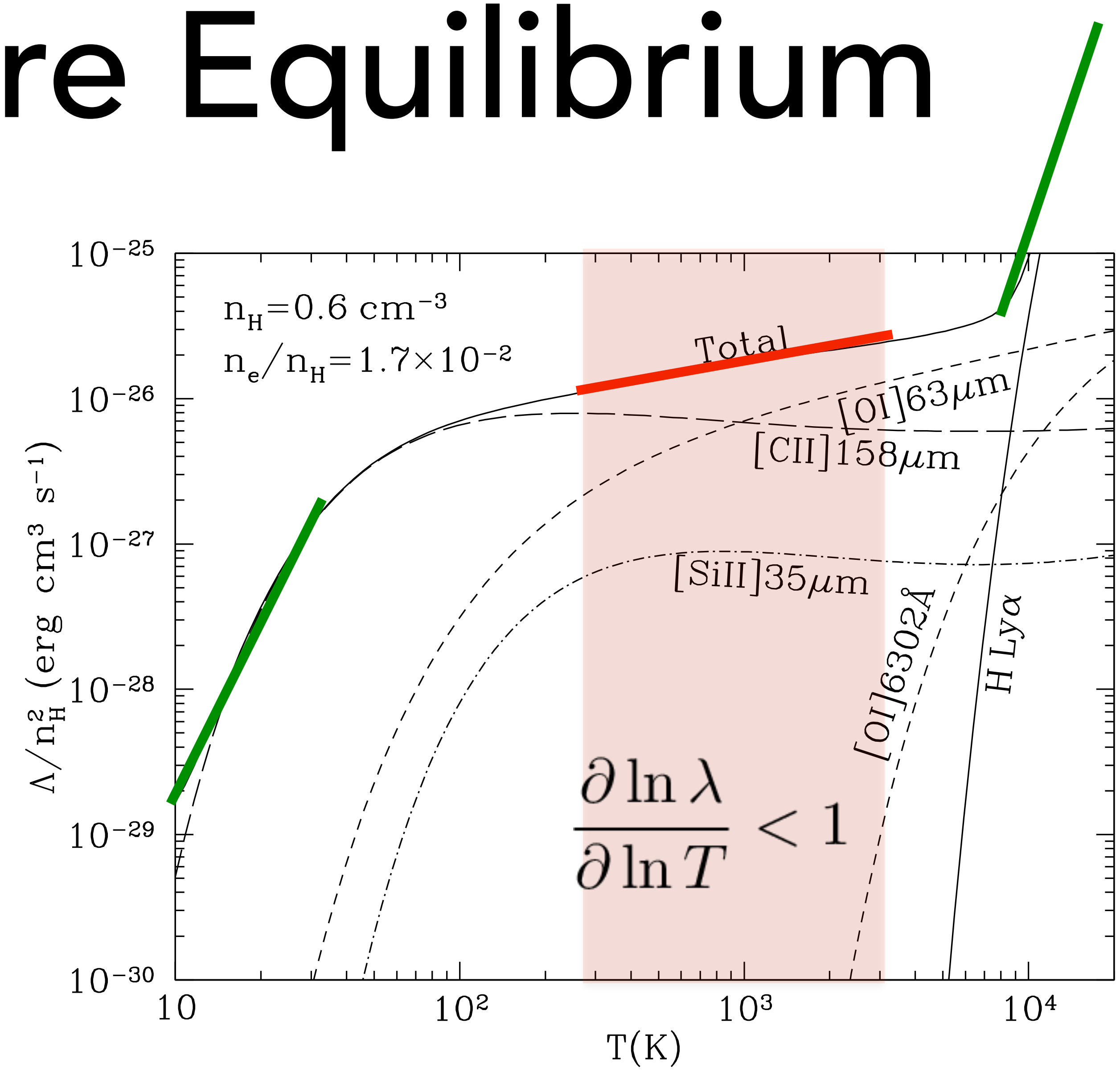




$$\frac{\partial \ln \lambda}{\partial \ln T} < 1$$

Phases in Pressure Equilibrium



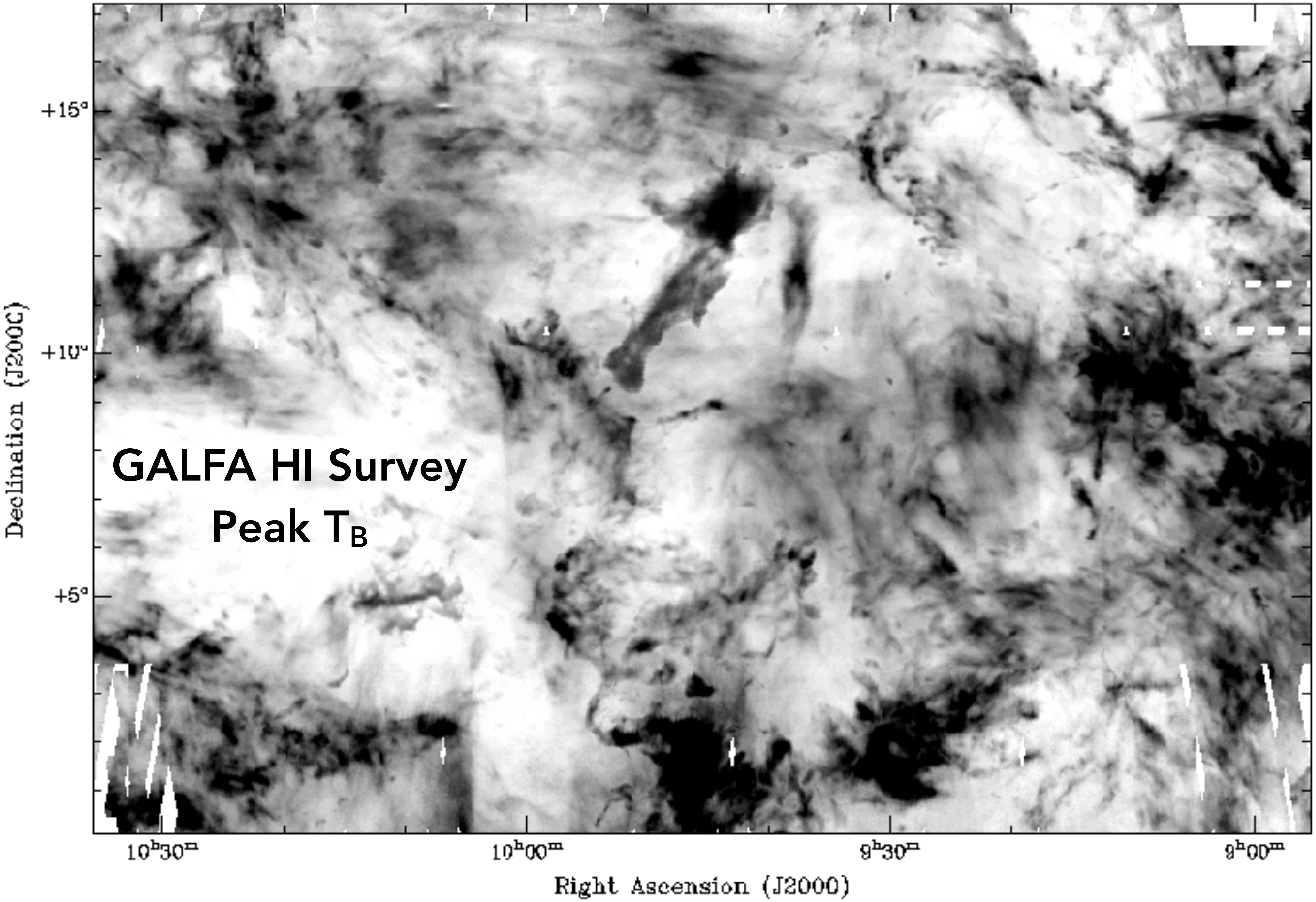


<u>[CII] 158 μm drives this behavior</u>

ΔE = 92 K, steep increase at lower T reflects increasing ability to populate upper level

Is the FGH model a good representation of the ISM?

https://sites.google.com/site/galfahi/galfa-hi-science


GALFA HI Survey
Peak T_B

© Karin Sandstrom, UC S

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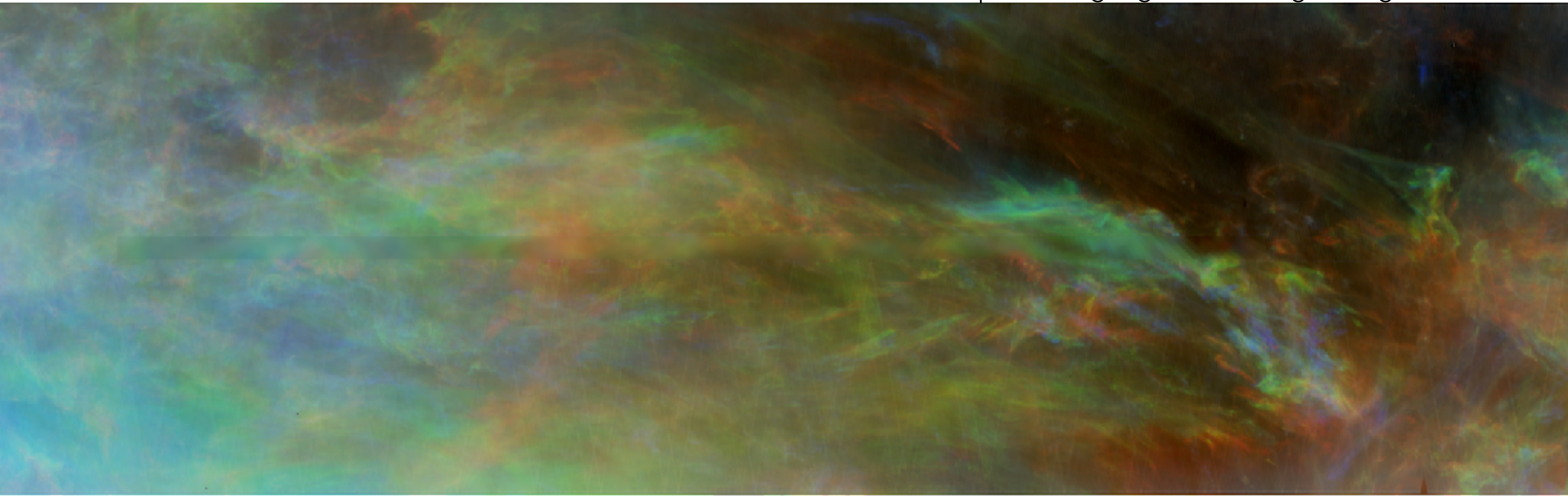

part of the GALFA HI Survey
colors = different velocity ranges

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Do we expect to find much gas at unstable n-T?

Compare thermal and dynamical timescales:

Is the FGH model a good representation of the ISM?

Do we expect to find much gas at unstable n-T?

Compare thermal and dynamical timescales:

$$\tau_{\text{cool}} = \frac{nkT}{\Lambda}$$

← thermal energy density = pressure

← cooling rate per unit volume

* note same
for heating
since $\Gamma = \Lambda$

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$\longleftarrow$ thermal energy density = pressure

$\longleftarrow$ cooling rate per unit volume

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$\tau_{\text{cool}} \sim 0.1$ Myr for unstable gas with
$T \sim 2000$ K and $n \sim 1.5$ cm^{-3}

Is the FGH model a good representation of the ISM?

Do we expect to find much gas at unstable n-T?

Compare thermal and dynamical timescales:

$$\tau_{\rm dyn} \sim \frac{L}{c_s}$$

where sound speed: $c_s = \sqrt{\frac{kT}{m}}$

$$\tau_{\rm dyn} \sim 6.7{\rm Myr}\left(\frac{L}{1{\rm pc}}\right)T^{-1/2}$$

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$$\tau_{\rm dyn} \sim 6.7 {\rm Myr} \left(\frac{L}{1 {\rm pc}}\right) T^{-1/2}$$

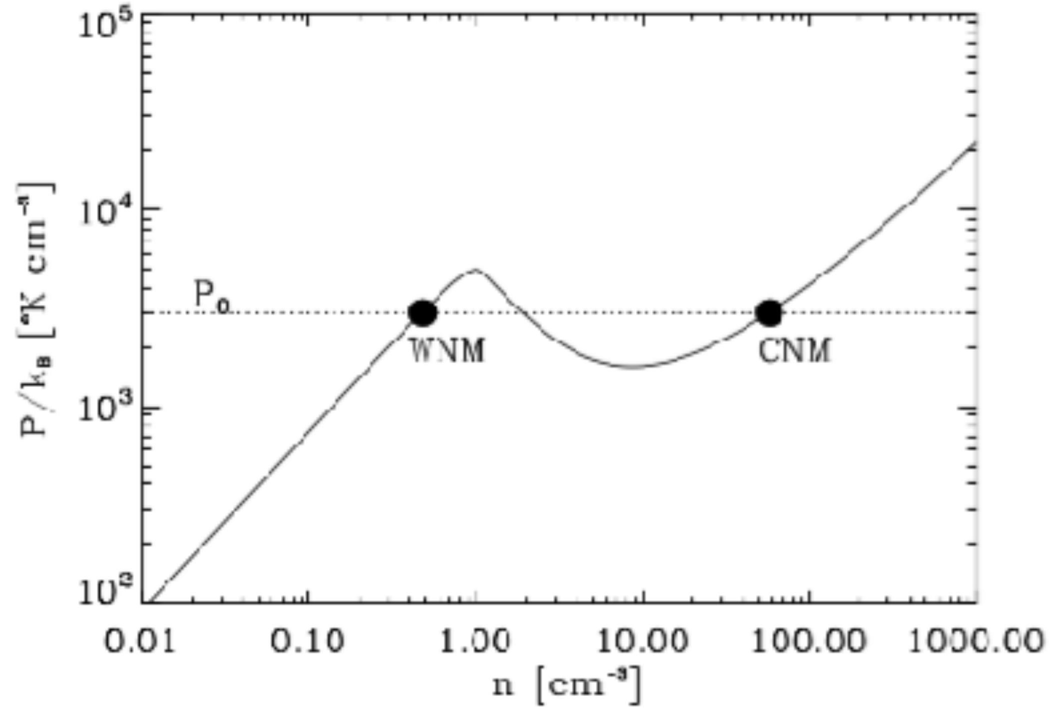
For L~10 pc, T~2000 K

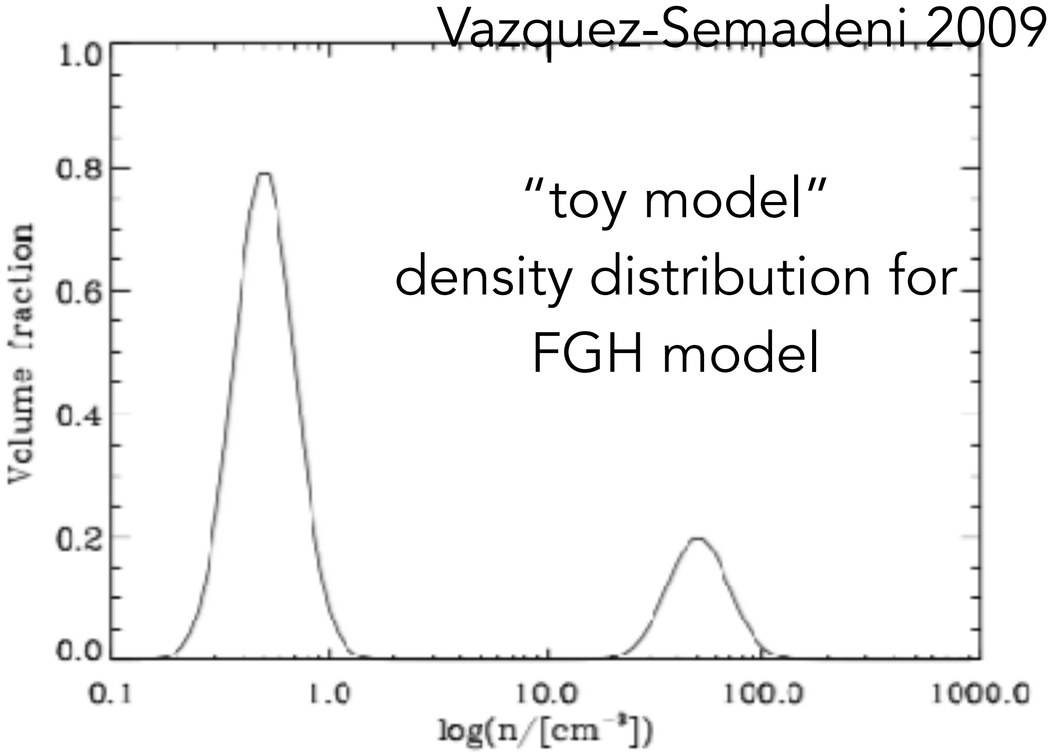
$\tau_{\rm dyn}$ ~ 1.5 Myr

Unstable gas should cool quickly relative to dynamical time.

Is the FGH model a good representation of the ISM?

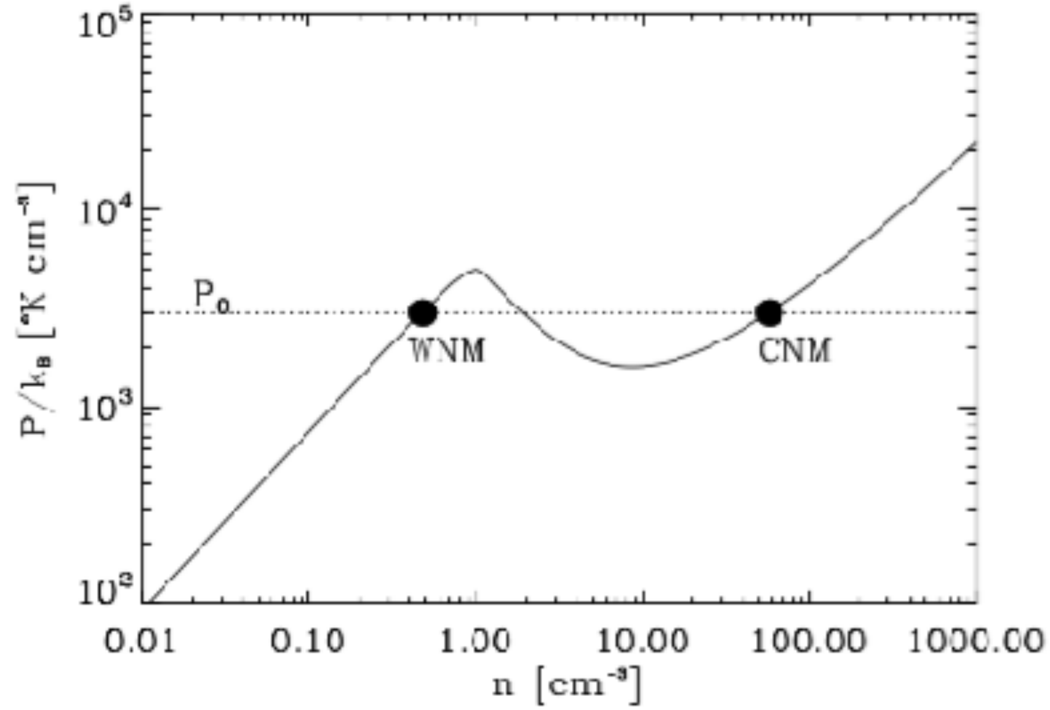
Vazquez-Semadeni 2009





"toy model"
density distribution for
FGH model

Is the FGH model a good representation of the ISM?



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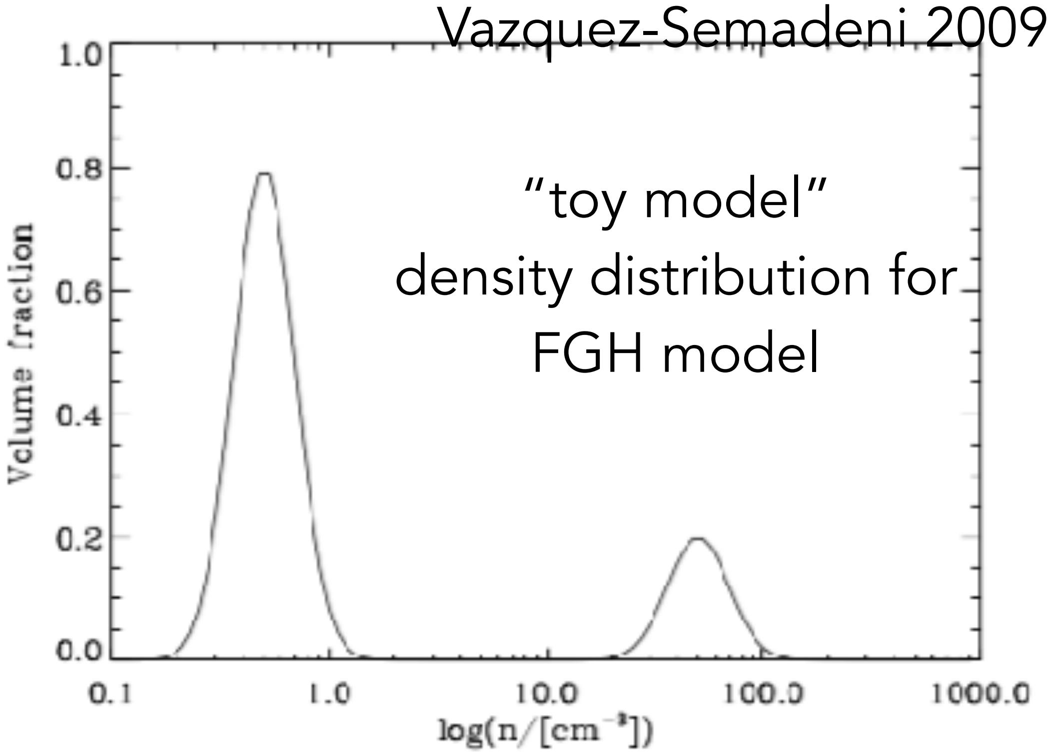

"toy model"
density distribution for
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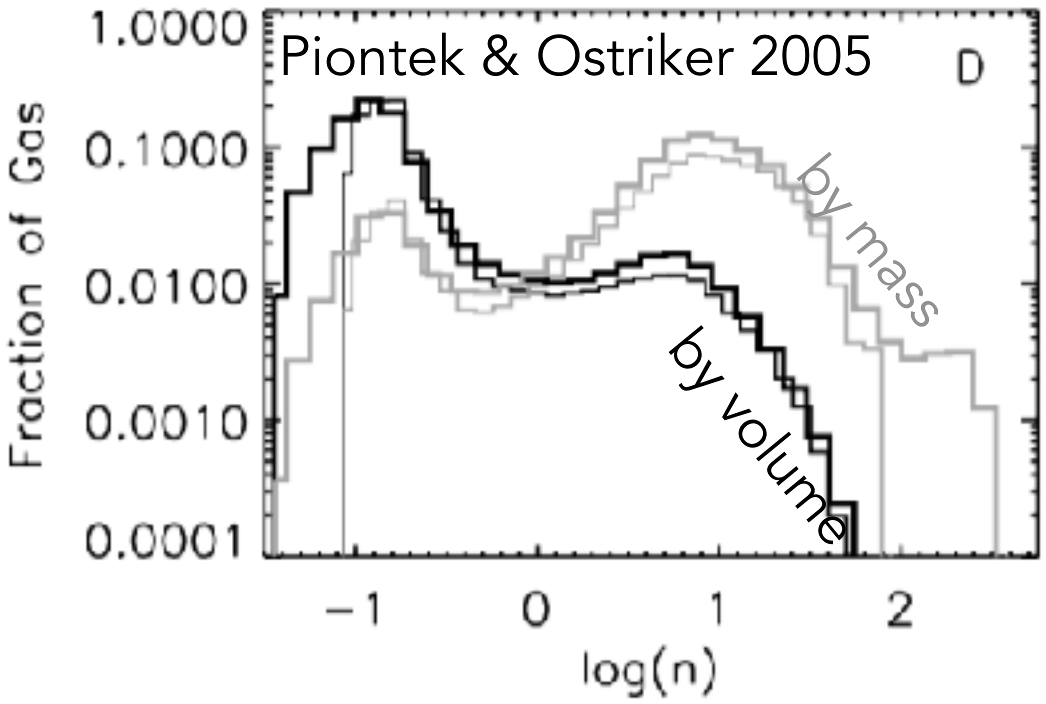
Simulations with turbulence suggest substantial amounts of gas between F&H phases



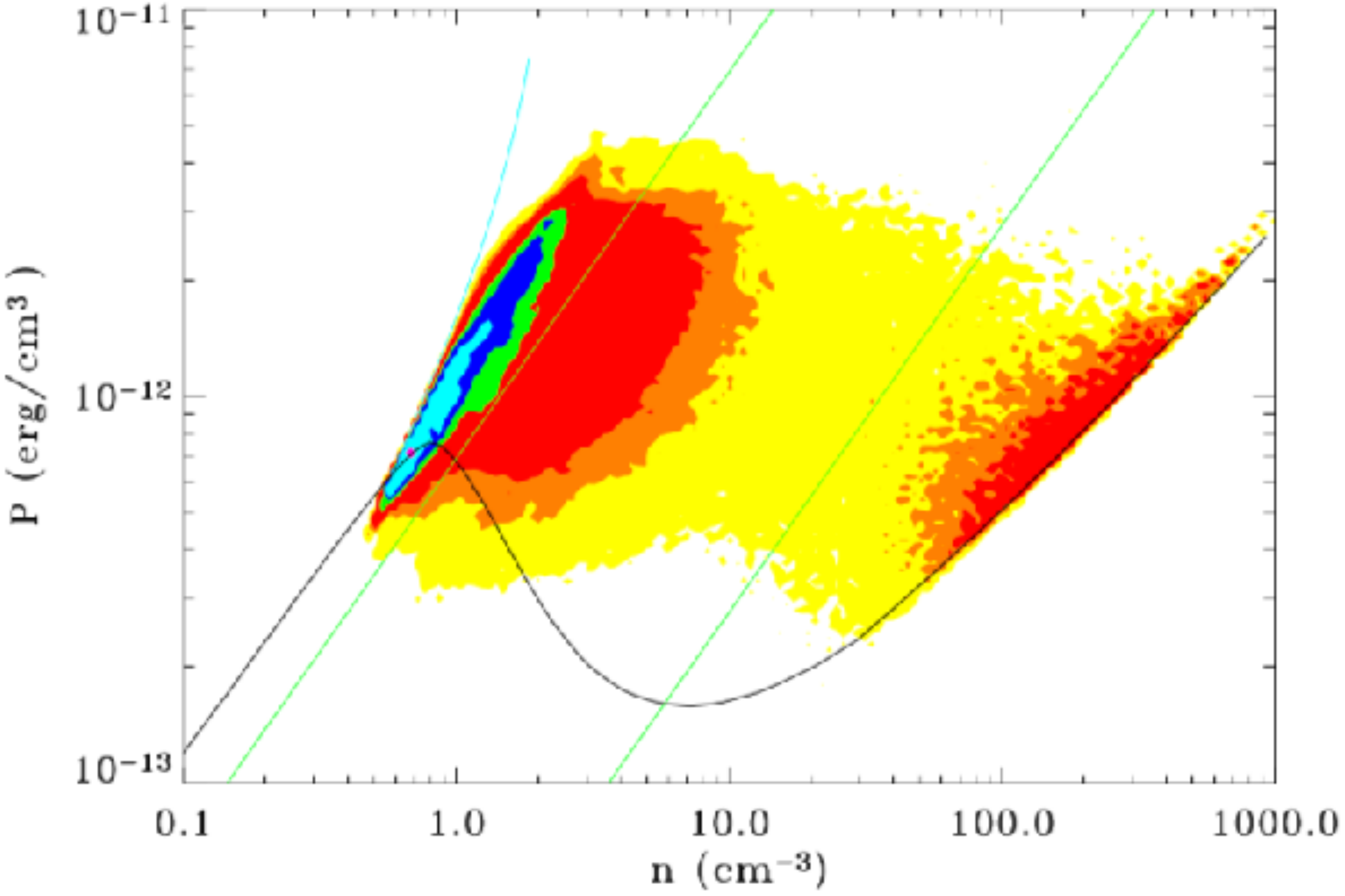
Piontek & Ostriker 2005

by mass

by volume

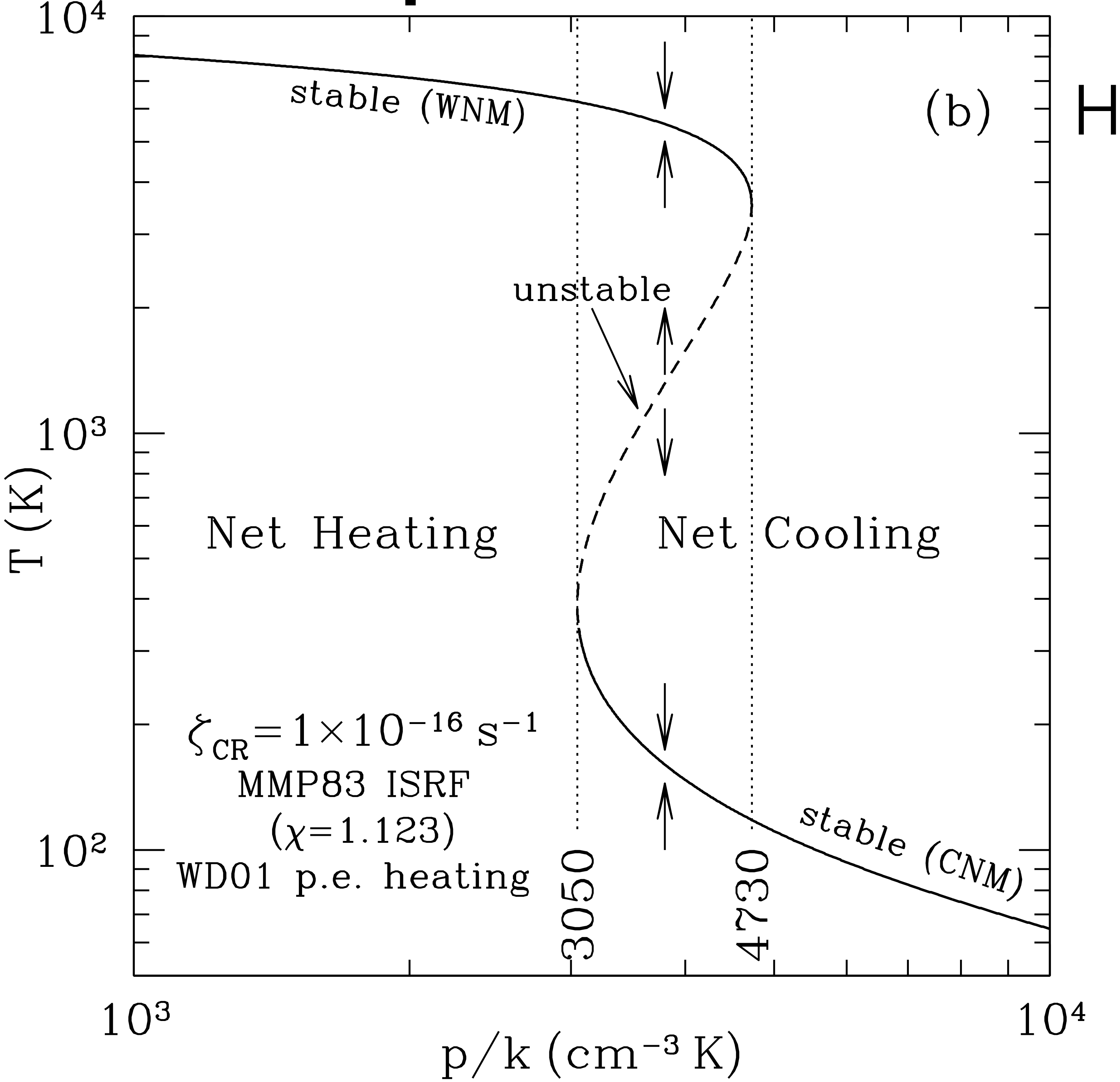
Is the FGH model a good representation of the ISM?

Audit & Hennebelle 2005



Turbulent simulations suggest lots of gas in “unstable” areas of the n,T diagram

Is the FGH model a good representation of the ISM?



How can we test this model?

Measure the
n & T of HI gas
and see if it matches
the predicted n,T ranges
for CNM and WNM
stable phases.

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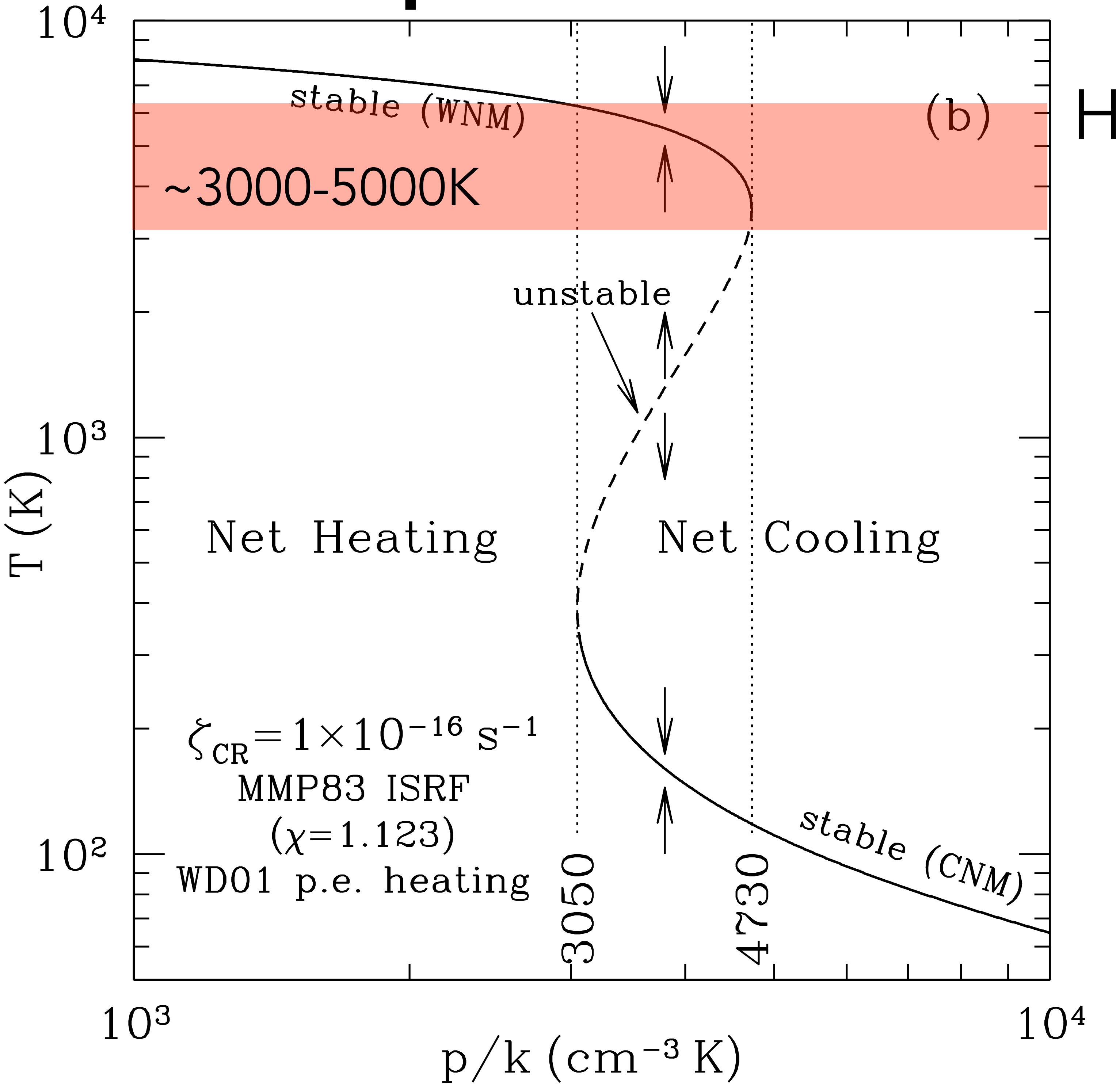

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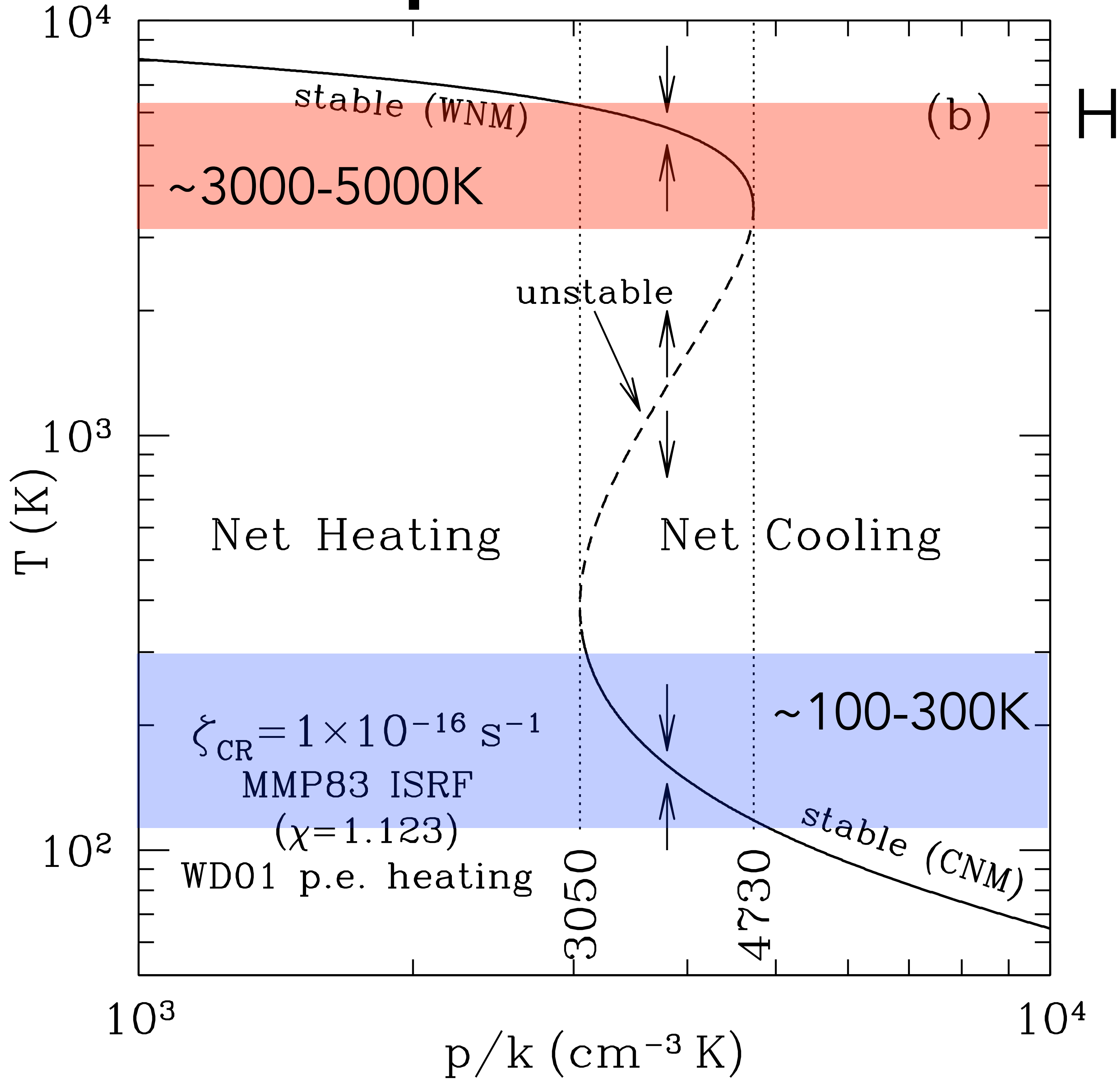

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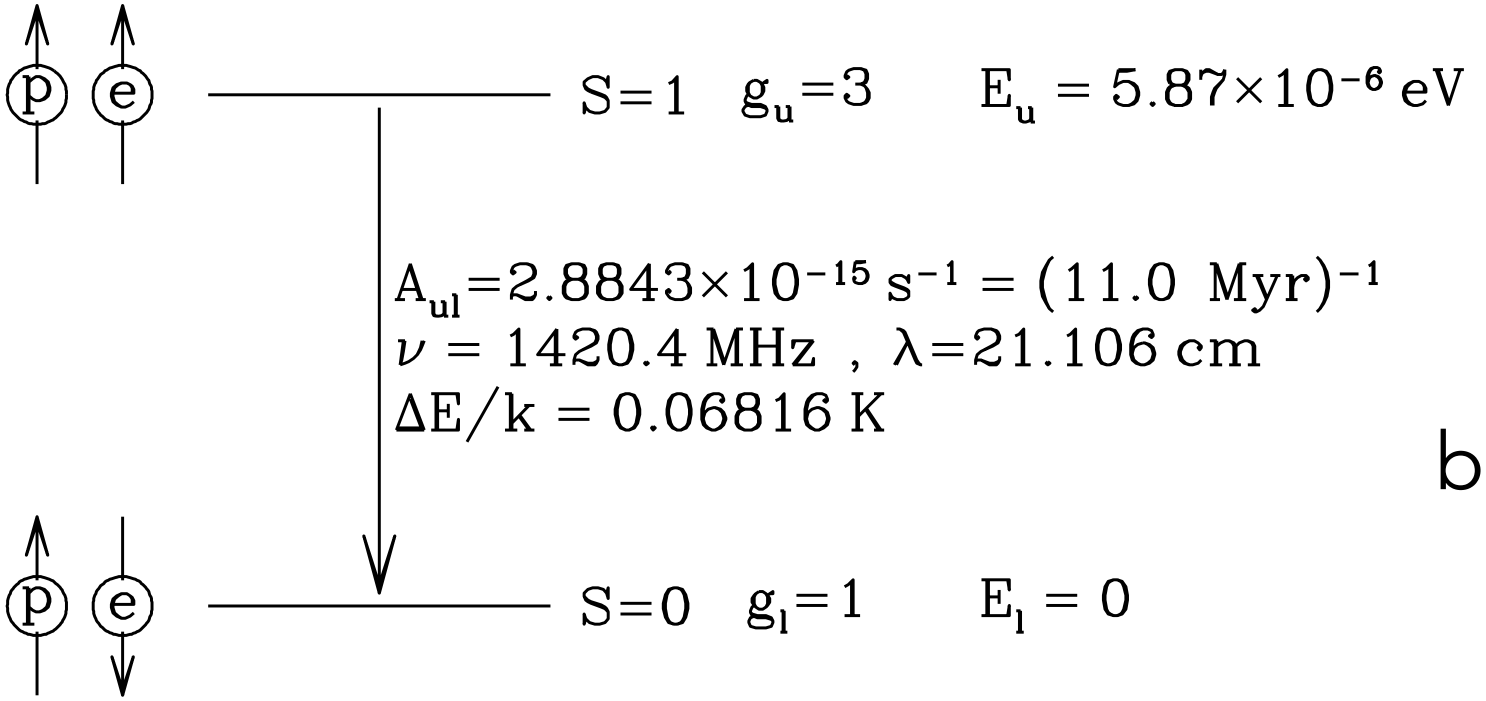
HI Spin Temperature



$S=1 \quad g_u=3 \qquad E_u = 5.87\times10^{-6}$ eV

$A_{ul}=2.8843\times10^{-15}\ \mathrm{s}^{-1} = (11.0\ \mathrm{Myr})^{-1}$

$\nu = 1420.4$ MHz , $\lambda=21.106$ cm

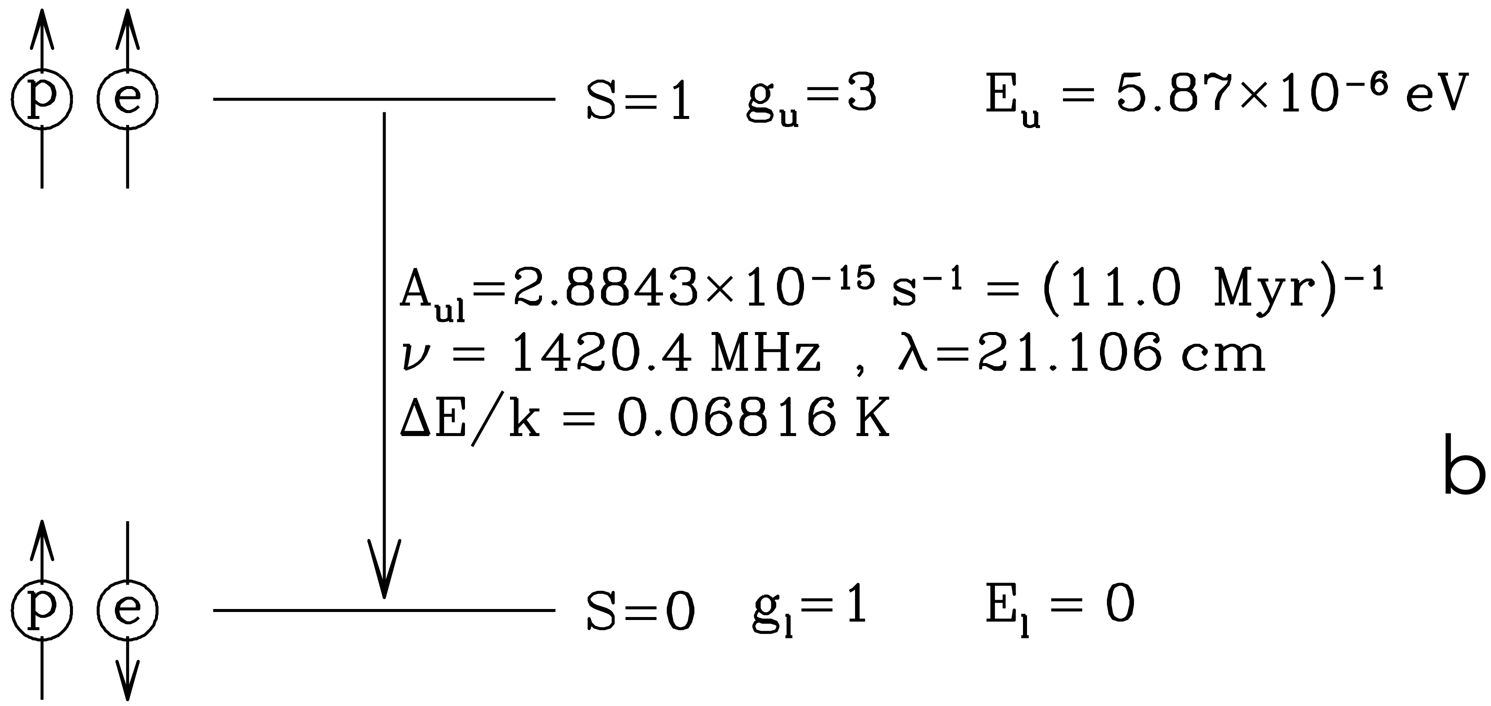
$\Delta E/k = 0.06816$ K

$S=0 \quad g_l=1 \qquad E_l = 0$

$T_{exc} \equiv T_{spin} \gg 0.0682$ K

because cosmic microwave background can populate levels

HI Spin Temperature



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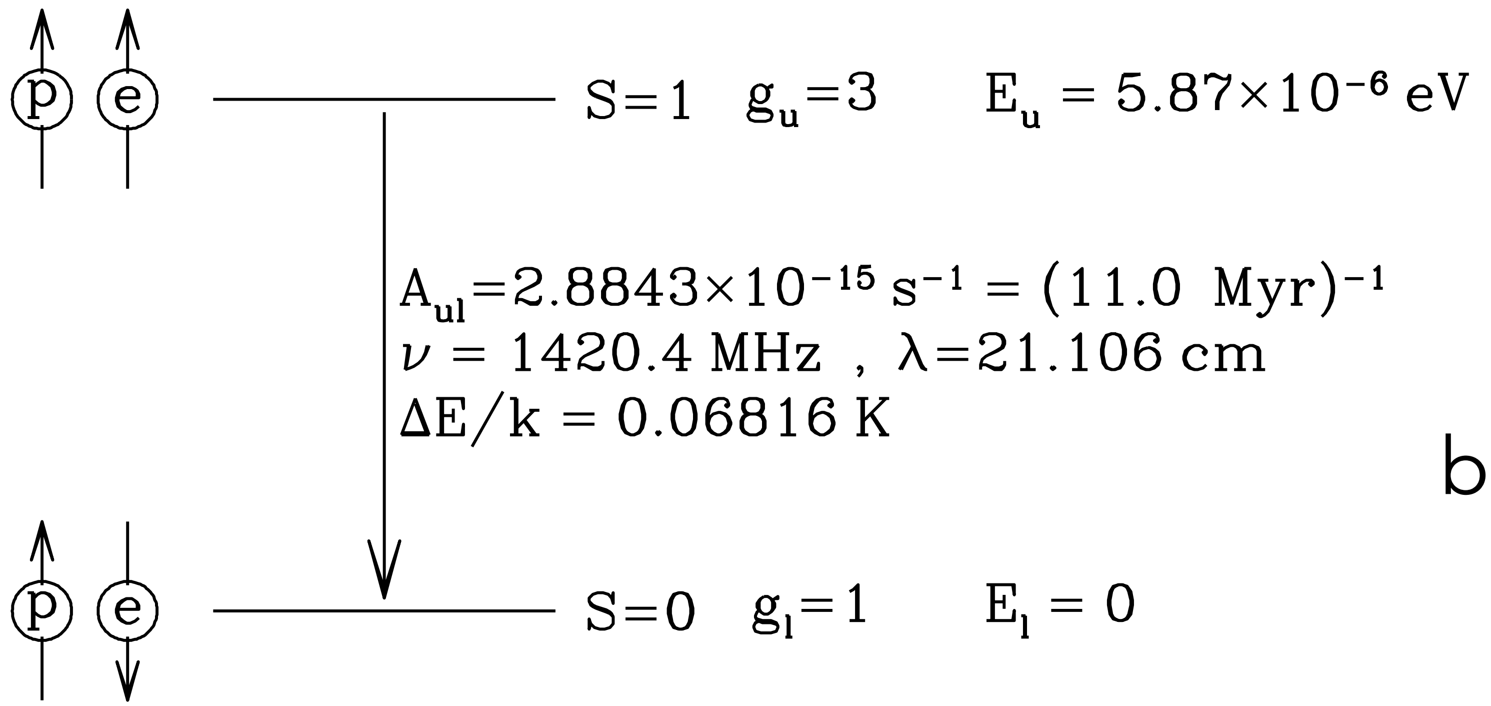
Under most ISM conditions, 75% of HI is in upper level. *Emissivity is independent of T_{spin}!!*

$$j_\nu = n_u \frac{A_{ul}}{4\pi} h\nu_{ul}\phi_\nu = \frac{3}{16\pi} A_{ul}\ h\nu_{ul}\ n(\mathrm{H\ I})\ \phi_\nu$$

HI Spin Temperature



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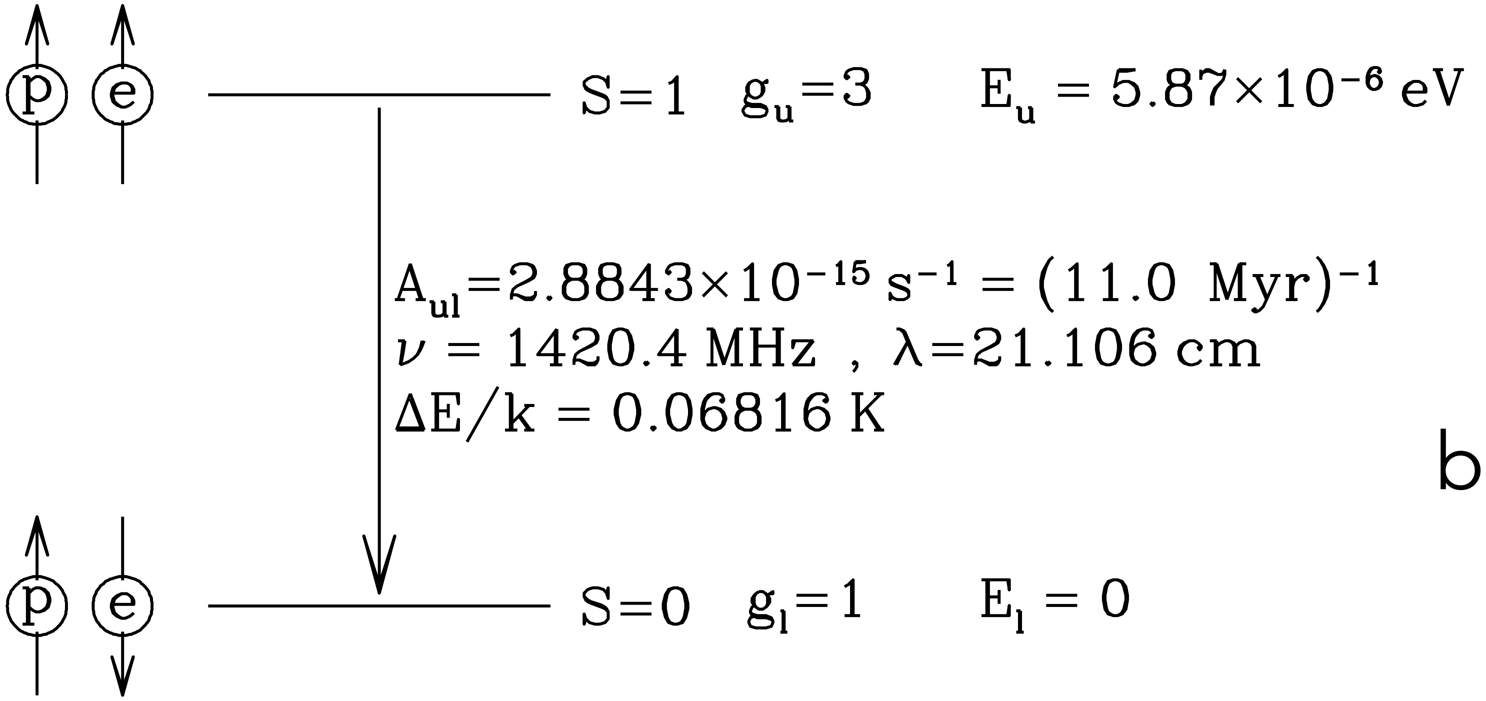
$T_{exc} \equiv T_{spin} \gg 0.0682$ K because cosmic microwave background can populate levels

absorption coefficient depends inversely on T_{spin} as a consequence of <u>stimulated emission</u> not being negligible!

$$\kappa_\nu \approx \frac{3}{32\pi} A_{ul} \frac{hc\lambda_{ul}}{kT_{spin}} n(\mathrm{H\ I})\phi_\nu$$

HI Spin Temperature



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$$\tau_\nu \propto \kappa_\nu L$$

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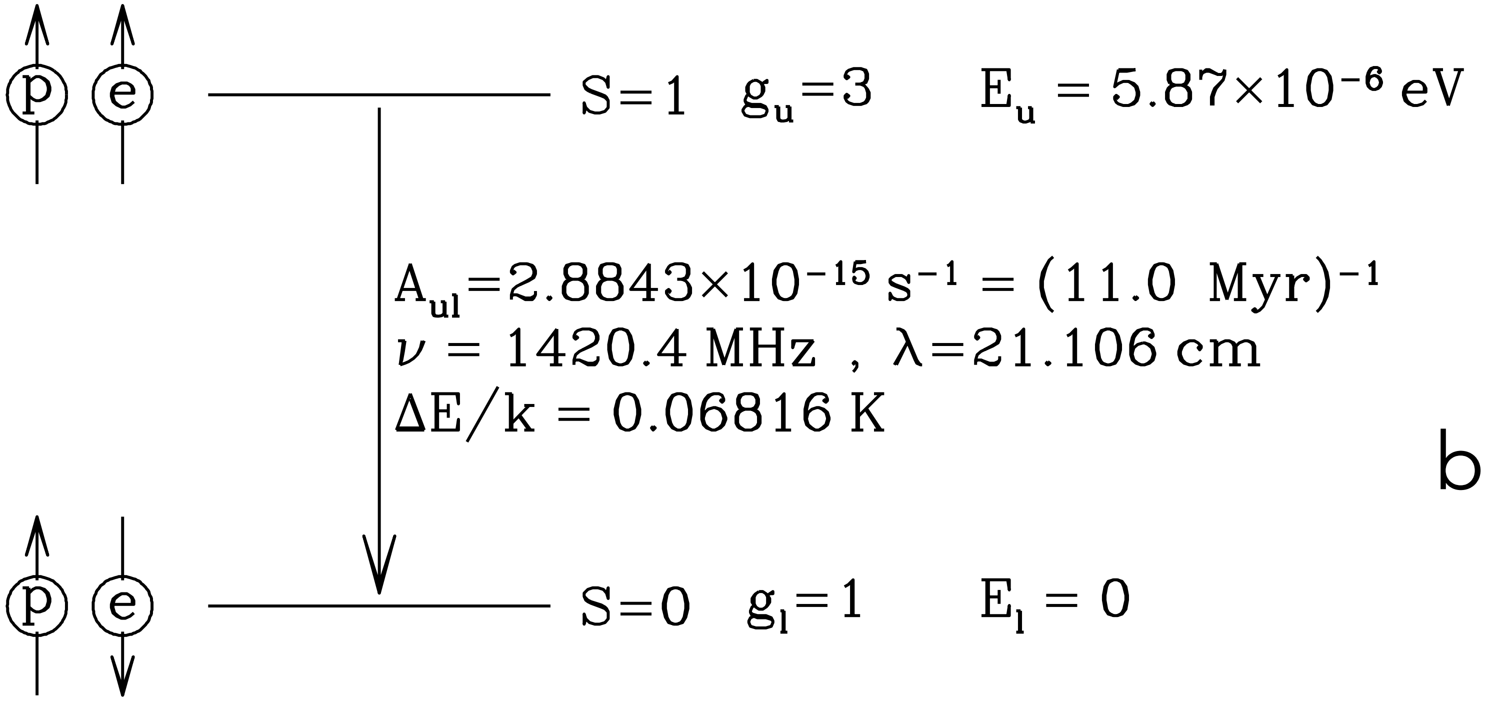

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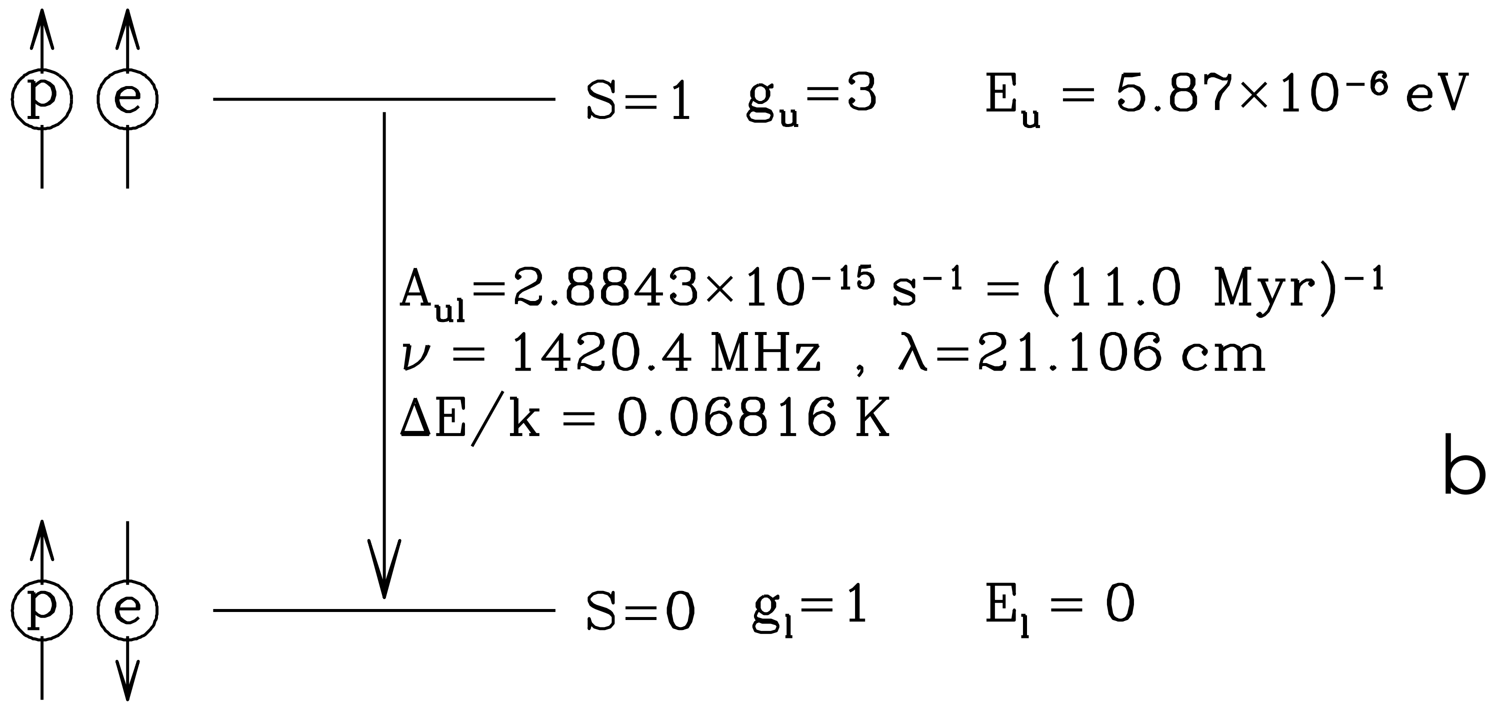
$$\tau_\nu \propto \kappa_\nu L \qquad \tau_\nu \propto \frac{n(\mathrm{HI})}{T_{spin}} L$$

HI Spin Temperature



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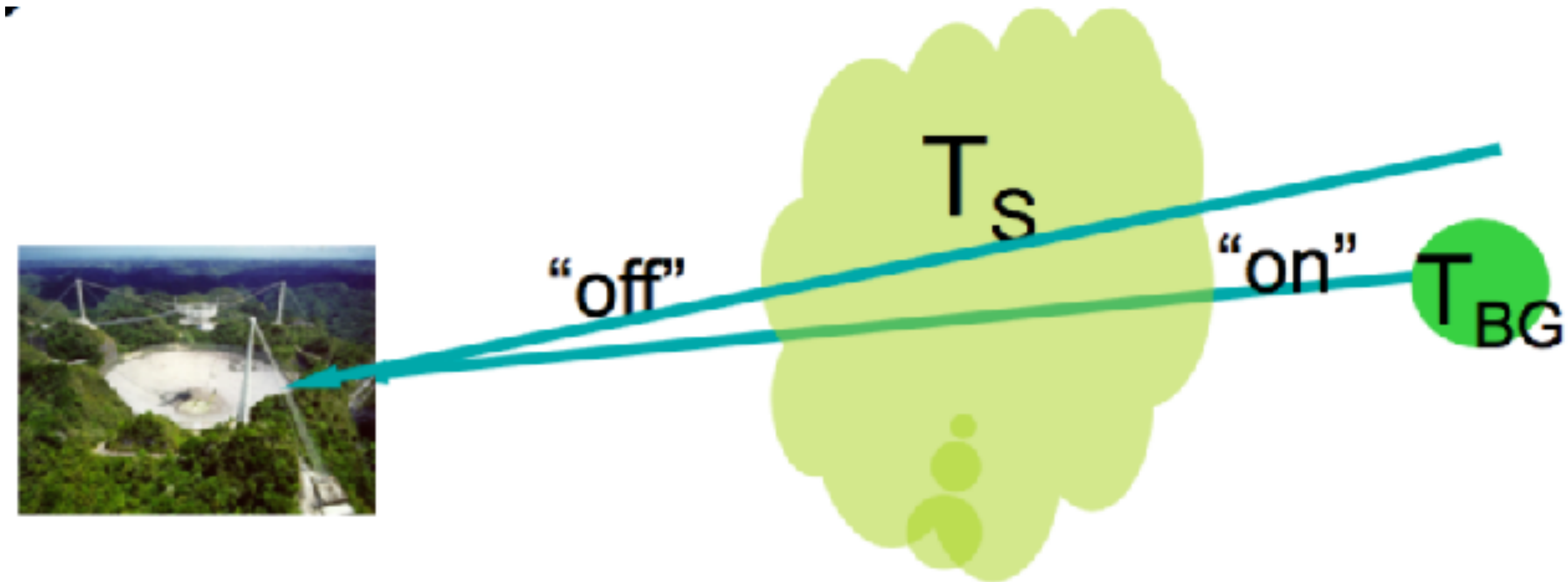
background can populate levels

absorption coefficient depends inversely on T_{spin}
as a consequence of stimulated emission not being negligible!

$$\tau_\nu \propto \kappa_\nu L \qquad \tau_\nu \propto \frac{n(\mathrm{HI})}{T_{spin}} L \qquad \tau_\nu \propto \frac{N(\mathrm{HI})}{T_{spin}}$$

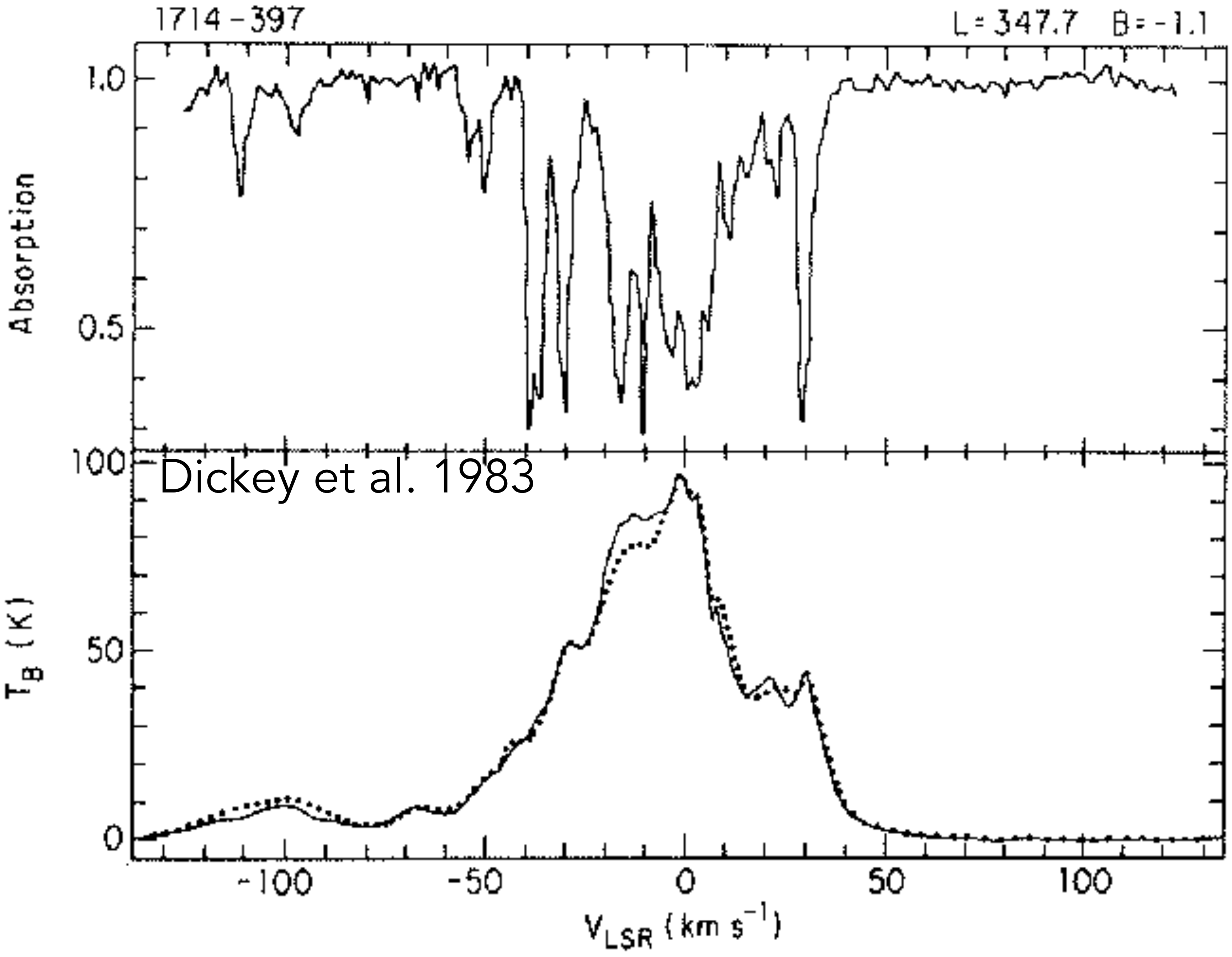
HI Spin Temperature

Measuring spin temperature



$$\begin{aligned} T_b^{on} &= T_{bg} e^{-\tau} + T_s (1 - e^{-\tau}) \\ T_b^{off} &= T_s (1 - e^{-\tau}) \end{aligned} \tag{1}$$

HI Spin Temperature

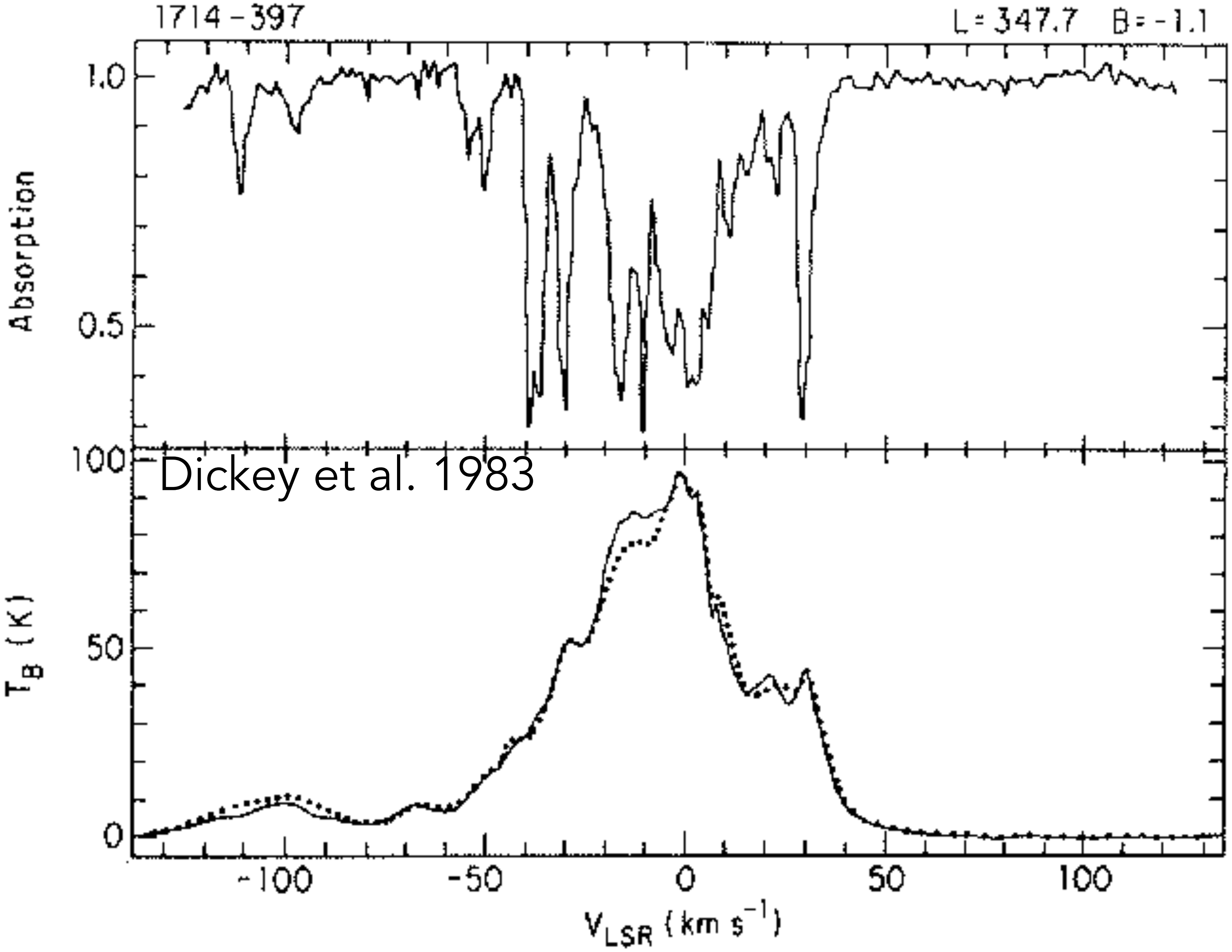


Dickey et al. 1983

Absorption - weighted to low T

Emission - independent of T

HI Spin Temperature



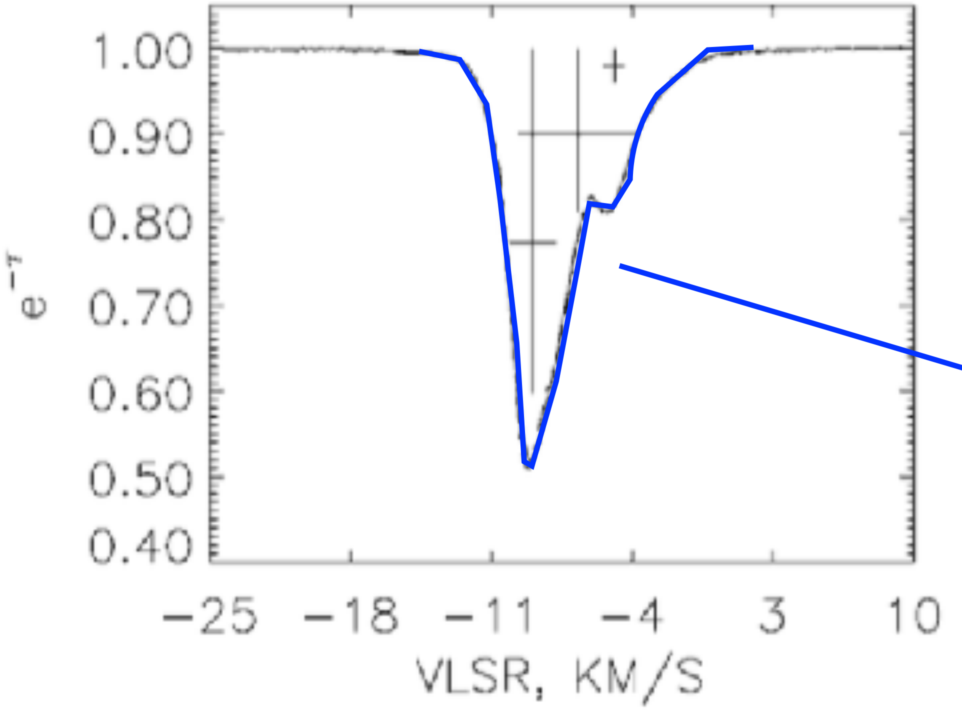
Dickey et al. 1983

Assume T_{WNM} is too big to contribute much to the absorption.

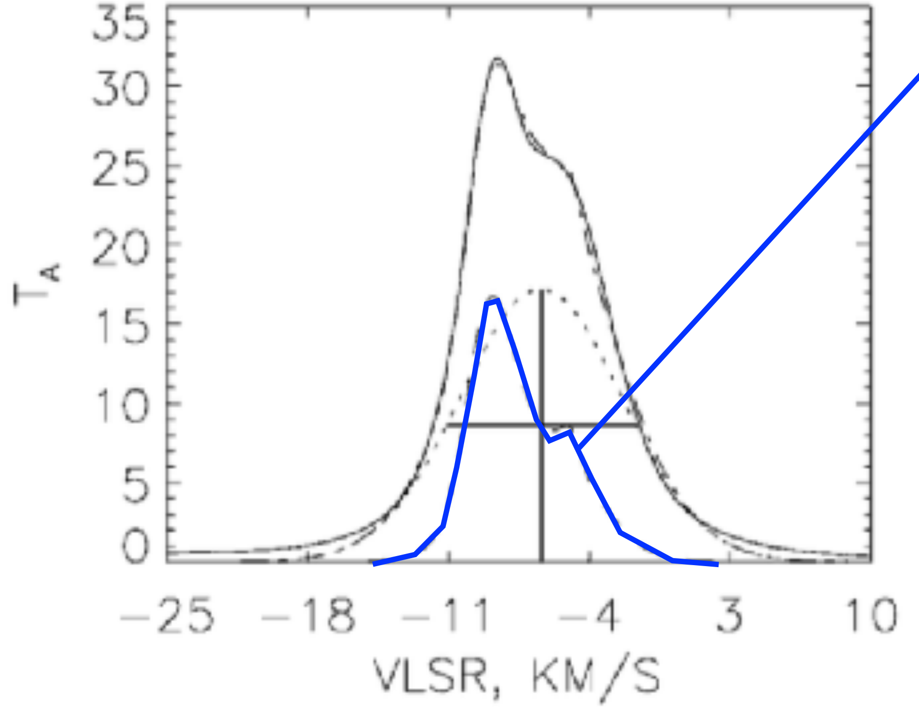
$\tau \sim N_{CNM}/T_{CNM}$

$T_B \sim N_{CNM} + N_{WNM}$

Observed HI Spin Temperature



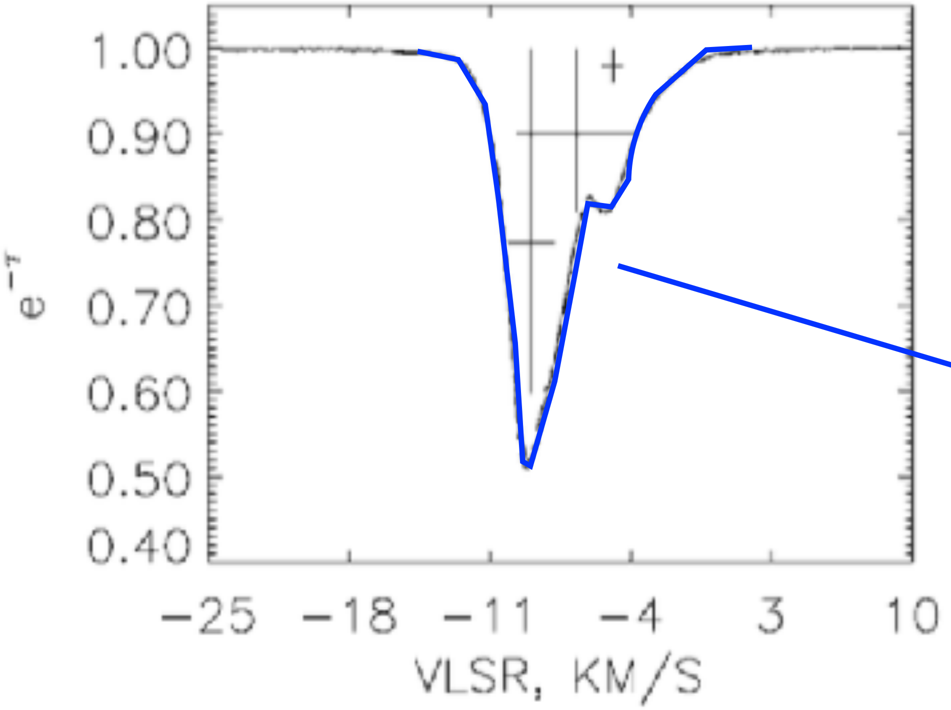
Heiles 2001



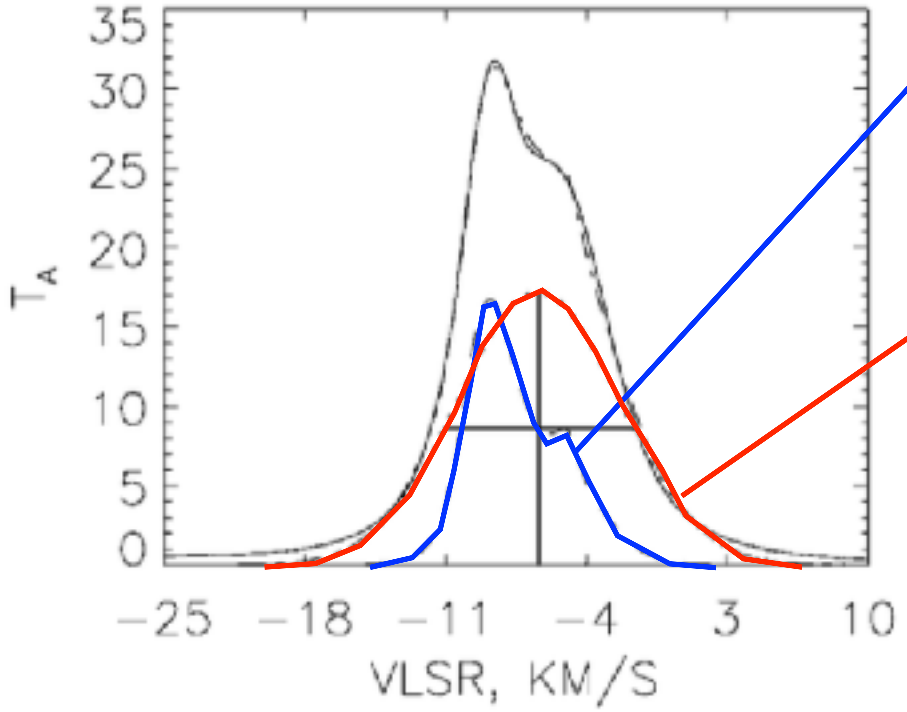
Assume CNM dominates absorption.

Fit absorption component and emission component with same Gaussian components (σ_V) to get N_{CNM}, T_{CNM}

Observed HI Spin Temperature



Heiles 2001

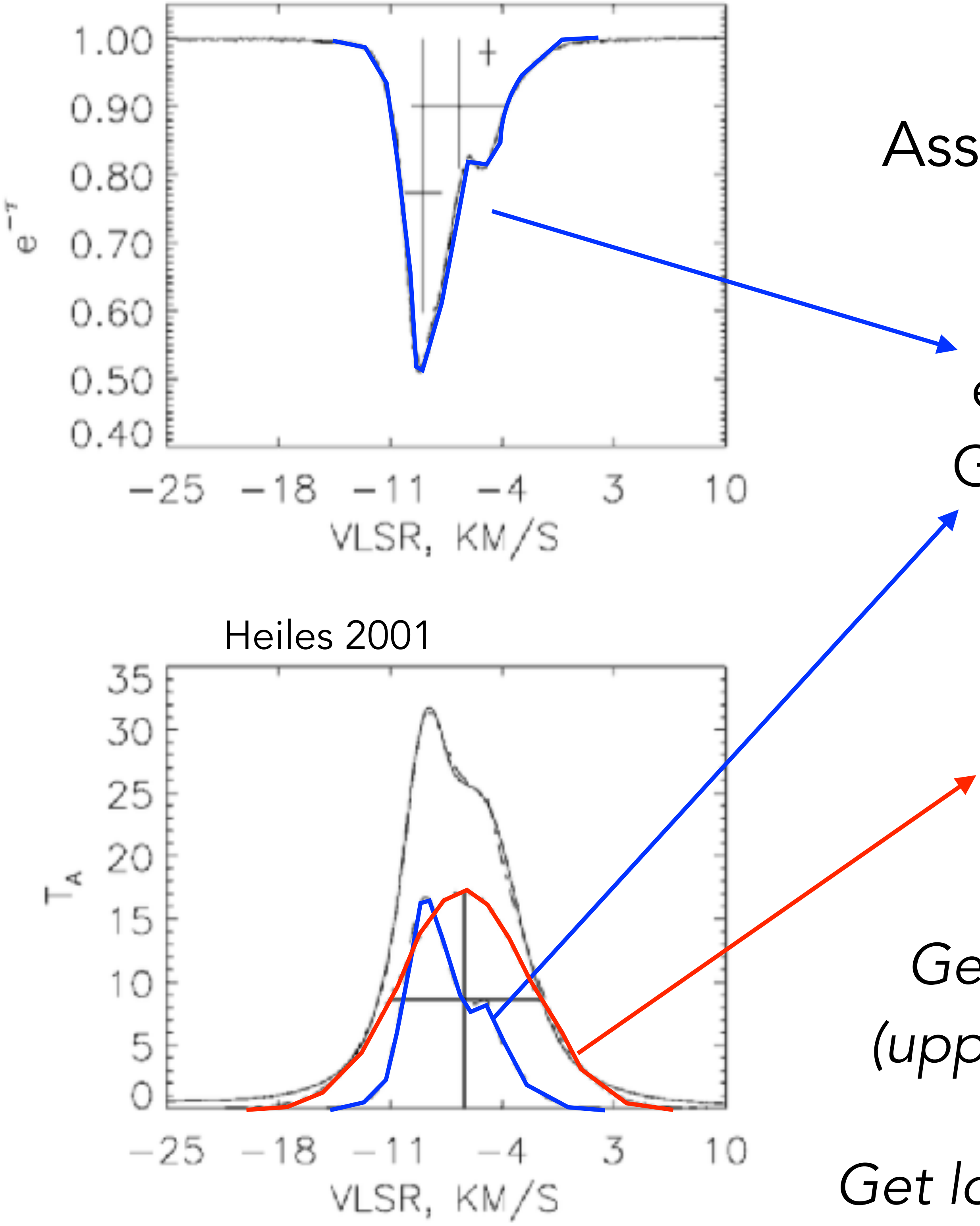


Assume CNM dominates absorption.

Fit absorption component and emission component with same Gaussian components (σ_V) to get N_{CNM}, T_{CNM}

Fit emission component with additional Gaussian and N_{WNM}.

Observed HI Spin Temperature



Heiles 2001

Assume CNM dominates absorption.

Fit absorption component and emission component with same Gaussian components (σ_V) to get N_{CNM}, T_{CNM}

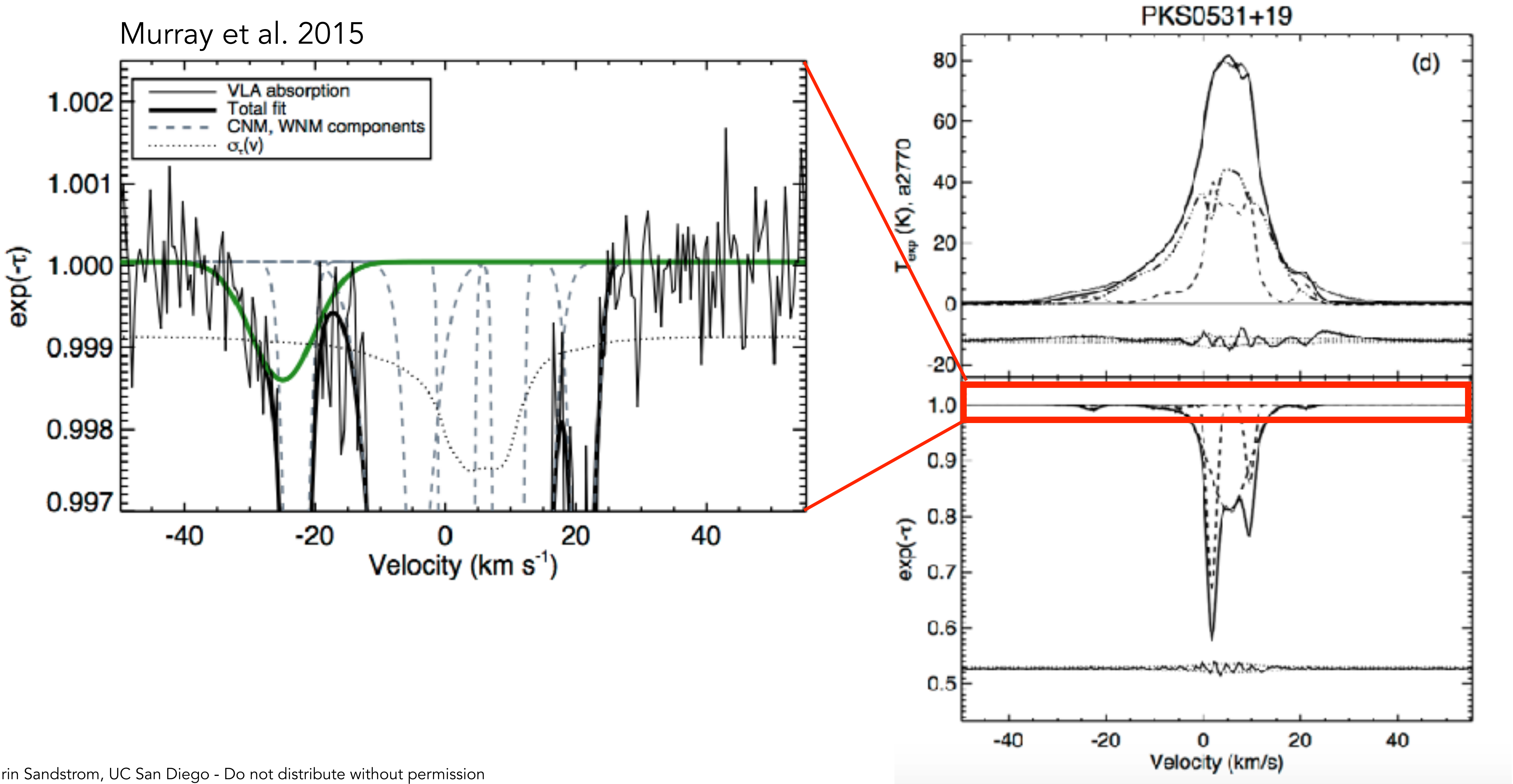
Fit emission component with additional Gaussian and N_{WNM}.

Get upper limit on T_{WNM} from velocity width (upper limit because of turbulent contribution).

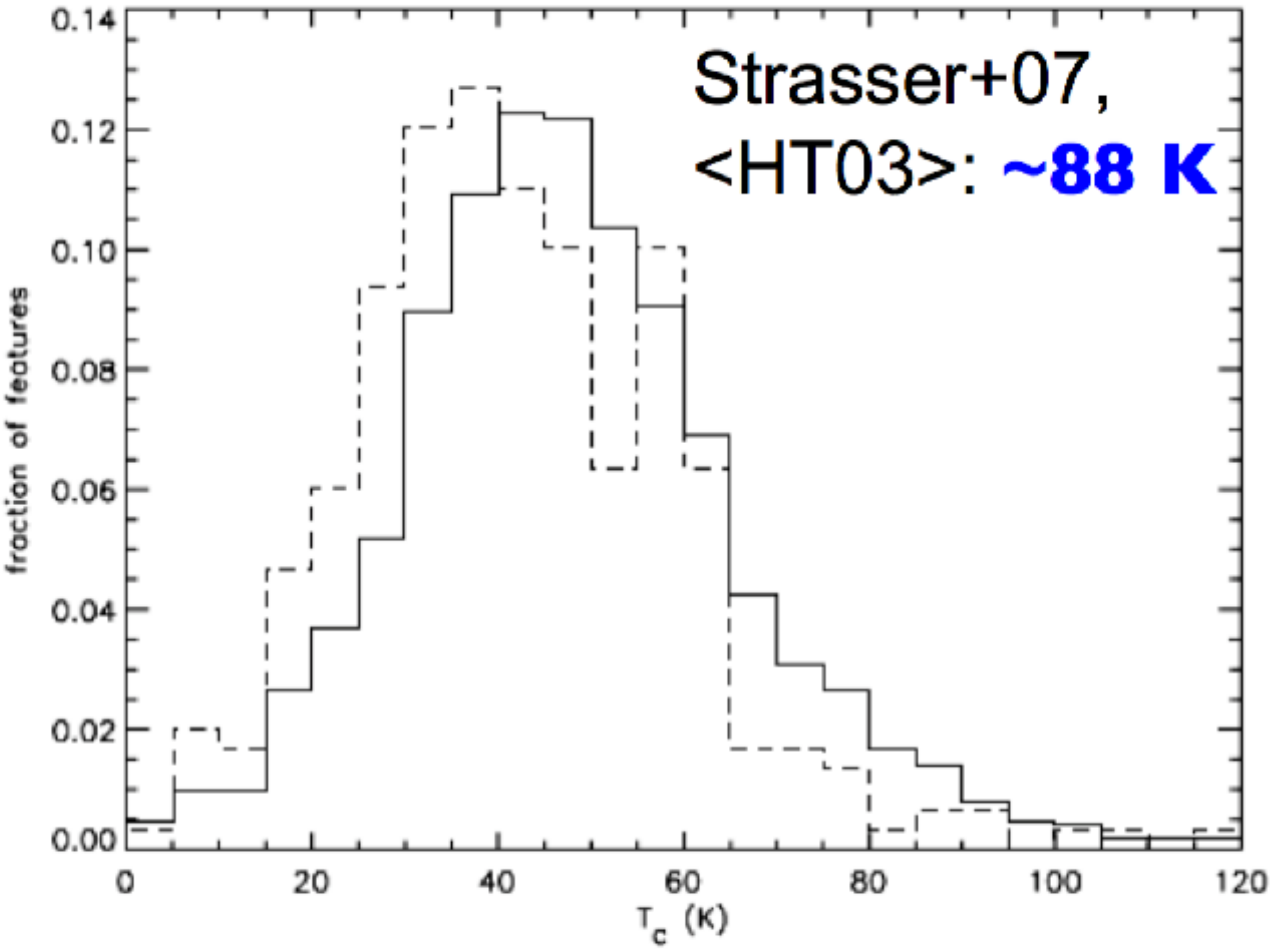
Get lower limit on T_{WNM} from residual absorption.

Observed HI Spin Temperature

Measuring absorption from the WNM requires very high S/N measurements.


Murray et al. 2015

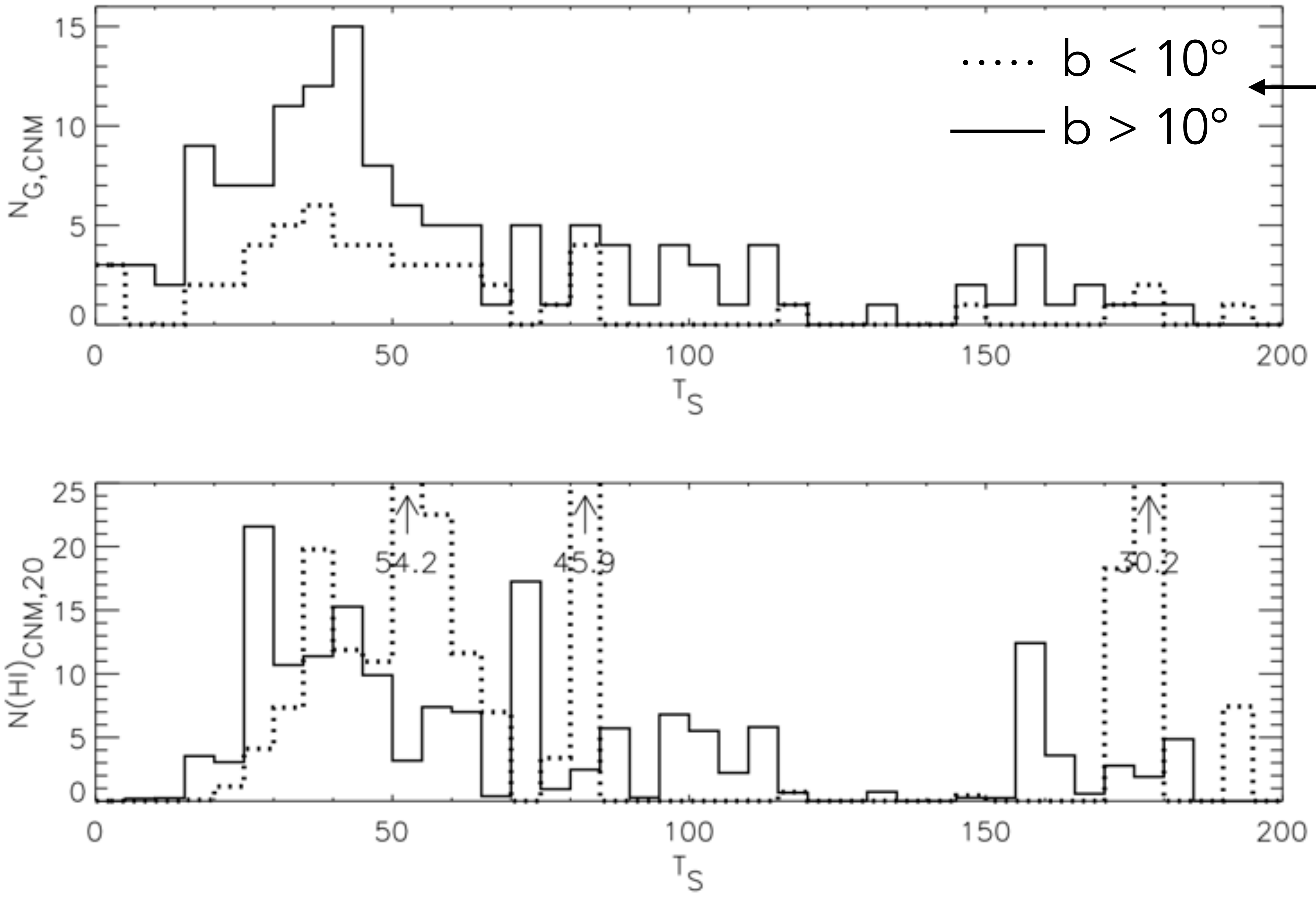
Observed HI Spin Temperature



observed CNM components have T ~ 40-80 K

Observed HI Spin Temperature

Heiles & Troland 2003 - The Millennium Arecibo 21-cm Absorption Line Survey

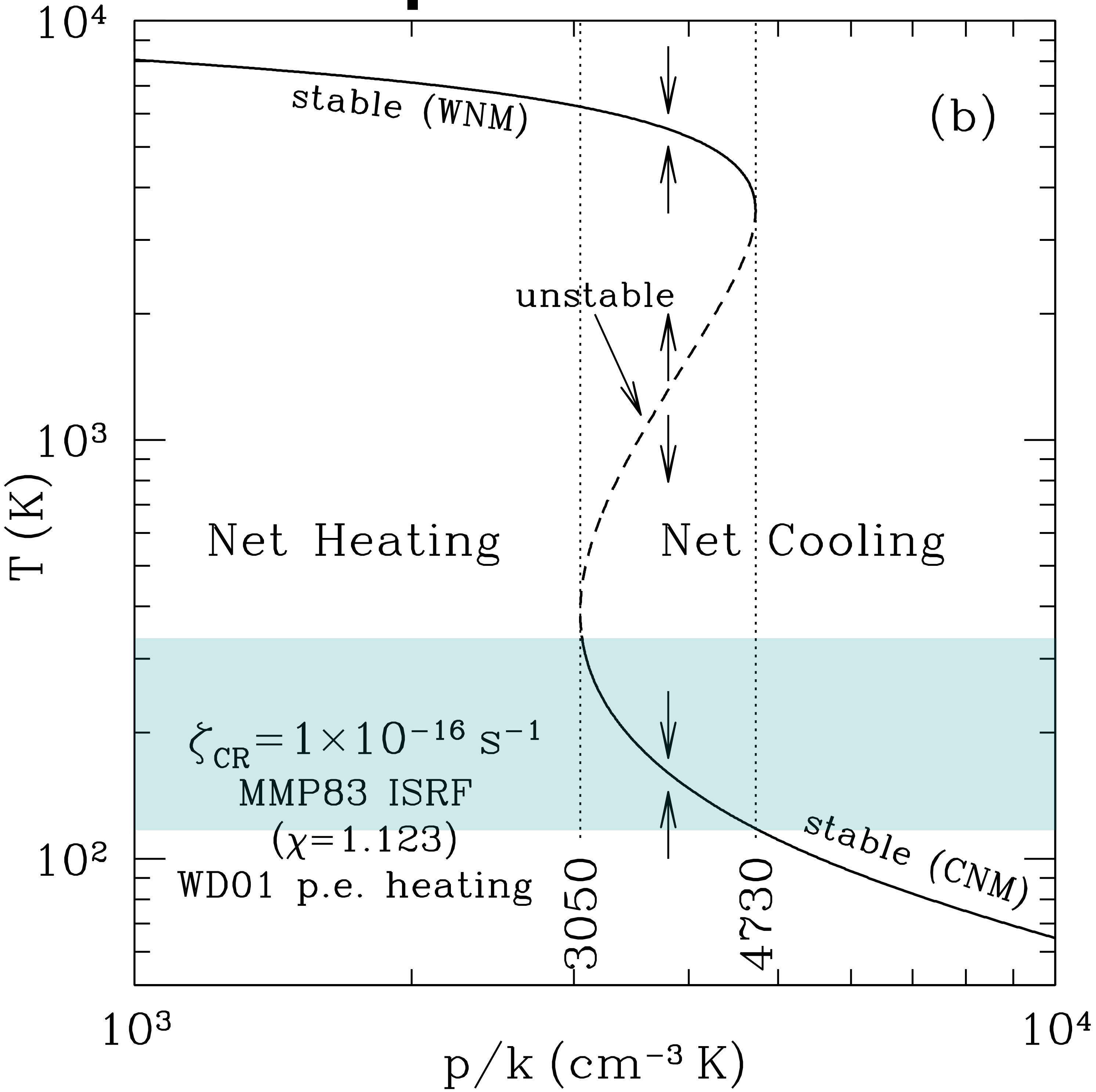


by number

Galactic latitude

by column density

Is the FGH model a good representation of the ISM?



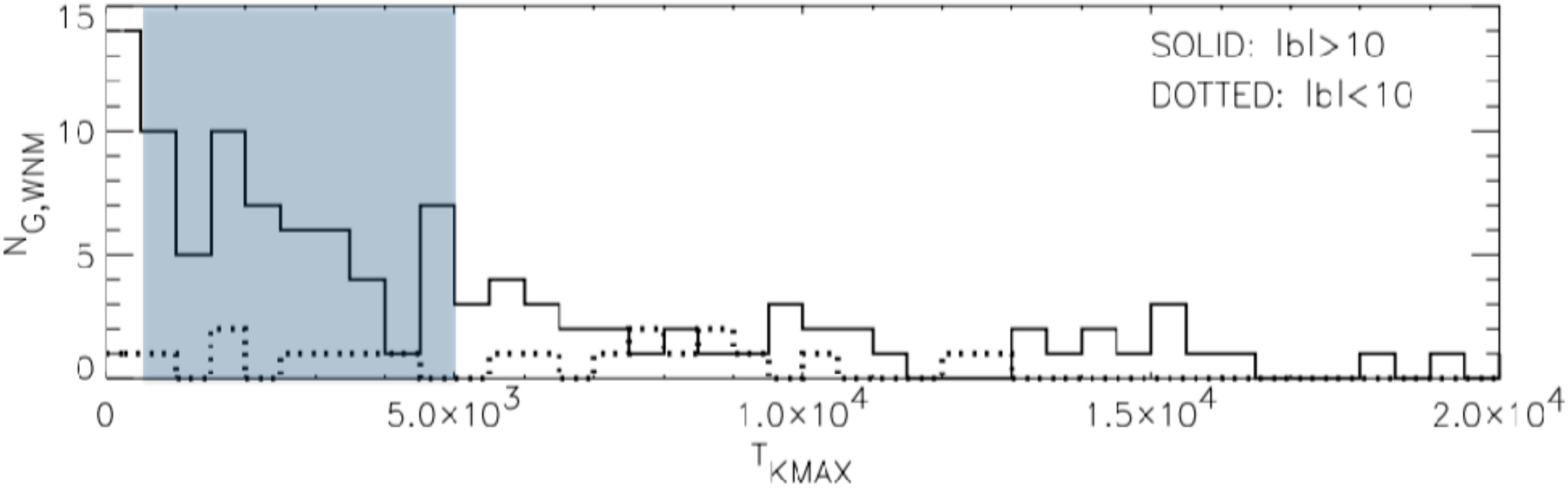
Measured CNM temperature of ~50-100 K is lower than what might be expected for p/k ~ 3000-4000 cm^{-3} K

expected

Observed HI Spin Temperature

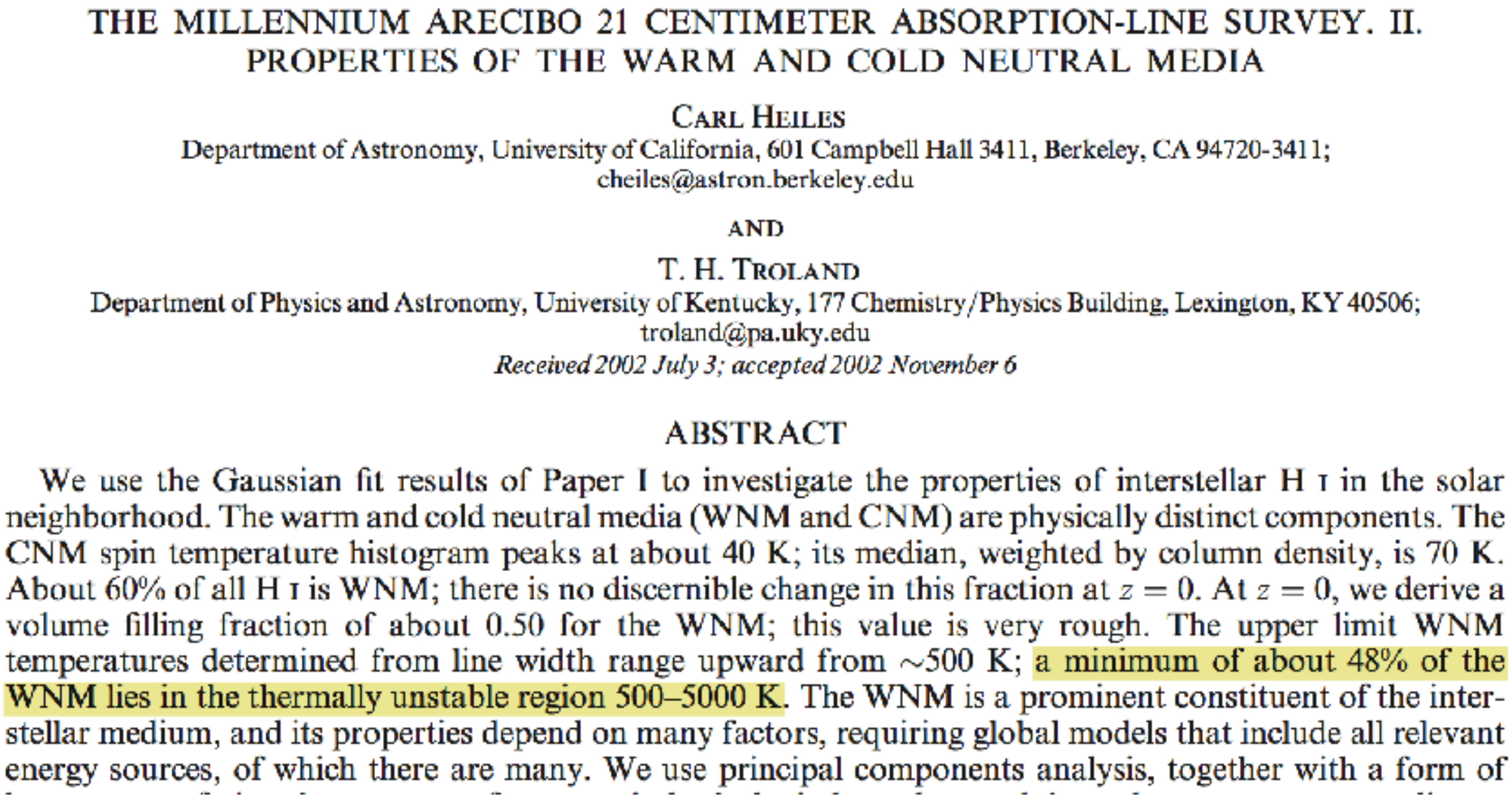
Evidence for “unstable” phase (500 < T < 5000)

Heiles & Troland 2003



Upper limit on T_{WNM}

Observed HI Spin Temperature



THE MILLENNIUM ARECIBO 21 CENTIMETER ABSORPTION-LINE SURVEY. II. PROPERTIES OF THE WARM AND COLD NEUTRAL MEDIA

CARL HEILES
Department of Astronomy, University of California, 601 Campbell Hall 3411, Berkeley, CA 94720-3411;
cheiles@astron.berkeley.edu

AND

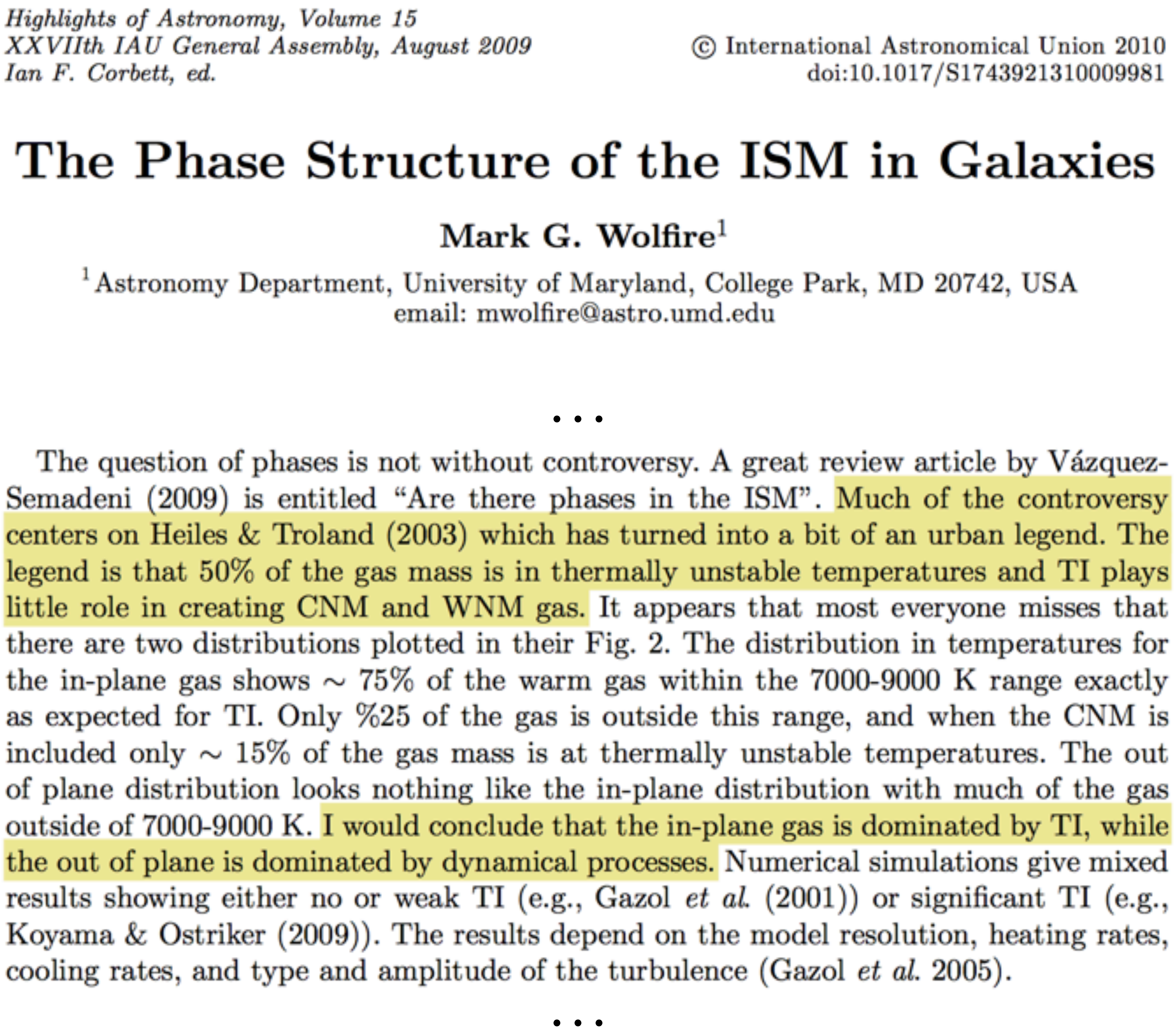
T. H. TROLAND
Department of Physics and Astronomy, University of Kentucky, 177 Chemistry/Physics Building, Lexington, KY 40506;
troland@pa.uky.edu

Received 2002 July 3; accepted 2002 November 6

ABSTRACT

We use the Gaussian fit results of Paper I to investigate the properties of interstellar H I in the solar neighborhood. The warm and cold neutral media (WNM and CNM) are physically distinct components. The CNM spin temperature histogram peaks at about 40 K; its median, weighted by column density, is 70 K. About 60% of all H I is WNM; there is no discernible change in this fraction at $z = 0$. At $z = 0$, we derive a volume filling fraction of about 0.50 for the WNM; this value is very rough. The upper limit WNM temperatures determined from line width range upward from ~500 K; a minimum of about 48% of the WNM lies in the thermally unstable region 500–5000 K. The WNM is a prominent constituent of the interstellar medium, and its properties depend on many factors, requiring global models that include all relevant energy sources, of which there are many. We use principal components analysis, together with a form of

Observed HI Spin Temperature



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Ian F. Corbett, ed.

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The Phase Structure of the ISM in Galaxies

Mark G. Wolfire[1]
[1] Astronomy Department, University of Maryland, College Park, MD 20742, USA
email: mwolfire@astro.umd.edu

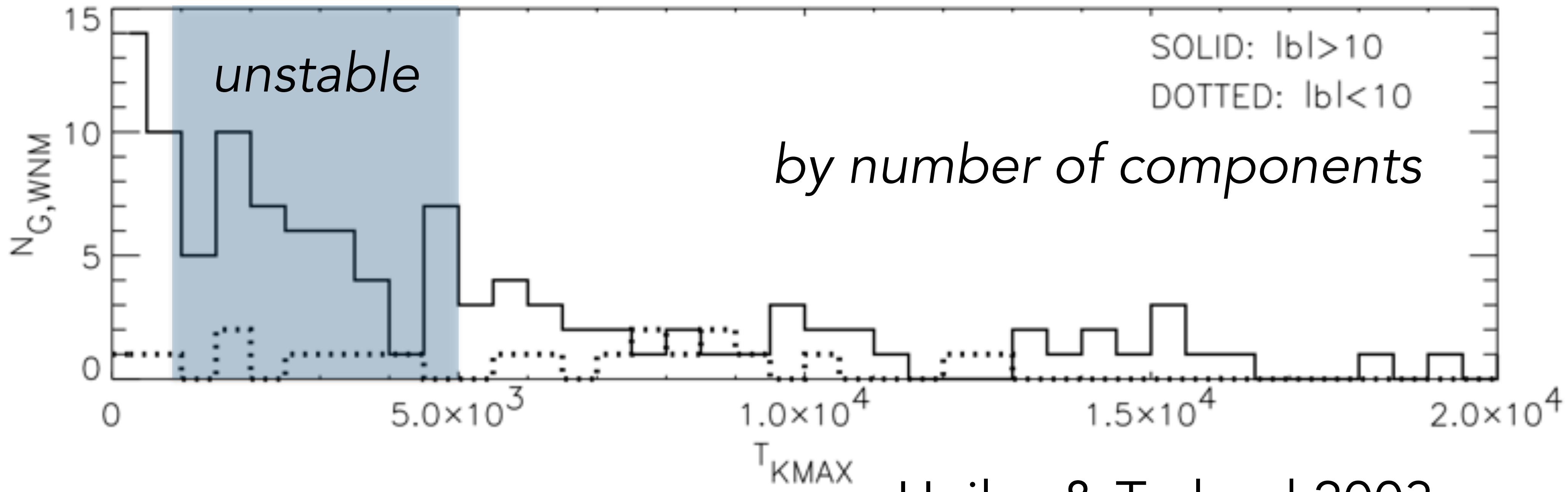
. . .

The question of phases is not without controversy. A great review article by Vázquez-Semadeni (2009) is entitled "Are there phases in the ISM". Much of the controversy centers on Heiles & Troland (2003) which has turned into a bit of an urban legend. The legend is that 50% of the gas mass is in thermally unstable temperatures and TI plays little role in creating CNM and WNM gas. It appears that most everyone misses that there are two distributions plotted in their Fig. 2. The distribution in temperatures for the in-plane gas shows ~ 75% of the warm gas within the 7000-9000 K range exactly as expected for TI. Only %25 of the gas is outside this range, and when the CNM is included only ~ 15% of the gas mass is at thermally unstable temperatures. The out of plane distribution looks nothing like the in-plane distribution with much of the gas outside of 7000-9000 K. I would conclude that the in-plane gas is dominated by TI, while the out of plane is dominated by dynamical processes. Numerical simulations give mixed results showing either no or weak TI (e.g., Gazol *et al.* (2001)) or significant TI (e.g., Koyama & Ostriker (2009)). The results depend on the model resolution, heating rates, cooling rates, and type and amplitude of the turbulence (Gazol *et al.* 2005).

. . .

Observed HI Spin Temperature

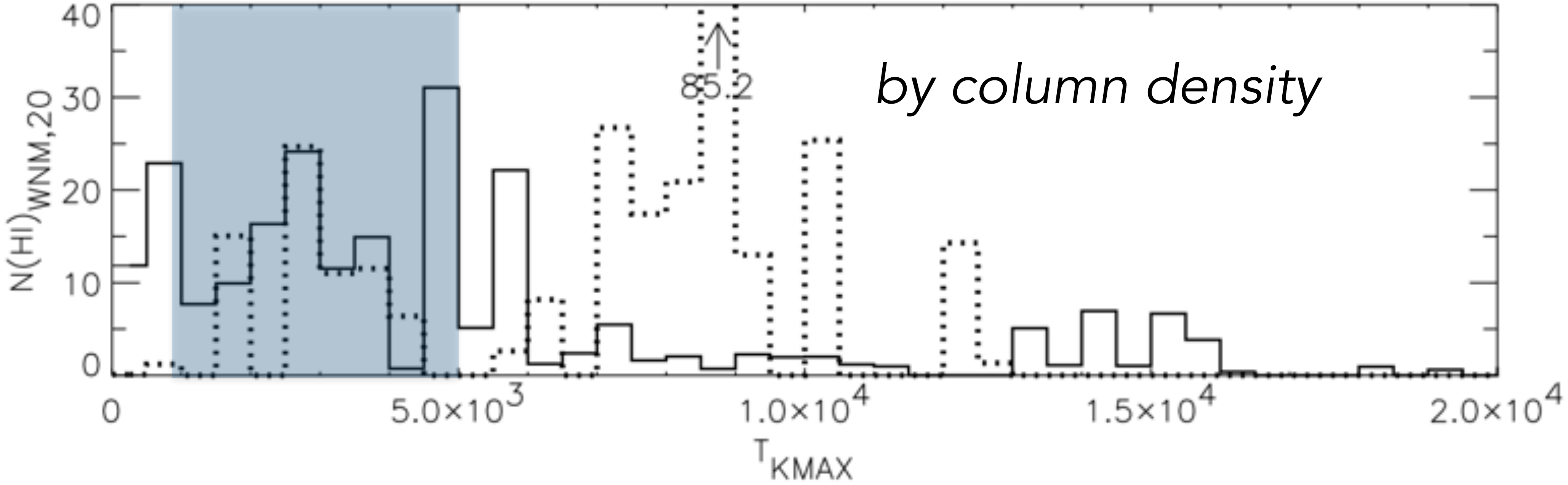
WNM Temperature



unstable

by number of components

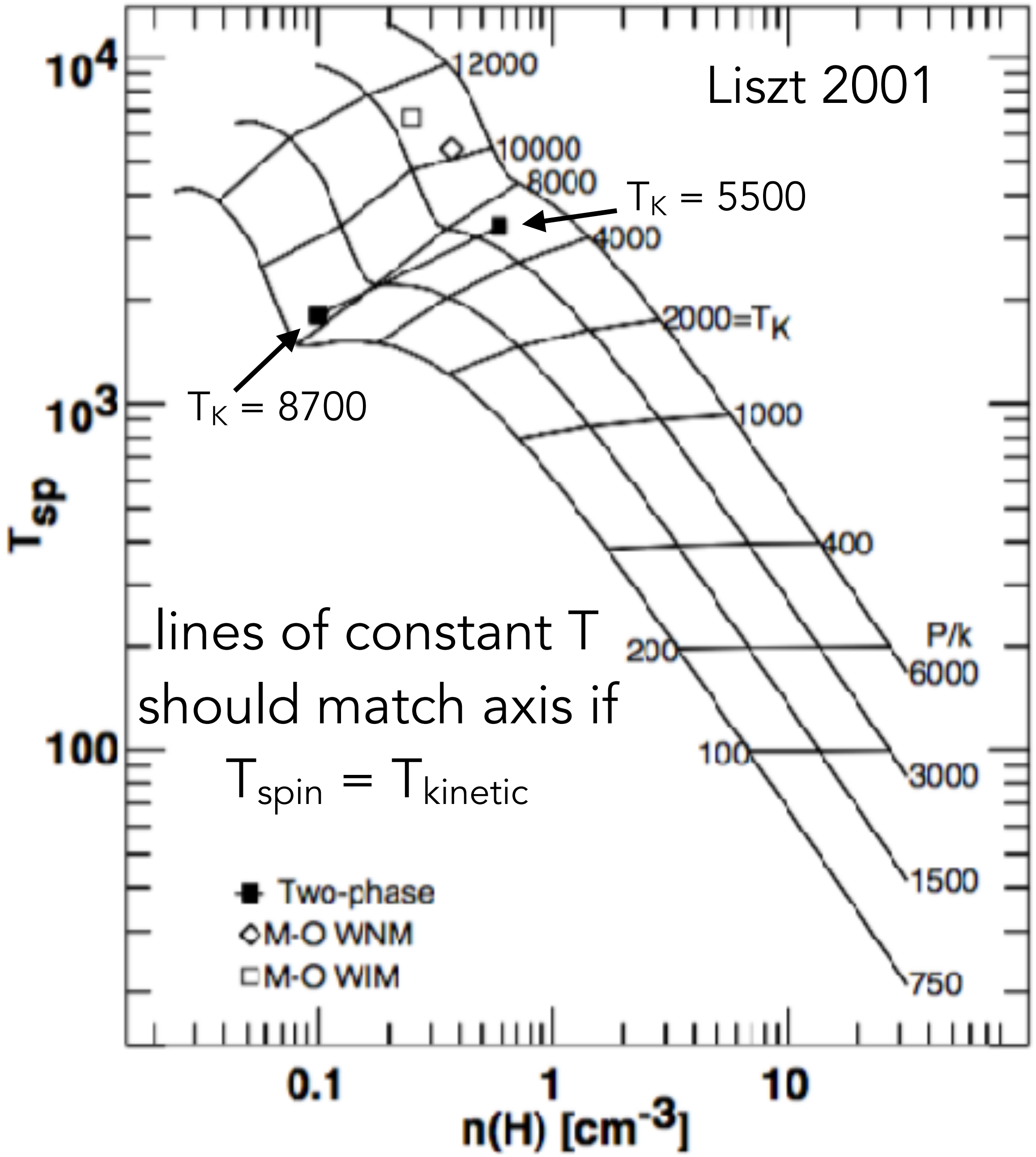
Heiles & Troland 2003



by column density

Observed HI Spin Temperature

Important wrinkle: thermalization of HI levels in WNM



Liszt 2001

T_K = 5500

T_K = 8700

lines of constant T should match axis if $T_{spin} = T_{kinetic}$

Density in the WNM is too low to thermalize levels to predicted WNM temperatures.

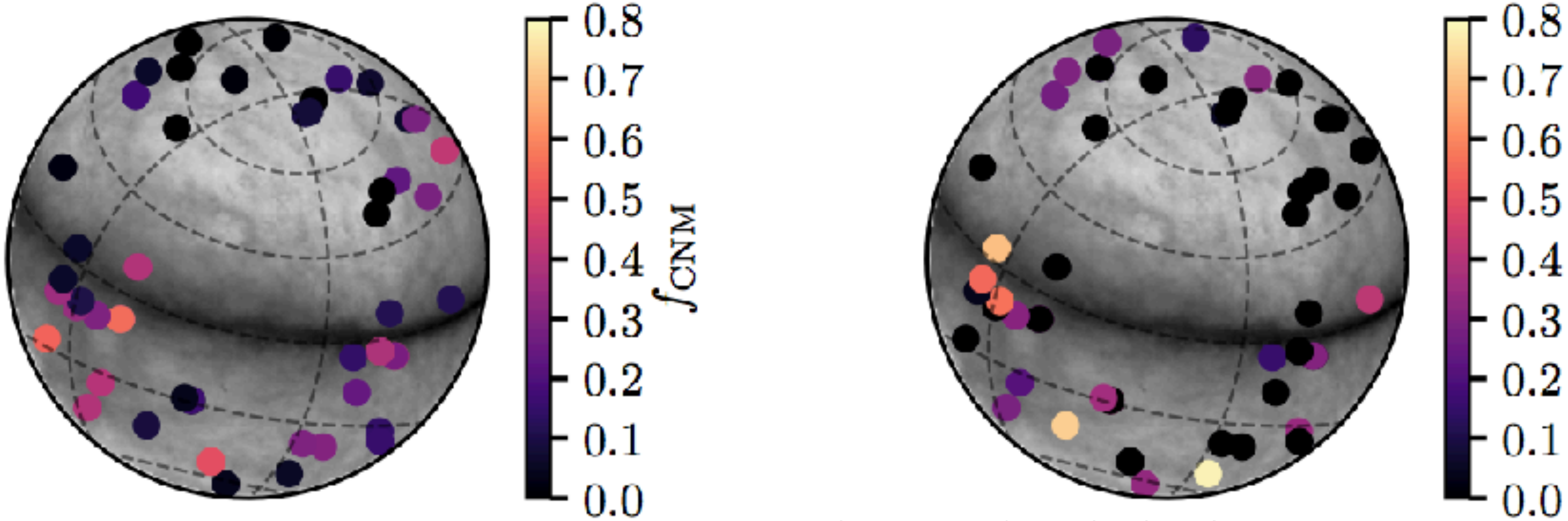
However, scattered Lyα radiation can contribute to thermalizing levels as well.

(Liszt 2001)

Observed HI Spin Temperature

Best recent constraints for the Milky Way:
28% CNM, 20% unstable, 52% WNM by mass

VLA 21SPONGE Survey - Murray et al. 2018



EBHIS survey & 21SPONGE targets

also: WNM is hotter than equilibrium models predict.