Physics 224
The Interstellar Medium

Lecture #11: ISM Phases & Neutral Gas

Outline

- Part I: “ISM Phases”
- Part II: Neutral Gas Heating & Cooling
- Part III: Neutral Gas Observations

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

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	$10^5 - 10^7$

Pressure equilibrium

What we are going to do next:

Understand what sets the properties of various ISM phases:

Neutral gas

Molecular gas

Ionized gas

Neutral Gas

~60% of gas in MW is in "HI regions"
where hydrogen is atomic (not ionized, not molecular)

Heating:

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

Cooling:

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

interaction rate

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

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	H & He
Photoionization of H & He	H & He
Photoionization of metals	C, O, Ne, Mg, Si (IP < 13.6 eV)
Photoelectric effect from dust	Dust
Shocks, turbulent dissipation, MHD phenomena	

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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Heating:

- Cosmic Ray Ionization
- Photoionization of H & He
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- Photoelectric effect from dust
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- ζ_{CR}
- $(u_\nu/h\nu)\ c\ \sigma_{H,He}(E)$
- $(u_\nu/h\nu)\ c\ \sigma_Z(E)$
- $(u_\nu/h\nu)\ c\ \langle Q_{abs,*}\rangle\ \pi a^2$ (integrate over a)

Depend on CR flux and radiation field strength.

interaction rate

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

density of whatever
is being ionized
X_H = abundance
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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

Depends on ionization state of gas, energy of collider & “work function”

interaction rate

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

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…

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

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

In the case where $n_c >> n_{crit}$, 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

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:

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

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

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

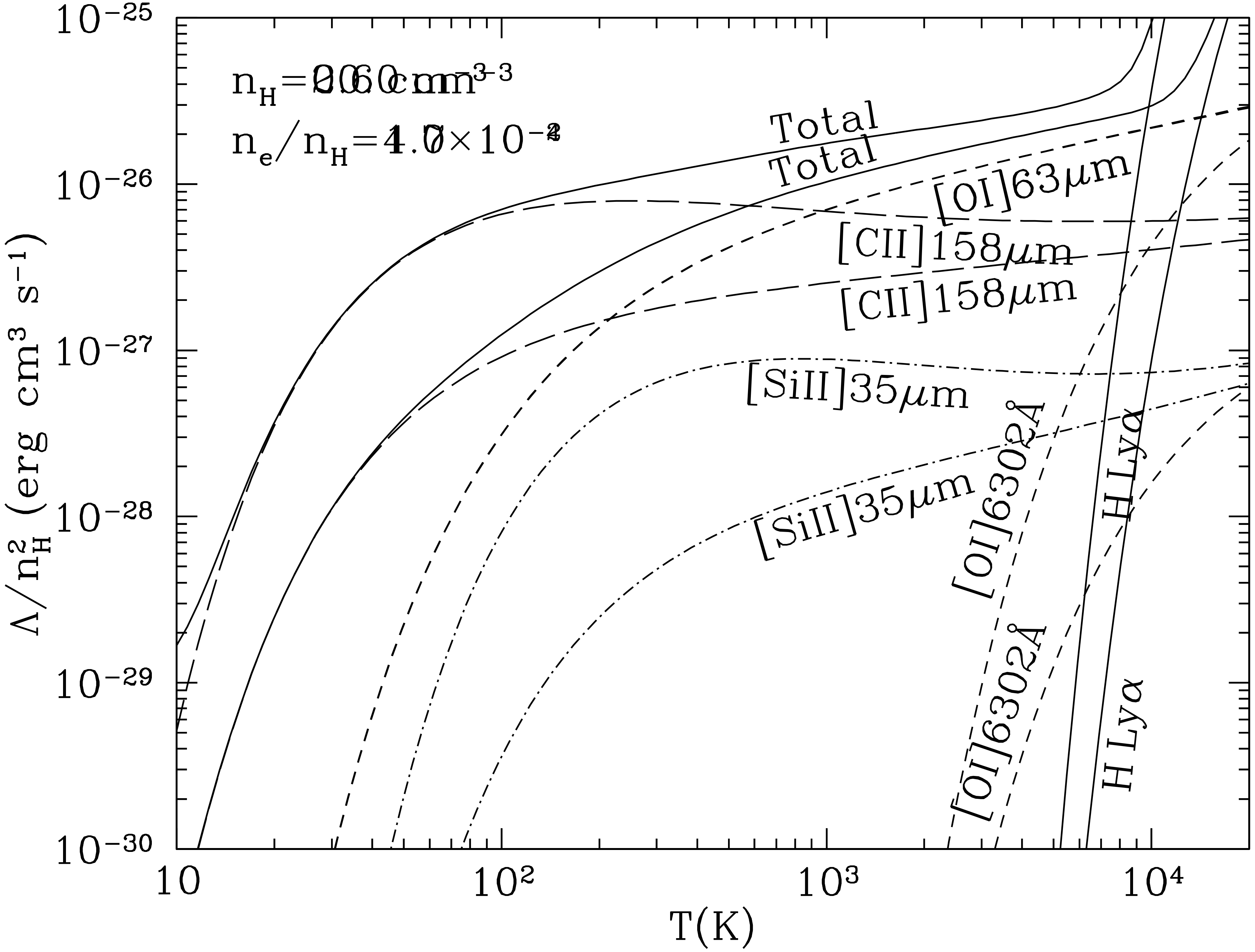
$\Lambda \sim n^2 \, \lambda(T) \, \text{const}$

$\lambda(T)$: function of gas temperature

const: quantum mechanics

Cooling:

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


$n_H = 0.6\ \mathrm{cm}^{-3}$
$n_H = 20\ \mathrm{cm}^{-3}$
$n_e/n_H = 1.7\times10^{-2}$
$n_e/n_H = 4.0\times10^{-4}$
Total
Total
[OI]63μm
[CII]158μm
[CII]158μm
[SiII]35μm
[SiII]35μm
[OI]6302Å
[OI]6302Å
H Lyα
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

Phases in Pressure Equilibrium

net heating
or cooling

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

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

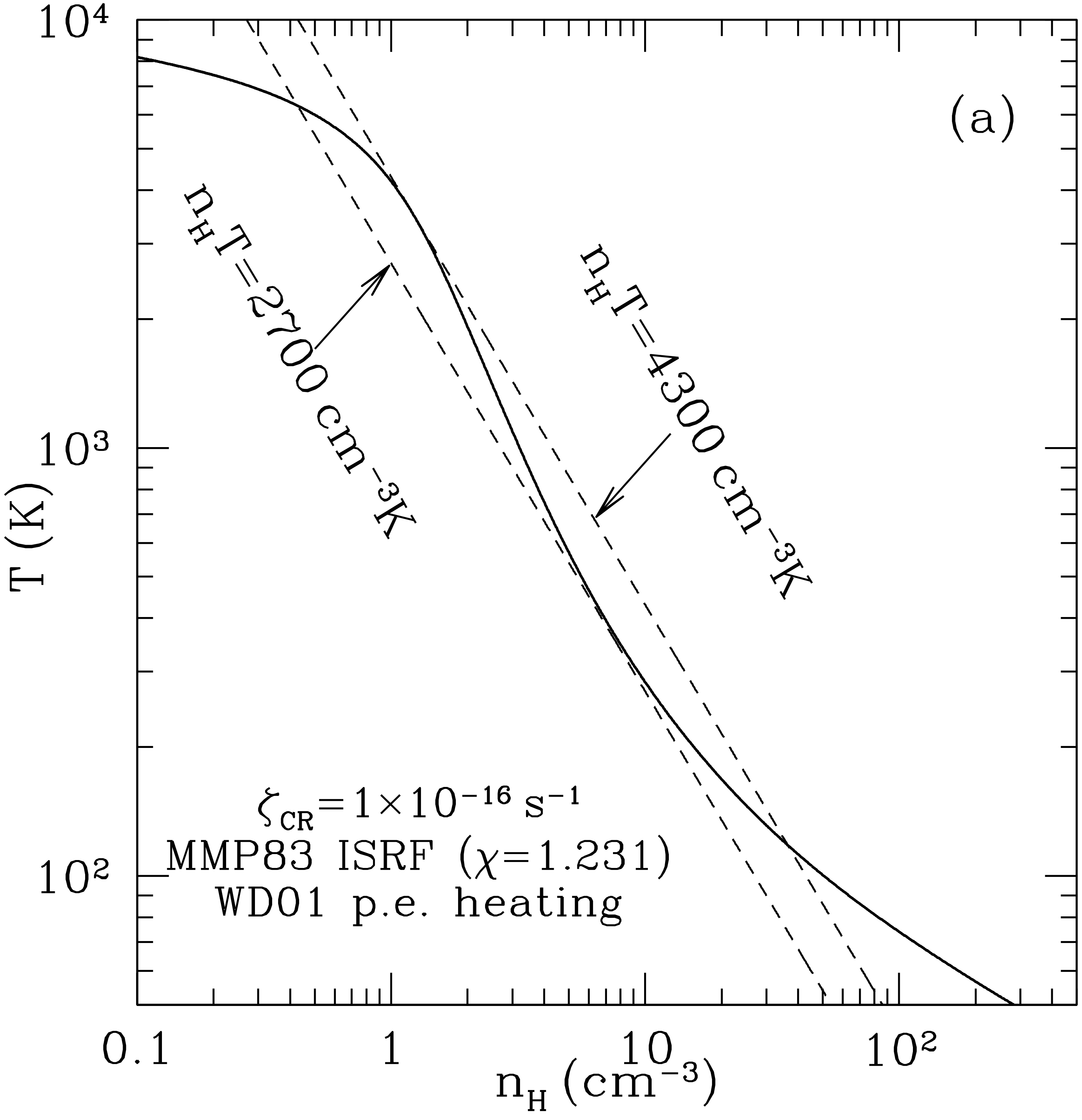
Recall:

$\Gamma \sim n\,\zeta$ ← 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

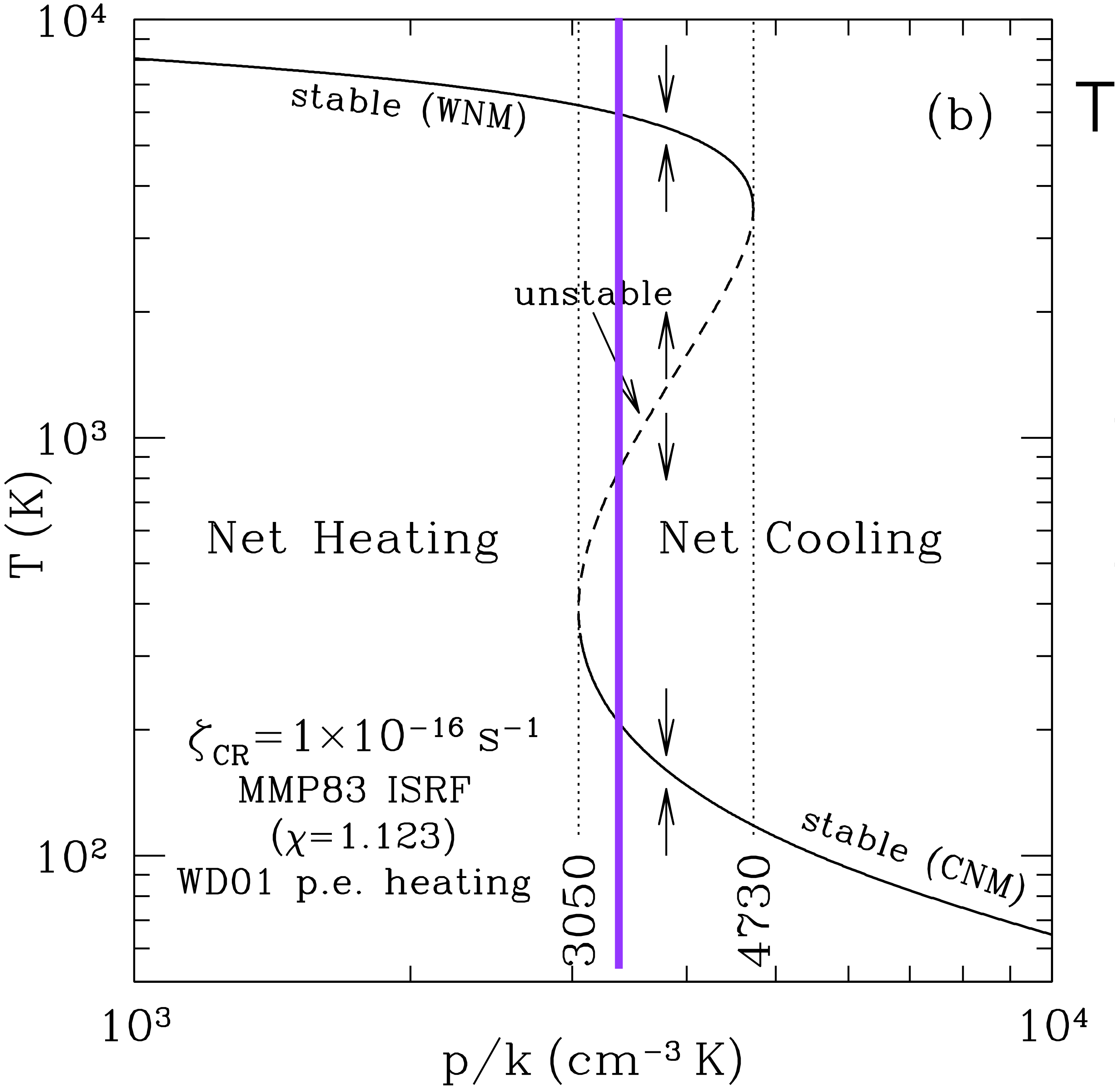


Solid line is L(n,T) = 0
heating/cooling equilibrium

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 ~ 10^3 - 10^4 branch = WNM

T ~ 10^1 - 10^2 branch = WNM

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

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

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

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

$$\left(\frac{\partial L}{\partial T}\right)_P = \left(\frac{\partial L}{\partial T}\right)_n + \frac{n_0}{T_0}\left(\frac{\partial L}{\partial n}\right)_T < 0$$

Phases in Pressure Equilibrium

net heating
or cooling

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

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

Recall:

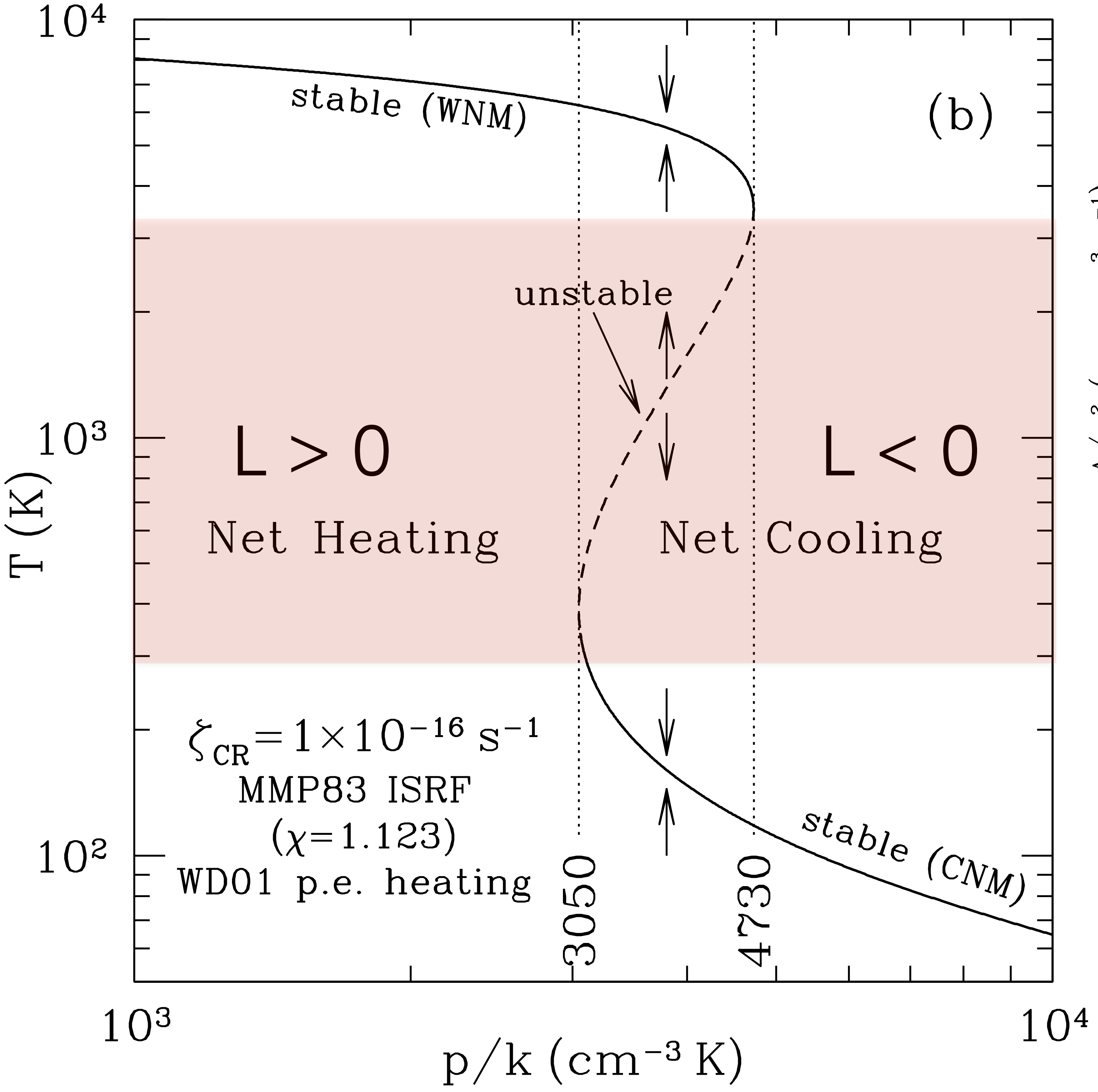
$\Gamma \sim n\,\zeta$ ← insensitive to T

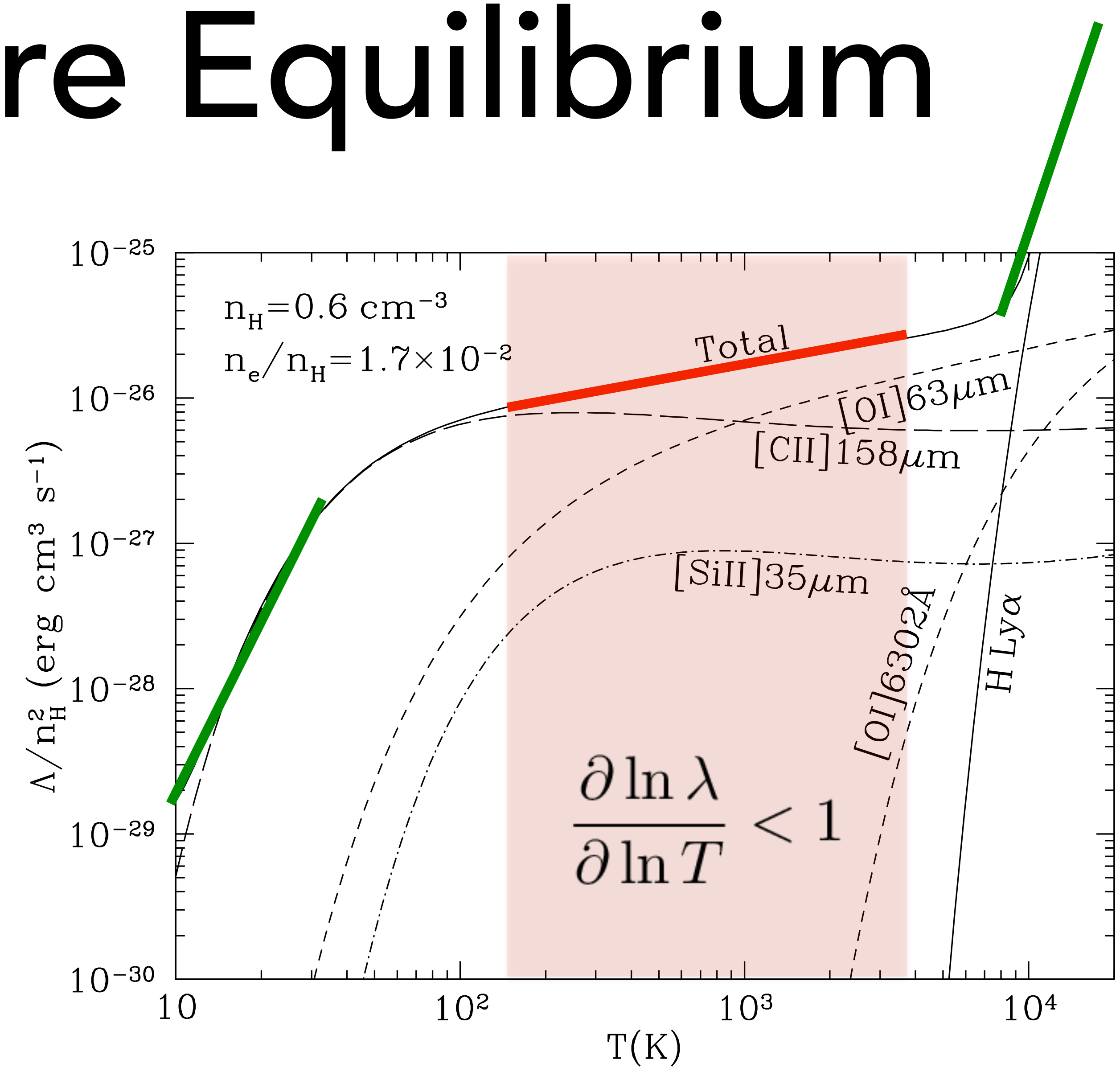
$\Lambda \sim n^2\,\lambda(T)$ const ← sensitive to T

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

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

Phases in Pressure Equilibrium



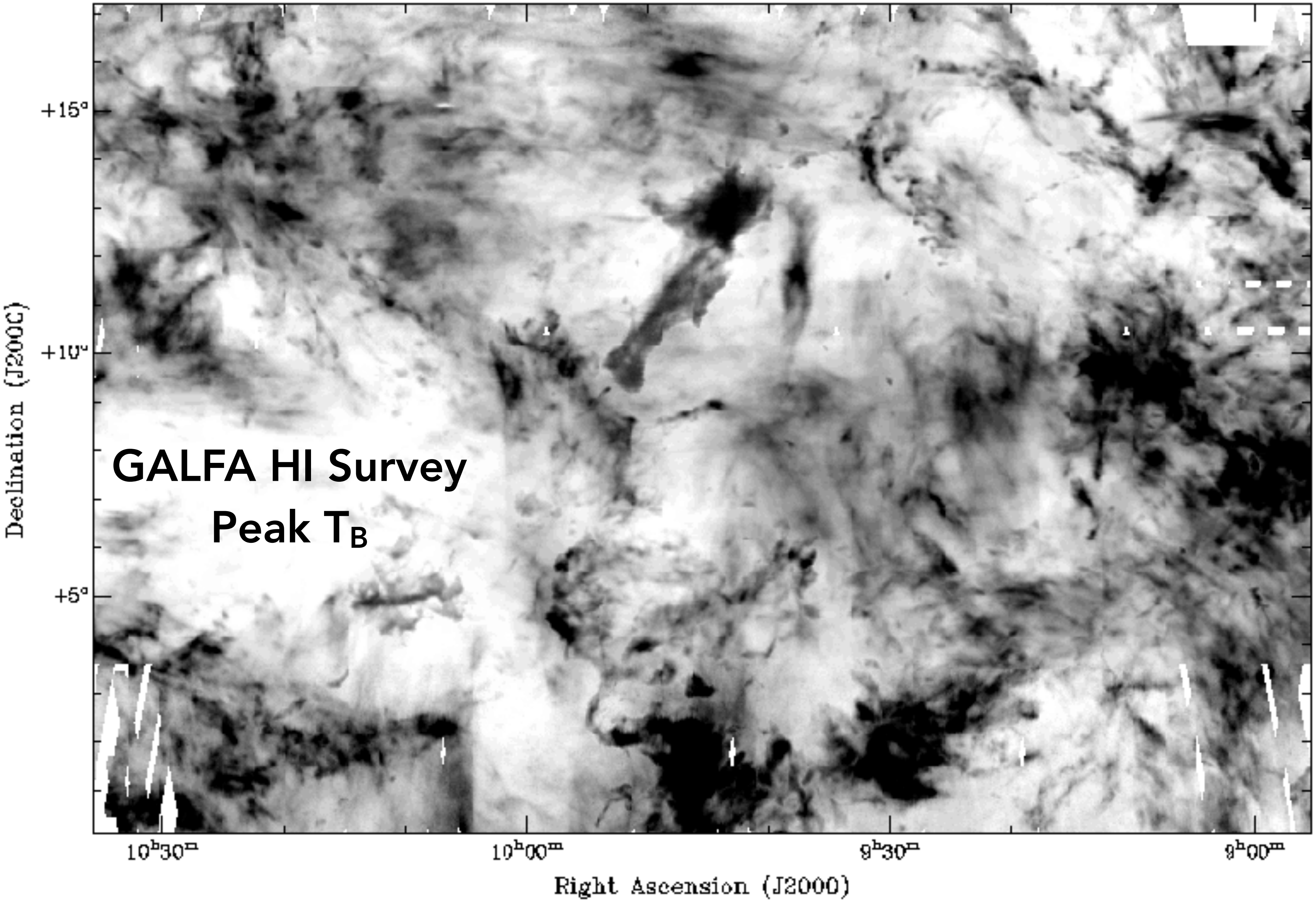


<u>[CII] 158 μm drives this behavior</u>

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

Is the FGH model a good representation of the ISM?

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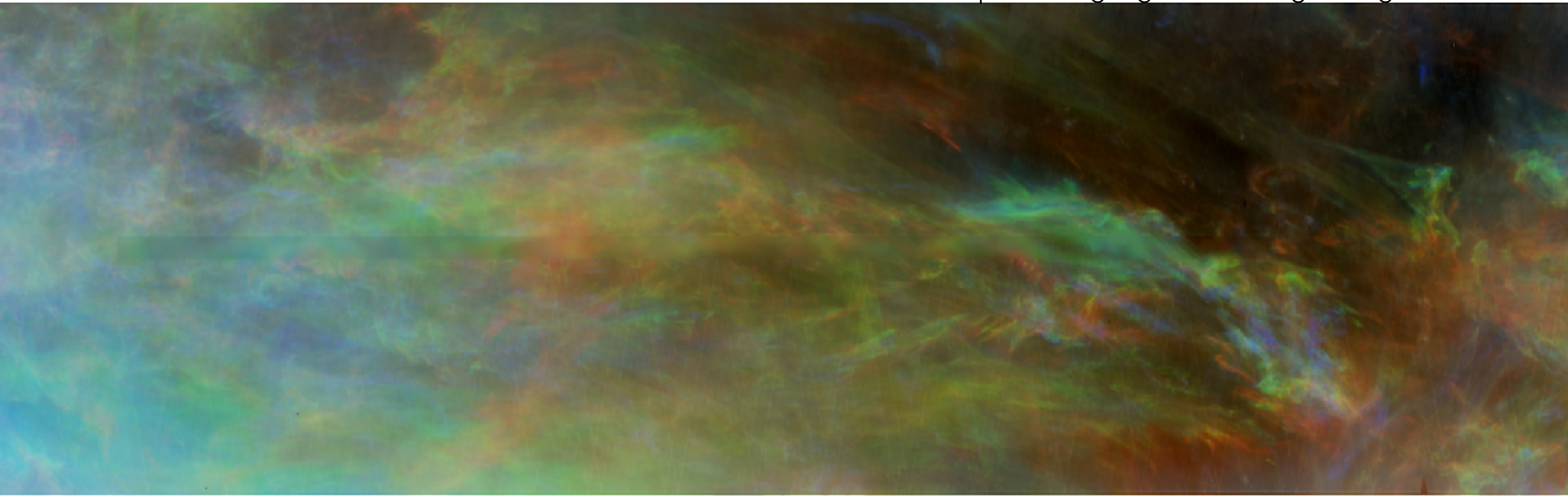


part of the GALFA HI Survey
colors = different velocity ranges

Is the FGH model a good representation of the ISM?

Do we expect to find much gas in the unstable region?

Compare thermal and dynamical timescales:

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

← thermal energy density = pressure

← cooling rate per unit volume

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

τ_{cool} ~ 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 in the unstable region?

Compare thermal and dynamical timescales:

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

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

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

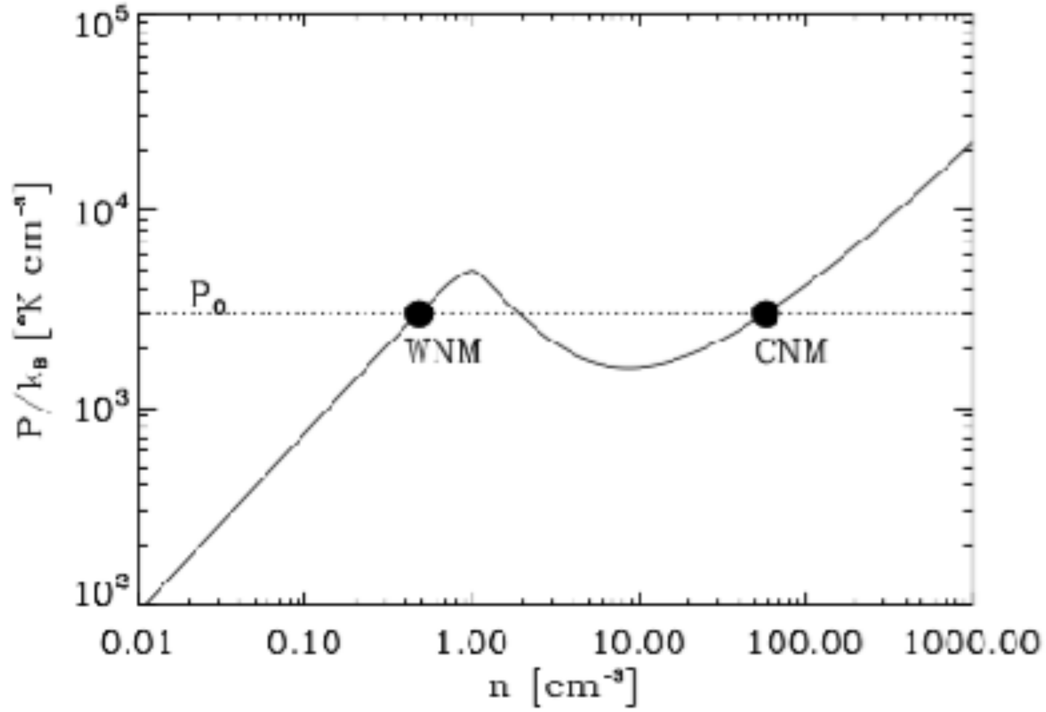
For L~10 pc, T~2000 K

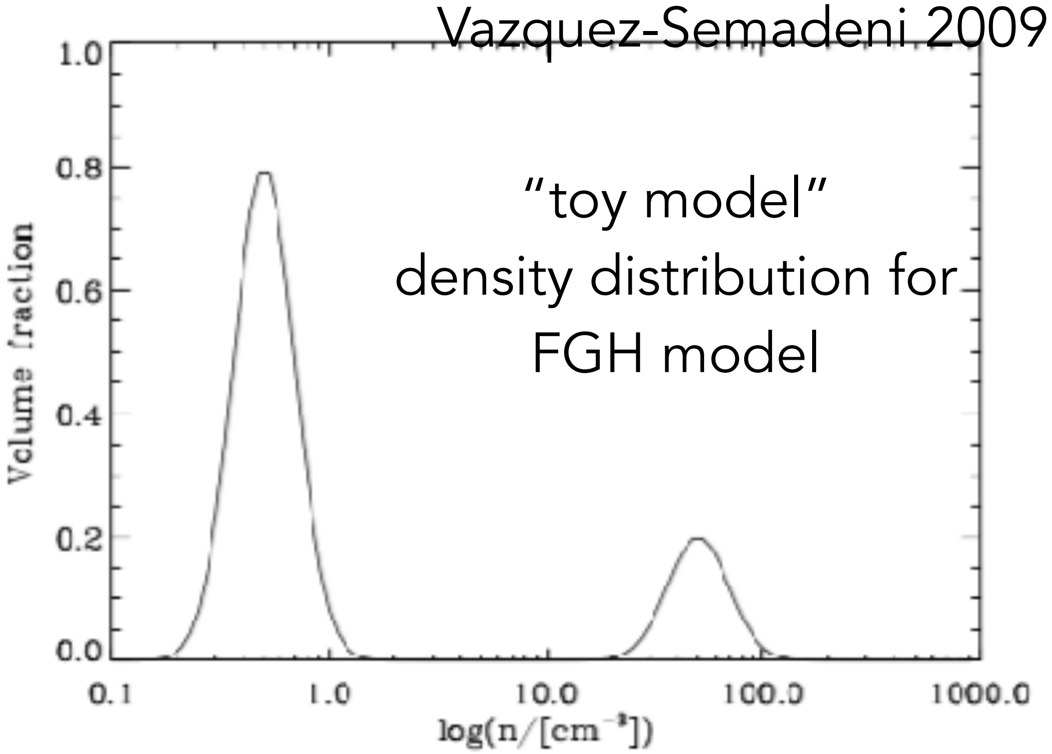
$\tau_{\rm dyn}$ ~ 1.5 Myr

Unstable gas should cool quickly relative to dynamical time.

Is the FGH model a good representation of the ISM?

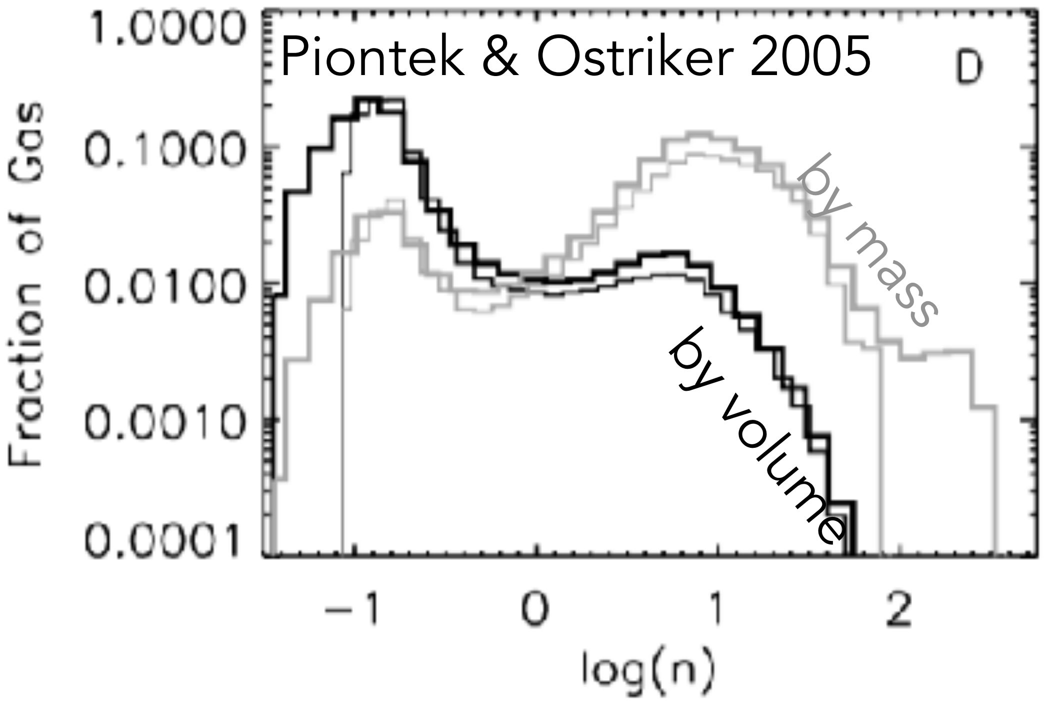
Vazquez-Semadeni 2009





"toy model"
density distribution for
FGH model

Simulations with turbulence suggest substantial amounts of gas between F&H phases



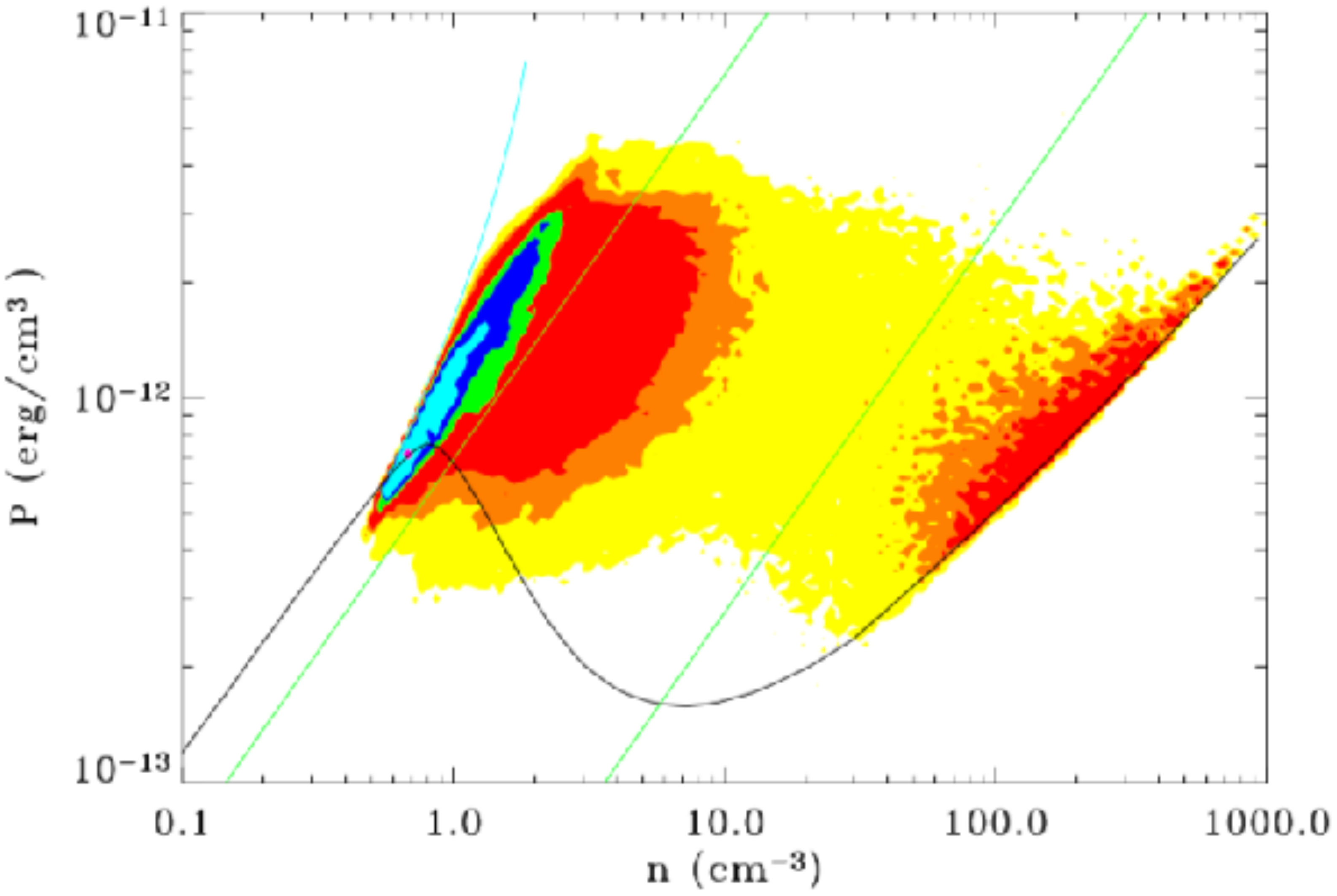
Piontek & Ostriker 2005

by mass

by volume

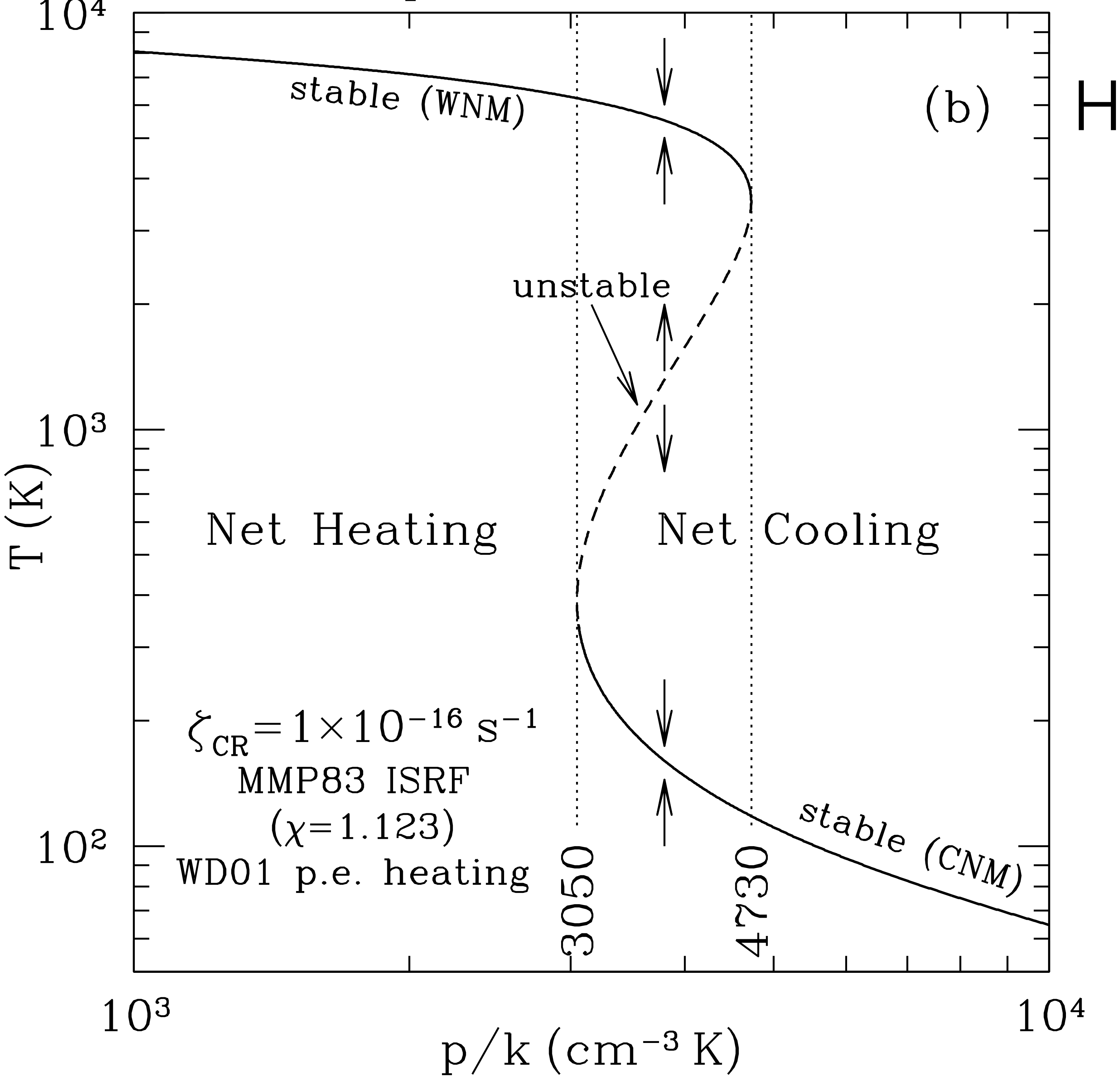
Is the FGH model a good representation of the ISM?

Audit & Hennebelle 2005



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

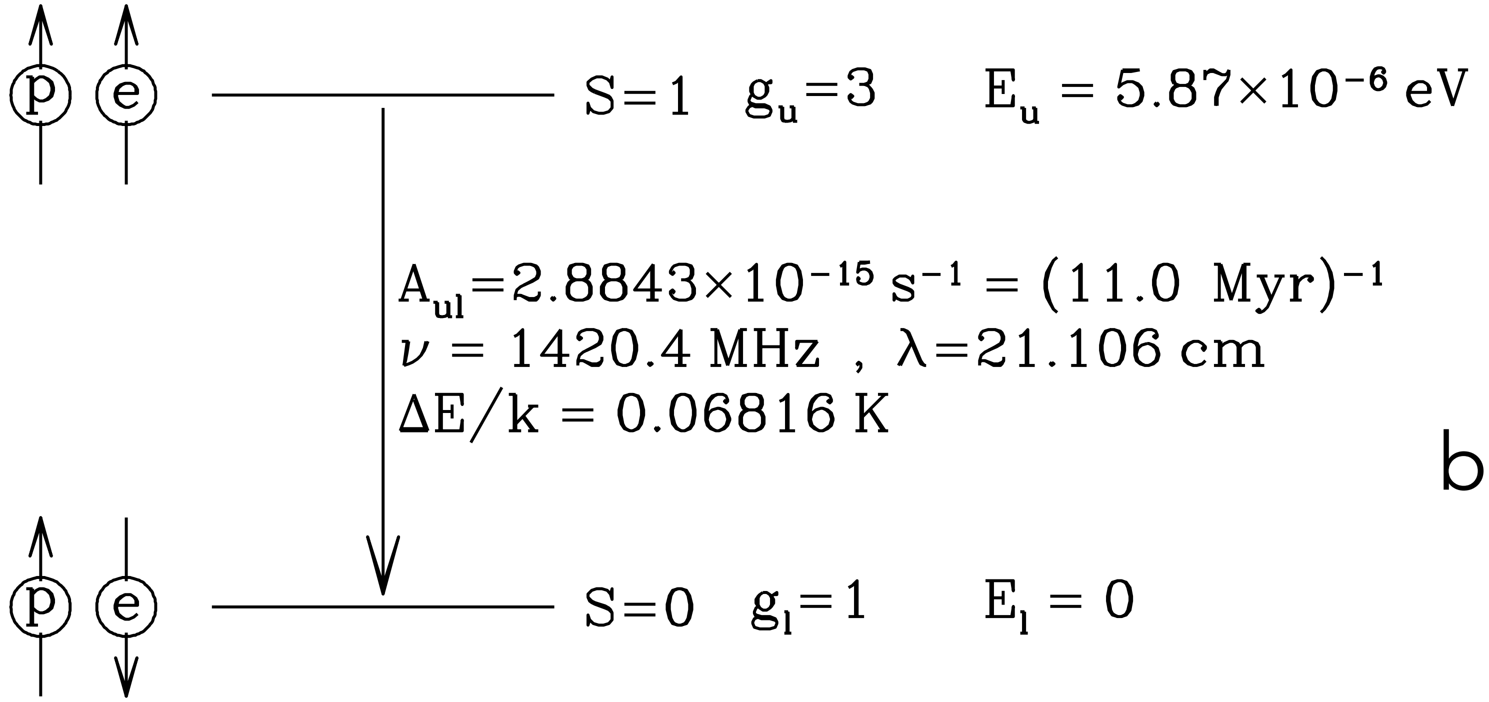
Is the FGH model a good representation of the ISM?



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.

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

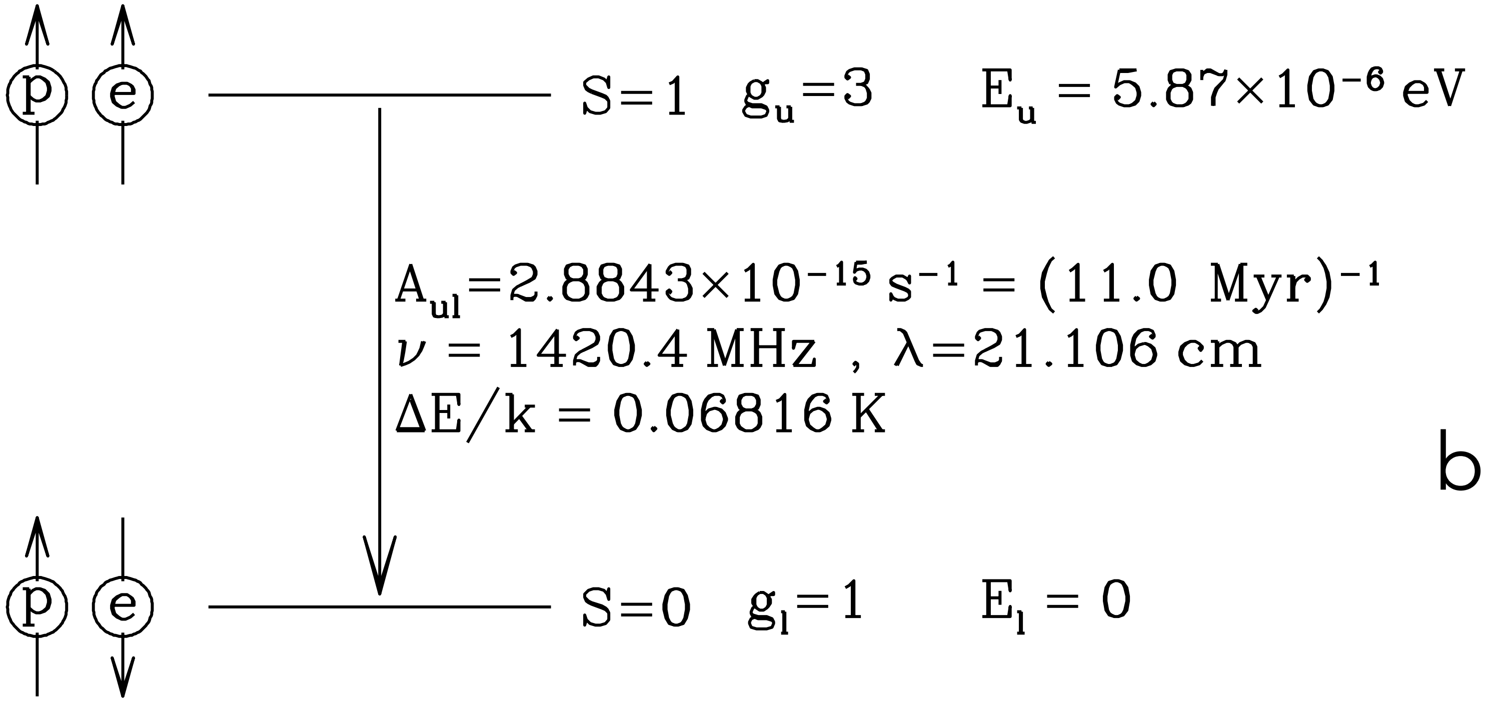
$S=0 \quad g_l=1 \qquad E_l = 0$

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

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



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

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ν = 1420.4 MHz , λ=21.106 cm
$\Delta E/k$ = 0.06816 K

S=0 $g_l=1$ $E_l = 0$

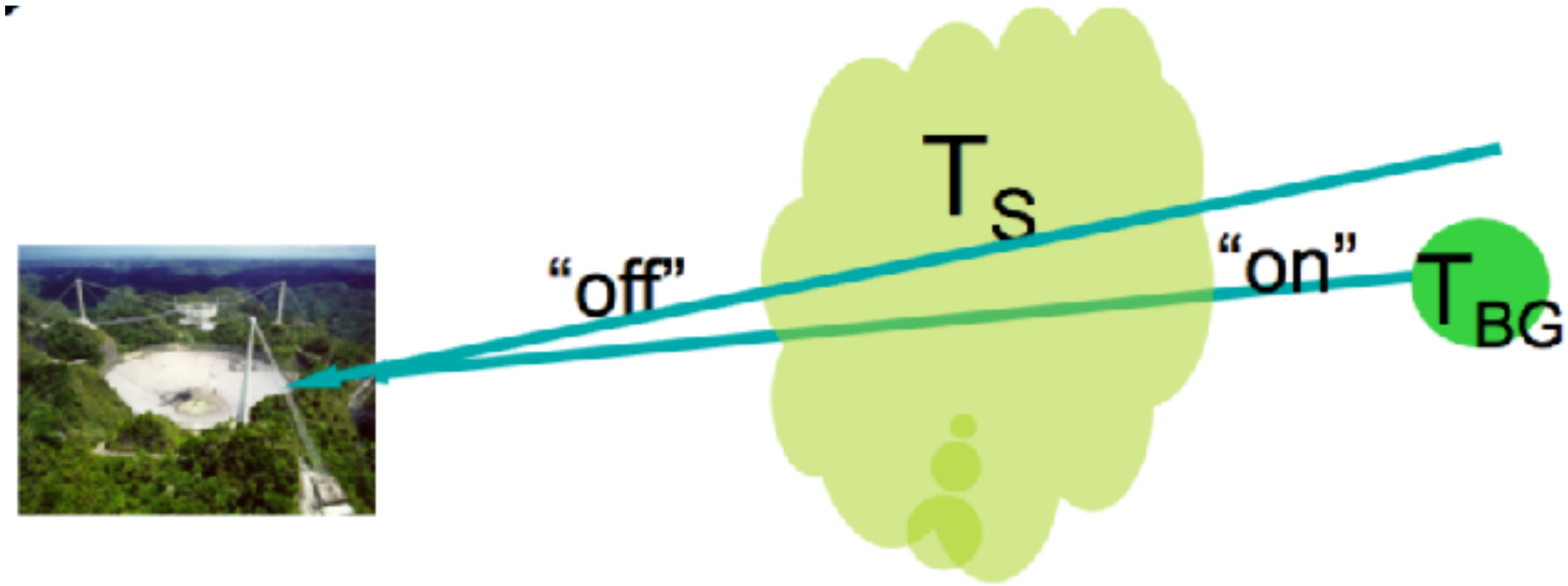
$T_{exc} \equiv T_{spin} \gg 0.0682$ K
because cosmic microwave
background can populate levels

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

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

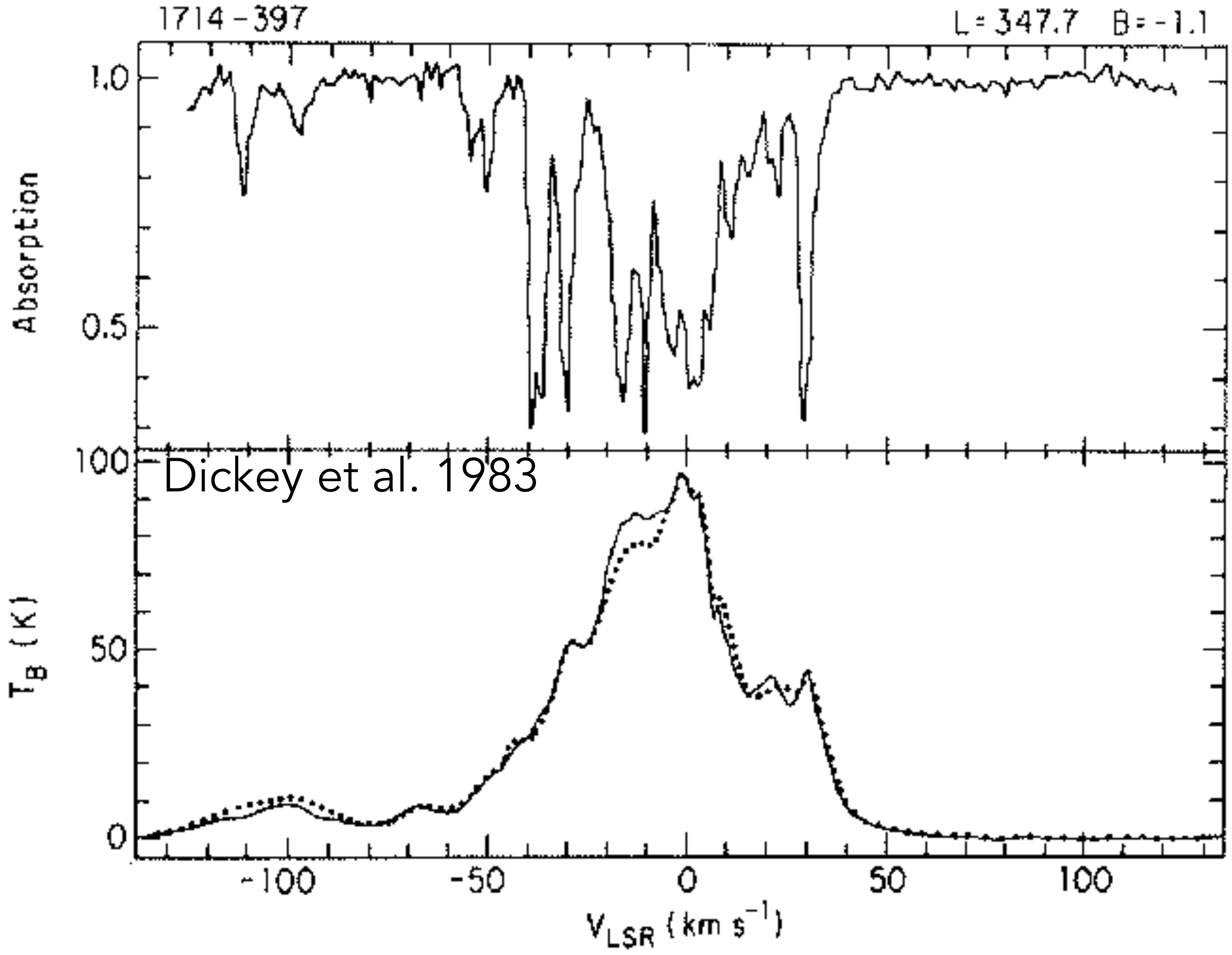
HI Spin Temperature

Measuring spin temperature



$$T_b^{on} = T_{bg} e^{-\tau} + T_s(1 - e^{-\tau})$$
$$T_b^{off} = T_s(1 - e^{-\tau}) \quad (1)$$

HI Spin Temperature



Dickey et al. 1983

Absorption - weighted to low T

Emission - independent of T

$\langle T_{spin} \rangle = T_B/(1-e^{-\tau})$