Physics 224
The Interstellar Medium

Lecture #11: Dust Composition, Neutral Gas

Outline

- Part I: Dust Composition
- Part II: "ISM Phases"
- Part III: Neutral Gas Heating & Cooling
- Part IV: Neutral Gas Observations

What is dust made of?

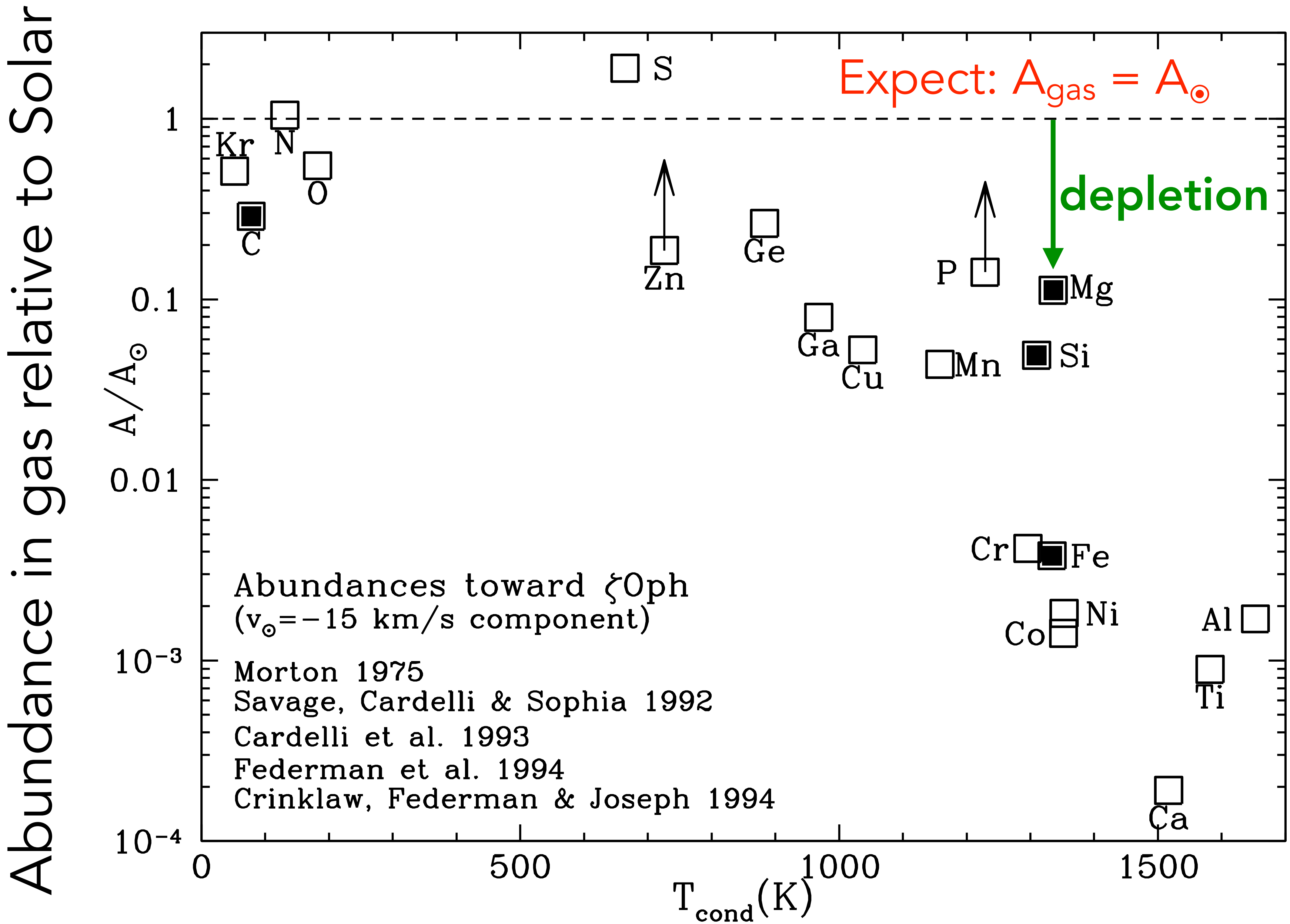
Dust Composition

✓ • Spectroscopic features in absorption

✓ • Spectroscopic features in emission

• Depletions of heavy elements from the gas

Depletions


Abundance in gas relative to Solar
Expect: $A_{gas} = A_{\odot}$
depletion
$A/A_{\odot}$
1
0.1
0.01
10^{-3}
10^{-4}
0
500
1000
1500
$T_{cond}(K)$
S
Kr
N
O
C
Zn
Ge
Ga
Cu
Mn
P
Mg
Si
Cr
Fe
Ni
Co
Al
Ti
Ca
Abundances toward ζOph
($v_{\odot}$=−15 km/s component)
Morton 1975
Savage, Cardelli & Sophia 1992
Cardelli et al. 1993
Federman et al. 1994
Crinklaw, Federman & Joseph 1994

Depletions

THE ASTROPHYSICAL JOURNAL, 700:1299–1348, 2009 August 1 doi:10.1088/0004-637X/700/2/1299

A UNIFIED REPRESENTATION OF GAS-PHASE ELEMENT DEPLETIONS IN THE INTERSTELLAR MEDIUM*

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Received 2009 February 23; accepted 2009 June 1; published 2009 July 13

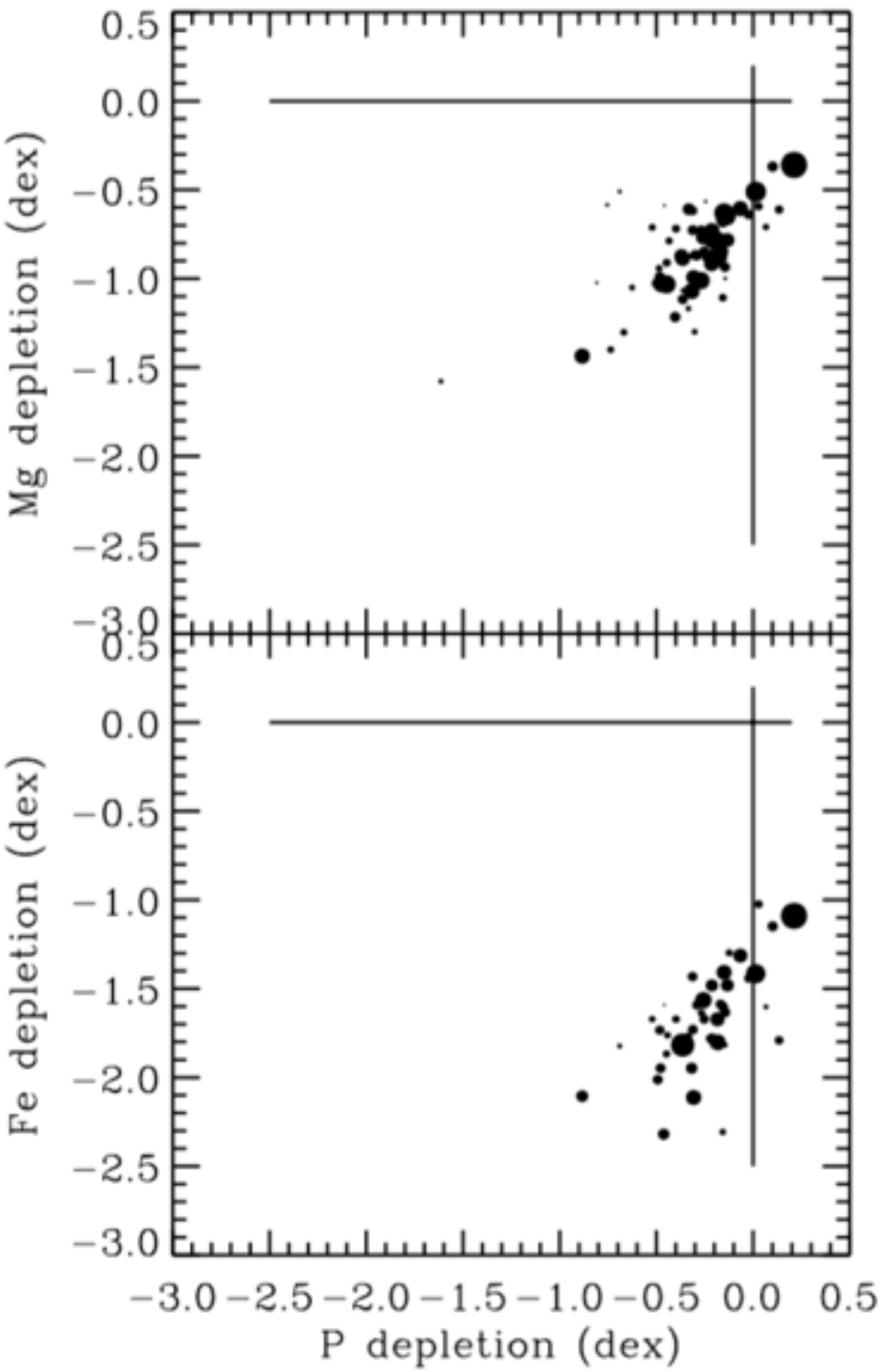
ABSTRACT

A study of gas-phase element abundances reported in the literature for 17 different elements sampled over 243 sight lines in the local part of our Galaxy reveals that the depletions into solid form (dust grains) are extremely well characterized by trends that employ only three kinds of parameters. One is an index that describes the overall level of depletion applicable to the gas in any particular sight line, and the other two represent linear coefficients that describe how to derive each element's depletion from this sight-line parameter. The information from this study reveals the relative proportions of different elements that are incorporated into dust at different stages of grain growth. An extremely simple scheme is proposed for deriving the dust contents and metallicities of absorption-line systems that are seen in the spectra of distant quasars or the optical afterglows of gamma-ray bursts. Contrary to presently accepted thinking, the elements sulfur and krypton appear to show measurable changes in their depletions as the general levels of depletions of other elements increase, although more data are needed to ascertain whether or not these findings are truly compelling. Nitrogen appears to show no such increase. The incorporation of oxygen into solid form in the densest gas regions far exceeds the amounts that can take the form of silicates or metallic oxides; this conclusion is based on differential measurements of depletion and thus is unaffected by uncertainties in the solar abundance reference scale.

Key words: ISM: abundances – ISM: atoms – ultraviolet: ISM

Online-only material: machine-readable tables

Depletions



Jenkins 2009:

compiled depletion measurements for 17 elements on ~250 lines-of-sight

Model for depletions includes:

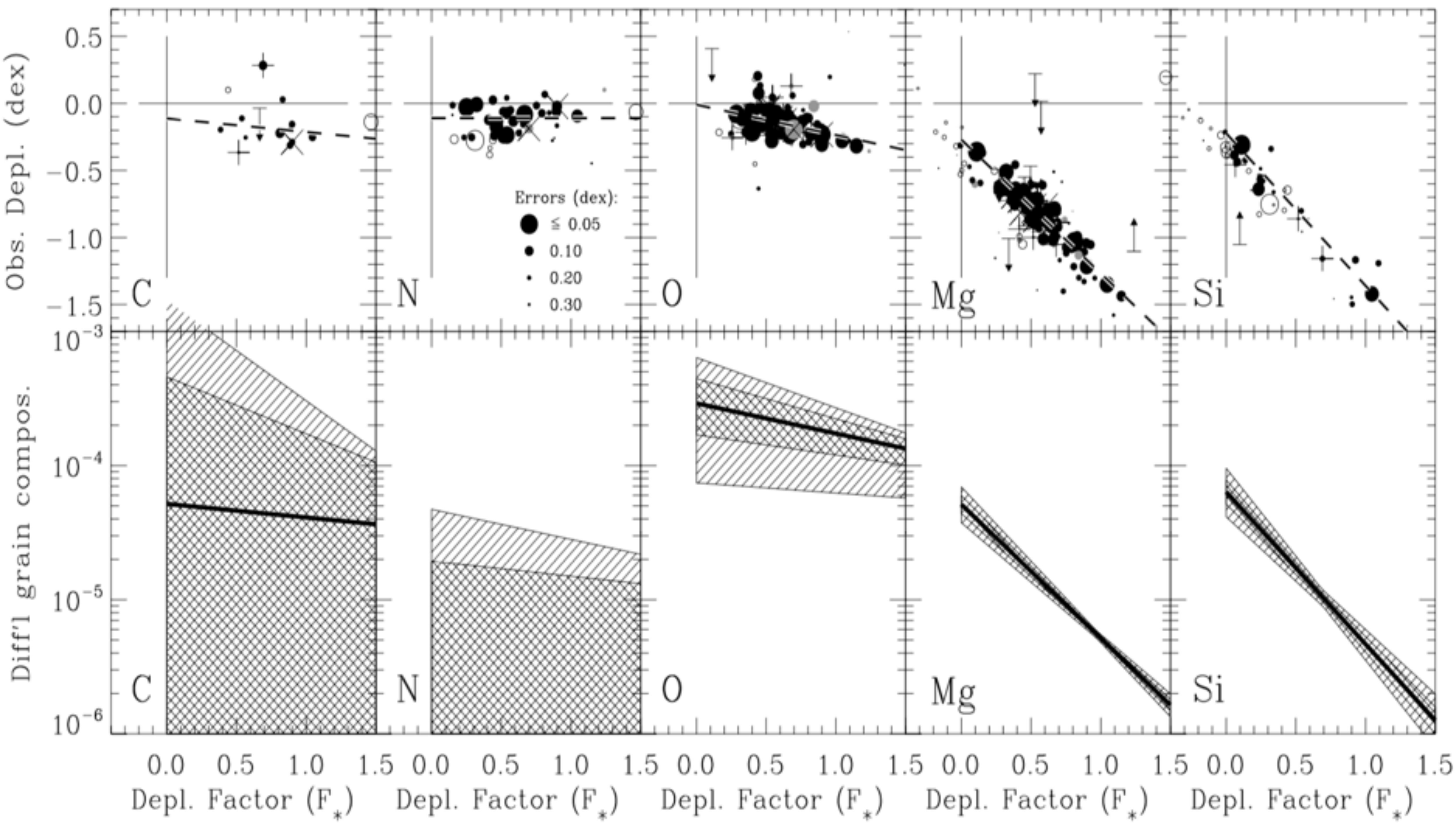
$F_\star$ = parameterization of overall depletion

$[X_{gas}/H]_0$ = “baseline” or “initial” depetion

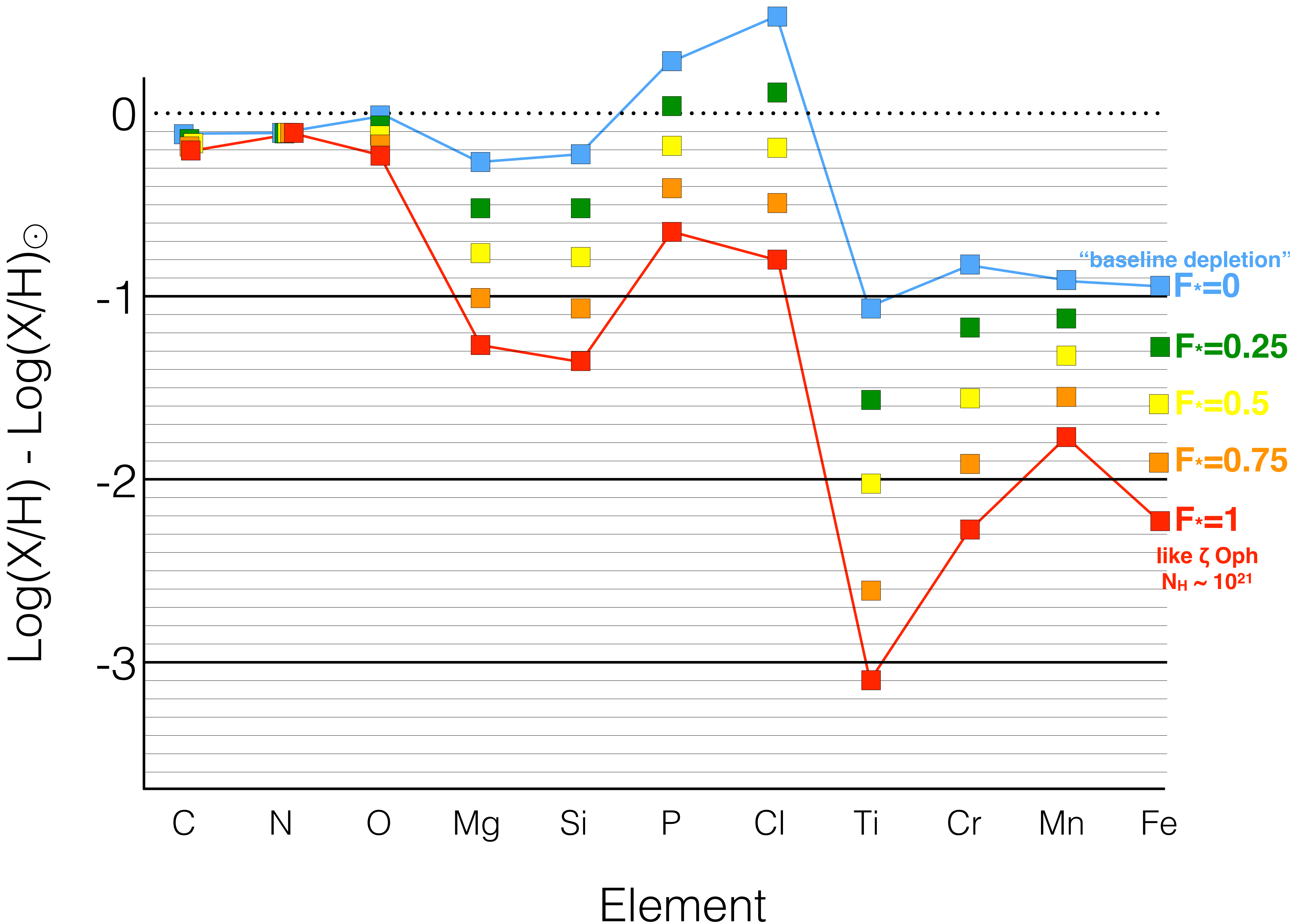
A_X = depletion rate for element X as a function of $F_\star$

$$[X_{\rm gas}/{\rm H}]_{\rm fit} = [X_{\rm gas}/{\rm H}]_0 + A_X F_*$$

Depletions

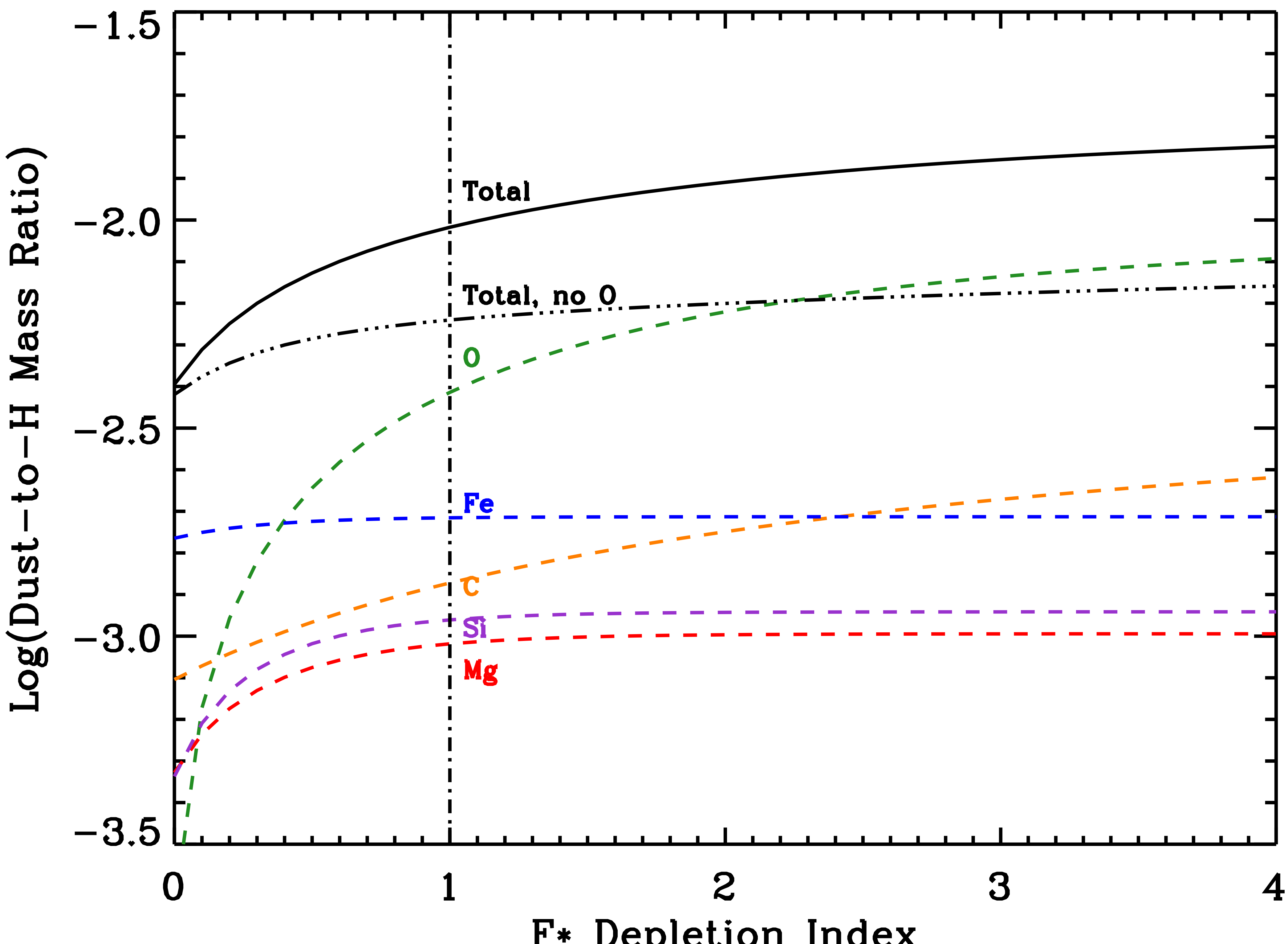


Obs. Depl. (dex)
0.5
0.0
−0.5
−1.0
−1.5
C
N
O
Mg
Si
Errors (dex):
≤ 0.05
0.10
0.20
0.30
Diff'l grain compos.
10−3
10−4
10−5
10−6
0.0 0.5 1.0 1.5
Depl. Factor (F*)

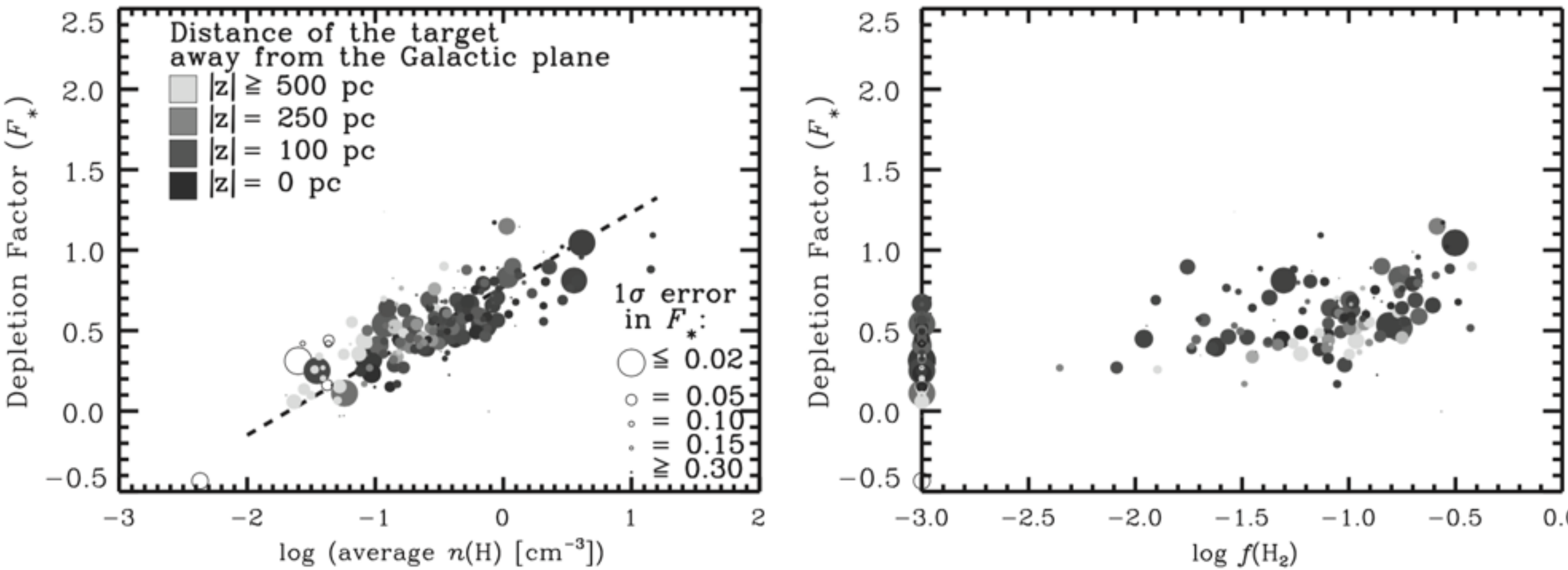


Log(X/H) - Log(X/H)⊙
0
-1
-2
-3
C
N
O
Mg
Si
P
Cl
Ti
Cr
Mn
Fe
Element
"baseline depletion"
F*=0
F*=0.25
F*=0.5
F*=0.75
F*=1
like ζ Oph
NH ~ 10^21

Dust Composition



Dust Composition



The observation that F⋆ depends on density and H2 fraction shows us that grains evolve in the ISM.

Dust is Awesome.

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	$0.2\text{-}10^4$	$2000 - 10^8$
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}	$10^3\text{-}10^6$	$10^5 - 10^7$

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

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 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

- H & He
- H & He
- C, O, Ne, Mg, Si (IP < 13.6 eV)
- Dust

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
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energy yield per interaction

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Heating:

- Cosmic Ray Ionization
- Photoionization of H & He
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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

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

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

energy yield per interaction

* Integrate this over the distribution of collider energies

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

Heating:

- Cosmic Ray Ionization
- Photoionization of H & He
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- Photoelectric effect from 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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energy yield per interaction

* Integrate this over the distribution of collider energies

Heating:

- Cosmic Ray Ionization
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- 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 $\sim n^2$

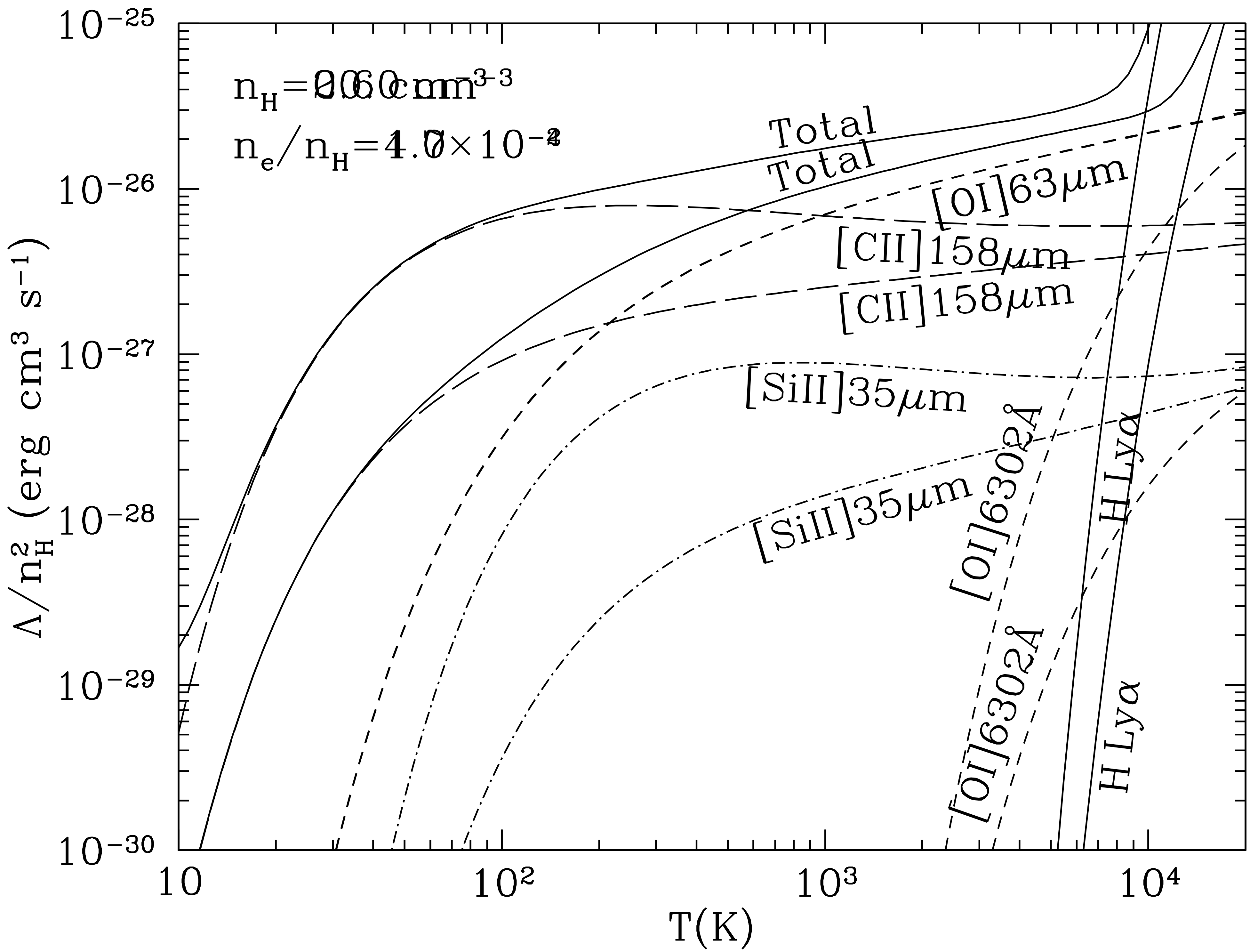
$\Lambda \sim n^2 \, \lambda(T)$ const

function of gas temperature

quantum mechanics

Cooling:

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



n_H=0.60 cm^{-3}
n_e/n_H=1.7×10^{-2}
Total
Total
[OI]63μm
[CII]158μm
[CII]158μm
[SiII]35μm
[SiII]35μm
[OI]6302Å
[OI]6302Å
H Lyα
H Lyα
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10
10^2
10^3
10^4
T(K)
Λ/n_H^2 (erg cm^3 s^{-1})

Phases in Pressure Equilibrium

net heating or cooling

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

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

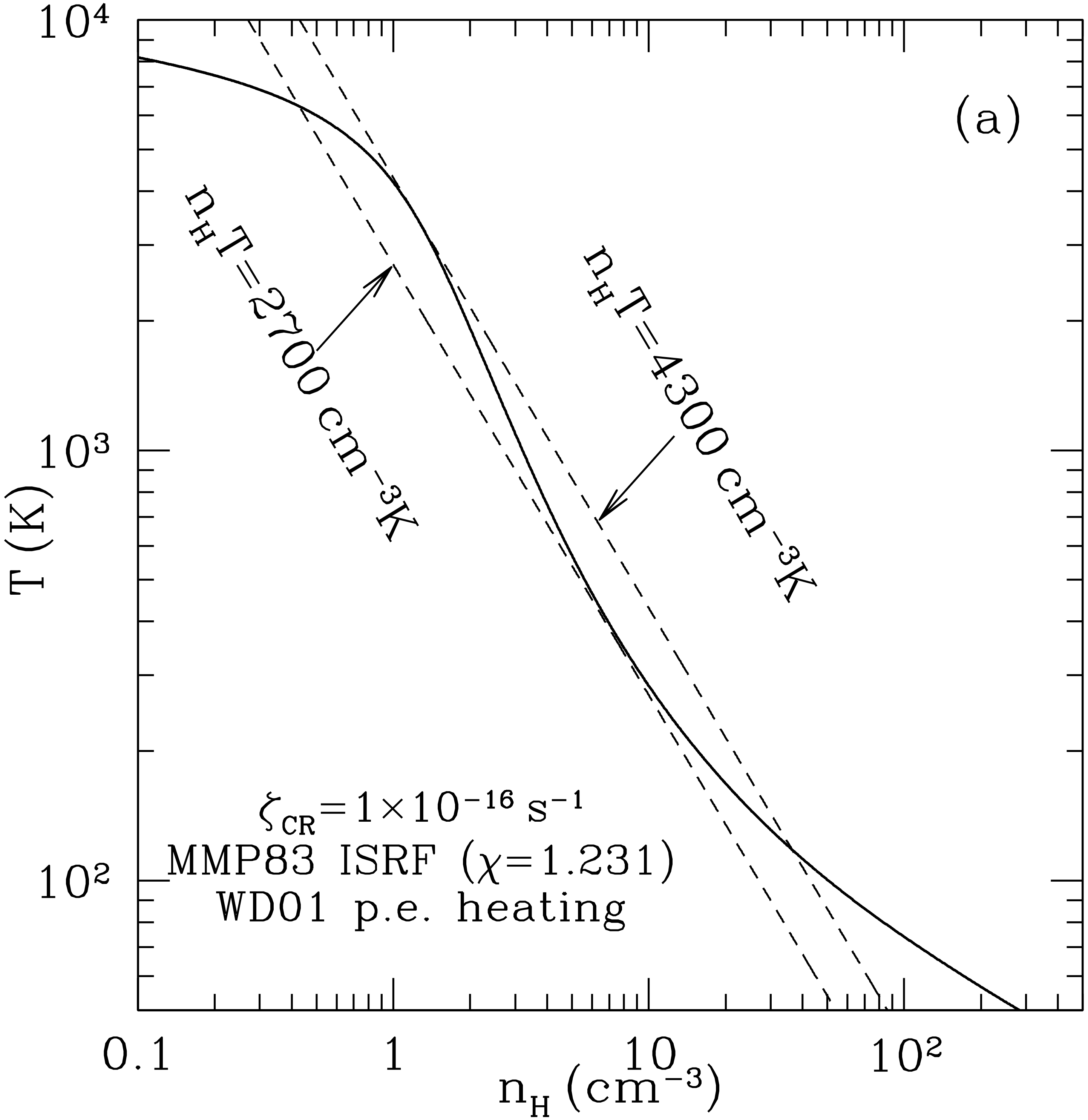
Recall:

$\Gamma \sim n\,\zeta$ ← 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

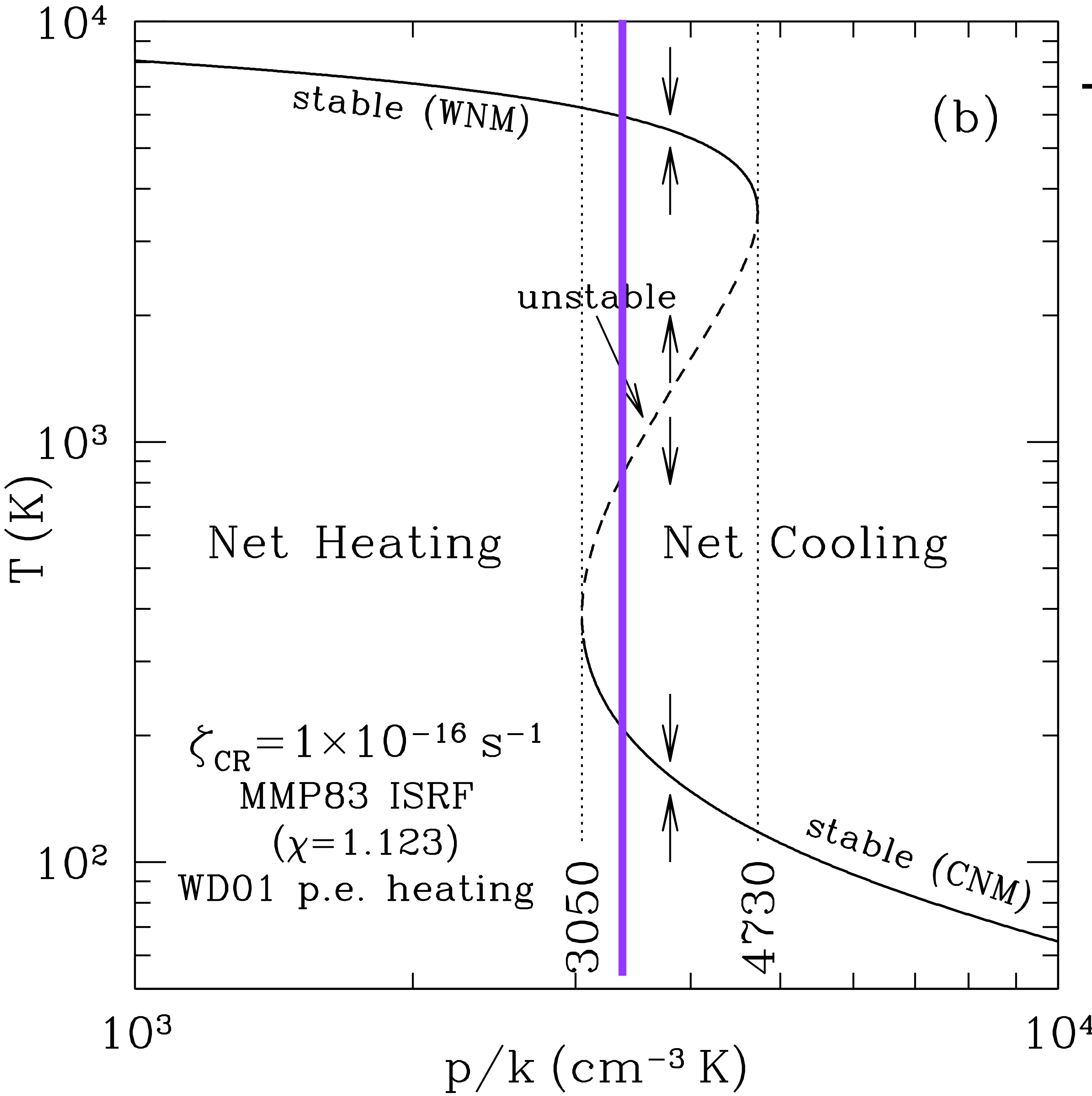


Solid line is L(n,T) = 0 heating/cooling equilibrium

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:

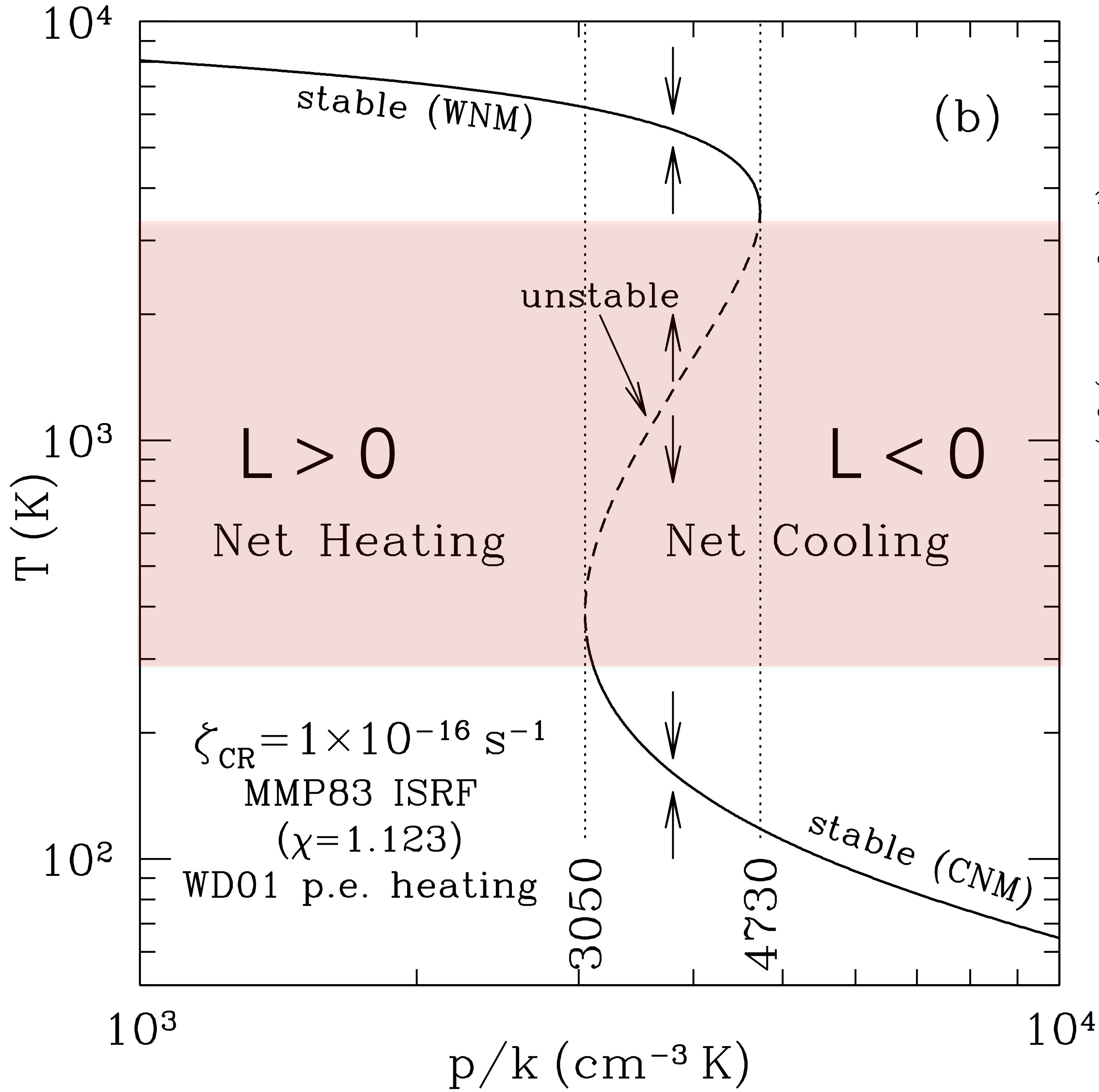
$\Gamma \sim n\,\zeta$ ← insensitive to T

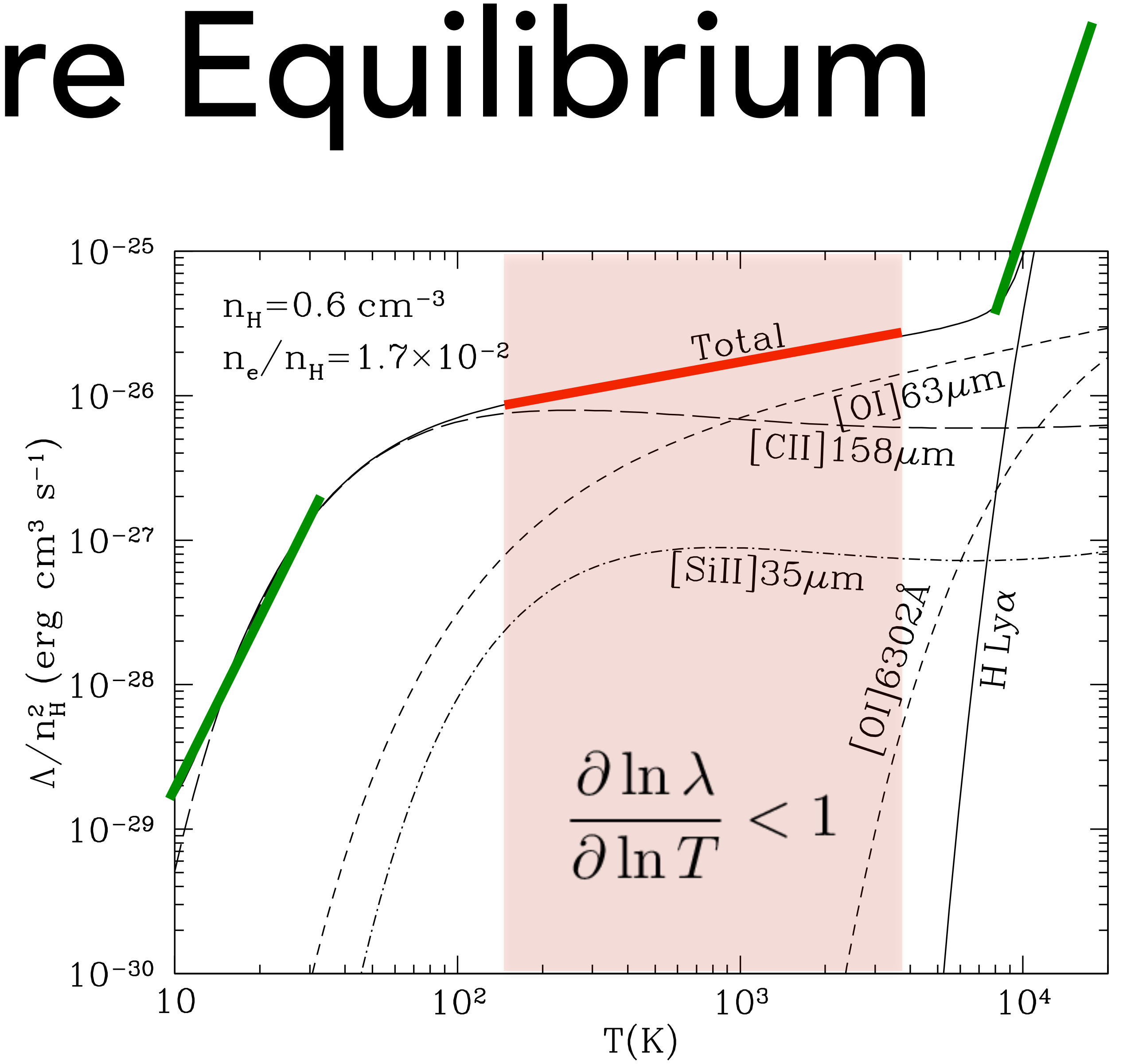
$\Lambda \sim n^2\,\lambda(T)$ const ← sensitive to T

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



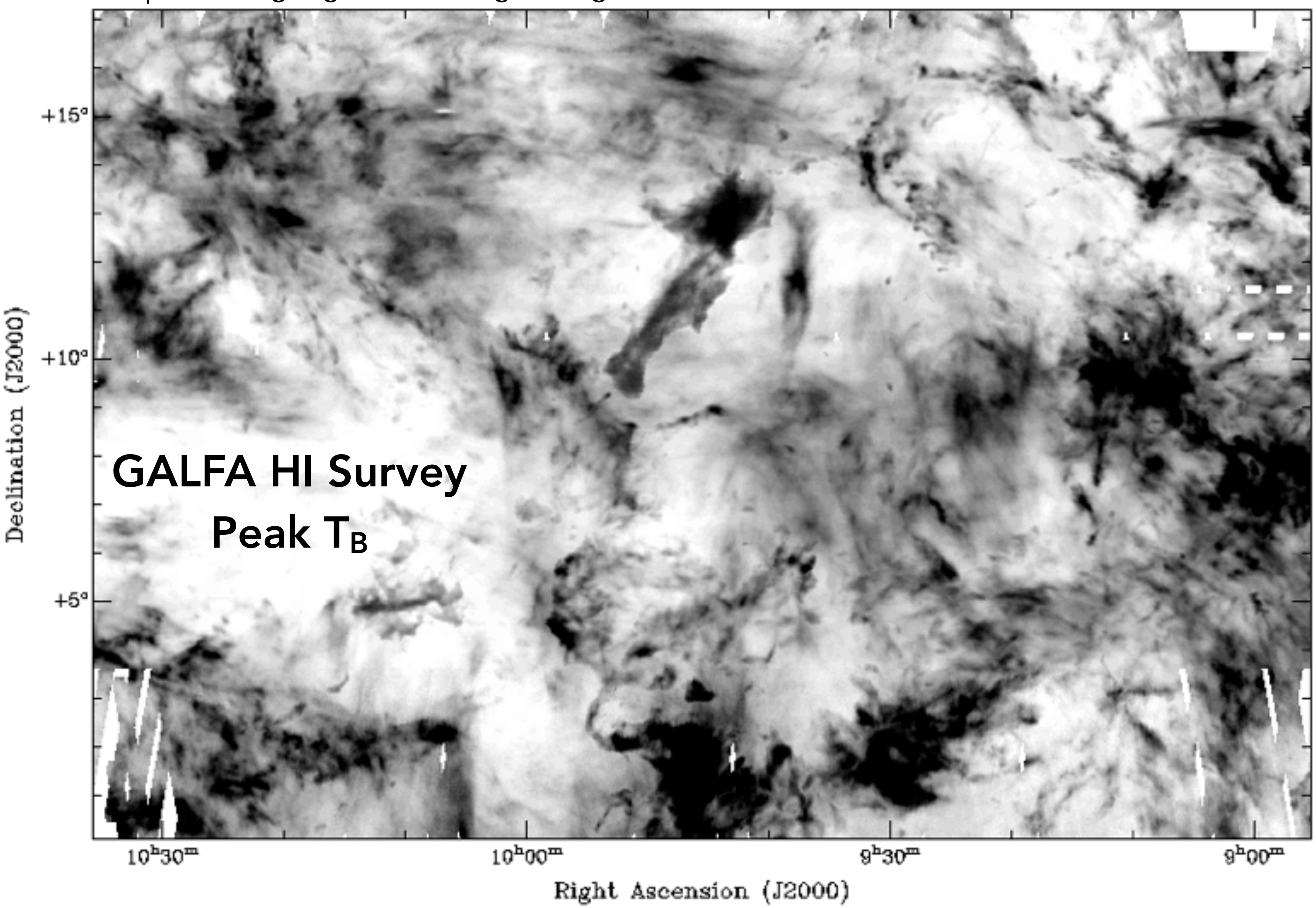


<u>[CII] 158 μm drives this behavior</u>

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

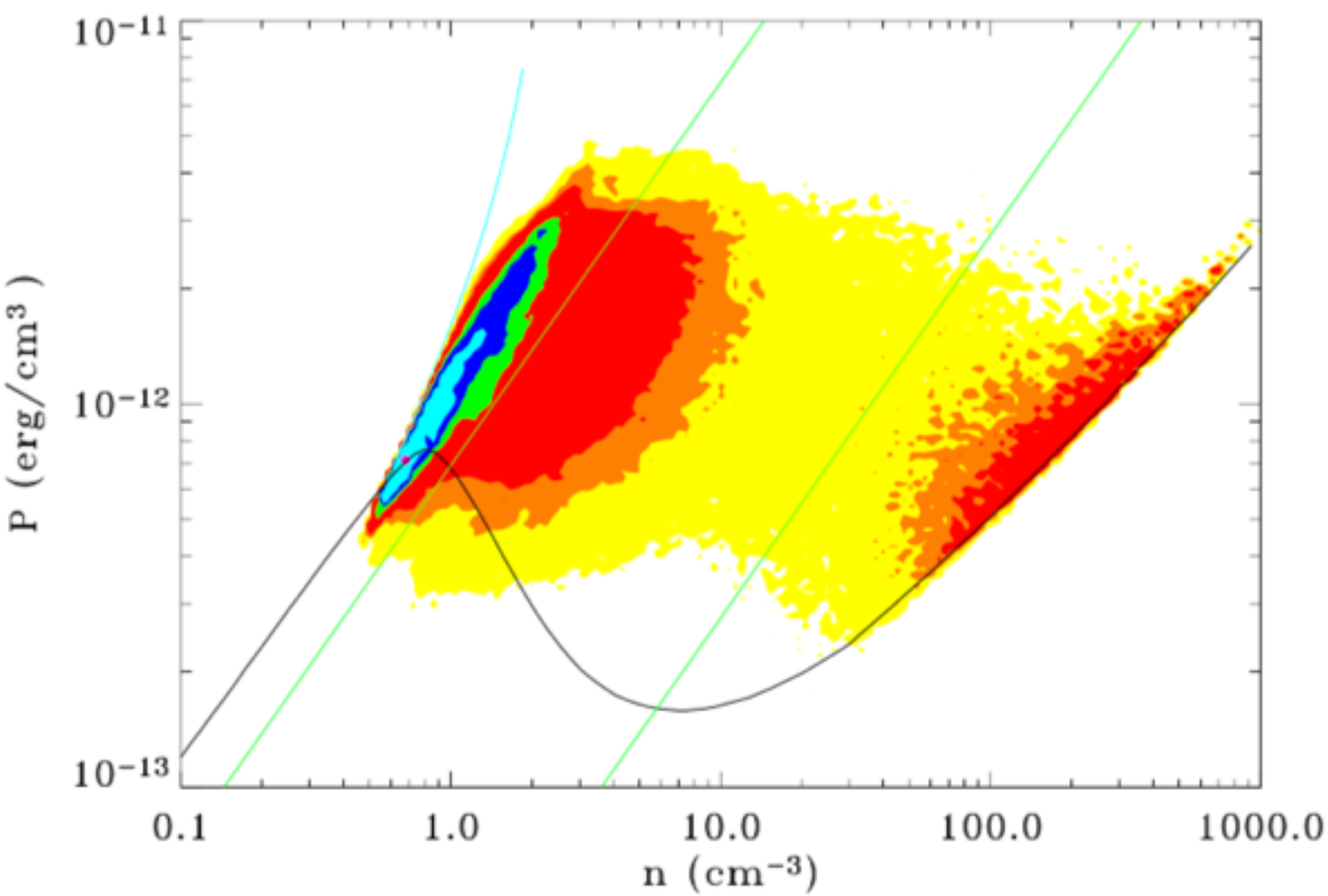
Is the FGH model a good representation of the ISM?

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



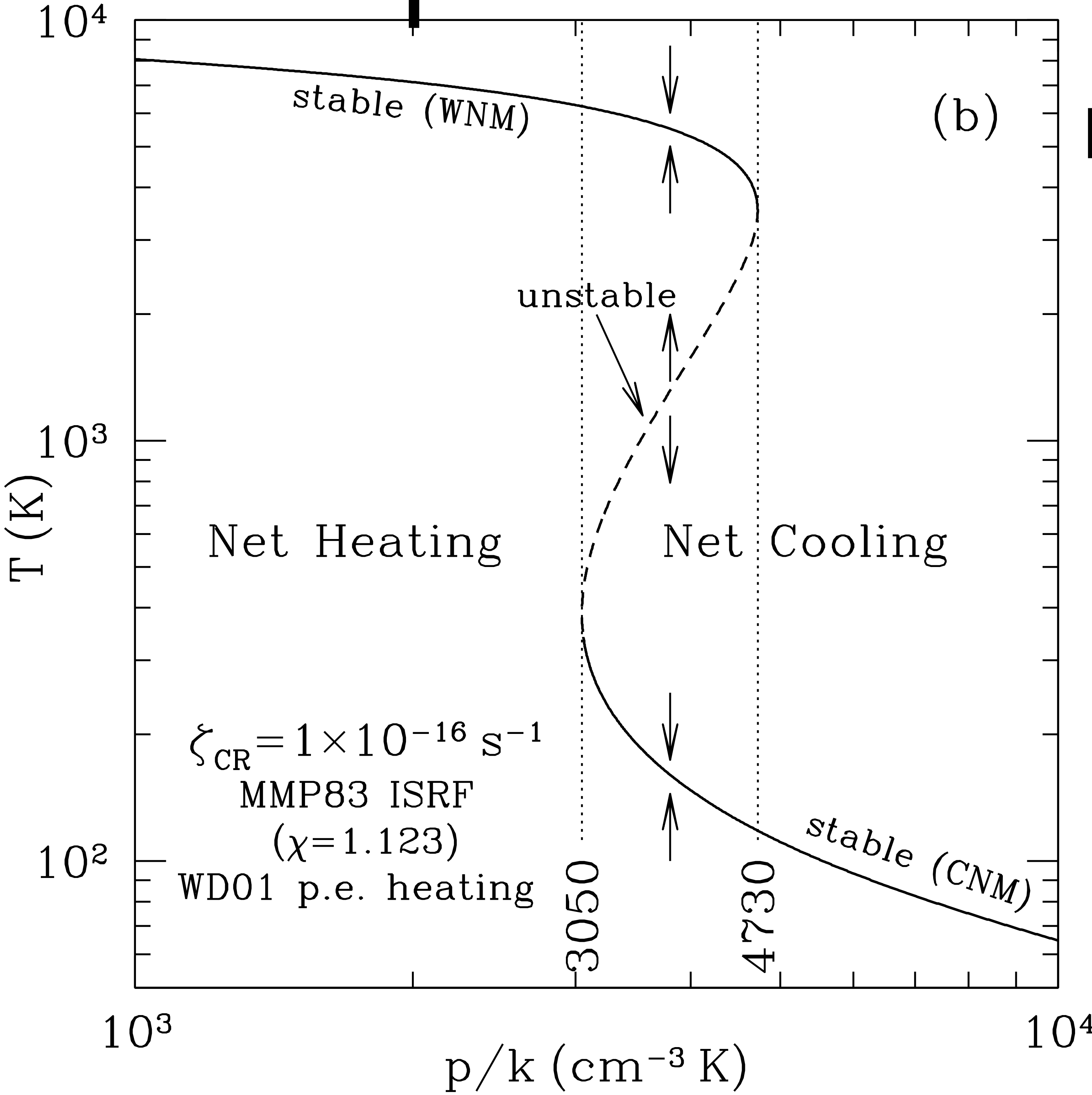
Is the FGH model a good representation of the ISM?

Audit & Hennebelle 2005



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

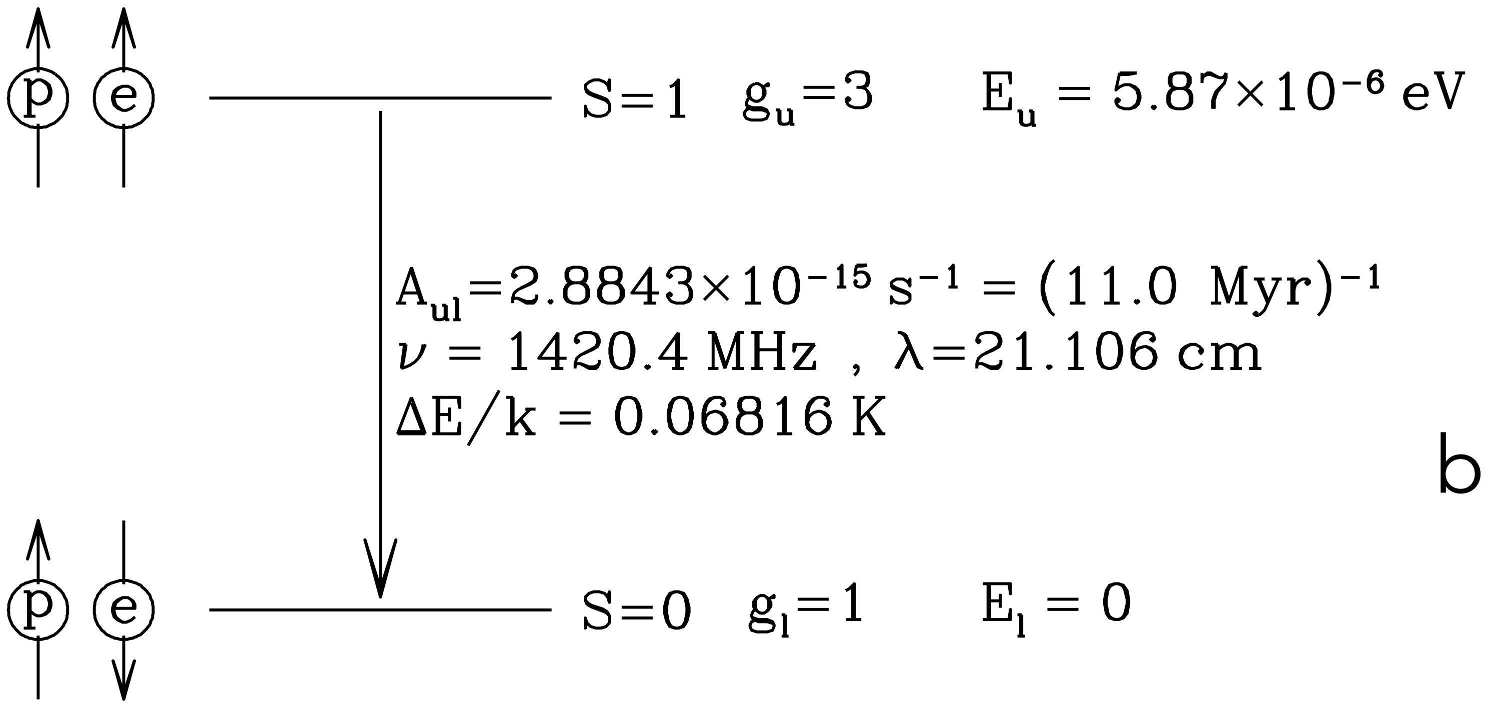
Is the FGH model a good representation of the ISM?



How can we test this model?

Measure the spin temperature of HI and see how much falls in the unstable area

HI Spin Temperature Review



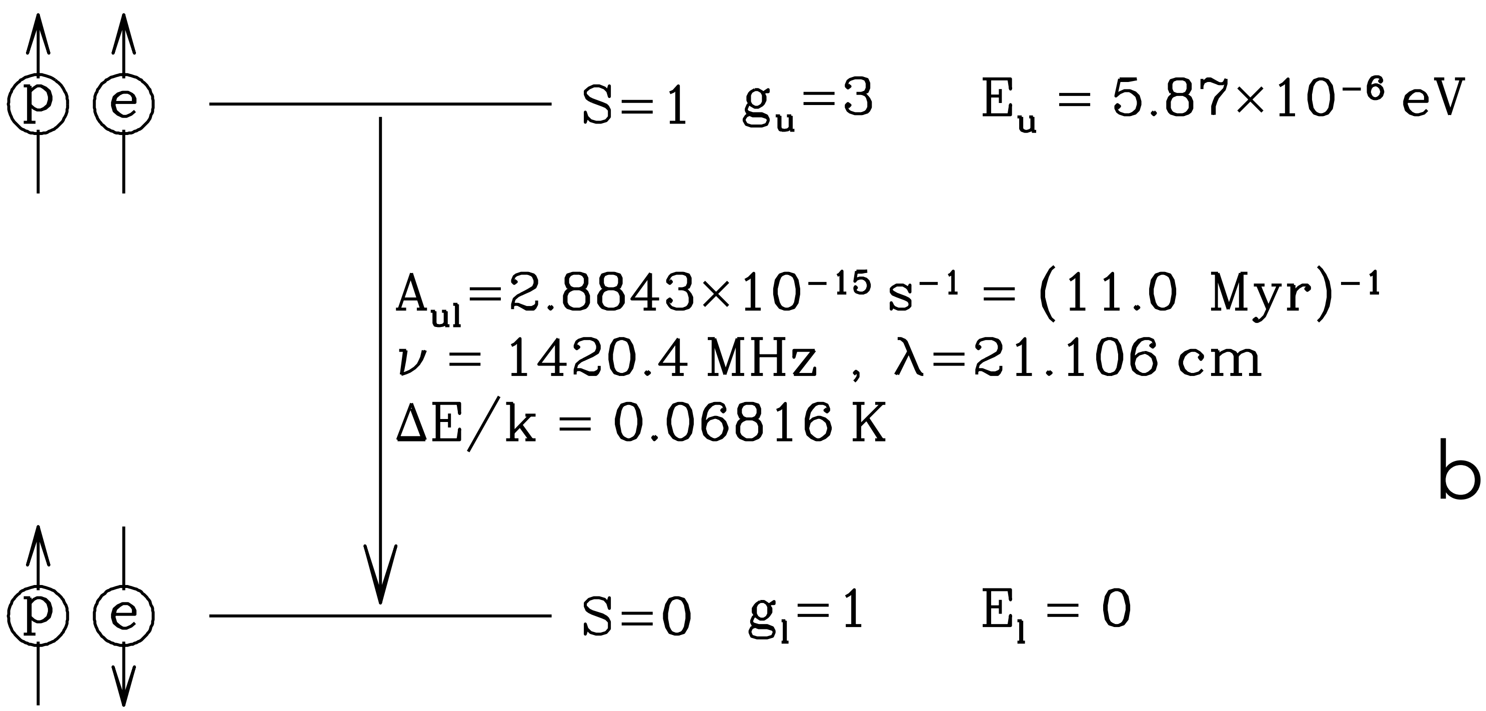
$T_{exc} \equiv T_{spin} \gg 0.0682$ K because cosmic microwave background can populate levels

Under all 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 Review



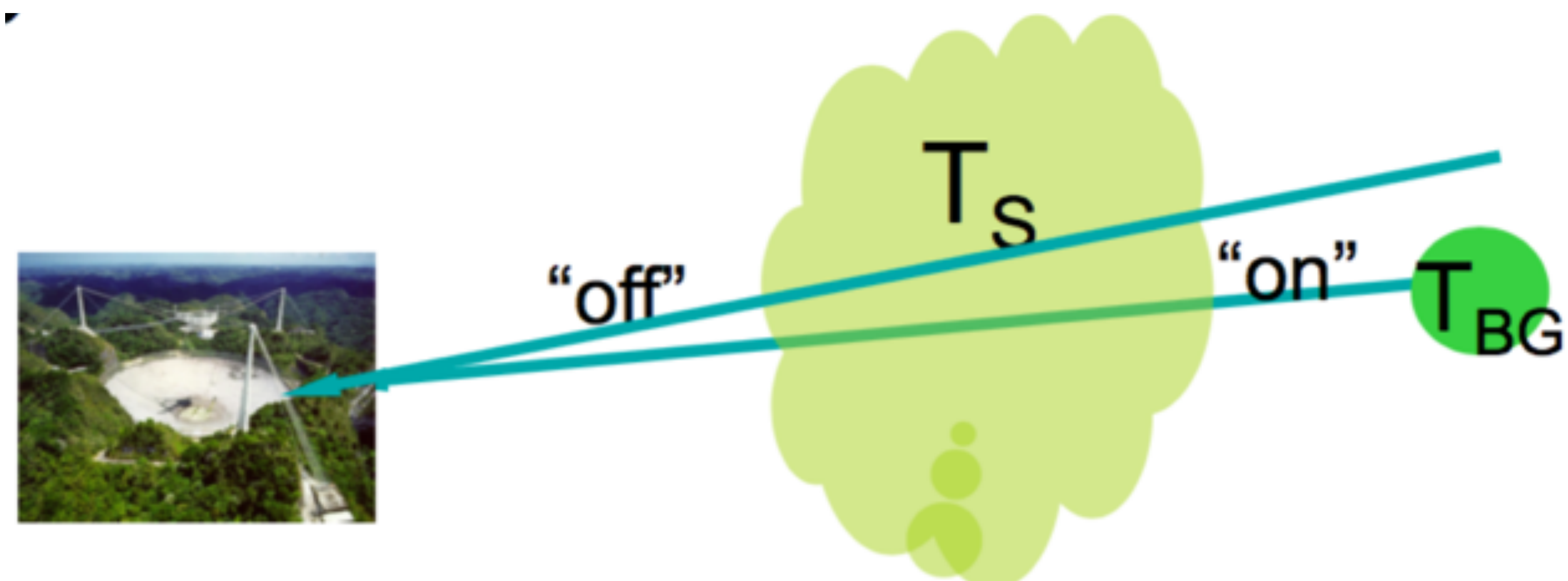
$T_{exc} \equiv T_{spin} \gg 0.0682$ K
because cosmic microwave
background can populate levels

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

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

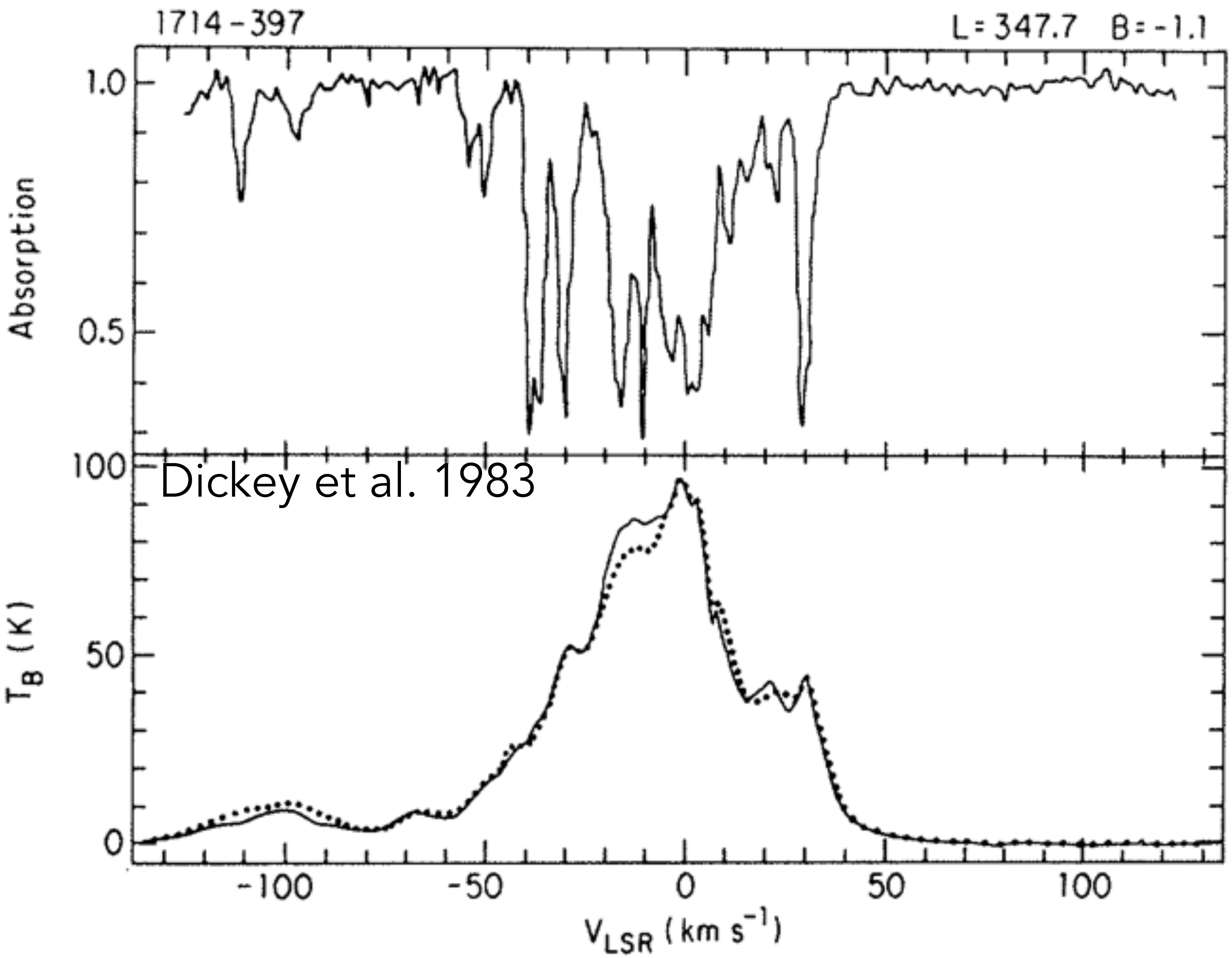
HI Spin Temperature Review

Measuring spin temperature



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

HI Spin Temperature Review



Absorption - weighted to low T

Emission - independent of T

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