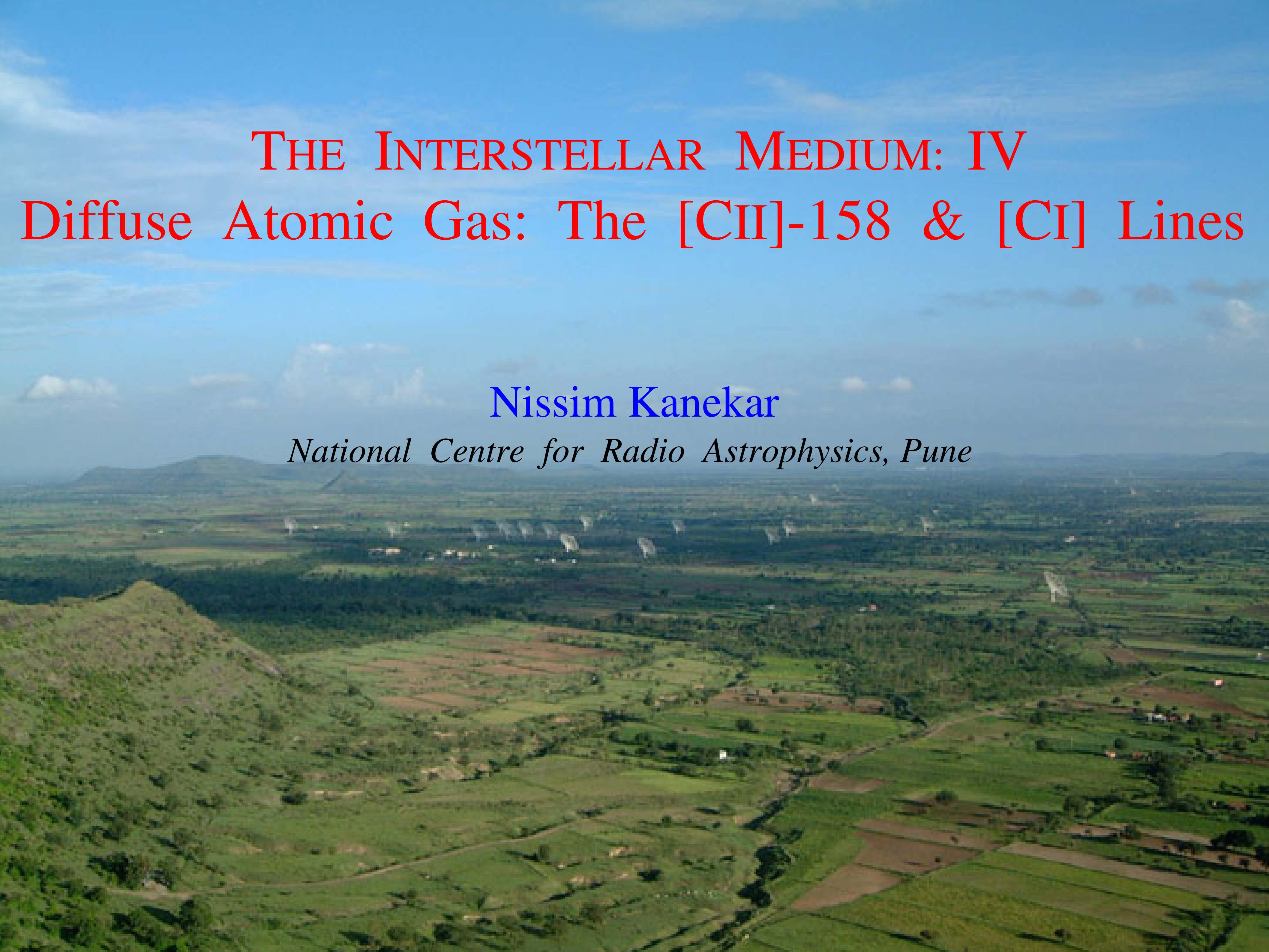
The Interstellar Medium: IV
Diffuse Atomic Gas: The [CII]-158 & [CI] Lines

Nissim Kanekar
National Centre for Radio Astrophysics, Pune



OUTLINE

- Background.
- HI-21cm studies.
- Interesting atomic lines: [CII]-158μm, [CI] 609/370-μm lines.
- More on the critical density.
- Conditions in diffuse clouds.

Background

- $A_{10} = 2.88 \times 10^{-15}$ s^{-1}. $h\nu/k \approx 0.07$ K ⇨ $(n_1/n_0) \approx 3\,(1 - h\nu/kT_S)$.

- Absorption: $N_{HI} = 1.8 \times 10^{18} \int T_S\, \tau_v\, dV$.

- Emission: $T_B = T_S\,(1 - e^{-\tau_v})$! $\tau_v \ll 1$ ⇨ $N_{HI} = 1.8 \times 10^{18} \int T_B\, dV$.

- HI-21cm studies: Estimates of N_{HI}, T_K, T_S, $B_{||}$, scale height.
  External galaxies: Mass, spatial distribution, velocity field,

- Collisional & radiative excitation / de-excitation: (2-level atom)

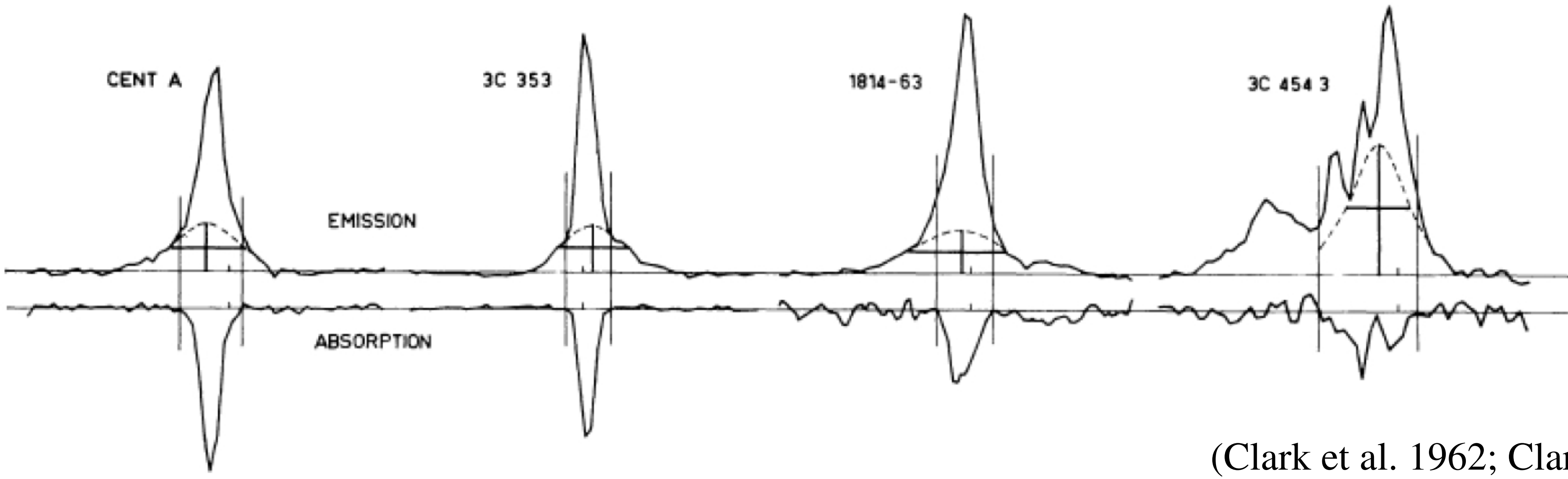
$$(n_1/n_0) = [n_c k_{01} + n_\gamma (g_1/g_0) A_{10}] \,/\, [n_c k_{10} + (1 + n_\gamma) A_{10}]$$

- Critical density: $n_{crit,u} = [\Sigma_{l<u} (1 + n_\gamma) A_{ul}] \,/\, [\Sigma_{l<u} k_{ul}]$
  If $n_c \gg n_{crit,u}$ ⇨ $T_X = T_K$; if $n_c \ll n_{crit,u}$ ⇨ $T_X = T_R$.

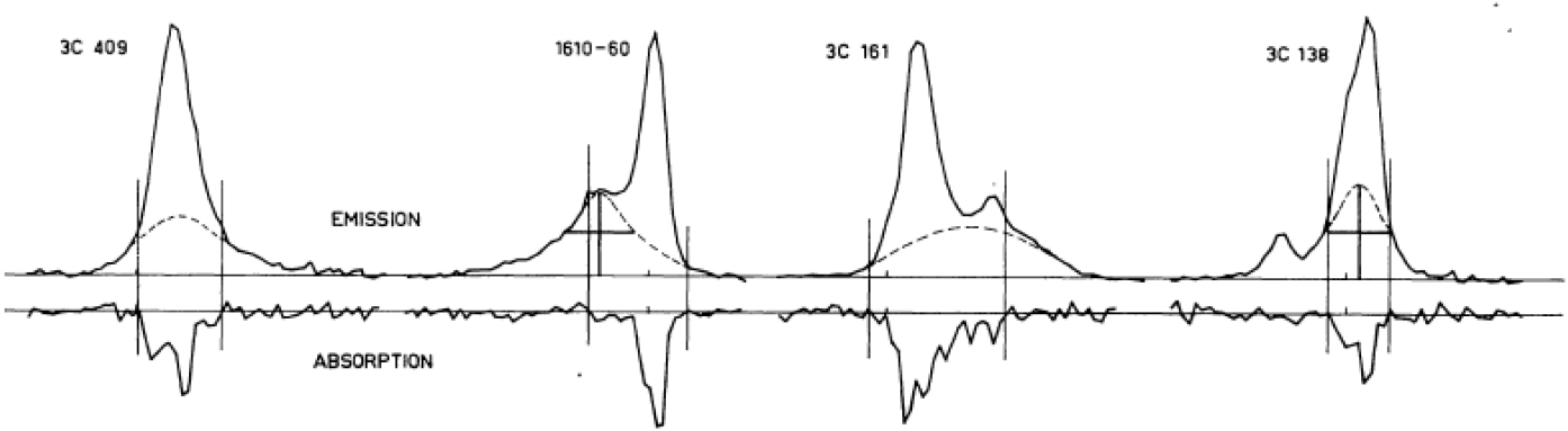
- HI-21cm: CNM ⇨ $T_S \approx T_K$; WNM ⇨ $T_S < T_K$!

A Two-Phase Neutral Medium

Wide HI-21cm emission profiles, narrow HI-21cm absorption.

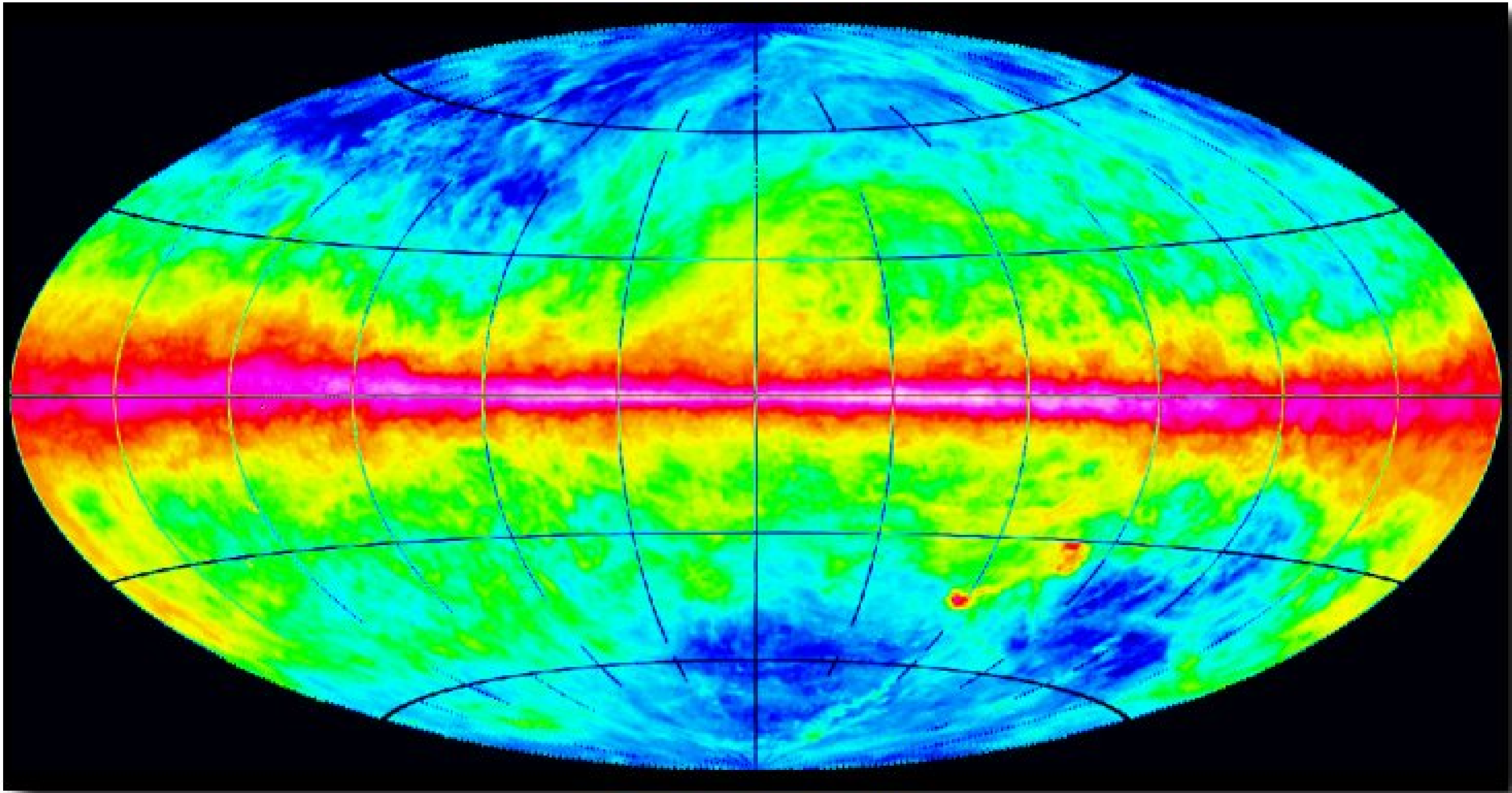


(Clark et al. 1962; Clark1965;
Radhakrishnan et al. 1972)



Clark (1965): “Two-phase” model.

All-Sky HI-21cm Emission Image



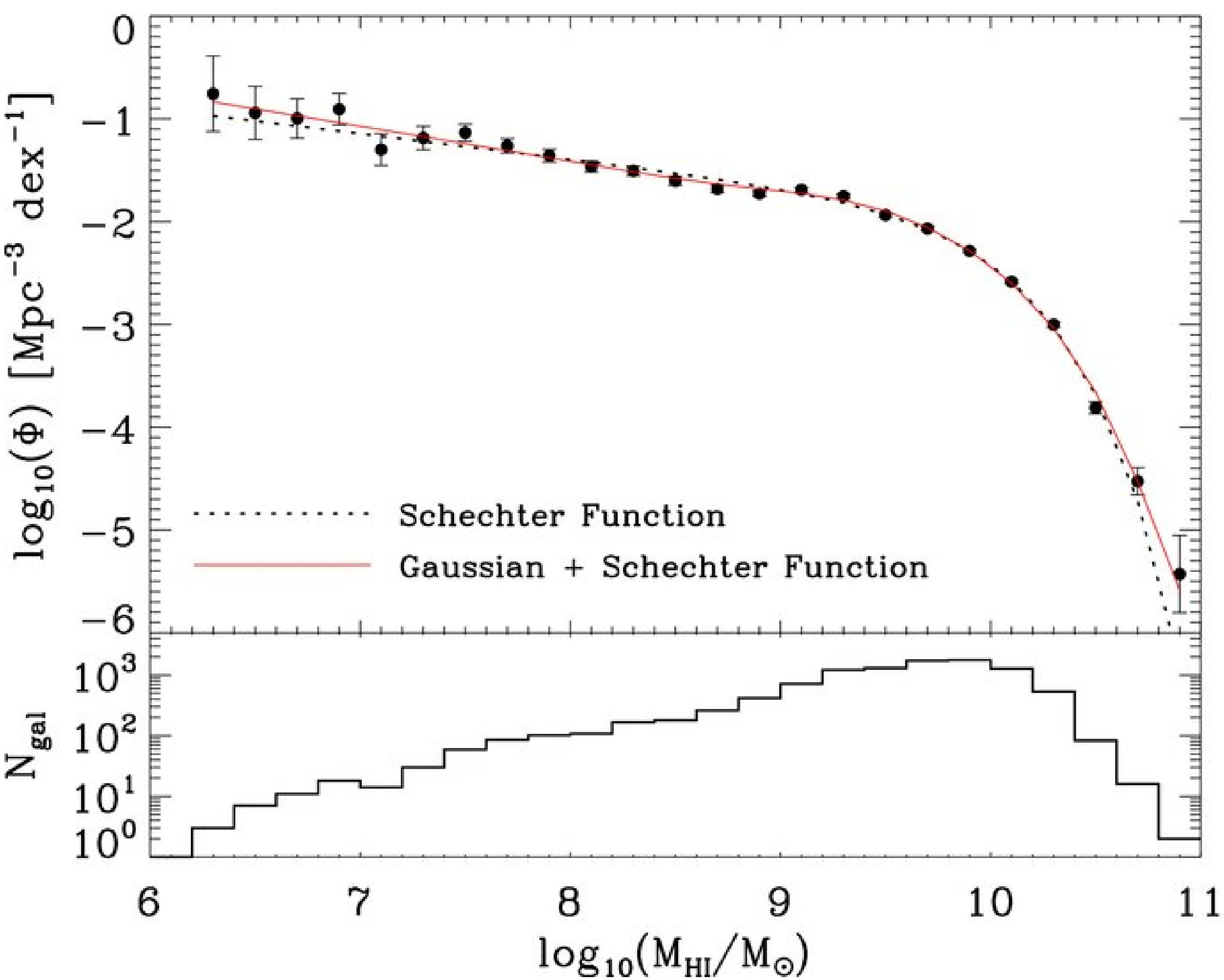
Leiden-Argentine-Bonn survey (Kalberla et al. 2005; Bajaja et al. 2005)

- Note: Assumed $\tau_v \ll 1$ to infer N_{HI} from the brightness temperature.
- Combine with the Galaxy's velocity field to infer the scale height!

(e.g. Heiles et al. 1985)

NEUTRAL GAS IN EXTERNAL GALAXIES

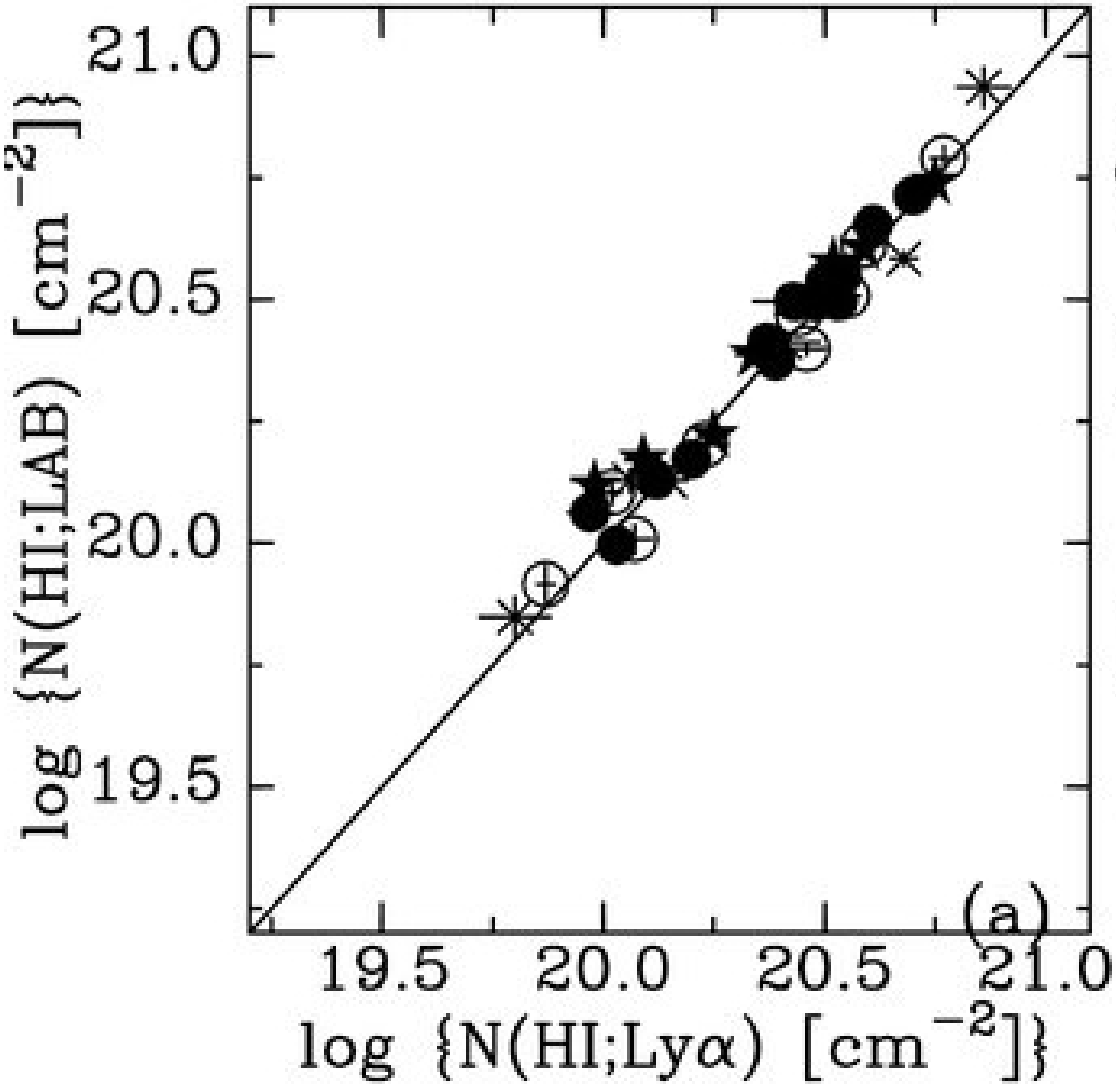
ALFALFA survey (Martin et al. 2010)



- Schechter function gives a good fit to the HI mass distribution.
- Cutoff at $M^*_{HI} = 10^{9.96}\, M_\odot$.

(e.g. Martin et al. 2010)

N_{HI} Estimates: HI-21cm Versus Lyman-α

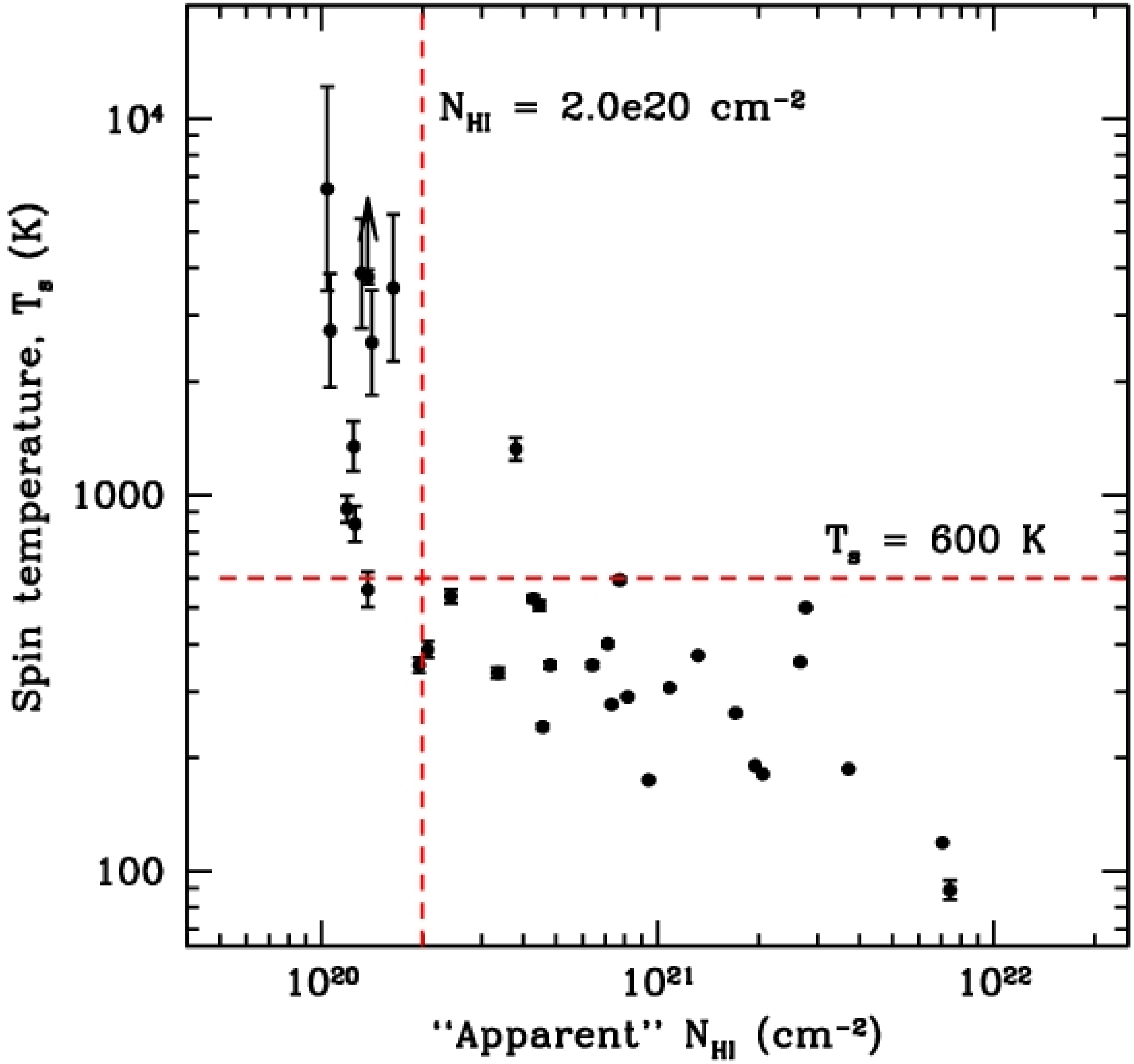


(Wakker et al. 2011)

- Excellent match (~ 10%) between N_{HI} values.
- Little small-scale structure ? But pulsar absorption, 3C138 ?

(e.g. Brogan et al. 2005)

Spin Temperatures in the Galaxy

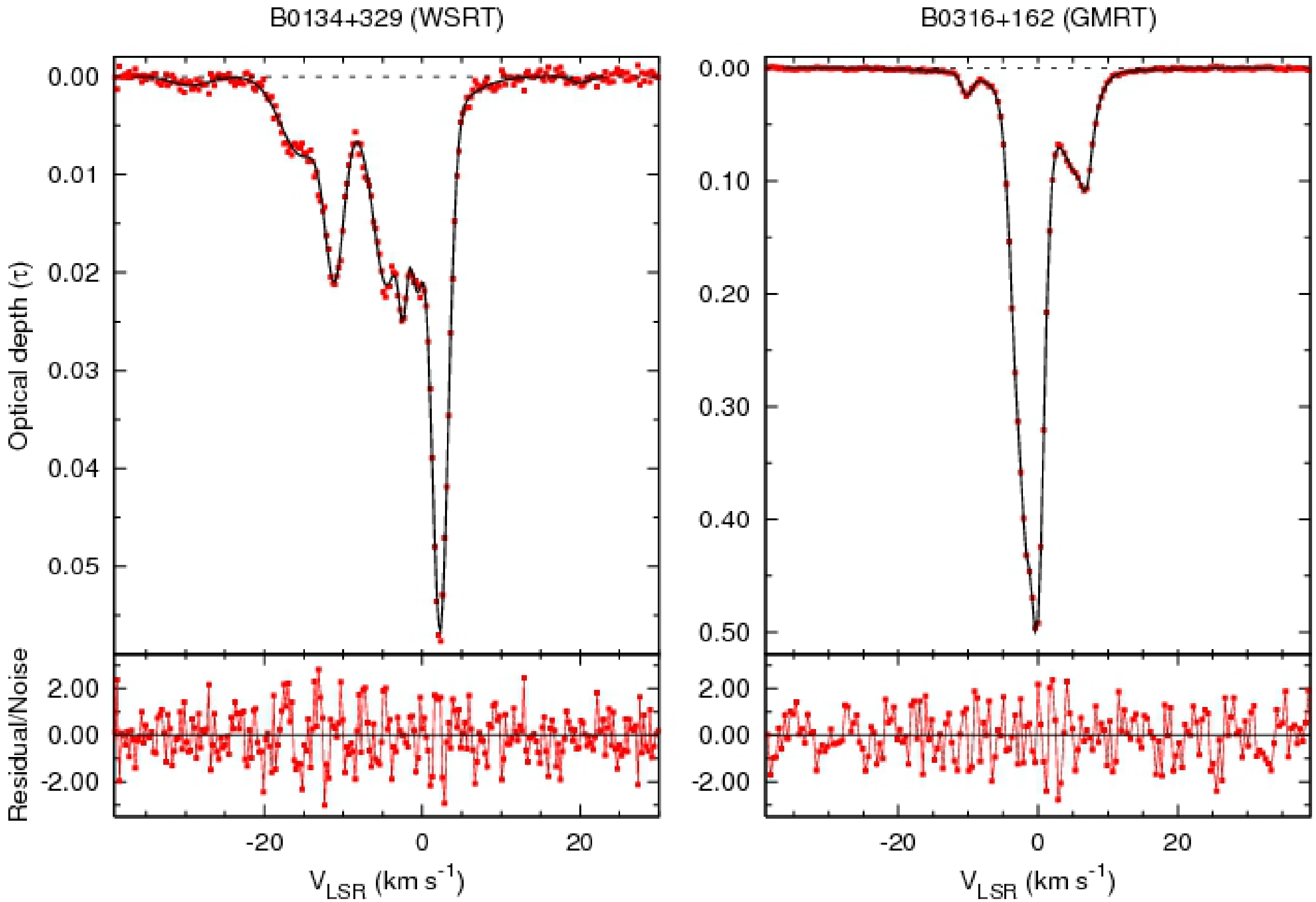


(NK et al. 2011)

- Typically, T_S <~ 100 K in the plane; < 600 K at all latitudes.
- An N_{HI} threshold for cold gas formation: $N_{HI} \sim 2 \times 10^{20}$ cm^{-2} ?

KINETIC TEMPERATURES IN THE GALAXY

- Based on Gaussian fitting: A pinch of scepticism needed!



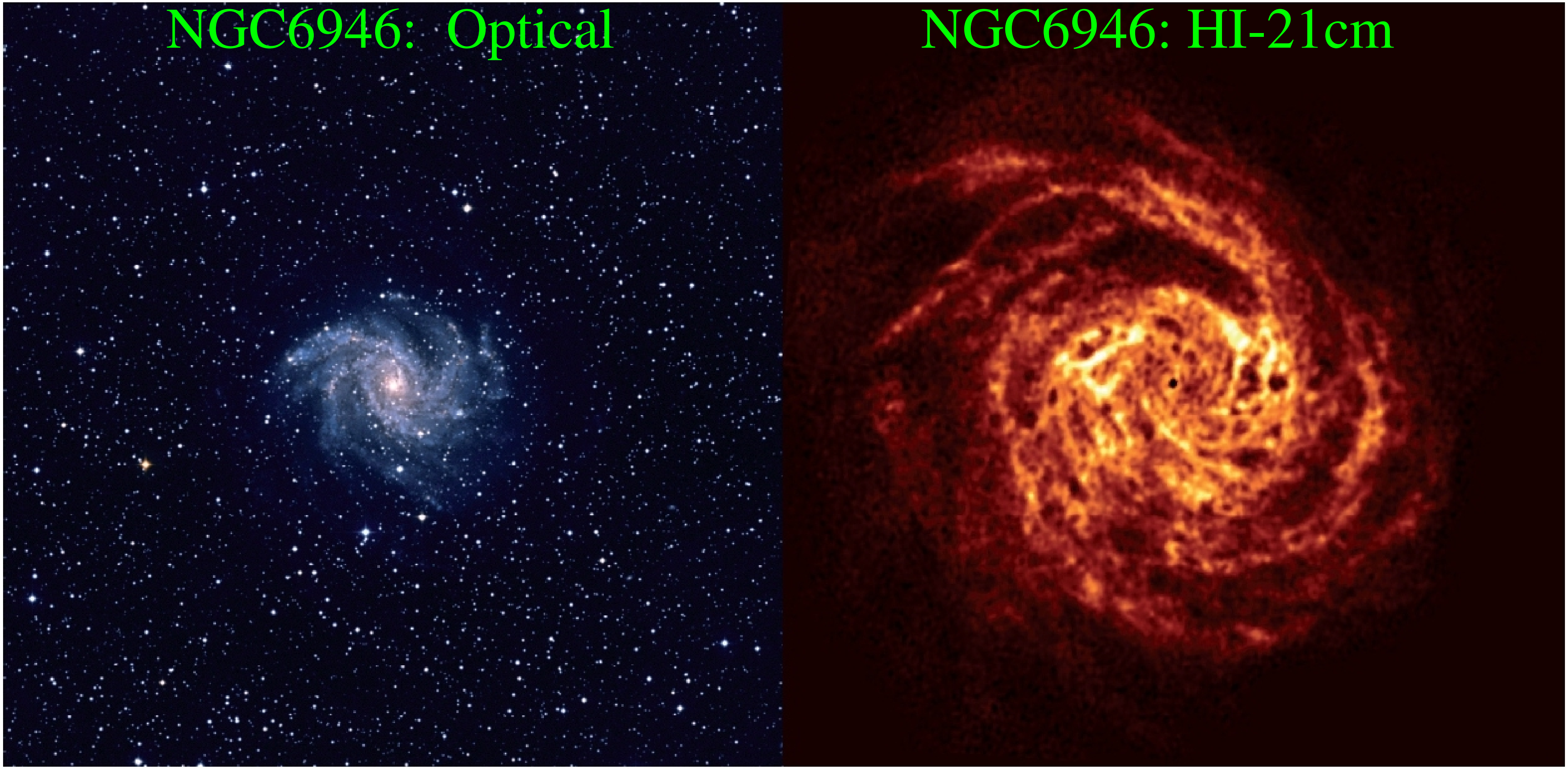
(Roy et al. 2013)

- Cold phase kinetic temperatures ~ 20 – 200 K.

- Large amounts of HI in the temperature range 500 – 5000 K.
  Very little detected gas in the WNM temperature range, > 5000 K.

(Heiles & Troland 2003; Roy et al. 2013)

SPATIAL DISTRIBUTION



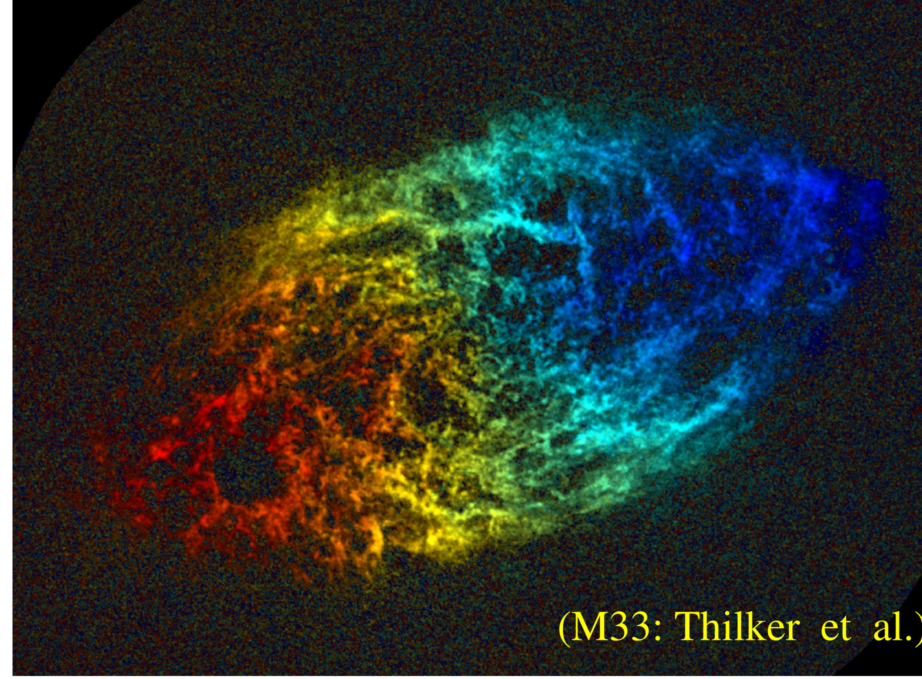
(Boomsma, PhD thesis)

- HI far more extended than stars, typically by a factor > 2.
- Scale height of cold gas in the Milky Way ~ 75 pc.
  Scale height of warm gas ~ 220 pc.

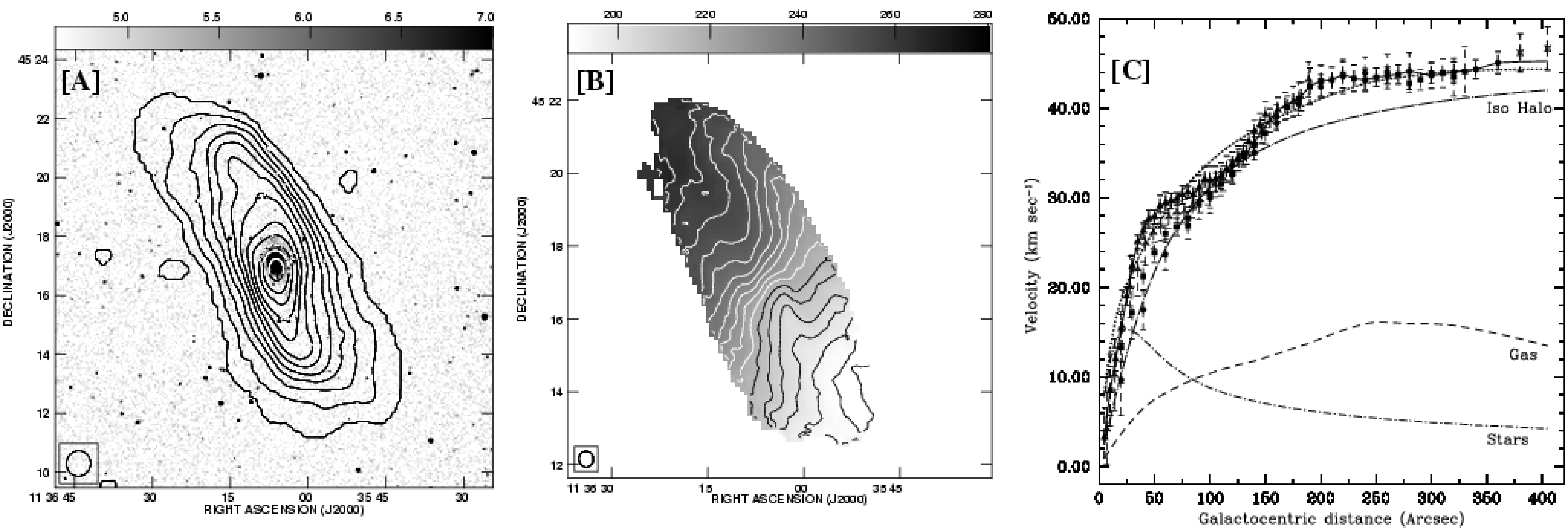
VELOCITY FIELDS

- *Assume* optically-thin HI-21cm line emission: Determine velocity field!

- For circular orbits, $V = [GM/R]^{1/2}$. Should have $V \propto R^{-1/2}$ at large R, as most mass is in inner regions.



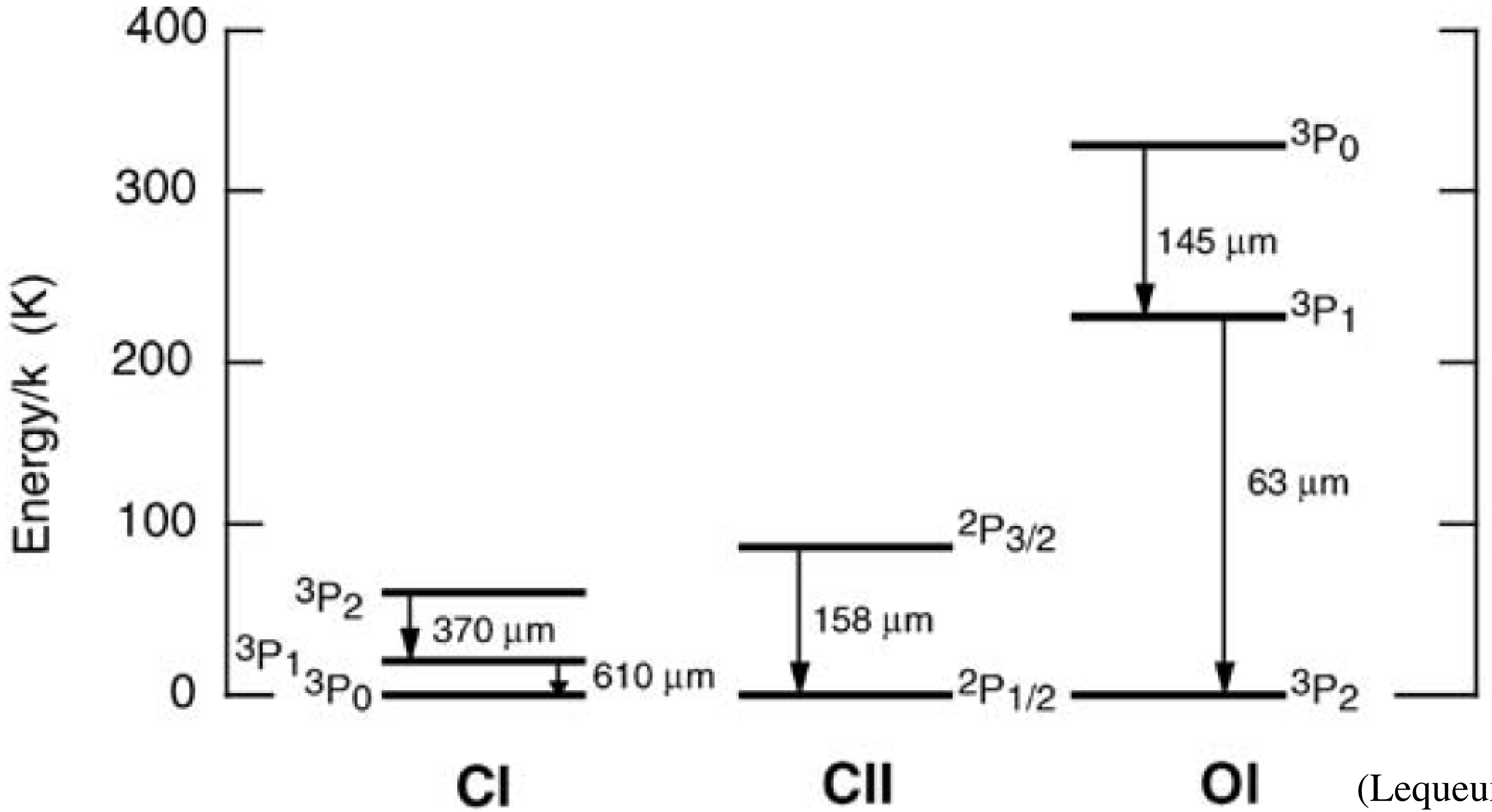
(M33: Thilker et al.)



But... Flat rotation curves ⇨ Dark Matter!

(e.g. Begum et al. 2005)

Other Atomic Spectral Lines



(Lequeux 2005)

- All are "forbidden" magnetic dipole fine-structure transitions.
- Low Einstein A-coefficients: $\sim 10^{-4} - 10^{-8}$ s^{-1}.

THE CRITICAL DENSITY

- For collisional excitation/de-excitation (i.e. ignoring radiation):

$$(dn_1/dt) = n_c\, n_0\, k_{01} - n_c\, n_1\, k_{10} - n_1\, A_{10}$$

k_{01} & k_{10} are rate coefficients: $k_{01} = (g_1/g_0)\ k_{10}\ e^{-h\nu/kT_K}$

In the steady state: $(n_1/n_0) = n_c k_{01} / [n_c\, k_{10} + A_{10}]$

- Including a radiation field, of specific energy density u_ν

$\Rightarrow\ (dn_1/dt) = n_0[n_c k_{01} + n_\gamma (g_1/g_0)A_{10}] - n_1[n_c k_{10} + (1 + n_\gamma)A_{10}]$

where n_γ is the photon occupancy number $= (c^3/8\pi h\nu^3)u_\nu$

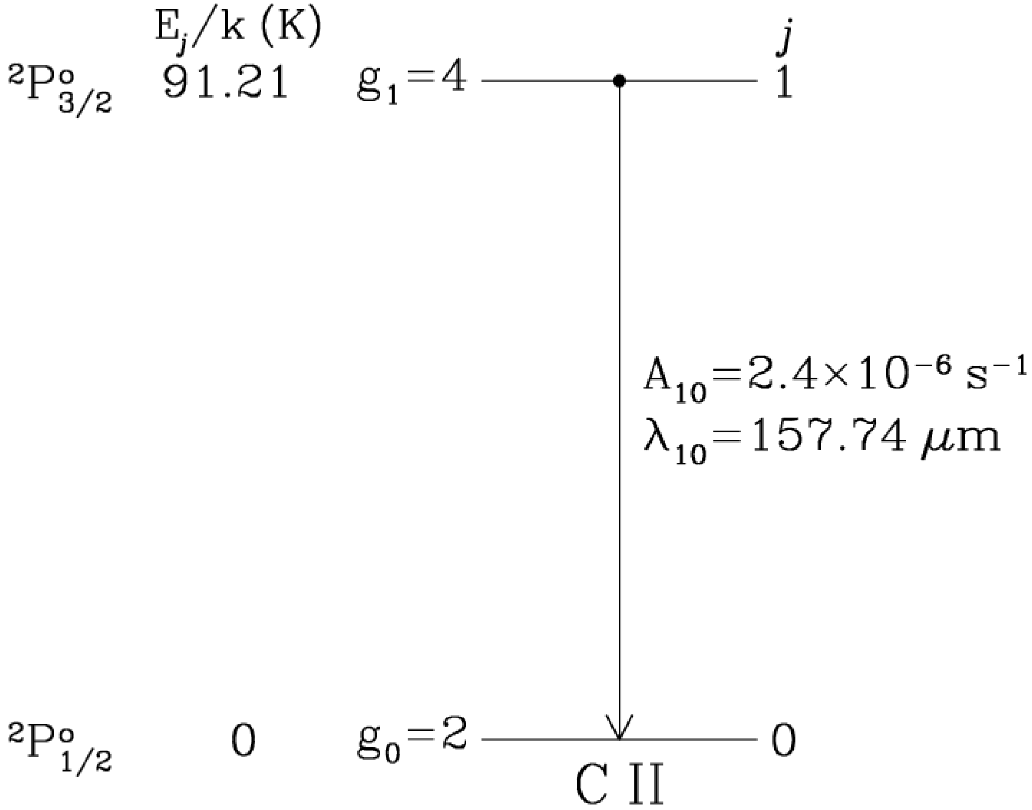
Steady state: $(n_1/n_0) = [n_c k_{01} + n_\gamma (g_1/g_0)A_{10}]/[n_c\, k_{10} + (1 + n_\gamma)A_{10}]$

- Critical density: Collisional de-excitation = Radiative de-excitation

$$n_{crit,u} = [\Sigma_{l<u}\ (1 + n_\gamma)A_{ul}\ ] \,/\, [\Sigma_{l<u}\ k_{ul}]$$

If $n_c \gg n_{crit,u}\ \Rightarrow\ T_X \approx T_K$; if $n_c \ll n_{crit,u}\ \Rightarrow\ T_X \approx T_R$.

The [CII]-158μm Line



(Draine 2011)

- $(n_1/n_0) = [n_c k_{01} + n_\gamma (g_1/g_0) A_{10}] \,/\, [n_c k_{10} + (1 + n_\gamma) A_{10}]$

  $n_\gamma \approx 10^{-5}$ ⇨ Critical density, $n_{crit,u} = \Sigma_{l<u} A_{ul} \,/\, \Sigma_{l<u} k_{ul}$

- Are the CII energy levels thermalized by collisions ???

  I.e. is $T_X \approx T_K$???

THE [CII]-158μM LINE

- $T \sim 100$ K: collisions with H atoms: $k_{10}(H) \sim 7.58 \times 10^{-10}$ cm^3 s^{-1}.

  $T \sim 10^4$ K: collisions with electrons: $k_{10}(e^-) \sim 4.53 \times 10^{-8}$ cm^3 s^{-1}.

(Keenan et al. 1986; Barinovs et al.. 2005)

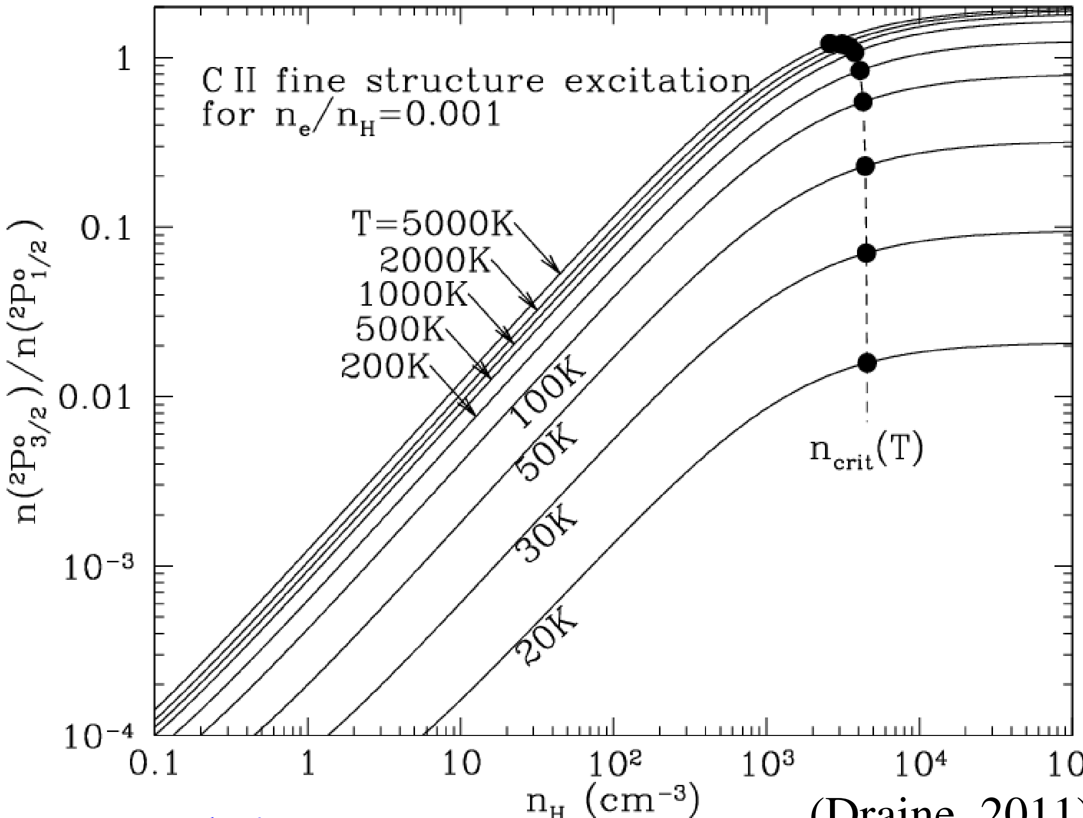
- $n_{crit} \sim 3000$ cm^{-3} !

- Diffuse clouds, $n < 100$ cm^{-3}

  ⇨ $T_X \ll T_K$!

- Collisional excitation but radiative de-excitation.

  ⇨ Radiative energy losses!



(Draine 2011)

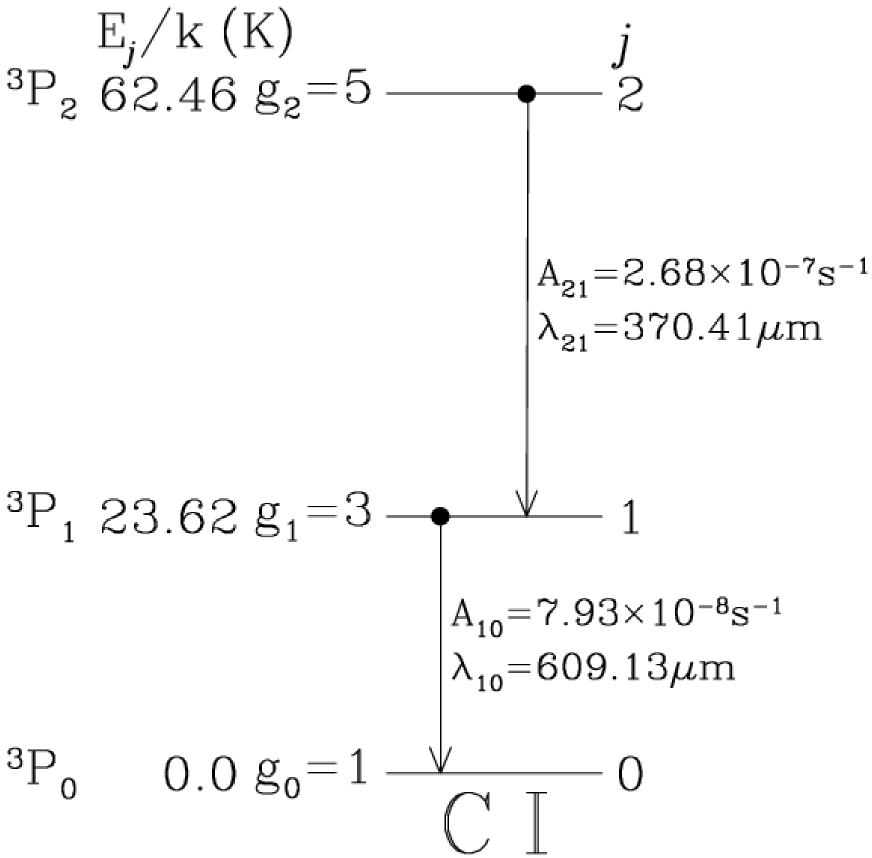
- Carbon most abundant of all the metals!

⇨ [CII]-158μm line most important cooling route in diffuse gas!
Radiates ~ 0.5% of a galaxy's luminosity!

(e.g. Stacey et al. 1991)

THREE LEVEL ATOMS: CI

- Three level system: More complex!



(Draine 2011)

- $(dn_2/dt) = R_{02}n_0 + R_{12}n_1 - (R_{20} + R_{21})n_2$
  $(dn_1/dt) = R_{01}n_0 + R_{21}n_2 - (R_{10} + R_{12})n_1$

- E.g. $R_{10} = C_{10} + (1 + n_{\gamma,10})A_{10}$;
  $R_{01} = (g_1/g_0)[C_{10}e^{-E_{10}/kT} + n_{\gamma,10}A_{10}]$...

- In steady state, $(dn_2/dt) = (dn_1/dt) = 0$.

- $(n_1/n_0) = (R_{01}R_{20} + R_{01}R_{21} + R_{21}R_{02})/(R_{10}R_{20} + R_{10}R_{21} + R_{12}R_{20})$
  $(n_2/n_0) = (R_{02}R_{10} + R_{02}R_{12} + R_{12}R_{01})/(R_{10}R_{20} + R_{10}R_{21} + R_{12}R_{20})$.

Three Level Atoms: CI

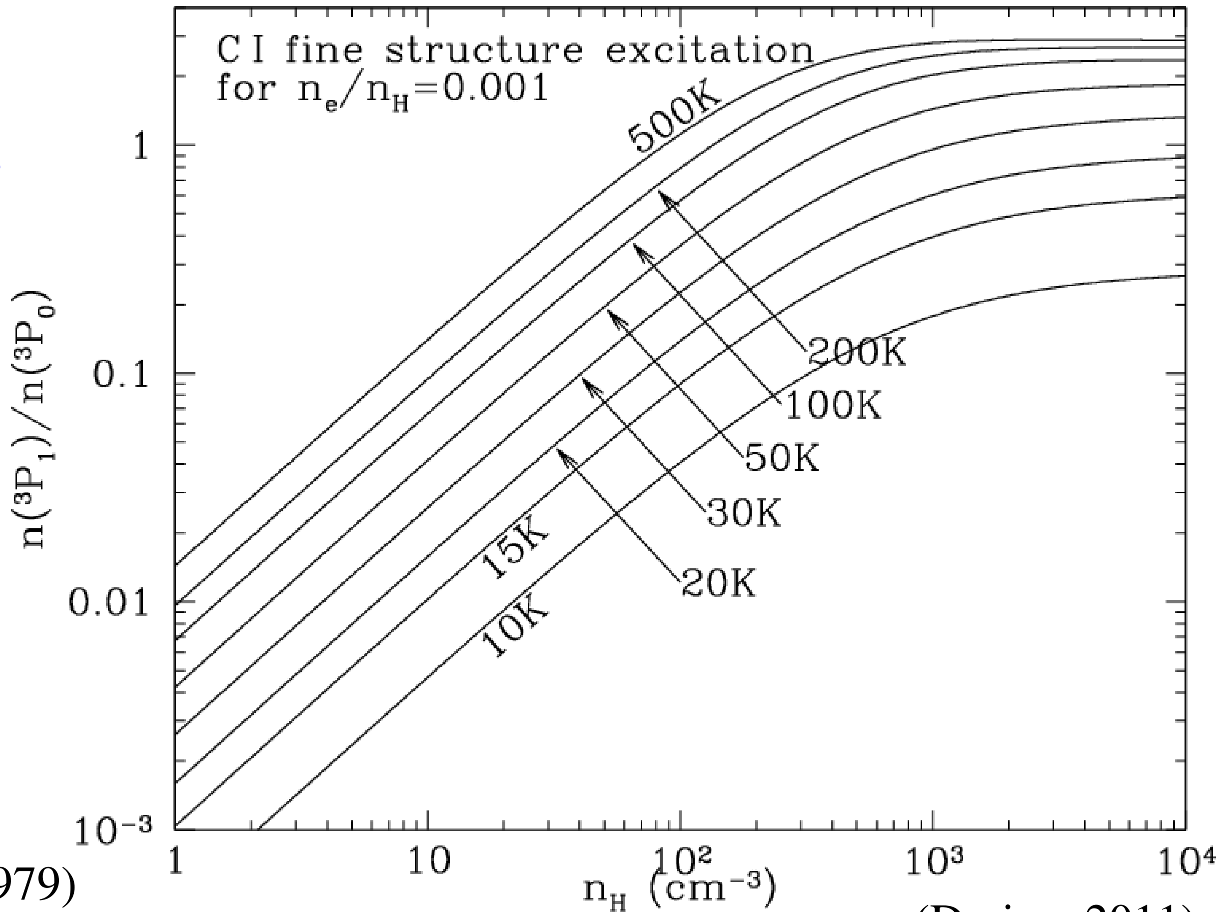
- $n_{crit} \sim 700\ cm^{-3}$ ($T_K \sim 100$ K) ; $n_{crit} \sim 150\ cm^{-3}$ ($T_K \sim 5000$ K).
  Densities in diffuse ISM much lower than critical density!

- Since $n < n_{crit}$, the level populations depend on n & T_K !

- Level populations obtained from strengths of UV lines to higher excited states.

- Three levels ⇨ Solve for density and temperature!
  ⇨ Infer thermal pressure!

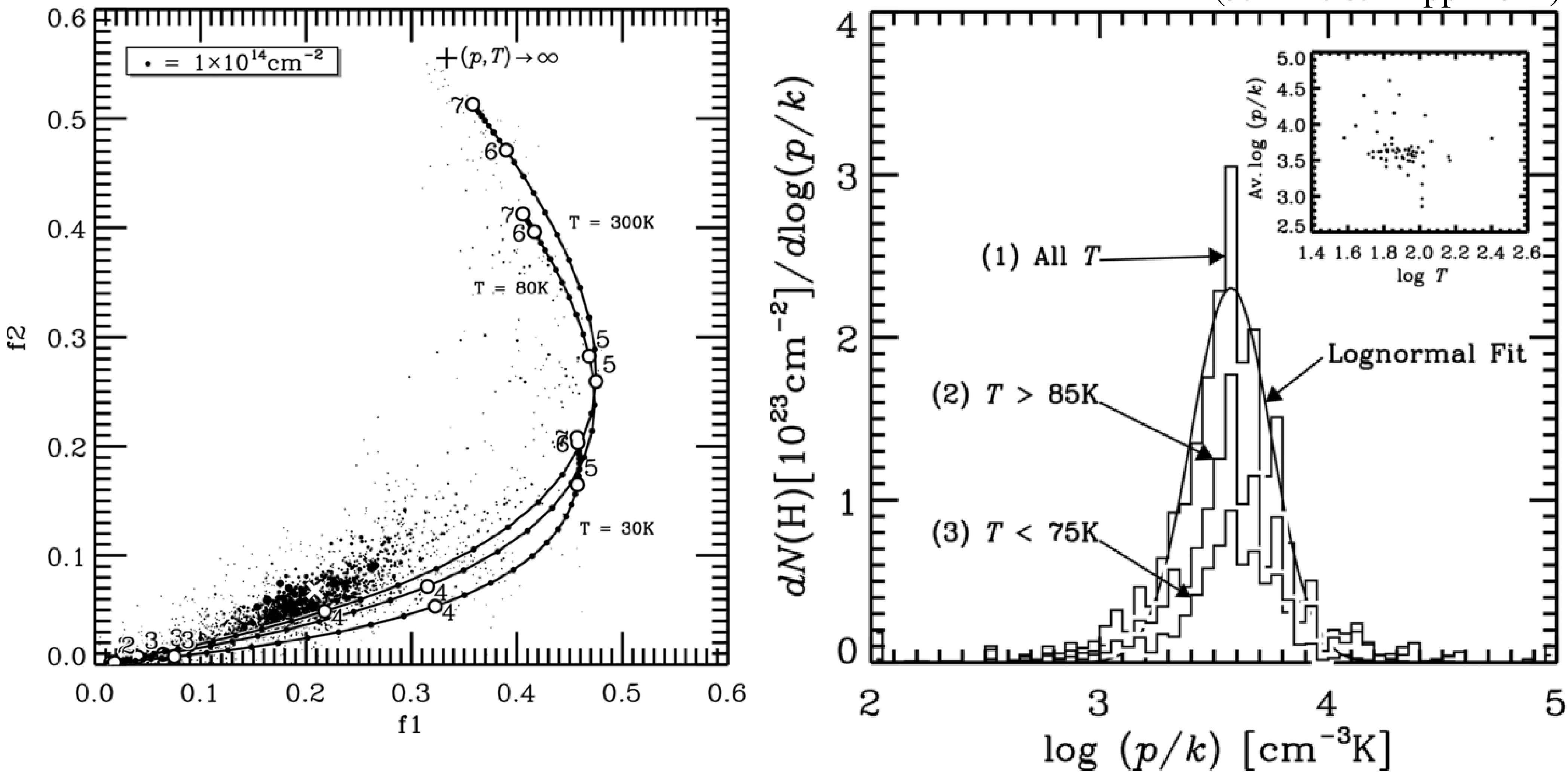
(Jenkins & Shaya 1979)



(Draine 2011)

THREE LEVEL ATOMS: CI

(Jenkins & Tripp 2011)



- Most points lie above and to the left of the curves!
  - ⇨ Two pressures, 3800 cm^{-3} K and > 10^4 cm^{-3} K ???

(Jenkins & Tripp 2011)

DIFFUSE CLOUDS: PROPERTIES

- Multi-phase medium: CNM with $T_K \sim 70$ K and high density.
  WNM with $T_K > 1000$ K and low density.
- Extended far beyond the stars in normal galaxies.
  Scale heights of ~ 75 pc (CNM) and ~ 220 pc (WNM).
- Cold phase formation at $N_{HI} \sim 2 \times 10^{20}$ cm^{-2} in the Galaxy.
- $T_S \sim T_K$ in the CNM; $T_S < T_K$ in the WNM.
- Magnetic field strengths of ~ 5 μG in the CNM.
- Pressures of ~ 3800 cm^{-3} K, from CI absorption. But...
- Important coolant: [CII]-158μm line.

CI Energy Levels

(Draine 2011)