Interstellar Medium 2020

Lecture 3: The Atomic Interstellar Medium

Sterrewacht Leiden

Paul van der Werf

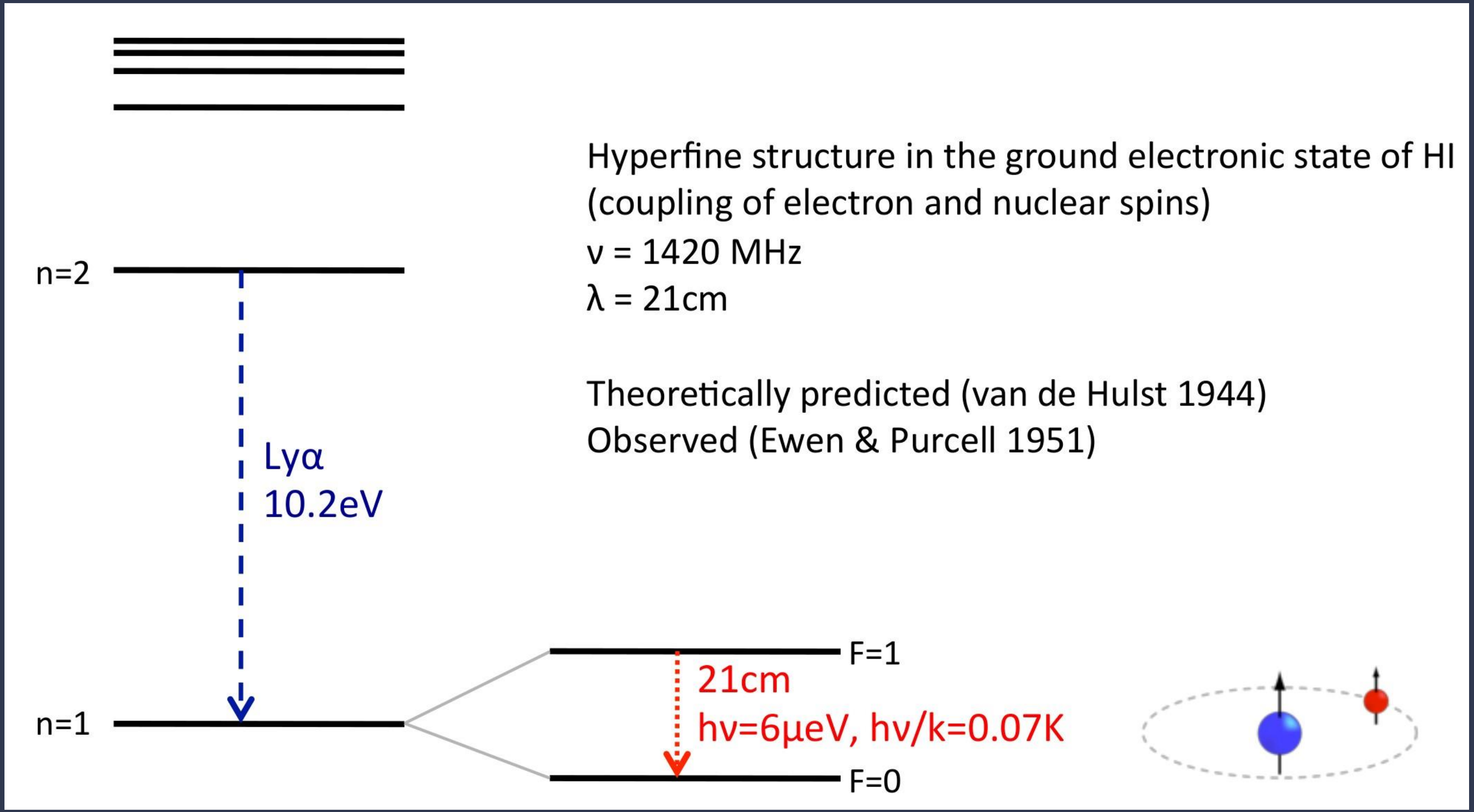
Course Contents

1. Introduction and ecology of the interstellar medium
2. Physical conditions and radiative processes
3. The atomic interstellar medium
4. Ionization and recombination
5. Photoionization and HII regions
6. Collisional excitation and nebular diagnostics
7. Molecular energy levels and excitation
8. Interstellar dust
9. Thermal balance
10. Molecular clouds
11. Shocks, supernova remnants and the 3-phase ISM
12. Extragalactic ISM and outlook

Today’s Lecture

1. The HI 21cm line
2. HI emission and absorption
3. The 2-phase interstellar medium
4. Optical/UV absorption lines and the Intergalactic Medium

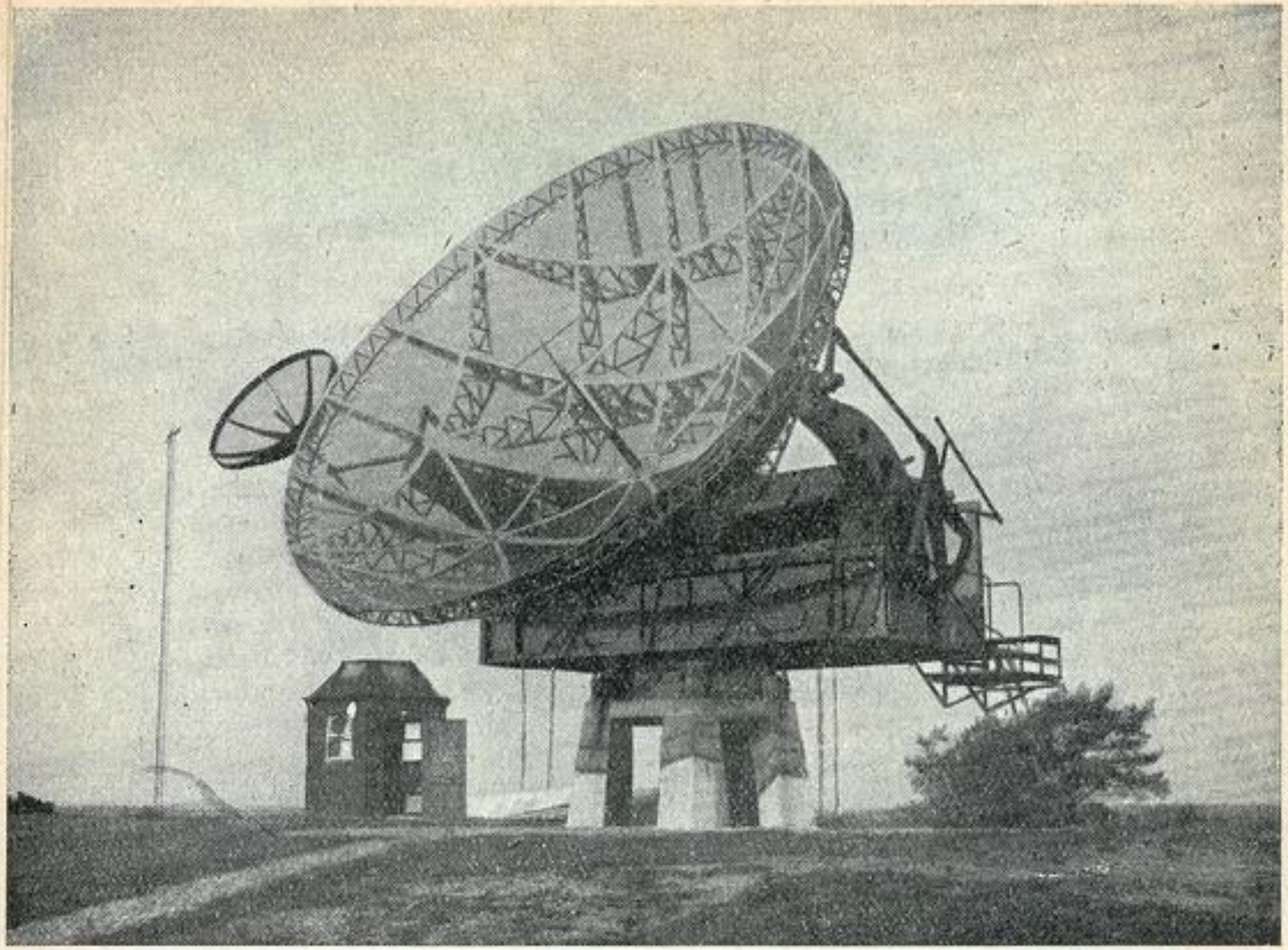
The HI 21cm hyperfine structure line



$g_u = 3$, $g_l = 1$
$A_{ul} = 2.9\ 10^{-15}\ \mathrm{s}^{-1}$
$\rightarrow t_{\mathrm{rad}} \approx 11$ Myr

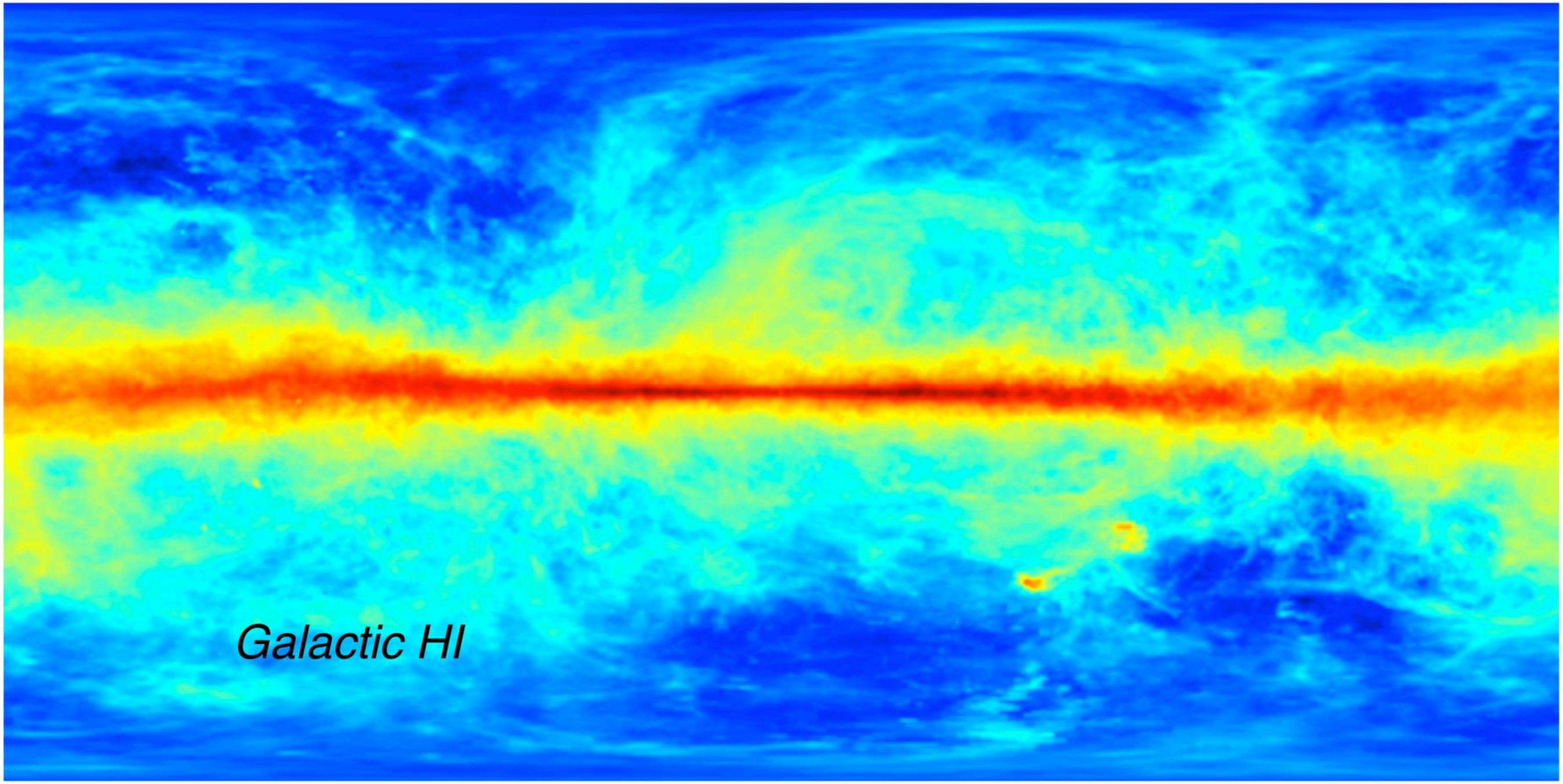
$E_{ul}/k = 0.0682$ K
$\nu_{ul} = 1420$ MHz
$\lambda_{ul} = 21.1$ cm

The HI 21cm line



De radio-telescoop te Kootwijk (zie ook de voorplaat). De middellijn van de spiegel is 7½ m. Het gevaarte kan op zijn voetstuk draaien. De spiegel zelf kan omhoog en omlaag gericht worden.

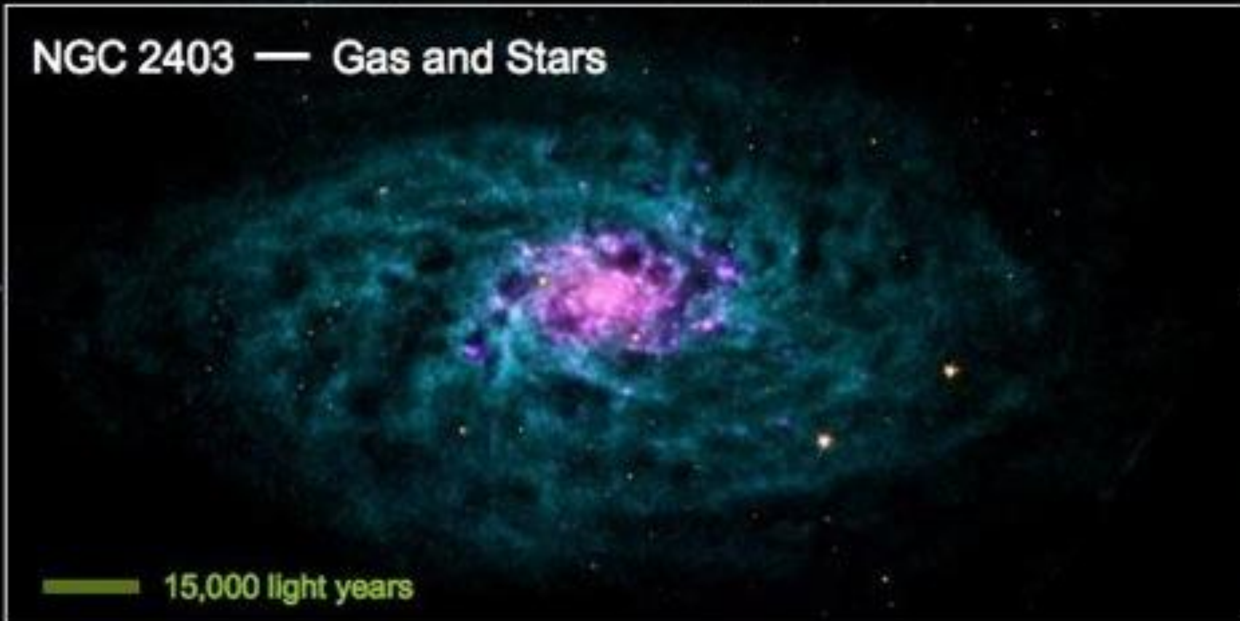
HI 21cm emission of the Milky Way



Kalberla et al. (2005)

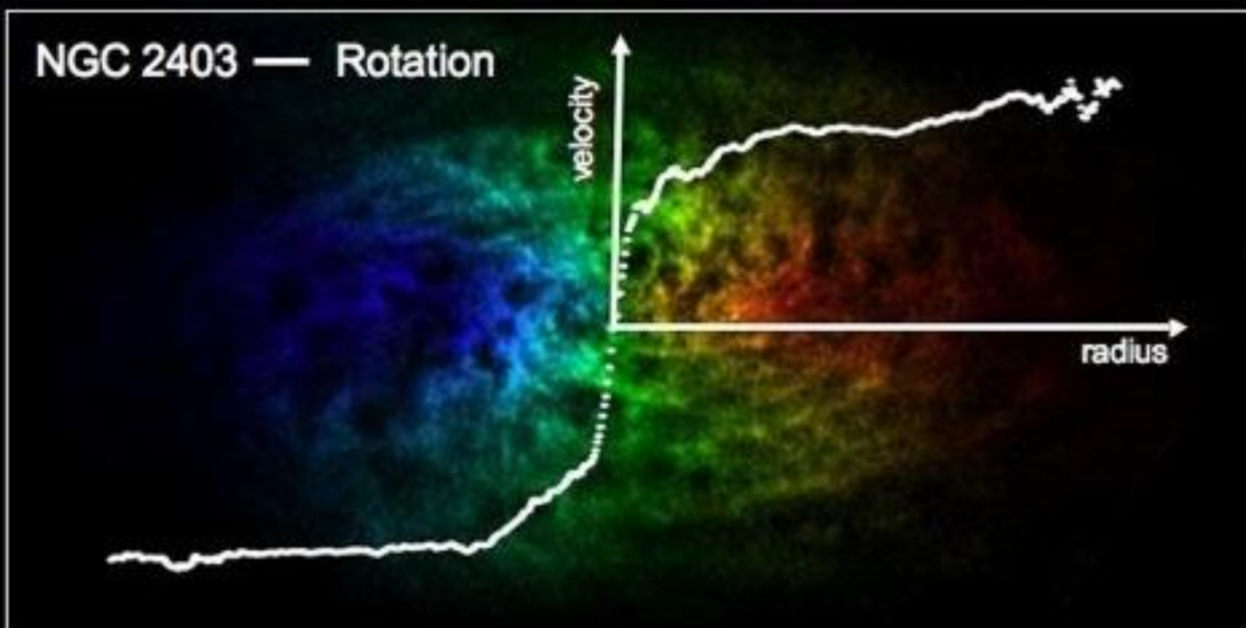

The HI Nearby Galaxy Survey
North + South
NGC 2841
NGC 1512
NGC 1510
NGC 1291
NGC 3621
NGC 7331
NGC 4826
(M64)
NGC 6946
NGC 3184
NGC 925
NGC 3351
(M95)
NGC 3198
NGC 5194
(M51)
IC 4710
NGC 2915
NGC 2976
NGC 1705
DDO 53
NGC 1569
NGC 3521
NGC 4214
Our Galaxy
HI
stars
M81dwB
M81dwA
NGC 2366
IC 2574
NGC 4449
NGC 5236
(M83)
NGC 3627
(M66)
Holmberg II
NGC 5055
DDO 154
NGC 7793
NGC 5408
NGC 4736
(M94)
NGC 3077
Holmberg I
NGC 2903
10 kpc
NGC 2403
NGC 628
(M74)
NGC 5457
(M101)
NGC 3031
(M81)
THINGS North: Walter et al 2008
THINGS South: de Blok et al 2008
Milky Way HI map: Oort, Kerr, Westerhout (1958)
Milky Way art: NASA/JPL, R. Hurt (SSC)

Galaxy Dynamics in THINGS — The HI Nearby Galaxy Survey



THINGS
The HI Nearby Galaxy Survey

Color Coding:
THINGS Atomic Hydrogen
(Very Large Array)
Old stars
(Spitzer Space Telescope)
Star Formation
(GALEX & Spitzer)



Color coding:
THINGS HI distribution:
Red-shifted (receding)
Blue-shifted (approaching)
Rotation Curve

Image credits:
VLA THINGS: Walter et al. 08
Spitzer SINGS: Kennicutt et al. 03
GALEX NGS: Gil de Paz et al. 07
Rotation Curve: de Blok et al. 08

Spin temperature

Recall $$T_b = T_c e^{-\tau_\nu} + T_s(1 - e^{-\tau_\nu})$$ (for a homogeneous medium)

We call the excitation temperature of the 21cm line the spin temperature T_s

Now $$\frac{n_u}{n_l} = \frac{g_u}{g_l} e^{-\frac{h\nu_{ul}}{kT_s}} = 3e^{-\frac{0.0682}{T_s}} \approx 3$$ to very high accuracy since $T_s > T_{CMB} = 2.73$ K

So to very high accuracy $$n_u = \frac{3}{4} n_{\mathrm{HI}} \text{ and } n_l = \frac{1}{4} n_{\mathrm{HI}}$$ where n_{HI} is the total density of hydrogen atoms.

Optical depth of the HI 21cm line

Recall $$\kappa_\nu = n_l \frac{g_u}{g_l}\frac{A_{ul}}{8\pi}\lambda_{ul}^2\varphi_\nu\left(1 - e^{-\frac{h\nu_{ul}}{kT_s}}\right)$$ stimulated emission

Since $kT_s >> h\nu_{ul}$, stimulated emission is important, and we can approximate $$e^{-\frac{h\nu_{ul}}{kT_s}} \approx 1 - \frac{h\nu_{ul}}{kT_s}$$

so we find $$\kappa_\nu = \frac{3}{32\pi}A_{ul}\frac{hc\lambda_{ul}}{kT_s}n_{\mathrm{HI}}\varphi_\nu$$

so $$\tau_\nu = \int \kappa_\nu ds = \frac{3}{32\pi}A_{ul}\frac{hc\lambda_{ul}}{kT_s}N(\mathrm{HI})\varphi_\nu$$

where N(HI) is the atomic hydrogen column density.

Note the dependence on $1/T_s$

HI 21cm optical depth

$$\tau_\nu = \frac{3}{32\pi} A_{ul} \frac{hc\lambda_{ul}}{kT_s} N(\mathrm{HI}) \varphi_\nu$$

Insert Gaussian for φ_ν $$\varphi_\nu = \frac{1}{\sqrt{2\pi}} \frac{c}{\nu_{ul}} \frac{1}{\sigma_v} e^{-\frac{u^2}{2\sigma_v^2}}$$ where u is velocity and σ_v is velocity dispersion.

Now $$\tau_\nu = \frac{3}{32\pi} \frac{1}{\sqrt{2\pi}} \frac{A_{ul}\lambda_{ul}^2}{\sigma_v} \frac{hc}{kT_s} e^{-\frac{u^2}{2\sigma_v^2}} N(\mathrm{HI})$$

or inserting numbers $$\boxed{\tau_\nu = 2.190 \frac{N(\mathrm{HI})}{10^{21}\mathrm{cm}^{-2}} \frac{100\ \mathrm{K}}{T_s} \frac{1\ \mathrm{km\ s}^{-1}}{\sigma_v} e^{-\frac{u^2}{2\sigma_v^2}}}$$

Note N(HI) ~ 10^{21} cm^{-2} often occurs, and $T_s \approx T_{kin}$ for HI (see lecture 6)

→ WNM optically thin, but CNM can get optically thick!

Optically thin HI 21cm line emission

$$\boxed{T_b = T_c e^{-\tau_\nu} + T_s\left(1 - e^{-\tau_\nu}\right)}$$

For simplicity assume no background source.

Then if optically thin: $$T_b = \tau_\nu T_s = \frac{3}{32\pi} A_{ul} \frac{hc\lambda_{ul}}{k} N(\mathrm{HI})\varphi_\nu$$

velocity

so $$\int T_b dv = \frac{3}{32\pi} A_{ul} \frac{hc\lambda_{ul}}{k} N(\mathrm{HI}) \int \varphi_\nu dv$$ with $$\frac{v}{c} = \frac{\nu}{\nu_{ul}}$$

frequency

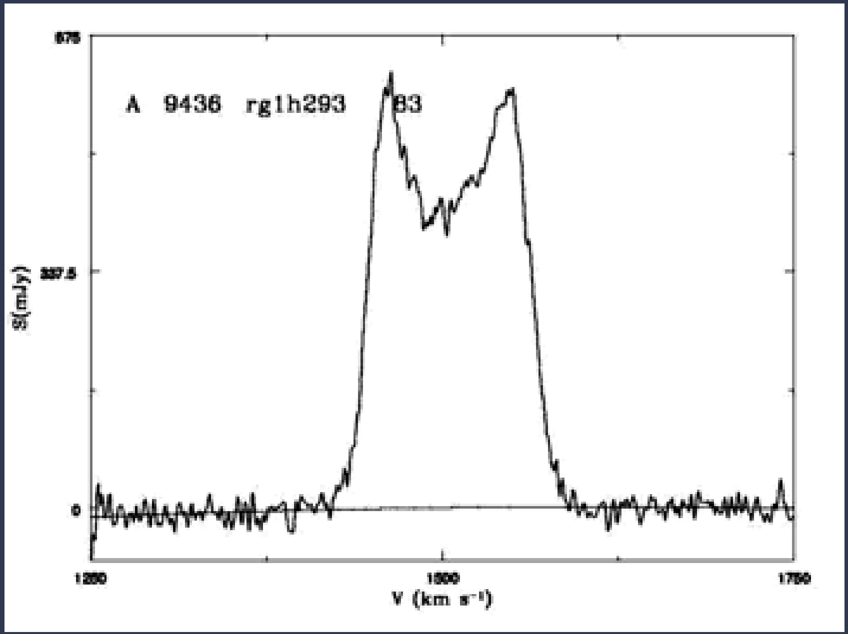
so $$\int T_b dv = \frac{3}{32\pi} A_{ul} \frac{hc\lambda_{ul}^2}{k} N(\mathrm{HI})$$ or $$\boxed{N(\mathrm{HI}) = \frac{32\pi k}{3hc\lambda_{ul}^2 A_{ul}} \int T_b dv}$$ (independent of T_s)

Inserting numbers: $$\boxed{\frac{N(\mathrm{HI})}{\mathrm{cm}^{-2}} = 1.813 \cdot 10^{18} \frac{\int T_b dv}{\mathrm{K\ km\ s^{-1}}}}$$

Calculating HI column density and mass

$$\frac{N(\mathrm{HI})}{\mathrm{cm}^{-2}} = 1.813 \cdot 10^{18} \frac{\int T_b dv}{\mathrm{K\ km\ s}^{-1}}$$

To calculate total HI mass, integrate over object (i.e., solid angle) and multiply by hydrogen atom mass m_{H}:



$$M(\mathrm{HI}) = \frac{16\pi m_{\mathrm{H}}}{3A_{ul}hc} D^2 \int F_\nu\, dv = \frac{2.343 \cdot 10^5}{M_\odot} \left(\frac{D}{\mathrm{Mpc}}\right)^2 \frac{\int F_\nu dv}{\mathrm{Jy\ km\ s}^{-1}}$$

(if optically thin)

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Dealing with optical depth

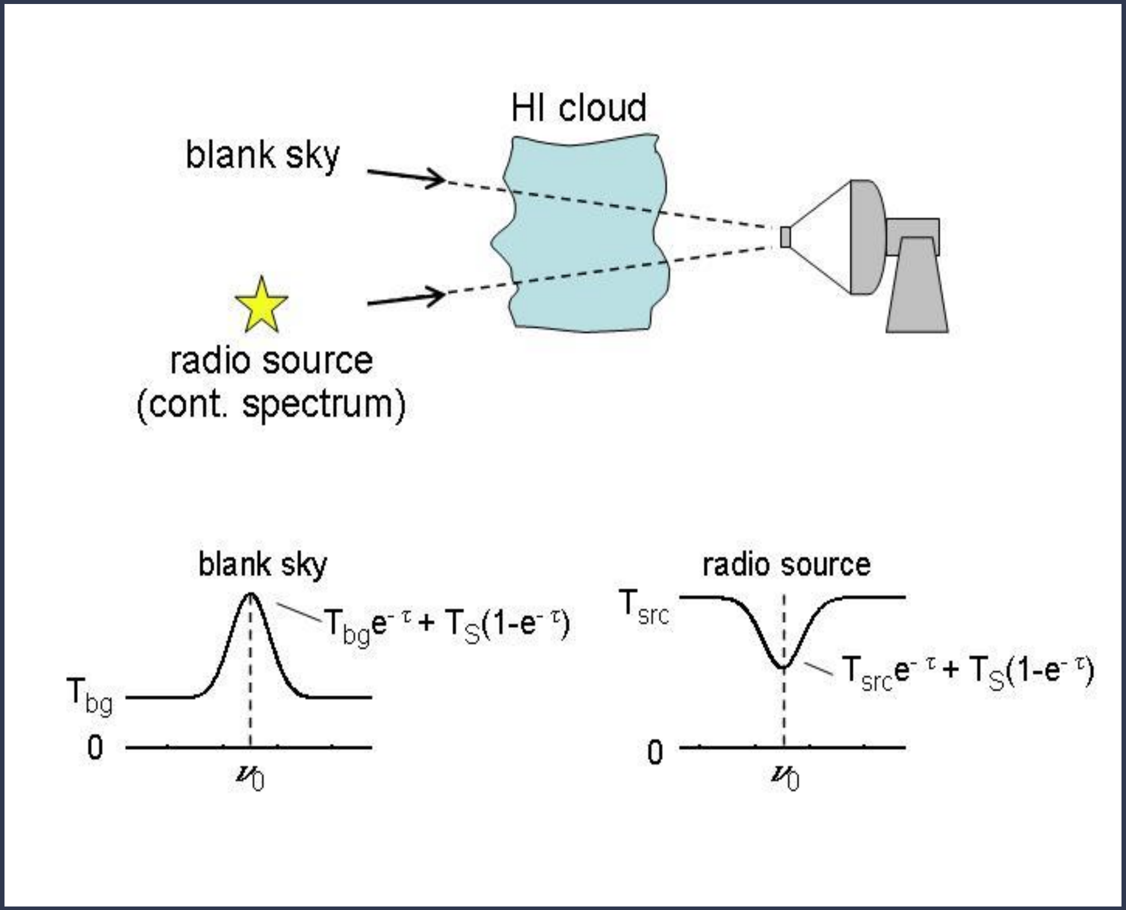
What if the line is not optically thin?

$$T_b = T_c e^{-\tau_\nu} + T_s(1 - e^{-\tau_\nu})$$

Now signal depends also on T_s which is unknown.

Trick: observe on and off a strong radio source

HI emission and absorption



$$T_{\mathrm{on}}(v) = T_{\mathrm{src}}e^{-\tau_v} + T_s(1 - e^{-\tau_v})$$

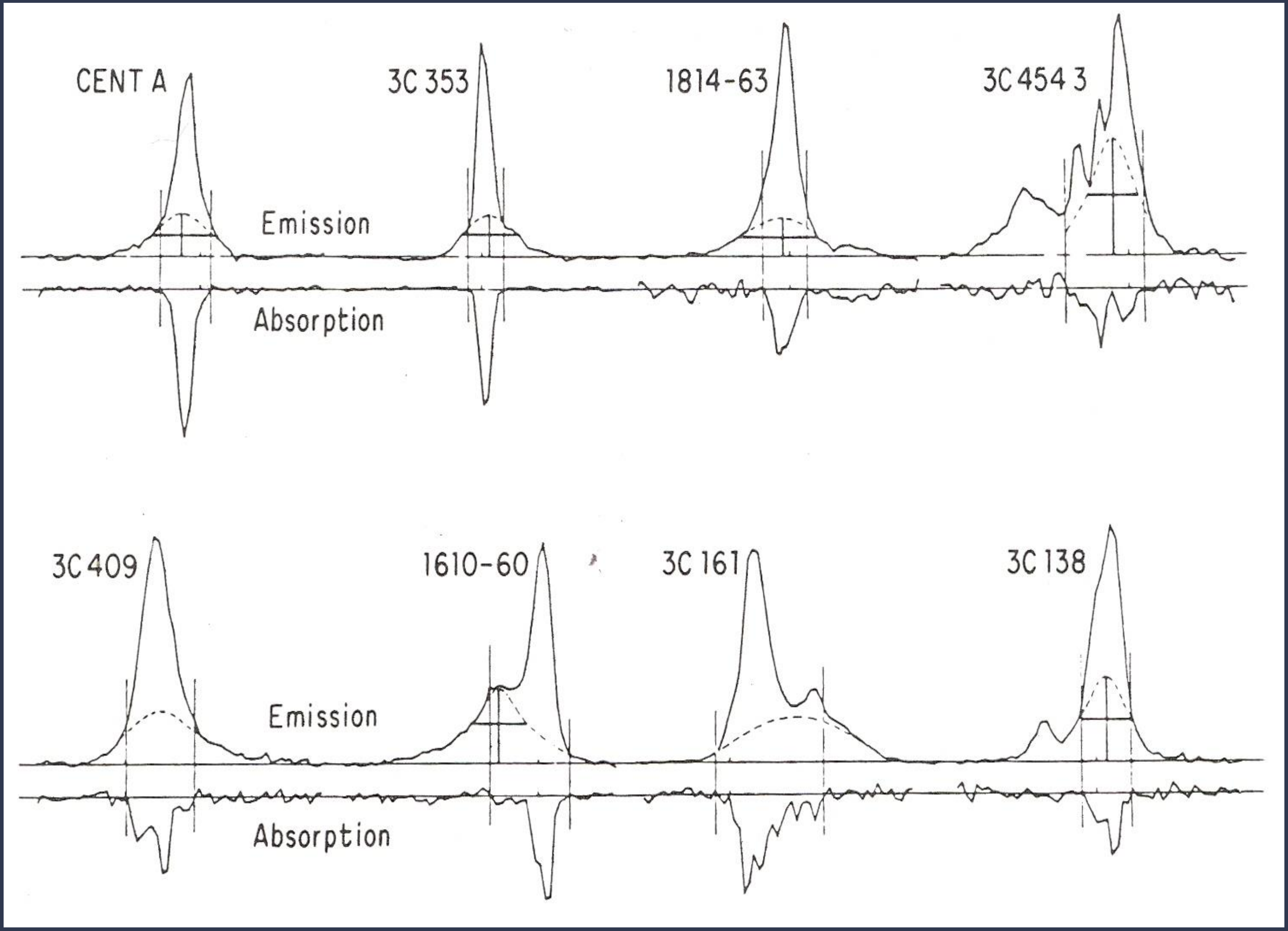
$$T_{\mathrm{off}}(v) = T_{\mathrm{bg}}e^{-\tau_v} + T_s(1 - e^{-\tau_v})$$

Assume that T_s and τ_v do not change between the on-source and off-source position.

Can now solve for T_s and τ_v separately.

Assumption: emission and absorption probe the same medium.
Is this true?

HI emission and absorption spectra



When emission, when absorption?

Take any HI spectrum, subtract the continuum (T_c), and call the result T_{sub}. Then an emission line will be positive in T_{sub} and an absorption line will be negative.

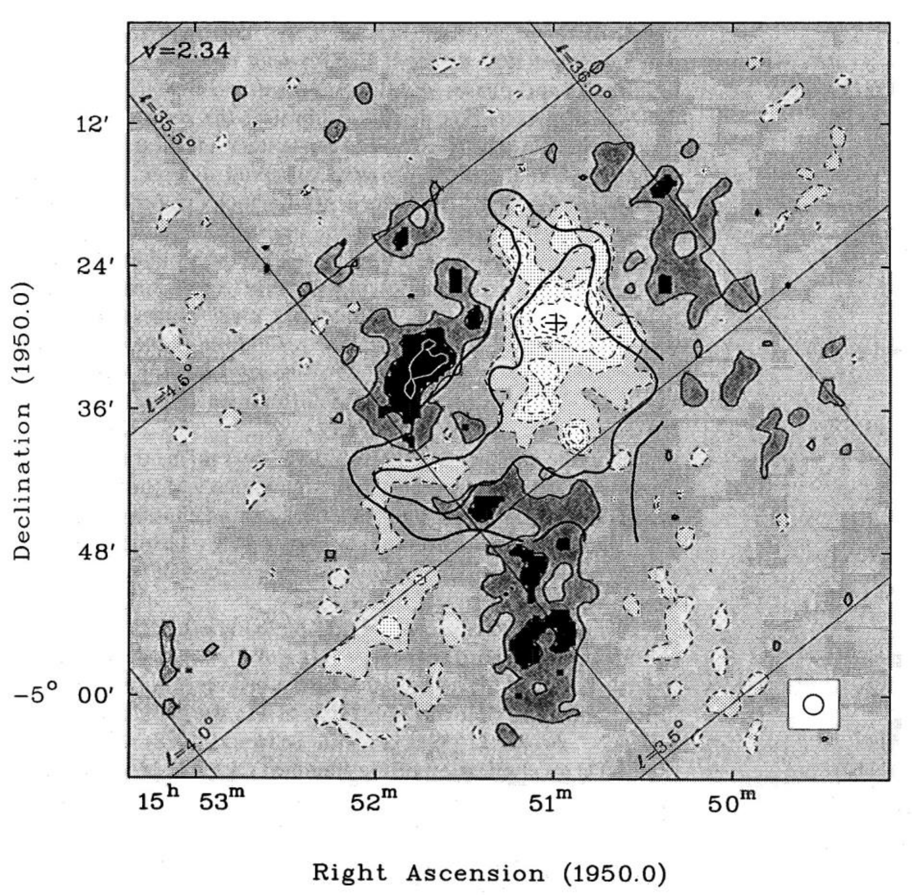
$$T_b = T_c e^{-\tau_\nu} + T_s(1 - e^{-\tau_\nu})$$

$$T_{\mathrm{sub}} = T_b - T_c = (T_s - T_c)(1 - e^{-\tau_\nu})$$

So: $T_s > T_c$ (weak background and/or warm gas): emission
$T_s < T_c$ (strong background and/or cold gas): absorption

note: gas with $T_s = T_c$ is invisible!

Temperature structure in the dark cloud L134



(Van der Werf *et al.*, 1988)

HI 21cm line emission from the dark cloud L134, observed with the VLA. The HI is seen against a warm background which is constant over the image. Dark shades are emission, light shades are absorption. Thick black contours denote optical extinction.

What do you conclude?

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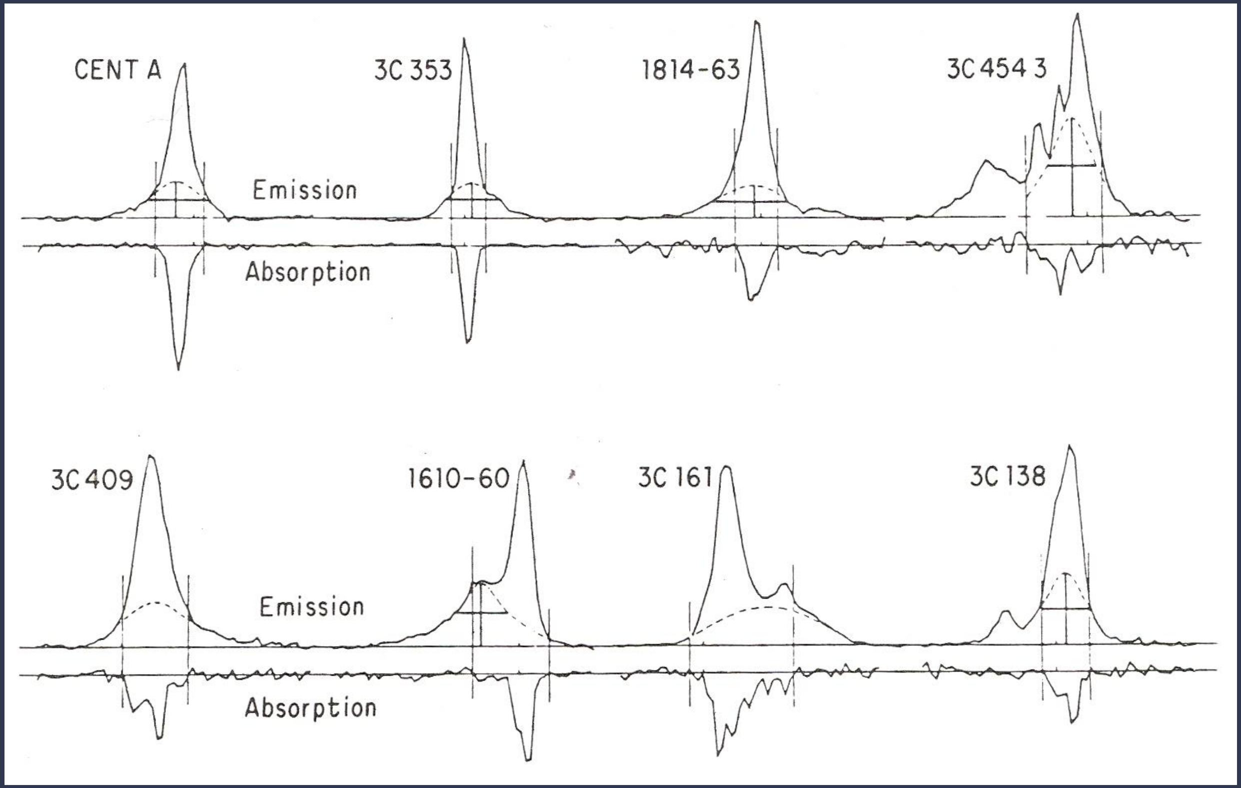
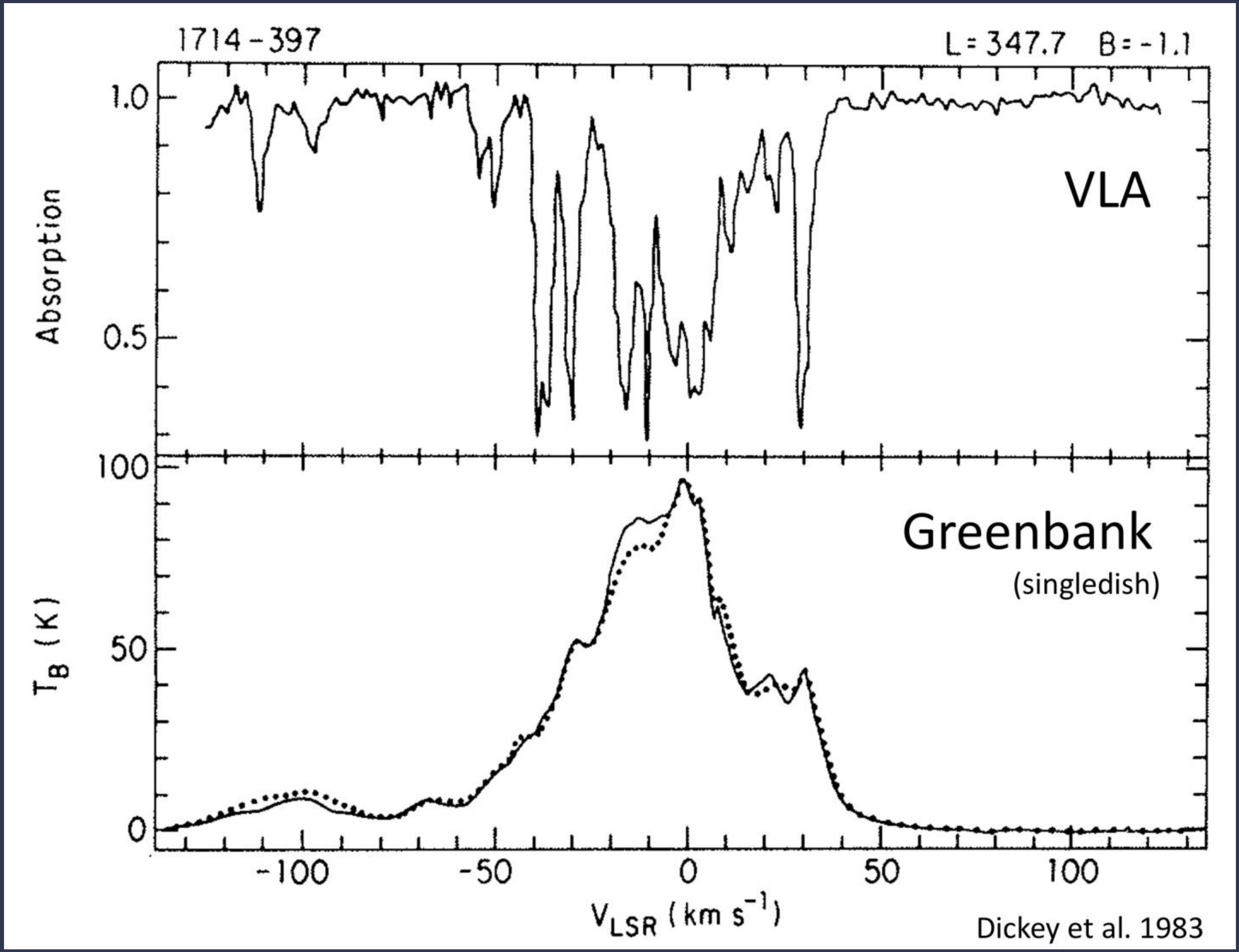
HI emission and absorption spectra



Note:
1. narrow emission peaks correspond to narrow absorption peaks
2. there are broad emission features without absorption

Evidence for 2 atomic phases: WNM and CNM



2-phase Interstellar Medium

Consider 2 clouds of equal *N*(HI)

- a cold cloud (T_{cold} < 100 K)
- a warm cloud (T_{warm} >> T_{cold})

Recall

$$\tau_\nu = \frac{3}{32\pi} \frac{1}{\sqrt{2\pi}} \frac{A_{ul}\lambda_{ul}^2}{\sigma_v} \frac{hc}{kT_s} e^{-\frac{u^2}{2\sigma_v^2}} N(\mathrm{HI})$$

So the cold cloud has a much higher optical depth (even more so because σ_v will also be smaller).

Emission from warm and cold clouds

Warm cloud: optically thin so

$$T_b = \tau_\nu T_s = \frac{3}{32\pi} A_{ul} \frac{hc\lambda_{ul}}{k} N(\mathrm{HI}) \varphi_\nu = \frac{220}{\mathrm{K}} \frac{N(\mathrm{HI})}{10^{21}\mathrm{cm}^{-2}} \frac{\mathrm{km\ s}^{-1}}{\sigma_v} e^{-\frac{u^2}{2\sigma_v^2}}$$

(for a Gaussian line)

So T_b scales with N(HI) (independently of T_{warm}) as long as the line is optically thin.

Cold cloud: optically thick so

$$T_b = T_{\mathrm{cold}}(1 - e^{-\tau_\nu}) < T_{\mathrm{cold}}$$

no matter how large N(HI) is.

So emission dominated by WNM, absorption by CNM

WNM and CNM

CNM: cool clouds with T_{kin} ~80 K cause the narrow emission peaks and the absorptions.

WNM: extended warm medium causes the broad emission features without detectable absorption.

Temperature hard to determine:

- Δv ~9 km s^{-1} → $T_{kin} < 10^4$ K
- limits on τ → $T_{kin} > 3000$ K → conclude that T_{kin} ~ 8000 K

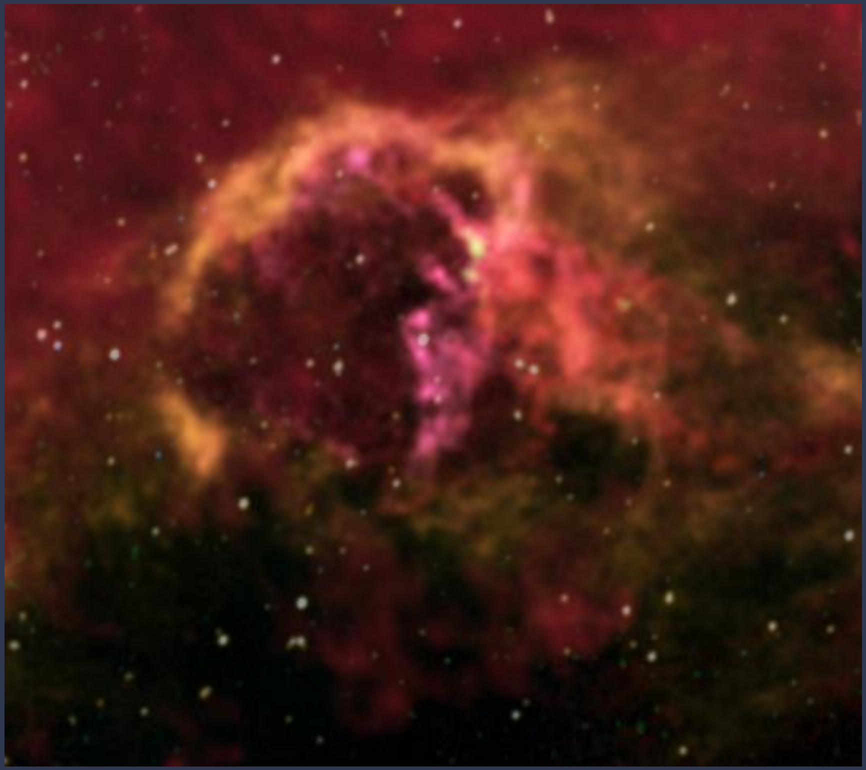
WNM is distributed throughout Milky Way with substantial filling factor

⇒ "raisin-pudding" model of ISM

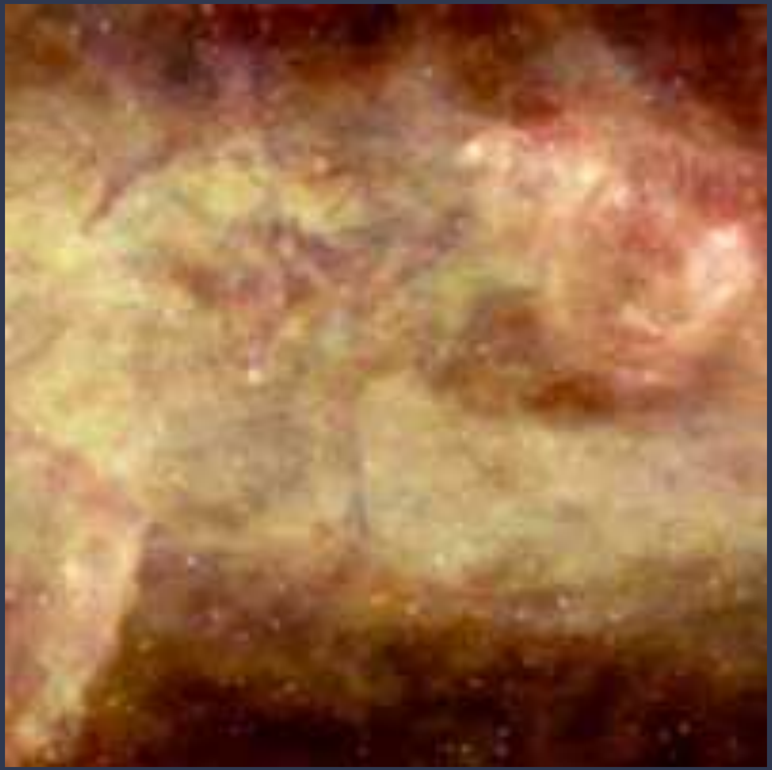
Scale height of WNM 250-500 pc >> scale height of CNM

Small scale structure in the HI emission

Canadian Galactic Plane Survey



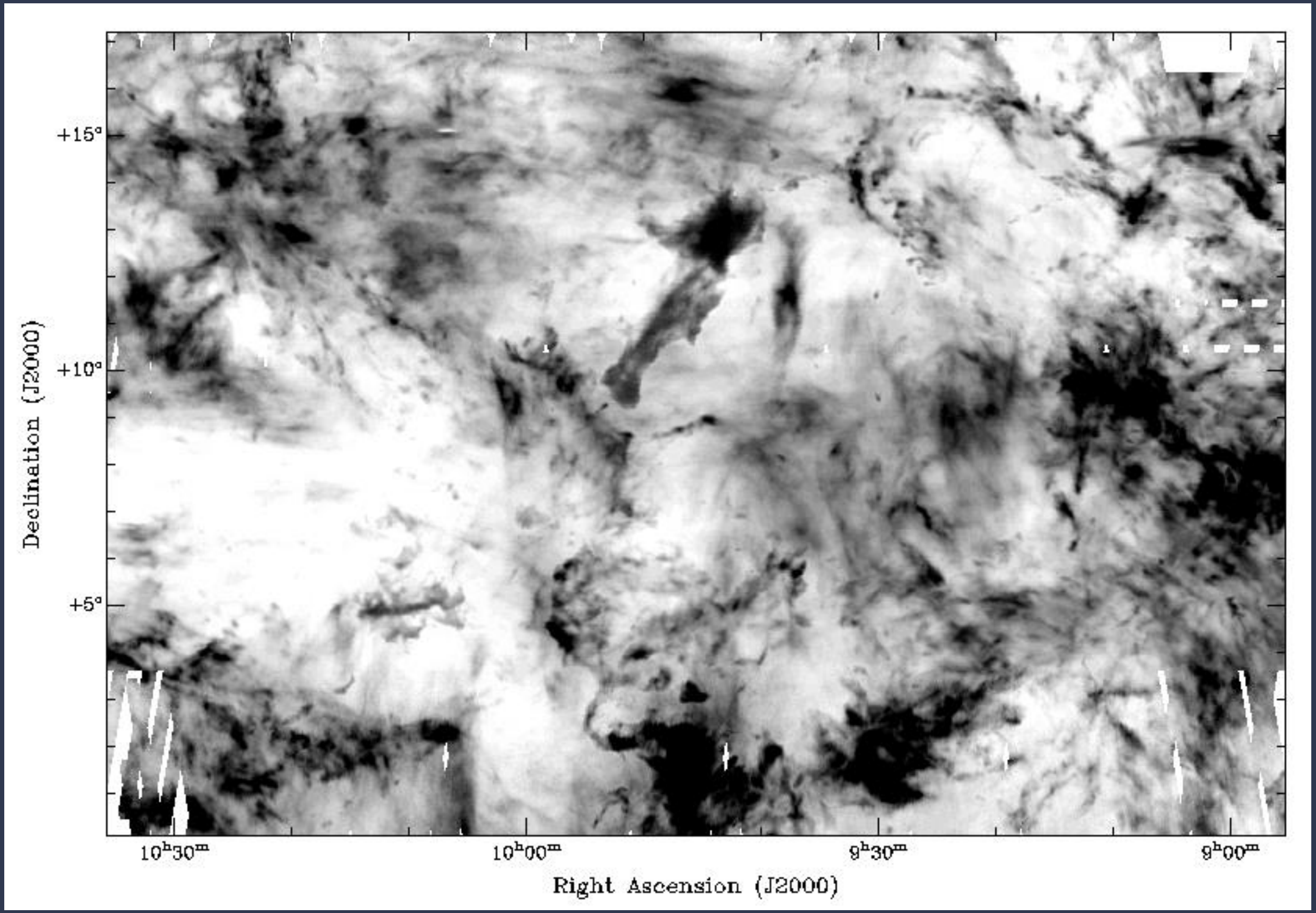
expanding shells



cool absorbing layers in front of a warm background

Small scale structure in the HI emission

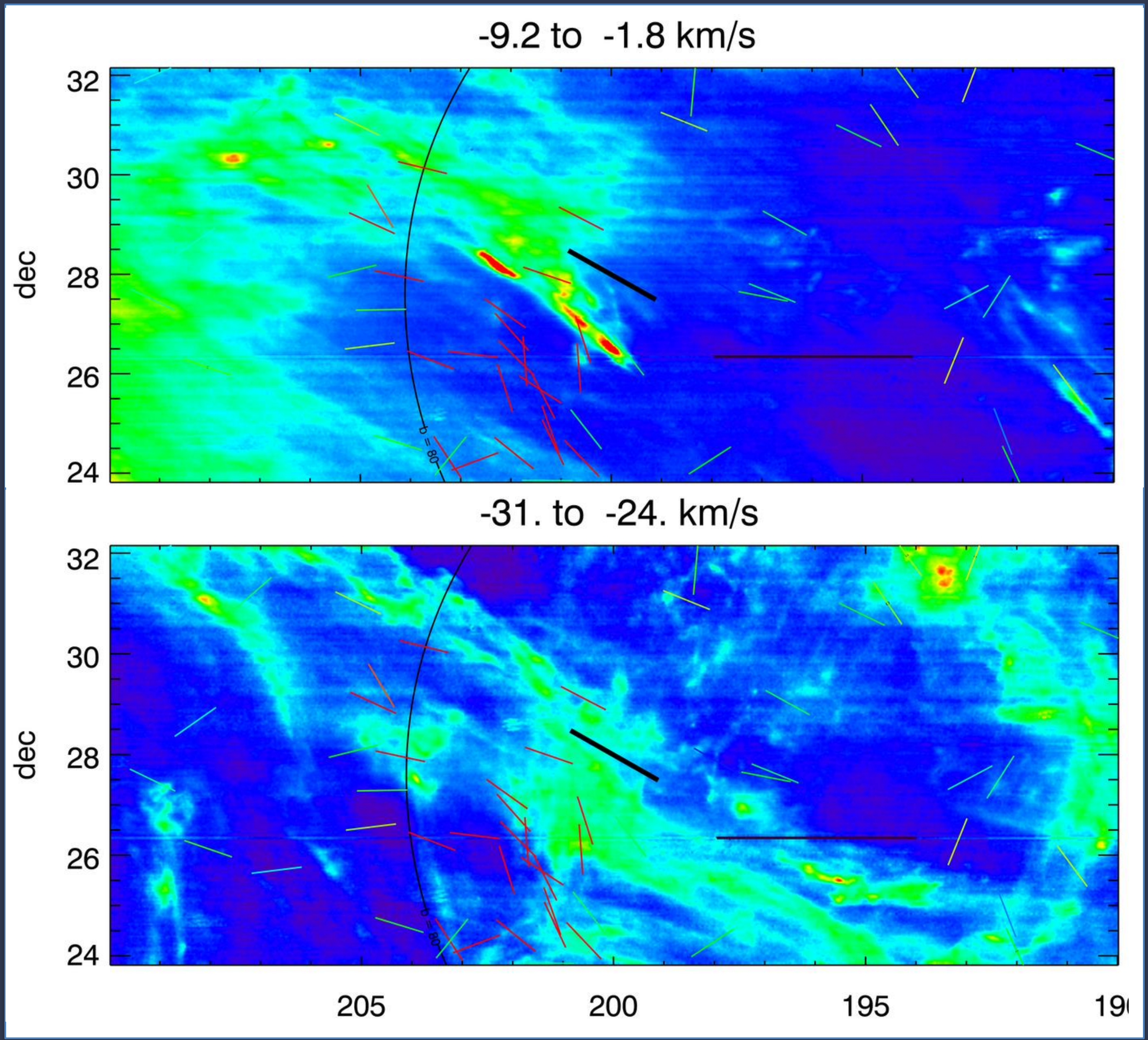
GALPHA Survey



What causes these structures? Shocks, turbulence, instabilities?

Narrow HI filaments

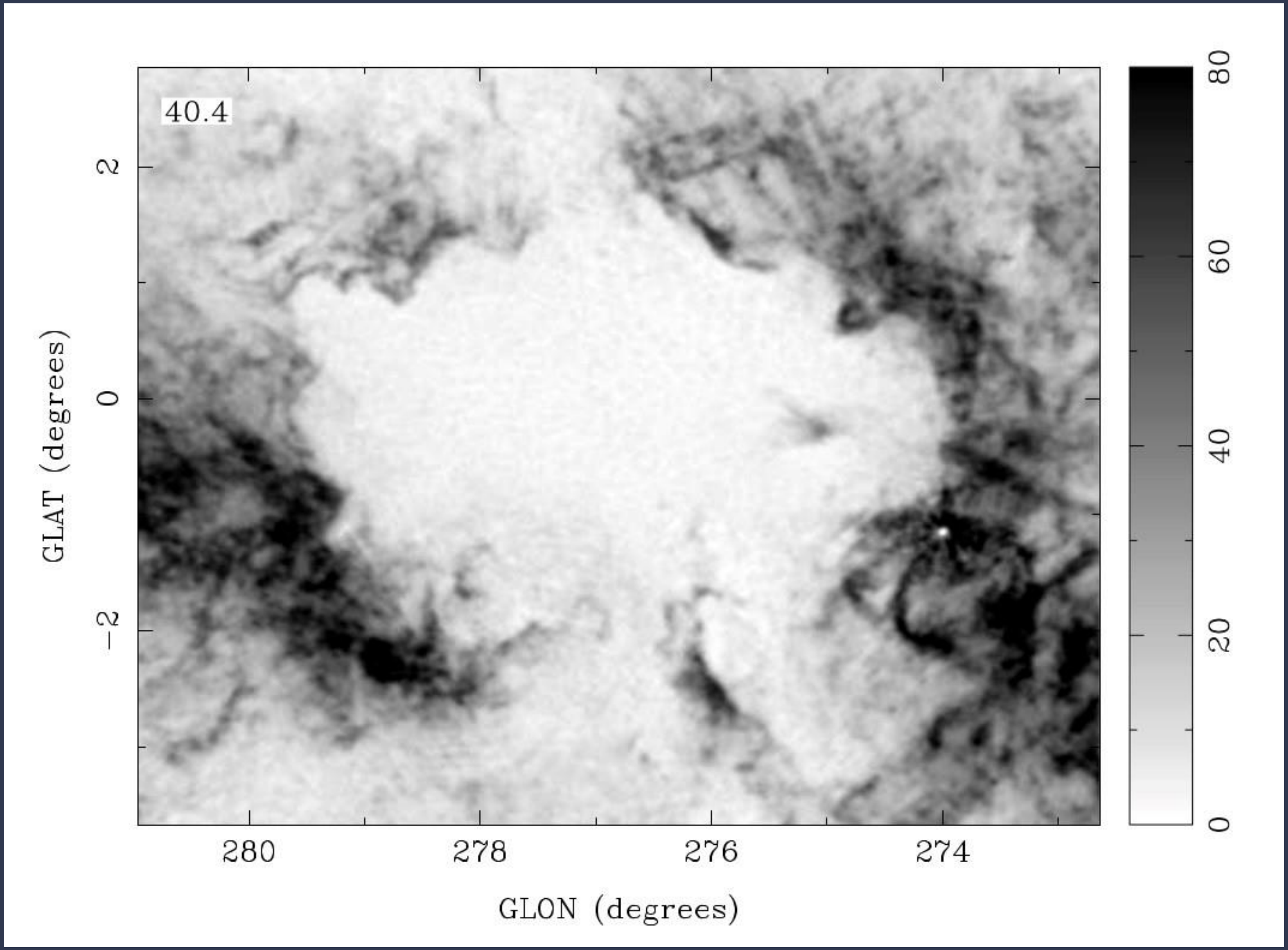
GALPHA Survey



bars show optical polarization (magnetic field); thick bar is vector average

thin filaments are aligned with the magnetic field

HI supershells and chimneys



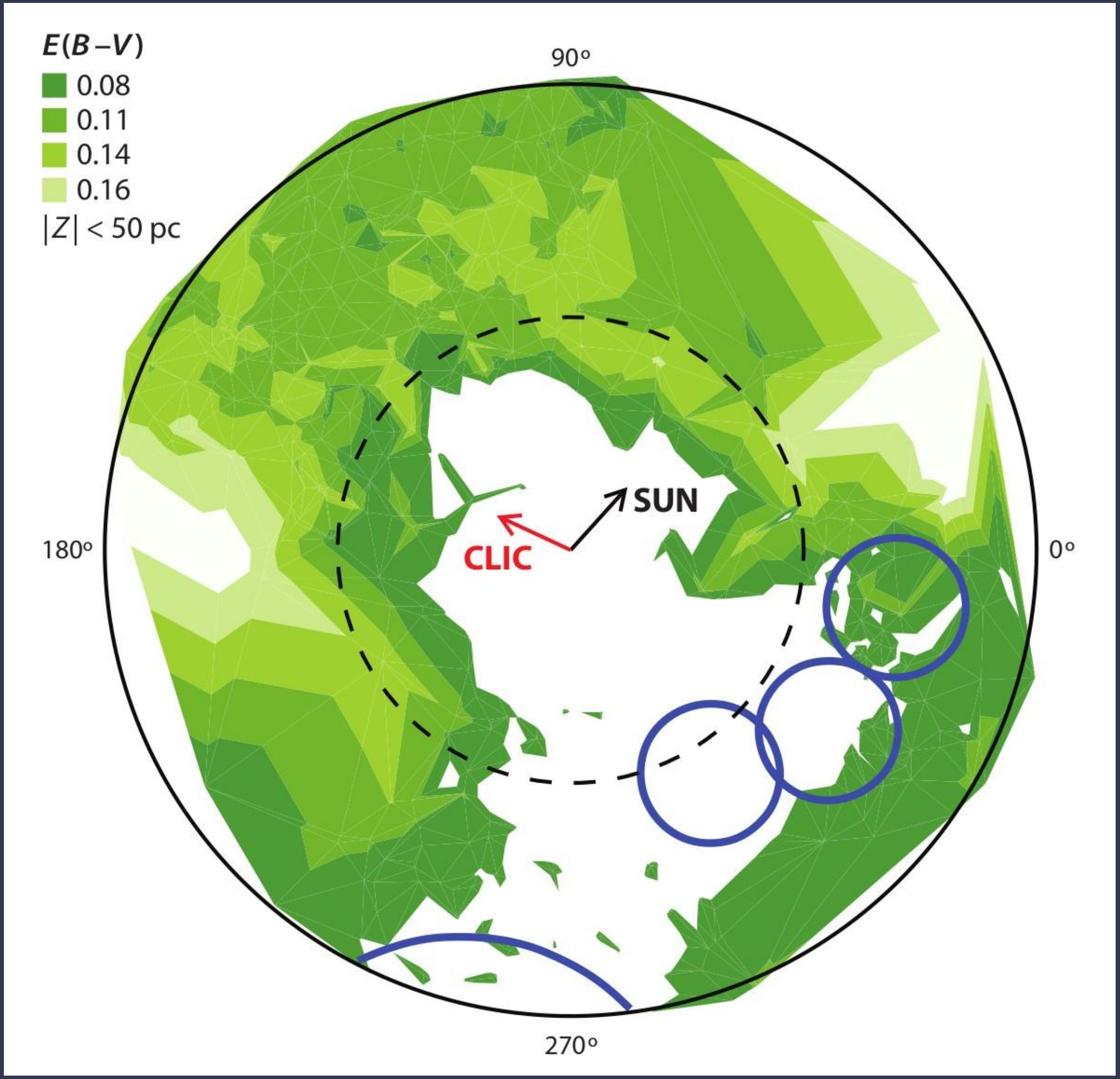
(McClure-Griffiths *et al.*, 2003)

The Local Bubble

CLIC: Complex of Local Interstellar Clouds

Blue circles: associations of nearby stars

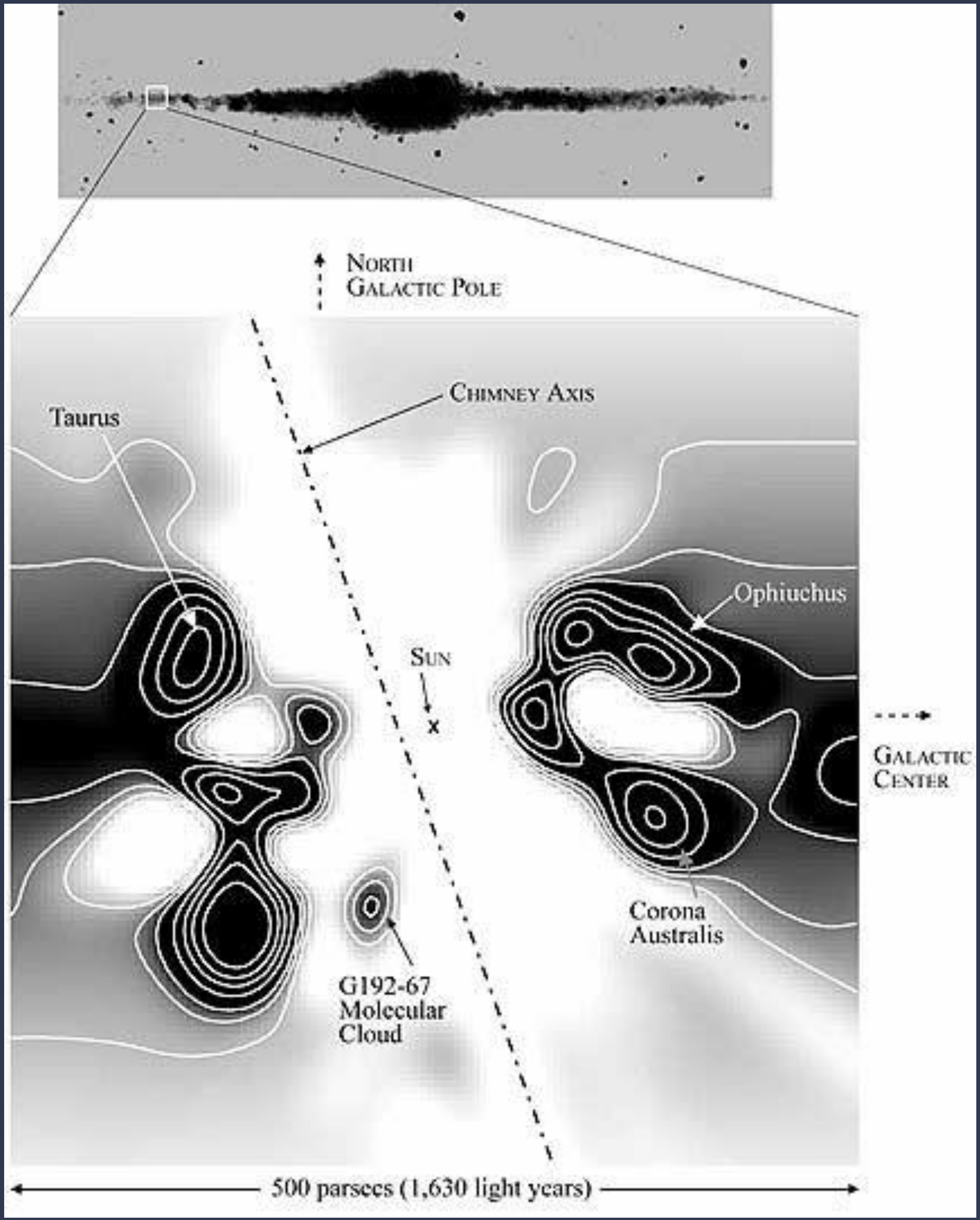
Outer black circle: radius 200 pc.



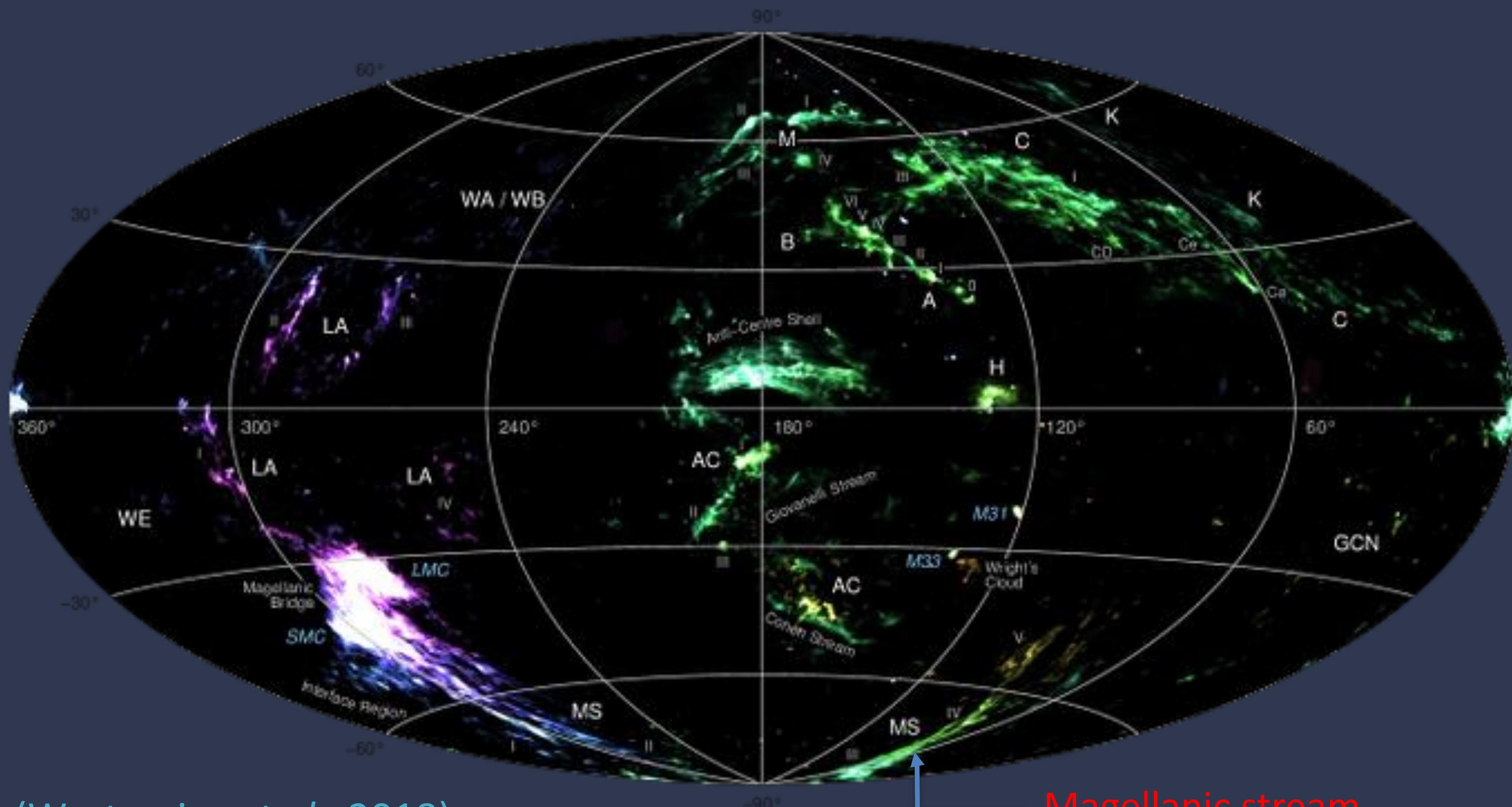
(Frisch *et al.*, 2011)

The Local Bubble

"Vertical" view



High-velocity clouds



Magellanic stream

(Westmeier *et al.*, 2018)

High velocity clouds

1. Distances hard to estimate → masses very uncertain

2. Some associated with tidal features from satellite galaxies (e.g., Magellanic stream)

3. Suggestions for origin (probably several correct answers):
   - Tidal debris
   - Left over from Milky Way formation (Oort)
   - Returning from Galactic fountain
   - Milky Way feeding from IGM
   - Massive gas reservoirs in Local Group (Blitz)

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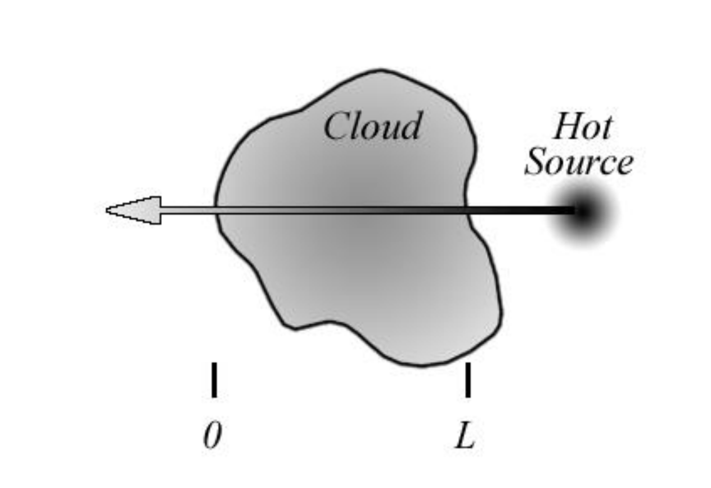
Optical/UV absorption lines

Recall $I_\nu = I_\nu(0)e^{-\tau_\nu} + B_\nu(T_{ex})(1 - e^{-\tau_\nu})$

In the optical/UV mostly permitted transitions with large A_{ul}

→ most particles are in ground state

→ T_{ex} extremely small

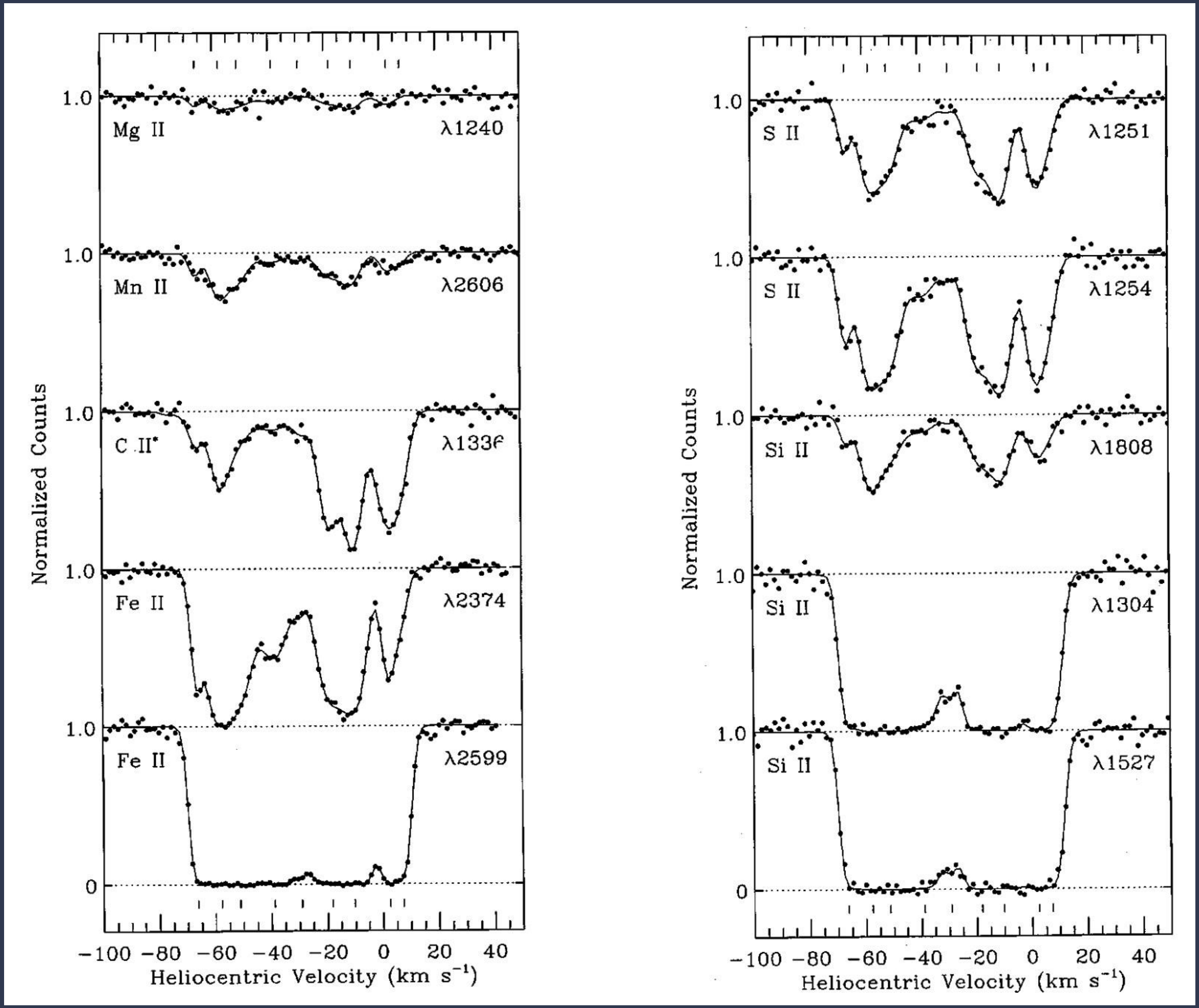


So $I_\nu = I_\nu(0)e^{-\tau_\nu}$

So flux density $F_\nu = F_\nu(0)e^{-\tau_\nu}$

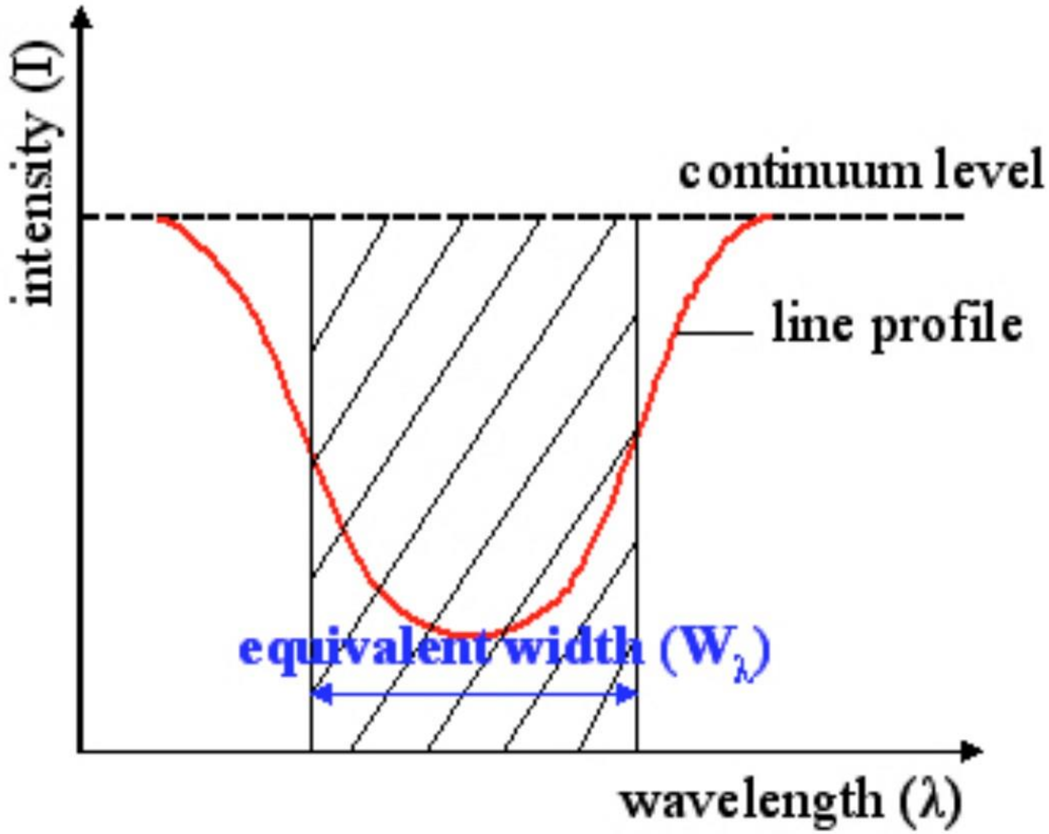
Measure optical depth to get lower level (= total) column density of the species.

Interstellar absorption lines



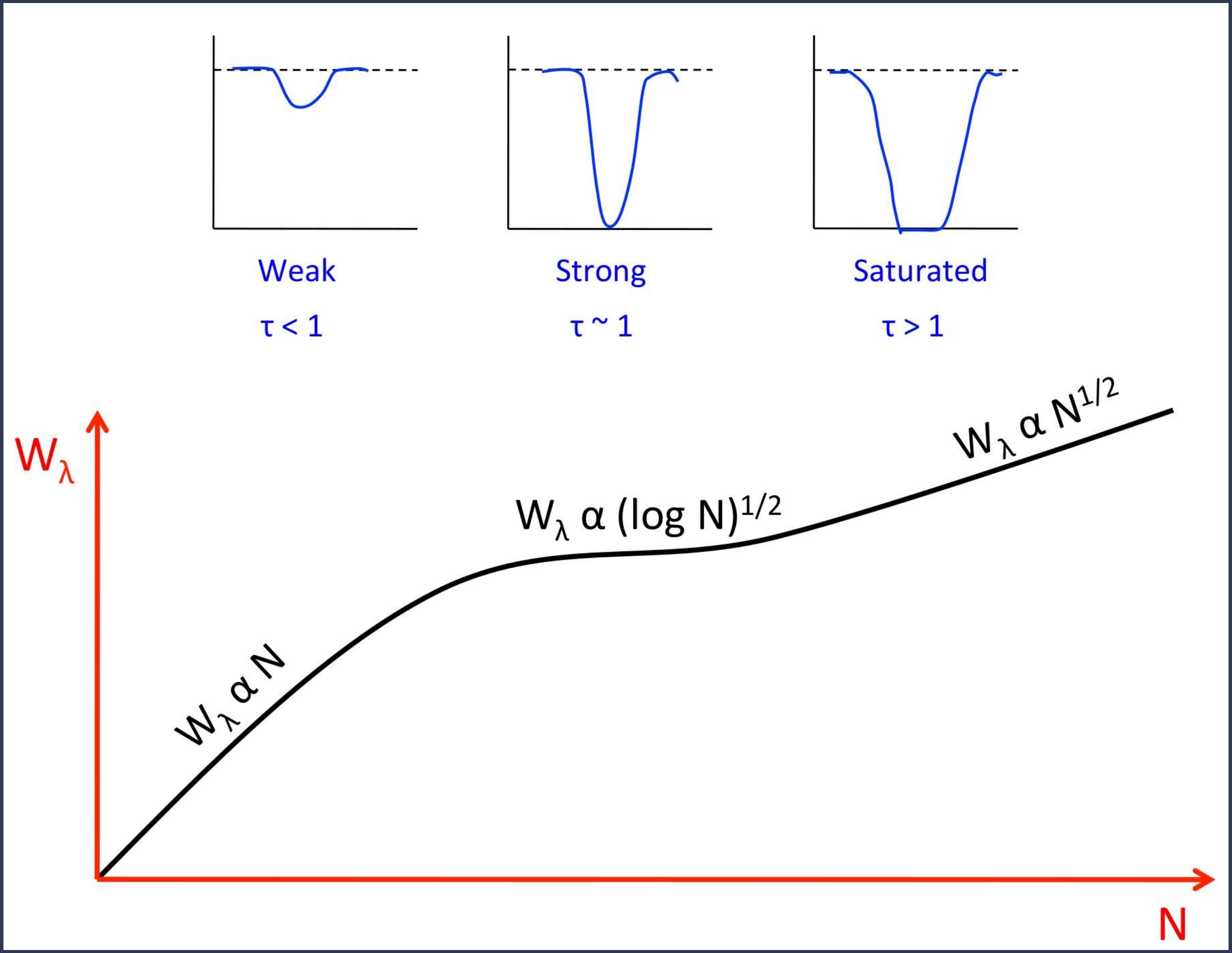
(Savage & Sembach, 1996)

Equivalent width



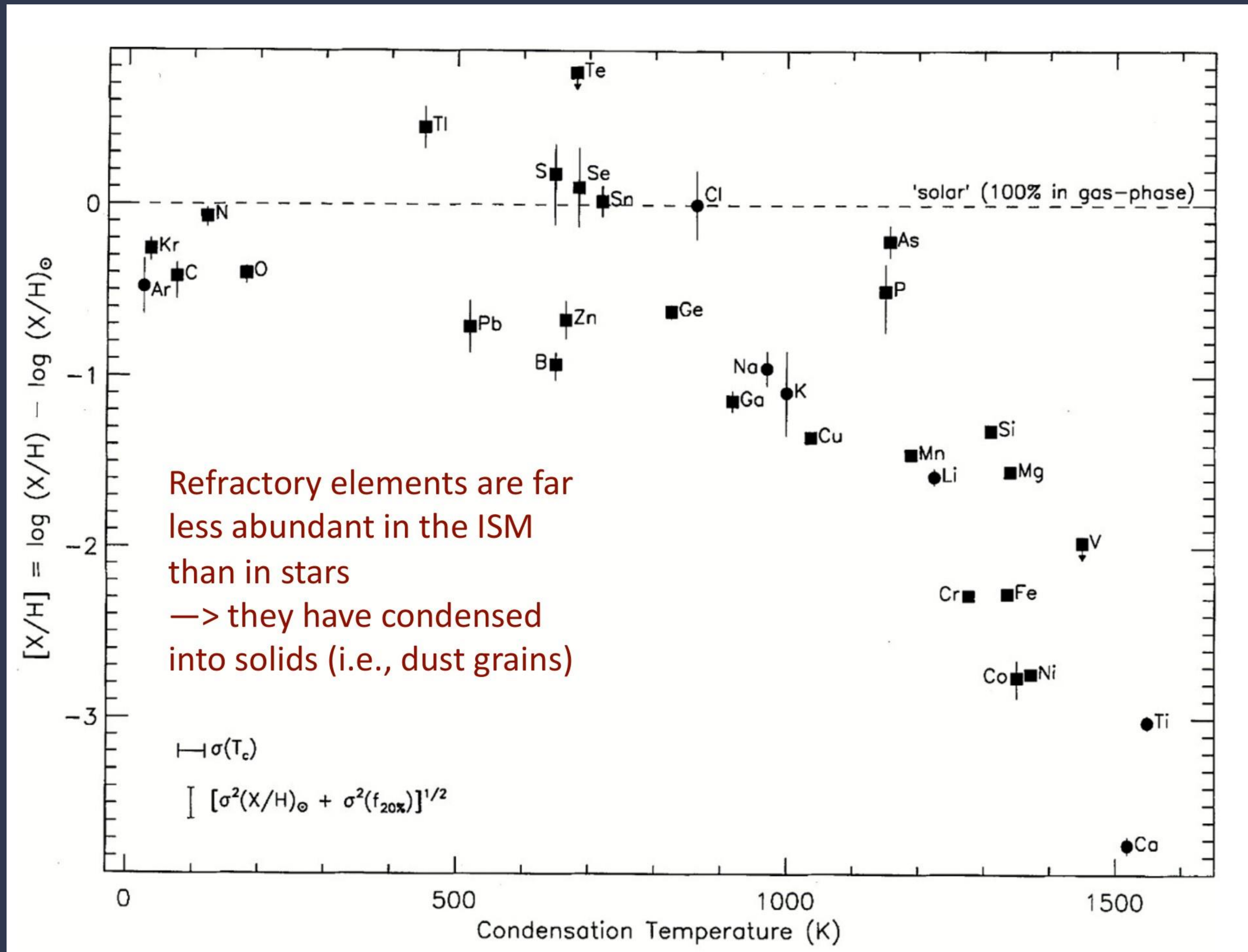
http://commons.wikimedia.org

Curve of Growth



(credit:
Jonathan Williams)

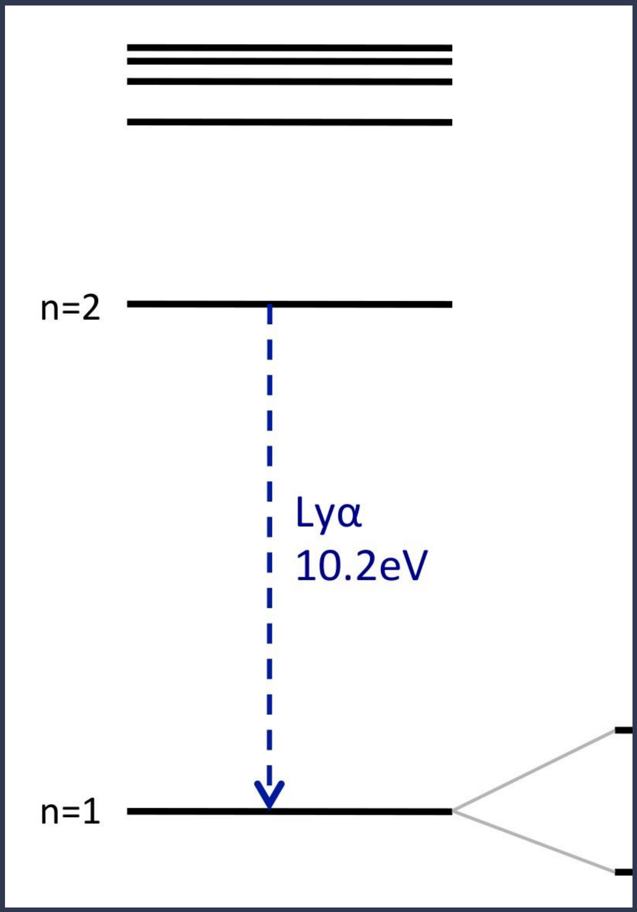
Depletion of heavy elements



Refractory elements are far less abundant in the ISM than in stars
—> they have condensed into solids (i.e., dust grains)

(Savage & Sembach, 1996)

Lyman α absorption



HI Lyα

n = 1 → 2

λ = 1215 Å

A_{ul} = 6.265 · 10^8 s^{-1}

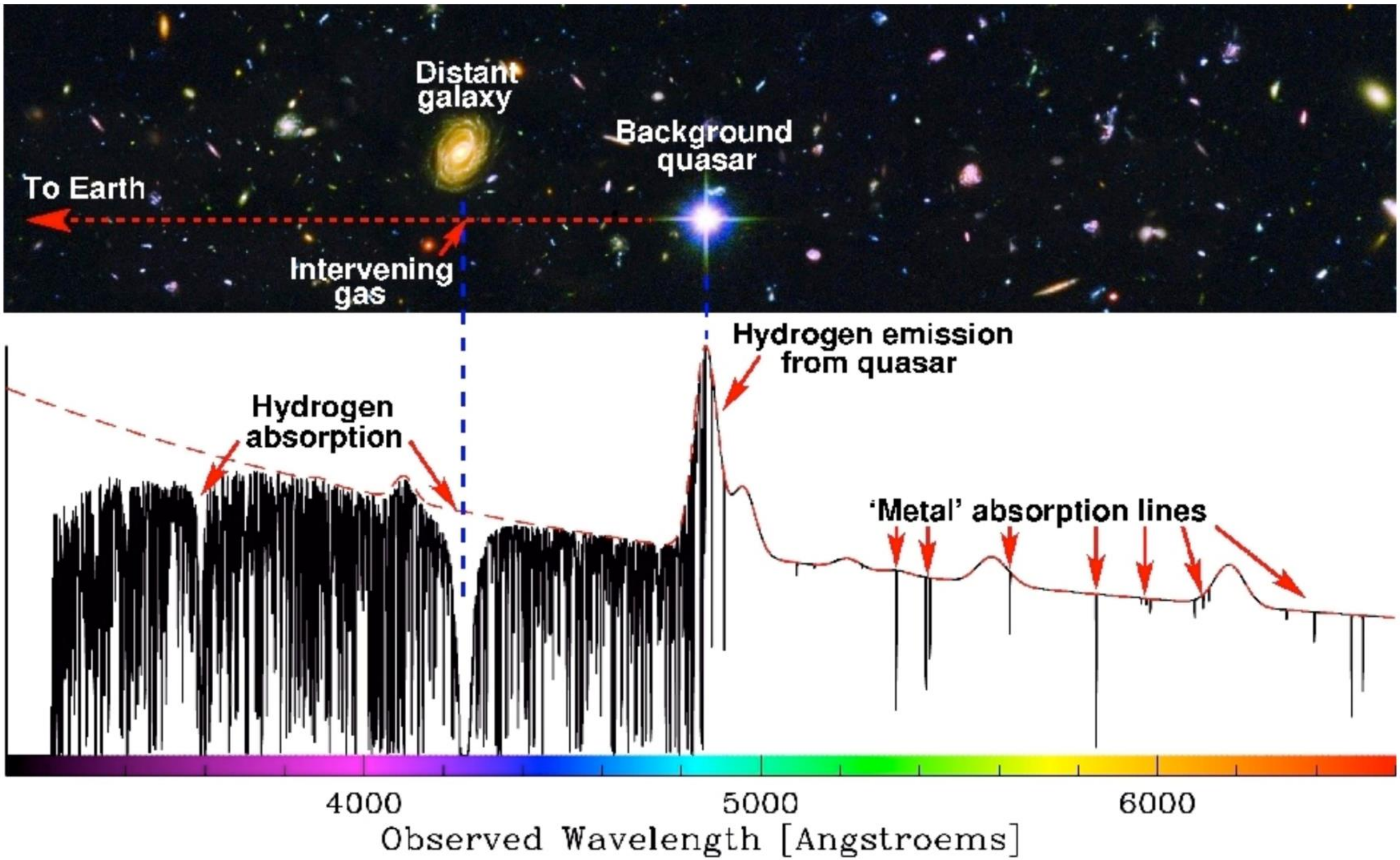
Using the same methods as before, we can derive

$$\tau_\nu = 0.54\, \frac{N(\mathrm{HI})}{10^{13}\mathrm{cm}^{-2}}\, \frac{10\ \mathrm{km\ s}^{-1}}{\sigma_v}\, e^{-\frac{u^2}{2\sigma_v^2}}$$

So Lyα absorption is sensitive to *extremely* small HI column densities

→ Lyman α forest (Intergalactic Medium)

Intergalactic absorption lines



Picture credit: J. Liske (ESO)

Damped Lyα systems

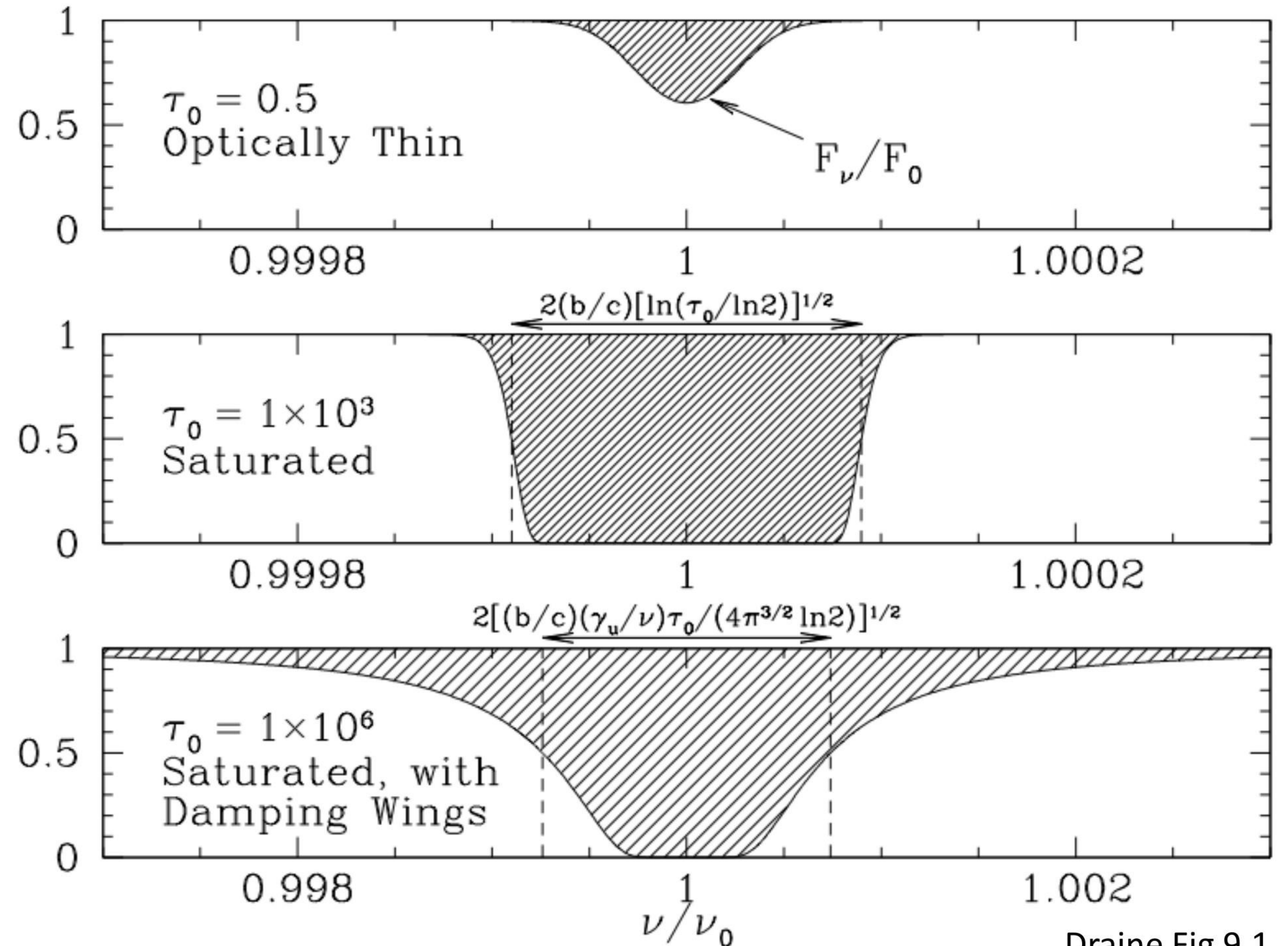
Galactic disks have $N(\mathrm{HI}) > 10^{20}$ cm^{-2}

→ τ_{peak} (Lyα) > 10^6

Absorption profiles are then totally dominated by "damping wings" (Lorentz profile): damped Lyman α systems.

These reveal galactic disks along the line of sight. Using metal absorption lines from the same disks, we can also measure abundances and some local excitation conditions.

Absorption line profiles



Draine Fig 9.1

Next lecture

Ionization and recombination

1. Photoionization
2. Radiative recombination
3. Recombination line spectra