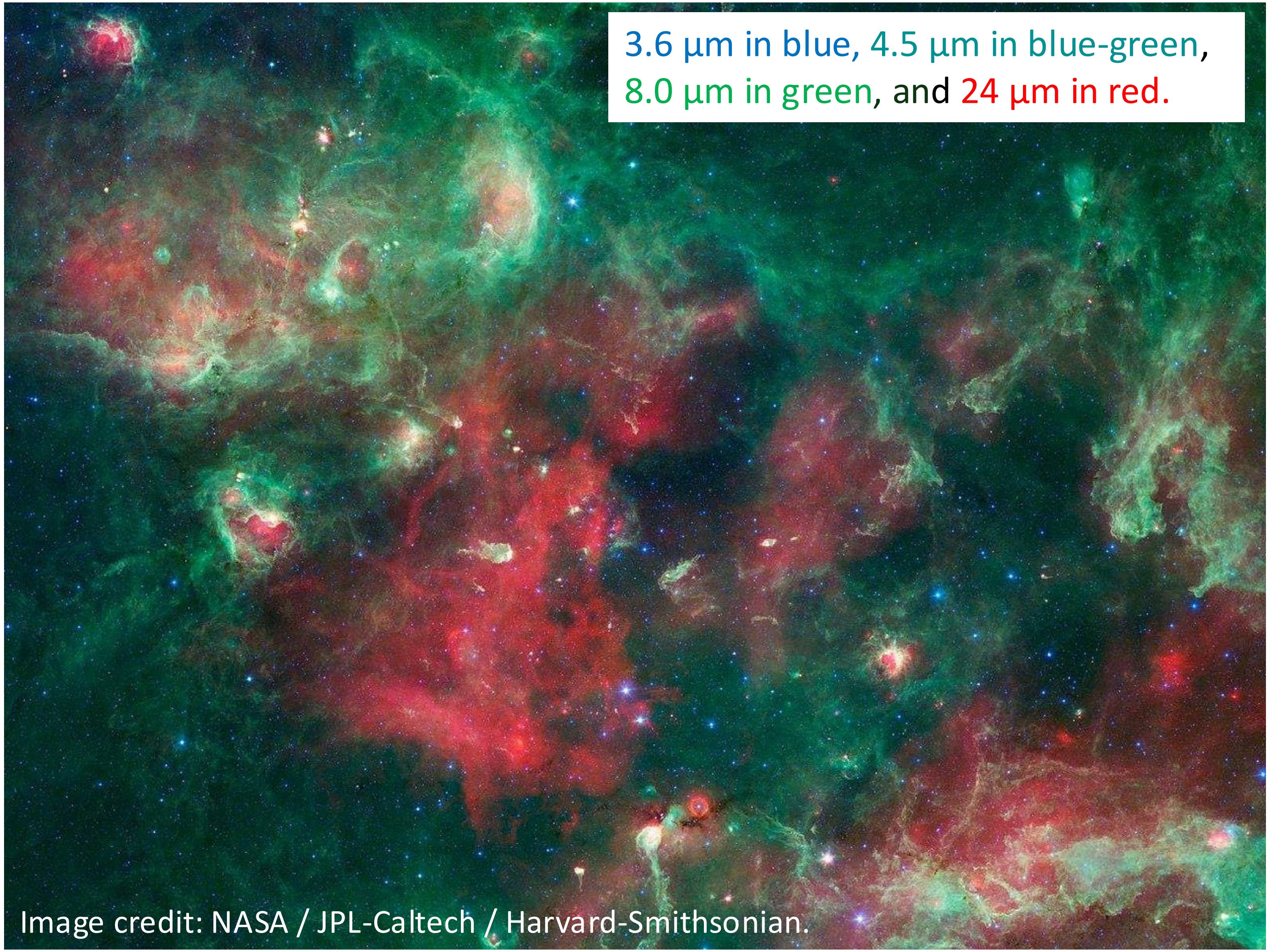
Ionized Gas

HII Regions
Recombination Lines
Free-Free Emission

Cygnus X Star Forming region as imaged by the Spitzer Space Telescope →



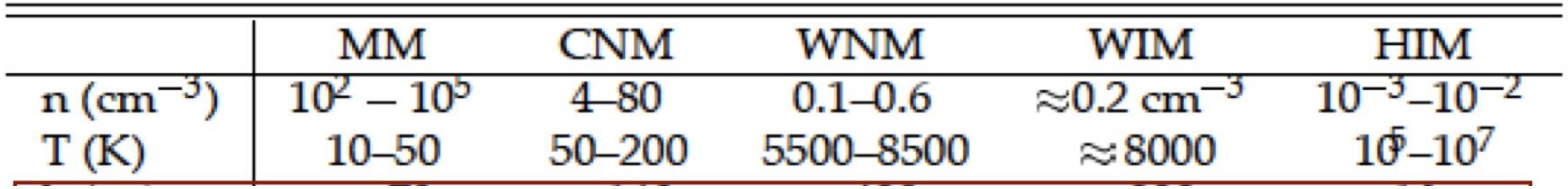
3.6 µm in blue, 4.5 µm in blue-green, 8.0 µm in green, and 24 µm in red.

Image credit: NASA / JPL-Caltech / Harvard-Smithsonian.

Reminder: ISM Phases

Main topics to cover:
- **Molecular Emission**
- **Recombination Lines**
- **HI 21cm line**
- **Masers**

- HIM: Hot ionized medium (e.g. X-rays)
- WIM: Warm ionized medium HII region(e.g. H⟨)
- WNM: Warm neutral medium (e.g. HI emission)
- CNM: Cold neutral medium (e.g. HI absorption)
- MM: Molecular medium (e.g. CO)



	MM	CNM	WNM	WIM	HIM
n (cm^{-3})	10^2 – 10^5	4–80	0.1–0.6	≈0.2 cm^{-3}	10^{-3}–10^{-2}
T (K)	10–50	50–200	5500–8500	≈8000	10^5–10^7

(See also Table 1.3 in Draine "Physics of the Interstellar and Intergalactic Medium")

Reminder: ISM Phases

HII Regions (ERA 4.2)

See also Draine, Section 1.1 & Chapter 11

- Interstellar gas is primarily hydrogen and helium, plus trace amounts of heavier elements such as carbon, nitrogen, oxygen, neon, silicon, and iron (aka **metals**)

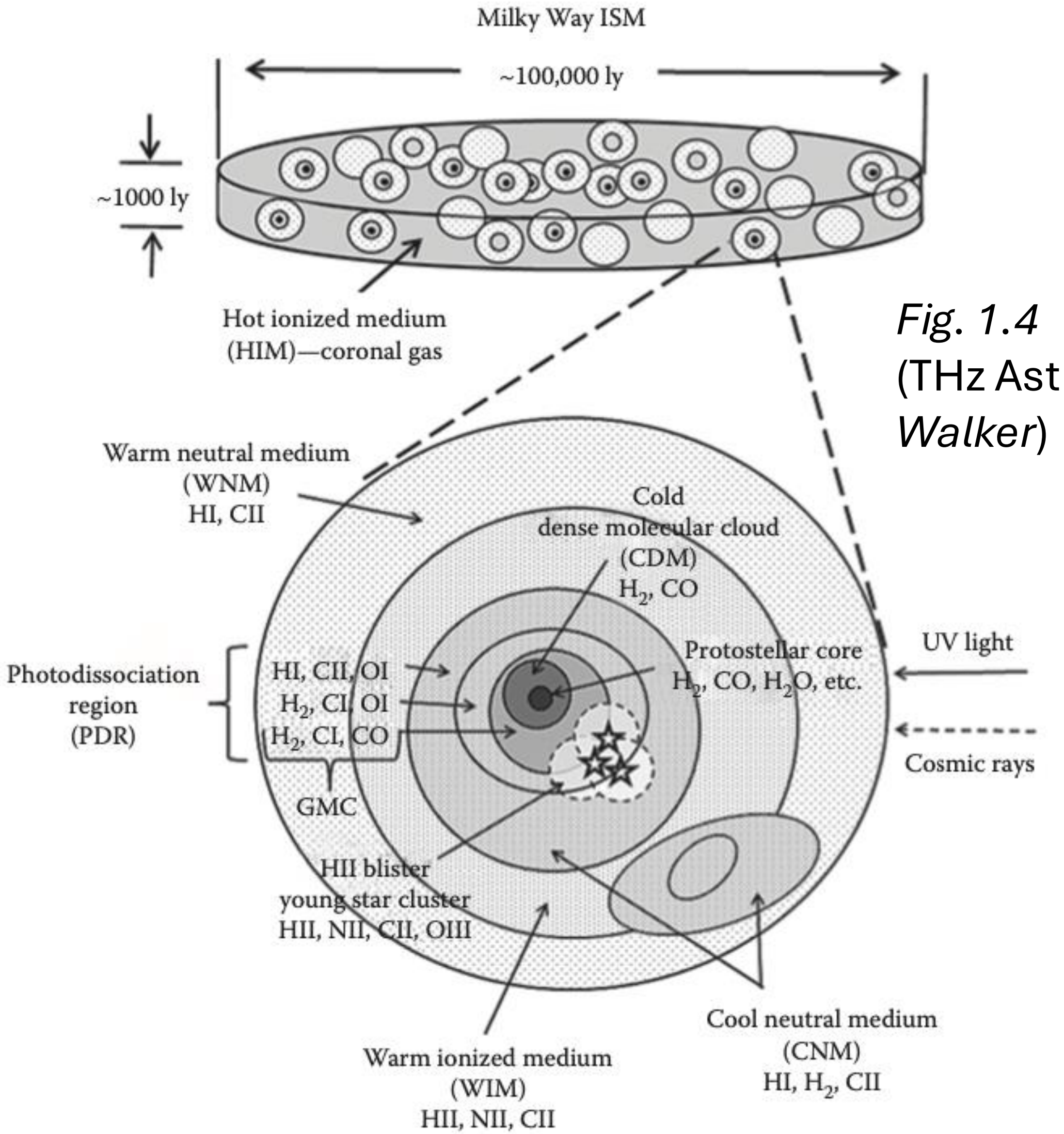


Fig. 1.4
(THz Astronomy, *Walker*)

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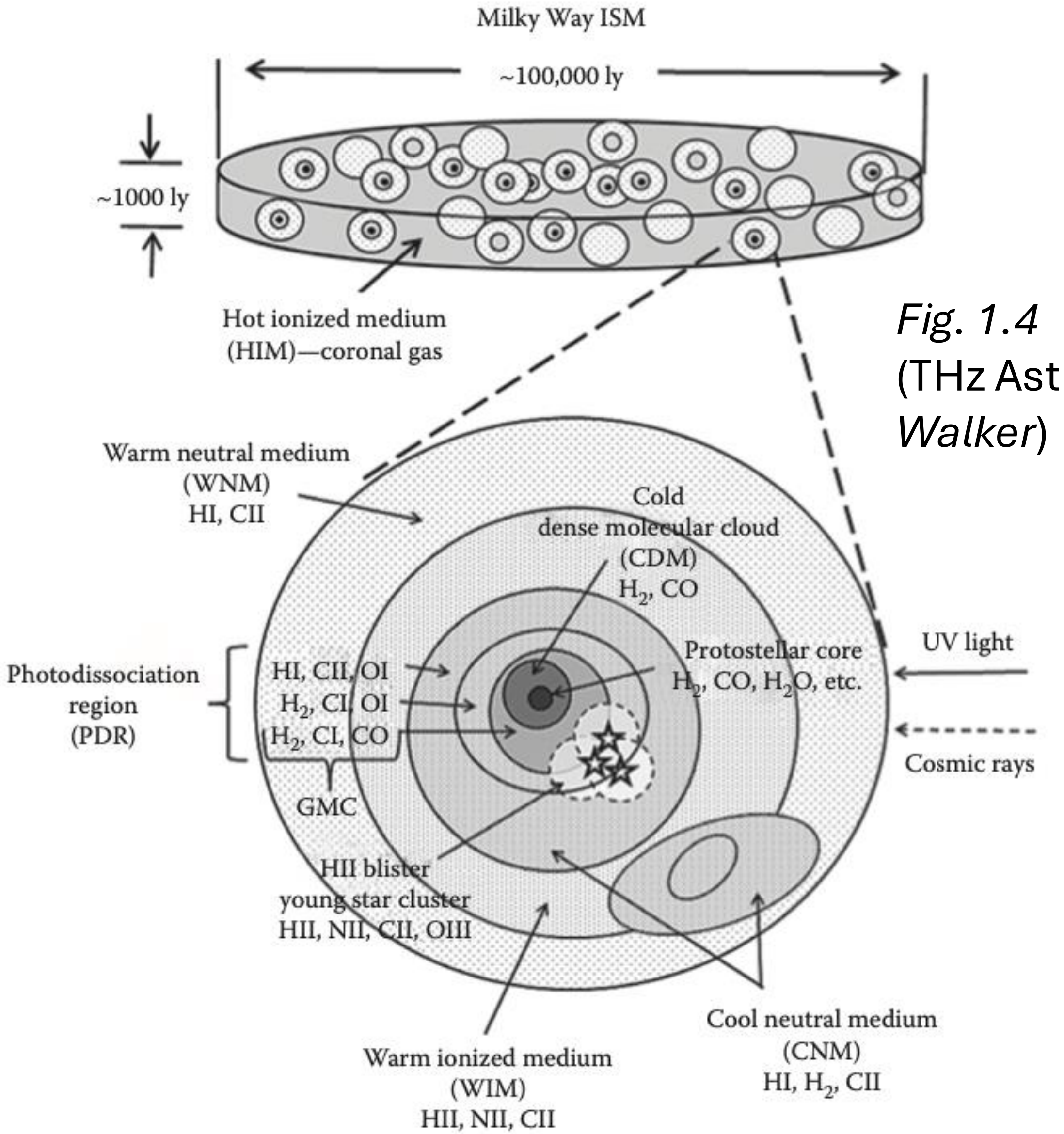
- Interstellar gas is primarily hydrogen and helium, plus trace amounts of heavier elements such as carbon, nitrogen, oxygen, neon, silicon, and iron (aka **metals**)
- Much of the interstellar hydrogen is in the form of neutral atoms (HI) or diatomic molecules (H2), but some is **ionized**



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(THz Astronomy, *Walker*)

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- Much of the interstellar hydrogen is in the form of neutral atoms (HI) or diatomic molecules (H2), but some is **ionized**
- The **singly ionized hydrogen atom** H+, when a single electron is stripped, it is **referred to as HII** by astronomers, doubly ionized oxygen O++ is called OIII, triply ionized carbon C+++ is called CIV, etc.

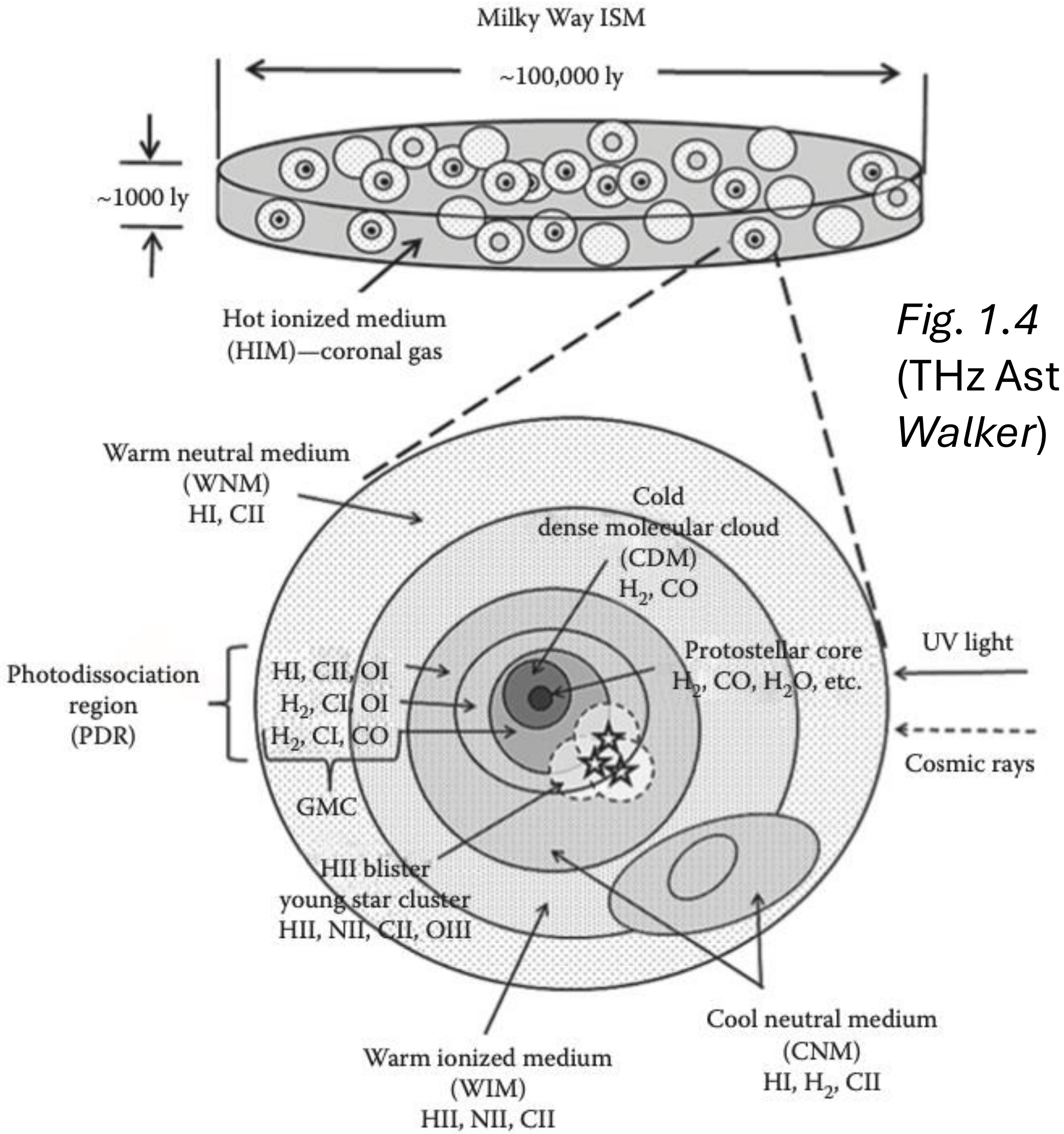

Fig. 1.4
(THz Astronomy, *Walker*)

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The **hot ionized medium (HIM—coronal gas) takes up half or more of the Milky Way's volume**, followed in relative volume by the warm neutral medium (WNM—warm HI gas), warm ionized medium (WIM—which includes dense and diffuse PDRs), cool neutral medium (CNM—cool HI clouds), and last, but not least, the cold dense medium (CDM—within GMCs), from which all stars are born.

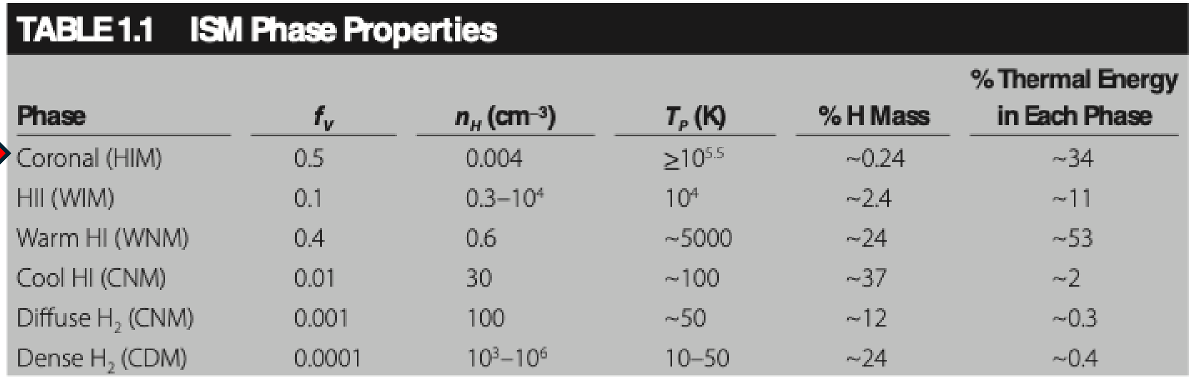
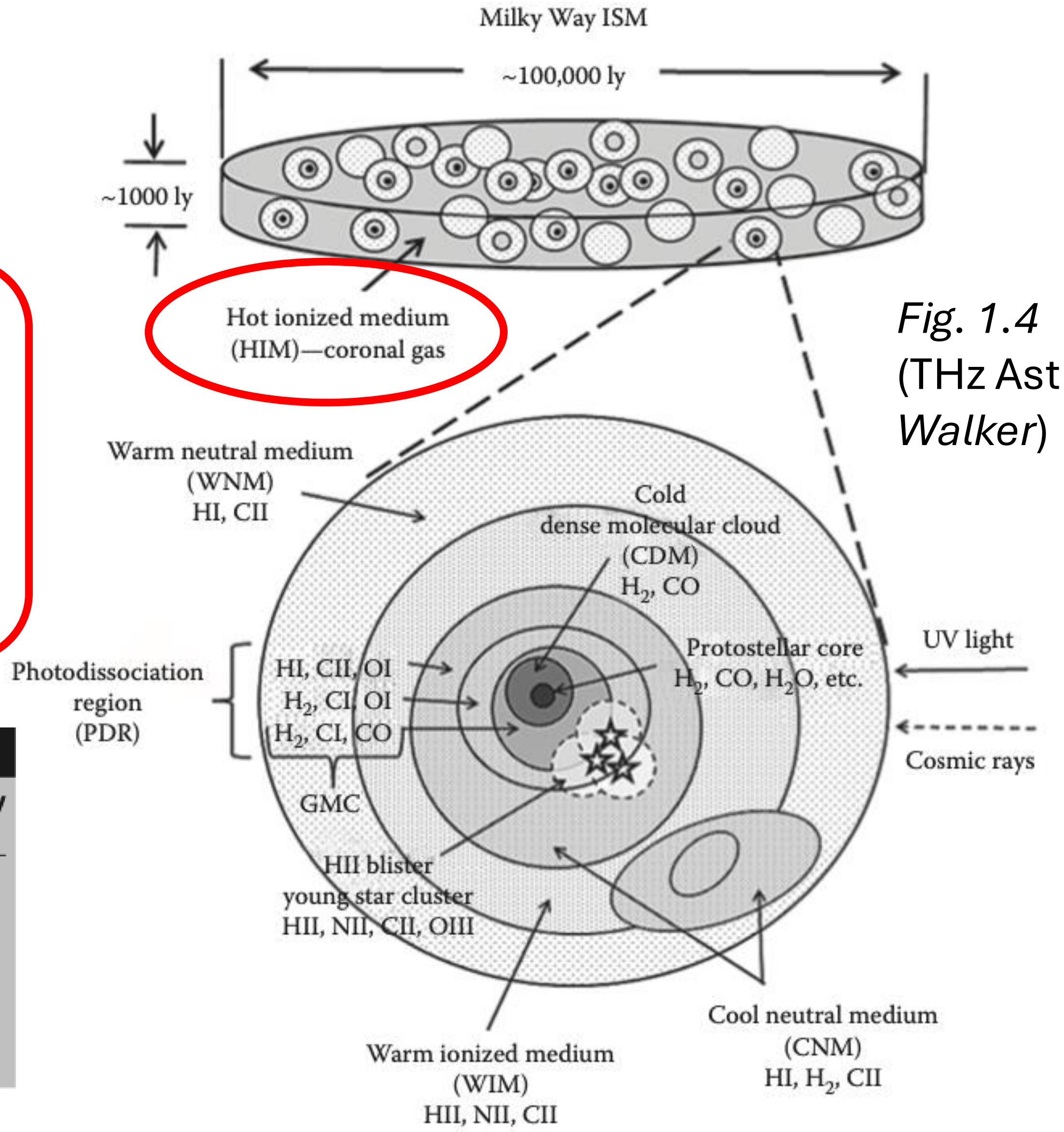


TABLE 1.1 ISM Phase Properties

Phase	f_V	n_H (cm^{-3})	T_P (K)	% H Mass	% Thermal Energy in Each Phase
Coronal (HIM)	0.5	0.004	$\geq 10^{5.5}$	~0.24	~34
HII (WIM)	0.1	0.3–10^4	10^4	~2.4	~11
Warm HI (WNM)	0.4	0.6	~5000	~24	~53
Cool HI (CNM)	0.01	30	~100	~37	~2
Diffuse H_2 (CNM)	0.001	100	~50	~12	~0.3
Dense H_2 (CDM)	0.0001	10^3–10^6	10–50	~24	~0.4



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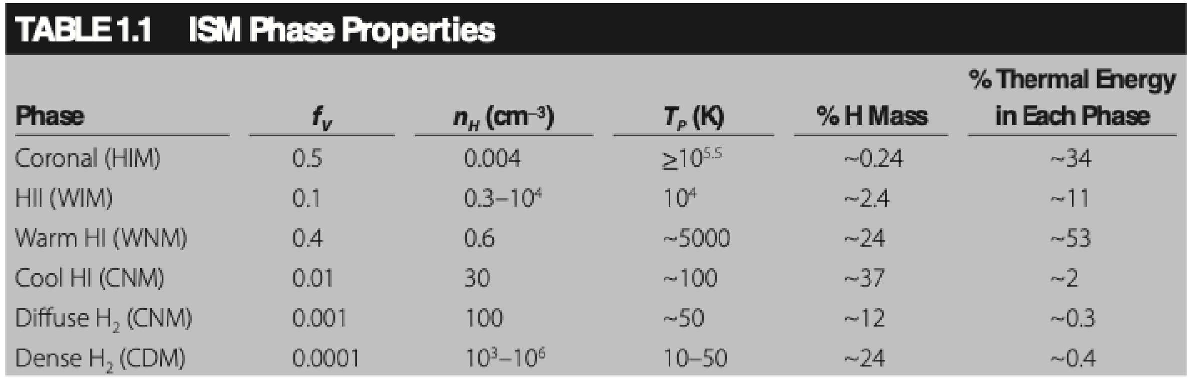

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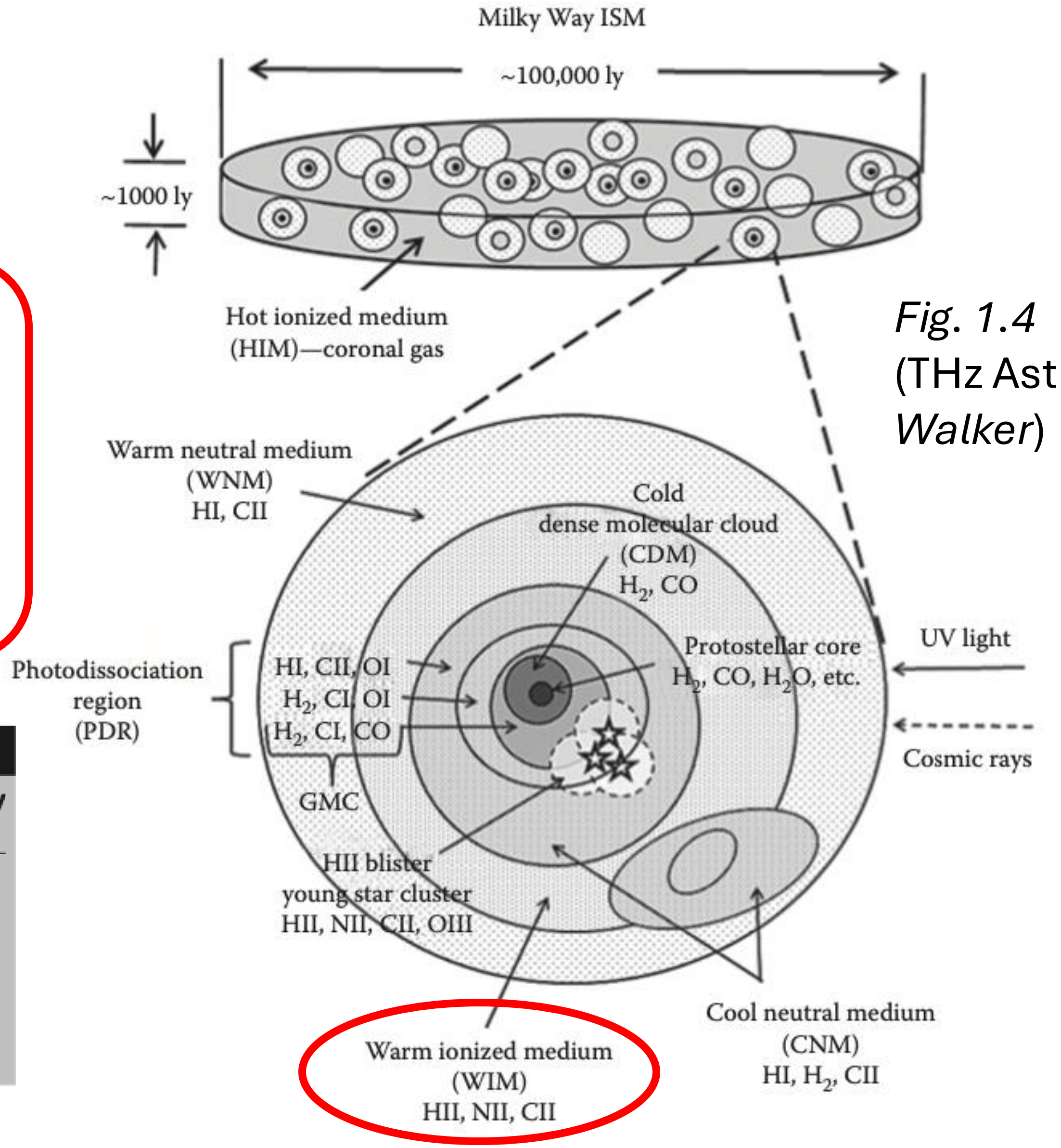

Fig. 1.4 (THz Astronomy, *Walker*)

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Warm Ionized Medium (WIM)

- Gas photoionized by extreme ultraviolet (EUV) and soft x-ray photons from massive O and B stars (found in or next to the dense molecular clouds from which they are formed)
- Referred to also as 'Diffuse Ionized Gas or DIG'
- Widely extended distribution
- Evidence from pulsar dispersion measures!

HII Regions

- The UV photons from the stars photodissociate nearby molecular gas, and the EUV photons ionize the atomic hydrogen, leading to the formation of a "blister HII (singly ionized hydrogen) region"
- H II regions associated with O stars only a minor constituent of ISM

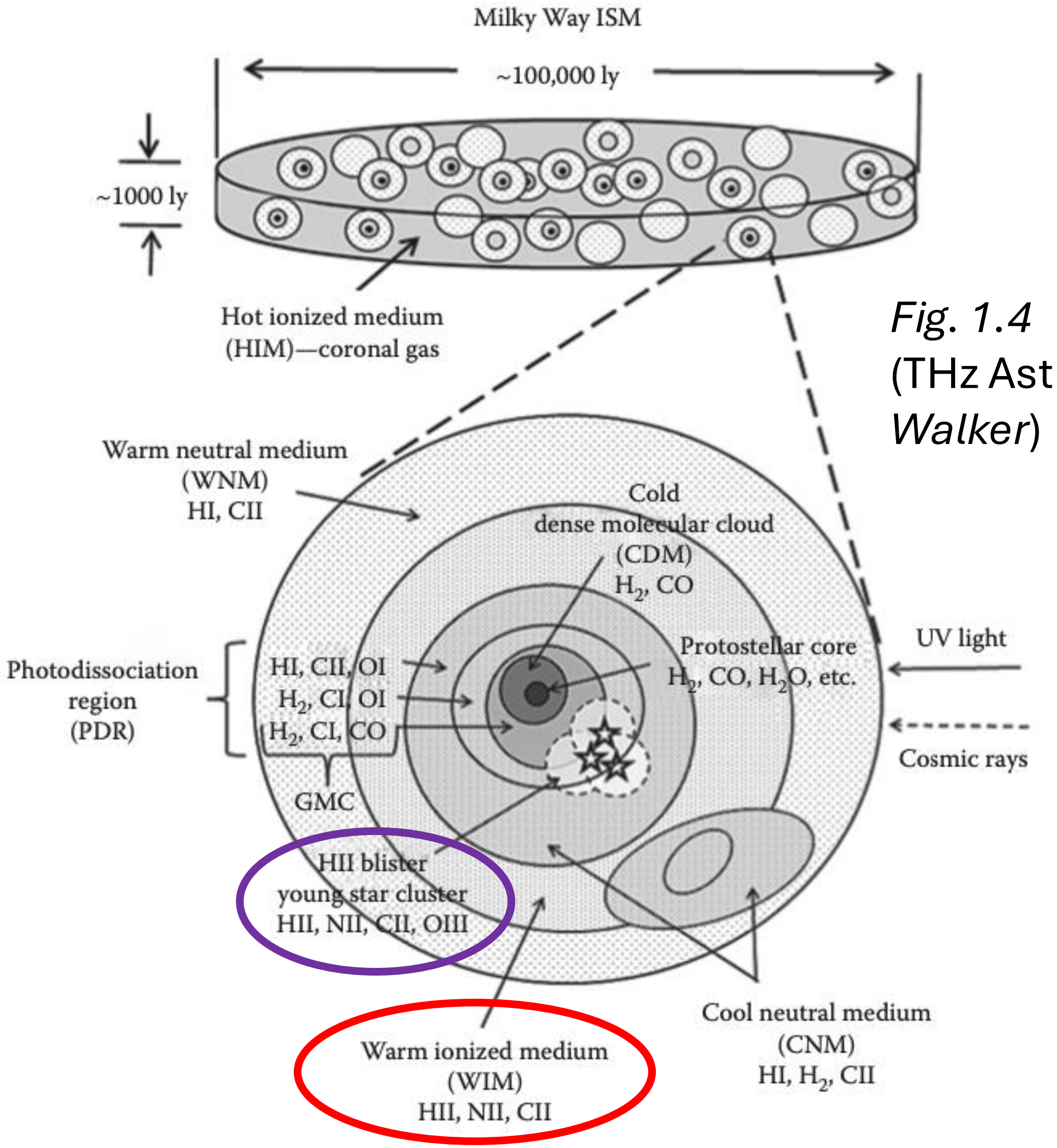


Fig. 1.4
(THz Astronomy, *Walker*)

HII Regions (ERA 4.2)

A more simplified picture, HII regions as **Strömgren spheres**:

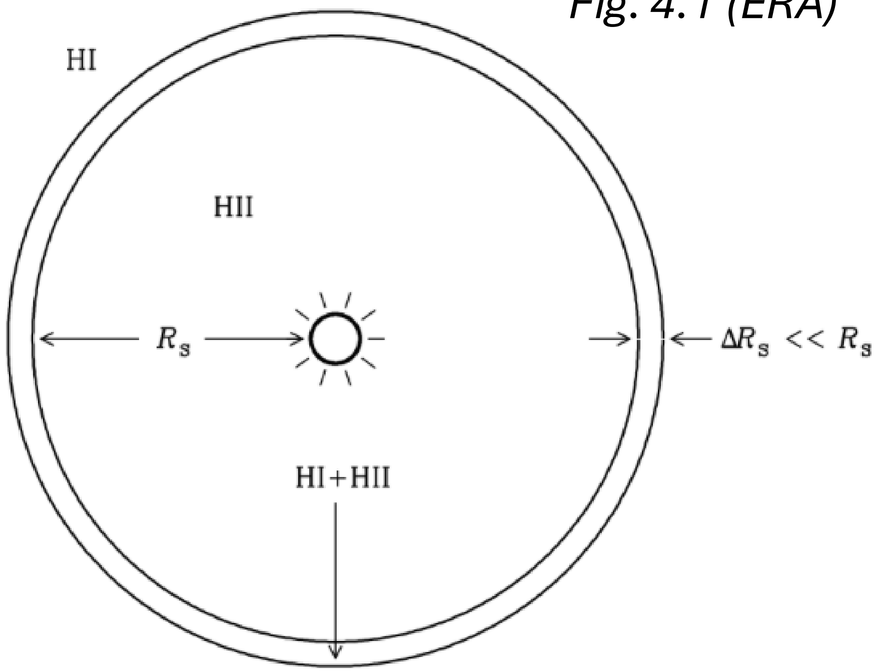
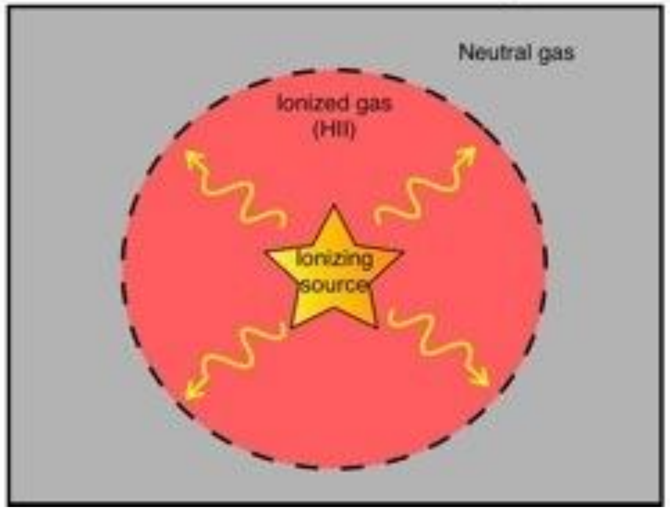


Fig. 4.1 (ERA)

Schematic of an Idealized HII Region



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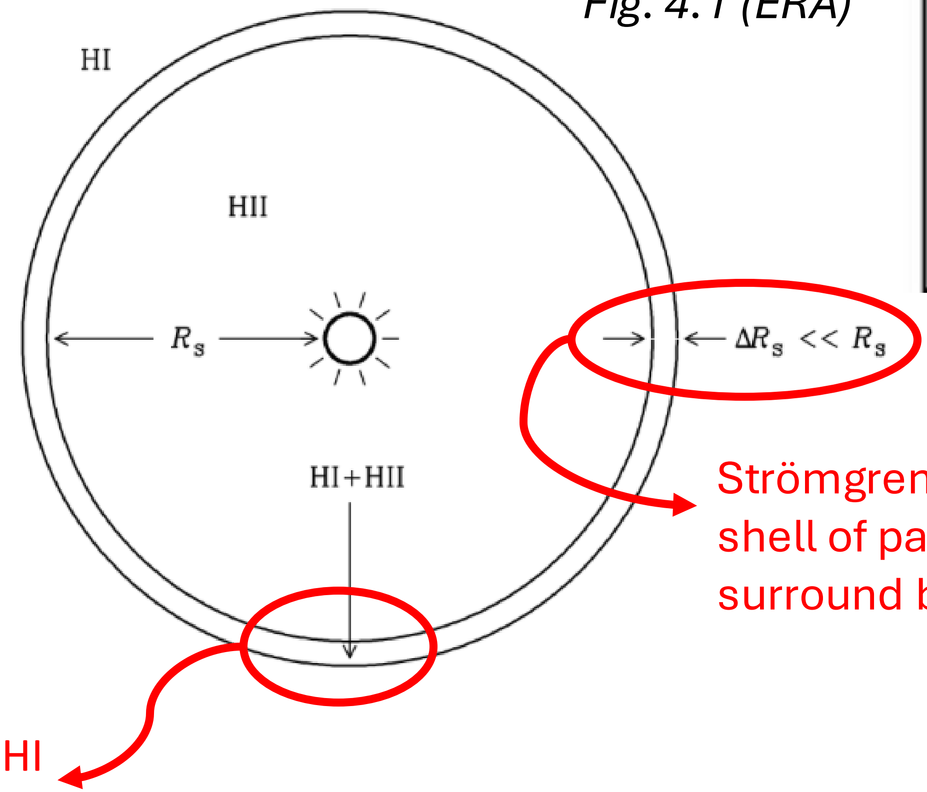
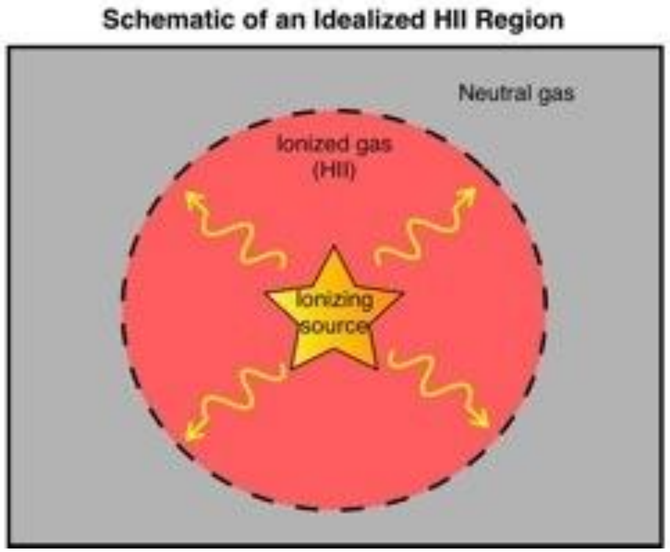


Strömgren radius, R_s is surrounded by thin shell of partially ionized (HI + HII) gas surround by neutral hydrogen, HI

Boundaries separating HI and HII regions very thin



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Main Takeaways:

- The hotter and more luminous the exciting star, the larger the Strömgren sphere.
- The denser the surrounding hydrogen gas, the smaller the Strömgren sphere.

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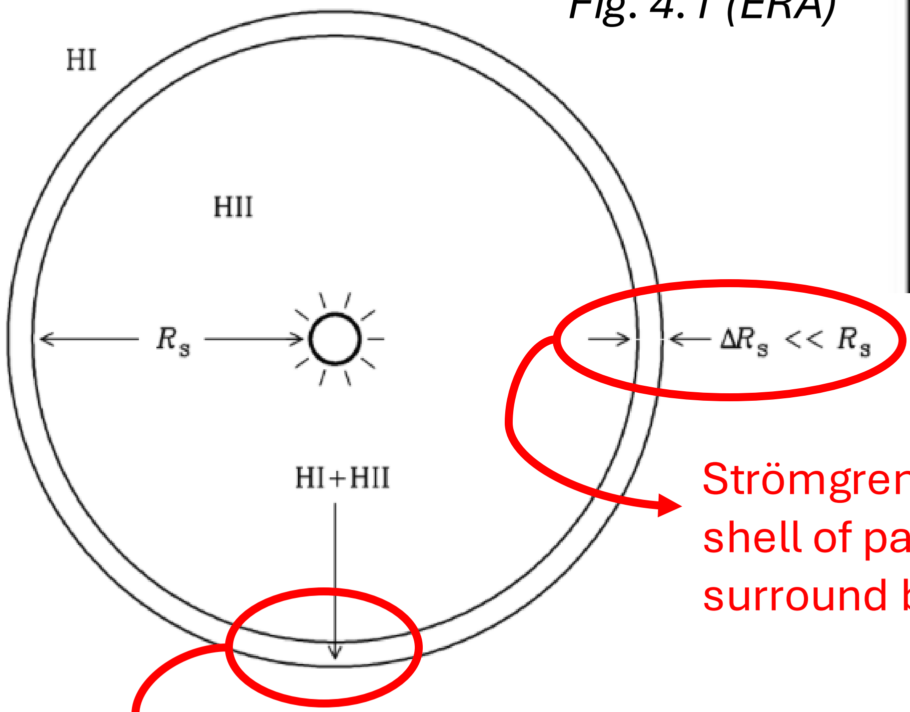

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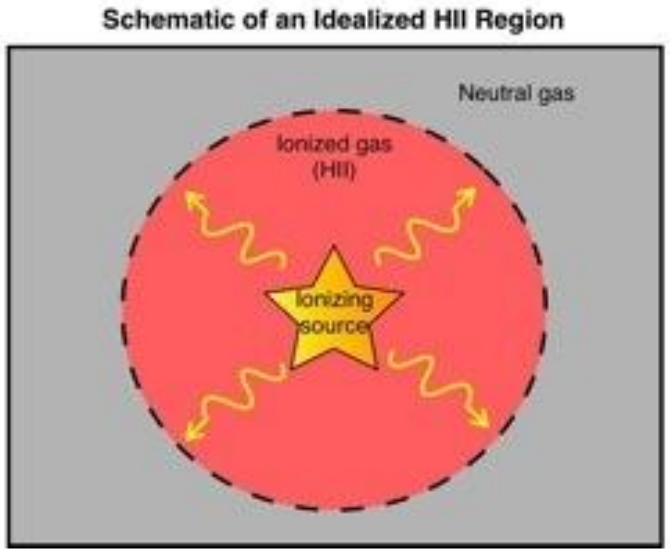

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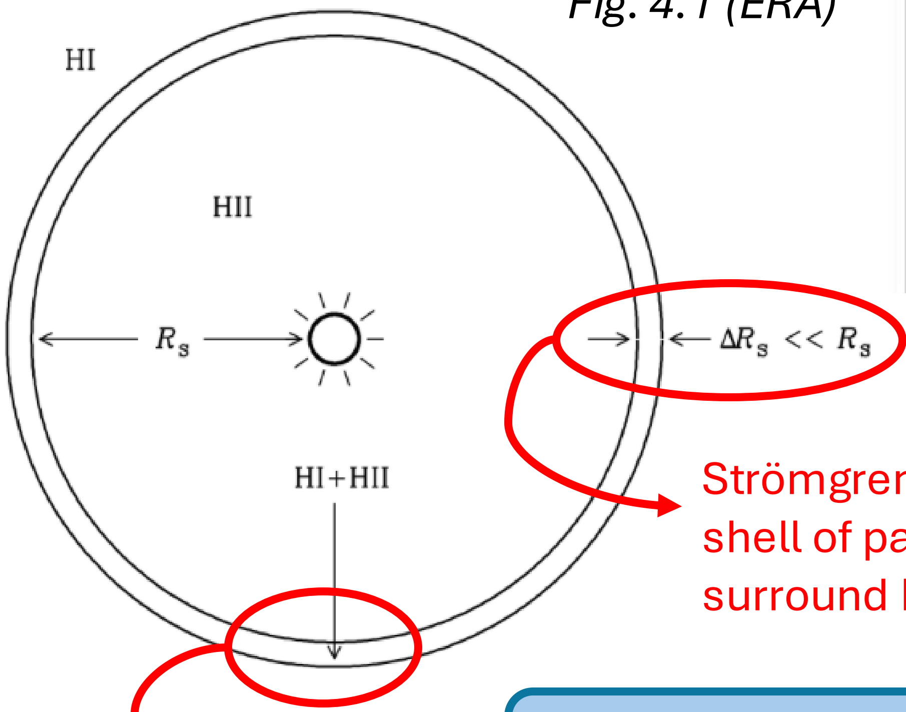

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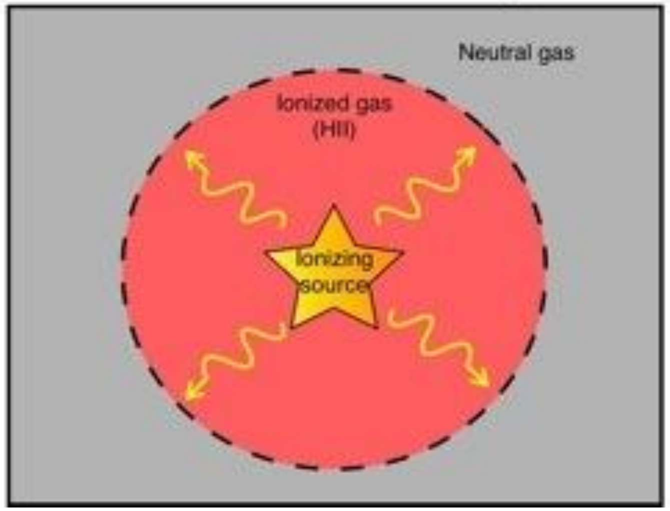


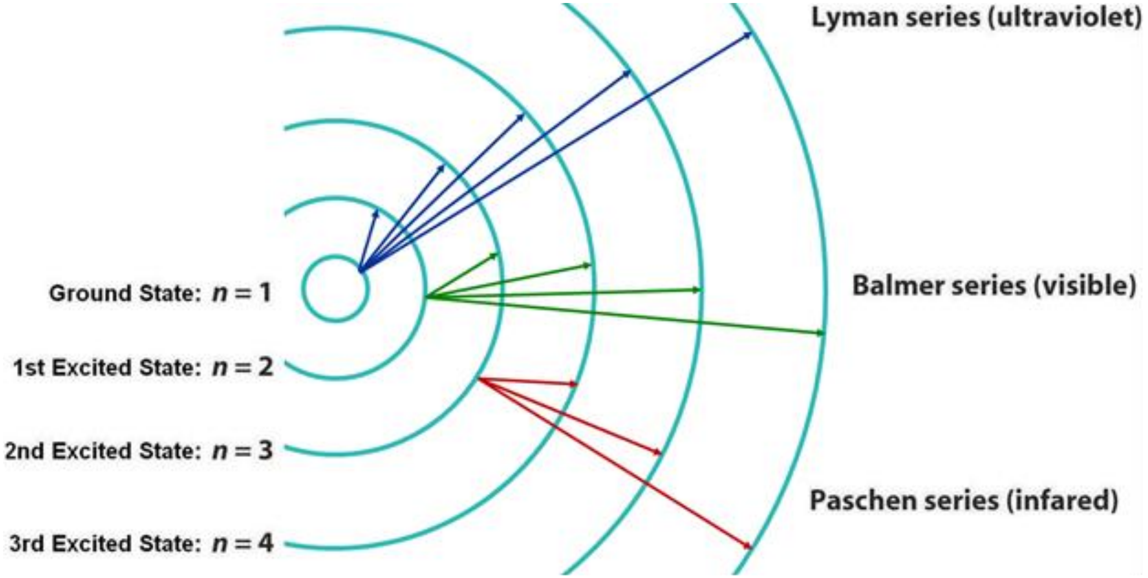
How did Strömgren get to this picture?

HII Regions (ERA 4.2)

Hydrogen atoms in the **ground state** can be **ionized by photons** with energy E ≥ 13.6 eV

(1 electron Volt ≈ 1.60×10^{-12} erg)

These energetic photons are at high frequencies/short wavelengths in the far-UV known as the **Lyman Series (< 912 Angstroms)**



Webassign.net

These Lyman continuum photons are produced in a significant number by the Wien tail of blackbody radiation for stars hotter than what temperature?

What kind of stars are these?

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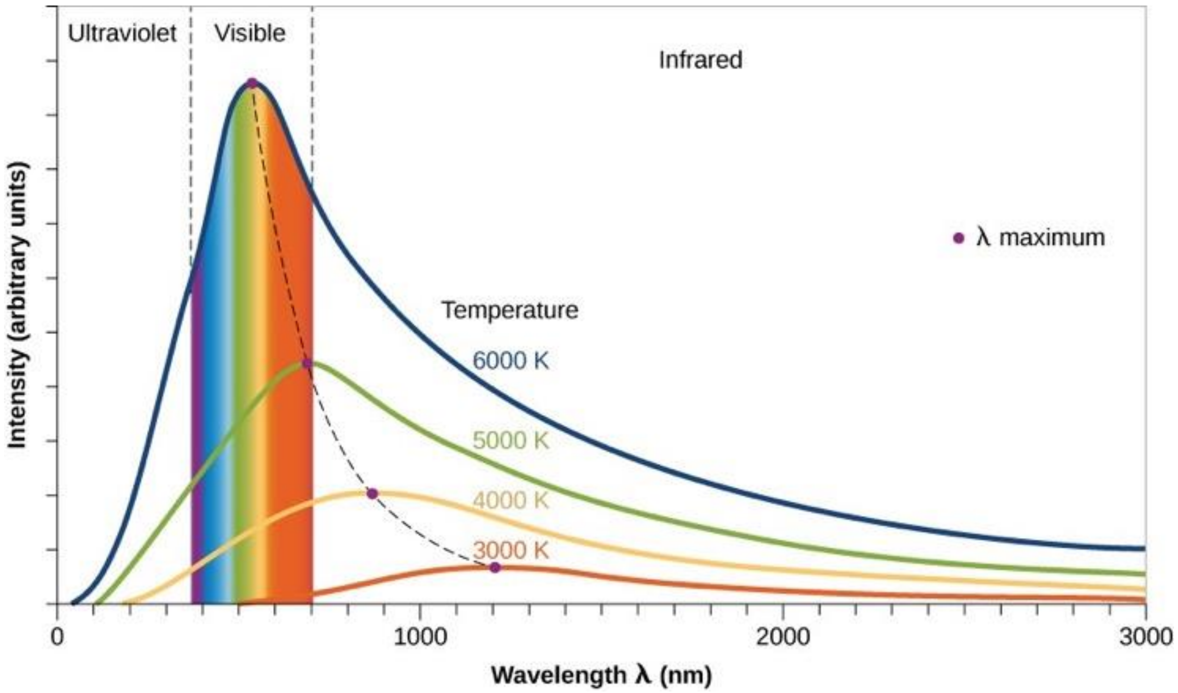

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> 30,000 K

What kind of stars are these?

O and B stars!

*Remember Wien's law :
λ_{max} [nm] = $(3 \times 10^6)/T$ [K]

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Hydrogen atoms in the **ground state** can be **ionized by photons** with energy $E \geq 13.6$ eV

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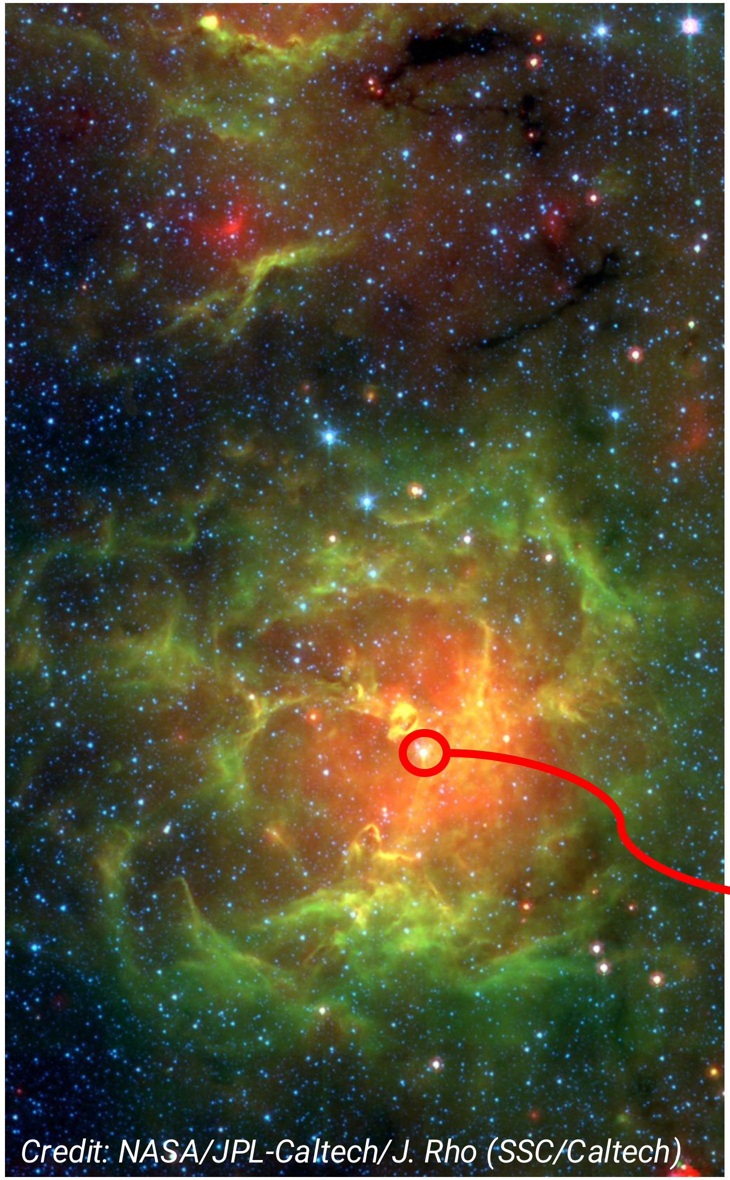


Credit: *NASA/JPL-Caltech/J. Rho (SSC/Caltech)*

Ionizing O star

The glowing Trifid Nebula HII region is revealed with near- and mid-infrared views from NASA's Spitzer Space Telescope.

HII Regions (ERA 4.2)

Strömgren spheres

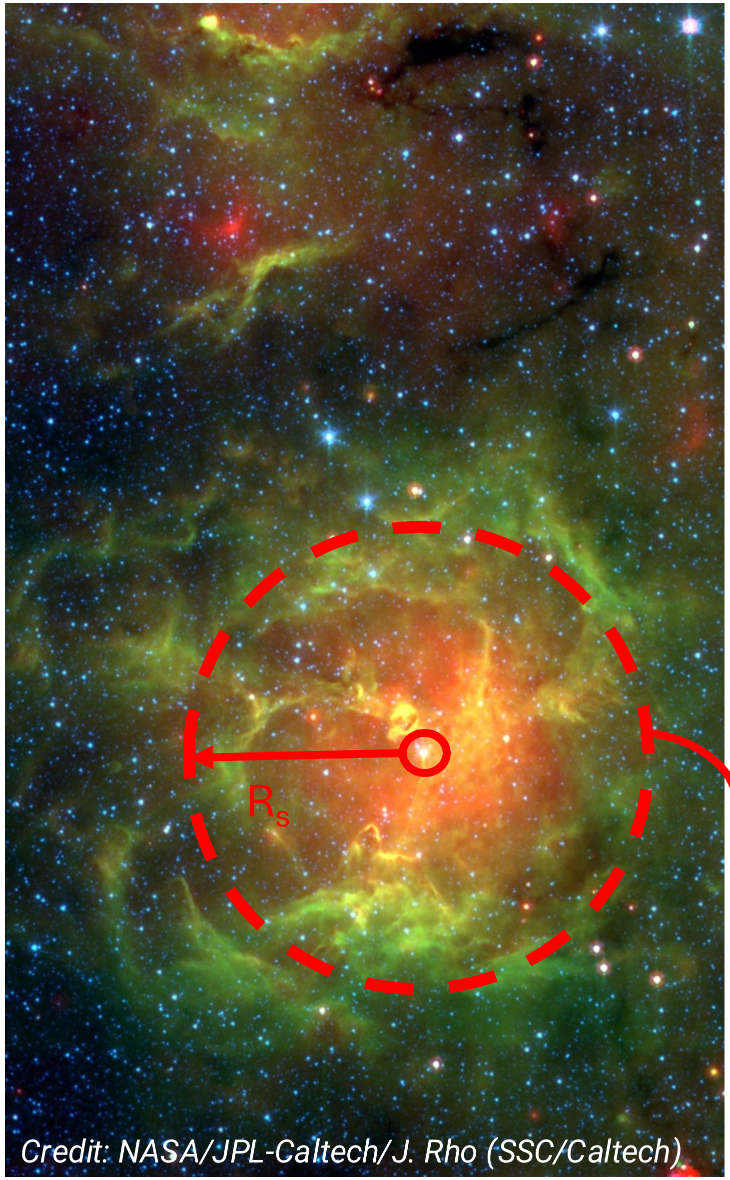
The thickness of the partially ionized shell surrounding a Strömgren sphere is,

$$\Delta R_S \approx (n_H \sigma)^{-1}. \qquad (4.4)$$

Where n_H is the neutral hydrogen density (~ 10^3 cm^{-3}) and is the absorption cross section, σ, which is large enough at ~ 10^{-17} cm^{-2} at energies just above 13.6eV so that **each ionizing photon is absorbed and produced a new ion shortly after it passes from the ionized sphere into the surrounding HI region**:

$$\Delta R_S \approx (10^3 \ \text{cm}^{-3} \times 10^{-17} \ \text{cm}^2)^{-1} \approx 10^{14} \ \text{cm} \ll 1 \ \text{pc}. \qquad (4.5)$$

Light travels ≈ 10^{14} cm per hour, so *an ionizing photon typically survives only about an hour in such an HI cloud before being absorbed*!



Credit: NASA/JPL-Caltech/J. Rho (SSC/Caltech)

Thickness, ΔR_S

The glowing Trifid Nebula HII region is revealed with near- and mid-infrared views from NASA's Spitzer Space Telescope.

HII Regions (ERA 4.2)

Strömgren spheres

Another key time is the **recombination time** defined as the ratio of volume density of elections, n_e, to the **recombination rate**, $\dot{n}_{\mathrm{H}}$

$$\tau \equiv \frac{n_{\mathrm{e}}}{\dot{n}_{\mathrm{H}}} \approx 3.3 \times 10^{9} \ \mathrm{s} \approx 10^{2} \ \mathrm{yr} \qquad (4.9)$$

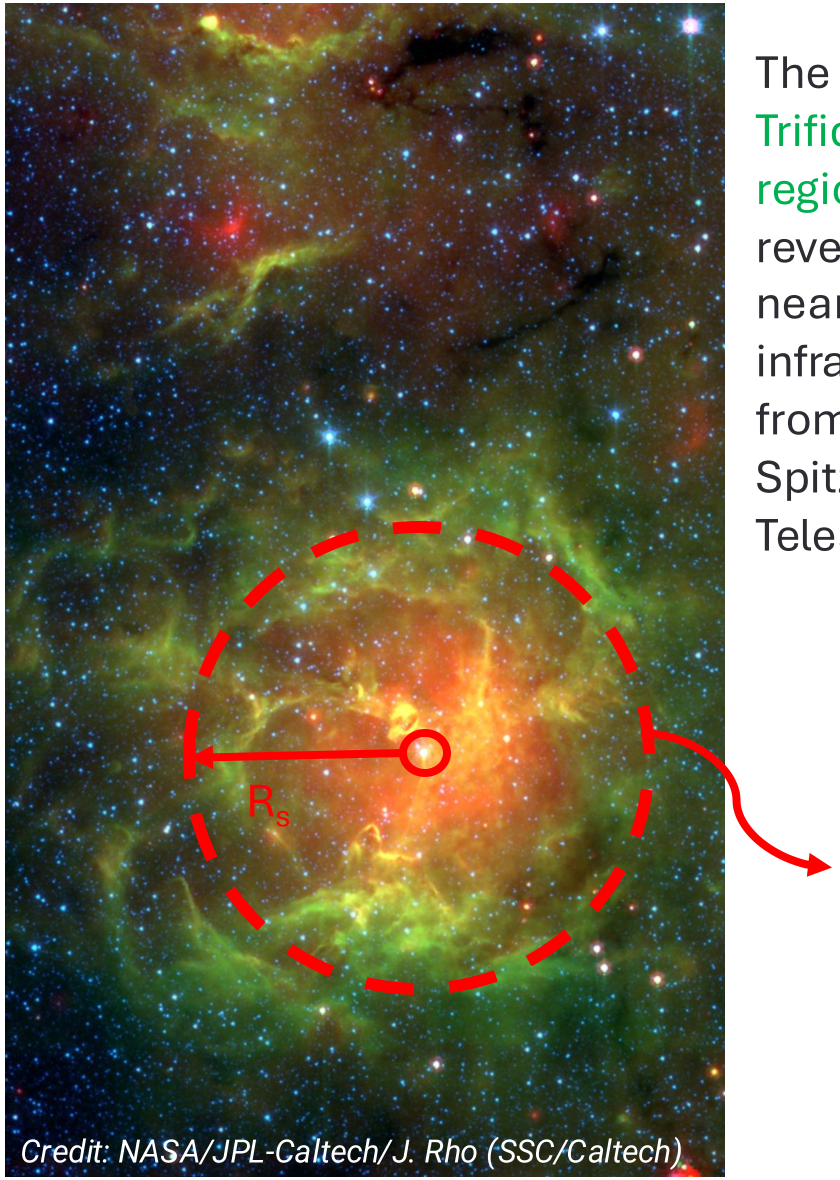
Where electrons and protons occasionally collide and recombine,

$$\dot{n}_{\mathrm{H}} \approx \alpha_{\mathrm{H}} n_{\mathrm{e}} n_{\mathrm{p}}, \qquad (4.6)$$

and α_H is the **recombination coefficient** for hydrogen (3×10^{-13} cm^3 s^{-1}).

KEY POINT: Recombination time is usually much shorter than the > 10^6 year lifetime of an ionizing star

If the surrounding HI cloud is small enough that the star can ionize it completely, the HII region is **"matter bounded"** or **"density bounded"**



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Thickness, ΔR_S

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HII Regions (ERA 4.2)

Strömgren spheres

The rate Q_H at which a star with spectral luminosity L_ν *produces photons that can ionize hydrogen atoms in the ground state is,*

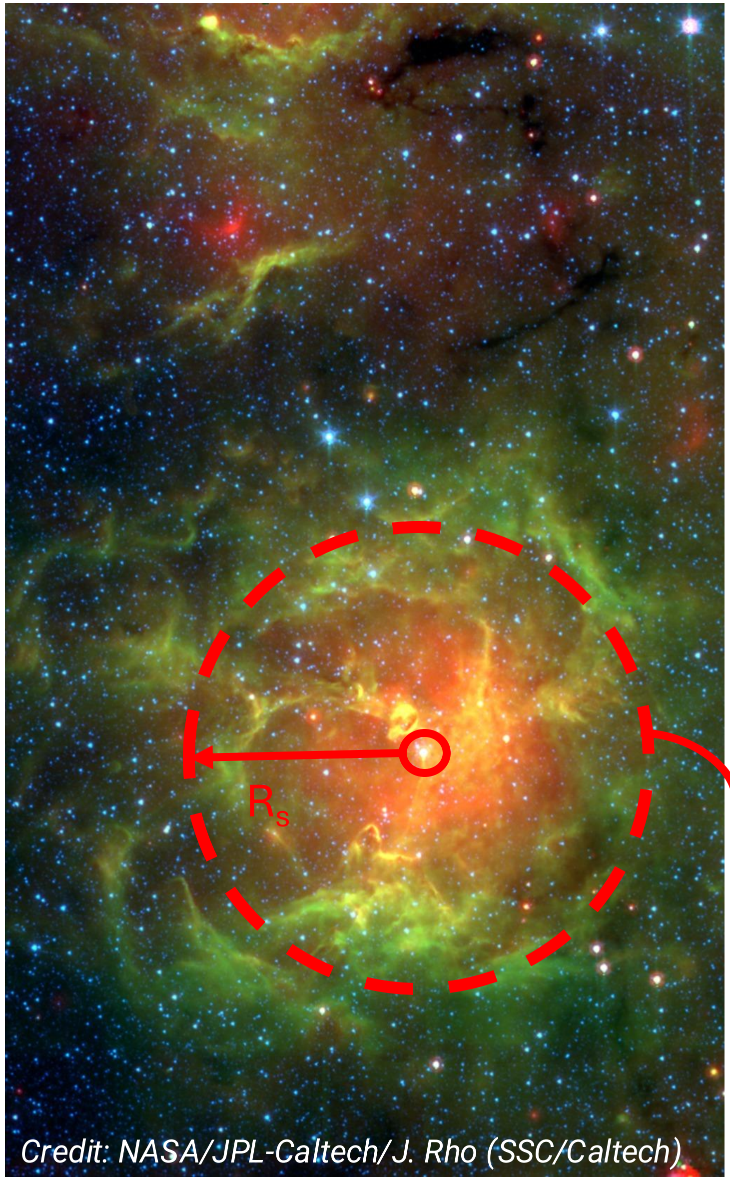
$$Q_{\mathrm{H}} = \int_{R_\infty c}^{\infty} \left(\frac{L_\nu}{h\nu} \right) d\nu. \qquad (4.3)$$

In equilibrium the volume, *V*, of an ionization-bounded HII region **grows until the total ionization and recombination rates in the Strömgren sphere are equal**,

$$Q_{\mathrm{H}} = \dot{n}_{\mathrm{H}} V = \alpha_{\mathrm{H}} n_{\mathrm{e}} n_{\mathrm{p}} \frac{4}{3} \pi R_{\mathrm{S}}^3 \qquad (4.10)$$

where α_{H}, remember, is the **recombination coefficient** for hydrogen (3×10^{-13} cm^3 s^{-1}). Solving for R_S, we find:

$$\boxed{R_{\mathrm{S}} \approx \left(\frac{3 Q_{\mathrm{H}}}{4 \pi \alpha_{\mathrm{H}} n_{\mathrm{e}}^2} \right)^{1/3}. \qquad (4.11)}$$



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The glowing Trifid Nebula HII region is revealed with near- and mid-infrared views from NASA's Spitzer Space Telescope.

Thickness, ΔR_S

HII Regions (ERA 4.2)

Strömgren spheres

For an O5 star $Q_H \sim 6 \times 10^{49}$ photons ,

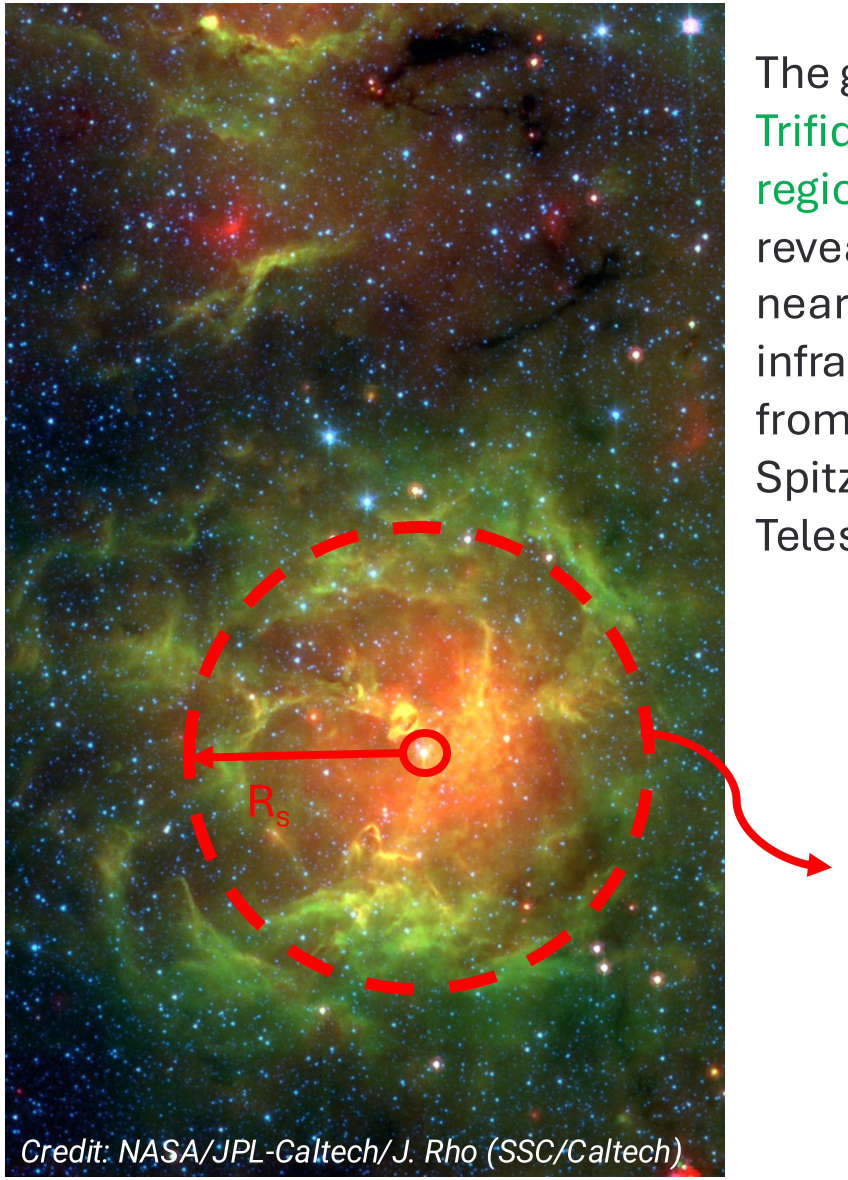
$$R_S \approx \left(\frac{3Q_H}{4\pi\alpha_H n_e^2}\right)^{1/3}.$$

$$\approx \left[\frac{3 \cdot 6 \times 10^{49}\ \mathrm{s}^{-1}}{4\pi \cdot 3 \times 10^{-13}\ \mathrm{cm}^3\ \mathrm{s}^{-1}(10^3\ \mathrm{cm}^{-3})^2}\right]^{1/3} \approx 3.6 \times 10^{18}\ \mathrm{cm} \approx 1.2\ \mathrm{pc}.$$

Compared to,

$$\Delta R_S \approx (10^3\ \mathrm{cm}^{-3} \times 10^{-17}\ \mathrm{cm}^2)^{-1} \approx 10^{14}\ \mathrm{cm} \ll 1\ \mathrm{pc}. \quad (4.5)$$

So yes, $R_S \gg \Delta R_S$, the ***radius of the fully ionized Strömgren sphere is much larger than the thickness of its partially ionized skin***



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HII Regions (ERA 4.2)

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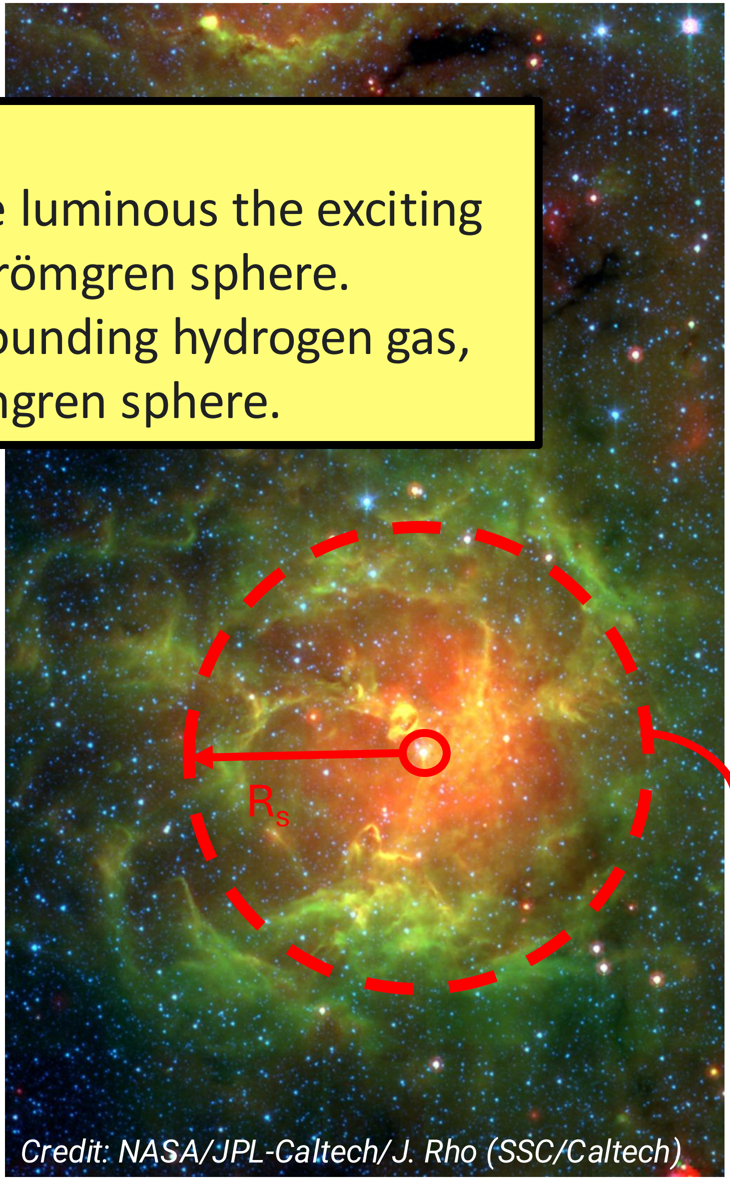

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HII Regions (ERA 4.2)

Typically, two distinct **kinds of stars** produce most of the **HII regions in our Galaxy**:

1. The most massive ($M \geq 15 M_\odot$) stars

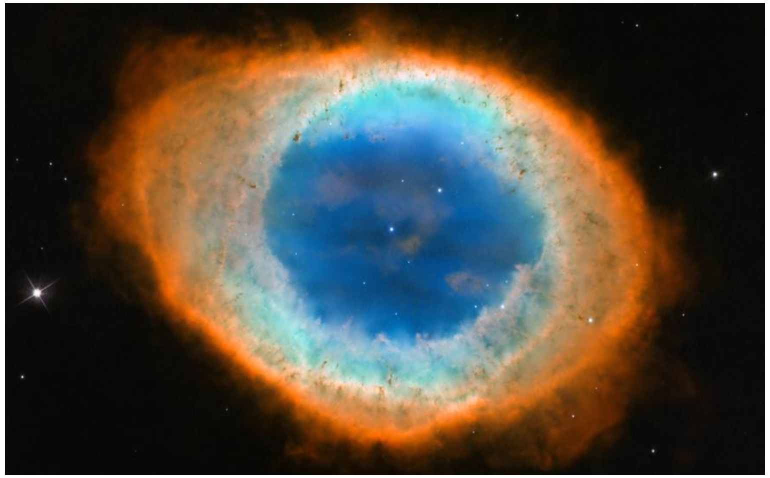
- Short-lived (lifetimes $\lesssim 10^7$ yr) main-sequence stars
- Big enough ($R \sim 10\ R_\odot$) and hot enough ($T \geq 3 \times 10^4$ K) to be very luminous sources of ionizing UV
- Such stars were recently formed by gravitational collapse and fragmentation of interstellar clouds containing neutral gas and dust grains

2. Old lower-mass ($1 < M/M_\odot < 8$) stars

- Main-sequence lifetimes are less than the age of our Galaxy ($\approx 10^{10}$ yr)
- Eventually become red giants and finally white dwarfs
- Young white dwarfs are small ($R \sim 10^{-2} R_\odot$) but hot enough to ionize the stellar envelope material that was ejected during the red giant stage, and these ionized regions are called **planetary nebulae** because many looked like planets to early astronomers using small telescopes

Orion Nebula

M57



HII Regions (ERA 4.2)

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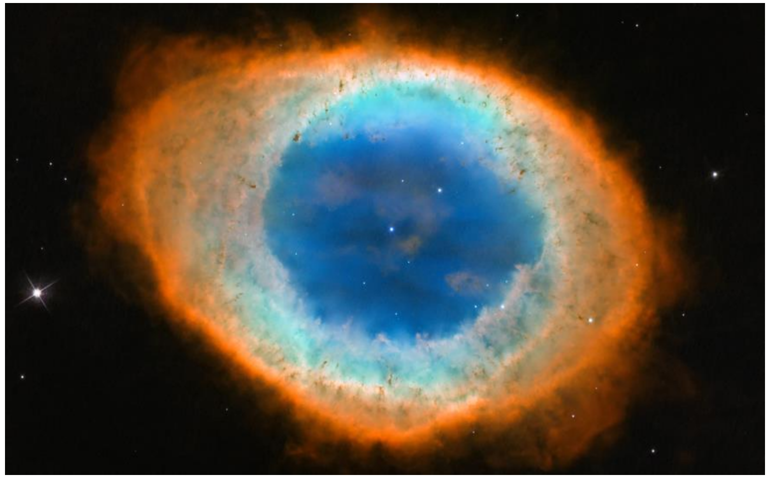
Radio recombination lines provide a powerful tool to study the characteristics of the ionized (+ neutral) phases of the ISM!

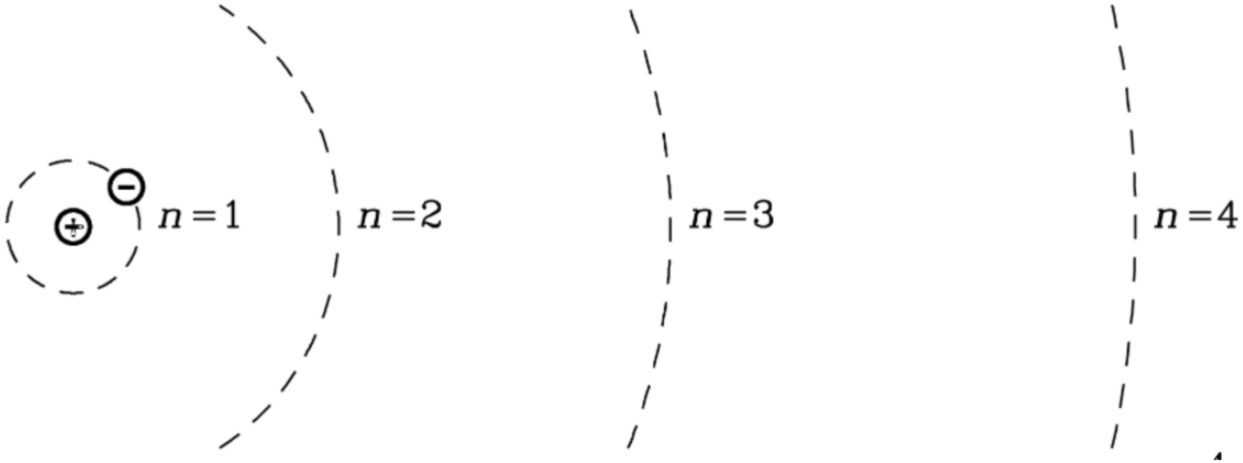
Orion Nebula

M57



Radio Recombination Lines (ERA 7.2, 7.6)

Fig. 7.1 (ERA)



Think of semiclassical **Bohr atom** →
electronic transitions!

Remember:

De Broglie wavelengths:

$$\lambda = \frac{h}{p} = \frac{h}{m_e v}, \qquad (7.2)$$

Where *p* is the electron's momentum and *v* is its speed.

*Only those orbits whose circumferences equal an integer number *n* of wavelengths correspond to standing waves and are permitted.

The Bohr radius is written as,

$$\boxed{a_n = \frac{n^2 \hbar^2}{m_e e^2}.} \qquad (7.6)$$

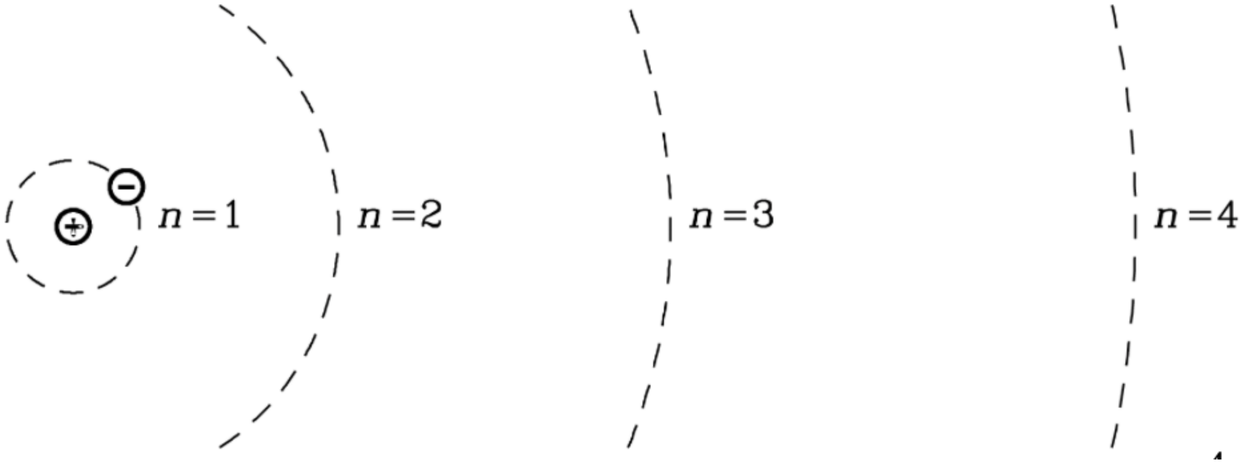
Main Takeaway:

The Bohr radius of a hydrogen atom in its ground electronic state ($n = 1$) is only $a_1 = 0.53 \times 10^{-8}$ cm

BUT at ($n \sim 100$) it is much larger $a_{100} \sim 10^{-4}$ cm = 1μm – *bigger than most viruses!*

Radio Recombination Lines (ERA 7.2, 7.6)

Fig. 7.1 (ERA)



Think of semiclassical **Bohr atom** →
**electronic transitions!*

<u>Remember:</u>

De Broglie wavelengths:

$$\lambda = \frac{h}{p} = \frac{h}{m_e v}, \qquad (7.2)$$

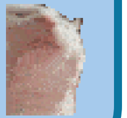
Where p is the electron's momentum and v is its speed.

*Only those orbits whose circumferences equal an integer number n of wavelengths correspond to standing waves and are permitted.

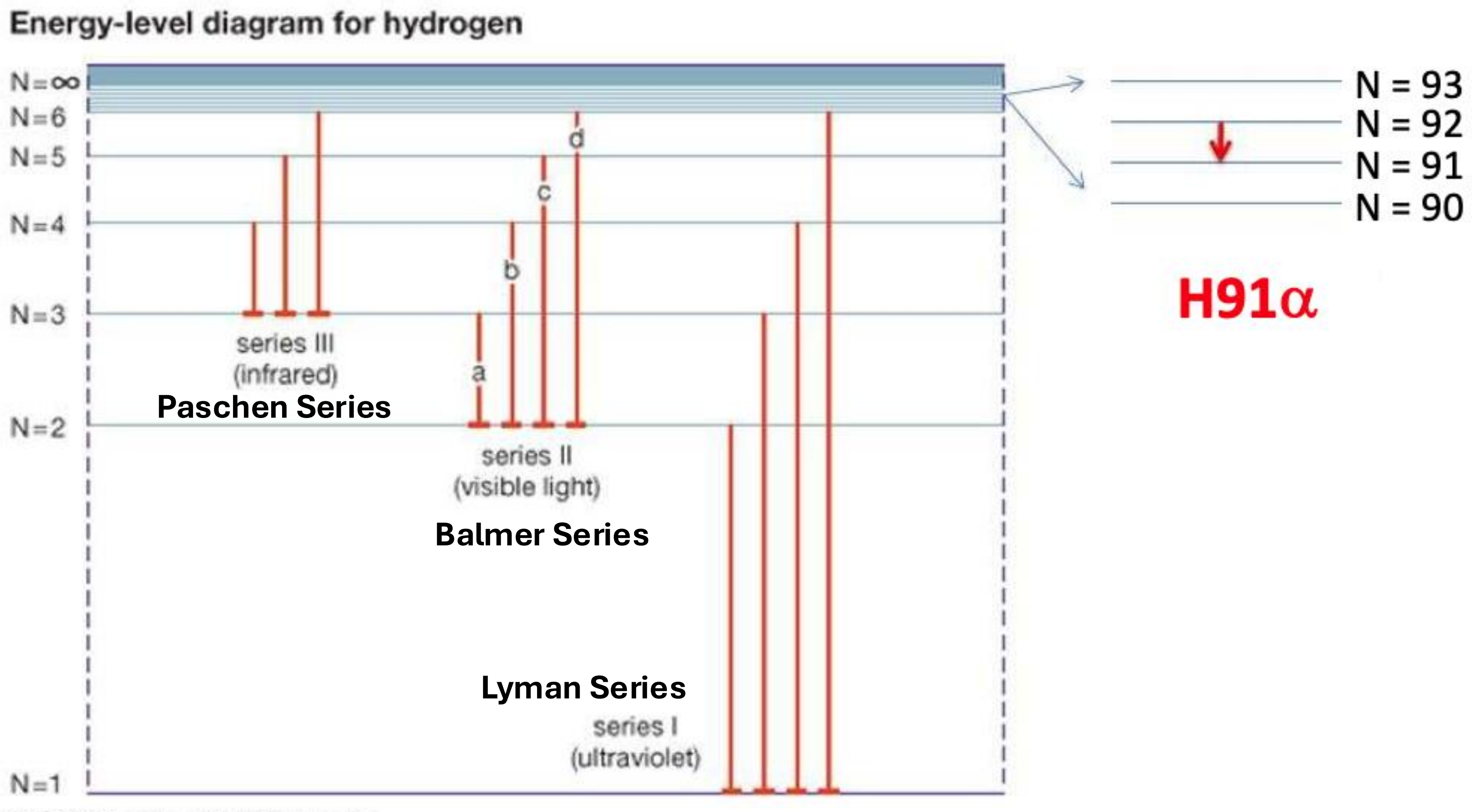
The Bohr radius is written as,

$$\boxed{a_n = \frac{n^2 \hbar^2}{m_e e^2}.} \qquad (7.6)$$

At the largest detected (δ; Δn = 4) transition in space of n = 1009 (Stepkin et al. 2007), the **Bohr diameter of an atom reaches ≈ 110 μm** — for scale, the average width of a human hair is roughly 75 μm!



Radio Recombination Lines (ERA 7.2, 7.6)



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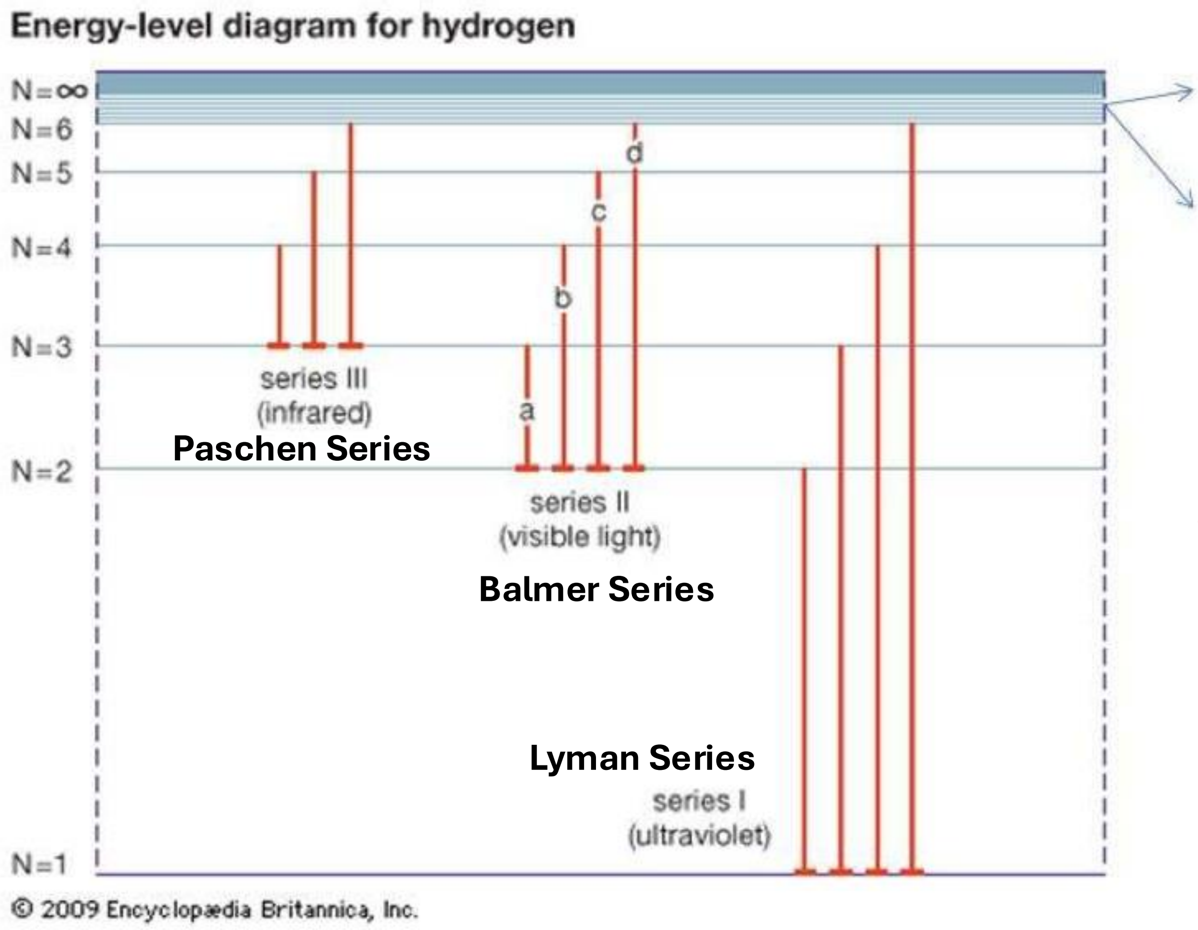
As ions and electrons recombine to form atoms, electrons left in high principal quantum numbers and which cascade to lower energy levels (or may be excited to higher energy levels) are observable through the spectral signature of **radio recombination lines (RRLs)!**

Radio Recombination Lines (ERA 7.2, 7.6)



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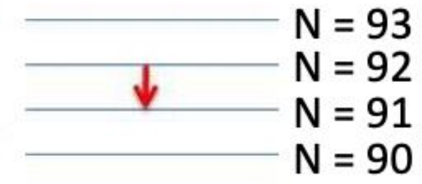

As ions and electrons recombine to form atoms, electrons left in high principal quantum numbers and which cascade to lower energy levels (or may be excited to higher energy levels) are observable through the spectral signature of **radio recombination lines (RRLs)!**

H91α

Name of element

Final level number, *n*

Successive letters in Greek alphabet to denote the level change Δn (e.g., α for Δn=1, β for Δn=2, γ for Δn=3, etc.,)

Radio Recombination Lines (ERA 7.2, 7.6)

The total electronic energy E_n is the sum of the kinetic (T) and potential (V) energies of the electron in the nth circular orbit:

$$E_n = T + V = -T = V/2 = -\frac{e^2}{2a_n} = -e^2\left(\frac{m_e e^2}{2n^2\hbar^2}\right) = -\left(\frac{m_e e^4}{2\hbar^2}\right)\frac{1}{n^2}. \qquad (7.7)$$

The electronic energy change ΔE going from level ($n + \Delta n$) to level n is equal to the energy $h\nu$ of the emitted photon:

$$\Delta E = \frac{m_e e^4}{2\hbar^2}\left[\frac{1}{n^2} - \frac{1}{(n+\Delta n)^2}\right] = h\nu, \qquad (7.8)$$

The photon frequency:

$$\nu = \left(\frac{2\pi^2 m_e e^4}{h^3 c}\right) c \left[\frac{1}{n^2} - \frac{1}{(n+\Delta n)^2}\right]. \qquad (7.9)$$

Radio Recombination Lines (ERA 7.2, 7.6)

Notice anything about this factor?

The photon frequency:

$$\nu = \boxed{\left(\frac{2\pi^2 m_e e^4}{h^3 c}\right)} c \left[\frac{1}{n^2} - \frac{1}{(n+\Delta n)^2}\right]. \qquad (7.9)$$

Radio Recombination Lines (ERA 7.2, 7.6)

Rydberg constant R_∞

$$R_\infty \equiv \left(\frac{2\pi^2 m_e e^4}{h^3 c}\right) = 1.09737312\ldots \times 10^5 \ \text{cm}^{-1}. \qquad (7.10)$$

Rydberg frequency

$$R_\infty c = 3.28984\ldots \times 10^{15} \ \text{Hz}. \qquad (7.11)$$

Notice anything about this factor?

<u>It's a constant!</u>

The photon frequency:

$$\nu = \left(\frac{2\pi^2 m_e e^4}{h^3 c}\right) c \left[\frac{1}{n^2} - \frac{1}{(n+\Delta n)^2}\right]. \qquad (7.9)$$

Radio Recombination Lines (ERA 7.2, 7.6)

Rydberg constant R_∞

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Rydberg frequency

$$R_\infty c = 3.28984\ldots \times 10^{15} \ \ \mathrm{Hz}. \qquad (7.11)$$

★

The photon frequency:

$$\boxed{\nu = R_M c\left[\frac{1}{n^2} - \frac{1}{(n+\Delta n)^2}\right], \qquad \text{where} \qquad R_M \equiv R_\infty\left(1 + \frac{m_e}{M}\right)^{-1},} \qquad (7.12)$$

Radio Recombination Lines (ERA 7.2, 7.6)

E.g.,

$$\nu\,(\mathrm{H}109\,\alpha) = 3.28805 \times 10^{15}\ \mathrm{Hz}$$

$$\left(\frac{1}{109^2} - \frac{1}{110^2}\right) \approx 5.0089 \times 10^9\ \mathrm{Hz}.$$

~ 5 GHz

Rydberg constant R_∞

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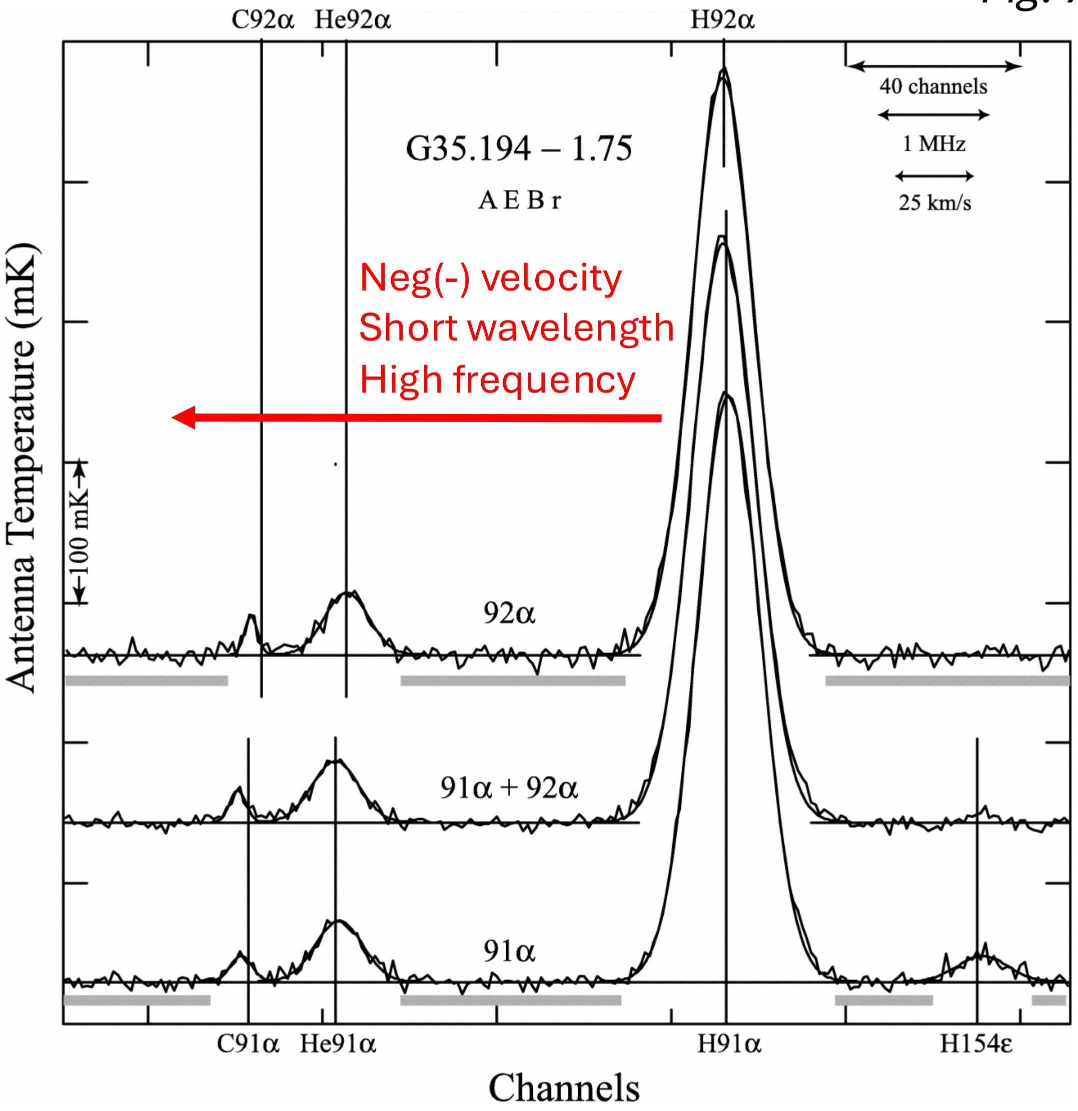
Radio Recombination Lines (ERA 7.2, 7.6)

Recombination lines of heavier atoms are very similar to those of hydrogen, but at the slightly higher frequencies →

Fig. 7.2 (ERA)



Radio Recombination Lines (ERA 7.2, 7.6)

Recombination lines of heavier atoms are very similar to those of hydrogen, but at the slightly higher frequencies →

+ Higher 'n' lower frequencies
H54α ~ 41 GHz vs. H109α ~ 5 GHz

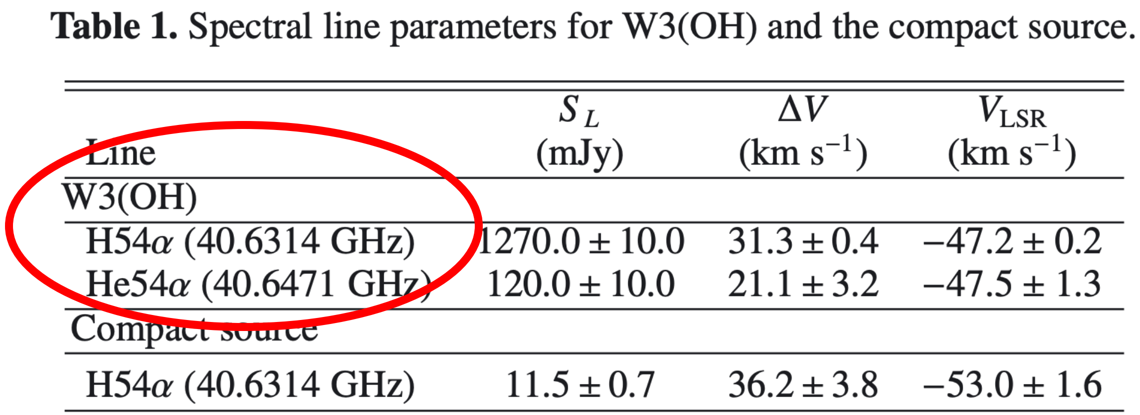
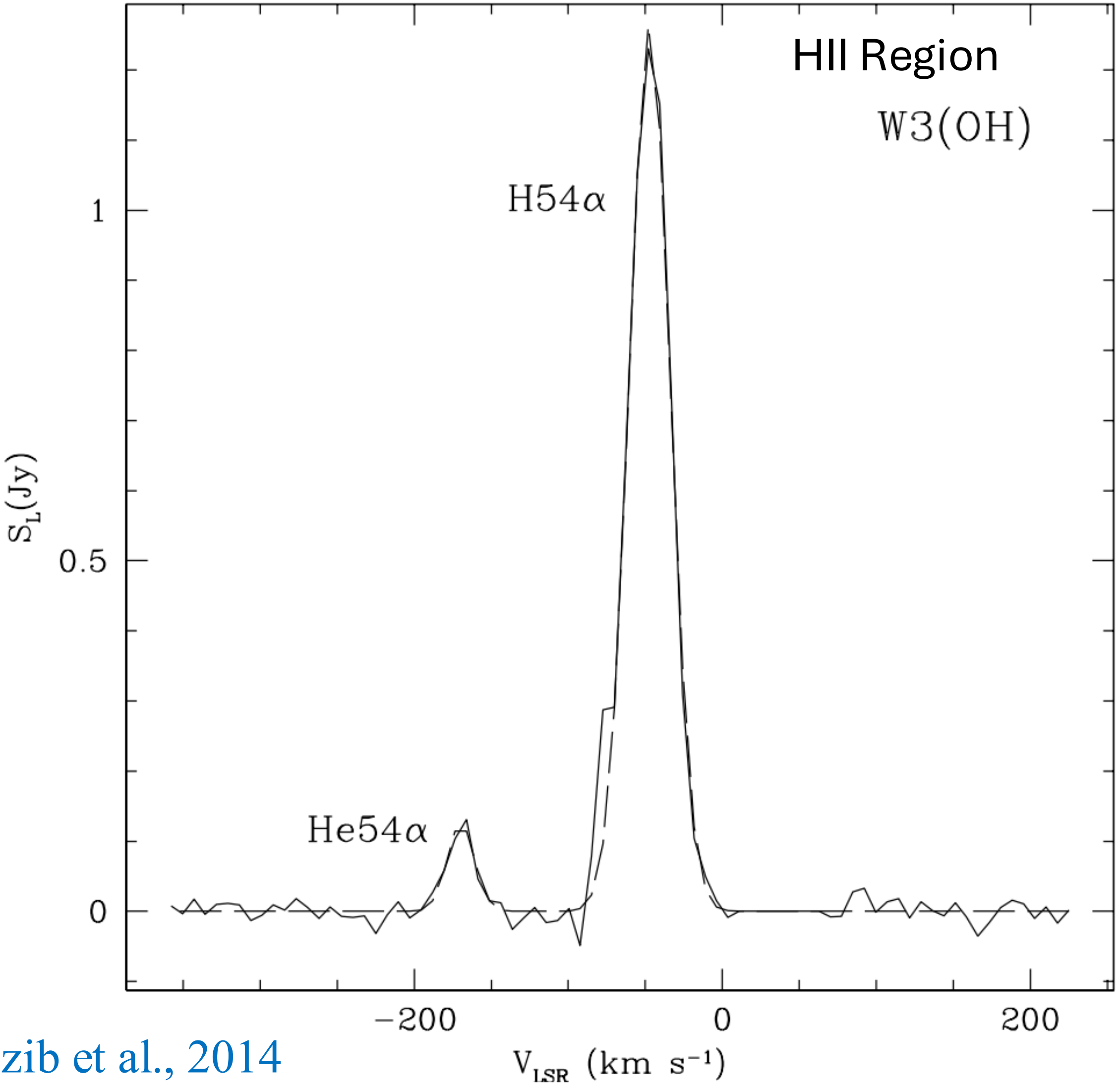


Table 1. Spectral line parameters for W3(OH) and the compact source.

Line	S_L (mJy)	ΔV (km s^{-1})	$V_{\rm LSR}$ (km s^{-1})
W3(OH)			
H54α (40.6314 GHz)	1270.0 ± 10.0	31.3 ± 0.4	−47.2 ± 0.2
He54α (40.6471 GHz)	120.0 ± 10.0	21.1 ± 3.2	−47.5 ± 1.3
Compact source			
H54α (40.6314 GHz)	11.5 ± 0.7	36.2 ± 3.8	−53.0 ± 1.6



Dzib et al., 2014

Radio Recombination Lines (ERA 7.2, 7.6)

Adjacent high-n (low-ν) radio recombination lines have such small fractional frequency separations that two or more transitions can often be **observed simultaneously and averaged, to reduce the observing time** needed to reach a given signal-to-noise ratio!

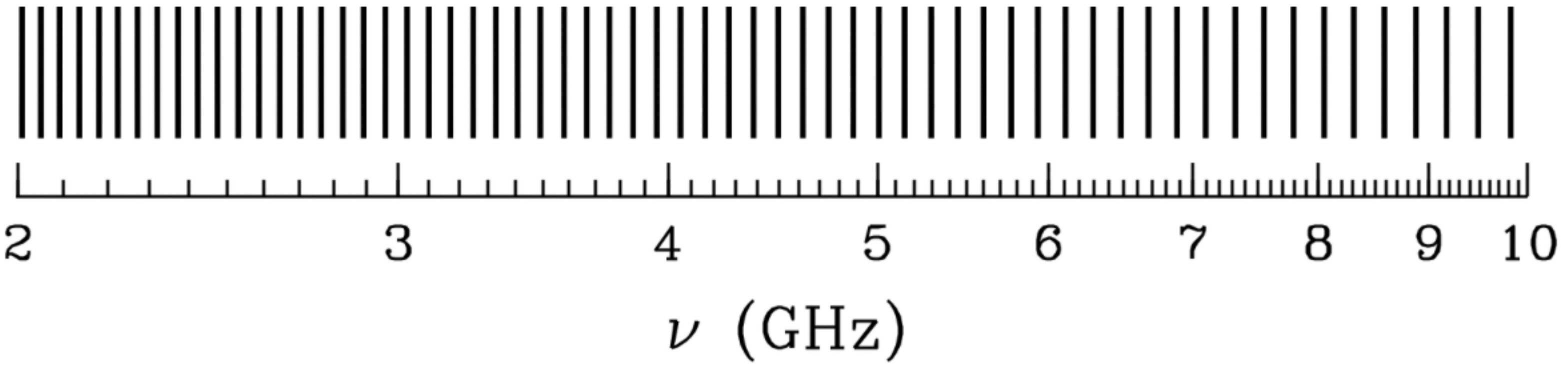


Figure 7.3: The $\Delta n = 1$ (α) radio recombination lines of singly ionized atoms, shown here as vertical bars, are closely spaced in frequency.

In the approximation $\Delta n \ll n$, the frequency separation between adjacent lines:

$$\boxed{\frac{\Delta \nu}{\nu} \approx \frac{3}{n}.} \qquad (7.15)$$

Recombination Line Data

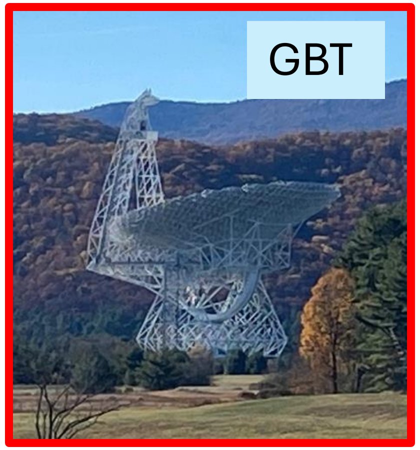
'Low' Frequency

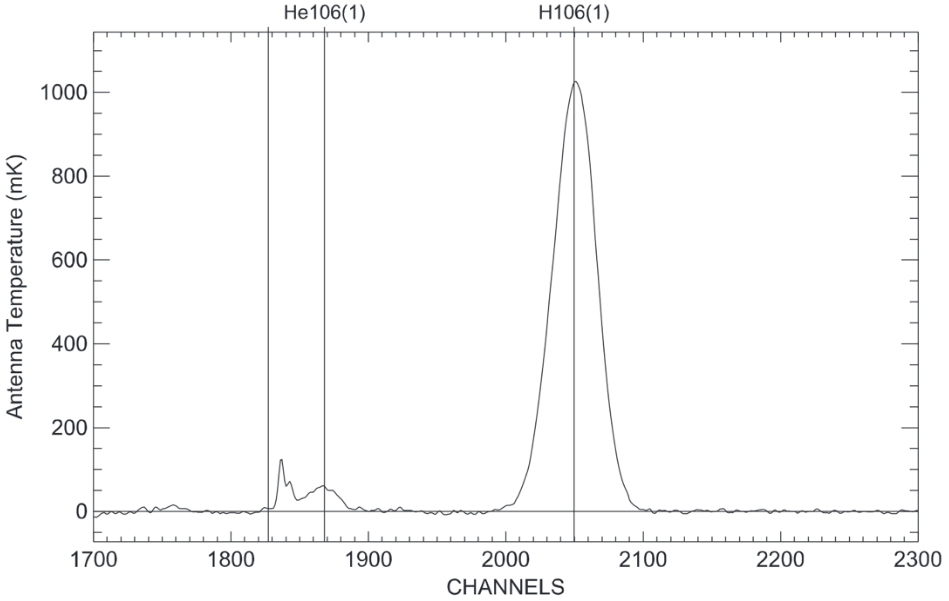
Table 1
RRL Transitions and Frequencies

Spectral Band Containing the α Line (1)	α Line Frequency (MHz) (2)	Other Transitions in this Band (3)
H102α	6106.84	H128β, H146γ
H103α	5934.51	H185ζ
H104 α	5762.89	H164δ, H178ò, H187ζ
H105 α	5600.54	H132β, H178ζ[a]
H106 α	5444.27	H152γ, H167ò
H107 α	5293.72	H202η
H108 α	5148.70	H155γ, H170δ, H183ò, H194ζ
H109 α	5008.93	H137β, H172δ, H185ò, H196ζ + H208 η[b]

Wilson et al., 2015

HII region NGC 1976
(Messier 42, Orion A) at ~ **5 GHz**



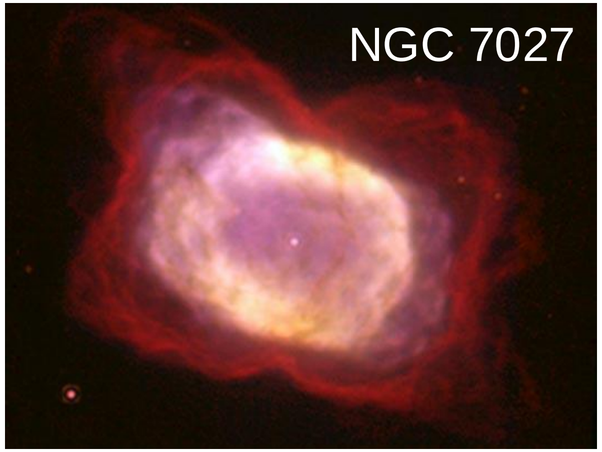


ASTR 5340 - Introduction to Radio Astronomy
Contact: sscibell@nrao.edu

Recombination Line Data

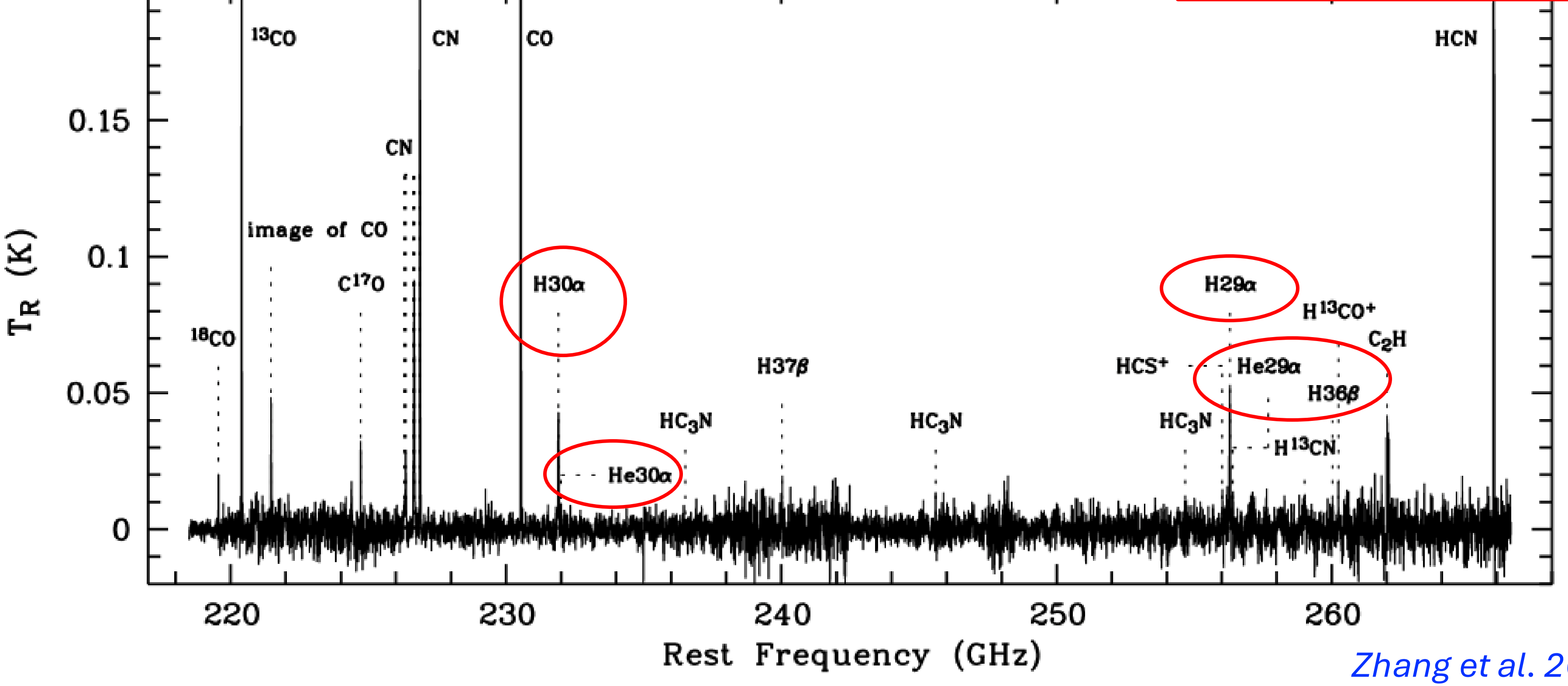
'High' Frequency

Planetary Nebula



Young PN: ***~ 700 years old***

T_{star} ~ 200,000 K



Zhang et al. 2008

Radio Recombination Lines (ERA 7.2, 7.6)

Line Strengths (7.2.2)

The Spontaneous Emission Coefficient for ‘H’ atoms from level *n* to level *(n-1)*:

$$A_{n+1,n} \approx \left(\frac{64\pi^6 m_e e^{10}}{3c^3 h^6} \right) \frac{1}{n^5}. \qquad (7.23)$$

$$A_{n+1,n} \approx 5.3 \times 10^9 \left(\frac{1}{n^5} \right) \quad \mathrm{s}^{-1}. \qquad (7.25)$$

The 5.0089 GHz H109α transition rate is $A_{110,109} \sim 0.3\ \mathrm{s}^{-1}$

Radio Recombination Lines (ERA 7.2, 7.6)

Line Strengths (7.2.2)

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Hydrogen RRLs at frequencies of around 5 – 20 GHz arising from **typical HII regions with densities of $10^3 - 10^4$ cm^{-3}** and electron temperatures of ~7000 K

The 5.0089 GHz H109α transition rate is $A_{110,109}$ ~ 0.3 s^{-1}

Higher critical densities

Radio Recombination Lines (ERA 7.2, 7.6)

Other RRLs can probe other phases of the ISM!

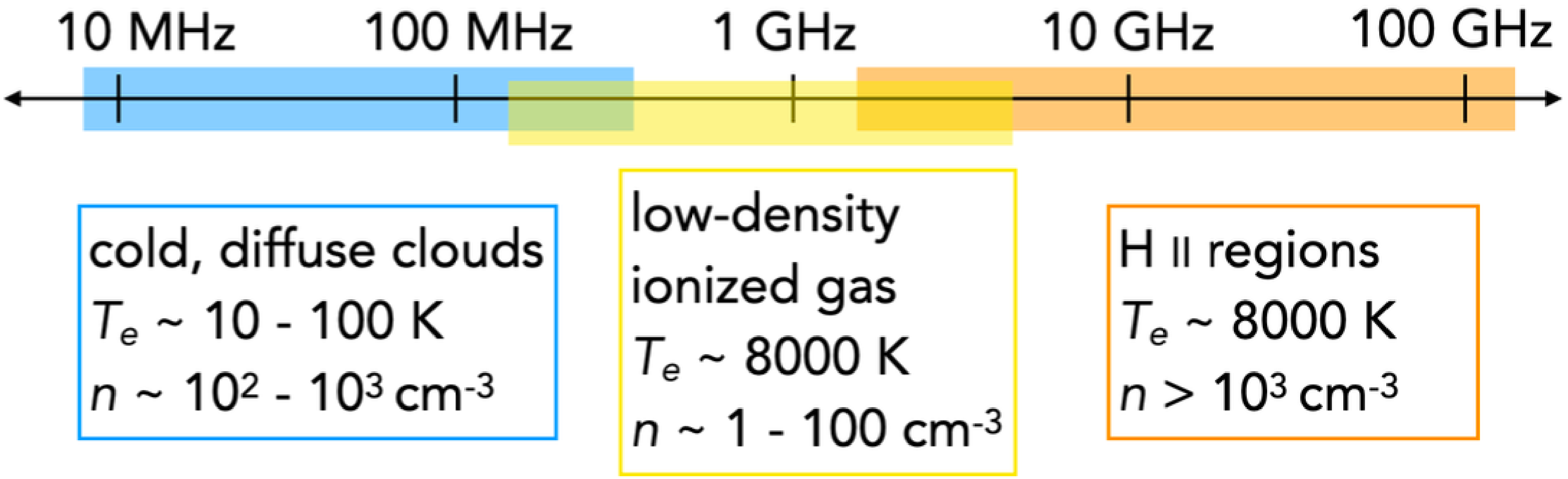
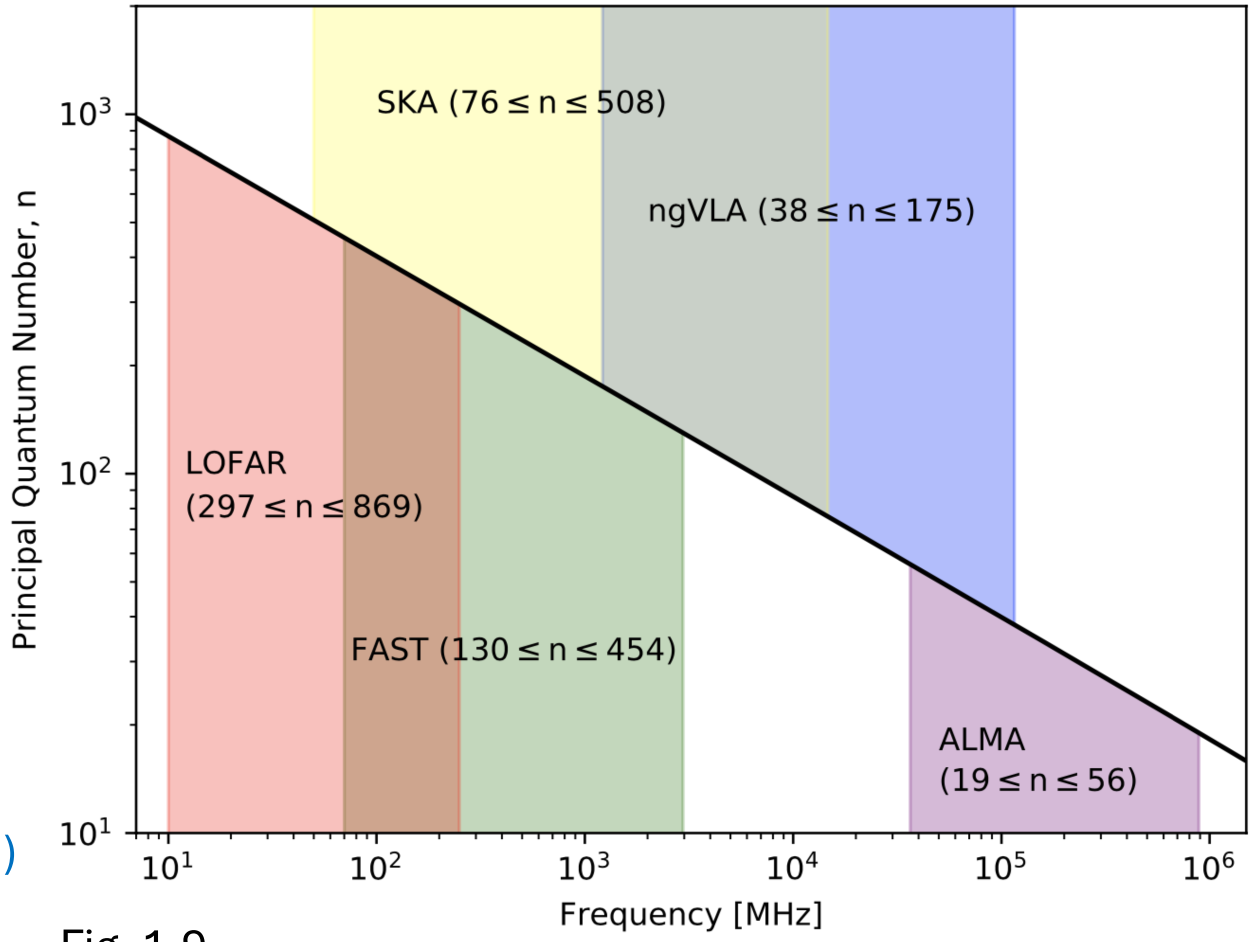


Figure 1.5: The gas components and their frequencies traced by radio recombination lines. Emission from cold diffuse clouds is probed by $\nu \lesssim 500$ MHz, low-density ionized gas by 300 MHz $\lesssim \nu \lesssim 5$ GHz, and classic H II regions by $\nu \gtrsim 1$ GHz.

Emig Thesis (2021)

Radio Recombination Lines (ERA 7.2, 7.6)

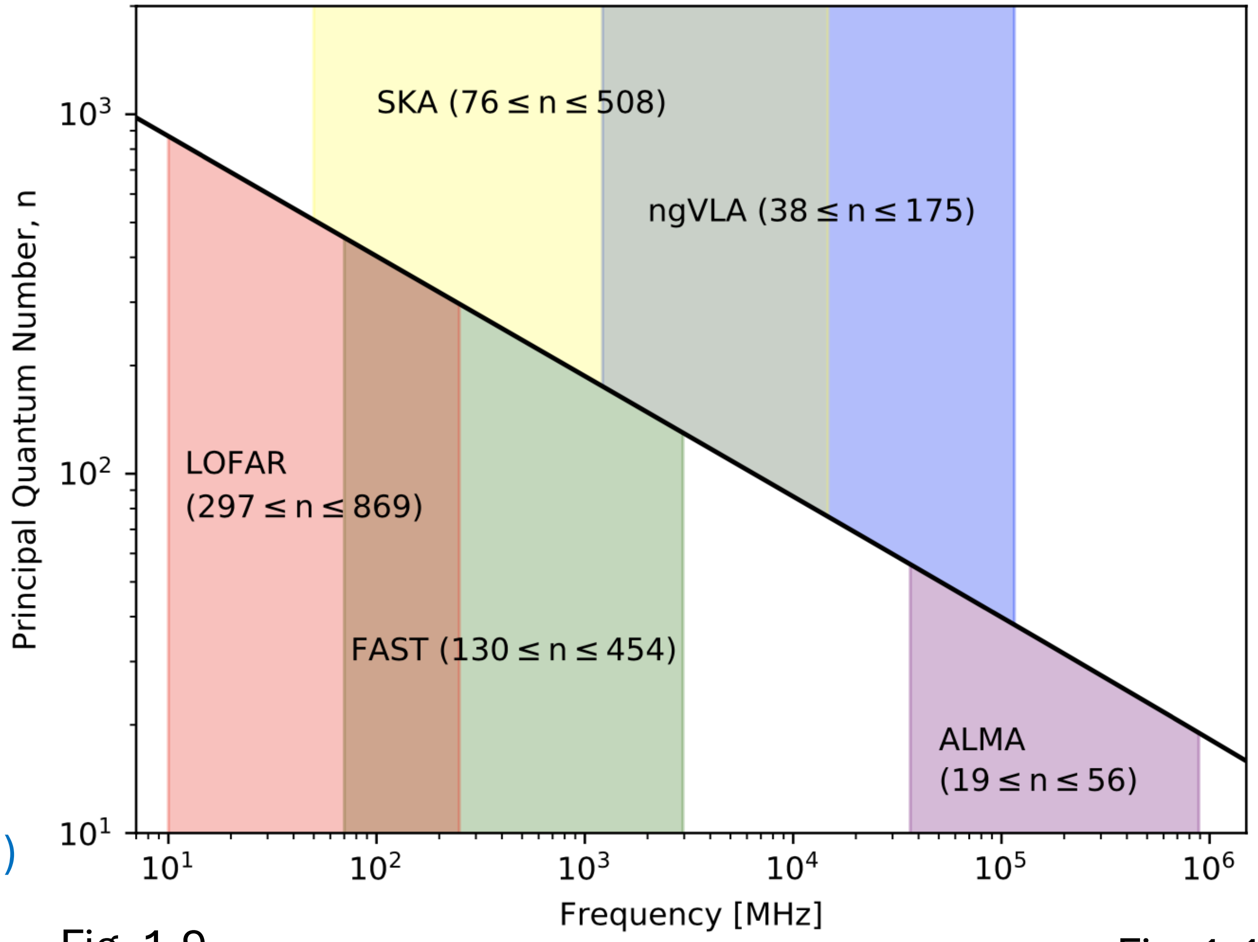
Many different radio telescopes can be used!



Emig Thesis (2021)

Fig. 1.9

Radio Recombination Lines (ERA 7.2, 7.6)

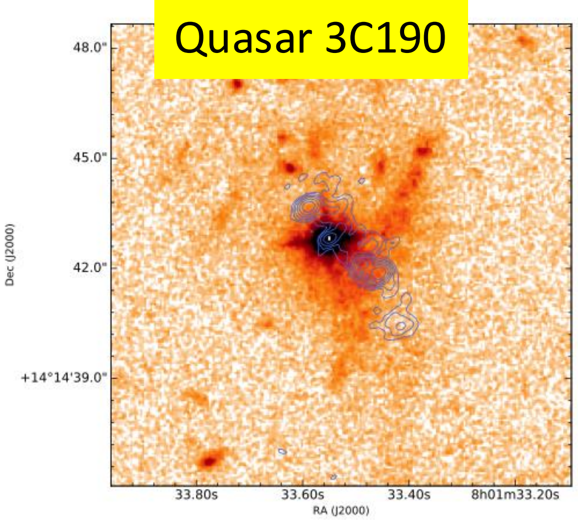


Emig Thesis (2021)

Fig. 1.9

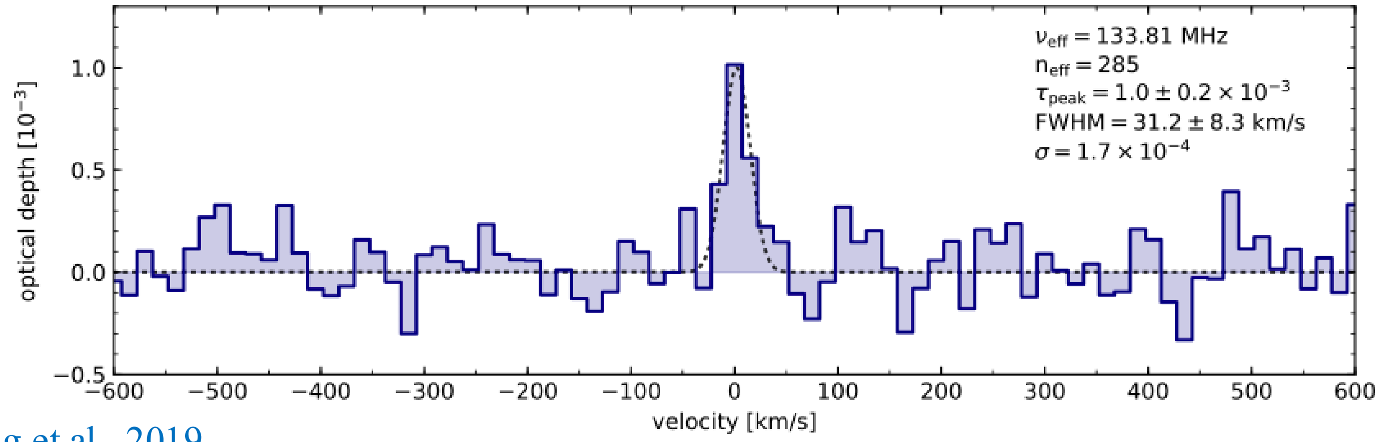
Fig. 1.10

Radio Recombination Lines (ERA 7.2, 7.6)



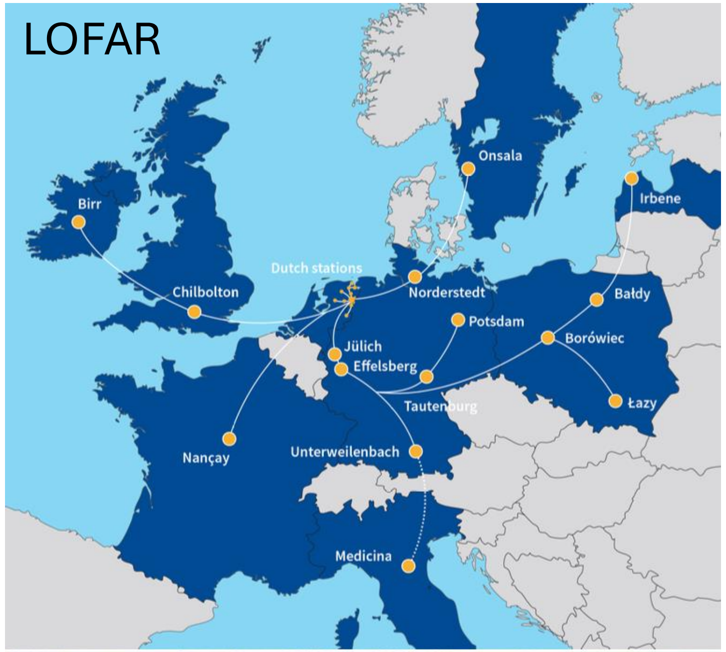
The first detection of radio recombination lines at cosmological distances!

- Observed b/w 109.77MHz and 189.84 MHz w/ LOFAR
- Stacking 13 α- transitions with principal quantum numbers n = 266−301 at $z = 1.124$
- Explained by either warmer/higher density H or cooler/lower density C emission in intervening dwarf galaxy ($M \sim 10^9\ M_\odot$), roughly 80Mpc from 3C 190



Emig et al., 2019

Fig. 1.10



Radio Recombination Lines (ERA 7.2, 7.6)

Line Widths (7.2.2)

Reminder: natural broadening is negligibly small at the large *n* that produce radio-frequency photons

Thermal broadening dominates (+collisional broadening negligible)

Thermal component of the line profile from a recombination-line source in LTE is determined by the **Maxwellian speed distribution** of atoms with **mass *M* and temperature *T***

The normalized line profile for thermal emission*:*

$$\boxed{\phi(\nu) = \frac{c}{\nu_0}\left(\frac{M}{2\pi kT}\right)^{1/2} \exp\left[-\frac{Mc^2}{2kT}\frac{(\nu-\nu_0)^2}{\nu_0^2}\right].} \quad (7.32)$$

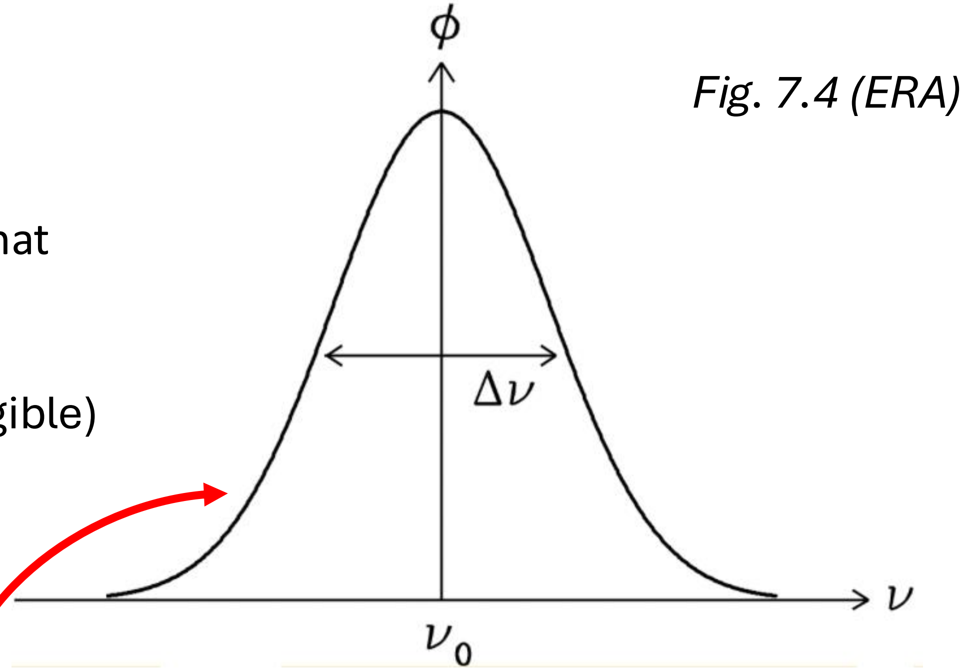


Fig. 7.4 (ERA)

The parameters of the normalized ($\int\varphi(\nu)d\nu = 1$) line profile $\varphi(\nu)$ are the center frequency ν_0, the **FWHM line width Δν**, and the profile height $\varphi(\nu_0)$ at the center frequency

Radio Recombination Lines (ERA 7.2, 7.6)

Line Widths (7.2.2)

The normalized line profile for thermal emission:

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This factor set equal to ½ to get FWHM:

$$\exp\left[-\frac{Mc^2}{2kT}\frac{(\Delta\nu/2)^2}{\nu_0^2}\right] = \frac{1}{2}, \quad (7.33)$$

$$\frac{Mc^2}{2kT}\frac{\Delta\nu^2}{4\nu_0^2} = \ln 2, \quad (7.34)$$

$$\boxed{\Delta\nu = \left[\frac{8\ln(2)\ k}{c^2}\right]^{1/2}\left(\frac{T}{M}\right)^{1/2}\nu_0. \quad (7.35)}$$

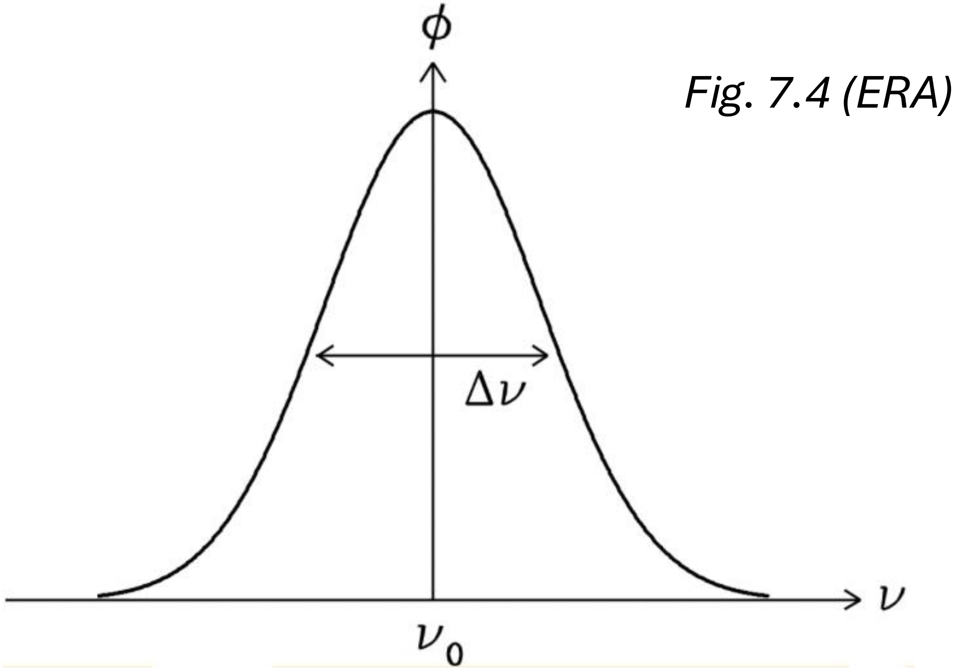

Fig. 7.4 (ERA)

The parameters of the normalized ($\int\varphi(\nu)d\nu = 1$) line profile $\varphi(\nu)$ are the center frequency ν_0, the **FWHM line width Δν**, and the profile height $\varphi(\nu_0)$ at the center frequency

IMPORTANT: dependence on temperature of the gas, *T*, and mass of the atom, *M*!

Radio Recombination Lines (ERA 7.2, 7.6)

Line Widths (7.2.2)

The normalized line profile for thermal emission:

$$\boxed{\phi(\nu) = \frac{c}{\nu_0}\left(\frac{M}{2\pi kT}\right)^{1/2} \exp\left[-\frac{Mc^2}{2kT}\frac{(\nu-\nu_0)^2}{\nu_0^2}\right].} \quad (7.32)$$

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Line width FWHM extract factor
8 ln(2))^1/2 here!

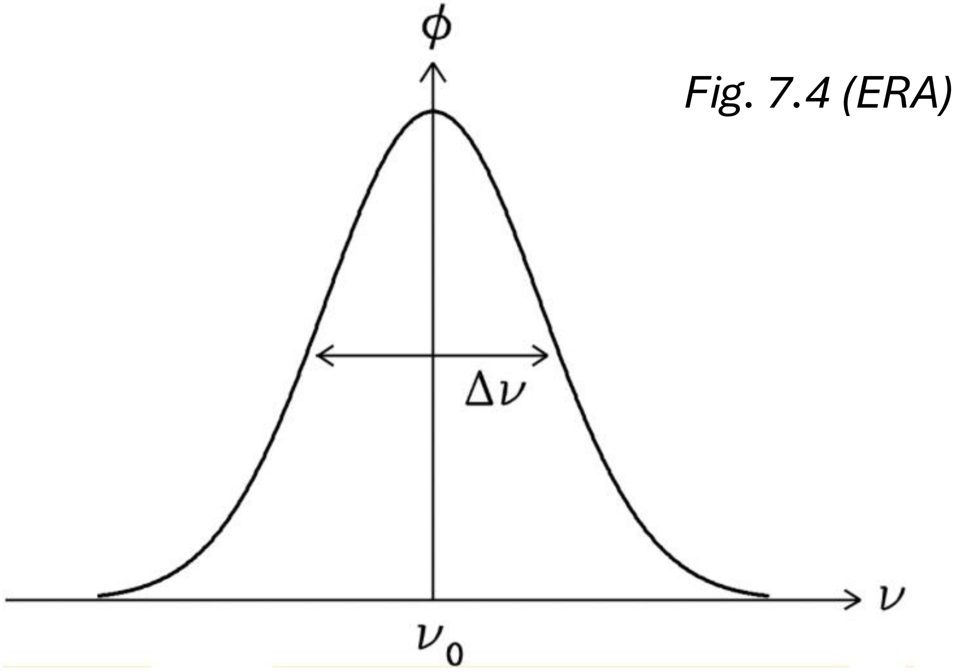

Fig. 7.4 (ERA)

BEWARE! If you are fitting your spectral line with a standard Gaussian function with a normal distribution you may need to multiply output width by this factor!

Radio Recombination Lines (ERA 7.2, 7.6)

Line Widths (7.2.2)

$$\phi(\nu_0) = \frac{c}{\nu_0}\left(\frac{M}{2\pi kT}\right)^{1/2} = \frac{c}{\Delta\nu}\left(\frac{8\ln 2\, kT}{Mc^2}\frac{M}{2\pi kT}\right)^{1/2}, \qquad (7.36)$$

$$\boxed{\phi(\nu_0) = \left(\frac{\ln 2}{\pi}\right)^{1/2}\frac{2}{\Delta\nu}.} \qquad (7.37)$$

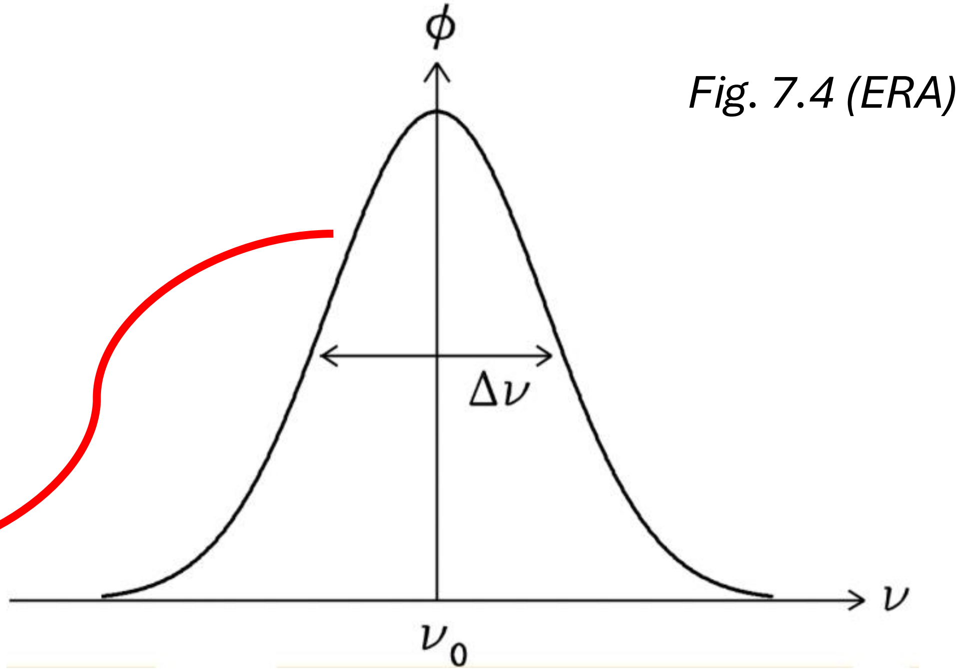

Fig. 7.4 (ERA)

The parameters of the normalized ($\int \varphi(\nu) d\nu = 1$) line profile $\varphi(\nu)$ are the center frequency ν_0, the **FWHM line width Δν**, and the profile height $\varphi(\nu_0)$ at the center frequency

- For a given **integrated (over frequency) line strength**, the line strength per unit frequency at any one frequency (e.g., at ν_0) is ***inversely proportional to the line width Δν***
- Integrated line strengths are frequently specified in the astronomically convenient units of Jy km s^{-1}, where 1 km s^{-1} ≈ ν_0 / 3.00 × 10^5.

Radio Recombination Lines (ERA 7.2, 7.6)

Line Widths (7.2.2)

For **recombination lines** the **natural line width** or intrinsic line width follows from the uncertainly principle where, for a change in time, *Δt*, for each energy level involved in the transition we can write in terms of spontaneous emission rate:

$$\Delta\nu \sim A_{n+1,n}/\pi \sim 0.1 \quad \text{Hz.} \qquad (7.26)$$

Compare this to FWHM of the H109α line (ν_0=5.0089 GHz) in a quiescent (no macroscopic motions) HII region with temperature T≈10^4 K:

$$\begin{aligned}\Delta\nu &\approx \left[\frac{8\ln 2 \cdot 1.38\times10^{-16}\ \text{erg K}^{-1}}{(3\times10^{10}\ \text{cm s}^{-1})^2}\right]^{1/2}\left(\frac{10^4\ \text{K}}{1836\cdot 9.11\times10^{-28}\ \text{g}}\right)^{1/2} \\ &\quad \times 5.0089\times10^9\ \text{Hz} \\ &\approx 3.6\times10^5\ \text{Hz.}\end{aligned}$$

Radio Recombination Lines (ERA 7.2, 7.6)

Line Widths (7.2.2)

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Thermal width much larger >> than natural line width!

Dominated by motions of the gas:

1) Microscopic (thermal motions of atoms) →

2) Macroscopic (large-scale turbulence, flows, outflows, rotation)