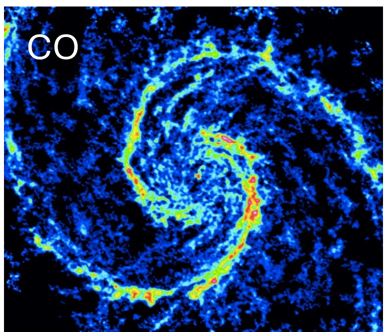
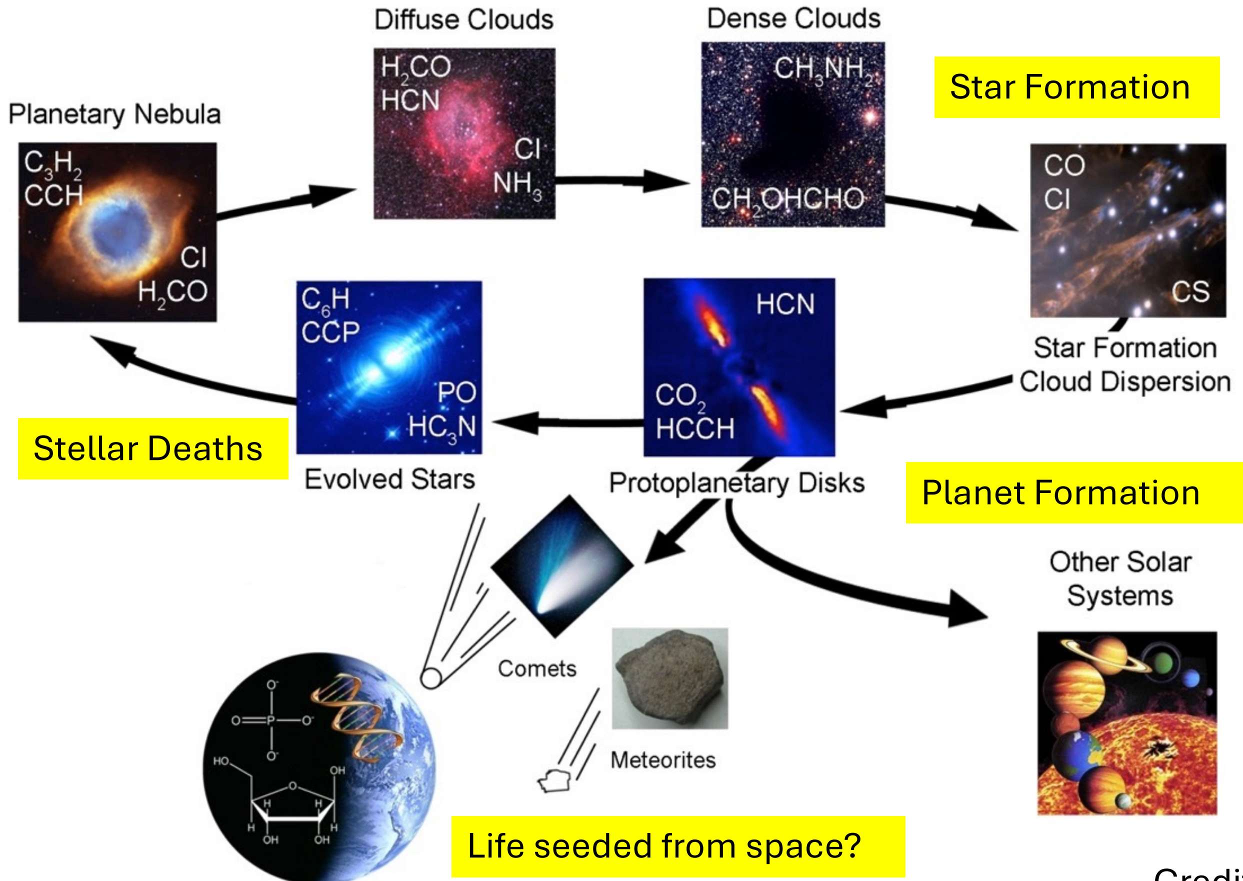
Molecular Life Cycle

Within Galaxies... →



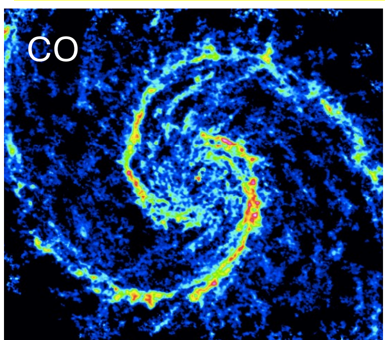
M51 – Whirlpool Galaxy



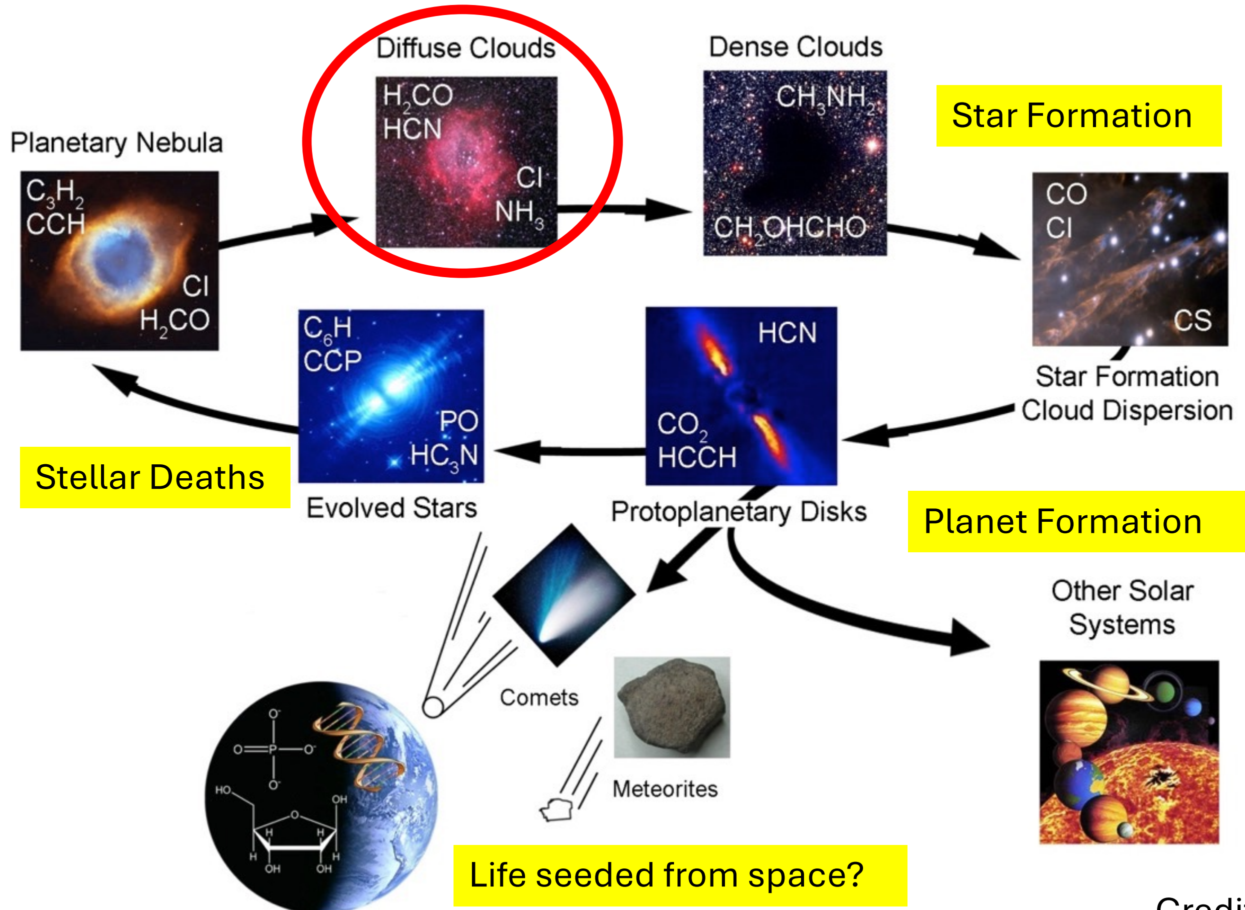
Credit: L. Ziurys

Molecular Life Cycle

Within Galaxies... →



M51 – Whirlpool Galaxy

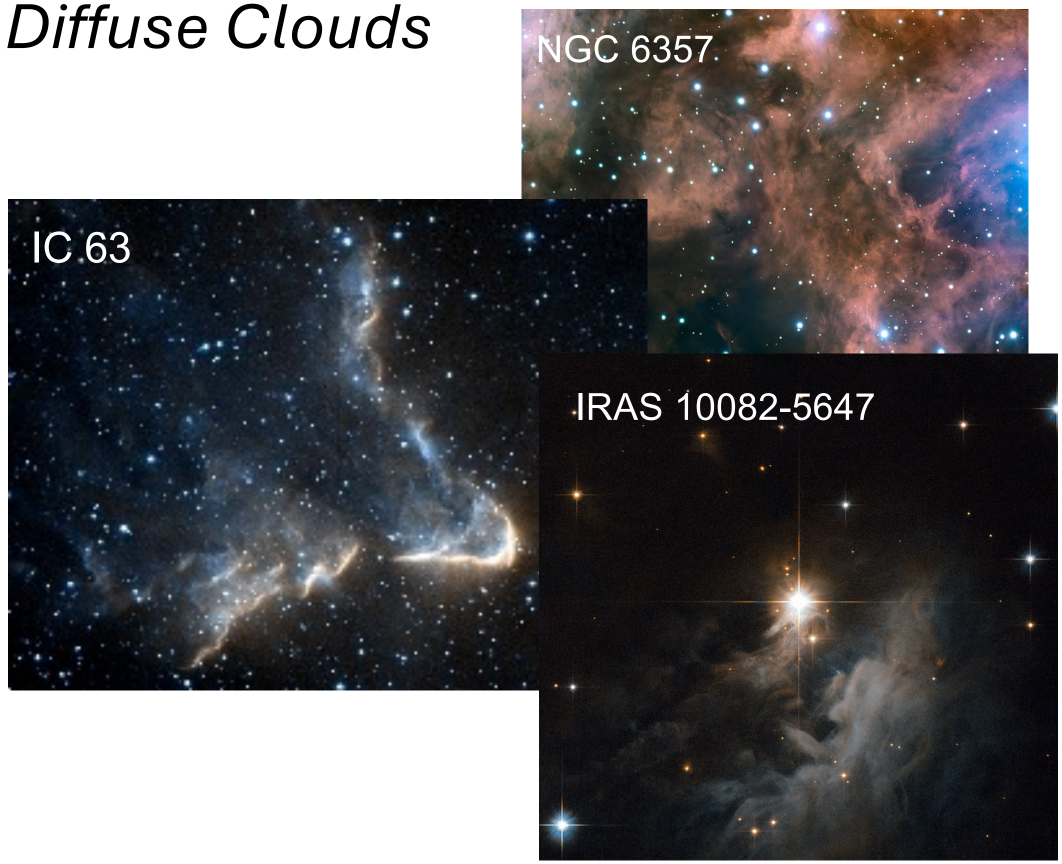


Credit: L. Ziurys

Diffuse Clouds

Lack a *Definite Morphology*

- Semi-transparent in the visible ($A_v \sim 1$)
- Total hydrogen column density: $N \sim 10^{21}$ cm^{-2}
- Readily penetrated by UV radiation



Credit: L. Ziurys

Diffuse Clouds

Lack a *Definite Morphology*

- Semi-transparent in the visible ($A_v \sim 1$)

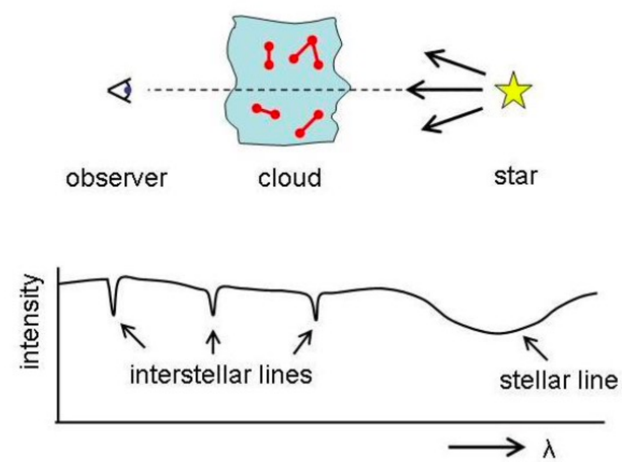
- Total hydrogen column density: $N \sim 10^{21}$ cm^{-2}

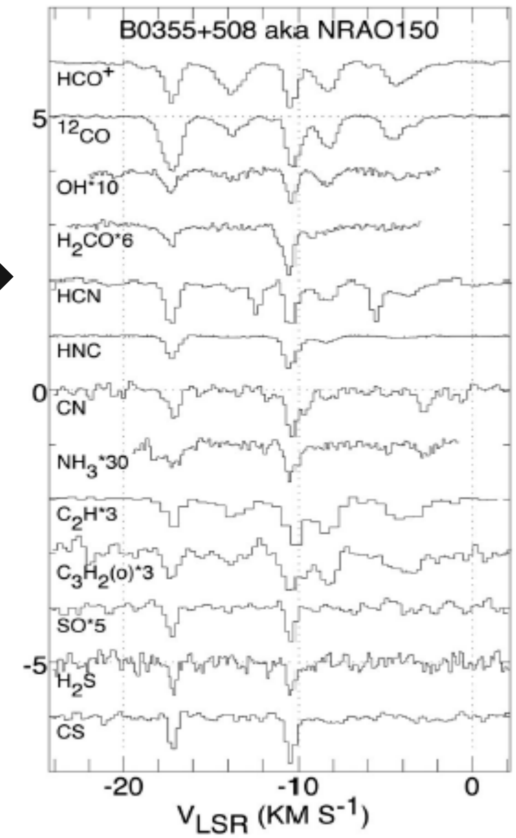
- Readily penetrated by UV radiation

- Densities low: No radio/mm emission lines
- Not sufficient density for collisional excitation
- Molecules observed in ABSORPTION
- Common molecules observed

  OH, H_2 (HD), CH, C_2, CH^+, NH, CO, H_3^+

*line of sight to the blazar/radio-continuum source ➔





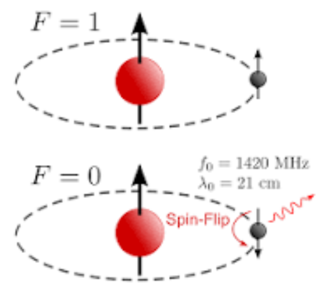
Credit: L. Ziurys

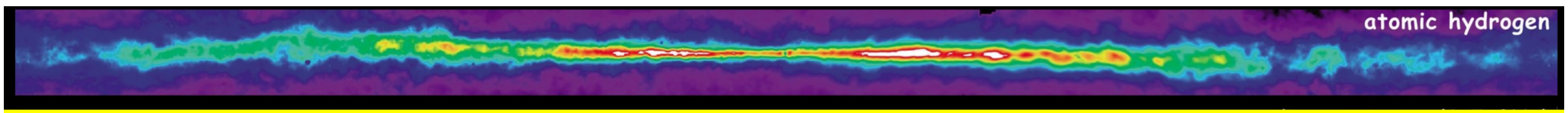
Diffuse Clouds

Lack a *Definite Morphology*

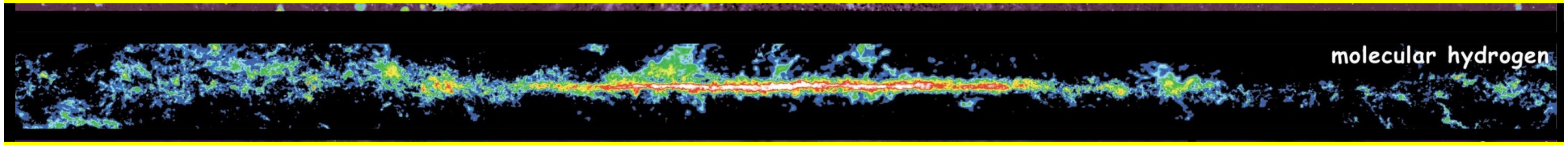
- Semi-transparent in the visible ($A_v \sim 1$)
- Total hydrogen column density: $N \sim 10^{21}$ cm^{-2}
- Readily penetrated by UV radiation

- Best traced by **21 cm HI line**
  - $T_k \sim$ 100 K
  - n ~ 1 - 100 particles/cm^3 ($H^0 + H_2$)
  - $x_e \sim 10^{-3}$ (*Fractional ionization*)





The Milky Way in **Atomic** Hydrogen (21cm line of HI) traces the diffuse clouds and intercloud medium ↑



The Milky Way in Molecular Hydrogen (mapped by CO!) traces Molecular Clouds ↑

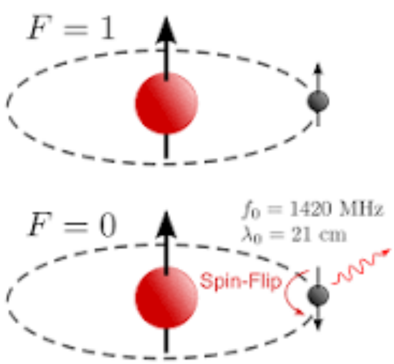
Reminder! Typical Conditions of Molecular Clouds: T ~ 10 – 50 K; n ~ $10^3 – 10^6$ cm^{-3}

Credit: L. Ziurys

HI 21 cm Hyperfine Line (ERA 7.8, *see also Draine Chapters 8 and 29*)

Main topics to cover:

- **Molecular Emission**
- Recombination Lines
- **HI 21cm line**
- **Masers**



Importance:

- 21 cm line is a major probe of ISM in the Galaxy as well as in external galaxies
- Most abundant element!
- Atomic H is a major constituent in most cases
- *Long wavelength*, no extinction
- Radio techniques afford very high spectral resolution + good angular resolution via interferometry
- Simple excitation of transition, LTE a good approximation

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. Hα)
- 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	$\approx 0.2\ cm^{-3}$	10^{-3}–10^{-2}
T (K)	10–50	50–200	5500–8500	≈ 8000	10^6–10^7

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

HI 21 cm Hyperfine Line (ERA 7.8, *see also Draine Chapters 8 and 29*)

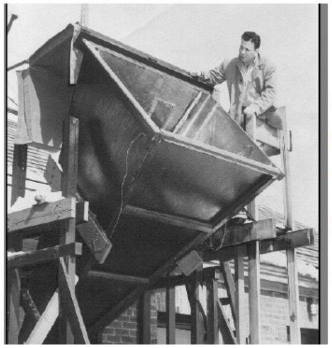
Some Brief History

First predicted by H.C. Van de Hulst in 1944 (while a grad student at Leiden Univ.)

- First detections in 1951 (near simultaneous)
- **Ewen & Purcell (Harvard)**
- Muller & Oort (Netherlands)
- Pawsey, Christiansen, & Hindman (Australia)

Ed Purcell, Taffy Bowen, & H.I. "Doc" Ewen (then a graduate student), at Harvard, 1950

Ewen with his frequency-switching receiver on March 25, 1951, date of 1st detection of HI



Ewen's horn antenna mounted on the Lyman Physics Lab at Harvard. The dielectric window was installed to keep rain from flooding the lab, and deflect snowballs thrown by Harvard students.

HI 21 cm Hyperfine Line (ERA 7.8, *see also Draine Chapters 8 and 29*)

Some Brief History

Extensive surveys published in the 70s and 80s:

- UC Berkeley telescope (Weaver & Williams 1973; Heiles & Habing 1974)
- NRAO (Burton 1985; Stark et al. 1992) with 300-foot transit telescope at Green Bank,WV
- Parkes 64-m (Australia) (Kerr et al. 1986)

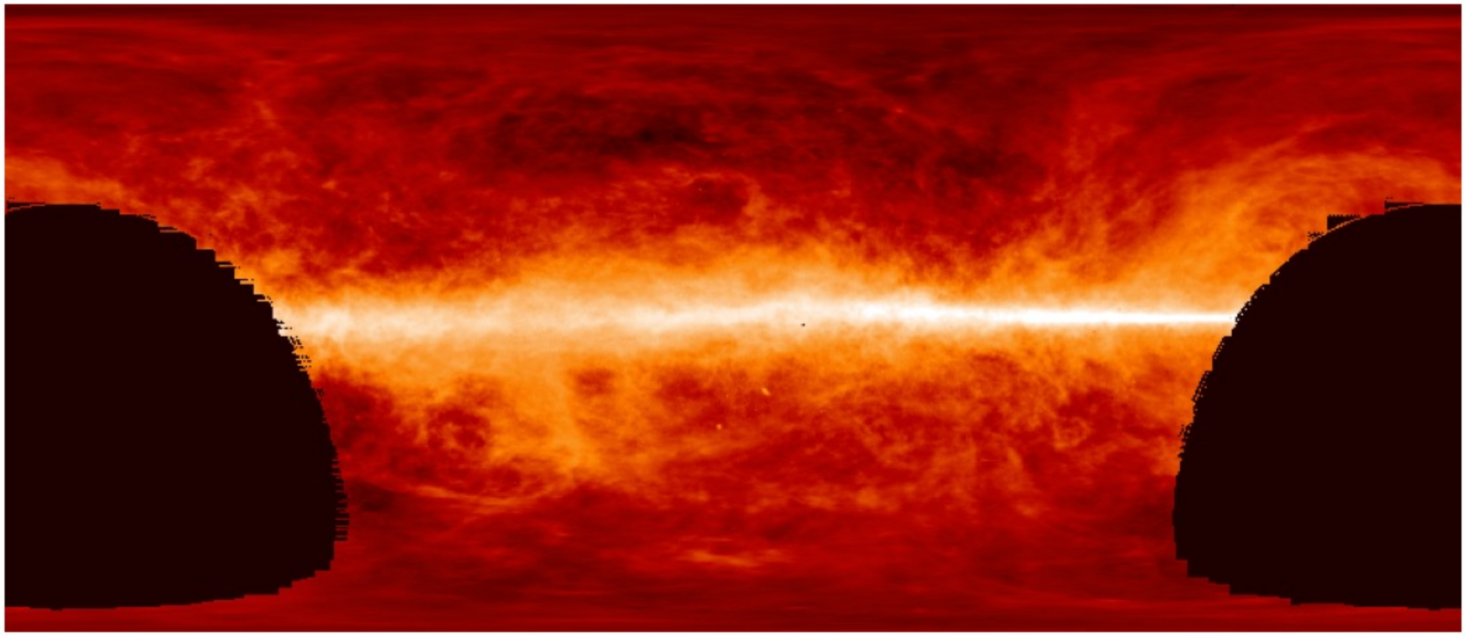
NRAO 300-foot transit telescope at Green Bank, WV, mapping H I in the glory days

After the fall (1988)

64-meter antenna operated by the Commonwealth Scientific and Industrial Research Organization (CSIRO) at Parkes, New South Wales, Australia.
Used extensively for mapping H I in the southern sky.

HI 21 cm Hyperfine Line (ERA 7.8, *see also Draine Chapters 8 and 29*)

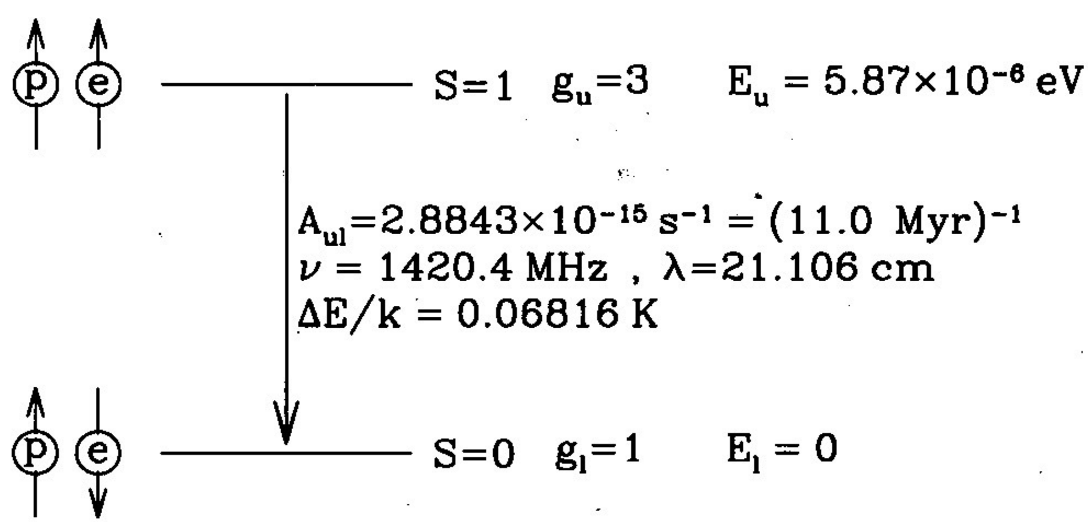
Some Brief History



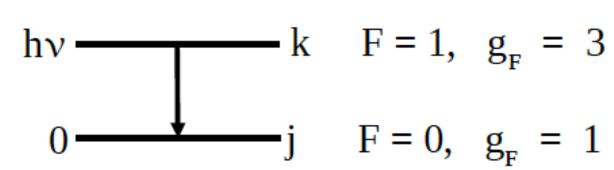
Integrated HI emission from the Leiden-Dwingeloo survey (25 m radio telescope in Netherlands)
Hartmann & Burton 1997

HI 21 cm Hyperfine Line (ERA 7.8, *see also Draine Chapters 8 and 29*)

"spin-flip" of electron relative to proton



Note: when you hear 'hyperfine' it always refers to an interaction with spin of nucleus!



(statistical weights 2F+1)

Two energy levels result from the magnetic interaction between the quantized electron and proton spins. When the **relative spins change** from parallel to antiparallel, a **photon is emitted**.

HI 21 cm Hyperfine Line (ERA 7.8, *see also Draine Chapters 8 and 29*)

The HI center frequency can be written as,

$$\nu_{10} = \frac{8}{3} g_I \left(\frac{m_e}{m_p}\right) \alpha^2 (R_M c) \approx 1420.405751 \ \text{MHz}, \qquad (7.141)$$

Where gI≈5.58569 is the **nuclear g-factor** for a proton, $\alpha \equiv e^2/(\hbar c) \approx 1/137.036$ is the dimensionless **fine-structure constant**, and R_{Mc} is the hydrogen Rydberg frequency (from equation 7.12):

$$R_M c = 3.28984 \times 10^{15} \ \text{Hz} \left(1 + \frac{1}{1836.1}\right)^{-1} = 3.28805 \times 10^{15} \ \text{Hz}.$$

(we will come back to this when we discuss recombination lines)

Sooo... what makes it such a good probe of low density, diffuse material?

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Sooo… what makes it such a good probe of low density, diffuse material? It all comes back to its Einstein A ! 

HI 21 cm Hyperfine Line (ERA 7.8, *see also Draine Chapters 8 and 29*)

Our emission coefficient of radiation by an electric dipole can be **written in terms of the magnetic dipole**:

$$A_{\mathrm{UL}} \approx \frac{64\pi^4}{3hc^3}\nu_{\mathrm{UL}}^3|\mu_{\mathrm{UL}}|^2, \qquad (7.142)$$

$$A_{\mathrm{UL}} \approx \frac{64\pi^4}{3hc^3}\nu_{\mathrm{UL}}^3|\mu_{\mathrm{B}}|^2, \qquad (7.143)$$

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Here μ_B is the mean magnetic dipole moment for Hi in the ground electronic state (n=1).
The magnitude $|\mu B|$ is called the **Bohr magneton**, and its value is

$$|\mu_{\mathrm{B}}| = \frac{e\hbar}{2m_e c} \approx 9.27401 \times 10^{-21} \text{ erg gauss}^{-1}. \quad (7.144)$$

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Such a low A implies an extremely low critical density ($n^* << 1$ cm^{-3}) ! 

Therefore:

$$A_{10} \approx \frac{64\pi^4 (1.42 \times 10^9 \text{ Hz})^3 (9.27 \times 10^{-21} \text{ erg gauss}^{-1})^2}{3 \cdot 6.63 \times 10^{-27} \text{ erg s } (3 \times 10^{10} \text{ cm s}^{-1})^3} \approx 2.85 \times 10^{-15} \text{ s}^{-1}, \qquad (7.145 \text{ \& } 7.146)$$

HI 21 cm Hyperfine Line (ERA 7.8, *see also Draine Chapters 8 and 29*)

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$$n^* \approx \frac{A_{UL}}{\sigma v}$$

A radiative "lifetime" is written as $1/A_{10} = 3.5 \times 10^{14}$ sec or **11 million years**!

- Expect collisions of H atoms to be much more frequent than radiative transitions
- The "natural linewidth" is very small, $\Delta\nu = 3 \times 10^{-15}$ Hz ($\sim A_{10}$)
- Observed line shapes entirely due to atomic motions and the Doppler shift, $\Delta V = c\ \Delta\nu/\nu$
- Easily observed at high resolution with radio heterodyne receivers

HI 21 cm Hyperfine Line (ERA 7.8, *see also Draine Chapters 8 and 29*)

Levels closely follow Boltzmann distribution where we can define an HI spin temperature T_s (analog of the molecular excitation temperature):

$$\boxed{\frac{n_1}{n_0} \equiv \frac{g_1}{g_0} \exp\left(-\frac{h\nu_{10}}{kT_{\rm s}}\right),} \qquad (7.148)$$

where statistical weights of the upper and lower spin states remember are g_1 = 3 and g_0 =*1*.

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Plugging numbers in we get **very low energy photons**

$$\frac{h\nu_{10}}{kT_s} \approx \frac{6.63 \times 10^{-27}\ \text{erg s} \cdot 1.42 \times 10^9\ \text{Hz}}{1.38 \times 10^{-16}\ \text{erg K}^{-1} \cdot 150\ \text{K}} \approx 5 \times 10^{-4} \ll 1 \tag{7.149}$$

So for any reasonable temperature ***$n_1 / n_o \sim g_1 / g_2 \sim 3$***

Therefore, ¾ of H-atoms are in F = 1 state at all times or ***$n_1 = 0.75\, n_{total}$!***

HI 21 cm Hyperfine Line (ERA 7.8, *see also Draine Chapters 8 and 29*)

Consequences when deriving cloud properties in your radiative transfer calculations:

- Volume emissivity does not depend on gas temperature
- Very different very typical 'nebular' emission lines
- Typically consider HI emission in the optically thin limit

Plugging numbers in we get **very low energy photons**

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HI 21 cm Hyperfine Line (ERA 7.8, *see also Draine Chapters 8 and 29*)

The opacity coefficient is:

$$\kappa(\nu) \approx \frac{3c^2}{32\pi} \frac{A_{10} n_{\rm H}}{\nu_{10}} \frac{h}{kT_{\rm s}} \phi(\nu), \tag{7.153}$$

And you can integrate up the column density along any line of sight,

$$\eta_{\rm H} \equiv \int_{\rm los} n_{\rm H}(s)\, ds. \tag{7.154}$$

Conveniently written as,

$$\left(\frac{\eta_{\rm H}}{\rm cm^{-2}}\right) \approx 1.82 \times 10^{18} \int \left[\frac{T_{\rm b}(v)}{\rm K}\right] d\left(\frac{v}{\rm km\ \ s^{-1}}\right), \tag{7.155}$$

where T_b is the observed 21-cm-line brightness temperature at radial velocity v and the velocity integration extends over the entire 21-cm-line profile.

In the optically thin limit, τ << 1, **the integrated HI emission brightness T_b is proportional to the column density of HI** and independent of spin temperature, T_s!

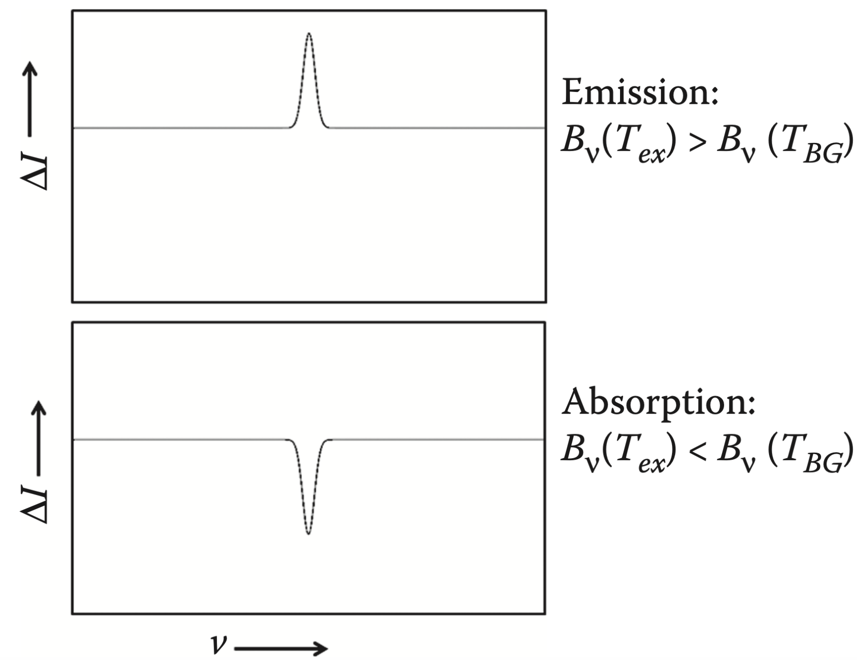
HI 21 cm Hyperfine Line (ERA 7.8, *see also Draine Chapters 8 and 29*)

In the optically thick limit, $\tau >> 1$, (as shown before):

$$\Delta I_\nu = [B_\nu(T_{ex}) - B_\nu(T_{BG})] \quad \text{for } \tau_\nu \gg 1$$

the integrated HI emission is shown in absorption where a continuum source is greater than the spin/excitation temperature (i.e., $T_{ex} < T_{BG}$)

The **kinetic temperature of the HI in our Galaxy can thus be estimated from the HI line brightness temperatures in this limit (and should be roughly the same in LTE)**!



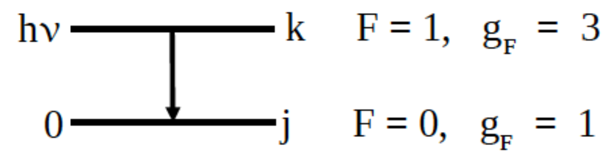
HI 21 cm Hyperfine Line (ERA 7.8, *see also Draine Chapters 8 and 29*)

Now, to **relate our 'spin' temperature to the gas kinetic temperature** one must consider the ...

Statistical equilibrium equation for a 2-level atom:

upward transitions = downward transitions

$$n_j\,(C_{jk} + R_{jk}) = n_k\,(C_{kj} + R_{kj})$$



where now we are dominated by **collision rate coefficients**, C, depend weakly on temperature where,

$$C_{kj} = n\,\sigma_{kj}\,v$$

And 'n' is the density of collision partners and v is the collision velocity.

HI 21 cm Hyperfine Line (ERA 7.8, *see also Draine Chapters 8 and 29*)

Now, to **relate our 'spin' temperature to the gas kinetic temperature** one must consider the ...

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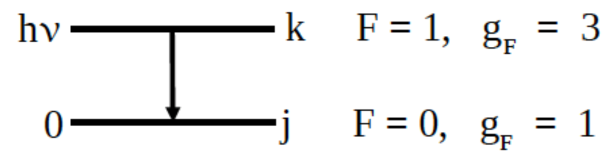


The **radiative rates** still come into play where,

Downward rate: $R_{kj} = A_{kj} + J\,B_{kj} = (1 + k <T_B> h\nu)\,A_{kj}$

Upward rate: $R_{jk} = J\,B_{jk} = (k <T_B> h\nu)\,A_{kj}$

where J is mean intensity of radiation at 21-cm averaged over the line, and $<T_B>$ is averaged over all directions and over line profile

HI 21 cm Hyperfine Line (ERA 7.8, *see also Draine Chapters 8 and 29*)

If we treat H atom as a 2-level system, can show that

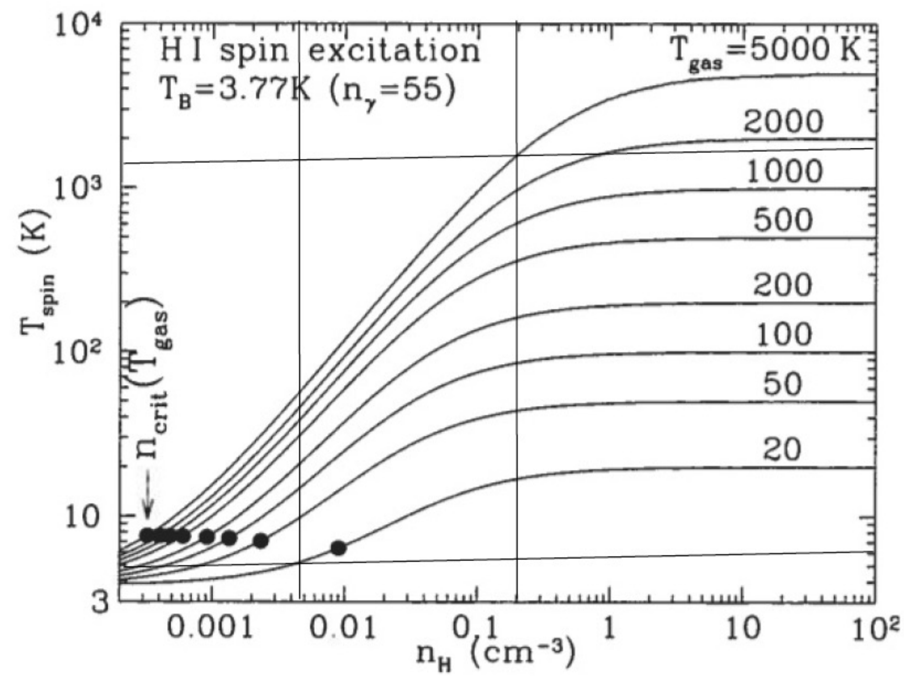
$$T_{ex} = [\, T_k + y \langle T_B \rangle \,] / (1 + y)$$

where $y = (kT_k/h\nu)\,(A_{kj}/C_{kj})$

Or conveniently: $y = (T_k / 1000\text{ K})/(nHI / 0.2\text{ cm}^{-3})$

Here T_{ex} is a weighted mean of gas temperature and 21-cm radiation brightness temperature

Example: Tk = 100 K, nHI = 30 cm-3, then
y = 0.0007 so **Tex ~ Tk to a very good approximation**!



Draine, p. 194

HI 21 cm Hyperfine Line (ERA 7.8, *see also Draine Chapters 8 and 29*)

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Example: Tk = 100 K, nHI = 30 cm-3, then
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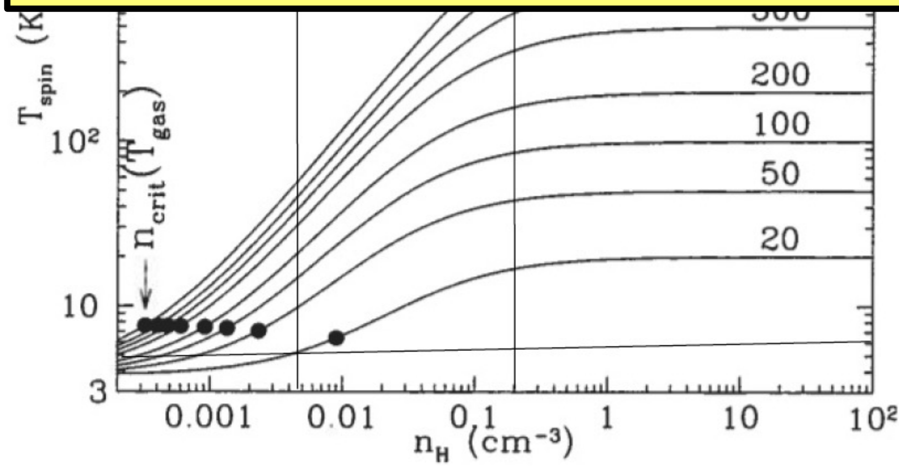
Main Takeaway: The HI 21-cm line excitation temperature should be close to the gas kinetic temperature under most conditions encountered in the galactic ISM



Draine, p. 194

HI 21 cm Hyperfine Line (ERA 7.8, *see also Draine Chapter 30*)

Two-components of HI: warm and cold

21 cm line observations imply existence of 2 major HI components, each with ~50% of total HI ("locally")

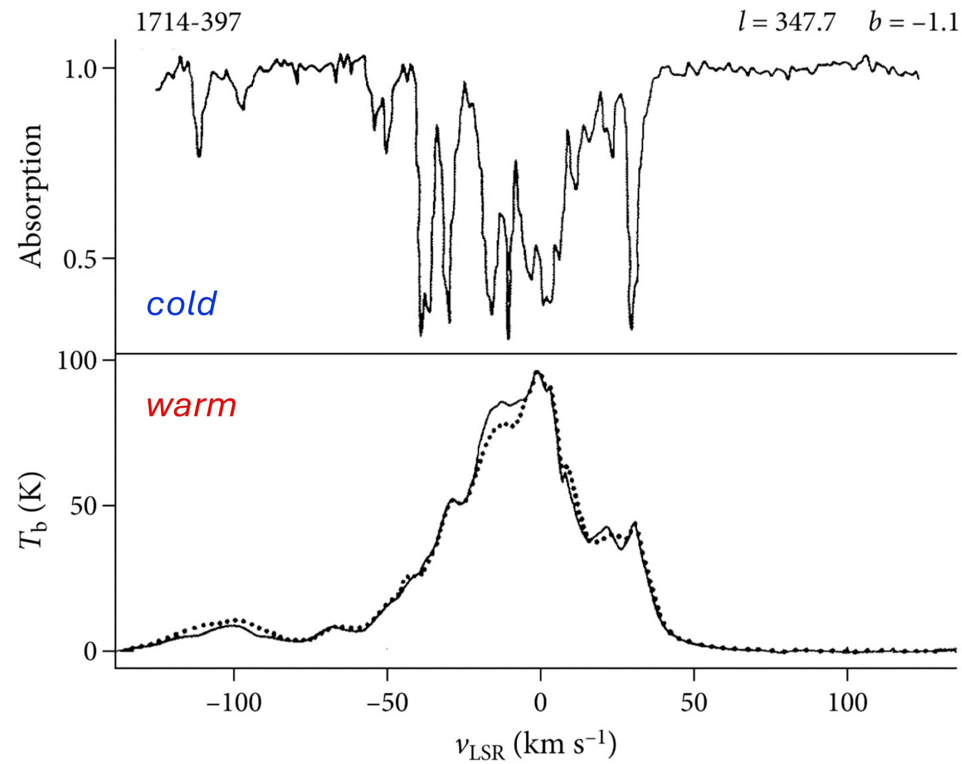


Figure 7.17: The HI absorption and emission spectra toward the source 1714-397 [35].

HI 21 cm Hyperfine Line (ERA 7.8, *see also Draine Chapter 30*)

Two-components of HI: warm and cold

21 cm line observations imply existence of 2 major HI components, each with ~50% of total HI ("locally")

(1) Warm neutral medium (WNM)

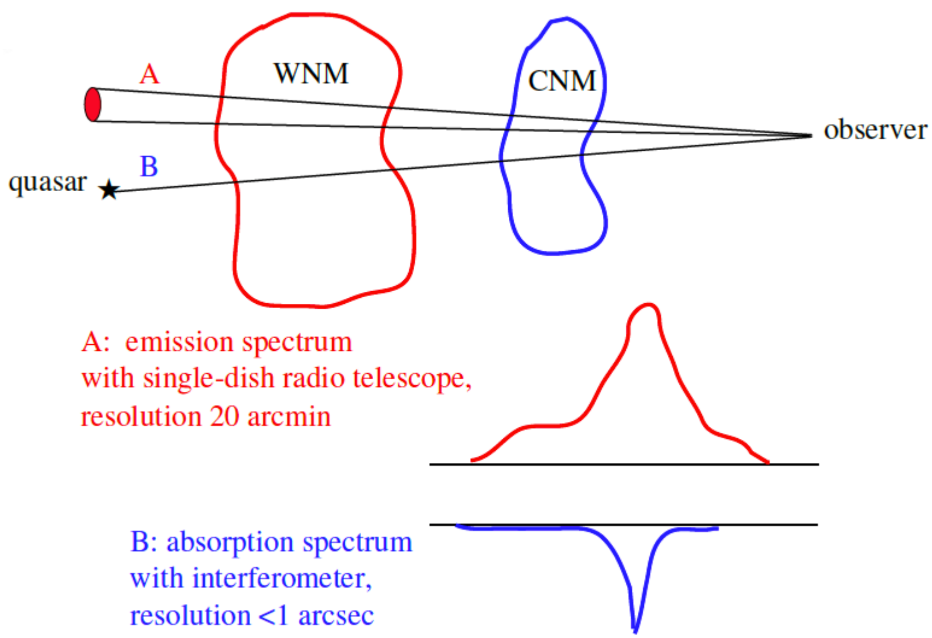
- broad wings ($\sigma_V \sim 9$ km s^{-1}) in H I emission spectra
- seen in all directions for |b| > 10^o (confused close to galactic plane)
- not seen in absorption toward continuum sources (i.e., too weak to detect, mostly)
- Recall that: τ(H I) ~ N(H I) / T
- Warm gas has low optical depth for given N(H I)

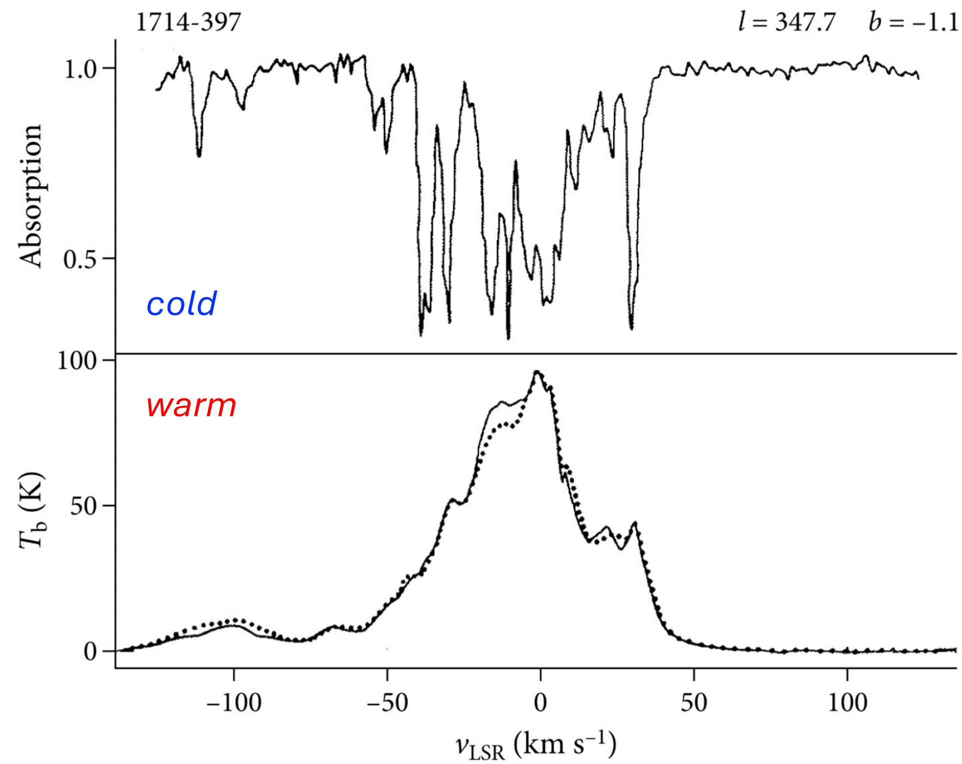
(2) Cold neutral medium (CNM)

- Distributed in relatively dense clouds, with very small volume filling factor (~1%)
- Detected in absorption against bright continuum sources
- Seen in ~1/3 of all directions, velocities
- Narrow spectral features, widths ~ 1 – 2 km s^{-1} in absorption components
- Absorption, emission spectra give Tex

HI 21 cm Hyperfine Line (ERA 7.8, *see also Draine Chapter 30*)

Two-components of HI: warm and cold





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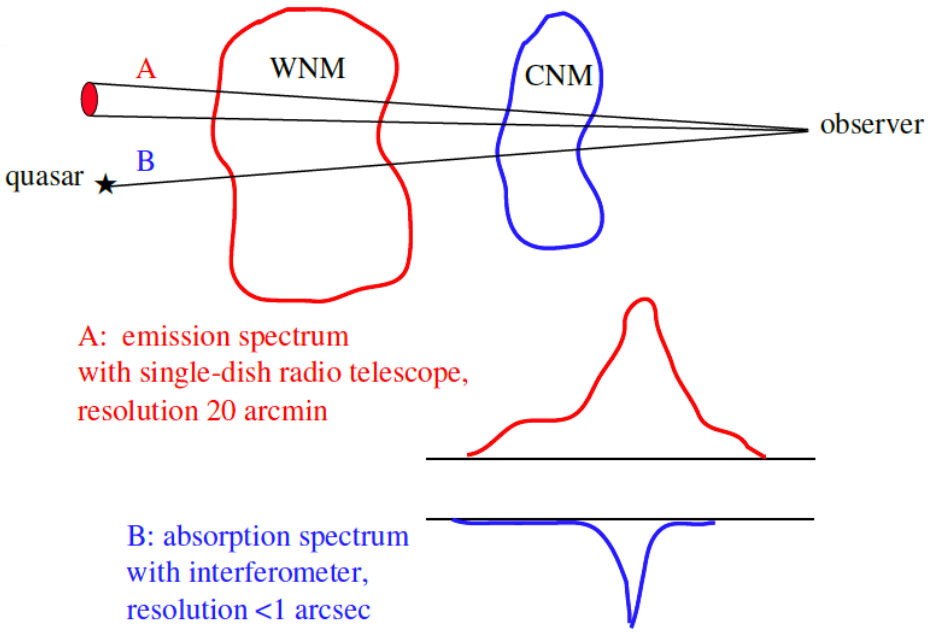
Two-components of HI: warm and cold



Application:

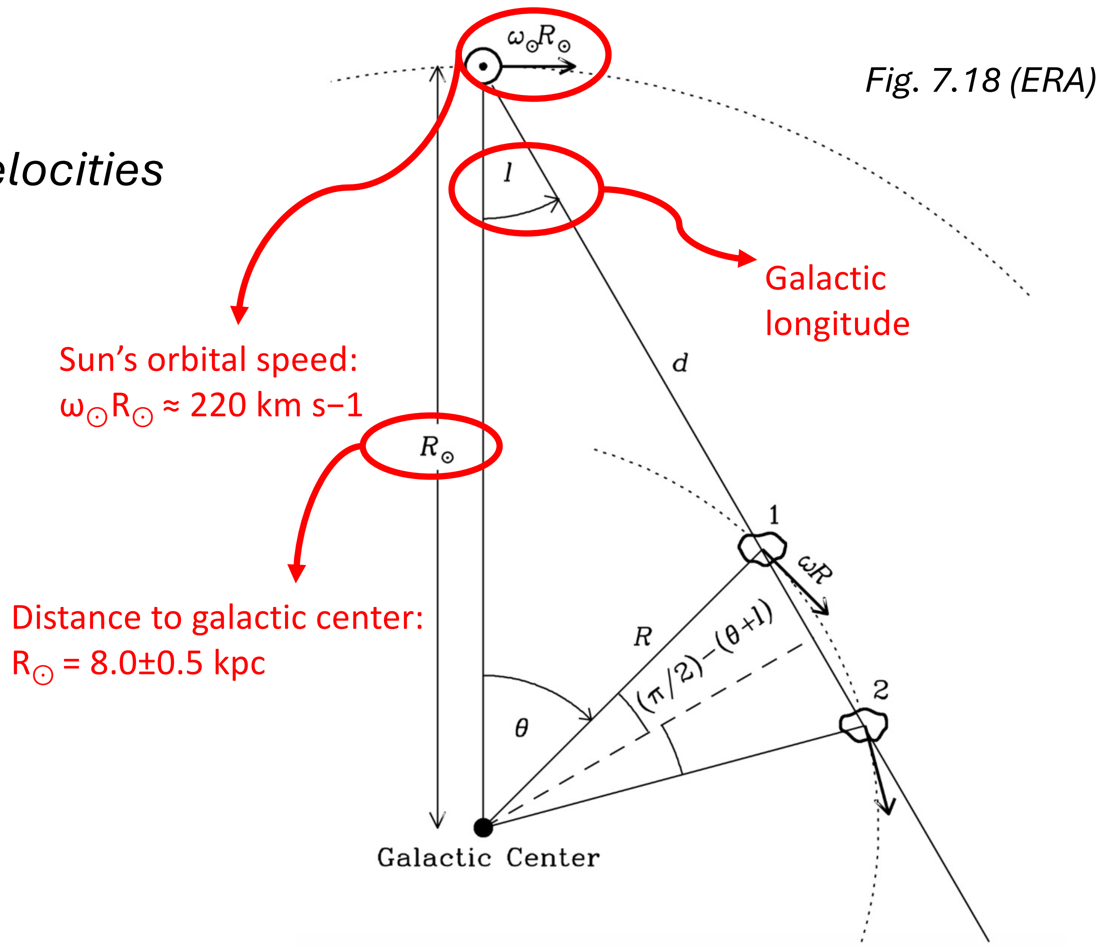
"Radial velocities measured from the Doppler shift of HI emission lines **encode information about the kinematic distances, *d***, of HI clouds, and the spectra of Hi absorption in front of continuum sources can be used to constrain their distances also"

Galactic HI (ERA 7.8.1)

Distances and Radial velocities

View of the Sun (⨀) that → lies in the disk and moves in a circular orbit around the Galactic center

Fig. 7.18 (ERA)



Galactic HI (ERA 7.8.1)

Distances and Radial velocities

Cloud 1 is at galactocentric azimuth θ on the line of sight at Galactic longitude l, the observed radial velocity v_r relative to the Sun is given by

$$v_r = \omega R \cos[\pi/2 - (l + \theta)] - \omega_\odot R_\odot \cos(\pi/2 - l). \quad (7.158)$$

$$\begin{aligned} v_r &= \omega R (\sin\theta \cos l + \cos\theta \sin l) - \omega_\odot R_\odot \sin l \\ &= R_\odot (\omega - \omega_\odot) \sin l. \end{aligned} \quad (7.159 \ \& \ 7.160)$$

(see text for rotation curve and 'terminal velocity' equations)

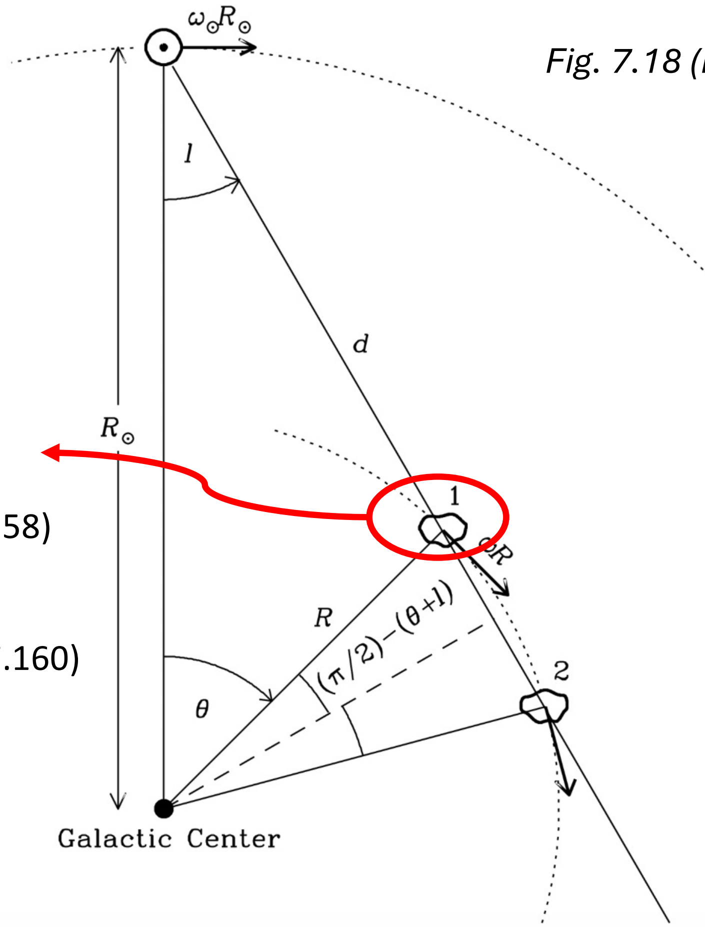


Fig. 7.18 (ERA)

HI 21 cm Observations

The Galactic Arecibo L-band Feed Array HI (GALFA-HI) Survey has mapped neutral hydrogen in and around our Galaxy with the Arecibo 305 meter telescope.

An image of the HI sky, 40 degrees in dec, scanning across 360 degrees in RA, fading through velocity channels
Shifting through velocity space, each velocity being a different color

HI in External Galaxies (ERA 7.8.2)

Important to get velocity conventions right, or your distant object (e.g., galaxy) could fall out of your radio band!

Radial velocities

We can also define radial velocities by 'astronomer' conventions

*Beware that astronomers still use inconsistent radial velocity conventions that were established when most observed radial velocities were much less than the speed of light!

Radio velocity: $$v_r\,(\text{radio}) \equiv c\left(\frac{\nu_e - \nu_o}{\nu_e}\right) \qquad (7.163)$$

Vs.

Optical velocity: $$v_r\,(\text{optical}) \equiv c\left(\frac{\lambda_o - \lambda_e}{\lambda_e}\right) = cz, \qquad (7.165)$$

Where ν_e is the line frequency in the source frame and ν_o is the observed frequency

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E.g., for galaxy UGC 11707 →

$$v_r\,(\text{radio}) \approx c\left(1 - \frac{\nu_o}{\nu_e}\right) \approx 3 \times 10^5 \ \text{km s}^{-1}\left(1 - \frac{1416.2 \ \text{MHz}}{1420.4 \ \text{MHz}}\right) \approx 890 \ \text{km s}^{-1},$$

$$v_r\,(\text{optical}) \approx c\left(\frac{\nu_e}{\nu_o} - 1\right) \approx 3 \times 10^5 \ \text{km s}^{-1}\left(\frac{1420.4 \ \text{MHz}}{1416.2 \ \text{MHz}} - 1\right) \approx 889 \ \text{km s}^{-1}.$$

HI in External Galaxies (ERA 7.8.2)

Radial velocities

Radial Velocity directly from our radio observations, V_r important for determining distances, *d:*

$$d \approx \frac{v_r\,(\text{optical})}{H_0} \approx \frac{889 \;\; \text{km} \;\; \text{s}^{-1}}{67.8 \;\; \text{km} \;\; \text{s}^{-1} \;\; \text{Mpc}^{-1}} \approx 13 \;\; \text{Mpc}.$$

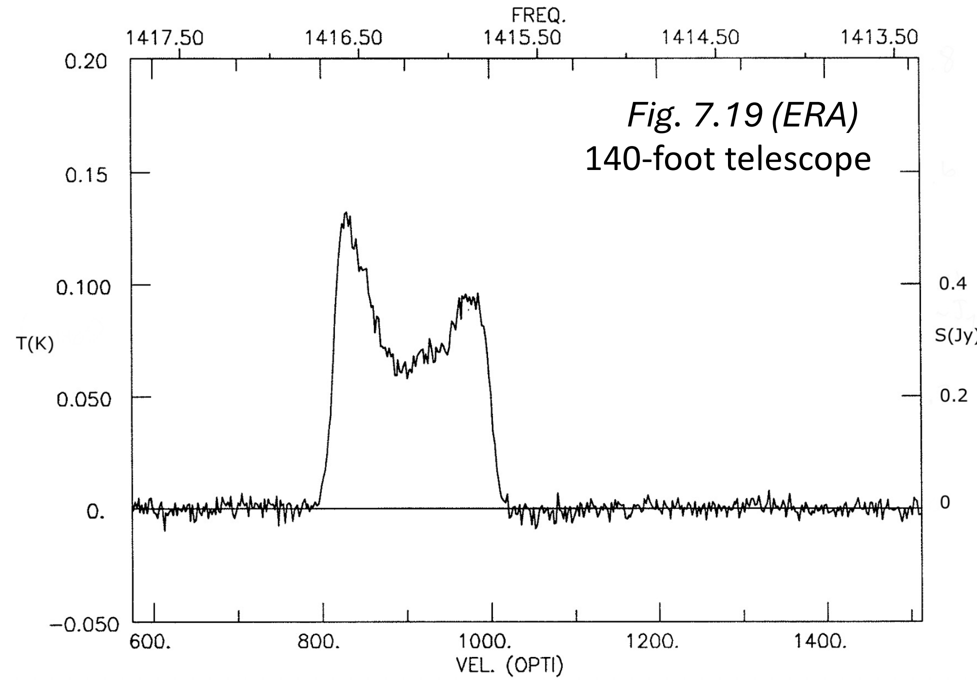

Fig. 7.19 (ERA)
140-foot telescope

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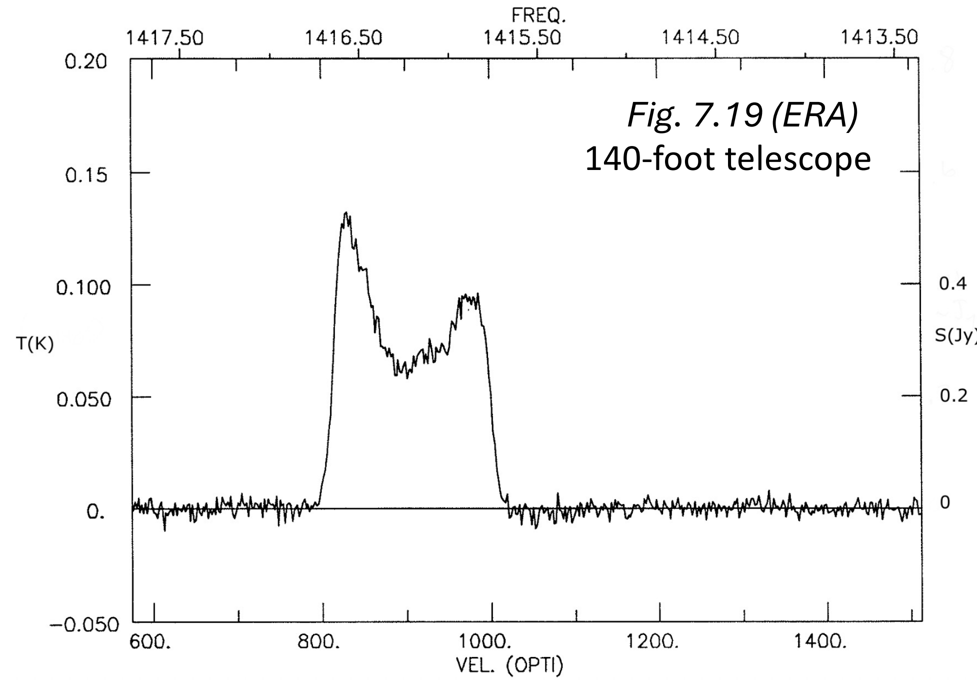
Contact: sscibell@nrao.edu

HI in External Galaxies (ERA 7.8.2)

Radial velocities

Why do we see this 'two-horned' profile?

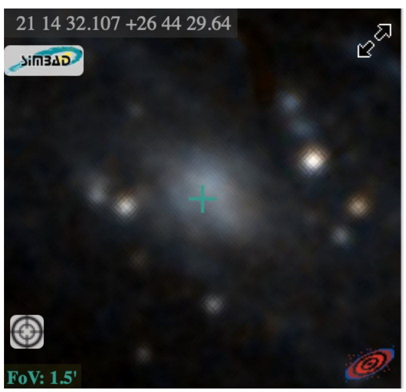


HI in External Galaxies (ERA 7.8.2)

Radial velocities

Why do we see this 'two-horned' profile?

Long 21cm line means....
Large beam!
Here ~ 20 arcmin!



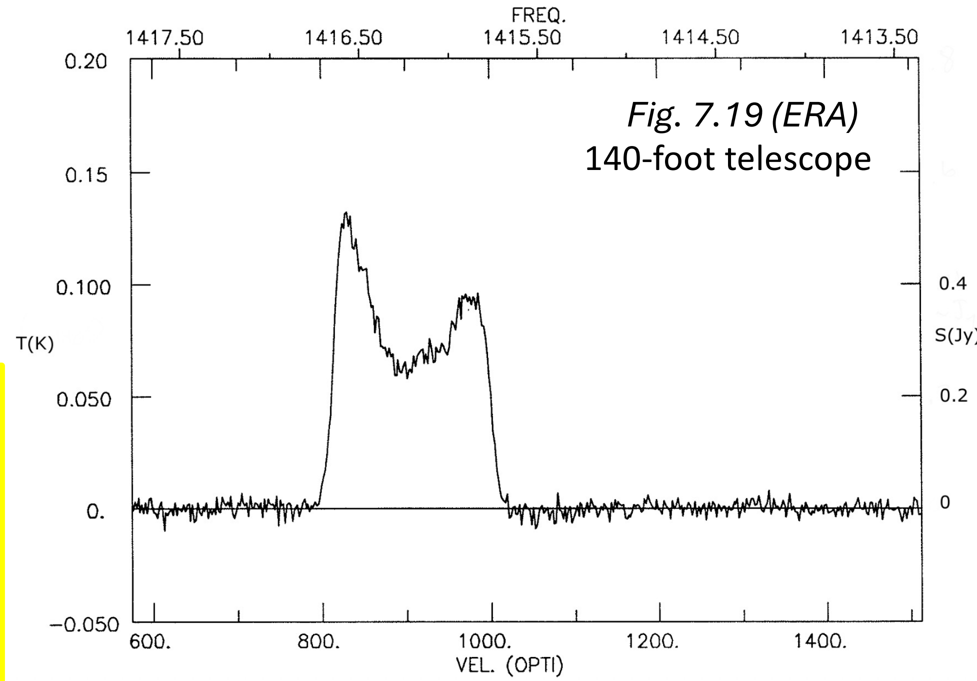


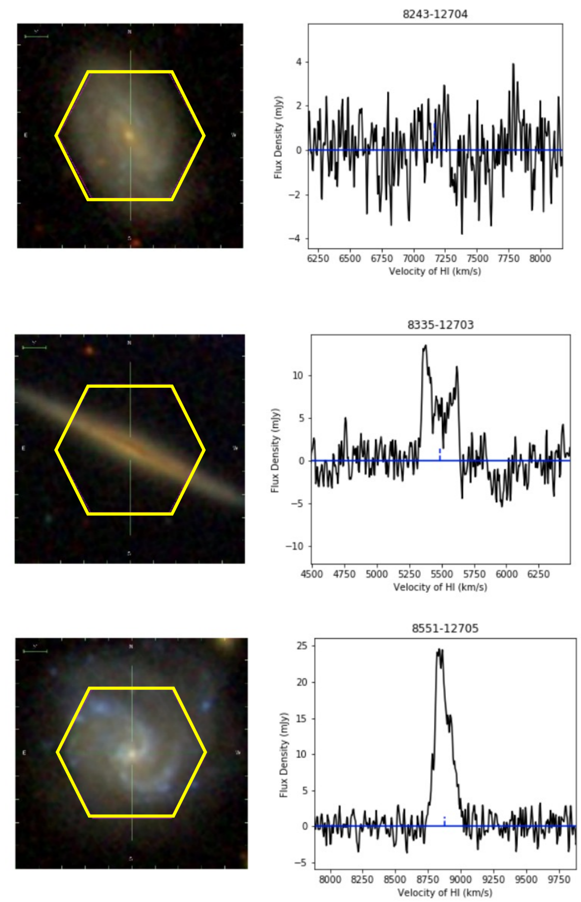
Fig. 7.19 (ERA)
140-foot telescope

HI 21 cm Observations

GBT SURVEY: HI-MaNGA is a 21cm follow-up program for the SDSS-IV MaNGA survey, a survey of 10,010 unique galaxies with an Integral Field Unit (for resolved optical spectroscopy). The **primary goal of HI-MaNGA is to observe all z < 0.05 MaNGA galaxies with the Green Bank Telescope** which lack HI data from other sources.

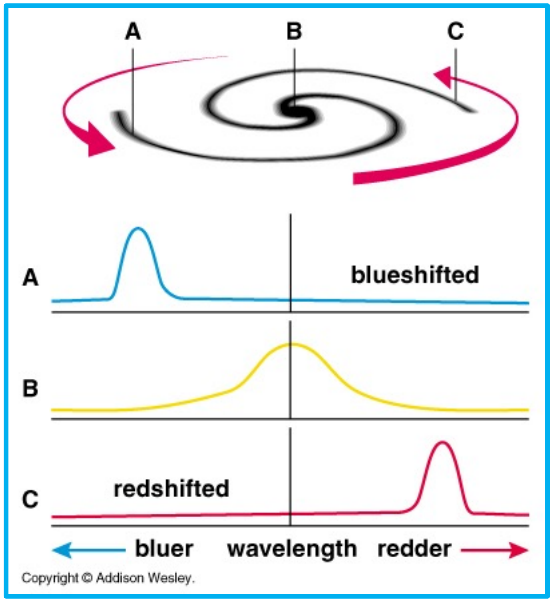
HI-MaNGA provides valuable information about the cold gas content of galaxies, which can help to address several of MaNGA's key science questions:

(1) How does gas accretion drive the growth of galaxies?
(2) What are the relative roles of stellar accretion, major mergers, and instabilities in forming galactic bulges and ellipticals?
(3) What quenches star formation? What external forces affect star formation in groups and clusters?
(4) How was angular momentum distributed among baryonic and non-baryonic components as the galaxy formed, and how do various mass components assemble and influence one another?



HI in External Galaxies (ERA 7.8.2)

Radial velocities



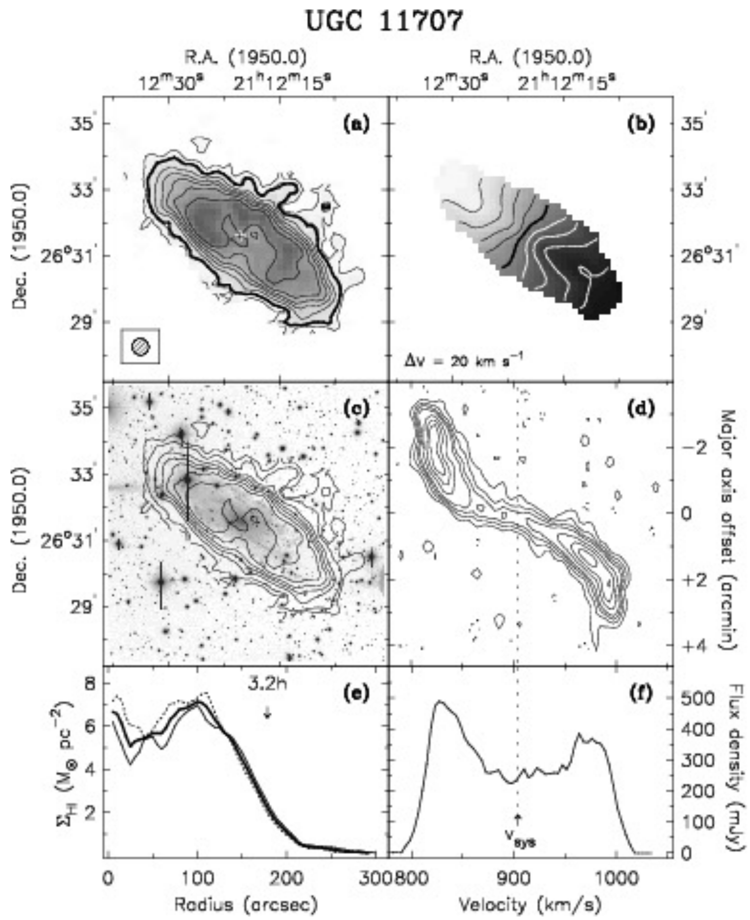


Fig. 7.20 (ERA)

HI in External Galaxies (ERA 7.8.2)

Mass Estimates:

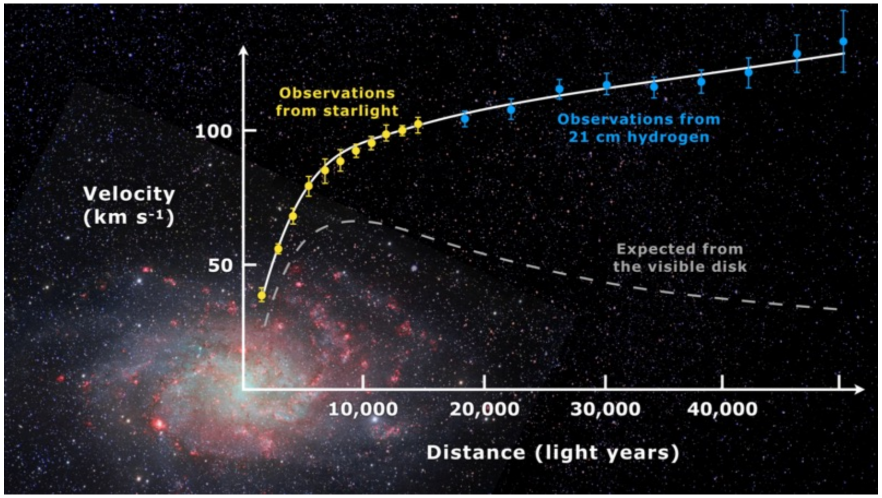
A total **HI mass** M_H of a galaxy:

$$\left(\frac{M_H}{M_\odot}\right) \approx 2.36 \times 10^5 \left(\frac{d}{\text{Mpc}}\right)^2 \int \left[\frac{S(\nu)}{\text{Jy}}\right] \left(\frac{dv}{\text{km s}^{-1}}\right) \quad (7.166)$$

A well-resolved Hi image of a galaxy yields the **total mass** M(r) enclosed within radius r of the center if the gas orbits in circular orbits

$$\left(\frac{M}{M_\odot}\right) \approx 2.3 \times 10^5 \left(\frac{v_{\text{rot}}}{\text{km s}^{-1}}\right)^2 \left(\frac{r}{\text{kpc}}\right). \quad (7.172)$$

Rotation curves flat at large *r* suggesting enclosed mass as far as we can see HI… These large total masses earlier evidence for cold dark matter in galaxies



HI 21 cm Observations

Fig. 8.11 (ERA)

Because detectable Hi is so extensive, Hi is an exceptionally **sensitive tracer of tidal interactions between galaxies**!

Long streamers and tails of Hi trace the interaction histories of pairs and groups of galaxies →

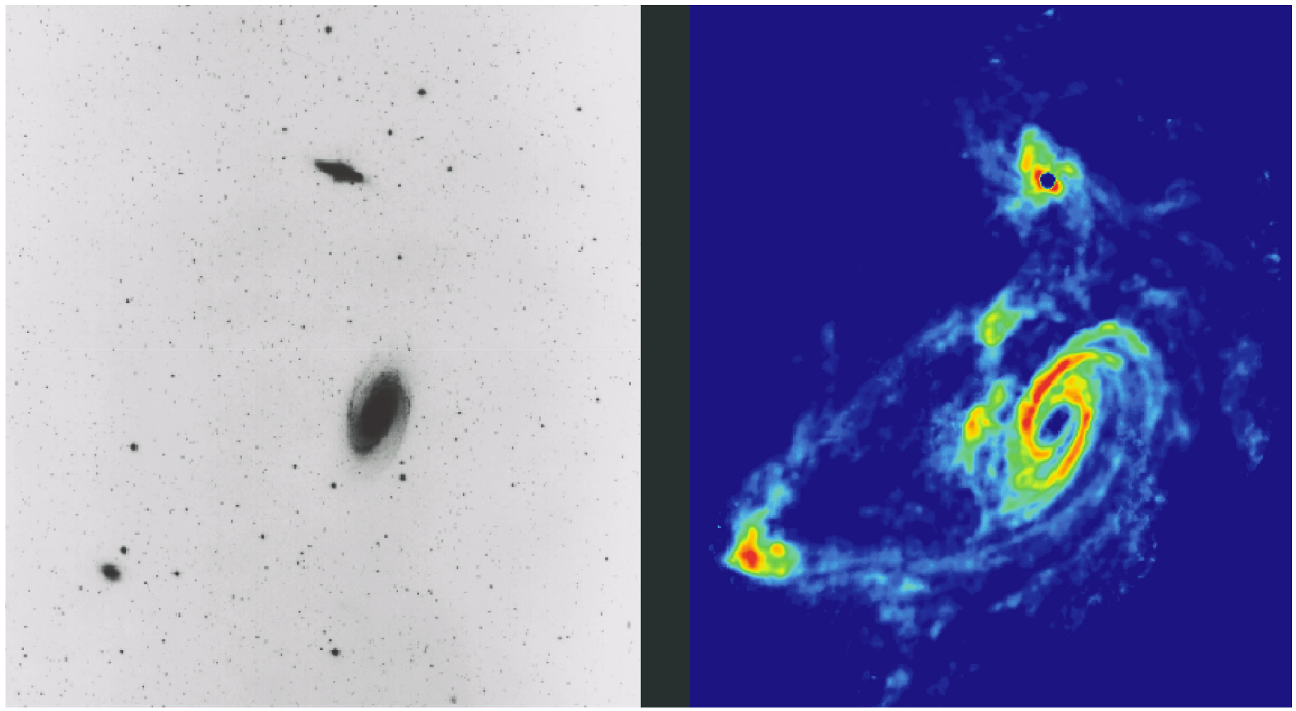


Image credit: NRAO/AUI/NSF Investigators: Min S. Yun, Paul T. P. Ho, & K. Y. Lo.

HI 21 cm Observations

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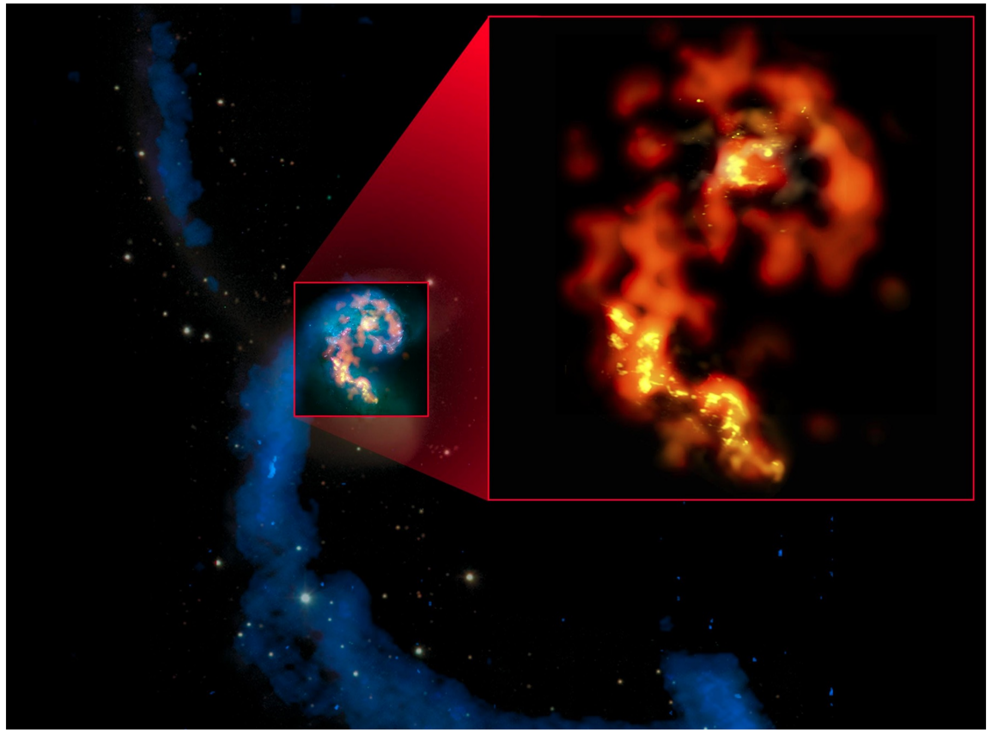
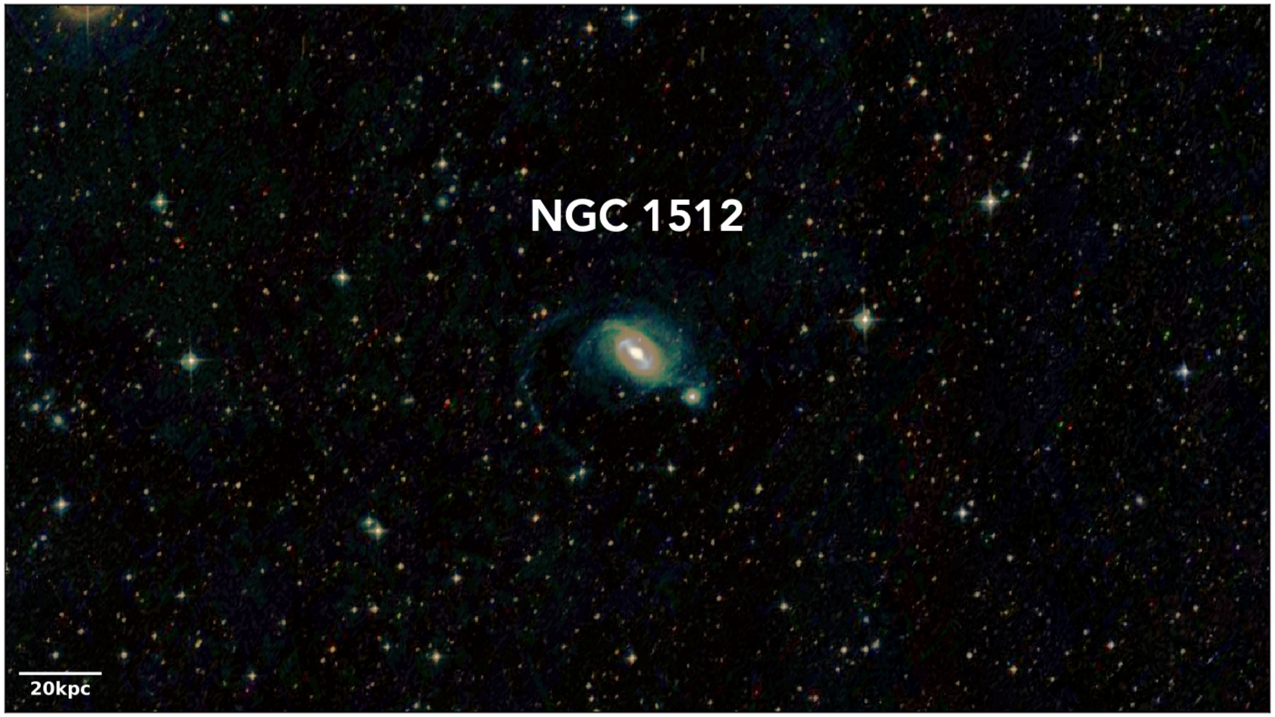
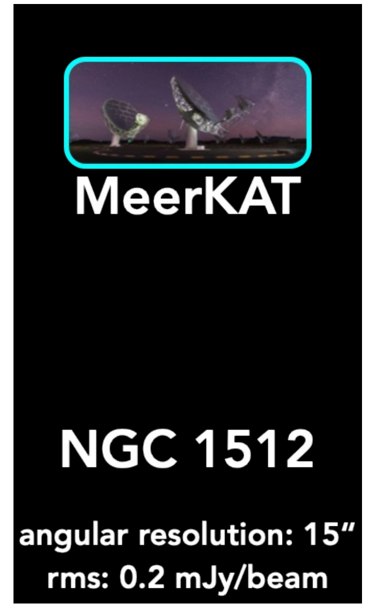


Fig. 8.12 (ERA)

Image credit: B. Saxton (NRAO/AUI/NSF) from data provided by ALMA (ESO/NAOJ/NRAO) and NASA/ESA

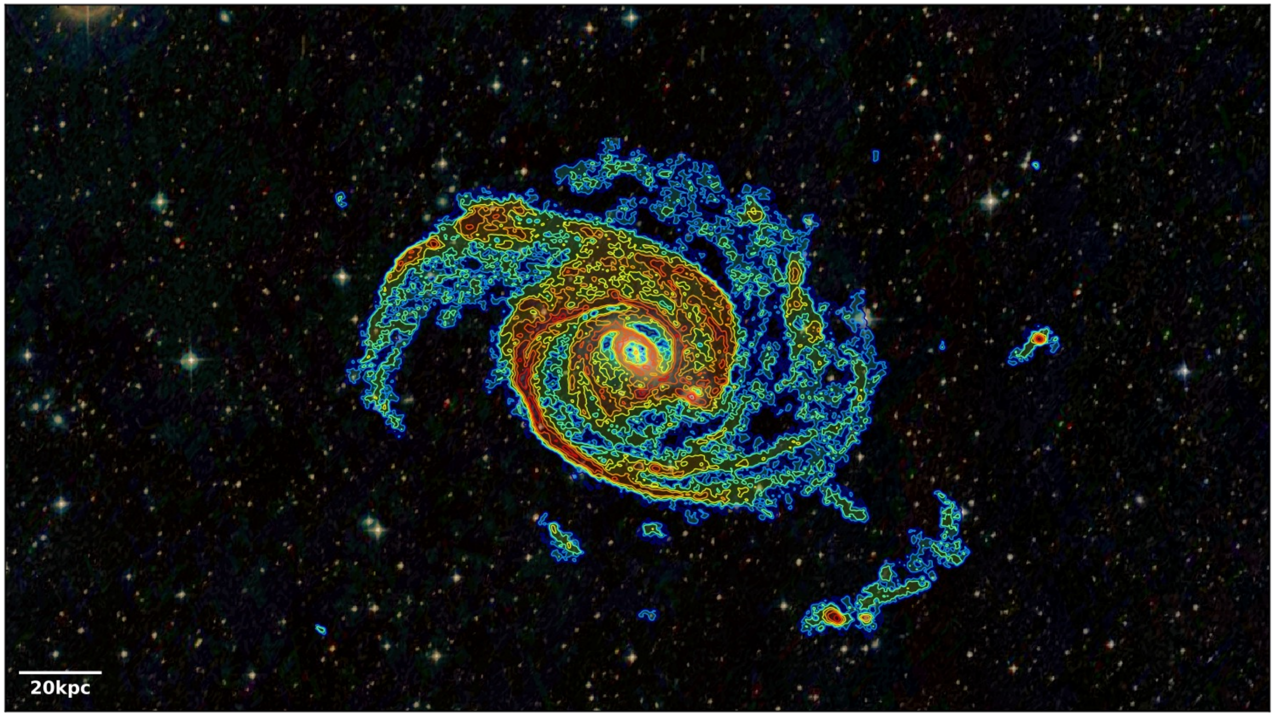
HI 21 cm Observations



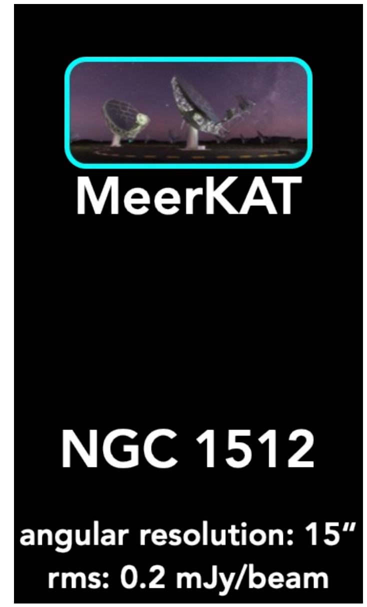


Credit: Cosima Eibensteiner

HI 21 cm Observations

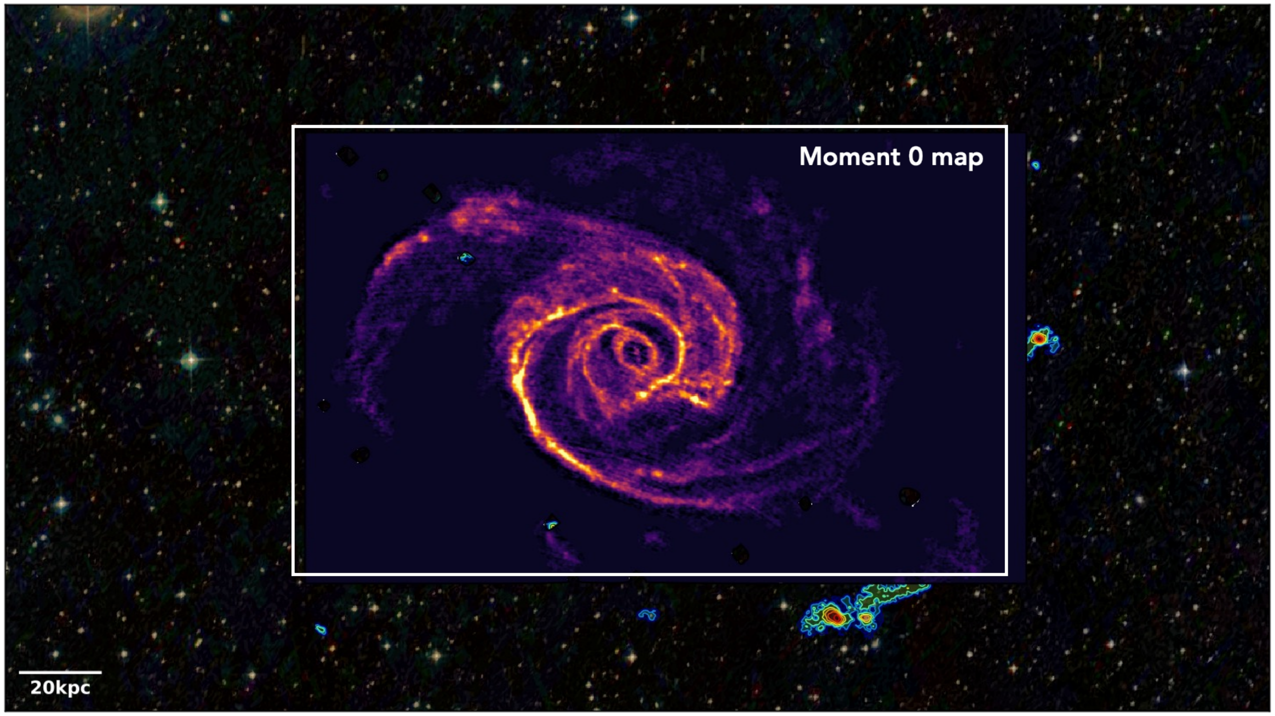


HI emission contour levels of $\log_{10}$ 0.25, 1, 1.5, 2, 2.25, 2.5, 2.75, 3



Credit: Cosima Eibensteiner +2024

HI 21 cm Observations



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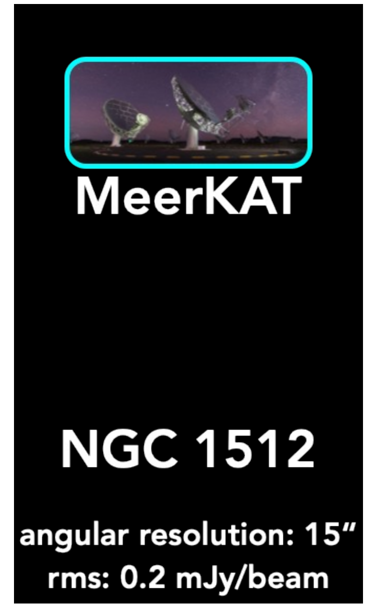
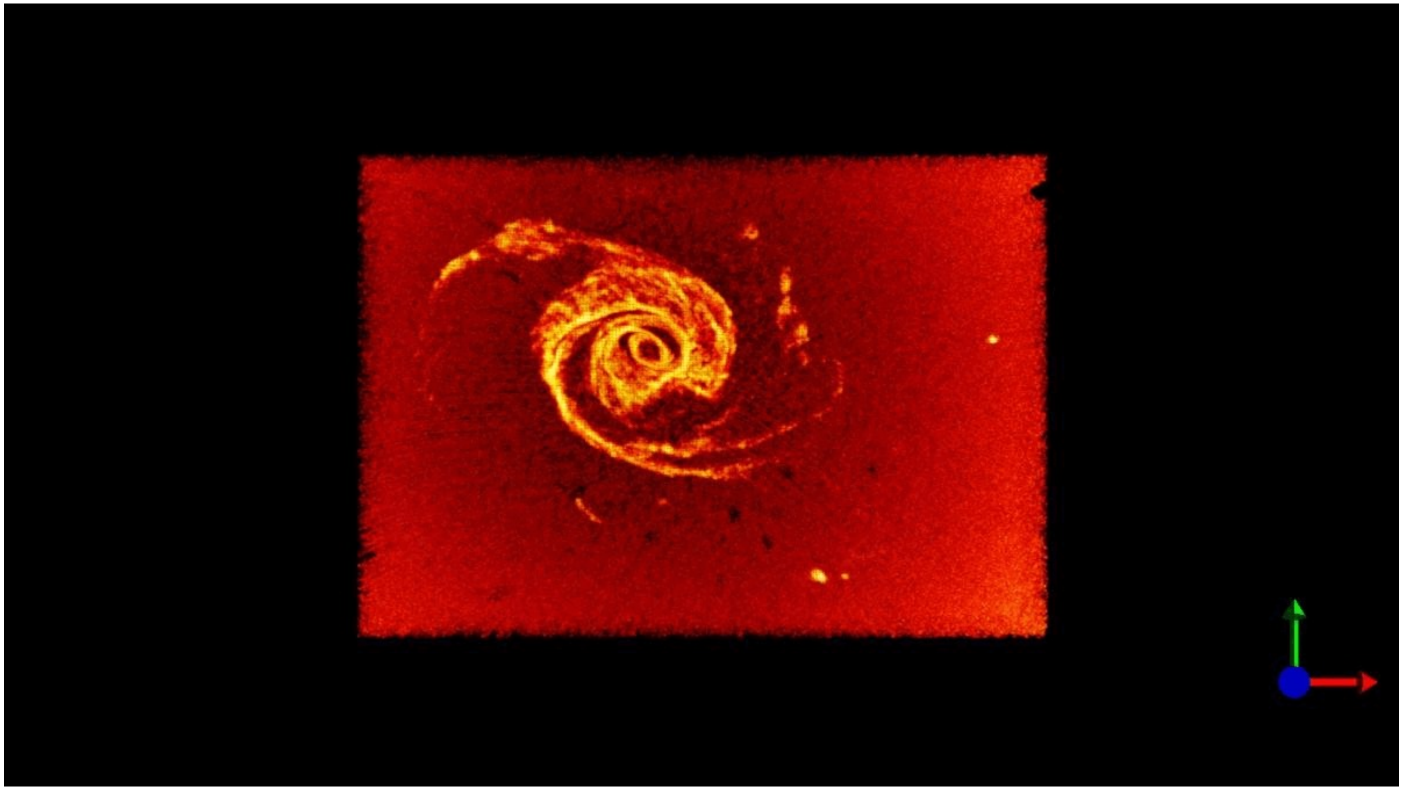
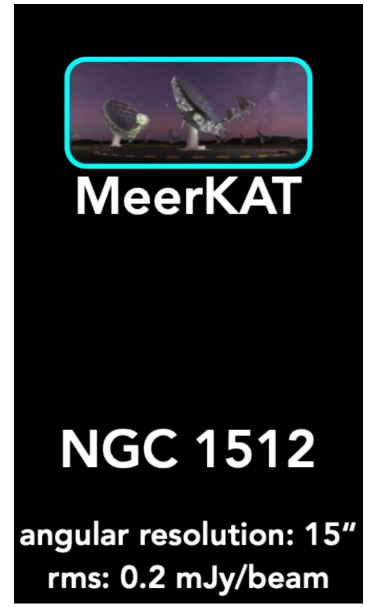


Credit: Cosima Eibensteiner +2024

HI 21 cm Observations





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HI 21 cm Observations