

# The interstellar medium



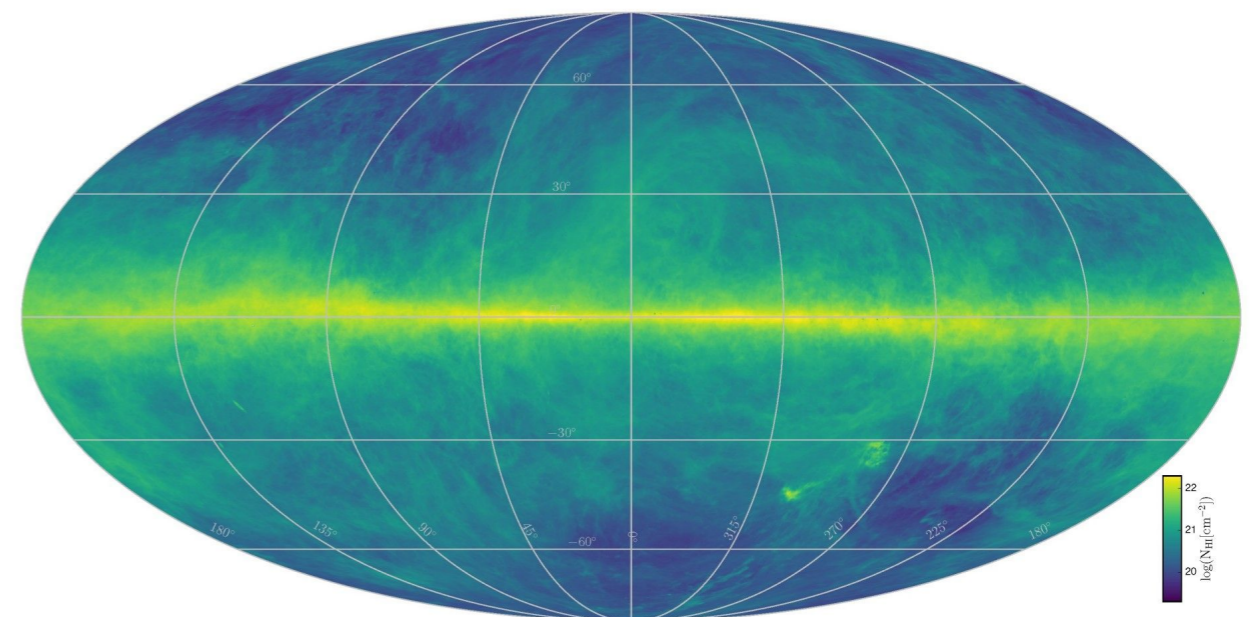
# The interstellar medium

- The Circumstellar Medium:
  - Individual astrophysical objects, generally associated to young and luminous stars or end-life-phases of stars



SN 1054 remnant

- The diffuse component  
-more generally defined  
Interstellar Medium (ISM)



# Circumstellar regions

## Emission nebulae in the Galaxy

Reflection Nebulae

HII regions

Planetary nebulae

Supernova remnants

## Reflection nebulae

- Non ionized circumstellar gas that scatters photons of a late-type star  
The the central star is not sufficiently hot to produce photons with  $h\nu > 13.6 \text{ eV}$   
Hydrogen is not ionized by stellar radiation
- The scattering of stellar photons is due to dust grains embedded in the gas

Example: Reflection Nebula V838



# HII regions

- Low-density clouds of partially ionized gas surrounding short-lived, early-type stars

## Mechanisms of ionization:

- radiation of early-type stars (UV stellar photons with  $h\nu > 13.6$  eV)
- collisional ionization, in presence of shocks due by stellar ejecta

- HII regions are typically associated with regions of recent star formation and with giant molecular clouds; they can be quite extended, sometimes a few hundred pc

- The main observational diagnostics of HII regions in the optical band is the H $\alpha$  emission line  
transition from  $n=3$  to  $n=2$  of the Balmer series

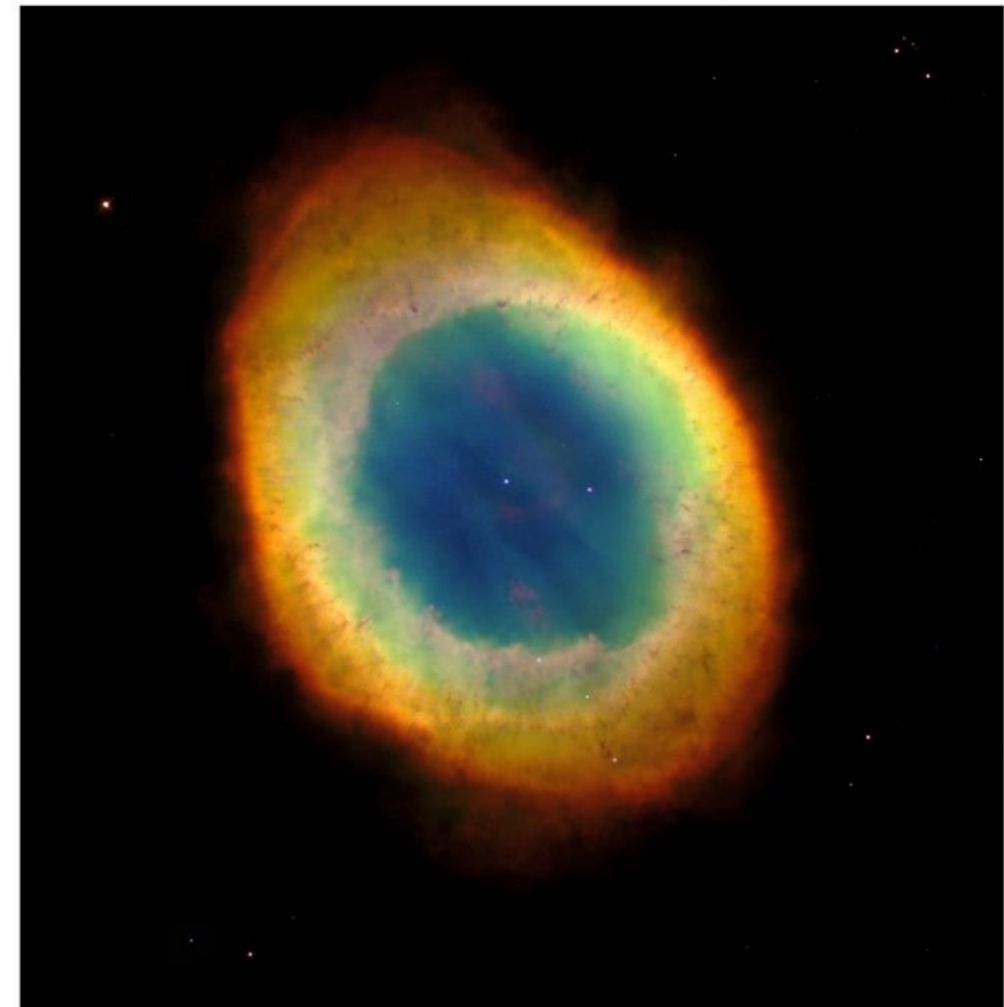
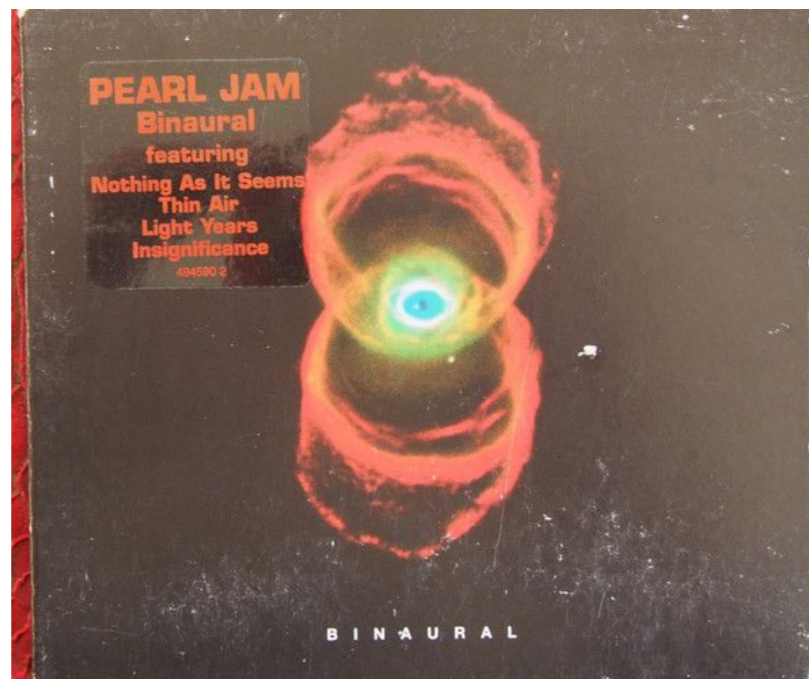


656.28 nm

Orion Nebula  
Hubble mosaic

# Planetary nebulae

- Expanding shell of ionized gas ejected from old red giant stars late in their lives
- During the red giant phase, the outer layers of the star are expelled by strong stellar winds
- After most of the red giant's atmosphere is dissipated, the remaining hot luminous core emits ultraviolet radiation that ionizes the ejected outer layers
- Absorbed ultraviolet light energises the shell of nebulous gas, causing it to appear as a brightly coloured planetary nebula



NGC 6720, The Ring Nebula  
STScI/AURA

Hourglass Nebula  
1996 (HST)

## Supernova remnants (SNRs)

- A supernova remnant is the structure resulting from the explosion of a star in a supernova
- The supernova remnant is bounded by an expanding shock wave, and consists of ejected material expanding from the explosion, and the interstellar material it sweeps up and shocks along the way
- The supernova explosion expels much or all of the stellar material with supersonic velocities (up to  $10^4$  km/s)
- A strong shock wave forms ahead of the ejecta, that heats the upstream plasma up to temperatures well above millions of K
- The shock continuously slows down over time as it sweeps up the ambient medium
- It can expand over tens of parsecs before its speed falls below the local sound speed.



SN 1054 remnant  
(Crab Nebula)

# Discovery of the Interstellar Medium

- 1795 → Sir William Herschell
- Stellar distribution was patch in the sky
- Existence of dark regions in the sky particularly devoid of stars:
  - “holes in heavens”



Dark cloud B68

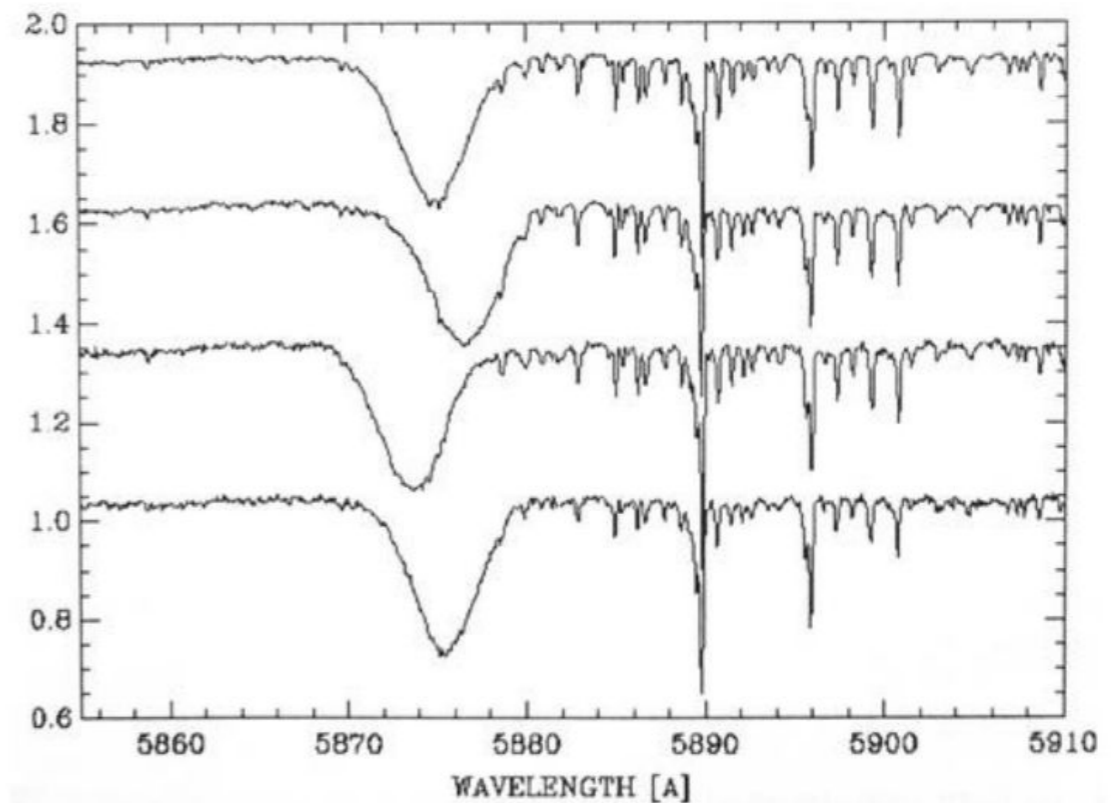
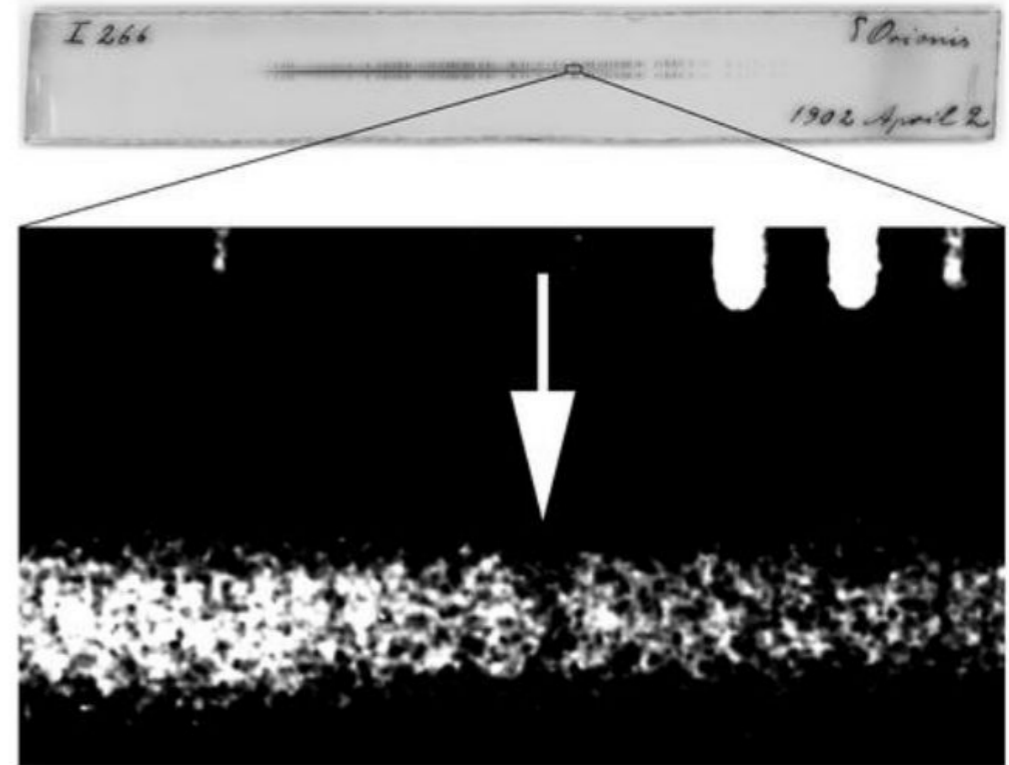


# Discovery of the diffuse interstellar medium

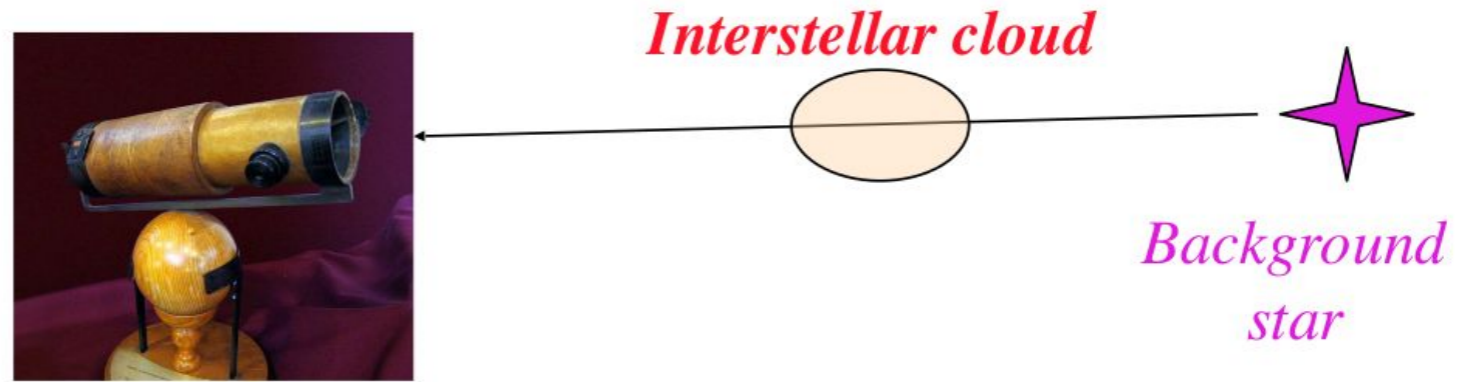
- **Hartmann, 1904**
  - “Stationary” CaII absorption lines in the spectrum of the spectroscopic binary  $\delta$  Ori
  - Circumstellar or interstellar origin?
- **Plaskett & Pearce, 1933**
  - The CaII absorption becomes stronger with increasing distance of the background star
  - Proven the interstellar origin

Example:

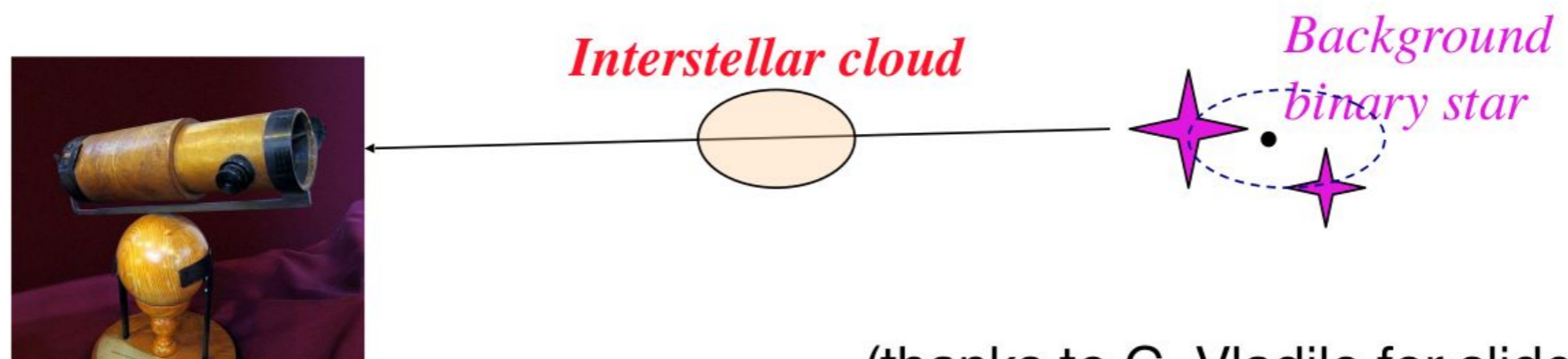
Stationary NaI lines in the spectrum of  $\delta$  Ori



# Discovery of the diffuse interstellar medium



- **Interstellar absorption spectroscopy**
  - Discrimination of interstellar lines from stellar lines by means of radial velocity analysis
  - The star and the gas along the line of sight have, in general, a different radial velocity
  - If the star is a spectroscopic binary, the stellar lines will regularly shift in radial velocity according to the orbital period of the binary system; interstellar lines, on the other hand, will be “stationary”



(thanks to G. Vladilo for slides with this style)

# Historical evidence for dust

The **apparent size** of an open cluster decreases like the inverse of the **diameter distance**.

The **total flux** of an open cluster decreases like the inverse square of the **luminosity distance**.

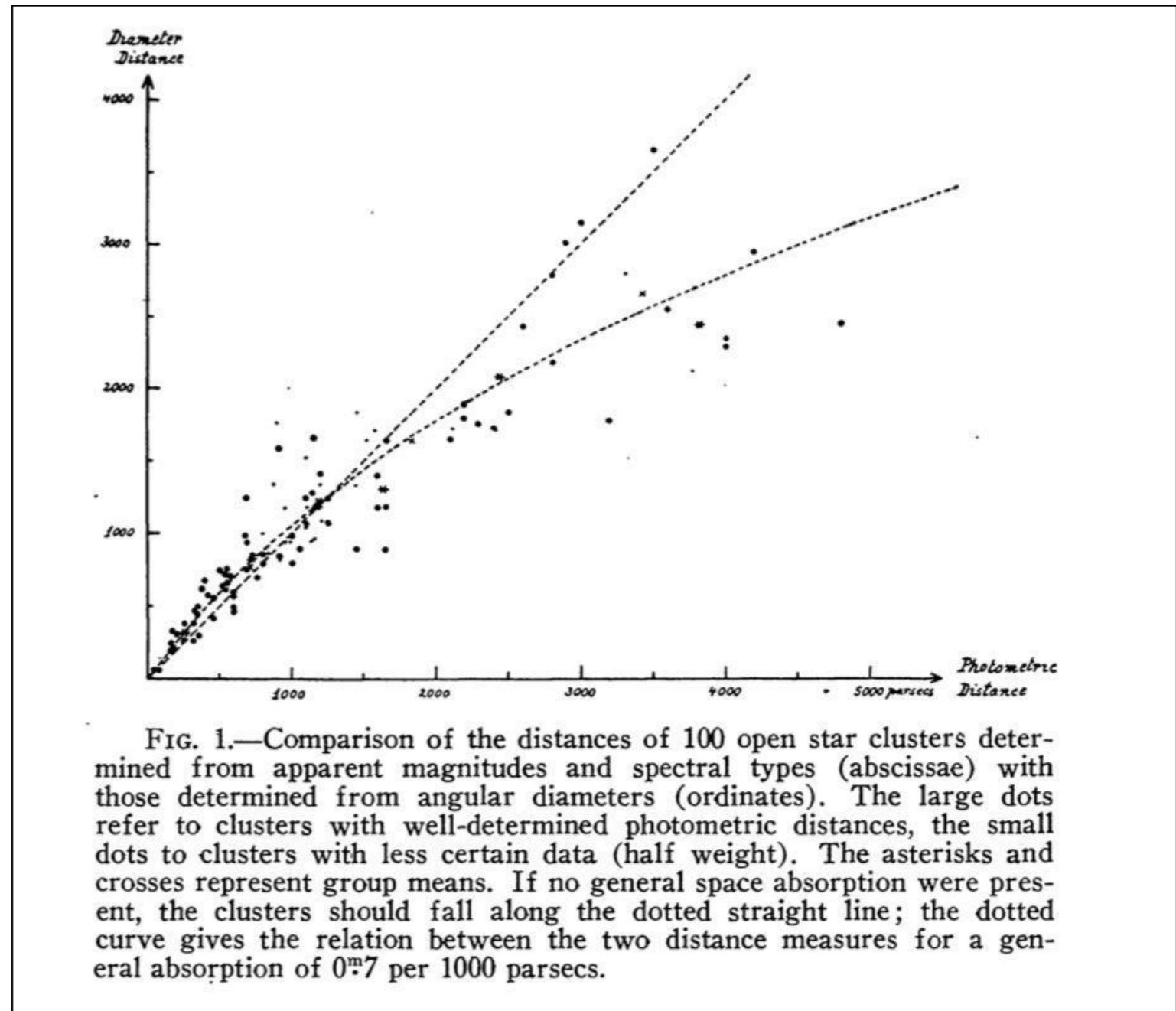
If open clusters have **on average the same size** and luminosity, one can get their luminosity ("photometric" in the plot) and diameter distances from observed flux and angular size.

As we are inside the galaxy, luminosity and diameter distances are **the same**.

Extinction of more distant objects is revealed by a **flattening** of the relation of luminosity vs diameter distance.

Because it is a continuum absorption, it must be due to **dust**. Where there is dust, there must be gas!

Trumpler, 1930



# Dust

- Today we now that apparent “holes in heavens” are opaque clouds of dust grains and molecules → Extinction of light



Dark cloud B68

# The Interstellar Medium (ISM)

The interstellar medium is characterized by:

- very low density (prohibited lines),
- a large range of temperatures, from  $\sim 10$  to  $10^6$  K,
- possibly different temperatures for electrons and ions,
- a large range of ionization states,
- complex geometry, complex kinematics,
- significant presence of dust,
- very long mean free paths for particles, thermodynamic equilibrium is hard to achieve,
- several coexistent phases in rough pressure equilibrium,
- rough vertical equilibrium with different, temperature-dependent scale heights for various phases,
- weak magnetic fields,
- significant presence of cosmic rays.

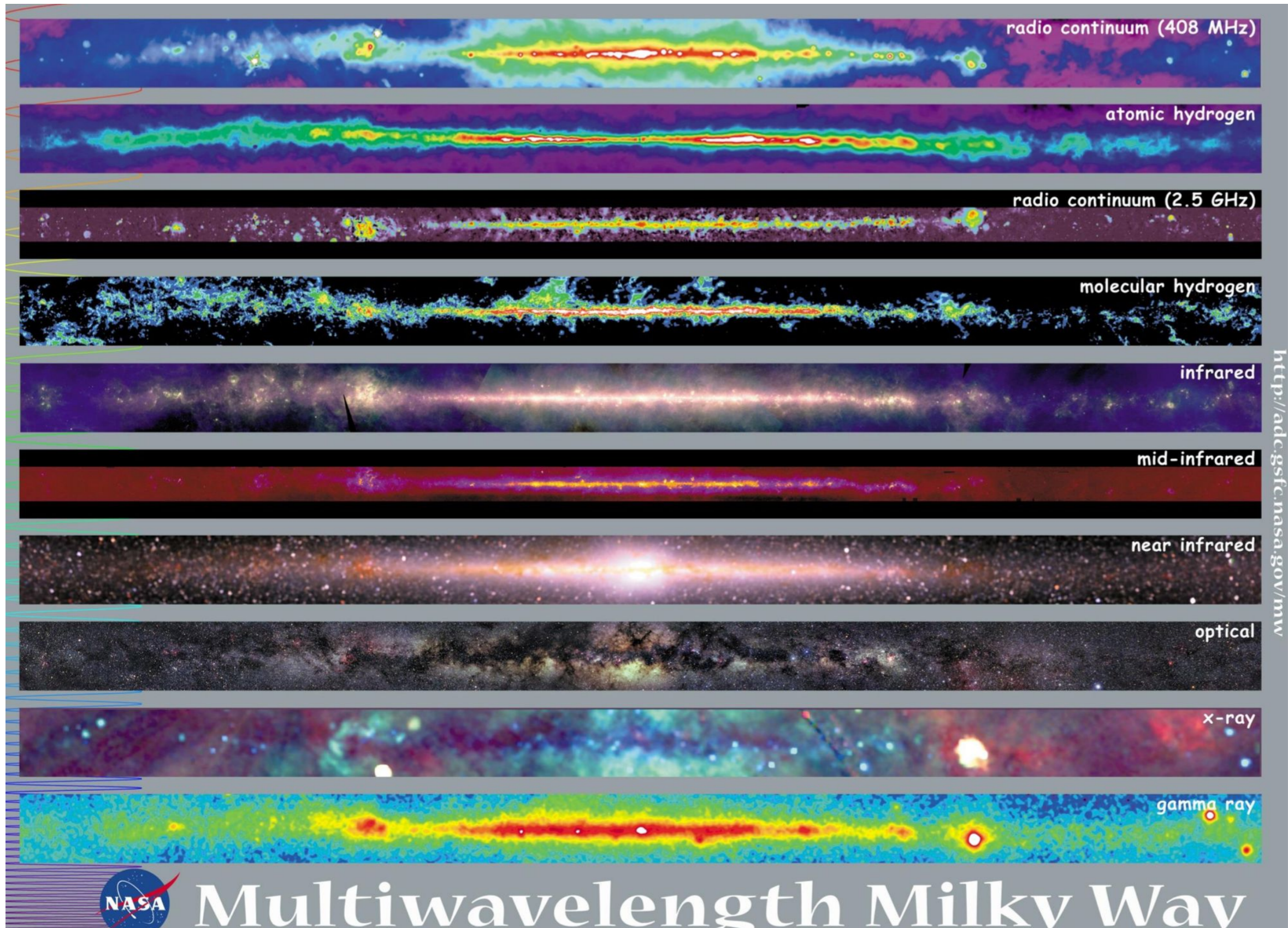
# ISM COMPOSITION

<i>Component</i>	<i>Description</i>	<i>Density</i> ( $\text{cm}^{-3}$ )	<i>Temperature</i> (K)	<i>Pressure</i> ( $p/k_B$ )	<i>Vertical extent</i>	<i>Mass</i> ( $\mathcal{M}_\odot$ )	<i>Filling factor</i>
Dust grains						$10^7\text{--}10^8$	Tiny
large $\lesssim 1\ \mu\text{m}$	Silicates, soot		$\sim 20$		150 pc		
small $\sim 100\ \text{\AA}$	Graphitic C		30–100				
PAH $< 100$ atoms <small>Polycyclic aromatic hydrocarbon</small>	Big molecules				80 pc		
Cold clumpy gas	Molecular: $\text{H}_2$	$> 200$	$< 100$	Big	80 pc	$(2) \times 10^9$	$< 0.1\%$
	Atomic: HI	25	50–100	2 500	100 pc	$3 \times 10^9$	2%–3%
Warm diffuse gas	Atomic: HI	0.3	8 000	2 500	250 pc	$2 \times 10^9$	35%
	Ionized: HII	0.15	8 000	2 500	1 kpc	$10^9$	20%
HII regions	Ionized: HII	$1\text{--}10^4$	$\sim 10\ 000$	Big	80 pc	$5 \times 10^7$	Tiny
Hot diffuse gas	Ionized: HII	$\sim 0.002$	$\sim 10^6$	2 500	$\sim 5$ kpc	$(10^8)$	45%
Gas motions	$\frac{3}{2} \langle \rho_{\text{HI}} \rangle \sigma_r^2$	$\langle n_{\text{H}} \rangle \sim 0.5$	$10\ \text{km s}^{-1}$	8 000			
Cosmic rays	Relativistic	$1\ \text{eV cm}^{-3}$		8 000	$\sim 3$ kpc	Tiny	
Magnetic field	$B \sim 5\ \mu\text{G}$	$1\ \text{eV cm}^{-3}$		8 000	$\sim 3$ kpc		
Starlight	$\langle \nu h_{\text{P}} \rangle \sim 1\ \text{eV}$	$1\ \text{eV cm}^{-3}$			$\sim 500$ pc		
UV starlight	11–13.6 eV	$0.01\ \text{eV cm}^{-3}$					

# The ISM: basic concepts

- Subject to gravity collapses and forms new stars
- Also gas pressure, magnetic forces, cosmic rays (complex!)
- Mass of gas not related to  $T \rightarrow$  hard to measure distances
- In optically thin emission, mass is proportional to intensity
- We need to find these optically thin regions!

# How do we observe the ISM?



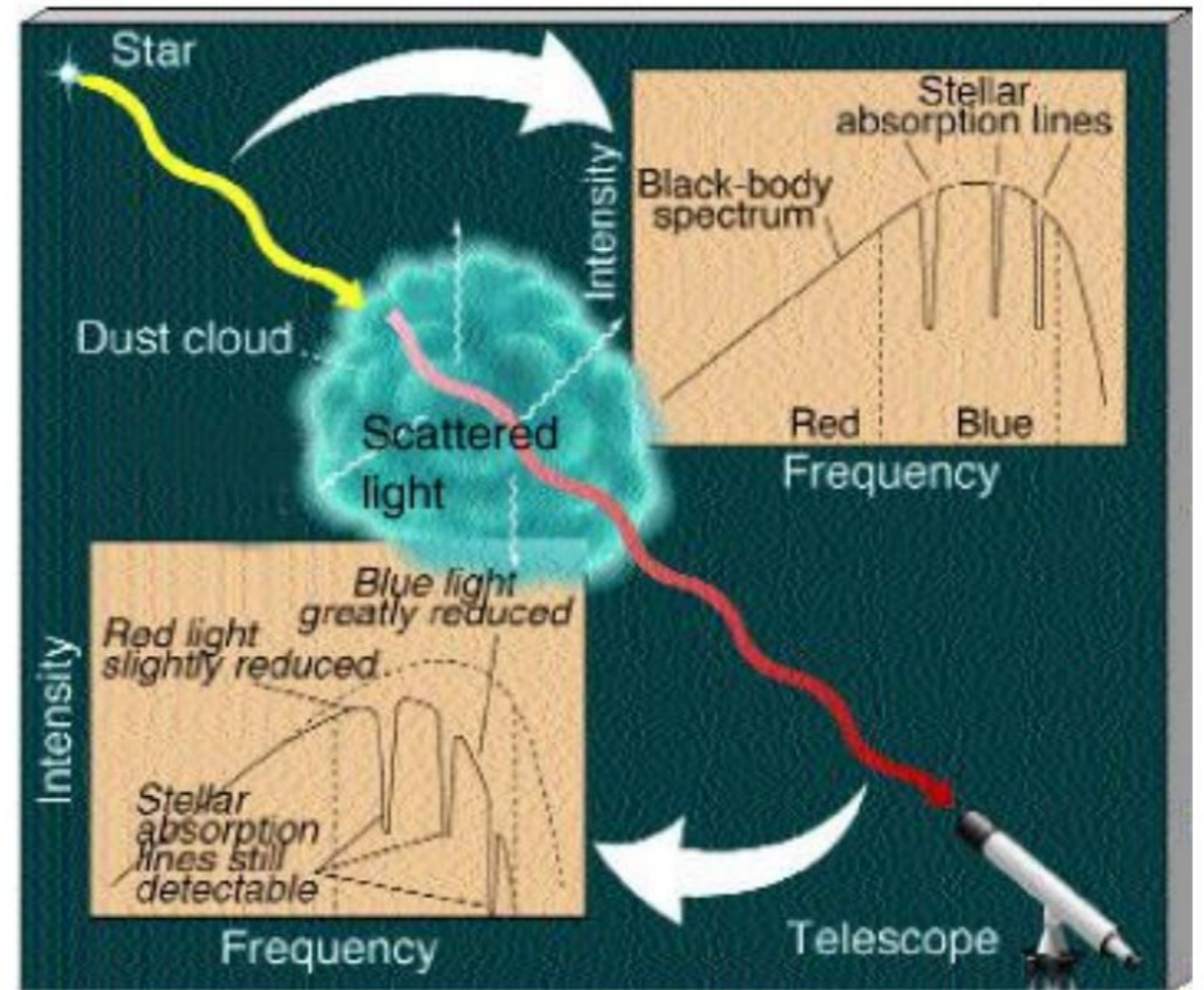


# The ISM of Galaxies

- Composed of:
  - Gas (~99%, of which ~90% is hydrogen)
  - Dust Particles
  - Magnetic field
  - Relativistic particles

Dust causes the extinction, and reddening!!

# The effect of dust



reddening: Color excess

$$E(B - V) := (B - V)_{\text{obs}} - (B - V)_{\text{true}}$$

extinction in the V band:

$$A_V = R_V E(B - V)$$

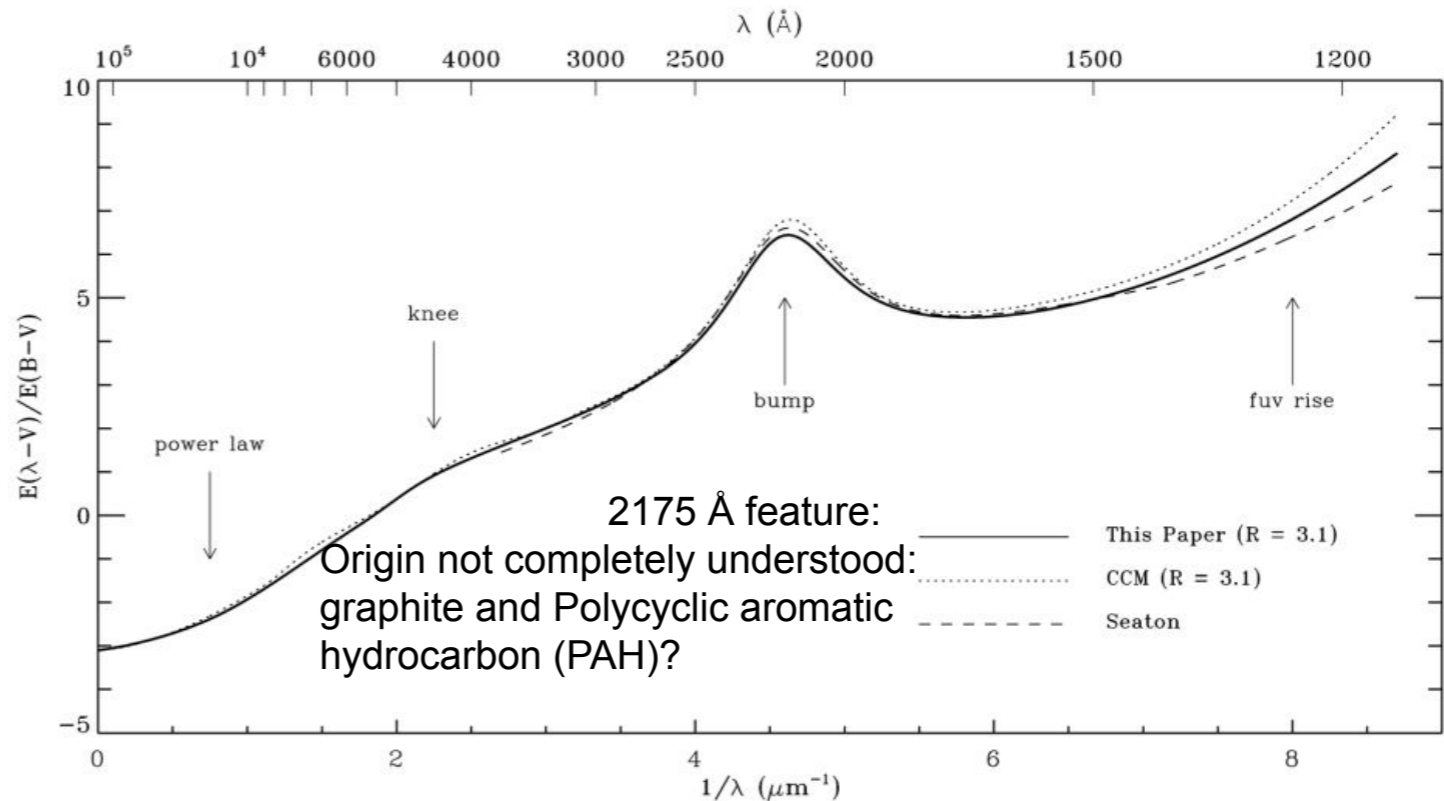
relative visibility

extinction at wavelength  $\lambda$ :

$$A_\lambda = R(\lambda) E(B - V)$$

$$A_\lambda \equiv 2.5 \log_{10} \left( \frac{F_\lambda^0}{F_\lambda} \right)$$

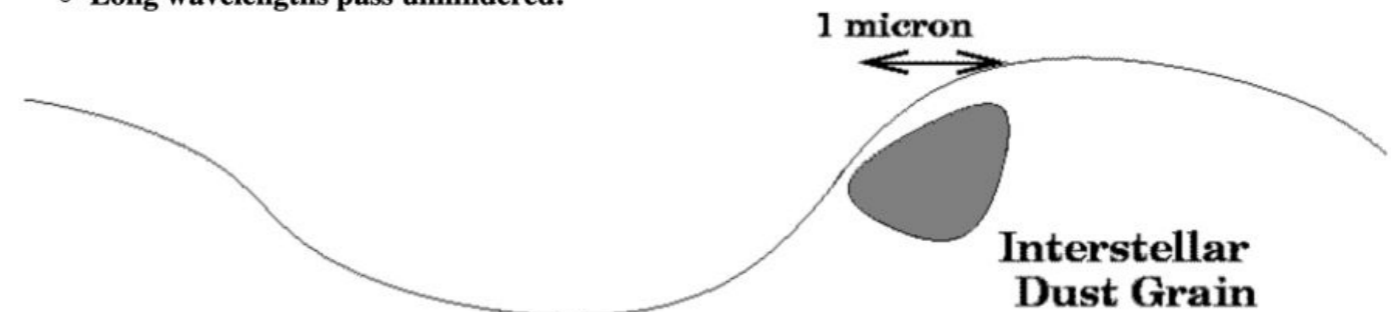
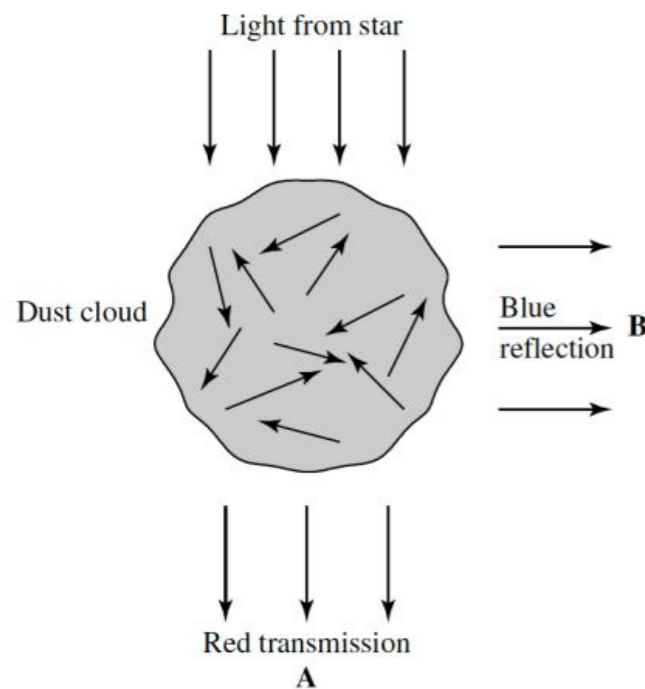
↑ "intrinsic" flux    ↑ observed flux



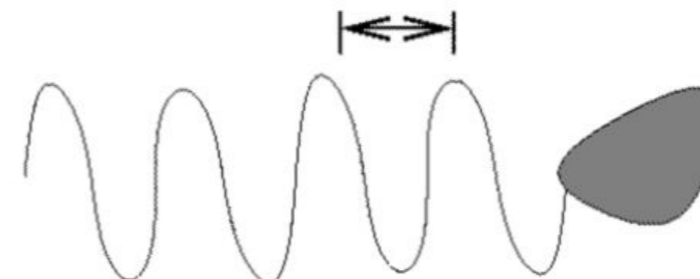
# • Absorption of starlight

- Caused by interstellar dust
- Scatter/absorb light at wavelength smaller than its characteristic size
- UV light is absorbed while infrared light passes

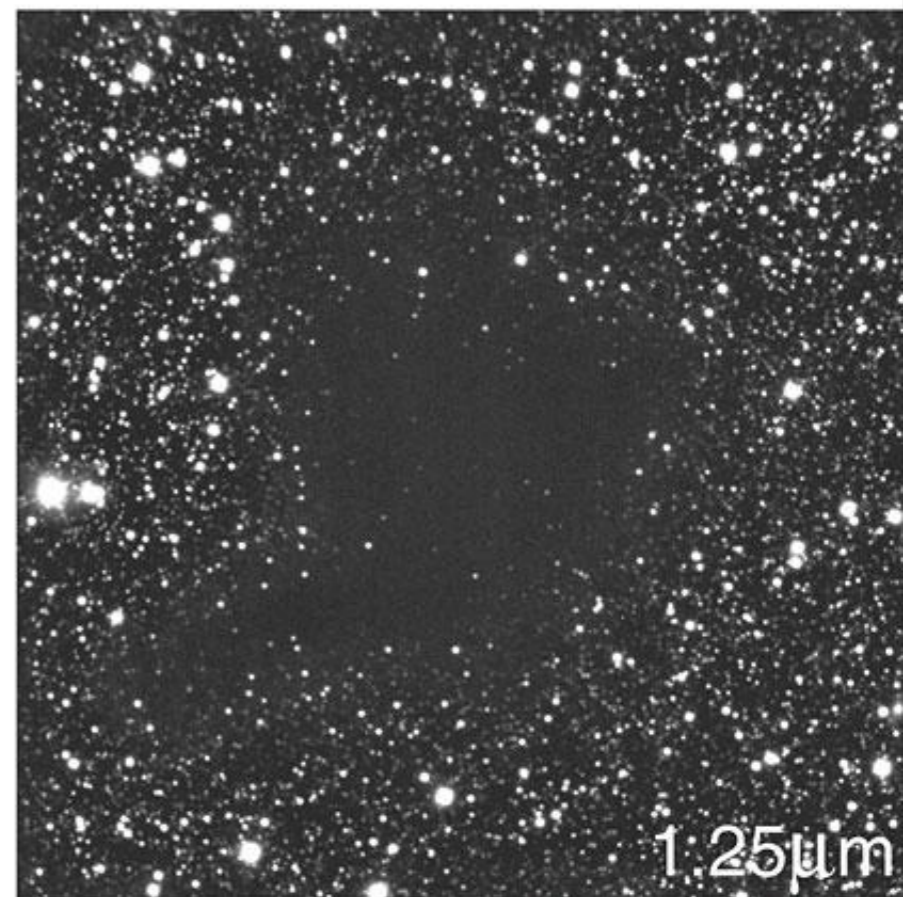
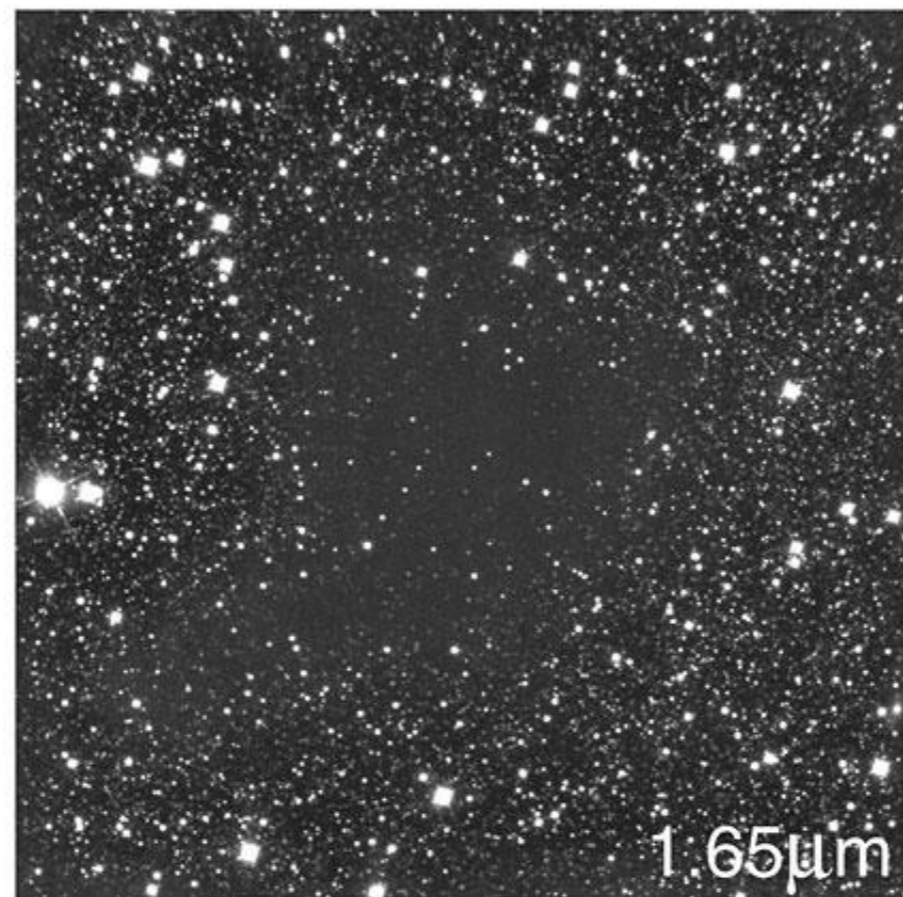
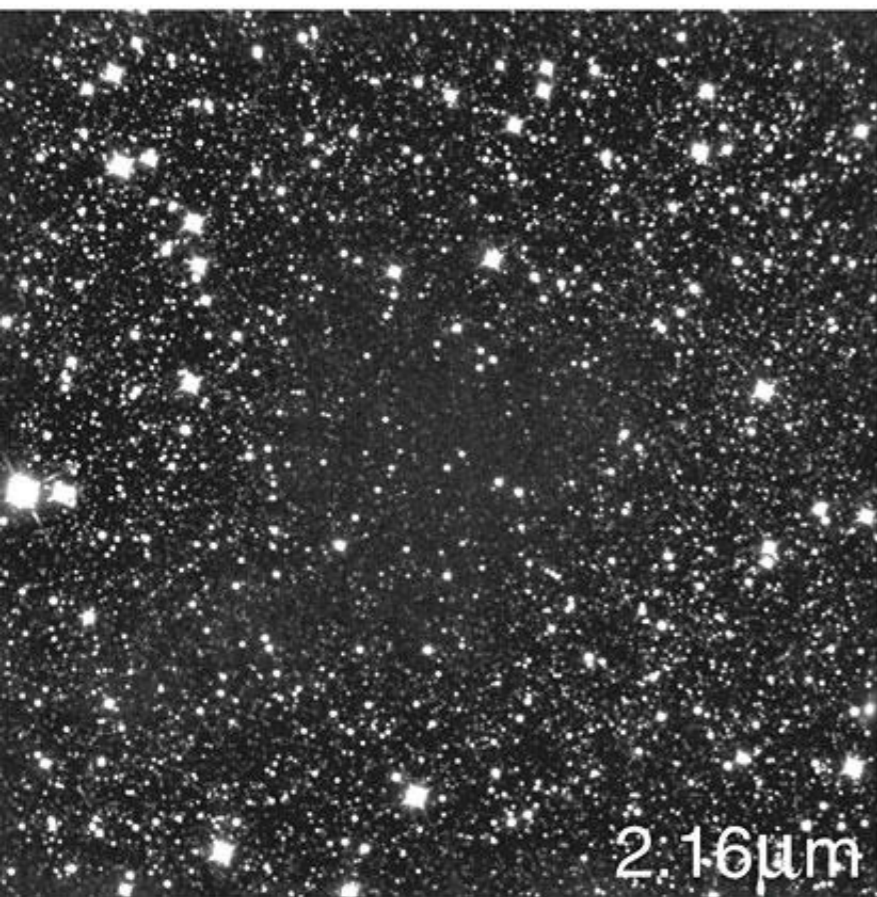
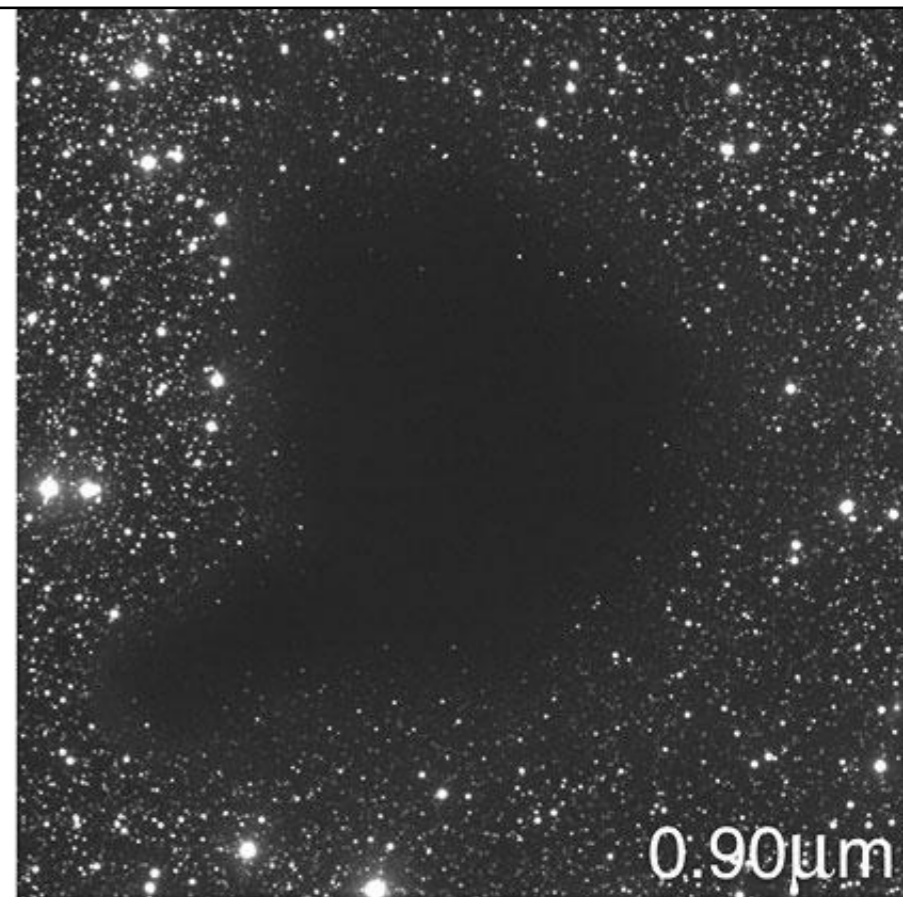
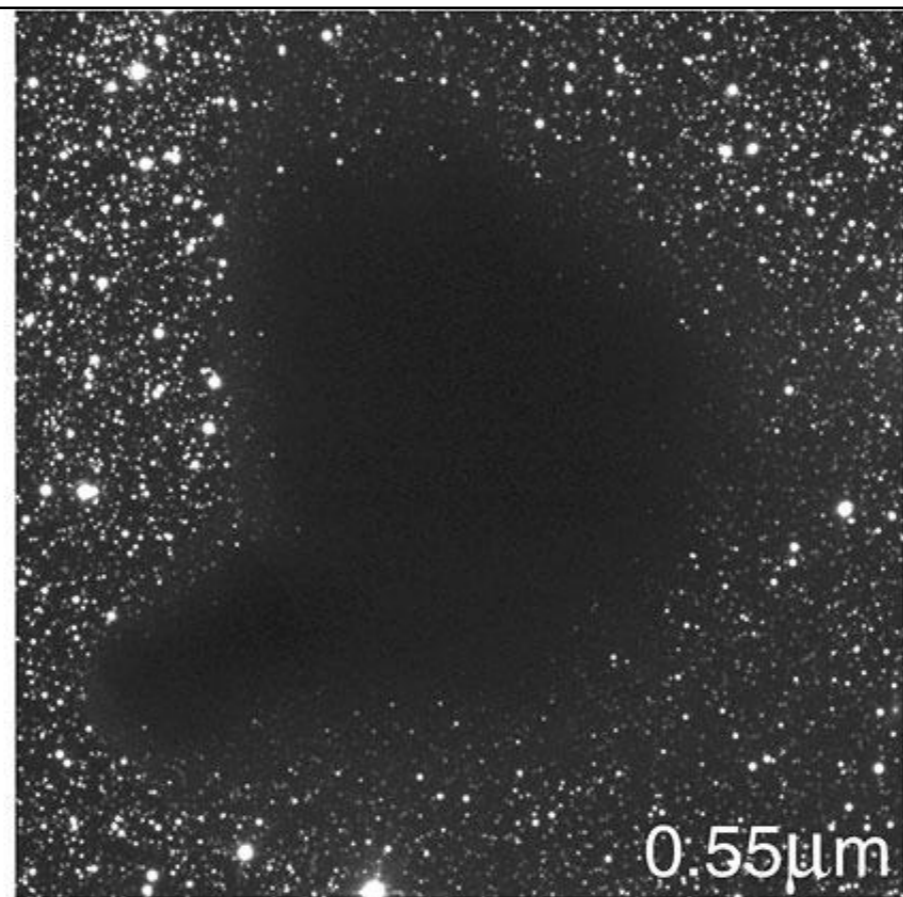
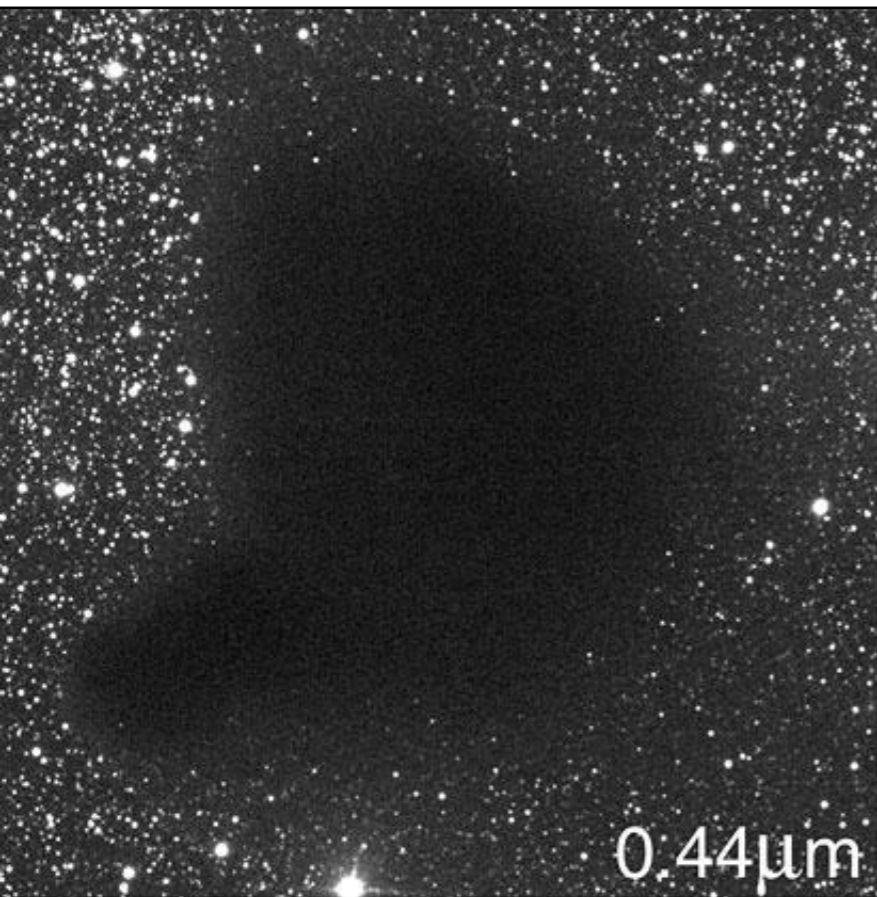
- Short wavelengths are absorbed/scattered.
- Long wavelengths pass unhindered.



**Long Wavelength Light ("Red")**



**Short Wavelength Light ("Blue")**




# Dust in the ISM

- Dust particles are grains of size of the order of 0.1  $\mu\text{m}$
- Dust is  $\sim 1\%$  of total ISM
- Absorbs and re-emits light (Interpretation of SFR)
- Dust as a coolant:
  - Dust as a catalyst for  $\text{H}_2$  (Star formation process)
  - Dust depletes metals (Metallicity and chemical abundances)

# Interstellar extinction: observations

- DIRBE: Diffuse InfraRed Background Experiment@COBE:
  - A direct measurement of the extragalactic background light in the 125 to 5000  $\mu\text{m}$  wavelength region by the Diffuse Infrared Background Experiment (DIRBE) and Far Infrared Absolute Spectrophotometer (FIRAS) on board the Cosmic Background Explorer (COBE).

**COBE Mission 1989-1993**



The history of a more detailed CMB mapping started with the launch of a satellite named COBE (Cosmic Background Explorer) mission by NASA in 1989.

The satellite carried three major instruments:

- 1 DMR (Differential Microwave Radiometer) to measure anisotropies in the CMB;
- 2 FIRAS (Far Infrared Absolute Spectrophotometer) to measure the spectrum of CMB and;
- 3 DIRBE (Diffuse Infrared Background Experiment) that would map dust emission.

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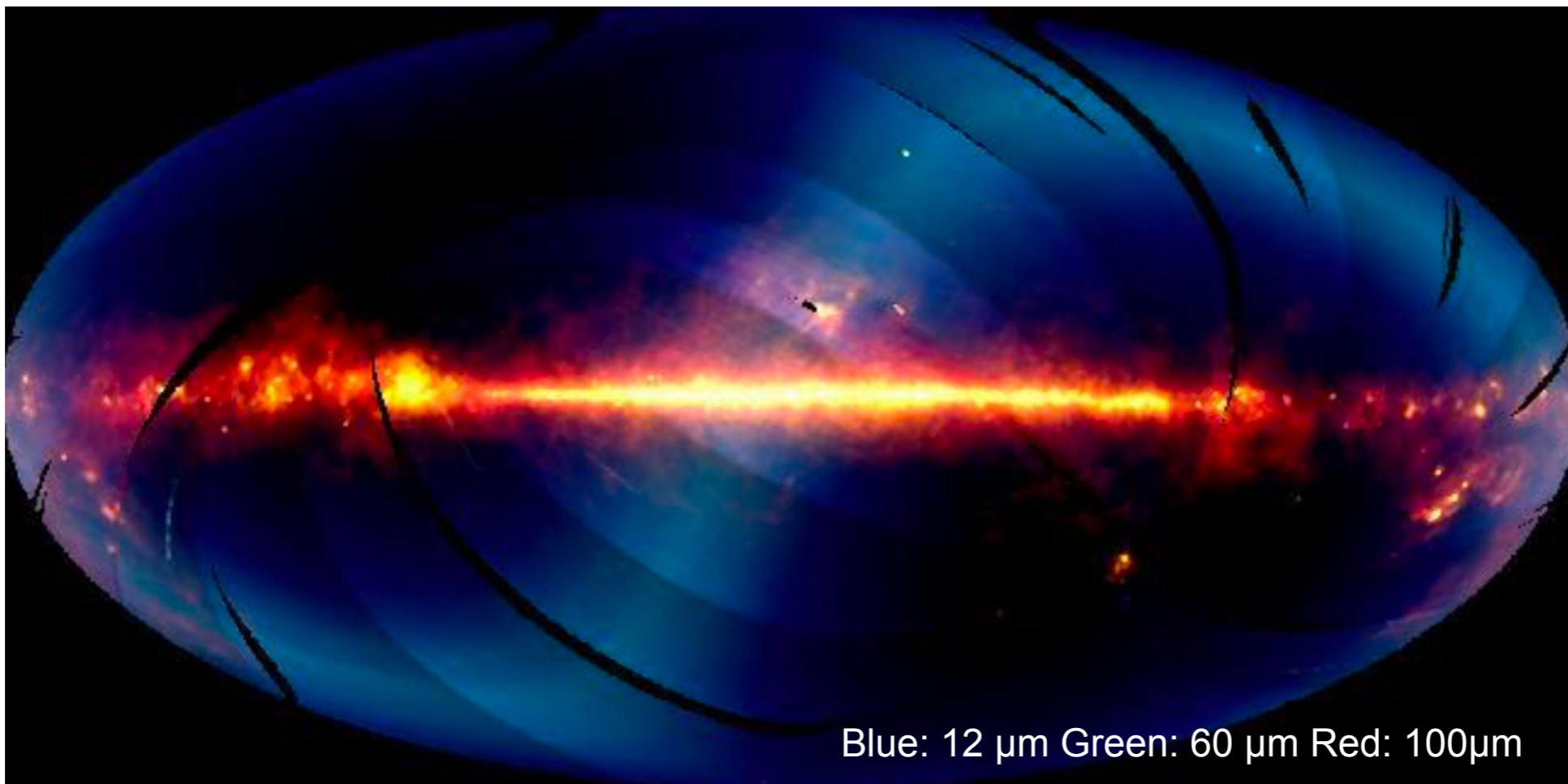
**Wien's law**

$$\lambda_{max} = \frac{0.0029 \text{ m}\cdot\text{K}}{T}$$

# Interstellar extinction: observations

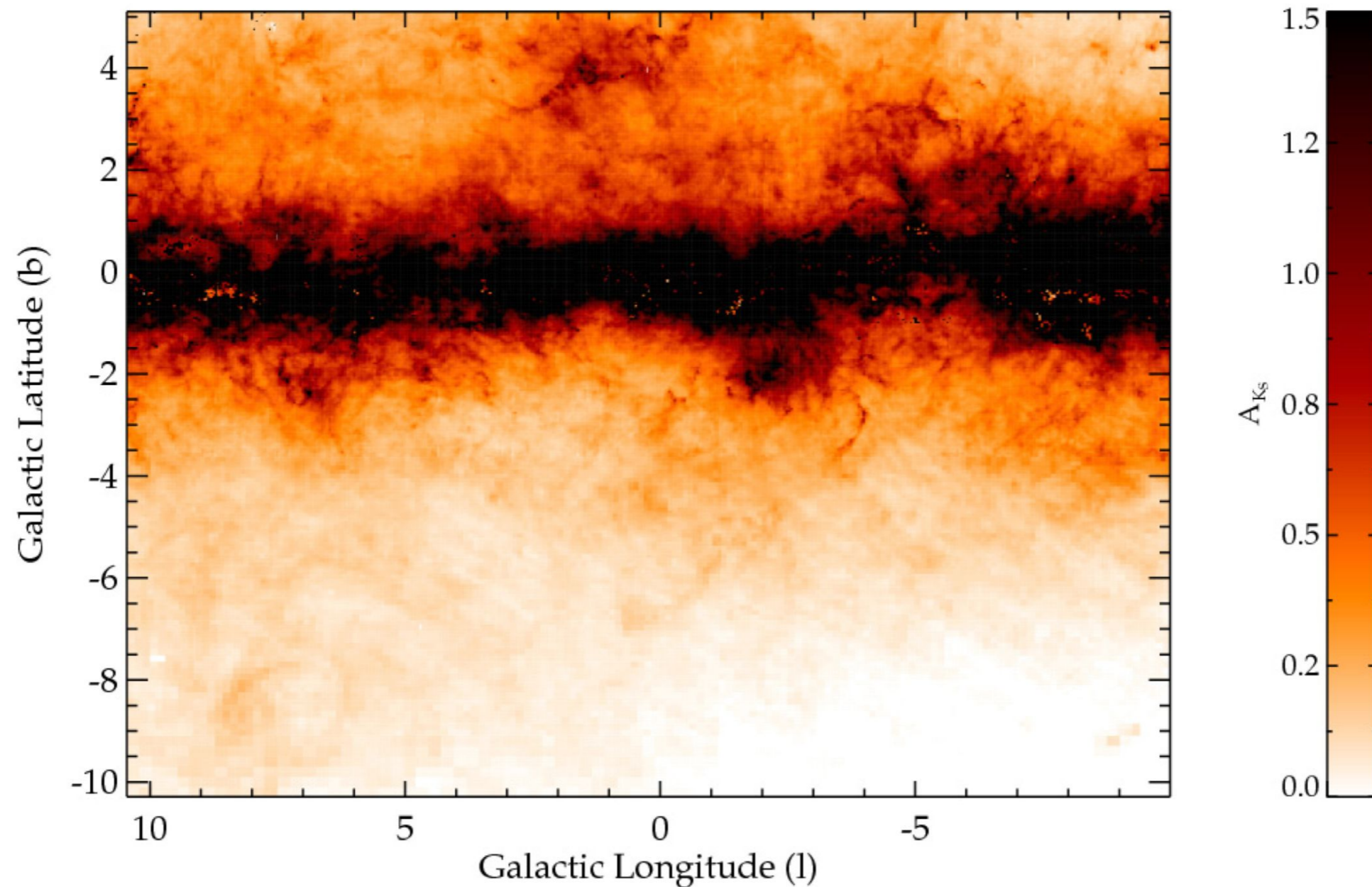
## ISSA: IRAS Sky Survey Atlas

- Scanned the MW at different wavelengths(12,25,60,100 $\mu\text{m}$ )
- Determined dust column density and then  $E(B-V)$  using B-V colours of elliptical galaxies
- Convert to extinction using standard  $R_V=3.1$
- Integrated extinction in the line of sight



# Interstellar extinction: observations

- Extremely high in the Galactic bulge

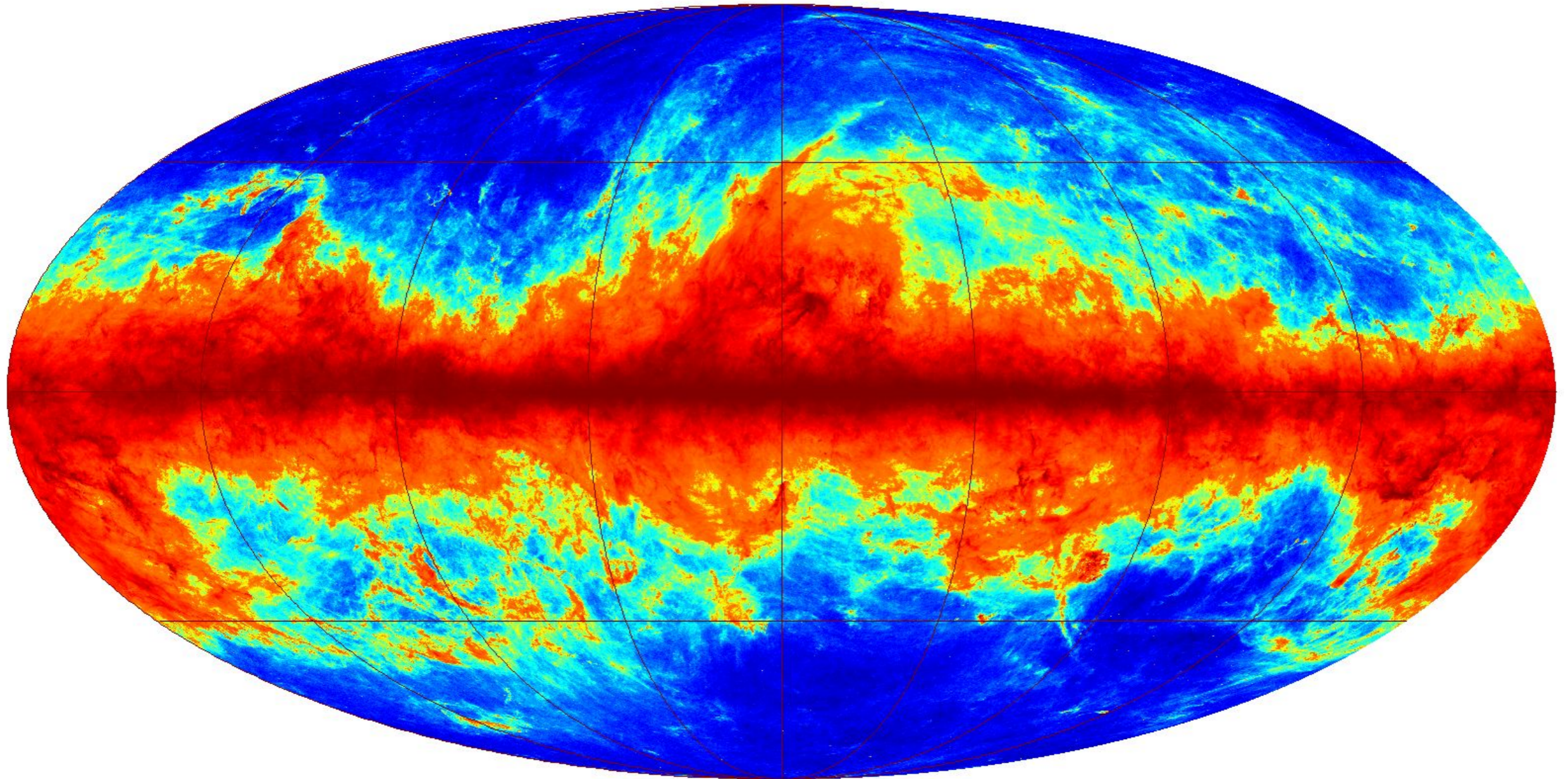




# Interstellar extinction: observations

HFLSkyMap\_857\_2048\_R1.10\_nominal I-STOKES

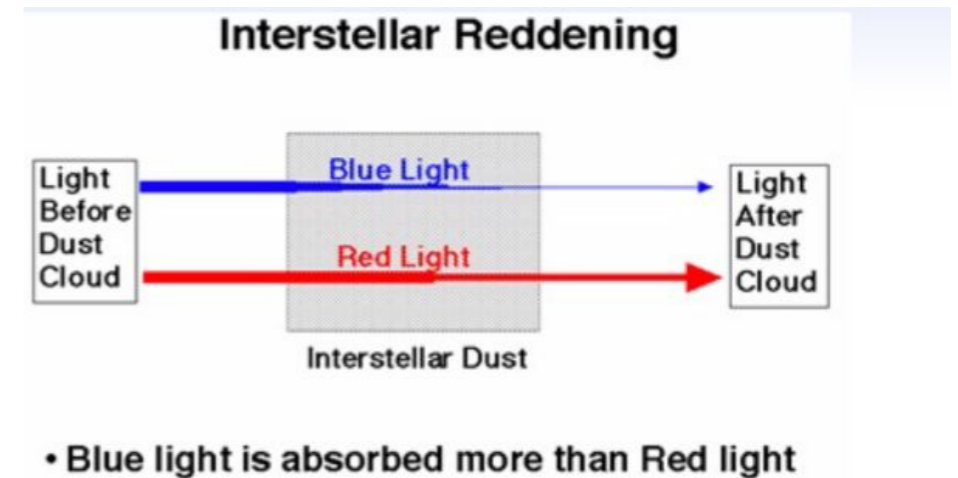
2048 NESTED GALACTIC



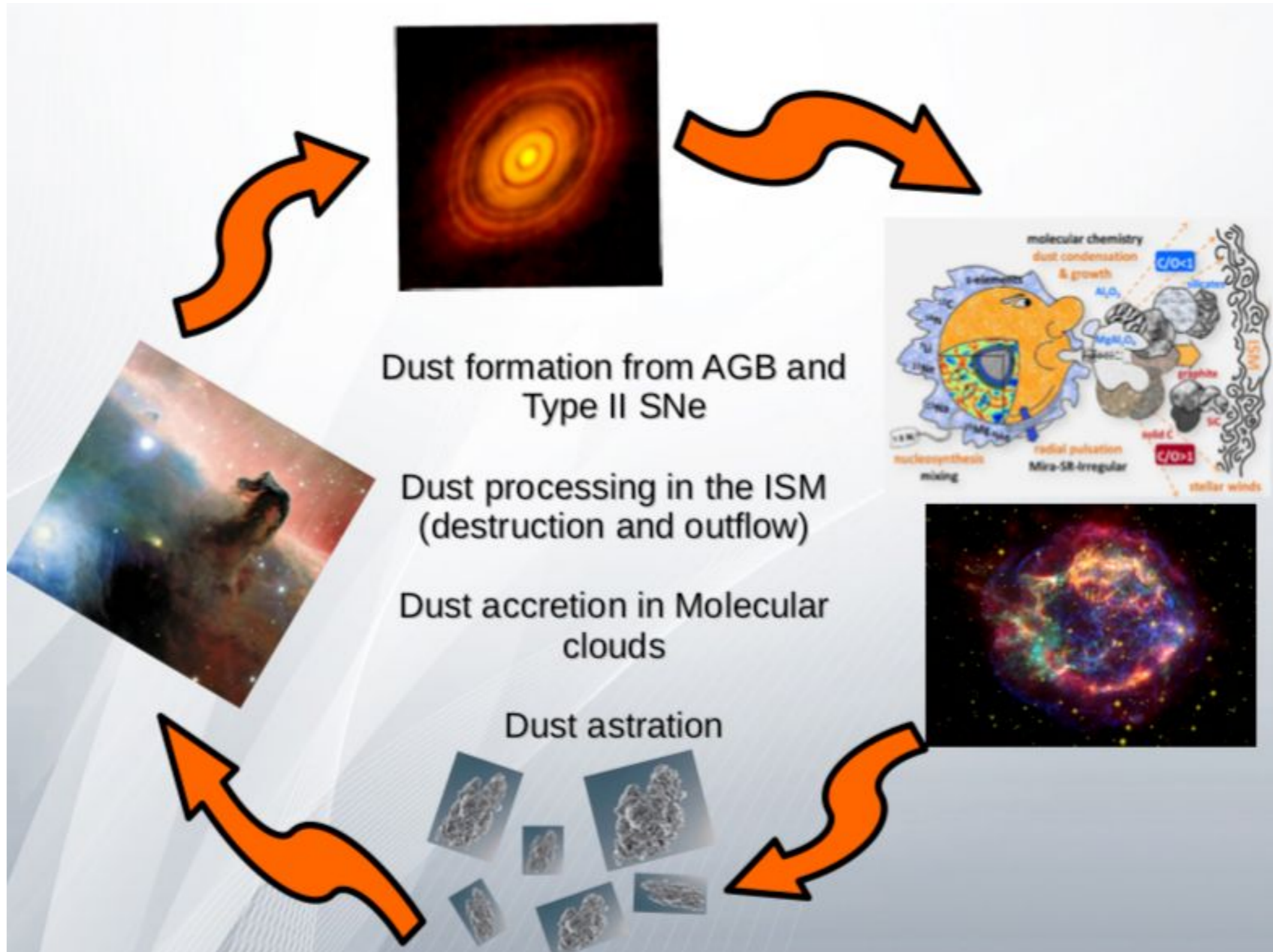
0  21036 MJy/sr

# Objects: Dark nebulae

- Dark bands straddle the Milky Way
- Dark clouds range from tiny (0.01 pc) so -called Bok globules, to tens of pc for large clouds; large range in  $A_V$
- Sometimes very faint reflected light and often bright in MID/Far IR
- Some even dark at mid - IR:  
Infrared Dark Clouds (IRDCs)



# Dust in the ISM



# Dust in the ISM

## Summary of the Evidence for Interstellar Dust:

- Extinction, reddening, polarization of starlight
- Dark clouds
- Scattered light:
  - reflection nebulae
  - diffuse galactic light
- Continuum IR emission:
  - diffuse galactic emission correlated with HI & CO
  - young and old stars with large infrared excesses
- Depletion of refractory elements from the interstellar gas (e.g., Ca, Al, Fe, Si)

# Molecular clouds: the cradles of star formation

density:  $\sim 100\text{-}1000\text{ cm}^{-3}$

temperature:  $\sim 10\text{ K}$

internal velocities:  $10\text{ km/s}$

supported by supersonic  
turbulence

cloud properties:

$$M \sim 10^6 M_{\odot}, \quad R \sim 50\text{ pc},$$

$$\Sigma_{\text{gas}} \sim 100 M_{\odot} \text{pc}^{-2}$$

gas tracers: CO, C<sup>+</sup>, HCN...



# HI regions, Cold Neutral Medium (CNM)

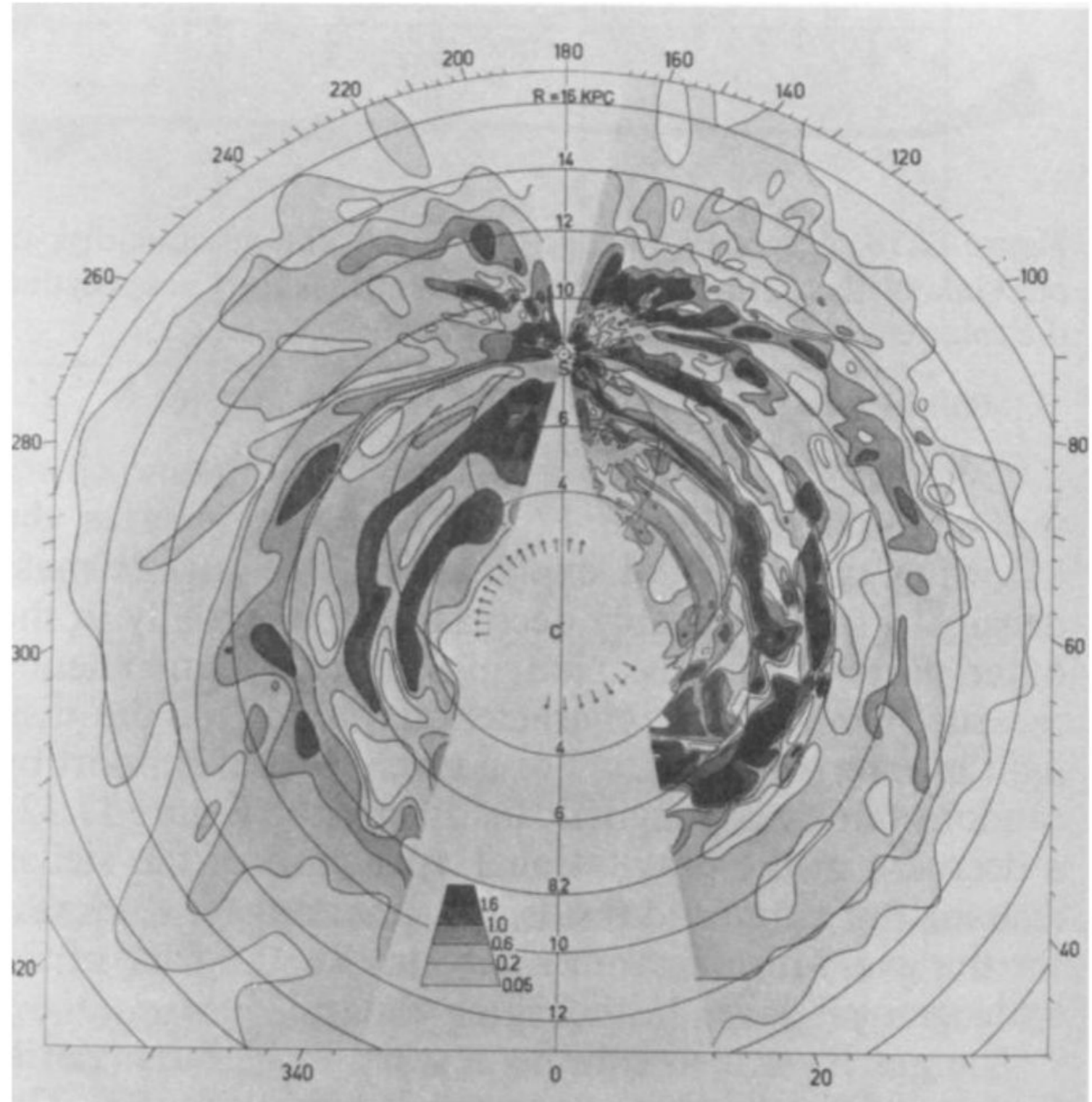
density:  $\sim 10 \text{ cm}^{-3}$

temperature:  $\sim 100 \text{ K}$

internal velocities:  $10 \text{ km/s}$

supersonic turbulence

gas tracer:  $21 \text{ cm}$



## Warm Neutral Medium (WNM), Warm Ionized Medium (WIM)

density:  $\sim 10^{-1} \text{ cm}^{-3}$

temperature:  $\sim 10^4 \text{ K}$

thermal velocities: 10 km/s

mildly supersonic turbulence

gas tracer: 21 cm (neutral),  
various nebular emission lines  
including H $\alpha$ , absorption  
lines



# Hot ionized medium

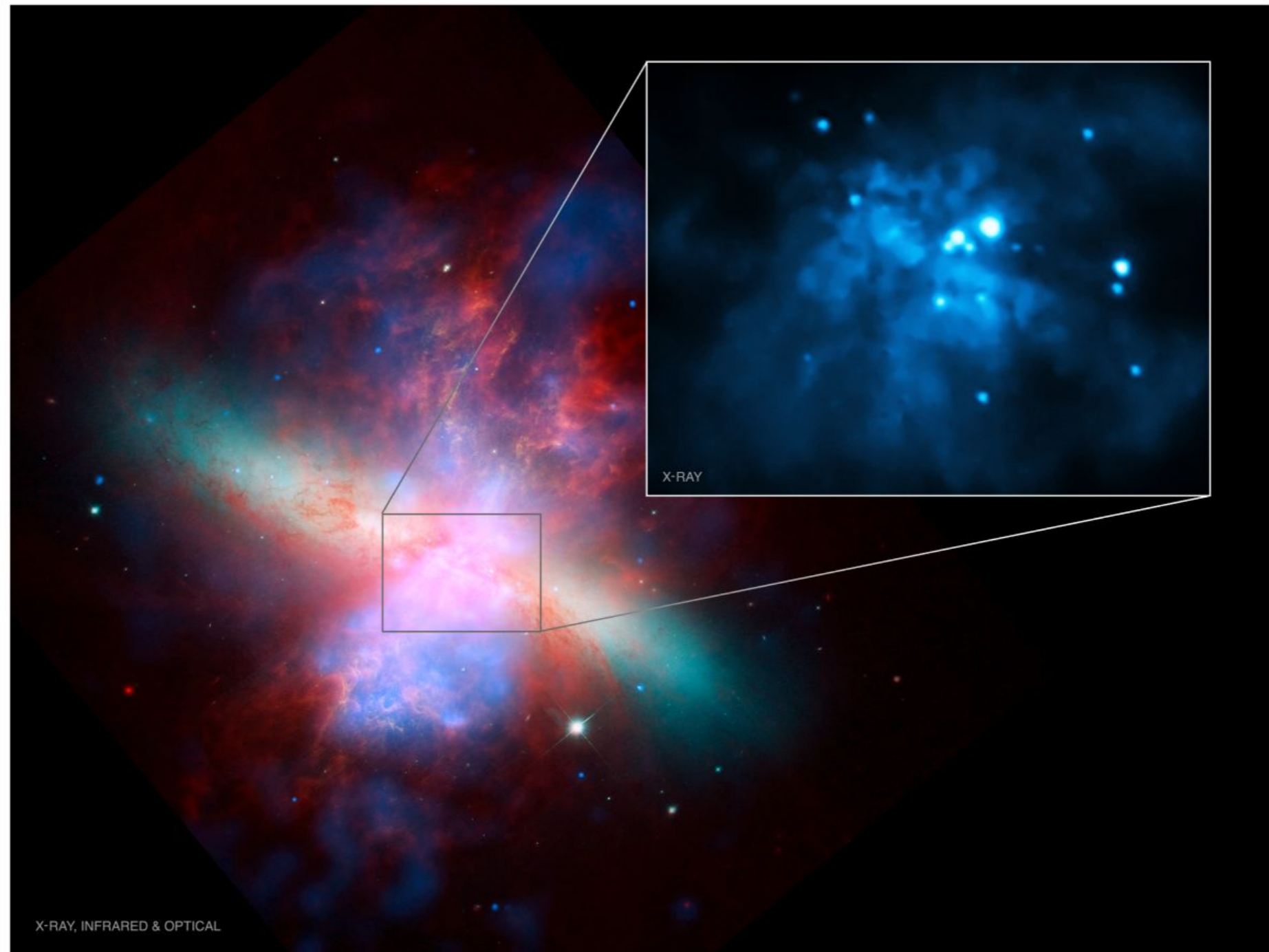
density:  $\sim 10^{-3} \text{ cm}^{-3}$

temperature:  $\sim 10^6 \text{ K}$

thermal velocities:  
100 km/s

complex kinematics

gas tracer: X-rays,  
high-ionization  
absorption lines:  
OVI, CIV, NV etc.





# Molecular clouds: the cradles of star formation

density:  $\sim 100\text{-}1000\text{ cm}^{-3}$

temperature:  $\sim 10\text{ K}$

internal velocities:  $10\text{ km/s}$

supported by supersonic  
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cloud properties:

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gas tracers: CO, C<sup>+</sup>, HCN...



# Molecular Gas

- Looking for Polar Molecules:

They have a non-zero electric dipole moment and so will radiate due to both rotational and vibrational modes.

A rotating molecule has an angular momentum that is quantized in units of

$$\hbar: L = n\hbar = I\omega$$

where  $I$  is the moment of inertia of the molecule and  $\omega$  is its angular frequency of rotation. The energy of the state with rotational quantum level  $J$  is

$$E_{\text{rot}} = \frac{J(J+1)\hbar^2}{2I}, \text{ where } J = 0, 1, 2, \dots$$

And only transitions between states  $J$  and  $J \pm 1$  are permitted:  $\Delta J = \pm 1$

The emitted frequency of a transition  $\nu = \frac{\hbar J}{2\pi m r_{\text{eq}}^2}$

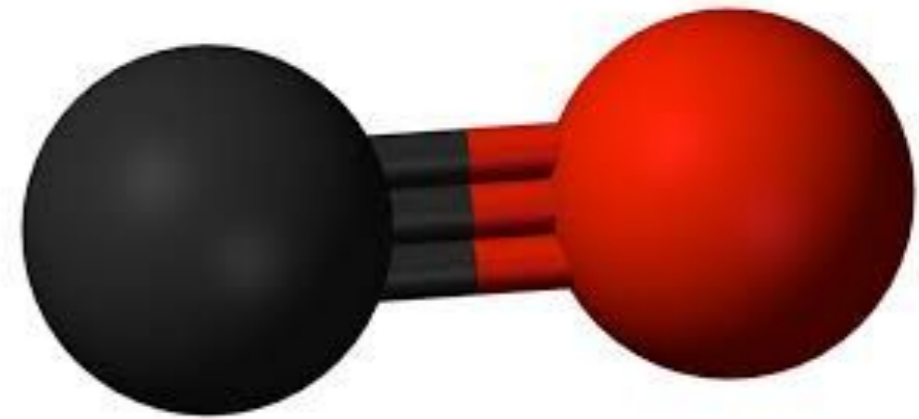
where  $m$  is the reduced mass of the molecule and  $r_{\text{eq}}$  is its equilibrium radius

# Molecular Hydrogen: H<sub>2</sub>

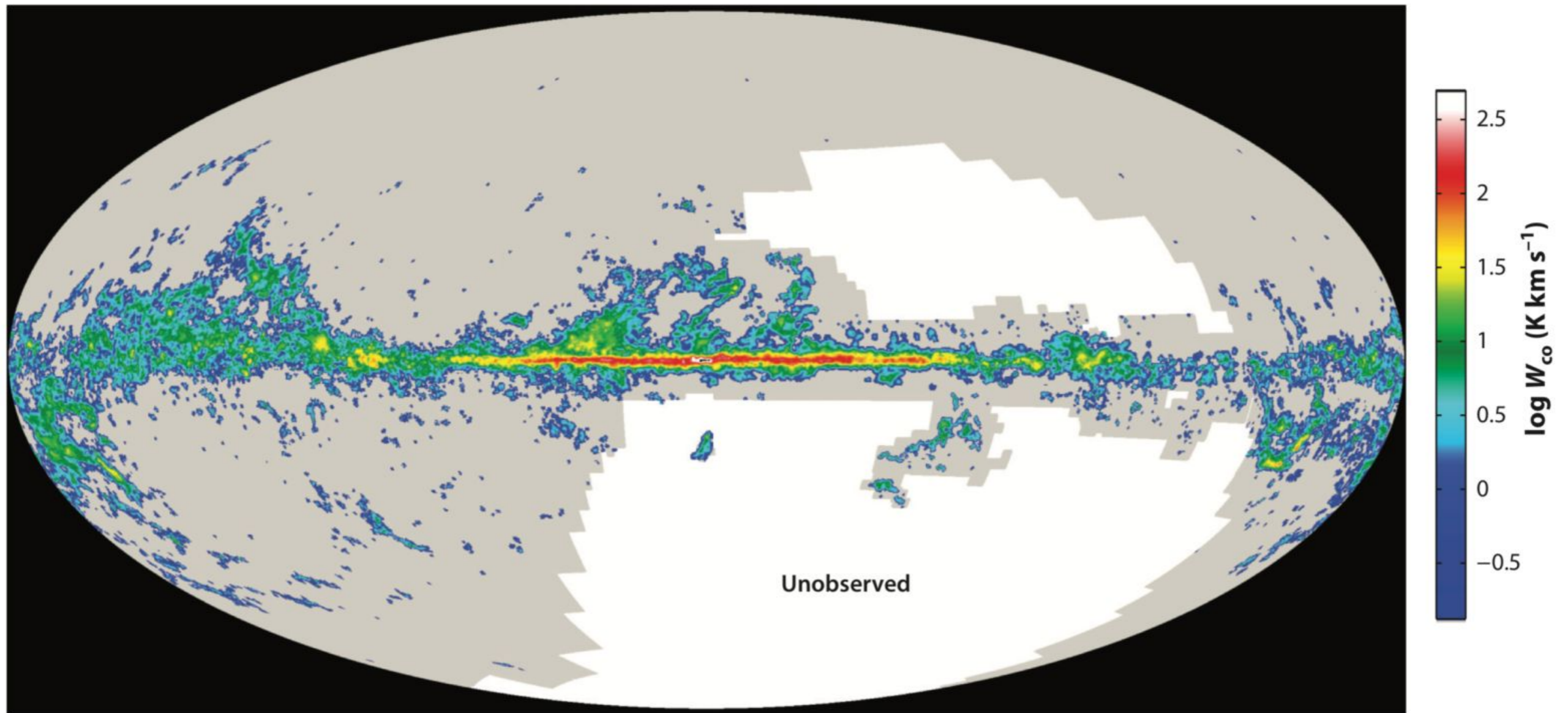
- Molecular hydrogen, H<sub>2</sub>, is symmetric and therefore has no permanent electric dipole moment. So despite the fact that H<sub>2</sub> is the most abundant molecule in the Universe, it only radiates when shocked or irradiated to  $T \geq 1000$  K, while most H<sub>2</sub> is at  $T \sim 10\text{--}100$  K.
- Because H<sub>2</sub> is very difficult to observe directly, we use CO to trace the molecular gas content of the Milky Way (and other galaxies, too!)
- We use a conversion between CO intensity and H<sub>2</sub> mass called the “X<sub>CO</sub>-factor”, which is roughly constant in the Milky Way, but is highly unlikely to be universal, and this uncertainty plagues extra-galactic CO observations (one part in 10<sup>5</sup>).

# CO

- CO is the second most abundant molecule in the galaxy (after H<sub>2</sub>), with J=0-1 and J=1-2 transitions at 2.6 mm (115 GHz) and 1.3 mm (230 GHz) respectively
- For CO J=0-1 and J=1-2, the excitation temperatures are ~11 K and 17 K, respectively
- The critical density, at which collisional excitation is in equilibrium with emission, for CO J=1-2 is 700 cm<sup>-3</sup>, typical of giant molecular clouds in the MW



# Phase: Molecular gas



**Figure 3**

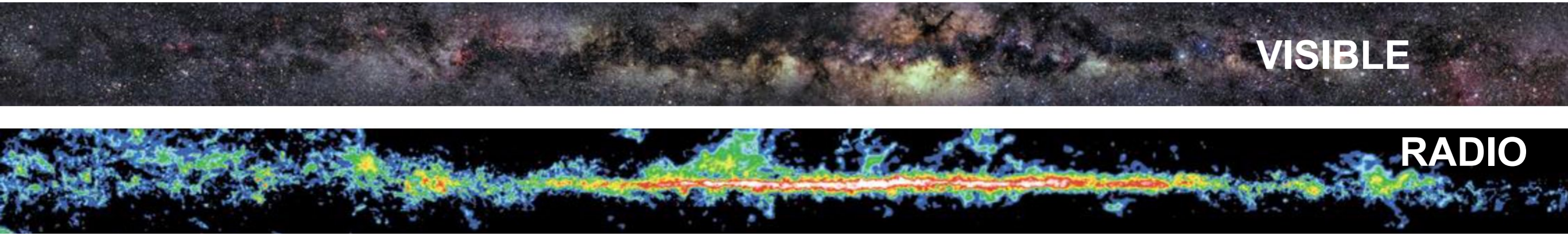
An image of  $^{12}\text{CO } J = 1-0$  emission constructed from the recent Center for Astrophysics campaign to examine the high-latitude sky and the composite surveys of Dame et al. (2001) and Mizuno & Fukui (2004).

# Phase: Molecular gas

## SUMMARY POINTS

1. The mass of H<sub>2</sub> gas in the Milky Way is  $1.0 \pm 0.3 \times 10^9 M_{\odot}$ . This value is derived from CO surveys assuming  $X_{\text{CO}} = 2 \times 10^{20} \text{ molecules cm}^{-2} (\text{K km s}^{-1})^{-1}$ ,  $R_{\text{Sun}} = 8.5 \text{ kpc}$ , and does not include the mass of associated helium. Most of the H<sub>2</sub> gas (60–70%) is located inside the solar circle.
2. The H<sub>2</sub> gas is largely confined to the plane of the Galaxy within a Gaussian layer with full width at half maximum thickness of 90 pc in the inner Galaxy that subsequently broadens to several hundred parsecs for radii greater than 10 kpc.
3. Molecular gas is mainly confined to the Galactic spiral arms.

# Radio observations (21cm line):



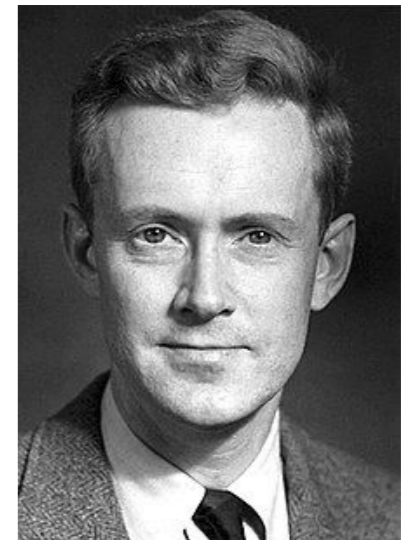
- By late 20s we knew MW was differentially rotating (dynamics of stars in our stellar neighbourhood)
- To study large scale rotations, we needed to observe the “other side” of our Galaxy
- Dust absorption limits our ability to map the MW
- Radio waves can travel through dust
- Hydrogen: hyperfine transition of HI
- Jan Oort (in Leiden) wondered if 21cm line could be observed from ISM

# History of 21cm line

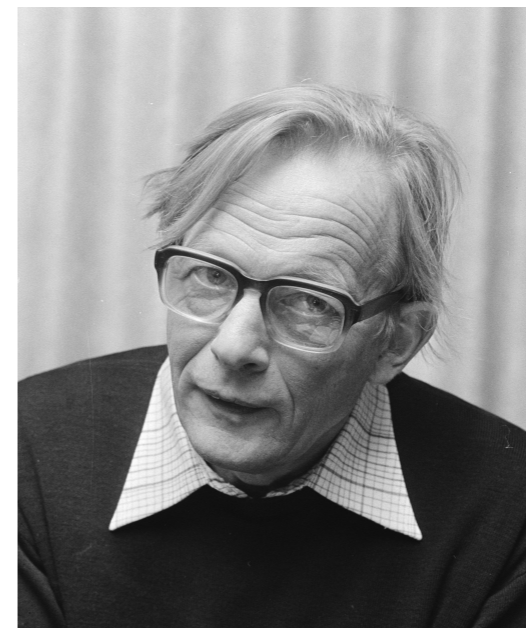
- 1947 → Van de Hulst predicted that 21cm line from ISM should be easily detectable
- Oort and his student Mueller used a radar antenna from WWII in Wurzburg to detect 21cm line:
  - A fire destroyed the equipment
- At the same time Edward and Ewen built a horn-antenna to detect 21cm line
- First time detected on easter of 1950
- Waited until Oort and Mueller rebuilt their experiment and published together (1951)



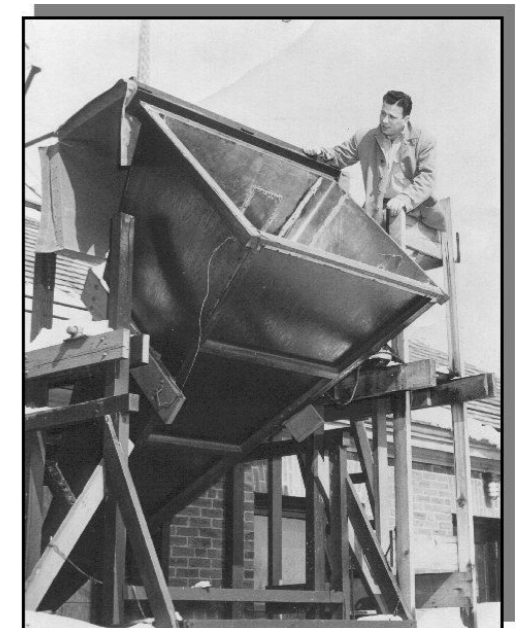
Jan Oort



Edward Mills Purcell



Henk van de Hulst



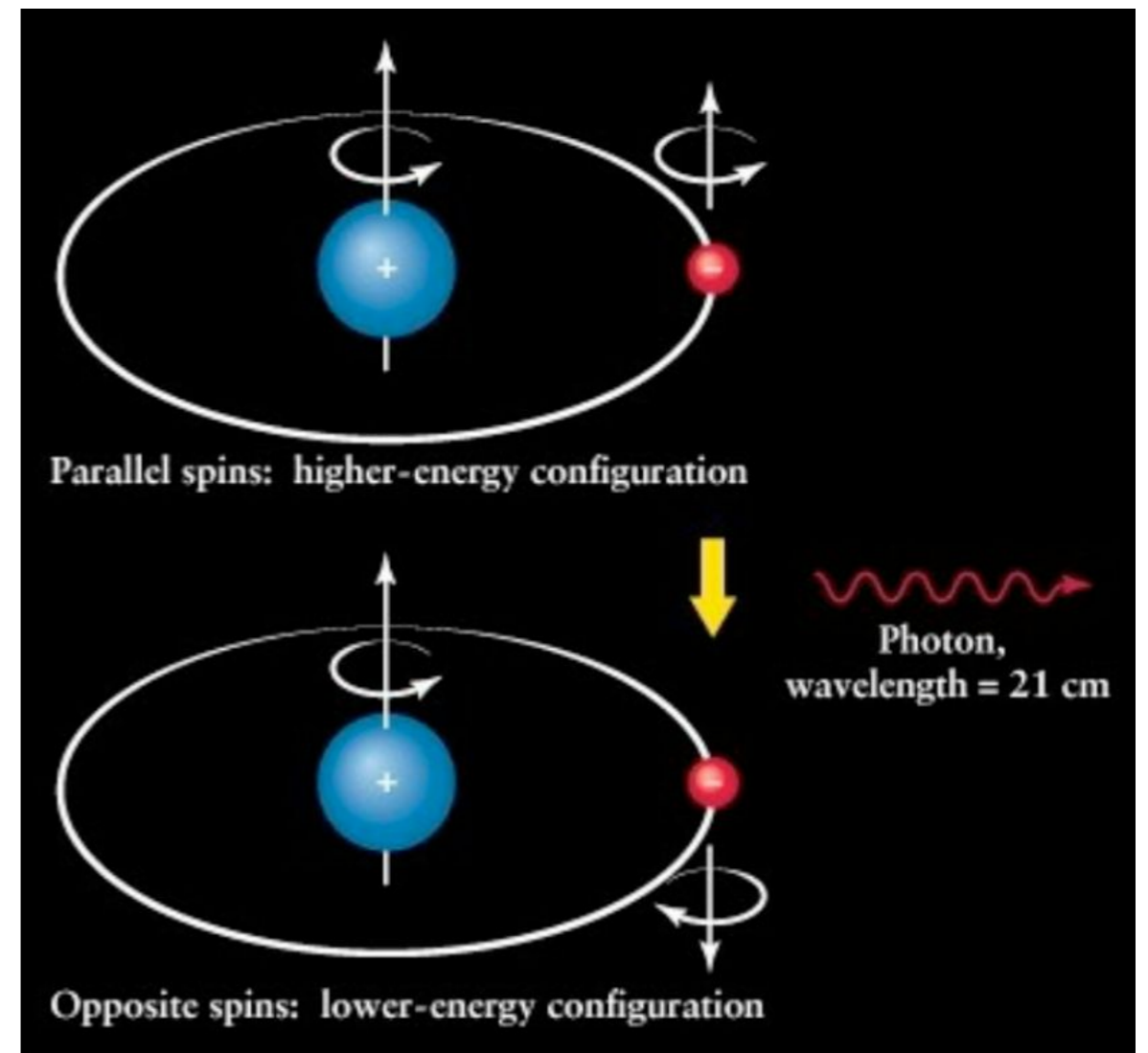
Harold Ewen



# Radio observations (21cm line):

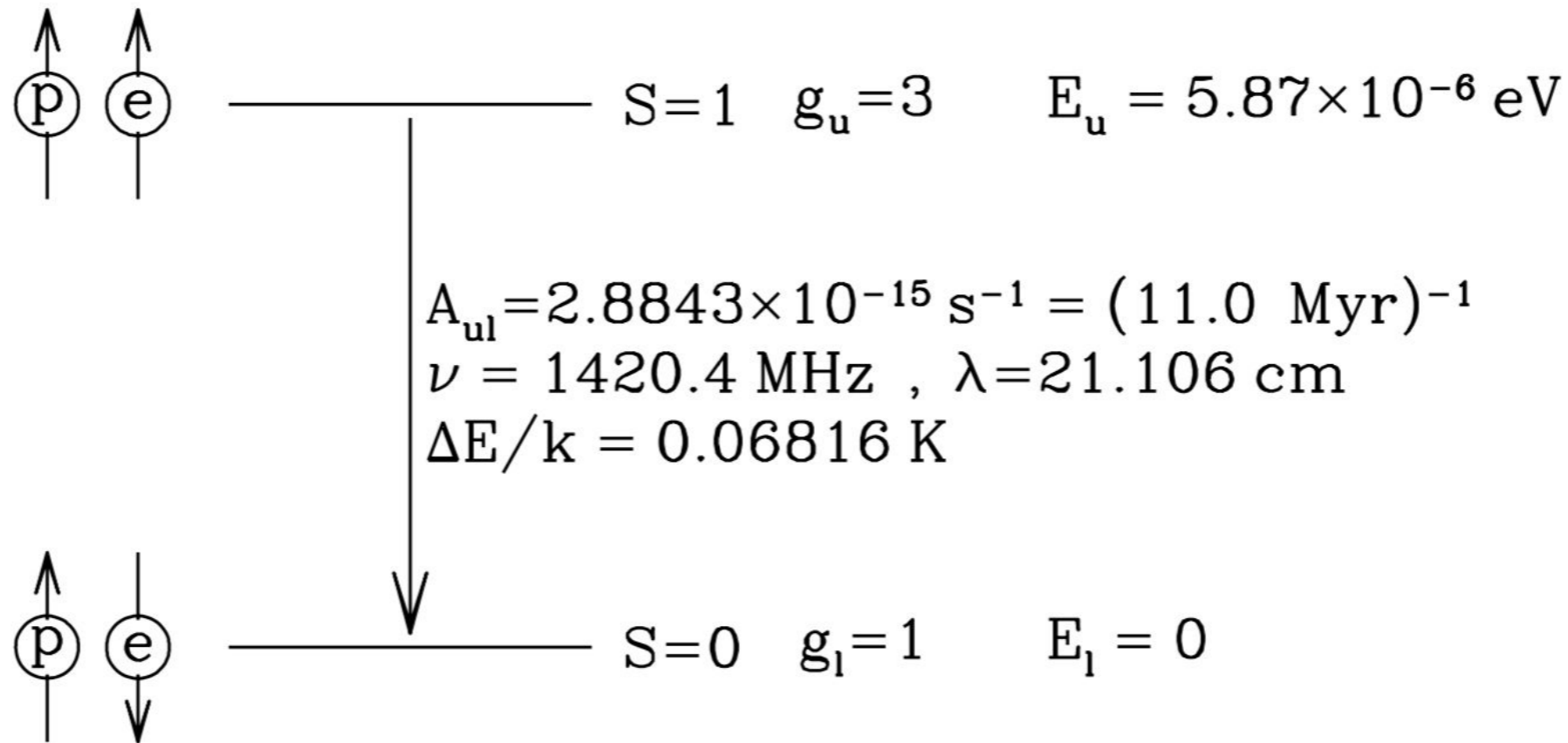
Hydrogen is the most abundant element in the Universe and in the interstellar medium (ISM) of the Milky Way. The cold interstellar gas does not emit radiation at visible wavelength...

... But at radio wavelengths due to a hyperfine line from two closely spaced energy levels in the ground state of the neutral H atom (HI). An HI atom with the spins aligned will spontaneously flip back to the lower energy, non-aligned, state after sometime.



Hyperfine transitions are a consequence of coupling between nuclear spin and the magnetic field generated by the orbiting electron.

# Radio observations (21cm line):



The frequency of the centre of this line is defined from quantum mechanics:

$$\nu_{10} = \frac{8}{3} g_I \left( \frac{m_e}{m_p} \right) \alpha^2 (R_M c) = 1420.406 \text{ MHz}$$

$g_I \approx 5.58569$  is the nuclear g-factor

$R_M c$  is the hydrogen Rydberg frequency

$\alpha$  is the fine structure constant

Radiative half-life  $\sim 11$  million years (small width)  $\rightarrow$  The average hydrogen atom takes a long time to make this transition; but, since hydrogen is by far the most abundant element, 21 cm radio emission is ubiquitous in the Galaxy.

# Mapping the Milky Way in HI

By measuring the radial velocity of the 21 cm line and its intensity, we can measure the distance to and amount of HI in the Milky Way

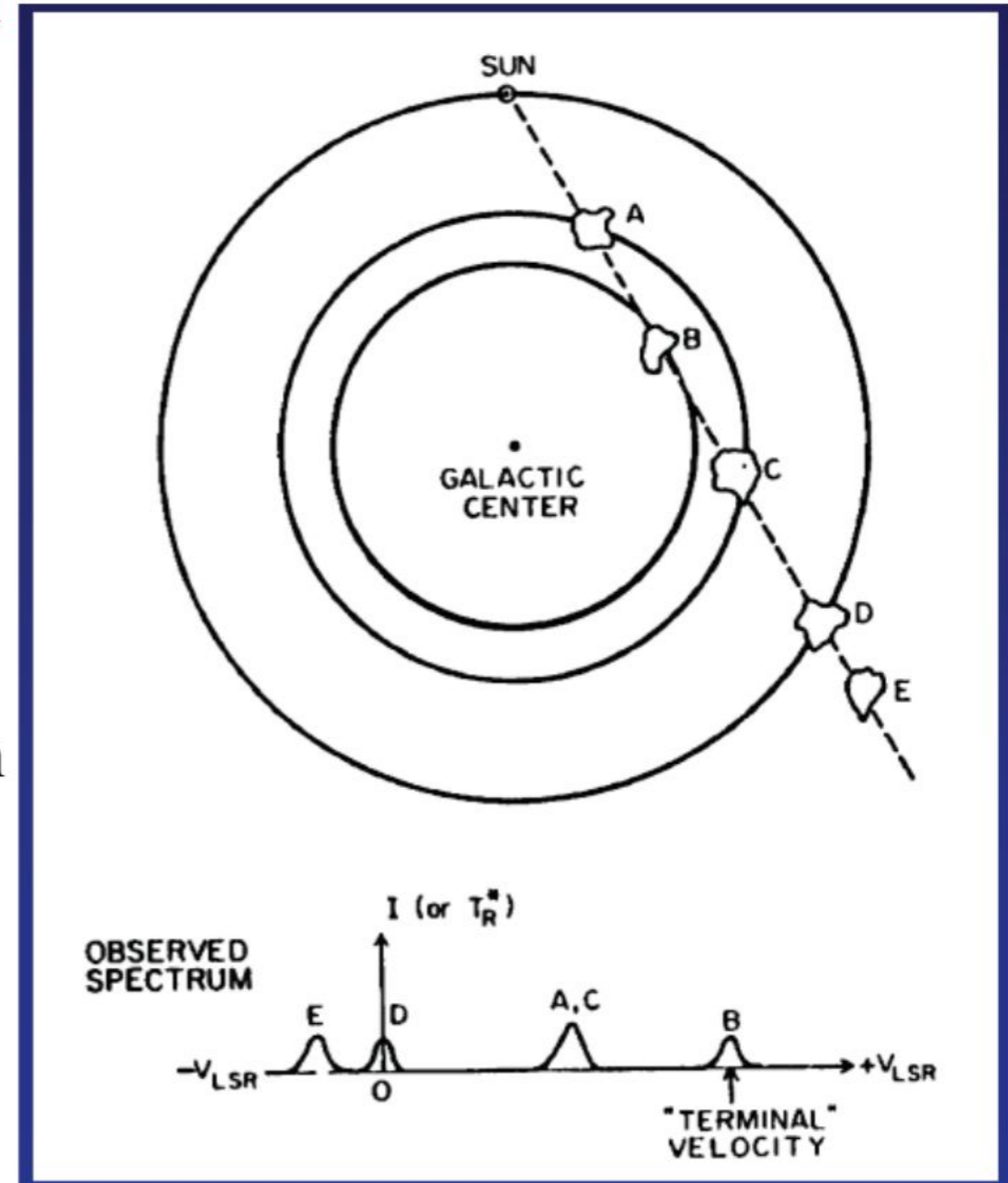
compare the observed frequency of the line with 1420.406 MHz to get the radial velocity:

$$z = \frac{\lambda_{\text{obs}} - \lambda_{\text{em}}}{\lambda_{\text{em}}} = \frac{\nu_{\text{em}} - \nu_{\text{obs}}}{\nu_{\text{obs}}} \text{ and } v = cz$$

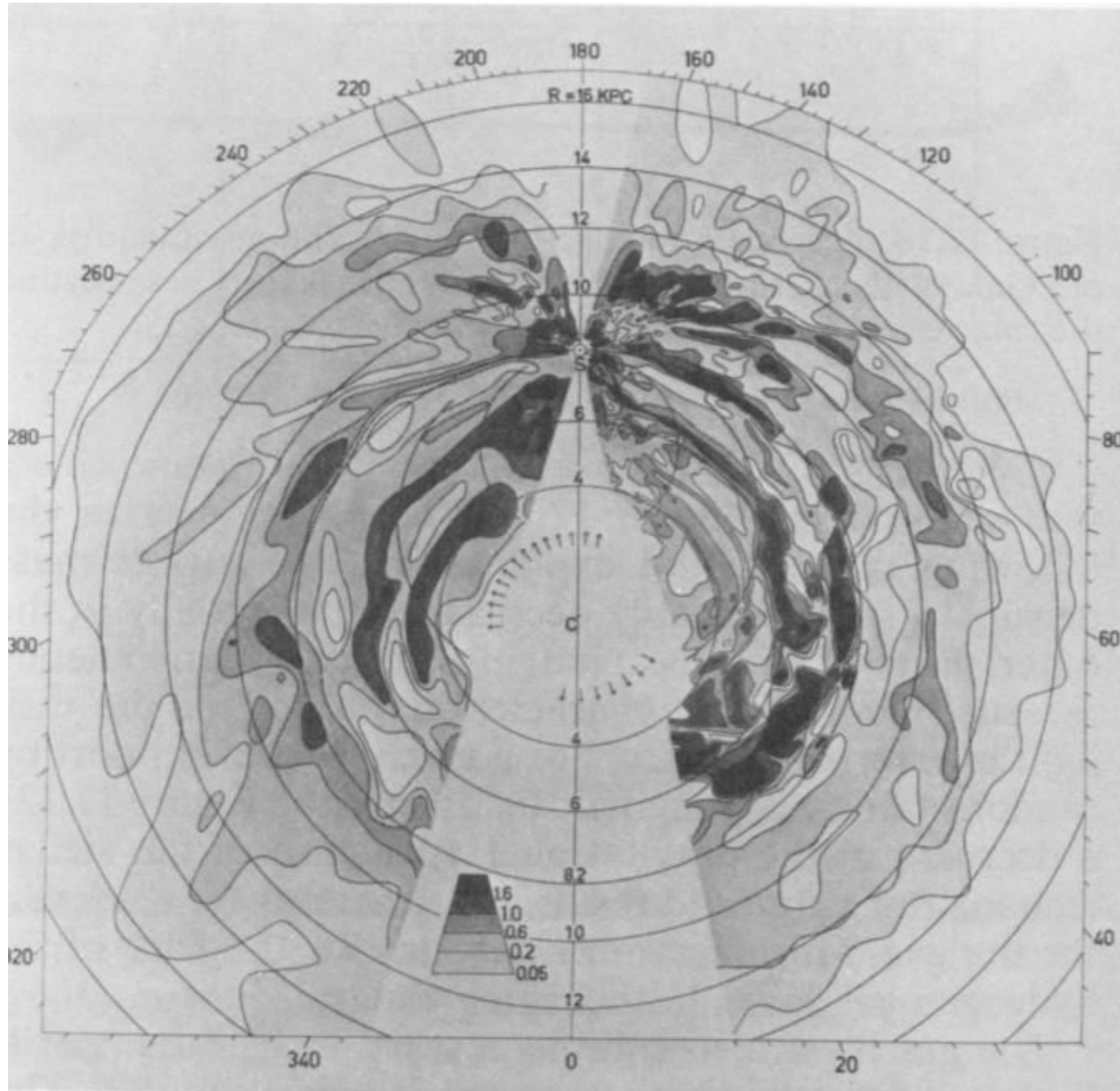
and integrate the observed intensity over frequency to get the column density ( $N_{\text{HI}}$  in  $\text{cm}^2$ ) of neutral hydrogen

# Distribution of the neutral gas in the Galactic plane

- The HI distribution can be reconstructed from a kinematical analysis of the 21-cm emission profiles observed at different Galactic longitudes
- The reconstruction is based on a kinematical model of Galactic rotation,  $w(R)$ 
  - It is assumed that interstellar clouds at Galactocentric distance  $R$  move in orbits with angular velocity  $\omega(R)$
  - From the observed radial velocity at a given longitude one can estimate the cloud distance
- The existence of spiral arms was first proven with this technique



# Mapping the Milky Way in HI



Oort et al. 1958, MNRAS

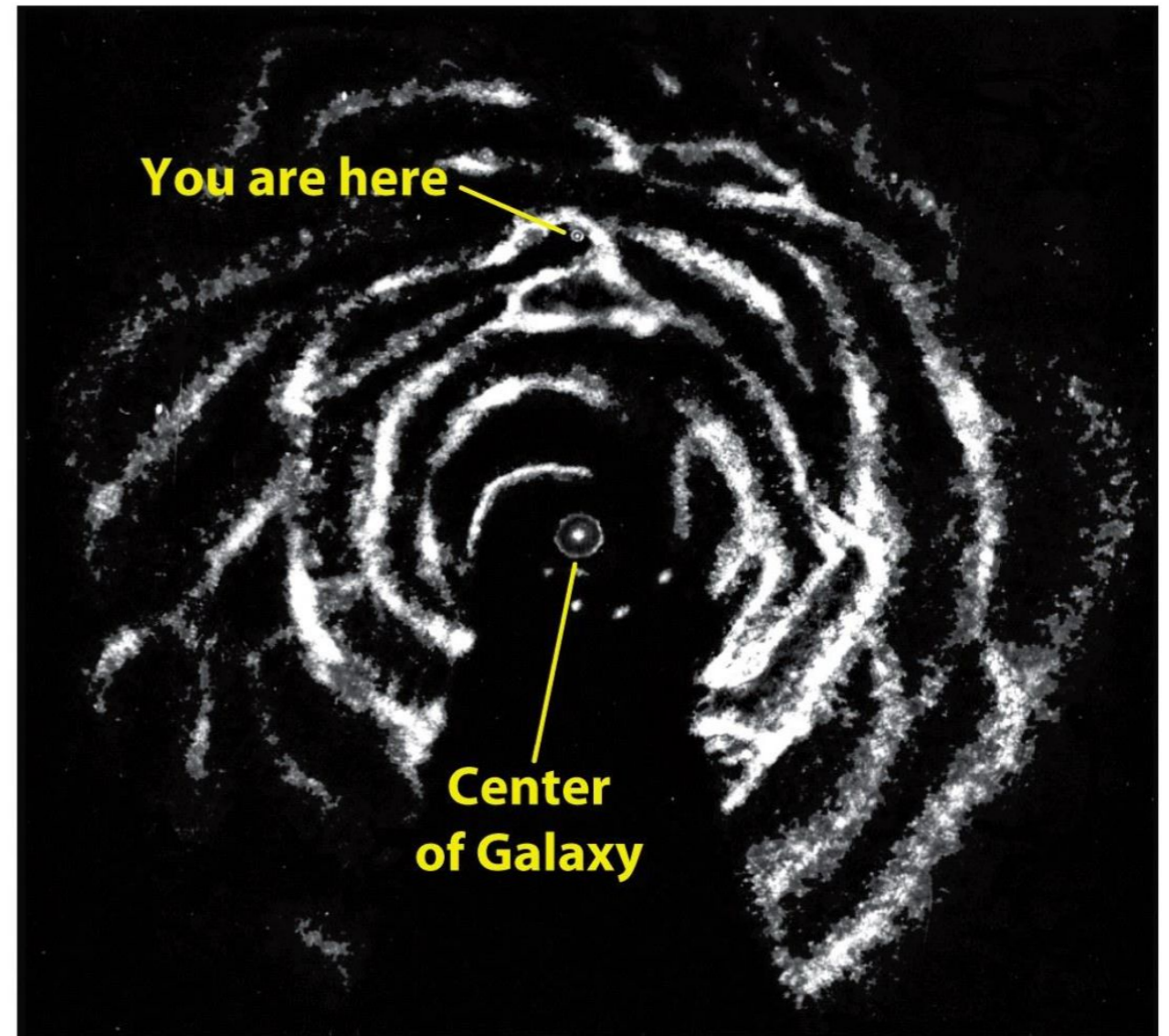
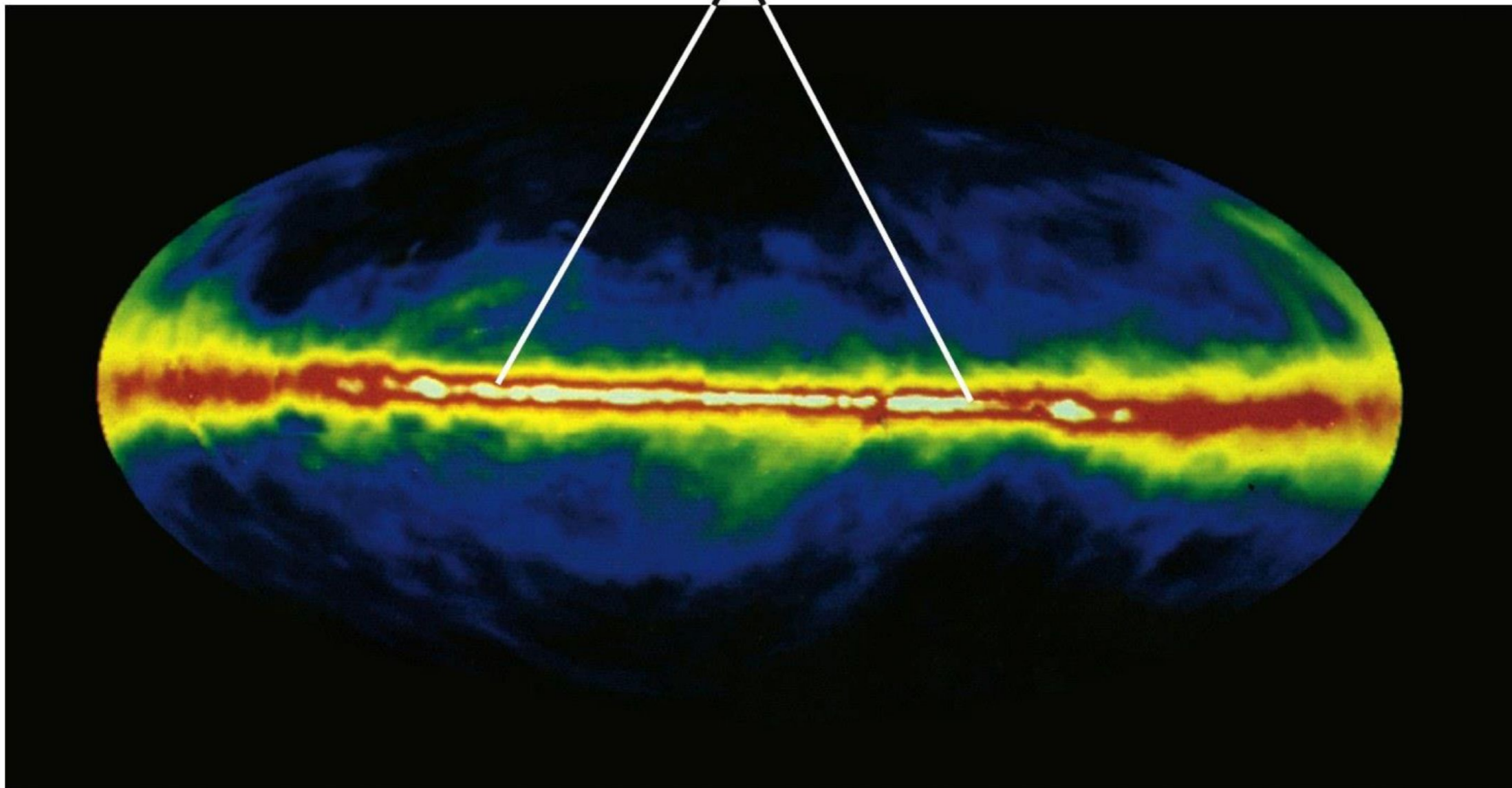


Figure 23-14  
Universe, Ninth Edition  
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Map of the Milky Way obtained by Doppler measurements of the 21-cm line.

# Mapping the Milky Way in HI

**21-cm emission shows that hydrogen gas is concentrated along the plane of the Galaxy**

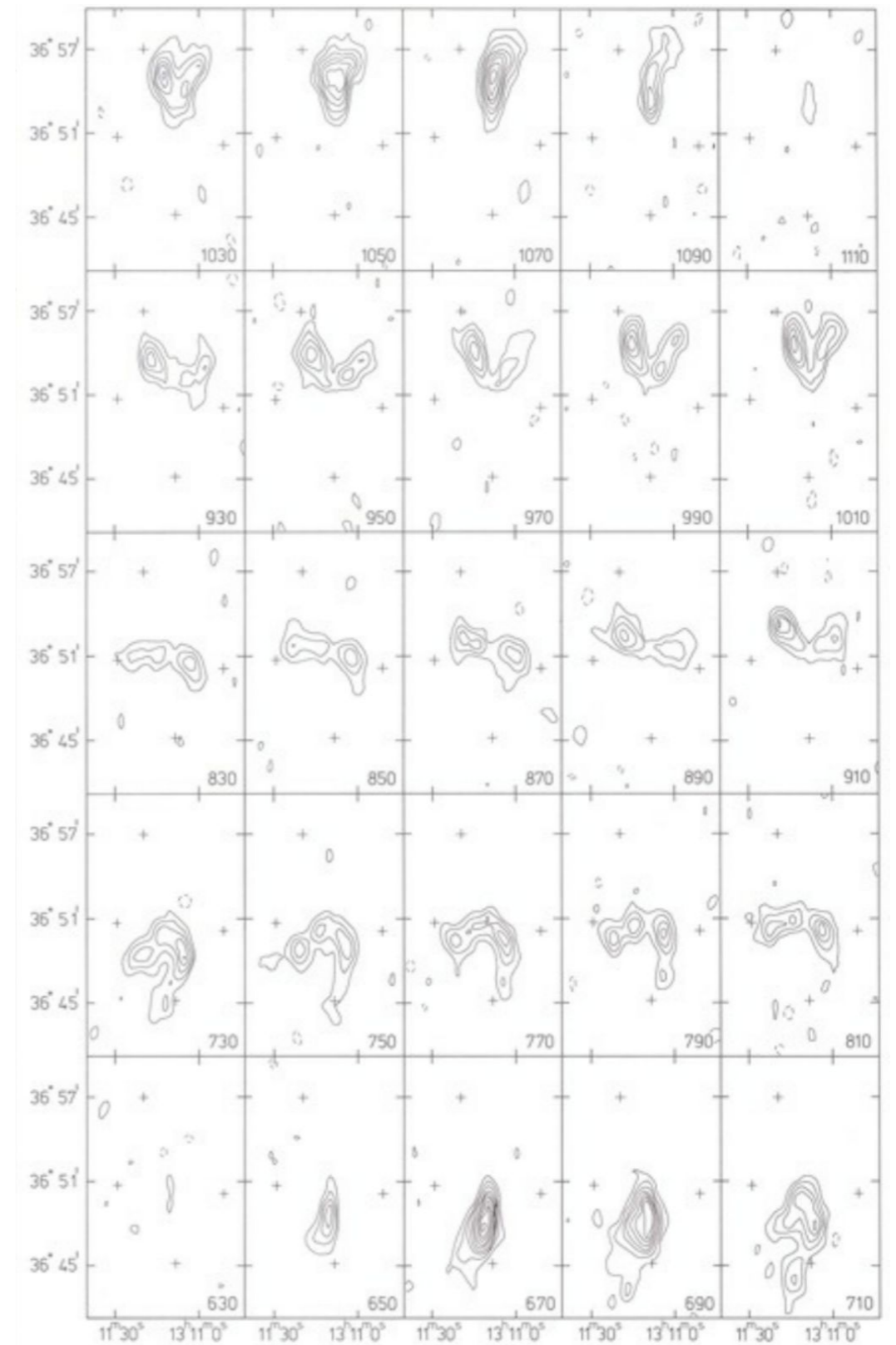


**Figure 23-12**  
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# The ISM of Galaxies

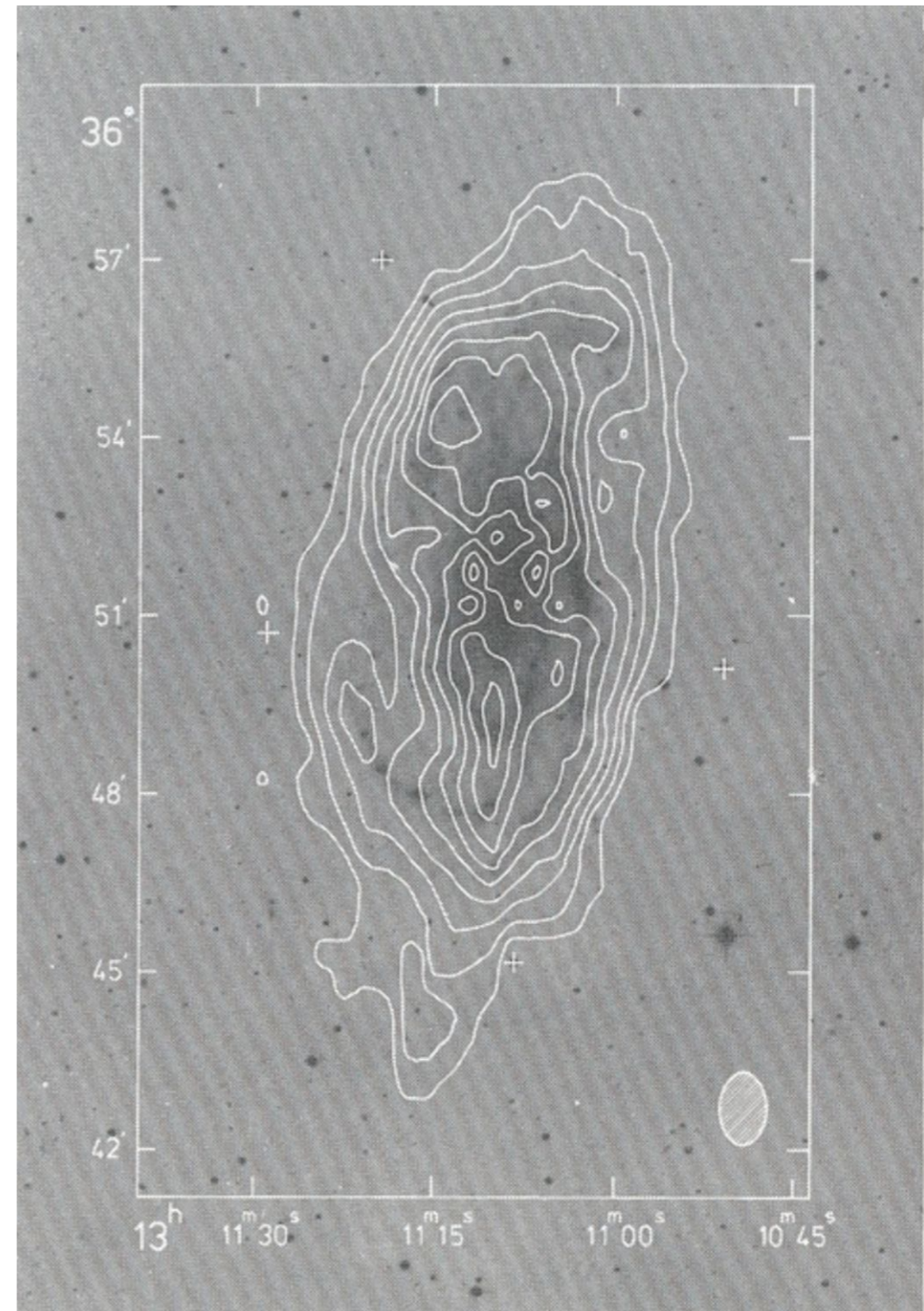
- Observations in e.g.,  $H_\alpha$  and 21cm line in galaxies
- Measurement of intensity from each position
- Done in narrow frequency ranges (channels)
- Doppler effect: results in a range of velocities

Maps of the 21 cm line radiation. The heliocentric velocity (in km/s of each channel map is indicated in the lower right corner; the crosses refer to star positions.



# The ISM of Galaxies

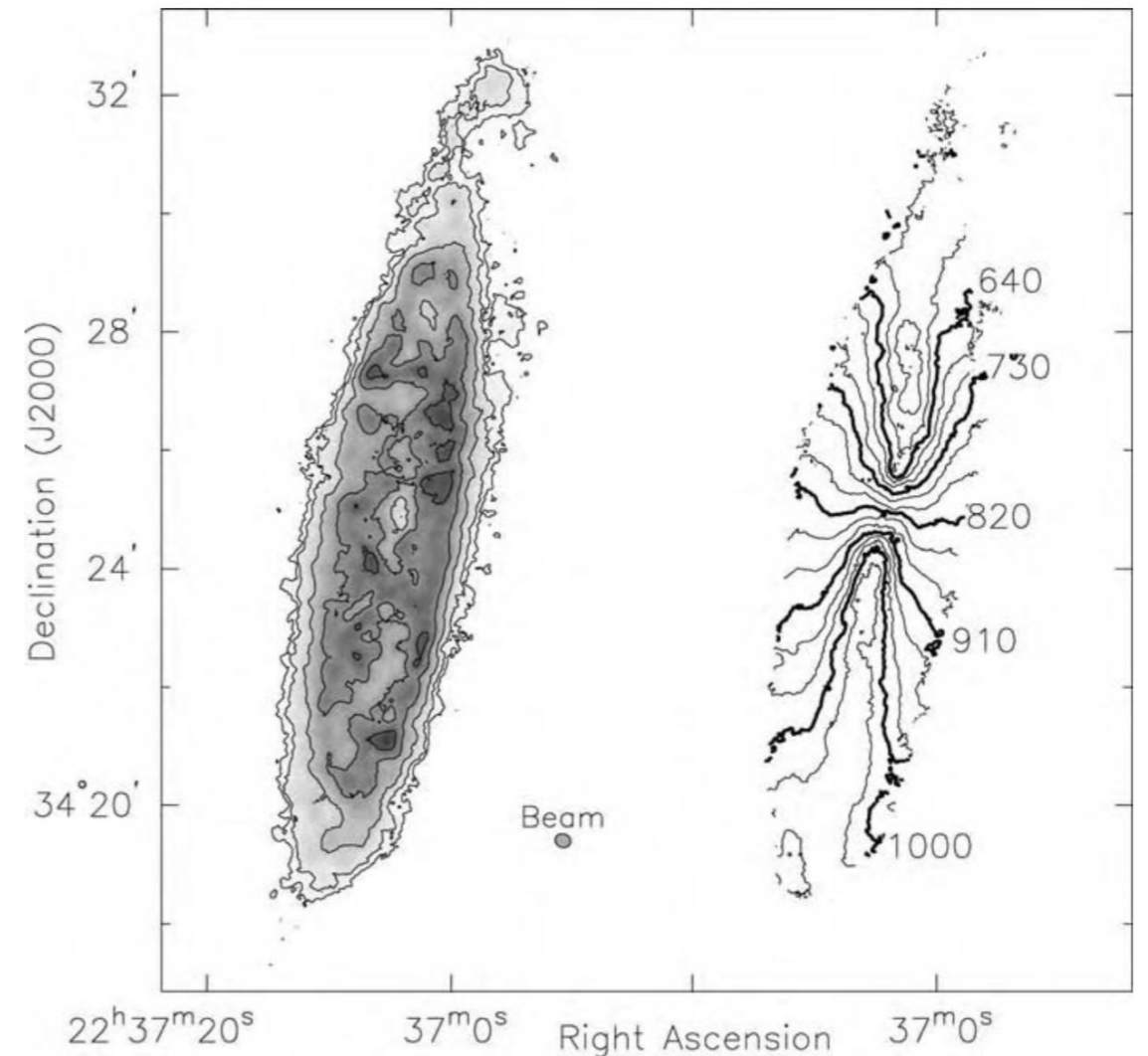
- Optically thin line: amount of material moving
- HI column density





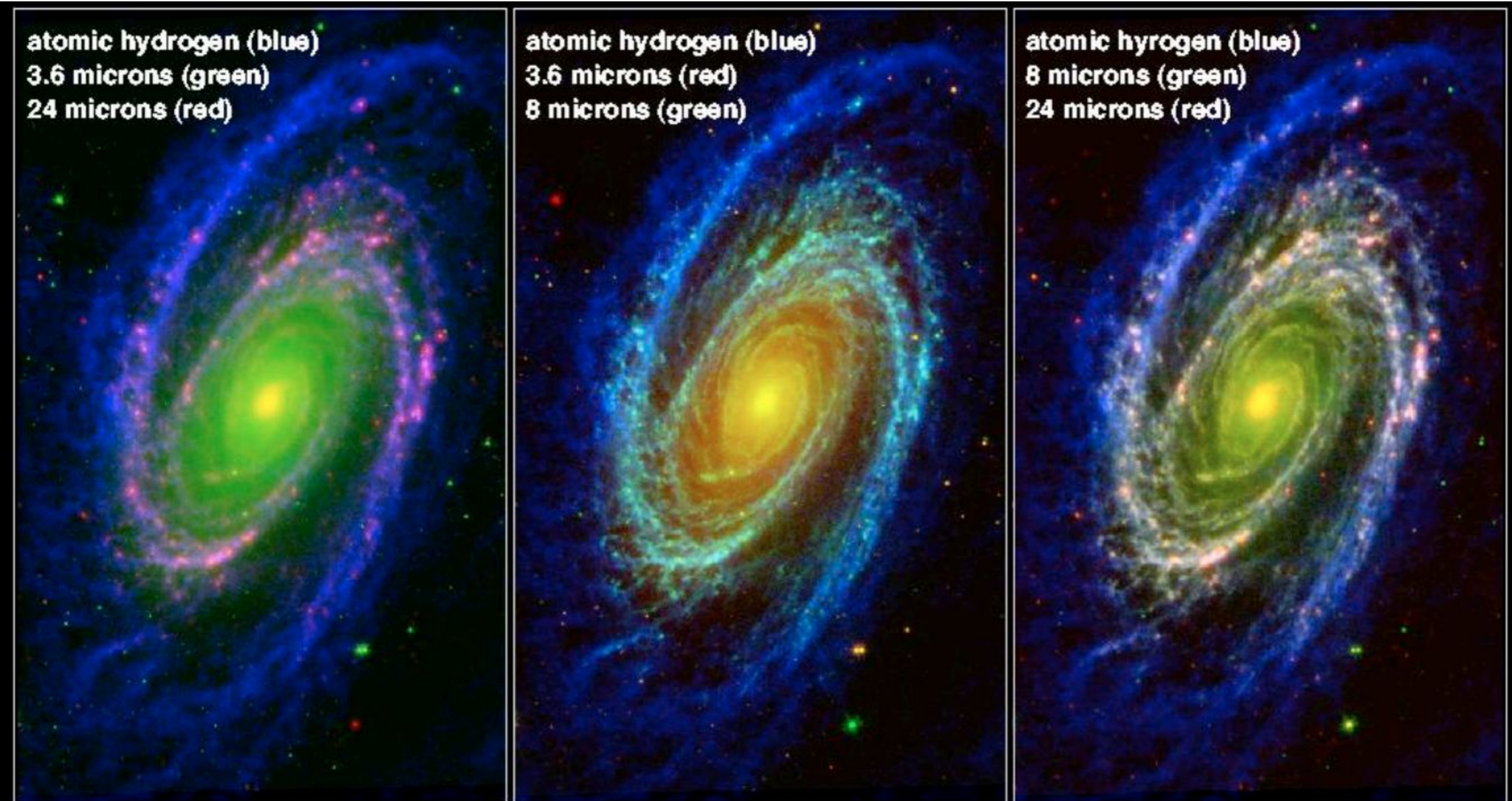
# Galaxy NGC 7331

- Since the gas is moving within the galaxy, its line emission is Doppler shifted according to the radial velocity  $V_r$ ;
- Set the telescope to observe simultaneously in a number of closely spaced frequency channels; typically, each covers a few kilometers per second in velocity.
- For the most part, HI in galaxy disks is optically thin; the 21 cm line suffers little absorption, so the mass of gas is just proportional to the intensity of its emission.



$$\mathcal{M}(\text{HI}) = 2.36 \times 10^5 \mathcal{M}_\odot \times d^2 \int F_\nu \left[ 1421 \text{ MHz} \times \left( 1 - \frac{V_r}{c} \right) \right] dV_r.$$

$1.1 \times 10^{10} \mathcal{M}_\odot$  of atomic hydrogen; this is twice as much as in M31.



### **Spiral Galaxy Messier 81**

### **NASA Spitzer Space Telescope and NRAO VLA**

Messier 81 is part of SINGS – The Spitzer Infrared Nearby Galaxy Survey (PI: R. Kennicutt, University of Arizona)

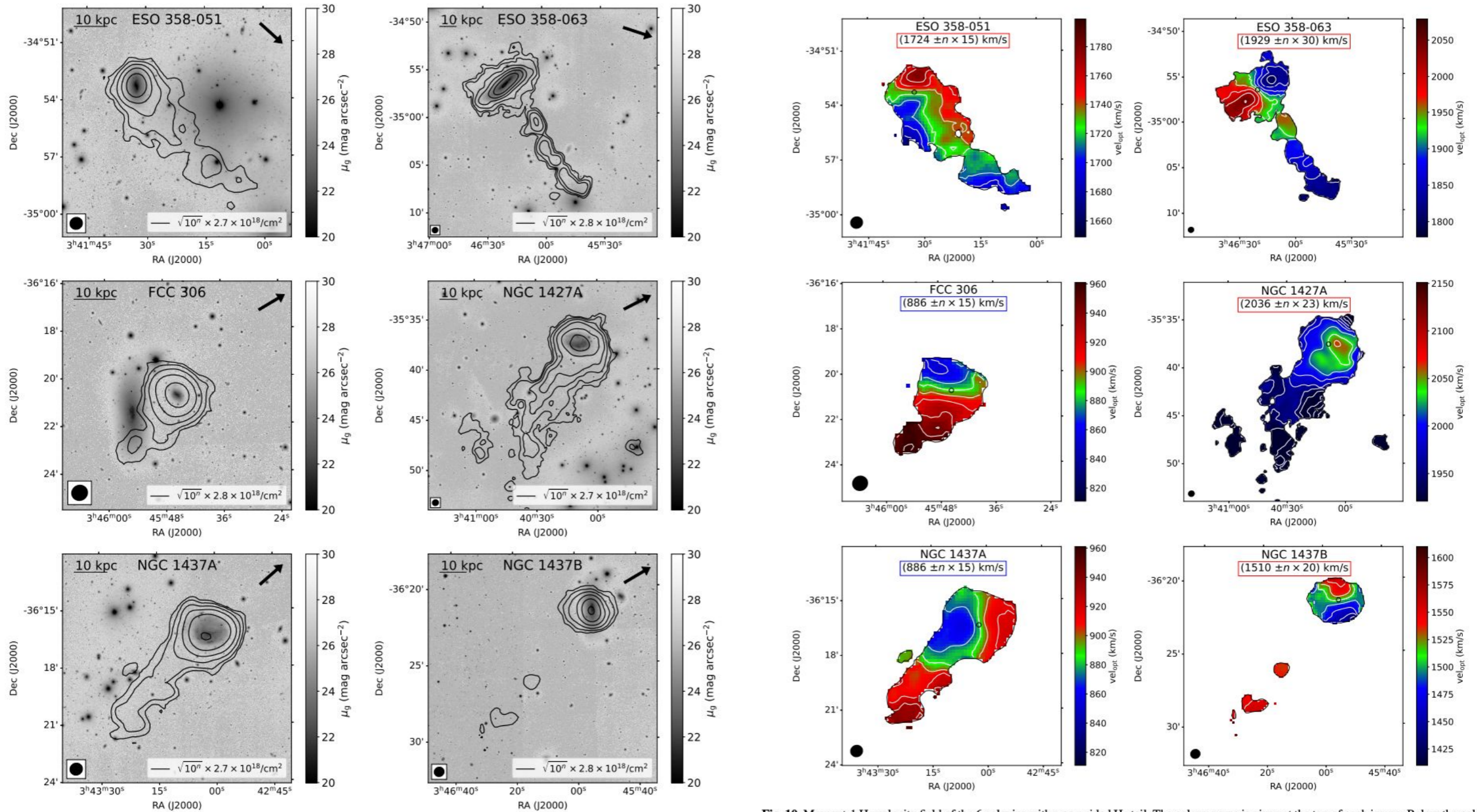
Spitzer Space Telescope Image Credit: NASA/JPL–Caltech/K. Gordon (University of Arizona)

& S. Willner (Harvard–Smithsonian Center for Astrophysics)

National Radio Astronomy Observatory: F. Walter (NRAO), E. Brinks (INAOE) & R. Kennicutt (University of Arizona)

- Neutral atomic gas (HI) and dust (seen in IR) are largely confined in the spiral arms

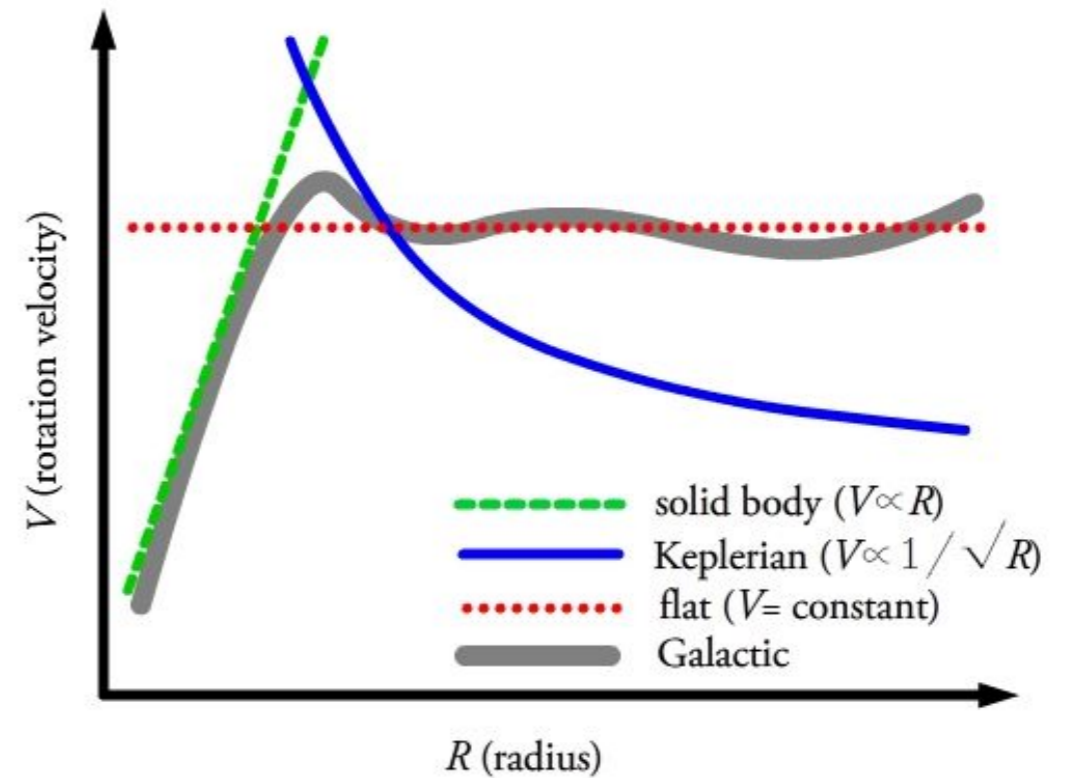
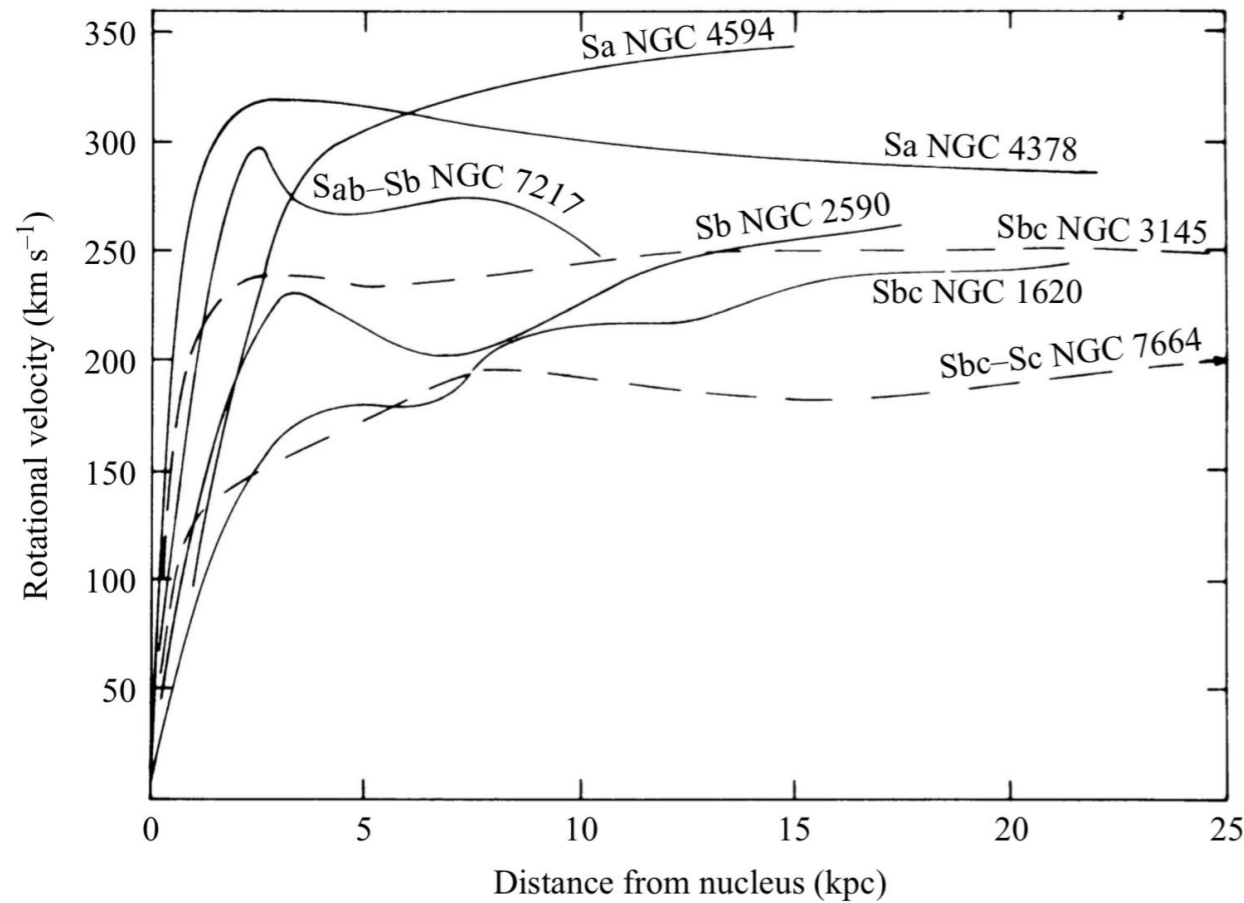
# MeerKAT - Fornax Survey (Serra+23)



**Fig. 9.** MeerKAT H I contours overlaid on a  $g$ -band image from the Fornax Deep Survey for the 6 galaxies with a one-sided H I tail. The galaxy name is given at the top of each image. The H I contour levels are given in the bottom-right legend ( $n = 0, 1, \dots$ ). The bottom-left black ellipse represents the 41'' H I resolution. The scalebar in the top-left corner indicates 10 kpc. The top-right arrow points towards NGC 1399 at the centre of Fornax.

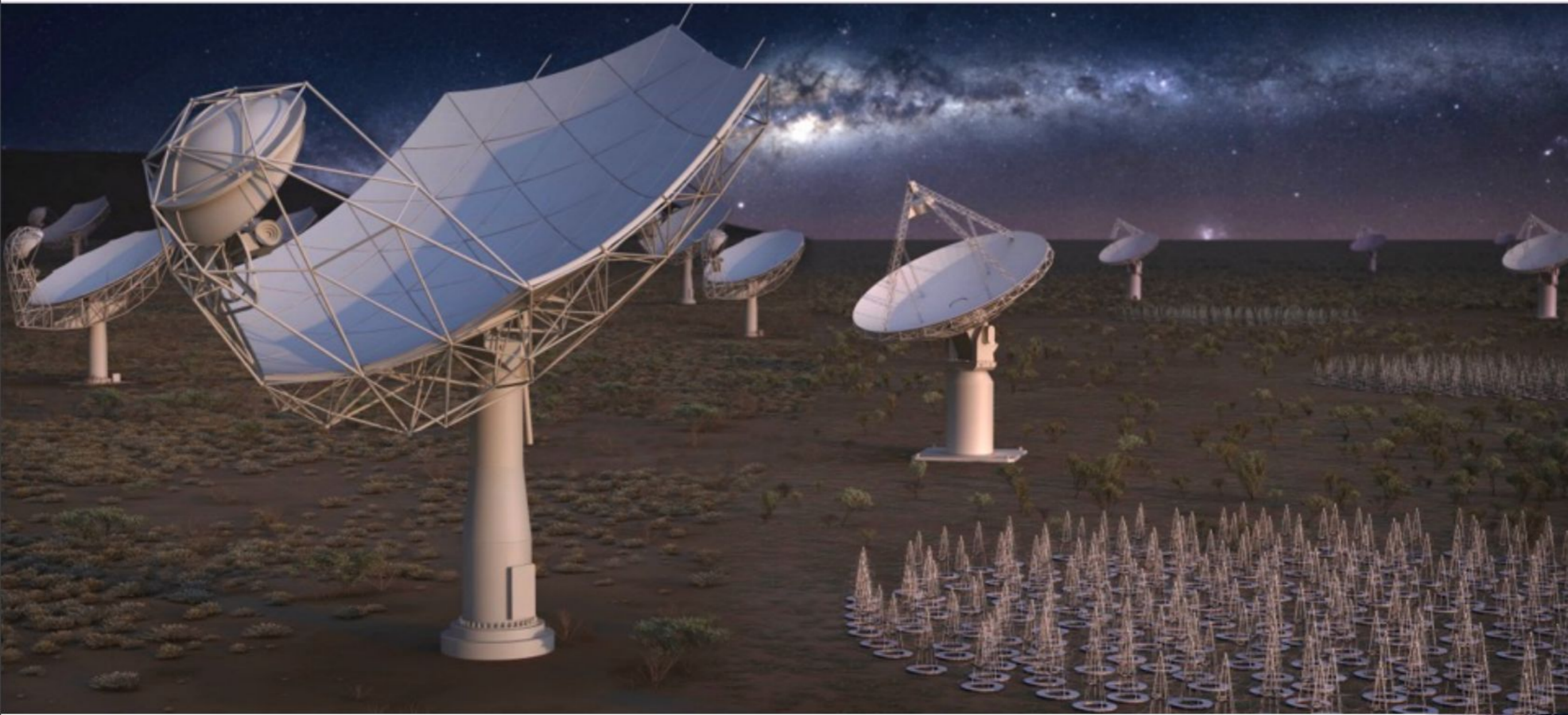
**Fig. 10.** Moment-1 H I velocity field of the 6 galaxies with a one-sided H I tail. The galaxy name is given at the top of each image. Below the galaxy name we indicate the H I systemic velocity, which is represented by the thick, white iso-velocity contour in the figure, as well as the levels of the other contours ( $n = 0, 1, \dots$ ). The coloured frame around the contour levels indicates whether a galaxy is blue- or red-shifted relative the NGC 1399, whose velocity is  $\sim 1425$  km s $^{-1}$ . The bottom-left black ellipse represents the 41'' H I resolution. The small, open black circle represents the galaxy centre. The thin black contour is the first H I contour shown in Fig. 9.

# Rotation Curves



- Vera Rubin observations ('70s)
- Second (after Zwicky in Galaxy Clusters) evidence for DM

# The Square Kilometre Array: Concluding our past, realising our future



# SKA– Key Science Drivers: The history of the Universe

Testing General Relativity  
(Strong Regime, Gravitational Waves)

Cosmic Dawn  
(First Stars and Galaxies)

Cradle of Life  
(Planets, Molecules, SETI)

Galaxy Evolution  
(Normal Galaxies  $z \sim 2-3$ )

Cosmic Magnetism  
(Origin, Evolution)

Cosmology  
(Dark Matter, Large Scale Structure)

Exploration of the Unknown

**Extremely broad range of science!**

# SKA– Key Science Drivers: The history of the Universe

21 cm redshift to  $z=6$  (200 MHz) to  $z=17$  (80 MHz)

Testing General Relativity  
(Strong Regime, Gravitational Waves)

Cosmic Dawn  
(First Stars and Galaxies)

Cradle of Life  
(Planets, Molecules, SETI)

Galaxy Evolution  
(Normal Galaxies  $z\sim 2-3$ )

Cosmic Magnetism  
(Origin, Evolution)

Cosmology  
(Dark Matter, Large Scale Structure)

Exploration of the Unknown

Extremely broad range of science!

# Hot ionized medium

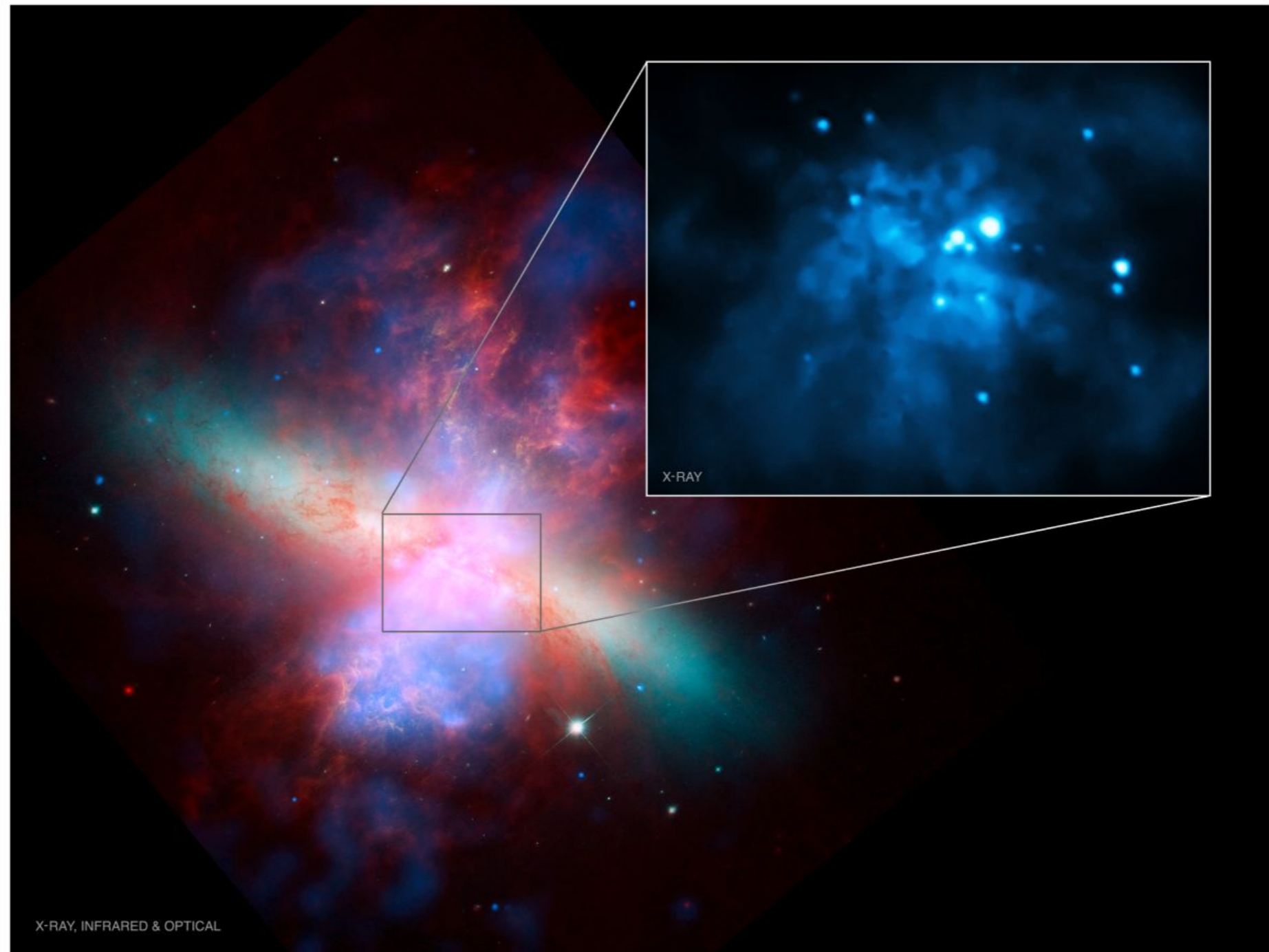
density:  $\sim 10^{-3} \text{ cm}^{-3}$

temperature:  $\sim 10^6 \text{ K}$

thermal velocities:  
100 km/s

complex kinematics

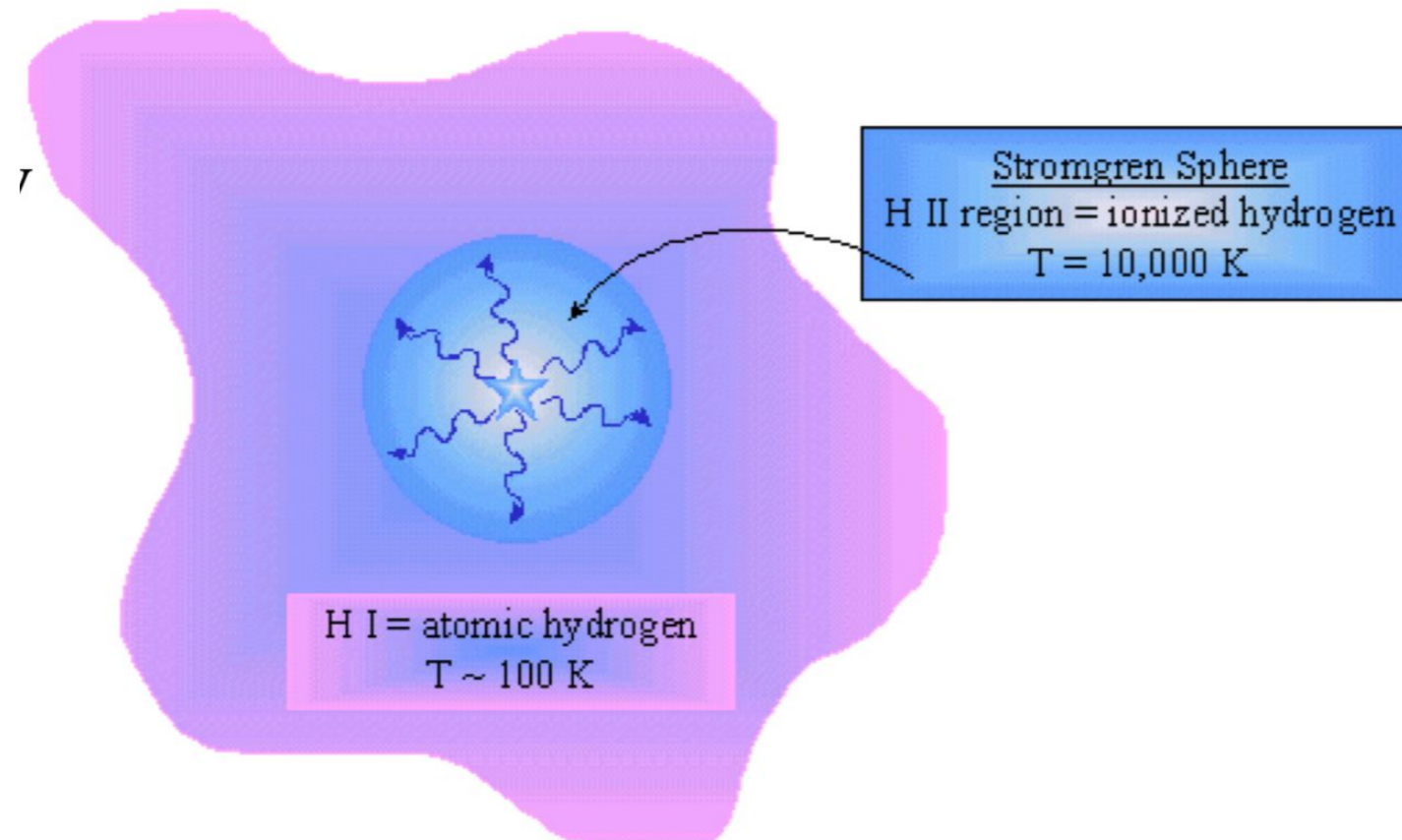
gas tracer: X-rays,  
high-ionization  
absorption lines:  
OVI, CIV, NV etc.





# HII Regions

- When hot, massive stars reach the zero age main sequence (ZAMS) with O or B spectral types, they do so shrouded in a cloak of gas and dust. The bulk of their radiation is emitted in the ultraviolet portion of the electromagnetic spectrum. Those photons that are produced with energies in excess of 13.6 eV can ionize the ground-state hydrogen gas (H I) in the ISM that still surrounds the newly formed star.



# Stromgren sphere

**H II regions** are in equilibrium, the rate of ionization must equal the rate of recombination; photons must be absorbed and ions must be produced at the same rate

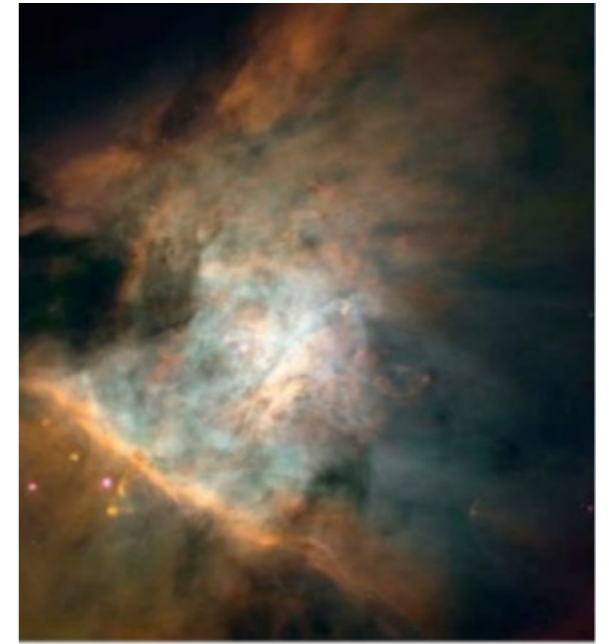
Let  $N$  be the number of photons *per second* produced by the O or B star with sufficient energy to ionize hydrogen from the ground state

$\alpha n_e n_H$  number of recombinations *per unit volume per second*,

If we assume that the gas is composed entirely of hydrogen and is electrically neutral, then for every ion produced, one electron must have been liberated, or  $n_e = n_H$  .

the expression for the recombination rate can be multiplied by the volume of the H II region,

$$r_S \simeq \left( \frac{3N}{4\pi\alpha} \right)^{1/3} n_H^{-2/3}$$



# Stromgren sphere

**Example 3.1.** The effective temperature and luminosity of an O6 star are  $T_e \simeq 45,000$  K and  $L \simeq 1.3 \times 10^5 L_\odot$ , respectively. According to Wien's law, the peak wavelength of the blackbody spectrum is given by

$$\lambda_{\max} = \frac{0.0029 \text{ m K}}{T_e} = 64 \text{ nm.}$$

Since this is significantly shorter than the 91.2-nm limit necessary to produce ionization from the hydrogen ground state, it can be assumed that most of the photons created by an O6 star are capable of causing ionization.

The energy of one 64-nm photon can be calculated giving

$$E_\gamma = \frac{hc}{\lambda} = 19 \text{ eV.}$$

Now, assuming for simplicity that all of the emitted photons have the same (peak) wavelength, the total number of photons produced by the star per second is just

$$N \simeq L/E_\gamma \simeq 1.6 \times 10^{49} \text{ photons s}^{-1}.$$

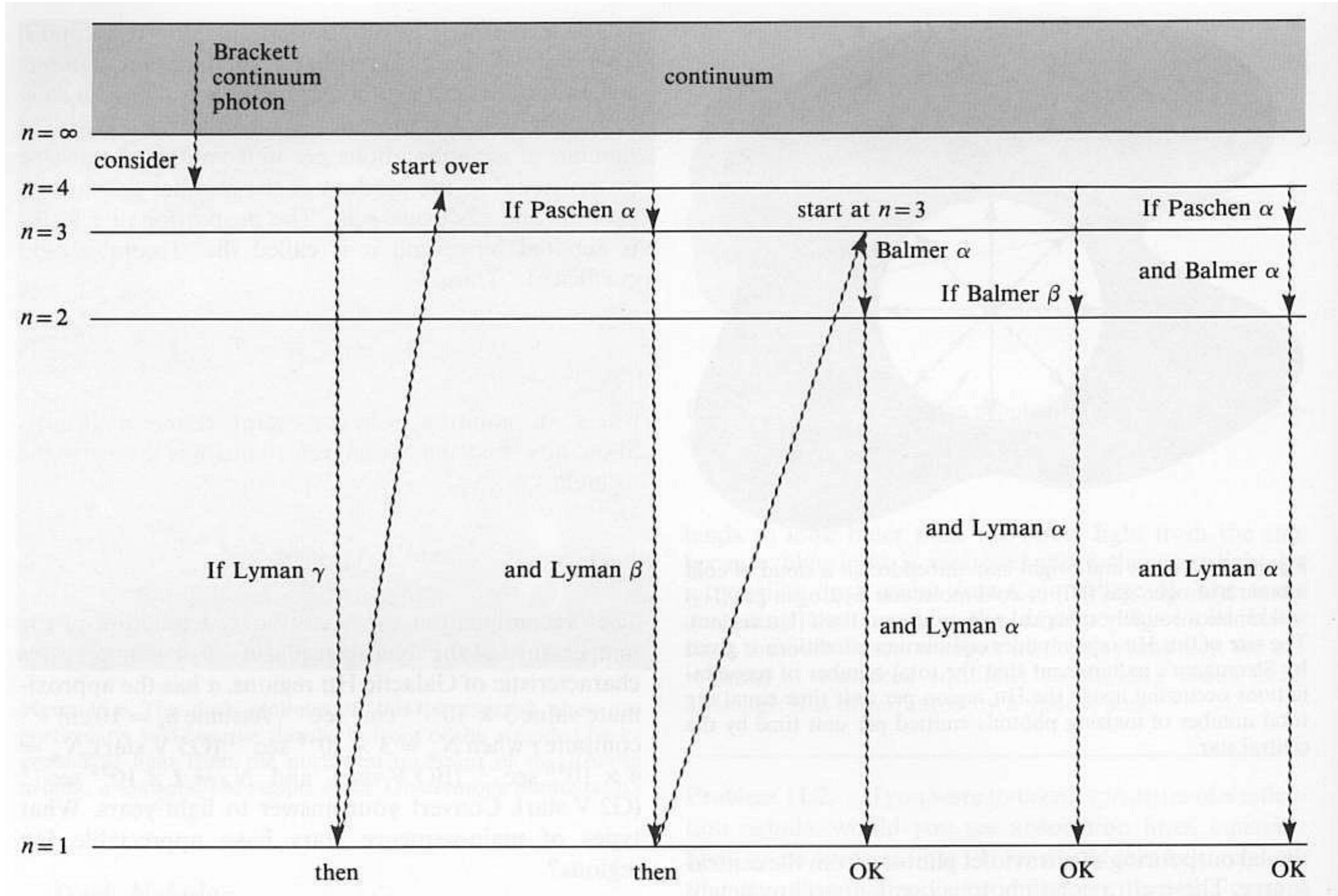
Lastly, taking  $n_H \sim 10^8 \text{ m}^{-3}$  to be a typical value in an H II region, we find

$$r_S \simeq 3.5 \text{ pc.}$$

Values of  $r_S$  range from less than 0.1 pc to greater than 100 pc.



# Resonant scattering of Lyman alpha: Fluorescence



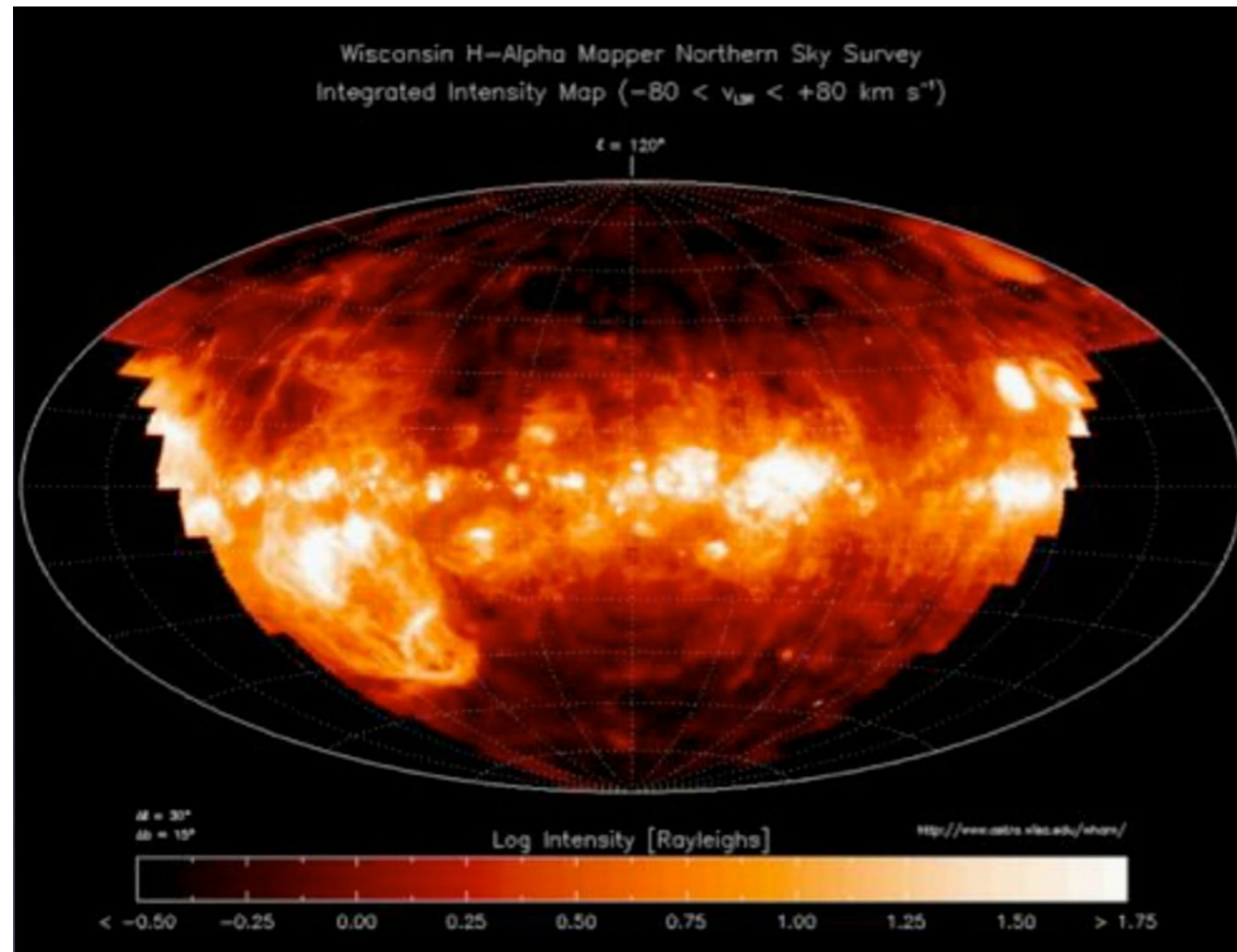
# HII Regions

- H II regions surrounding early - type ( $<B2$ ,  $T_{\text{eff}} > 25,000$  K) stars, emitting lots of photons beyond Lyman limit (13.6 eV) ionized gas, bright visible nebulous objects
- Associated with massive star - forming regions optical spectra dominated by H and He recombination lines (**fluorescence**)
- Collisionally excited, (forbidden) optical lines from ions like [O II], [O III], and [N II]
- Volume contained is called Strömgren sphere
- Balmer lines emit prominently in optical
- Dust absorbs blue light stronger than red
- Ratio of  $H_{\beta}$  to  $H_{\alpha}$  tells us about dust properties (absorption)
- Strong sources of thermal radio emission (free - free) + infrared emission from warm dust

H- $\alpha$	H- $\beta$
6563	4861

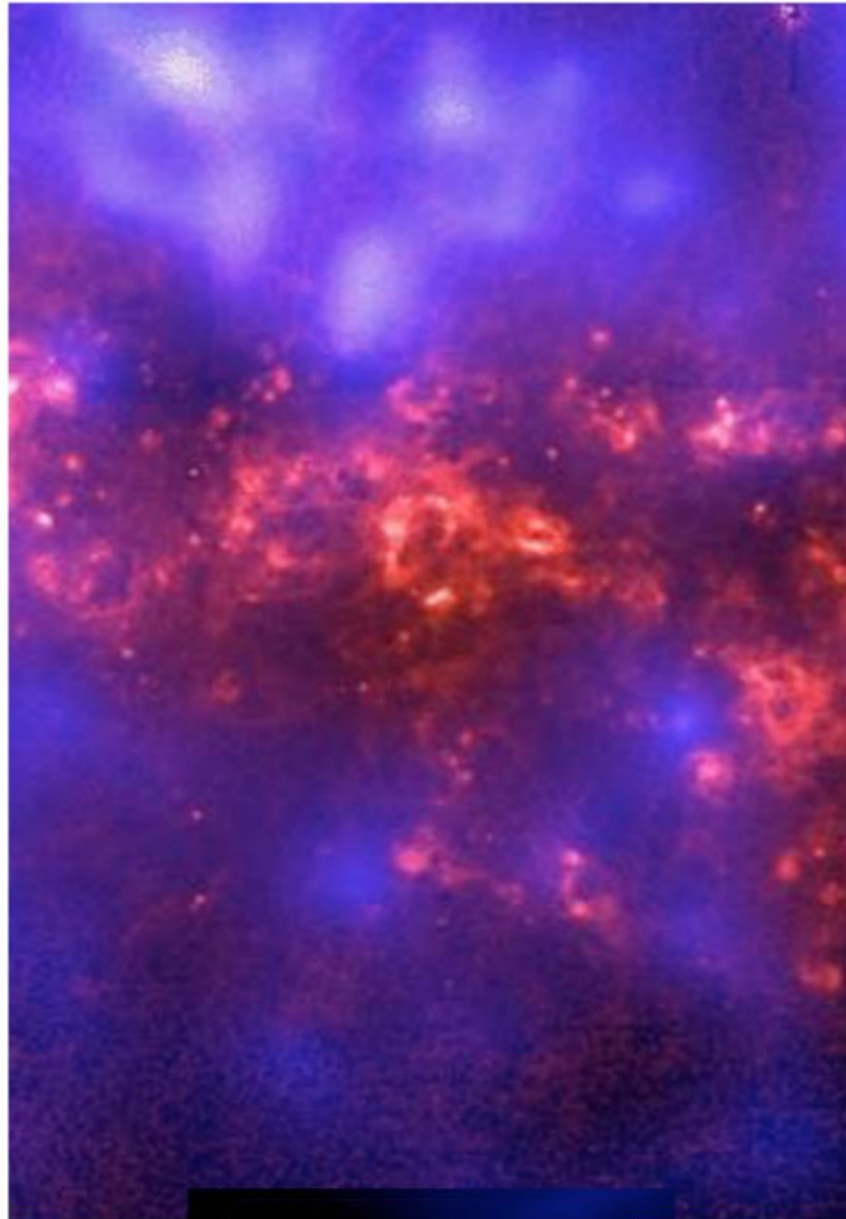
# Diffuse ionized gas (DIG)

Also called warm ionized medium (WIM) – Not to be confused with Warm Hot Intergalactic Medium (WHIM)



- H $\alpha$  emission dominated by H II regions, but most ionized gas resides in a huge, diffuse reservoir ( $10^9 M_\odot$ )
- Diffuse Ionized Medium,  $0.2 \text{ cm}^{-3}$ , 8000 K
- Ionized by photons escaped from HII regions
- Produces a faint emission-line spectrum that is seen in every direction of the Galaxy
- Constitutes 90% of the ionized hydrogen mass in the Galaxy

# Diffuse ionized gas

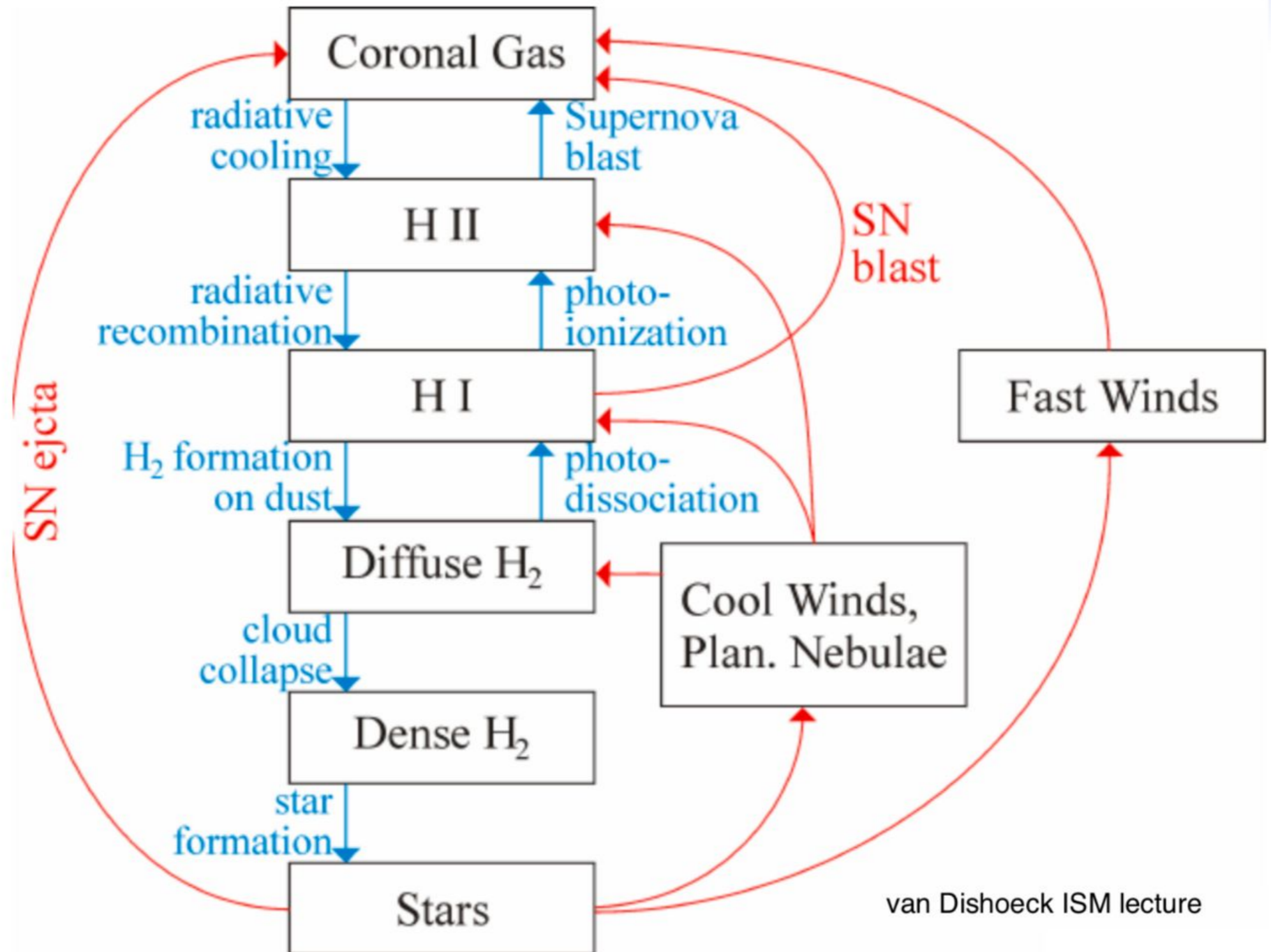


NGC 4631  
HST/WFPC2 H $\alpha$   
Chandra 0.3-0.9KeV

- In other galaxies, the DIG is observed to be in the form of discrete structures, such as loops, filaments, and shells.  
  
(which are not obviously associated with discrete HII regions)
- Responsible for producing a faint but pervasive H  $\alpha$  emission.
- The observed H  $\alpha$  luminosities of the DIG are considerable and account for 30%-50% of the total H  $\alpha$  emission of each galaxy.

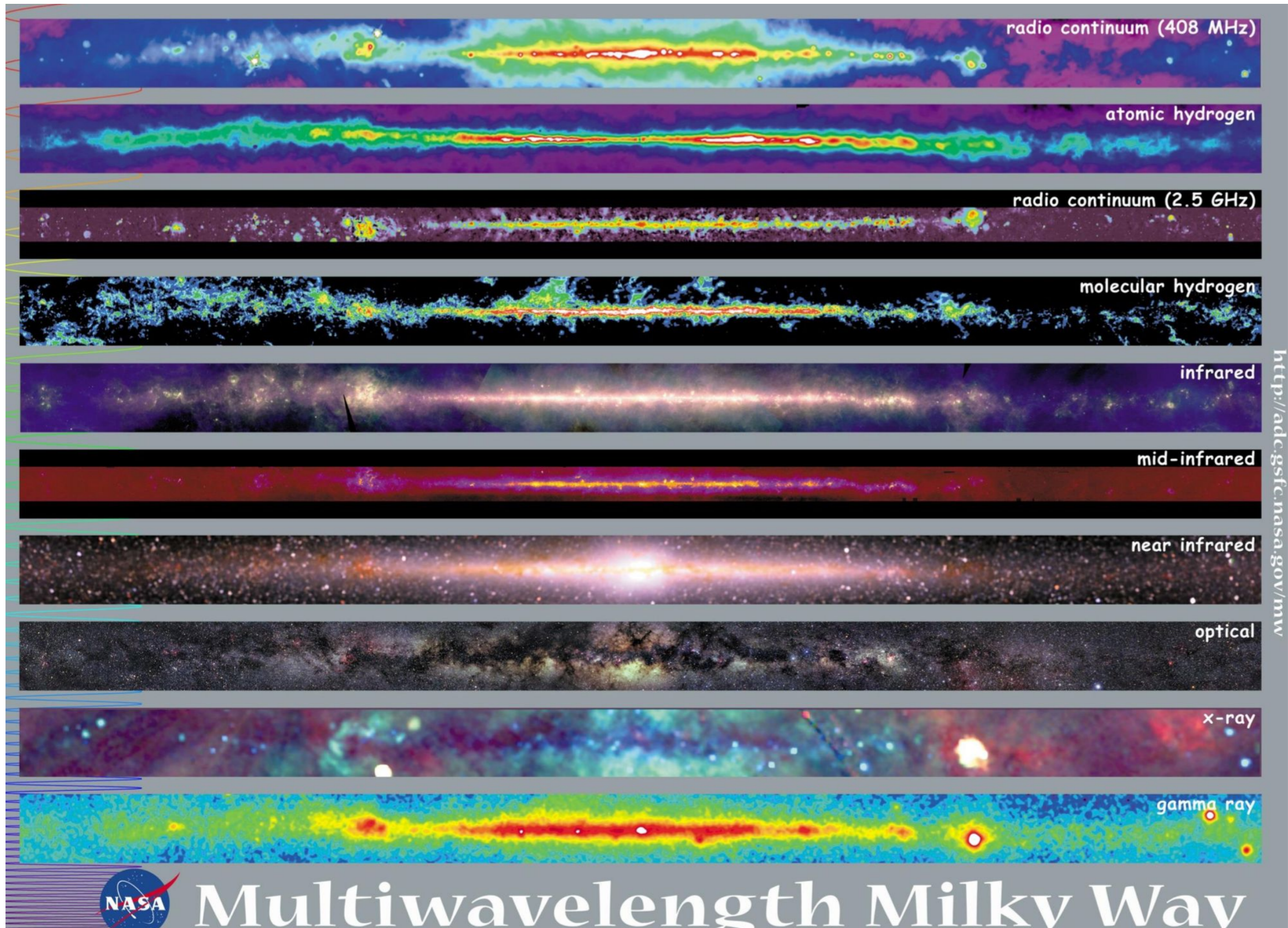
(Ferguson et al. 1996)

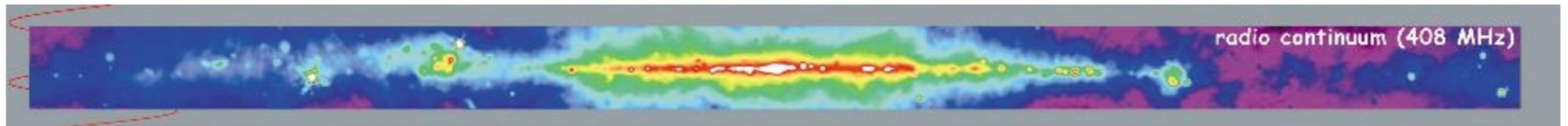
# The ISM in general





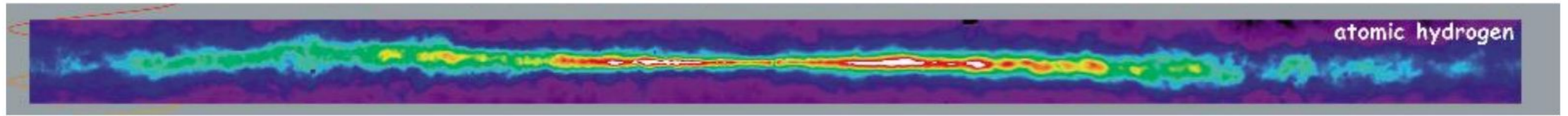
# How do we observe the ISM?



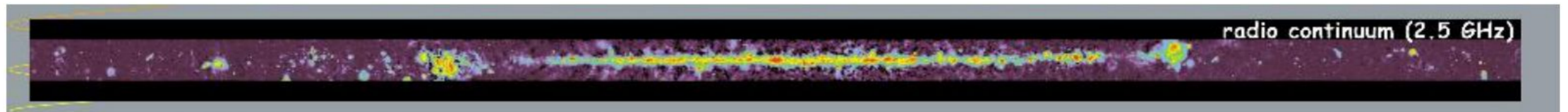


## Synchrotron radiation

Generated by relativistic electrons accelerated by SN shocks and pulsars, traveling in the  $\sim \mu G$  magnetic field of the galaxy.



21 cm radiation from neutral (atomic) hydrogen



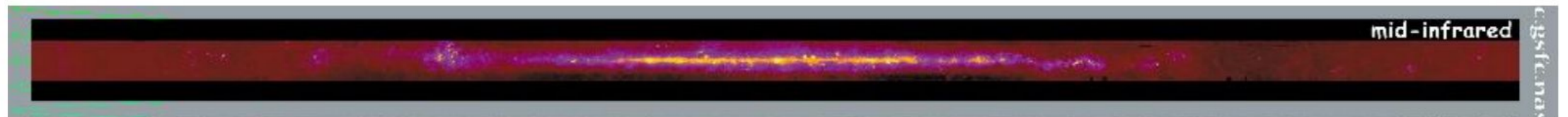
Synchrotron radiation from electrons,  
bremsstrahlung radiation from supernova remnants  
and from hot gas in general

## Far IR



Thermal emission from dust,  
heated by old stars (diffuse dust or cirrus)  
or by young massive stars in molecular clouds

Line emission from polycyclic aromatic hydrocarbons (PAH)  
in the diffuse dust component



Emission from old stars (main sequence and giants)  
with little dust absorption



# Emission from stars, with dust absorption





X-ray binaries and some emission from hot gas,  
some absorption from diffuse hydrogen



Compact sources, gamma-ray photons from collisions  
of cosmic rays with diffuse gas

