The interstellar medium

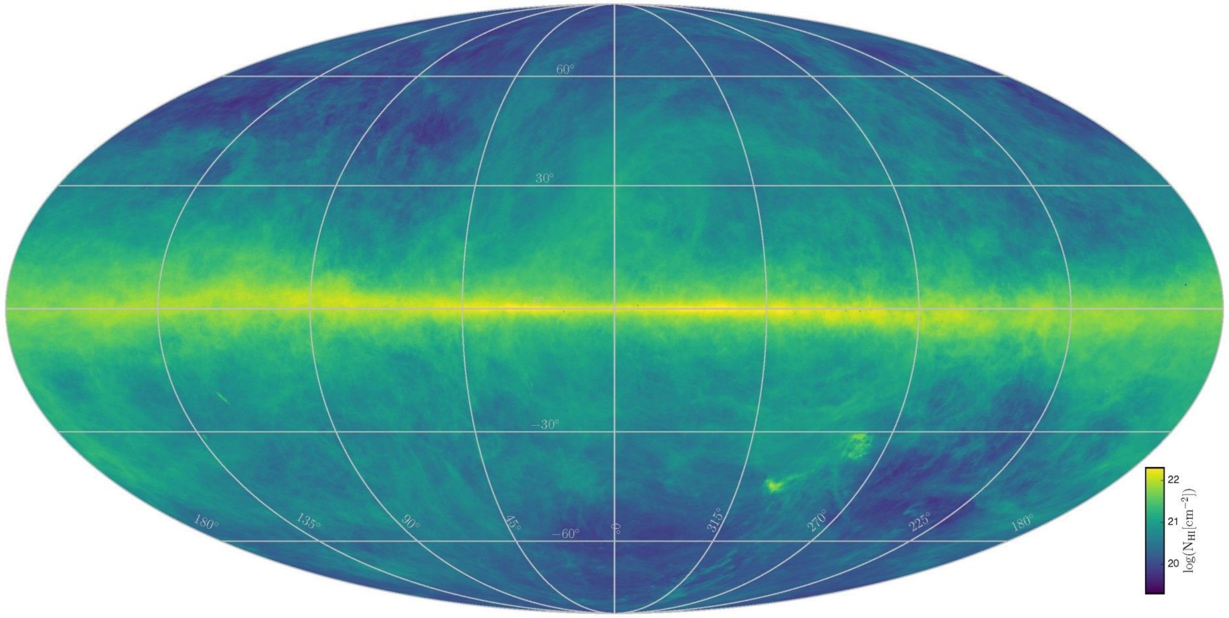
Courtesy of Monaco. See also http://adlibitum.oats.inaf.it/monaco/Lectures/ISM.pdf

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 $h\nu > 13.6$ 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

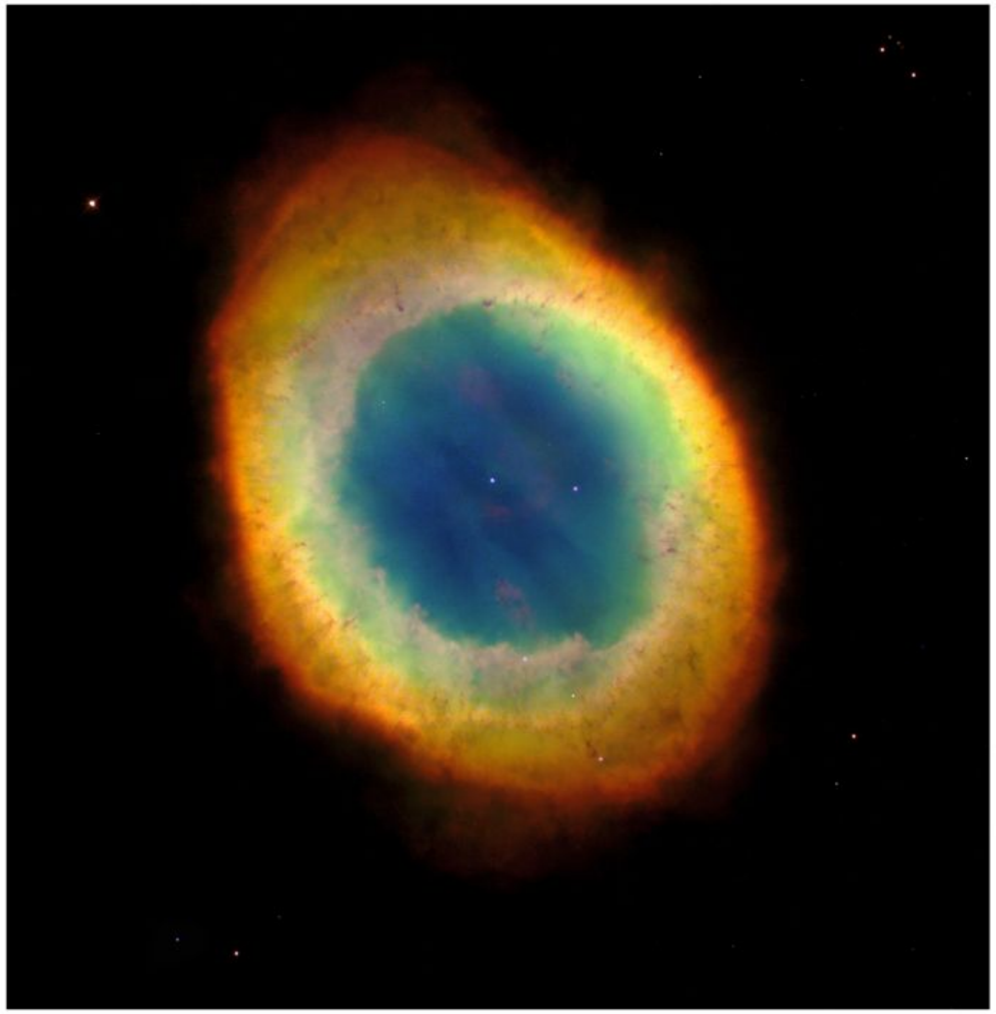
- The main observational diagnostics of HII regions in the optical band is the Hα emission line ← 656.28 nm

  transition from n=3 to n=2 of the Balmer series

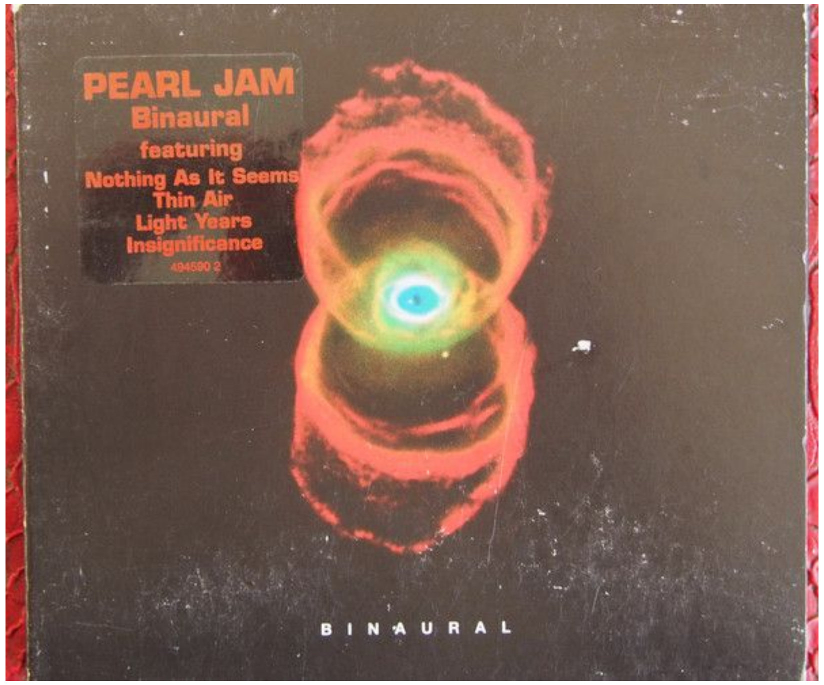
Orion Nebula
Hubble mosaic

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

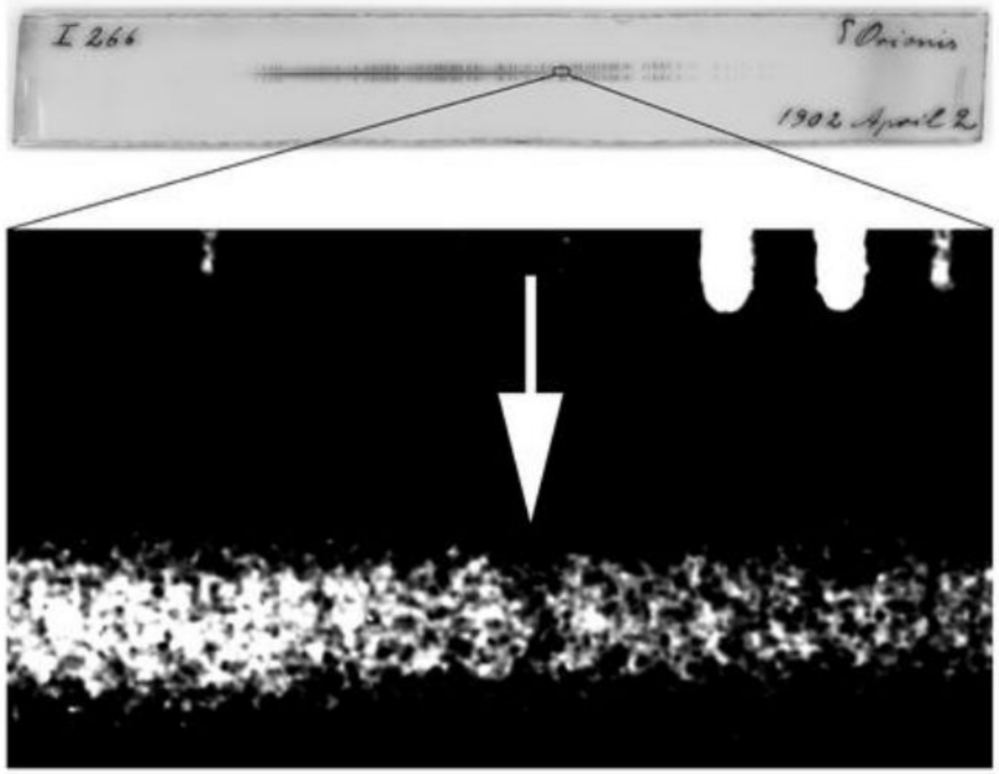
- 1795 → Sir William Herschell
- Stellar distribution was patch in the sky
- Existence of dark regions in the sky particularly devoid of stars:
  - “holes in heavens”

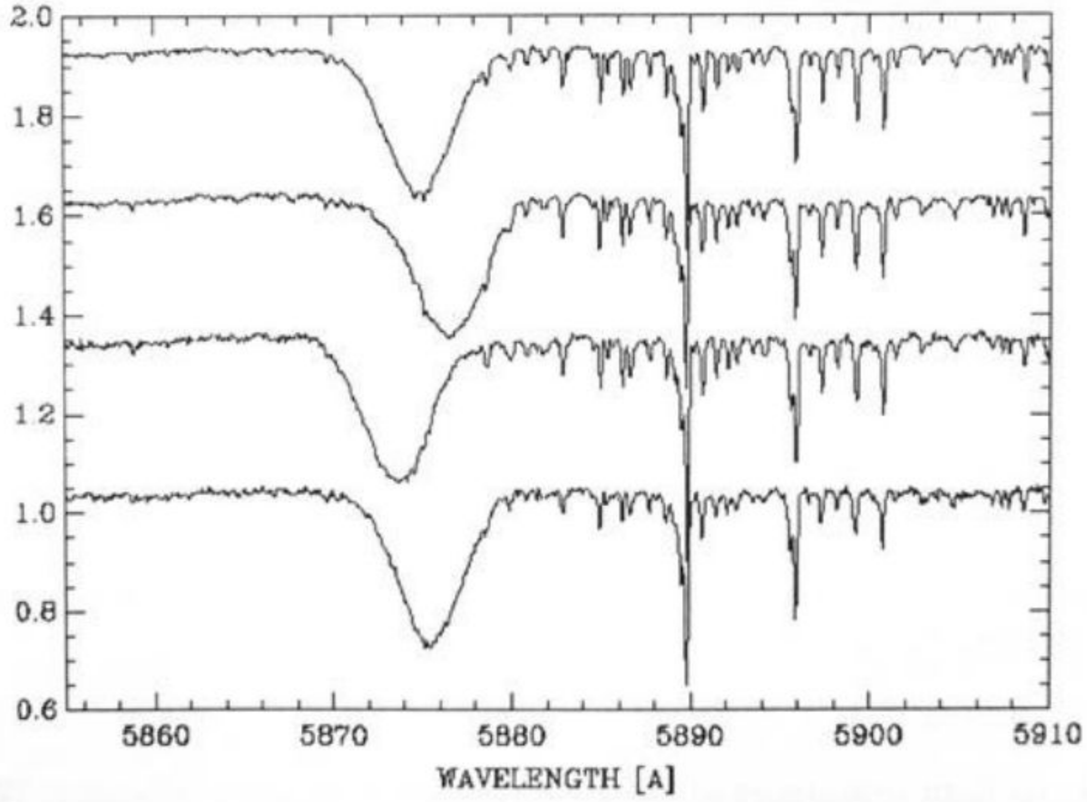
Dark cloud B68

Discovery of the diffuse interstellar medium

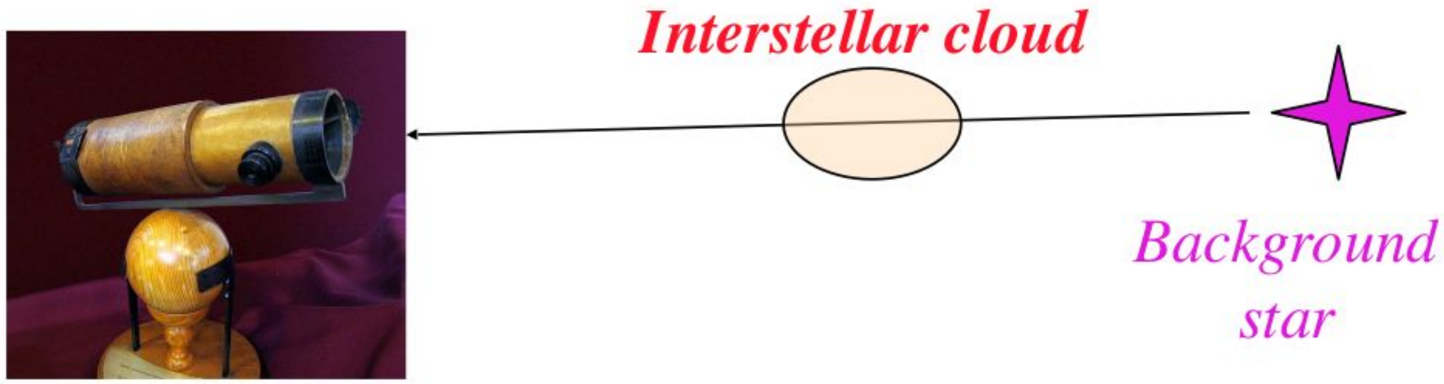
- Hartmann, 1904
  - “Stationary” CaII absorption lines in the spectrum of the spectroscopic binary δ Ori
    Circumstellar or interstellar origin?
- Plaskett & Pearce, 1933
  - The CaII absorption becomes stronger with increasing distance of the background star
    Proven the interstellar origin

  Example:
    Stationary NaI lines in the spectrum of δ Ori

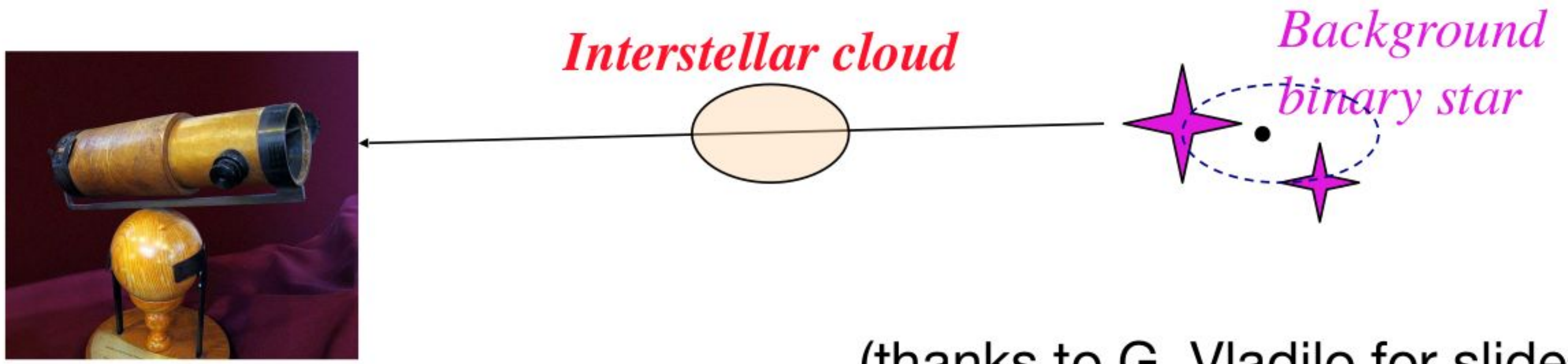




Discovery of the diffuse interstellar medium



- 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

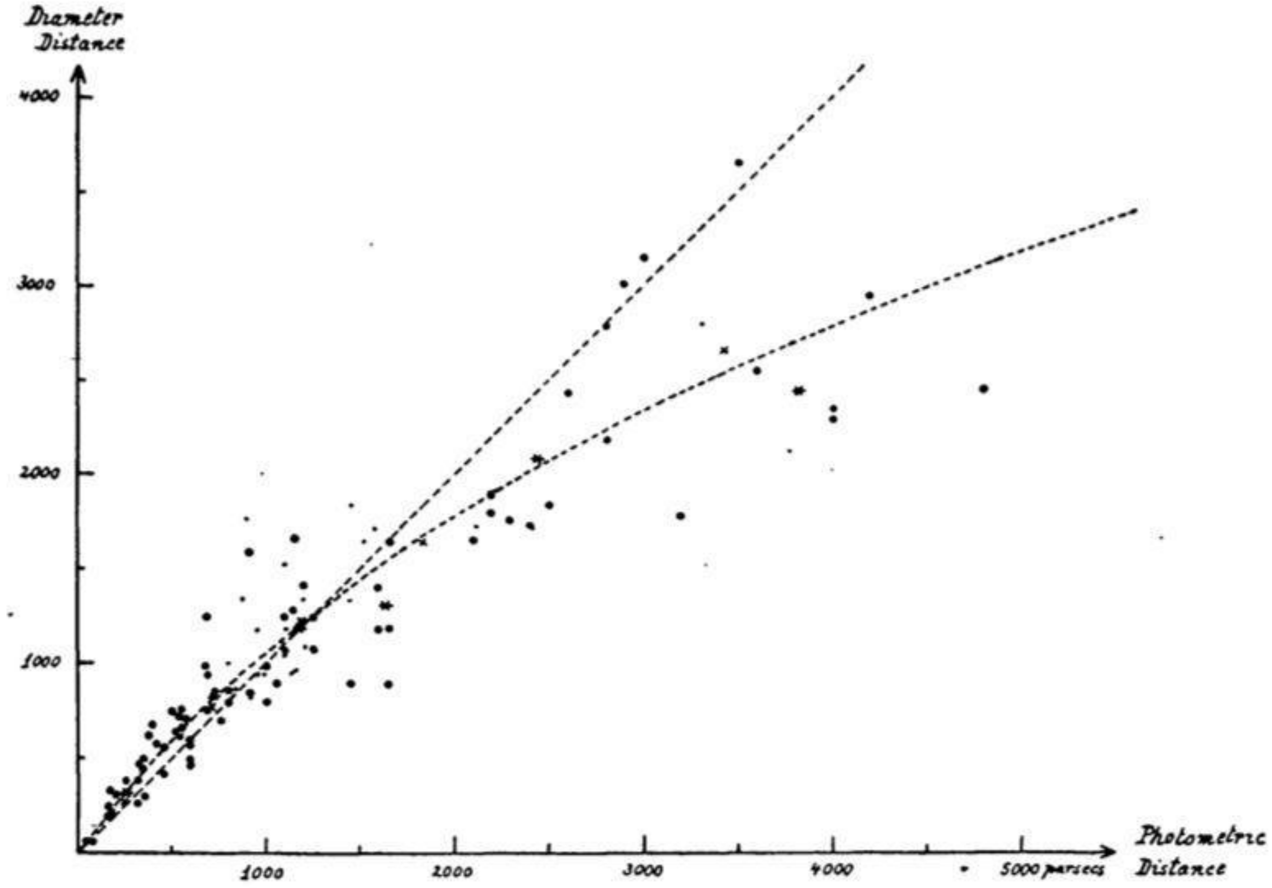


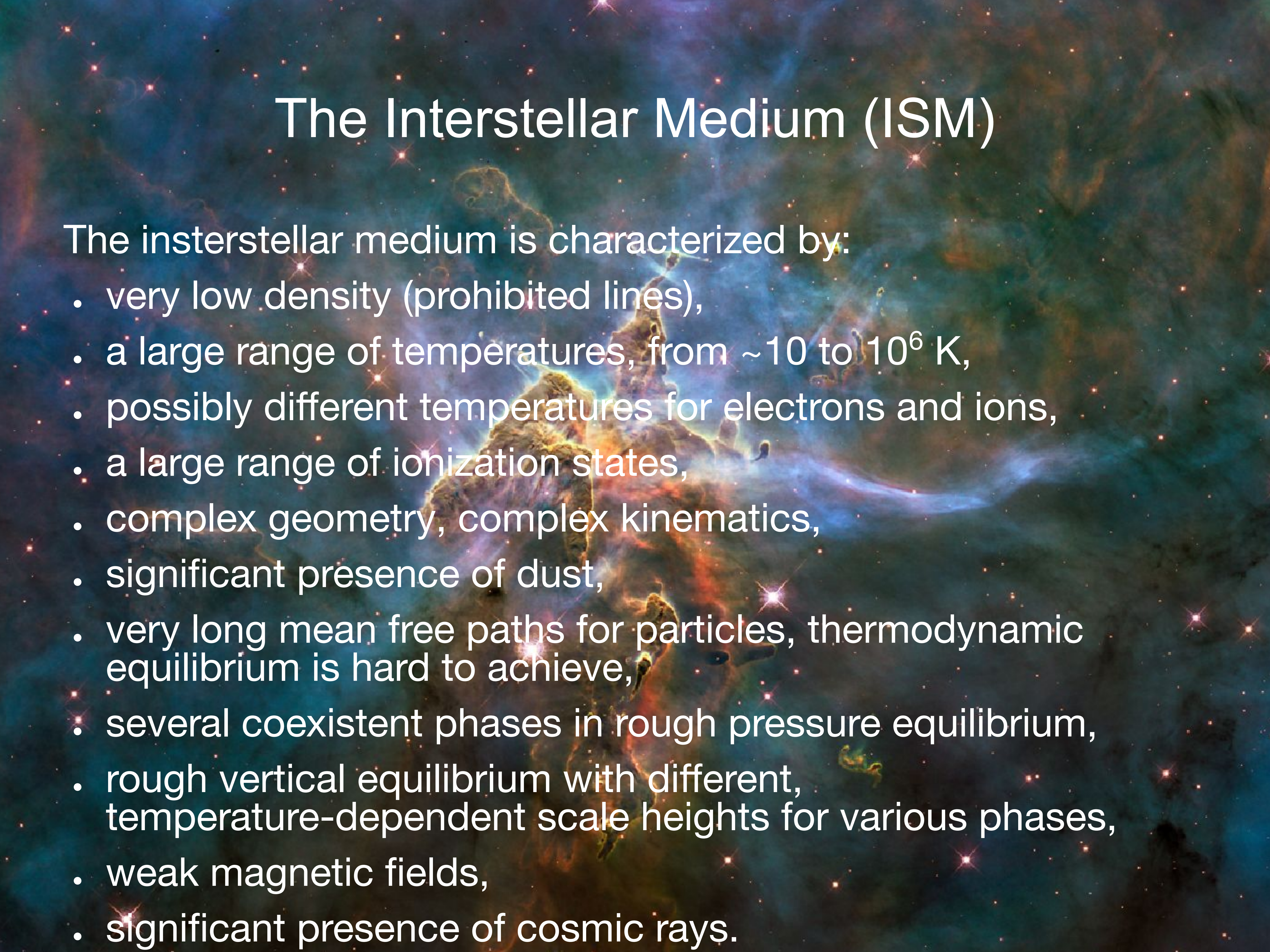
Fig. 1.—Comparison of the distances of 100 open star clusters determined from apparent magnitudes and spectral types (abscissae) with those determined from angular diameters (ordinates). The large dots refer to clusters with well-determined photometric distances, the small dots to clusters with less certain data (half weight). The asterisks and crosses represent group means. If no general space absorption were present, the clusters should fall along the dotted straight line; the dotted curve gives the relation between the two distance measures for a general absorption of $0^{m}.7$ per 1000 parsecs.

Dust

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

Dark cloud B68

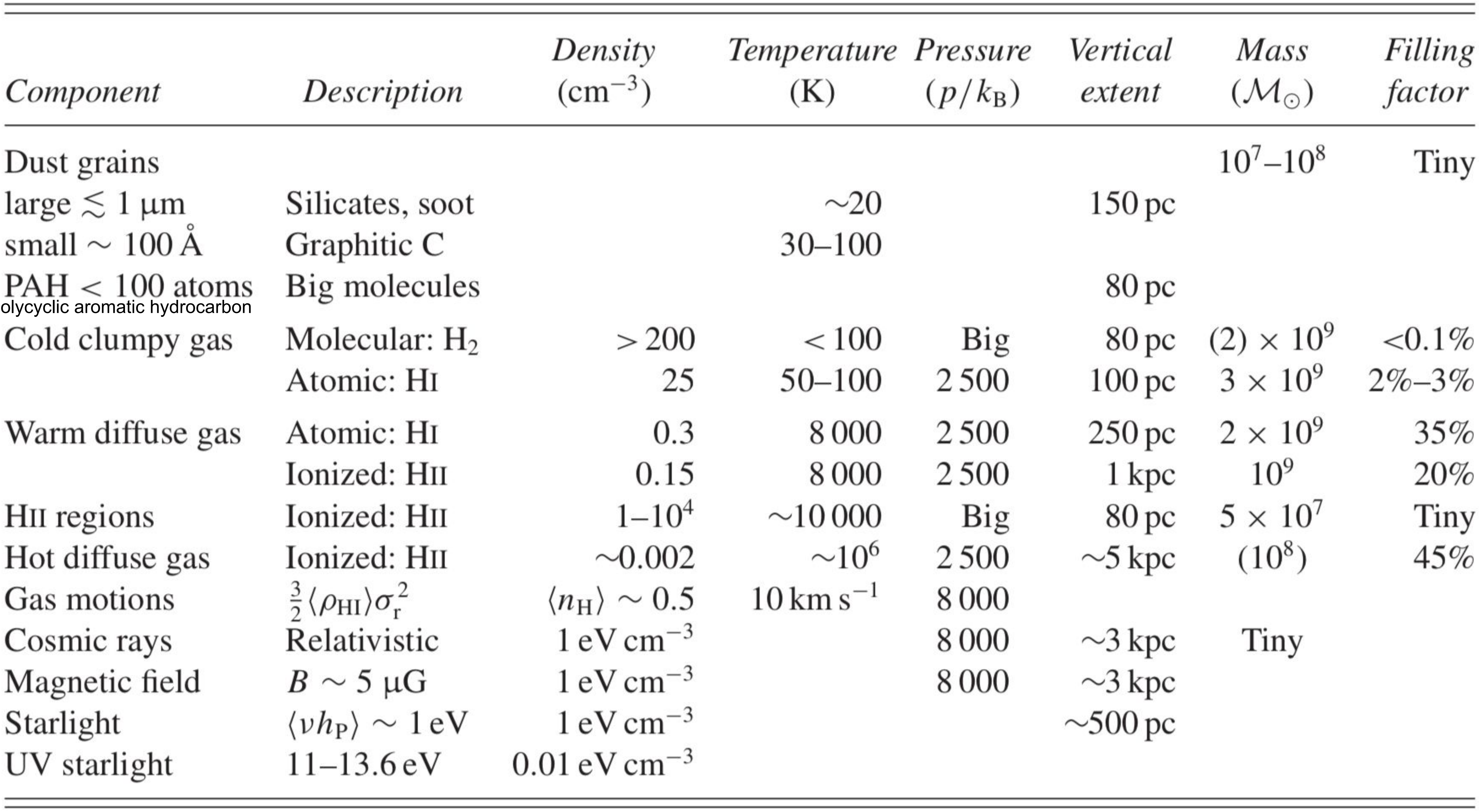
The Interstellar Medium (ISM)



The insterstellar medium is characterized by:

- very low density (prohibited lines),
- a large range of temperatures, from ~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



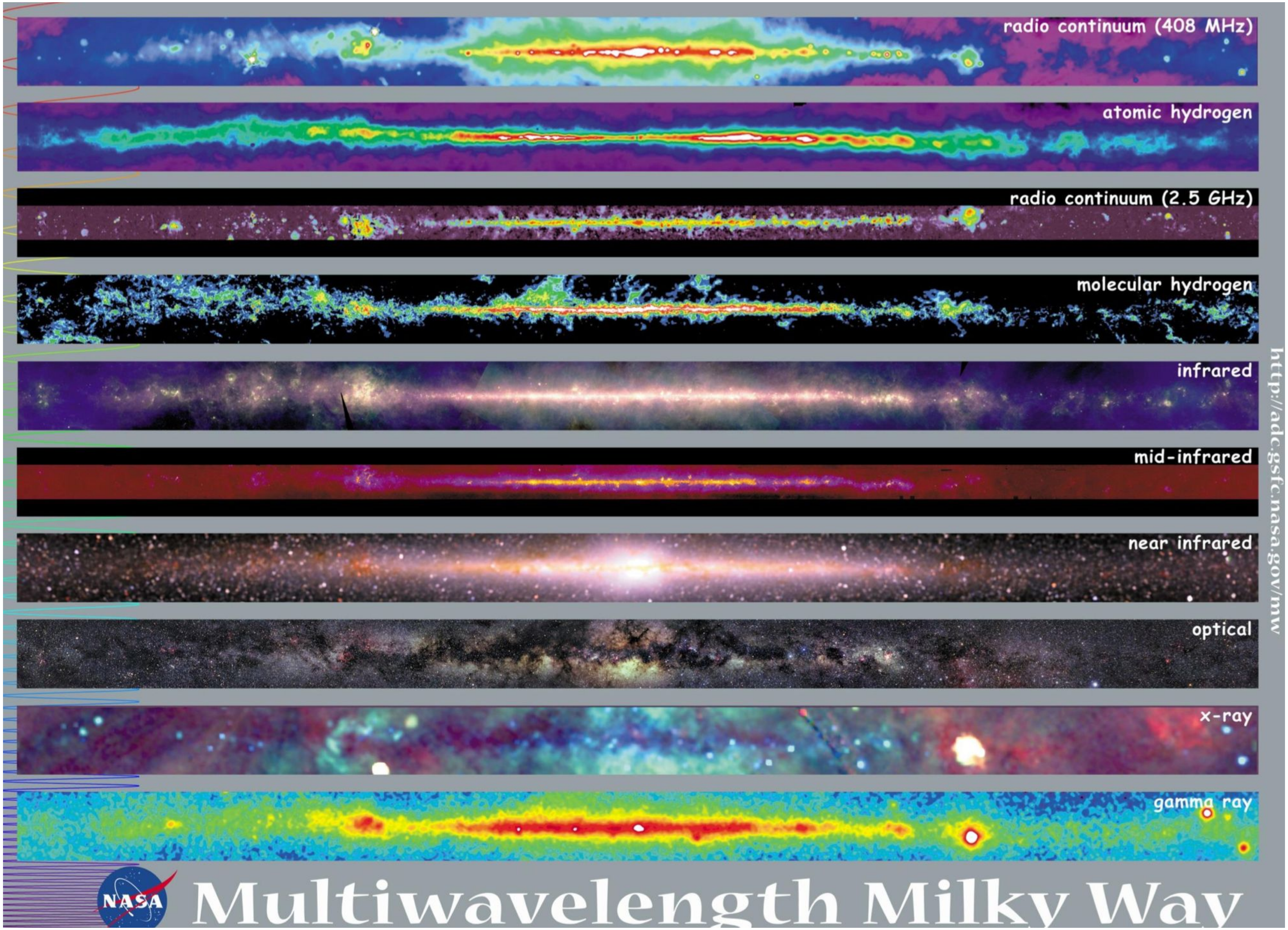
Component	Description	Density (cm^{-3})	Temperature (K)	Pressure (p/k_B)	Vertical extent	Mass ($\mathcal{M}_\odot$)	Filling factor
Dust grains						10^7–10^8	Tiny
large $\lesssim 1\ \mu\mathrm{m}$	Silicates, soot		~ 20		150 pc		
small ~ 100 Å	Graphitic C		30–100				
PAH < 100 atoms	Big molecules				80 pc		
Cold clumpy gas	Molecular: H_2	> 200	< 100	Big	80 pc	$(2) \times 10^9$	<0.1%
	Atomic: HI	25	50–100	2 500	100 pc	3×10^9	2%–3%
Warm diffuse gas	Atomic: HI	0.3	8 000	2 500	250 pc	2×10^9	35%
	Ionized: HII	0.15	8 000	2 500	1 kpc	10^9	20%
HII regions	Ionized: HII	1–10^4	$\sim 10\,000$	Big	80 pc	5×10^7	Tiny
Hot diffuse gas	Ionized: HII	~ 0.002	$\sim 10^6$	2 500	~ 5 kpc	(10^8)	45%
Gas motions	$\frac{3}{2}\langle\rho_{\mathrm{HI}}\rangle\sigma_r^2$	$\langle n_{\mathrm{H}}\rangle \sim 0.5$	$10\ \mathrm{km\,s^{-1}}$	8 000			
Cosmic rays	Relativistic	$1\ \mathrm{eV\,cm^{-3}}$		8 000	~ 3 kpc	Tiny	
Magnetic field	$B \sim 5\ \mu\mathrm{G}$	$1\ \mathrm{eV\,cm^{-3}}$		8 000	~ 3 kpc		
Starlight	$\langle \nu h_{\mathrm{P}}\rangle \sim 1$ eV	$1\ \mathrm{eV\,cm^{-3}}$			~ 500 pc		
UV starlight	11–13.6 eV	$0.01\ \mathrm{eV\,cm^{-3}}$					

Polycyclic aromatic hydrocarbon

The ISM: basic concepts

- Subject to gravity collapses and formes new stars
- Also gas pressure, magnetic forces,cosmic rays (complex!)
- Mass of gas not related to T→ 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 reddeninig!!

The effect of dust

reddening:

Color excess

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

extinction in the V band:

relative visibility

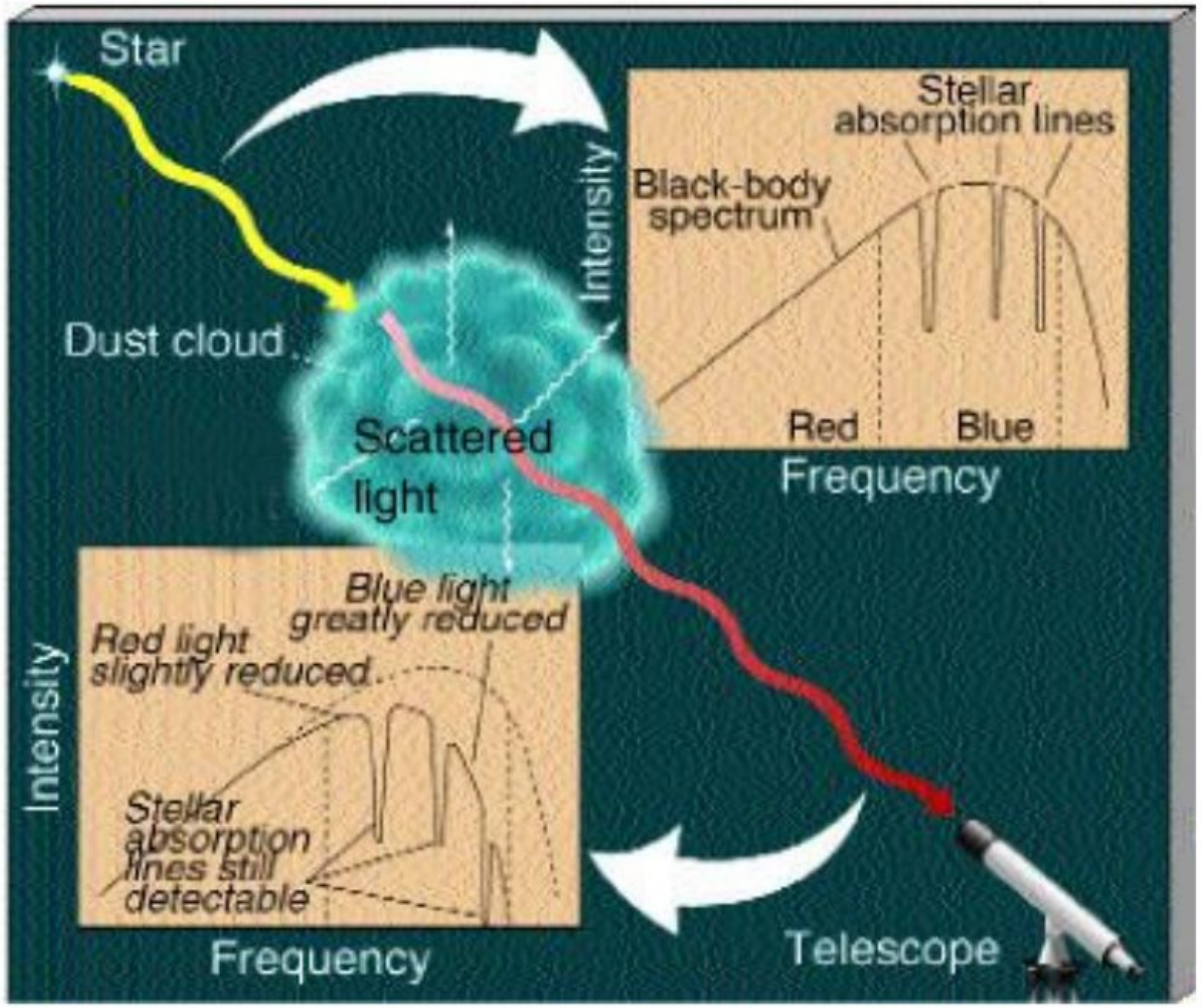
$$A_V = R_V\, E(B-V)$$

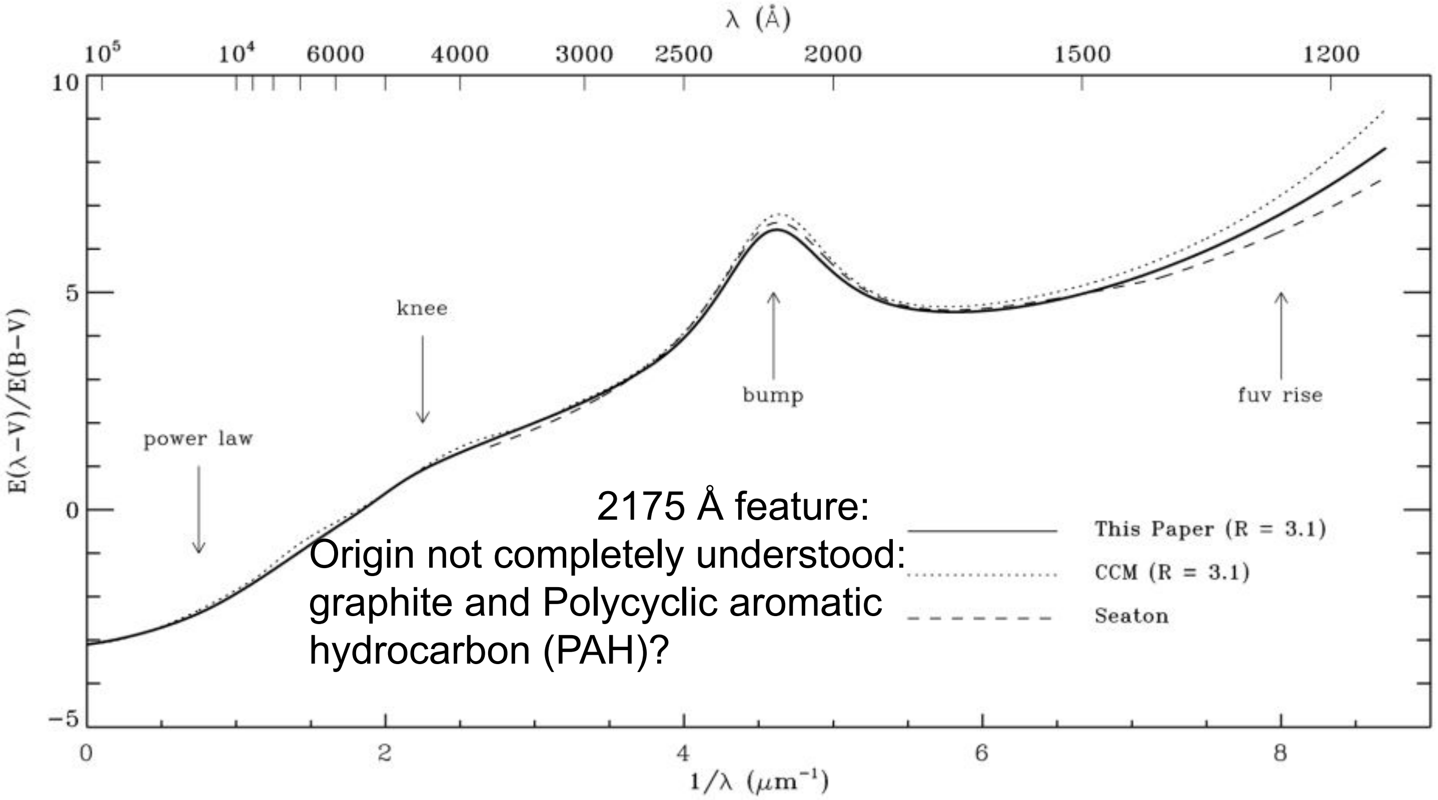
extinction at wavelength λ :

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

$$A_\lambda \equiv 2.5 \log_{10}(F_\lambda^0 / F_\lambda)$$

"intrinsic" flux **observed flux**

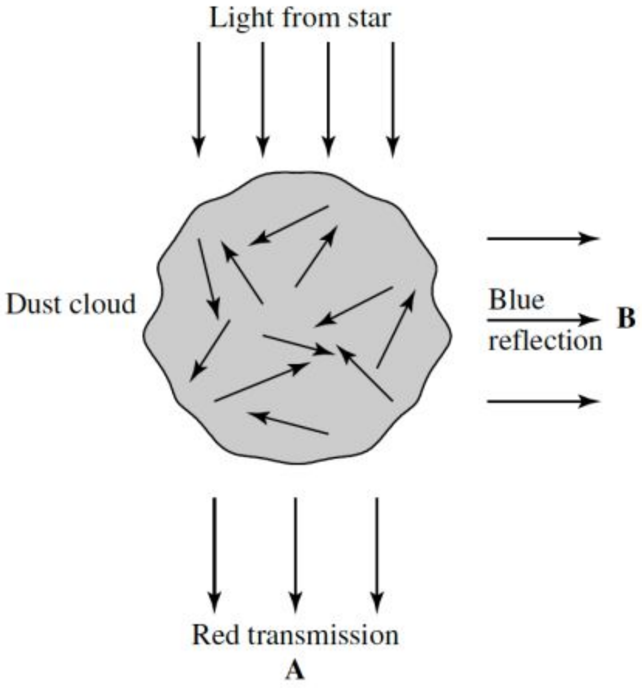


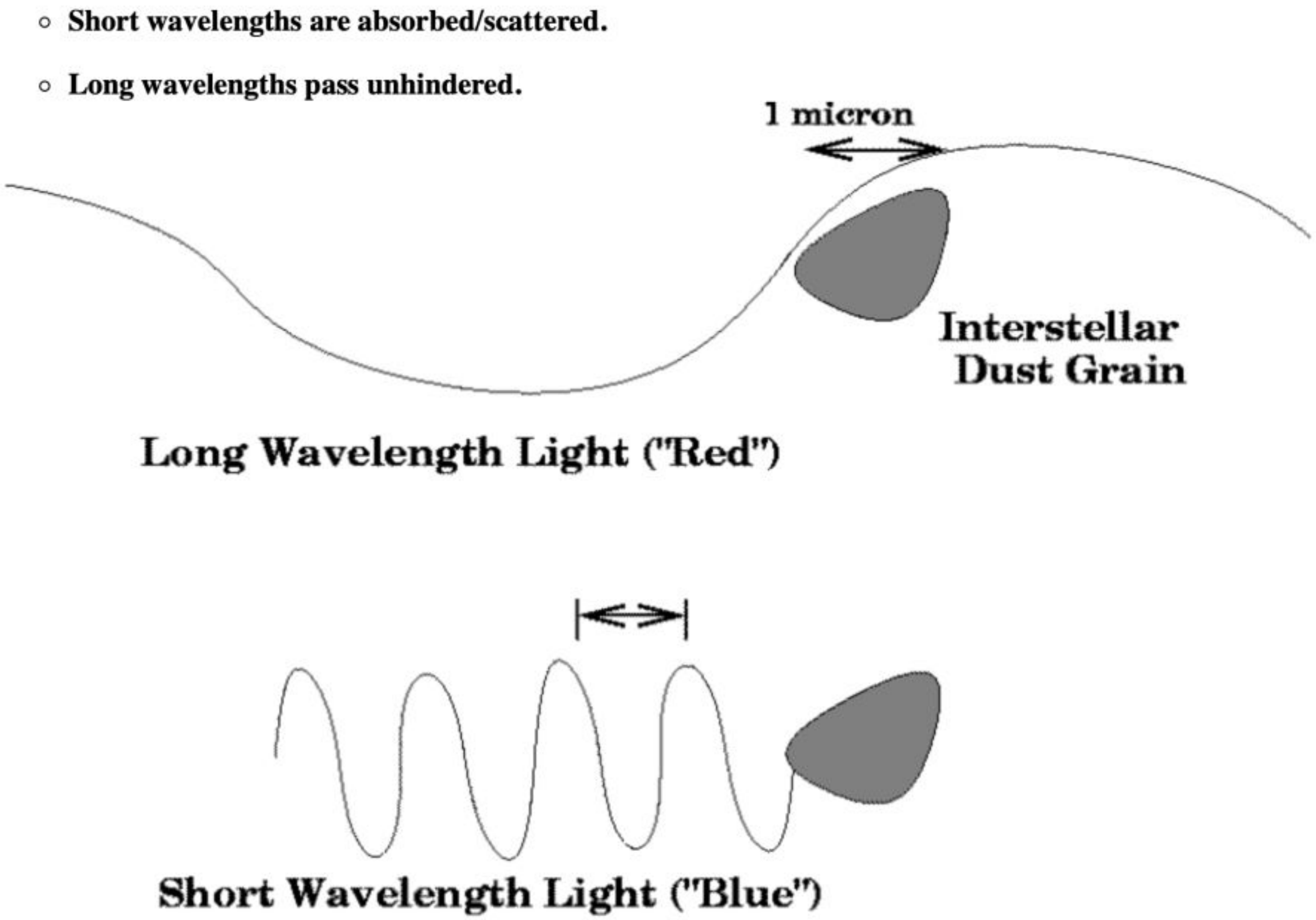


2175 Å feature:
Origin not completely understood:
graphite and Polycyclic aromatic hydrocarbon (PAH)?

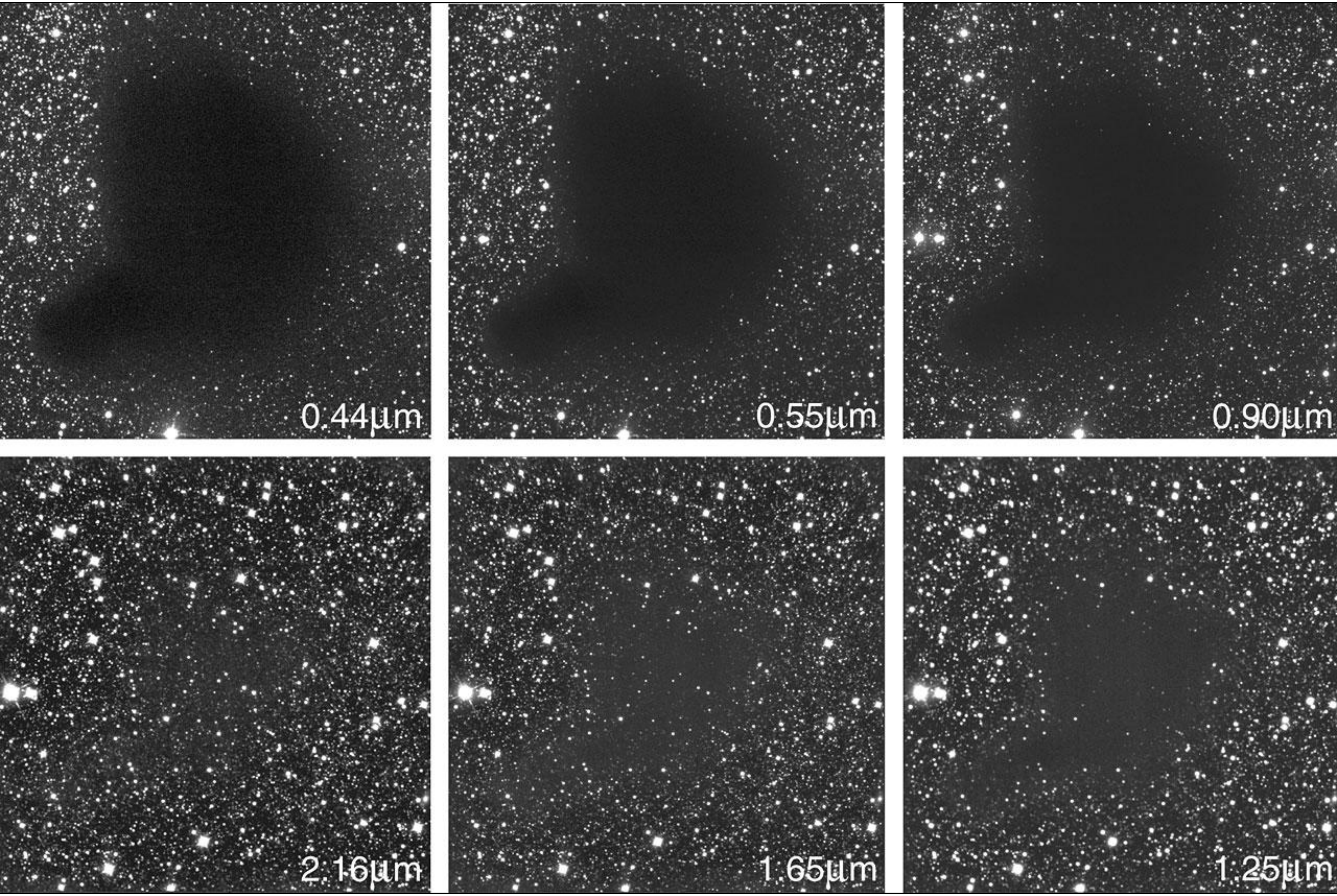
Absorption of starlight

- 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.

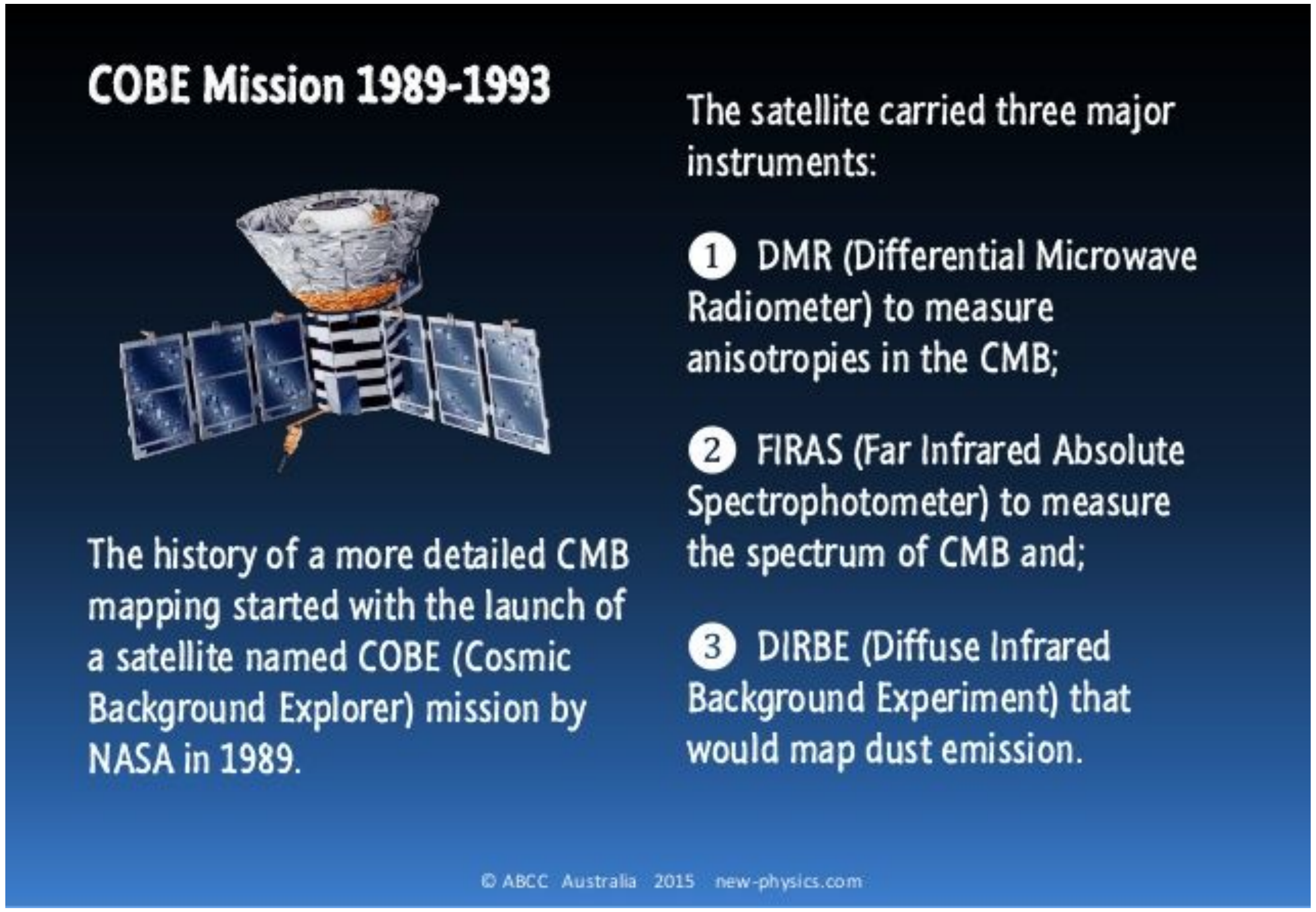

0.44µm
0.55µm
0.90µm
2.16µm
1.65µm
1.25µm

Dust in the ISM

- Dust particles are grains of size of the order of 0.1 um
- Dust is ~1% of total ISM
- Absorbs and re-emits light (Interpretation of SFR)
- Dust as a coolant:
  - Dust as a catalyst for 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 μm 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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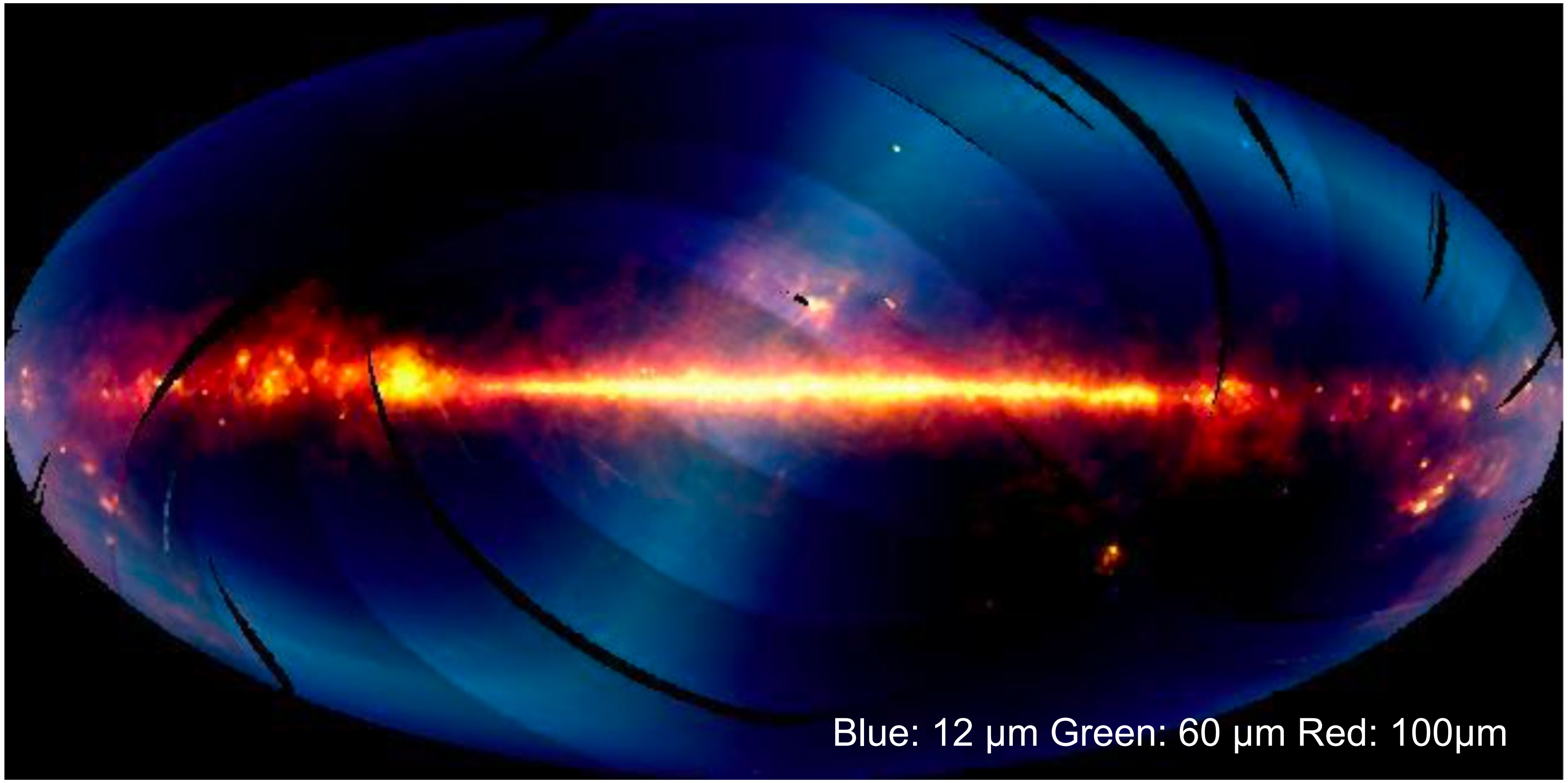
Interstellar extinction: observations

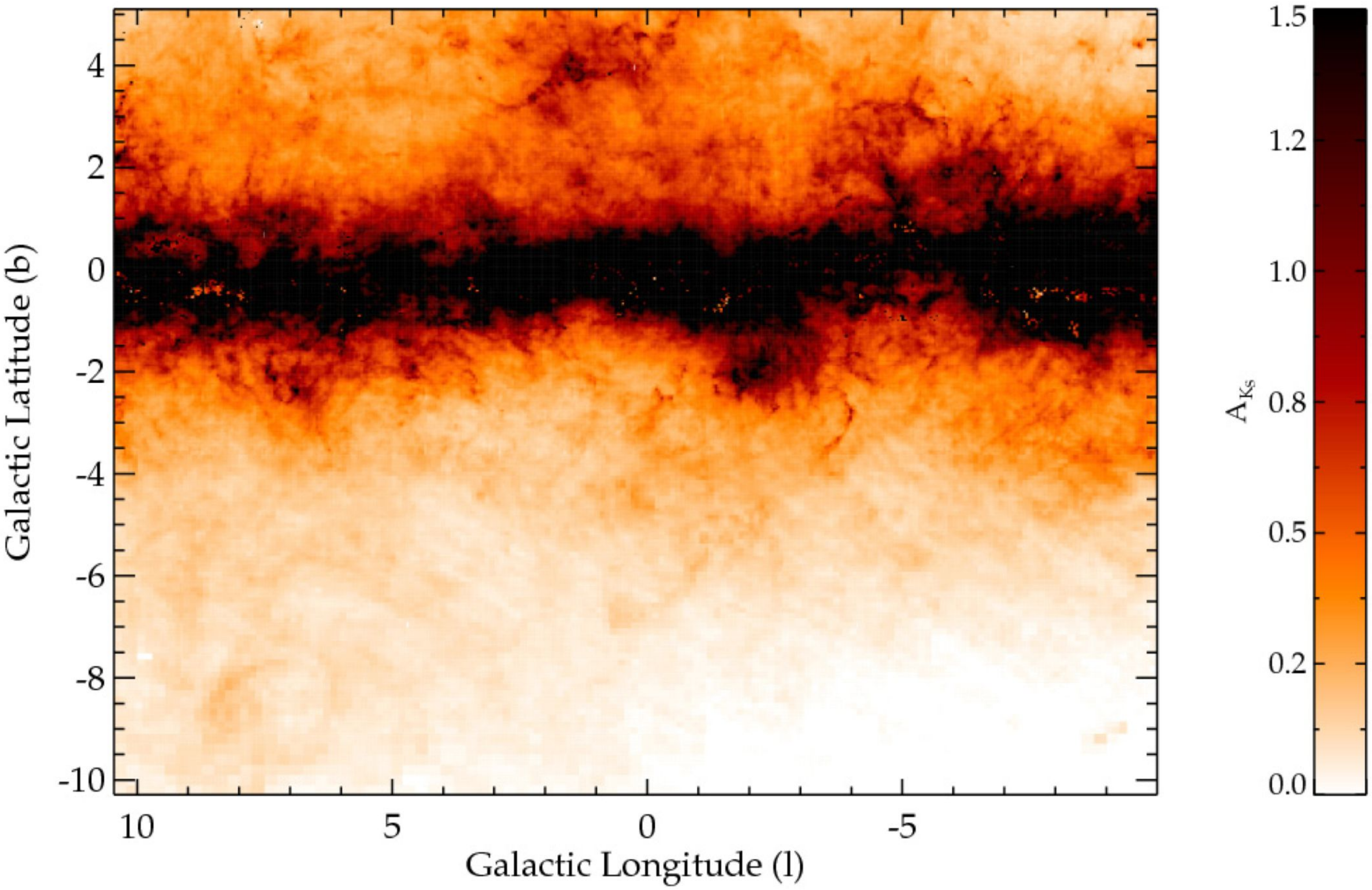
ISSA: IRAS Sky Survey Atlas

- Scanned the MW at different wavelengths(12,25,60,100μm)
- Determined dust column density and then E(B-V)using B-V colours of elliptical galaxies
- Convert to extinction using standard Rv=3.1
- Integrated extinction in the line of sight



Interstellar extinction: observations

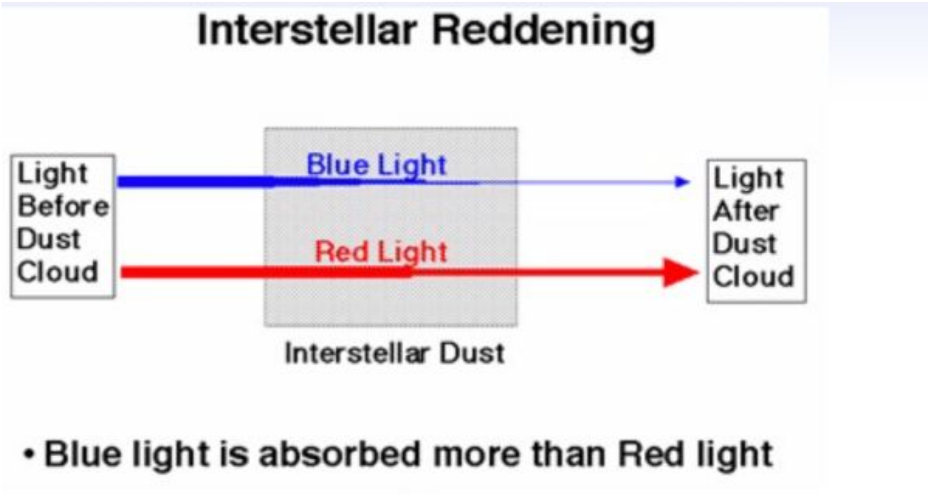
- Extremely high in the Galactic bulge



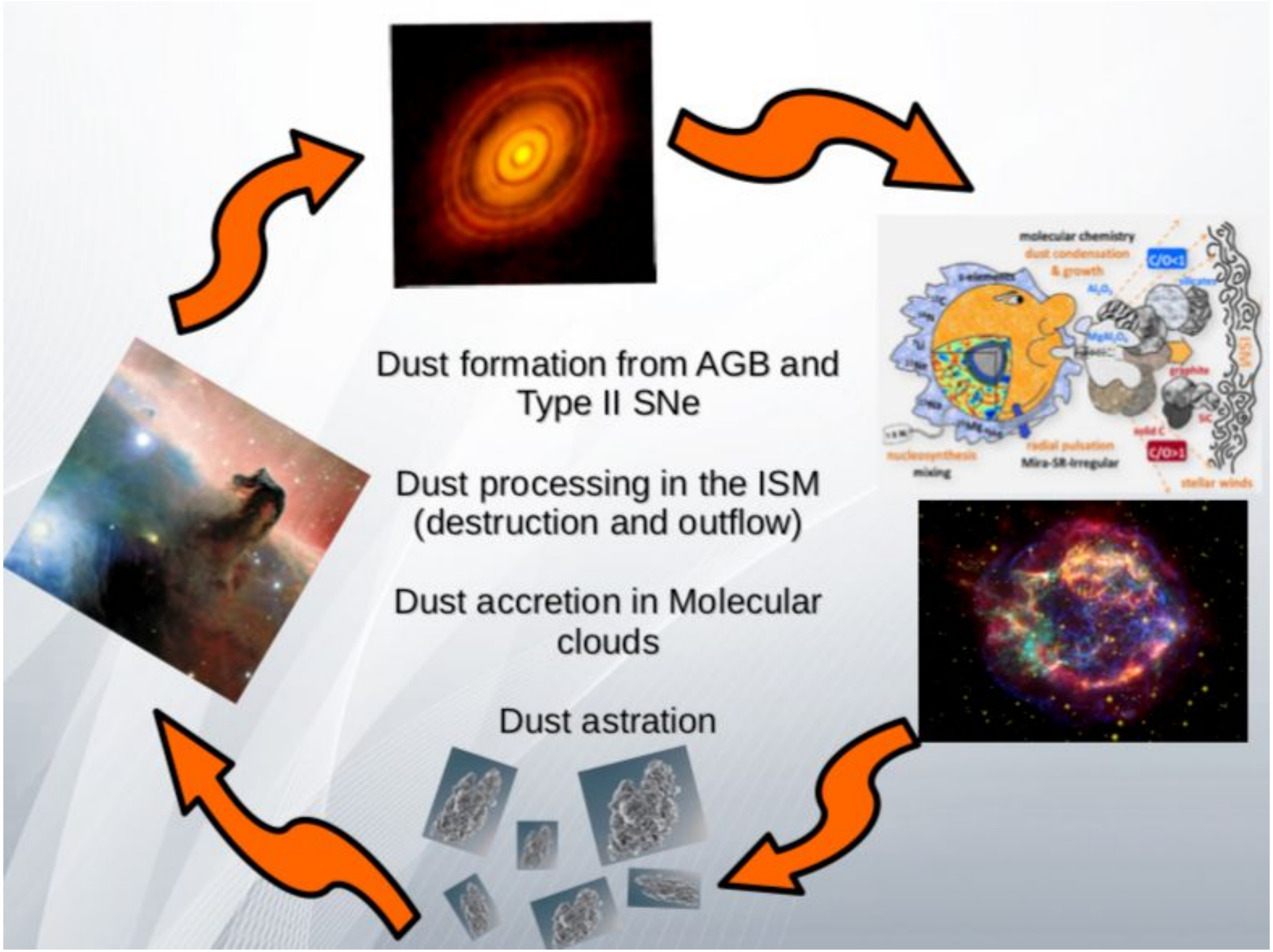
Gonzalez et al. 2012, A&A

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 AV
- 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 formation from AGB and Type II SNe

Dust processing in the ISM (destruction and outflow)

Dust accretion in Molecular clouds

Dust astration

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: ~100-1000 cm-3

temperature: ~10 K

internal velocities: 10 km/s

supported by supersonic turbulence

cloud properties:

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

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

gas tracers: CO, C^+, HCN...

HI regions, Cold Neutral Medium (CNM)

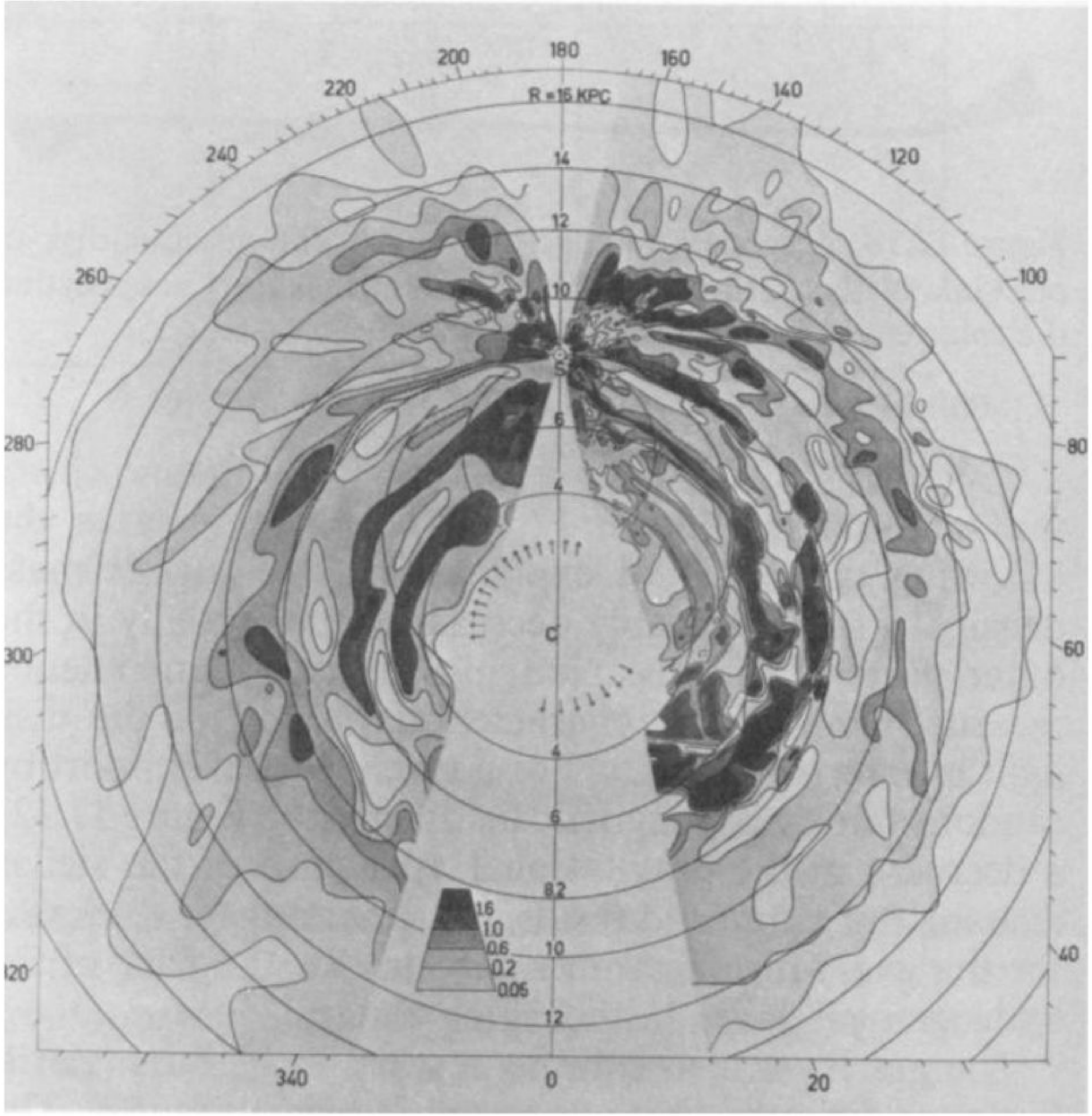
density: ~10 cm-3

temperature: ~100 K

internal velocities: 10 km/s

supersonic turbulence

gas tracer: 21 cm



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

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

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

thermal velocities: 10 km/s

mildly supersonic turbulence

gas tracer: 21 cm (neutral), various nebular emission lines including Halpha, absorption lines

Hot ionized medium

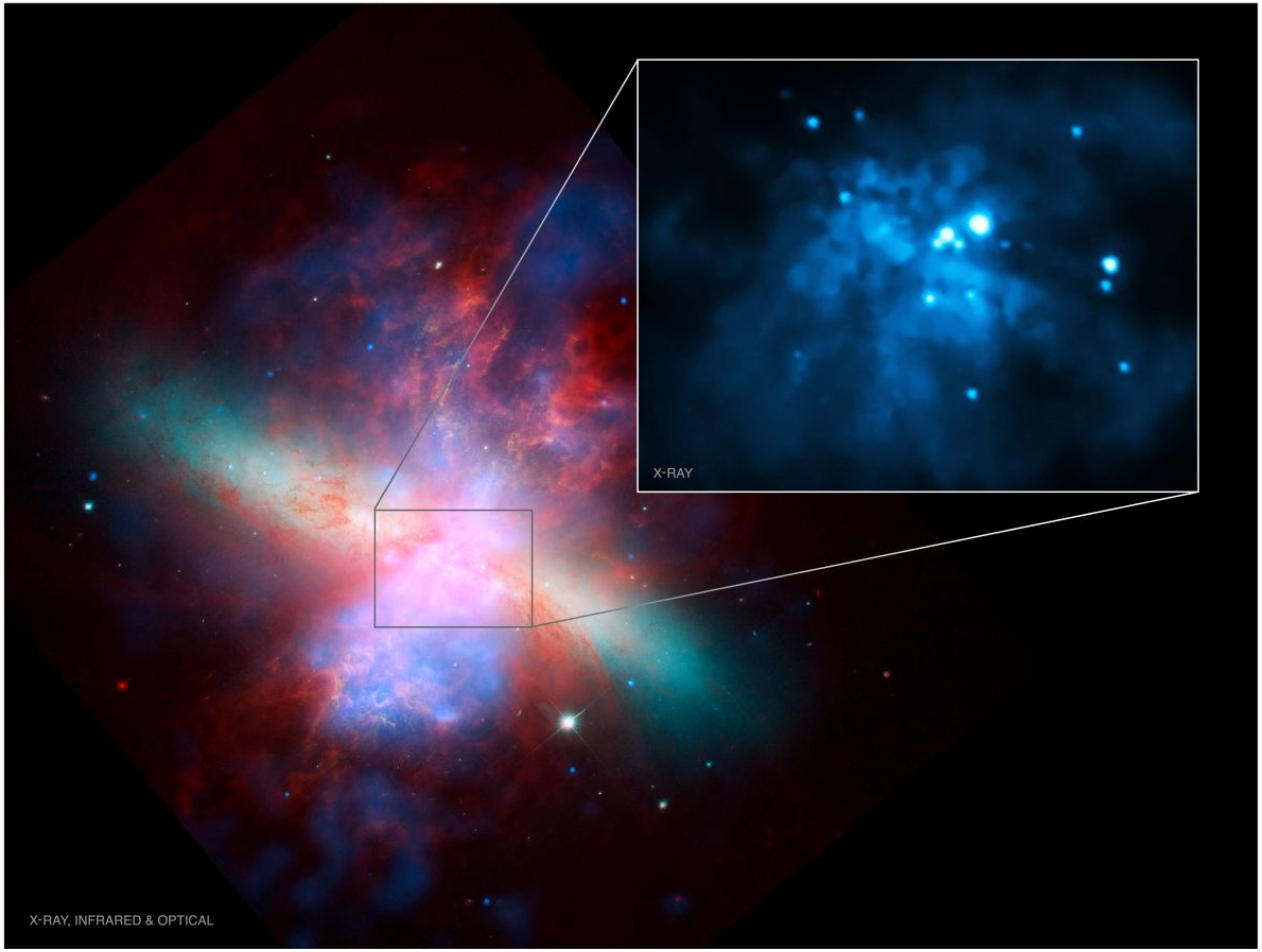
density: ~10^{-3} cm-3

temperature: ~10^{6} K

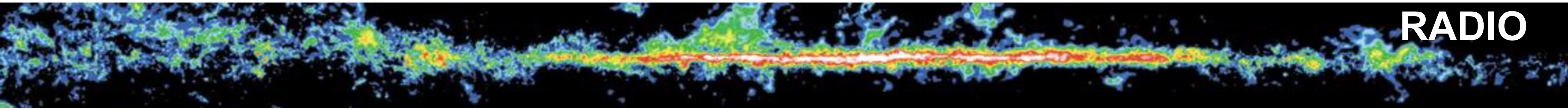
thermal velocities:
100 km/s

complex kinematics

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



Radio observations (21cm line):

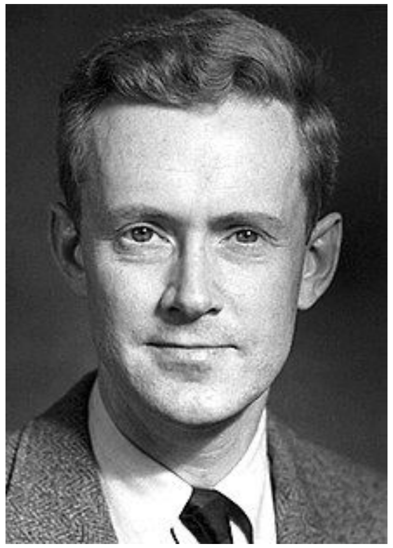


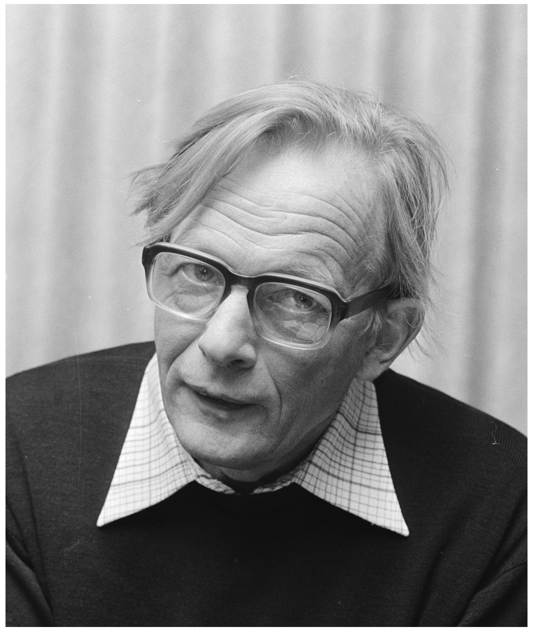
- By late 20s we knew MW was differentially rotating (dynamics of stars in our stellar neighbourhood)
- To study large scale rotations, we needed to observe the “other side” of our Galaxy
- Dust absorption limits our ability to map the MW
- Radio waves can travel through dust
- Hydrogen: hyperfine transition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

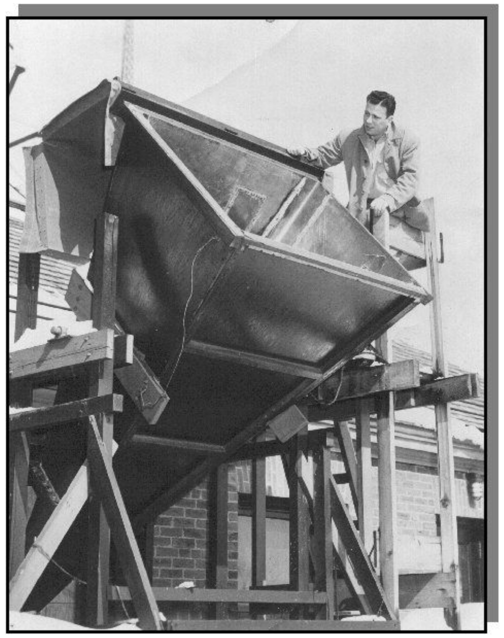
History of 21cm line

- 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

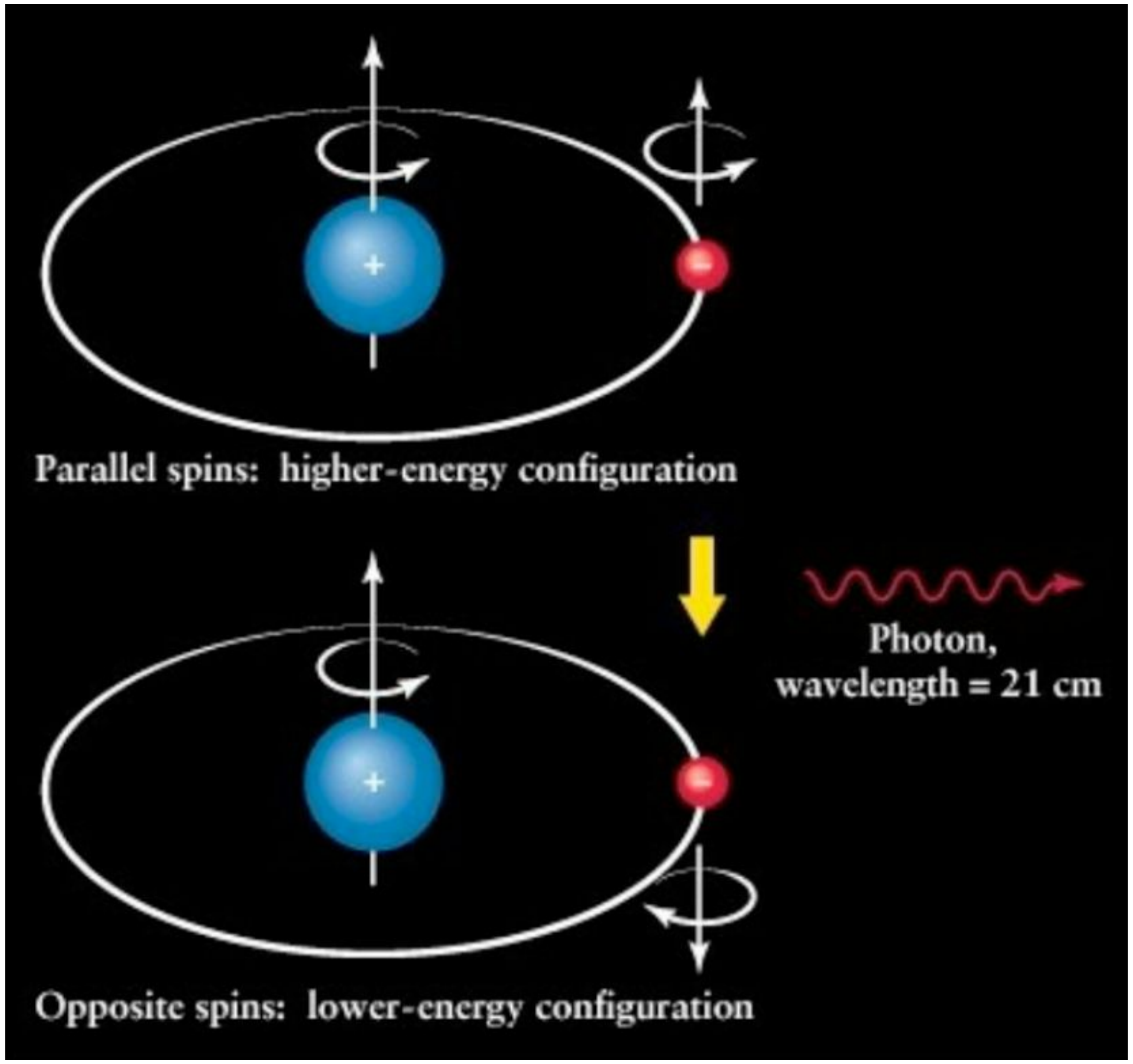

Henk van de Hulst


Harold Ewen

Radio observations (21cm line):

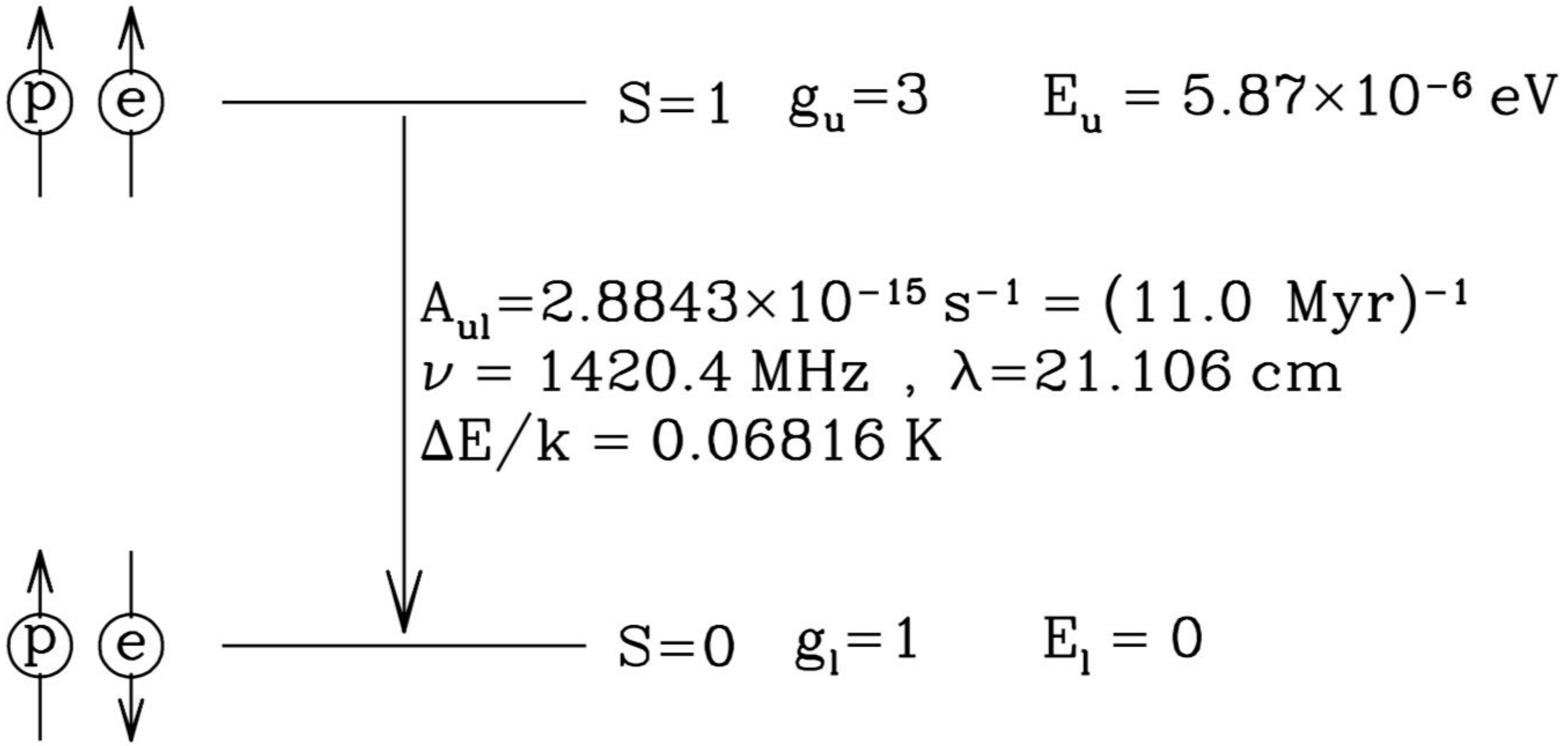
Hydrogen is the most abundant element in the Universe and in the interstellar medium (ISM) of the Milky Way. The cold interstellar gas does not emit radiation at visible wavelength…

... 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):



$S=1 \quad g_u=3 \qquad E_u = 5.87\times10^{-6}\,\mathrm{eV}$

$A_{ul}=2.8843\times10^{-15}\,\mathrm{s}^{-1} = (11.0\ \mathrm{Myr})^{-1}$

$\nu = 1420.4\ \mathrm{MHz}\ ,\ \lambda=21.106\ \mathrm{cm}$

$\Delta E/k = 0.06816\ \mathrm{K}$

$S=0 \quad g_l=1 \qquad E_l = 0$

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

$$\nu_{10} = \frac{8}{3} g_I \left(\frac{m_{\mathrm{e}}}{m_{\mathrm{p}}}\right) \alpha^2 (R_{\mathrm{M}} c) = 1420.406\,\mathrm{MHz}$$

R_Mc is the hydrogen Rydberg frequency

g_I ≈5.58569 is the nuclear g-factor

α is the fine structure constant

Radiative half-life ~11million years (small width) → 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 21cm line and its intensity, we can measure the distance to and amount of HI in the Milky Way

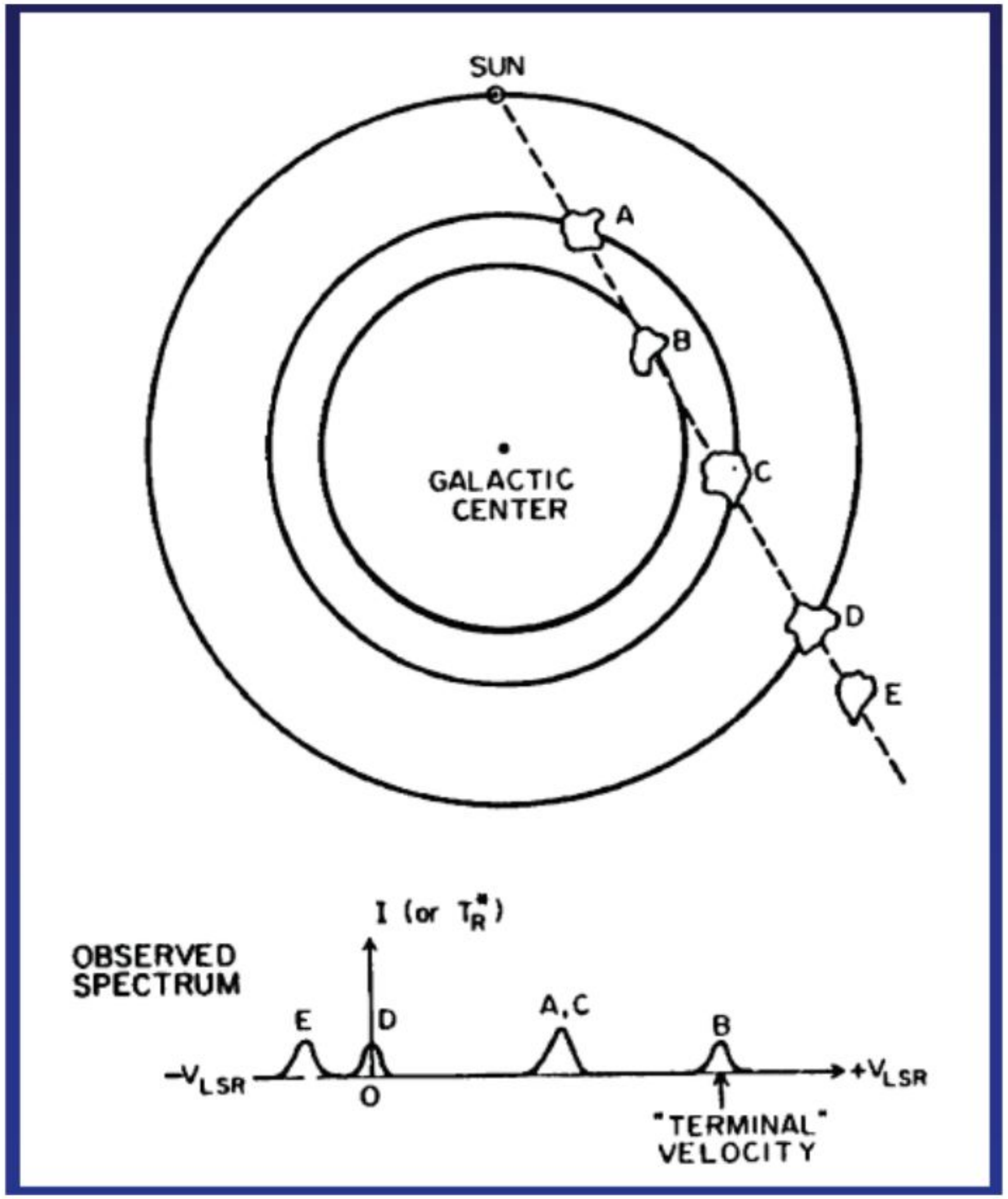
compare the observed frequency of the line with 1420.406 MHz to get the radial velocity:

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

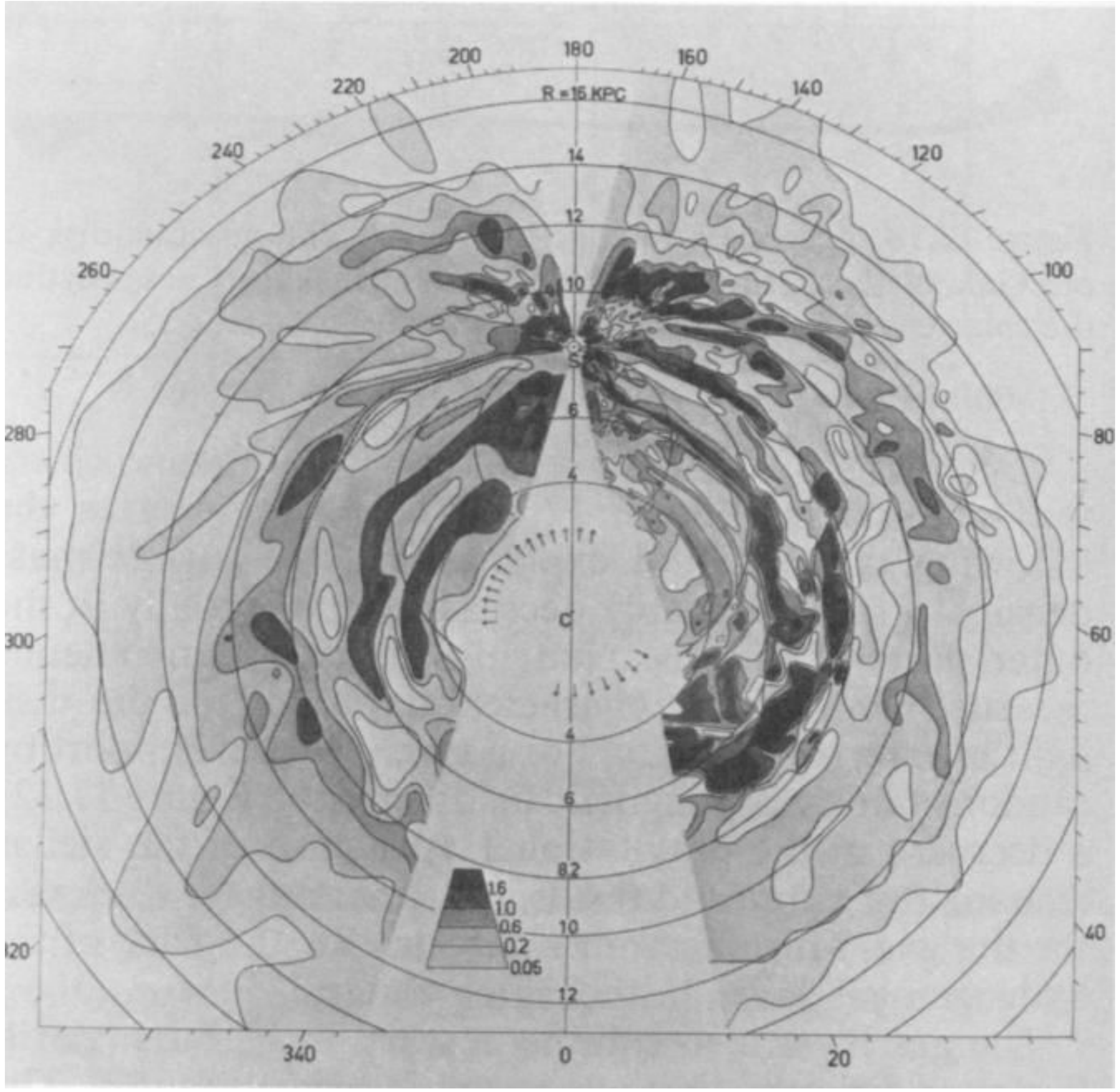
and integrate the observed intensity over frequency to get the column density ($N_{\rm HI}$ in cm^2) of neutral hydrogen

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 ω(*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

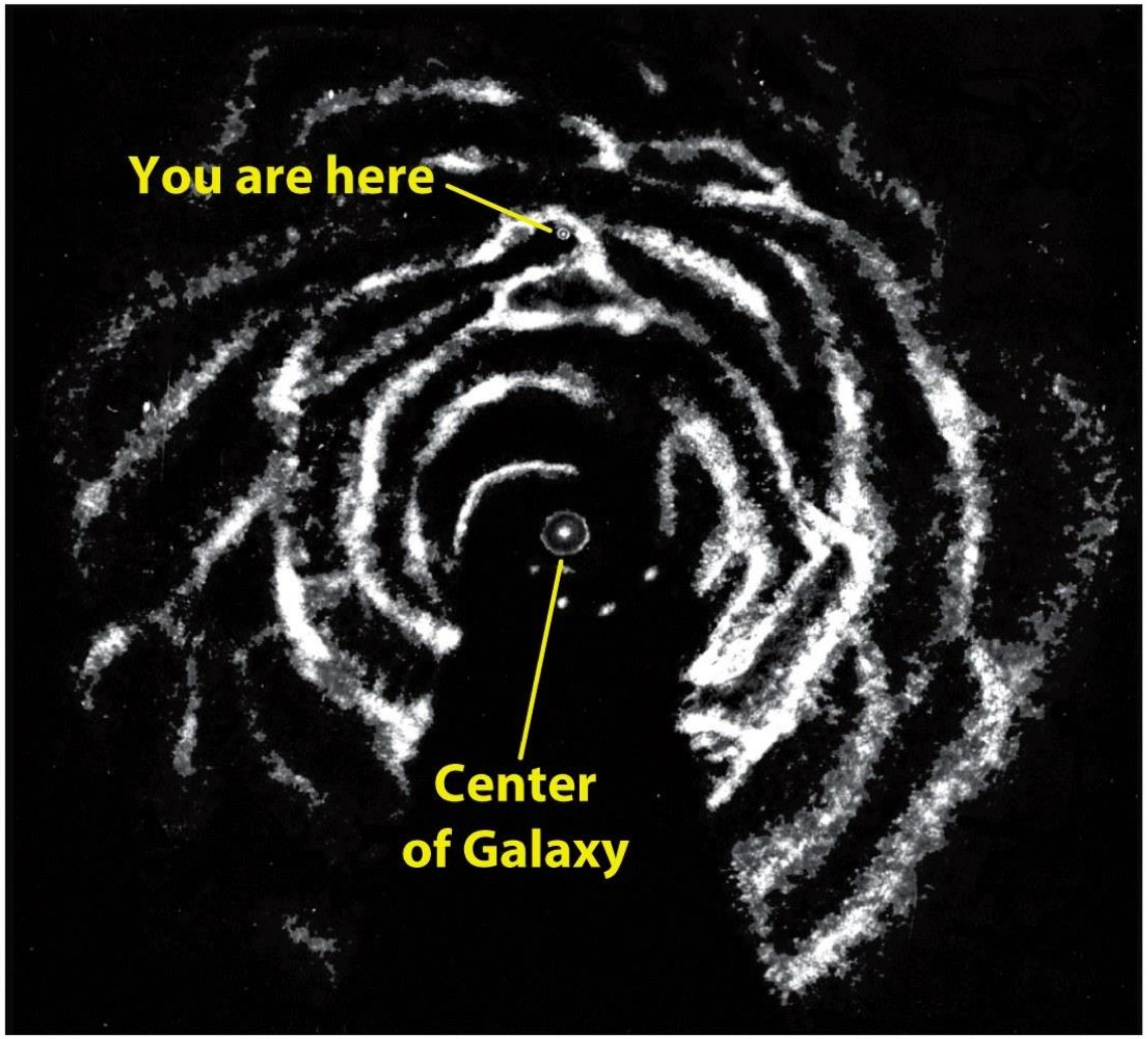


Figure 23-14
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Map of the Milky Way obtained by Doppler measurements of the 21-cm line.

Mapping the Milky Way in HI

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

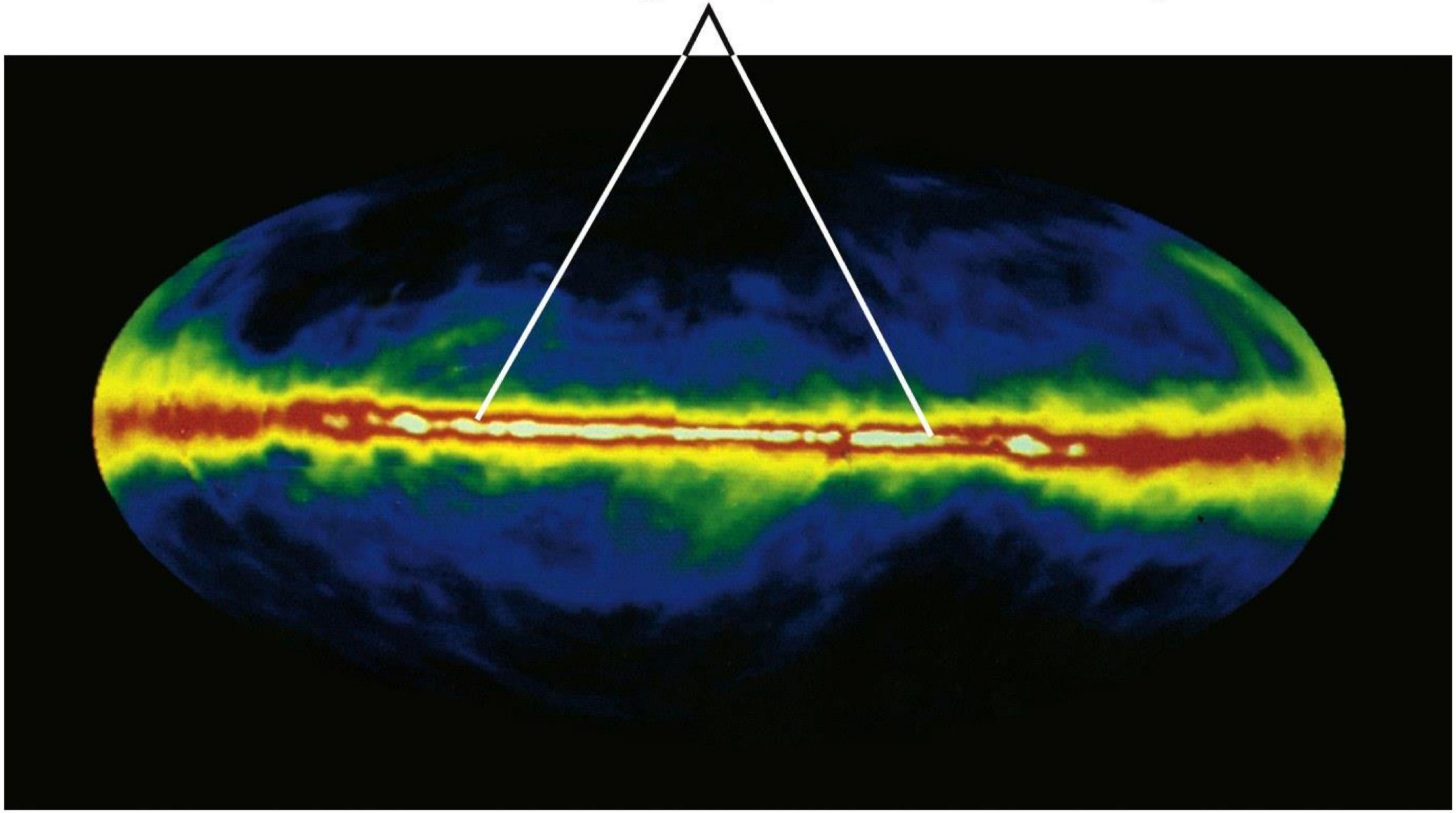

Figure 23-12
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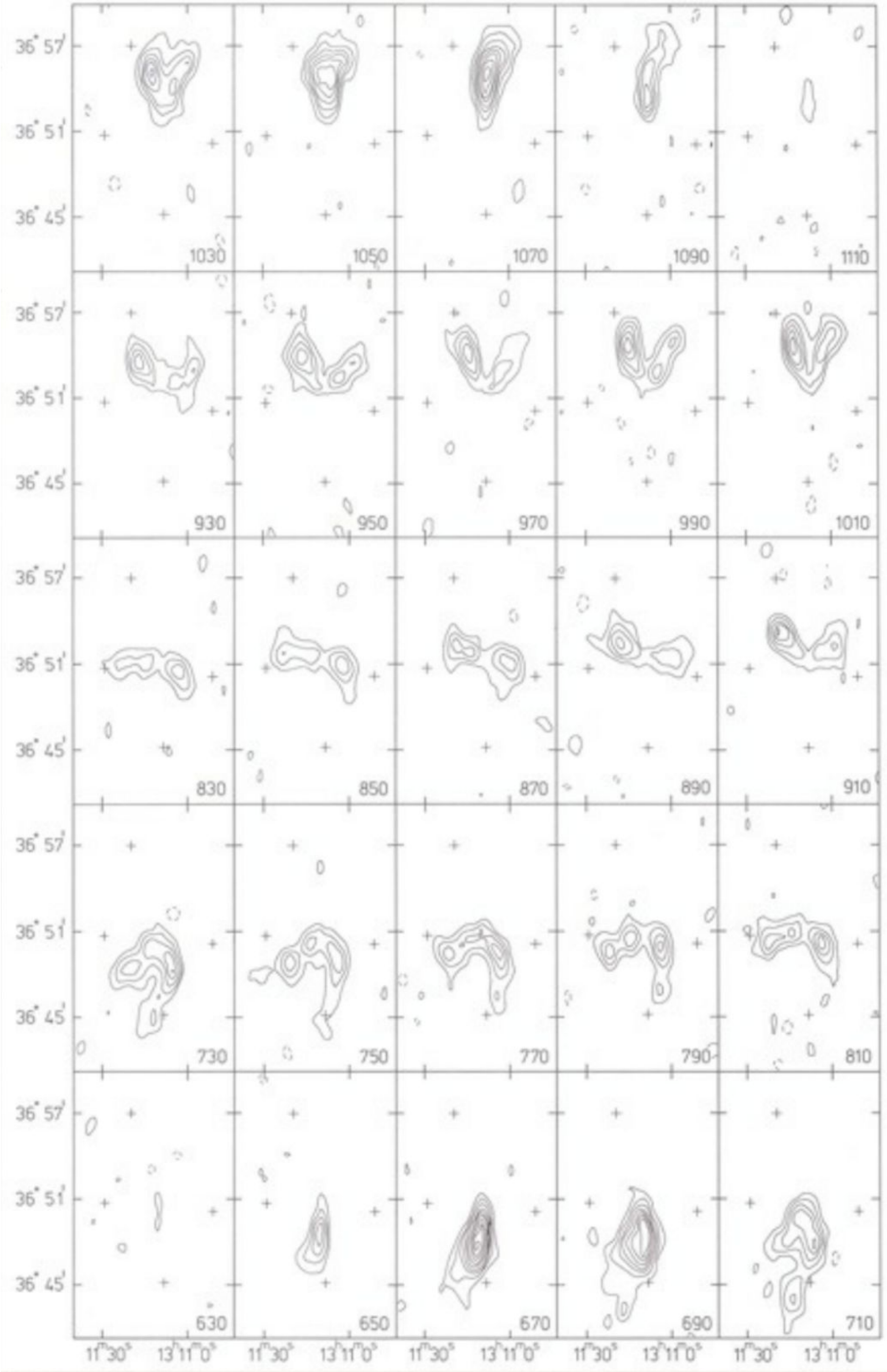
The ISM of Galaxies

- Observations in e.g.,H_α 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



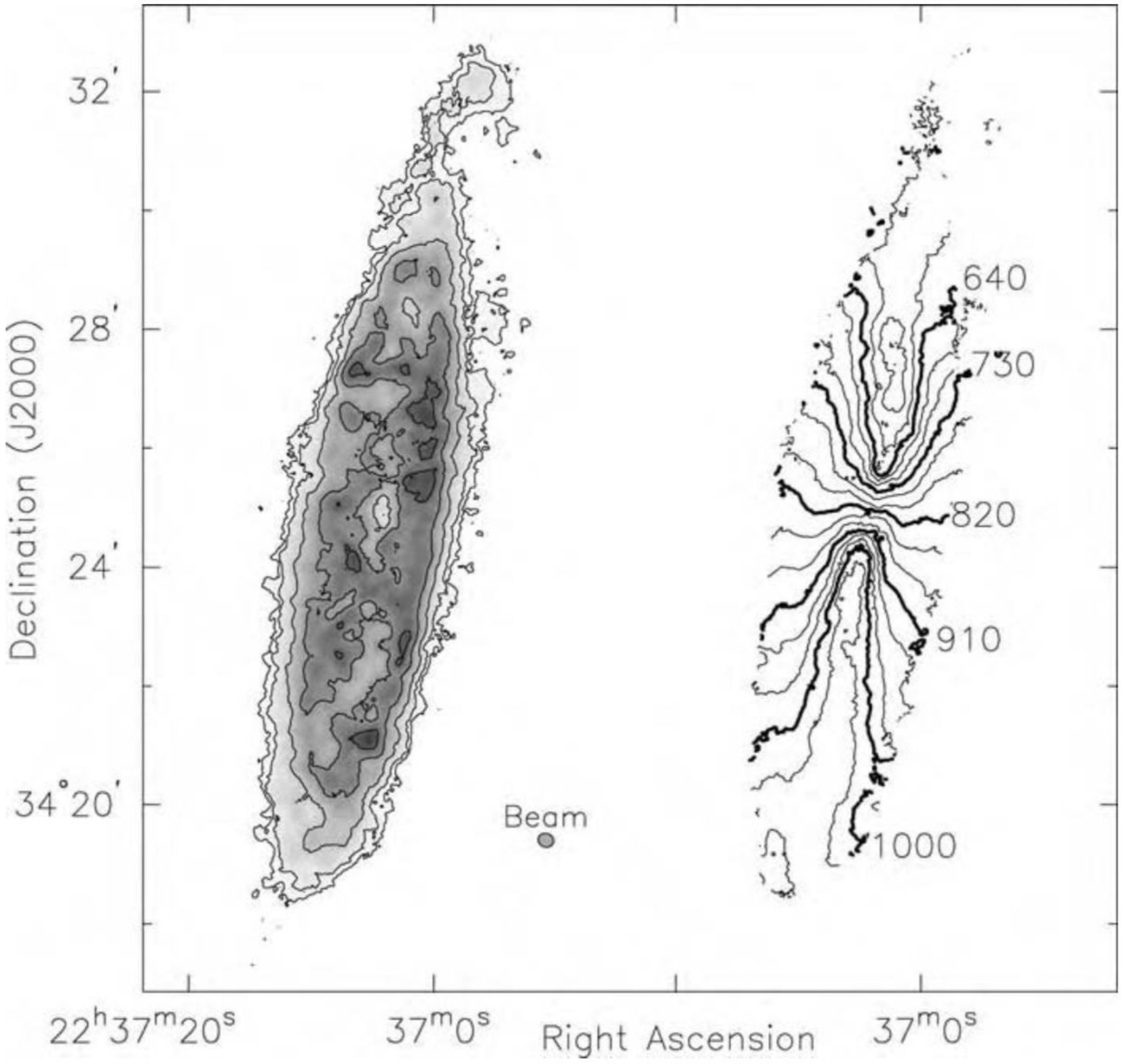
Maps of the 21 cm line radiation. The heliocentric velocity (in km/s of each channel map is indicated in the lower right corner; the crosses refer to star positions.

The ISM of Galaxies

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

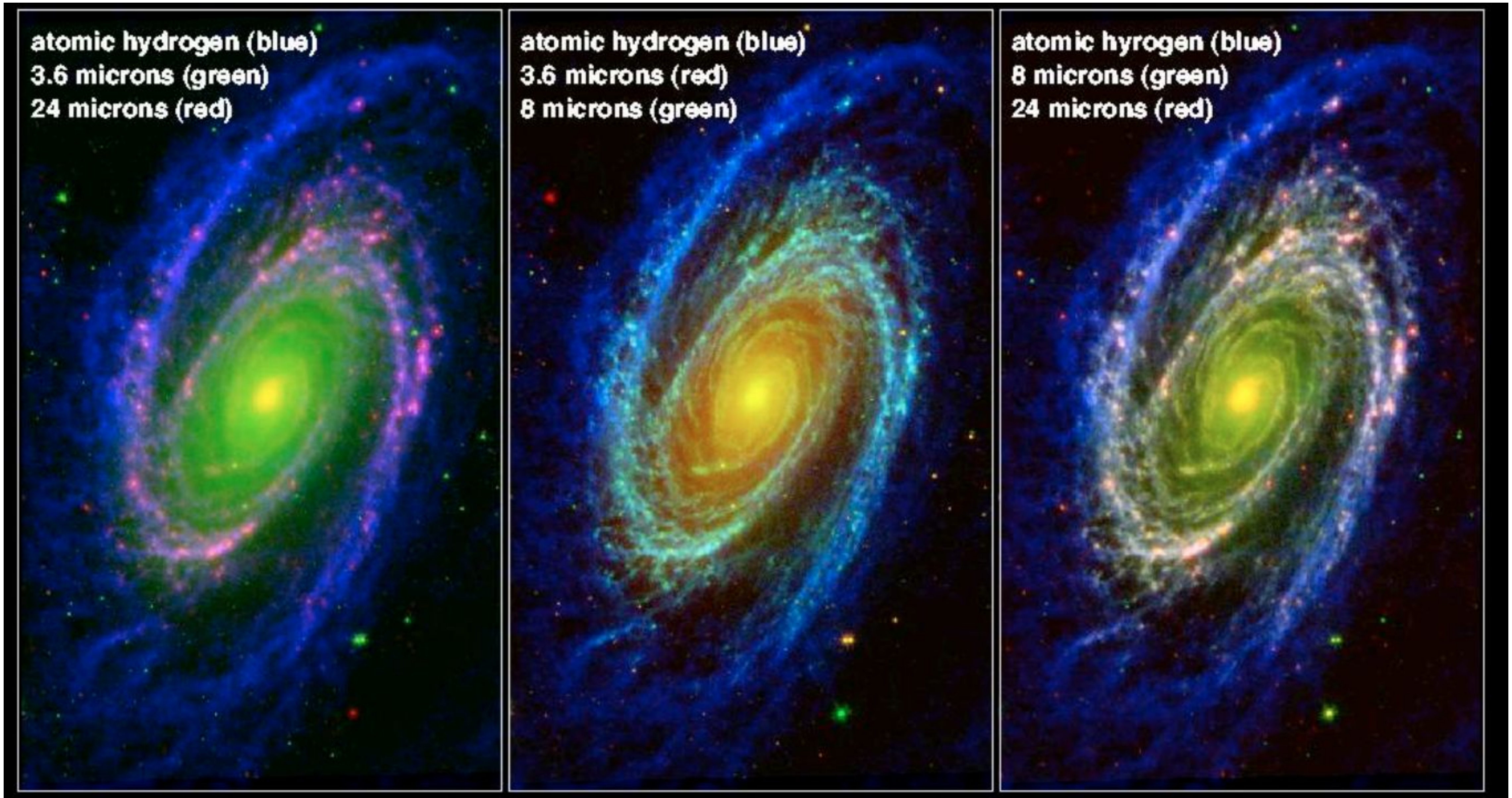
Galaxy NGC 7331

- 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.



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

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

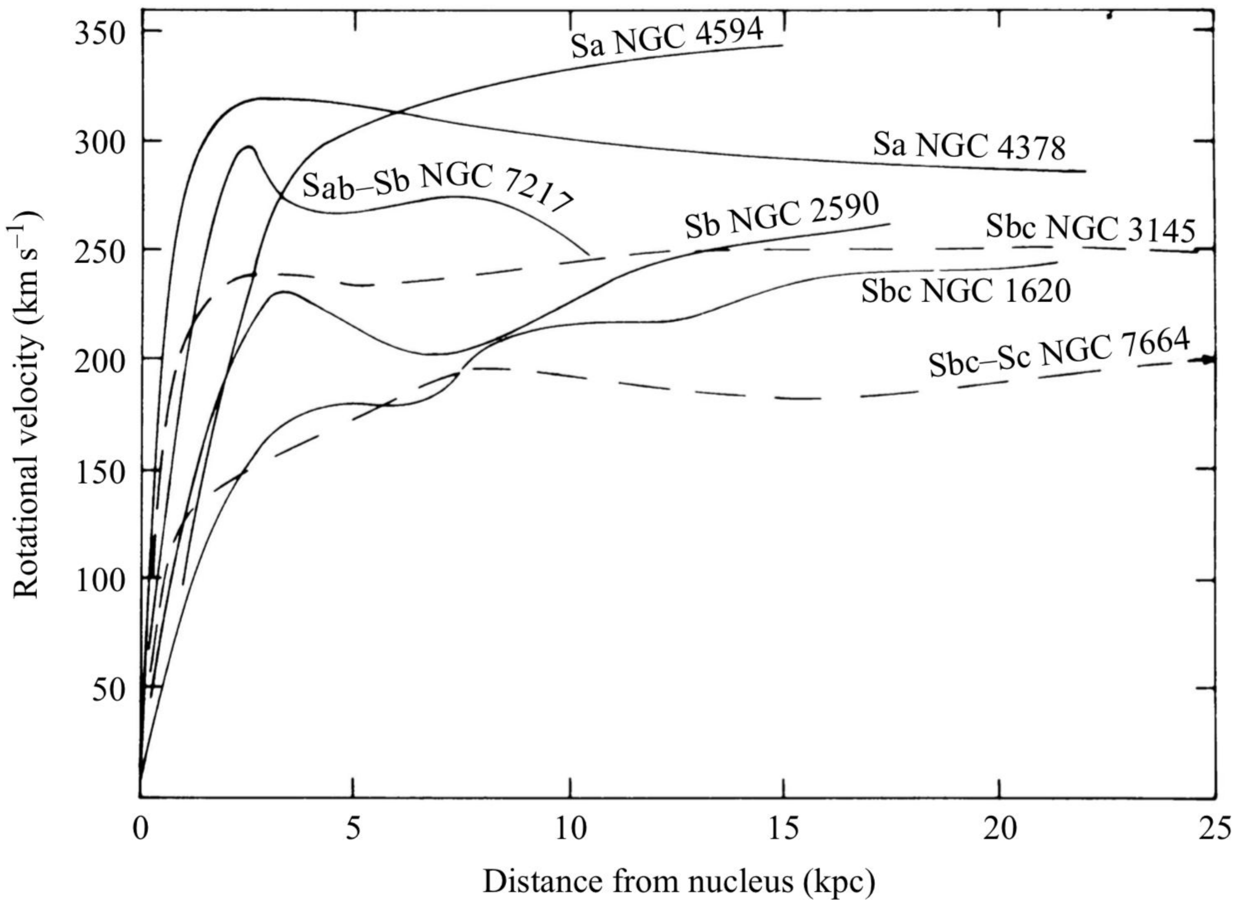


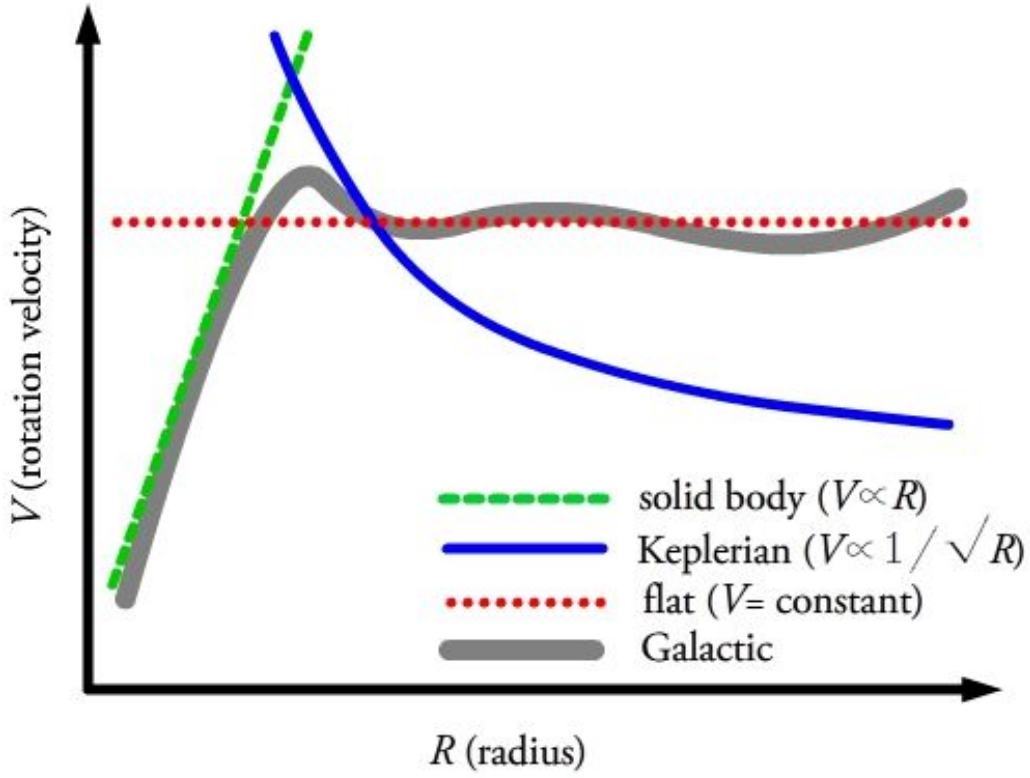
Spiral Galaxy Messier 81 **NASA Spitzer Space Telescope and NRAO VLA**

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

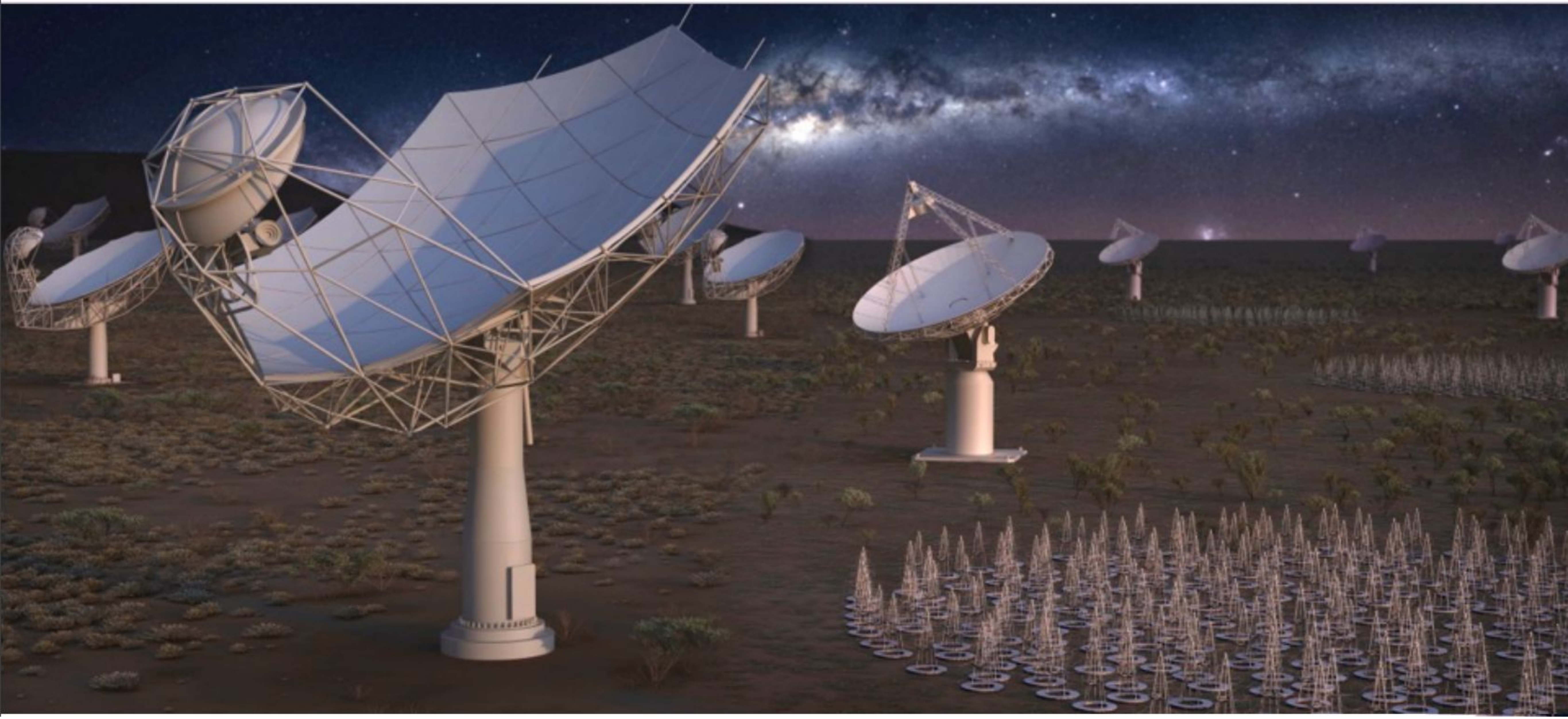
Rotation Curves



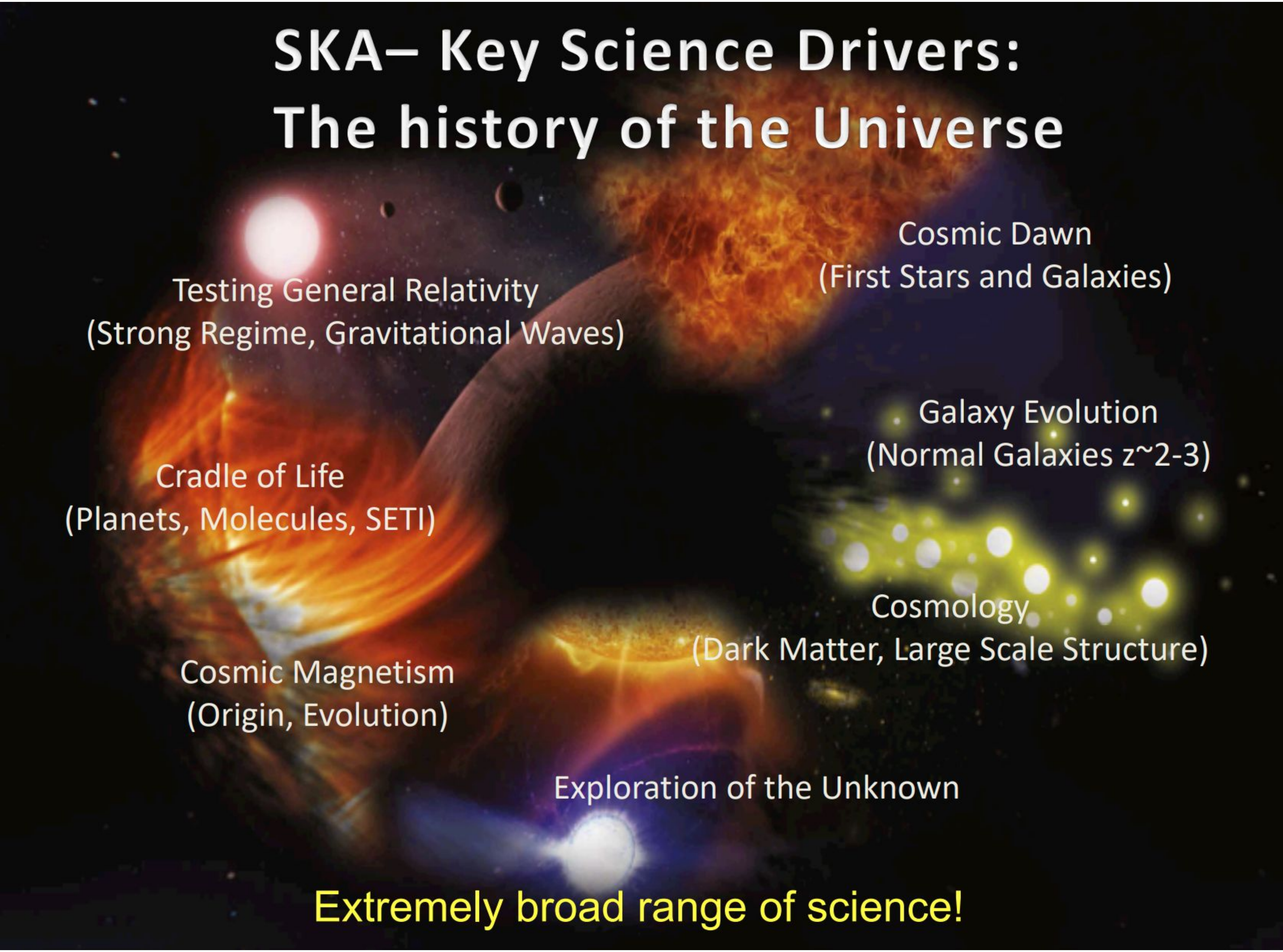


- Vera Rubin observations (‘70s)
- Second (after Zwicky in Galaxy Clusters) evidence for DM

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



SKA– Key Science Drivers: The history of the Universe



Cosmic Dawn
(First Stars and Galaxies)

Testing General Relativity
(Strong Regime, Gravitational Waves)

Galaxy Evolution
(Normal Galaxies z~2-3)

Cradle of Life
(Planets, Molecules, SETI)

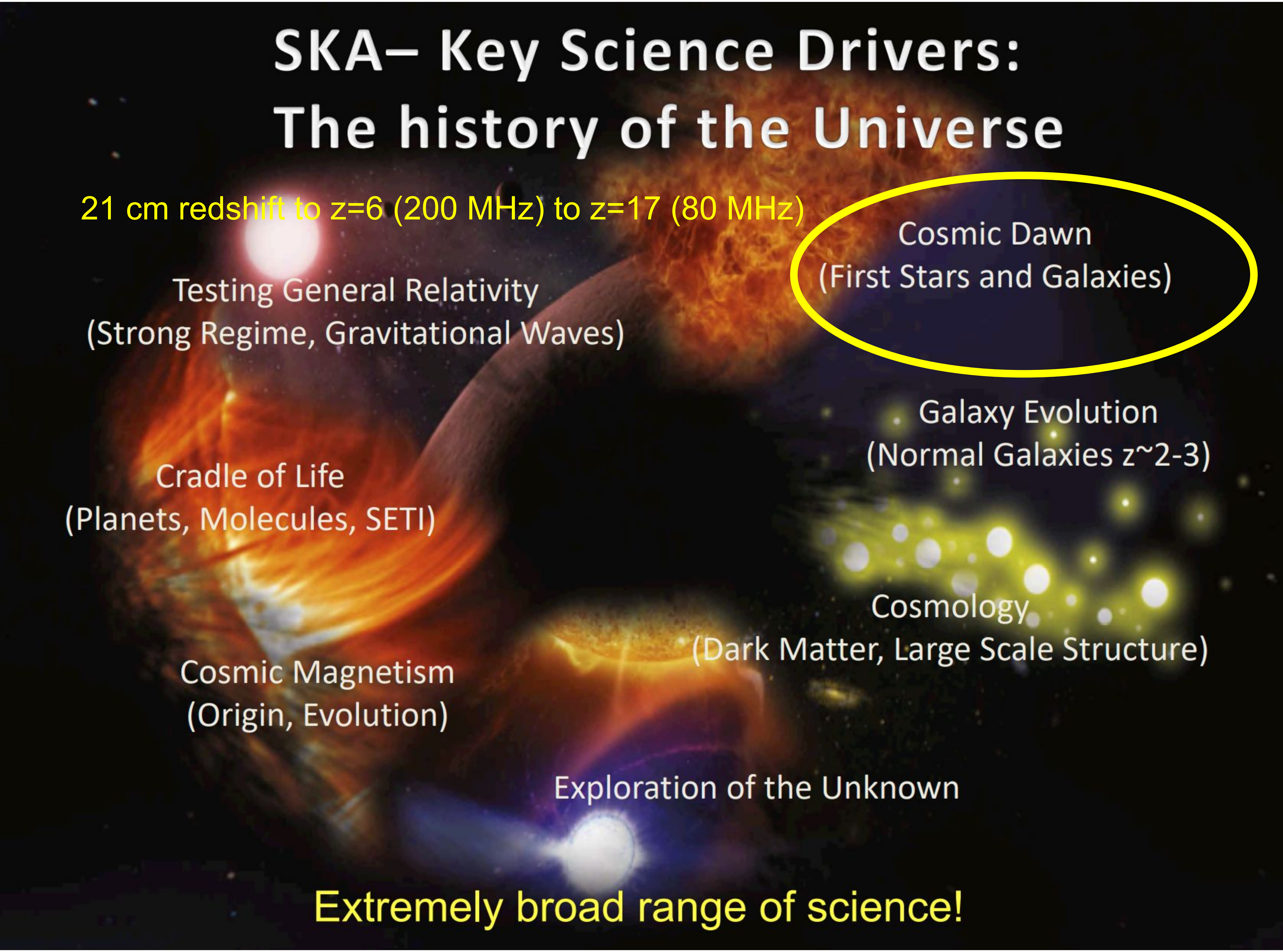
Cosmology
(Dark Matter, Large Scale Structure)

Cosmic Magnetism
(Origin, Evolution)

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)

Cosmic Dawn
(First Stars and Galaxies)

Testing General Relativity
(Strong Regime, Gravitational Waves)

Galaxy Evolution
(Normal Galaxies z~2-3)

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(Planets, Molecules, SETI)

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Exploration of the Unknown

Extremely broad range of science!

Molecular clouds: the cradles of star formation

density: ~100-1000 cm-3

temperature: ~10 K

internal velocities: 10 km/s

supported by supersonic turbulence

cloud properties:

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

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

gas tracers: CO, C^+, 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 moment that is quantized in units of

$$\hbar\text{:}\ L = n\hbar = I\omega$$

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

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

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

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

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

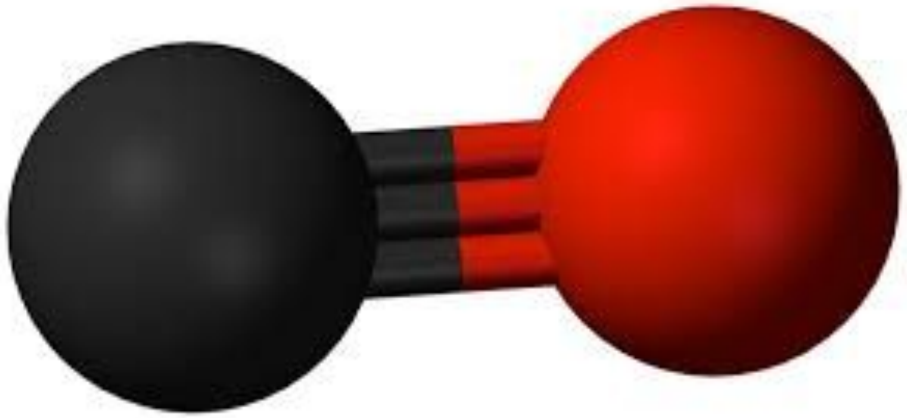
Molecular Hydrogen: H_2

- Molecular hydrogen, H_2, is symmetric and therefore has no permanent electric dipole moment. So despite the fact that H_2 is the most abundant molecule in the Universe, it only radiates when shocked or irradiated to $T \geq 1000$ K, while most H_2 is at $T \sim 10–100$ K.

- Because H_2 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_2 mass called the "X_{CO}-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 10^5).

CO

- CO is the second most abundant molecule in the galaxy (after H_2), 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^{-3}, typical of giant molecular clouds in the MW



Phase: Molecular gas

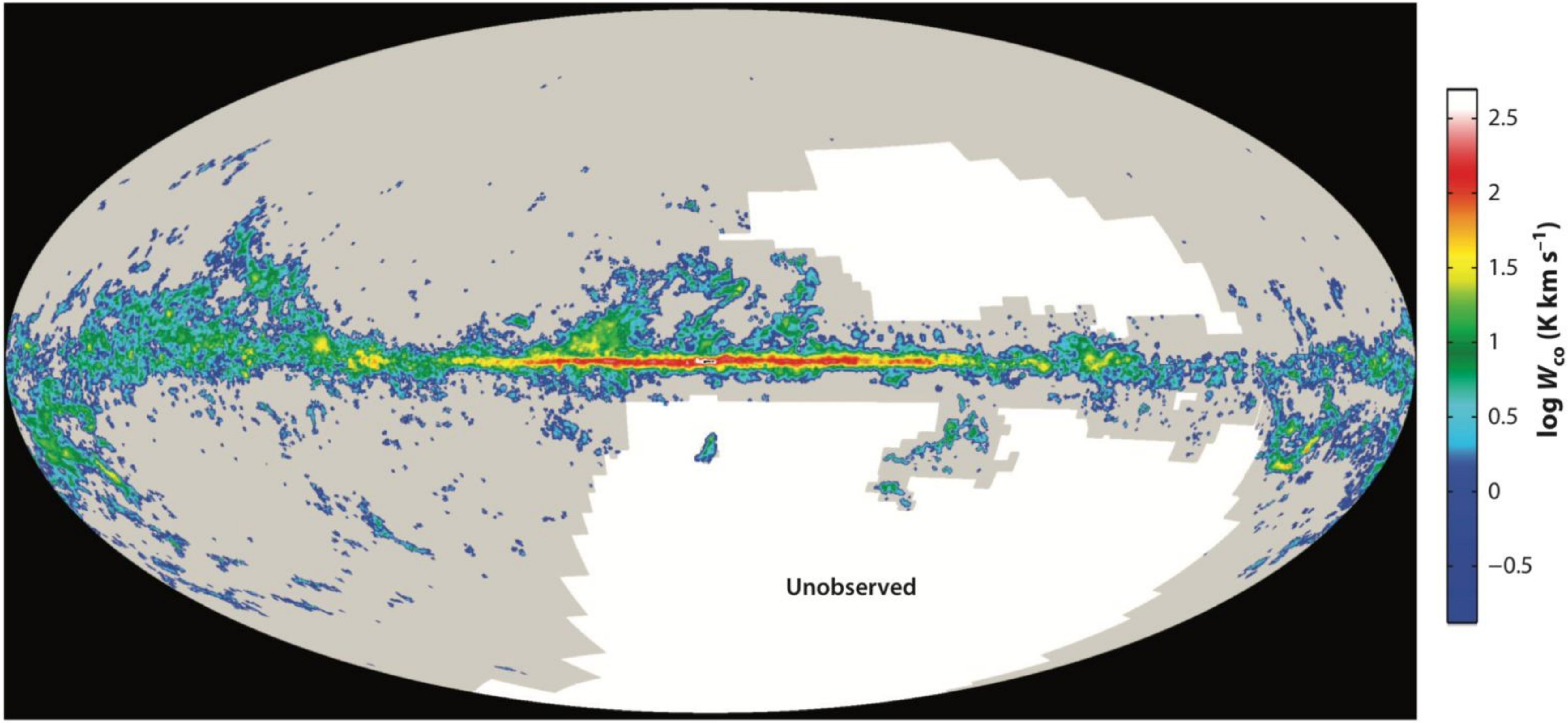
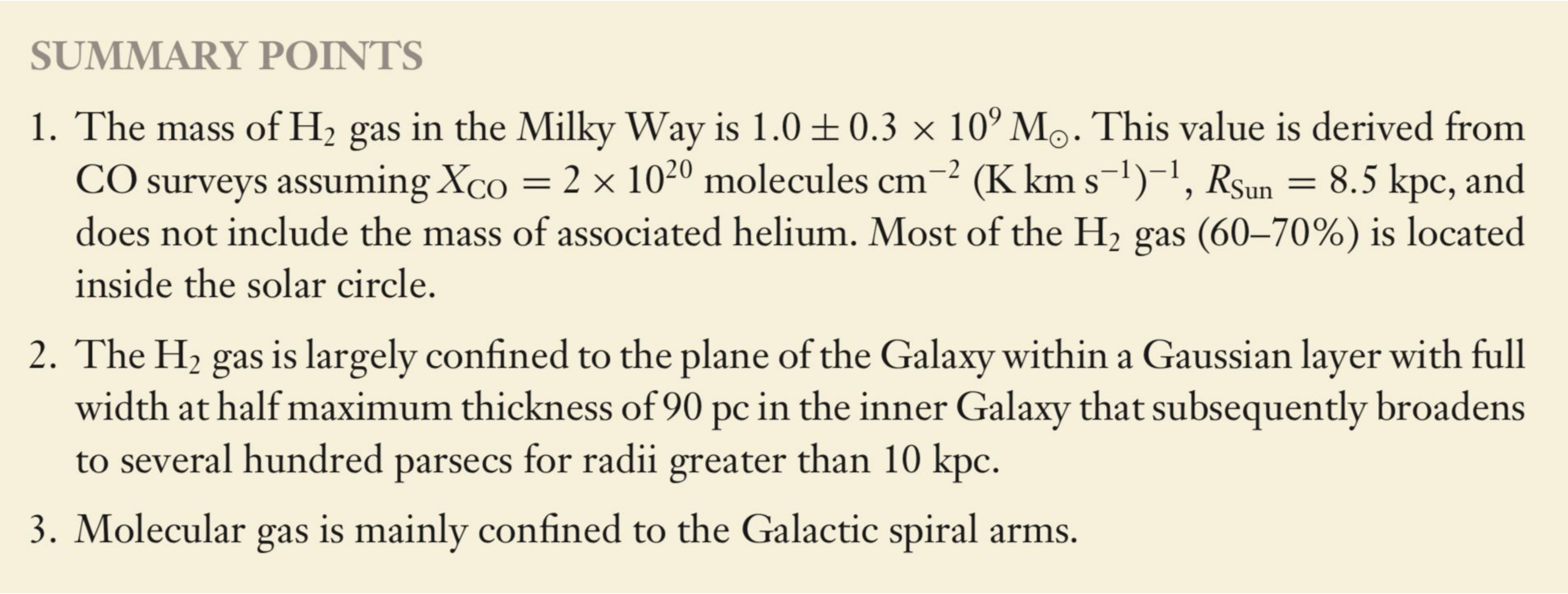


Figure 3

An image of ^{12}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_2 gas in the Milky Way is $1.0 \pm 0.3 \times 10^9\ M_\odot$. This value is derived from CO surveys assuming $X_{CO} = 2 \times 10^{20}$ molecules cm^{-2} $(K\ km\ s^{-1})^{-1}$, $R_{Sun} = 8.5$ kpc, and does not include the mass of associated helium. Most of the H_2 gas (60–70%) is located inside the solar circle.
2. The H_2 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.

Heyer & Dame (2015)

Hot ionized medium

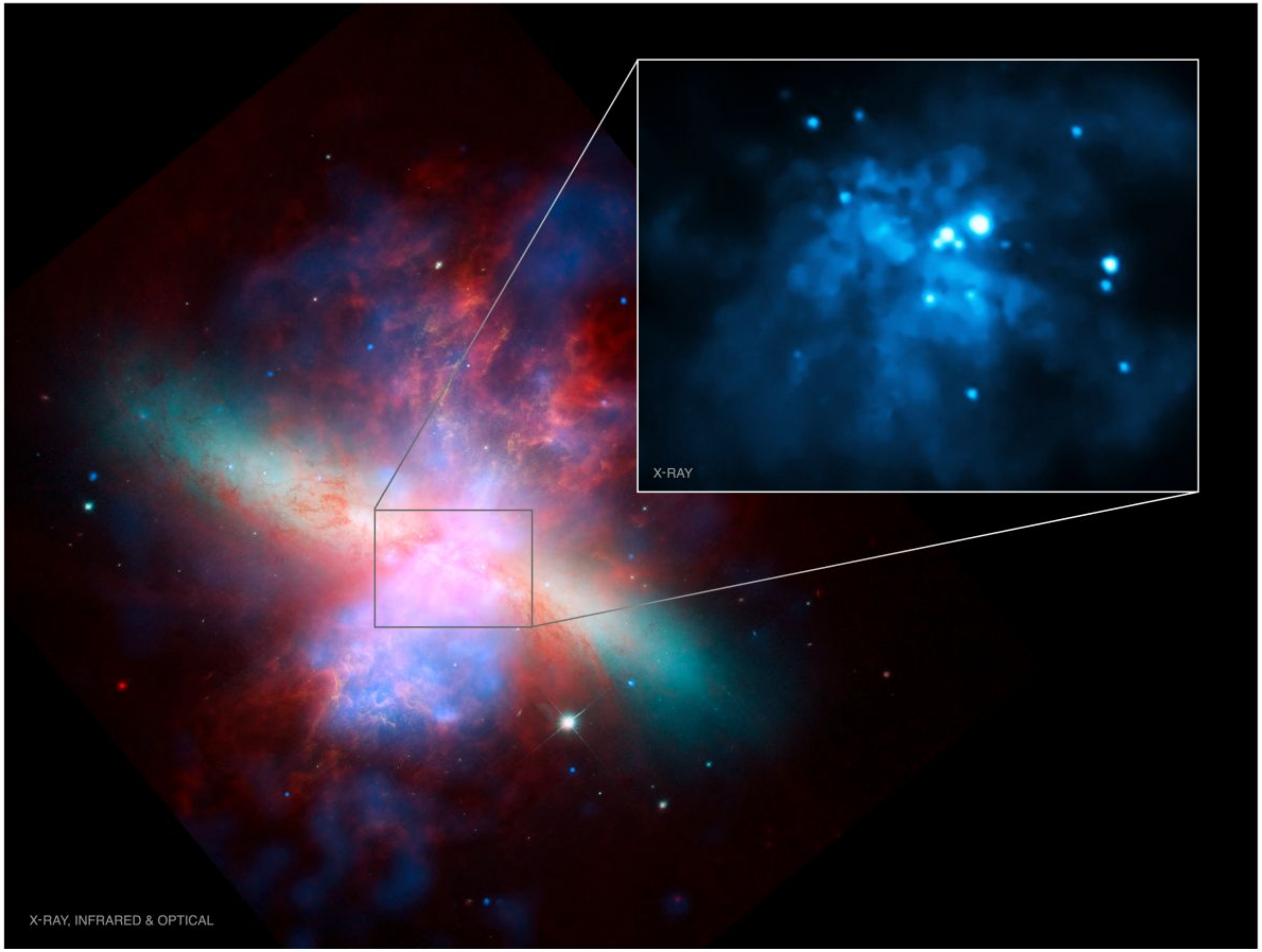
density: ~10^{-3} cm-3

temperature: ~10^6 K

thermal velocities: 100 km/s

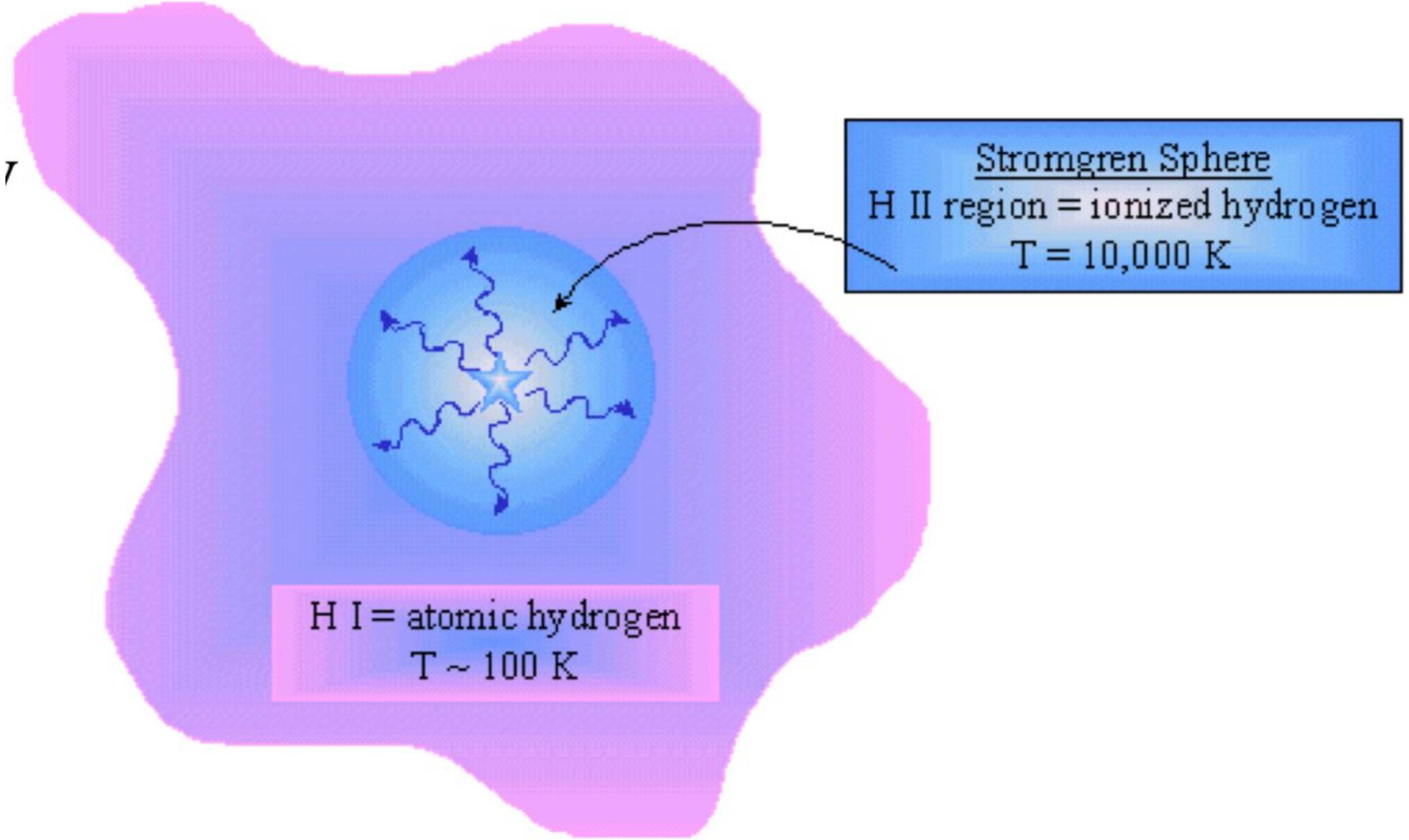
complex kinematics

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

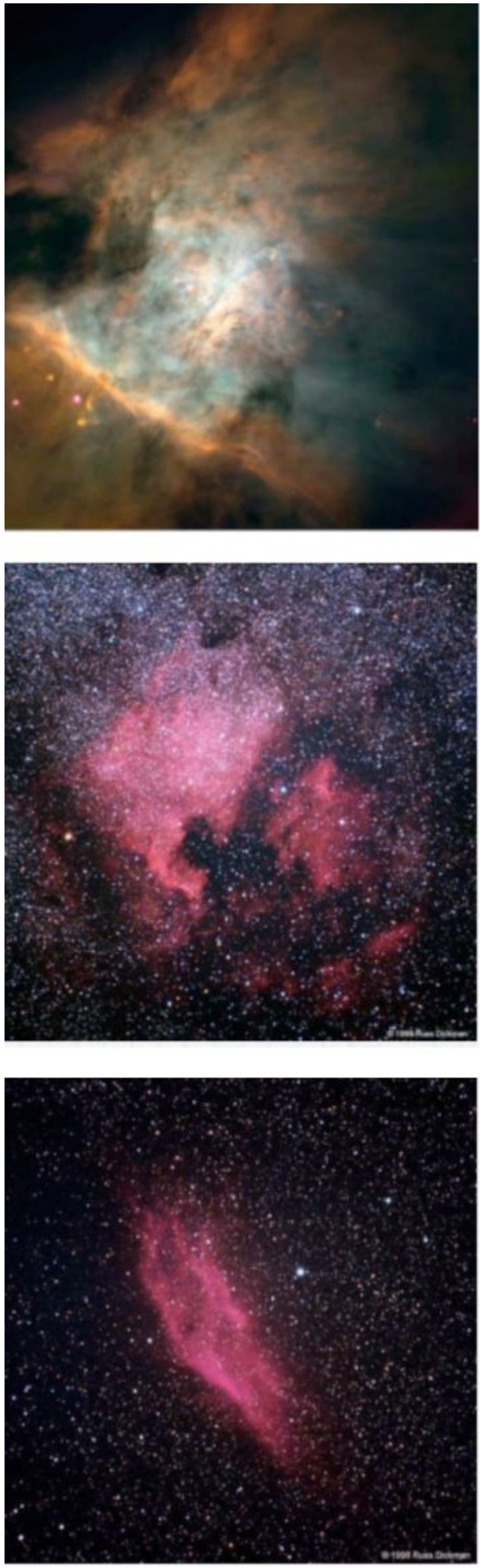
Let N be the number of photons *per second* produced by the O or B star with sufficient energy to ionize hydrogen from the ground state

$\alpha n_e n_H$ 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 $T_e \simeq 45{,}000\,\mathrm{K}$ and $L \simeq 1.3 \times 10^5\,\mathrm{L}_\odot$, respectively. According to Wien's law, the peak wavelength of the blackbody spectrum is given by

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

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

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

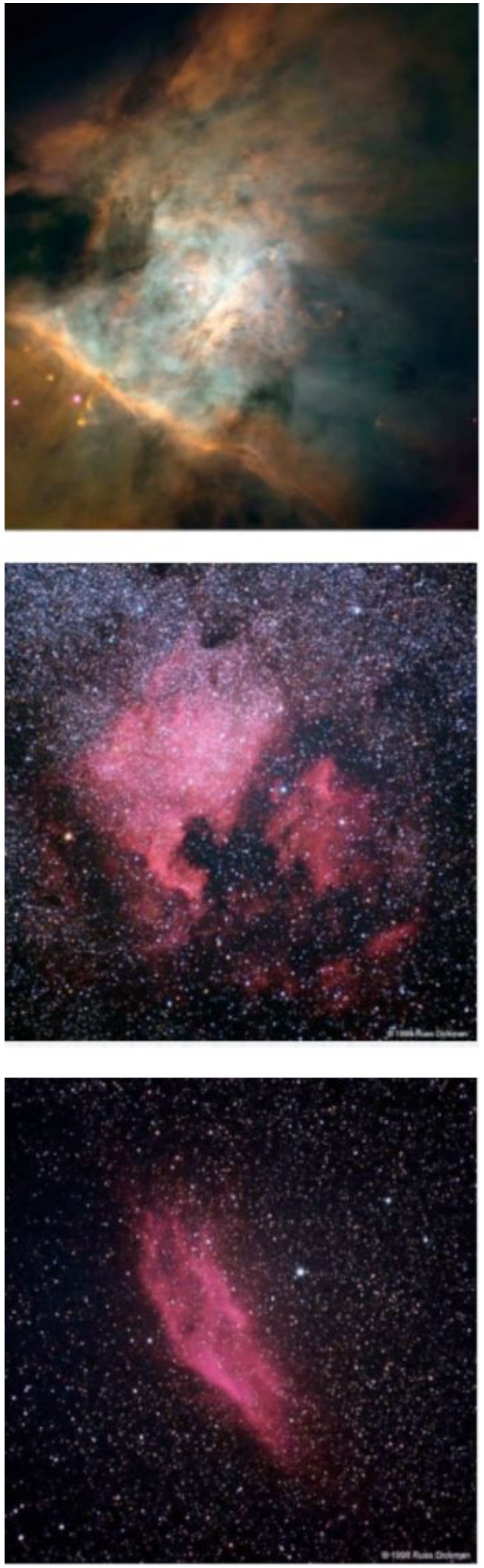
Now, assuming for simplicity that all of the emitted photons have the same (peak) wavelength, the total number of photons produced by the star per second is just

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

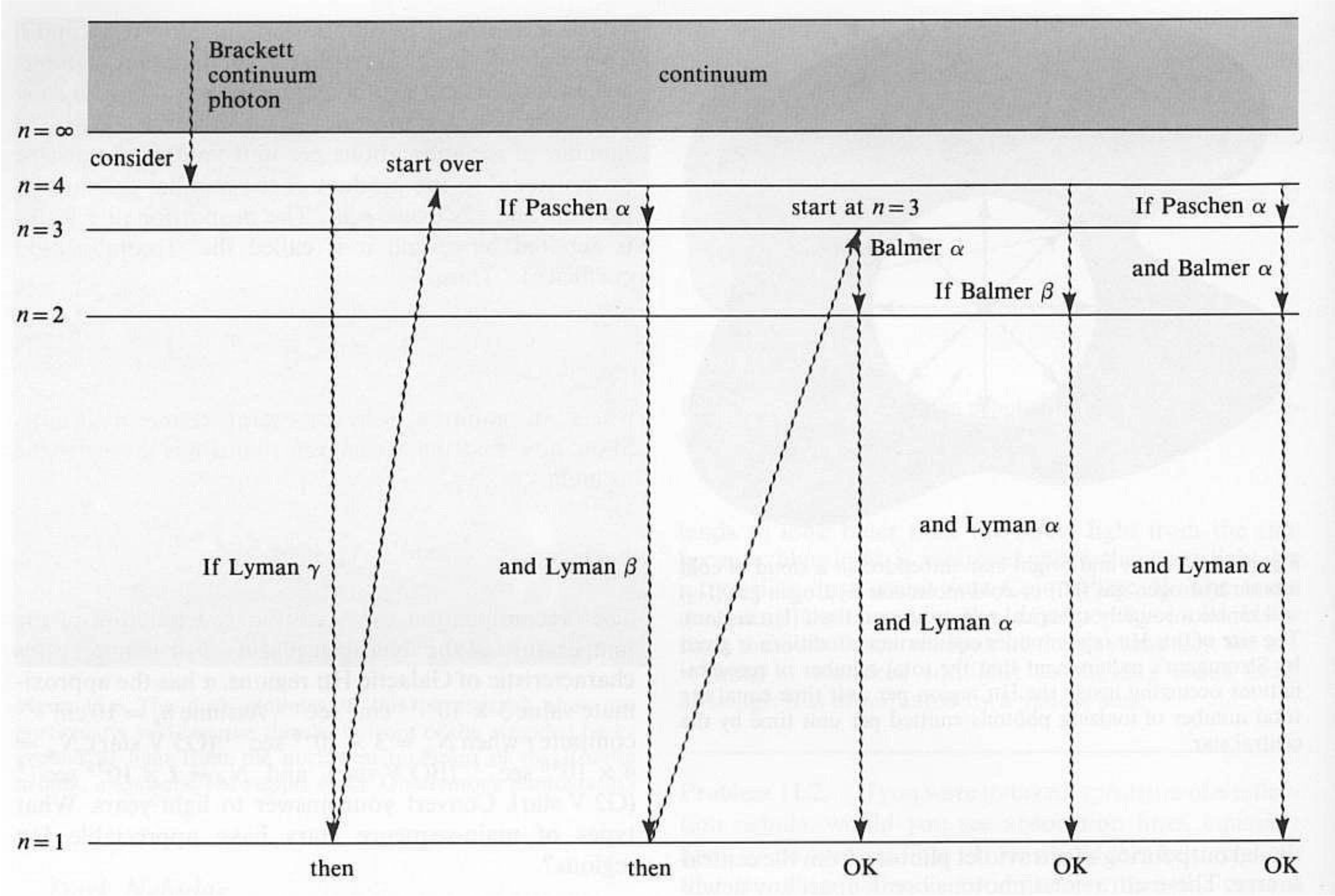
Lastly, taking $n_H \sim 10^8\ \mathrm{m}^{-3}$ to be a typical value an H II region, we find

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

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

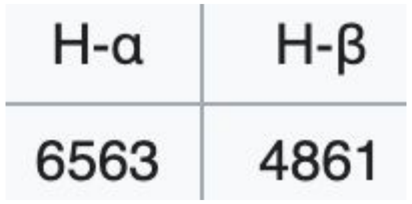


Resonant scattering of Lyman alpha: Fluorescence



HII Regions

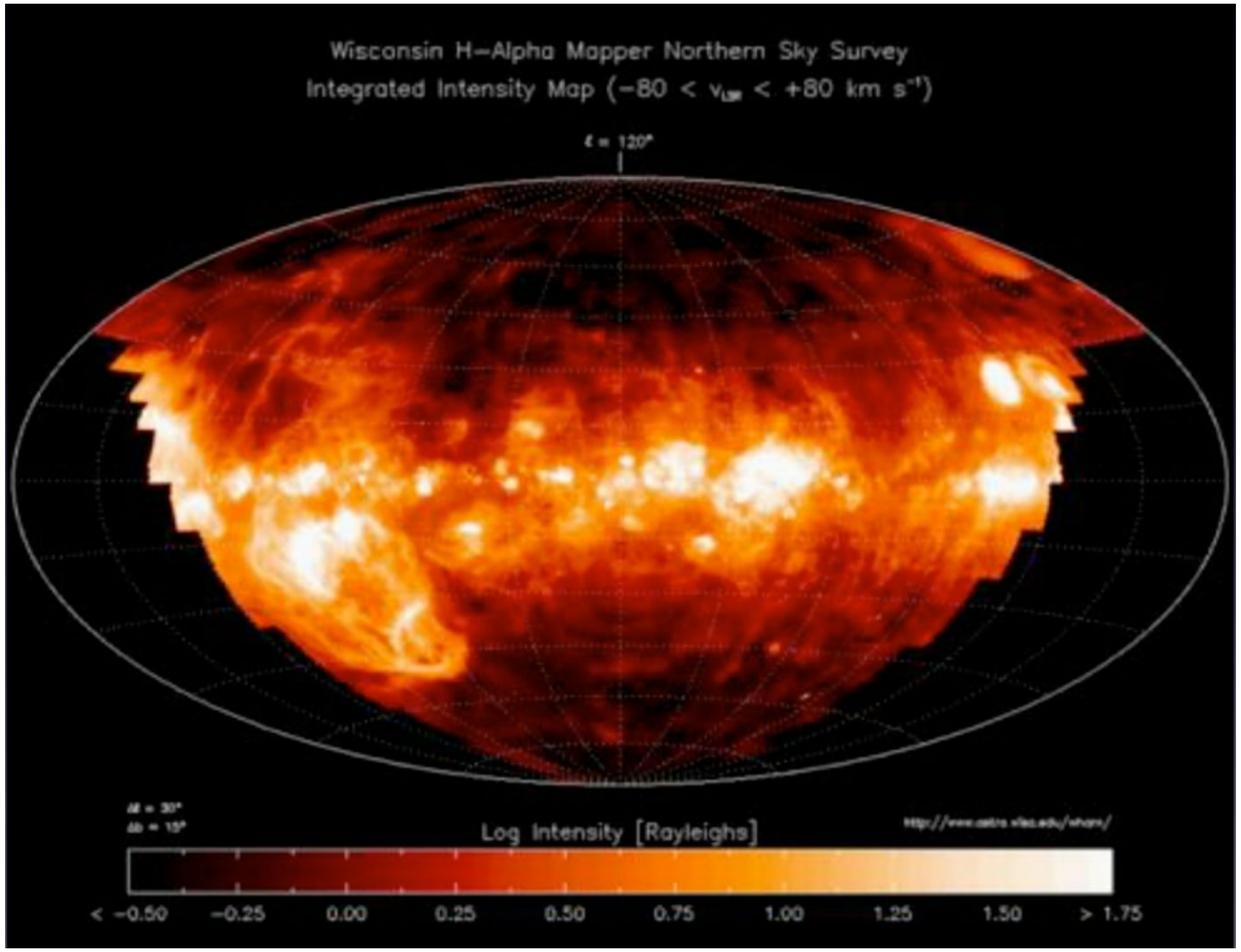
- H II regions surrounding early - type (<B2, T_{eff} >25,000 K) stars, emitting lots of photons beyond Lyman limit (13.6 eV) ionized gas, bright visible nebulous objects
- Associated with massive star - forming regions optical spectra dominated by H and He recombination lines (**fluorescence**)
- Collisionally 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_β to H_α tells us about dust properties (absorption)
- Strong sources of thermal radio emission (free - free) + infrared emission from warm dust



H-α	H-β
6563	4861

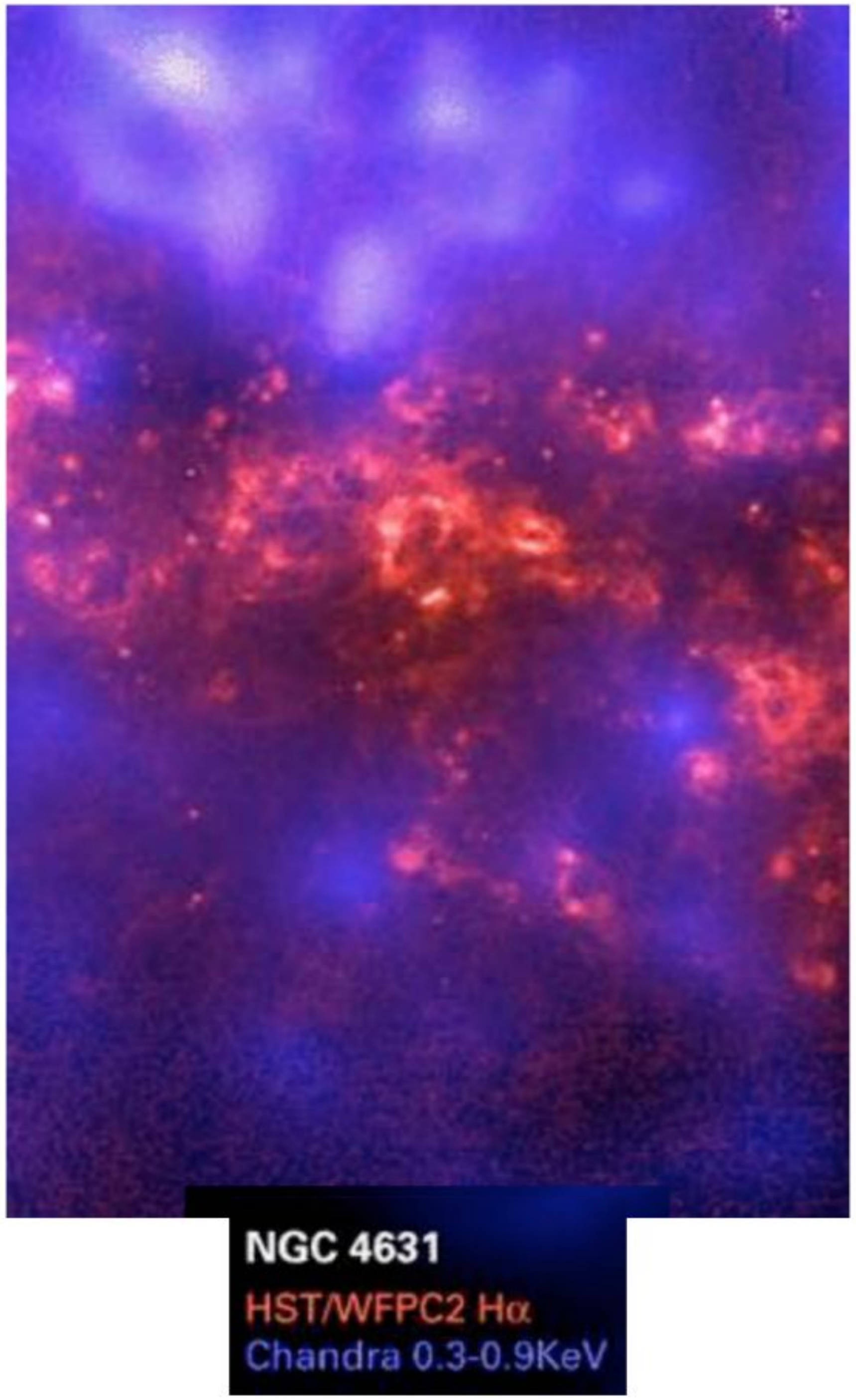
Diffuse ionized gas (DIG)

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



- Hα 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 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



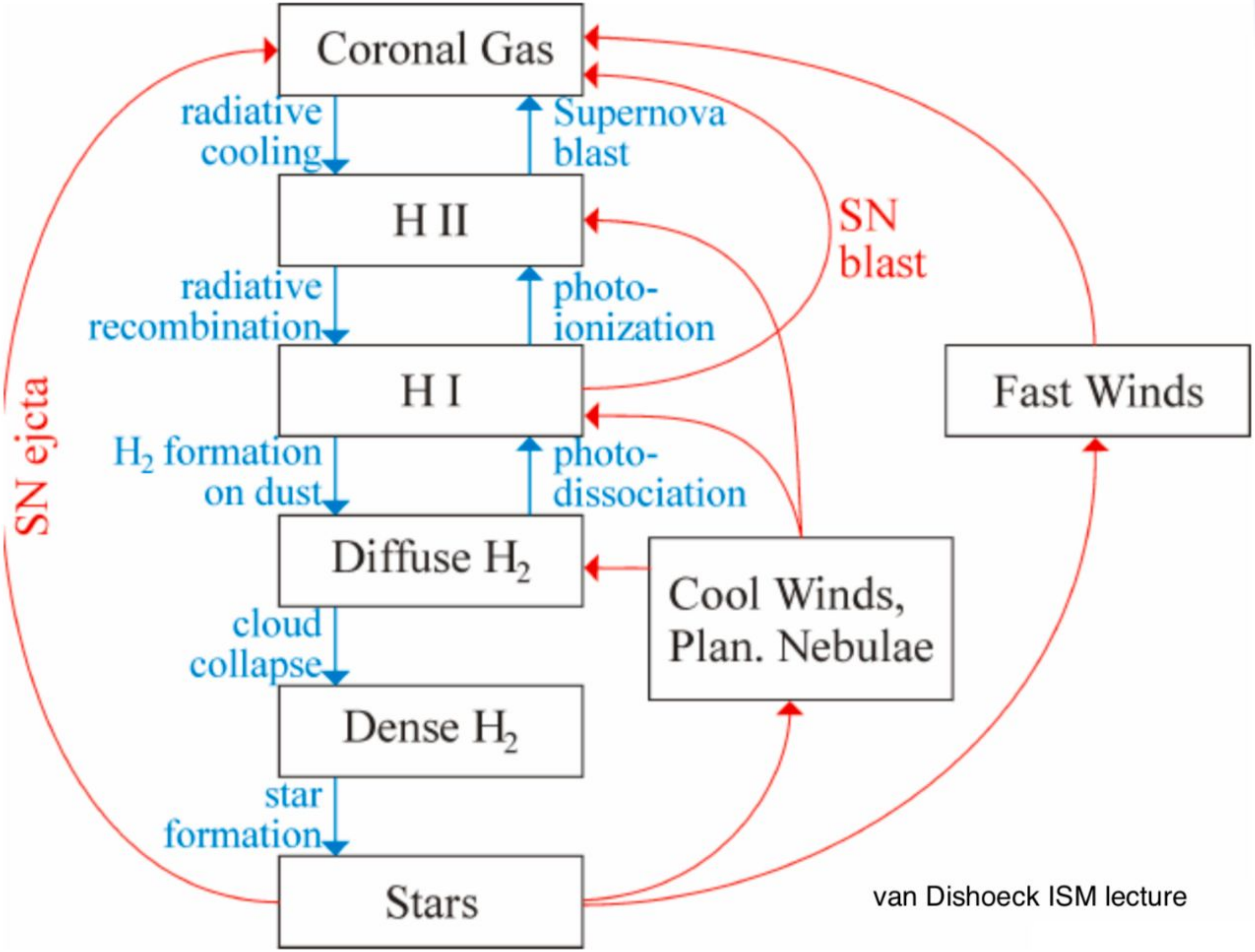
- In other galaxies, the DIG is observed to be in the form of discrete structures, such as loops, filaments, and shells.

  (which are not obviously associated with discrete HII regions)

- Responsible for producing a faint but pervasive H α emission.
- The observed H α luminosities of the DIG are considerable and account for 30%-50% of the total H α emission of each galaxy.

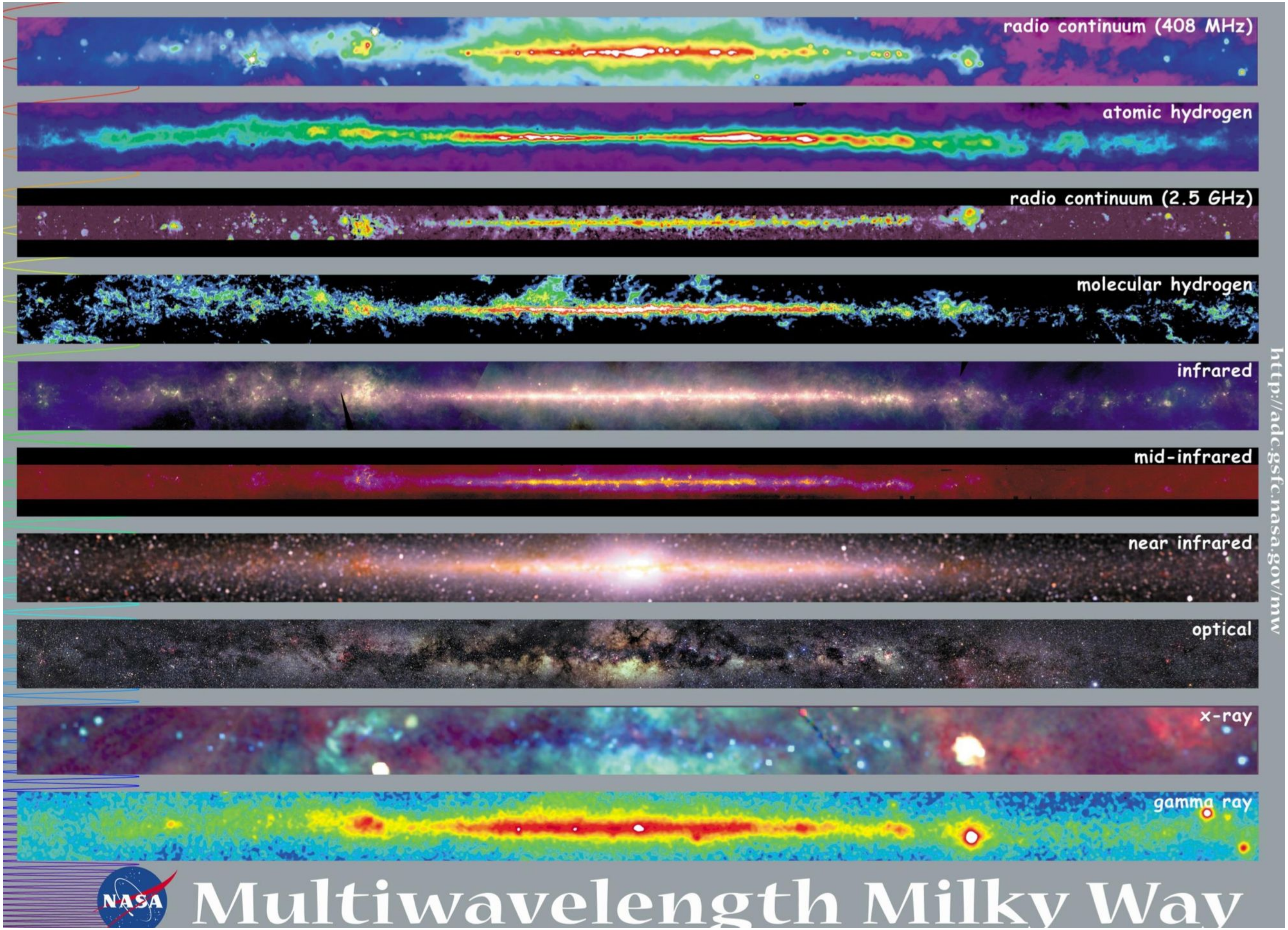
(Ferguson et al. 1996)

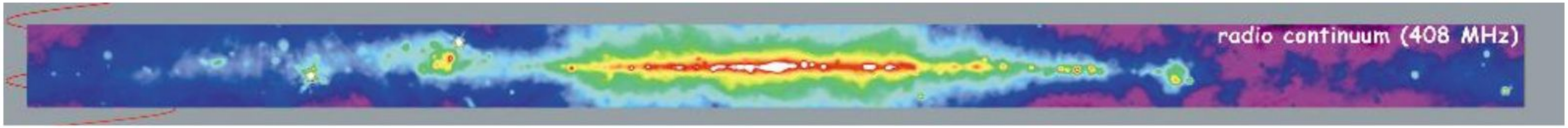
The ISM in general



van Dishoeck ISM lecture

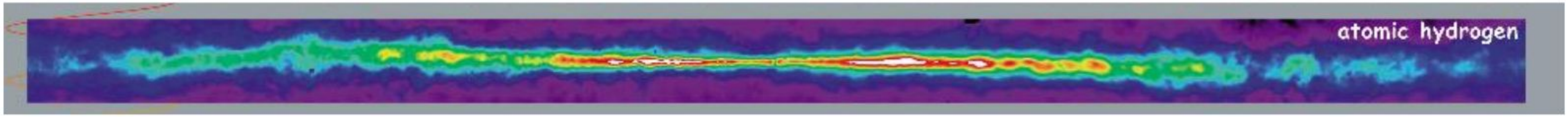
How do we observe the ISM?



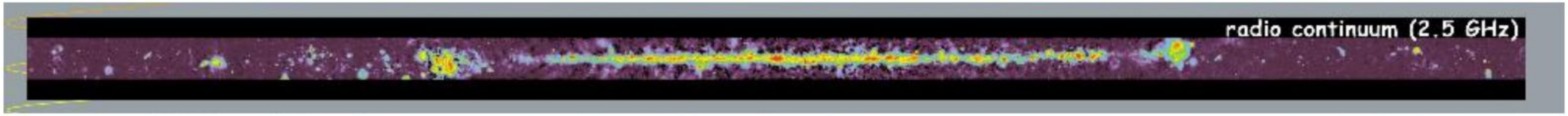


Synchroton radiation

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

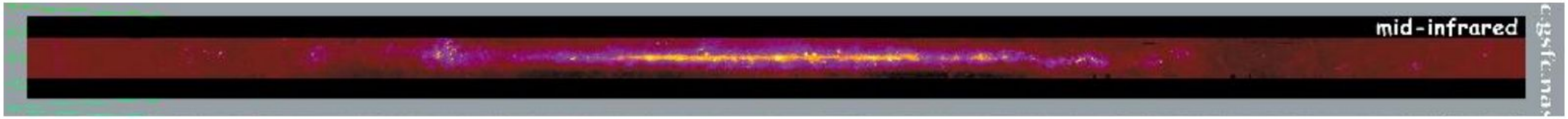


Synchroton radiation from electrons,
bremsstrahlung radiation from supernova remnants
and from hot gas in general

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