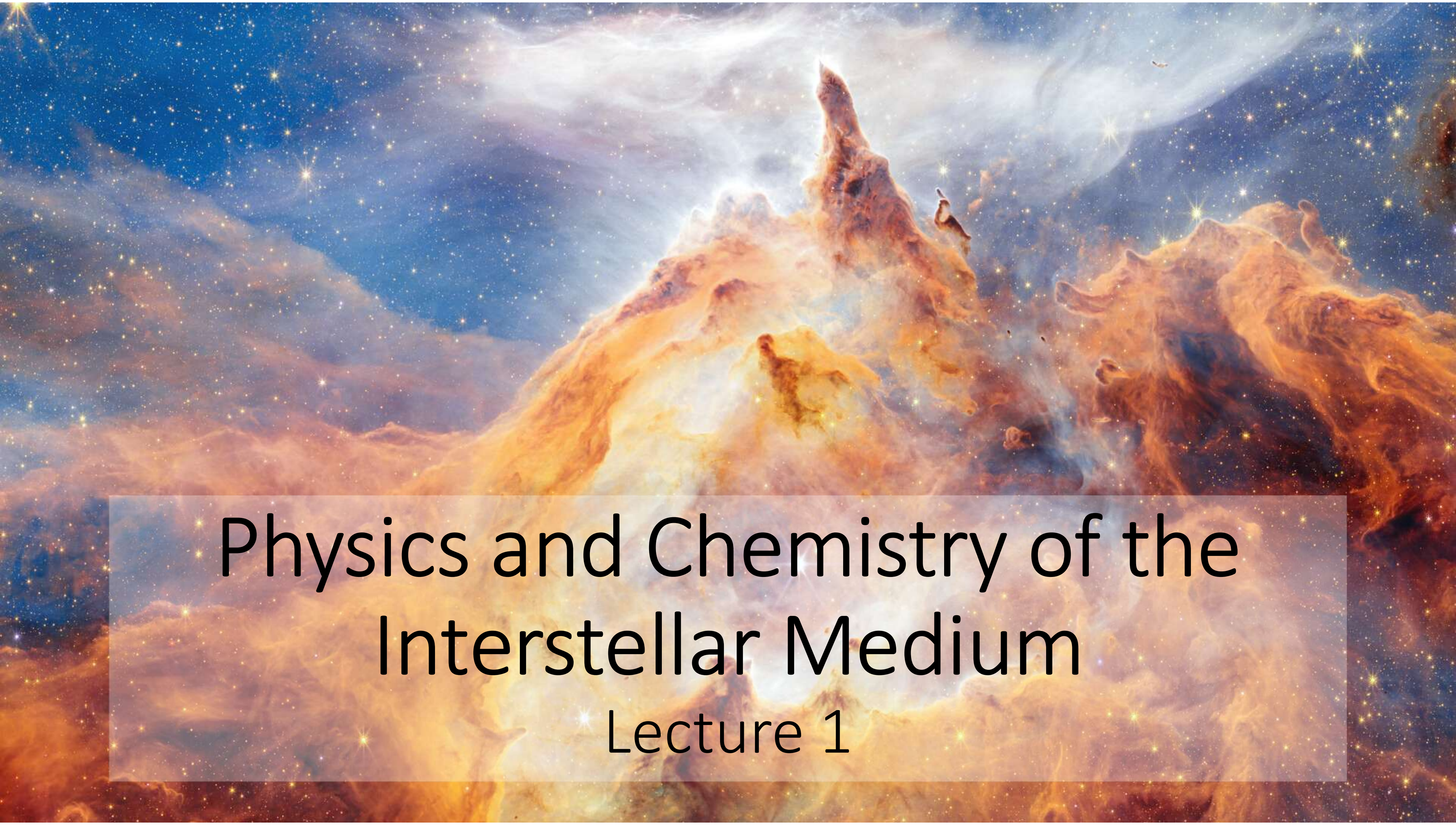
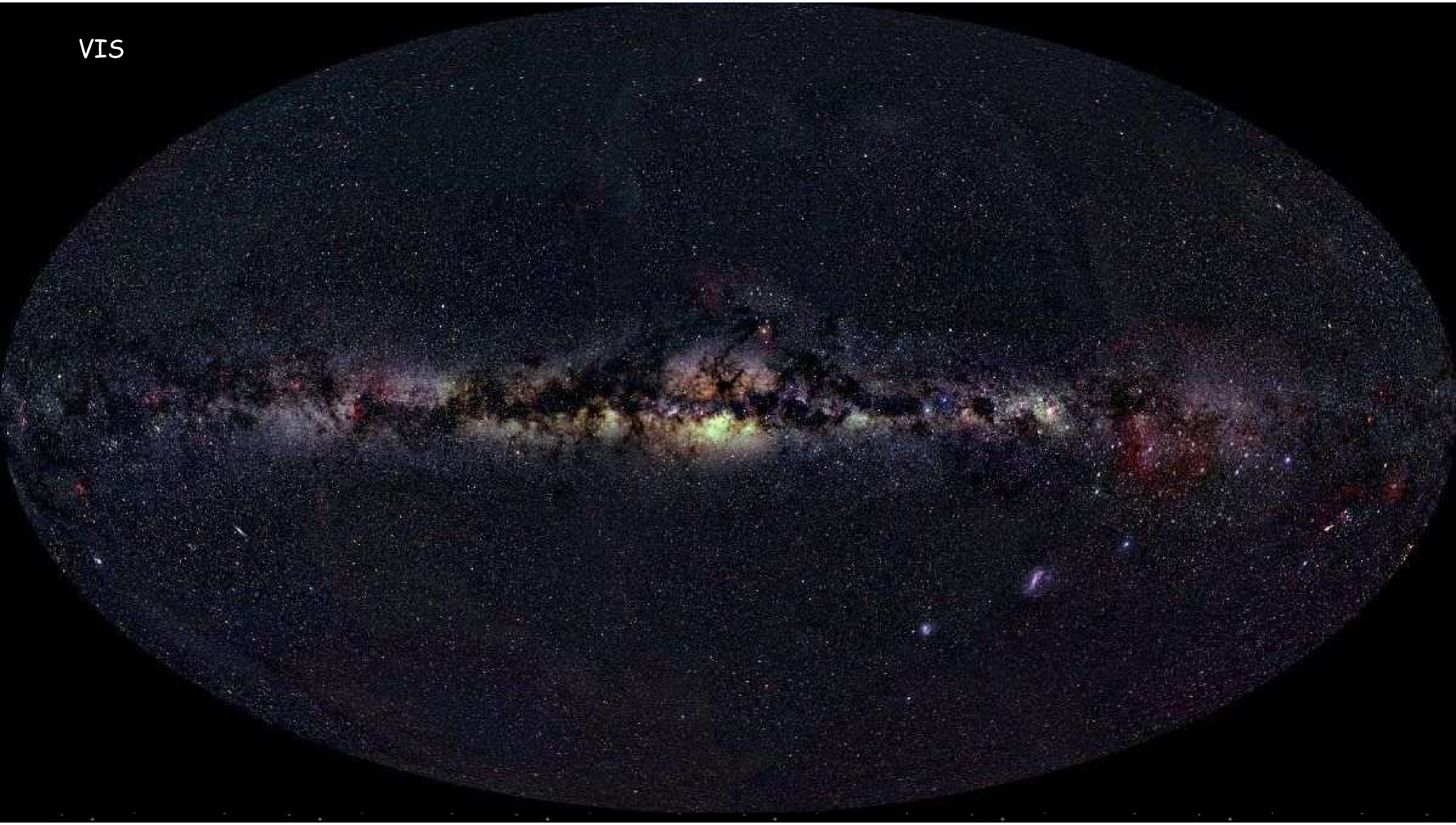


Physics and Chemistry of the Interstellar Medium

Lecture 1

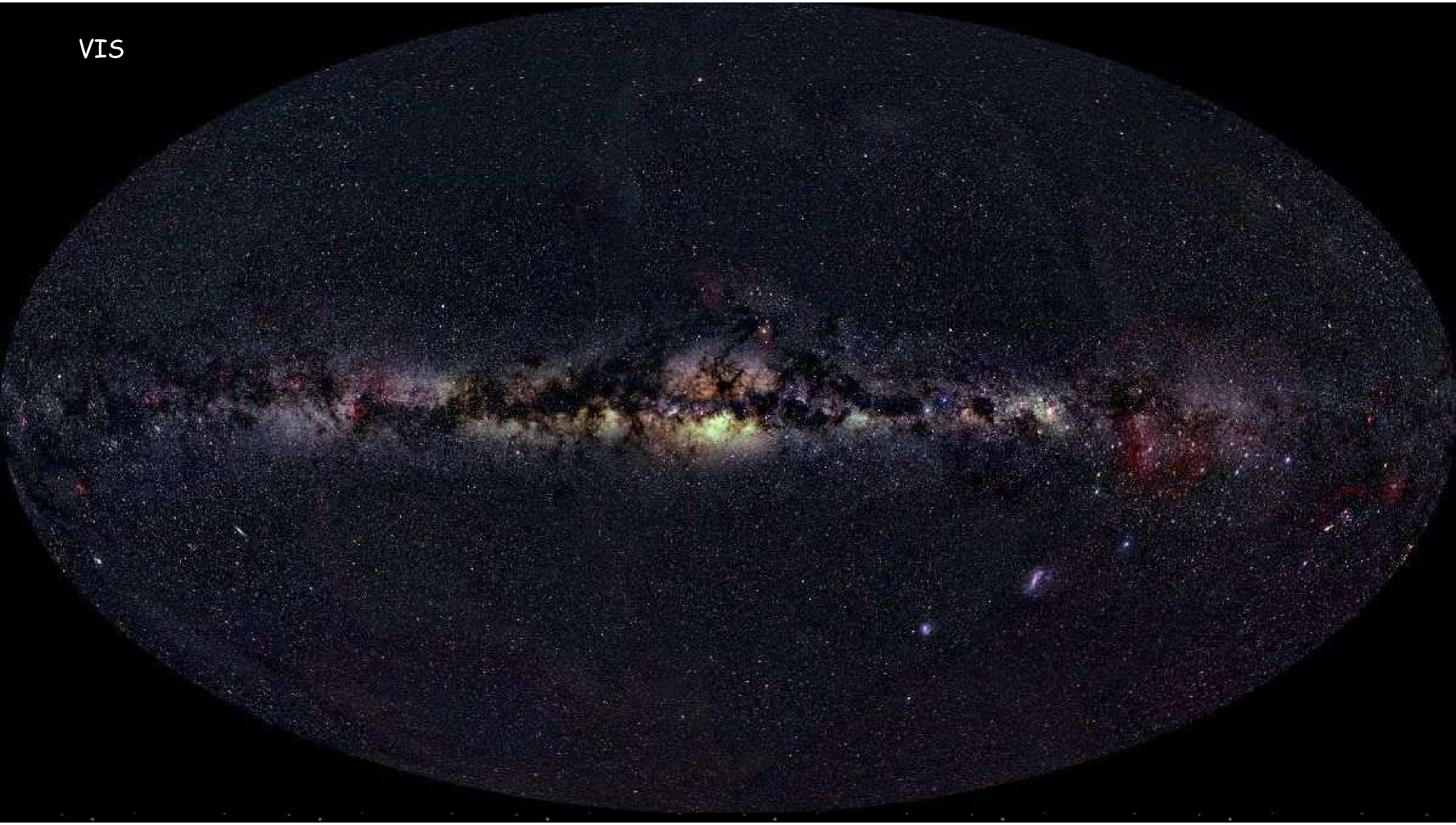
Motivation

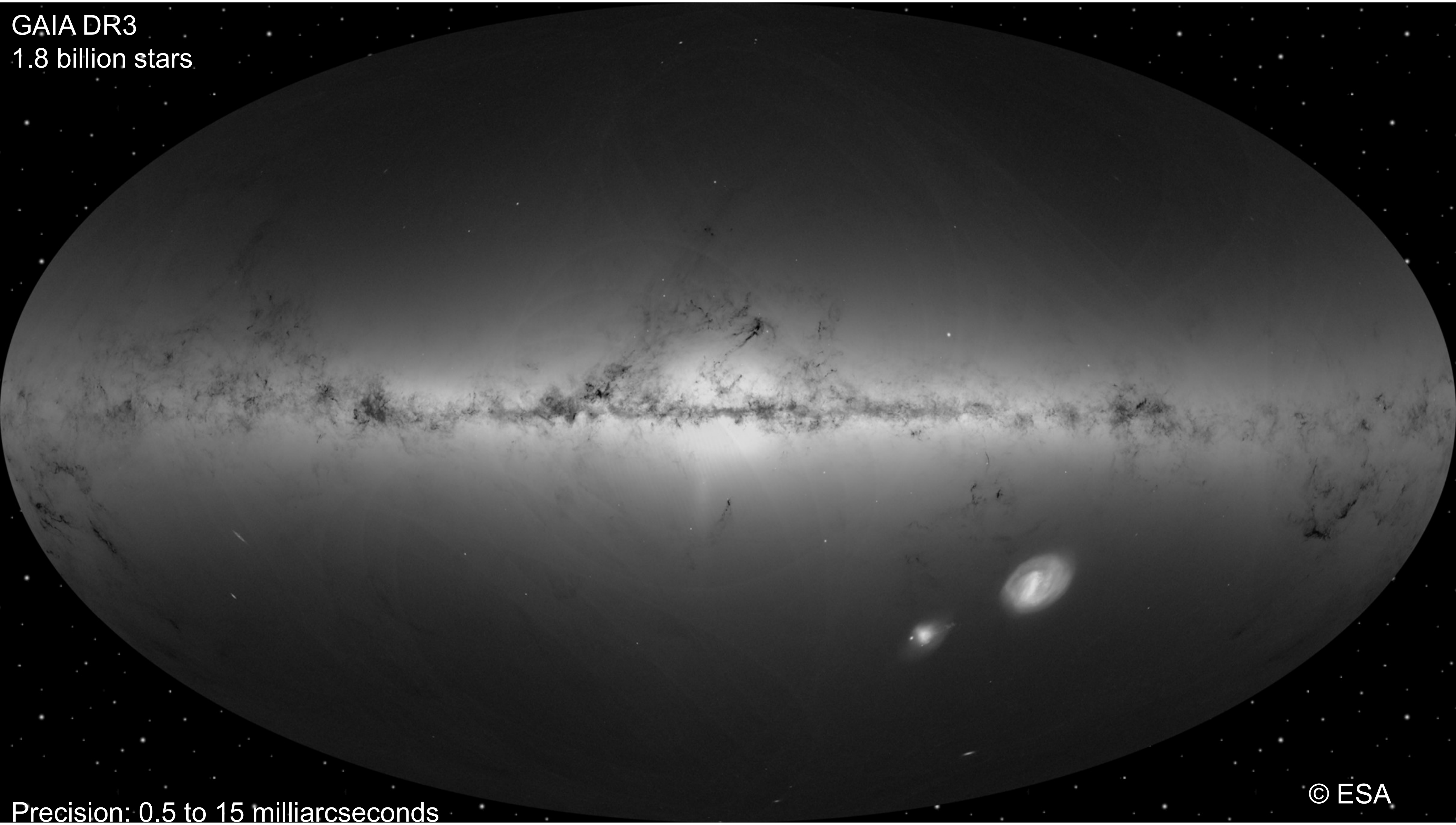
- What do we see on the sky?
  - Optical wavelengths:

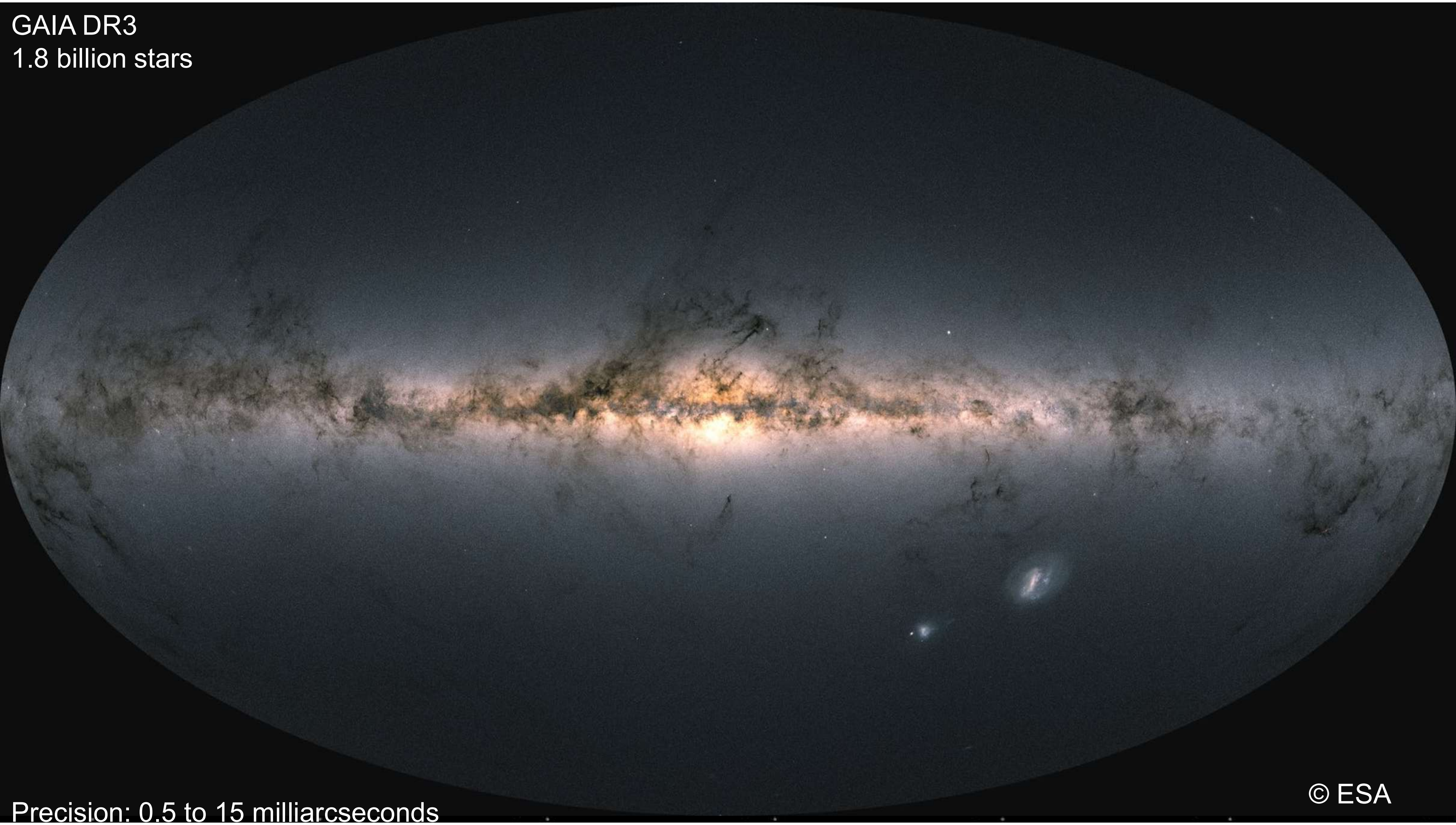

VIS

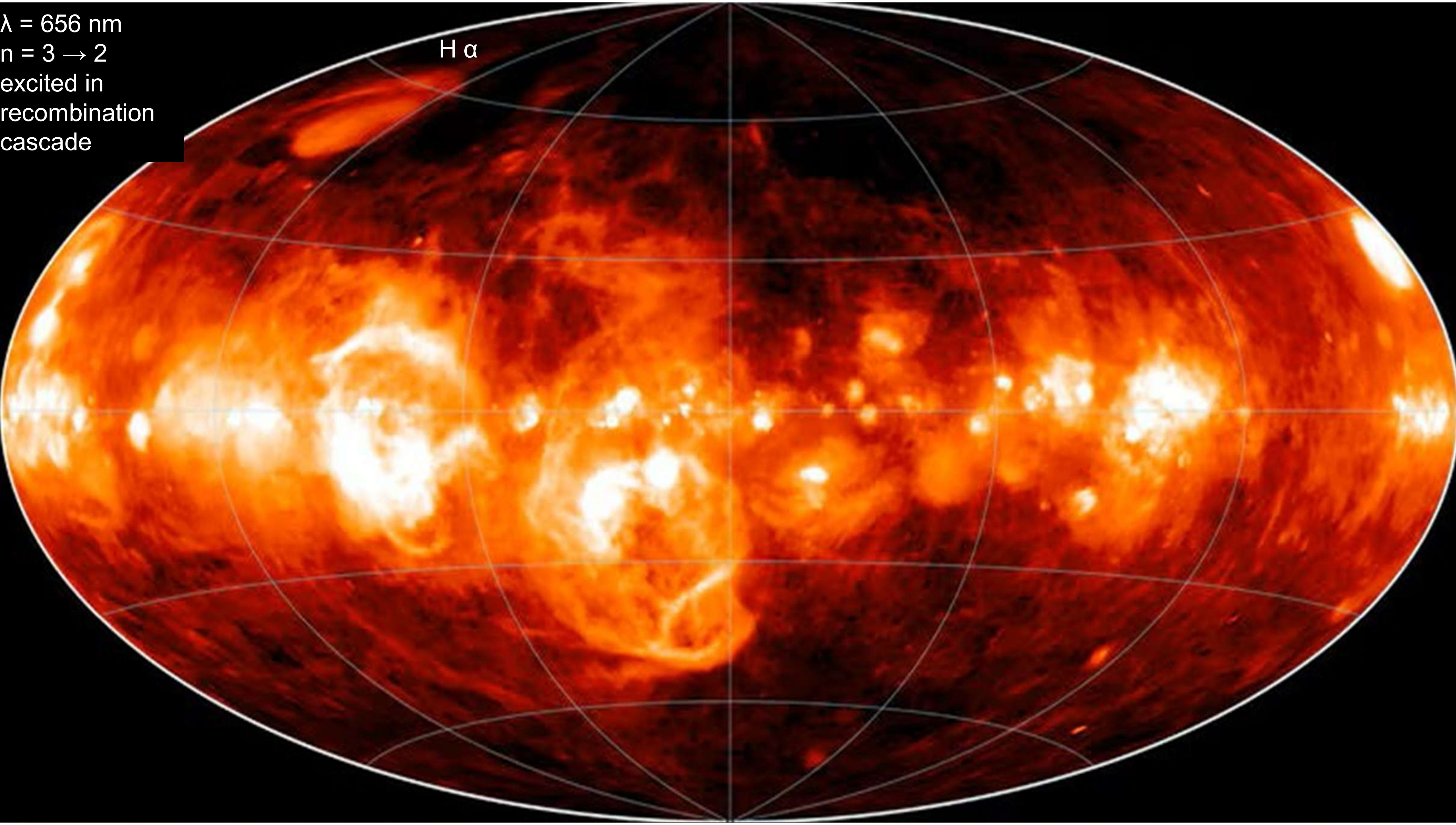
Motivation

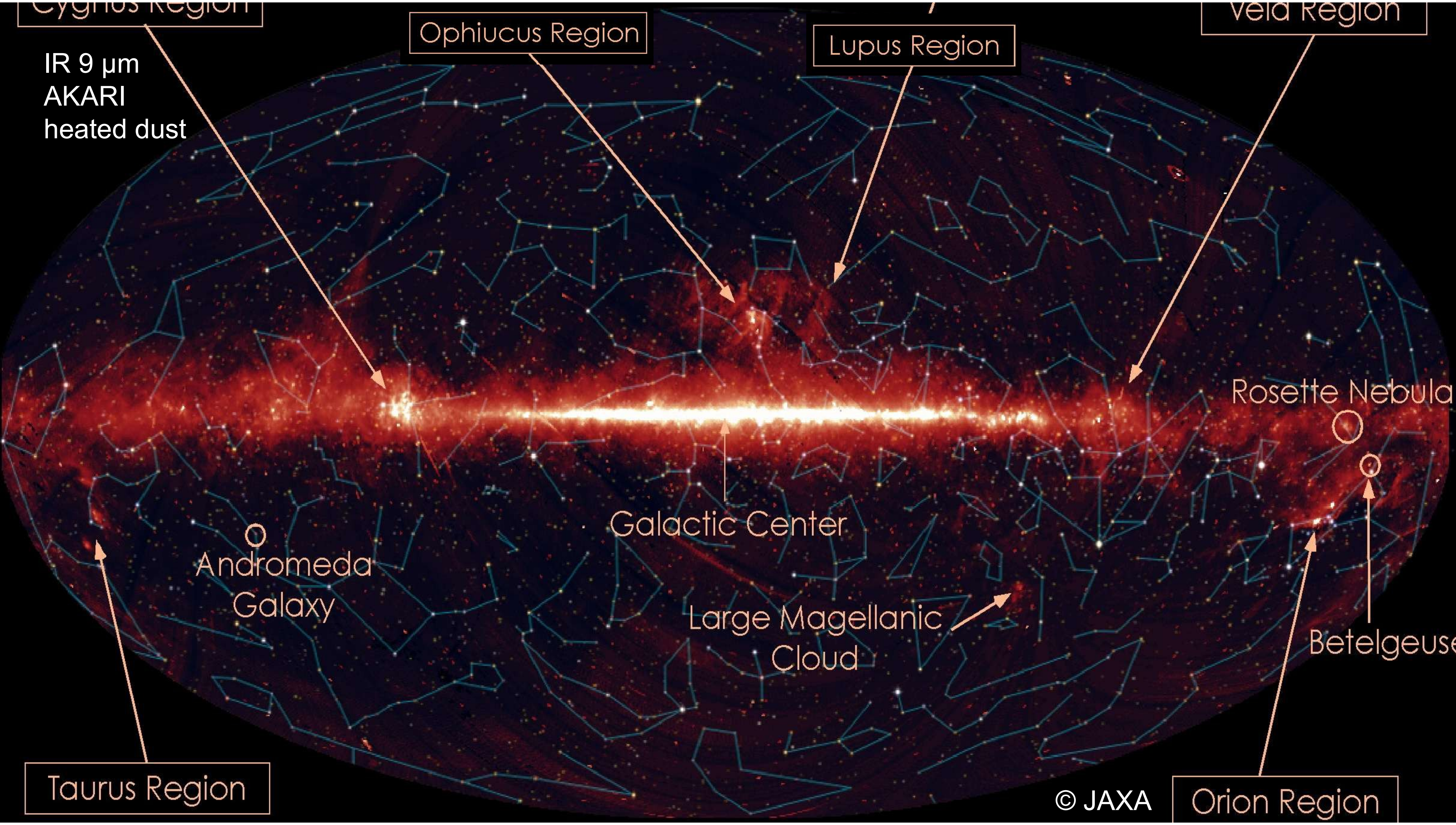
- What do we see on the sky?
  - Optical wavelengths:
  - All other wavelengths:
  - Covers the whole space between the stars

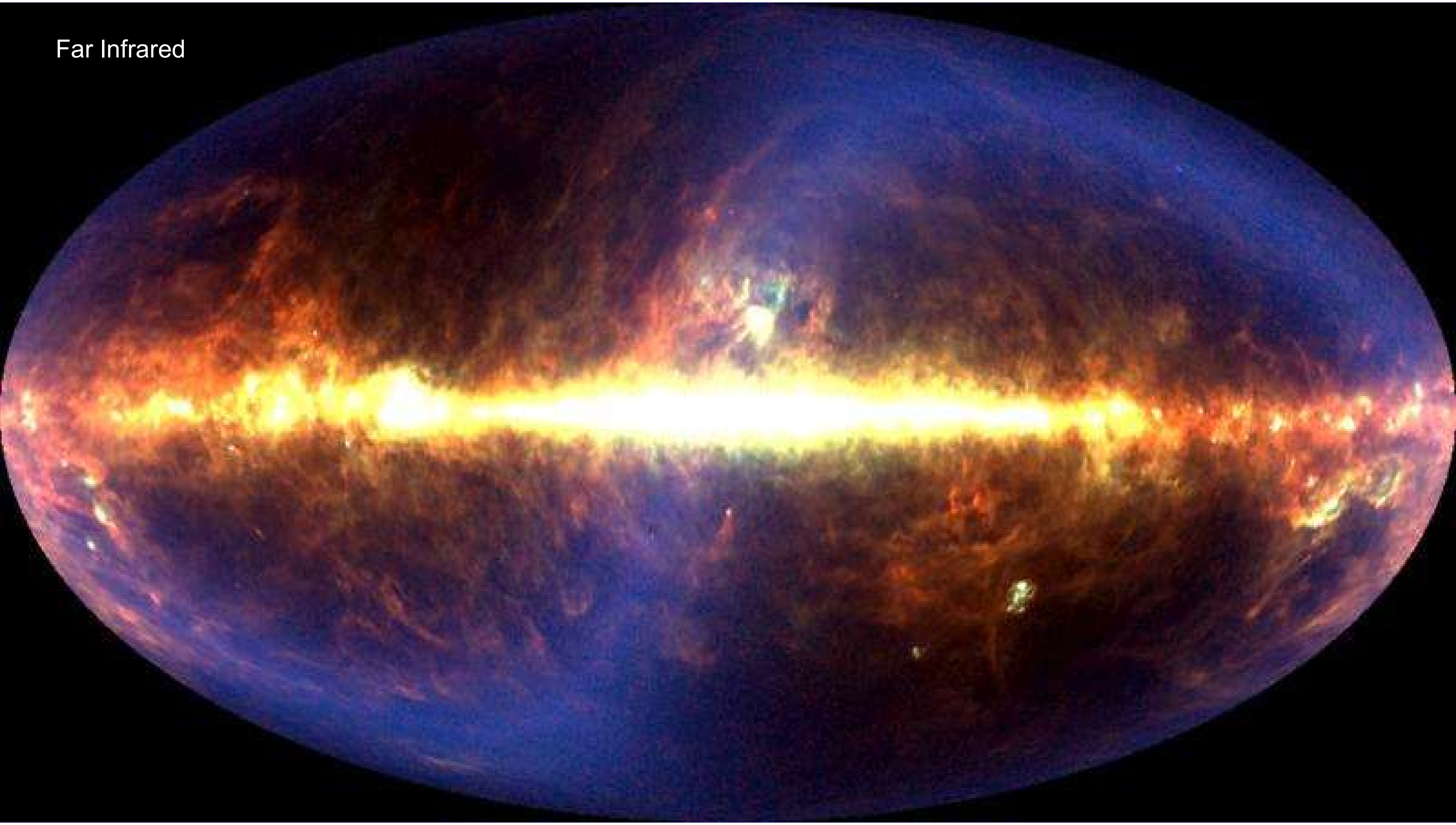

VIS

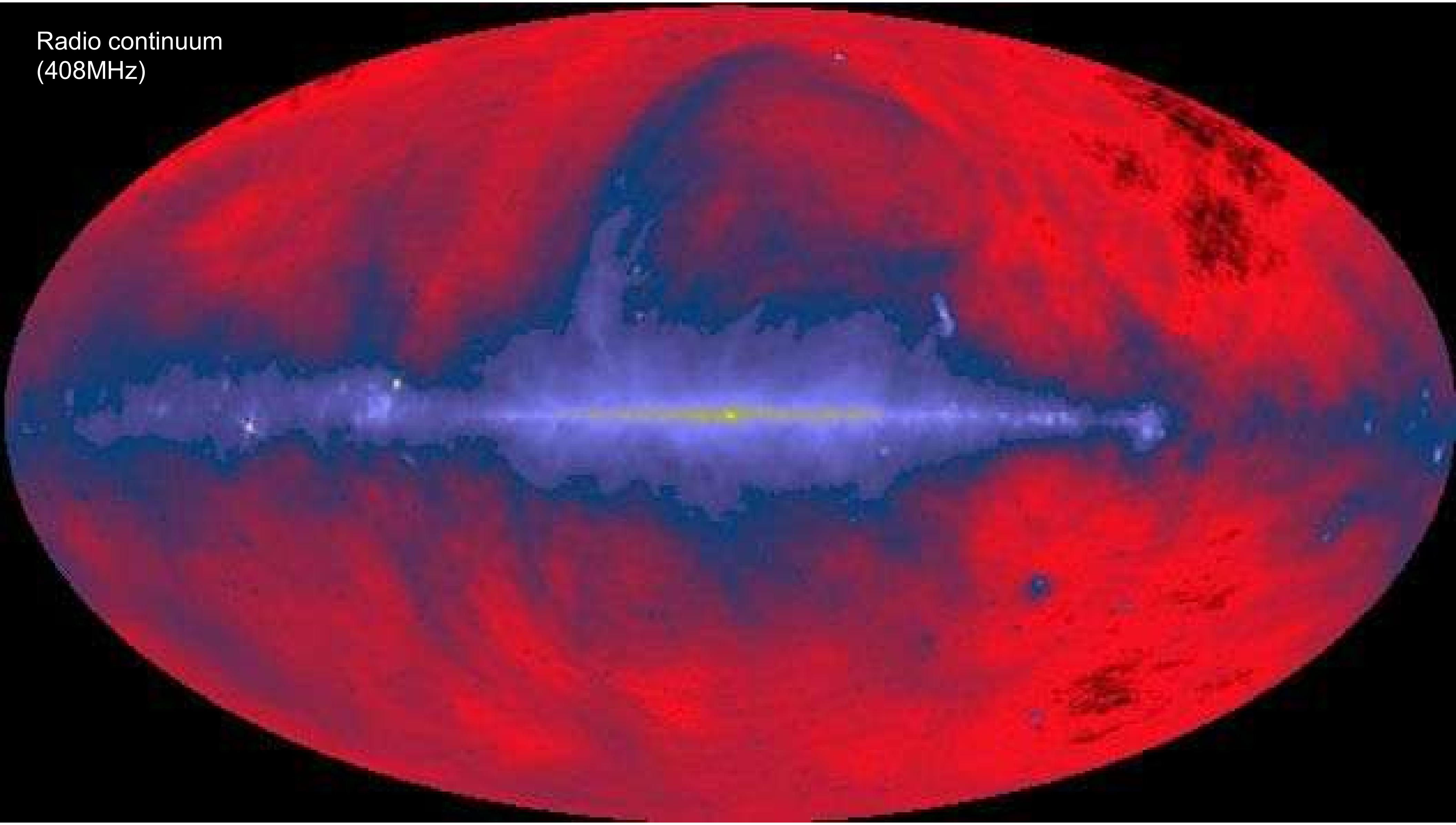

GAIA DR3
1.8 billion stars
Precision: 0.5 to 15 milliarcseconds
© ESA

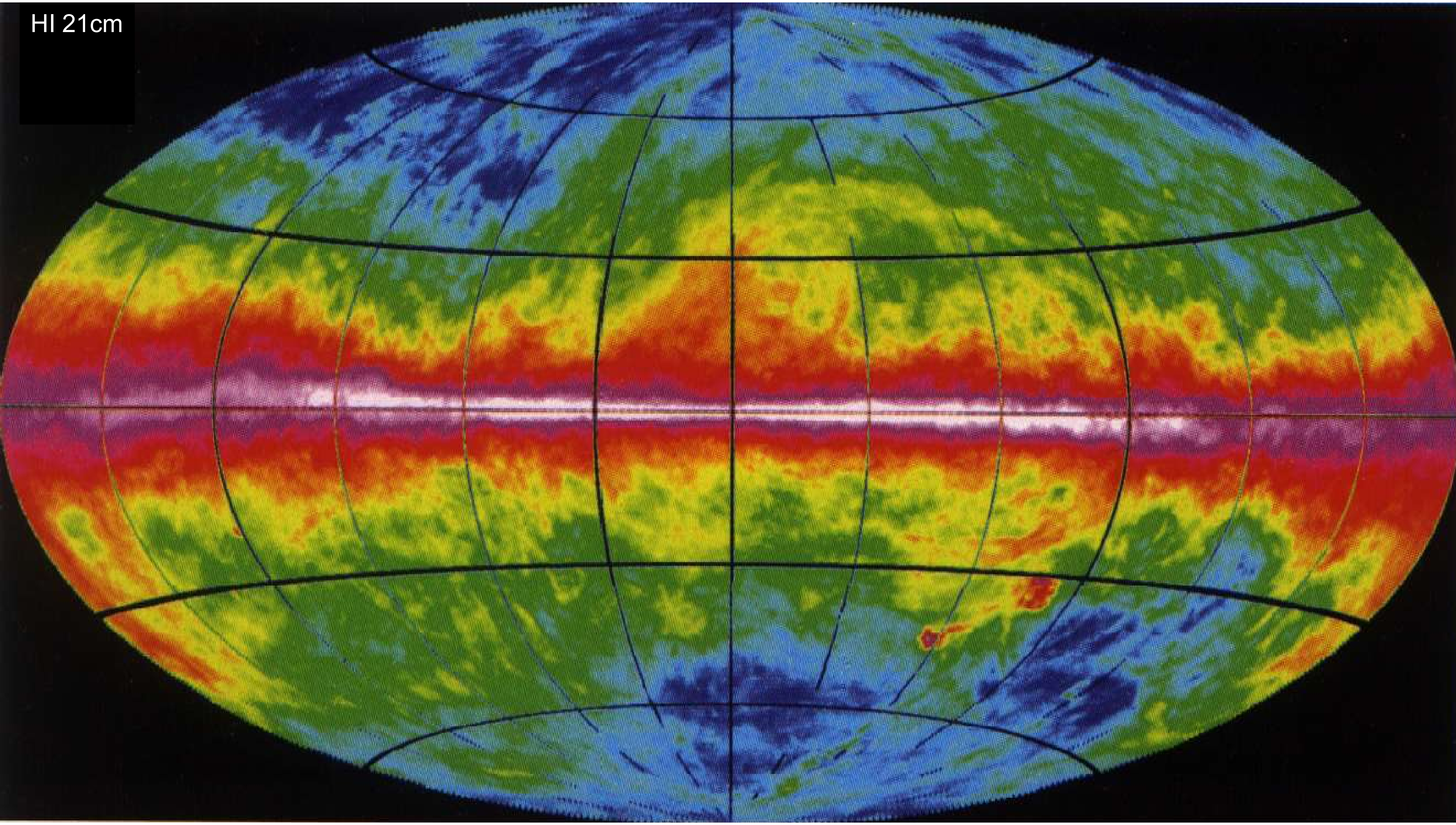

GAIA DR3
1.8 billion stars
Precision: 0.5 to 15 milliarcseconds
© ESA

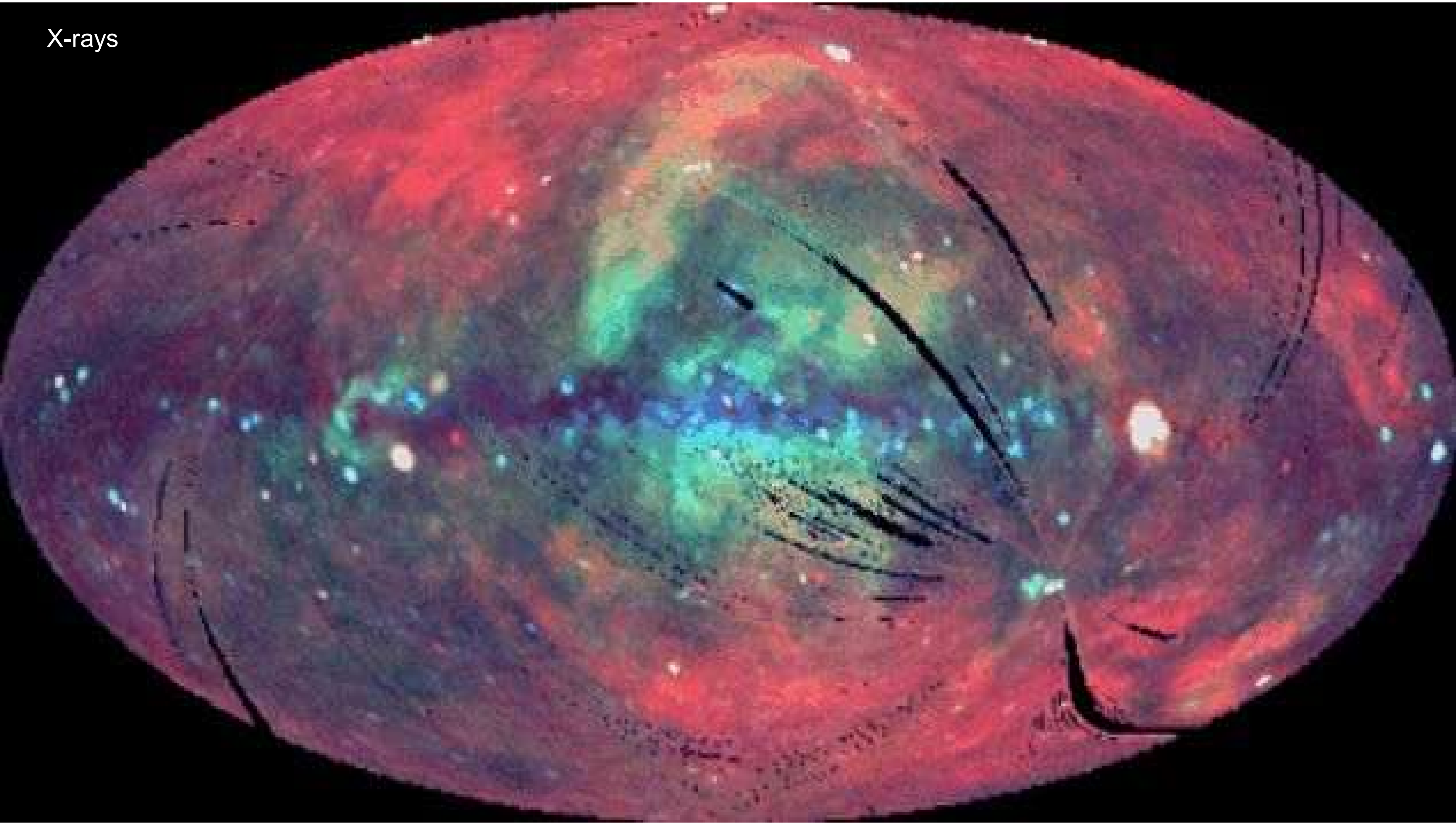

λ = 656 nm
n = 3 → 2
excited in
recombination
cascade
H α


Cygnus Region
IR 9 µm
AKARI
heated dust
Ophiucus Region
Lupus Region
Vela Region
Rosette Nebula
Galactic Center
Andromeda
Galaxy
Large Magellanic
Cloud
Betelgeuse
Taurus Region
© JAXA
Orion Region

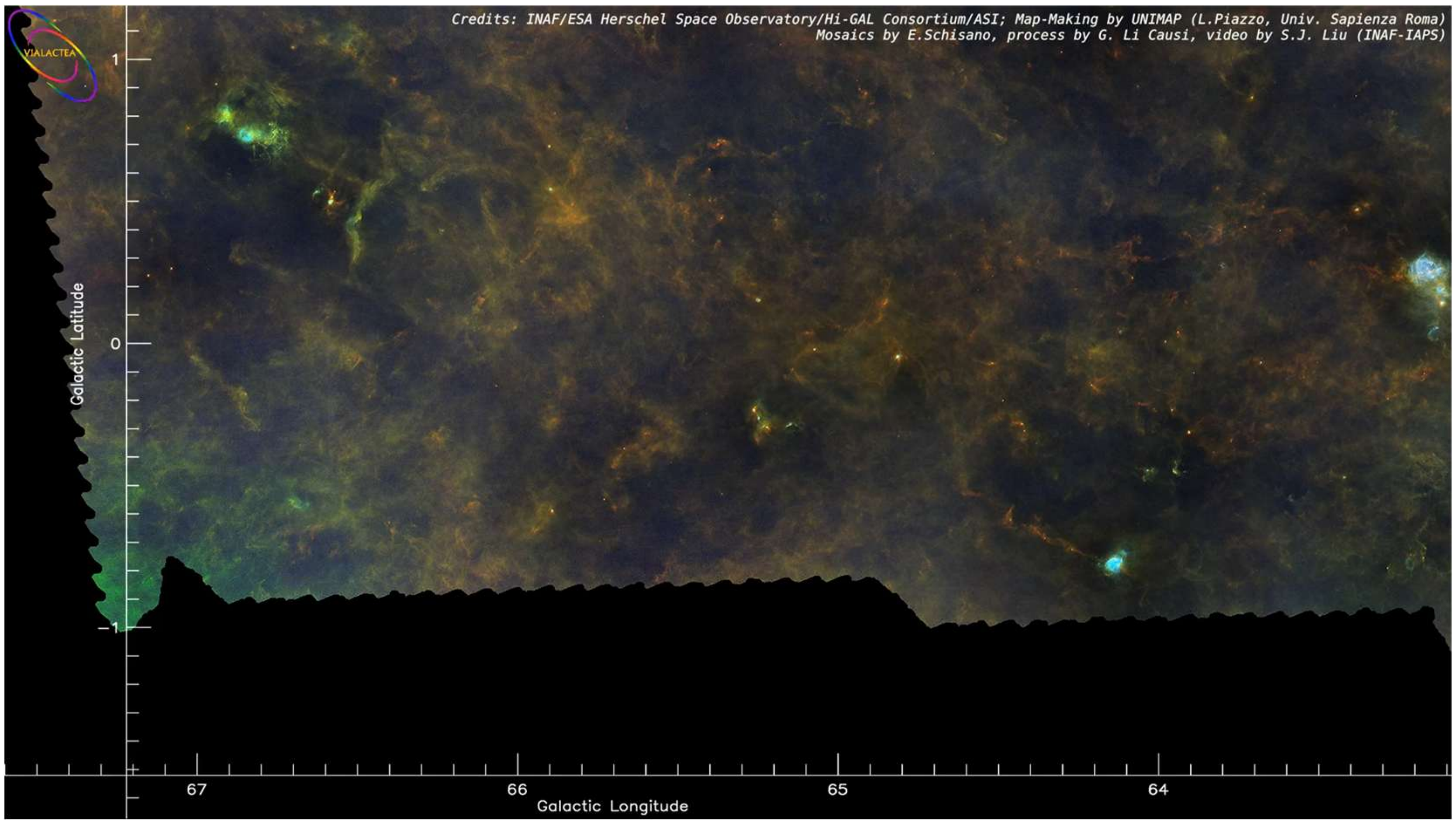

Far Infrared


Radio continuum
(408MHz)


HI 21cm


X-rays

HiGal - the Herschel infrared Galactic Plane Survey



Content

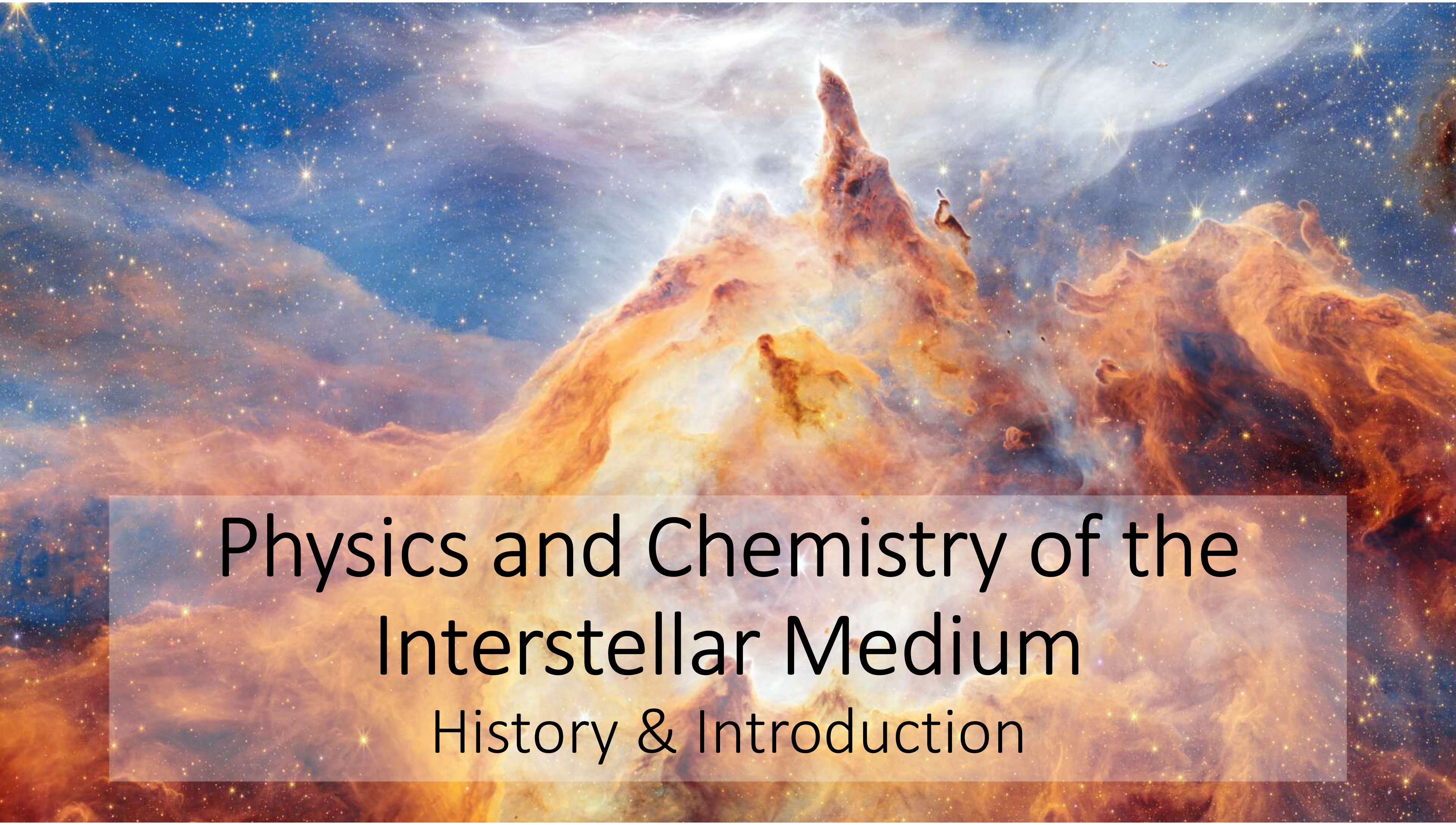
- History and Introduction
- The dynamics of the interstellar gas
  - Hydrodynamics and magnetohydrodynamics
  - Hydrodynamic instabilities
  - Turbulence
- Radiation
  - Line radiation
  - Continuum radiation
- Interstellar dust
  - Scattering theory
  - Composition

Content

- Energy balance
  - Gas heating
  - Cooling processes
  - Thermal instability
  - Phases of the ISM
- Special interstellar regions
  - HII regions
  - Photon-dominated regions
  - Interstellar shocks and supernova remnants
  - Intergalactic gas

The Physics and Chemistry of the Interstellar Medium

- Literature:
  - B. T. Draine, Physics of the Interstellar and Intergalactic Medium
  - M. Bartelmann, Theoretical Astrophysics
  - A.G.G.M. Tielens, The Physics and Chemistry of the Interstellar Medium
  - K. Lang, Astrophysical Formulae



Physics and Chemistry of the Interstellar Medium

History & Introduction

History and Introduction

- The history of nebulae
  - Dust extinction
  - Gas absorption lines
  - Radio astronomy
    - Nonthermal radiation
    - HI
    - CO
    - interstellar molecules
  - IR astronomy
    - PAHs

NGC 6726 Credits: Loke Kun Tan (StarryScapes)

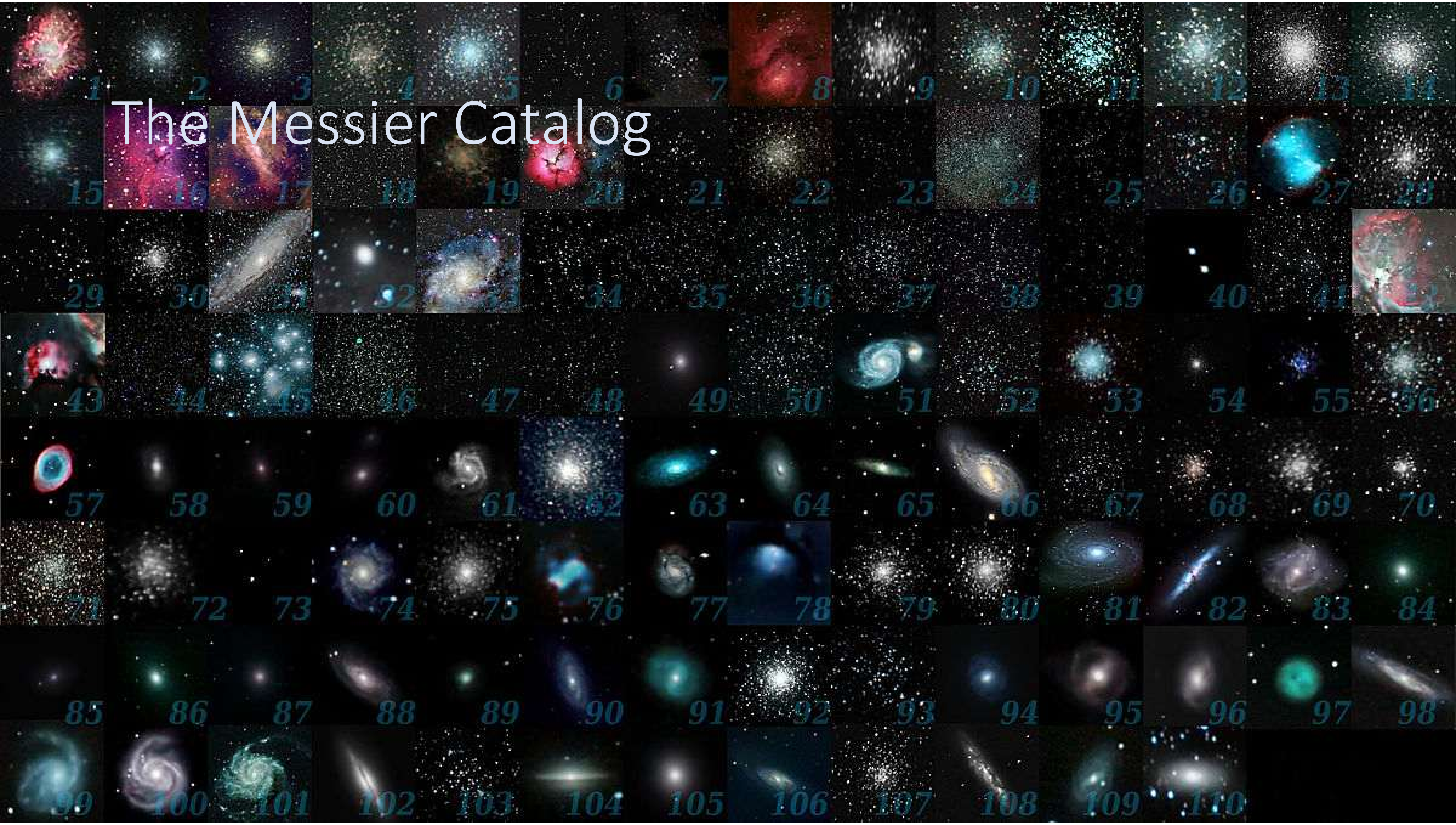
Historical Approach

Nebulae

- **1781 Charles Messier**:
  catalogue of “Nebulae”

- **1900-1920**:
  identification of some nebulae
  as interstellar clouds
  (only 6 Messier-Nebulae)

The Messier Catalog



Interstellar nebulae

1859 Wilhelm Tempel: Nebulosity around stars in Plejades

1912 Vesto Slipher:
spectroscopy of the nebulosity shows stellar spectrum

→ reflected stellar light

→ Reflection nebulae

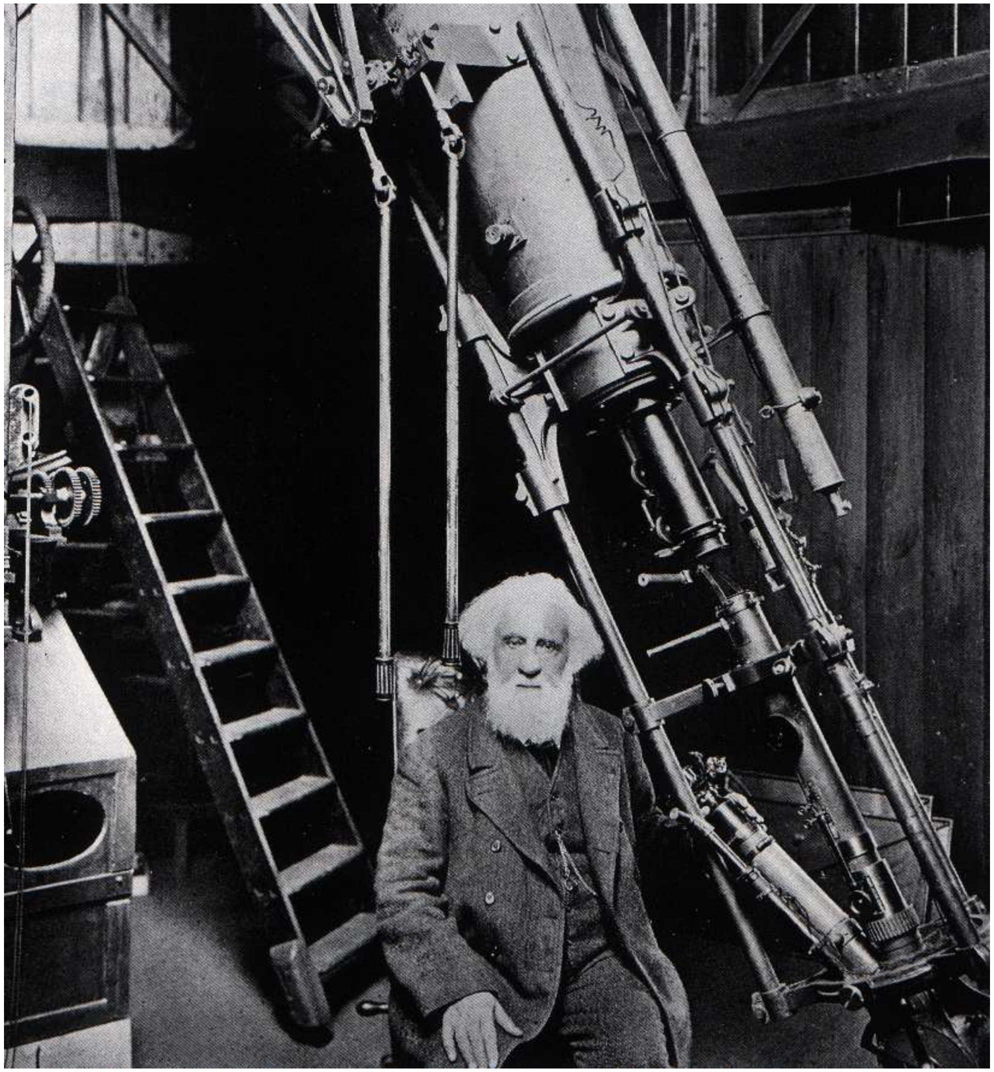
Interstellar nebulae

1864 William Huggins:

Spectroscopy of Nebulae

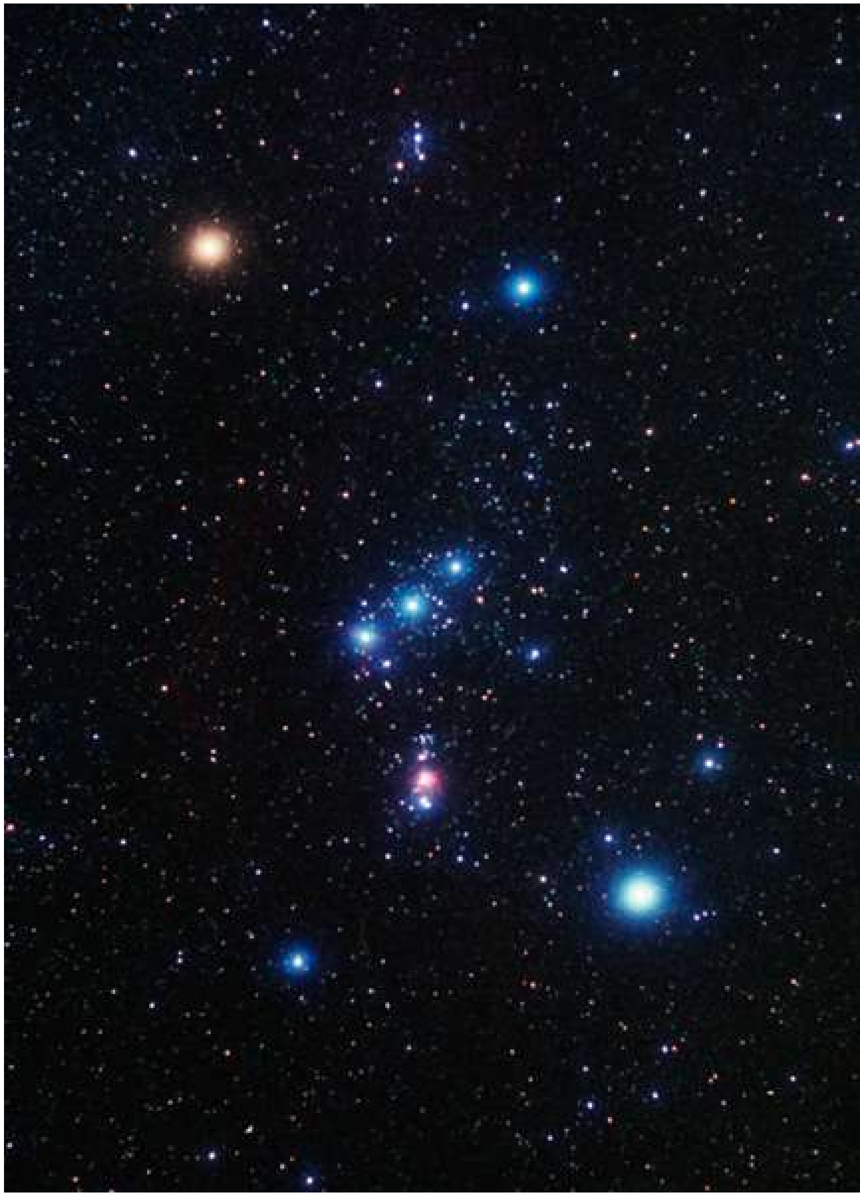
→ about 1/3 showing only line emission

(2/3 stellar spectra = external galaxies or reflection nebulae)



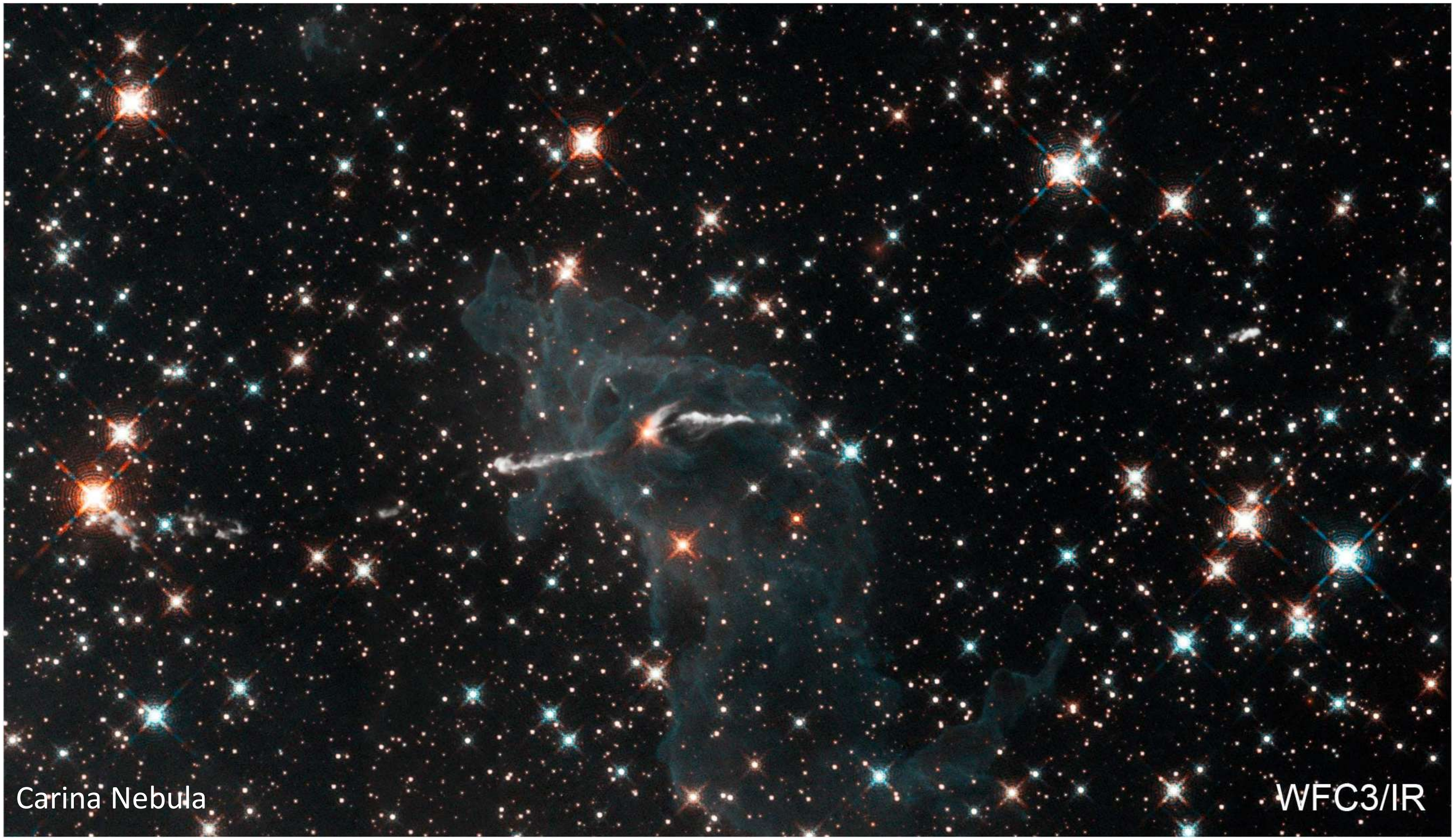
Interstellar nebulae

Emission nebulae




NASA, ESA, CSA / Science leads and image processing: M. McCaughrean, S. Pearson

Interstellar nebulae



Interstellar nebulae

Emission nebulae

- Comparison with spectra measured 1859 by Bunsen & Kirchhoff

→ Gaseous emission nebulae

  - Identification of elements in gas
  - First interstellar abundances

- 1928 Ira Bowen identifies the "Nebulium" lines as transitions of highly ionized gas ([NII], [OII],[OIII])

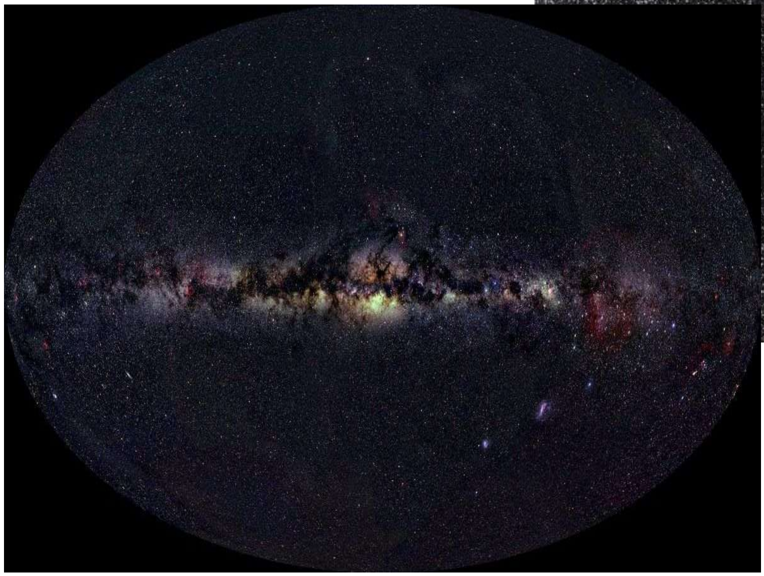
→ Emission nebulae are

  - Internally heated
  - Mainly ionised H (HII)

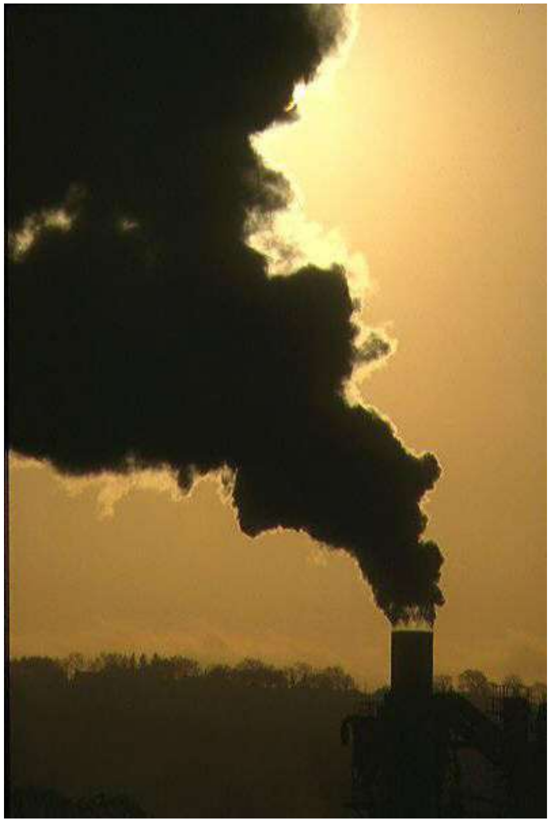
Dark Clouds

- **1907-1923**
  Edward E. Barnard:
  Catalogue of photographs of dark clouds

- still considered as "holes in the sky" at that time



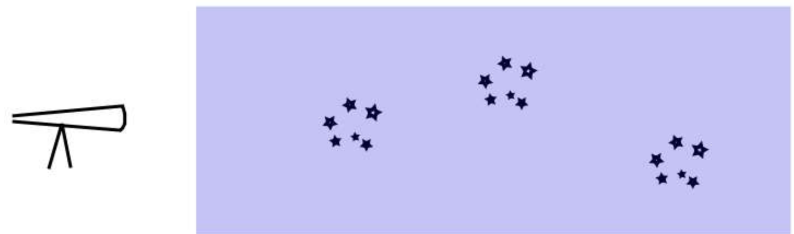
Dark Clouds



Interstellar Extinction

- Even until the late
    - 1920s the existence
      of a general ISM was not accepted

- **1930 Trümpler**:
    - Distant weak clusters
      are larger than nearby
      clusters



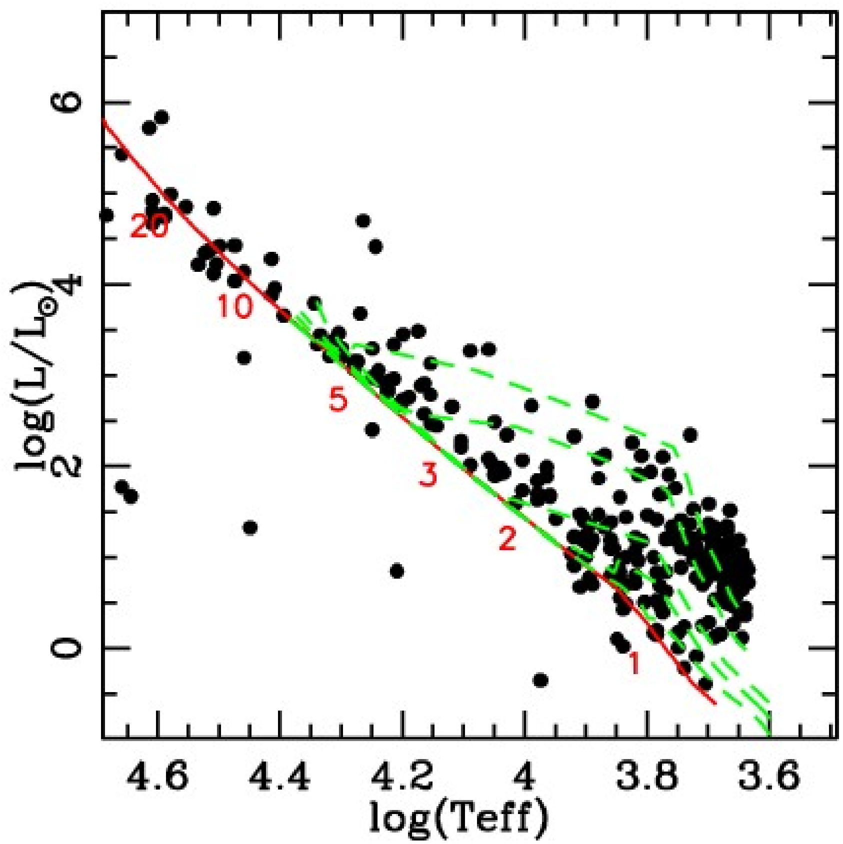
→ Distance estimate from apparent brightness wrong

→ Brightness reduction not only by distance, but also by extinction

Interstellar Extinction

- **1930 Trümpler**:
  - Distant weak clusters are larger than nearby clusters
  - Distant clusters are too red for the main sequence

→ Brightness reduction by extinction accompanied by simultaneous redenning

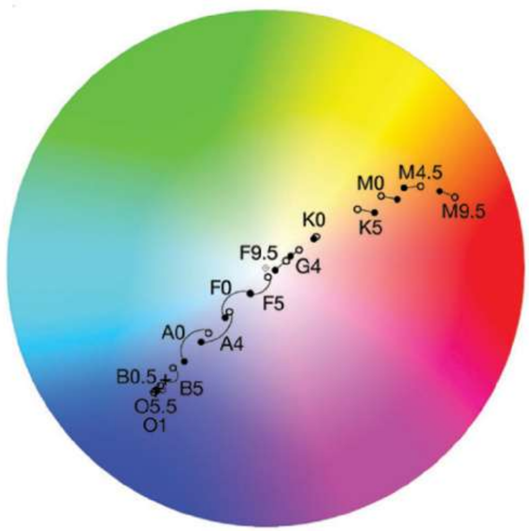


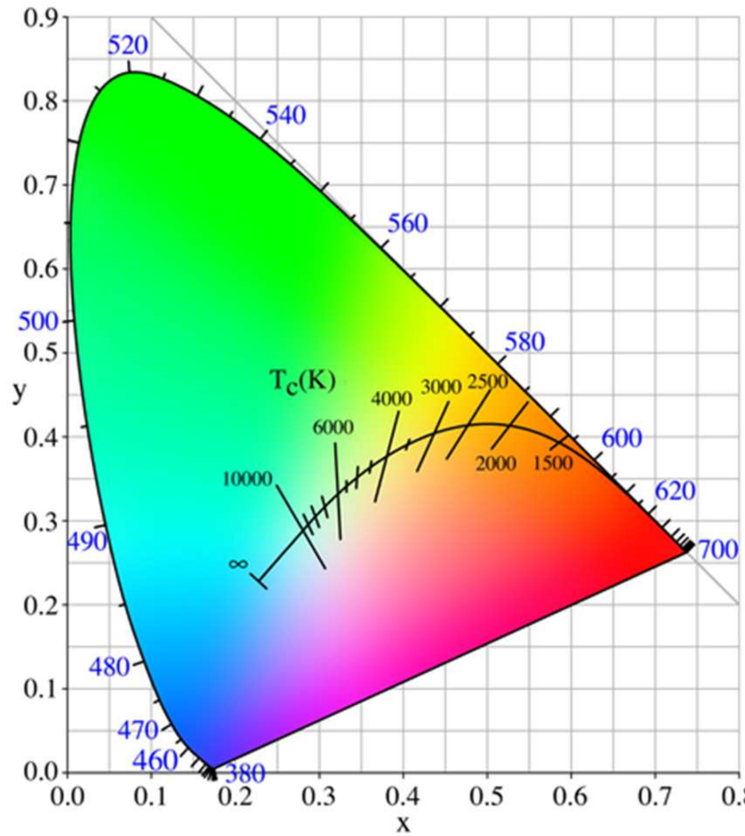
HR diagram of open clusters

Interstellar Extinction

- **1930 Trümpler**:
  - Distant weak clusters are larger than nearby clusters
  - Distant clusters are too red for the main sequence

→ Brightness reduction by extinction accompanied by simultaneous redenning



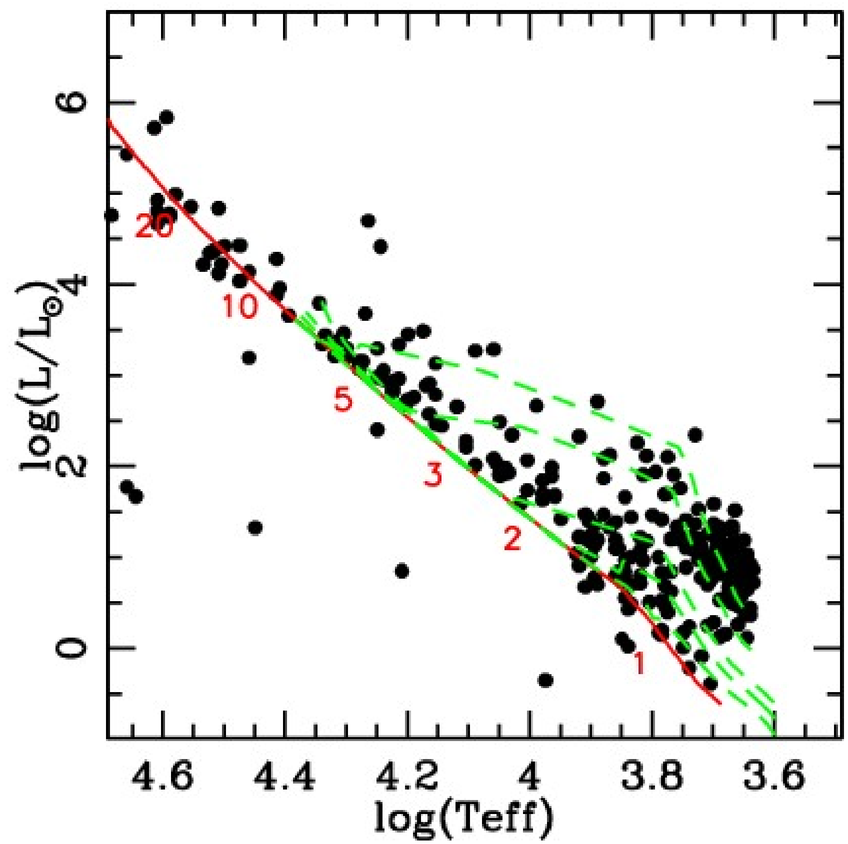


Color-Temperature-Relation

Interstellar Extinction

- **1930 Trümpler**:
  - Distant weak clusters are larger than nearby clusters
  - Distant clusters are too red for the main sequence

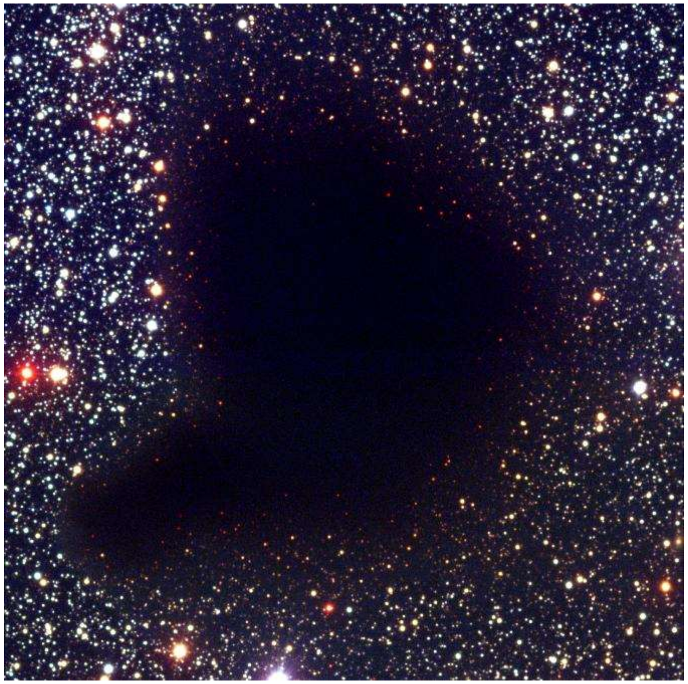
→ Brightness reduction by extinction accompanied by simultaneous redenning



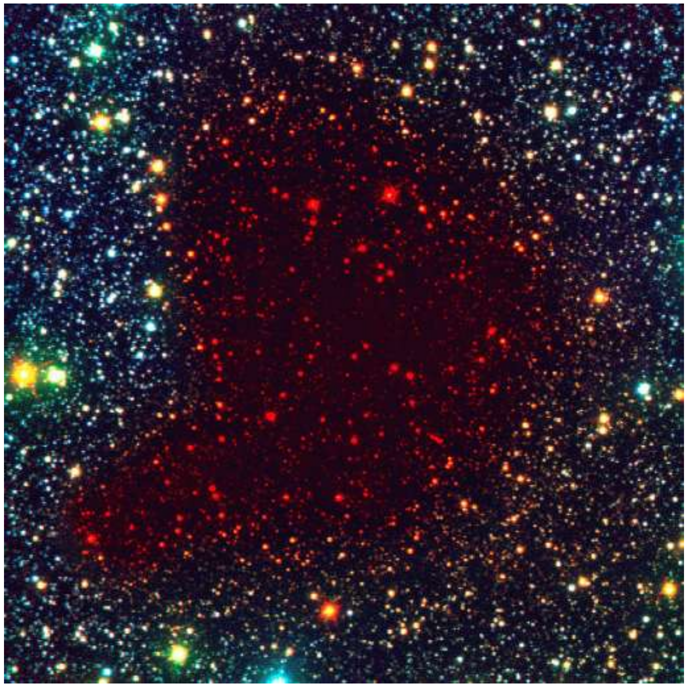
HR diagram of open clusters

Interstellar Reddening

Wavelength dependent extinction = reddening



Barnard 68: VIS



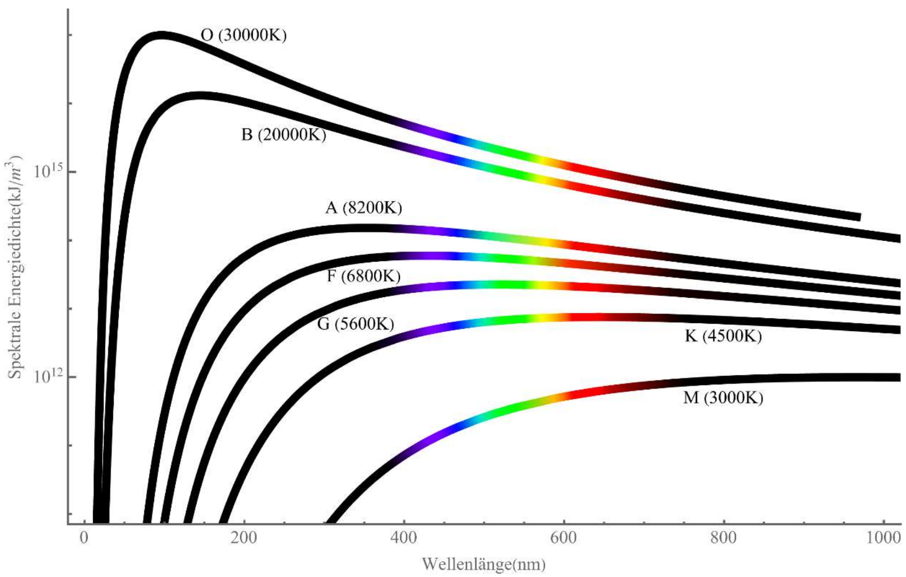
470, 870, 2200 nm

Description

- Wavelength dependent extinction:

- Normalization to λ=550nm (V-filter): A_V - visual extinction
  - Typical value:
    (Bohlin, Savage & Drake 1978)
- Reddening: B-filter: λ =350nm
  - Typical value in diffuse clouds: R=3.1
    (Johnson 1968, Lee 1968, Martin 1971, Harris 1972)

Color Index

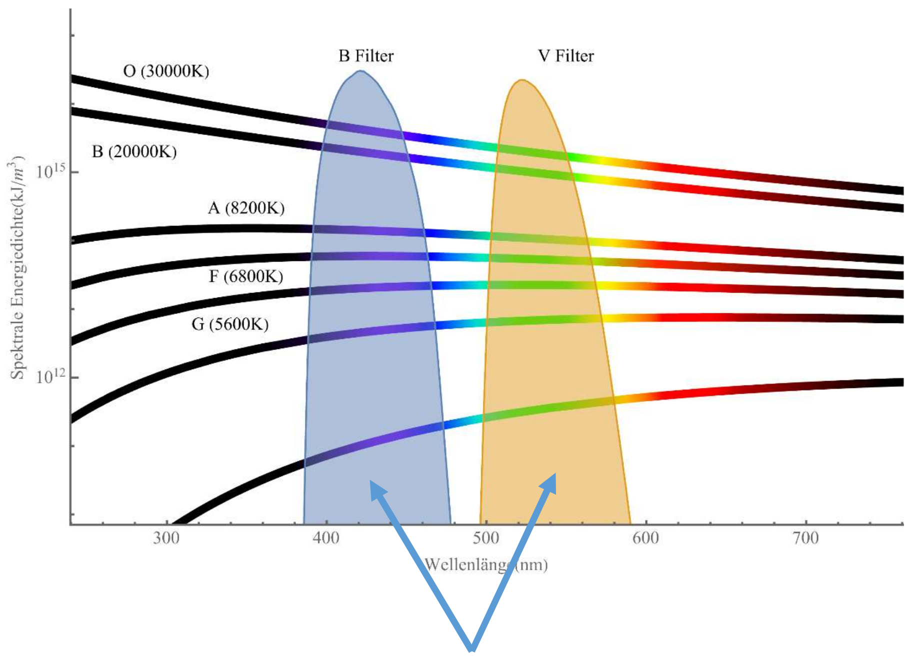


- Difference between B and V brightness

$$B - V = m_B - m_V$$

- Negative index: blue(ish)
- Positive index: red(ish)

Farbindex



Filter curves

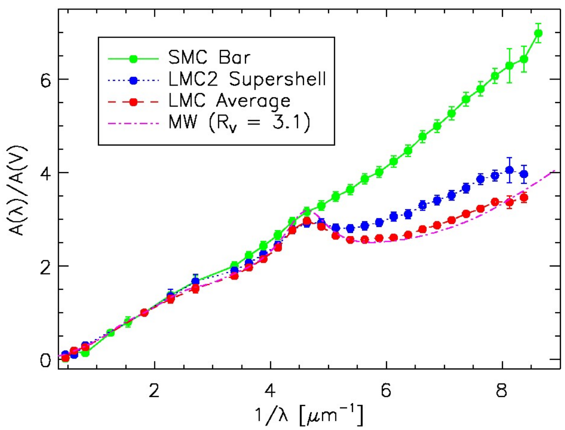
- Difference between B and V brightness

$$B - V = m_B - m_V$$

- Negative index: blue(ish)
- Positive index: red(ish)

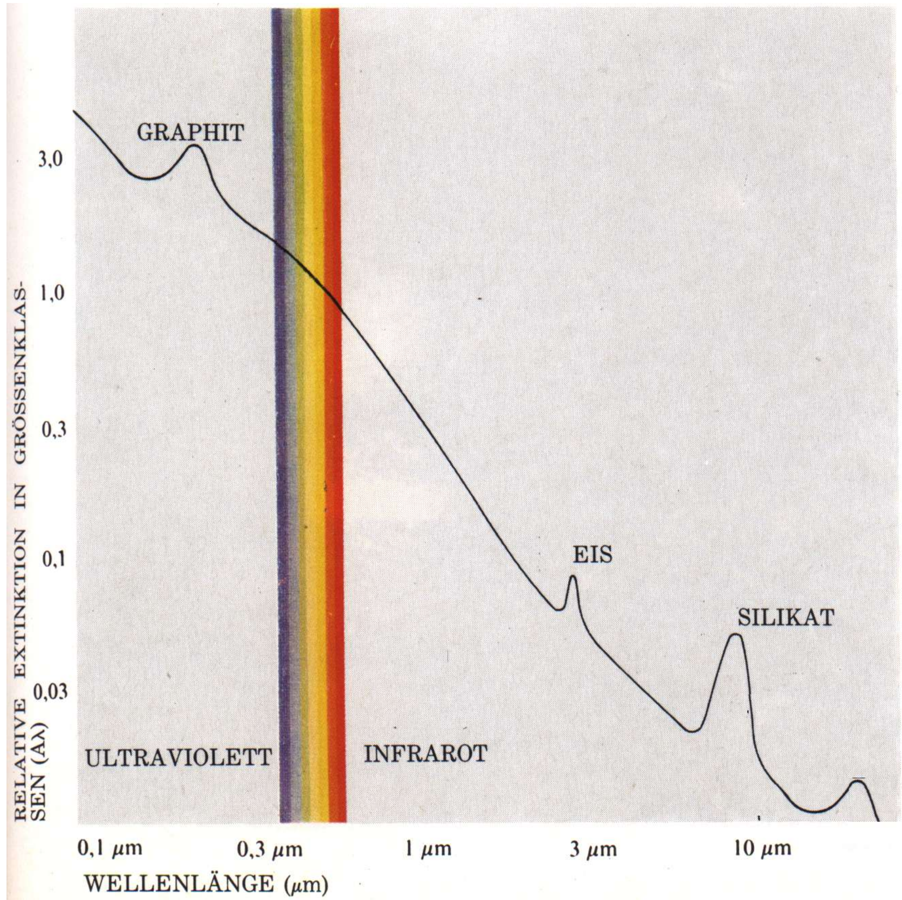
Interstellar Extinction

- Extinction curves vary



Interstellar extinction curves in the Milky Way and other galaxies

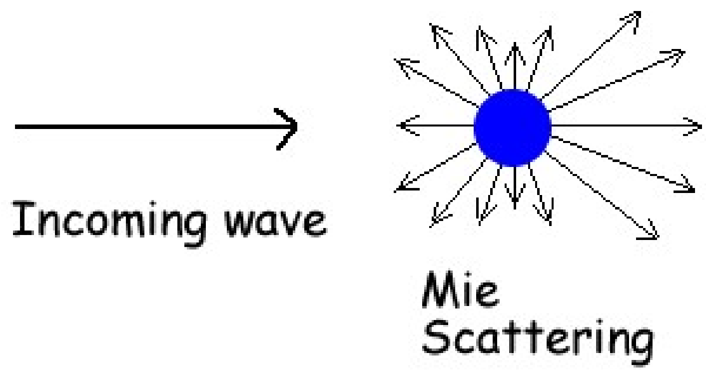
Bumps in the UV and infrared allow to infer chemical composition



Interstellar Extinction

Quantitative description: Mie theory

Gustav Mie (1908)



Extinction+Scattering

= solution of Maxwell equations for a spherical geometry:
and complex refractive index:

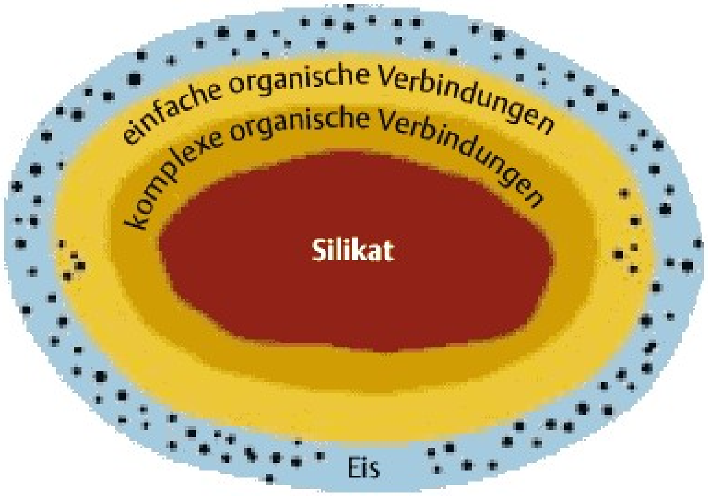
→ Wavelength-dependent extinction law

→ allows to infer and from observation

Interstellar Dust

- Comparison of observed spectra with lab data
  - Terrestrial analogues (minerals)

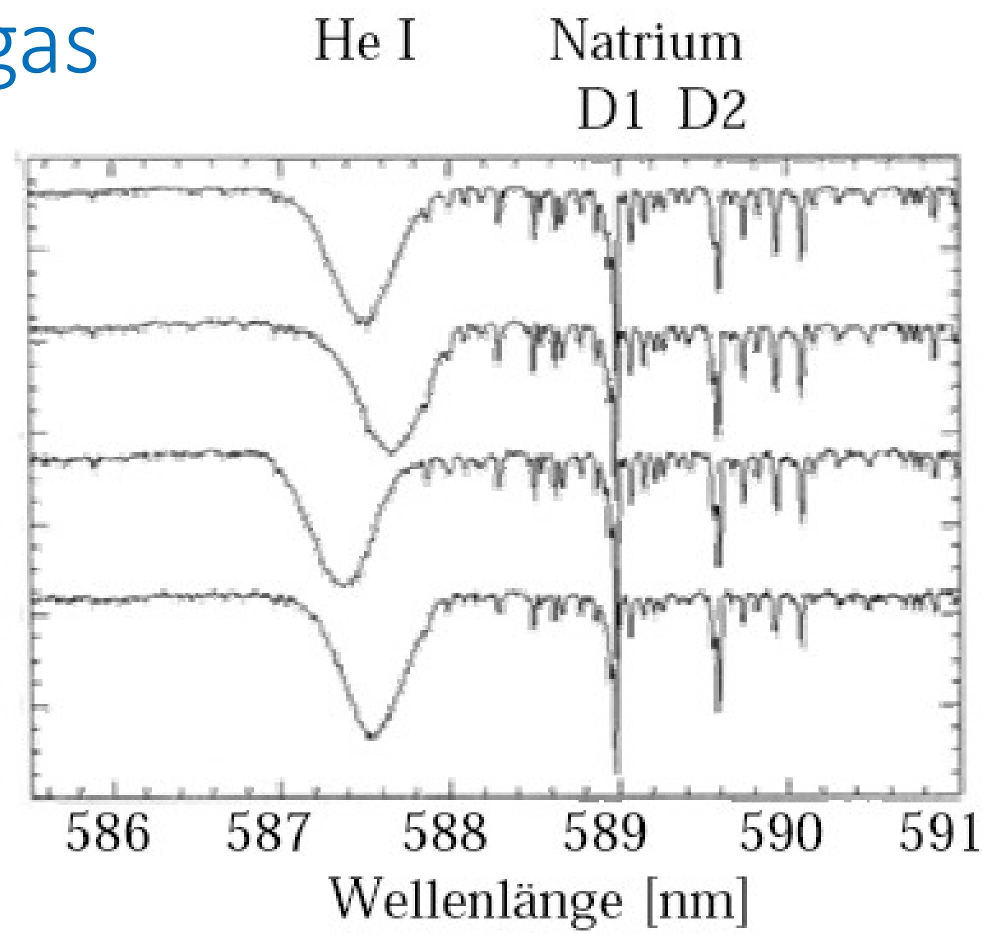
→ 4 Components:
  - Silicates
  - Carbonaceous grains (amorphous/graphitic)
  - Ice mantles
  - PAHs (see later)



Greenberg dust (**Mayo Greenberg 1973**)

Diffuse interstellar gas

- **1904 Lee Hartmann** finds Ca II absorption lines towards δ Ori at optical wavelengths
- **1933 Flasken & Pierce** show that Ca II absorption grows with distance and radial velocity ~ $v_*/2$
- Diffuse interstellar gas accompanying the dust everywhere



Spectra towards δ Ori at different observing dates

Interstellar gas

1937 Swings & Rosenfeld, McKellar, Adams: Detection of first interstellar molecules: CH, CN, CH^+

Elemental abundances:

	number abundance	in gas phase
H	100	> 99%
He	9	100%
O	0.032	80%
C	0.013	50%
N	0.008	> 95%
Al	0.0003	< 2%

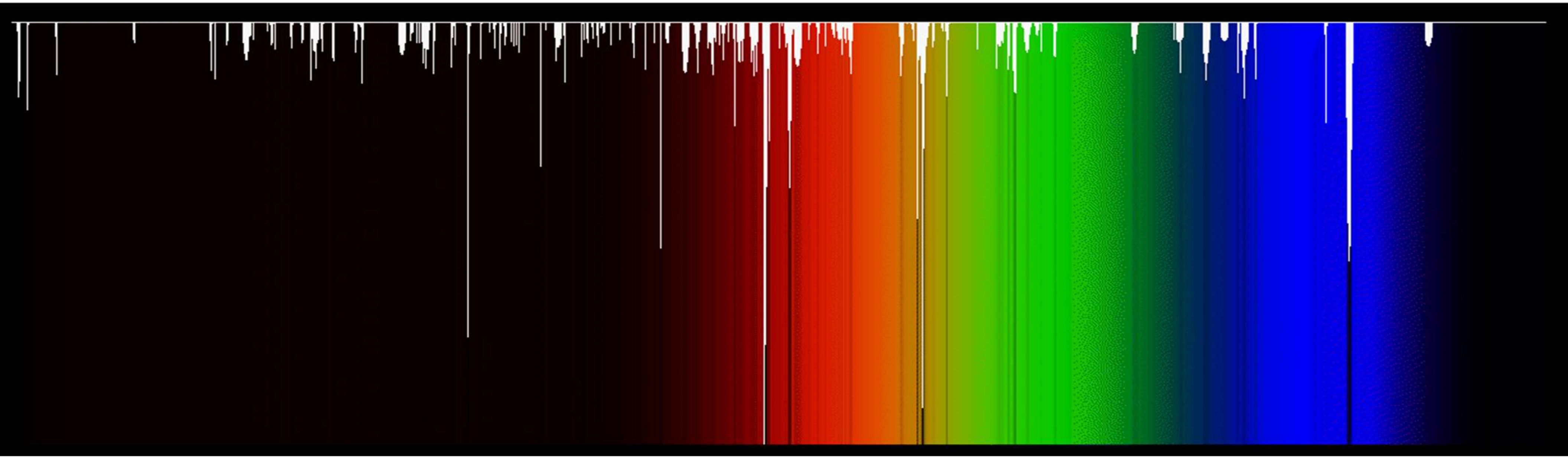
- "Missing" elements condensed to dust.
- Dust/gas ratio ~ 1/100, but dust dominates overall energy balance

Interstellar gas

- **1932 Mary Heger**: Detection of diffuse interstellar bands

→ still not fully understood

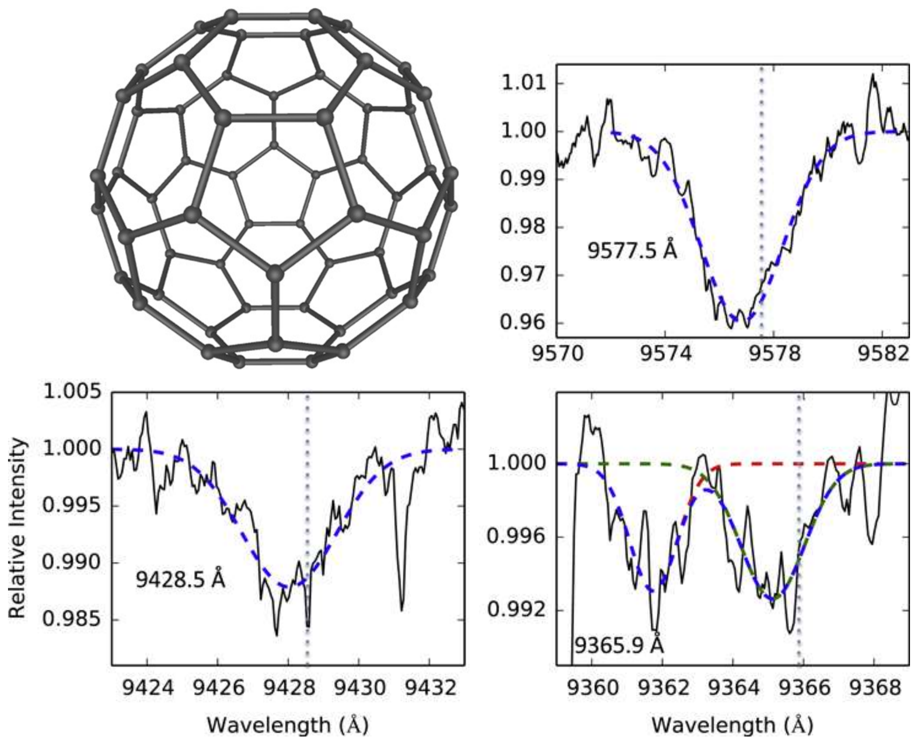
Oldest unsolved astrophysical problem



Diffuse interstellar bands

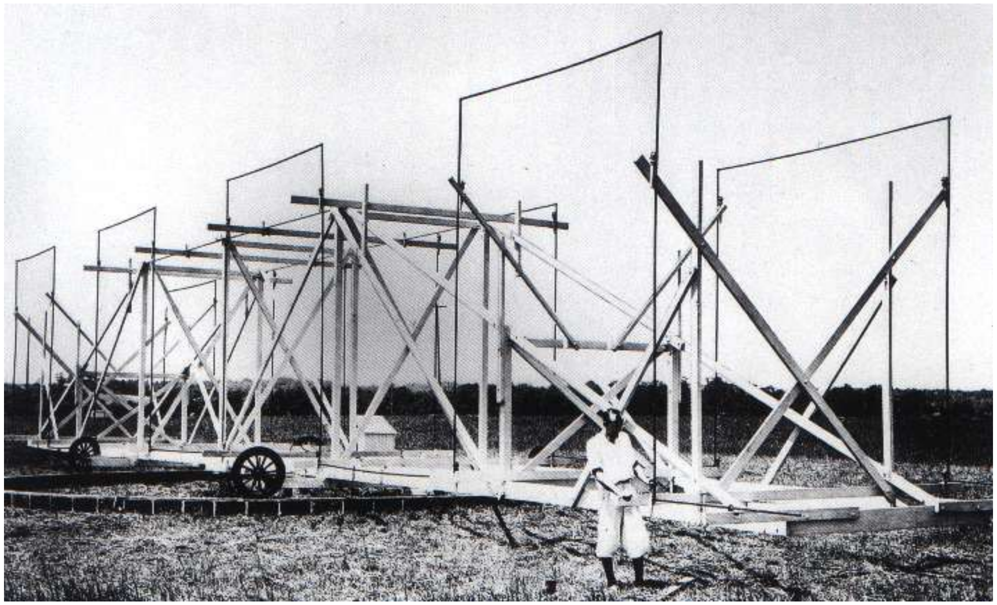
- Broader than gas lines but narrower than solid state resonances

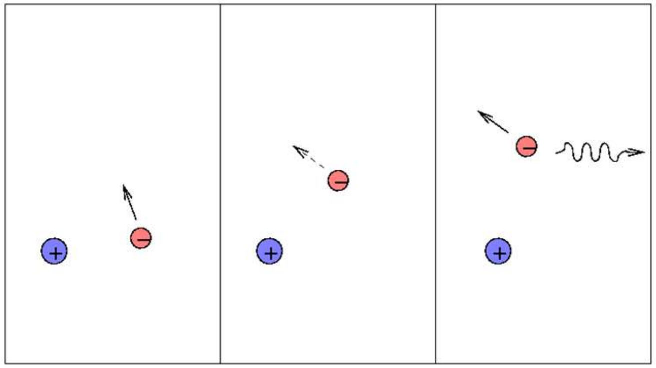
- Strongest bands at 443, 624, 618 nm
- Variation of the band ratios in different lines of sight
- First explanation: **Campbell et al. (2015)**
  - C_{60}^+
- Other diffuse bands:
  - Other ionized hydrocarbons and fullerenes ?



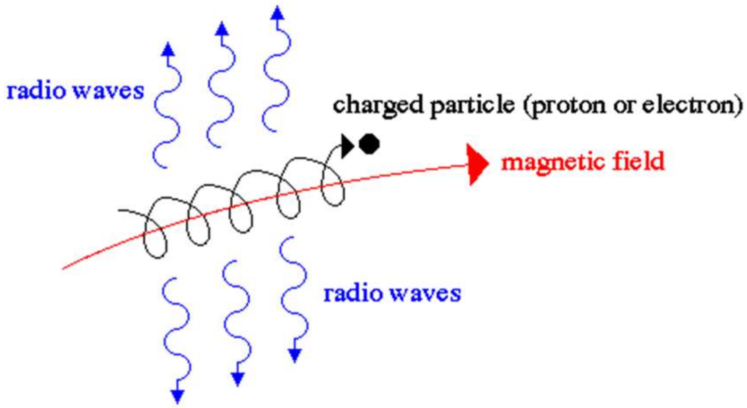
Radio Astronomy

- **1932 Karl Jansky**:
  Detection of radio waves from the Milky Way
  → Hot gas
- Continuous radiation from free electrons: Bremsstrahlung



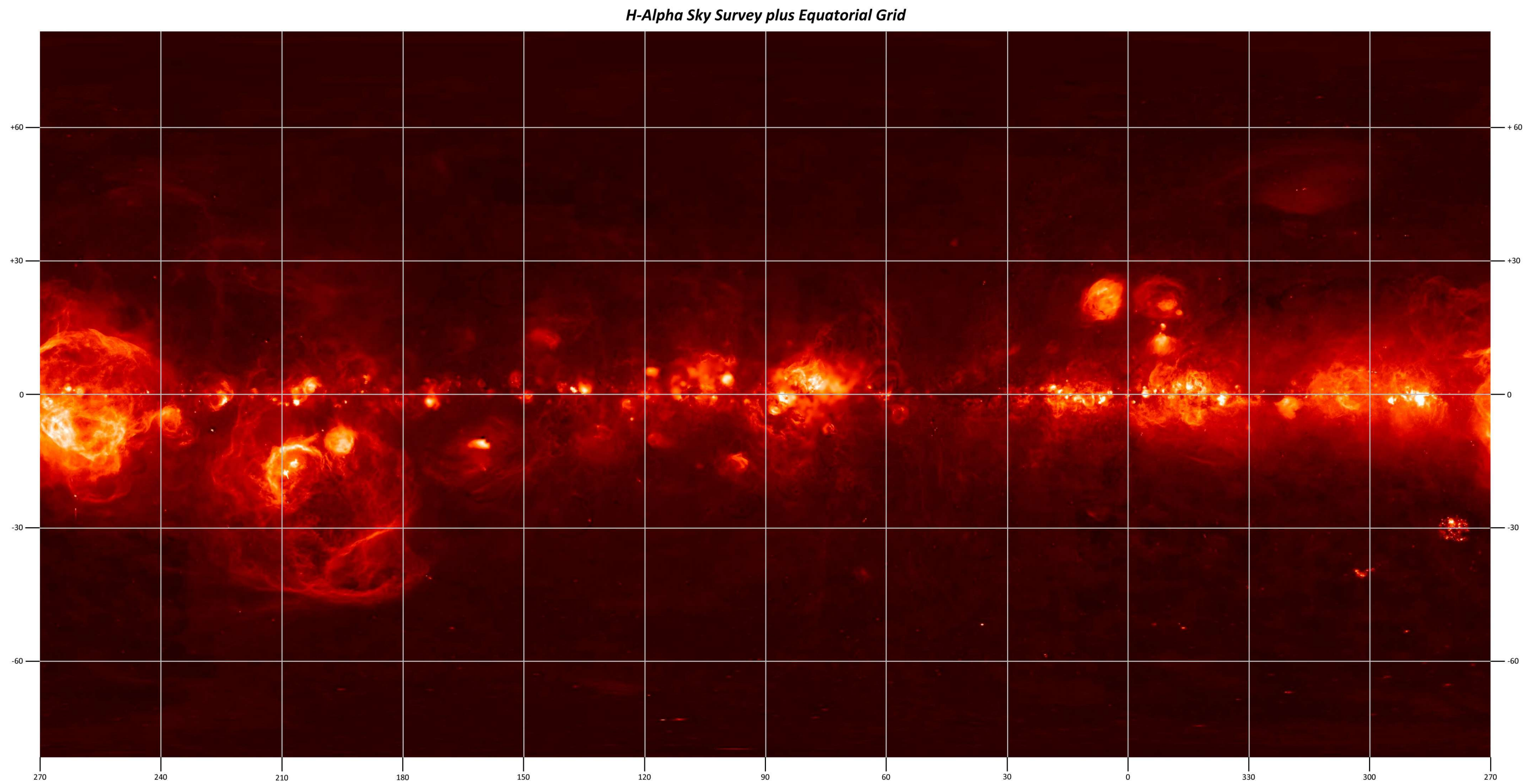


free-free radiation



synchrotron radiation

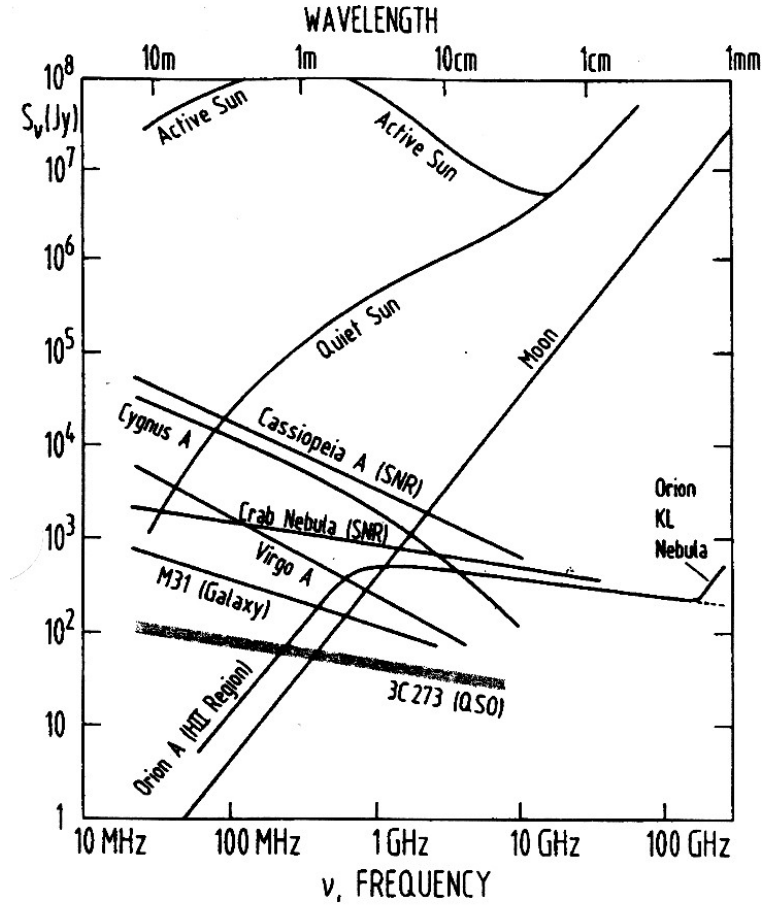
Thermal emission from HII regions



H alpha map of the inner Galaxy (Wisconsin H alpha mapper WHAM)

Radio Observations

- Characteristic spectrum of ionized gas based on energy distribution of electrons and magnetic field

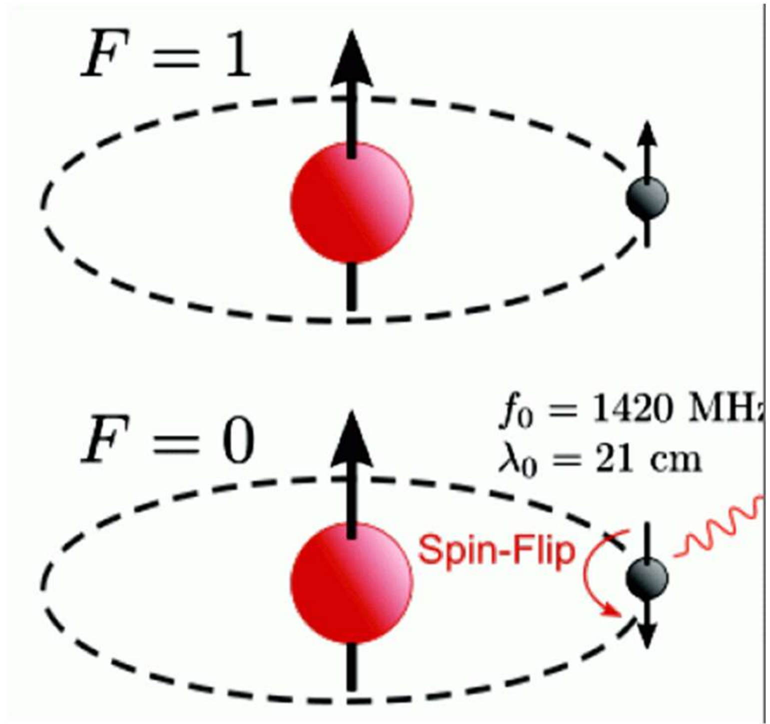


- **1960**: First detection of soft X rays from hot ionized gas

Neutral gas

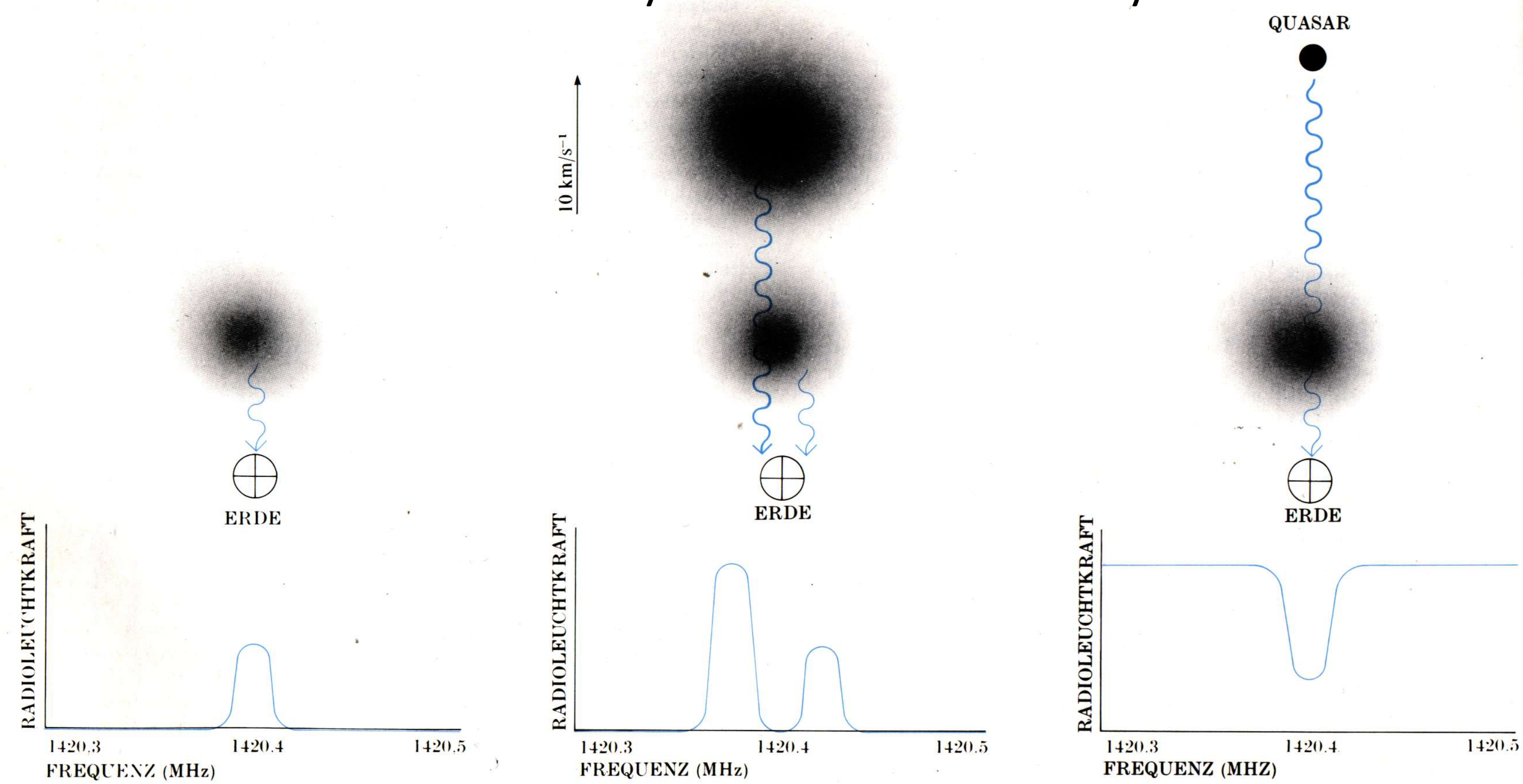
- **1945 Hendrik van der Hulst**: Prediction of the 21 cm spin-flip (hyperfine structure) transition of atomic hydrogen
  - Forbidden line
  - $A = 2.9\times10^{-15}\ s^{-1}$

    → $t=10^7$ a
- **1950 Ewen & Purcell, Oort & Müller**: first HI detection



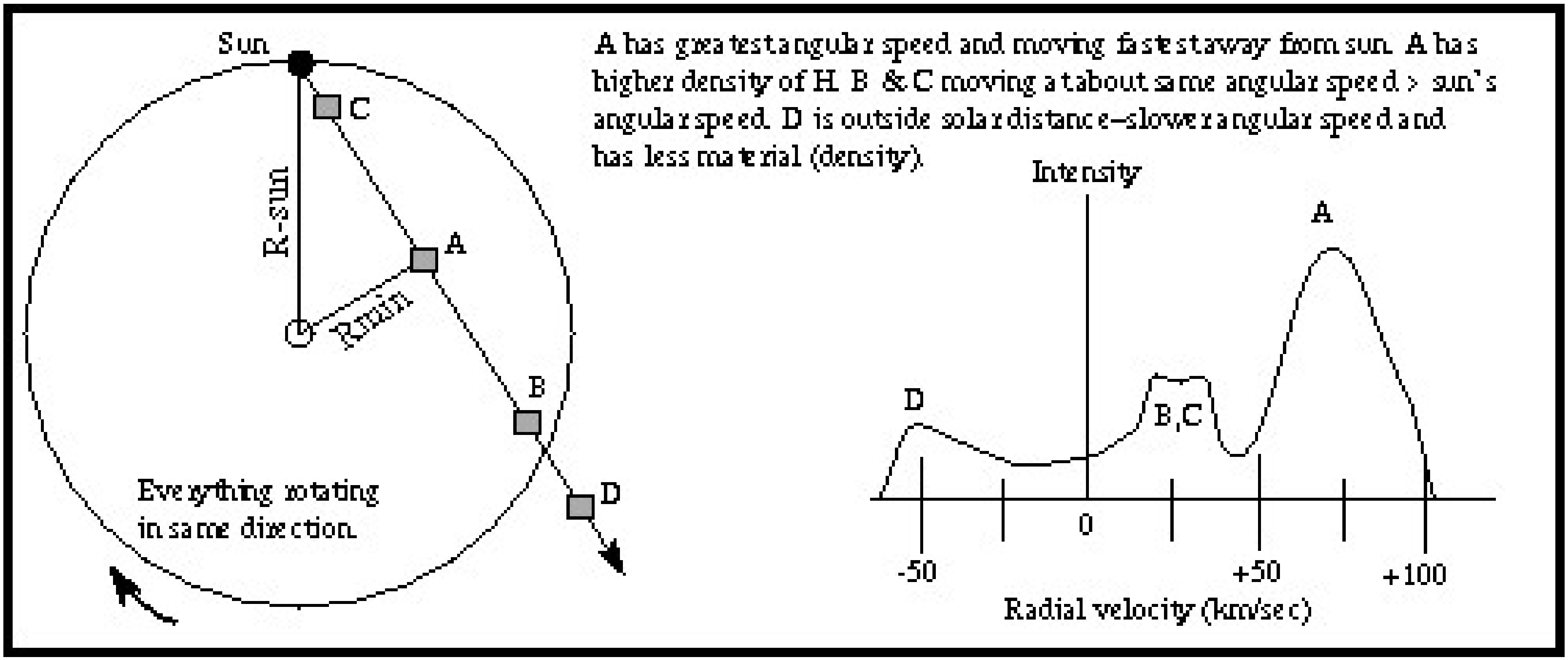
Neutral Gas

Allows to measure velocity structure of the Galaxy



HI spectral line mapping

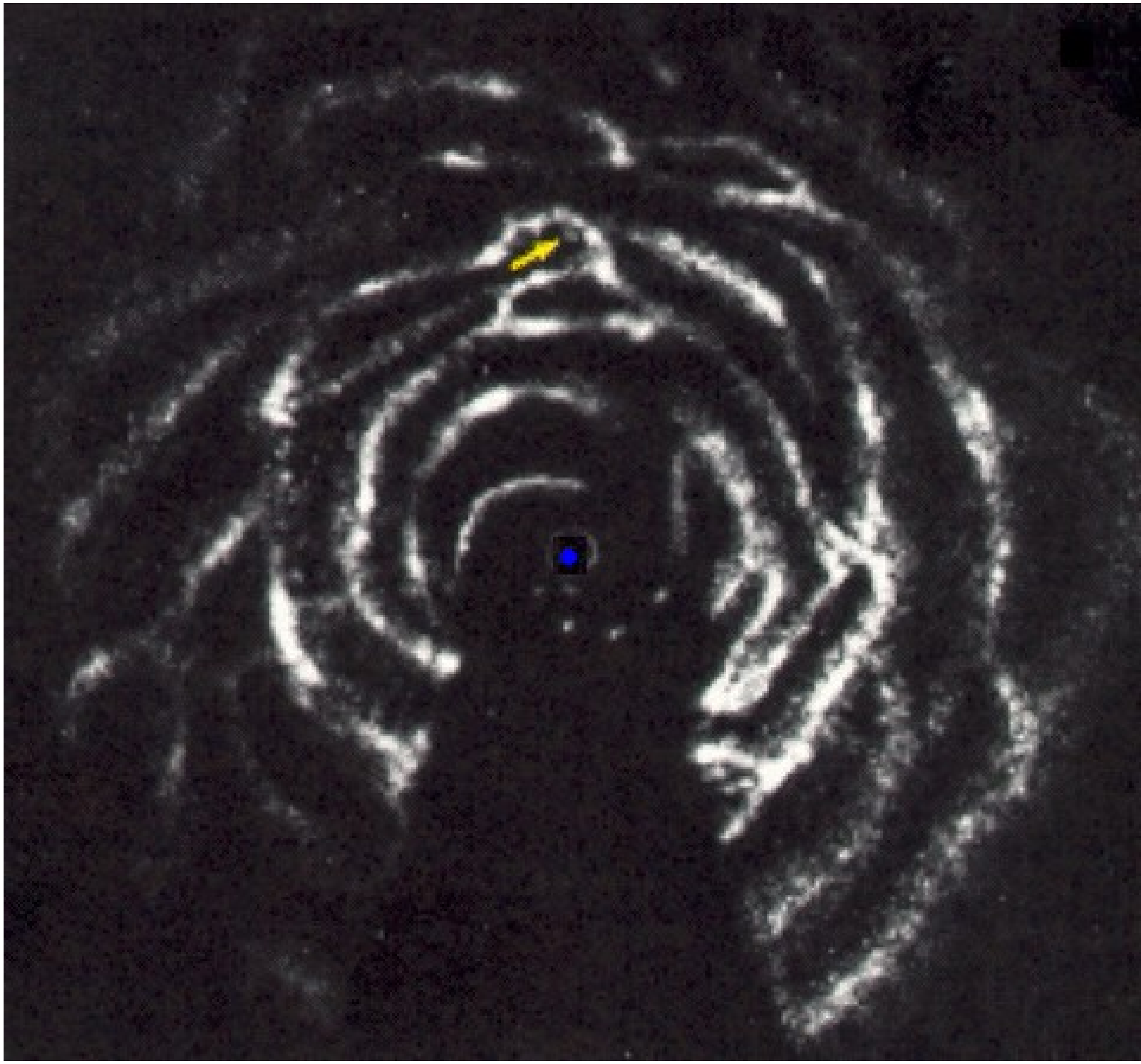
Observation = Convolution of the Galactic density structure with the Galactic rotation curve



Interstellar gas

- **1951 Lyman Spitzer**: mapping of the Milky Way

  → spiral structure in HI gas

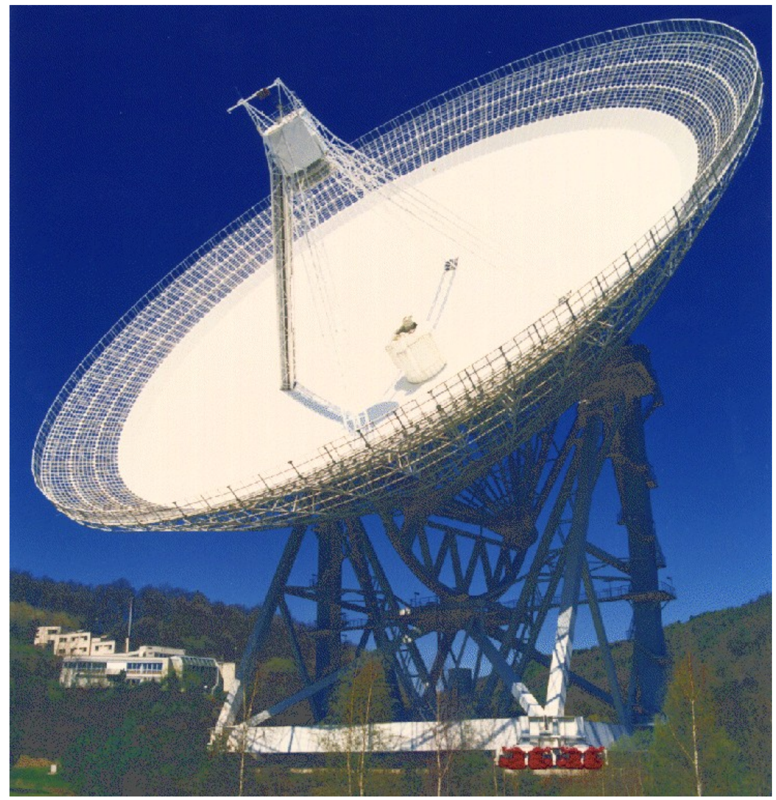


Modern Radio Astronomy

- **1963 Barrett, Meeks & Weinreb**:
  discovery of OH at 18cm

- **1968 Charlie Townes**:
  NH_3

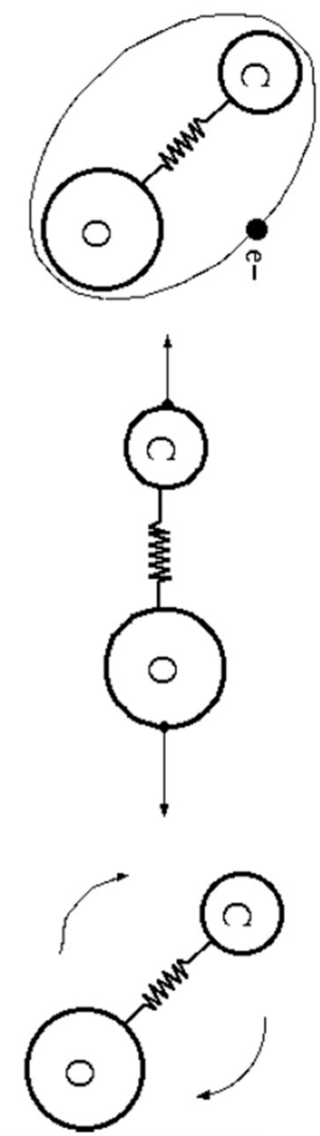
- **1970 Wilson, Jefferts & Penzias**:
  CO 2.6mm (115 GHz)



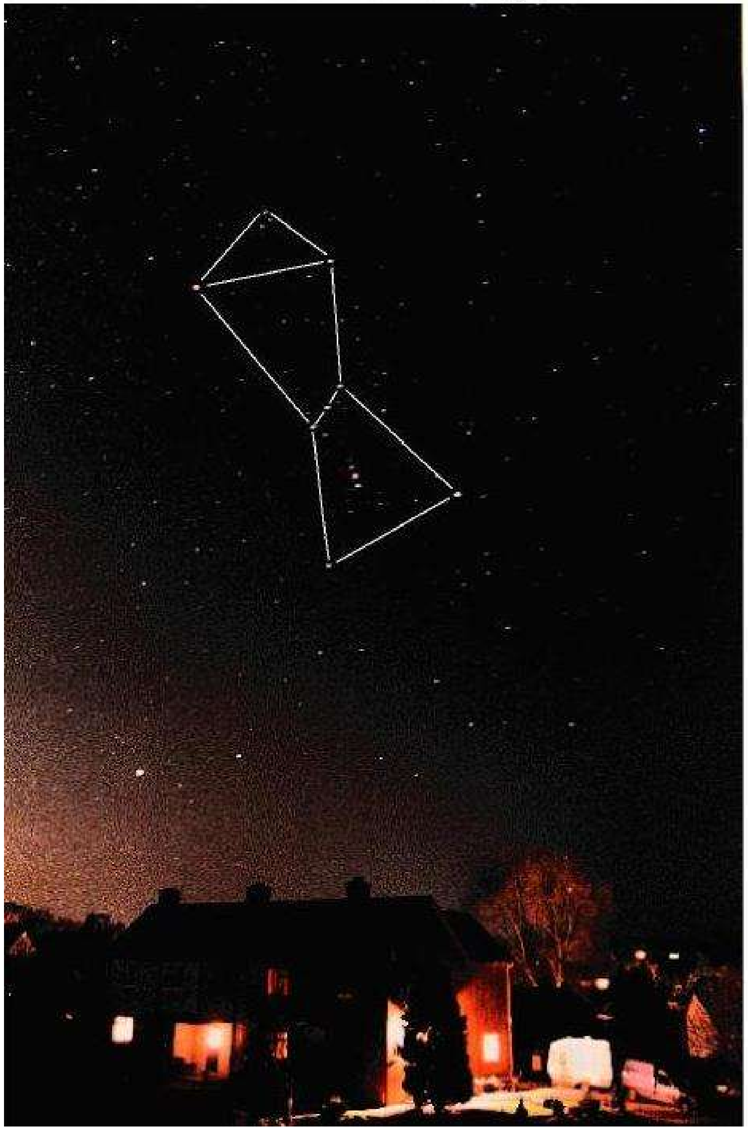
Effelsberg 100m radio telescope (1971)

Molecular clouds

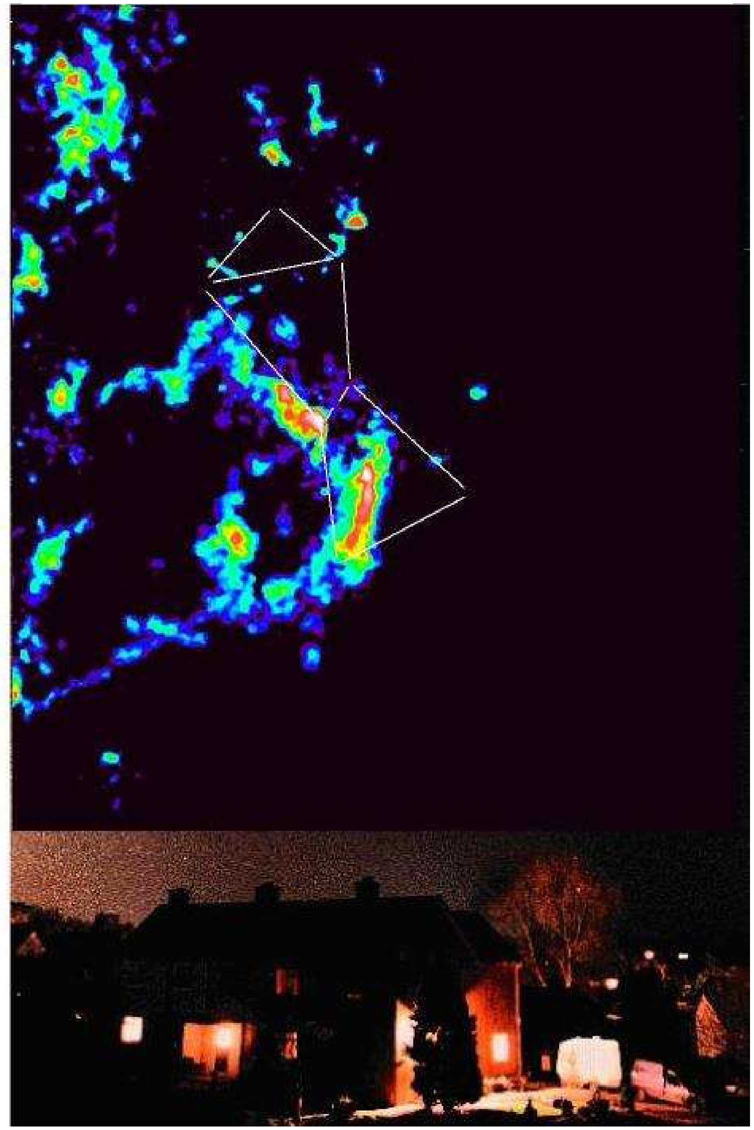
- H turns molecular at high densities
- No permanent electric dipole moment of H_2:
  - No ground-state rotational transitions
  - No electric dipole vibrational transitions
  - Only hot H_2 visible via quadrupole transitions
- CO main tracer of molecular gas: $N(CO)/N(H_2) \sim 2x10^{-4}$



Orion Constellation: As you see it

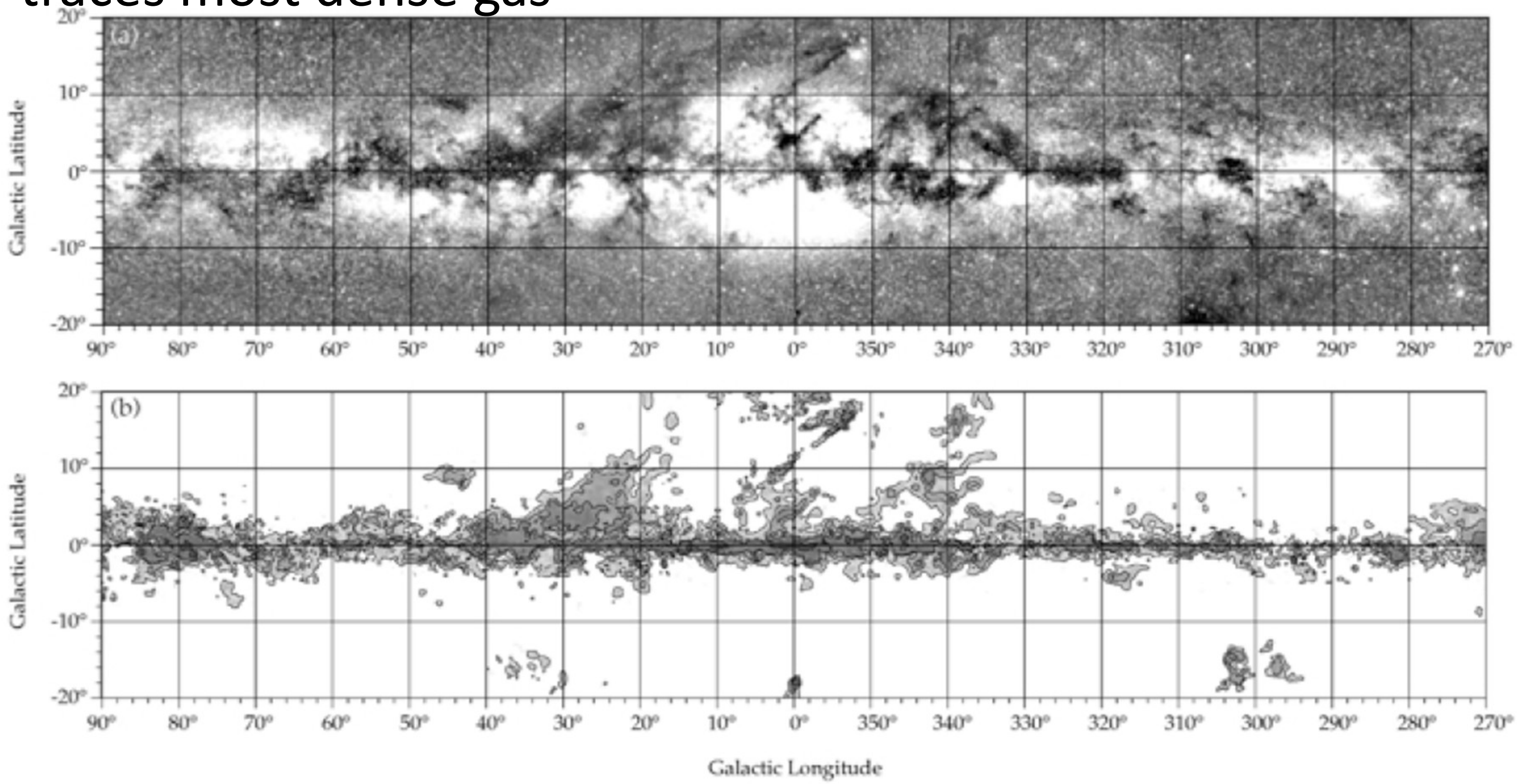


CO $J=1 \rightarrow 0$



Molecular Clouds

- CO traces most dense gas



^{13}CO in the inner Galaxy: lots and lots of structure

148

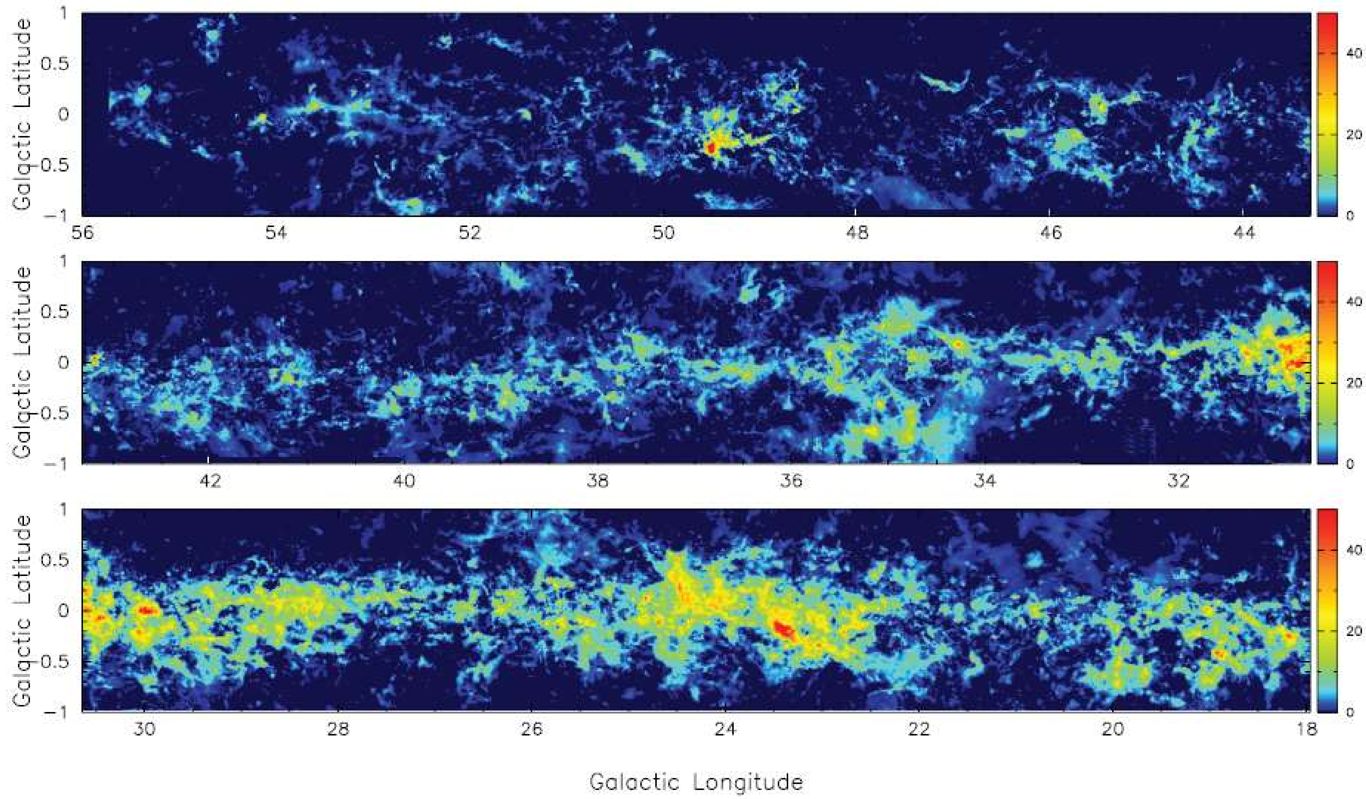


FIG. 1.—Integrated intensity image (zeroth-moment map) of GRS ^{13}CO emission integrated over all velocities ($V_{LSR} = -5$ to 135 km s^{-1} for Galactic longitudes $l \leq 40°$ and $V_{LSR} = -5$ to 85 km s^{-1} for Galactic longitudes $l > 40°$). The image shows that most of the emission is confined to $b \sim 0°$, with concentrations at $l \sim 23°$ and $\sim 31°$. A striking aspect of the image is the abundance of filamentary and linear structures and the complex morphology of individual clouds. The image is in units of K km s^{-1}.

Clouds are not smooth, but complex, filamentary, fractal.

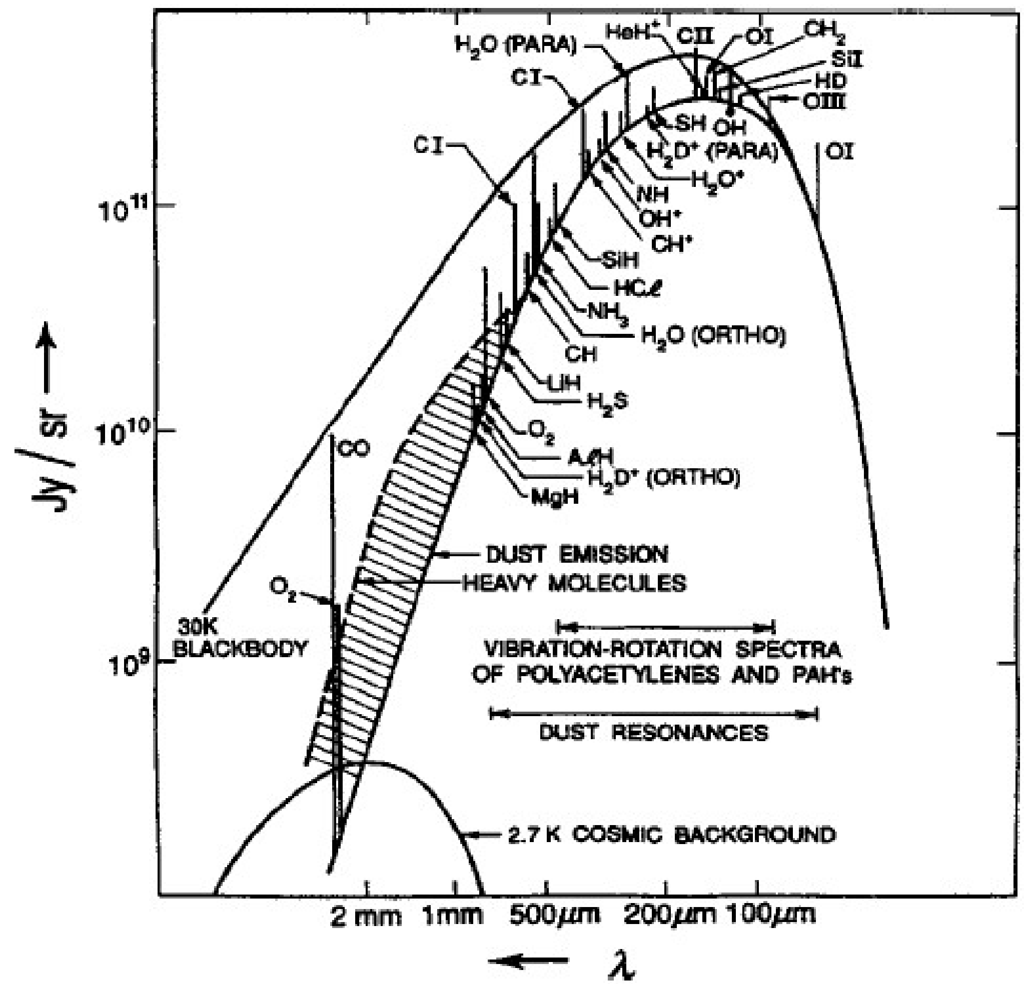
- fractal structures are created by a cascade of interstellar turbulence

Submm-Astronomy

- Wealth of lines discovered with telescopes build in the 1980s

Total spectrum of M82:
Dust and gas

SOFIA observatory US/Germany



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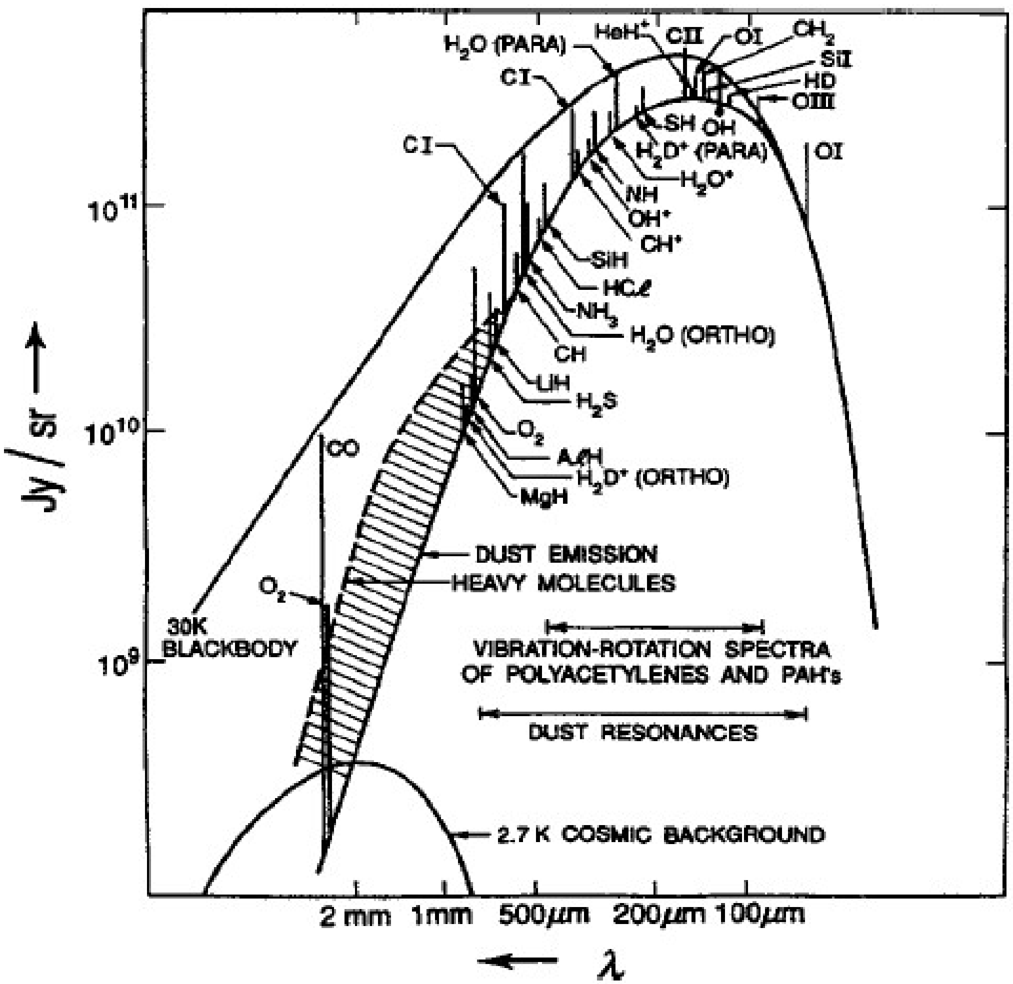
- Wealth of lines discovered with telescopes build in the 1980s

Total spectrum of M82:
Dust and gas

ALMA Observatory Chile/ESO



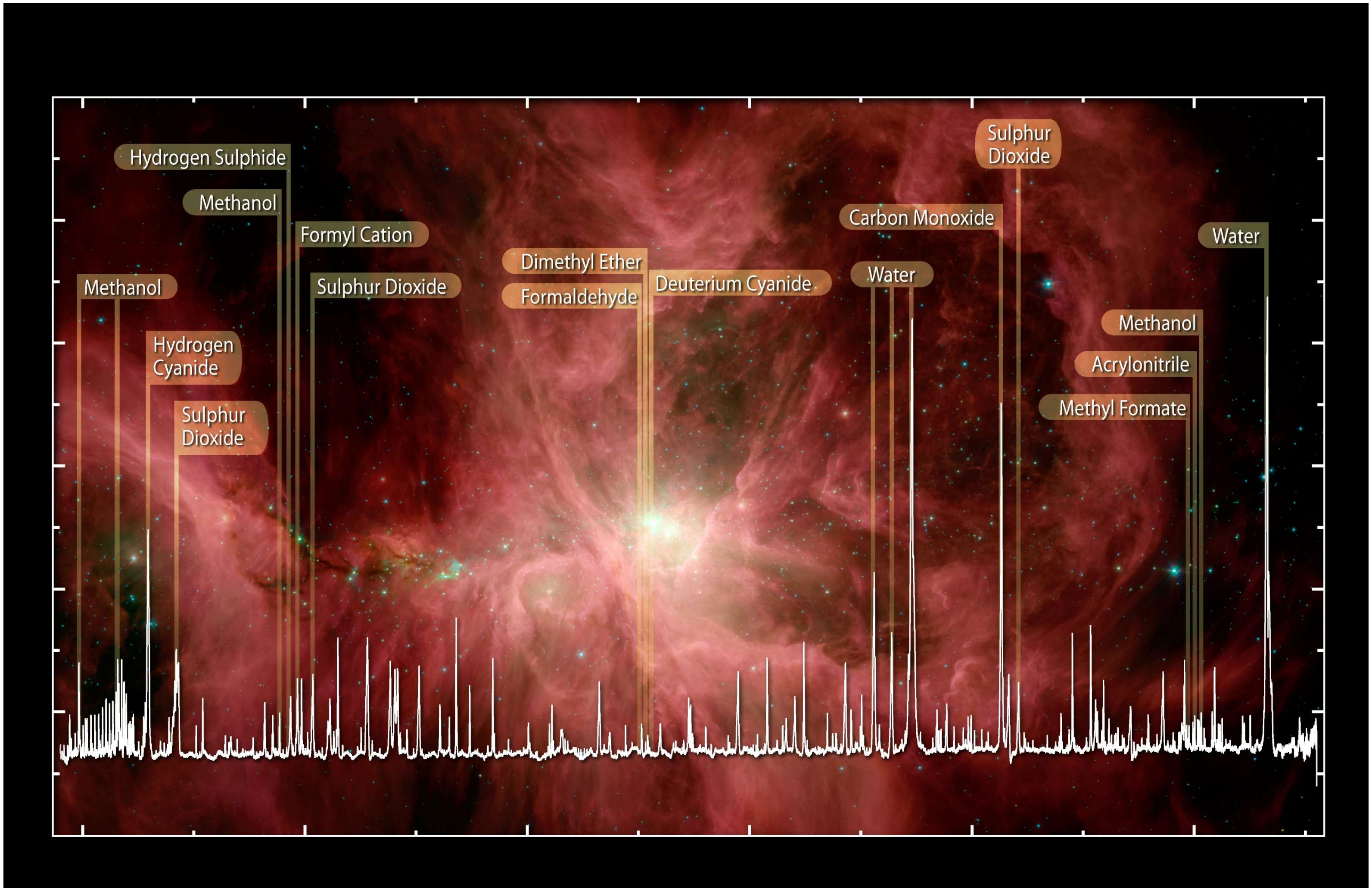
2 atoms	3 atoms	4 atoms	5 atoms	6 atoms	7 atoms	8 atoms	9 atoms	10 atoms	11 atoms	12 atoms	>12 atoms
CH^+	H_2O	NH_3	HC_3N	CH_3OH	CH_3CHO	$HC(O)OCH_3$	$(CH_3)_2O$	$(CH_3)_2CO$	HC_9N	c-$C_6H_6^*$	C_{60}^*
CH	HCO^+	H_2CO	HCOOH	CH_3CN	CH_3C_2H	CH_3C_3N	CH_3CH_2OH	$(CH_2OH)_2$	CH_3C_6H	n-C_3H_7CN	C_{70}^*
CN	HCN	HNCO	H_2CNH	NH_2CHO	CH_3NH_2	C_7H	CH_3CH_2CN	CH_3CH_2CHO	C_2H_5OCHO	i-C_3H_7CN	C_{60}^{+*}
OH	OCS	H_2CS	H_2NCN	CH_3SH	CH_2CHCN	CH_3COOH	HC_7N	CH_3C_5N	$CH_3OC(O)CH_3$	$C_2H_5OCH_3$	c-C_6H_5CN
CO	HNC	$C_2H_2^*$	H_2C_2O	$C_2H_4^*$	HC_5N	C_6H_2	CH_3C_4H	CH_3CHCH_2O	$CH_3C(O)CH_2OH$	1-c-C_5H_5CN	$HC_{11}N$
H_2	H_2S	C_3N	C_4H	C_5H	C_6H	CH_2OHCHO	C_8H	CH_3OCH_2OH	c-C_5H_6	2-c-C_5H_5CN	1-$C_{10}H_7CN$
SiO	N_2H^+	HNCS	SiH_4^*	CH_3NC	c-C_2H_4O	l-HC_6H^*	$CH_3C(O)NH_2$	c-C_6H_4	$HOCH_2CH_2NH_2$	CH_3C_7N (?)	2-$C_{10}H_7CN$
CS	C_2H	$HOCO^+$	c-C_3H_2	HCCCHO	H_2CCHOH	CH_2CHCHO	C_8H^-	H_2CCCHC_3N	H_2CCCHC_4H	n-C_3H_7OH	c-C_9H_8
SO	SO_2	C_3O	H_2CCN	l-C_4H_2	C_6H^-	CH_2CCHCN	C_3H_6	C_2H_5NCO	$C_{10}H^-$	i-C_3H_7OH	1-c-C_5H_5CCH
SiS	HCO	l-C_3H	C_5^*	HC_3NH^+	CH_3NCO	H_2NCH_2CN	CH_3CH_2SH	$C_2H_5NH_2$ (?)	$H_2C(CH)_3CN$?	$(CH_3)_2C{=}CH_2$	2-c-C_5H_5CCH
NS	HNO	$HCNH^+$	SiC_4	C_5N	HC_5O	CH_3CHNH	CH_3NHCHO	HC_7NH^+	$CH_3CH(OH)CHO$ (2026)		c-$C_5H_4CCH_2$
C_2^{**}	HCS^+	H_3O^+	l-C_3H_2	l-HC_4H^*	$HOCH_2CN$	CH_3SiH_3	HC_7O	E-$CH_3CHCHCN$	CH_3OCH_2CHO (2026)		2-C_9H_7CN
NO	HOC^+	C_3S	CH_4^*	l-HC_4N	HCCCHNH	$H_2NC(O)NH_2$	HCCCHCHCN	Z-$CH_3CHCHCN$	2,5-c-C_6H_6S (2026)		C_6H_5CCH
HCl	c-SiC_2	c-C_3H	HCCNC	c-H_2C_3O	HC_4NC	$HCCCH_2CN$	H_2CCHC_3N	$CH_3C(CN)CH_2$			$CH_3OCH_2CH_2OH$ (2024)
NaCl	C_2S	HCCN	HNC_3	H_2CCNH	c-C_3HCCH	HC_5NH^+	$H_2CCCHCCH$	CH_2CHCH_2CN			1-$C_{12}H_7CN$ (2024)
KCl	C_3^*	H_2CN	H_2COH^+	C_5N^-	l-H_2C_5	CH_2CHCCH	HOCHCHCHO (2024)	$HOCH_2C(O)NH_2$			5-$C_{12}H_7CN$ (2024)
AlCl	CO_2^*	c-SiC_3	C_4H^-	HNCHCN	MgC_5N	MgC_6H	HC_7N^+ (2024)	CH_3CH_2CCH (2024)			1-$C_{16}H_9CN$ (2024)
AlF	CH_2	CH_3^*	HC(O)CN	SiH_3CN	CH_2C_3N	$C_2H_3NH_2$	$CH_2(CCH)_2$ (2024				2-$C_{16}H_9CN$ (2025)
PN	C_2O	C_3N^-	HNCNH	C_5S	NC_4NH^+	$(CHOH)_2$	$(CH_3)_2S$ (2025)				4-$C_{16}H_9CN$ (2025)
SiC	MgNC	PH_3	CH_3O	MgC_4H	MgC_5N^+	$HC_2(H)C_4$					$C_{24}H_{11}CN$ (2025)
CP	NH_2	HCNO	NH_4^+	CH_3CO^+	HC_5N^+ (2024)	C_7N^-					$C_{13}H_{10}$ (2025)
NH	NaCN	HOCN	H_2NCO^+	C_3H_3	HNC_5 (2024)	CH_3CHCO					3-$C_{12}H_7CN$ (2026)
SiN	N_2O	HSCN	$NCCNH^+$	H_2C_3S	$CH_2(CN)_2$ (2024	MgC_6H^+					4-$C_{12}H_7CN$ (2026)
SO^+	MgCN	H_2O_2	CH_3Cl	HCCCHS	HCCCHCN (2025)	Z-$(CH)_2(CN)_2$ (2024					c-$C_{11}H_8$ (2026)
CO^+	$H_3^{+(*)}$	C_3H^+	MgC_3N	C_5O	CH_3CHS (2025)	CH_2CHCHS (2025)					
HF	SiCN	HMgNC	NH_2OH	C_5H^+	SiC_6 (2025)						
SiH?	AlNC	HCCO	HC_3O^+	$HCCNCH^+$							
FeO?	SiNC	CNCN	HC_3S^+	c-C_3C_2H							
O_2	HCP	HONO	H_2C_2S	HC_4S							
CF^+	CCP	MgC_2H	C_4S	$HMgC_3N$							
PO	AlOH	HCCS	HC(O)SH	MgC_4H^+							
AlO	H_2O^+	HNCN	HC(S)CN	$H_2C_3H^+$							
OH^+	H_2Cl^+	H_2NC	HCCCO	H_2C_3N							
CN^-	KCN	$HCCS^+$	NaCCCN	$(HO)_2CO$							
SH^+	FeCN	CH_3^+	MgC_3N^+	H_2CNCN (2024)							

SH	HO_2	HCNS (2024)	HC_3N^+ (2024)	NCHCCS (2024)
HCl^+	TiO_2	$HOCS^+$ (2024)	HC_3S (2024)	c-H_2C_3S (2025)
TiO	C_2N	HNSO (2024)	NC_3S (2024)	SiC_5 (2025)
ArH^+	Si_2C	l-SiC_3 (2025)		l-H_2C_3O (2026)
N_2	HS_2			
NO^+	HCS			
NS^+	HSC			
HeH^+	NCO			
PO^+	CaNC			
SiP ?	NCS			
FeC	MgC_2			
MgS (2024)	HSO			
NaS (2024)	CaC_2 (2024)			
CaS (2025)				

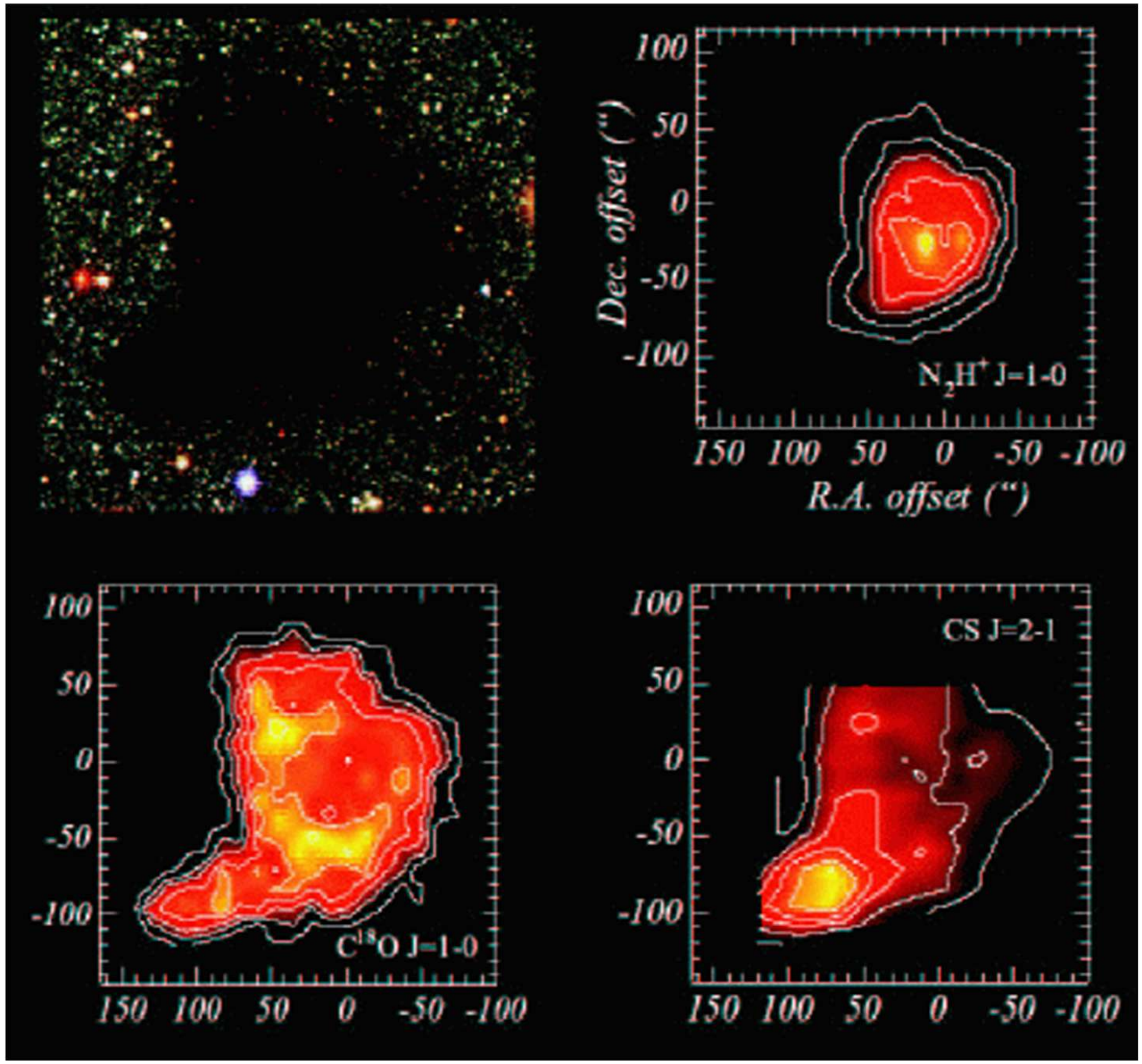
Interstellar molecules

(04/2026) ~350 detected

Interstellar molecules



Molecules in Barnard 68



FIR/THz astronomy

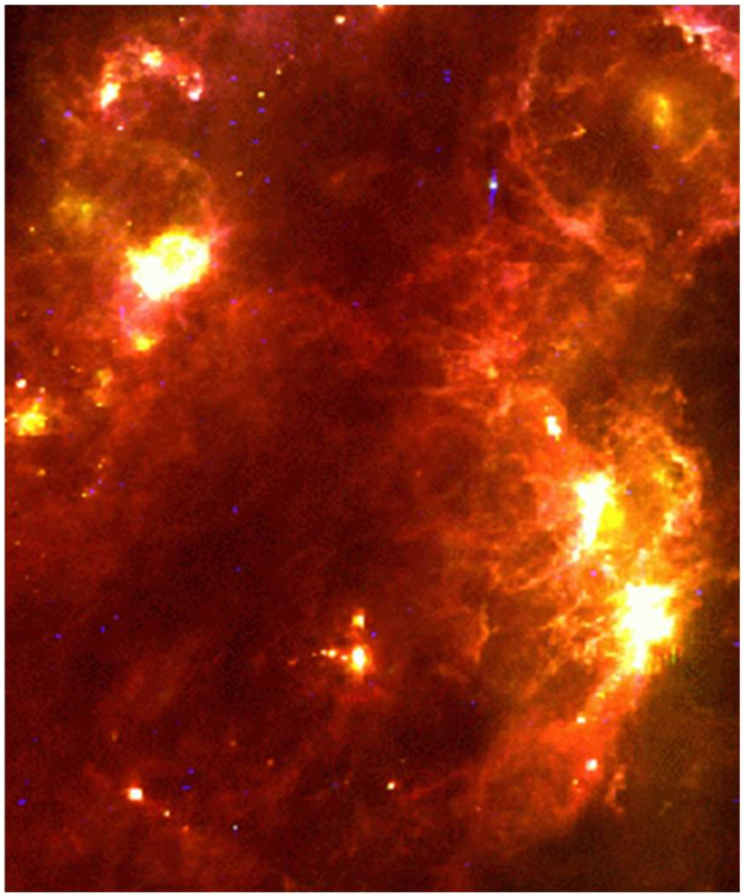
- **IRAS (1983-1984)**
  - 12, 25, 60, 100µm
- **ISO (1995-1998)**
  - Spectroscopy from 2.5 to 240µm

Thermal dust emission:

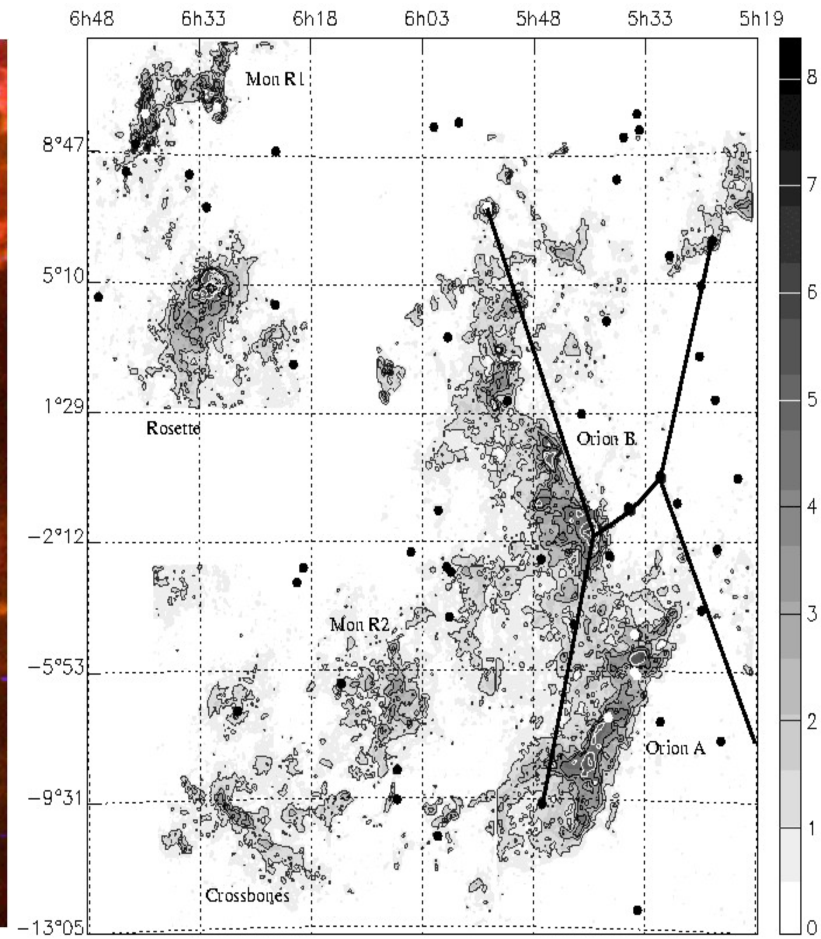
Temperatures:

- diffuse clouds: 30K → emission: 100µm
- dense clouds: 10K → emission: 300µm

IRAS 100 mm

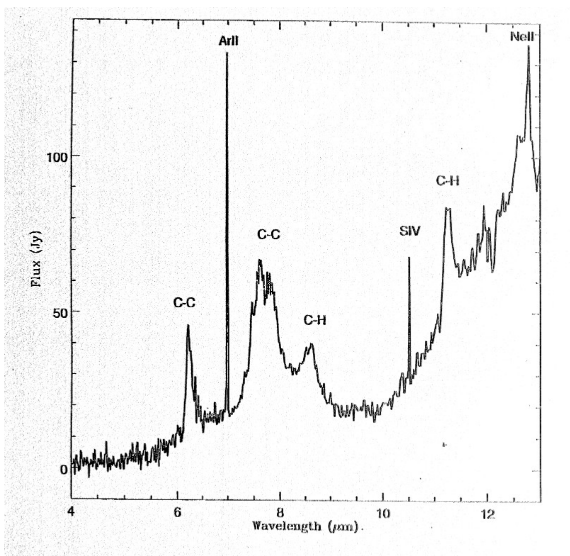


Starcounts

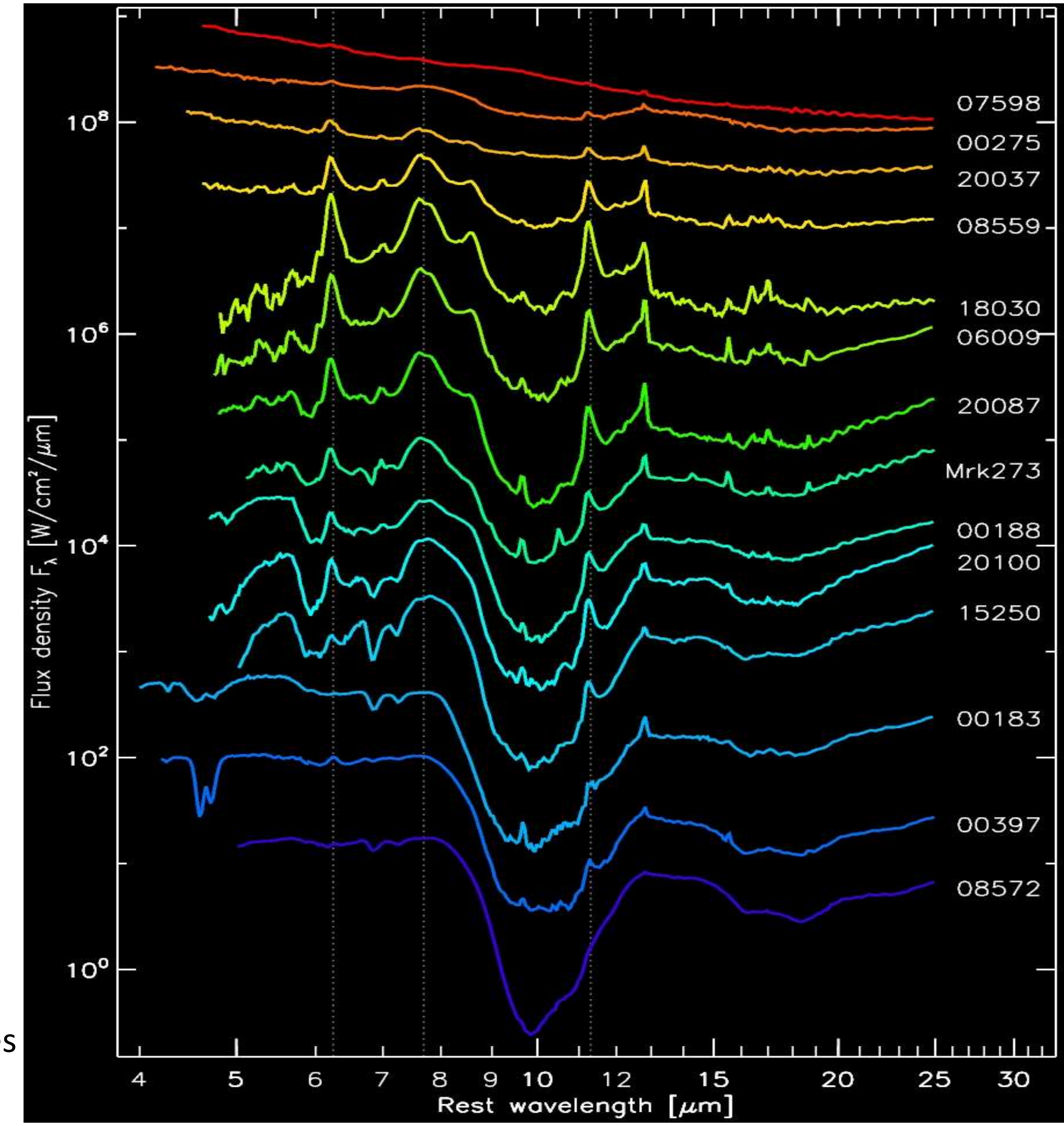


Infrared Spectra

- Mixture of emission and absorption
- Many narrow features
  - Hot dust with C-C and CH-bonds

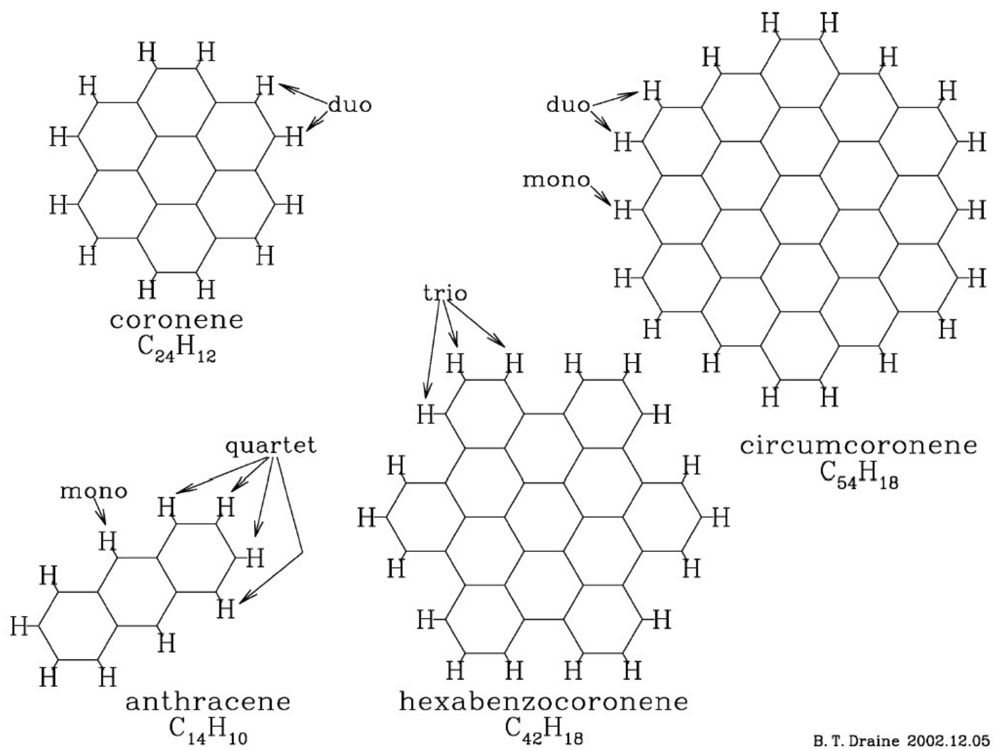


Infrared spectra of ultra-luminous galaxies (Lahuis et al. 2005)

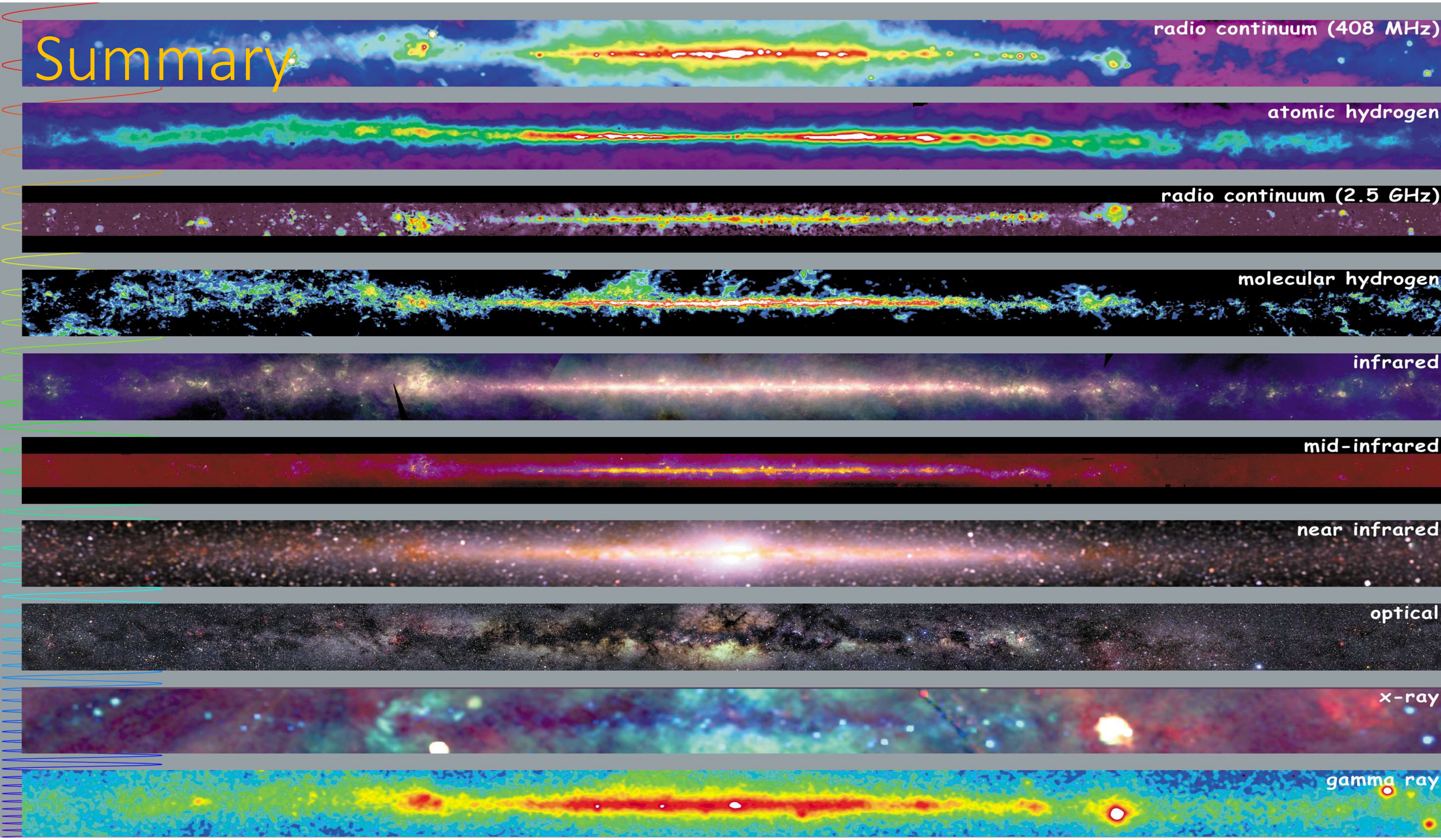


Polycyclic Aromatic Hydrocarbons (PAHs)

- Macro-molecules or very small dust grains
- Not in thermal equilibrium
- 10-500 C atoms
    - Peaks at ~50 and ~500 C atoms
- sp^2 binding configuration



Summary



http://adc.gsfc.nasa.gov/mw