



Physics and Chemistry of the Interstellar Medium

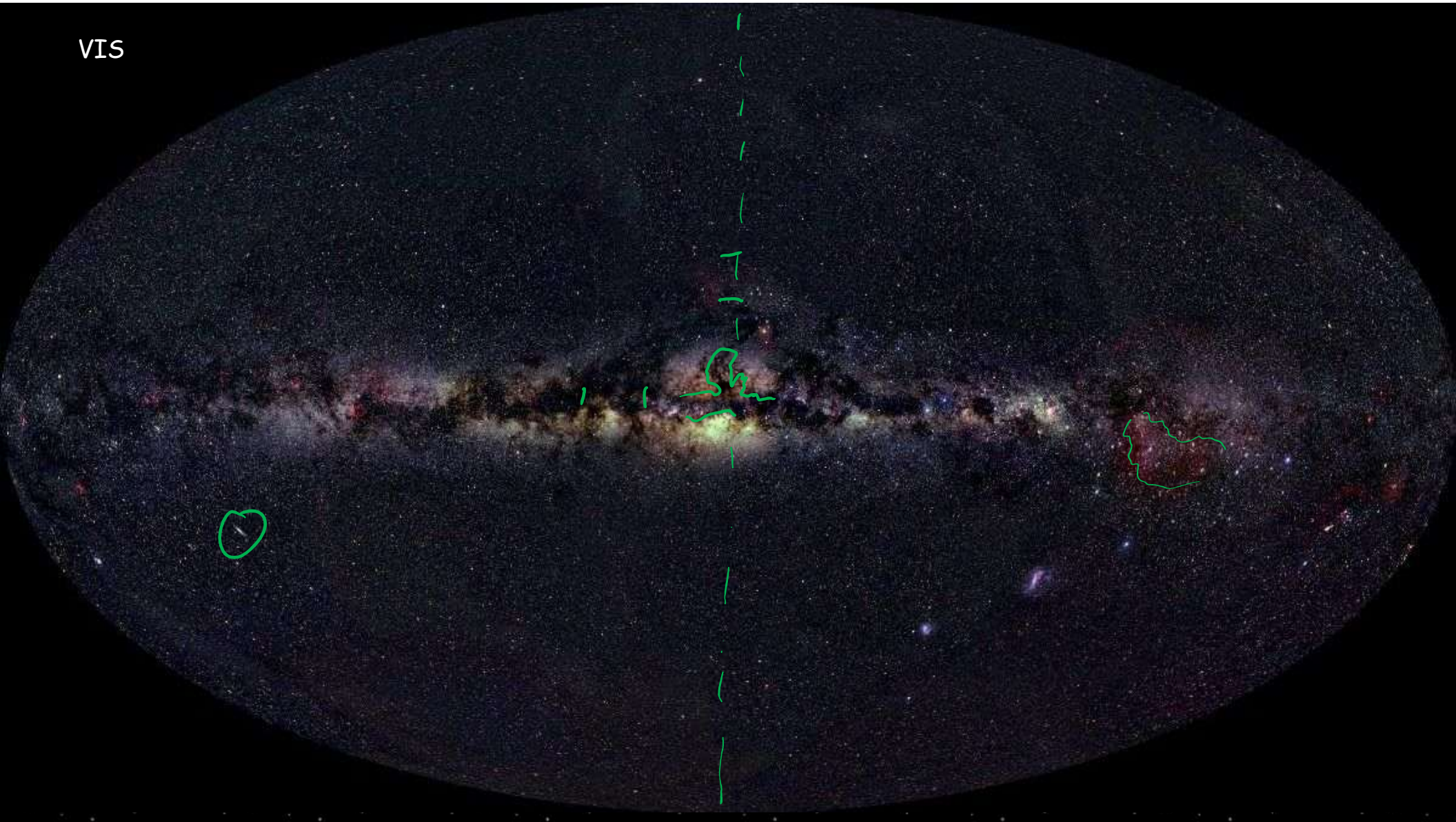
Lecture 1

Motivation

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

Stars

VIS



Motivation

- What do we see on the sky?
 - Optical wavelengths: *stars*
 - All other wavelengths: *ISM = gas + dust*
 - Covers the whole space between the stars

silicates

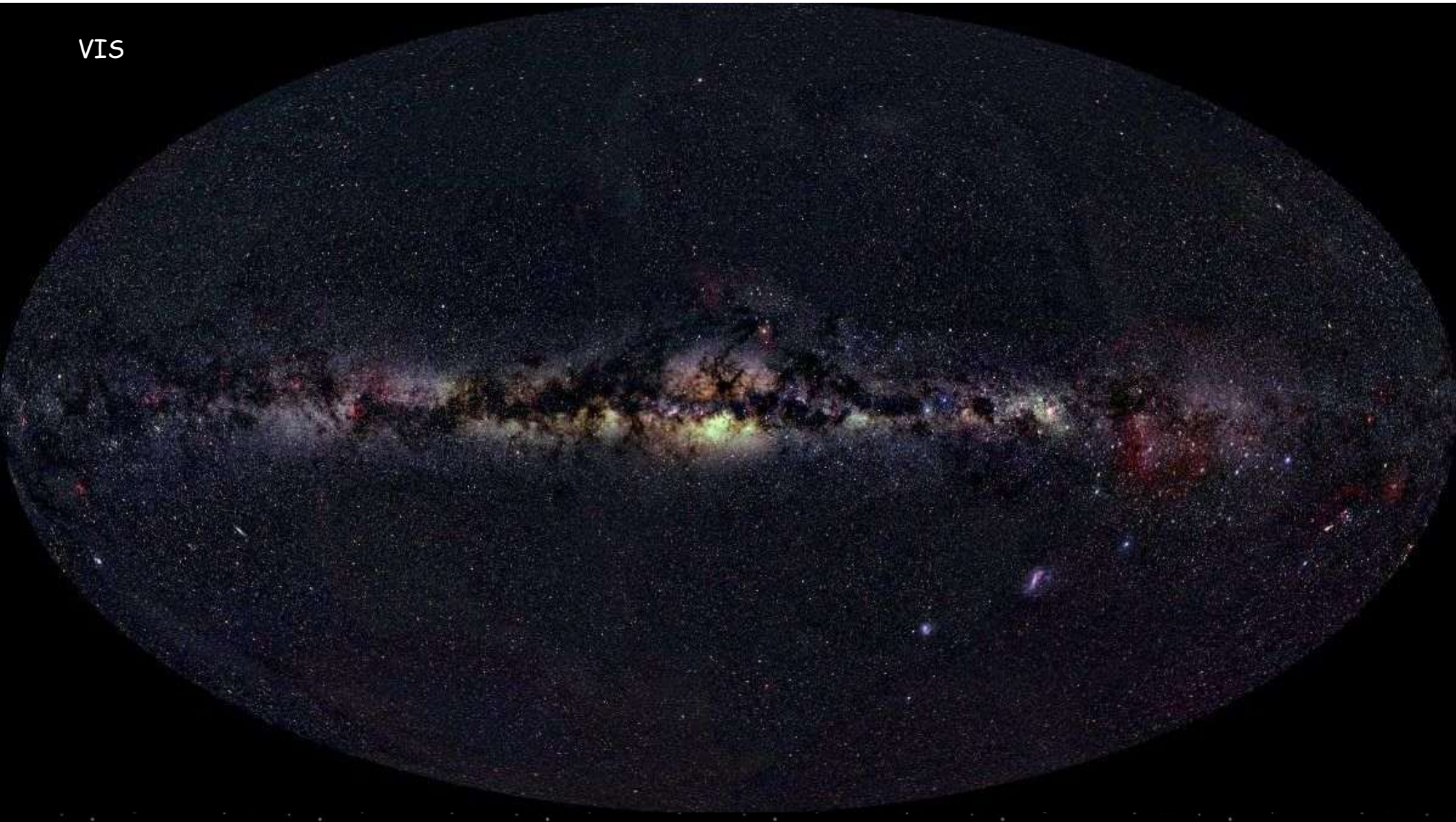
carbonaceous

PAH

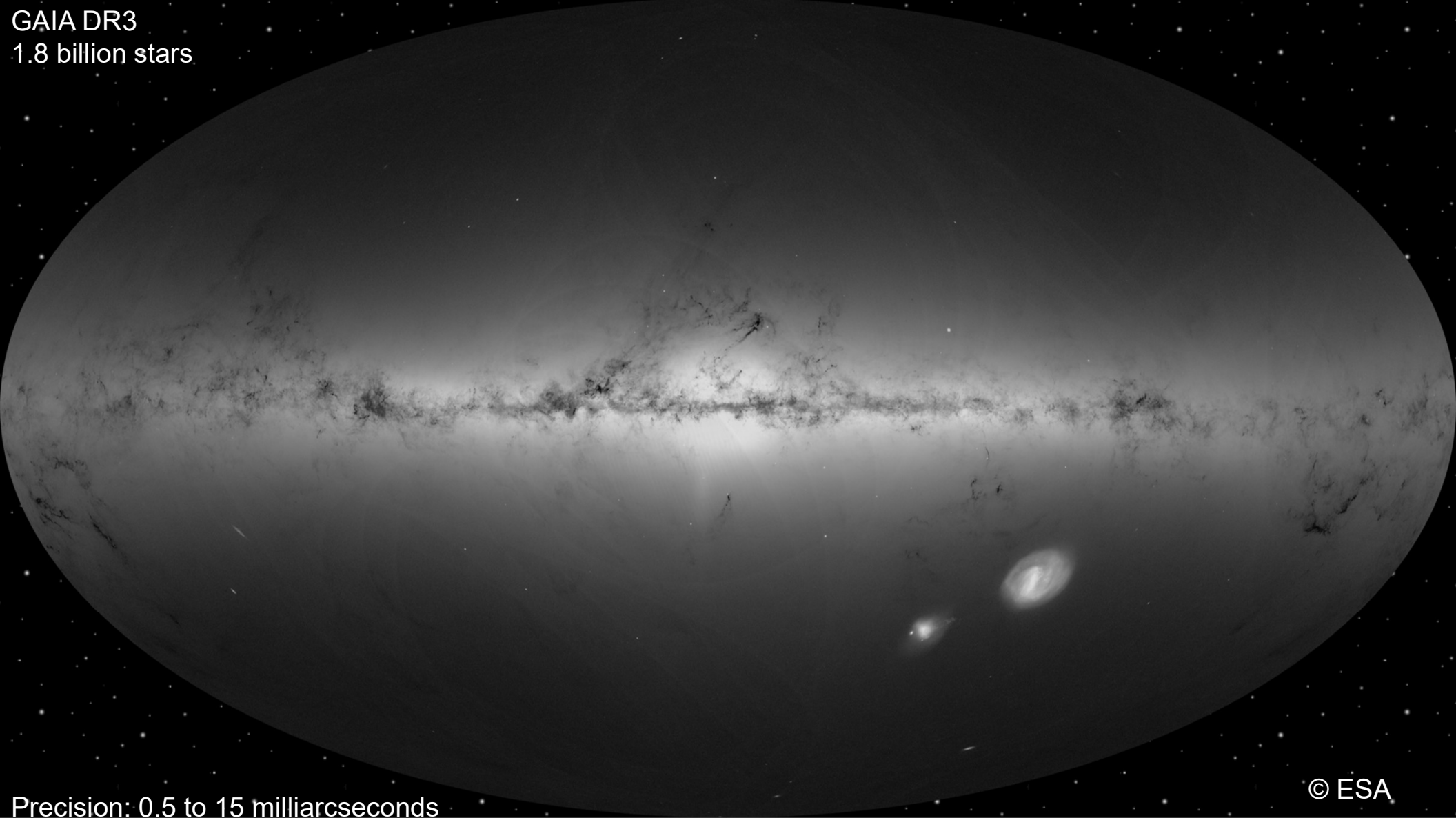
H, H₂, He

CO, NH₃, CH₃OH

VIS



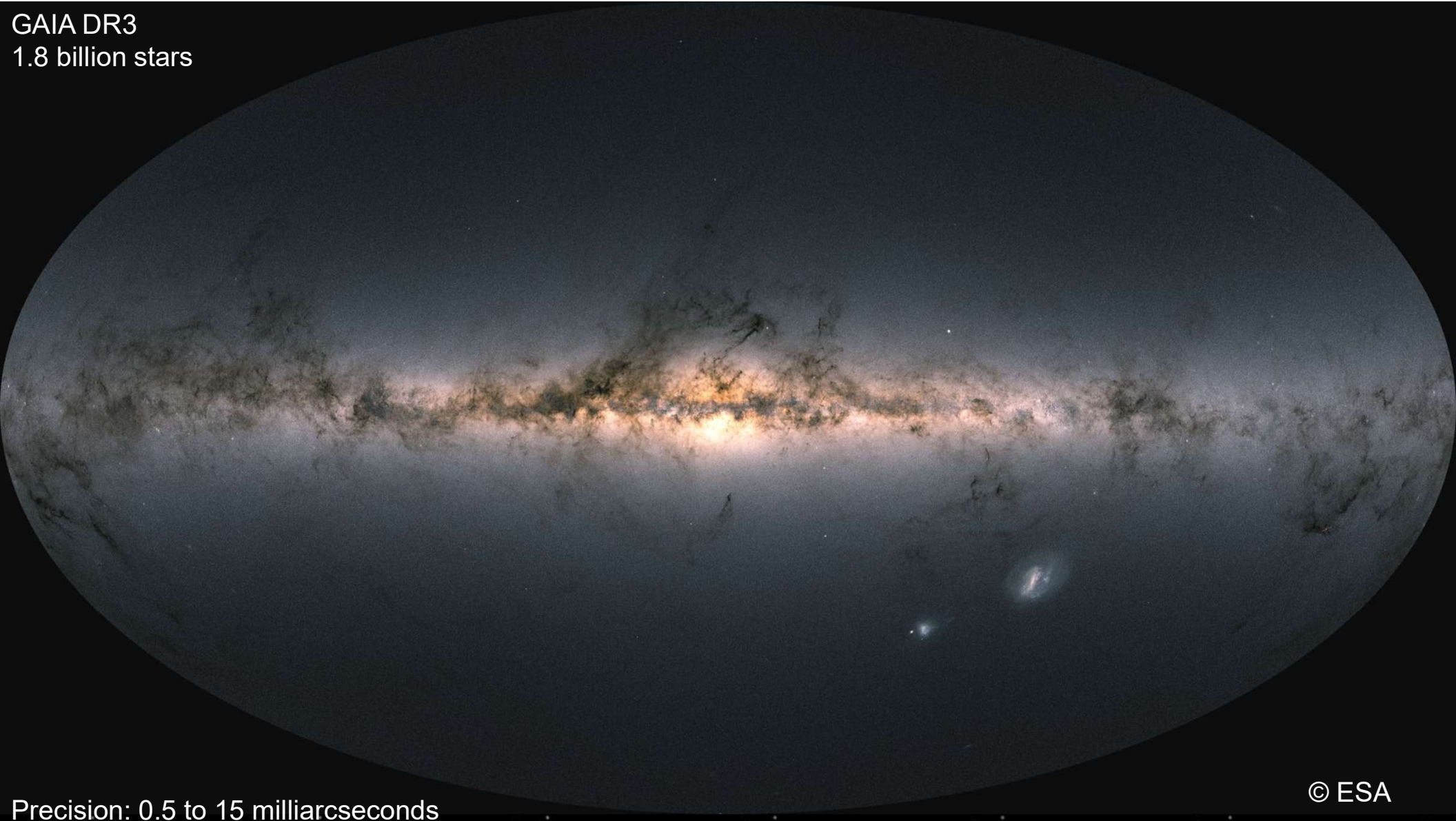
GAIA DR3
1.8 billion stars



Precision: 0.5 to 15 milliarcseconds

© ESA

GAIA DR3
1.8 billion stars

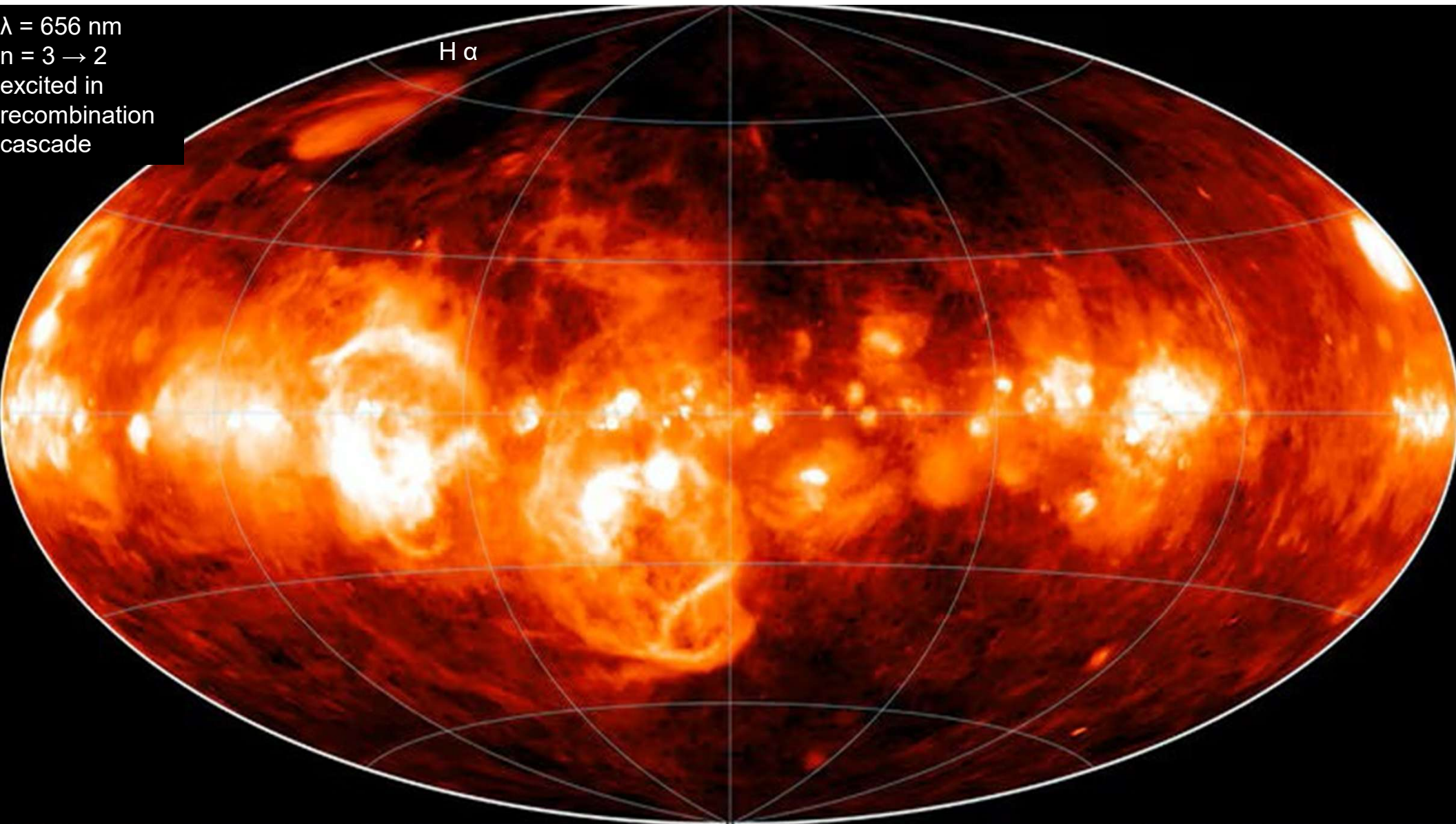


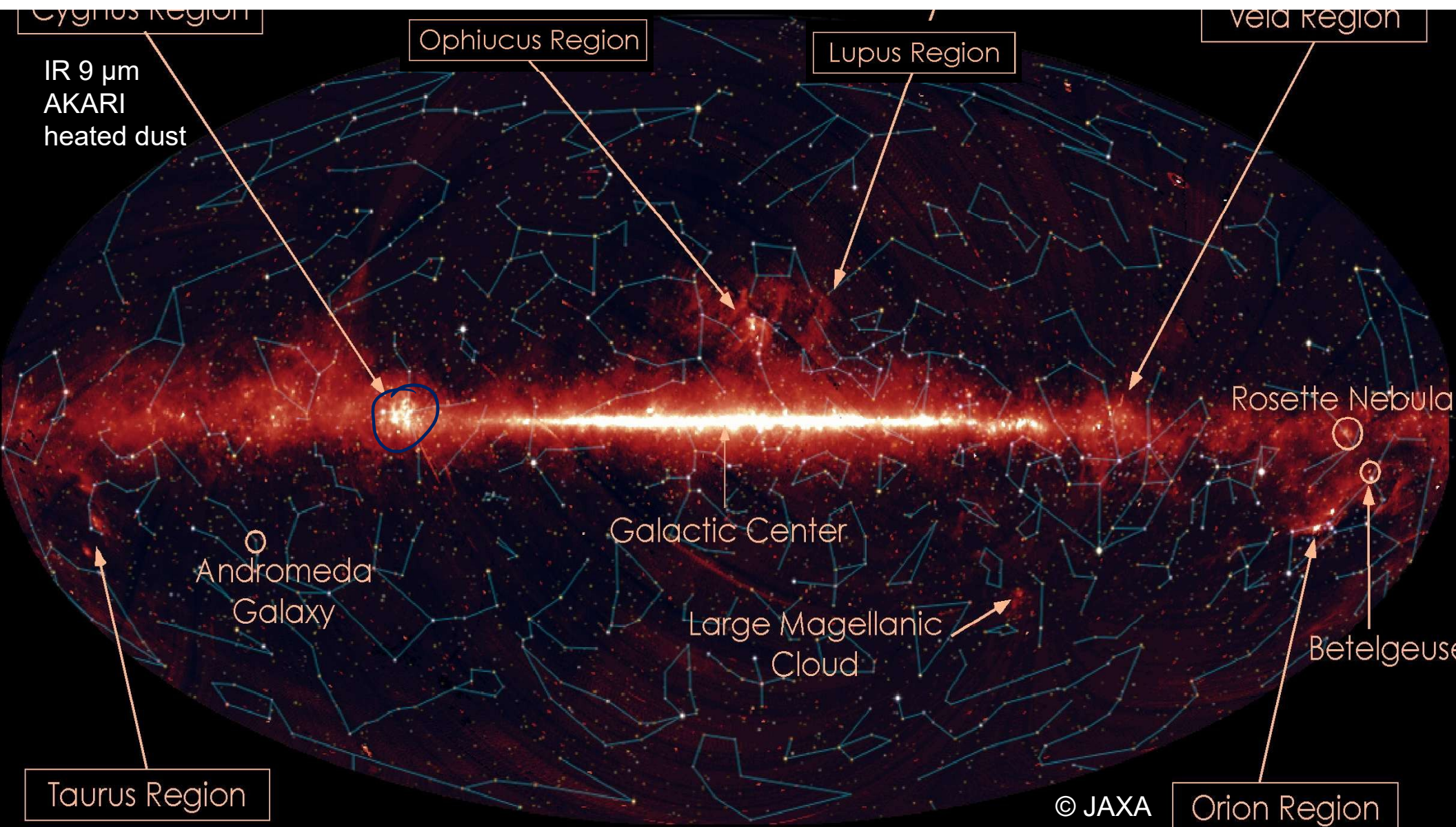
Precision: 0.5 to 15 milliarcseconds

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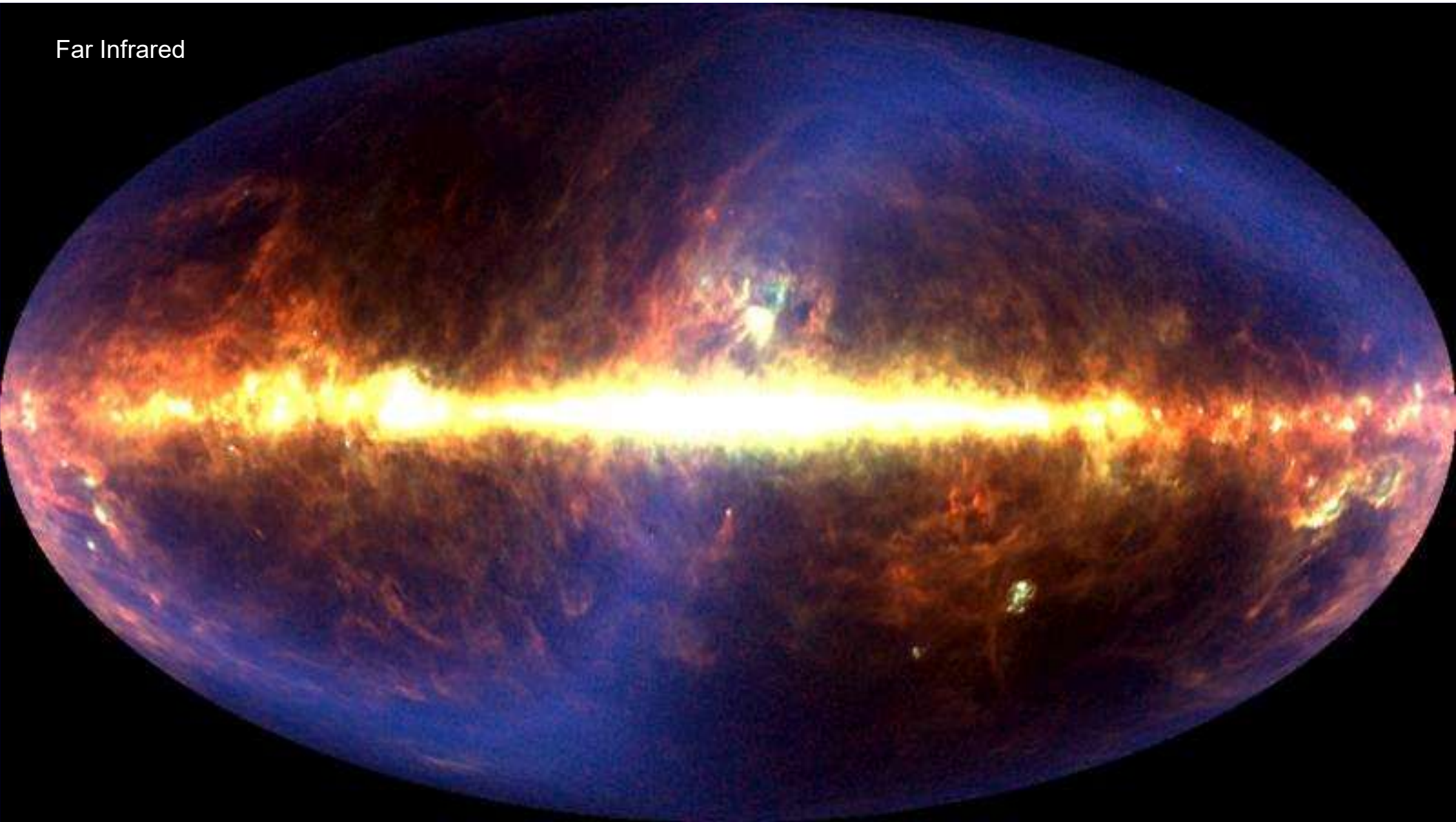
$\lambda = 656 \text{ nm}$
 $n = 3 \rightarrow 2$
excited in
recombination
cascade

H α

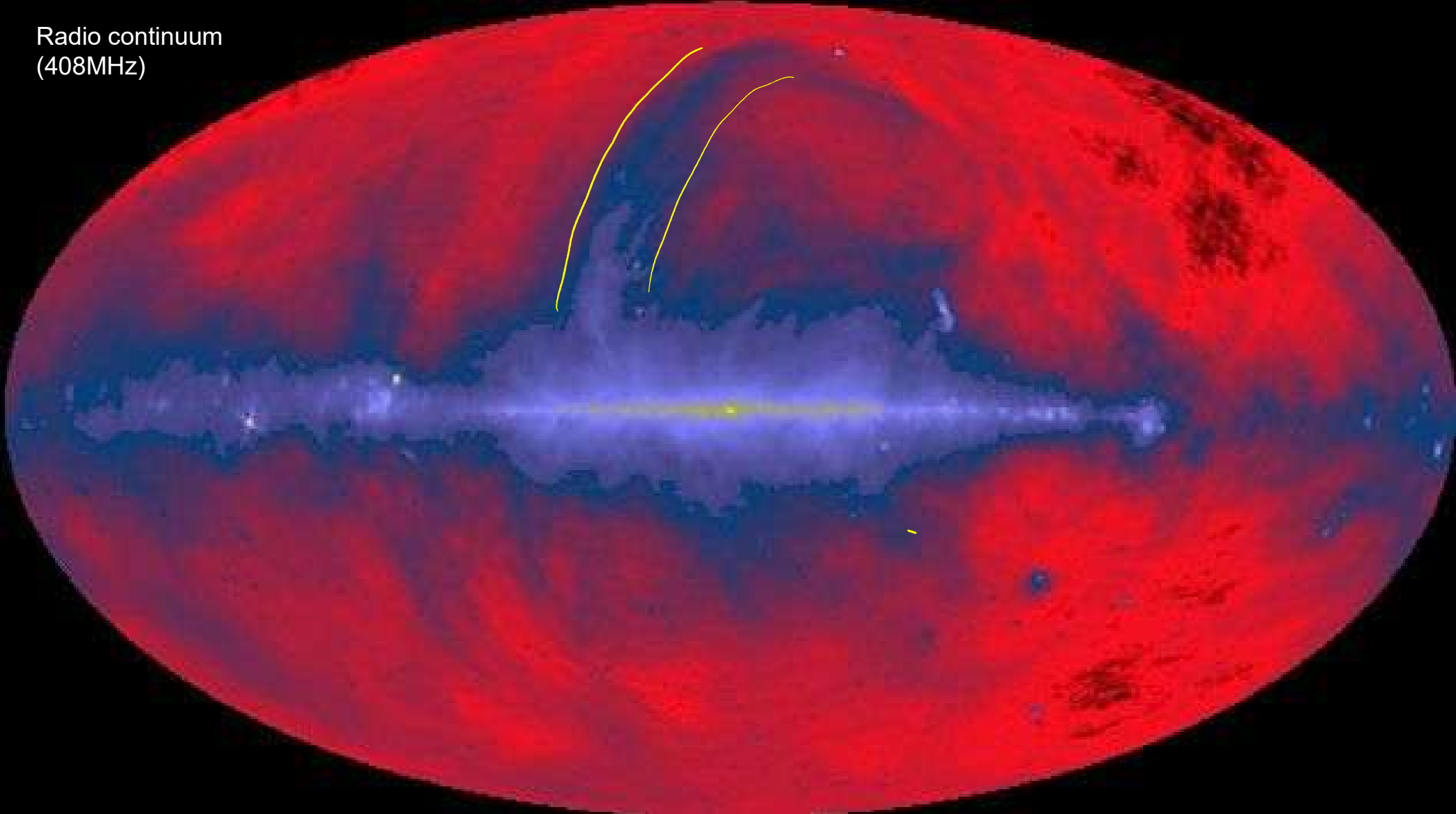




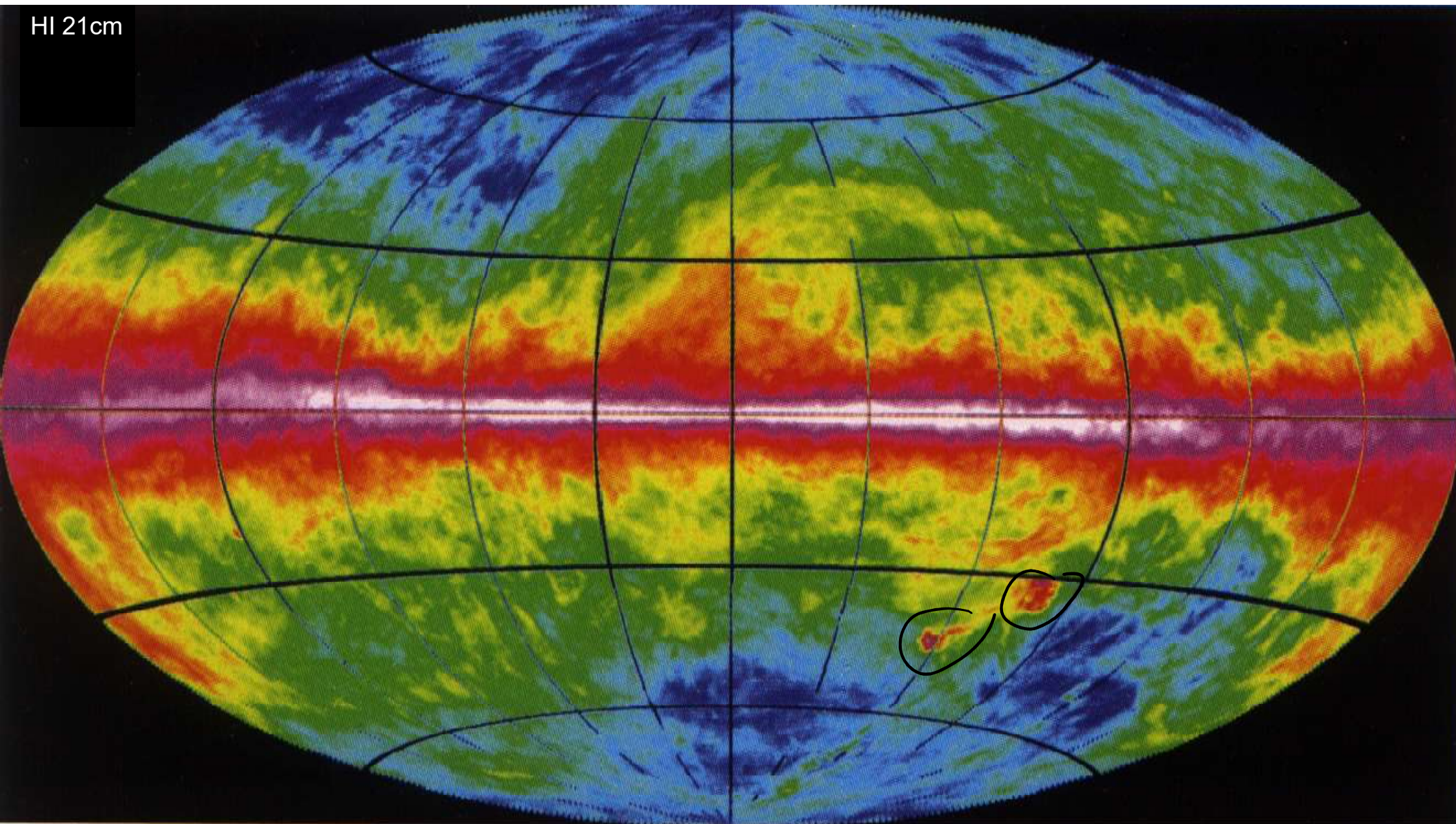
Far Infrared



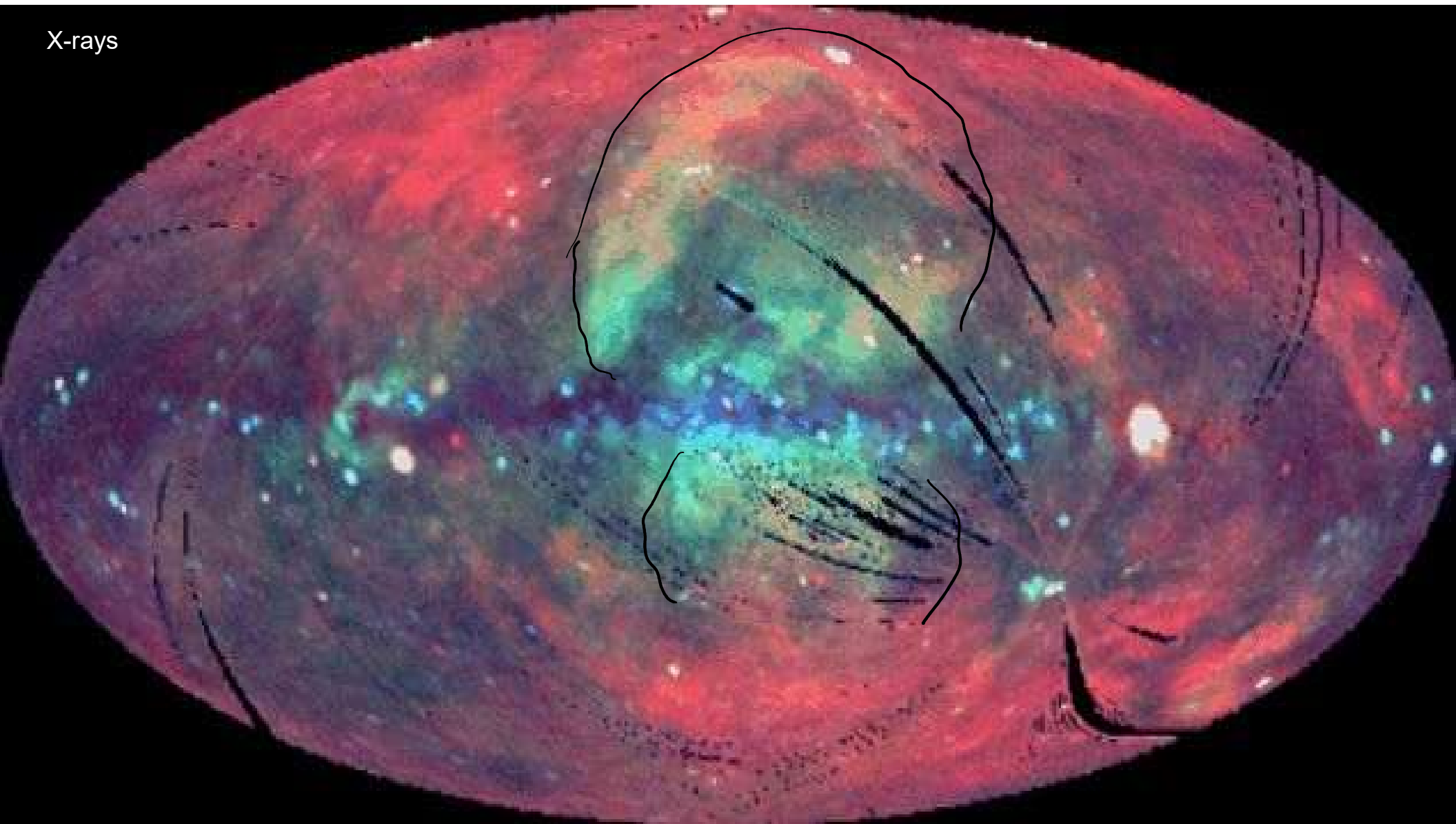
Radio continuum
(408MHz)



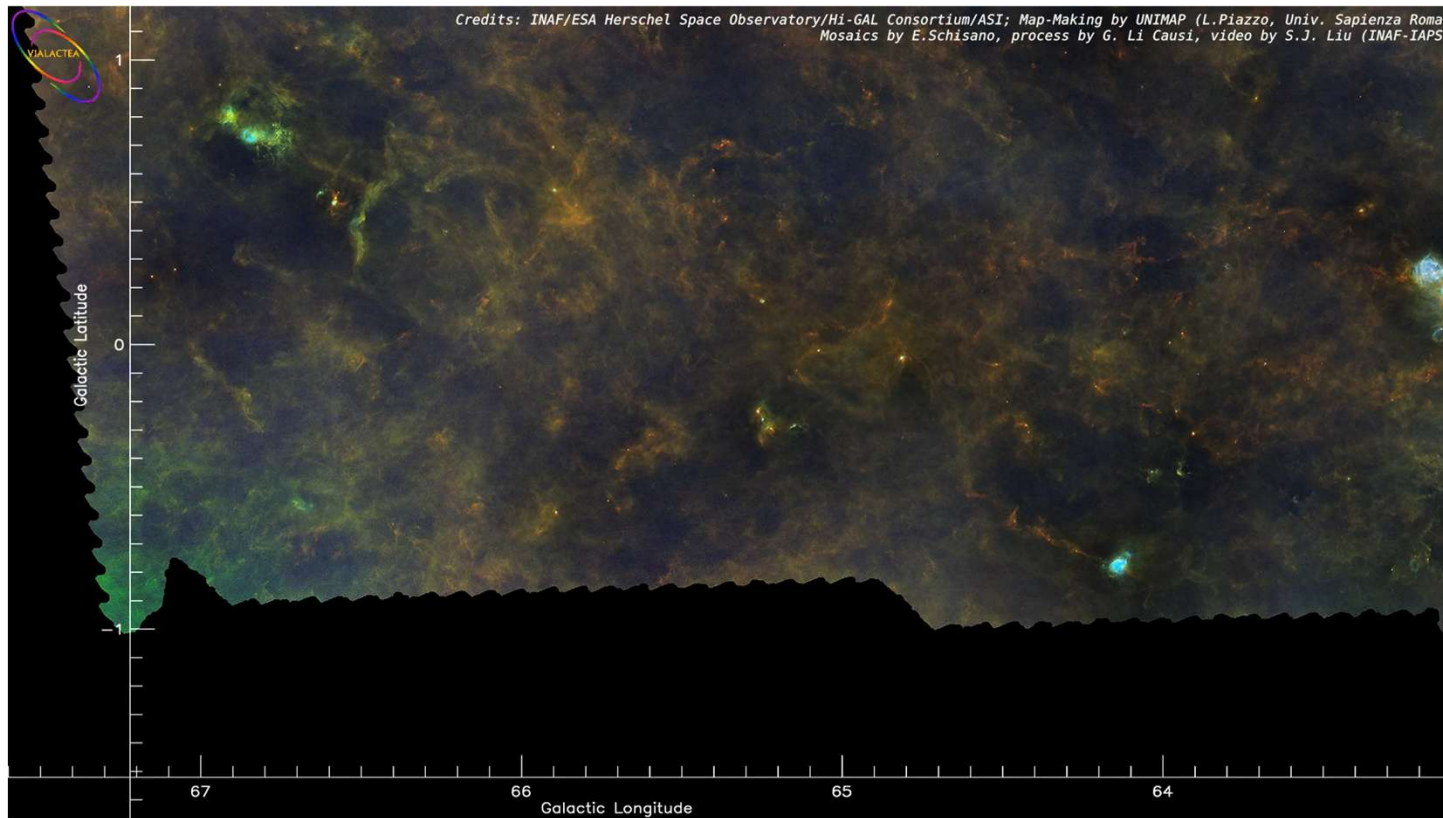
HI 21cm



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



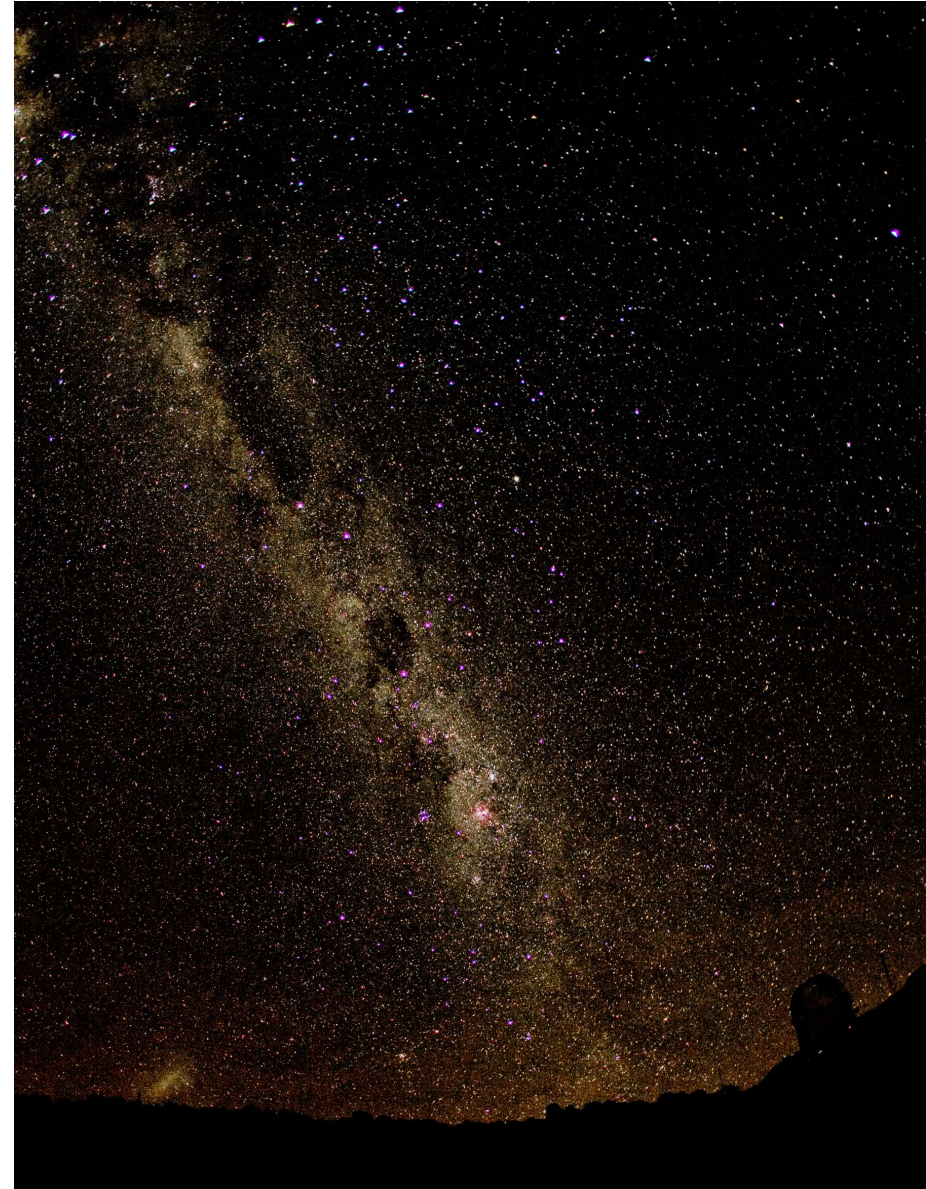
NGC 6726

Credits: Loke Kun Tan ([StarryScapes](#))

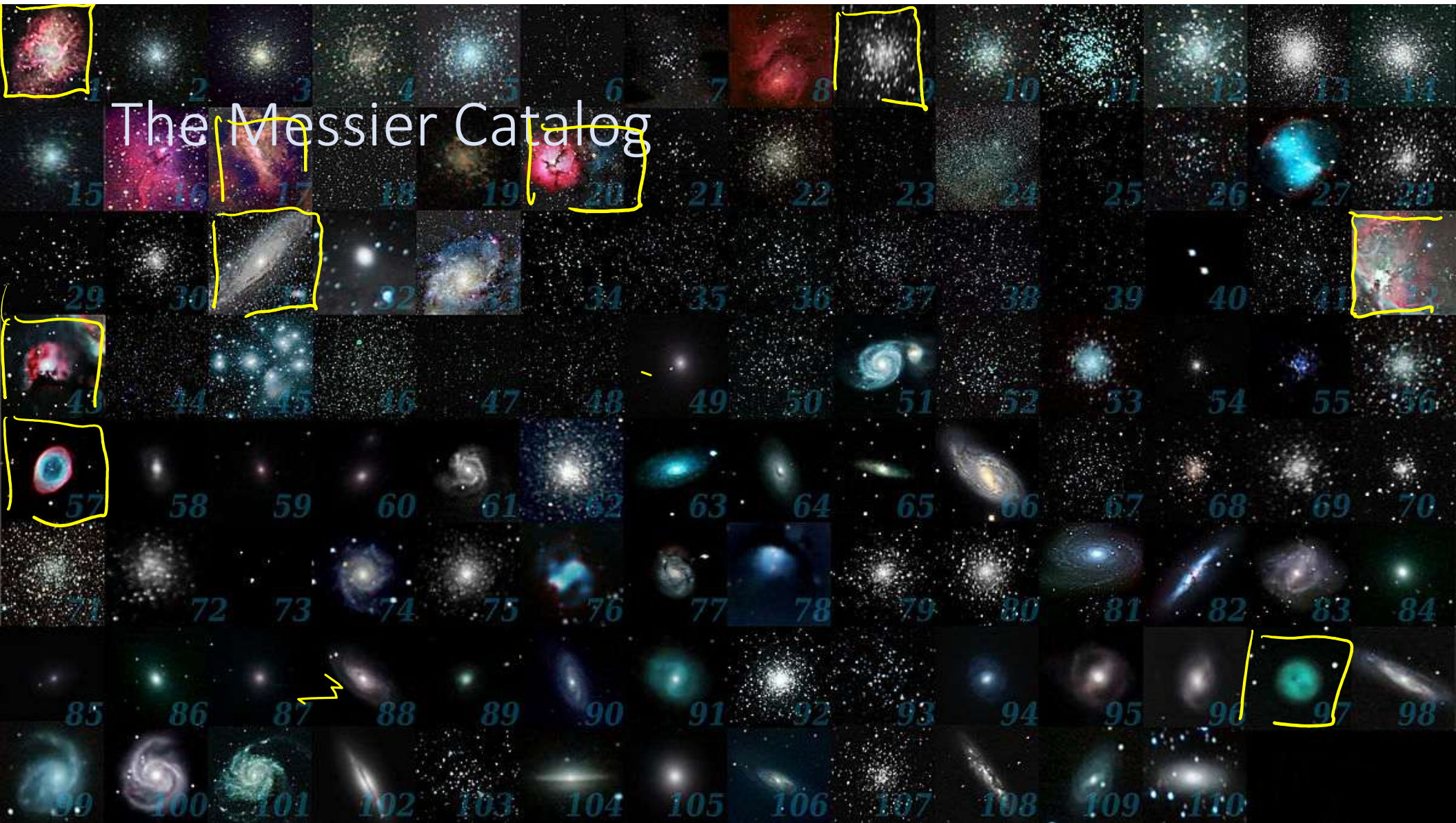
Historical Approach

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

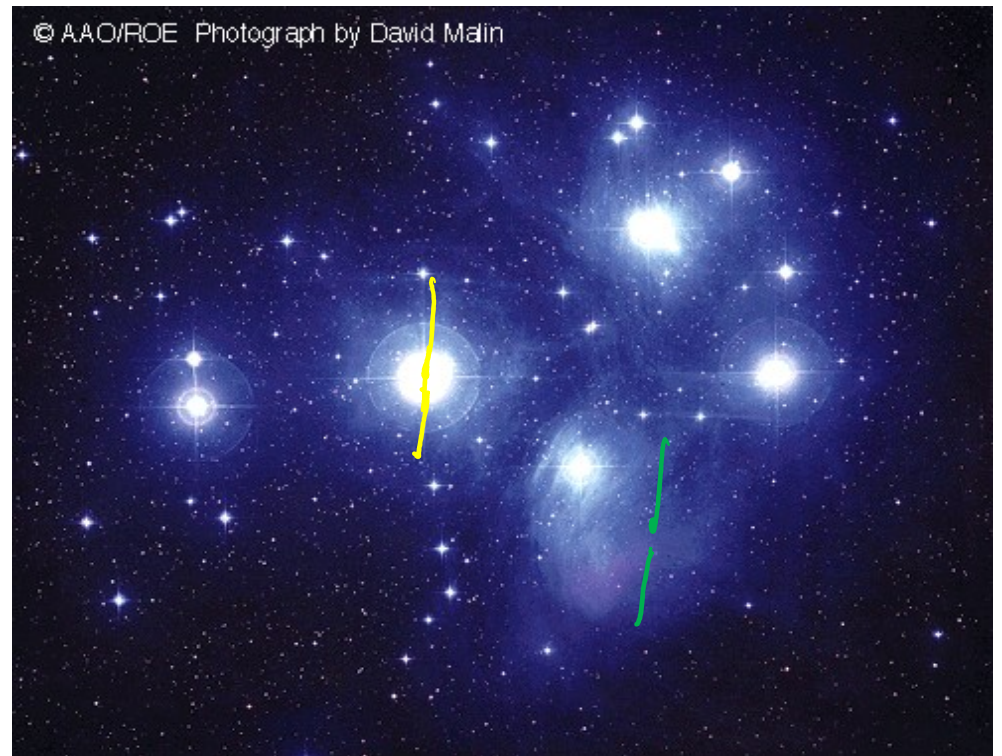
1859 Wilhelm Tempel: Nebulosity around stars in Plejades

1912 Vesto Slipher:

spectroscopy of the nebulosity
shows stellar spectrum

→ reflected stellar light

→ **Reflection nebulae**



Interstellar nebulae

1864 William Huggins:

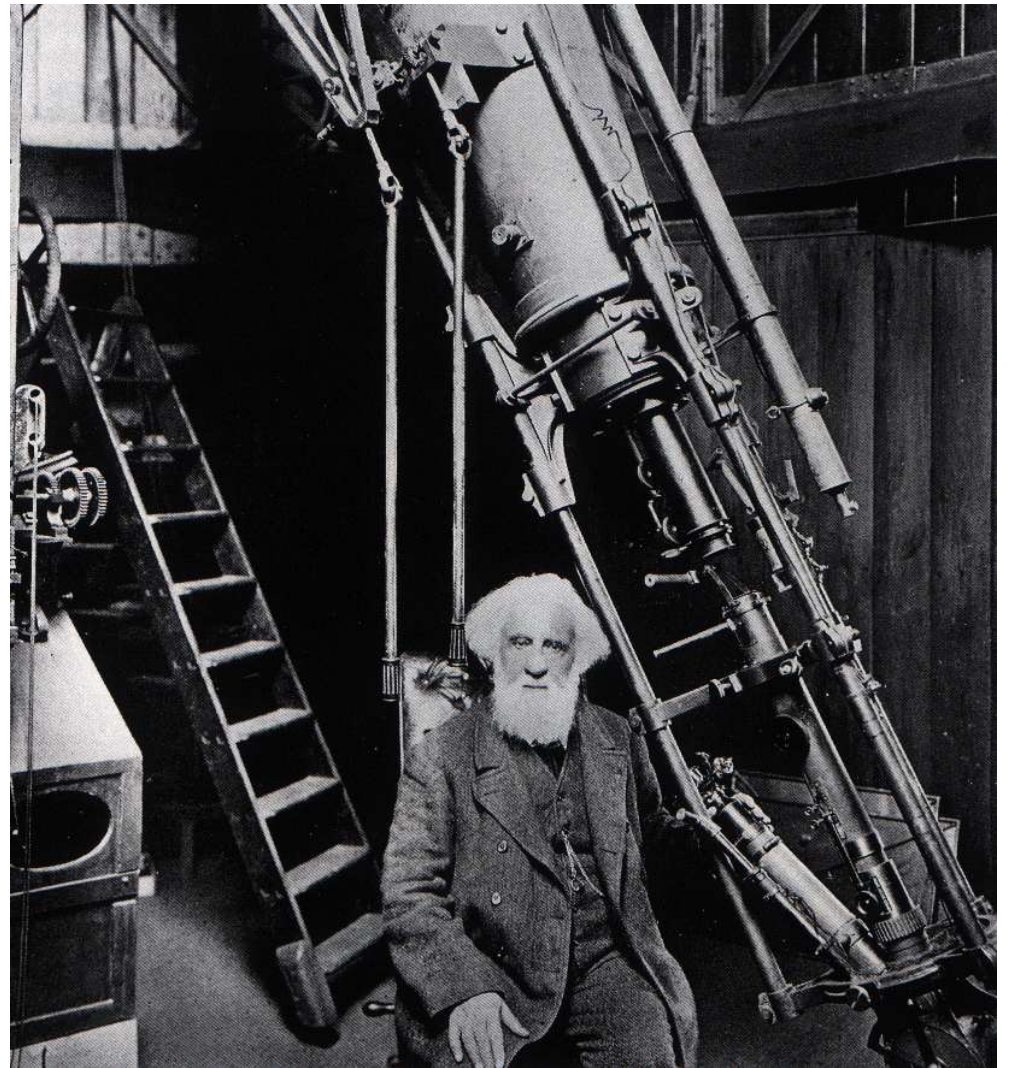
Spectroscopy of Nebulae

Nebulium

→ about 1/3 showing
only line emission

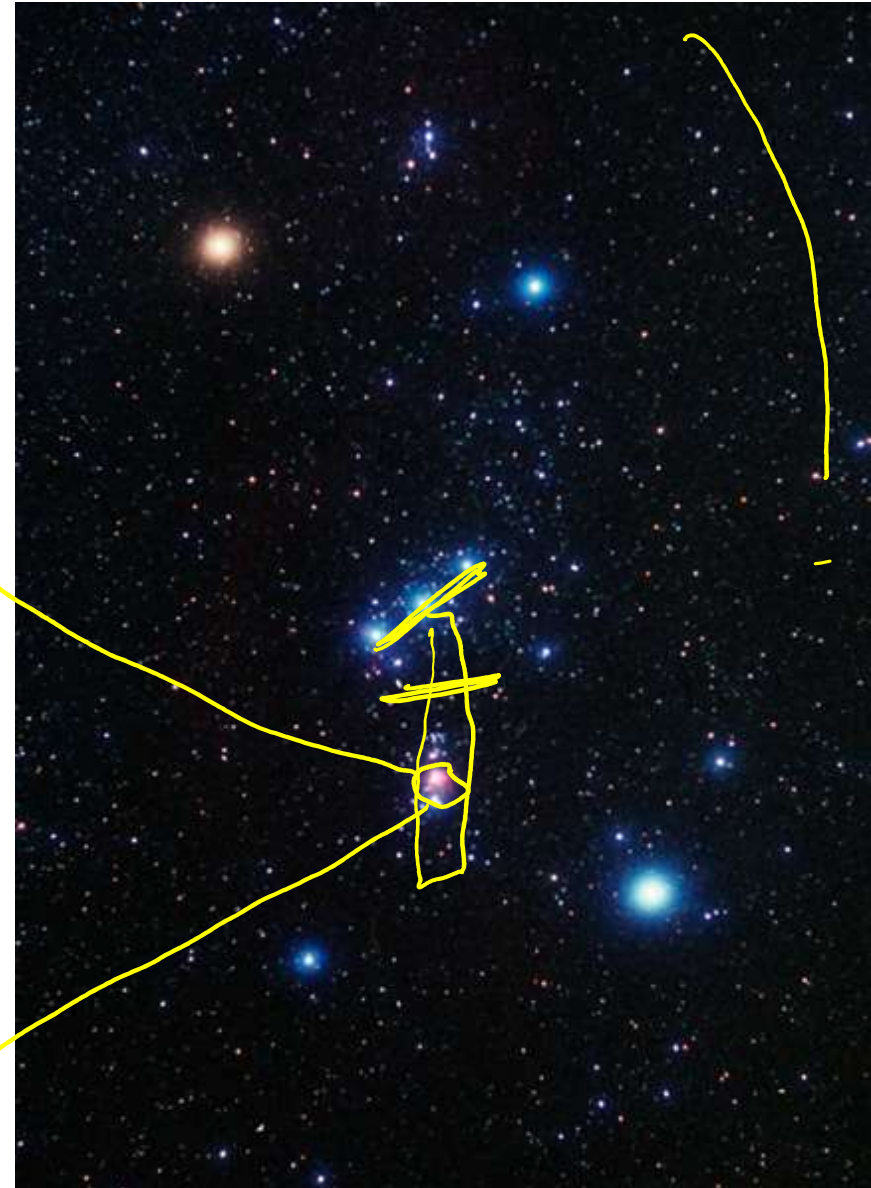
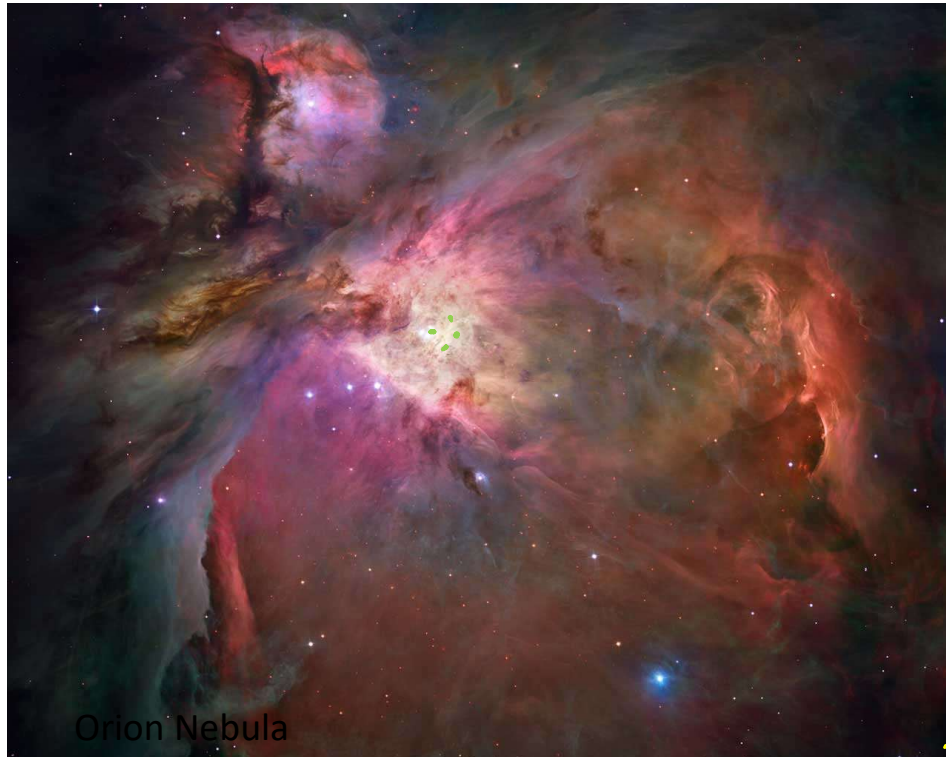
(2/3 stellar spectra = external
galaxies or reflection nebulae)

[O III], [N III]

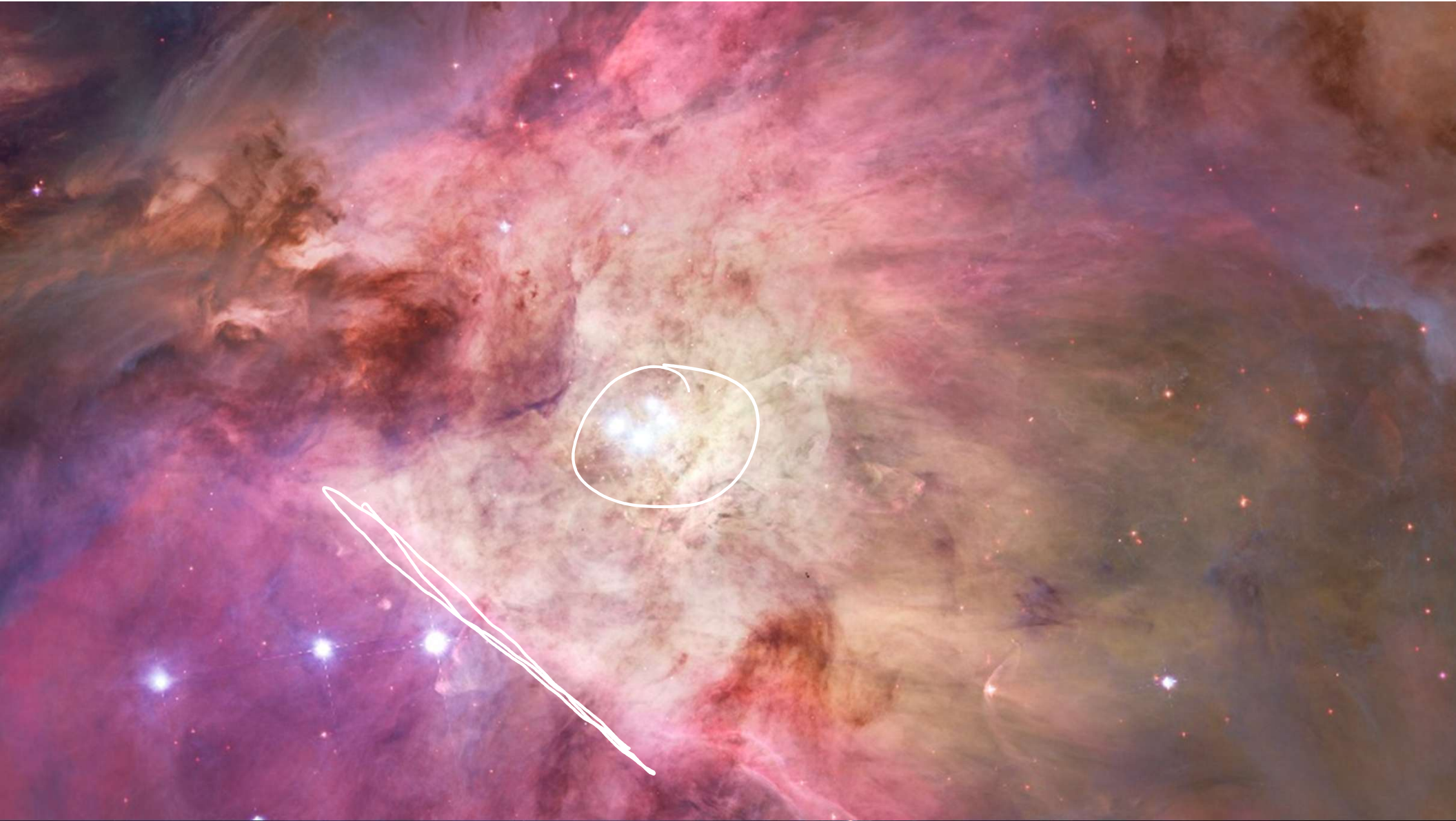


Interstellar nebulae

Emission nebulae



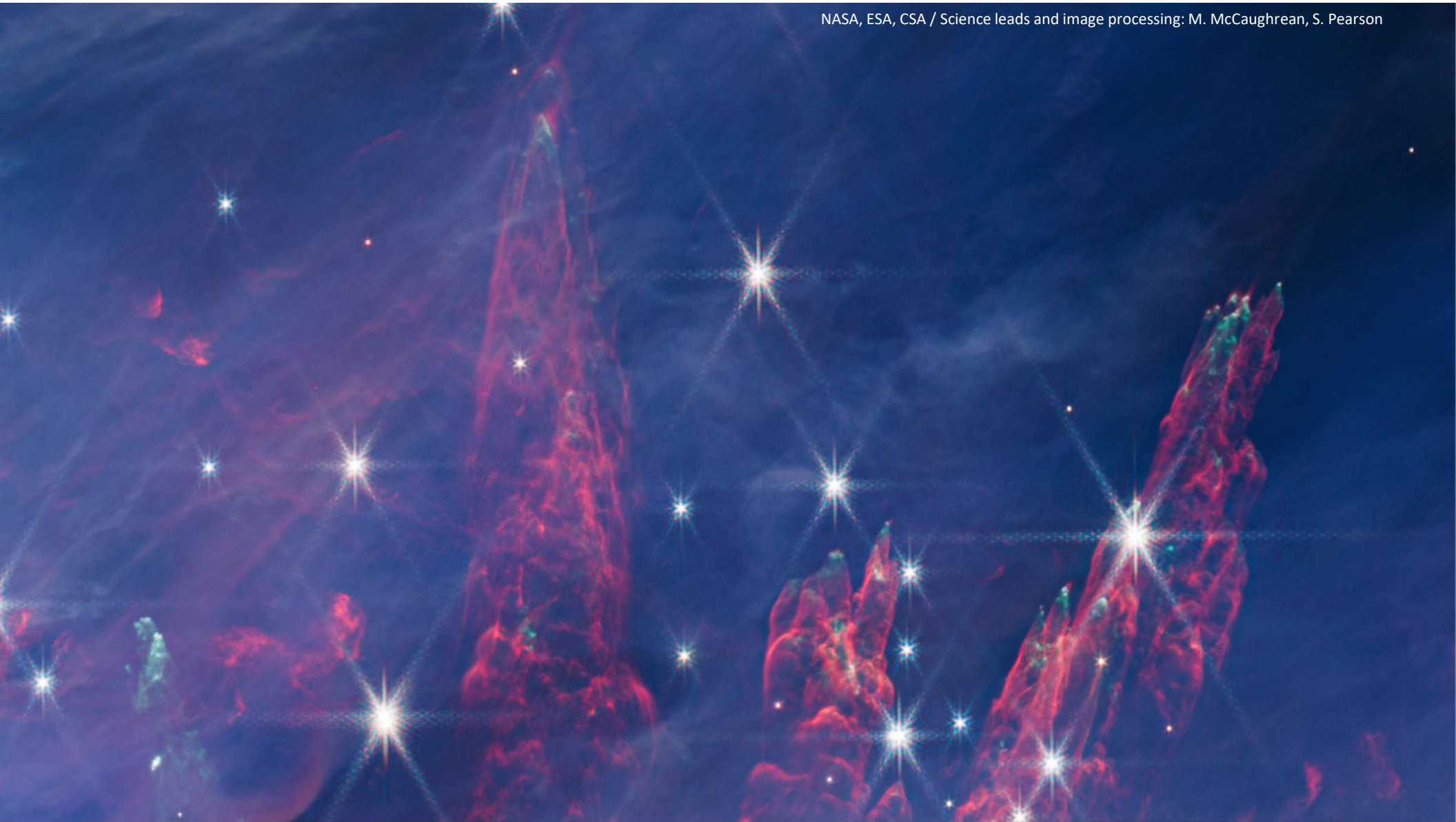




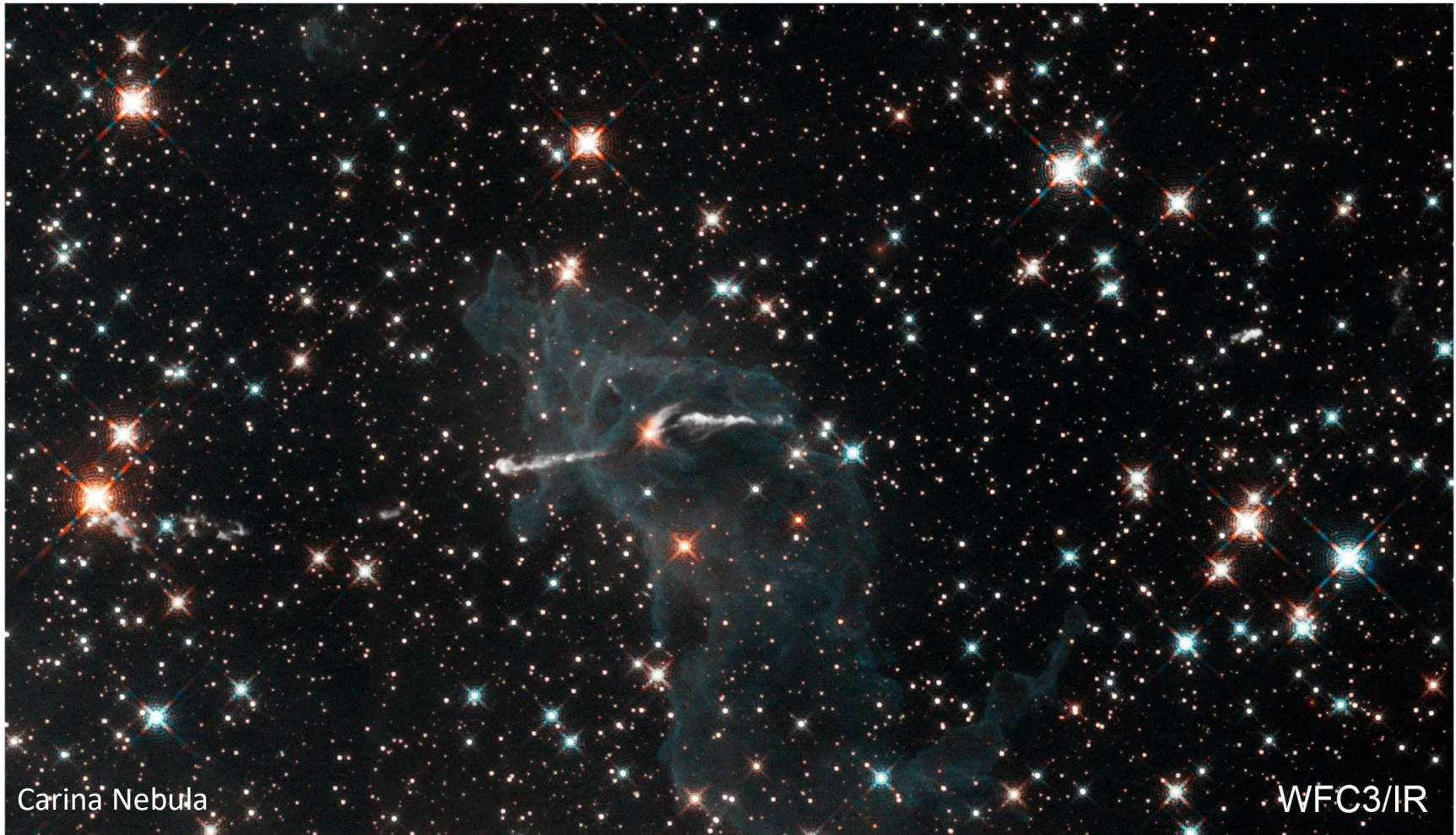




NASA, ESA, CSA / Science leads and image processing: M. McCaughrean, S. Pearson



Interstellar nebulae



Carina Nebula

WFC3/IR

Interstellar nebulae



Carina Nebula

WFC3/UVIS

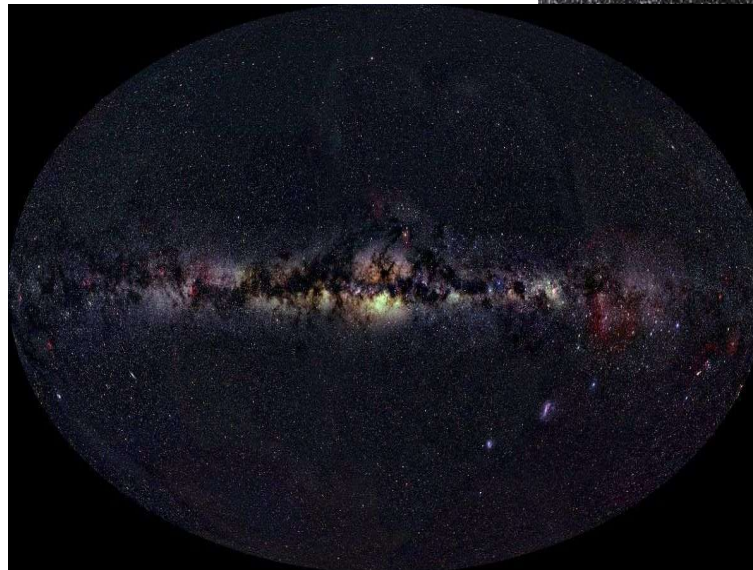


Emission nebulae

- 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

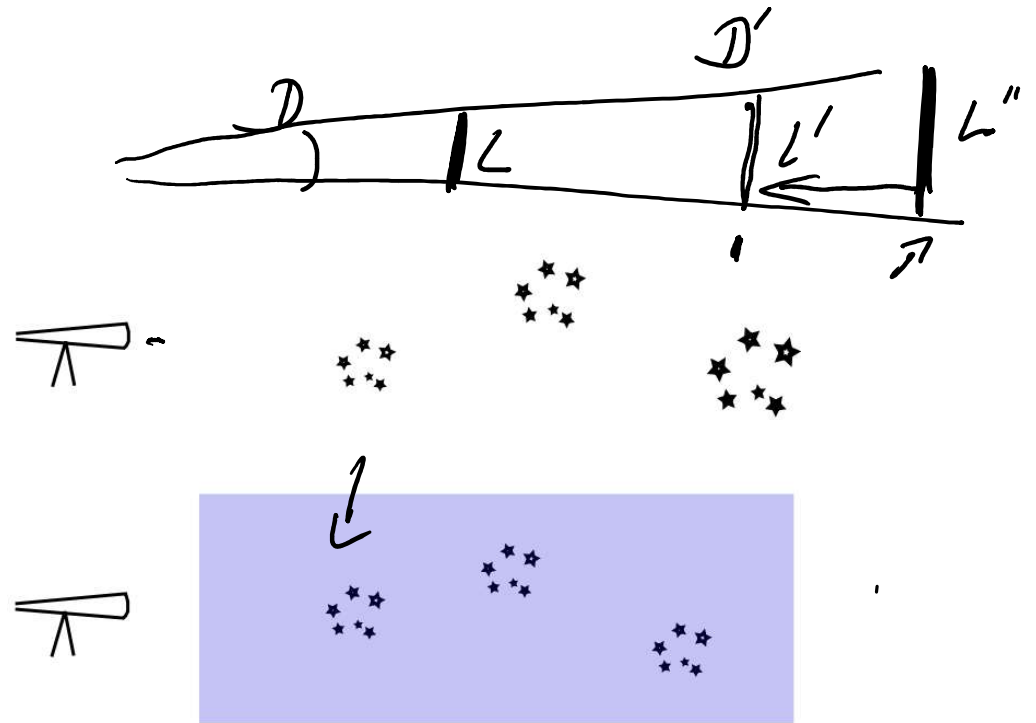


Dark Clouds



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

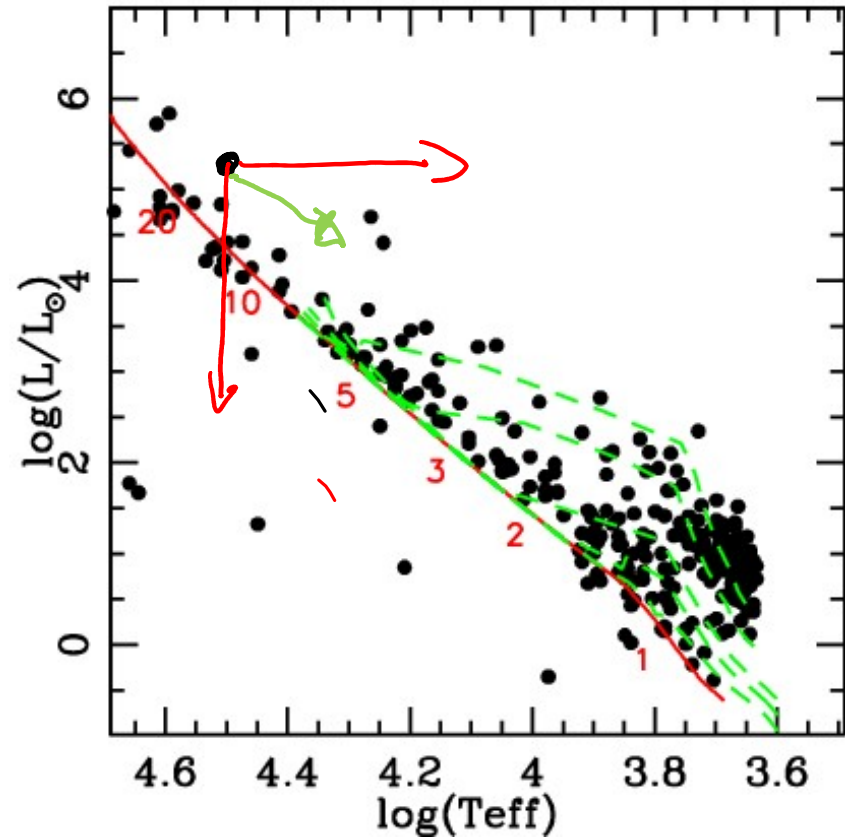
$$L_{\text{obs}} \sim \frac{1}{D^2}$$

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 reddenning



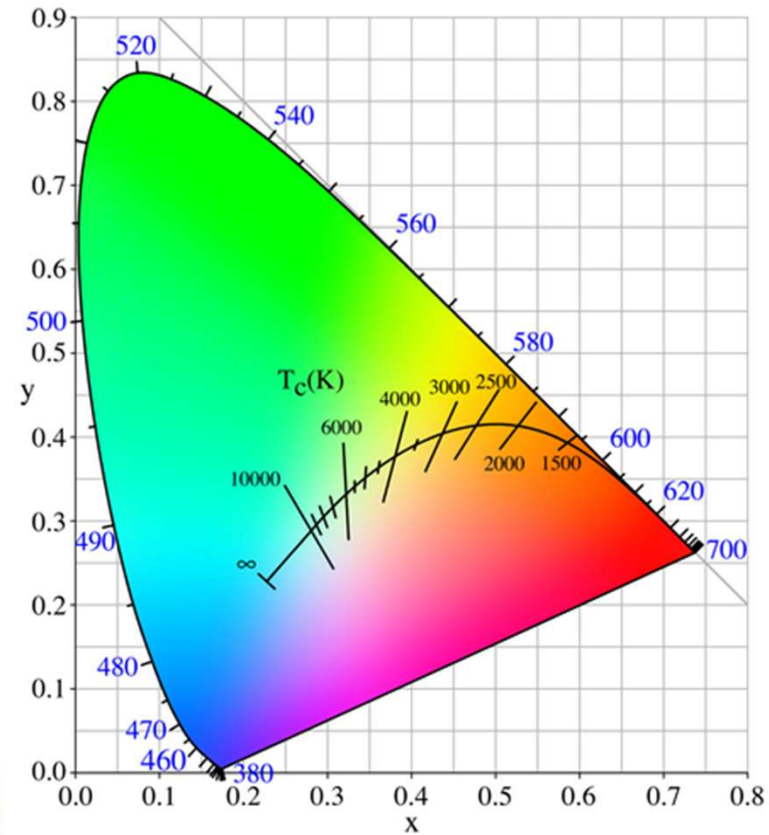
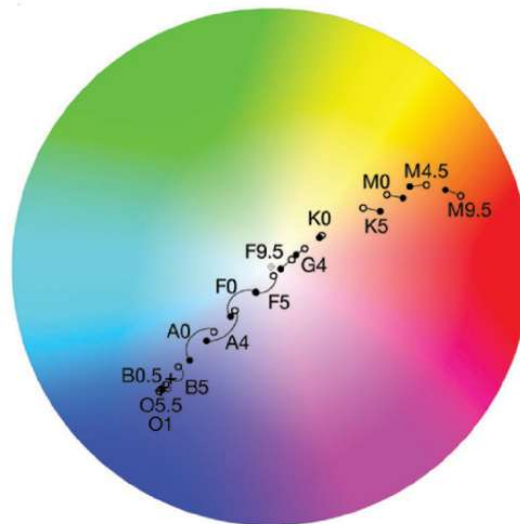
HR diagram of open clusters

Interstellar Extinction

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→ Brightness reduction by extinction accompanied by simultaneous reddenning



Color-Temperature-Relation

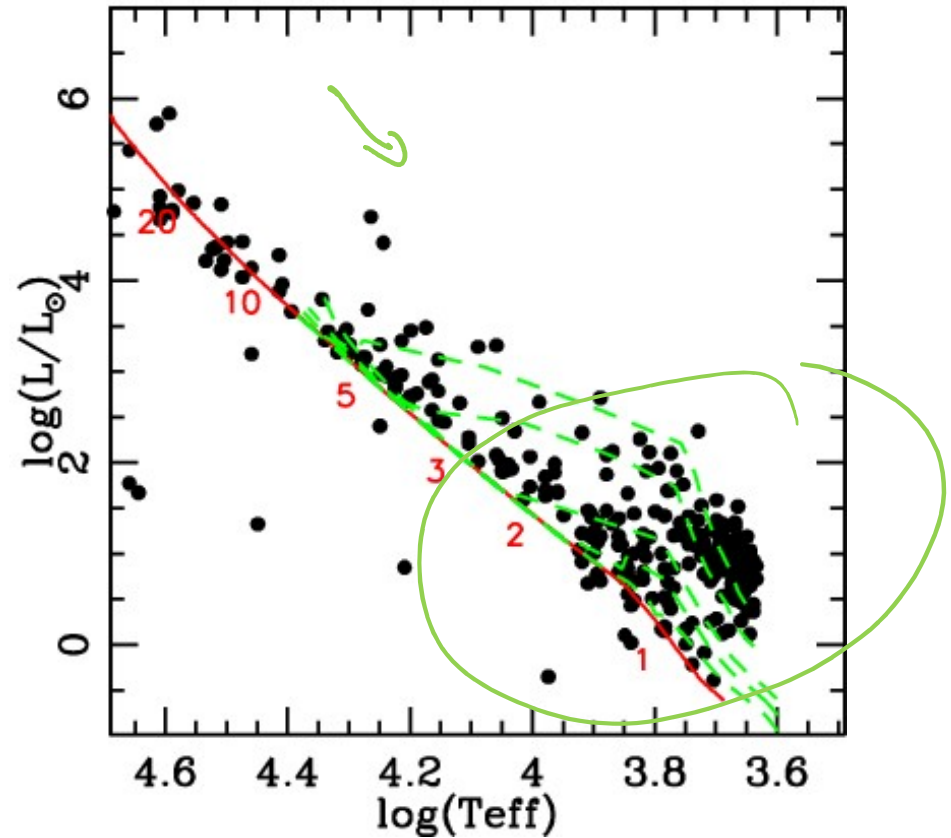


Interstellar Extinction

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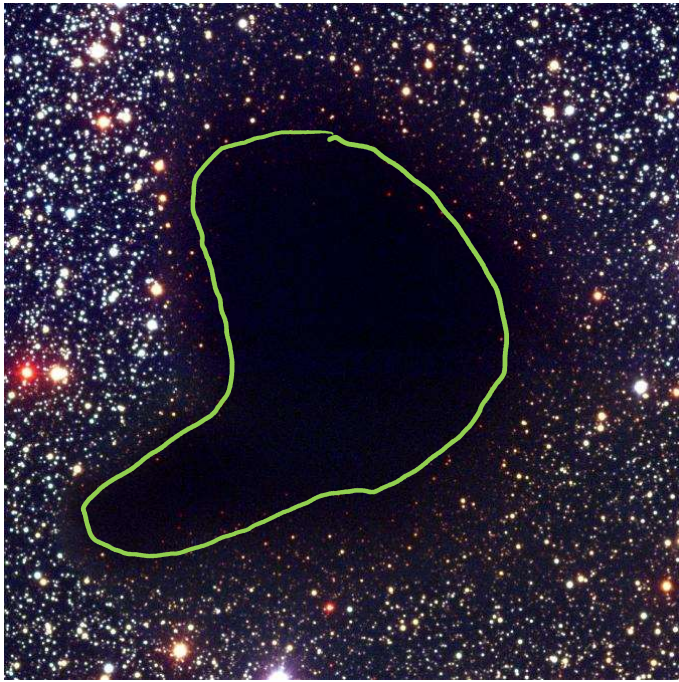
→ Brightness reduction by extinction accompanied by simultaneous reddenning



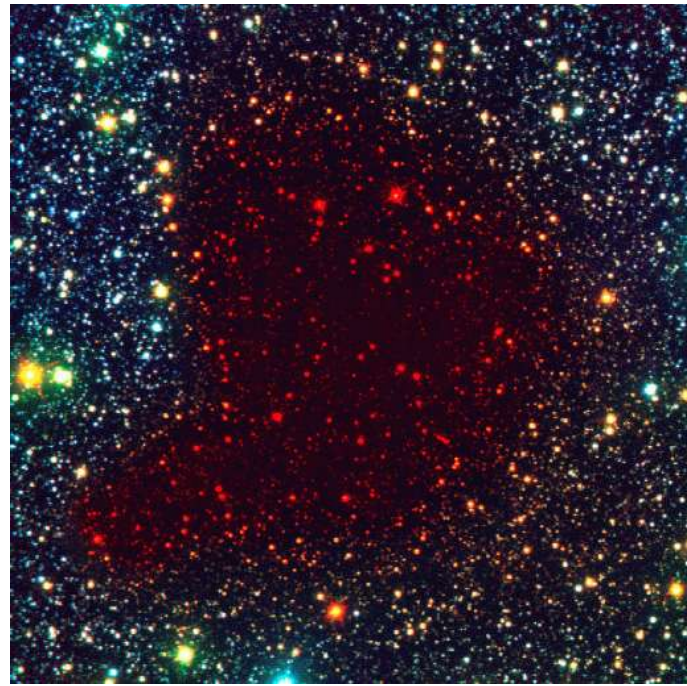
HR diagram of open clusters

Interstellar Reddening

Wavelength dependent extinction = reddening



Barnard 68: VIS



470, 870, 2200 nm

$$M = 1, \dots, 6$$

$$1 \dots 6 \leq 100$$

$$1 \rightarrow 2 : 2.5 \text{ doch dunkler}$$

Description

- Wavelength dependent extinction:

$$A_{\lambda} = M_{\lambda, \text{obs}} - M_{\lambda, *}$$

- Normalization to $\lambda=550\text{nm}$ (V-filter): A_V - visual extinction

- Typical value:
(Bohlin, Savage & Drake 1978)

$$\frac{N_H}{A_V} = 1.9 \times 10^{21} \frac{\text{cm}^{-2}}{\text{mag}}$$

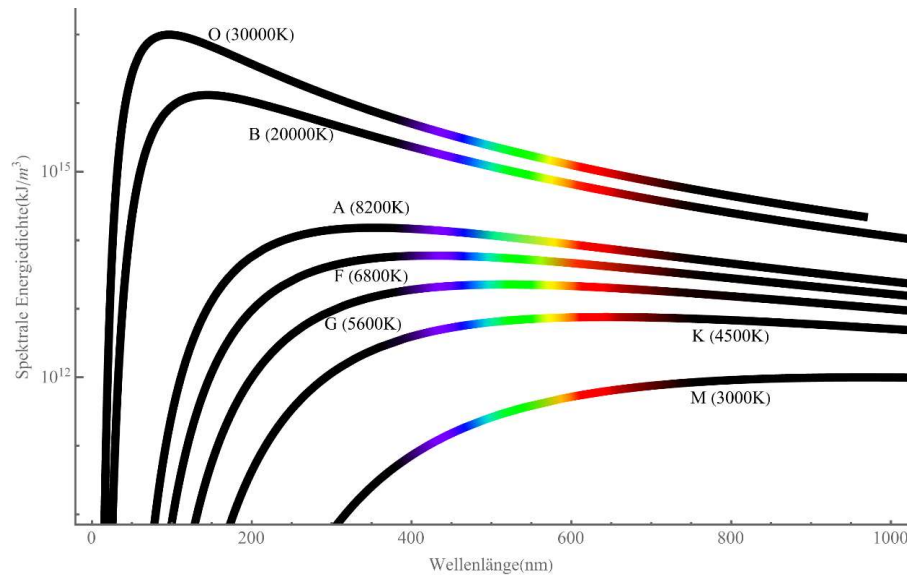
- Reddening:

B-filter: $\lambda = 350\text{nm}$

- Typical value in diffuse clouds: $R=3.1$
(Johnson 1968, Lee 1968, Martin 1971, Harris 1972)

$$R = \left(\frac{A_B - A_V}{A_V} \right)^{-1} \quad N_H = \int n_H dl \quad [n_H] = \text{cm}^{-3}$$

Color Index

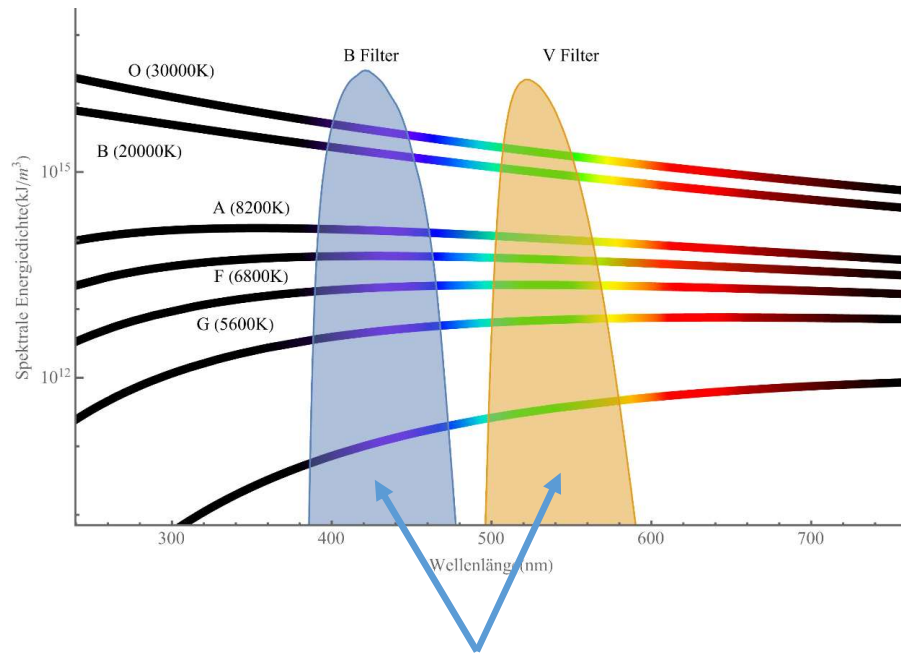


- Difference between B and V brightness

$$B - V = m_B - m_V$$

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

Farbindex



Filter curves

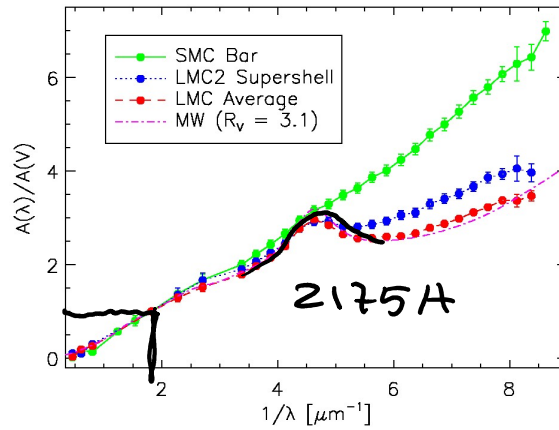
- Difference between B and V brightness

$$B - V = m_B - m_V$$

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

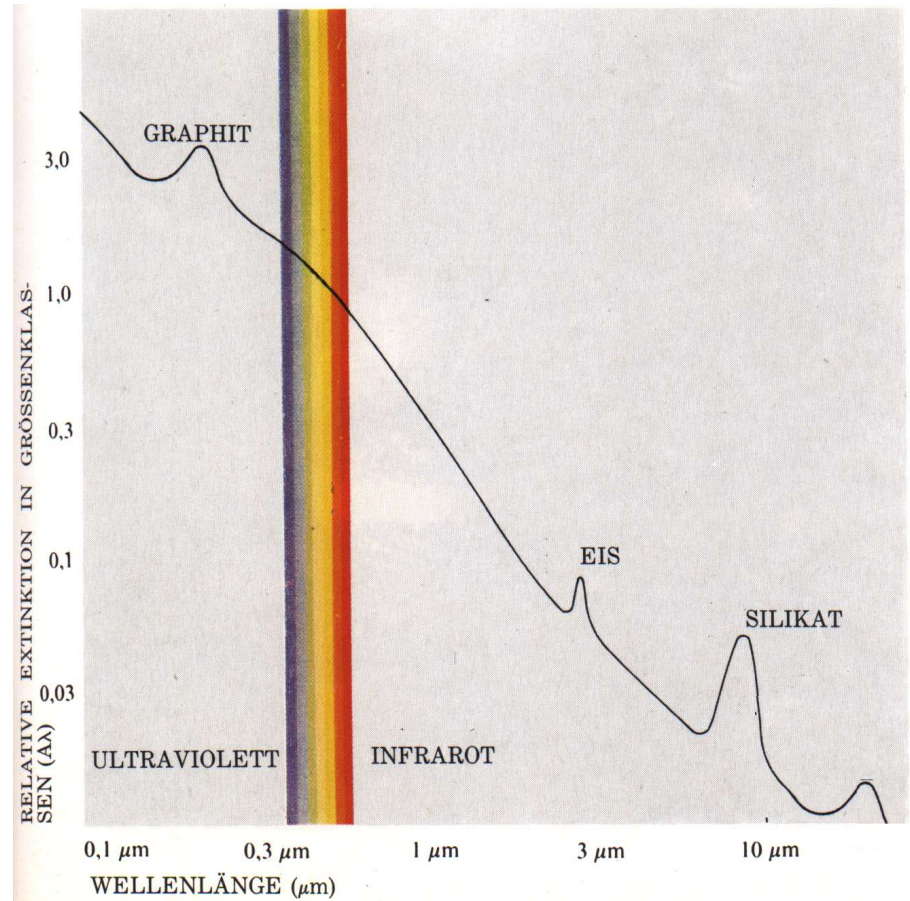
Interstellar Extinction

- Extinction curves vary



Interstellar extinction curves in the Milky Way and other galaxies

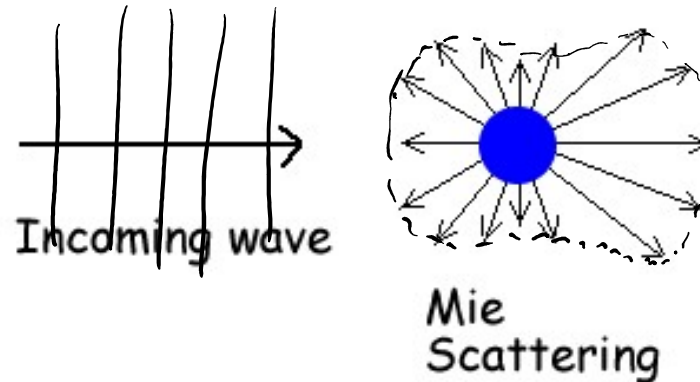
Bumps in the UV and infrared allow to infer chemical composition



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 τ and A_{λ} from observation

