Interstellar Astrophysics

PHAS2525

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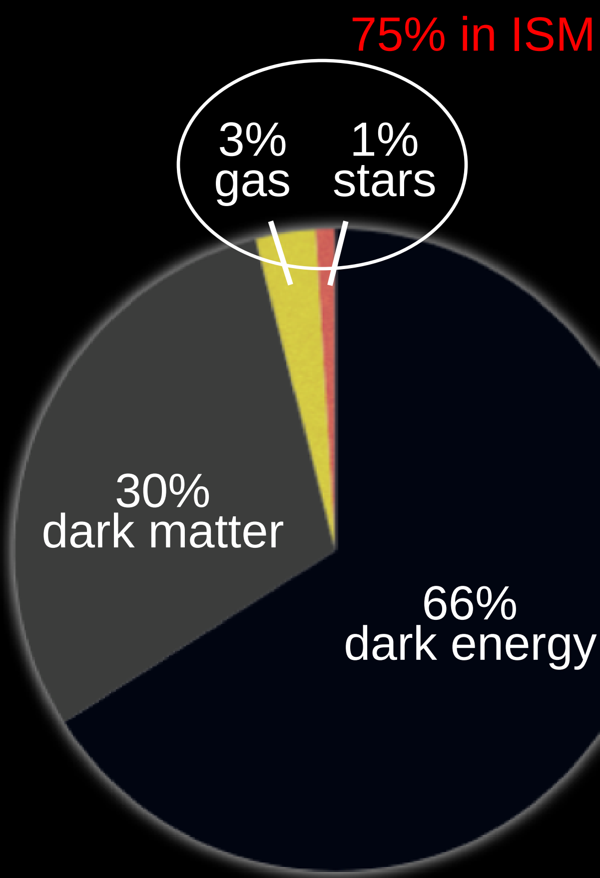
Interstellar: the material between stars, the **Interstellar Medium (ISM)**

Astrophysics: the study of astronomy and physics (mainly observational)


75% in ISM
3%
gas
1%
stars
30%
dark matter
66%
dark energy

Interstellar Astrophysics

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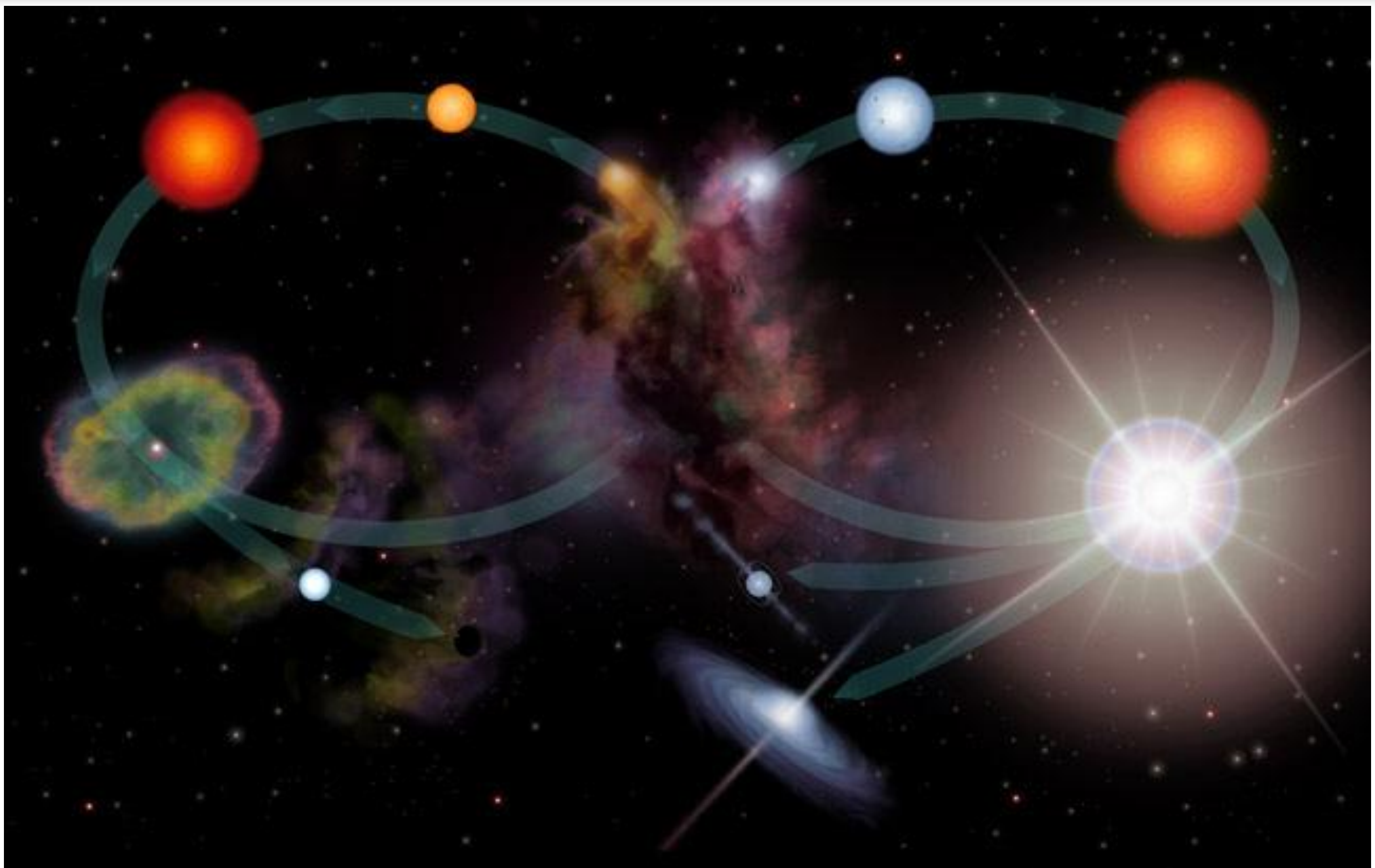


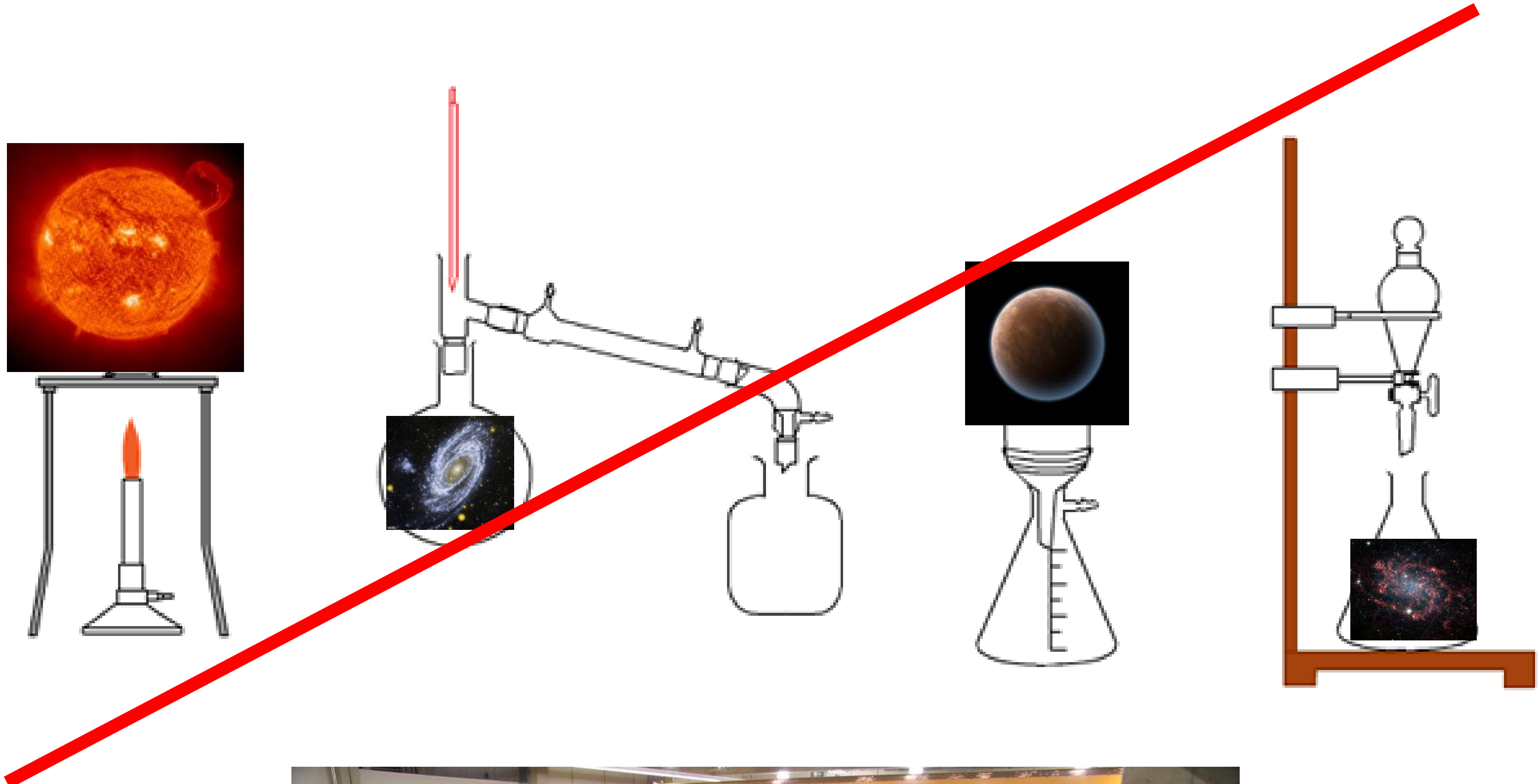
Exploring: How do we find out about far-away places?

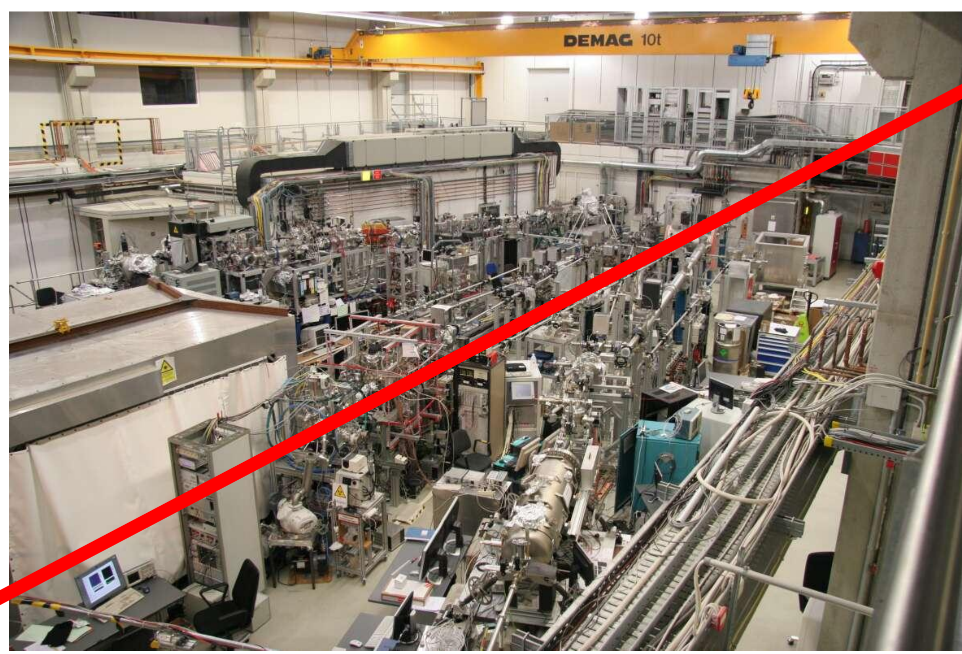
>> Go there ourselves

>> Learn from the people there

>> Send probes

>> Recreate conditions

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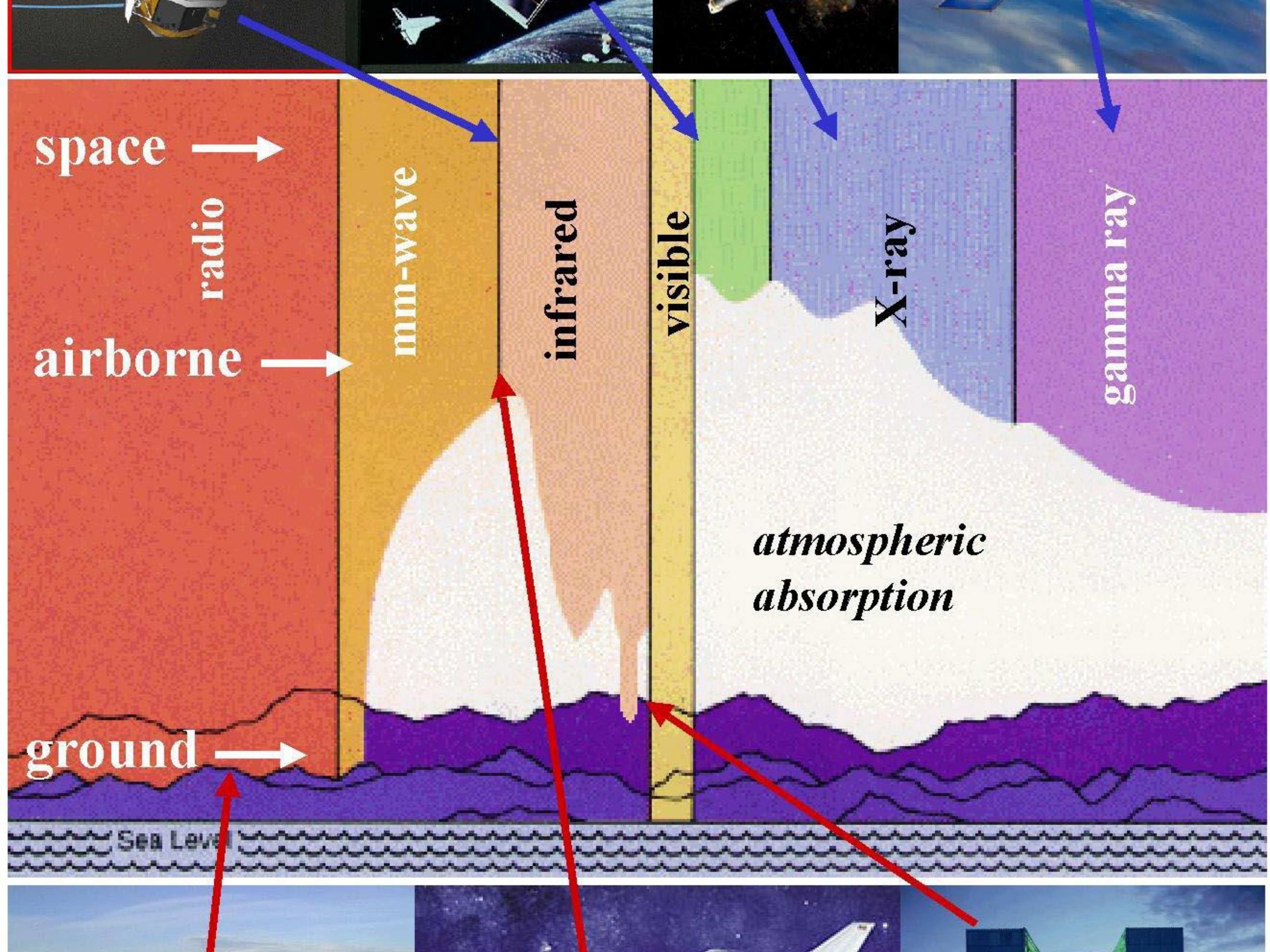
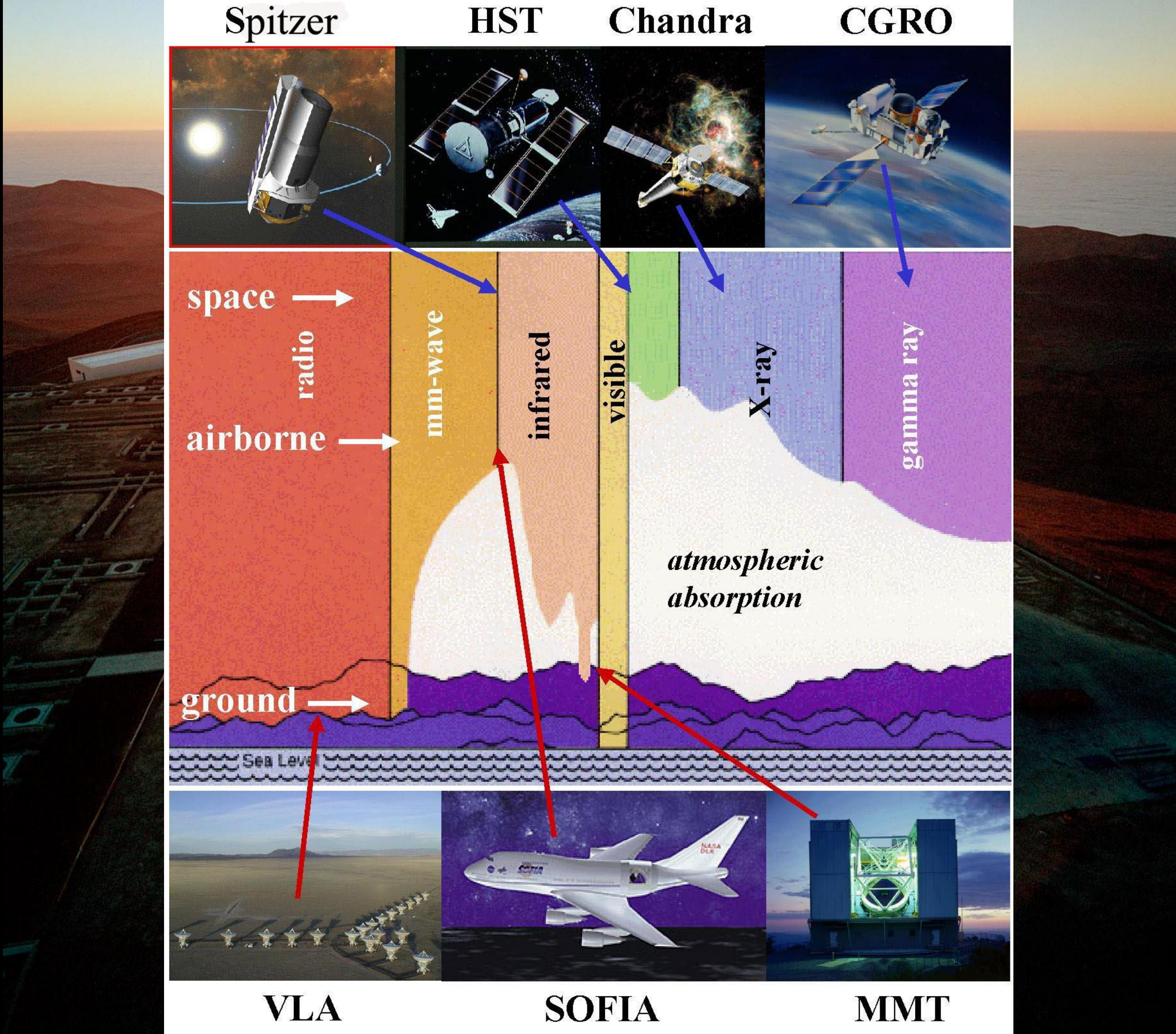

space
airborne
ground
radio
mm-wave
infrared
visible
X-ray
gamma ray
atmospheric absorption
Sea Level


Spitzer
HST
Chandra
CGRO
space
airborne
ground
radio
mm-wave
infrared
visible
X-ray
gamma ray
atmospheric absorption
Sea Level
VLA
SOFIA
MMT

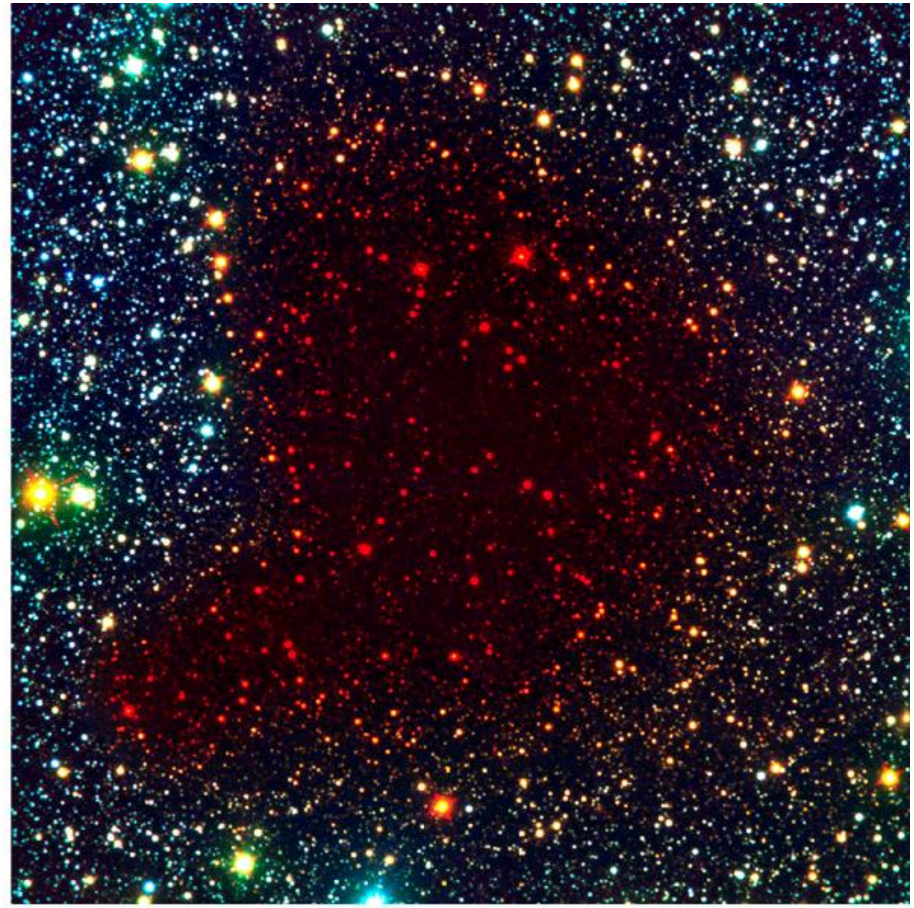
Why study the ISM?

APOD/
Larry
Landolfi

The Tarantula Nebula in the LMC
(MPG/ESO 2.2-m + WFI)

ESO PR Photo 14a/02 (7 June 2002)

B, V, I



B, I, K

Pre-Collapse Black Cloud B68 (comparison)
(VLT ANTU + FORS 1 - NTT + SOFI)

ESO PR Photo 02c/01 (10 January 2001)

www.chromoscope.net

density, n

temperature, T

radiation field

(chemistry)

(magnetic field)

HIGHER EDUCATION CERTIFICATE IN ASTRONOMY

Interstellar Astrophysics: SYLLABUS 2011

Dr. PAUL WOODS

density, n

temperature, T

radiation field

(chemistry)

(magnetic field)

(1) OVERVIEW OF THE INTERSTELLAR MEDIUM

- Evidence for the existence of the ISM
- Basic physical and chemical properties of the ISM
- Dust, interstellar extinction and reddening
- Types of clouds: H II regions, Dark clouds, Reflection nebulae
- Phases of the ISM: cold, warm and hot

(2) PHOTOIONIZED NEBULAE – H II REGIONS

- Photoionization and recombination of Hydrogen
- Heating and cooling processes in H II regions
  - Forbidden lines
  - Temperature and density diagnostics
- Sizes of H II regions: Strömgren spheres
- Heating and cooling of Diffuse Interstellar Clouds

(3) DIFFUSE CLOUDS

- Heating and cooling mechanisms
- Absorption line formation
- Gas phase chemical abundances & depletion
- Dust, extinction & reddening
- Giant molecular clouds, molecules and radio/(sub-)mm emission

Hotter, less dense

Colder, denser

(4) STAR FORMATION

- How does it happen?
  - Hydrostatic equilibrium
  - Fragmentation and the Jeans' Mass
  - Pre-main sequence evolution
- Observational signatures of star formation
  - T Tauri stars, Proplyds, Protostar jets
- Classification of protostars
- Triggering mechanisms

Course webpages

http://www.star.ucl.ac.uk/~pmw/courses/phas2525/

Notes

Slides

Problem sheets

Useful links

Today:

Overview of the interstellar medium (ISM)

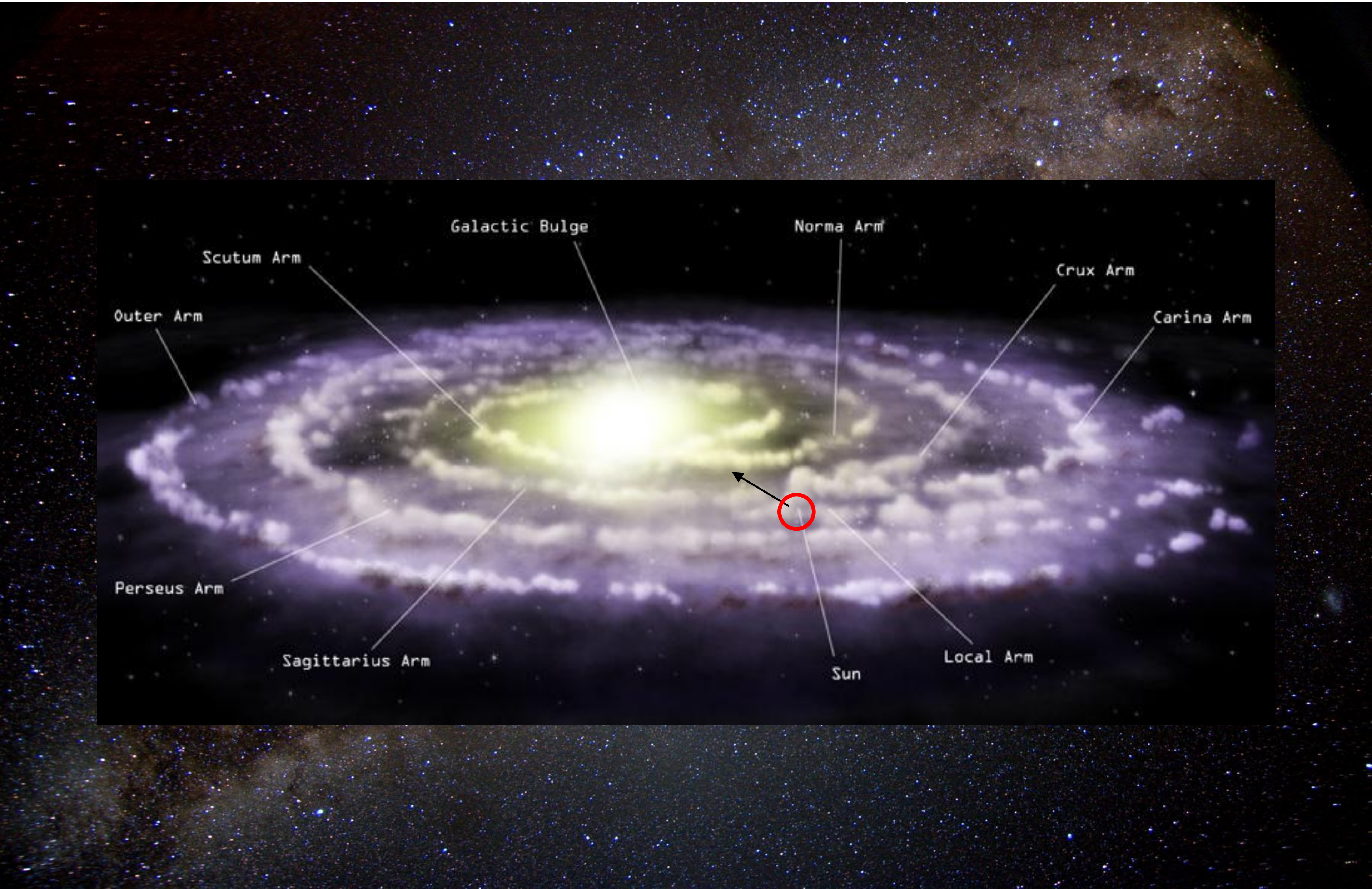
- Basic properties of the ISM
  - HII regions, dark nebulae, reflection nebulae
  - Cold, warm and hot phases of the ISM

- Space between stars is NOT empty
- Occupied by very low density gas (by terrestrial standards) and dust particles – how dense?

Average ISM: 1 atom/cm^3
Dense ISM: 10^5 /cm^3

cf. air density ~30,000,000,000,000,000,000 ($3x10^{19}$) molecules/cm^3,
or stellar atmosphere ~ 10^{15} /cm^3

Galactic centre (8 kpc away towards Sagittarius)
- great dust clouds get in the way



- 1 *light year (ly)* = 300 000 *km/s* $\times$ 365 days $\times$ 24 hours $\times$ 3600 secs

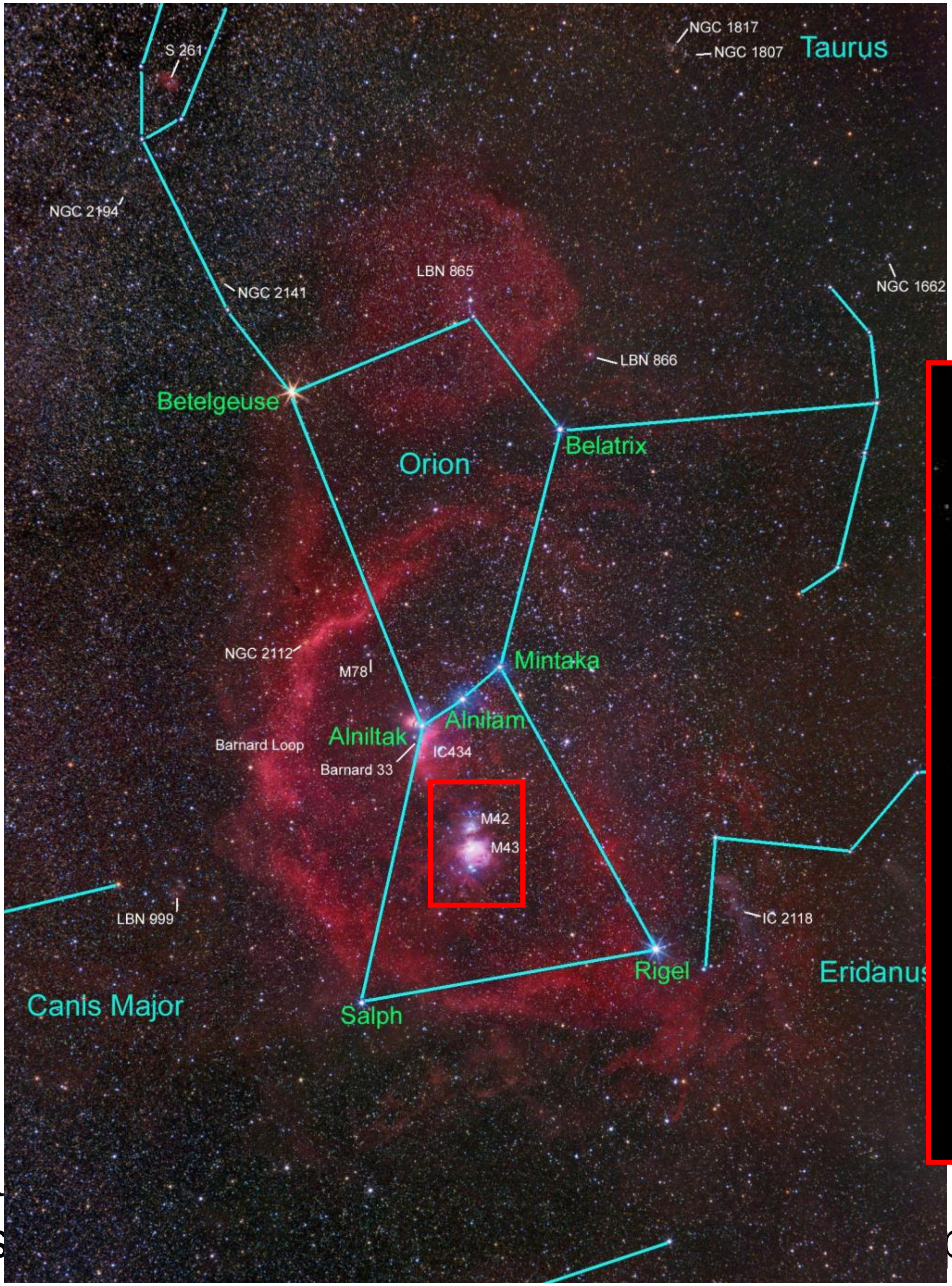
  = 9.5 x 10^{12} *km*

- 1 *pc* = 3.3 *ly* = 206 265 Astronomical Units (*AU*)

- 1 *AU* = 150 000 000 *km* (average Sun-Earth distance)

- *The solar system is about 10 light hours across … but the galactic centre is 228 460 800 light hrs (26 000 ly) away !!! (or in astronomers' terms, about 8 000 pc = 8 kpc)*

the great Orion nebula



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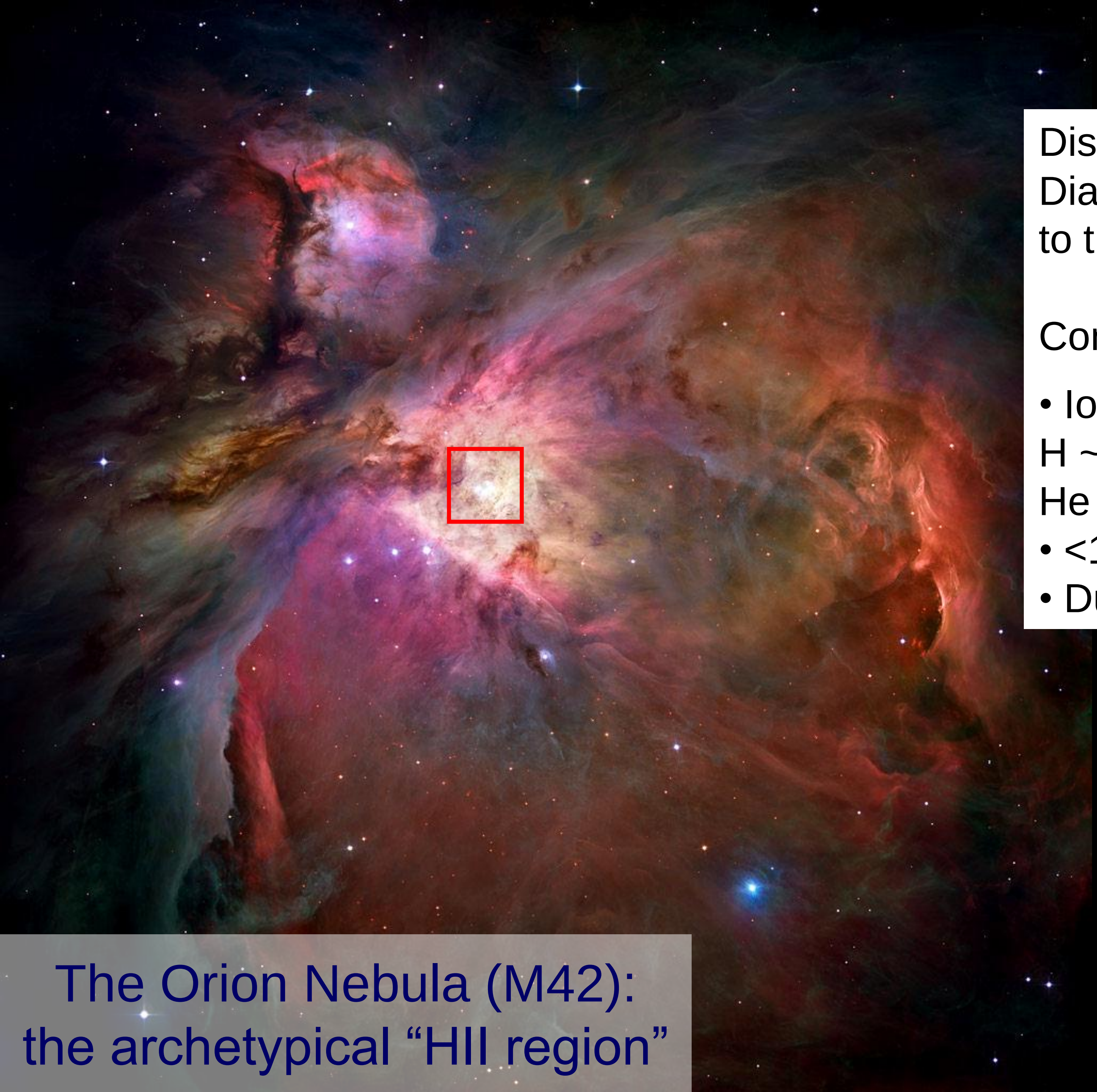
• vis   phere

The Orion Nebula (M42): the archetypical “HII region”

Distance = 450 pc
Diameter ~ 1° (similar to the full moon)

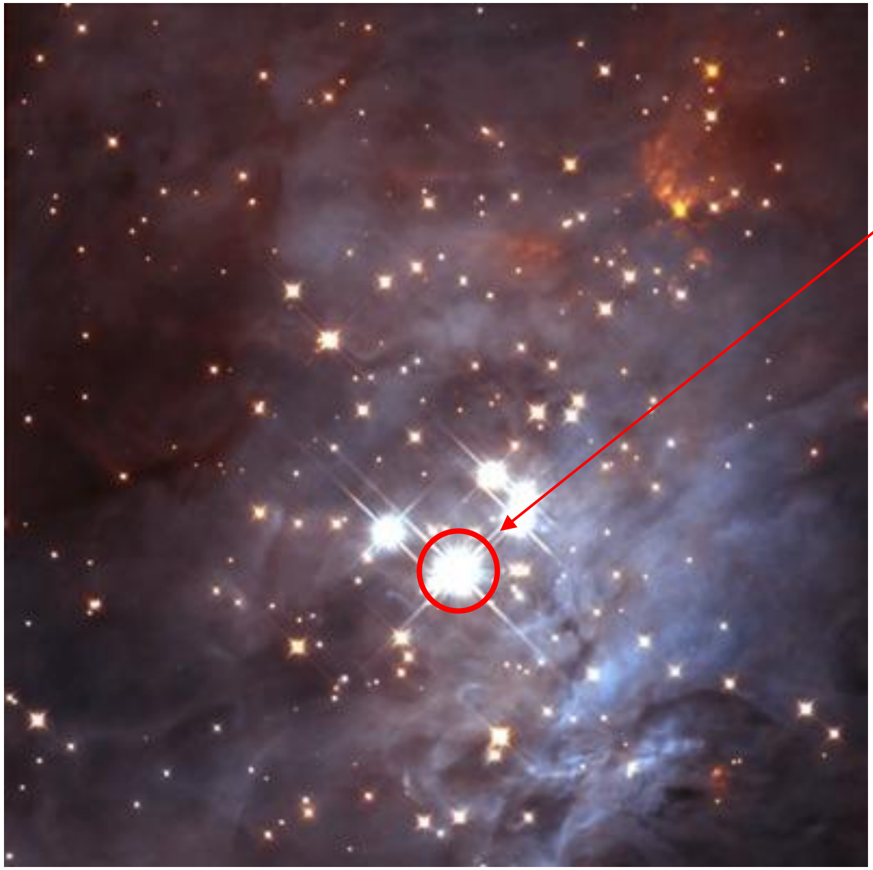
Composition:

- Ionized gas:

H ~ 90% (by number)
He ~ 10% (by number)

- <1% Heavier element
- Dust

The Trapezium Cluster



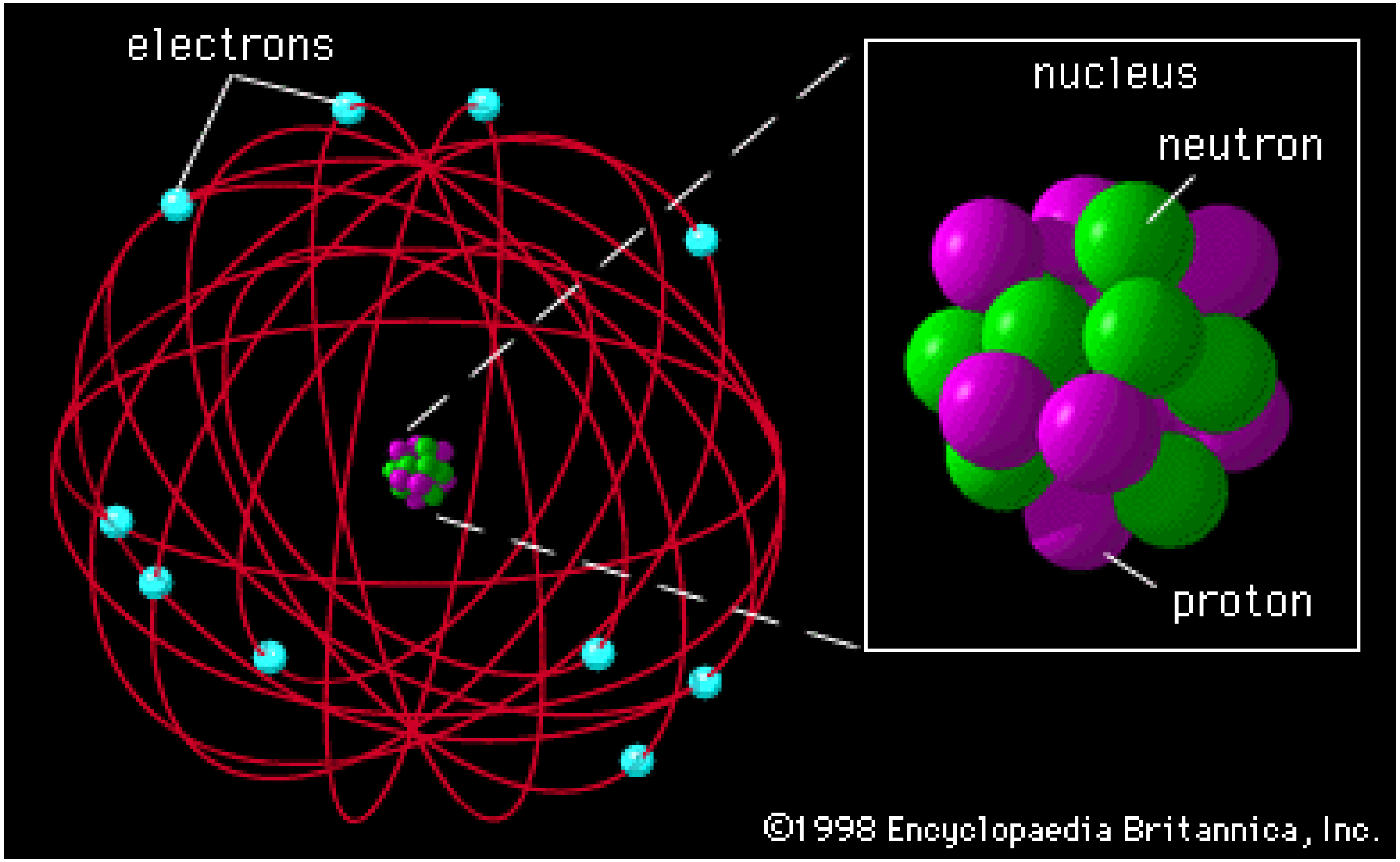
dominant star: θ^1 *Ori-C*
spectral type O6V: T ~ 20 000 K

emits a great number of energetic photons that ‘light up’ the gas

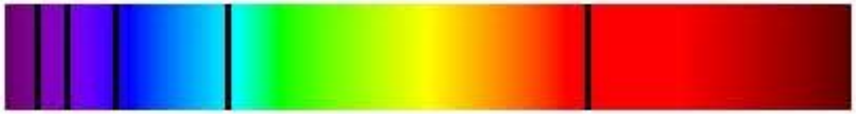
What does this mean?

Evidence for the gaseous nature of the ISM

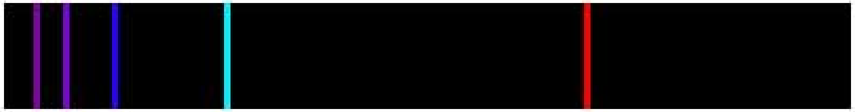
- Emission nebulae
- Spectra of binary star systems
- Atomic and molecular lines


electrons
nucleus
neutron
proton
©1998 Encyclopaedia Britannica, Inc.

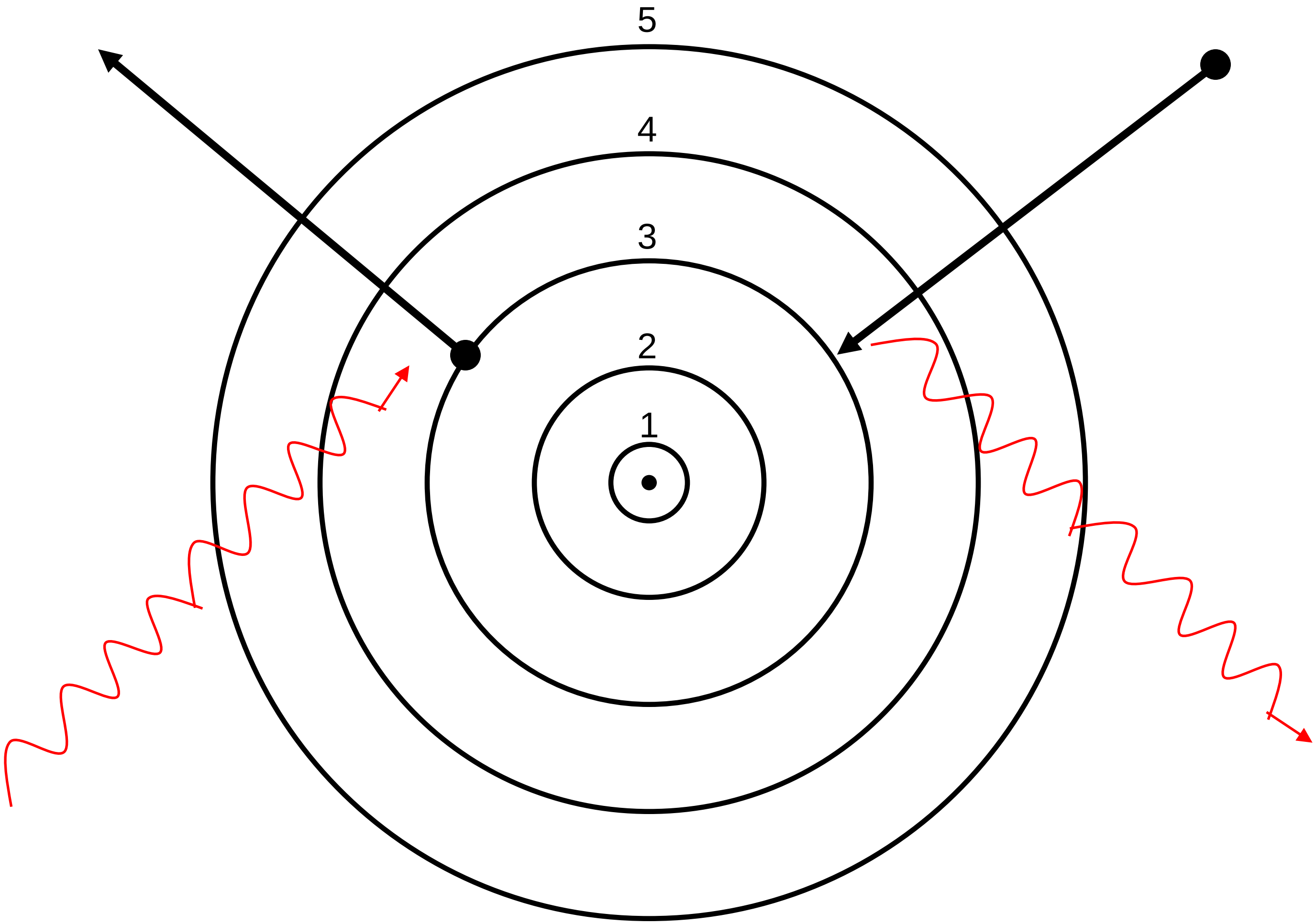
Hydrogen Absorption Spectrum

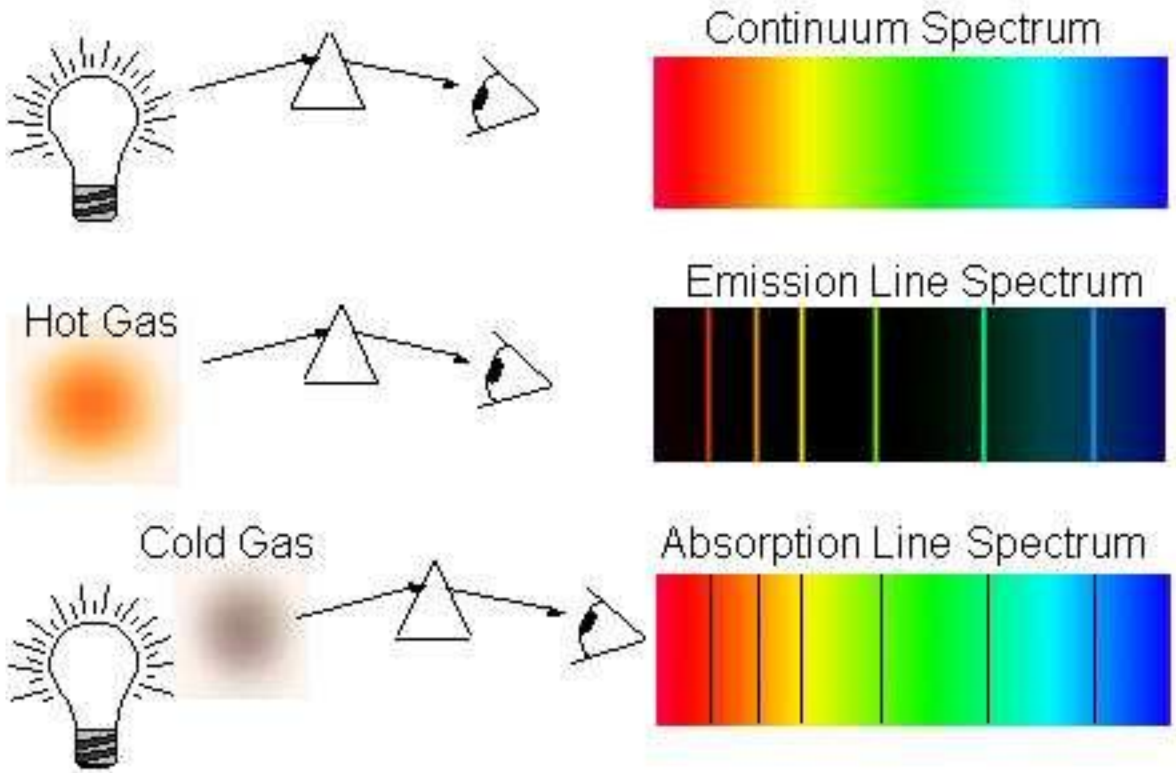


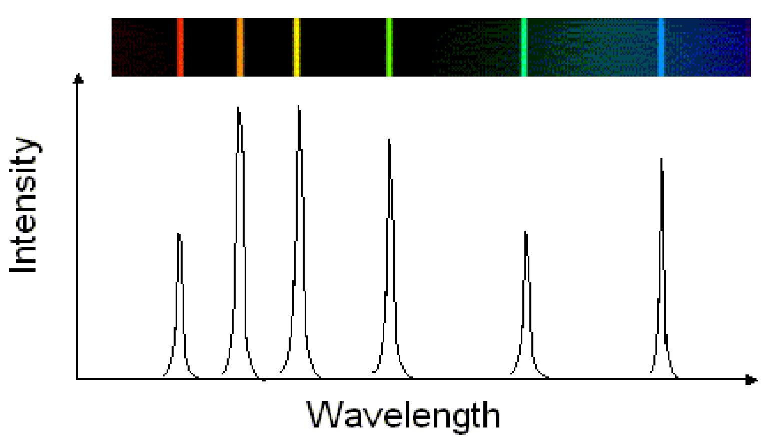
Hydrogen Emission Spectrum

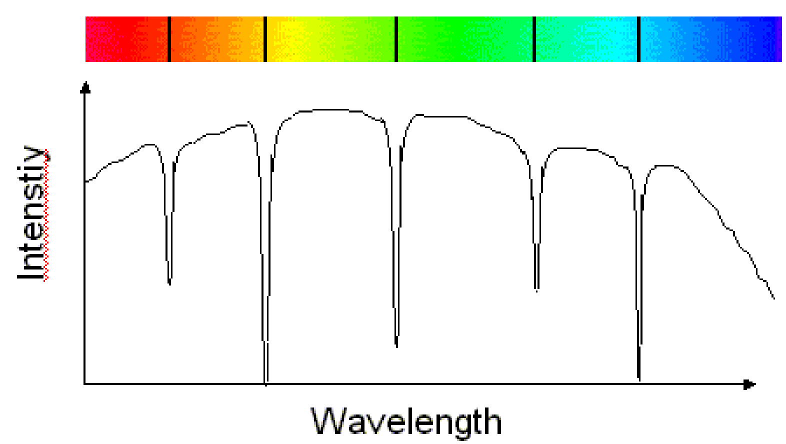


Pages 116-120 & Fig 5-23


5
4
3
2
1


Continuum Spectrum
Hot Gas
Emission Line Spectrum
Cold Gas
Absorption Line Spectrum

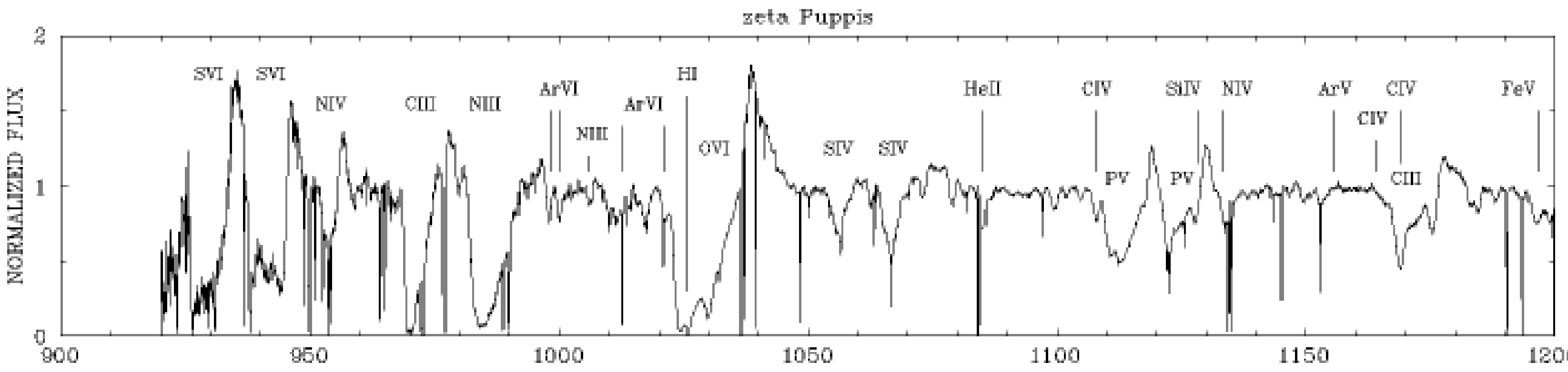

Intensity
Wavelength

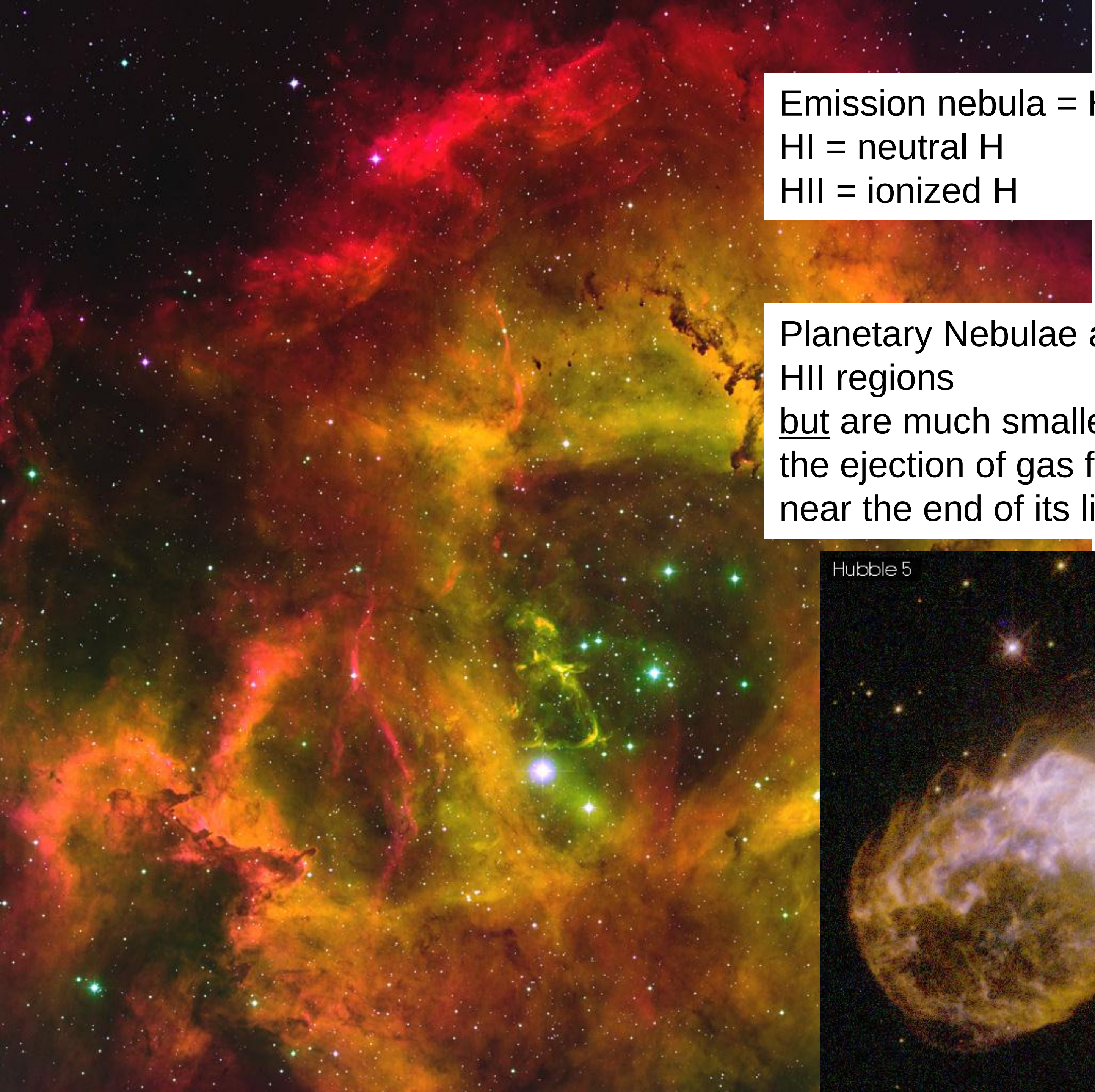

Intenstiy
Wavelength

Spectroscopic evidence of the ISM

- <u>Method</u>: observe spectrum of a bright source (e.g. a star) and you see many absorption lines
  - this is caused by light being absorbed by intervening gas

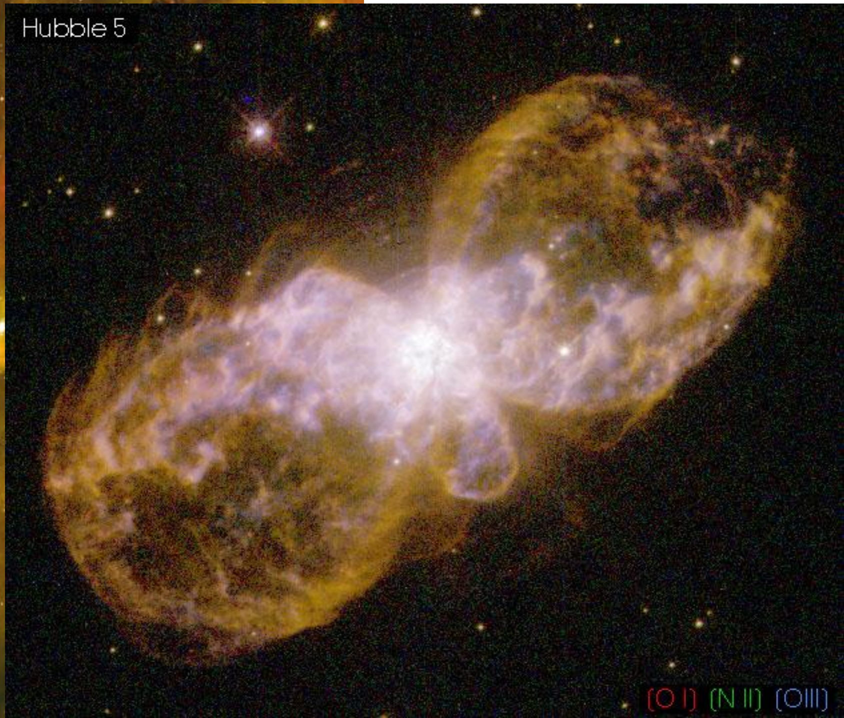
- Optical: NaI 5895 Å (sodium); CaII 3968,3933 Å (calcium)
- UV (esp. far-UV): *many* ISM absorption lines from many atoms (C, N, S, Ar, Fe, …)





Emission nebula = HII region
HI = neutral H
HII = ionized H

Planetary Nebulae are also technically HII regions
<u>but</u> are much smaller and are formed by the ejection of gas from a low-mass star near the end of its lifetime

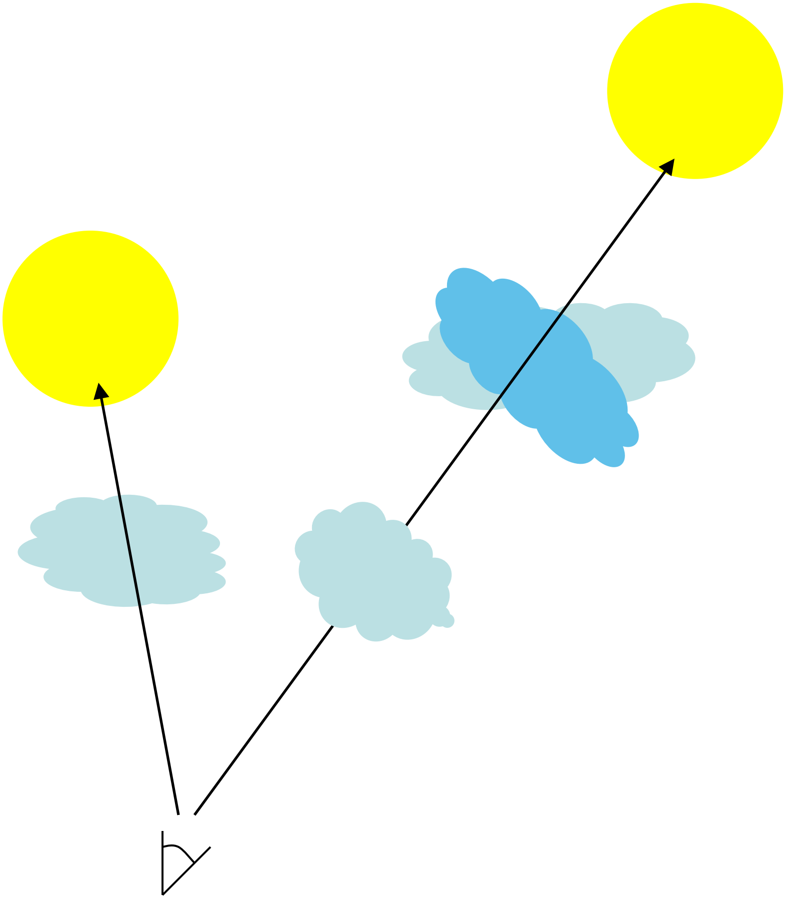


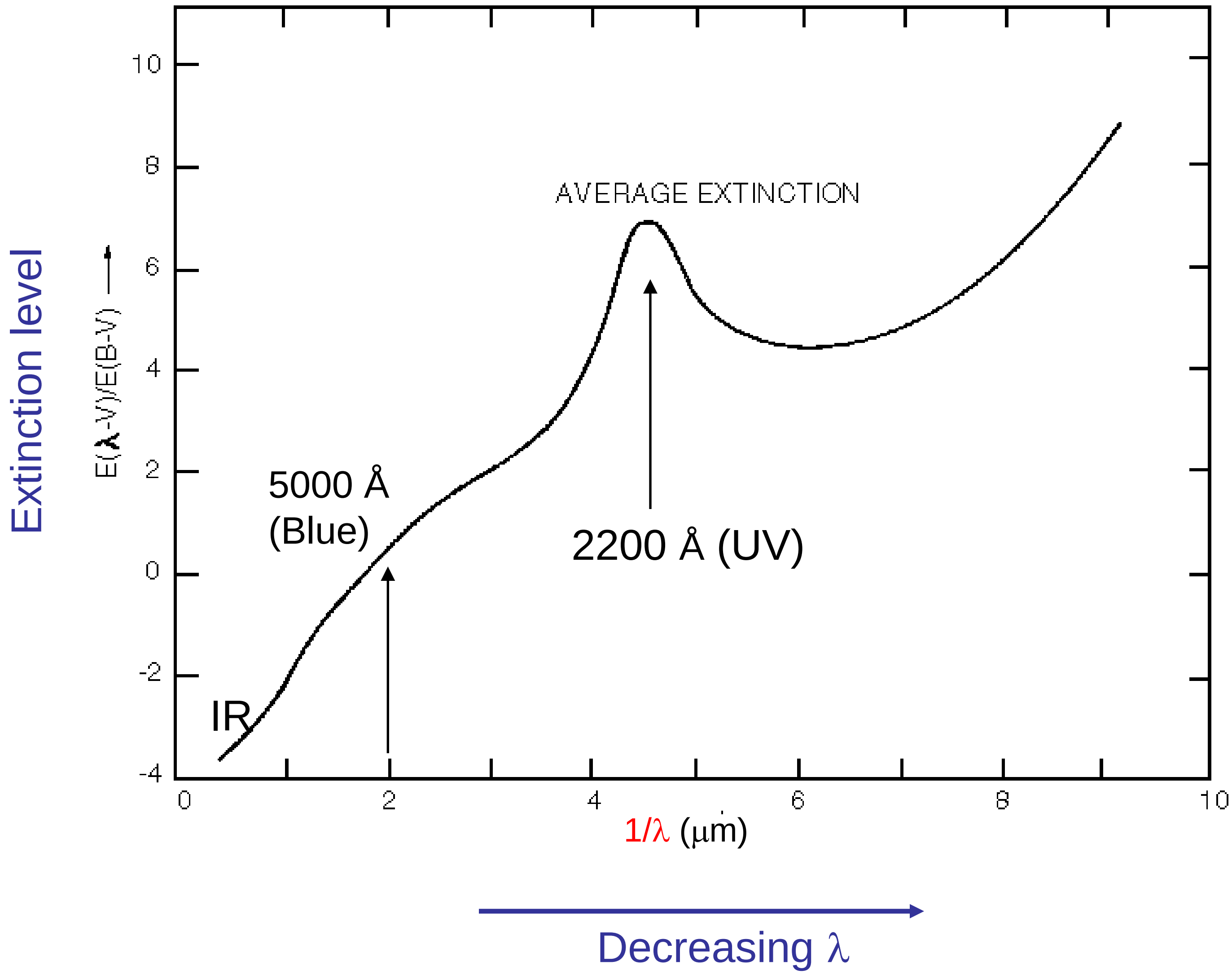
Evidence for the dusty nature of the ISM

- Reflection nebulae
- Dark clouds
- Extinction
- Reddening
- Solid-state features (minerals, ices)
- Depletion of molecules

<u>Method</u>: Observe spectra from intrinsically identical stars, but at different distances (and thus different amounts of dust extinction) -- and compare

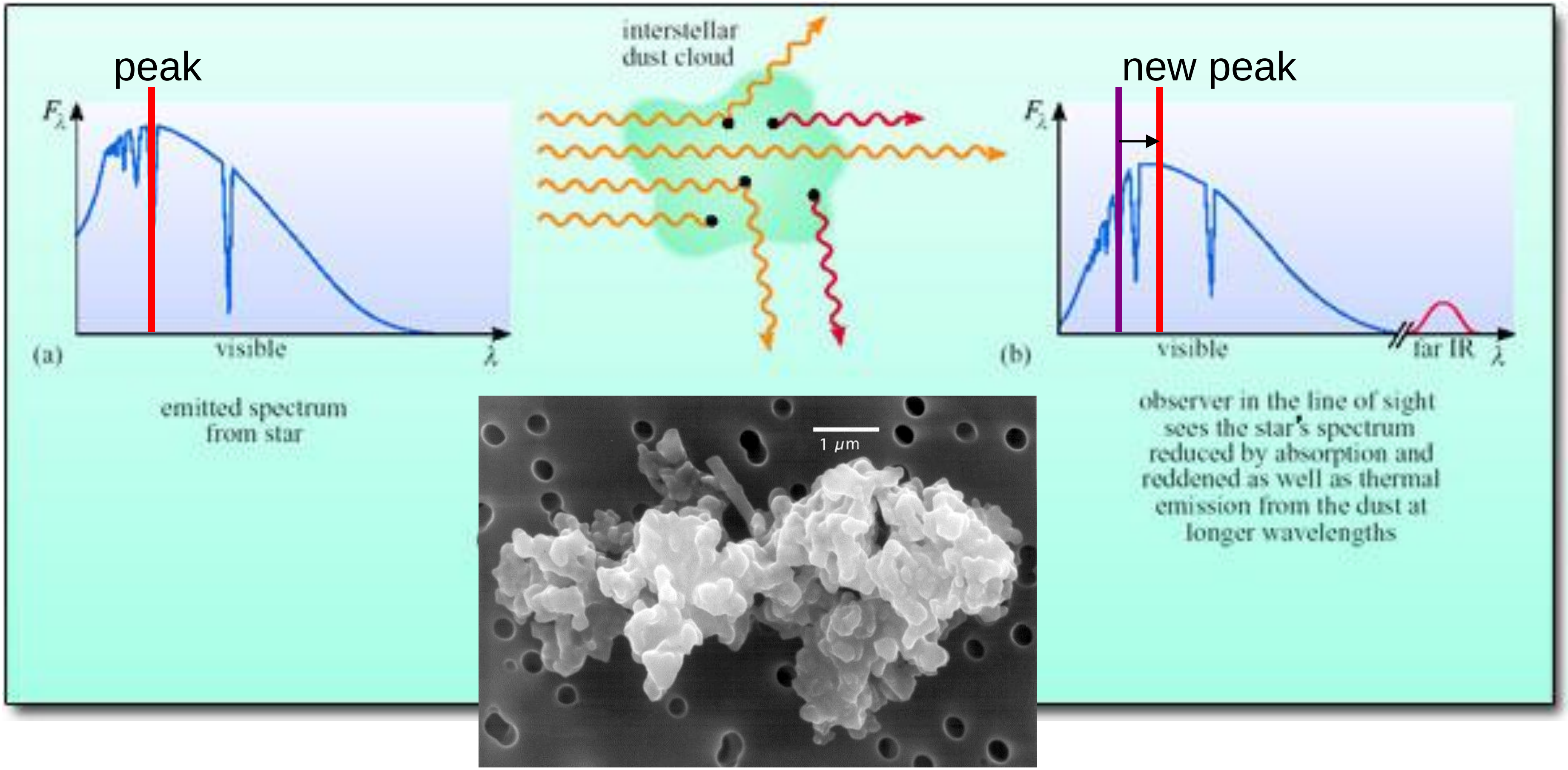
<u>Result</u>: Determine the detailed scattering/absorption properties of the dust *as a function of wavelength*





Extinction level
E(λ-V)/E(B-V) →
AVERAGE EXTINCTION
5000 Å
(Blue)
2200 Å (UV)
IR
10
8
6
4
2
0
-2
-4
0
2
4
6
8
10
1/λ (μm)
Decreasing λ

Interstellar reddening and extinction

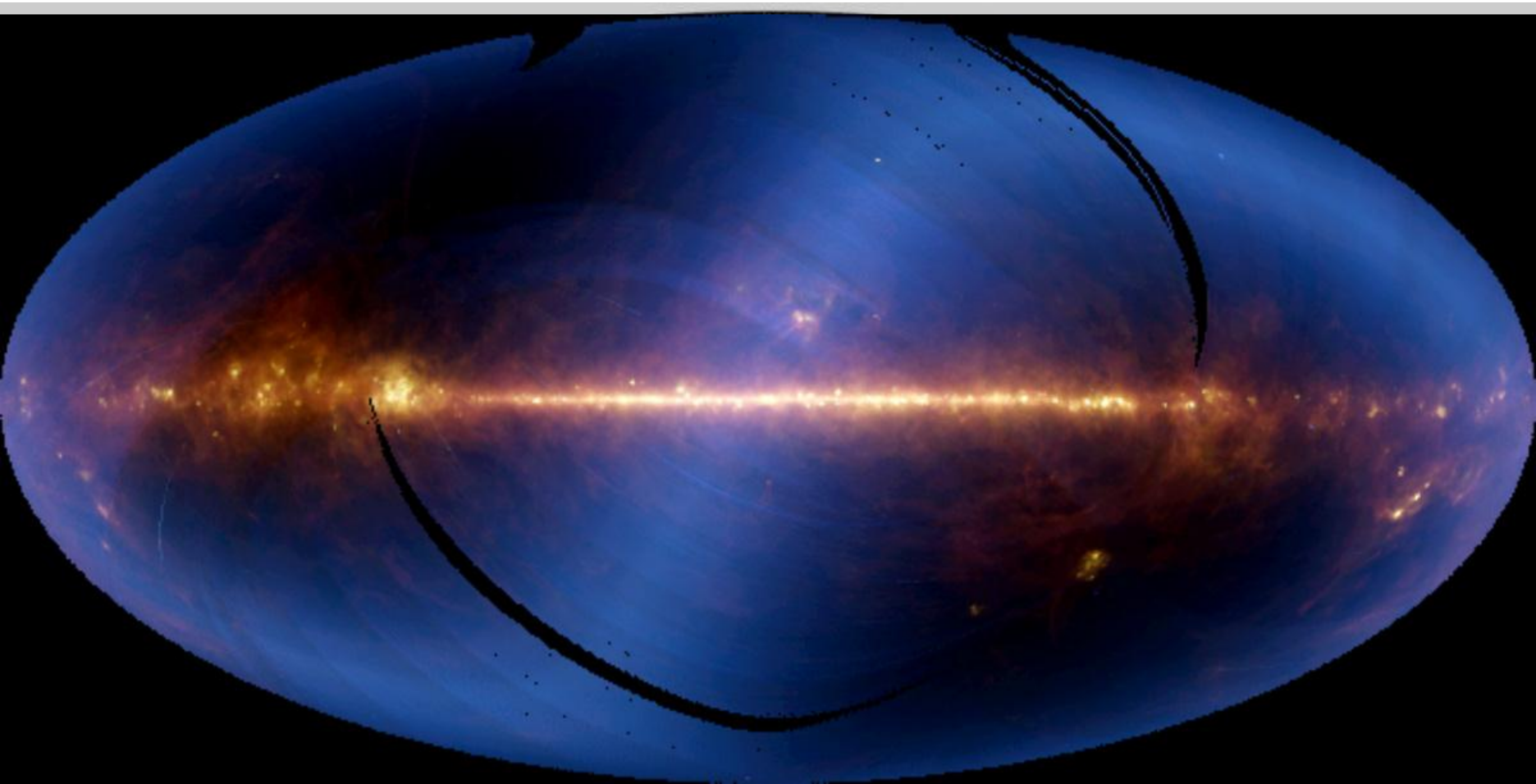


porous chondrite

Other evidence for the presence of dust: IR observations

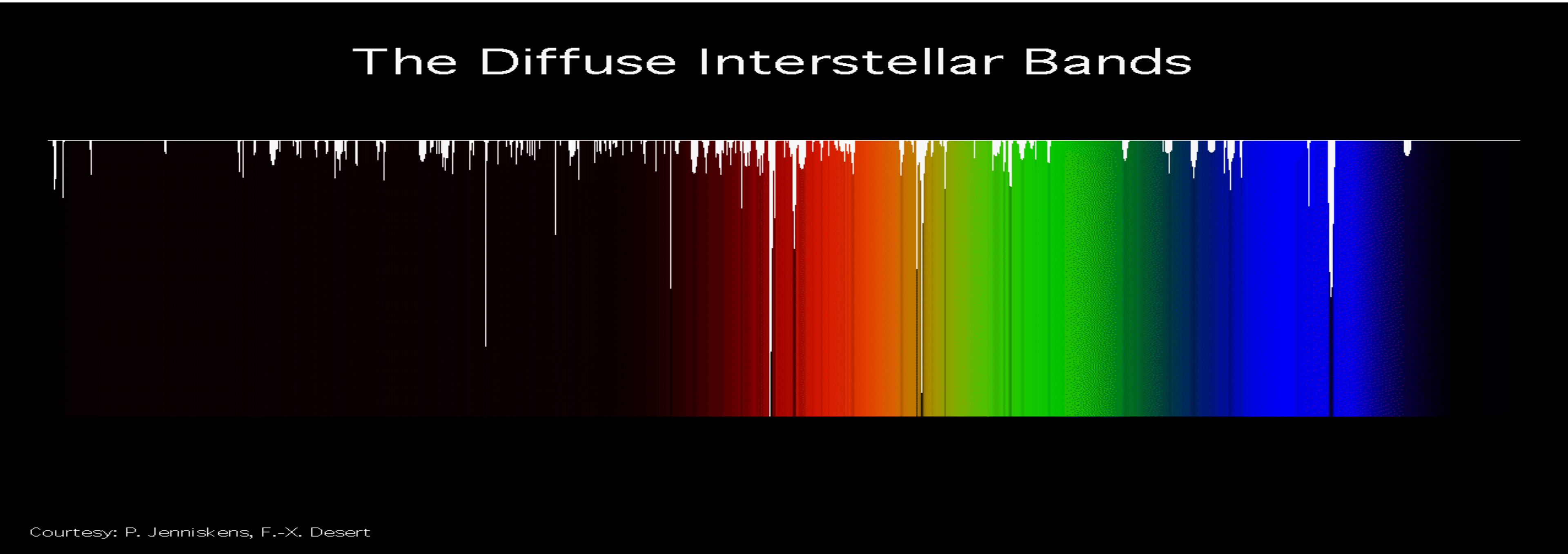
1. Image taken at 2 μm by 2MASS survey
2. Composite image at 12 μm, 60 μm, 100 μm by *IRAS* satellite

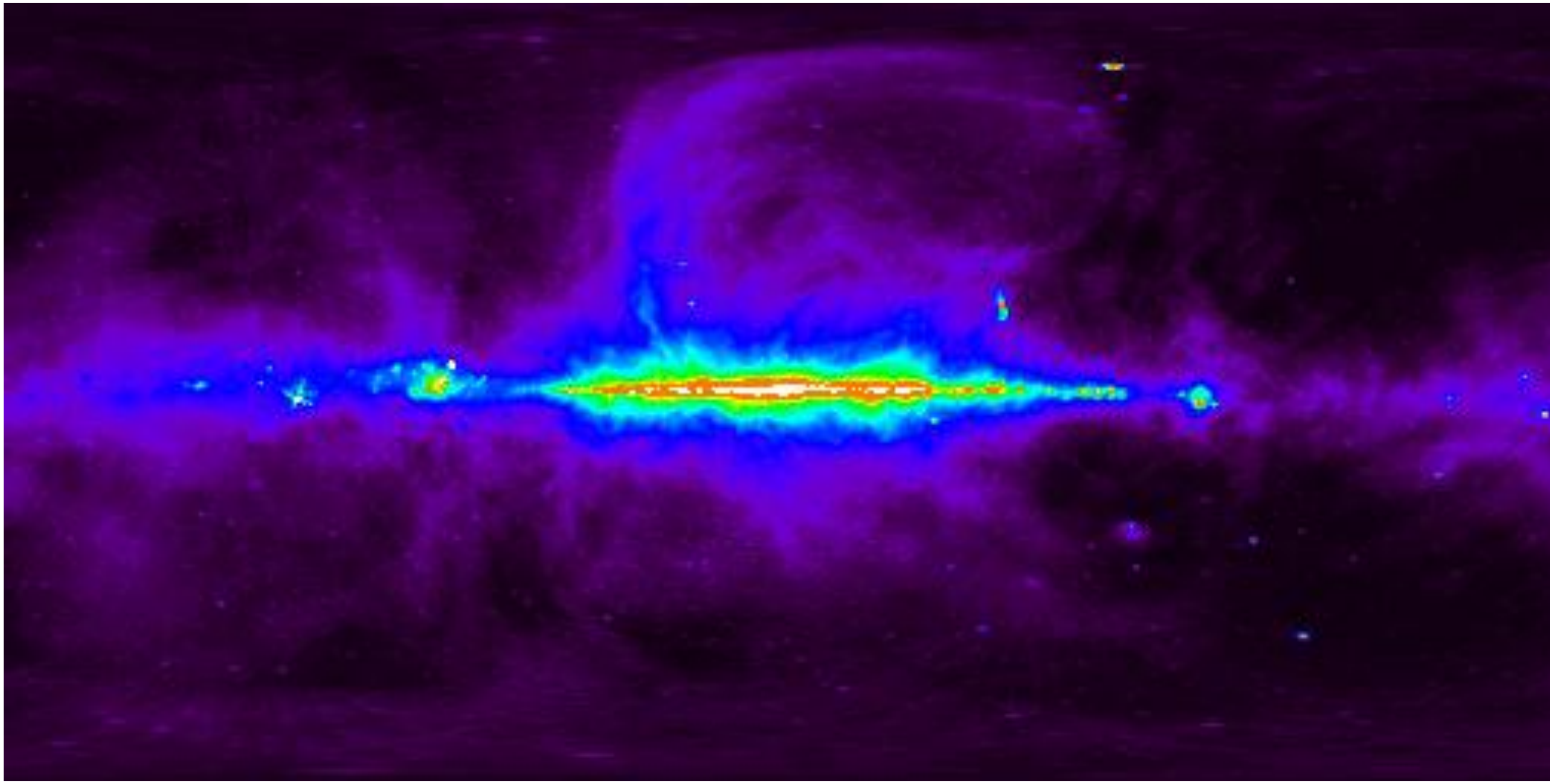
Dust warmed by far-UV starlight re-radiates light in the IR
"Wien's law": λ (re-emitted light) ~ 1/T (dust)



Evidence for the other or unknown nature of the ISM

- Unidentified spectral lines
  - Unidentified infrared features (UIRs)
  - Diffuse interstellar bands (DIBs)





Scattering of free electrons in interstellar plasmas (hot, ionized interstellar gas) ➔ emission at 408MHz (radio) due to synchrotron processes

Can we classify the ISM?

• Diffuse emission nebulae: When in the vicinity of OB-type stellar associations (i.e. near young stars), they become ionized are called HII regions:

- The gas emits photons due to recombination.
- Generally found near the plane of the Galaxy, at heights of $\geq$ 50 pc.
- Masses ~ 100–10 000 $M_\odot$; Sizes ~ few pc; Temps ~ 10 000 K; Densities ~ 10^3 hydrogen ions/cm^3

(compare with air density of 10^{19} /cm^3, or stellar atmosphere ~ 10^{15} /cm^3)

• Dark clouds are denser and colder
$>10^4$ /cm^3 and T ~ 10–100K - are potential sites of star-formation.
They block most optical radiation.
H_2 molecules form within them on the surface of dust grains.
Variety of sizes: pc-sized up to Giant Molecular Clouds

• Reflection nebulae near bright stars appear bluish due to the efficient scattering, by dust particles, of blue-wavelength light (say 400 nm) – same process as that which makes the sky blue

Bok globules

• relatively much denser that general diffuse ISM clouds:

densities ~10^4 - 10^9 particles per cm^3

• made up of atoms, molecules and <u>dust particles</u>

• have low temperatures of 10-100 K.

The denser ISM

• Diffuse emission nebulae: When in the vicinity of OB-type stellar associations (i.e. near young stars), they become ionized are called HII regions:

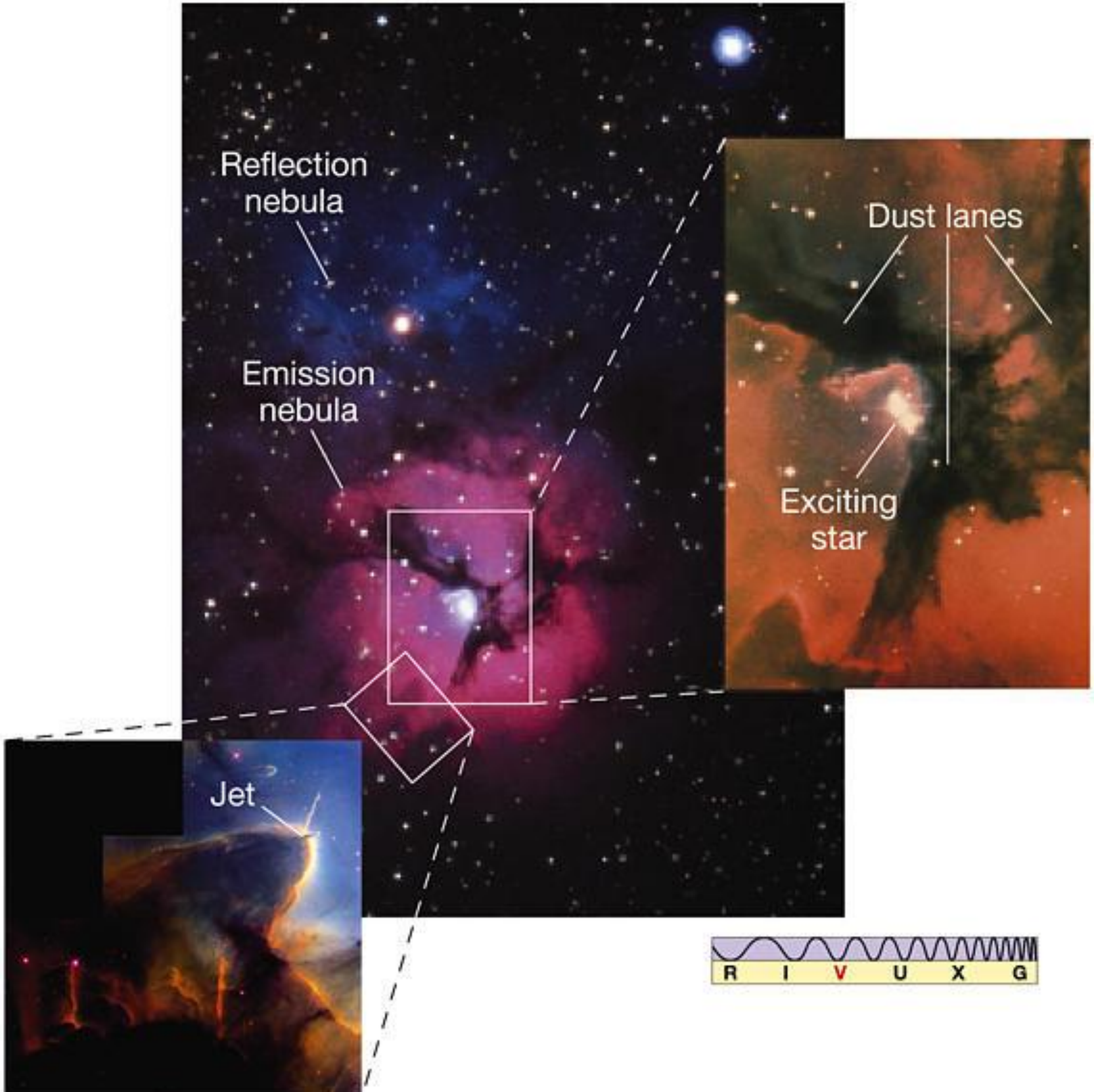
- They emit following recombination cascades of hygrogen.
- Generally found near the plane of the Galaxy, at heights of $\geq$ 50 pc.
- Masses ~ 100–10 000 $M_{\odot}$; Sizes ~ few pc; Temps ~ 10 000 K; Densities ~ 10^3 hydrogen ions/cm^3

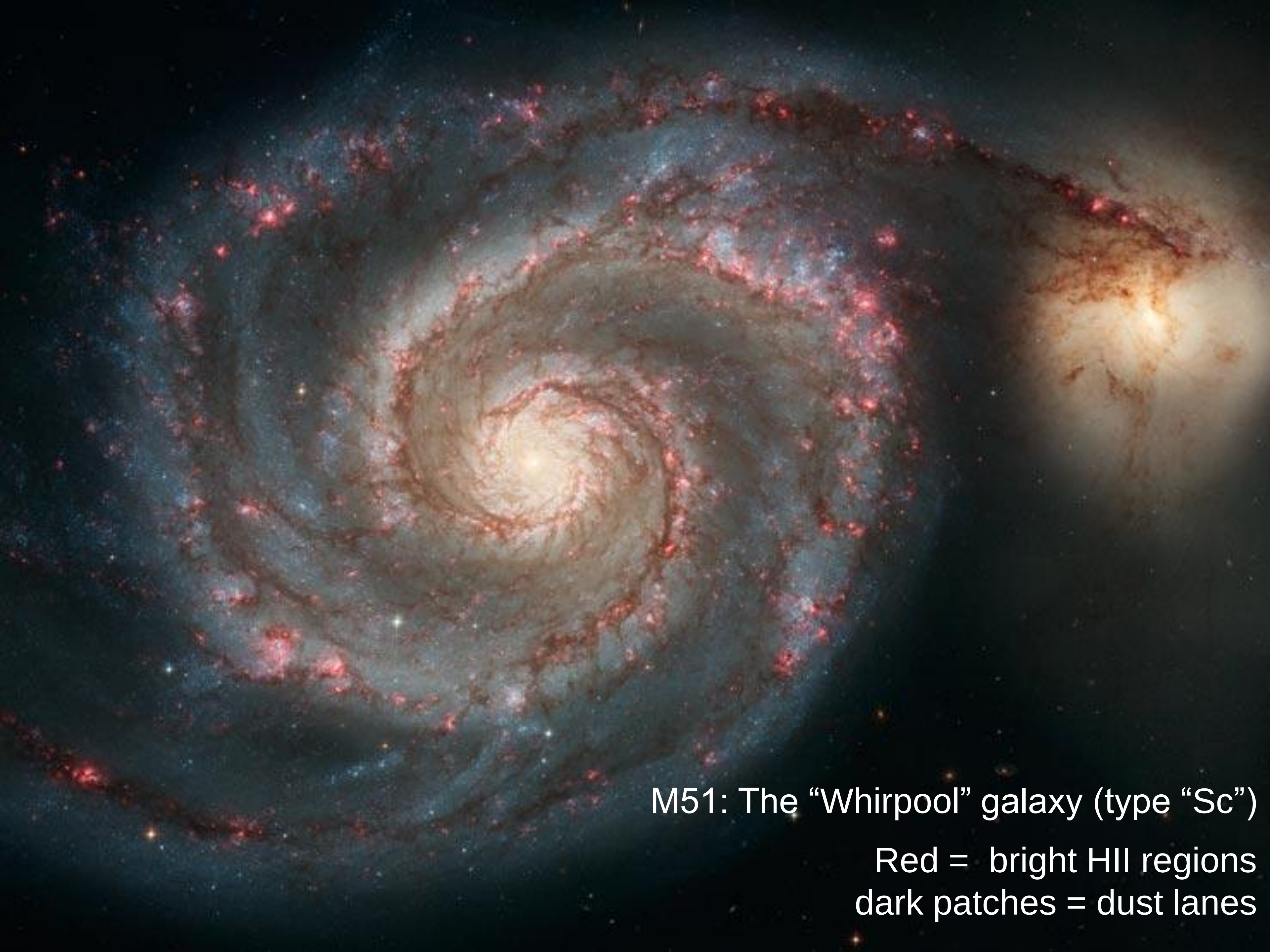
(compare with air density of 10^{19} /cm^3, or stellar atmosphere ~ 10^{15} /cm^3)

• Dark clouds are denser and colder @ 10^4 /cm^3 or more and T ~ 10–100K and are potential sites of star-formation. They block most optical radiation from passing through. H_2 molecules form within them on the surface of dust grains. Variety of sizes: pc-sized up to Giant Molecular Clouds

• Reflection nebulae near bright stars appear bluish due to the efficient scattering of blue light by dust particles of ~400–500 nm in size – same process as that which makes the sky blue

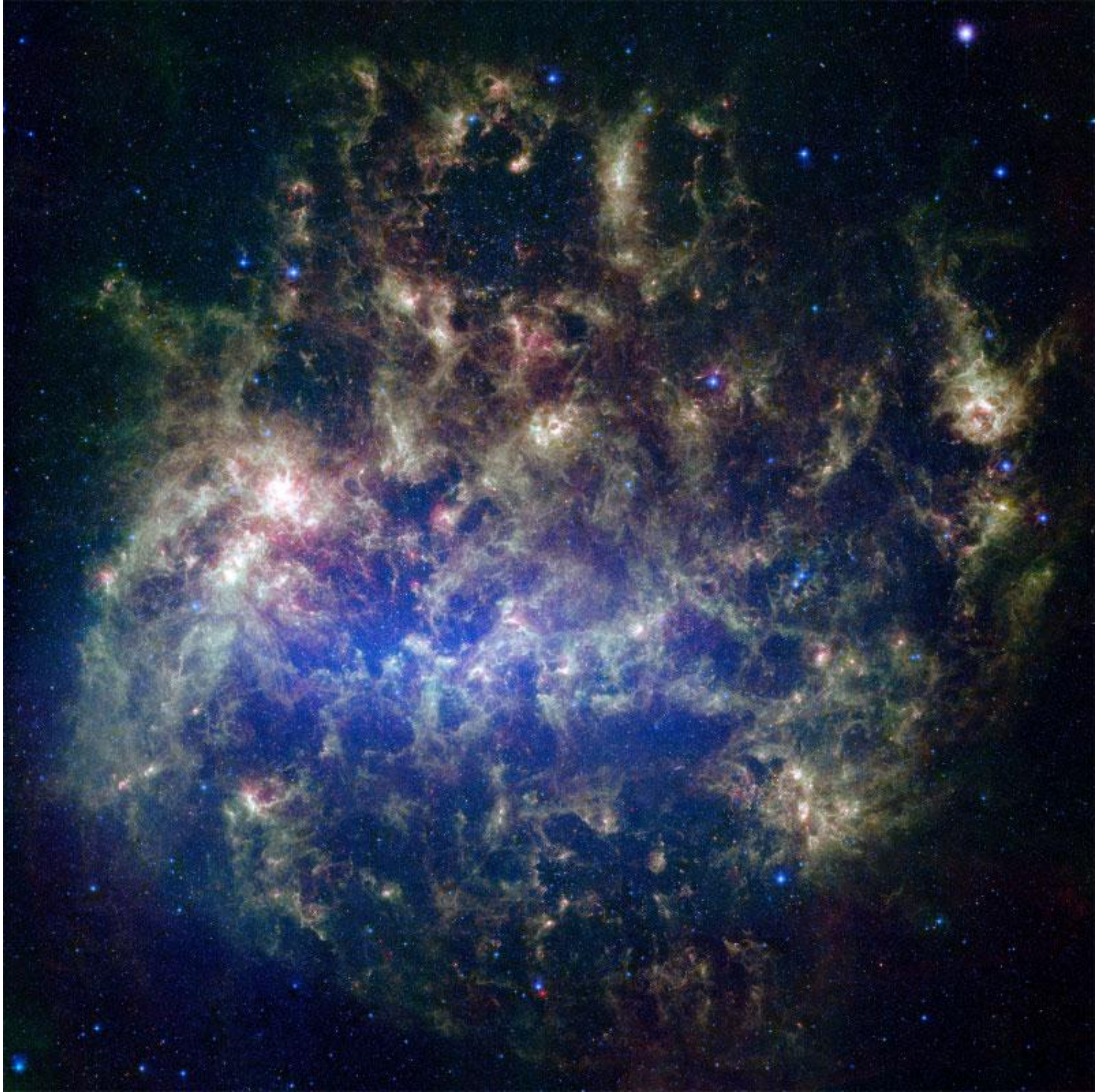

SUBARU


Reflection nebula
Emission nebula
Dust lanes
Exciting star
Jet
R I V U X G



M51: The “Whirpool” galaxy (type “Sc”)

Red = bright HII regions
dark patches = dust lanes



ISM: average properties

• Mean density of ISM (in our Galaxy) ~ 1 particle/cm^3 but is HIGHLY CLUMPED

• The GAS is mainly:

Hydrogen (~90%)
Helium (~10%)
metals (C,N,O, ... Fe) <1% by number

• Dust grains : gas atoms ratio = approx 1 : 10^{12}
• Dust grains have a power-law size distribution
radii ~ $5\times10^{-9} - 2\times10^{-7}$ m (smaller grains are more abundant)

A global model:
the 3+1 phases of the ISM

- Cold, neutral medium (CNM)
  $n \sim 1\text{–}10^3$ /cm^3, $T < 100$ K, volume fraction: ~1–5%

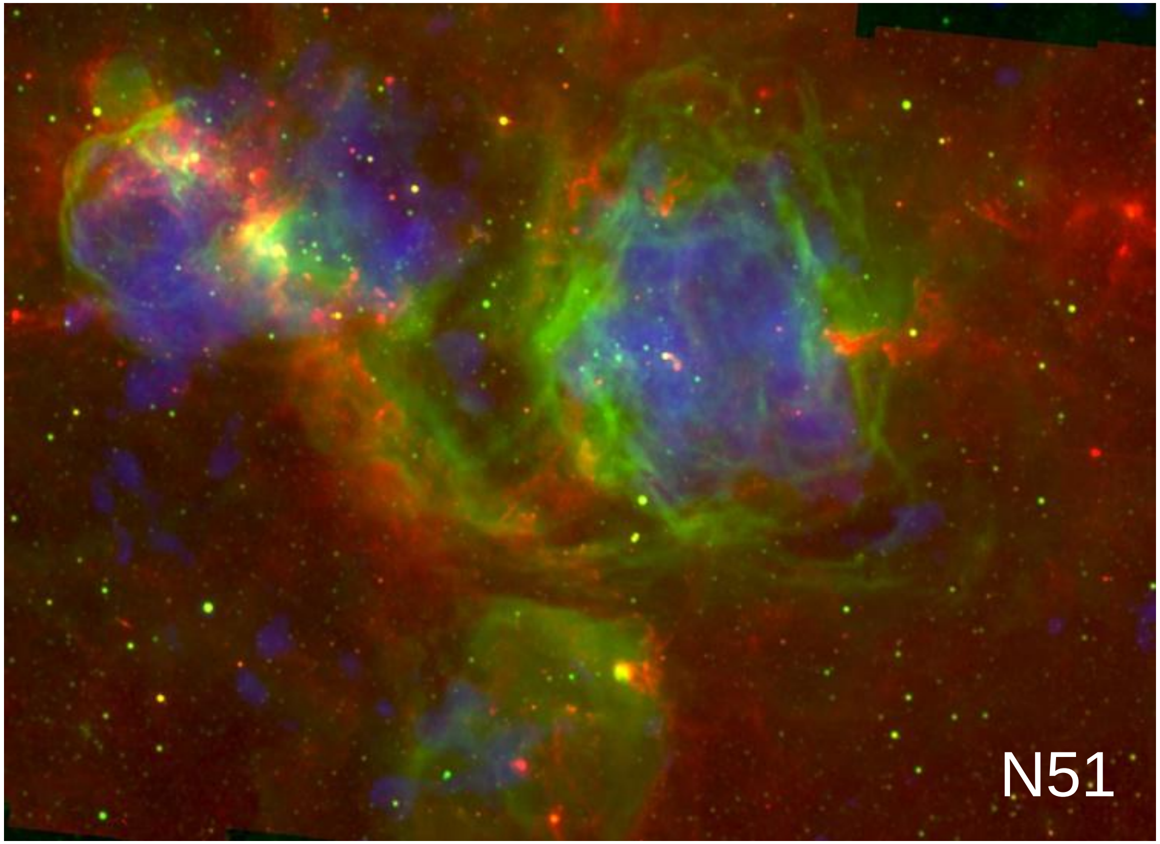
- Hot, ionized medium (HIM)
  $n \sim 10^{-4}\text{–}10^{-2}$ /cm^3, $T \sim 10^6\text{–}10^7$ K, volume fraction: ~30–70%

- Warm interface media
  - Warm ionized medium (WIM)
    $n \sim 0.01$ /cm^3, $T \sim 1000$ K, volume fraction: ~20–50%
    hydrogen ionization fraction (X_H) ~ 70%
  - Warm neutral medium (WNM)
    $n \sim 0.1\text{–}10$ /cm^3, $T \sim 1000\text{–}5000$ K, volume fraction: ~10–20%
    hydrogen ionization fraction (X_H) ~ 10%

⊕ Dark neutral (molecular) clouds
  $n \sim 10^3$□10^6 /cm^3, $T \sim 10$□50 K, volume fraction: <1%

Hot, ionized medium (HIM)

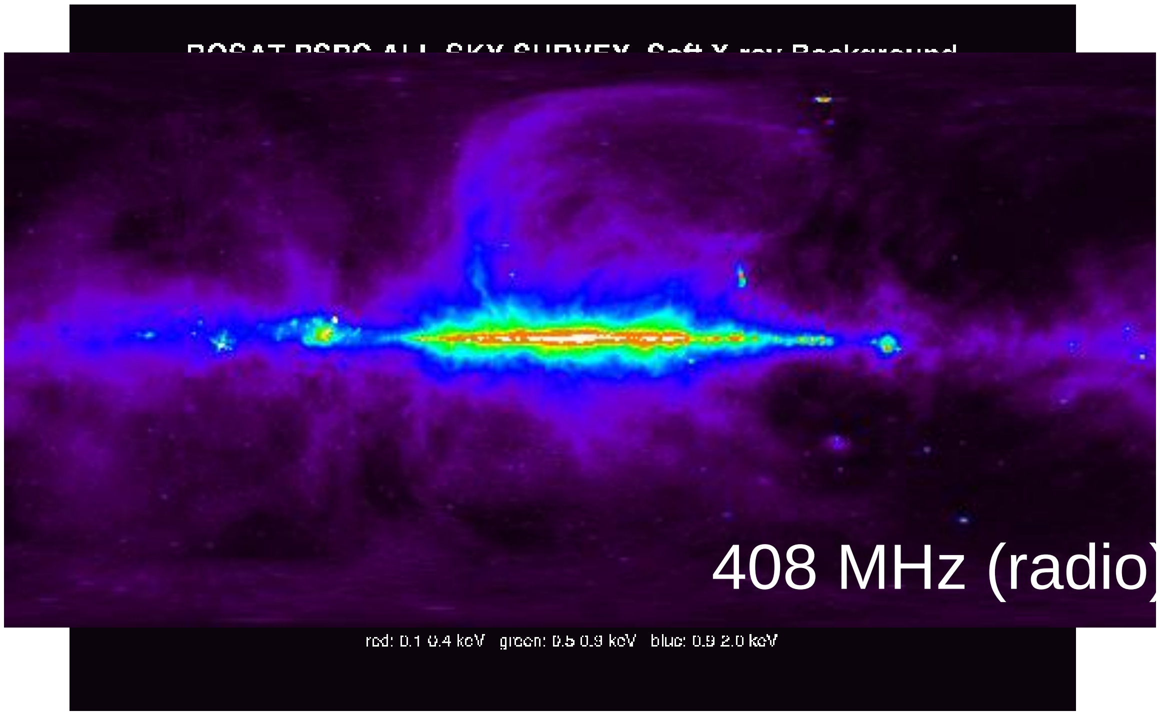
Arises through the heating and energy input from overlapping Supernova explosions and their remnants: directly seen in X-rays.



Optical = red and green
X-ray = blue

Hot, ionized medium (HIM)

Arises through the heating and energy input from overlapping Supernovae explosions and their remnants: directly seen in X-rays.



- Supernovae occur in the Galactic plane: causes hot gas to rise to high distances above/below the plane of the Galaxy
- Gives rise to a halo of hot gas around the galaxy.
- This gas then cools and falls back to the galactic plane, and is replenished by further SN: the Galactic Fountain model.

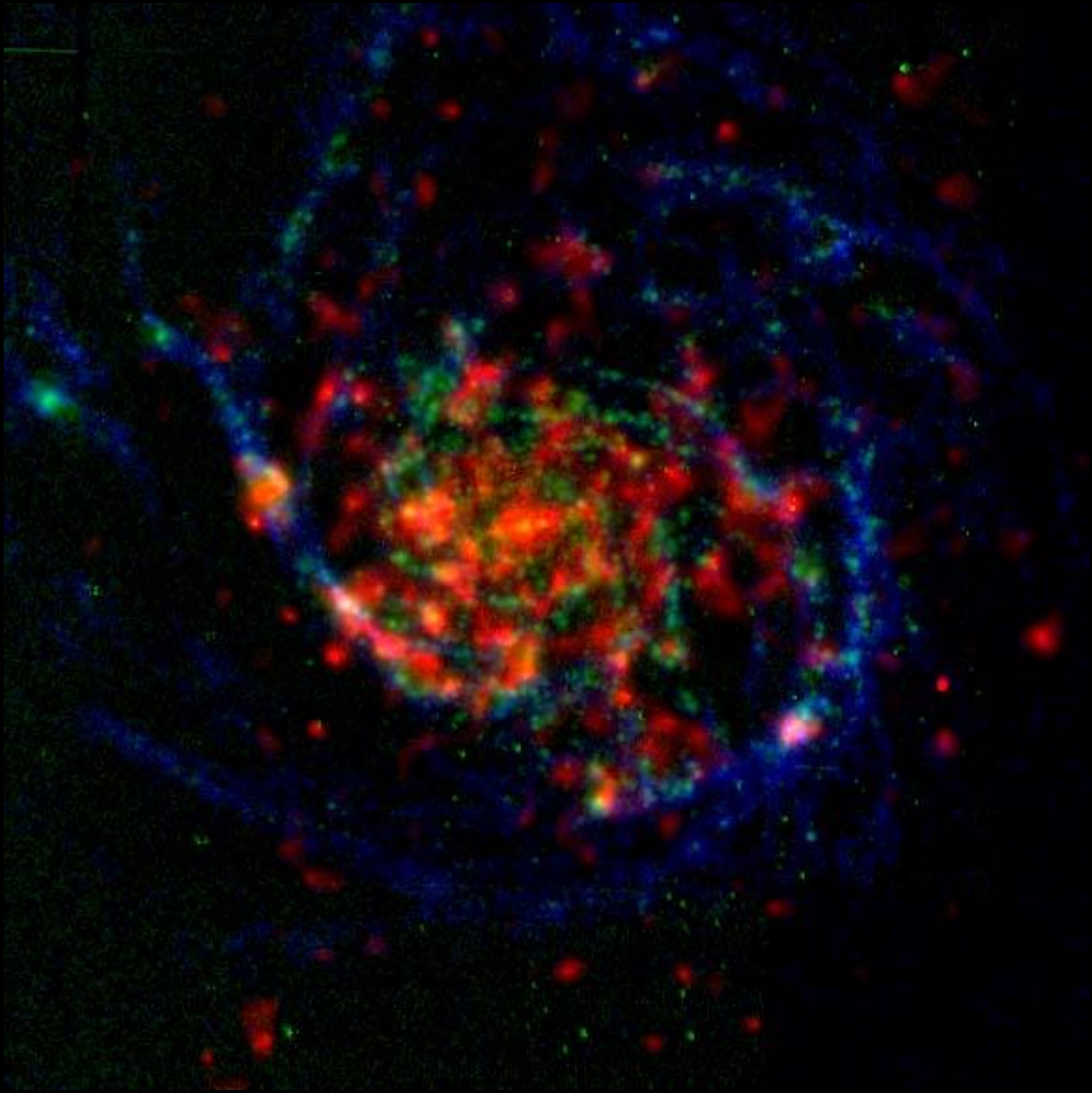
Cold, neutral medium (CNM)

• dominated by diffuse clouds with $n \sim 10^1$–10^3 /cm^3, $T \sim 30$–100 K, individual cloud radii = few pc

• cold enough that simple molecules can form, e.g. H_2 and CO.

• <u>however,</u> most INTERSTELLAR MOLECULES are mainly found in the denser DARK CLOUDS (Barnard Objects and Bok Globules) with $n \sim 10^4$–10^9 /cm^3 and $T \sim 10$ K.

• Still denser regions are the GIANT MOLECULAR CLOUDS with $n \sim 10^{10}$ /cm^3 and $T \sim 50$ K. These are associated with sites of new STAR FORMATION.



M101