INTERSTELLAR MEDIUM

- Stefano Bovino -

The interstellar dust

Dust

- We have talked about gas-radiation, all processes occurring at specific frequencies (absorption) or range of frequencies (ionization)
- Dust interact with light in a wide range of wavelengths

The role of dust in the ISM

- Dust accounts for 1% of the total matter in the ISM
- Formed by micro-sized particles
- Extremely important for
  - Chemistry and physics of the ISM
  - Energy balance of Galaxy (heating/cooling/extinction)
  - Evolution of interstellar clouds and SF
  - Depletion and evaporation of heavy elements

Interaction matter-dust-radiation

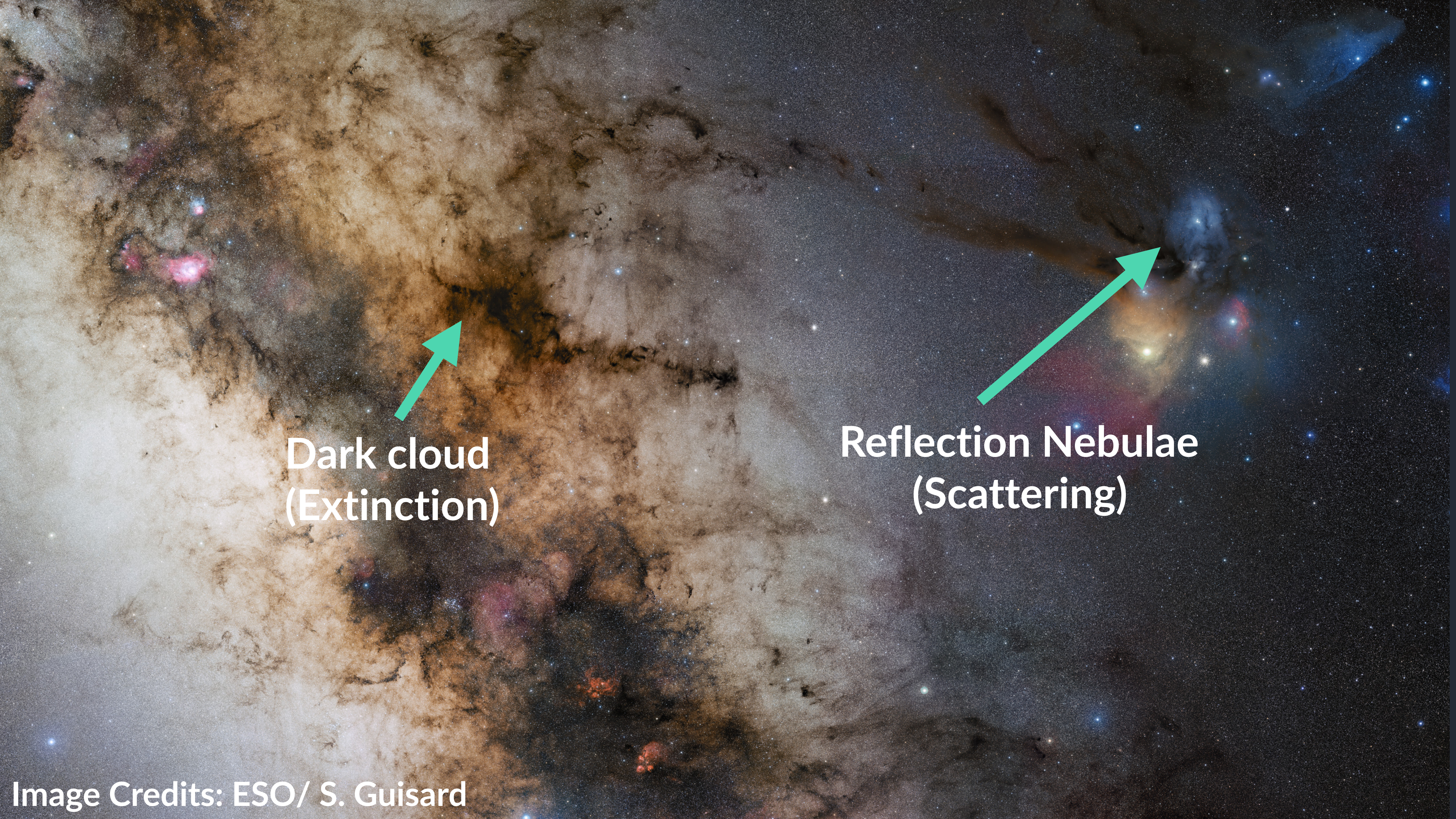
- Dust scatters, absorbs, and re-radiates starlight
    - Reflection nebula (blue scattered light)
    - Transmitted light (reddening)
- $1:10^{12}$ photons reaches our telescope because of extinction
- Energy is absorbed and re-emitted in the IR (~20% of the total luminosity of the Galaxy)

Interaction matter-dust-radiation

- Photoelectric heating
- Surface mantle or ices (gas-grain interaction)
- Chemistry

How do we learn about dust

- Extinction: wavelength dependence of how dust attenuates (absorbs & scatters light)
- Polarization
- Thermal emission from grains
- Depletion of elements from the gas relative to expected abundance


Dark cloud
(Extinction)
Reflection Nebulae
(Scattering)
Image Credits: ESO/ S. Guisard

Dust history

1784 - William Herschel “Hole in the sky”

By eyes - Ophiuchus, Barnard 86: observed regions devoid of stars!

Dust history

1847 - Wilhelm Struve

- Star counts (distribution of stars with distance)
- Number of stars over volume declines with distance from the Sun
- Struve proposed:
  - The existence of some obscuring material
  - Uniformly distributed in space
  - That affects the intensity of starlight

- Stars less bright (because of dust) and apparently further away

Dust history

William Herschel

1784

Ophiuchus, Barnard 86

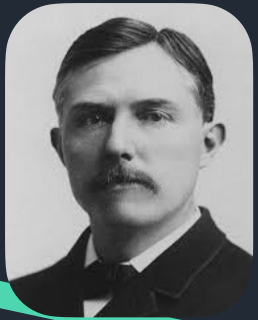
obs. regions devoid of stars?

Wilhelm Struve

1847

Starlight suffers absorption!

Edward Emerson Barnard



1910-1927

Some interstellar material obscures (absorb and scatter) starlight! **They are not “holes in the sky”.**

Dust history

1930s - Robert Trumpler

1. He used two different methods to determine the distance to each cluster

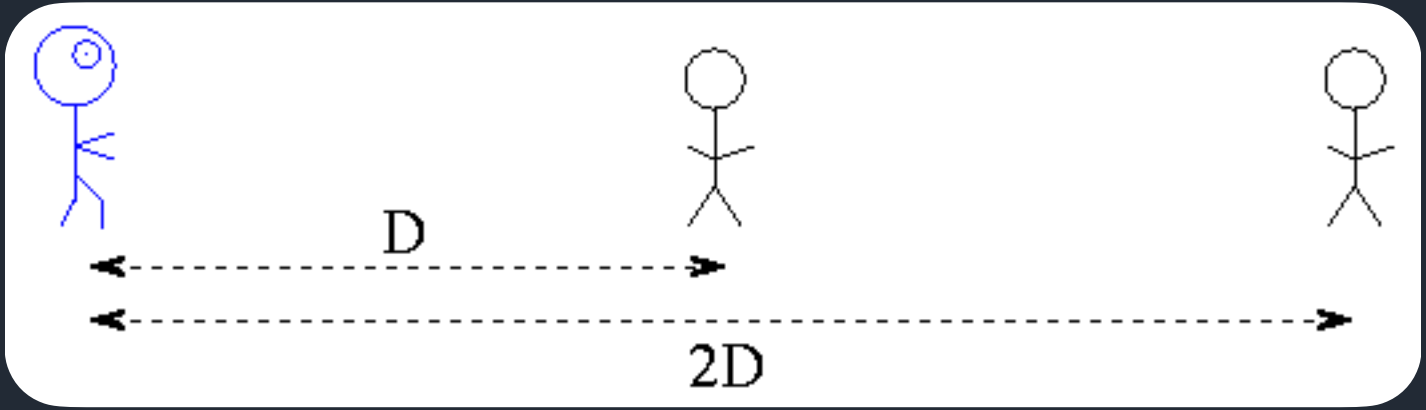
   - one based on brightness
   - the other based on size

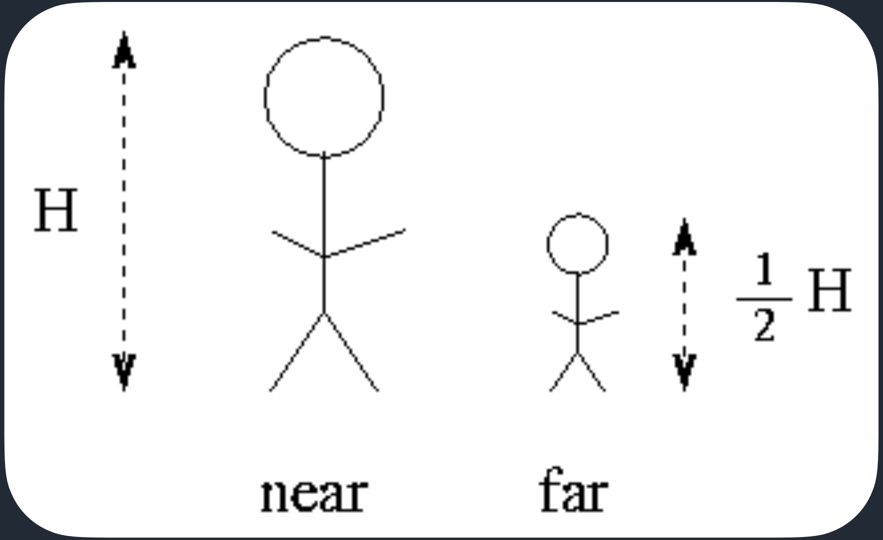
Diameter distance

1. First, he divided the clusters into groups, based on the number of stars in each and the degree of central concentration
2. He assumed that clusters in the same group had the same size
3. From the size he calculated the distance (small far / large near)

Dust history

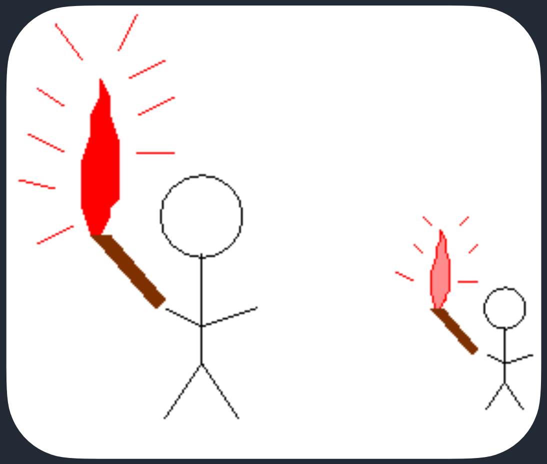
1930s - Robert Trumpler





Dust history

1930s - Robert Trumpler



1. He applied the inverse square law to individual star
   - spectral class of a star yielded its absolute magnitude
   - photographic plates provided each star's apparent magnitude

Photometric distance

1. Assuming that light travelled freely through space, he calculated the distance to each star, and averaged them to find the distance to each cluster.

Dust history

1930s - Robert Trumpler

1. Followed Struve's hypothesis
2. Calculated the average amount of extinction per unit distance (incredibly close to what we know now)

ABSORPTION OF LIGHT IN THE GALACTIC SYSTEM

By Robert J. Trumpler 1930, PASP, 42, 214

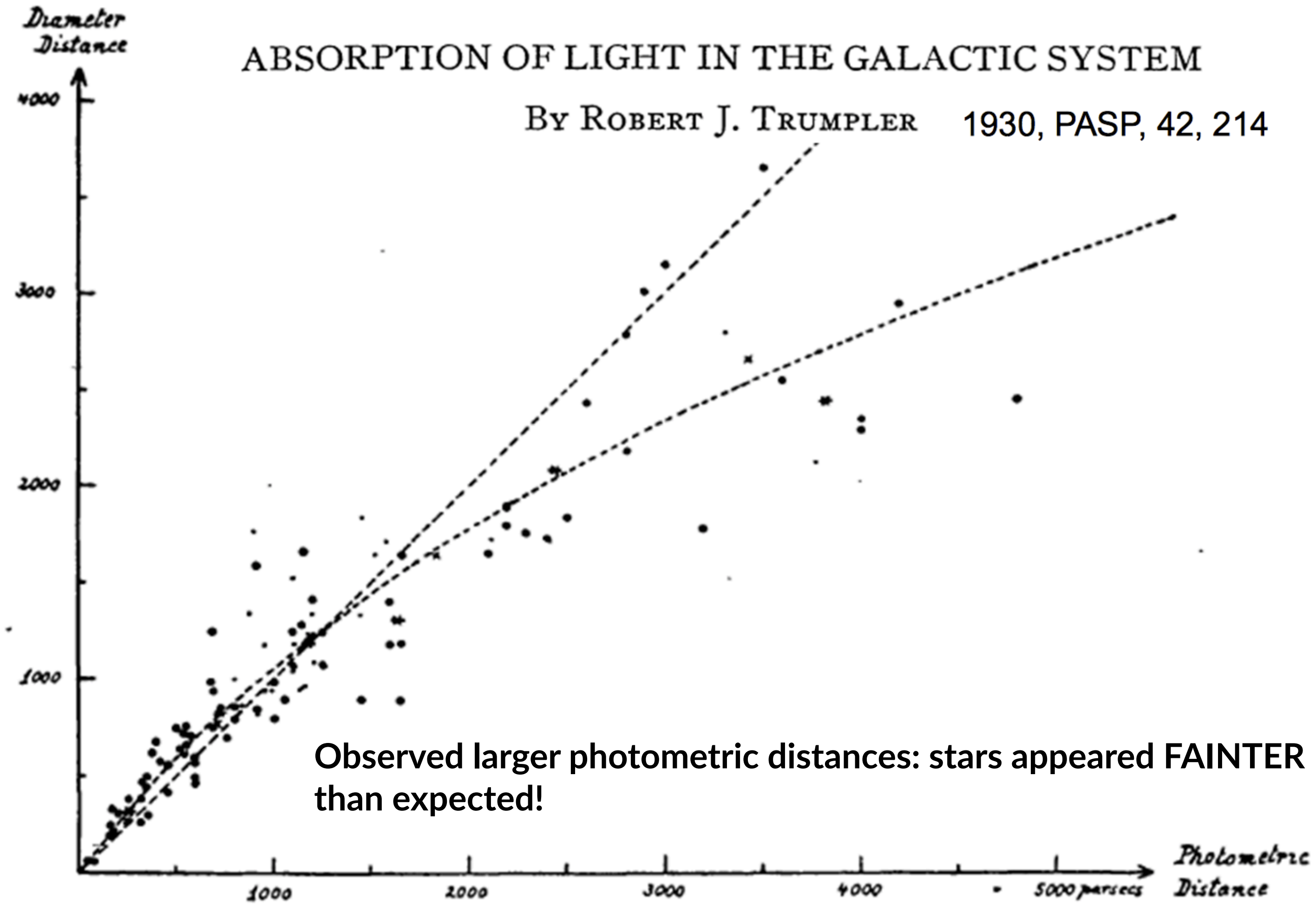
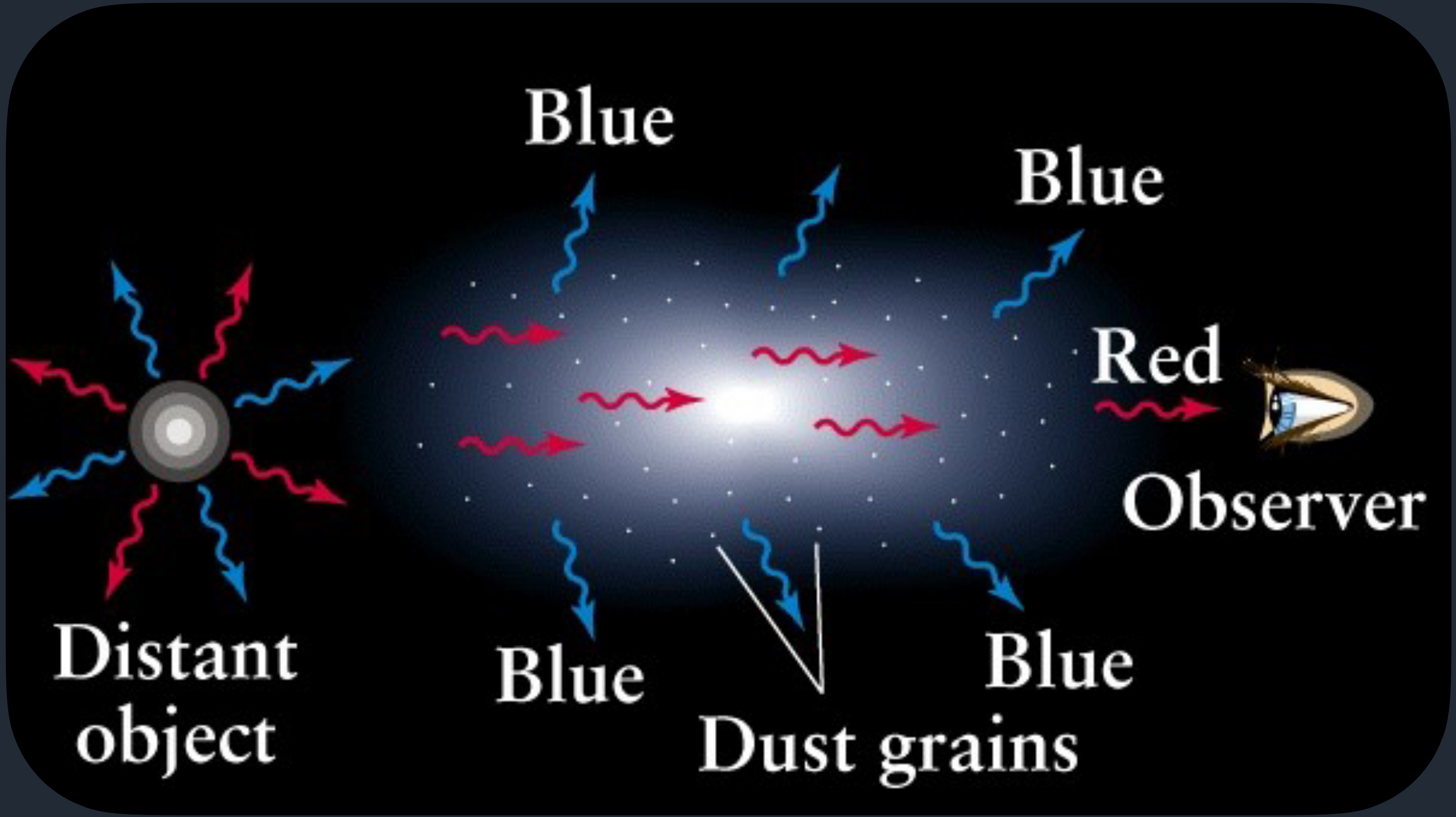


Fig. 1.—Comparison of the distances of 100 open star clusters determined from apparent magnitudes and spectral types (abscissae) with those determined from angular diameters (ordinates). The large dots refer to clusters with well-determined photometric distances, the small dots to clusters with less 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 history

1930s - Robert Trumpler: interstellar reddening

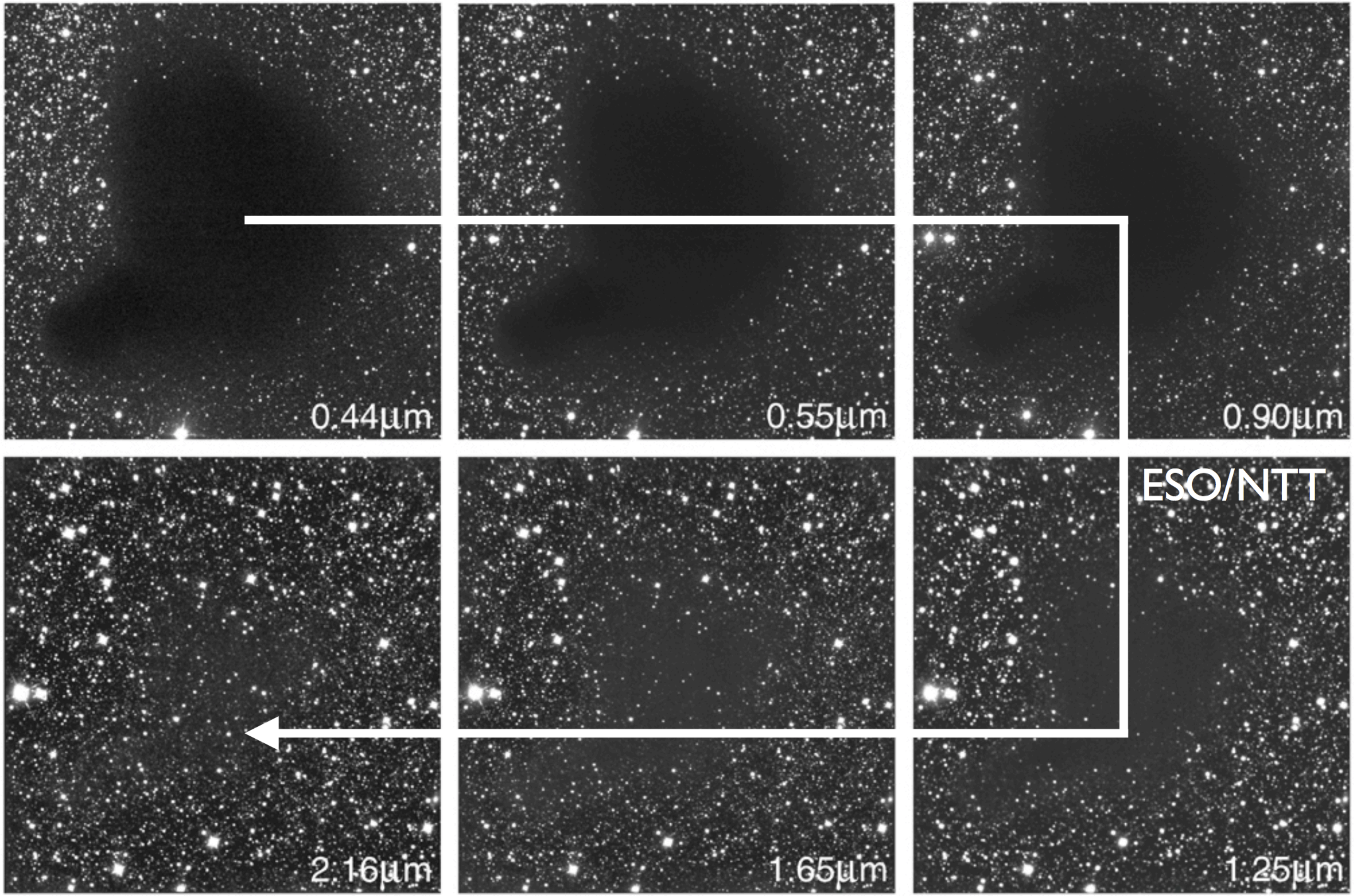


1 - Blue-light strongly absorbed and scattered by dust (size similar to blue wavelengths)

2 - Objects appears redder that they really are

$$A_\lambda \propto \lambda^{-1}$$

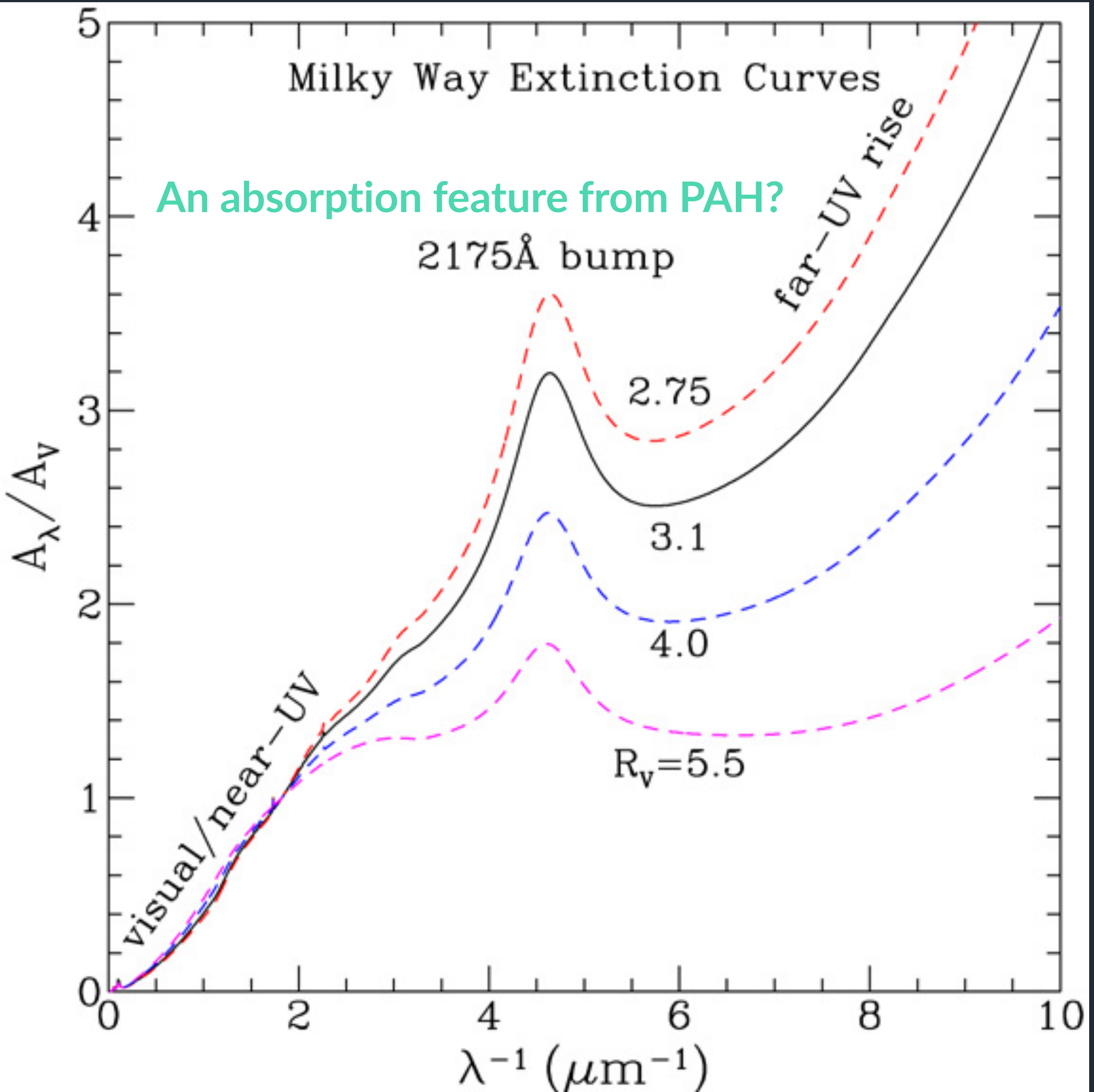
Joel Stebbins 1939


0.44μm
0.55μm
0.90μm
ESO/NTT
2.16μm
1.65μm
1.25μm

Extinction: Absorption + Scattering

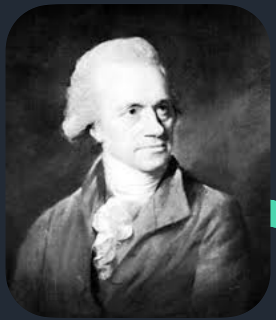
- Decrease in luminosity of a star when seen through a cloud
- Depends upon grain composition, size distribution, shape, and wavelength

$$I(\lambda) = I_0(\lambda)10^{-(A_\lambda/2.5)} = I_0(\lambda)e^{-\tau_\lambda}$$



Dust history

Herschel



1784

Ophiuchus,
Barnard 86

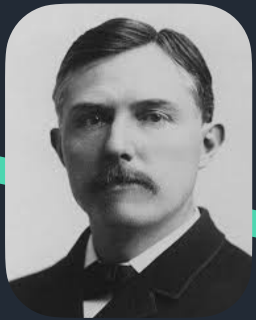
obs. regions devoid of stars?

Struve

1847

Starlight suffers absorption!

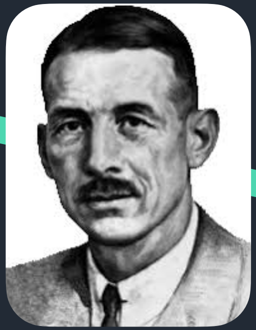
Barnard



1910-1927

Some interstellar material obscures (absorb and scatter) starlight! **They are not "holes in the sky".**

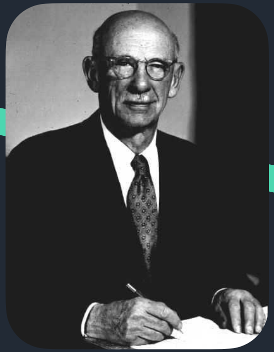
Trumpler



1930

First estimate of the extinction coefficient

Stebbins



1939

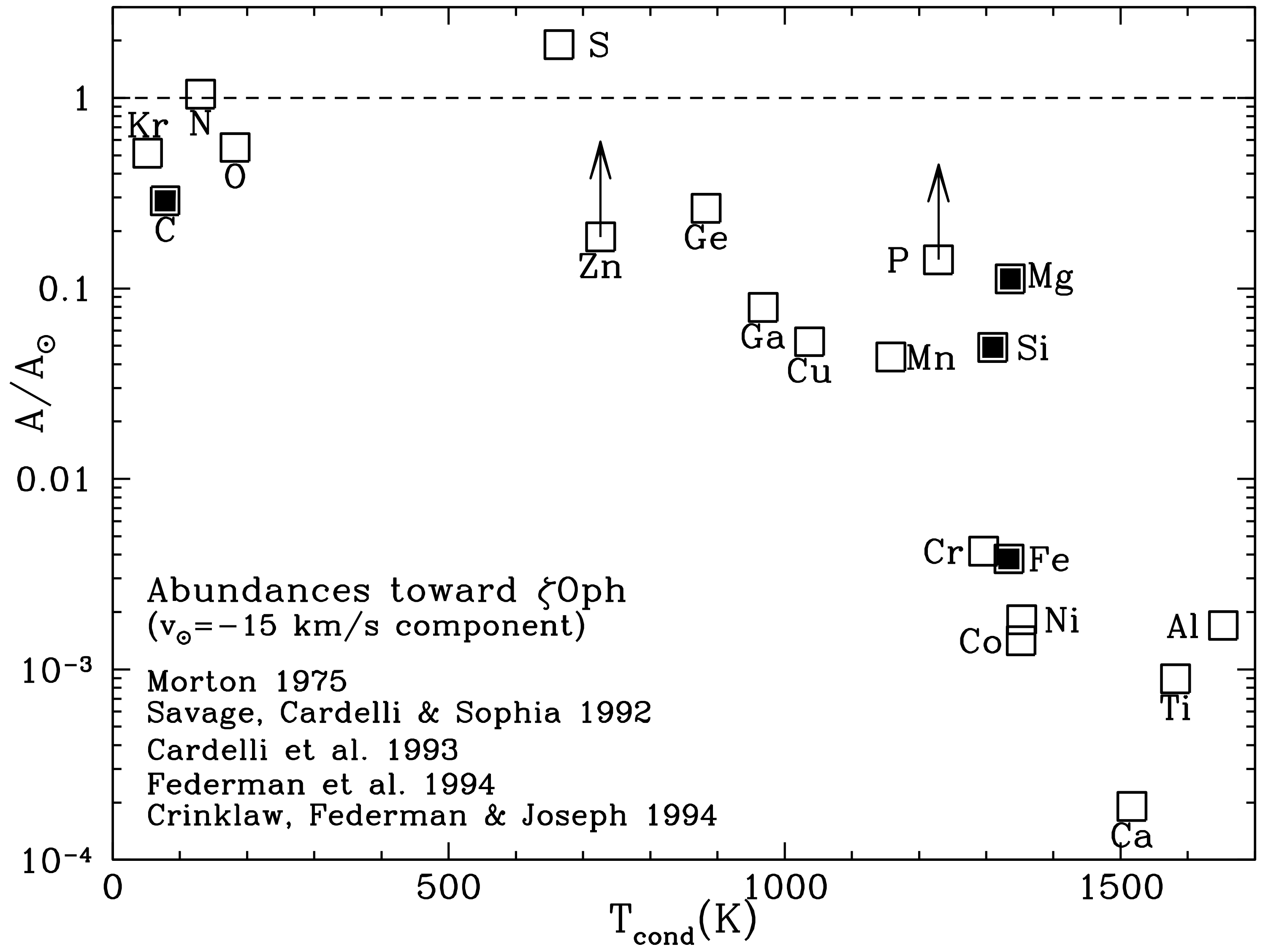
They are solid particles!

What is made of the interstellar dust?

- Ideal approach: spectroscopic features
  - Would uniquely identify the material
  - Would allow to measure the amounts of each material
- For dust is difficult
  - Optical and UV absorption is continuum
  - Spectral features are broad, difficult to identify

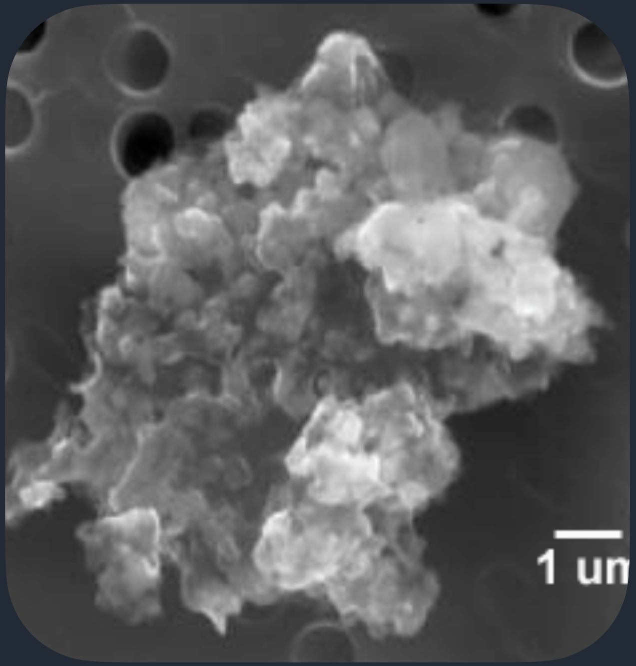
What materials could plausibly be present in the ISM?

Abundances constraints



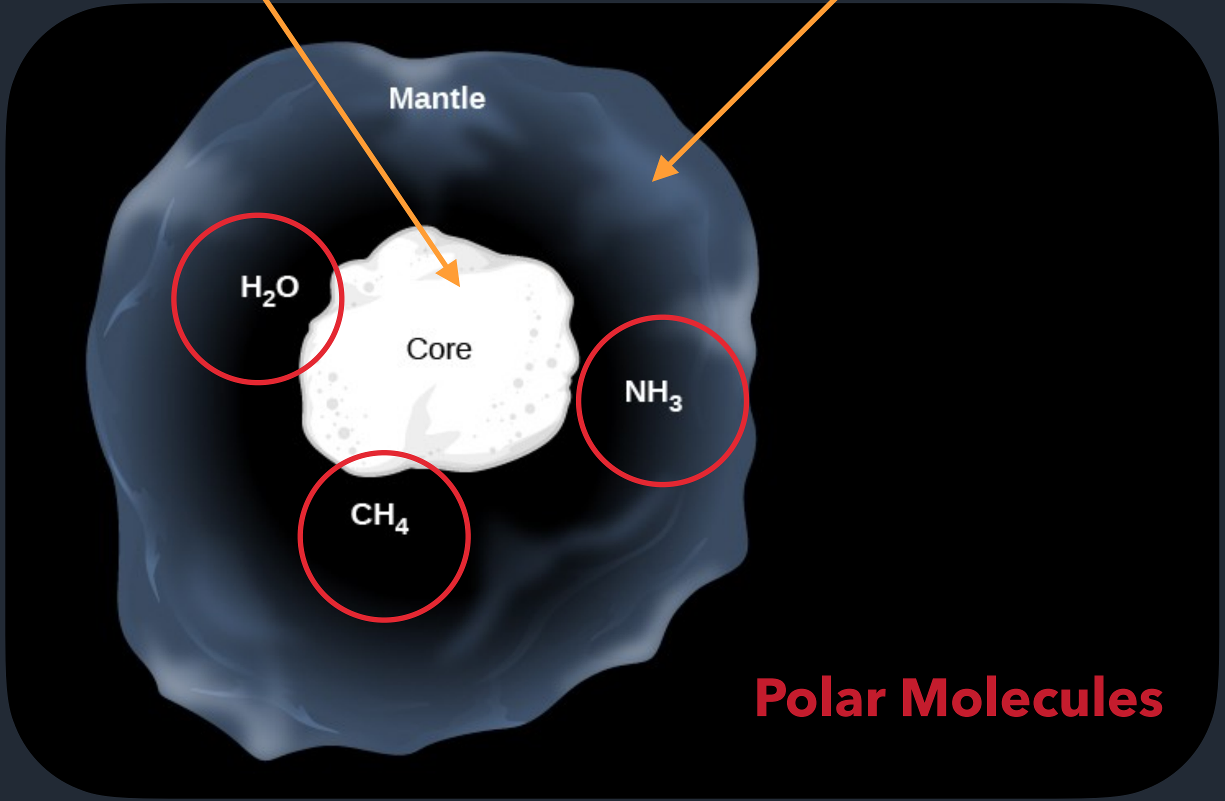
- Silicates, pyroxene, olivine
- Oxides of Si, Mg, Fe
- Carbon solids
- Hydrocarbons (PAH)
- Carbides
- Metallic Fe

What is made of the interstellar dust?

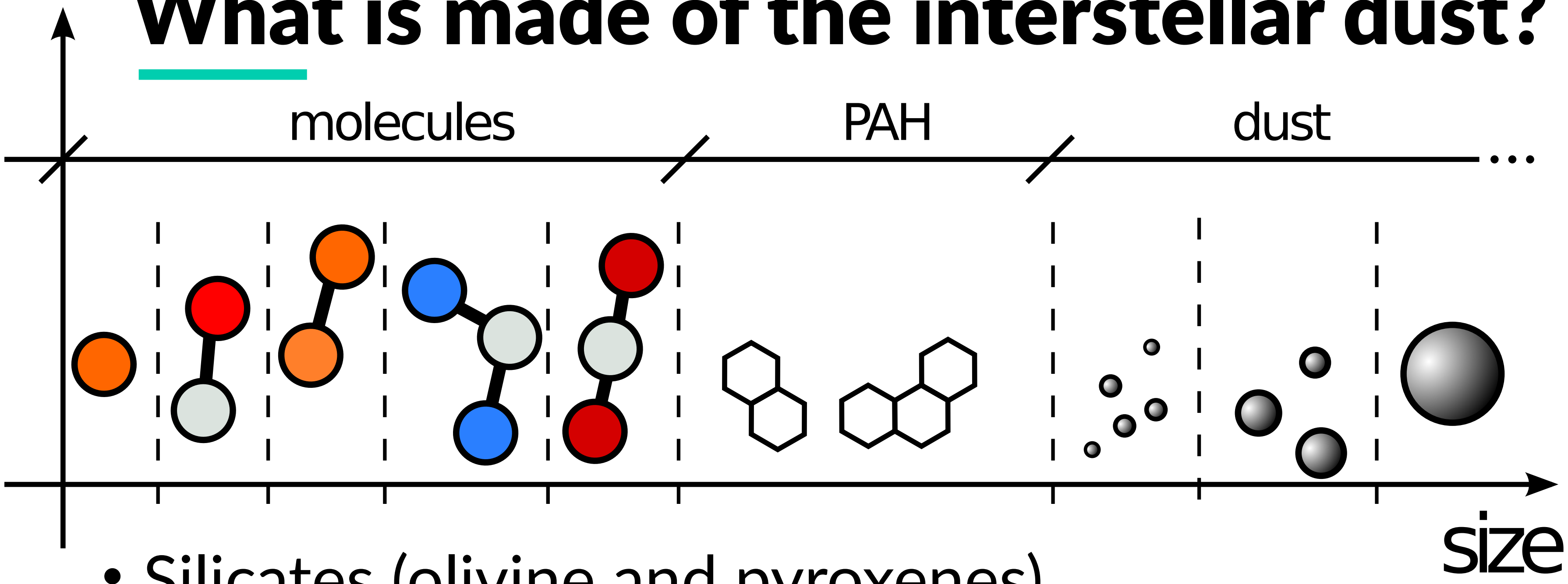


Silicates/Carbonaceous

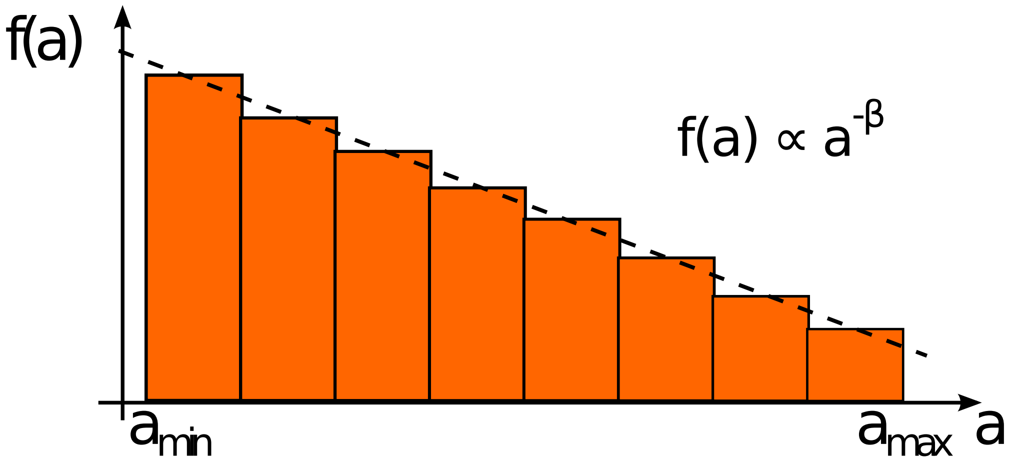
Ice mantles



What is made of the interstellar dust?

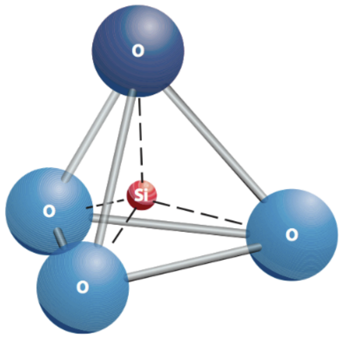


- Silicates (olivine and pyroxenes)
- Carbonaceous (HAC + PAH)
- Typical size ~ 0.1 micron
- MRN distribution (power-law, does not include PAH)

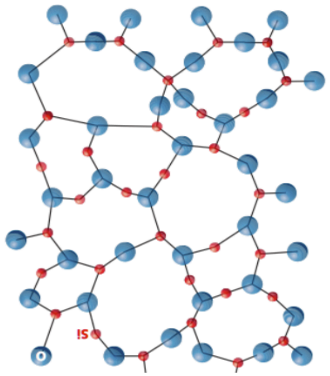


Silicates

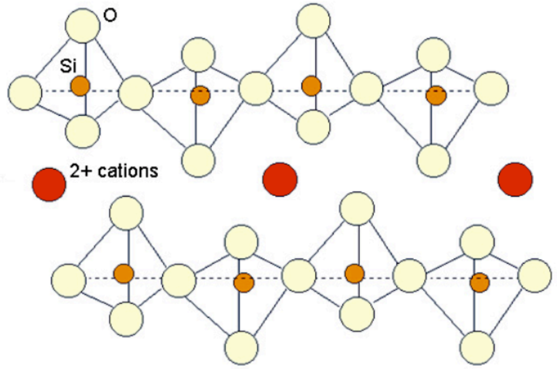
- 9.7 μm Si-O stretching mode
- 18 μm O-Si-O bending mode
- Low crystallinity in the ISM, increasing in brown dwarf disks



Basic building block

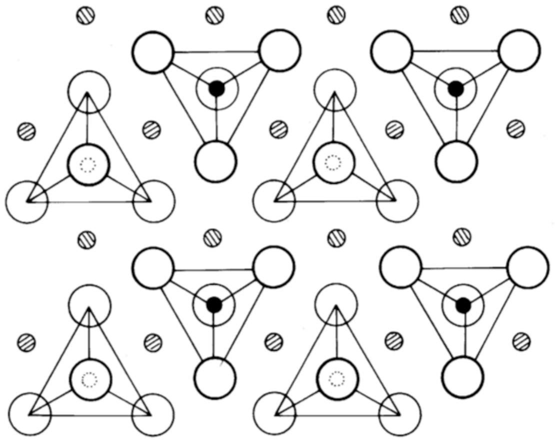


Amorphous silicate



Pyroxene $Mg_x Fe_{1-x}SiO_3$

Henning 2010

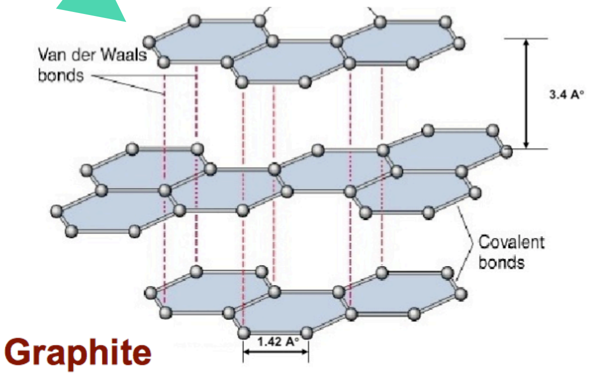


Olivine $Mg_{2x} Fe_{2-2x}SiO_4$

Each of these sheets is graphene

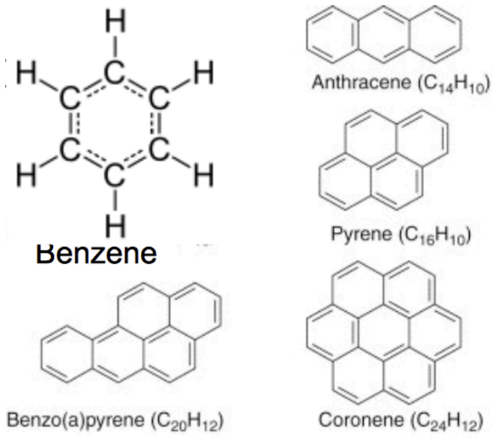
Carbonaceous

- **Graphite** (Stecher 1965, Draine&Lee1984, Li&Draine2001)
  - C atoms: three sp2 (sigma) + π orbitals
  - π + **217.5** nm → π*
  - BUT: variations in the peak position!
- **Hydrogenated amorphous carbon (HAC, a–C:H)**
  - Mennella et al. (1998) – 217 nm bump due to UV processed HAC
  - **3.4** μ m feature - aliphatic C-H stretch
  - Jones et al. – HAC is less resilient than graphite – reproduces better variations of C gas phase abundances
  - Jones PoS(LCDU2013)001: review of current knowledge about ISM dust
- **Polycyclic aromatic hydrocarbon (PAH)**
  - Strong extinction in 200–250 nm region
  - Solid state emission 3.3, 6.7, 7.6, 8.6, and 11.3 μ m

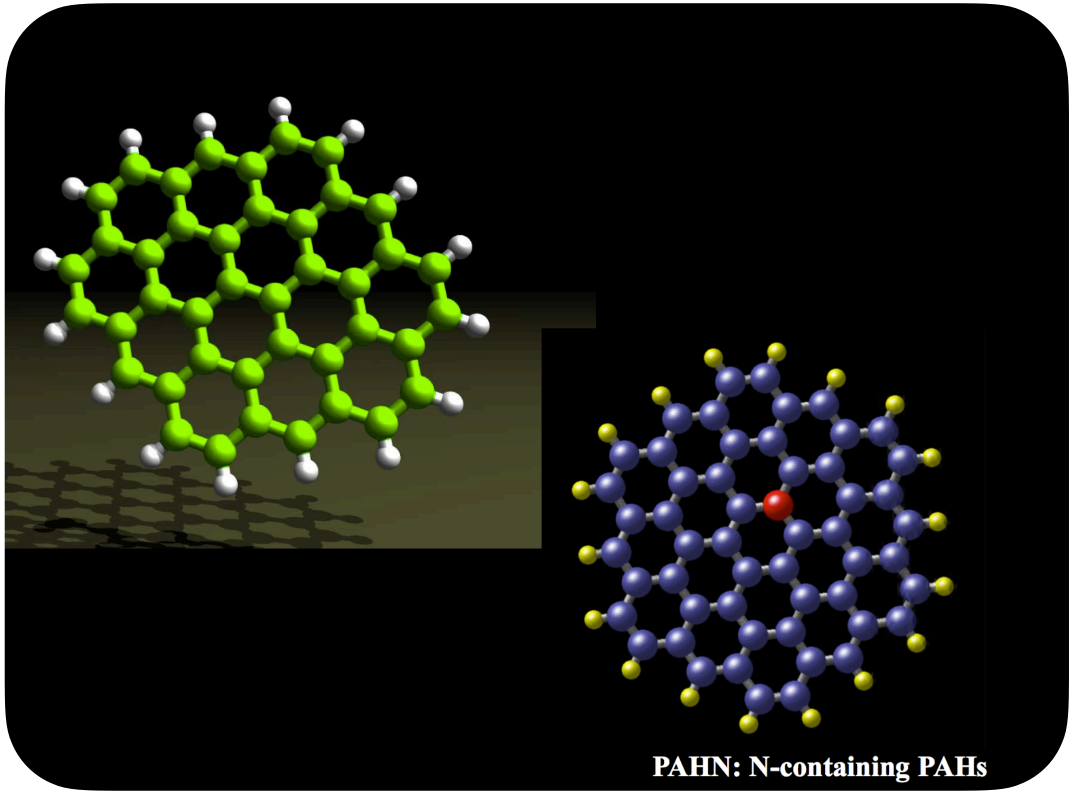


Graphite

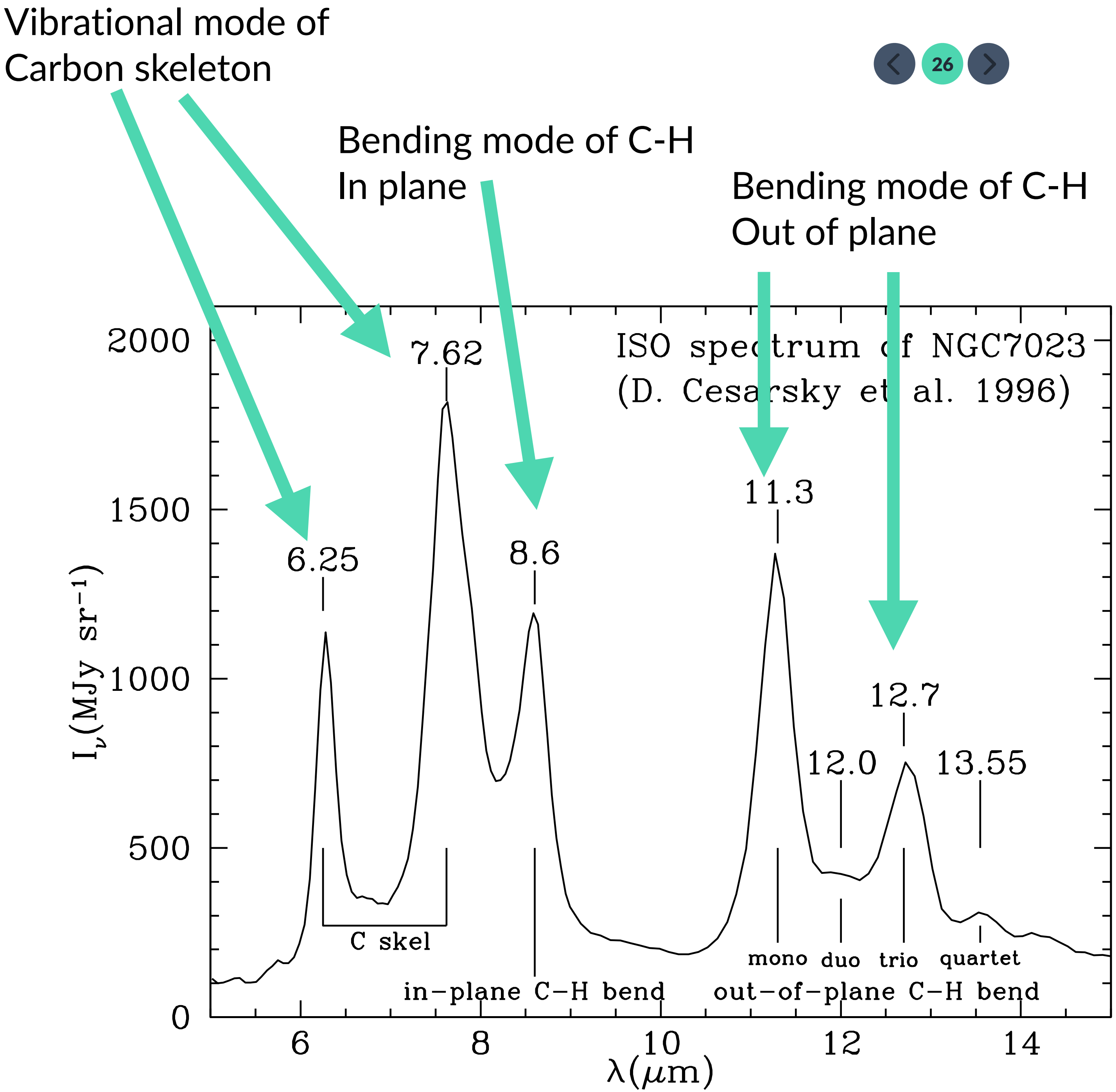
PAH



PAH

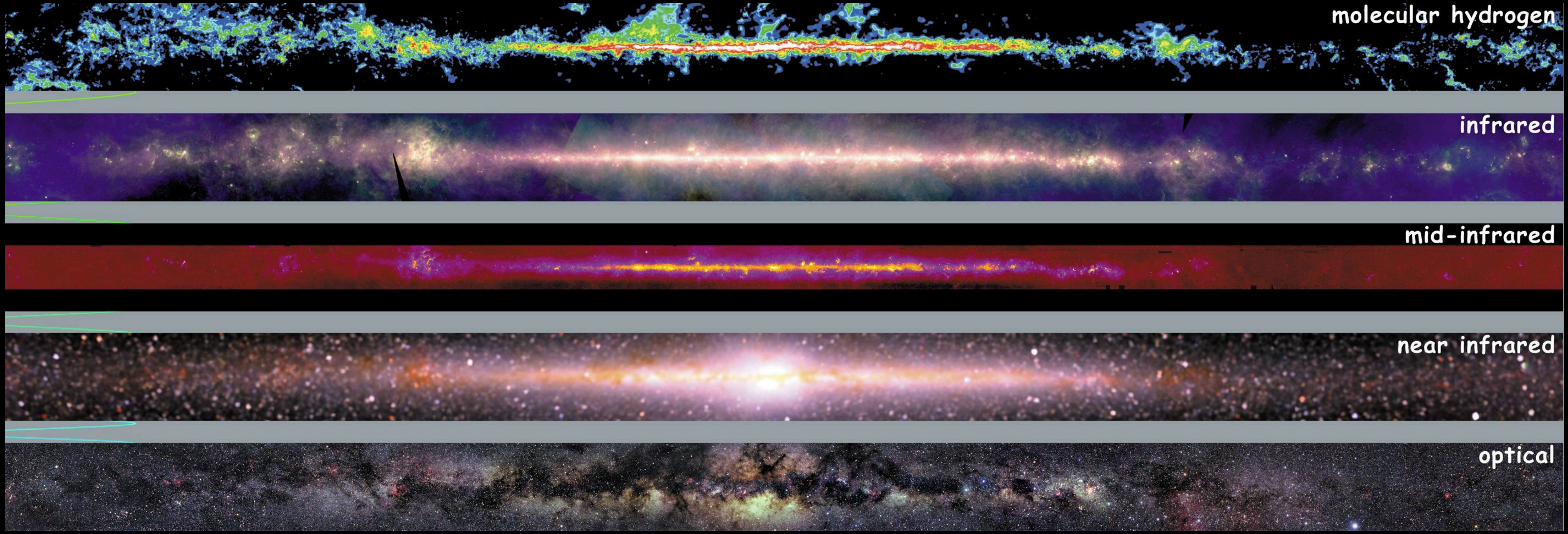


- vibrational emission bands at 3.3, 6.2, 7.7, 8.6, 11.3 and 12.7 micron



How does the dust appear to us globally?

Milky Way galactic plane

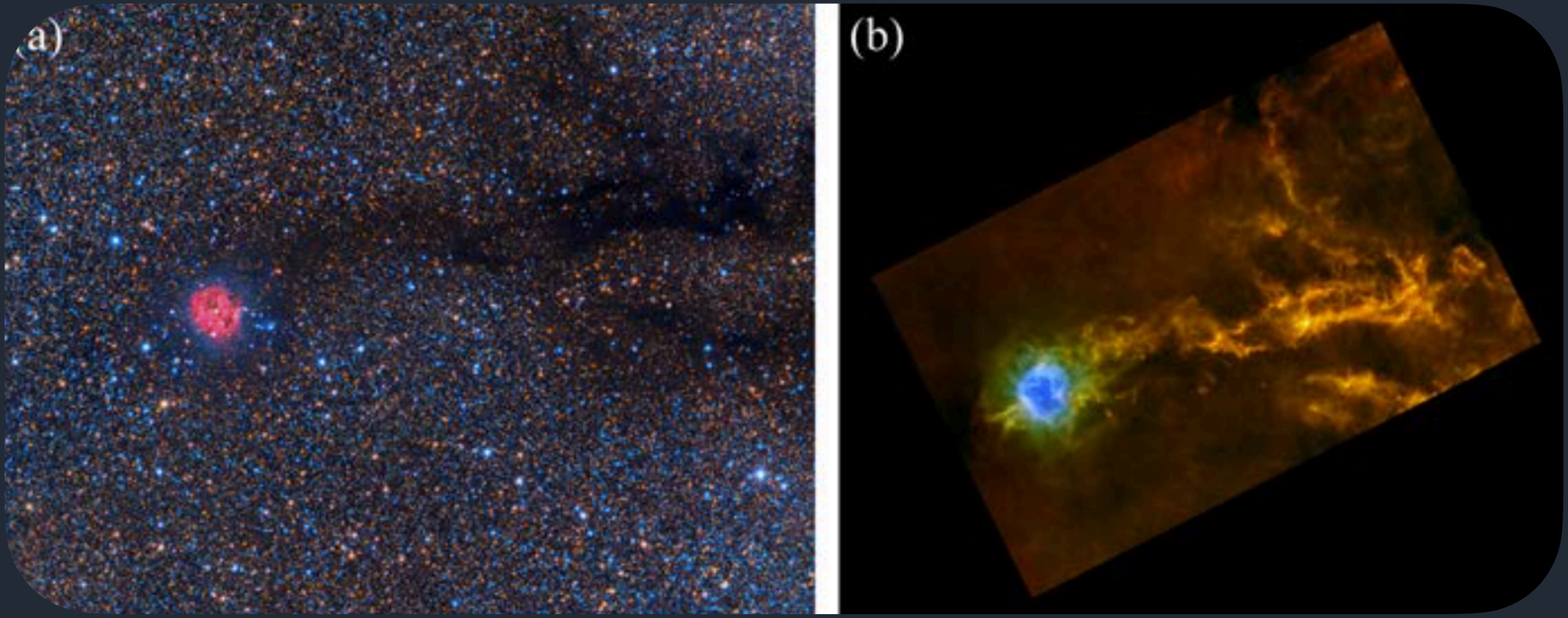


How does the dust appear to us globally?

Cocoon Nebula and trail of dark interstellar dust clouds:

(a) in the visible (credit and copyright: Tony Hallas);

(b) in the infrared (credit: ESA, SPIRE & PACS Consortia, Doris Arzoumian [CEA, Saclay] *et al.*);



Summarising

- **Up to mid-20th century**: dust was an annoying “fog” that prevented clear view of stars and galaxies
- The main task was to disperse that fog (theoretically)
- **Now**: dust affects every aspects of the formation of stars, galaxies and planets

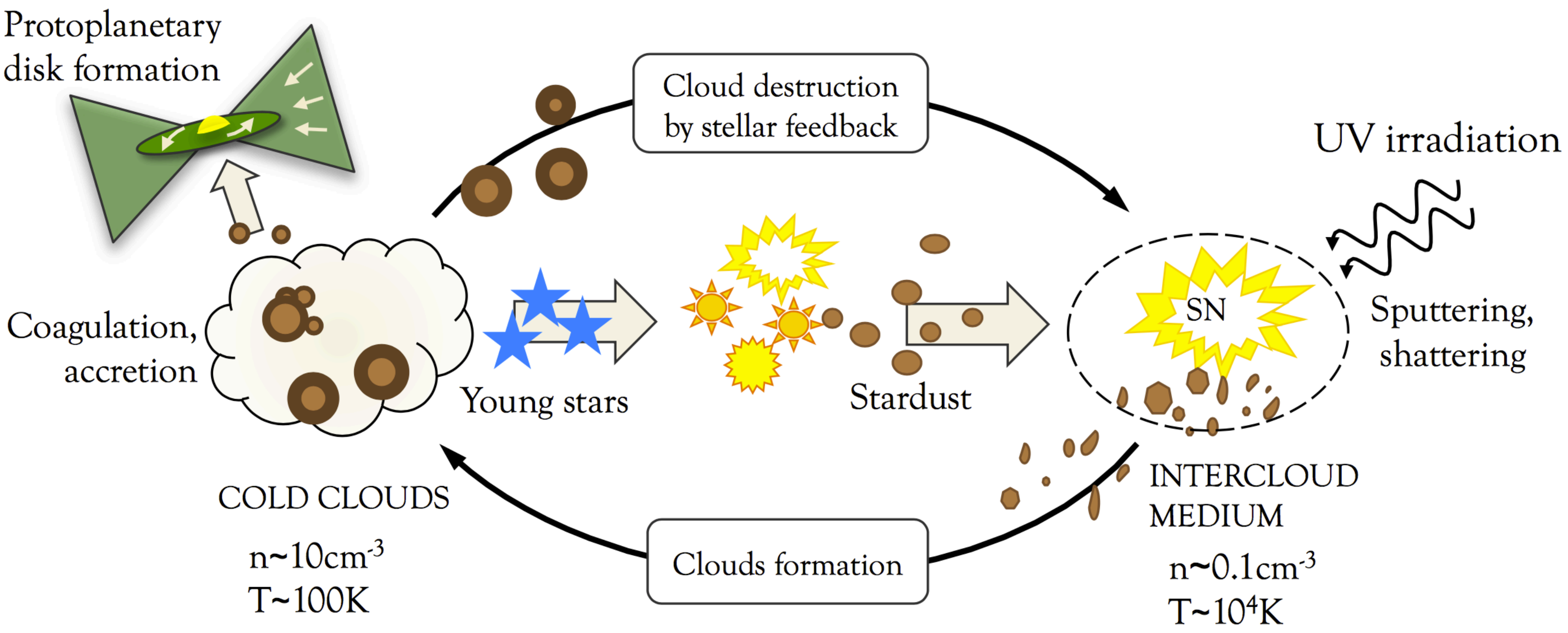
How and where dust form?

- Dust form mainly in AGB stars and SNe
- Once formed is injected in the ISM
- In the ISM can be re-processed via radiation and chemical reactions
- This can change their chemical structure and nature
- Main formation process: nucleation (and condensation)
- Need to enter a zone with high pressure and high temperature

AGB stars

- Cool stars at the end of their lives
- Already burned most of H and He
- Their envelopes contain a richness of dust-related elements (C, Si, O) -> result of thermonuclear reactions
- The envelope eventually drifts away from the star
- AGB stars: C-rich and O-rich

Lifecycle of dust grains



- Gas-grain interactions
- Photon-grain interactions
- Grain-grain interactions

adapted from Gail&Zhukovska 2012

Table 5.1 A list of the main contributors to gas and dust in the Milky Way, with estimated injection rates[a] ($M_{\odot}$ pc^{-2} Myr^{-1}).

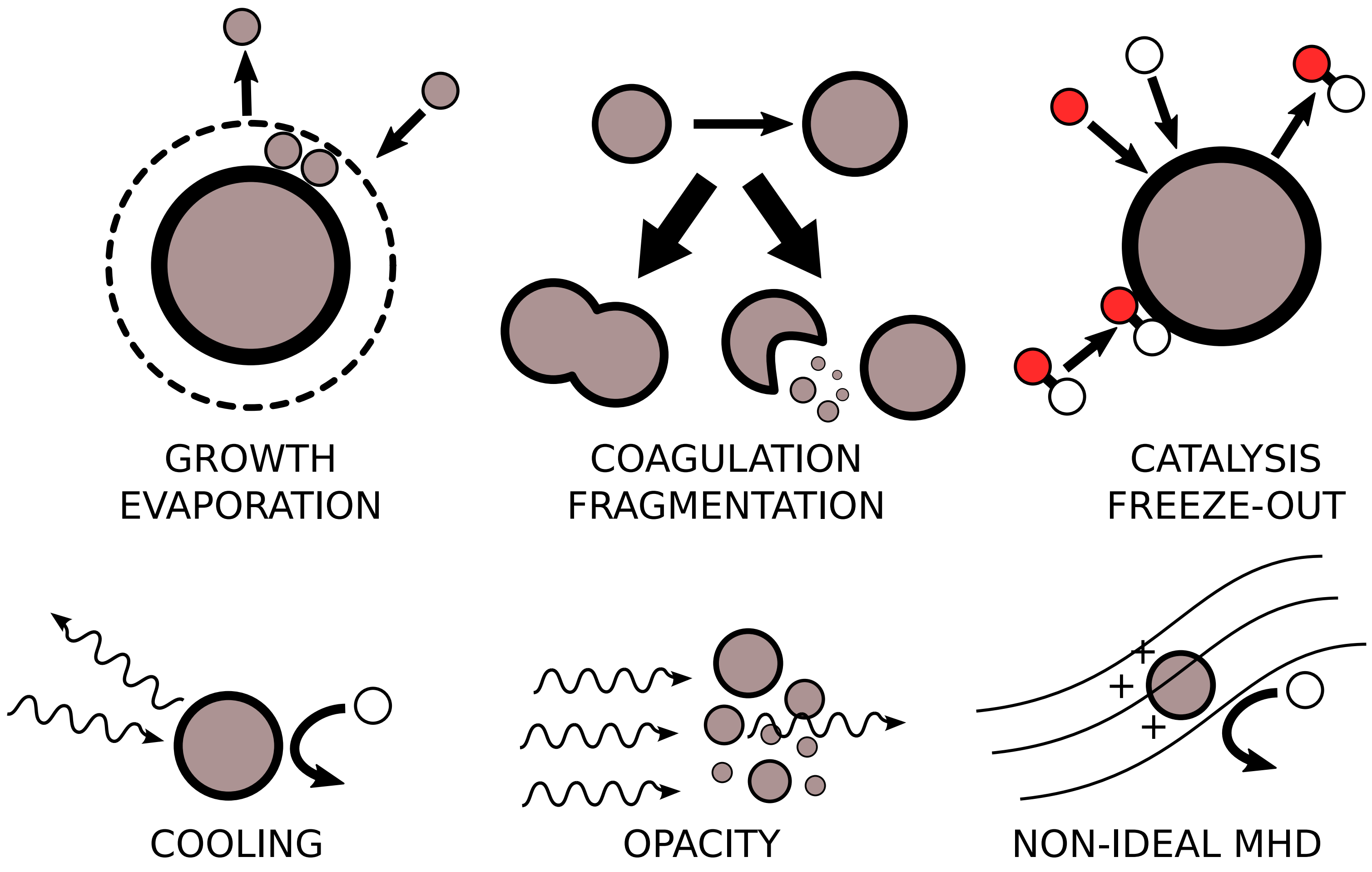
Source	Gas	Carbon dust	Silicate dust
AGB (C-rich)	750	3	
AGB (O-rich)	750		5
OB stars	30		
Wolf–Rayet	100	0.1	
Red supergiants	20		0.03
Novae	6	0.3	0.03
SN type Ia		0.3	2
SN type II	100	2	10

[a]Data are taken from Tielens *et al.* (2005),[4] Massey *et al.* (2005),[5] and Ferrarotti & Gail (2006).[6]

Table 5.5 Chemical inventory in dust factories.

Material	AGB	Post-AGB	PN	Nova	RSG	WR	LBV	SN
Amorphous silicates	X	X	X	X	X		X	X
Crystalline forsterite	X	X	X		X		X	
Crystalline enstatite	X	X	X		X		X	
Chromite	X							X
Aluminium oxide	X			X				X
Spinel	X							X
TiO_2	X				X			
Hibonite	X							
MgO	X							
Fe	X							X
PAHs	X	X	X	X	X	X	X	
a-C:H	X	X	X	X		X		
Graphite	X	X		X				X
Diamond		X						X
SiC	X	X	X	X				X
Other carbides	X							X
Si_3N_4								X
MgS	X	X	X				X	

DUST PHYSICS: SHATTERING–SPUTTERING–GROWTH



SHATTERING

- Grain-Grain collisions
- Redistribute grain mass into units of smaller sizes
- Distribution favors small size grains
- Can also cause vaporization and remove smaller grains entirely

SPUTTERING

- Gas-Grain collisions
- Sufficiently high-energy needed
- Erosion
- Atoms and molecules can be ejected into the gas-phase
- Interstellar shocks