Interstellar Medium 2020

Lecture 10: Interstellar dust

Sterrewacht Leiden

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Course Contents

1. Introduction and ecology of the interstellar medium
2. Physical conditions and radiative processes
3. The atomic interstellar medium
4. Ionization and recombination
5. HII regions
6. Collisional excitation and nebular diagnostics
7. Molecules and their spectra
8. Molecular clouds
9. Thermal balance
10. Interstellar dust
11. Molecular clouds and molecular lines
12. Shocks, supernova remnants and the 3-phase ISM

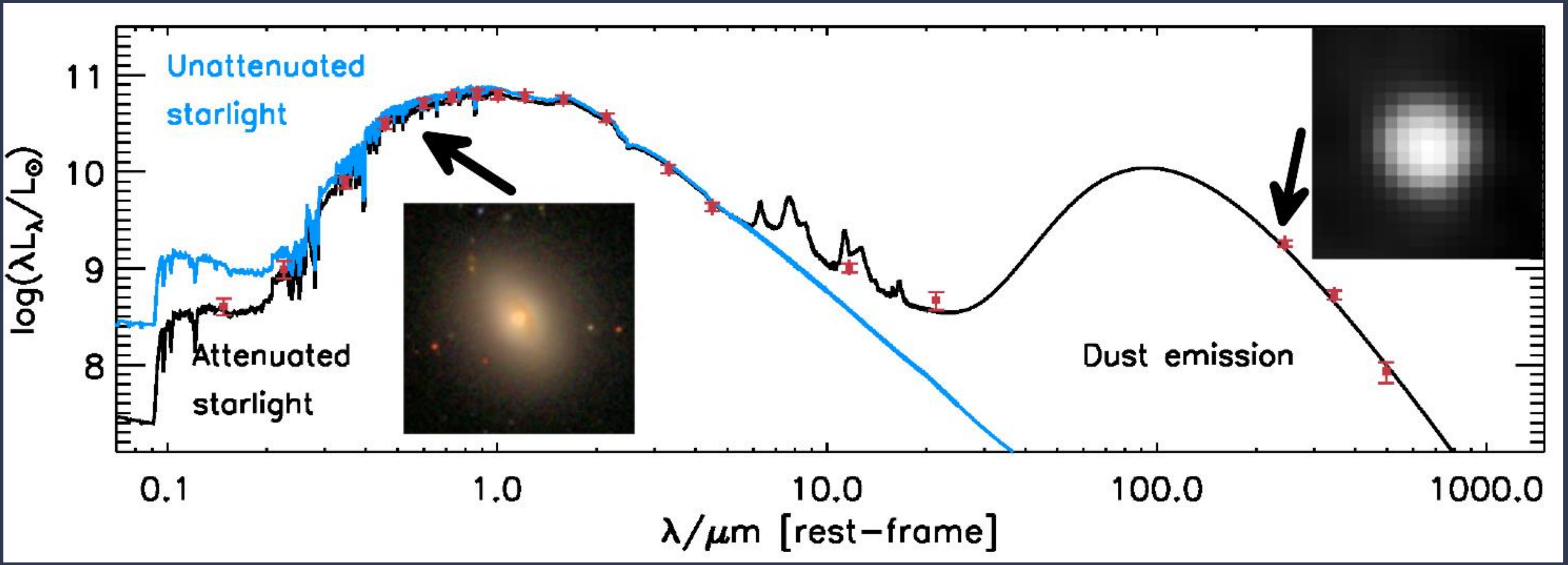
Today's lecture

Interstellar dust

- Importance of dust
- Absorption by dust: the extinction curve
- Dust models
- Small grains, PAHs, ices
- Dust formation and destruction
- Dust temperature
- Infrared emission

Corresponding textbook material: Draine, parts of Ch. 21-24
(see Brightspace for details)

Galaxy Spectral Energy Distributions (SEDs)



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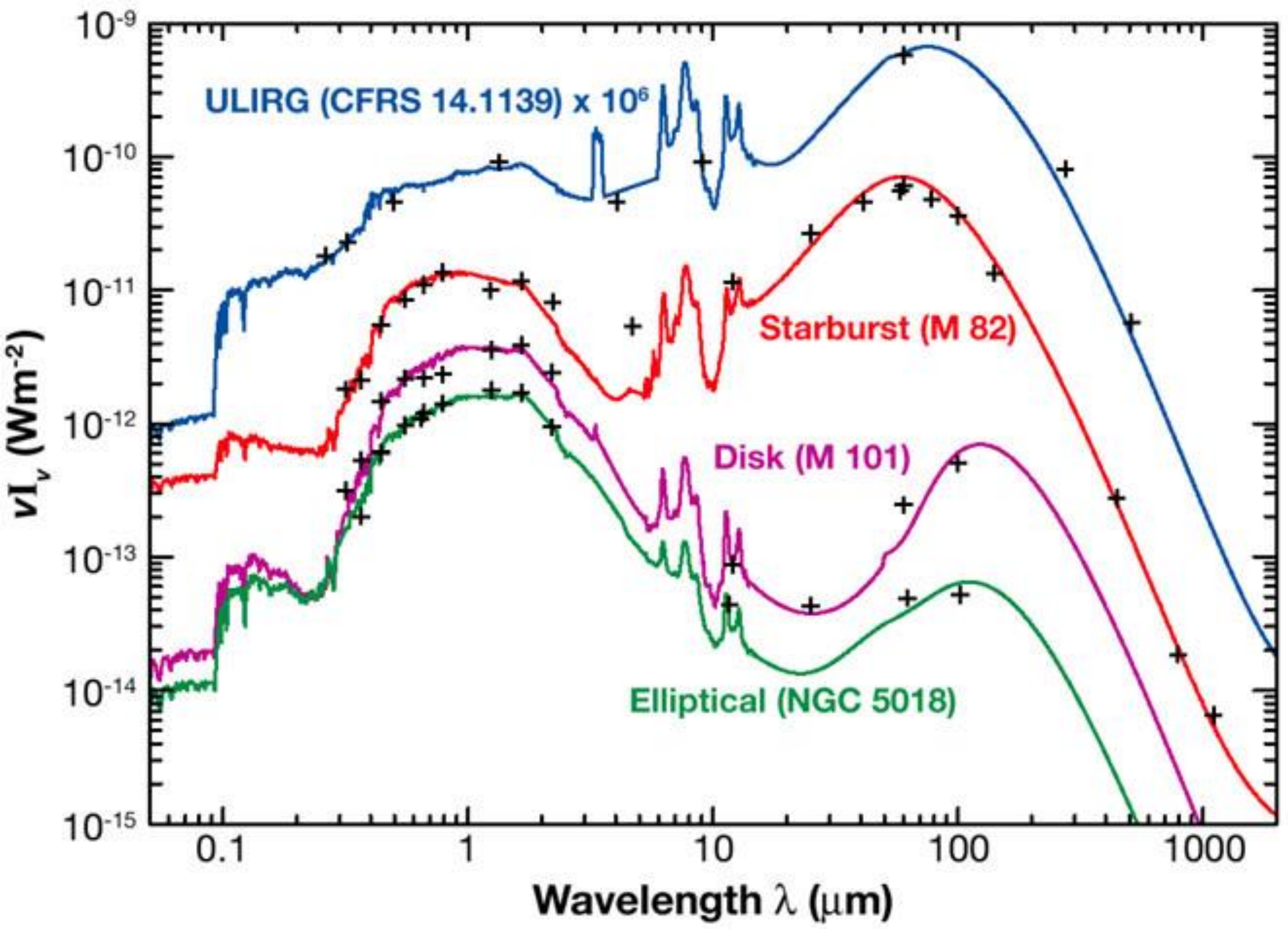
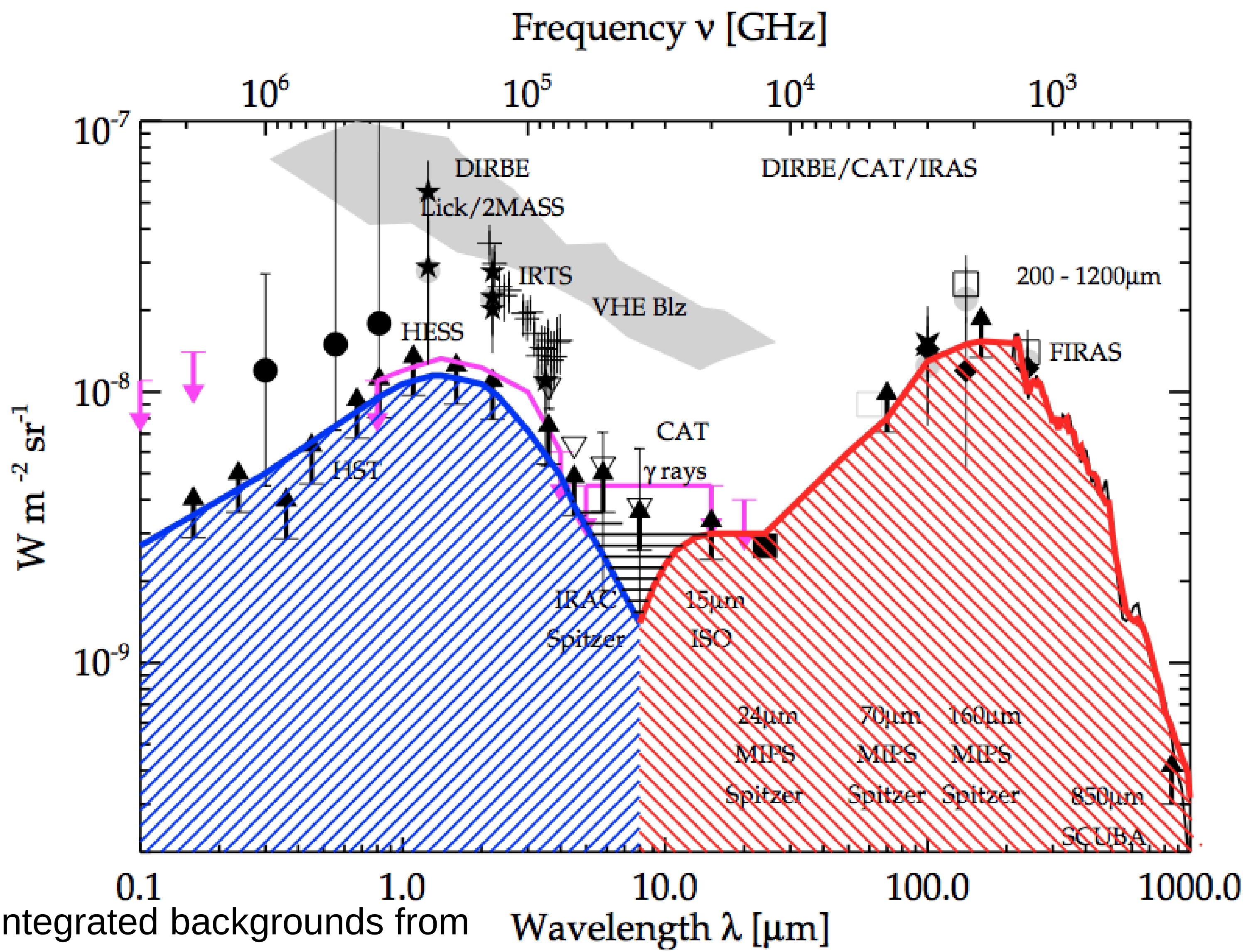
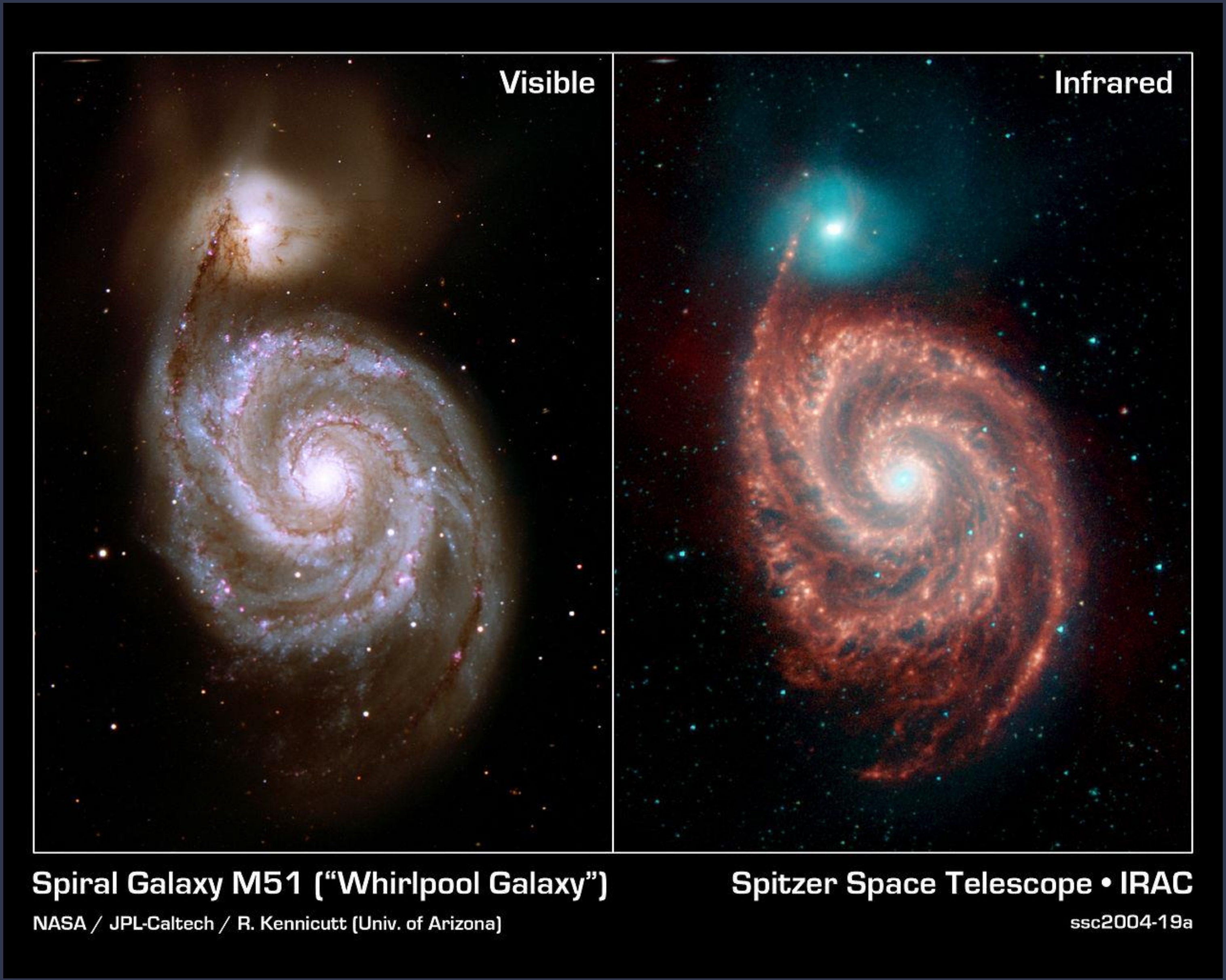


~50% of cosmic emission hidden by dust



Integrated backgrounds from Dole *et al*. 2006

M51 optical and infrared



Observable effects of interstellar dust

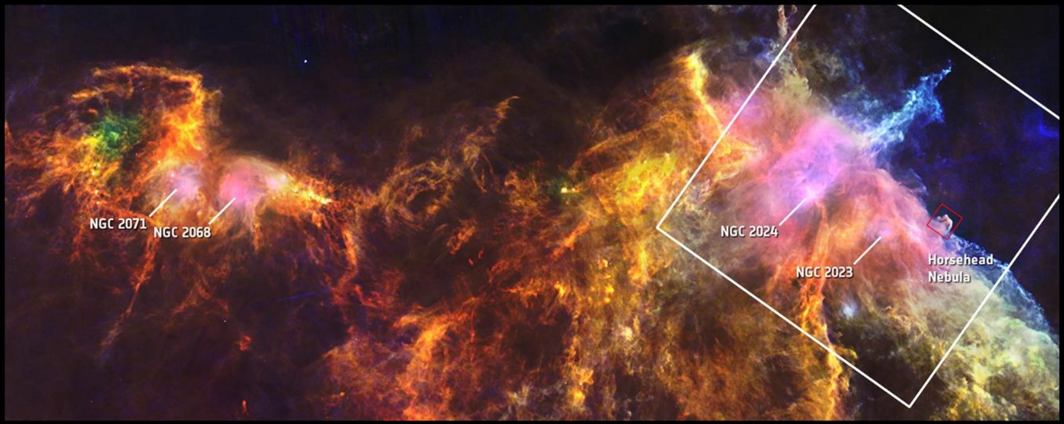
- Dark clouds: absence of stars in optical imaging
- Reddening of starlight
- Reflection nebulae
- Polarization of starlight
- Infrared continuum emission from interstellar clouds

Dark cloud B68 with reddening of starlight

ESO/VLT
Alves *et al.*, 2001

The Horsehead Nebula

→THE ORION B MOLECULAR CLOUD AND THE HORSEHEAD NEBULA

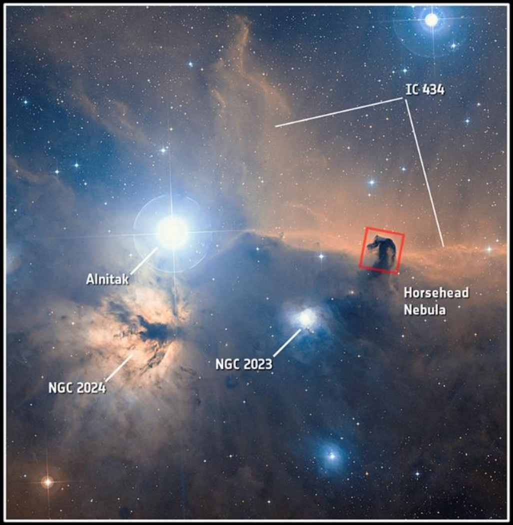


Far-infrared

herschel

Near-infrared

hubble space telescope



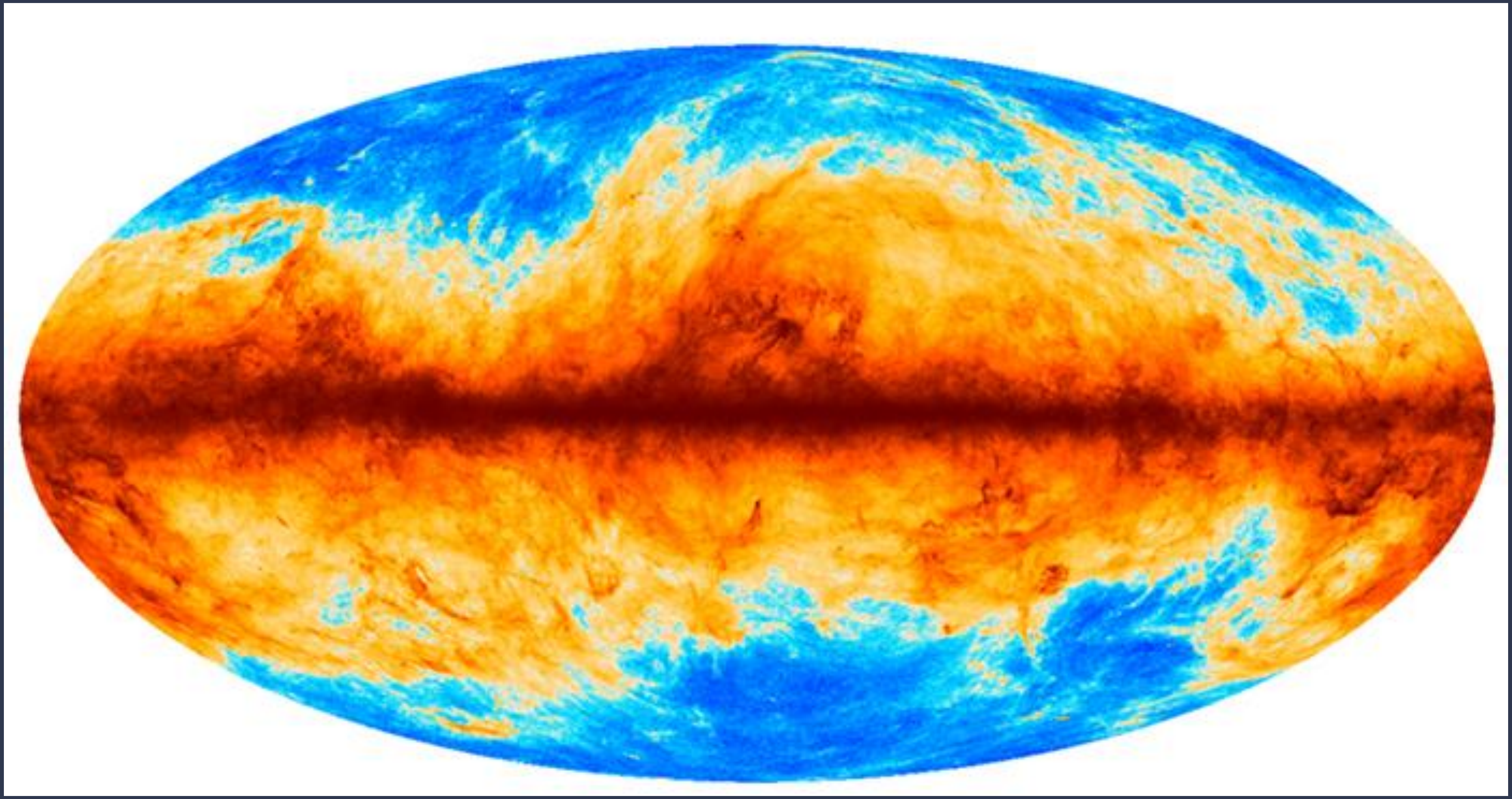
Visible

dss2

www.esa.int

European Space Agency

Dust emission observed by Planck



Planck
857 GHz

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Extinction curve

Dust extinction can be expressed as optical depth τ_λ or extinction A_λ in magnitudes with $A_\lambda = 1.086\,\tau_\lambda$

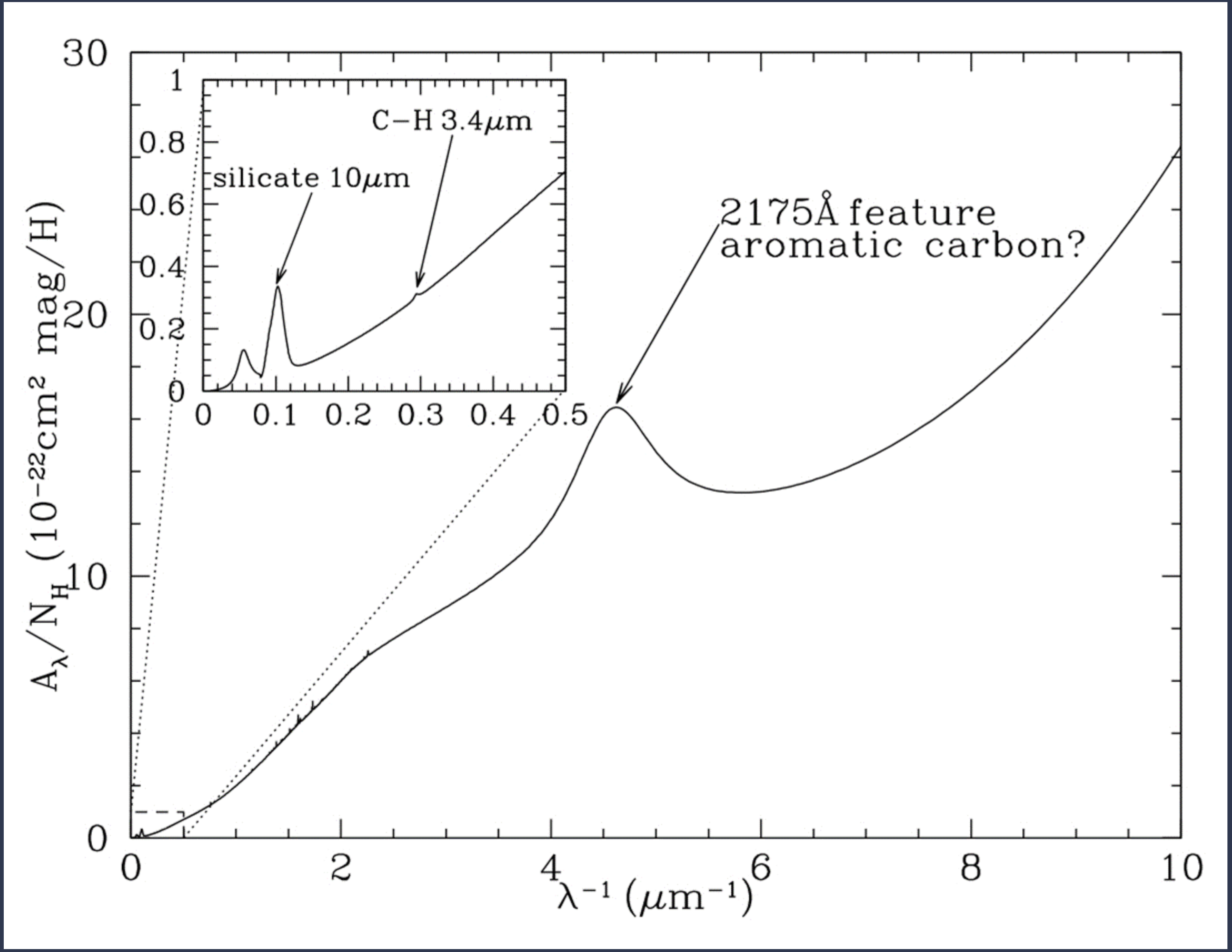
The shape of the extinction curve gives information on:

- dust grain size distribution
- dust chemical composition

Since the dust is well-mixed with the gas, the extinction curve is often shown as A_λ / N_H (units e.g., mag / 10^{22} H atoms).

Since the extinction rises towards the blue (in the optical region) it is sometimes referred to as the “reddening law”.

Extinction curve

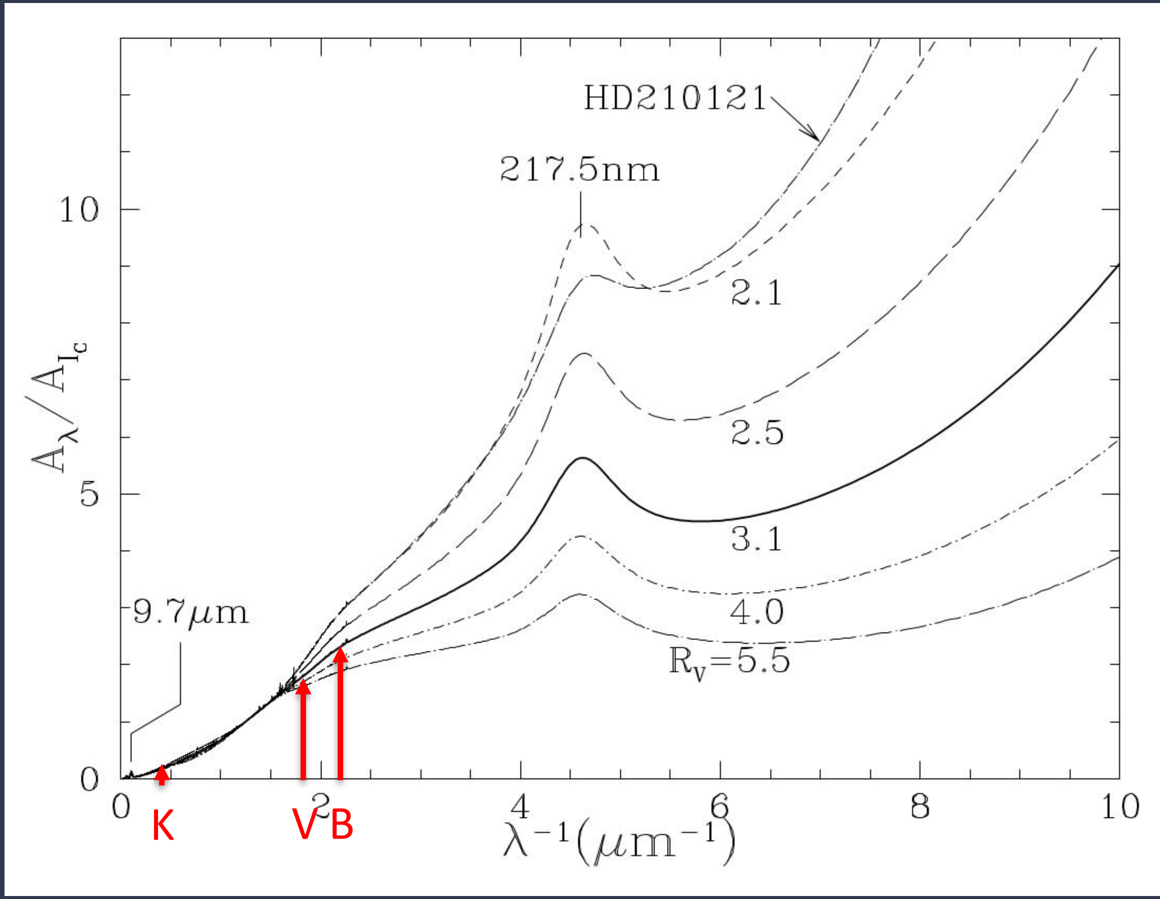


(Draine, Fig. 21.1)

Extinction curves

Extinction curves vary with line-of-sight.

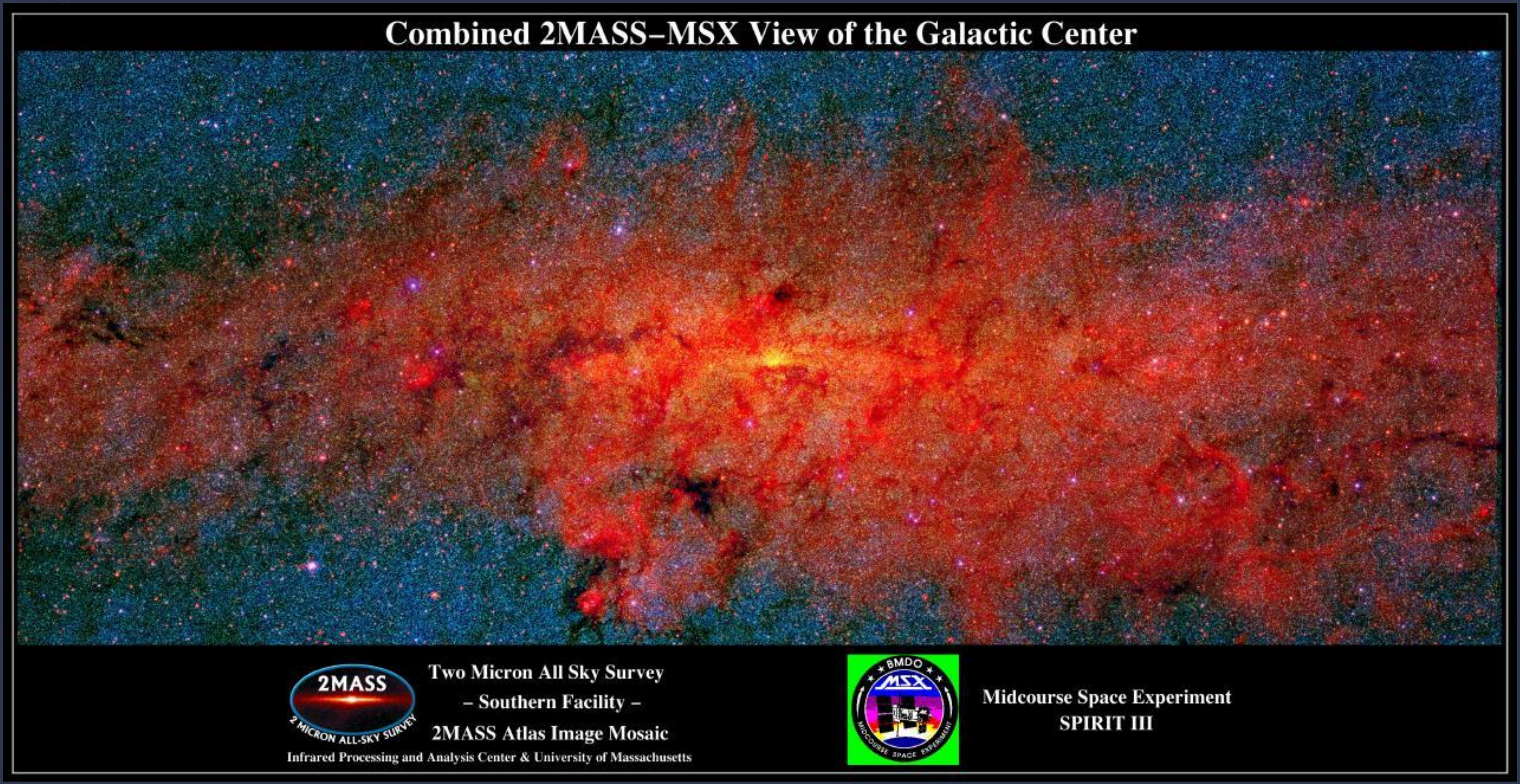
This is parametrized by the reddening parameter R_V (which measures 1/slope of the extinction curve between B and V bands): $R_V = \frac{A_V}{A_B - A_V}$



(Draine, Fig. 21.2)

The "standard" Milky Way extinction curve has R_V = 3.1 and N(H) / $A_V \approx 1.9 \cdot 10^{22}$ cm^{-2} mag^{-1}.

The Galactic Centre observed in *K*-band



$\frac{A_K}{A_V} \approx 0.12$ (see Draine, Table 21.1)

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Cross sections for absorption and scattering

Definitions:

- Absorption cross section at wavelength λ : $C_{\mathrm{abs}}(\lambda)$ [cm^2]
- Scattering cross section at wavelength λ : $C_{\mathrm{sca}}(\lambda)$ [cm^2]
- Extinction cross section at wavelength λ : $C_{\mathrm{ext}}(\lambda) = C_{\mathrm{abs}} + C_{\mathrm{sca}}$ [cm^2]
- Albedo at wavelength λ : $\omega(\lambda) = \dfrac{C_{\mathrm{sca}}}{C_{\mathrm{ext}}}$ ~ 0.5 in the optical

Absorption and scattering efficiencies

In practice we often use efficiencies, which are cross sections normalized by the geometric cross section (of a volume-equivalent sphere):

- Absorption efficiency at wavelength λ : $$Q_{\mathrm{abs}}(\lambda) = \frac{C_{\mathrm{abs}}}{\pi a_{\mathrm{eff}}^2}$$
- Scattering efficiency at wavelength λ : $$Q_{\mathrm{sca}}(\lambda) = \frac{C_{\mathrm{sca}}}{\pi a_{\mathrm{eff}}^2}$$

where a_{eff} (for a grain with volume V) is defined by $$V = \frac{4\pi}{3} a_{\mathrm{eff}}^3$$

How do these depend on intrinsic dust grain properties?
This requires solving Maxwell's equations. Result depends on material (dielectric function), size and shape of grain.

Calculating efficiencies

Three regimes:

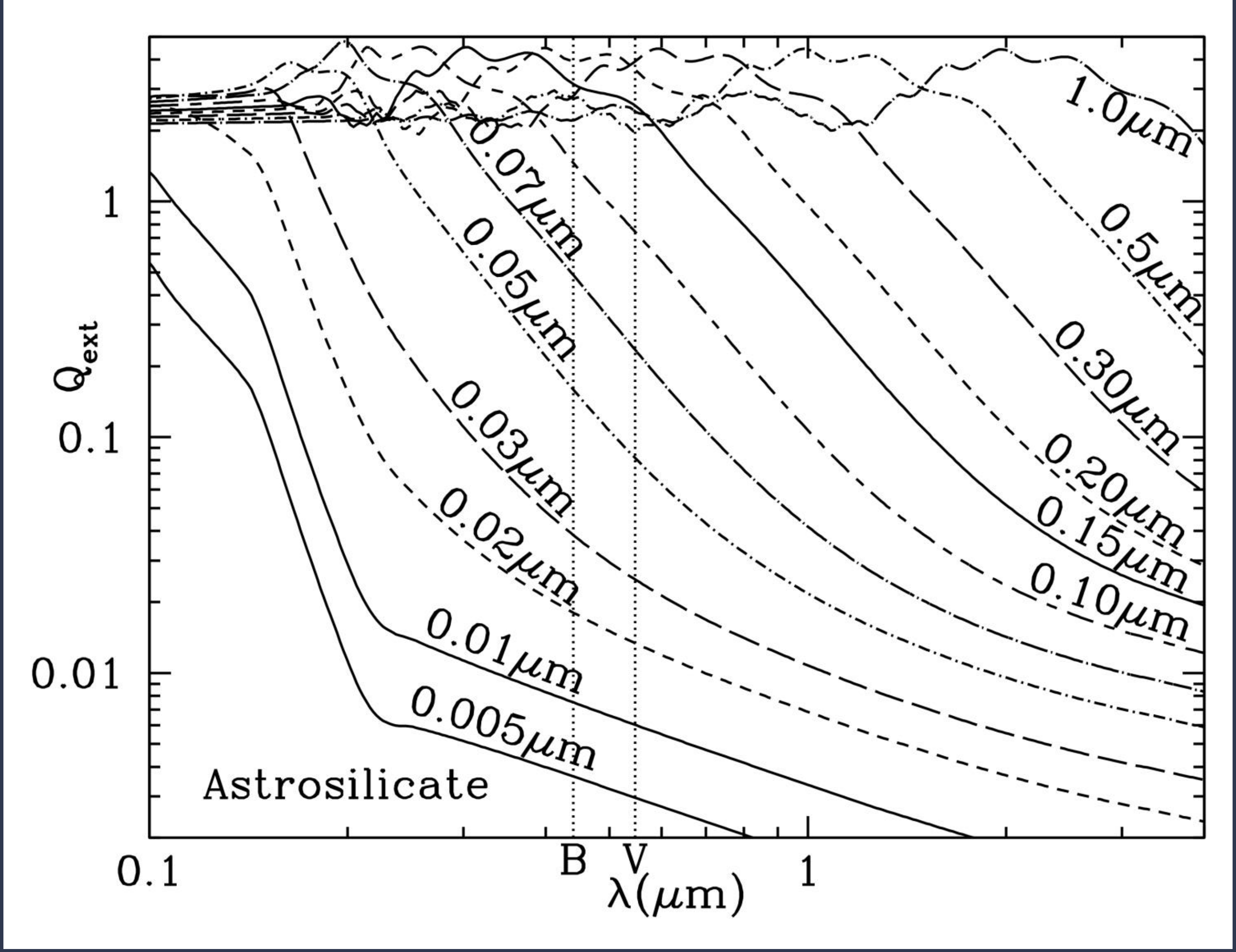
- λ << a (geometric optics regime) : $Q_{\mathrm{abs}}(\lambda) \approx 1$ $Q_{\mathrm{sca}}(\lambda)$ small
  (independent of material)

- λ >> a (Rayleigh scattering) : $C_{\mathrm{abs}}(\lambda) \propto \lambda^{-2}$ $C_{\mathrm{sca}}(\lambda) \propto \lambda^{-4}$
  (independent of material)

  so: 1) at long λ, absorption will dominate.
  2) dust becomes transparent at long λ → reddening

- λ ~ a : Mie theory (Mie 1908), see Draine Sect. 22.5

Extinction efficiencies for different grain radii



(Draine, Fig. 22.7a)

Constraints on dust grain models

- UV-rise of extinction curve: there must be grains with $a \ll \lambda_{UV}$ $\rightarrow a_{min} < 10$ nm

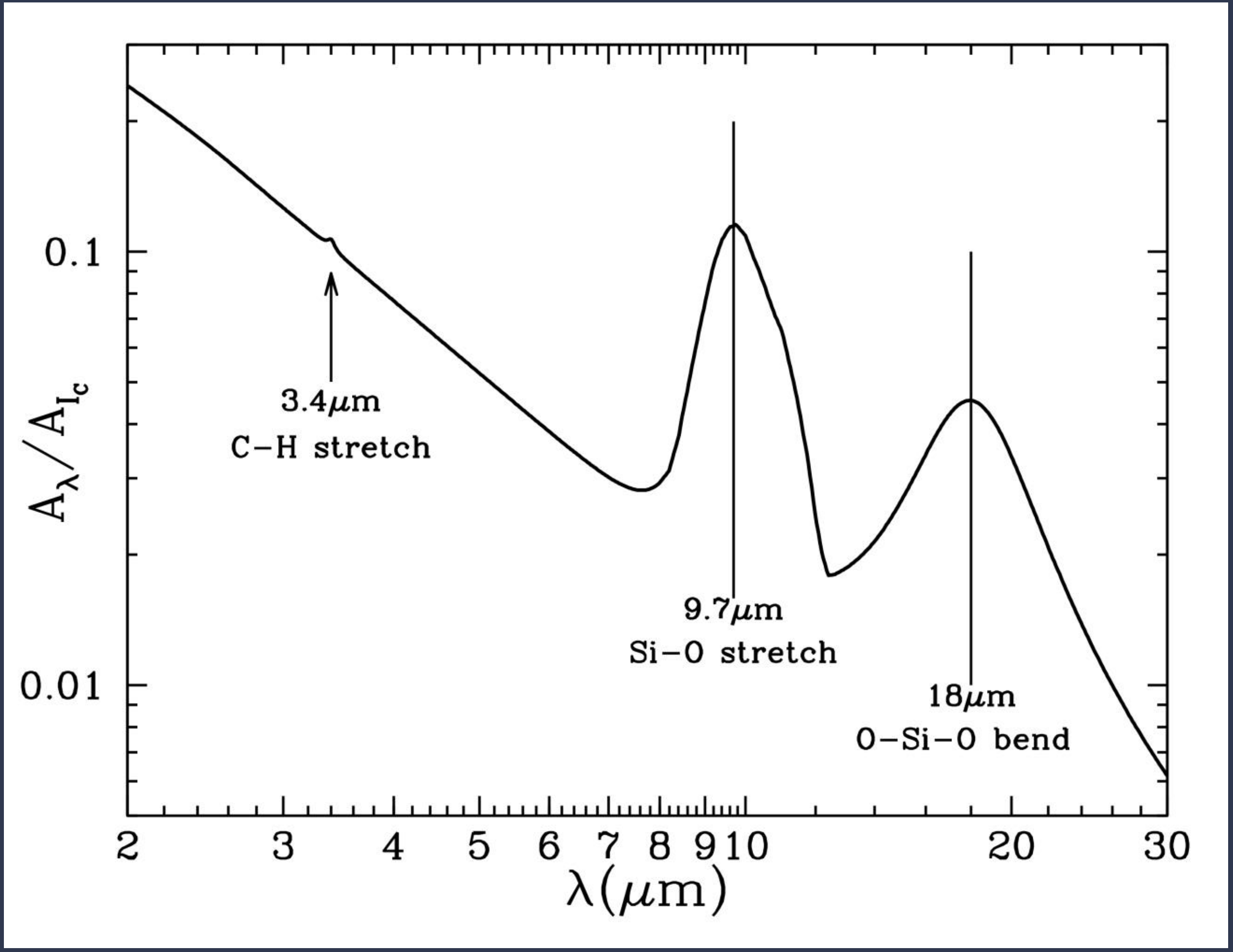
- slope of extinction curve → grain size distribution

- features on the extinction curve → dust composition

- dust mass limit: $M_{dust} < 0.013\, M_{gas}$ (from Milky Way metallicity)

- scattering
- polarization (shapes, material)
- long-wavelength emission

Extinction curve features



(Draine, Fig. 23.2)

Features on the extinction curve require combination of:

- silicate grains
- Carbonaceous grains

Dust models

- Classical model: MRN model (Mathis, Rumpl & Nordsieck 1977): power law size distribution of graphite and silicate grains; in approximately equal number densities *n*

$$\frac{dn}{da} \propto a^{-3.5} \qquad a_{\min} < a < a_{\max}$$

- $a_{max} \approx 0.25$ µm from fit to visual/NIR extinction curve
- $a_{min} \approx 0.005$ µm from fit to UV extinction curve

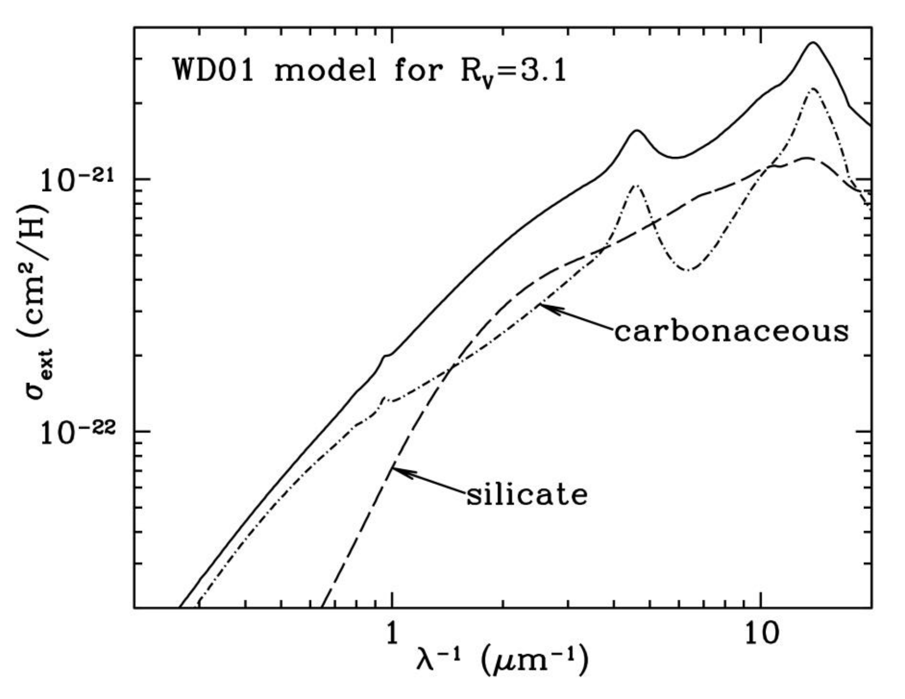
- MRN power law has most mass in large particles, most area in small particles:

$$\int_{a_{\min}}^{a_{\max}} a^3 \frac{dn}{da} da \propto a_{\max}^{0.5} - a_{\min}^{0.5} \qquad \int_{a_{\min}}^{a_{\max}} a^2 \frac{dn}{da} da \propto a_{\min}^{-0.5} - a_{\max}^{-0.5}$$

More recent dust models

A typical Milky Way dust model:

- more complex size distribution than MRN (but broadly similar)
- ~ 2/3 of carbon in carbonaceous grains
- essentially all Mg, Fe, Si and 20% of O in silicate grains: $(Mg,Fe)_2SiO_4$



(Draine, Fig. 23.11b)

Gas/dust ratio: $\frac{M_{gas}}{M_{dust}} \approx 100$

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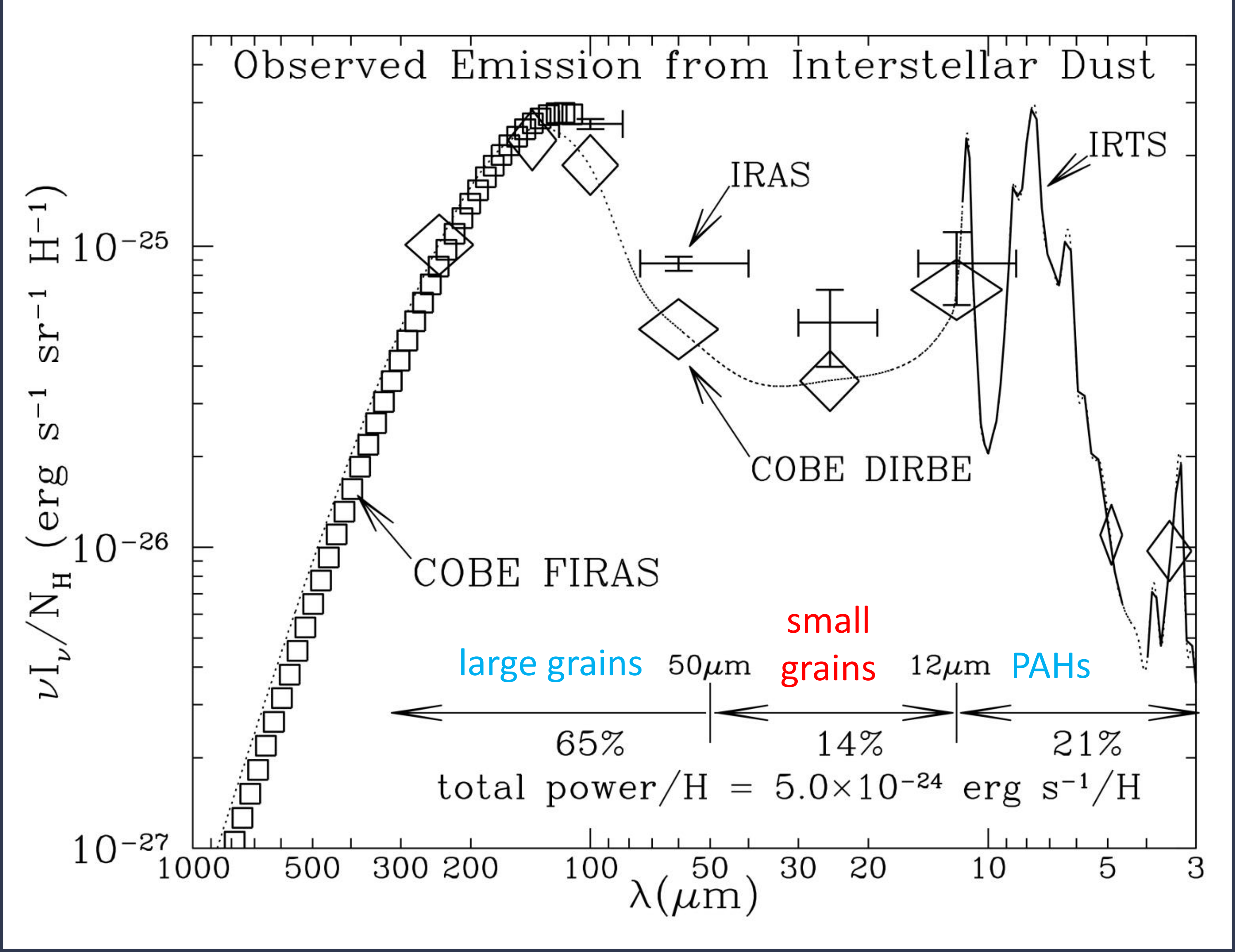
Additional features required by observations

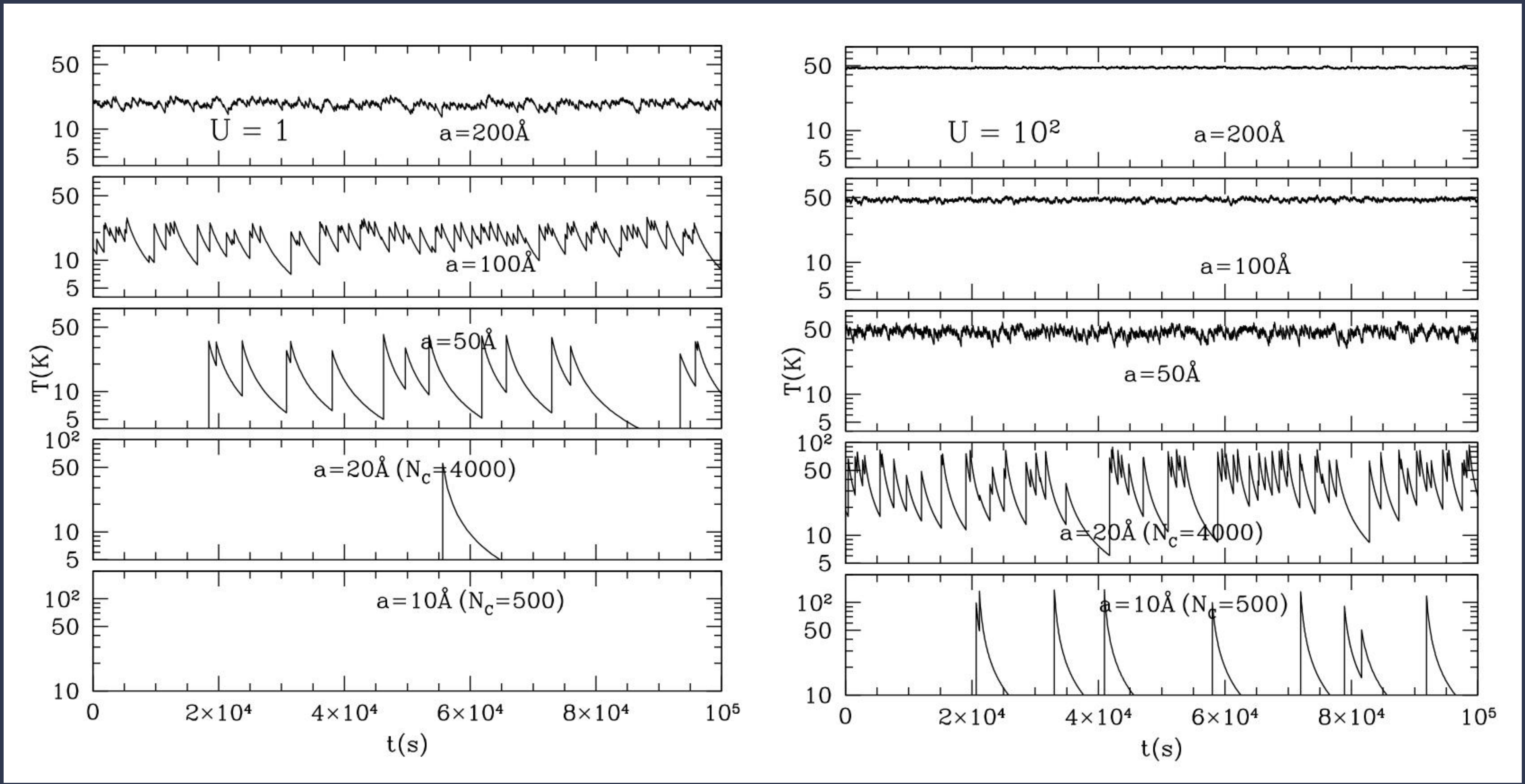
1. Very small dust grains
2. PAHs
3. Ices

Evidence for very small grains



(Draine, Fig. 21.6)

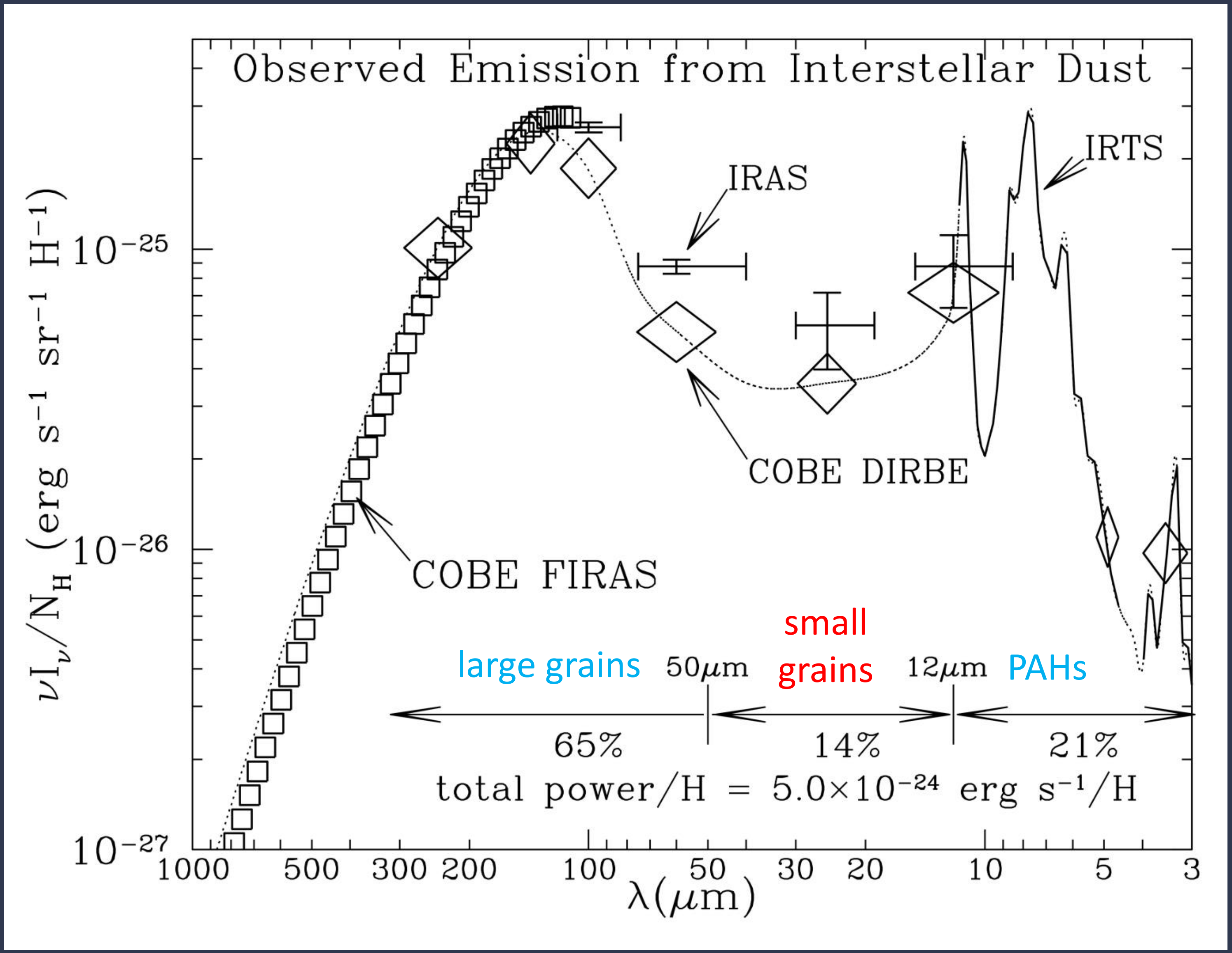
Temperature fluctuations of small grains



(Draine, Fig. 24.5)

≥5% of grain mass must be in very small particles with *a* ~ 5 - 50 Å

Evidence for very small grains



(Draine, Fig. 21.6)

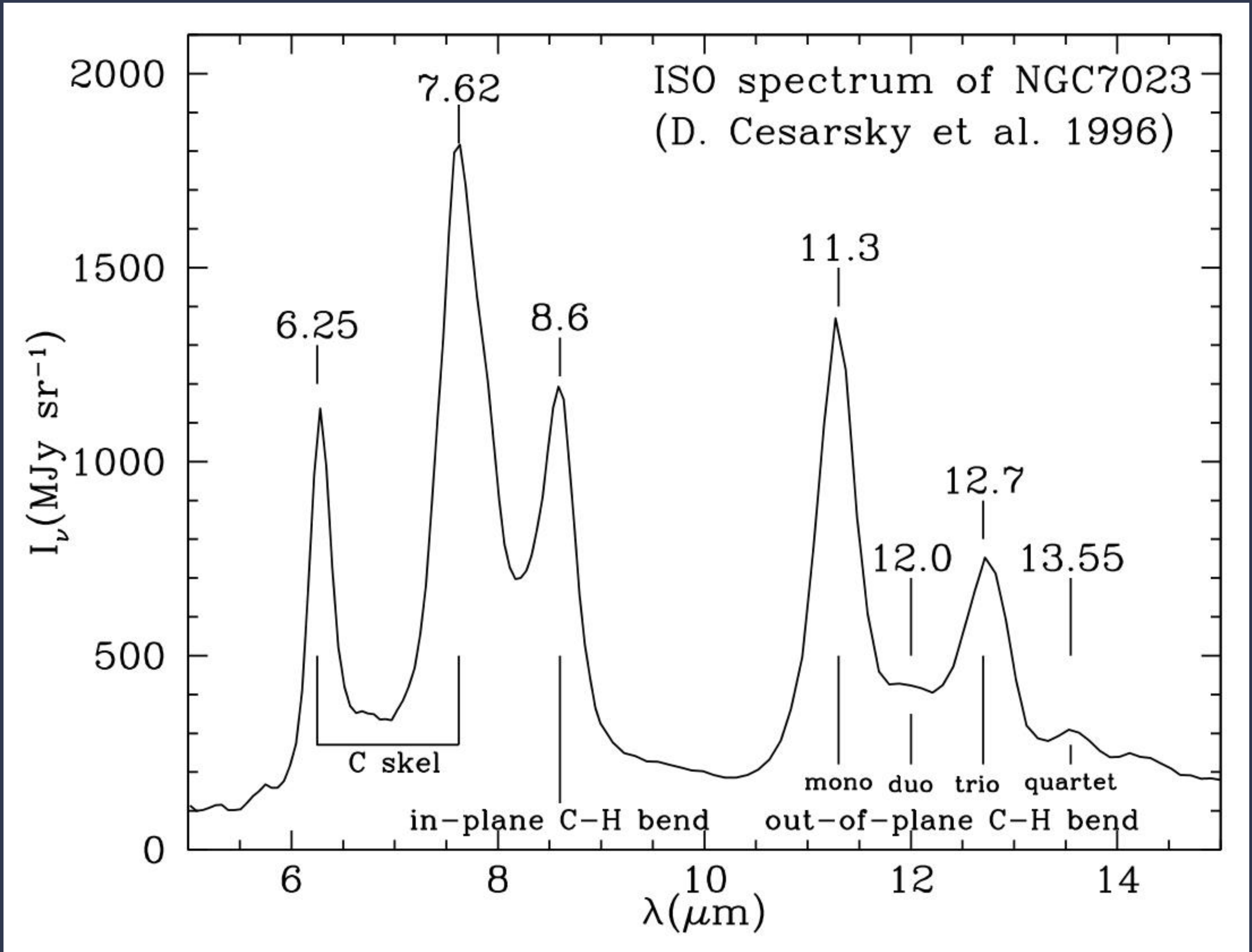
PAHs

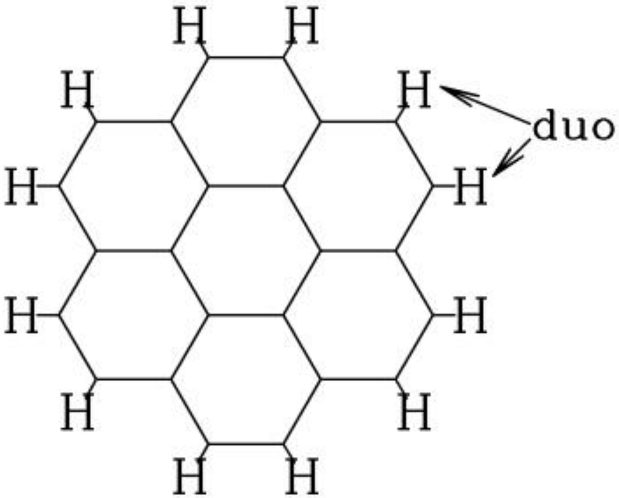
- The smallest "graphite" particles are molecules known as "PAH"s (= Polycyclic Aromatic Hydrocarbons)

- Collections of benzene rings but can also be viewed as fragments of graphite sheets with hydrogen atoms at the edge

- Characteristic emission features at 3.3 μm, 6.2 μm, 7.7 μm, 11.3 μm etc., which have been observed in spectra of reflection nebulae, HII regions, AGB stars, local and high-redshift galaxies

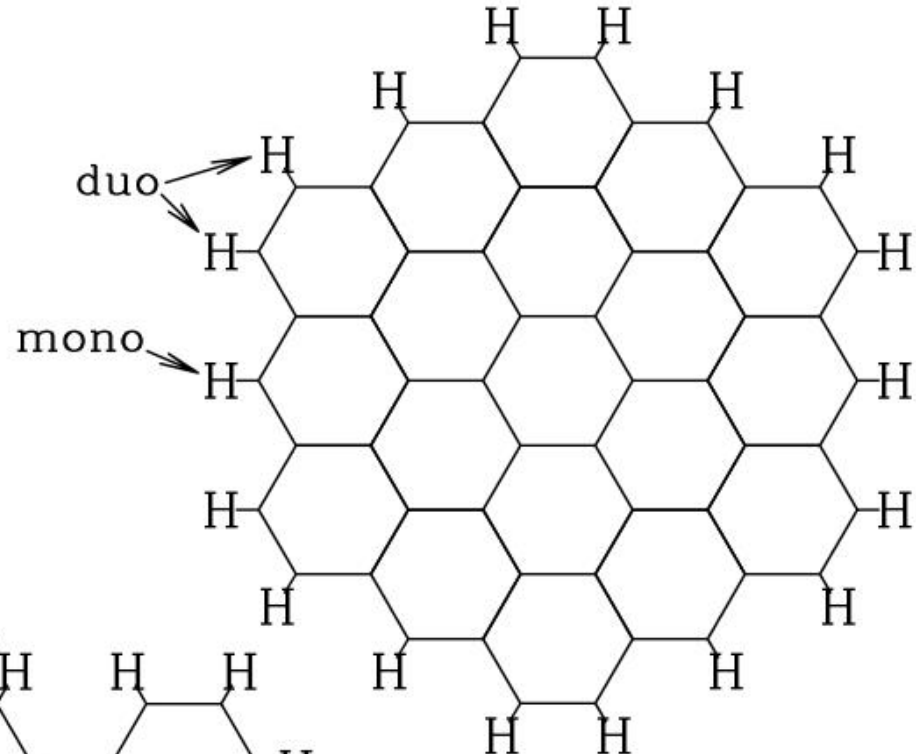
PAH spectrum





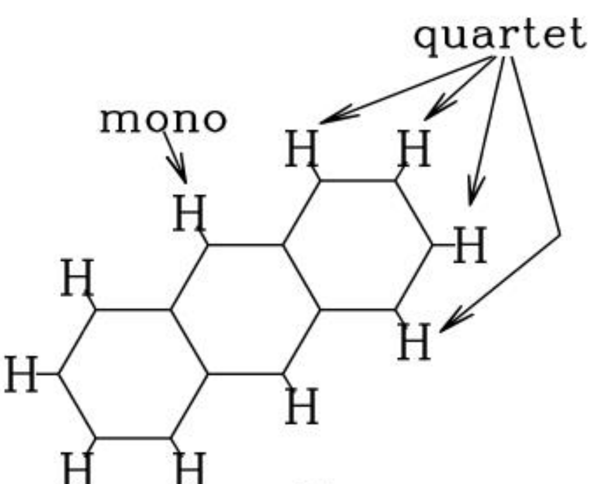
coronene

$C_{24}H_{12}$



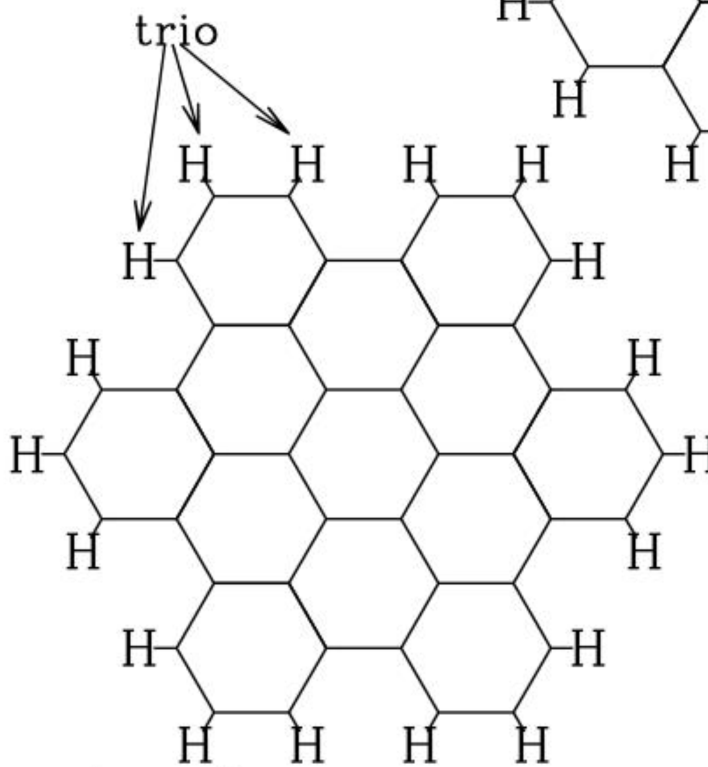
circumcoronene

$C_{54}H_{18}$



anthracene

$C_{14}H_{10}$



hexabenzocoronene

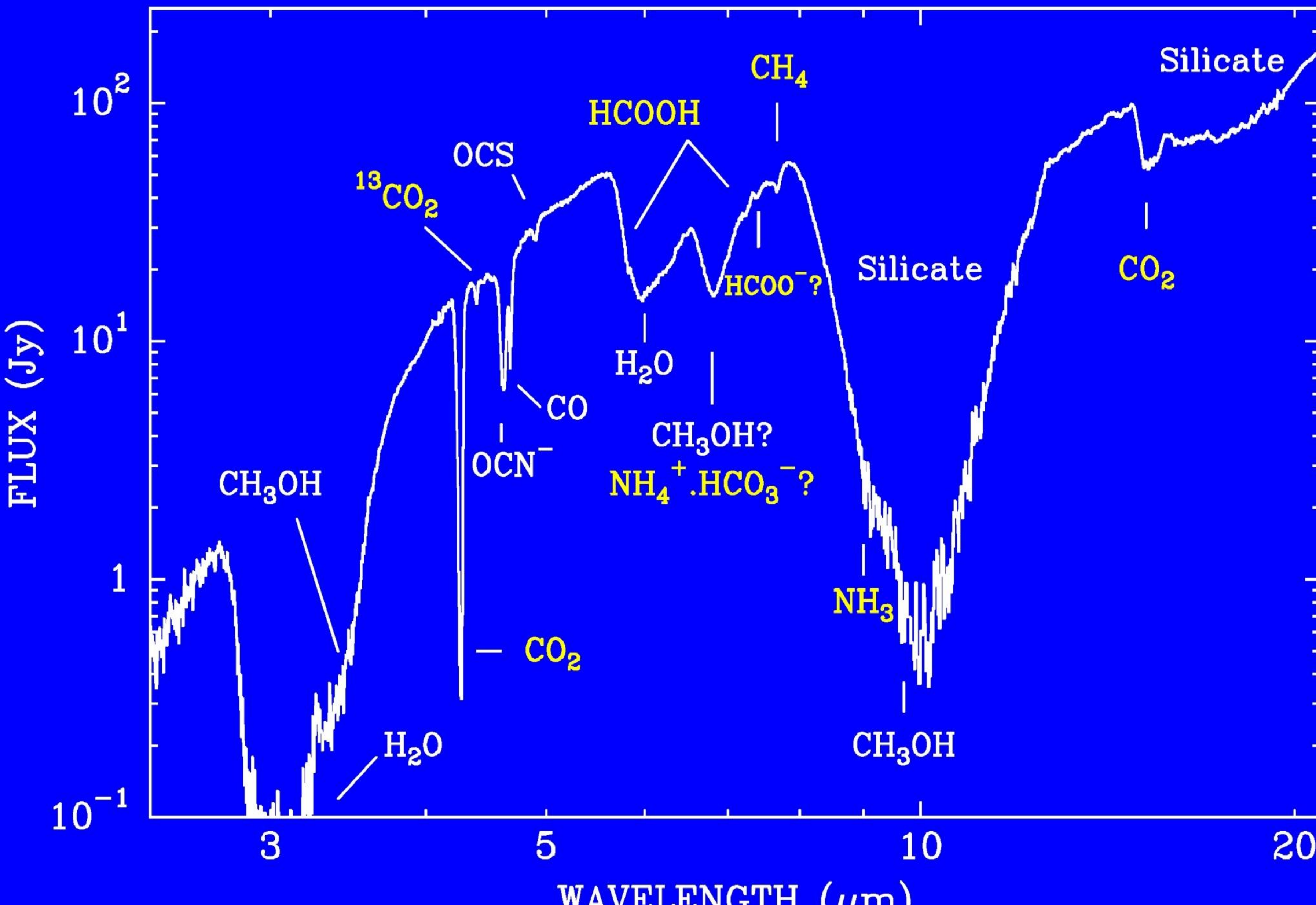
$C_{42}H_{18}$

Some simple PAHs

Ices

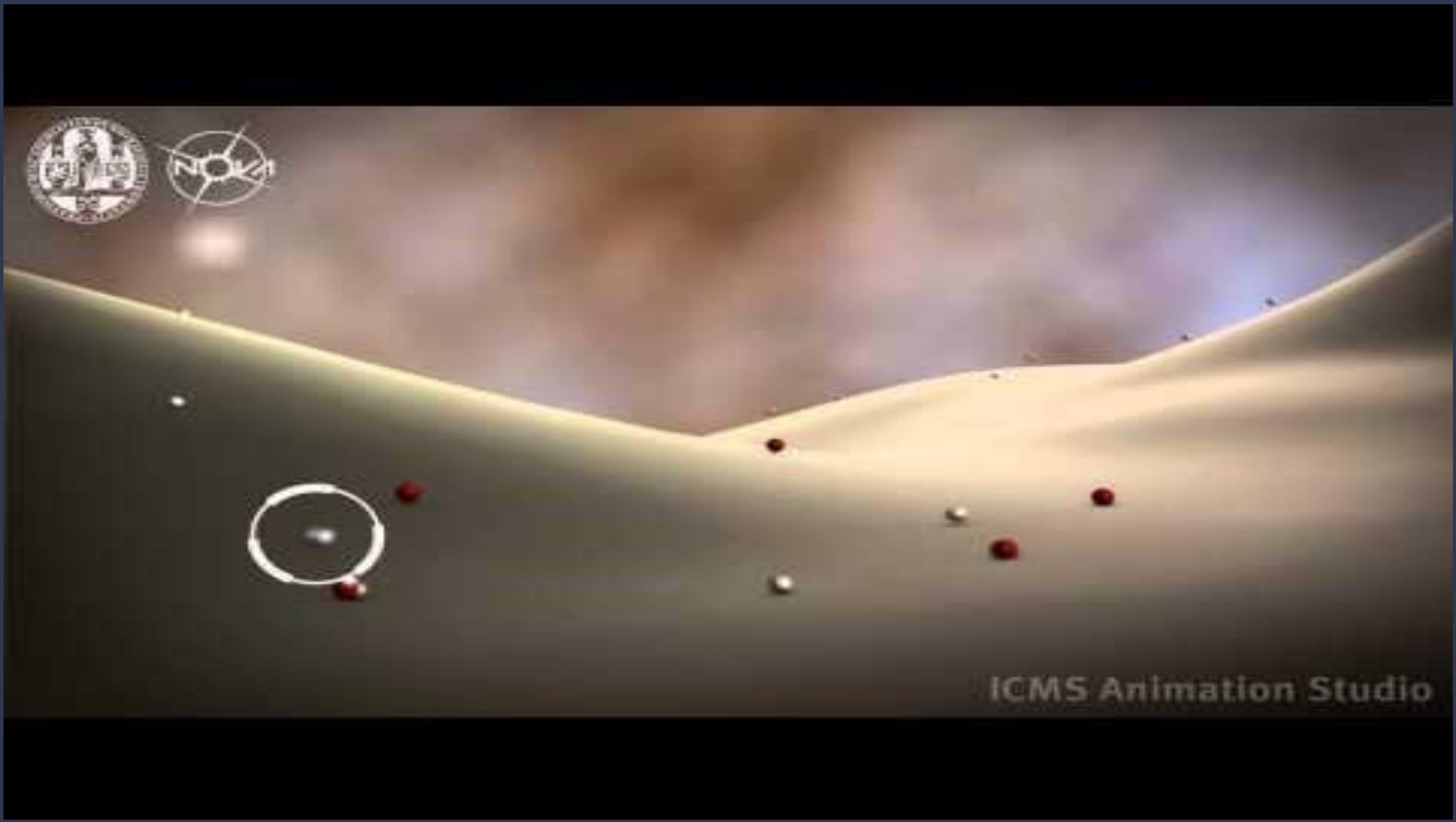
- Grains may acquire mantles of molecular ices consisting of mix of H_2O, CO, CO_2, CH_3OH, …

- This produces absorption bands due to solid-state features in dense clouds towards embedded and background IR sources.



Gibb *et al.*, 2000

Formation of ice mantles on dust grains



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Dust formation and destruction

Formation of dust grains (very poorly understood!):

- envelopes of AGB stars
- supernova explosions
- growth in the ISM

Destruction of dust grains:

- sputtering (abrasion) and shattering in shocks
- consumption by star formation

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Dust heating and cooling

- Heating: photon absorption
  → need expression for attenuation coefficient κ_ν

- Cooling: infrared radiation
  → need expression for emissivity j_ν

Consider grains with number density n_{gr} and radius a
then attenuation coefficient is $\kappa_\nu = n_{\mathrm{gr}} C_{\mathrm{abs}} = n_{\mathrm{gr}} Q_{\mathrm{abs}} \pi a^2$

Then the emissivity follows from Kirchhoff's Law $\frac{j_\nu}{\kappa_\nu} = B_\nu(T_d)$

so $j_\nu = n_{\mathrm{gr}} Q_{\mathrm{abs}} \pi a^2 B_\nu(T_d)$

Calculating the dust temperature

- Energy gain per grain by photon absorption:

$$\left(\frac{dE}{dt}\right)_{\mathrm{abs}} = \frac{1}{n_{\mathrm{gr}}}\iint \kappa_\nu I_\nu \, d\nu \, d\Omega = \iint Q_{\mathrm{abs}}\pi a^2 I_\nu \, d\nu \, d\Omega = \int Q_{\mathrm{abs}}\pi a^2 c u_\nu \, d\nu$$

- Energy loss per grain by infrared emission:

$$\left(\frac{dE}{dt}\right)_{\mathrm{em}} = \frac{1}{n_{\mathrm{gr}}}\iint j_\nu \, d\nu \, d\Omega = 4\pi \int Q_{\mathrm{abs}}\pi a^2 B_\nu(T_d) \, d\nu$$

This must be solved numerically, using $Q_{\mathrm{abs}}(a, \nu,$ material$)$.

The resulting temperature will depend on *a* and material.

Resulting dust temperature

The resulting dust temperature is approximately:

$$T_d \approx 16.4\ \mathrm{K} \left(\frac{a}{0.1\ \mu\mathrm{m}}\right)^{-\frac{1}{15}} \left(\frac{u}{u_{\mathrm{ISRF}}}\right)^{\frac{1}{6}}$$

for silicate grains

$$T_d \approx 22.3\ \mathrm{K} \left(\frac{a}{0.1\ \mu\mathrm{m}}\right)^{-\frac{1}{40}} \left(\frac{u}{u_{\mathrm{ISRF}}}\right)^{\frac{1}{6}}$$

for graphite grains

For calculating the infrared emission spectrum (at fixed radiation field u), we then need to integrate over the grain size distribution and sum over materials.

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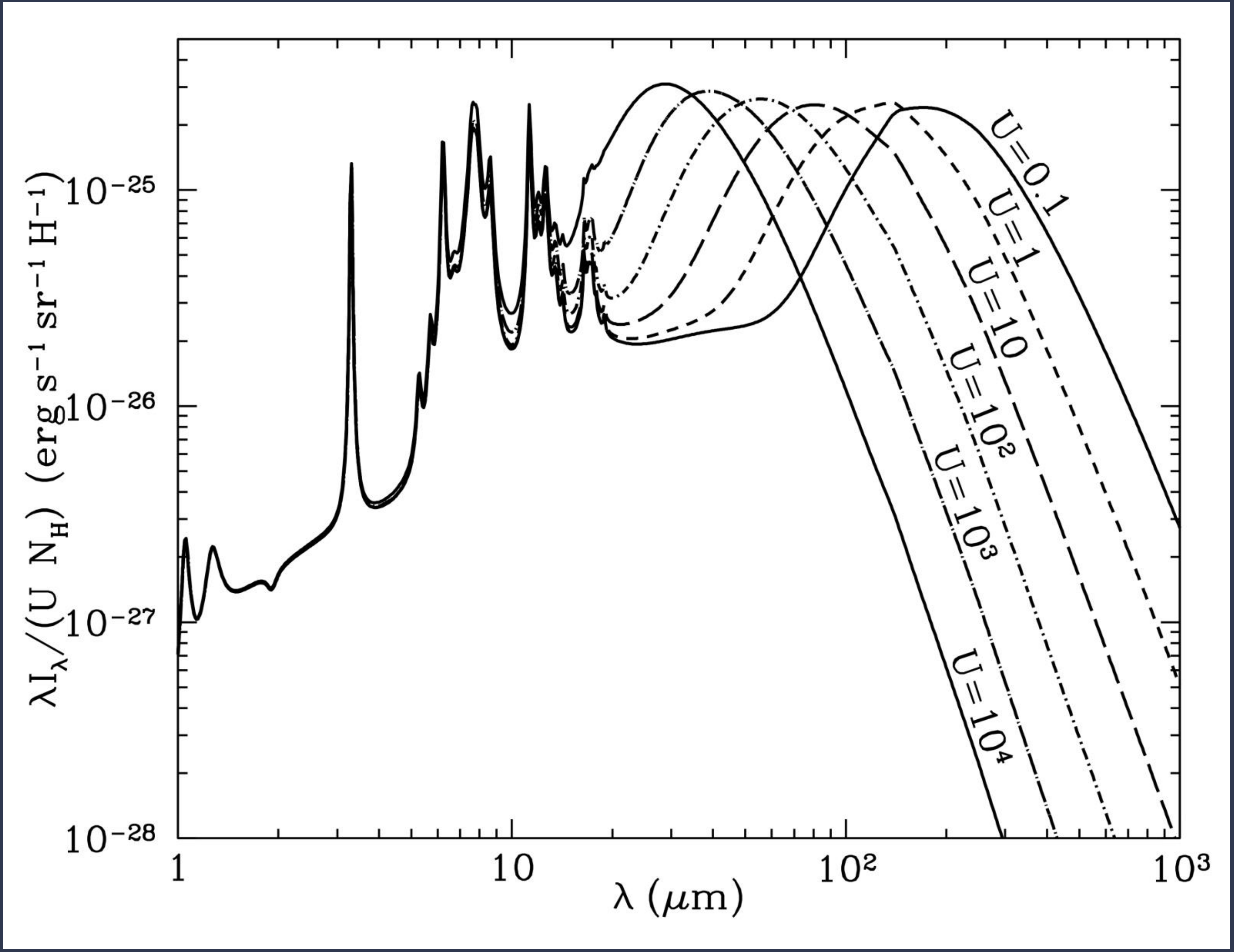
Resulting infrared emission



U = 1:
ISRF

Draine, Fig. 24.7

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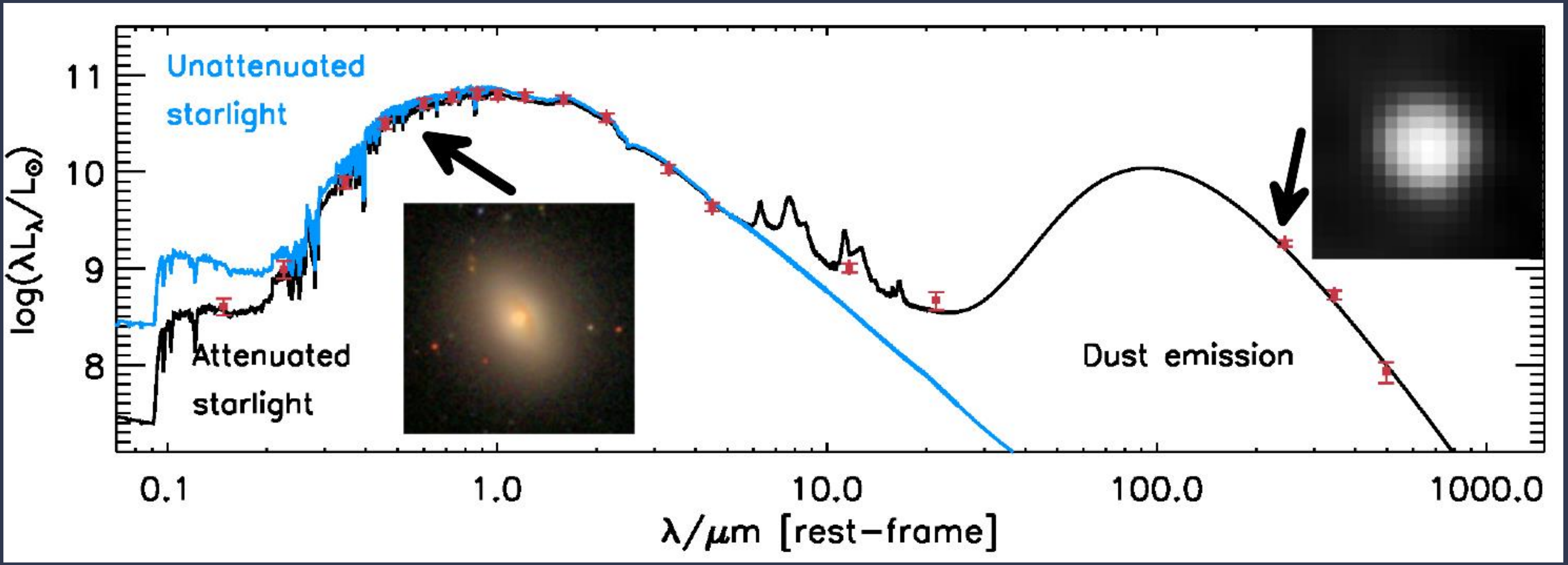

Next lecture

Molecular clouds

- Radiative trapping
- Optically thick molecular emission lines
- Measuring molecular gas mass