# INTERSTELLAR DUST PROPERTIES

## Part 1

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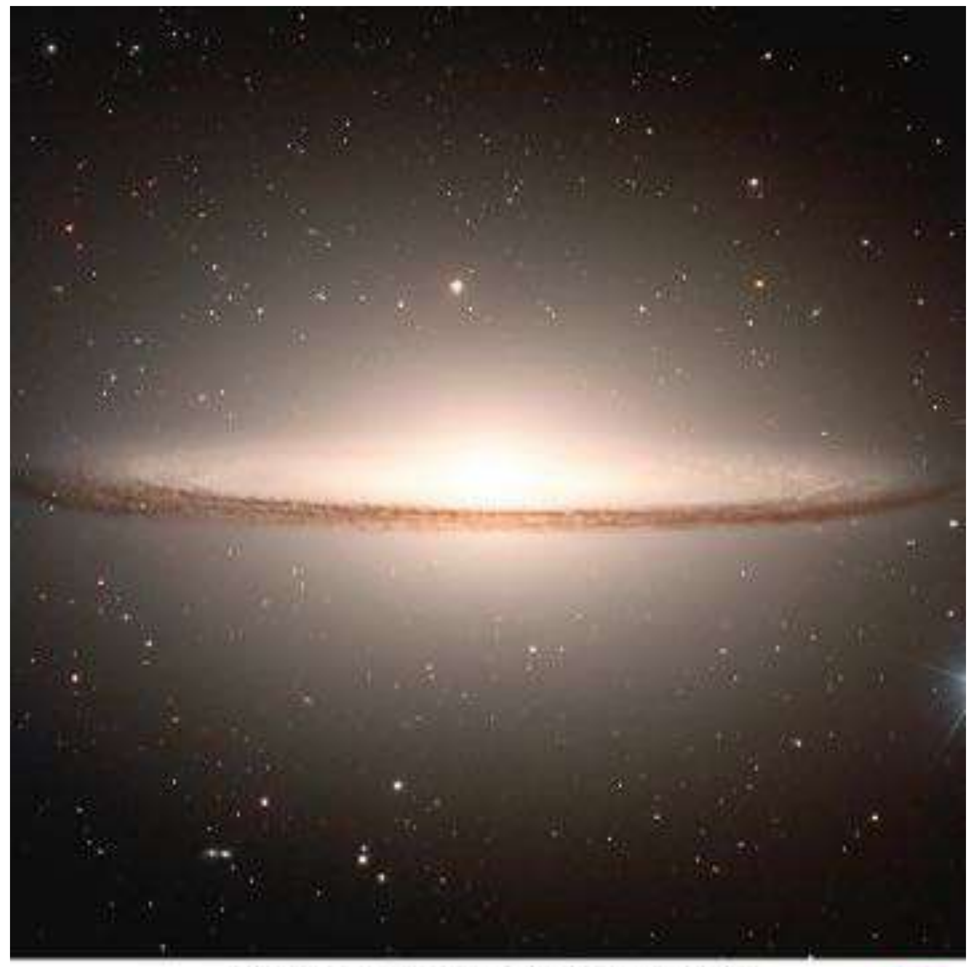
# Outline

- Introduction
- Observational constraints on dust
- Modelling the dust extinction and emission
- Main dust constituents and cosmic dust models
- Dust properties and evolution across the ISM cycle

# Dust is everywhere



The Sombrero Galaxy (VLT ANTU + FORS1)

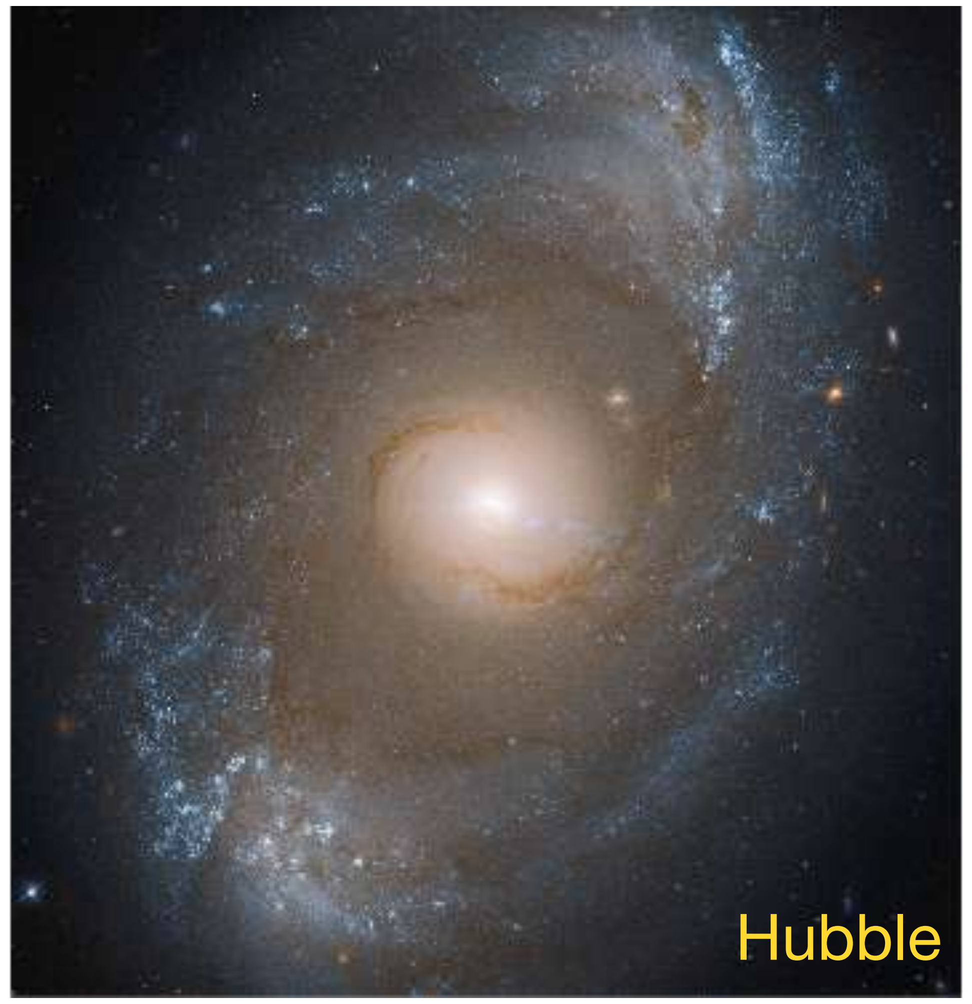
© European Southern Observatory

- Gas and dust represent less than 10% of the Milky Way mass
- Dust represents ~ 1% of this mass

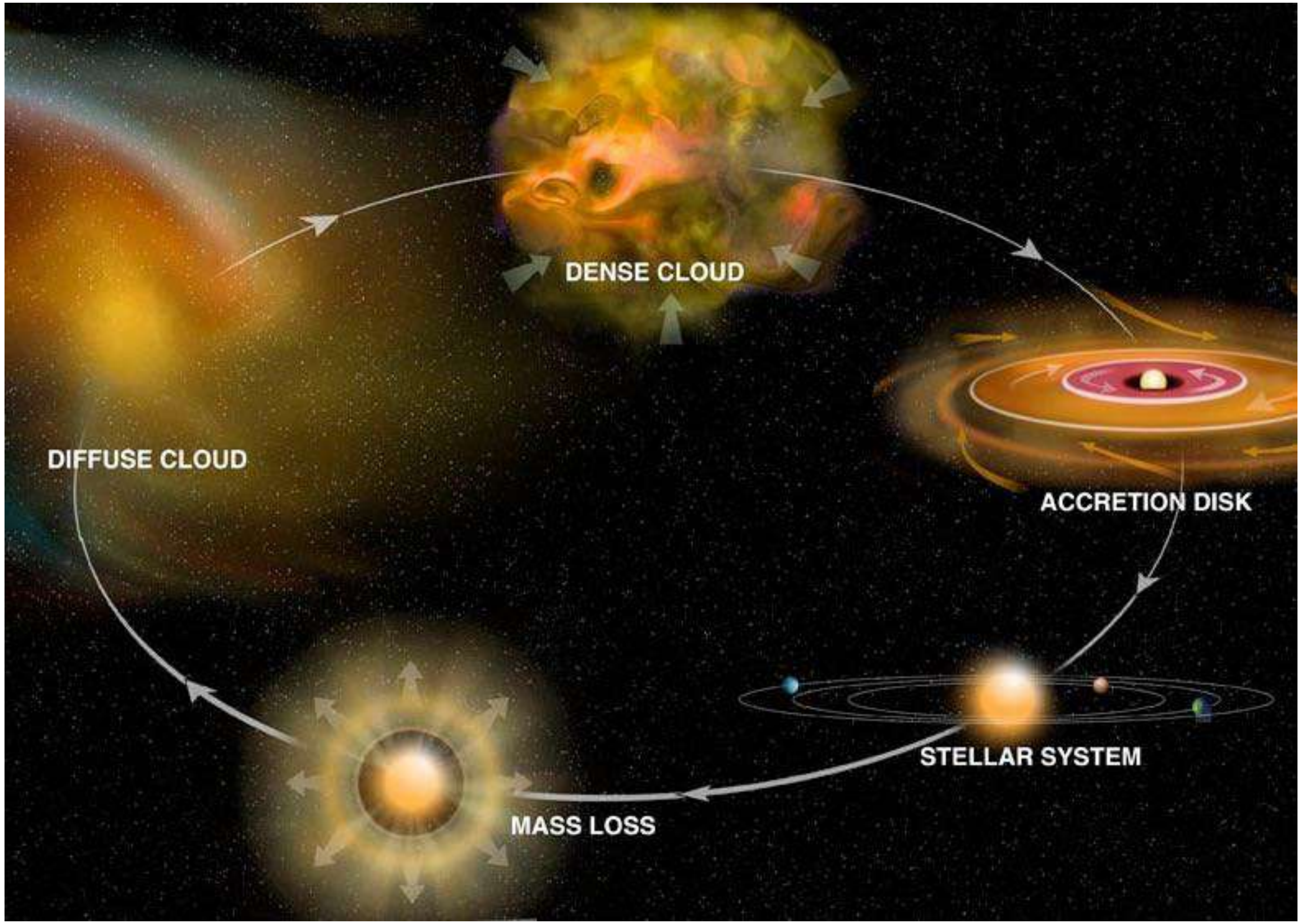
BUT dust

- is everywhere
- is well coupled to the gas
- is a good tracer of matter

- has a fundamental role in the evolution of astrophysical environments and of galaxies



# Dust and the ISM cycle



- The life cycle of the ISM, of stars and dust are intimately related
- Dust is a probe of the physical and chemical conditions of astronomical environments
- Dust is one of the drivers of ISM evolution and hence of galactic evolution
- Dust is key to promote chemical complexity

# How can we determine and study dust properties ?

## Observational constraints :

Extinction
Emission
Polarization
Depletion
Presolar grains

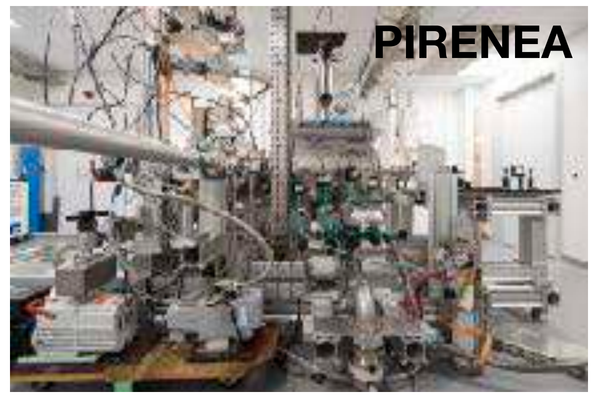
## Experimental data :

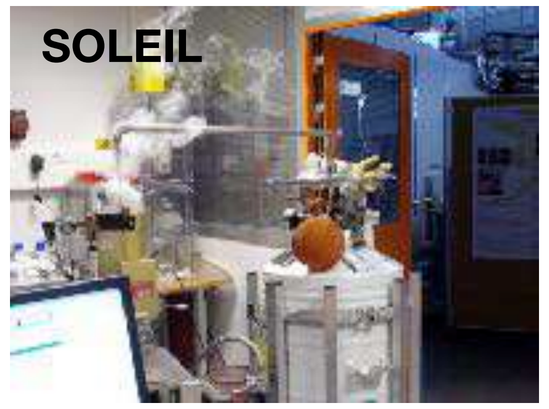
Synthesis of dust analogues
Spectroscopic characterisation
Simulation of chemical and physical processes
Astrophysical conditions

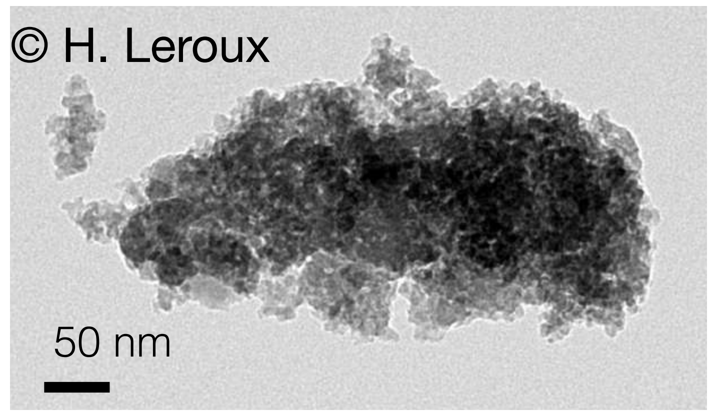
## Modelling :

Cosmic dust models
Radiative transfer codes
Chemical models
MHD simulations

THEMIS





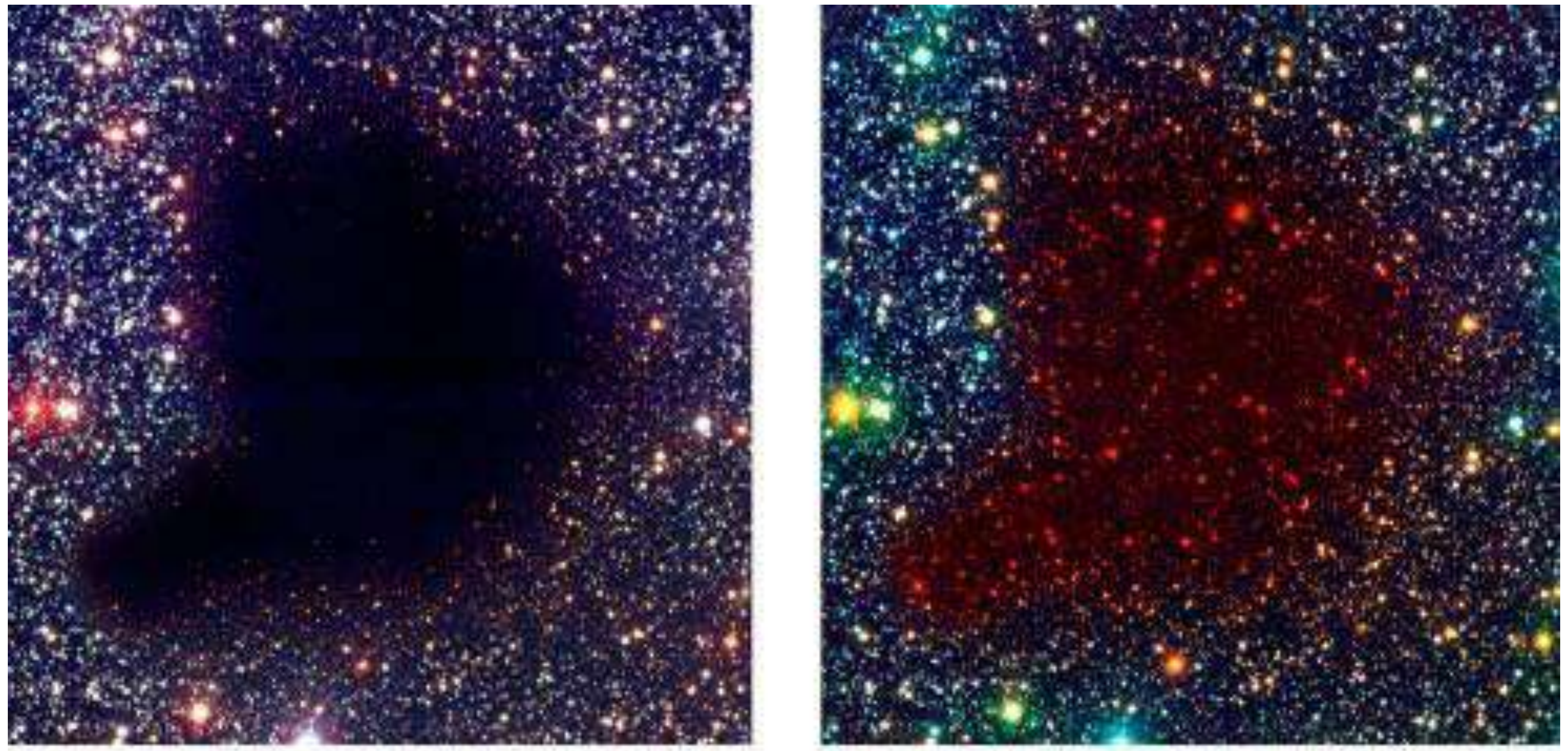


KIDA KINETIC DATABASE FOR ASTROCHEMISTRY

DustEM
Interstellar dust physics

# Observational constraints on dust

# Extinction



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

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

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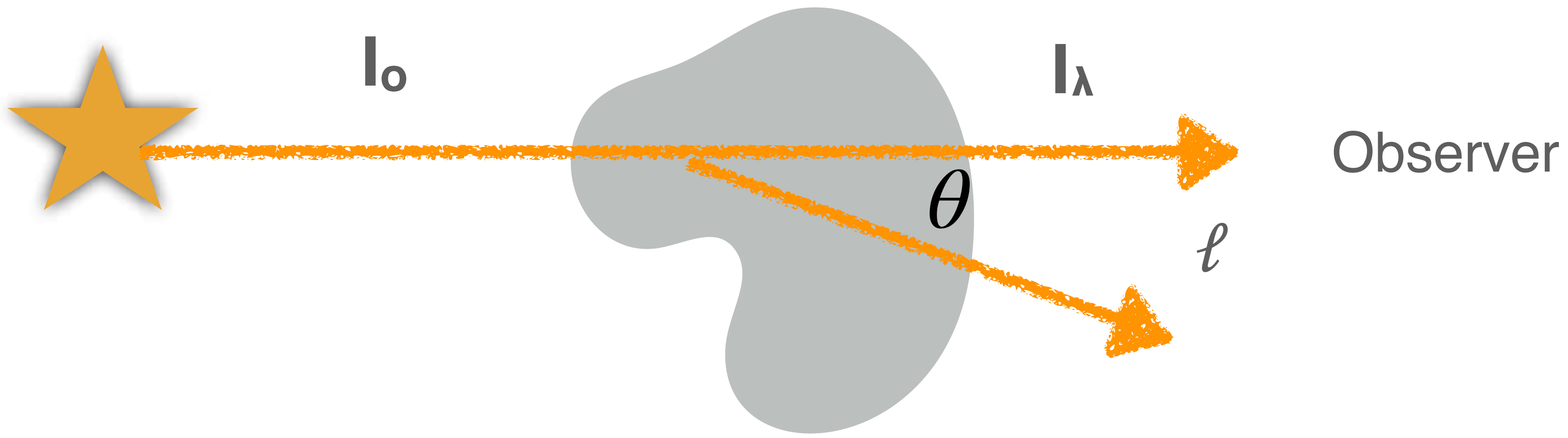
- 1930: Trumpler proposes that matter attenuates the visible light from stars depending on their distance
- 1934 : Stebbins makes the first measures of extinction in the UBV bands
- 1940-50: Stellar reddening by comparison of stars of the same spectral type



$$I_\lambda = I_{\lambda 0} e^{-\tau_\lambda}$$

$$\tau(\lambda) = \int k_{ext}(\lambda) dl$$

$$A_\lambda = -2.5 log_{10}\left(\frac{I_\lambda}{I_{\lambda 0}}\right) = 1.086\tau_\lambda$$

$I_\lambda$ : Specific intensity ($W.m^{-2}.sr^{-1}$)

$k_{ext}$ : Extinction coefficient ($m^{-1}$)

$A_\lambda$ : extinction

$\tau$ : optical depth

# The extinction curve

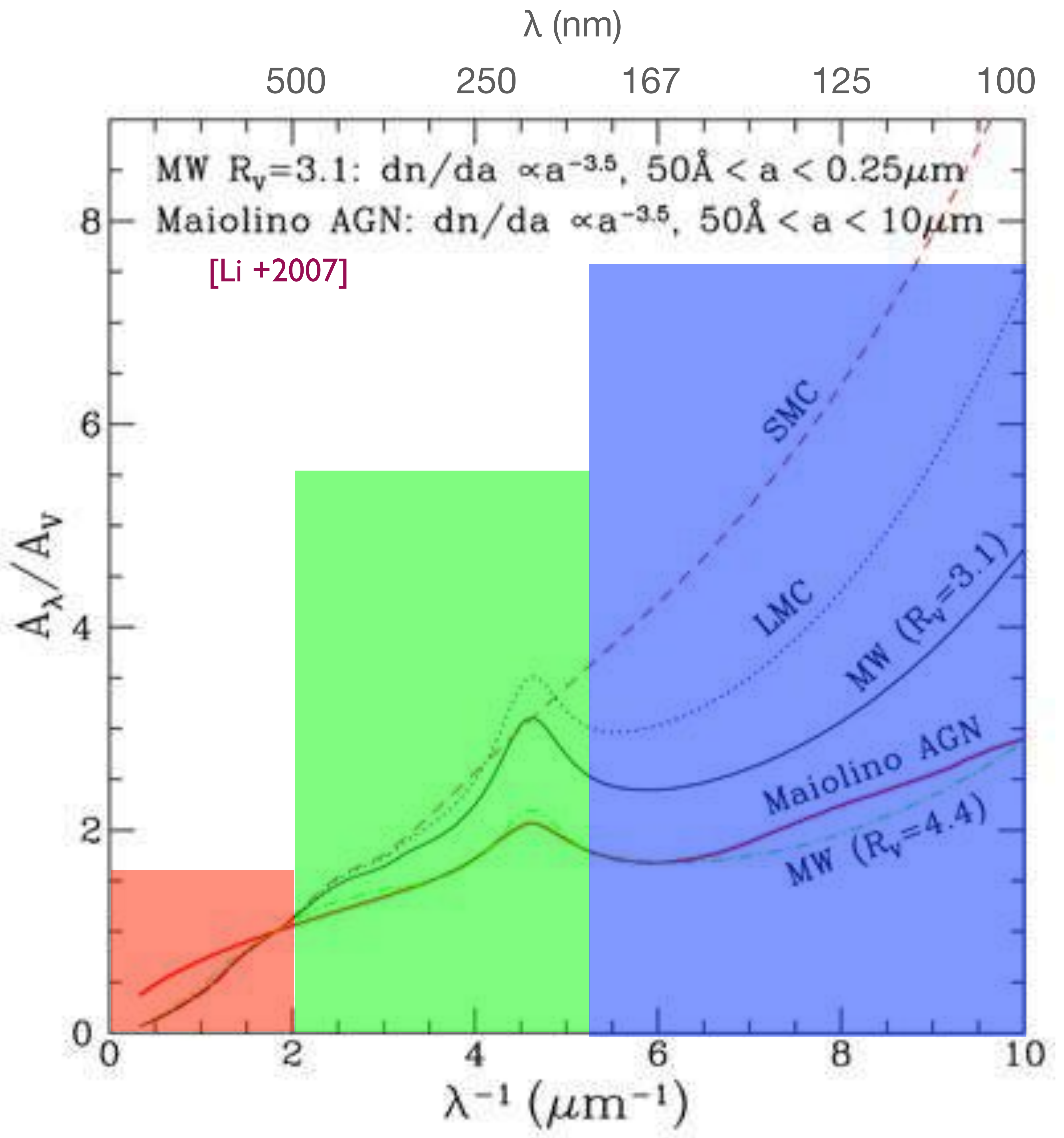
**The extinction curve gives information on the size and composition of grains:**

- UV rise ⇒ grains with radius a ≪$\lambda$ ie. a < 10 nm
- 2175 Å bump ⇒ carbonaceous grains (electronic transition)
- U, B, V bands ⇒ extinction in $\lambda^{-1}$ ⇒ grains with radius a ~ $\lambda$ ie. a ~ 0.1 µm

Color excess: $E(B-V) = A_B - A_V$

Total-to-selective visual extinction ratio: $R_V = \dfrac{A_V}{E(B-V)}$

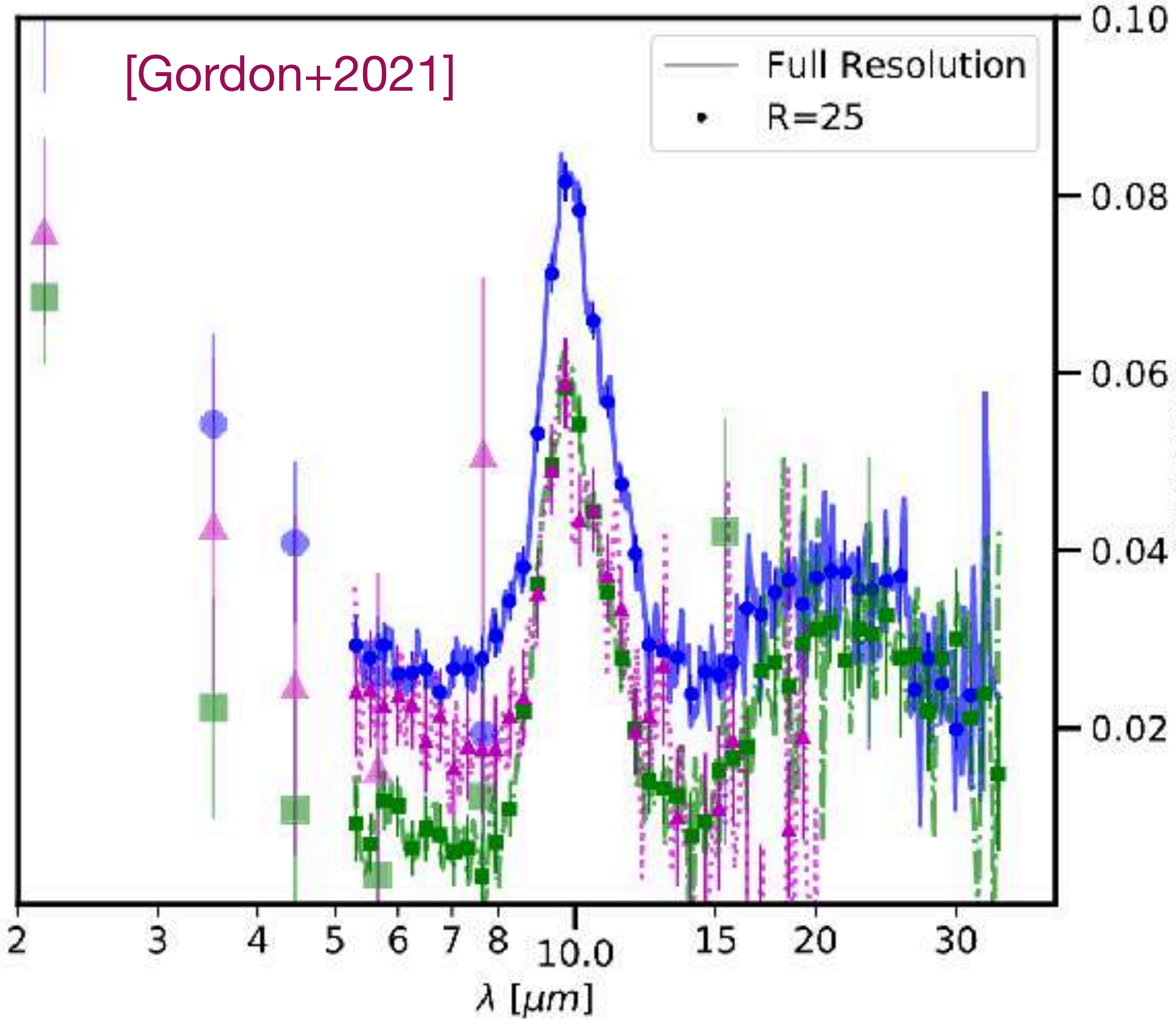
$R_V$ characterise the extinction curve

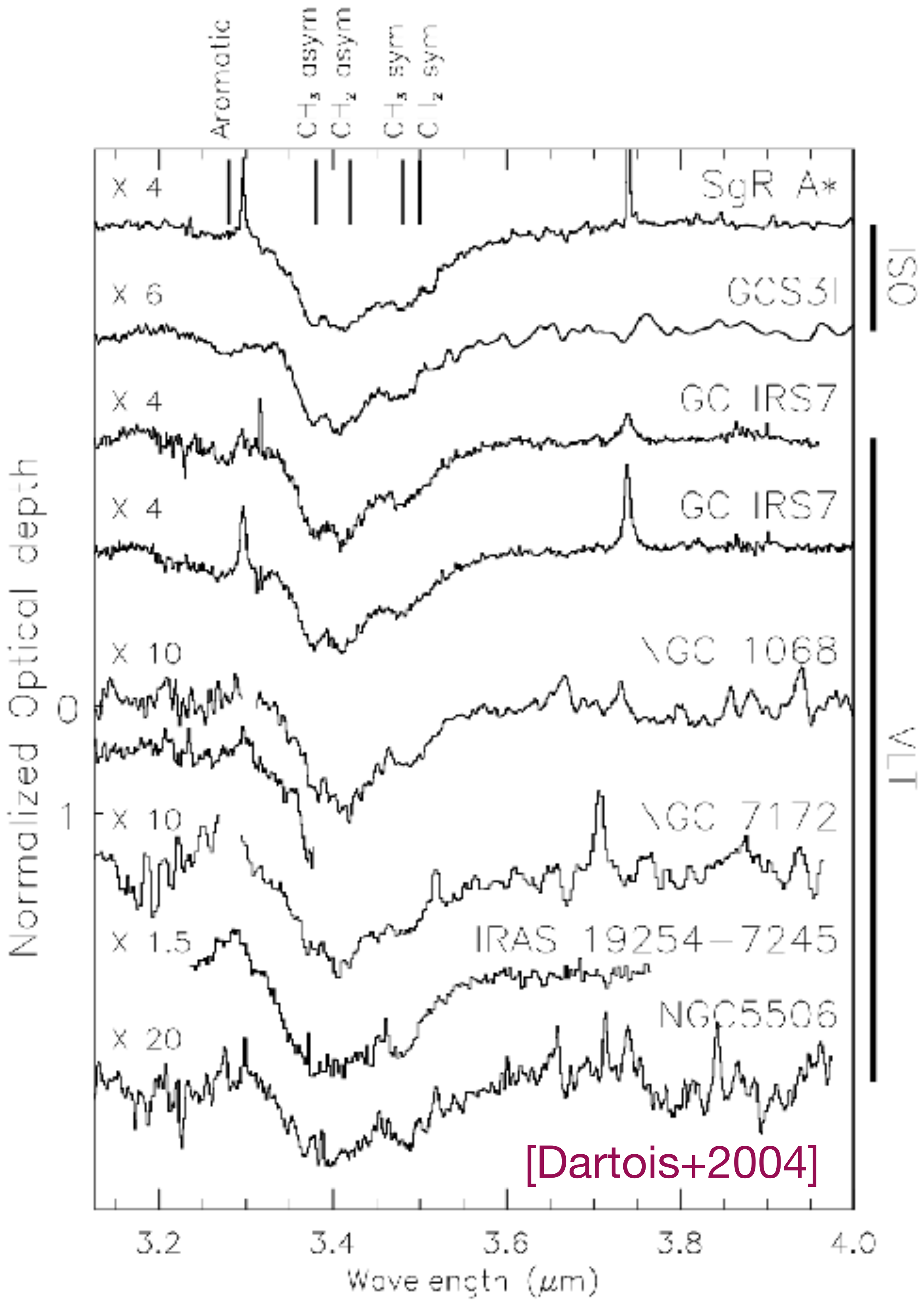


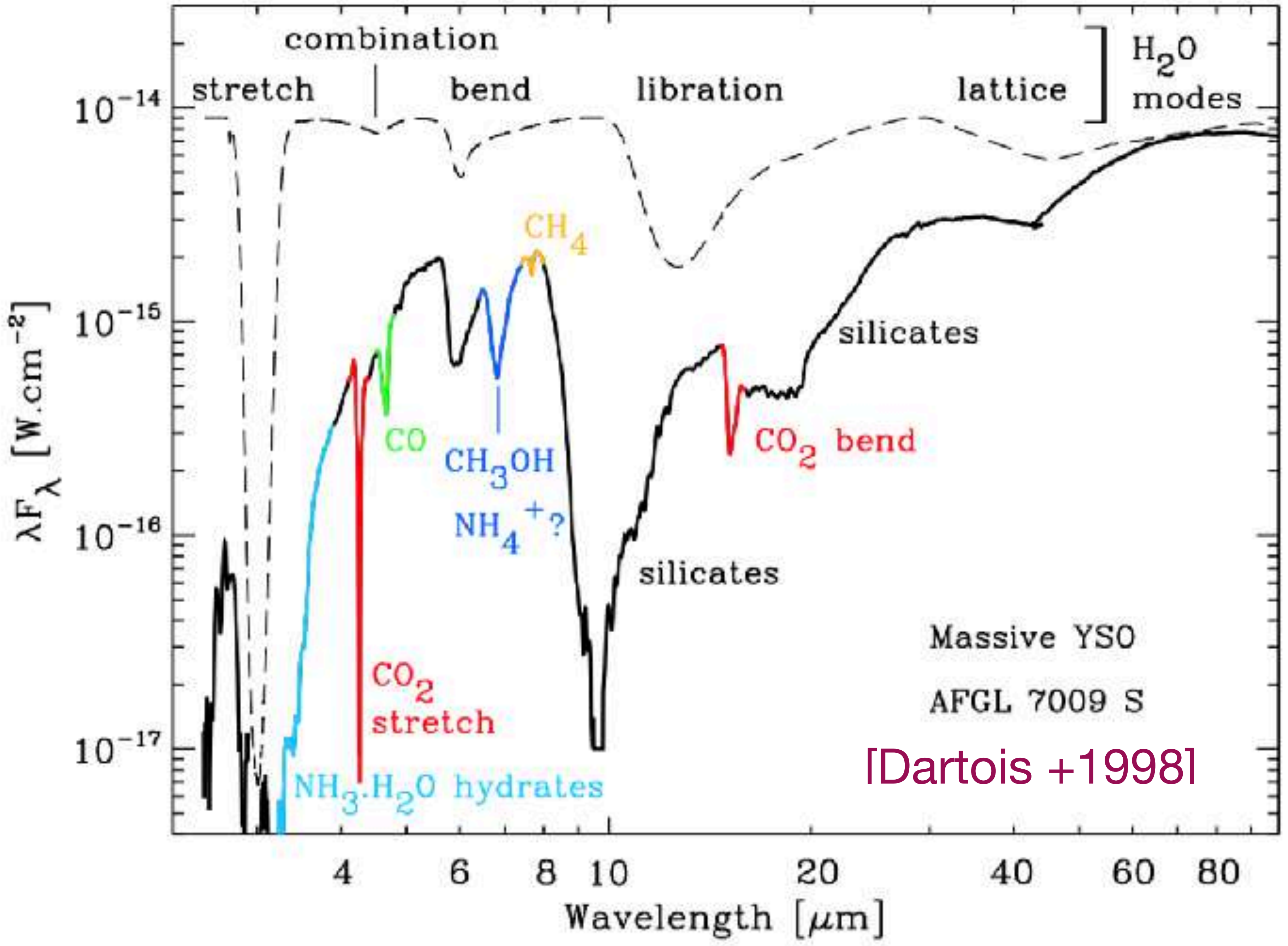
# Extinction in the mid infrared

- MIR domain : vibrational transitions ⇒ grain composition

Spitzer - diffuse and dense ISM


[Gordon+2021]


[Dartois+2004]


[Dartois +1998]

Silicates

Hydrogenated amorphous carbon

Ices

# Scattering

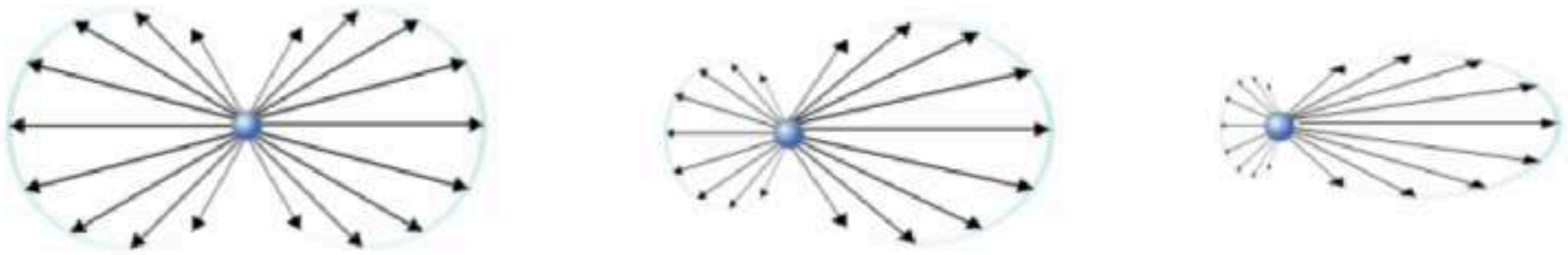
- **Scattering depends on the size, shape and composition of the grains**
- Grains of radius a ~ 0.1 µm scatter light in the visible
- Larger grains scatter light at longer wavelengths, in the NIR

- Scattering depends on the albedo $\omega$ and the phase function g

$$\omega = Q_{sca}/Q_{ext}$$

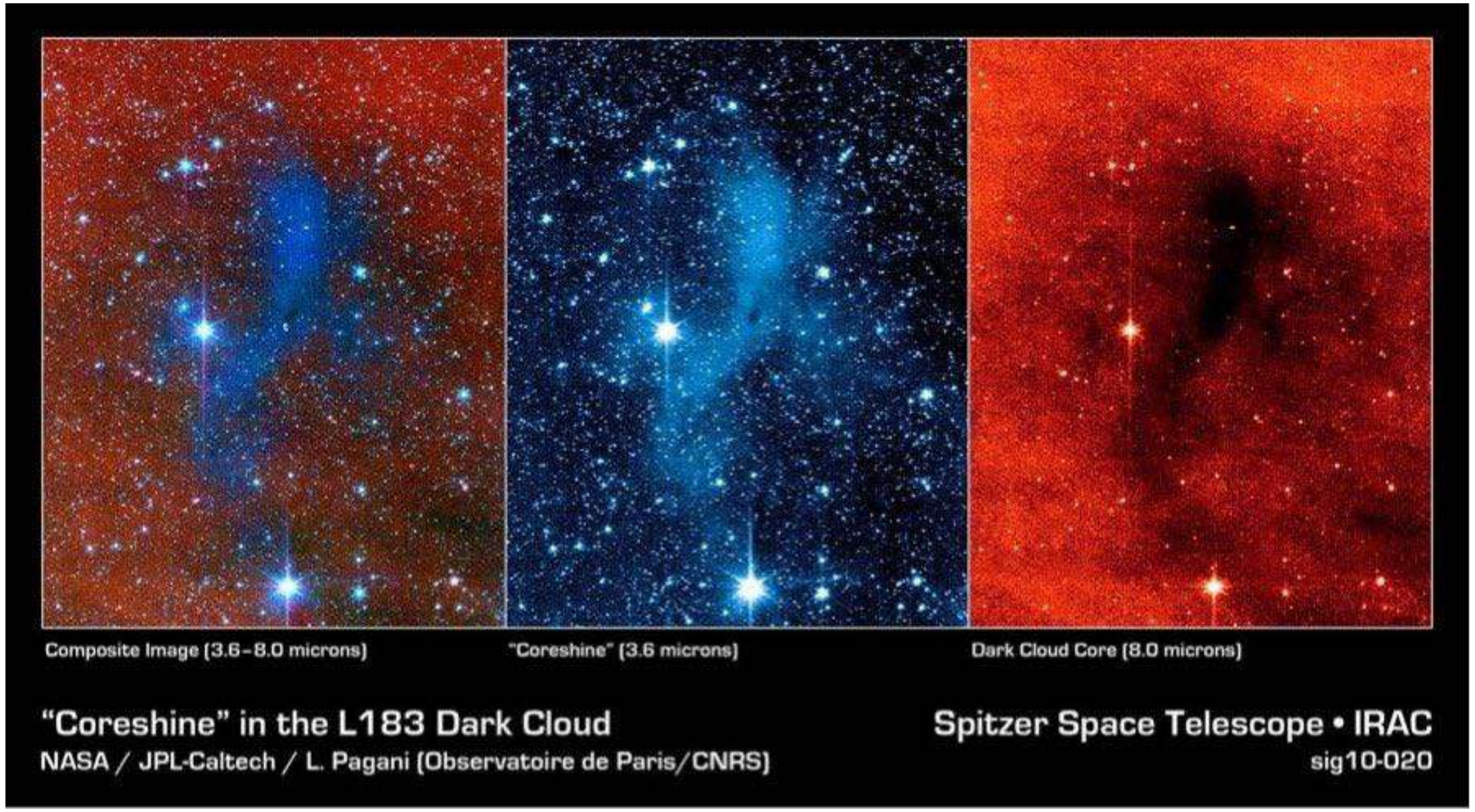
$$g = < cos(\theta) > = \frac{\int_0^\pi I(\theta)cos(\theta)d\Omega}{I(\theta)d\Omega}$$

Rayleigh and Mie scattering phase function



$\frac{2\pi a}{\lambda} \ll 1$ $\frac{2\pi a}{\lambda} \approx 1$ $\frac{2\pi a}{\lambda} \gg 1$

Crédit : Sharayanan CC-BY-SA



Composite Image (3.6–8.0 microns) "Coreshine" (3.6 microns) Dark Cloud Core (8.0 microns)

"Coreshine" in the L183 Dark Cloud

NASA / JPL-Caltech / L. Pagani (Observatoire de Paris/CNRS)

Spitzer Space Telescope • IRAC

sig10-020

# Emission

On a given line of sight, dust emission depends on:

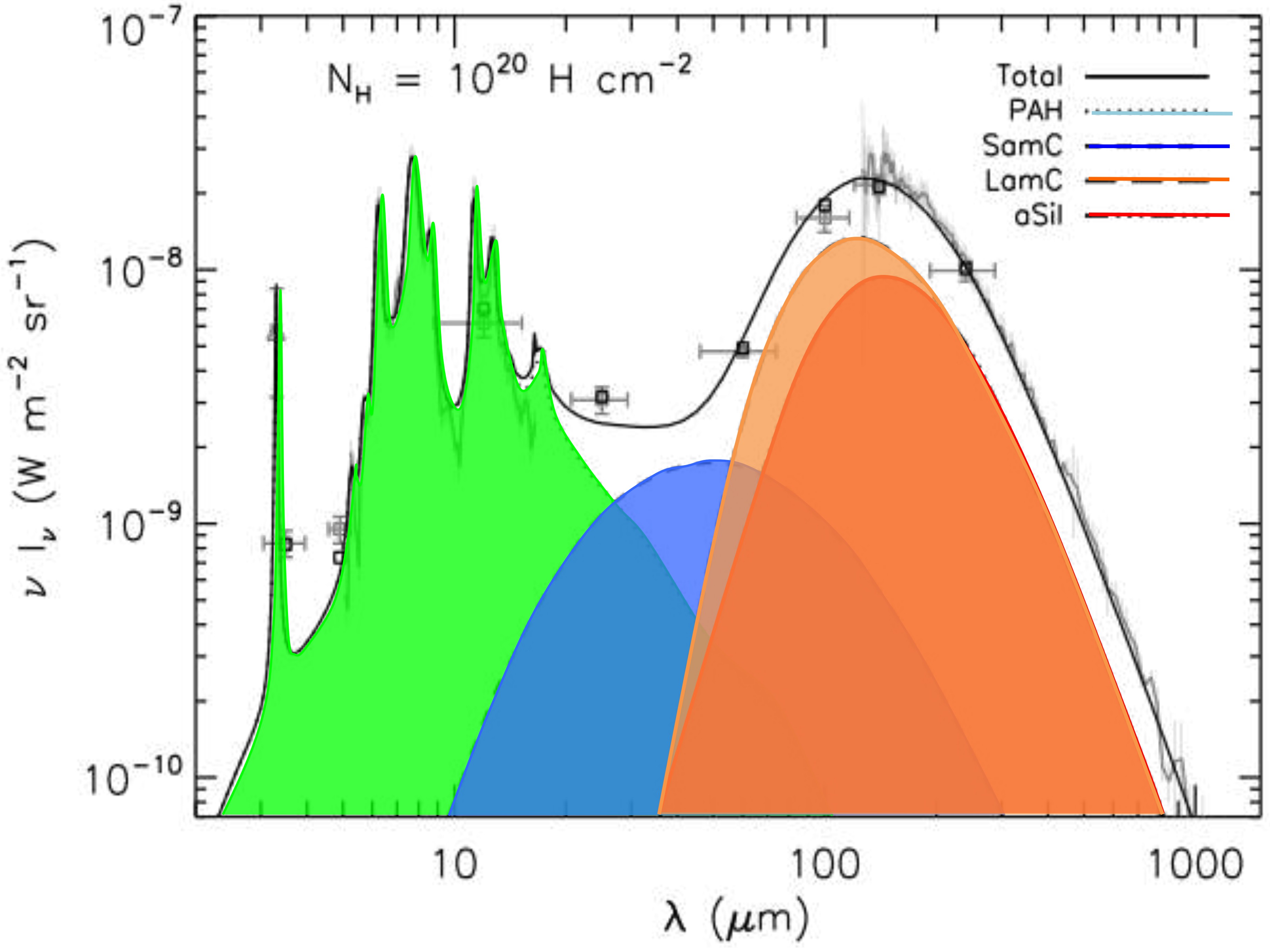
$$I_\nu \propto \int_{LOS} \epsilon \times N_H \times X_d \times ISRF$$

$N_H$ (cm$^{-2}$) : gas column density
$X_d$ : dust abundance
Intensity of the ISRF
$\epsilon$ (erg.s$^{-1}$.sr$^{-1}$.cm$^{-1}$.g$^{-1}$) : dust emissivity

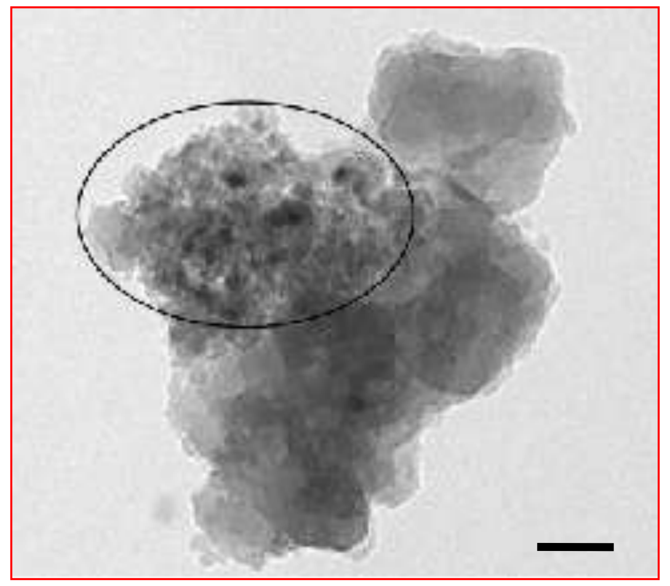
- Kirchoff law ⇒ at thermal equilibrium, emitted power = absorbed power $\Longleftrightarrow$ $\kappa_{abs} \propto \epsilon$

*Different emission mechanisms depending on the grain size and nature*

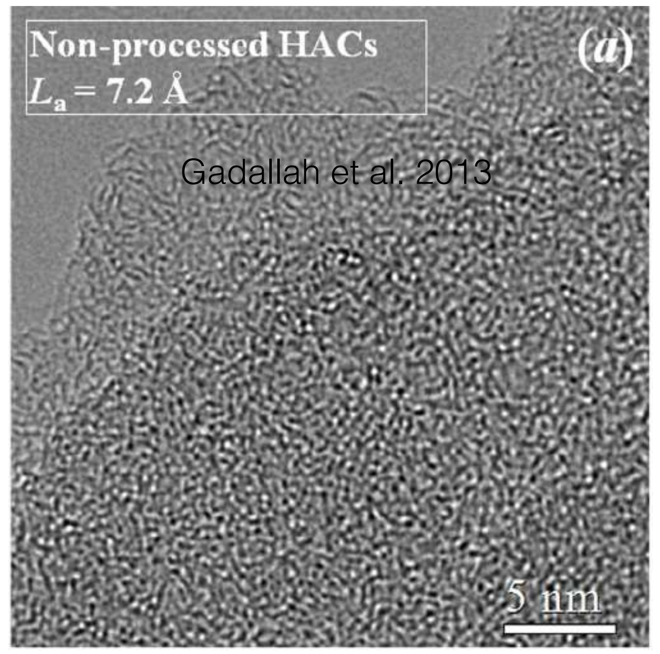
Diffuse ISM emission: [Compiègne+2011]



**SILICATES**
**10-300 nm**

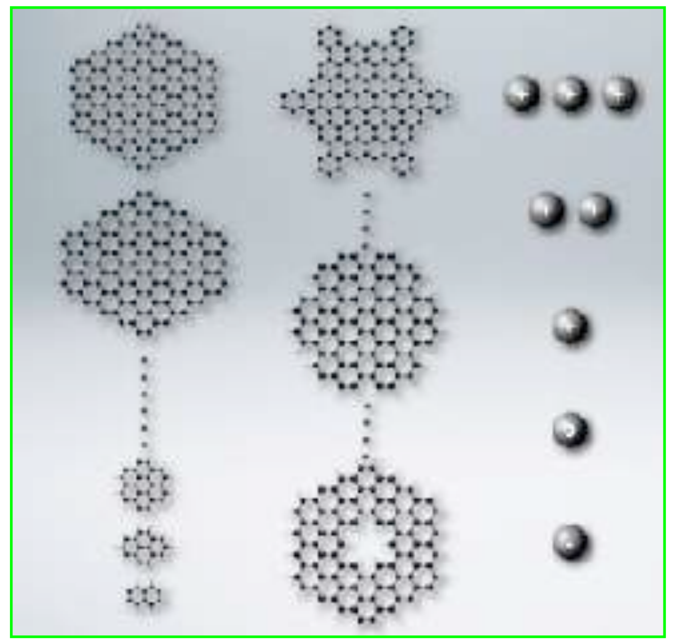


**Amorphous carbon**



Gadallah et al. 2013

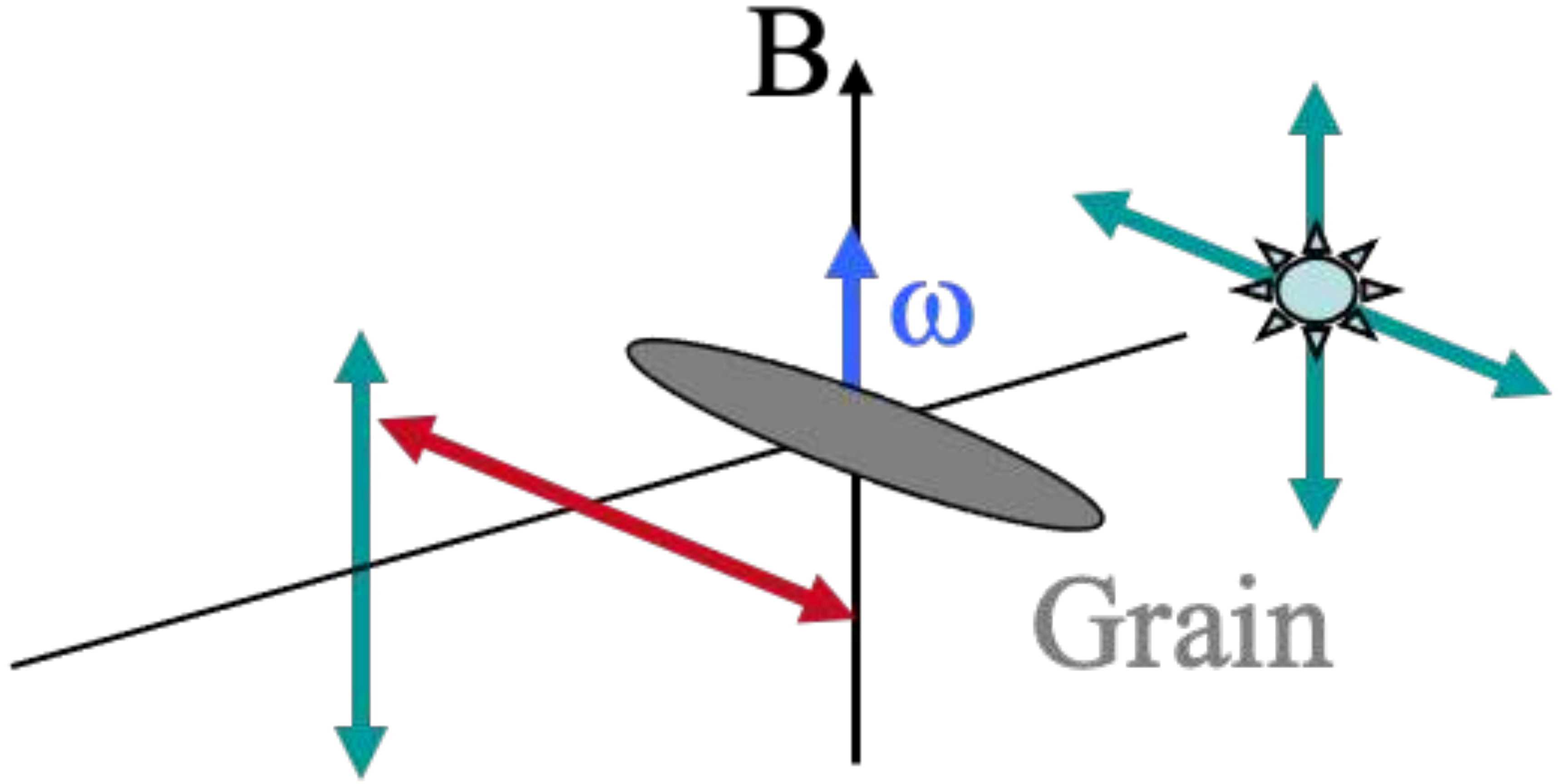
**PAHs**



**VSG 5-10 nm**

Dartois et al. 2005

# Polarization



- Due to the presence of non-spherical and partially aligned grains containing paramagnetic inclusions

- In absorption starlight is polarised // to the B field lines

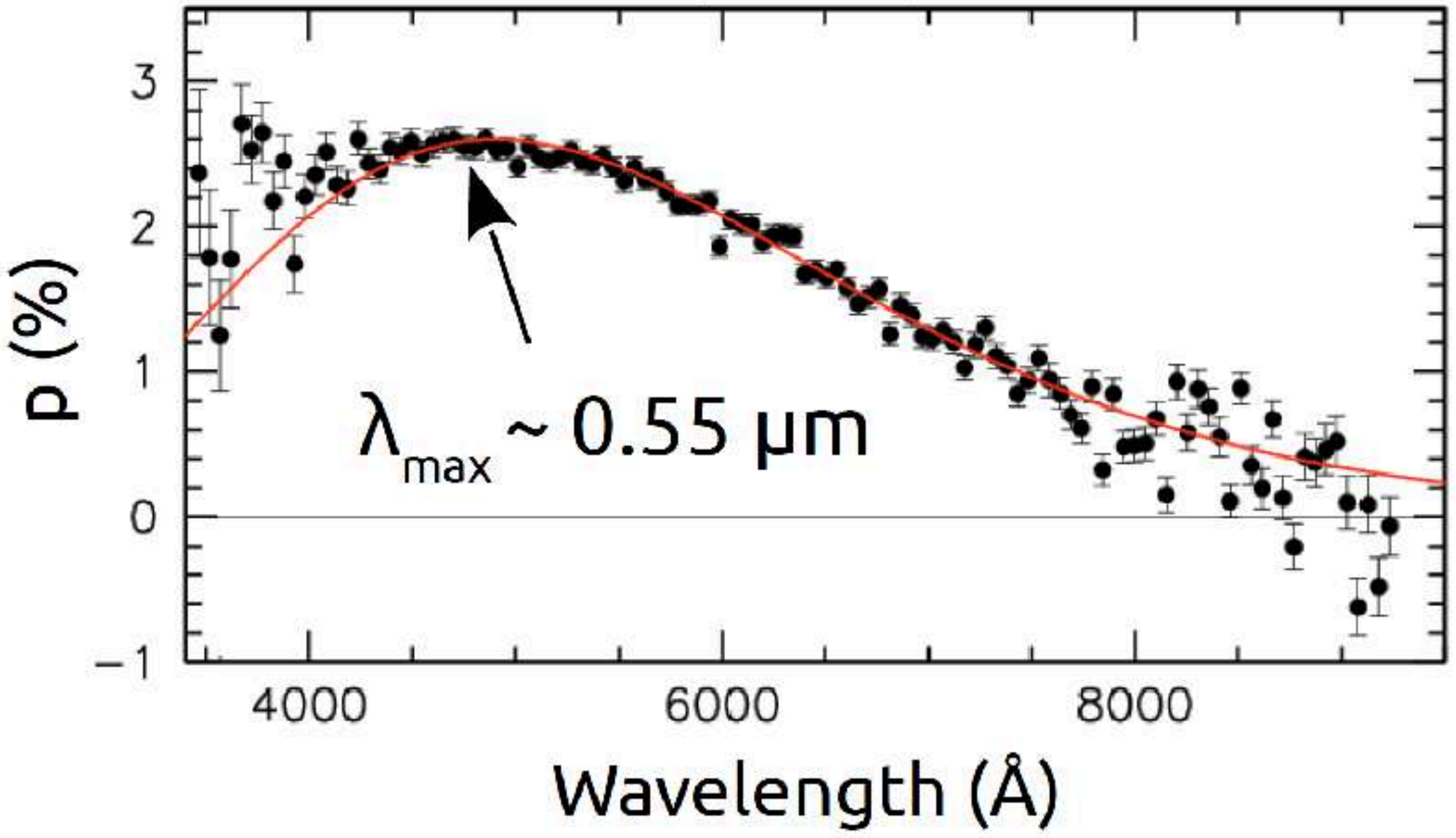
$$p_\lambda = p_{max} e^{-k_p (ln(\lambda_{max}/\lambda))^2}$$

[Serkowski 1975]

- $\lambda_{\rm max}$ ~ 0.55 μm ⇒ grain radius ~ 0.1 μm

- The peak position is sensitive to grain size
- $p_{\rm max}$ ~ a few %
- Correlated to extinction
- The 10 μm feature is polarised

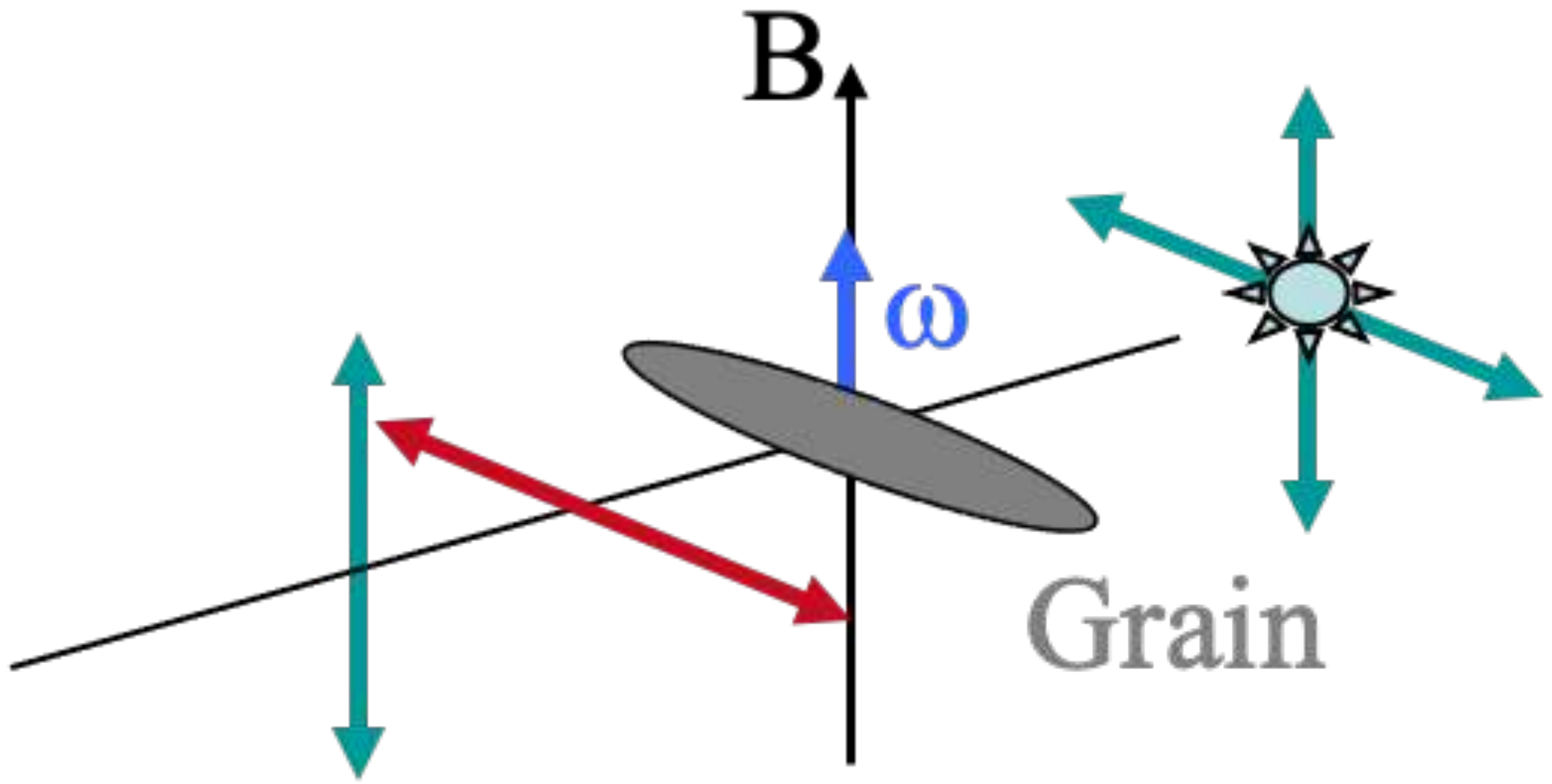
Patat et al. (2010): diffuse ISM



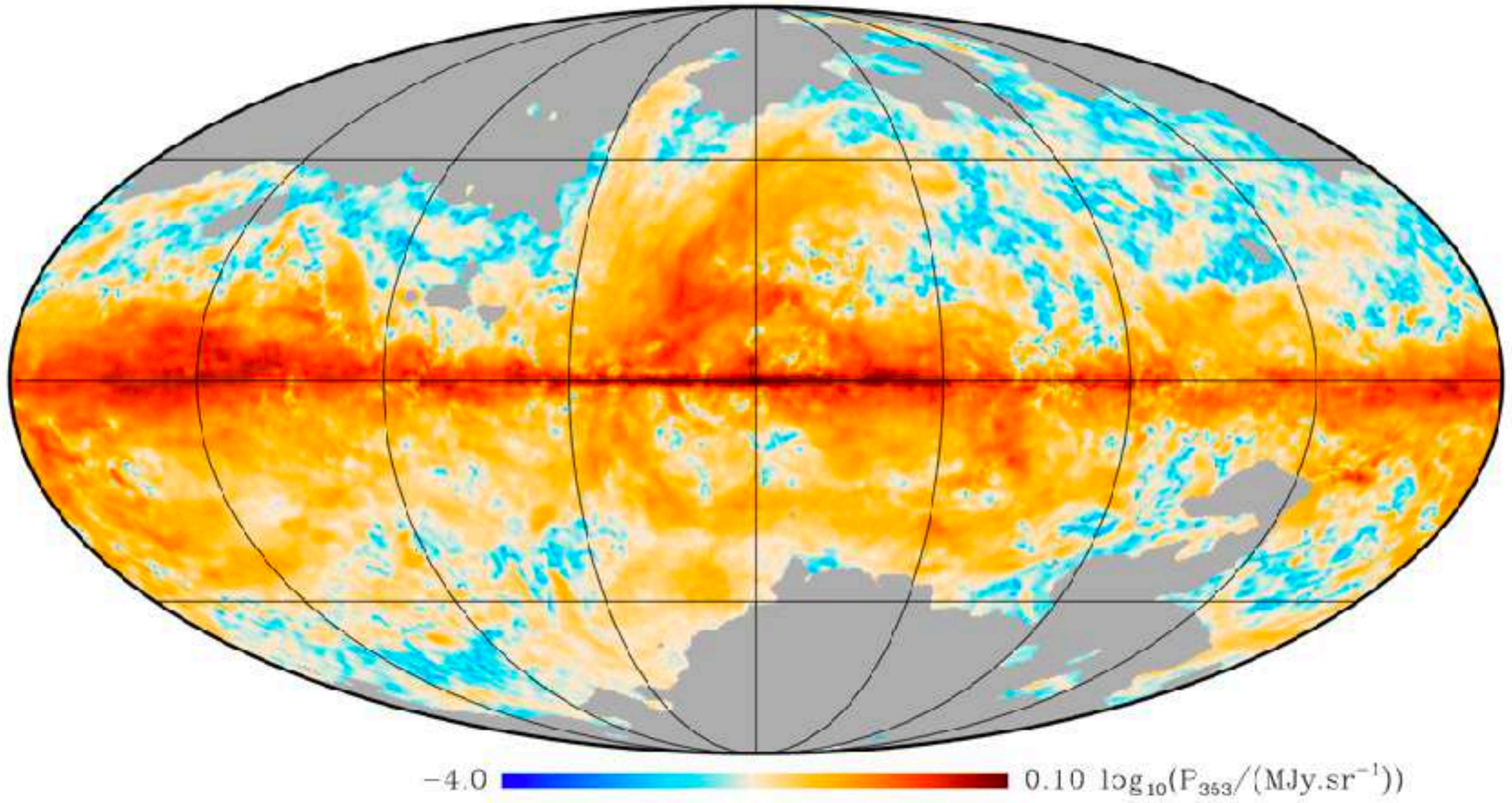
# Polarization

- Due to the presence of non-spherical and partially aligned grains

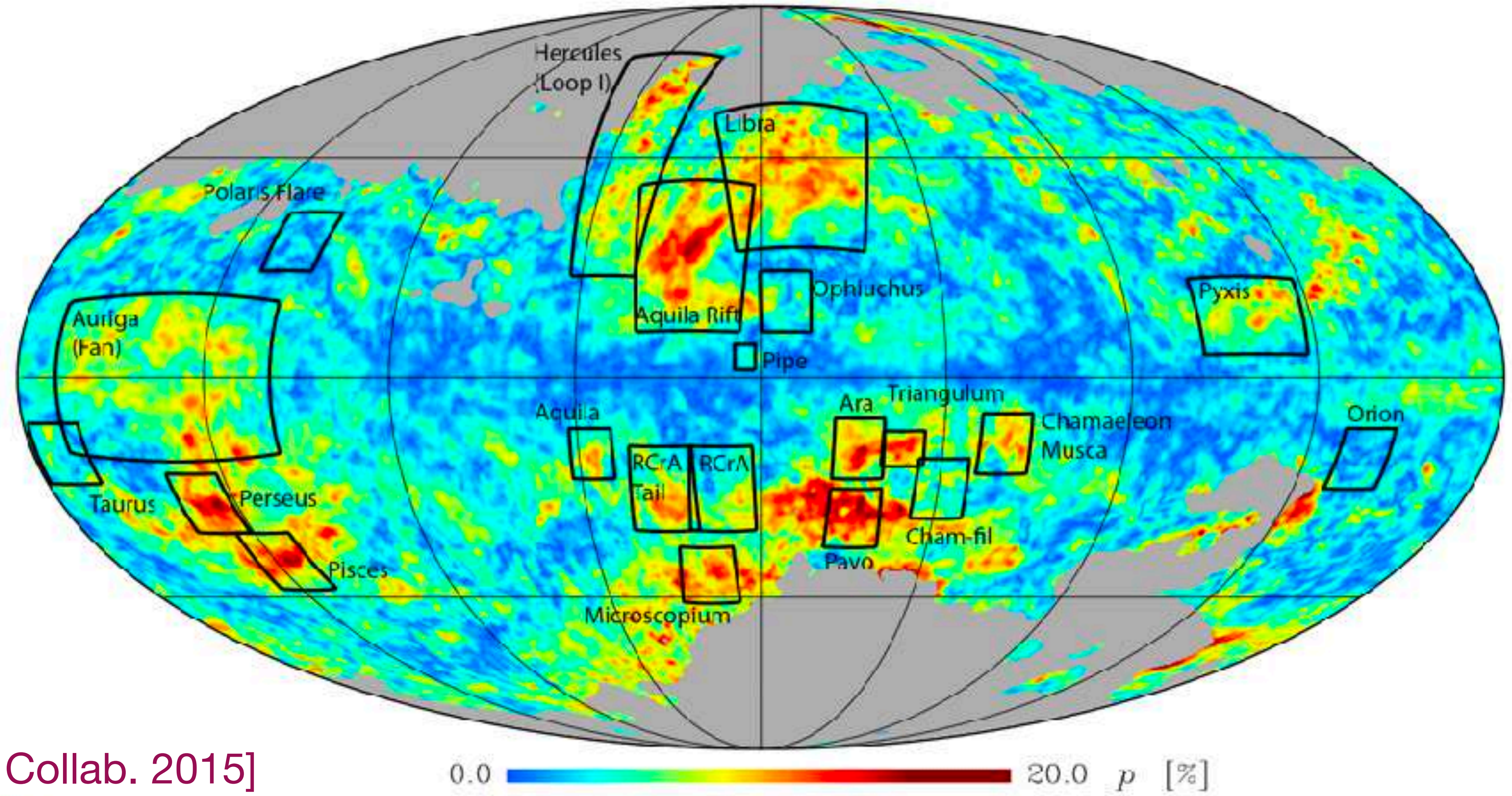
- Polarized emission is ⊥ to B field lines
- P/I = polarisation fraction in the FIR/submm
- Observed by ARCHEOPS, WMAP, Planck



Polarised emission (Planck)



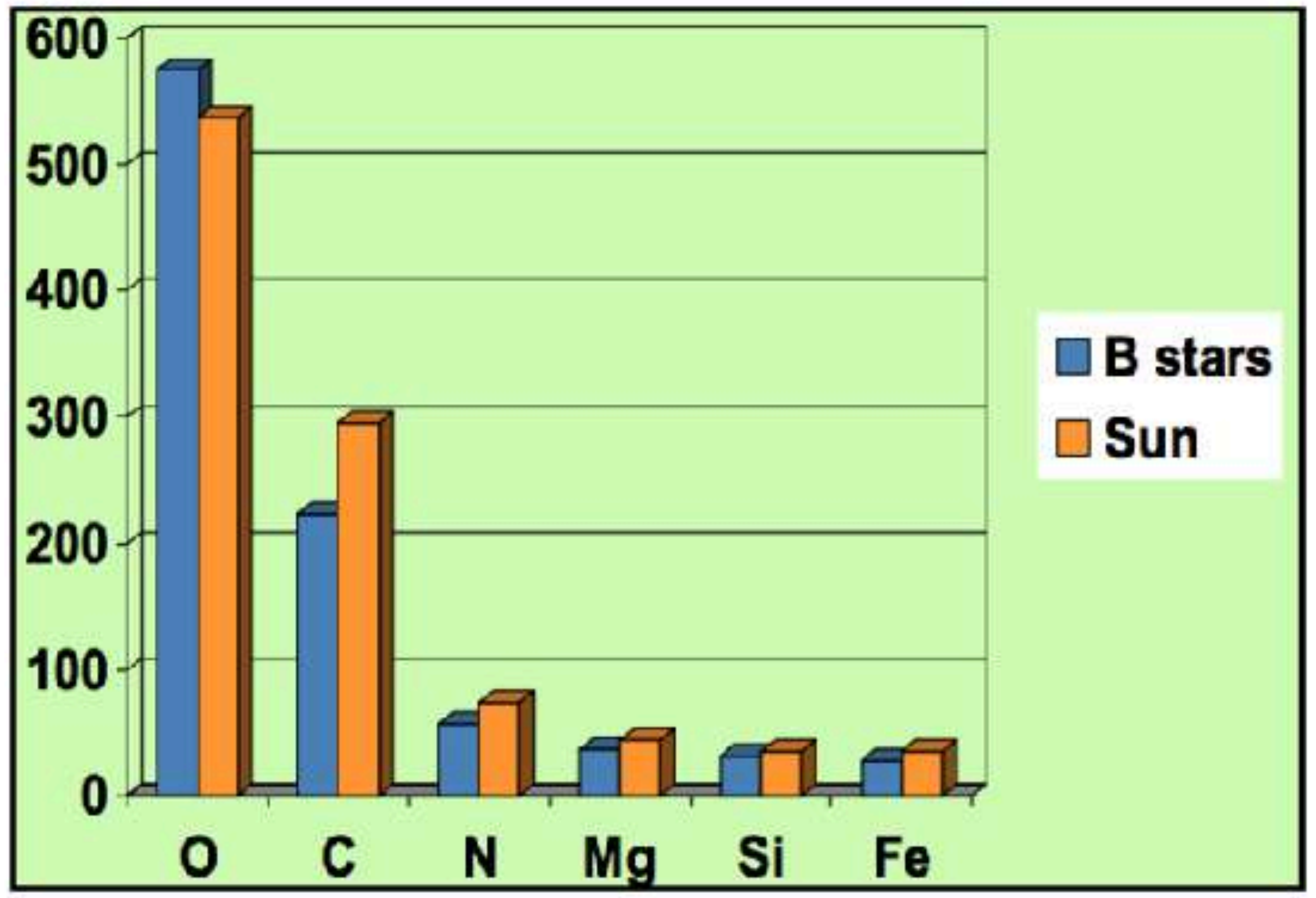
Polarisation fraction (Planck)



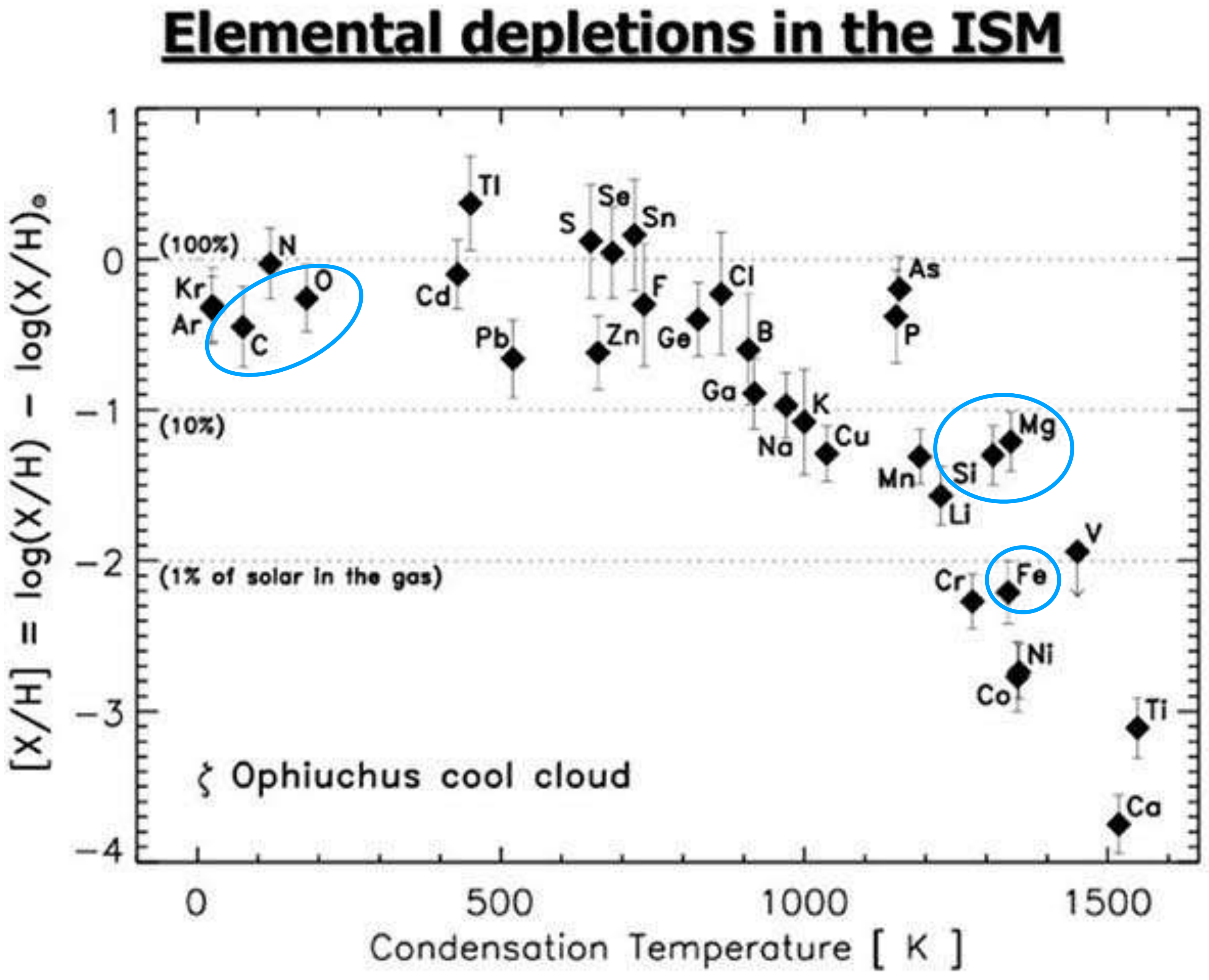
[Planck Collab. 2015]

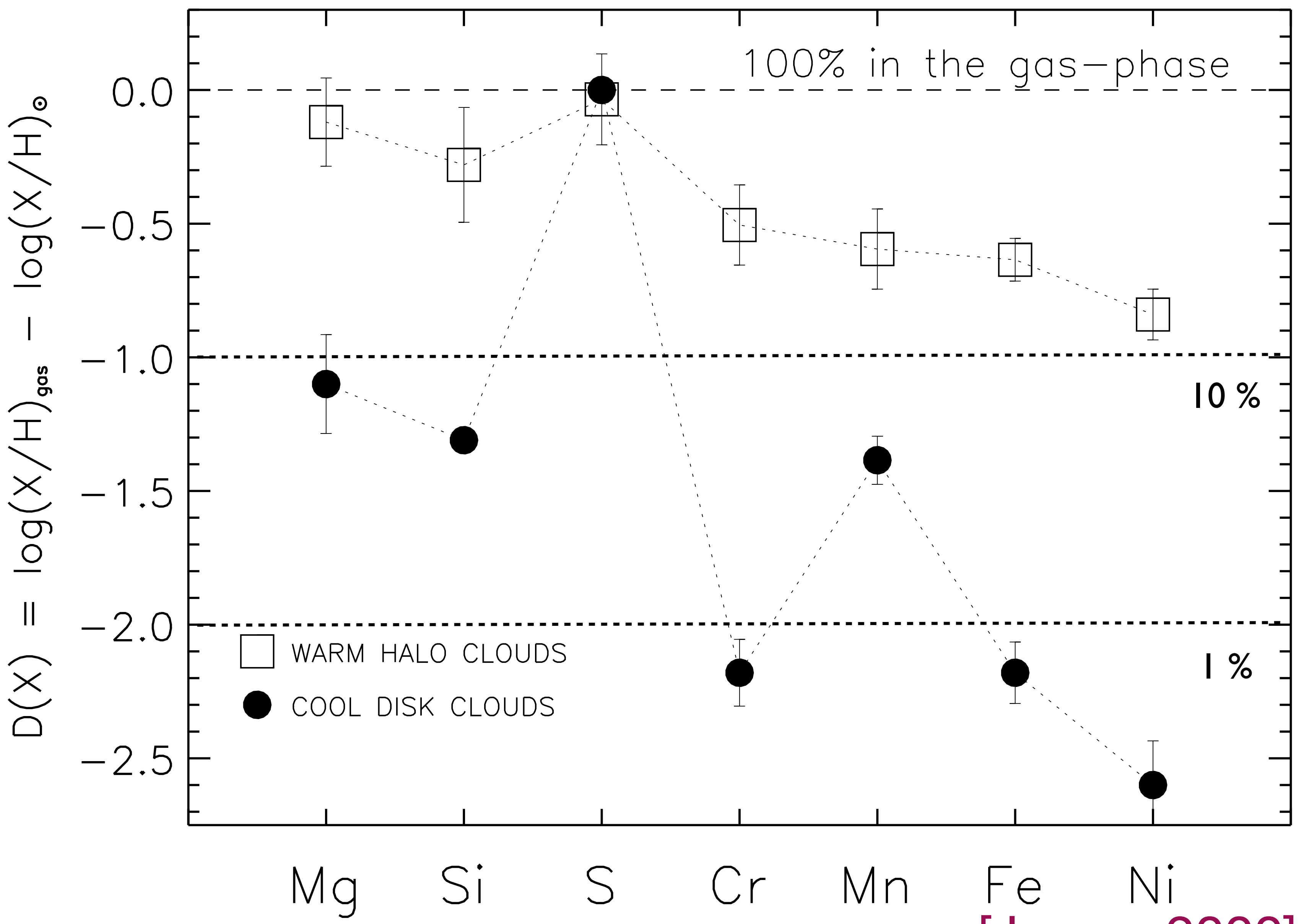
# Depletion

[Jenkins 2009, 2013]



- Electronic absorption lines of atoms or ions
- In the UV spectra of O and B stars
- Copernicus (1972), HST (90’s), FUSE (1999)
- Depletion factor: $D(X) = \left[\frac{X_{gas}}{H}\right] = log\left(\frac{N(X)}{N(H)}\right)_{obs} - log\left(\frac{X}{H}\right)_{ref}$
- Depletion varies from one element to the other
- Depletion increases with condensation temperature of the elements





[Jones+2000]

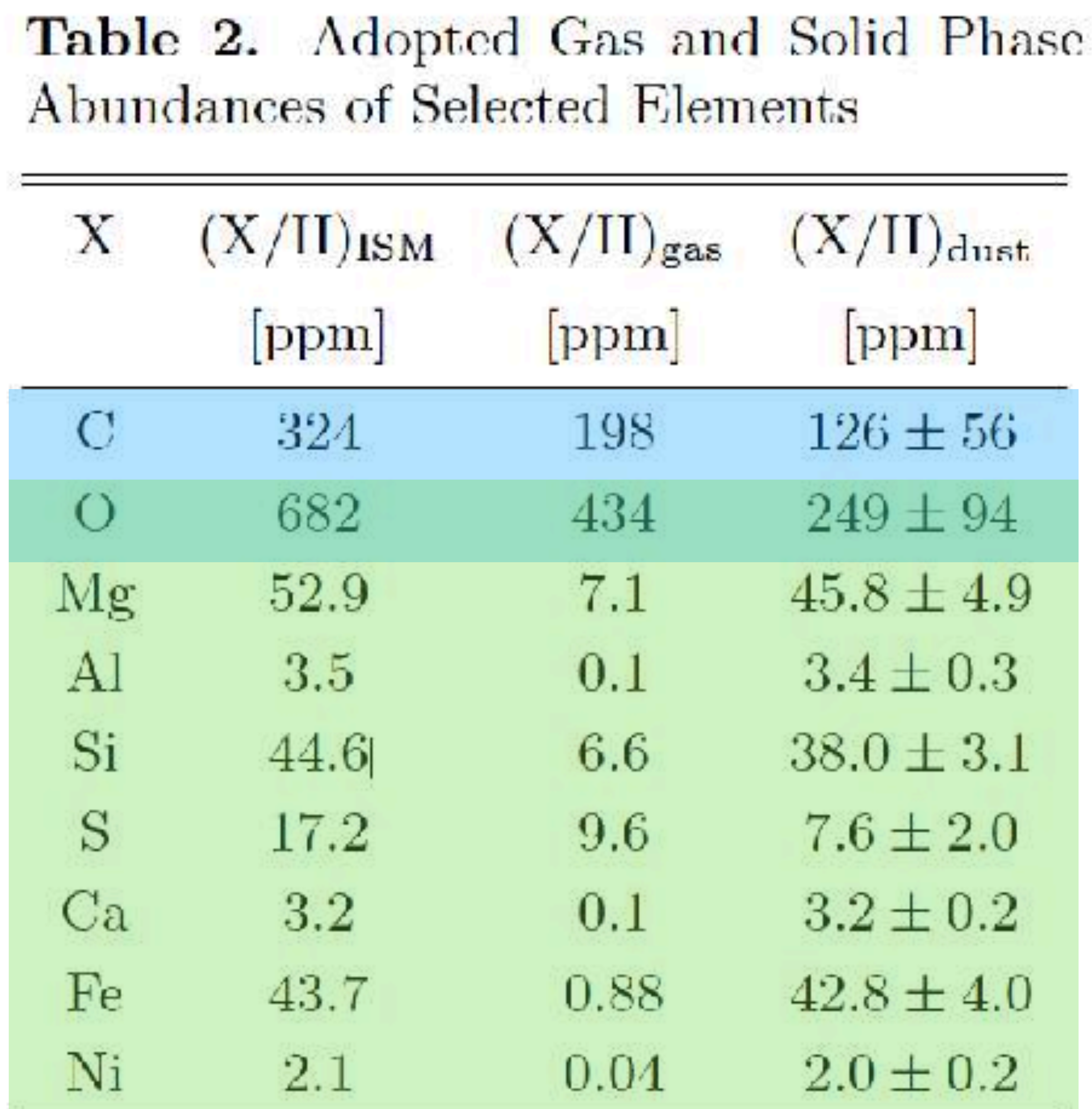


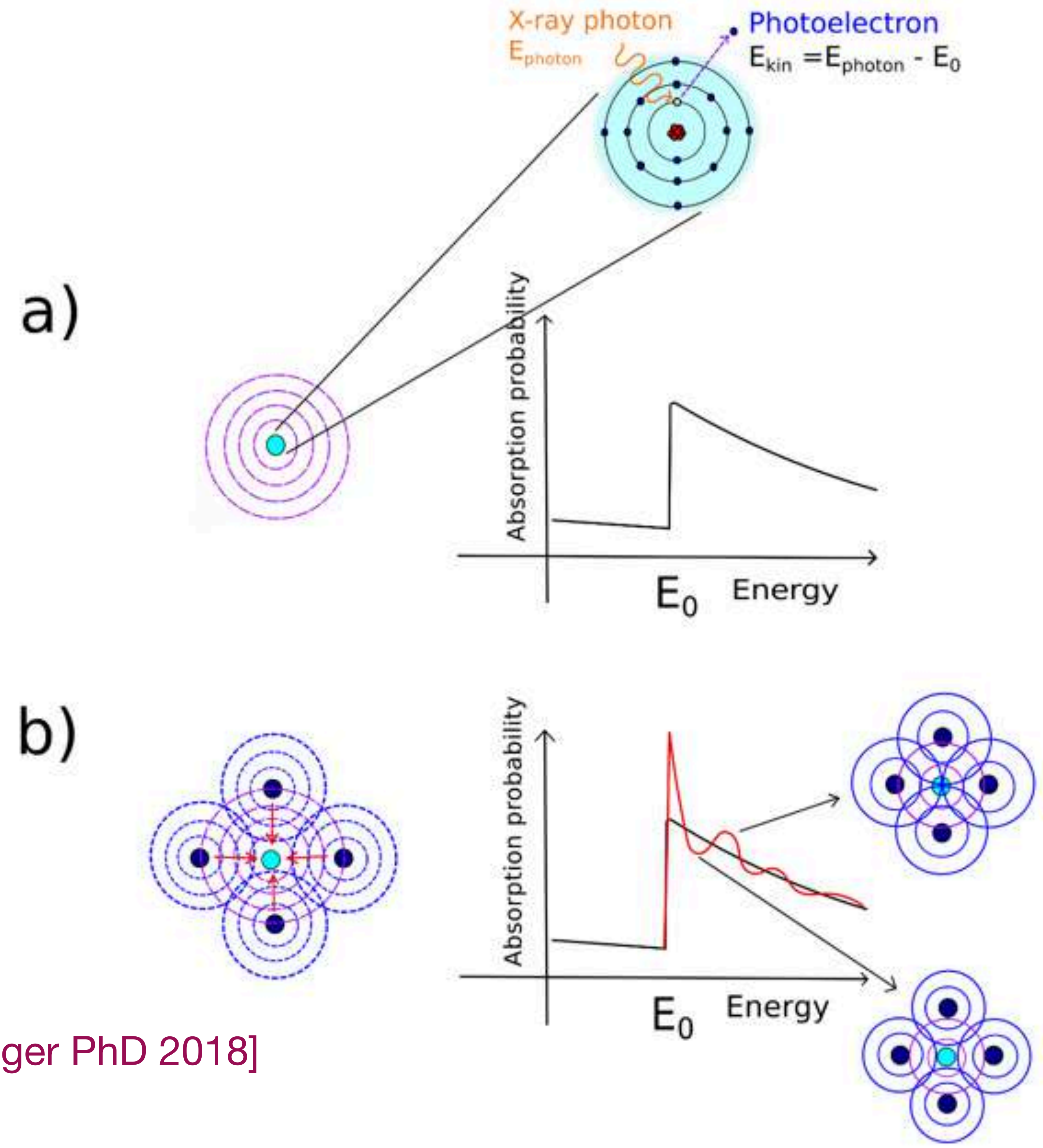
Table 2. Adopted Gas and Solid Phase Abundances of Selected Elements

| X | $(X/H)_{ISM}$ [ppm] | $(X/H)_{gas}$ [ppm] | $(X/H)_{dust}$ [ppm] |
|---|---|---|---|
| C | 324 | 198 | $126 \pm 56$ |
| O | 682 | 434 | $249 \pm 94$ |
| Mg | 52.9 | 7.1 | $45.8 \pm 4.9$ |
| Al | 3.5 | 0.1 | $3.4 \pm 0.3$ |
| Si | 44.6 | 6.6 | $38.0 \pm 3.1$ |
| S | 17.2 | 9.6 | $7.6 \pm 2.0$ |
| Ca | 3.2 | 0.1 | $3.2 \pm 0.2$ |
| Fe | 43.7 | 0.88 | $42.8 \pm 4.0$ |
| Ni | 2.1 | 0.04 | $2.0 \pm 0.2$ |

[Hensley&Draine+2021]

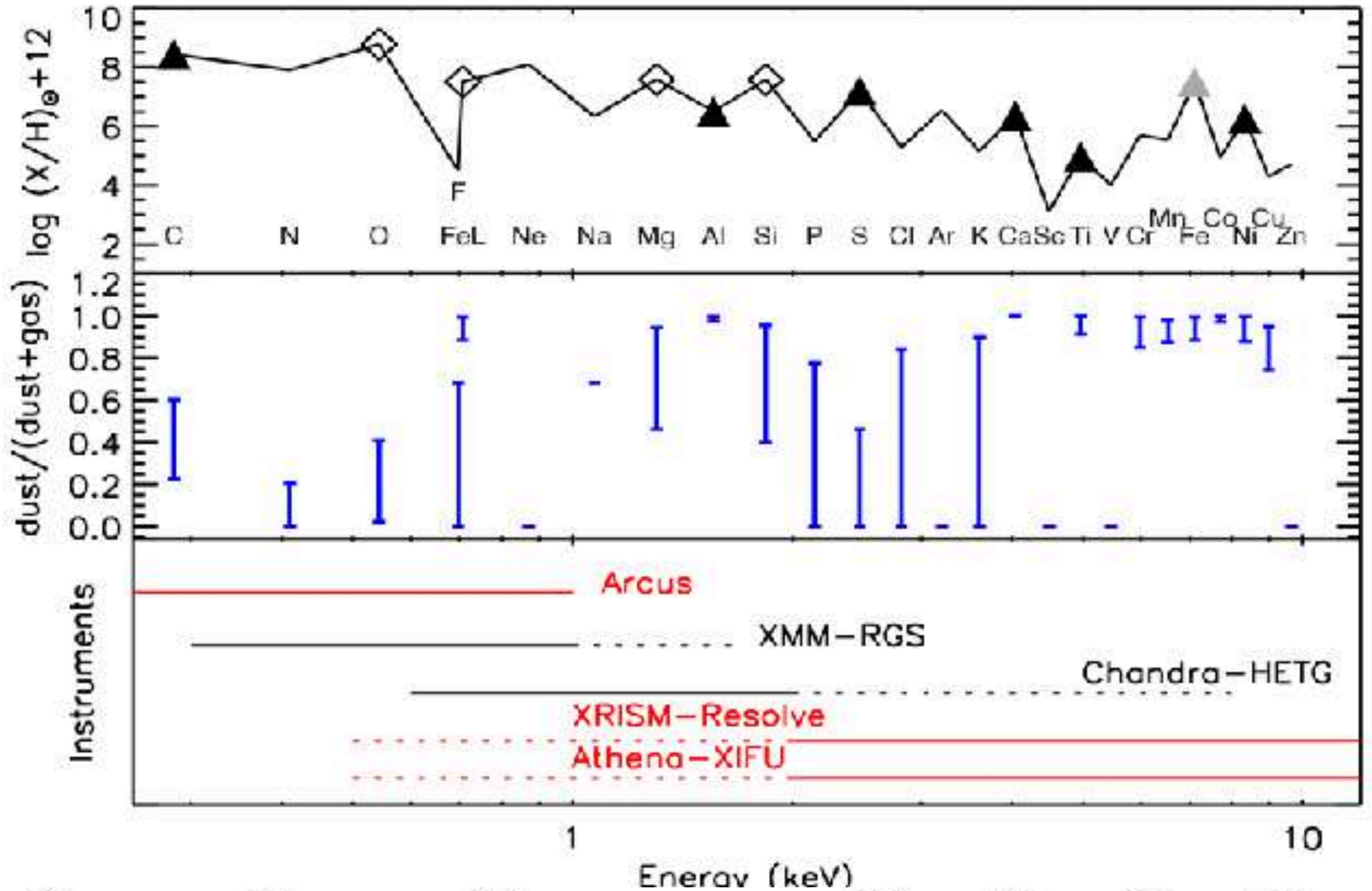
# X-ray observations

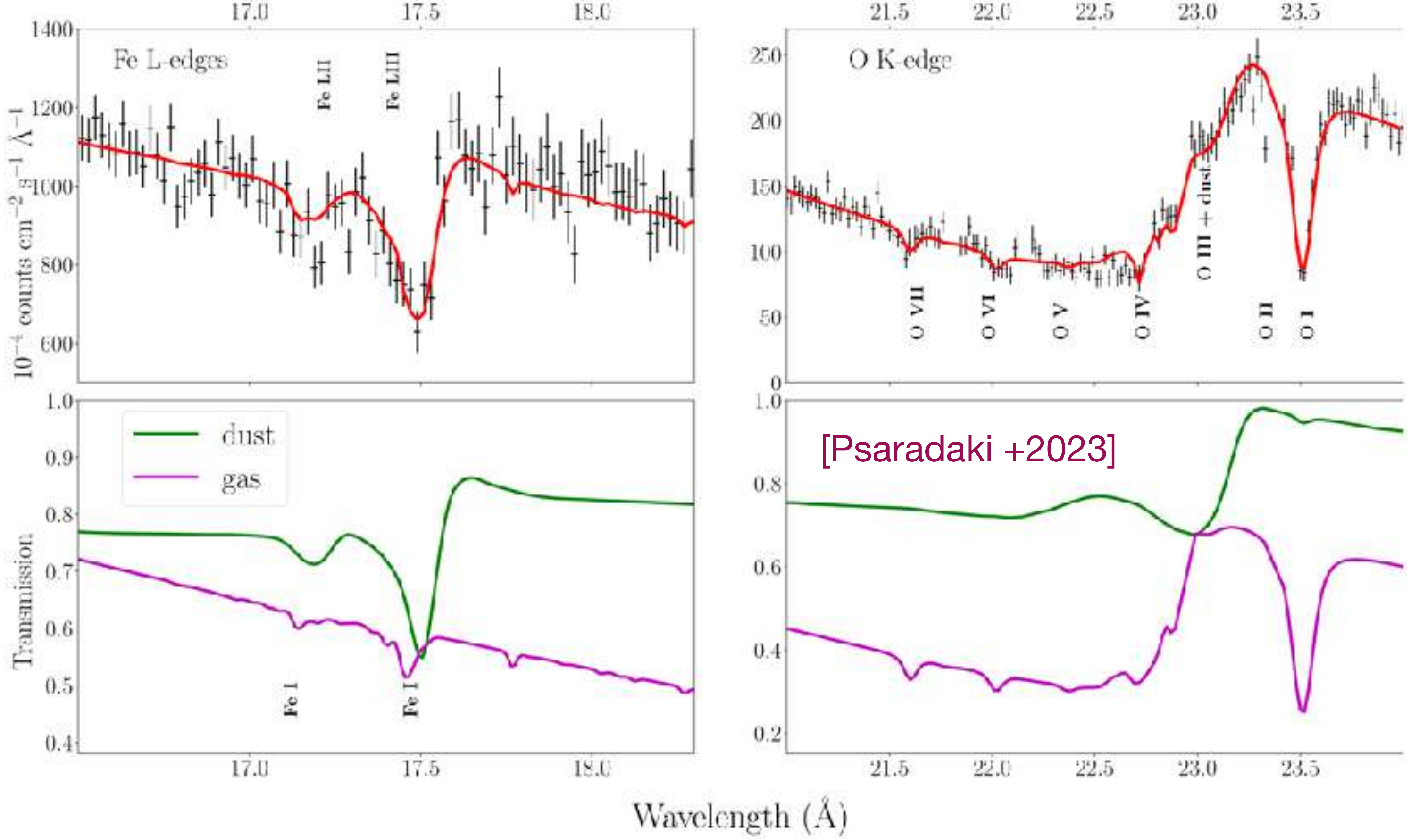
- Photo-electric absorption edges
- Gas and dust simultaneously
- Mg, Fe, Si, Ca, Ti …
- Chandra, XMM-Newton
- More data to come with Athena and XRISM



[Zeeger PhD 2018]

[Costantini +2019]

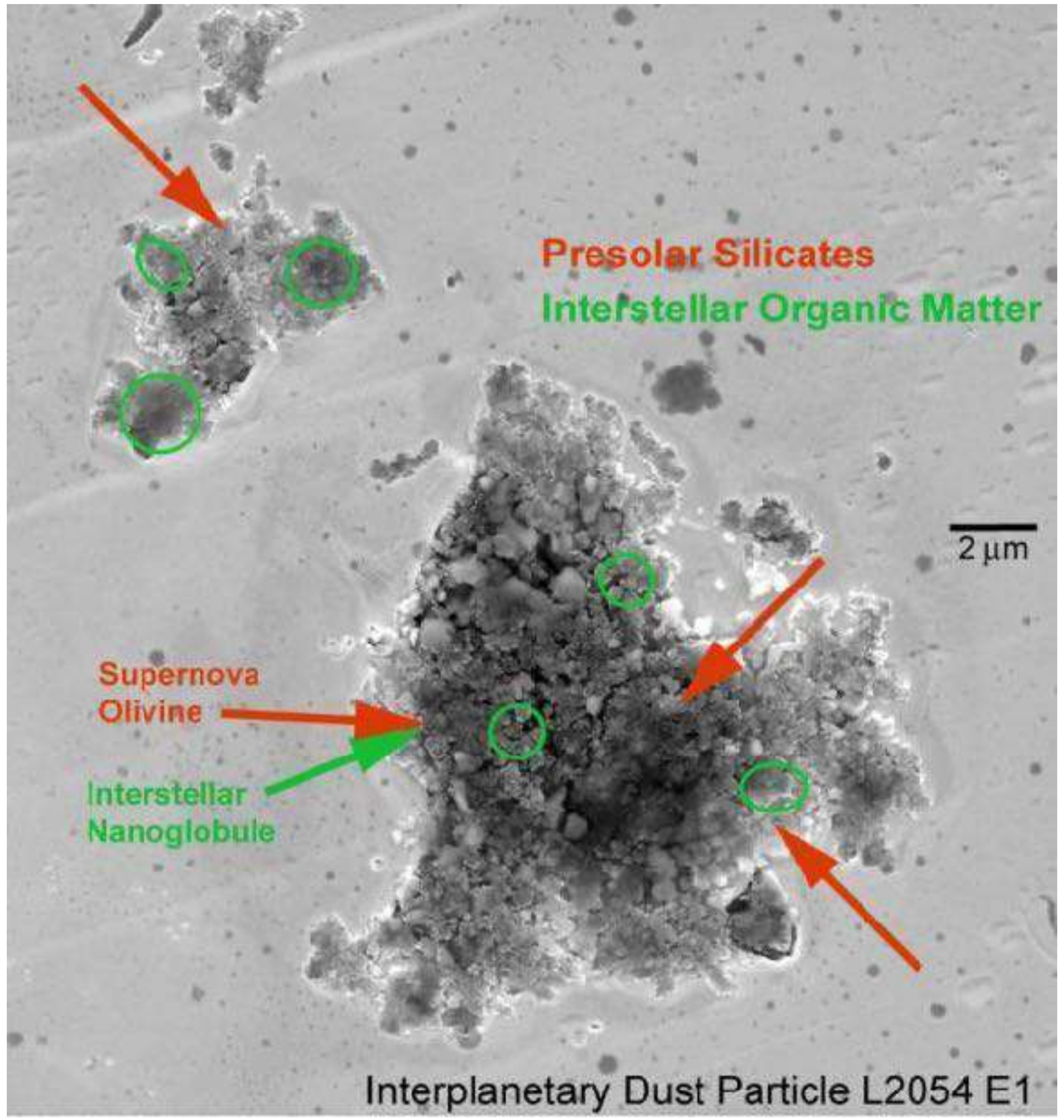




[Psaradaki +2023]

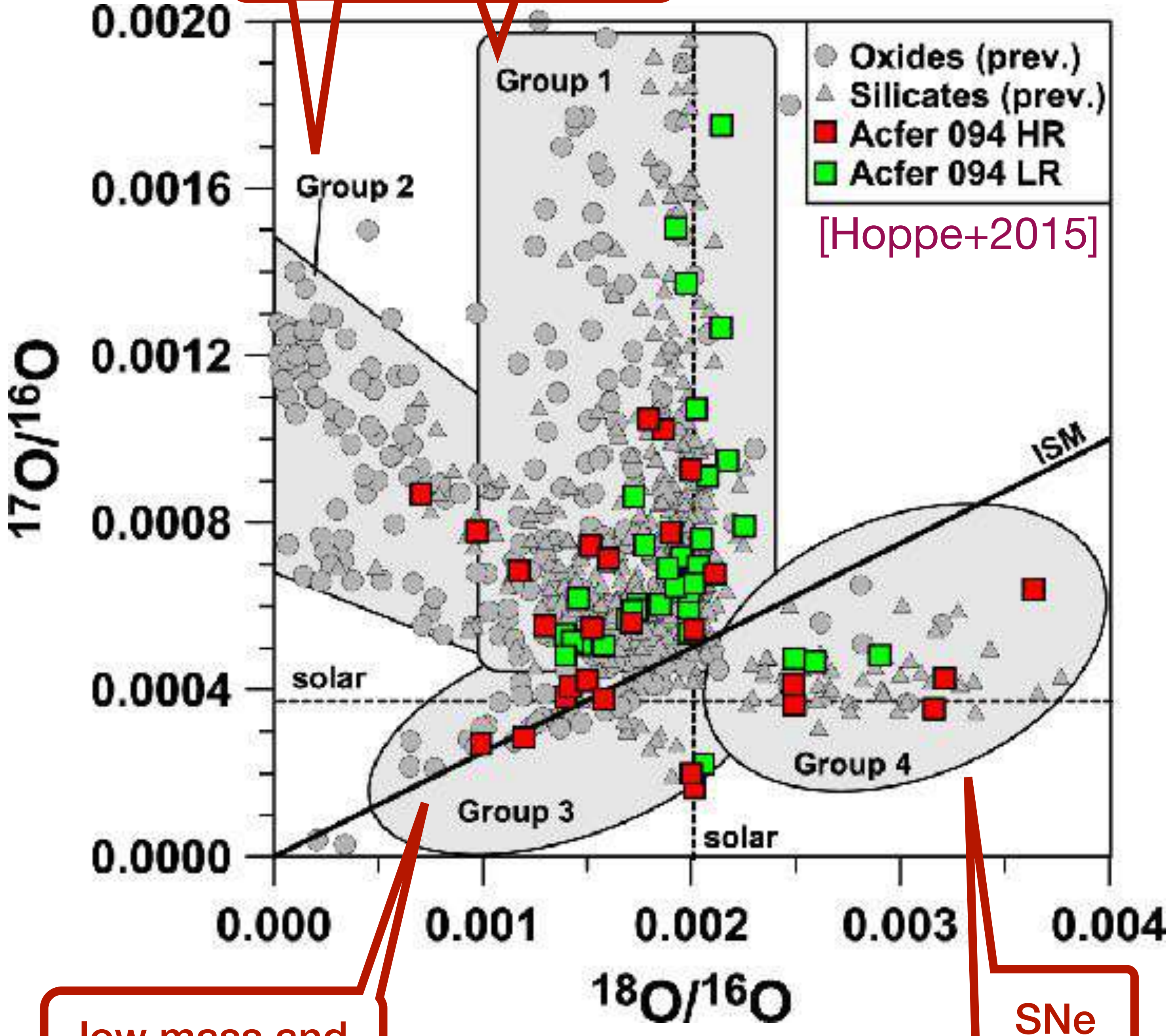
# Pre-solar grains

- Sample return missions : STARDUST, HAYABUSA, OSIRIS-Rex
- Interplanetary grains (MIR stations, stratospheric flights)
- Inclusions in meteorites
- Micro-meteorites



Red giants, AGB stars, ~1-2 Msol

meteorite ACFER 094



low mass and metallicity AGB stars, SN

SNe

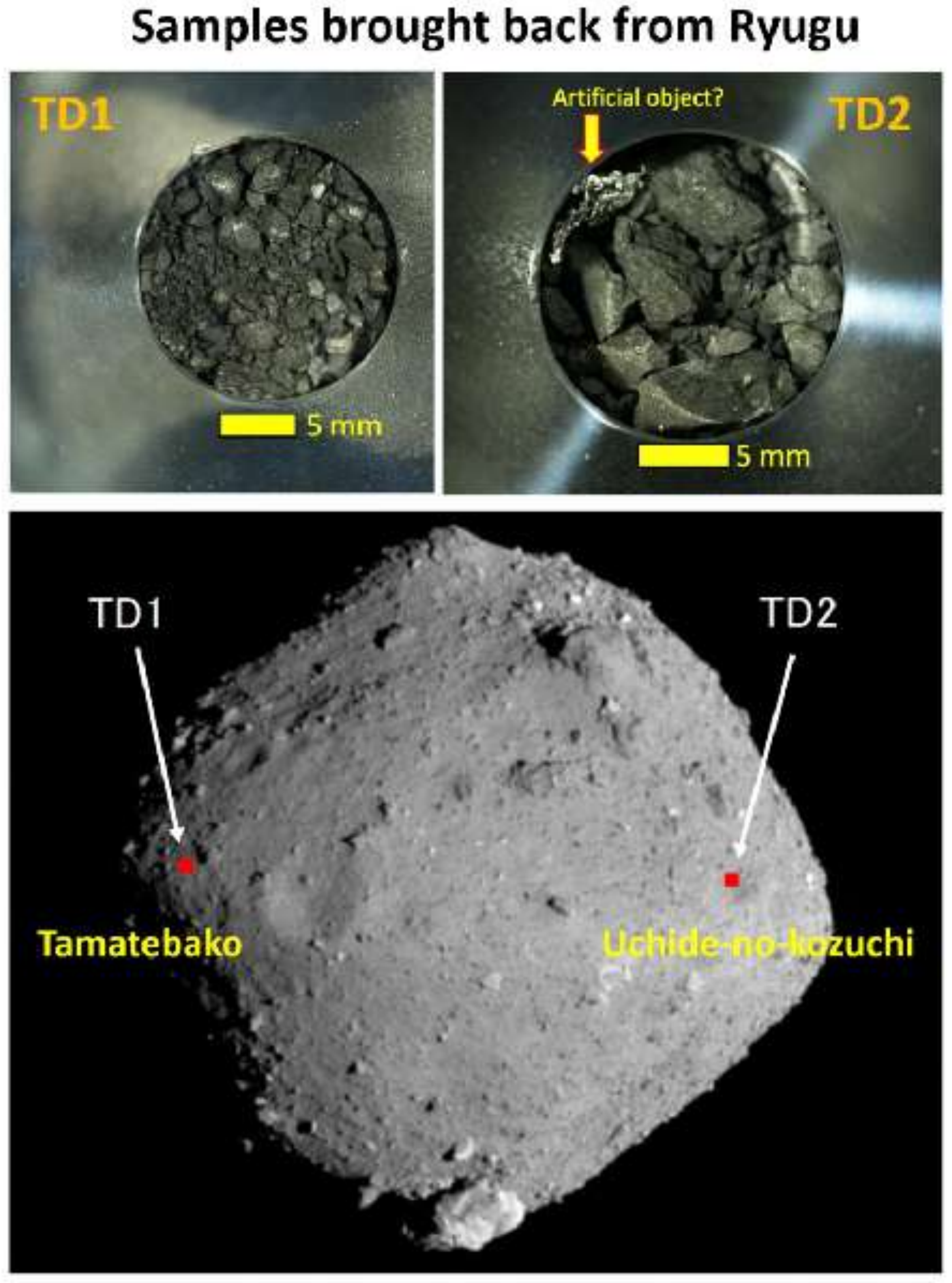


Image credit: JAXA, University of Tokyo, Kochi University, Rikkyo University, Nagoya University, Chiba Institute of Technology, Meiji University, University of Aizu, AIST

# Dust properties: size distribution

- Constrained by the extinction curve and depletion measurements

- The most used is the MRN size distribution (for spherical grains silicate and graphite grains): [Mathis, Rumpl, Nordsieck, 1977]

$N(a) \propto a^{-\beta_s}$ with $a_{min}$ = 5 nm, $a_{max}$ ~ 250 nm
$\beta_s$ ~ 3.3 -3.6

- Many updated versions of the MRN size distribution exist, in particular to include the PAH grain population [see dust models from Compiègne+2011, Weingartner & Draine 2001].

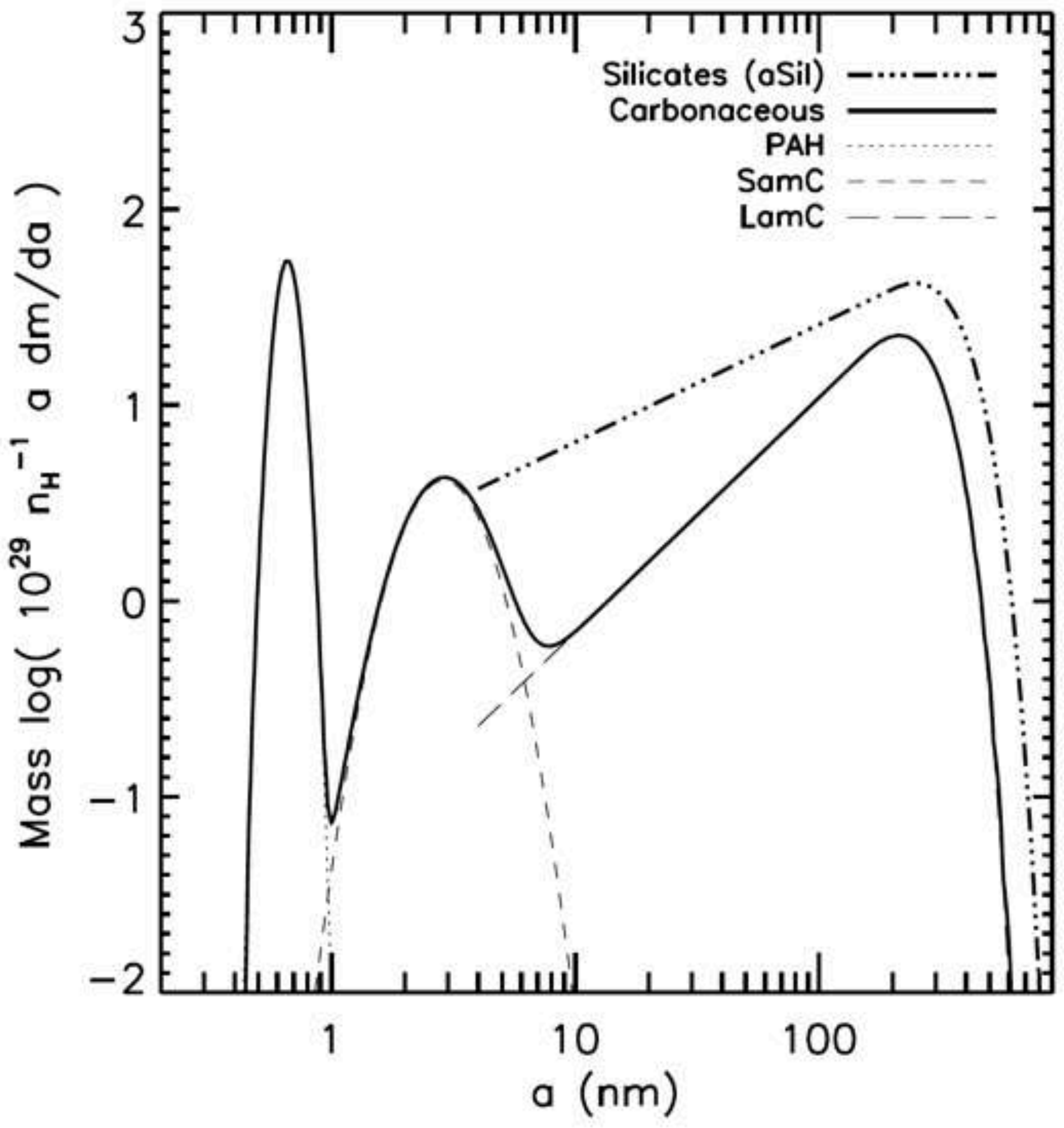
- Log-normal grain size distributions are also proposed for large grains [see the THEMIS 1 & 2 dust models from Jones+2013, Ysard+2024]

- grain destruction ⇒ power-law size distribution
- grain coagulation ⇒ log-normal size distribution

**⇒ the dust mass is in big grains**

**⇒ the dust surface is provided by small grains**

[Compiègne+2011]



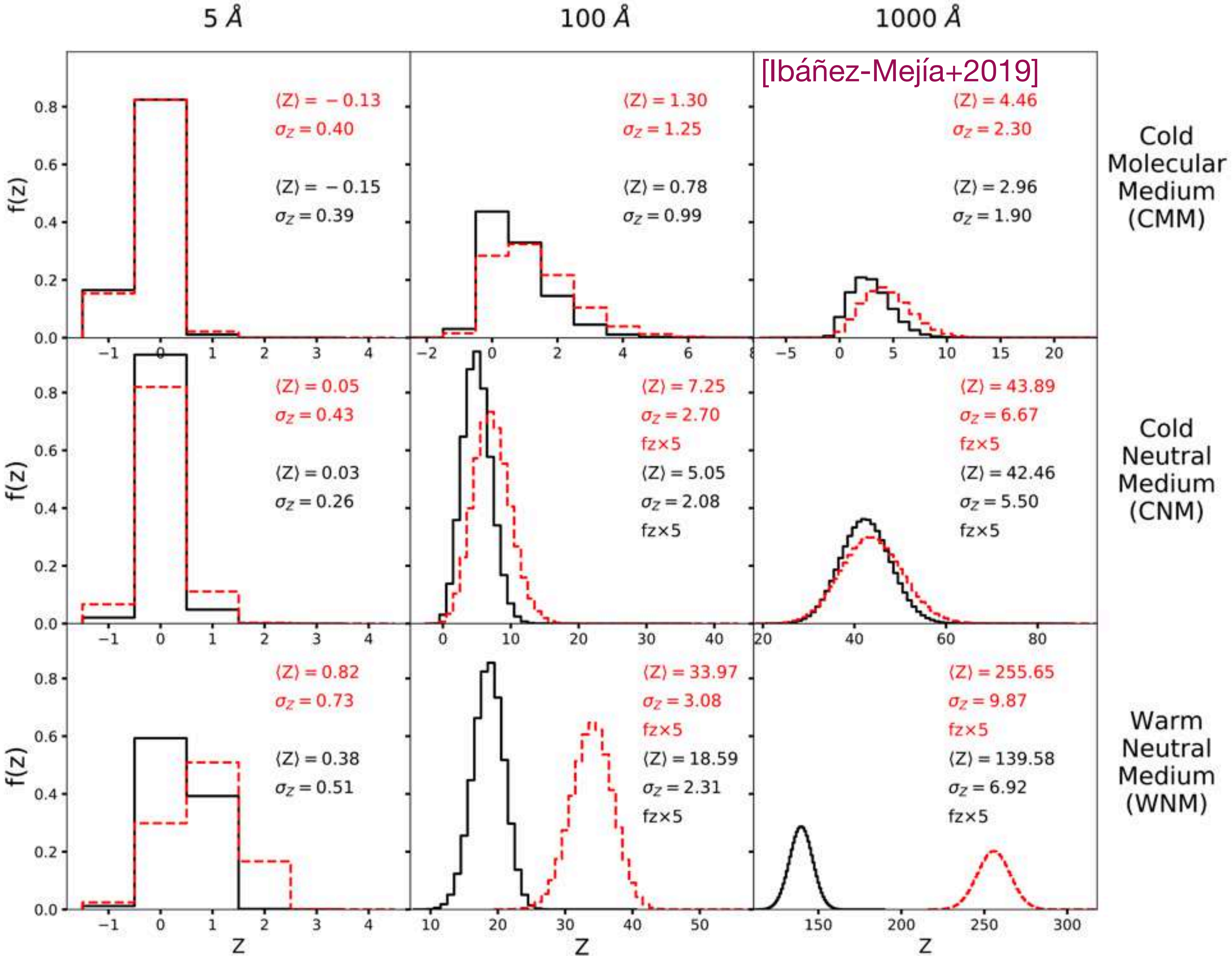
# Grain charge

Balance between :
- ion recombination
- photo-ionisation
- electron recombination

- Neutral or positively charged in CNM, WNM
- Negatively charged in CMM for small grains

- The charge depends on :
  - grain size
  - grain composition
  - ISM phase (density, temperature)
  - Radiation field
  - cosmic ray ionisation rate

- Grains charge distribution impacts:
  - properties and propagation of shocks
  - gas-grain coupling
  - surface chemistry
  - grain growth and destruction



[Ibáñez-Mejía+2019]

T=14.4K
$n_H = 3.10^4$ cm$^3$
$G_{tot} = 7.9\text{x}10^{-4}$
$\chi_e = 9\text{x}10^{-8}$
$x_{H2} = 0.99$

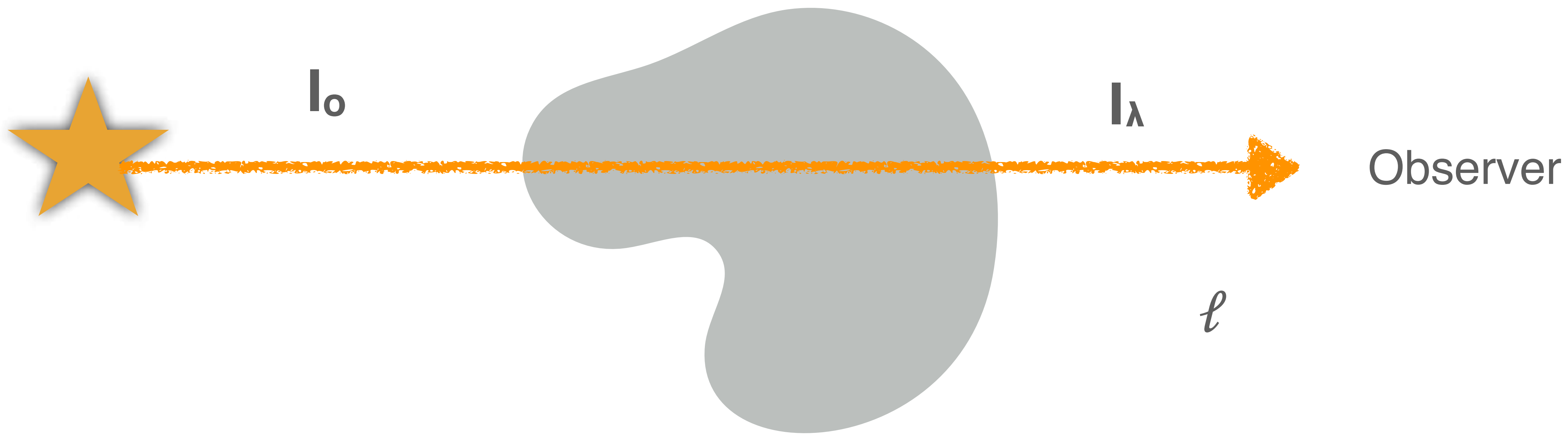
T=70K
$n_H = 36$ cm$^3$
$G_{tot} = 0.60$
$\chi_e = 1.8\text{x}10\text{-}4$
$x_{H2} = 0.15$

T=7000K
$n_H = 0.9$ cm$^3$
$G_{tot} = 1.52$
$\chi_e = 0.012$
$x_{H2} = 4.6\text{x}10^{-5}$

silicate grains
carbonaceous grains

# Modelling the dust extinction and emission

# Modelling the extinction



$$I(\lambda) = I_0(\lambda) \times e^{-\tau(\lambda)}$$

$$\tau(\lambda) = \int k_{ext}(\lambda) dl$$

Extinction coefficient (cm$^{-1}$)

$$k_{ext} = C_{ext} \times n = (C_{abs} + C_{sca}) \times n$$

Extinction cross section (cm$^2$)

$$Q_{ext} = \frac{C_{ext}}{\sigma_{gr}} = \frac{(C_{abs} + C_{sca})}{\sigma_{gr}}$$

Extinction efficiency

$$\kappa_{ext} = \frac{C_{ext}}{V_{gr}\rho_{gr}}$$

Opacity or mass extinction coefficient (cm$^2$. g$^{-1}$)

n : number density of dust grains (cm$^{-3}$)
N : column density of dust grains (cm$^{-2}$)
$\sigma_{gr}$ : grain geometrical cross section (cm$^2$)
V$_{gr}$ : grain volume (cm$^3$)

$$\tau(\lambda) = lk_{ext} = NC_{ext} = \sigma_{gr} N Q_{ext} = N m_{gr} \kappa_{ext}$$

¡¡ C$_{ext}$, Q$_{ext}$, $\kappa_{ext}$ refer to an individual grain !!

C$_{ext}$, Q$_{ext}$, $\kappa_{ext}$ contains the information on the dust properties

# Modelling the dust extinction

- To calculate the absorption, scattering, emission and polarisation cross section of the grains, one needs to understand the interaction of small particles with the electromagnetic radiation

- This interaction is specified by the dielectric function $\varepsilon$ or optical constants $m$ of the grain material:

$$\varepsilon = \varepsilon_1 + i\varepsilon_2 \qquad m = n + ik = \sqrt{\varepsilon}$$

refraction index

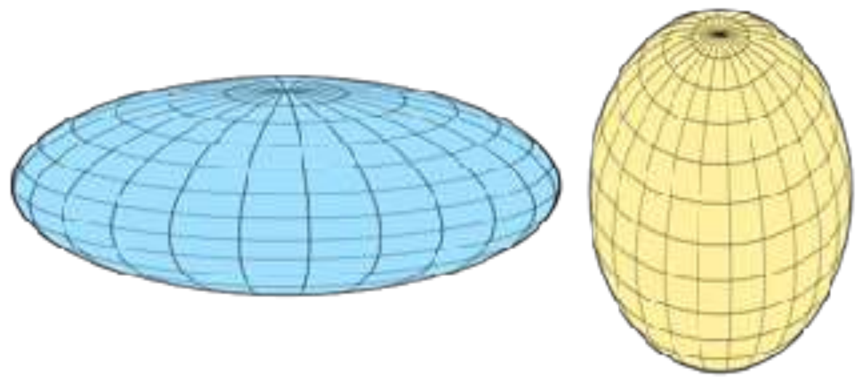
absorption index ← (sometimes called extinction coefficient!)

- Solution first formulated by Mie in 1908 for spherical grains [See books from Bohren & Huffman (1988) or Van de Hulst (1958)]

- For a spherical grain small compared to the wavelength :

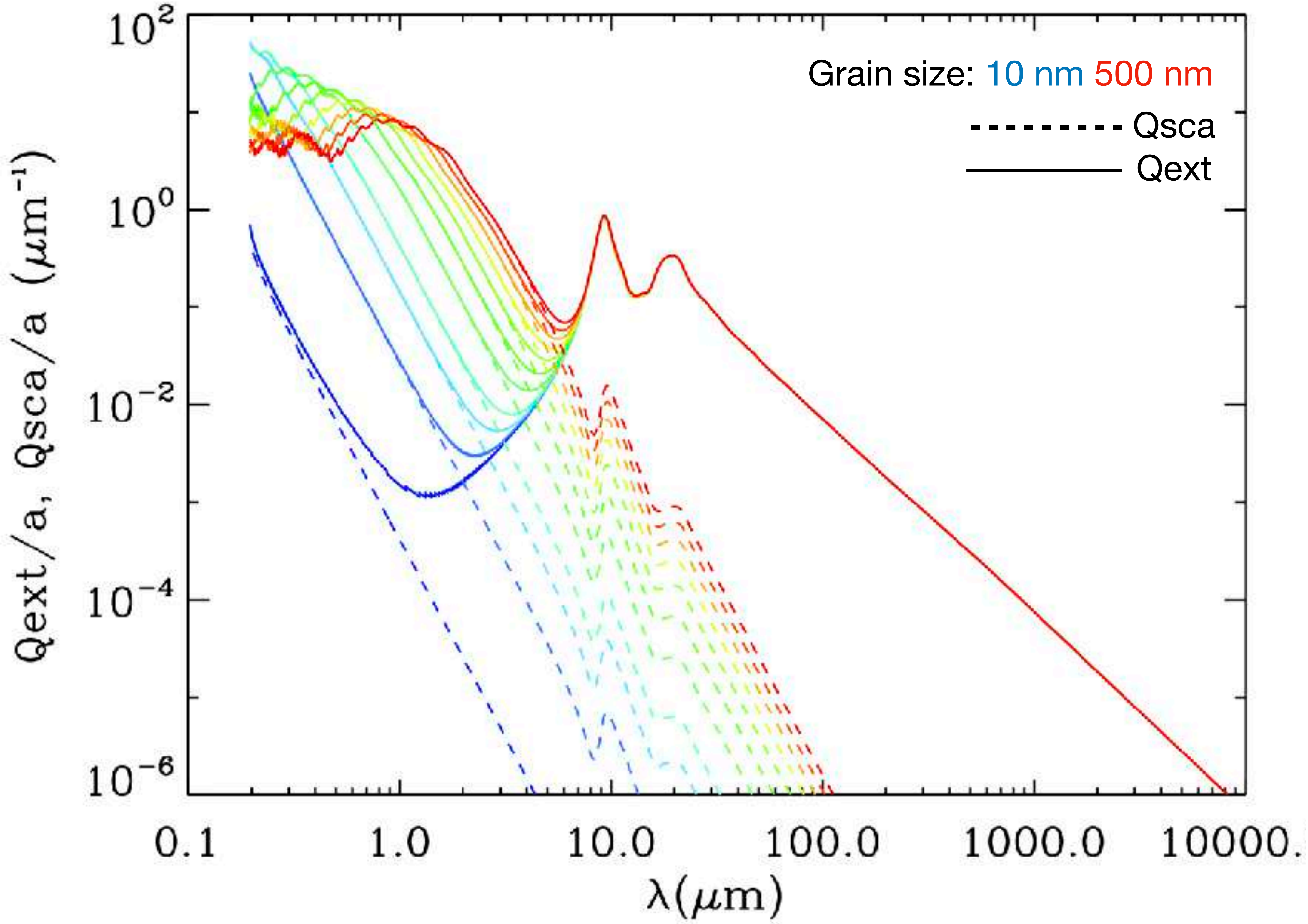
$$C_{abs} = \frac{18\pi V}{\lambda} \frac{\varepsilon_2}{(\varepsilon_1 + 2)^2 + \varepsilon_2^2} \qquad C_{sca} = \frac{24\pi^3 V^2}{\lambda^4} \left| \frac{\varepsilon - 1}{\varepsilon + 2} \right|^2$$

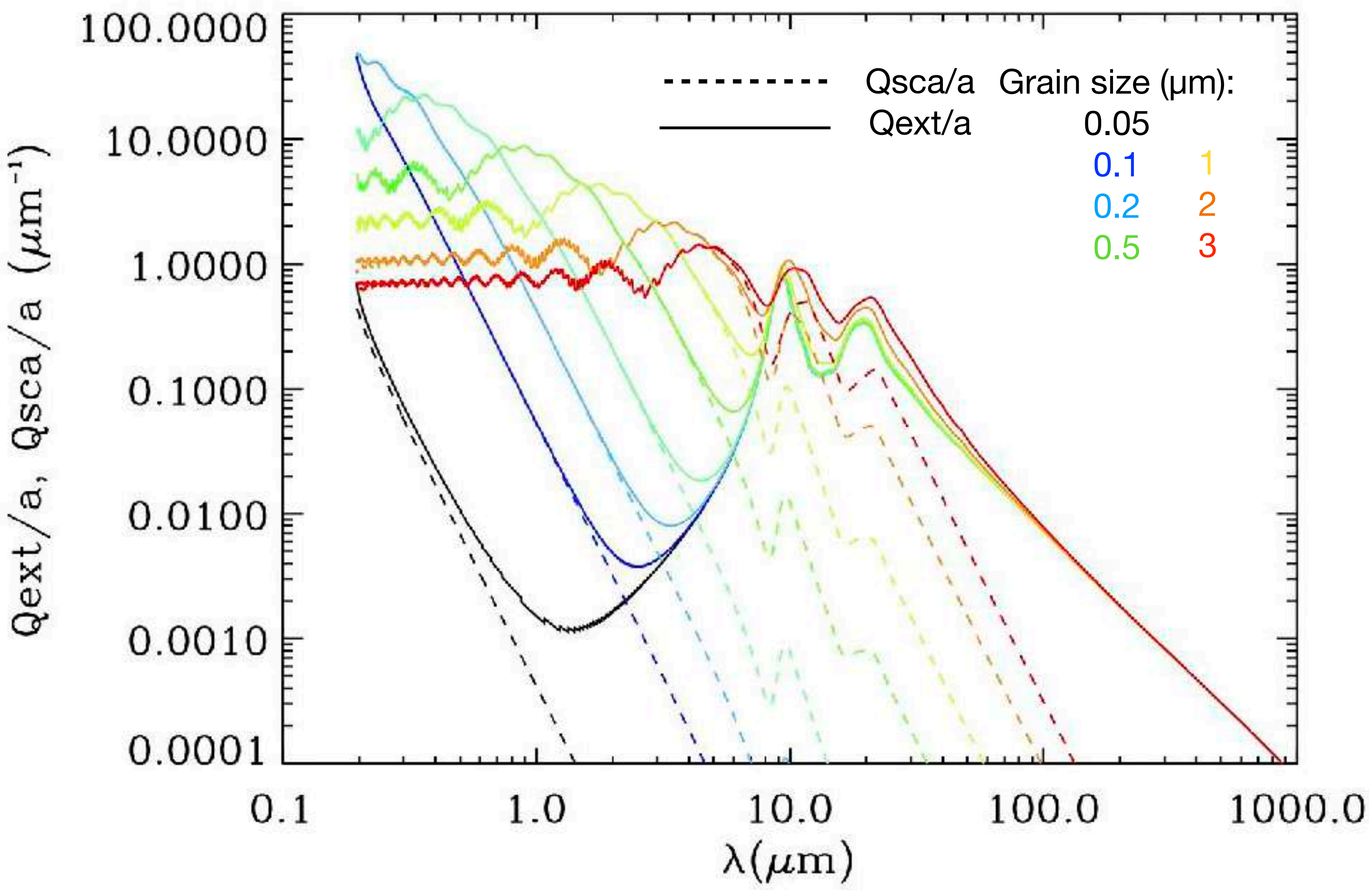
- Reasonably simple expression also exists for spheroids



# Extinction as a function of size: spherical grains

- When the particle size a ≈ λ, one has to use different methods to calculate $C_{abs}$ and $C_{sca}$
- If the particles are spherical one can use **Mie Theory** (many public codes exist)





- for a ≪ $\lambda$, the absorption and scattering properties do not depend on the dust size
- for a ≈ $\lambda$ the absorption and scattering properties depend on the grain size

# Extinction cross section of complex grains

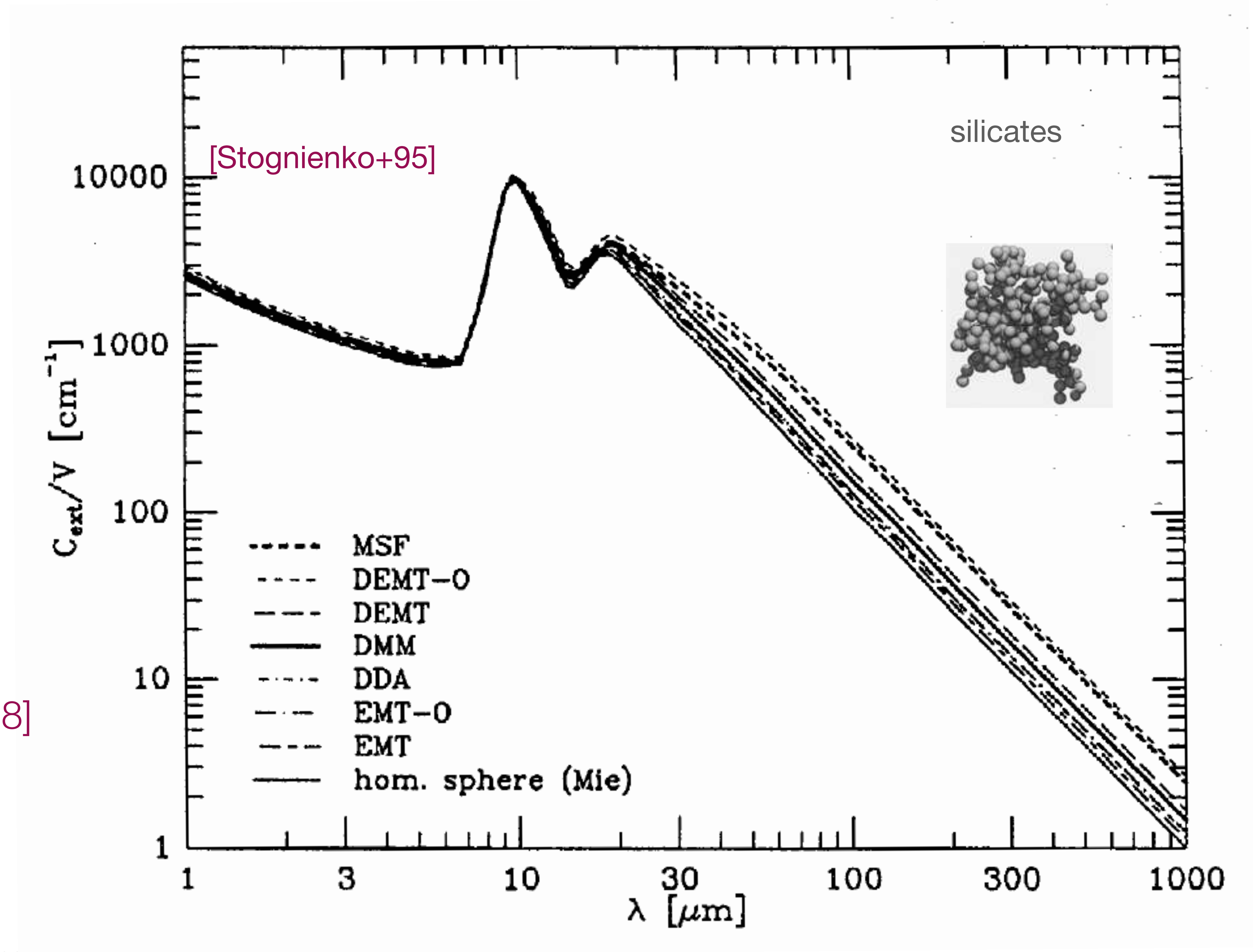
- If the particles are not spherical or spheroidal
- If grains are aggregated
- If grains are complex in term of composition and structure :
  - core-mantle grains
  - composite grains with inclusions
  - aggregates of grains of different compositions

➡ Different methods are used (some codes are public):

  - DDA [Draine & Flatau 2010]
  - T-Matrix [Mischenko+1996]

➡**Effective medium theories (EMTs)** [see eg. Min+2008]

- *Each theory has its own limitations*



[Stognienko+95]

silicates

# Dust temperature (1/2)

- **Grains are heated by**:
  - absorption of a photon from the radiation field
  - collision with atoms, electrons, cosmic rays, grains
  - energy delivered by chemical reactions at grains surface
  - ➡ Radiative heating is the most important in the ISM

- **Grains cool down via:**
  - emission of a photon
  - collision with cold atoms and molecules
  - ejection of electrons, atoms or molecules from the surface
  - ➡ Radiative cooling is dominant

energy absorbed by surface unit

$$E_{abs} = \int_0^\infty \boxed{S_{gr}}\,\boxed{Q_{abs}(\nu)\pi\boxed{\frac{cu_\nu}{4\pi}}}\,d\nu$$

grain surface

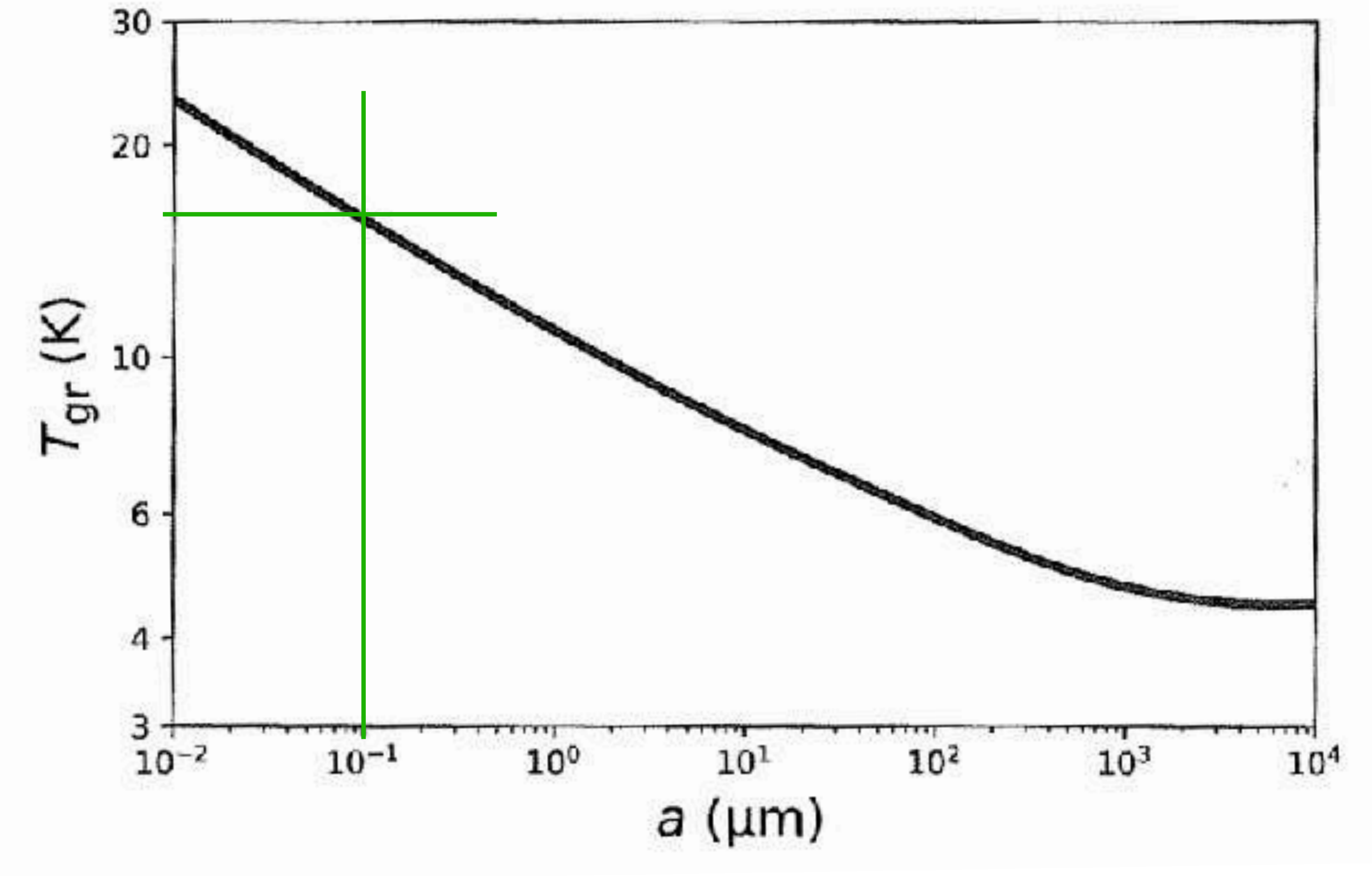
flux per steradian

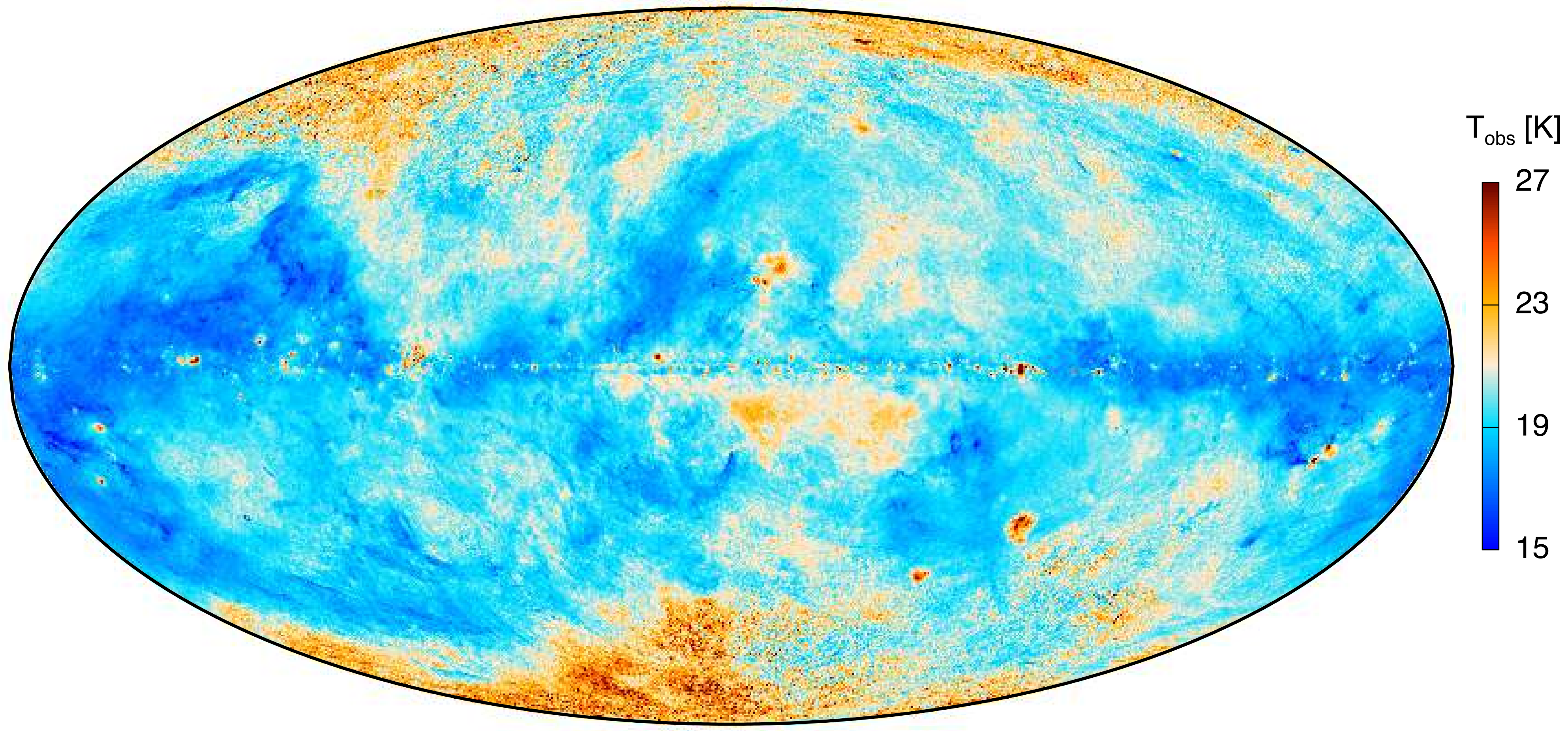
grain surface

power emitted per frequency unit

$$E_{em} = \int_0^\infty \boxed{S_{gr}}\,Q_{abs}(\nu)\boxed{\pi B_\nu(T)}\,d\nu$$

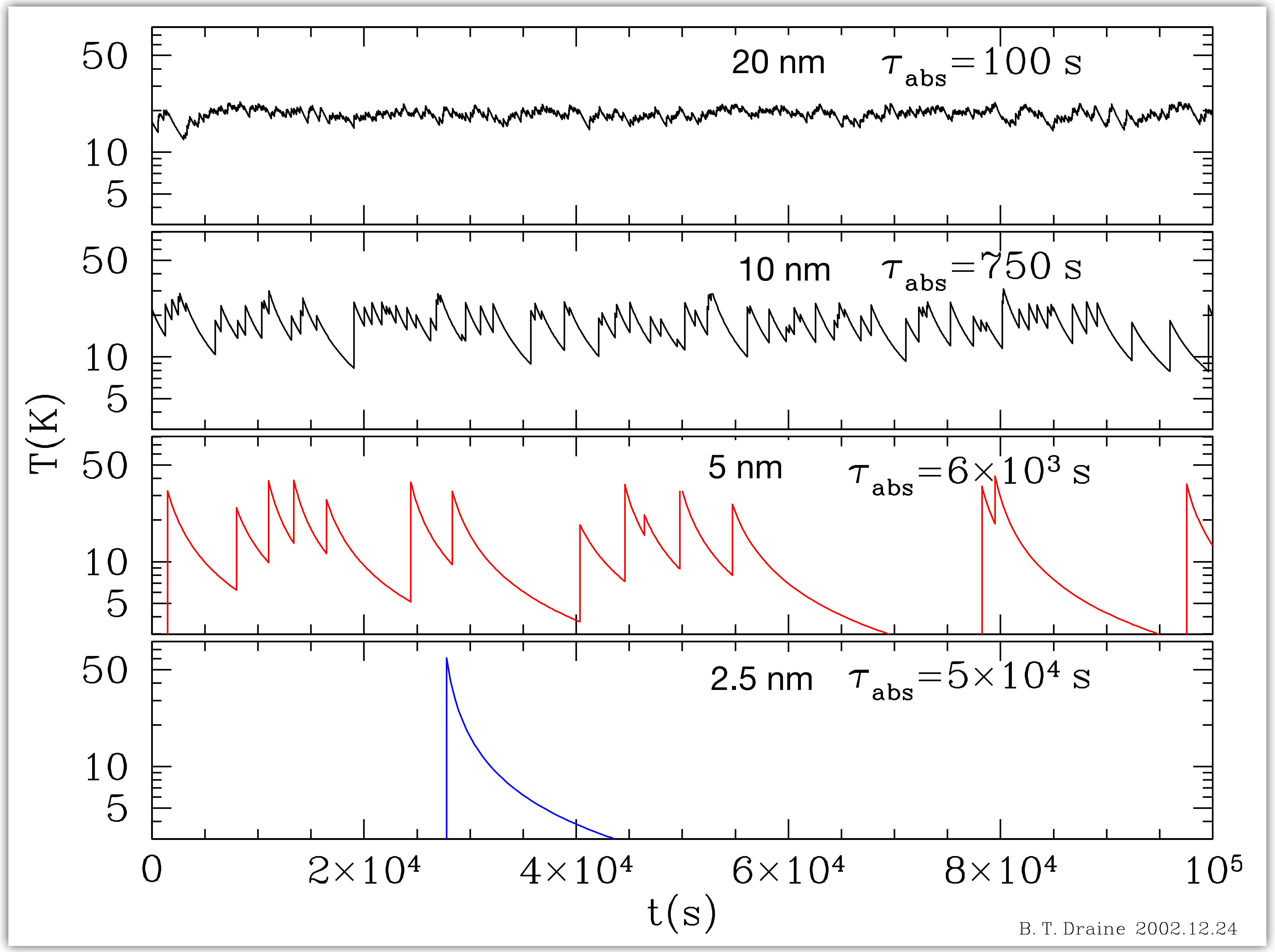
$E_{em} = E_{abs}$ gives $T_{eq}$





All sky Planck observations [Planck Collaboration 2013]

# Dust temperature (2/2)



- Big grains have a constant temperature

- Small grains :
  - absorb fewer photons than larger particles
  - reach higher temperature than larger ones (small heat capacity : $C(T) \approx 3N_{at}k_B$)
  - exhibit higher temperature fluctuations than larger ones

$$T \approx \frac{h\nu}{C(T)} \approx \frac{h\nu}{3N_{at}k_B}$$

  - 30 atoms (~0.5 nm) + <$h\nu$> = 8 eV ⇒ T ~ 1000 K (eg PAHs)

# Modelling grains emission: the big grains

- Medium is optically thin
- Grains in thermal equilibrium
- No temperature gradient on the line of sight

Modified Black Body model:

$$I_\nu = B_\nu(T_d)(1 - e^{-\tau_\nu}) \approx B_\nu(T_d) \times \tau_\nu$$

with : $\tau(\lambda) = N m_{gr} \kappa_{ext}$

- ISM big grains have T ≲ 20-30 K ⇒ emit in the FIR/mm domain
- In the FIR/mm, semi-classical physical models assume an asymptotic behaviours : $\kappa_\lambda = \kappa_{\lambda_0} \left(\frac{\lambda}{\lambda_0}\right)^{-\beta}$ with :
  - $\beta$ = 2 from Lorentz model
  - $\beta$ = 1-2 for phonons model

$$I_\nu \approx \tau B_\nu(T) = \frac{M_{dust} B_\nu(T)}{d^2 \Omega} \kappa_0 \left(\frac{\nu}{\nu_0}\right)^\beta$$

In the Rayleigh-Jeans limit : $I_\nu \approx \frac{M_{dust} 2k T_{dust}}{d^2 \Omega c^2} \left(\frac{\kappa_0}{\nu_0^\beta}\right) \nu^{2+\beta}$

# Modelling dust emission : small grains

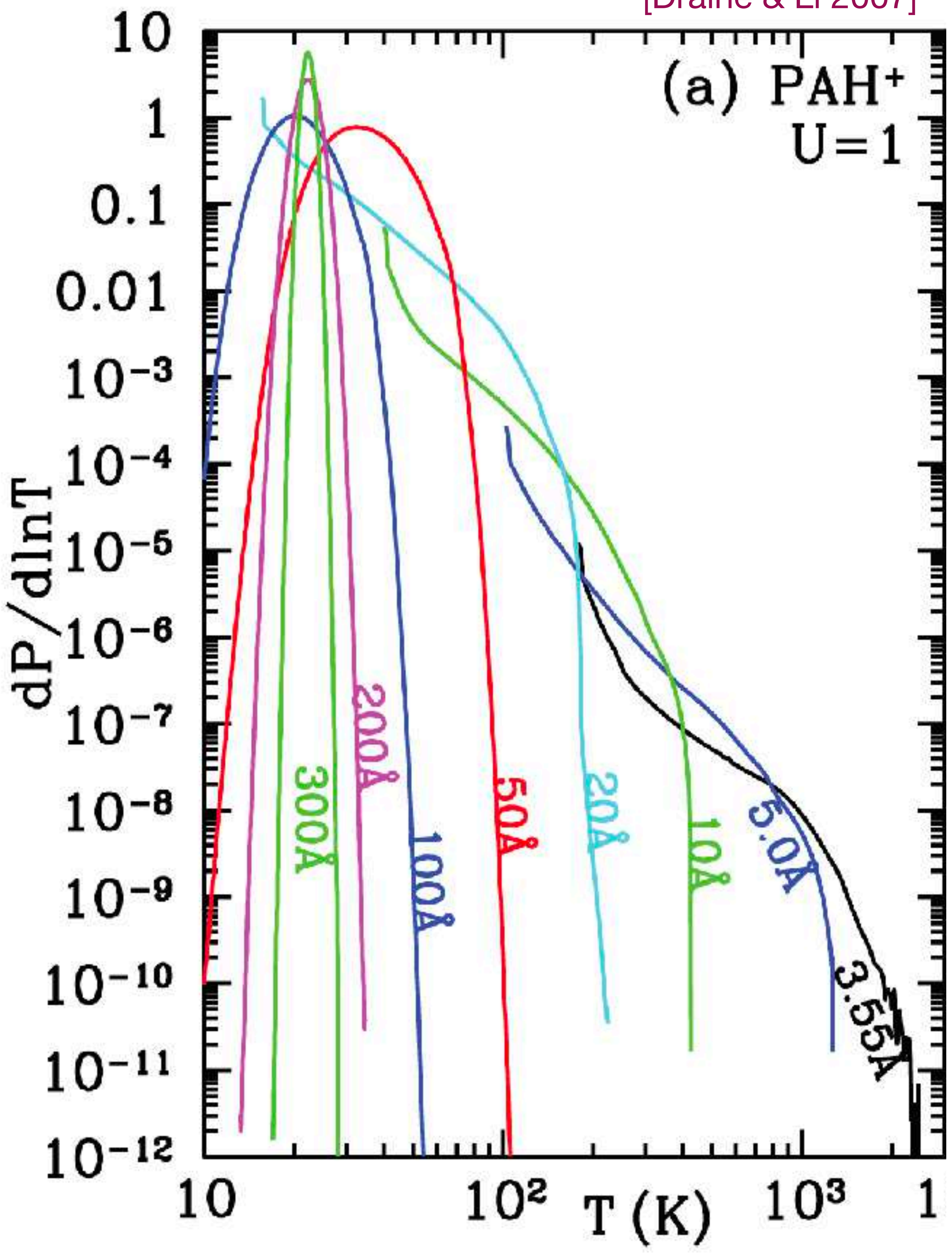
- Stochastic heating induced by the absorption of photons of the ISRF
- Strong temperature fluctuation if $h\nu_m > \int_0^{T_{eq}} C(T)dT$

starting from $h\nu = \int_0^{T} C(T)dT$ cooling as $\frac{dT}{dt} = \frac{1}{C(T)} \int_0^{\infty} S_{gr}Q_{abs}(\nu)\pi B(T)d\nu$

$$\Big\Downarrow$$

$$E_{em}(\nu) = \int_0^{\infty} S_{gr}Q_{abs}(\nu)\pi B(T)\frac{dP}{dT}dT$$

- Need to know the heat capacity of the species to calculate the temperature probability distribution of the different species



[Draine & Li 2007]

# Modelling dust polarisation

Polarisation requires alignment of dust grains with the magnetic field

- Magnetic dissipation
- Radiative torque alignment (RAT)

See also
Hoang & Lazarian 2016
Siebenmorgen+2014
Voshchinnikov+2016

Polarised intensity depends on

- Grain alignement
- Polarisation properties of the grains (composition, shape)

From Guillet+2017, used in DustEm :

Fraction of align dust (in mass) :

$$f(a) = \frac{1}{2} f_{\mathrm{max}} \left(1 + \tanh\left(\frac{\ln\left(a/a_{\mathrm{alig}}\right)}{p_{\mathrm{stiff}}}\right)\right)$$

Polarisation cross section :

$$\sigma_{\mathrm{pol}}(\lambda) = \sum_{j,i} n_j(a_i)\, f_j(a_i) \left(\frac{C_{2,\mathrm{ext}} - C_{1,\mathrm{ext}}}{2}\right)(j,i)$$

$C_{1,abs}$, $C_{1,sca}$, $C_{1,ext}$: E // $B_{pos}$
$C_{2,abs}$, $C_{2,sca}$, $C_{2,ext}$: E ⊥ to $B_{pos}$

Total polarised intensity :

$$P_\nu(\lambda) = \sum_{j,i} n_j(a_i)\, f_j(a_i) \left(\frac{C_{2,\mathrm{abs}} - C_{1,\mathrm{abs}}}{2}\right)(j,i)\, B_\nu(\lambda, T_j(a_i))$$

# Summary

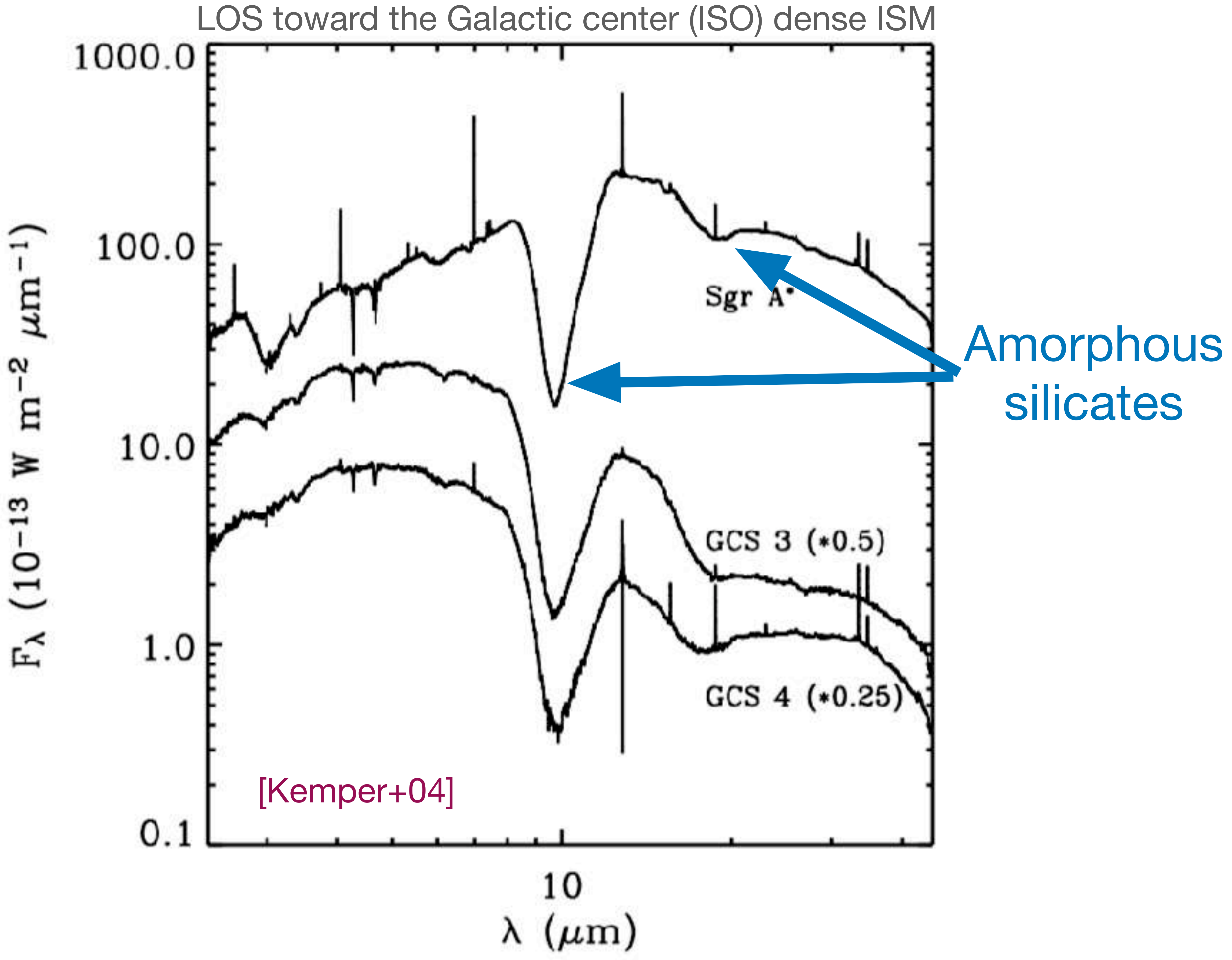
- Observational constraints : depletion, extinction, emission, scattered light, polarisation from X-ray to mm
- Spectroscopic observations provide information on the dust composition and structure
- Analysis of presolar grains provide information on dust composition and formation site

- Several components of dust exist: silicates, carbonaceous grains, ices, PAHs
- Distribution of size: from ~ 0.5 nm to up to ~0.5 µm in the ISM
- Grains are not spherical and are partially aligned
- Silicates represent ~70% in mass

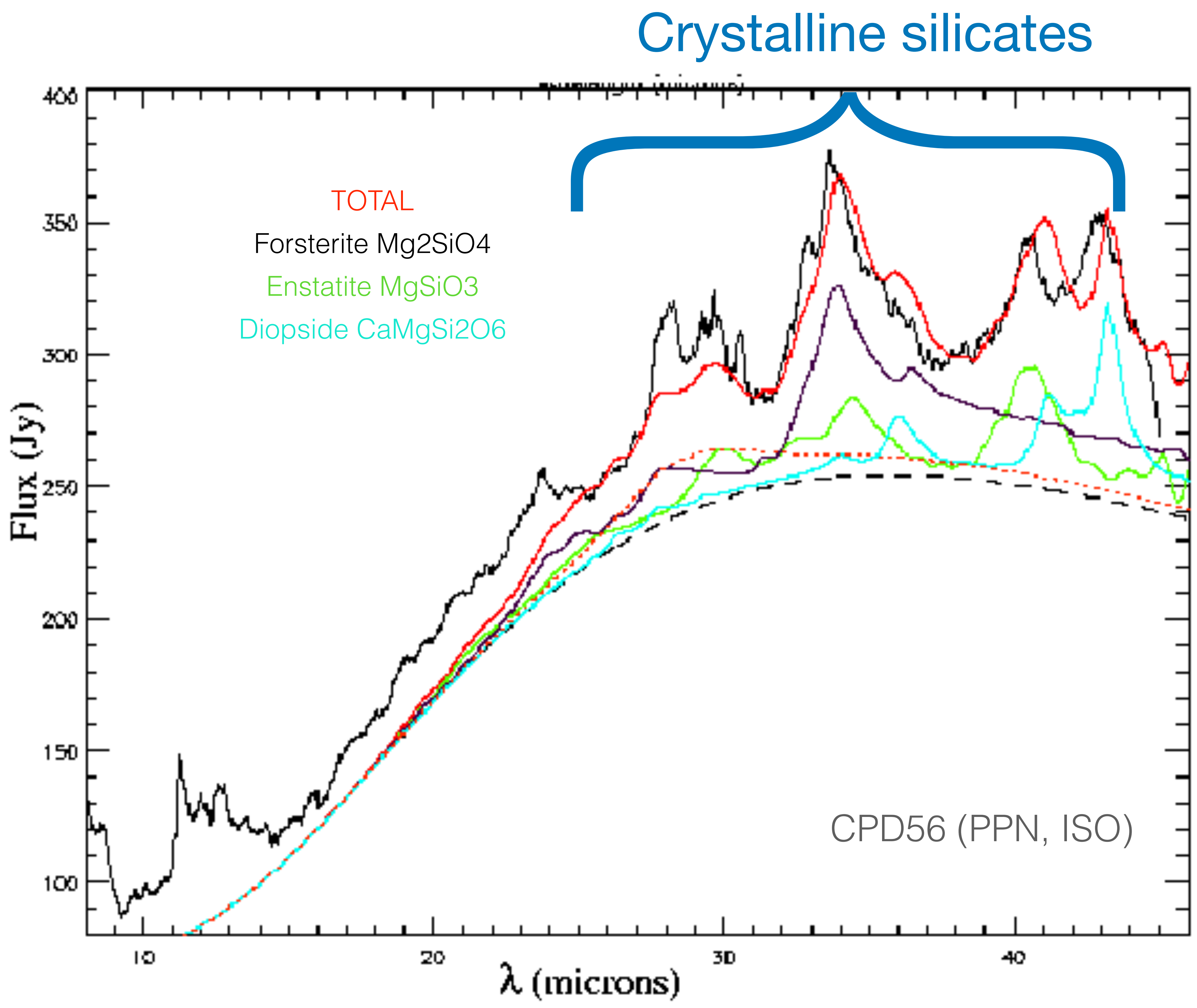
# Main dust constituents and cosmic dust models

# Silicates : the 9.7 & 18 µm features

- Main dust component : ~ 70 % in mass
- Mainly amorphous
- Crystalline and amorphous in circumstellar environments
- Mostly Mg-rich silicates such as amorphous enstatite ($MgSiO_3$) and forsterite ($Mg_2SiO_4$)

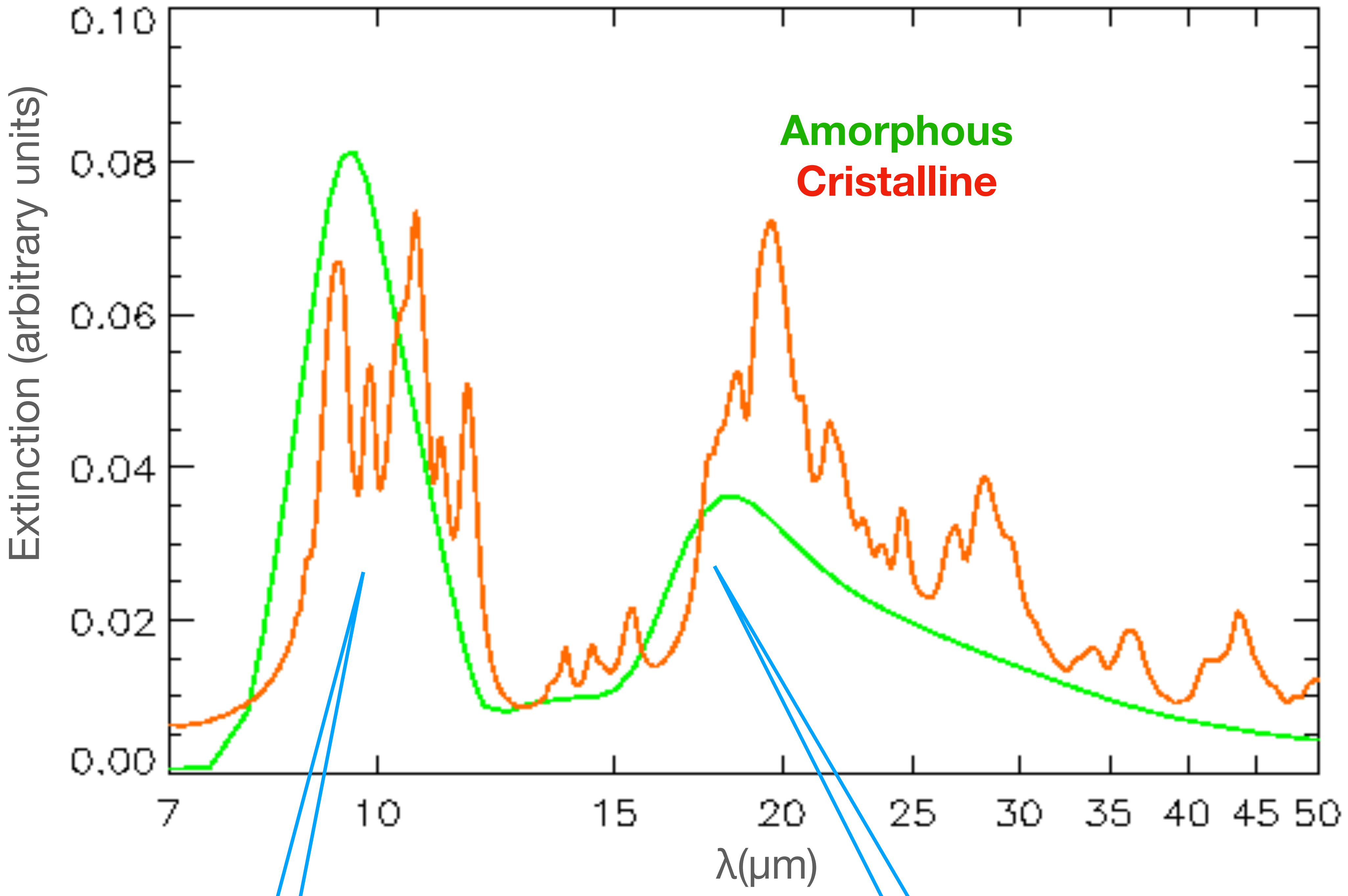

LOS toward the Galactic center (ISO) dense ISM

[Kemper+04]


CPD56 (PPN, ISO)

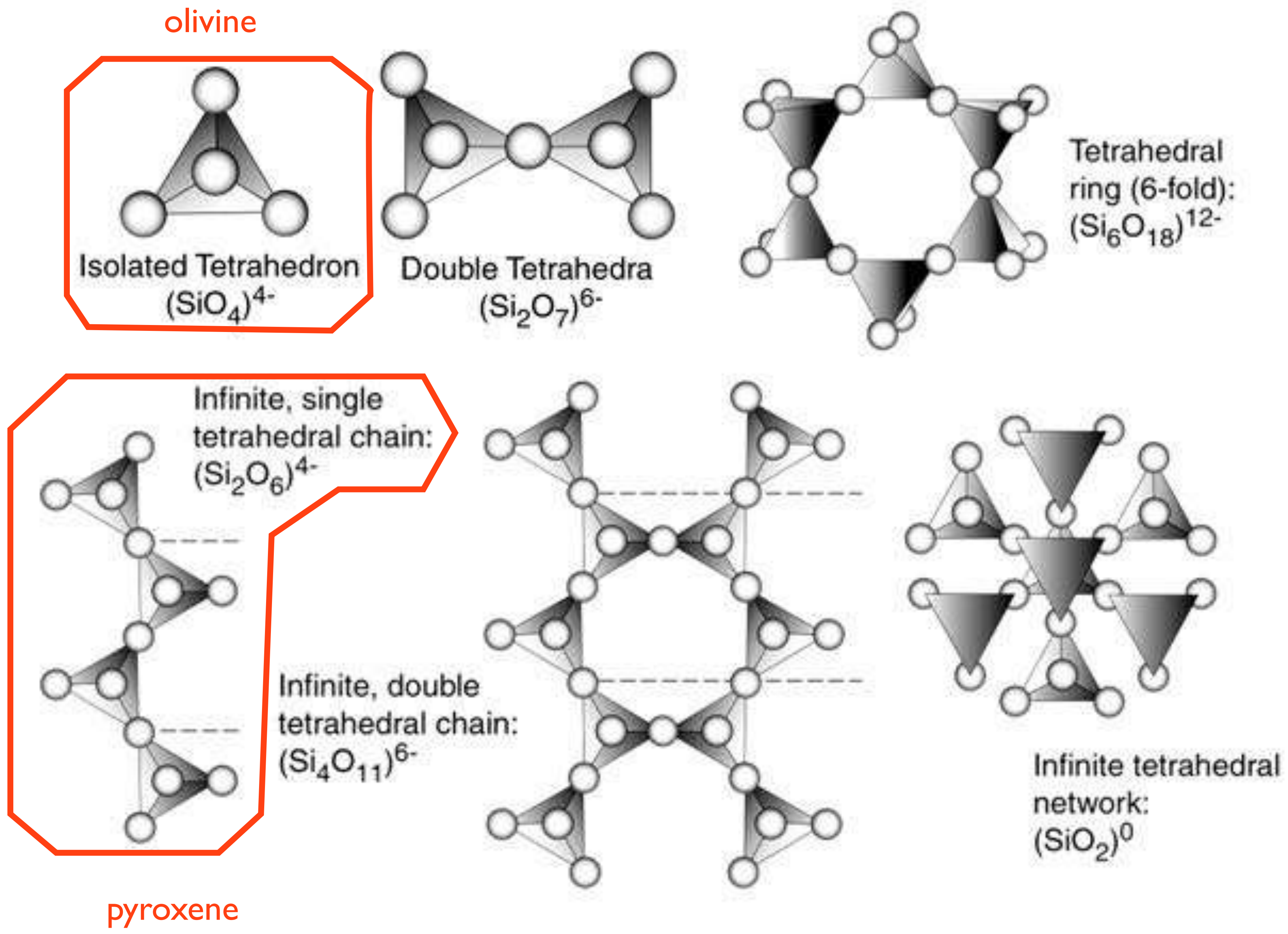
# Silicates : composition and structure

MIR spectrum of $MgSiO_3$ grains



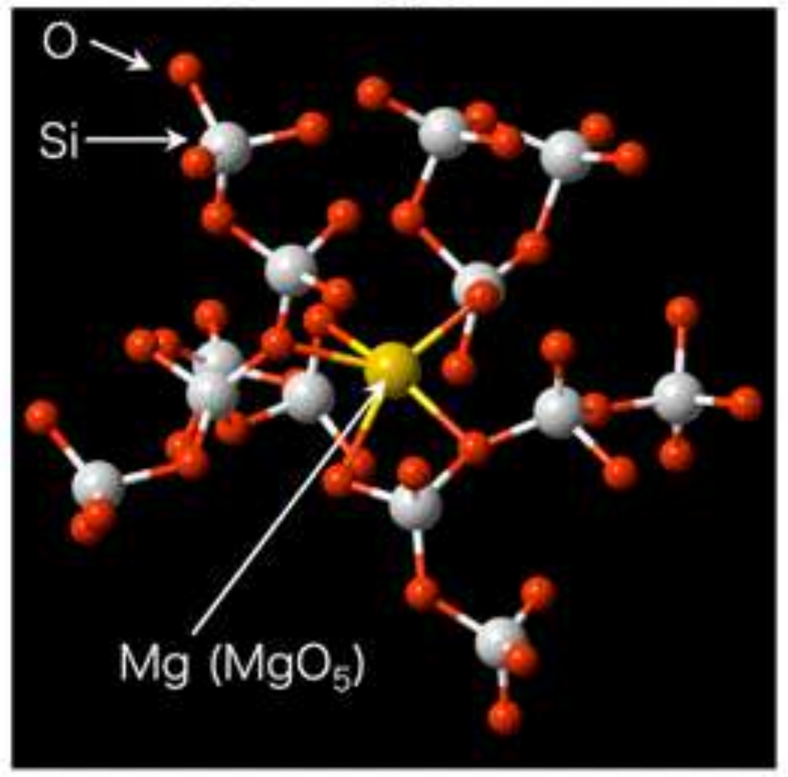
9.7 μm: Si-O stretching mode

18 μm: Si-O bending mode

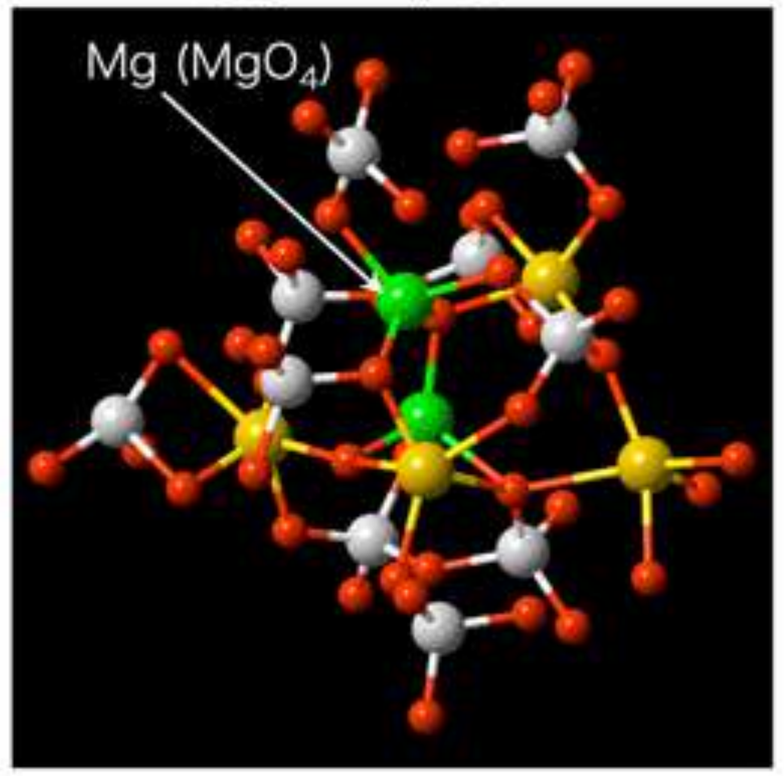


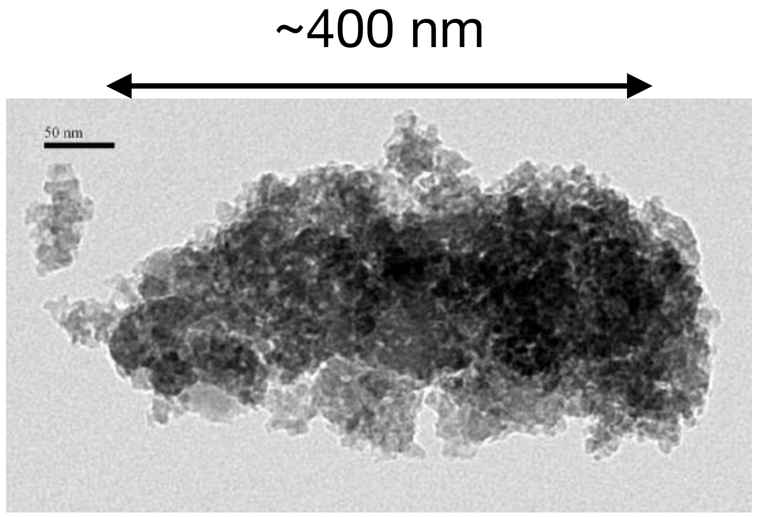
Olivine

$MgSiO_3$ glass



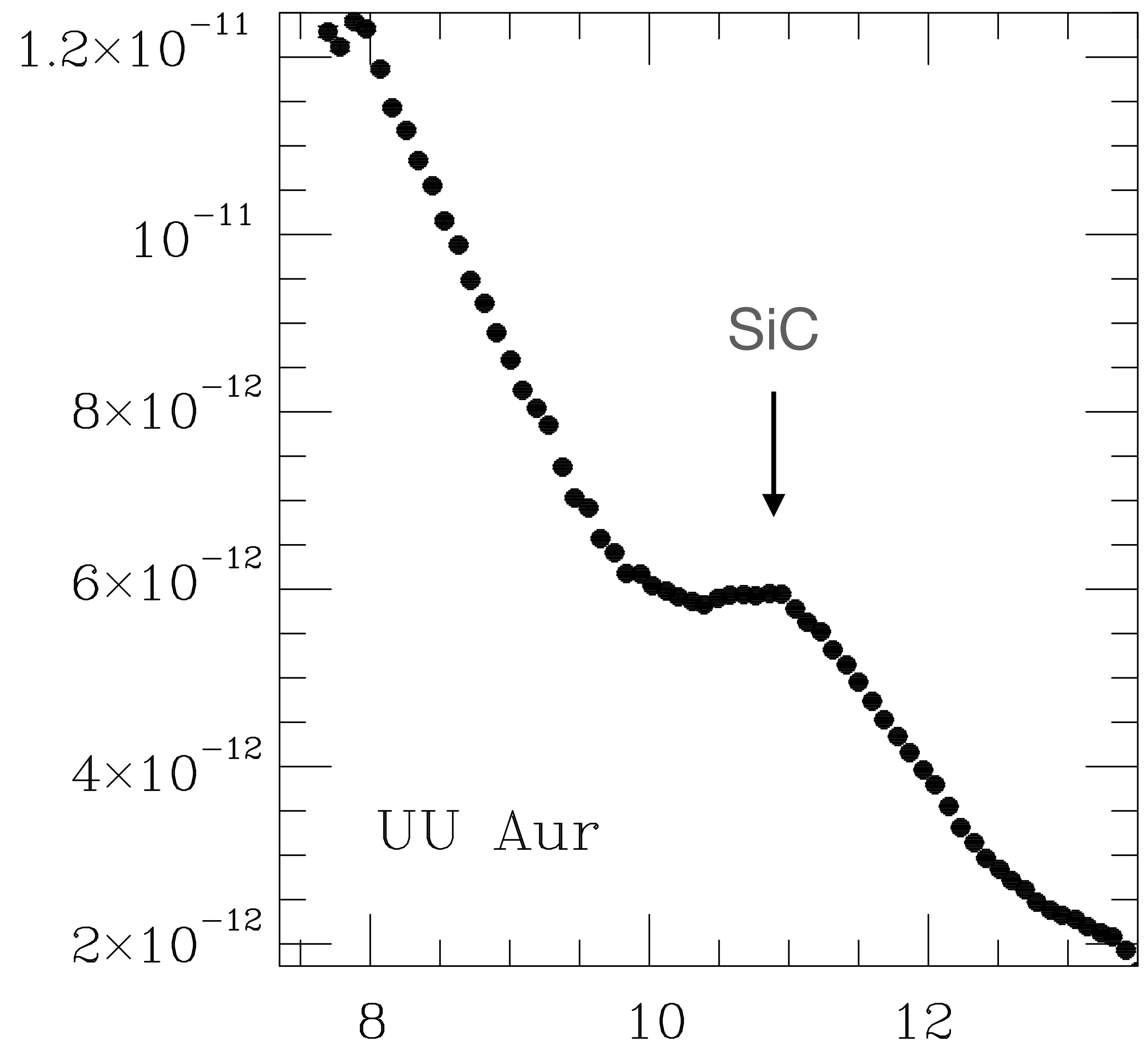
$Mg_2SiO_4$ glass



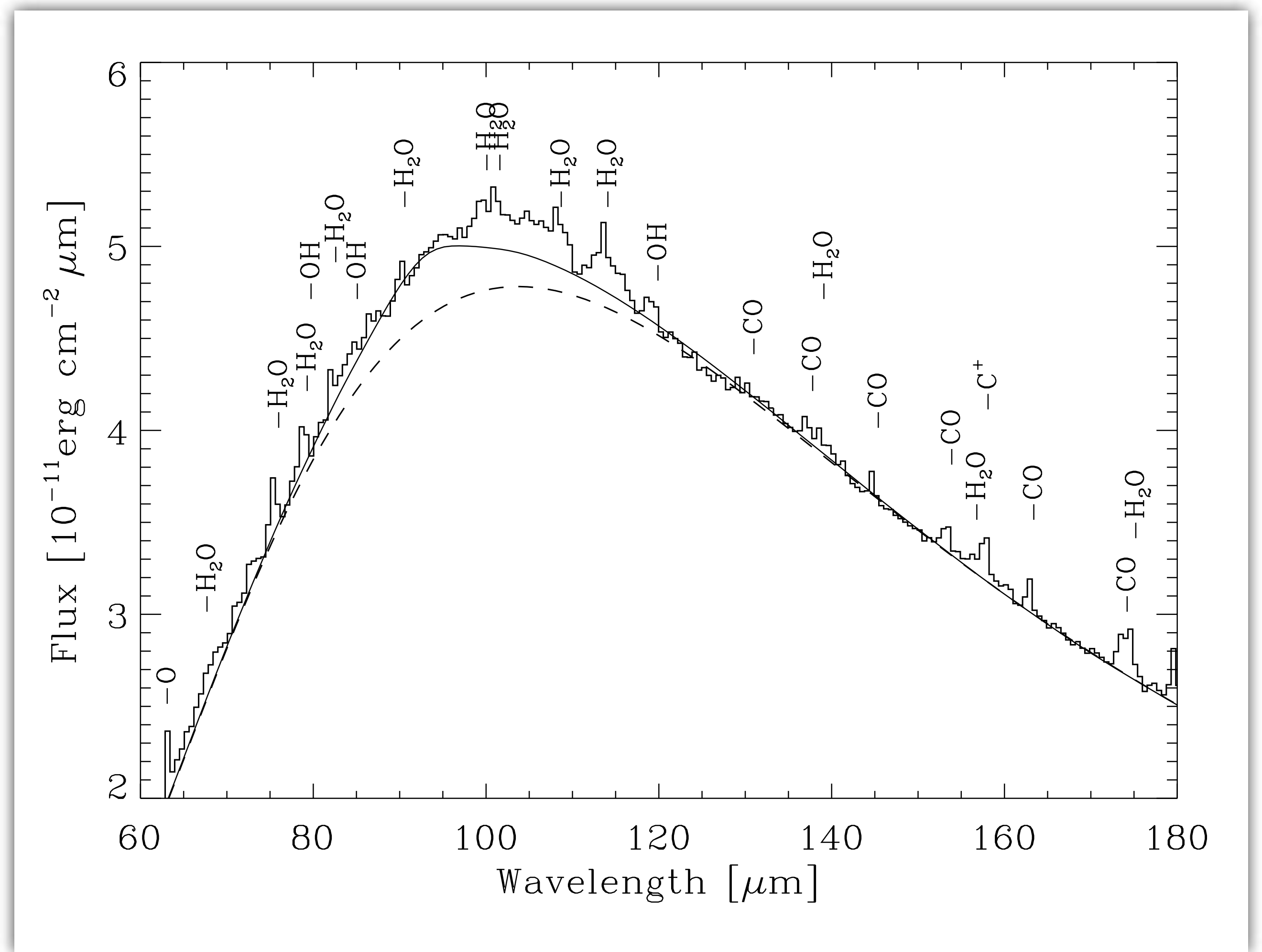


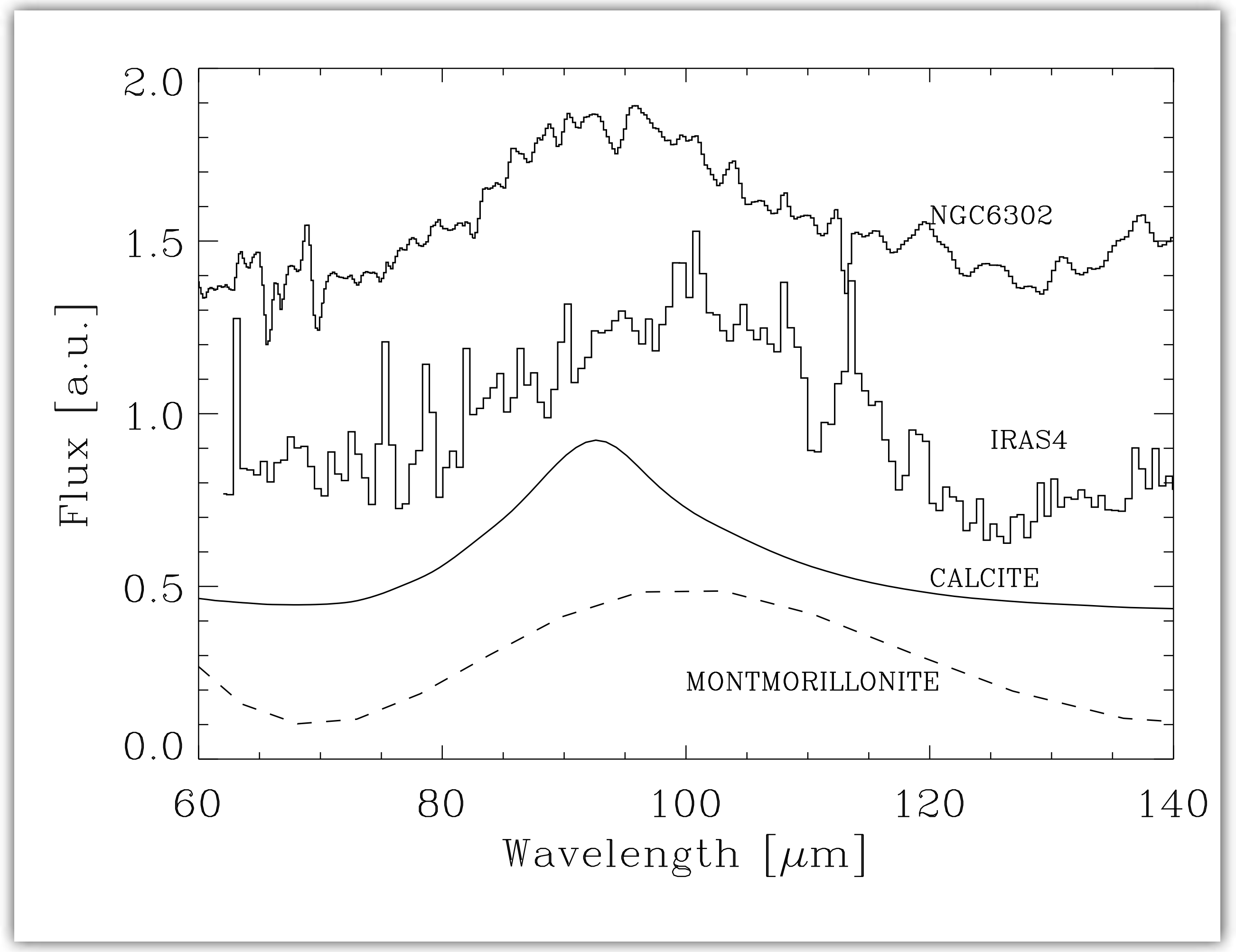
# Other large grains

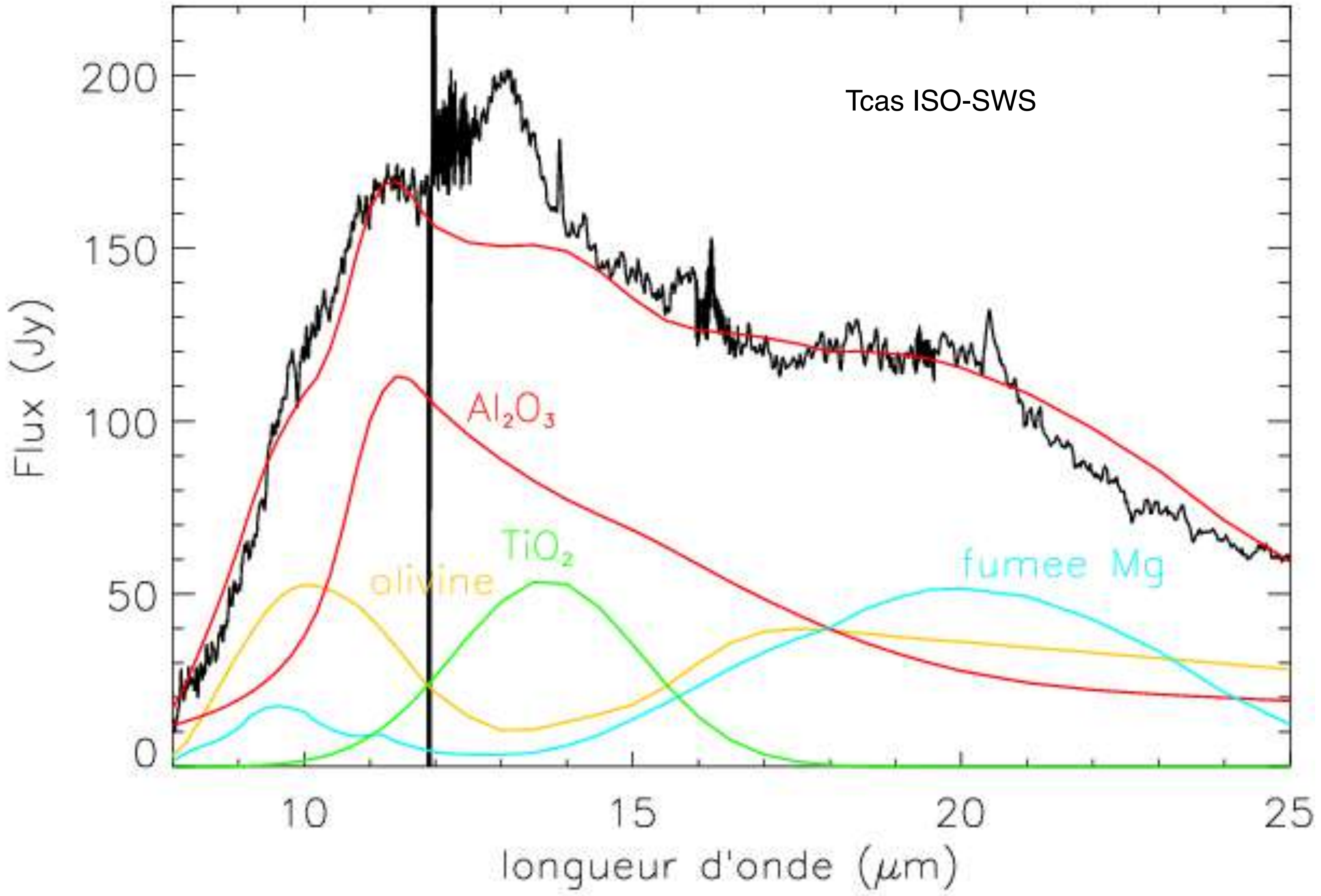
- SiC
- Oxides : $Al_2O_3$, $TiO_2$, $Mg_xFe_{1-x}O$
- MgS ?
- TiC?
- The most refractory could be nucleation seeds
- Difficult to observe because of spectral blending



- Broad band at 90-100 µm :
  - Hydrated silicates?
  - Carbonates?





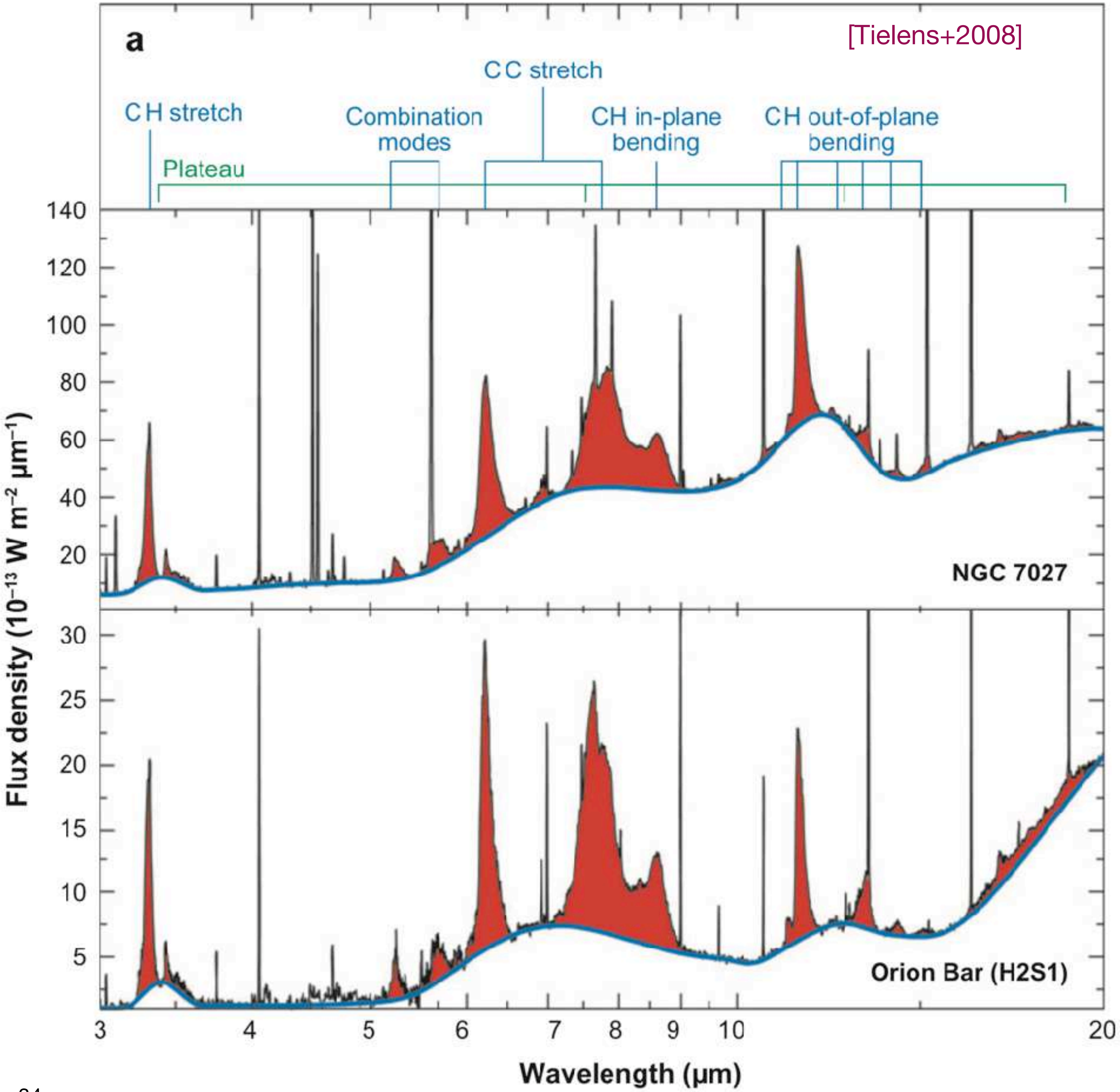


# Aromatic dust: the Aromatic Infrared Bands

- Observed in photo-dominated regions, circumstellar shells and disks around evolved and young stars

- ~10-20 % of cosmic carbon
- ~ 5 % of the dust mass

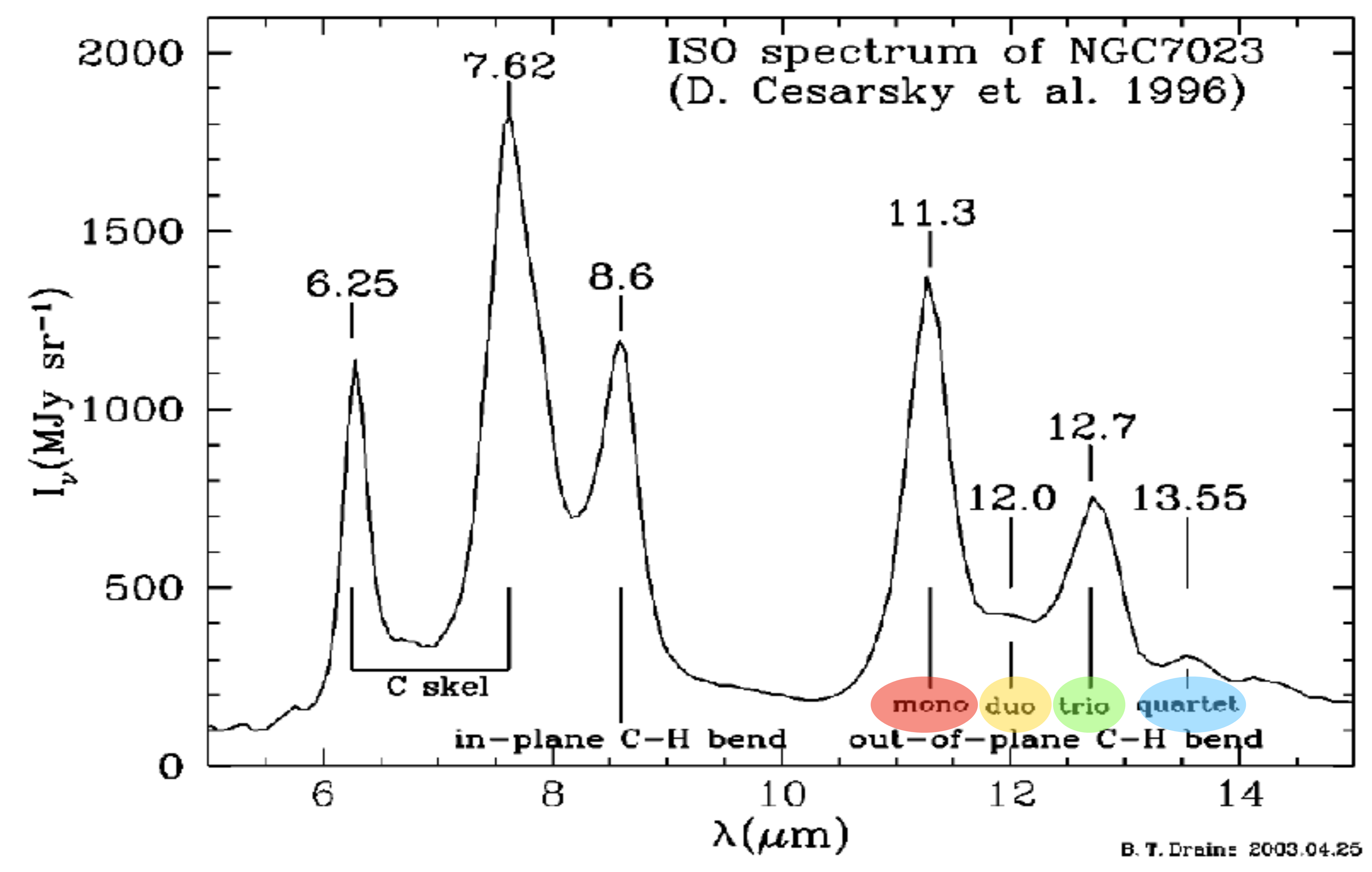
- Heated stochastically
- Band strengths and band ratios vary with the environments
  - $I_{7.7\mu m}/I_{11.3\mu m}$ ↗ with charge
  - $I_{3.3\mu m}$ stronger for small particles and.or strong radiation field

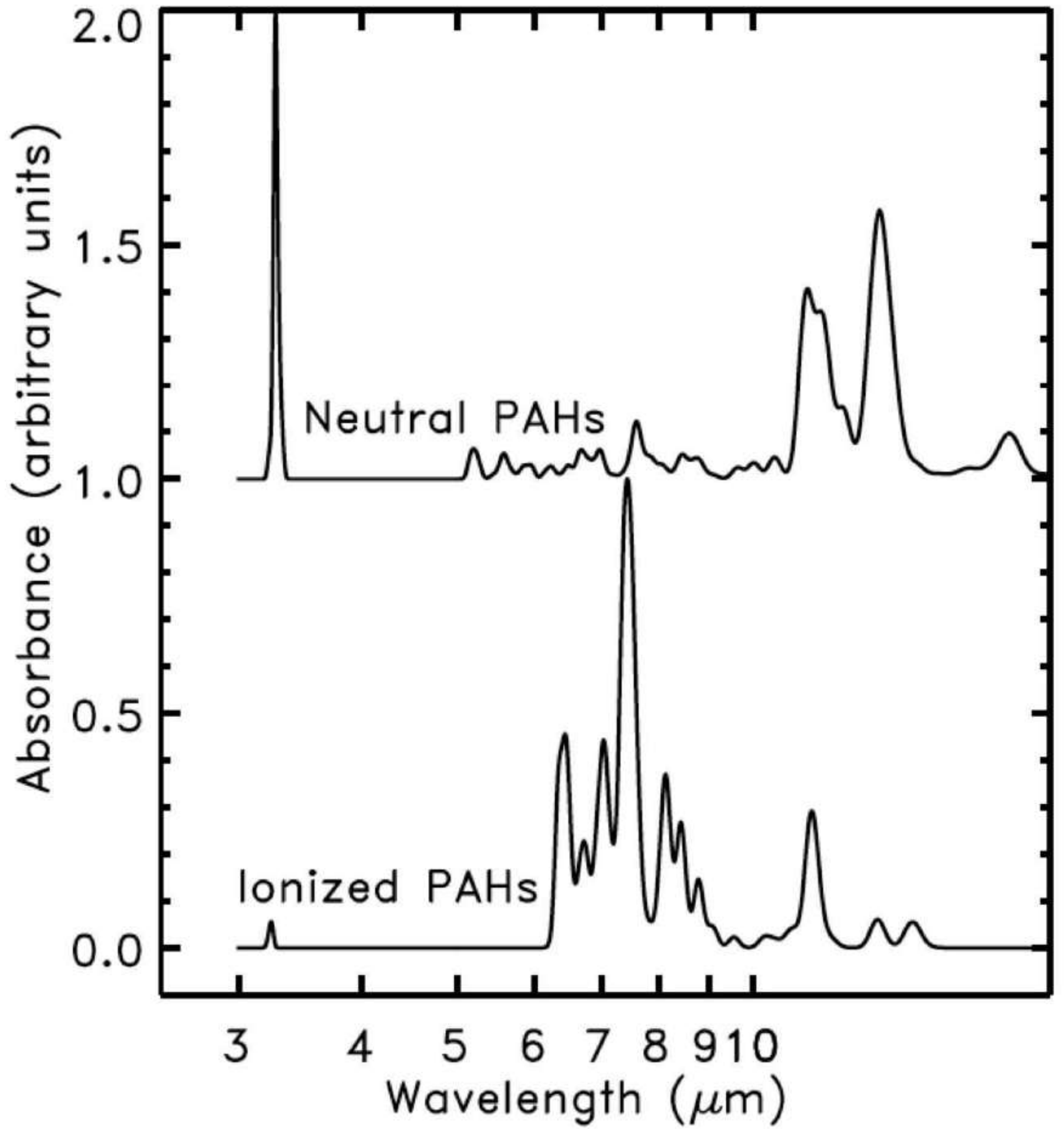


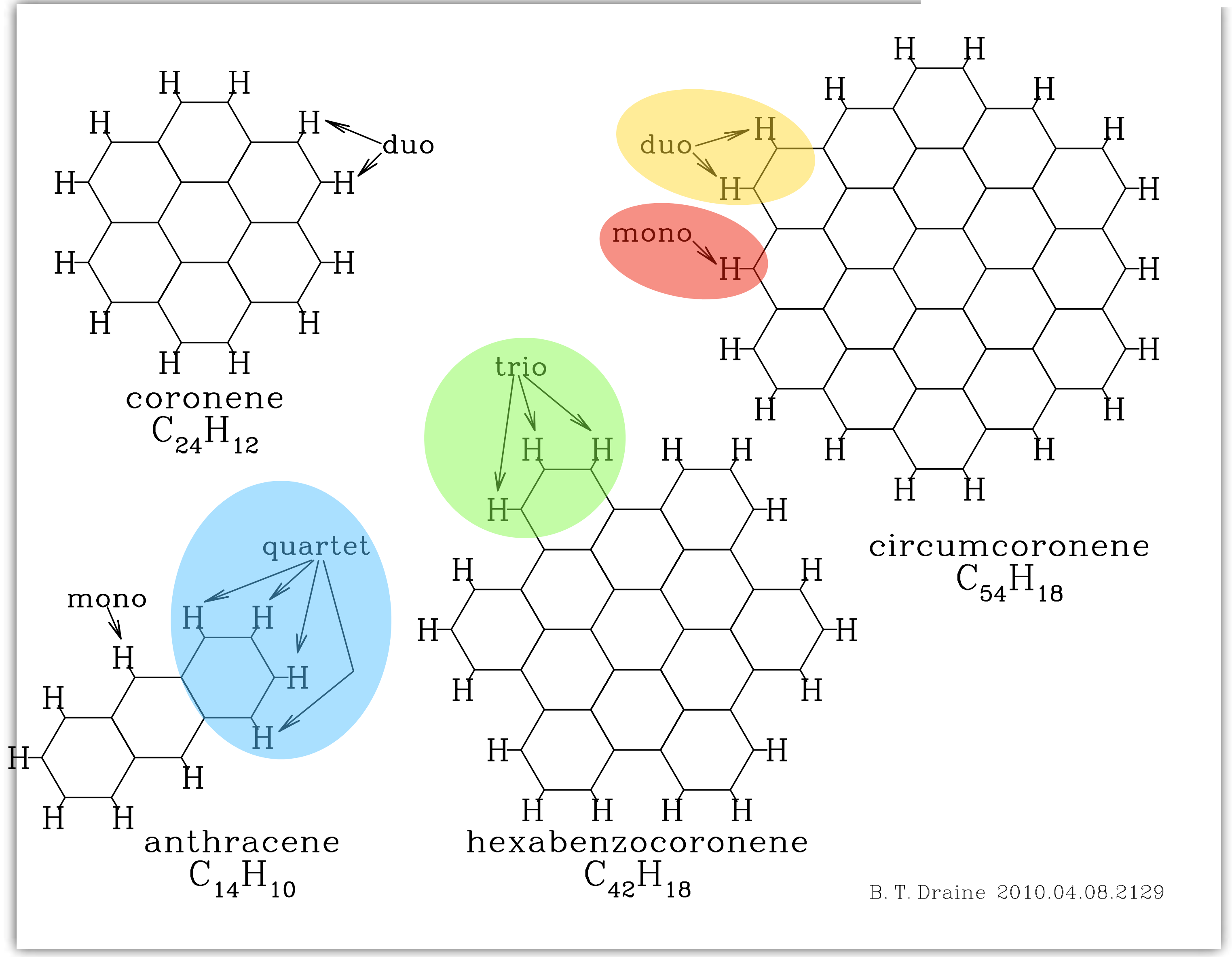
# Aromatic dust: Polycyclic Aromatic Hydrocarbons

- Aromatic molecule such as PAHs
  - distribution of size : ~ several tens of C atoms
  - no single identification
  - could explain some DIBs (ionised PAH)

[See review from Tielens 2008]



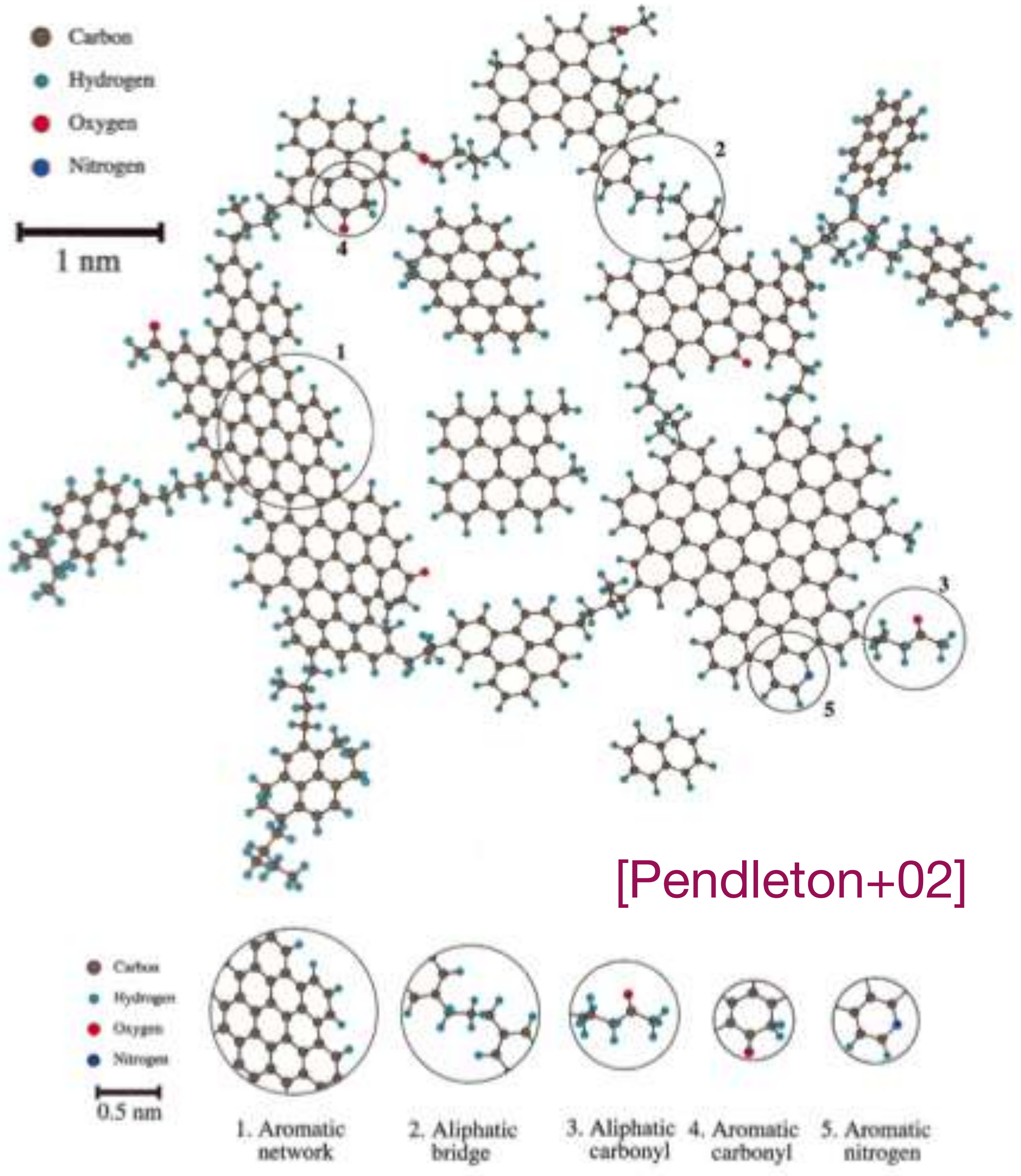




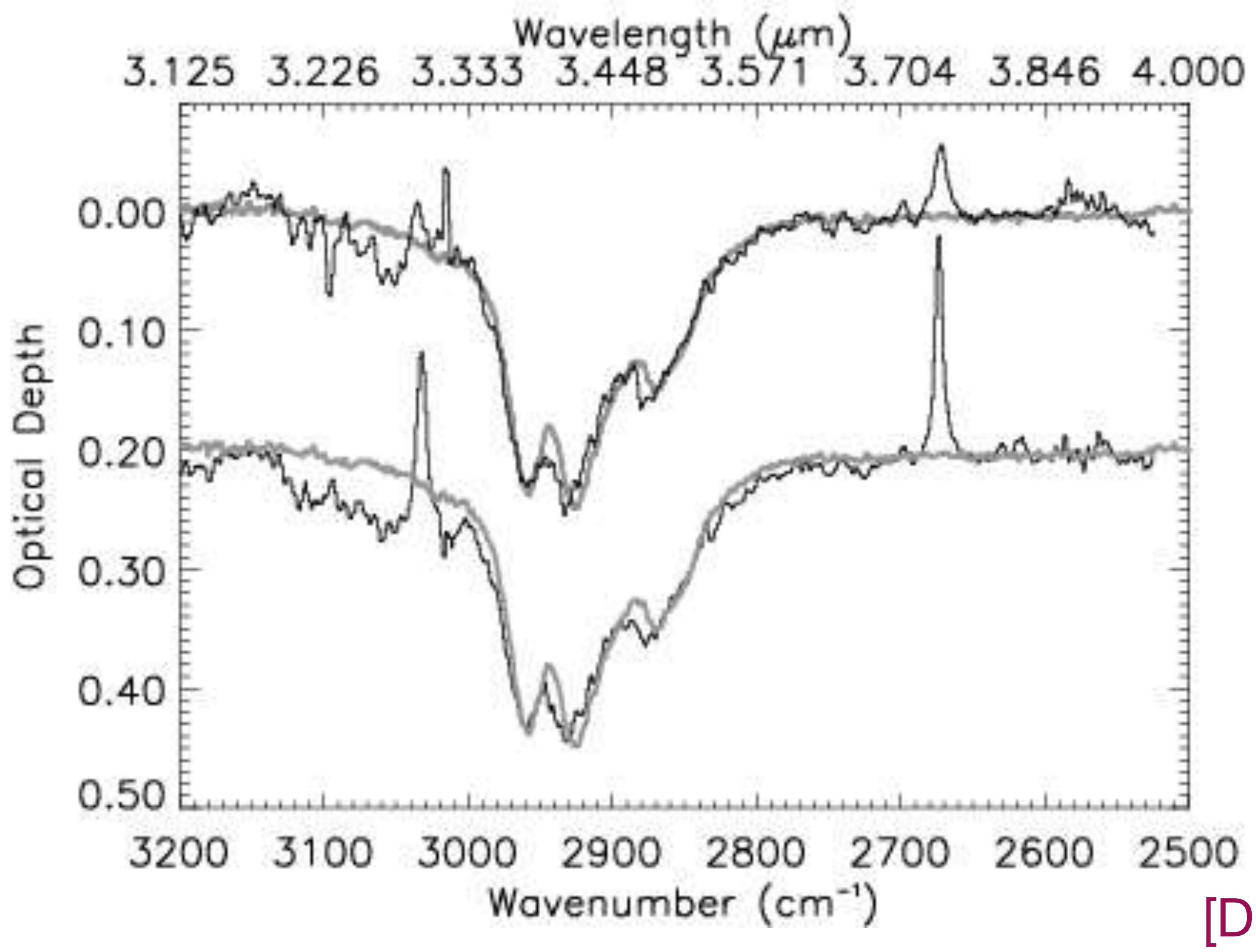
# Hydrogenated amorphous carbon

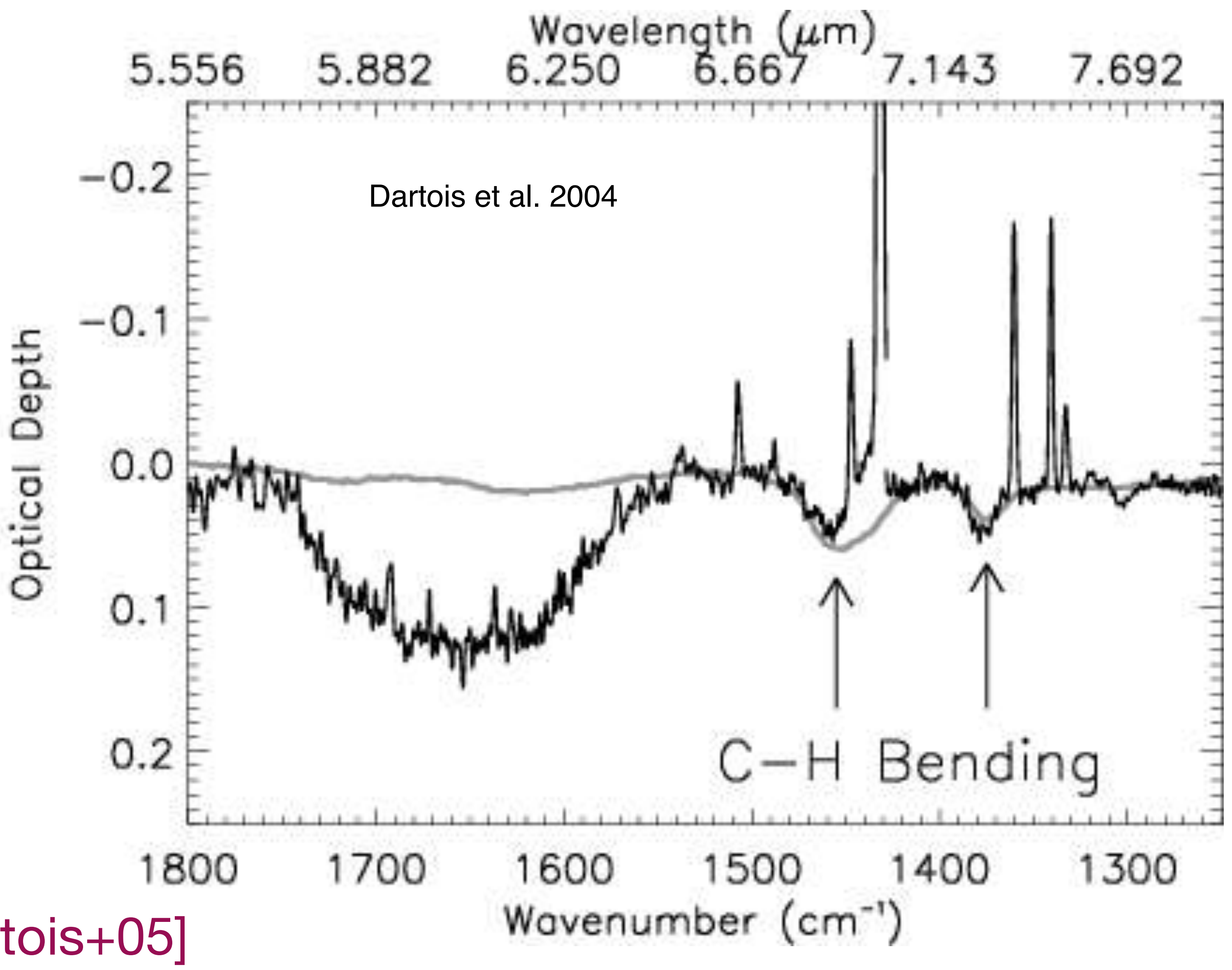
- **Hydrogenated amorphous carbon (HAC or a-C:H) :**
  - In absorption in sightlines with sufficient $N_H$
  - 3.38, 3.42, 6.85 et 7.25 µm features : stretching and bending of C-H bonds in $CH_2$ and $CH_3$ groups
  - ratio aliphatic/ aromatic variable:
    - < 15 % aromatic in Dartois+2004
    - ~ 85 % aromatic in Pendelton+2002


[Dartois+05]



[Pendleton+02]

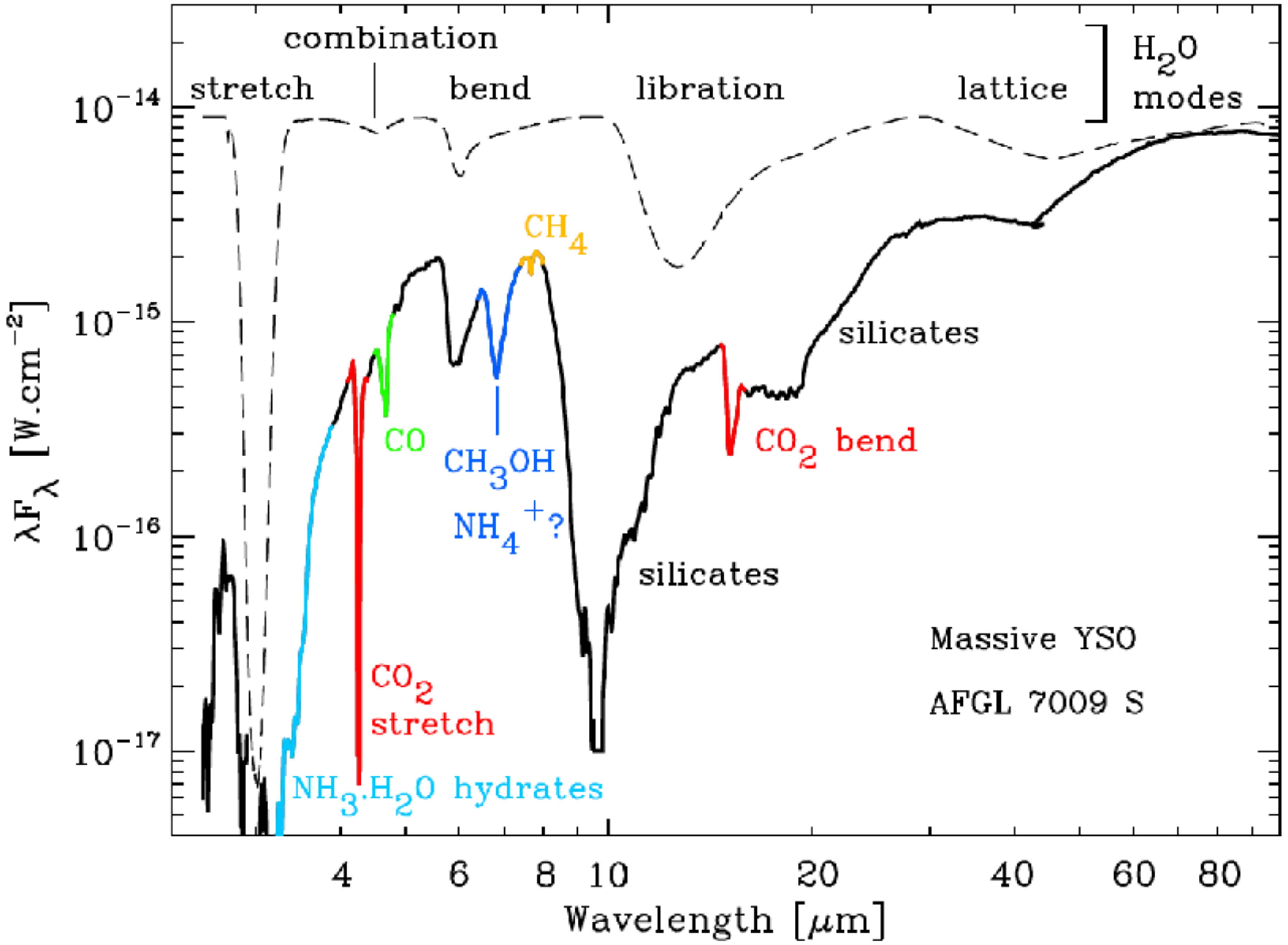




[Dartois+05]

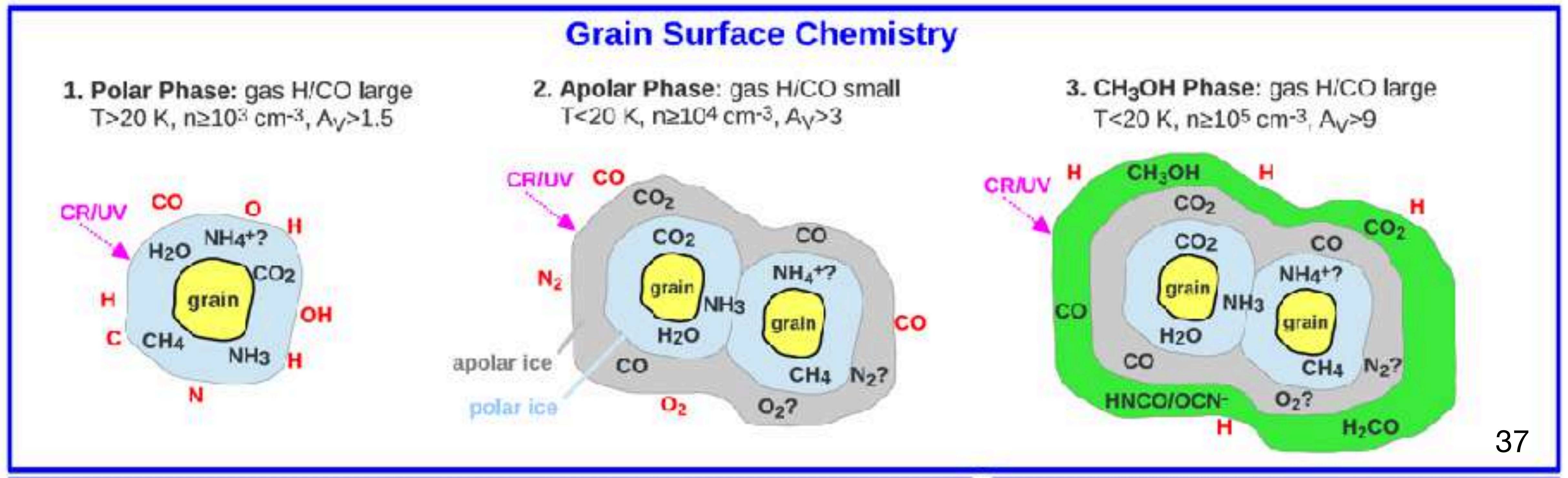
# Volatile dust : ices

[Dartois +1998 in Boogert 2015]



- **Ices mantles form at $A_V \lesssim$ 2-3**
- Dense clouds
- Protostars of all masses
- Circumstellar shells of OH/IR stars and some AGB
- Elemental budget => grain mantle of 5-10 nm

- Main species: $H_2O$, CO, $CO_2$, $CH_3OH$, $NH_3$, $CH_4$
- Others likely species: $H_2CO$, $OCN^-$, OCS, HCOOH, $CH_3CH_2OH$, $HCOO^-$, $CH_3CHO$, $NH_4^+$,$SO_2$, PAH

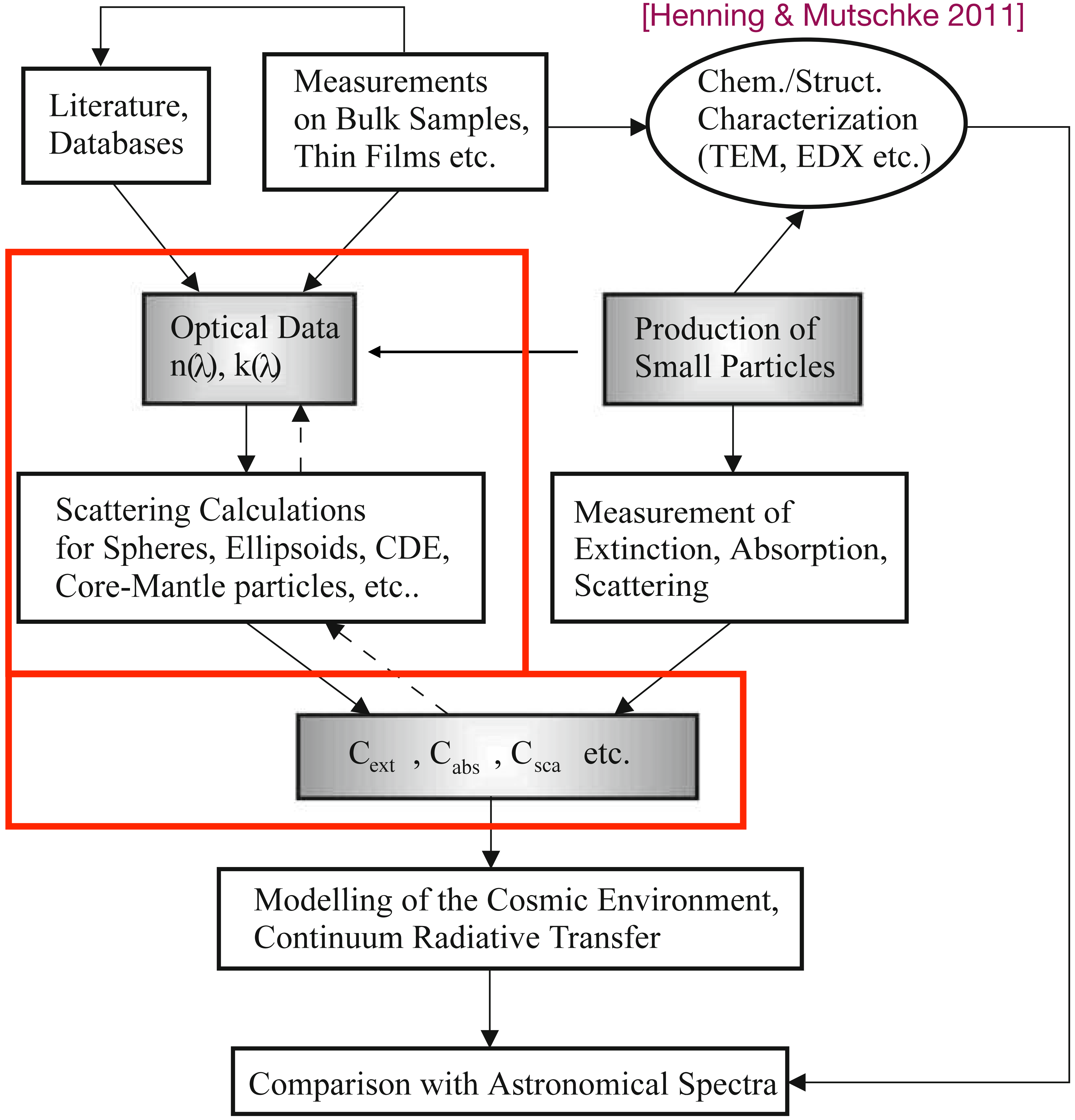


[See review from Boogert+2015]

| | |
|---|---|
| $H_2O$ | 100 |
| CO | 7-25 |
| $CO_2$ | 15-28 |
| $CH_3OH$ | 6-9 |
| $NH_3$ | 3-10 |
| $CH_4$ | 1-11 |

# Cosmic dust models

- Based on the physical characteristics of the dust :
  - dielectric constants
  - heat capacity for emission modelling
  - photo absorption cross-section
- These data come from laboratory astrophysics studies of dust analogues
- Consider various dust populations, shape and size distributions
- Constrained on a set of observations and cosmic abundances



[Henning & Mutschke 2011]

# Some dust models for the DISM

**Constraints from extinction & emission (old models):**

- Draine & Lee (1984) and later versions [eg. Weingartner & Draine 2001,Draine & Fraisse 2009]: *astrosilicates* & graphite & PAHs
- Compiègne et al. 2011: *astrosilicates* & amorphous carbon & PAHs & PAHs$^+$
- Zubko et al. 2004: *astrosilicates* & graphite or amorphous carbon & PAHs & $H_2O$ ice and organic refractory
- Jones et al. 2013, 2017, Koehler et al. 2015: THEMIS model : lab silicates (MIR) & a-C(:H)

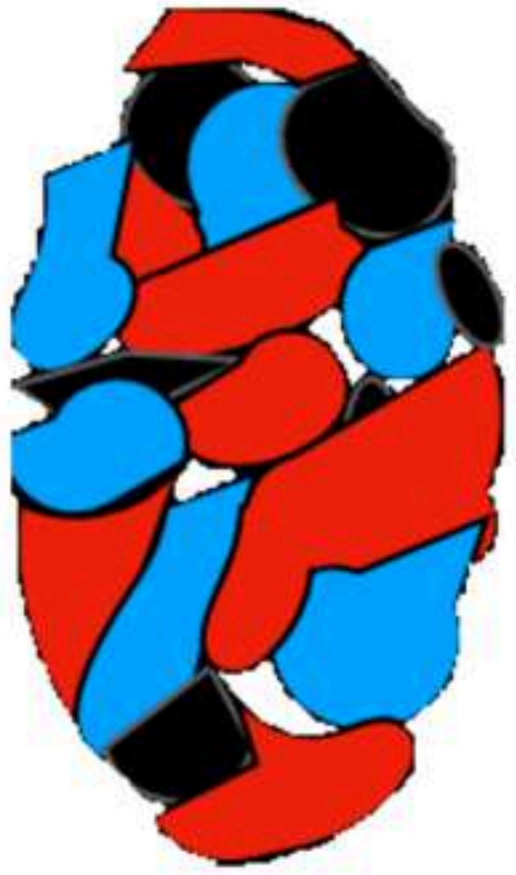
**Constraints from extinction, emission & polarisation (new models):**

- Siebenmorgen et al. 2014, 2017: *astrosilicates* & amorphous carbon & PAHs— *polarised extinction*
- Guillet et al. 2018: *astrosilicates* & amorphous carbon & PAHs — *polarised extinction and emission*
- Draine & Hensley (2021): *Astrodust* + PAHs — *polarised extinction*
- Ysard et al. 2024 : The THEMIS II model: lab silicates (MIR/FIR) at low T & a-C(:H) — *polarised extinction and emission*

# Astrodust & THEMIS models for the DISM

## Astrodust

- Reproduces grain evolution in the DISM: destruction and re-condensation
- Two dust components:
  - astrodust: porous mixture of silicates & carbonaceous matter on grain surface
  - PAHs
- Spheroidal grains



Assumption about composition:

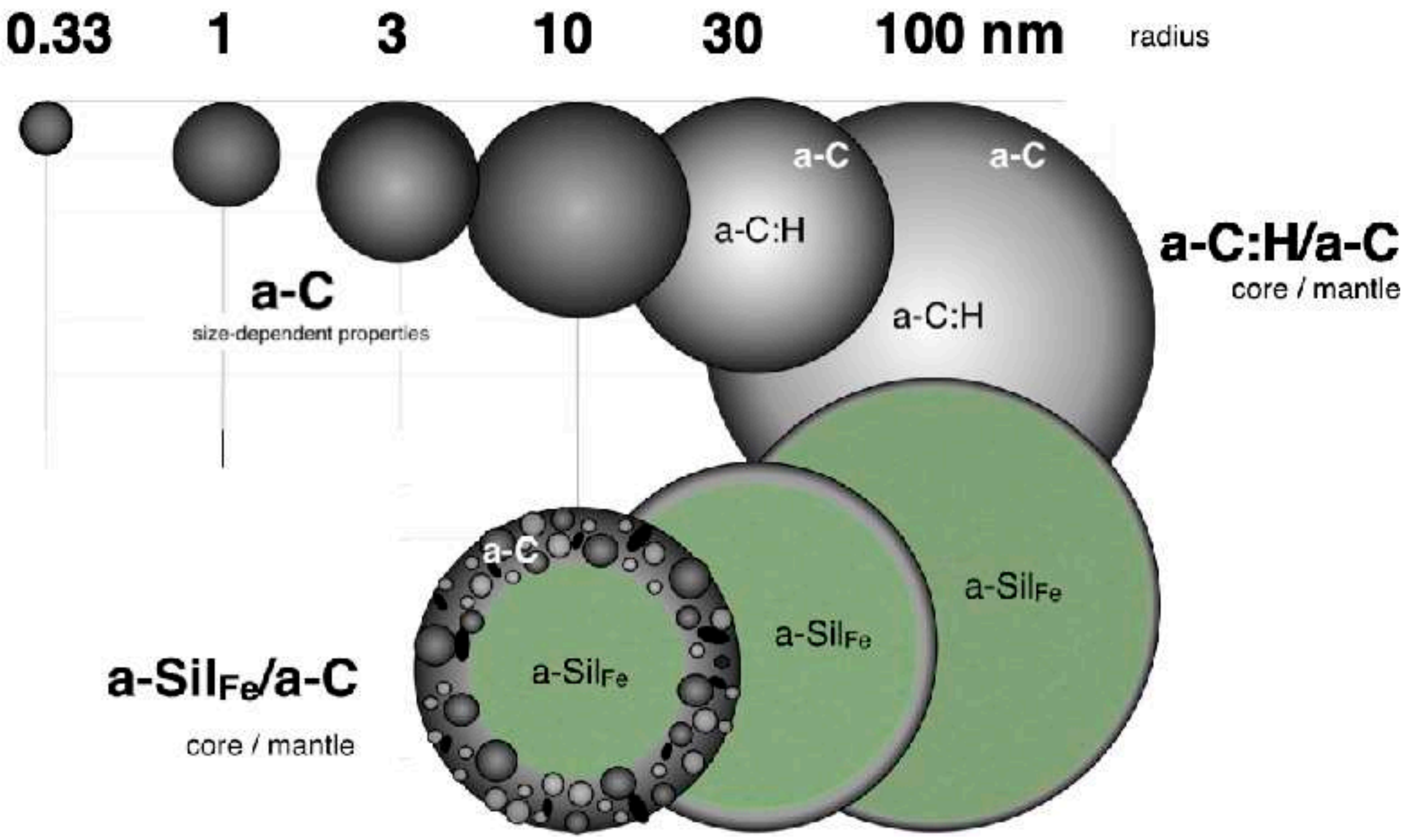
amorphous silicate
hydrocarbon material
other materials (e.g. Fe oxides, $Al_2O_3$, $CaCO_3$)

Hensley & Draine 2020, 2023 Draine & Hensley 2021

https://dataverse.harvard.edu/dataverse/astrodust;jsessionid=6ad4b0855ffdf13379ecb46eb838

## THEMIS

- Reproduces grain evolution in the DISM: mantle accretion and processing
- Core/mantle grain model
- Aromatic carbon (a-C), hydrogenated hydrocarbons (a-C:H) and silicates (low temperature experimental data) with Fe inclusions



https://www.ias.u-psud.fr/themis/
[Jones +2013, Köhler +2014, 2015] [Ysard+2024]

# Some dust models for dense environments

- Pollack (1994) model: lab silicates, Fe, organic C —molecular clouds and transition disks
- Ossenkopf et al (1994): lab silicate and amorphous carbon grains, ices - dense protostellar cores
- Zubko et al. 2004: astrosilicates & graphite or amorphous carbon & PAHs & $H_2O$ ice and organic refractory
- Jones et al. 2013, 2017, Koehler et al. 2015: THEMIS model : core-mantle aggregates with lab silicates (MIR), a-C(:H) & $H_2O$ ice
- Under progress: THEMIS 2 model : core-mantle aggregates with lab silicates (MIR), a-C(:H) & $H_2O$ ice

# Some dust models used in disk models

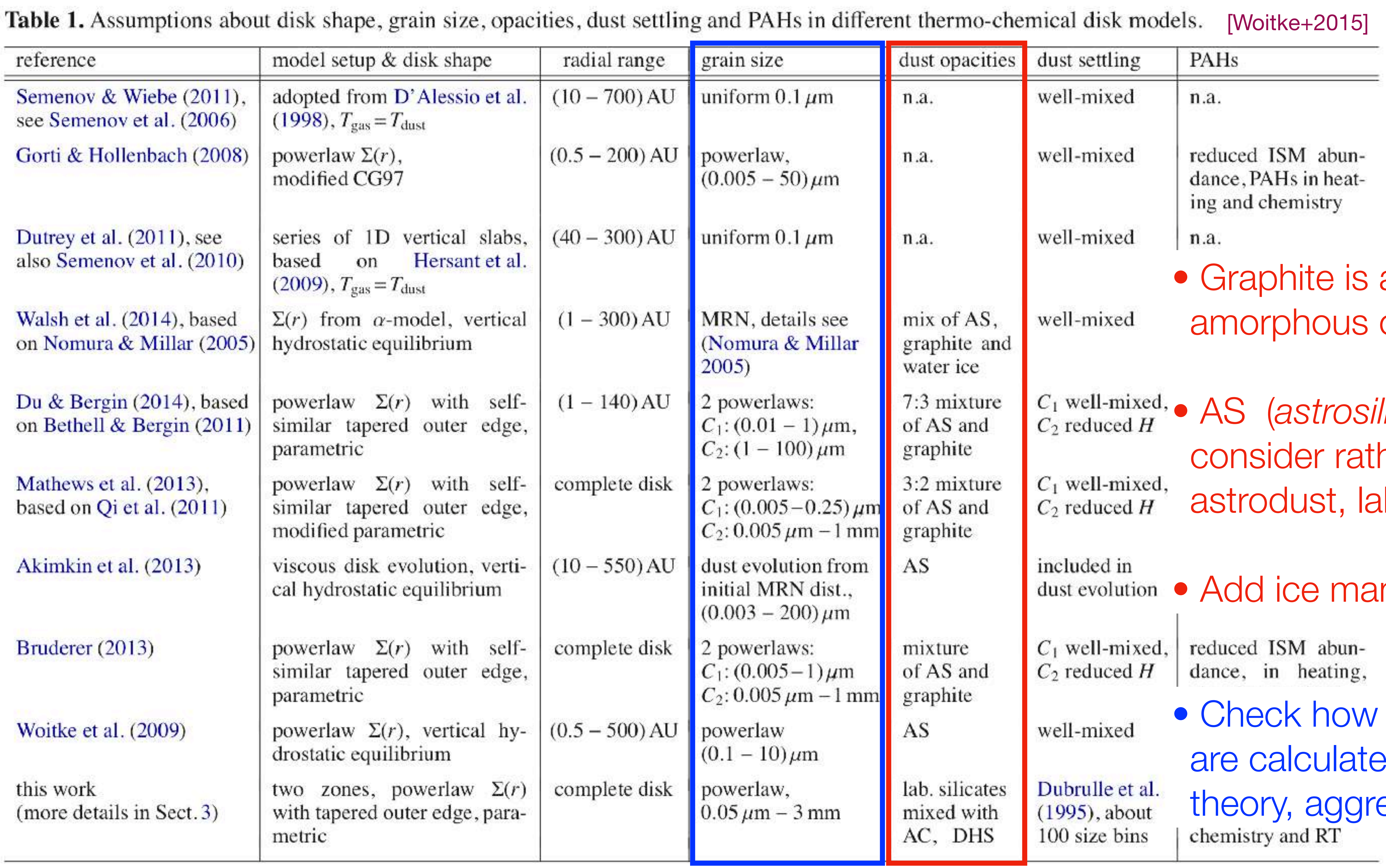


**Table 1.** Assumptions about disk shape, grain size, opacities, dust settling and PAHs in different thermo-chemical disk models. [Woitke+2015]

| reference | model setup & disk shape | radial range | grain size | dust opacities | dust settling | PAHs |
|---|---|---|---|---|---|---|
| Semenov & Wiebe (2011), see Semenov et al. (2006) | adopted from D'Alessio et al. (1998), $T_{\rm gas} = T_{\rm dust}$ | (10 – 700) AU | uniform 0.1 $\mu$m | n.a. | well-mixed | n.a. |
| Gorti & Hollenbach (2008) | powerlaw $\Sigma(r)$, modified CG97 | (0.5 – 200) AU | powerlaw, (0.005 – 50) $\mu$m | n.a. | well-mixed | reduced ISM abundance, PAHs in heating and chemistry |
| Dutrey et al. (2011), see also Semenov et al. (2010) | series of 1D vertical slabs, based on Hersant et al. (2009), $T_{\rm gas} = T_{\rm dust}$ | (40 – 300) AU | uniform 0.1 $\mu$m | n.a. | well-mixed | n.a. |
| Walsh et al. (2014), based on Nomura & Millar (2005) | $\Sigma(r)$ from $\alpha$-model, vertical hydrostatic equilibrium | (1 – 300) AU | MRN, details see (Nomura & Millar 2005) | mix of AS, graphite and water ice | well-mixed | |
| Du & Bergin (2014), based on Bethell & Bergin (2011) | powerlaw $\Sigma(r)$ with self-similar tapered outer edge, parametric | (1 – 140) AU | 2 powerlaws:<br>$C_1$: (0.01 – 1) $\mu$m,<br>$C_2$: (1 – 100) $\mu$m | 7:3 mixture of AS and graphite | $C_1$ well-mixed,<br>$C_2$ reduced $H$ | |
| Mathews et al. (2013), based on Qi et al. (2011) | powerlaw $\Sigma(r)$ with self-similar tapered outer edge, modified parametric | complete disk | 2 powerlaws:<br>$C_1$: (0.005–0.25) $\mu$m<br>$C_2$: 0.005 $\mu$m – 1 mm | 3:2 mixture of AS and graphite | $C_1$ well-mixed,<br>$C_2$ reduced $H$ | |
| Akimkin et al. (2013) | viscous disk evolution, vertical hydrostatic equilibrium | (10 – 550) AU | dust evolution from initial MRN dist., (0.003 – 200) $\mu$m | AS | included in dust evolution | |
| Bruderer (2013) | powerlaw $\Sigma(r)$ with self-similar tapered outer edge, parametric | complete disk | 2 powerlaws:<br>$C_1$: (0.005 – 1) $\mu$m<br>$C_2$: 0.005 $\mu$m – 1 mm | mixture of AS and graphite | $C_1$ well-mixed,<br>$C_2$ reduced $H$ | reduced ISM abundance, in heating, |
| Woitke et al. (2009) | powerlaw $\Sigma(r)$, vertical hydrostatic equilibrium | (0.5 – 500) AU | powerlaw (0.1 – 10) $\mu$m | AS | well-mixed | |
| this work (more details in Sect. 3) | two zones, powerlaw $\Sigma(r)$ with tapered outer edge, parametric | complete disk | powerlaw, 0.05 $\mu$m – 3 mm | lab. silicates mixed with AC, DHS | Dubrulle et al. (1995), about 100 size bins | chemistry and RT |

- Graphite is a wrong assumption use amorphous carbon instead
- AS (*astrosilicates*) are obsolete => consider rather THEMIS 2 silicates, astrodust, labdata
- Add ice mantles
- Check how the extinction efficiencies are calculated for grains > 1 µm : Mie theory, aggregates?

# Summary

- There are many cosmic dust models

- Their differences are sometimes subtle because many models use the same or partly the same observational constraints and dust components.

- Some criteria to classify dust models:
  - The environment they are supposed to represent: diffuse vs dense medium
  - The observational constraints they consider
  - The adopted description of the dust: empirical (observational) vs experimental (measurement on cosmic dust analogues)

- No dust model is unique or perfect
- But they improve little by little as new observational constraints are available and as new results are obtained on dust analogues