INTERSTELLAR DUST PROPERTIES AND COSMIC DUST MODELS

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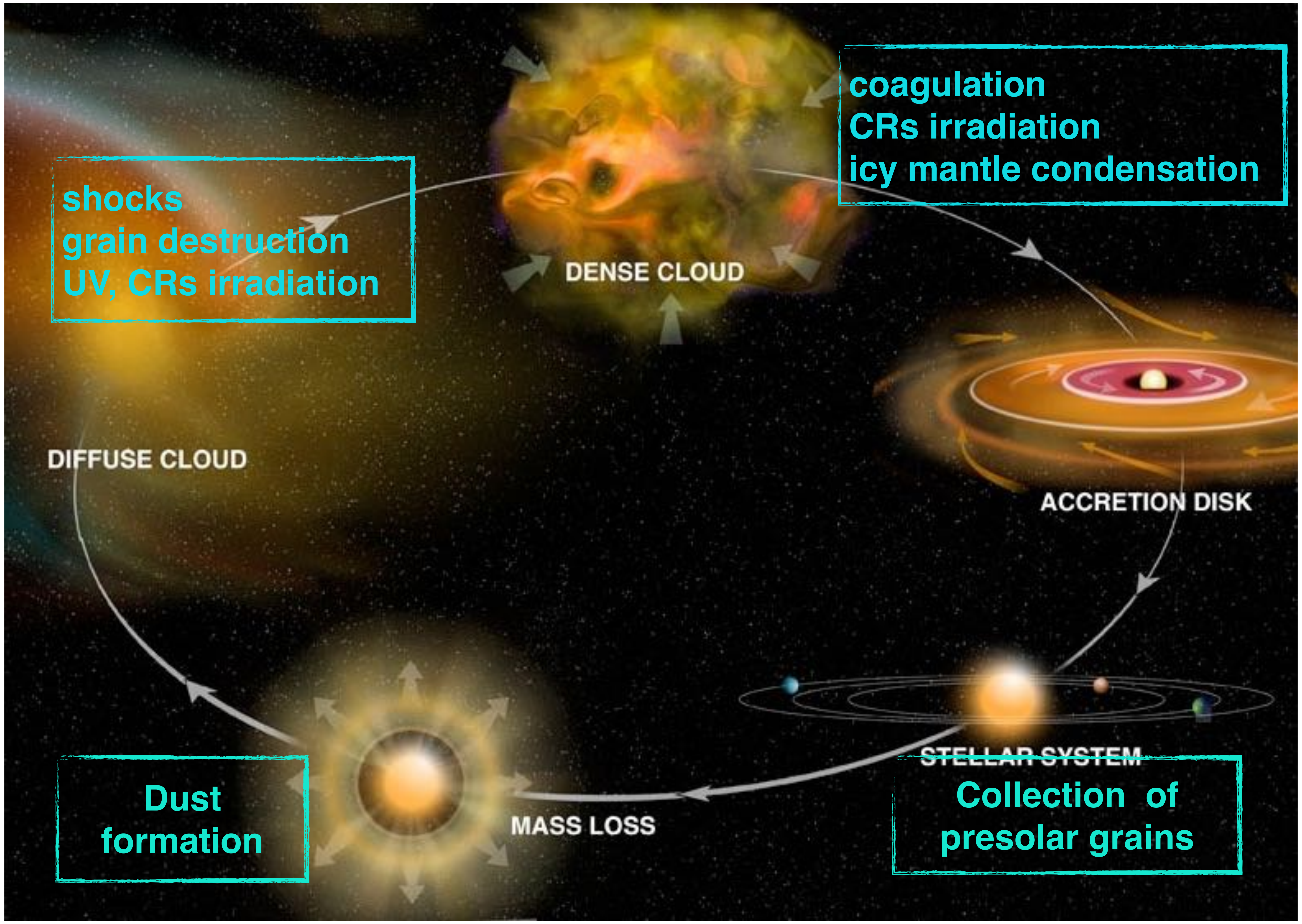
Outline

- Observational constraints & dust properties
- Dust evolution
- Modelling dust extinction and emission
- Cosmic dust models

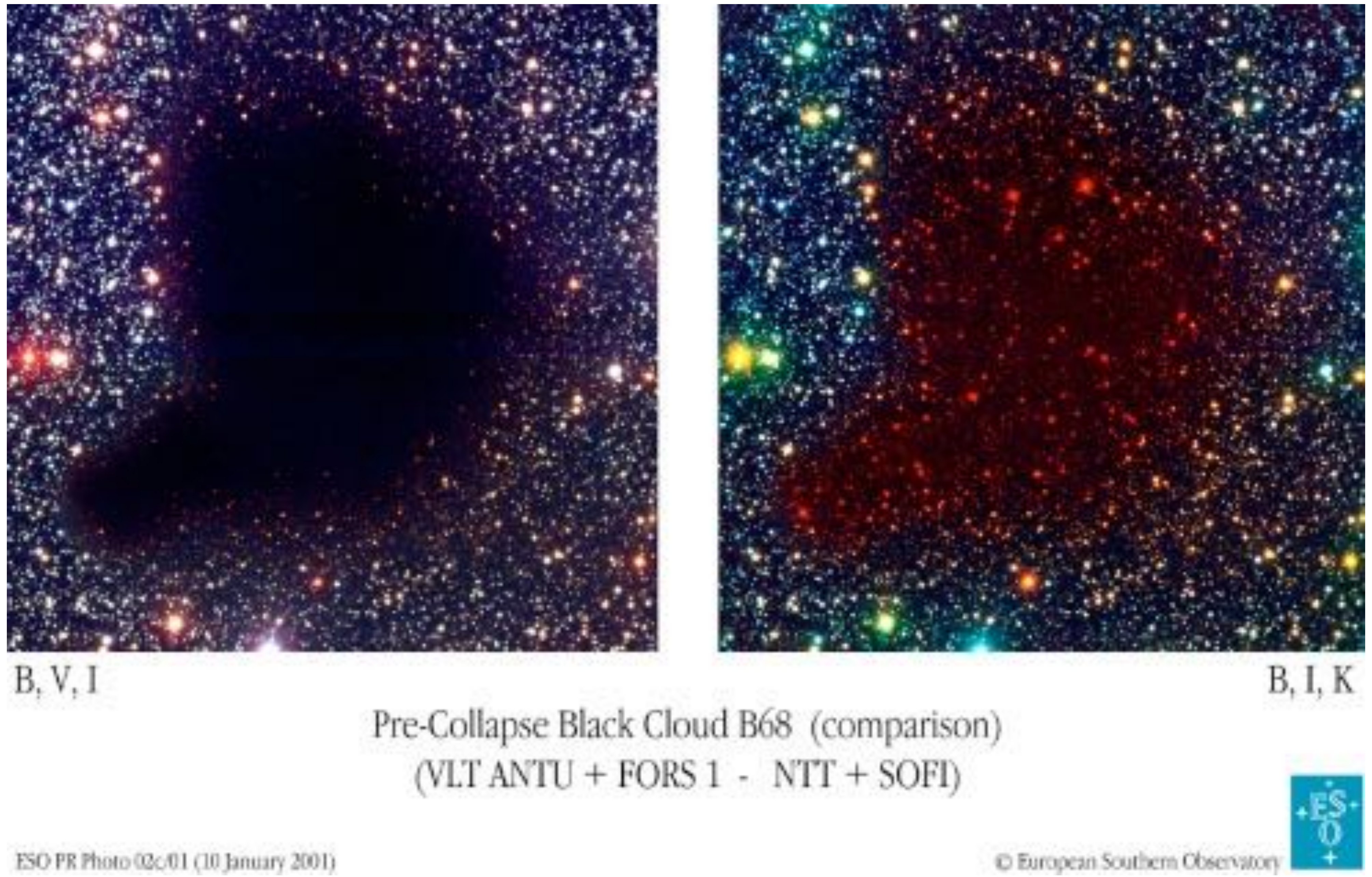
The dust cycle

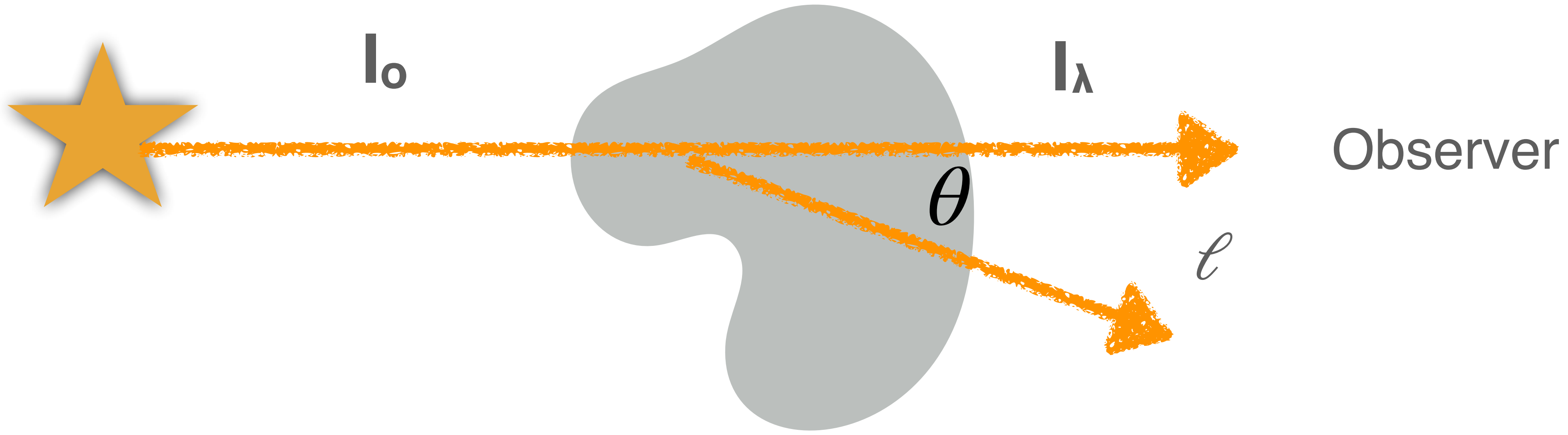


- The life cycle of the ISM, of stars and dust are intimately related
- Dust is everywhere
- Dust is a probe of the physical and chemical conditions of astronomical environments
- Dust is one of the drivers of ISM evolution and hence of galactic evolution
- Dust is key to promote chemical complexity

Observational constraints & dust properties

Extinction





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

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

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

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

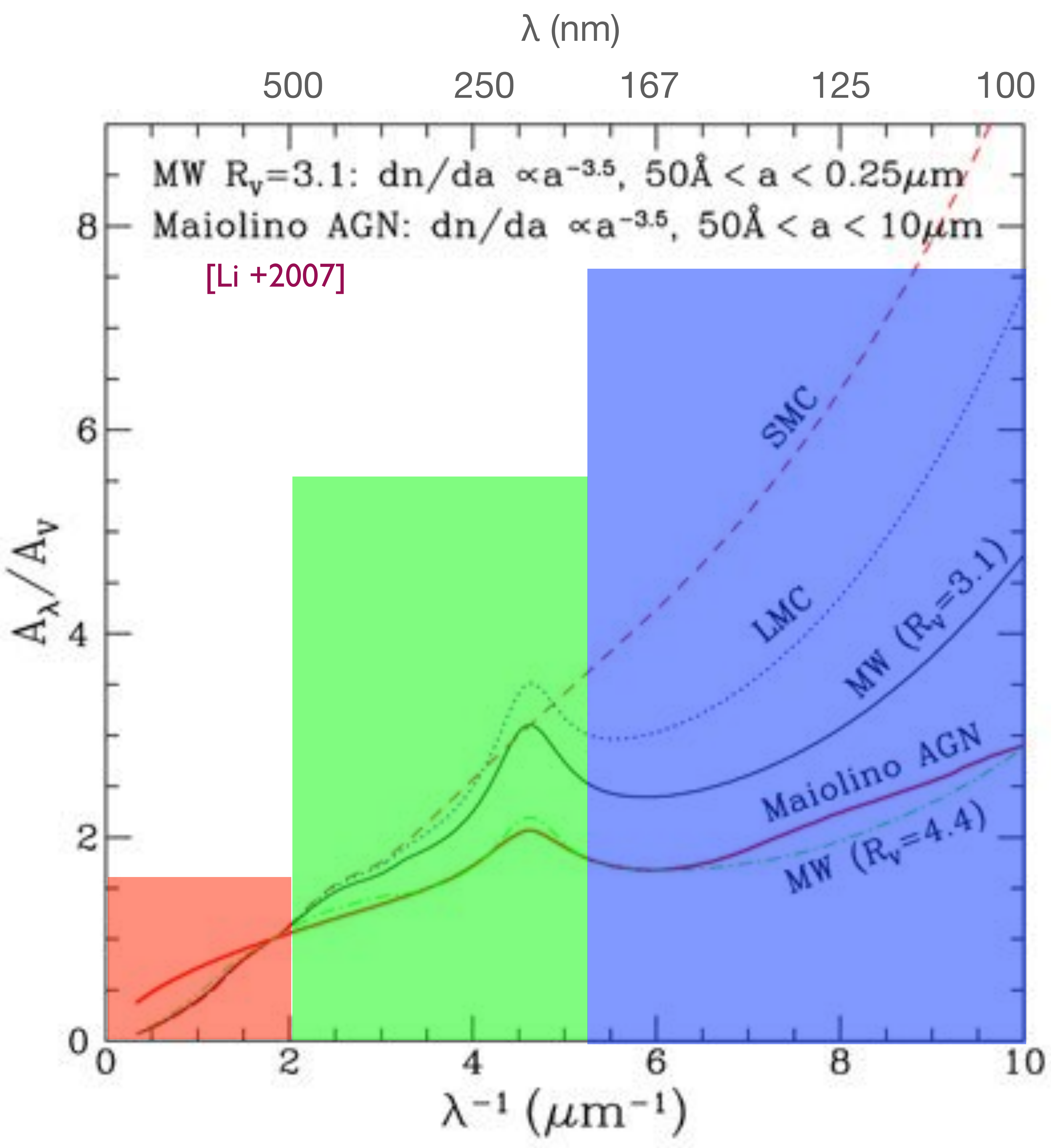
k_{ext} : Extinction coefficient (m^{-1})

- 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

The extinction curve

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

- UV rise ⇒ grains with radius a ≪ λ ie. a < 10 nm
- 2175 Å bump ⇒ carbonaceous grains (electronic transition)
- U, B, V bands ⇒ extinction in λ^{-1} ⇒ grains with radius a ~ λ ie. a ~ 0.1 µm
- MIR domain : vibrational transitions ⇒ silicates, carbonaceous dust, ices



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

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

Scattering

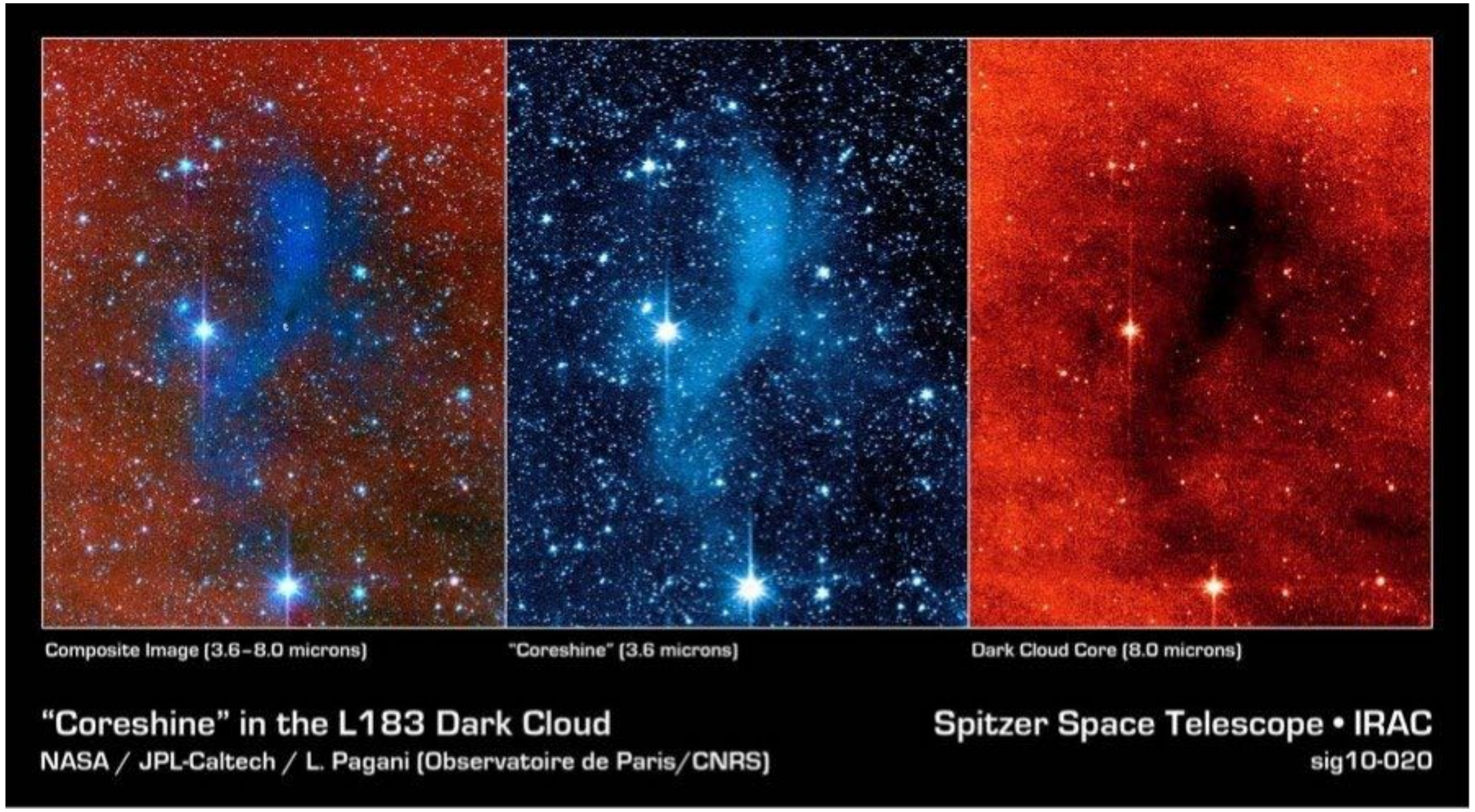
- **Scattering depends on the size, shape and composition of the grains**
- Grains of radius a ~ 0.1 µm scatter light in the visible
- Larger grains scatter light at longer wavelengths, in the NIR

- Scattering depends on the albedo ω and the phase function g

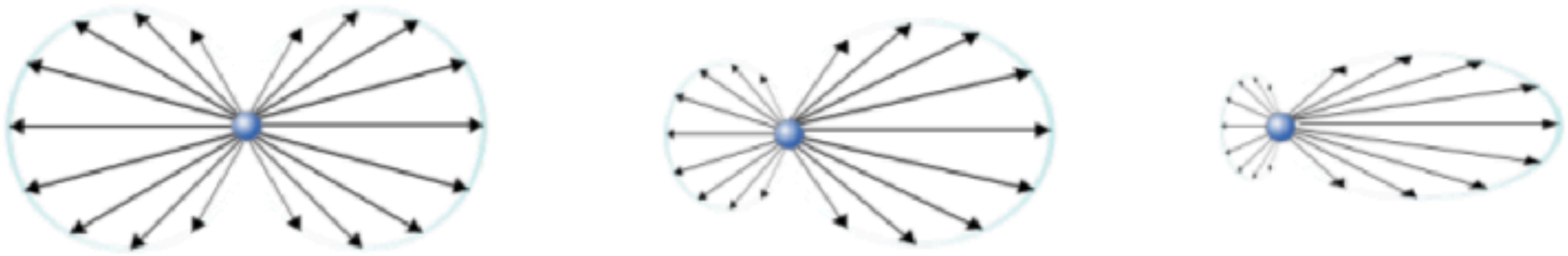
Pléiades (Rogelio Bernal Andreo)

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

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



Rayleigh and Mie scattering phase function



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Emission

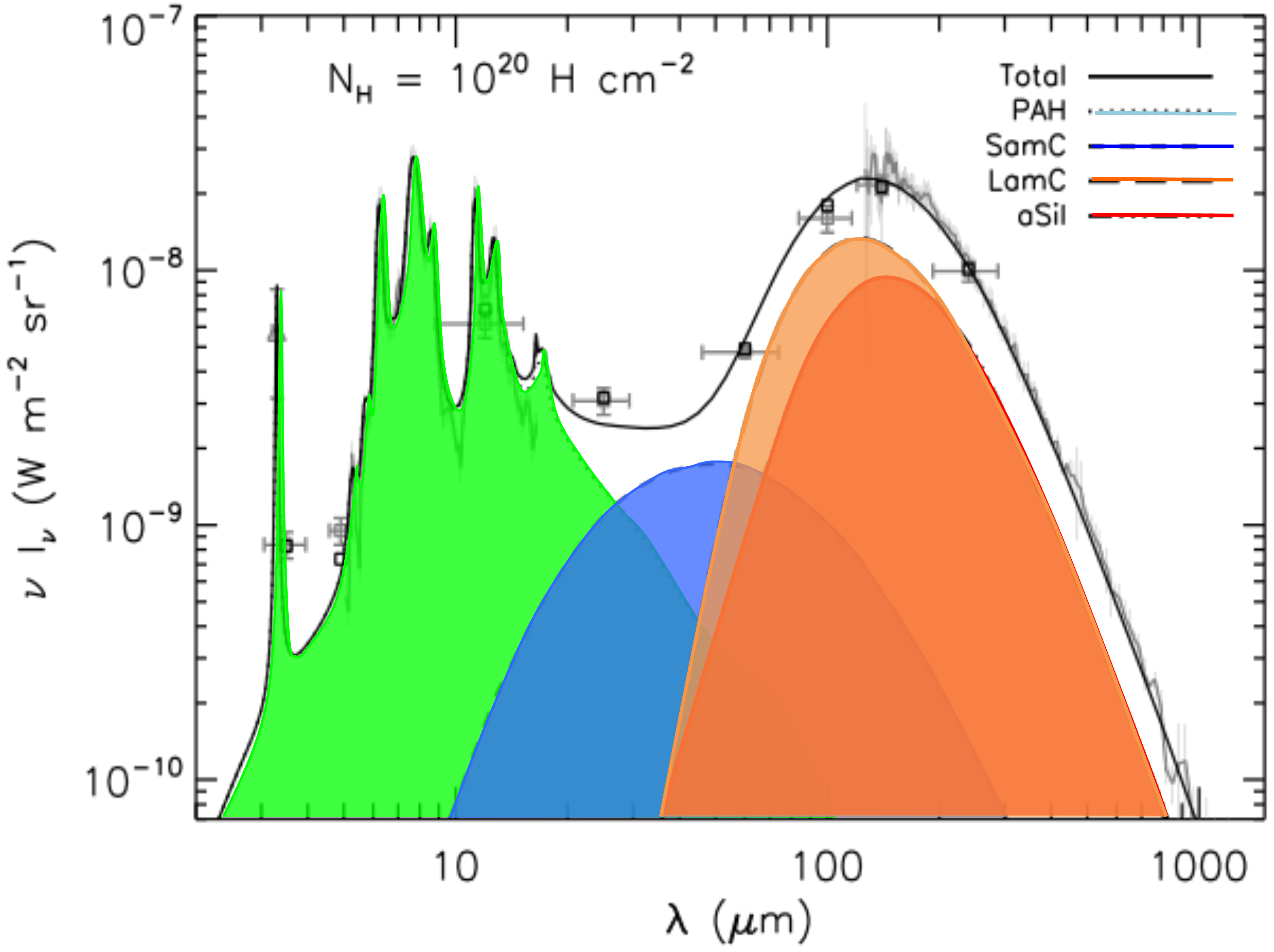
On a given line of sight, dust emission depends on:

- Column density of gas: N_H (cm^{-2})
- Dust abundance: X_d
- Intensity of the ISRF
- Emissivity of dust: ϵ ($erg.s^{-1}.sr^{-1}.cm^{-1}.g^{-1}$)

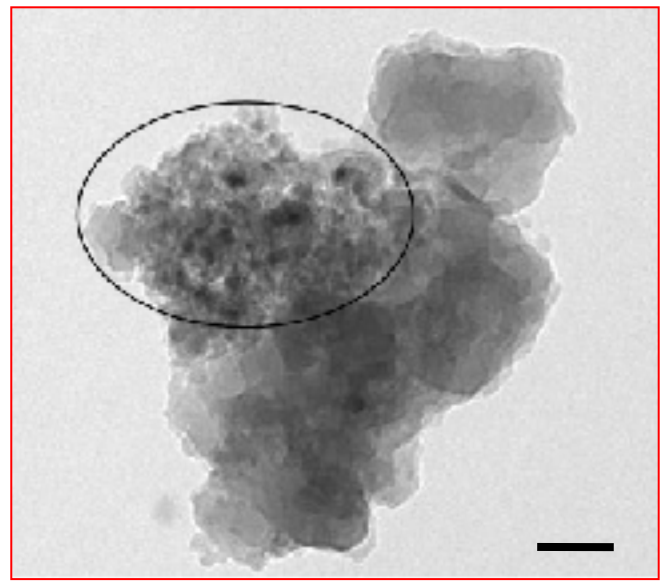
$$I_\nu \propto \int_{LOS} \epsilon \times N_H \times X_d \times ISRF$$

Different emission mechanisms depending on the grain size and nature

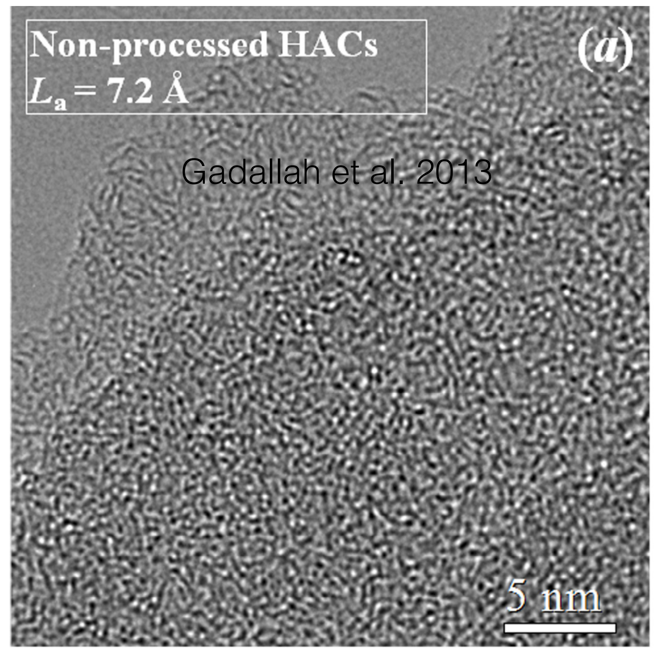
Diffuse ISM emission: [Compiègne+2011]



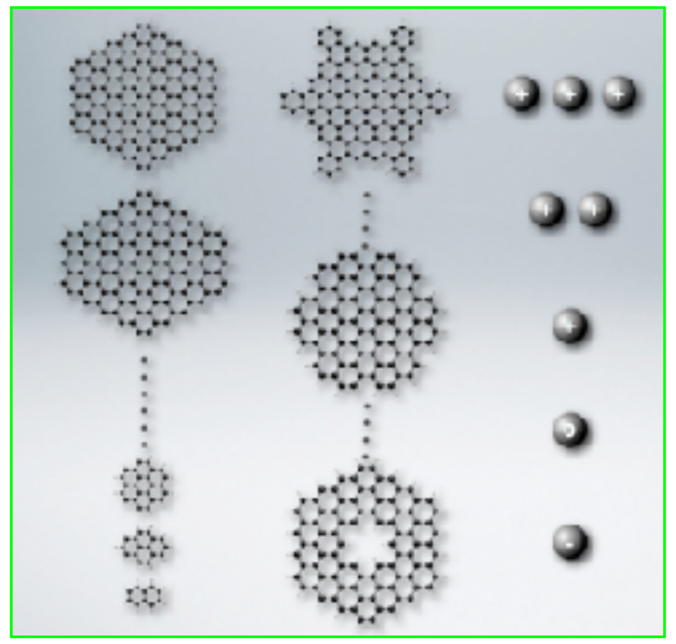
SILICATES 10-300 nm



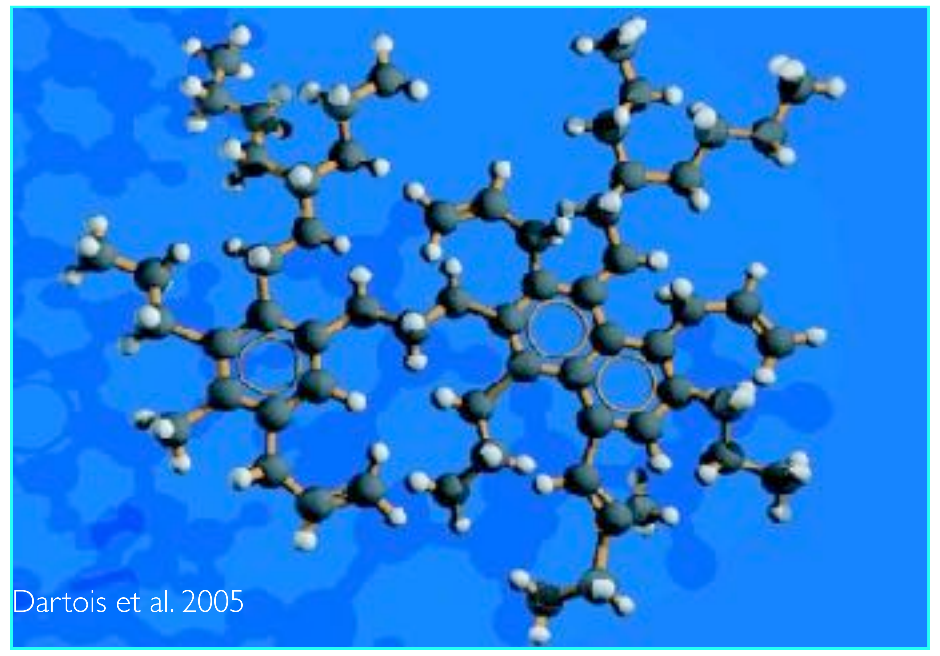
Amorphous carbon



PAHs

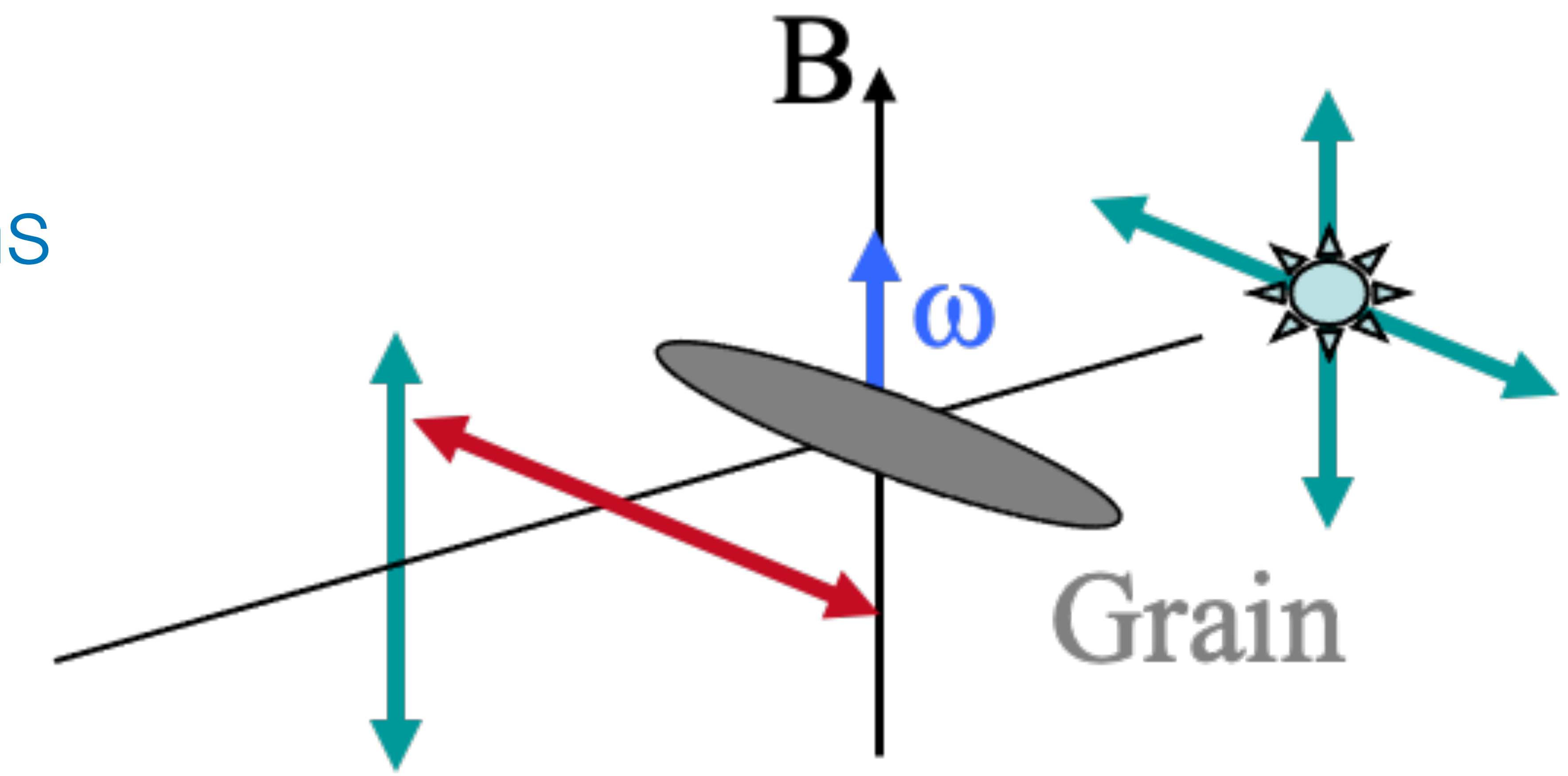


VSG 5-10 nm



Polarization

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

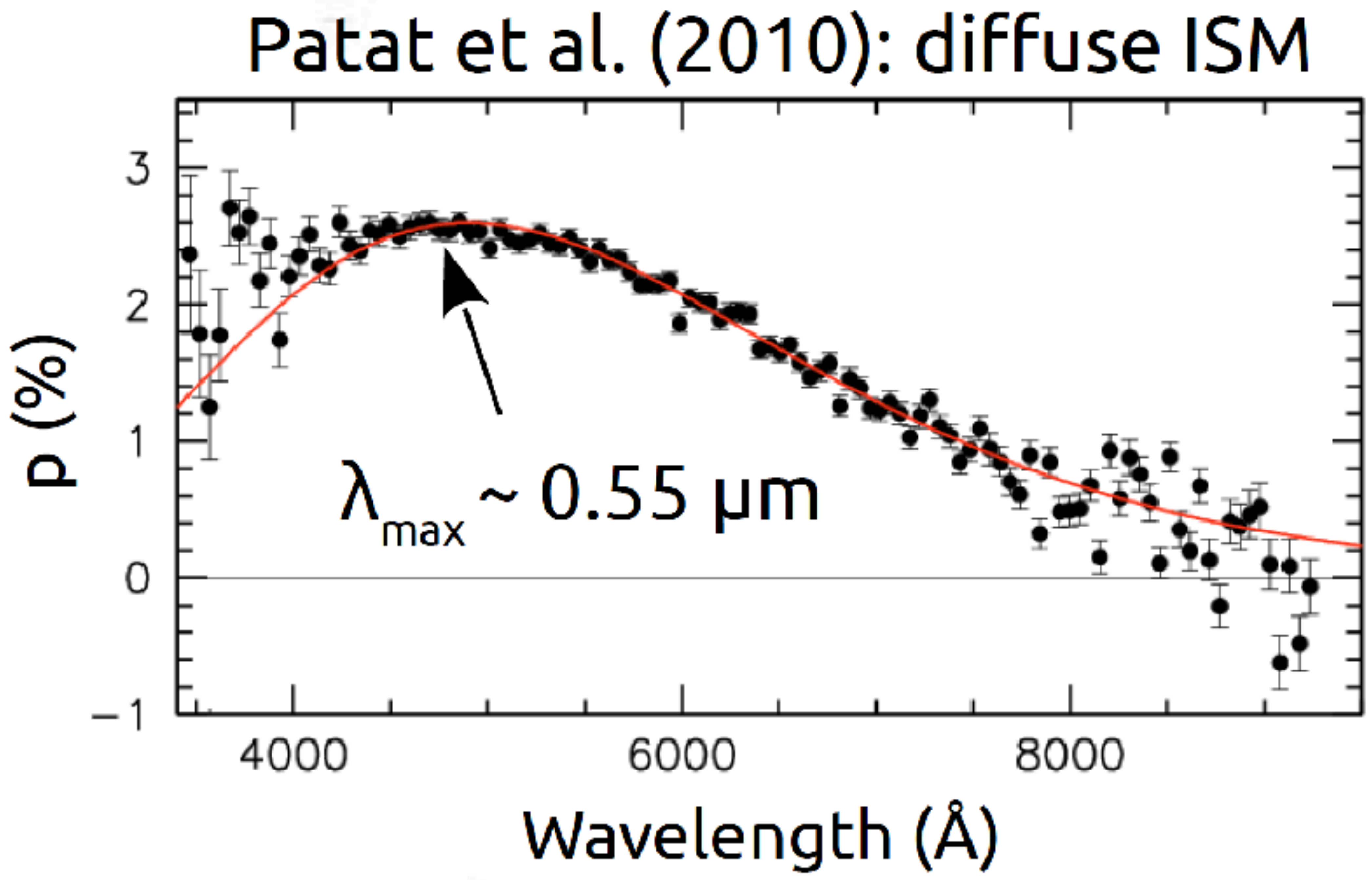


  - In absorption starlight is polarised // to B field lines

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

[Serkowski 1975]

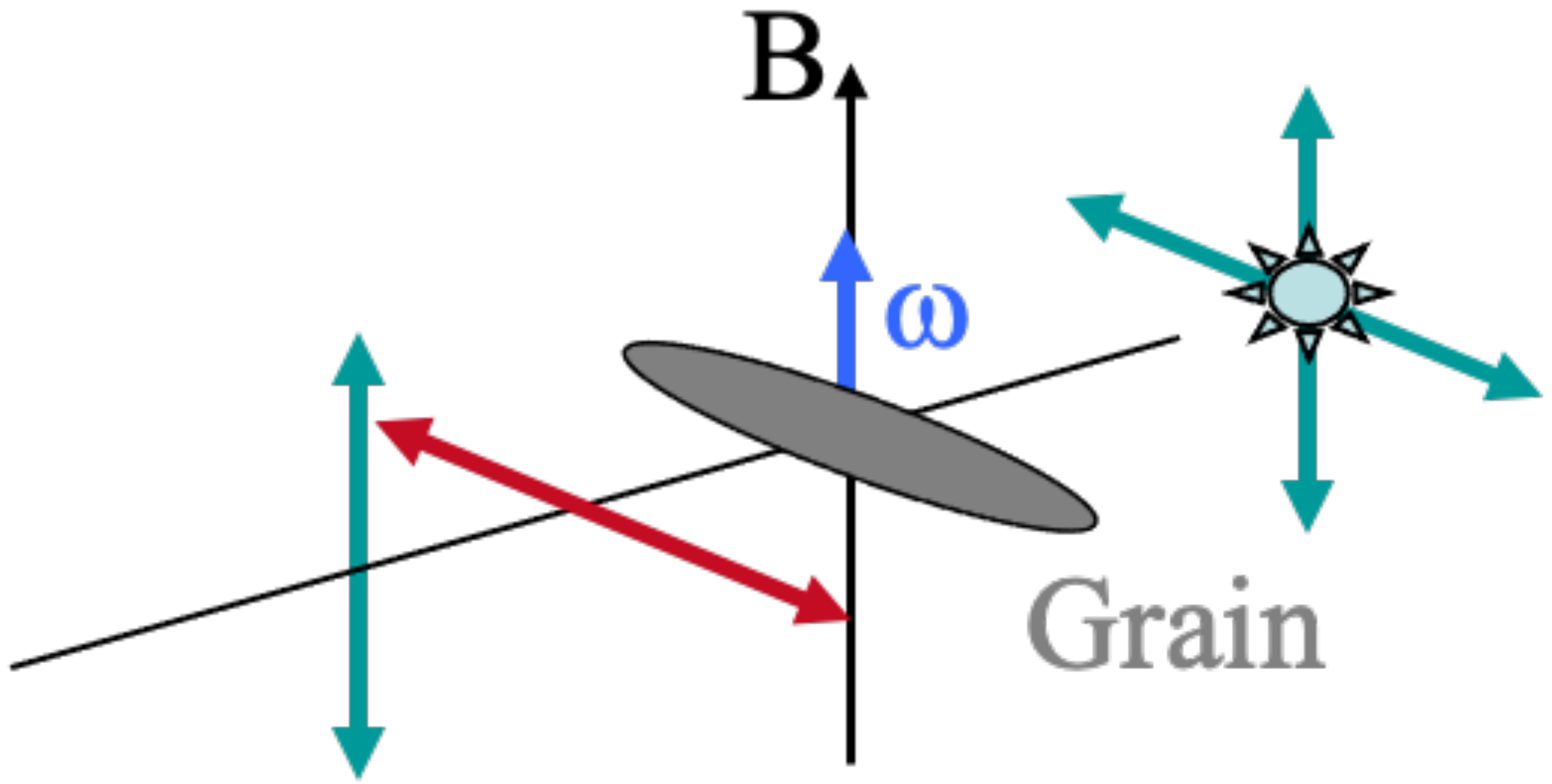
  - λ_{max} ~ 0.55 µm ⇒ grain radius ~ 0.1 µm
  - The peak position is sensitive to grain size
  - p_{max} ~ a few %
  - The 10 µm feature is polarised



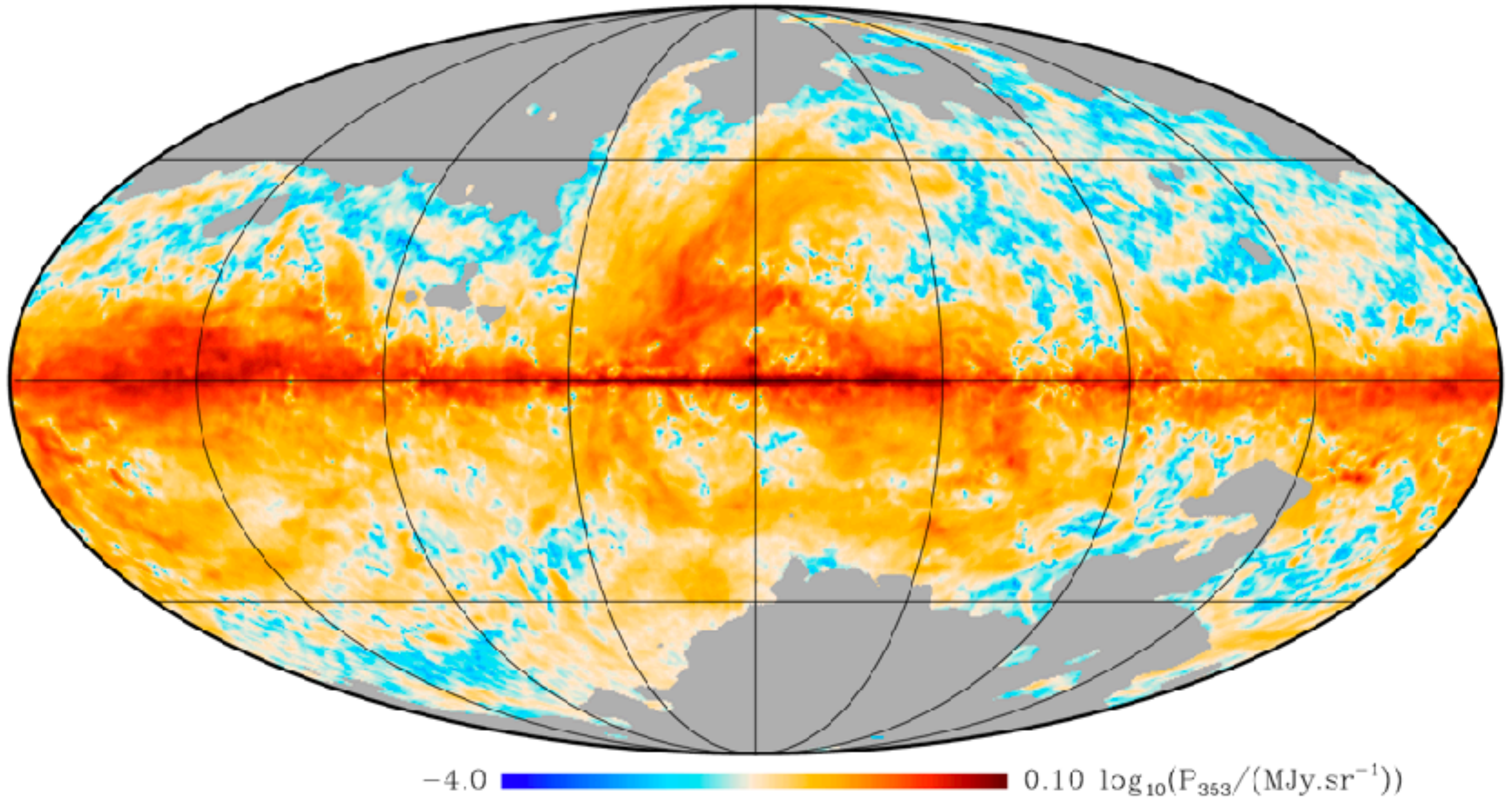
Polarization

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

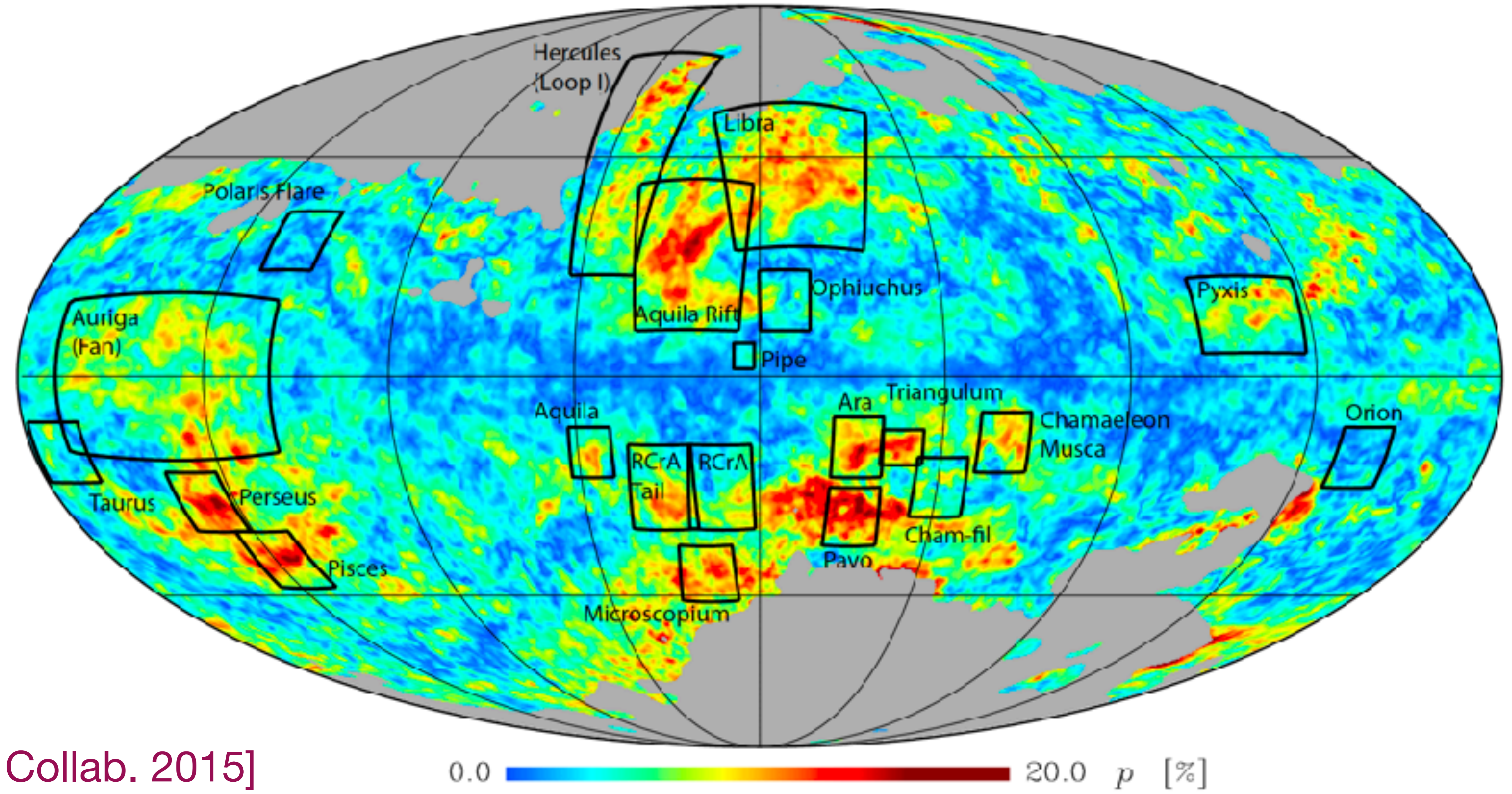
- Polarized emission is ⊥ to B field lines
- P/I = polarisation fraction in the FIR/submm
- Observed by ARCHEOPS, WMAP, Planck



Polarised emission (Planck)



Polarisation fraction (Planck)

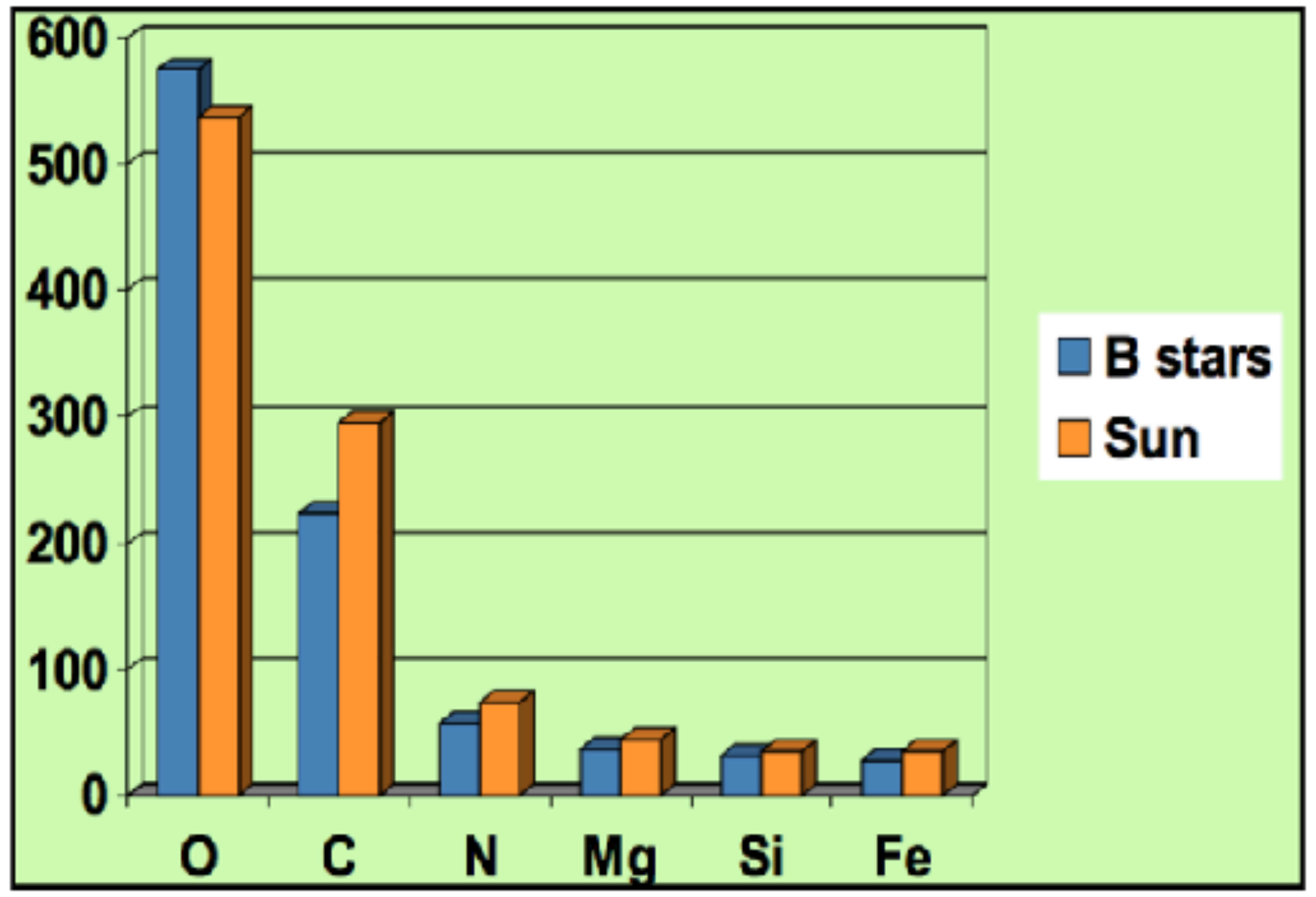


[Planck Collab. 2015]

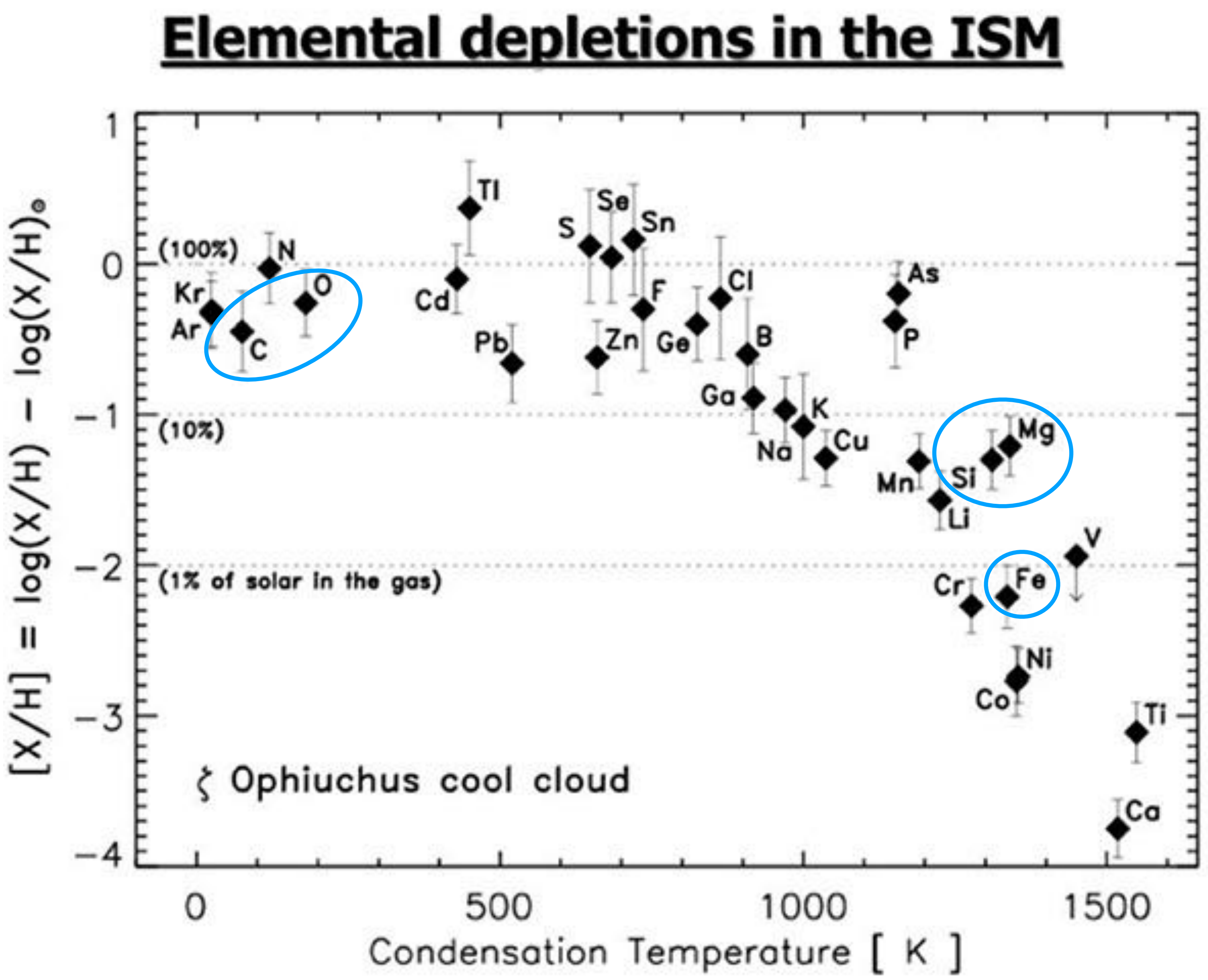
Depletion

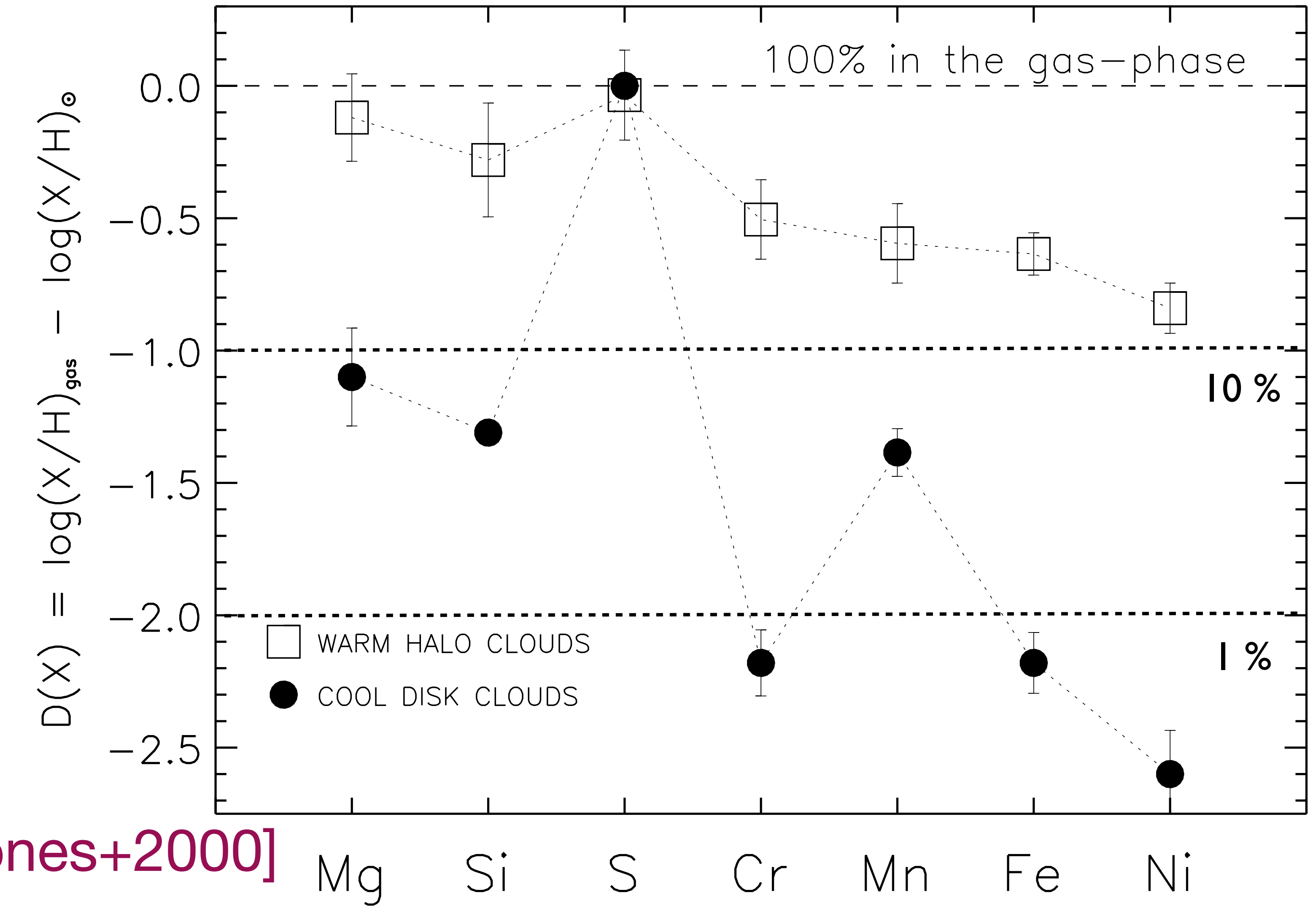
[Jenkins 2009, 2013]

- 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: $\left[\frac{X_{gas}}{H}\right] = log\left(\frac{N(X)}{N(H)}\right)_{obs} - log\left(\frac{X}{H}\right)_{ref} \approx log\left(\frac{X}{H}\right)_0 + A_X \times F_*$



- Elements in dust: $(X_{dust}/H) = (X/H)_{ref} - (1 - 10^{[X_{gas}/H]})$
- Low density clouds and high velocity gas have less depletion than dense clouds





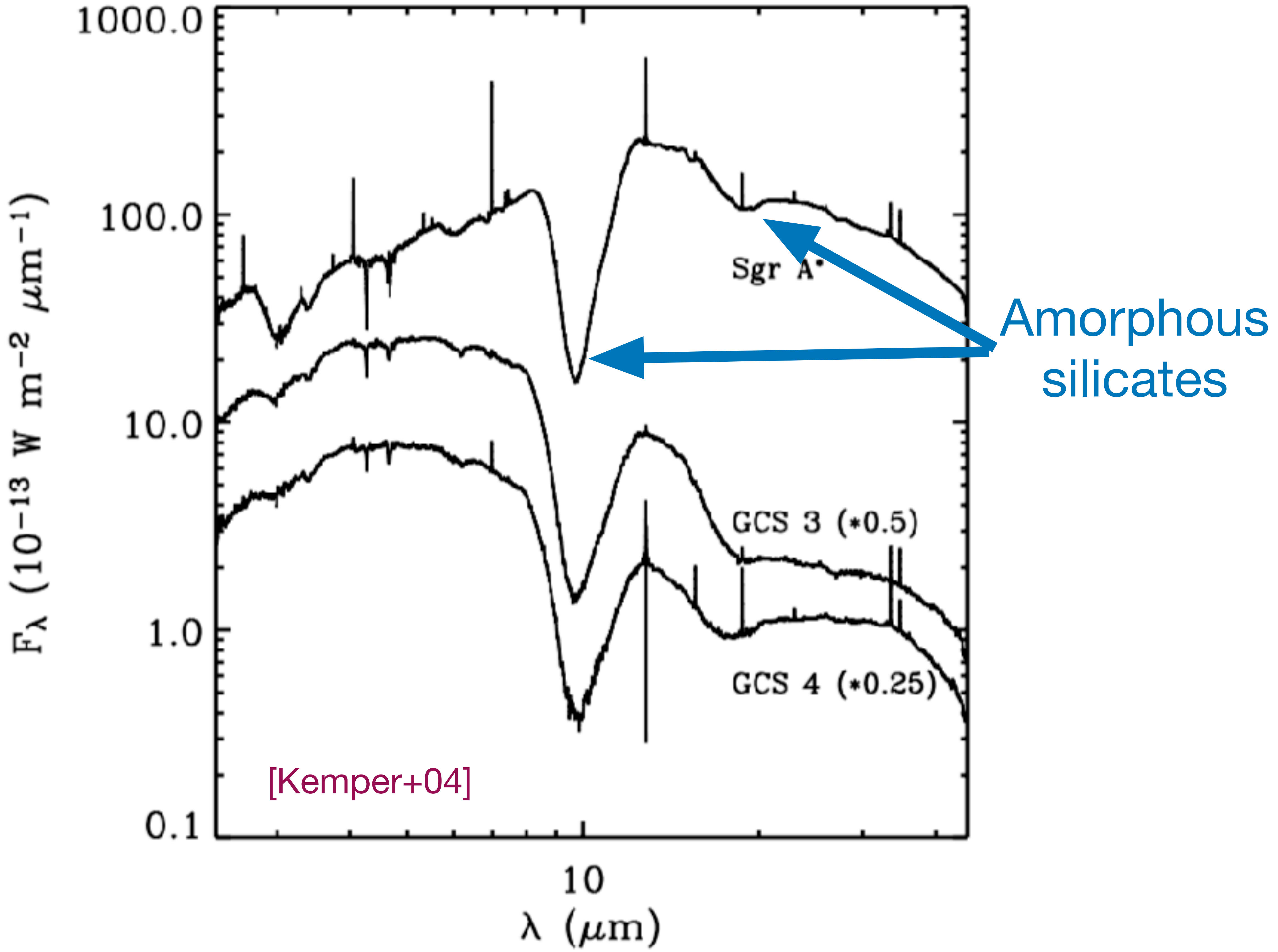
[Jones+2000]

- Depletion varies from one element to the other
- Depletion increases with condensation temperature of the elements

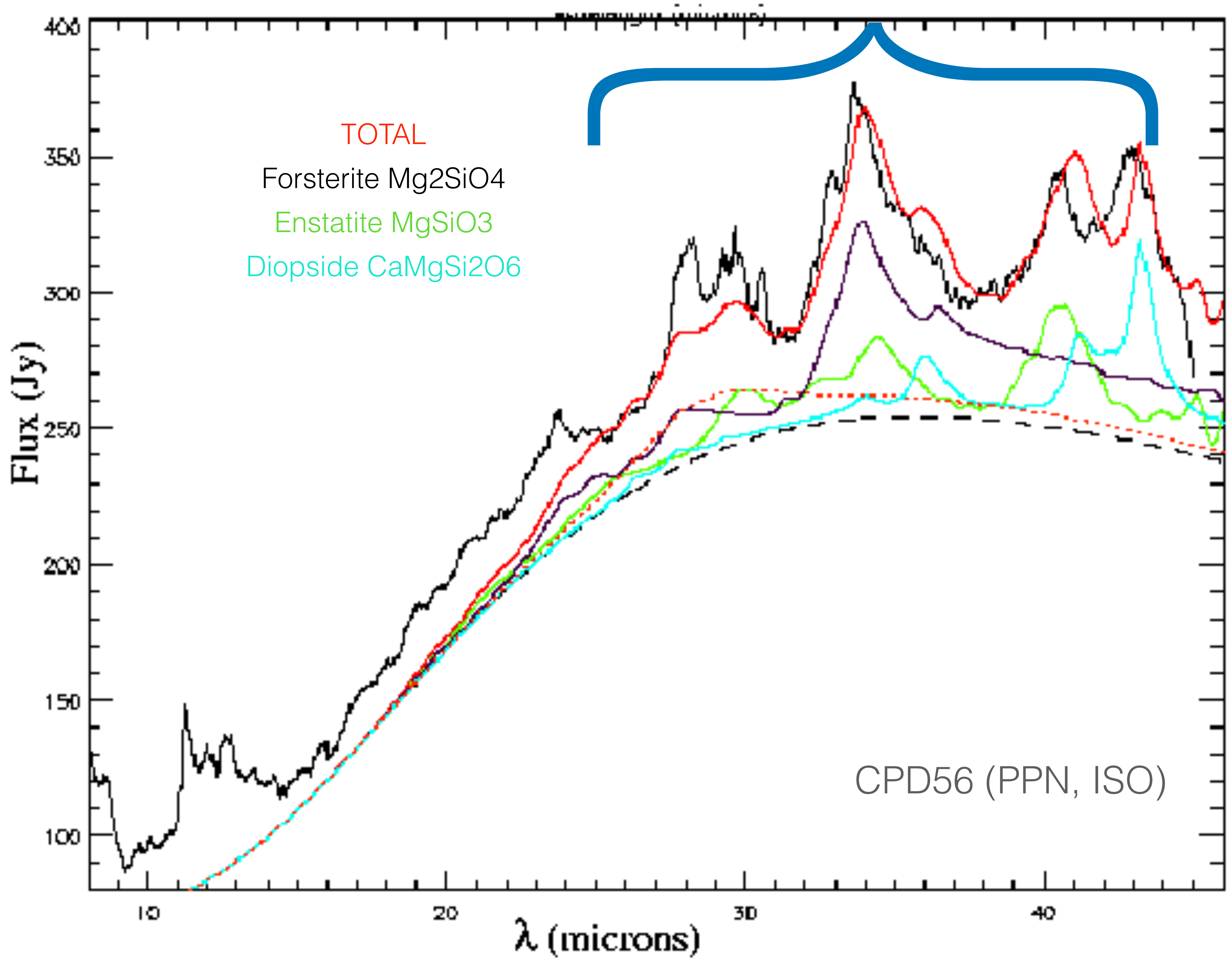
Silicates grains

- Composition and structure constrained by MIR spectroscopic observations
- Silicate grains are submicronic: radius a ~ 0.1 µm
- Silicate dust in the ISM is amorphous, at most 1-2 % of crystalline silicates [Kemper+04]
- Mostly Mg-rich silicate such as amorphous enstatite ($MgSiO_3$) and forsterite (Mg_2SiO_4)

LOS toward the Galactic center (ISO) dense ISM

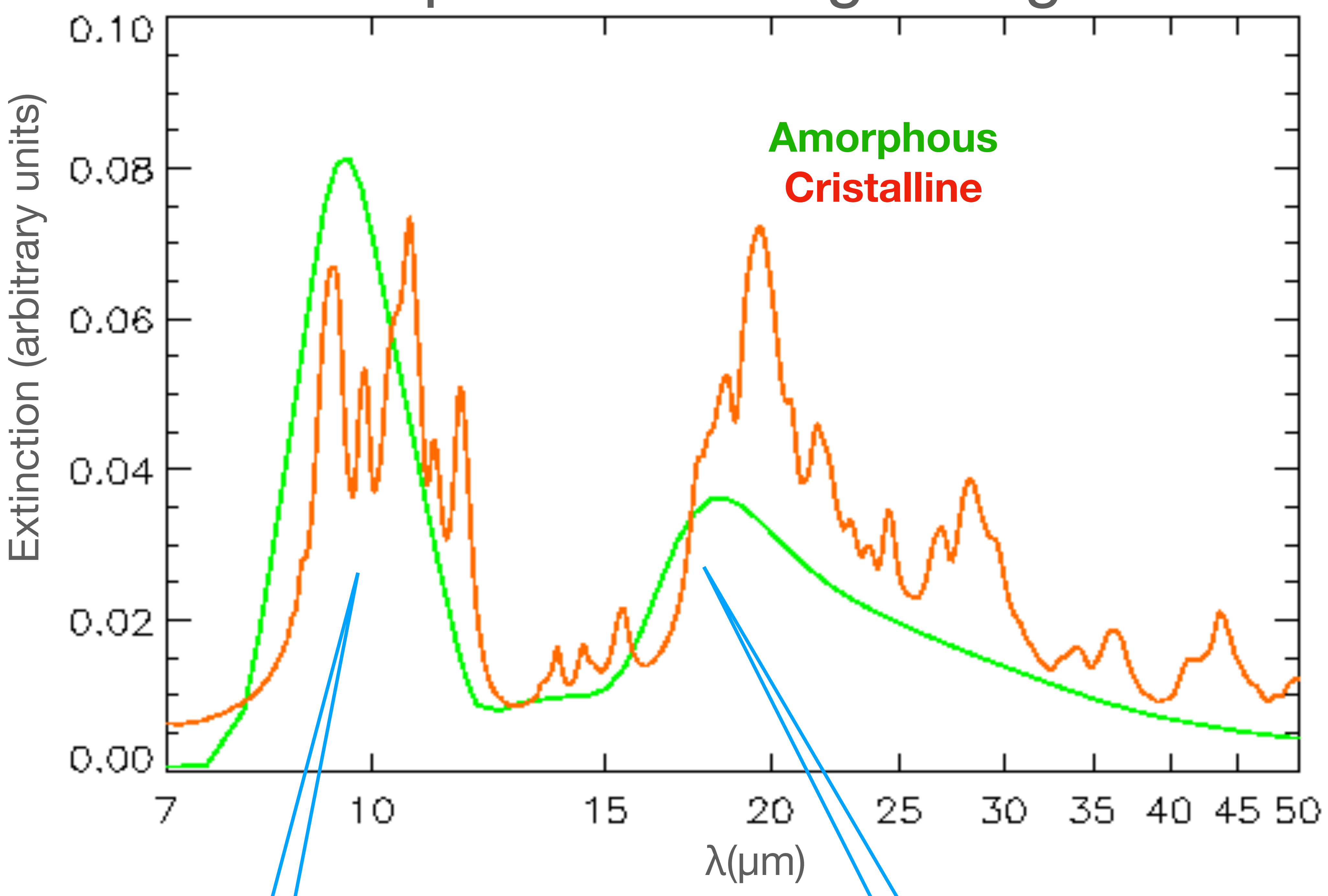


Cristalline silicates



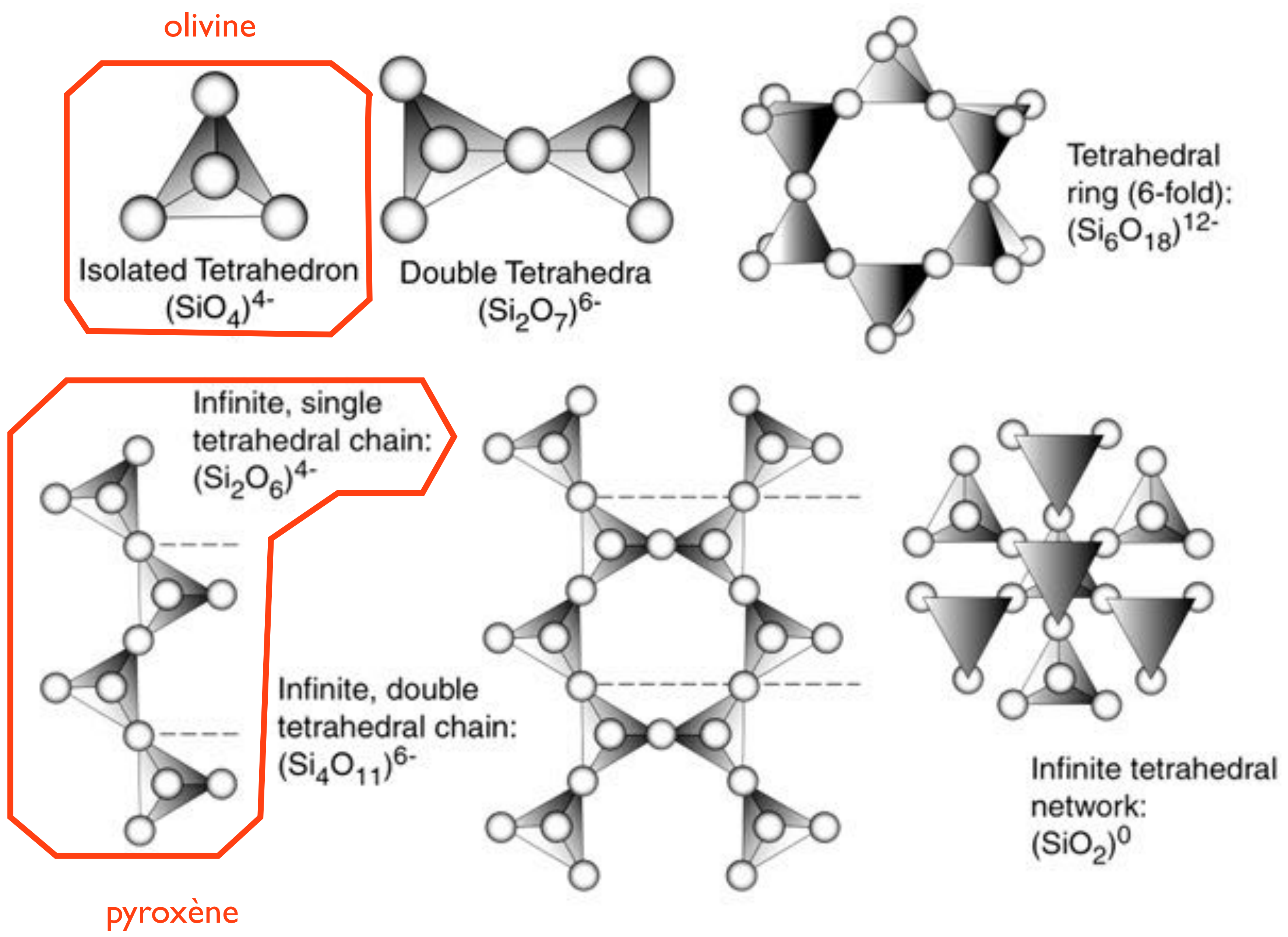
Silicates

MIR spectrum of $MgSiO_3$ grains

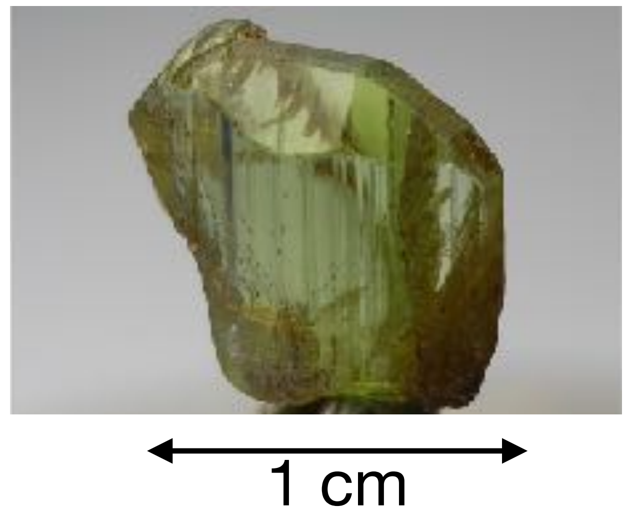


9.7 µm: Si-O stretching mode

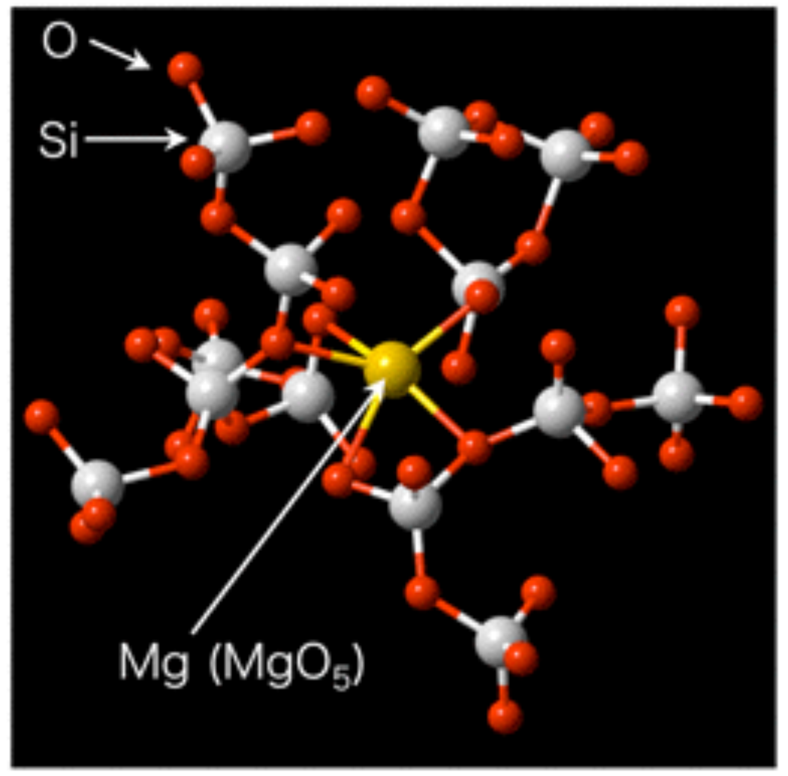
18 µm: Si-O bending mode



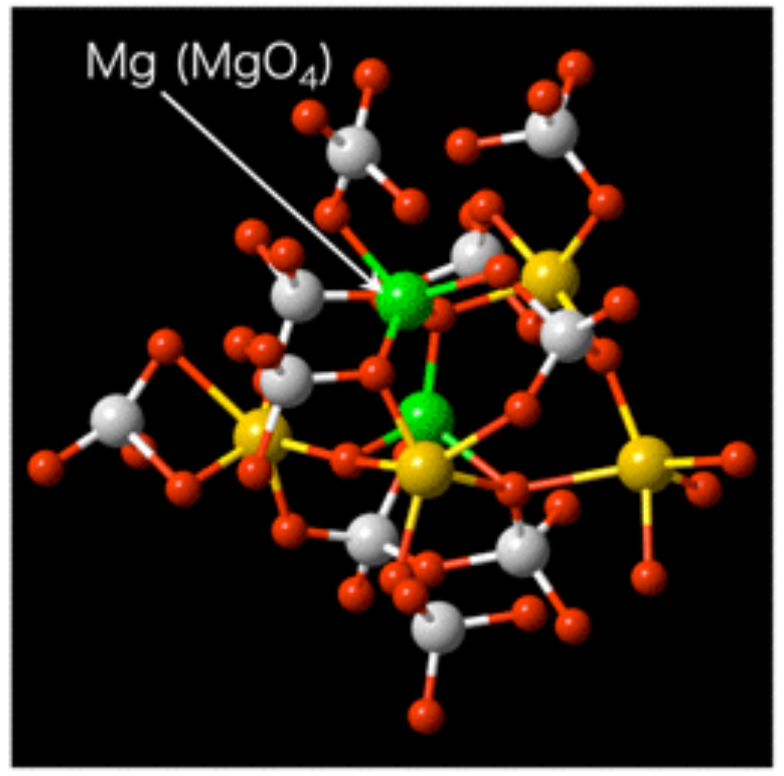
Olivine

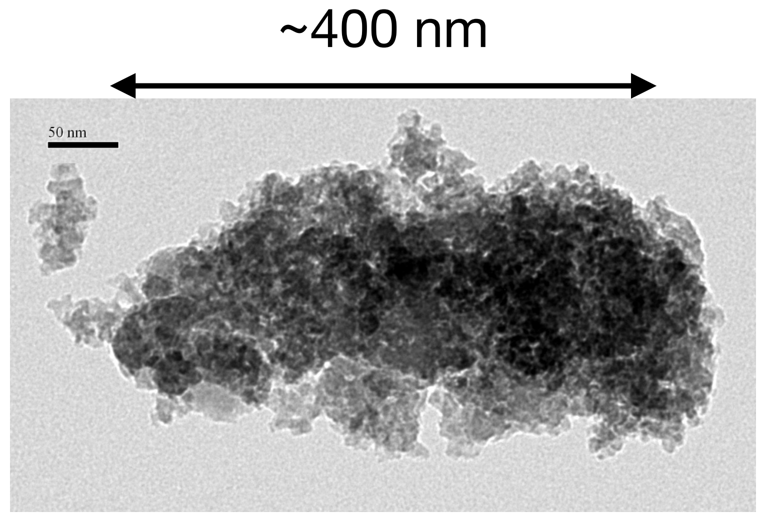


$MgSiO_3$ glass



Mg_2SiO_4 glass



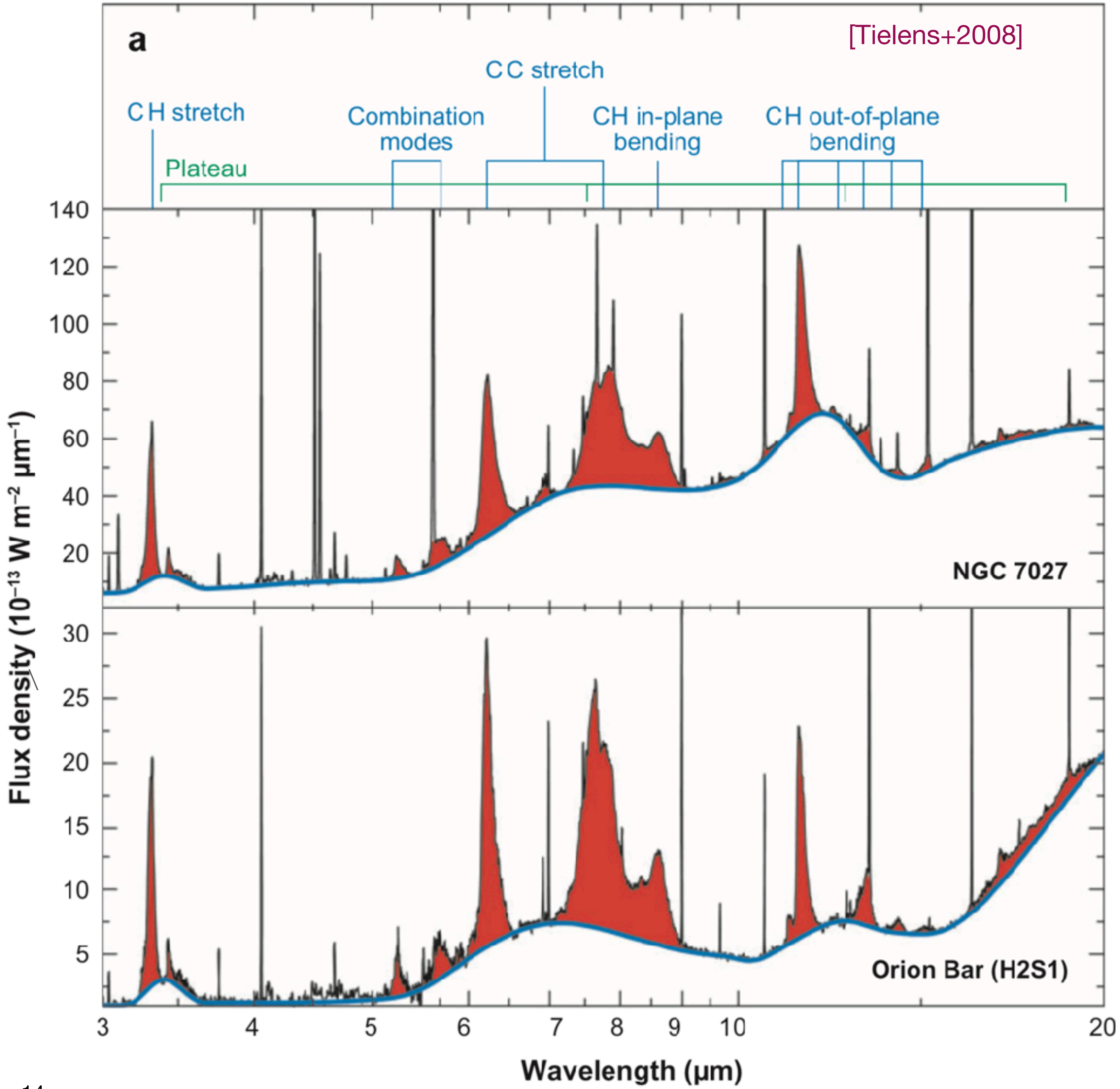


Aromatic carbon-rich dust: the Aromatic Infrared Bands

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

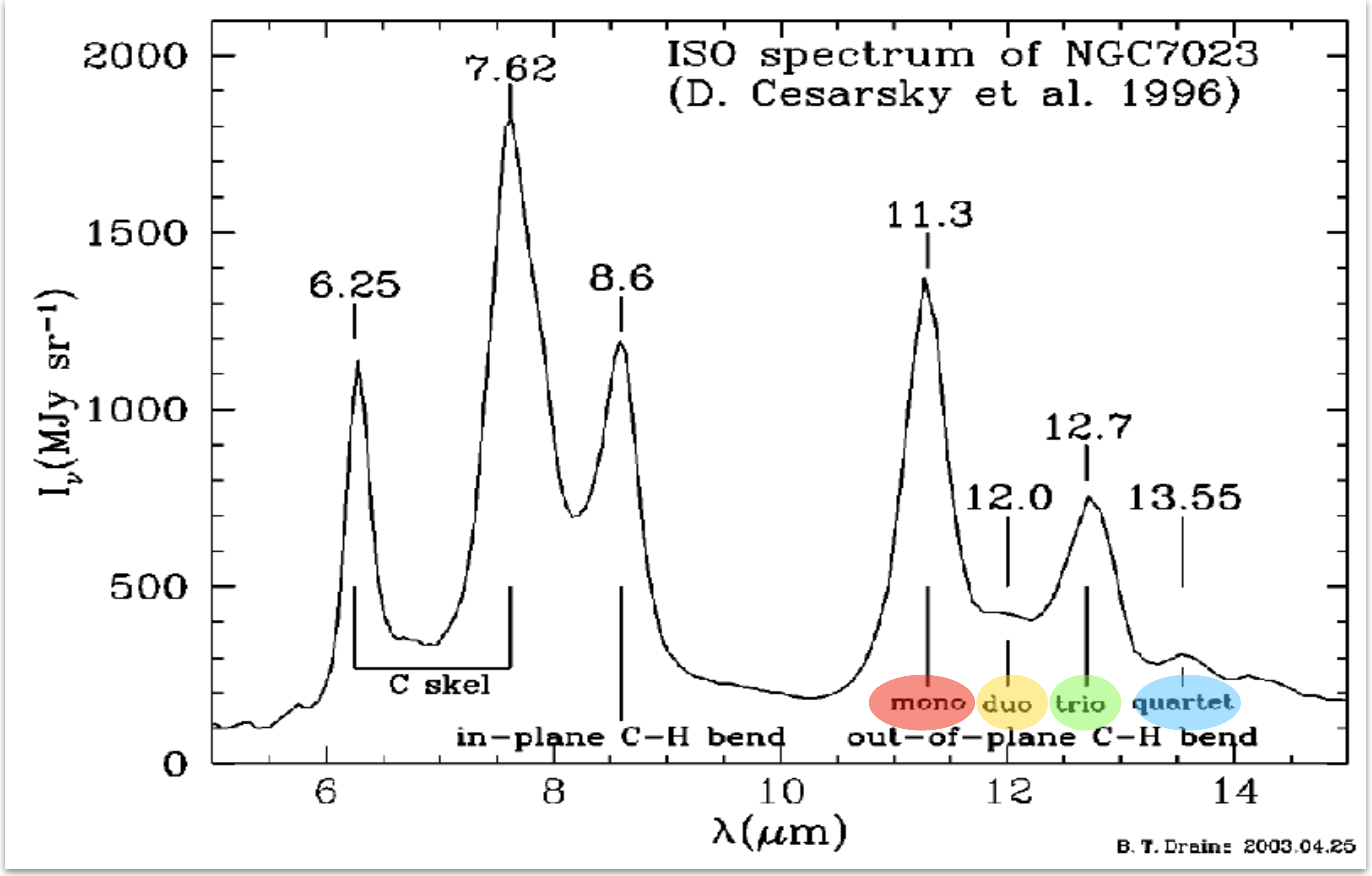
- ~10-20 % of cosmic carbon
- ~ 5 % of the dust mass

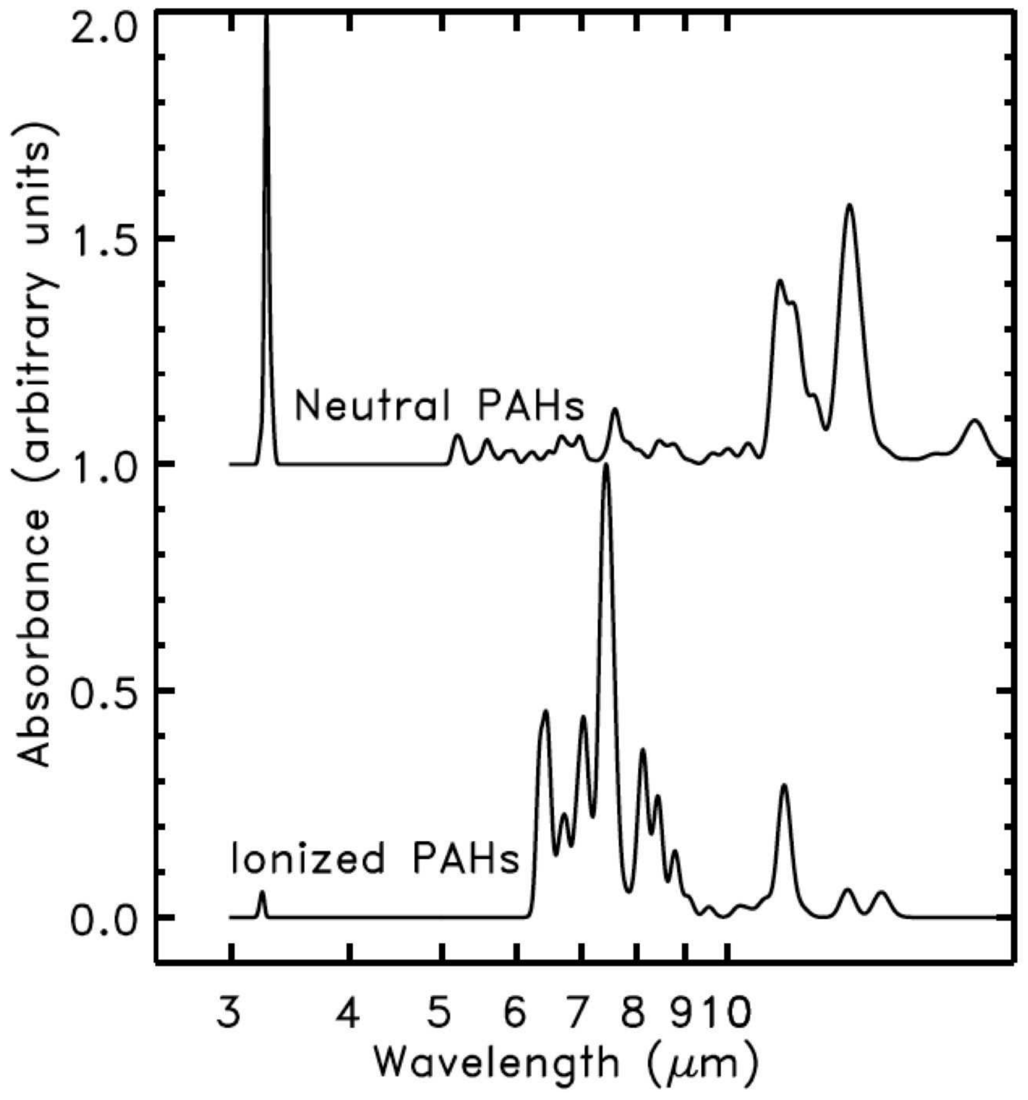
- Band strengths and band ratios vary with the environments



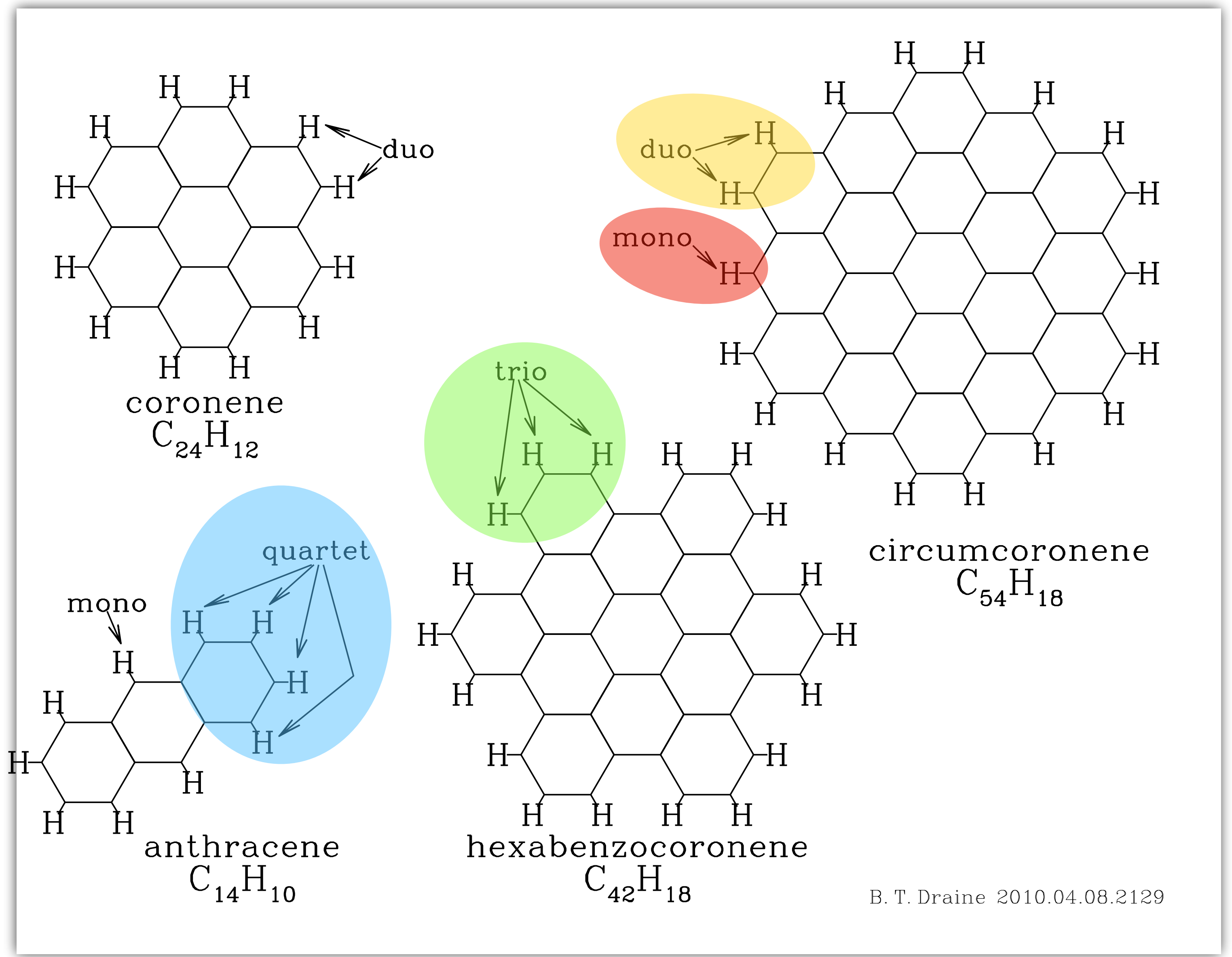
Aromatic carbon-rich dust: PAHs

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



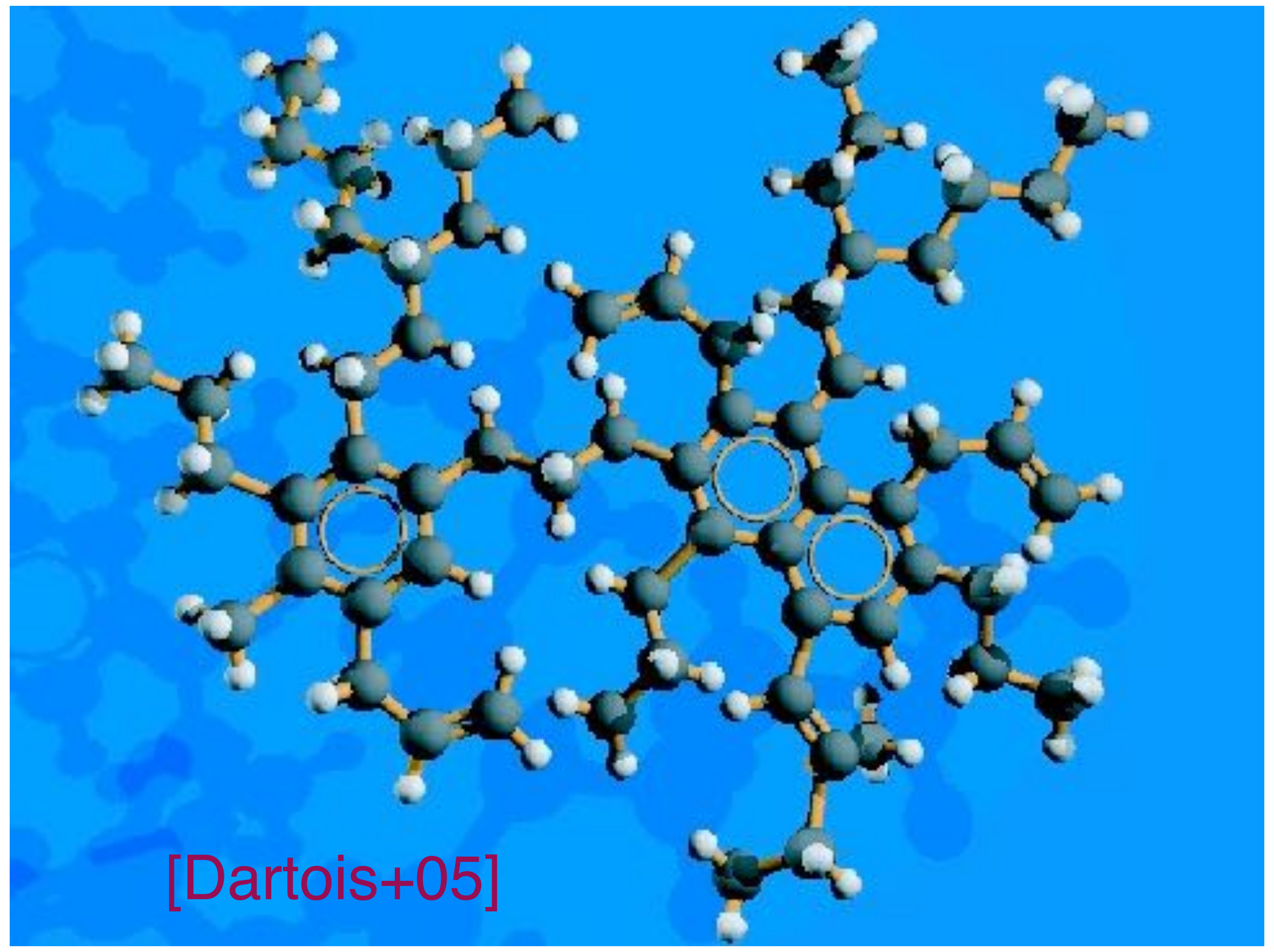


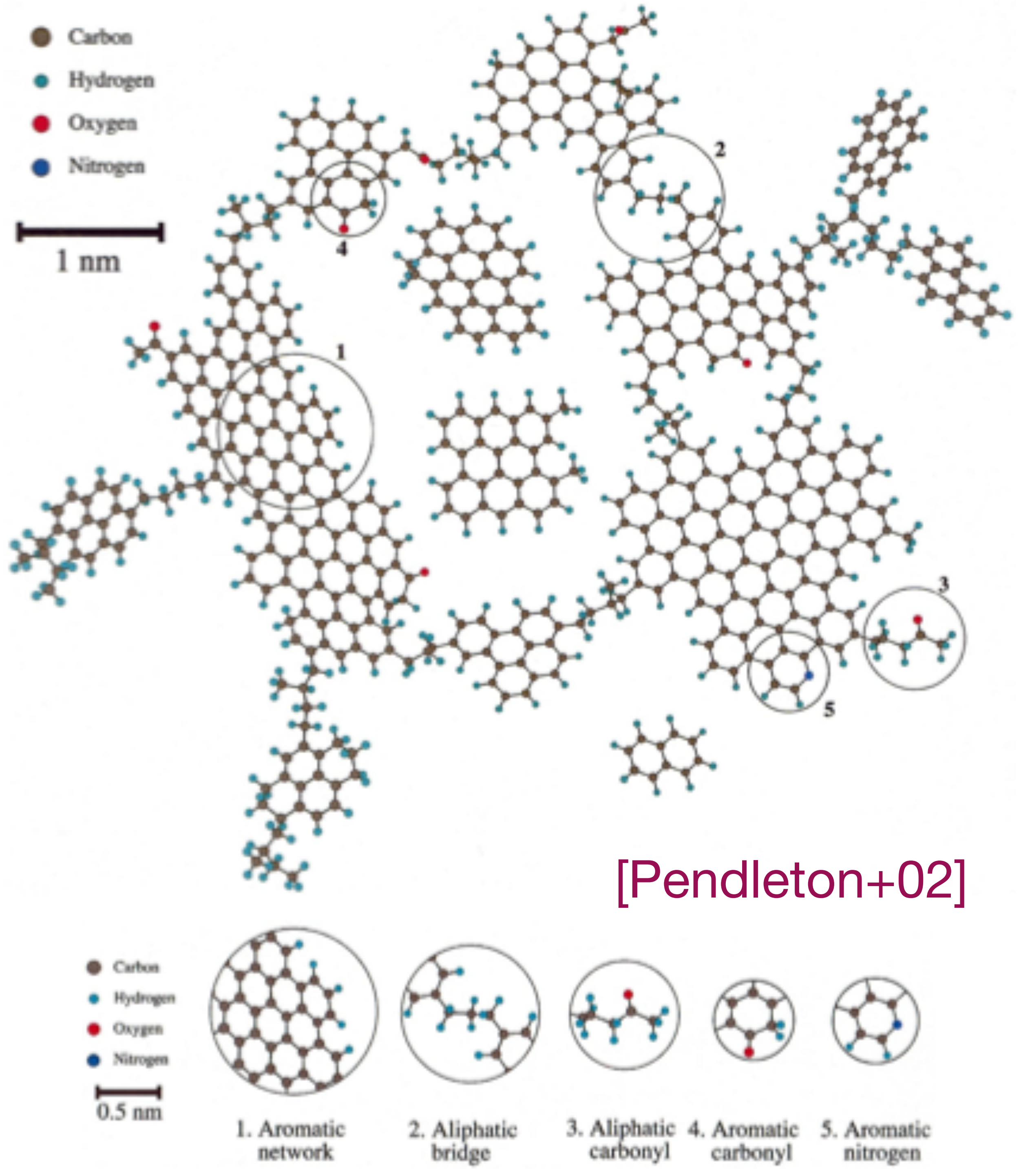
[See review from Tielens 2008]

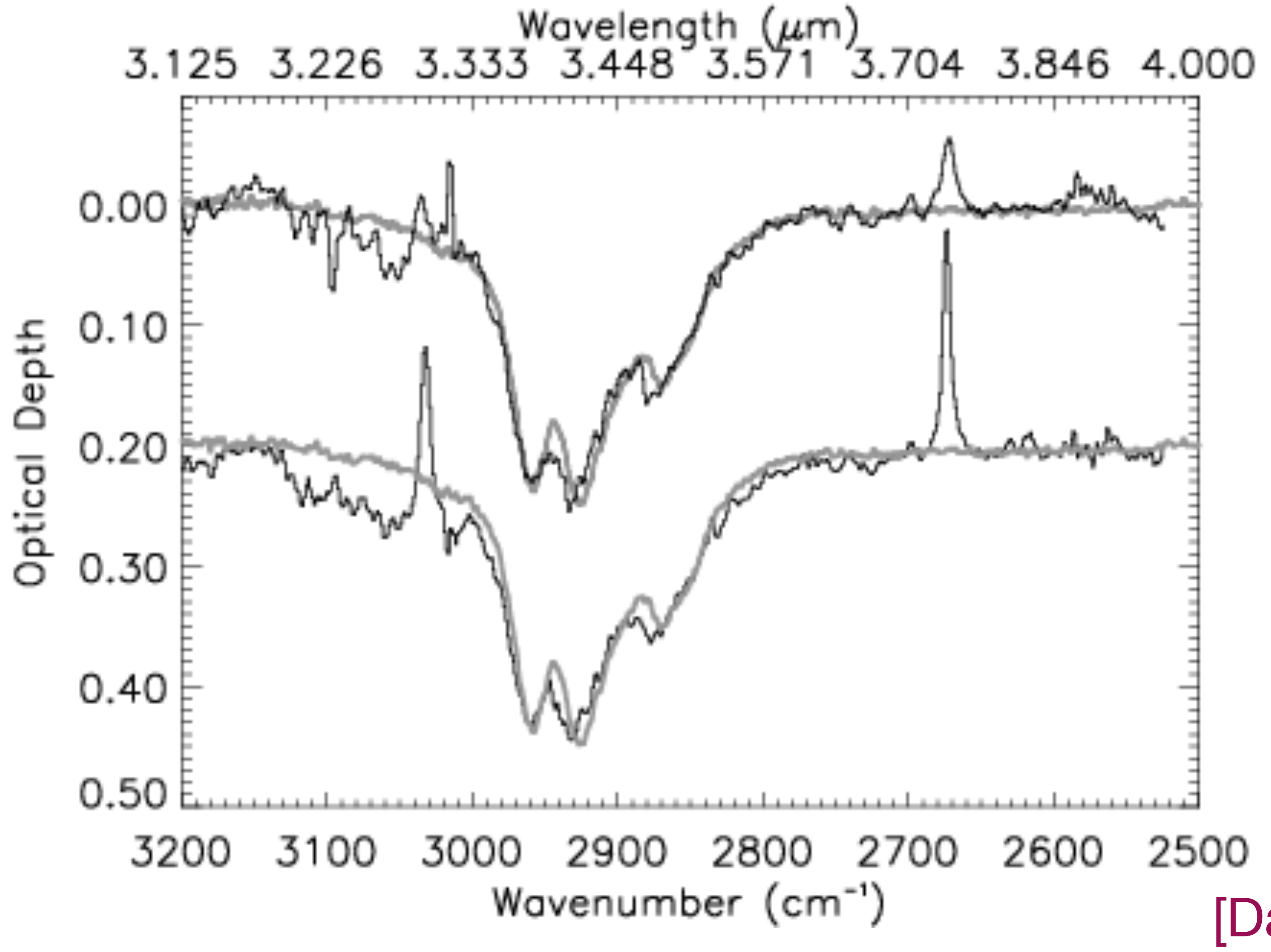


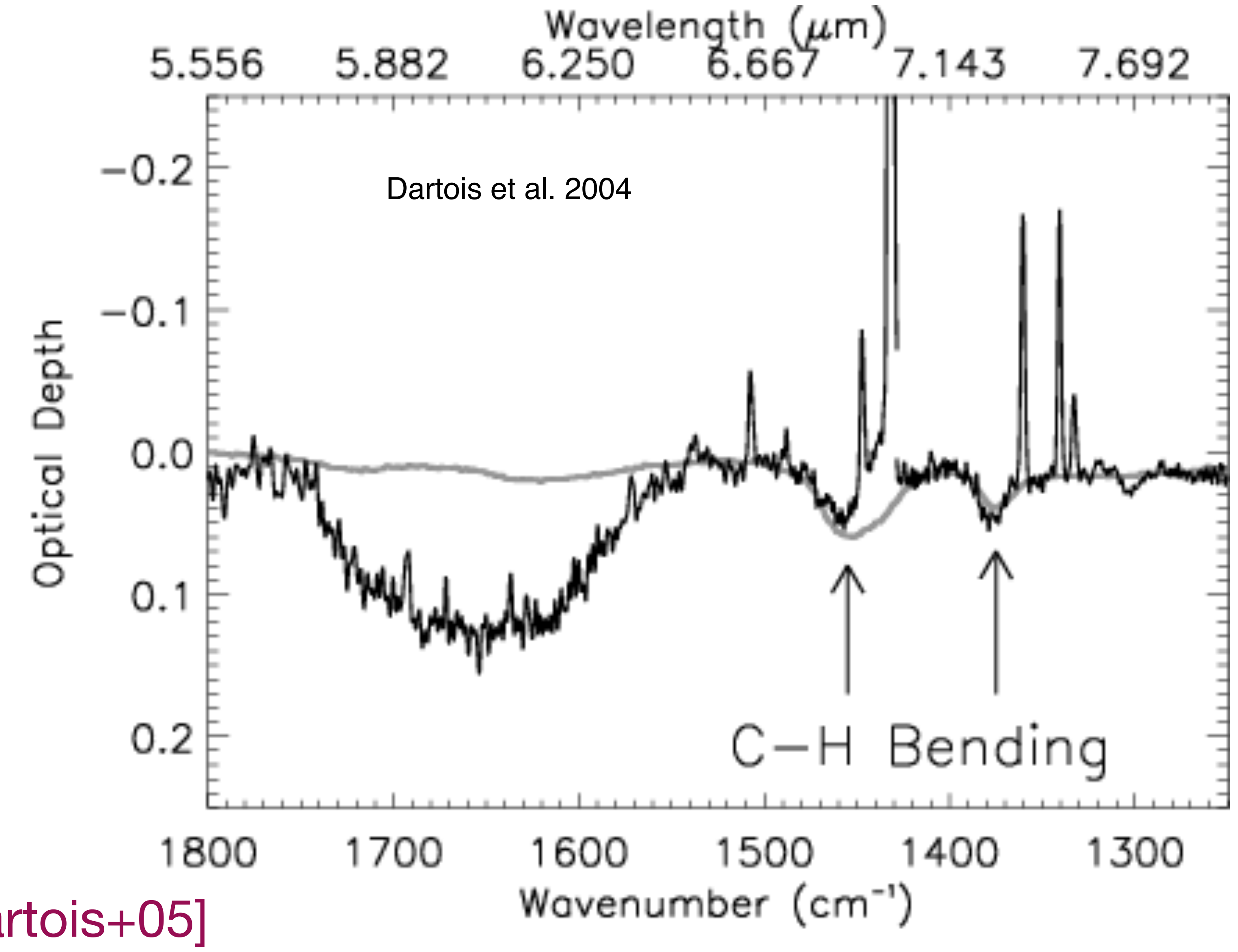
Aliphatic carbon-rich dust: hydrogenated amorphous carbon

- **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+04
    - ~ 85 % aromatic in Pendelton+02





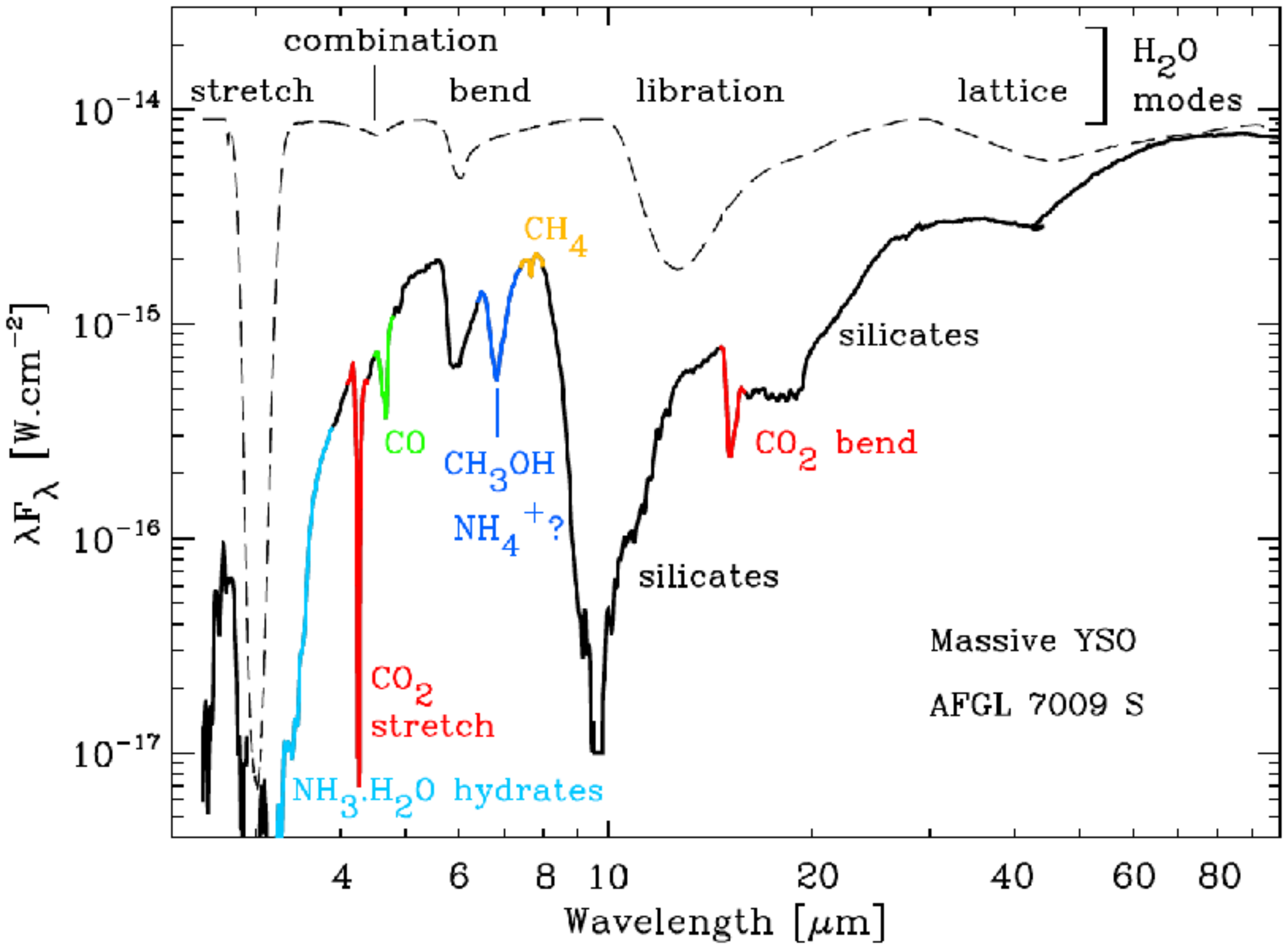




[Dartois+05]

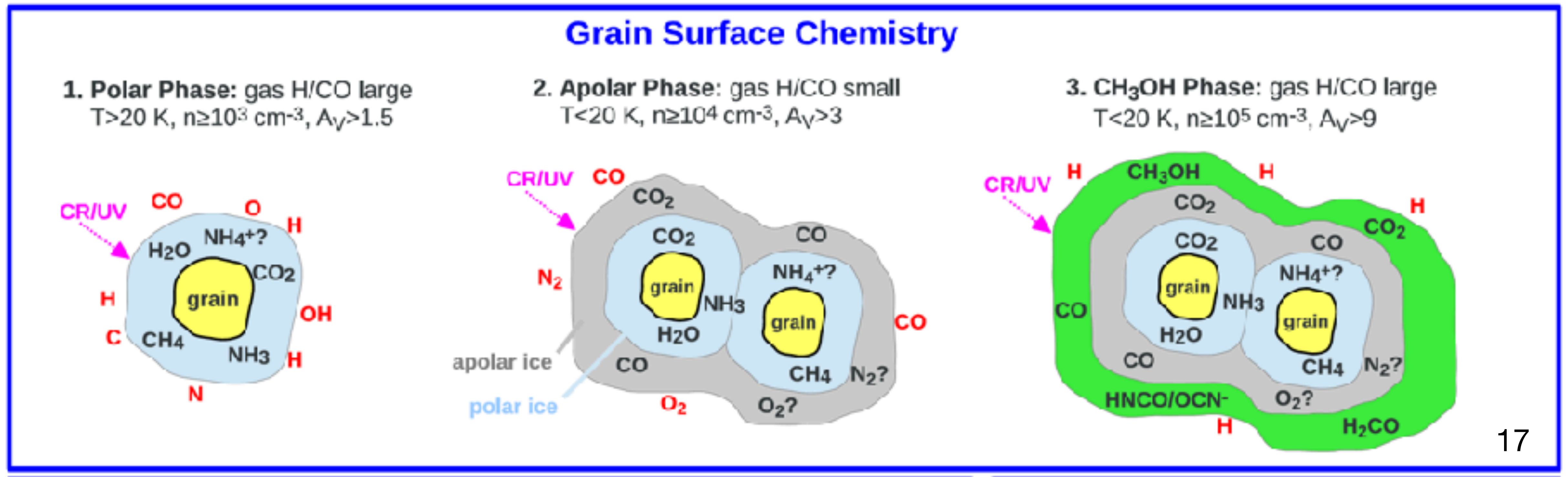
Volatile dust: ices

[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

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, β_s ~ 3.3 -3.6

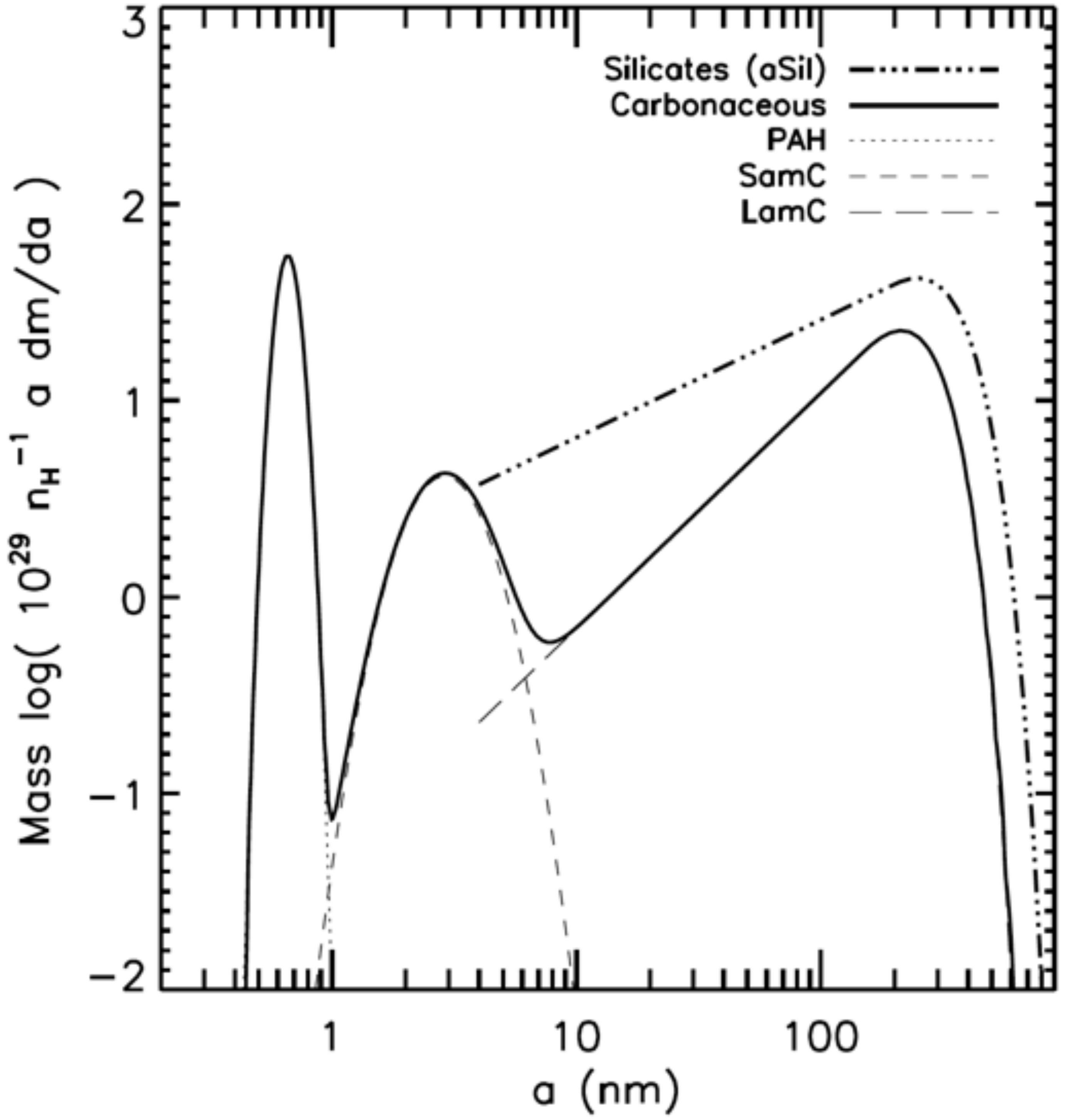
- Many updated versions of the MRN size distribution exist, in particular to include the PAH grain population [see dust models from Compiègne +11, Weingartner & Draine 2001].

- Log-normal grain size distributions are also proposed for large grains [see the THEMIS dust model Jones et al. 2013]

⇒ **the dust mass is in big grains**

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

[Compiègne+2011]



Observational constraints & dust properties: summary

- Observational constraints : depletion, extinction, emission, scattered light, polarisation from X-ray to mm
- Spectroscopic observations provide information on the dust composition and structure
- Additional considerations/constraints should/could guide us:
  - the analysis of presolar grains
  - the dust formation processes

- Several components of dust exist: silicates, carbonaceous grains, ices, PAHs
  - Other minor dust components: oxydes (eg. Al_2O_3, TiO_2), SiC, TiC?, MgS?, carbonates?
- 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 ~75% in mass, carbonaceous dust ~ 25%
- Grains evolve in the ISM

Dust evolution

Dust evolution

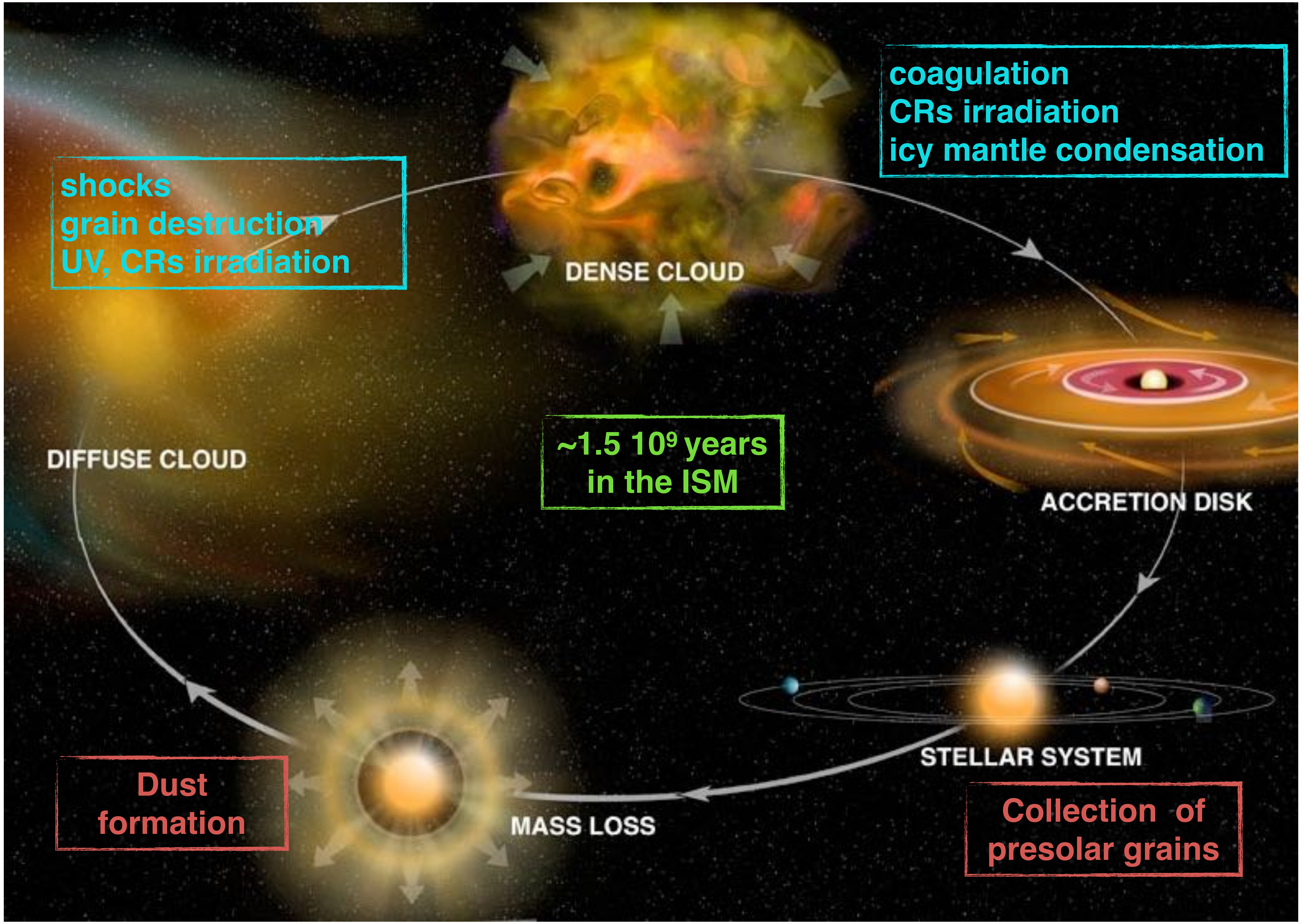
- **Grain-grain collisions:**
  - At low velocity (1-2 km.s^{-1}) → coagulation
  - At intermediate velocity (~20 km.s-1) → fragmentation
  - At high velocity (> 20 km.s-1) → sputtering & vaporisation

- **Gas-grain reactions:**
  - Grain growth: condensation of molecules on the dust surface
  - Erosion by the hot gas

- **Interaction with photons (UV, X…)**
  - Chemistry on grain surface and within icy mantles
  - Influence the ionisation and stability of PAHs and nano a-C(:H) grains

- **Interaction with cosmic rays (CRs)**
  - Chemistry within icy mantles
  - Changes of the grain structure (amorphization)

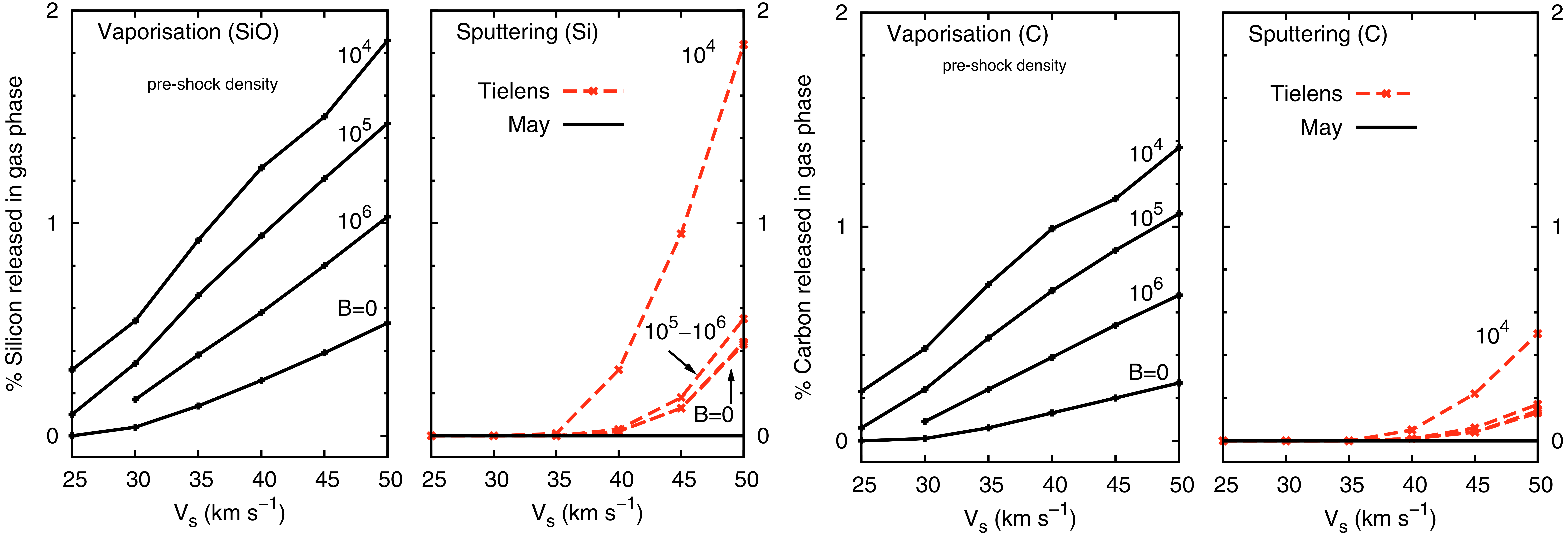
Dust evolution along the ISM life cycle



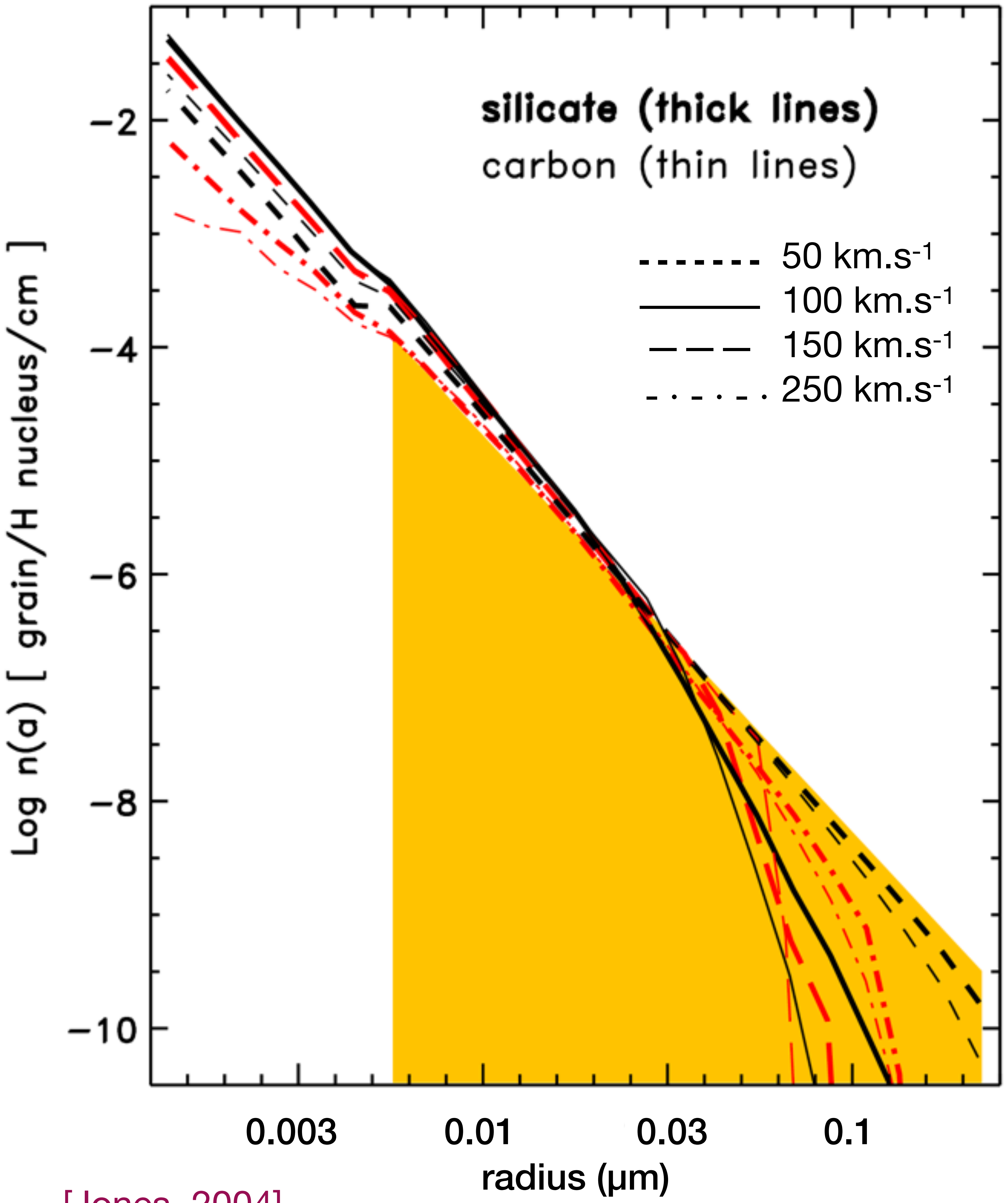
Dust evolution in shocks

- **Gas phase enrichment** with the elements and molecules constituting the grains, both volatile and refractory:
  - vaporisation (complete grain destruction)
  - sputtering (partial destruction)

See Guillet et al. « Shocks in dense clouds I, II, II (2007, 2009, 2011)

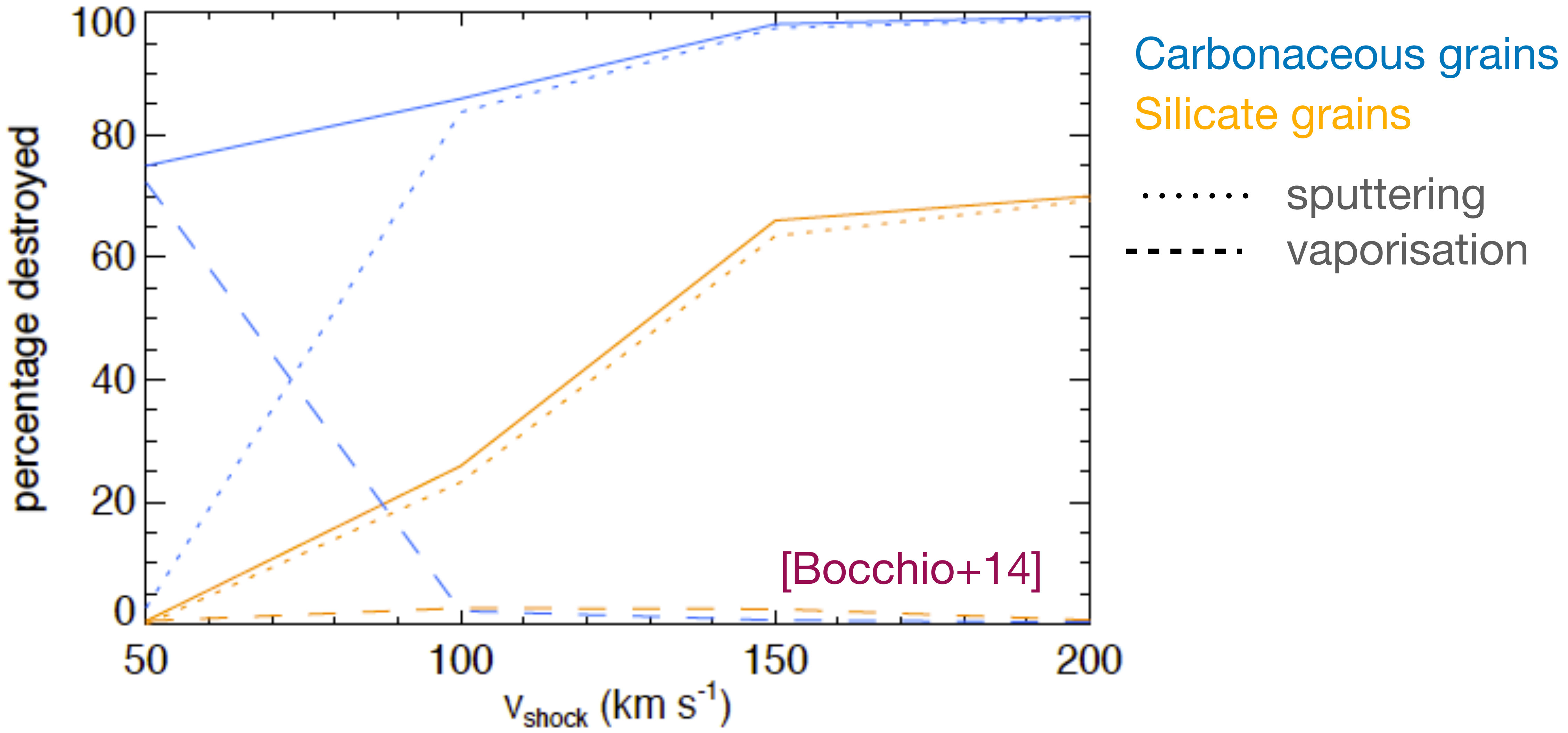


Dust evolution in shocks



[Jones, 2004]

- **Grain size distribution changes:**
- **Fragmentation**:
  - diminution of the number of big grains increase of smalls grains, M_{dust} is constant
  - more important at high density
- **Sputtering**:
  - decrease of grain size and M_{dust}
- **Grain destruction :**



Dust lifetime

- Grain residence time in the ISM before incorporation in new stars: ~ 1.5 Gyr
- Grain life time against destruction by high velocity (SN) shocks: ~ 0.5 Gyr
- Hydrodynamical models of Giant Molecular Clouds + elemental depletion constraints

[see eg. Jones & Nuth 2011, Bocchio+14, Slavin+15, Zukhoska+2016,2018, Dwek+15,…]

↓

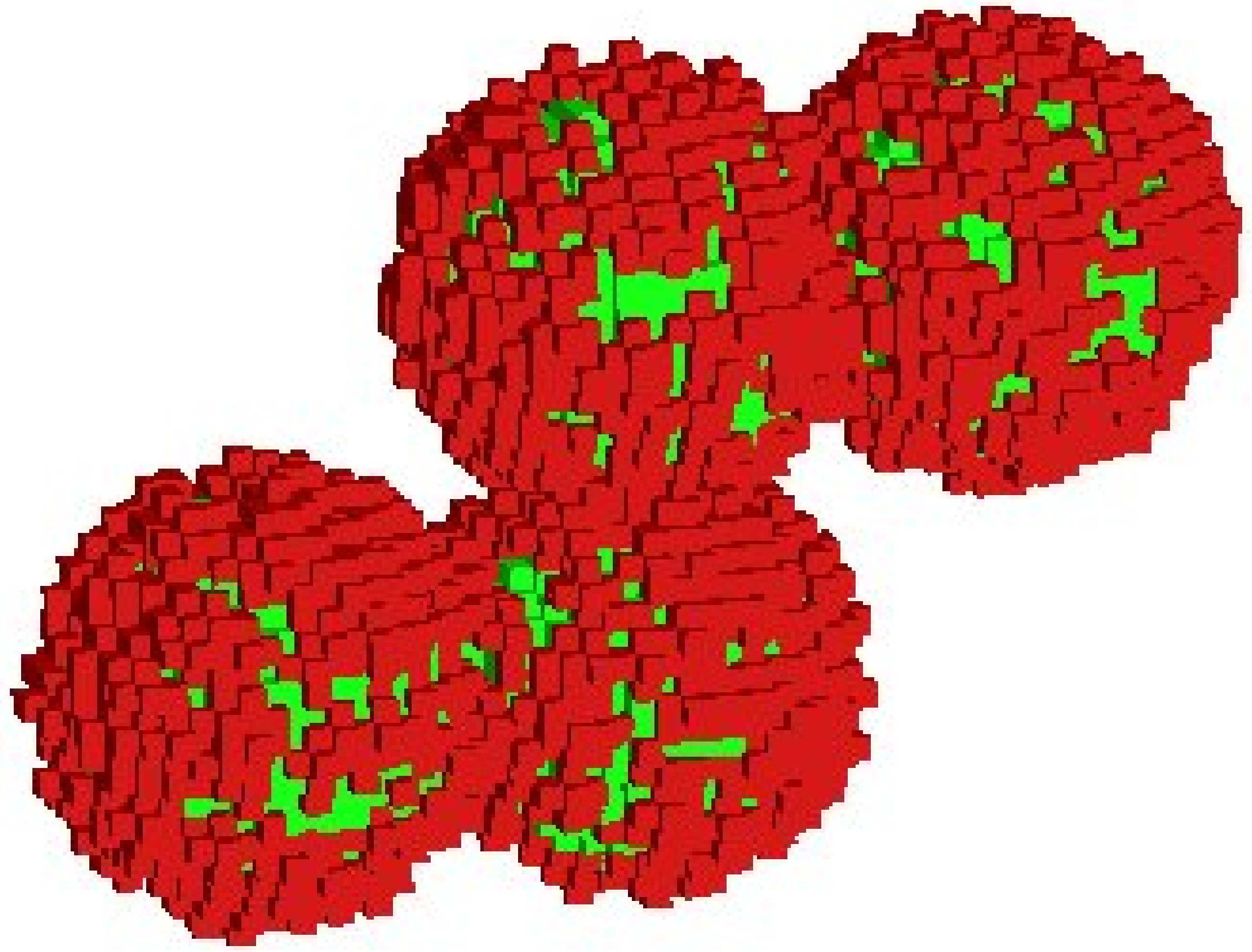
- Most cosmic dust grains are destroyed in the ISM before being incorporated into new stars

↓

- Grains must be formed *in situ* in the ISM
- The proportion of the dust that is formed in the ISM depends on many parameters which are not well constrained
  - Need more observational constraints, more modelling
  - Need experiments on dust growth on the cold surface of grains [Rouillé+2020]

Dust coagulation in dense clouds

- In dense environments: cold clouds, pre-stellar cores, protoplanetary disks



- Coagulation time for a mixture of grains : [Draine+85, Stepnik+03]

$$t_{coa} = \frac{1}{\sigma_{1/2} n_1 v_{1/2}}$$

n_1 : number density of grain 1

$v_{1/2}$: relative velocity between the two grains

$\sigma_{1/2}$: coagulation cross section: $\sigma_{1/2} = \pi \times (a_1 + a_2)^2$

Molecular cloud with $n_H = 4 \times 10^3$ cm^{-3} and a relative velocity of 0.1 km/s

Type of coagulation	Coagulation time-scale [yr]	n_g [cm^{-3}]
VSG on **VSG**	1.4×10^5	1.52×10^{-5}
VSG on **BG**	1.6×10^3	1.52×10^{-5}
BG (car) on **BG**	1.1×10^6	6.17×10^{-9}
BG (sil) on **BG**	4.3×10^5	1.60×10^{-8}

[Köhler+12]

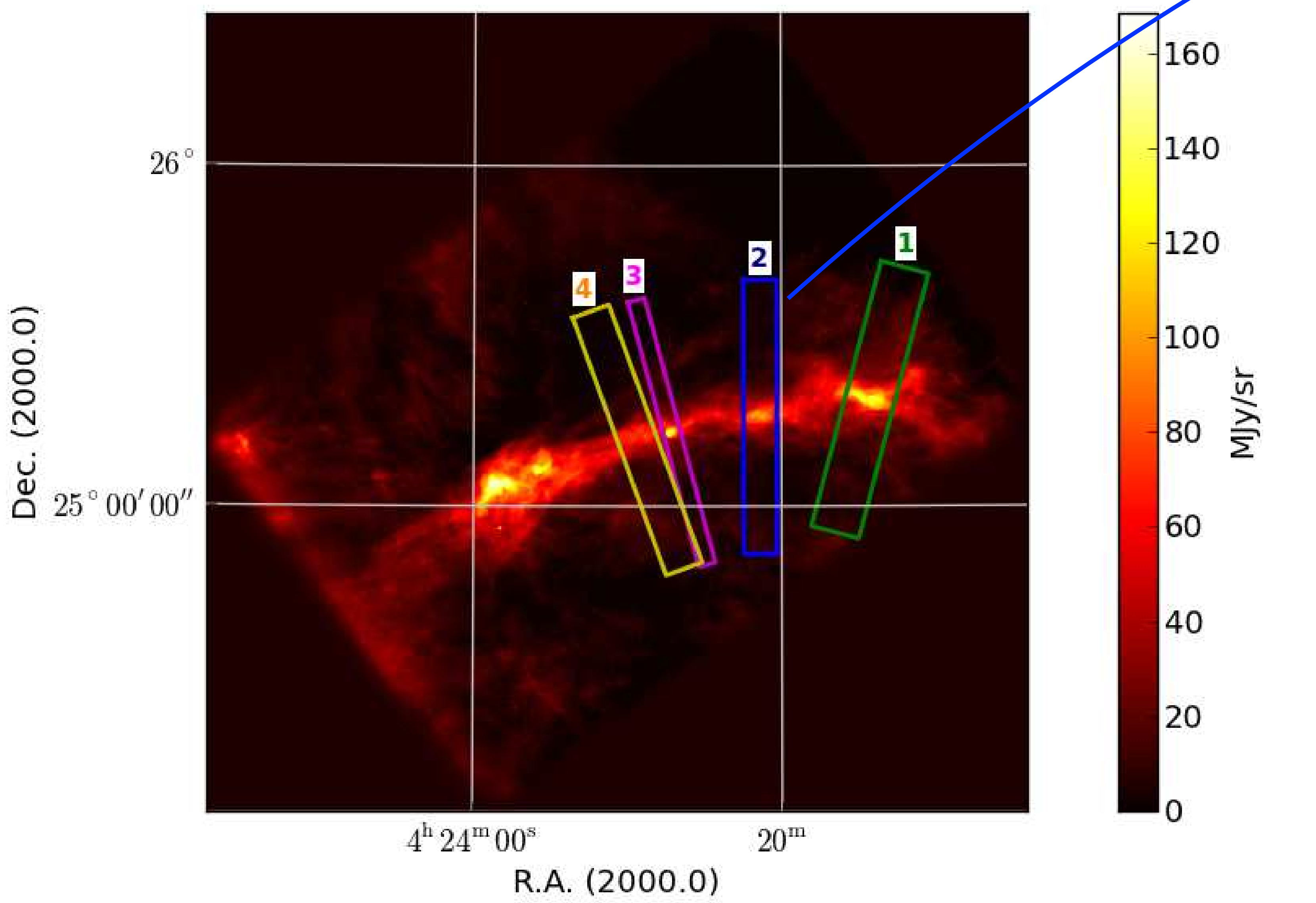
- The time for coagulation is rapid ⇒ grain have time to coagulate

before cloud collapse and star formation (in ~ 10^6-10^7 years)

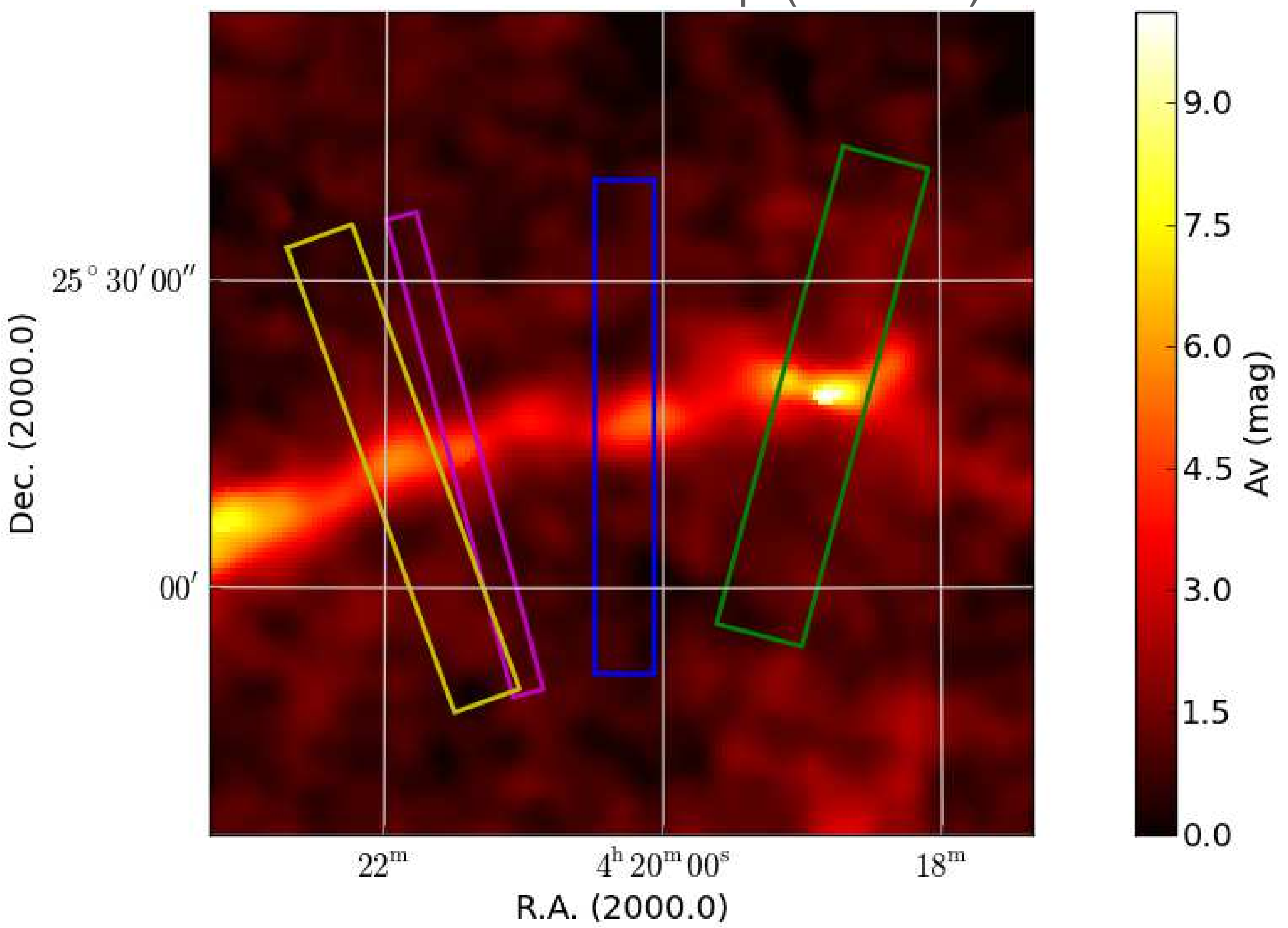
Dust coagulation in dense clouds

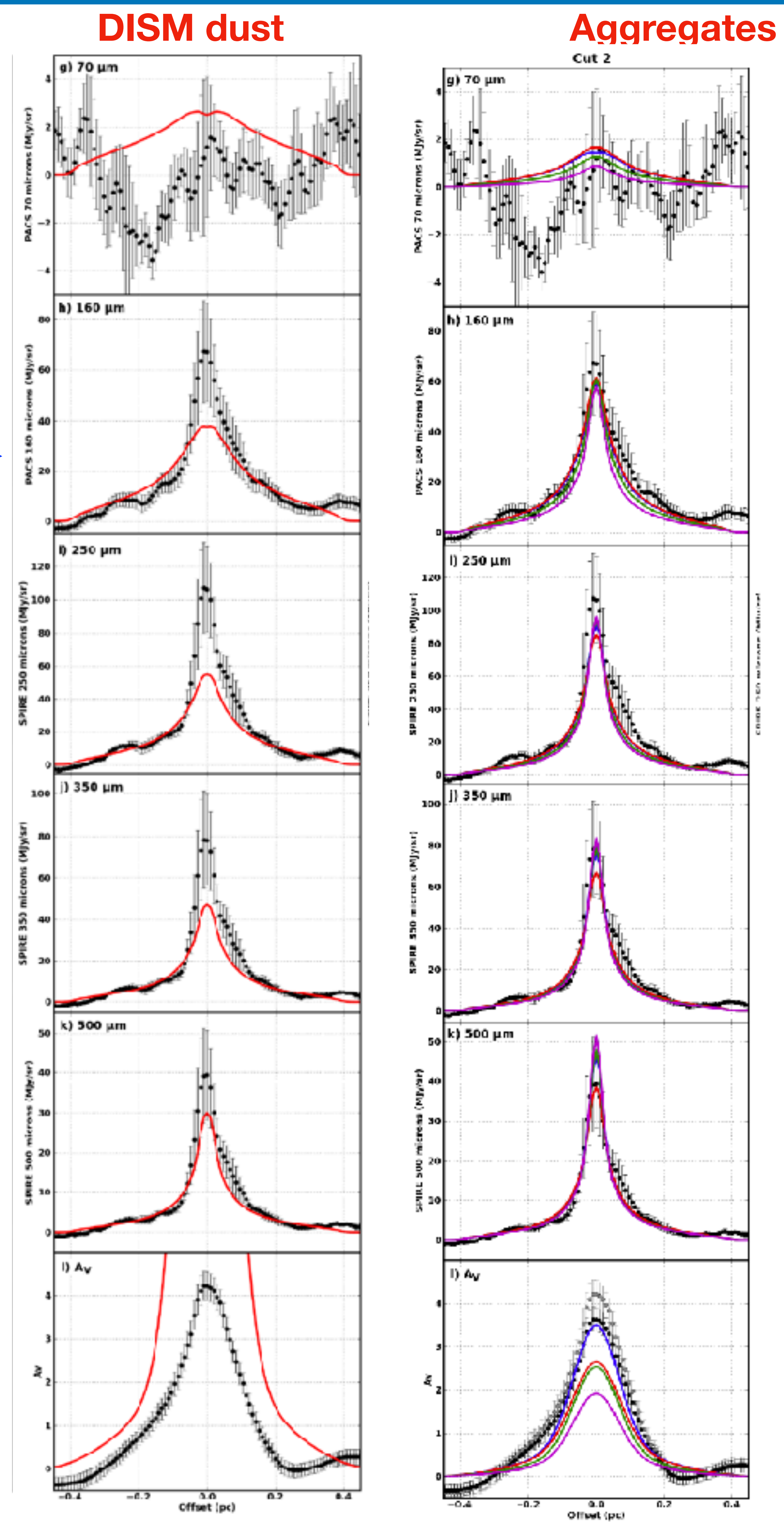
- Herschel map of the filament L1506 in the Taurus
- Modelling of the emission along several cuts across the filament
- Aggregates are needed to reproduced simultaneously the extinction and emission data
    - Dust opacity at 250 µm is raised by 1.8-2.2
    - Grain size increases by a factor 5

Brightness map at 250 µm (Herschel)



Extinction map (2MASS)





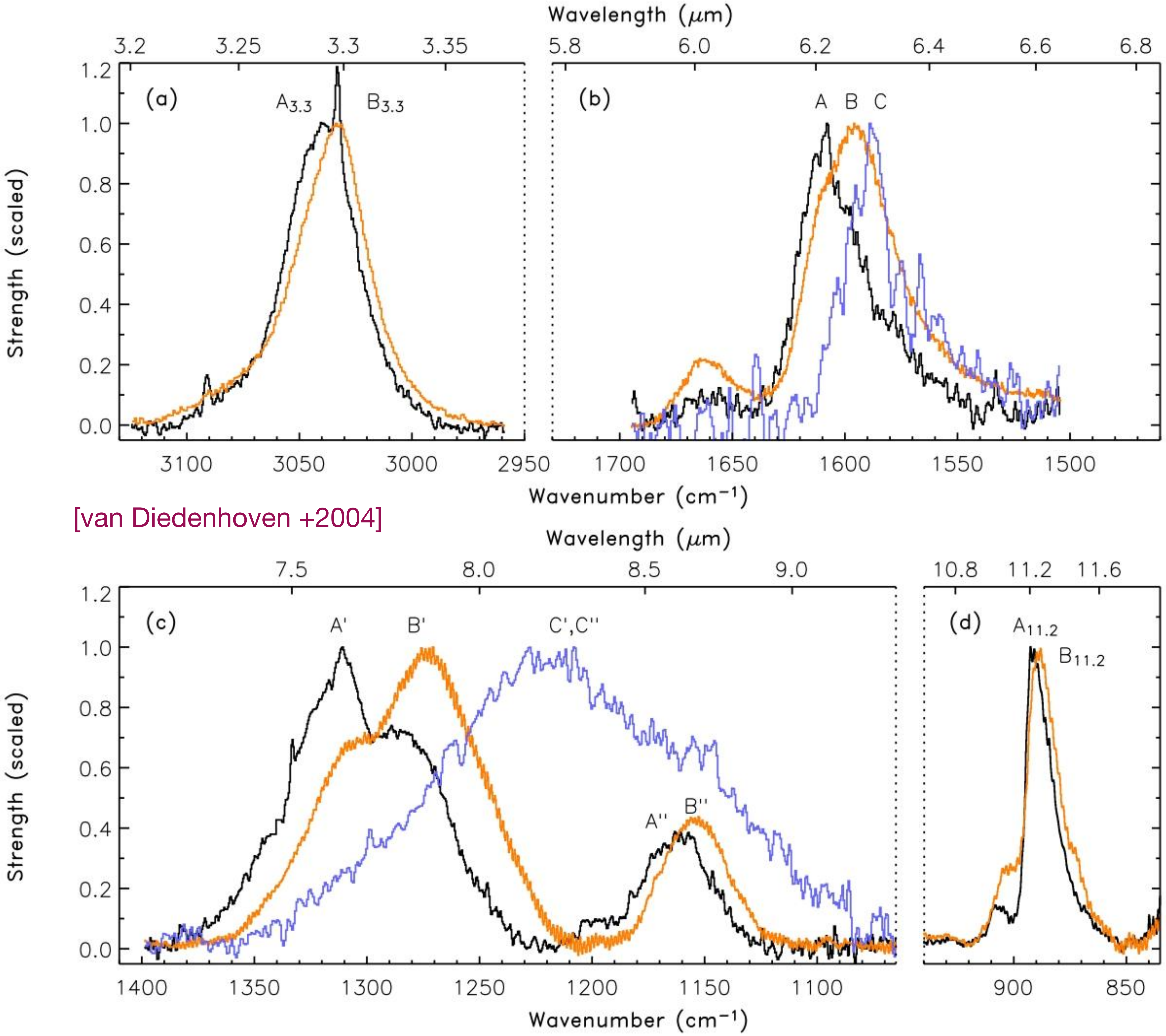
Evolution of carbon dust: the AIB

- A (the most common) : HII regions, Herbig AeBe stars, reflexion nebula, post-AGB stars, PPNs, extragalactic sources

- B: Some isolated Herbig AeBe stars, AGB stars, and PPNs

- C: Some post AGB stars and young PPNs

- The AIBs are sensitive to the radiation field → change of the ionisation state & size of the carriers
  - ⇒ band ratios are diagnostics of the physical conditions of environments and of its chemical evolution, see [Galliano+18]

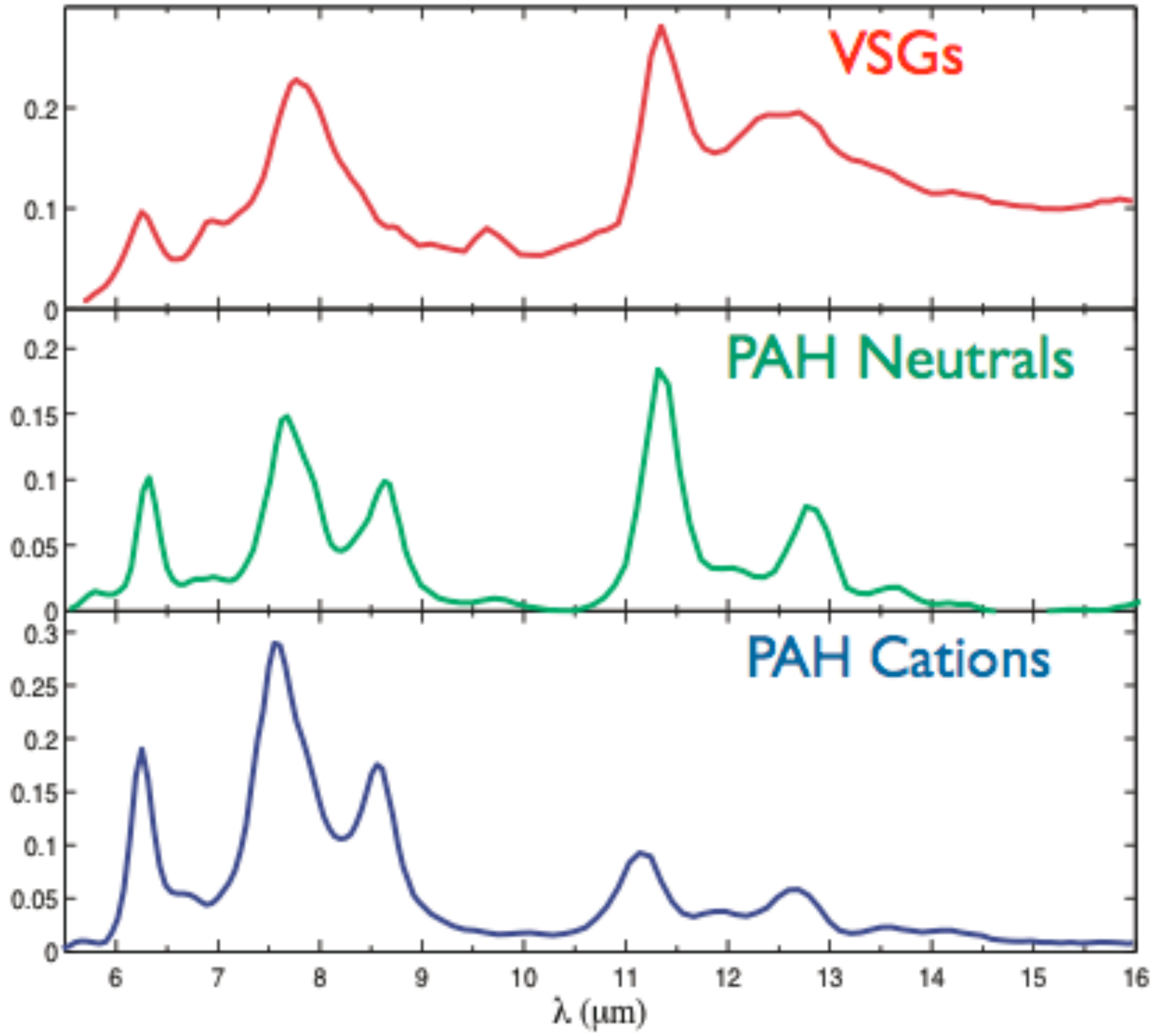


[van Diedenhoven +2004]

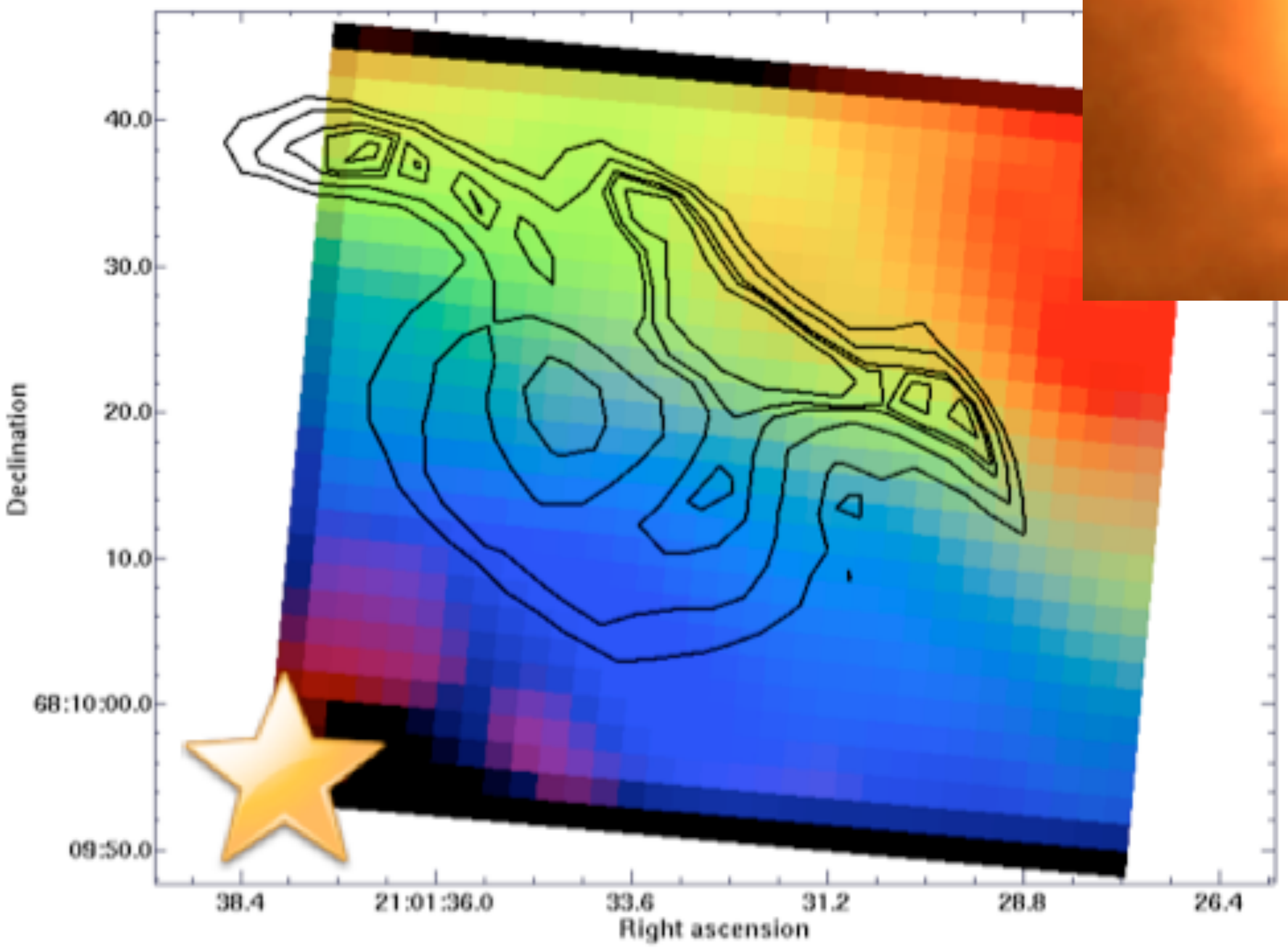
Evolution of PAHs

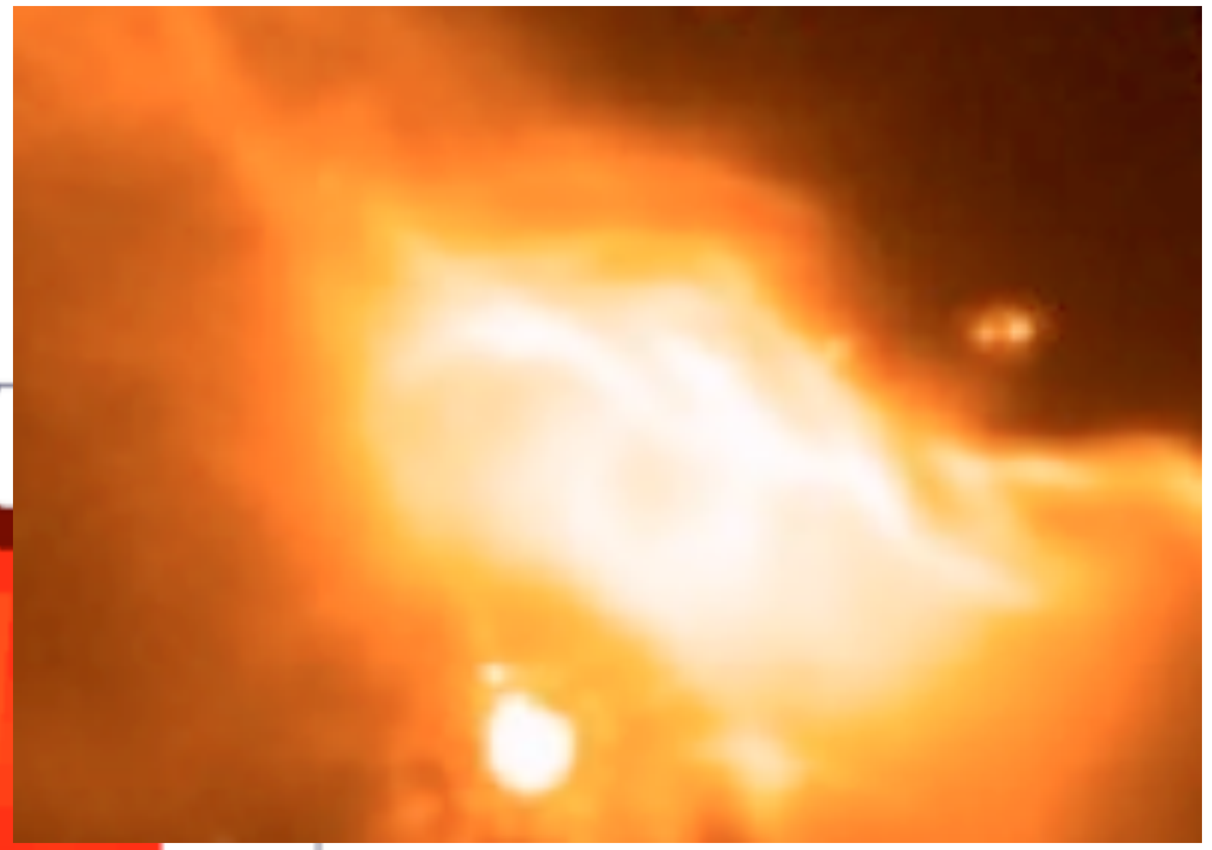
UV processing

Extracted spectra [Berné +2007, 2010]



Spatial distribution





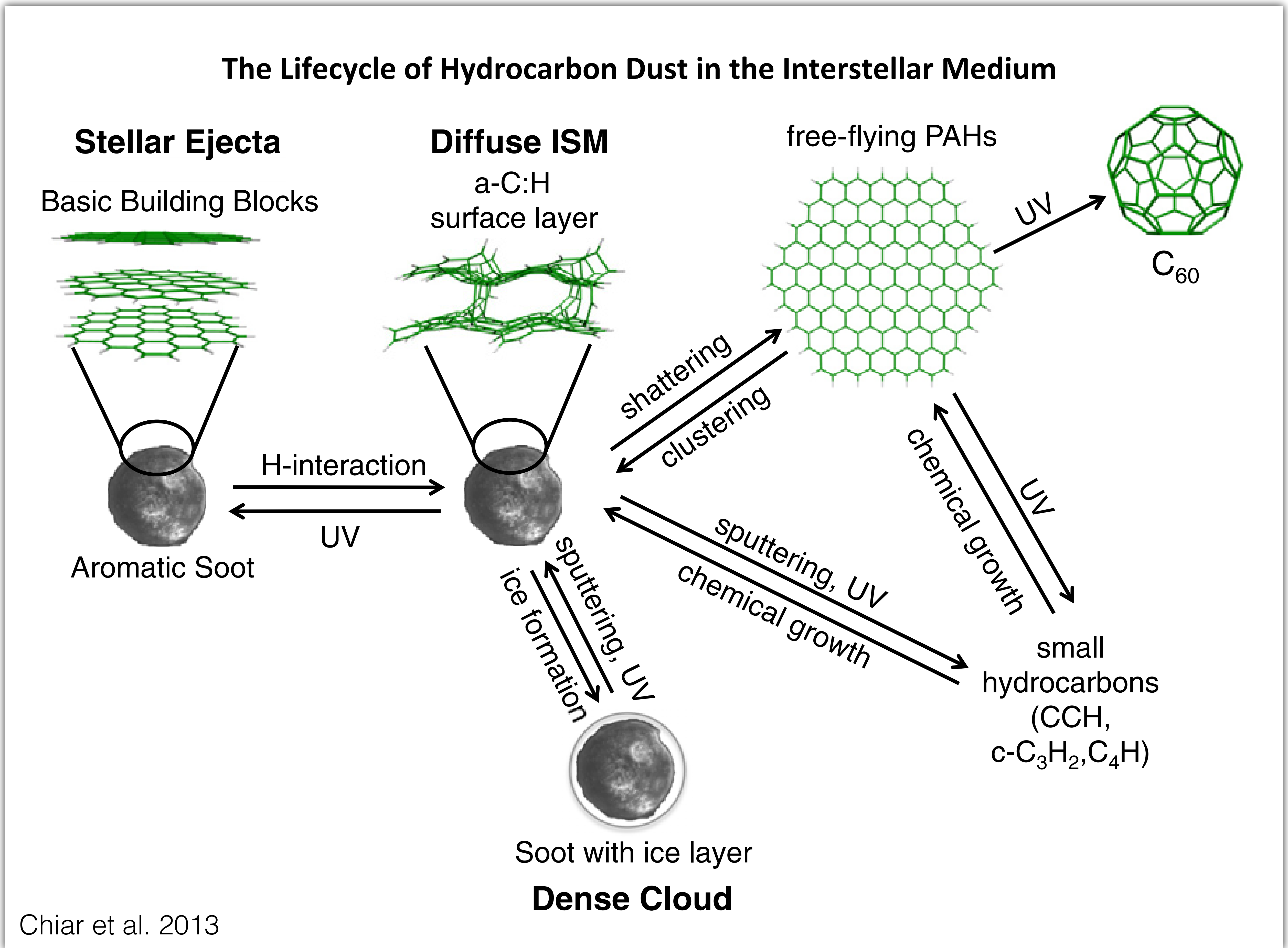
NGC 7023 reflexion nebulae (Spitzer)

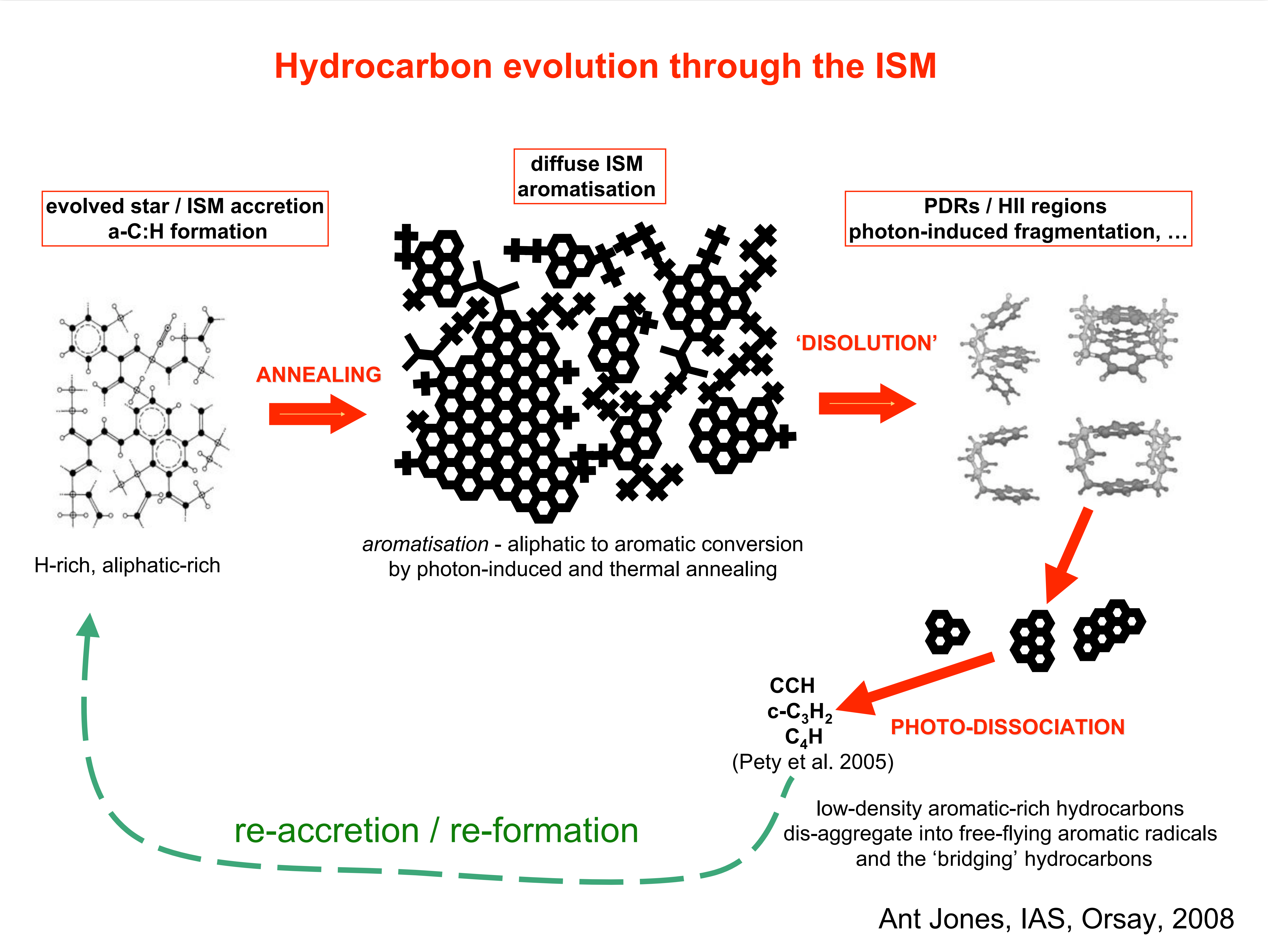
- High radiation field: photo-destruction of VSGs & production of PAHs, ionisation of PAHs
- Possible release of small hydrocarbons from PAHs destruction [Pety +2005]

Evolution of the AIBs

Adapted from the JWST ERS project « Radiative feedback from massive stars as traced by multi band imaging and spectroscopic mosaics » PI O. Berné, E. Habart, E. Peters

Evolution of hydrocarbon dust





See also Goto+2003, Carpentier+2012

Dust evolution: summary

- Dust properties change along the life cycle of the ISM

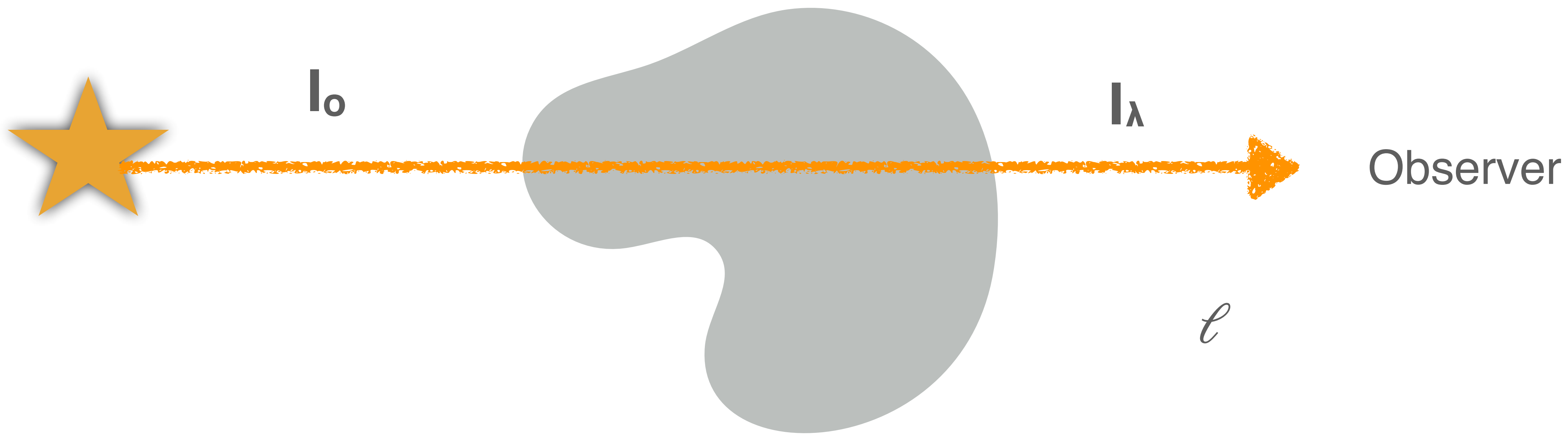
- Grains are destroyed in shocks
  - the size distribution changes
  - the ISM is enriched in molecules and heavy elements
  - this suggests that dust grains must be formed also *in situ* the ISM

- In dense clouds, protostars and protoplanetary disks grains coagulate
  - the size distribution changes
  - a complex chemistry occurs on grain surfaces and in ice mantles
- This complexity is partly inherited by the new stellar systems

- Carbonaceous dust composition, structure and ionisation state changes with the interaction with UV photons as well as with the interaction with gas

Modelling 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 (cm^{-3})
N : column density of dust (cm^{-2})
σ_{gr} : geometrical cross section of the grains (cm^2)

$$\tau(\lambda) = l k_{ext} = N C_{ext} = \sigma_{gr} N Q_{ext}$$

k_{ext}, C_{ext}, Q_{ext}, κ_{ext} contains the information on the dust properties

Modelling the extinction

- To calculate the absorption, scattering, emission and polarisation cross sections of the grains for each grain population, one needs to understand the interaction of small particles with the electromagnetic radiation

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

$$\varepsilon = \varepsilon_1 + i\varepsilon_2$$

$$m = n + ik = \sqrt{\varepsilon}$$

n: refraction index

k: extinction coefficient

- Need to solve Maxwell's equations with appropriate boundary at the grain surface

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

Grains smaller than the wavelength

- Electric dipole limit (**Rayleigh limit**) : when the particle size a is $\ll \lambda$, it experiences an EM field nearly uniform. Then :

$$C_{abs} = \frac{4\pi\omega}{c} Im(\alpha) \qquad C_{sca} = \frac{8\pi\omega^4}{3c^4} |\alpha|^2$$

where α is the electric polarisability of the grains, the electric dipole moment P = αE

- The polarisability has a simple analytical expression for spheres, spheroids and ellipsoids:

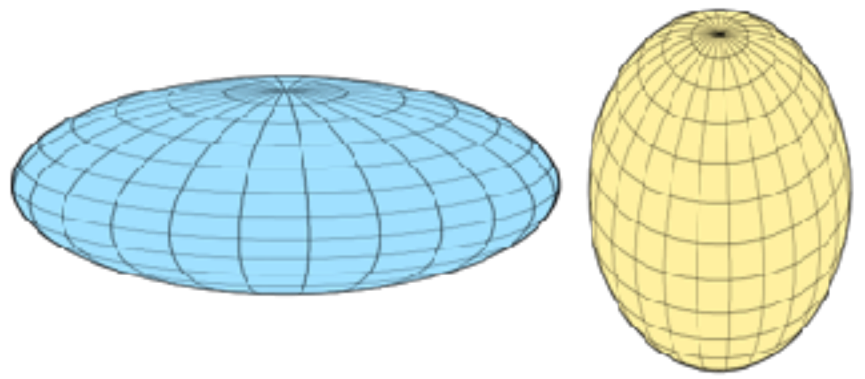
$$\alpha_j = \frac{V}{4\pi}\left[\frac{\varepsilon - 1}{(\varepsilon - 1)L_j} + 1\right]$$

where L_j is the shape factor, $L_1 + L_2 + L_3 = 1$

- **For a spherical grain (L_i =1/3) small compared to the wavelength :**

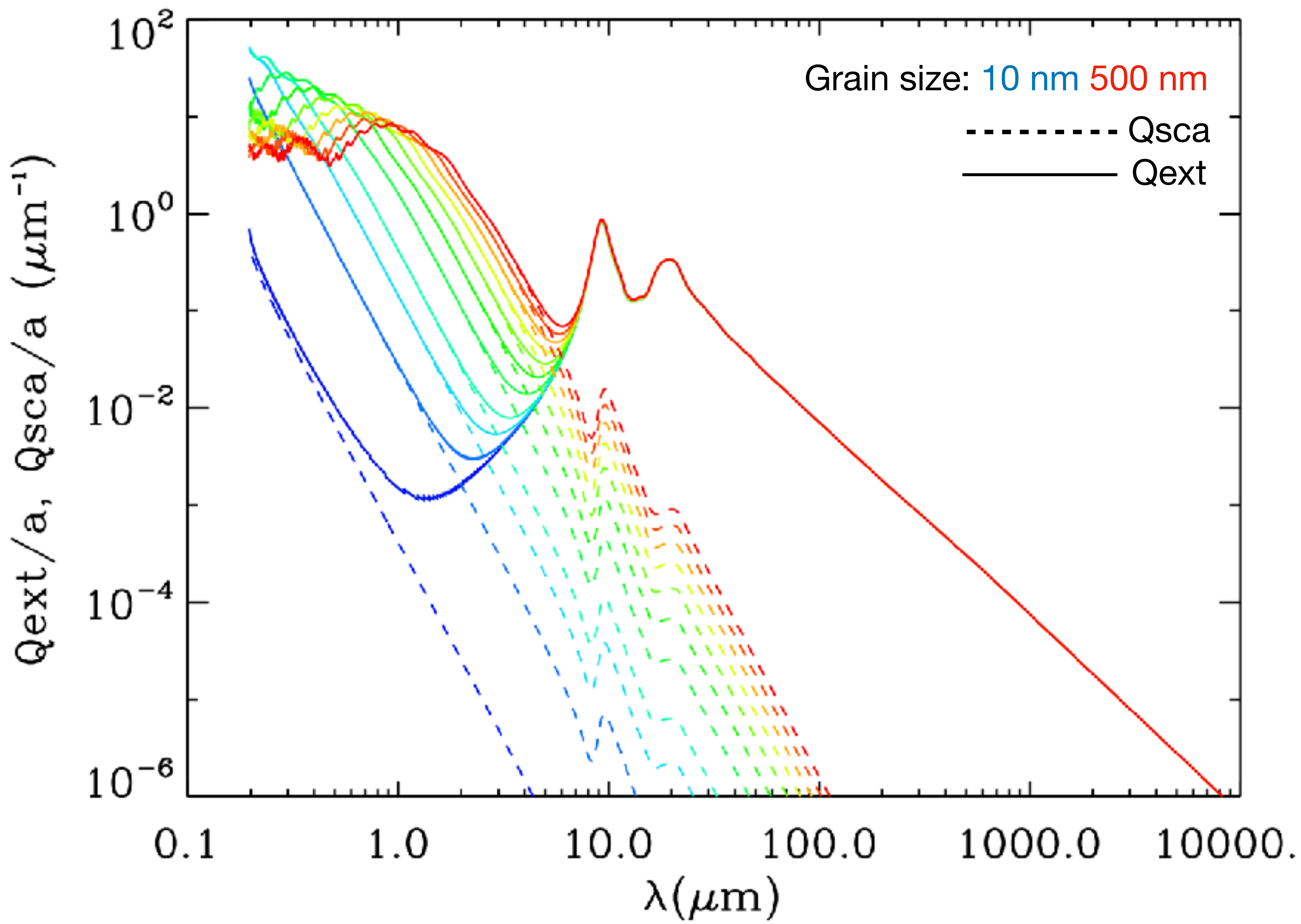
$$C_{abs} = \frac{18\pi V}{\lambda} \frac{\varepsilon_2}{(\varepsilon_1 + 2)^2 + \varepsilon_2^2} \qquad C_{sca} = \frac{24\pi^3 V^2}{\lambda^4} \left| \frac{\varepsilon - 1}{\varepsilon + 2} \right|^2$$

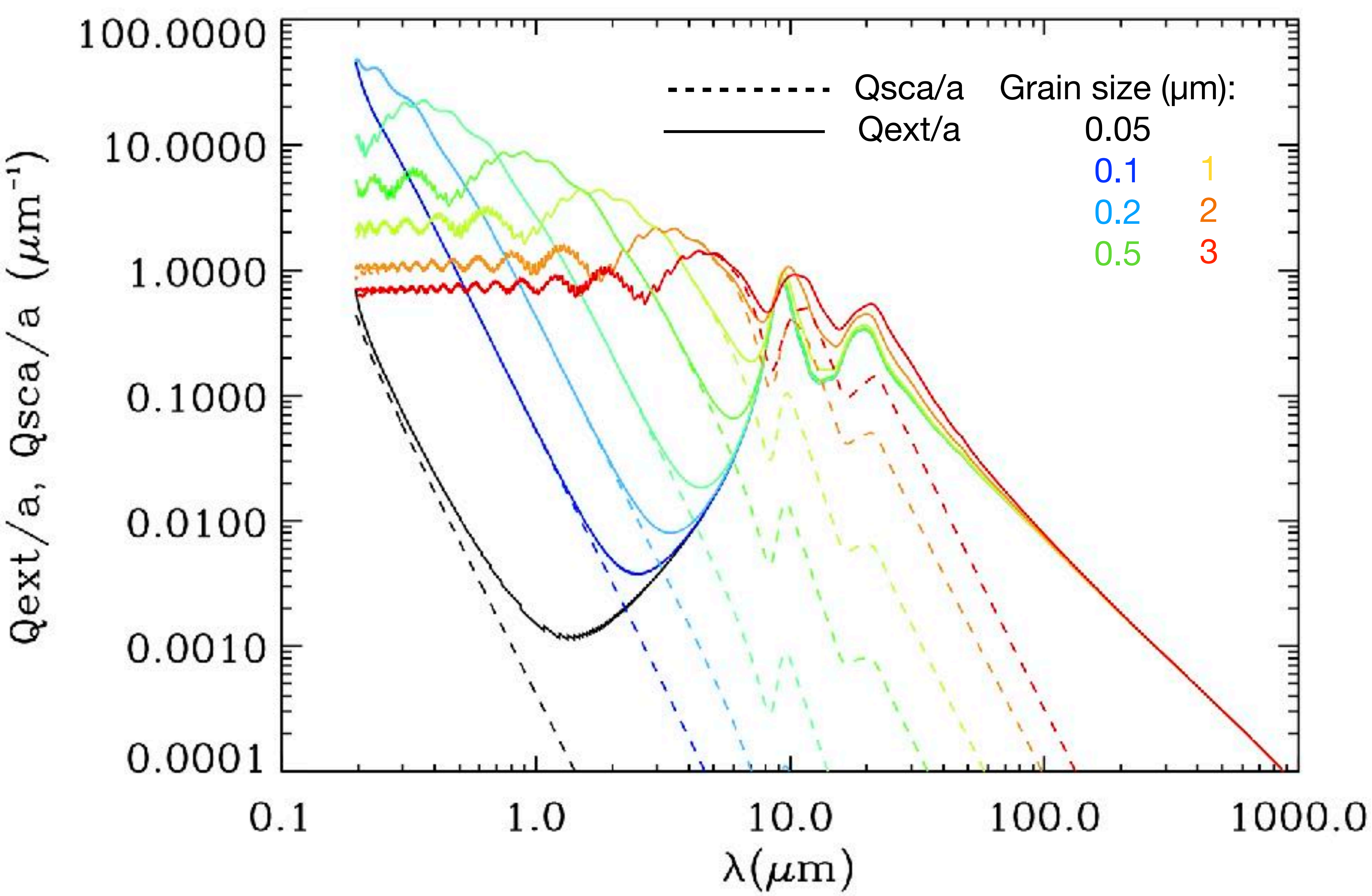
- **Reasonably simple expression also exists for spheroids**



Extinction as a function of size: spherical grains

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





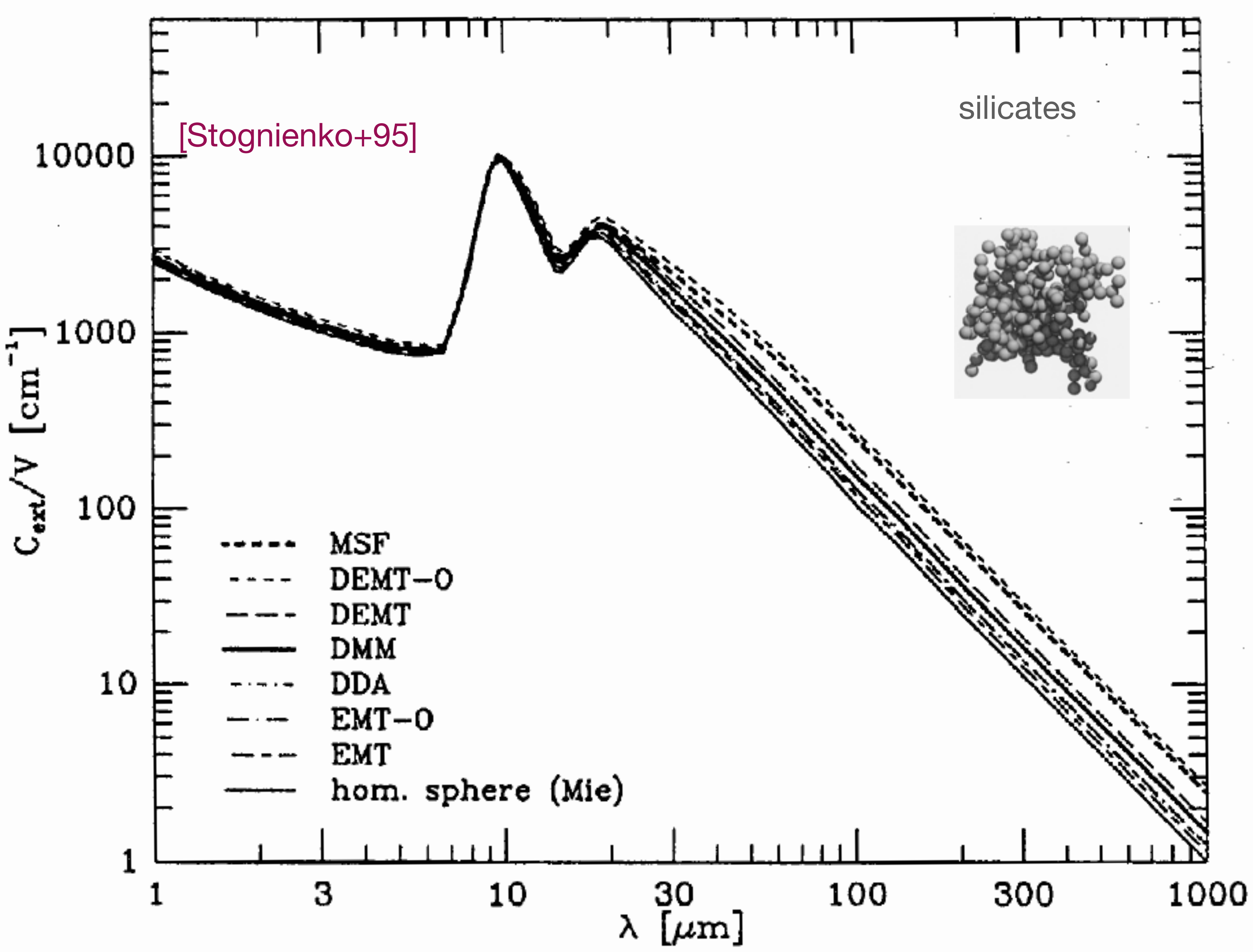
- for $a \ll \lambda$, the absorption and scattering properties do *not* depend on the dust size
- for $a \approx \lambda$ the absorption and scattering properties depend on the grain size

Extinction cross section of aggregates

- If the particles are not spherical or if grains are aggregated, calculation are more complicated. Different methods are used such as DDA [Draine & Flatau 2010], T-Matrix [Mischenko+1996]. Some codes are public.

- Complex dust grains in term of composition and structure can be treated with **effective medium theories (EMTs)**:
  - core-mantle grains
  - composite grains with inclusions
  - aggregates of grains of different compositions (approached method)
  - [see eg. Min+2008]

- *Each theory has its own limitations*



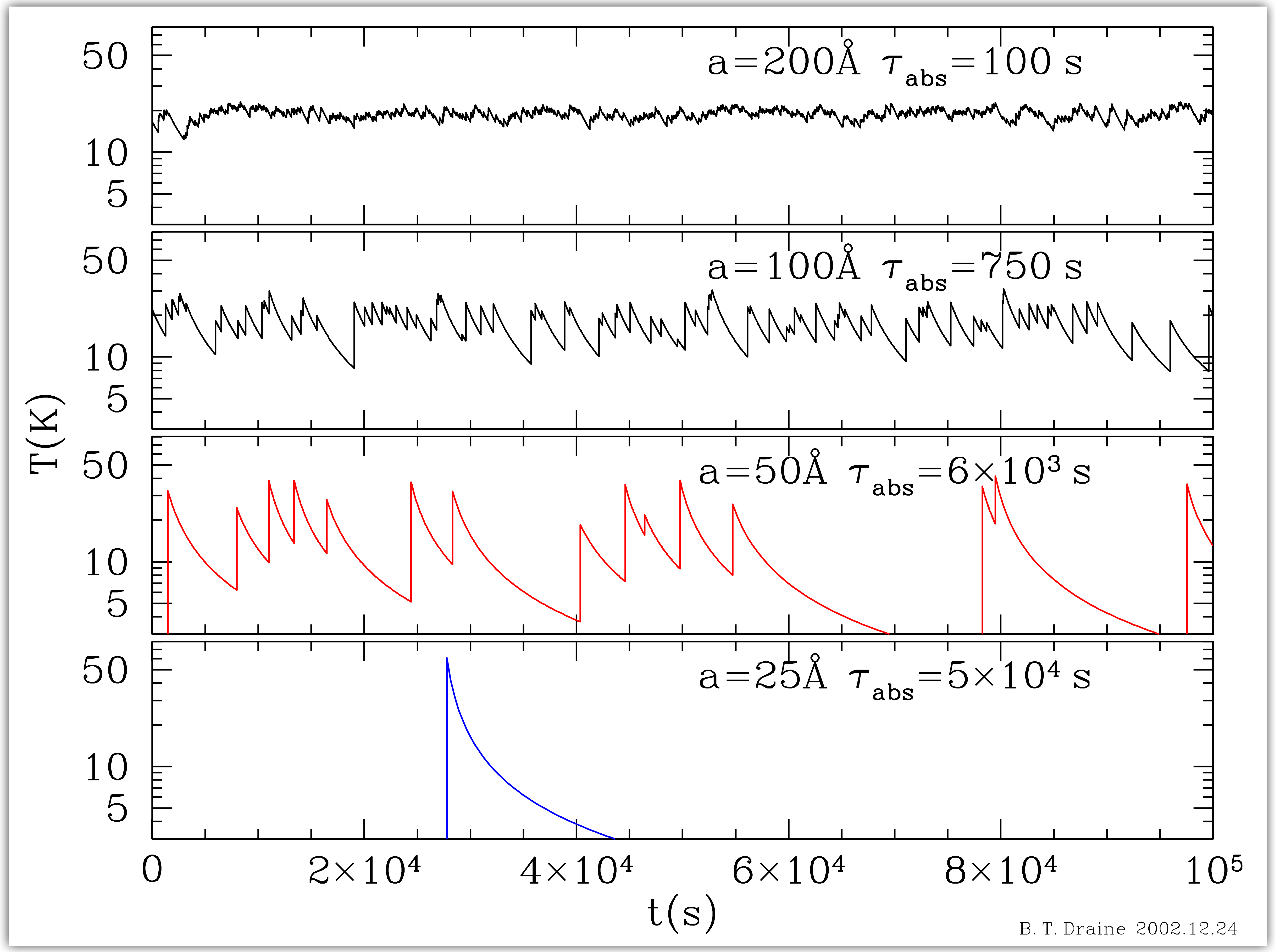
Dust properties: heating & cooling

- **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 because of the large energy density of starlight (~ 0.5 eV/cm^3) and the high opacity of grains to starlight

- **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

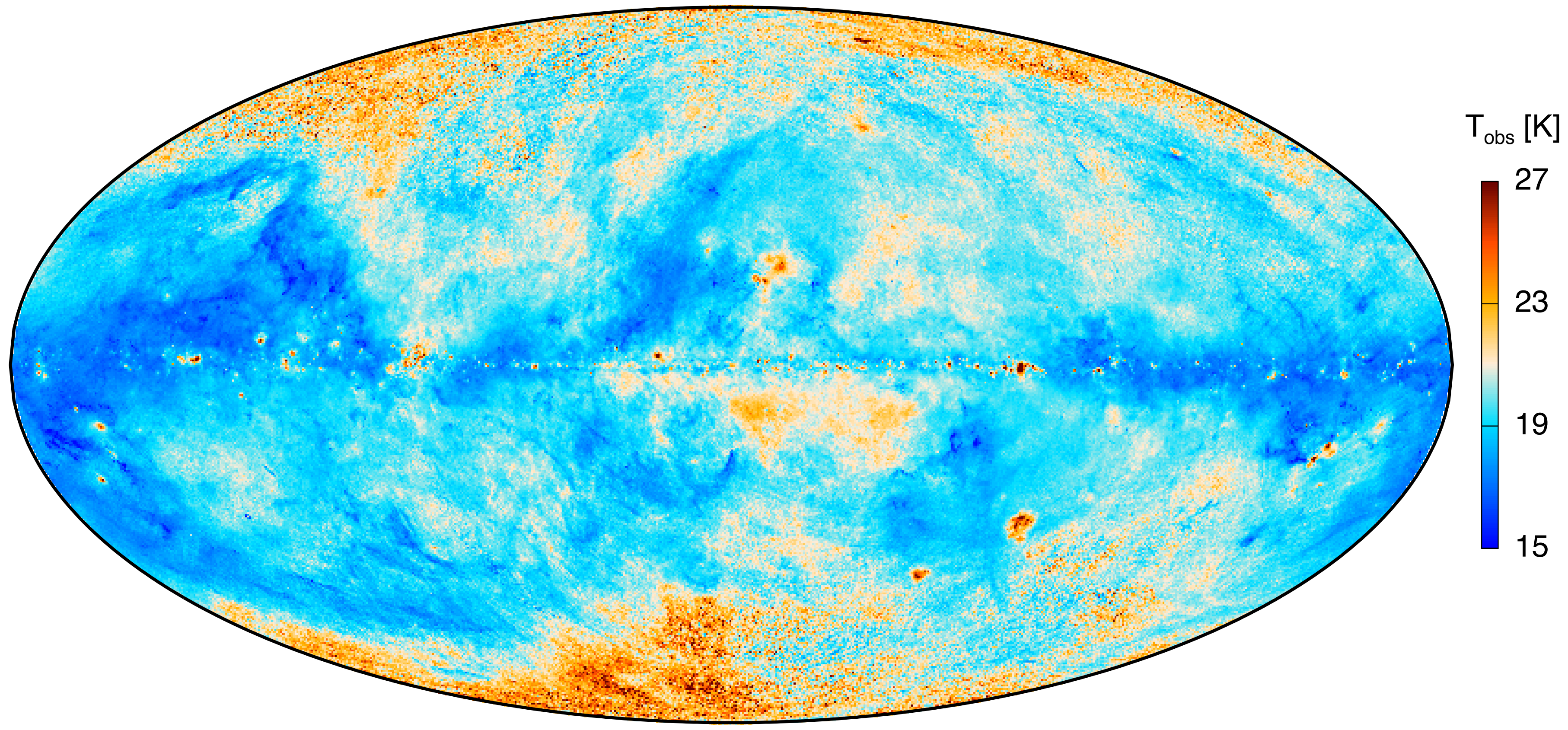
Dust temperature

- Stochastic heating induced by the absorption of photons of the ISRF



- Small grains absorb fewer photons than large particles
- Small grains reach higher temperature than large grains
- Small grains exhibit higher temperature fluctuations than larger ones
- Big grains have a constant temperature
- Big grains in the ISM are cold : 10-100K

All sky Planck observations [Planck Collaboration 2013]



Modelling grains emission: the big grains

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

- Assuming:
  - the medium is optically thin
  - grains in thermal equilibrium
  - no temperature gradient on the line of sight
- the emission may be modelled with the Modified Black Body model:

$$I_\nu \propto B_\nu(T) \times \kappa_\nu$$

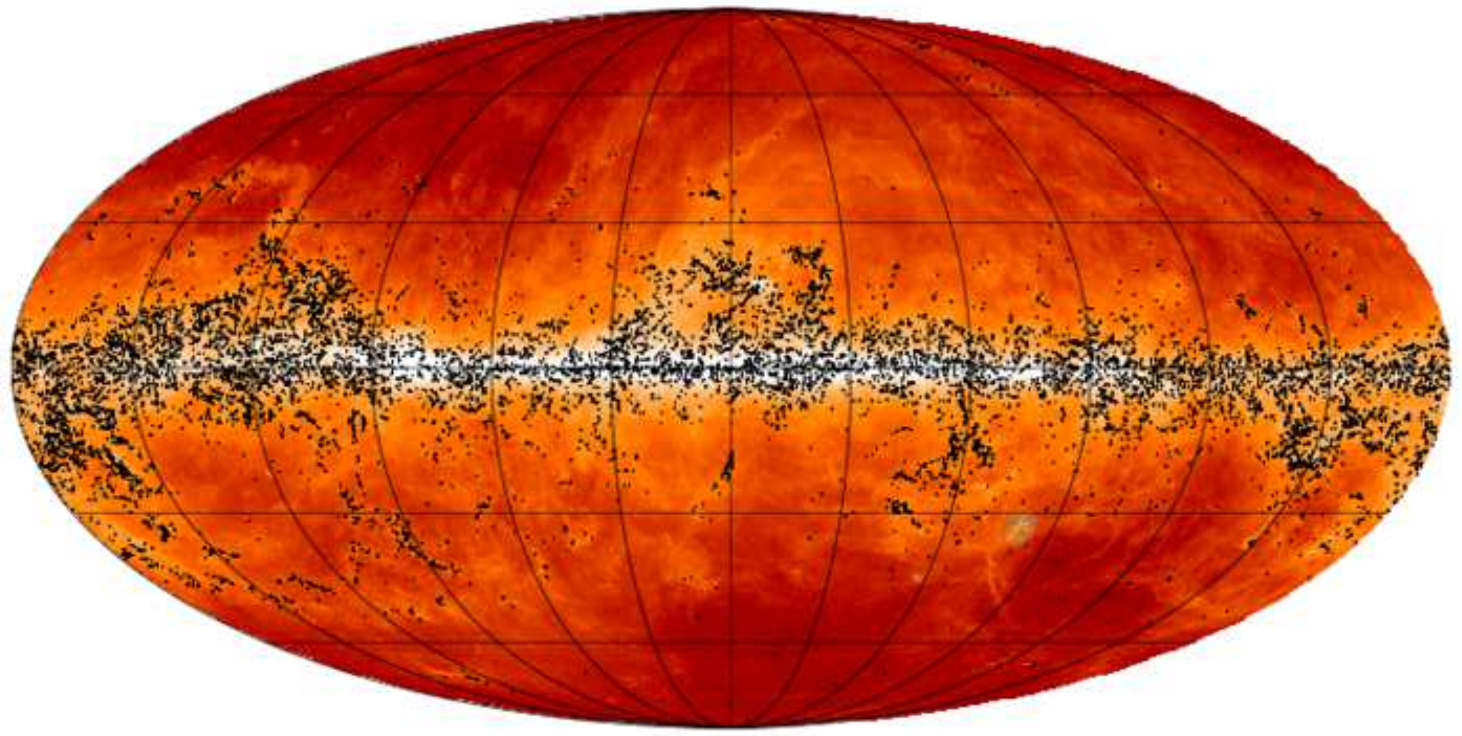
with :

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{(h\nu/kT)} - 1}$$

- ISM big grains have T ≲ 100 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:
  - β = 2 from Lorentz model
  - β = 1-2 for phonons model

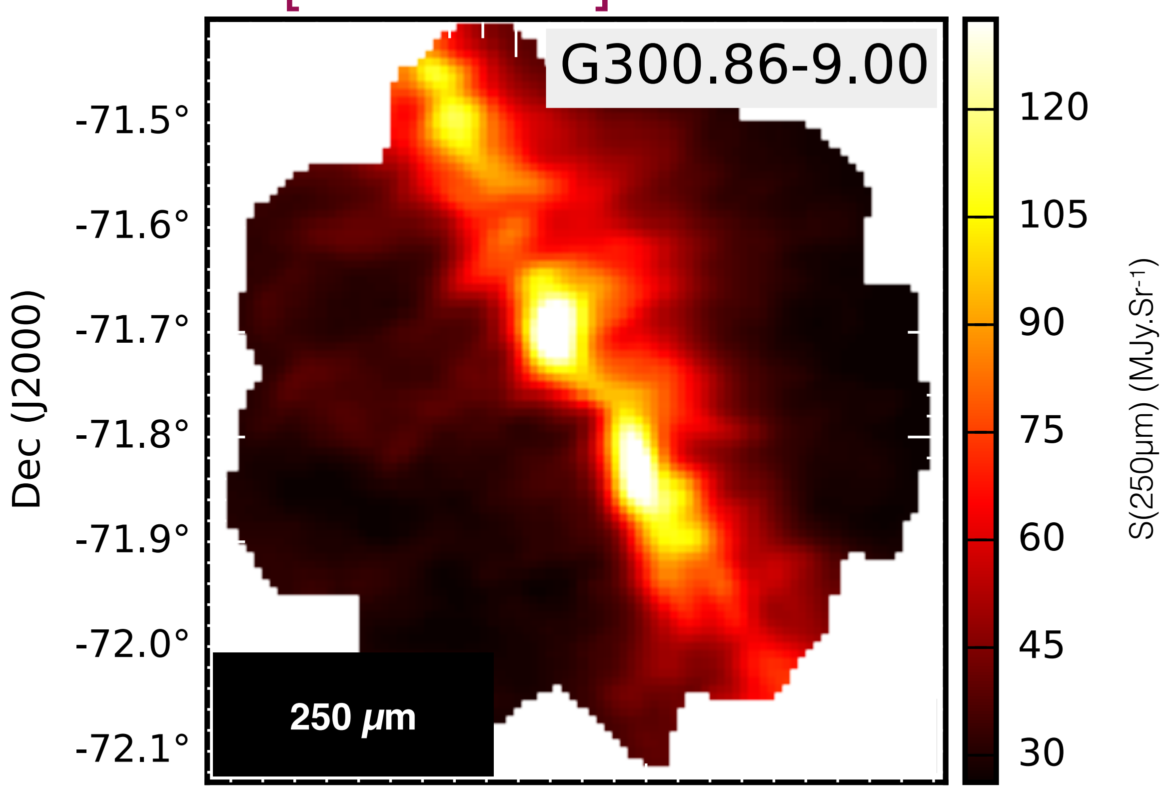
Variation of grain emissivity in the ISM

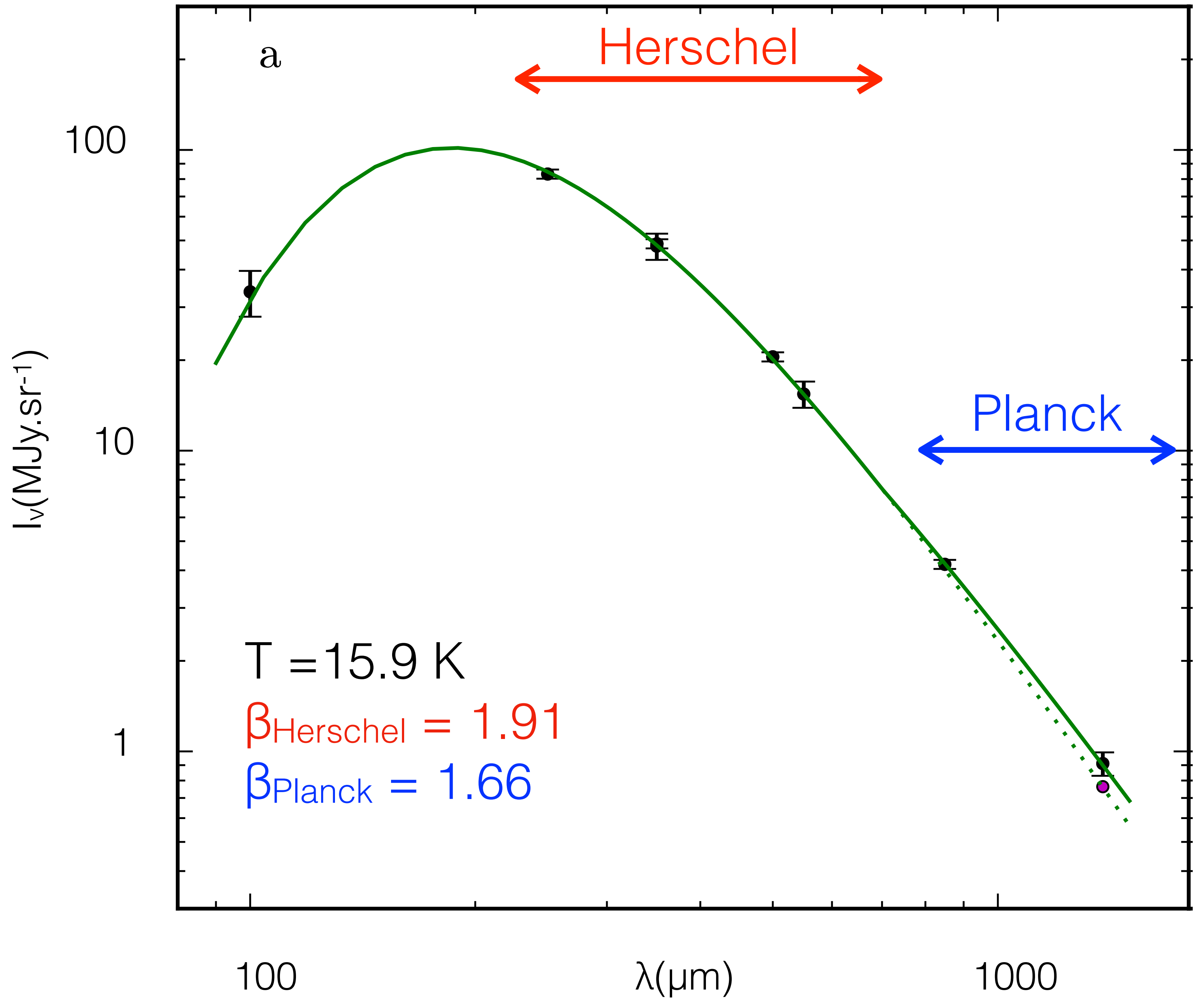
- Planck: 13188 Galactic Cold Cores:
- Herschel-PACS/SPIRE: 136 cores mapped [Juvela+12]

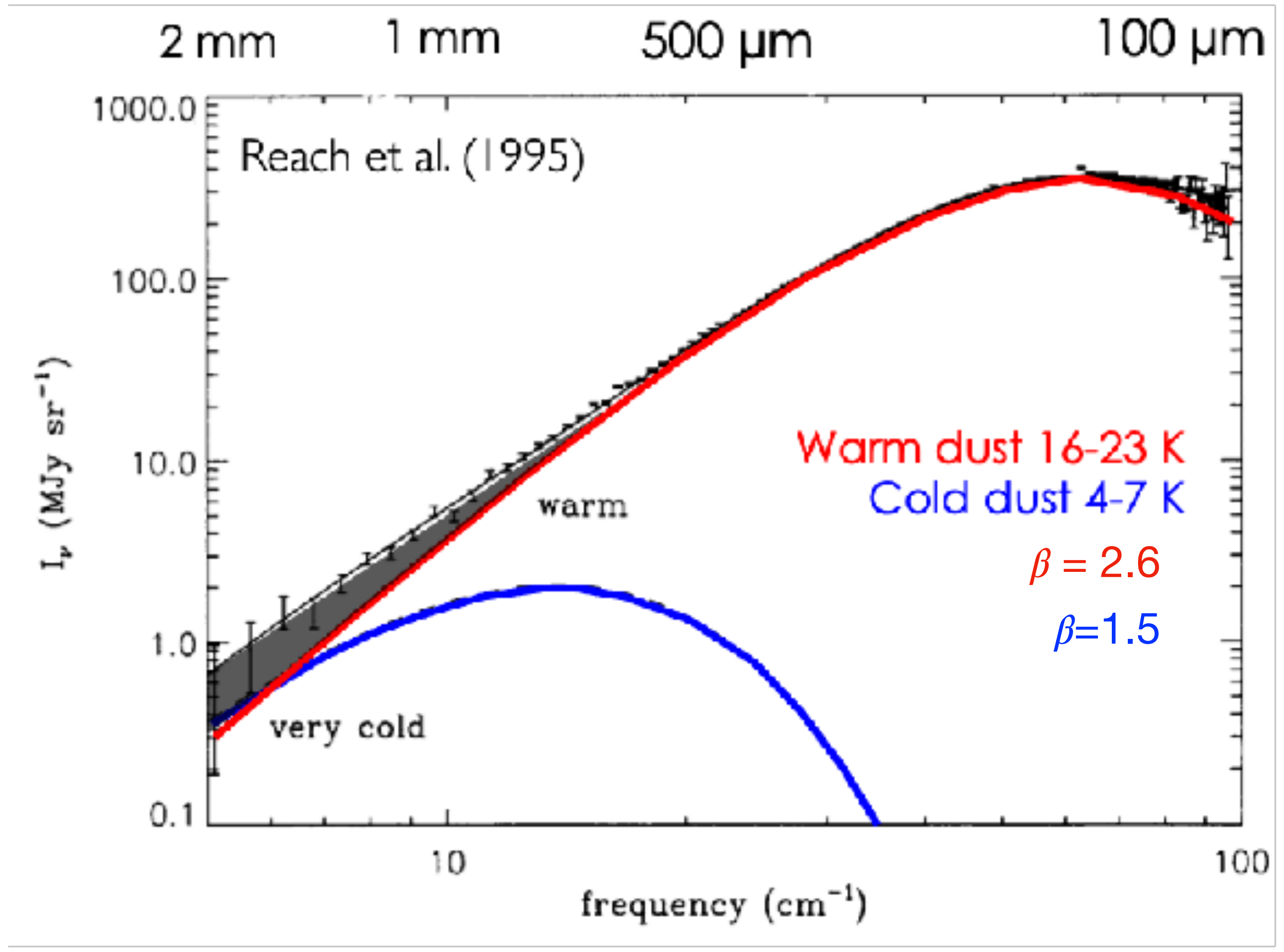


[Planck 2015 XXVII]

[Juvela+15]

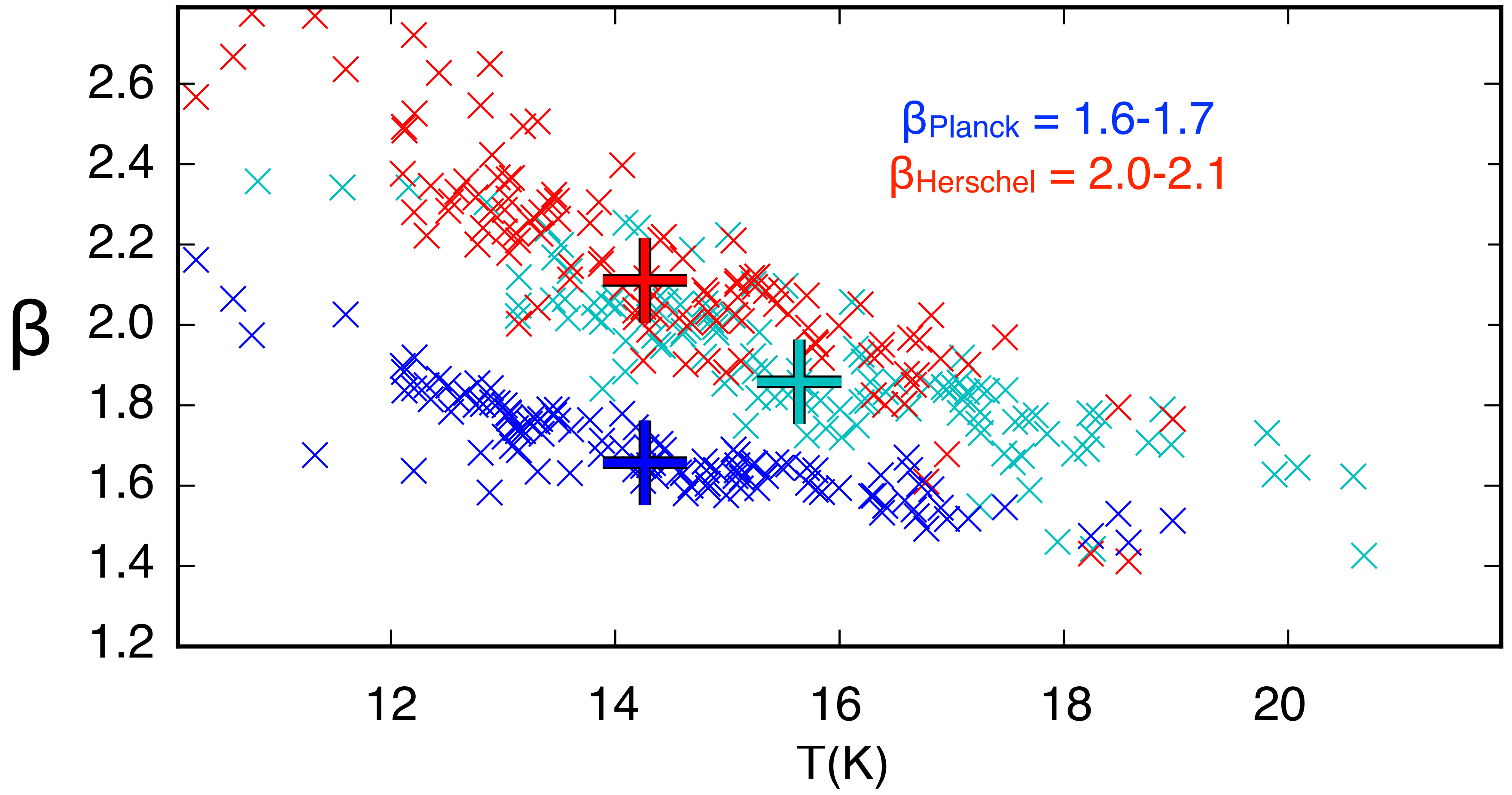






➡ $\beta \neq 2$ and may be > 2

➡ β varies with λ: flattening at large λ



Modelling big grains emission: cloud mass

- In optically thin medium:

$$I_\lambda = \tau B_\lambda(T) = \frac{M_{dust}\kappa_\lambda B_\lambda(T)}{d^{-2}\Omega^{-1}} \Rightarrow M_{dust} = \frac{I_\lambda d^2 \Omega}{B_\lambda(T)\kappa_\lambda}$$

- The determination of the mass depends on the dust temperature and on the dust opacity

- Assuming: $\kappa_\lambda = \kappa_{\lambda_0}\left(\frac{\lambda}{\lambda_0}\right)^{-\beta}$

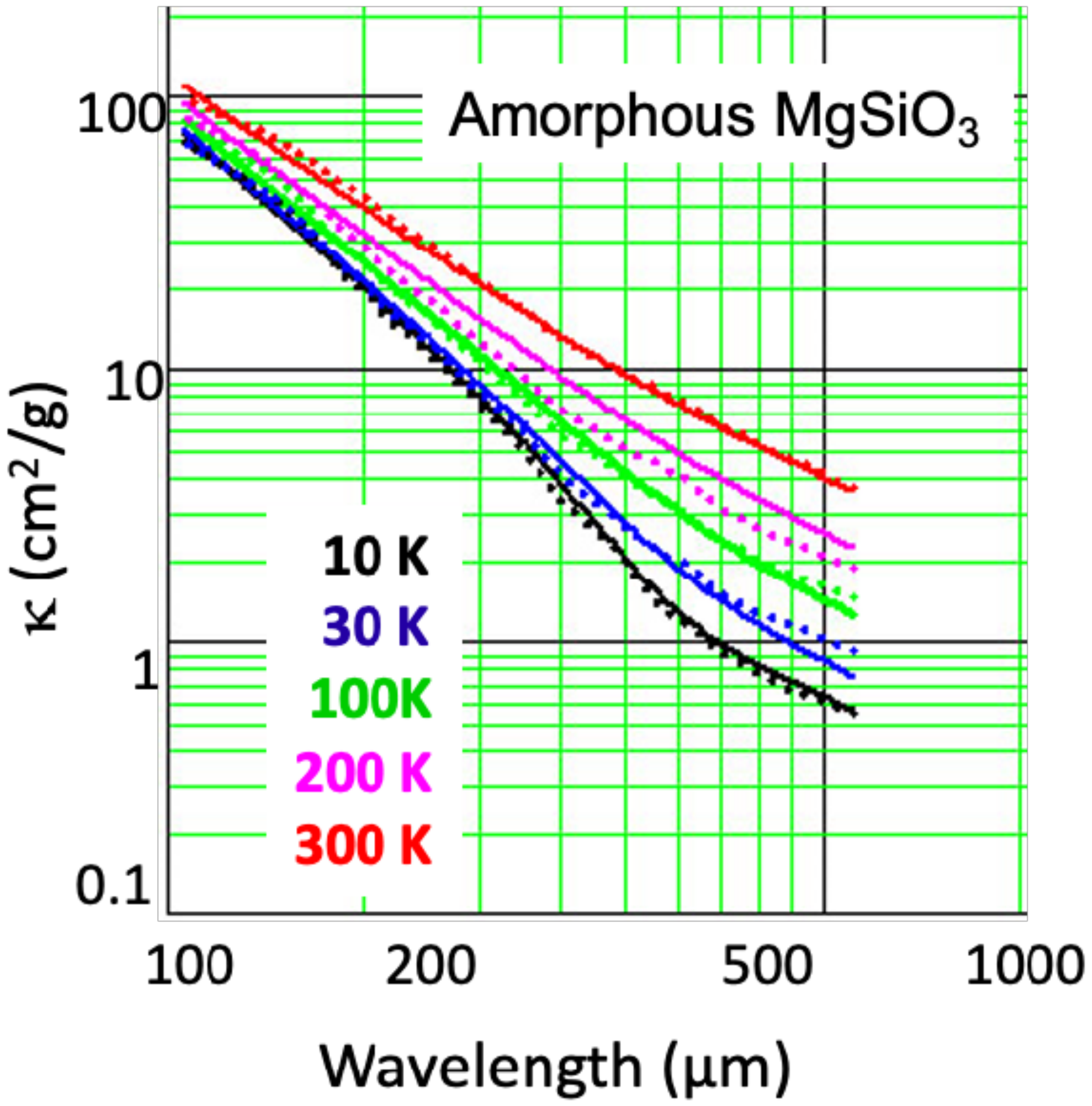
$$\Rightarrow M_{dust} = \frac{I_\lambda d^2 \Omega}{B_\lambda(T)\kappa_{\lambda_0}}\left(\frac{\lambda}{\lambda_0}\right)^{\beta}$$

- If β varies with the temperature and wavelength
- and if the emissivity (κ_0) varies in the ISM

⇒ The mass determination is wrong

Modelling grains emission: the TLS model

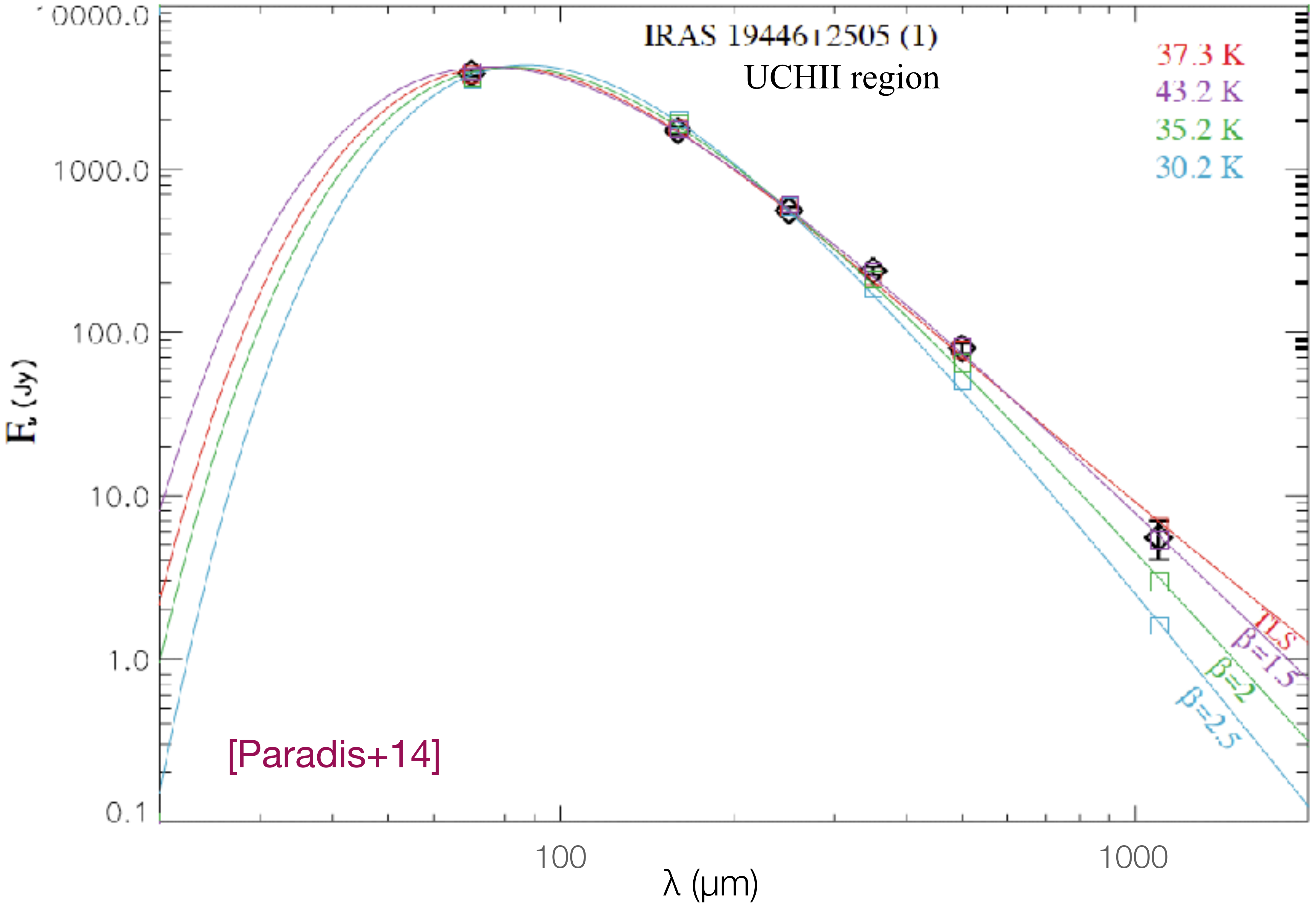
- Proposed by solid state physicists to describe the low temperature behaviour of disorder material
- Adapted for astrophysical studies by Meny et al. 2007
- Sum of two different models: DCD and TLS:
  - temperature dependent absorption mechanisms
  - β values greater than 2 and β variation with λ



1000

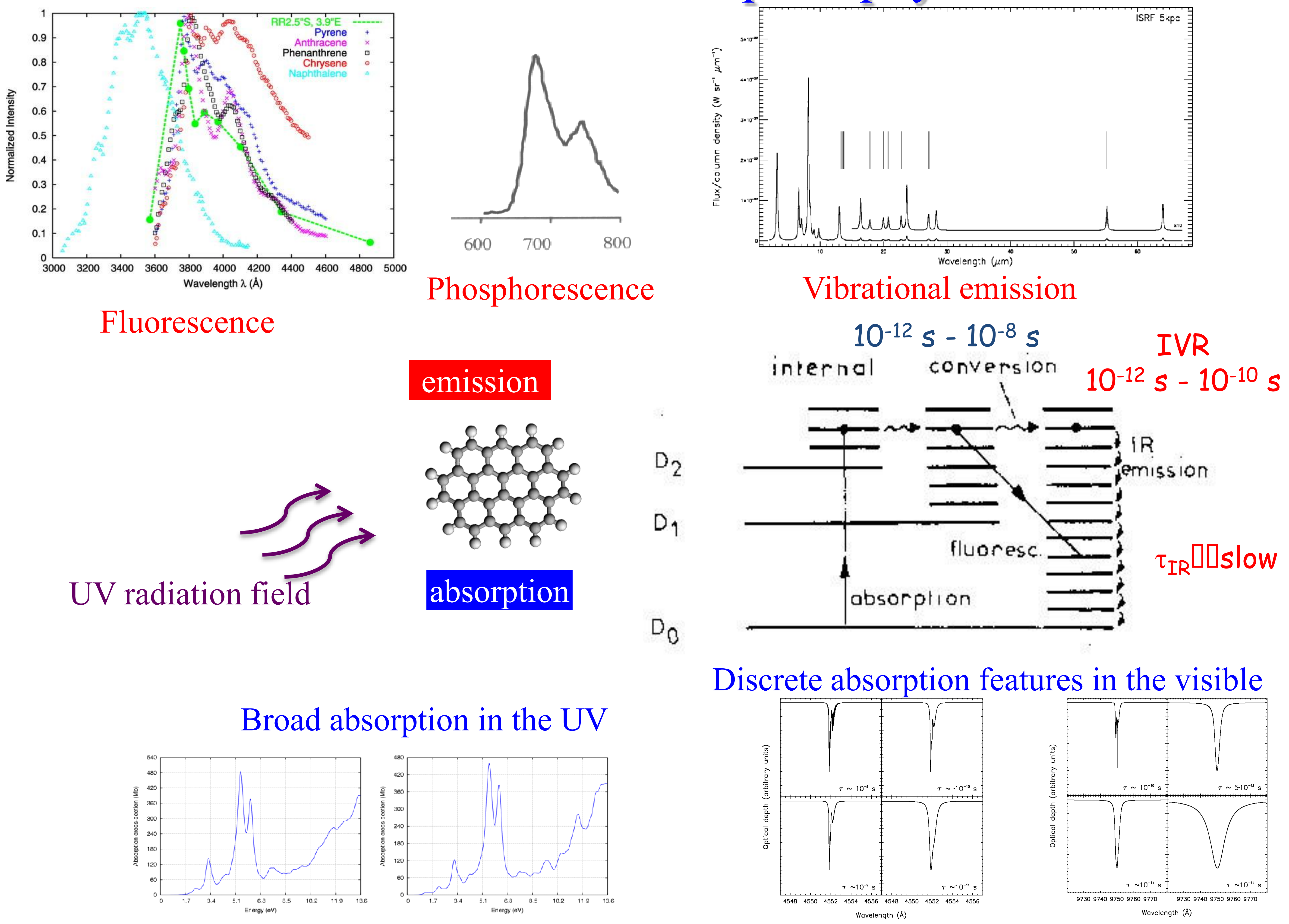
- The TLS model is able to reproduce the SED of warm and cold regions [Paradis+12,14]

$$\kappa_{dust} = \kappa_{IR} + \kappa_{DCD} + \kappa_{TLS}$$



Modelling the AIBs:

A unified vision of PAH photophysics



- Modelling of AIB emission requires to simulate the spectrum of a family of PAH in a given radiation field knowing :
  - the excitation conditions (physical conditions, UV)
  - molecular complexity
  - photo-absorption cross-sections
  - vibrational modes
  - IR band positions and widths as a function of T
- Detailed physical model very time consuming [see eg. Joblin+02, Mulas+06]

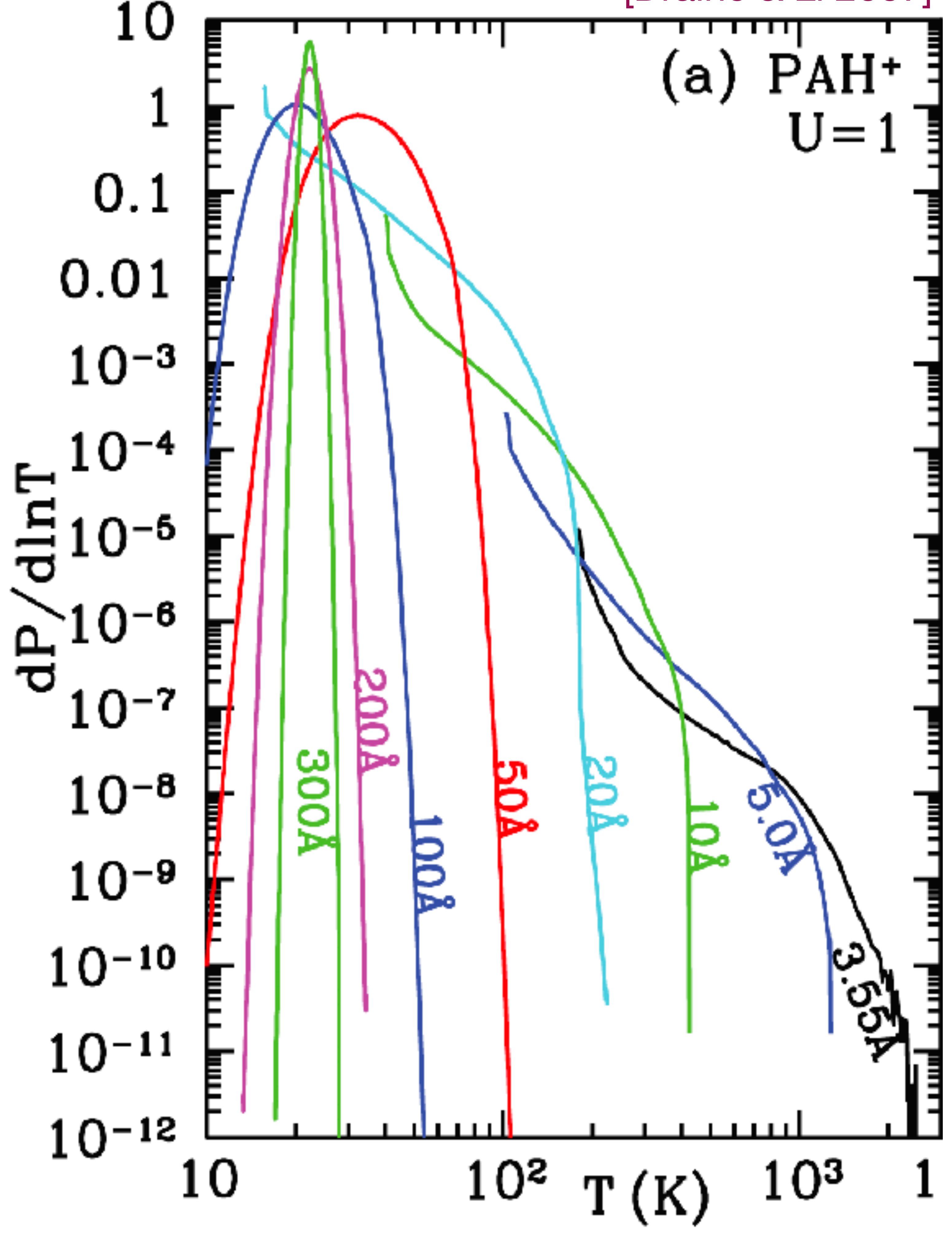
Modelling the AIBs:

- Other approaches: [eg. Désert+90, Draine & Li 2001]
  - C_{abs} taken from laboratory measurements (but very few data [eg. Joblin+95]) and/or quantum chemical theoretical calculations [eg. Bauschlicher 2009]
  - C_{abs} calculated from the Drude model (classical Lorentz oscillators model modified for conducting material to take into account free electrons)
  - C_{abs} calculated from optical constants simulated with the new optEC model developed from solid state physical models for amorphous hydrocarbon materials [Jones 2012a,b,c]

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

- Empirical approach:
  - from a combination of templates spectra derived from observations [eg PAHTAT toolbox, Pilleri+2010]

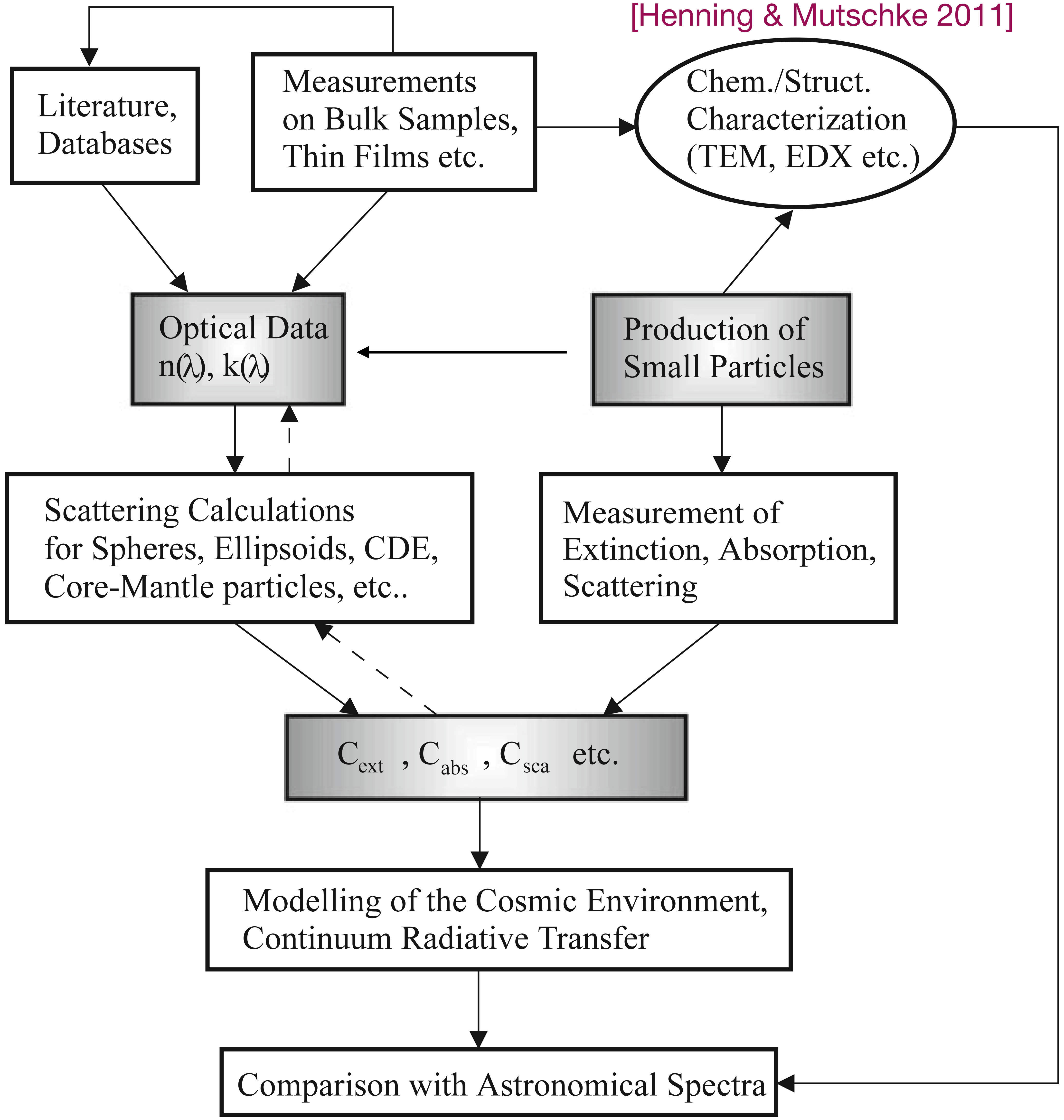
[Draine & Li 2007]



Modelling dust extinction and emission: summary

- Modelling dust extinction and emission relies on the description of the interaction of matter with light
- It is necessary to know the physical characteristics of the dust :
  - dielectric constants
  - size distribution, shape distribution
  - heat capacity for emission modelling
  - photo absorption cross-section
- These data comes from laboratory astrophysics studies of dust analogues

[Henning & Mutschke 2011]



Cosmic dust models

From observations to cosmic dust models

- Cosmic dust models are built to interpret observations of various astrophysical environments

- Many dust models exist, they differ because they consider different:
  - sets of observations used to constrain the dust populations
  - reference abundances
  - grain components: nature, number, size distribution…

- For each dust components :
  - They provide the optical constants
  - They calculates the extinction cross sections for a given grain shape and size distribution

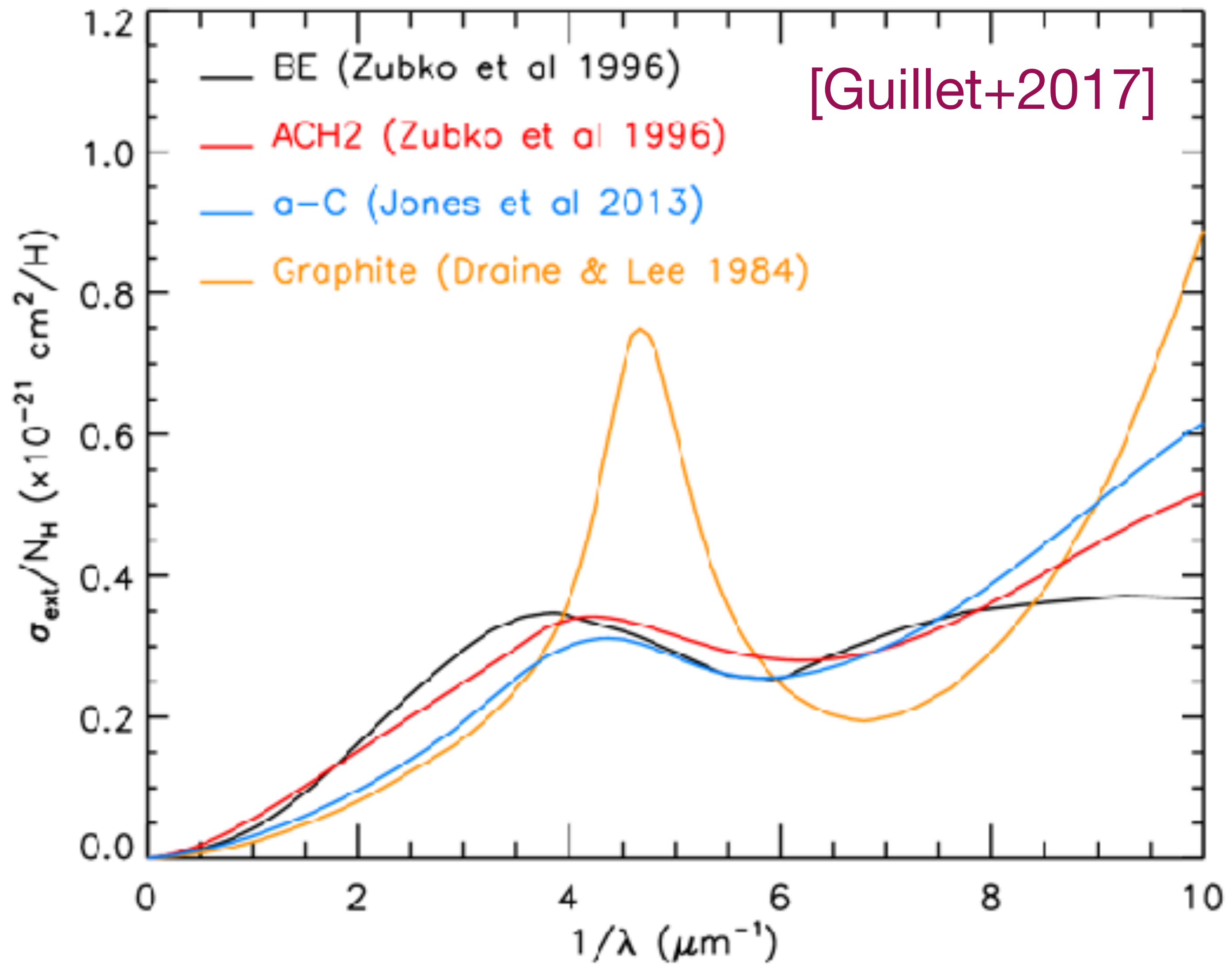
- These cross sections may be used in astronomical modelling

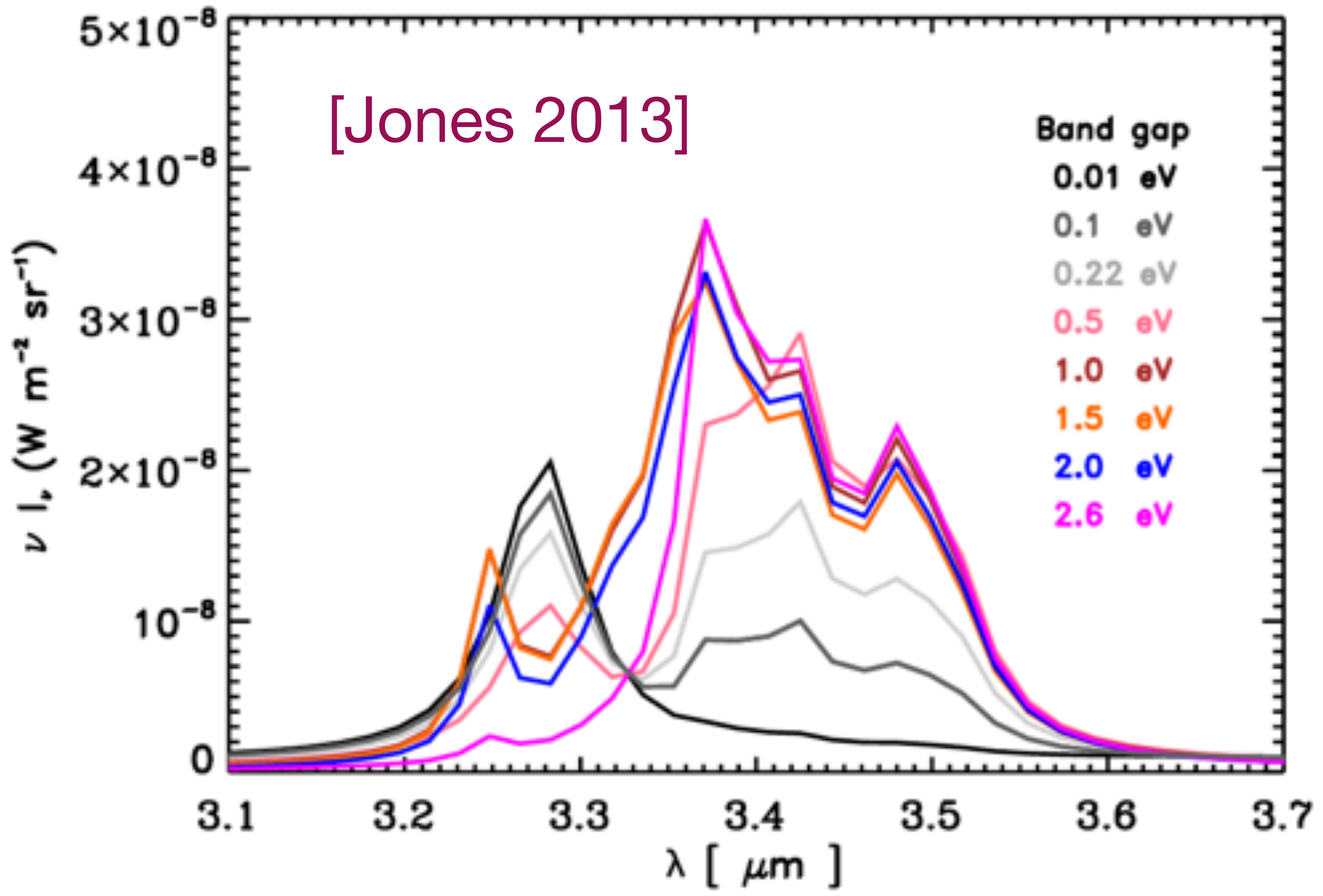
Optical constants used in cosmic dust models:

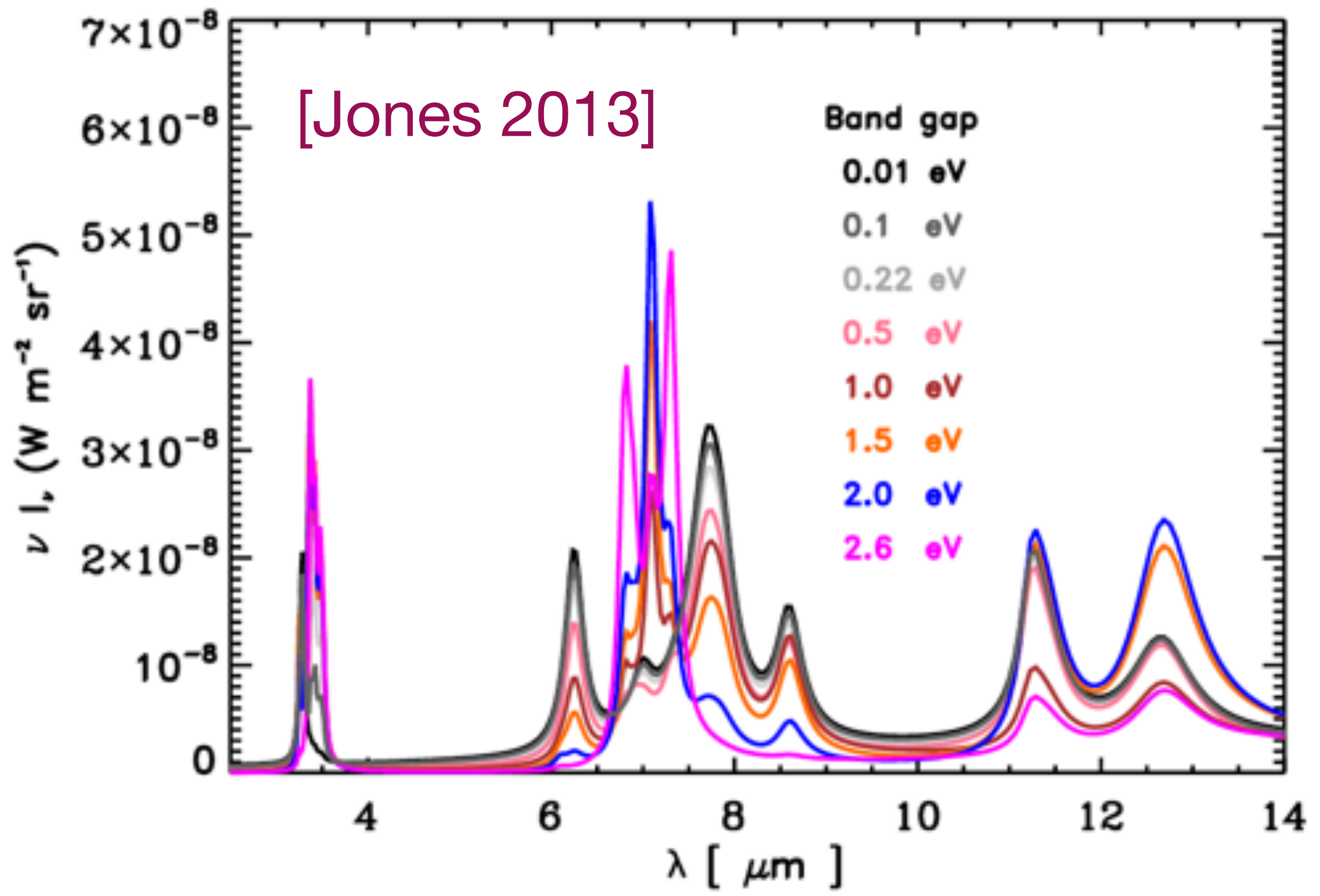
- Optical constants are derived by inversion of :
  - laboratory measurements of spectra of dust analogues
  - theoretical calculations from physical description of dust analogues
  - observational constraints
  - extrapolations

- Amorphous carbon
  - Lab data from Zubko et al. 1996 in the MIR-FIR domain for more or less hydrogenated material (BE & ACH)
  - a-C(:H) : theoretical calculations (eRCN and DG models) [Jones 2012]

- PAHs : lab data & theoretical calculations for neutral and ionised PAHs



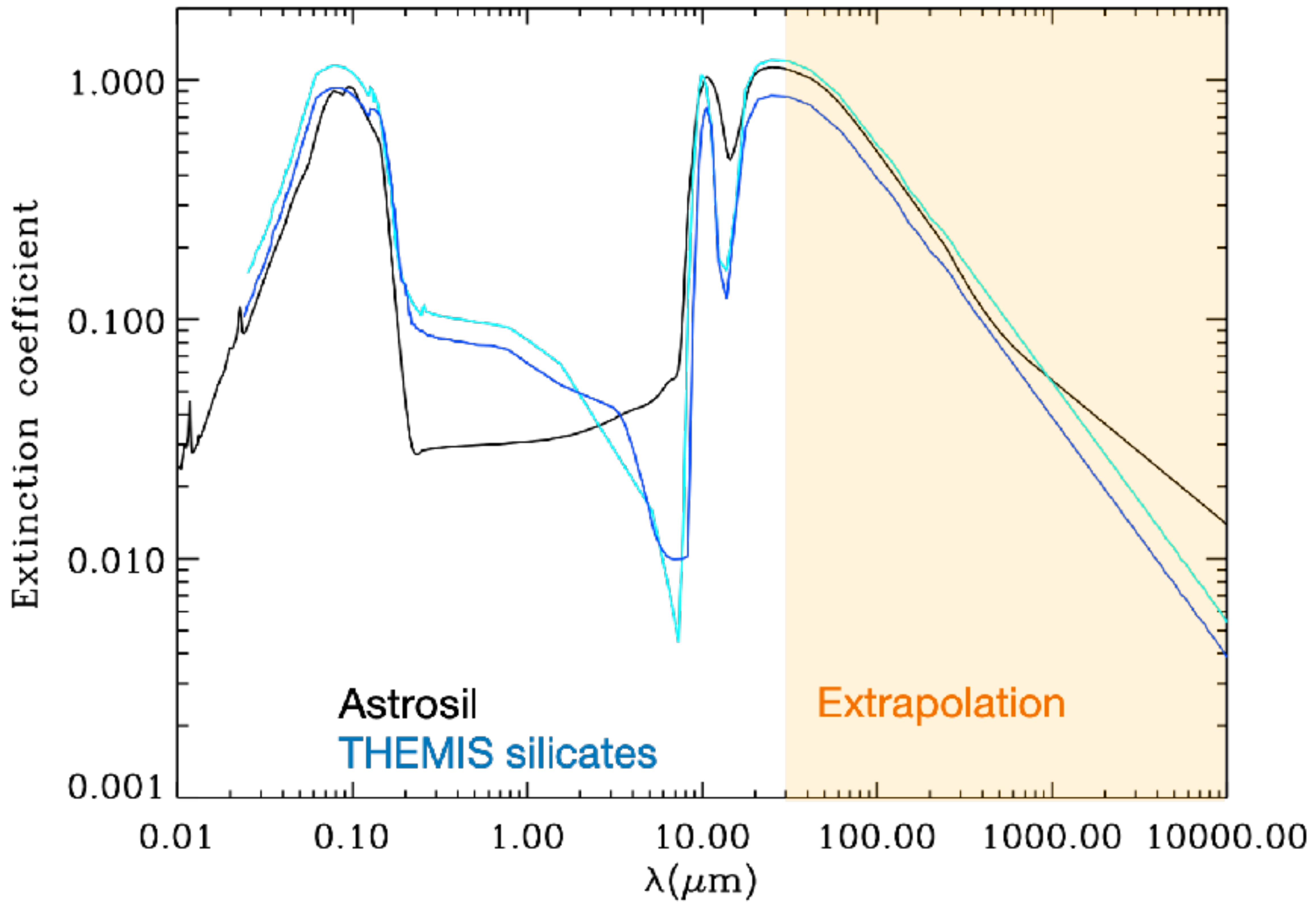




Optical constants used in cosmic dust models:

- *astrosilicates* :
  - MIR : optical constants constructed from the astronomical observations
  - NIR - UV: experimental data on crystalline silicates
  - FIR: extrapolation

- Lab data for $MgSiO_3$ and $MgSiO_4$
  - MIR from Scott & Duley (1996) and Day (1981)



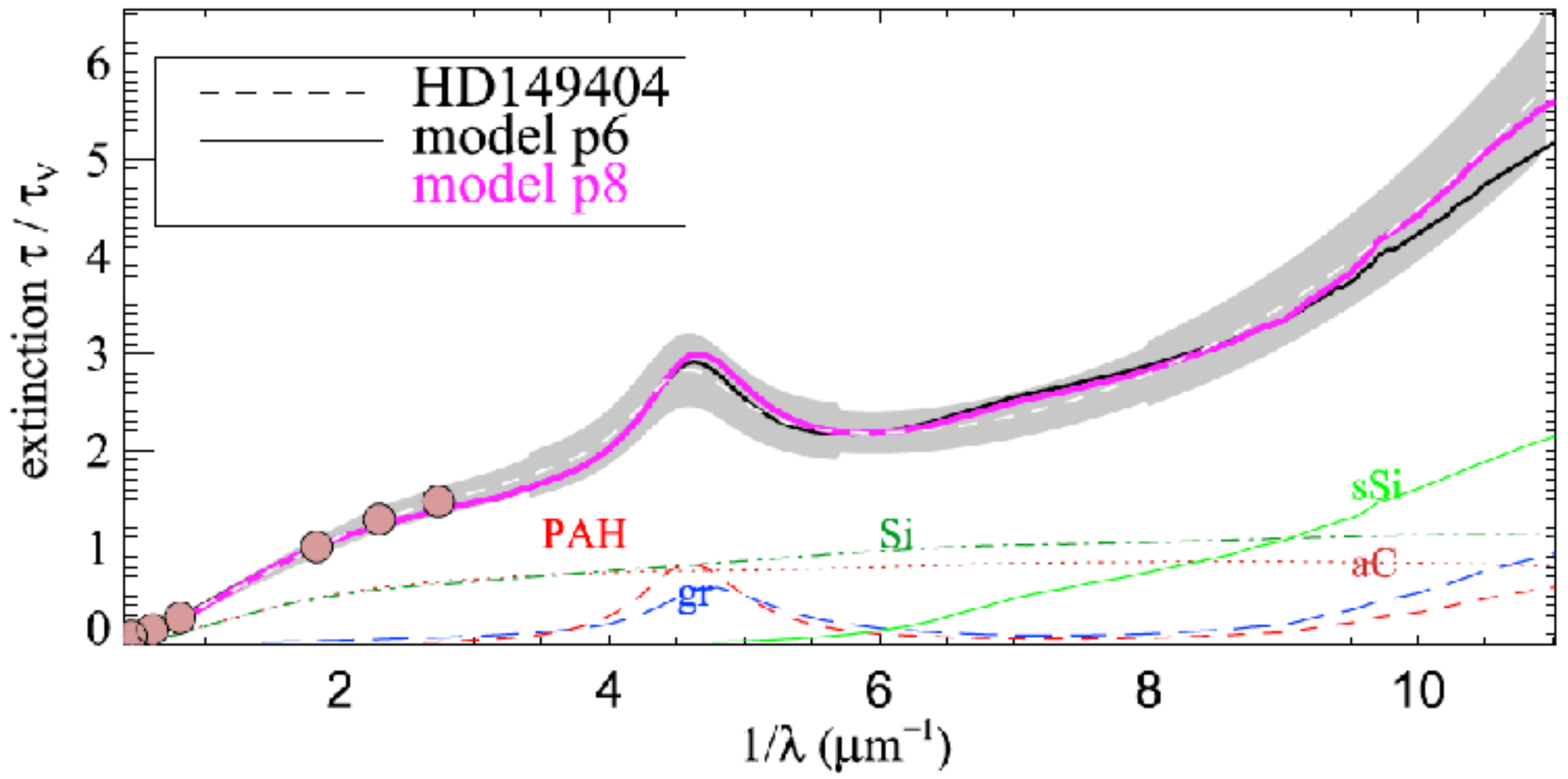
- See the DOCCD and STOPCODA databases on the SHAADE portal [Schmitt+2018] for more optical constants on silicates :
  - https://www.sshade.eu/db/doccd
  - https://www.sshade.eu/db/stopcoda

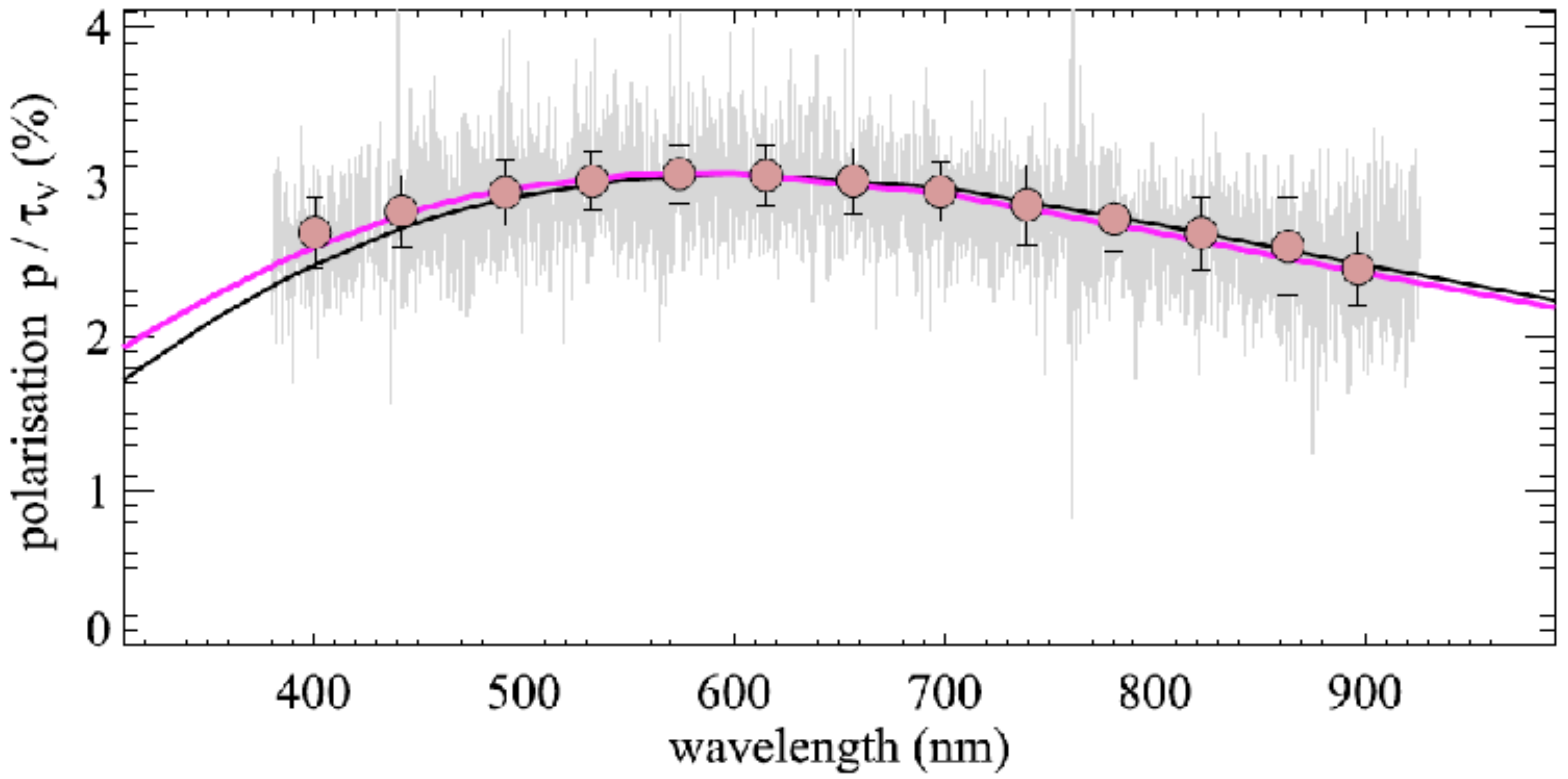
Cosmic dust models for the DISM

Model from Siebenmorgen et al. 2017:

- DISM environments towards the Sco OB1 association
- Constraints on extinction and spectra-polarimetry (not on emission)

- Big spheroidal grains of
  - *astrosilicates*
  - amorphous carbon (Zubko+96 and Jones+12)
  - up to 350 nm, power law
- VSG (spherical) with Drude profile for the UV bump
  - 0.5 - 6 nm
  - graphite and silicates
- PAHs with 60 and 150 atoms



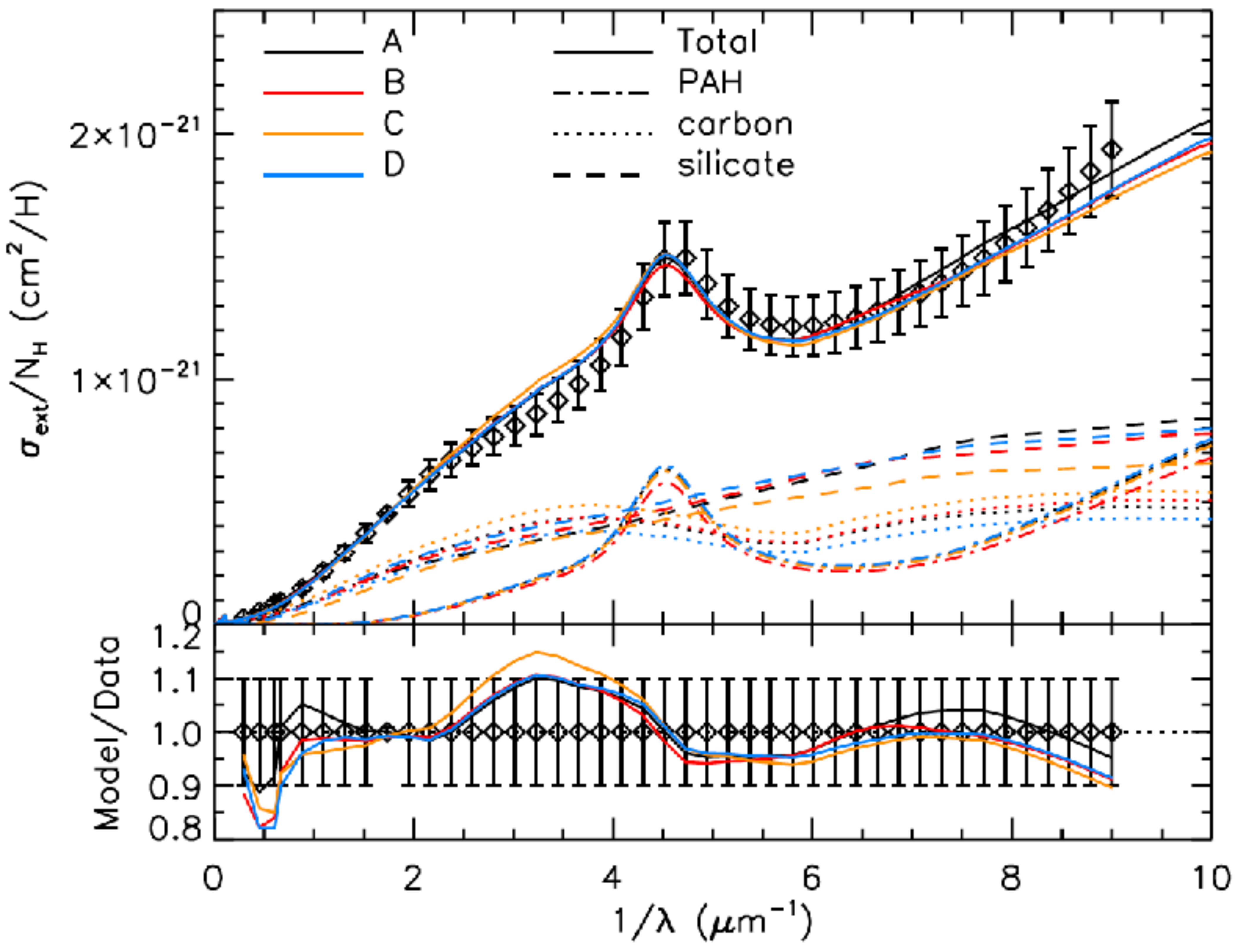


Cosmic dust models for the DISM :

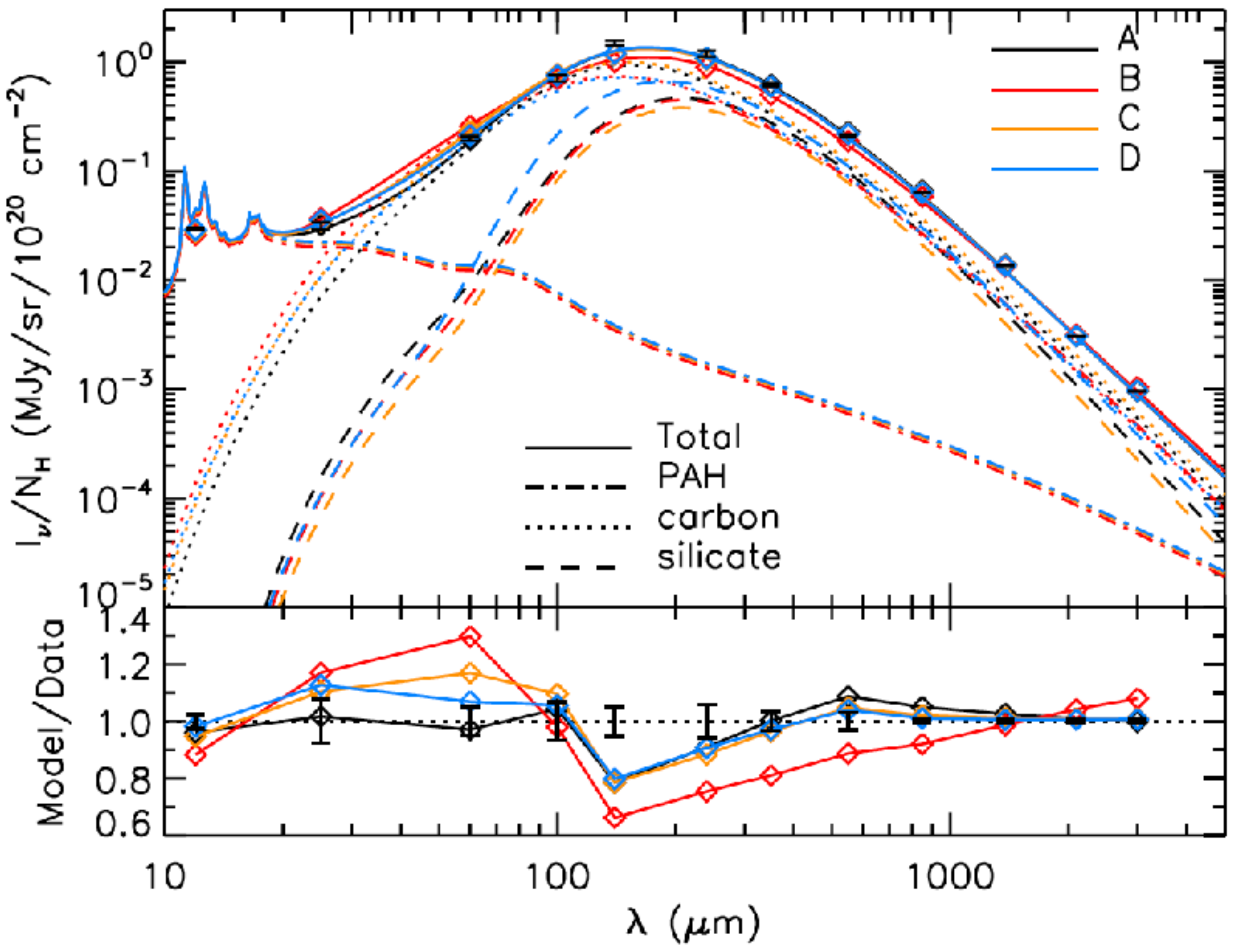
Model from Guillet et al. 2018 (1/2):

- Constraint on translucent lines of sight ($0.5 < A_V < 2.5$)
- Adaptation of Compiègne et al. 2011 model :
- Consider *astrosilicates* prolate grains with porosity (20%), amorphous carbon inclusions, different size distribution

Extinction cross section per H atom



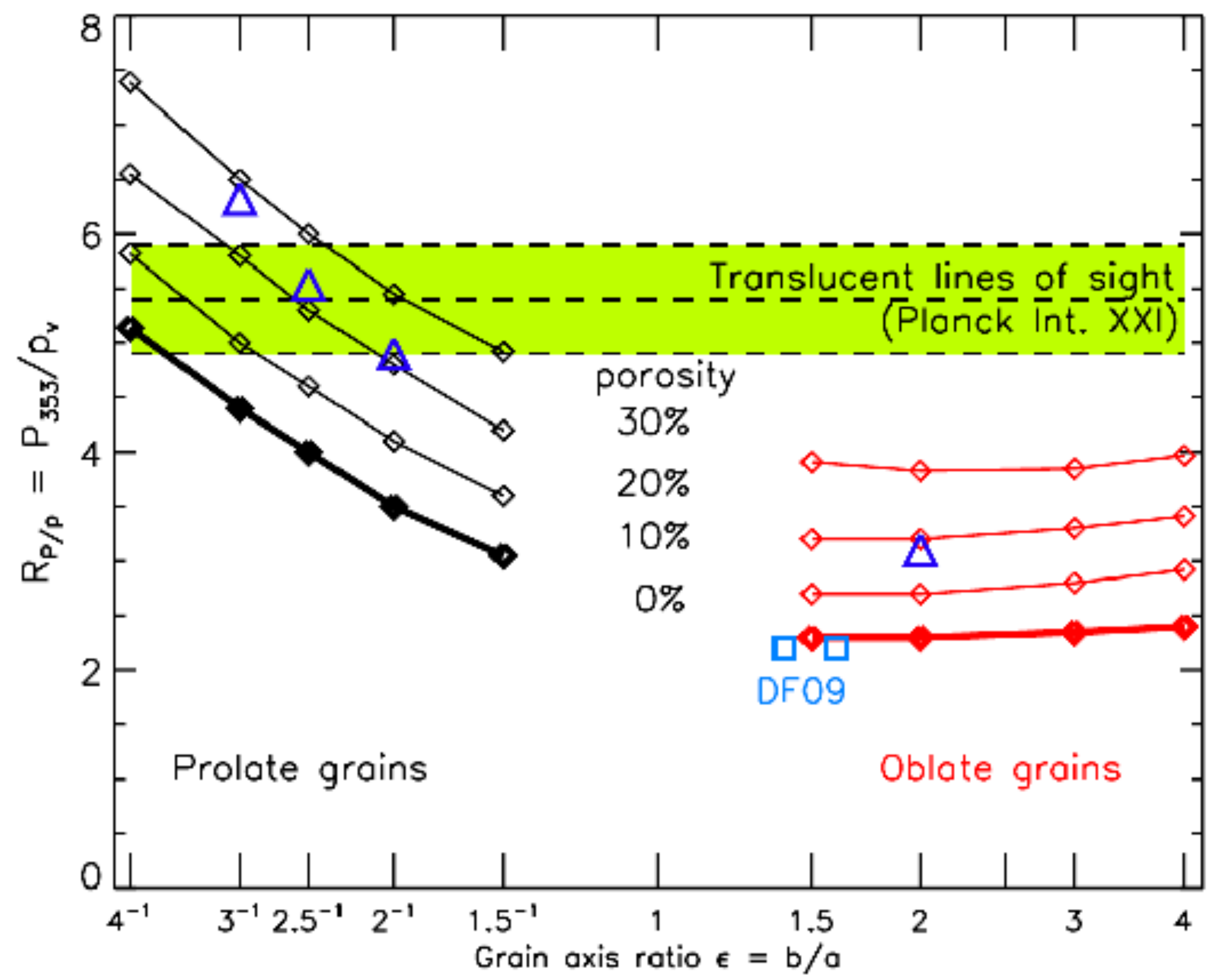
Dust emission SED



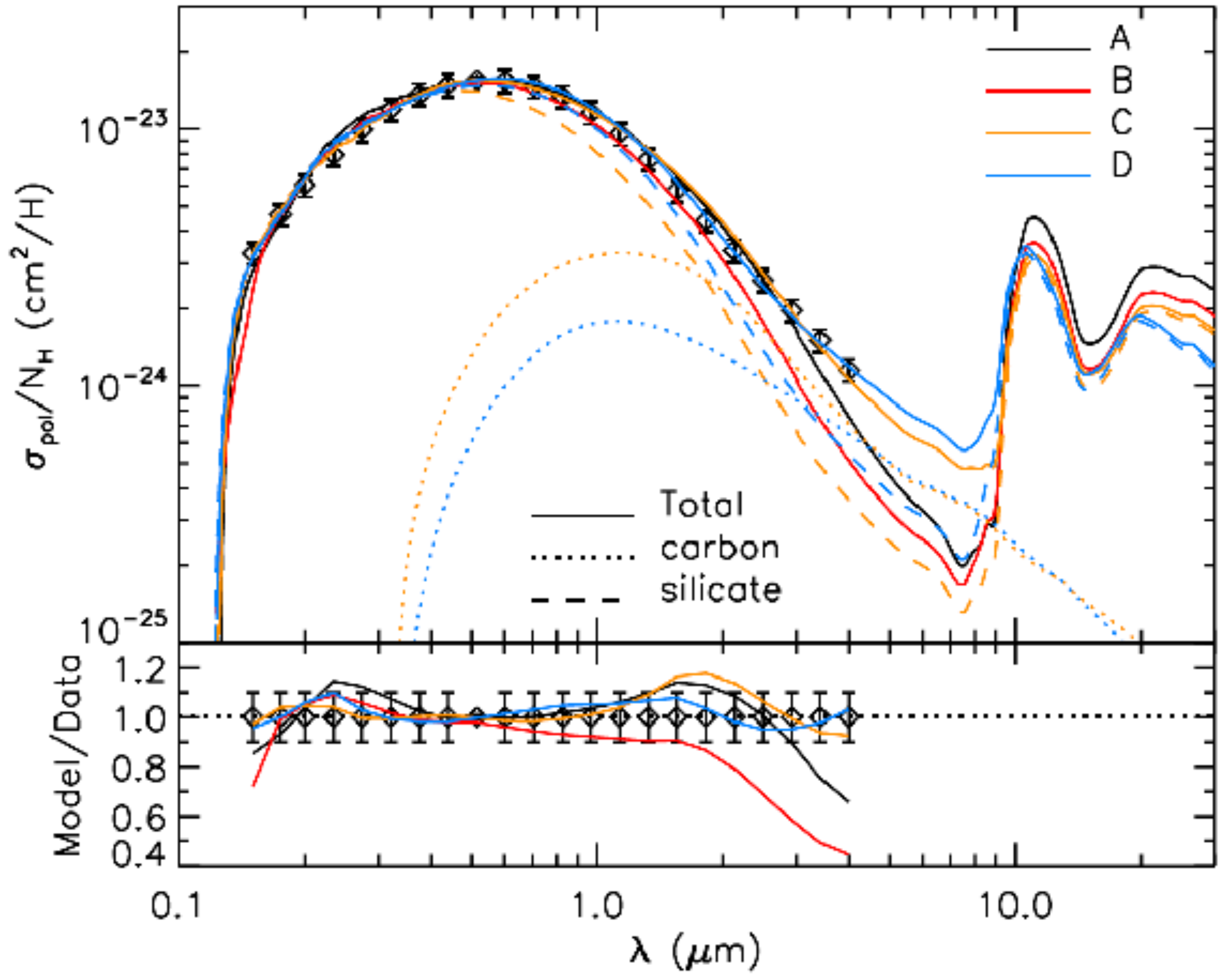
Cosmic dust models for the DISM

Model from Guillet et al. 2018 (2/2):

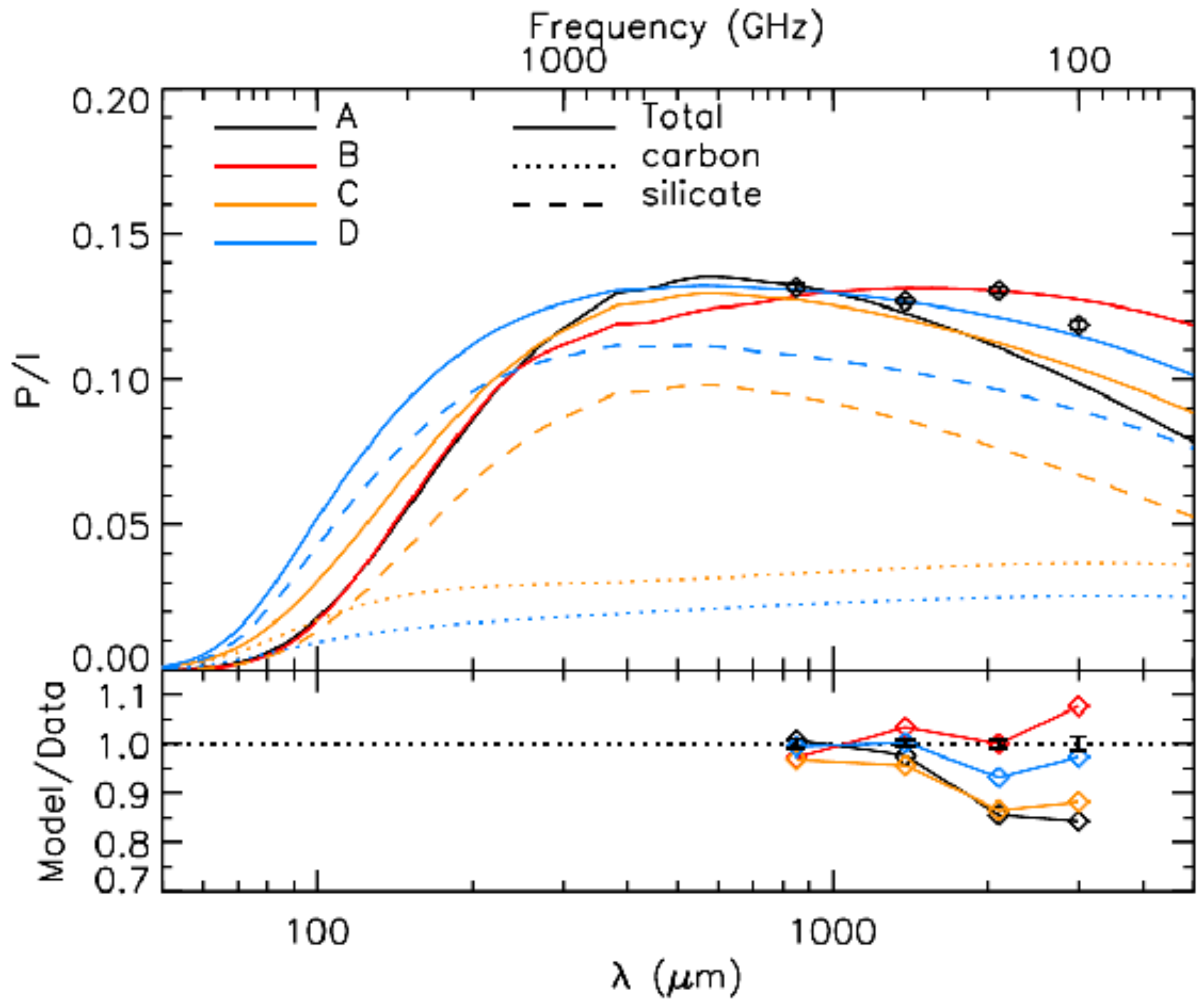
- Prolate grains are more emissive than oblate grains ⇒ better fit of the emission to extinction polarisation data fromPlanck data
- The addition of a-C in the silicate grains is equivalent to porosity

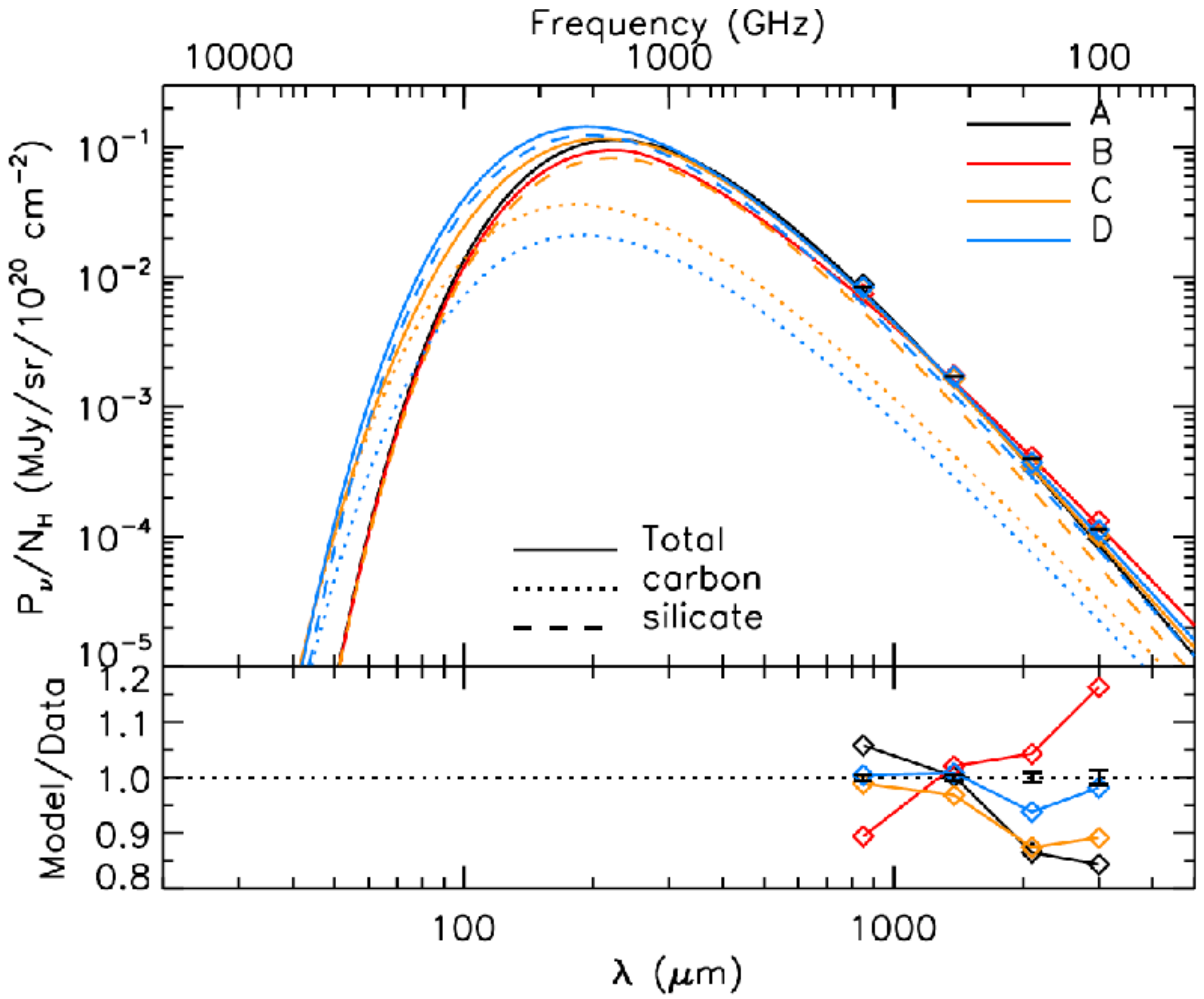


Polarisation cross section per H atom



Polarisation fraction in emission





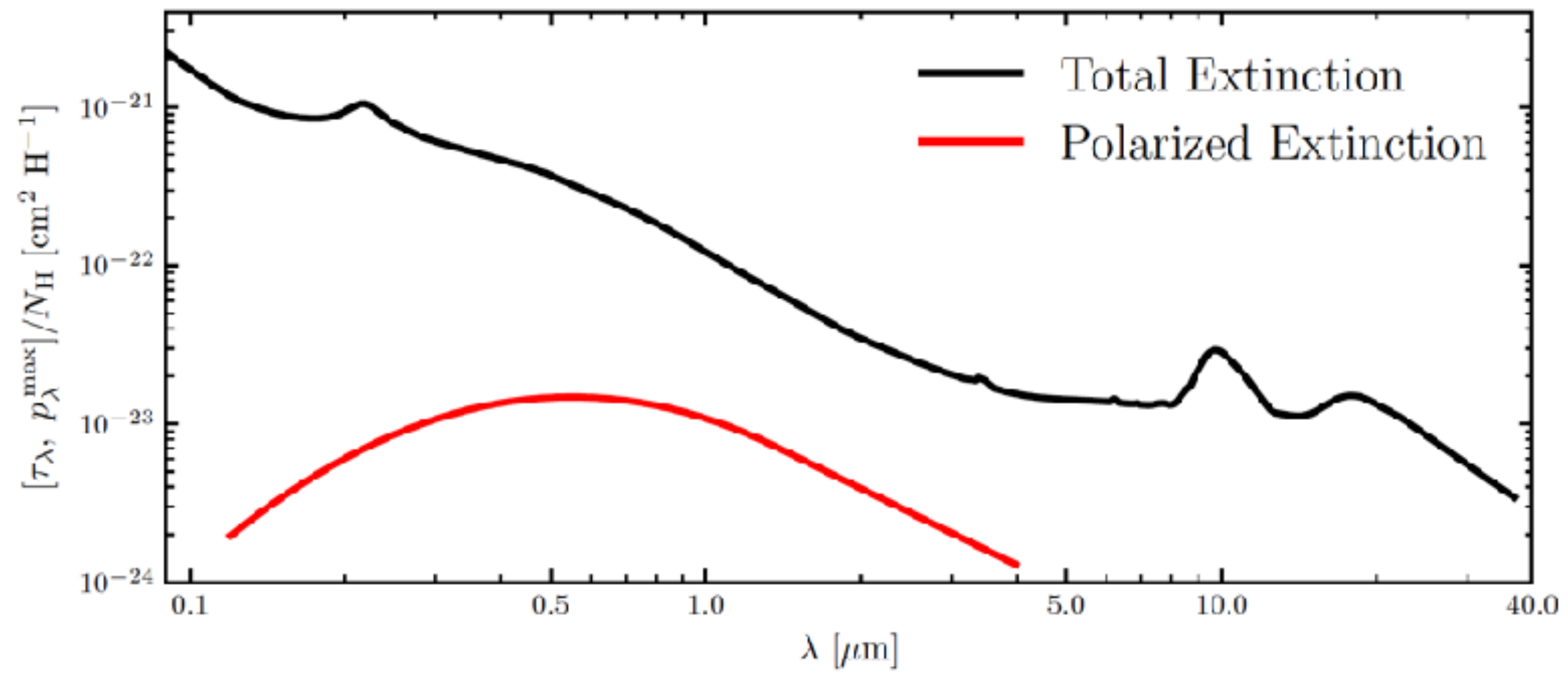
Cosmic dust models for the DISM

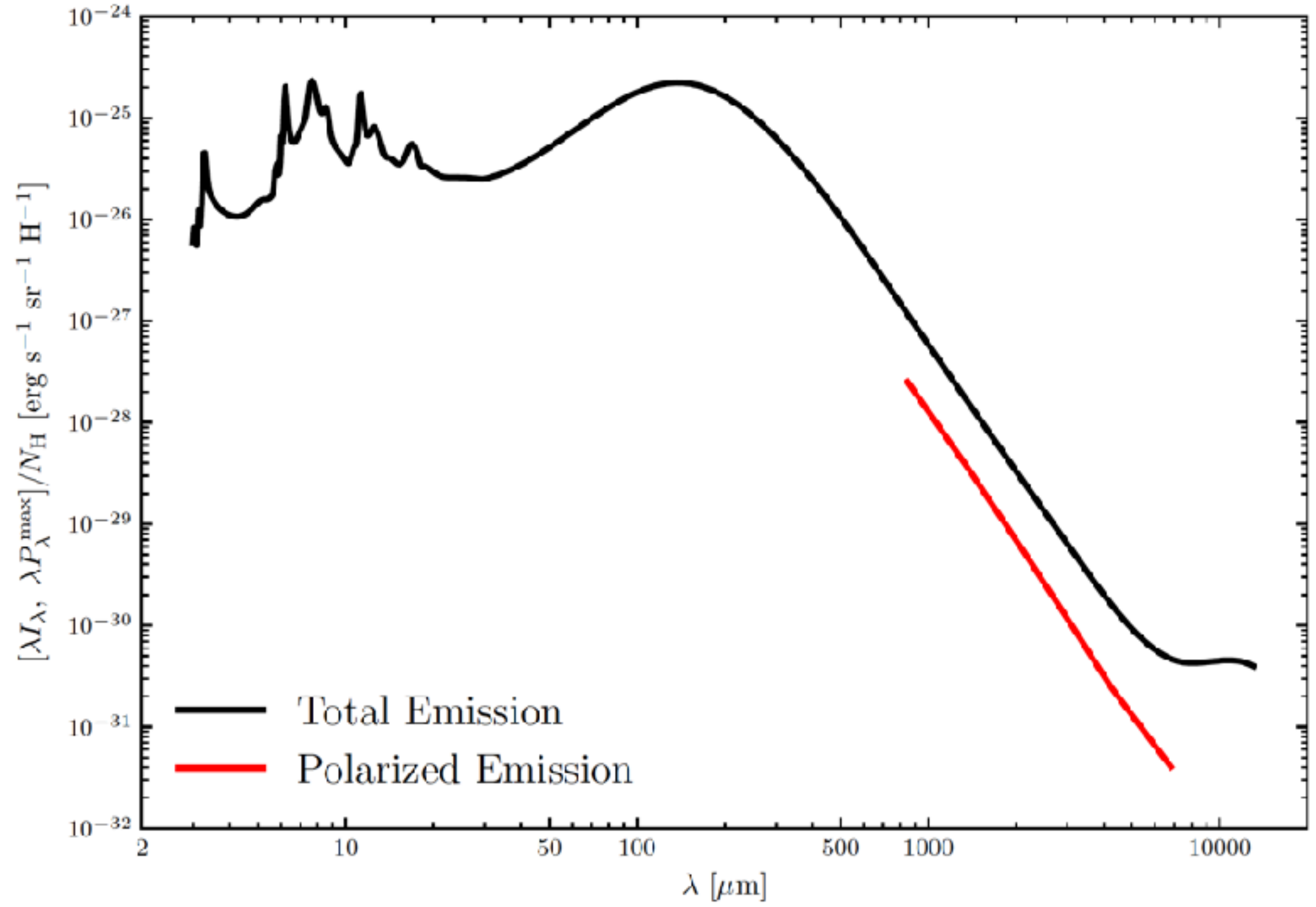
Model from Draine & Hensley (2021) (1/2):

- Observational constraints and adopted cosmic abundances: Hensley & Draine 2020
- Many sets of extinction and emission observations through different DISM sightlines from X-rays to mm
- Polarisation is calculated in the submm but not used to constrain the model

Table 5. Adopted Values of Select Quantities for the Diffuse ISM

Quantity	Value	Reference
Reference Quantities		
$A(5500\,Å)/E(4400\,Å - 5500\,Å)$	3.02	Fitzpatrick et al. (2019)
A_H/A_{K_s}	1.55	Indebetouw et al. (2005)
$N_H/E(B-V)$	$8.8 \times 10^{21}\,cm^{-2}\,mag^{-1}$	Lenz et al. (2017)
$[p_V/E(B-V)]_{max}$	$0.13\,mag^{-1}$	Planck Collaboration XII (2018)
$p_{353}/(p_V/\tau_V)$	4.31	Planck Collaboration XII (2018)
Derived Quantities		
Quantity	Value	Reference
R_V	3.1	Fitzpatrick et al. (2019)
A_V/N_H	$3.5 \times 10^{-22}\,mag\,cm^2$	
p_{353}^{max}	19.6%	
P_{353}/p_V	$4.8\,MJy\,sr^{-1}$	

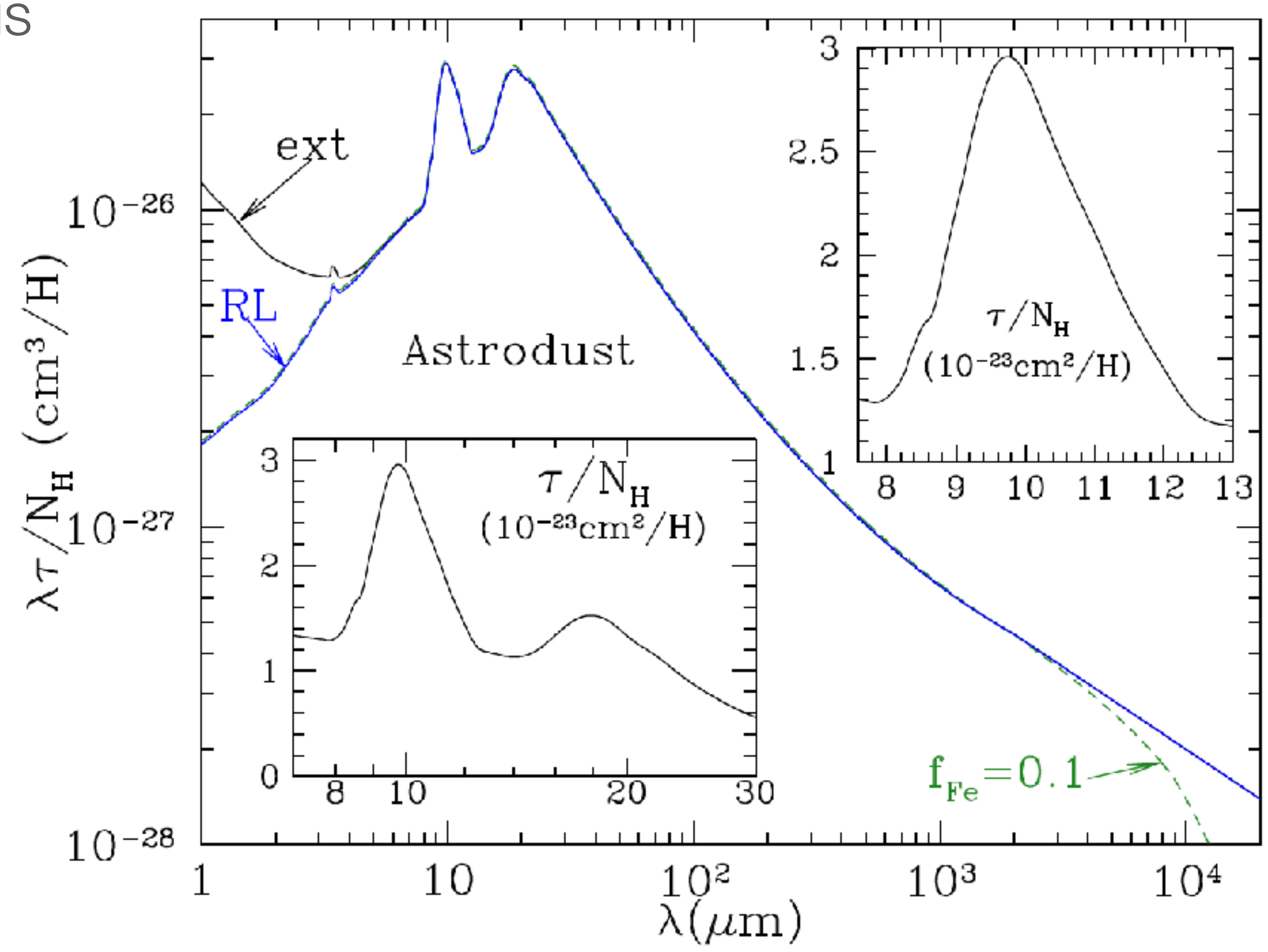




Cosmic dust models for the DISM

Model from Draine & Hensley (2021) (1/2):

- Two dust components:
  - astrodust: porous mixture of silicates & carbonaceous matter on grain surface
  - PAHs
- Optical constants build from:
  - observations in the X-ray - VIS domain
  - 300 oscillators in the IR (Lorentz model)
- Constrained from the silicates and aliphatic bands in extinction and polarisation

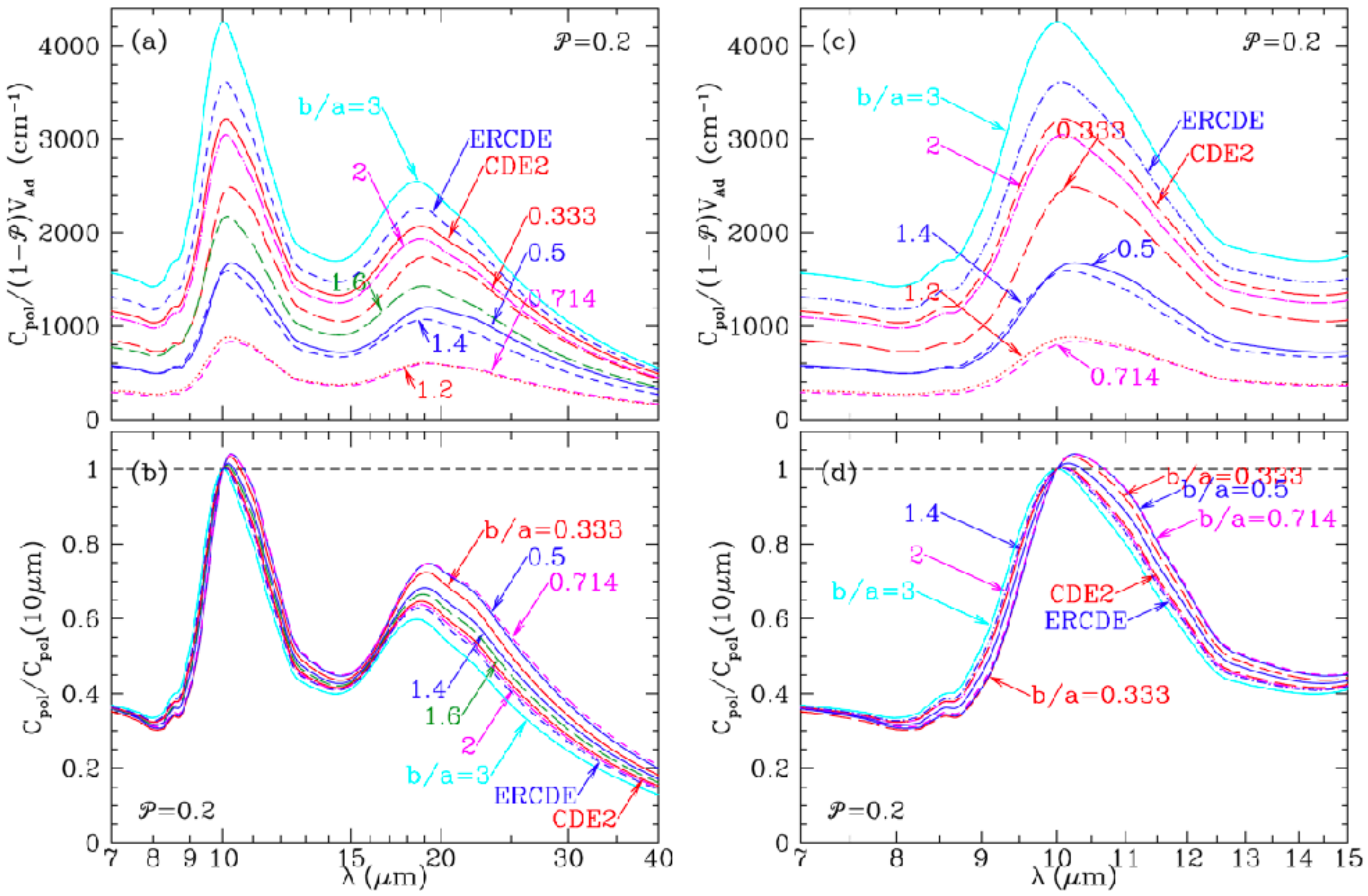


Cosmic dust models for the DISM

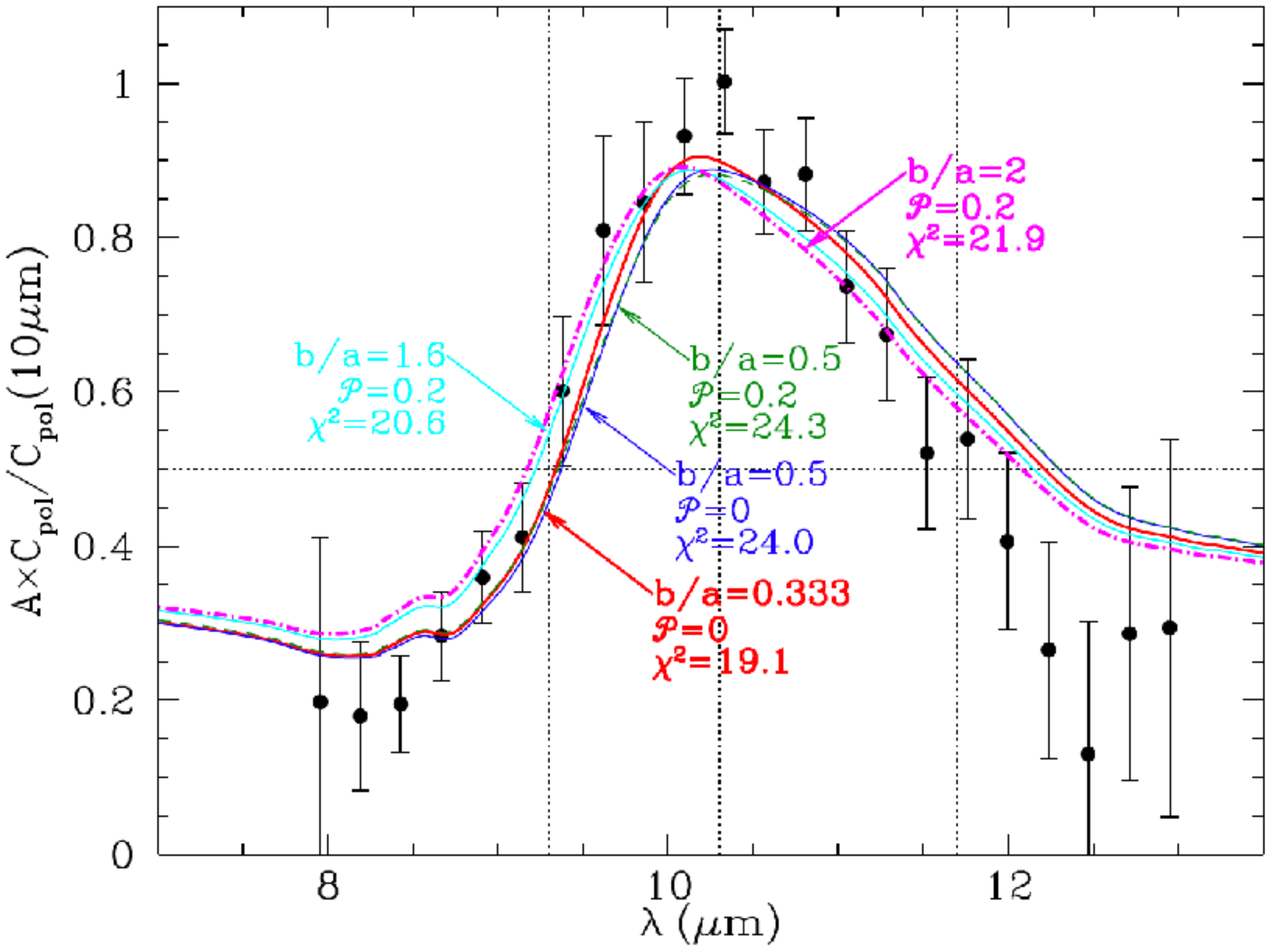
Model from Draine & Hensley (2021) (1/2):

- Spheroidal grains to reproduce polarisation observations
- Explore various shape, size distribution and porosity → more data is needed to lift degeneracy

Polarisation cross section for various grain shape and size distribution



Average polarisation through the DISM



Cosmic dust models for the DISM

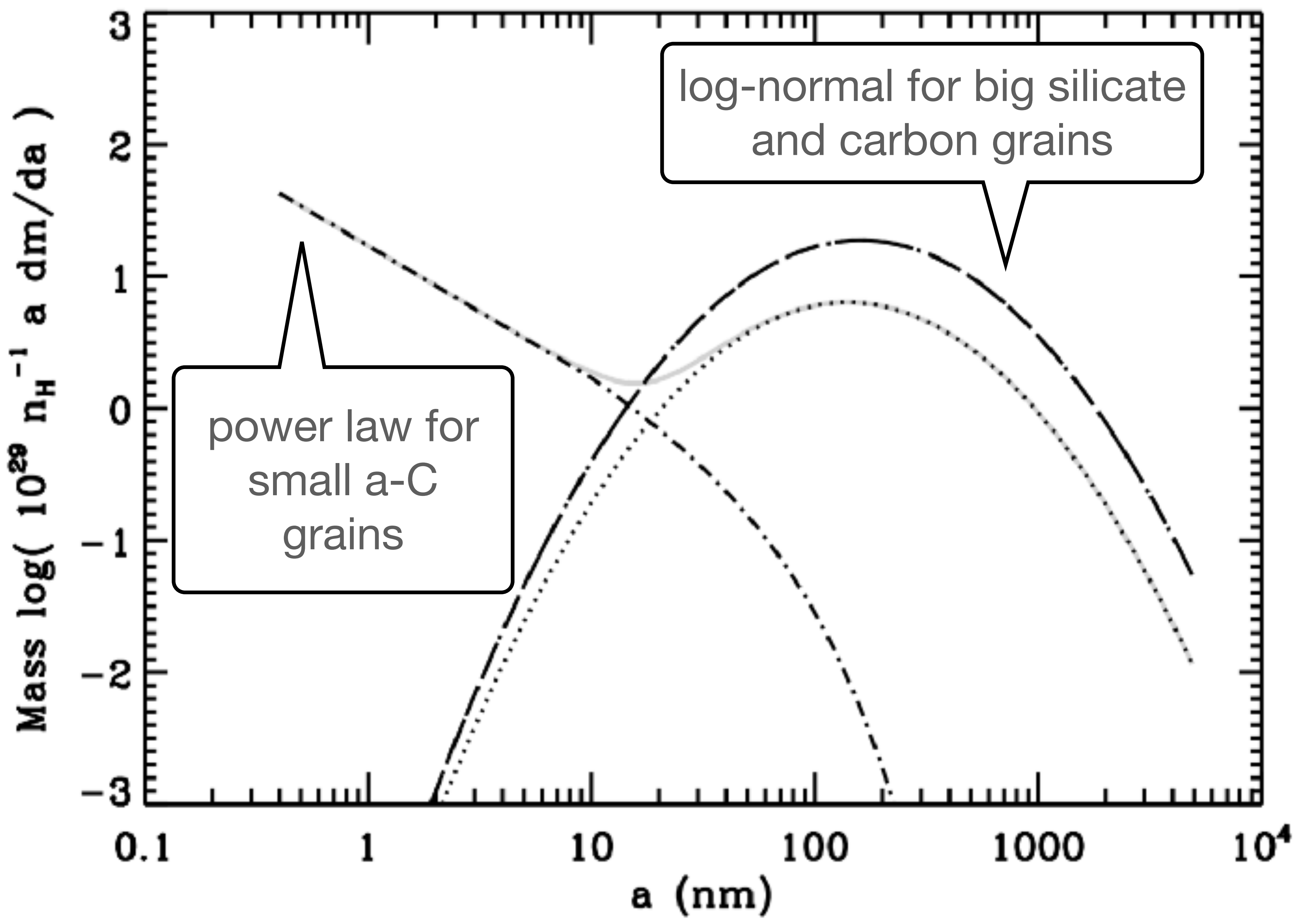
THEMIS: The Heterogeneous Evolution Model of ISM Solids

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

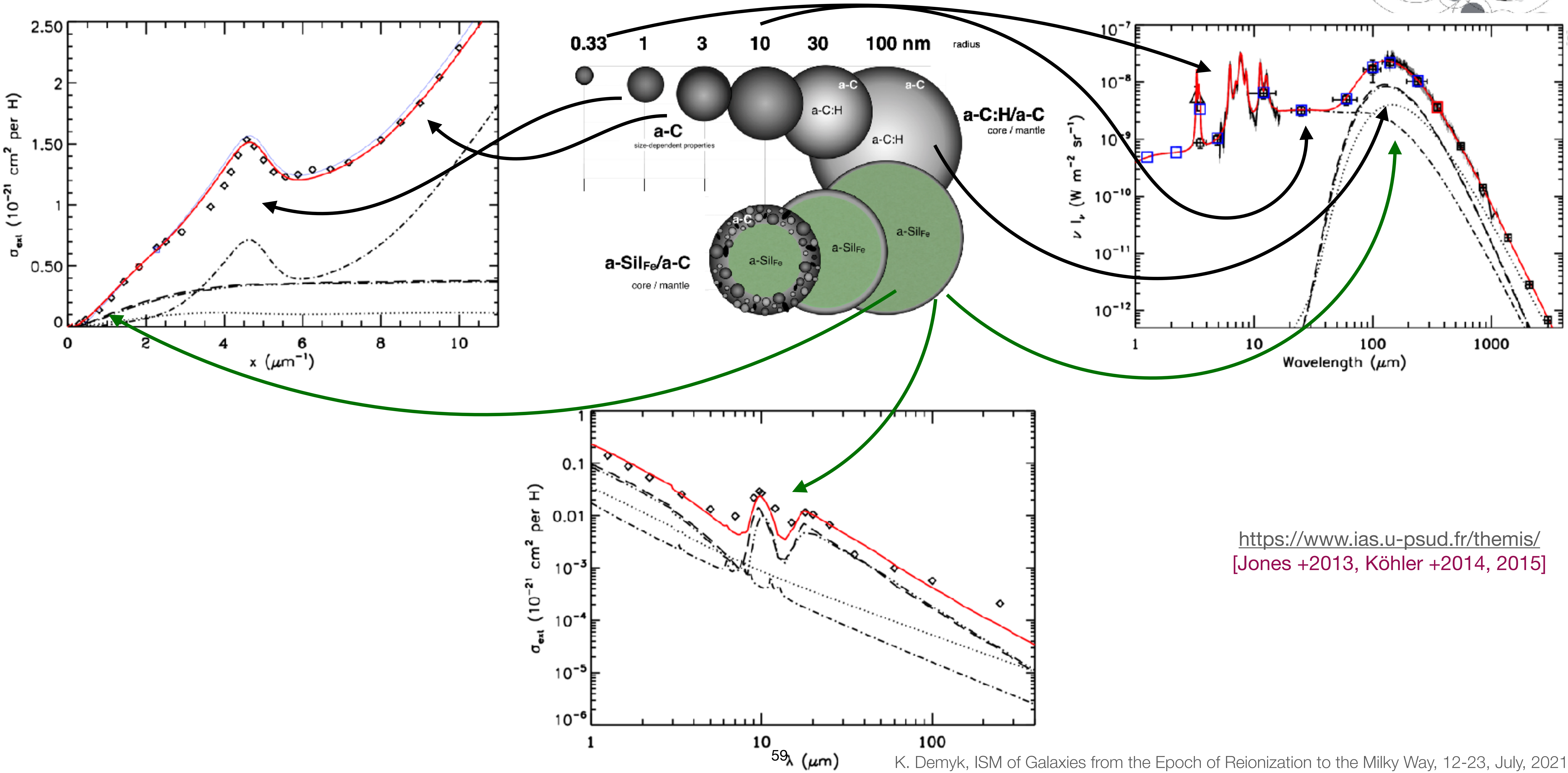
- Reproduces grain evolution in the ISM: mantle accretion and dust coagulation
- Core/mantle grain model
- Mixed solid phases of aromatic carbon (a-C), hydrogenated hydrocarbons (a-C:H) and silicates

- Two silicates dust component: amorphous enstatite ($MgSiO_3$) and forsterite (Mg_2SiO_4) with Fe and FeS inclusions

- a-C(:H) : hydrogenated amorphous carbon grains with varying optical properties with size and surface, calculated from physical models [see Jones 2012]



Cosmic dust models for the DISM



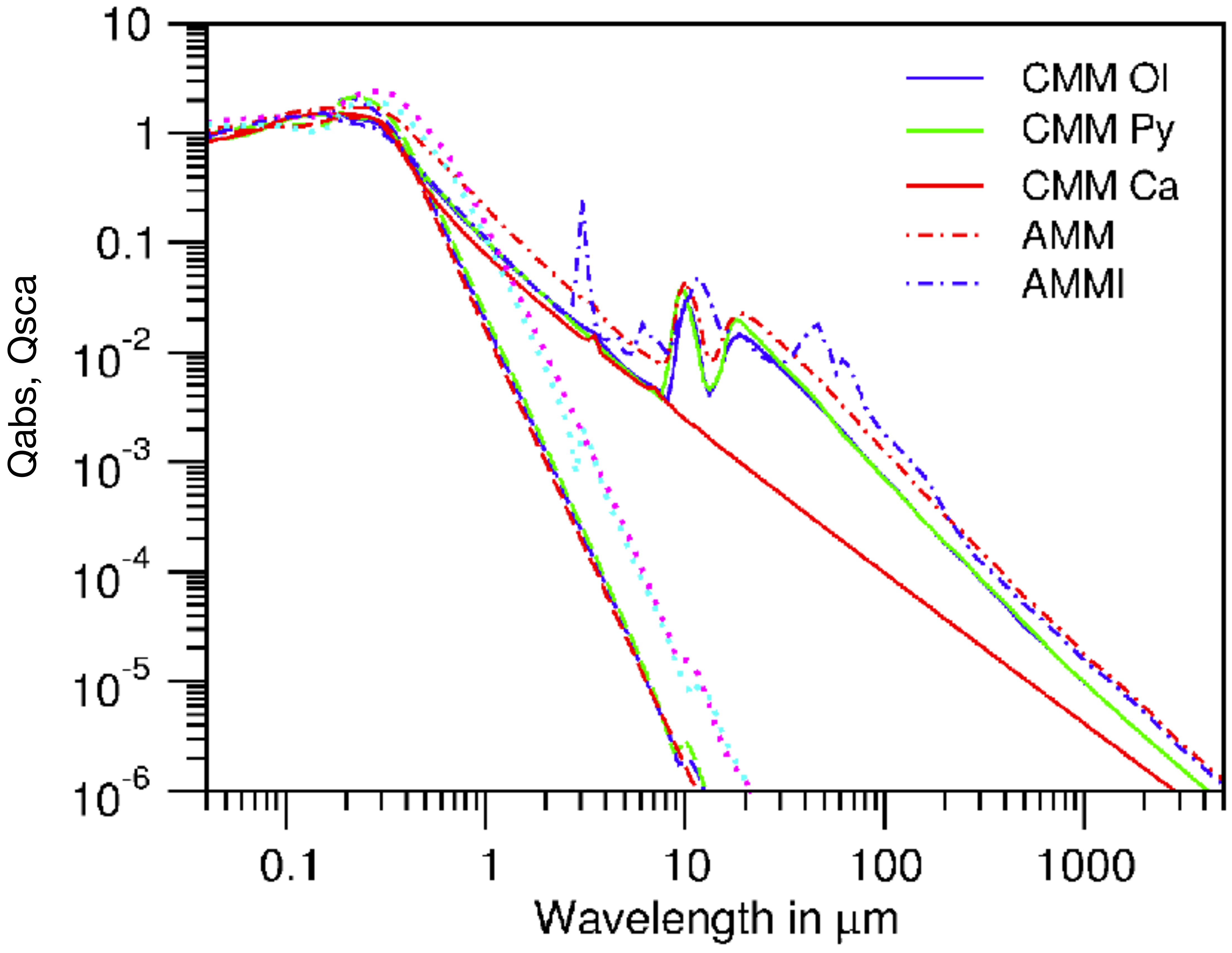
https://www.ias.u-psud.fr/themis/

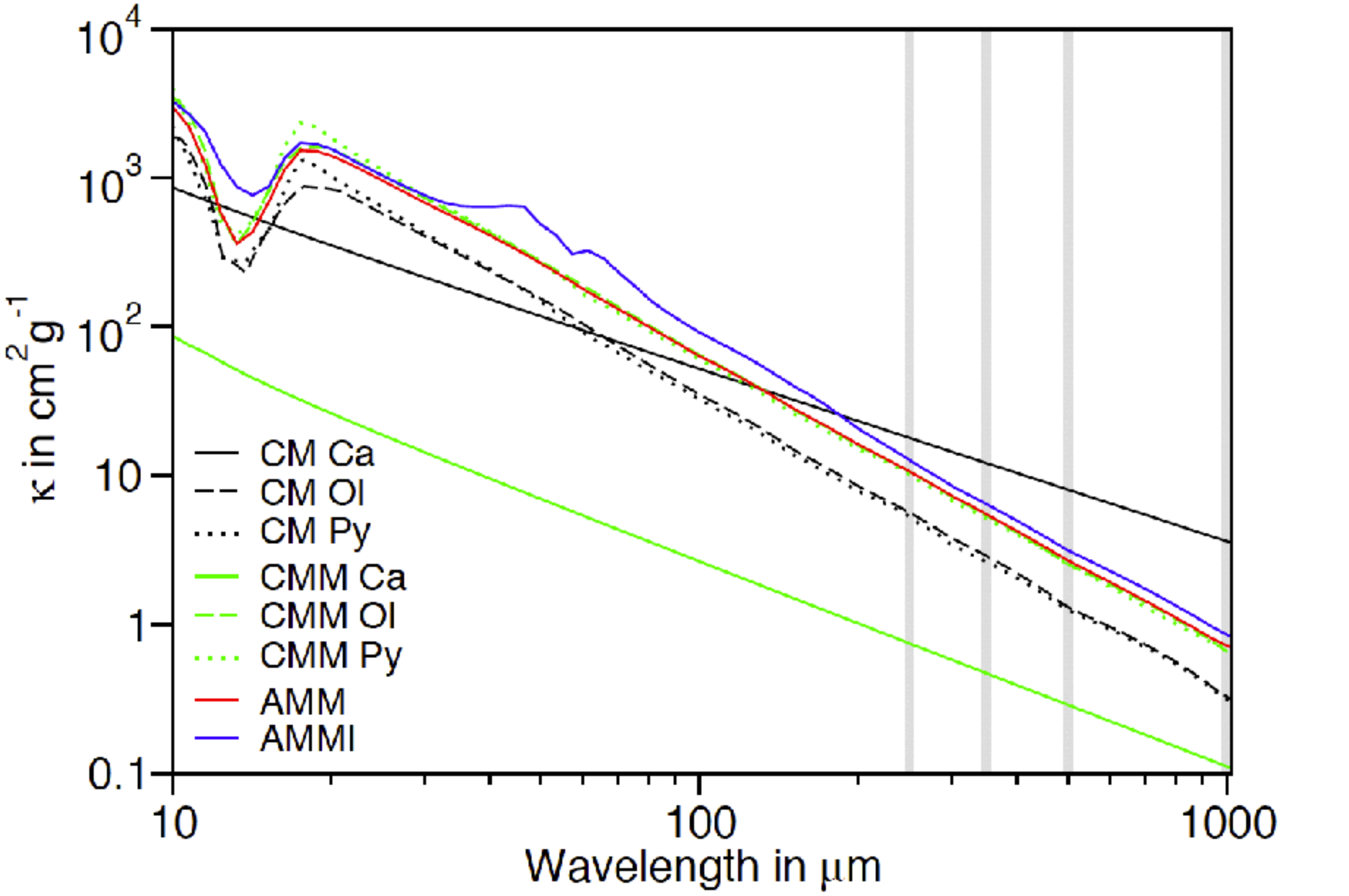
[Jones +2013, Köhler +2014, 2015]

Cosmic dust models for the dense ISM

THEMIS adaptation for the dense ISM:

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

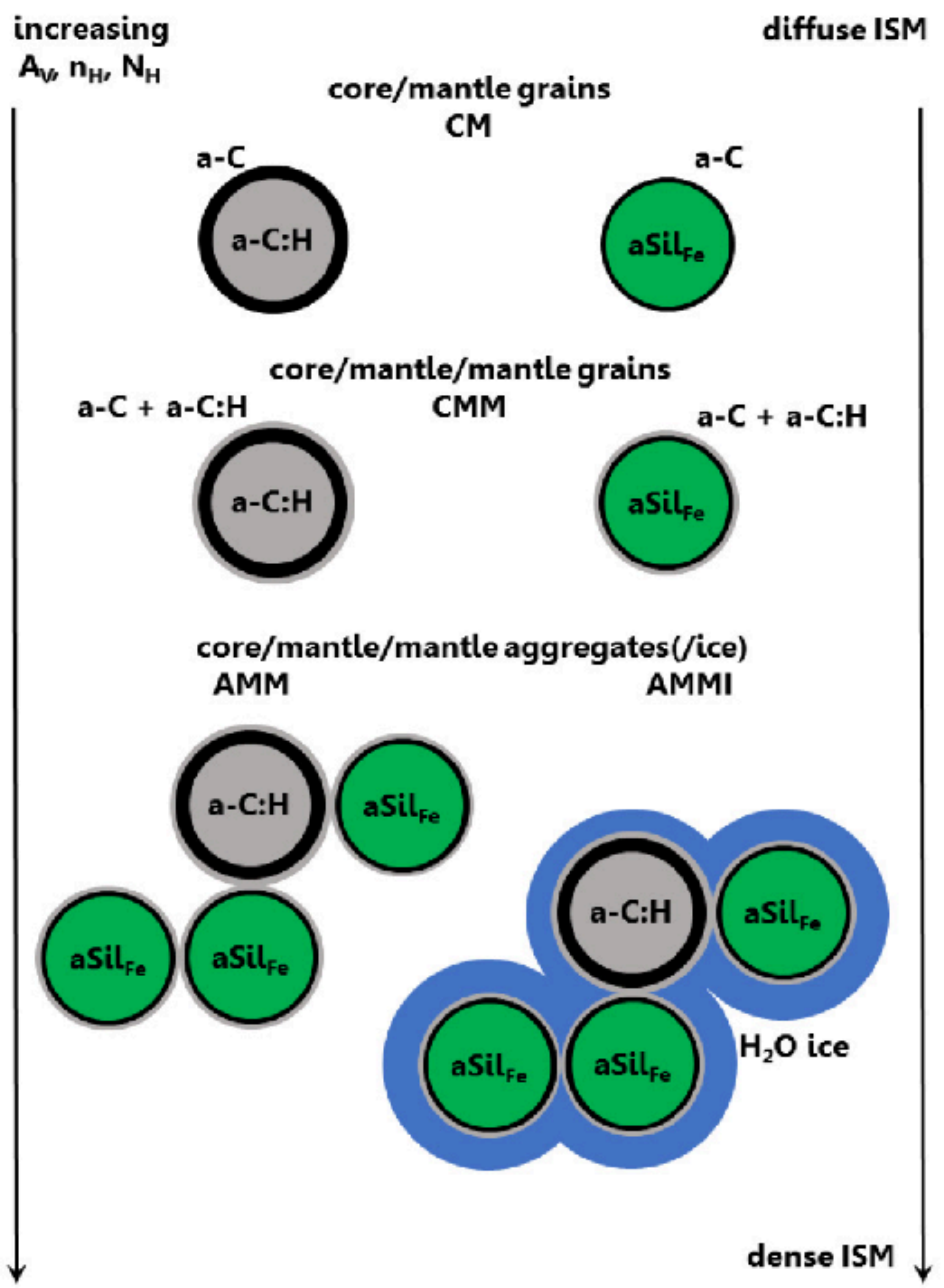


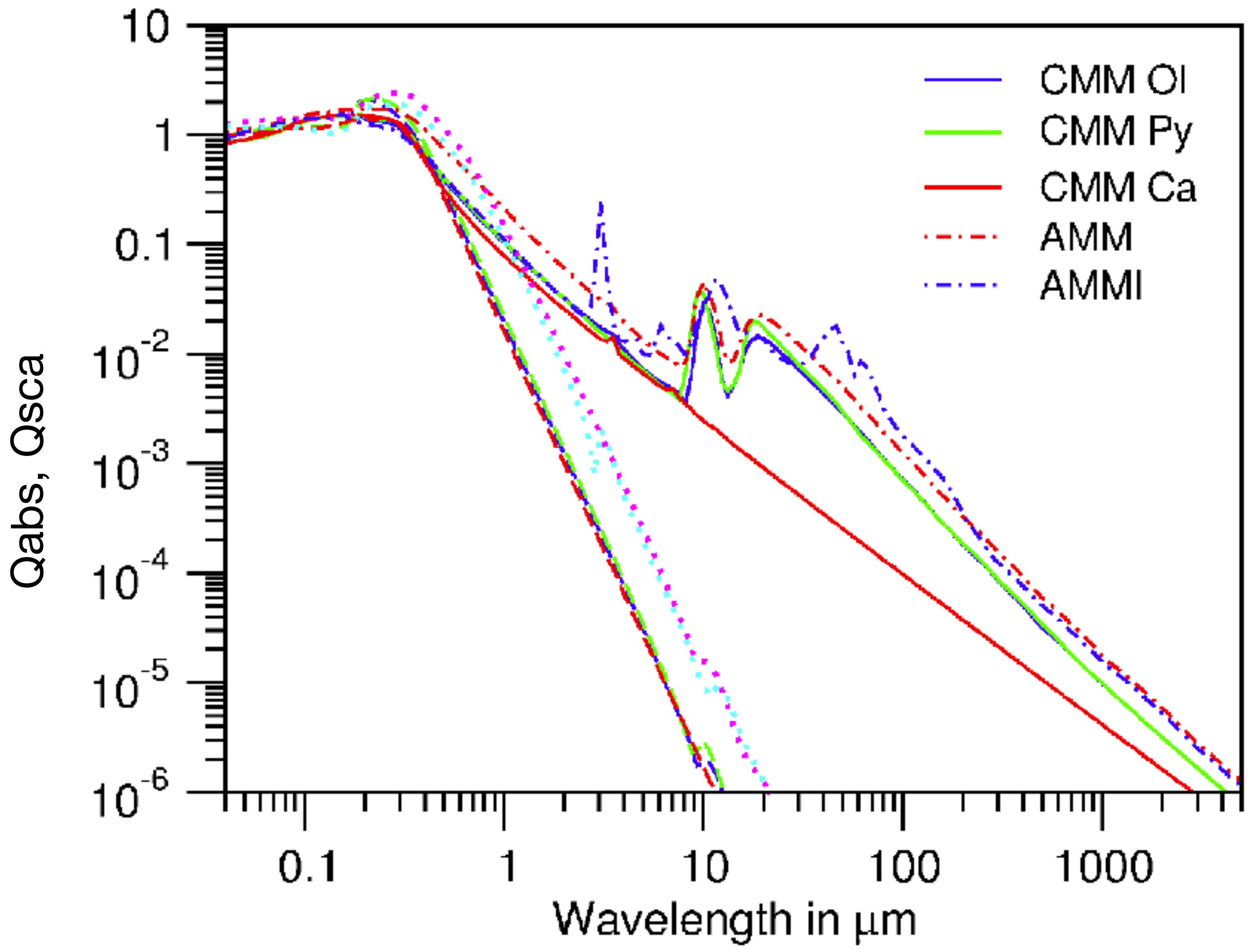


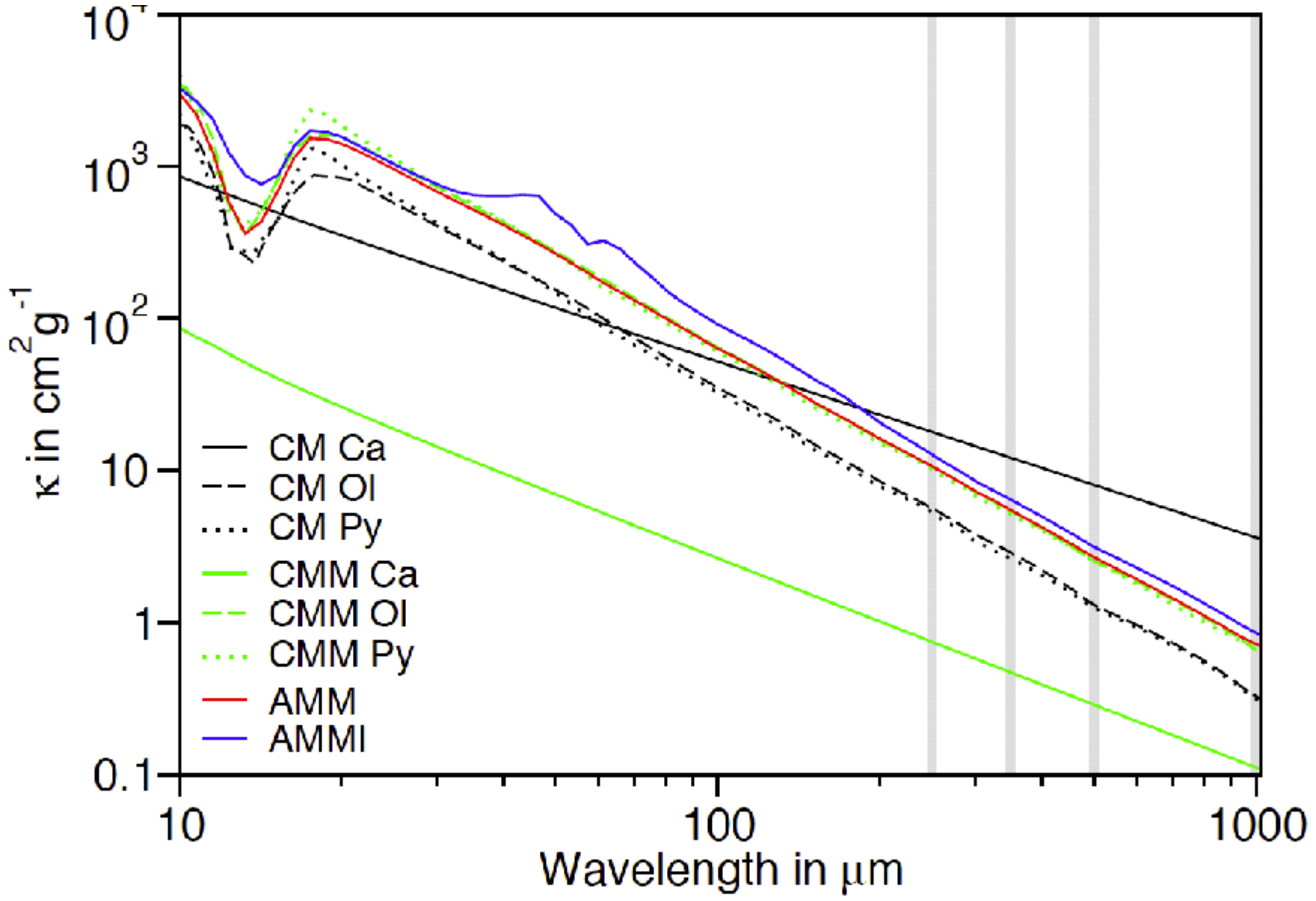
Cosmic dust models for the dense ISM

THEMIS adaptation for the dense ISM:

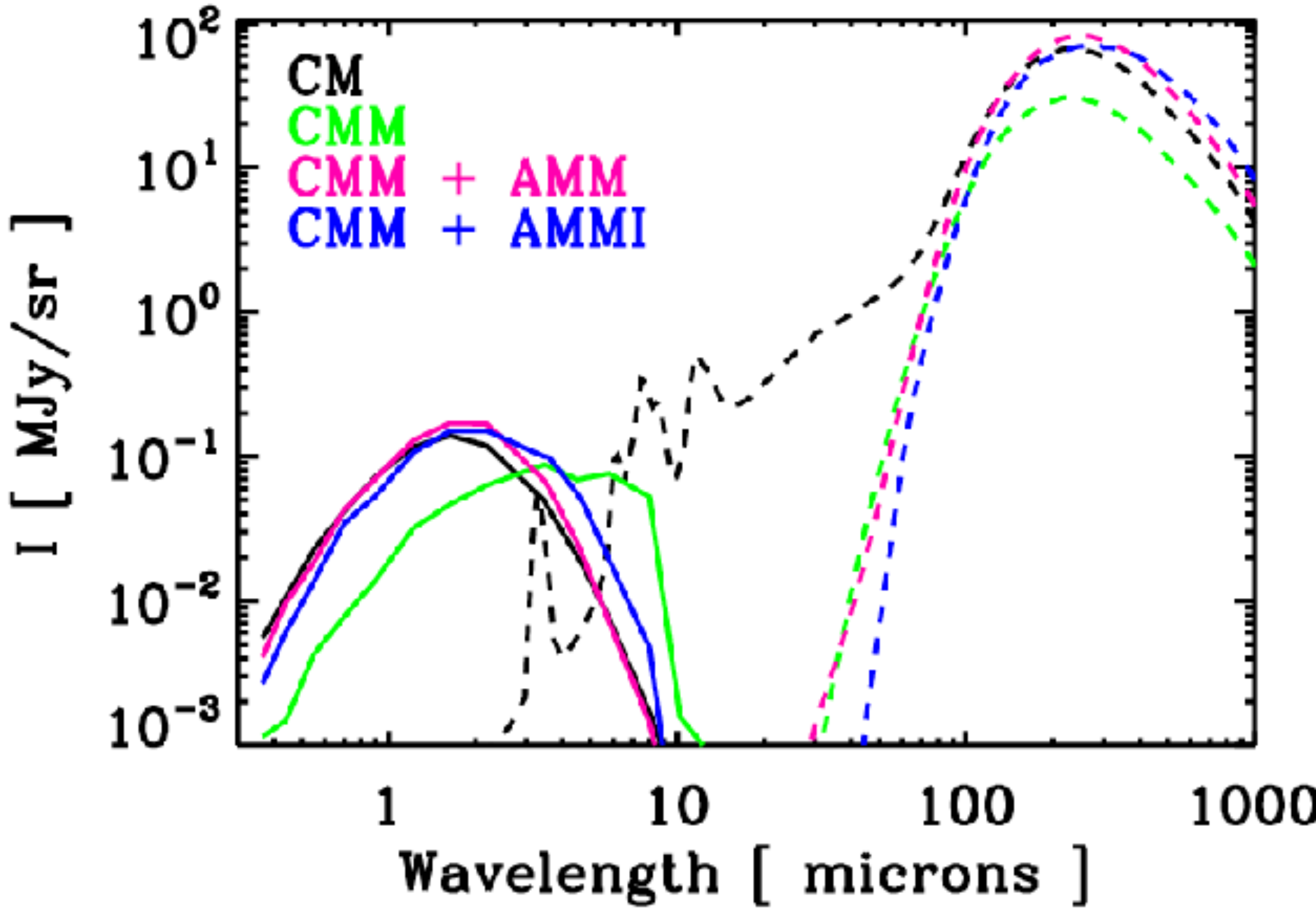
https://www.ias.u-psud.fr/themis/
[Jones +2013, Köhler +2014, 2015]

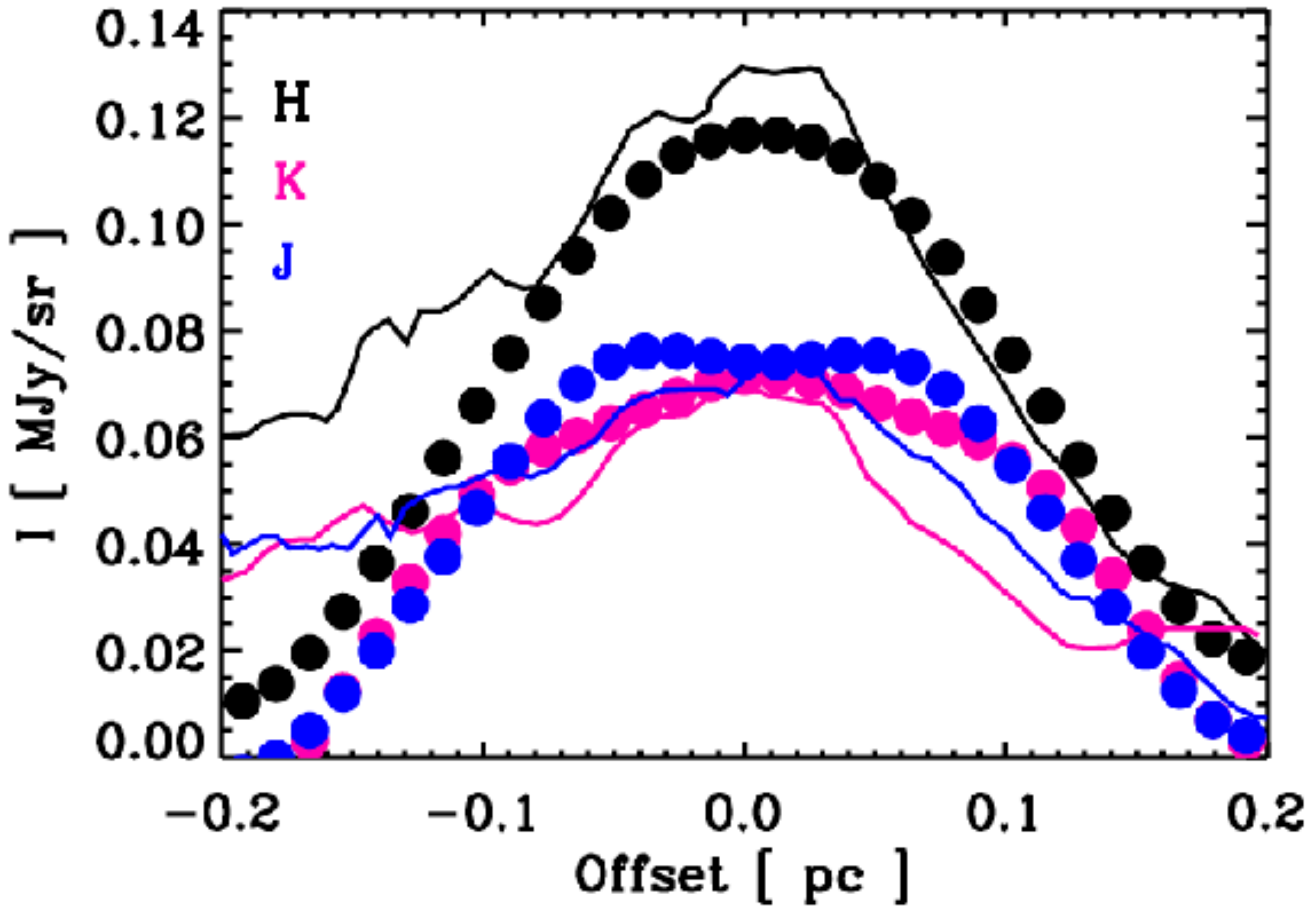






Coreshine effect [Ysard+2016]





Some dust models for the DISM

Constraints from extinction & emission:

- 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
- The THEMIS model [Jones et al. 2013, 2017, Koehler et al. 2015]: lab silicates & a-C(:H)

Constraints from extinction, emission & polarisation:

- 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*
- The THEMIS II model [Ysard et al. 2022]: lab silicates at low T & a-C(:H) — *polarised extinction and emission*

Some dust models for the dense ISM

Constraints from extinction & emission:

- Pollack (1994) model: lab silicates, Fe, organic C —molecular clouds and transition disks — extinction & emission
- Ossenkopf et al (1994): lab silicate and amorphous carbon grains, ices - dense protostellar cores — extinction & emission
- Zubko et al. 2004: astrosilicates & graphite or amorphous carbon & PAHs & H_2O ice and organic refractory
- The THEMIS model [Jones et al. 2013, 2017, Koehler et al. 2015]: lab silicates & a-C(:H) — extinction & emission

Cosmic dust models : 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 physical (measurements on cosmic dust analogues or theory)
  - Their capacity to follow grain evolution and to adapt to other astrophysical environments

- 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