INTERSTELLAR DUST PROPERTIES

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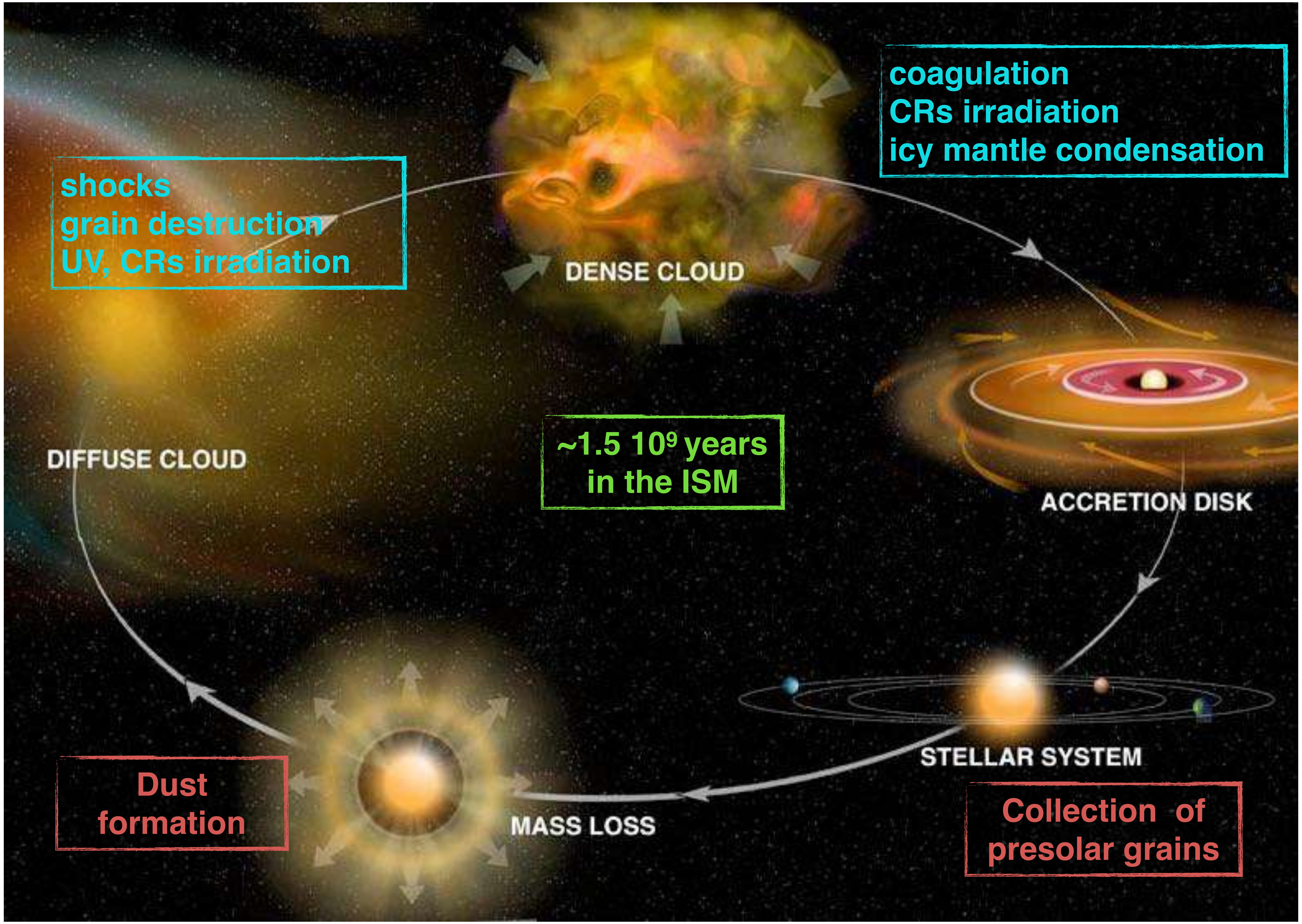
Outline

- 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 properties and evolution across the ISM cycle

Dust evolution along the ISM life cycle



coagulation
CRs irradiation
icy mantle condensation

shocks
grain destruction
UV, CRs irradiation

~1.5 10^9 years
in the ISM

Dust
formation

Collection of
presolar grains

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 (sputtering)

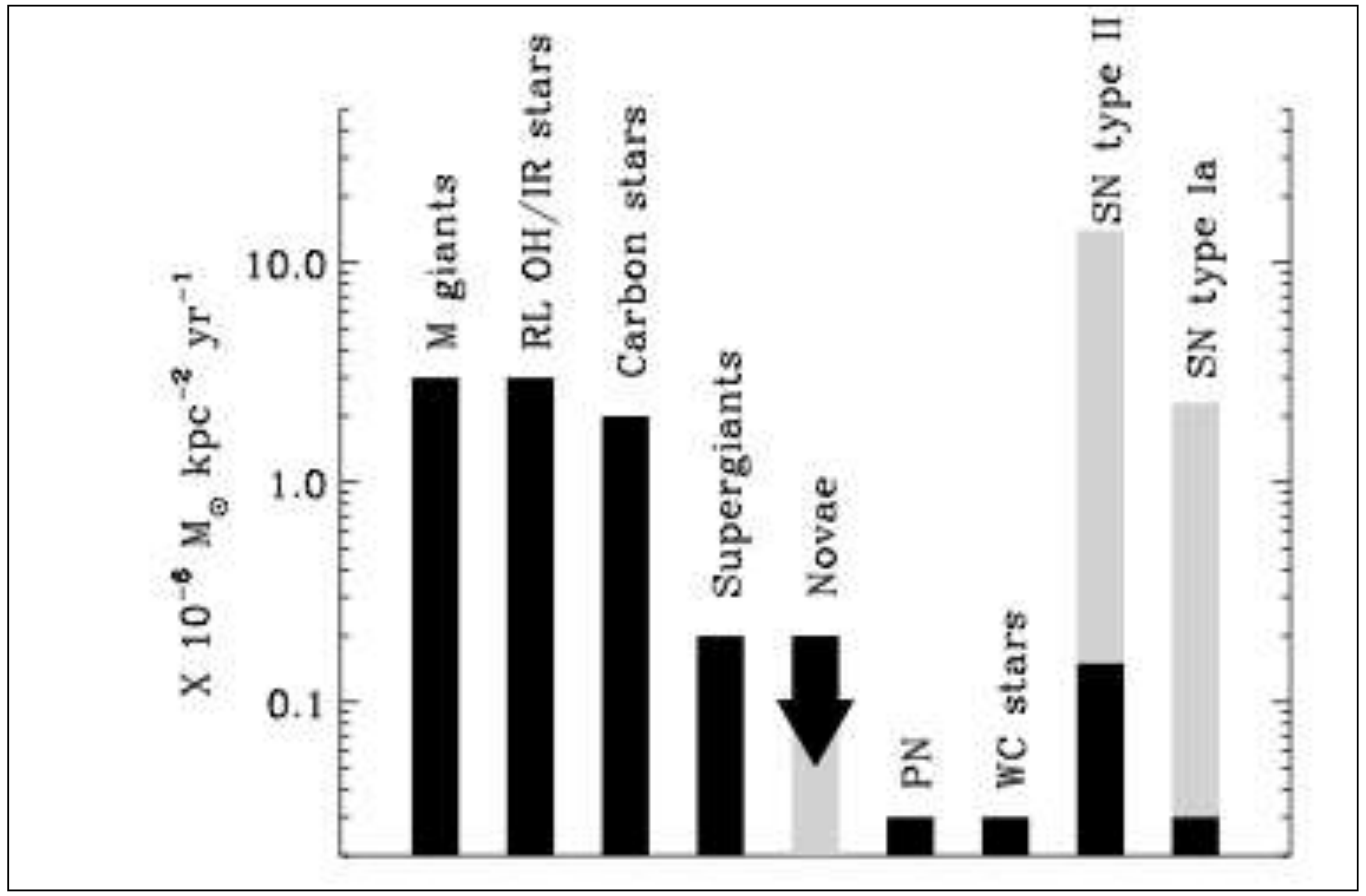
- **Interaction with photons (UV, X…)**
  - Chemistry on grain surface and within icy mantles
  - Influence the ionisation and stability of PAHs and nano a-C(:H) grains

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

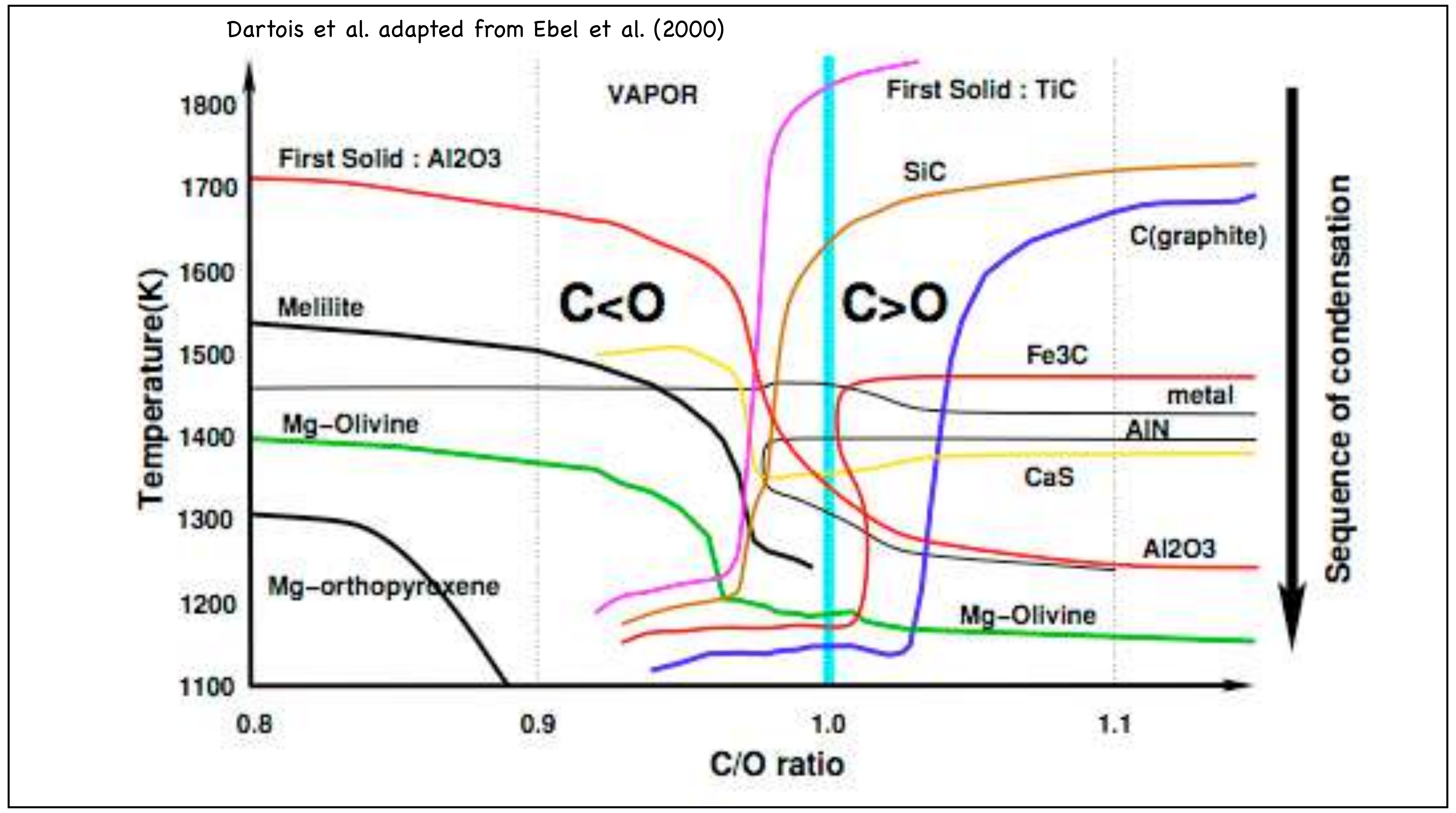
Newly formed dust

- Produced in :
  - Circumstellar shells around evolved stars
  - Supernovae (also destroy dust)
  - The ISM (also destroy dust)

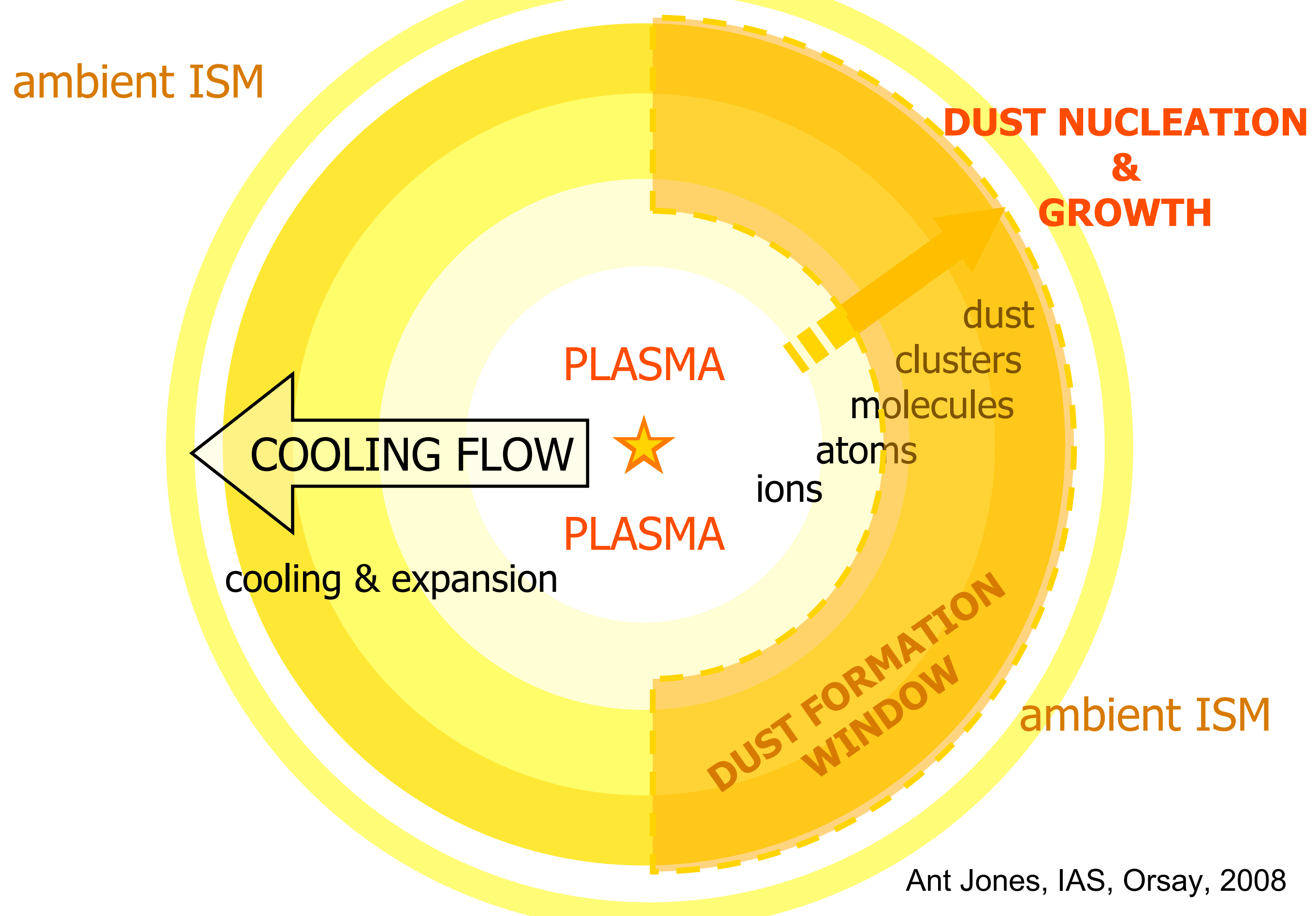
- Two-steps process involving 1) nucleation and 2) grain growth
- Depends on time, dynamic,…



Dartois et al. adapted from Jones et al. (2001)


Dartois et al. adapted from Ebel et al. (2000)

Stardust formation in CS shells

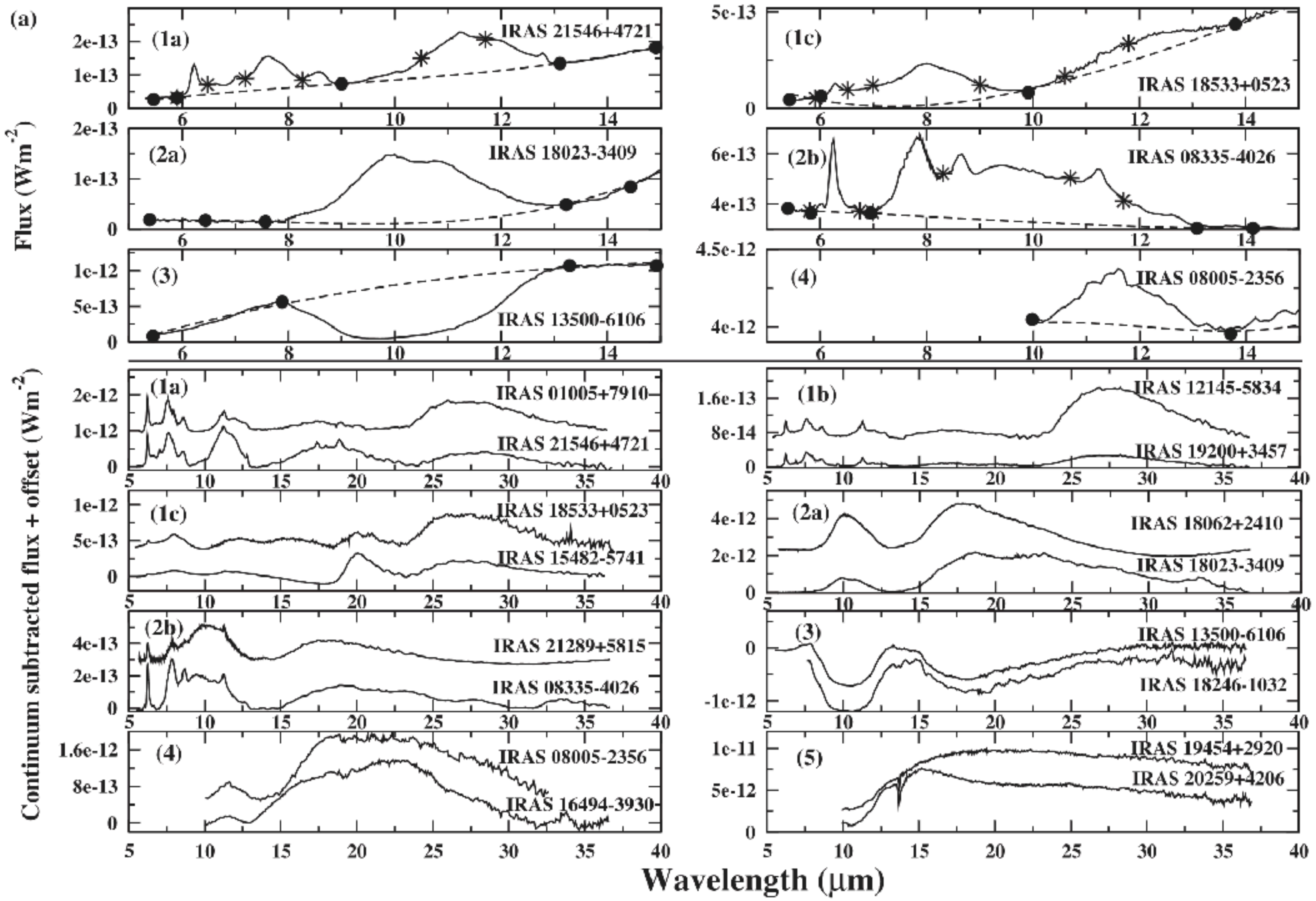


Ant Jones, IAS, Orsay, 2008

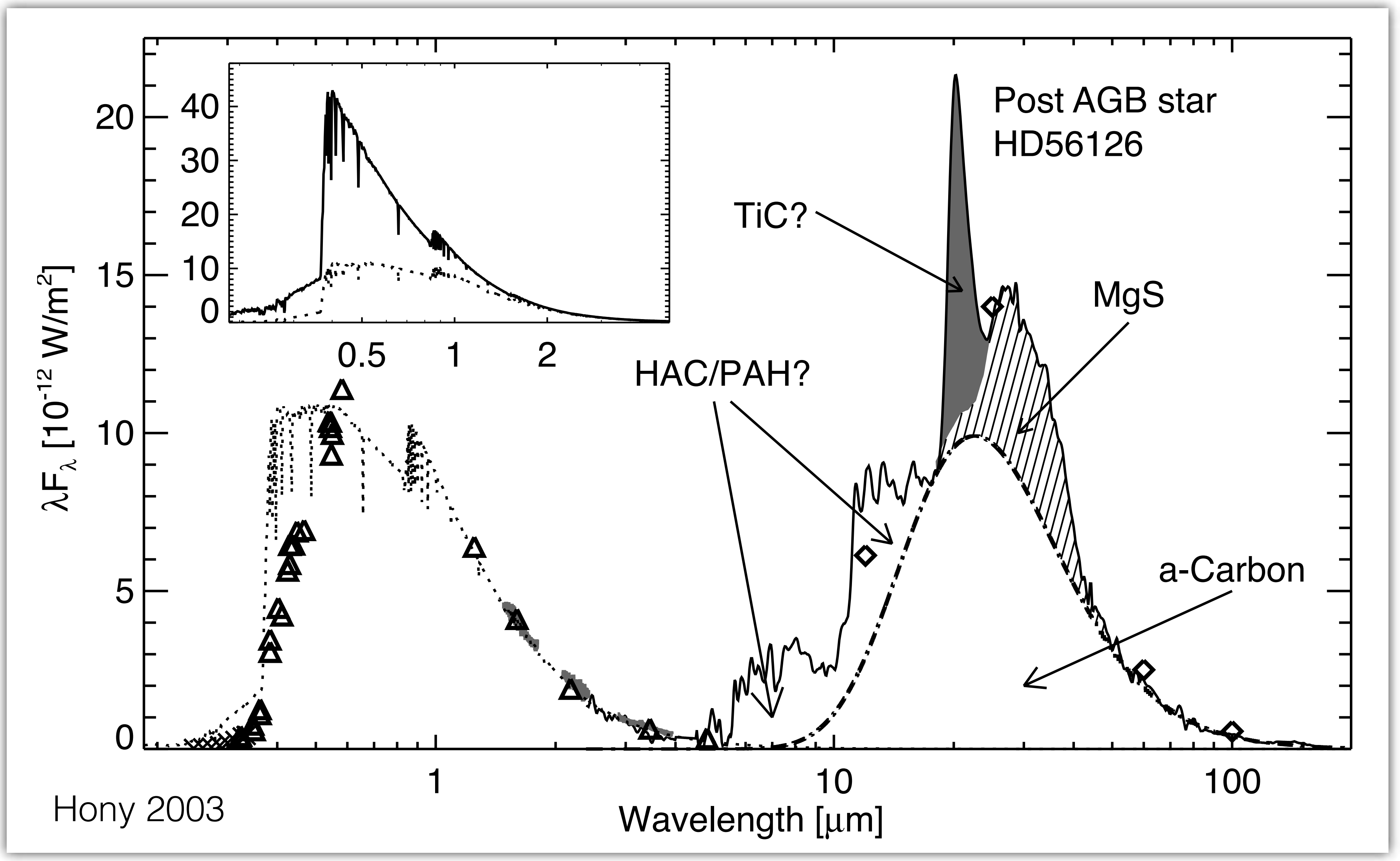
Newly formed dust : silicates

- Amorphous & crystalline silicates
- Oxides

[Jiang+2023]



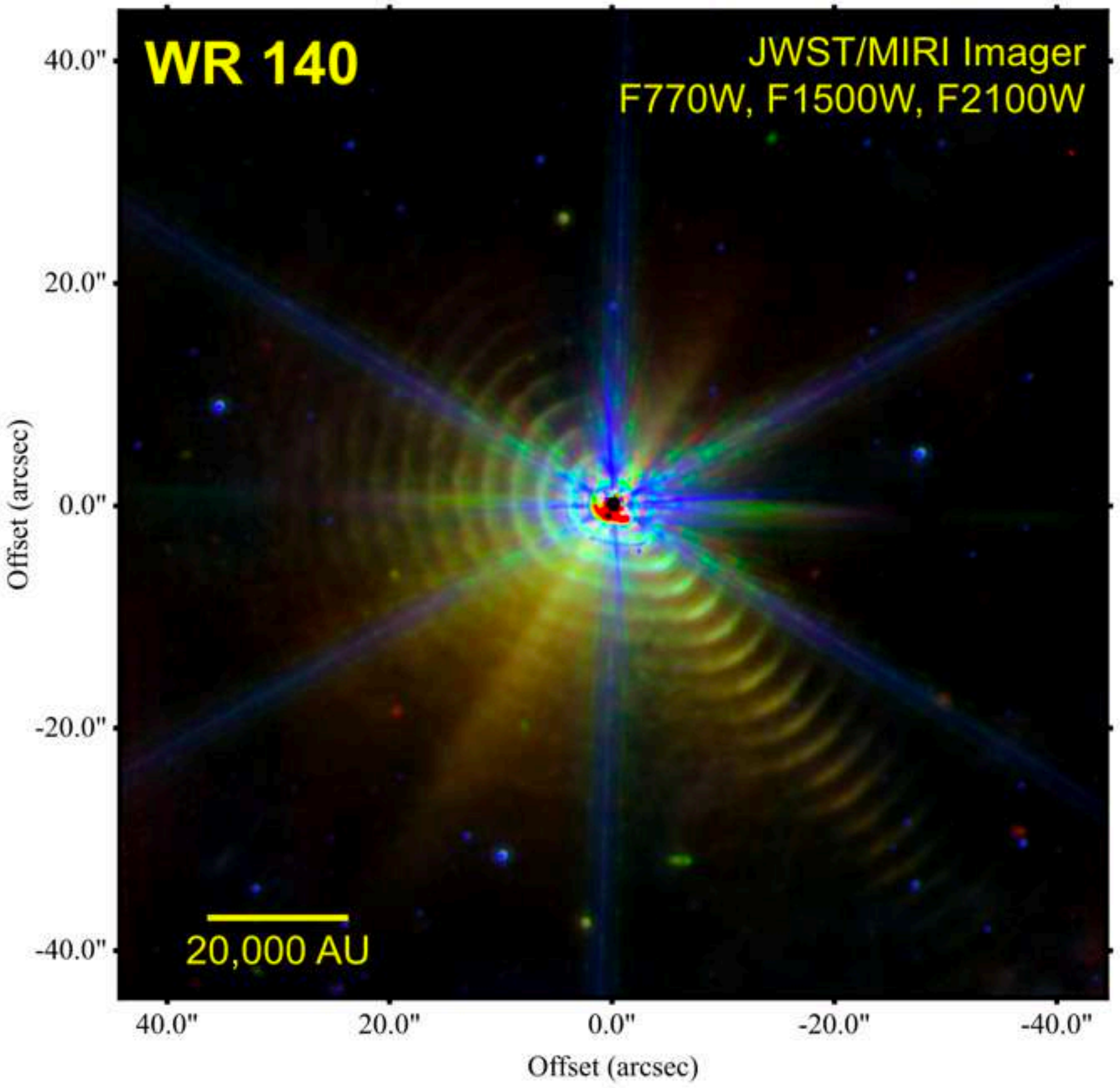
- Evolution from O-rich to C-rich stars
- Evolved stars with C/0~1



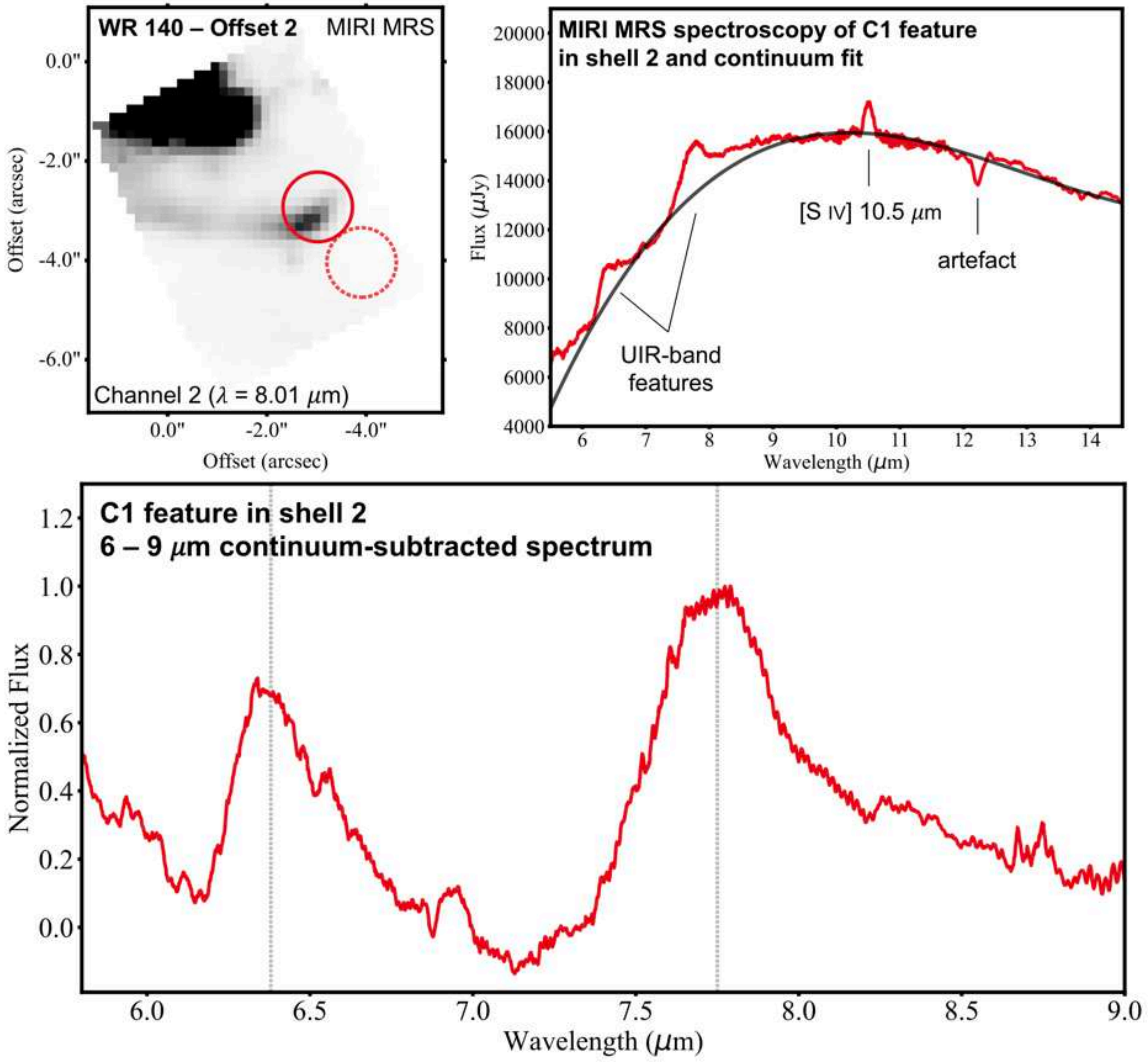
Hony 2003

Newly formed dust : circumstellar shells

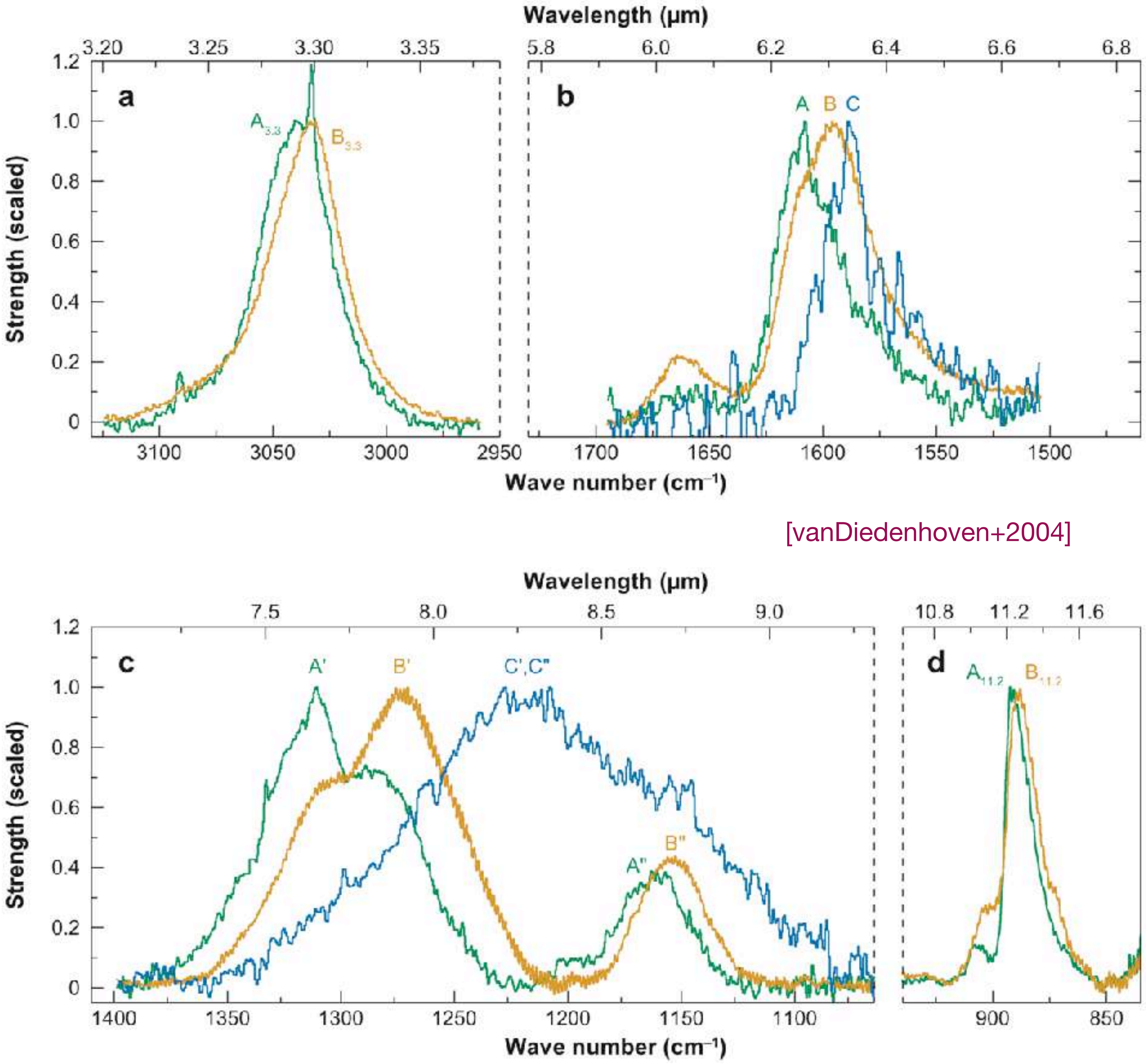
- High mass evolved stars
- 17 dust shells
- Aromatic dust characteristic of H poor environments



[Lau+2022]



Newly formed dust : circumstellar shells



[vanDiedenhoven+2004]

- Amorphous carbon dust (featureless)
  [Volk+2011, Honny+2002]
- PAHs
- Hydrogenated amorphous carbons

- HerbigAeBe, HII regions, RN, post-AGB, PPNs, extragalactiques sources
- Isolated Herbig AeBe, post-AGB, PPNs
- post-AGB, young PPNs

- Increase of aliphatic content from class A to class C [Pino+08, Carpentier+12]

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

[Jones & Nuth 2011, Bocchio+14, Slavin+15, Zukhoska+2016,2018, Dwek+15, Kirchschlager+2022]

↓

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

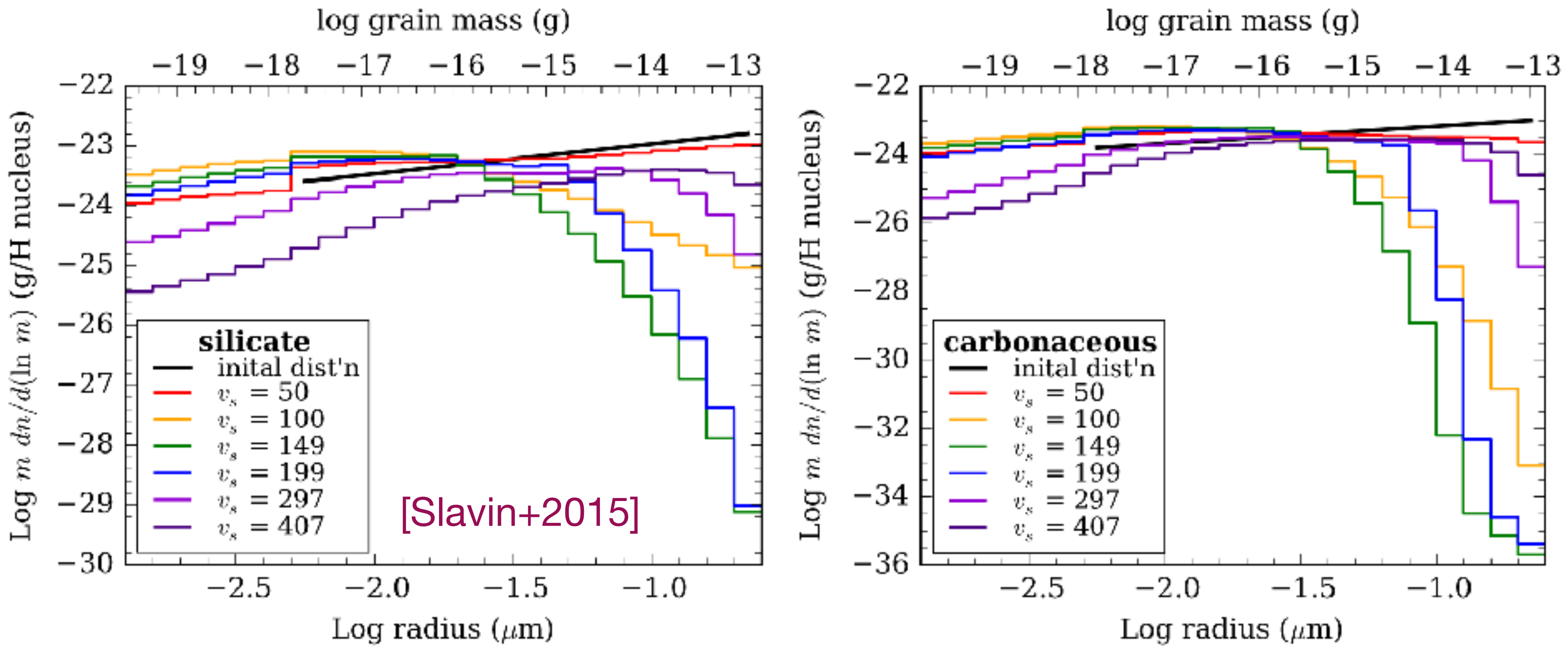
↓

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

Dust evolution in shocks

Effect of high velocity shock propagation in the ISM :

- **Grain size distribution changes:**



[Slavin+2015]

- **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 :**

[Slavin+2015]

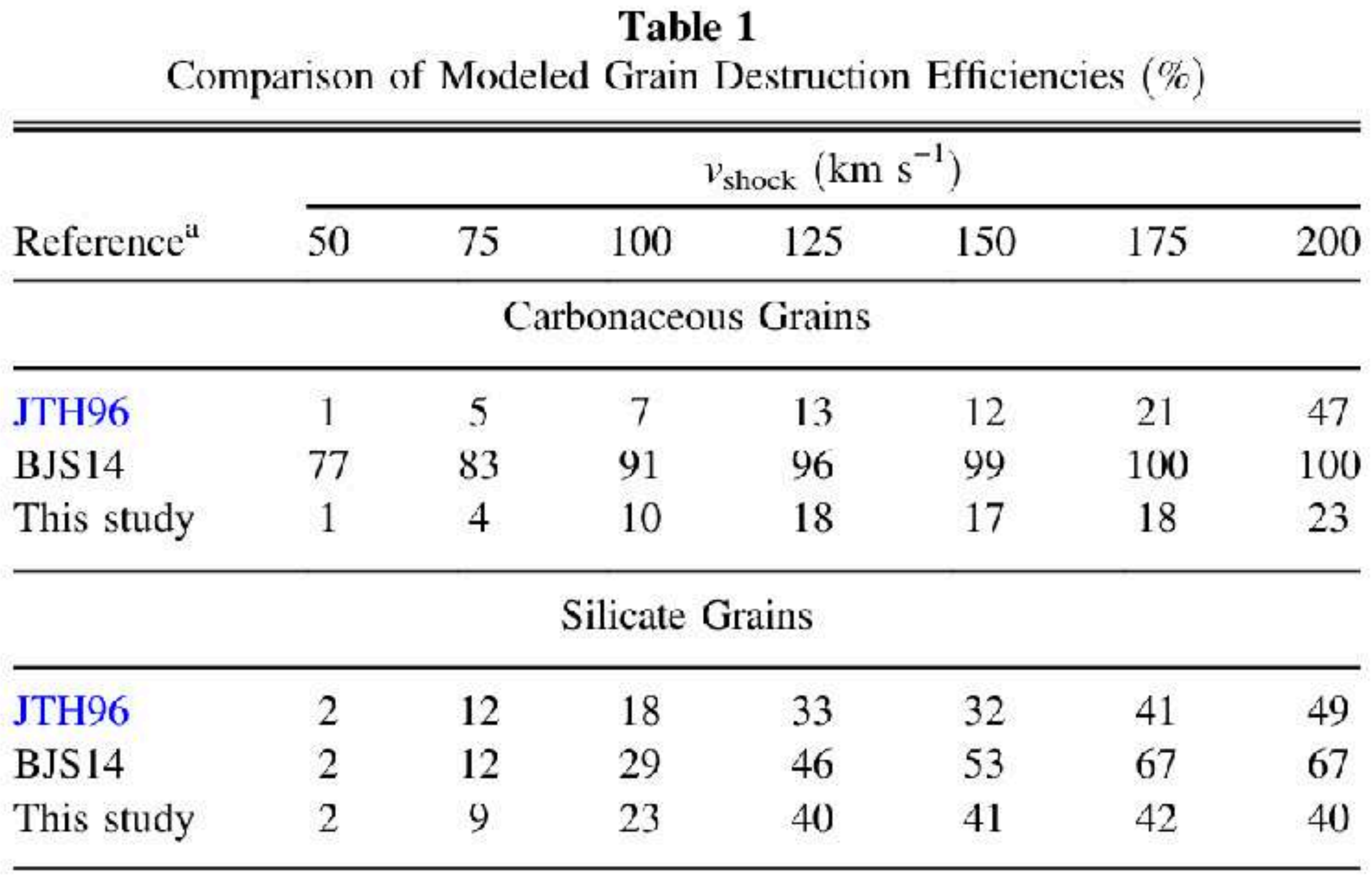


Table 1

Comparison of Modeled Grain Destruction Efficiencies (%)

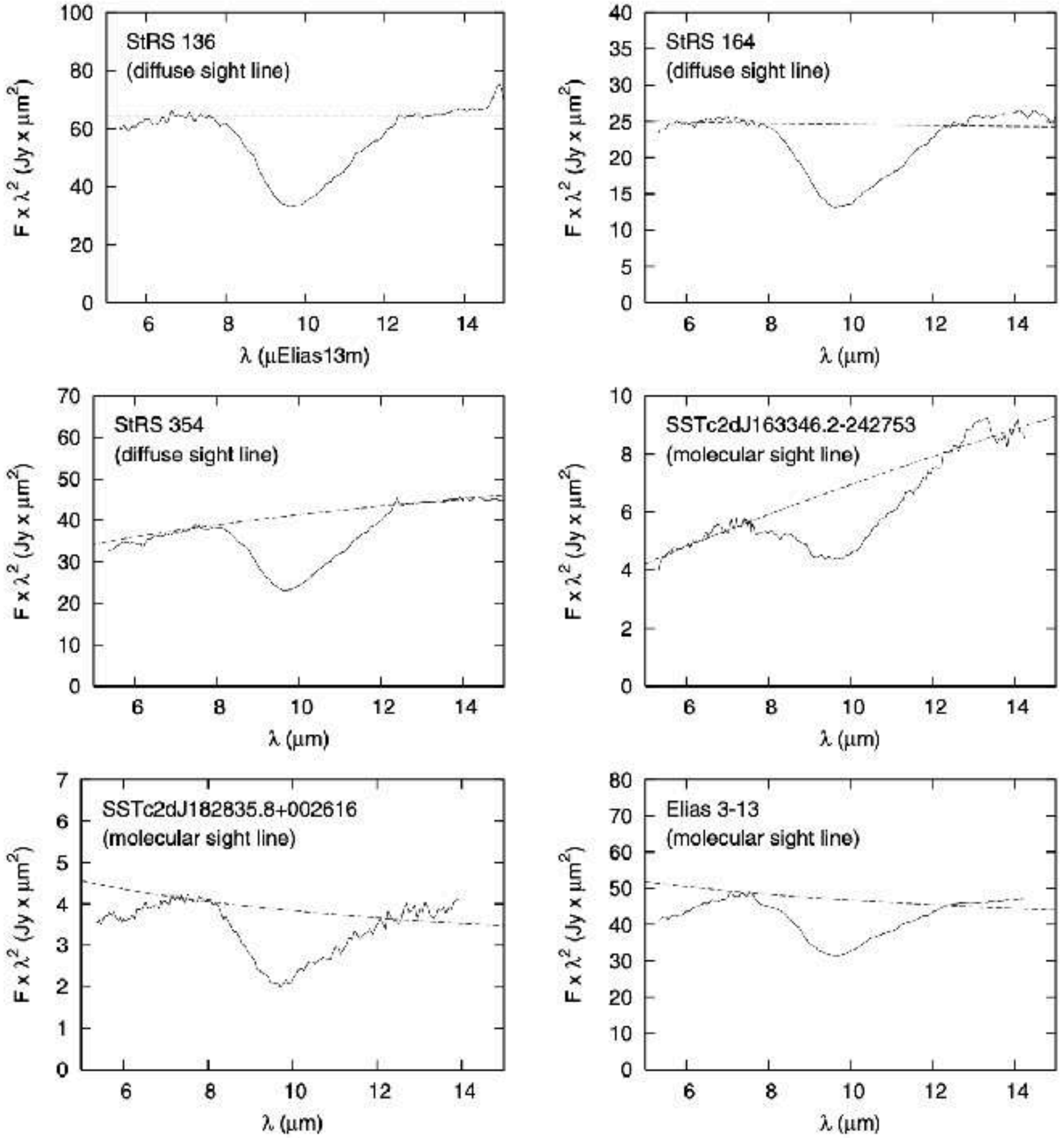
	$v_{\rm shock}$ (km s^{-1})						
Reference[a]	50	75	100	125	150	175	200
	Carbonaceous Grains						
JTH96	1	5	7	13	12	21	47
BJS14	77	83	91	96	99	100	100
This study	1	4	10	18	17	18	23
	Silicate Grains						
JTH96	2	12	18	33	32	41	49
BJS14	2	12	29	46	53	67	67
This study	2	9	23	40	41	42	40

- Thermal history of shocked gas matters
- Dust destruction timescales might be shorter than previous estimates

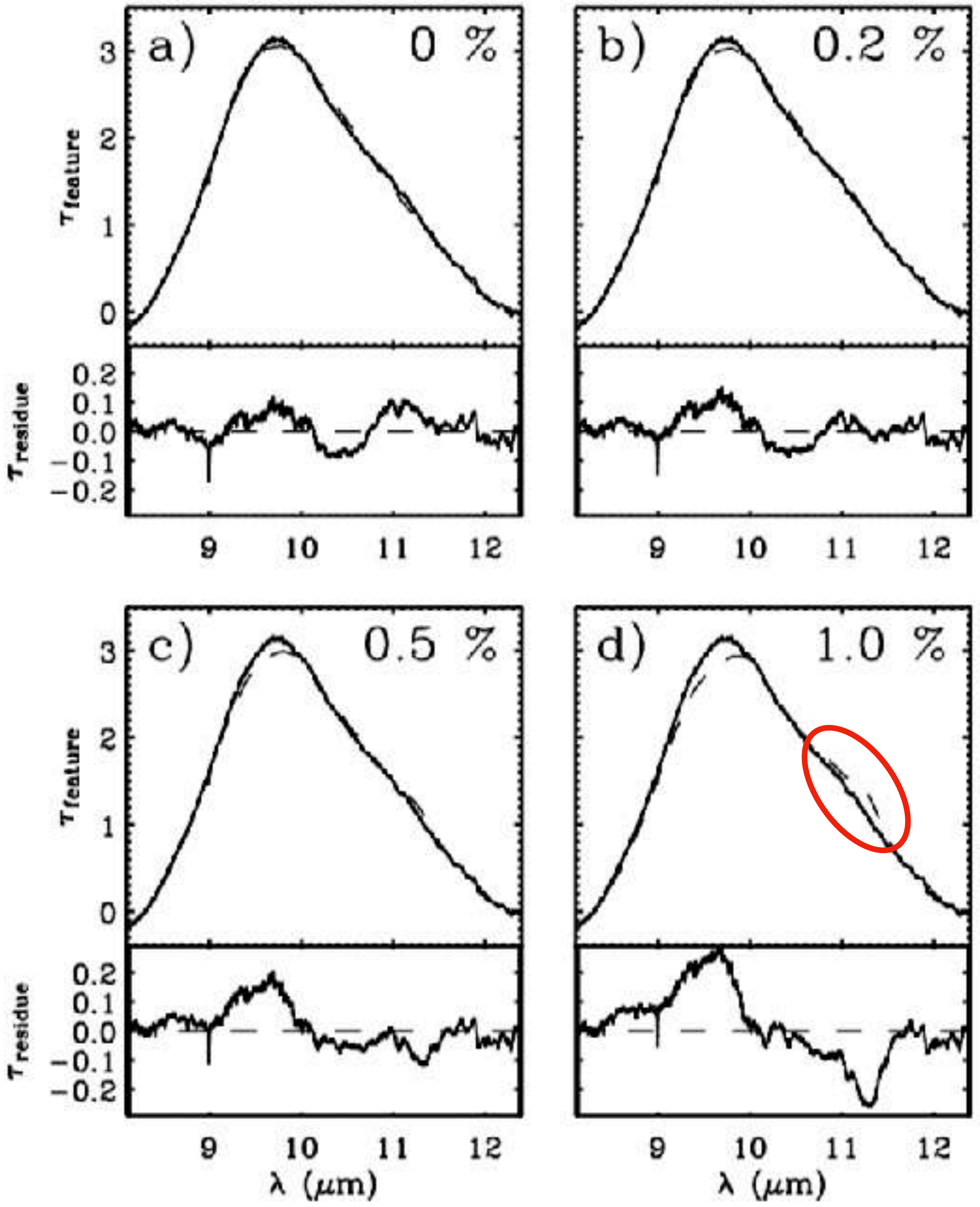
Silicate dust in the diffuse ISM

- Interstellar silicates are ~ 95-98 % amorphous [Kemper+2004, Li+2007]

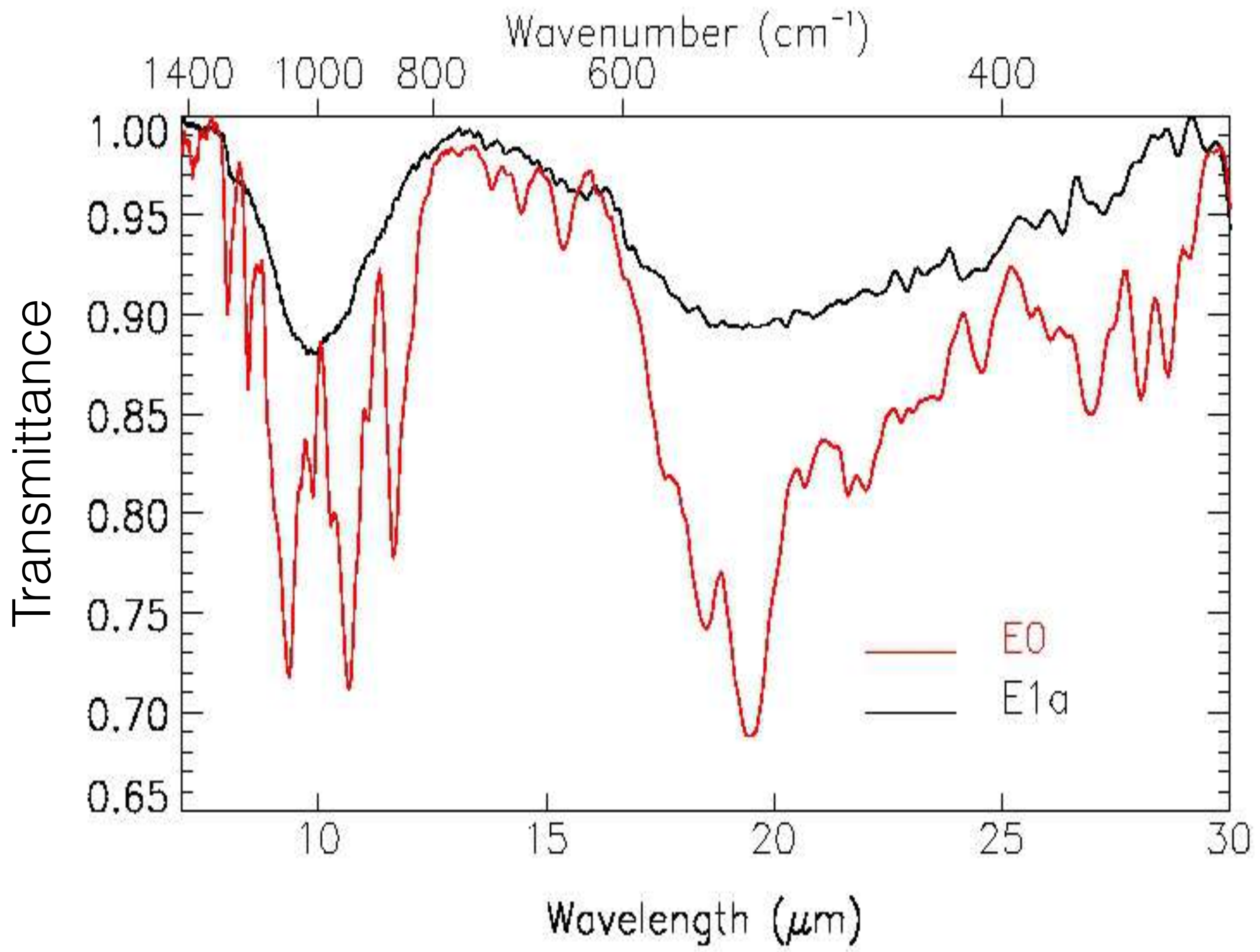
[van Breemen+2011]



[Kemper+2004]



- Crystalline silicates amorphised in shocks
- Increase of porosity
- Chemical evolution : loss of O and Mg, Fe reduction [Demyk+2001, Jäger+2002, Brucato+2004]

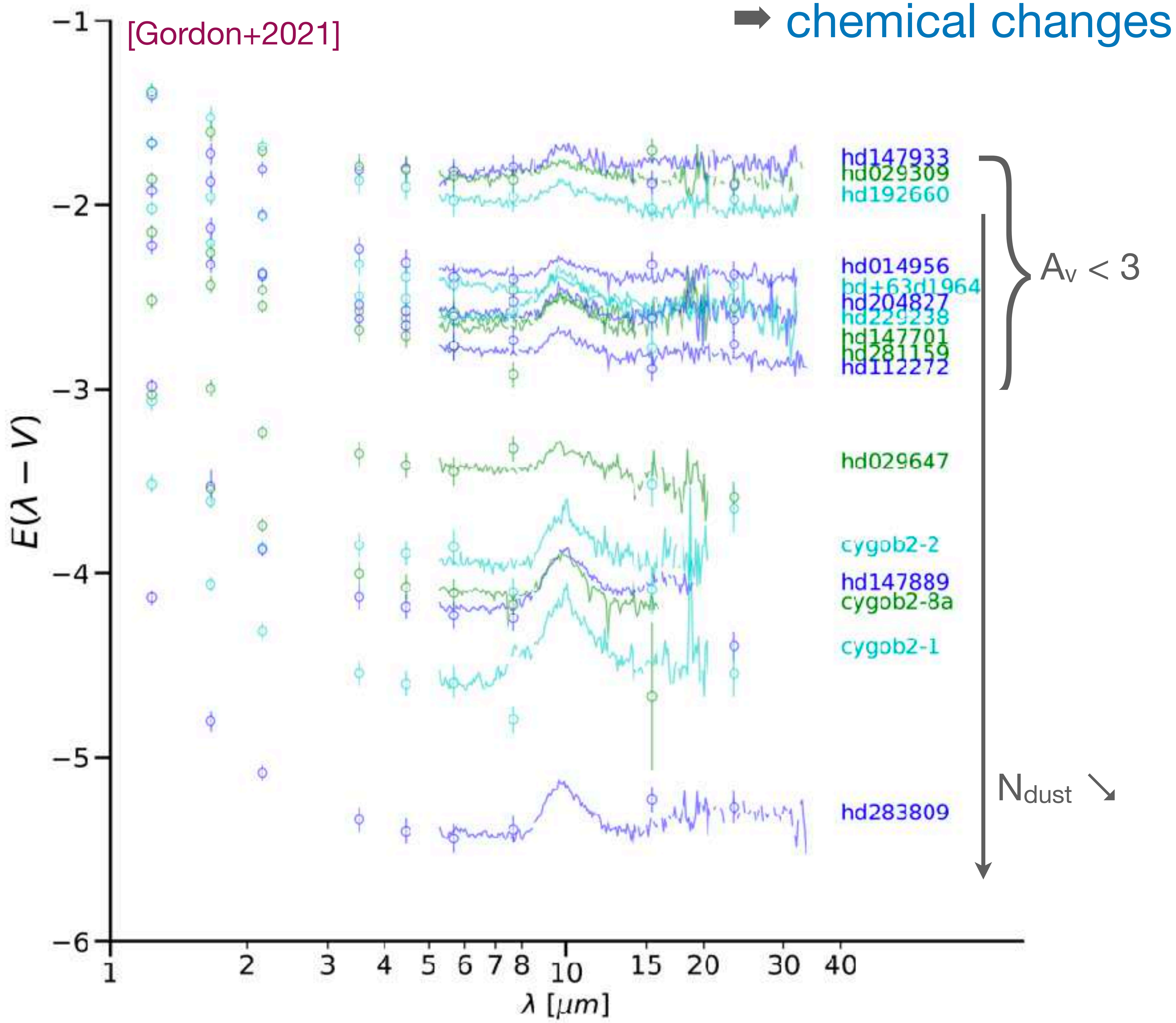


Dust variation in the diffuse ISM

- $\tau_{silicate}$/continuum ↘ when Av ↗
- small variations in the NIR

➡ grain growth [Decleir+2022] ?

➡ chemical changes of grains ?



[Gordon+2021]

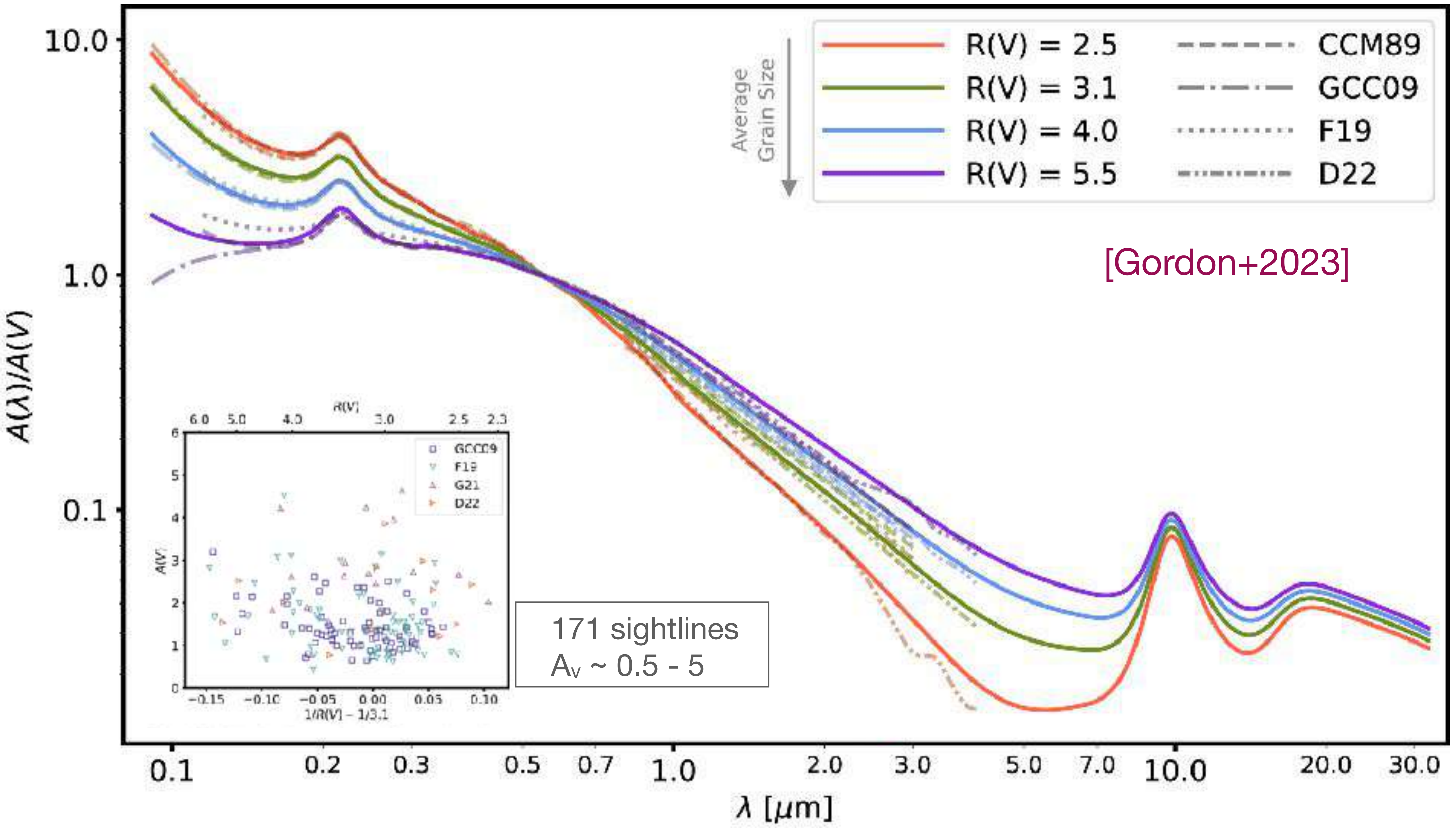
$A_V < 3$

N_{dust} ↘

Parametrisation of the extinction curve with Rv from 912 Å to 32 µm :

$$\frac{A(\lambda)}{A(V)} = a(\lambda) + b(\lambda)\left(\frac{1}{R(V)} - \frac{1}{\boxed{3.1}}\right)$$

average MW value

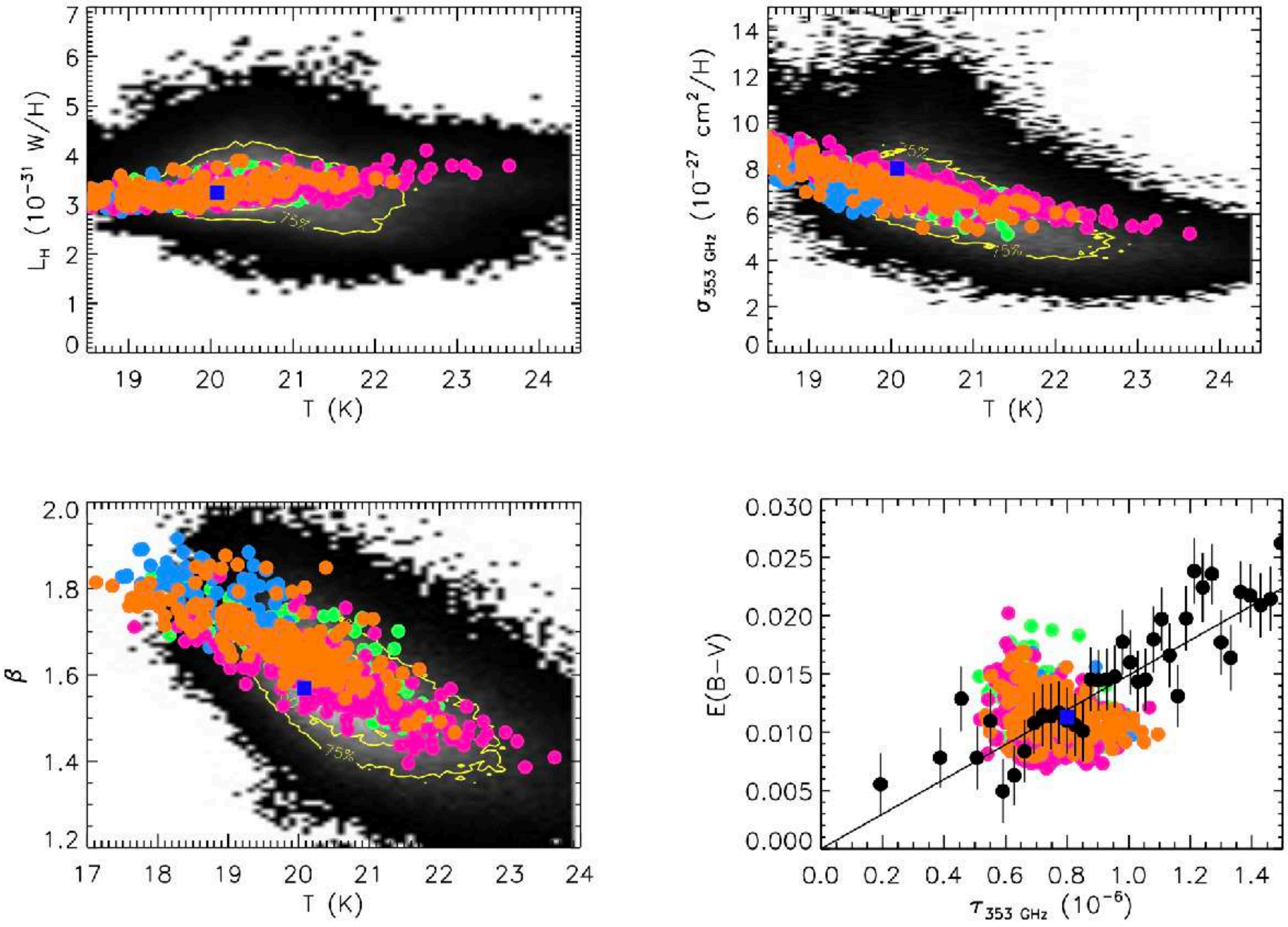


[Gordon+2023]

171 sightlines
A_V ~ 0.5 - 5

Dust variations in the diffuse ISM

[Ysard+*2024*]



- ➡ IRAS 100µm & Planck 350-550-850 µm of DISM [PlanckColl. XI 2014]
  - ➡ $N_H < 3 \times 10^{20}$ H/cm^2
- ➡ MBB fit with the THEMIS 2 dust model
- ➡ Good fit of the emission, extinction of DISM, total and polarised
- ➡ Good fit of the observed variations of dust properties

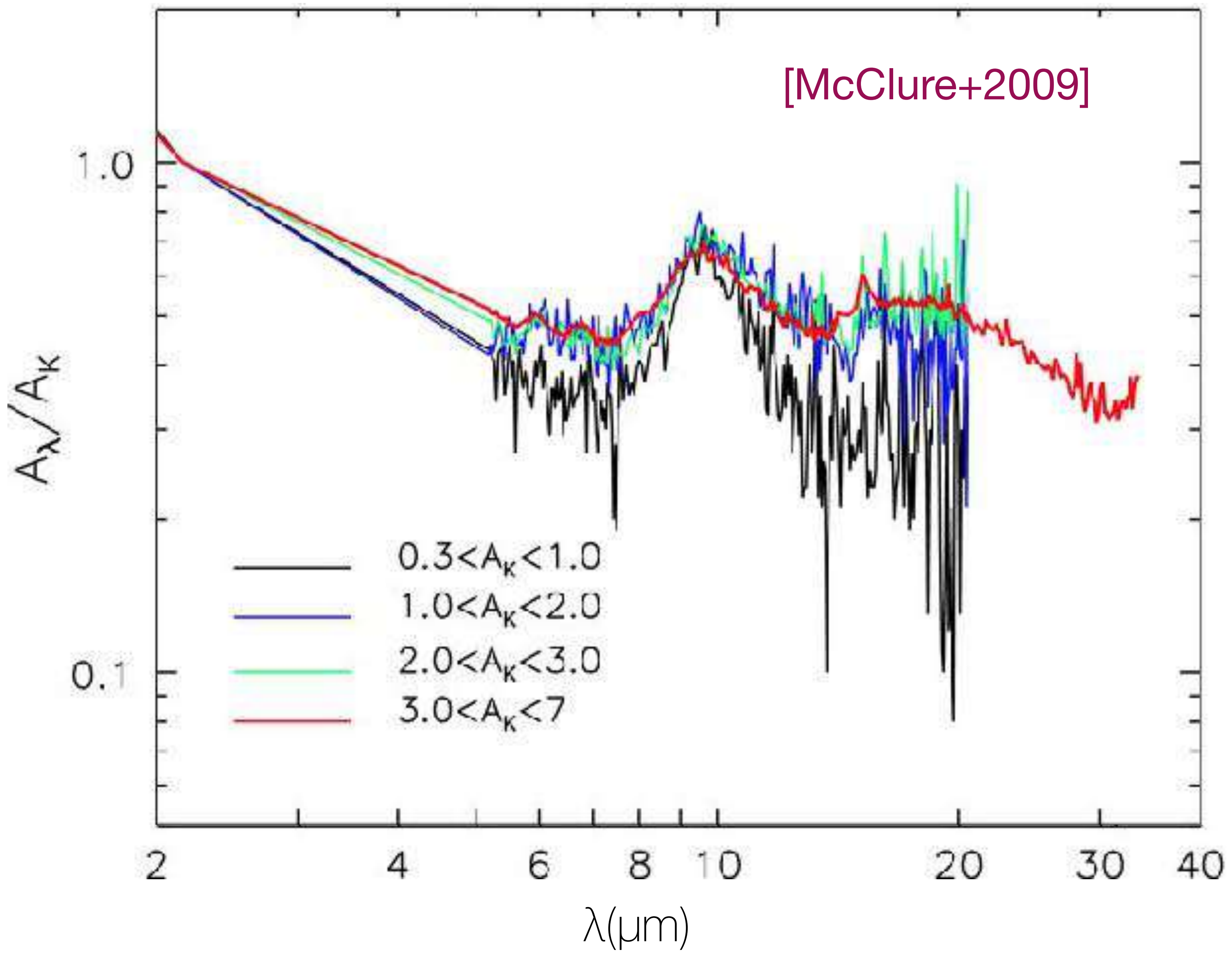
Different NH/E(B-V) & pV/E(B-V) values :

- 8.8×10^{21} atoms/cm2/mag [Lenz+2017], 9%, 13%
- 58×10^{21} atoms/cm2/mag [Bohlin+1978] 9%, 13%

From diffuse to dense ISM

➡ The extinction curve varies from diffuse to dense lines of sights

- Extinction curve flattens
- Silicate bands broaden
- Peak position unchanged
- Variations correlated with ice features

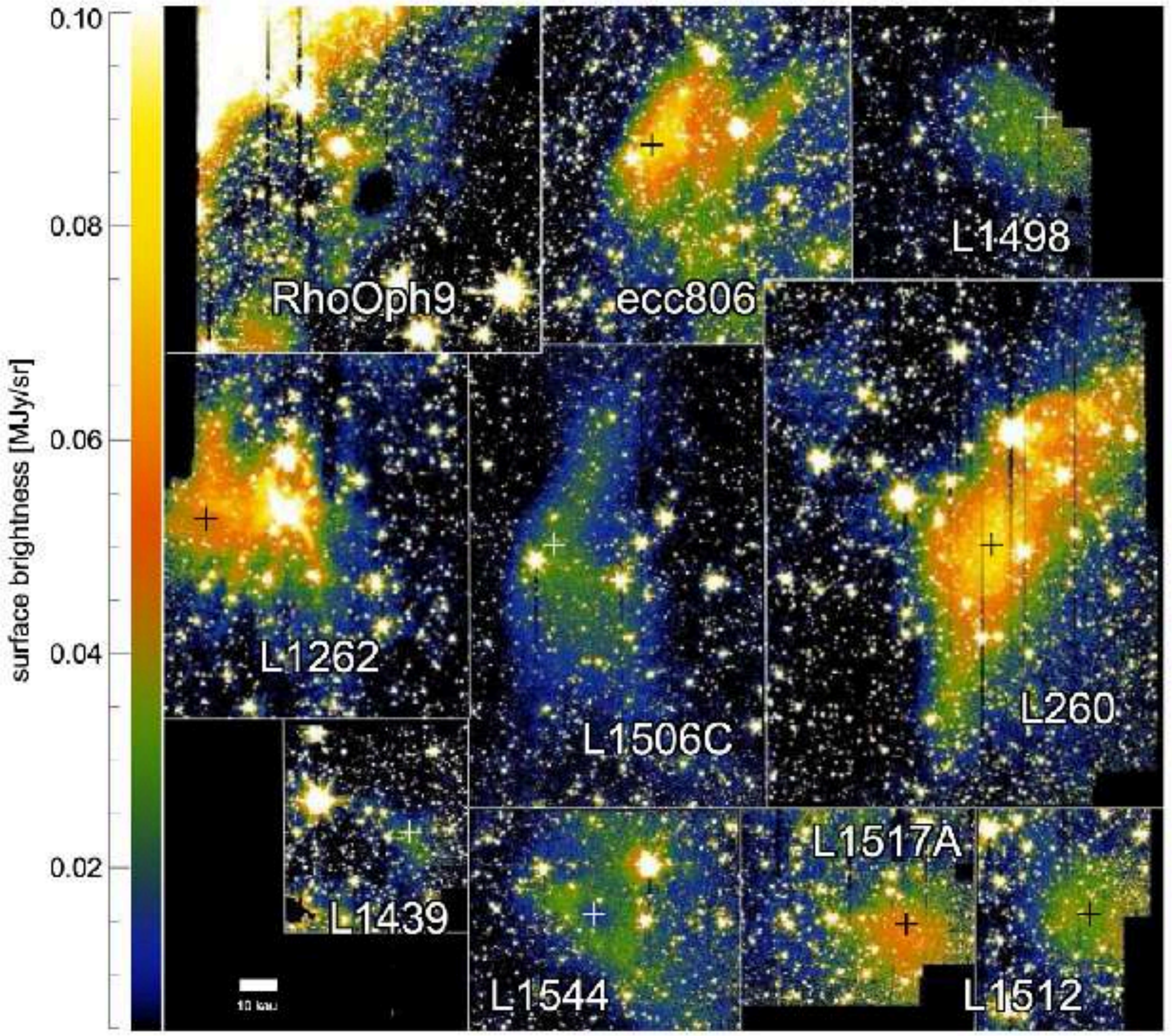


[McClure+2009]

➡ Cloudshine & Coreshine

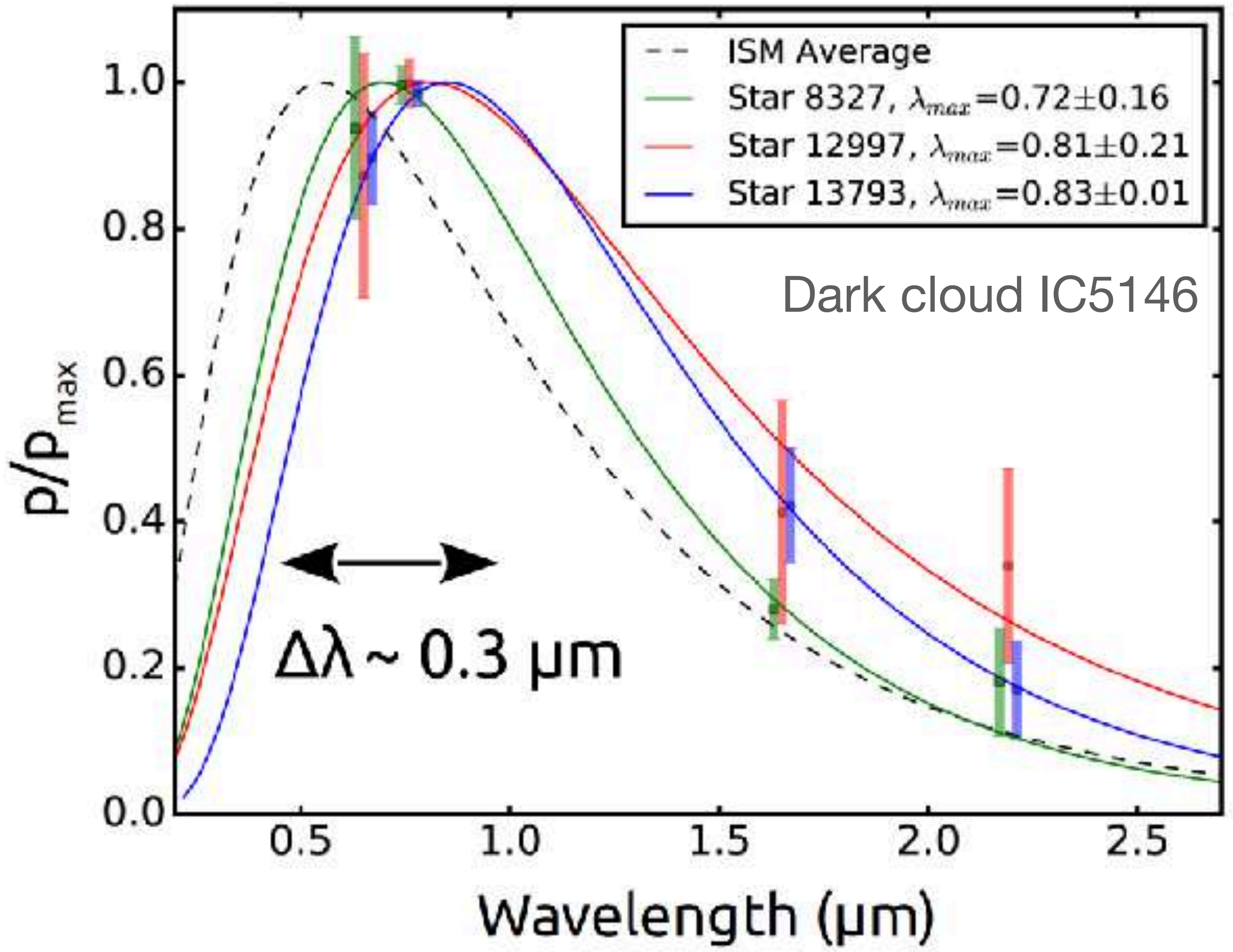
- NIR and MIR
- Scattering by grains bigger than DISM grains

[Steinacker+2014]



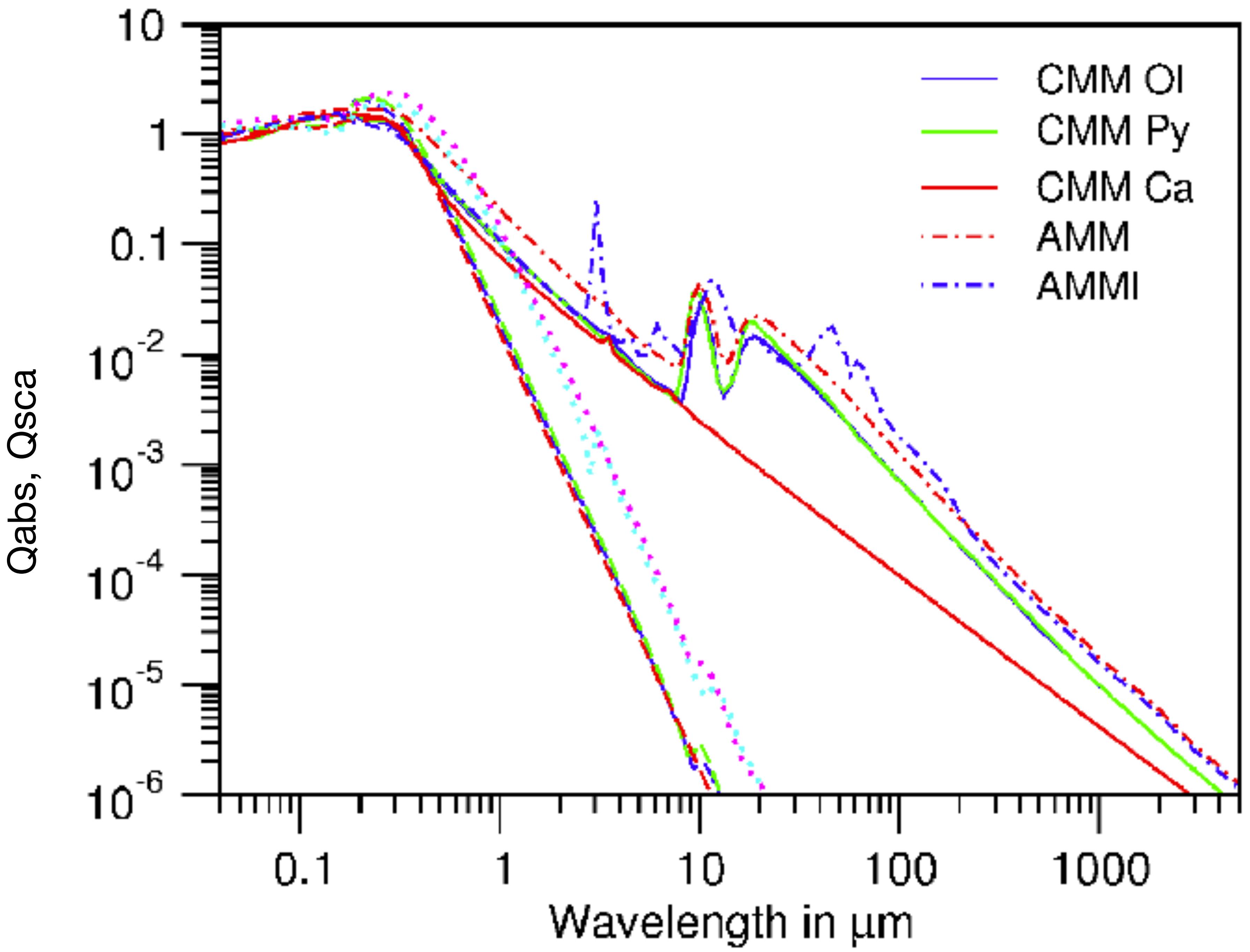
➡ Position of the polarization max increases

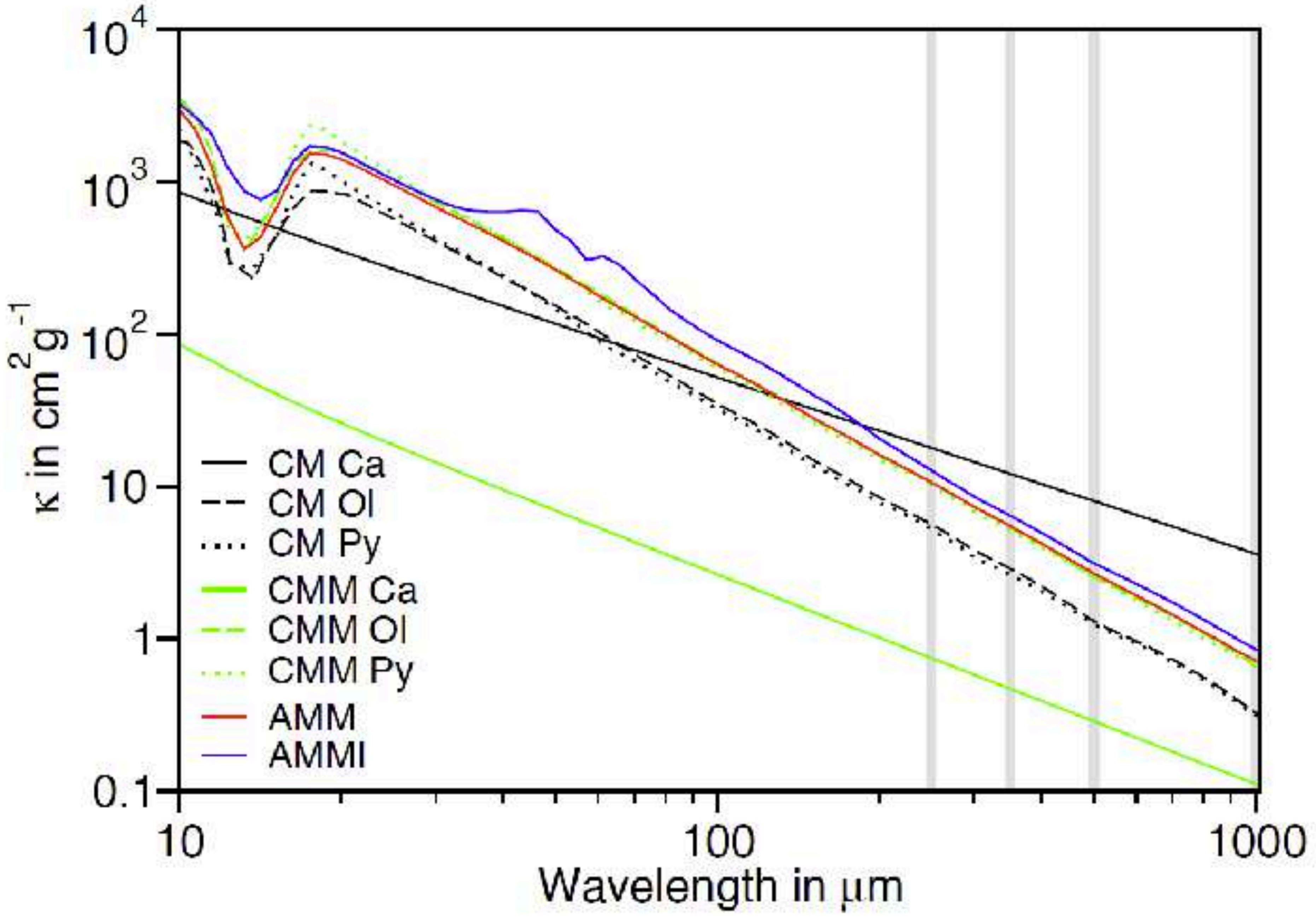
[Wang+2017]



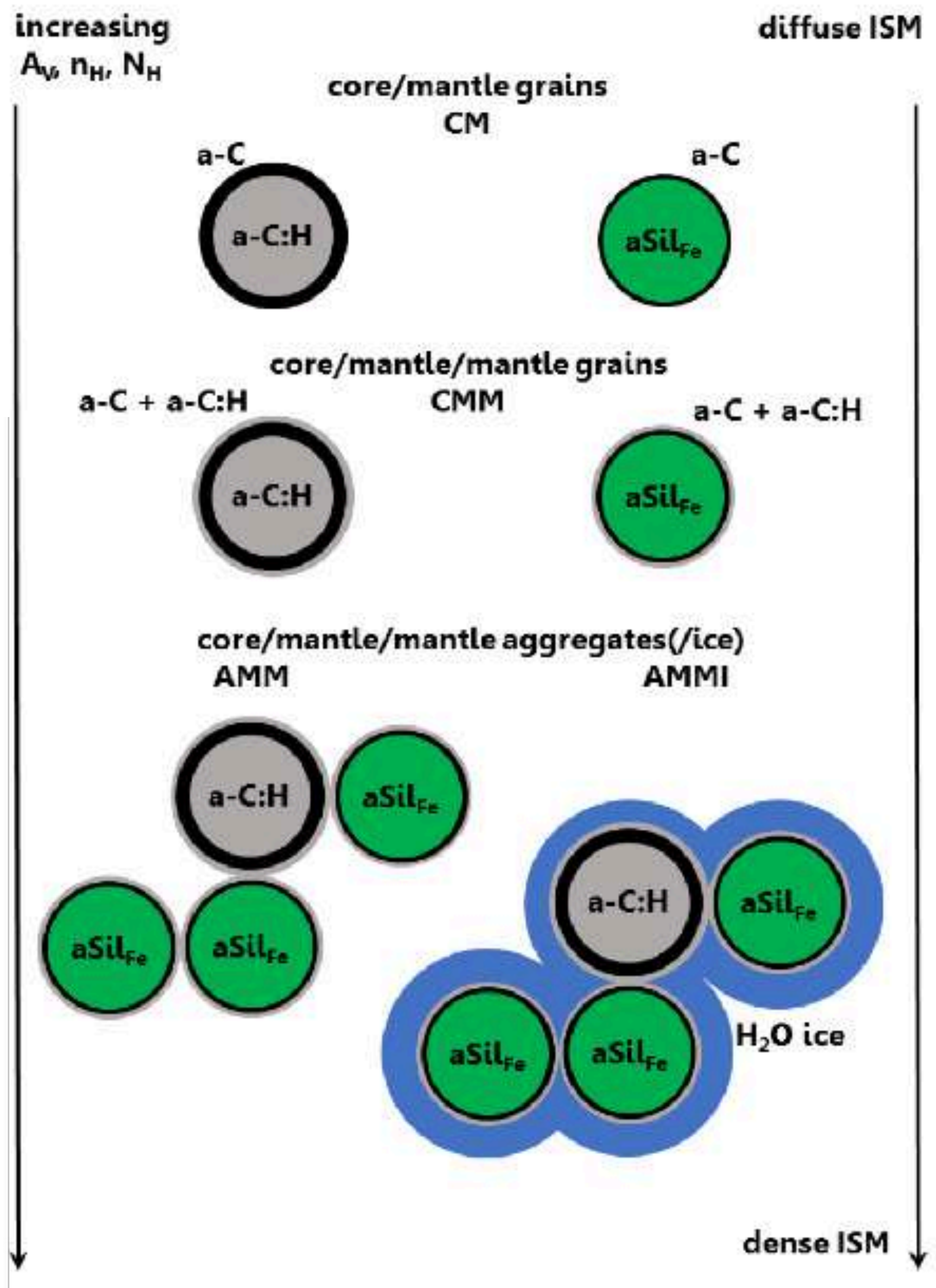
From diffuse to dense ISM: dust growth and coagulation

- In dense environments: cold clouds, pre-stellar cores, protoplanetary disks
- Small grains stick onto big grains
- Big grains coagulate to form aggregates
- Ices freeze on big grains and/or the aggregates for Av ≲ 3





THEMIS adaptation for the dense ISM:



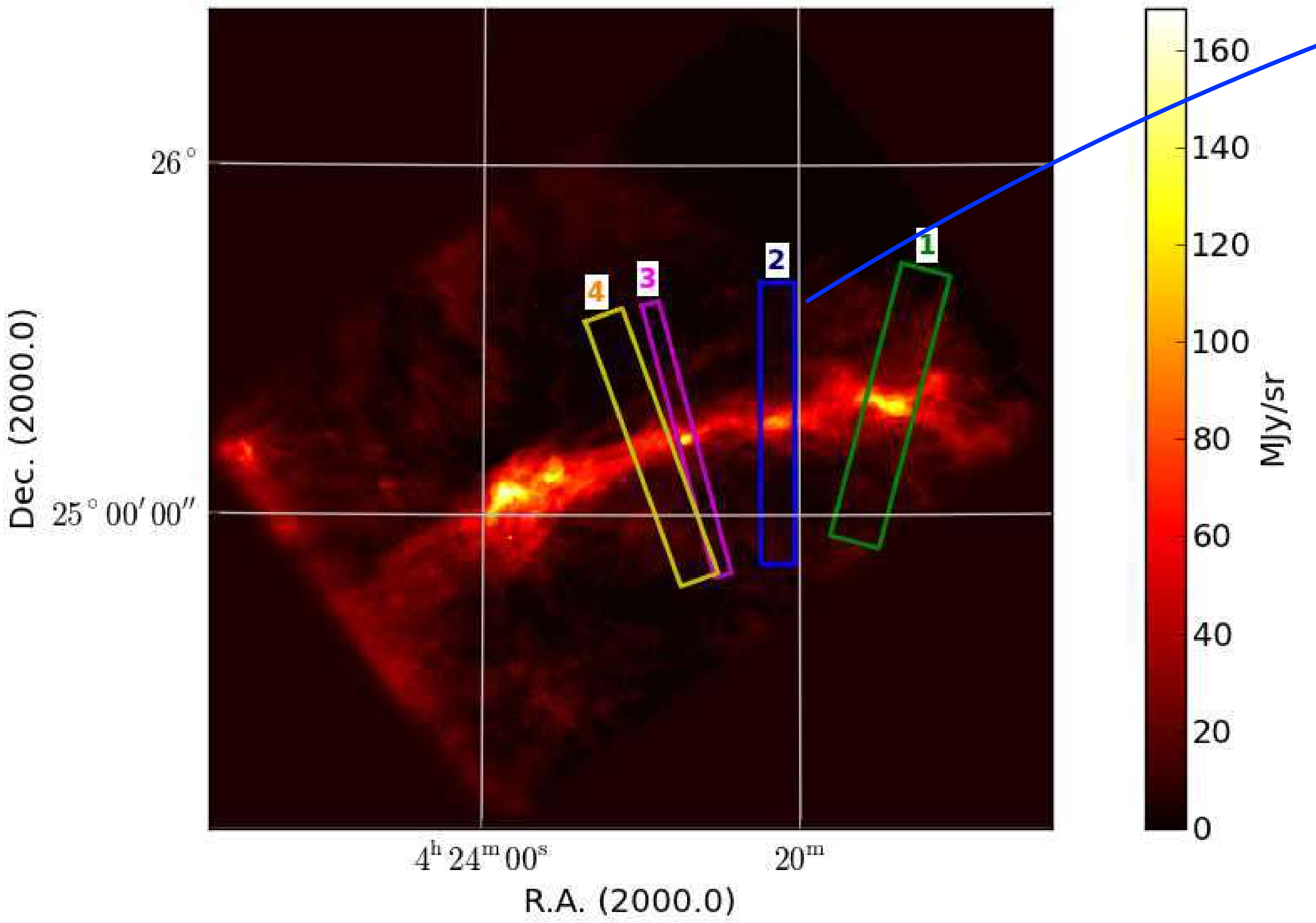
https://www.ias.u-psud.fr/themis/

[Jones +2013, Köhler +2014, 2015]

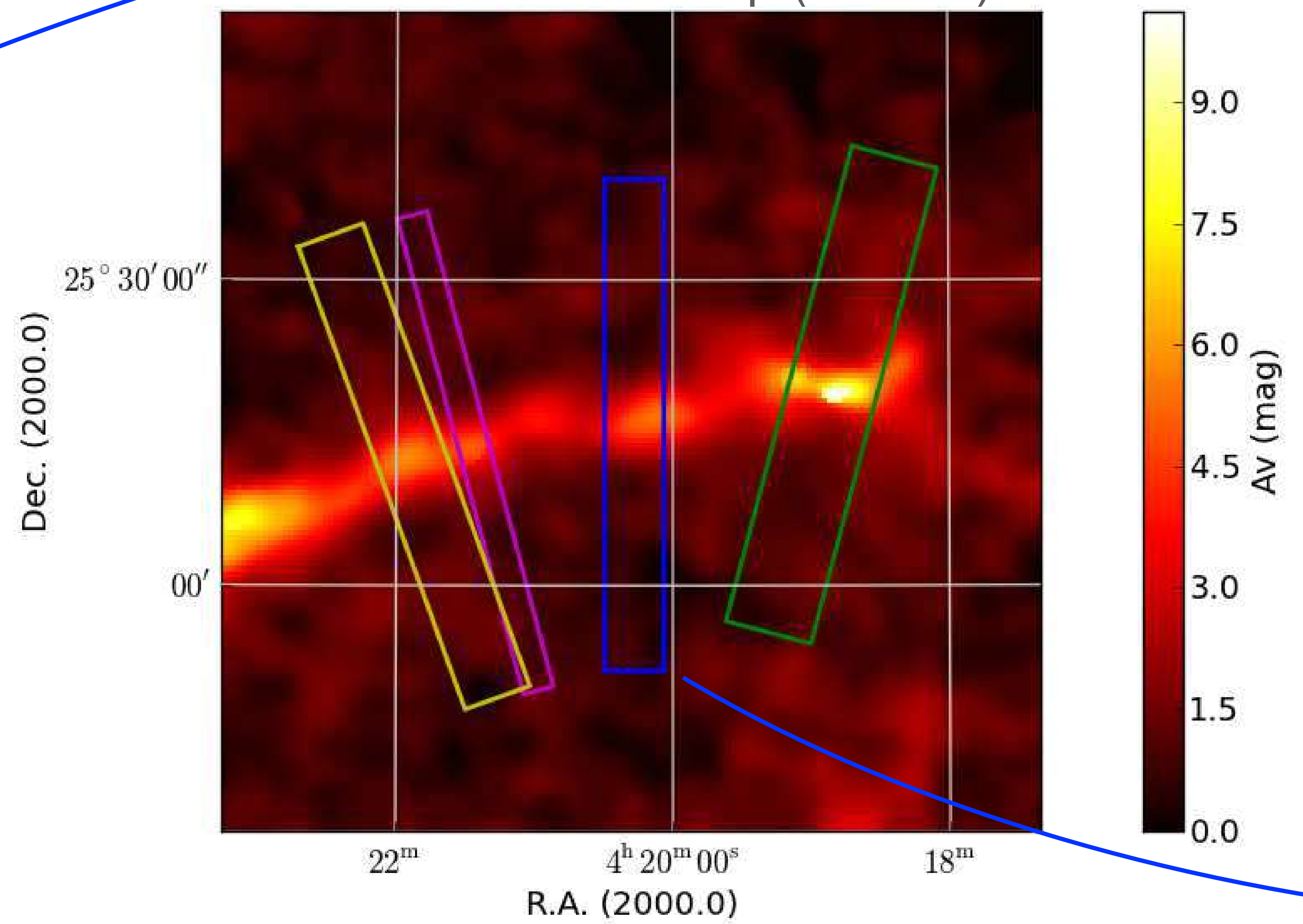
Dense ISM : variation of dust emissivity

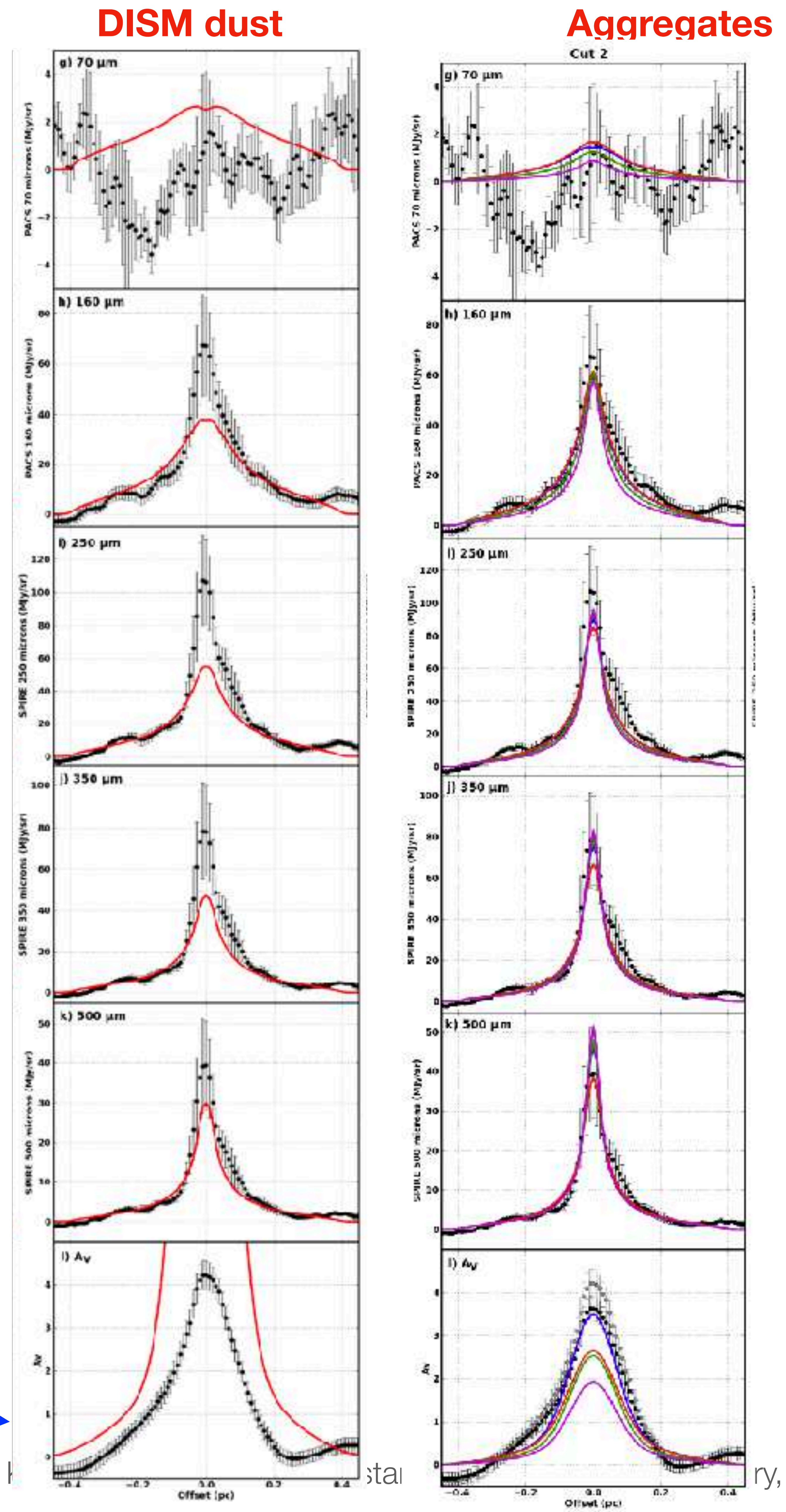
- Herschel map of the filament L1506 in the Taurus
- Modelling of the emission along several cuts across the filament
- Aggregates are needed to reproduced simultaneously the excitation and the emission data
  - dust opacity at 250 µm is raised by 1.8-2.2
  - grain size increases by a factor 5

Brightness map at 250 µm (Herschel)



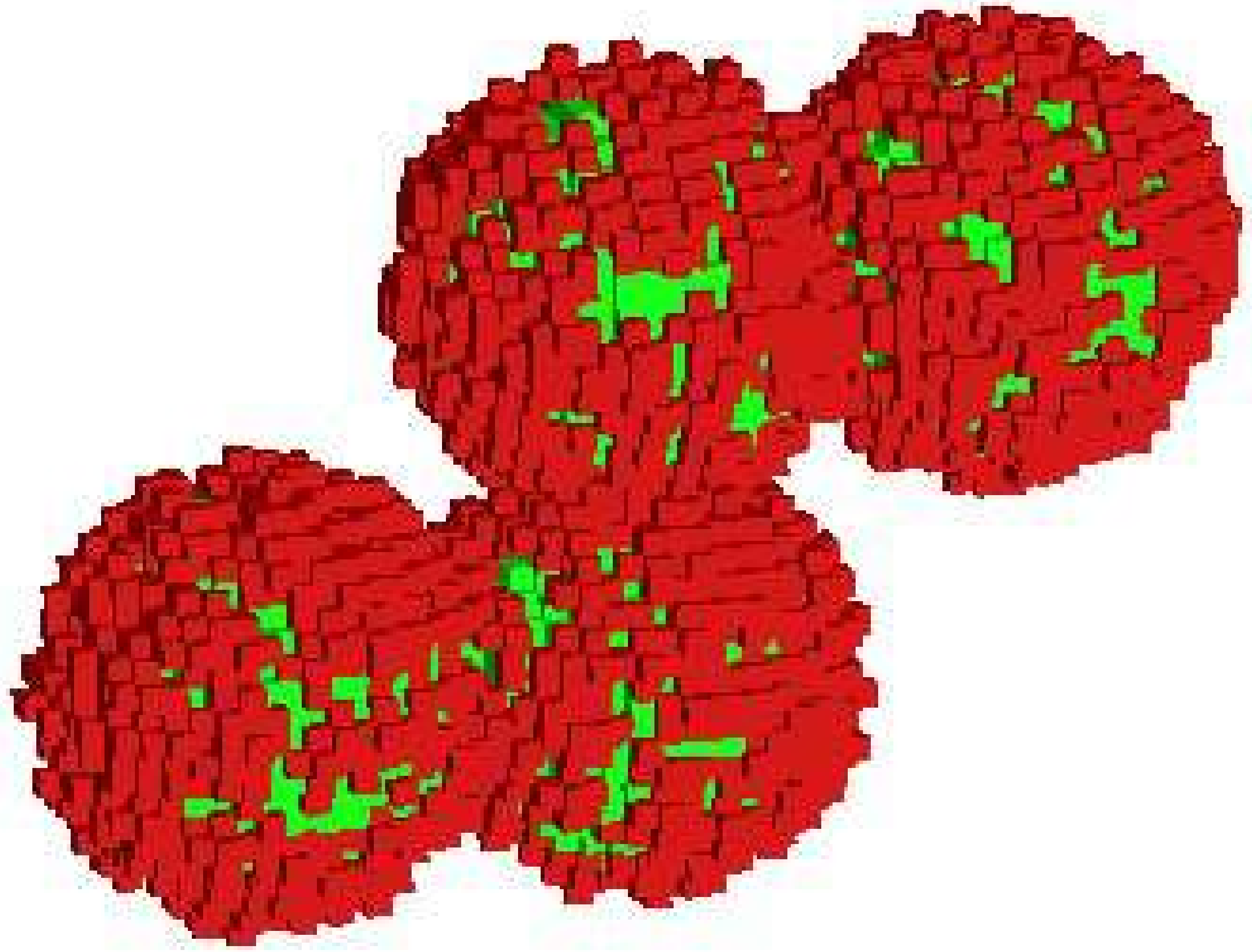
Extinction map (2MASS)





Dust coagulation in dense clouds

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

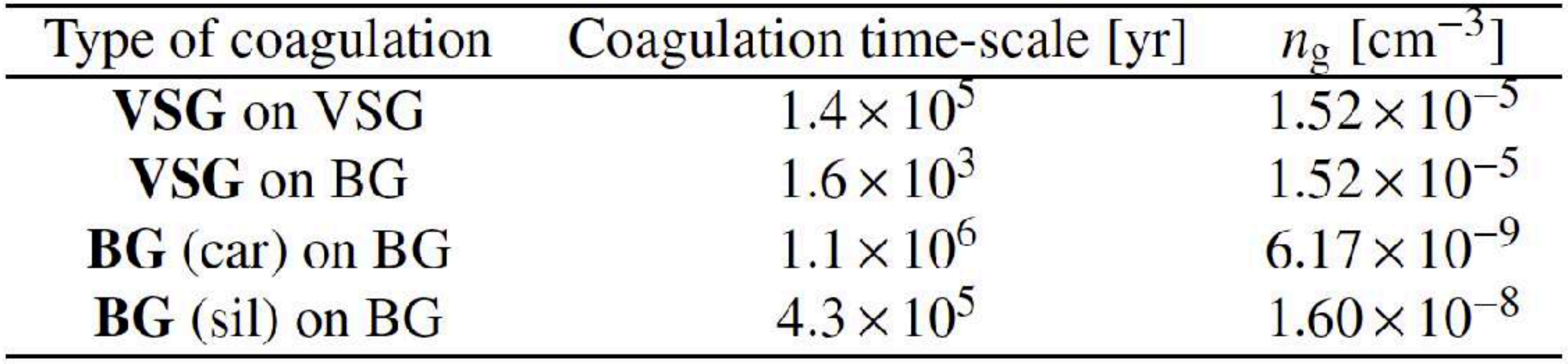


- Coagulation time for a mixture of grains : [Draine+85, Stepnik+03]

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

n_1 : number density of grain 1
$\upsilon_{1/2}$: 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 $n_H = 4\text{x}10^3$ 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]

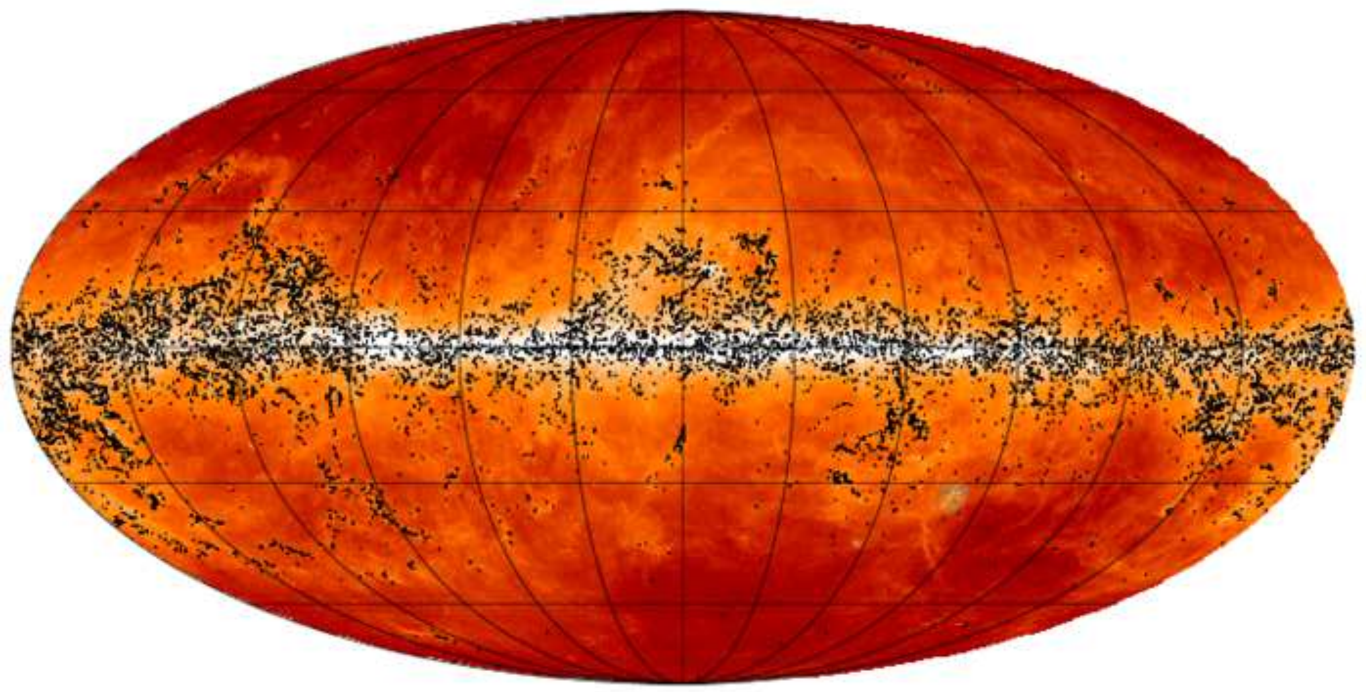
- The time for coagulation is rapid

⇒ grain have time to coagulate

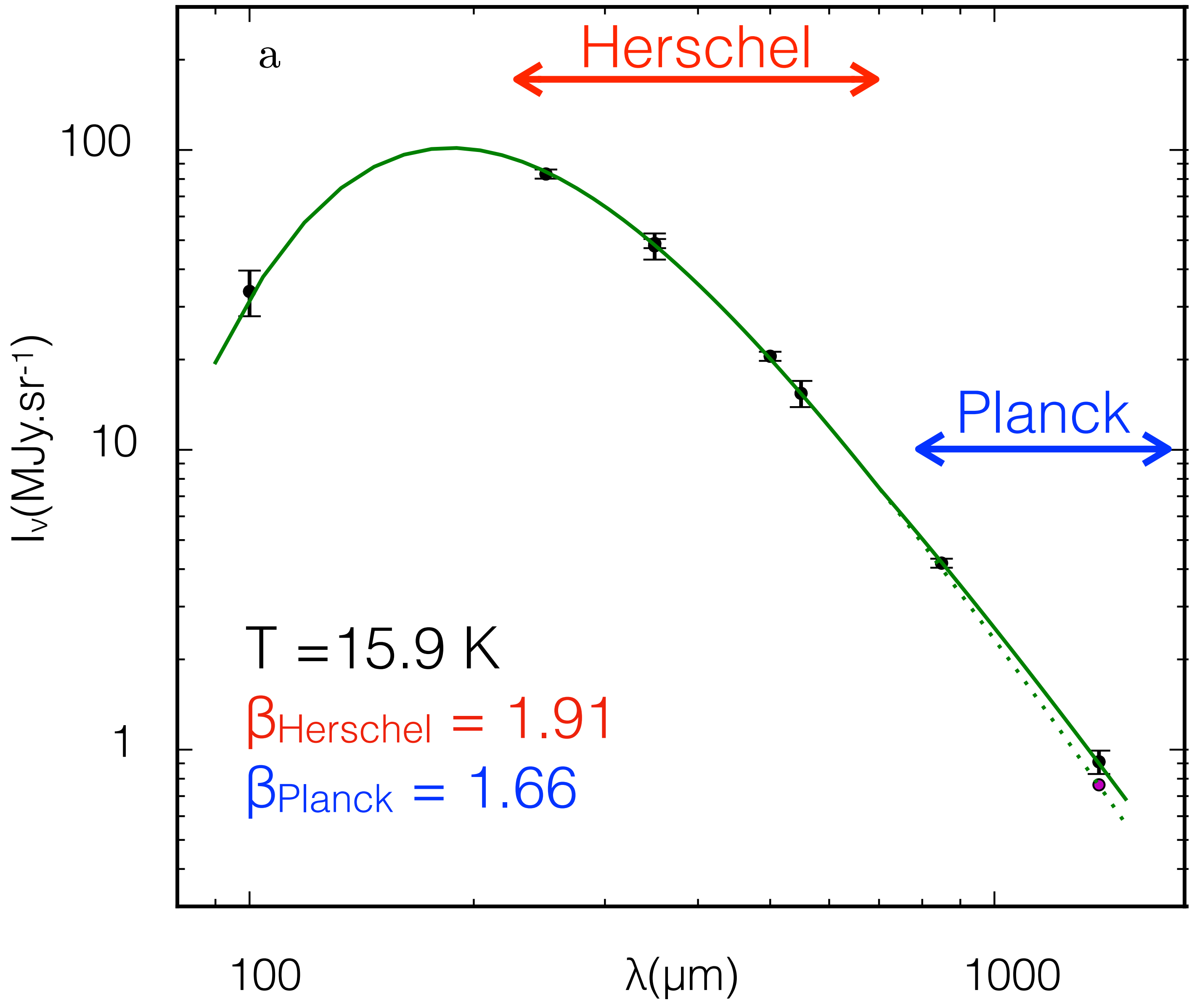
before cloud collapse and star formation (in ~ 10^6-10^7 years)

Dense ISM : variation of dust spectral index

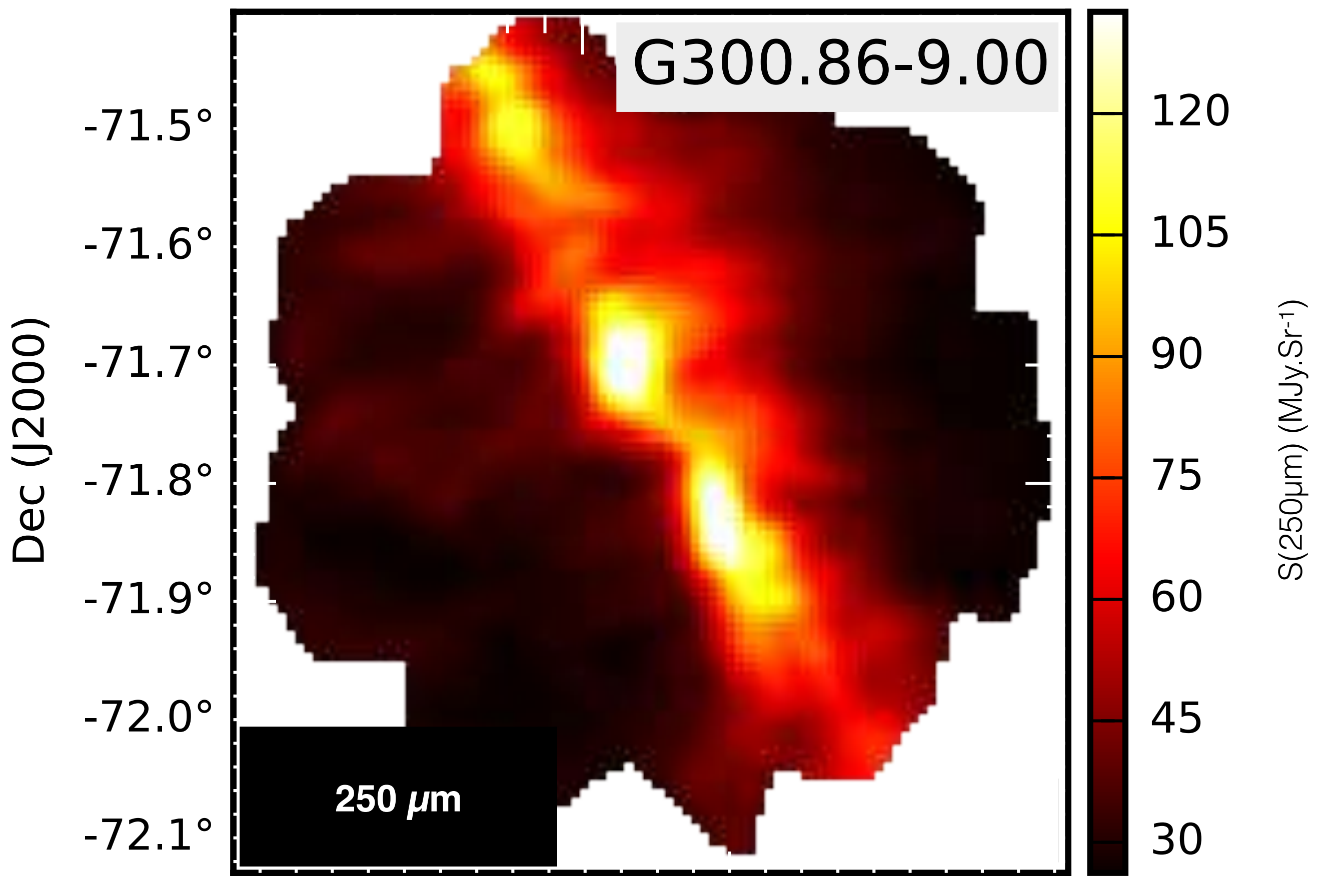
Planck: 13188 Galactic Cold Cores



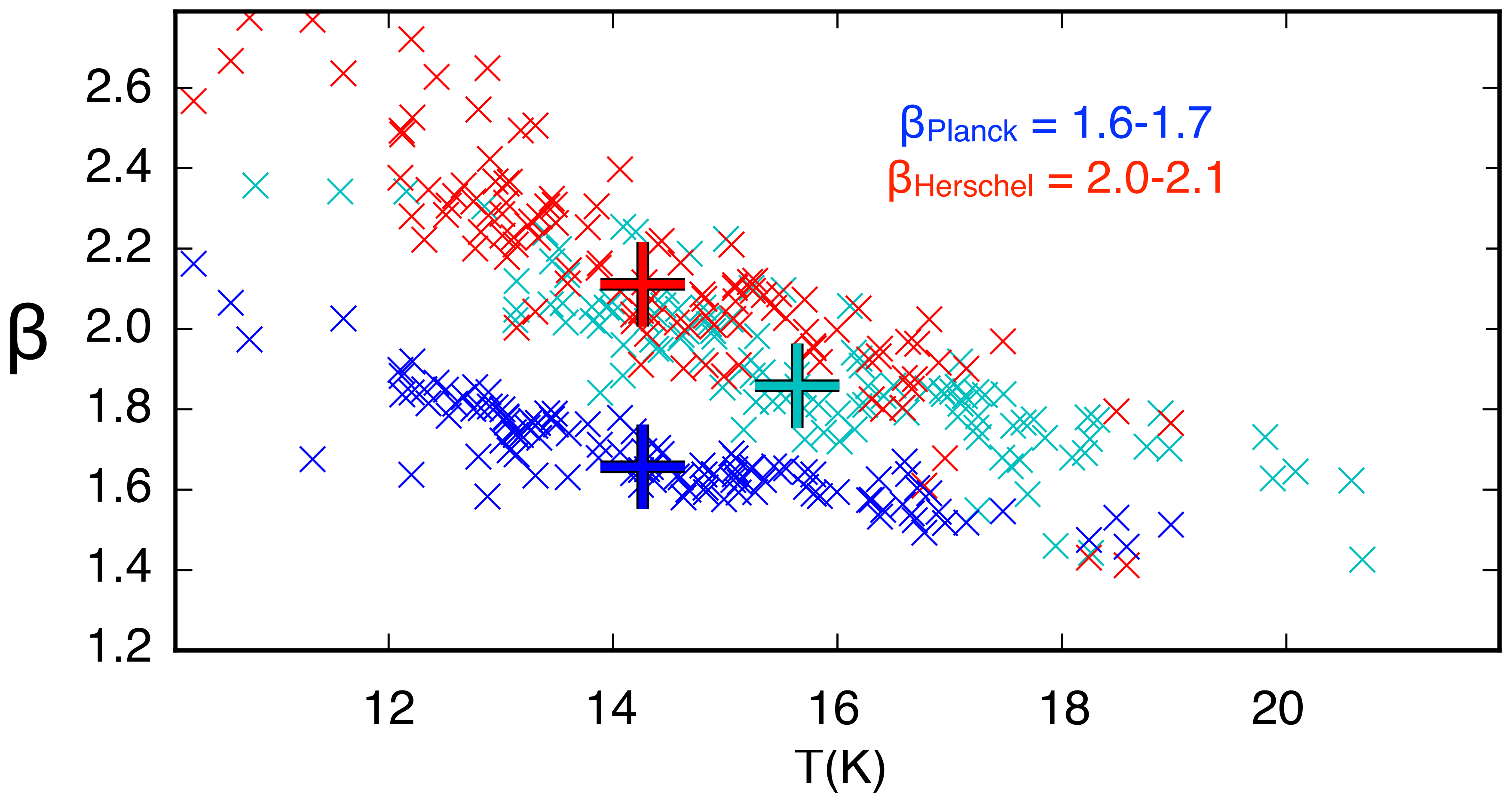
[Planck 2015 XXVII]



Herschel-PACS/SPIRE:
136 cores mapped [Juvela+12]



[Juvela+15]



- In optically thin medium :

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

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

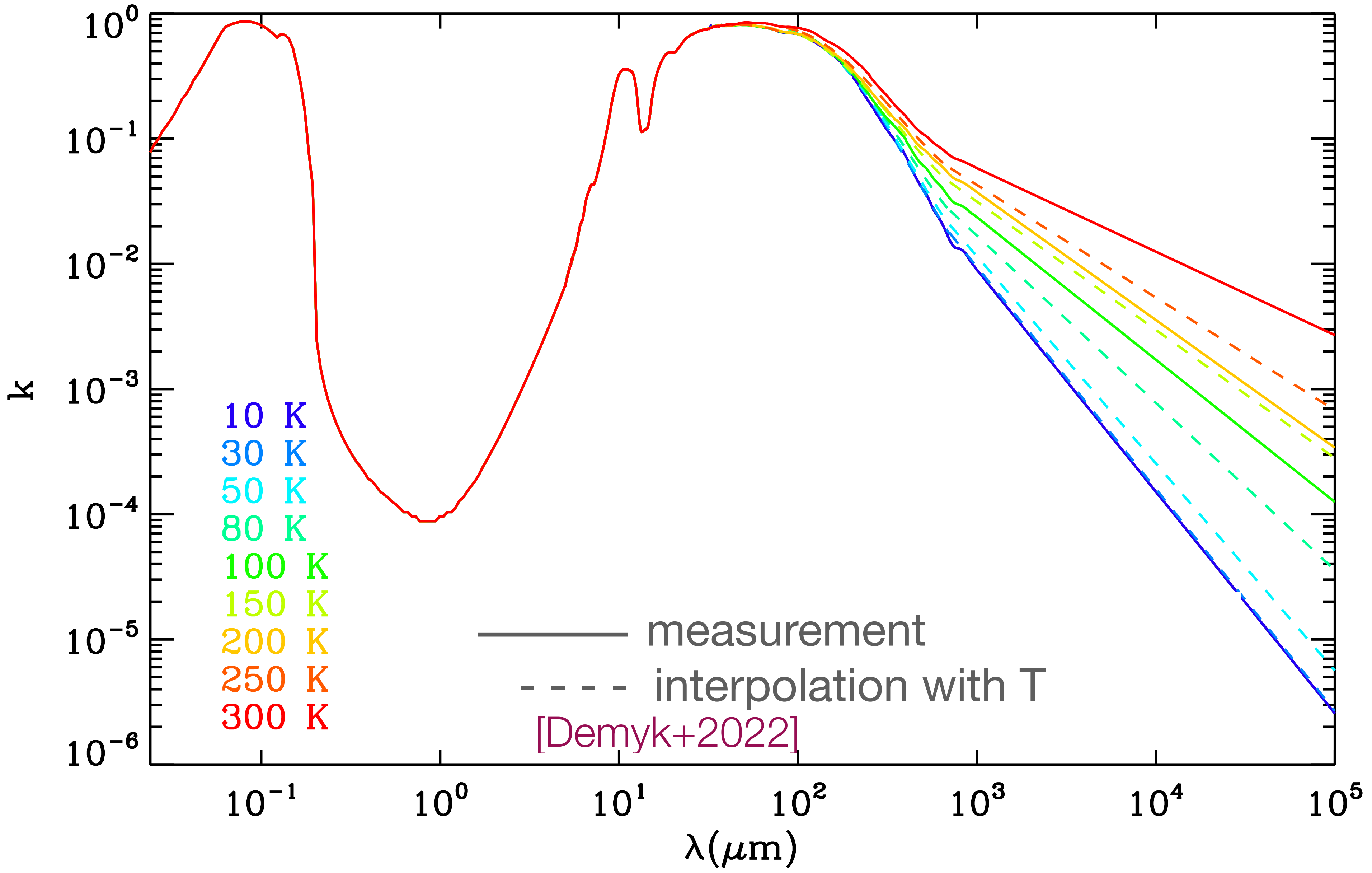
➡ $\beta \neq 2$ and may be > 2

➡ β varies with λ

- This is not a bias
- Not an effect of noise
- Not an effect of temperature mixing along the line of sight

Temperature dependent dust opacity

Extinction coefficient of amorphous silicate



Demyk+2017a,b
Coupeaud+2011
Boudet+2005
Mennella+1998
Agladze+1996

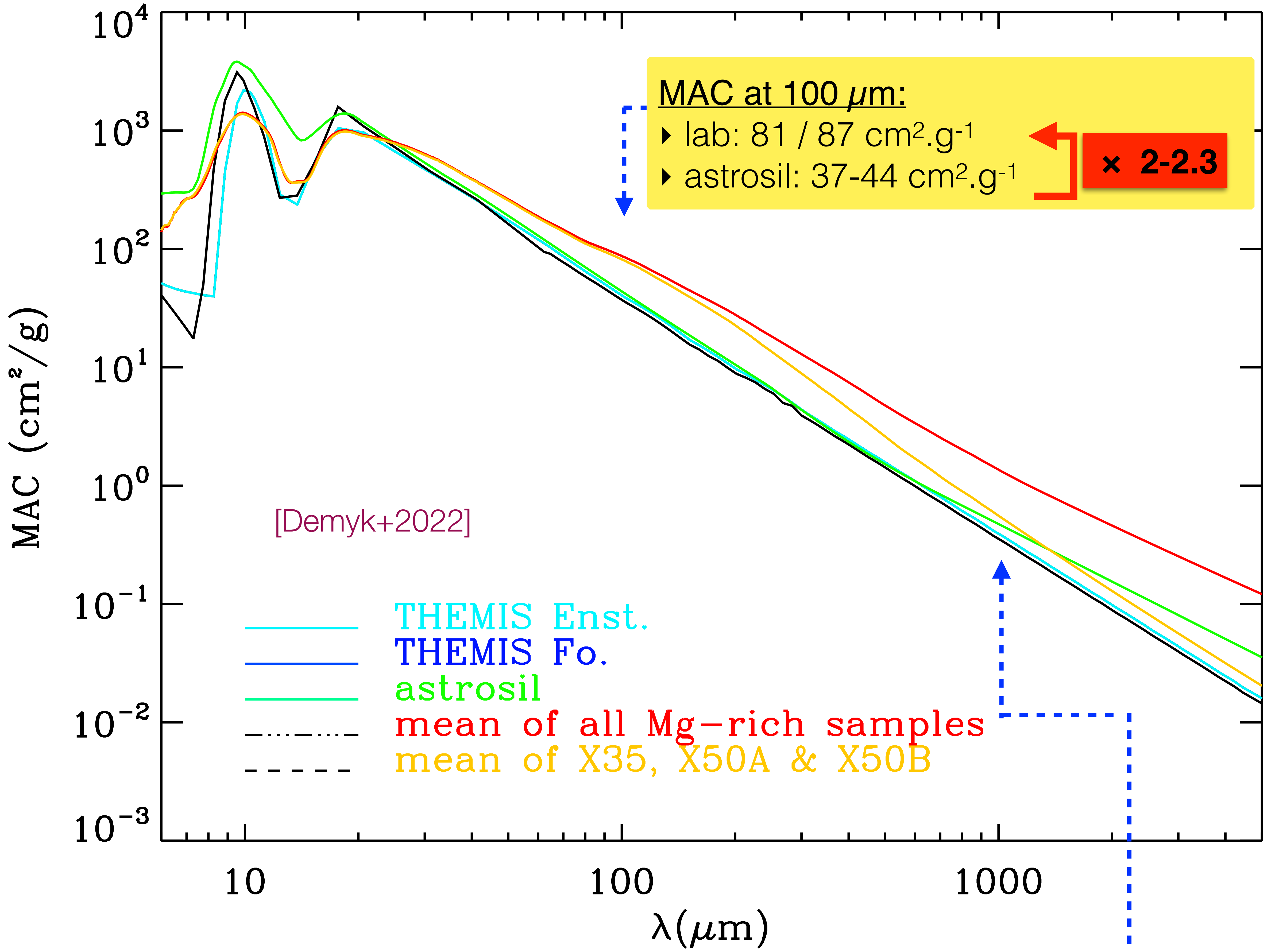
➡ MAC ↗ when T ↗

➡ β varies with λ and T

➡ β(λ) ↗ when T ↘

- DCD and TLS model [Meny+2007]
- Able to reproduce SED of warm and cold regions [Paradis+2012,2014]

MAC of small prolate grains (a/b=1.5)



MAC at 100 μm:
- lab: 81 / 87 cm².g^{-1}
- astrosil: 37-44 cm².g^{-1}

× 2-2.3

MAC (cm².g^{-1}) at 1 mm:
- lab: 0.56 - 1.36 at 10K
- astrosil: 0.35 - 0.47

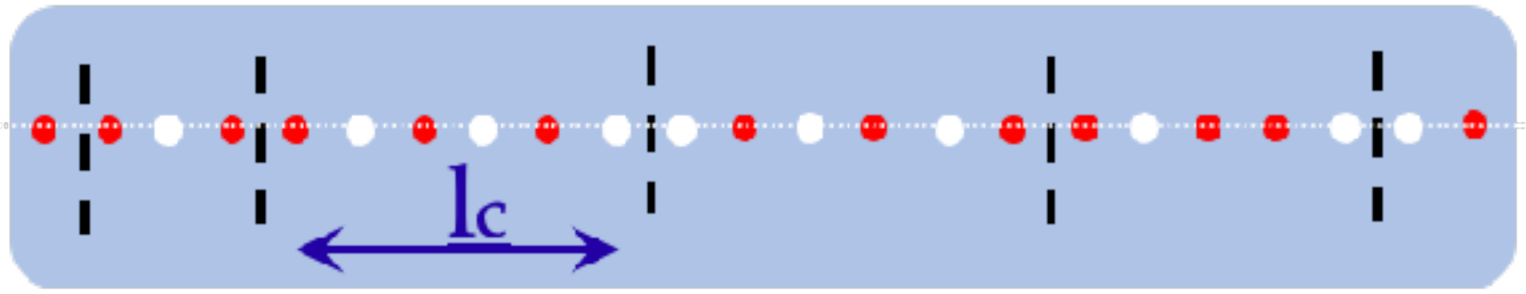
× 1.6 - 3.9 at 10K

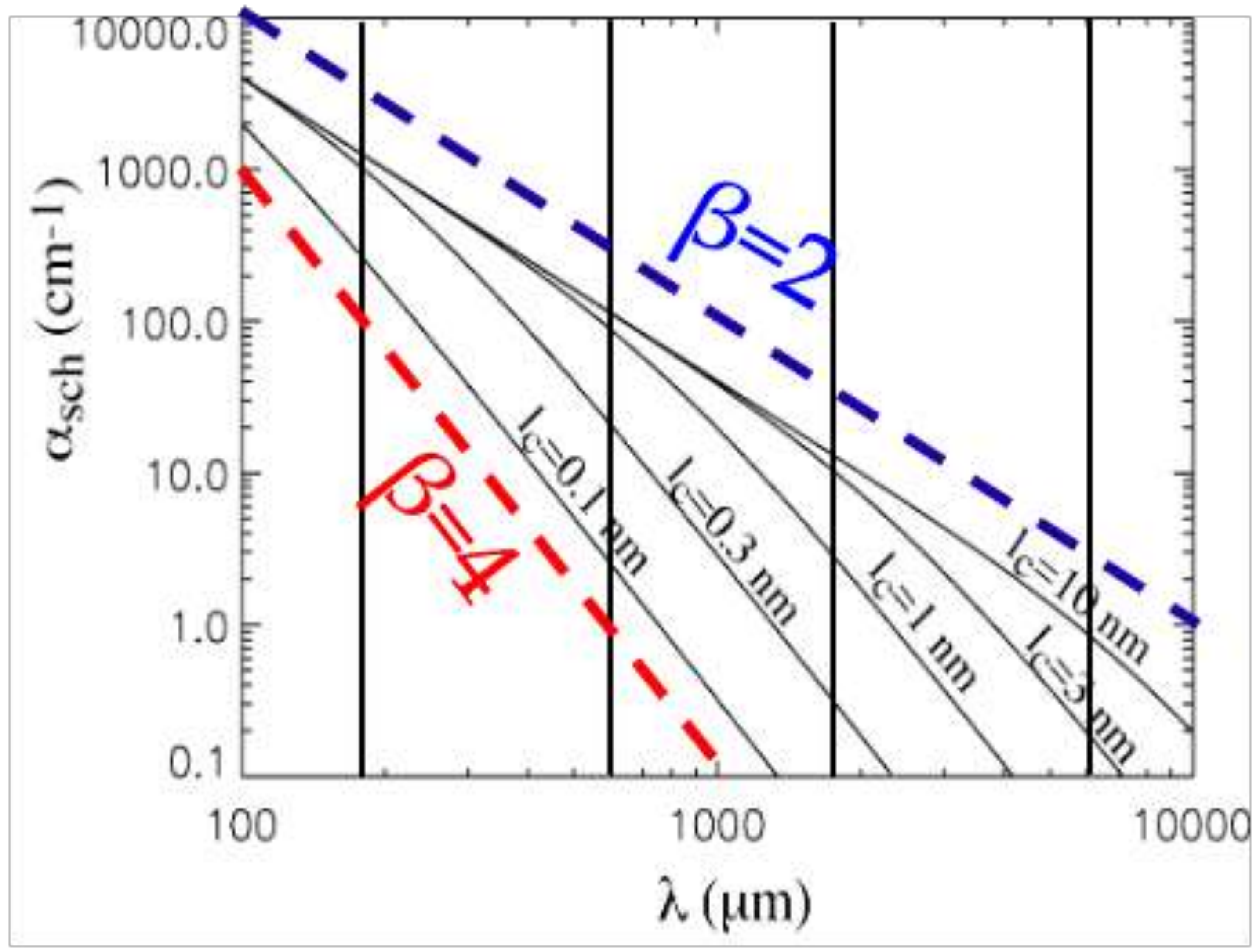
Modelling grains emission: the big grains & the TLS model

- Proposed by solid state physicists to describe the low temperature behaviour of disorder material
- Sum of two different models: DCD and TLS

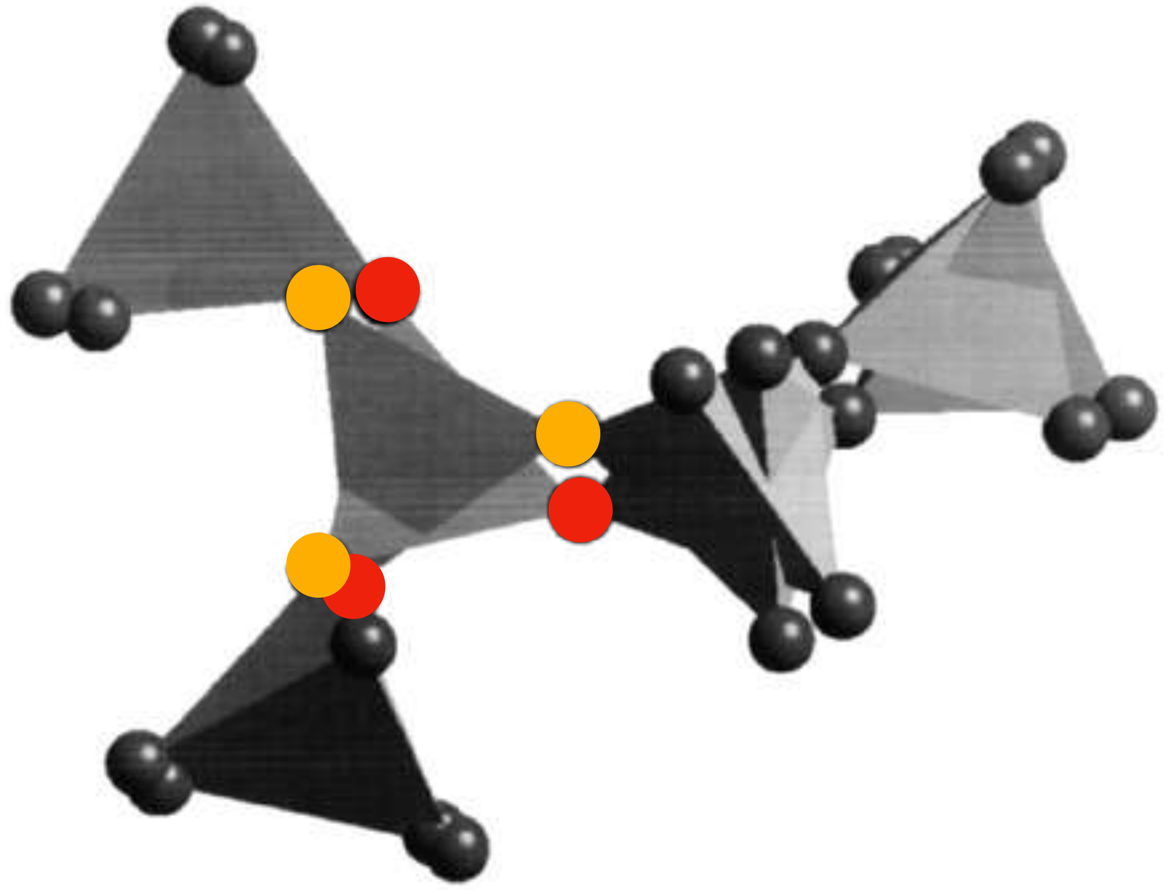
[Meny+2007]

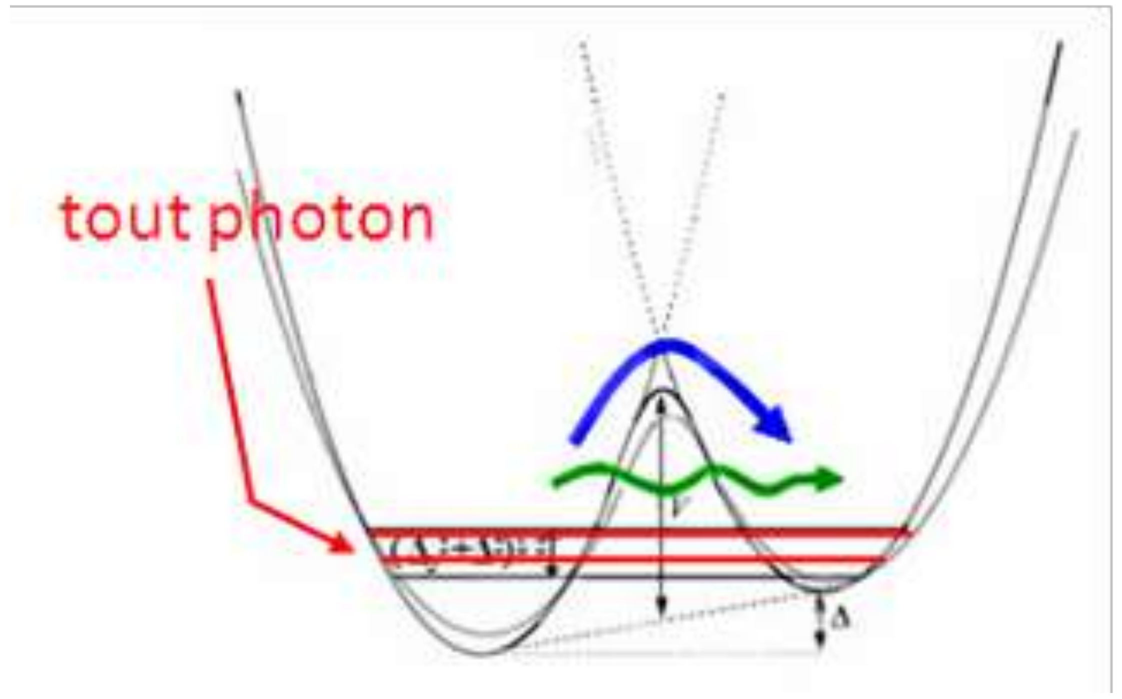
- DCD: Disorder Charge Distribution
  - independent of the temperature
  - depend on the typical distance on which charge is neutralised

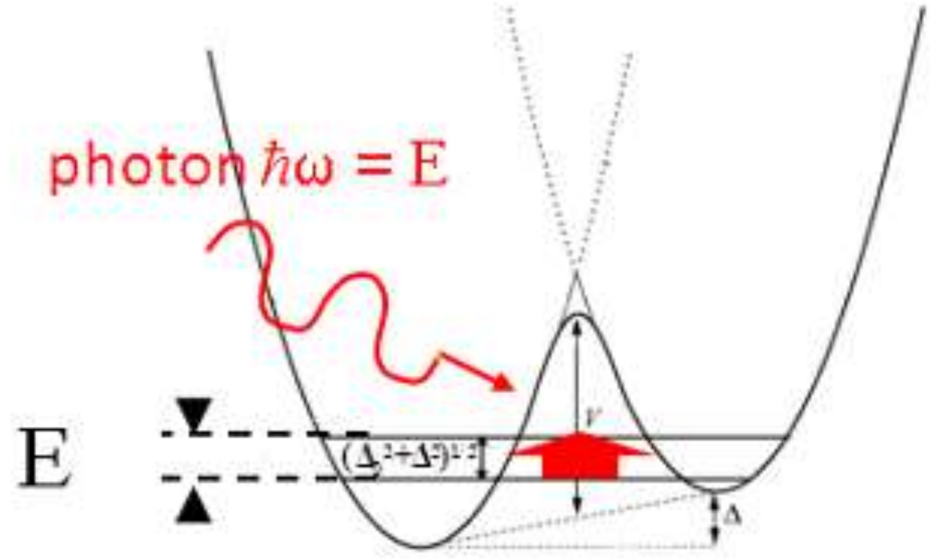




- TLS: Two Levels System
  - temperature dependent
  - 3 mechanisms for transitions between two levels system of the disordered structure



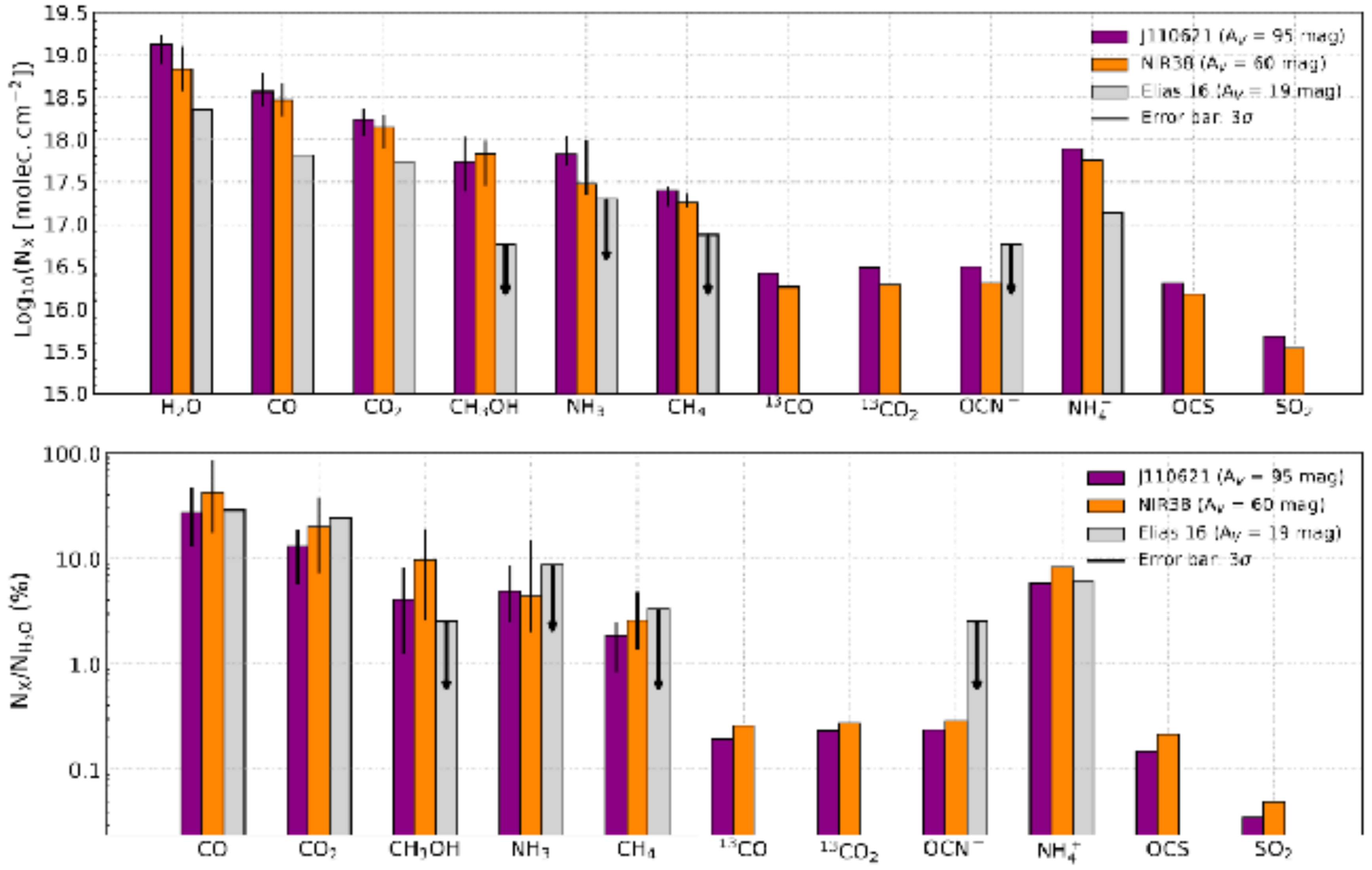




$$\kappa_{grain} = \kappa_{IR} + \kappa_{DCD} + \kappa_{TLS}$$

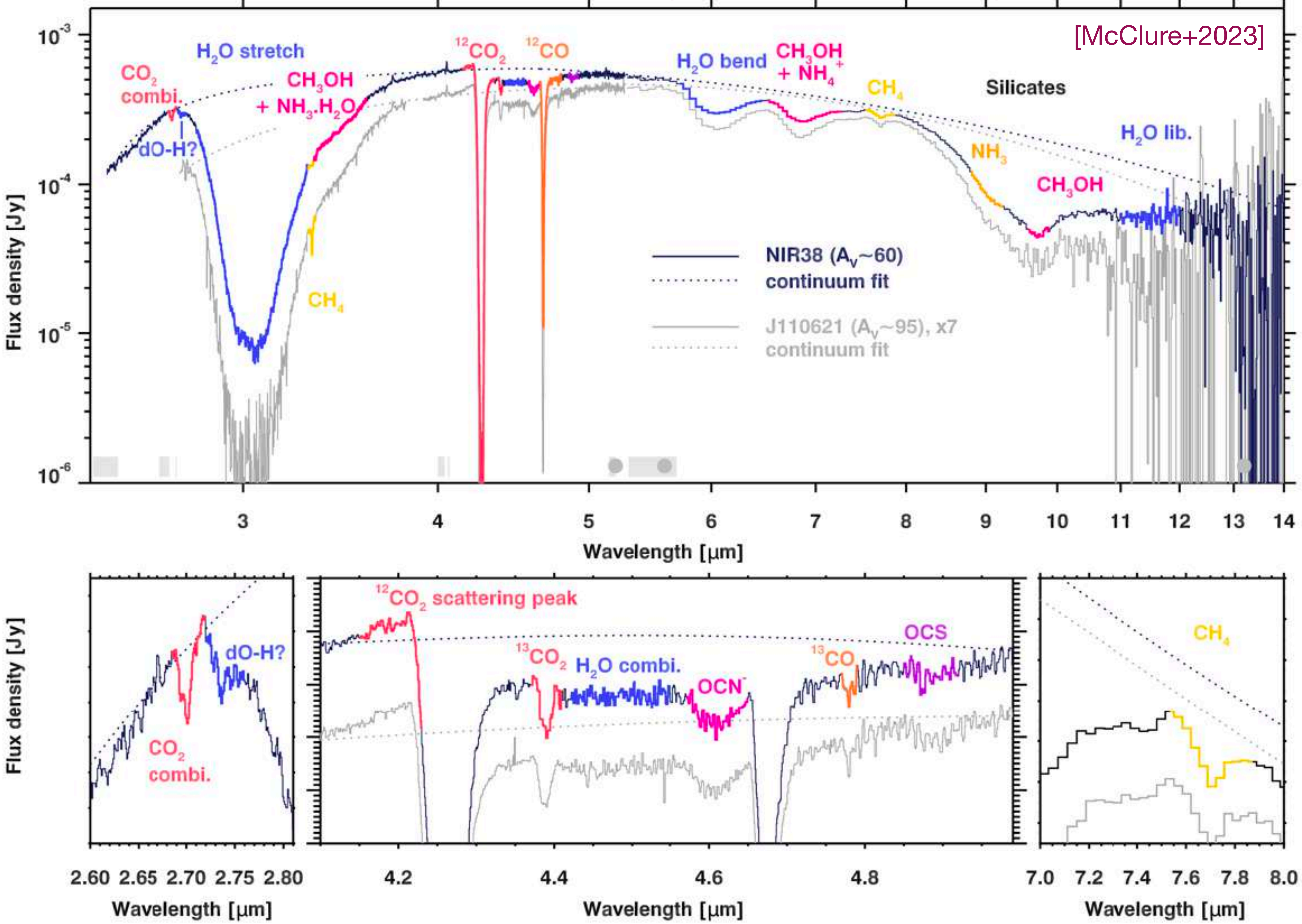
Dust in dense clouds : ices

- Low mass star forming region Chameleon I
- Lines of sight outside the infalling enveloppe of the class 0 YSO Cha MMS1
- High extinction: Av ~ 60 & 95
- Pristine ices
- Very rich ice composition :
  - N-rich species
  - S-rich species



More JWST results on YSOs : Rocha+2023, Nazari+2024,…

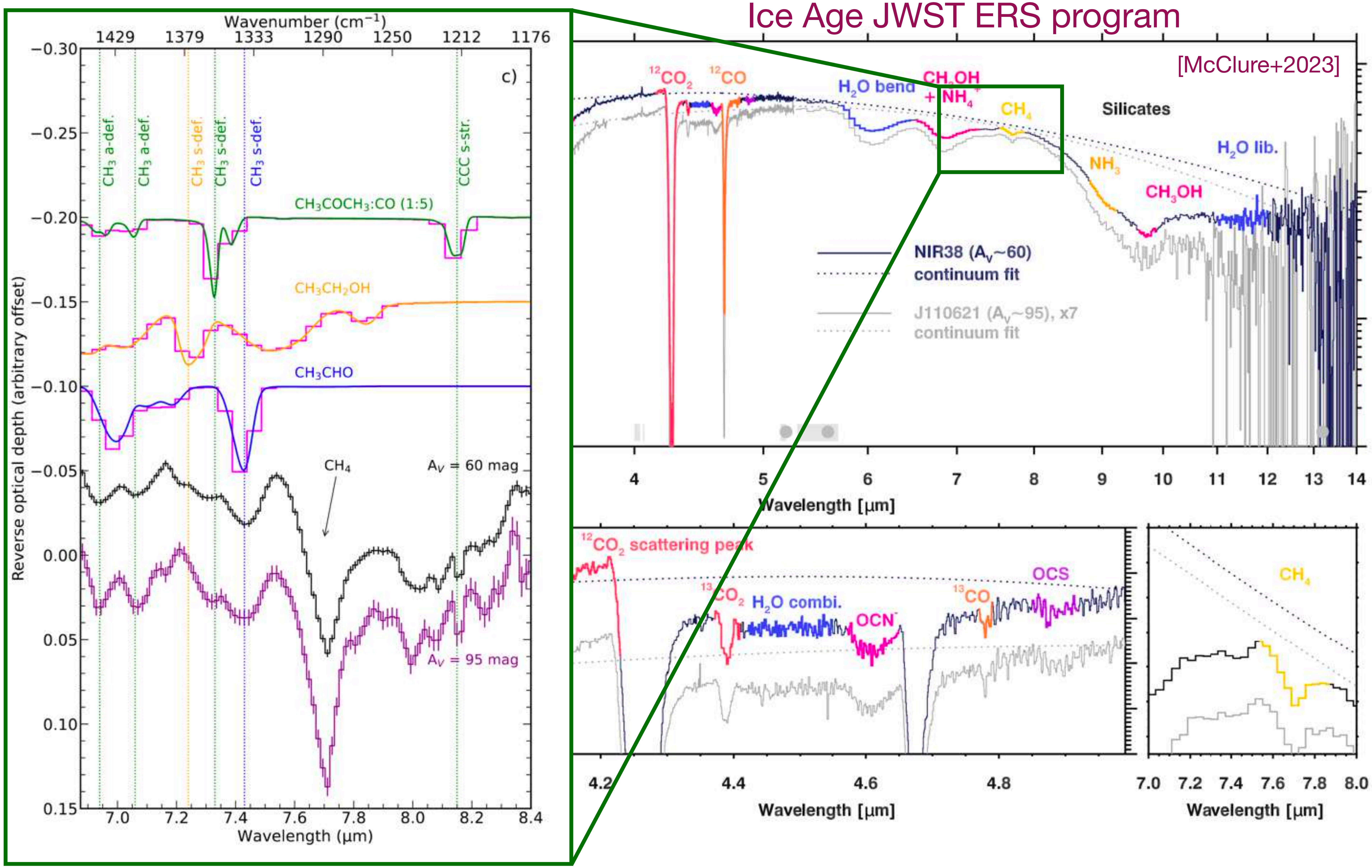
Ice Age JWST ERS program



Dust in dense clouds : ices

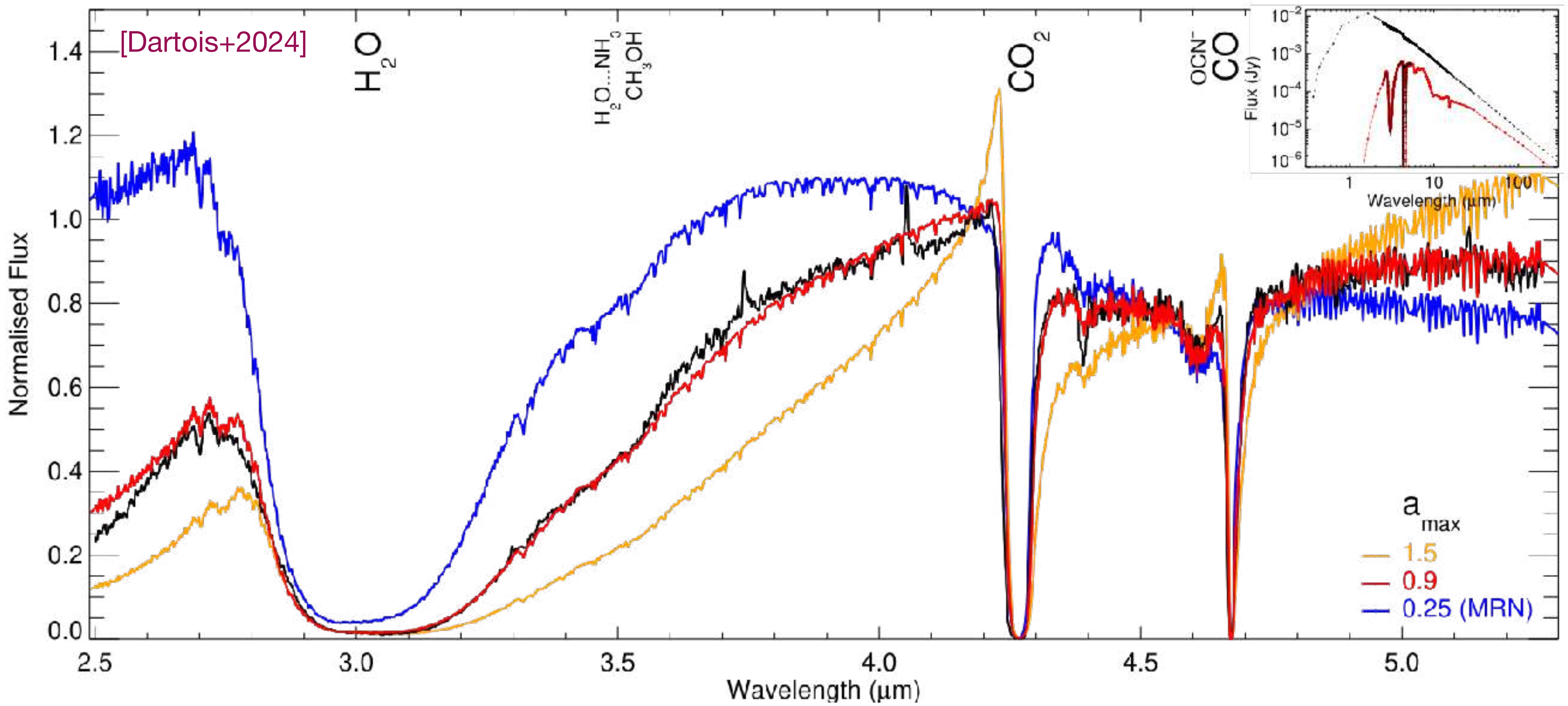
- Detection of COMs (commonly observed and abundant in the gas phase in the mm) :
  - acetone CH_3COCH_3
  - ethanol CH_3CH_2OH
  - acetaldehyde CH_3CHO

Ice Age JWST ERS program



Dust in dense clouds : grain growth and aggregation

Ice Age JWST ERS program


[Dartois+2024]

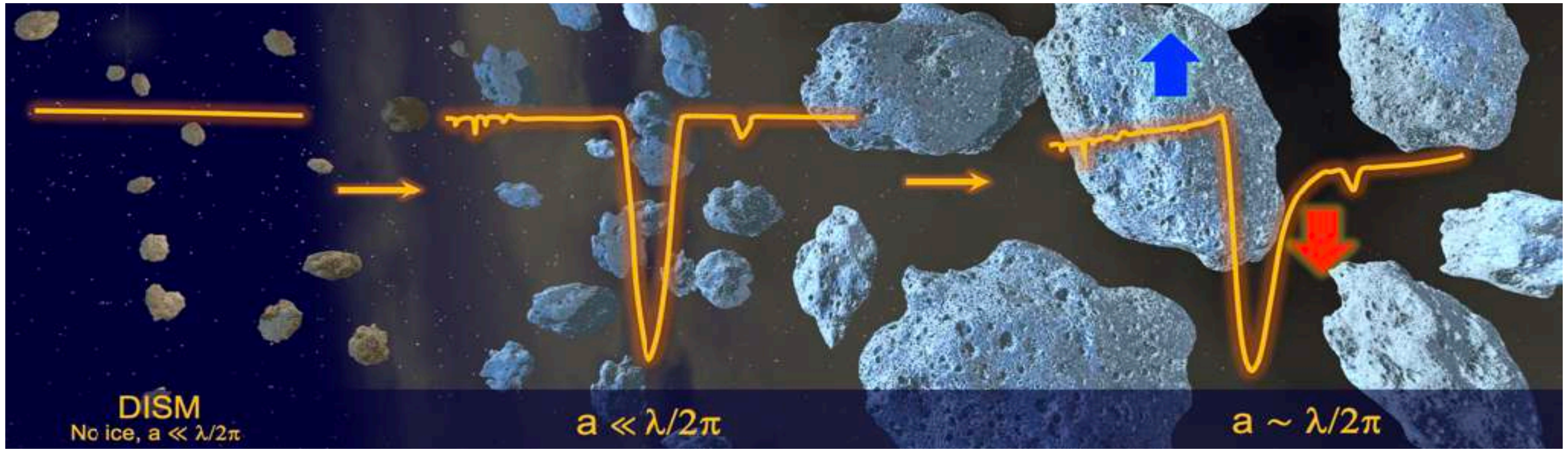
Spectroscopic sizing of grains

- RT modelling
- Optical constant ices, refractory matter
- DDA modelling for large grains
- MRN size distribution

➡ $a_{max} = 0.9 \pm 0.1$ μm

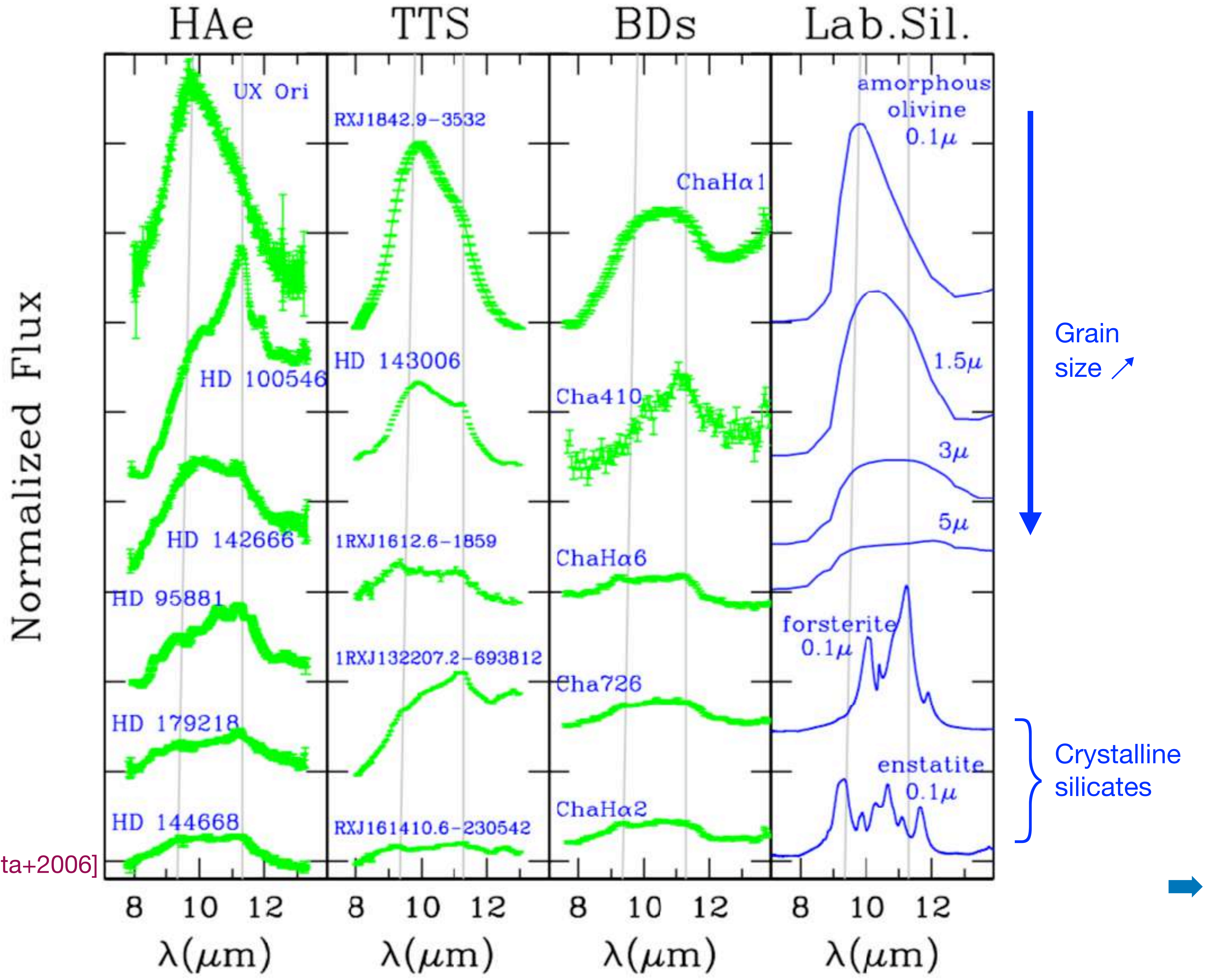
$$\frac{Snew}{S_{MRN}} = 0.46 \pm 0.04$$

$$\frac{M(a \geq 0.25\mu m)}{M(a \leq 0.25\mu m)} = 1.2 \pm 0.15$$



➡ dynamical evolution of dense clouds
➡ chemistry
➡ external radiation field penetration and propagation

Silicates in disks



[Natta+2006]

➡ Large variability of spectral shapes:
- Narrow or broad feature
- High or low contrast wrt continuum
- Sub-structure in the 9.8 µm band

➡ As grains grow to µm-size:
- Shift in peak position
- Band width increases
- $\tau_{9.8\mu m}$/continuum decreases

➡ In the MIR we do not see large grains !

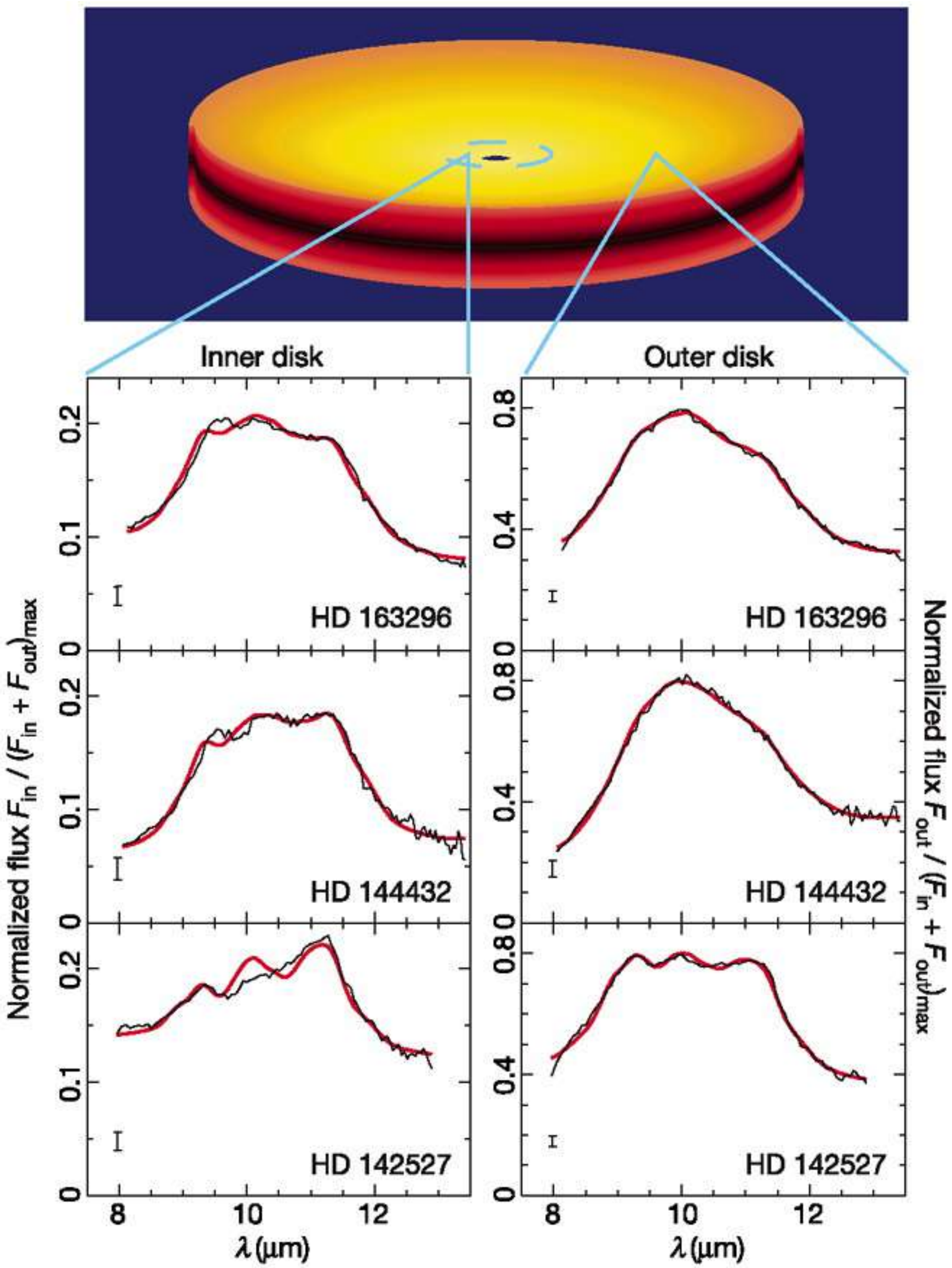
➡ Presence of crystalline silicates:
- Sharp peaks in the 9.8 µm band

➡ Grain growth and crystallisation in disks

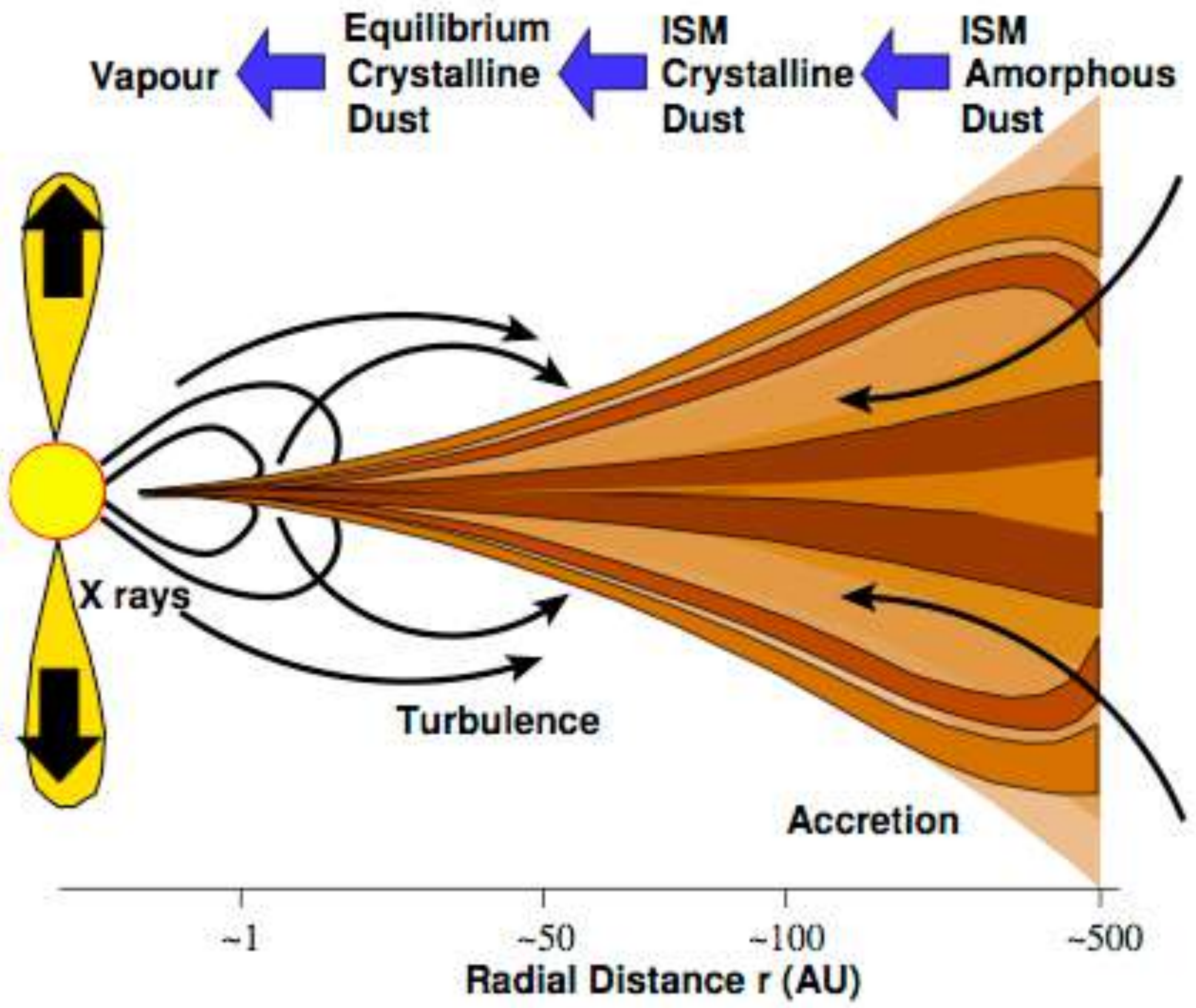
Silicate crystallization in PPDs

- ISM dust is amorphous
- Crystalline silicates in disks and in comets
- Vaporisation and re-condensation of the dust grains?
- In situ crystallisation in disks: need to reach temperature higher than T~800-1300K
- For T > 770K -> structural changes occur for time scales < 10^6 years
- Depending on the temperature, the stoichiometry of the crystallised sample changes from forsterite to enstatite [Roskosz+2011]

[Van Boekel+2004]



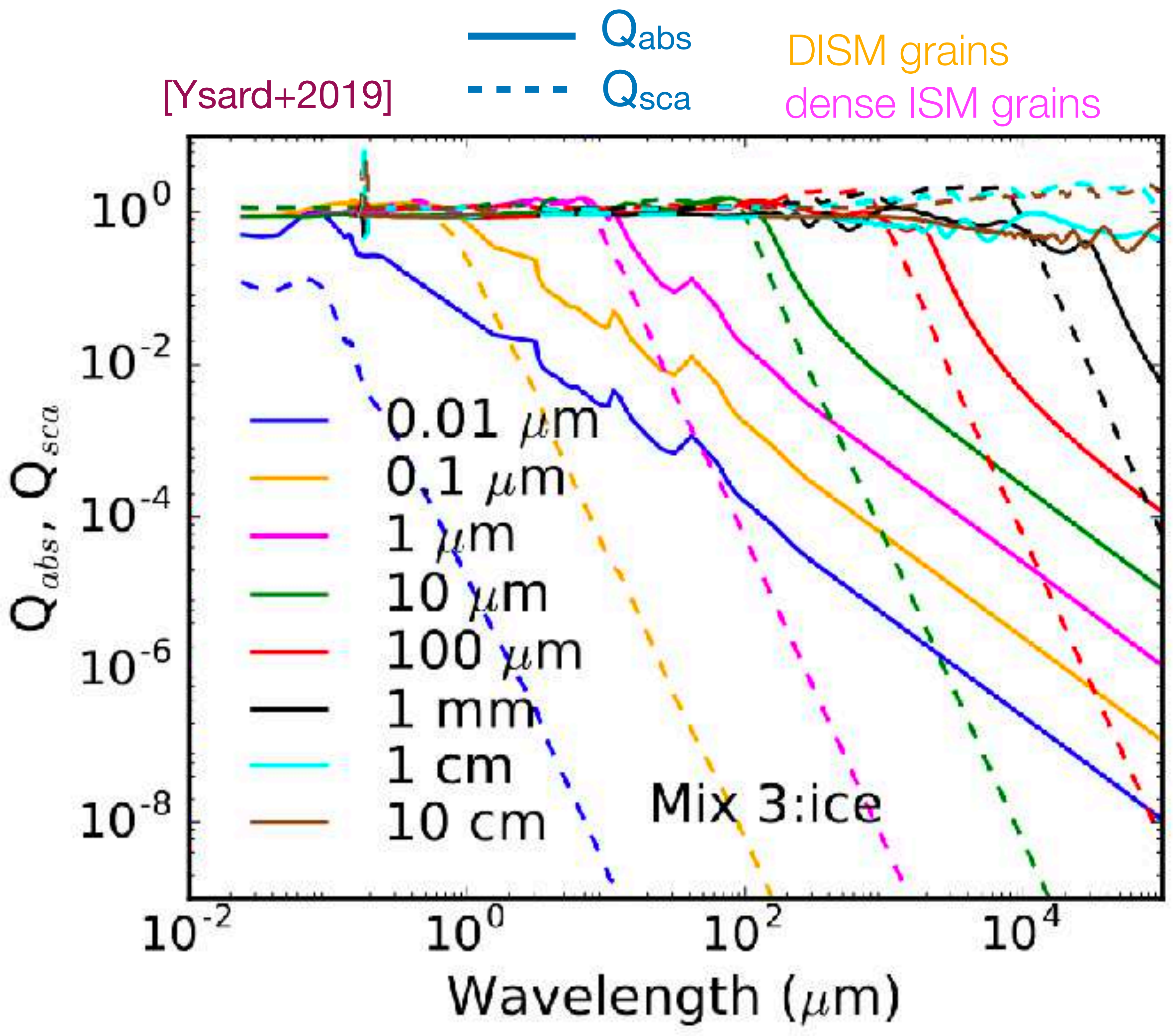
- Need radial mixing mechanism to transport of the crystallised dust to the outer part of the disks
- and/or local processes such as lightening or shocks

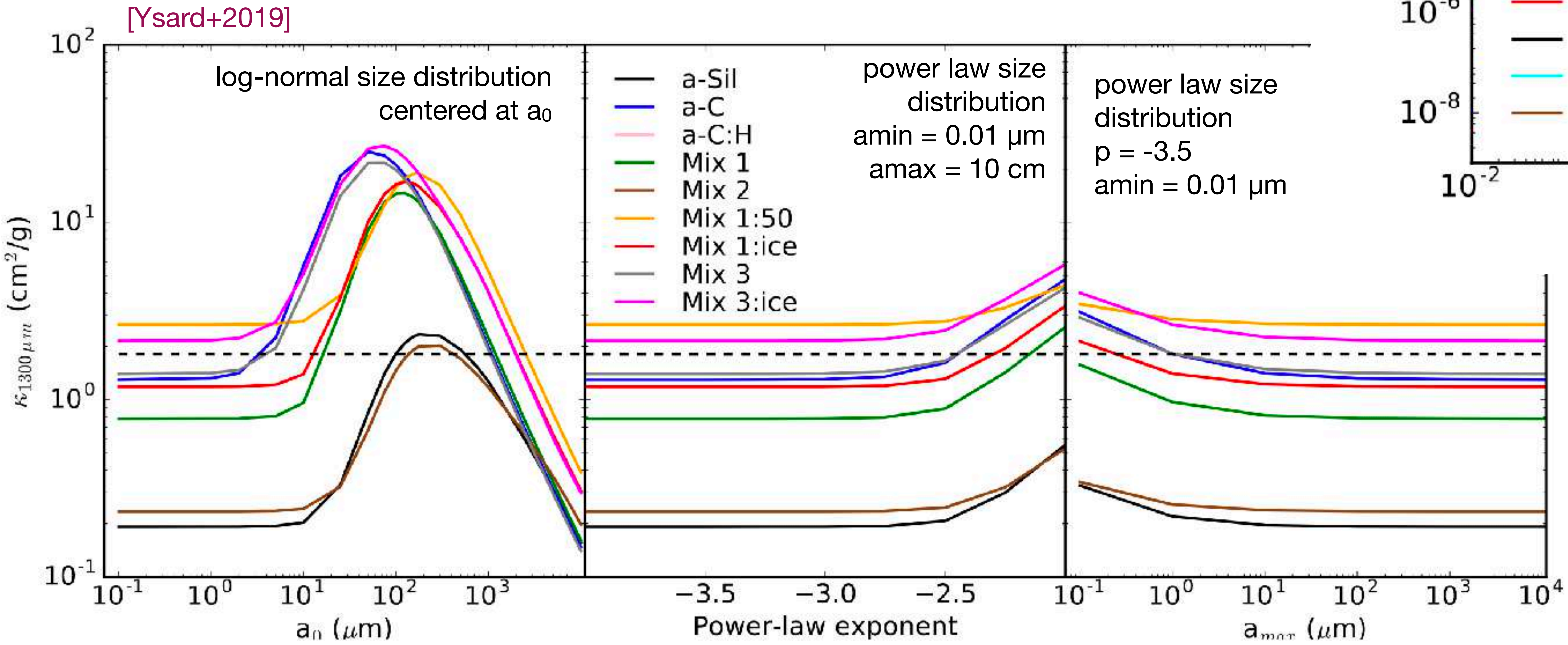


Opacity of mm- and cm-size grains :

Grain must grow to mm, cm-size in disks

- Dust opacity varies with : grain composition (~ x3)
  size
  size distribution
- Dust scattering important at long wavelength for large grains

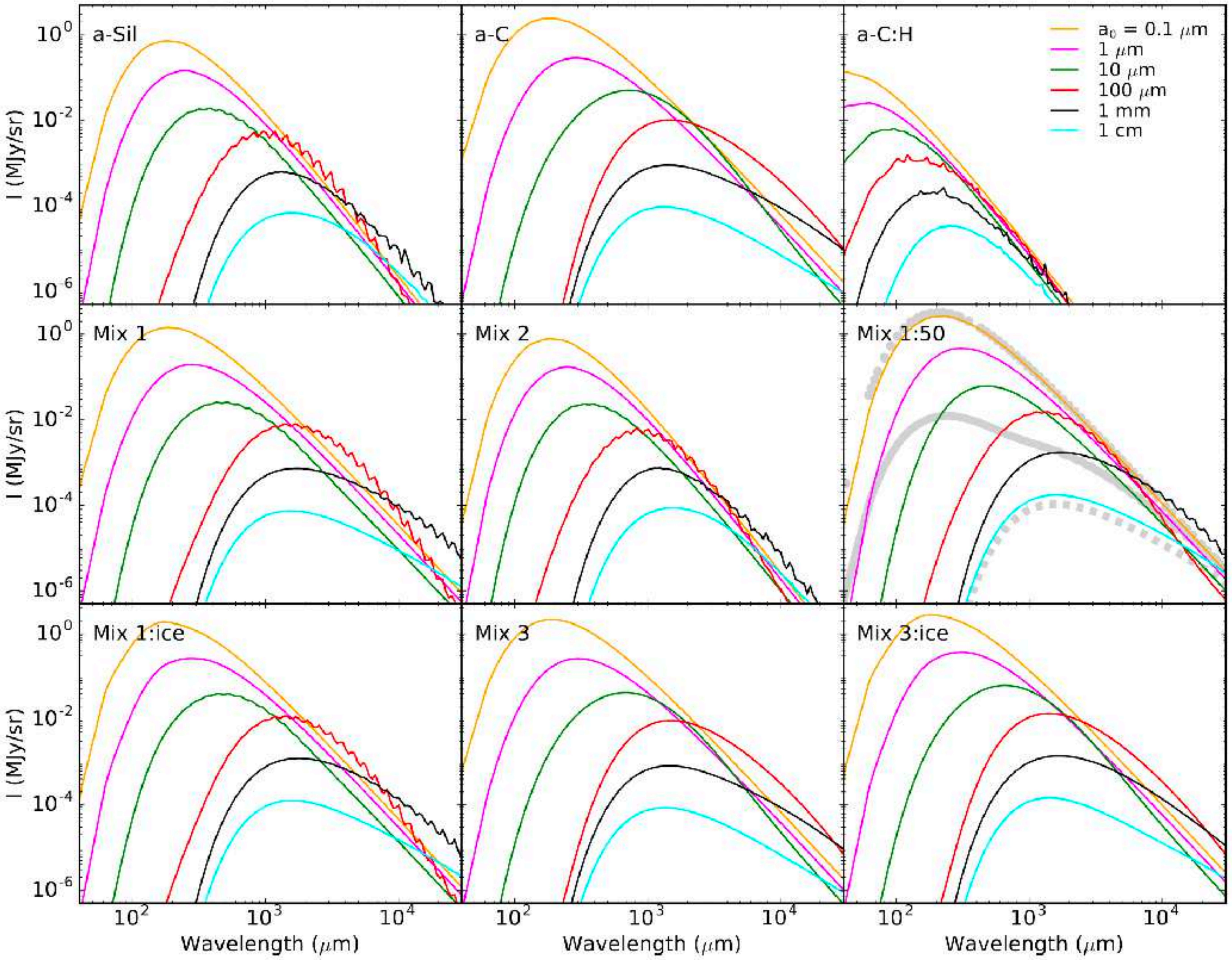

[Ysard+2019]


[Ysard+2019]

κ = 1.8 cm^{2}g^{-1}
used in most models :
Beckwith+1990, D'alessio+2001,
Andrews+2009, Birnsteil+2018

Opacity of mm- and cm-size grains :

[Ysard+2019]

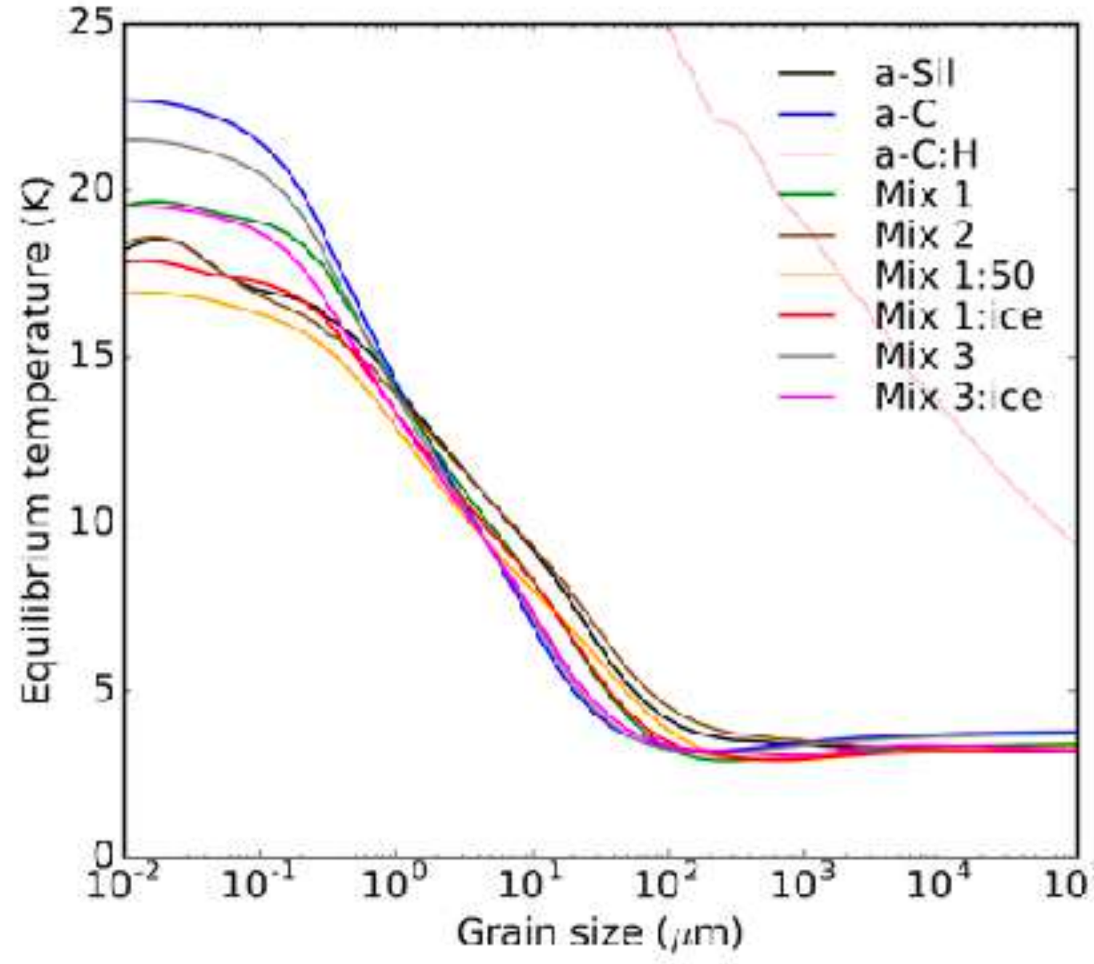


SED calculated using DustEM for :

- optically thin medium ($N_H = 10^{20}$ H/cm^2)
- standard ISRF
- log-normal distribution (colour)
- power-law distribution amin = 0.01 µm (grey)
  - p=-3.5, amax = 1 µm (solid)
  - p=-3.5, amax =10 cm (dotted)
  - p=-2 amax = 10 cm (dashed)

➡The SED peak shifts with the grains size because the grain temperature varies with the grain size and composition

[Ysard+2019]



Opacity of mm- and cm-size grains :

- Dust spectral index $\beta(\lambda)$ calculated over 1GHz frequency steps
- Circles = β calculated from MBB fit of the SED in the Wien part

➡ $\beta(\lambda)$ varies with grain size

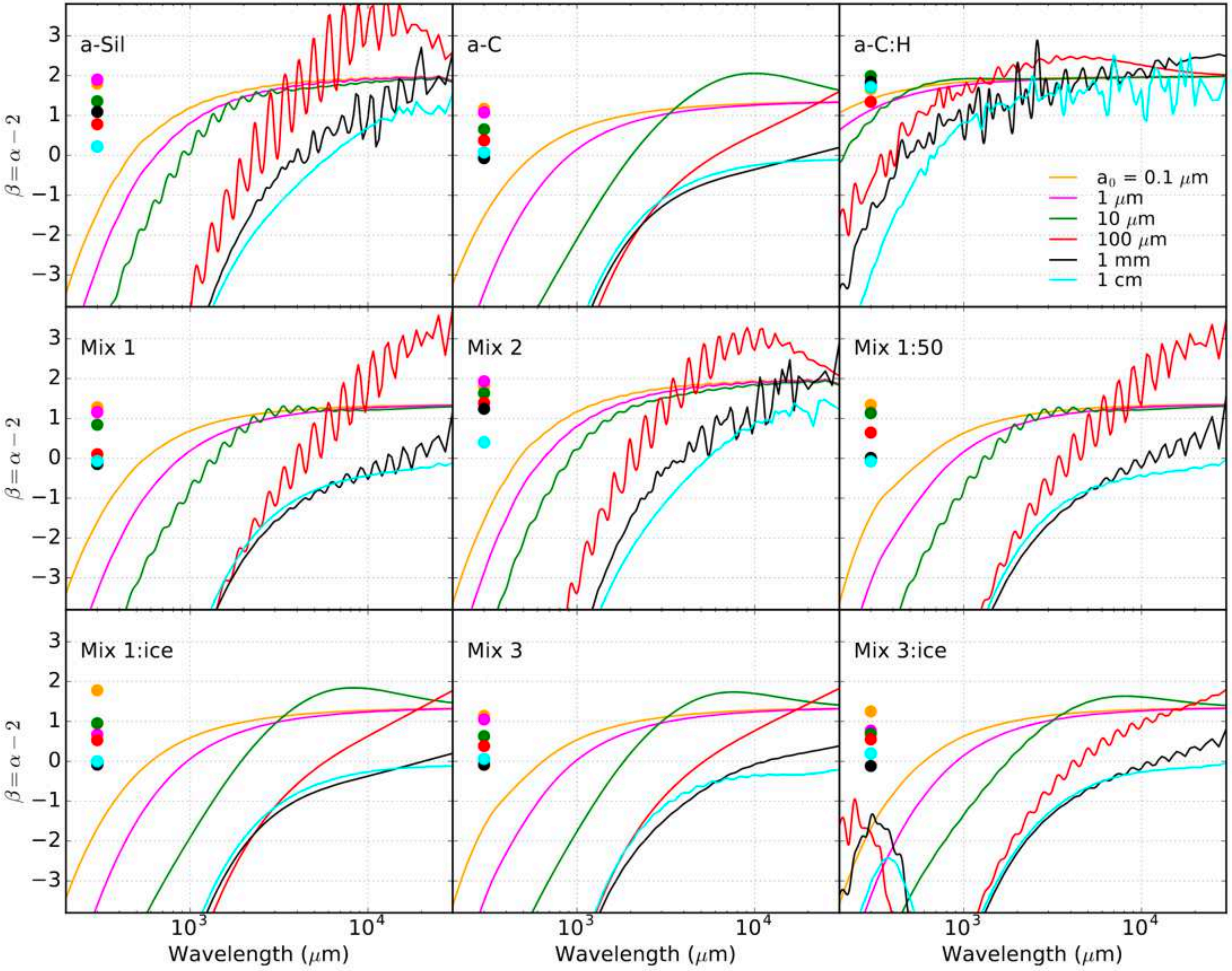
➡ $\beta(\lambda)$ varies with grain composition

➡ $\beta(\lambda)$ is different from the $\beta(\lambda)$ of the constituent

- a ≲ 10 µm : $\beta \approx \beta$ of the material Q_{abs}
- a > 10 µm : $\beta < \beta$ of the material Q_{abs} as long as $\lambda \lesssim 10\, a_0$

> "Based solely on (sub)millimetre/centimetre β measurements, for a0 smaller than 100 µm, it would be very difficult to determine the grain sizes for most of the grain compositions considered in this study."

[Ysard+2019]



See Ysard+2019 for the optically thick case without and with an embedded source

Implications for mass determination :

- In optically thin medium : $I_\lambda = \tau B_\lambda(T) = \dfrac{M_{dust}\kappa_\lambda B_\lambda(T)}{d^2\Omega}$
- Approximation for the dust emissivity in the FIR : $\kappa_\lambda = \kappa_{\lambda_0}\left(\dfrac{\lambda}{\lambda_0}\right)^{-\beta}$

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

- if β and κ_0 varies with
  - the temperature and wavelength (physical processes)
  - the grain size (grain coagulation)

The mass estimation might be
- wrong (over-estimated)
- different in the FIR and mm

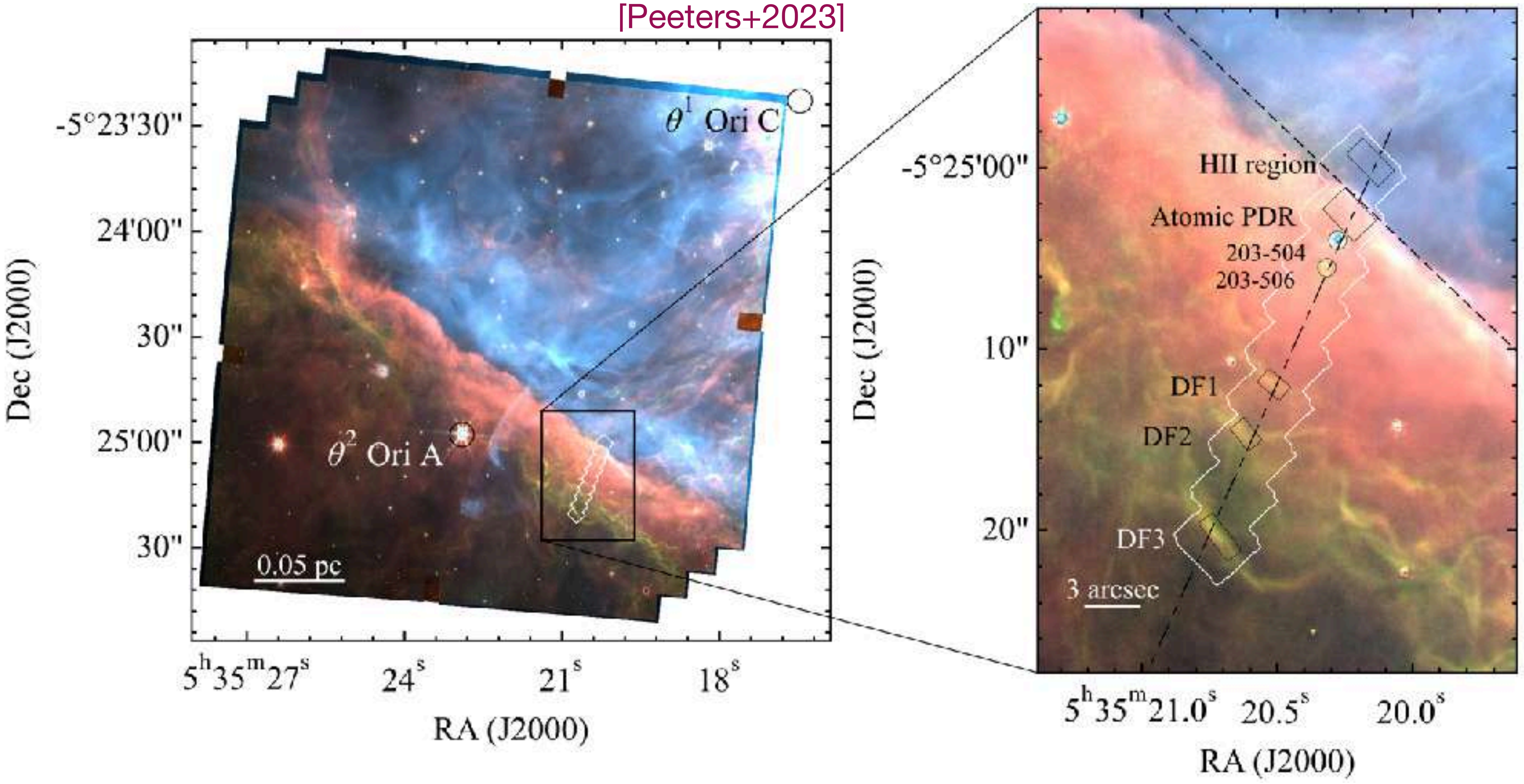
The use of $\kappa_\lambda = \kappa_{\lambda_0}\left(\dfrac{\lambda}{\lambda_0}\right)^{-\beta}$ in the FIR does not properly describe grain physics

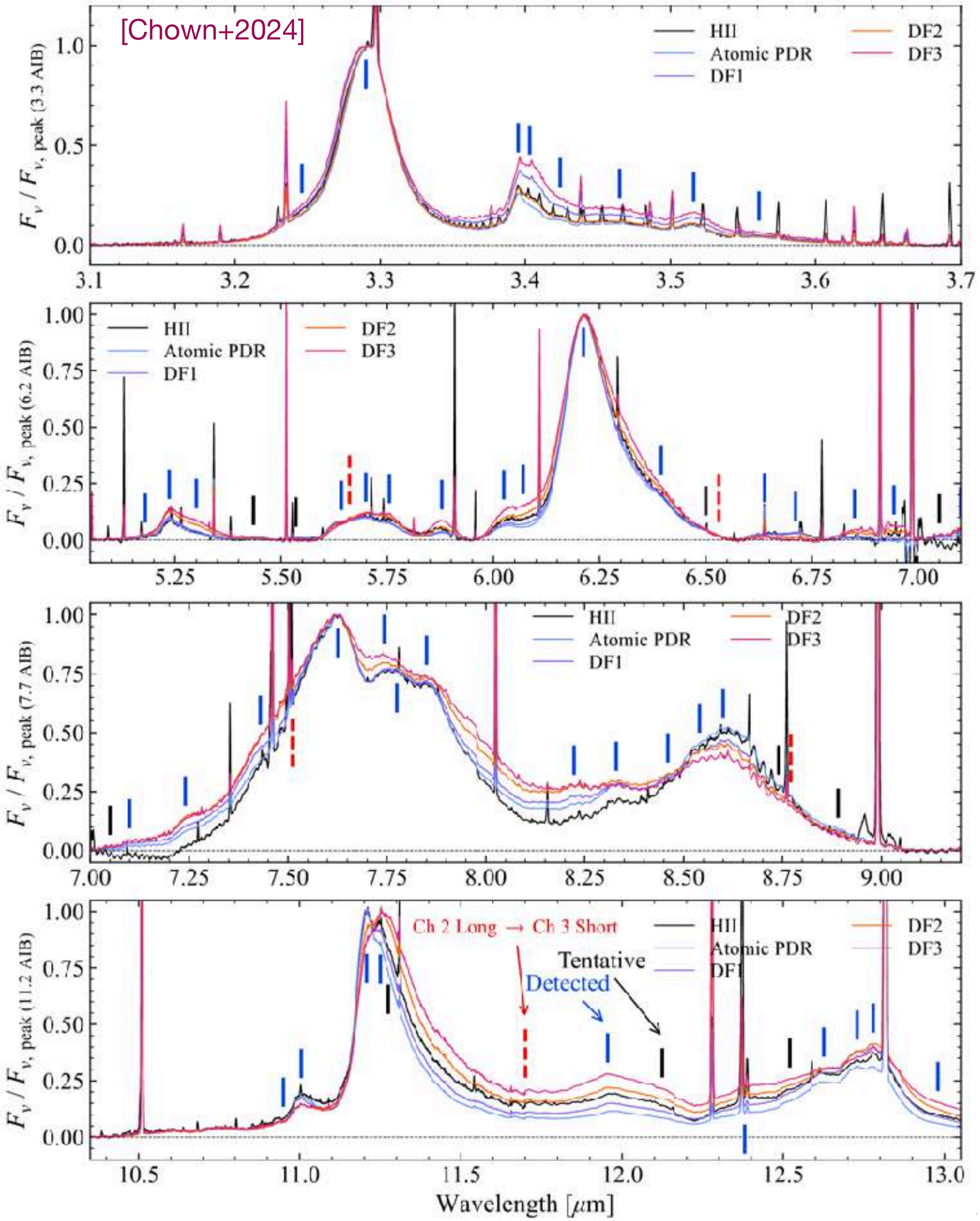
The observed β is not always the same as the one of grain constituents

Dust in PDRs : Orion

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

[Peeters+2023]

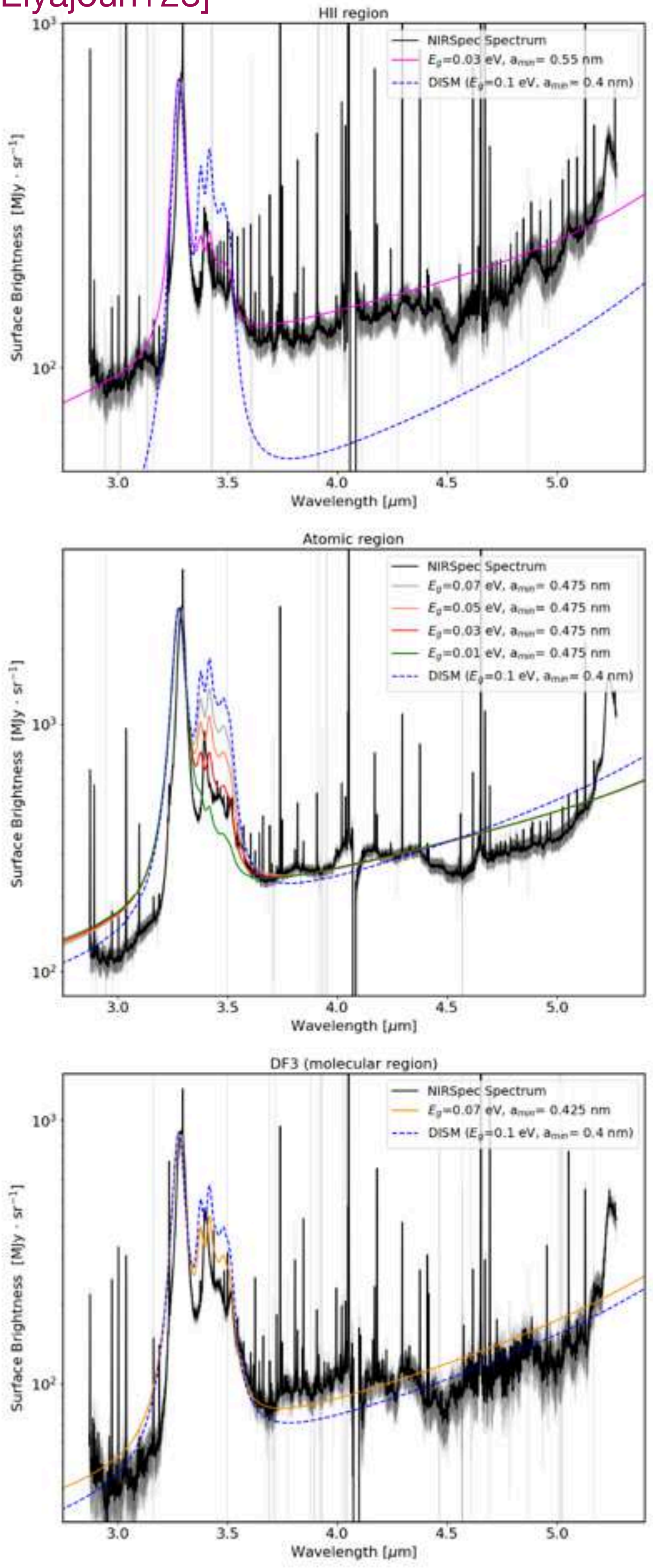




NIR & MIR images and spectra
Probe the evolution of matter as a function of UV field

Dust in PDRs : Orion

[Elyajouri+23]

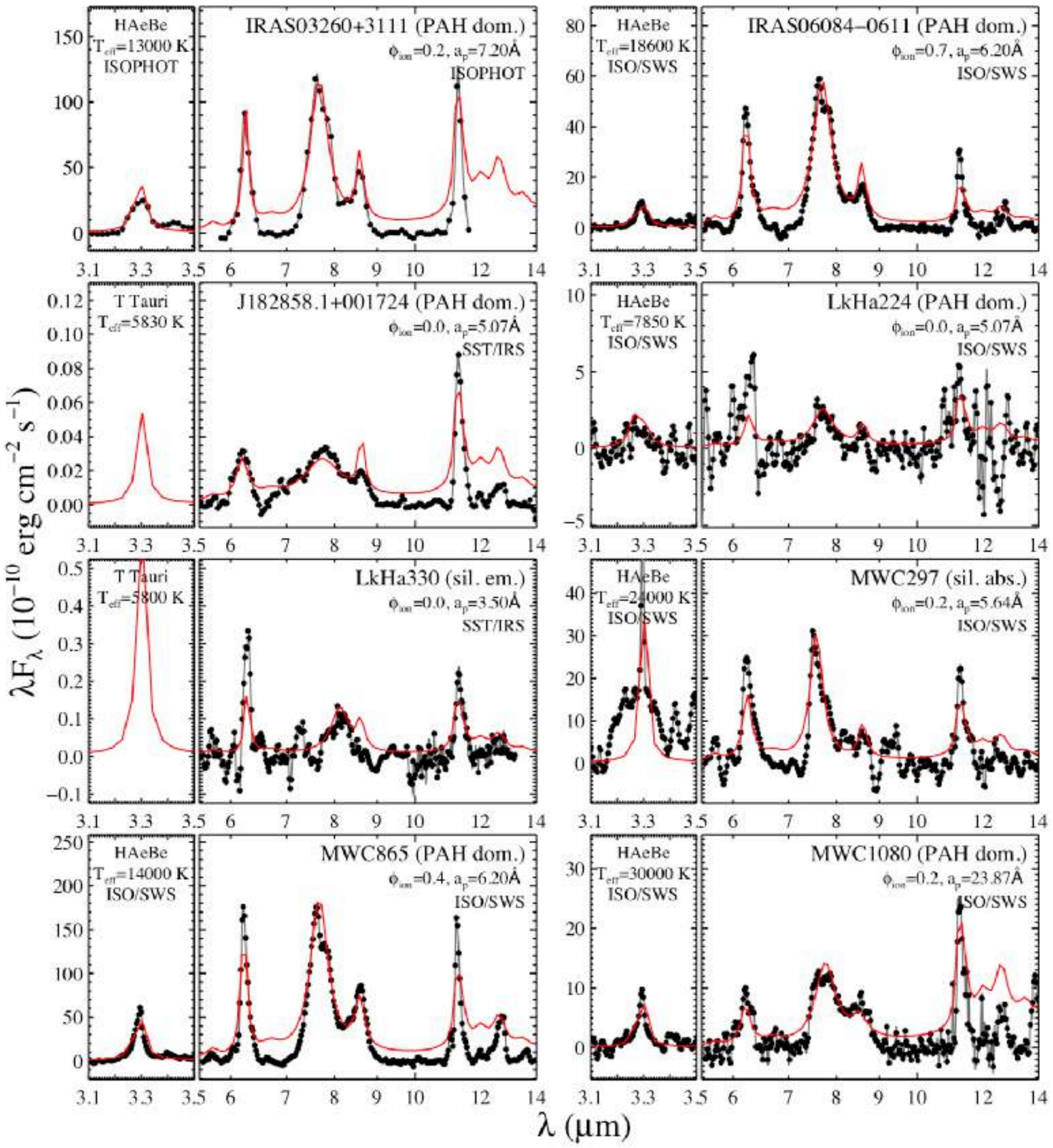


JWST ERS project « Radiative feedback from massive stars as traced by multi band imaging and spectroscopic mosaics » PI O. Berné, E. Habart, E. Peeters

- 3.3 µm band of aromatic dust : PAHs
- 3.4 µm band of aliphatic-rich dust : HAC or hydrogenated/methylated PAHs?
- 3.3µm/3.4µm decreases with decreasing UV field
- band-to-continumm ratio varies

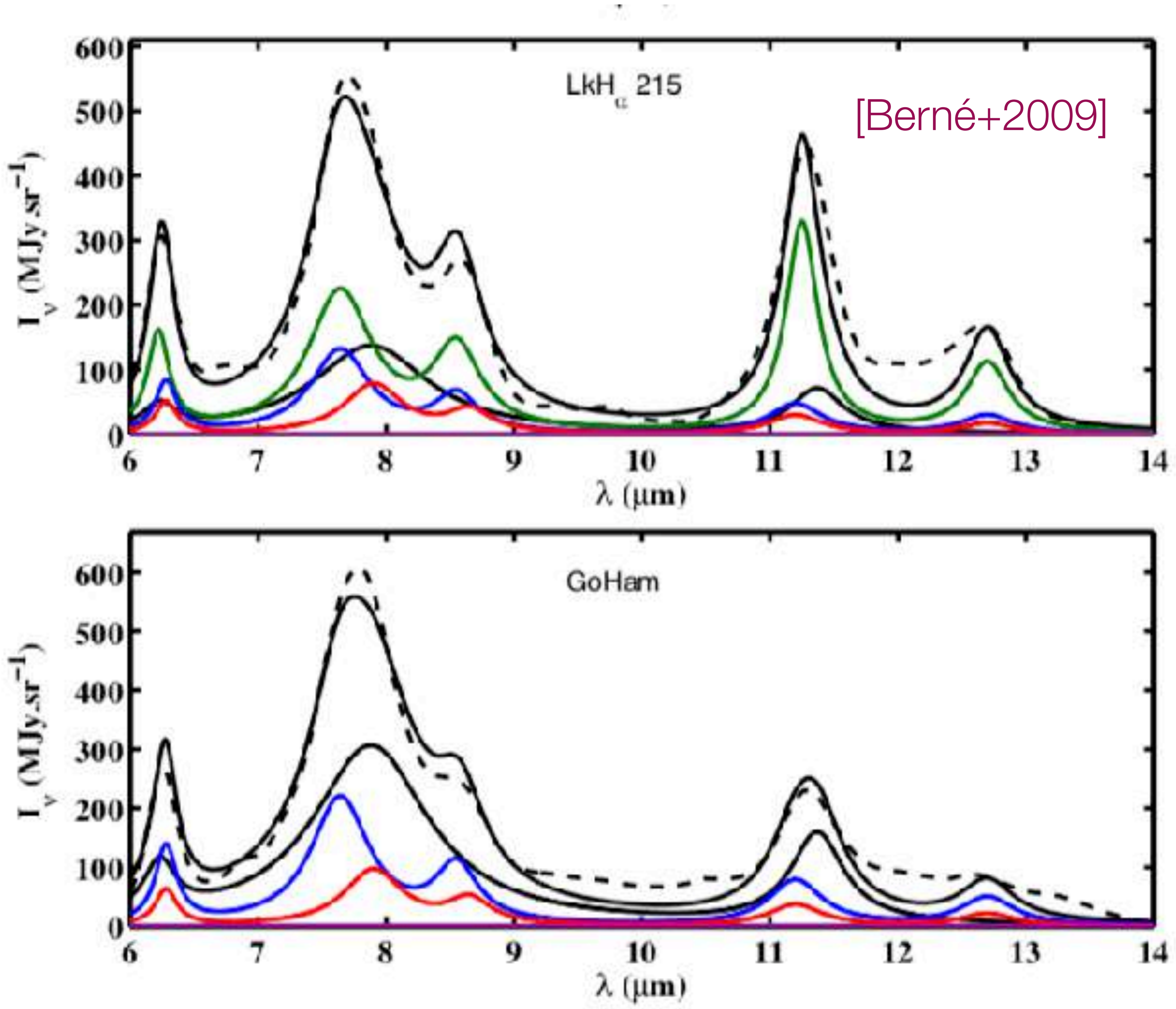
- THEMIS model :
  - 3.3µm/3.4µm different in Orion than for DISM dust (THEMIS model)
  - Nano-carbon grains least hydrogenated near the star
    ➡ photdissociation
  - Nano-carbon grains most hydrogenated in molecule region (dissociation front)
  - a_{min} of grains decreases when UV field increases
    ➡Strong depletion of small grain compare to the diffuse ISM

Observations of AIBs in disks



[Seok & Li 2017]

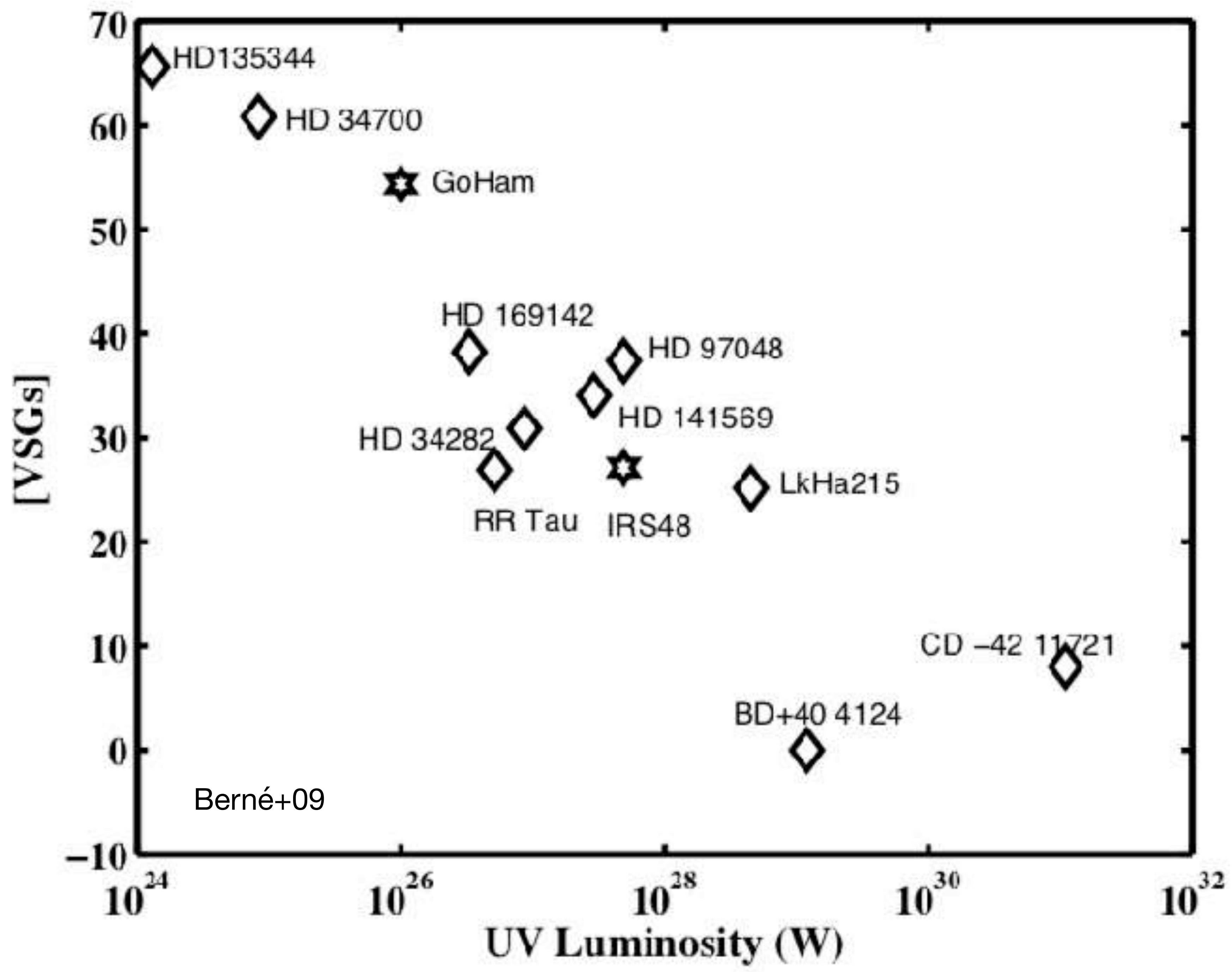
- AIBs observed in the MIR in Herbig AeBe stars
- Marginally detected in TTauri stars
- More extended than the continuum emission
- Stronger emission bands in flared disks
- Strong spectral variations form one object to the others



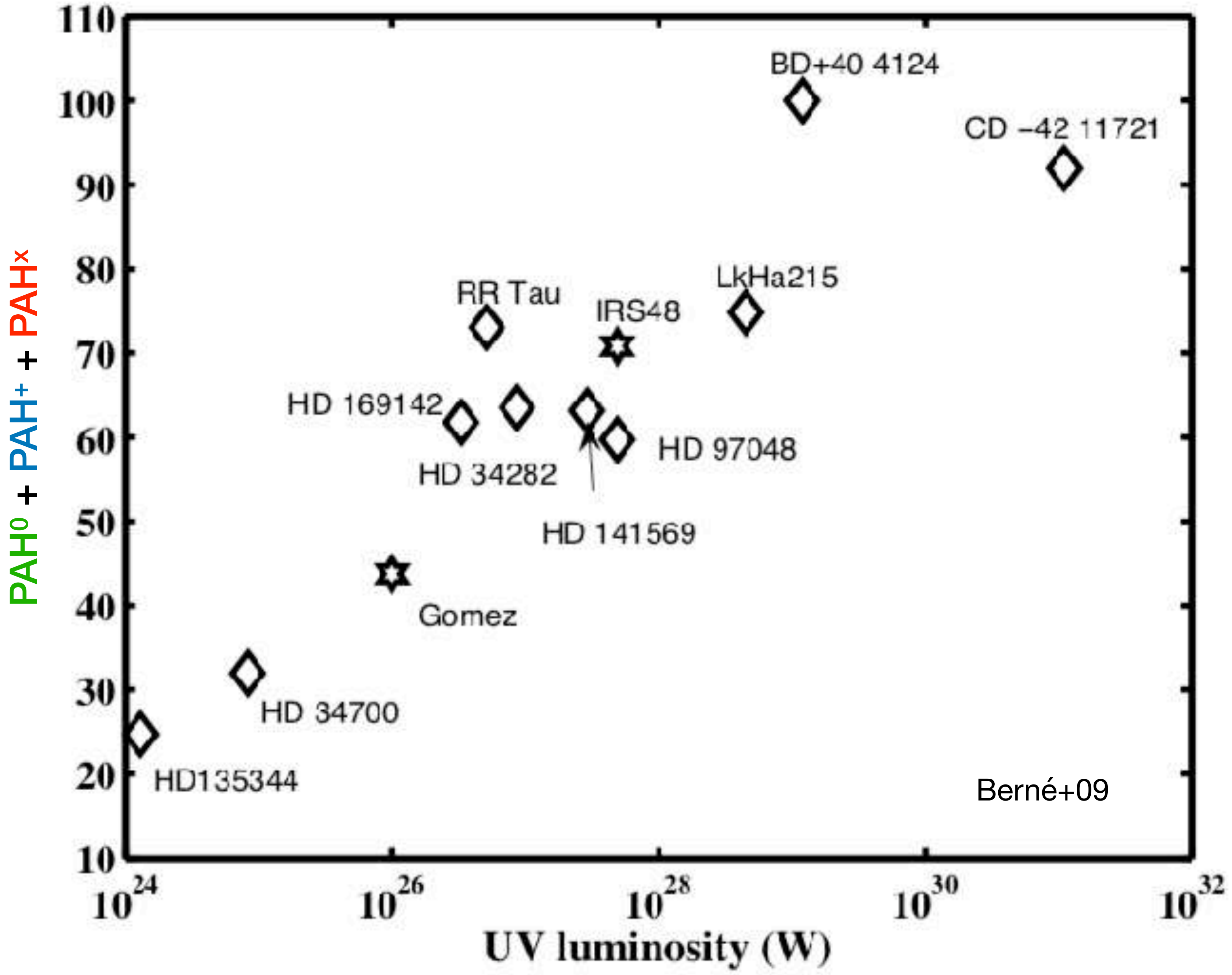
[Berné+2009]

- neutral
- cations
- very large PAHs ionised
- VSGs
- 8.3 μm feature

PAHs and VSGs in disks



Berné+09

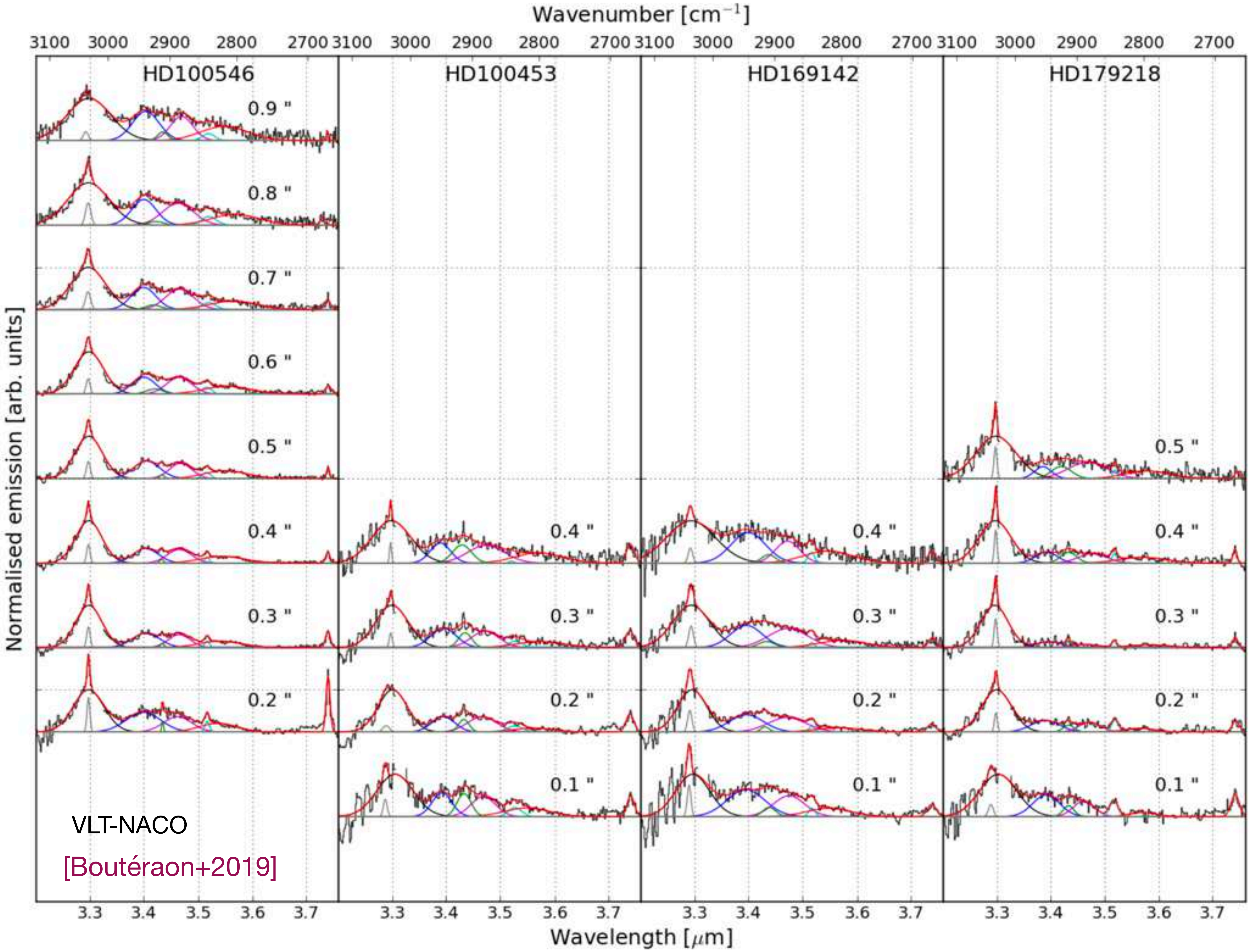


Berné+09

- Fraction of VSGs decreases with increasing UV luminosity : destruction
- Fraction of PAH increases with increasing UV luminosity

- See also Seok & Li 2017: similar study on a larger samples
- Need mechanisms to replenish the disk in small PAH which abundance tends to decrease with increasing stellar age.

Resolved carbonaceous dust in disk



VLT-NACO

[Boutéraon+2019]

- aromatic, aliphatic, olefinic signatures
- 10 to 150-100 au
- also in inner gaps devoid of large grains

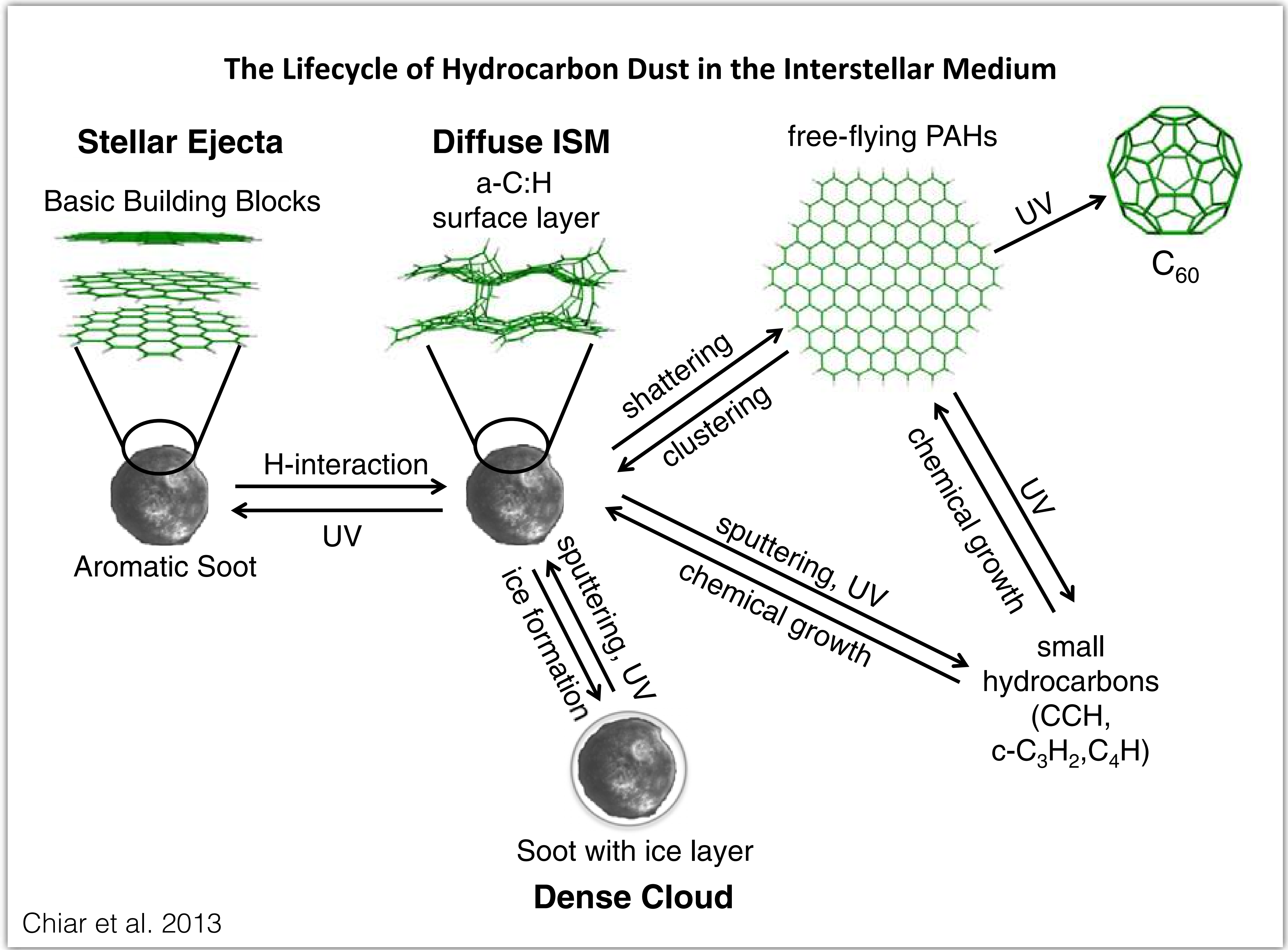
- aliphatic/aromatic ≈ constant
  ➡ same carriers
    ➡ nanometric hydrocarbons grains
    ➡ or PAHs with aliphatic groups?

- easily destroyed by UV photons
  ➡ continuous replenishment at the disk surface

- certainly more to come from JWST

Evolution of hydrocarbon dust

Some views of carbon-rich dust evolution



The Lifecycle of Hydrocarbon Dust in the Interstellar Medium

Stellar Ejecta
Basic Building Blocks
Aromatic Soot

Diffuse ISM
a-C:H
surface layer

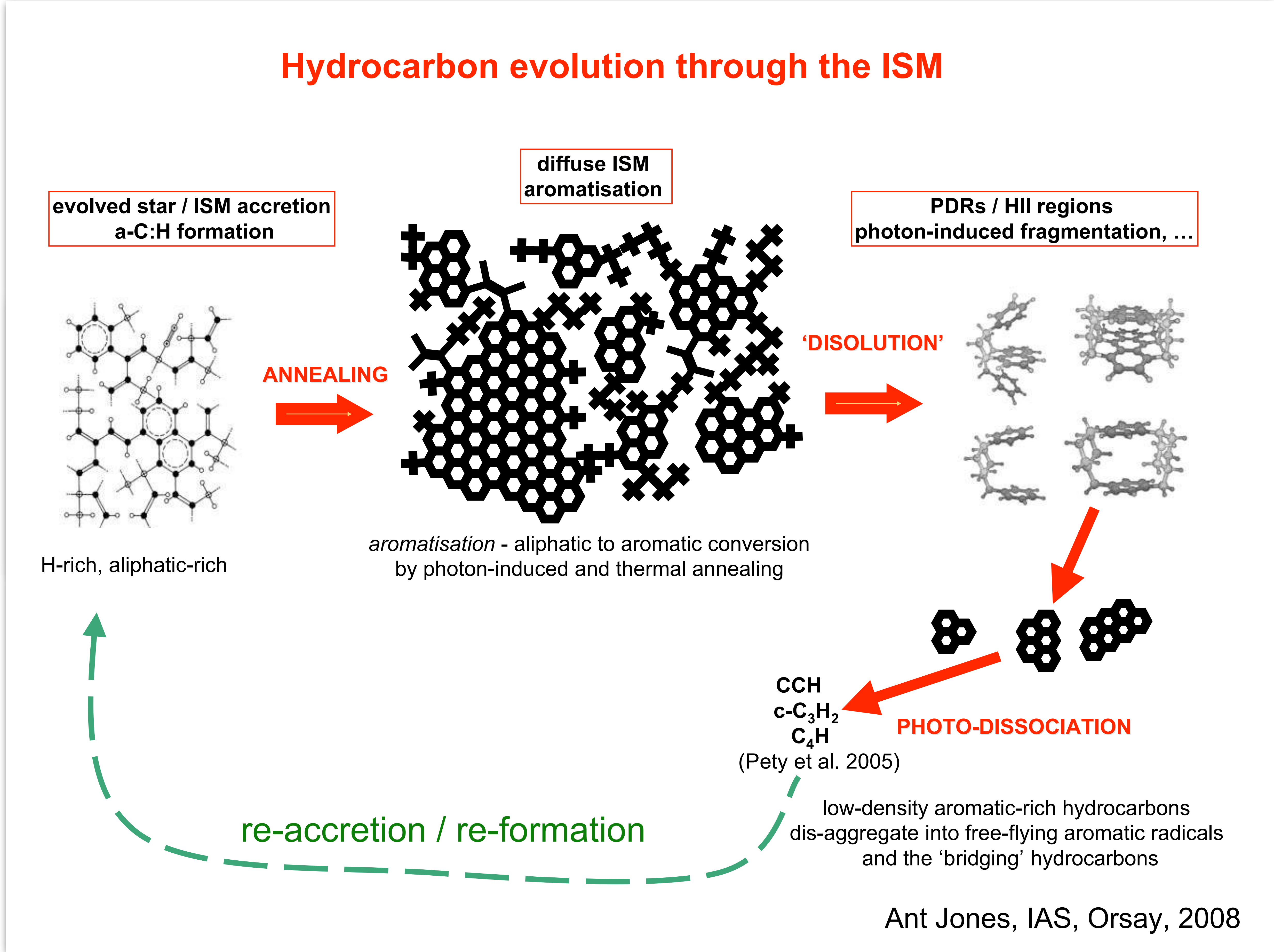
H-interaction
UV

free-flying PAHs
shattering
clustering
UV
C_{60}

chemical growth
UV
sputtering, UV
chemical growth
small hydrocarbons (CCH, $c\text{-}C_3H_2$,C_4H)

sputtering, UV
ice formation
Soot with ice layer
Dense Cloud

Chiar et al. 2013



Hydrocarbon evolution through the ISM

evolved star / ISM accretion
a-C:H formation

H-rich, aliphatic-rich

ANNEALING

diffuse ISM
aromatisation

aromatisation - aliphatic to aromatic conversion
by photon-induced and thermal annealing

'DISOLUTION'

PDRs / HII regions
photon-induced fragmentation, ...

PHOTO-DISSOCIATION

CCH
$c\text{-}C_3H_2$
C_4H
(Pety et al. 2005)

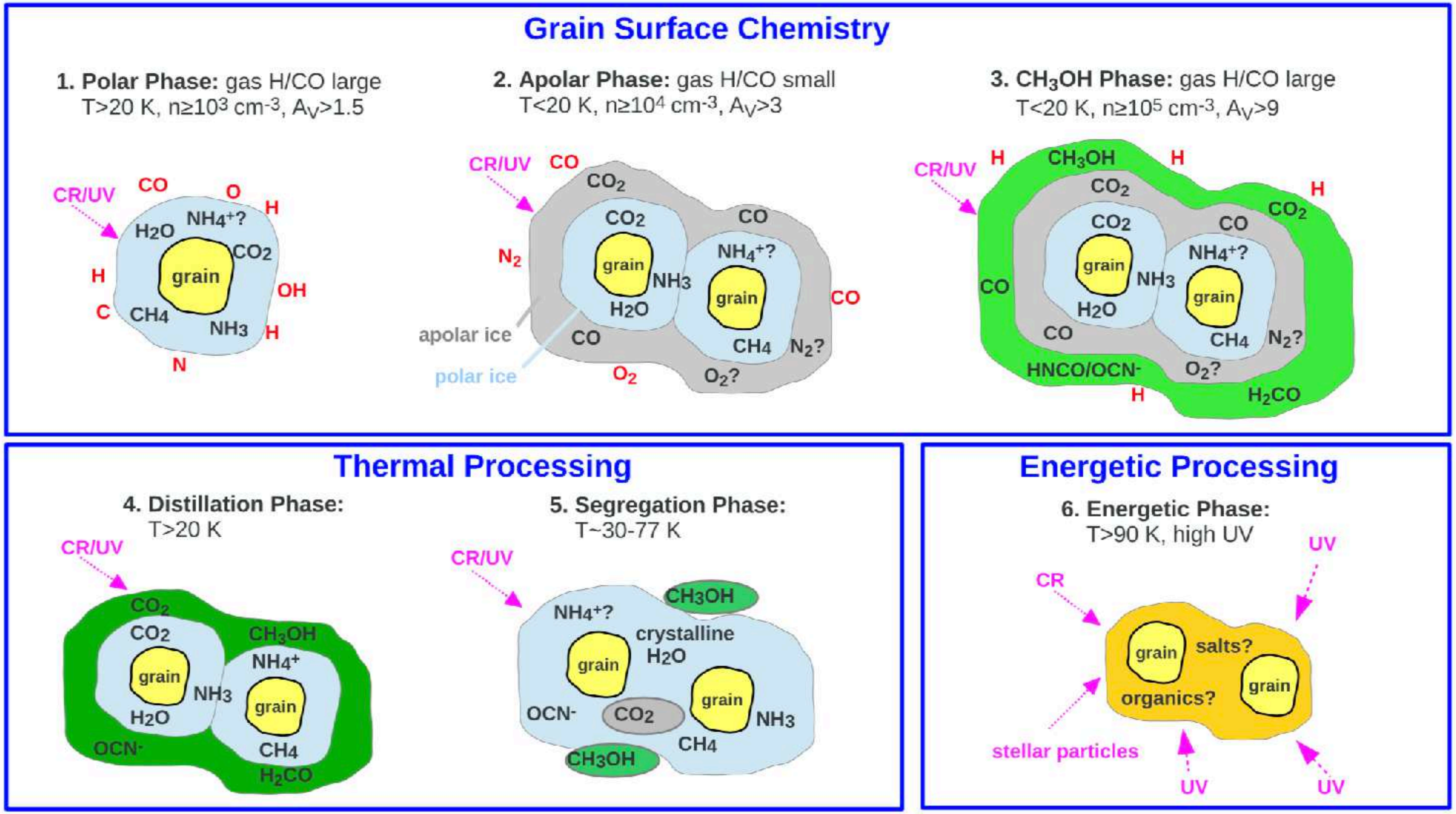
low-density aromatic-rich hydrocarbons
dis-aggregate into free-flying aromatic radicals
and the 'bridging' hydrocarbons

re-accretion / re-formation

Ant Jones, IAS, Orsay, 2008

See also Goto+2003, Carpentier+2012

Ice evolution in the ISM



[Boogert+2015]

Summary 1/2

- Dust properties change along the life cycle of the ISM

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

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

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

Summary 2/2

- MIR spectroscopy probes micron-size grains

- Submm/FIR dust emission :
  - The use of $\kappa_\lambda = \kappa_{\lambda_0}(\lambda/\lambda_0)^{-\beta}$ in the FIR does not properly describe the grain physics
  - but it is simple and will continue to be used
  - however it must be used with caution:
    - κ_0 and β varies with temperature
    - κ_0 varies with grain size
    - β varies with composition and grain size
    - β_{observed} may be different than β_{dust}

    ➡ couple extinction to emission who possible

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