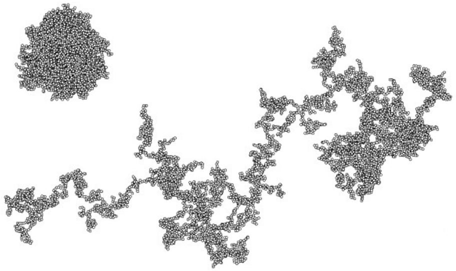
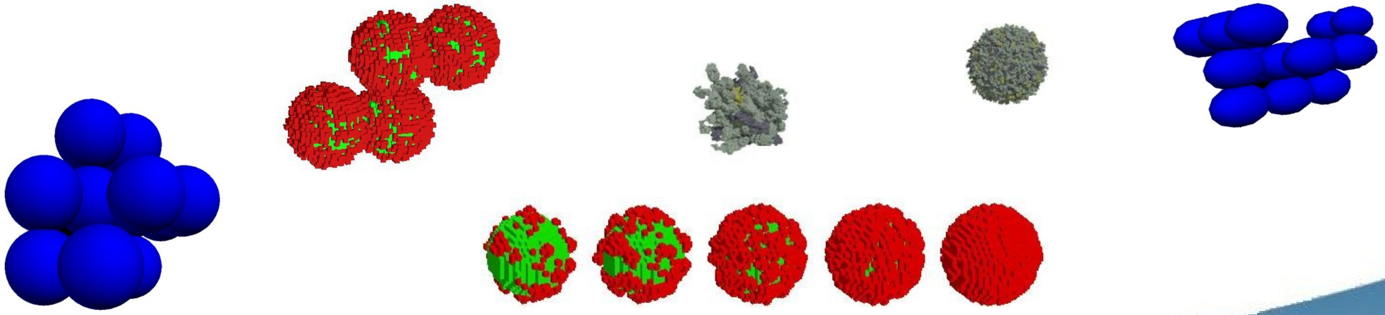
DUST EVOLUTION FROM THE DIFFUSE TO THE DENSE ISM

N. Ysard (IAS, CNRS, Université Paris Saclay)



Mukai et al. (1992)
Koehler et al. (2011, 2012)
Min et al. (2016)
Ysard et al. (2018)

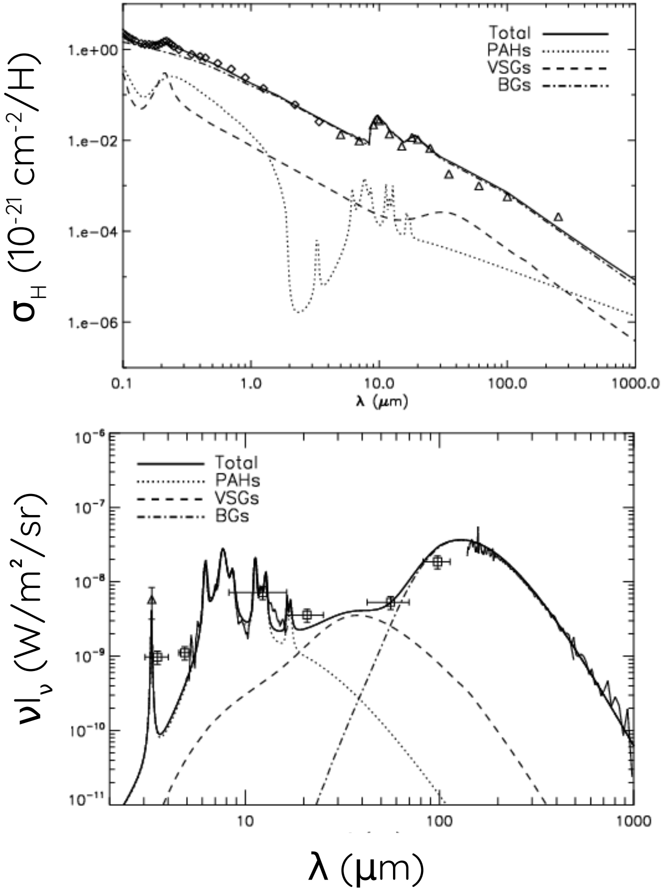


FROM OBSERVATIONS TO GRAIN PROPERTIES

A few constraint examples

From observations to grain properties

What do we have to constrain the grain properties ?



- Depletion measurements + X-ray → composition
- Extinction
  - $E(B-V) = A_B - A_V$ & $R_V = A_V / E(B-V)$
  - mid-IR silicate bands at ~ 10 and 18 μm
- Emission
  - mid-IR to far-IR ratio
  - modified BB fit → $I_\nu = N_H \, \sigma_{\nu 0} \, B_\nu(T) \, (\nu/\nu_0)^\beta$
  - optical depth → $\tau_{\nu 0} = N_H \, \sigma_{\nu 0}$
- Scattered light from visible to mid-IR → size
- Polarisation
  - λ_{max} → peak wavelength of starlight polarisation
  - P/I → polarisation fraction in far-IR/submm

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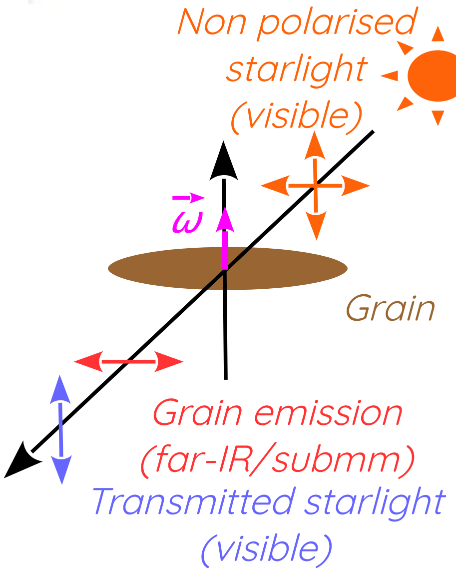

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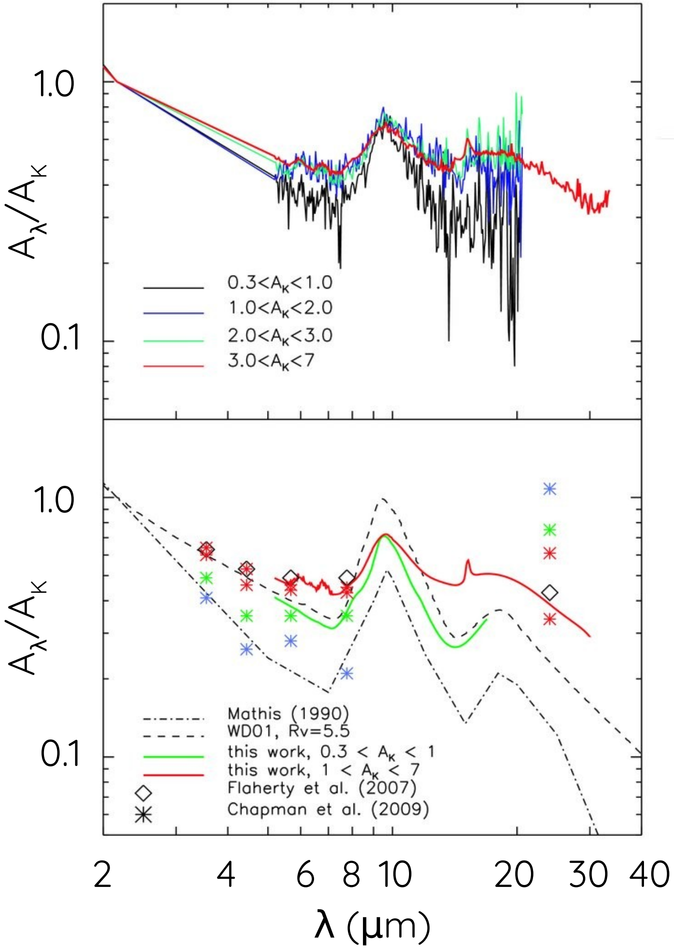
➡ *Grain composition, abundance, size, shape…*

Variations in the silicate mid-IR features
McClure (2009)



- Sample
  - 24 G0-M4 III stars behind dark clouds
  - Chameleon, Serpens, Taurus
  - Barnard 68, Barnard 59, IC 5146
- Normalisation to K band at 2.2 μm (2MASS)
- Observational results for $A_K > 0.5$ (⇔ $A_V \sim 4$)
  - extinction curve flattening
  - widening of both bands
  - BUT peak positions unchanged
  - variations correlated with ice features

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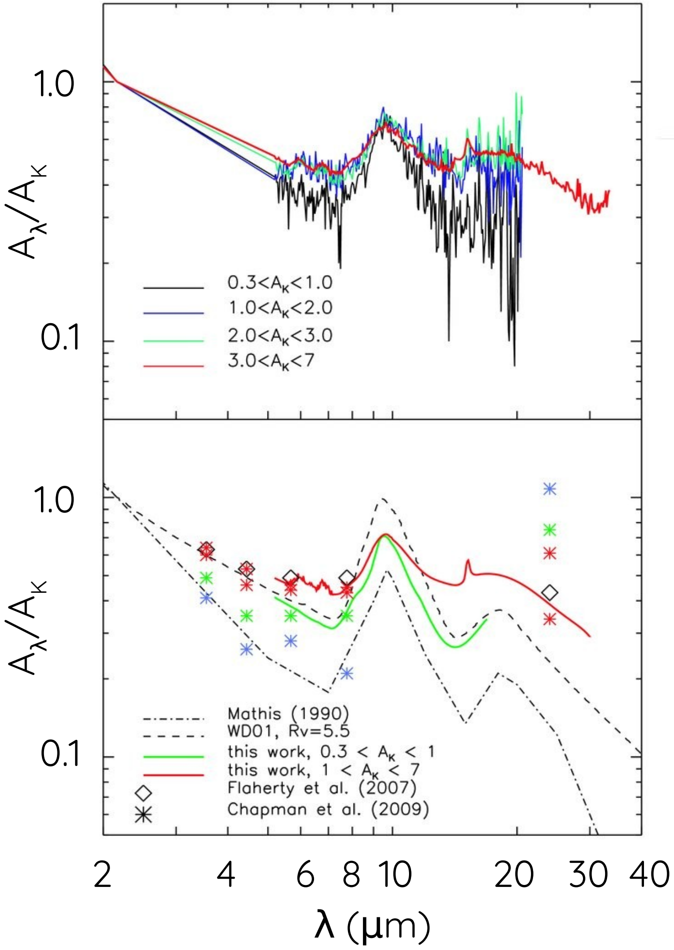

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Grain size cannot exceed ~ 1 μm

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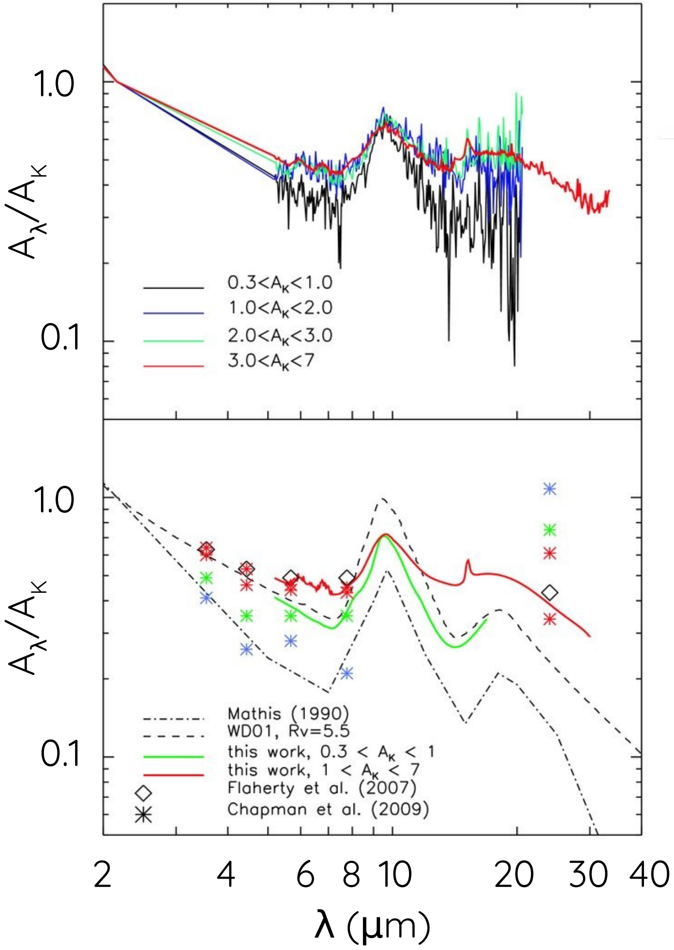

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Carbon accretion ?

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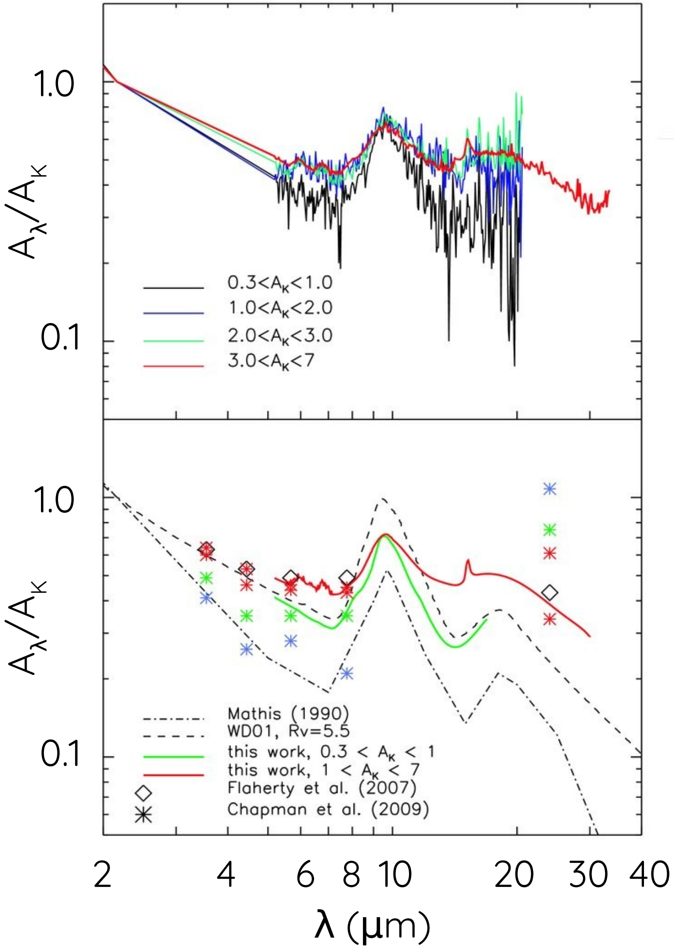

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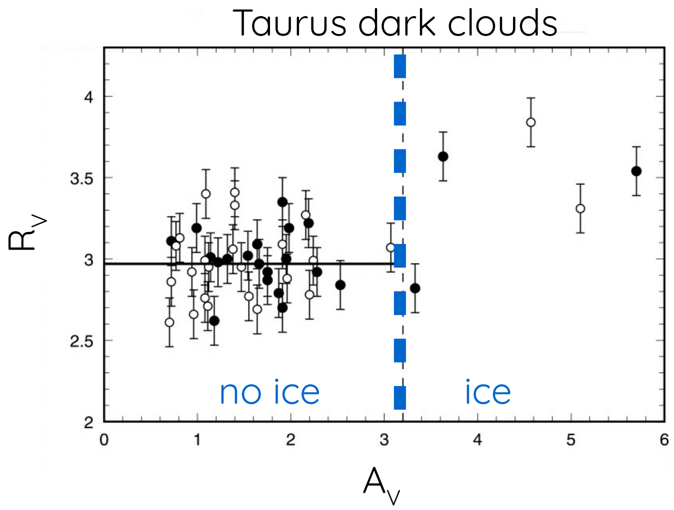
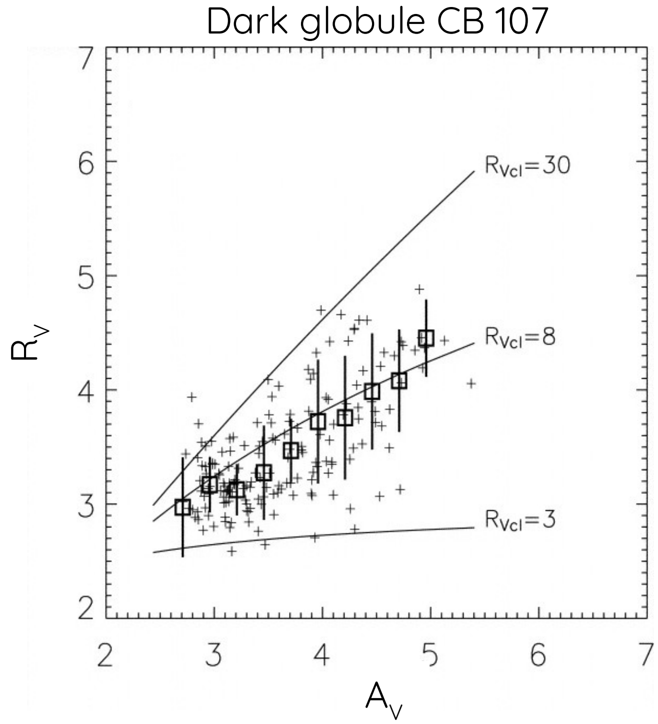
Grain size cannot exceed ~ 1 μm
Carbon accretion ?
Carbon and ice accretion ?
From isolated grains to icy aggegates ?
→ widening only of the 18 μm band

Variations in total-to-selective extinction R_V

Whittet et al. (2001)



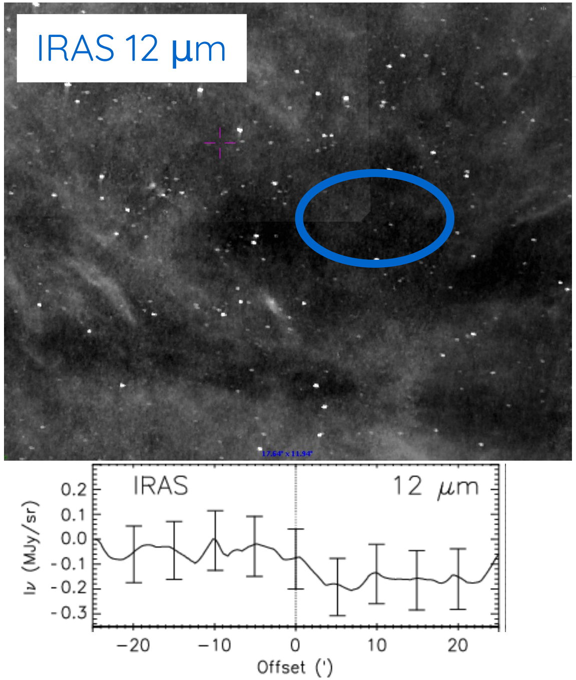
Campeggio et al. (2007)



- Increase in R_V with A_V
- Increase when water ice features are detected

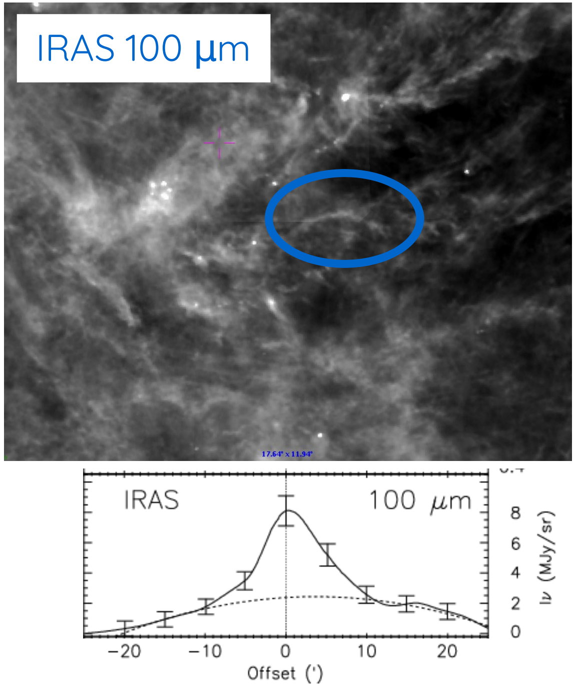
↳ **Grain growth** **associated to ice accretion**

Variations in the mid- to far-IR SED
Stepnik et al. (2003)



Taurus molecular cloud

L1506 filament



- No emission in from the mid-IR to ~ 70 µm
  → small grains disappear from the diffuse to the dense ISM

↳ **Small grain accretion onto larger grains → grain growth**

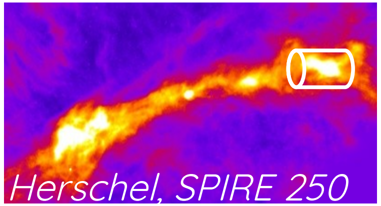
Visible extinction vs. far-IR SED
Ysard et al. (2013)

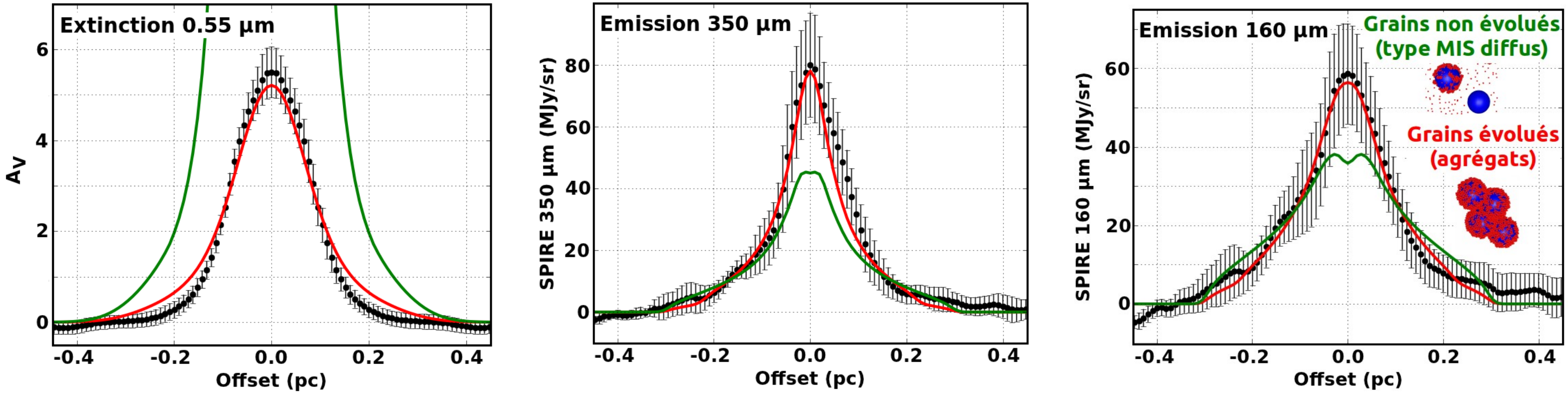
- Aggregates for $1000 < n_H < 2000$ H/cm^3
  → A_V ~ 2 to 4

- Same as increase in R_V, ice features, mid-IR silicate bands

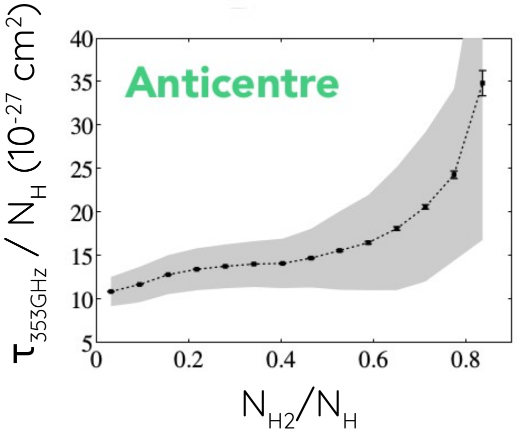
→ **Grain growth**
→ **From isolated grains to aggregates**

Ysard et al. (2013)



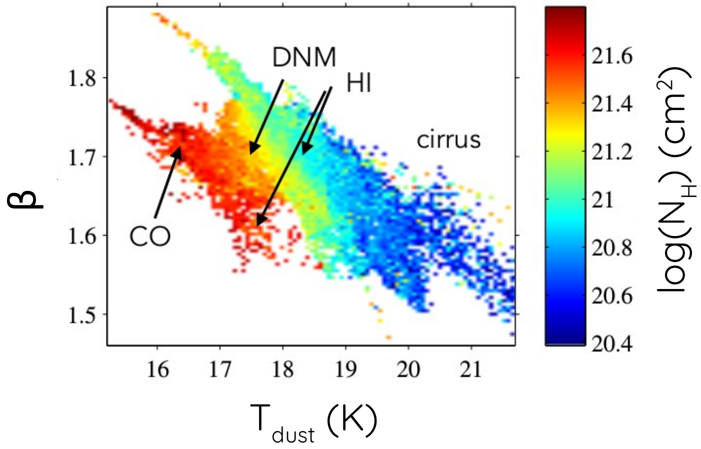


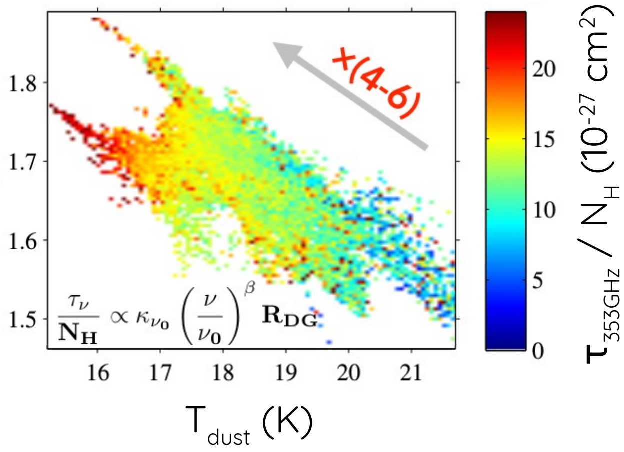
Variations in the far-IR SED
Rémy et al. (2017, 2018)



- Observations of 6 nearby anti-centre clouds
- Usual behaviour of dense clouds
  - → T_{dust} ↘
  - → $\tau_{submm/FIR}$ and β ↗

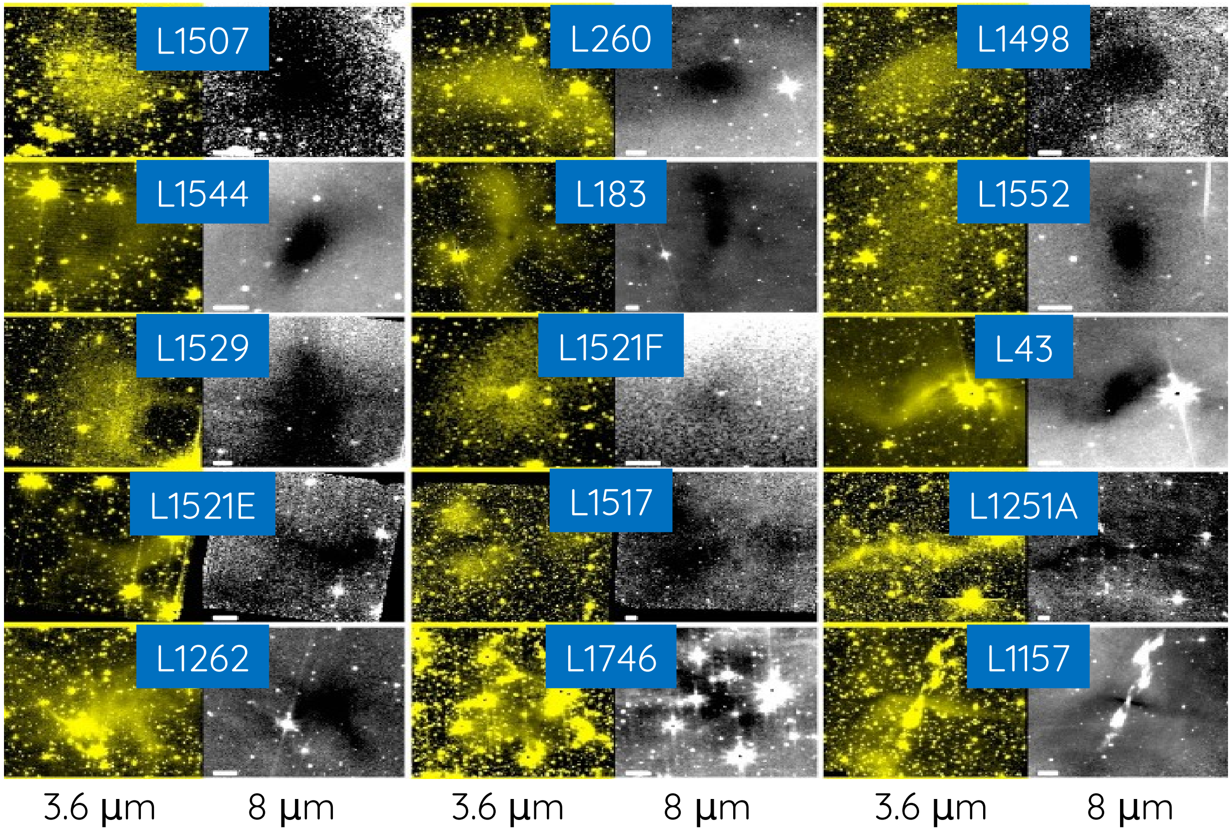
Grain growth
From isolated grains to aggregates
Carbon accretion ? DCD-TLS ?





- Gradual evolution across phases
  significant in DNM
  stronger in CO

Variations in the dust scattering efficiency
Cloud- & Core-shine

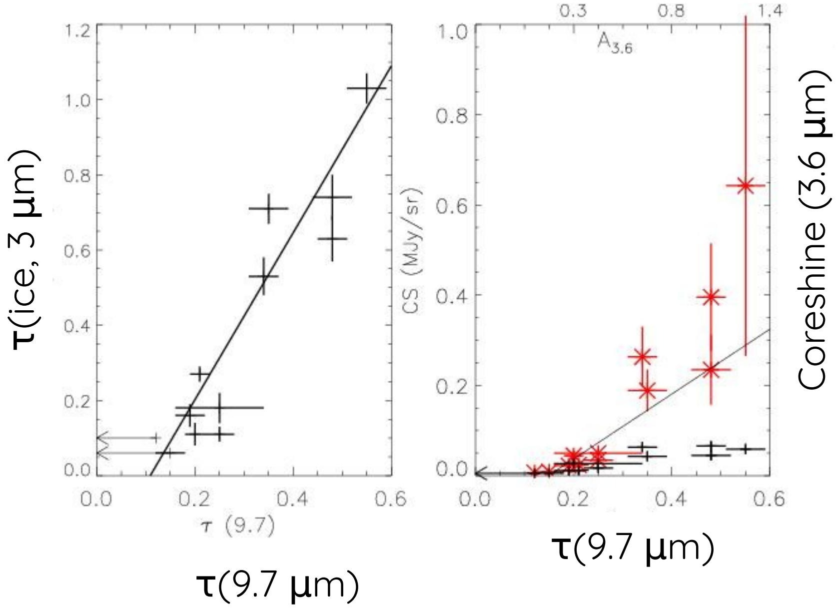


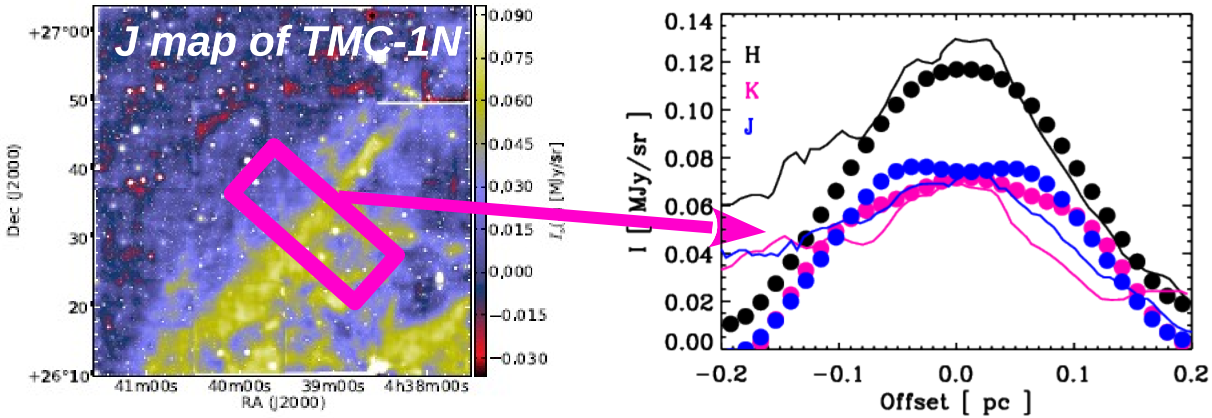
- In the visible: 30’s
  Struve & Elvey (1936)
- In the near-IR: 90’s
  Witt et al. (1994)
- In the mid-IR: 2010
  Pagani et al. (2010)
- Albedo and asymmetry parameter
  Mattila (1970ab, 2018)
- Scattering by bigger grains than in the diffuse ISM
  Steinacker et al. (2010)
  Lefèvre et al. (2014)

Grain growth

Variations in the dust scattering efficiency
Andersen et al. (2014) & Ysard et al. (2016)

- Andersen et al. (2014)
  → common density threshold for coreshine & ice feature at 3 μm
- Ysard et al. (2016)
  need for aggregates when $1000 < n_H < 2000$ H/cm^3
  → $A_V \sim 2$ to 4





Malinen's data

•••••• THEMIS model

Grain growth
Aggregates?
Ice accretion ?
Carbon accretion ?

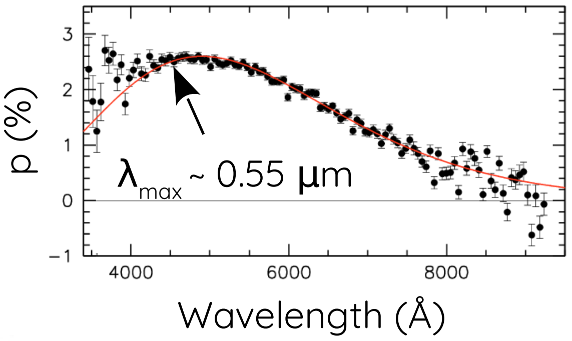
Variations in the visible starlight polarisation
Vaillancourt et al. (2020)

- Linear polarisation of starlight in the visible
  → λ_{max} proportional to aligned <grain size>

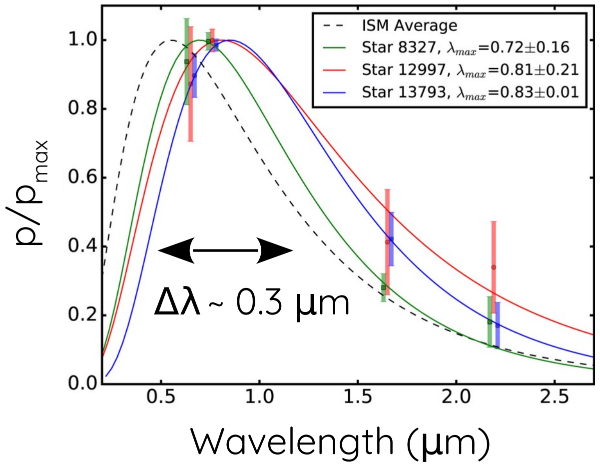
- Increase in λ_{max} & decrease in $p_{max}/E(B-V)$ in dense clouds
  → threshold around A_V = 3-4

↳ **Grain growth**

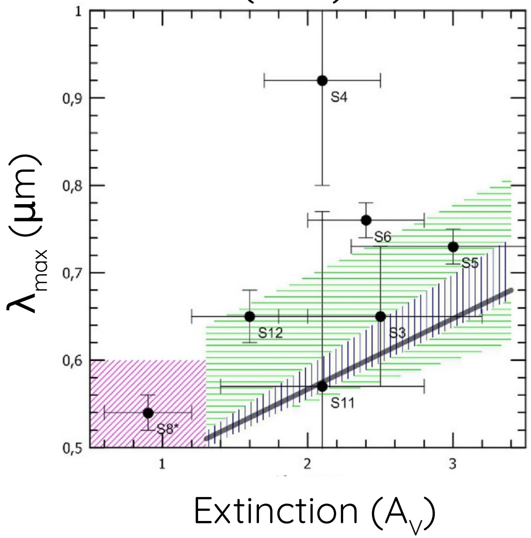
Patat et al. (2010): diffuse ISM



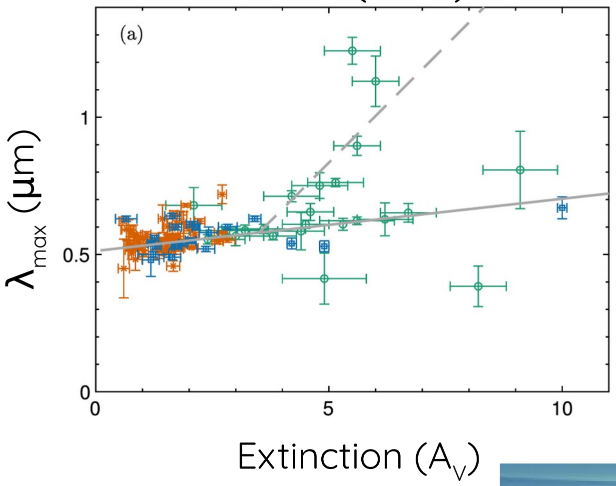
Wang et al. (2017): dark cloud IC5146



Il'in et al. (2018): Barnard 5



Vaillancourt et al. (2020): Taurus MC



Variations in dust polarisation
Fanciullo et al. (2017), Juvela et al. (2018)

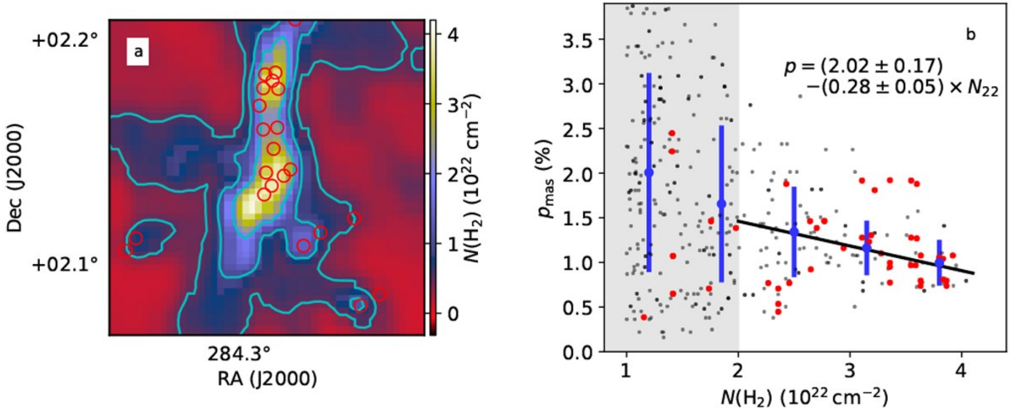
- Lower polarisation fraction P/I than in diffuse ISM
  → sharp drop above $N_H \sim 2\times10^{22}$ H/cm^2

- Decrease in efficiency of grain alignement with the magnetic field

- Fanciullo et al. (2017): P/p to constrain grain properties
  → increase in size not enough => structure, composition

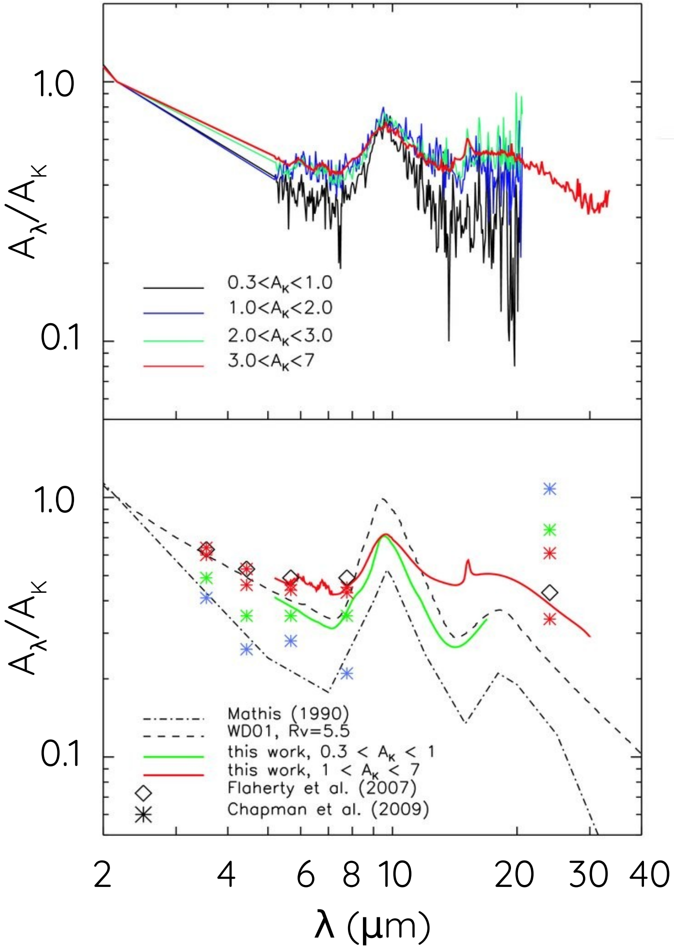
Grain growth to 0.8 – 1 µm
Aggregates?
Ice accretion ?

Juvela et al. (2018): massive IRDC G035.39-00.33



GRAIN SIZE DETERMINATION
Effects of grain structure

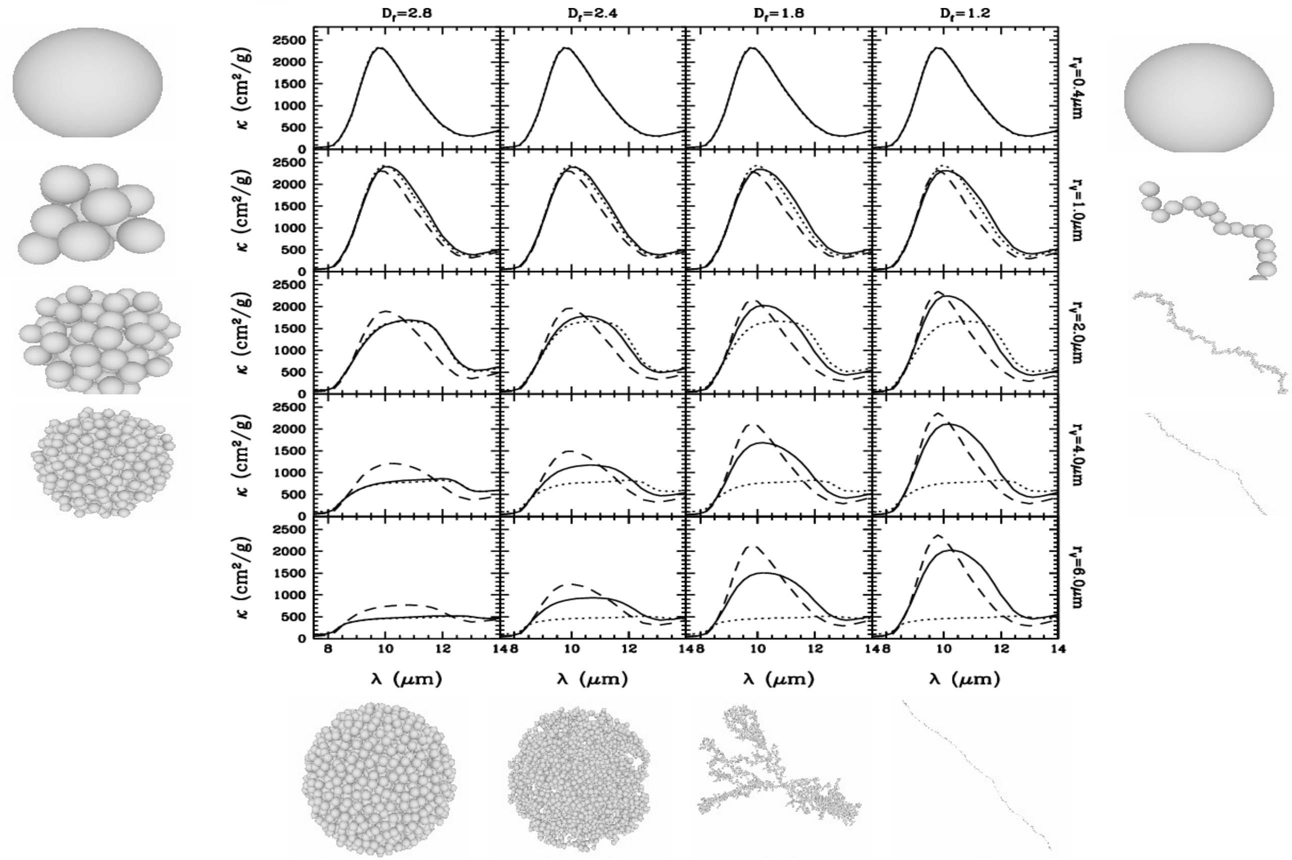
Exemple: silicate mid-IR features
McClure (2009) → observations



- Broader features than in the diffuse ISM
- Lower constrast with continuum

⇨ significant grain growth ?

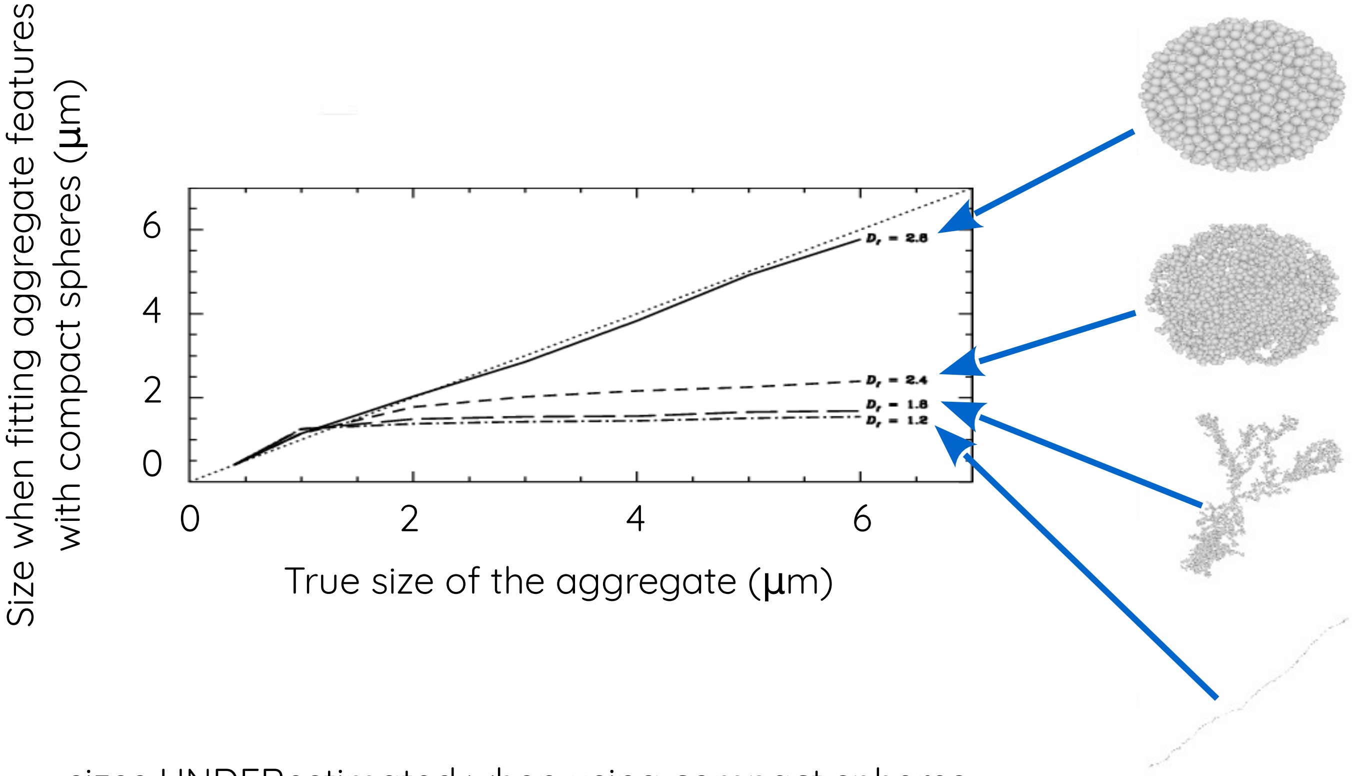
Exemple: silicate mid-IR features
Min et al. (2016) → fractal dimension



—— aggregate
– – volume equivalent compact sphere
········ equivalent porous sphere

amorphous "olivine"
monomer radius a_0 = 0.4 μm

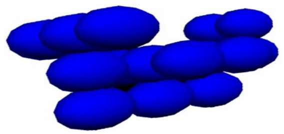
Exemple: silicate mid-IR features
Min et al. (2016) → fractal dimension

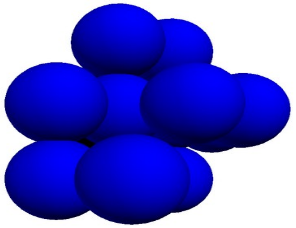


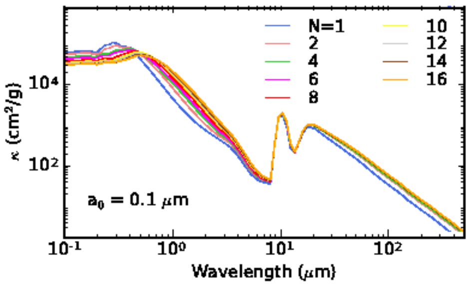
→ sizes UNDERestimated when using compact spheres
sizes OVERestimated when using porous spheres

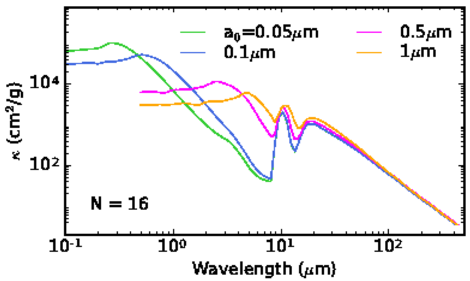
Exemple: silicate mid-IR features
Ysard et al. (2018) → monomers

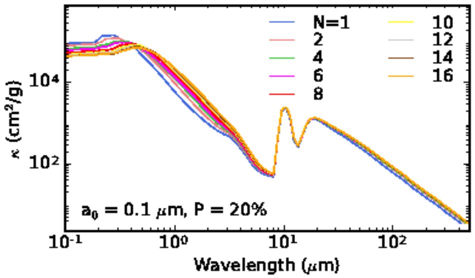
- Amorphous olivine
- Aggregates with D_f = 2.5
- Three monomer shapes: spheres, oblates, prolates
- Four monomer sizes: a_0 = 0.05, 0.1, 0.5, and 1 μm
- Porous monomers: 20% of vacuum

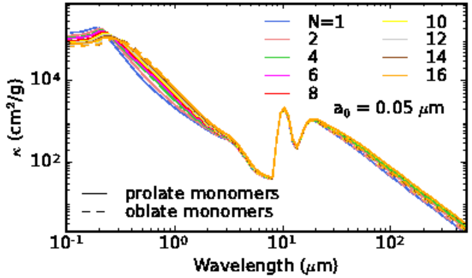












Exemple: silicate mid-IR features
Ysard et al. (2018) → monomers

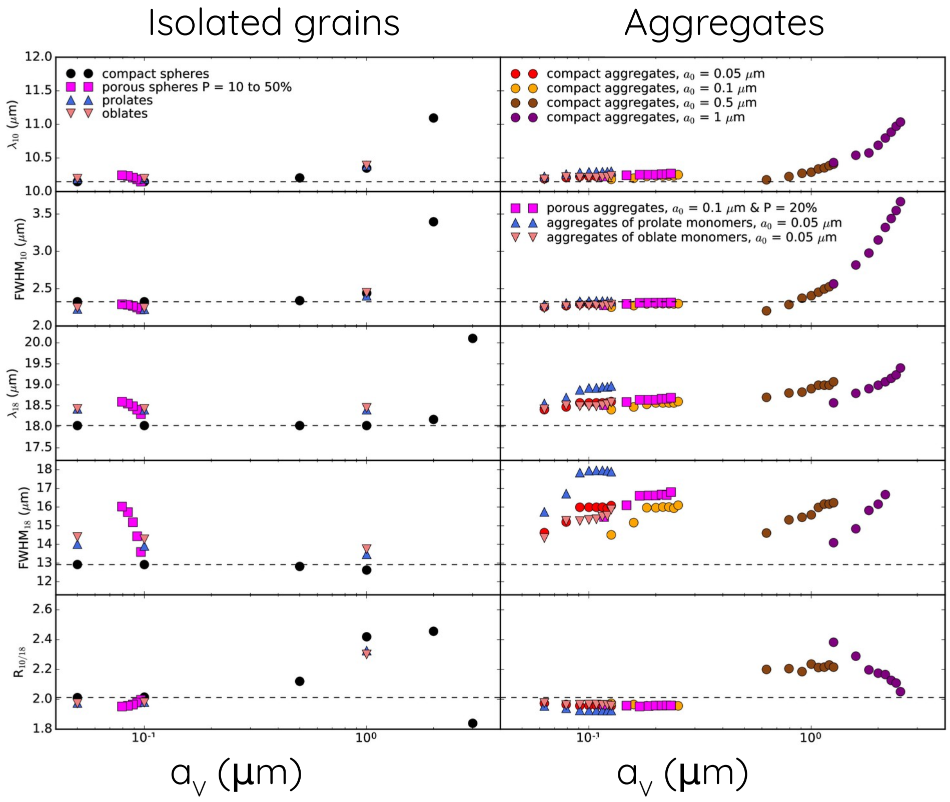
10 μm feature peak position

10 μm feature width

18 μm feature peak position

18 μm feature width

κ_{10}/κ_{18}



→ Very difficult to determine grain shapes and sizes from the mid-IR features only

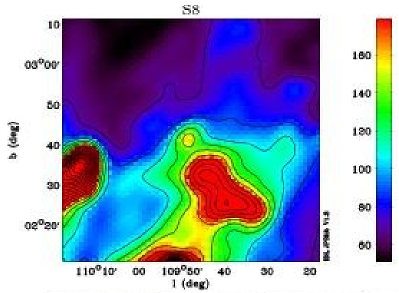
CLOUD MASS DETERMINATION
Effects of size distribution & grain composition

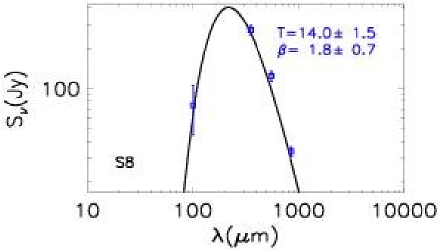
→ following figures based on Ysard et al. (2018, 2019)

Many mass estimates based on MBB fits

- Mass estimates based on modified blackbody fits for dense ISM regions
  - ↳ molecular clouds & prestellar cores (e.g. Planck Collaboration 2011 XXII)
  - ↳ young stellar objects & protoplanetary discs (e.g. Busquet et al. 2019)

- Assume a dust opacity at a given wavelength
  - ↳ pb. 1: depends on grain size distribution
  - ↳ pb. 2: depends on grain composition
  - ↳ pb. 3: depends on grain structure
  - ↳ pb. 4: depends on temperature distribution





Why is it important to determine n(a) ?
And not only a_{max}

- Mass estimates based on modified blackbody fits for dense ISM regions
  - ↳ molecular clouds & prestellar cores (e.g. Planck Collaboration 2011 XXII)
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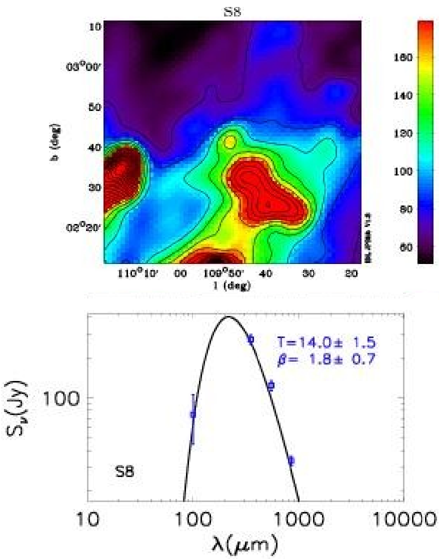

- Assume a dust opacity at a given wavelength
  - ↳ **pb. 1: depends on grain size distribution**
  - ↳ pb. 2: depends on grain composition
  - ↳ pb. 3: depends on grain structure
  - ↳ pb. 4: depends on temperature distribution

- Classical choice for pb. 1: power-law size distribution
  - ↳ Weidenschilling (1997)
  - ↳ Natta & Testi (2004)
  - ↳ Draine (2006)
  - ↳ ...

What do the latest laboratory experiments tell us?

Coagulation model based on laboratory results

- Modelling question
  - ↳ shape of the size/mass distribution?
  - ↳ a_{min}? a_{max}?
- Solution based on lab: Lorek et al. (2018)
  - ↳ local growth of grains in discs
  - ↳ mass distribution
- Laboratory inputs
  - ↳ Güttler et al. (2010)
  - ↳ Windmark et al. (2012)

  } outcomes of grain-grain collisions (Δv, $a_{projectile}$, a_{target}): sticking, bouncing, fragmentation, erosion, mass transfer

  - ↳ Güttler et al. (2010)
  - ↳ Blum & Wurm (2008)
  - ↳ Gundlach et al. (2011)
  - ↳ Gundlach & Blum (2015)

  } sticking properties of water ice and silicate monomers

  - ↳ Güttler et al. (2009)
  - ↳ Weidling et al. (2009)
  - ↳ Landeck (2016)

  } bouncing of aggregates rather than just compact grains
- Model of Lorek et al. (2018)
  - ↳ monomer size (0.1 or 1 μm)
  - ↳ radial position in the disk
  - ↳ turbulence
  - ↳ gas surface density...

  → pebble sizes in agreement with pebbles on comet 67P/Churyumov-Gerasimenko (Poulet et al. 2016)

Coagulation model based on laboratory results

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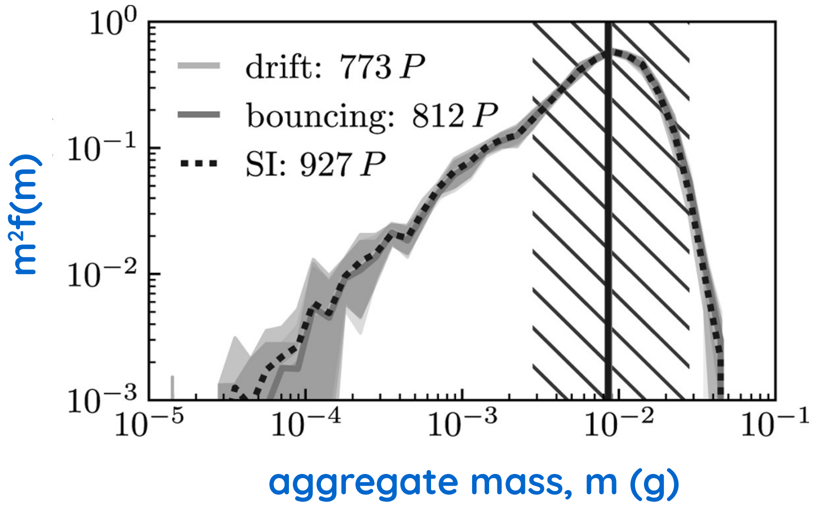
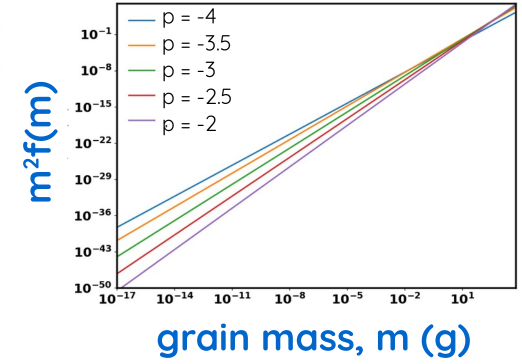


0.1 µm monomers
dust-to-ice ratio = 5
R_{disc} = 30 AU

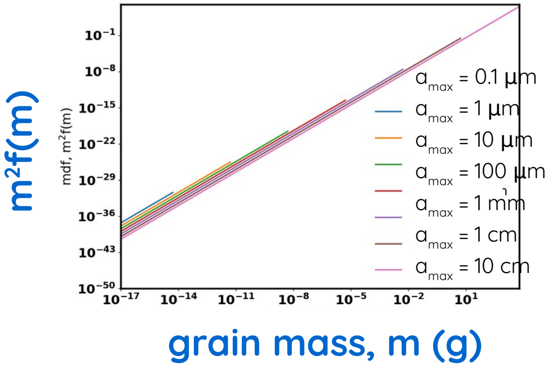
→ strong departure from a classical power-law size/mass distribution

Influence on the dust opacity in the millimetre

Power-law size distribution

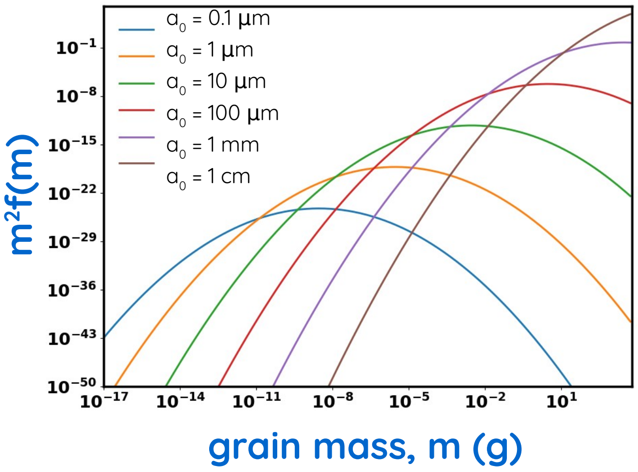


$$\frac{dm}{da} \propto a^{p}$$



$$\frac{dm}{da} \propto a^{-3.5}$$

Log-normal size distribution



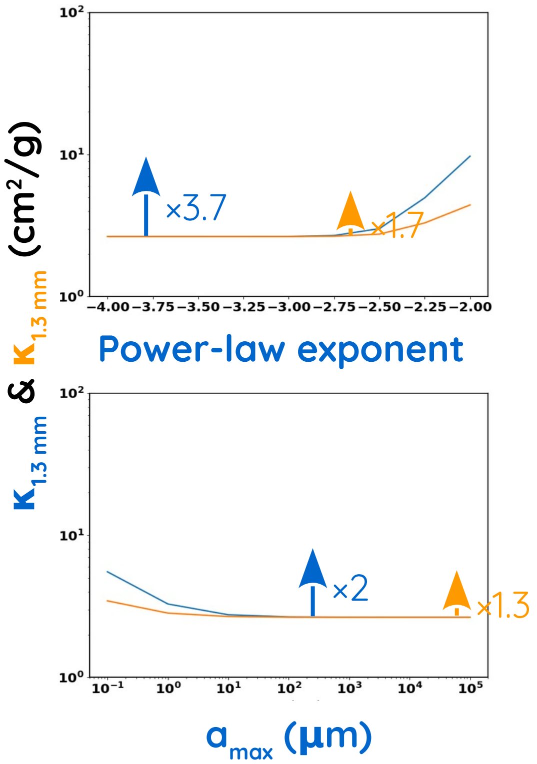
$$\frac{dm}{da} \propto \exp\left\{-\frac{1}{2}\left[\frac{\ln(a/a_0)}{\sigma}\right]^2\right\}$$

In both cases: a_{min} = 0.01 µm, a_{max} = 10 cm, M_{gas}/M_{dust} = 100

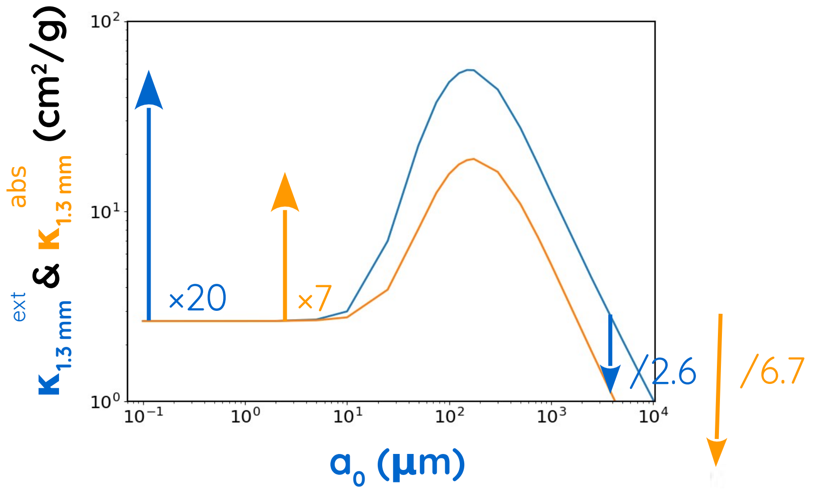
2/3 silicate + 1/3 amorphous carbon + 50% porosity → spherical grains

Influence on the dust opacity in the millimetre

Power-law size distribution



Log-normal size distribution



$$\kappa^{ext}\,[cm^2/g] = \frac{3}{4\rho}\,\frac{Q_{abs} + Q_{sca}}{a}$$

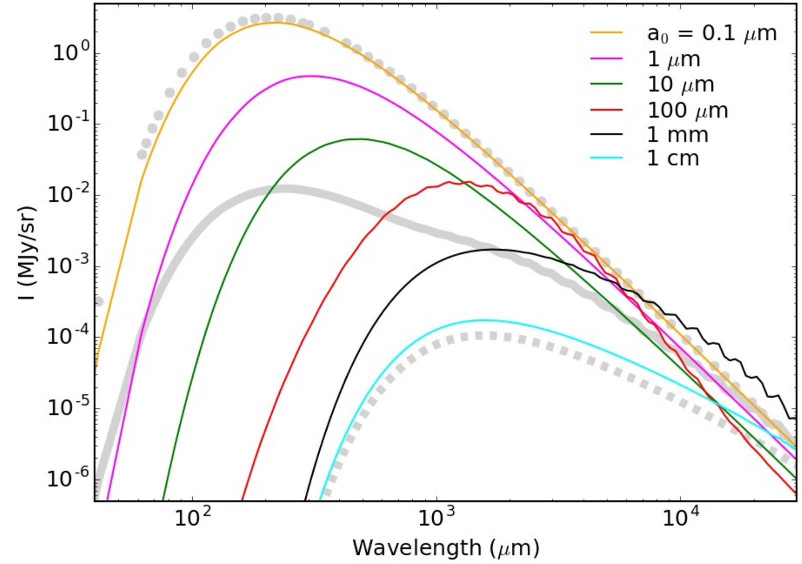
$$\kappa^{abs}\,[cm^2/g] = \frac{3}{4\rho}\,\frac{Q_{abs}}{a}$$

In both cases: a_{min} = 0.01 µm, a_{max} = 10 cm, M_{gas}/M_{dust} = 100

2/3 silicate + 1/3 amorphous carbon + 50% porosity → spherical grains

Influence on the dust SED

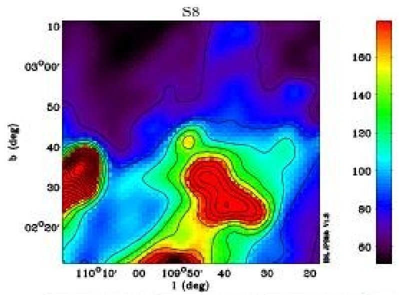
Power-law size distribution: p = -3.5 with a_{max} = 1 µm
p = -3.5 with a_{max} = 10 cm
p = -2 with a_{max} = 10 cm

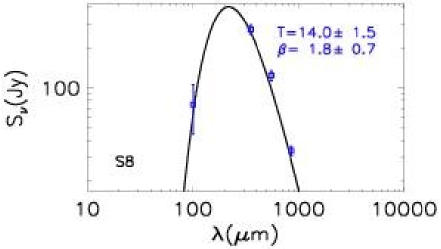


Log-normal size distribution: a_{min} = 0.01 µm, a_{max}= 10 cm and variable a_0

Why is it important to determine the grain composition ?
And not only their size

- Mass estimates based on modified blackbody fits for dense ISM regions
  - ↳ molecular clouds & prestellar cores (e.g. Planck Collaboration 2011 XXII)
  - ↳ young stellar objects & protoplanetary discs (e.g. Busquet et al. 2019)

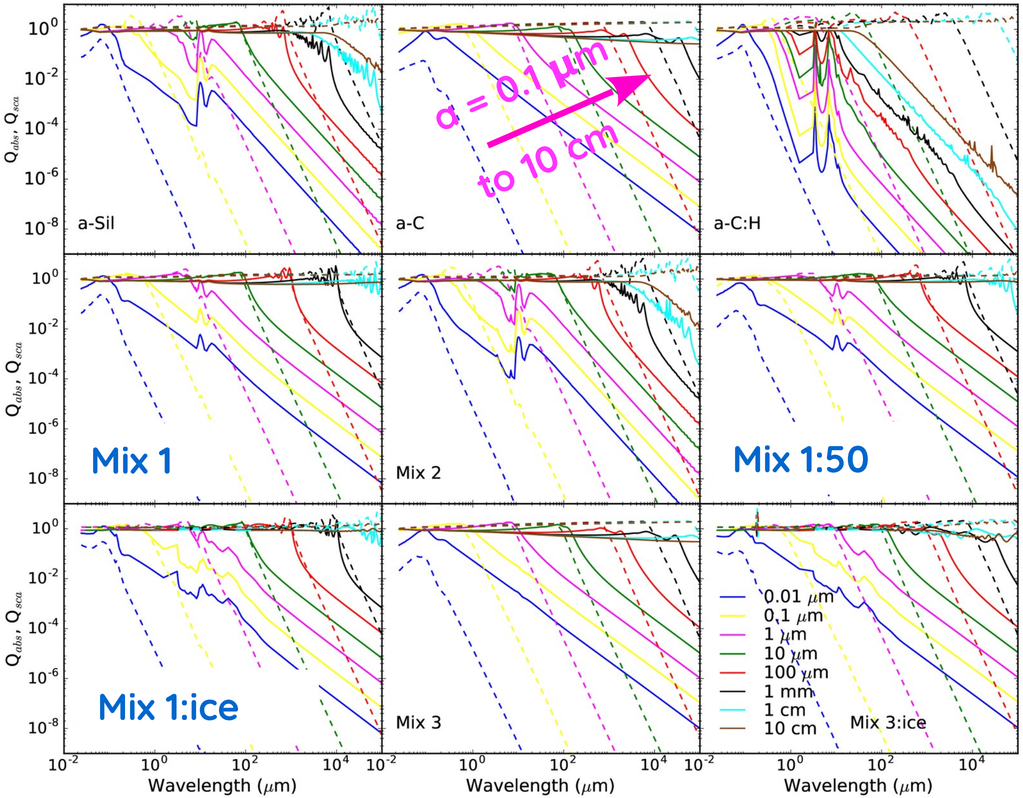




- Assume a dust opacity at a given wavelength
  - ↳ pb. 1: depends on grain size distribution
  - ↳ **pb. 2: depends on grain composition**
  - ↳ pb. 3: depends on grain structure
  - ↳ pb. 4: depends on temperature distribution

- Classical choice for pb. 2: fixed κ value with fixed β
  - ↳ any dust model from the litterature

Absorption and scattering efficiencies

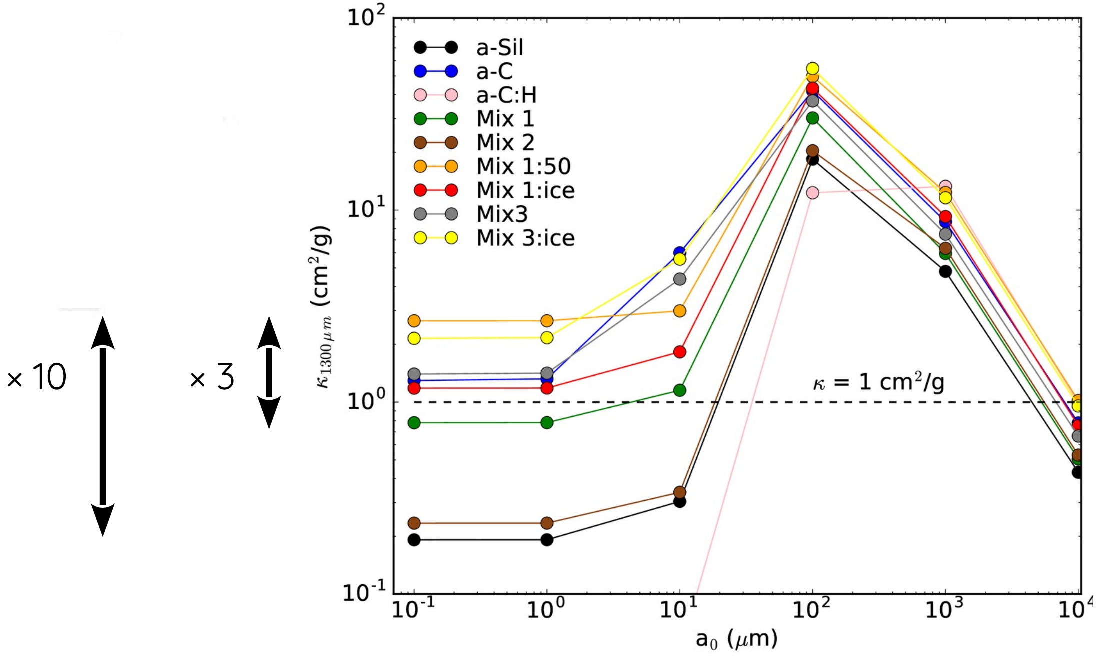


Mix 1 ~ compact AMM
Mix 1:50 ~ AMM
Mix 1:ice ~ compact AMMI

Mix 3 & Mix 3:ice ~ Pollack (1994)

a-Sil →THEMIS amorphous silicates
a-C→THEMIS Eg = 0.1 eV
a-C:H →THEMIS Eg = 2.5 eV
Mix 1 → 2/3 aSil + 1/3 a-C
Mix 2 → 2/3 aSil + 1/3 a-C:H
Mix 1:50 →porous Mix 1 ~ AMM
Mix 1:ice →Mix 1 with an ice mantle
Mix 3 → 20% a-Sil + 80% a-C
Mix 3:ice →Mix 3 with an ice mantle

Mass absorption coefficients at 1.3 mm

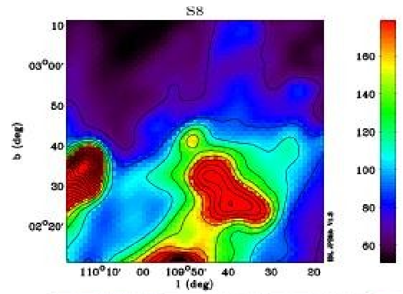


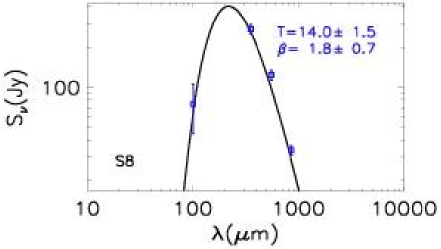
$$\frac{\mathrm{Mgas}}{\mathrm{Mdust}} = 100$$

$$\frac{dn}{da} \propto \exp\left\{-\frac{1}{2}\left[\frac{\ln(a/a_0)}{\sigma}\right]^2\right\}$$

Why is it important to determine the grain composition ?
And not only their size and composition

- Mass estimates based on modified blackbody fits for dense ISM regions
  - ↳ molecular clouds & prestellar cores (e.g. Planck Collaboration 2011 XXII)
  - ↳ young stellar objects & protoplanetary discs (e.g. Busquet et al. 2019)



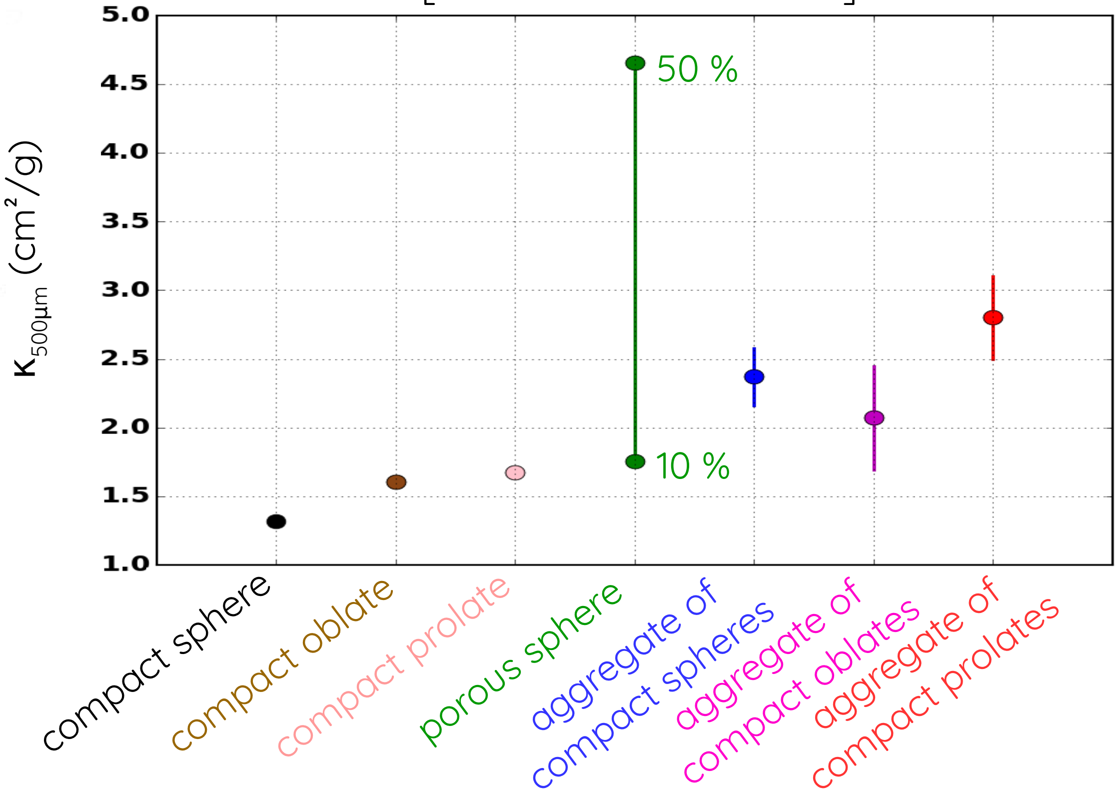


- Assume a dust opacity at a given wavelength
  - ↳ pb. 1: depends on grain size distribution
  - ↳ pb. 2: depends on grain composition
  - ↳ **pb. 3: depends on grain structure**
  - ↳ pb. 4: depends on temperature distribution

- Classical choice for pb. 3
  - ↳ignore the problem

Mass absorption coefficients at 500 µm

100% silicate, mass equivalent size of 0.1 µm
[no size distribution here]



Conclusion

- Dust evolution gradual across all phases
  → BUT biggest changes occur for A_V ~ 3 or n_H ~ a few 1000 H/cm^3

- When ice features start being detected
  → increase in R_V
  → flattening of the mid-IR extinction
  → disappearance of the smallest grains
  → increase in scattering efficiency
  → increase in λ_{max}
  → decrease in P/I
  → increase in depletion

- When modelling dust evolution, many parameters of equal importance
  - composition
  - material “mixture”
  - size distribution
  - grain shape

- No model can reproduce all the variations at once