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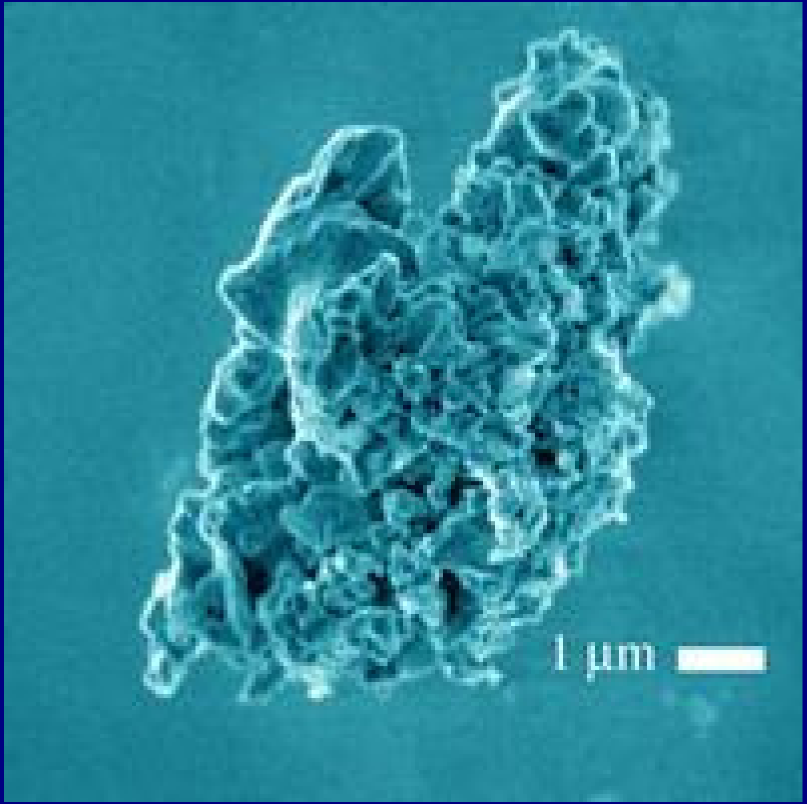
Cosmic Dust
Physical Properties and Laboratory Experiments



From Dust to Galaxies, Paris, June 2011

Motivation
Cosmic Dust Studies

- Dust extinction, polarization, spectroscopy, continuum emission as diagnostic tools

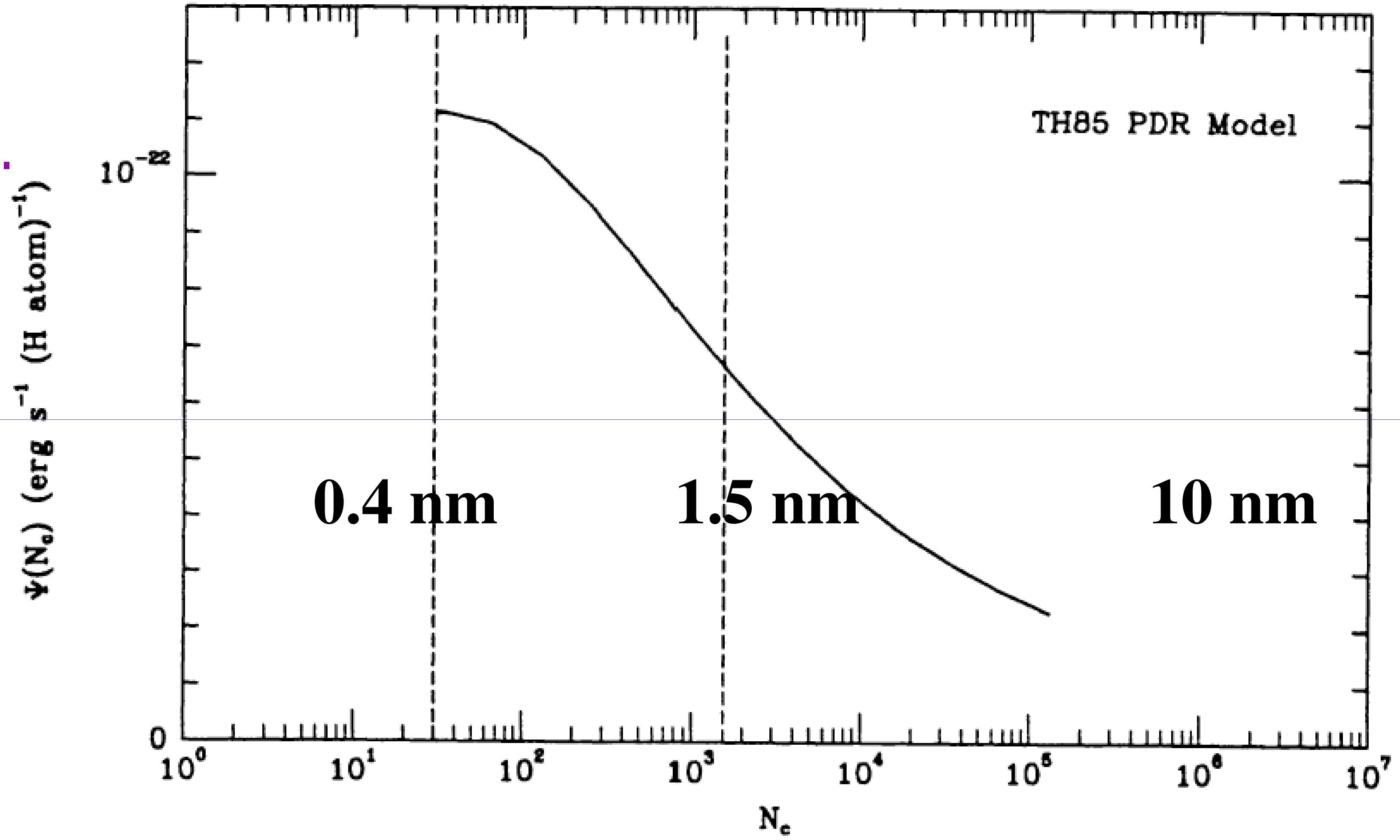
  (Optical depth, mass, magnetic fields, temperature, chemistry, growth processes and mixing, …)

- Thermal, dynamical, and chemical structure

- Interesting structural and optical behaviour

  (Tunneling processes at low temperatures, vacuum cleaner, …)

Photoelectric heating



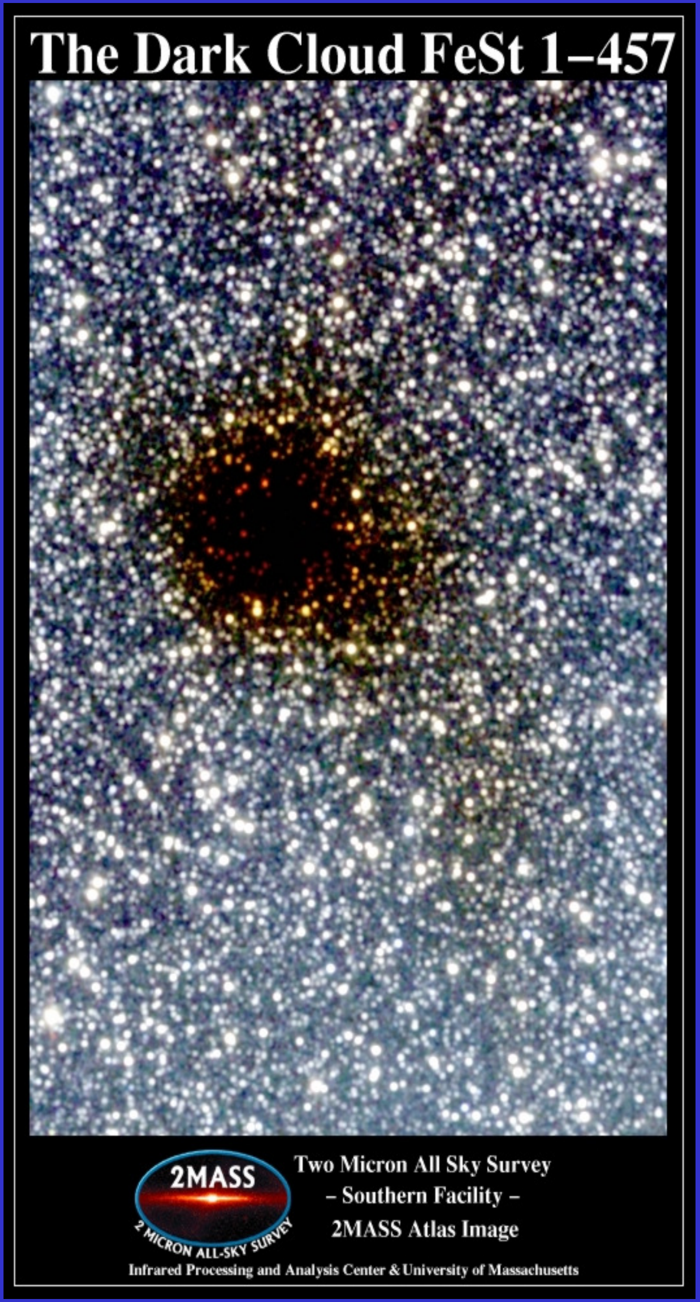
0.4 nm 1.5 nm 10 nm

Bakes and Tielens (1994)

The Facts

- Silicates and carbonaceous ISM dust
- Broad size distribution
- Additional materials in circumstellar envelopes

  (carbides, nanodiamonds, fullerenes, …)
- Molecular ices in cold clouds
- Grain growth in pp disks
- Crystalline silicates and molecular ices in pp disks



(For silicates: Henning, ARAA, 48, 21, 2010)

Dust emission spectrum

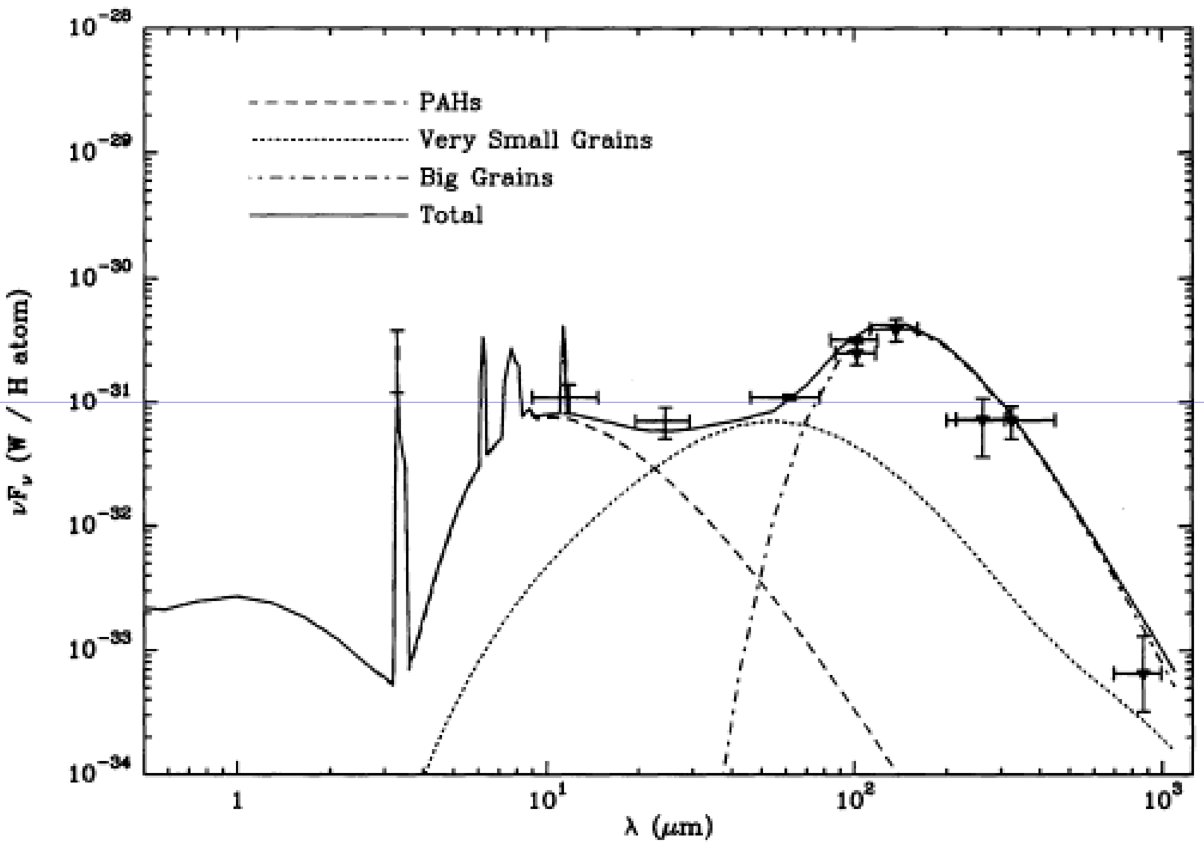
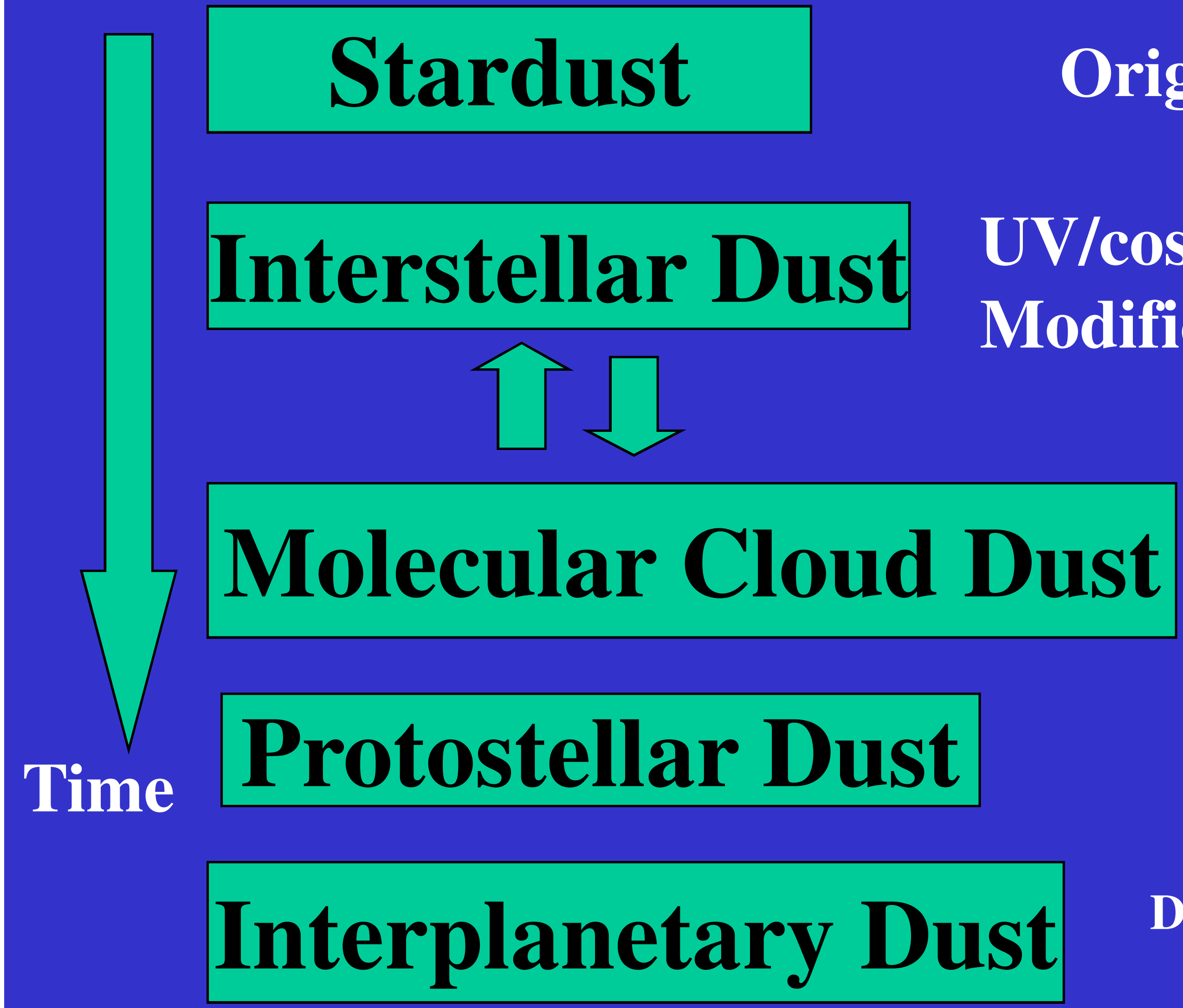


Fig. 4. Dust emission spectrum. Observations (crosses) pertain to the "cirrus" interstellar diffuse medium (see Table 1 and text). The horizontal bars represent the filter width used in the observations (given in Table 1). The model resulting spectrum (continuous line) is the sum of the three components that are PAHs, VSGs, and BGs.

Désert, Boulanger & Puget (1990)
More to come: Compiègne et al. (2011)

Basic Types of Dust Mixtures



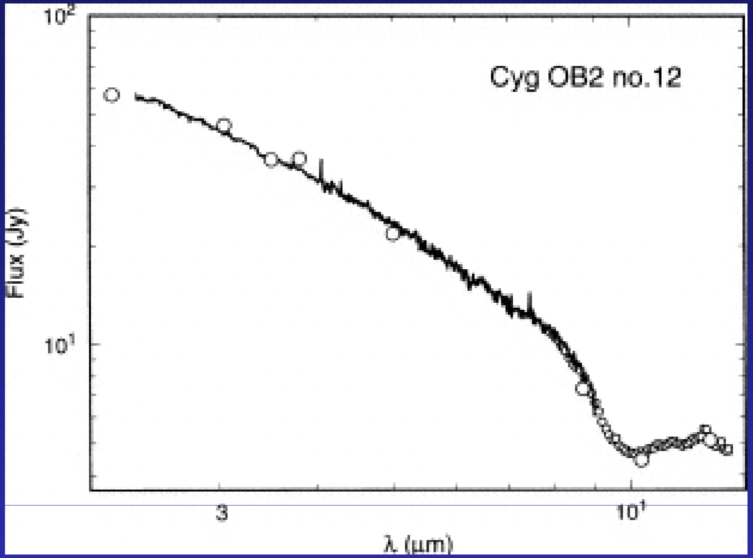
Original dust formation

UV/cosmic ray processing;
Modification by shocks

Surface chemistry;
Ice mantles,
Coagulation

Dorschner & Henning (1995)

Dust in the Diffuse Galactic ISM



Whittet et al. 1997

See Chiar et al. 2000,
Chiar & Tielens (2006),
Van Breemen et al. (2011)

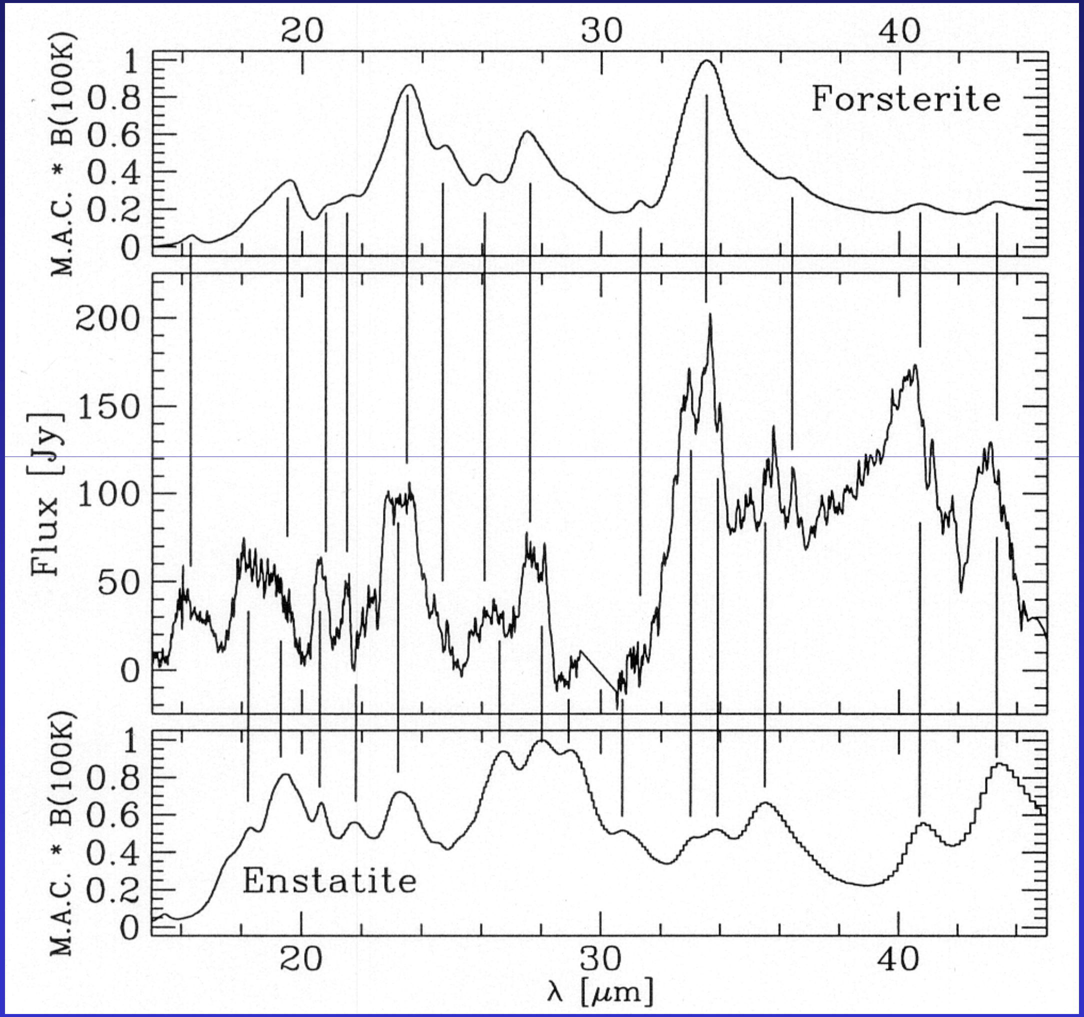
- No evidence for crystalline silicates in the diffuse ISM (<2%, e.g., Li & Draine 2001, Jäger et al. 2003, Kemper et al. 2004)

- Amorphization by cosmic rays/shock processing in ISM/ recondensation of amorphous silicates in the ISM (e.g. Jäger et al. 2003)

- 3.4 micron absorption feature – Aliphatic hydrocarbons (e.g. Pendleton & Allamandola 2002)

Crystalline Revolution (ISO and Spitzer)

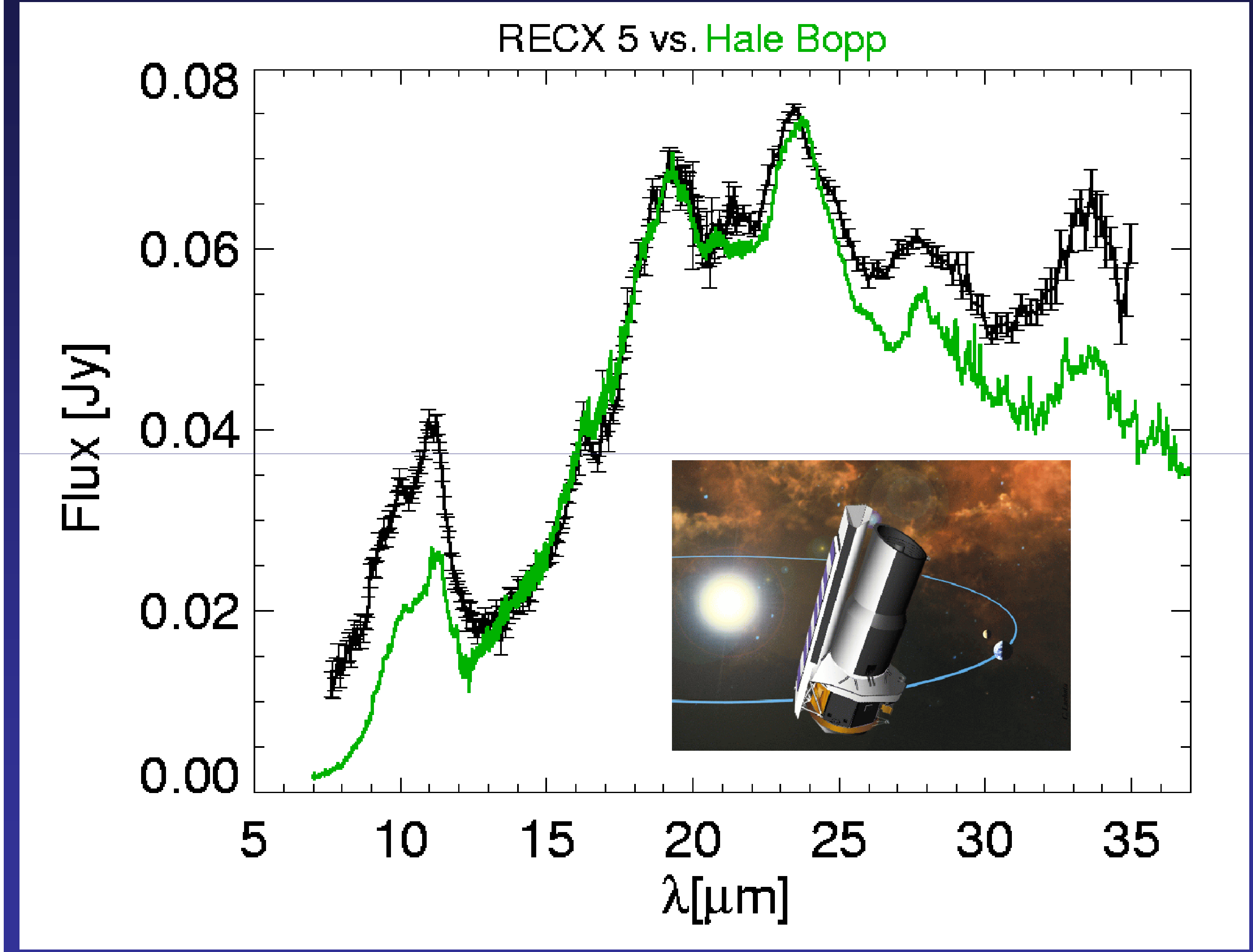
AFGL 4106



T=100 K

Jäger et al. (1998)

RECX5: Hale Bopp Formation around an M4 star?

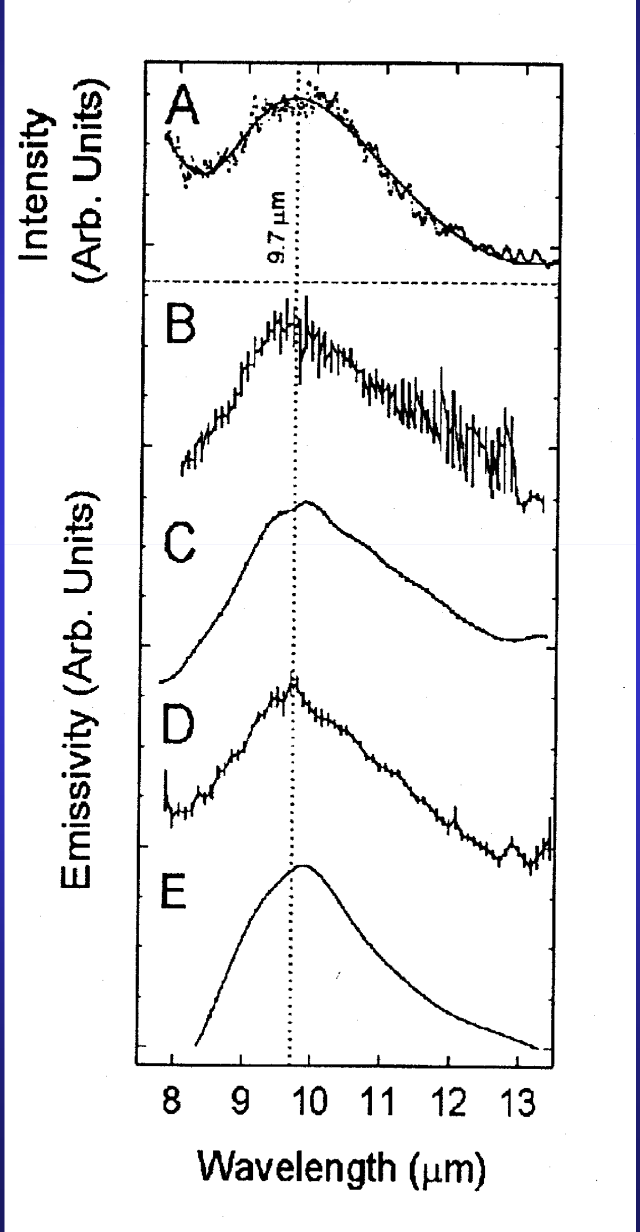


IRS (5-40 μm long slit, R=150, 10-38 μm echelle, R=600)

Crovisier et al. (1997), see also Wooden et al. (1999, 2000)

Bouwman et al. (2010)

Comparison of the 10 µm Si-O stretch band



Spectral ambiguity ….

A	GEMS in IDP L2011*B6
B	Elias 16
C	Trapezium
D	DI Cep (T Tauri star)
E	µ Cep (M supergiant)

GEMS:

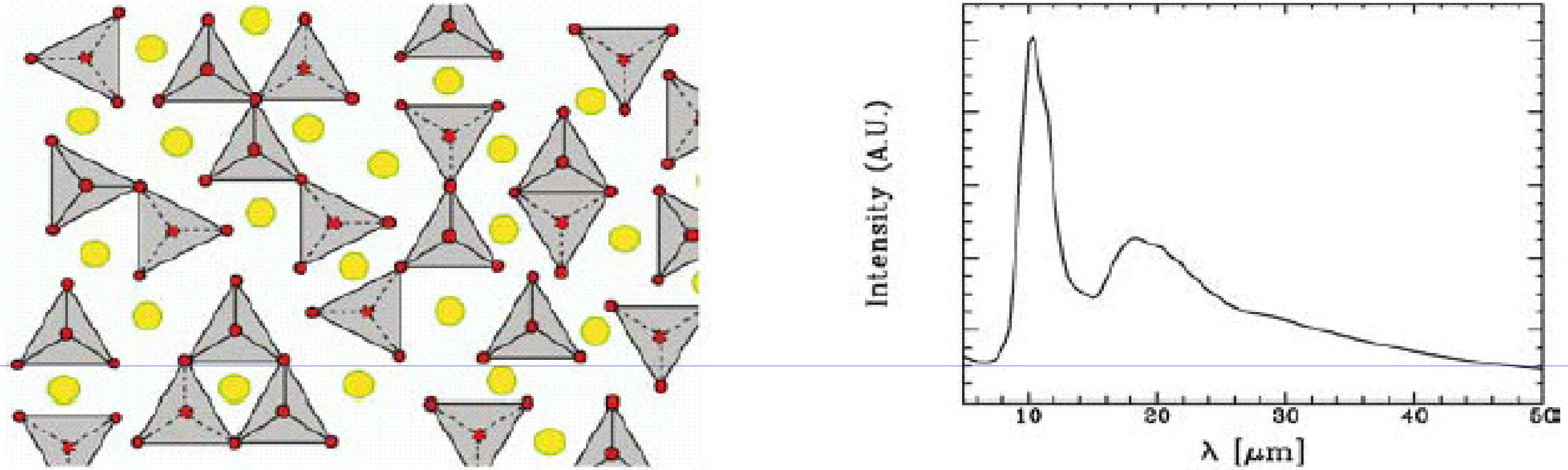
(Mg+Fe)/Si~0.7 (Keller & Messenger 2004)

Mg/Si=0.6 and Fe/Si=0.4 (Ishii et al. 2008)

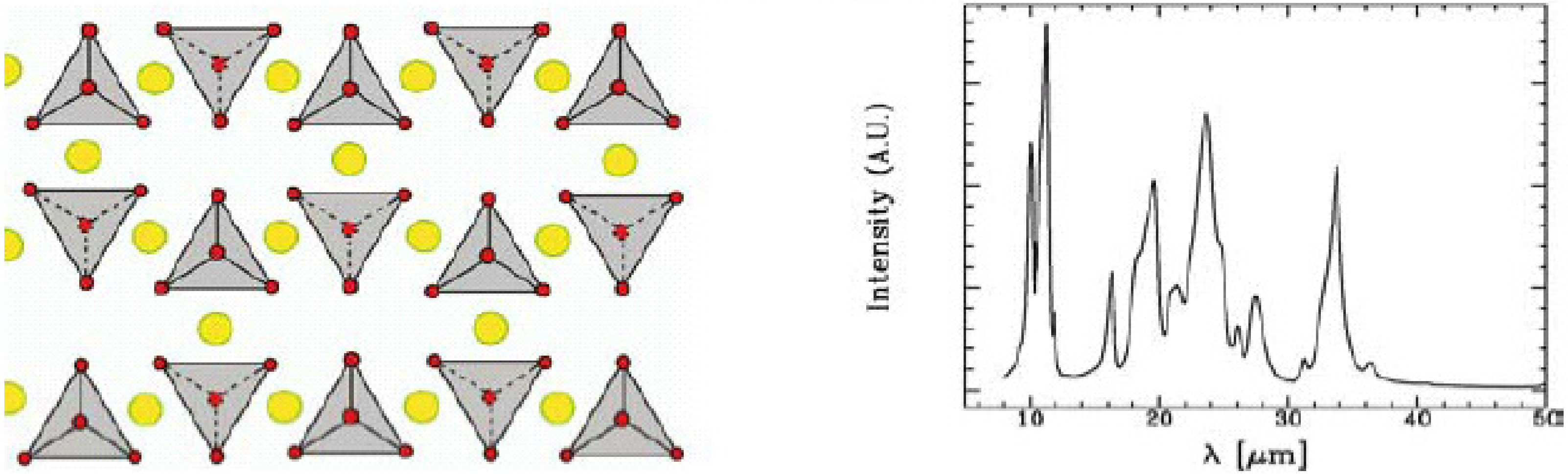
Bradley et al. (1999), Chiar & Tielens (2006), van Breemen et al. (2011)

IR Properties of Silicates – Amorphous vs. Crystalline Structures

Amorphous structure



Crystalline structure



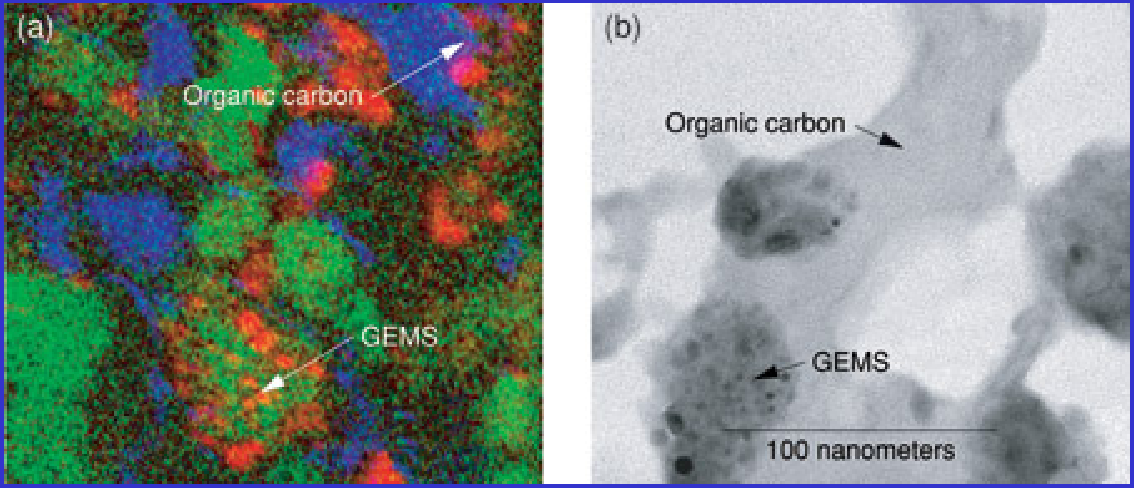
IR Properties of Silicates – Amorphous vs. Crystalline Structures

- 10µm band due to Si-O stretching; position depends on level of SiO_4 polymerization (e.g. band shifts from 9.0 µm for SiO_2 to 10.5 µm for $Mg_{2.4}SiO_{4.4}$ – Jäger et al. 2003)

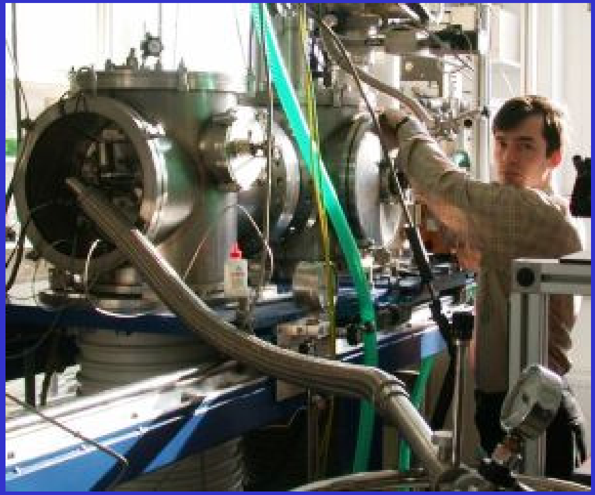
- 18 µm band additionally broadened (coupling of the Si-O bending to the Me-O stretching vibration)

- Crystalline silicates: Bands beyond 20 µm caused by translational motion of metal cations within the oxygen cage and complex translations involving Me and Si atoms

Laboratory Investigations of Cosmic Dust



EELS – Fe (red),
Mg (green), C (blue); J. Bradley/H. Ishii



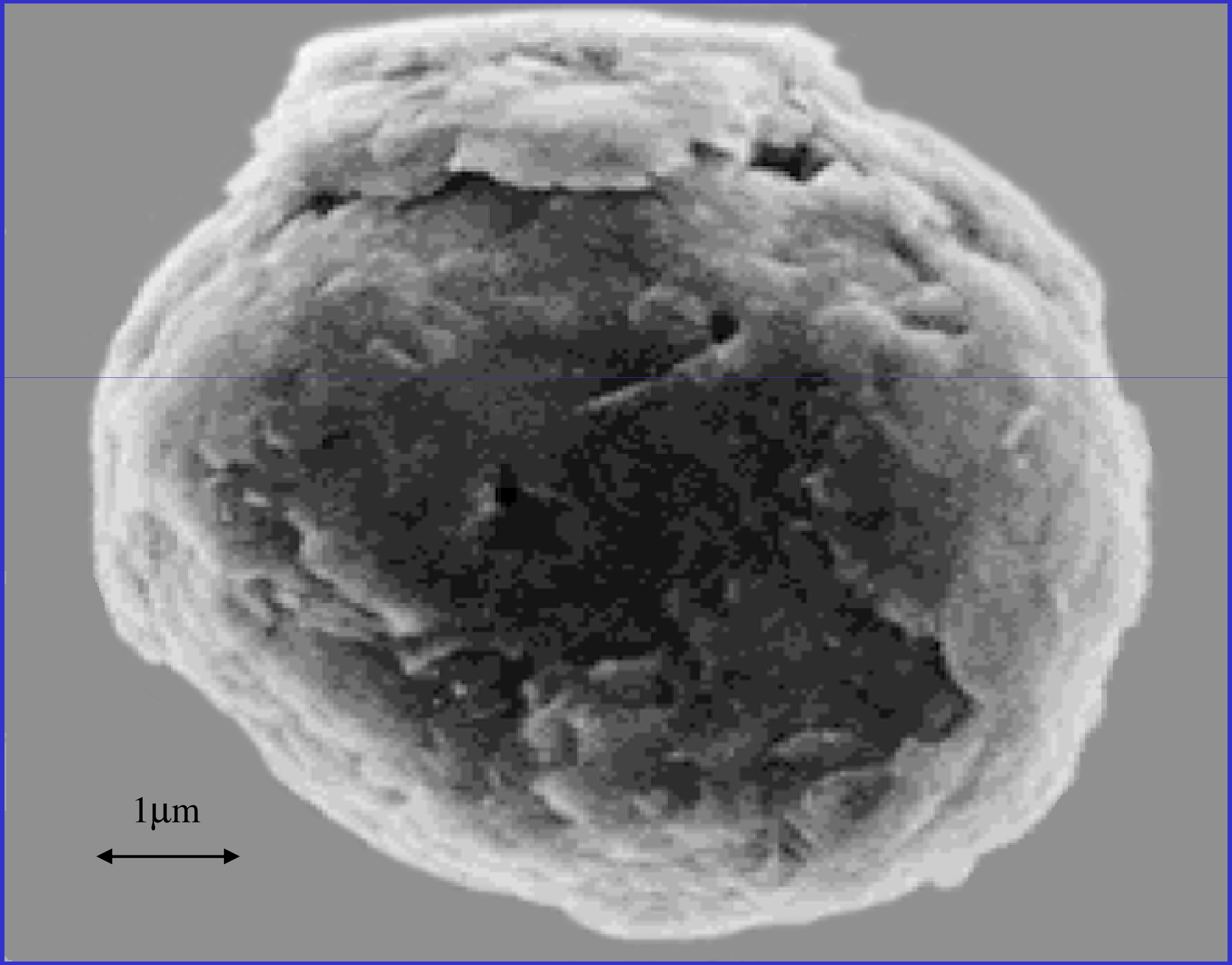
MPIA Jena
He droplet experiment

- Interplanetary dust particles and stardust in meteorites
- Optical properties of cosmic dust analogues
- Formation and modification of dust grains

Stardust in primitive meteorites and IDPs

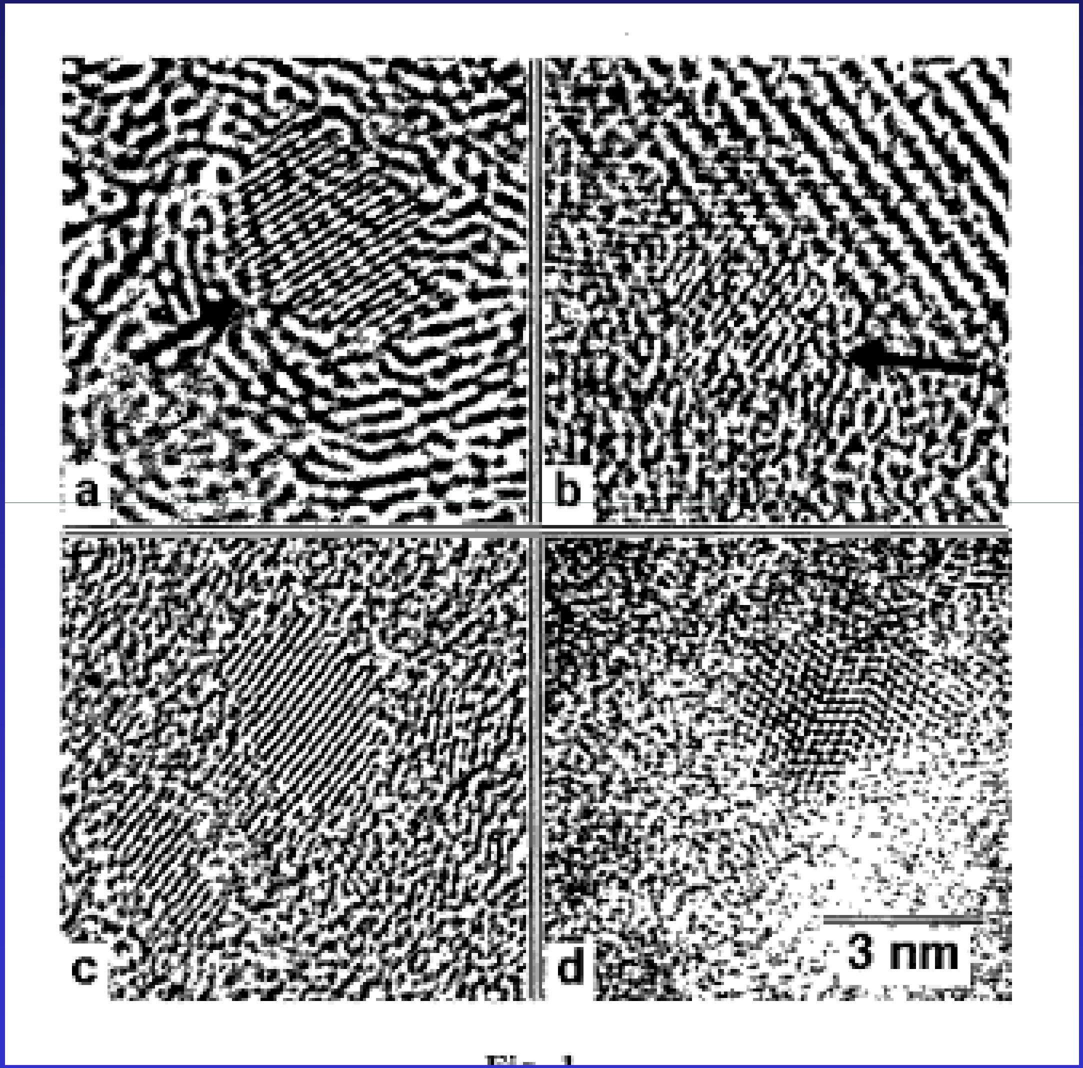
Graphite	10 ppm	1-20 µm	Novae, SN, AGB	
Diamond	1400	0.002	SN(?)	
SiC	14	0.3-20	AGB (mainstream), SN	
Al_2O_3	0.01	0.5-3	Red giants, AGB, SN	
Si_3N_4	0.002	1	SN	

Onion-like presolar graphite particle - Murchison meteorite



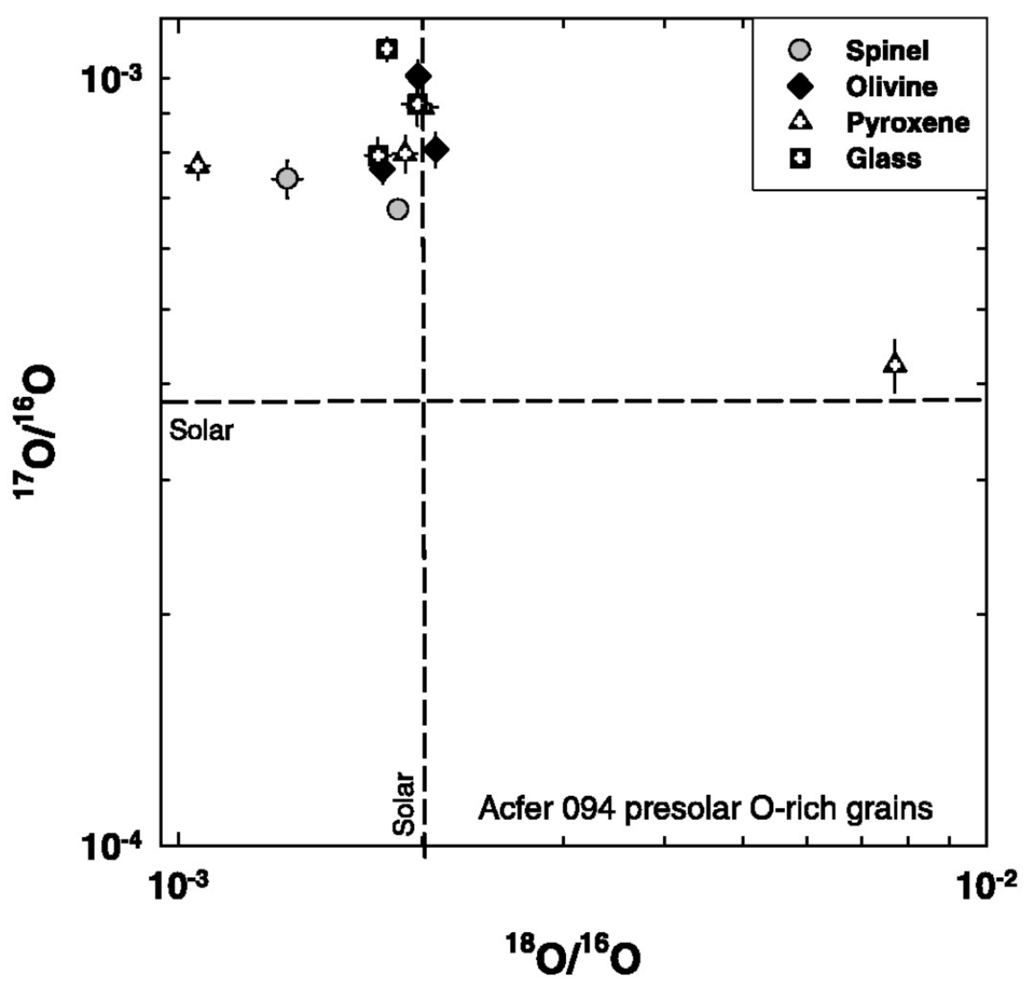
Clayton et al.

Detection of nanodimanonds in unprocessed Allende



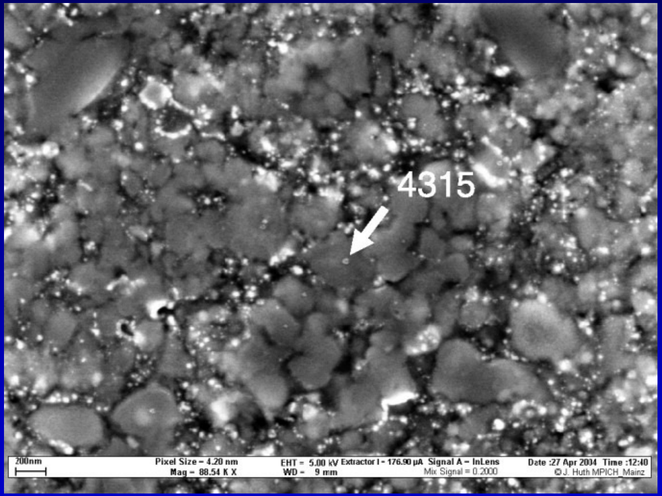
Banhart et al. (1998)

Silicates from Space



AGB or RGB origin

SEM Image



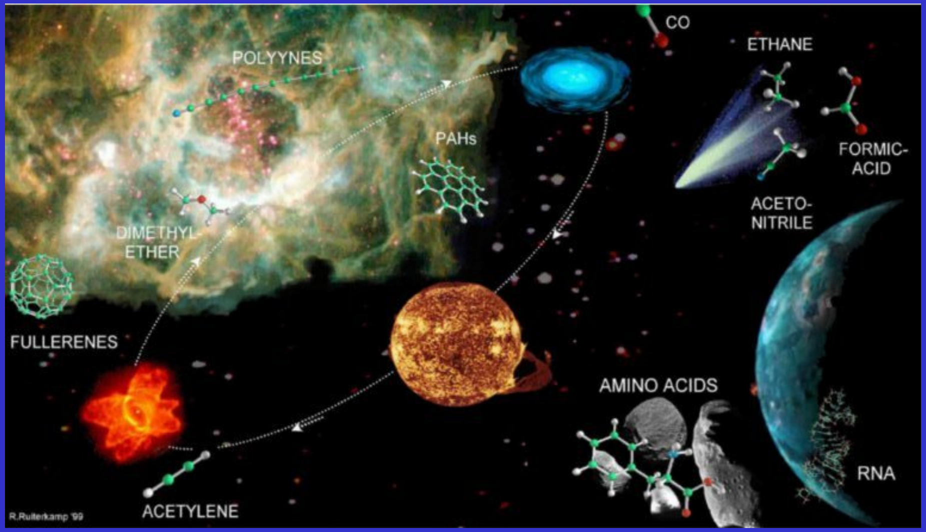
Scale bar: 200 nm

- 3 Olivine grains
- 4 Pyroxene grains
- 3 Glass-like grains

Hoppe et al. 2005

(see also Messenger et al. 2003)

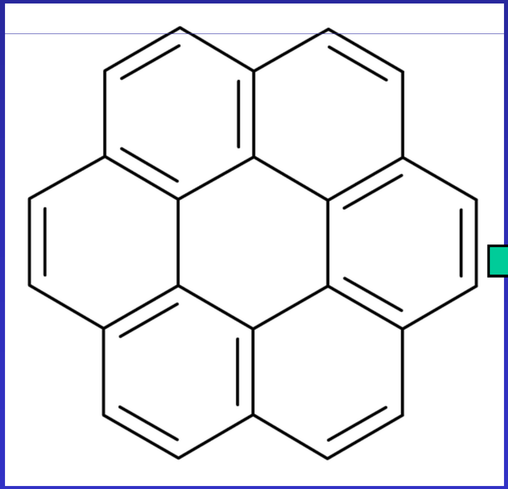
Why does interstellar dust exist?



- Dust destruction in diffuse ISM more efficient than production by AGB stars (see Jones & Nuth 2011)
- SN dust production rate seems to be very low
- „Homogeneous“ dust models (Draine & Lee) vs. core-mantle models (Greenberg) vs. „inhomogenous dust“ (Mathis)
- What is the nature of the VSG?
- Why don´t we see SiC grains in the diffuse ISM?

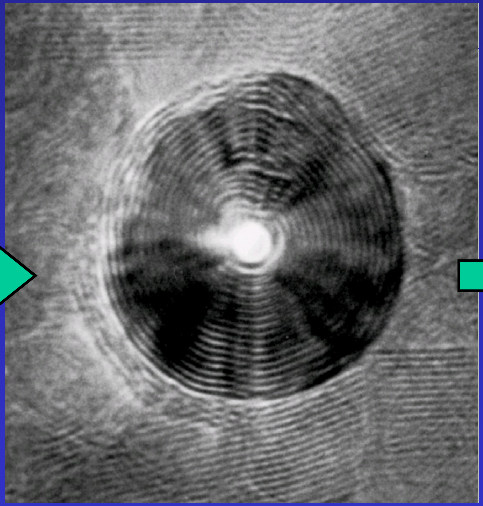
Grain Sizes – From „Nano to Micro“

Coronene



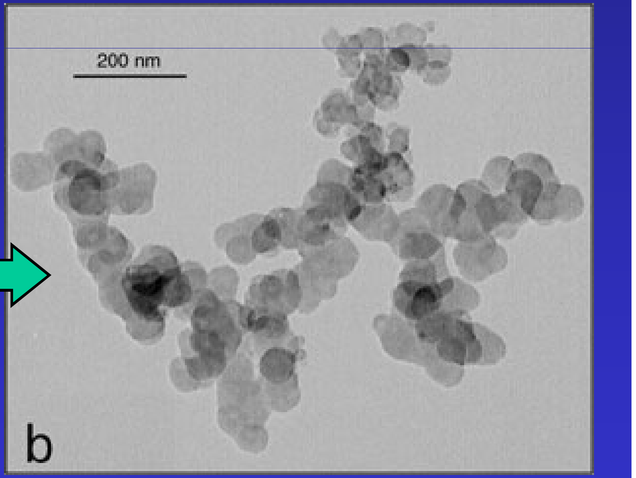
36 atoms
1 nm

Carbon Onion



10^5 atoms
15 nm

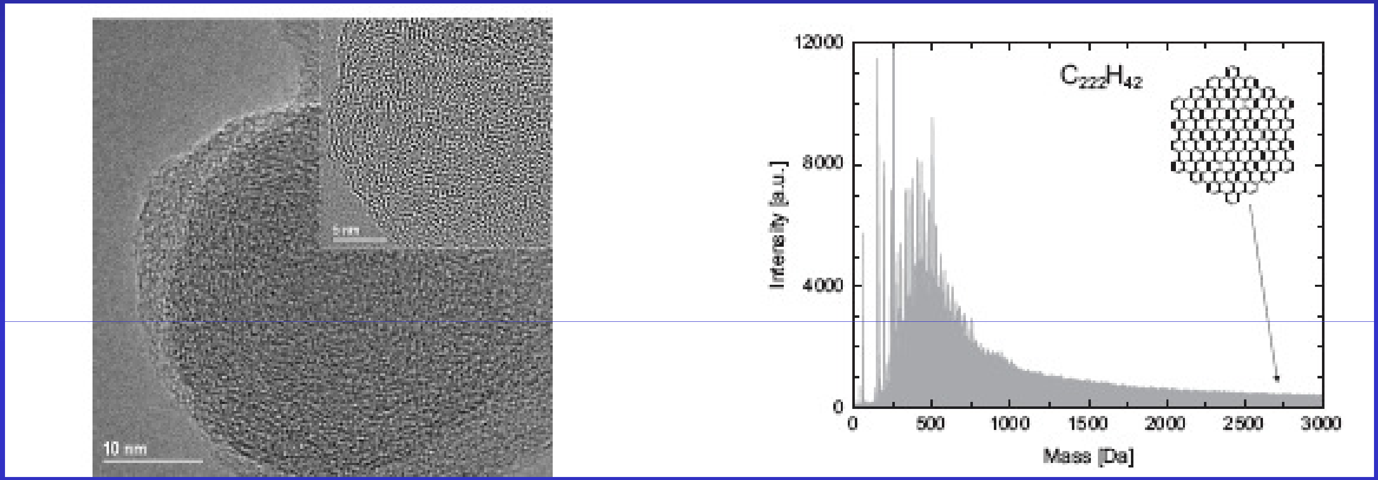
Soot Particle



10^7 atoms
200 nm

Formation of Dust

Grain formation experiments under high-T conditions



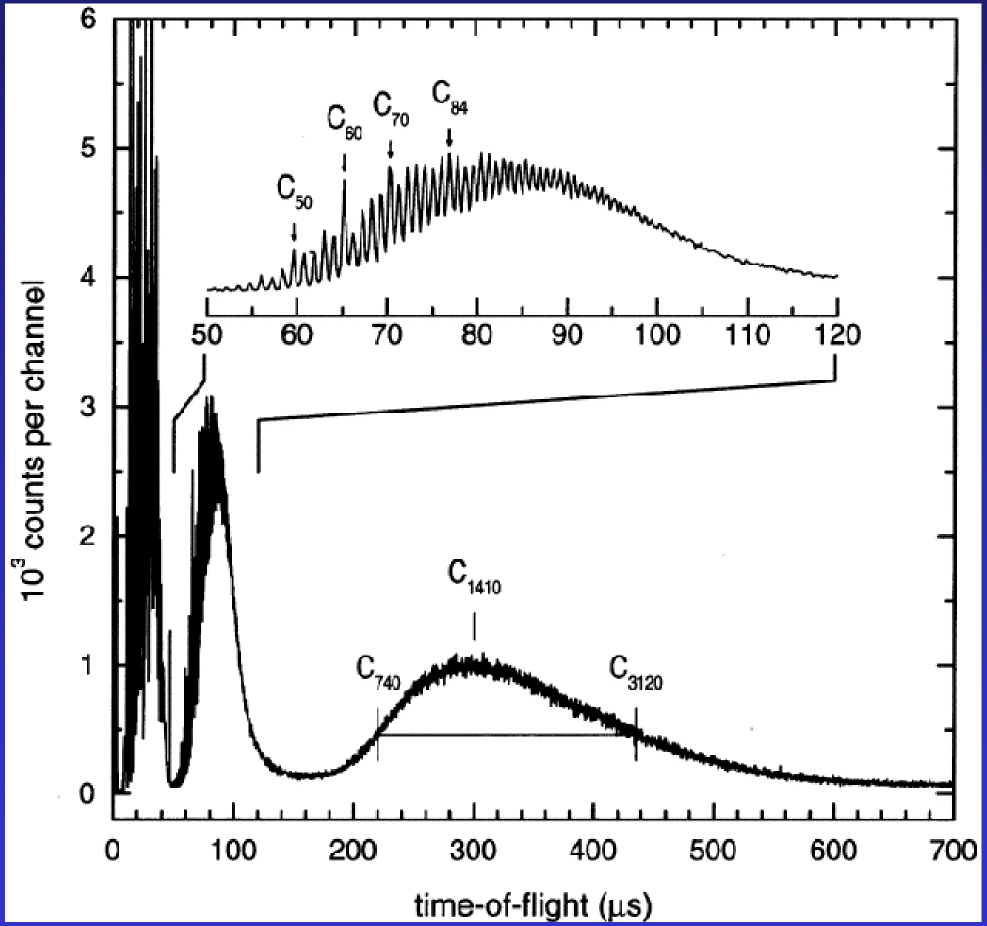
Jäger ea. 09

HT (≥3500 K): Very small fullerene-like carbon grains
LT (≤1700 K): Synthesis of PAH-based structures

Grain formation experiments under low-T conditions

Nuth & Moore (1989): Silicate material from molecular precursors
Dartois et al. (2005): Formation of HAC polymers produced by UV photolysis at low T

Transition from Carbon Clusters to Solid Particles



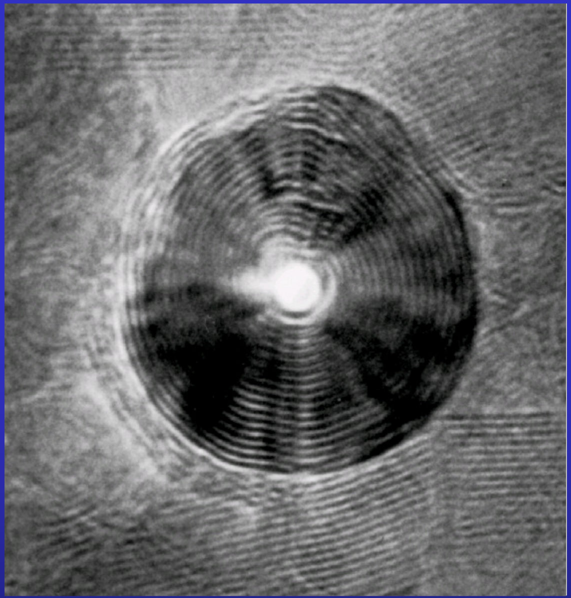
Non-crystalline disordered carbons

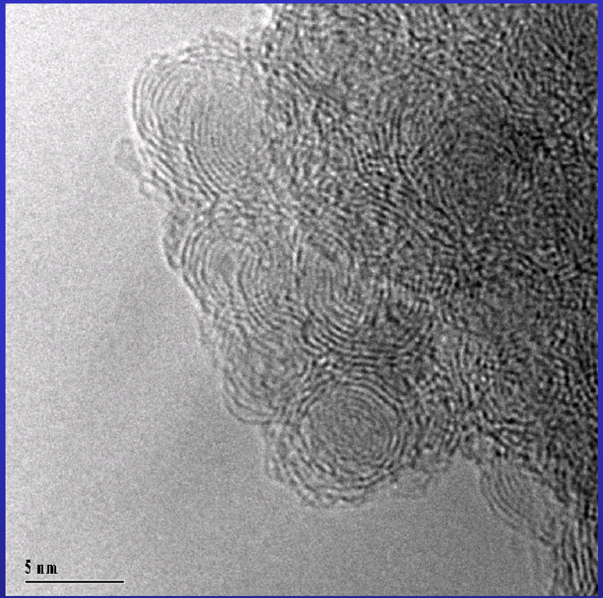
Soot Particles (without hydrogen/oxygen):

Curved and closed structures or polycrystalline materials

Soot Particles (with hydrogen):

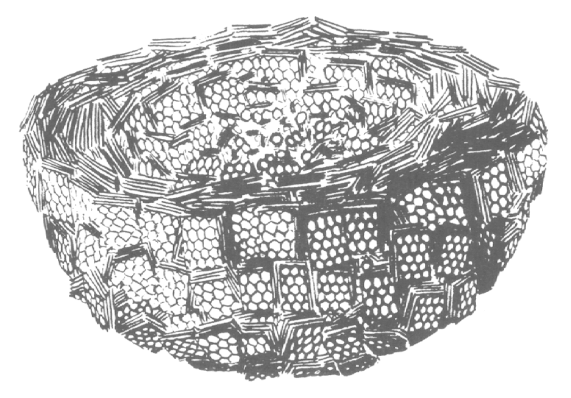
Smaller grains preferably formed: Curved structures

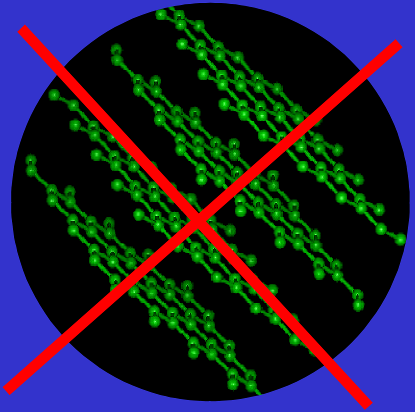


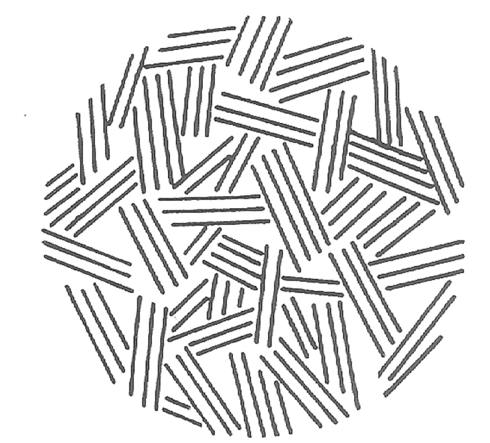


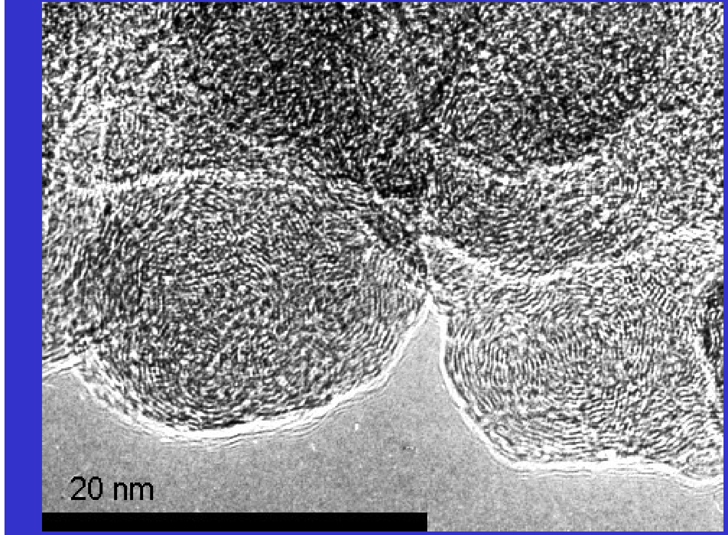
Arc discharges, laser ablation, thermal sublimation methods, sputtering, laser pyrolysis, combustion

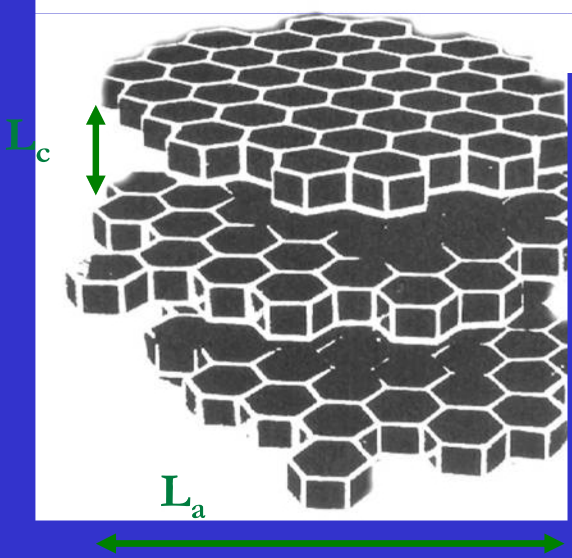
Gas-phase condensed soot particles

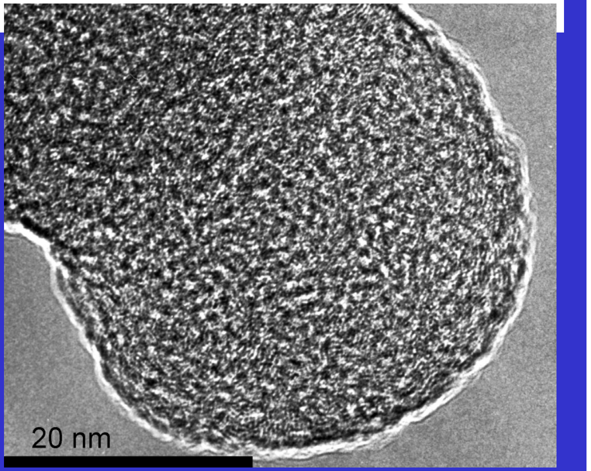




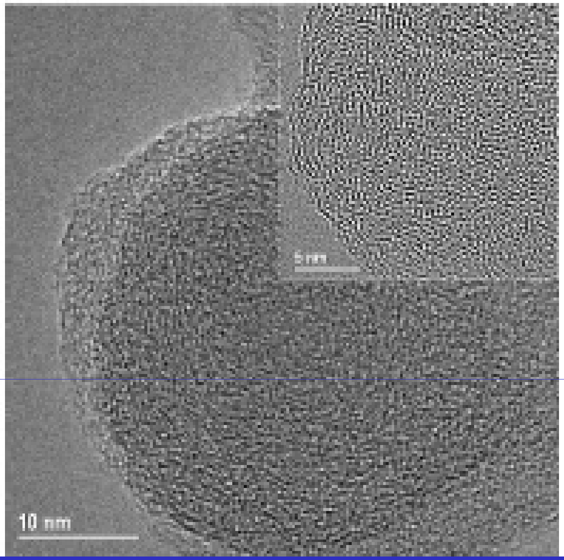


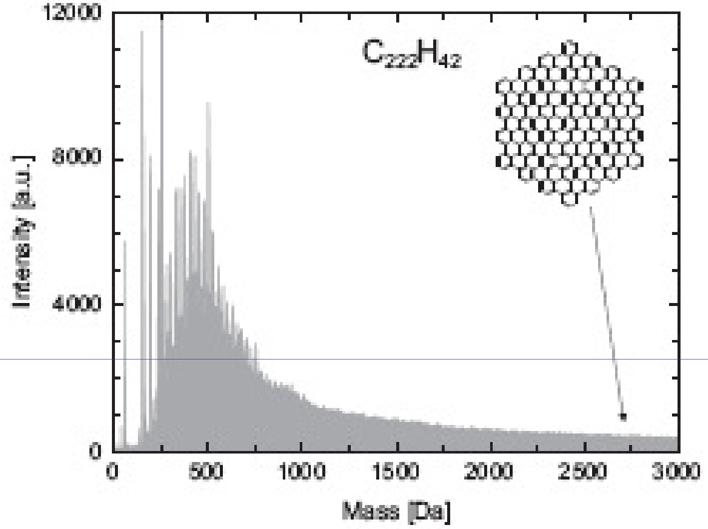






Grain formation at high temperatures





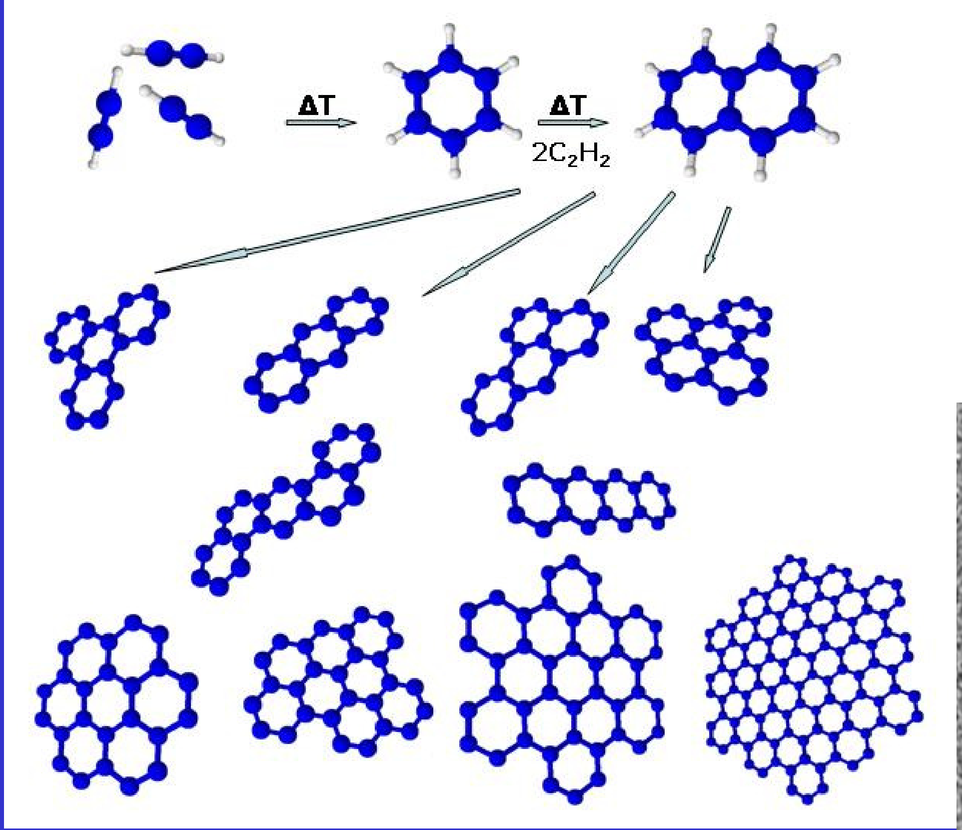
Jäger ea. 09

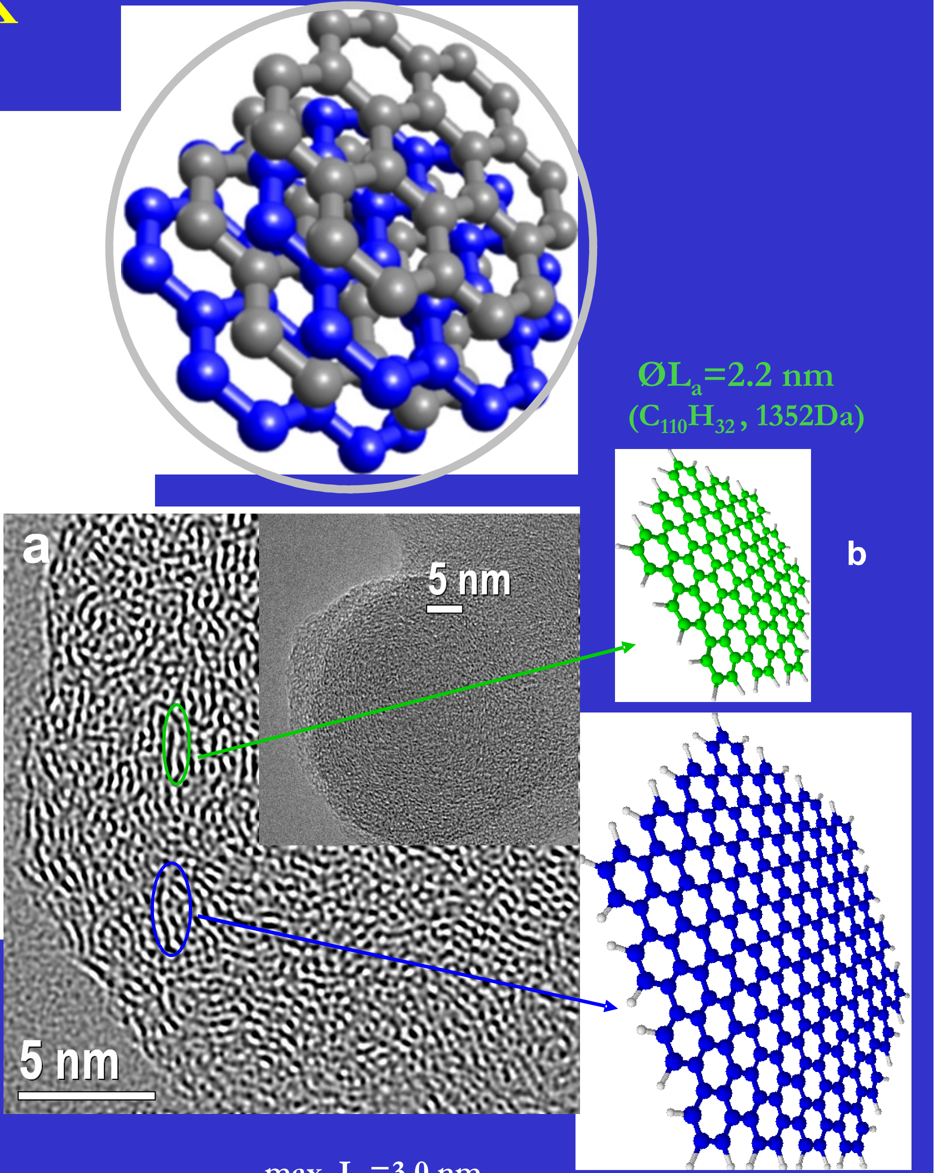
HT (≥3500 K): Very small fullerene-like carbon grains

LT (≤1700 K): Synthesis of PAH-based structures

Soot formation Pathways

LT condensation process T ≤ 1700 K





ØL_a=2.2 nm
($C_{110}H_{32}$, 1352Da)

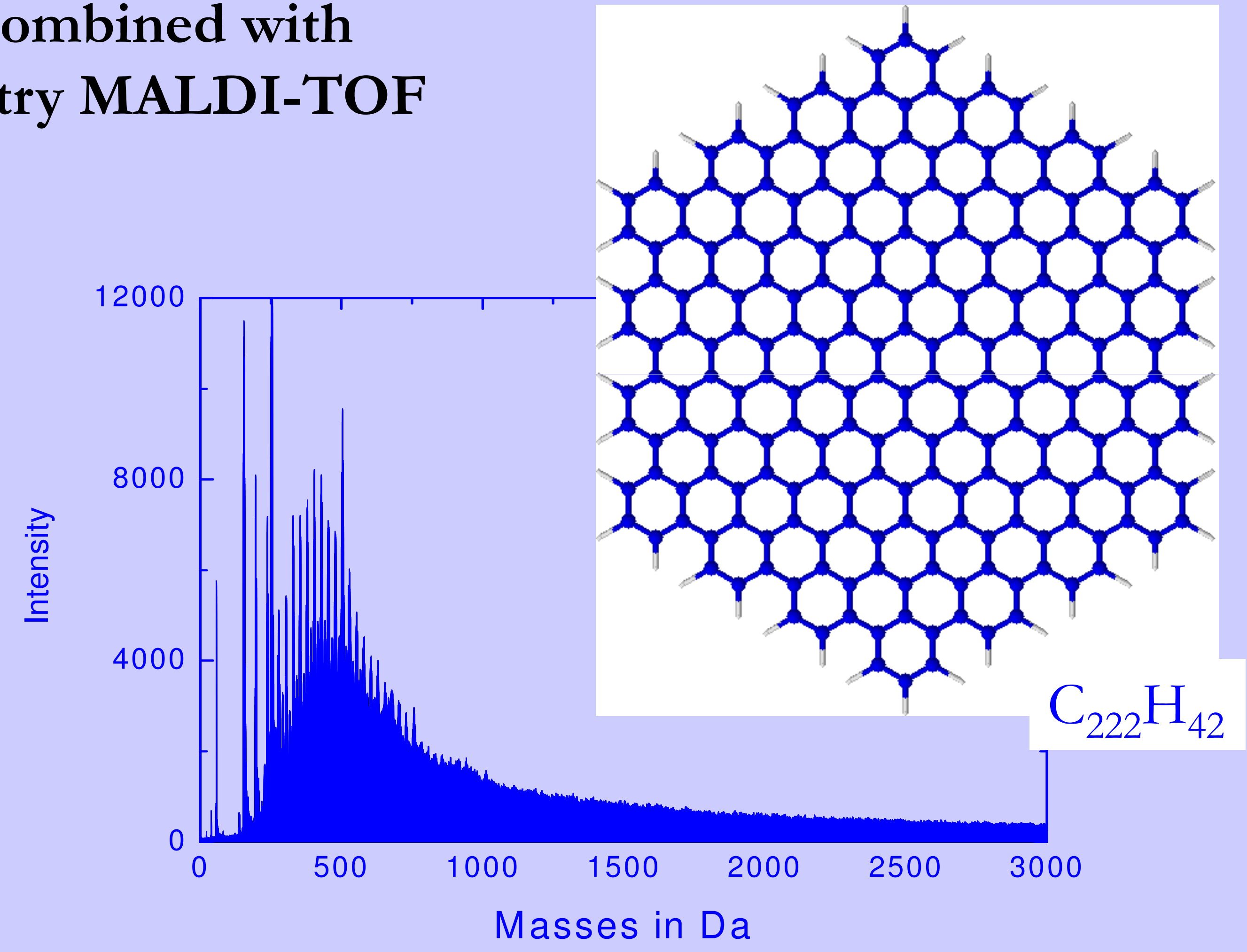
max. L_a=3.0 nm
($C_{222}H_{42}$, 2700Da)

Soot grains & PAHs
or only PAHs as condensates

Characterization of the PAHs in LT condensate

Matrix-Assisted-Laser Desorption and Ionization combined with mass spectrometry MALDI-TOF

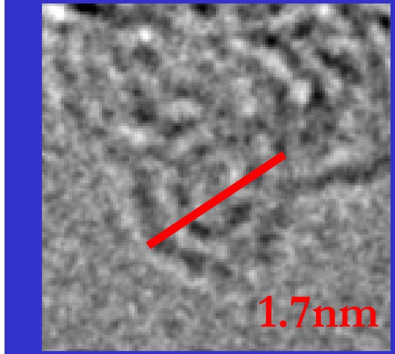
PAHs with masses up to 3000 Da were found



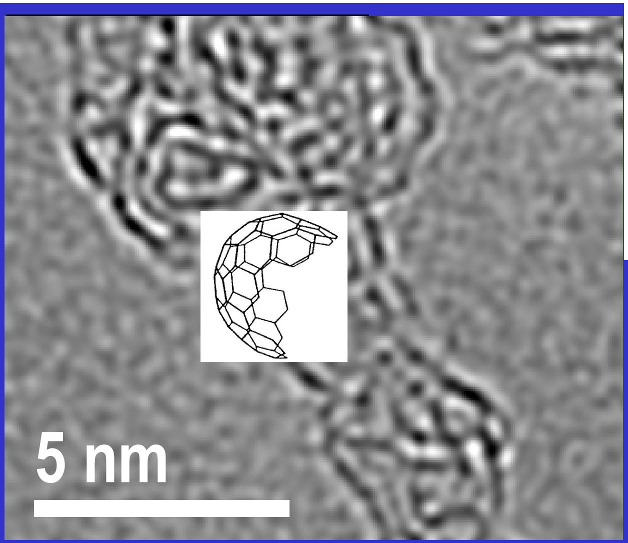
Soot formation pathways

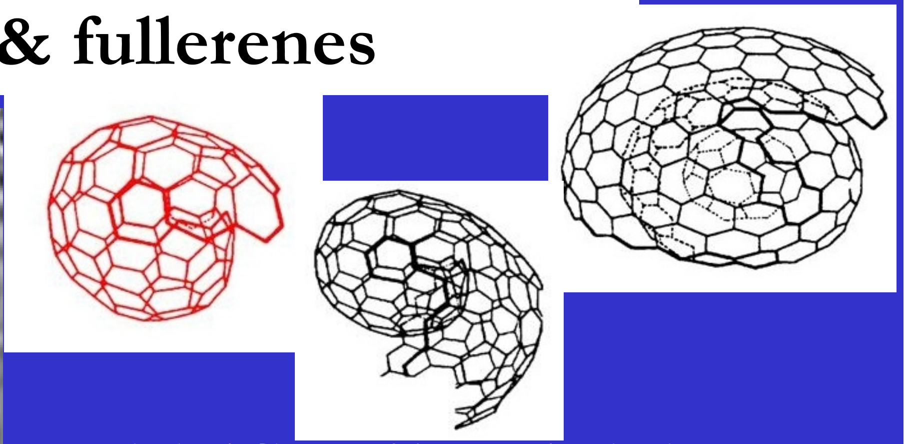
HT Condensation Process T ≥ 3500 K

Fullerene-like carbon seeds & fullerenes

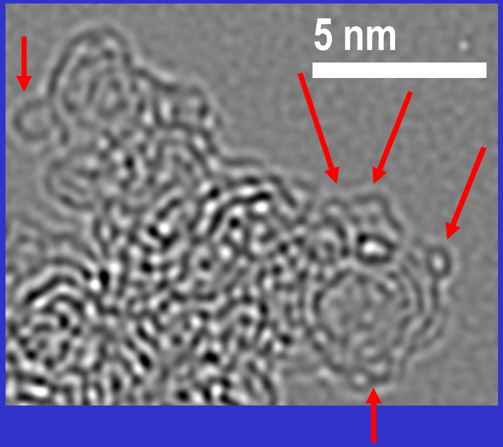


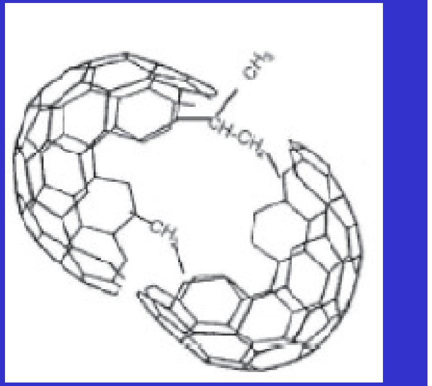
$C_{240}@C_{60}$

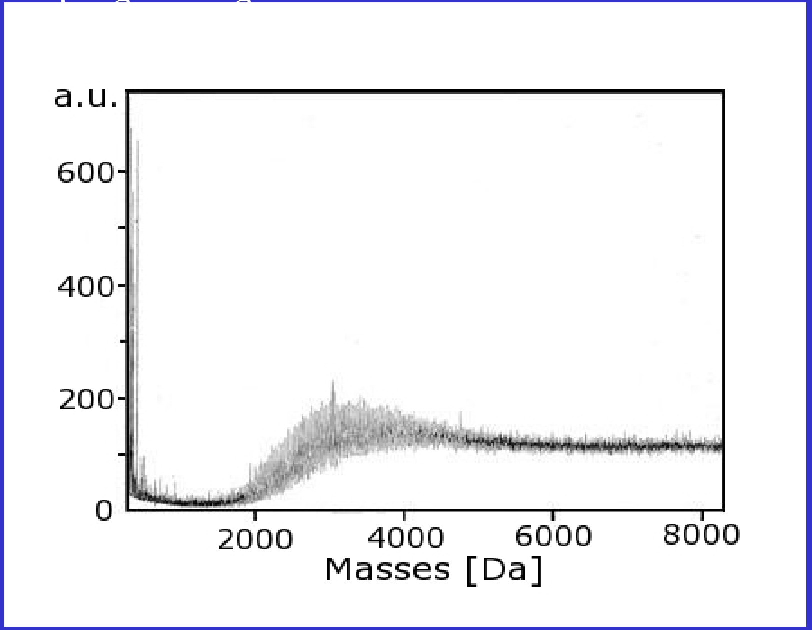




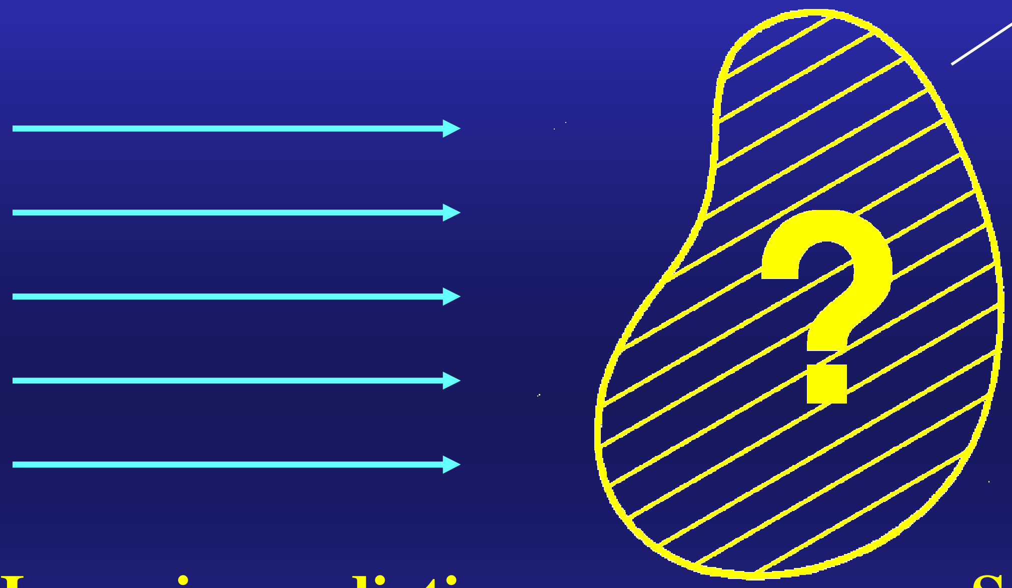
Haberland, Clusters of Atoms and Molecules I, Springer Verlag.







Dust and Radiation



Absorption

- Transformation of energy to some other form
- Re-emission at different wavelengths

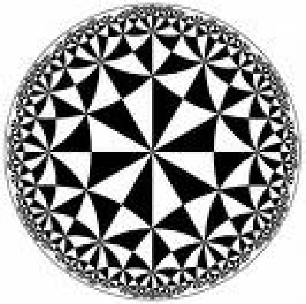
Incoming radiation

- plane waves
- polarised somehow
- some spectrum

Scattering (elastic)

- Change in direction
- Change in polarization
- No change in wavelength

Let us construct a model …



1. Assume chemical composition, shape, size, internal structure distribution

2. Select the relevant laboratory data for n, k (material structure? temperature?)

3. Calculate the cross sections (scattering codes)

4. Construct appropriate mean values

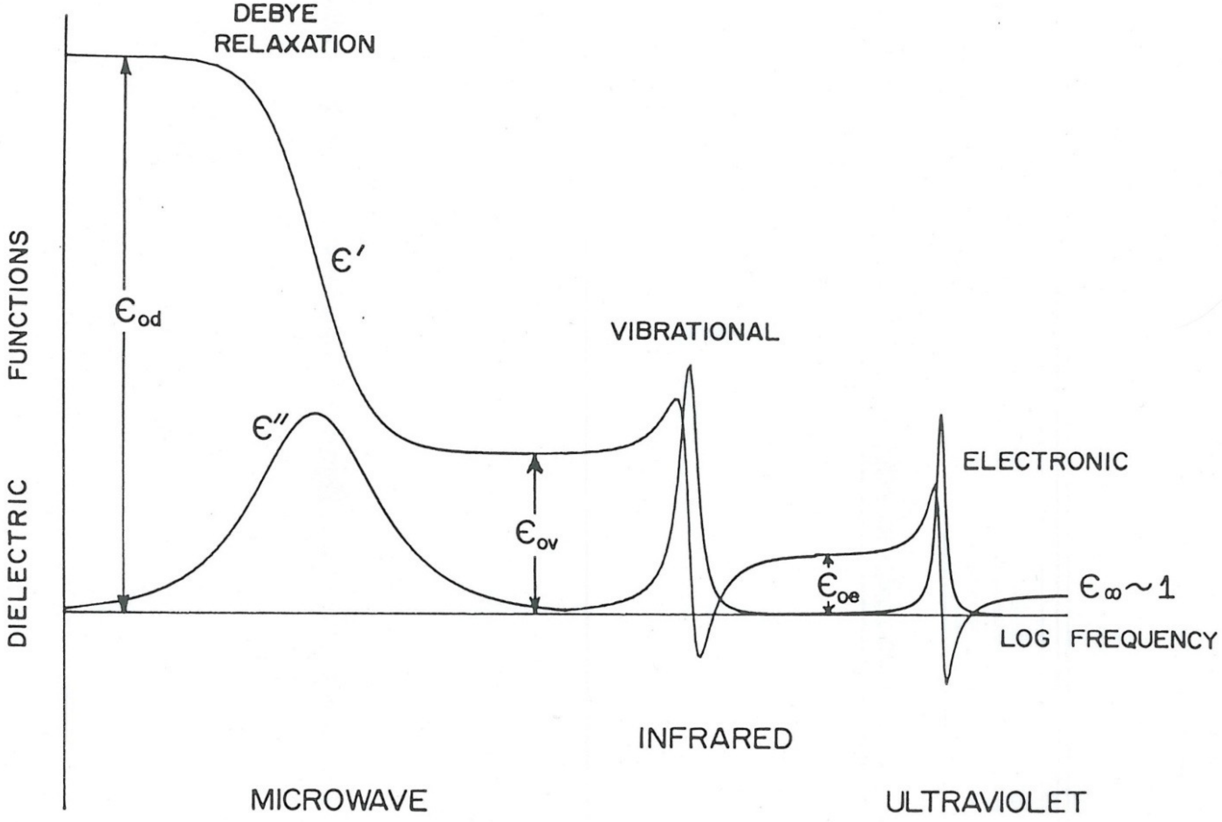
5. Apply these data in your radiative transfer calculation (or simple fitting procedure)

Interstellar Dust Grains – Opportunity and Challenge

„It is a difficult experimental task to produce particles a few hundred angstroms in size, keep them completely isolated from one another and all other solids, maintain them in ultra-high vacuum and at low temperatures, and study photon interactions with the particles from far infrared to extreme ultra-violet. This is the opportunity we have in the case of interstellar dust.“

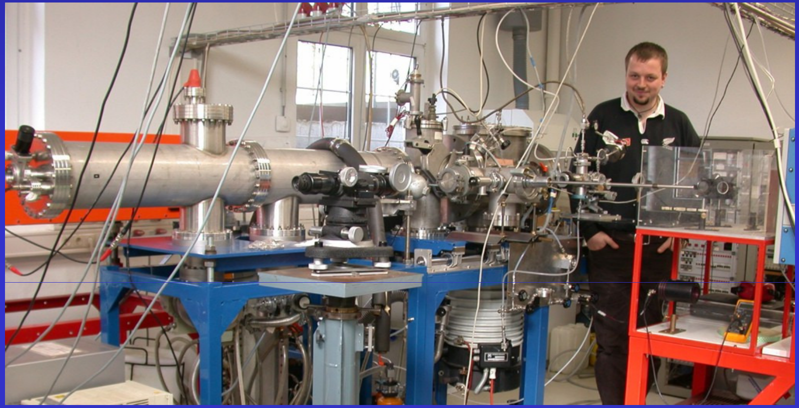
Donald D. Huffman
Adances in Physics, 26, 129 (1977)

Basic Optical Properties of Solid Particles



Basic Optical Data
Cosmic Dust Analogues

- Broad Wavelength Range
- Appropriate Structure
  (Fe/Mg, am./cryst. …)
- Isolated Small Particles
- Temperature Range

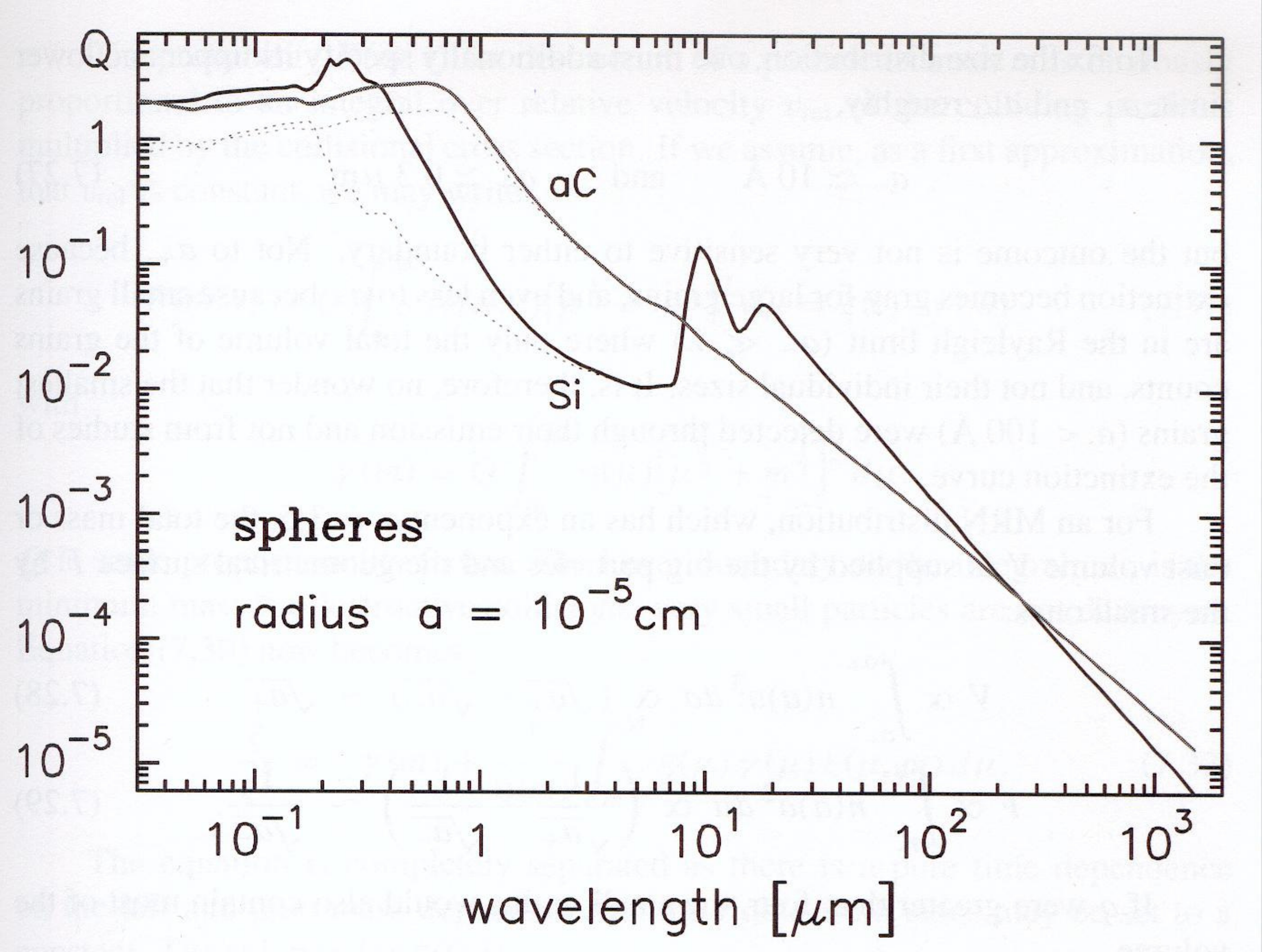


MPIA Lab Astrophysics
Group at the University of Jena

Heidelberg-Jena-Petersburg database of optical constants
(Henning et al. 1999)

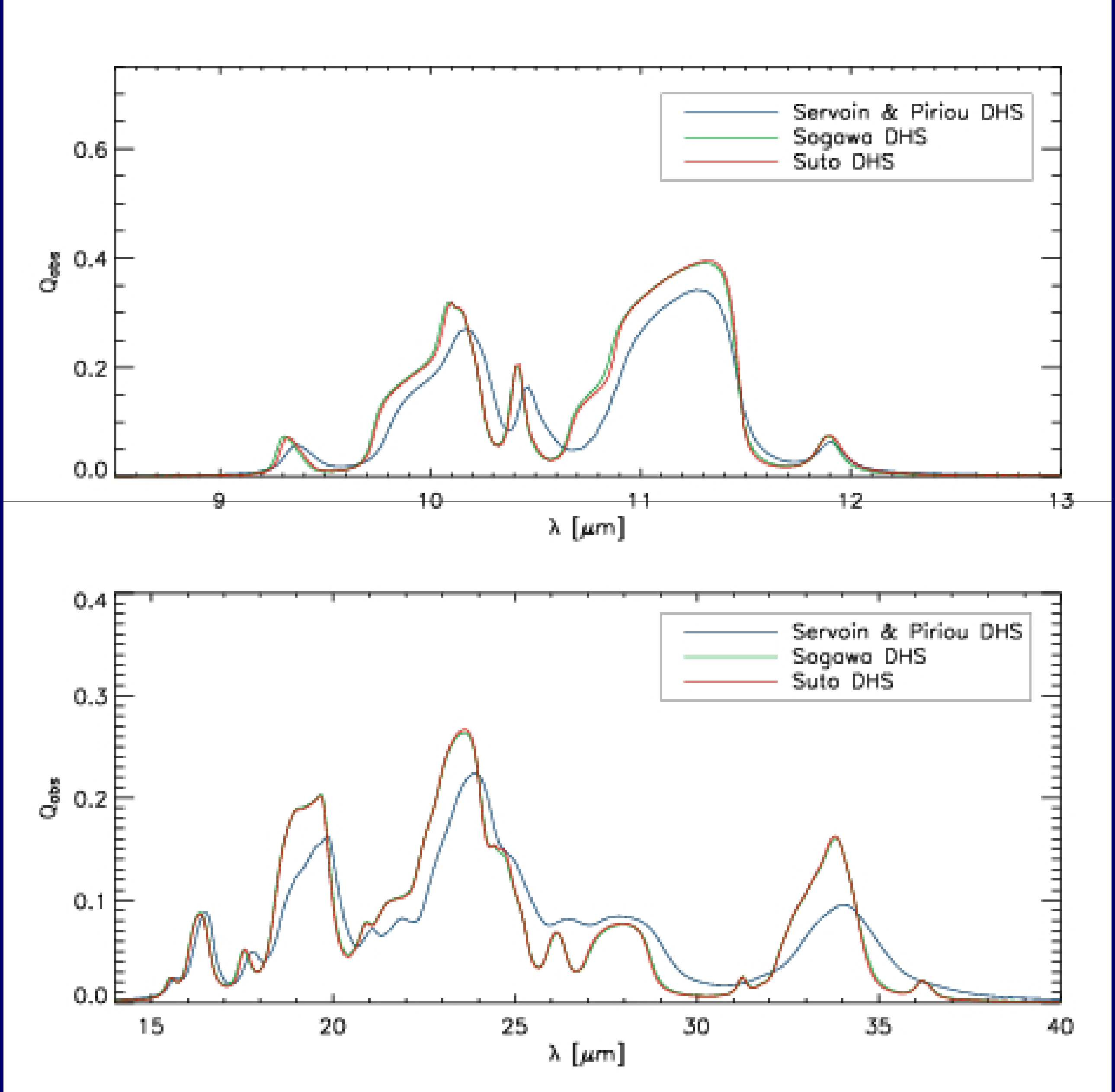
http://www.mpia-hd.mpg.de/HJPDOC/

Optical behaviour of small particles

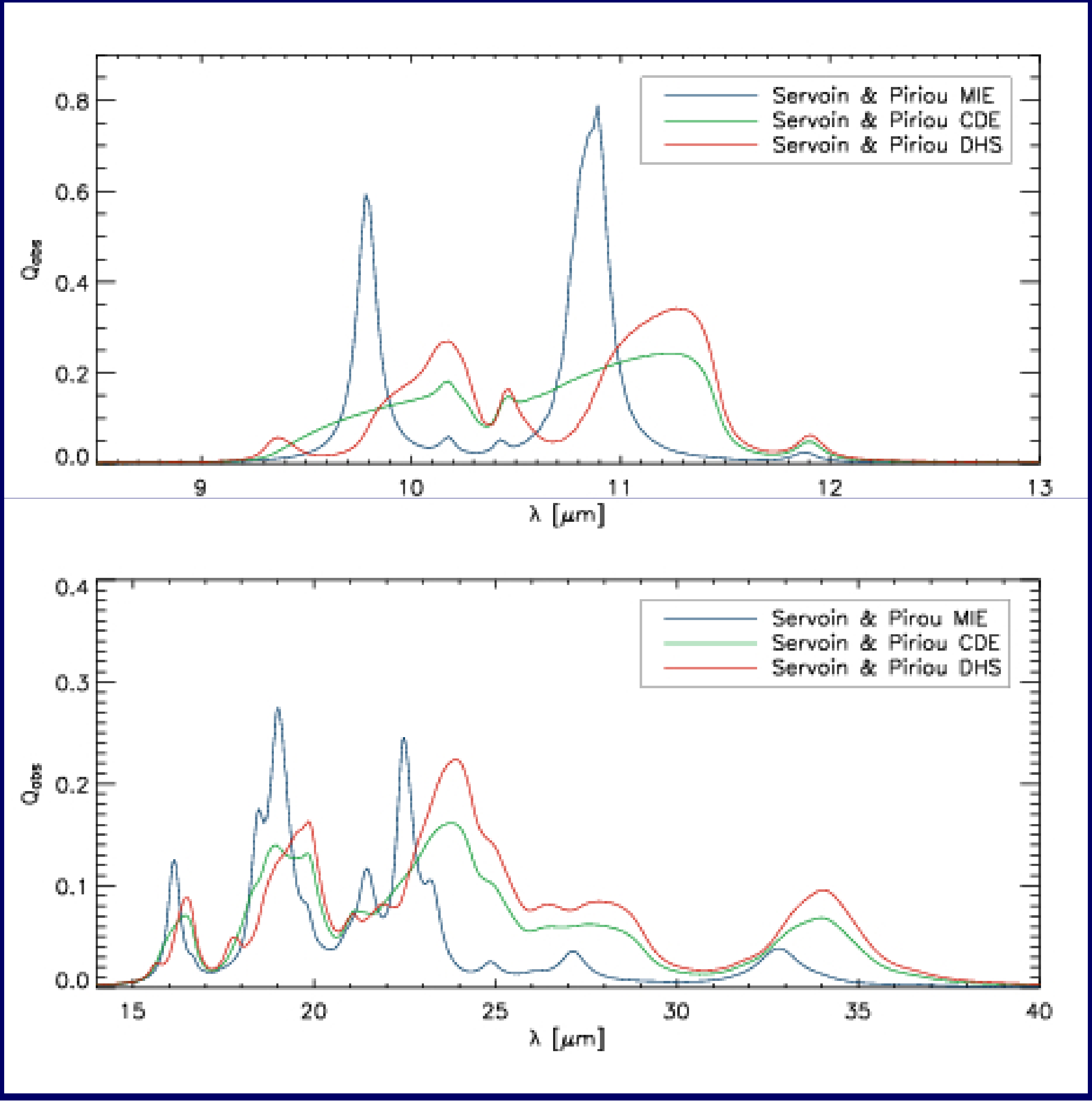


After Krügel (2003, p.235) – Absorption (dots), extinction (solid line)

What you need to know …

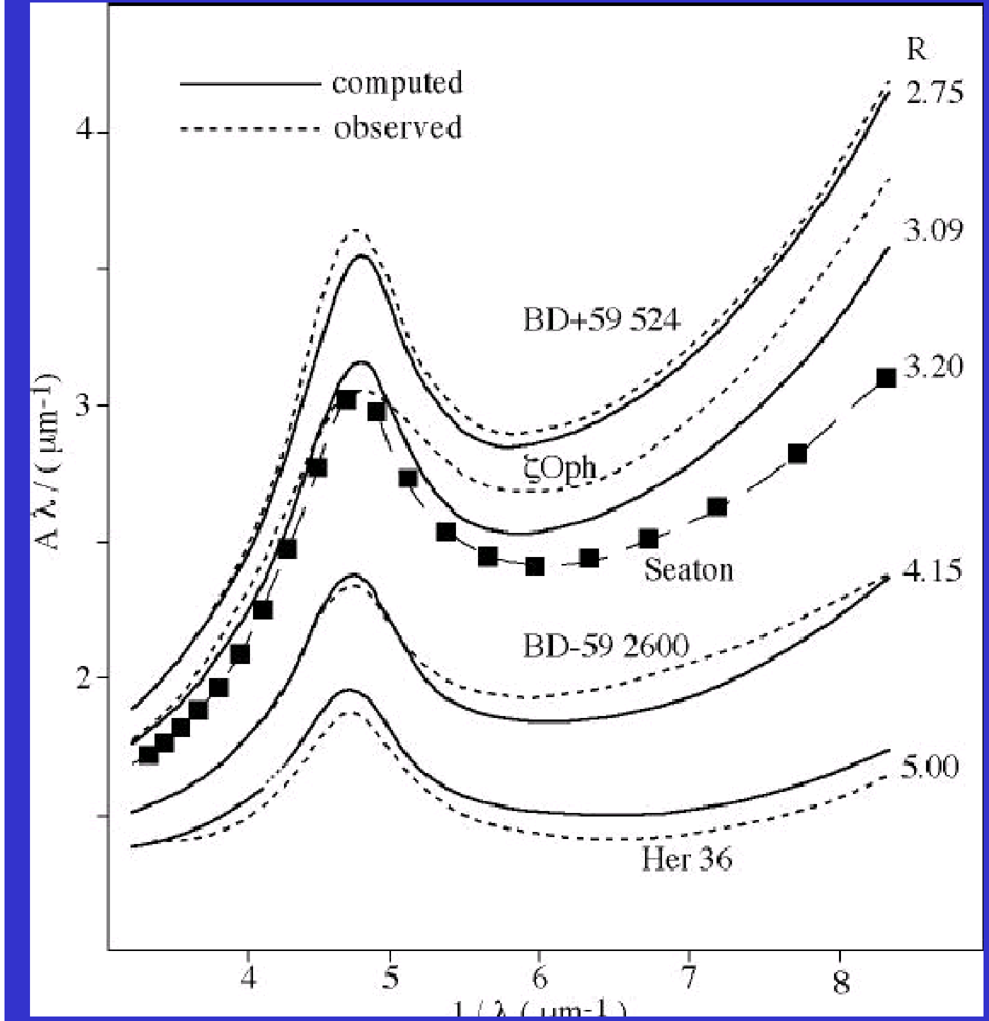


What you need to know …



- Interstellar UV bump
- Near-infrared extinction properties
- Far-infrared absorption properties

Origin of the Strong UV Resonance



- Remarkable constancy of peak position (4.60 μm^{-1}; variations smaller 1%)
- Peak width varies around mean value of 1.0 μm^{-1} (variations smaller 25%)
- Lack of correlation between variation of peak position and width (except for the widest bumps: systematic shift to larger peak wavenumbers)
- Strength of the feature requires abundant element as part of the carrier
- Feature is pure absorption feature

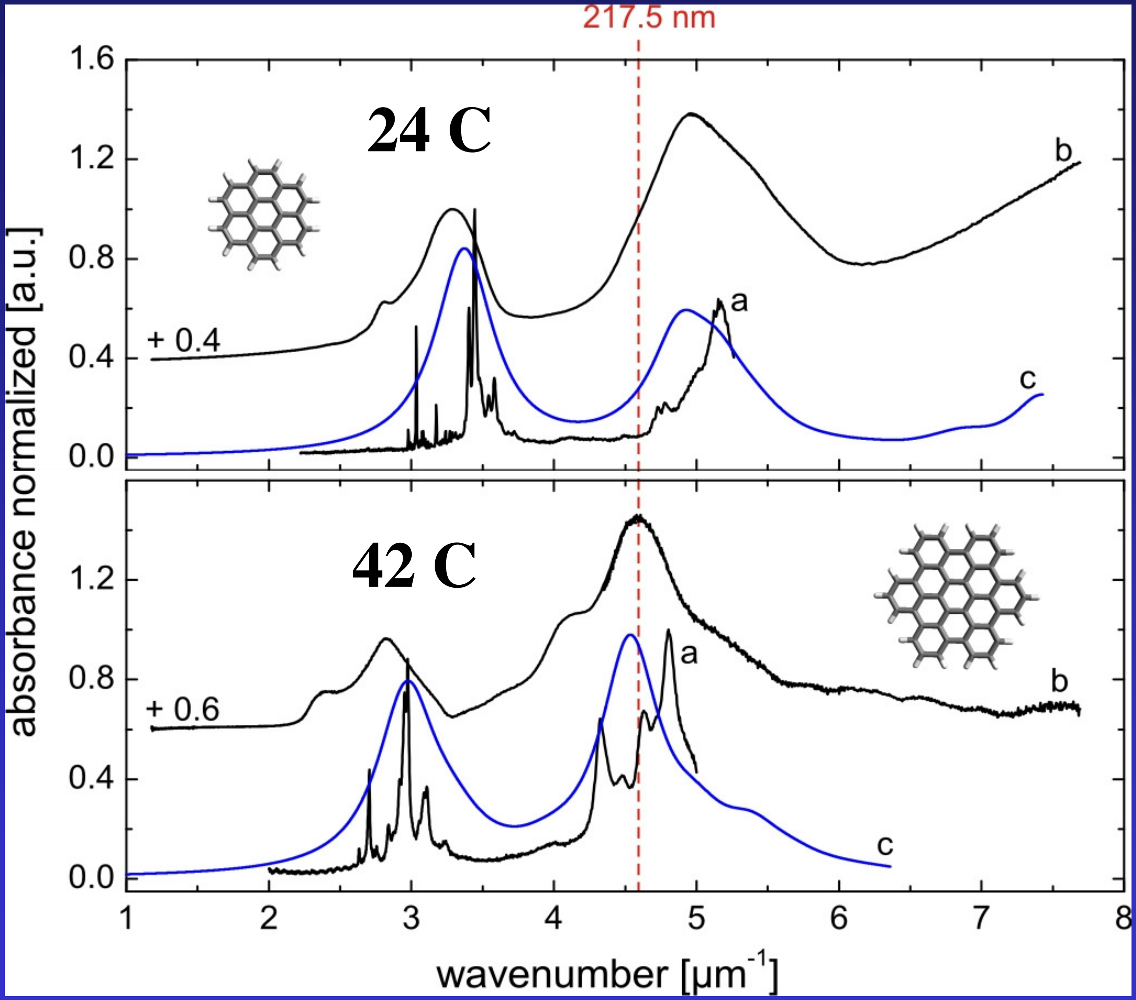
What is the carrier?

- **HAC nanoparticles**

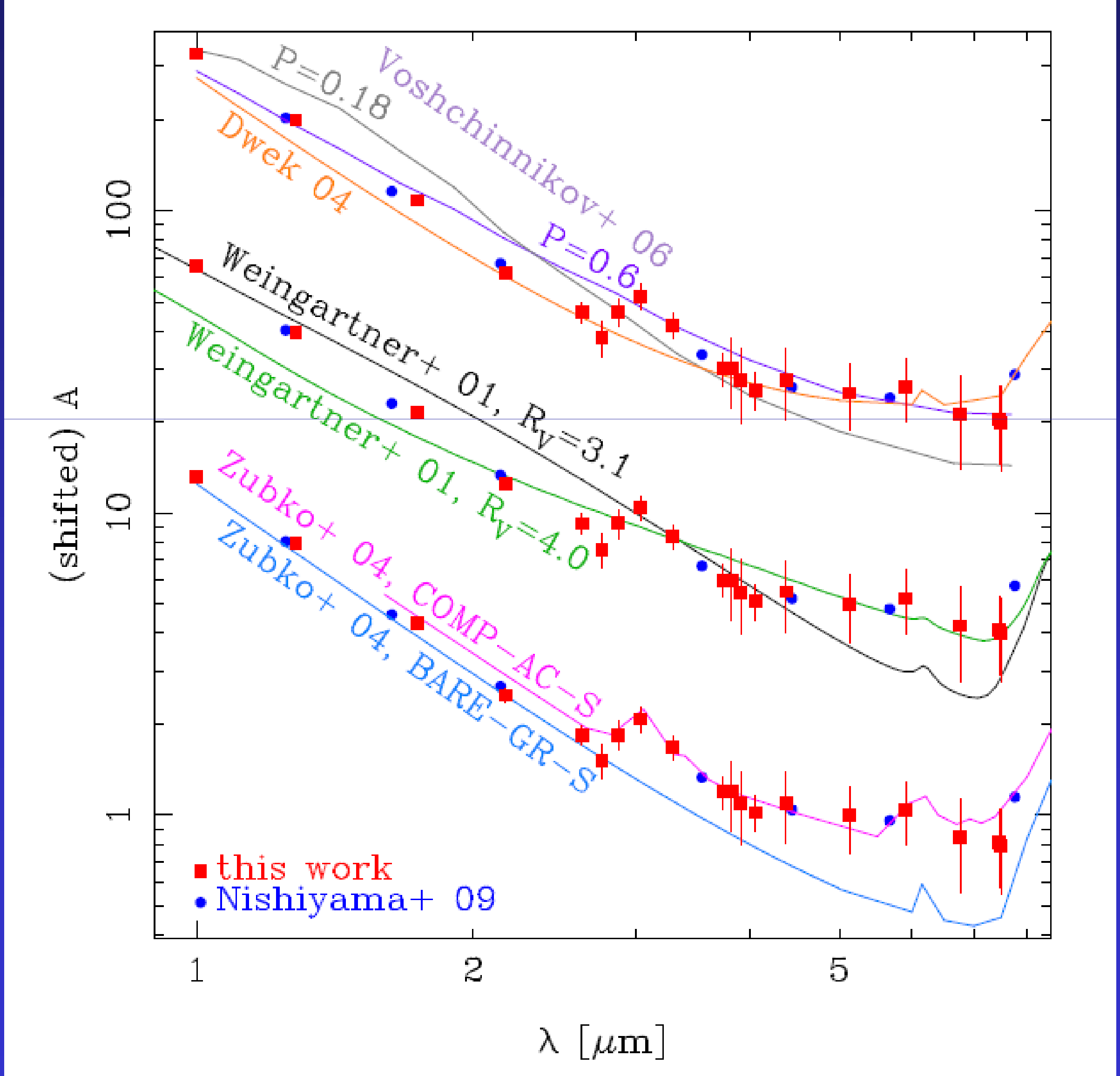
  (e.g. Schnaiter et al. 1998, Gaballah et al. 2011)

- **Large PAHs**

  (e.g. Beegle et al. 1997, Steglich et al. 2010)



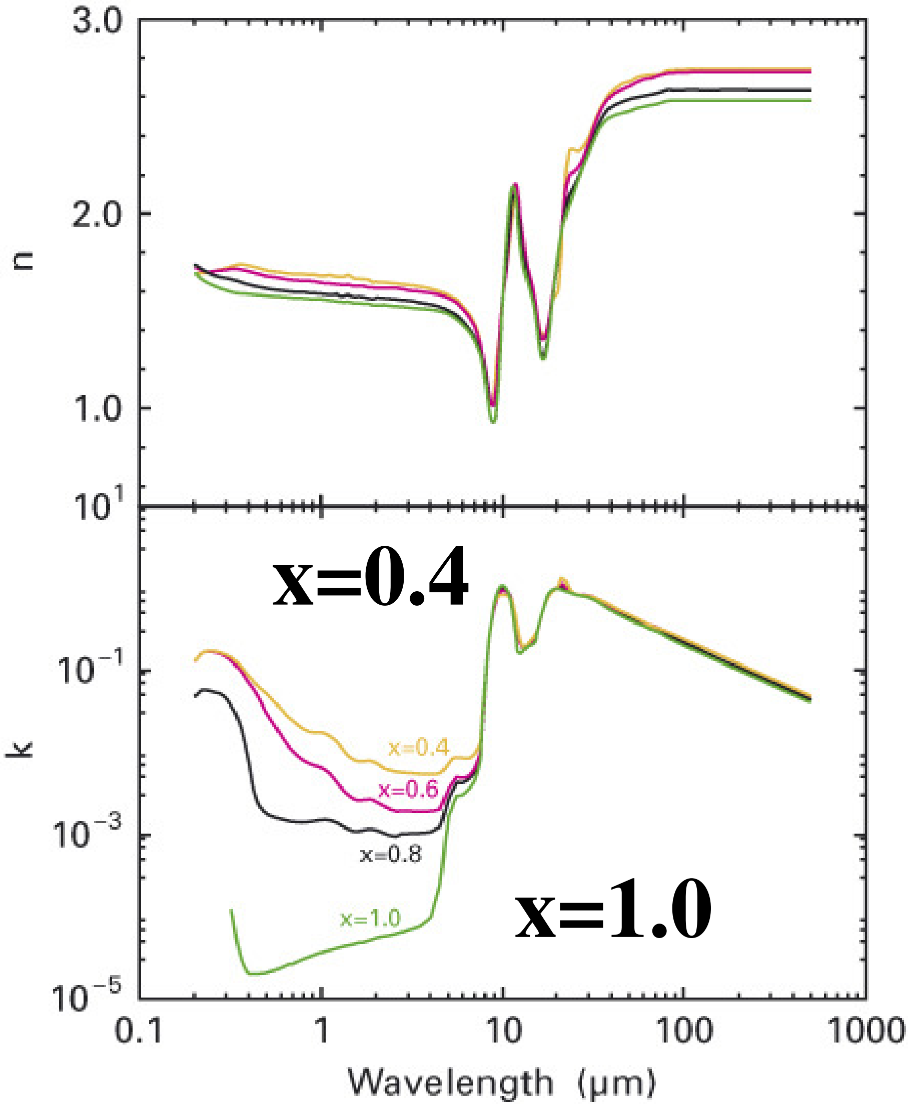
Near-infrared Extinction Law



Fritz et al. 11

Optical Data of Amorphous Silicates: $Mg_xFe_{1-x}SiO_3$

Increase of NIR absorptivity with Fe content



x=0.4

x=1.0

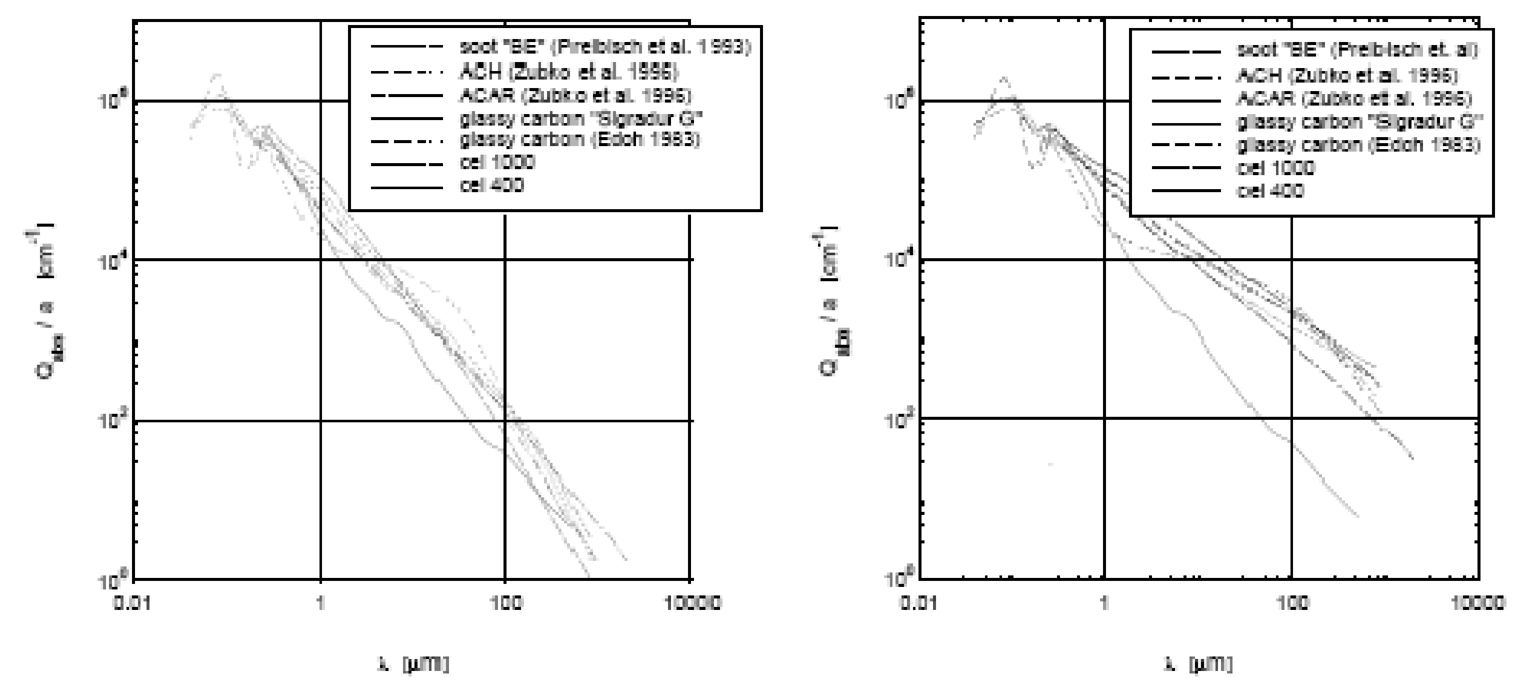
(J. Dorschner, B. Begemann, Th. Henning, C. Jäger and H. Mutschke, A&A 1995)

What are the FIR Properties of the materials?

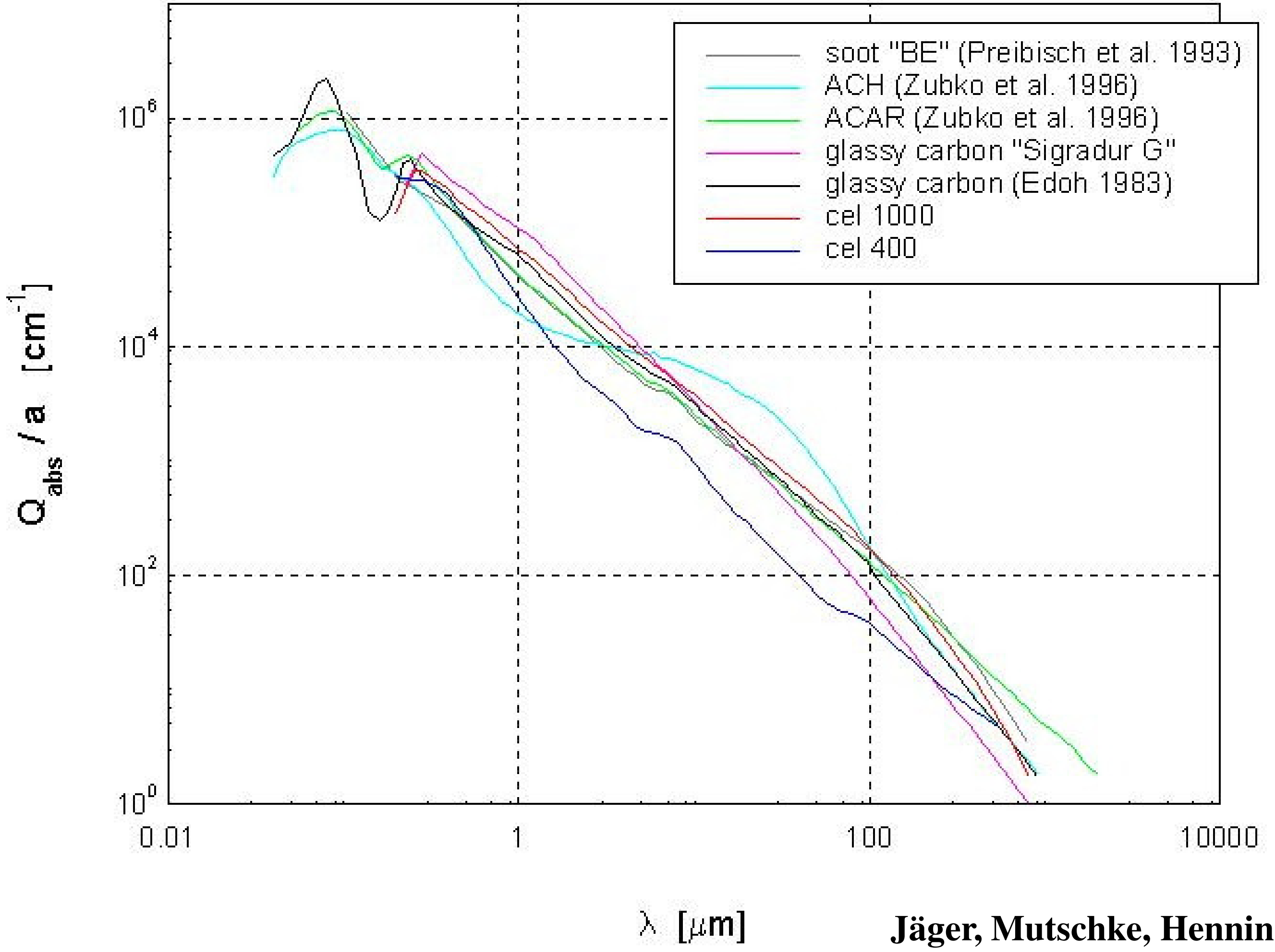
- Structural composition of the material (e.g. Jäger et al. 1998)

- Grain size and agglomeration state
  (e.g. Henning & Stognienko 1996)

- Temperature of the material – to be discussed

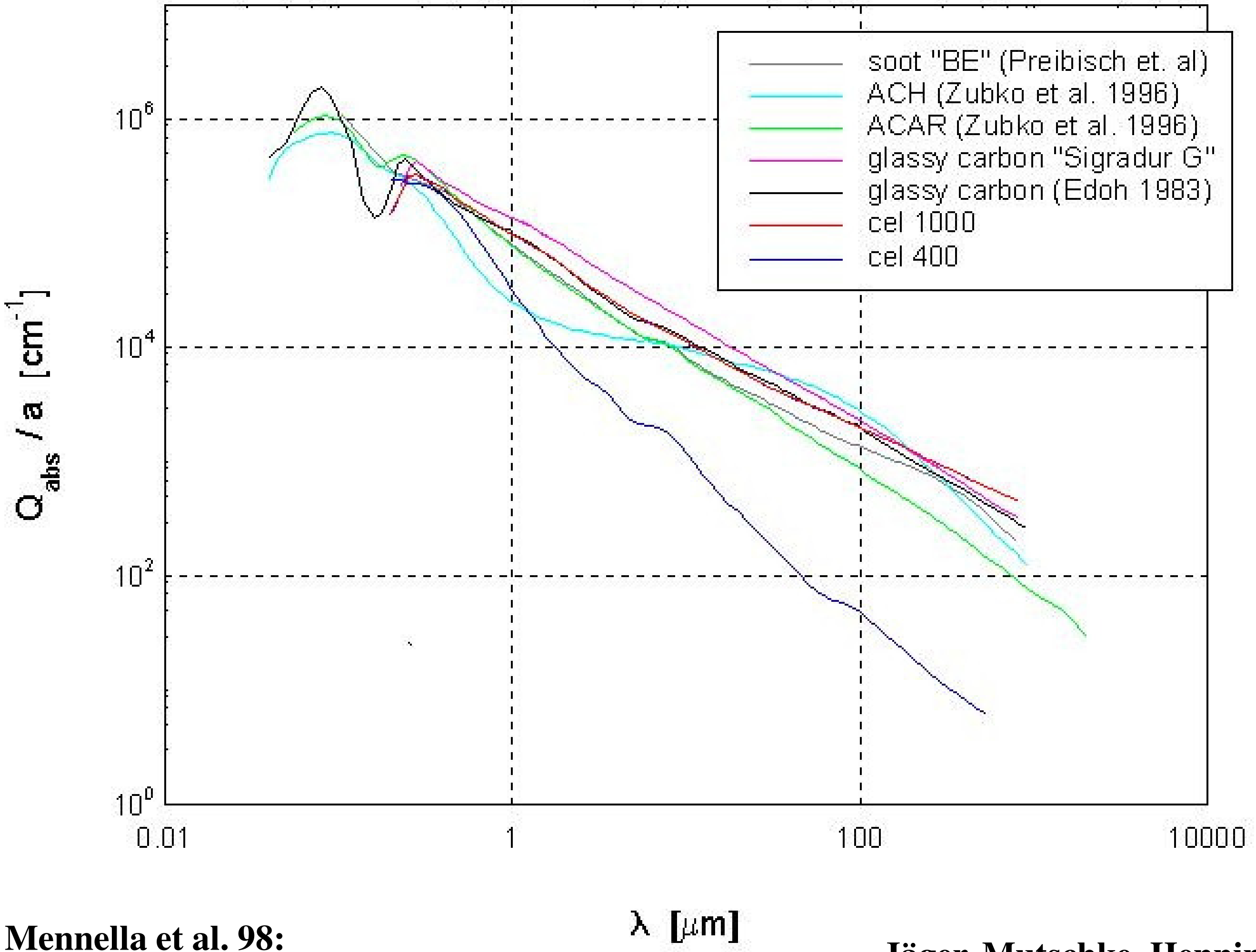


FIR Absorption Efficiency/Spherical Particles



Jäger, Mutschke, Henning (1998)

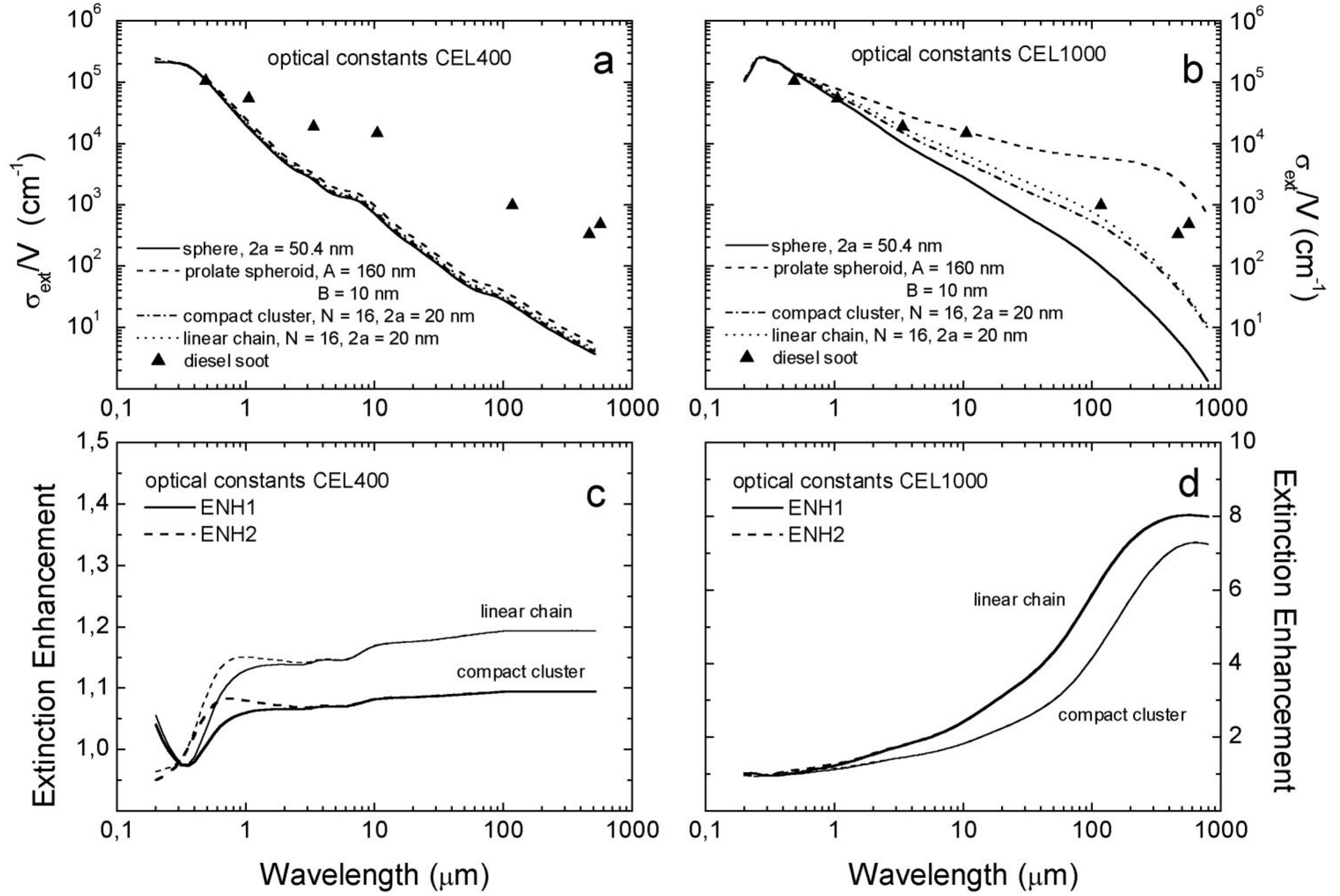
FIR Absorption Efficiency/CDE



(see Mennella et al. 98:
for low T experiments)

Jäger, Mutschke, Henning (1998)

Extinction Spectra of Carbonaceous Materials



Quinten, Kreibig, Henning, Mutschke (2002)

LOW-TEMPERATURE EFFECTS

Henning and Mutschke (1997)

Crystalline Dielectric Solids

- IR bands (single phonon transitions):
  Sharpening because of decreased damping, shift to shorter wavelengths
- FIR absorption (phonon difference processes):
  significant reduction because of decreasing phonon number

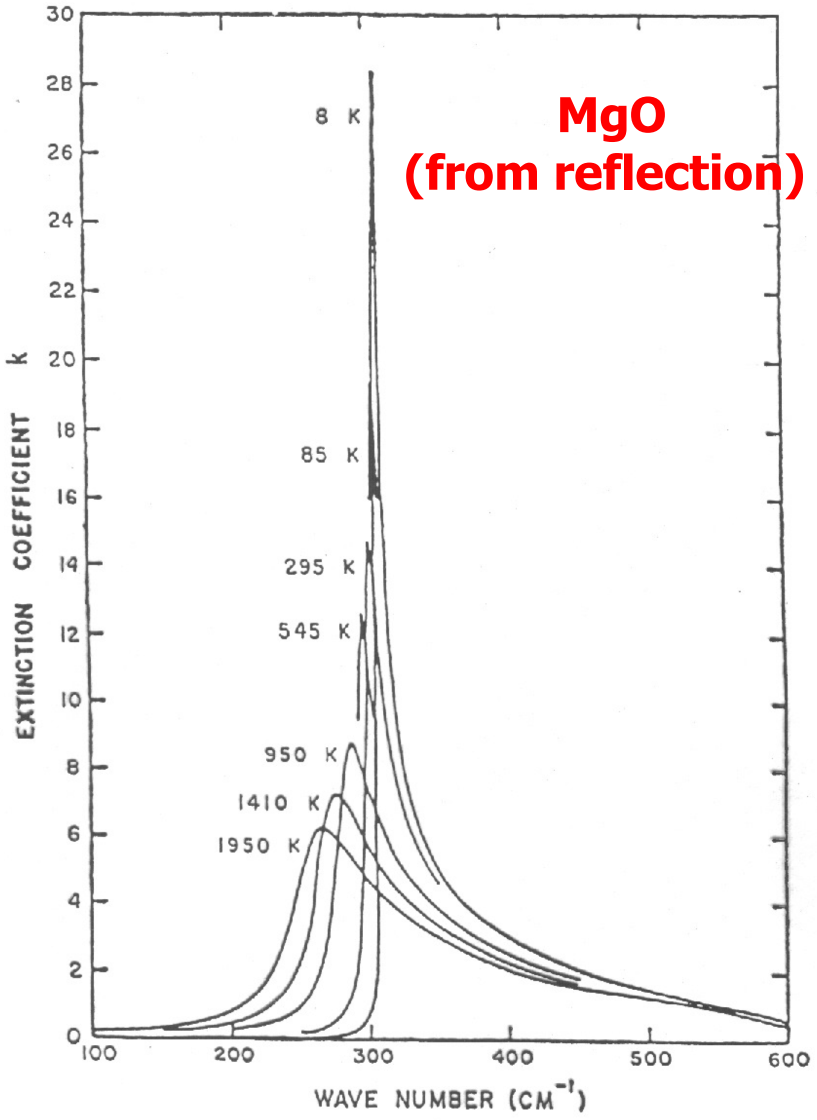
Amorphous Dielectric Solids

- FIR absorption:
  Dominated by disorder-induced single phonon processes, no temperature dependence
- Millimeter range:
  highly temperature-dependent low energy processes, e.g. tunneling transitions in glasses

Semiconductors

- free charge carrier absorption:
  vanishes because conduction band is depopulated

What is expected ?

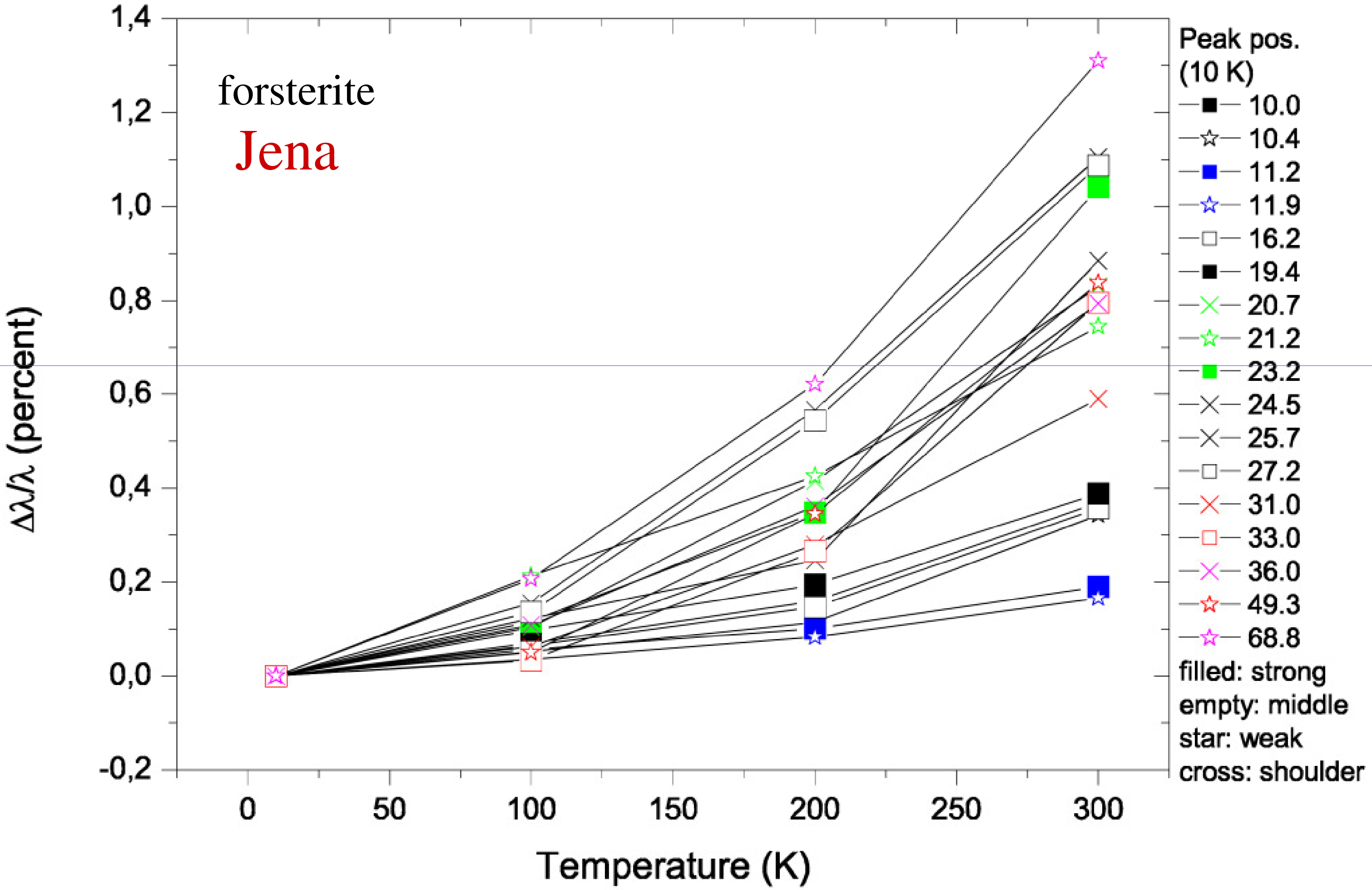


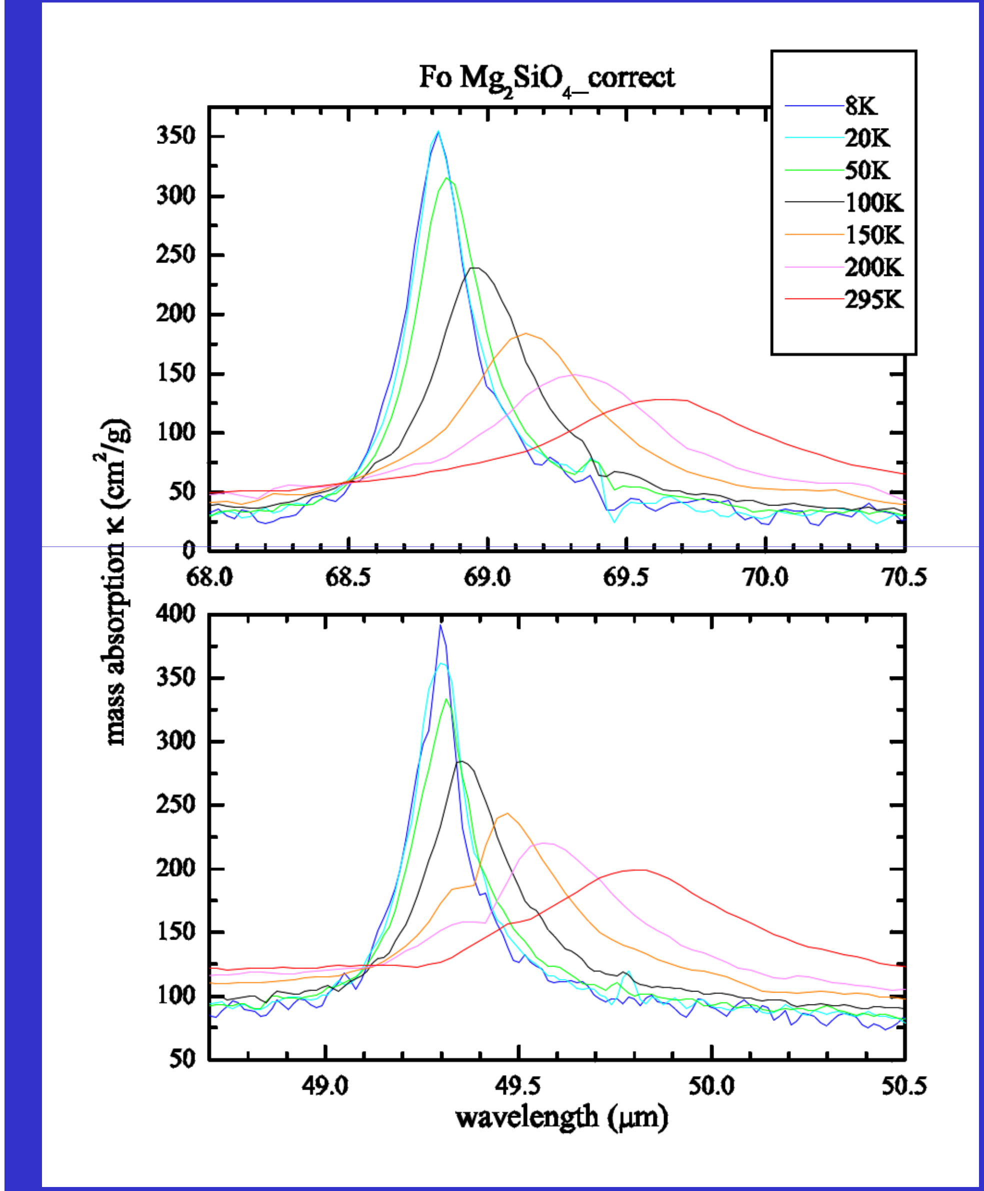
MgO (from reflection)

Fig. 9. Computed extinction coefficients of MgO as functions of wave number and temperature. (From Jasperse *et al.* [12].) 1966

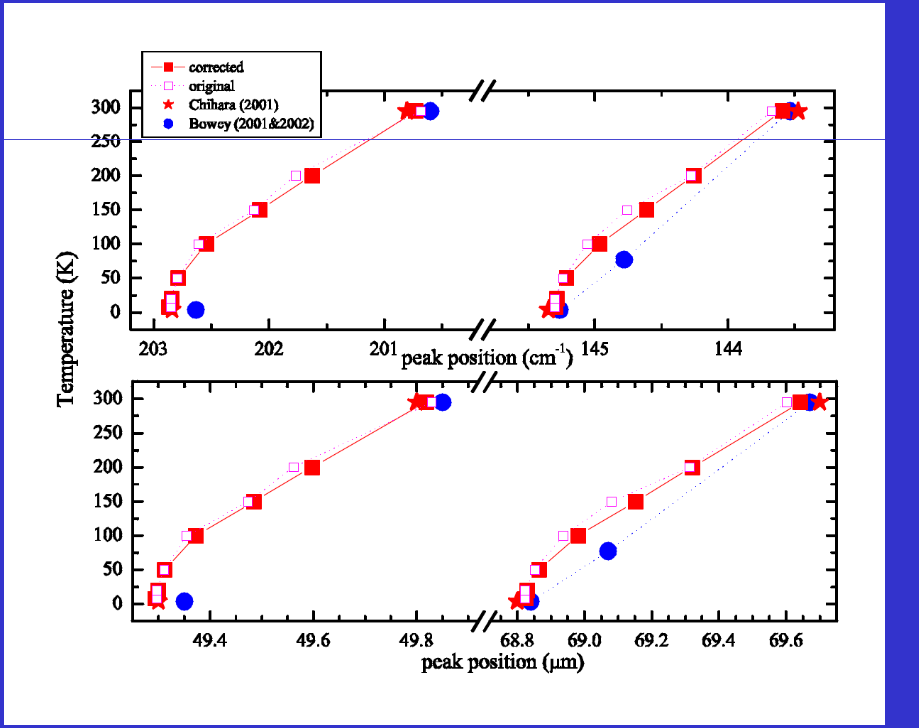
=>Bands are broadened and shifted to lower frequencies with higher temperature

How big is the relative peak shift ?





Long-wavelength forsterite bands as thermometer



Koike et al. (2006)

Temperature Dependence – Laboratory Studies

- **Bösch (1978):** silica glass
  (500 µm – 5 mm, 1.2 – 300 K)

- Agladze et al. (1996): crystall. and amorphous silicates
  (700 µm – 3 mm, 1.2 – 30 K)

- Mennella et al. (1998): am. carbon, crystalline silicates,
  am. fayalite
  (20 µm – 2 mm, 24 – 294 K)

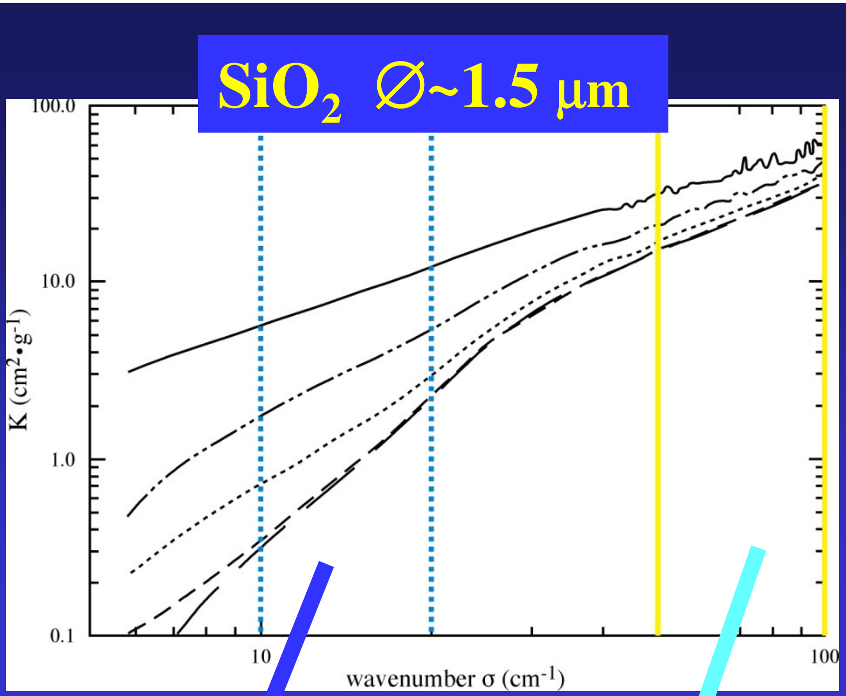
- **Boudet al. (2005):** am. silica, am. silicate
  (100 µm – 2 mm, 10 – 300 K)

Between 500 µm and 2 mm: Anticorrel. between T and ß

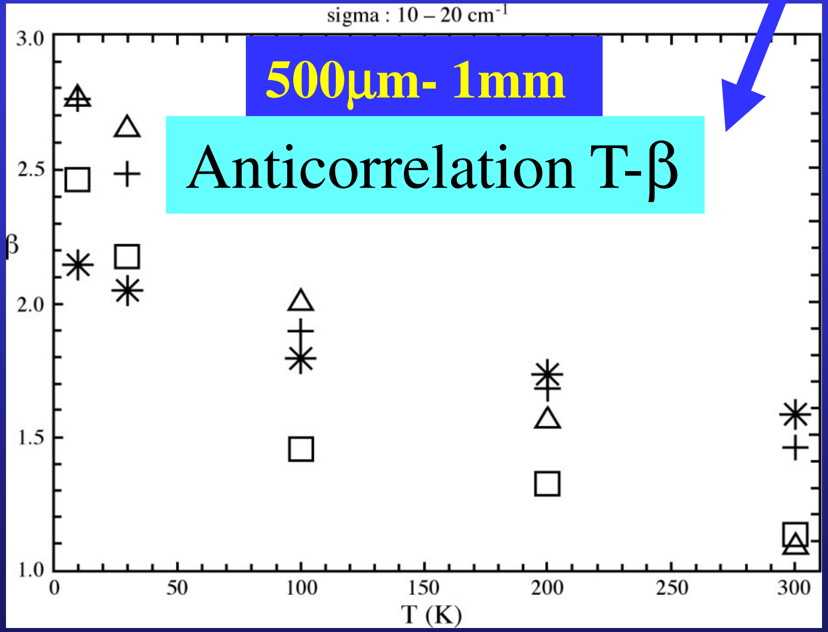
Boudet ea. 2005

β(T, ν)

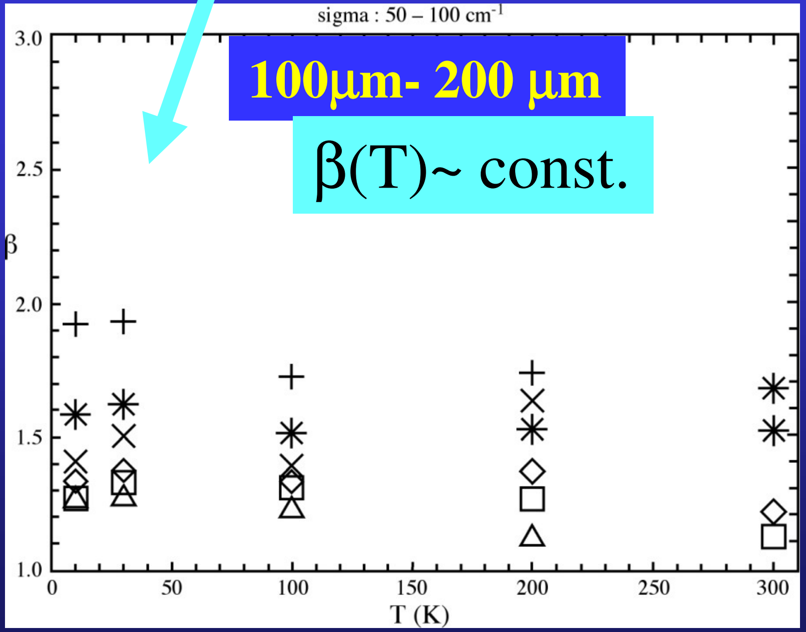
- △ SiO_2 1.5µm
- □ SiO_2 fumed
- \+ $MgSiO_3$ sol-gel
- ★ $MgSiO_3$ glass


SiO_2 ∅~1.5 µm

Break in the absorption law ~30cm^{-1}: Different frequency dependence


500µm- 1mm

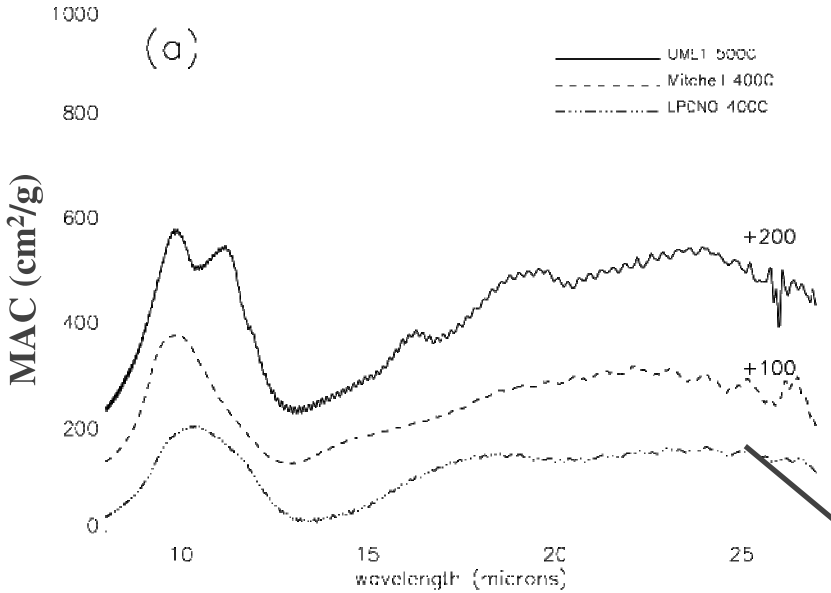
Anticorrelation T-β

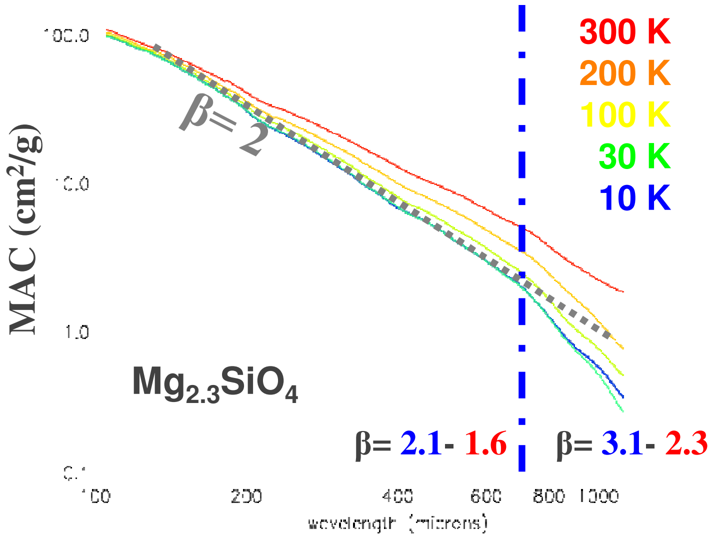

100µm- 200 µm

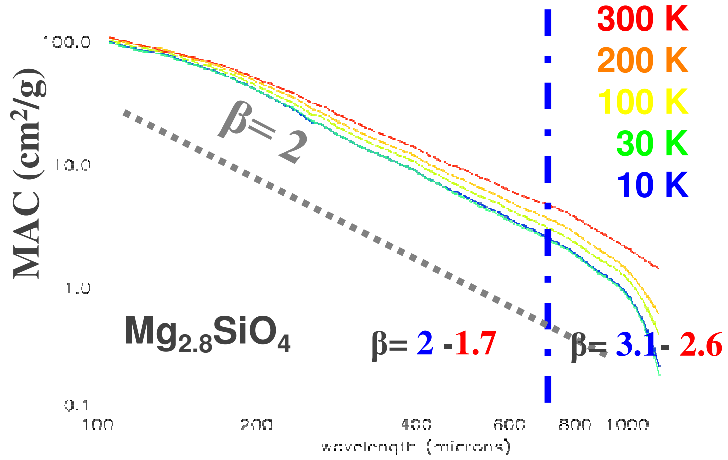
β(T)~ const.

Am. silicate grains with olivine composition (Mg_xSiO_4)

Experiments by K. Demyk et al.







β changes with λ :

150 < λ < 700/800 μm : β ~ 1.6 – 2.1

700/800< λ < 1200/1300 μm : β ~ 3.1 – 2.3

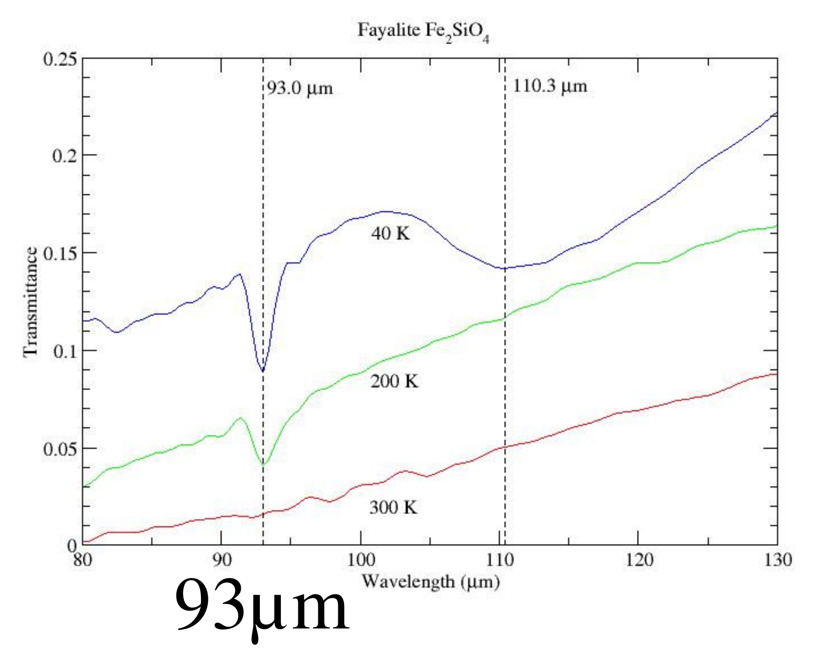
β increases with decrease of T

Mass absorption coefficient (MAC) decreases with decrease of T

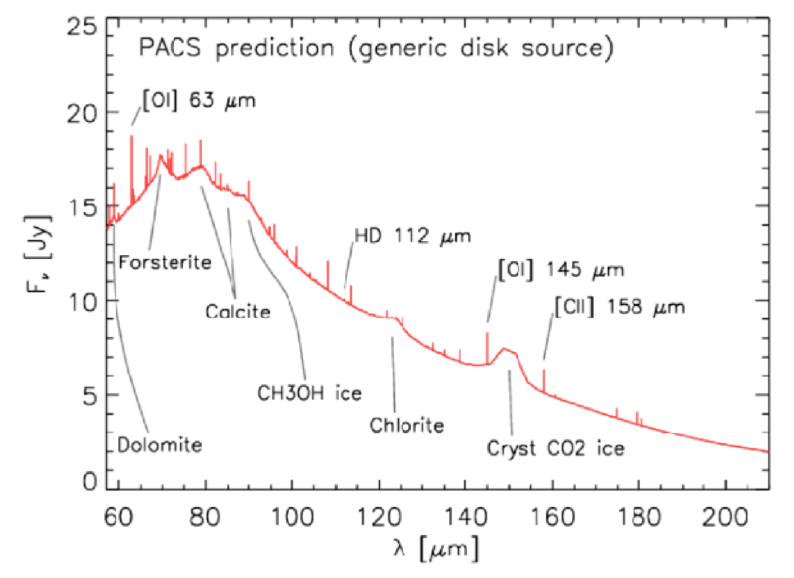
Which new dust features can we expect to see with Herschel?

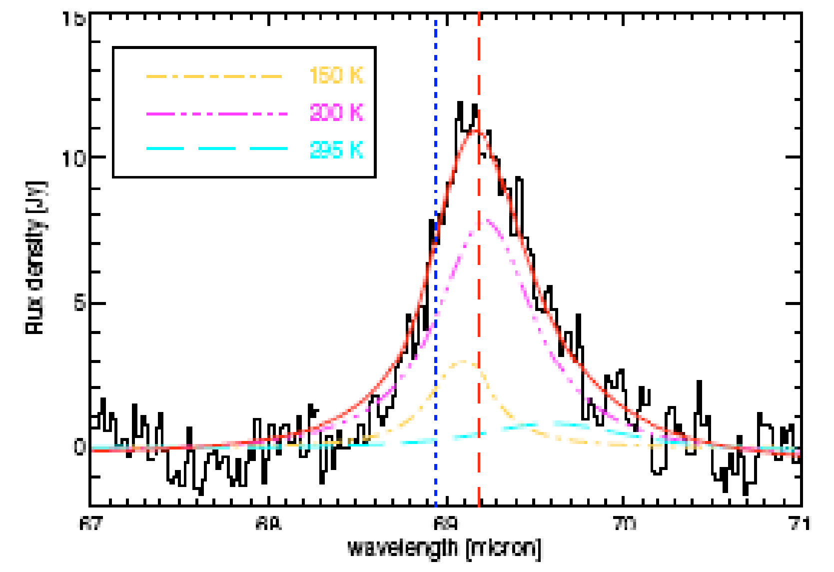
FIR: Lattice vibrations of heavy ions or ion groups with low bond energies (example KBr: transverse optical mode at 86 µm); PACS: 57-210 µm

- Forsterite 69 µm band
- Fayalite 93-94 µm and 110 µm band
- Crystalline Diopside 65-66 µm
- Hydrous silicates 100-110 µm (e.g. montmorillonite)
- Calcite $CaCO_3$ 92 µm



Herschel – Predictions and PACS Spectra





HD 100546, DIGIT Program
Sturm, Bouwman, Henning et al. (2010)

Measured position is 69.2 μm
(Cold (50 K) iron-free forsterite has a peak at 69.0 μm)

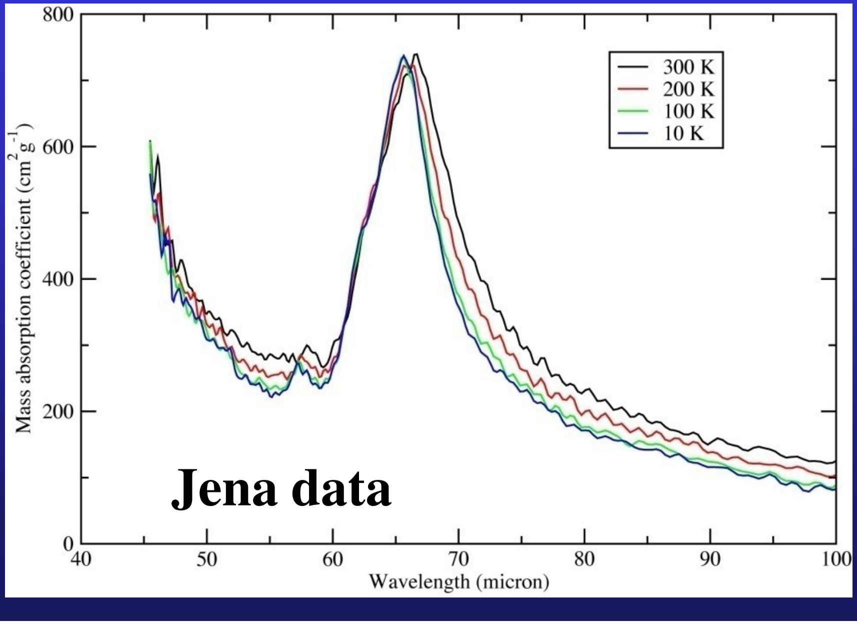
a) **Warm iron-free grains create the shift (150-200 K) (Mulders et al. 2011)**

b) **Cold forsterite with a few percent iron shifts feature**

FIR optical data of interesting materials

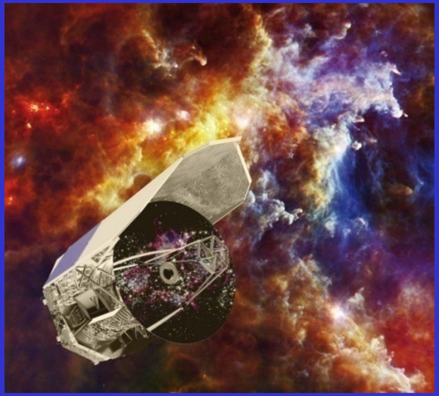
Carbonates, silicates, hydrous silicates at low temperatures

- Hydrous silicates: Mutschke et al. (2008)
- Carbonates: Posch et al. (2007)
- Olivine: Bowey et al. (2001), Suto et al. (2006), Koike et al. (2006)
- Diopside: Bowey et al. (2001), Chihara et al. (2001)



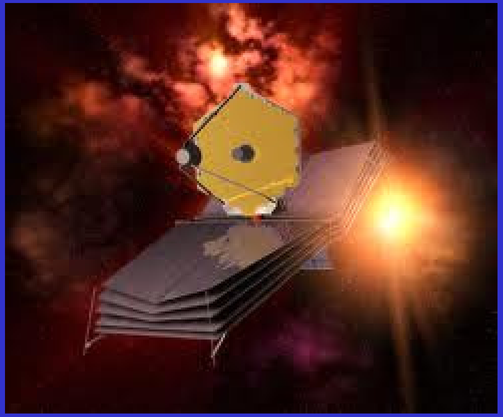
$CaMg[Si_2O_6]$

Towards a Dusty Universe ….



Herschel/Planck

ALMA



JWST

- Basic understanding of grain properties
- Diversity of grain properties in galaxies
- Formation and evolution of grains - Next challenge