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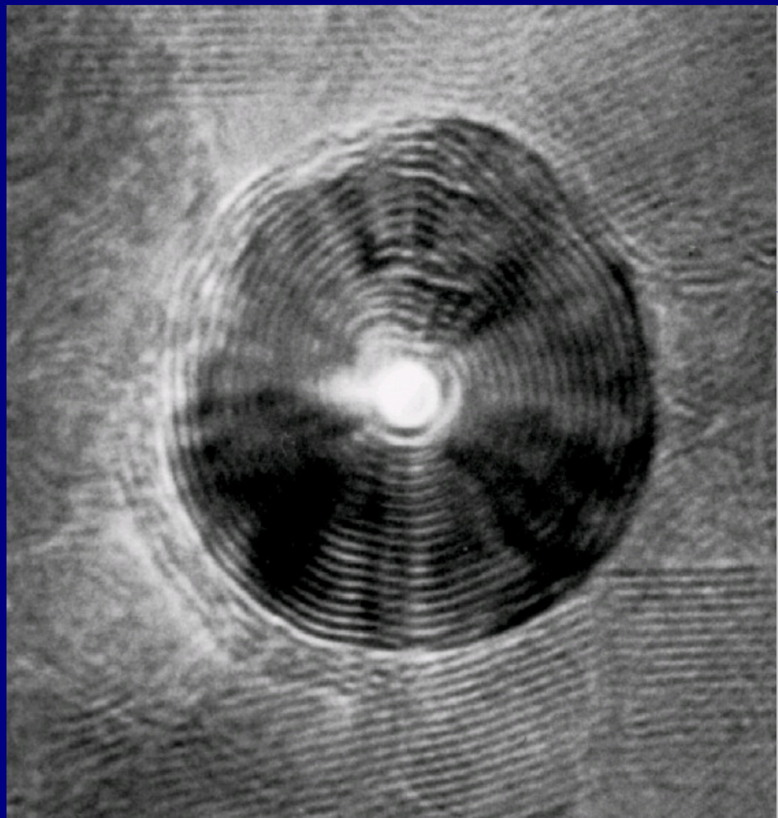
Laboratory Astrophysics of Cosmic Dust



Astronomical Colloquium, Heidelberg, December 2011

Motivation
Cosmic Dust Studies

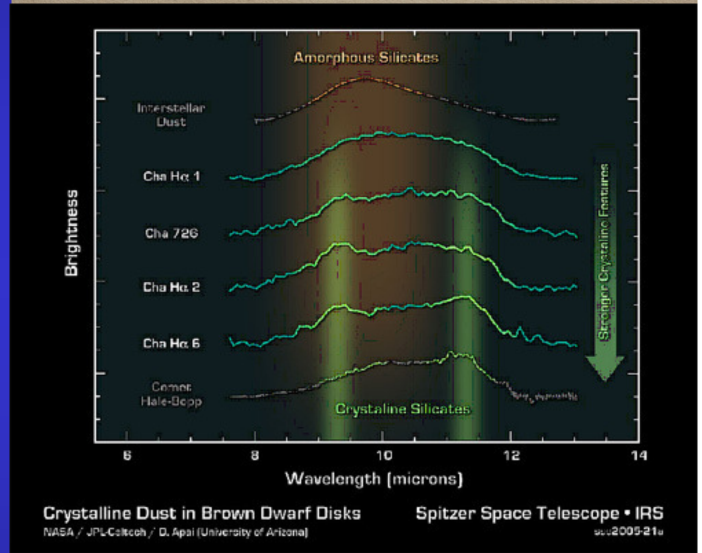
- Dust extinction, polarization, spectroscopy, continuum emission as diagnostic tools (Optical depth, mass, magnetic fields, temperature, chemistry, growth processes, mixing, …)

- Dust: Thermal, dynamical, and chemical structure

- Interesting structural and optical behaviour (Tunneling processes at low temperatures)

Foundation of Spectrocopy

Two Heidelberg Giants



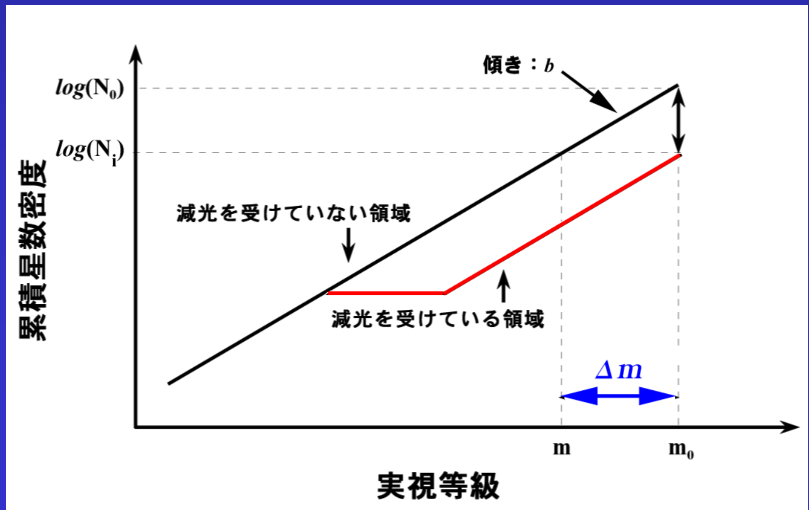
Gustav Kirchhoff (1824-1887), Robert Bunsen (1811-1899)

Chemical Analysis by Observation of Spectra
Ann. der Physik und Chemie 110, 161-189, 1860

Heidelberg - A Dusty Place

M. Wolf – The German who discovered North America

Distinguished astrophotographer and discoverer of the Wolf diagram (1863-1932)



1891-Horsehead Region

Dusty Heidelberg – A few milestones

Helios – December 1974

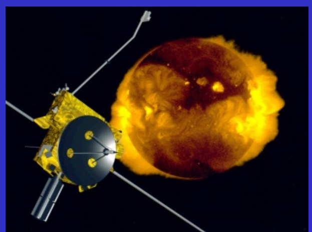
Interplanetary Dust – C. Leinert

Mass spectroscopy of Halley‘s dust - 1986

Discovery of CHON particles – J. Kissel

Efficient Production Technique of Fullerenes

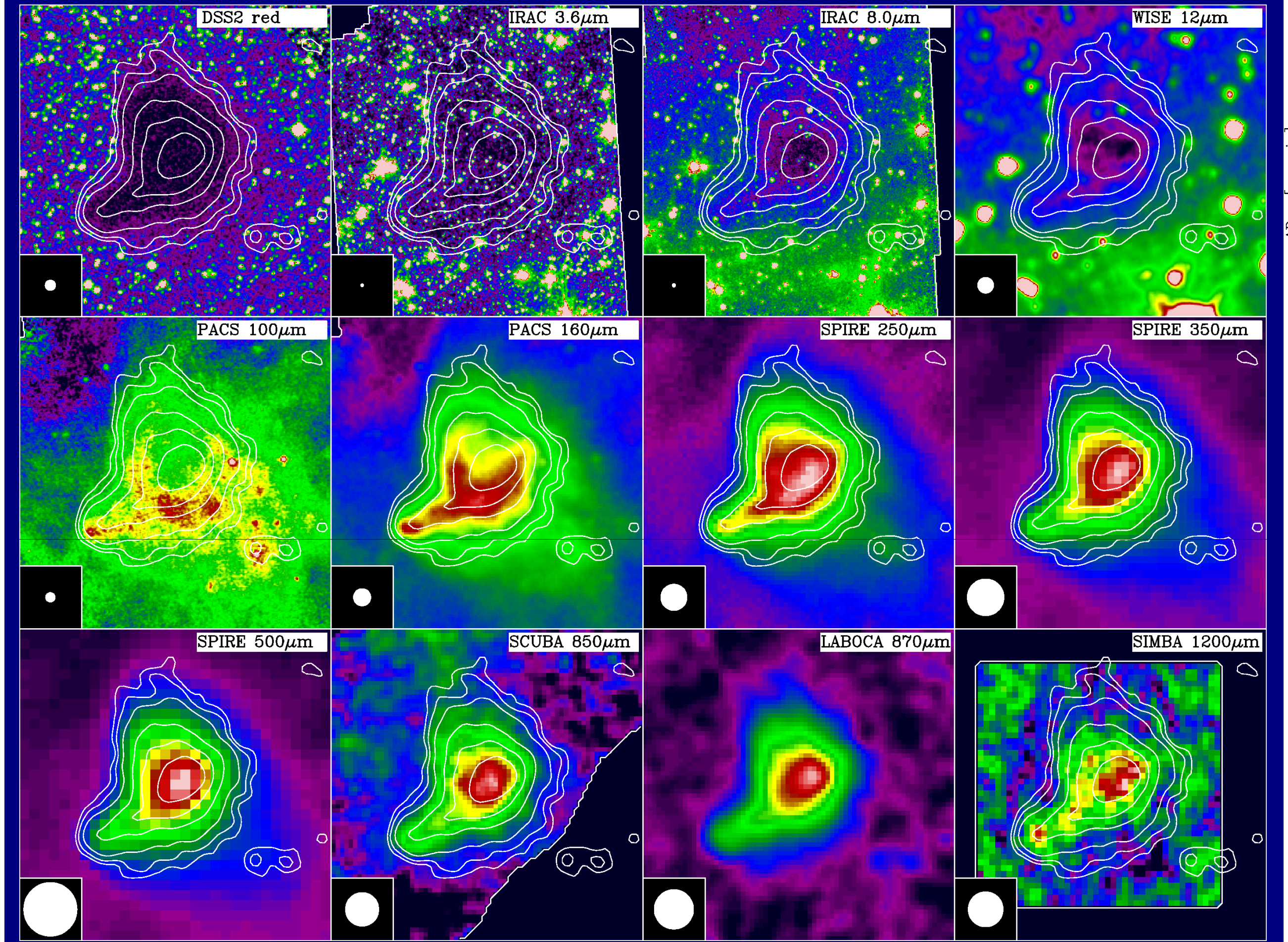
– 1990 W. Krätschmer

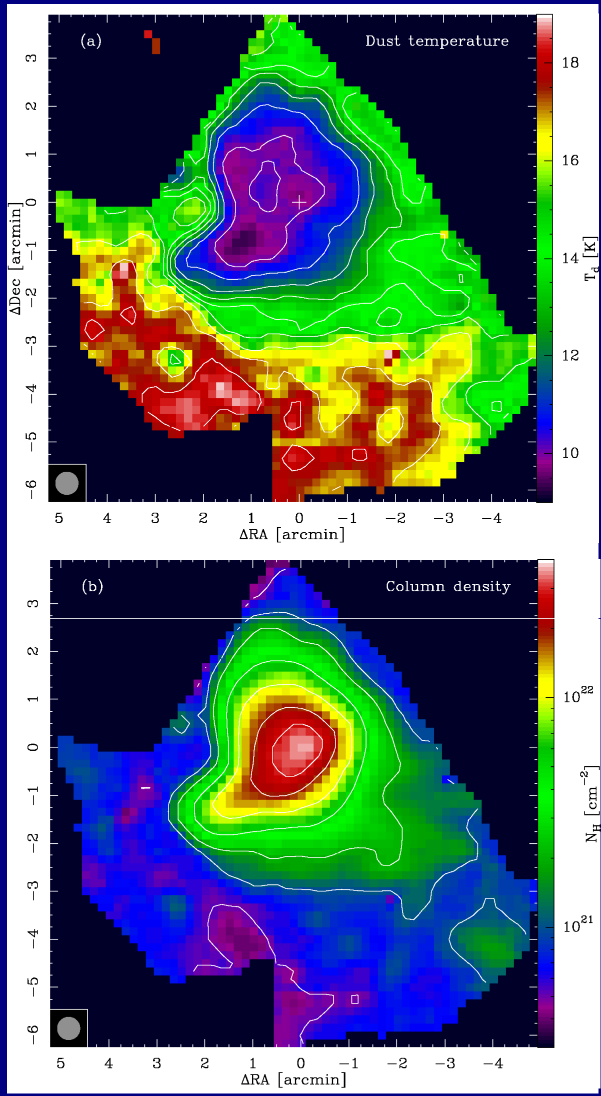


Ulysses Dust Experiment (1990-)

E. Grün – Discovery of Jovian Dust Streams and Interstellar Grains in the Solar System

B 68 – From Spitzer to WISE and Herschel





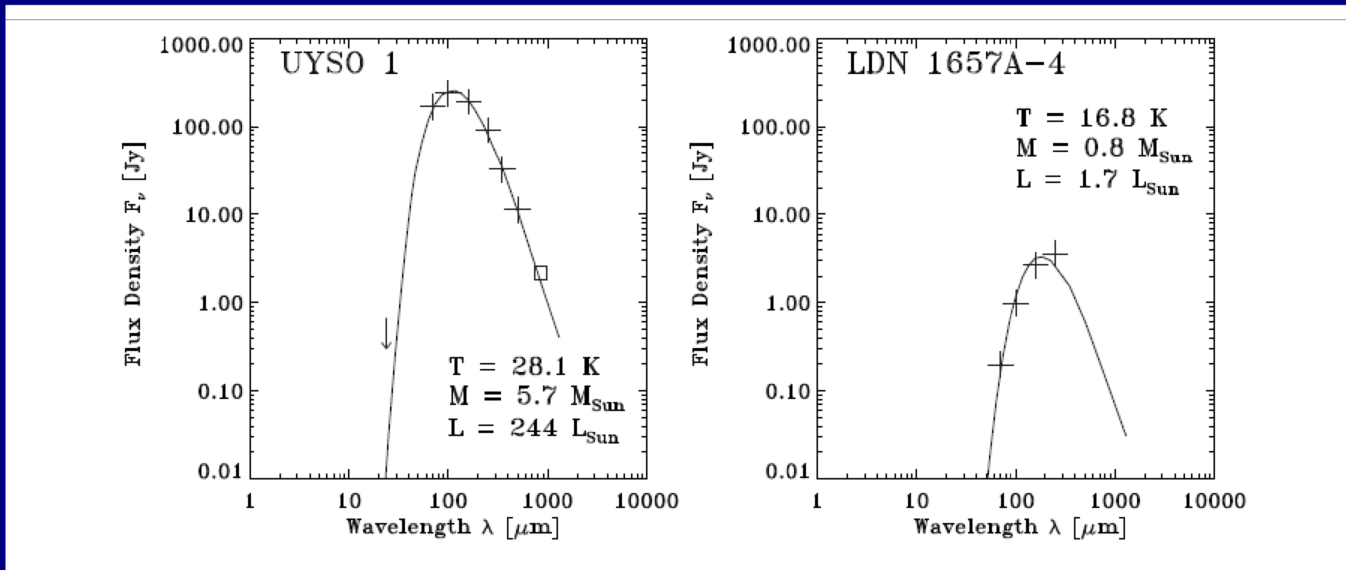
Dust continuum data

Modelled by ray tracing

Nielbock et al. 2011, in prep. Herschel/EPOS project

How to interpret SEDs at long wavelengths?

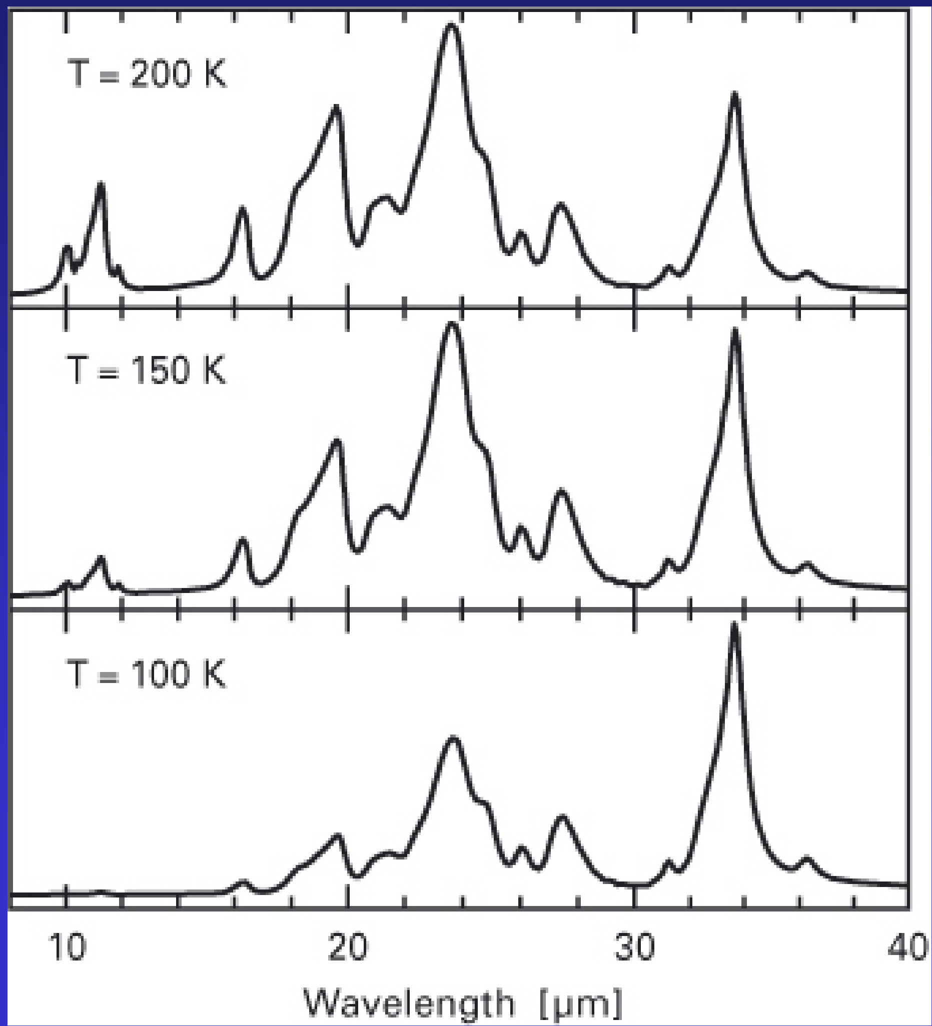
- **Presence of very cold dust**
- **Dust mass estimates**
  (protoplanetary disks, molecular cores, galaxies, quasars, …)
- **General characterization of spectral energy distributions**



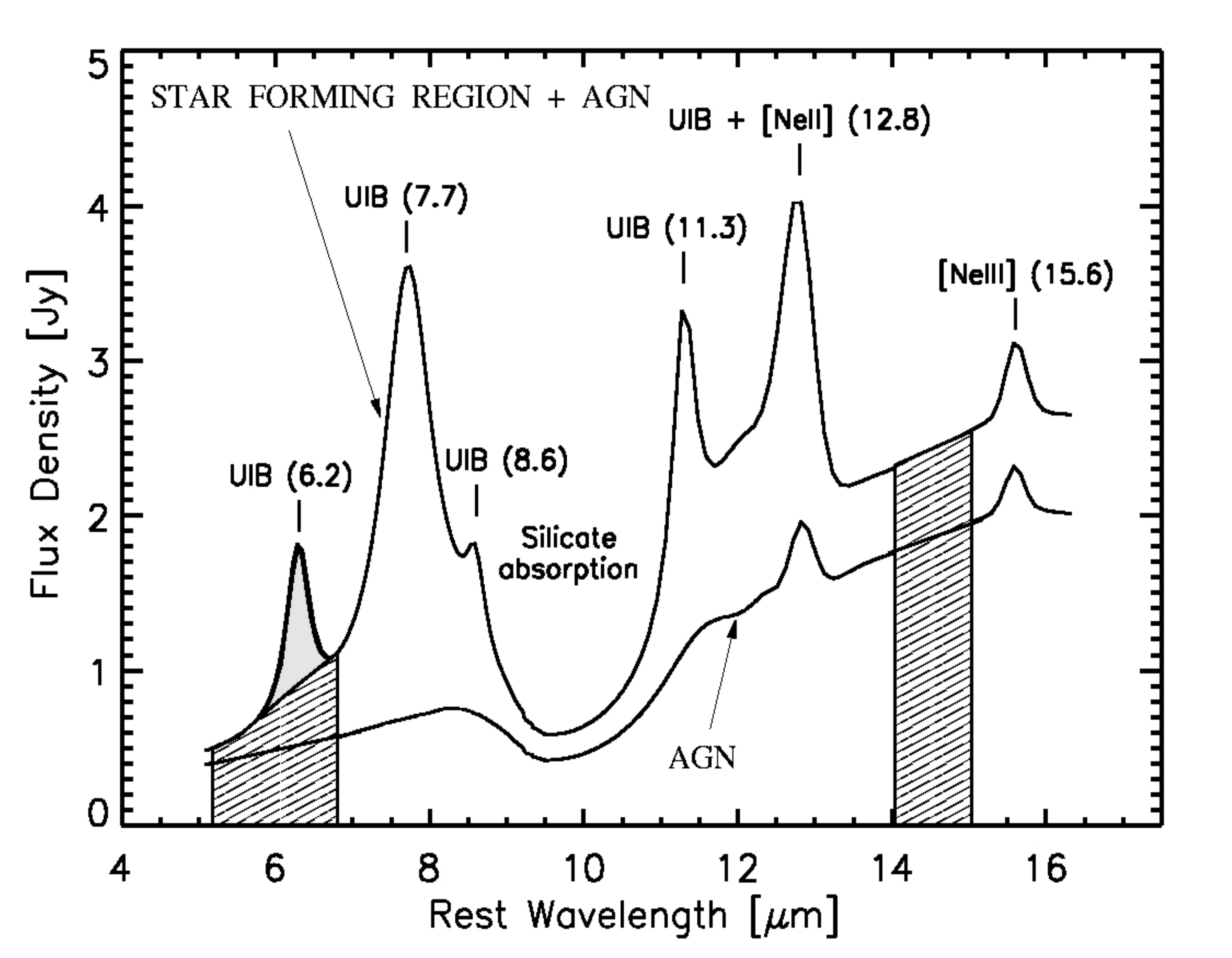
Linz et al. (2010)

Example: Spectrum of forsterite particles at different temperatures

Flux

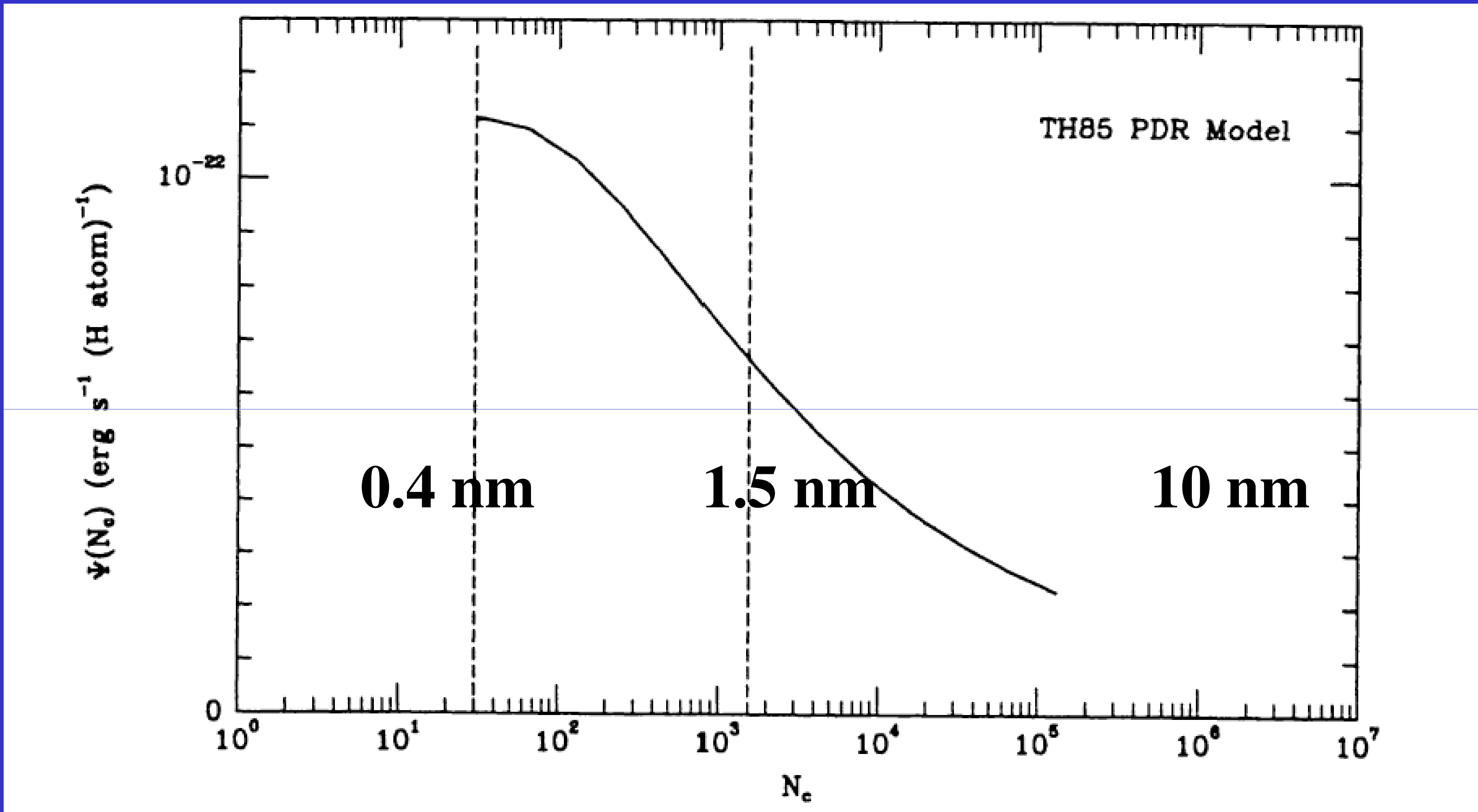


PAH emission: AGNs vs. Starburst Galaxies



Laurent et al. (2000)

Photoelectric heating

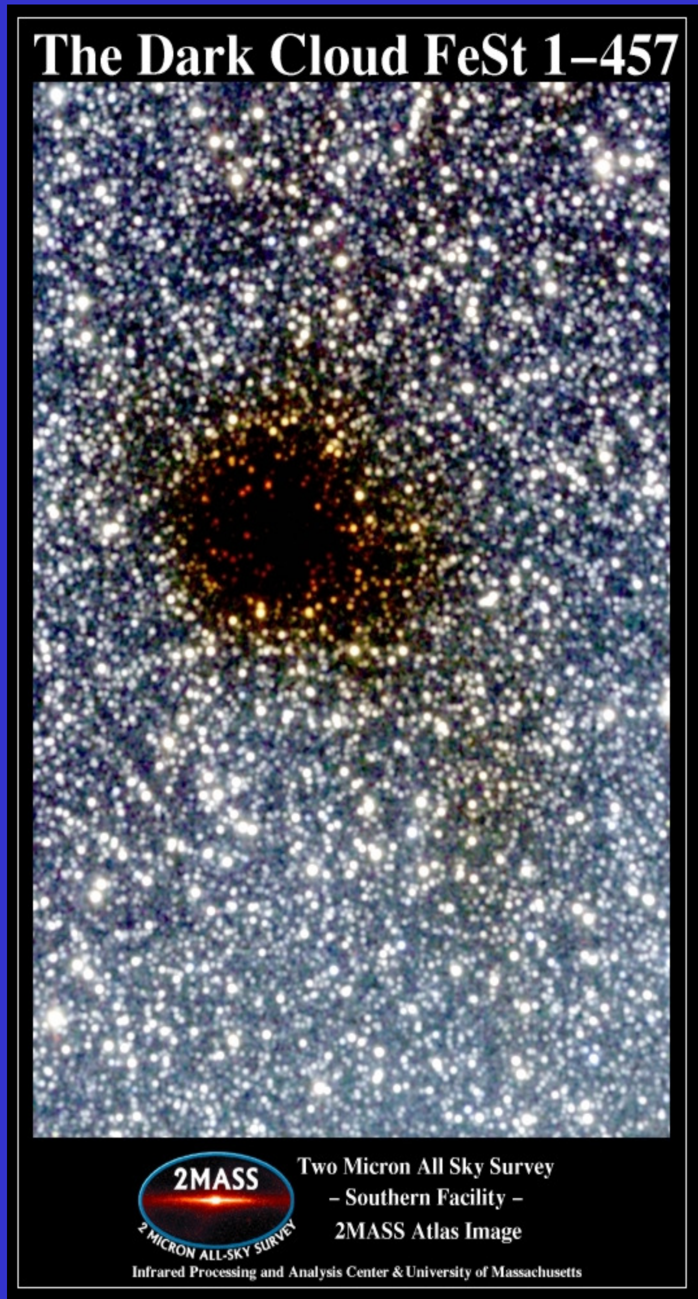


Bakes and Tielens (1994)

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 disks
- Crystalline silicates and molecular ices in disks



Silicates: Henning, ARAA, 48, 21, 2010

Carbonaceous Solids: Jäger et al., EAS Publ. Ser. 46, 293, 2011

Dust emission spectrum

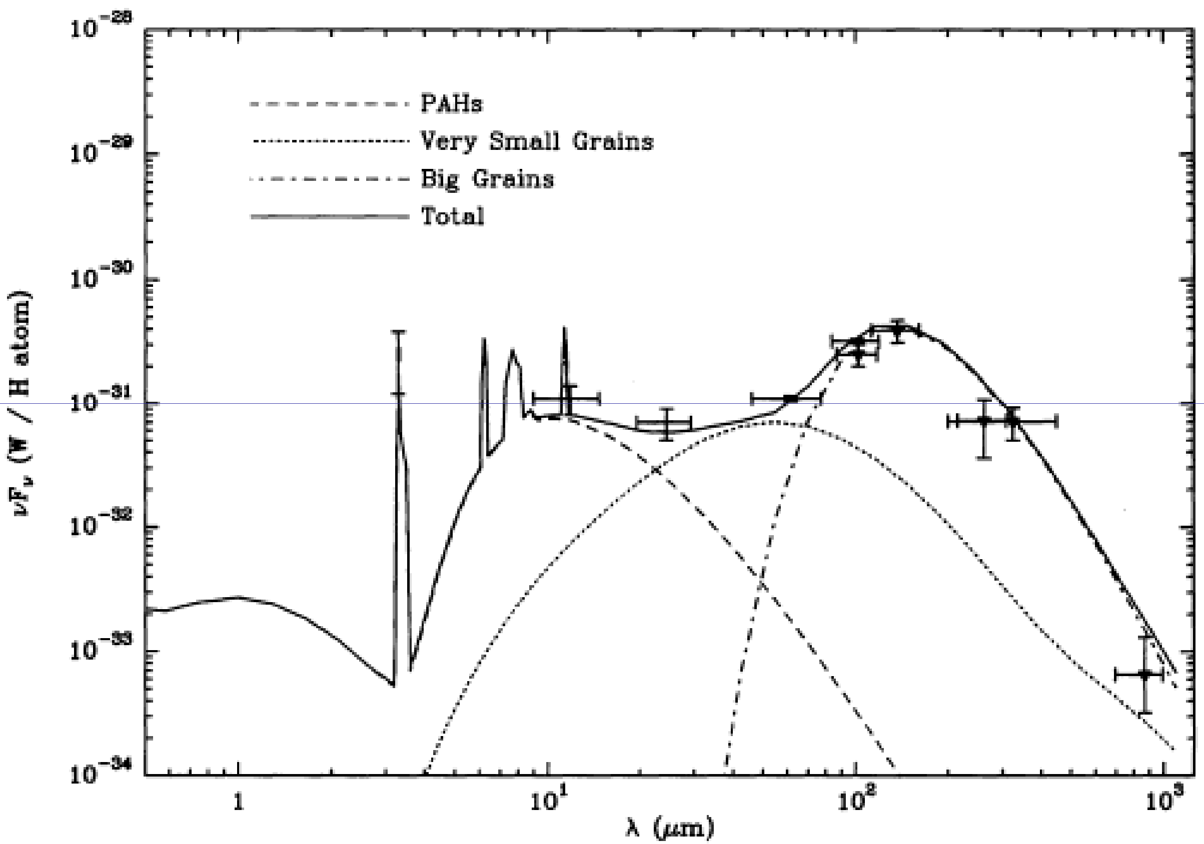
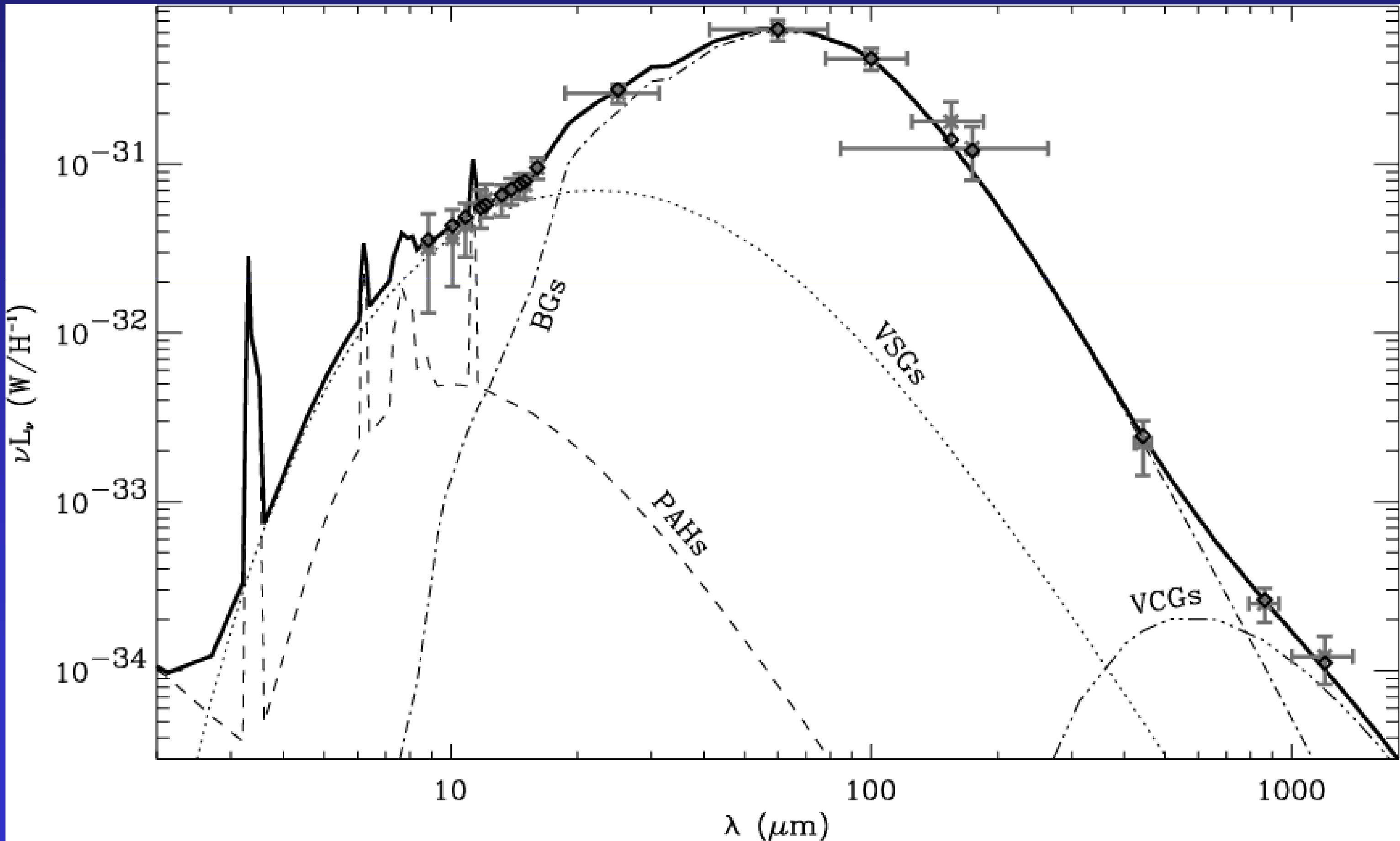


Fig. 4. Dust emission spectrum. Observations (crosses) pertain to the "cirrus" interstellar diffuse medium (see Table 1 and text). The horizontal bars represent the filter width used in the observations (given in Table 1). The model resulting spectrum (continuous line) is the sum of the three components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

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

Dust emission spectrum
Dwarf Galaxy NGC 1569
(Low-metallicity Environment)



Galliano et al. 2003

Basic Types of Dust Mixtures

Stardust — Original dust formation

Interstellar Dust — UV/cosmic ray processing; Modification by shocks

Molecular Cloud Dust — Surface chemistry, Ice mantles, Coagulation

Protostellar Dust

Interplanetary Dust

Time

Dorschner & Henning (1995)

$dM_{stardust}/dt \sim 0.005\ M_{sun}/yr$, Gas: $\sim 1.2\ M_{sun}/yr$ (Draine 2009)

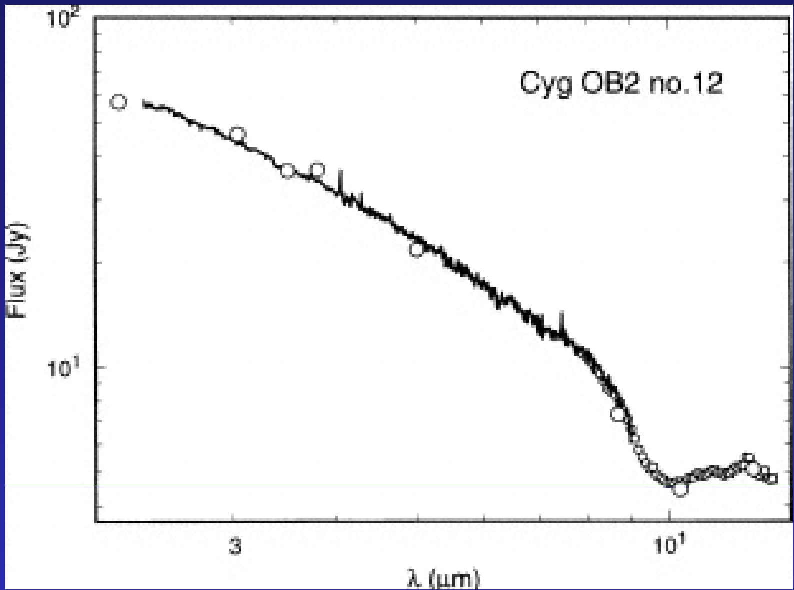
(Type II SN 1987a $\sim 8\times10^{-4}\ M_{sun}$ Ercolano et al. 2007

SN 2003gd $\sim 2\times10^{-2}\ M_{sun}$ Sugerman et al. 2006)

$M_{stardust}/M_{ismdust} \sim 1.6 \times 10^{6}\ M_{sun}/2.5 \times 10^{7}\ M_{sun} \sim 0.06$

h1

Dust in the Diffuse 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)

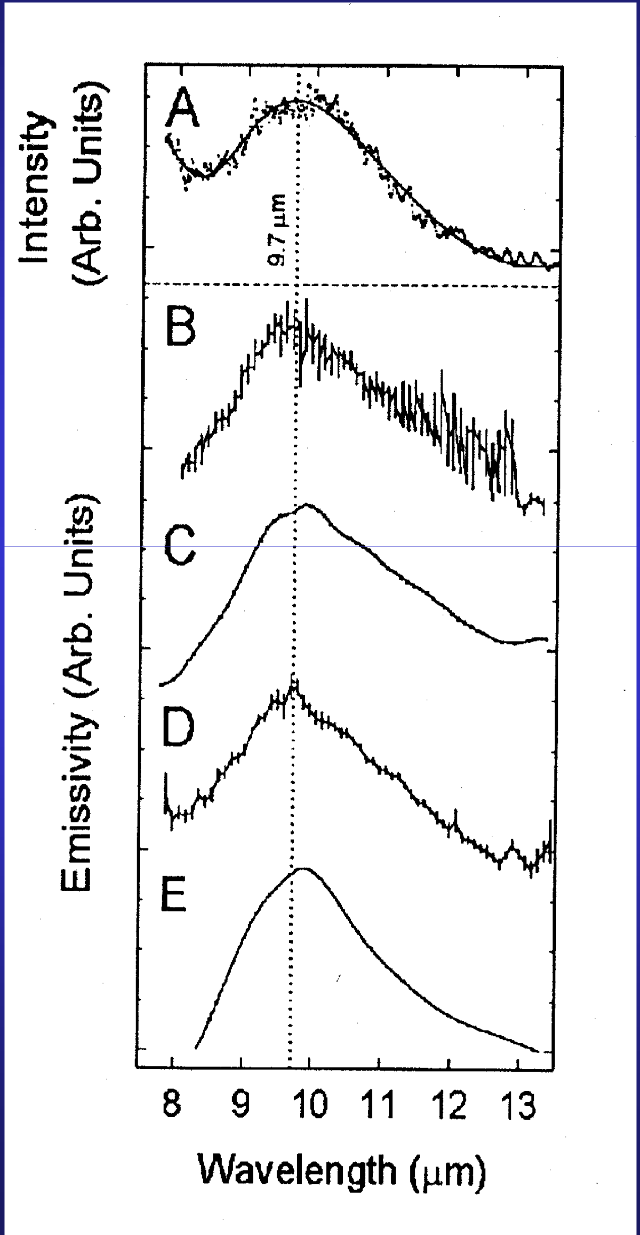
Amorphization by cosmic rays/shock processing in ISM/re-condensation of amorphous silicates in the ISM (Jäger et al. 2003)

3.4 micron absorption feature – aliphatic hydrocarbons (Pendleton & Allamandola 2002)

Folie 15

h1 Amorphization easier for Fe-rich silicates
henning; 10.08.2005

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:

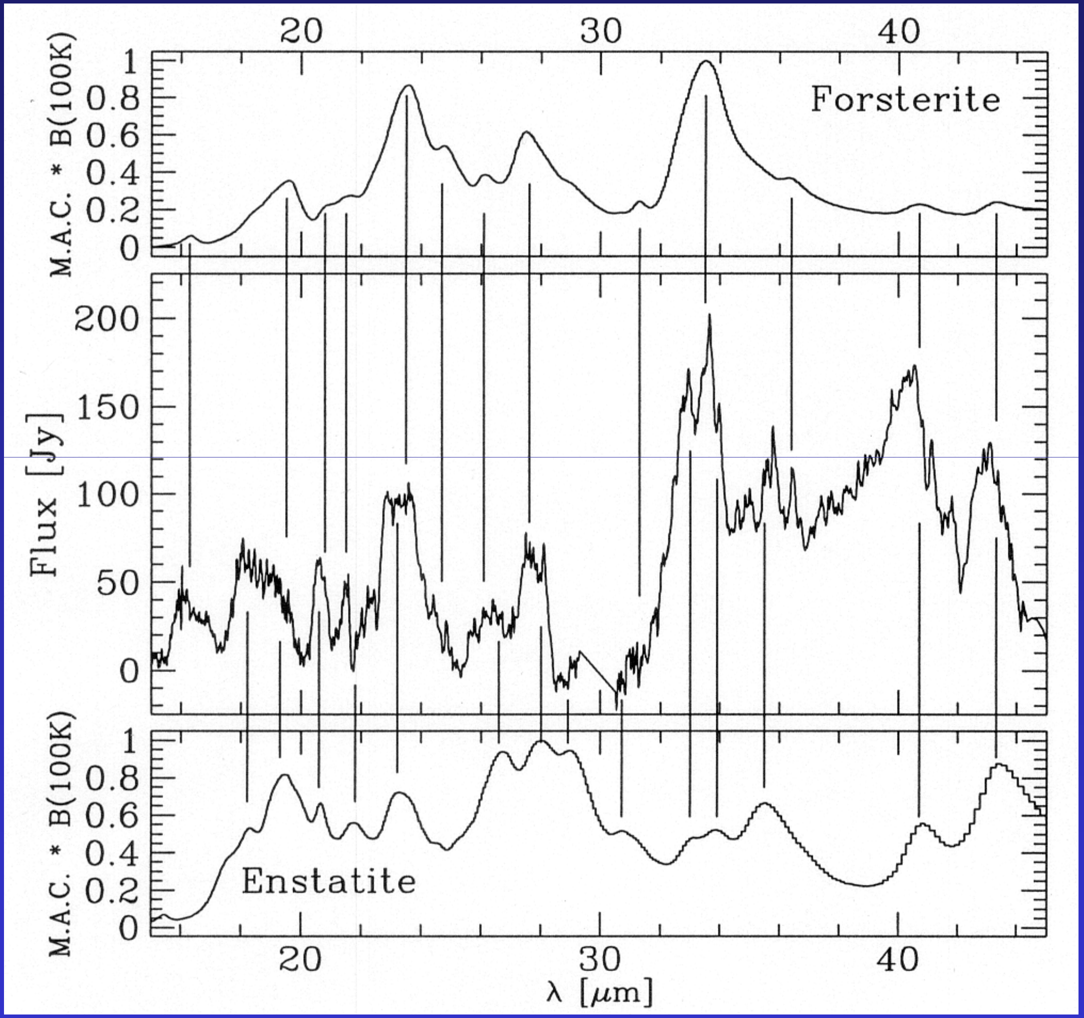
(Mg+Fe)/Si~0.7 (Keller & Messenger 2004)

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)

Crystalline Revolution (ISO and Spitzer)

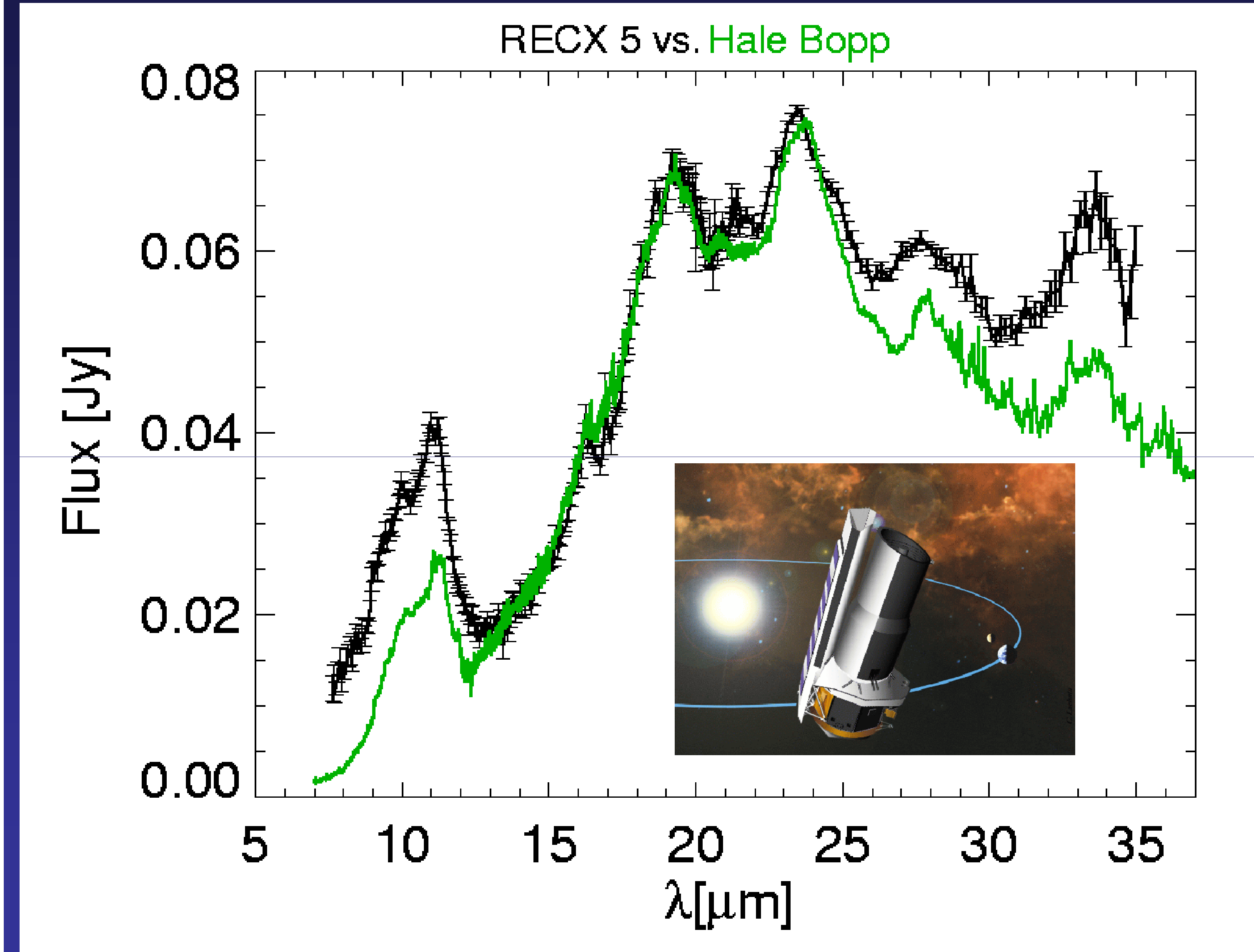
AFGL 4106



T=100 K

Jäger et al. (1998)

RECX5: Hale Bopp Formation around an M4 star?

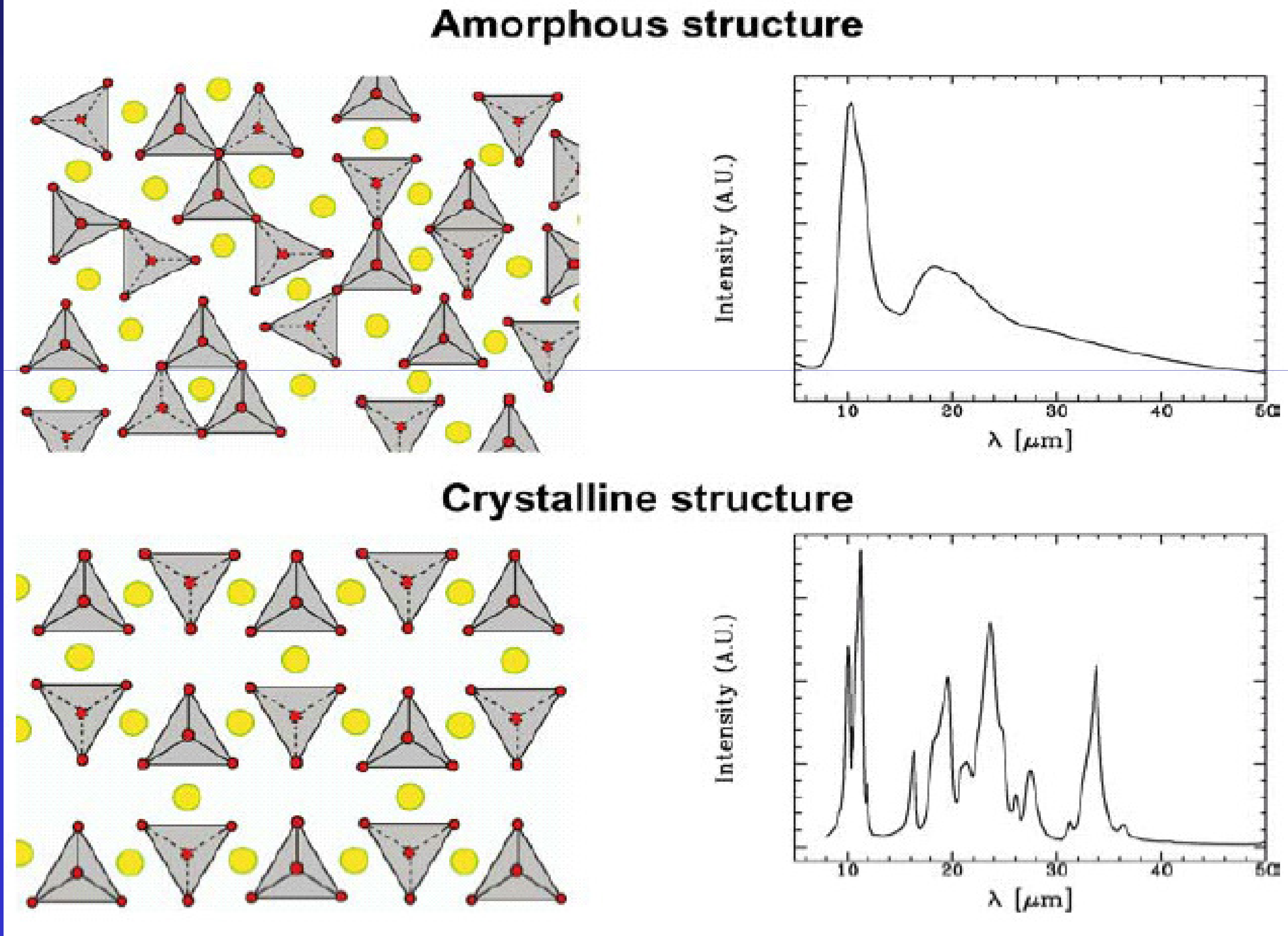


IRS (5-40 μm long slit, R=150, 10-38 μm echelle, R=600)

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

Bouwman et al. (2010)

IR Properties of Silicates – Amorphous vs. Crystalline Structures



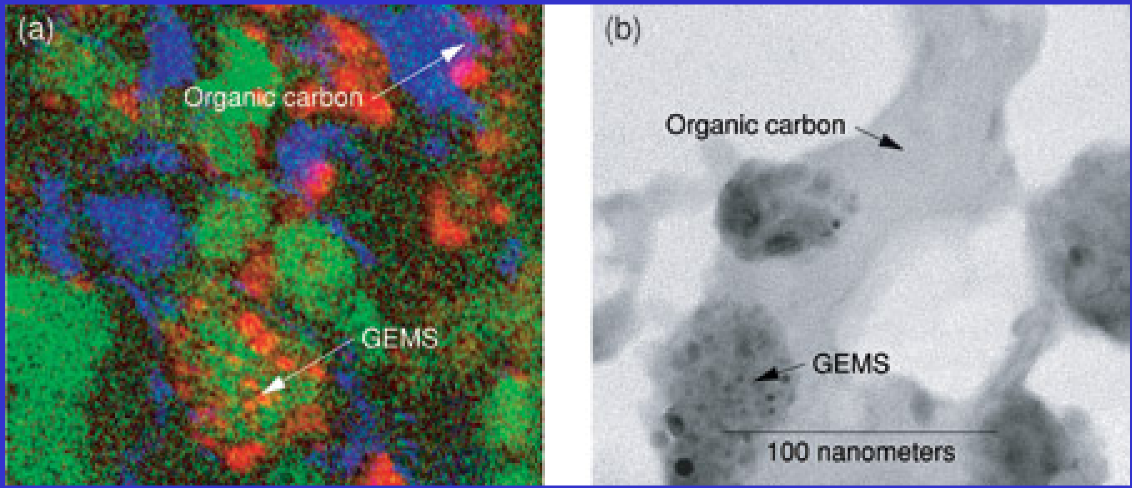
IR Properties of Silicates – Amorphous vs. Crystalline Structures

- 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

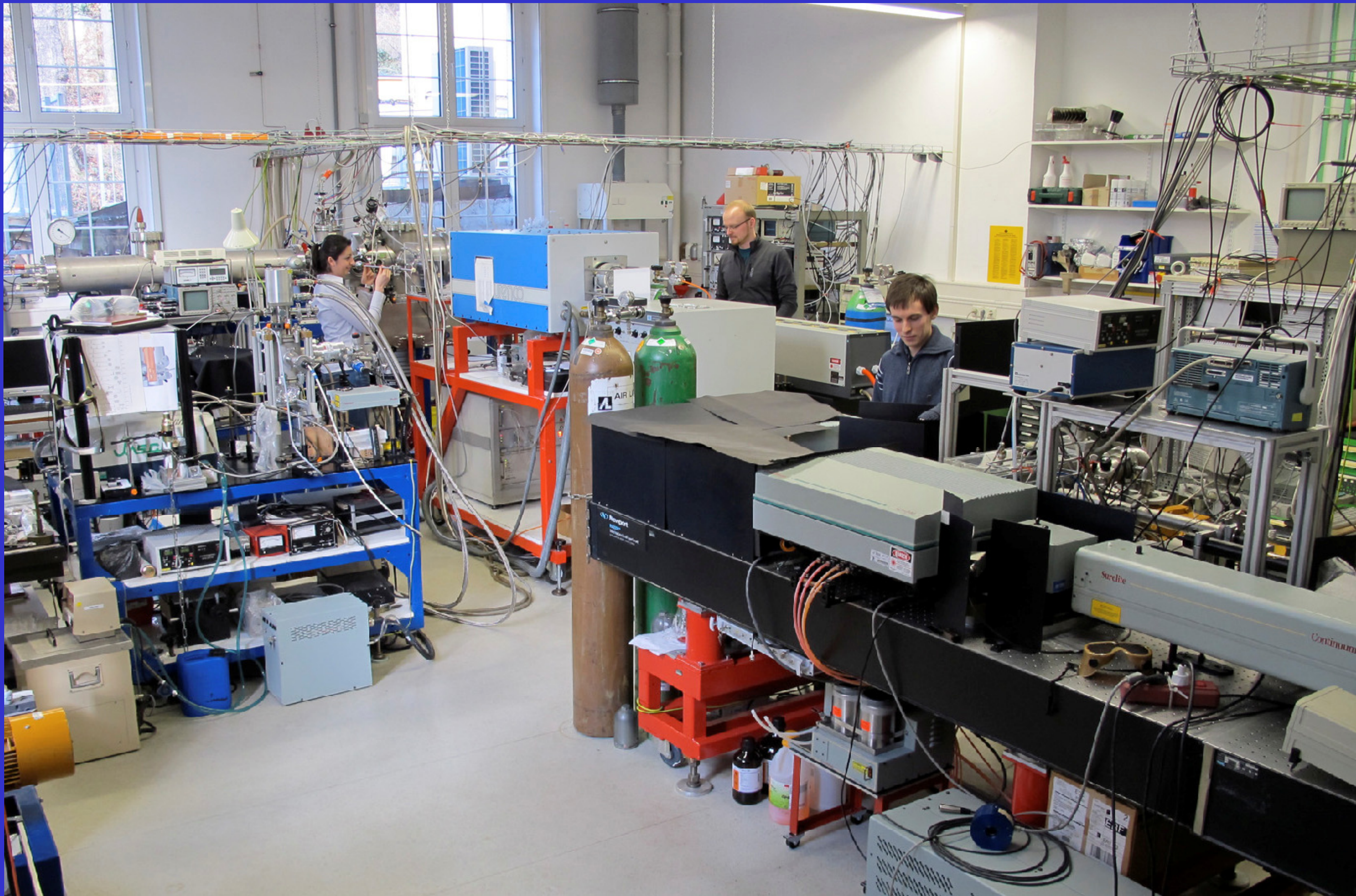


EELS – Fe (red), Mg (green), C (blue); J. Bradley/H. Ishii

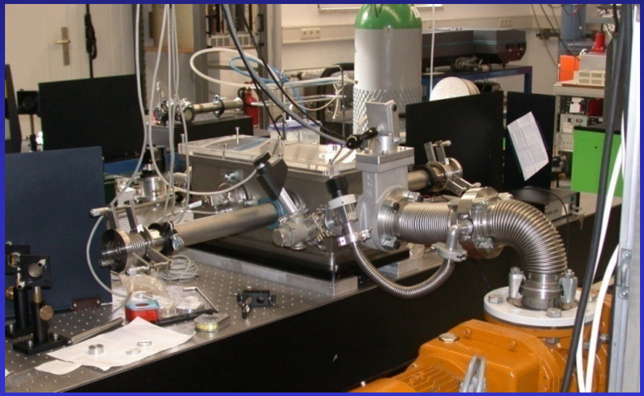
MPIA Jena He droplet experiment

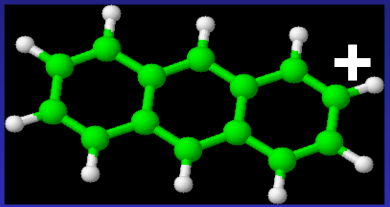
- Interplanetary dust particles and stardust in meteorites
- Optical properties of cosmic dust analogues
- Formation and modification of dust grains

MPIA Laboratory Astrophysics Facility @ U Jena

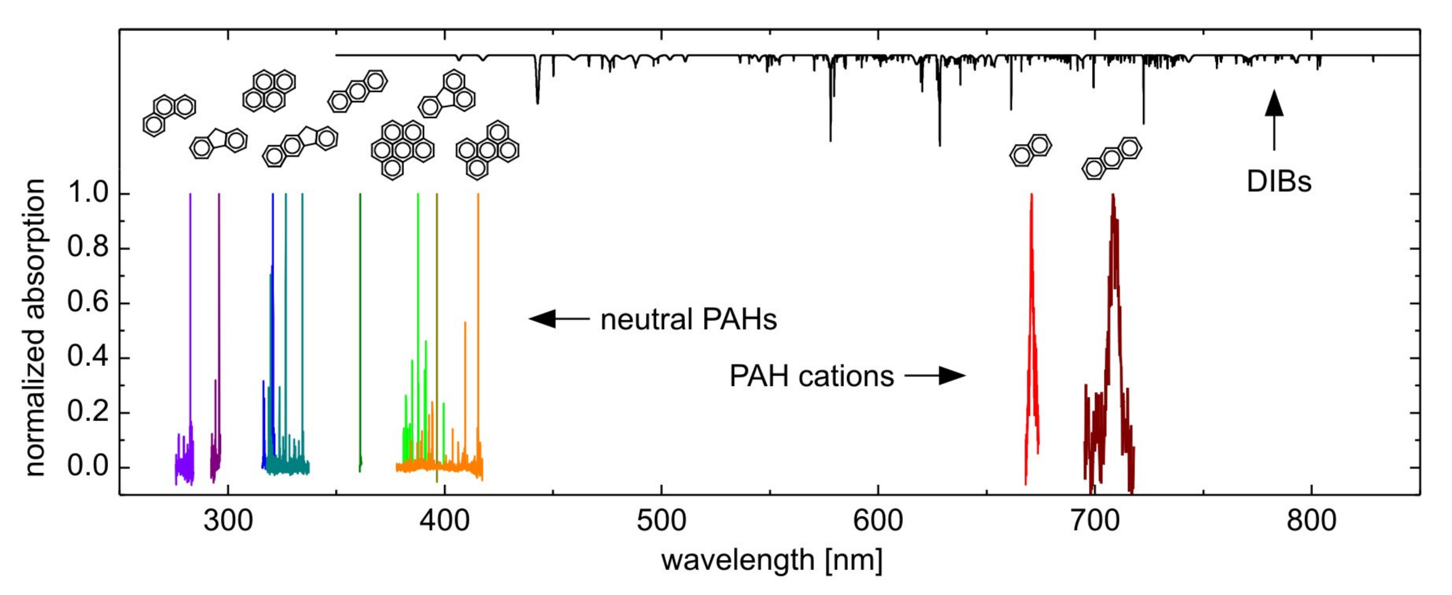


Cavity Ring-Down Spectroscopy of PAHs



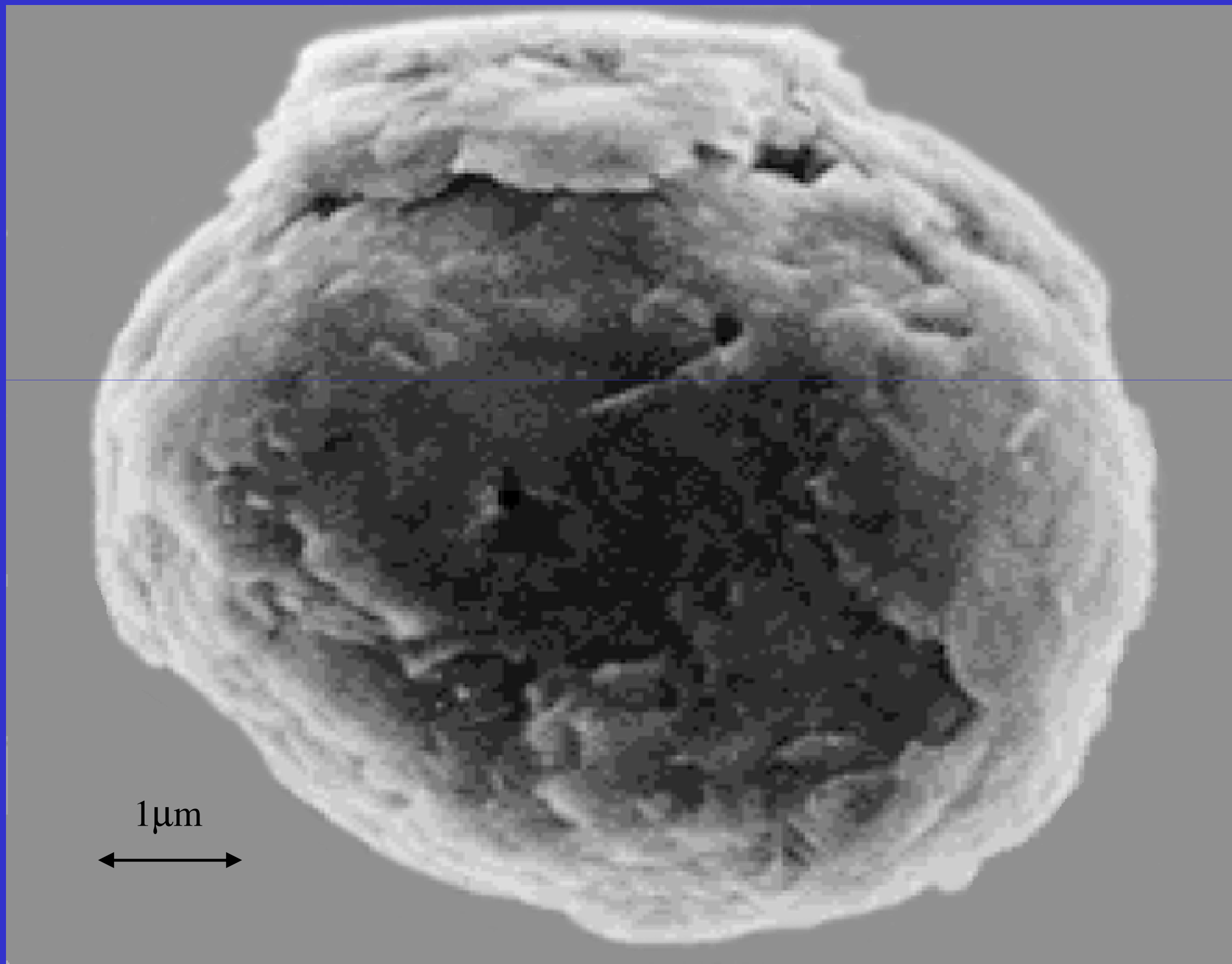


Rouille ea. 2009, JCP 131, 204311
Staicu ea. 2008, JCP 129, 074302
Rouille ea. 2008, Chem.Phys.Chem. 9, 2085



Comprehensive dataset for electronic PAH spectra

Onion-like presolar „graphite" particle - Murchison meteorite

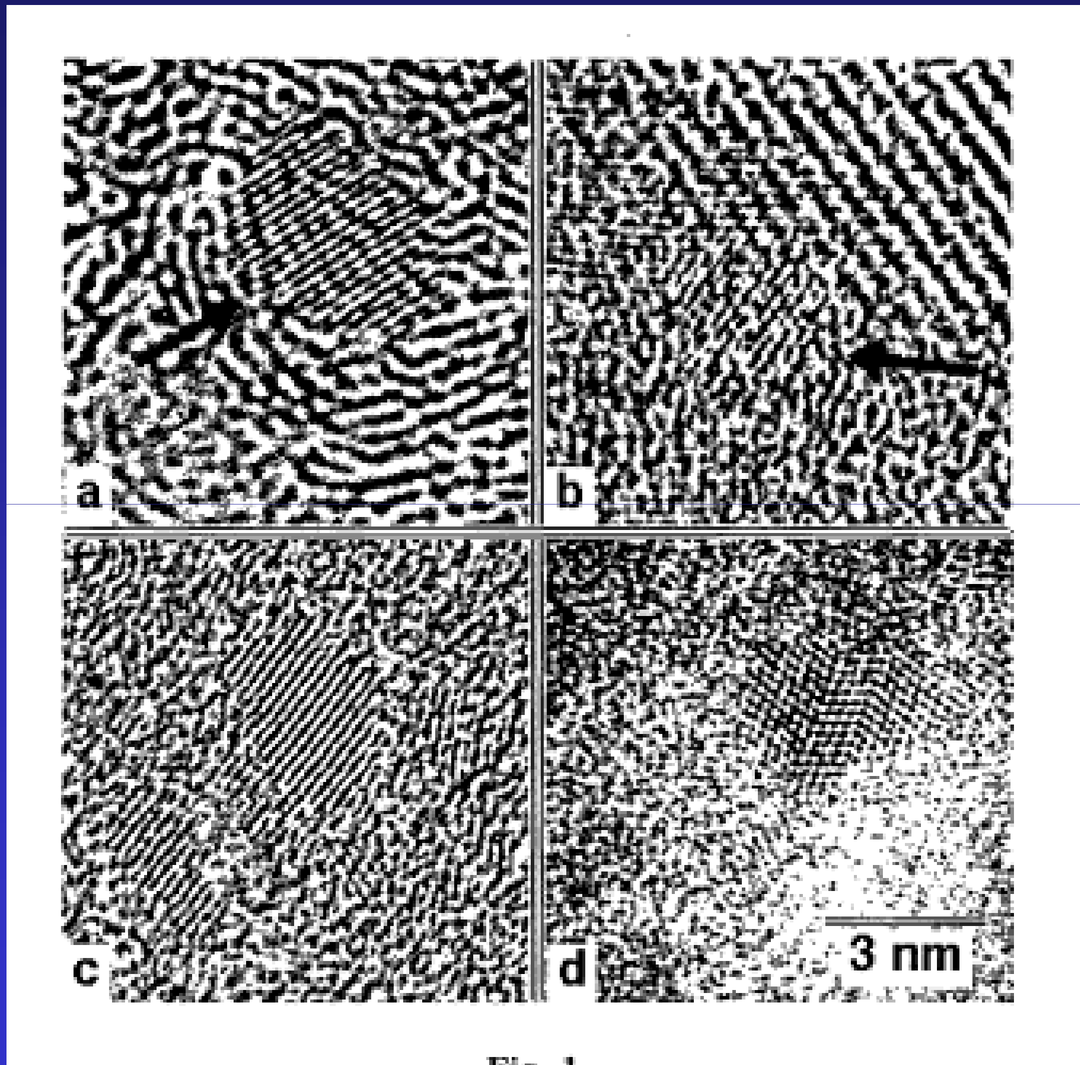


Clayton et al.

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	

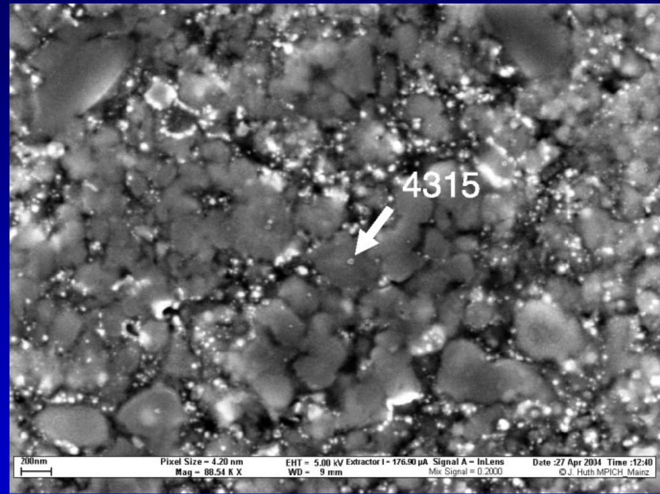
Detection of nanodiamonds in unprocessed Allende



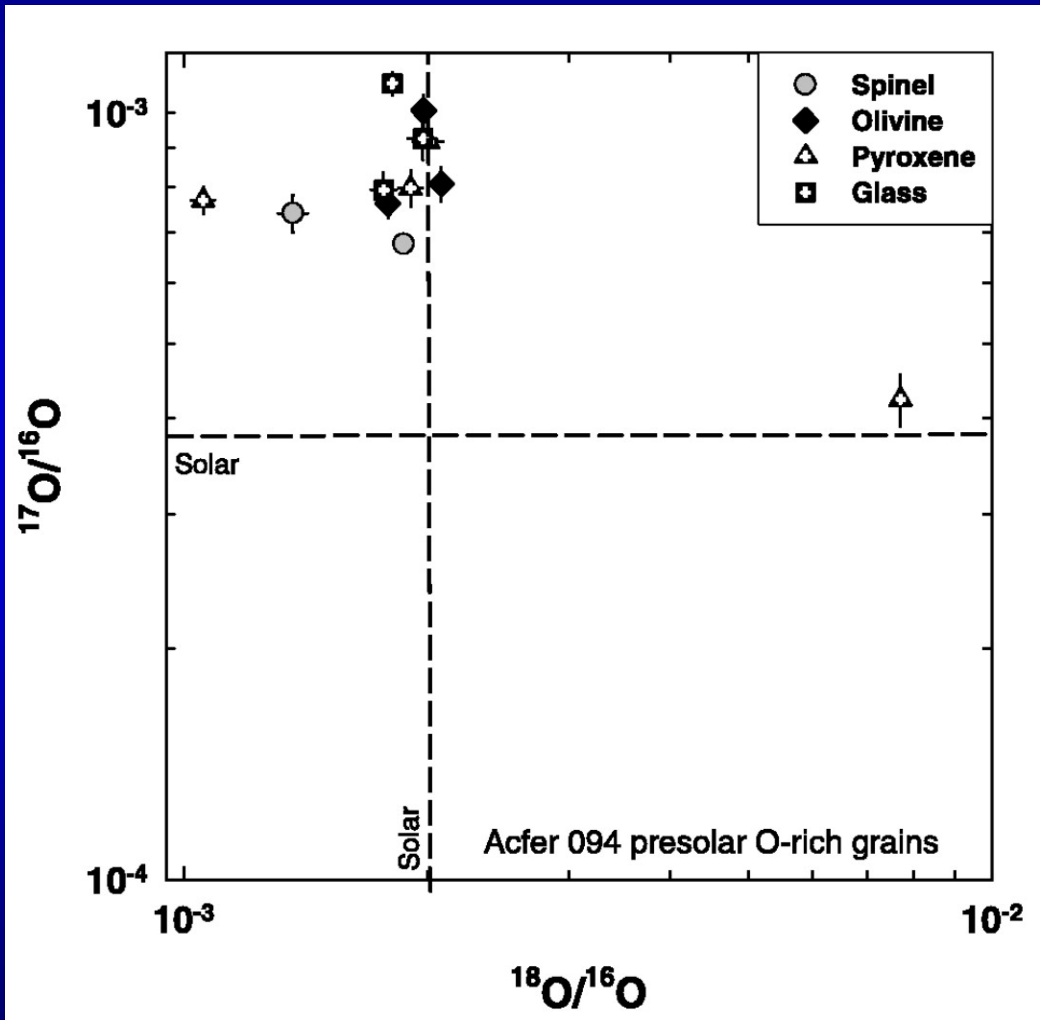
Banhart et al. (1998)

Silicates from Space

SEM Image



Scale bar: 200 nm



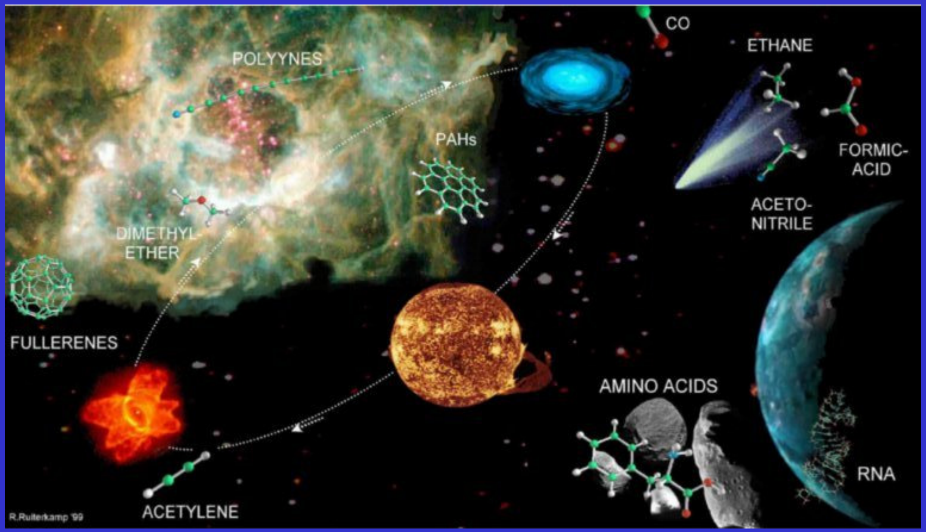
AGB or RGB origin

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

Hoppe et al. 2005

(see also Messenger et al. 2003
Vollmer et al. 2008, 2009)

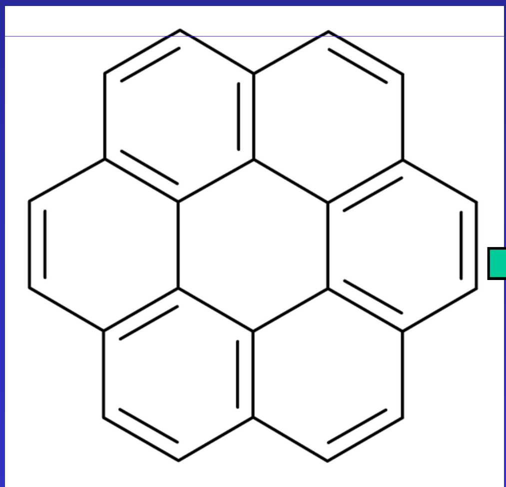
Why does interstellar dust exist?



- 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 VSGs?
- Why don´t we see SiC grains in the diffuse ISM?

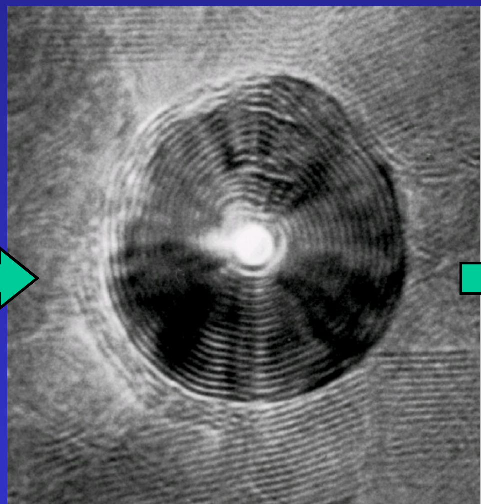
Grain Sizes – From „Nano to Micro“

Coronene



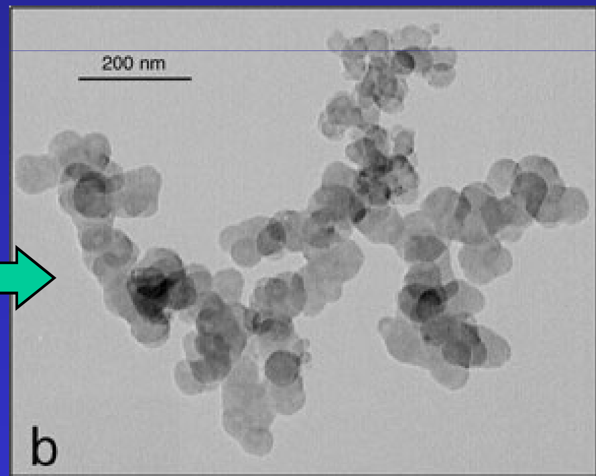
36 atoms
1 nm

Carbon Onion



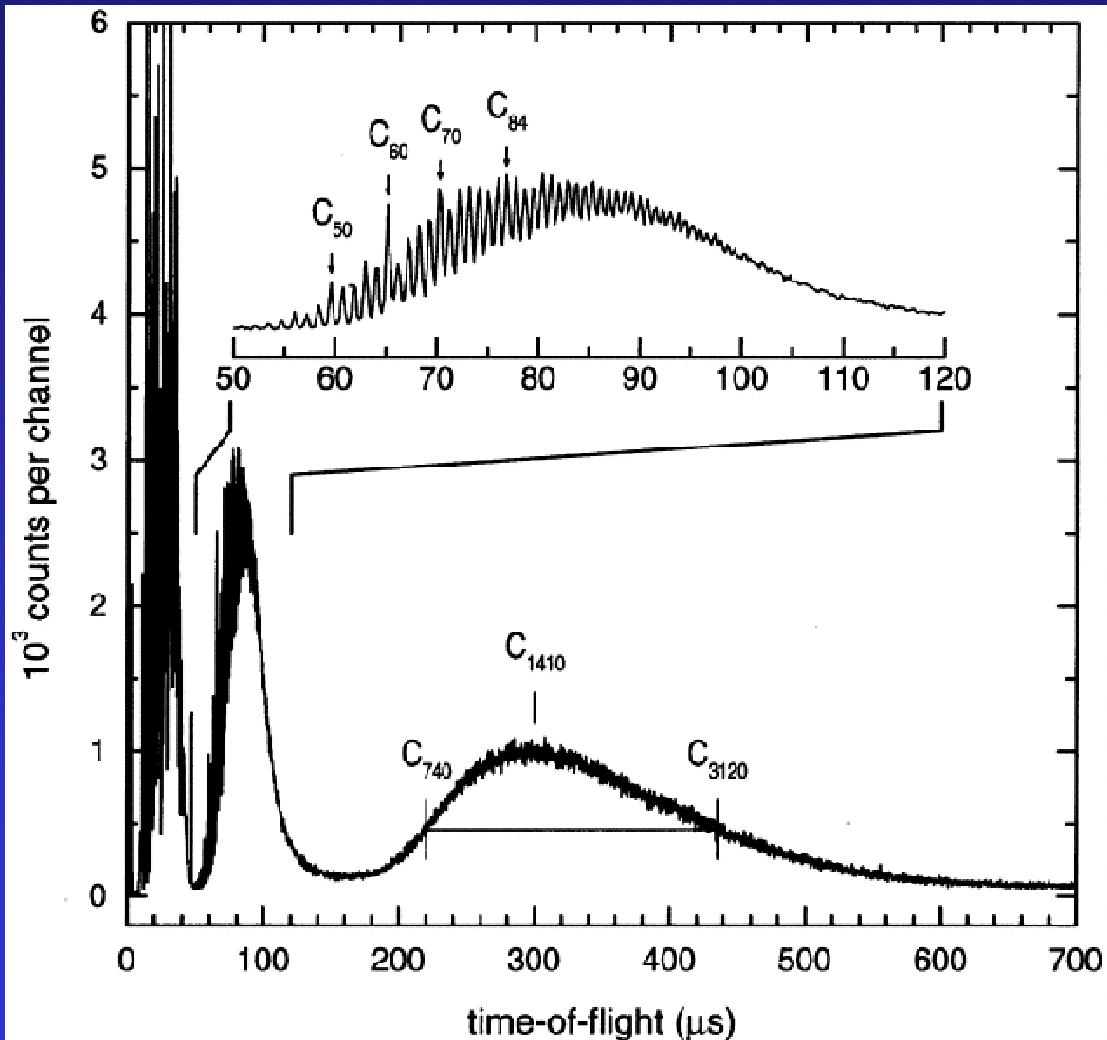
10^5 atoms
15 nm

Soot Particle



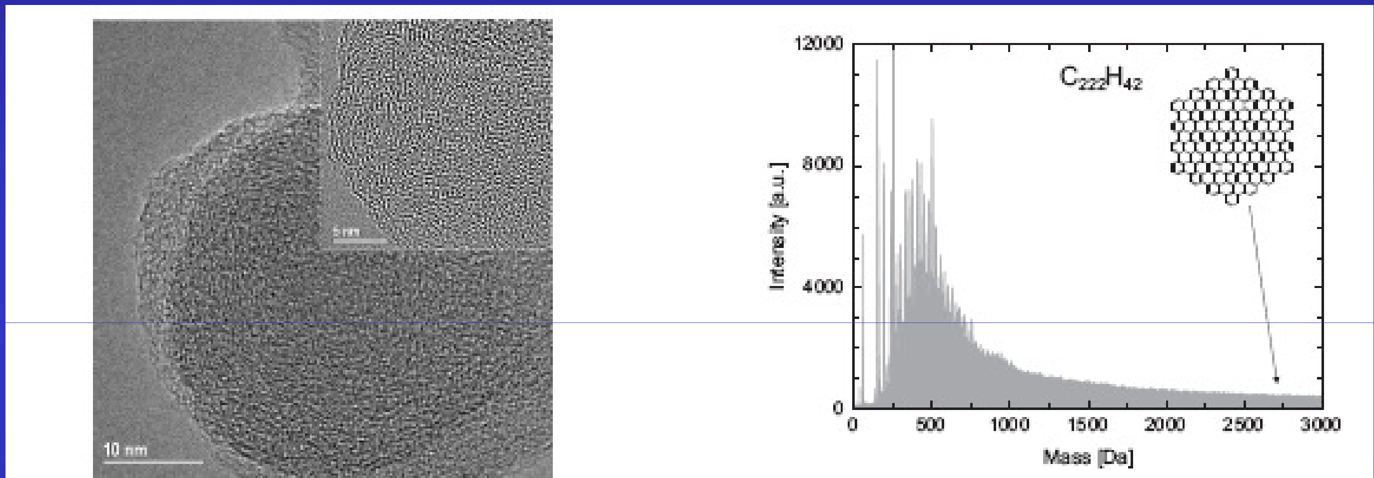
10^7 atoms
200 nm

Transition from Carbon Clusters to Solid Particles



Formation of Dust

Grain formation experiments under high-T conditions



Jäger ea. 09

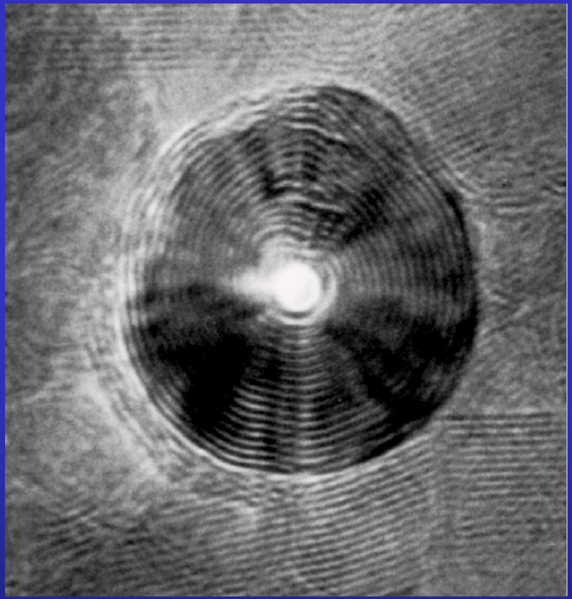
HT (≥3500 K): Very small fullerene-like carbon grains
LT (≤1700 K): Synthesis of PAH-based structures

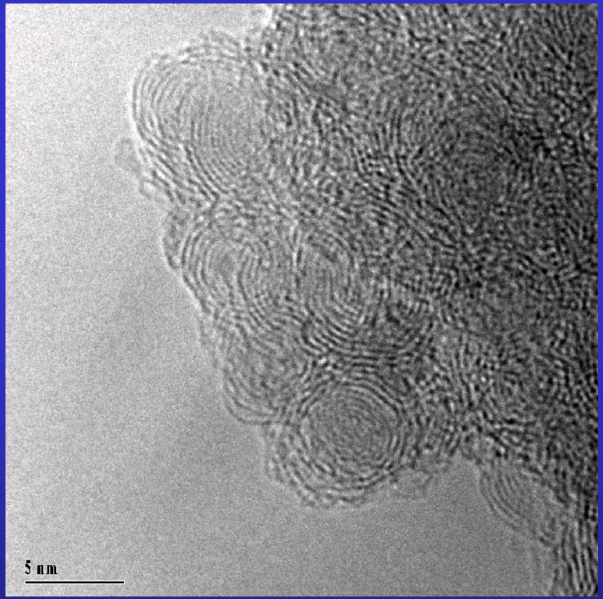
Grain formation experiments under low-T conditions

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

Non-crystalline disordered carbons

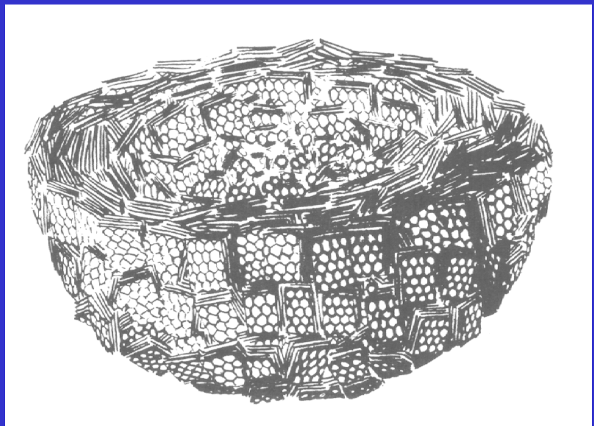
Soot Particles (without hydrogen/oxygen):
Curved and closed structures or polycrystalline materials
Soot Particles (with hydrogen):
Smaller grains preferably formed: Curved structures

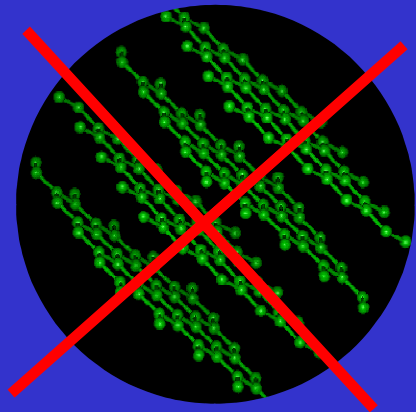


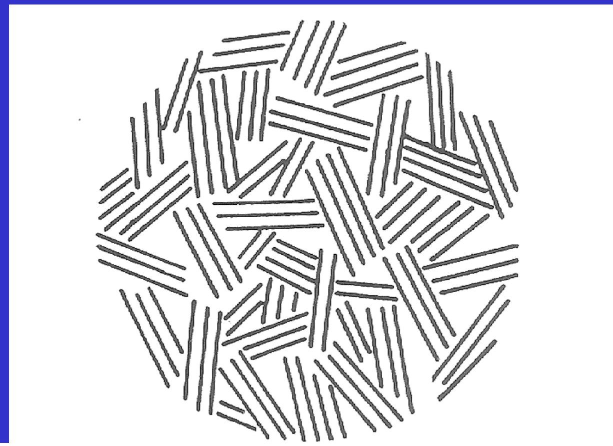


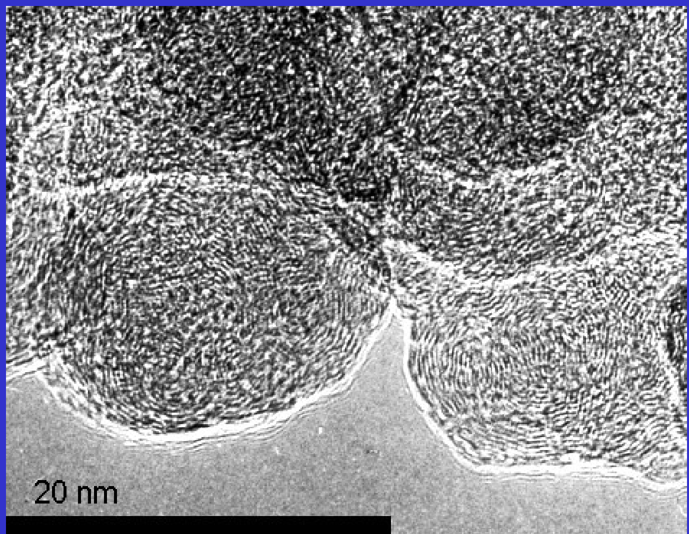
Arc discharges, laser ablation, thermal sublimation methods, sputtering, laser pyrolysis, combustion

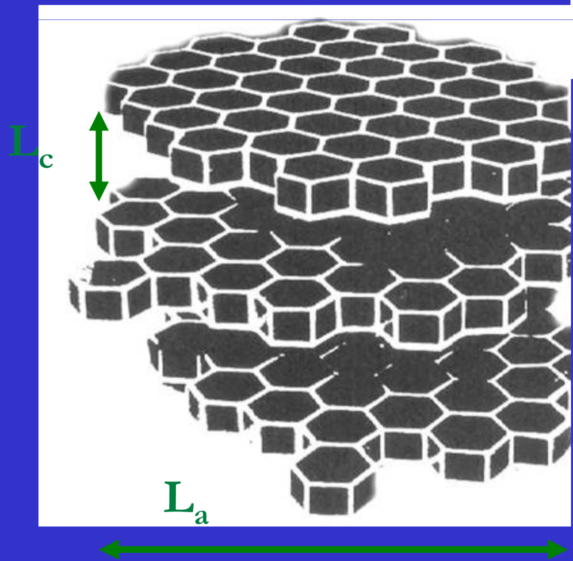
Gas-phase condensed soot particles

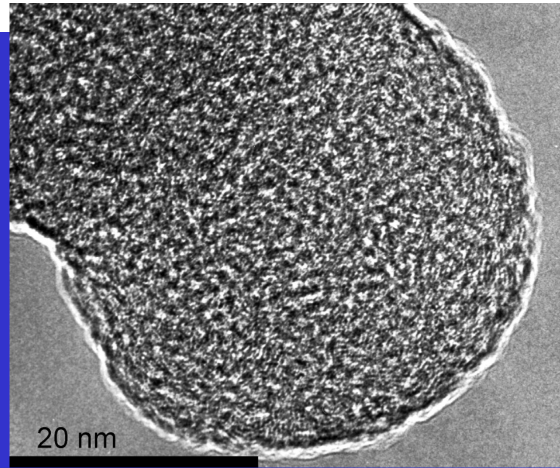






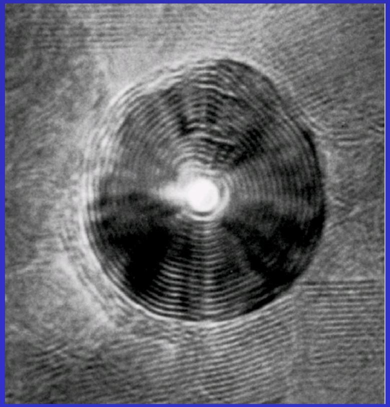






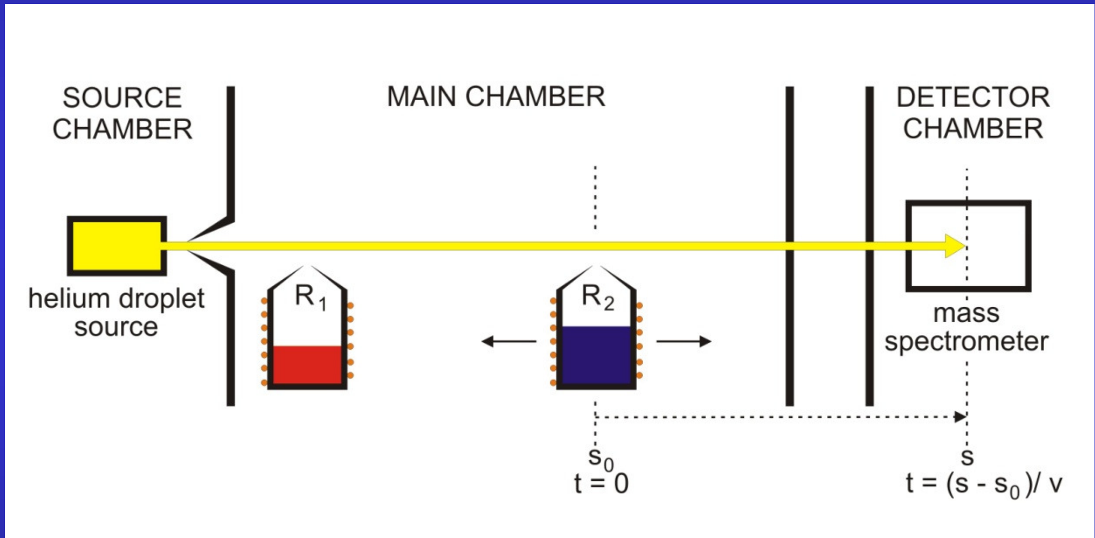
Reactivity of carbonaceous surfaces

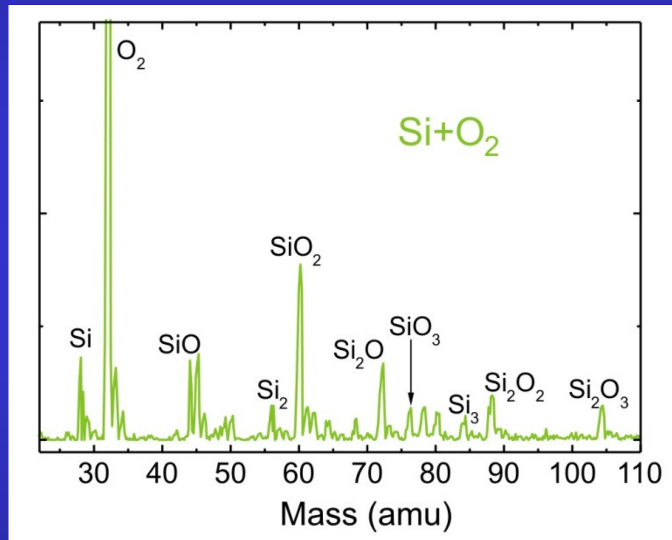
- Agglomerated carbon particles provide large surface area
- Curved carbon structures are very reactive (mechanical tension)
- Curved carbon structures have larger number of docking sites than graphite
- Carbon onions: „Production“ and „Absorption“ of electrons



Chemical Reactions in Helium Droplets

Oxidation reactions of period 3 elements (Mg, Al, and Si) studied at ultra-low temperature (0.37 K) in liquid helium droplets

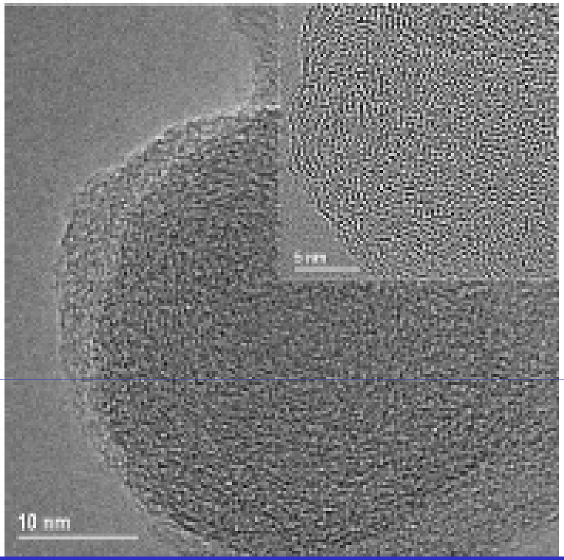


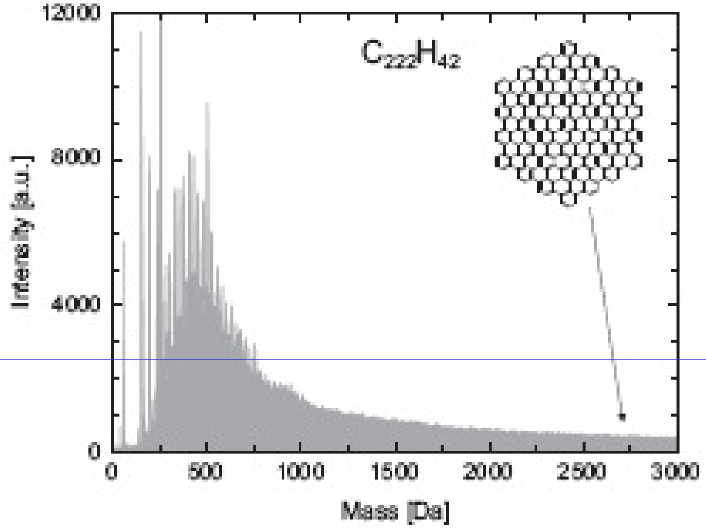


In Mg + O_2 reactions: Observation of chemiluminescence provides reaction rates.
Various reaction channels revealed for oxidation of silicon atoms and clusters by O_2.

(Krasnokutski & Huisken 2010)

Grain formation at high temperatures





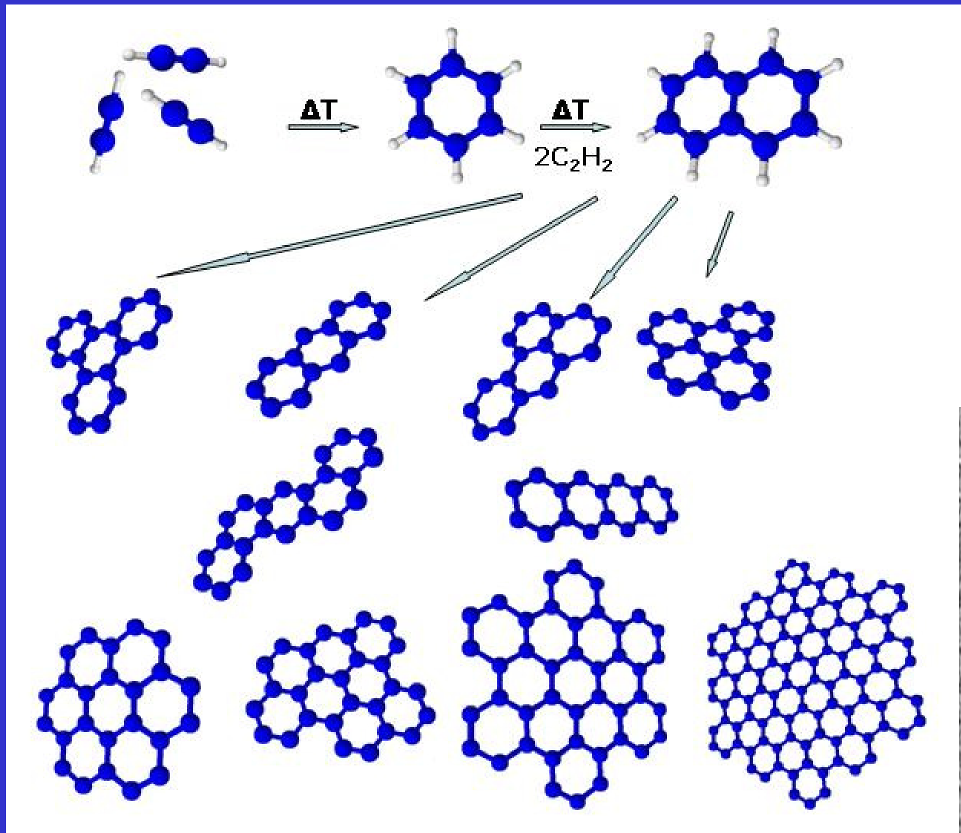
Jäger ea. 09

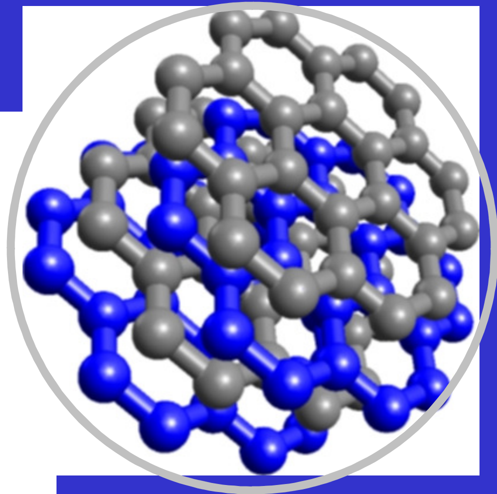
HT (≥3500 K): Very small fullerene-like carbon grains

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

Soot formation Pathways

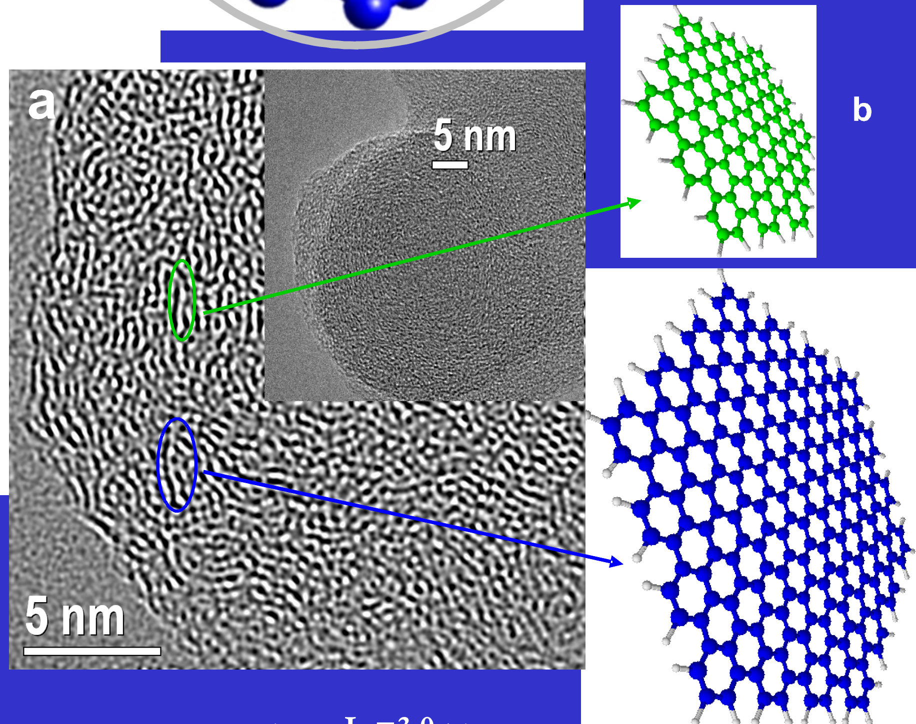
LT condensation process T ≤ 1700 K





Soot grains & PAHs
or only PAHs as condensates

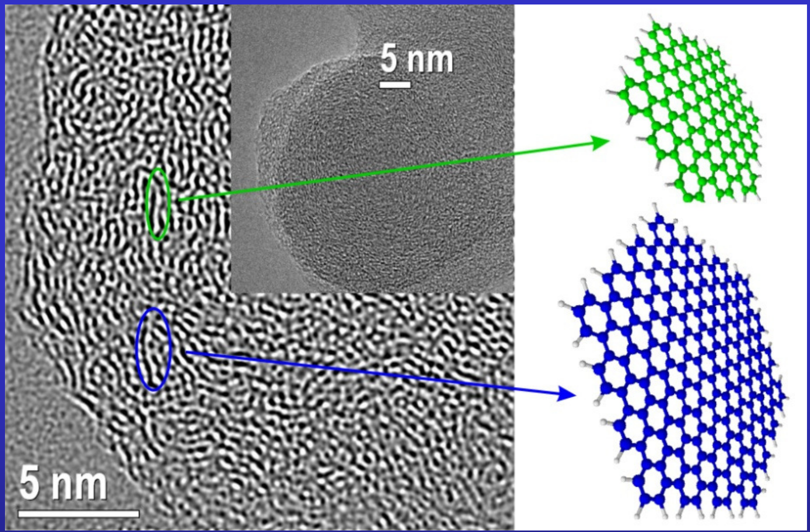
$ØL_a$=2.2 nm
($C_{110}H_{32}$, 1352Da)

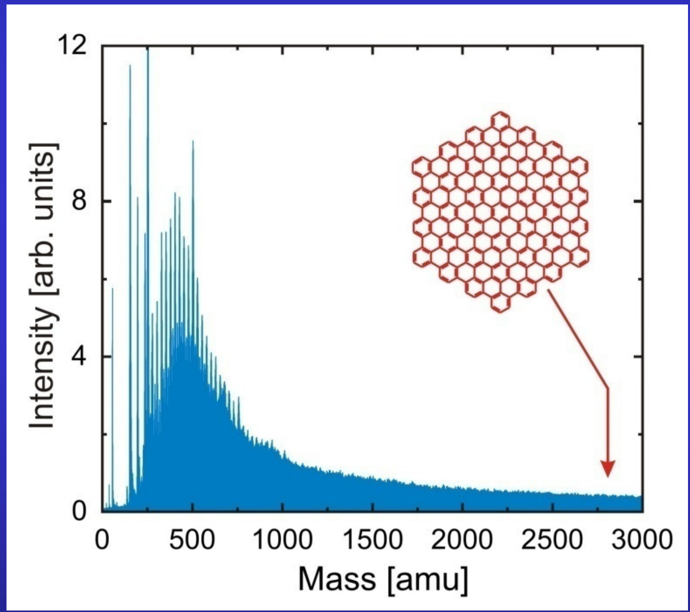


max. L_a=3.0 nm
($C_{222}H_{42}$, 2700Da)

Gas-Phase Synthesis of PAHs

CO_2 laser pyrolysis of hydrocarbons at (low) temperature is used to produce carbonaceous grains and PAHs under conditions encountered in circumstellar environments.





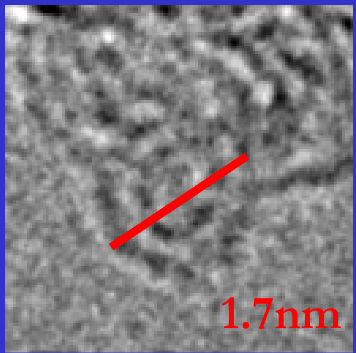
Jäger et al: 2008, ApJ 689, 249; 2009, ApJ, 696, 706.

HRTEM and MALDI-TOF reveal formation of large PAHs with masses up to 3000 amu.

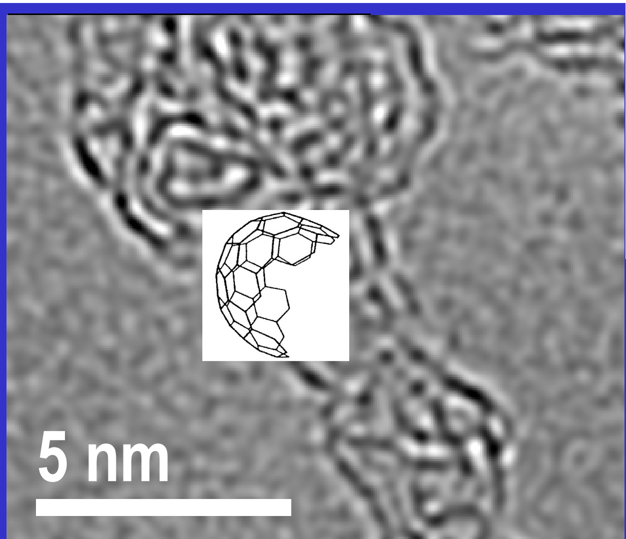
Soot formation pathways

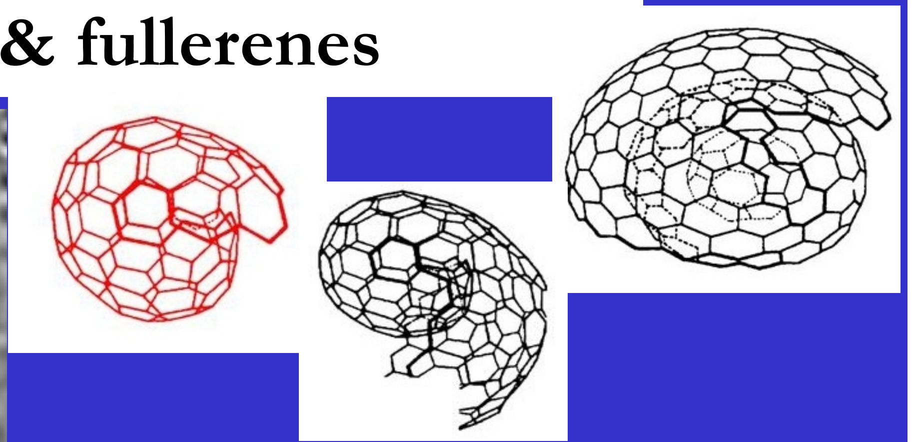
HT Condensation Process T ≥ 3500 K

Fullerene-like carbon seeds & fullerenes

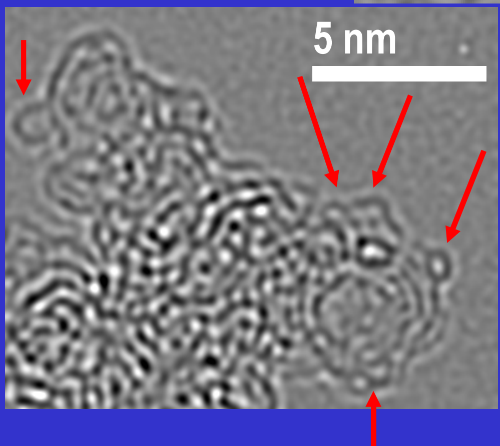


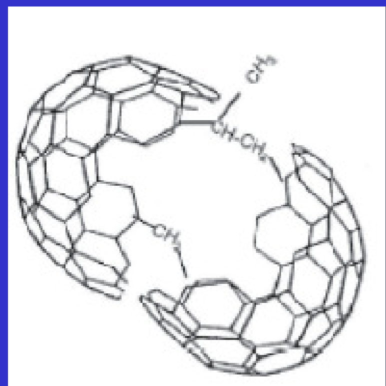
$C_{240}@C_{60}$

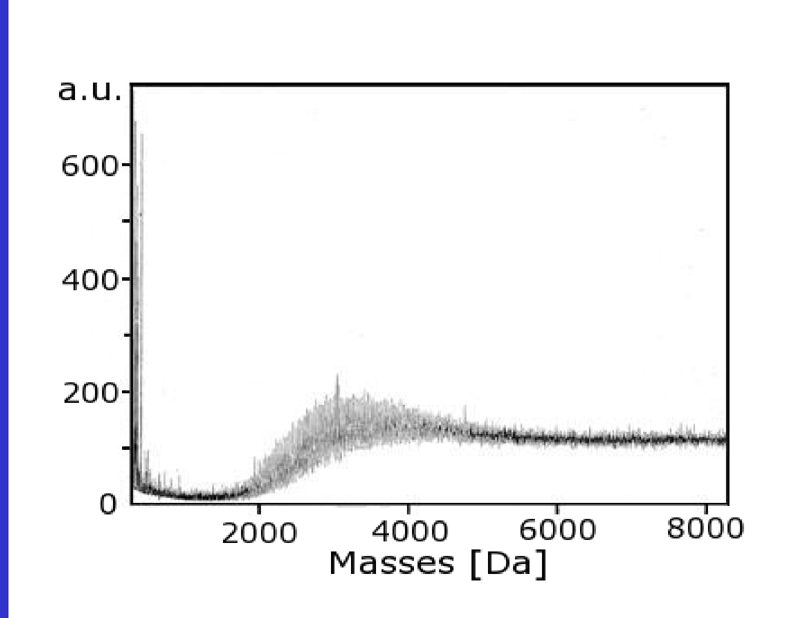




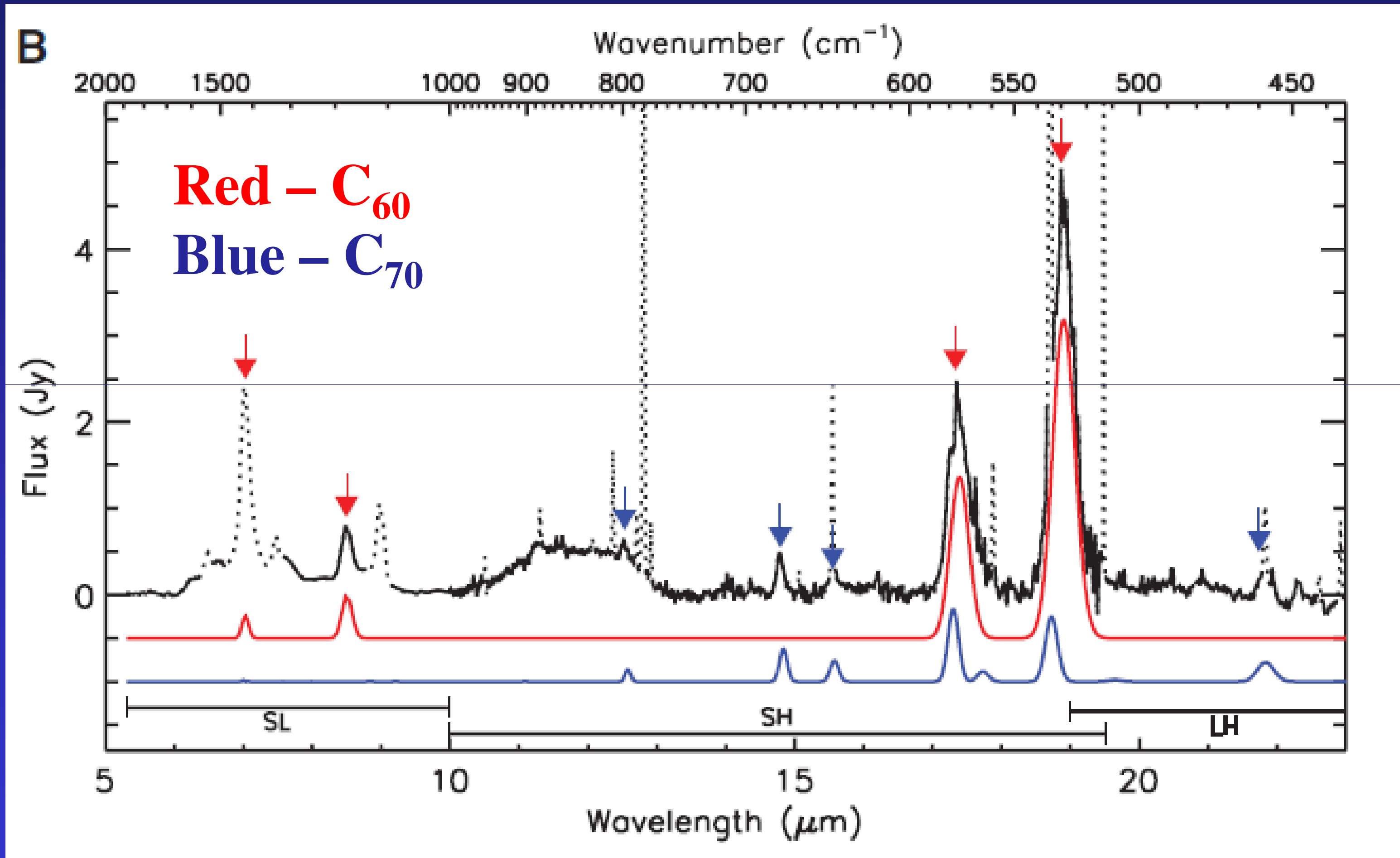
Haberland, Clusters of Atoms and Molecules I, Springer Verlag.





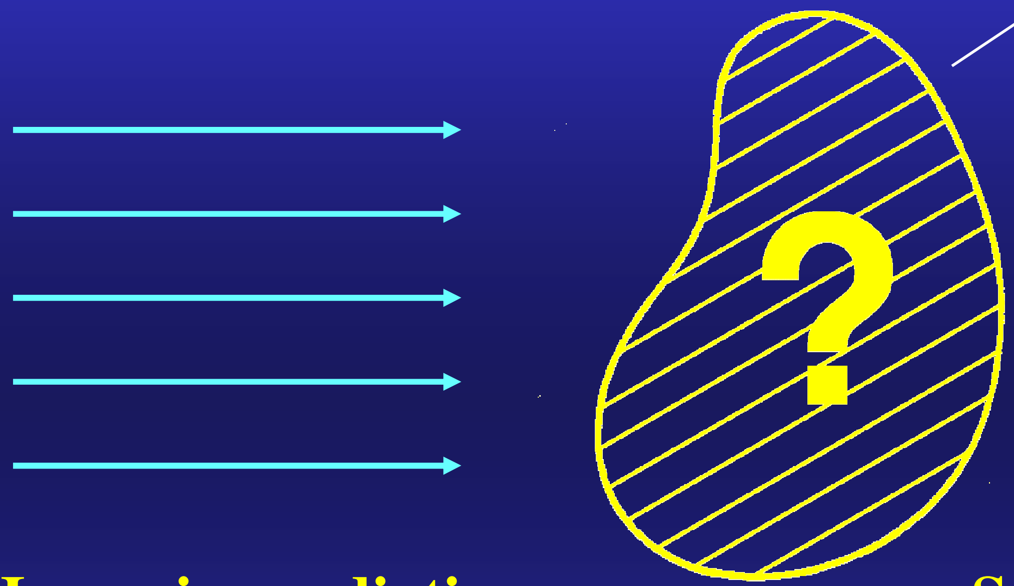


Discovery of C_{60} and C_{70} in a PN



Cami et al. (2010, Continuum Subtracted Spitzer Spectrum)

Dust and Radiation



Absorption

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

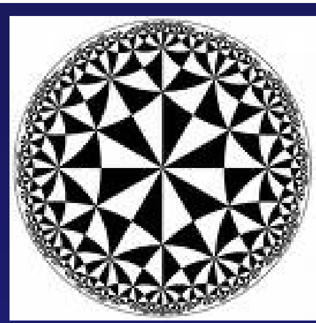
Incoming radiation

- 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**

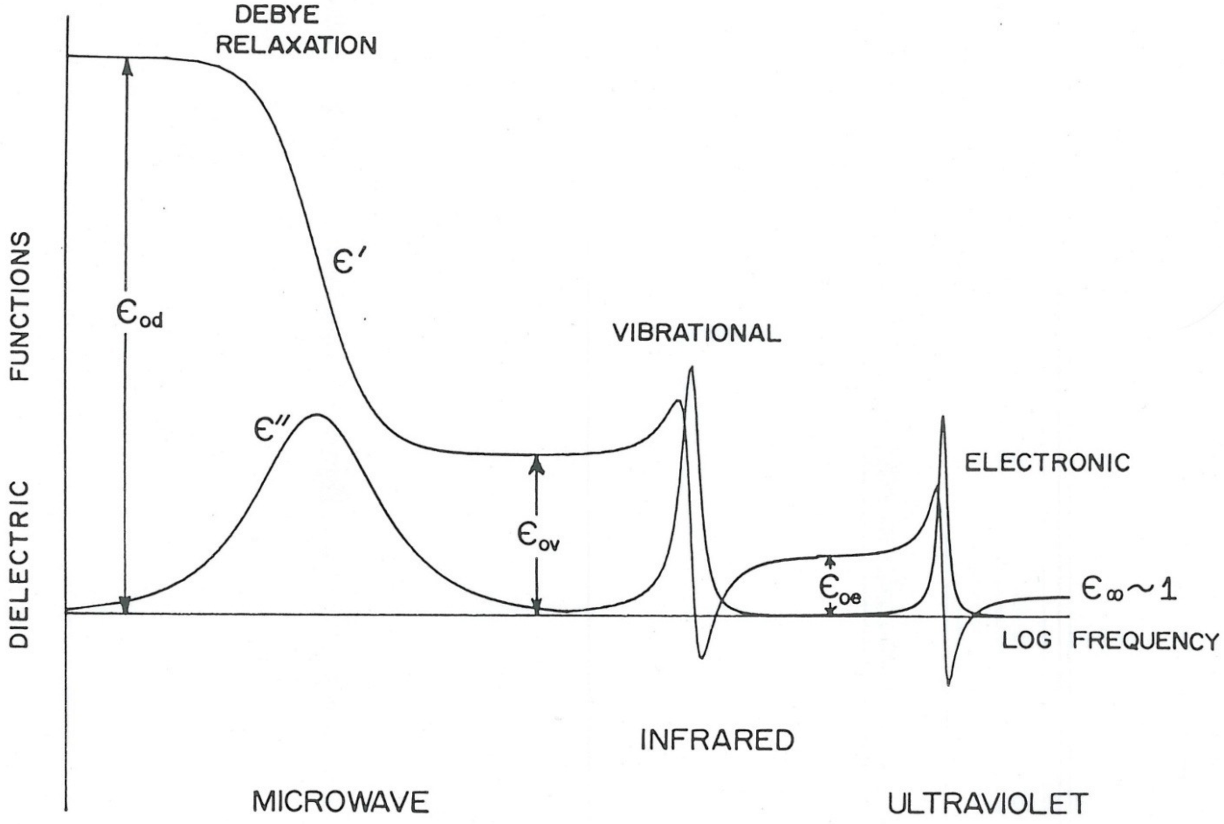
2. **Select the relevant laboratory data for n, k (material structure? temperature?)**

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)**

Basic Optical Properties of Solid Particles



Basic Optical Data
Cosmic Dust Analogues

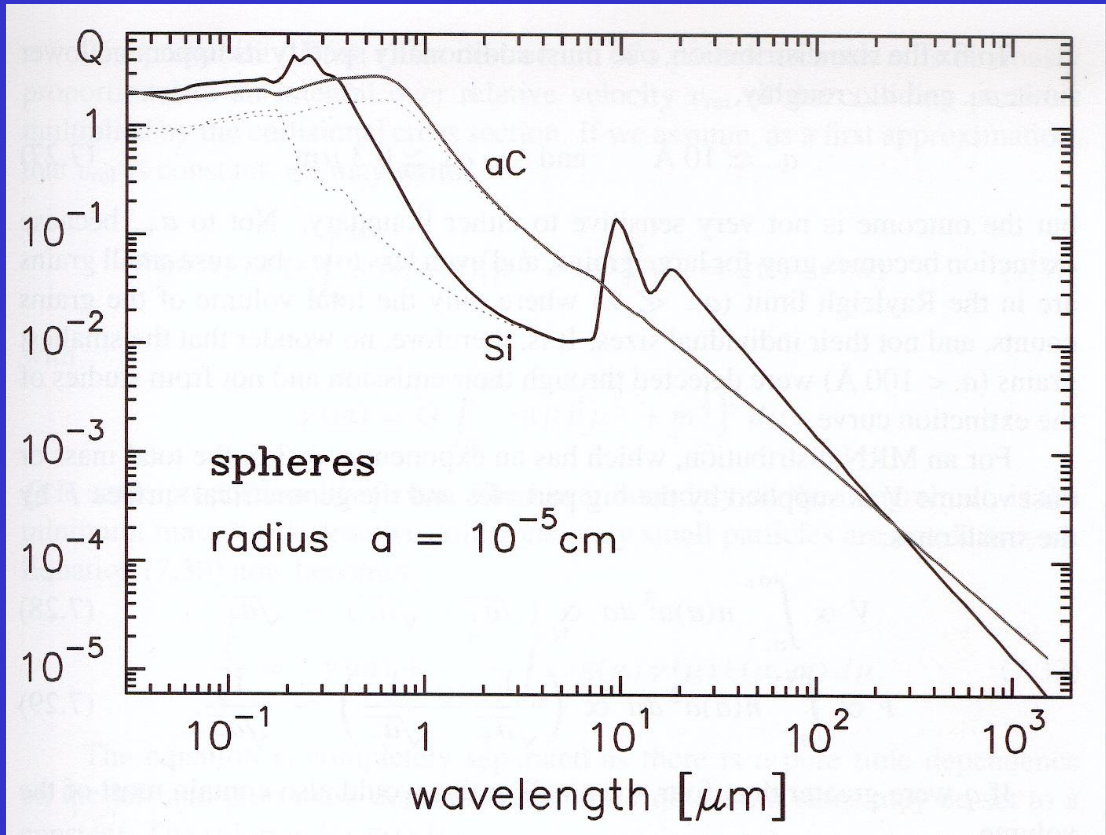
- Broad Wavelength Range
- Appropriate Structure
  (Fe/Mg, am./cryst. …)
- Isolated Small Particles
- Temperature Range

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/

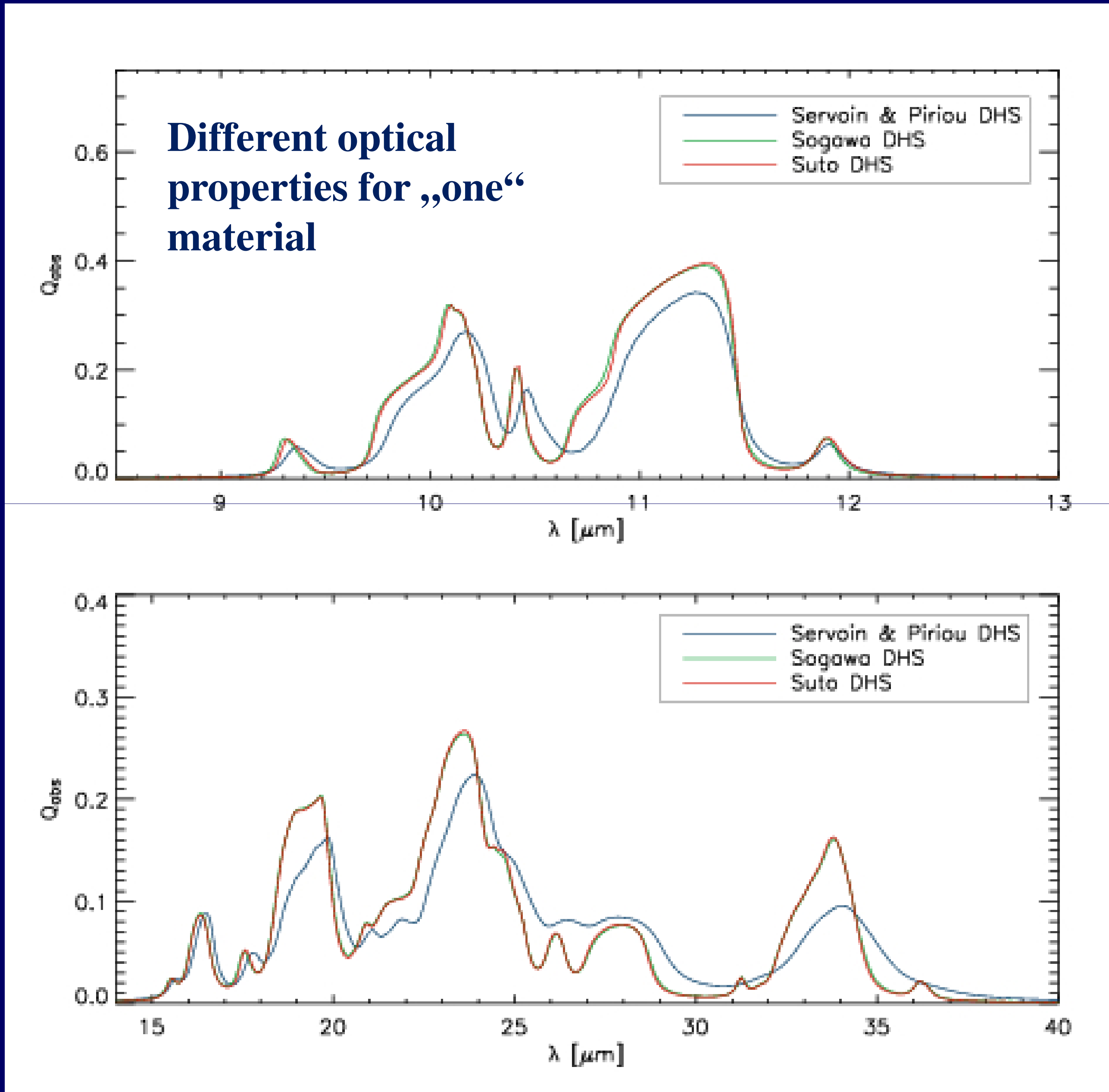
Optical behaviour of small particles



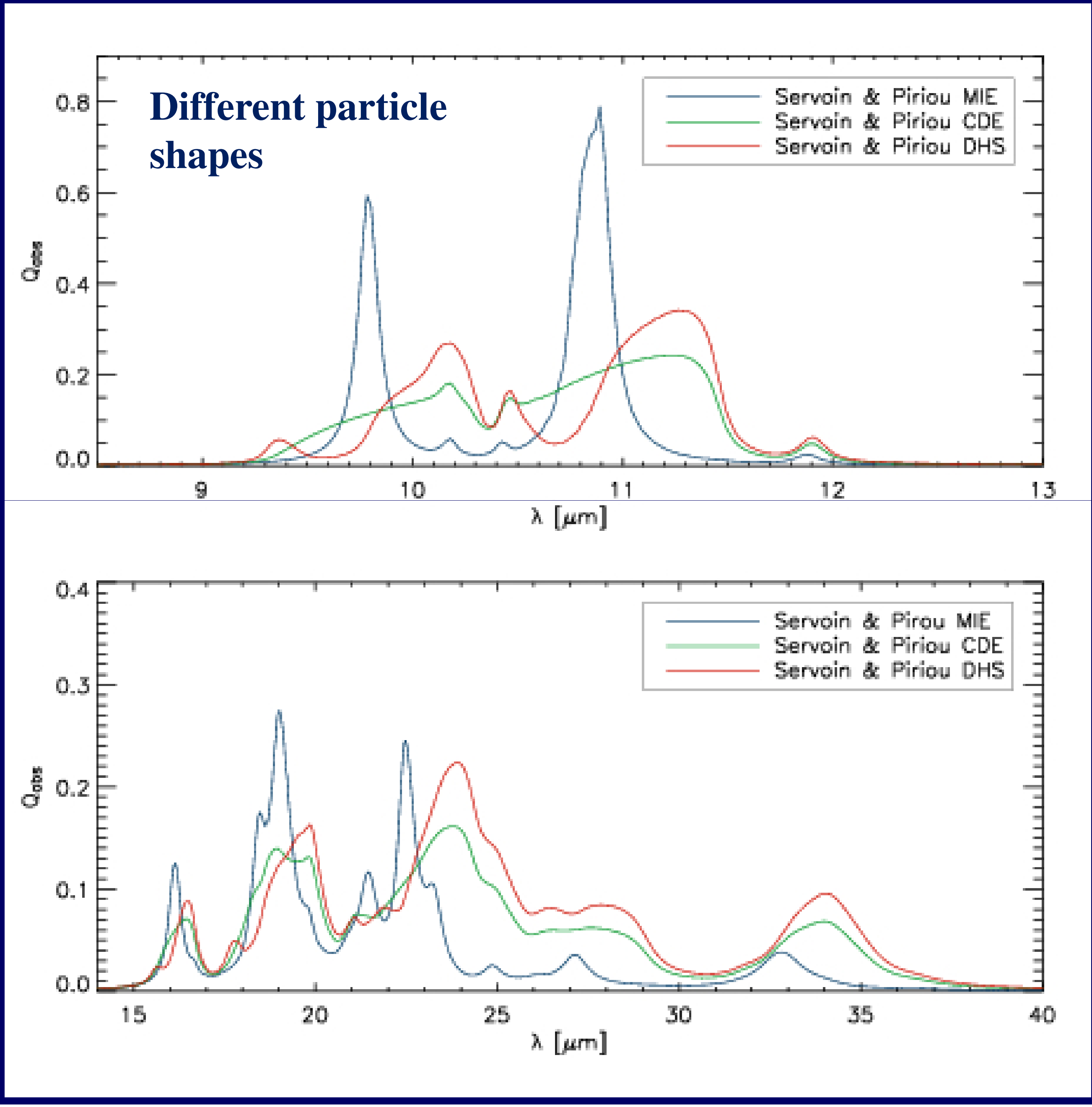
After Krügel (2003) – Absorption (dots), extinction (solid line)

But: COBE Data – No single power-law emissivity law (Finkenbeiner et al. 1999)

What you need to know …

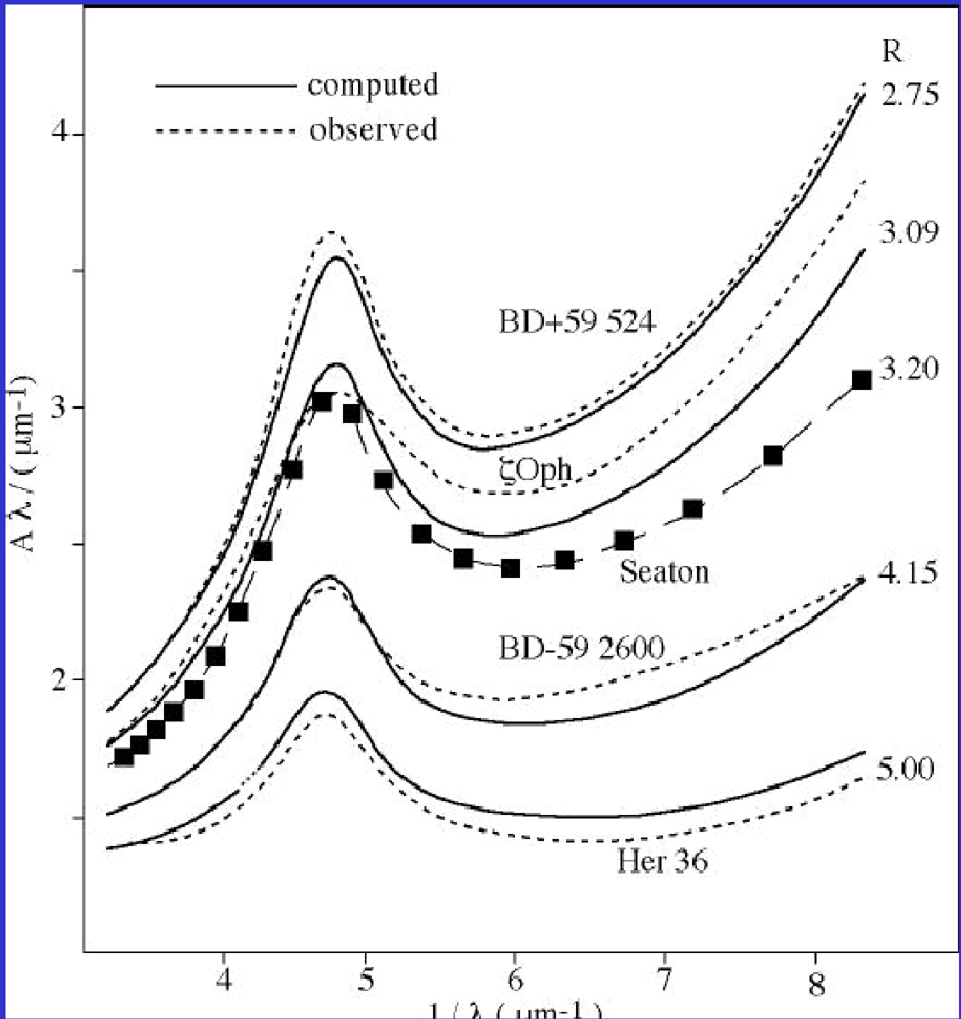


What you need to know …



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

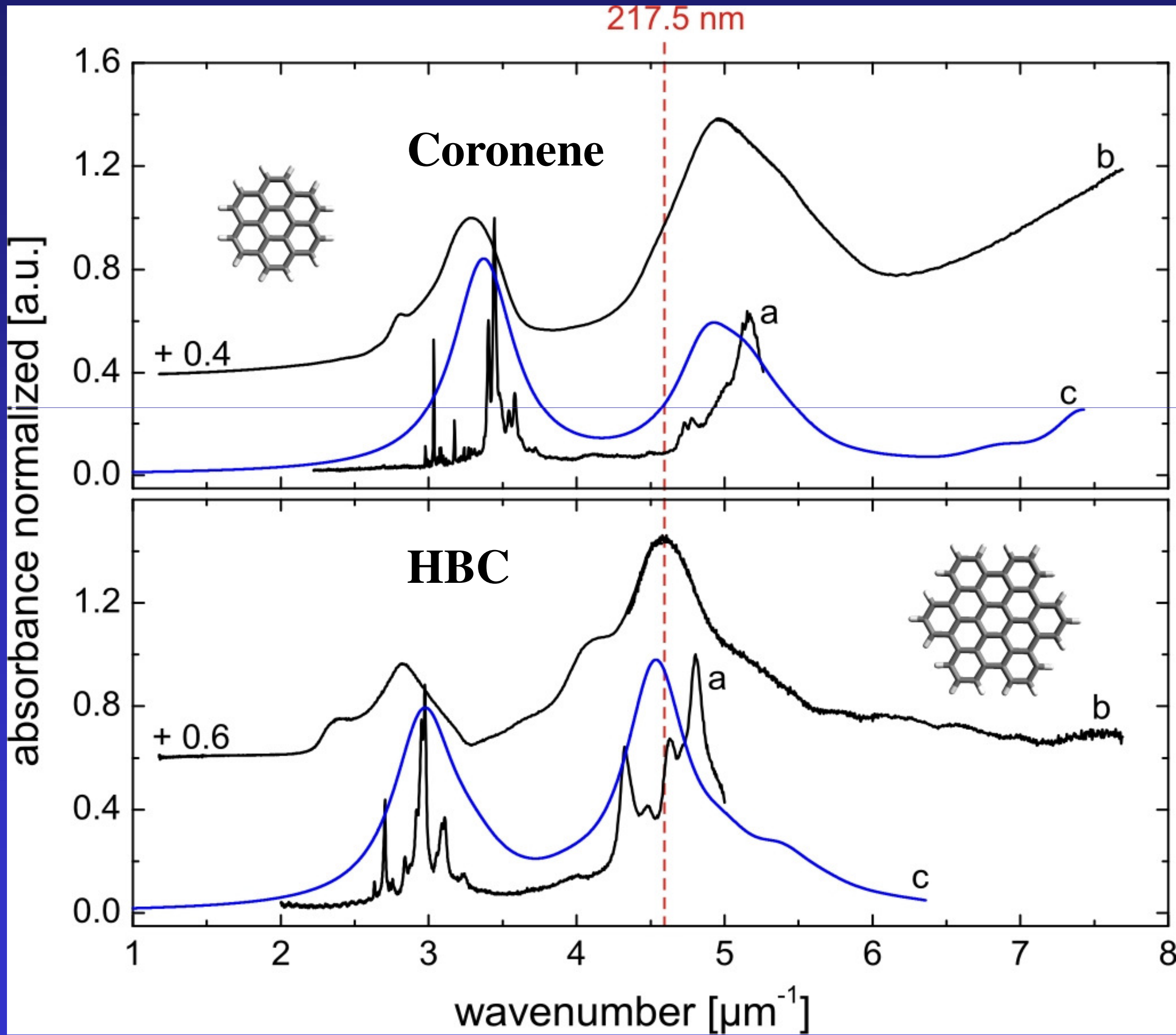
Origin of the Strong UV Resonance



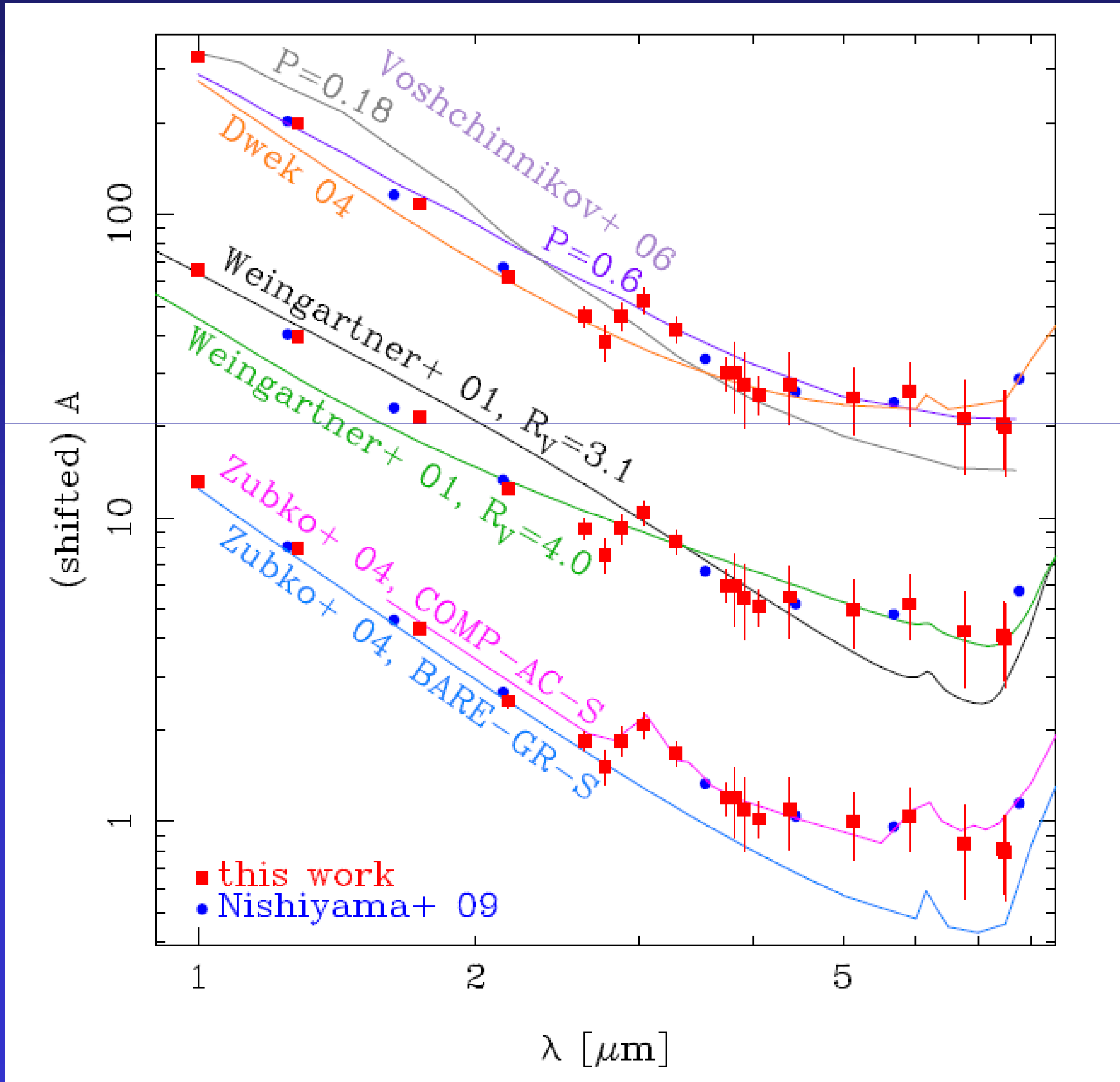
- Remarkable constancy of peak position (4.60 µm^{-1}; variations smaller 1%)
- Peak width varies around mean value of 1.0 µm^{-1} (variations smaller 25%)
- Lack of correlation between variation of peak position and width (except for the widest bumps: systematic shift to larger peak wavenumbers)
- Strength 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)



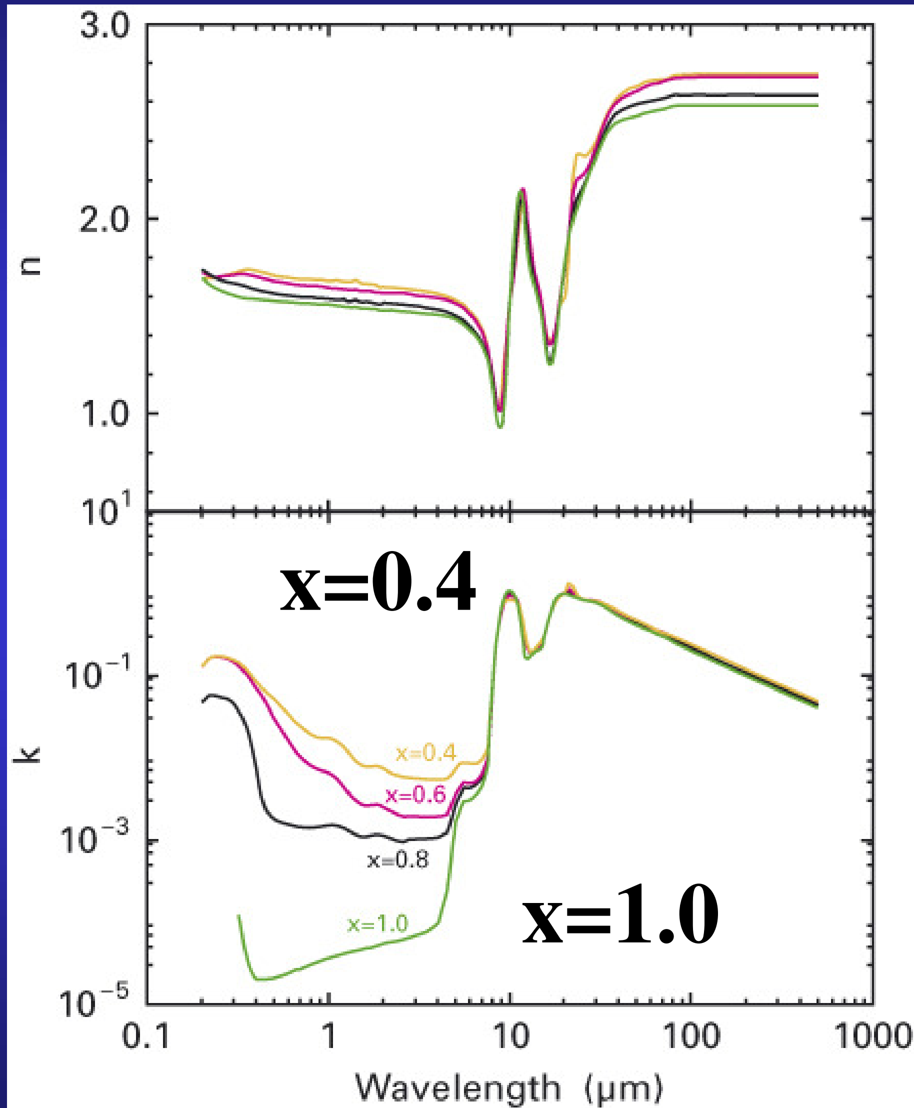
Near-infrared Extinction Law



Fritz et al. 11

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

Increase of NIR absorptivity with Fe content



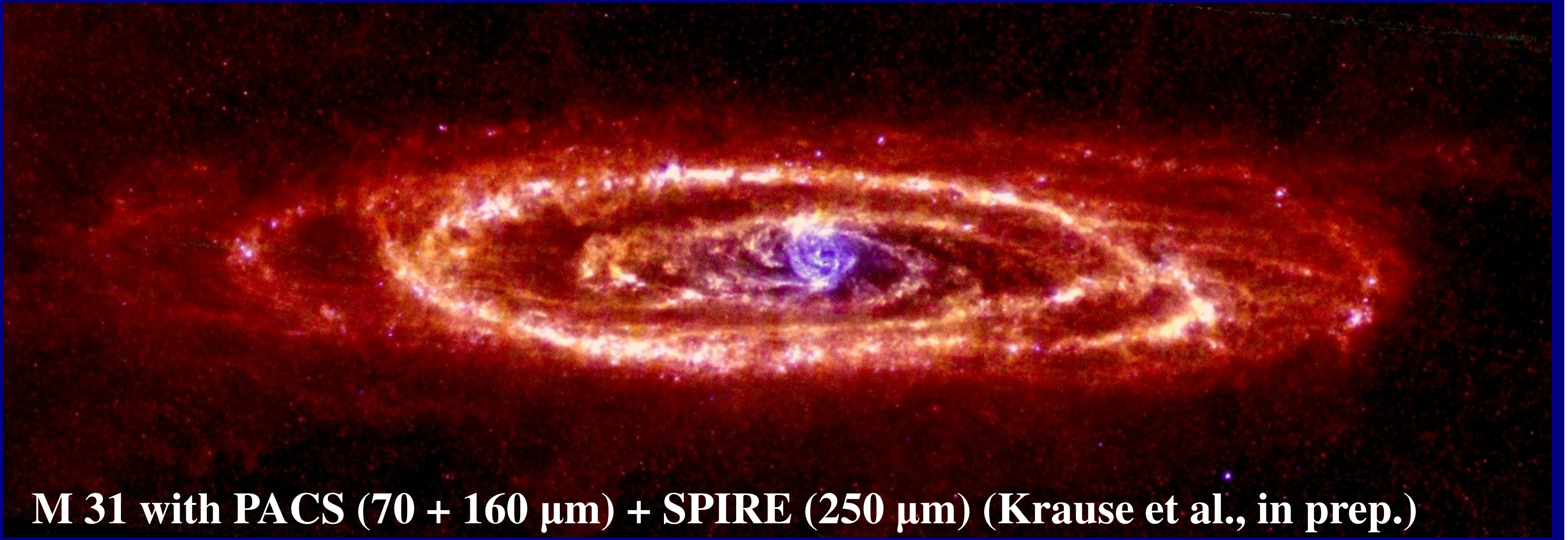
(J. Dorschner, B. Begemann, Th. Henning, C. Jäger and H. Mutschke, A&A 1995)

What are the FIR Properties of the materials?

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

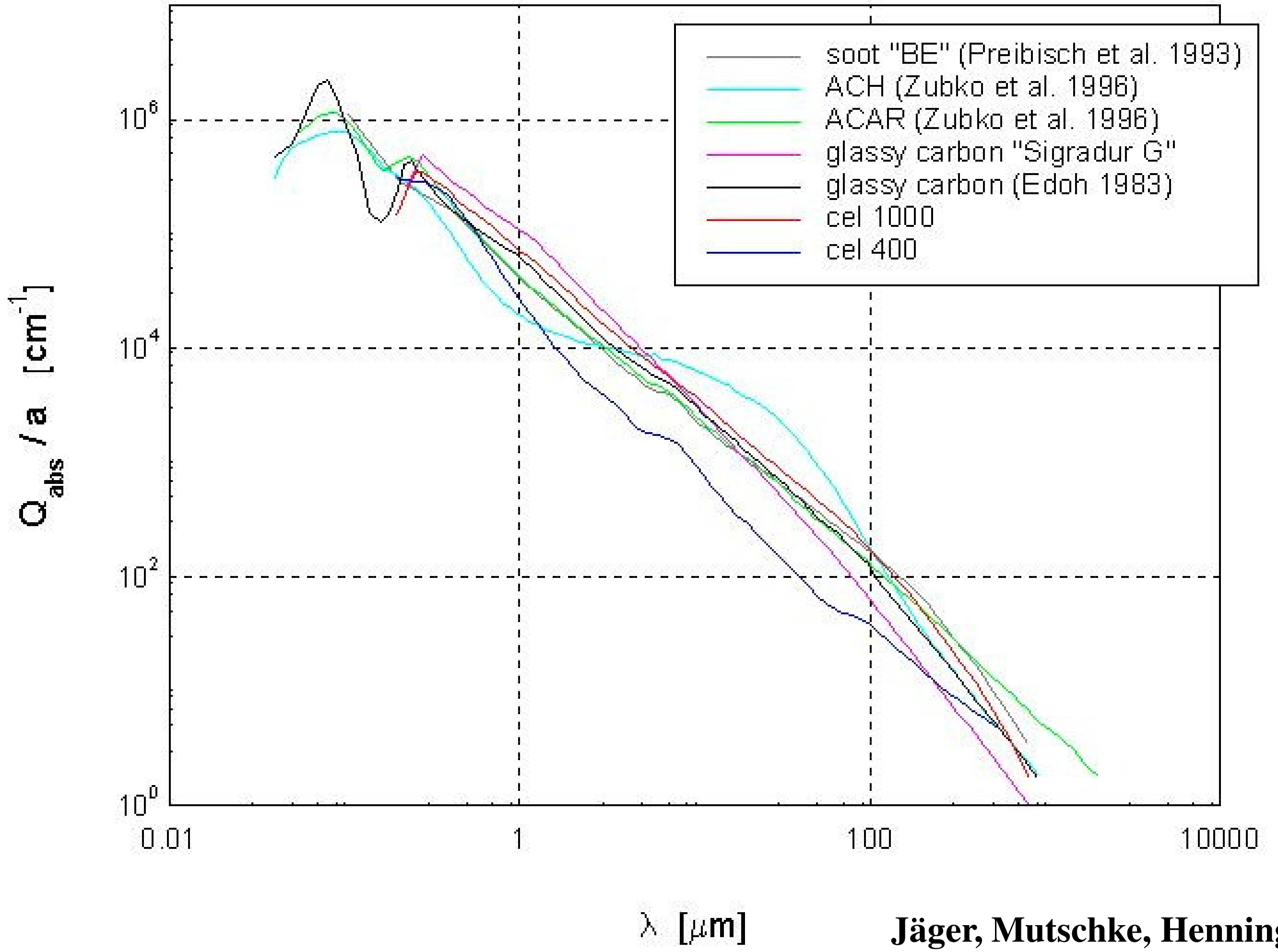
- Grain size and agglomeration state (e.g. Henning & Stognienko 1996)

- Temperature of the material (e.g. Boudet et al. 2005)



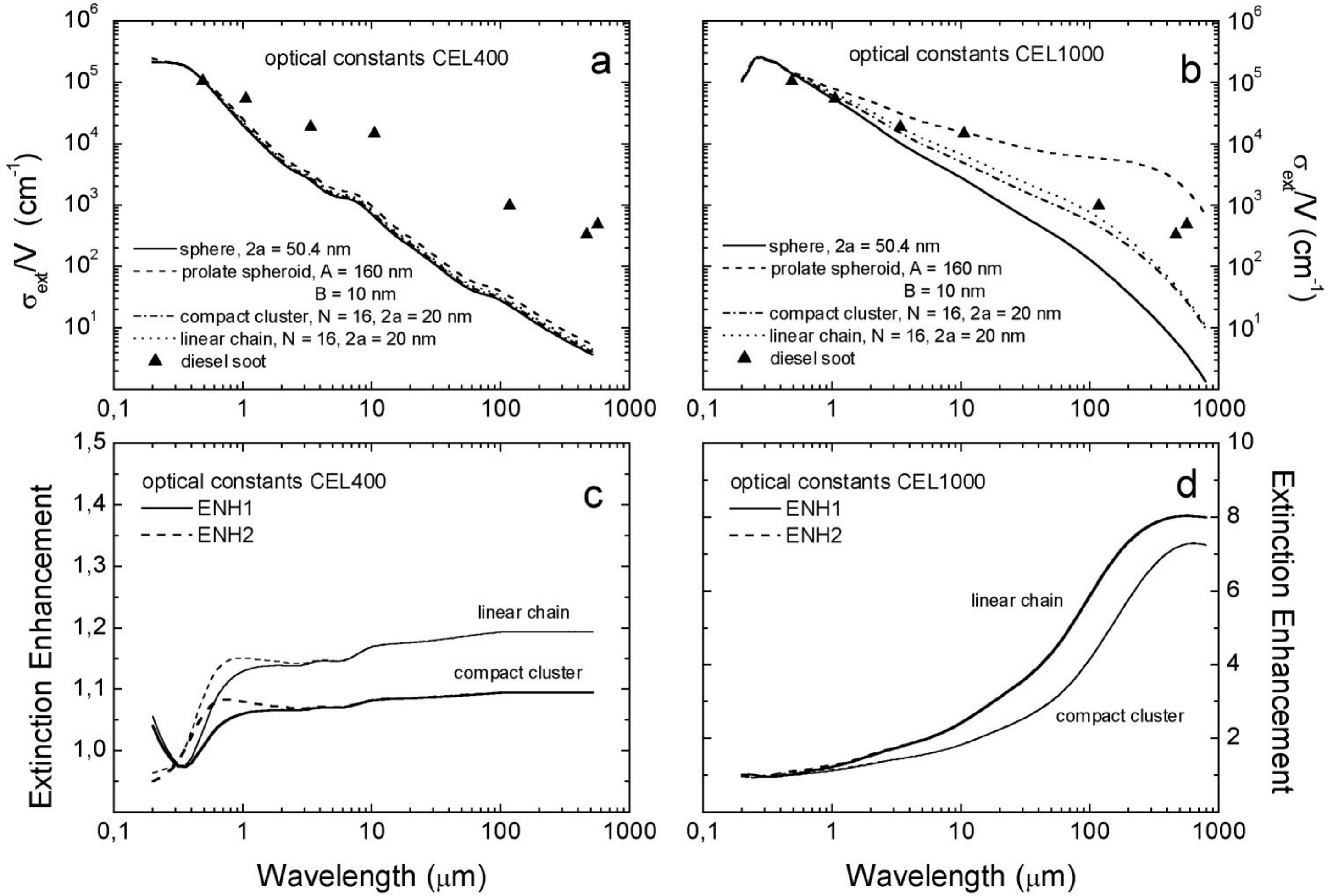
M 31 with PACS (70 + 160 µm) + SPIRE (250 µm) (Krause et al., in prep.)

FIR Absorption Efficiency/Spherical Particles



Jäger, Mutschke, Henning (1998)

Extinction Spectra of Carbonaceous Materials



Quinten, Kreibig, Henning, Mutschke (2002)

What is expected ?

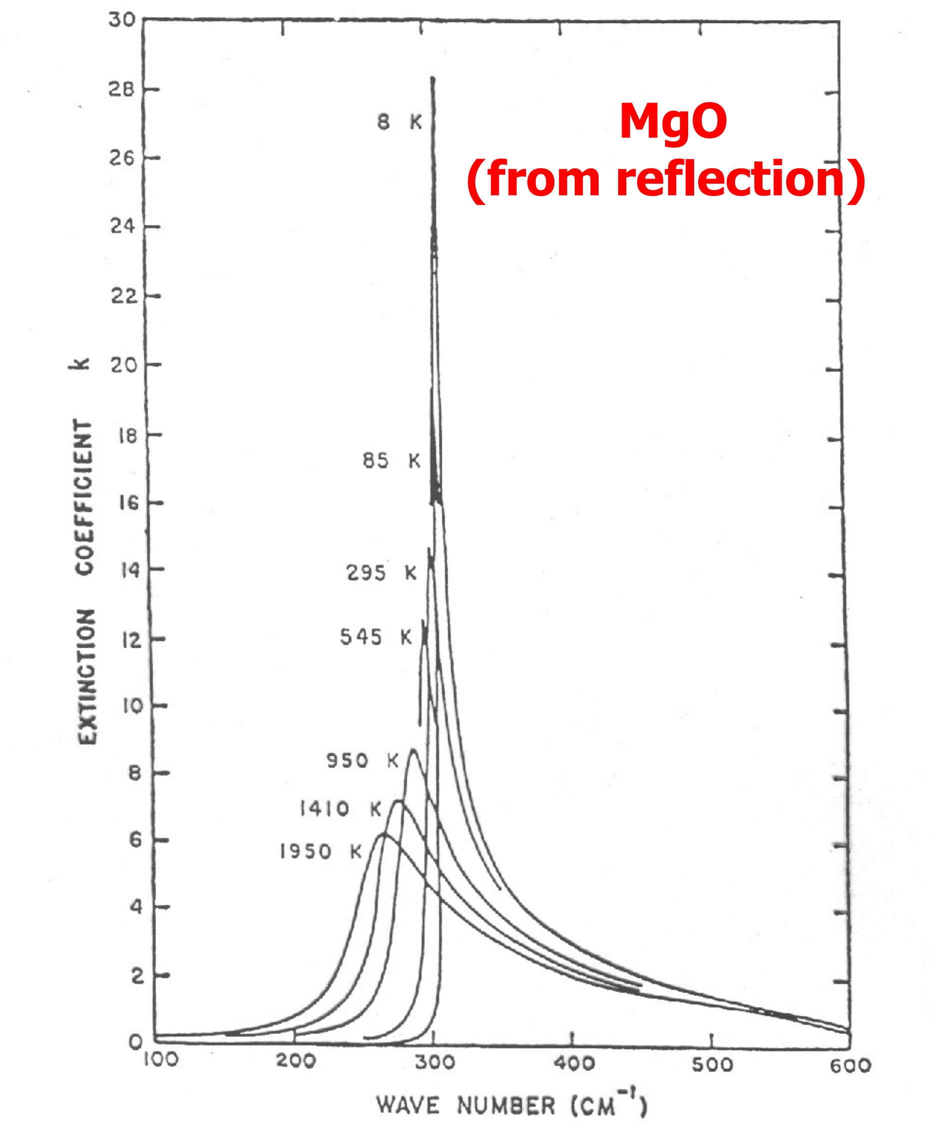
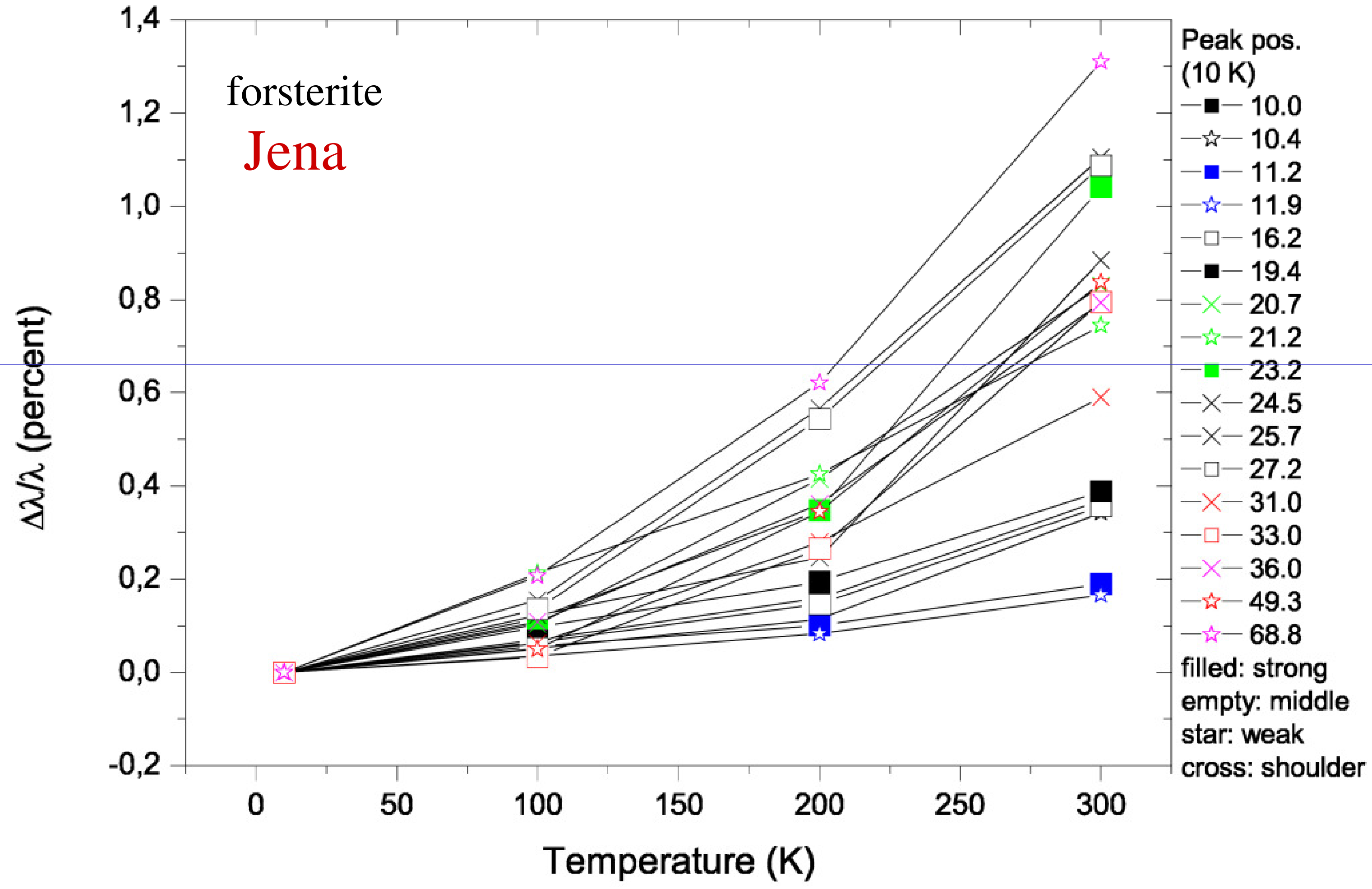
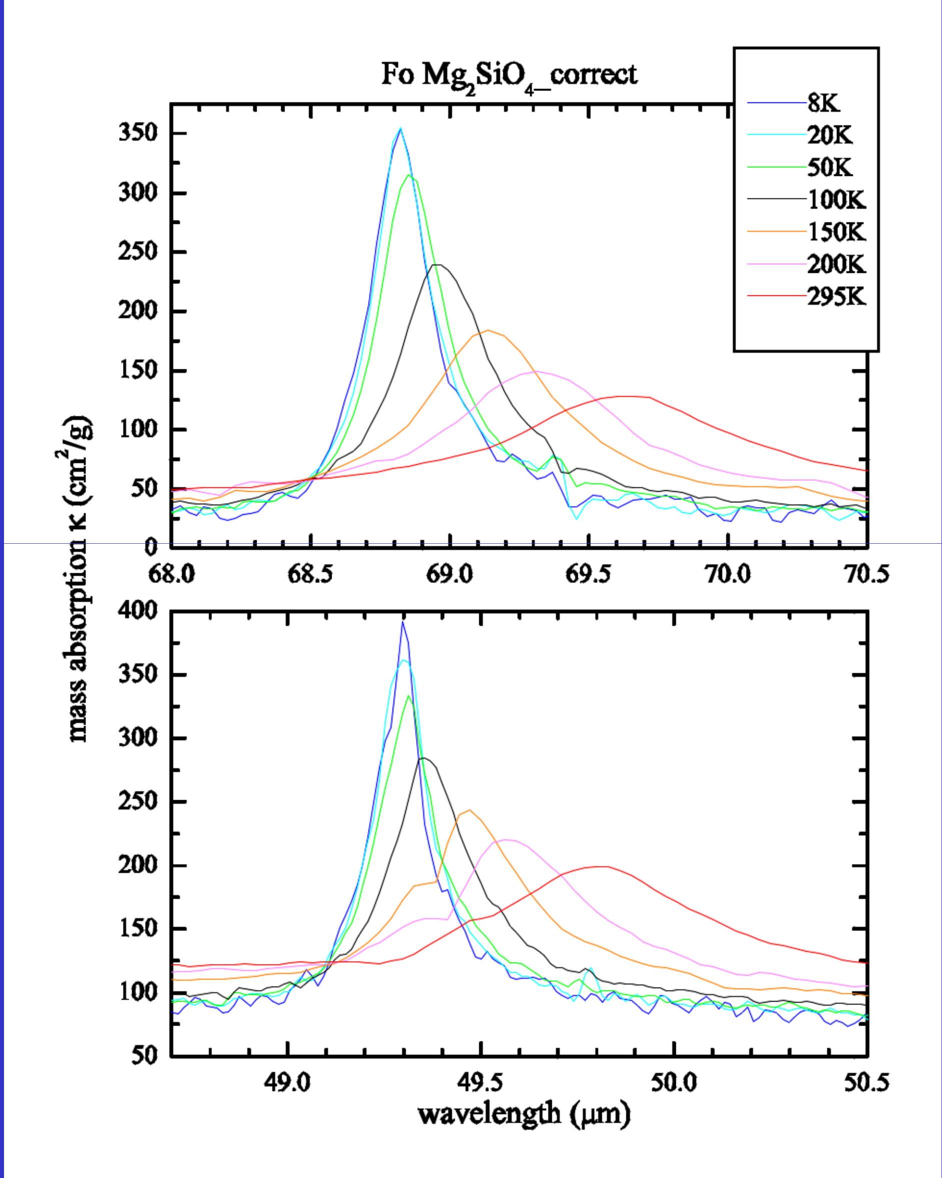


Fig. 9. Computed extinction coefficients of MgO as functions of wave number and temperature. (From Jasperse *et al.* [12].) 1966

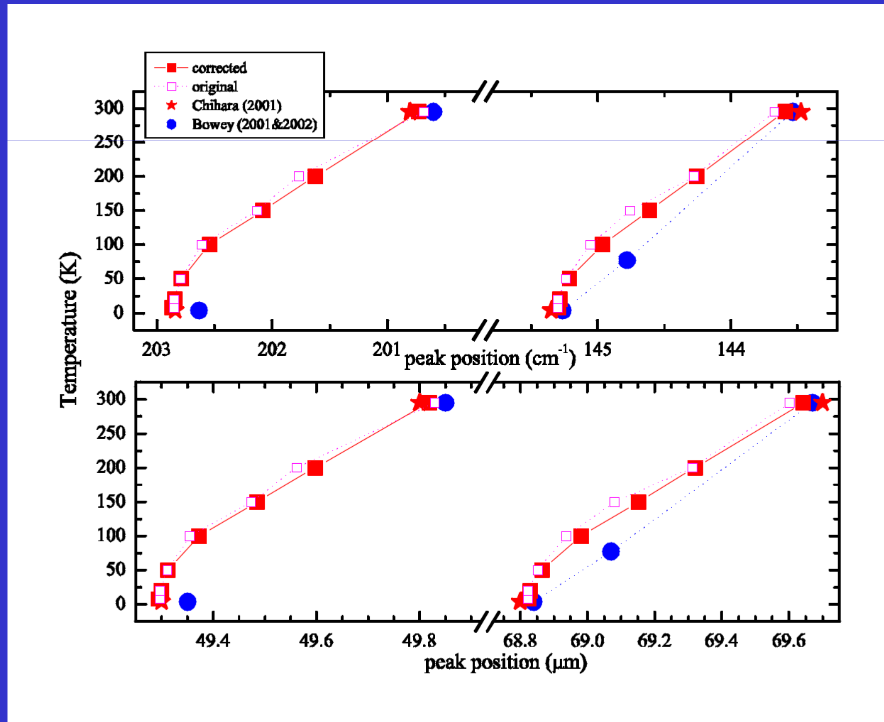
=>Bands are broadened and shifted to lower frequencies with higher temperature

How big is the relative peak shift ?





Long-wavelength forsterite bands as thermometer

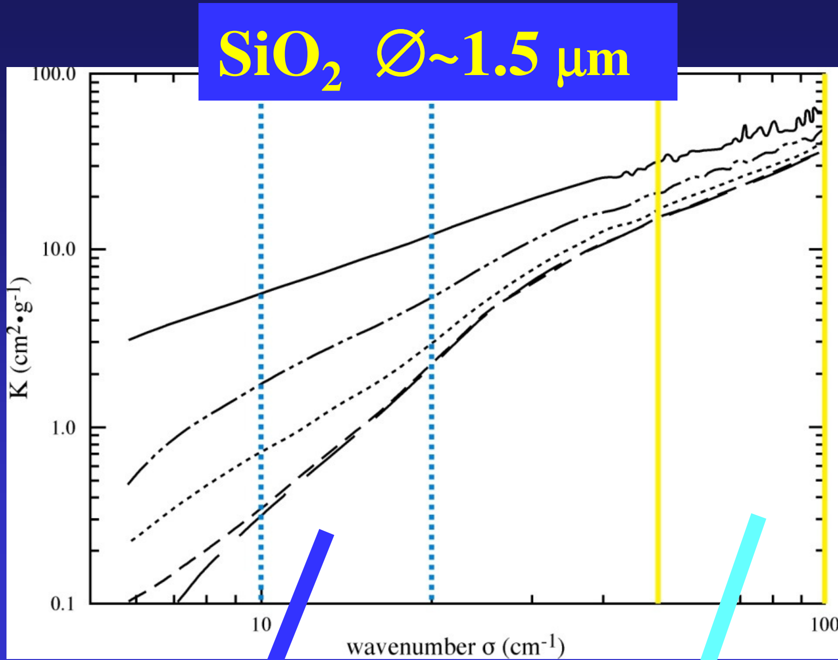


Koike et al. (2006)

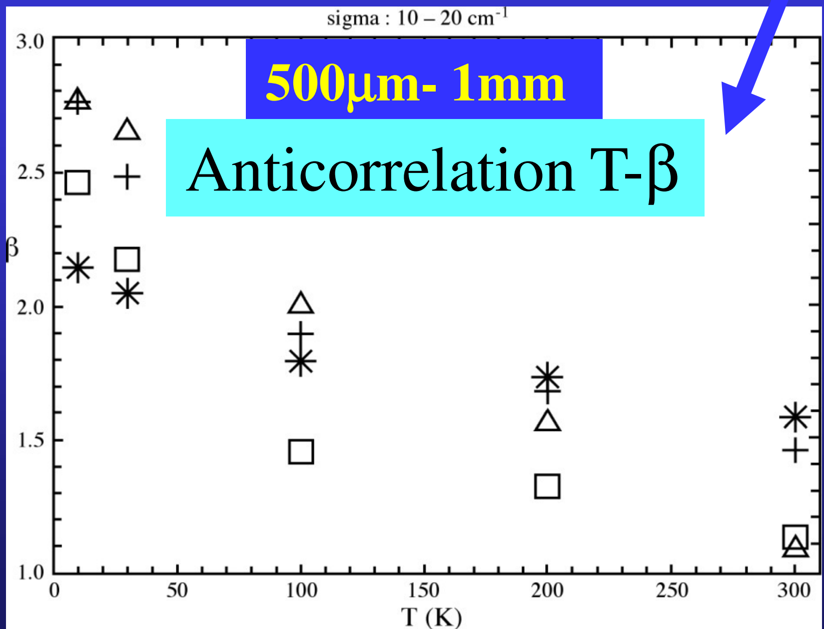
β(T, ν)

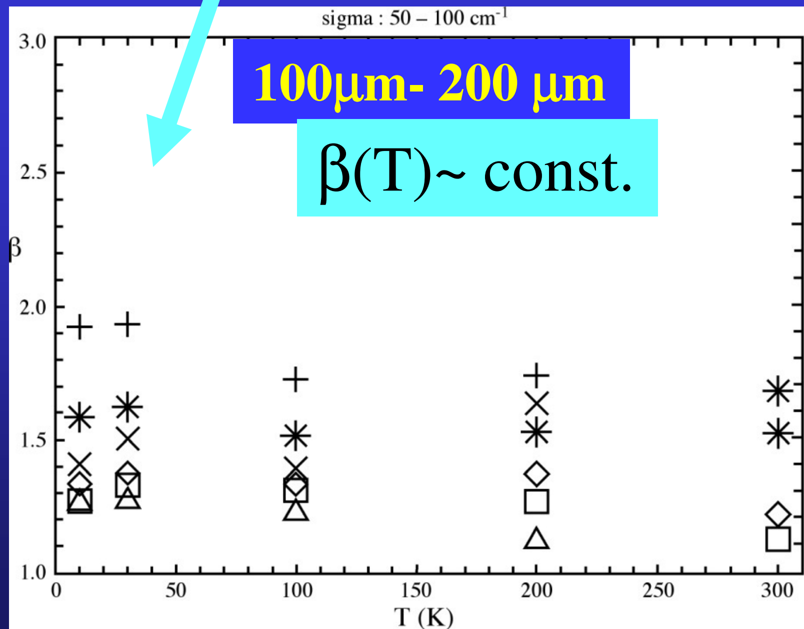
△ SiO_2 1.5μm
□ SiO_2 fumed
+ $MgSiO_3$ sol-gel
★ $MgSiO_3$ glass

Boudet ea. 2005



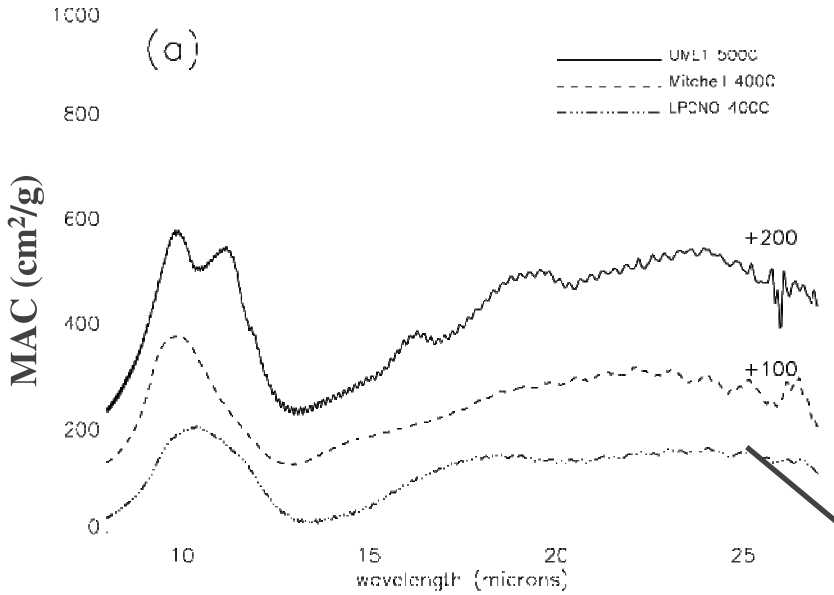
Break in the absorption law ~30cm^{-1}: Different frequency dependence

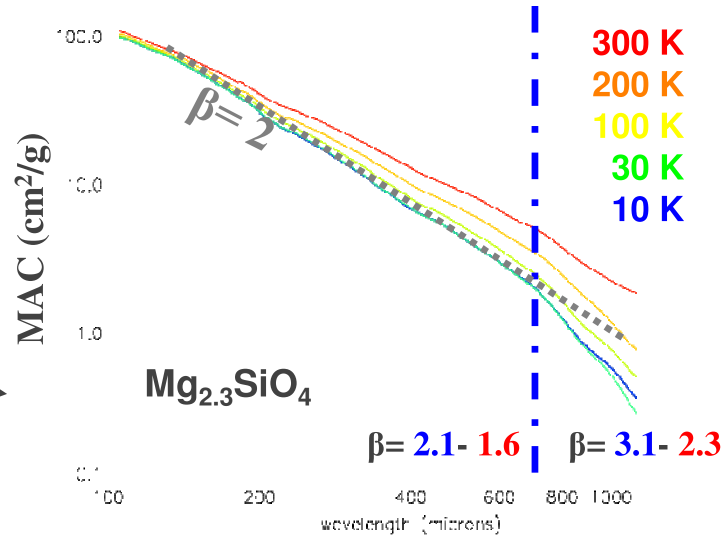


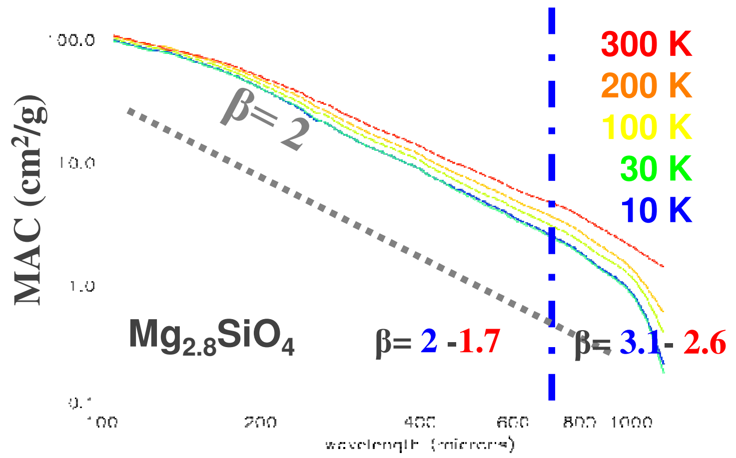


Am. silicate grains with olivine composition (Mg_xSiO_4)

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

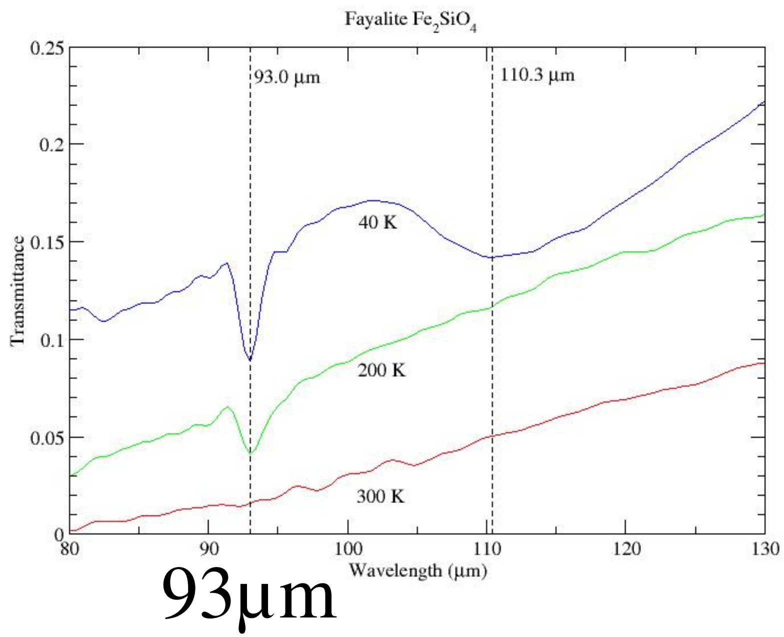
β increases with decrease of T

Mass absorption coefficient (MAC) decreases with decrease of T

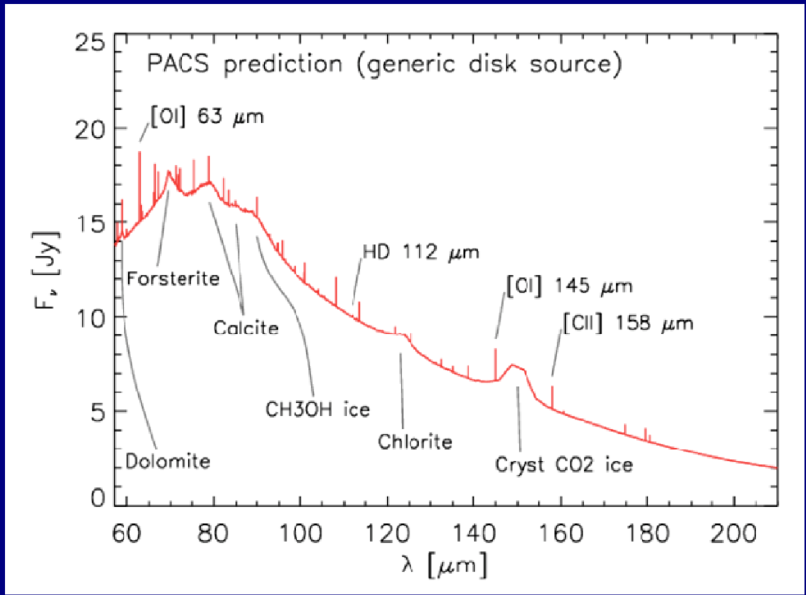
Which new dust features can we expect to see with Herschel?

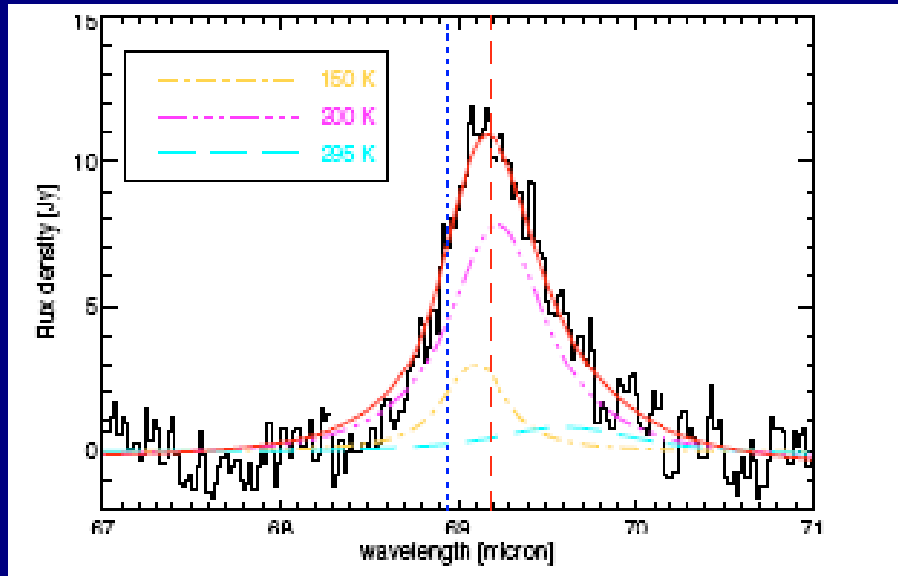
FIR: Lattice vibrations of heavy ions or ion groups with low bond energies (example KBr: transverse optical mode at 86 μm); PACS: 57-210 μm

- 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





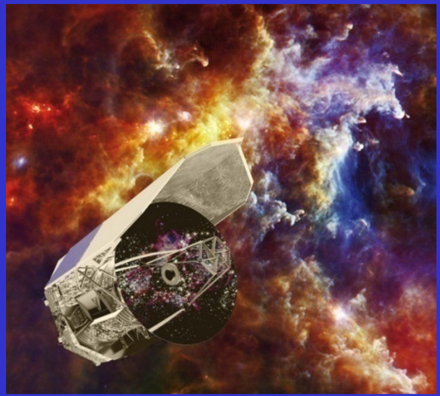
HD 100546, DIGIT Program
Sturm, Bouwman, Henning et al. (2010)

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)**

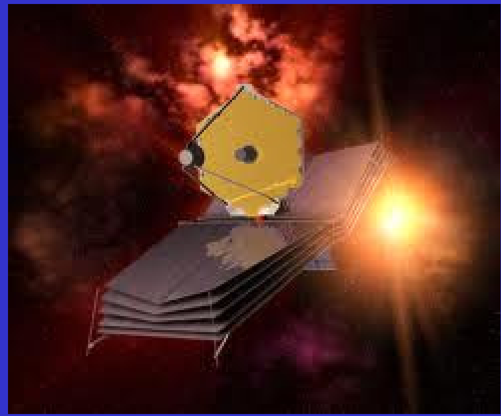
b) **Cold forsterite with a few percent iron shifts feature**

Towards a Dusty Universe ....



Herschel/Planck

ALMA



JWST

- Basic understanding of grain properties
- Formation and evolution of grains - next challenge

Absorption, scattering, and emission by interstellar material produces enough puzzles, even of identification, to keep the proverbial seven spectroscopists with seven brooms busy for at least seven years.

Trimble & Aschwaden (1998)

"Sure it's beautiful, but I can't help thinking about all that interstellar dust out there."