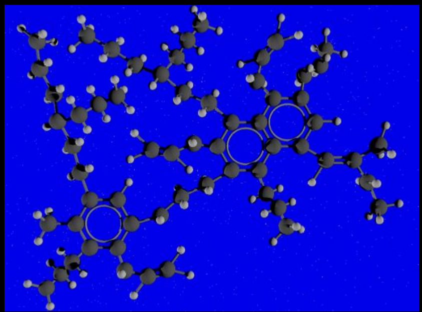
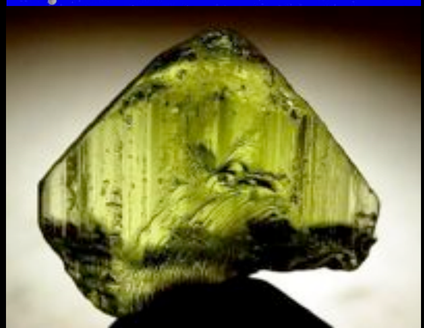
(A biased glimpse into …)

Solid matter: from ISM to (the) protoplanetary disk(s)





E. Dartois, ISMO, Orsay, France

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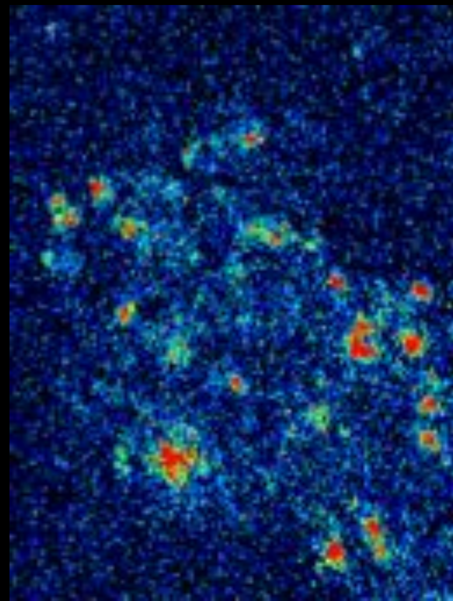
9th July 2018

ICISE 2018

Quy Nhon - Vietnam



Acknowledgments

M. Chabot
A. Jallat

T. Pino
K. Béroff
I. Alata

G. M. Muñoz Caro
R. Martin-Doménech
G. A. Cruz Diaz

D. Severin
M. Bender
C. Trautmann

Ph. Boduch
H. Rothard

C. Engrand
J. Duprat
B. Augé
M. Godard
N. Bardin
L. Delauche

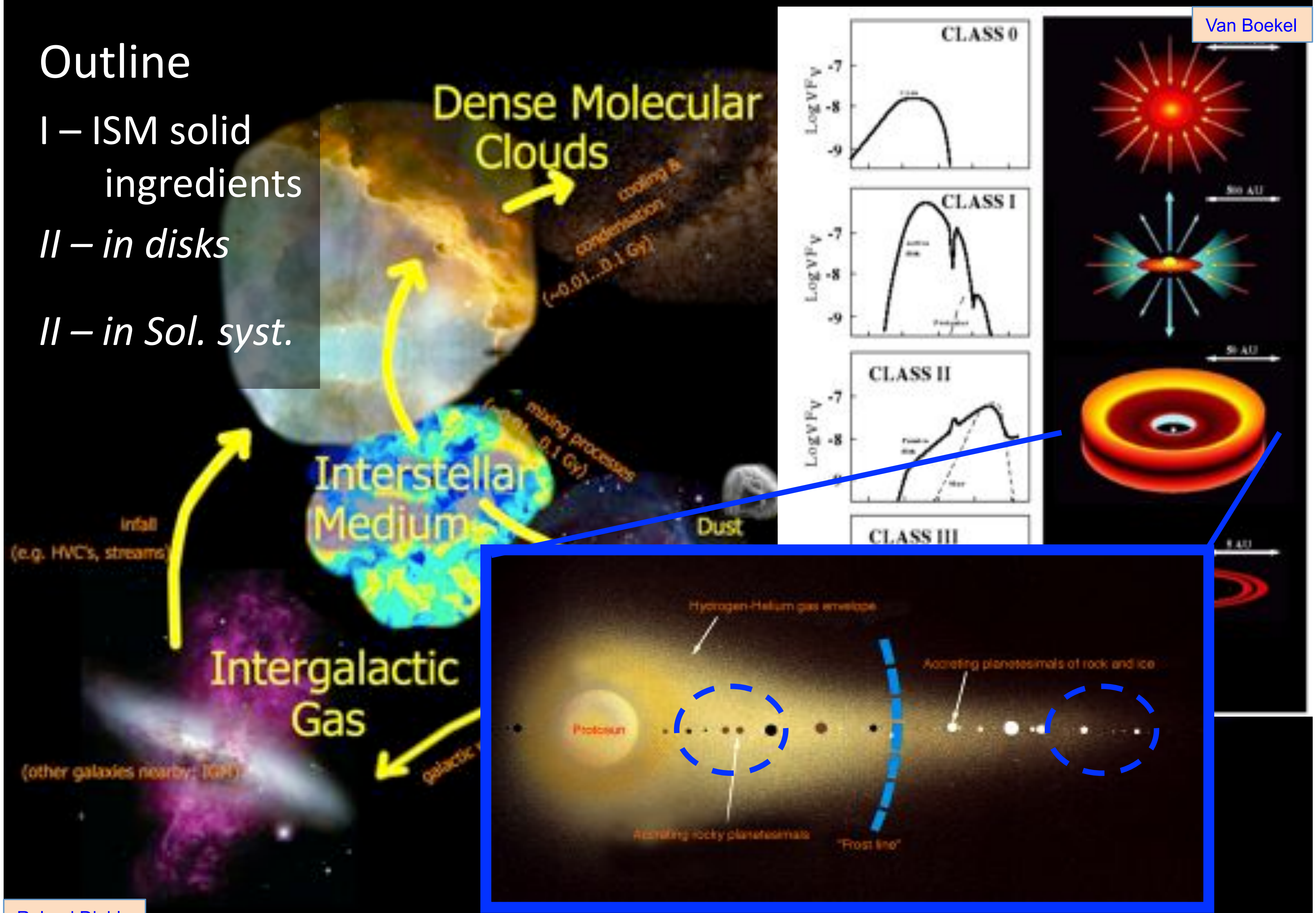
Ch. Sandt
P. Dumas
F. Borondics

Outline

I – ISM solid ingredients

II – in disks

II – in Sol. syst.

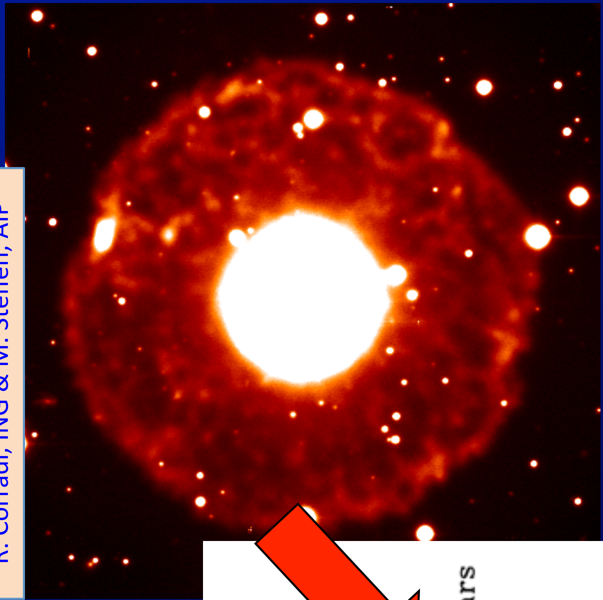


Interstellar dust budget

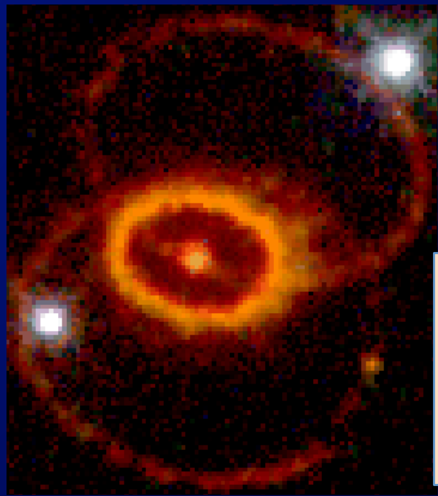
Stellar mass losses contribute significantly to dust production

Dust observed at later evolutionary stages

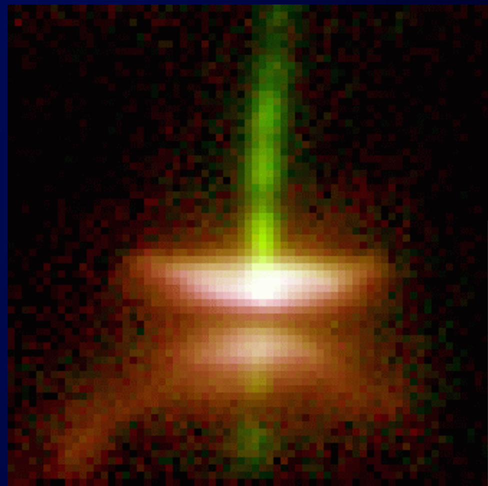
93% M>1



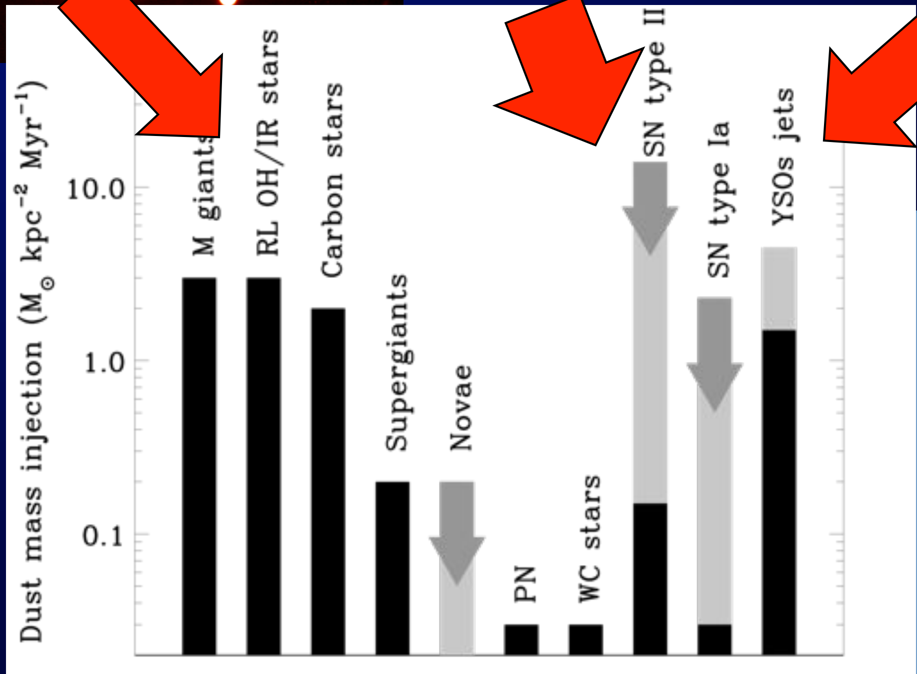
R. Corradi, ING & M. Steffen, AIP



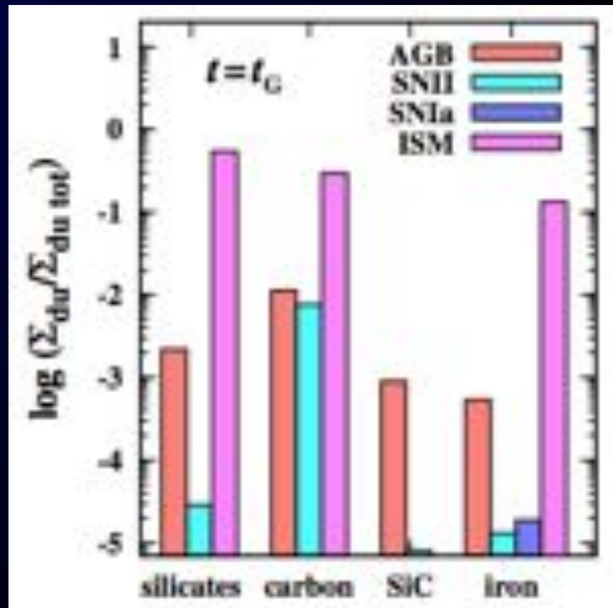
SN1987A - HST



HH30- HST



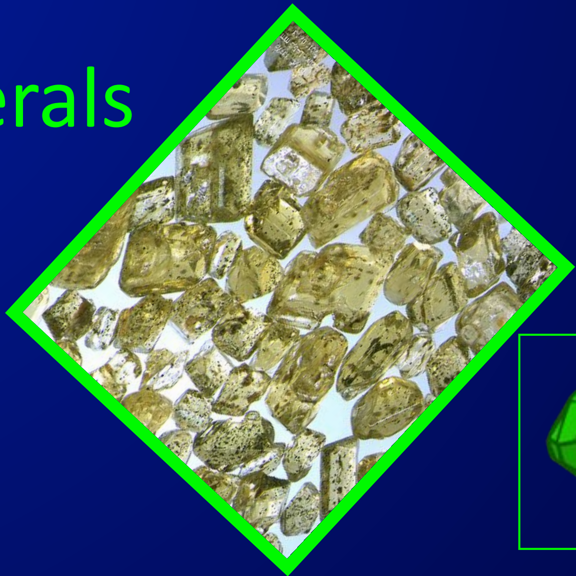
Jones 2001, Tielens 2005, Robitaille 2010, Matsuura 2011



Zhukovska2008+

The simplified picture of ISM solids

Minerals



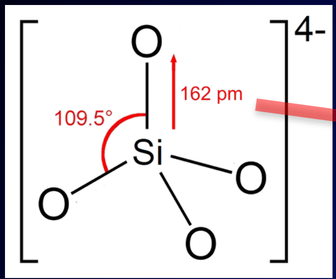
"Refractory" solids

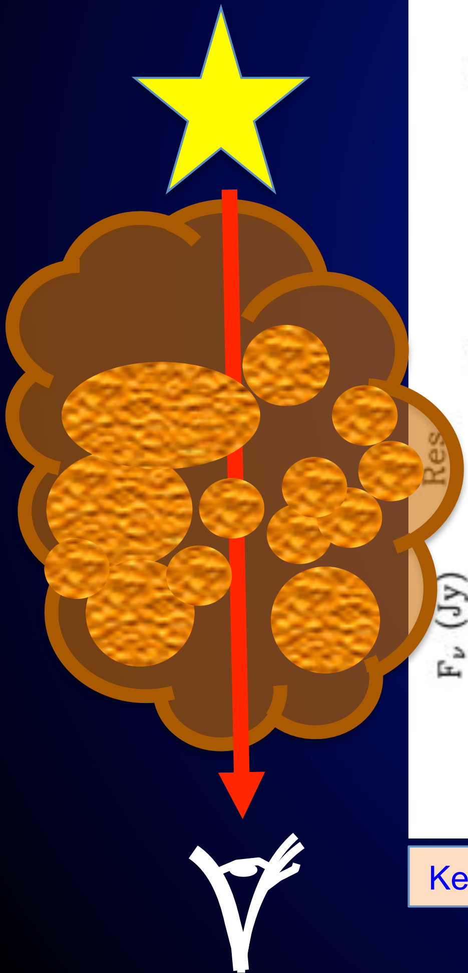
Volatile" solids

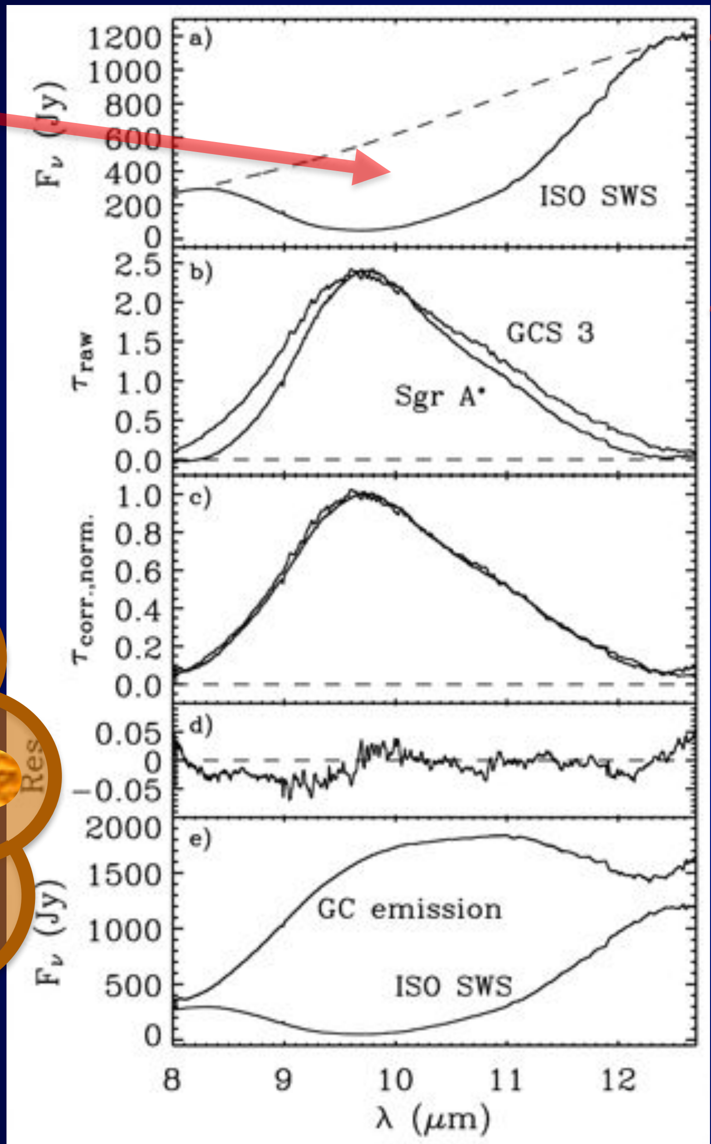
Ice mantles

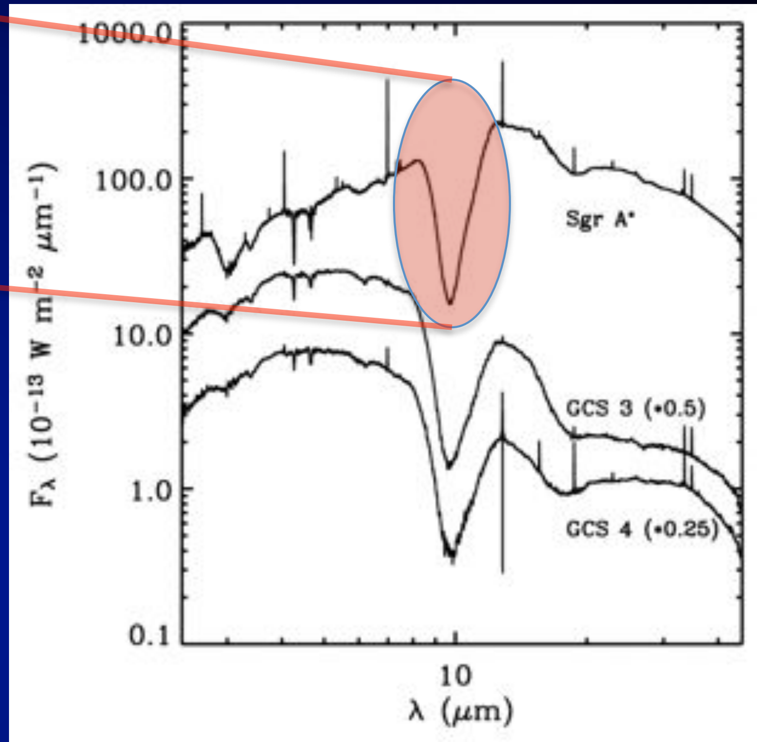
"Carbonaceous" matter

Silicates in the diffuse interstellar medium (DISM)









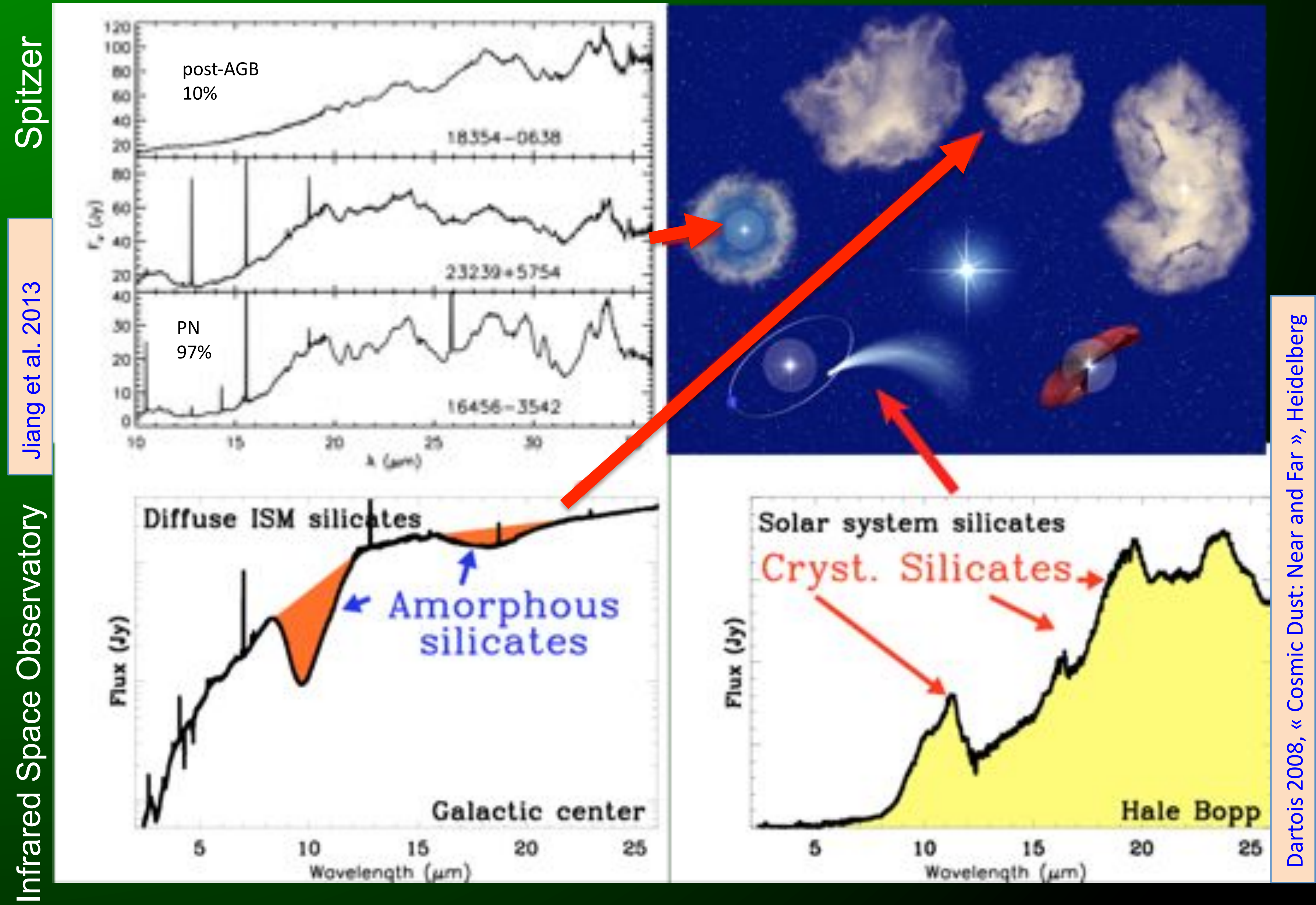
Kemper+2004, Jäger +2003 , Li & Draine 2001

ISM silicates almost fully « amorphous »

<2.2% crystalline (1.1% ± 1.1)
Kemper et al. 2004 + erratum

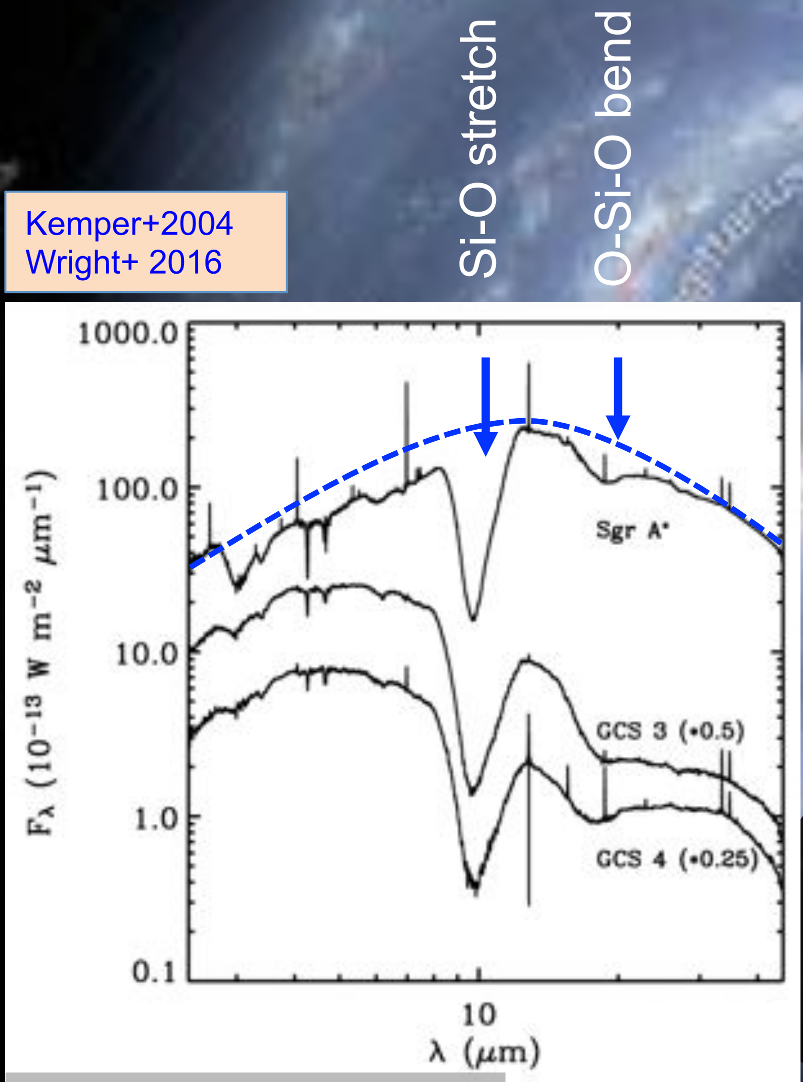
And in the Rayleigh limit (small)

Silicates : crystals are locally formed/(re-)processed

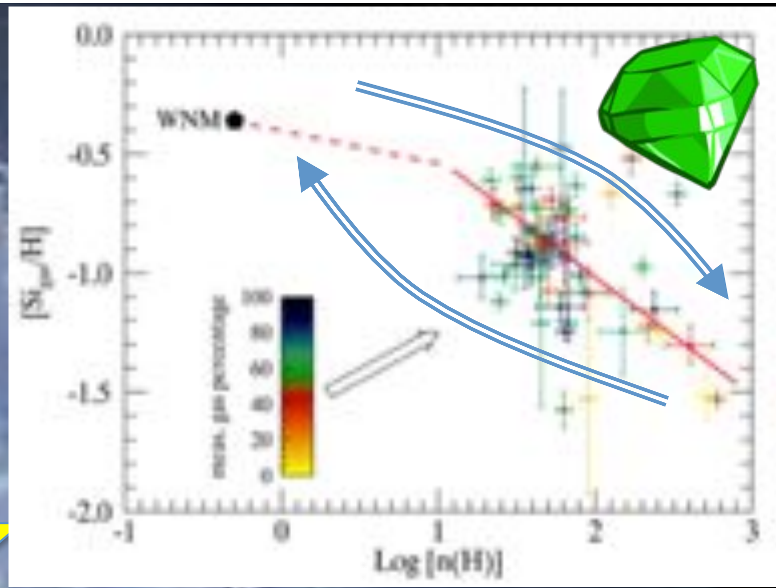


Why amorphous silicates in the DISM?

Kemper+2004
Wright+ 2016



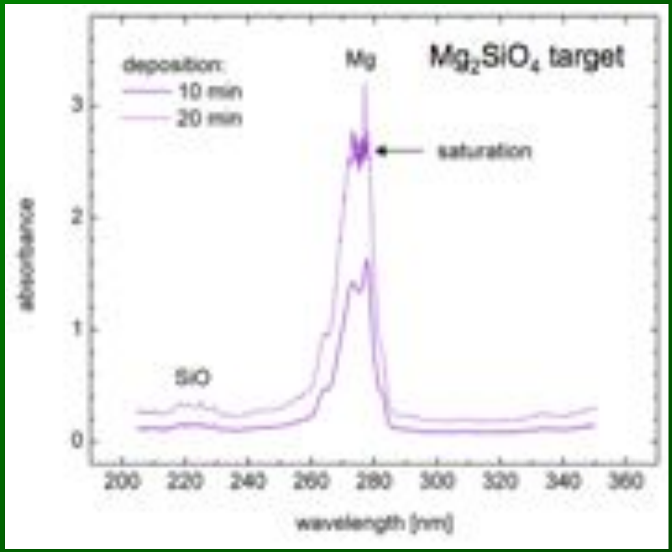
1.1% ± 1.1cristallins

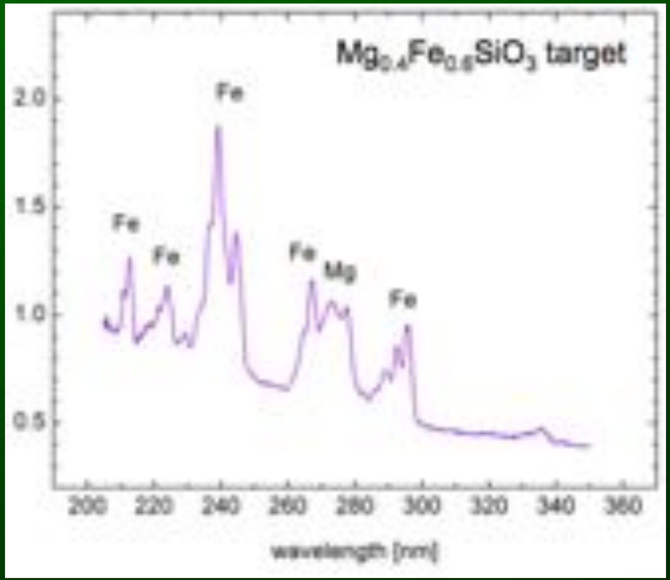


Zuhkovska+ 2016, Jenkins 2011

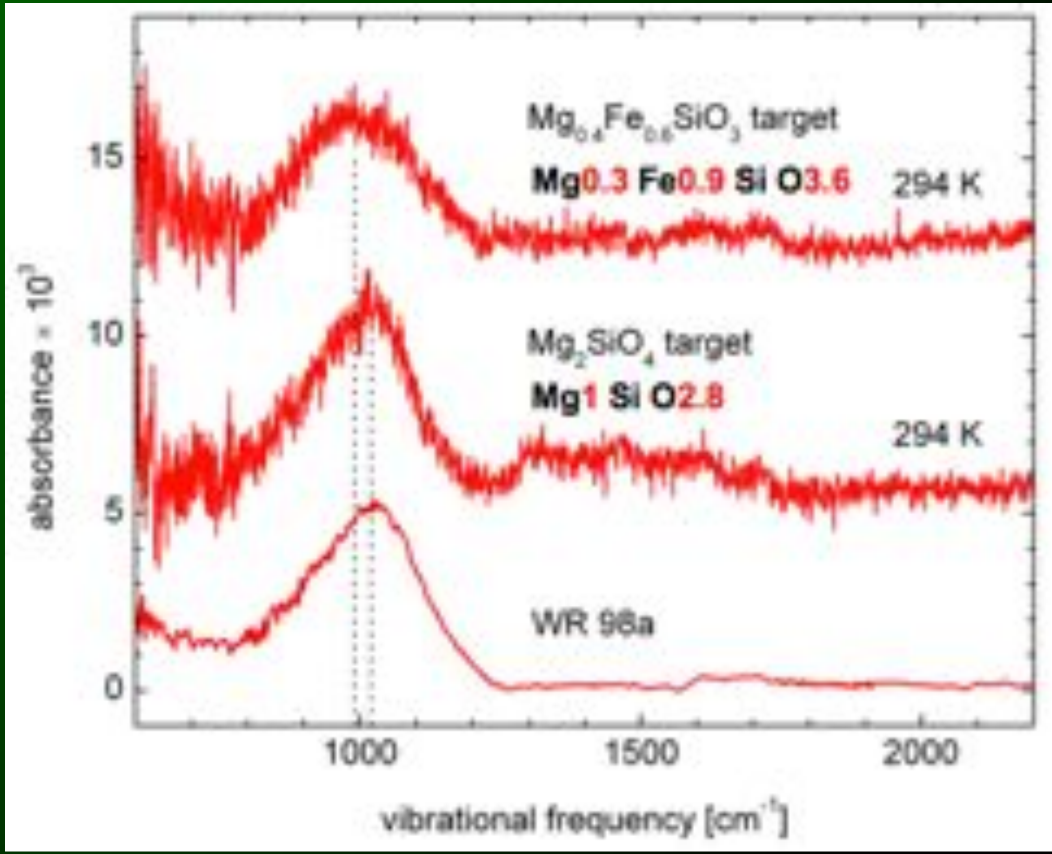
Proportion inherited from stars vs growth by accretion in ISM ?

Amorphous silicates from gas in the lab





Lab work on condensation of an amorphous phase from atoms at very low T

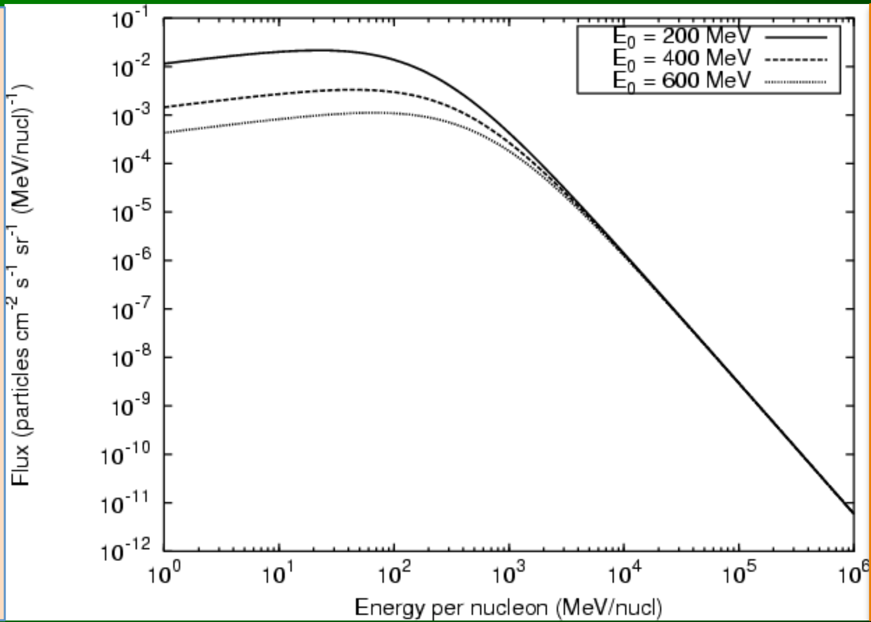


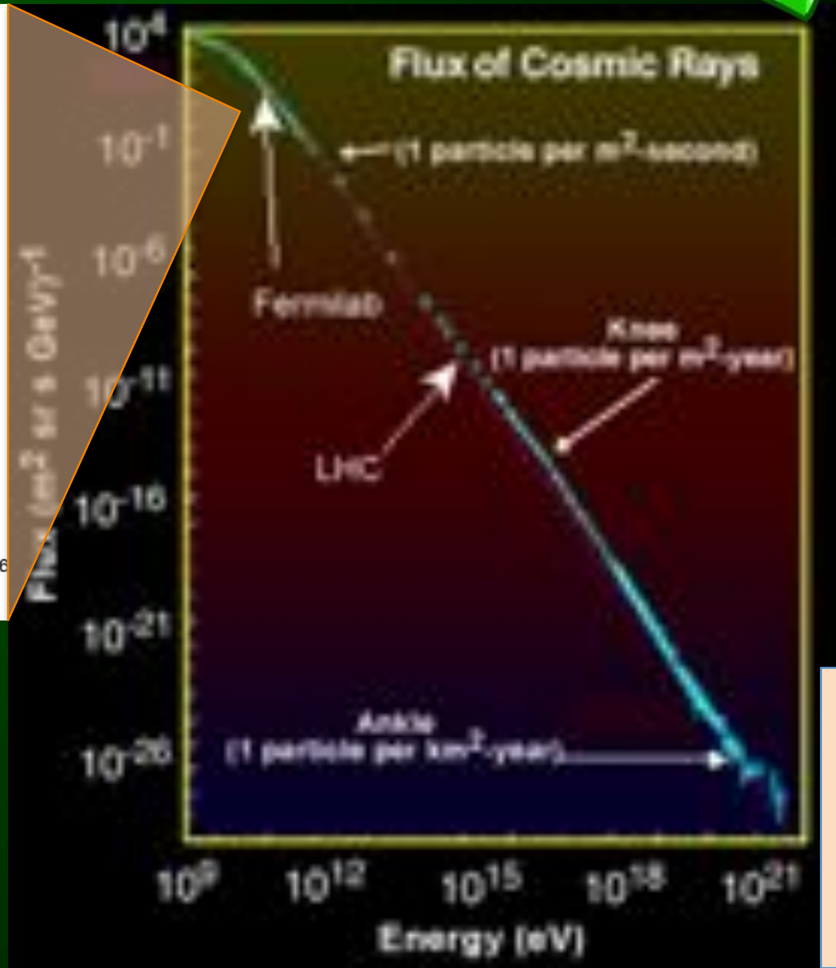
Rouillé+2014

e.g. Yang+2018, Fulvio+2017, Nuth & Moore1989 Donn+1981, Khanna +1981

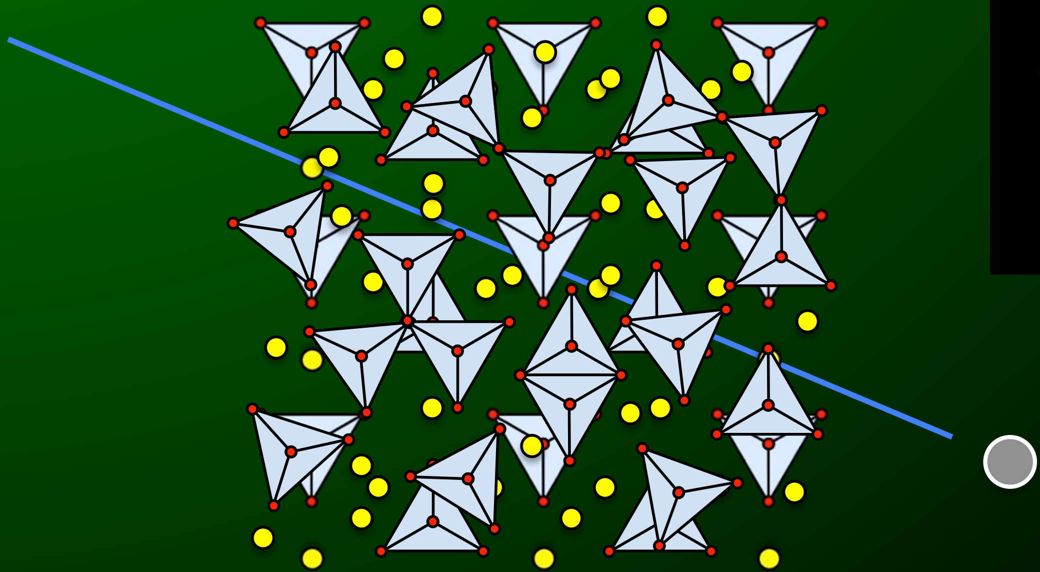
Cosmic rays amorphisation

Webber & Yushak 1983, Shen 2004



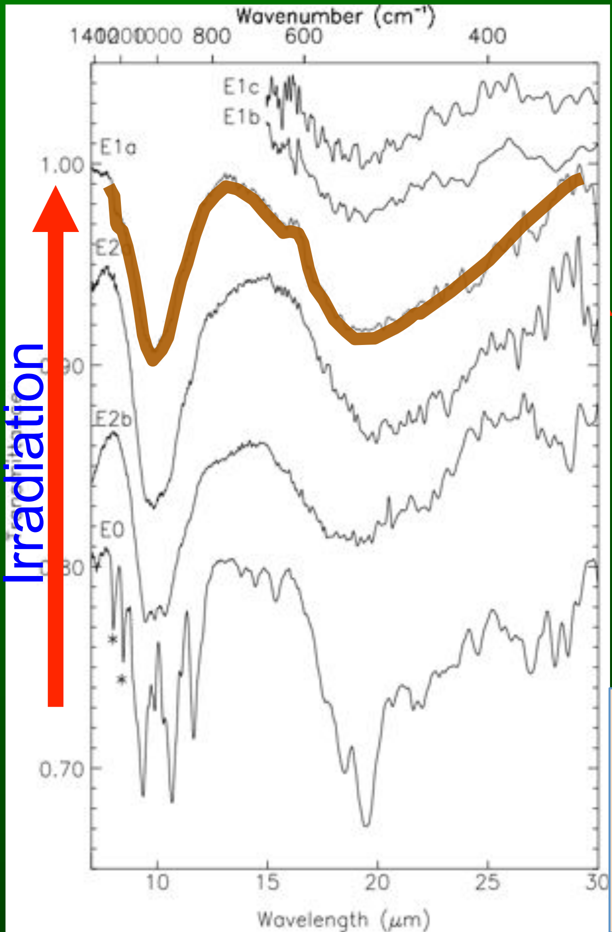


LPSC Grenoble

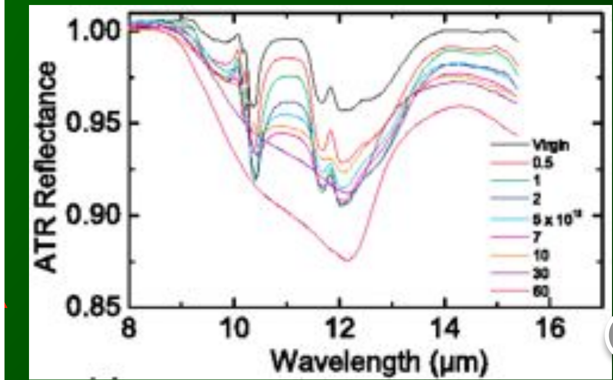


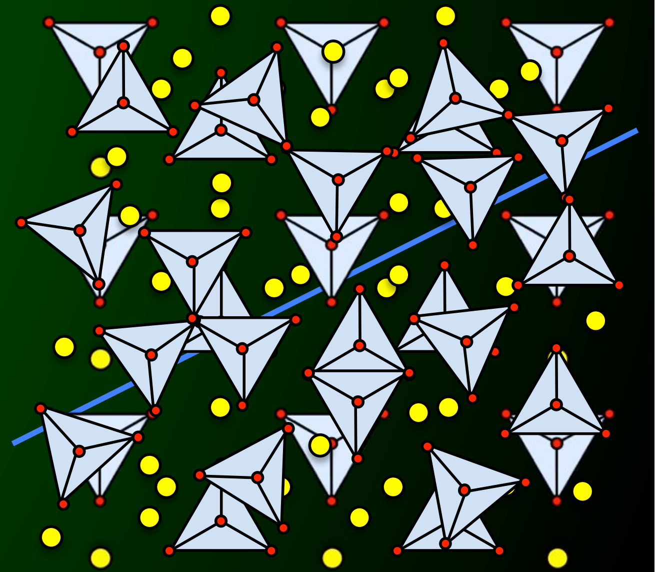
Amorphous silicates & CR in the laboratory

CR irradiation simulations 20-50keV He
+ irradiation of Enstatite ($MgSiO_3$)

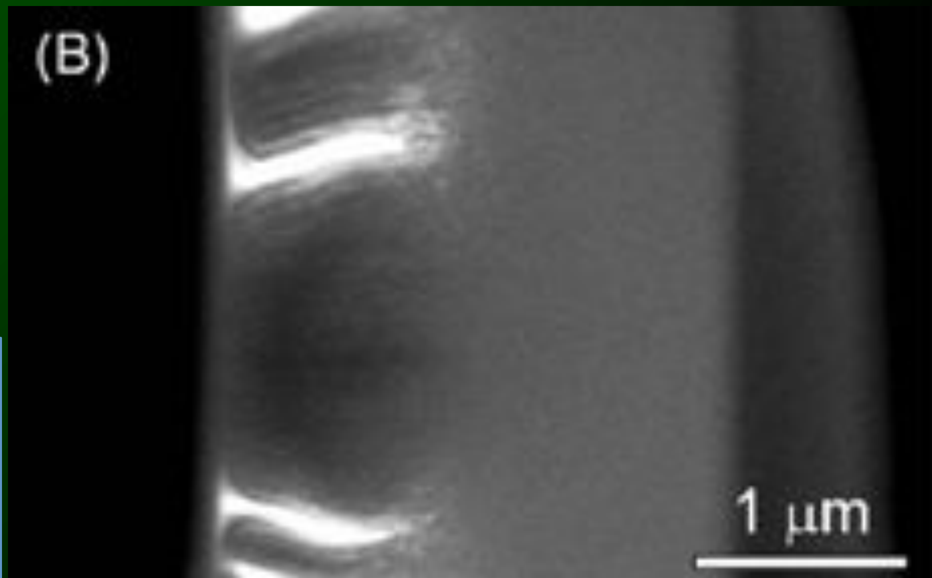


Demyk+2004



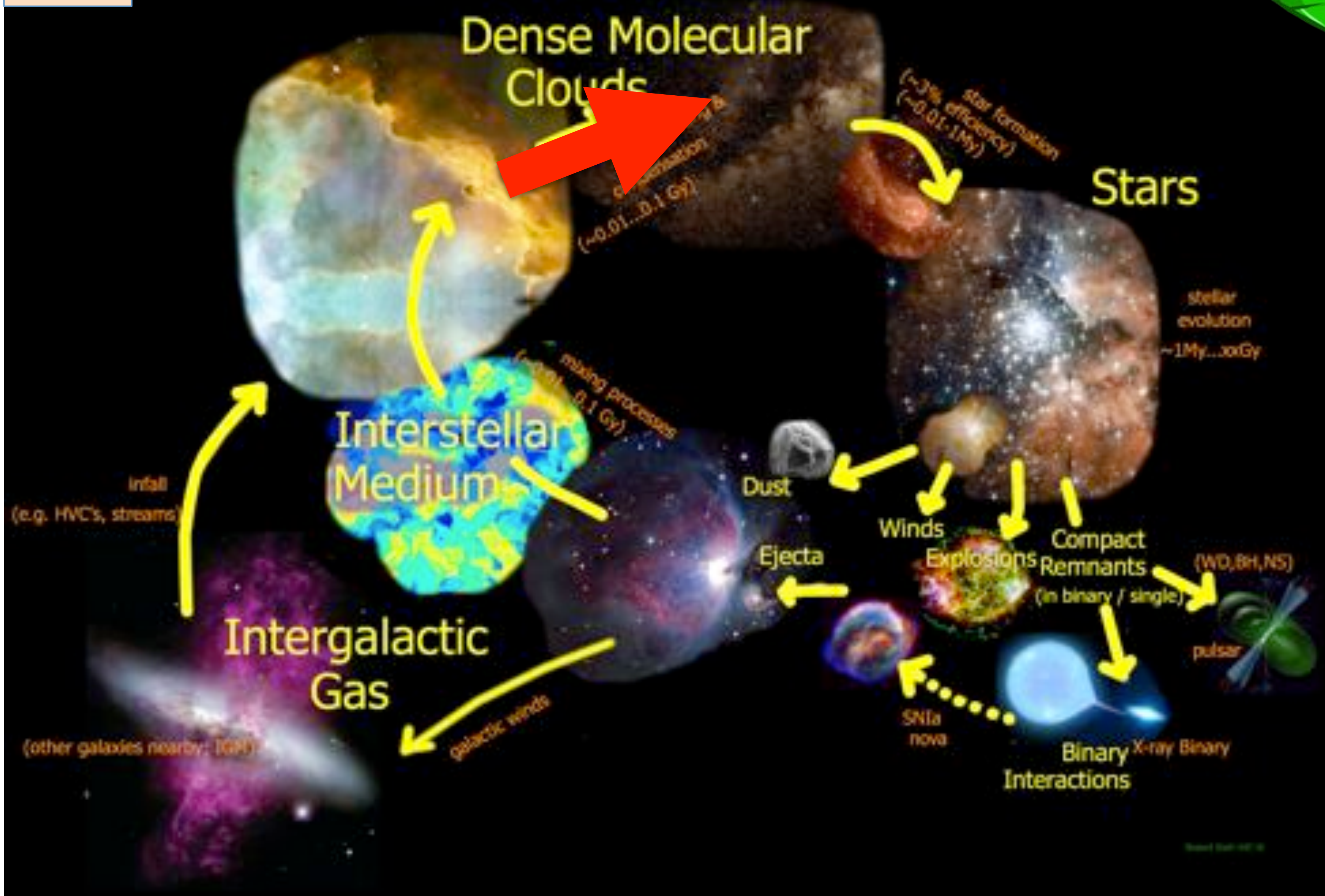


Bringa+2007



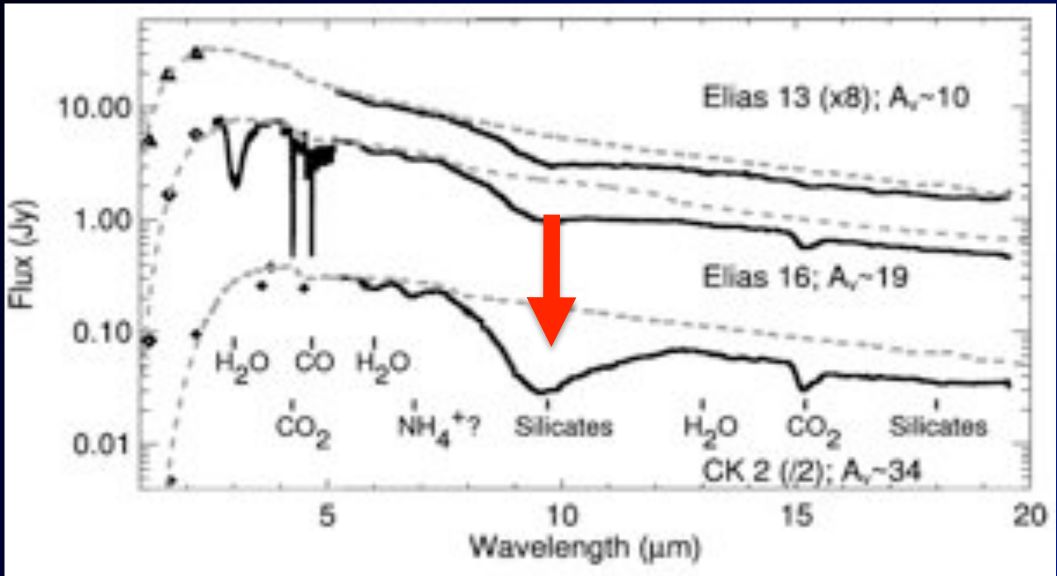
e.g. Jaeger+2013, Sczenes+2010, Bringa+2007, Stratzzulla+2005, Demyk+2004, Brucato+2003, 2004, Carrez+2002, Shrempel+2002

R. Diehl

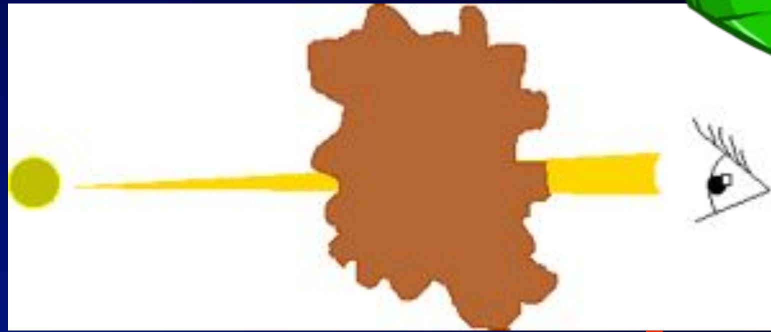


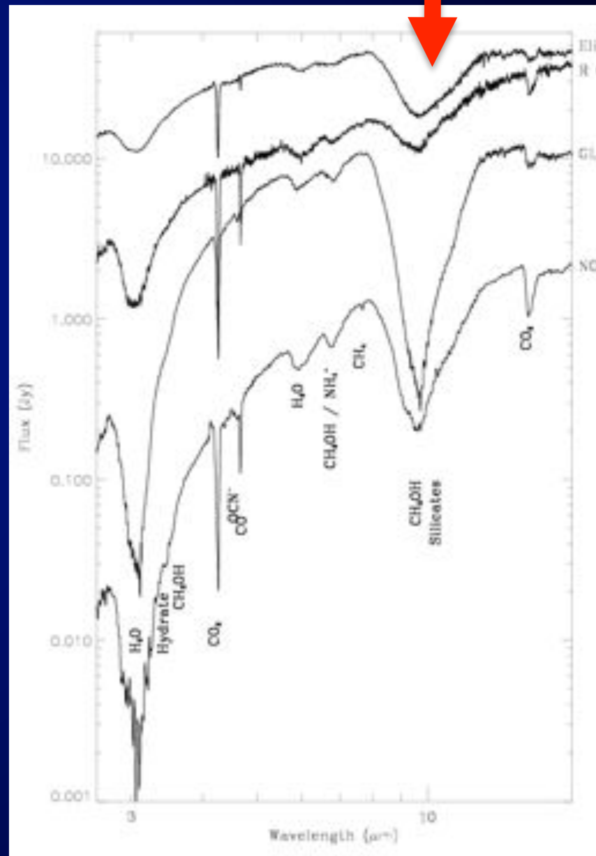
E.Dartois

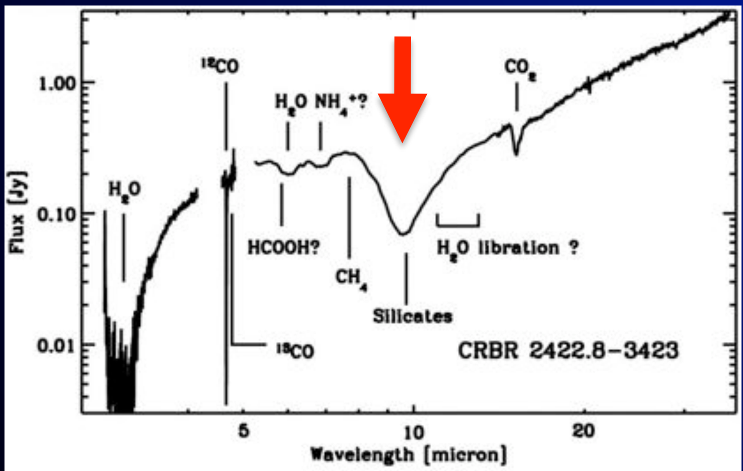
Silicates in the MC phase : still mostly amorphous…

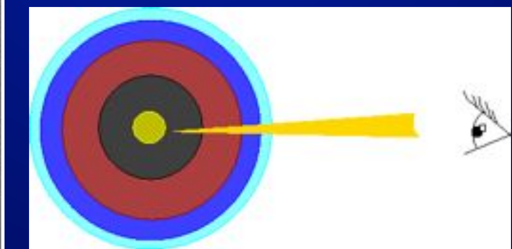


e.g. Knez+2005, Bergin+2005





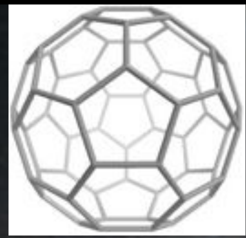




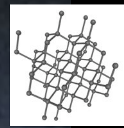
Spitzer/VLT, Pontoppidan+2005

ISO database extract

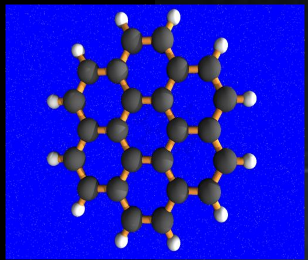
Main carbonaceous solid ingredients observed in the ISM



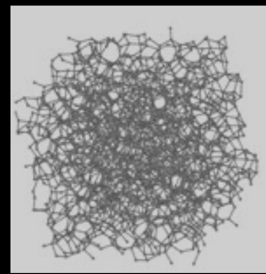
Fullerenes



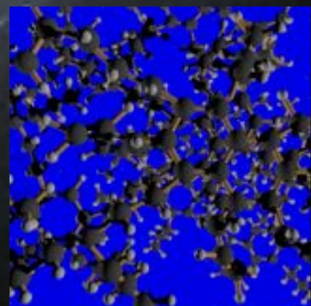
Nano-Diamond



AIBs (« PAHs »):
Class A to D



Amorphous carbon



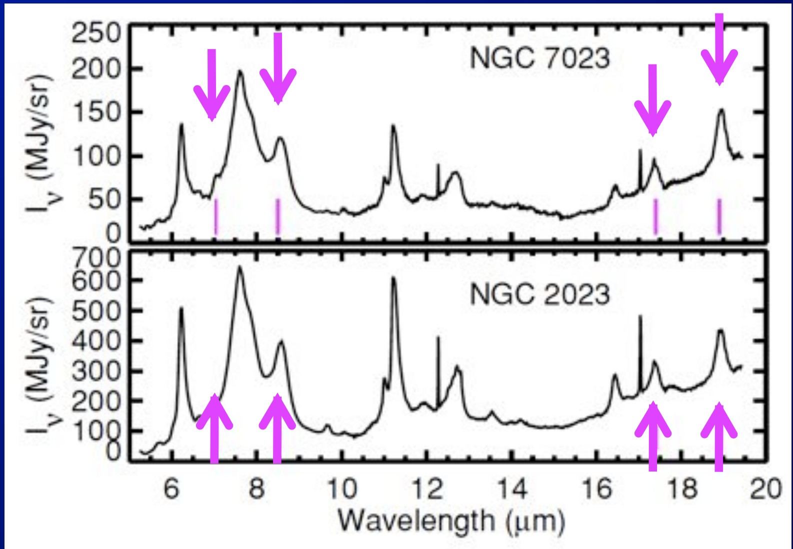
Hydrogenated amorphous carbon

Black eye galaxy, WFPC2, AURA/STScI

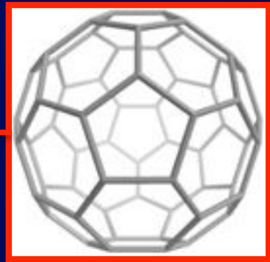
Fullerenes in a nutshell

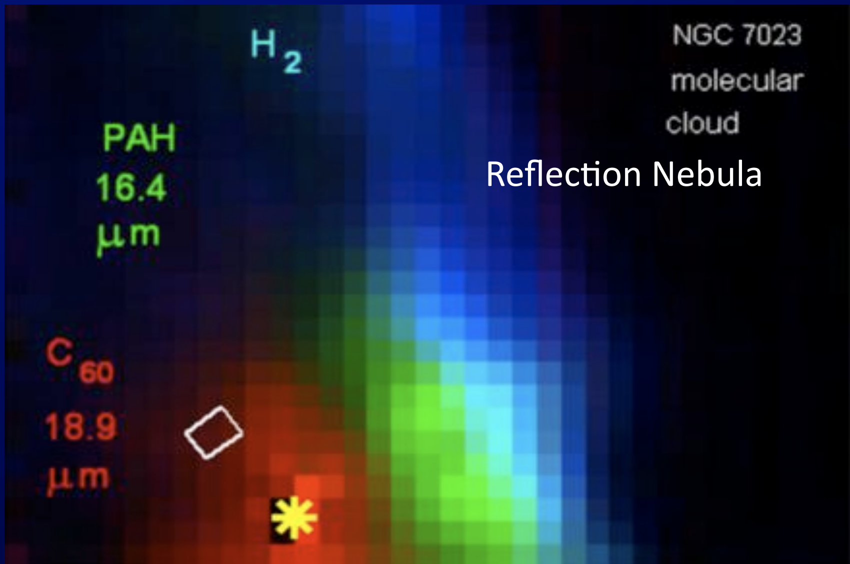
A long search with upper limits:
visible DIBs & IR

e.g. Fulara+1993; Foing & Ehrenfreund 1994, Moutou+1999, Herbig 2000



Sellgren+2009, 2010





Spatially resolved C_{60} in Reflection Nebulae

Sellgren et al. AAS 2009, Sellgren et al. ApJL 2010

Fullerenes in a nutshell

A long search with upper limits: visible DIBs & IR

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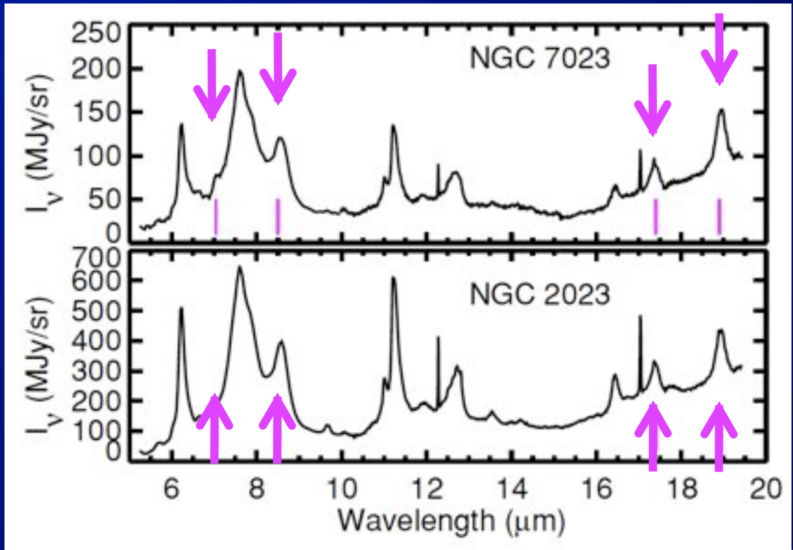
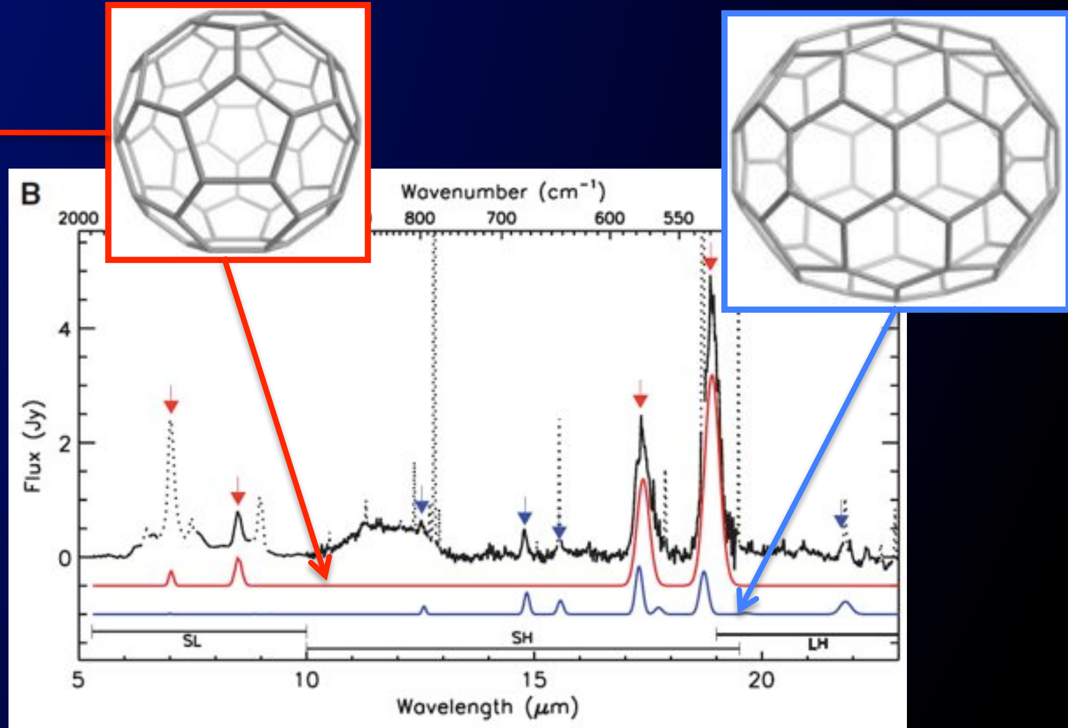
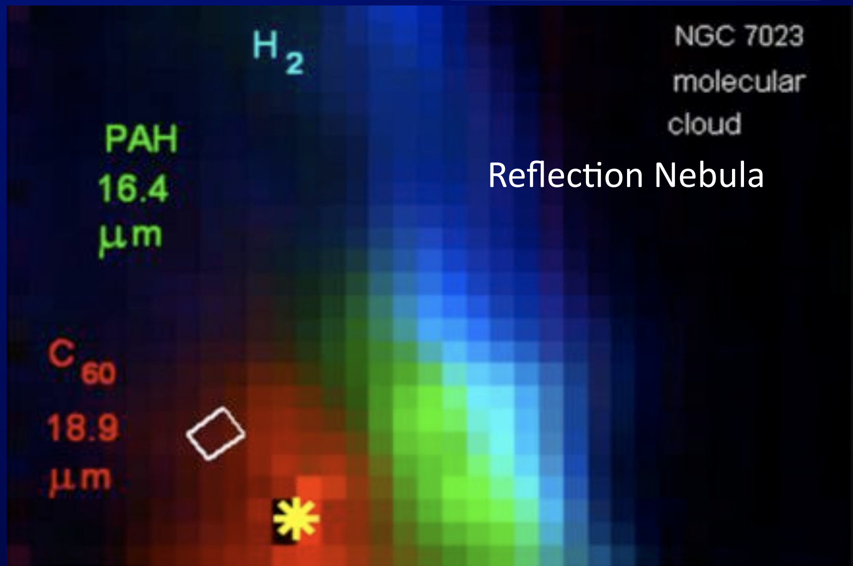


Sellgren+2009, 2010



PN (white dwarf) with low H

Cami et al. Science 2010



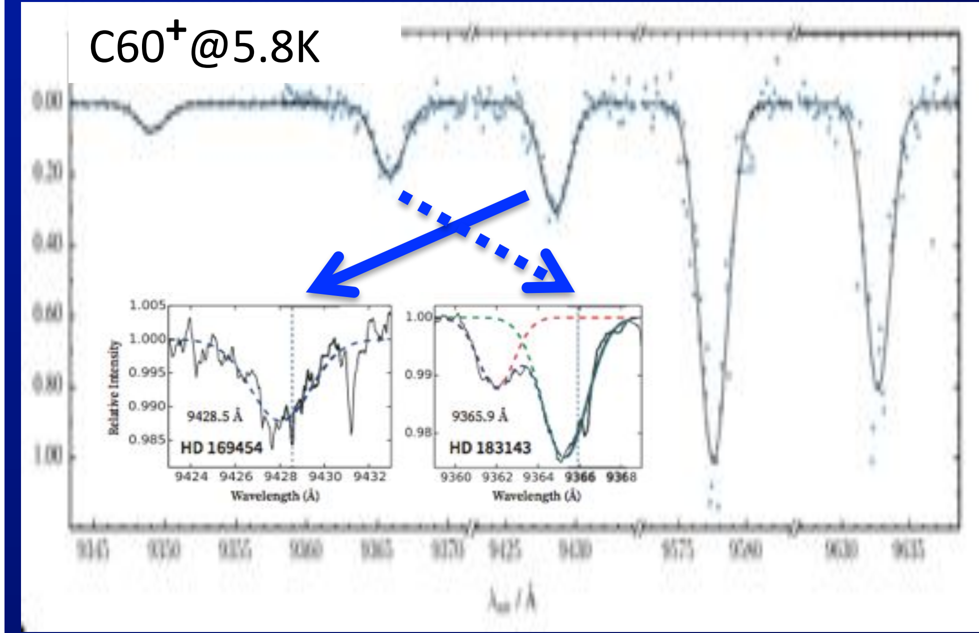
Spatially resolved C_{60} in Reflection Nebulae

Sellgren et al. AAS 2009, Sellgren et al. ApJL 2010

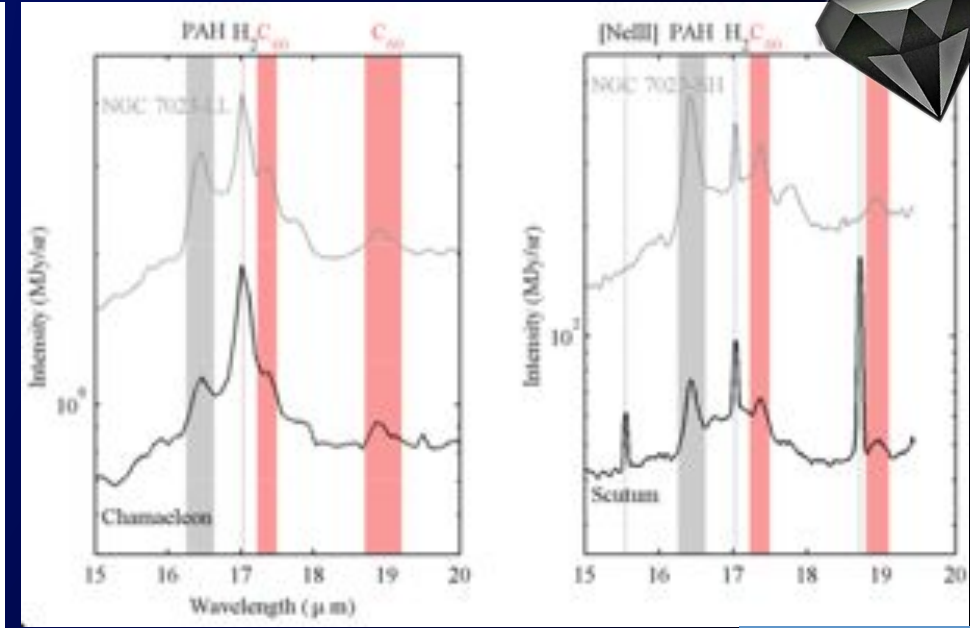
Observed in IR mainly in PNe (<5% C-rich) & many other objects (RN, AGB, Post-AGB, PPN, Herbig Ae/Be)

Cami+2010, García-Hernández+2010,2011,2012, Gielen+2011, Otsuka+2013, Zhang & Kwok 2011, Rubin+2011, Peeters+2012, Boersma+2012, Berné & Tielens 2012, Roberts+2012, Omont 2016

Fullerenes in the DISM



Campbell+2015, Walker+2015, Strelnikov+2015, Campbell+2016



Berné+2017

C60+ f value measured in Ne

% of C taking [C] = 1.6 × 10−4

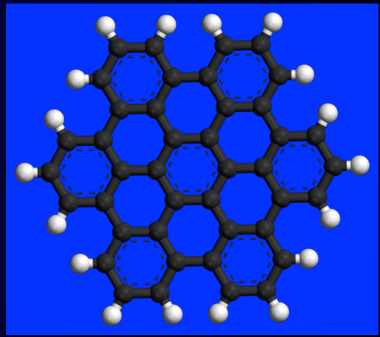
Fraction of C locked in detected fullerenes $X_C \sim 10^{-3}$-10^{-5}

$N_{C60}/N_H \sim 10^{-8}$-10^{-11}

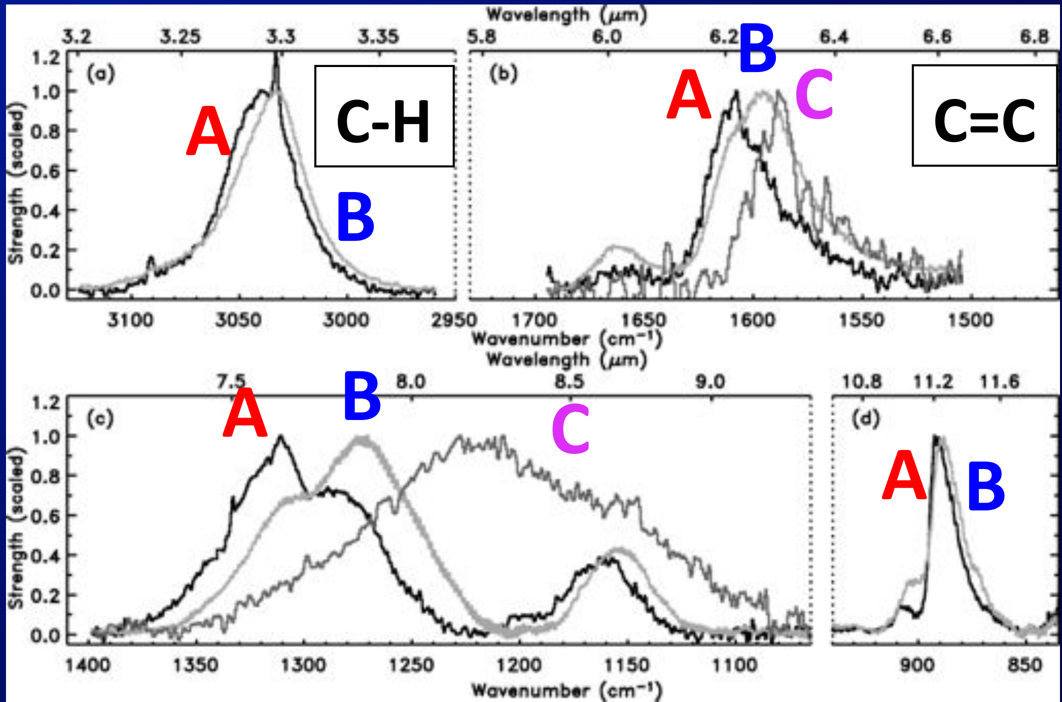
Detectability of C_{60}^+ bands more and more constrained (VLT/EDIBLES) Lallement+2018

	Emission	Absorption
	Star-forming regions	
C_{60}^+	0.01*	–
C_{60}	0.04–0.06**	–
	Diffuse ISM	
C_{60}^+	0.2 *,†	0.06–0.1*
C_{60}	0.03-0.4*	–
	Evolved stars	
C_{60}^+	–	1.2 **
C_{60}	0.1–3.0***	–

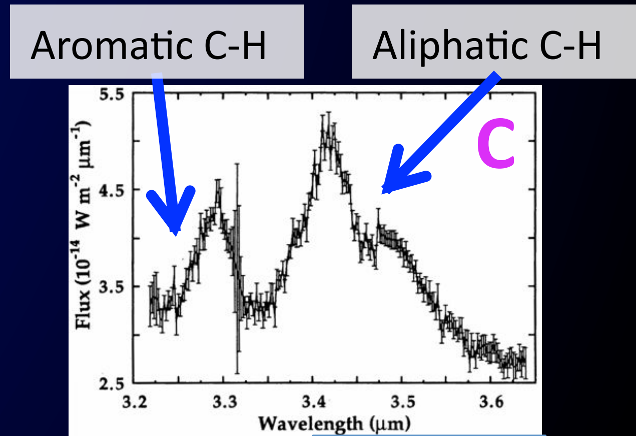
AIBs ("Polycyclic Aromatic Hydrocarbons hypothesis")



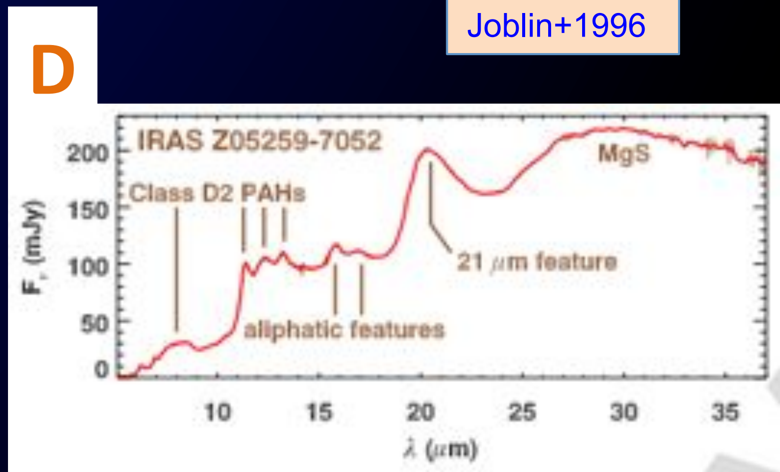
Class A, B, C, D



Van Diedenhoven+2004, Sloan+2014



Joblin+1996



Sloan+2017

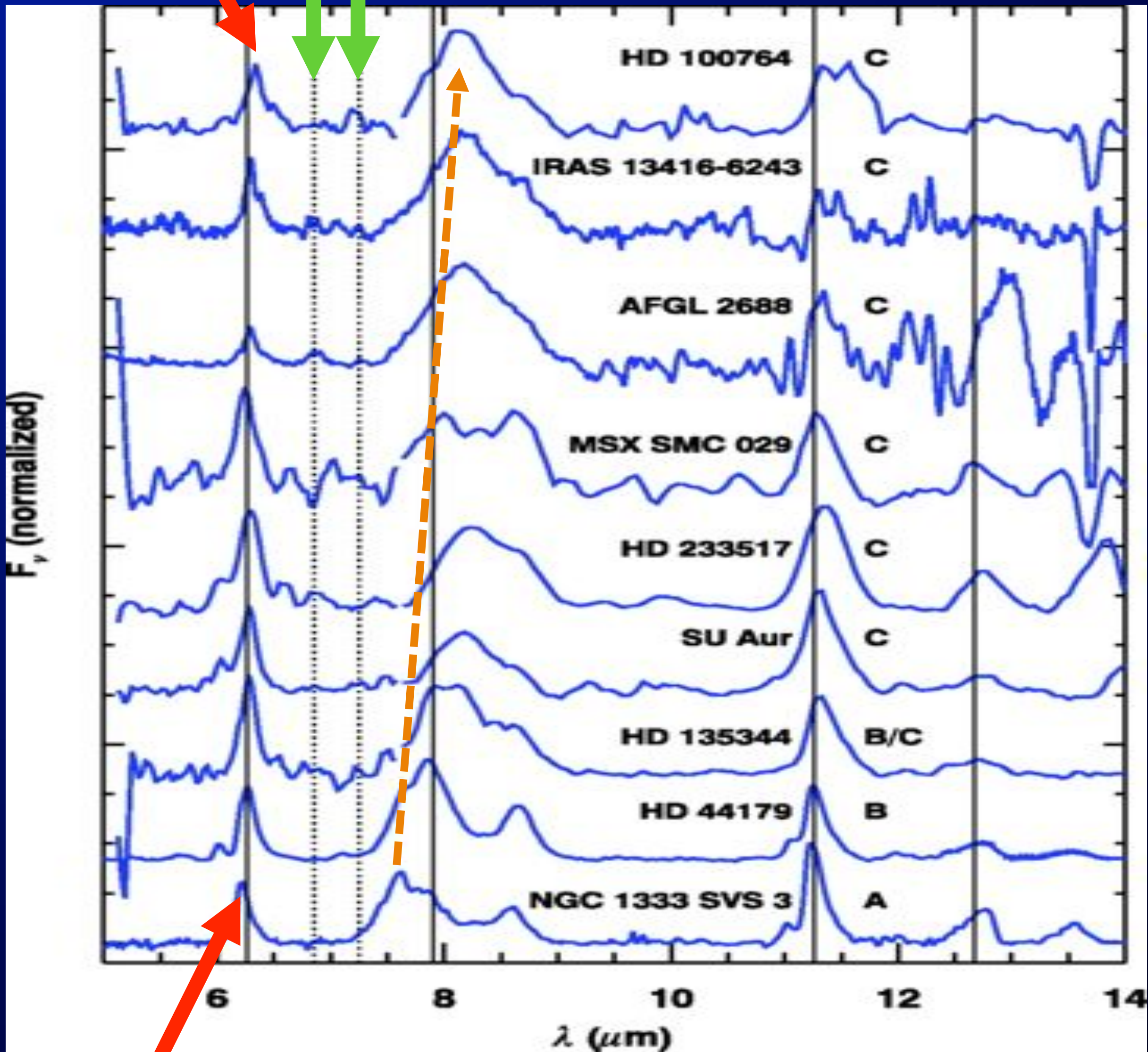
\# sources observed : class A >> class B > class C - D

Aliphatic/aromatics mixed in class C/D

5-20% C

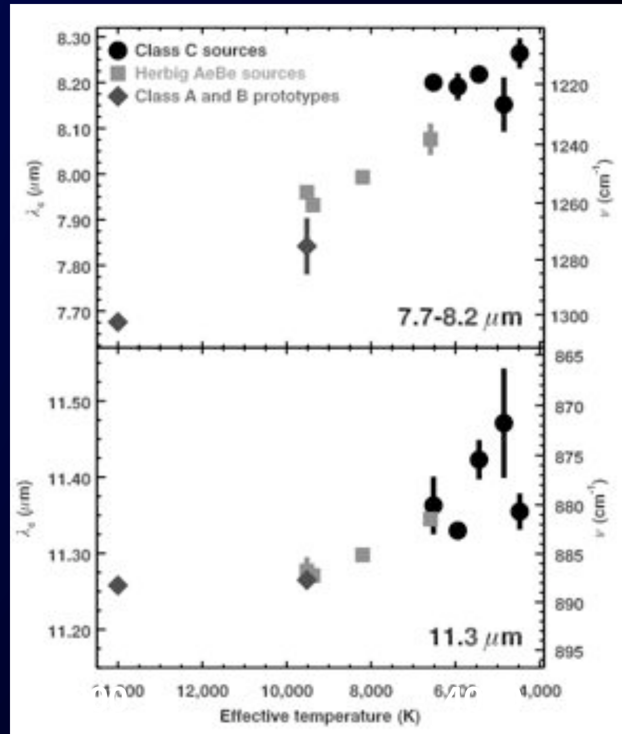
6.3 μm sp^3 deformation modes

6.85/7.25 μm



6.2 μm

Sloan+2007, Keller+2008, Acke+2010

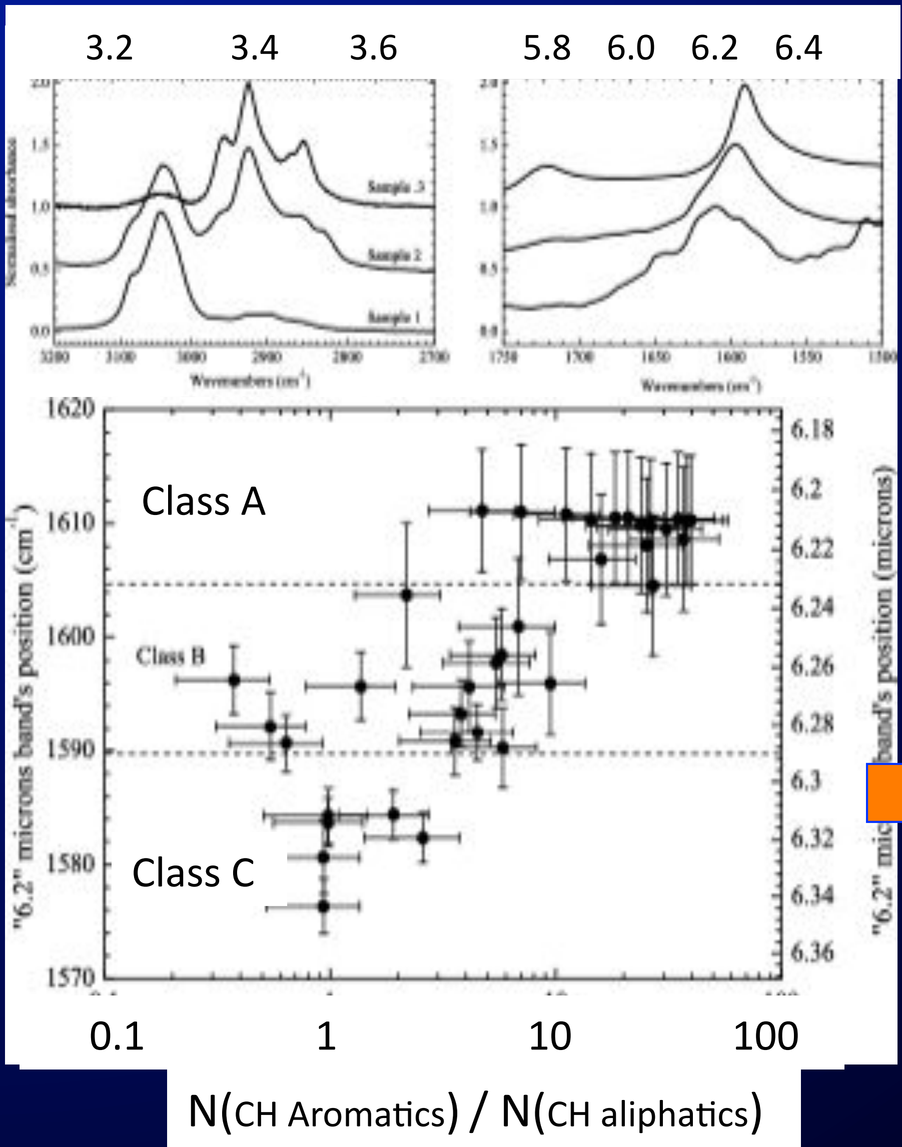


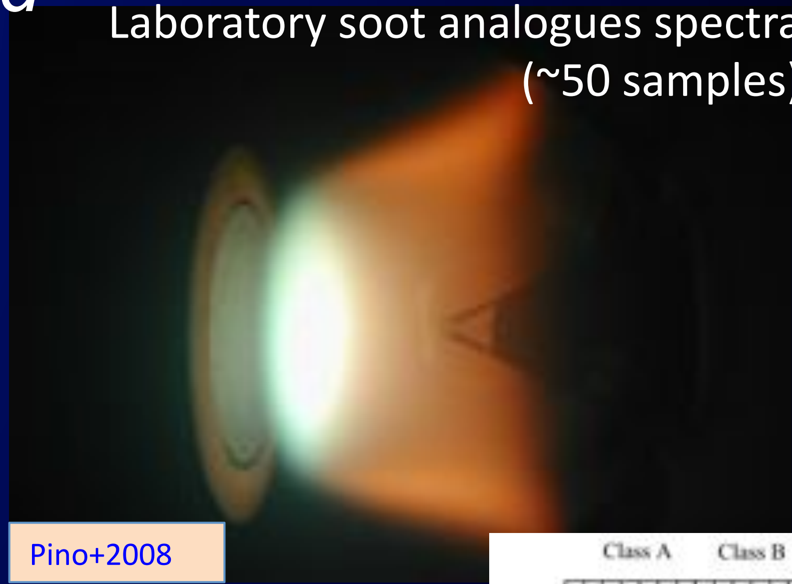
Teff

Planet. Ne and RNe not aligned
-> Xstry + UV

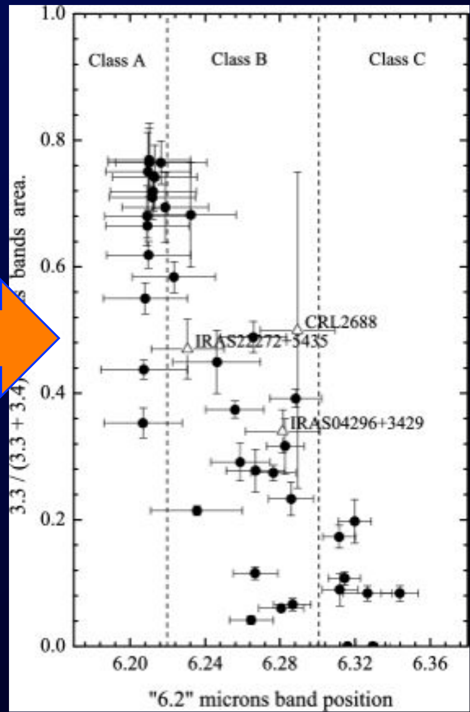
Aromatic C=C shift induced by aliphatics *sp3 CH bonds ?*

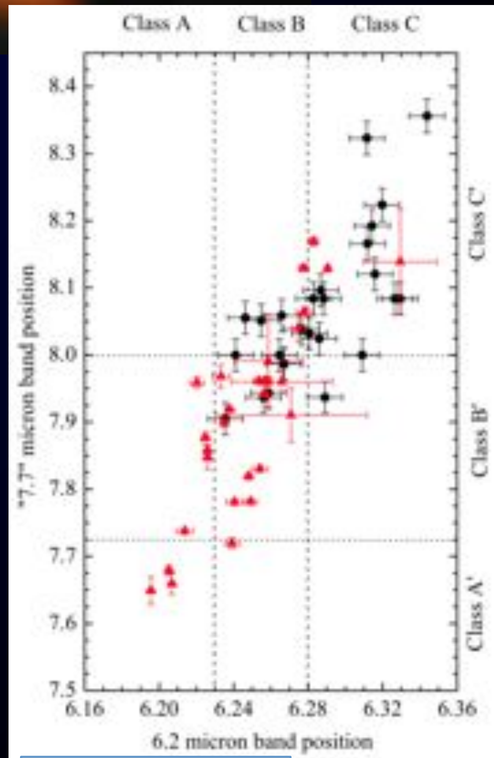
Premixed low pressure flame
Laboratory soot analogues spectra
(~50 samples)





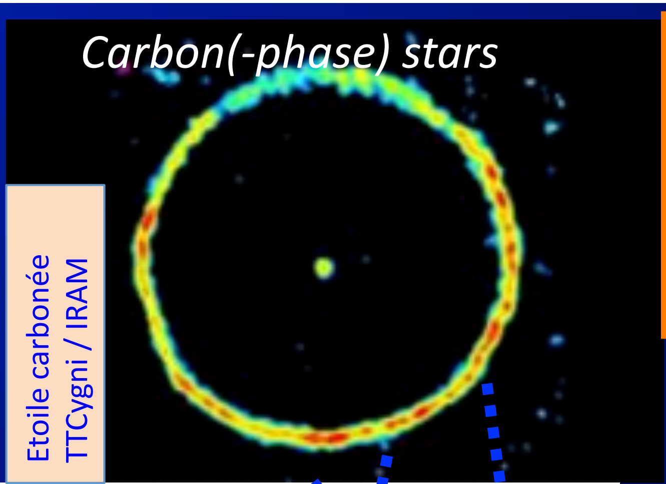
Pino+2008

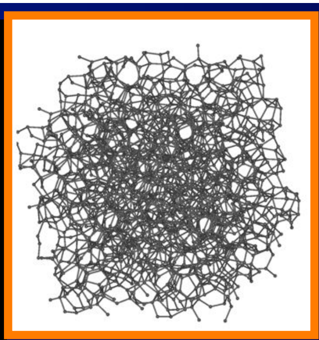




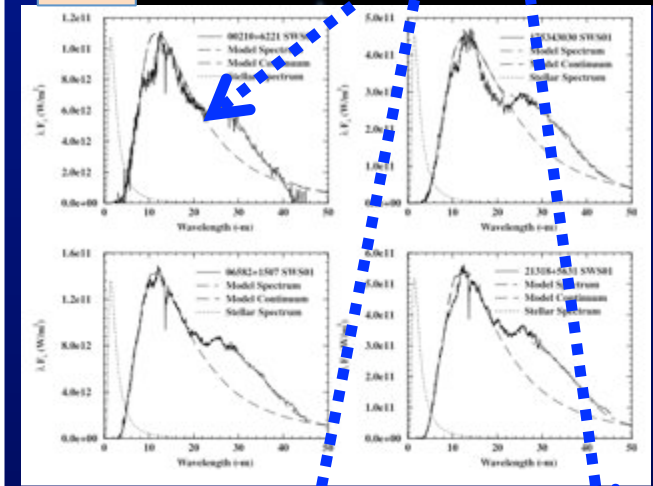
Carpentier+2012

Kwok&Zhang2013

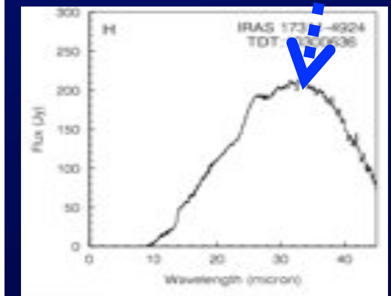


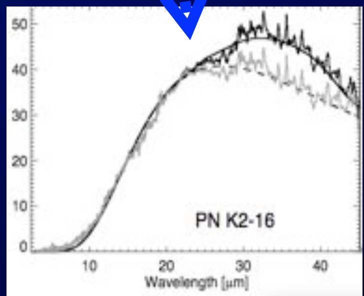


Amorphous carbon (a-C)



Volk+ 2001



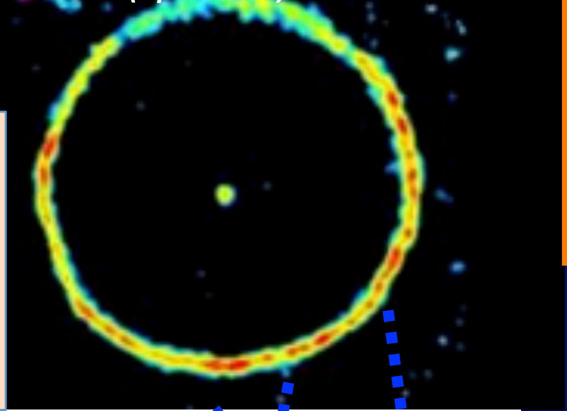


Chen+ 2010, Gauba 2004

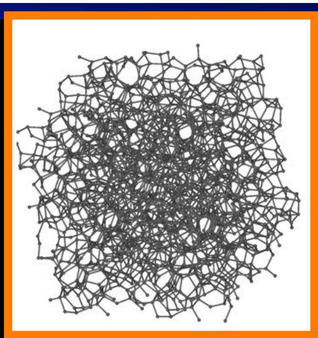
Hony+ 2002

C rich PPNs progenitors like AFGL 2688 (class C) & PNs like NGC 7027

Carbon(-phase) stars



Etoile carbonée
TTCygni / IRAM

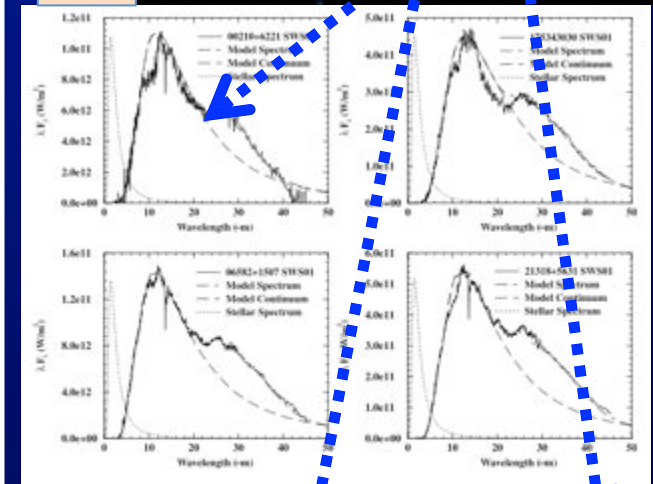


C

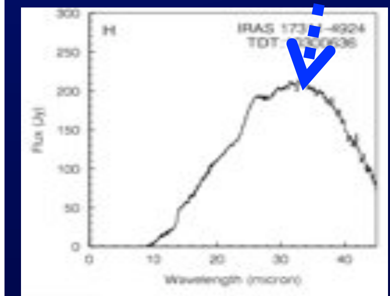
Amorphous carbon (a-C)

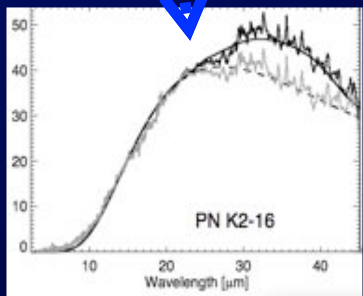
Large fraction of the C in a-C needed in the DISM dust models

Dwek 1997, Compiègne+ 2011, Zubko+2004, Jones+ 2013, Siebenmorgen 2014, Wang+ 2014, …



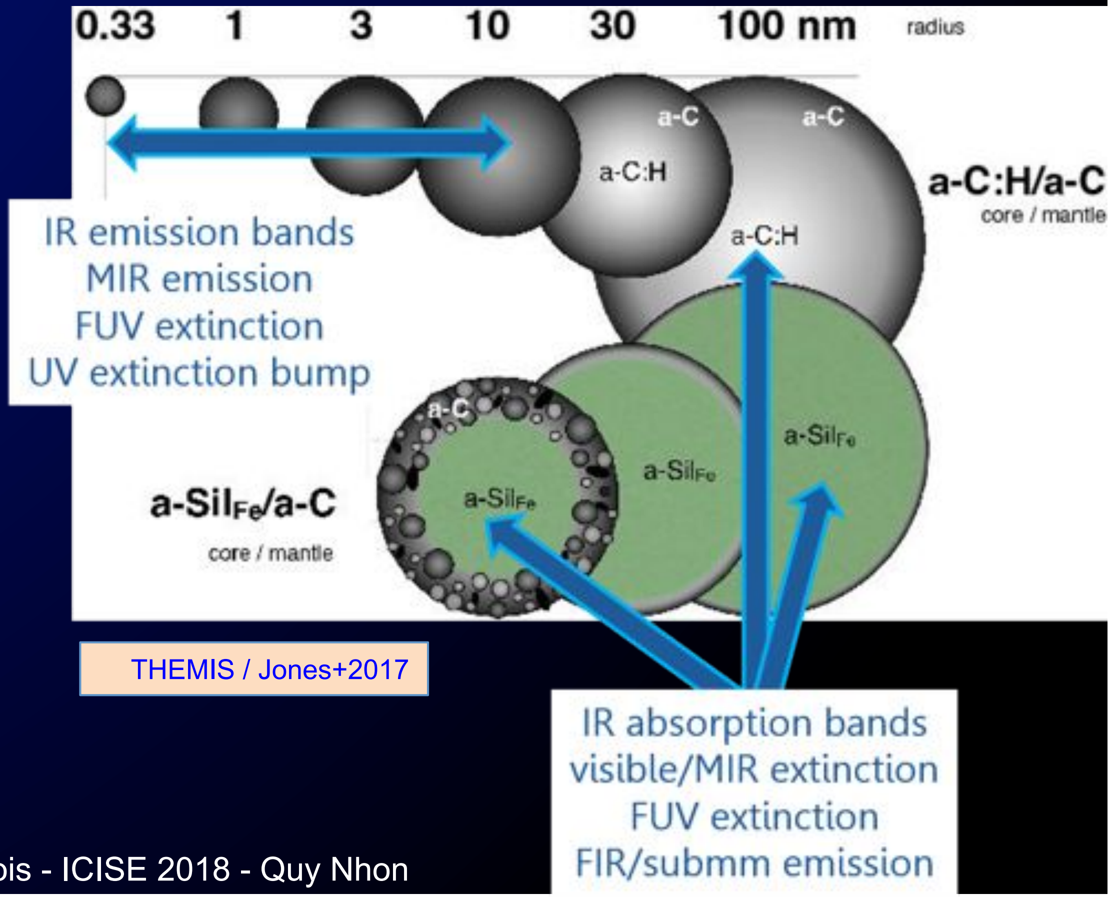
Volk+ 2001





Chen+ 2010, Gauba 2004

Hony+ 2002



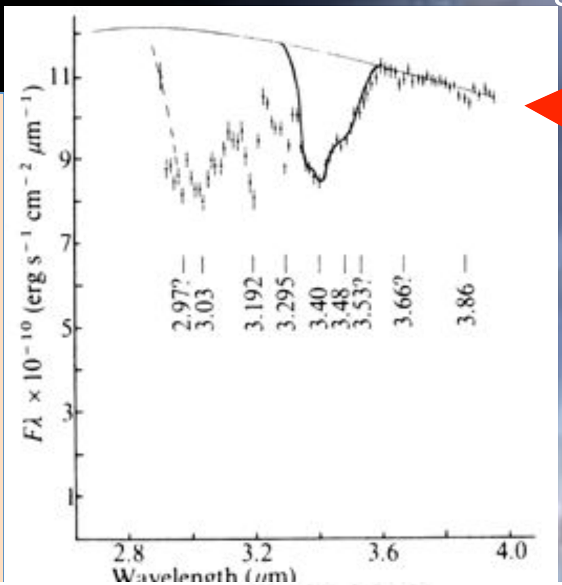
THEMIS / Jones+2017

C rich PPNs progenitors like AFGL 2688 (class C) & PNs like NGC 7027

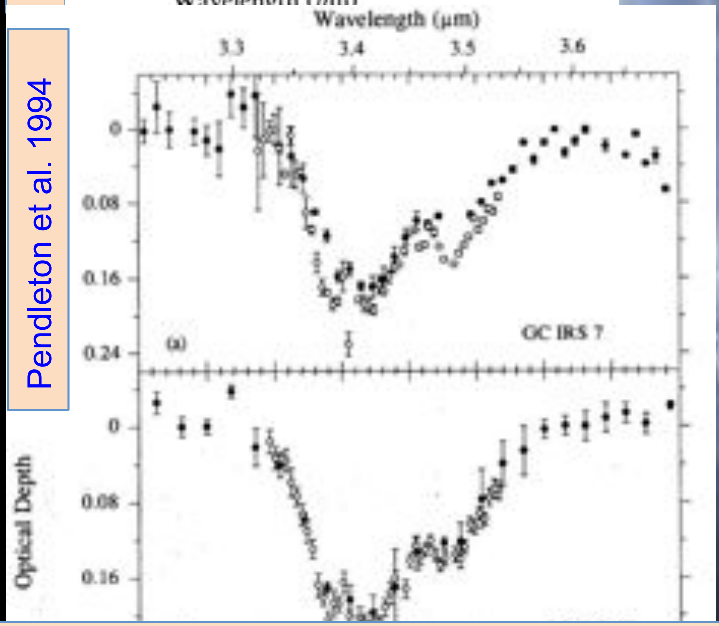
Hydrogenated amorphous carbons (a-C:H or HAC)

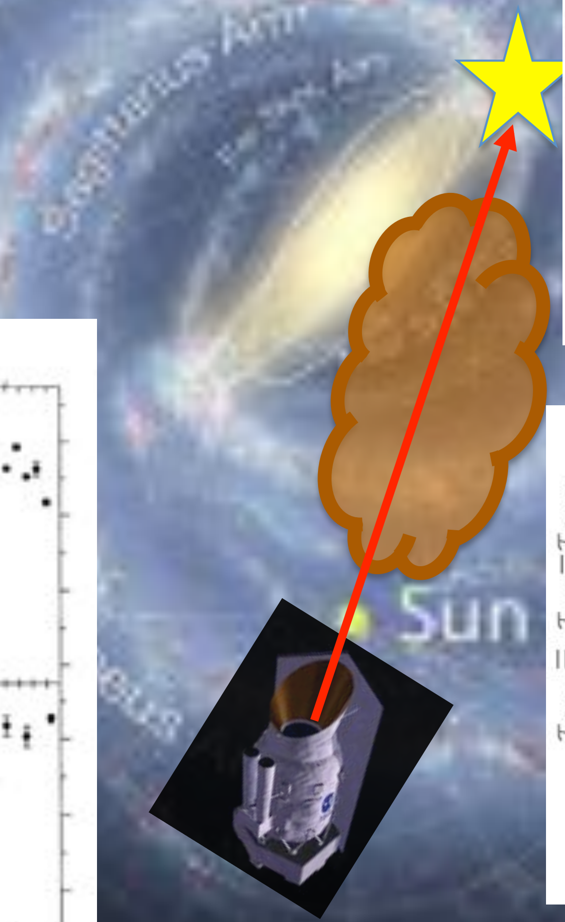
CH stretch abs. observed against IR bkgd sources

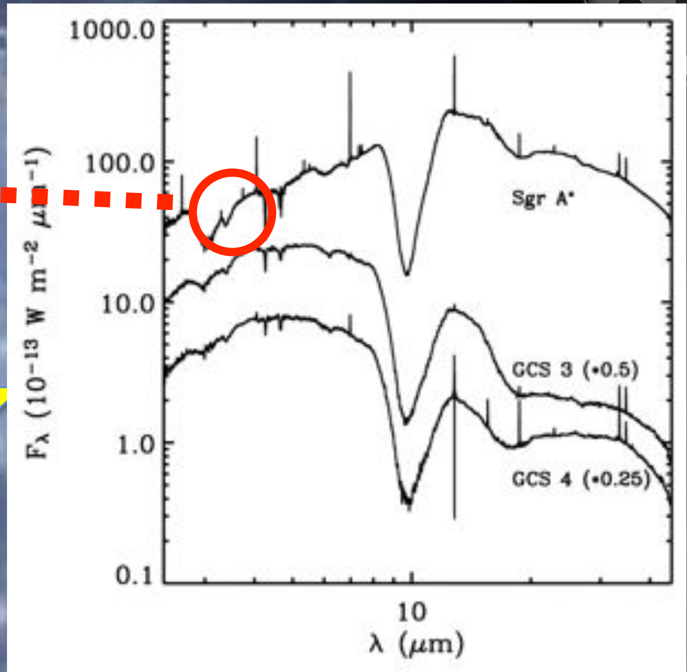
Allen & Wickramasinghe 1981

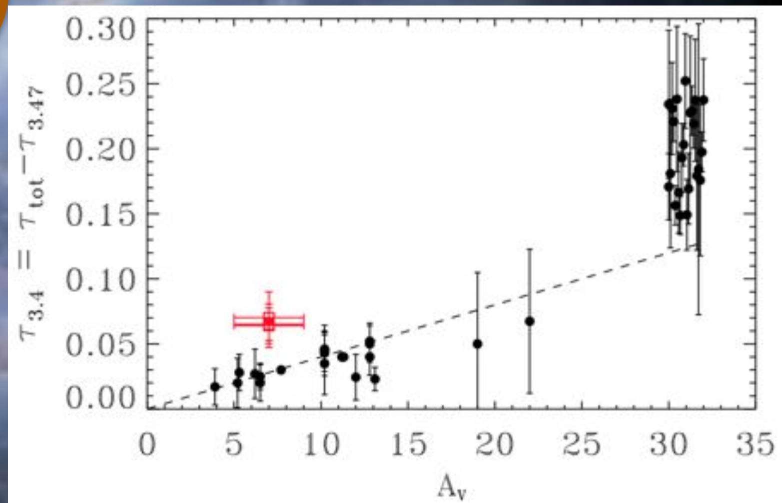


Pendleton et al. 1994







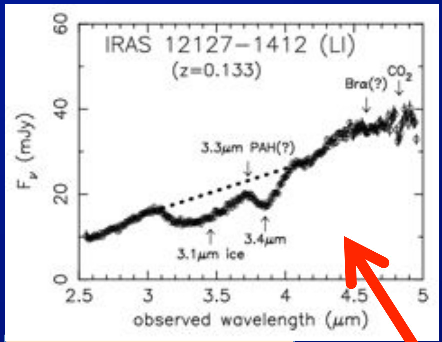


Godard et al. 2013

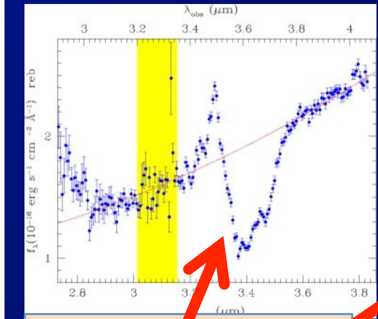
Sandford et al. ApJ 1991, 1995, Pendleton et al. ApJ 1994; Duley et al. ApJ 1994, 1998; Dartois et al. 1997

Up to 35% (lab HAC) du C cosmique

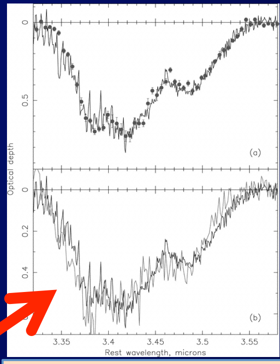
Extragalactic sources ISM observed with a-C:H



Imanishi et al. AJ 2010

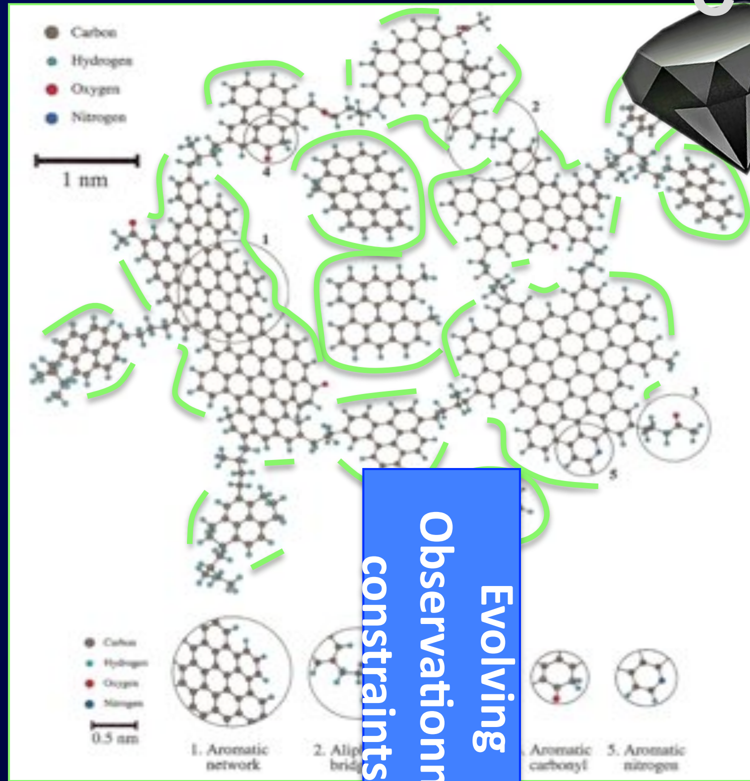


Risaliti et al. MNRAS 2006



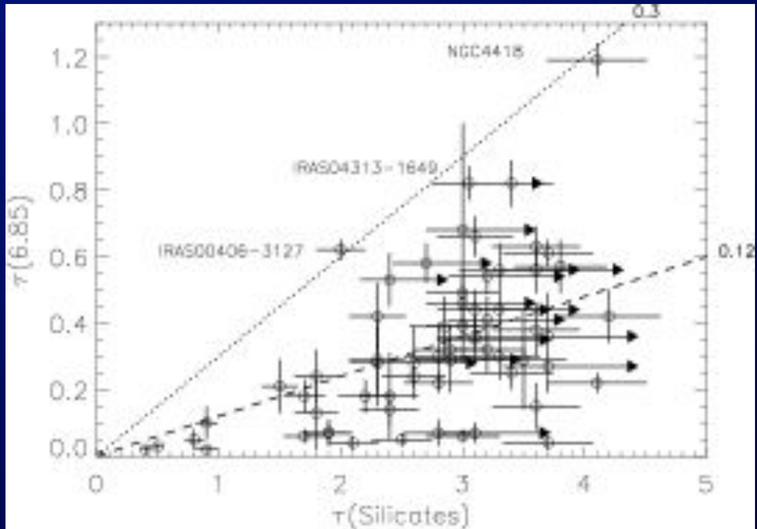
Mason et al. ApJ 2004

CH stretch



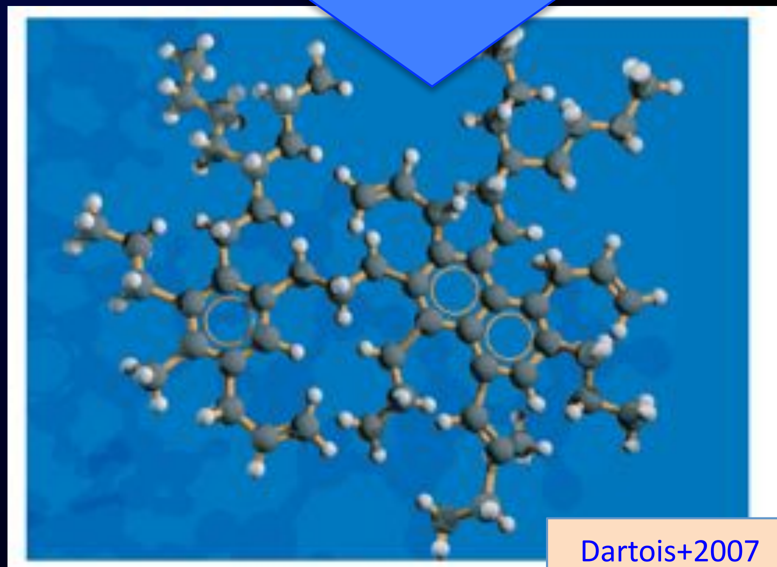
Pendleton & Allamandola ApJ 2002

Evolving Observational constraints



e.g. Risaliti+2006, Imanishi +2006; Mason+2004, 1998; Pendelton+1994

Dartois & Munoz Caro 2007



Dartois+2007

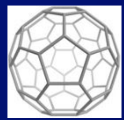
τ(6.85) ~ 0.12 τ(Silicates)

15% +-7% of the cosmic carbon

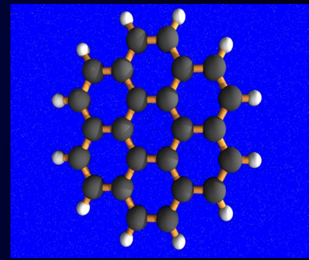
Up to 40% in extreme cases ?

Which ISM carbonaceous solids ingredients for models ?

Fullerenes

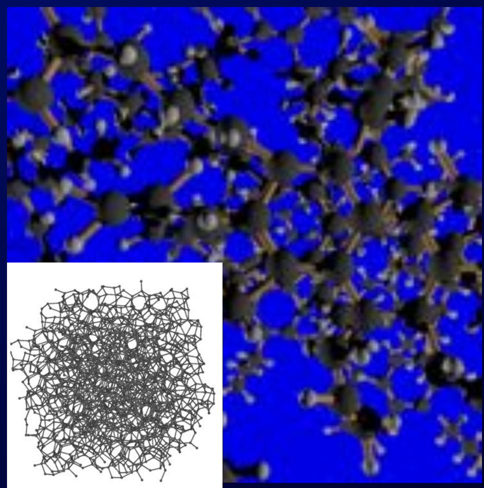


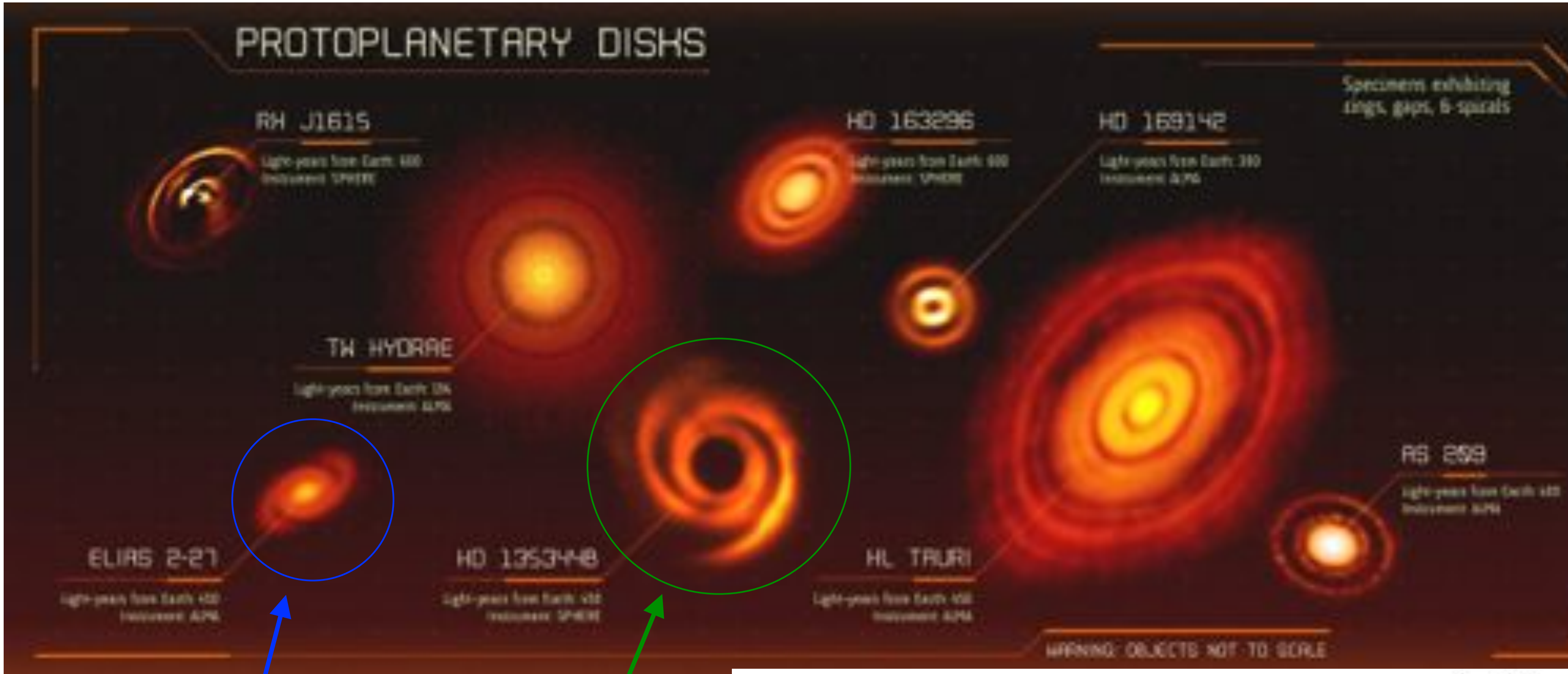
AIBs-PAHs :
Class A to C



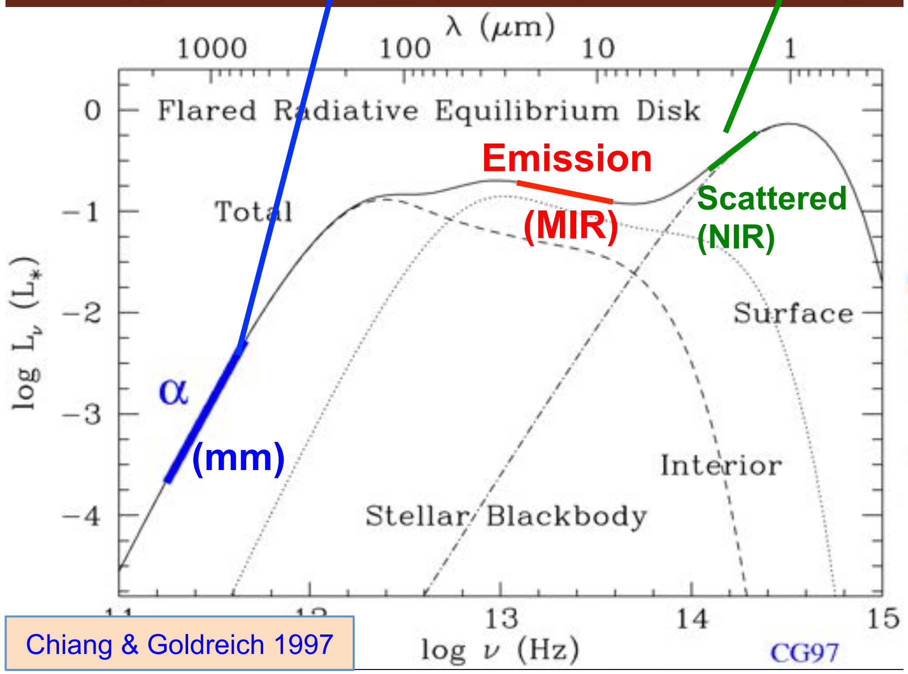
Hydrogenated amorphous carbon

Amorphous carbon

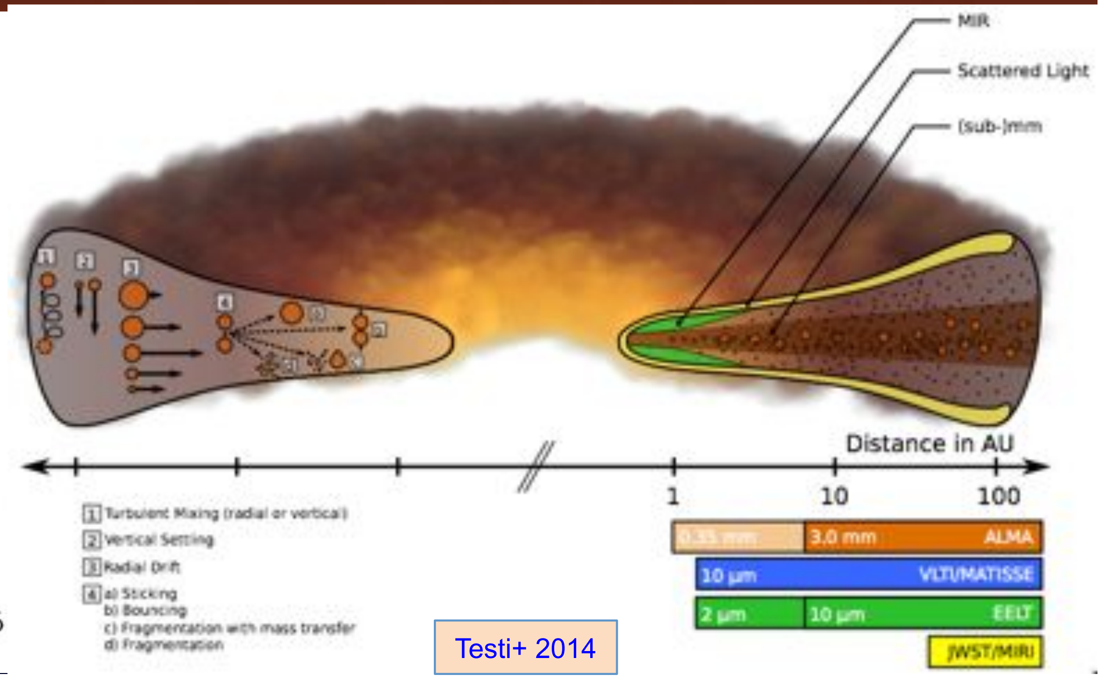




ALMA & SPHERE / ESO / Quanta 2018

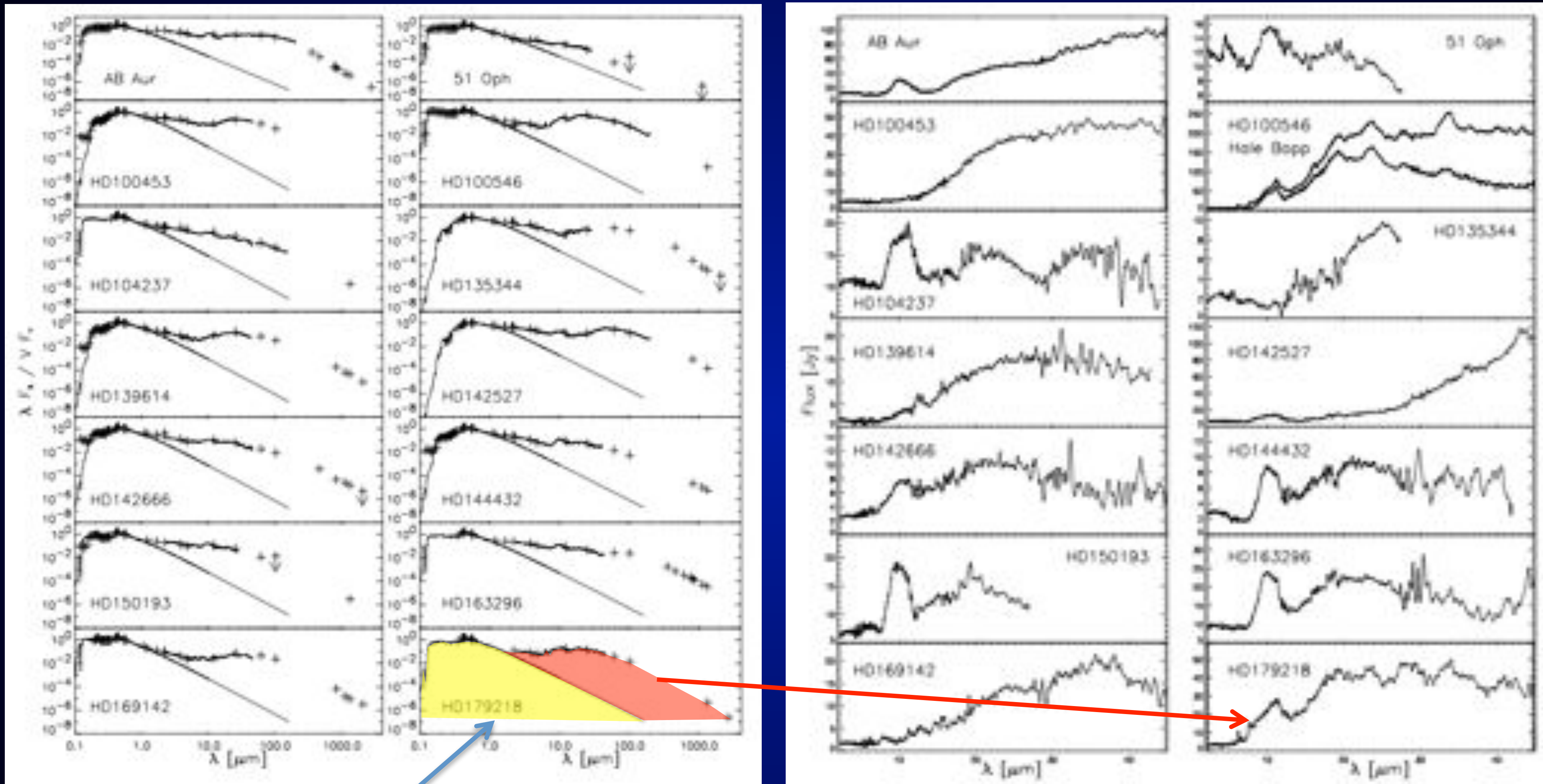


Chiang & Goldreich 1997



Testi+ 2014

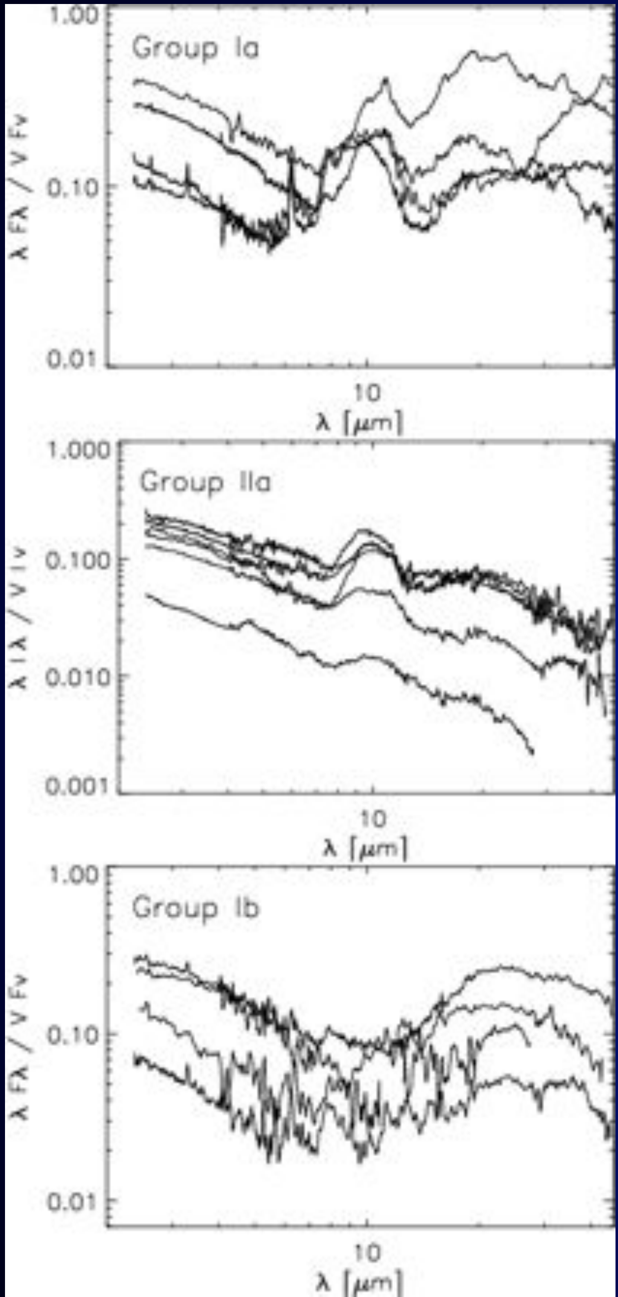
Silicates in circumstellar disks (Herbig Ae/Be)

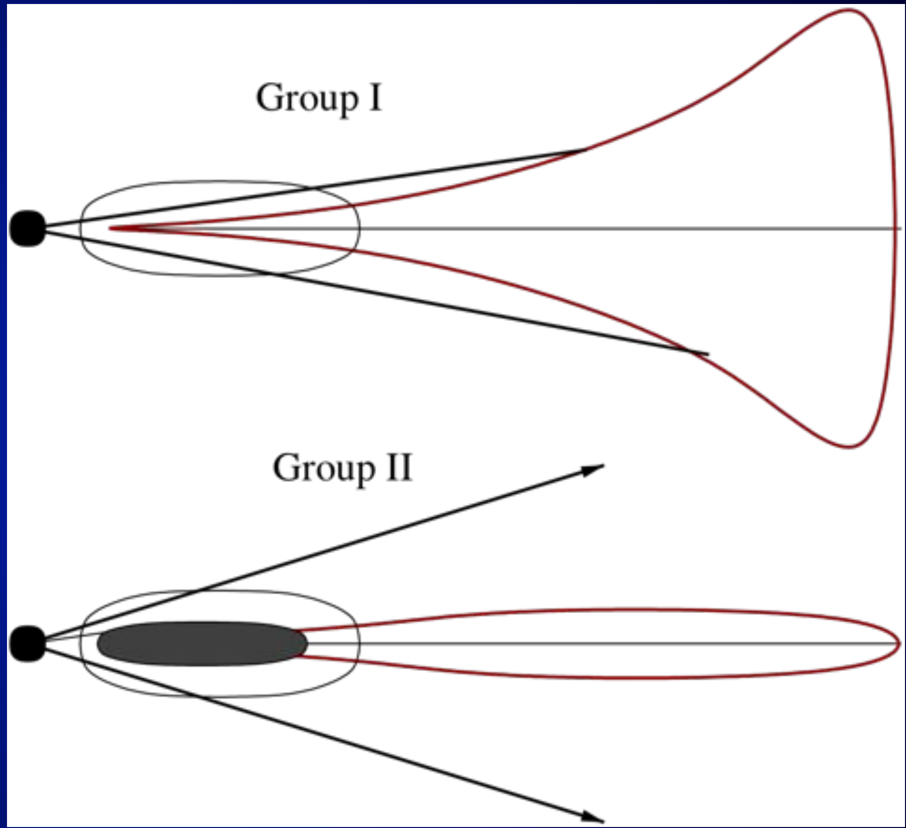


Modèle de Kurucz

Meeus et al. 2001

Silicates in disks

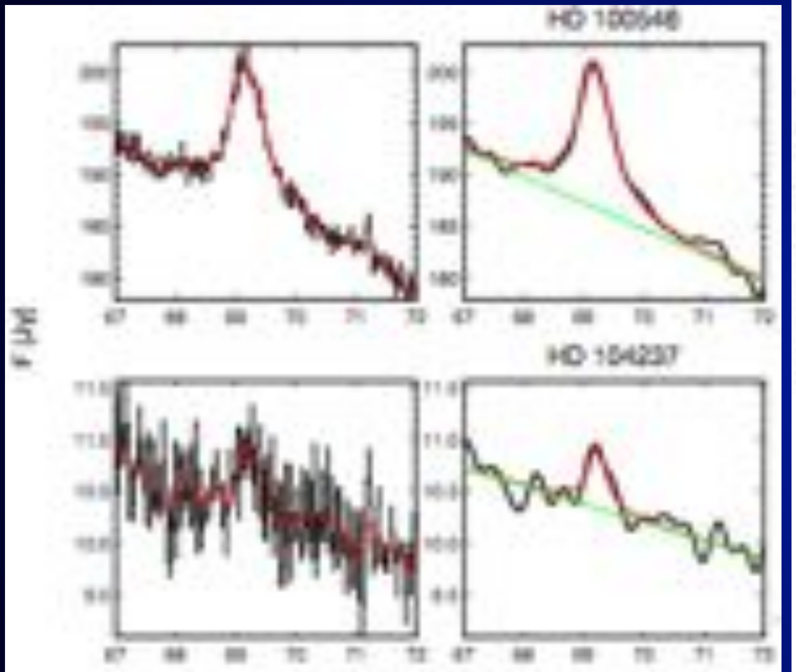




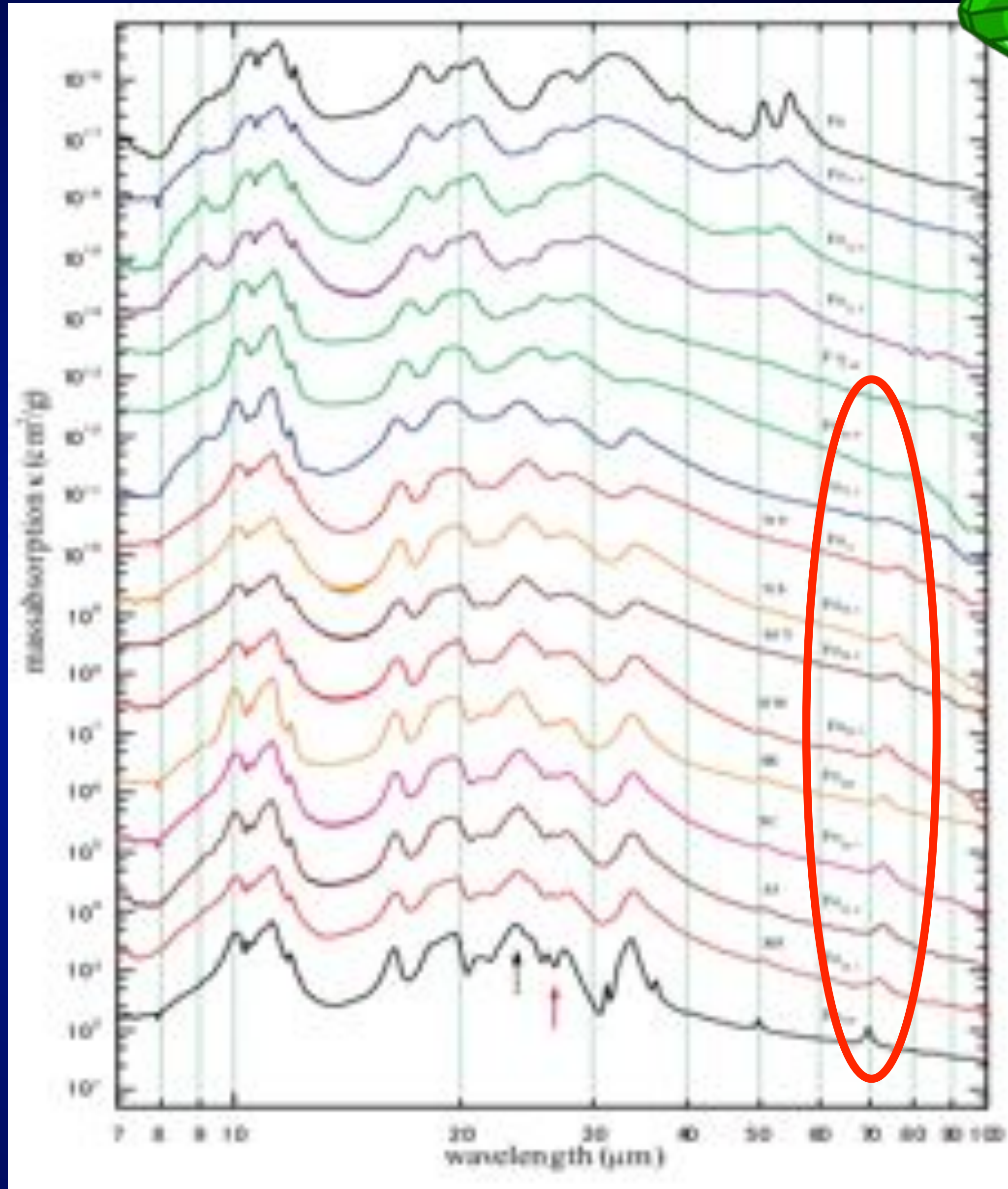
Meeus et al. 2001

Silicates in disks: Specific features

Herschel



Sturm+ 2013, Malfait+ 1998

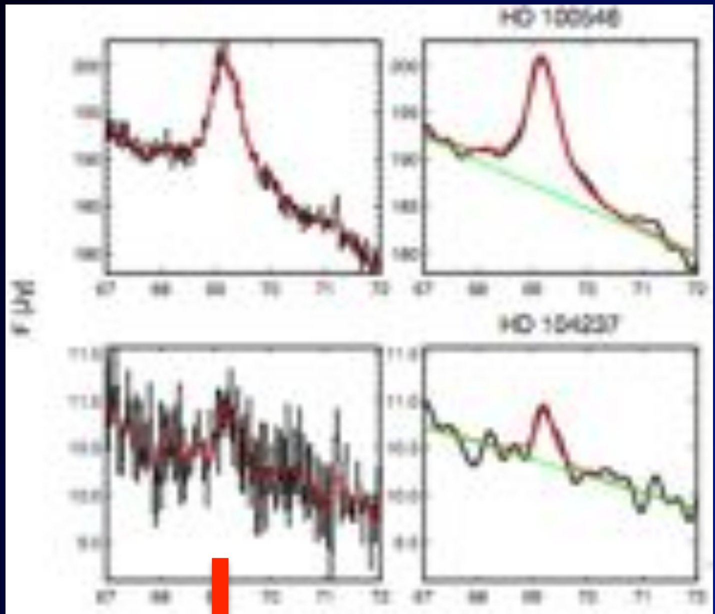


Fe content

Koike et al. 2003

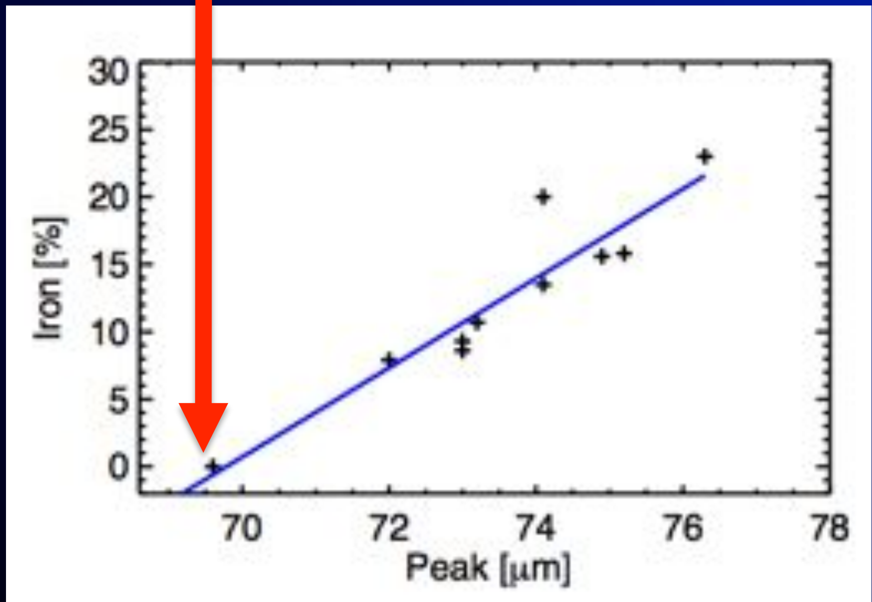
Silicates in disks

Herschel



Star	Iron fraction [%] min	max	Temperature [K] min	max	distance [AU] min	max
AB Aur	1.9	3.5	74	273	16	221
HD 100546	0.1	0.3	184	223	20	29
HD 104237	0.4	1.2	60	184	31	289
HD 141569	0.0	1.2	107	>300	<9	72
HD 179218	0.4	0.7	126	173	104	196
HD 144668	0.0	0.4	130	224	25	74
IRS 48	0.1	0.6	124	195	17	43
AS 205	0.0		121		32	

Sturm et al. 2013



32 disk sources observed.
8 sources with 69 µm olivine feature
Except 1 T Tauri star, disks associated with Herbig Ae/Be stars.
Most of the olivine grains are iron-poor less than ~2% iron (forsterite like).
AB Aur is the only source where the emission cannot be fitted with iron-free forsterite, requiring approximately 3–4% of iron.
T-position -> Iron content + location

Silicates in disks: snapshot

Bouwmann 2008

Amorphous:
- range of Mg/Si ratio's.

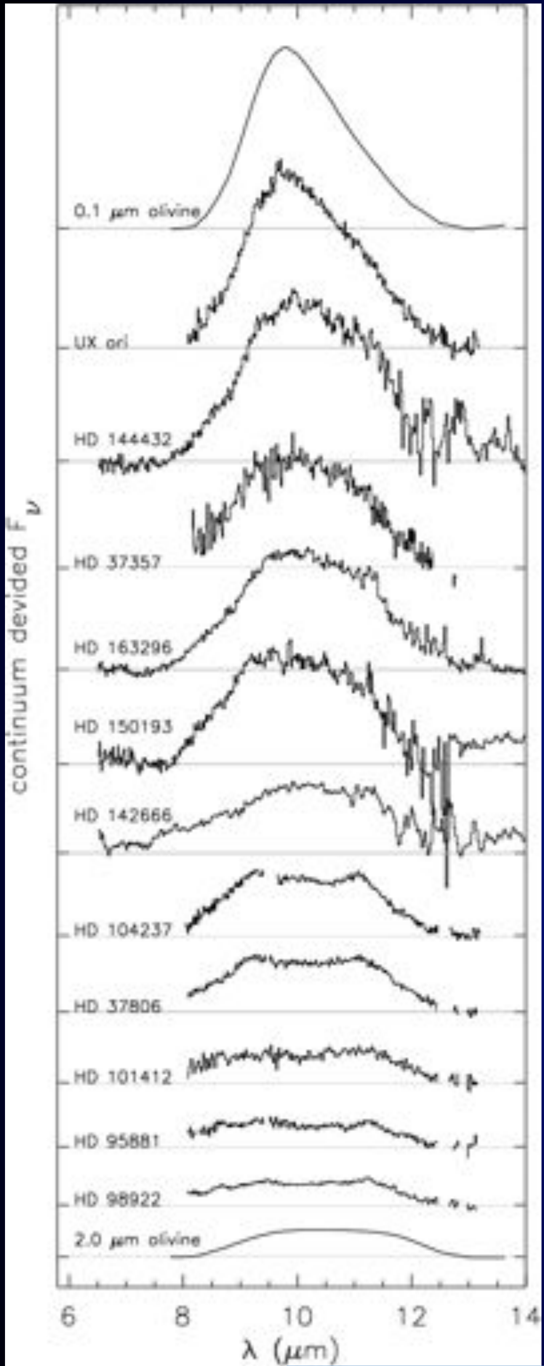
- do they contain iron ?

Crystalline:
-Olivine + Pyroxene:
dominated by Mg poles Forsterite & Enstatite

-Observed Diopside ?

-No hydrated silicates observed

- Iron remains extremely difficult to detect

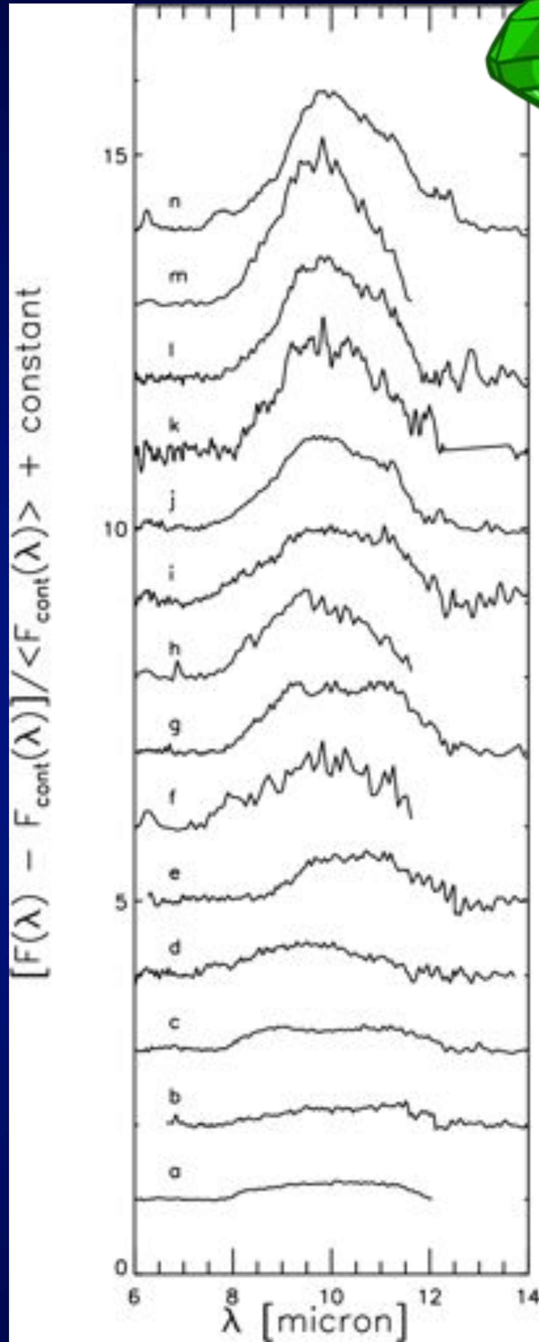


Van Boekel+ 2003

Spectral evidence of grain growth in Herbig Ae/Be

Above a few microns the grain becomes spectroscopically « like a planet » in the IR
-> mm interferometry

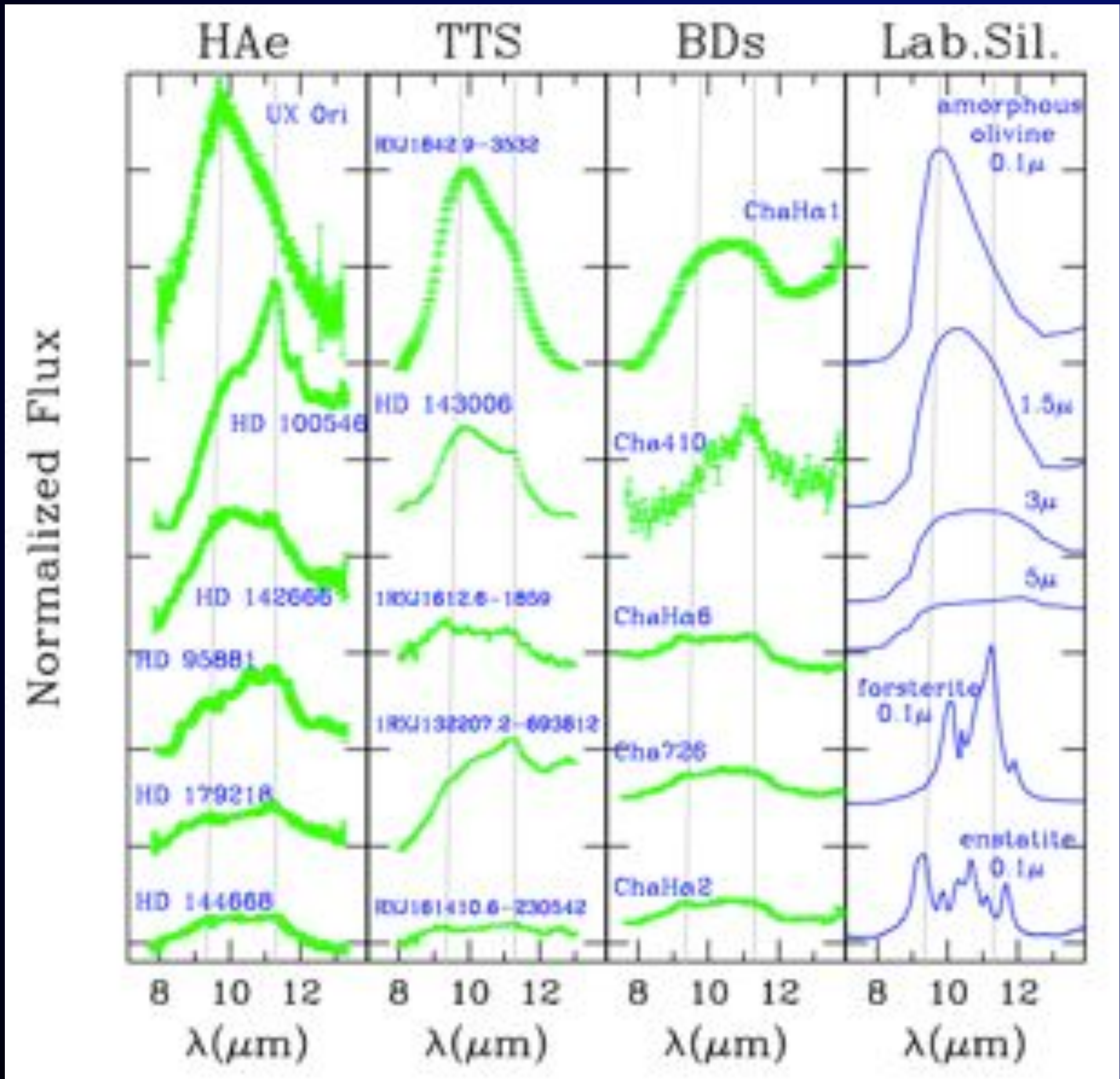
The dynamical mass in some disks imply bigger grain sizes



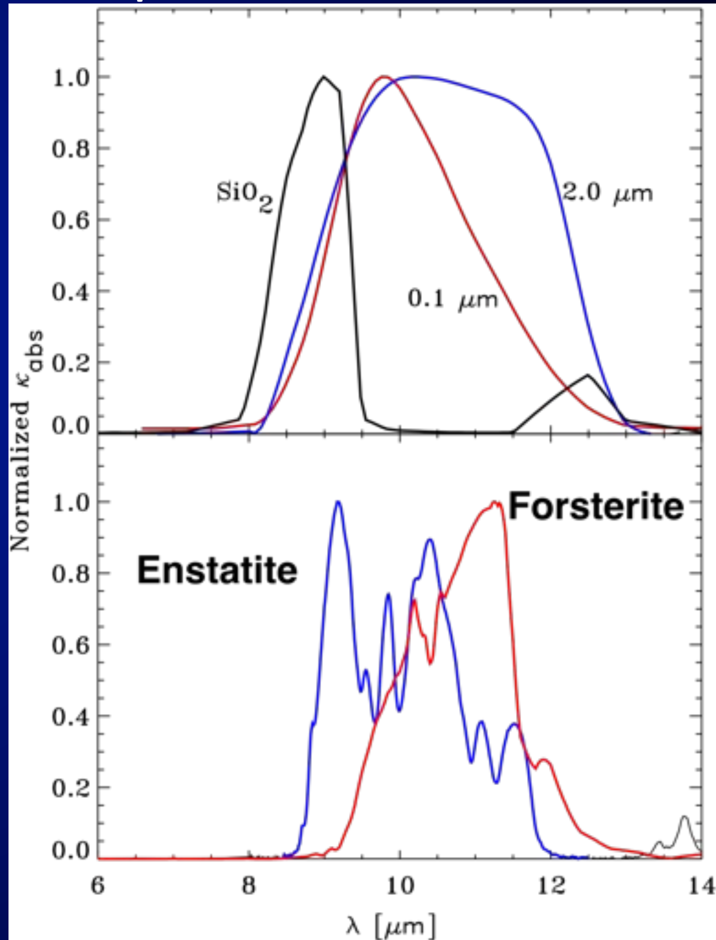
Acke & van den Ancker 2004

Extracting properties:

Several components:
- χ composition (mineralogy)
- Size/shape effects
- Phase (am./cryst.)
- Temperature

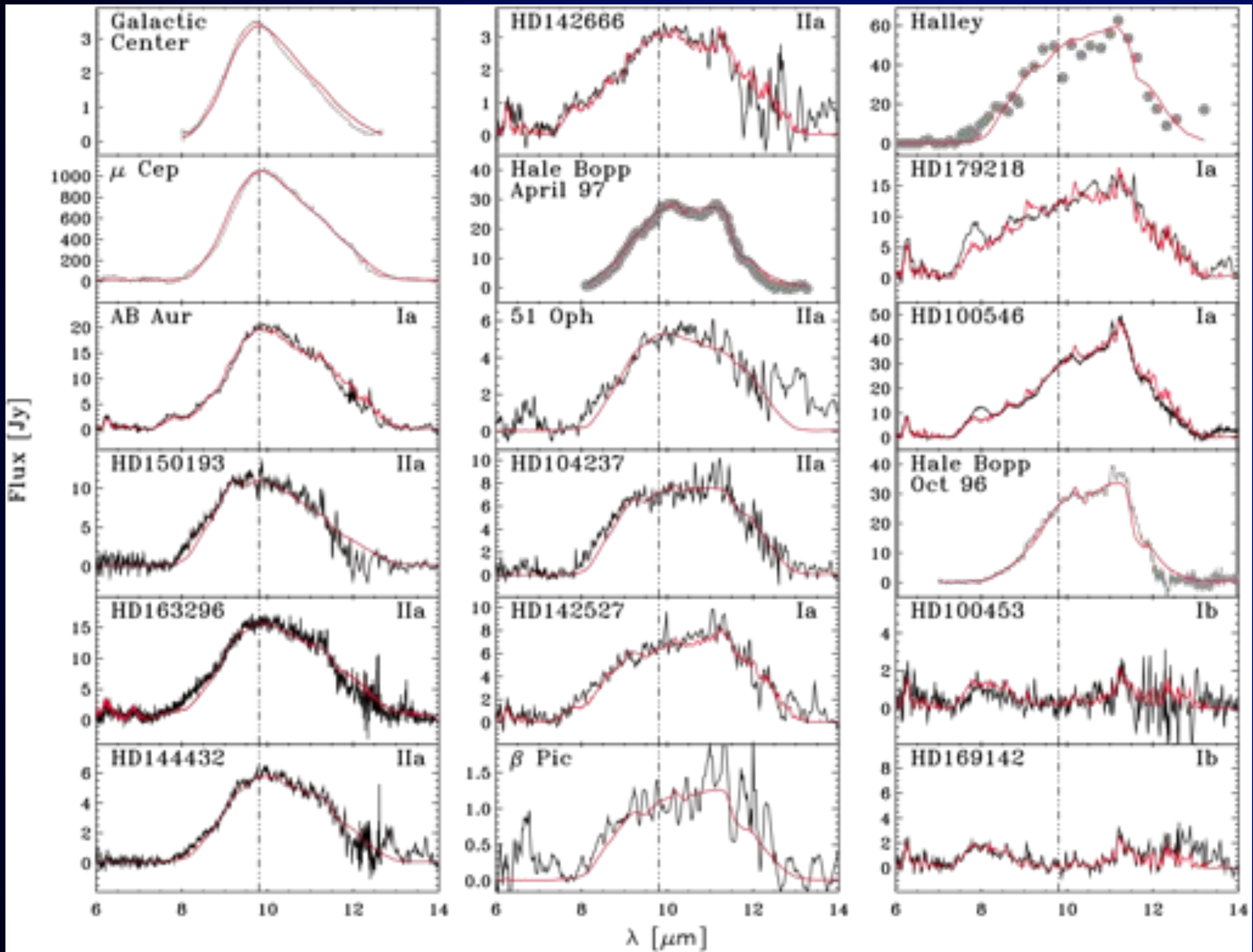


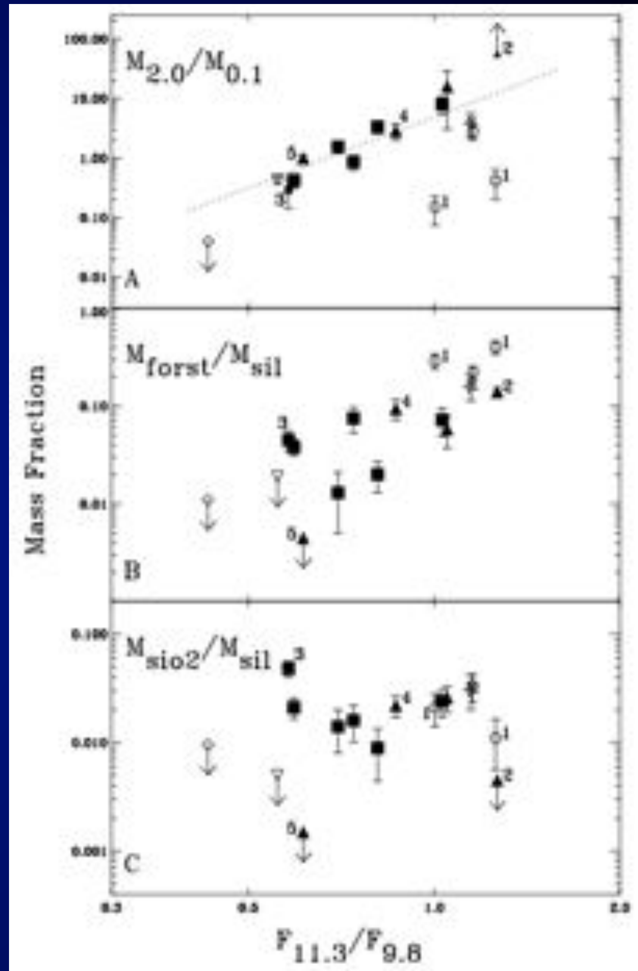
Natta+2006



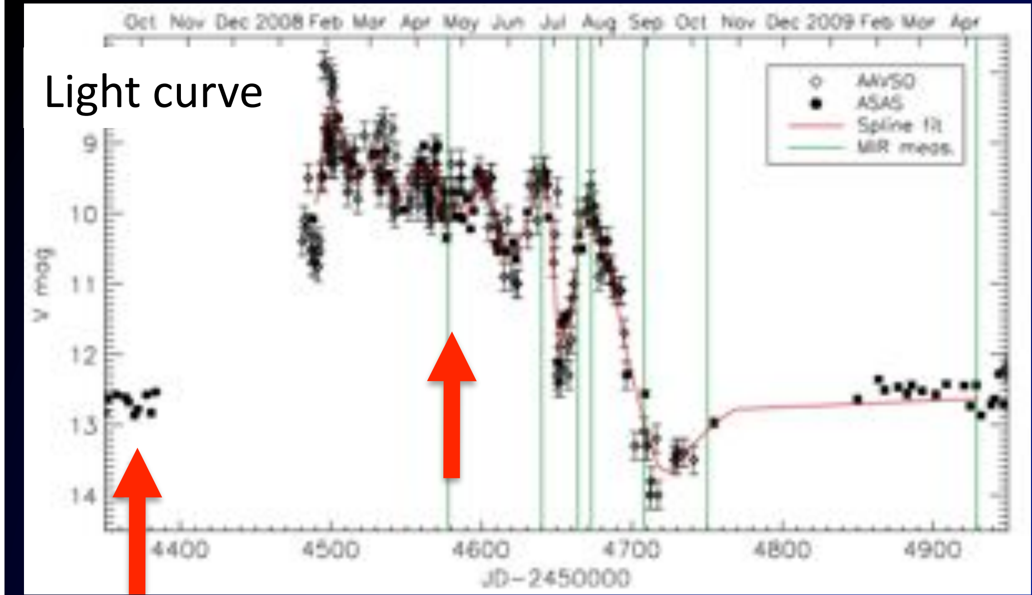
Bouwman et al. 2001

Spectral fit to extract correlations



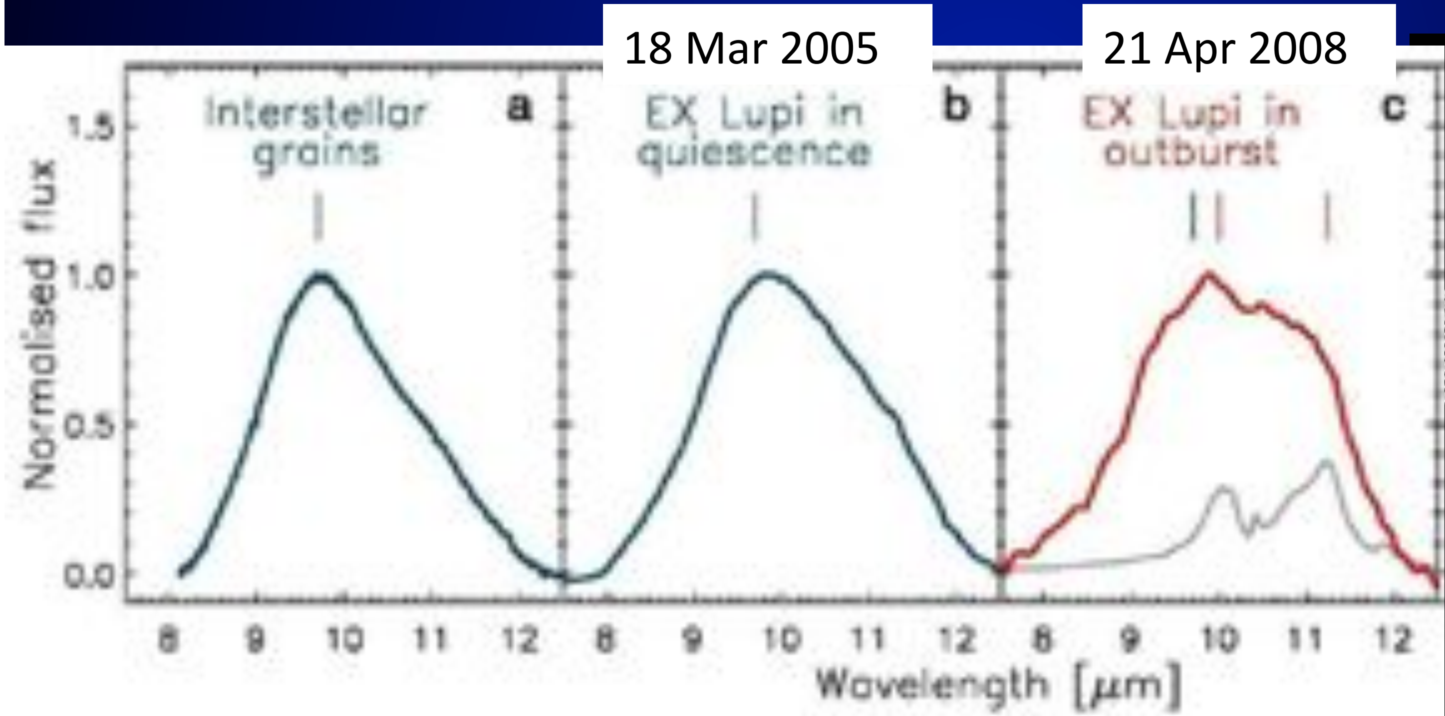


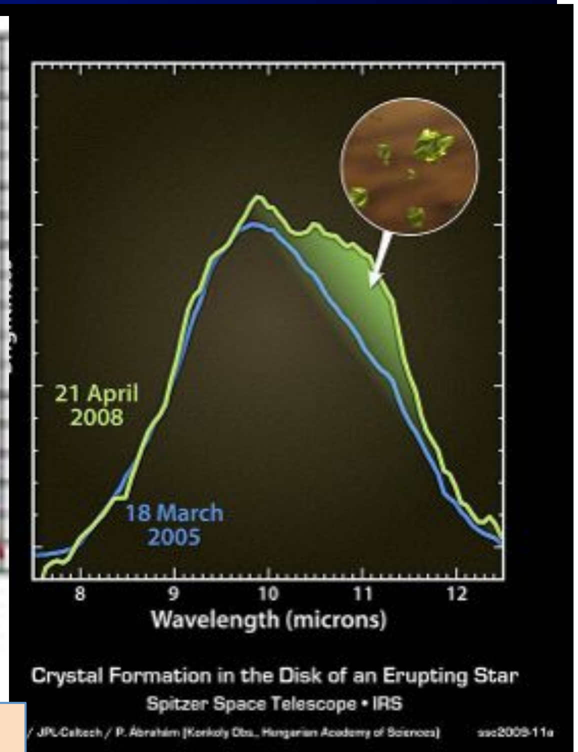
Bouwman et al. 2001



Special events formation around stars:

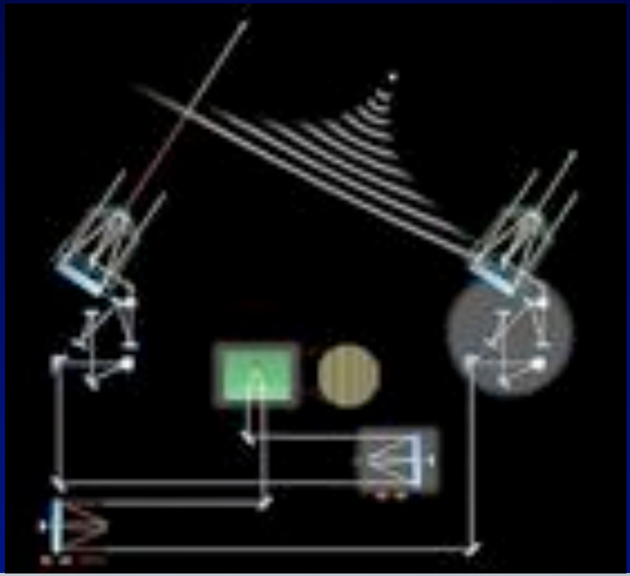
Formation in outburst of EX Lup (eruptive young star):
silicate crystals in motion

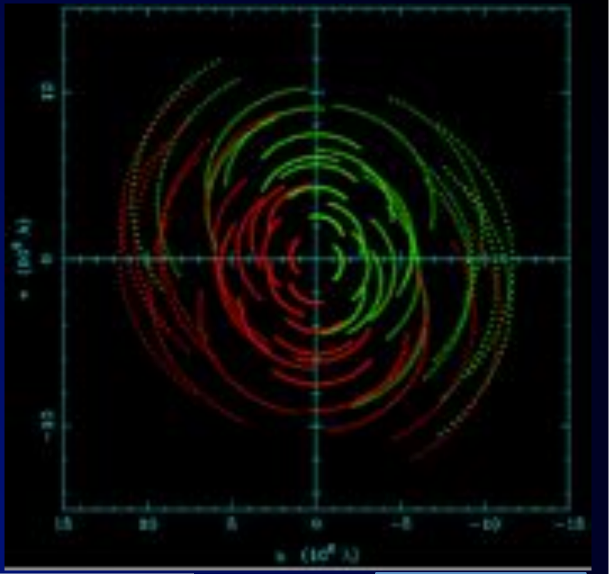




Abraham+2009, Juhasz et al. 2010, Audard+2014

IR Interferometry : silicates in disks



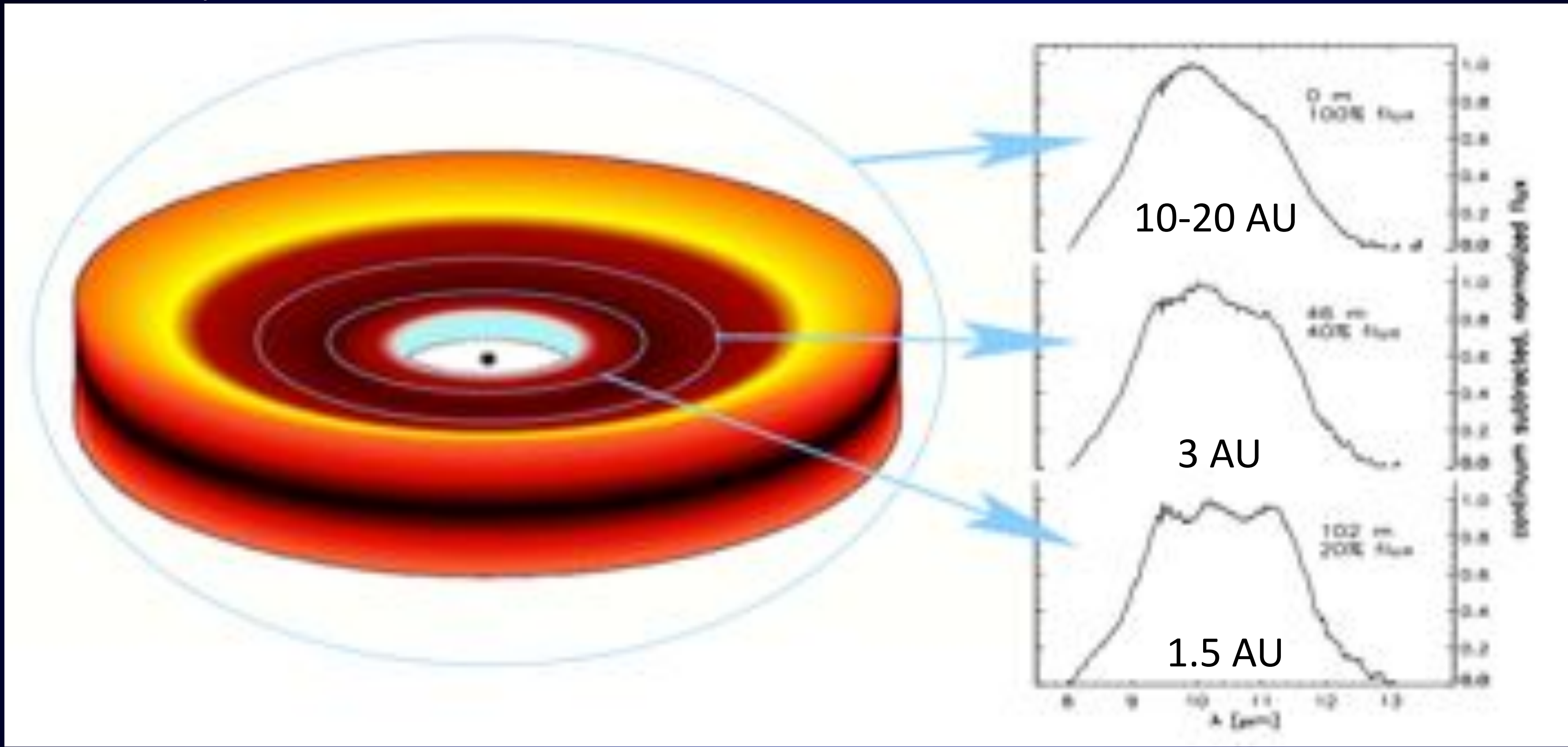


Haniff 2010

VLTI / ESO

IR Interferometry : silicates in Herbig Ae Be

HD 144432/ MIDI on different baselines



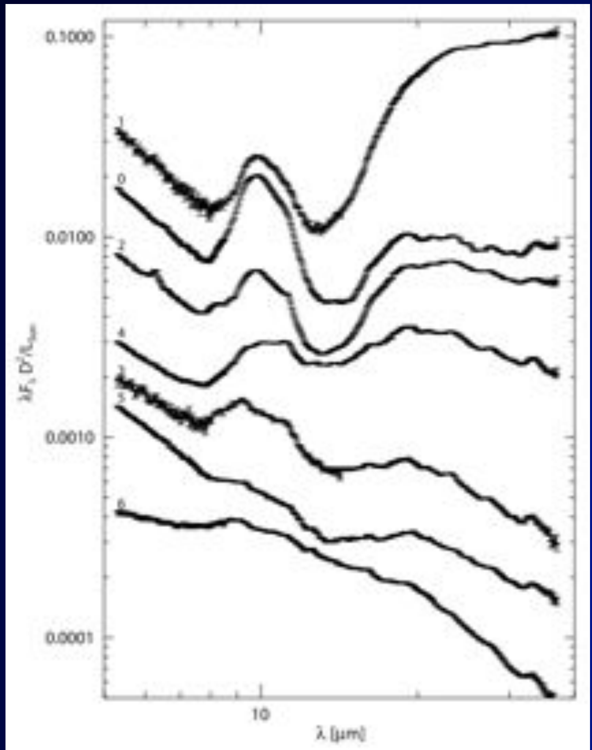
van Boekel+2010

Crystallinity and average grain size in disk surface layer decrease with distance to star

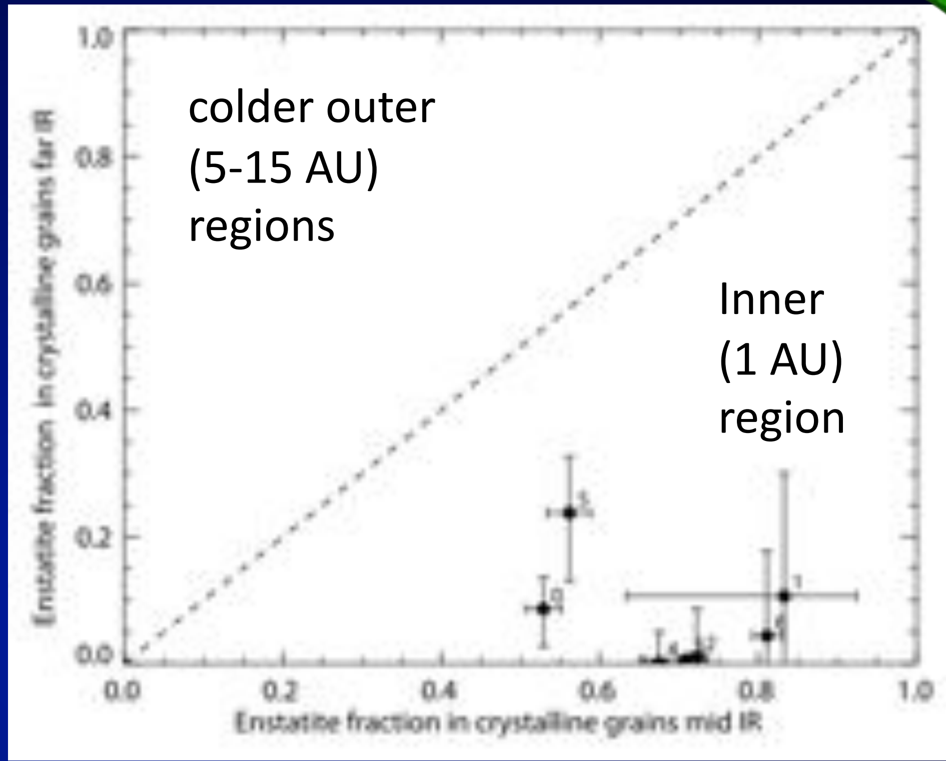
A chemical gradient in the composition of the crystals:
forsterite dominated spectrum closest to the star &more enstatite at larger radii.

Support the radial mixing scenario for the origin of crystalline silicates?

Silicates in T Tauri



enstatite mass fraction of crystalline silicates



Species	State	Chemical Formula
Amorphous silicate (Olivine stoichiometry)	A	$MgFeSiO_4$
Amorphous silicate (Pyroxene stoichiometry)	A	$MgFeSi_2O_6$
Forsterite	C	Mg_2SiO_4
Clino Enstatite	C	$MgSiO_3$
Silica	A	SiO_2

Bouwman et al. 2008

size of the enstatite grains (1 μm) larger than forsterite grains (0.1 μm)
mass fraction: larger enstatite fraction in warmer inner disk than colder outer
Enstatite inner / Forsterite outer
No strong radial mixing at this stage ?

Influence of size increase in the mm:

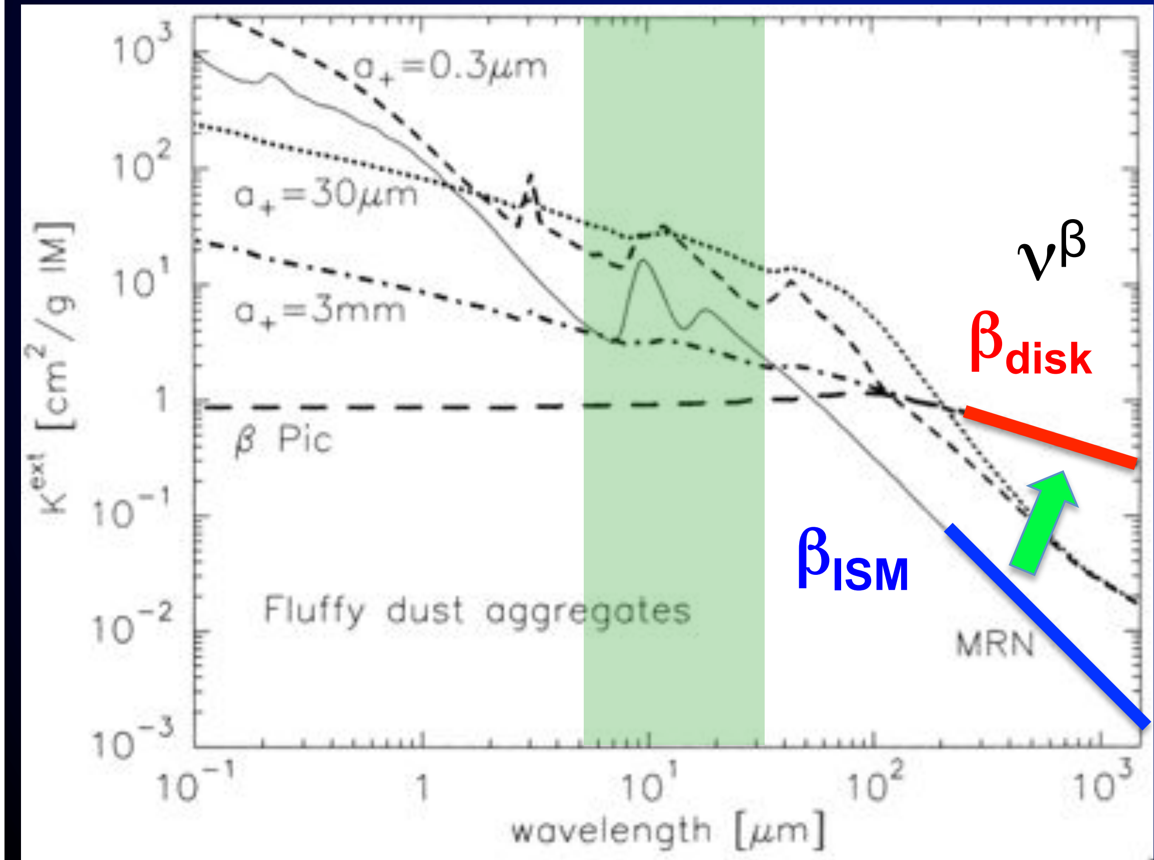
Flux received from a disk

Optically thin: $F(\nu) \propto \kappa(\nu)[cm^2.g^{-1}]\, B_\nu\, (T_{dust})\, M_{dust} / d^2$

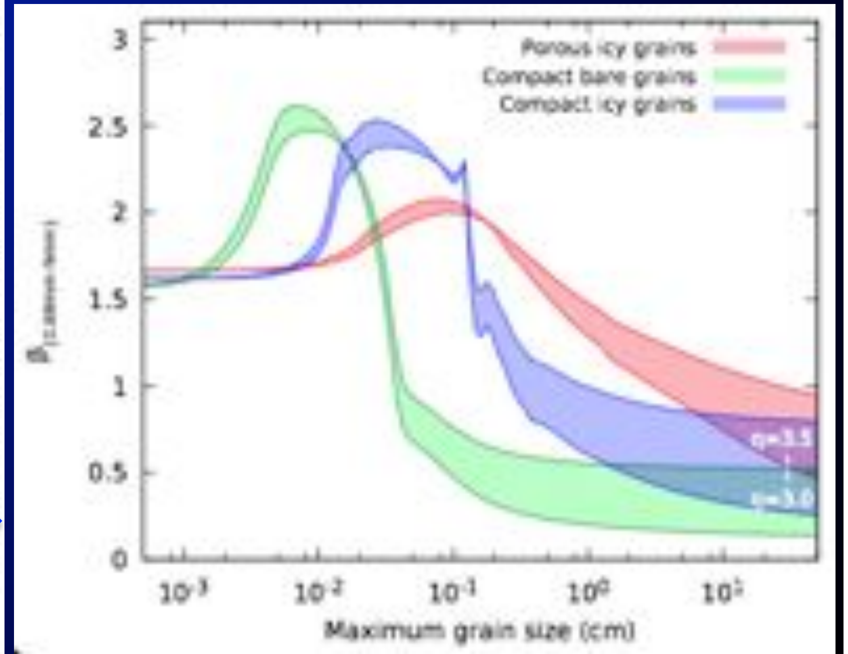
Rayleigh-Jeans limit : $F(\nu) \propto \nu^2\, \kappa(\nu)[cm^2.g^{-1}]\, T_{dust}\, M_{dust} / d^2$

Outside the solid material strong absorption bands If $\kappa(\nu) \propto \nu^\beta$ then $F(\nu) \propto \nu^{\beta+2}$

The β of dust can be infered from the observed flux slope minus 2.



Krugel & Siebenmorgen 1994



Testi et al. 2014

Influence of size increase in the mm:

Flux received from a disk

Optically thin: $F(\nu) \propto \kappa(\nu)[cm^2.g^{-1}]\, B_\nu\, (T_{dust})\, M_{dust} / d^2$

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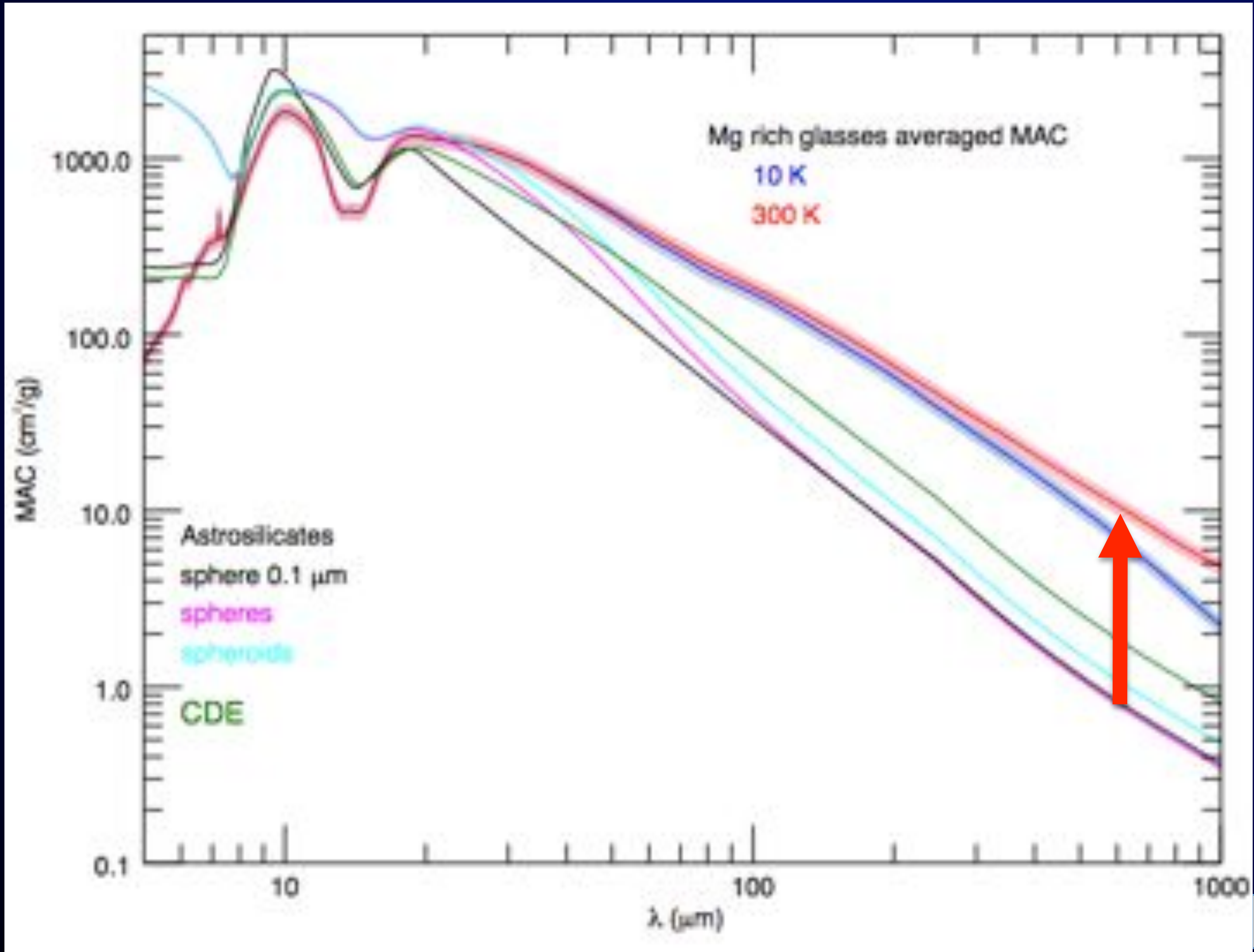
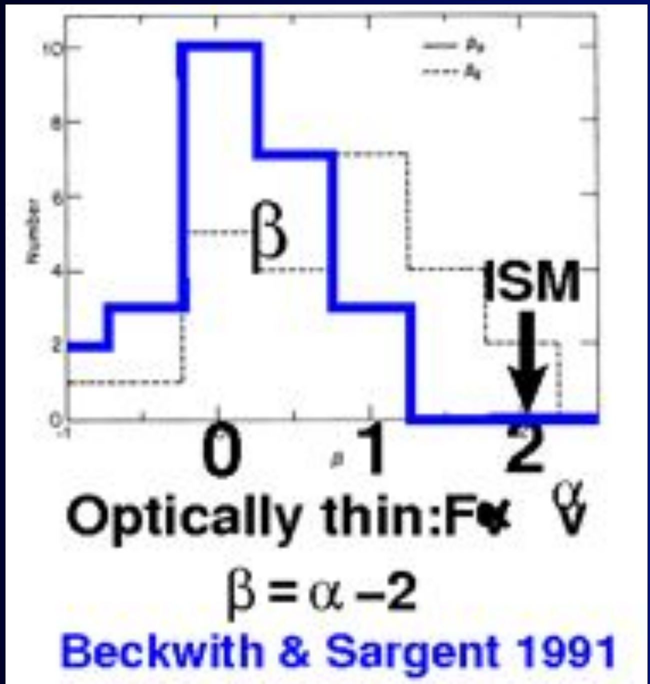


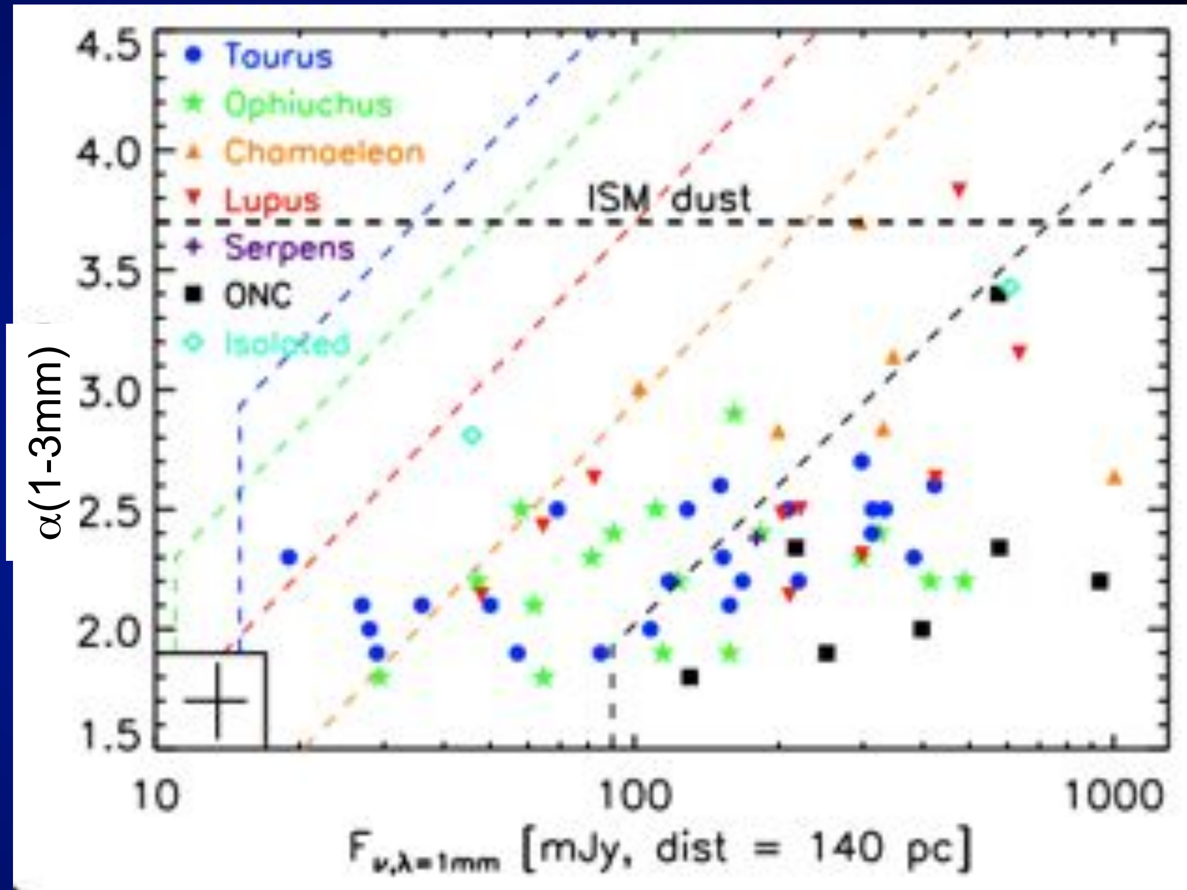
Masses overestimated by models ?

Demyk+2017

Dust in circumstellar disks (mm) : index change

$\alpha=\beta+2$



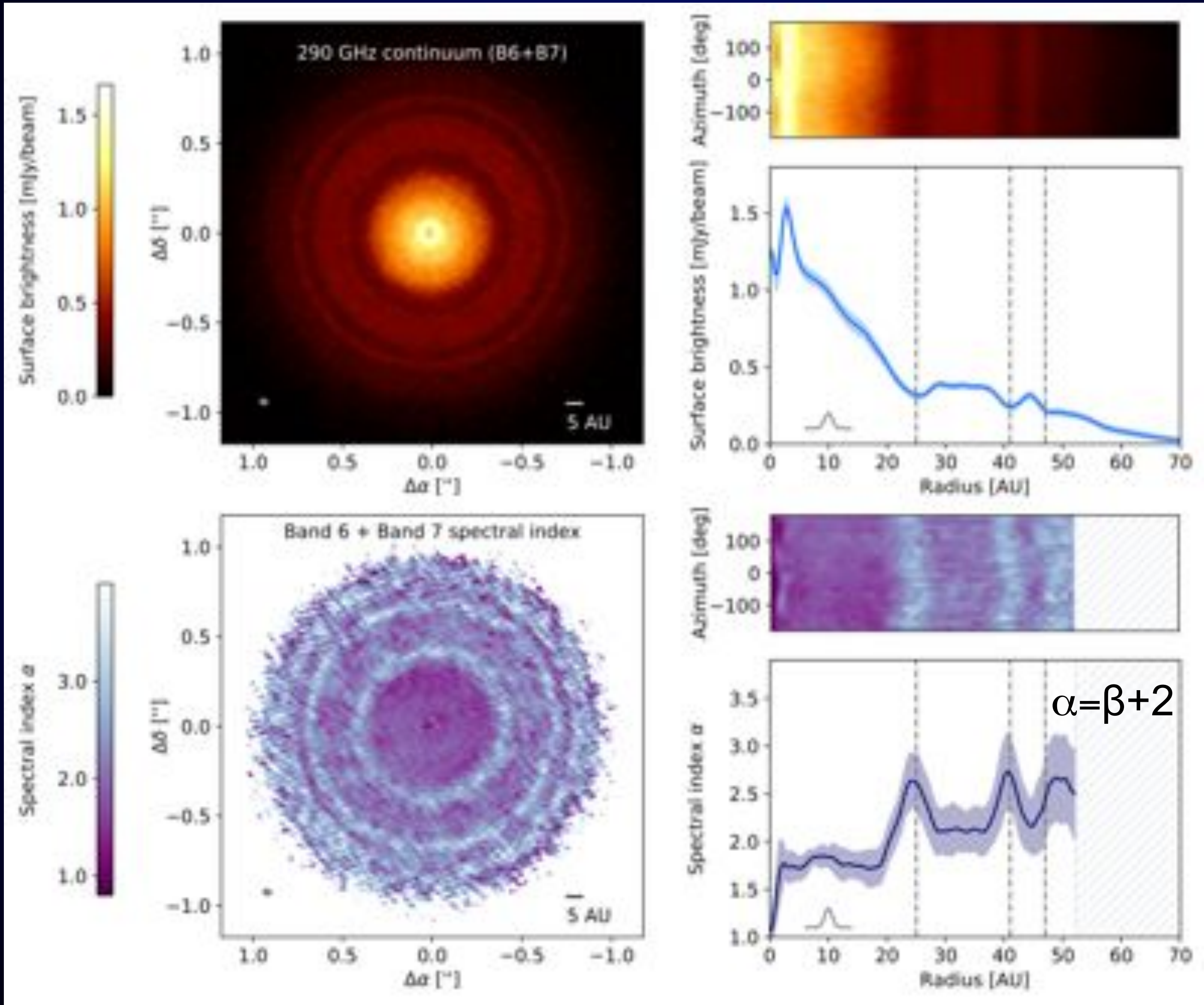


Testi et al. 2014

outer disk regions appears to have grown to sizes of at least 1 mm

The dynamical mass requires change in mass absorption coefficient otherwise unstable disks

Dust in circumstellar disks (mm) : radial index change



Huang+2018

AIBs

Detection rates in disks

Acke + 2011

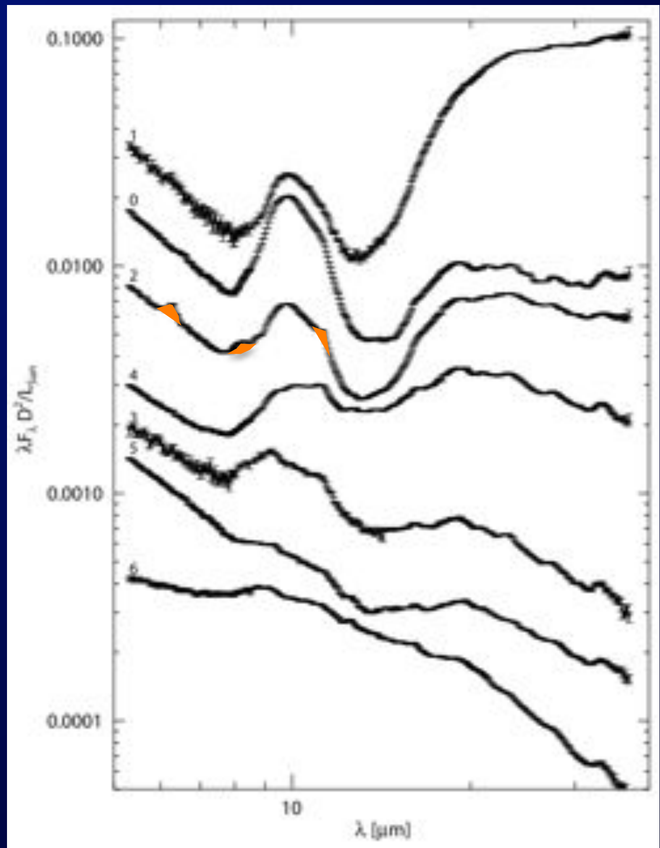
T Tauri stars

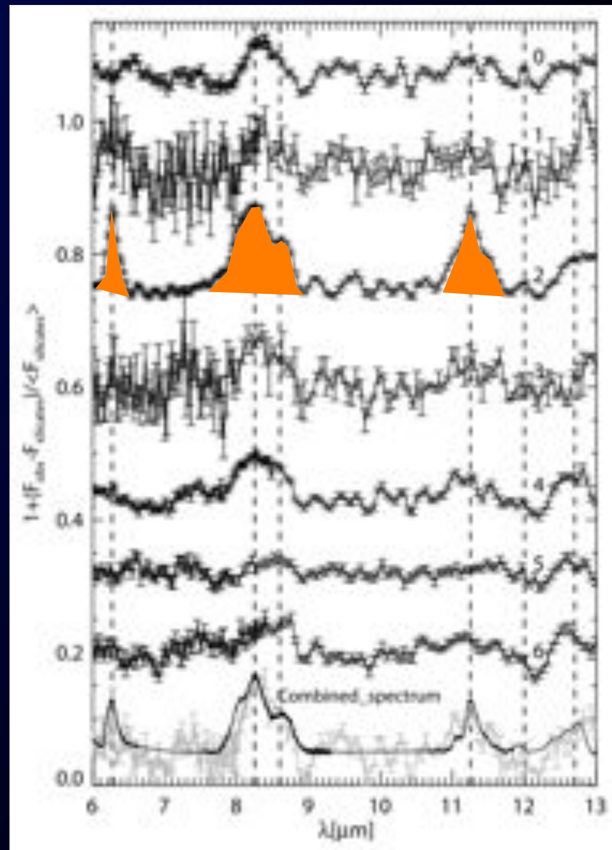
11–14% (/37), with no detections for stars with spectral type later than G8 — Geers+ 2007

3–4% in Taurus and Serpens star-forming regions — Furlan+ 2006, Oliveira+2010

Features are weak wrto continuum and silicate emission, and more class C like, thus more difficult to detect.

Bouwman+ 2008





Carriers 10–100 times lower than ISM ?

The high T Tauri X-ray luminosities have been invoked to explain this deficiency

AIBs

Herbig Ae/Be stars

Highest detection rate in Ae (~70%)

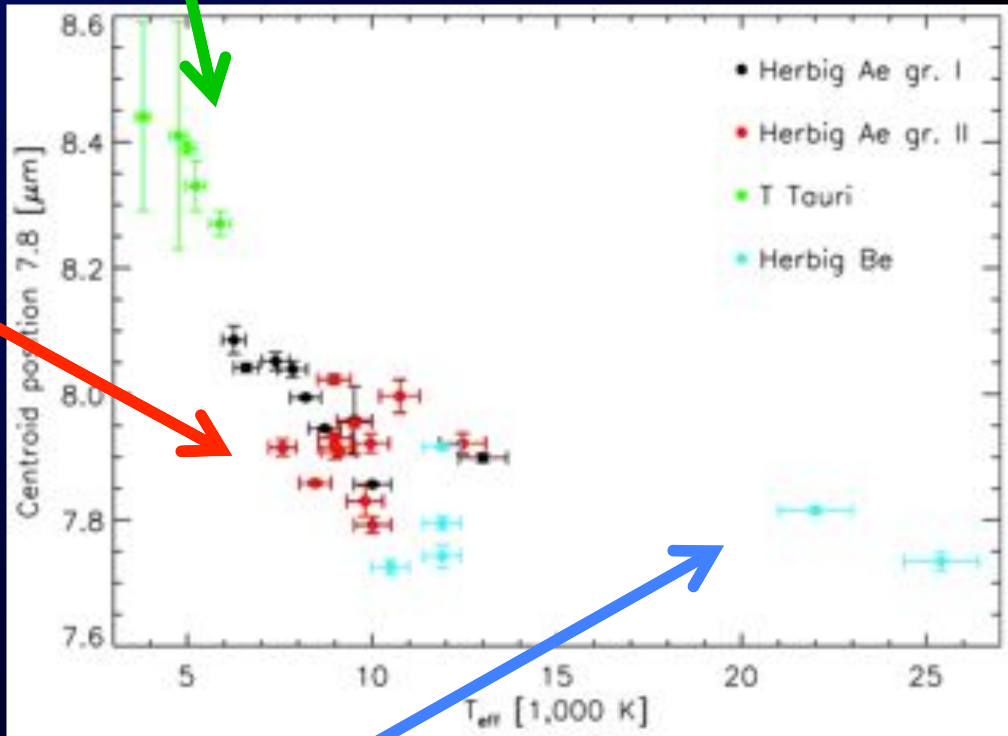
~50% in Be, but confusion with enveloppe/cloud

Acke & van den Ancker 2004, Acke+2010

Spectral evolution of the AIB class among the T.Tauri to Herbig objects

T.Tauri

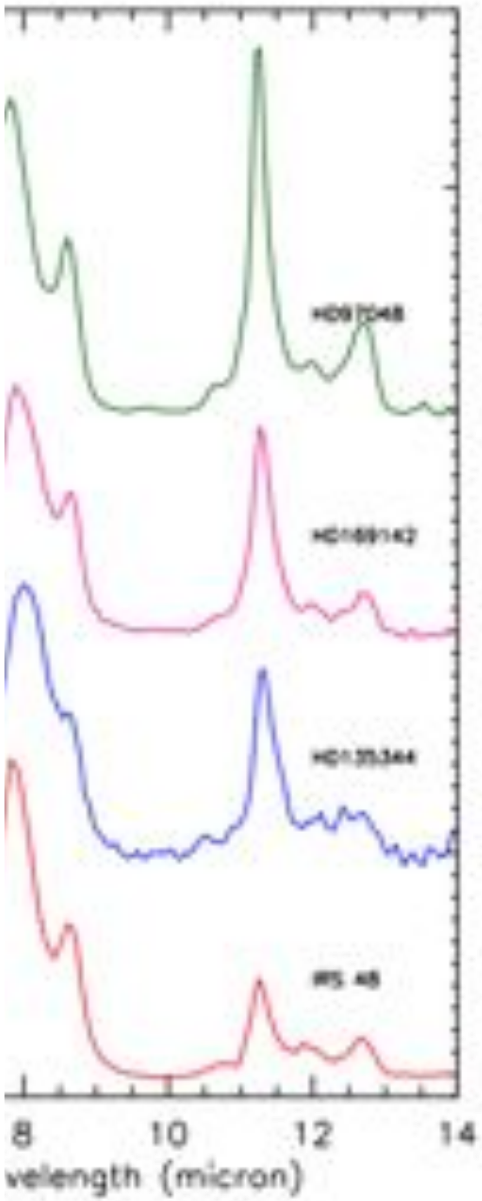
Herbig Ae

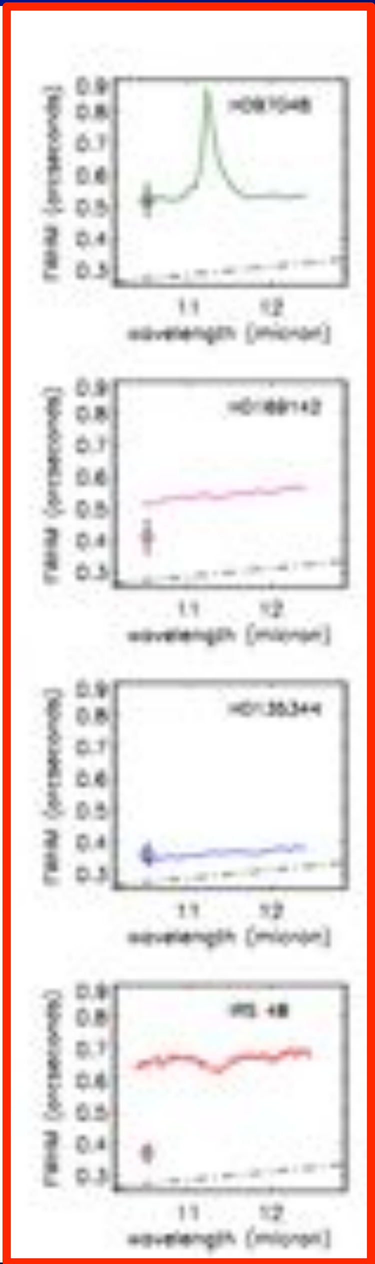


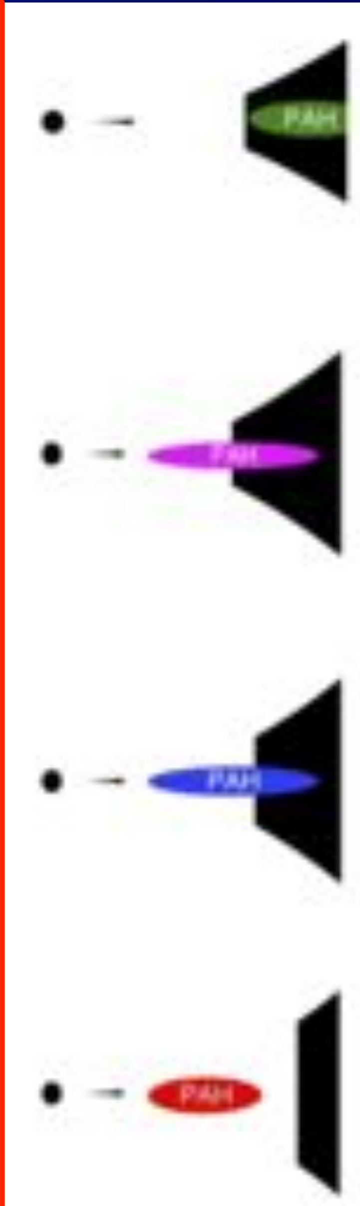
Herbig Be

Acke+ 2010

AIBs Spatial information



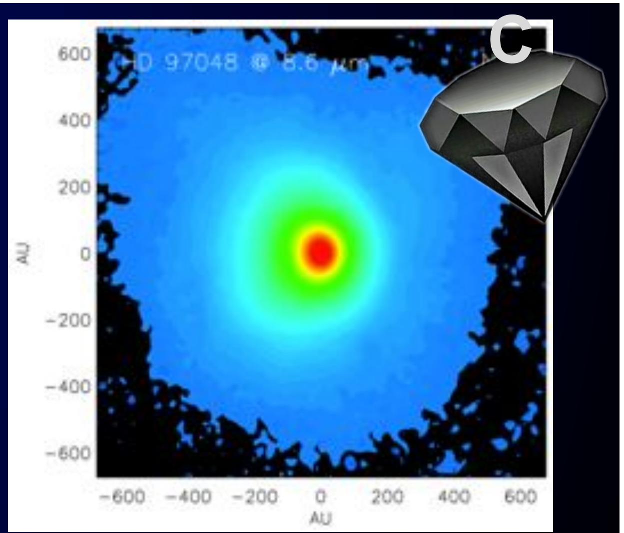




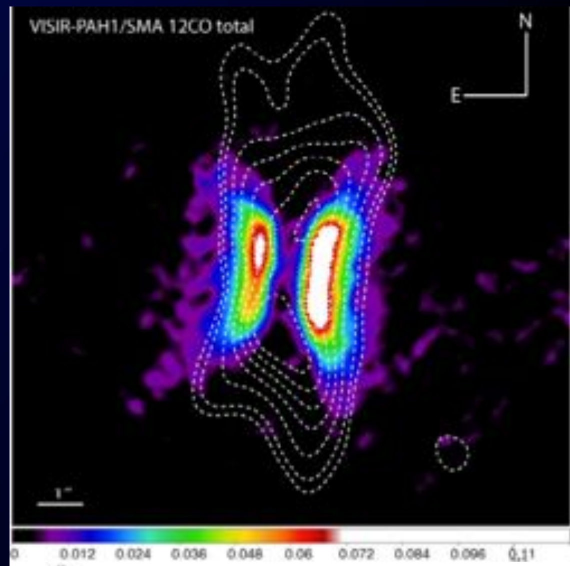
Maaskant+ 2014

Taha+ 2017

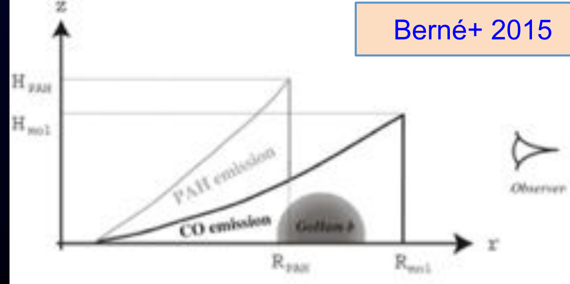
PAH 8.6 / HD 97048



Lagage+ 2006

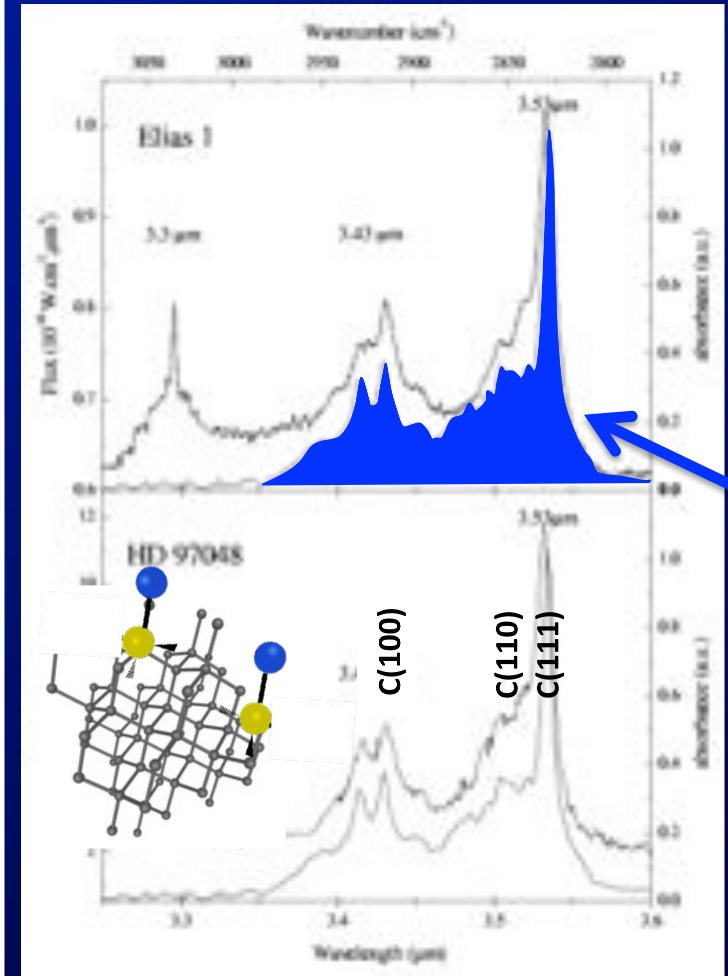


Berné+ 2015

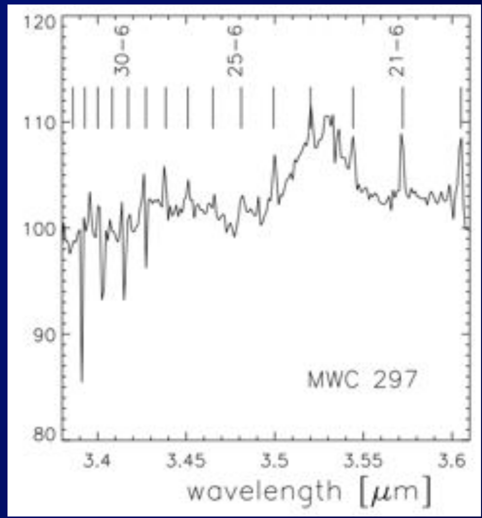


Nano-diamonds

Herbig Ae/Be stars

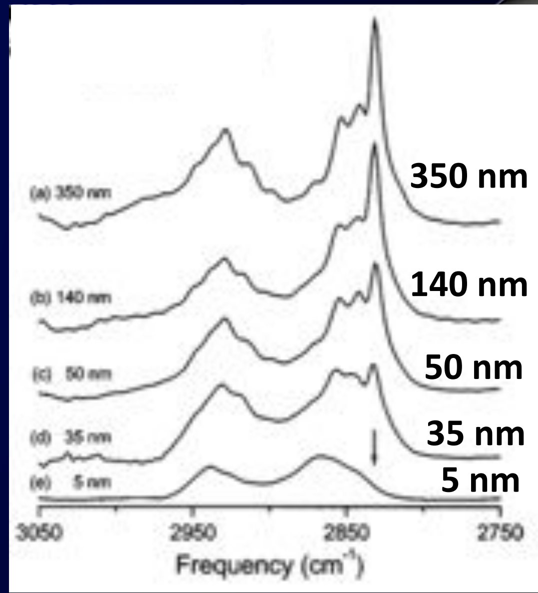


Guillois+1999, Chen+ 2003 Chang+ 1995



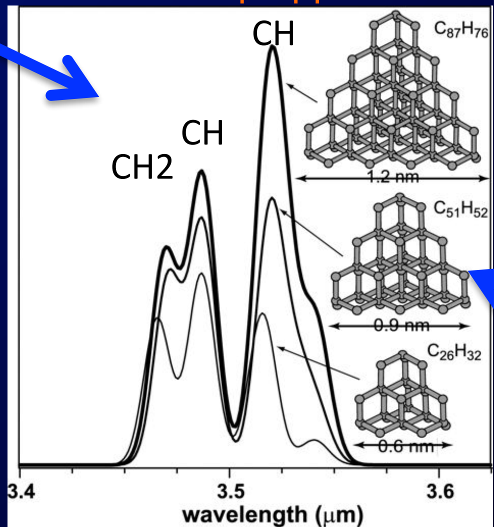
Acke+ 2007

Lab Top down approach > 35nm

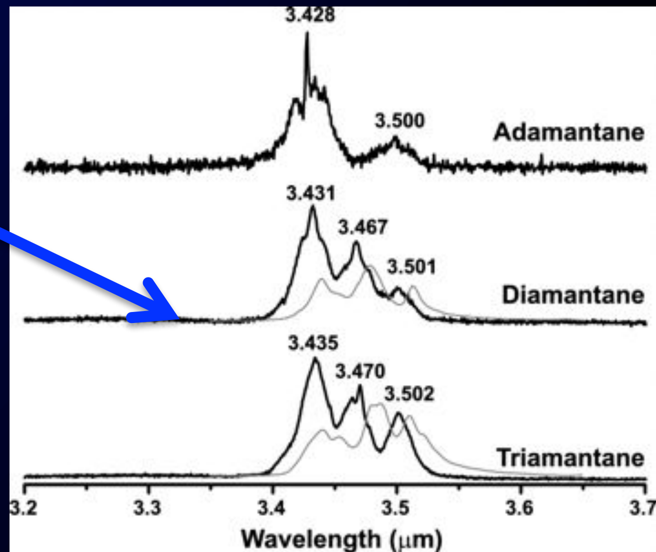


Chen+2003

Lab Bottom up approach ~ 130 C



size dependence



Pirali+ 2007

Jones & d'Hendecourt 2000; Van Kerckhoven+2002, Chen+2003, Jones+2004

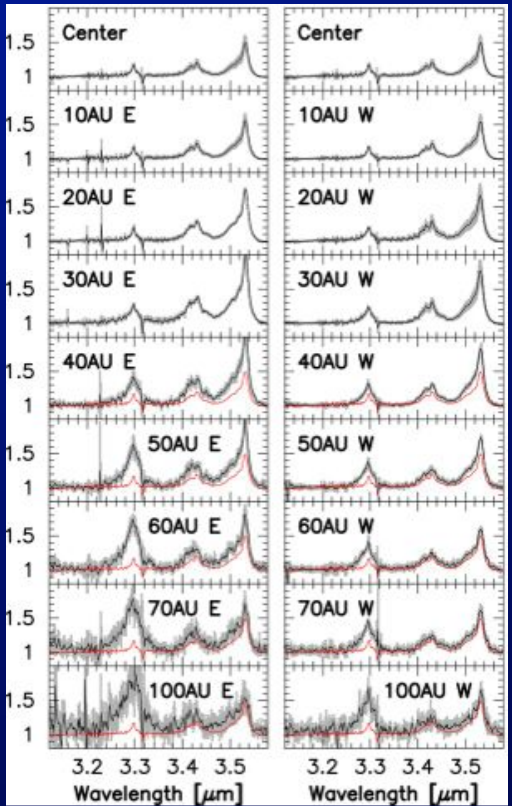
Nanodiamond approach : Non relaxed surface for nanodiamonds < 35nm

Molecular approach : Observed I(3.53μm/3.43μm) = analogues around 130 C atoms

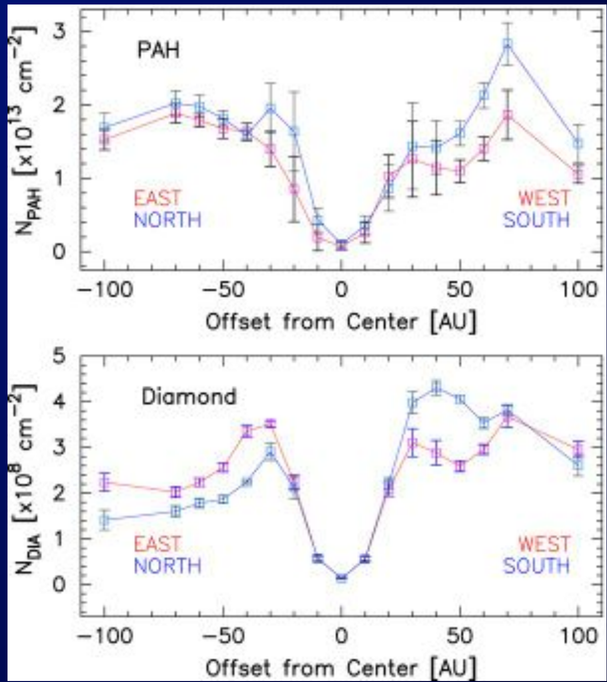
Nano-diamonds: resolved observations

Herbig Ae/Be stars

Observed close to the star

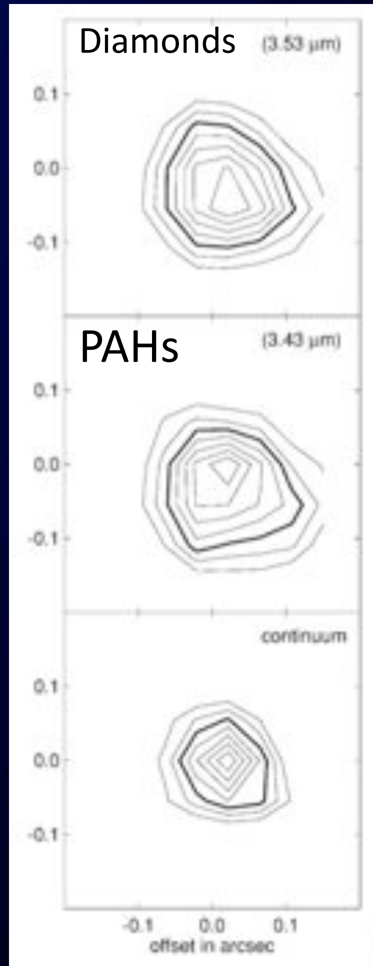


Elias 3-1

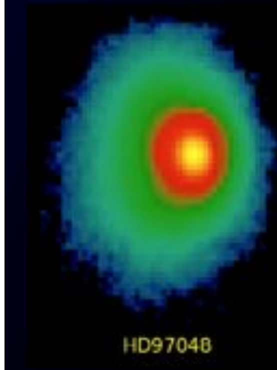


Goto et al. ApJ 2009

HD 97048



Habart+ 2004, 2006



Doucet+ 2007

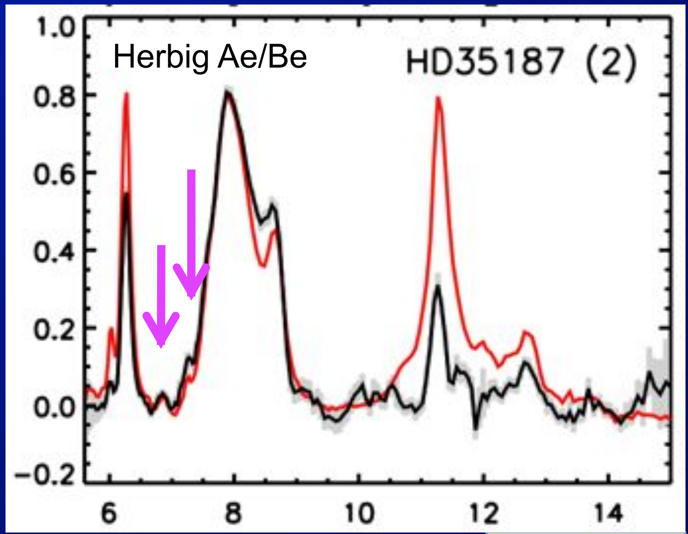
- Survey of 30 Herbig Ae/Be stars

Acke et al. A&A 2006

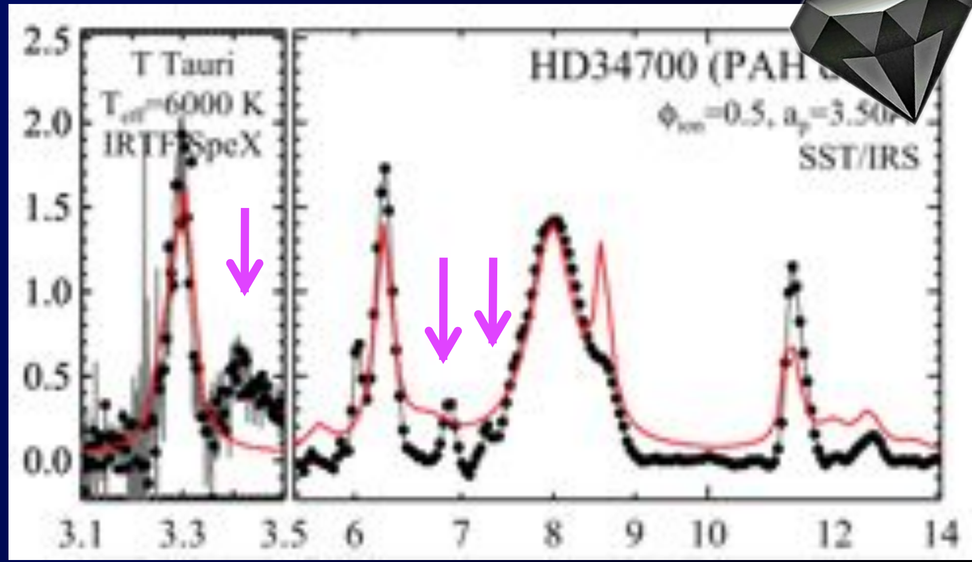
< 4% of the targets with characteristic emission @3.43 and/or 3.53 μm

“Aliphatics”

Detection rate in Herbigs (~50%) and in few TTauri

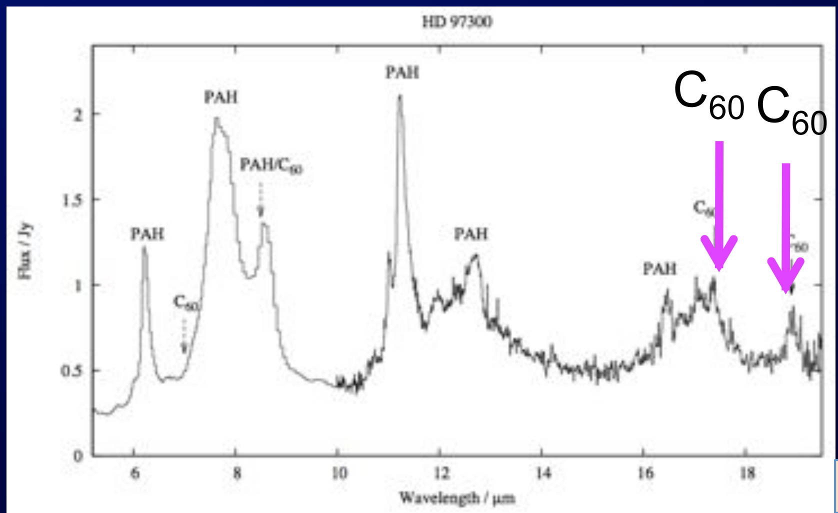


Acke+ 2010



3.4 detection difficult, but clear detections

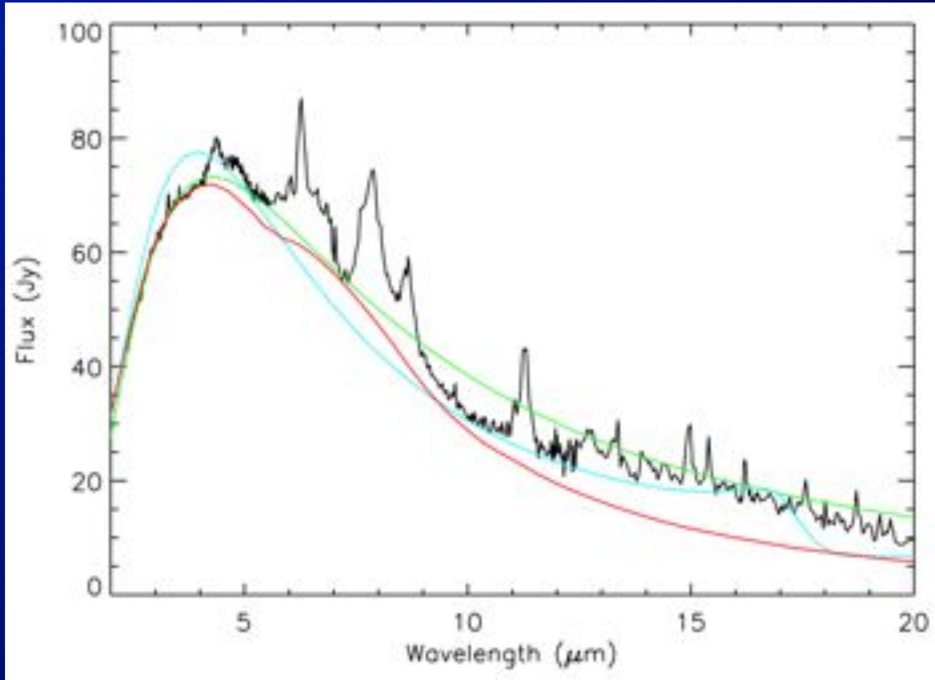
Fullerene



Roberts+2012

Detection reported in an Herbig Ae/Be

Amorphous carbon (a-C / carbonaceous VSG)

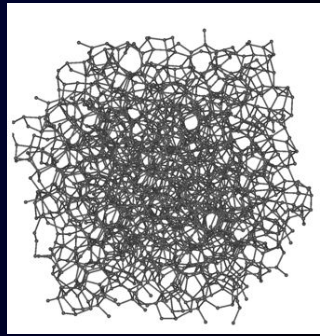


Provide featureless continuum emission in circumbinary disk HR4049

Acke + 2013

Invoked in disk modeling

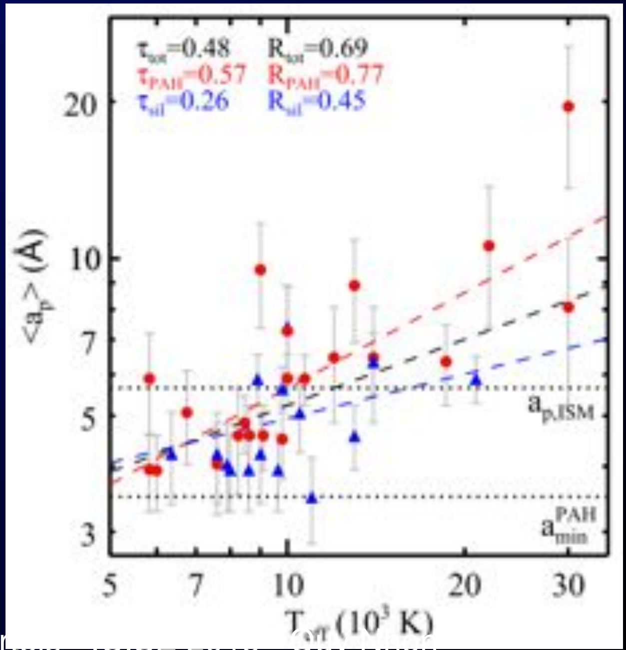
e.g. Schworer+ 2017



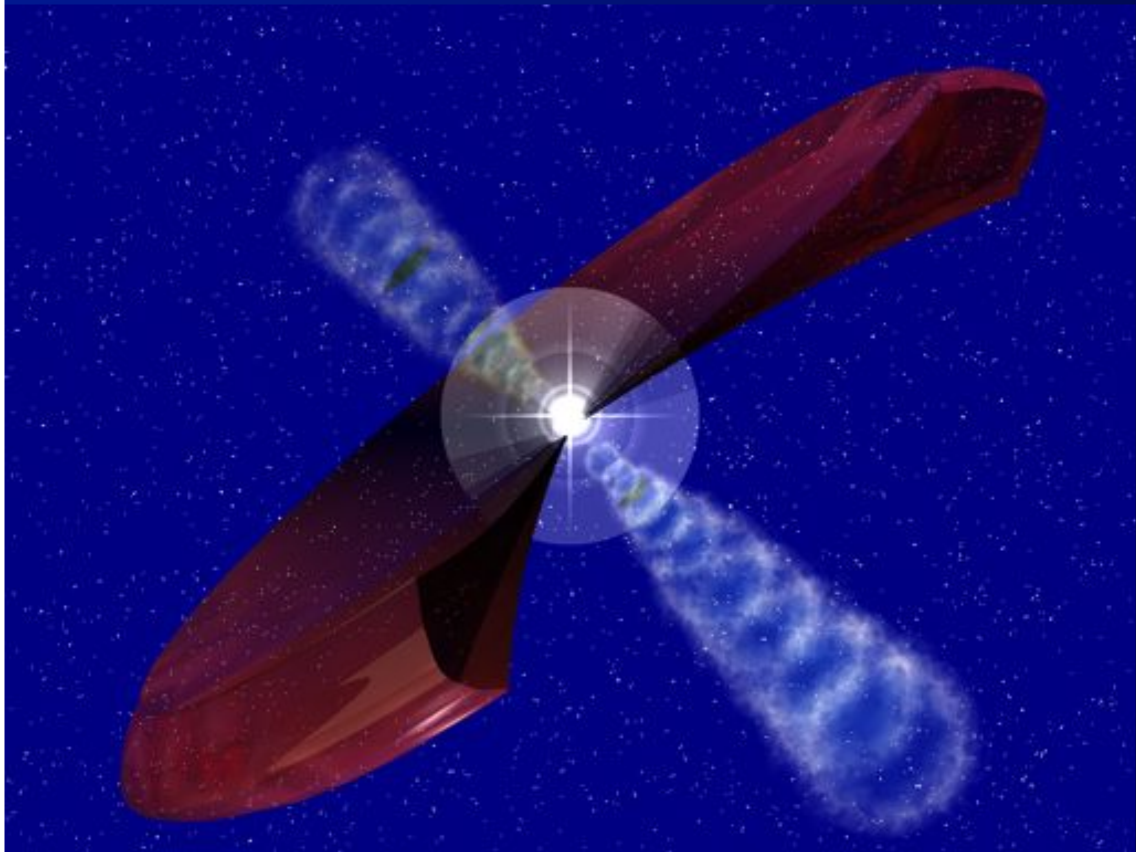
Extended NIR emission around Herbig stars with the presence of carbonaceous, quantum heated particles.

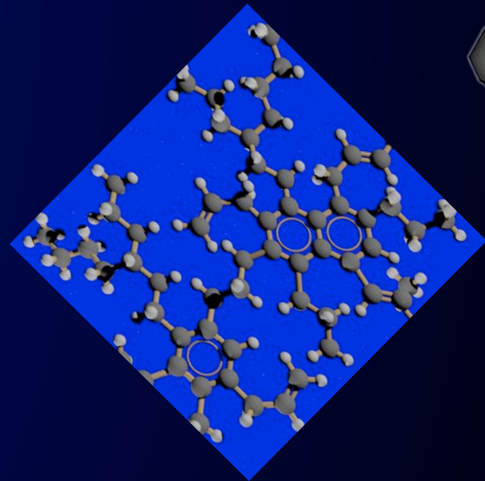
Klarmann+2017

The increase of PAH content/size with stellar Teff is done @ the expense of VSG destruction ?



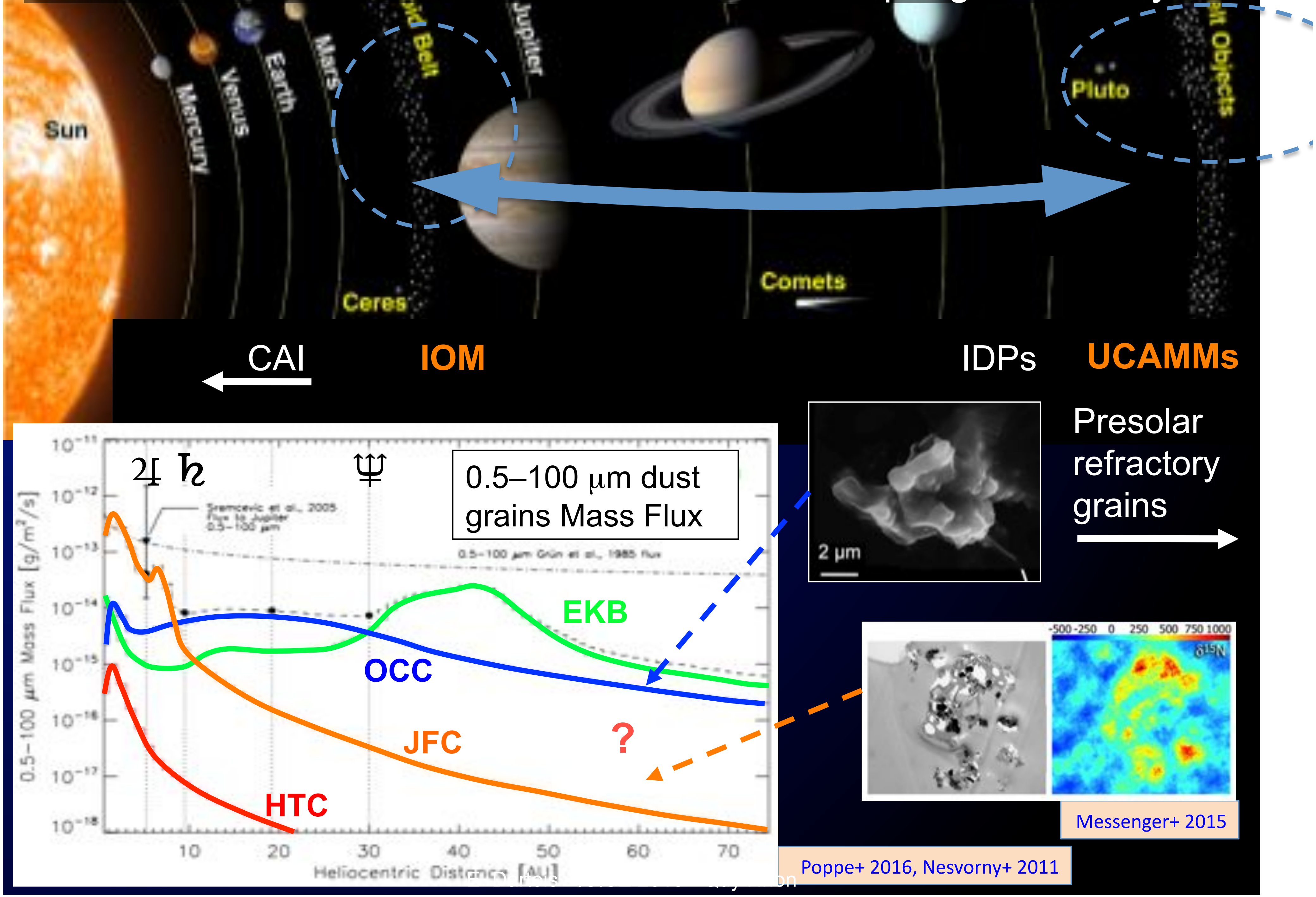
Seok & Li 2017, Berné+2009





C solids within solar system matter ?

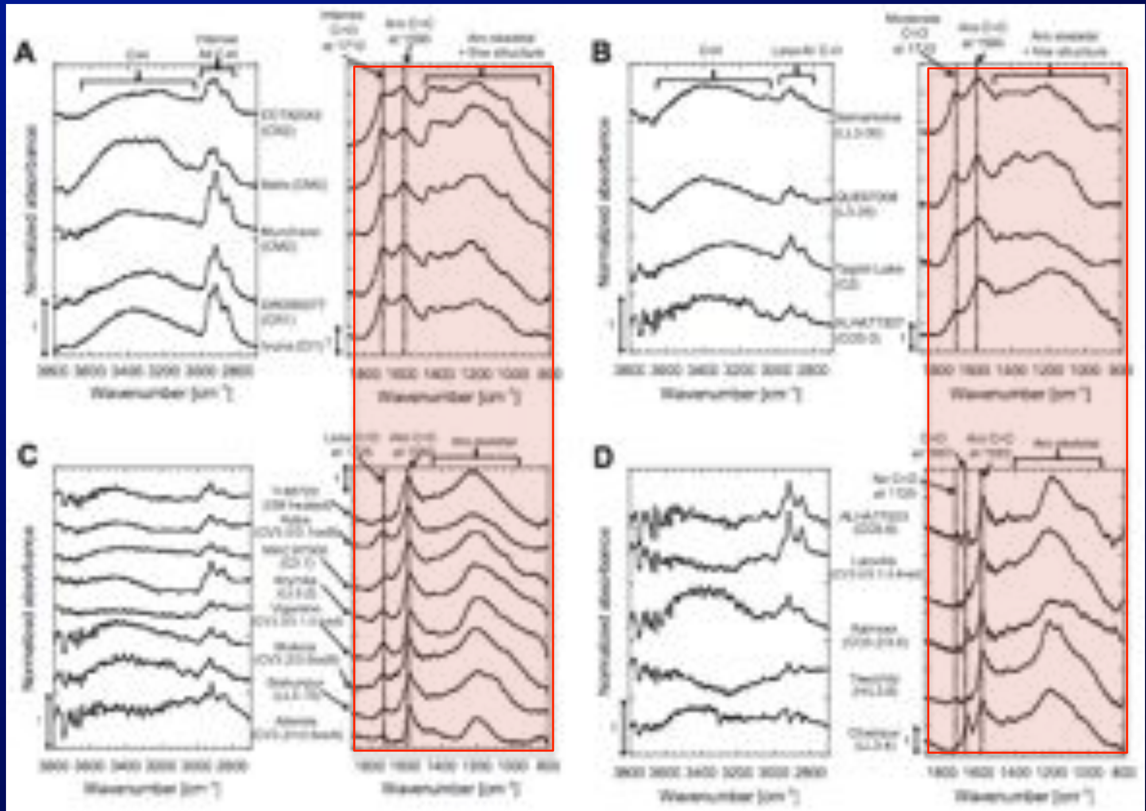
C in meteorites, IDPs & micrometeorites : sampling the sol. syst.

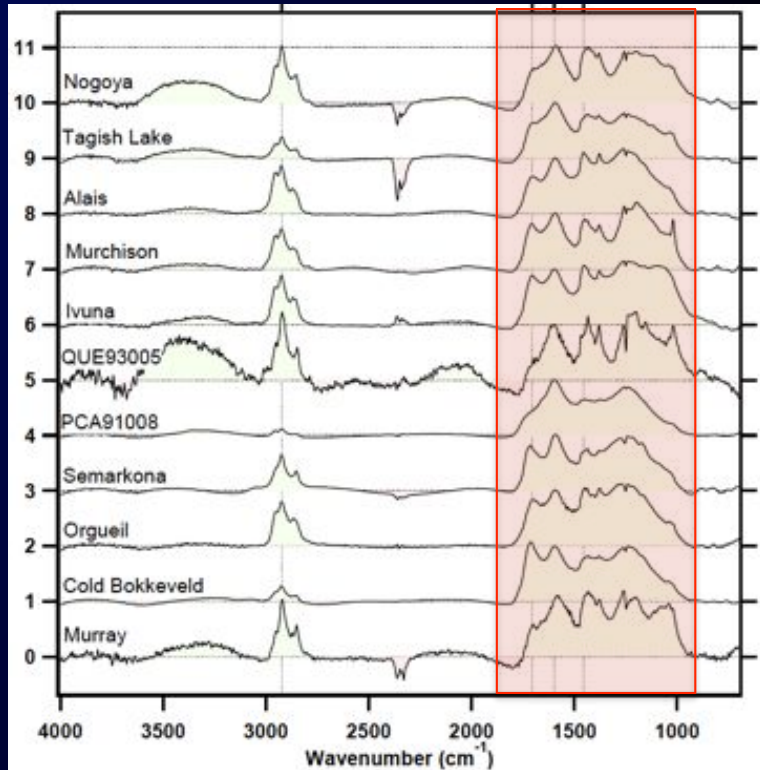


Messenger+ 2015

Poppe+ 2016, Nesvorny+ 2011

Insoluble Organic Matter (IOM)





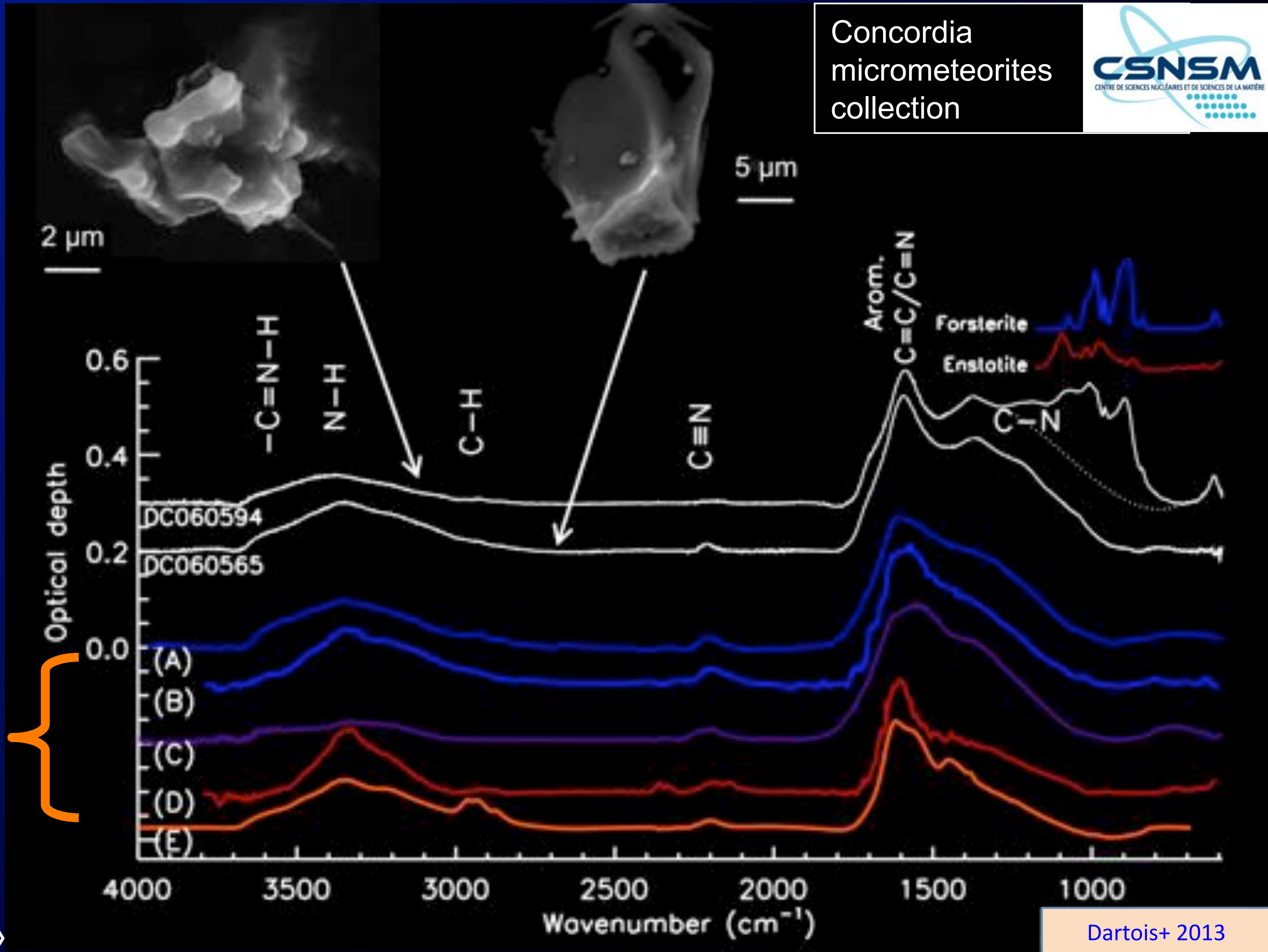
Kebukawa et al. 2011

Orthous Daunay 2011

Many absorptions in the mid-IR fingerprints region

UCAMMs : « natural » N-rich organic micrometeorites

Nakamura+ 2005, Duprat+ 2010



Laboratory Analogs

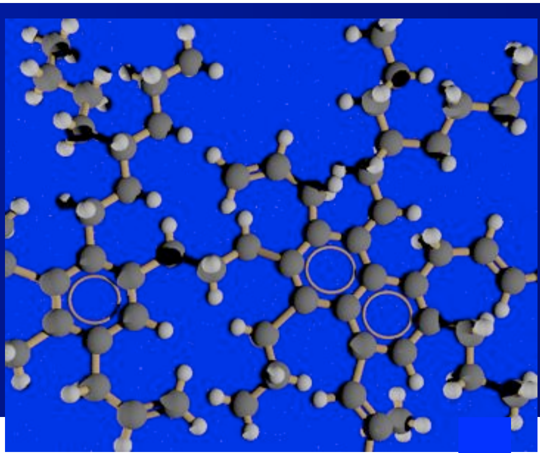
« polyaromatic hydrogenated carbon nitride »

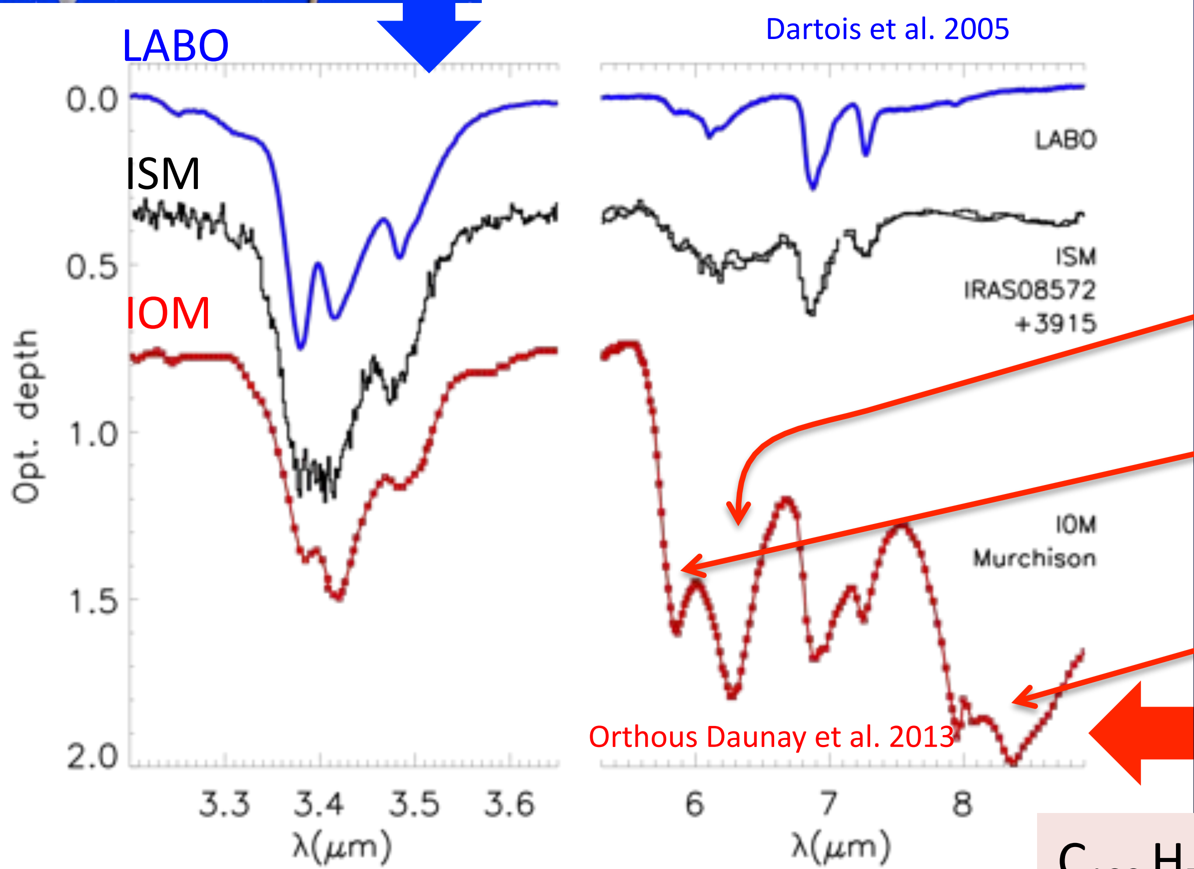
Dartois+ 2013

Ong+ 1996, Hammer+ 2000, Fanchini+ 2002, Rodil+ 2001, Quirico+ 2008

Comparison between IOM & ISM a-C:H

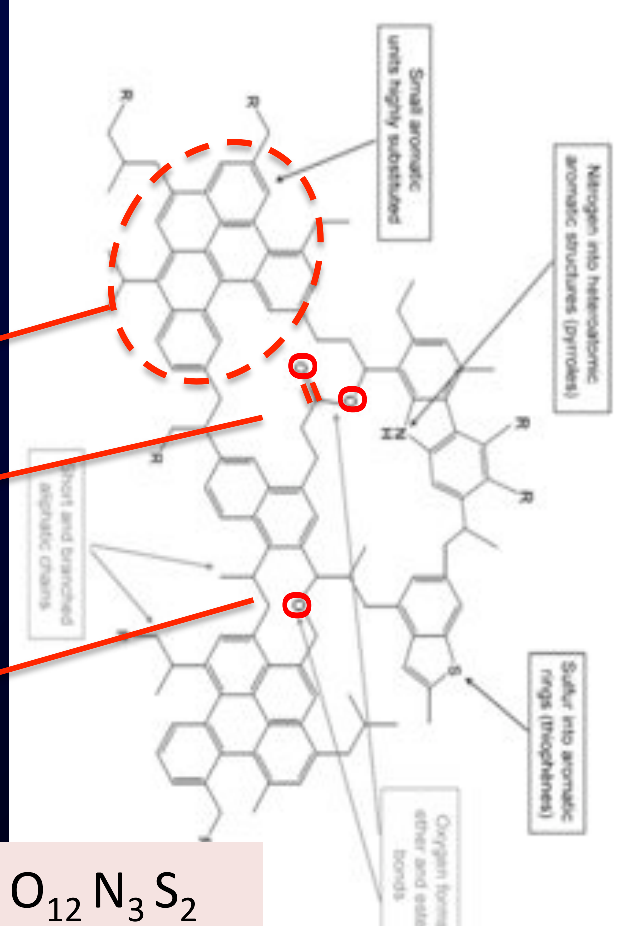
Incorporation of ISM obs/labo C within solar system matter ?



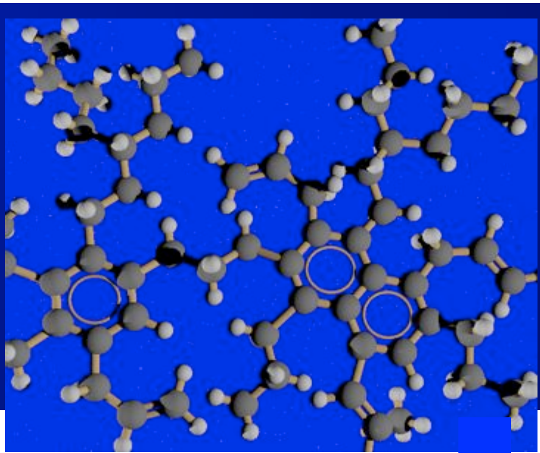


$C_{100}H_{70}O_{12}N_3S_2$

Hayatsu et al. A&A 1980

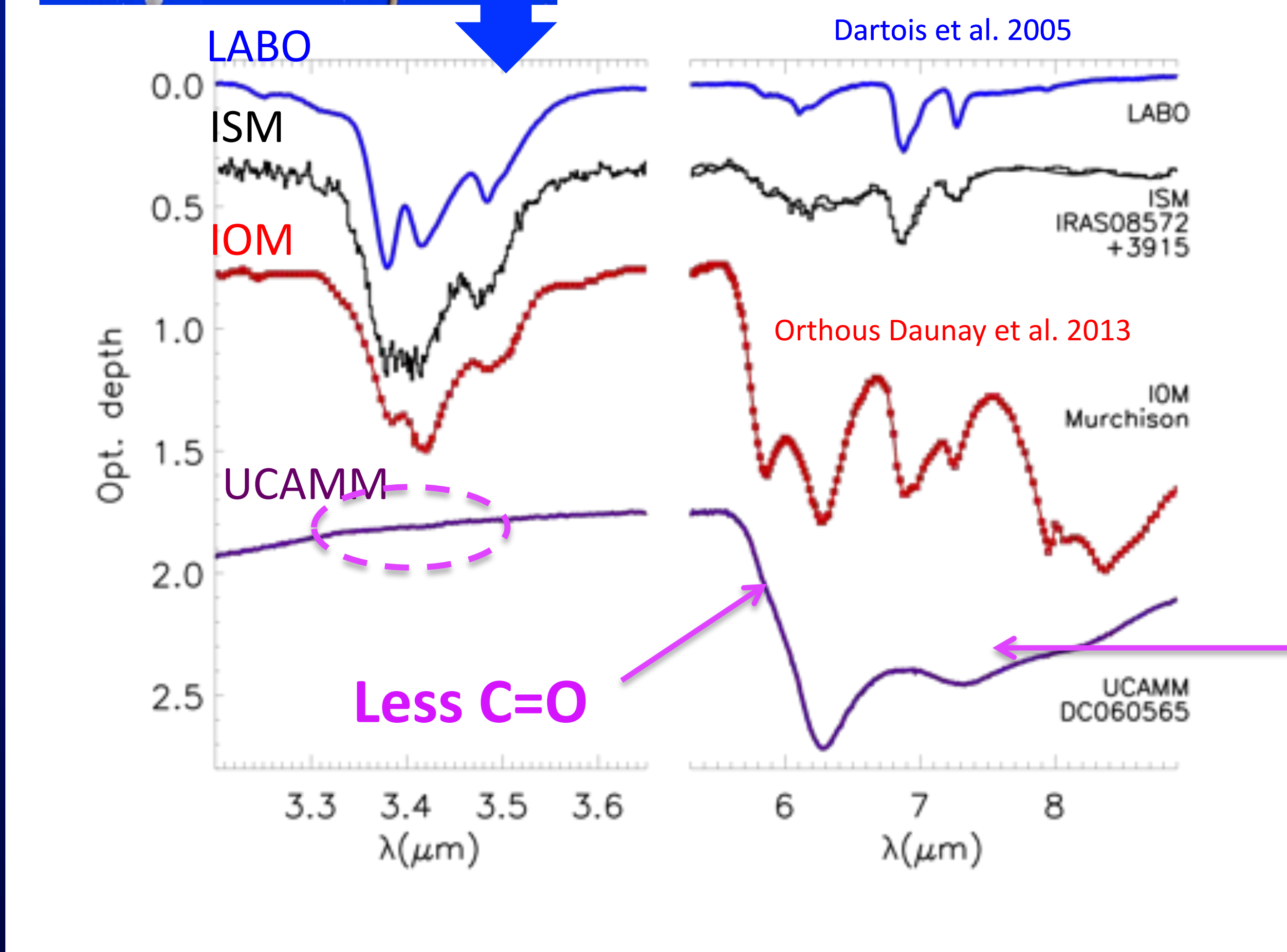


Remusat et al. 2007



Incorporation of ISM obs/labo a-C:H within solar system matter ?

Comparison between IOM, UCAMMs & ISM a-C:H

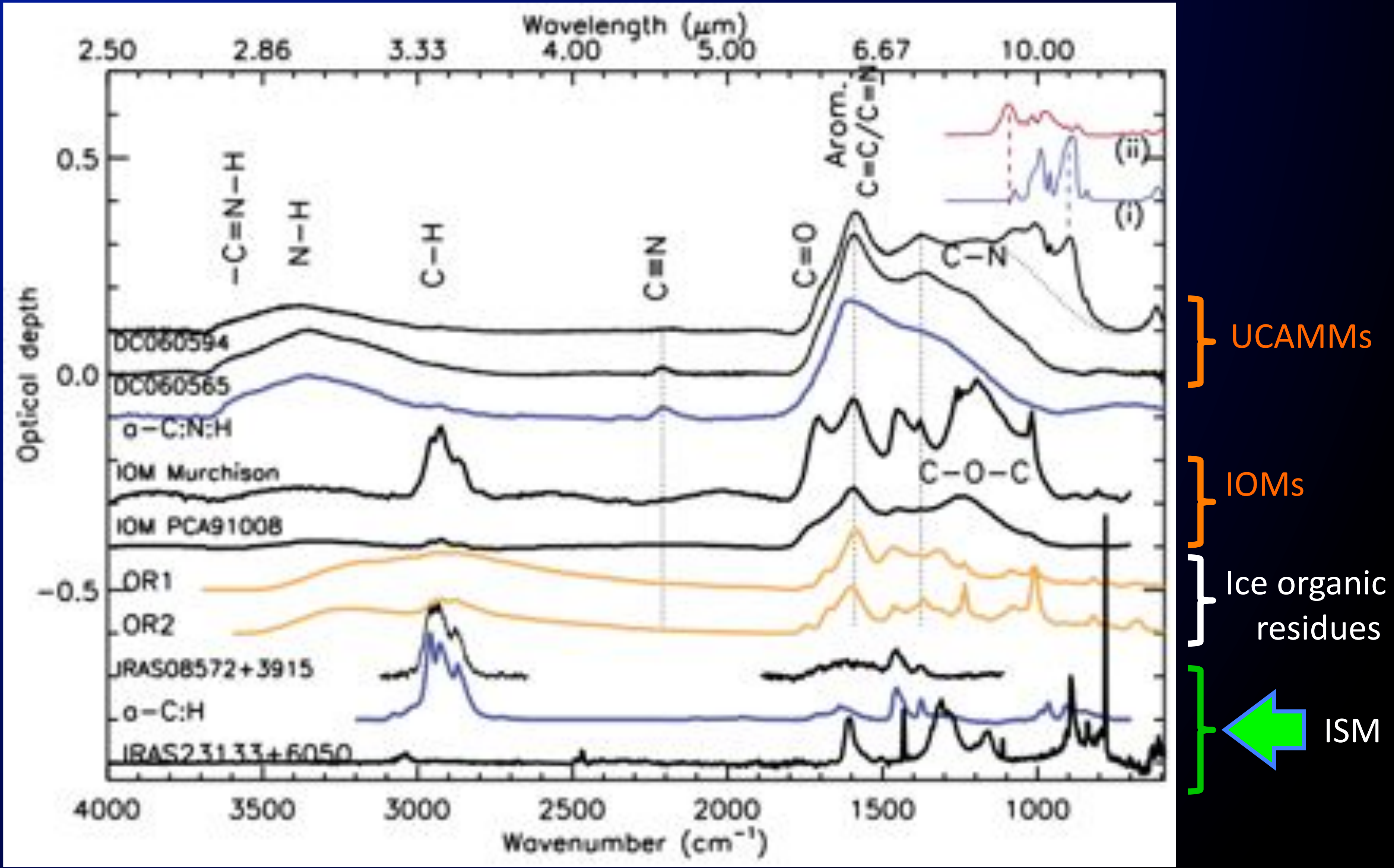


Low amount of inorganics (silicates)

>C-N<

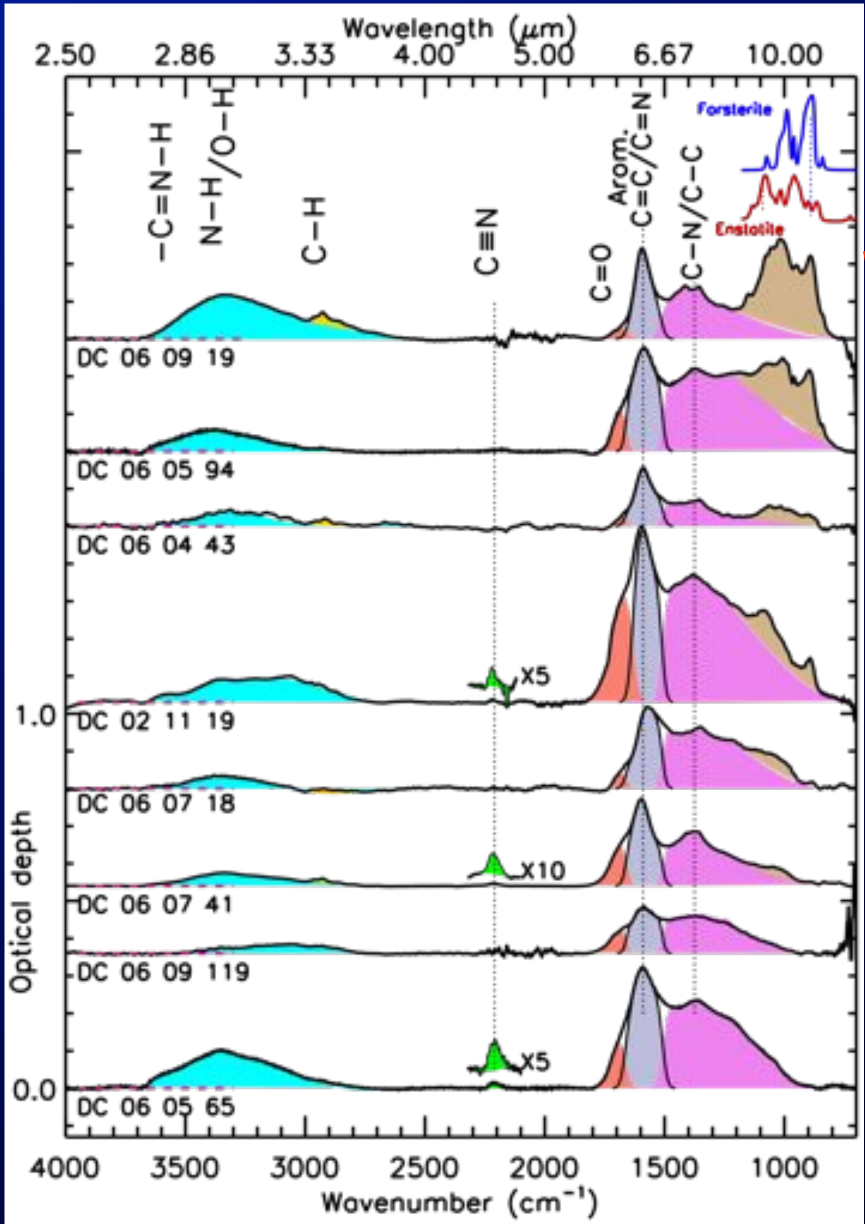
& >C=N, -C≡N

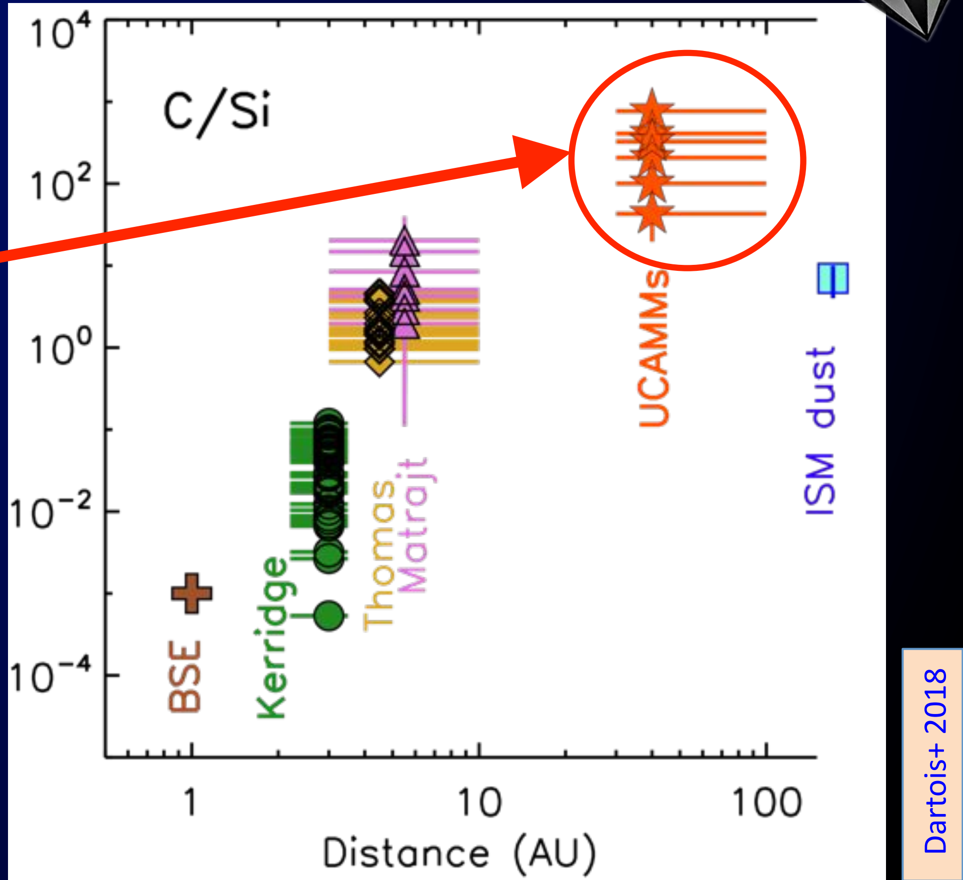
Comparing UCAMMs, IOM, lab ice residues & a-C:H/ ISM a-C:H /AIBs



Dartois+ 2014

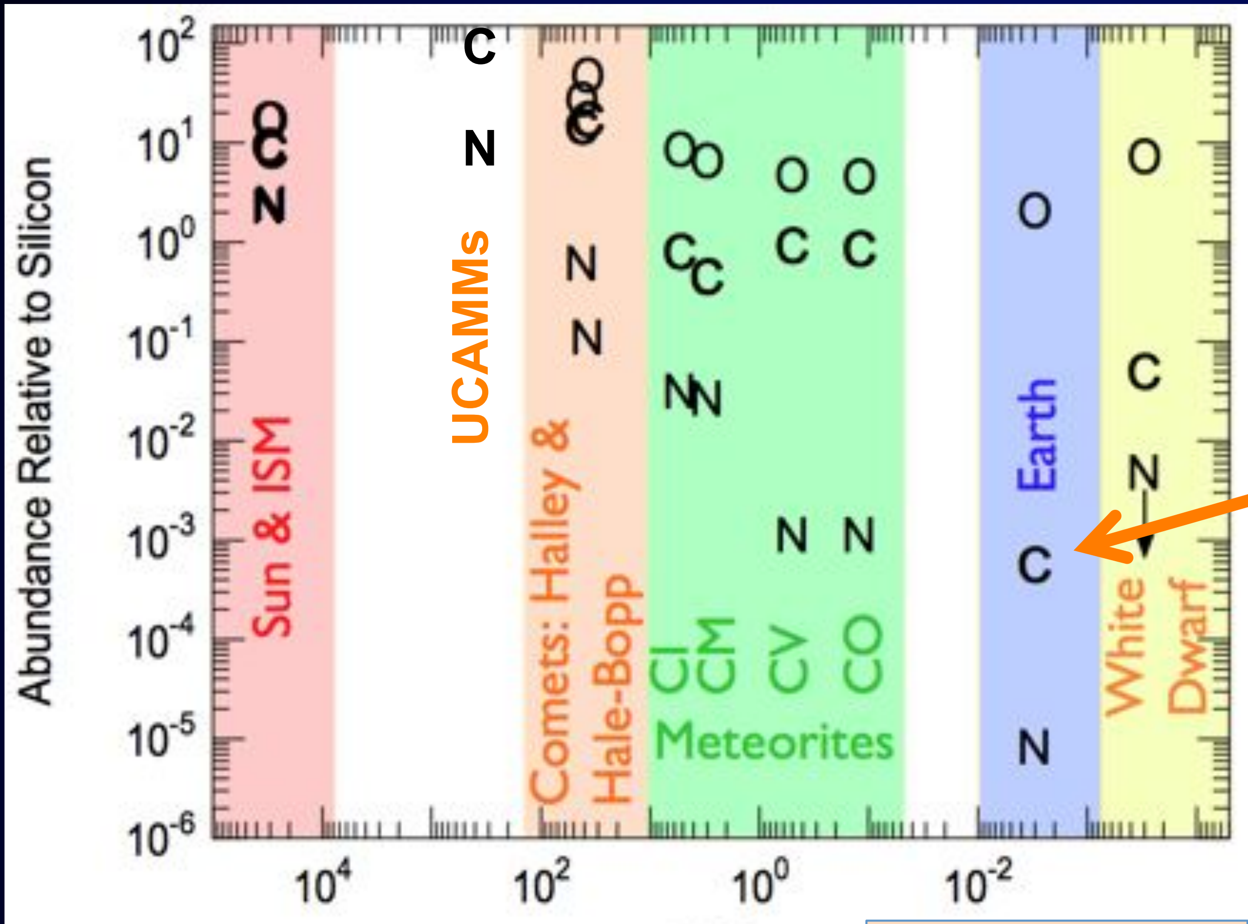
The radial organic to silicates abundance ratio issue





+ a lower IR contrast than silicates contribute to why these carbonaceous dust remains elusive in ppdisks observations

Gradient of C in the Sol. Syst. and ISM comparison



Pontoppidan+2014

Earth C depleted.
Quid for the other telluric planets ?

Lee+2010, Bergin+2015

Mercury surface C rich?

Peplowski+ 2016

C grains destroyed in the inner region (wrto Si-based minerals) ?
erosion of C materials by photons or atomic O in surface layers of the PP disk ?
Destruction may be more effective in an actively accreting disk

Anderson+ 2017

C locked in the outer disks regions ?

McLure+, in preparation

~~Conclusion~~ *… A few naïve questions*

- Actual solids *spectroscopic (bands)* constraints in disks highly dominated by the surface (e.g. AIBs/VSGs for C-based ones)
- models require featureless opacities, big grains in the mm, carriers to be constrained

MAC of silicates: which to select ?

What is the actual radial consensus on radial composition of silicates ?
Cosmochemistry versus astrochemistry ?
Is Forsterite to Enstatite or Enstatite to Forsterite radial transition generic ?
Size/cryst/T effect on reverse engineering blurs it all ?

Sol. Syst. points toward a radial organic to silicates abundance ratio:
- Carbon preferentially locked in the outer disk ?
- Organics destroyed when entering the inner region ?

--What is the fraction of the ISM/cloud phase inherited in disks ?
--Tracing mostly nebular physico-chemical processes/reset ?