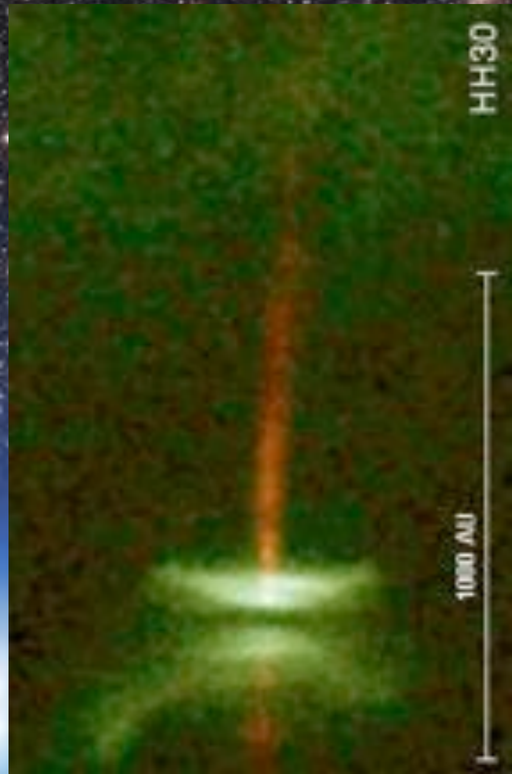
Nature of interstellar dust grains, and their evolution in the presolar nebula Sun

Les Houches 2017



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IAS Institut d'Astrophysique Spatiale Orsay

UMET Unité Matériaux Et Transformations

Lupus 3 dark cloud © ESO/F. Comeron

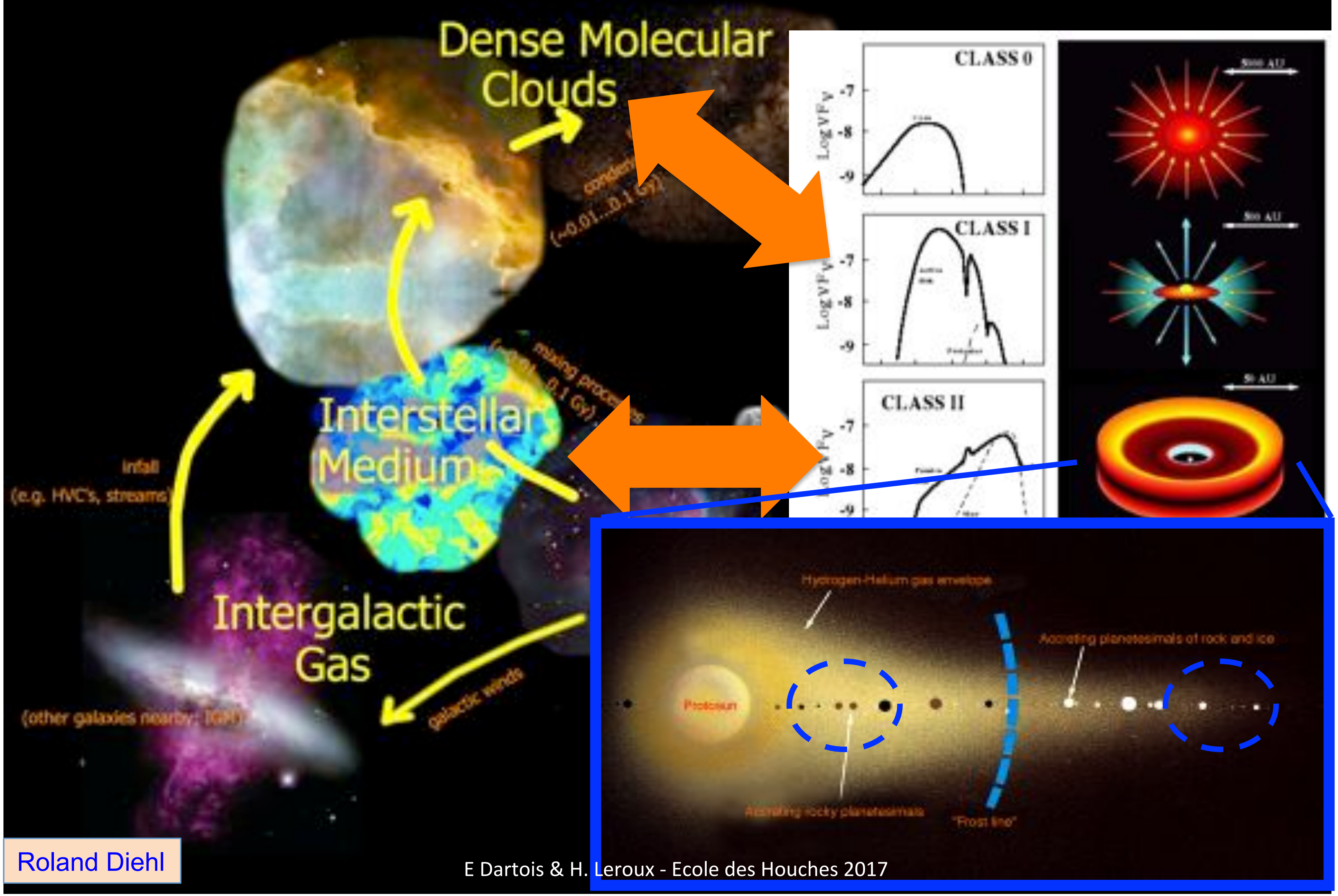
General introduction
Solid matter life cycle, cosmic abundances, interstellar solids,
Interstellar dust sources
Silicates
in stellar envelopes, the diffuse interstellar medium, in disks

Silicates in primitive objects of the protoplanetary disk

Fine-grained material in primitive objects
Silicates in comets, with a special focus on the Stardust Mission
Silicates in interplanetary dust particles and in fine-grained micrometeorites
Silicates in the matrix of primitive chondrites; earliest evolution in parent bodies
Silicate evolution in the protoplanetary disk: from the ISM to protoplanets

Which carbon allotropes & organic matter observed in the ISM
Nanodiamants, Fullerenes, amorphous carbon, hydrogenated amorphous carbon (a-C :H ou HAC), AIBs (PAHs), mixed a-C :H-PAHs, organic residues
Transition diffuse to dense ISM
Signatures for the ISM solids incorporation in the solar syst (remote observations) ?
Comparison IOM meteorites & UCAMMs / ISM a-C:H

Interstellar dust temporal lifecycle



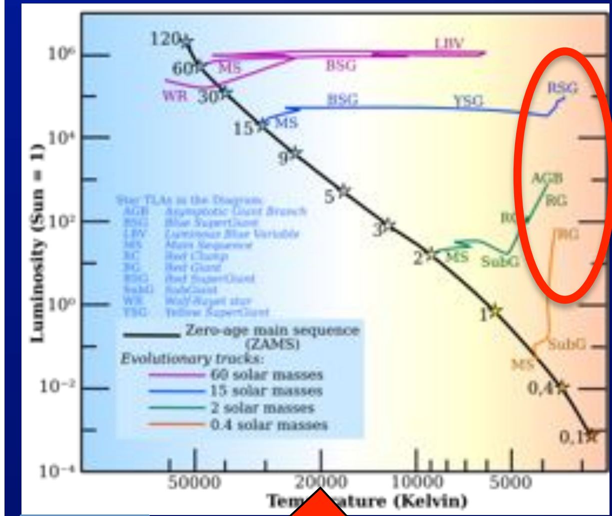
The « multi-phase » ISM model

Phase	nH (cm−3)	T (K)	x	Mass (%)
MC	$>10^3$	<50	$<10^{-5}$	30
CNM	10–100	500-100	$\sim 10^{-4}$	25
WNM	0.1–1	$10^4 - 10^3$	~0.01	25
…				
WIM	*0.1–1*	$\sim 10^4$		
HII	10^2-10^4	$\sim 10^4$		
HIM	10^{-2}-10^{-4}	$\sim 10^6$-10^7		

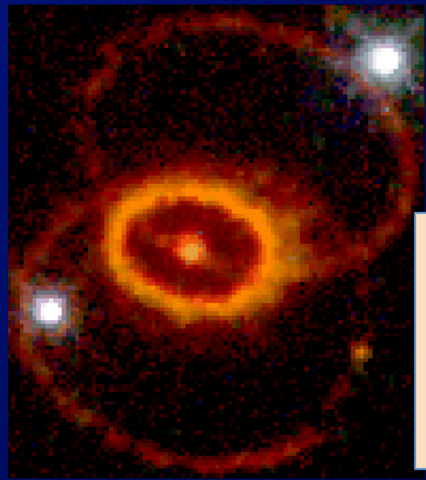
Verstraete 2011, Wolfire 2003

Interstellar dust budget

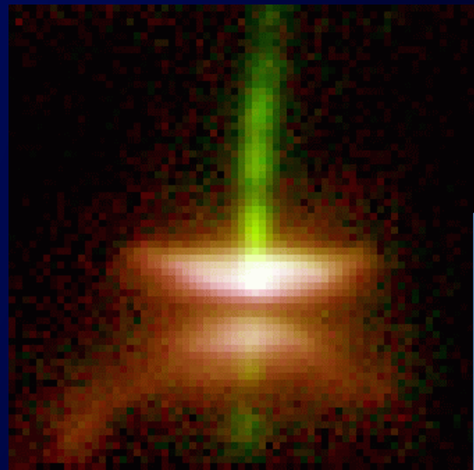
- Stellar mass losses contribute significantly to dust production
- Dust observed at later evolutionary stages



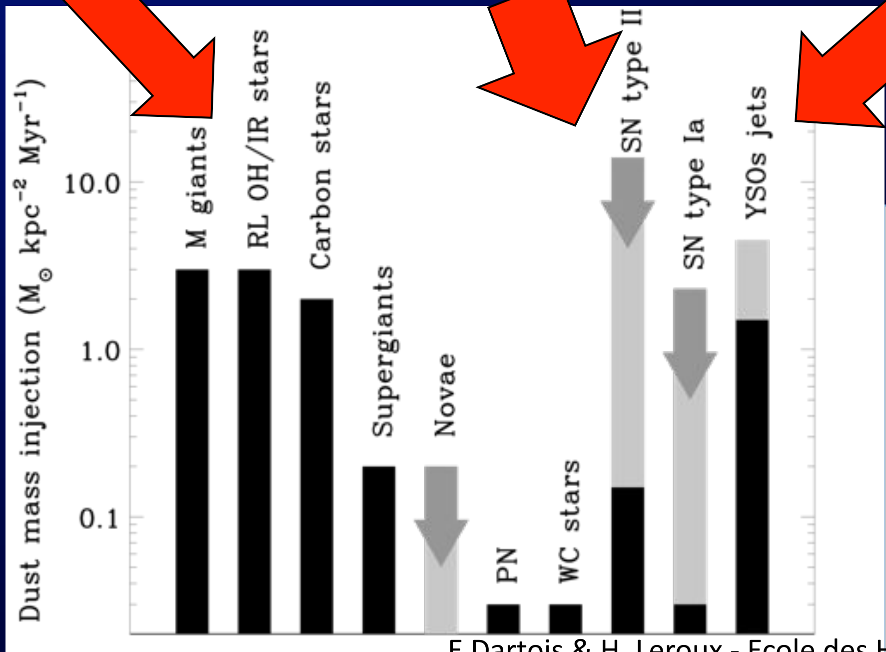
Rursus



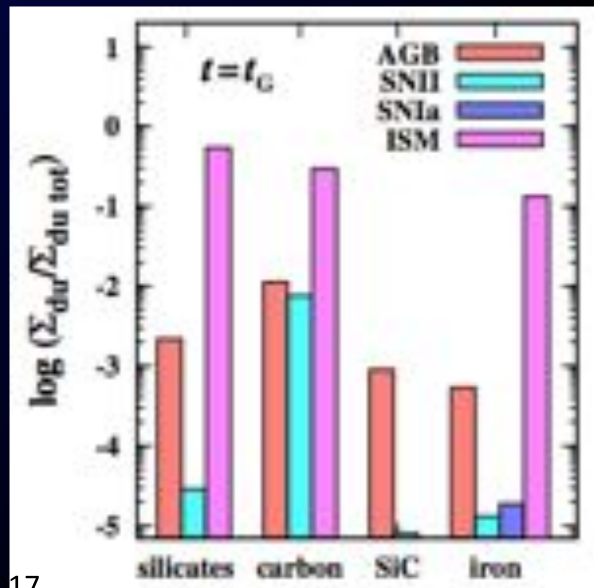
SN1987A - HST



HH30- HST



Jones 2001, Tielens 2005, Robitaille 2010, Matsuura 2011

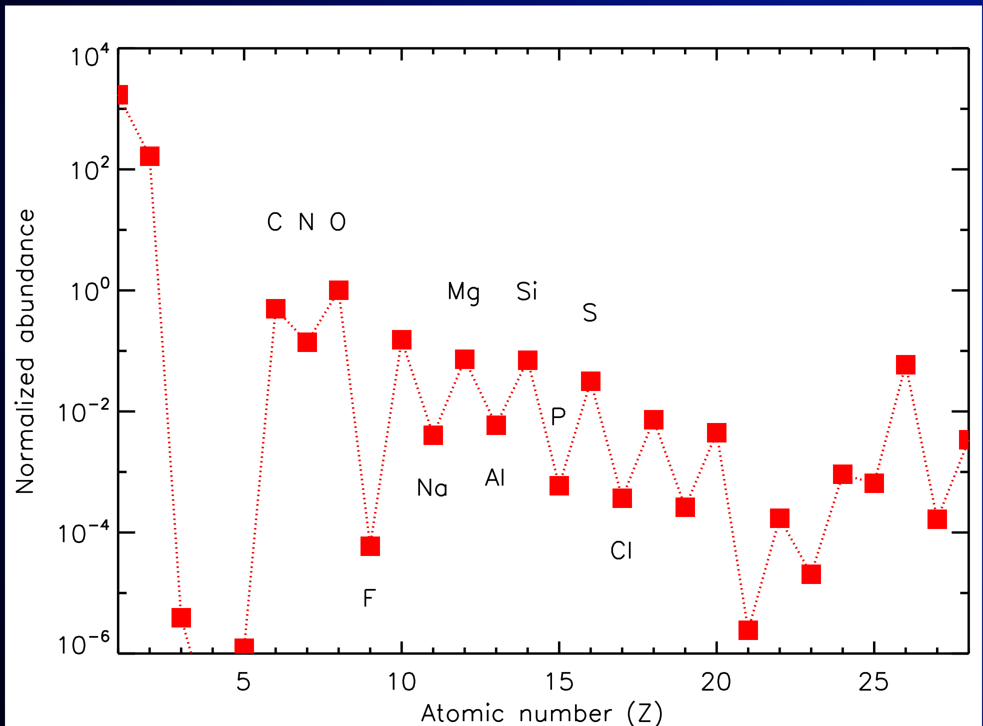


Zhukovska2008+

What to expect for dust grains ?

Elemental cosmic abundances
(DISM, $N_H \sim 100\ cm^{-3}$)

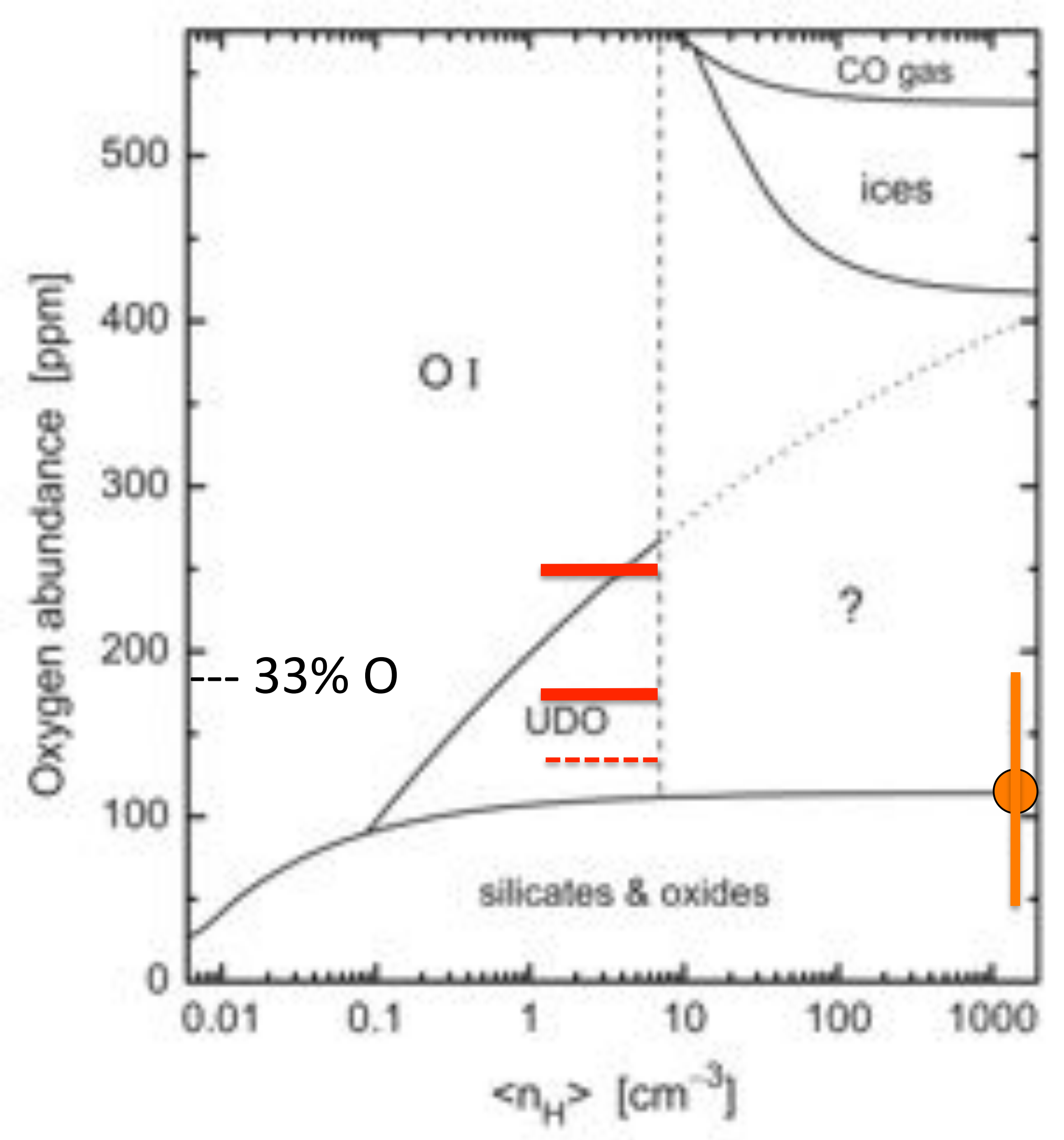
"Carbonaceous" matter



"Minerals"

Element	[X/H]IS (ppm)	δX (%)
He	$7.8\ 10^4$	0
C	288.4	38.7
N	79.4	22.2
O	575.4	41.9
Mg	41.7	94.6
Si	40.7	95.6
S	18.2	80.7
Fe	34.7	99.4

Lodders 2003, Jenkins 2009, Verstraete 2011



UDO = unidentified depleted oxygen

O depletion

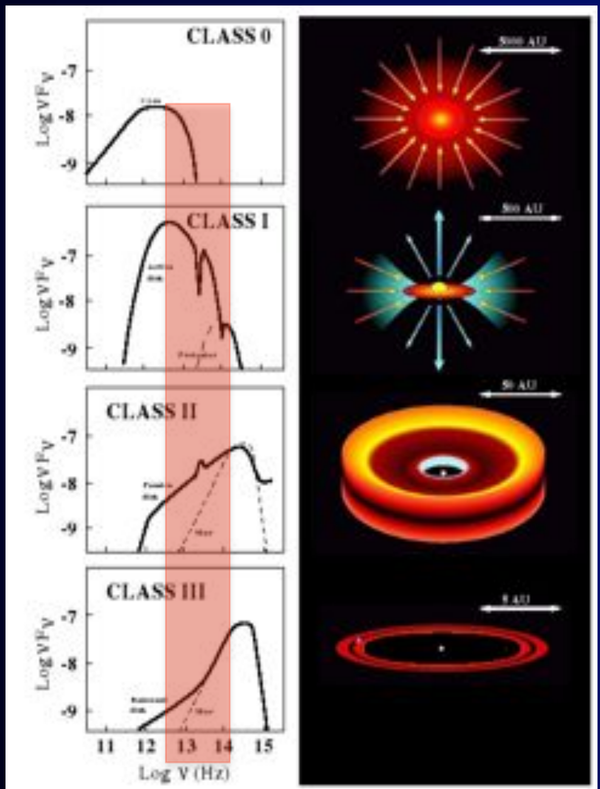
4x[Si]

3x[Si]

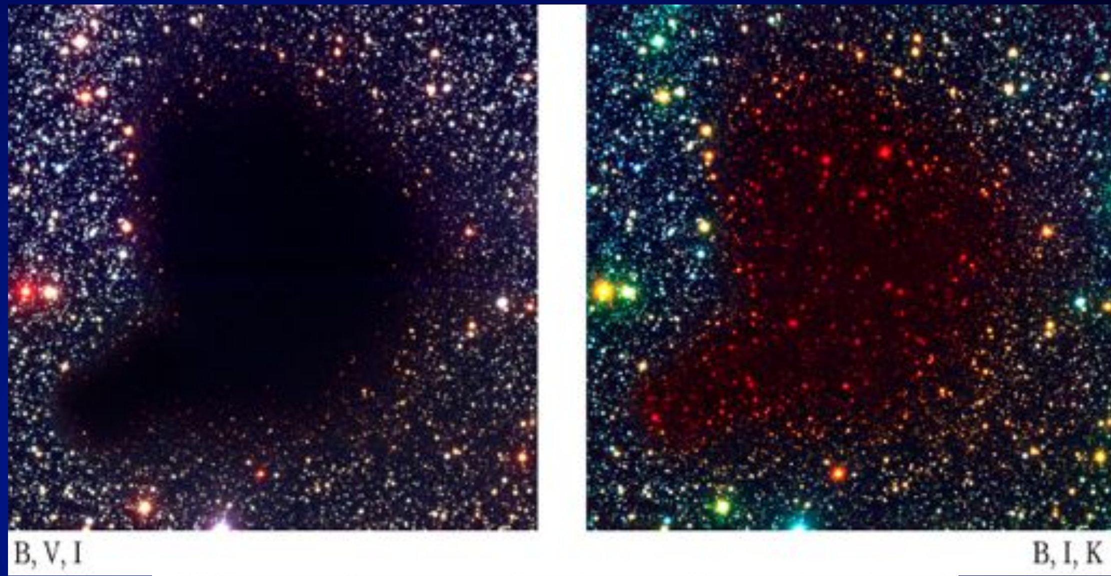
Whittet2010

Wavelengths of interest:

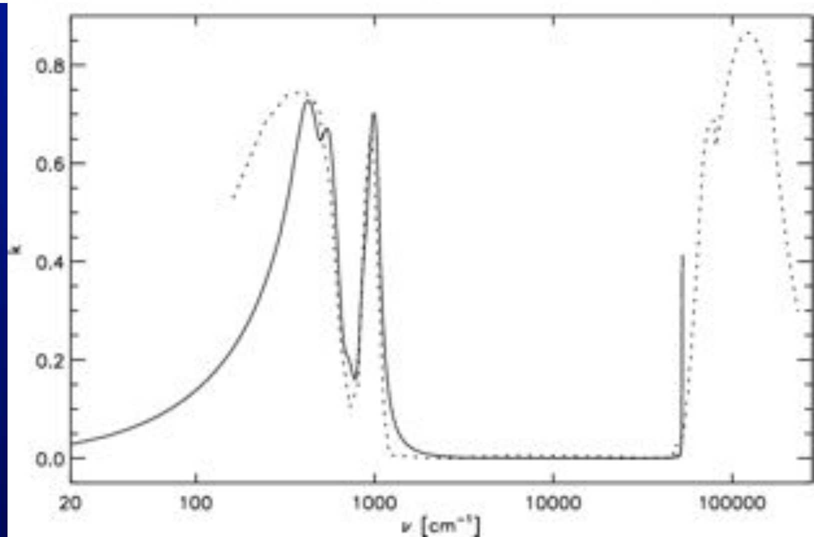
Trade-off between wavelength accessibility & spectral signatures



Van Boekel

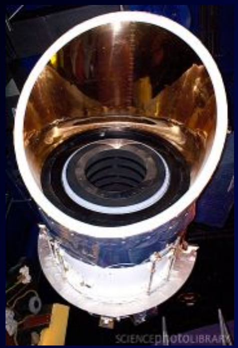


ESO



Jaeger 2003

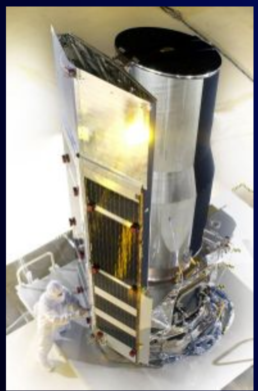
(sub)-mm FIR - Infrared - NIR Visible - UV



IRAS

ISO

Akari



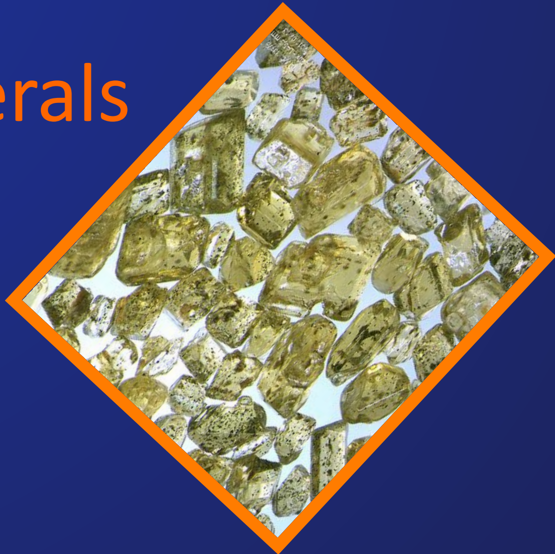
Spitzer

Herschel

JWST

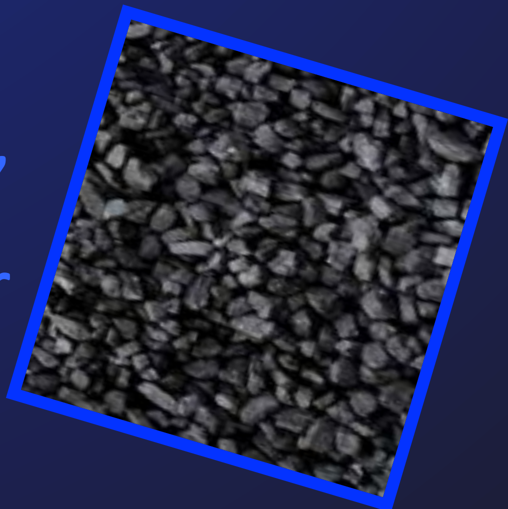
The simplified picture of ISM solids

Minerals



"Refractory" solids

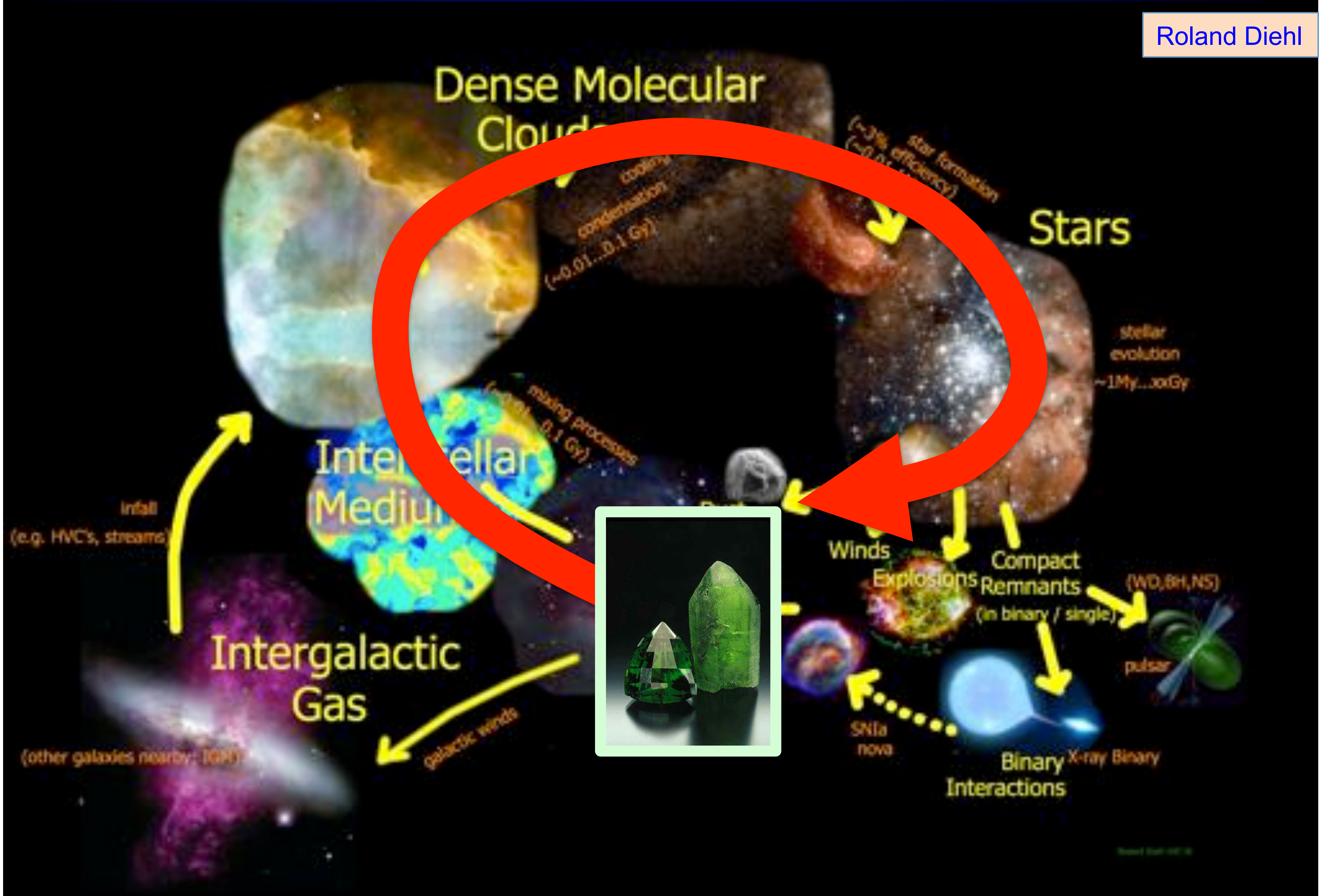
"Carbonaceous" matter



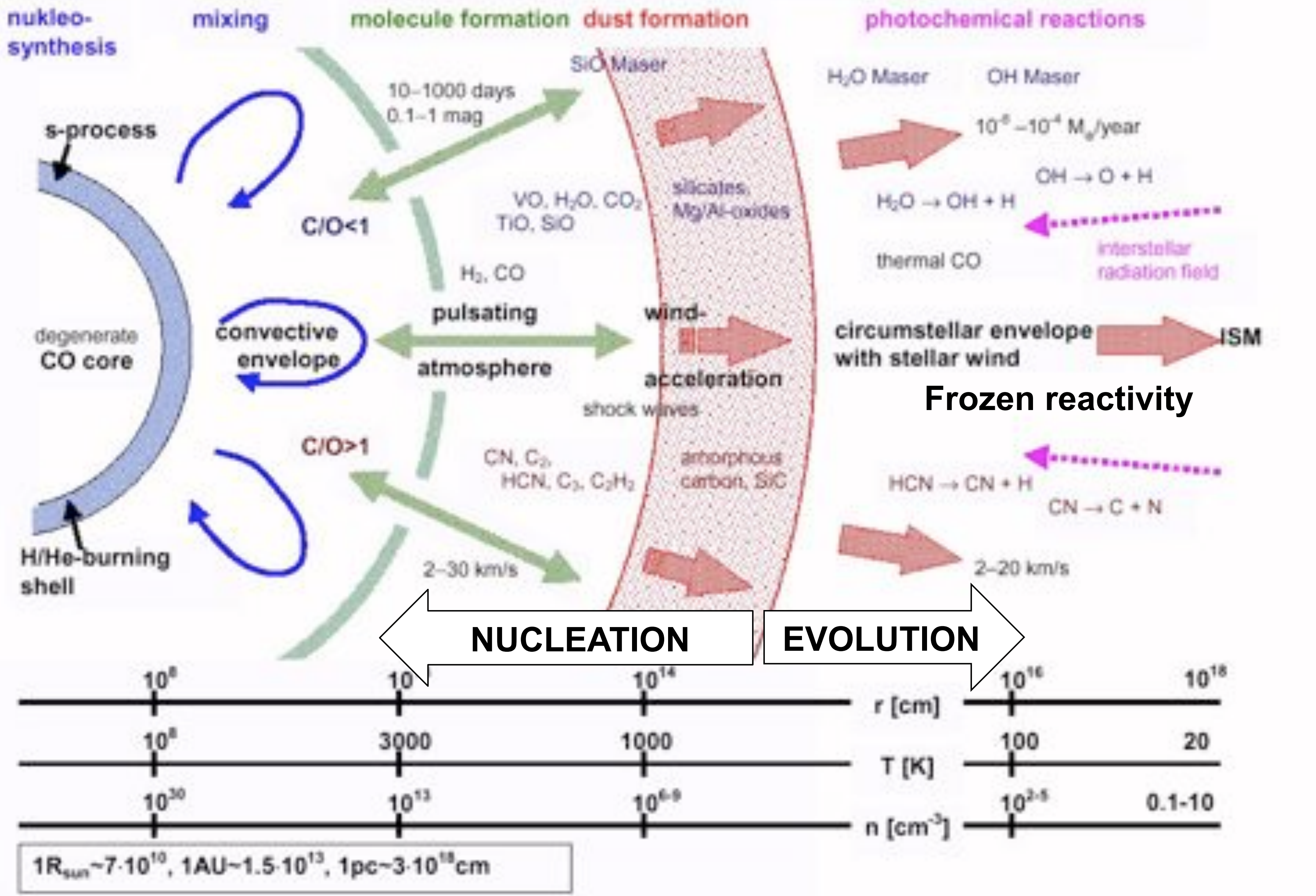
Volatile" solids

Ice mantles

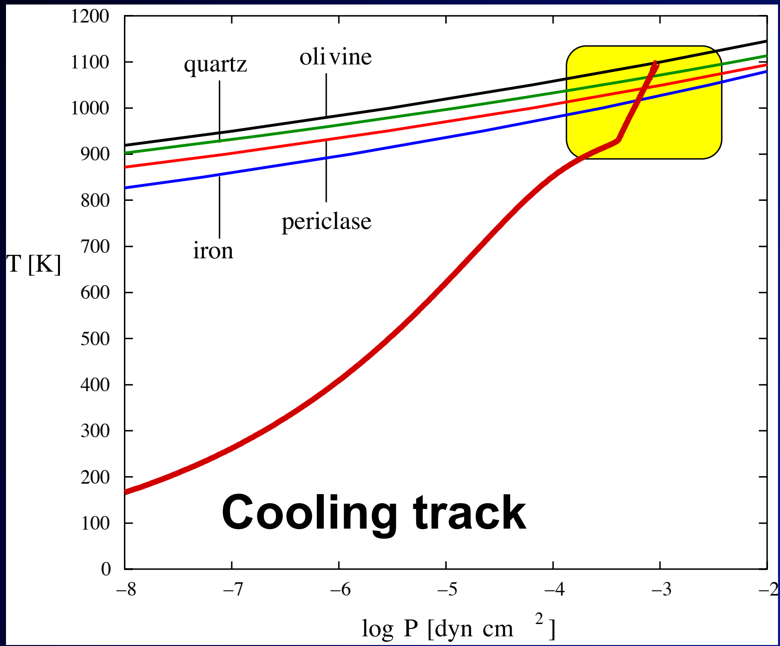
Inorganic dust

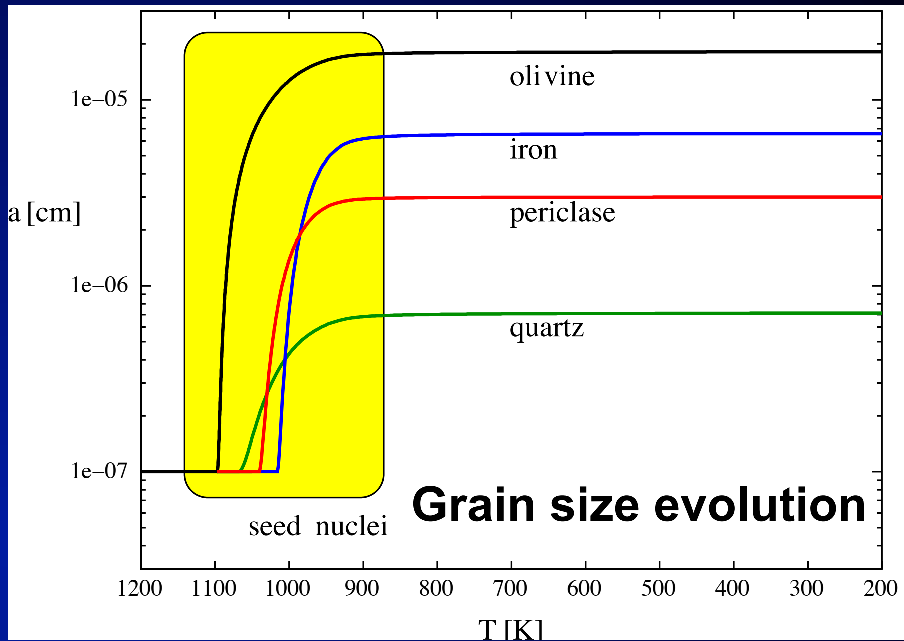

Roland Diehl
Dense Molecular
cooling
condensation
Stars
stellar
evolution
~1My...xxGy
mixing processes
infall
(e.g. HVC's, streams)
Winds
Explosions
Compact
Remnants
(in binary / single)
(WD,BH,NS)
pulsar
Intergalactic
Gas
galactic winds
(other galaxies nearby; IGM)
SNIa
nova
Binary
Interactions
X-ray Binary

Schematic view of an AGB stellar flow



Stellar wind model





Gail & Sedlmayr 1999

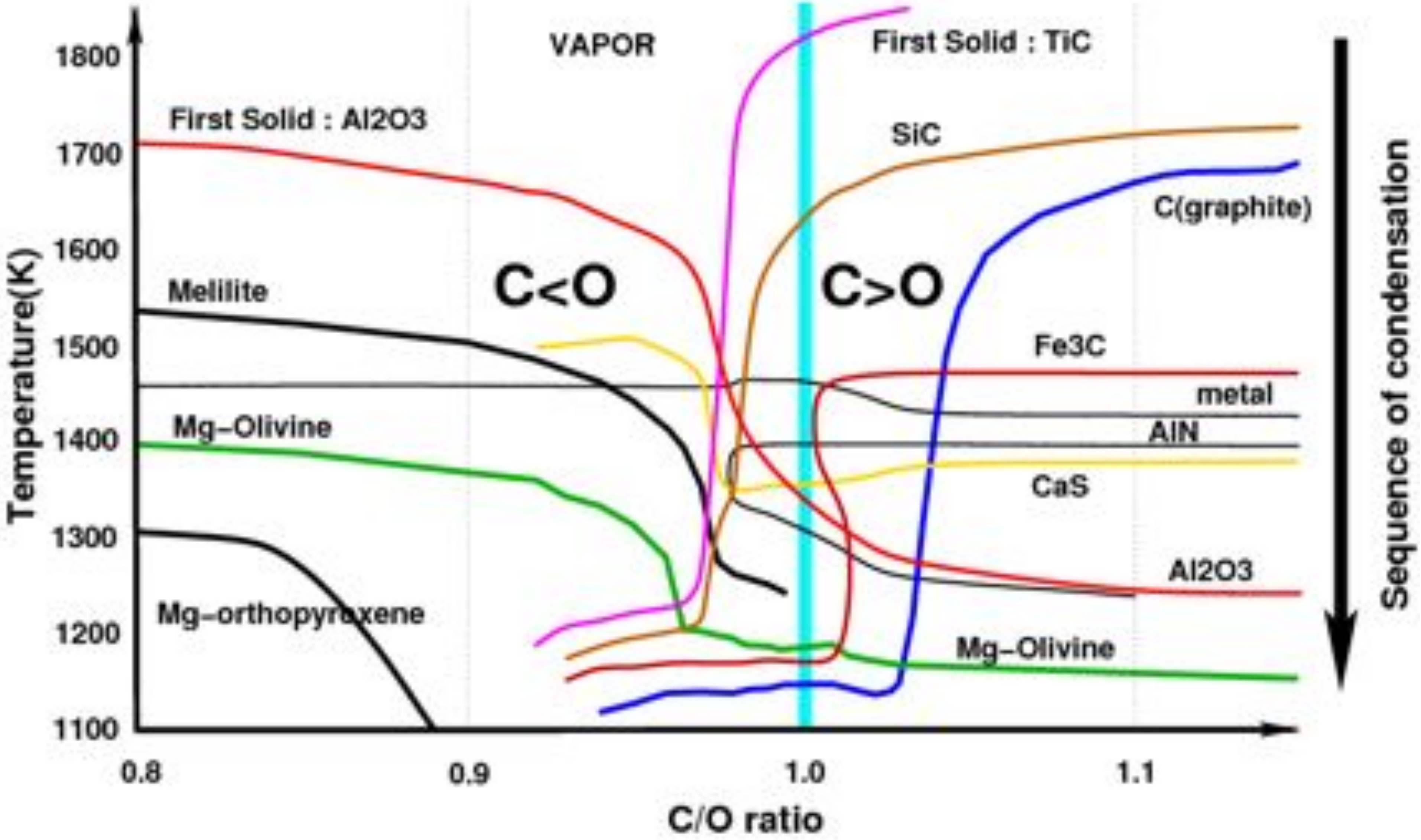
Condensation far from ETL T~1000K, P~10(-10)atm

Critical phase: molecular agregates to form seed particles (10-100 atoms)

These seeds less stable than bigger particles & require sursaturation / solide

Competition between caracteristic formation & ejection time scales (reactions « frozen »)

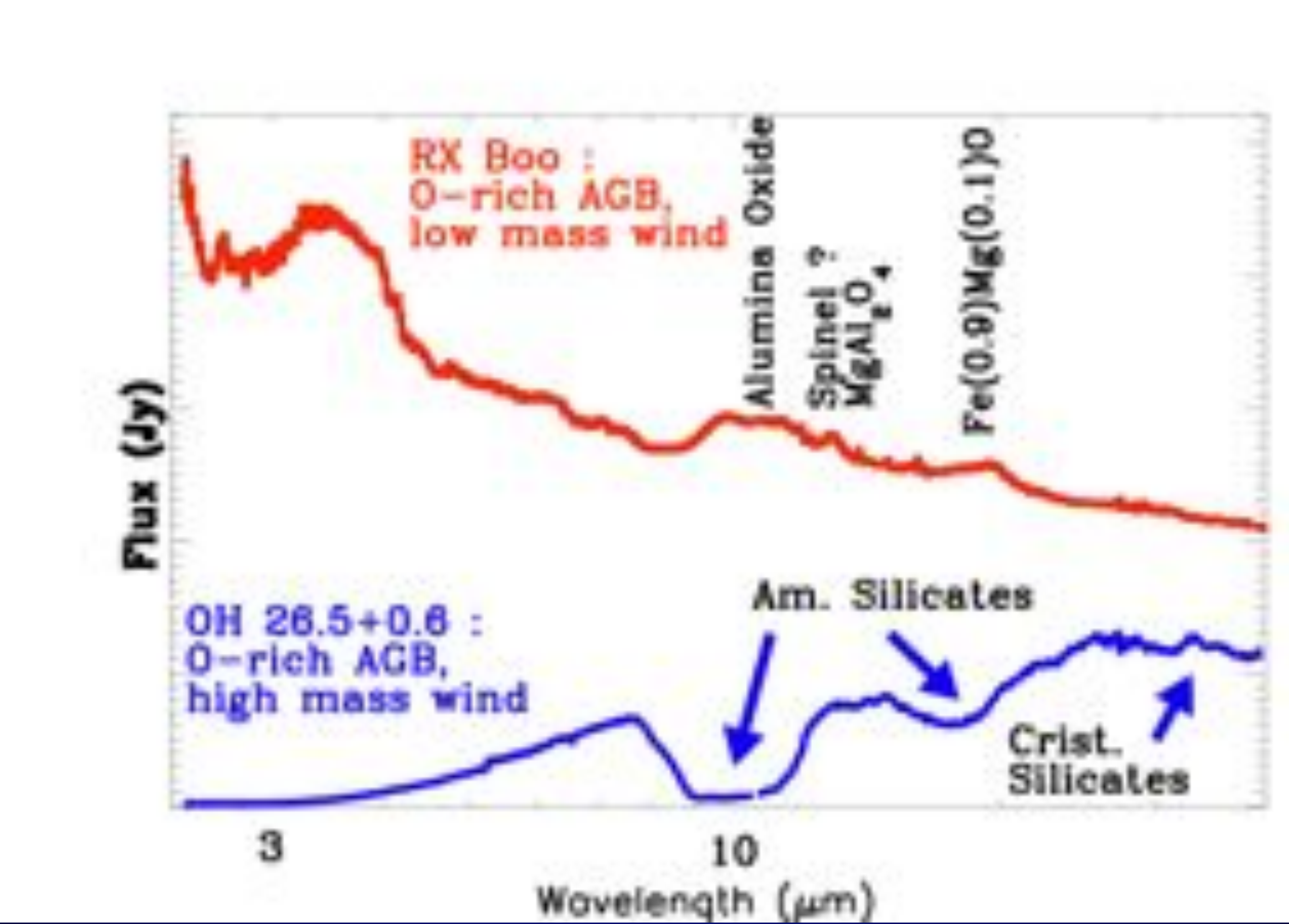
χ



VAPOR
First Solid : TiC
First Solid : Al2O3
SiC
C(graphite)
C<O
C>O
Melilite
Fe3C
metal
AlN
Mg–Olivine
CaS
Al2O3
Mg-orthopyroxene
Mg–Olivine
Temperature(K)
1800
1700
1600
1500
1400
1300
1200
1100
0.8
0.9
1.0
1.1
C/O ratio
Sequence of condensation

Ebel 2000

ϕ



Molster et al. 2002, Posch et al. 2002, Cami 2002 ...

Silicates "mineralogy"

Olivines ($Mg_{2x}Fe_{2-2x}SiO_4$)

Mg_2SiO_4 Forsterite

Fe_2 SiO_4 Fayalite

Pyroxenes ($Mg_xFe_{1-x}SiO_3$)

$Mg_2Si_2O_6$ Enstatite

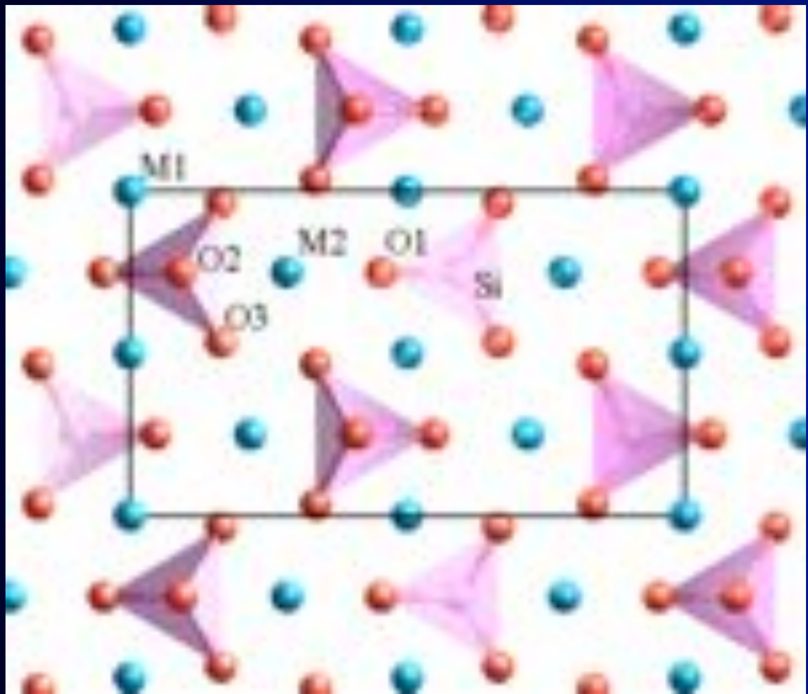
$Fe_2Si_2O_6$ Ferrosilite (hypersthene)

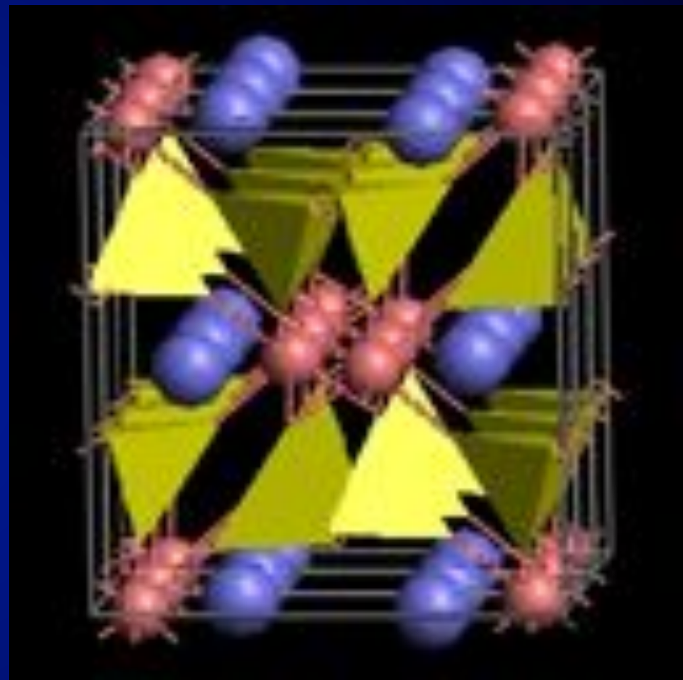
$CaMgSi_2O_6$ Diopside

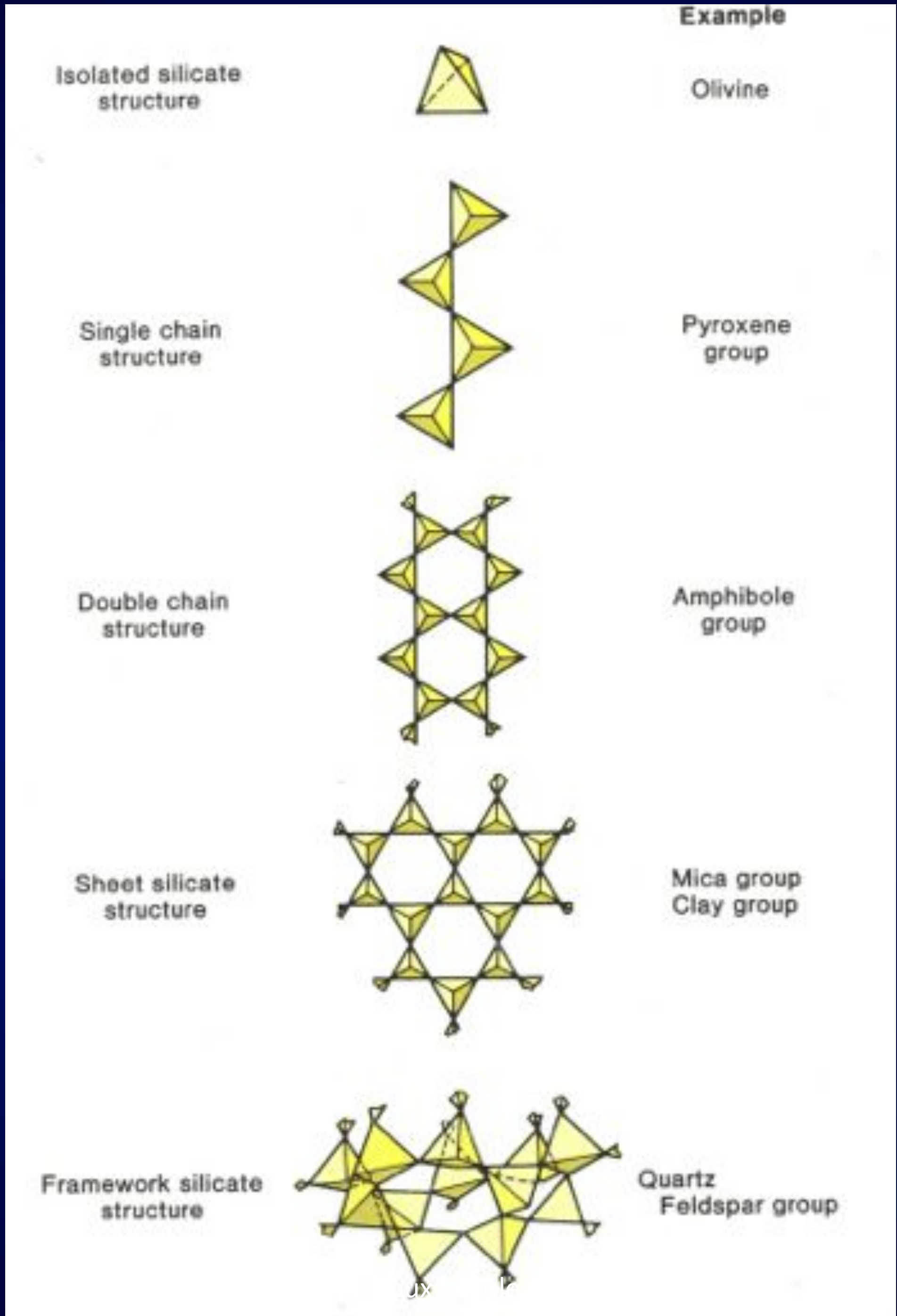
$CaFeSi_2O_6$ Hedenbergite

Olivine

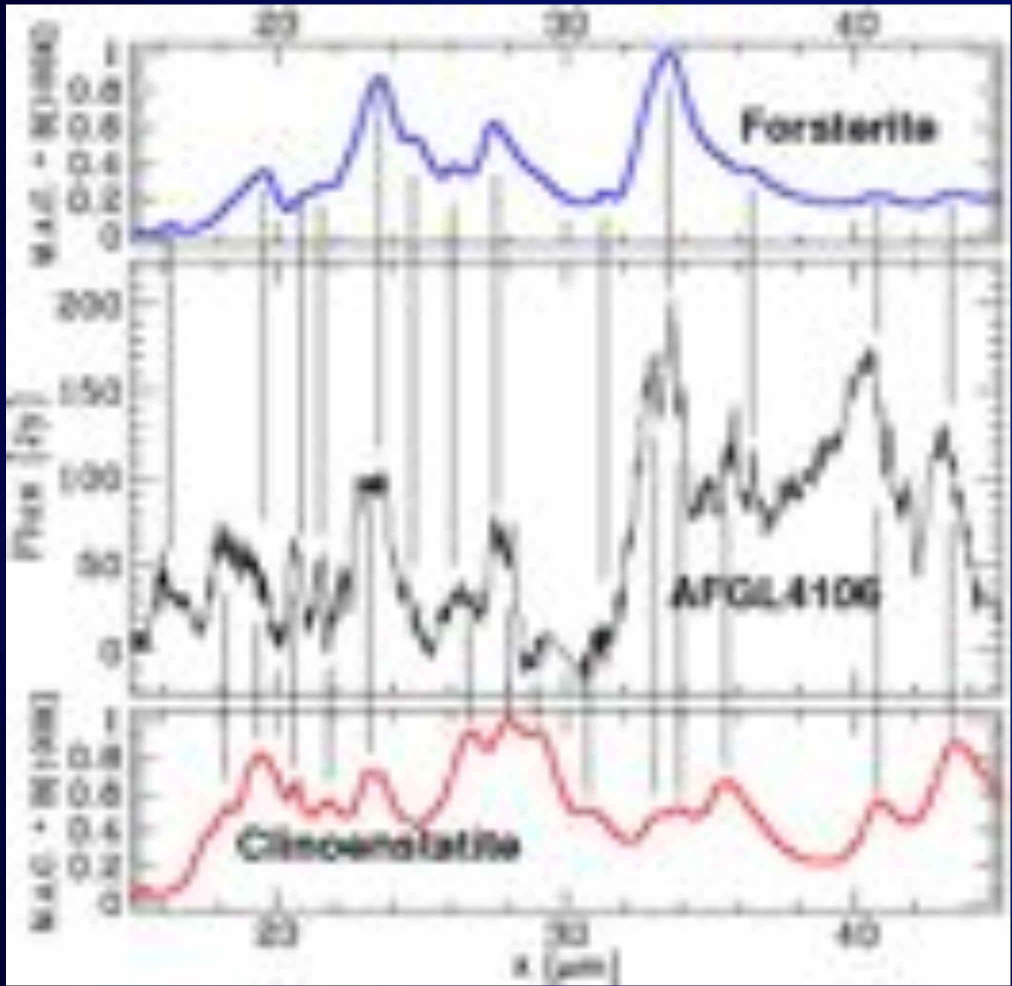
Pyroxène






Example
Isolated silicate structure
Olivine
Single chain structure
Pyroxene group
Double chain structure
Amphibole group
Sheet silicate structure
Mica group
Clay group
Framework silicate structure
Quartz
Feldspar group

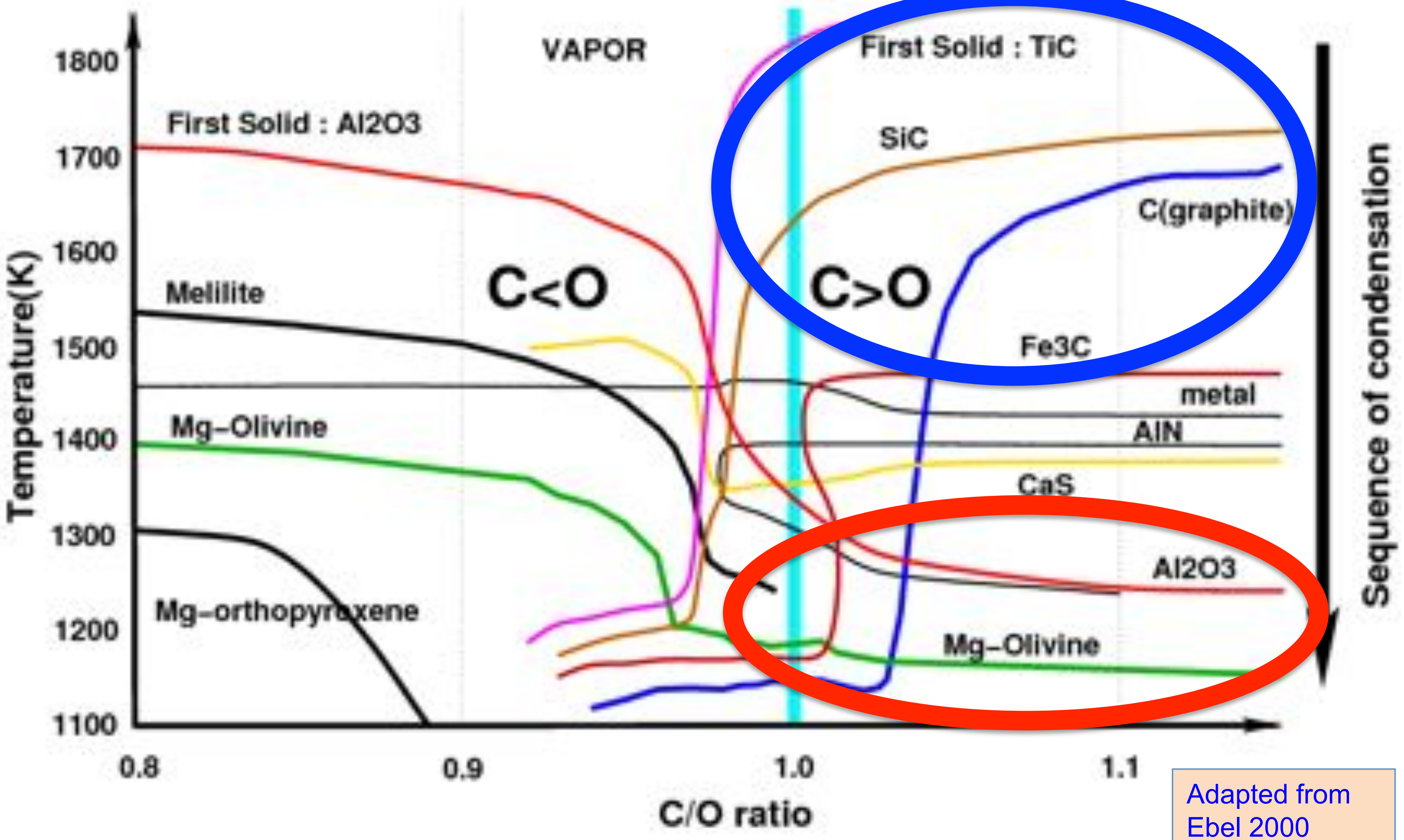
The crystalline « revolution »



ISO

Jaeger et al. 1998

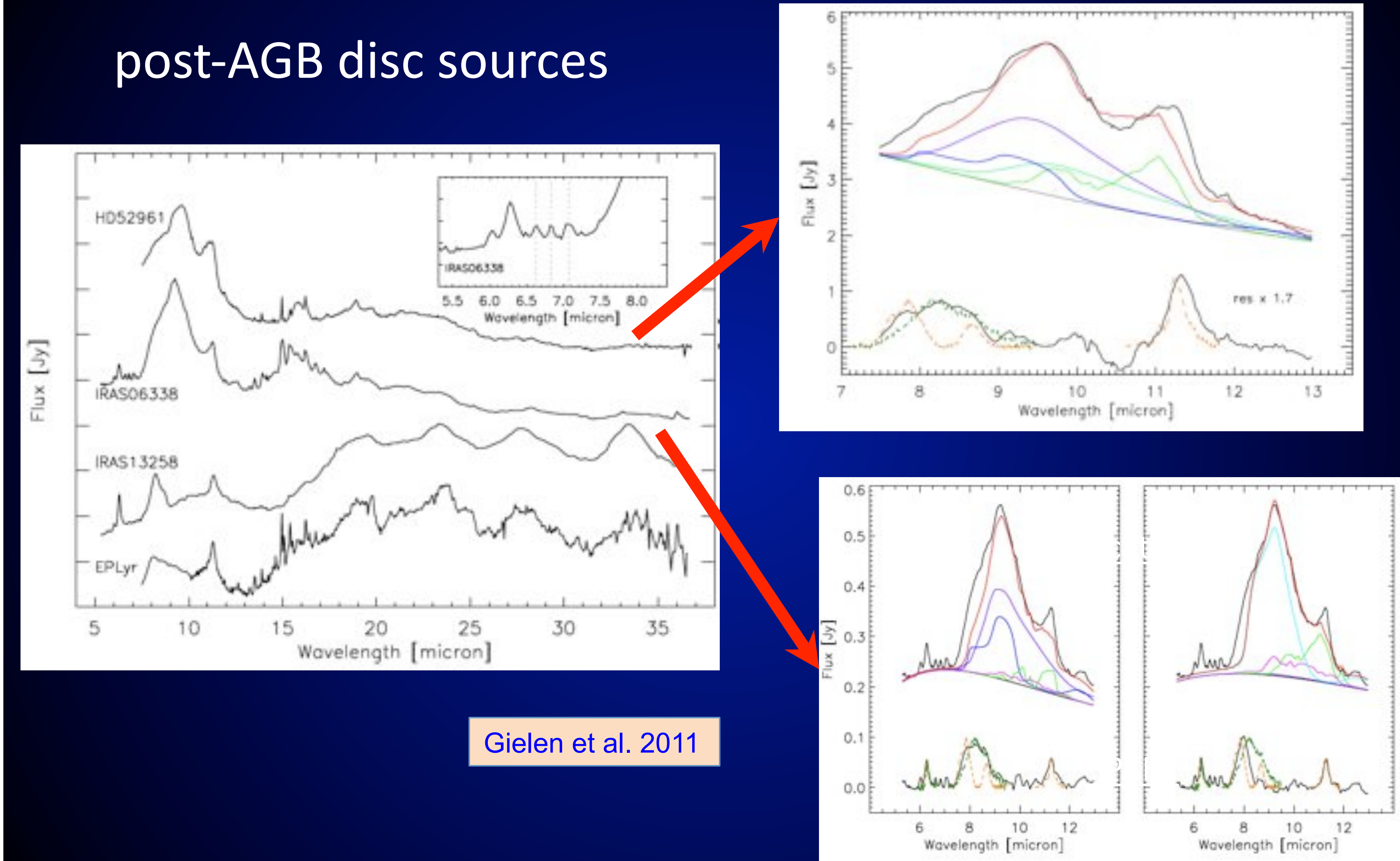
Chemical sequences



Adapted from
Ebel 2000

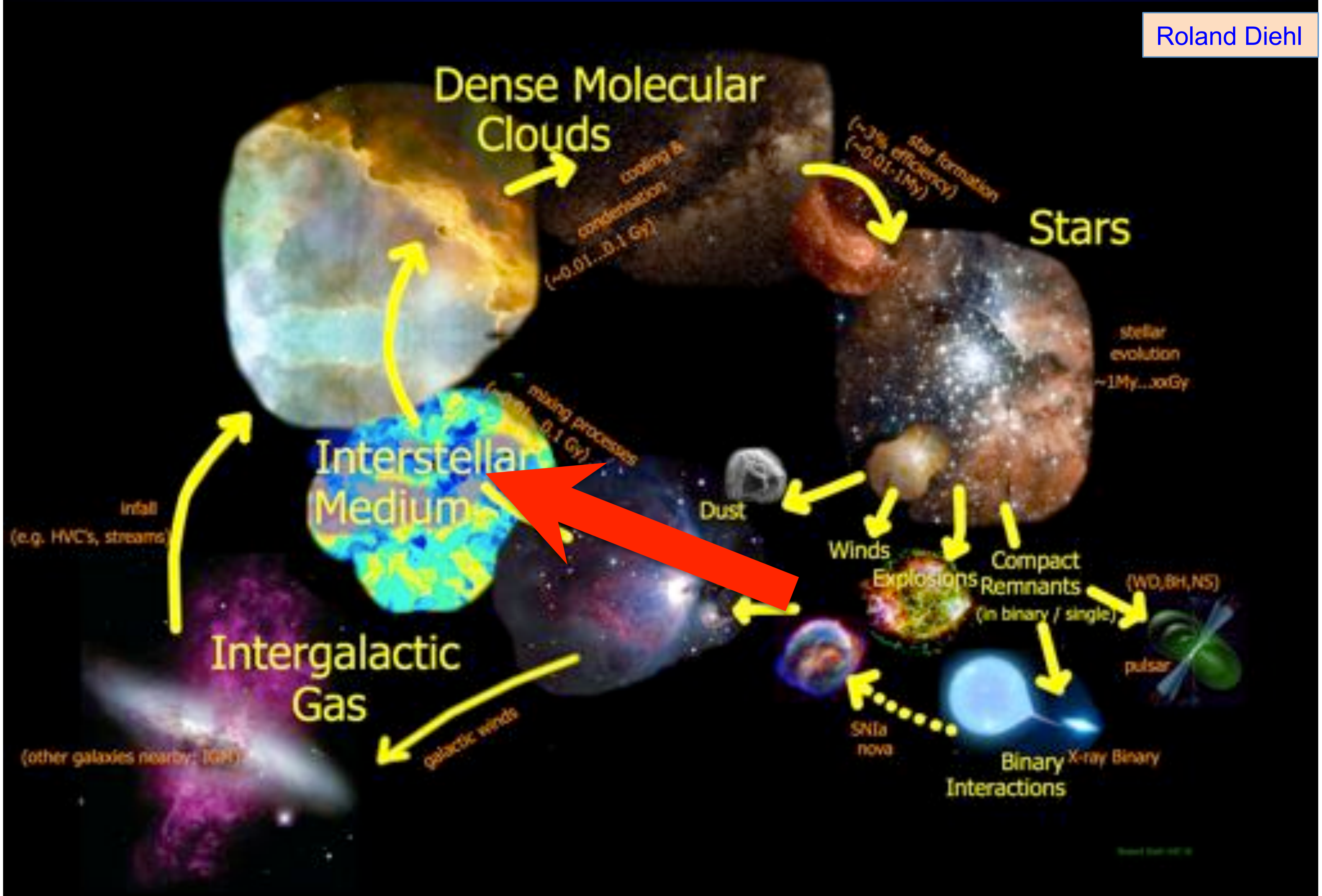
Exemple of mixed sequences

post-AGB disc sources

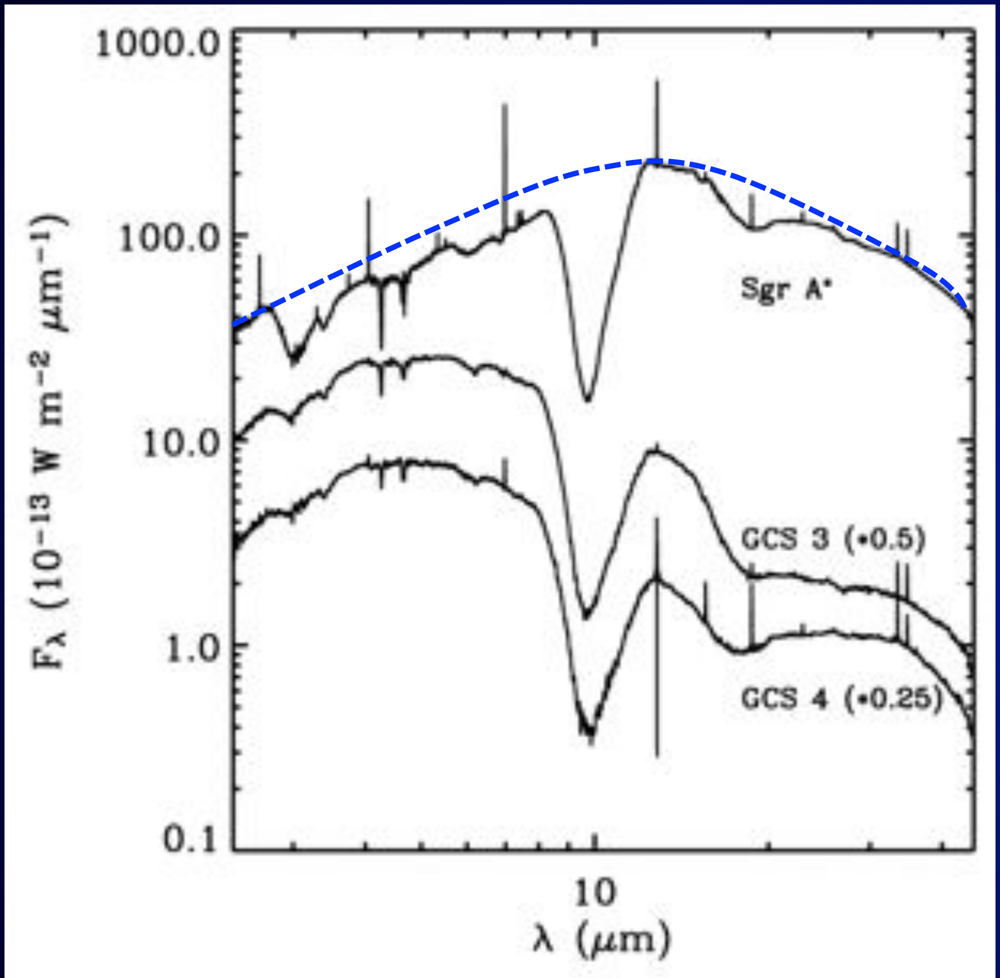


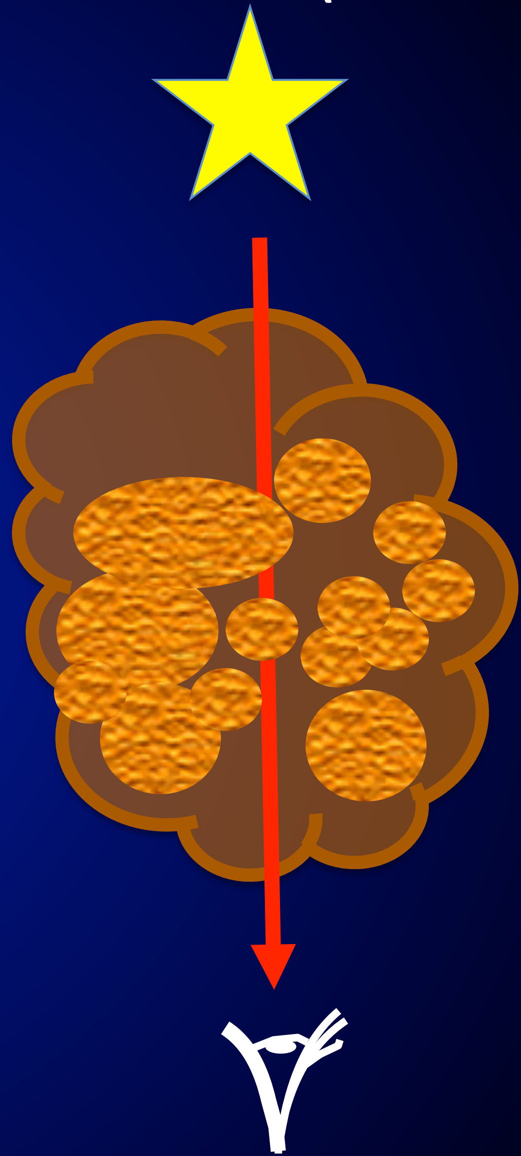
Gielen et al. 2011

Roland Diehl



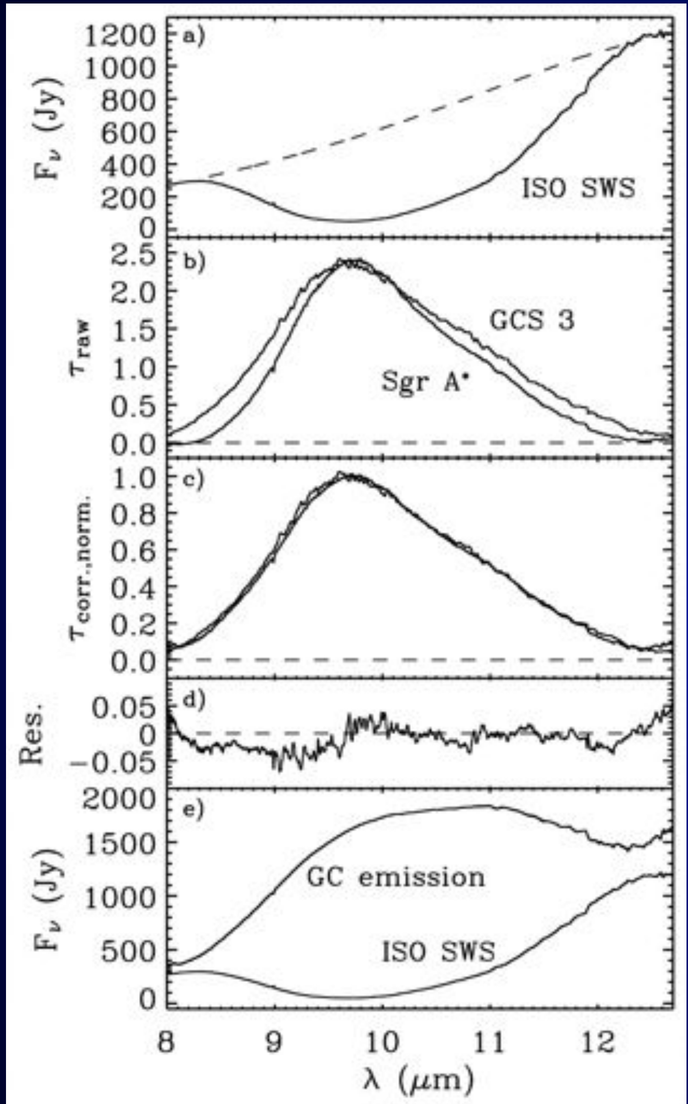
Silicates in the diffuse interstellar medium (DISM)



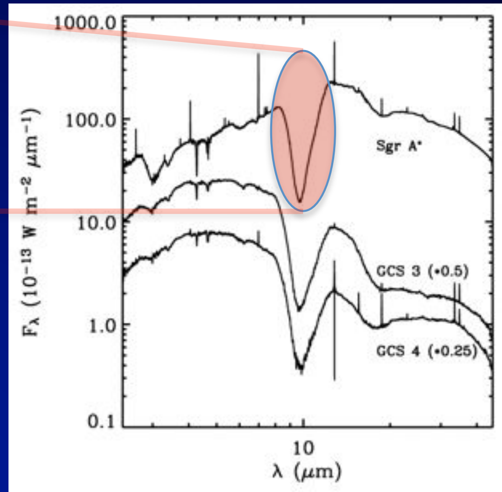


Kemper et al. 2004

Silicates in the diffuse interstellar medium (DISM)



Kemper et al. 2004

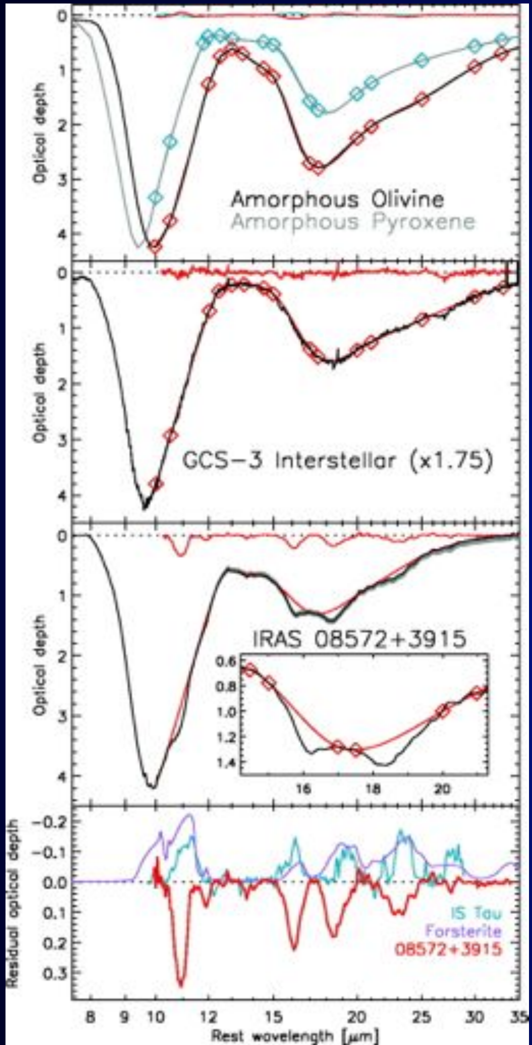


ISM silicates almost fully « amorphous »

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

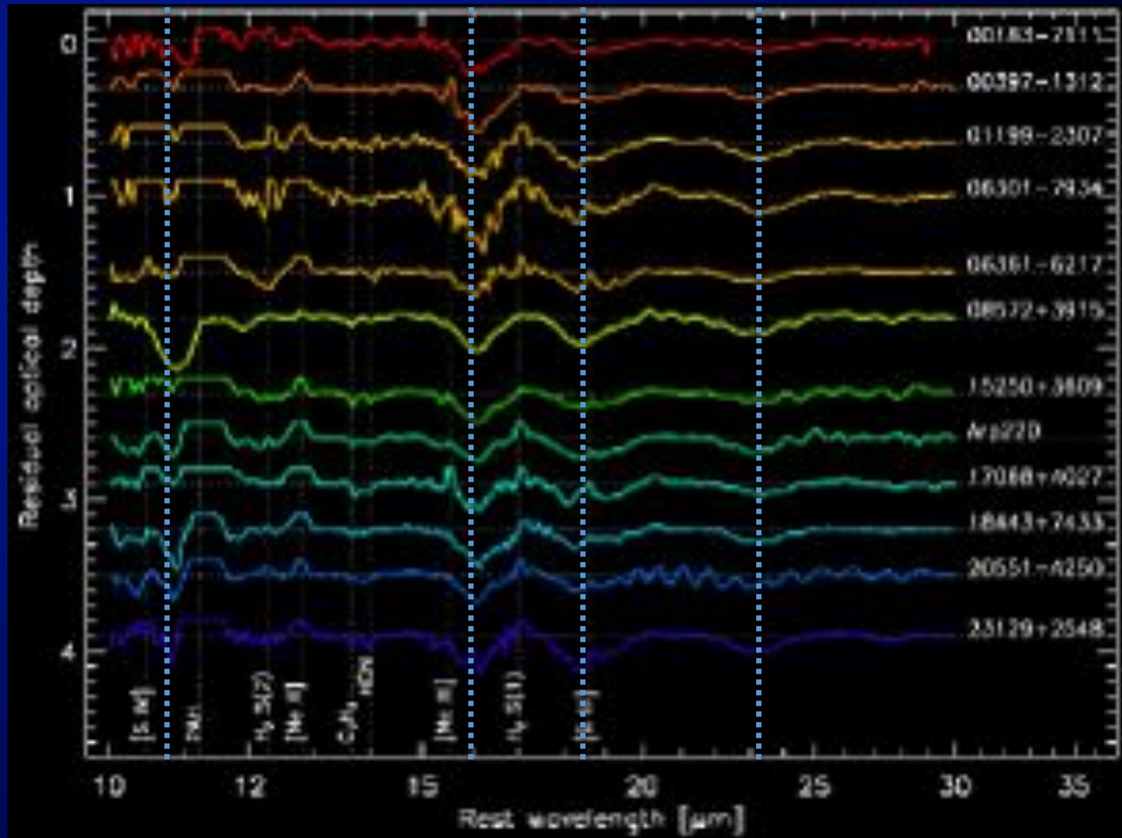
And in the Rayleigh limit (small)

Exception : ULIRGs' ISM

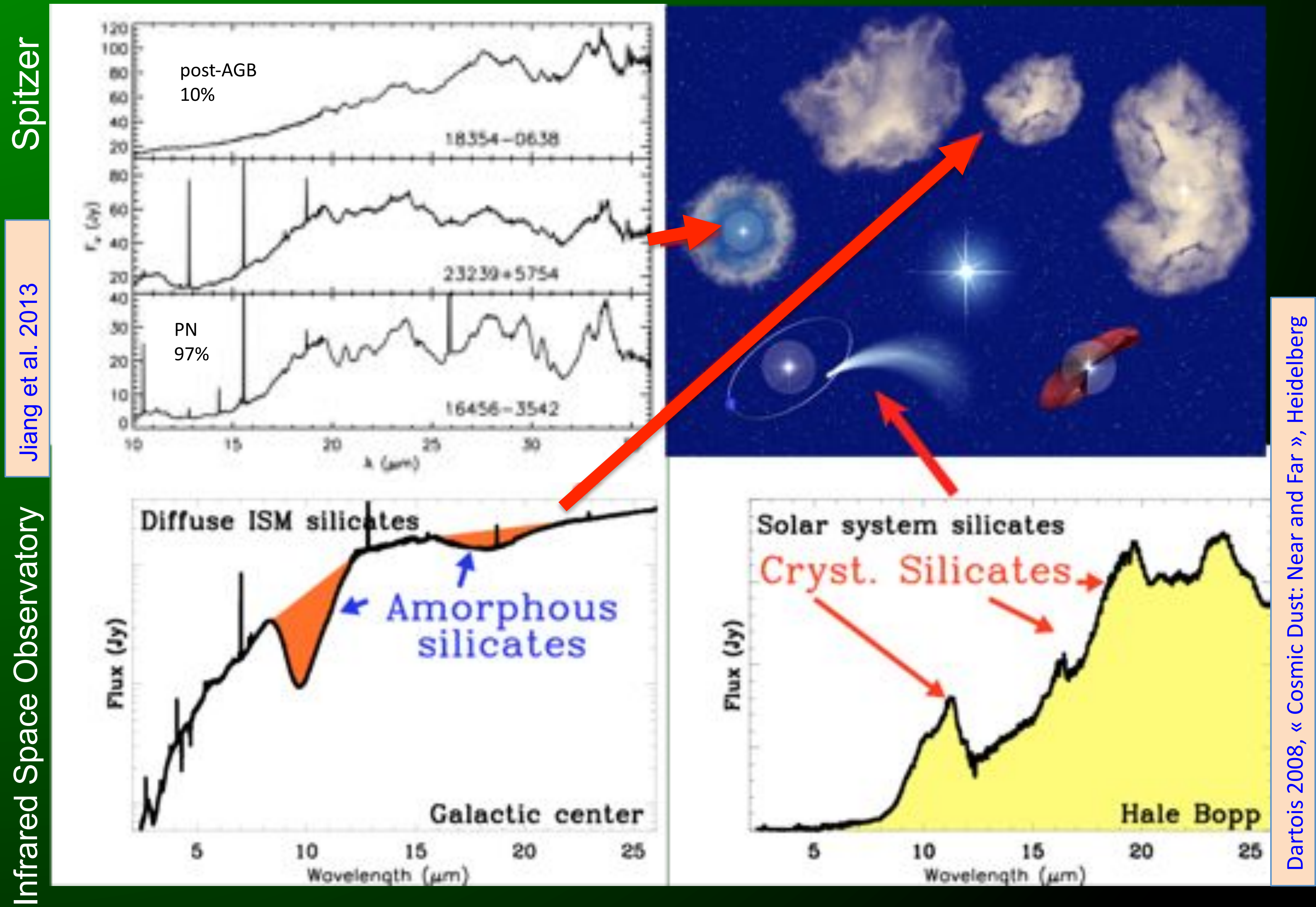


Spoon et al. 2006

Arp220, Hubble

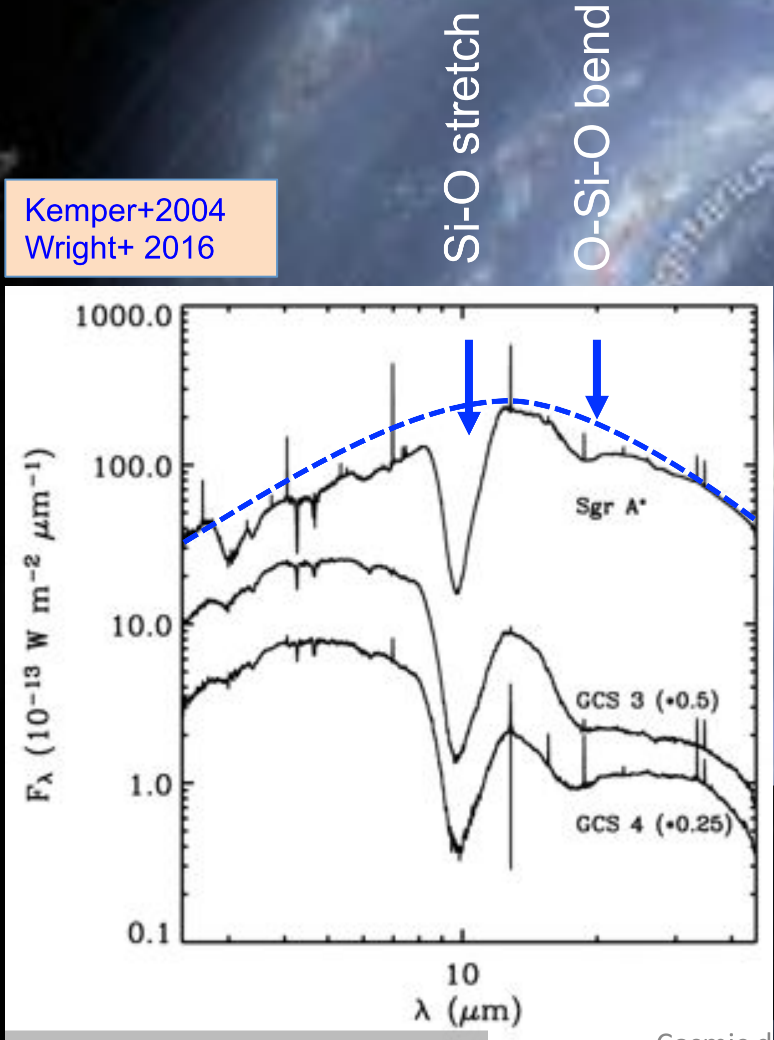


Silicates : crystals are locally formed/(re-)processed

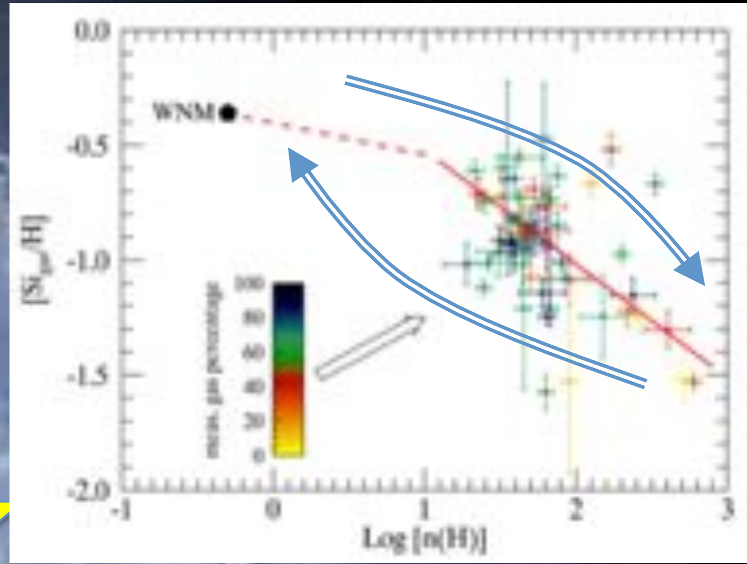


Why amorphous silicates in the DISM?

Kemper+2004
Wright+ 2016



1.1% ± 1.1cristallins

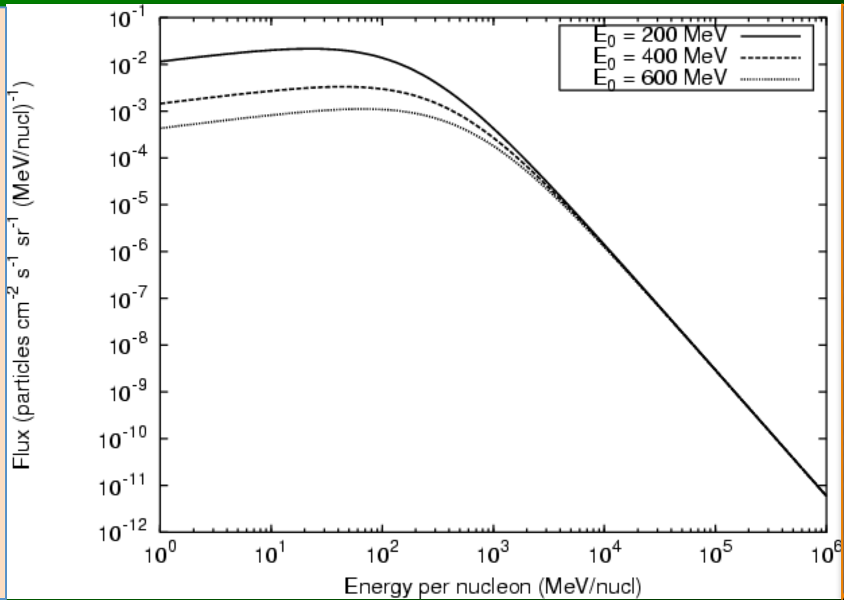


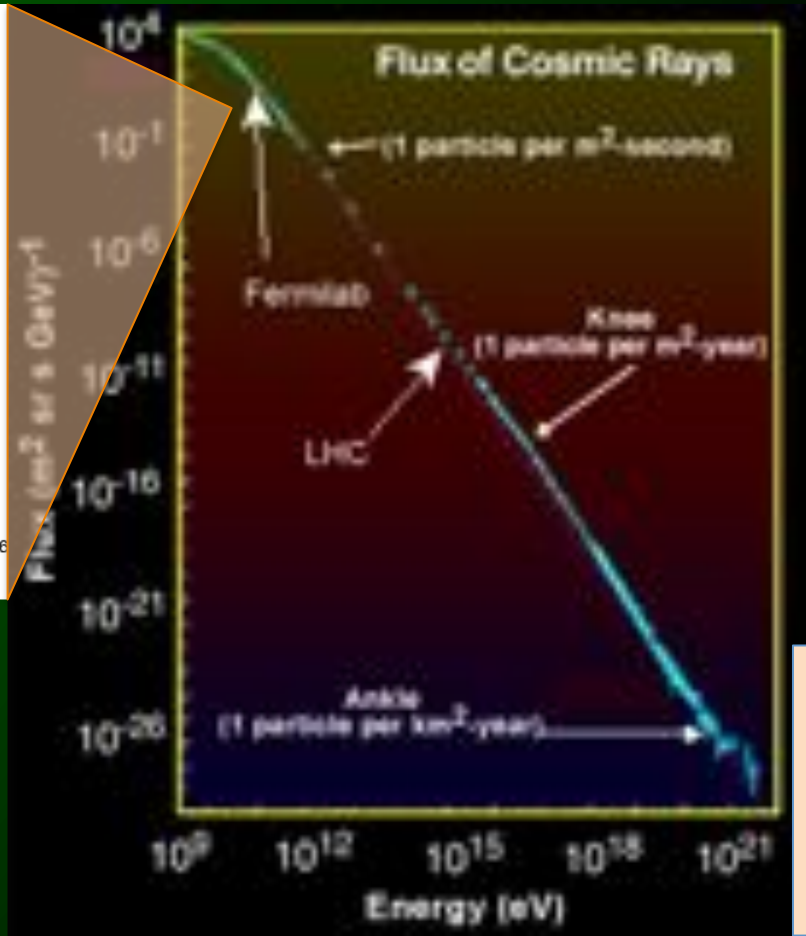
Zuhkovska+ 2016, Jenkins 2011

Proportion inherited from stars vs growth by accretion in ISM ?

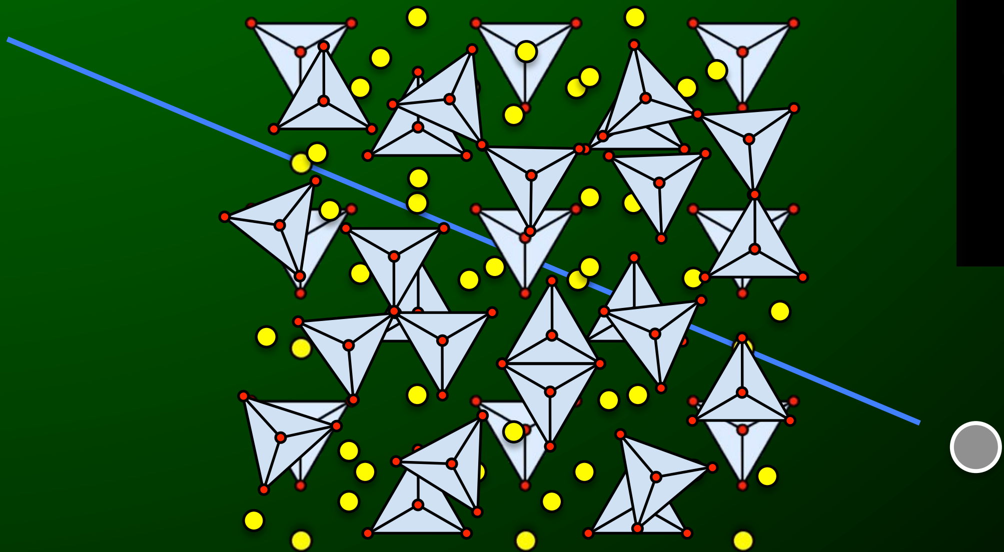
Influence of cosmic rays

Webber & Yushak 1983, Shen 2004



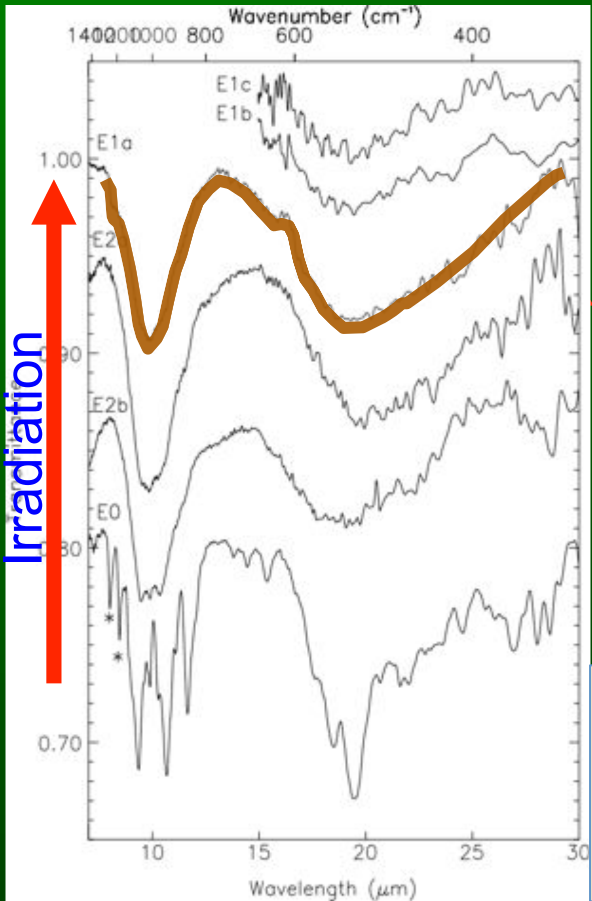


LPSC Grenoble

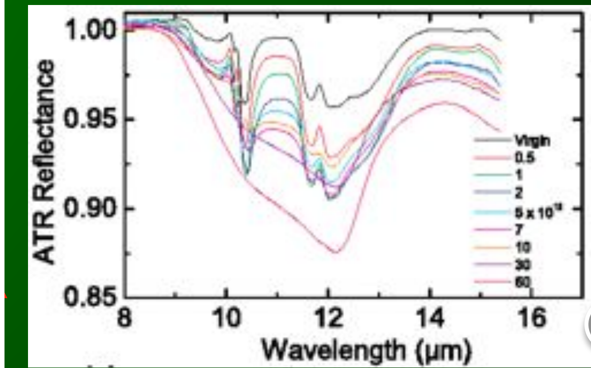


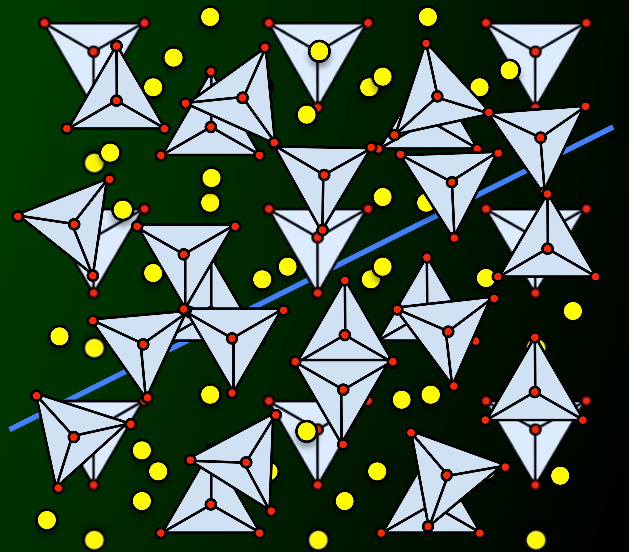
Amorphous silicates & CR in the laboratory

CR irradiation simulations 20-50keV He
+ irradiation of Enstatite (MgSiO3)

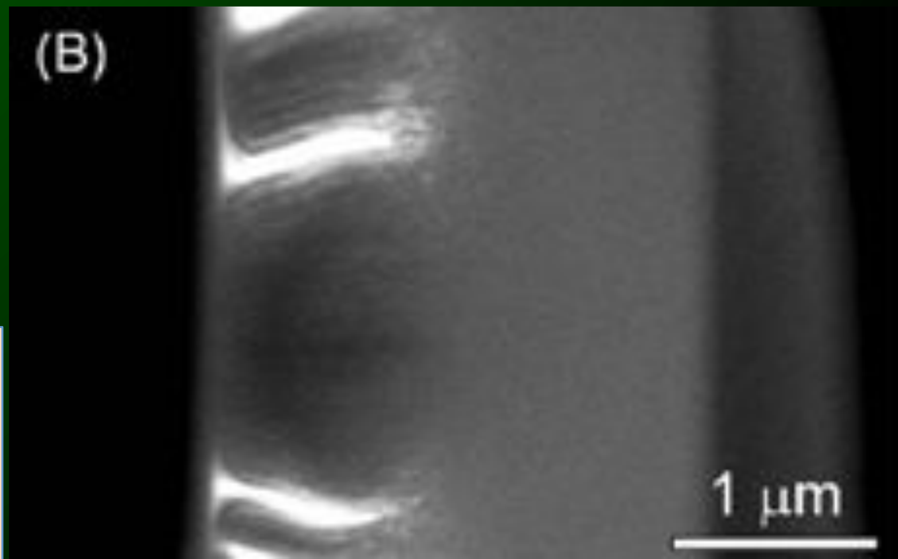


Demyk+2004



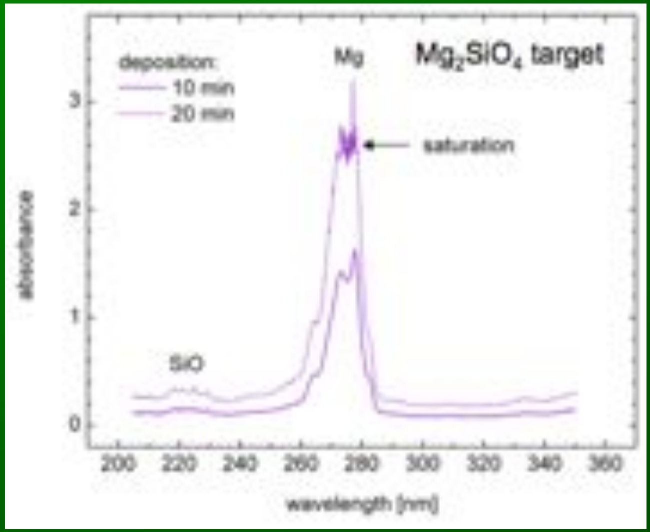


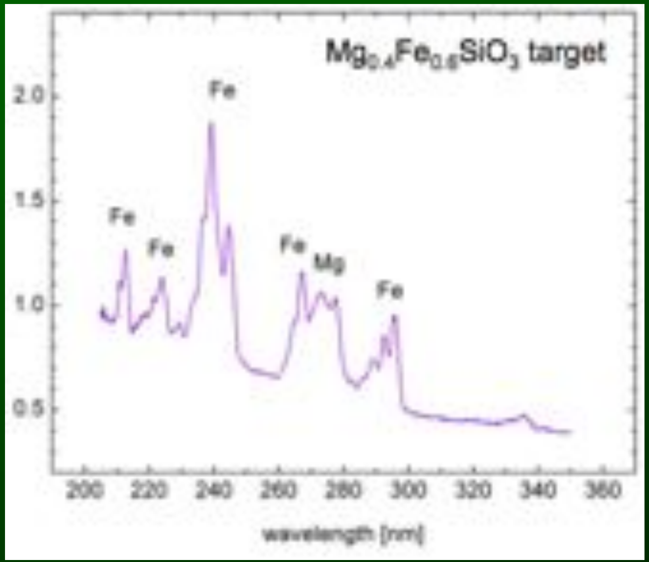
Bringa+2007



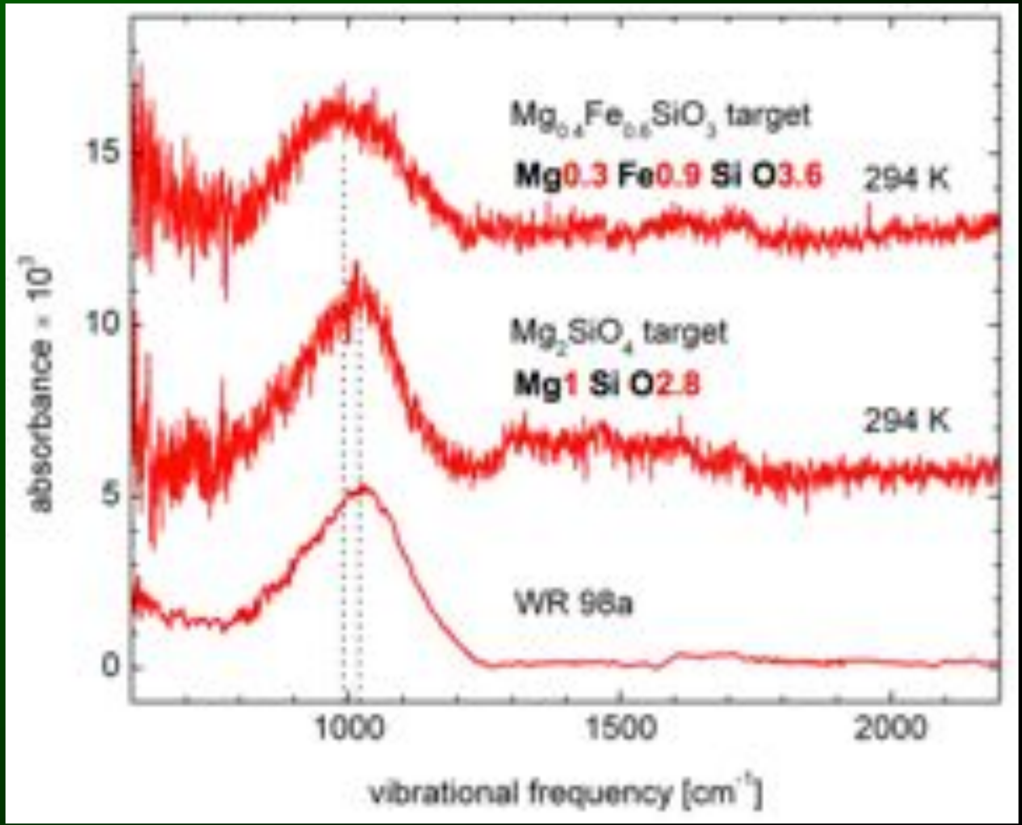
e.g. Sczenes+2010, Bringa+2007, Stratzzulla+2005, Demyk+2004, Brucato+2003, 2004, Carrez+2002, Shrempel+2002

Amorphous silicates from gas in the lab

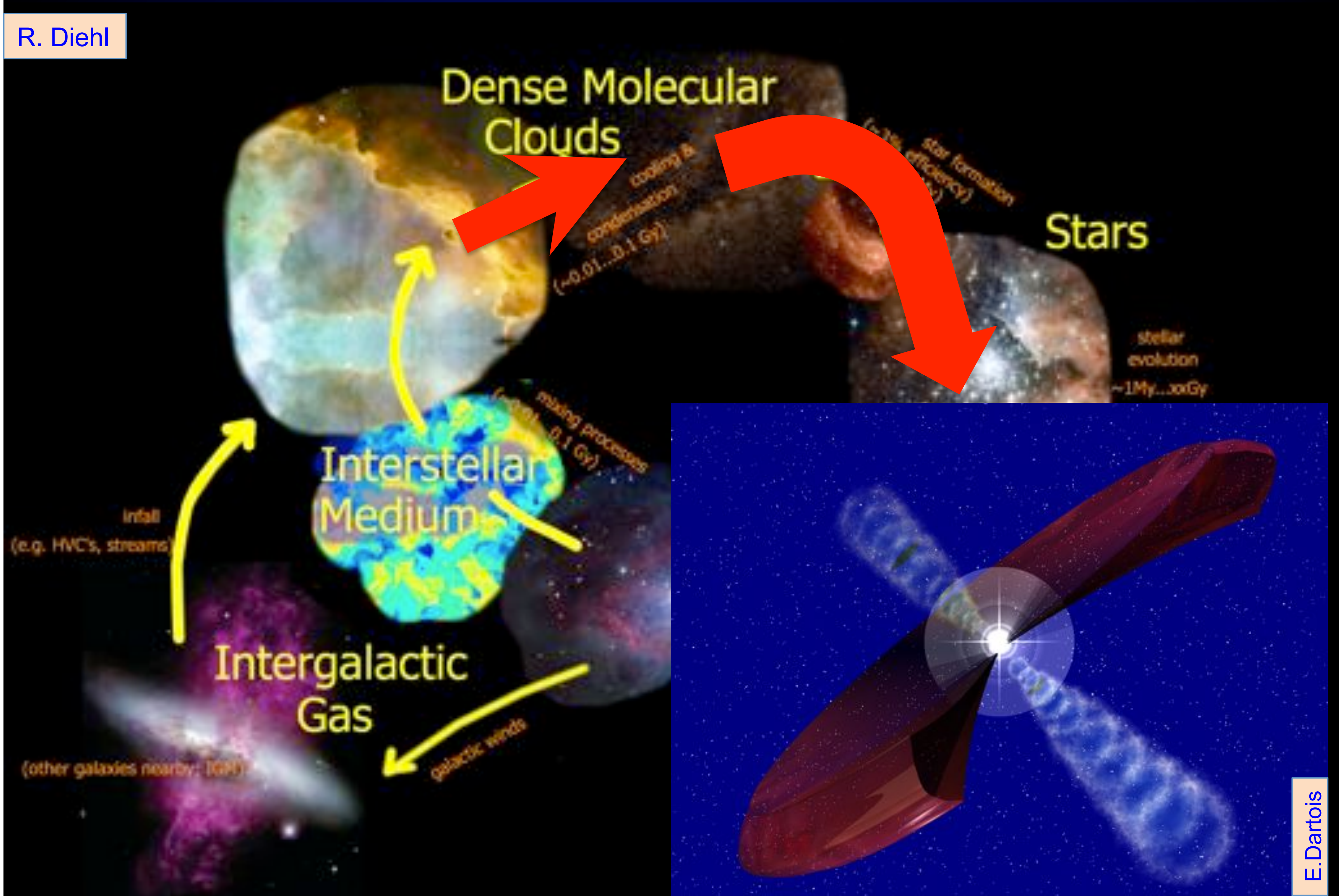




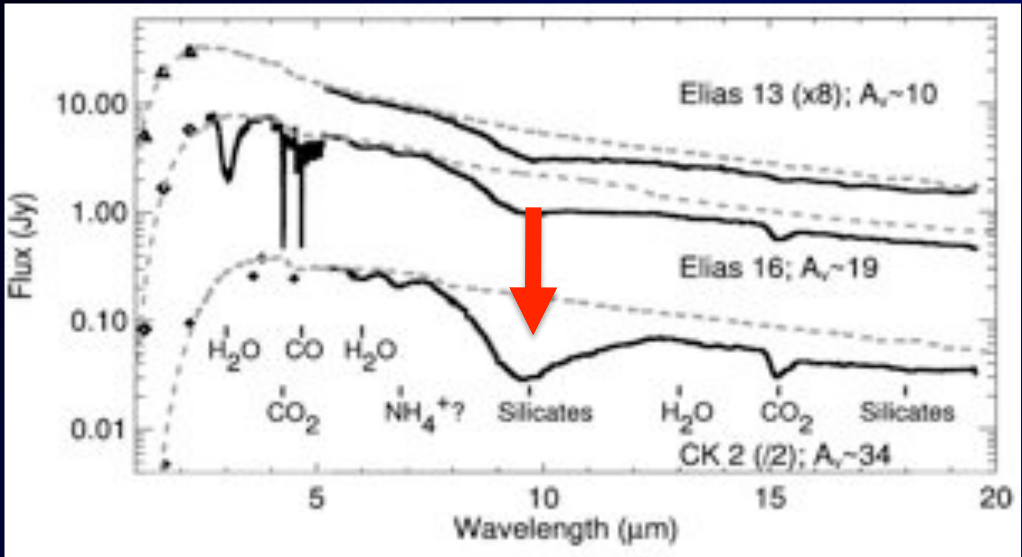
Lab work on condensation of an amorphous phase from atoms at very low T



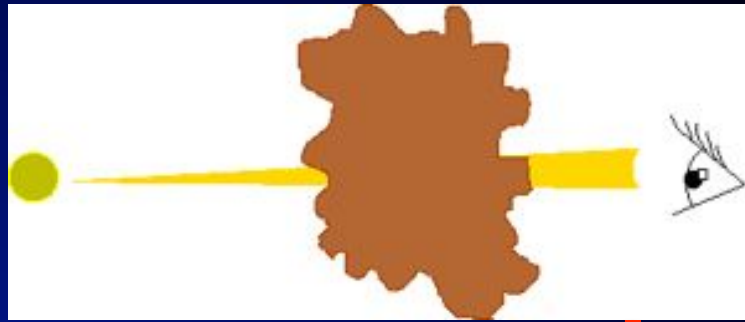
e.g. Rouillé+2014, Nuth & Moore1989
Donn+1981, Khanna+1981

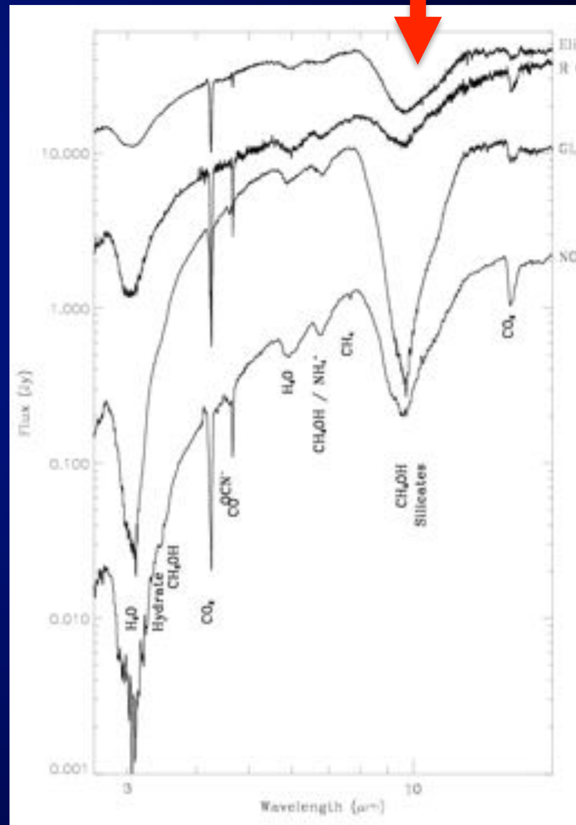

R. Diehl
Dense Molecular Clouds
cooling & condensation
(~0.01...0.1 Gy)
star formation
Stars
stellar evolution
Interstellar Medium
mixing processes
infall
(e.g. HVC's, streams)
Intergalactic Gas
galactic winds
E.Dartois

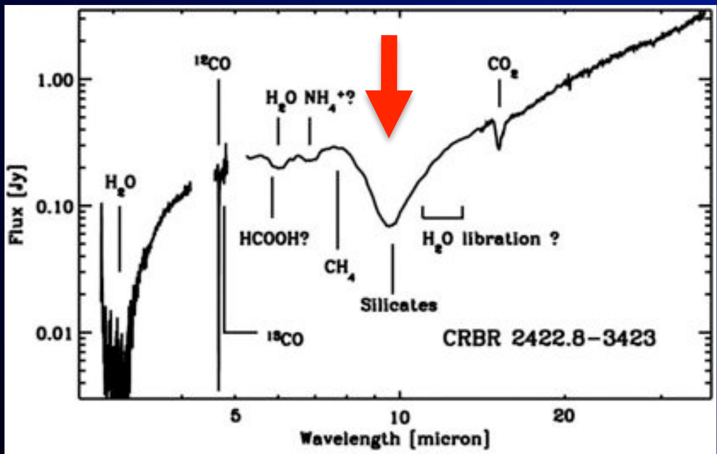
Silicates in the MC phase in a nutshell…

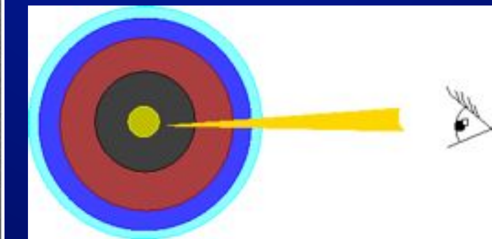


e.g. Knez+2005, Bergin+2005





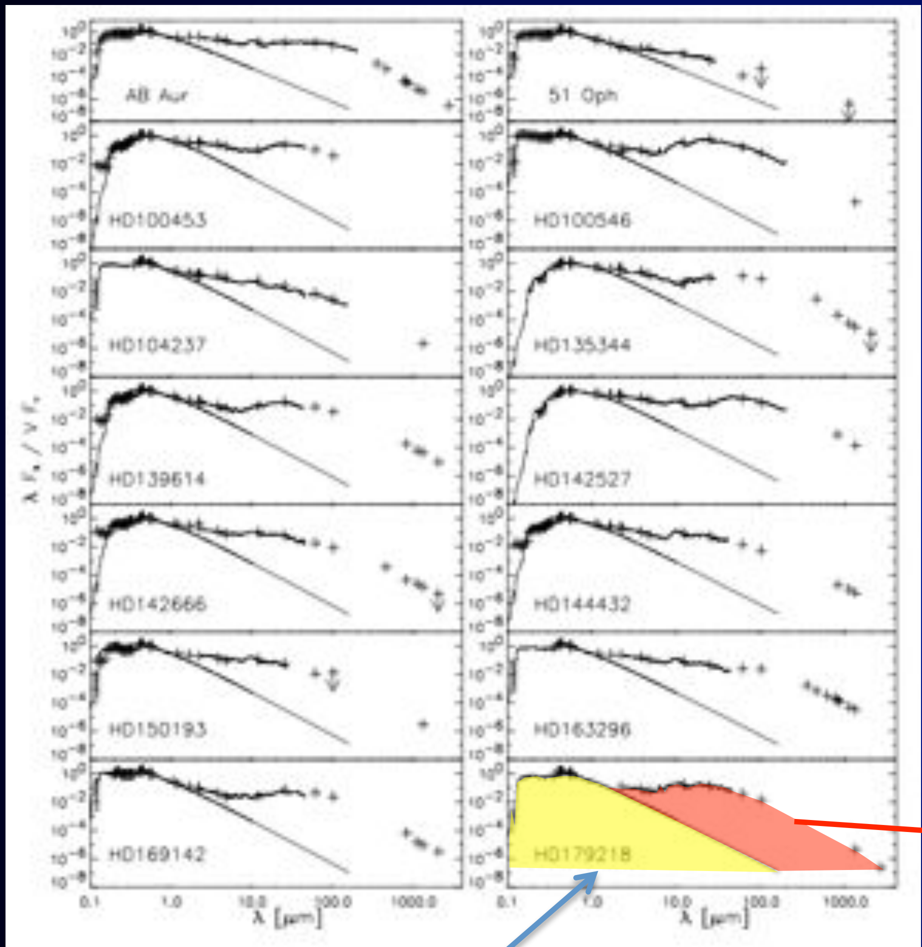


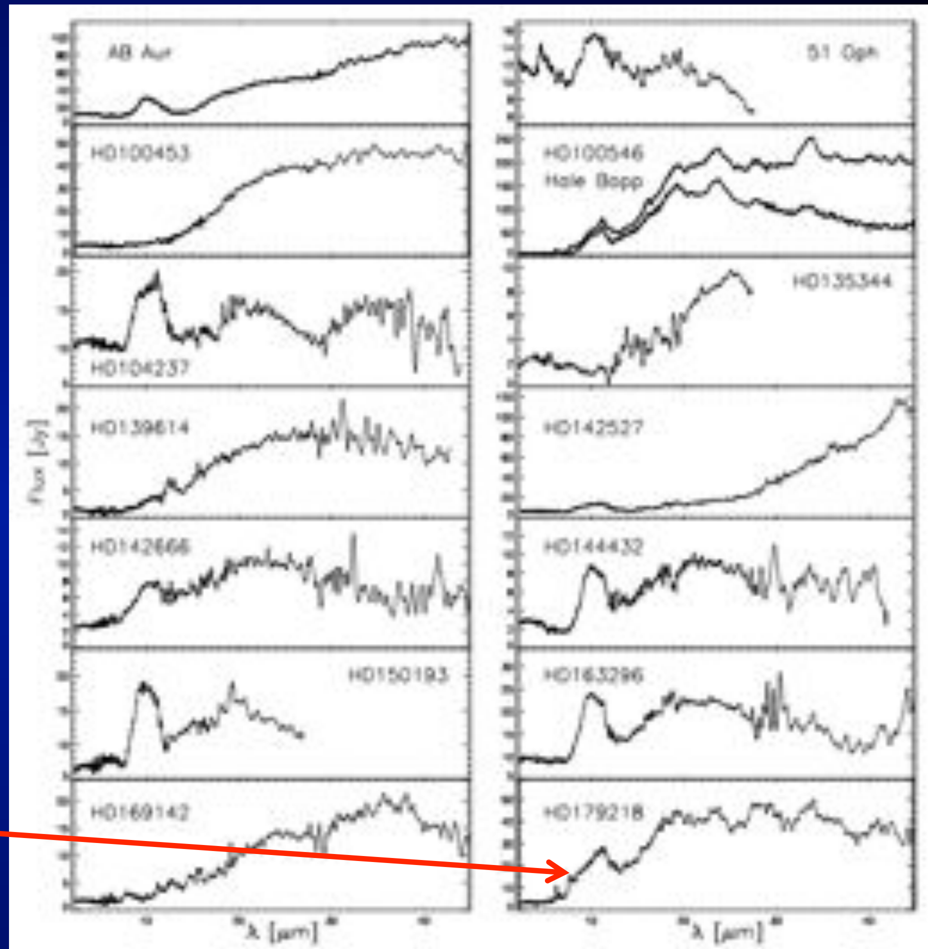


Spitzer/VLT, Pontoppidan+2005

ISO database extract

Silicates in circumstellar disks (Herbig Ae/Be)



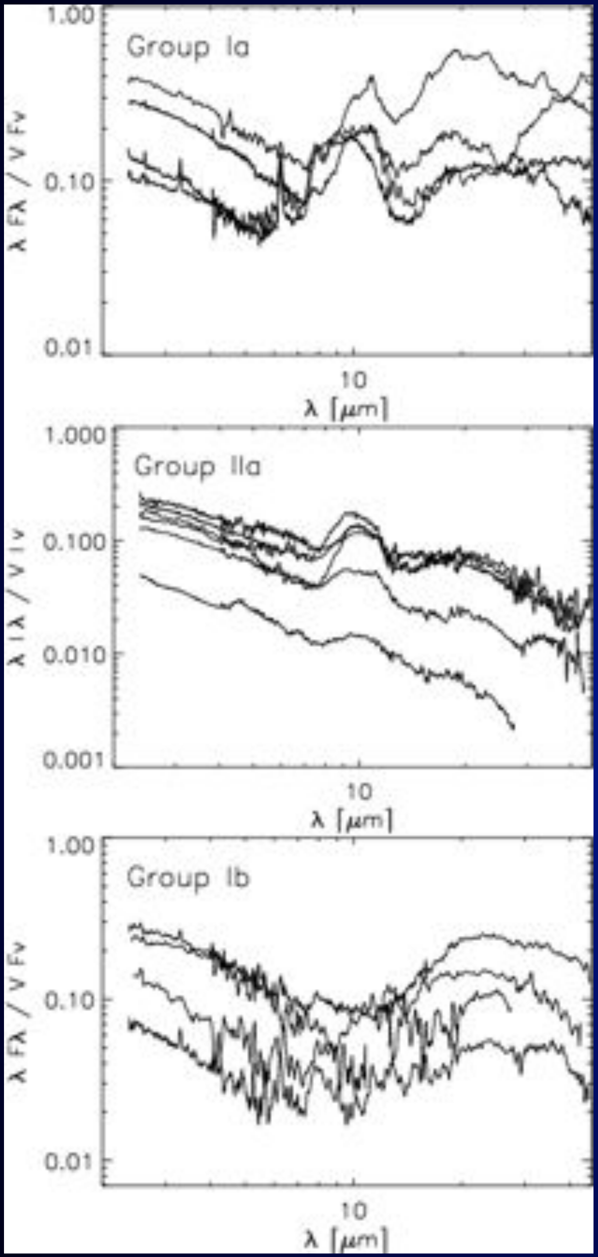


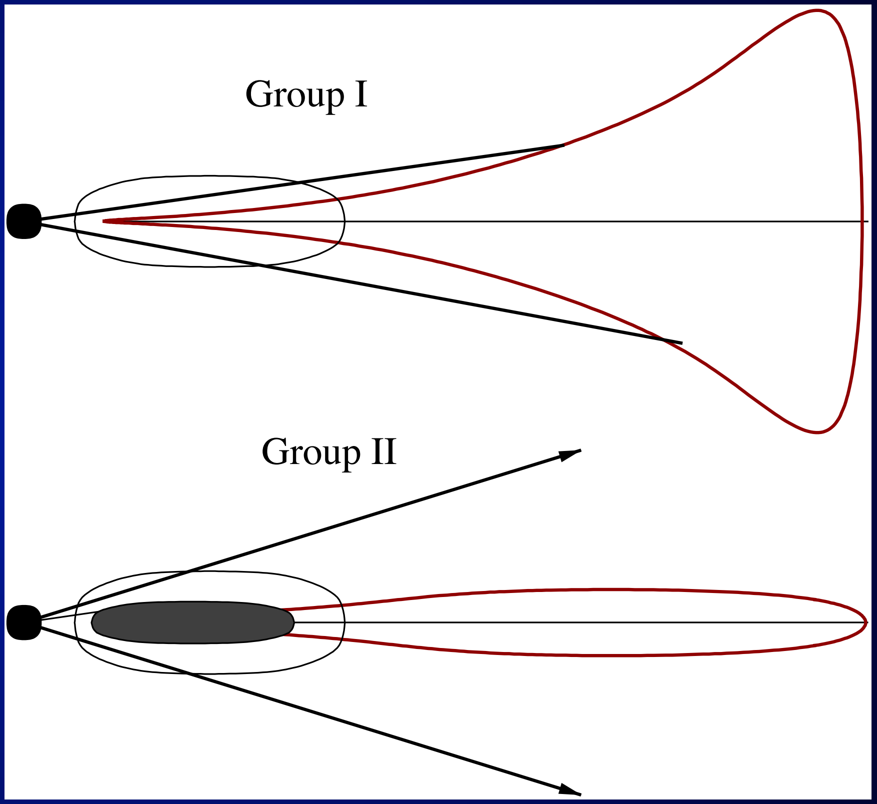
Modèle de Kurucz

Meeus et al. 2001

E Dartois & H. Leroux - Ecole des Houches 2017

Silicates in disks

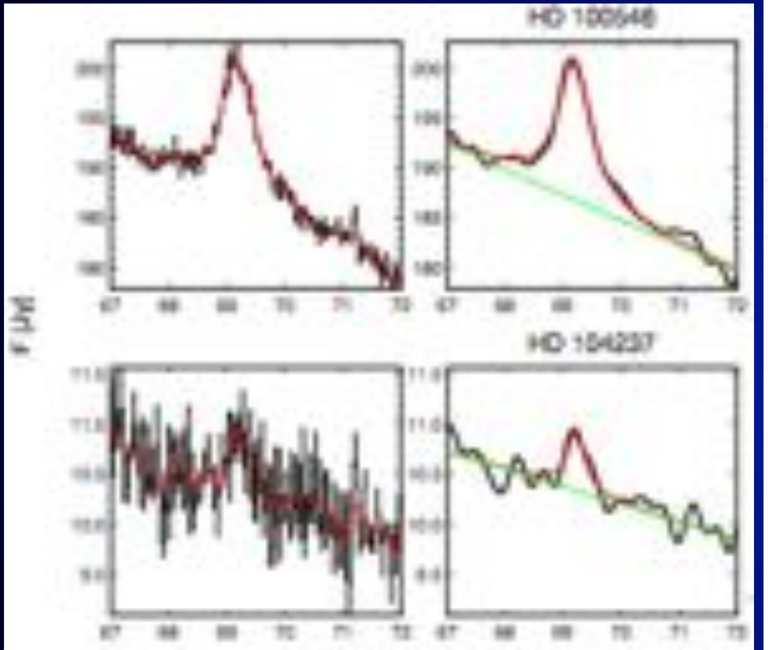




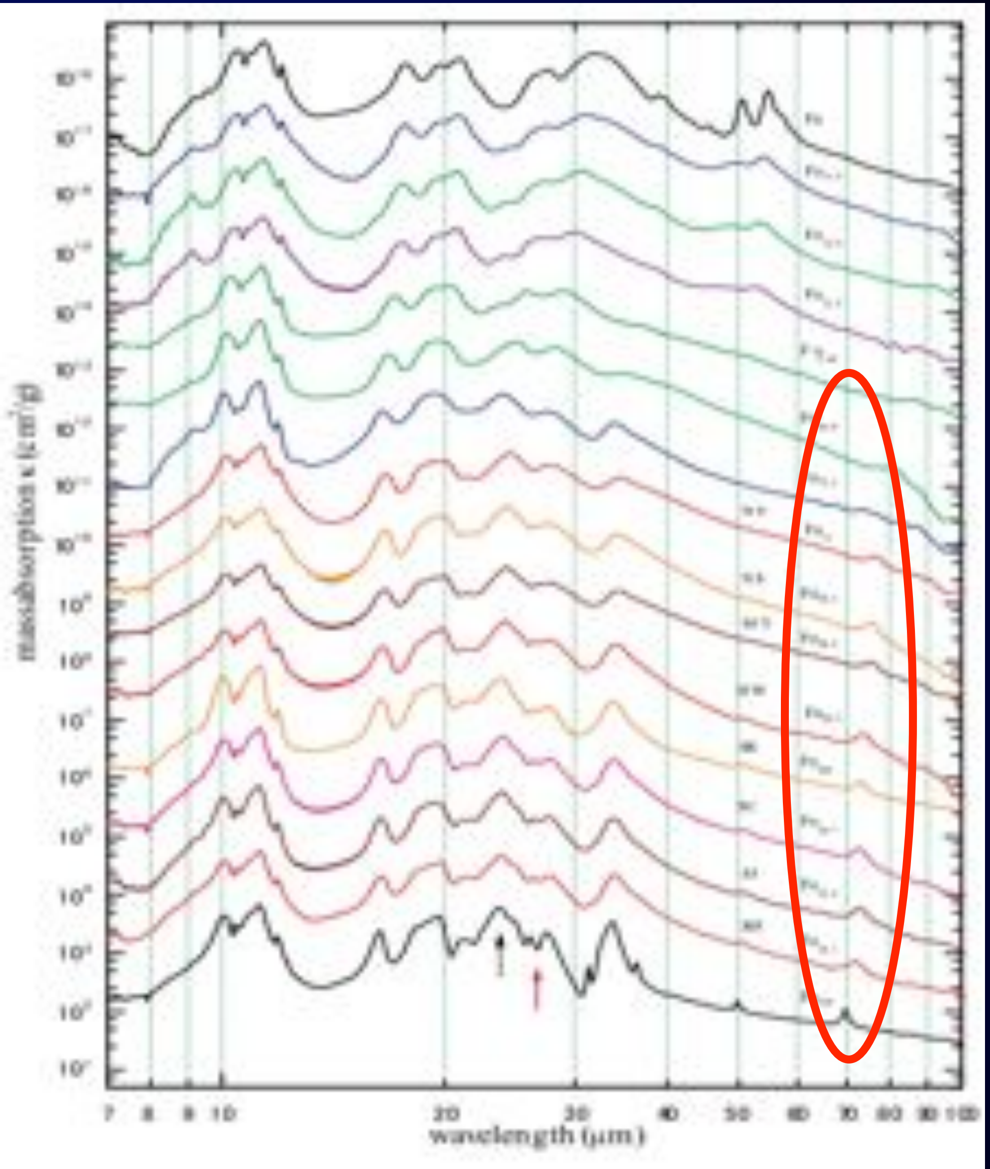
Meeus et al. 2001

Silicates in disks

Herschel



Sturm+ 2013, Malfait+ 1998

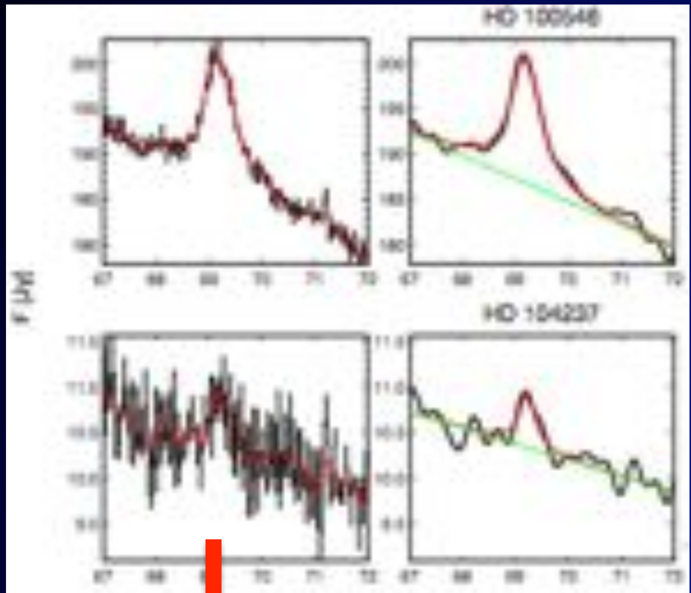


Fe content

Koike et al. 2003

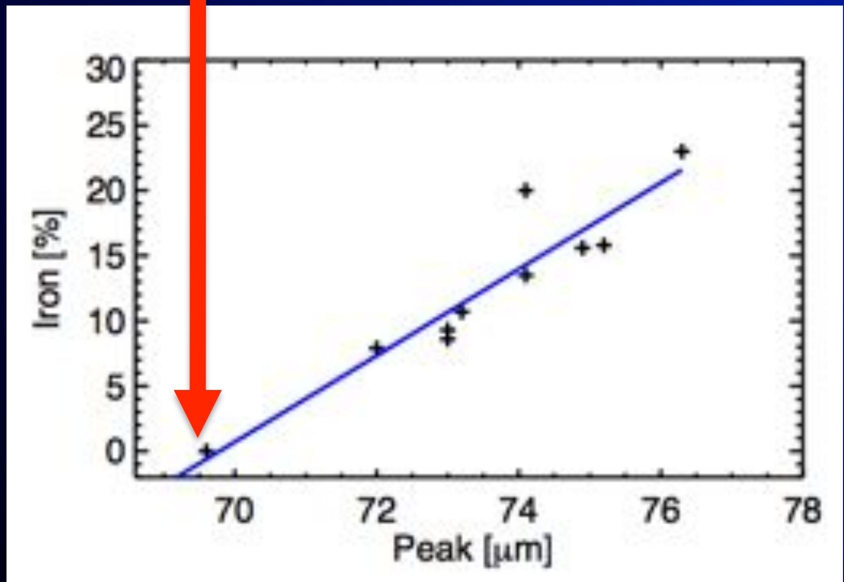
Silicates in disks

Herschel



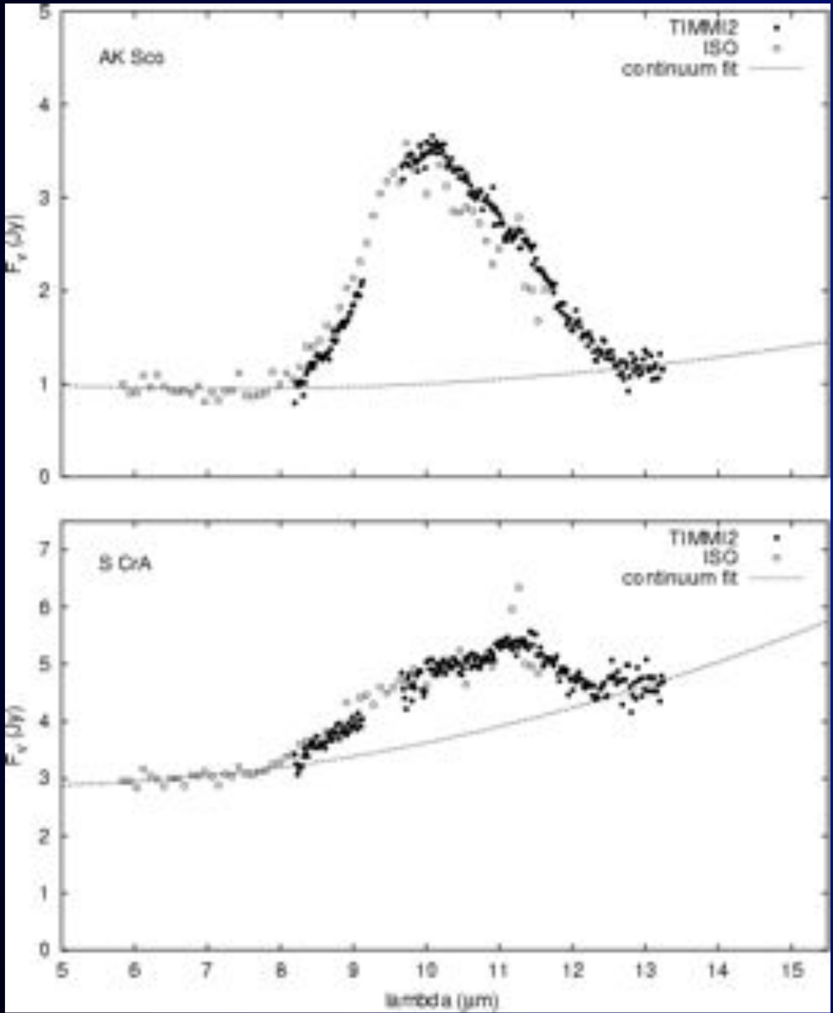
Star	Iron fraction [%] min	Iron fraction [%] max	Temperature [K] min	Temperature [K] max	distance [AU] min	distance [AU] max
AB Aur	1.9	3.5	74	273	16	221
HD 100546	0.1	0.3	184	223	20	29
HD 104237	0.4	1.2	60	184	31	289
HD 141569	0.0	1.2	107	>300	<9	72
HD 179218	0.4	0.7	126	173	104	196
HD 144668	0.0	0.4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

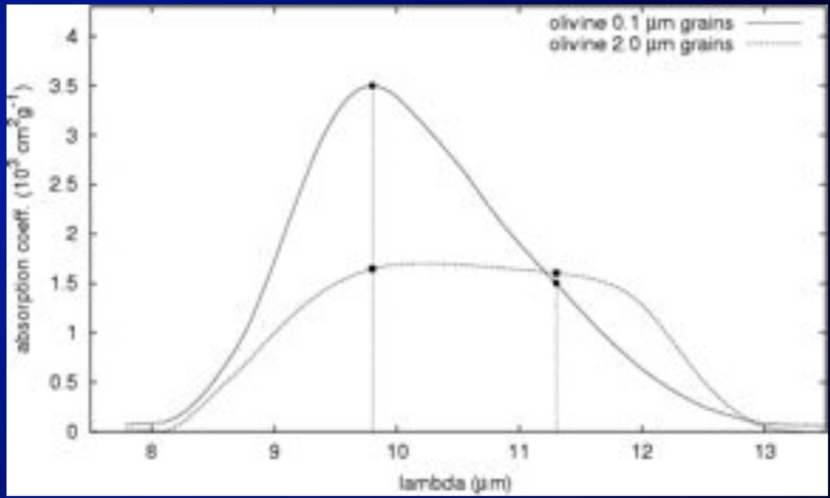
Sturm et al. 2013



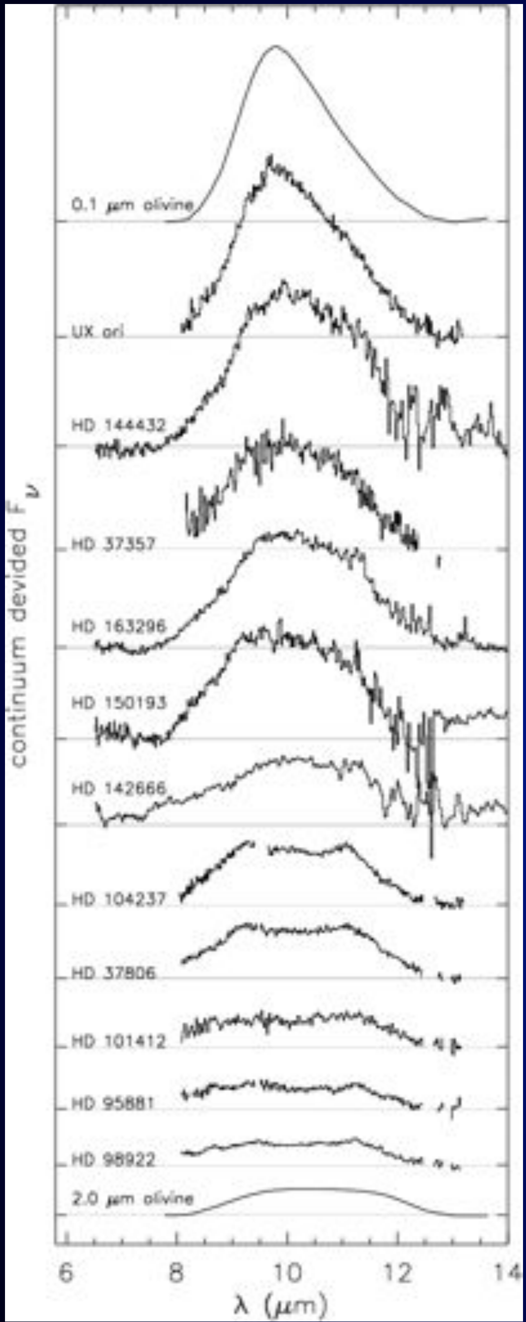
32 disk sources observed.
8 sources with 69 µm olivine feature
Except 1 T Tauri star, disks associated with Herbig Ae/Be stars.
Most of the olivine grains are iron-poor less than ~2% iron (forsterite like).
AB Aur is the only source where the emission cannot be fitted with iron-free forsterite, requiring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

Spectral evidence of silicate grains growth In T Tauri disks





Przyggoda et al. 2003



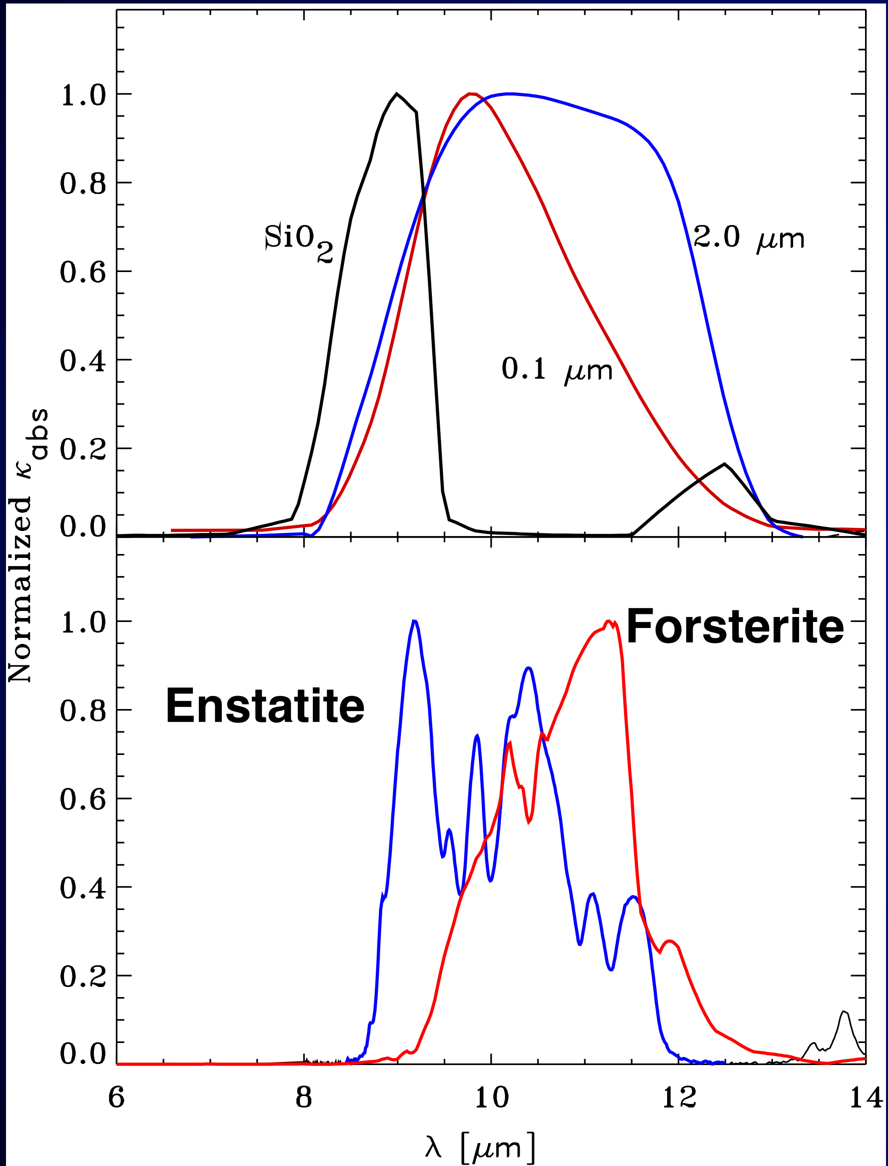
Spectral evidence of grain growth in Herbig Ae/Be

The dynamical mass in some disks imply bigger grain sizes

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

Van Boekel+ 2003

Mineralogy : dust in Herbig Ae Be

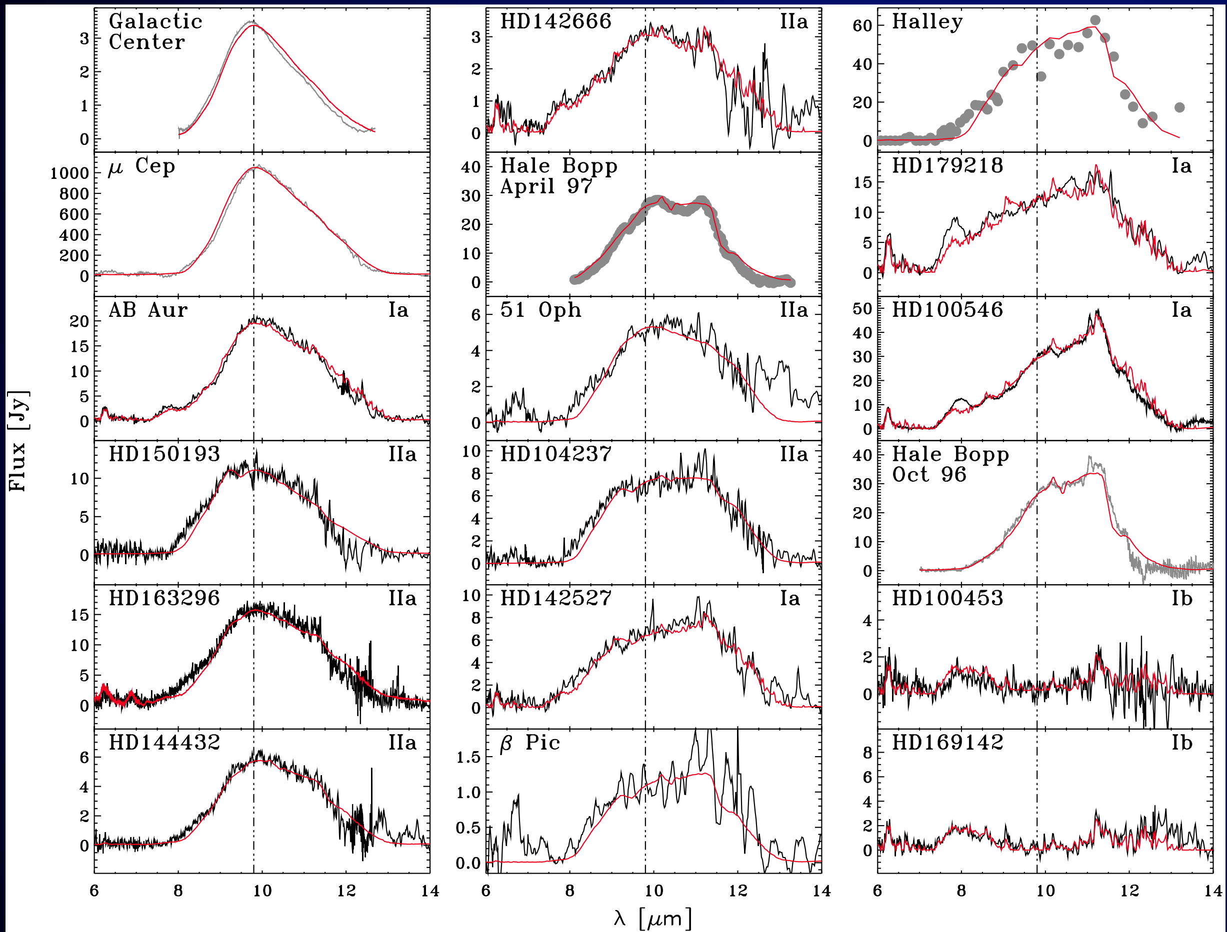


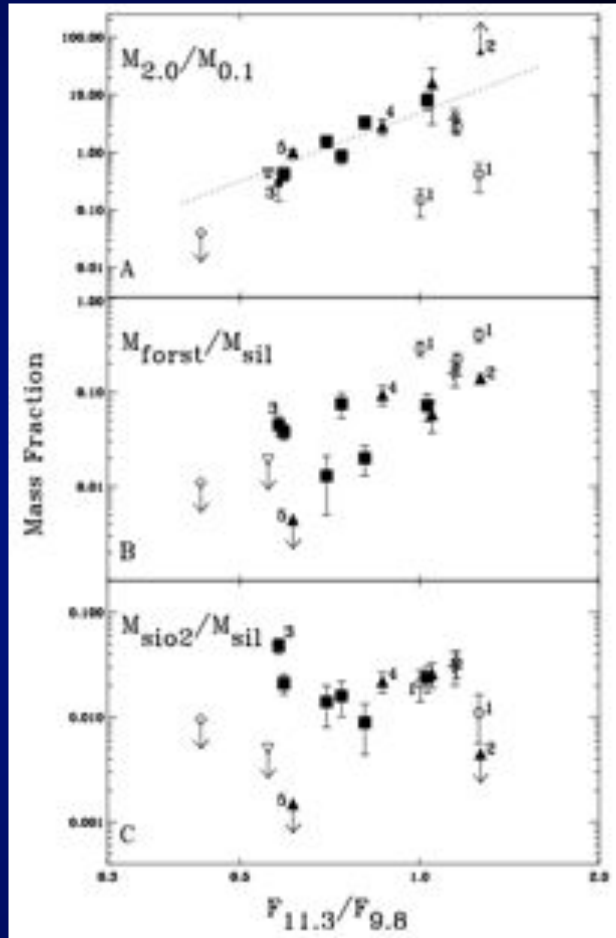
Several components:

- χ composition
- size
- Phase (am./cryst.)

Bouwman et al. 2001

Spectral fit to extract correlations

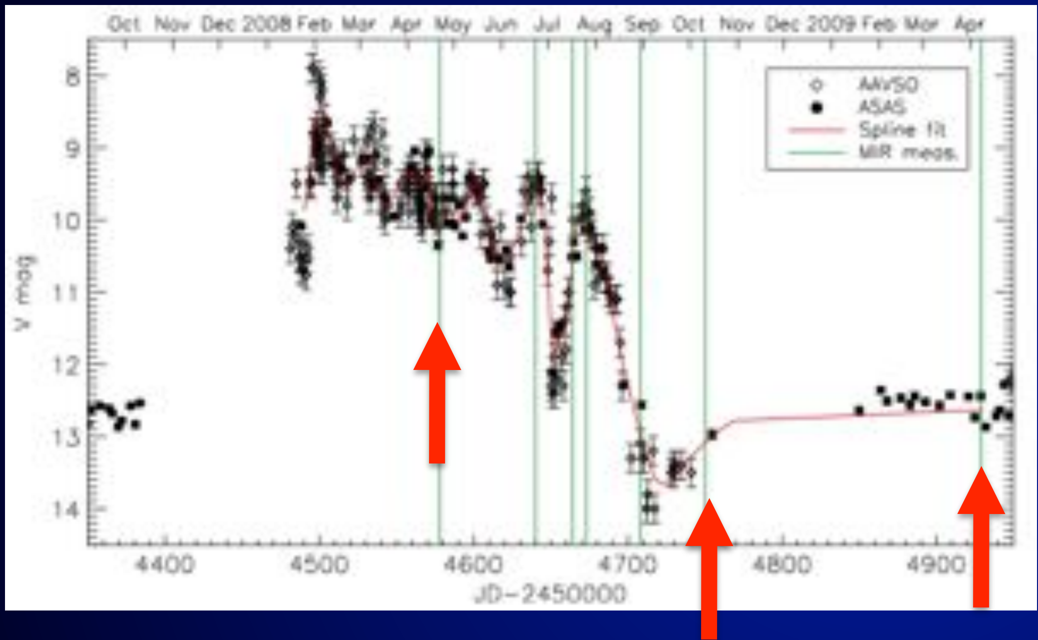


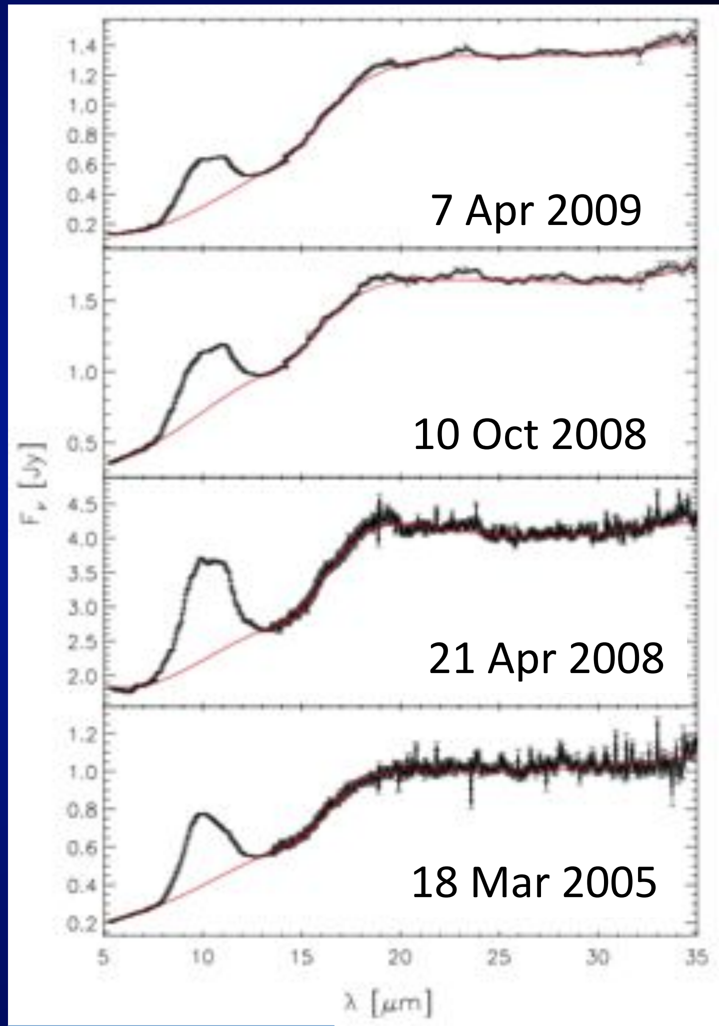


Bouwman et al. 2001

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

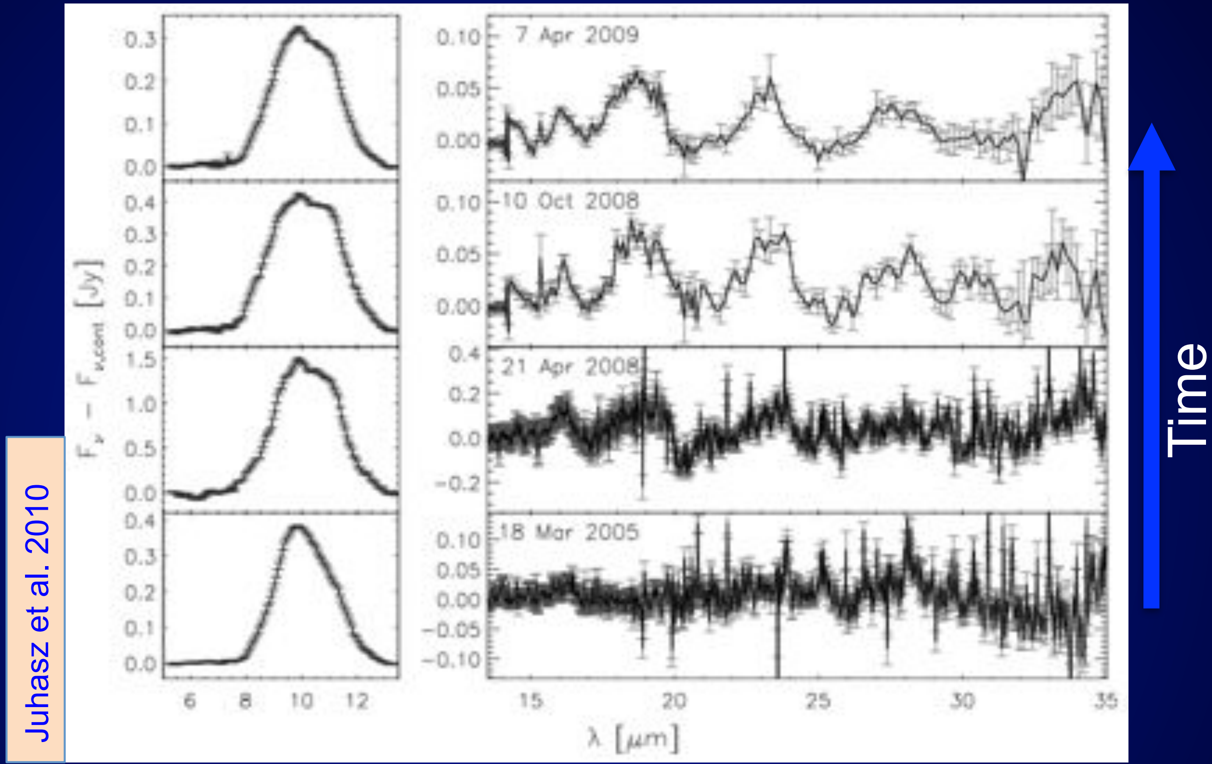
Light curve





Juhasz et al. 2010

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



March 2005 :

dominated by small amorphous grains (grain size of 0.5 µm)

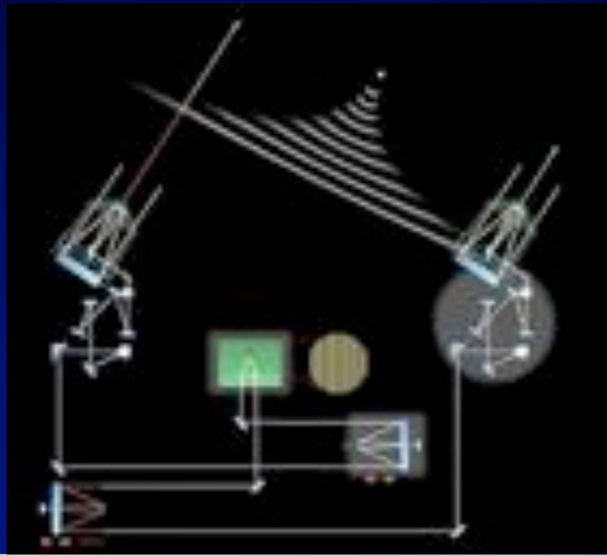
-crystalline silicates in the disk atmosphere is negligible

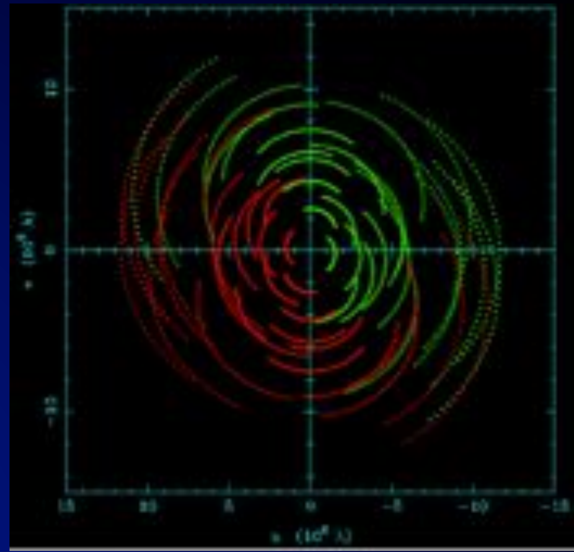
April 2008 :

absolute flux level increased by about an order of magnitude

Dominated by crystalline forsterite formed within 1.1 AU from the central star

IR Interferometry : silicates in disks

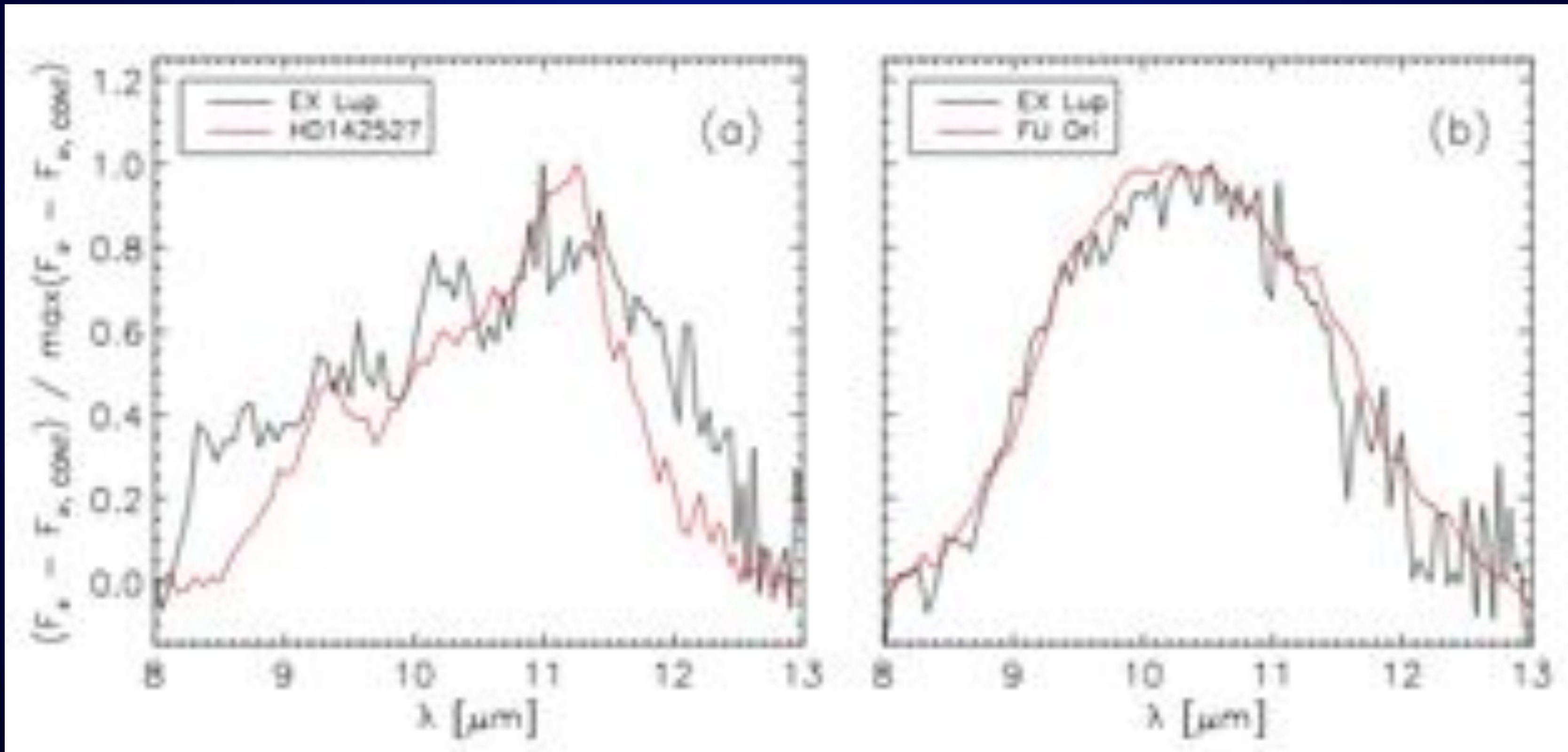




Haniff 2010

VLTI / ESO

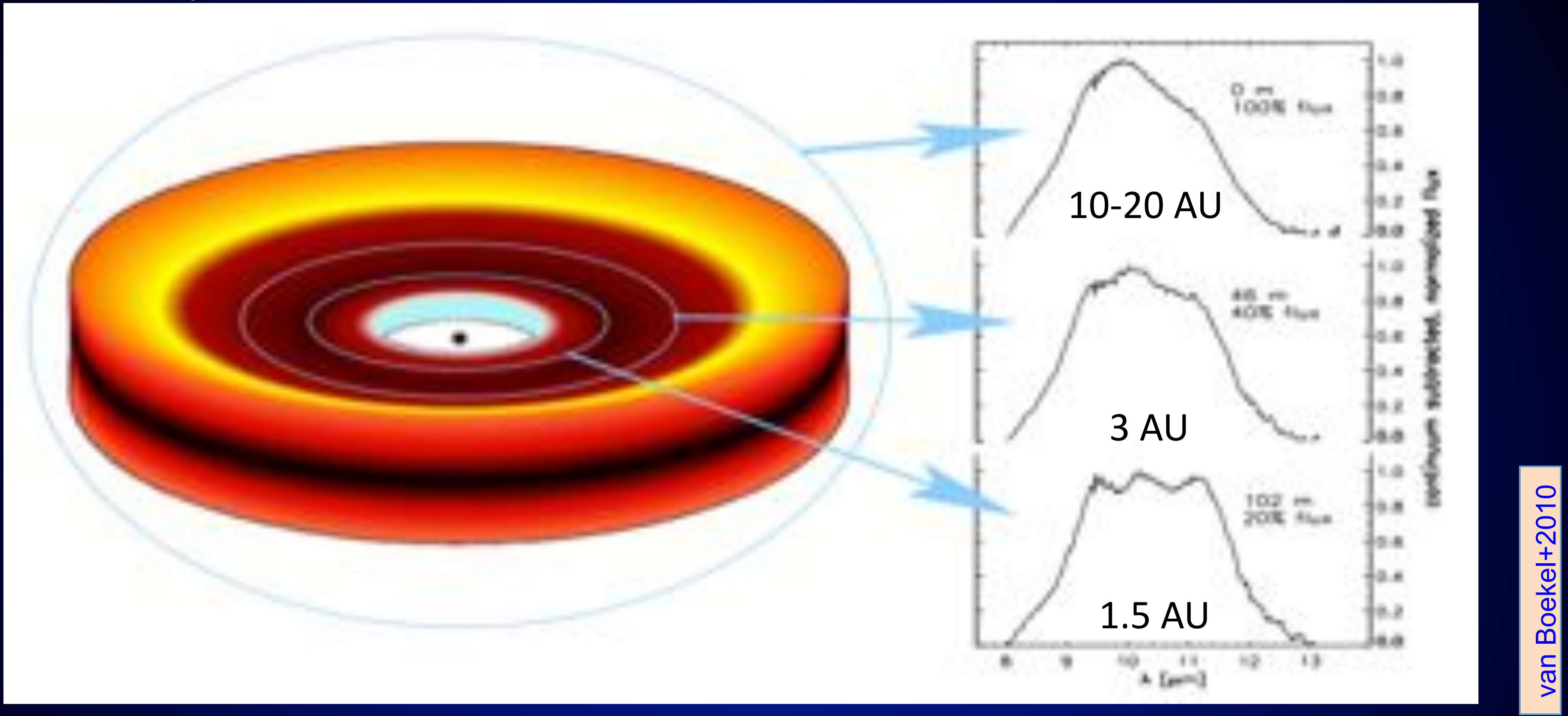
IR Interferometry : silicates in disks



Juhasz et al. 2010

IR Interferometry : silicates in Herbig Ae Be

HD 144432/ MIDI on different baselines



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?

IR Interferometry : silicates in Herbig Ae Be

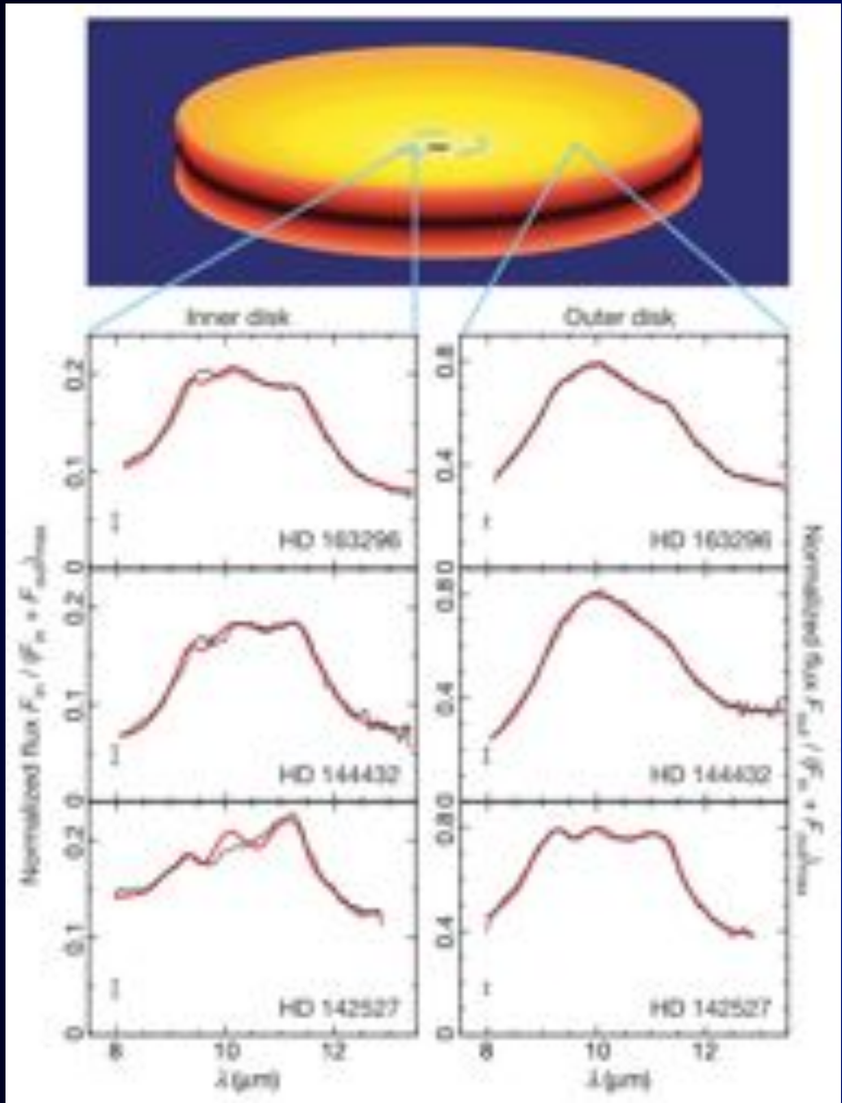
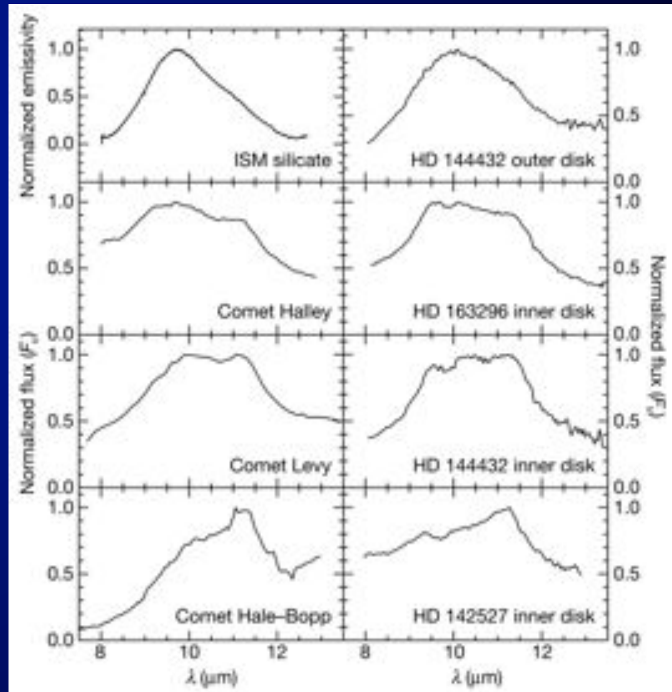


Table 1 **Dust properties in the inner and outer disk**

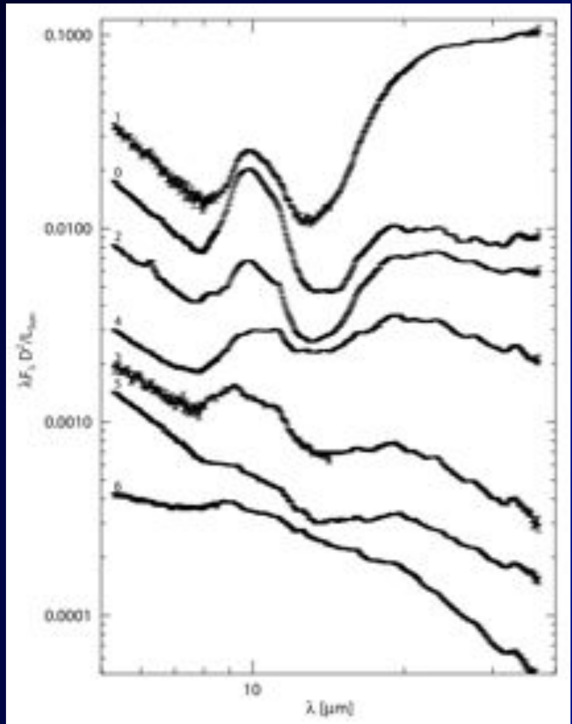
	Crystallinity (%)		Fraction of large grains (%)		Crystalline olivine to pyroxene ratio	
	Inner disk	Outer disk	Inner disk	Outer disk	Inner disk	Outer disk
HD 163296	40^{+20}_{-20}	15^{+10}_{-10}	95^{+5}_{-10}	65^{+20}_{-20}	$2.3^{+3.7}_{-0.5}$	–
HD 144432	55^{+30}_{-20}	10^{+10}_{-5}	90^{+10}_{-10}	35^{+20}_{-20}	$2.0^{+1.8}_{-0.6}$	–
HD 142527	95^{+5}_{-15}	40^{+20}_{-15}	65^{+15}_{-10}	80^{+10}_{-30}	$2.1^{+1.3}_{-0.7}$	$0.9^{+0.2}_{-0.1}$

van Boekel et al. 2004



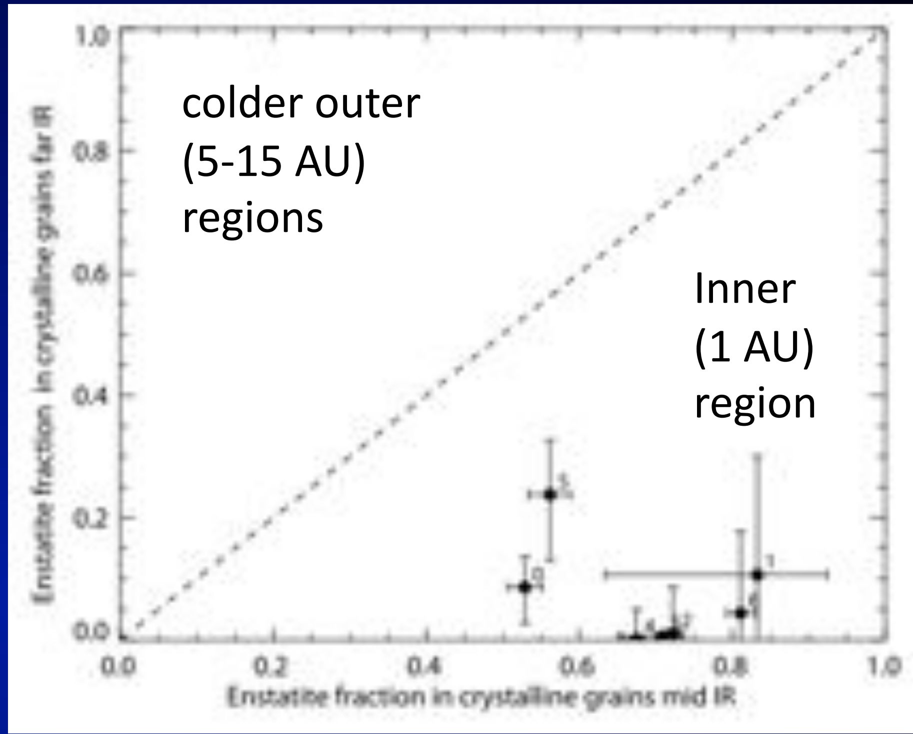
A chemical gradient in the composition of the crystals is seen, with a forsterite dominated spectrum closest to the star, and more enstatite at larger radii.

Silicates in T Tauri



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

enstatite mass fraction of crystalline silicates

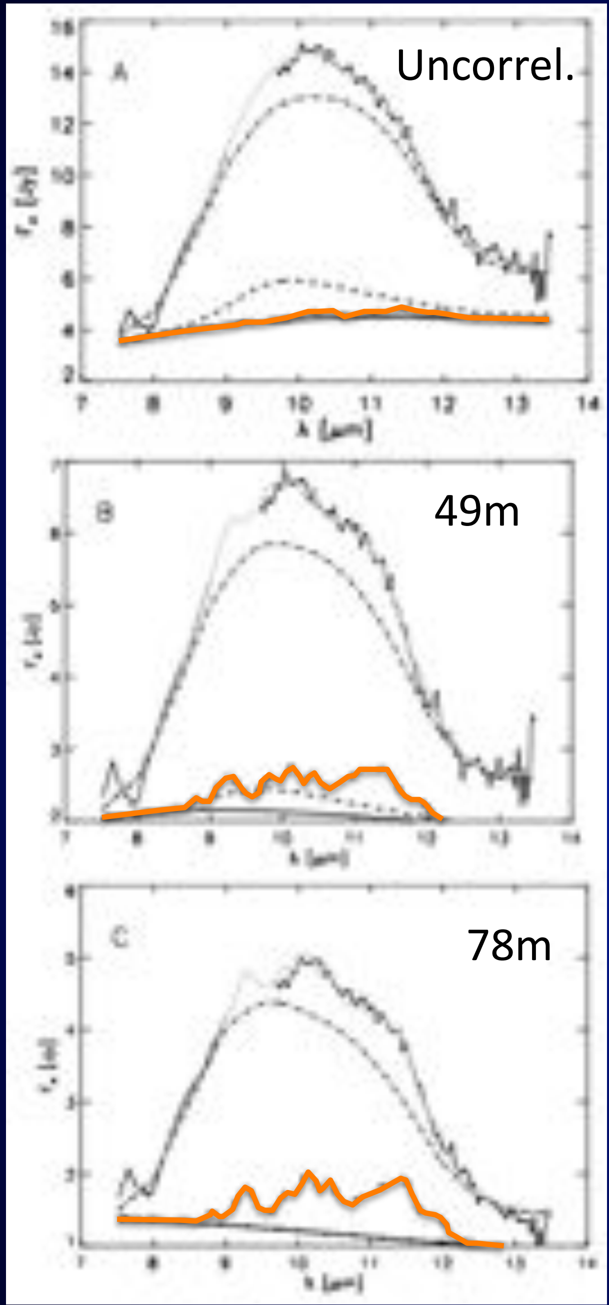


Bouwman et al. 2008

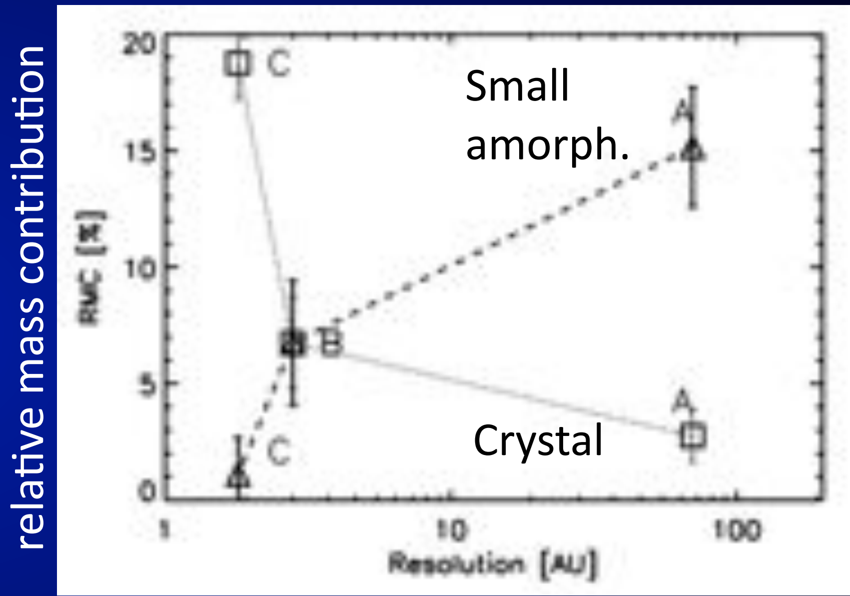
size of the enstatite grains (1 μm) larger than forsterite grains (0.1 μm)
mass fraction: larger enstatite fraction in warmer inner disk than colder outer
Enstatite inner / Forsterite outer
No strong radial mixing at this stage ?

RY Tau

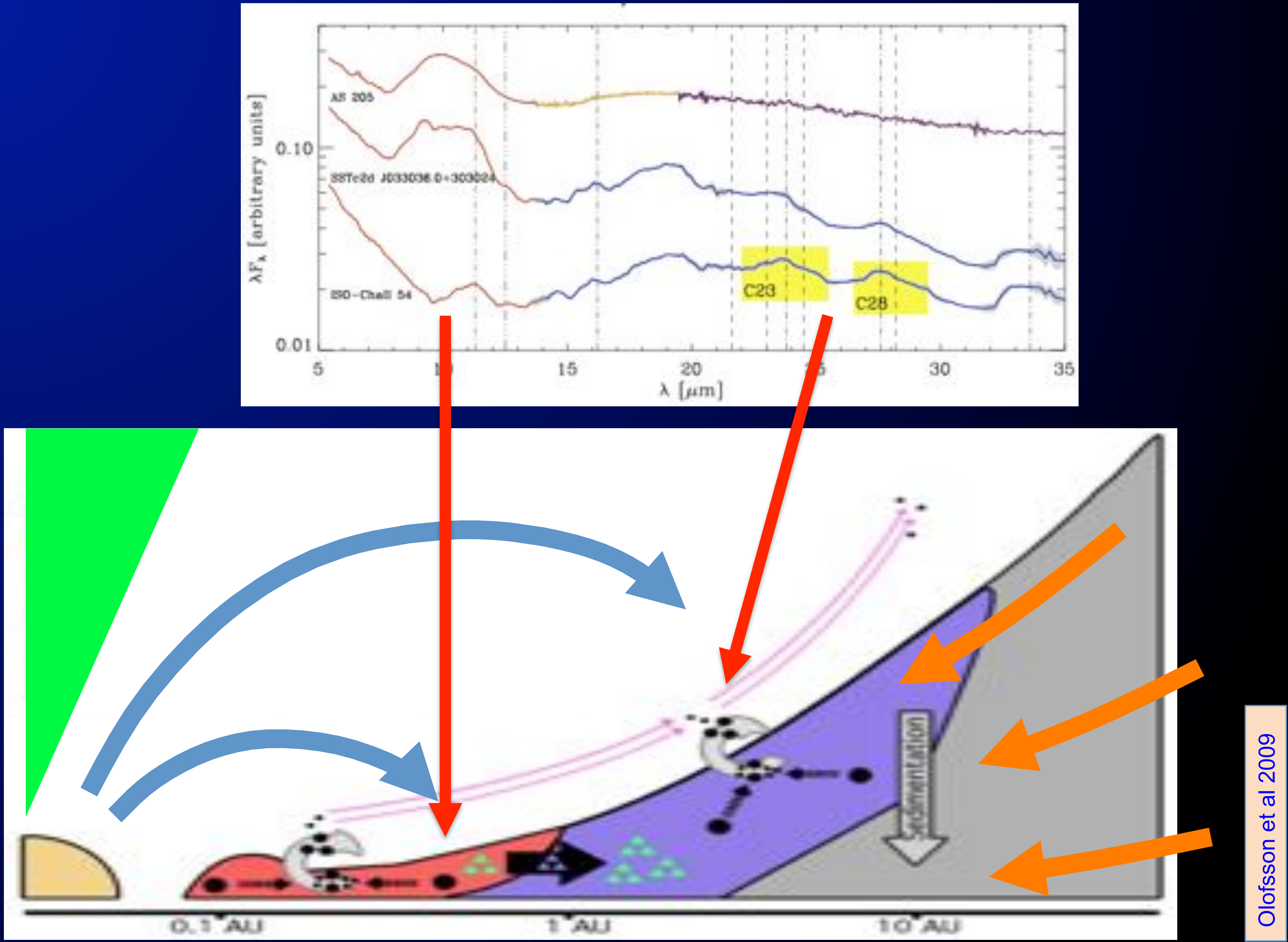
Silicates in T Tauri

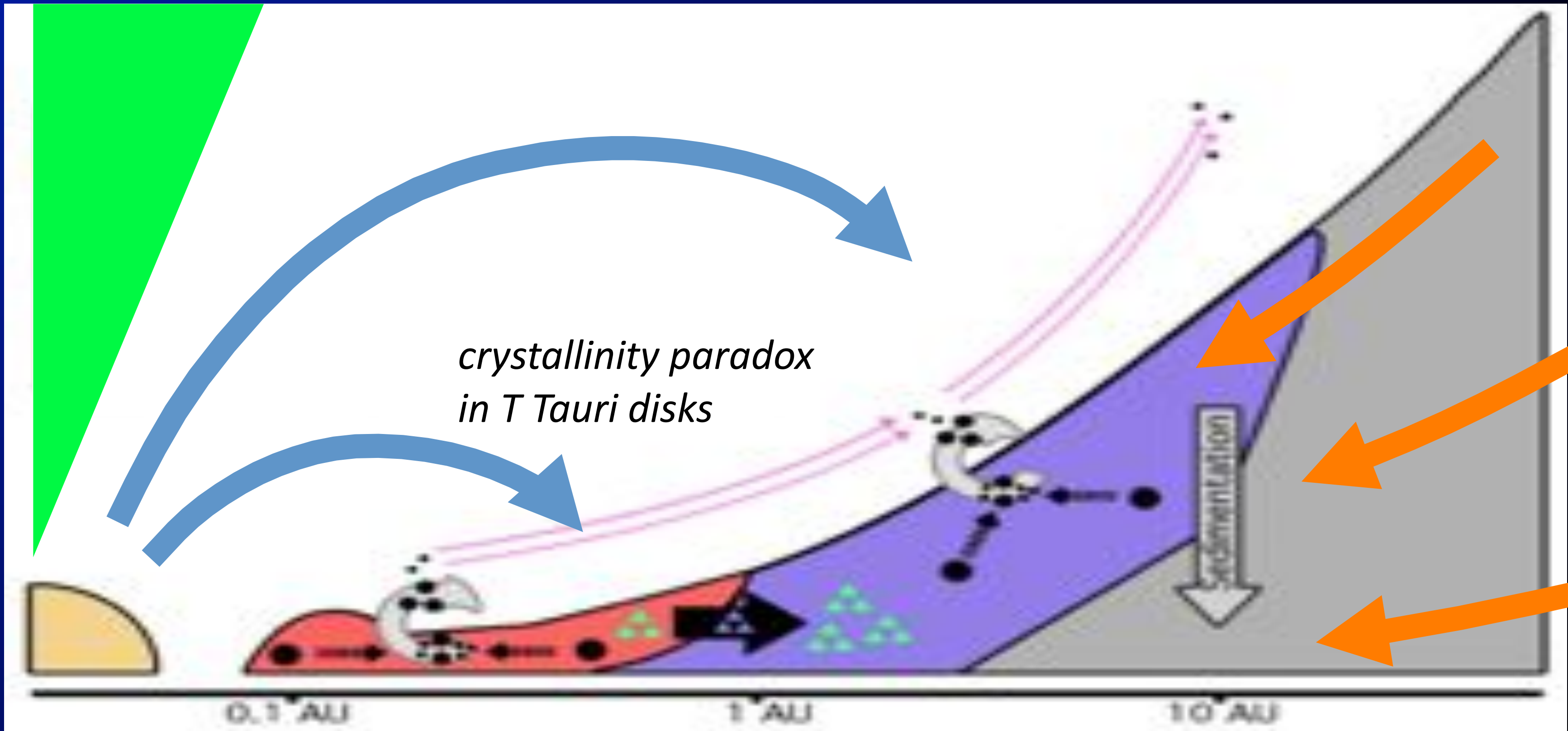


Radial size

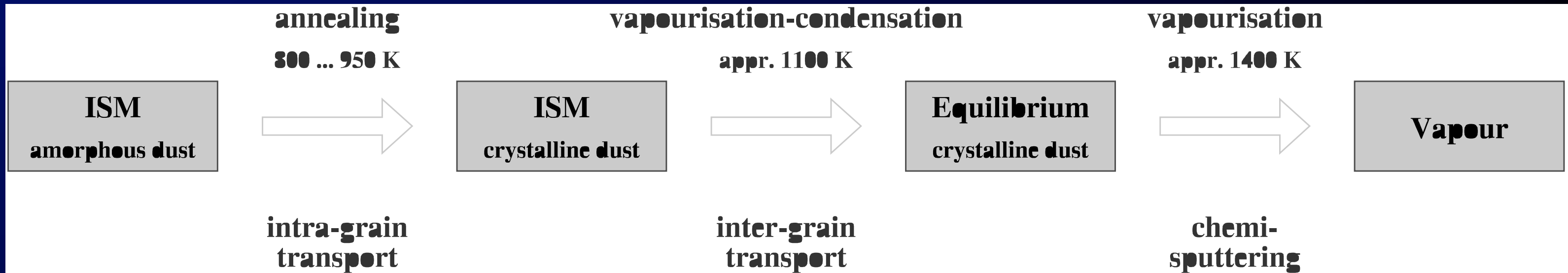


Schegerer et al. 2008


AS 205
SSTc2d J033036.0+303024
ISO-ChaII 54
C23
C28
λF_λ [arbitrary units]
λ [μm]
Sedimentation
0.1 AU
1 AU
10 AU
Olofsson et al 2009



Olofsson et al 2009



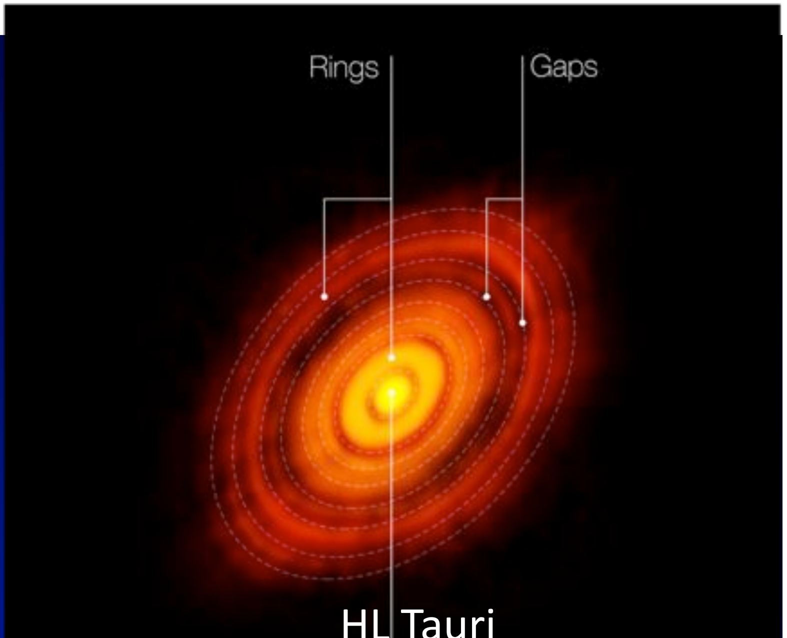
Gail 2004

Gail 2004, Oliveira et al. 2011, Roskosz et al. 2011, Juhasz et al. 2010, Olofsson et al.2010, 2009

Not simple picture with crystalline grains close to the central object and amorphous content in the outer regions.

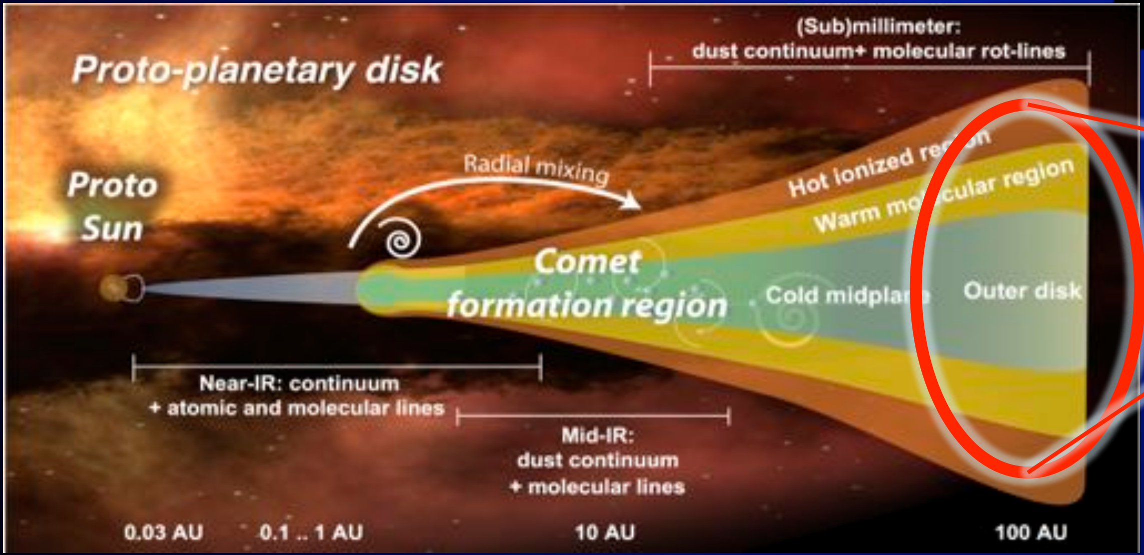
Amount of radial mixing ?

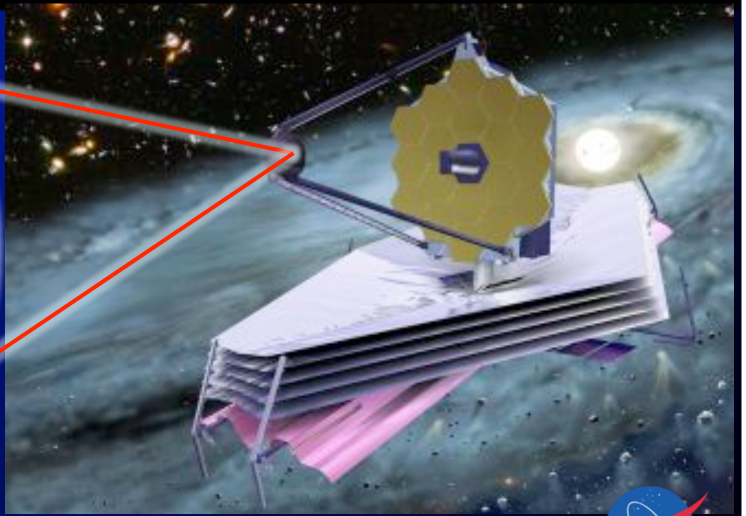
Filiation or reprocessing dominant ?



HL Tauri

ALMA (ESO/NAOJ/NRAO)





JWST

The JWST successor of the HST:
6.5 m Infrared telescope in Space