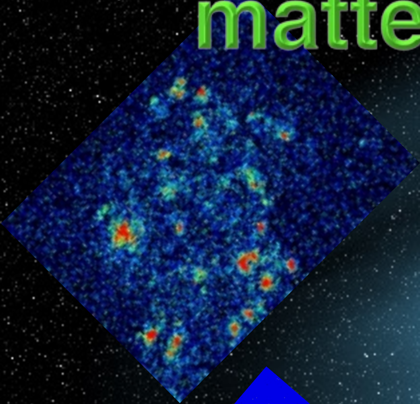
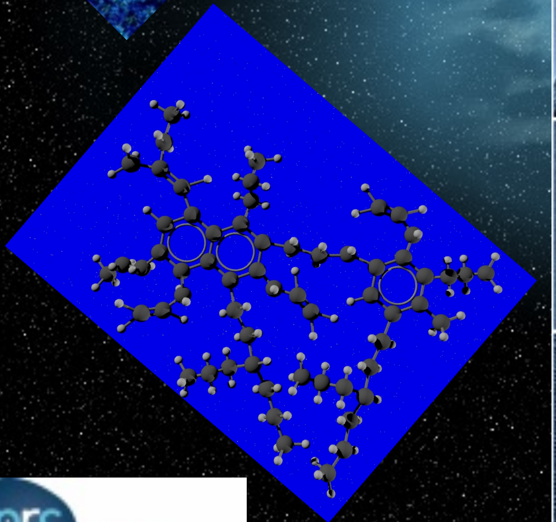
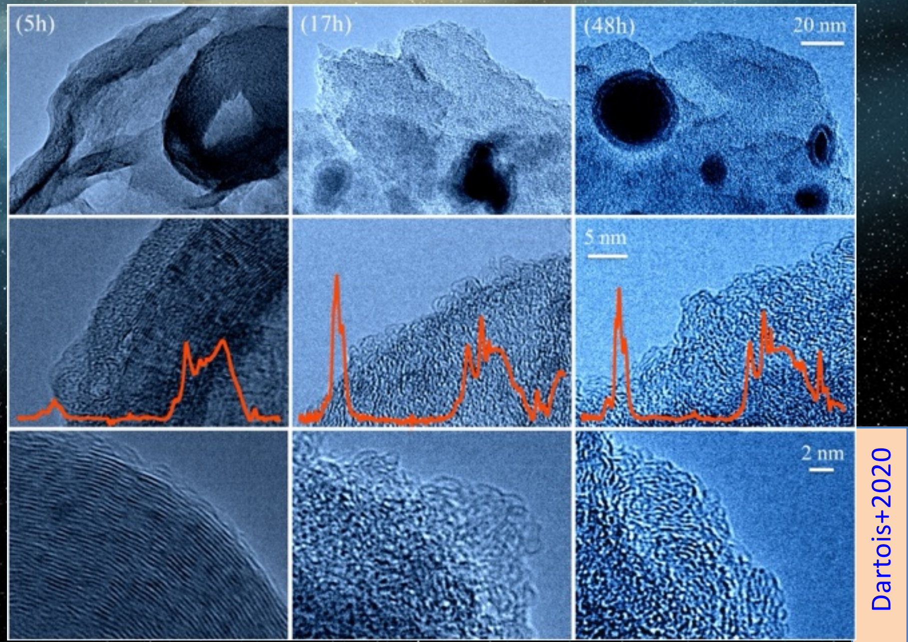
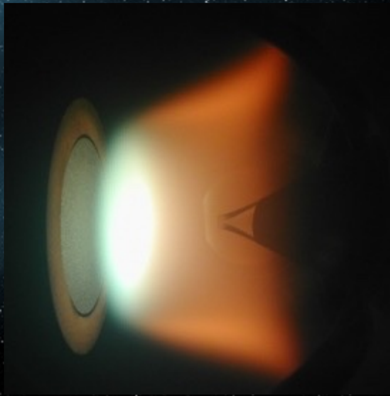
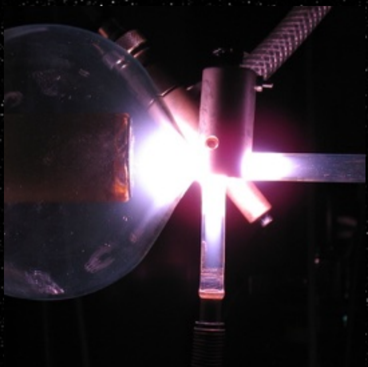
Interstellar grains and extraterrestrial solid matter: generation, ID, & processing





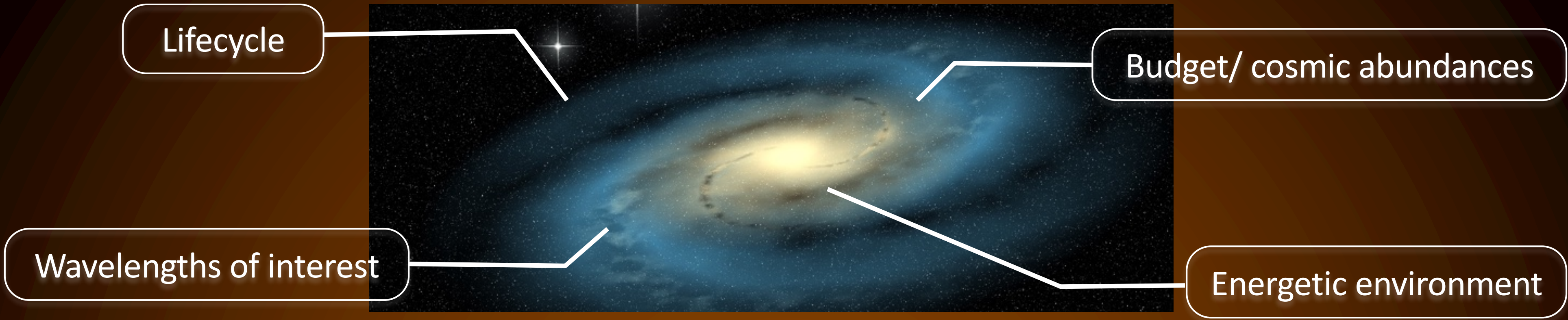






E. Dartois, ISMO, Orsay, France
emmanuel.dartois@universite-paris-saclay.fr
GISM3 - 2025

Introduction: some key ingredients to study interstellar solids in the laboratory



Silicates

in stellar envelopes, the diffuse interstellar medium, in disks

Which carbon allotropes & organic matter observed in the ISM

Nanodiamants, Fullerenes, amorphous carbon, hydrogenated amorphous carbon (a-C :H ou HAC), AIBs (« astro-PAHs »), mixed a-C :H-PAHs, organic residues

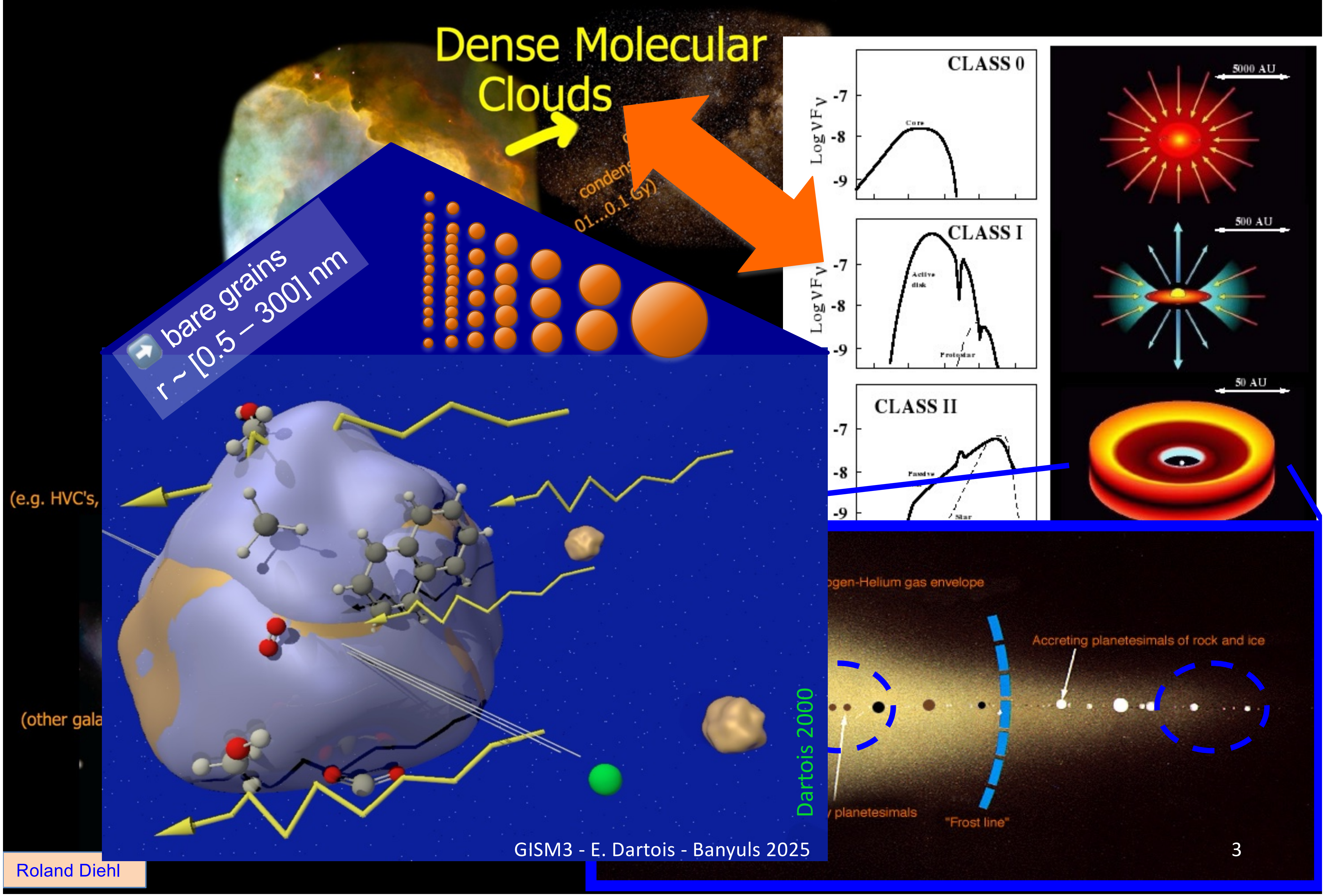
Transition diffuse to dense ISM

Signatures for the ISM solids incorporation in the solar syst (remote observations) ?

Comparison IOM meteorites & UCAMMs / ISM a-C:H

See GISM1 (K.Demyk) and GISM2 (N. Ysard) lectures !...

Interstellar dust temporal lifecycle

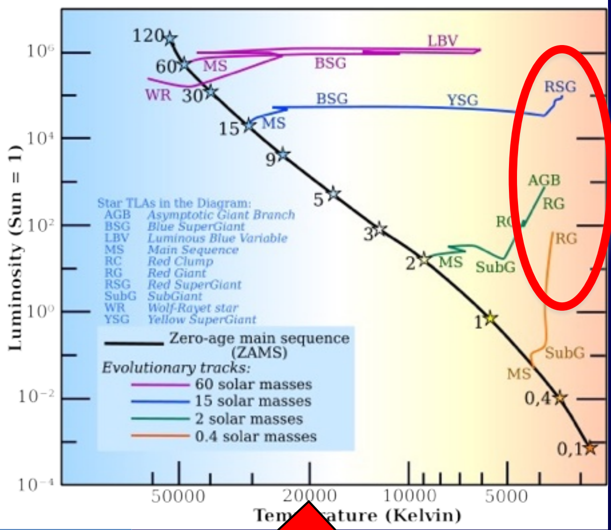


Roland Diehl

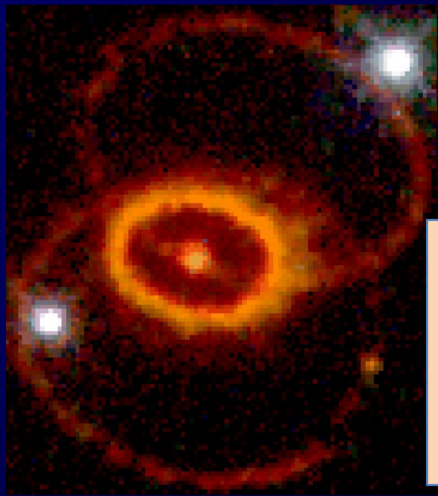
Interstellar dust budget (the ingredients…)

Stellar mass losses contribute significantly to dust production

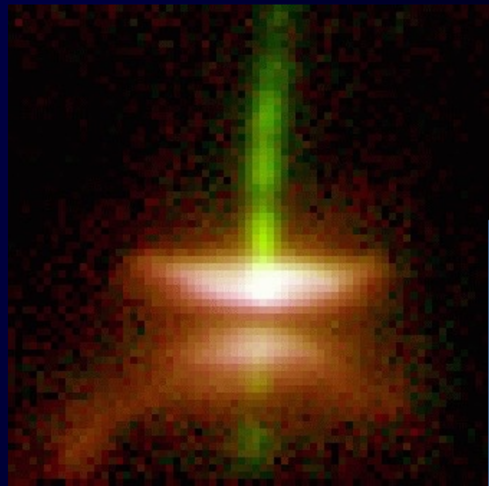
Dust observed at later evolutionary stages



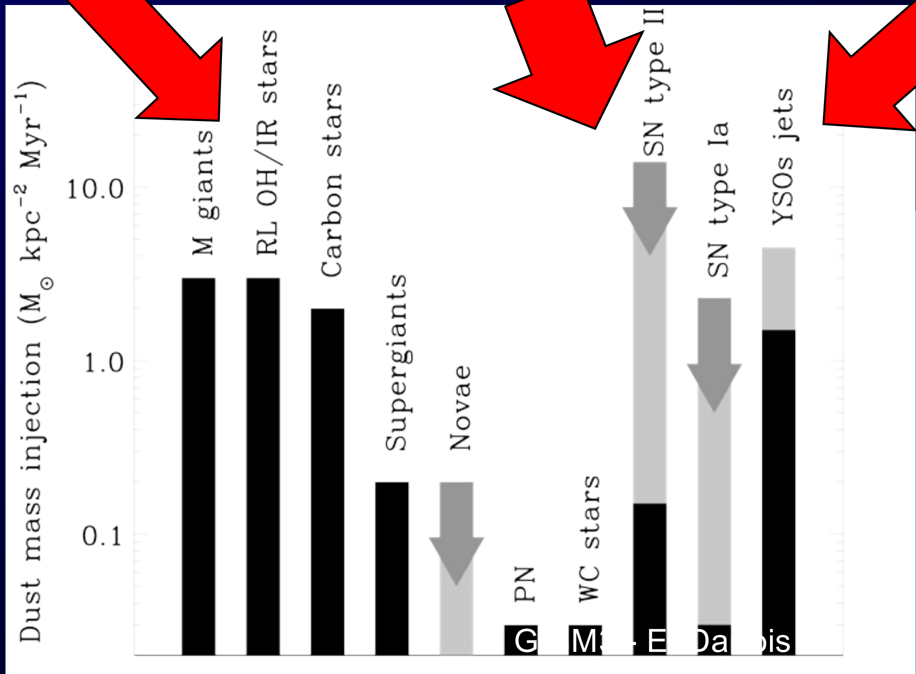
Rursus



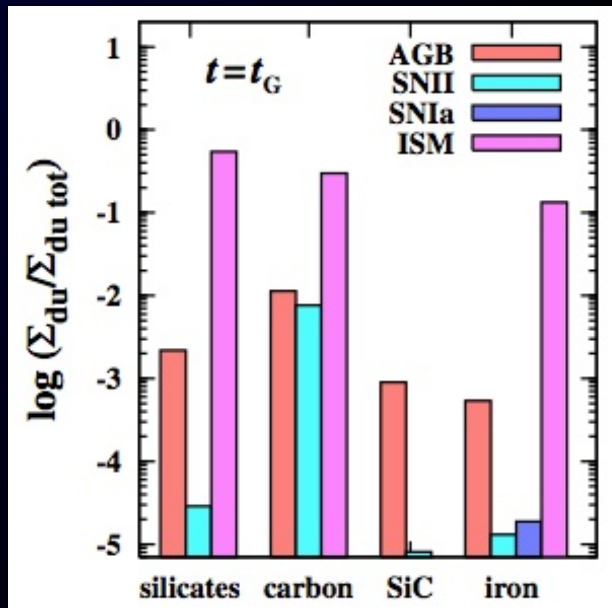
SN1987A - HST



HH30- HST



Jones 2001, Tielens 2005, Robitaille 2010, Matsuura 2011



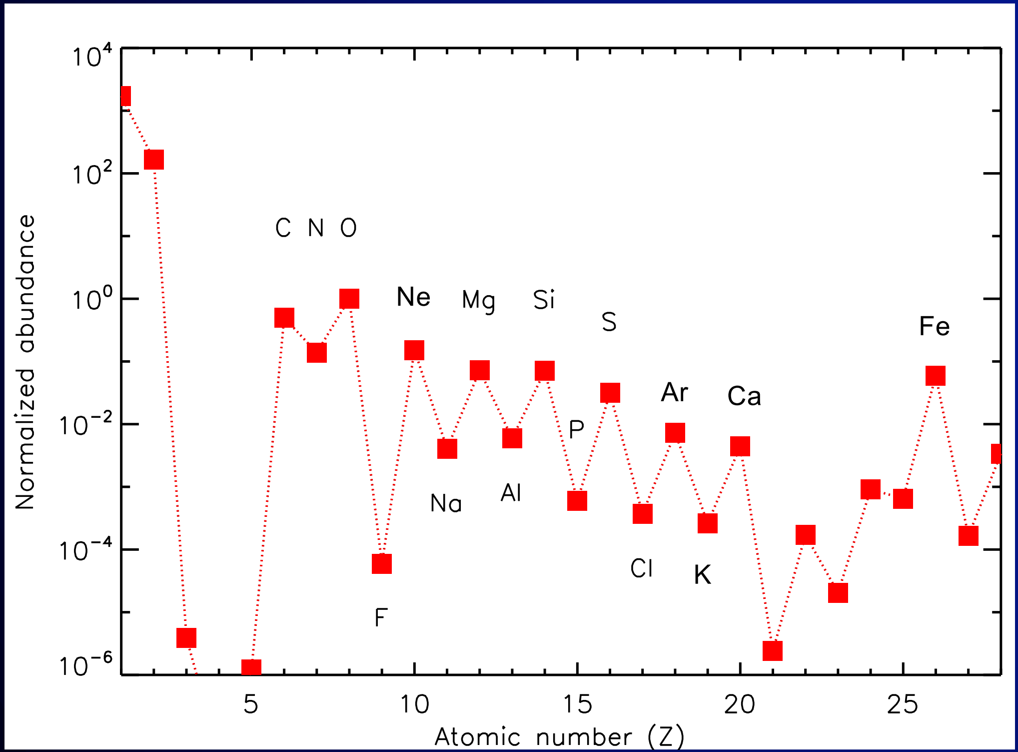
Zhukovska2008+

Elemental cosmic abundances

What to expect for dust grains ?

(DISM, N_H~ 100 cm^{-3})

"Carbonaceous" matter



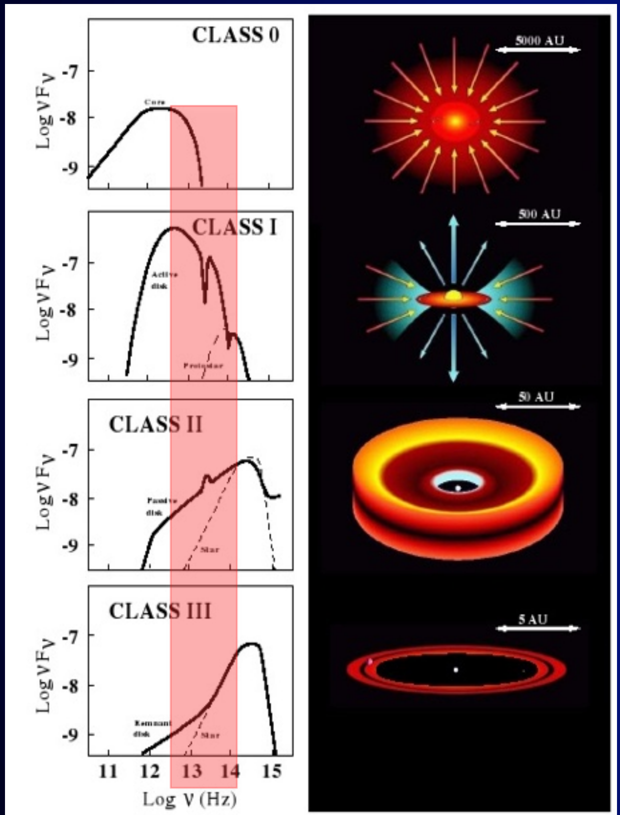
"Minerals"

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

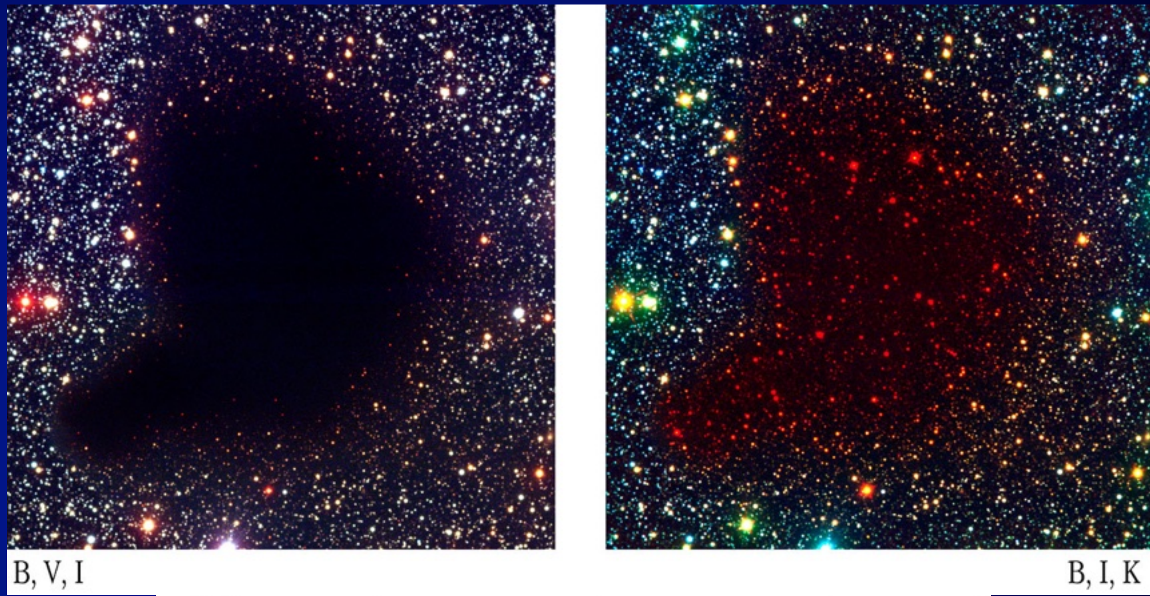
Asplund+2021, Nieva & Przybilla 2011, Verstraete 2011, Jenkins 2009, Lodders 2003,...

Wavelengths of interest:

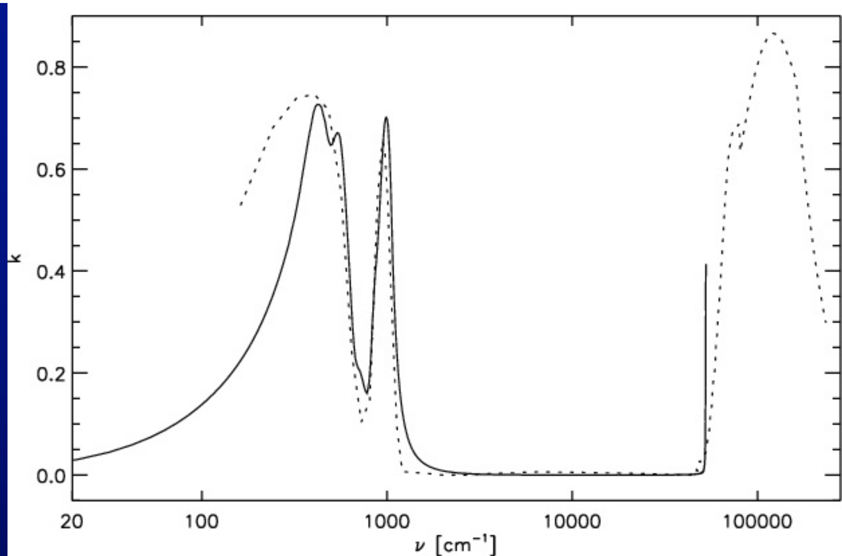
Trade-off between wavelength accessibility & spectral signatures



Van Boekel

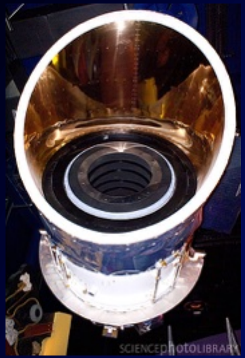


ESO



Jaeger 2003

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

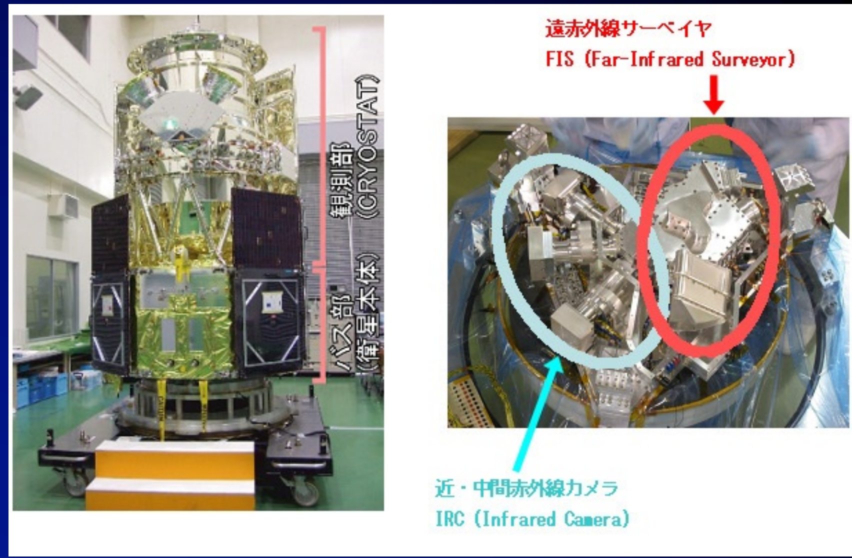


IRAS

0.57m / 1983 (10 months) NASA

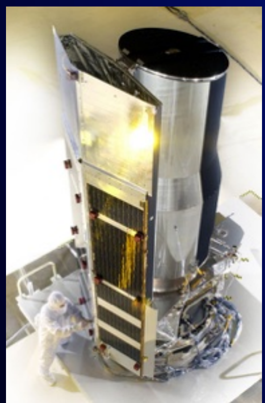
ISO

0.6m / 1995-1998 ESA



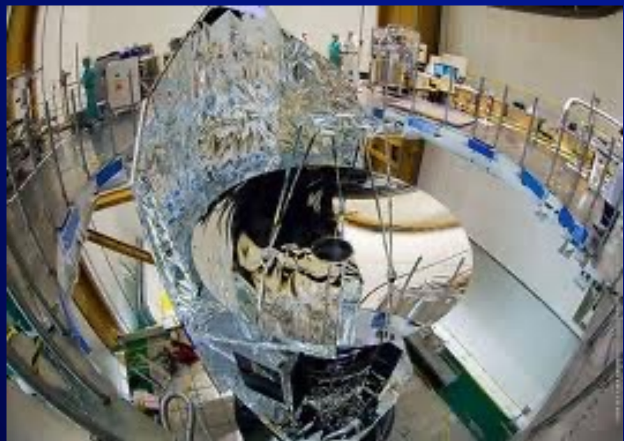
Akari

0.67m / 2006-2011 JAXA



Spitzer

0.85m / 2003-2020 NASA



Herschel

FIR / 3.5m / 2009-2013 ESA

JWST

6.5m / 2022 NASA/ESA

Energetic sources of evolution

<u>Photon sources</u>

VUV photolysis:
- ambient
- stellar
- CR induced

X-Rays

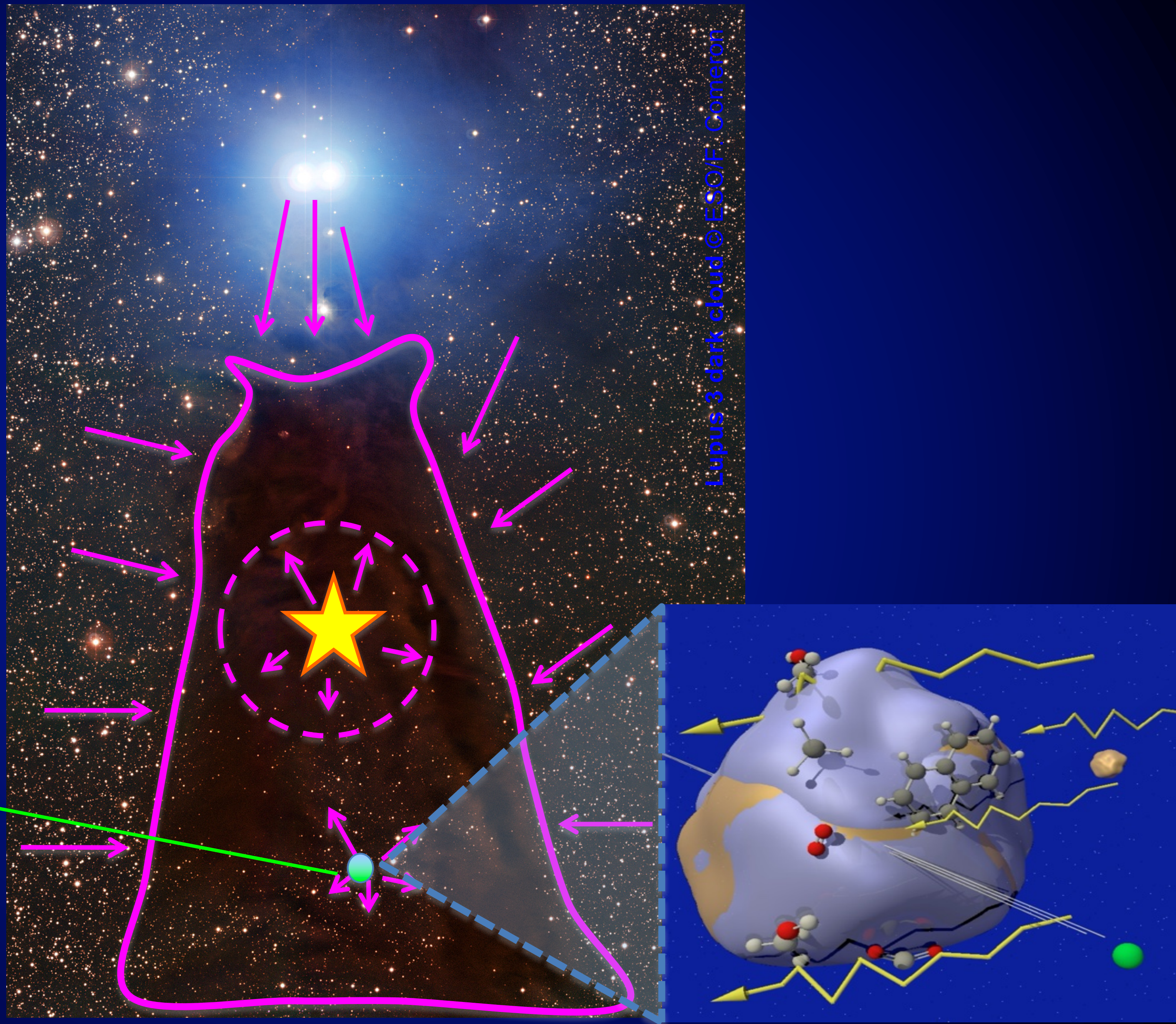
<u>Particles sources</u>

electrons

Cosmic rays

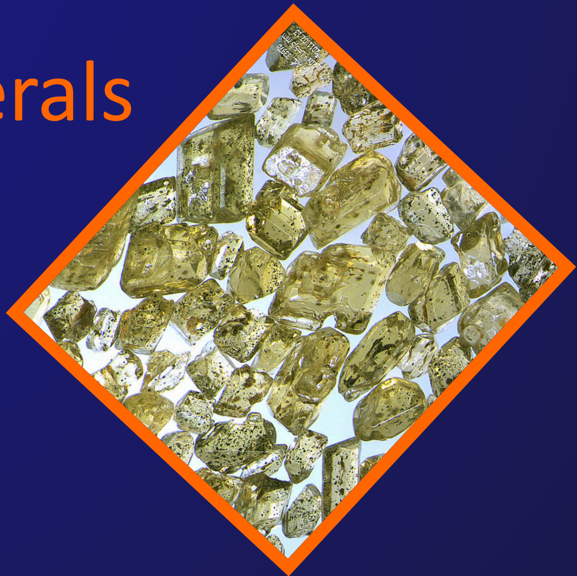
<u>Thermal</u>

<u>Shocks (C,J,…)</u>



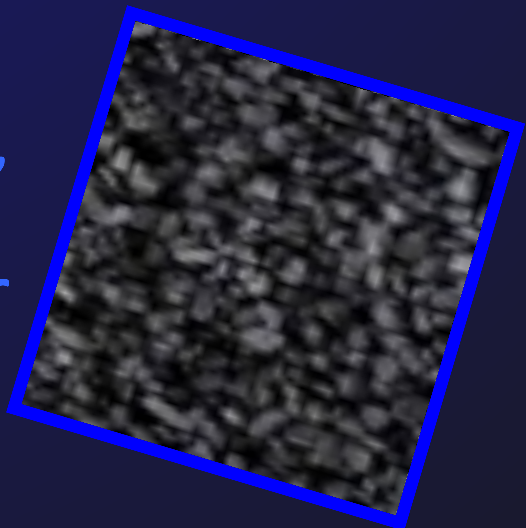
The simplified picture of ISM solids

Minerals



"Refractory" solids

"Carbonaceous" matter



"Volatile" solids

Ice mantles

Inorganic dust

Some important minerals

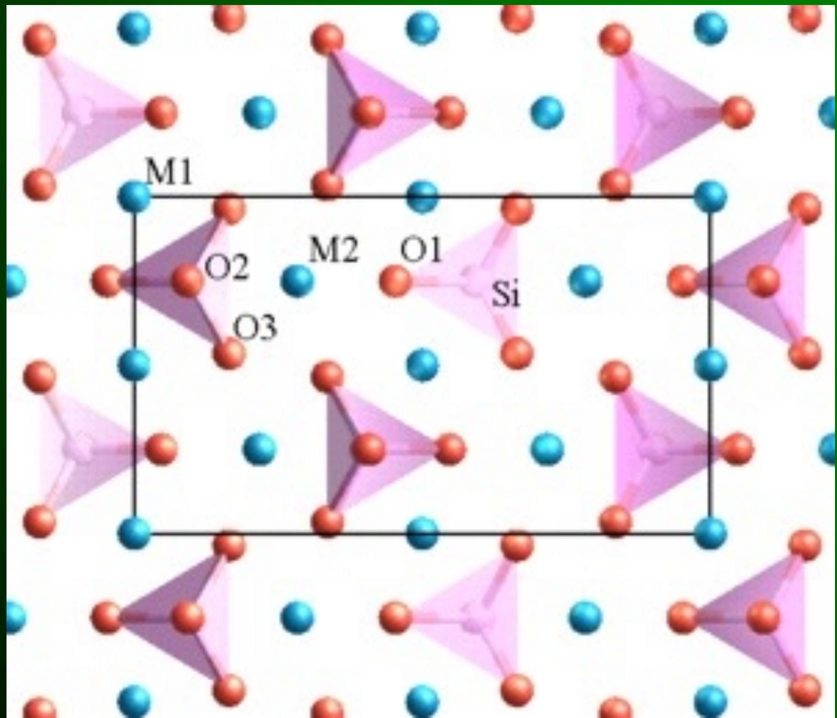
Olivine

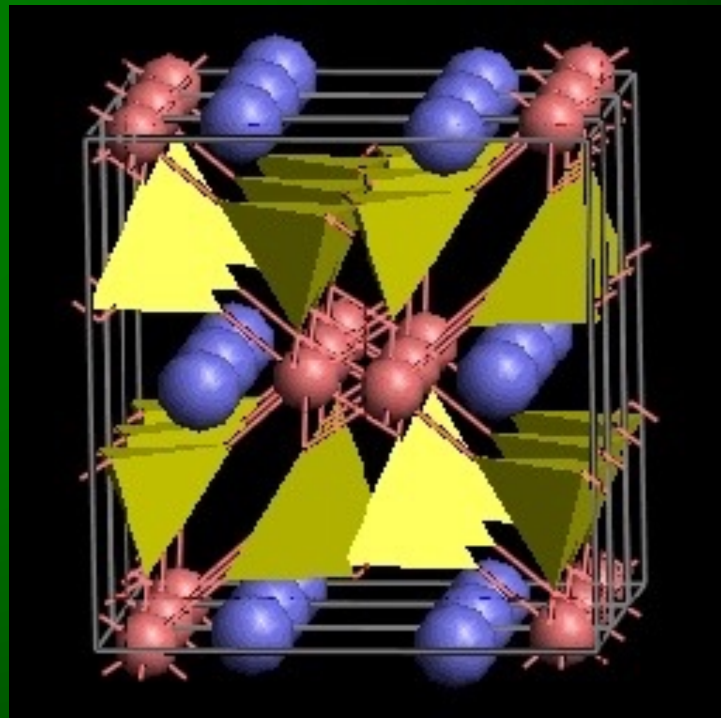
$M_1M_2SiO_4$

Pyroxene

$M_1M_2Si_2O_6$

M_1 & M_2 :divalent cations





Silicates "mineralogy"

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

Mg_2SiO_4 Forsterite

$Fe_2\,SiO_4$ Fayalite

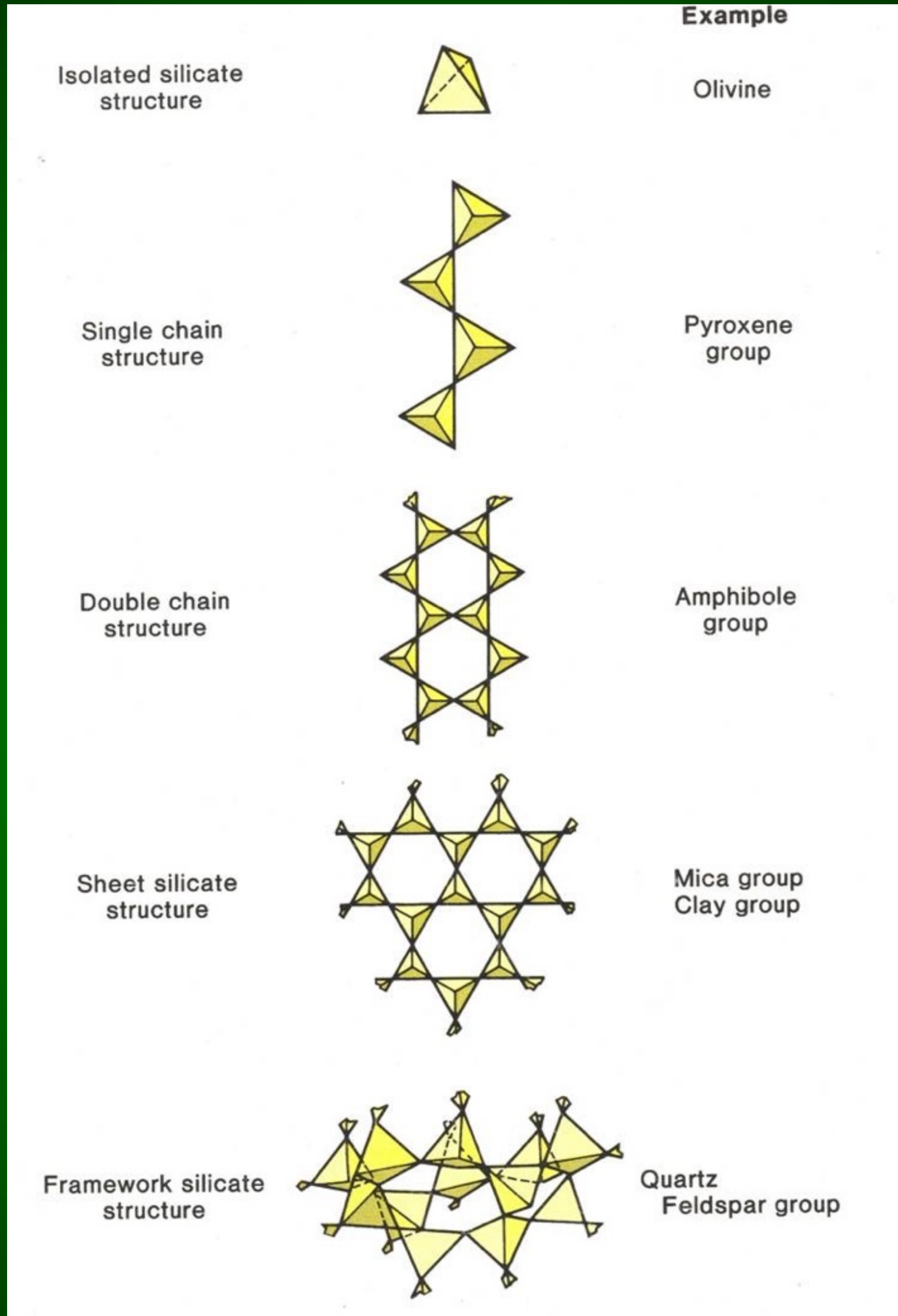
Pyroxenes ($Mg_xFe_{1-x}SiO_3$)

$Mg_2Si_2O_6$ Enstatite

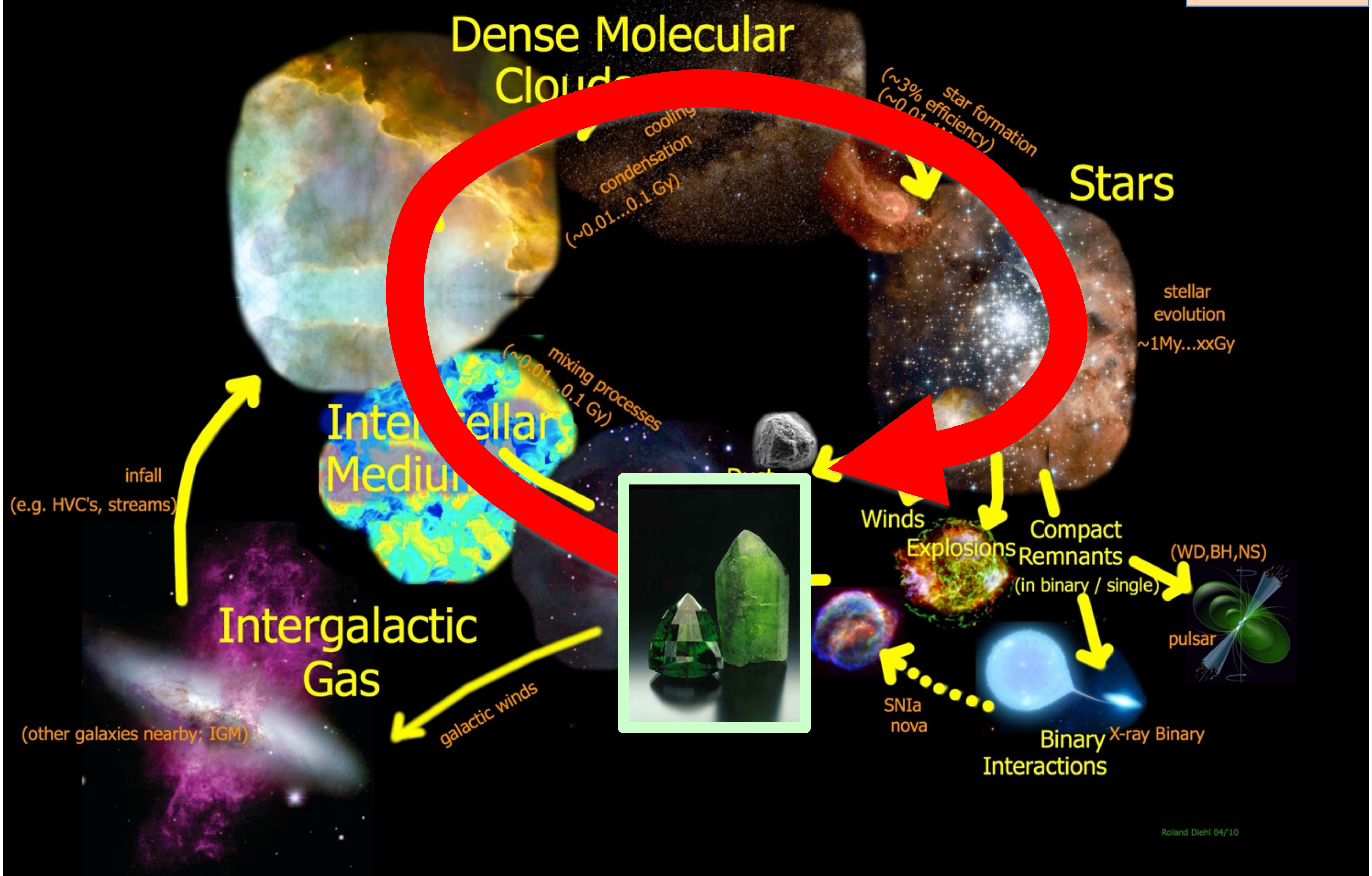
$Fe_2Si_2O_6$ Ferrosilite (hypersthene)

$CaMgSi_2O_6$ Diopside

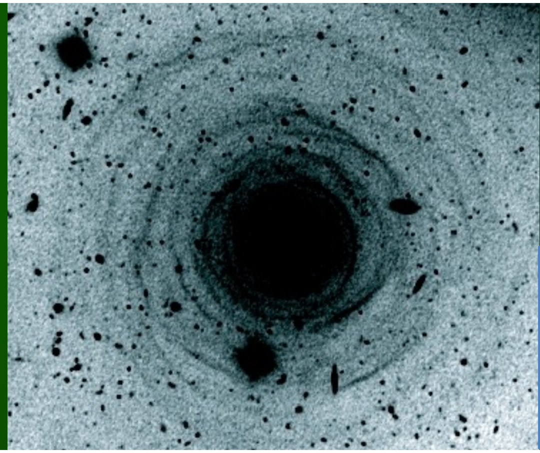
$CaFeSi_2O_6$ Hedenbergite


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

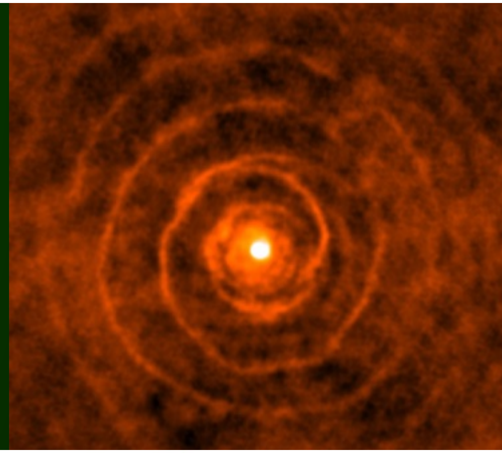
Roland Diehl



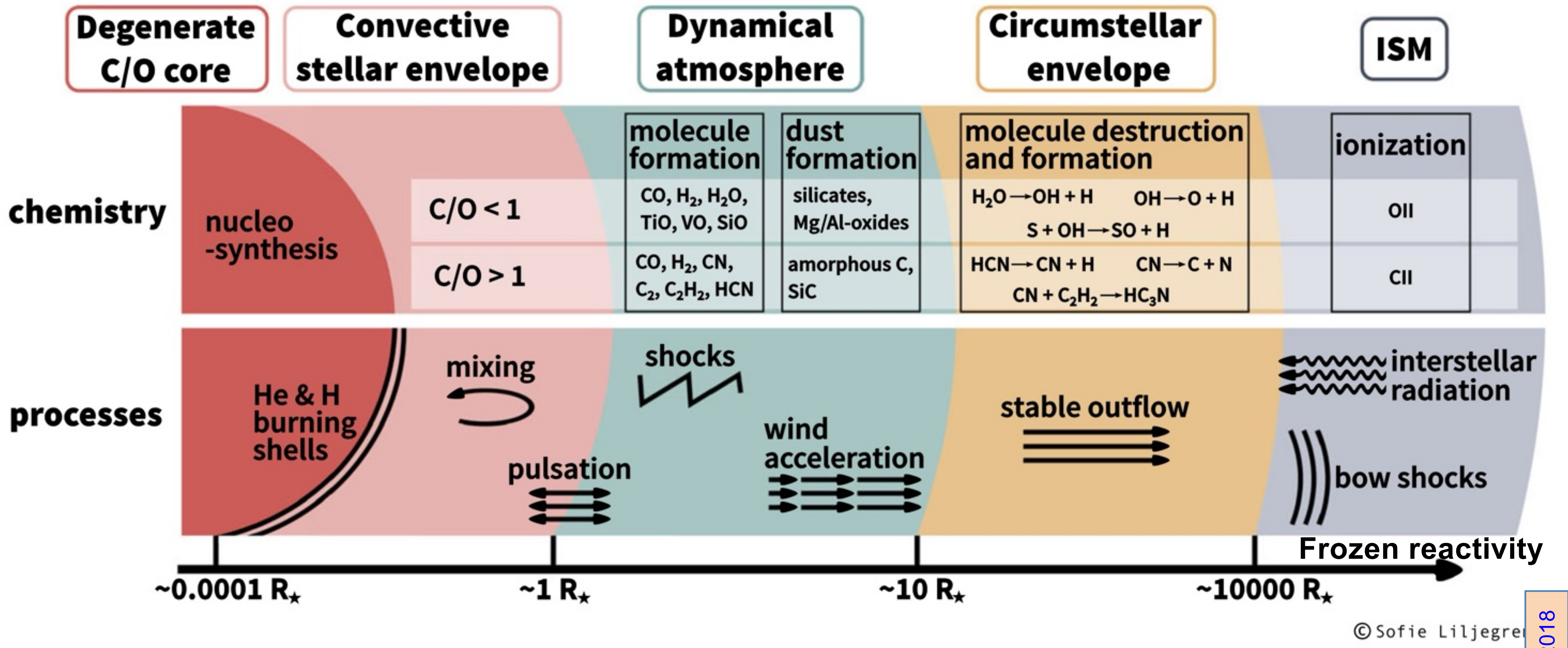
Schematic view of an AGB stellar flow



Leao + 2006



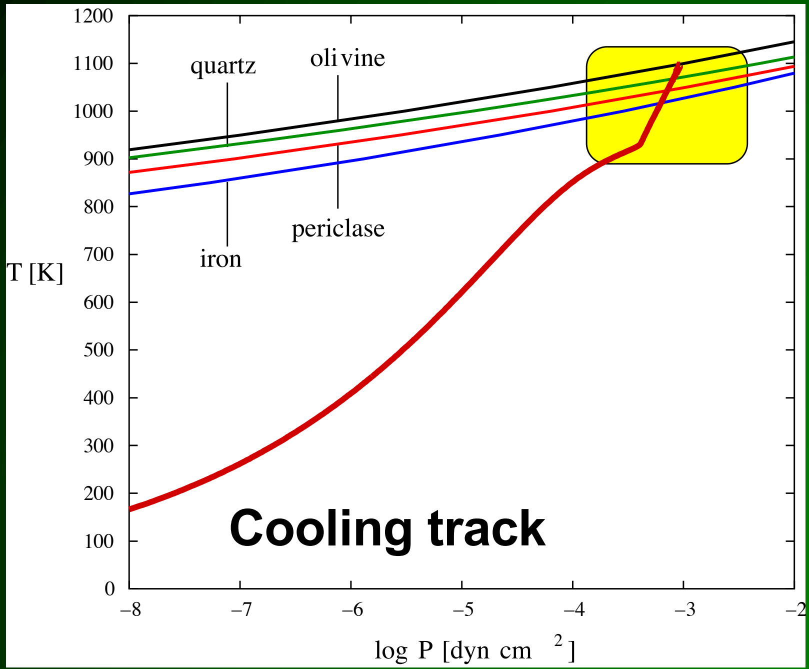
Kim+ 2017

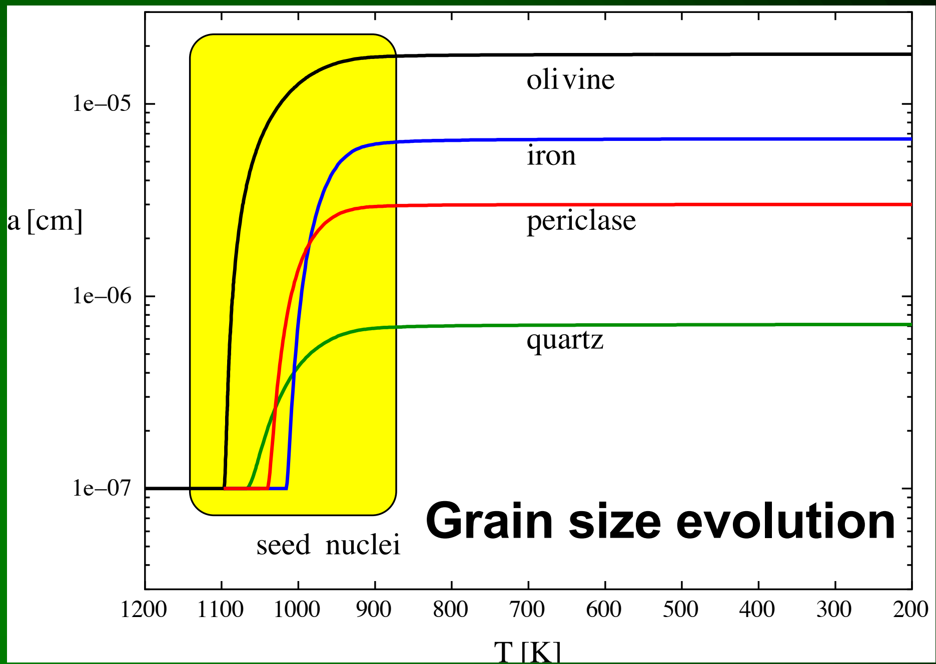


Hofner+ 2018

NUCLEATION EVOLUTION

Stellar wind model





Gail & Sedlmayr 1999

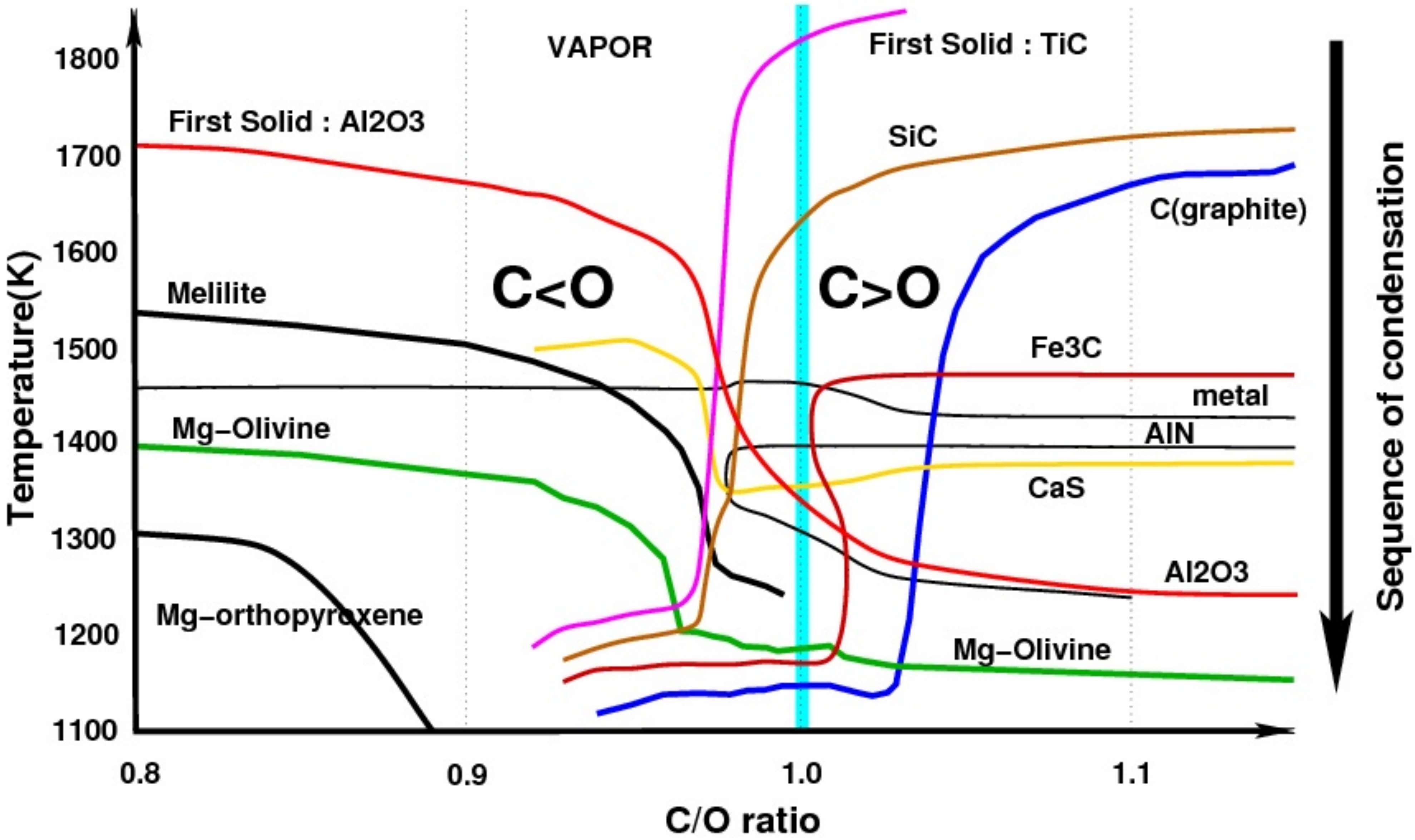
Condensation far from ETL T~1000K, P~10(-10) atm

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

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

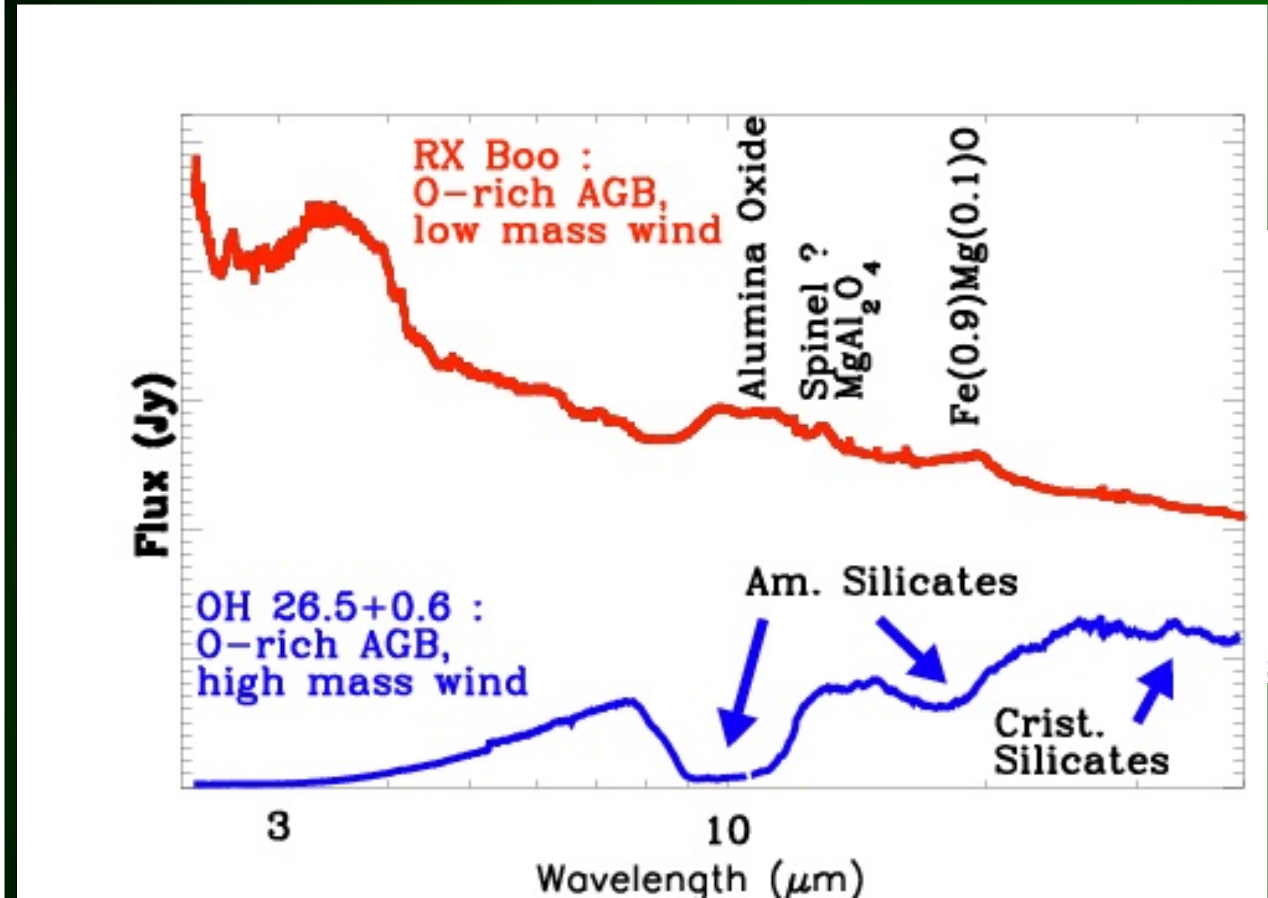
Competition between caracteristic formation & ejection time scales (reactions « frozen »)

χ

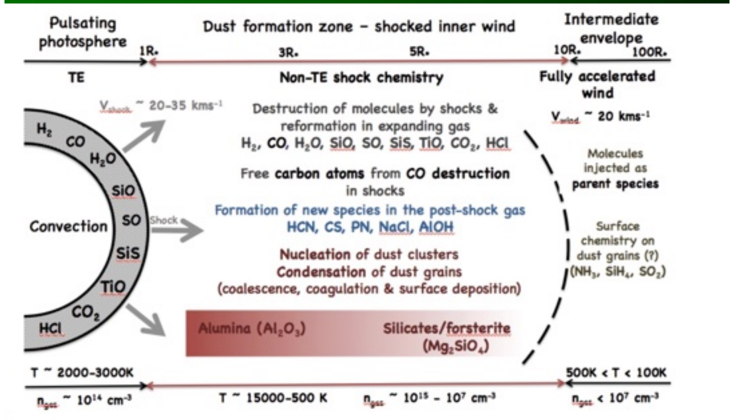


e.g. Gobrecht+2022, Ebel 2000, Gail & Seyldmar 1999

ϕ



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

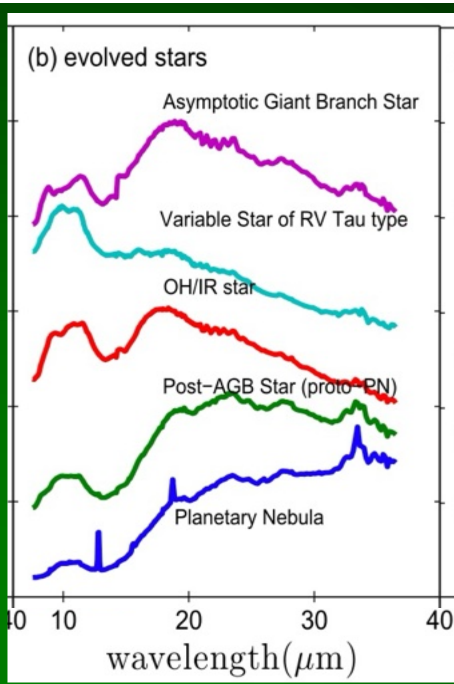


. Schematic view of the dust formation zone in O-rich AGB stars, which includes typical physical parameters and the prevalent chemical
sses related to dust production. Molecules present under TE in the photosphere are shown.

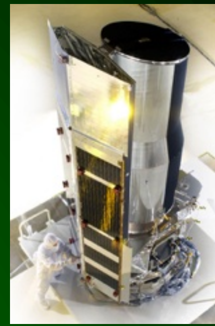
Gobrecht+2016

The crystalline « revolution »

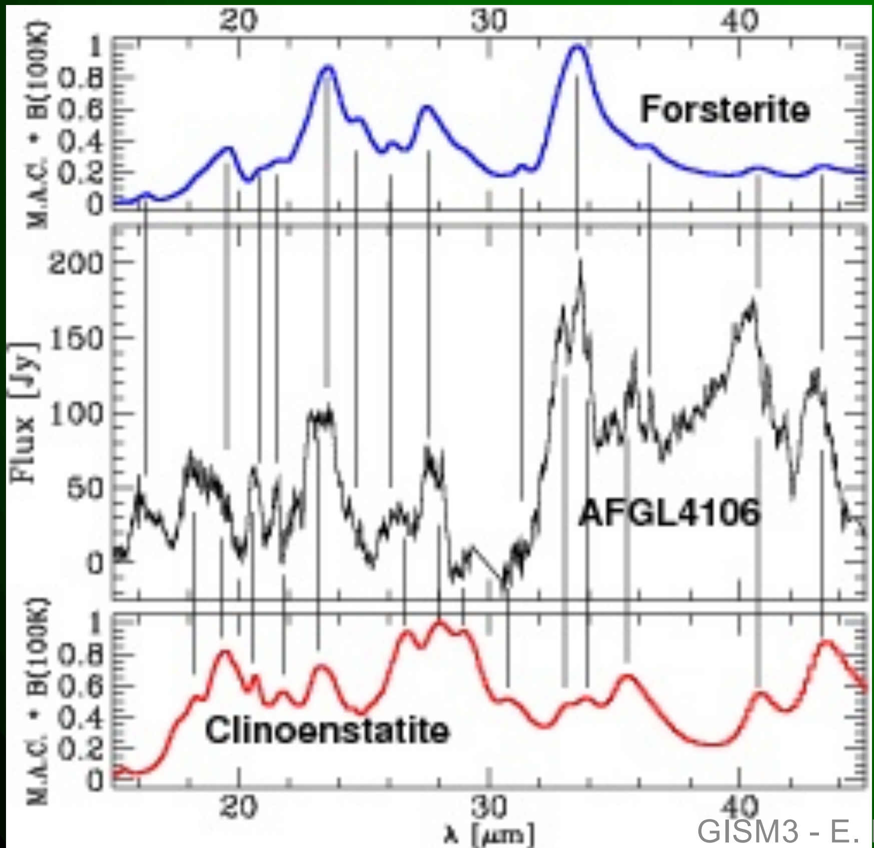
ISO



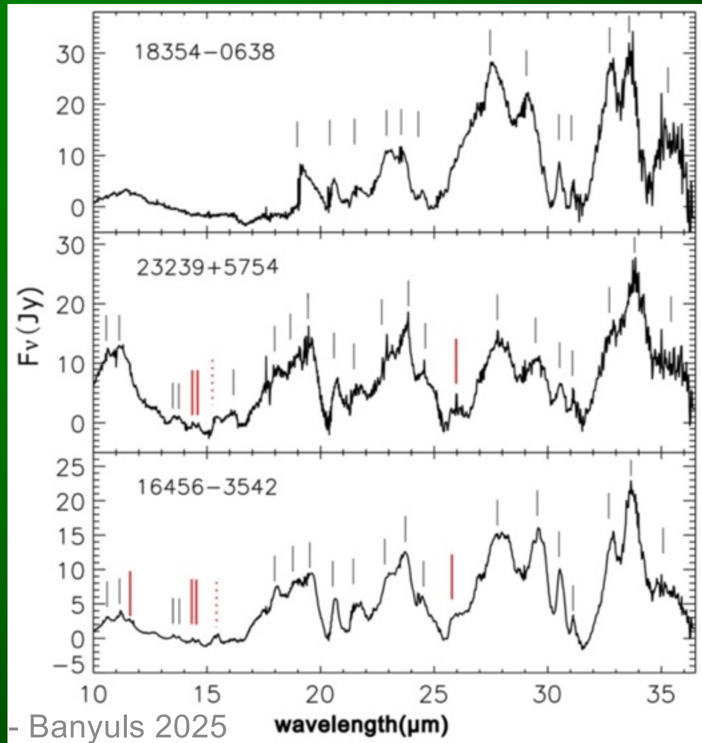
Chen+ 2016



Spitzer

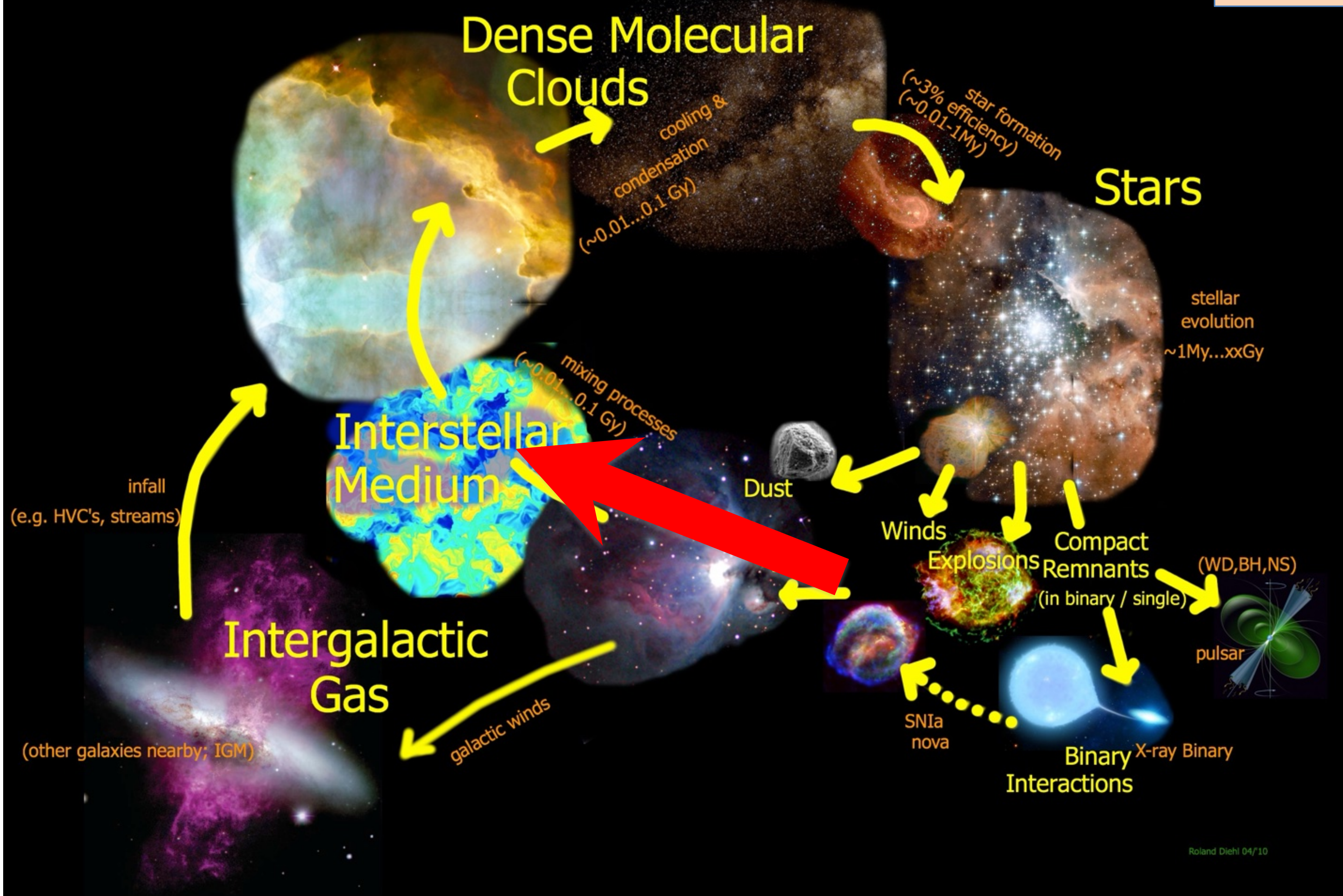


Jaeger + 1998

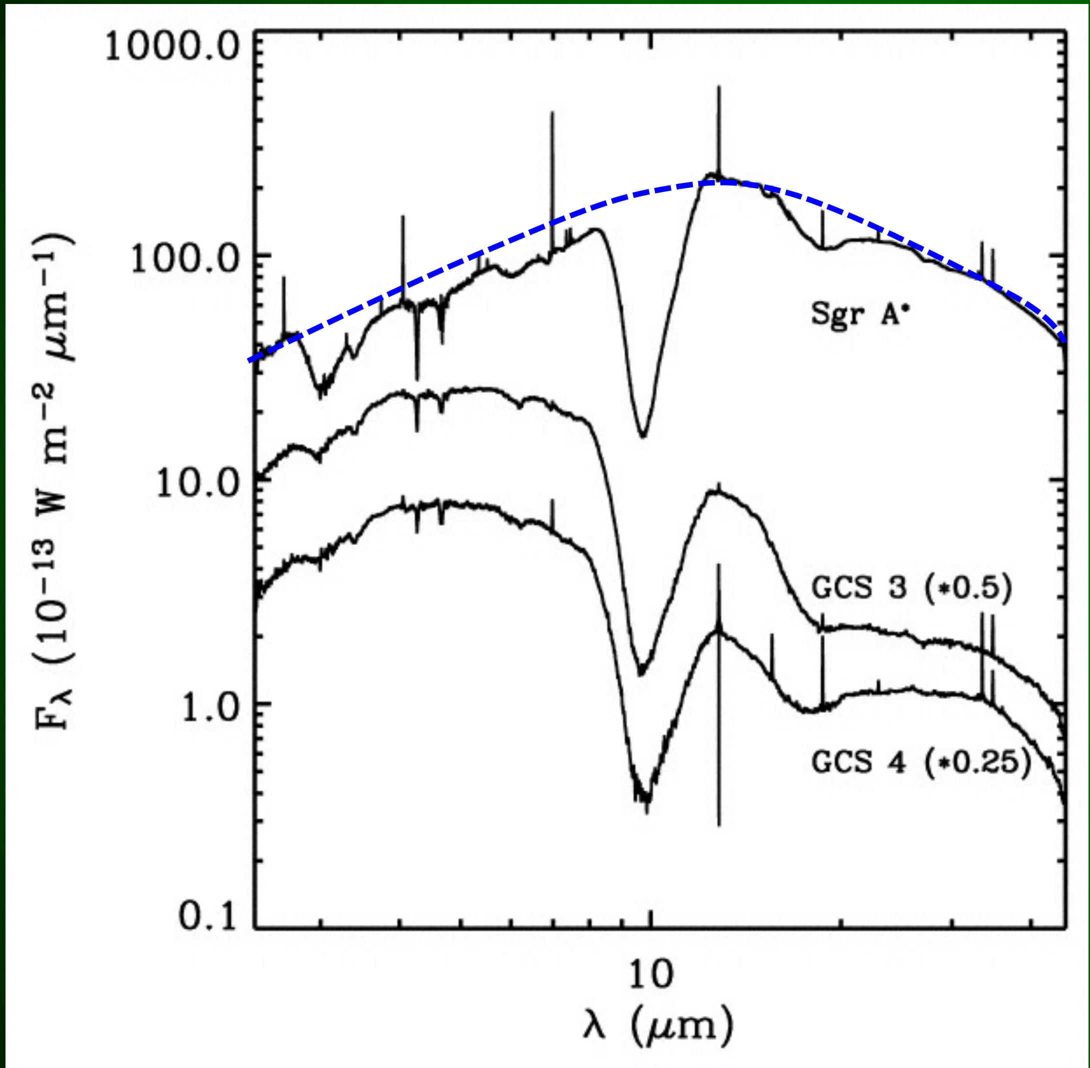


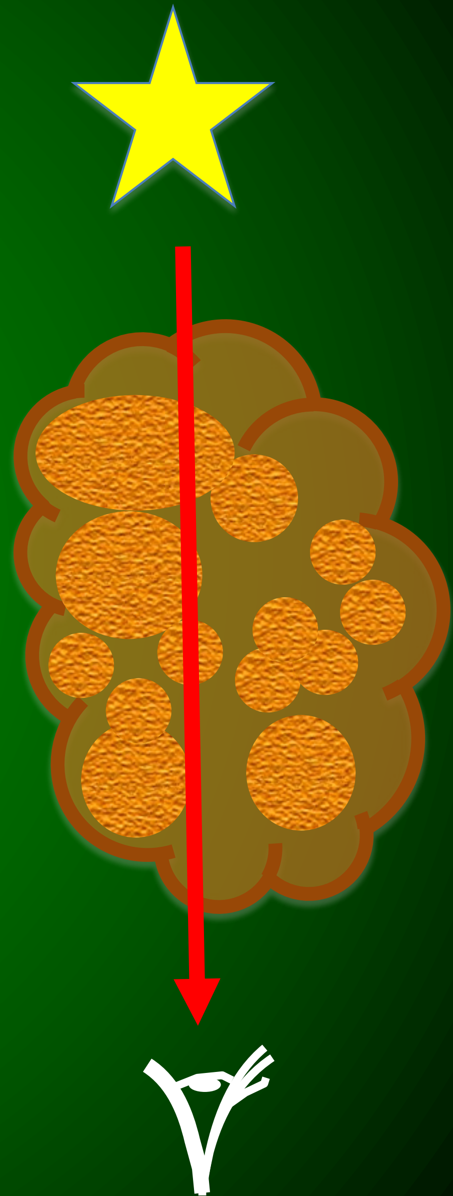
Jiang + 2013

Roland Diehl



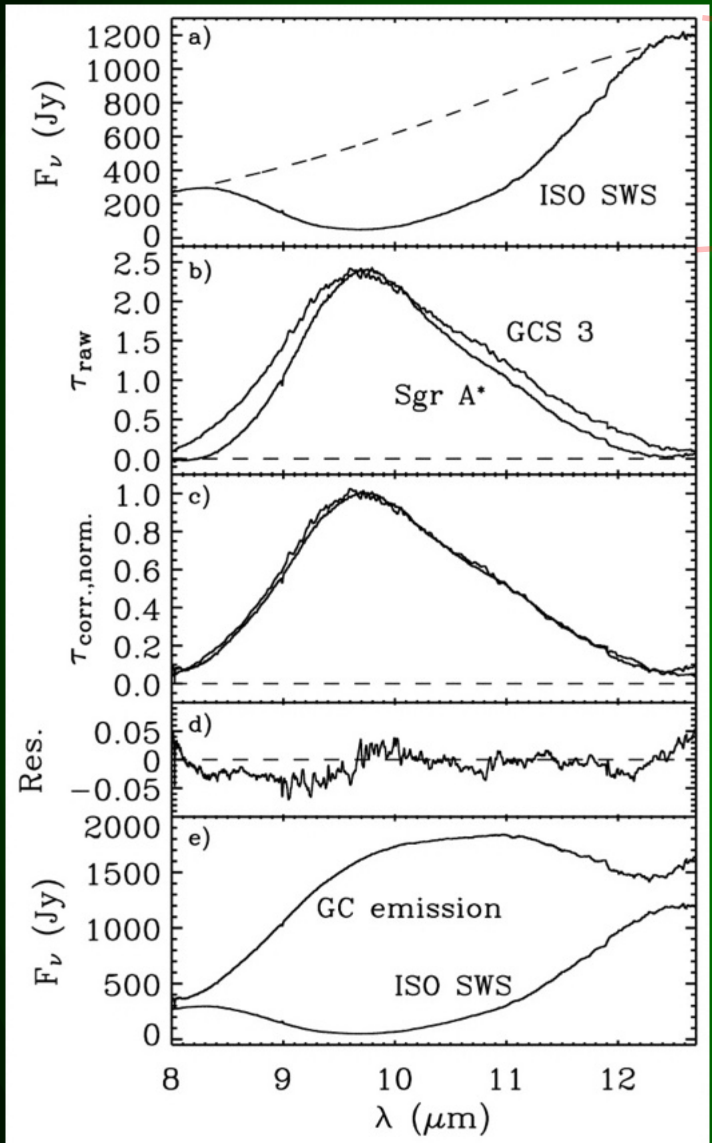
Silicates in the diffuse interstellar medium (DISM)



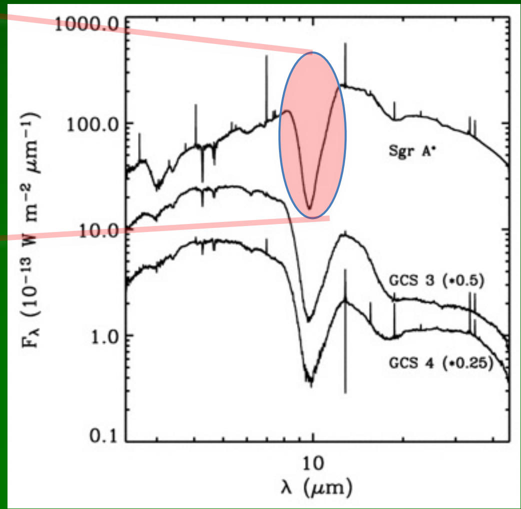


ISO, Kemper+ 2004

Silicates in the diffuse interstellar medium (DISM)



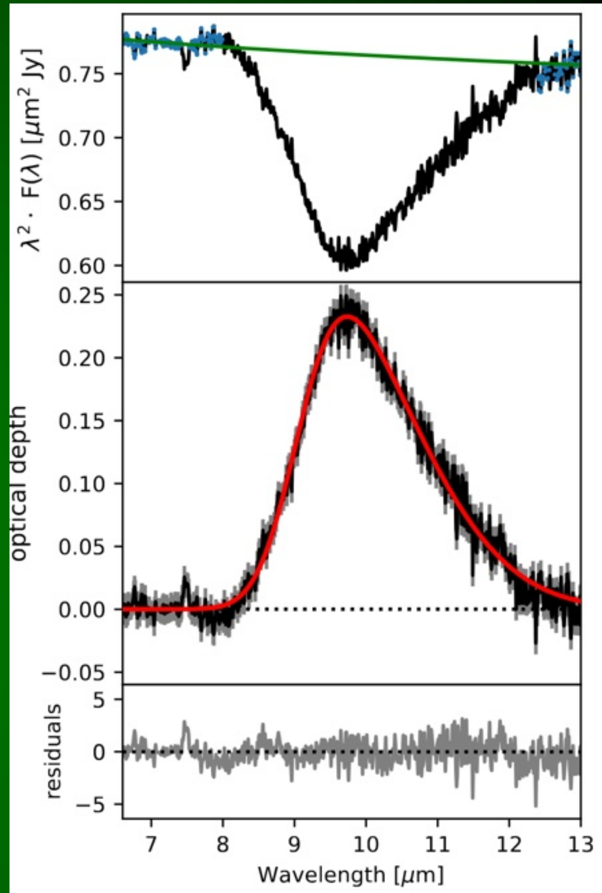
Kemper et al. 2004



ISM silicates almost fully « amorphous »

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

And mostly in the Rayleigh limit (small)

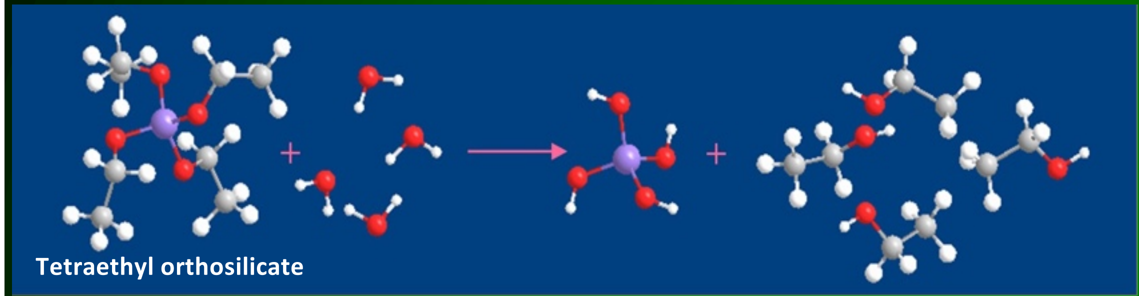


JWST, Zeegers+ 2025

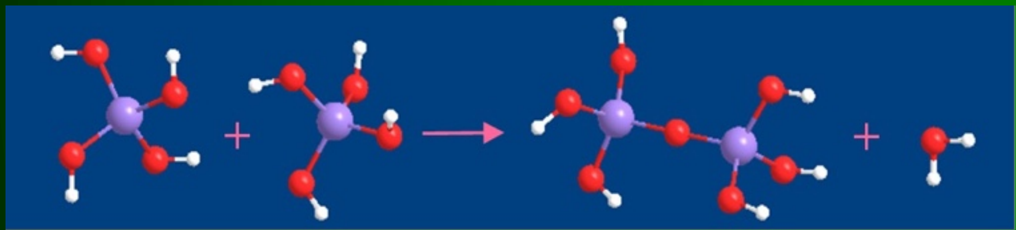
Lab determination of ISM silicates

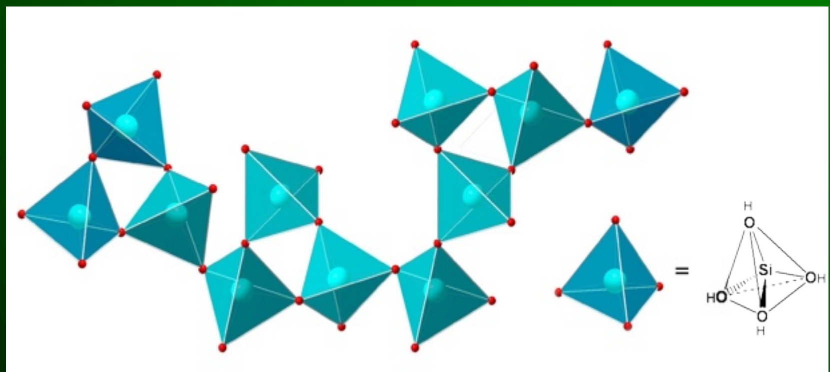
Amorphous silicates synthesised by different methods: solgel, quenching, laser ablation,…

$M(OR)_n$ hydrolysis



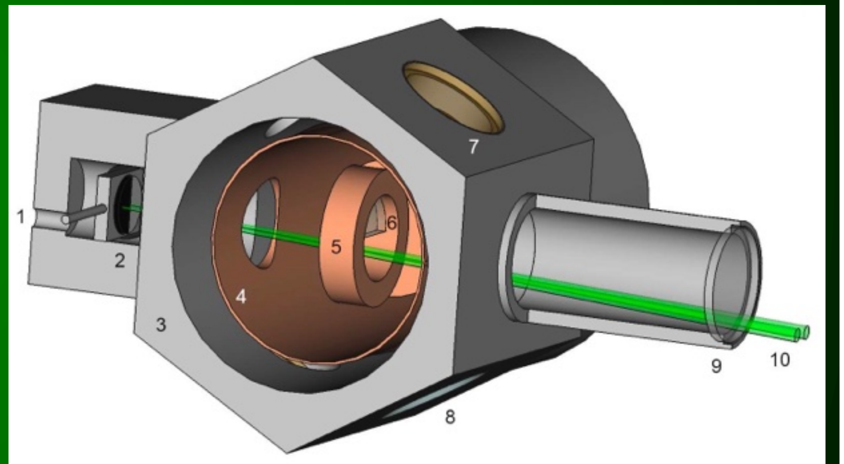
condensation





Wikipedia

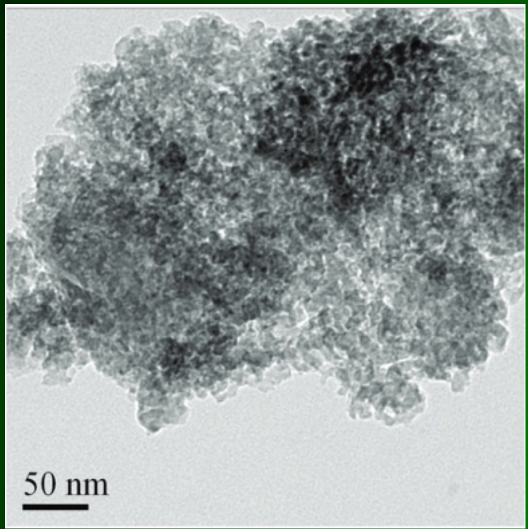
Solid Target ablation/recondensation

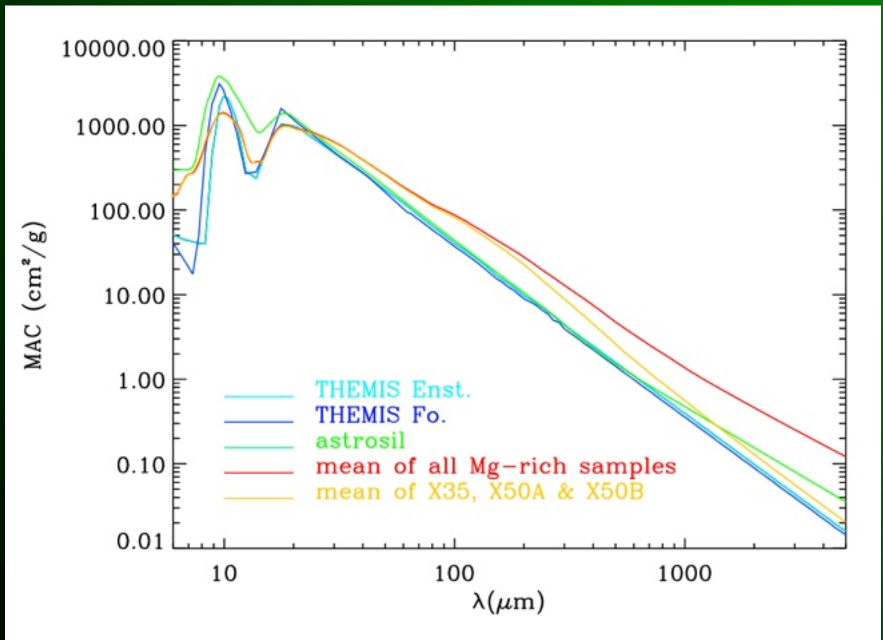


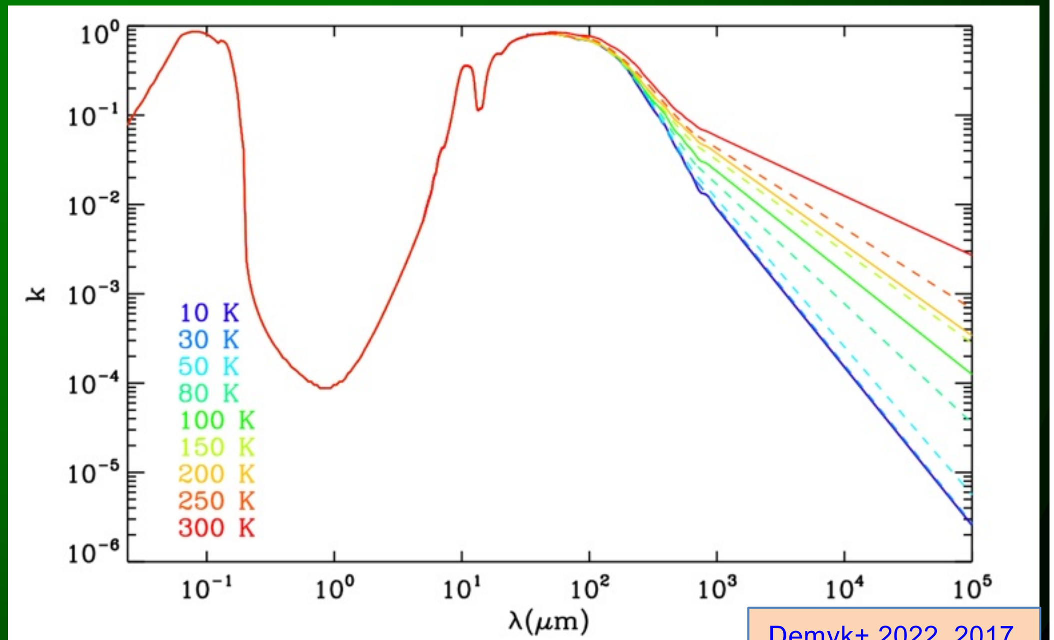
Rouillé 2020

Lab determination of ISM silicates

Optical constants determination and T dependence



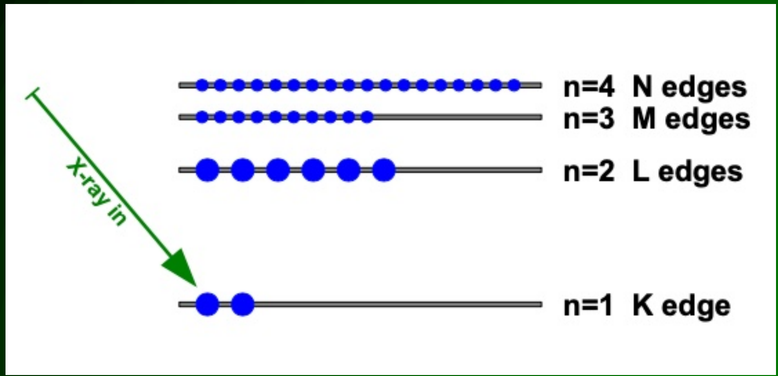


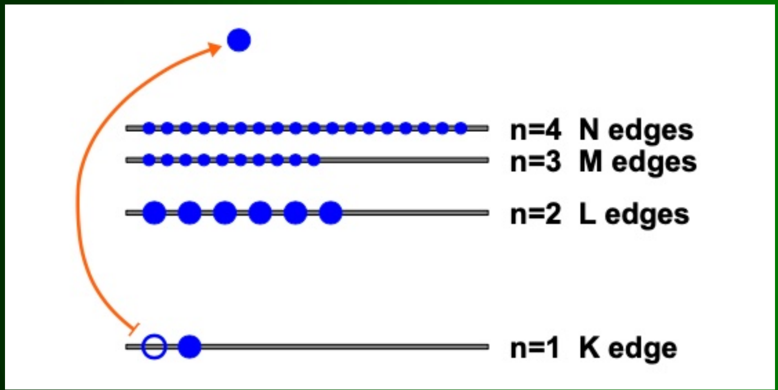


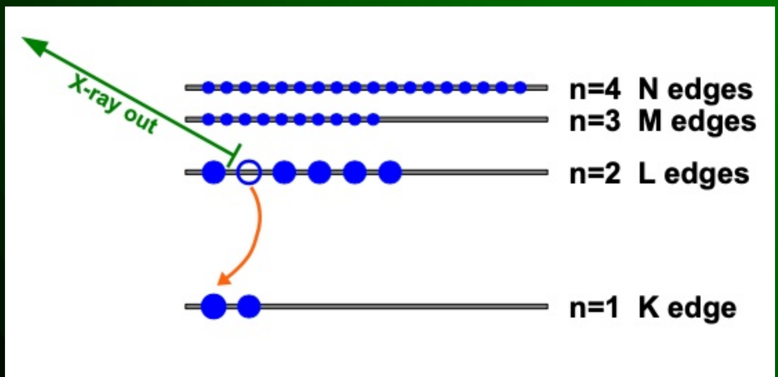
Demyk+ 2022, 2017

Potapov+2018, Zeidler+2015,; Koike+2006, Boudet+2005, Jäger+2003, Mennella+1998, …

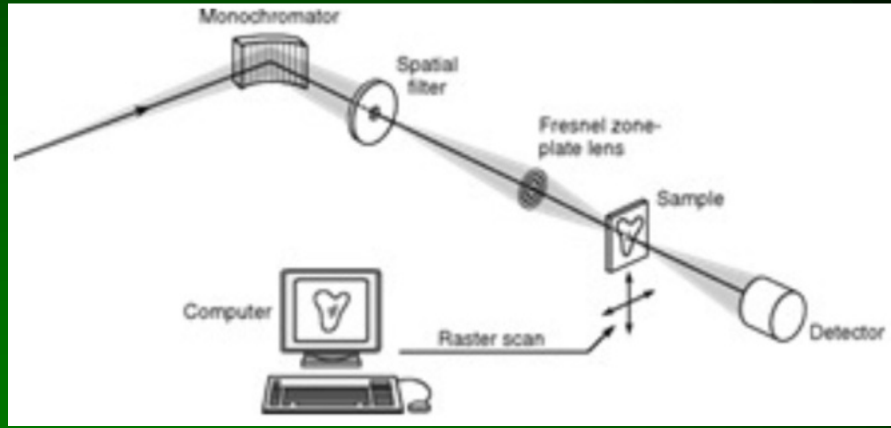
ISM composition from X-rays lab probe

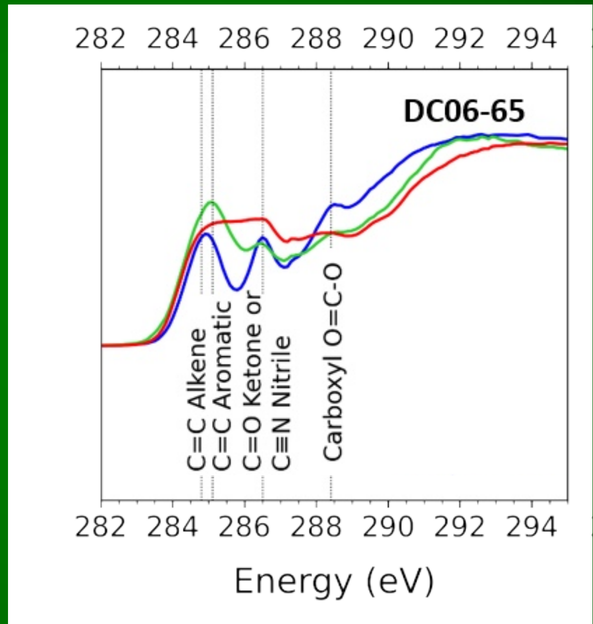






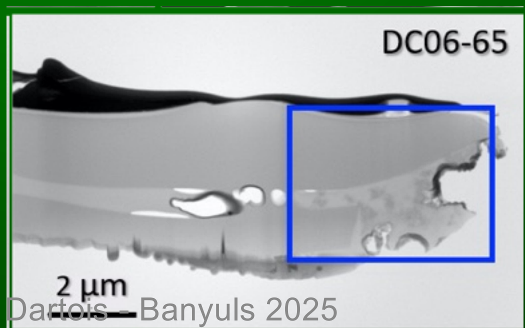
Ravel 2015

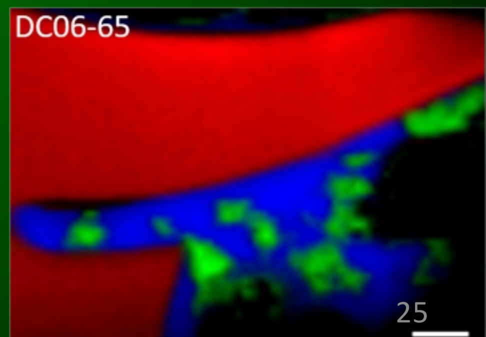




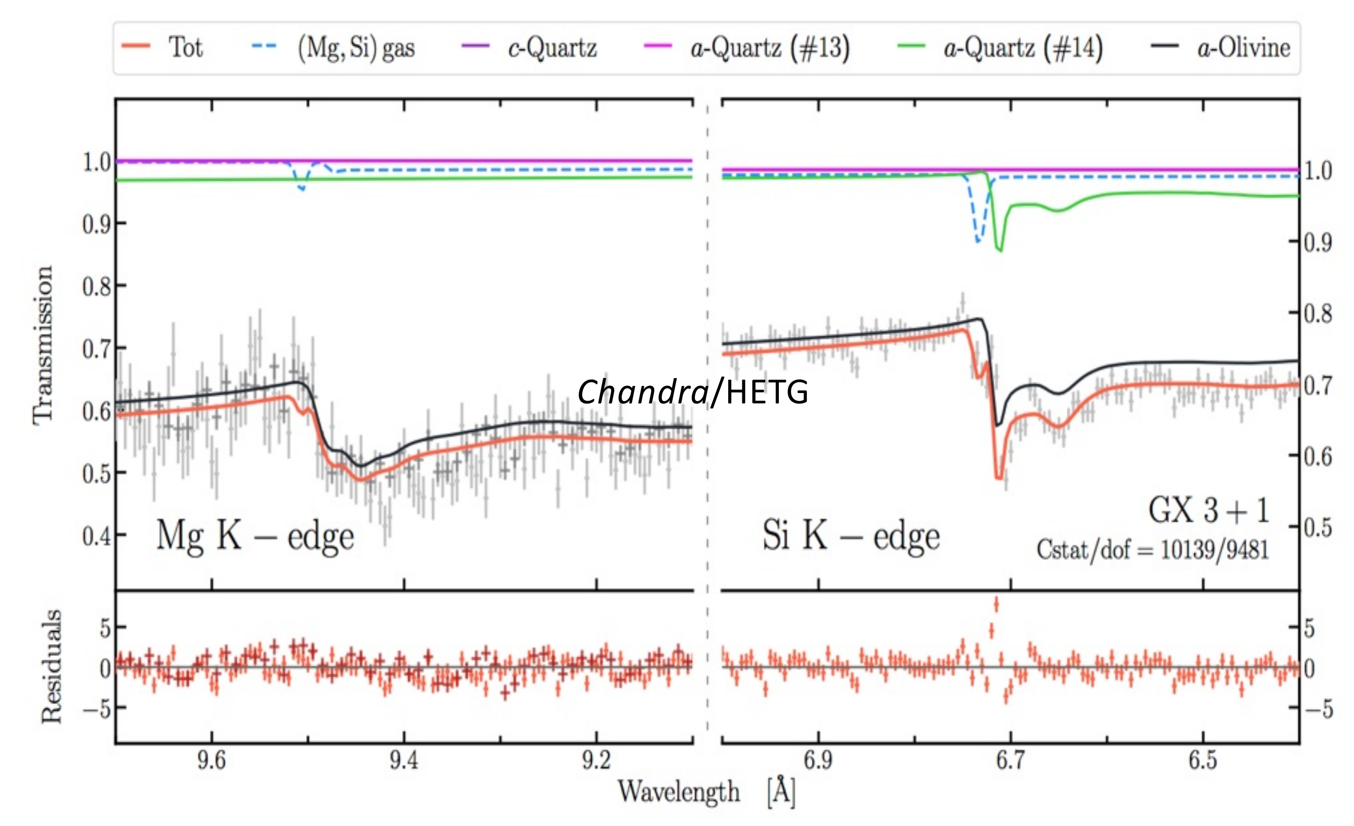
Applied to extraterrestrial material: Ultracarbonaceous micrometeorites

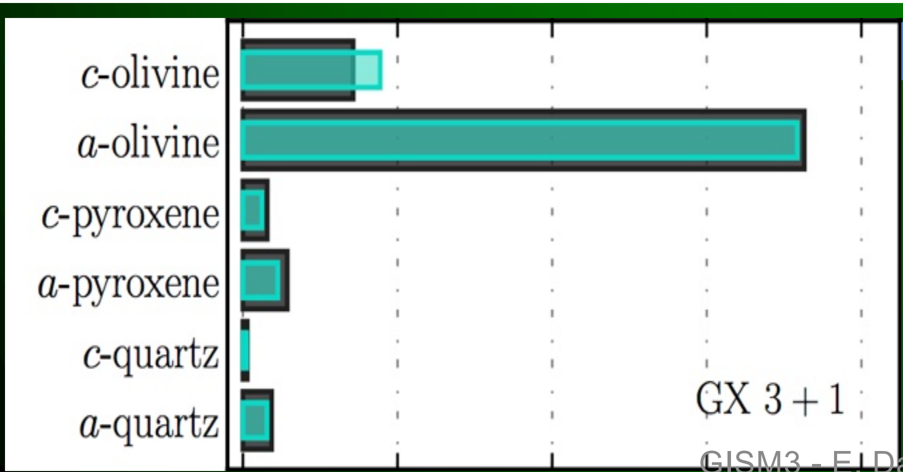
Guerin 2023



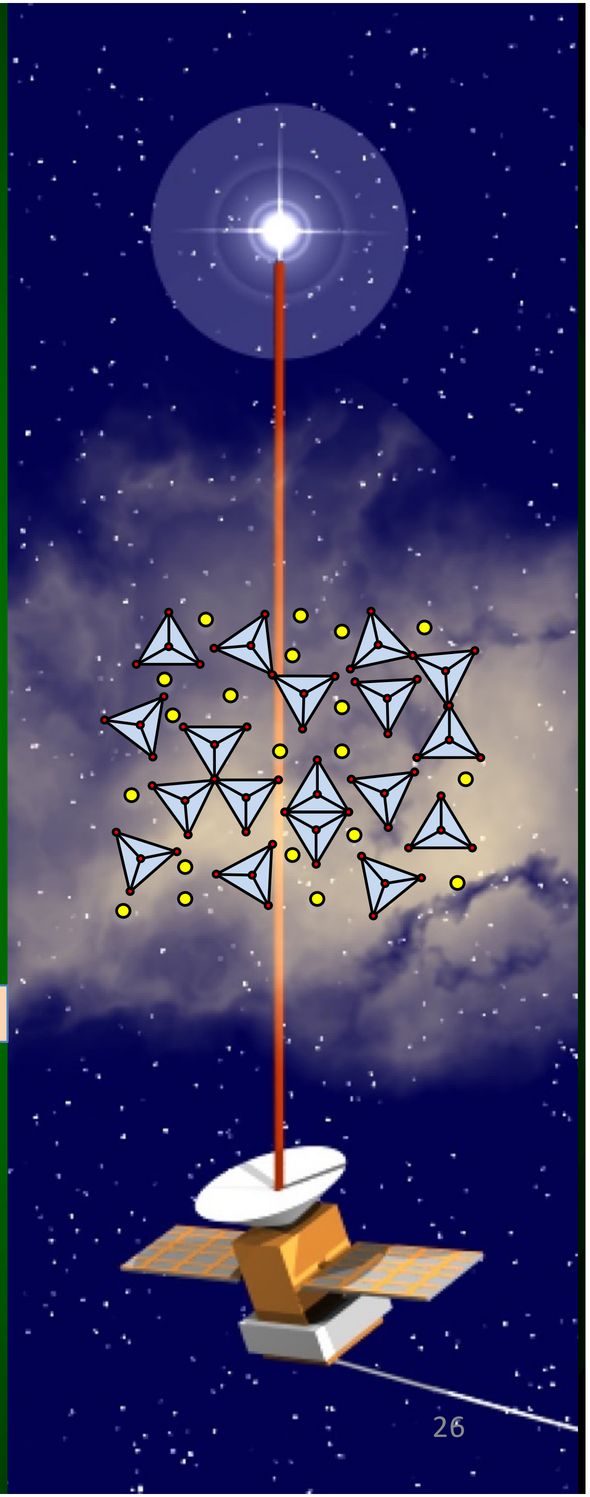


ISM composition from X-rays lab probe

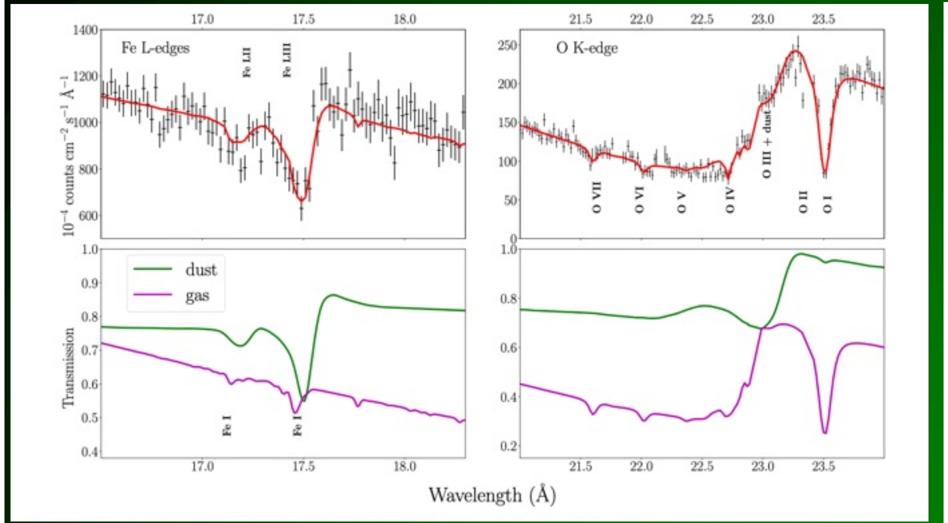




Rogantini+2020, Psaradaki+2022

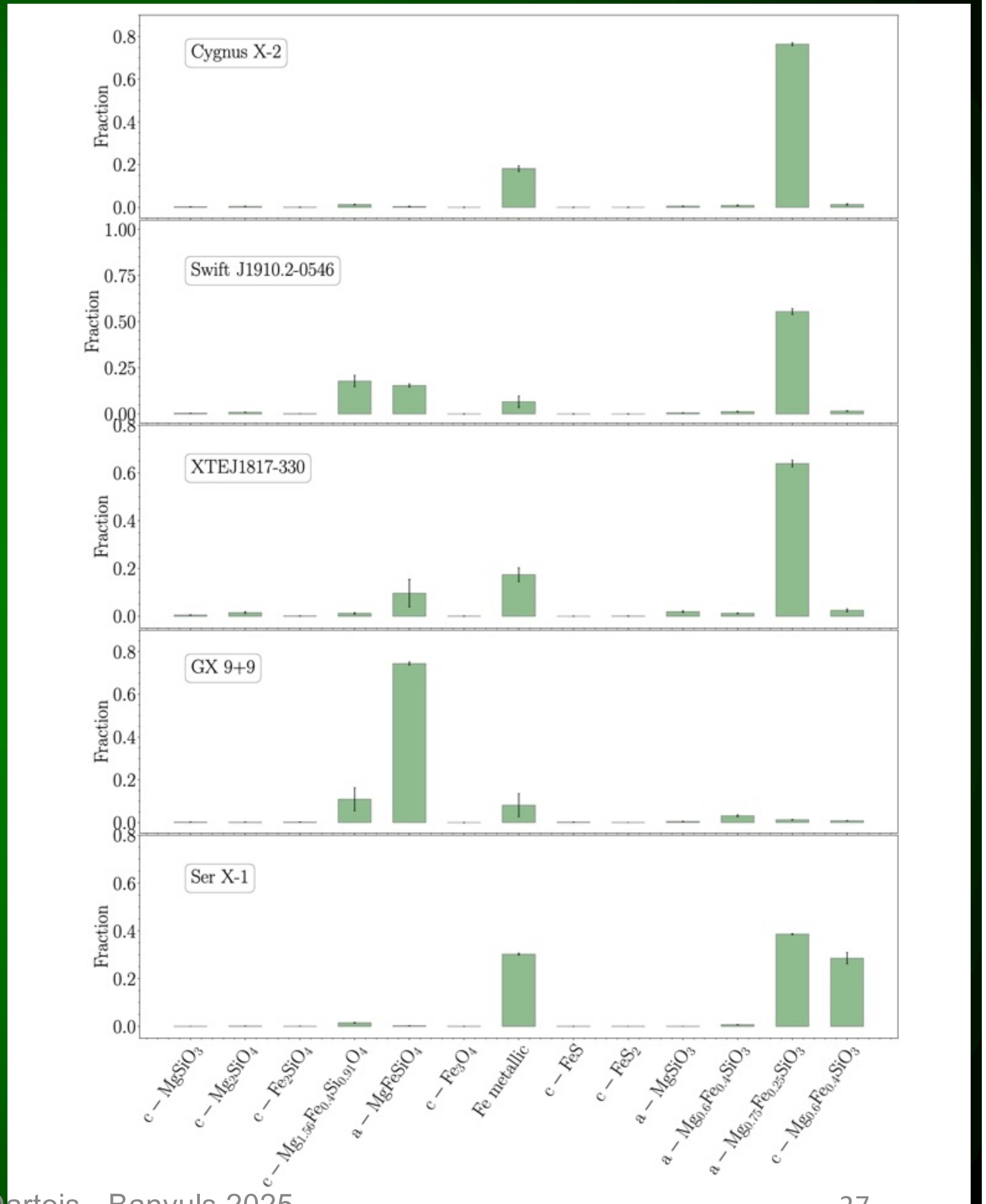


ISM composition from X-rays lab probe

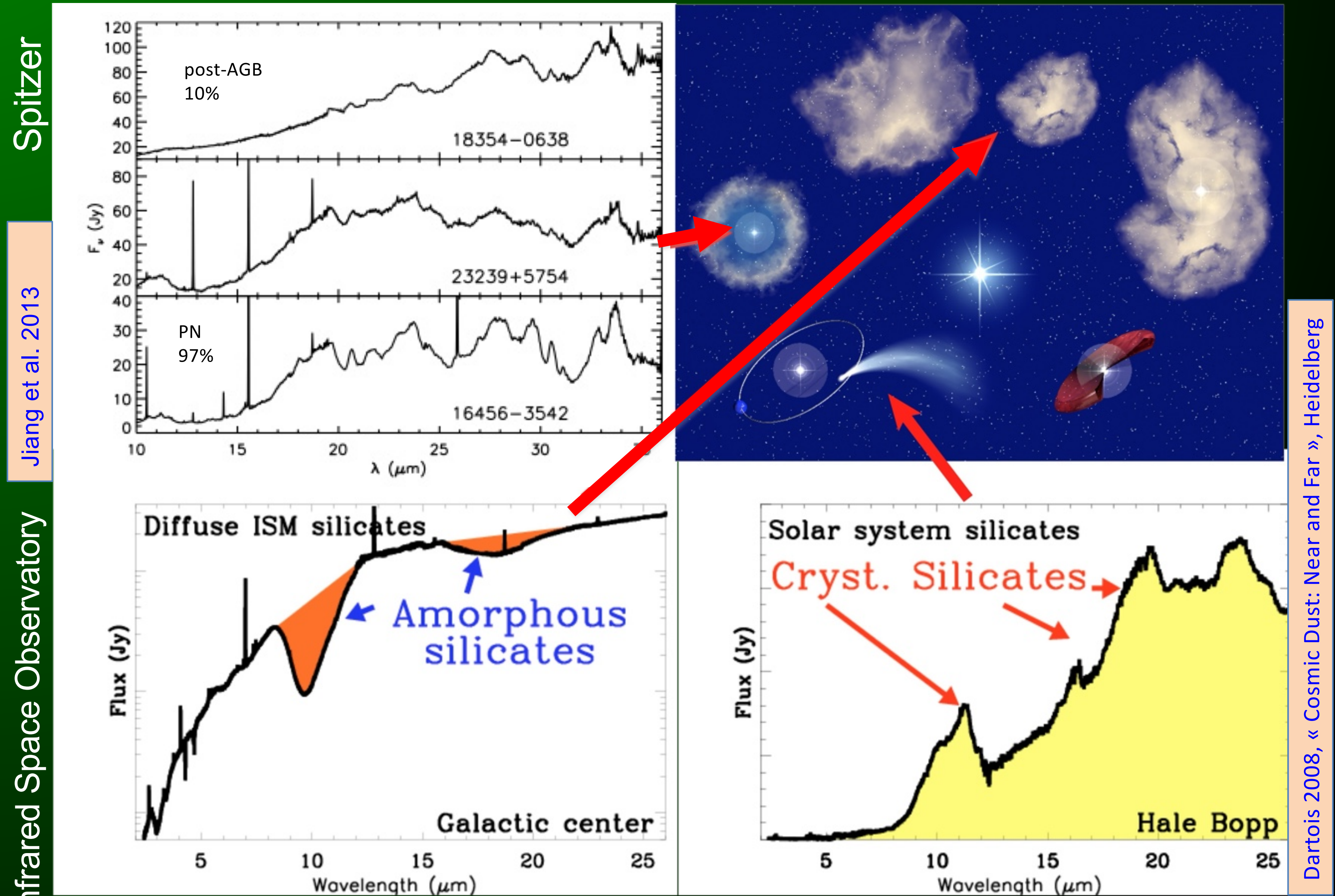


Psaradaki+2023

Mg-rich amorphous pyroxene ($Mg_{0.75}Fe_{0.25}SiO_3$) largest fraction of dust towards most of the X-ray sources, about 70% on average.
~15% of the dust column density in lines of sight could be in metallic Fe.
No strong evidence for ferromagnetic compounds, such as Fe_3O_4 or iron sulfides (FeS, FeS_2).

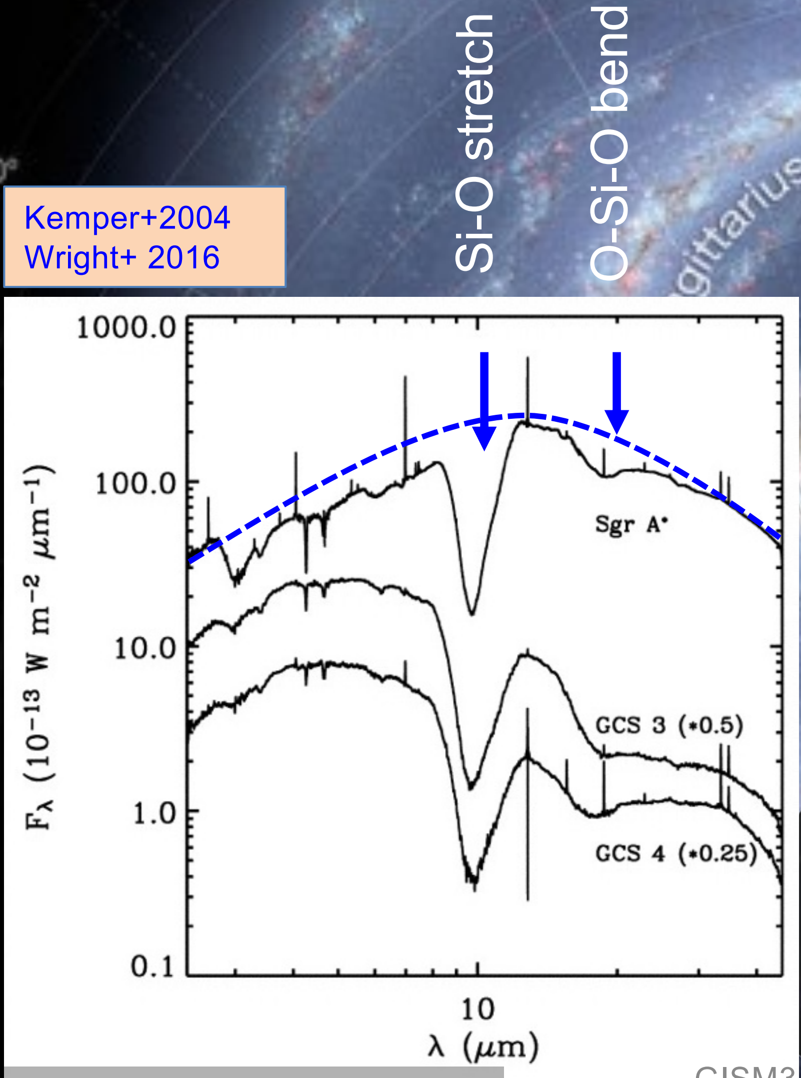


Silicates : crystals are locally formed/(re-)processed

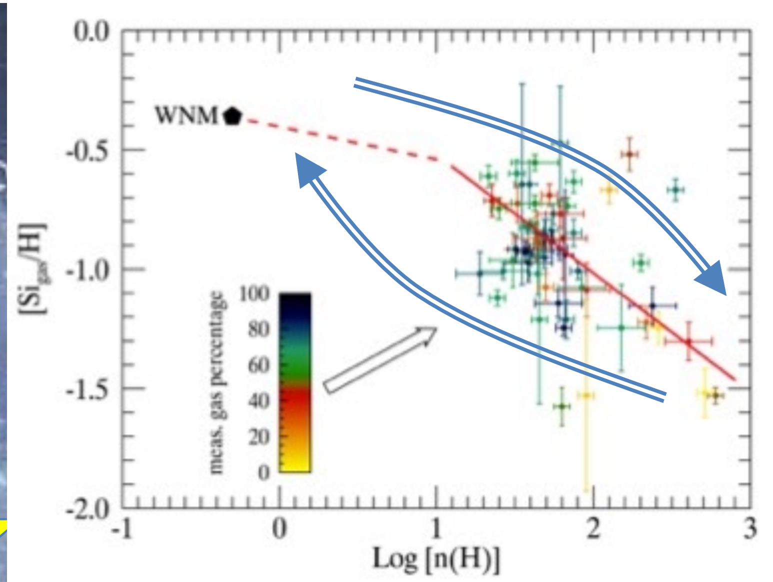


Why amorphous silicates in the DISM?

Kemper+2004
Wright+ 2016



1.1% ± 1.1cristallins

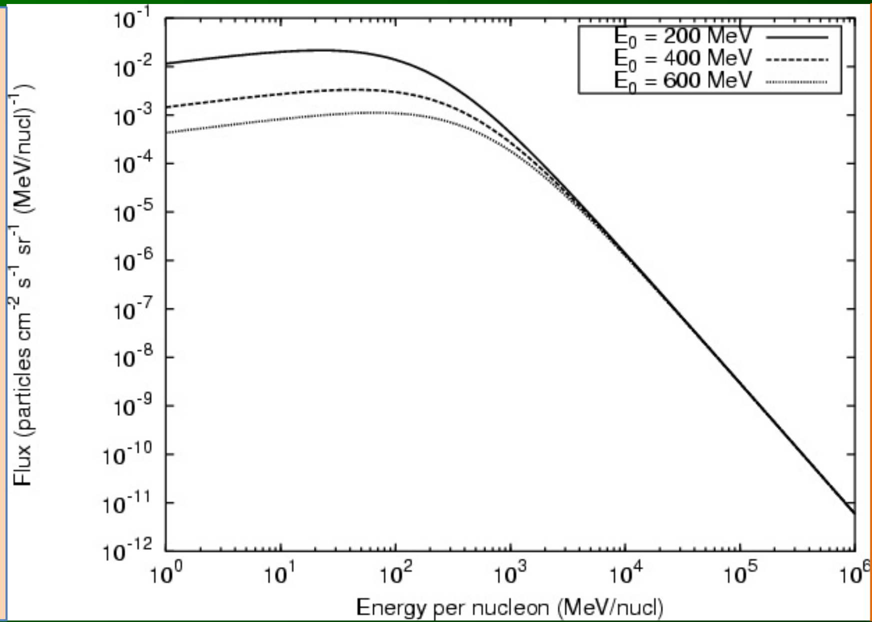


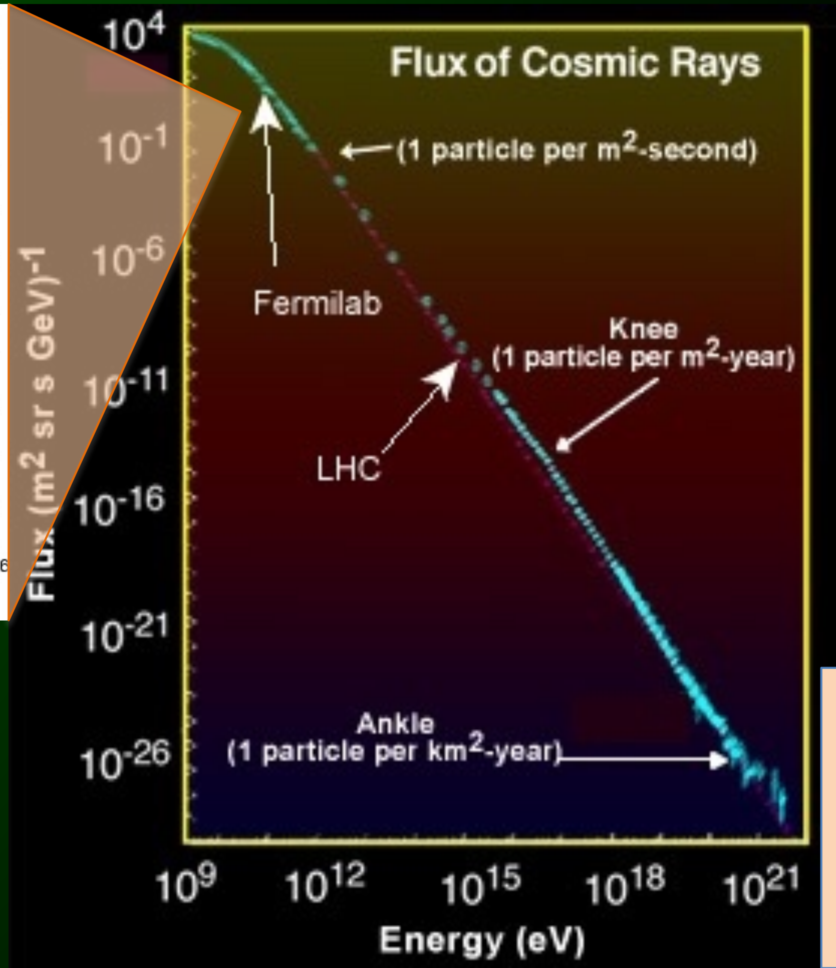
Zhukovska+ 2018, Jenkins 2011

Proportion inherited from stars vs growth by accretion in ISM ?

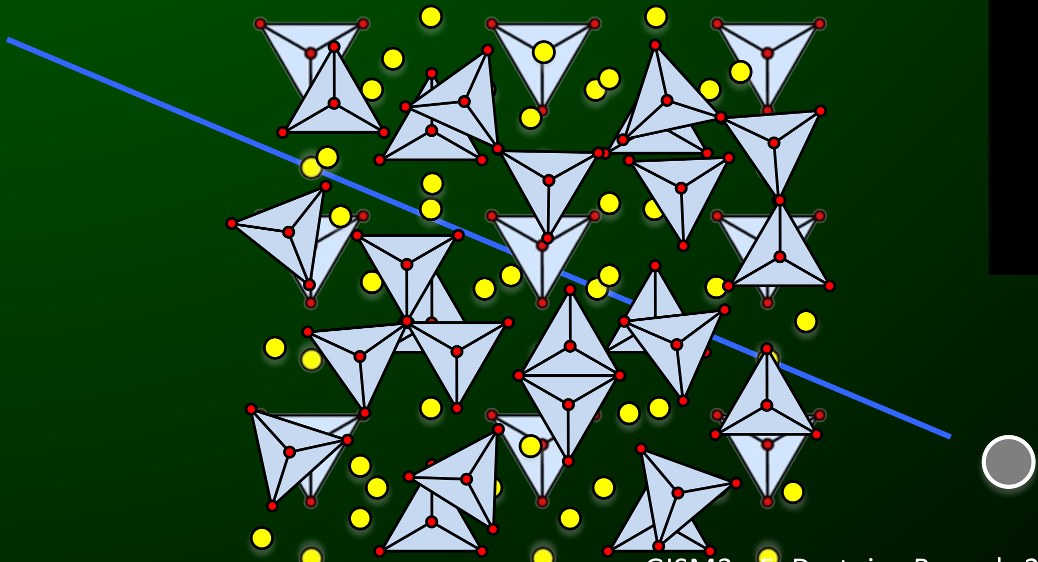
Influence of cosmic rays

Webber & Yushak 1983, Shen 2004



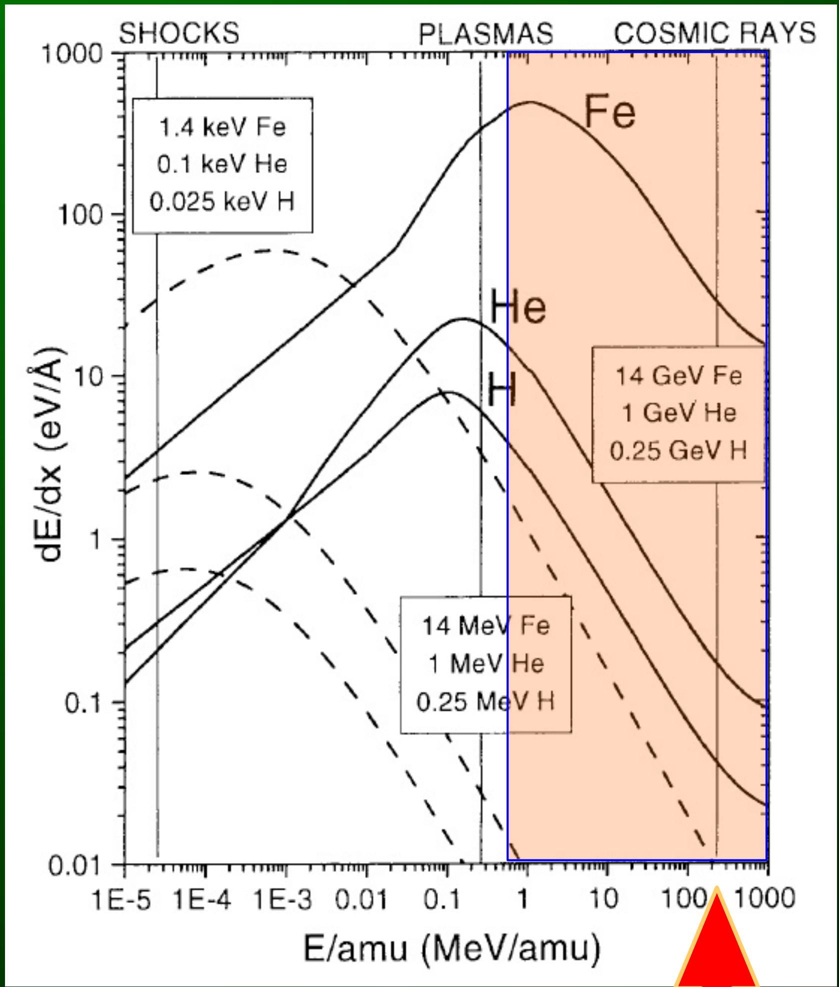


LPSC Grenoble



Energy deposition in astrophysical solids

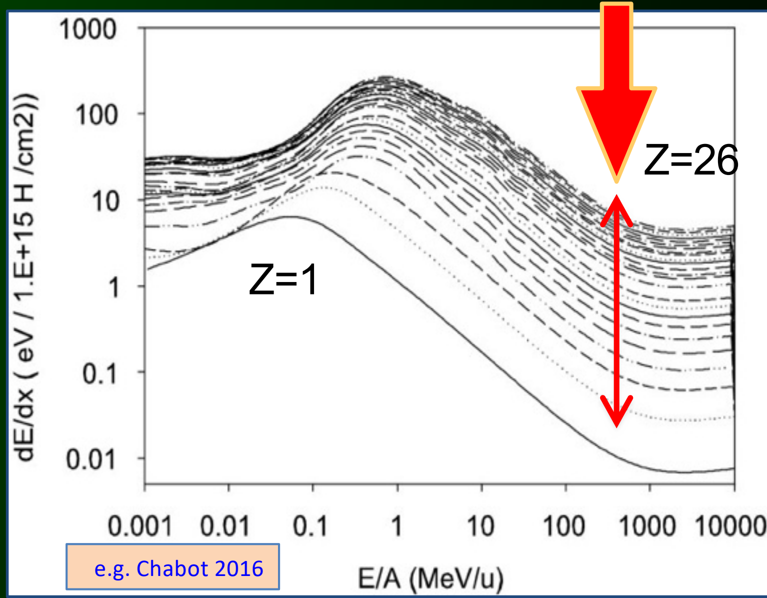
Nrj ~ a few 100 MeV/nucl



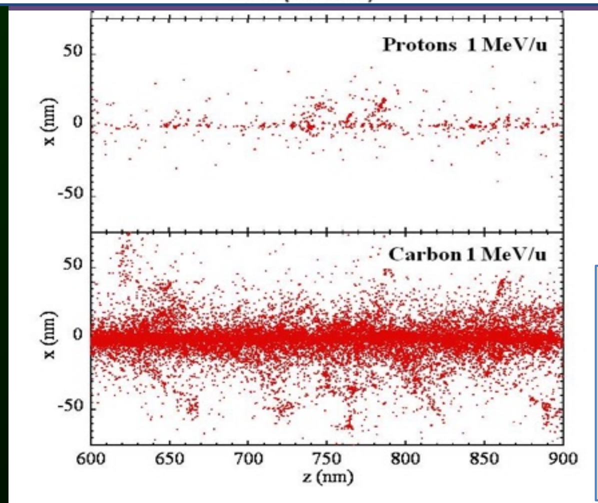
Bringa 2003

Ion matter interactions scale with dE/dx

$S_e = dE/dx \propto Z^2$



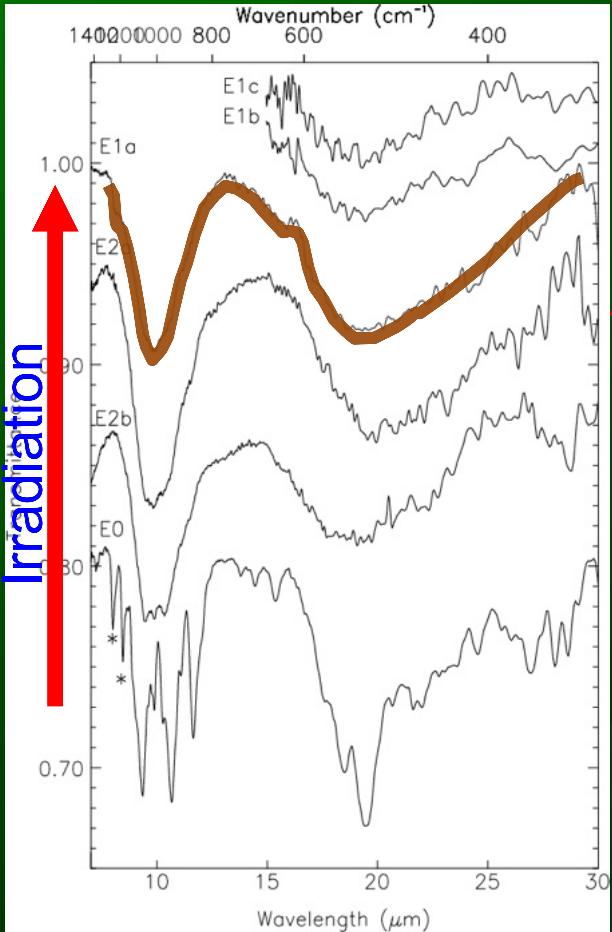
e.g. Chabot 2016



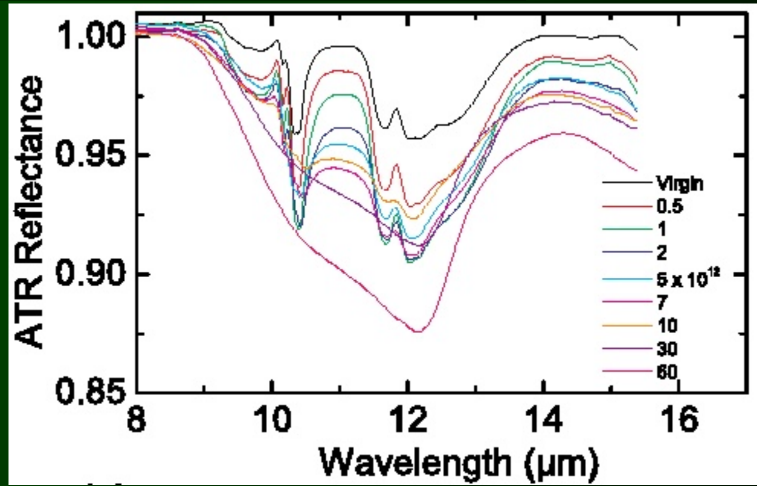
SRIM/TRIM

Amorphous silicates & CR in the laboratory

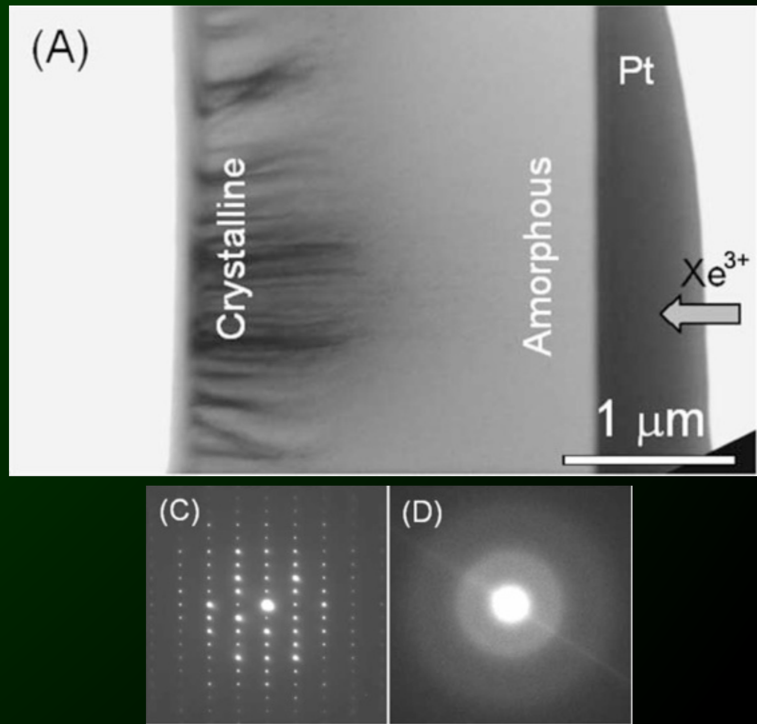
CR irradiation simulations 20-50keV
He+ irradiation of Enstatite ($MgSiO_3$)



Demyk+2004



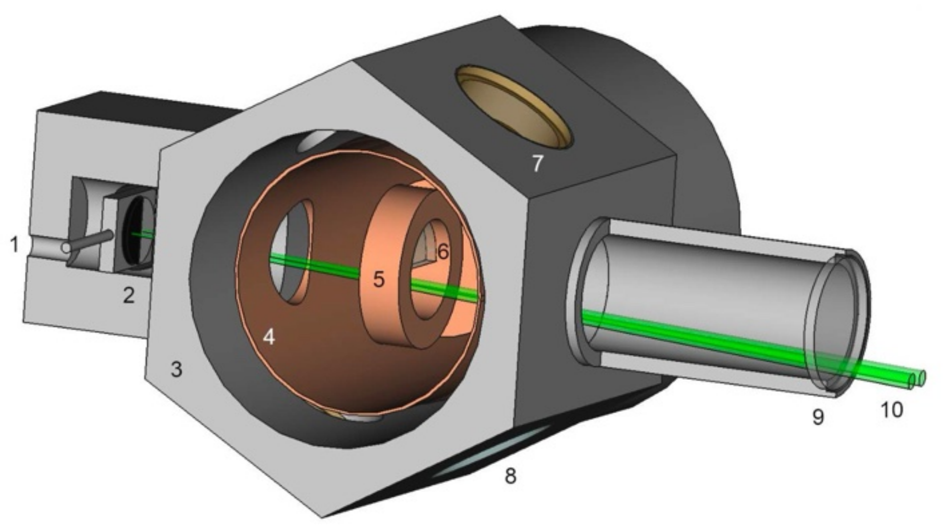
Bringa+2007

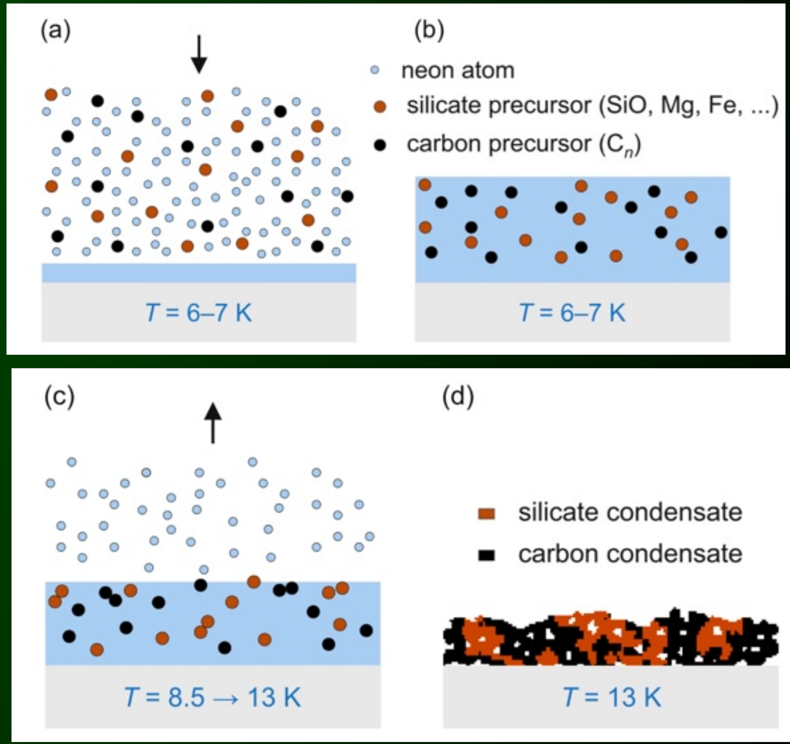


e.g. Sczenes+2010, Bringa+2007, Stratzzulla+2005, Demyk+2004, Brucato+2003, 2004, Carrez+2002, Shrempel+2002

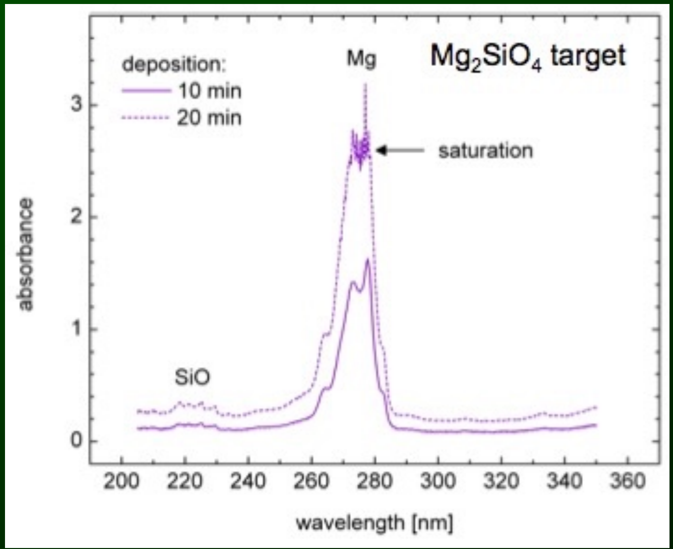
« 0.1-5.0 GeV heavy-ion cosmic rays can rapidly (~70 Myr) amorphize crystalline silicate »

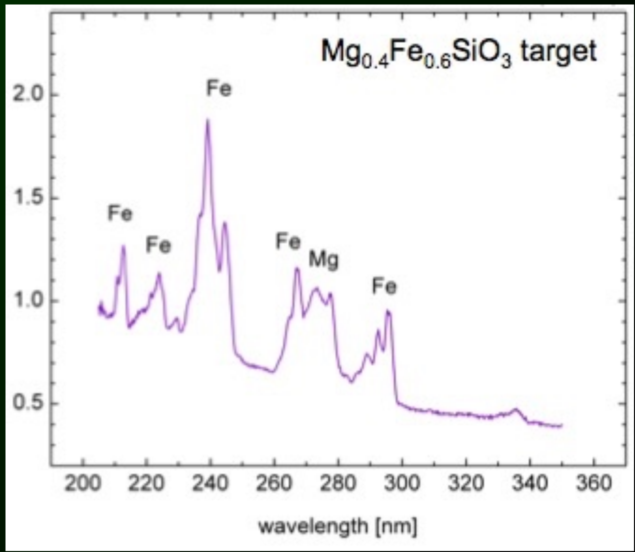
Amorphous silicates from gas in the lab





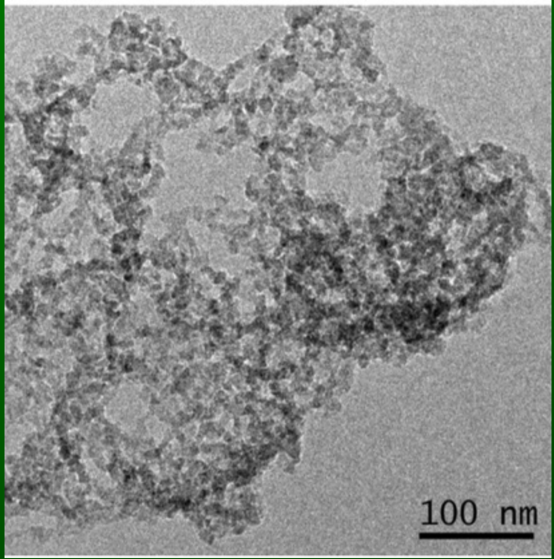
Rouillé 2020

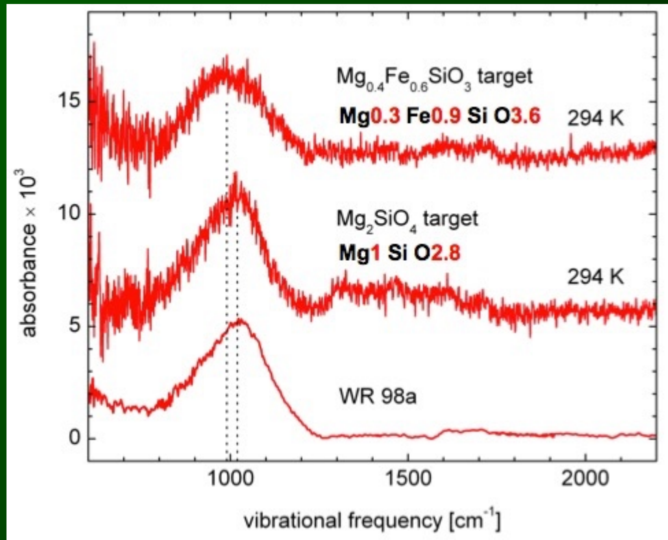


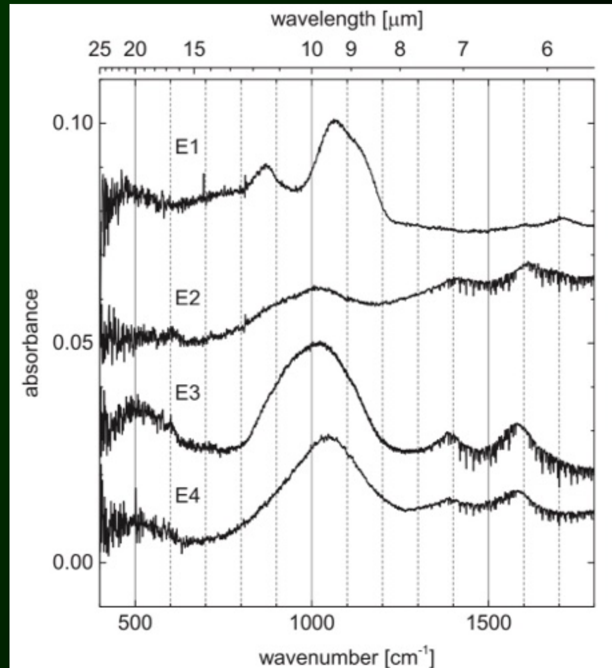


Amorphous silicates from gas in the lab

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







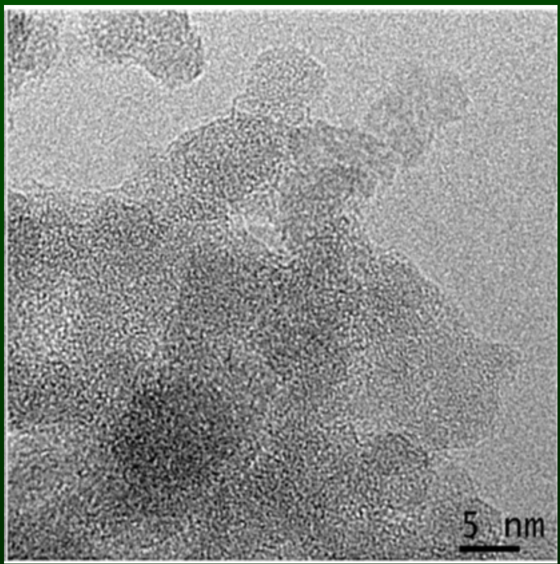
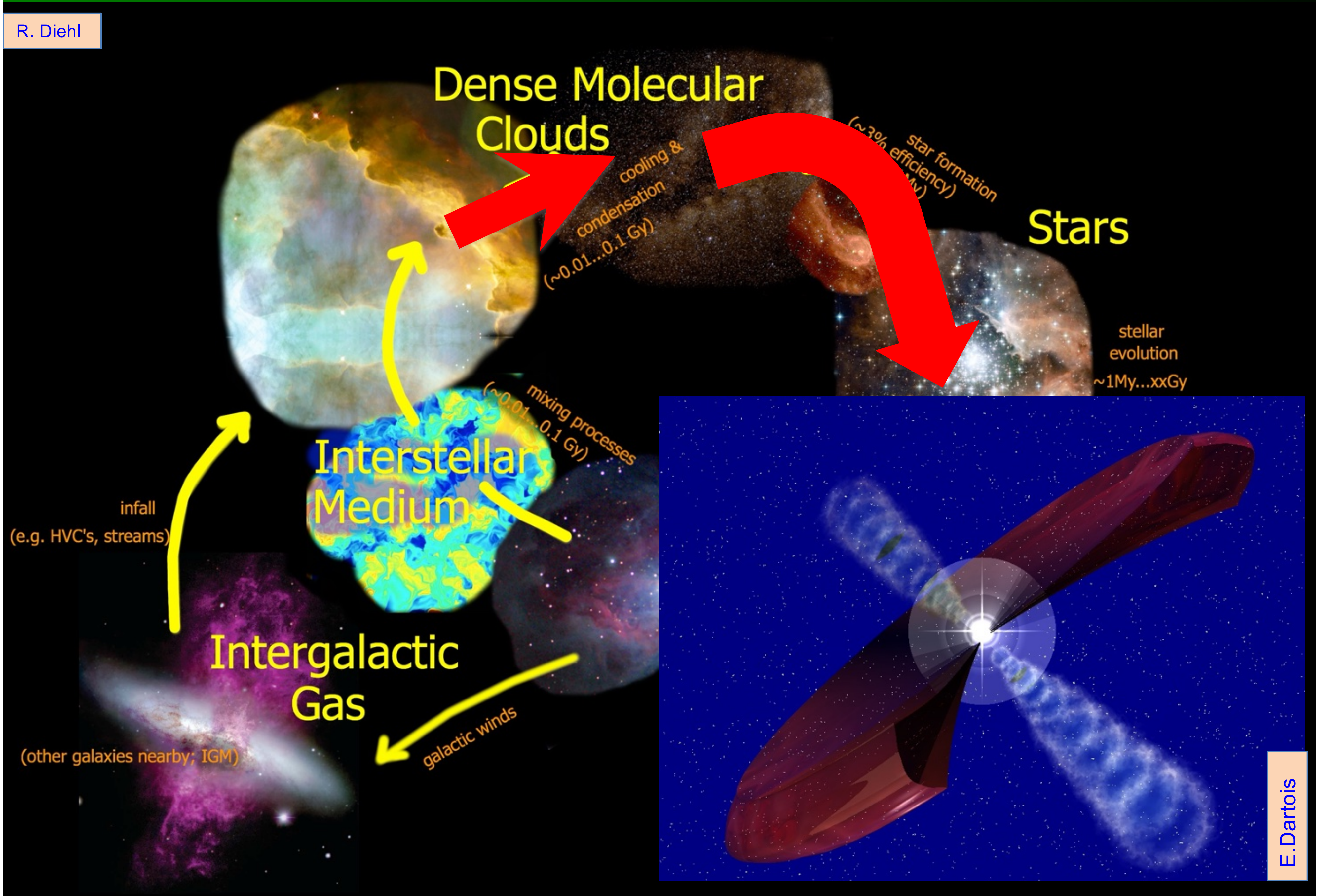
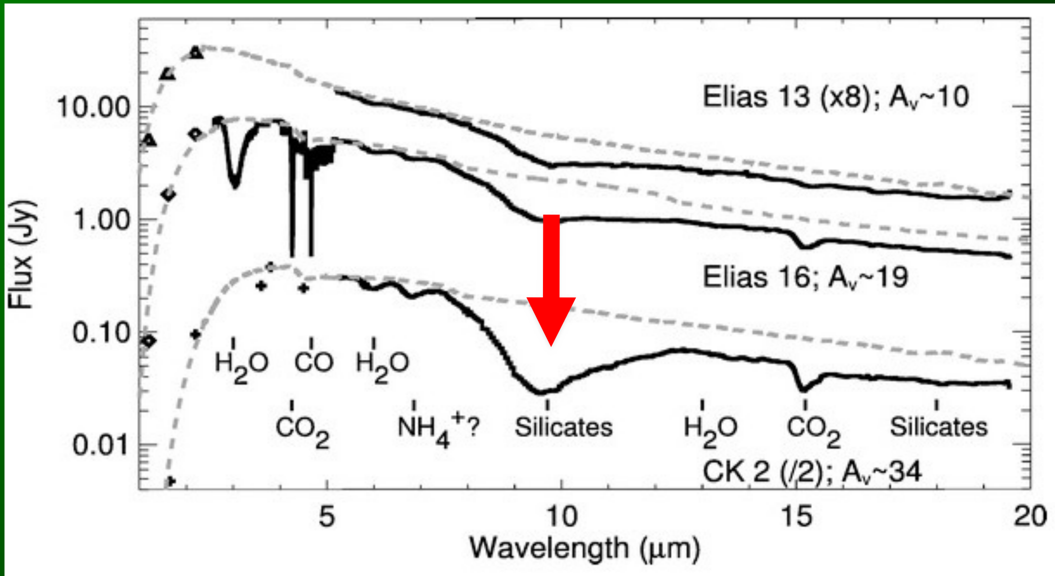


Table 1
Average Concentrations[a] of Matrix-isolated Species

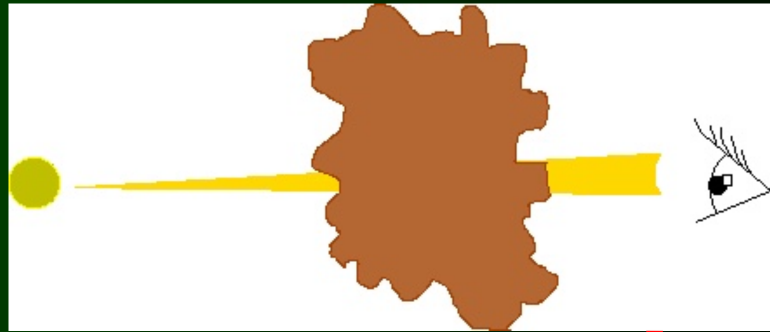
Species	E1[b]	E2	E3	E4
Mg	···	10.06	1.55	1.64
Fe	···	···	19.2	16.2
SiO	26.0	19.6	59.3	41.1
SiO_2	···	6.63	17.9	11.3
Si_2O_2	16.4	···	8.81	15.9
Si_3O_3	6.76	···	···	1.14
C_2	···	1.53	2.83	4.99
C_3	10.0	4.90	11.7	35.2
C_4	0.538	2.41	2.17	4.58
C_5	2.02	3.41	3.53	8.49
C_6	2.55	1.15	5.15	9.91
C_7	0.297	1.72	0.551	1.00
C_8	0.243	0.0972	0.390	···
C_9	0.498	0.156	0.554	1.55
CO	8.92	610	477	458
CO_2	5.85	70.4	65.8	51.5
C_3O	0.330	14.5	13.2	19.0
H_2O[c]	425	213	483	180
O_3	···	24.9	30.2	13.9

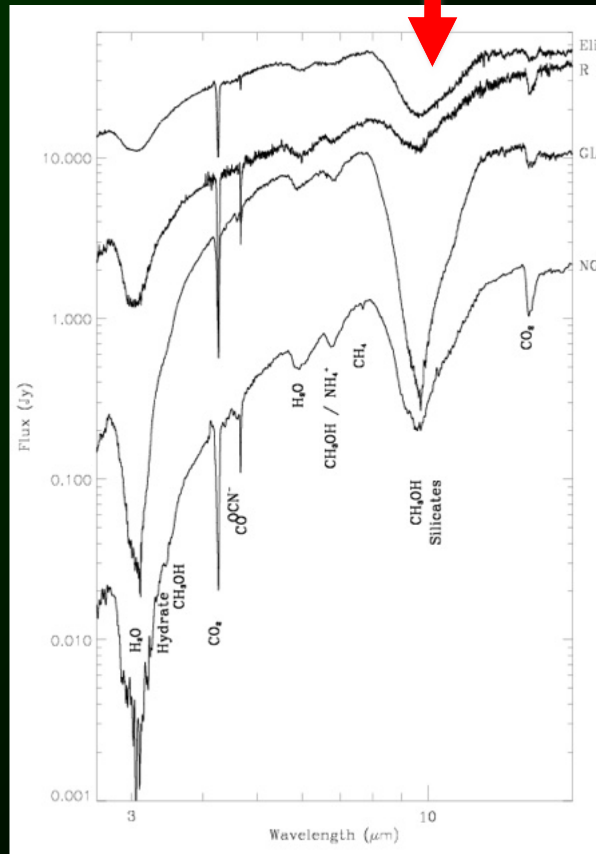
e.g. Rouillé+2020, 2014, Nuth & Moore1989 Donn+1981, Khanna+1981

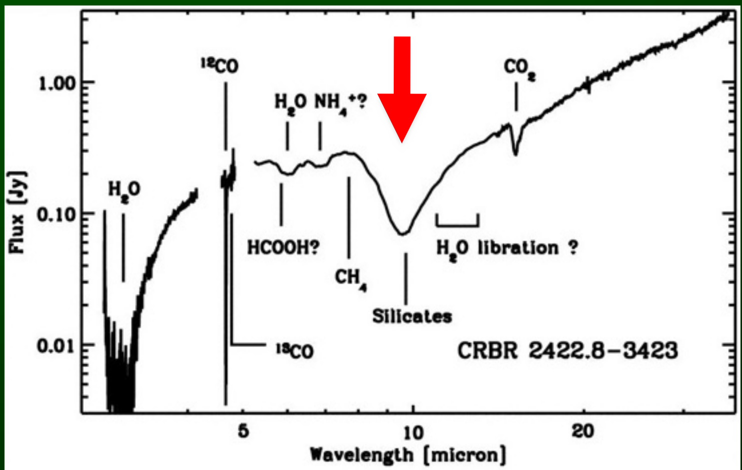

R. Diehl
Dense Molecular Clouds
cooling & condensation
(~0.01...0.1 Gy)
star formation
(~3% efficiency)
Stars
stellar evolution
~1My...xxGy
Interstellar Medium
mixing processes
(~0.01...0.1 Gy)
infall
(e.g. HVC's, streams)
Intergalactic Gas
galactic winds
(other galaxies nearby; IGM)
E.Dartois

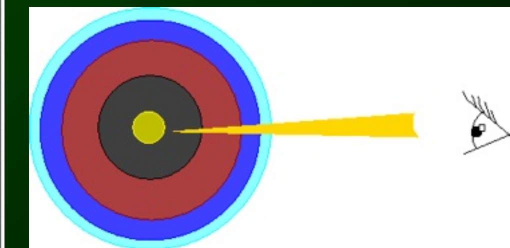


e.g. Knez+2005, Bergin+2005





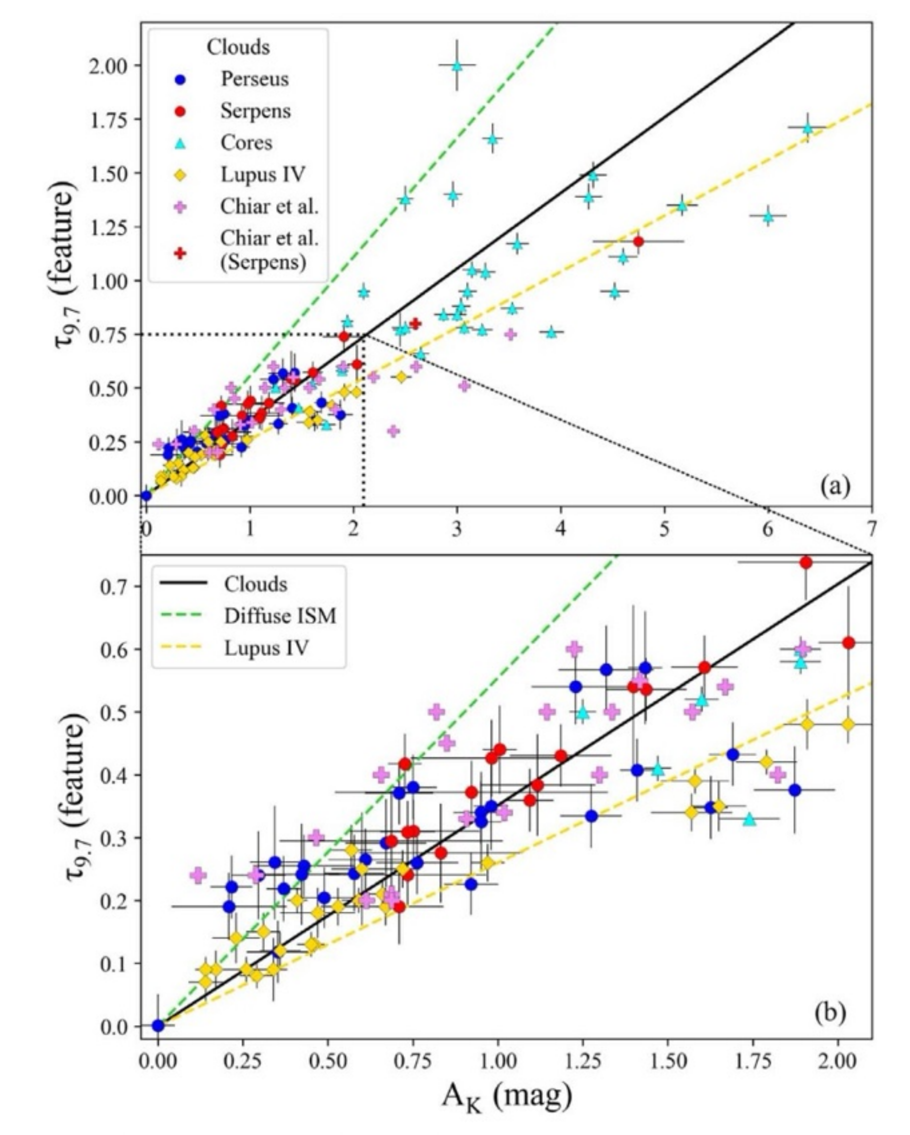




Spitzer/VLT, Pontoppidan+2005

ISO database extract

Silicates in dense clouds/cores



τ9.7/AK from DISM values (~0.55) to lower ratios (~0.26).

AK >~ 1.2 (AV ~ 10; Perseus, Lupus, dense cores) and ~2.0 (AV ~ 17; Serpens), the τ9.7/AK ratio is lowest.

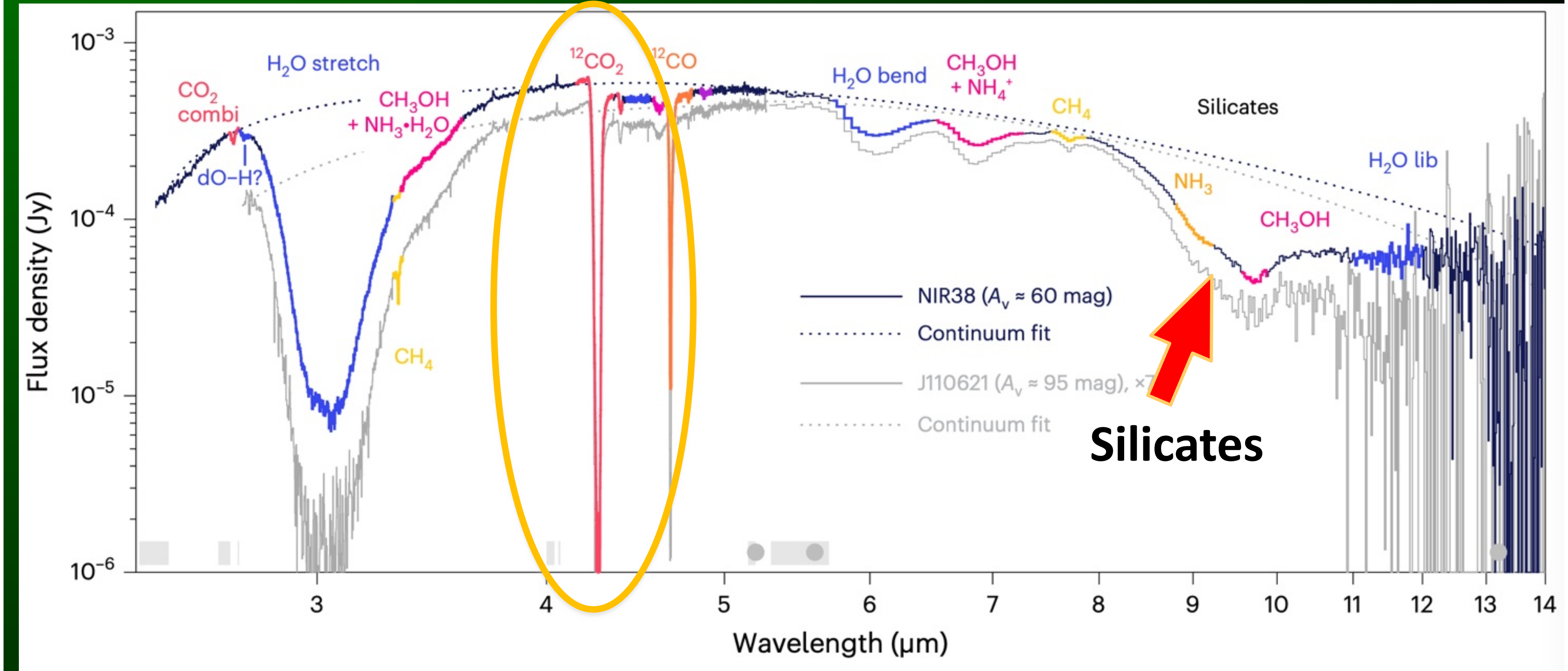
τ9.7/AK reduction from diffuse to dense clouds consistent with moderate grain growth(~0.5 µm)

NIR excess increase (AK) but not affecting much silicate band profiles.

Madden+ 2022

Silicates at highest extinction

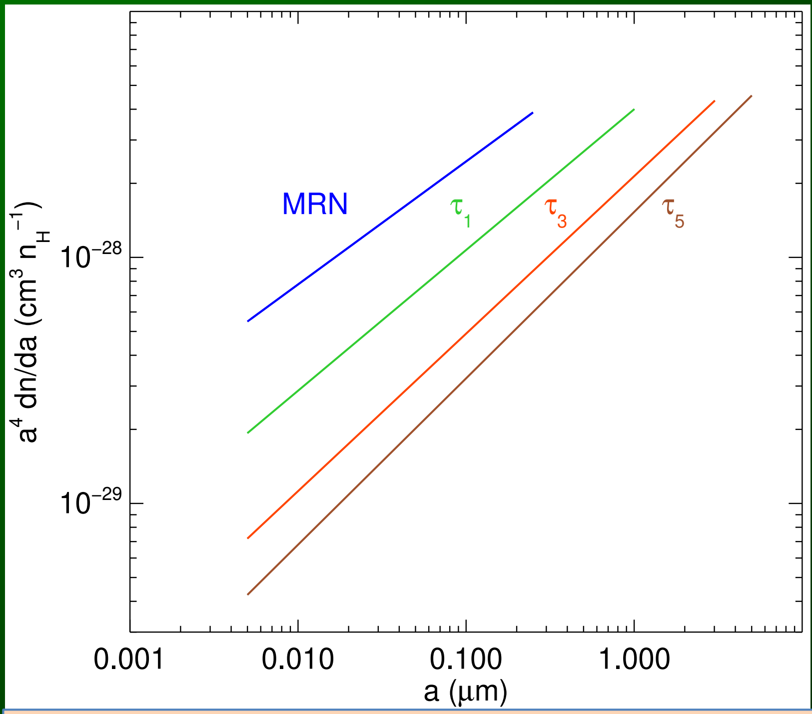
JWST spectra of densest cloud ices to date!



McClure+ 2023

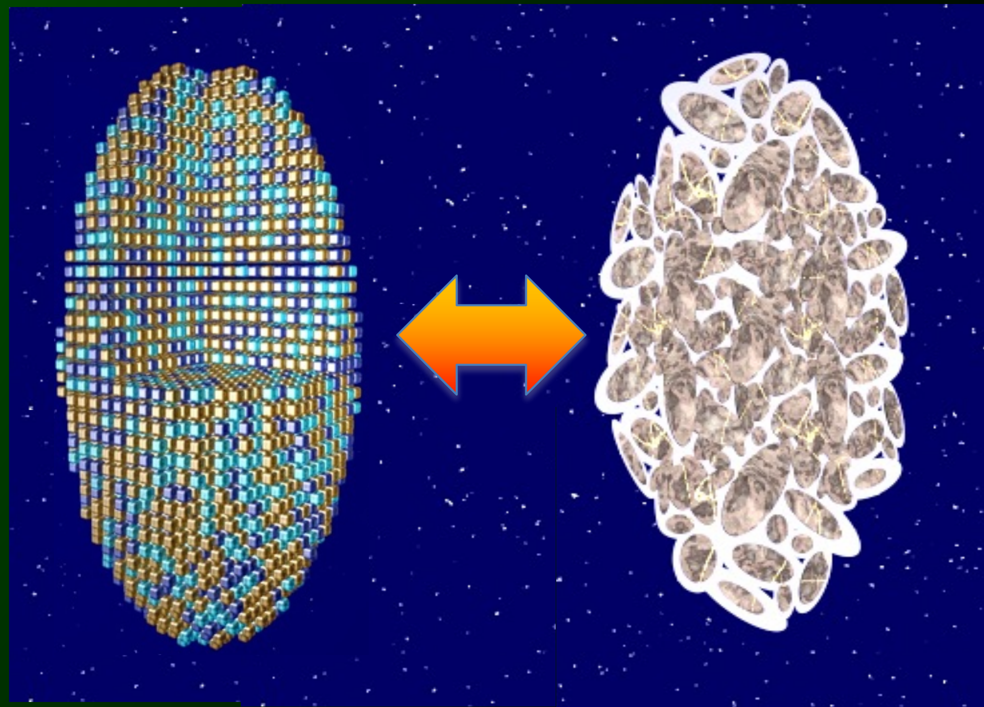
Exploring dust grains growth and size distribution

Distribution evolution

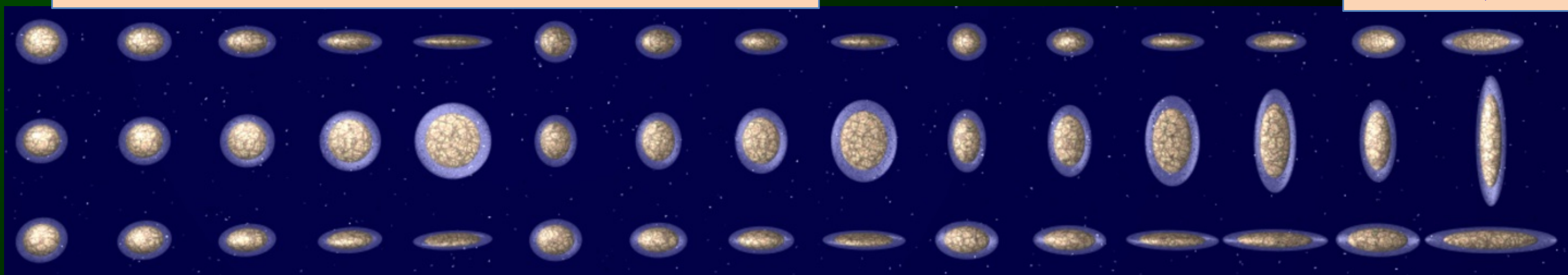


Silsbee+ 2020; Paruta+ 2016; Ormel+ 2011, 2009; Weingartner & Draine 2001

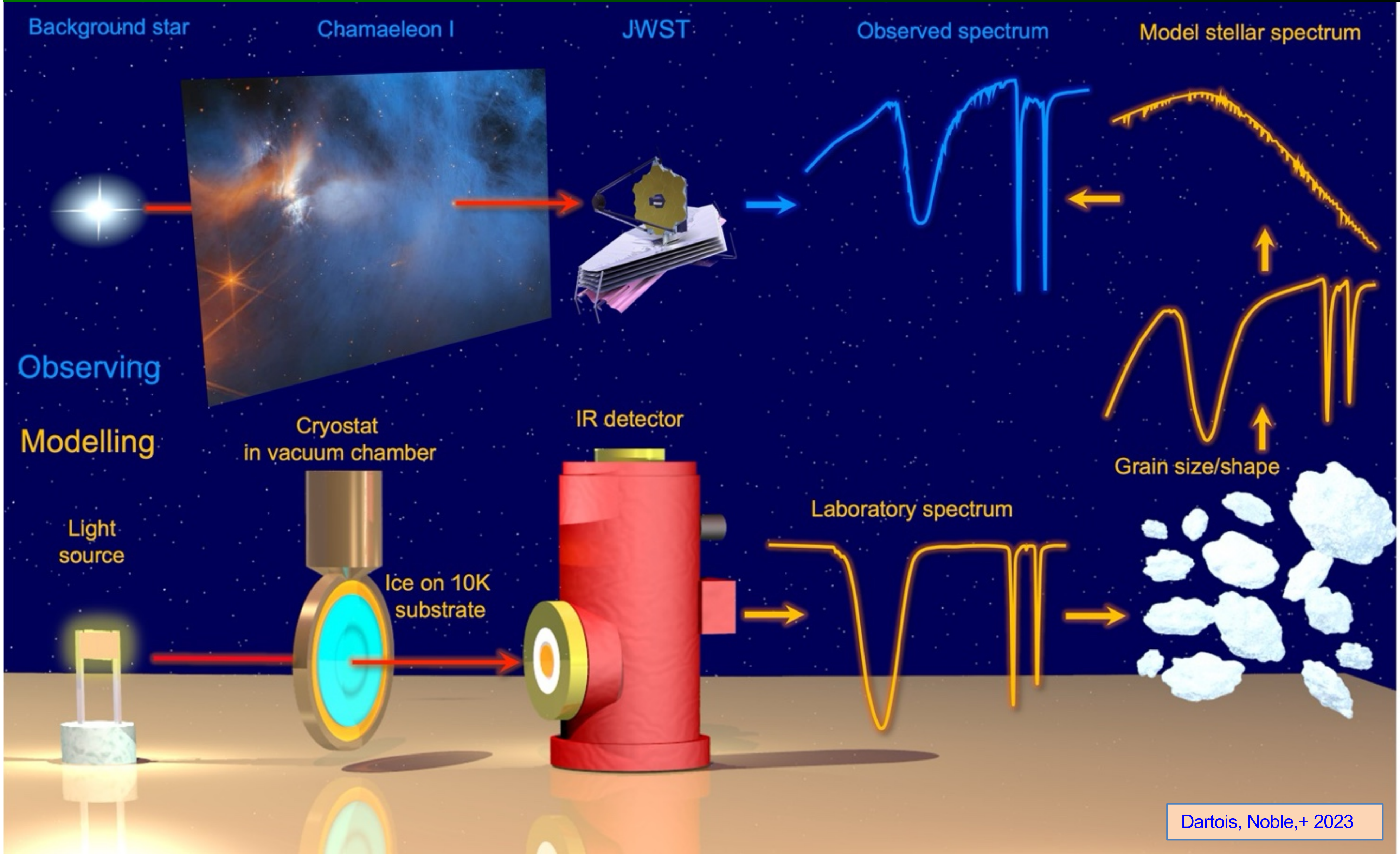
modelling



Dartois+2022, 2025

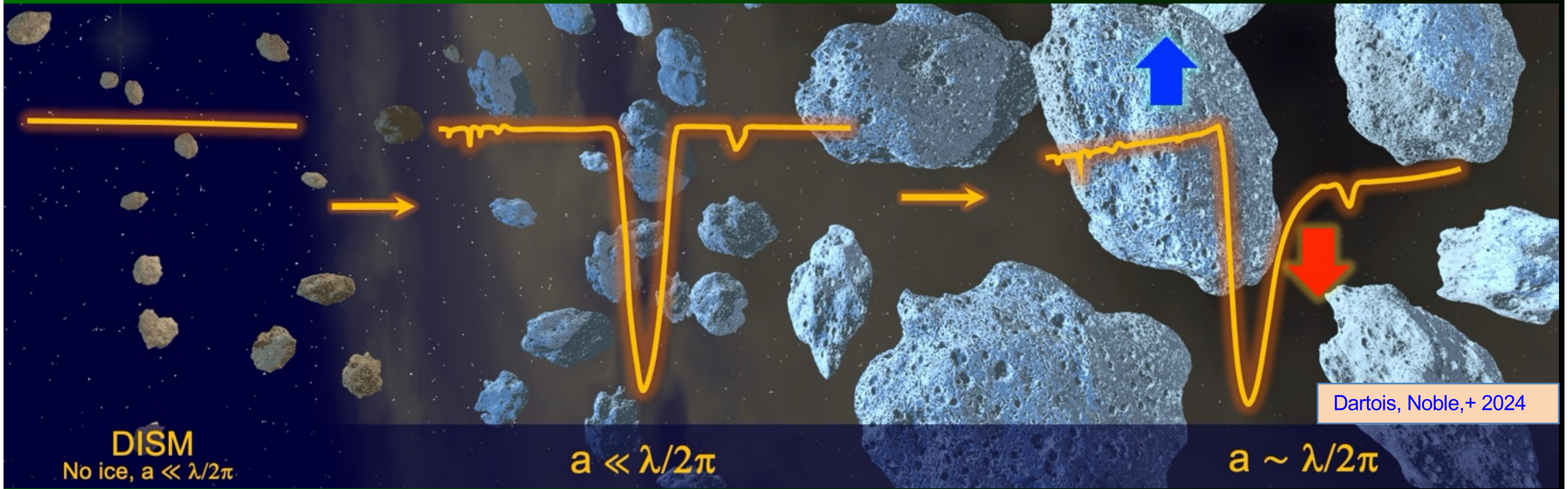


The process of modelling the observed NIR38 and J110621 spectra



Dartois, Noble,+ 2023

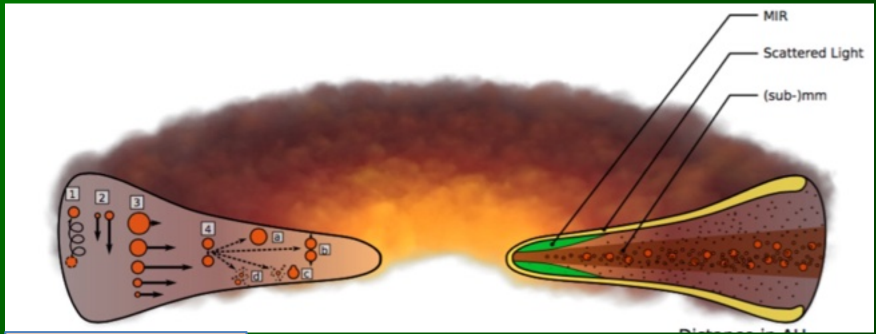
- grain growth will impact the observed band profiles



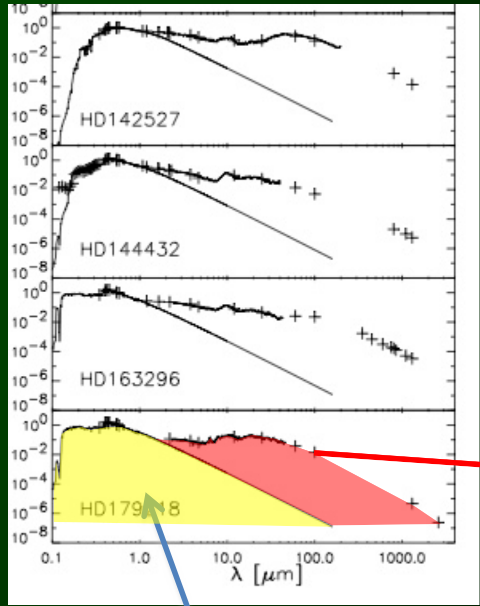
- Observed growth to the micron size with JWST in Ice Age ERS dense cloud high Av previous to class 0

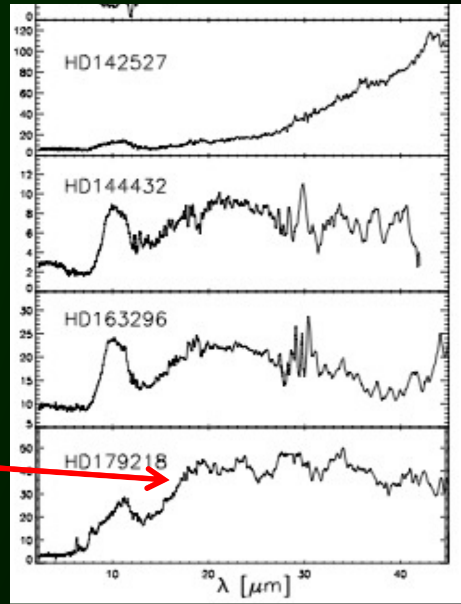
- Will potentially affect the available surface for astrochemistry

Silicates in circumstellar disks (Herbig Ae/Be)



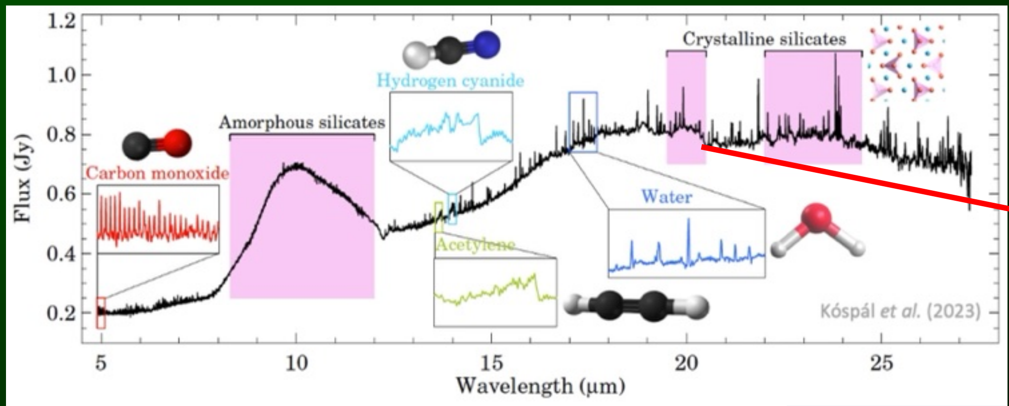
Testi+ 2014



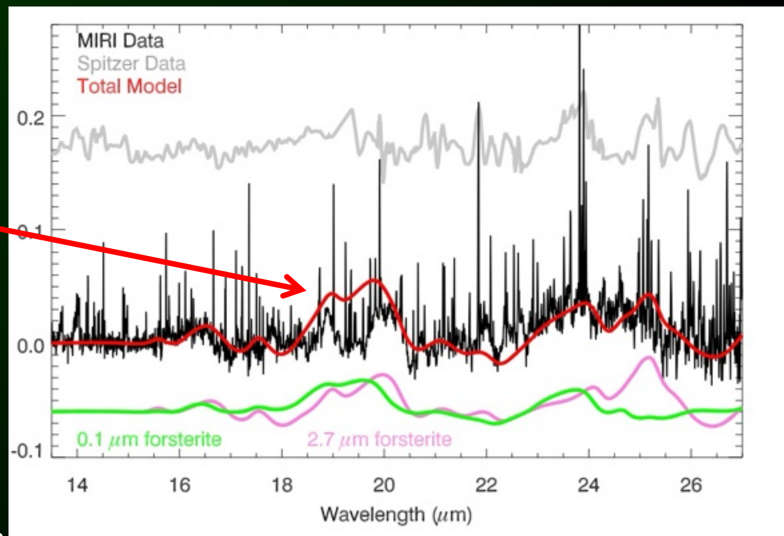


Kurucz model

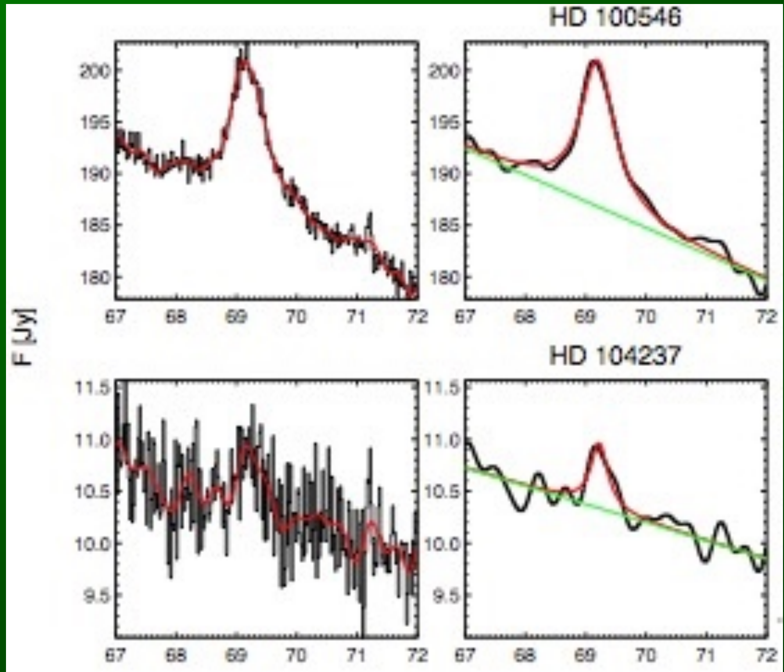
Meeus+ 2001



Kospal+ 2023

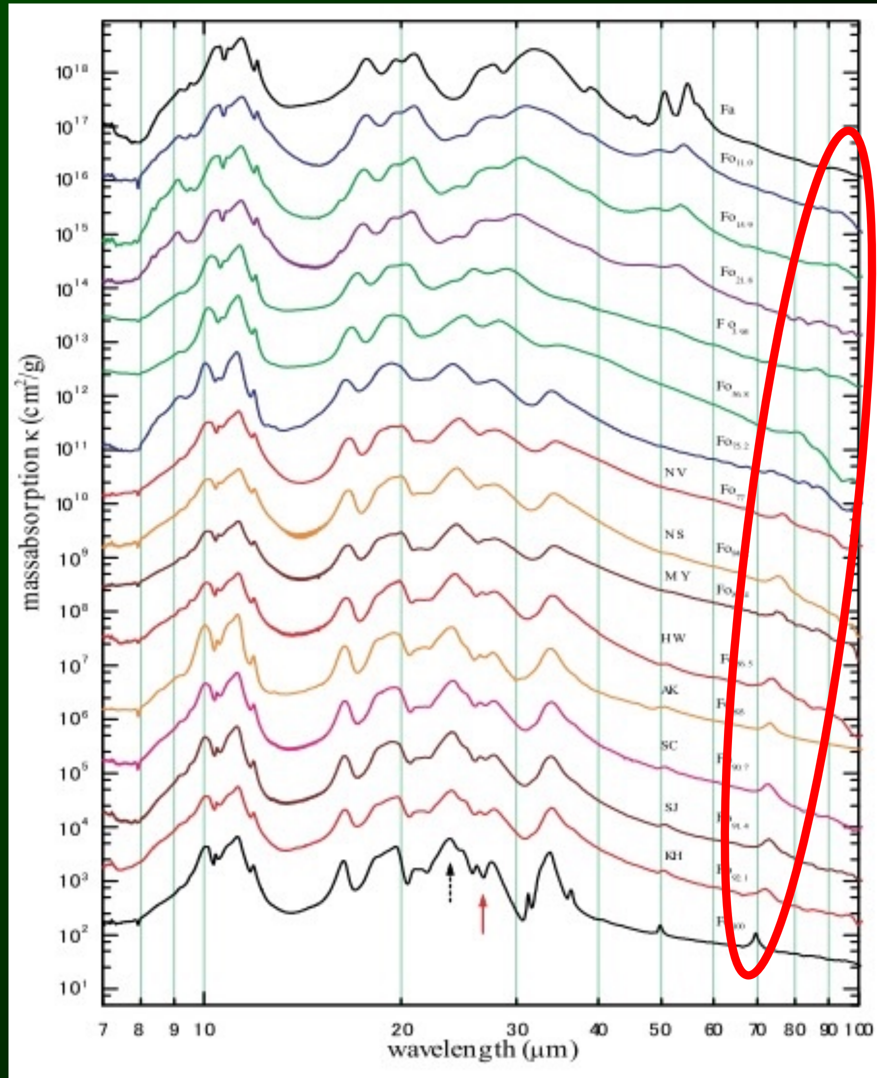


Silicates in disks
Comparison to lab data



Sturm+ 2013, Malfait+ 1998

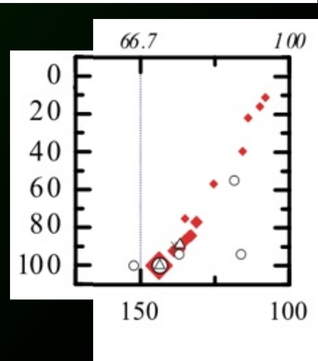
Herschel



Koike+ 2003

Fe content

Mg content



Silicates in disks
Comparison to lab data

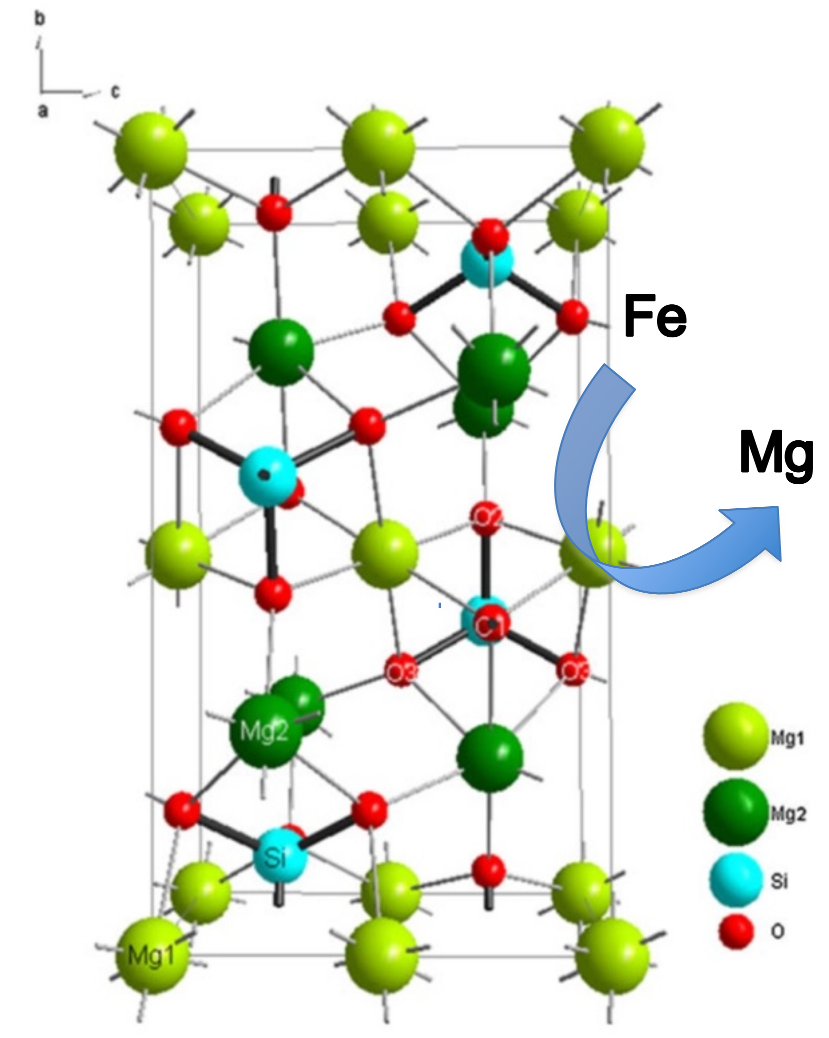
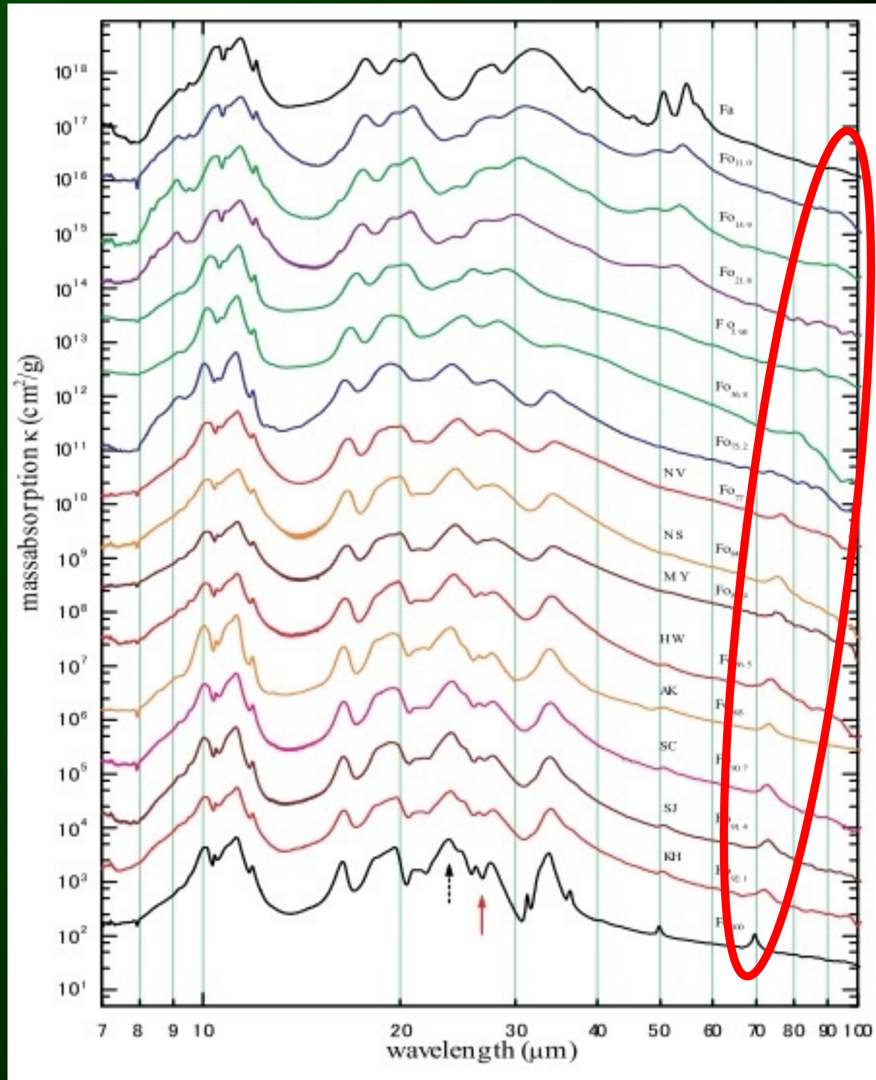


Fig. 1 Crystal structure of forsterite (Mg_2SiO_4)

Eckes+ 2013

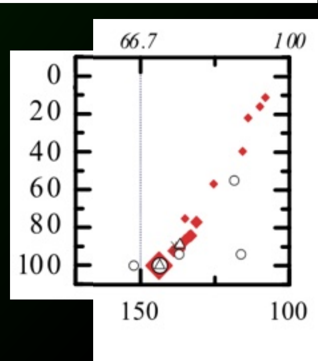
$T(SiO_4)$ $T(Mg_1)$



Fe content

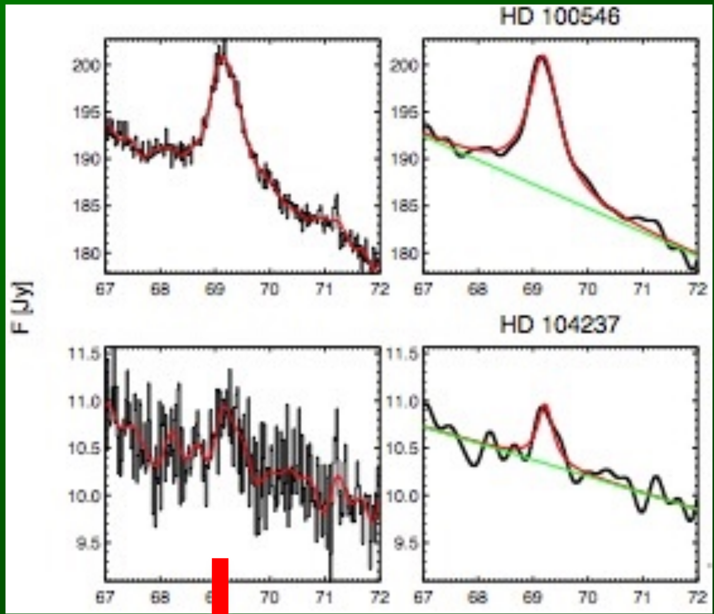
Koike+ 2003

Mg content



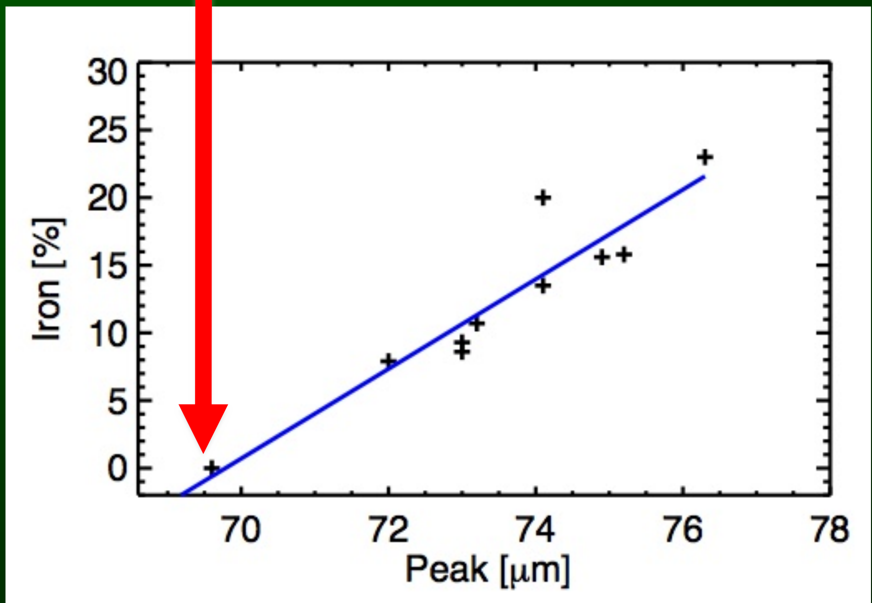
Silicates in disks

Herschel

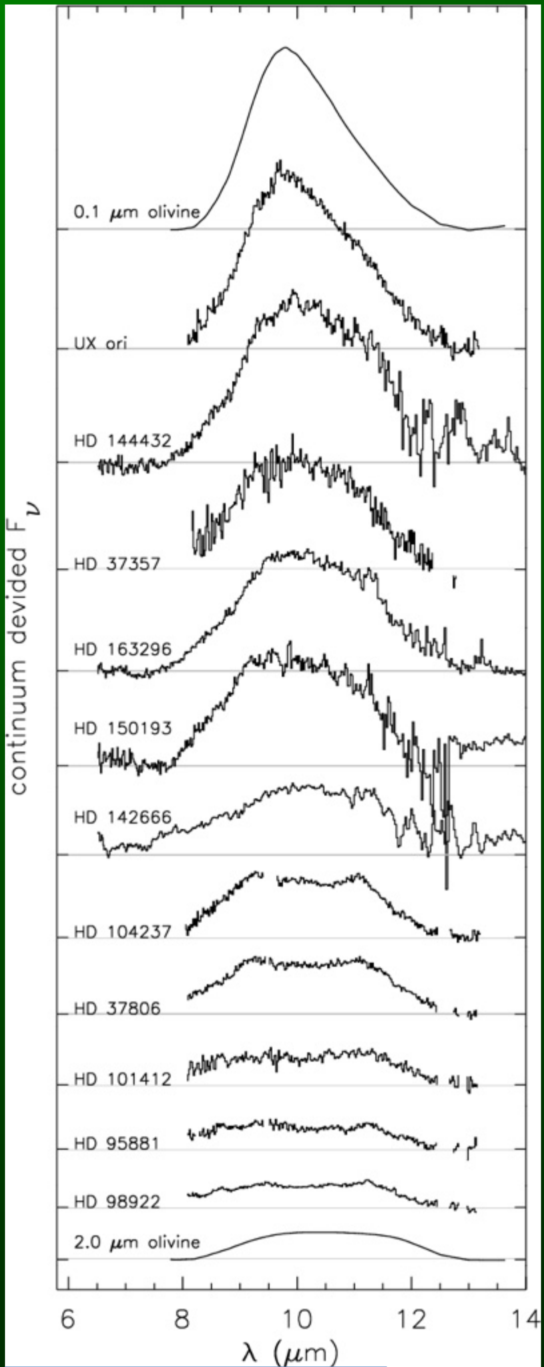


Star	Iron fraction [%] min	Iron fraction [%] max	Temperature [K] min	Temperature [K] max	distance [AU] min	distance [AU] max
AB Aur	1.9	3.5	74	273	16	221
HD 100546	0.1	0.3	184	223	20	29
HD 104237	0.4	1.2	60	184	31	289
HD 141569	0.0	1.2	107	>300	<9	72
HD 179218	0.4	0.7	126	173	104	196
HD 144668	0.0	0.4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

Sturm et al. 2013



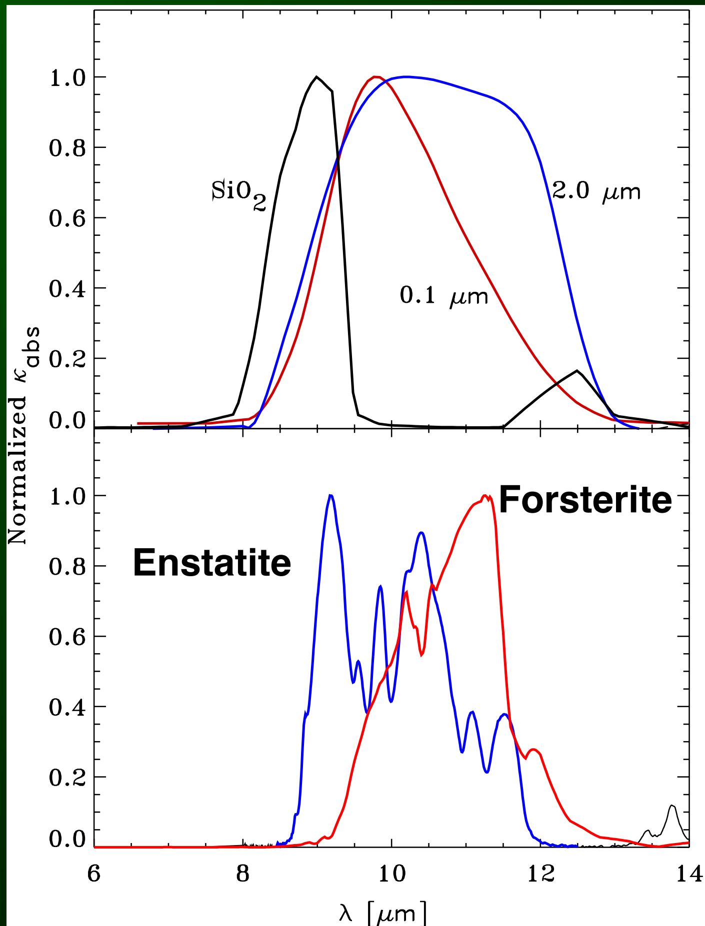
32 disk sources observed.
8 sources with 69 µm olivine feature
Except 1 T Tauri star, disks associated with Herbig Ae/Be stars.
Most of the olivine grains are iron-poor less than ~2% iron (forsterite like).
AB Aur is the only source where the emission cannot be fitted with iron-free forsterite, requiring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



Van Boekel+ 2003

Spectral evidence of grain sizes in emission

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

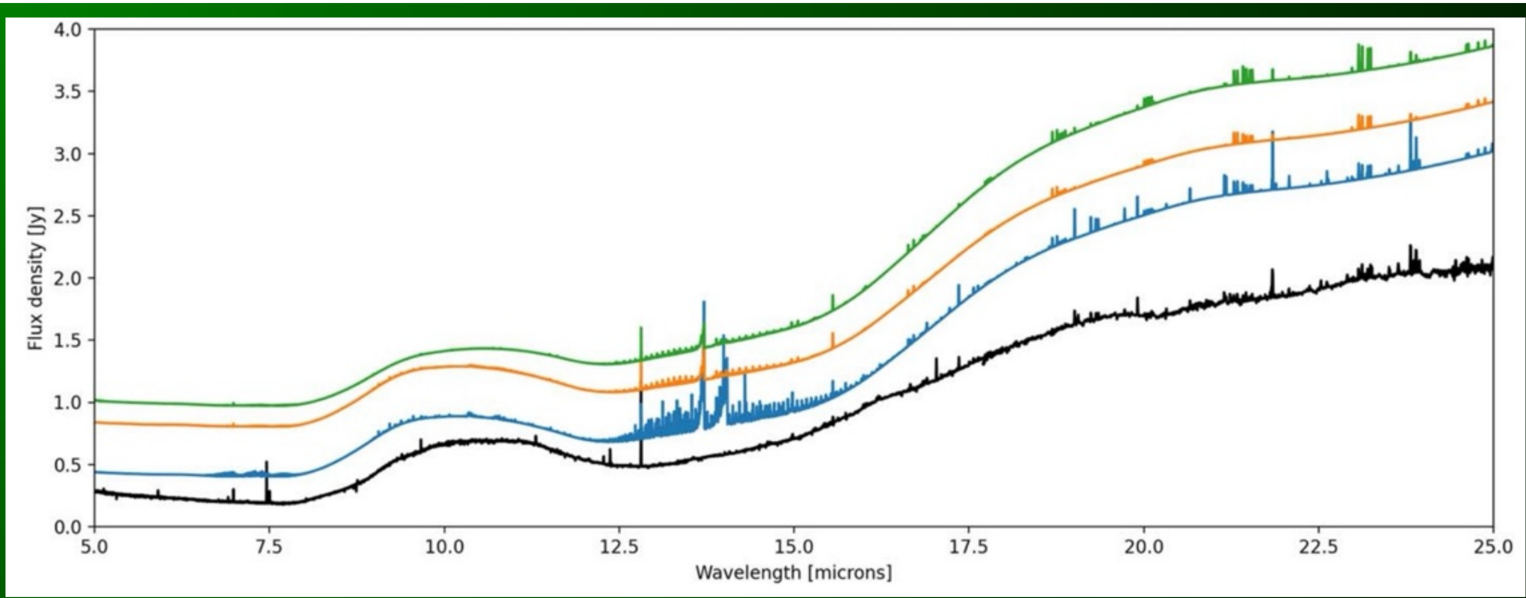


Bouwman+2001

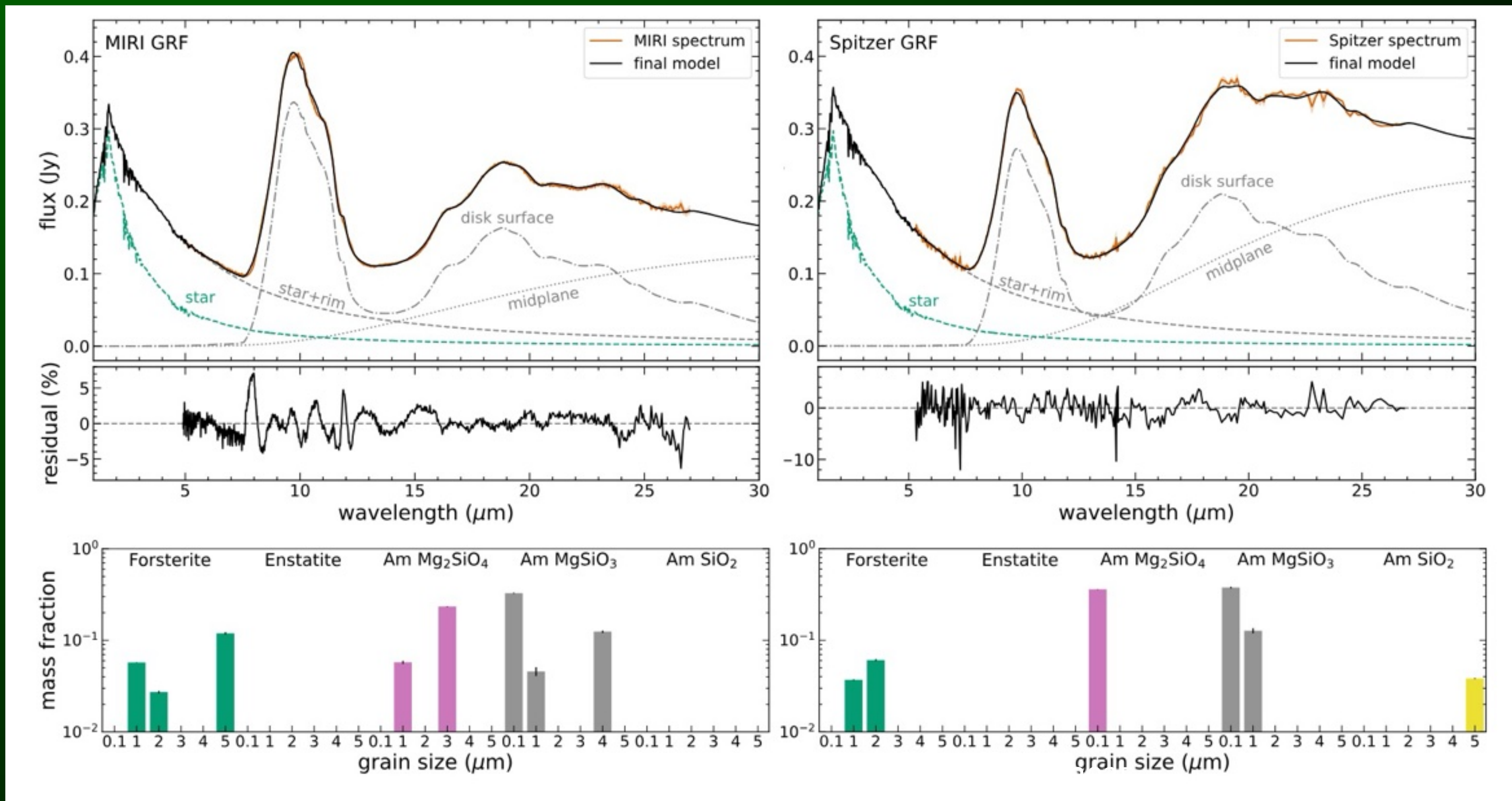
Mineralogy : dust in Herbig Ae Be

Several components:

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



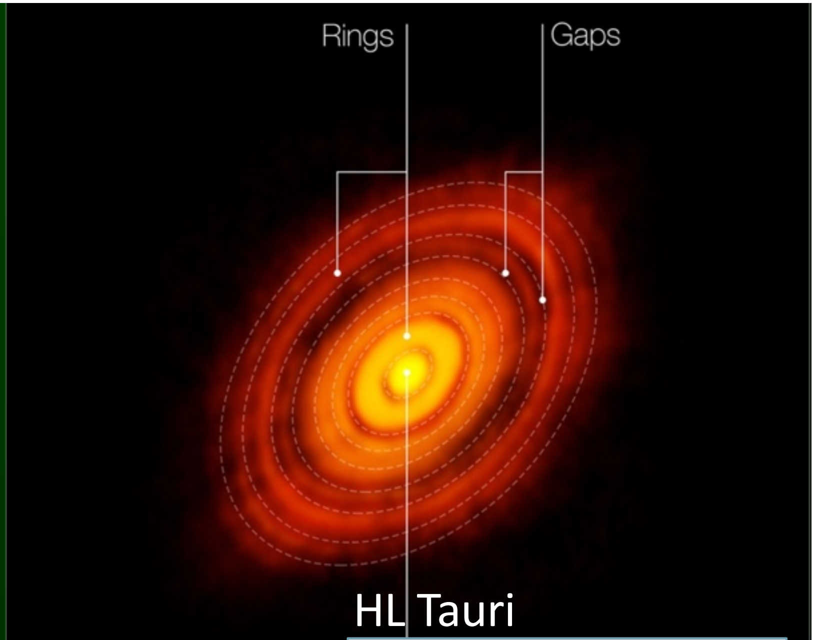
Henning+2024



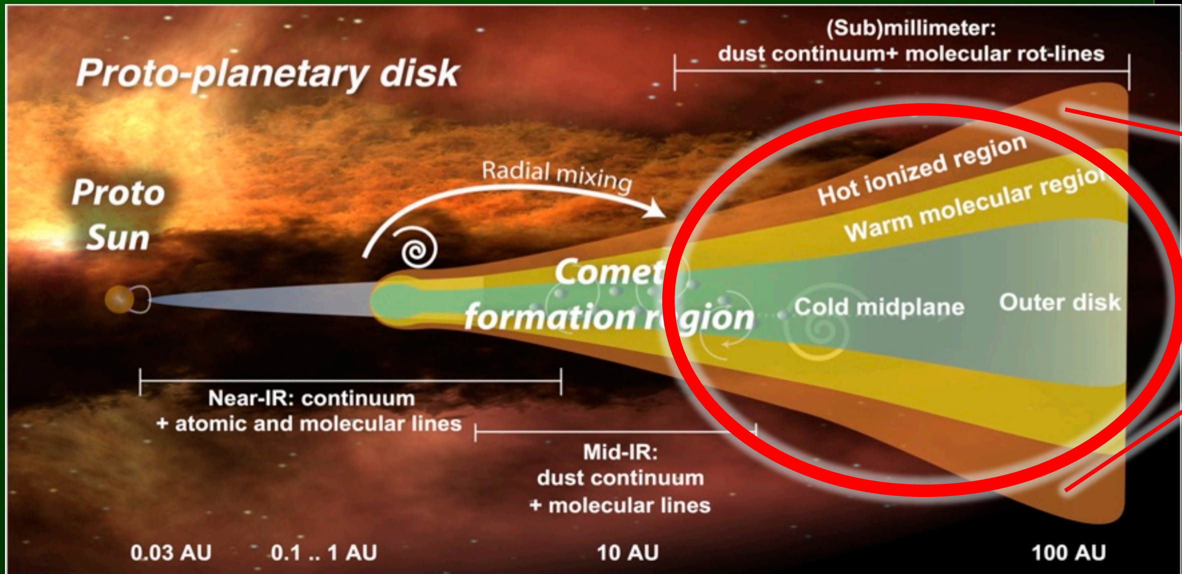
Jang+2024

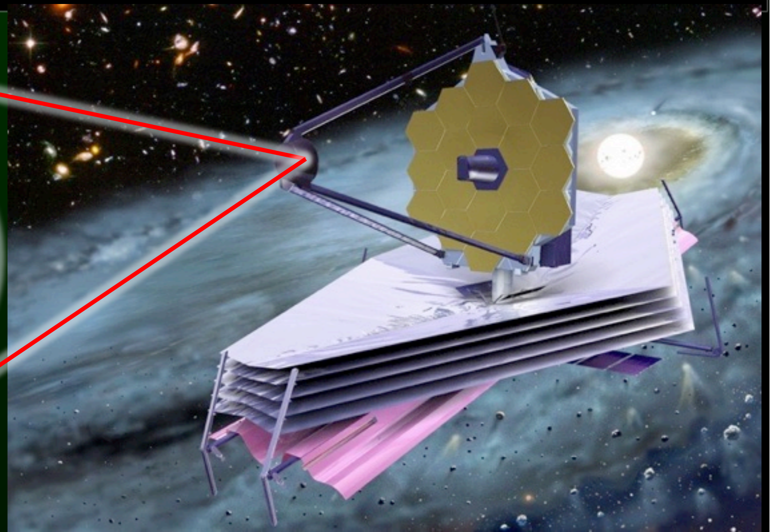
Amount of radial mixing ?

Filiation or reprocessing dominant ?



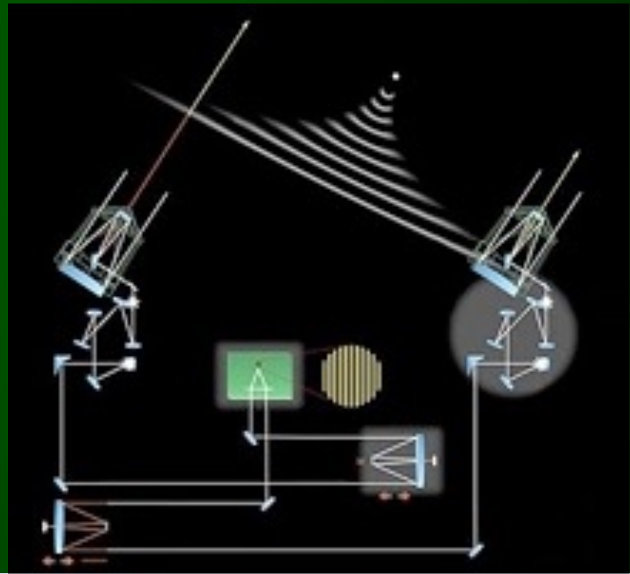
ALMA (ESO/NAOJ/NRAO)

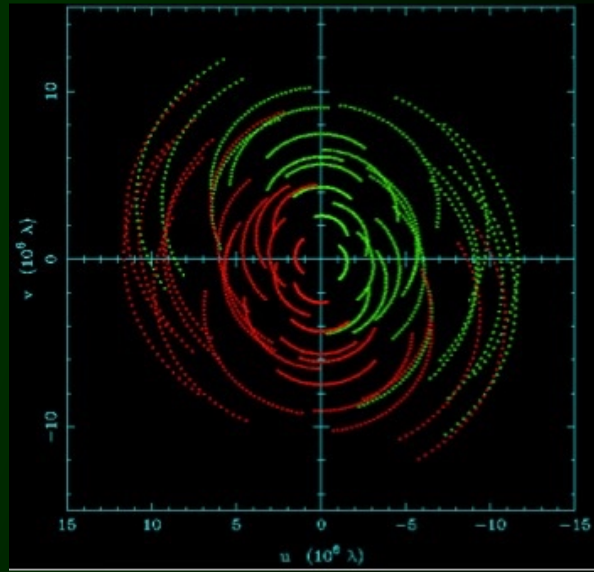




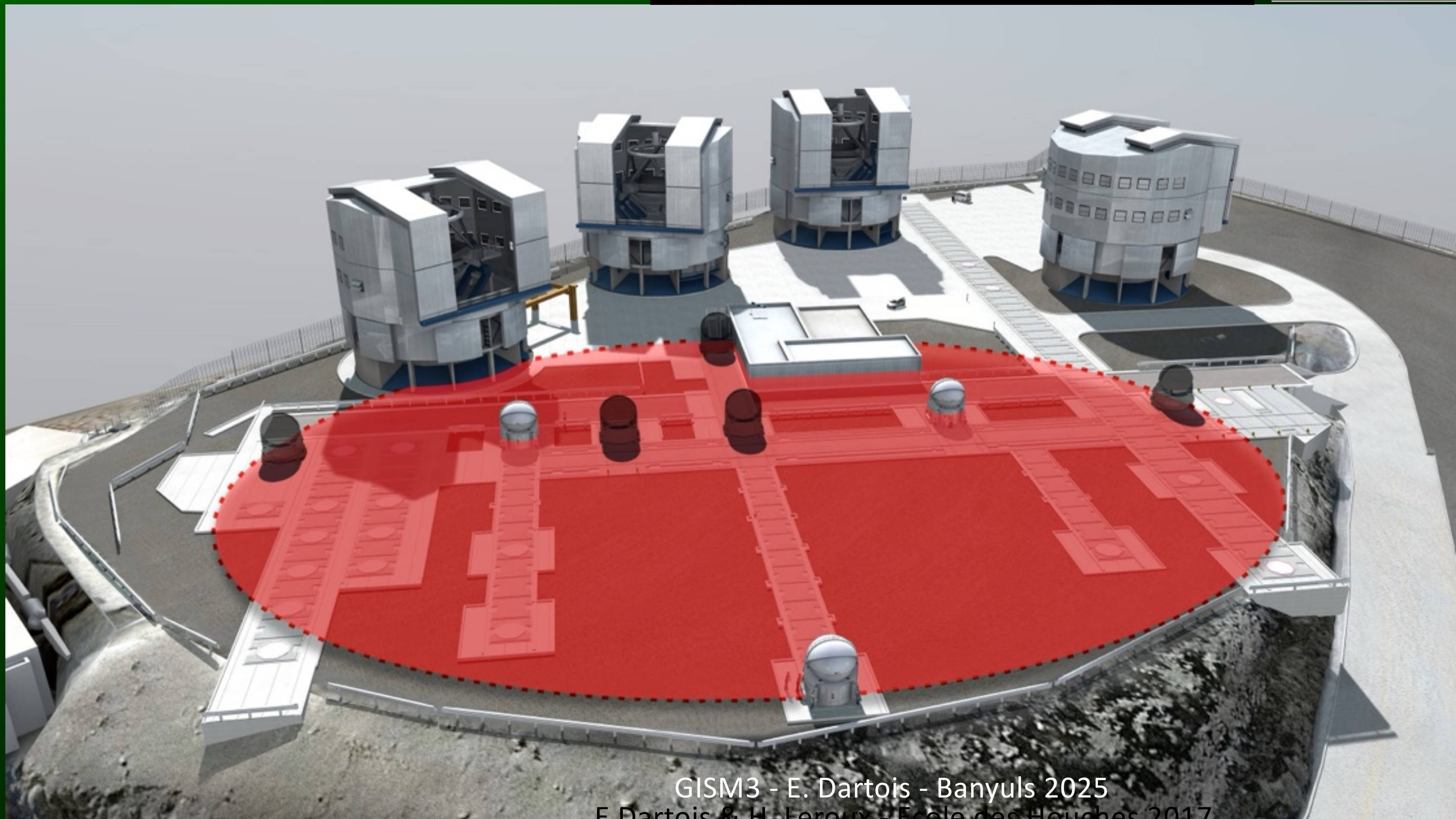
JWST

IR Interferometry: silicates in disks





Haniff 2010



VLTI / ESO

IR Interferometry : silicates in Herbig Ae Be

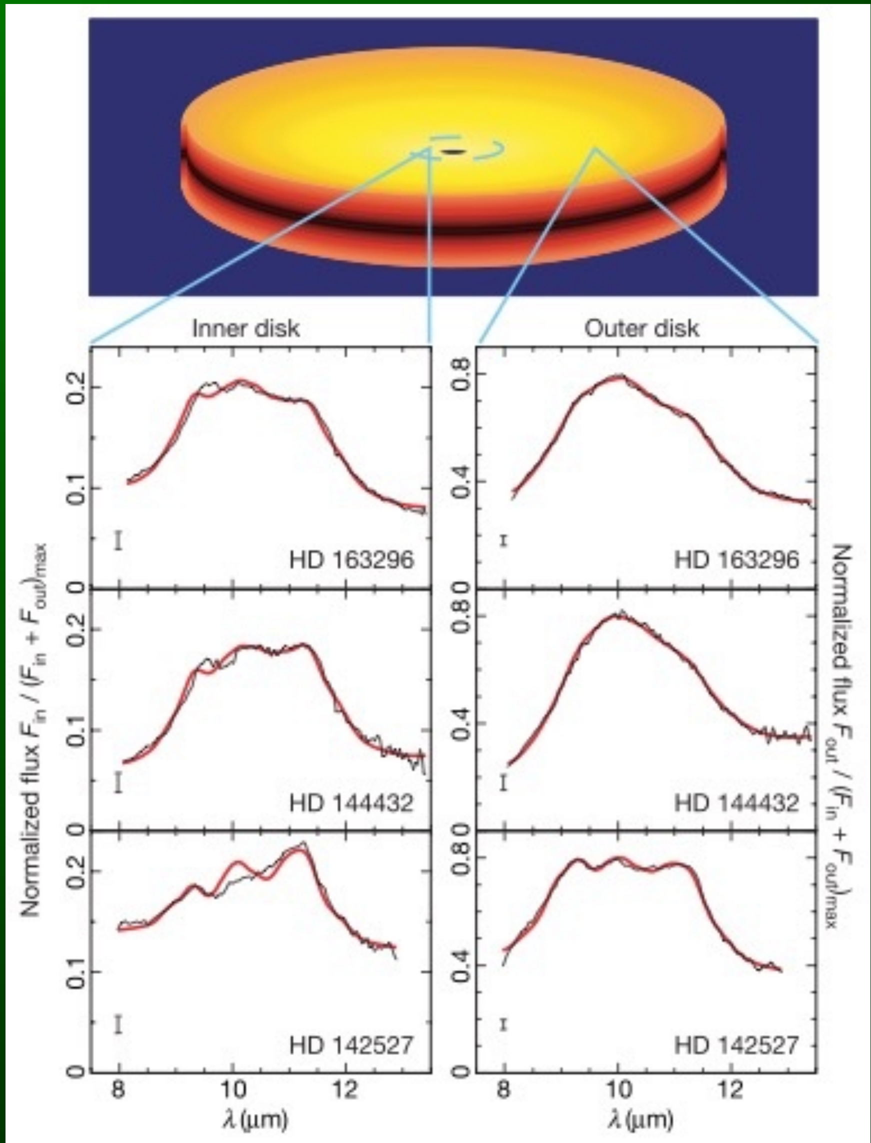
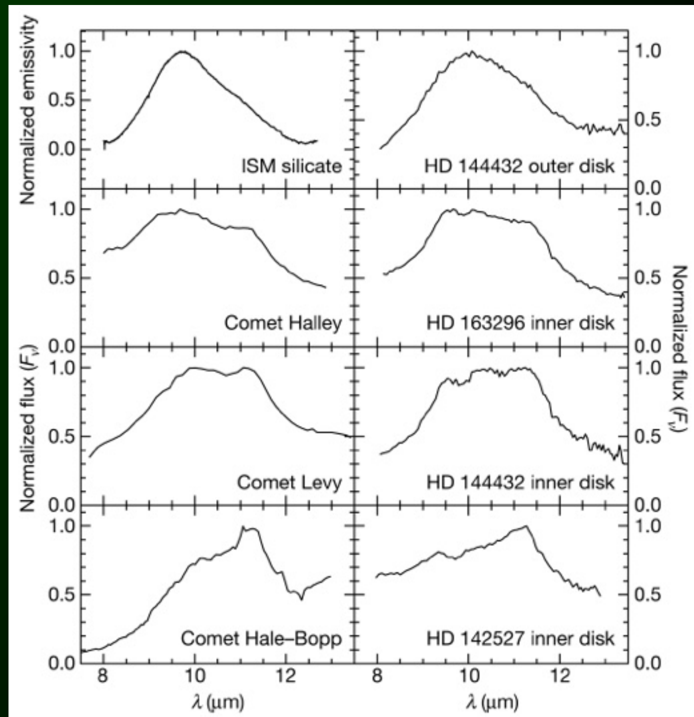


Table 1 **Dust properties in the inner and outer disk**

	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+2004

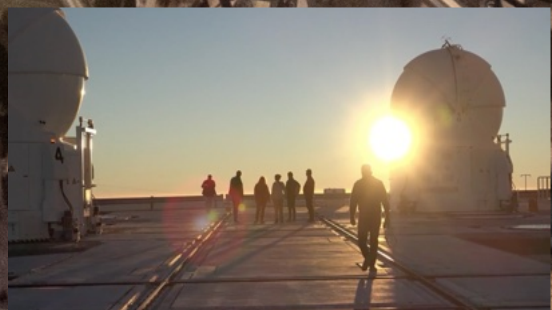


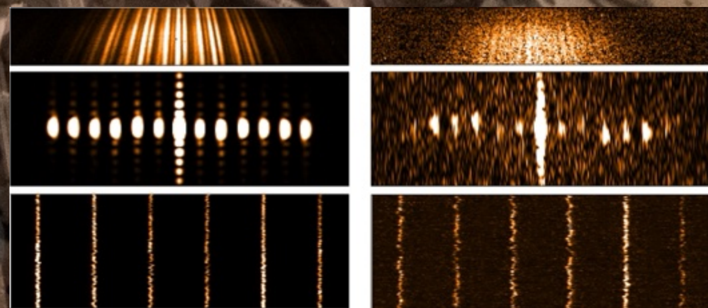
A chemical gradient in the composition of the crystals is seen, with a forsterite dominated spectrum closest to the star, and more enstatite at larger radii.

B. Lopez, S. Lagarde and MATISSE Consortium

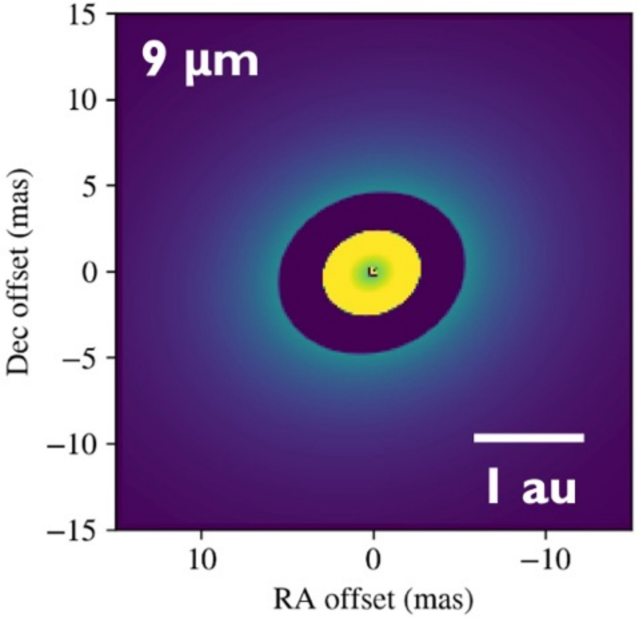
Spectro-imaging exploration with 4 telescopes
Collecting power of the VLT
L, M and N band spectral domains from 3 to 13 μm

=> Extension of the VLTI spectral exploration from H, PIONER, K, GRAVITY, L, M and N, MATISSE





circumstellar disk of the Herbig Ae star
HD 144432
gap and silicate mineralogy



Temperature gradient modeling of L- (ATs) and N-band (UTs) MATISSE data and SED data

- hot inner region (≳1500k)
- gap (0.4 < r < 0.9 au)
- warm outer disk (r > 0.9 au)

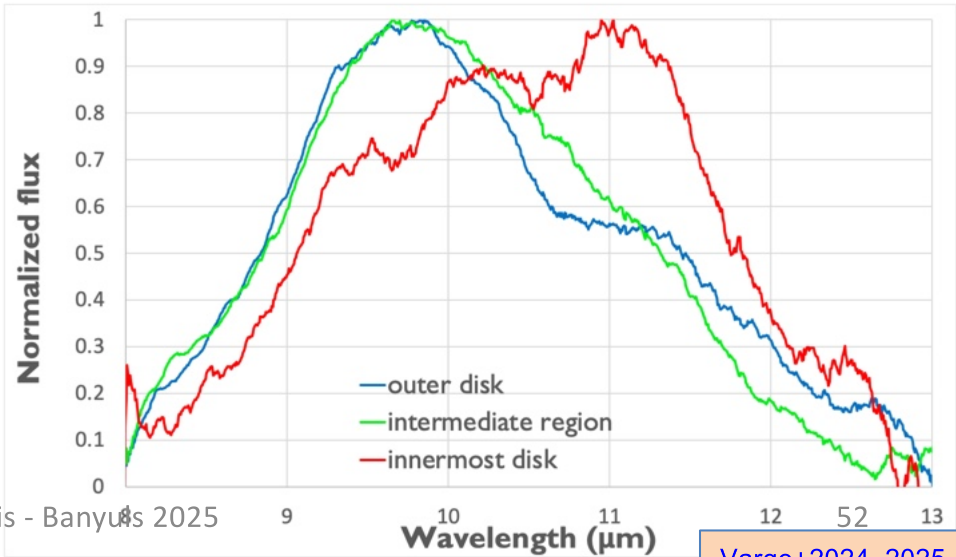
N-band closure phase changed over 1 year

- time-variable asymmetry at r ~ 1 au

Radial variation in silicate composition

- outer disk: small & large amorphous grains
- intermediate region: small amorphous

inside (probably near the gap outer edge):
crystalline & large amorphous grains

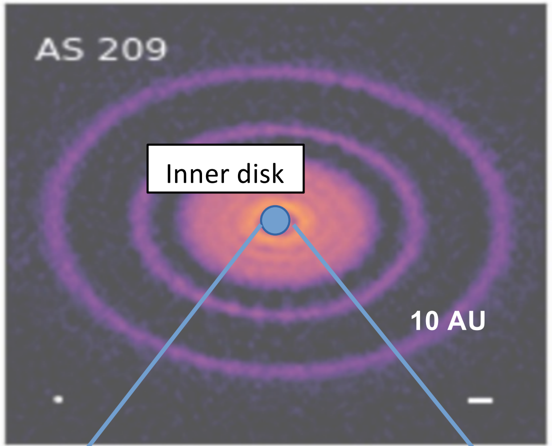


Varge+2024, 2025

Inner disk structure of T Tauri and dust mineralogy

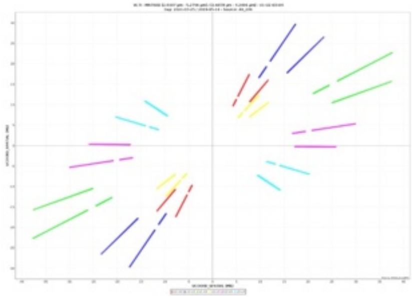
T Tauri star AS 209

ALMA image (Andrews et al., 2018)



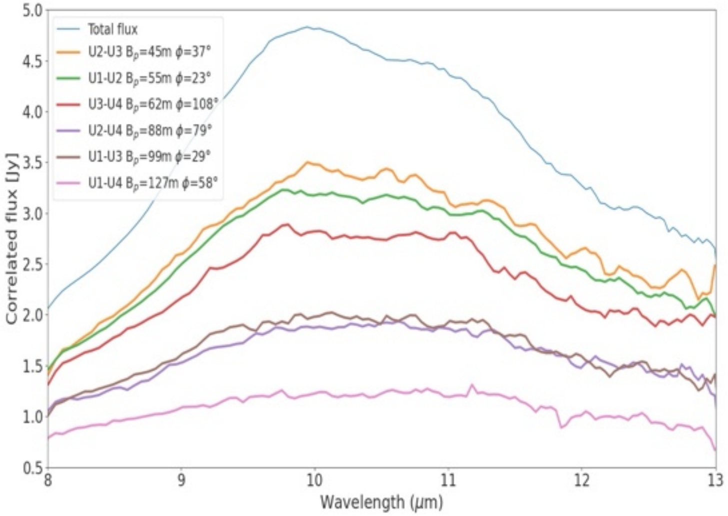
A. Matter et al., in preparation for A&A

Fourier plane coverage for MATISSE observations



Grain processing / mineralogy gradients ?

MATISSE N-band correlated fluxes

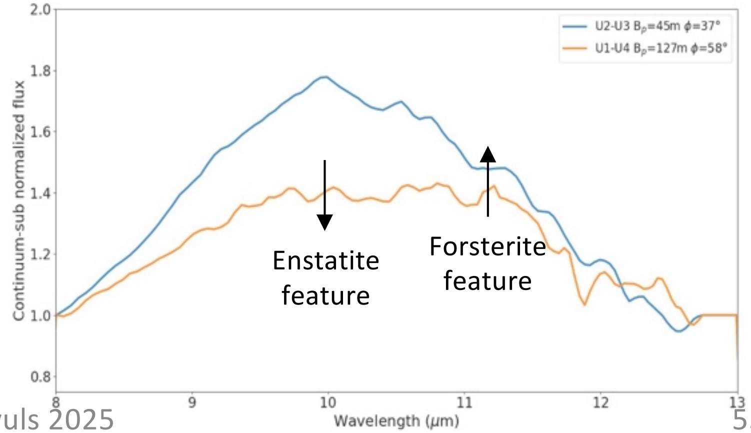


Smaller and more amorphous grains

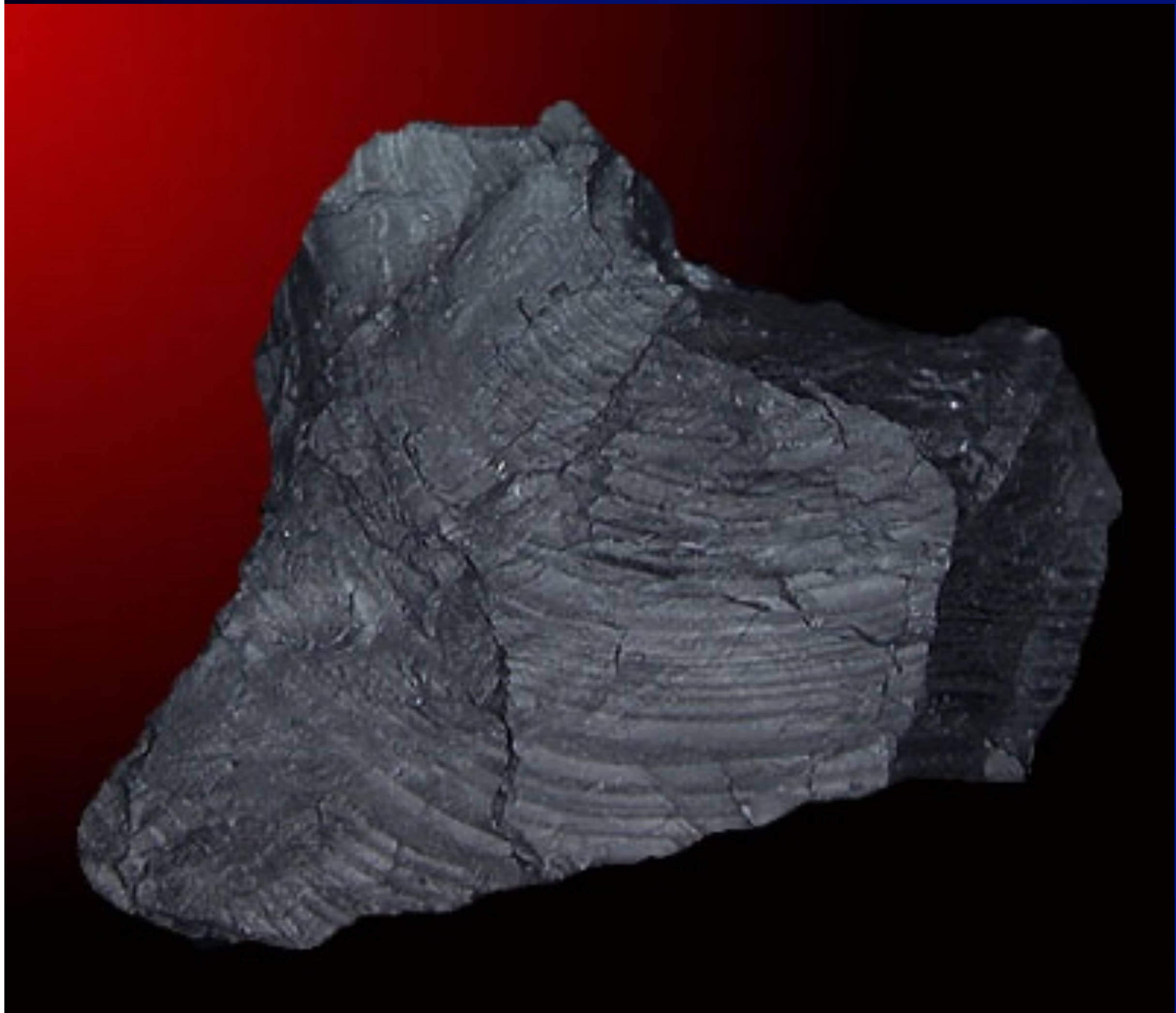
Baseline length

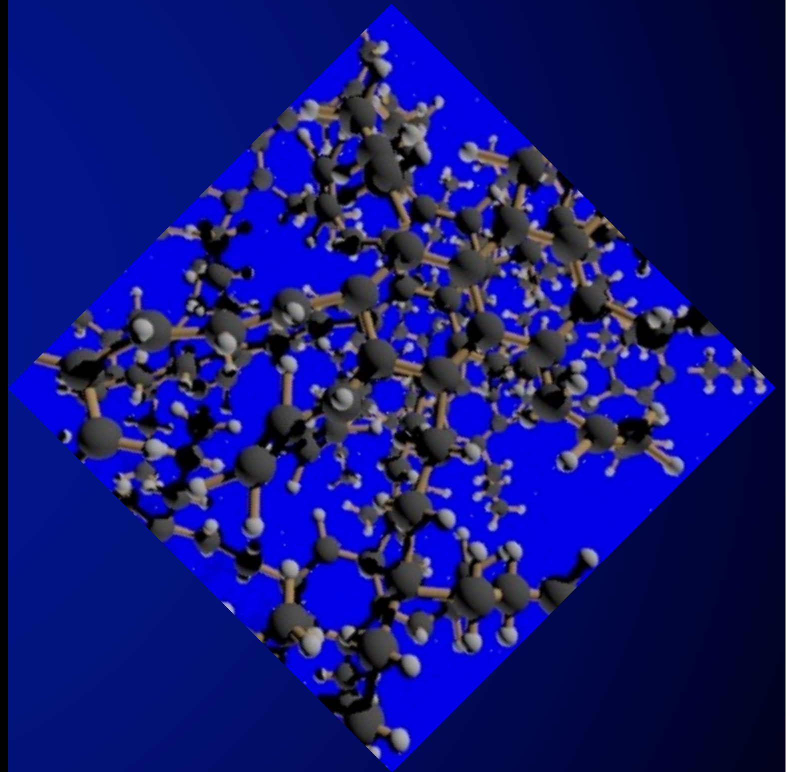
Bigger and more crystalline grains

MATISSE N-band correlated fluxes



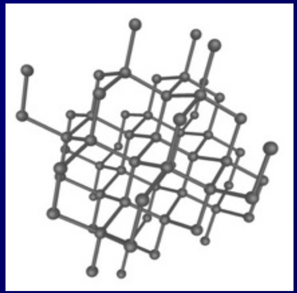
ISM « Carbonaceous » dust



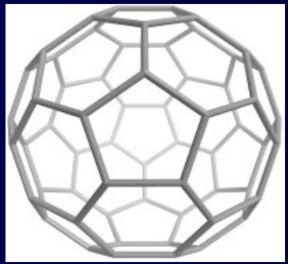


Main carbonaceous solids observed in the ISM

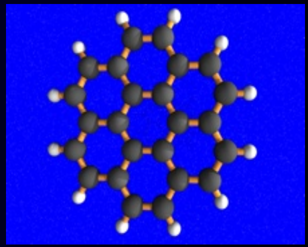
Diamond



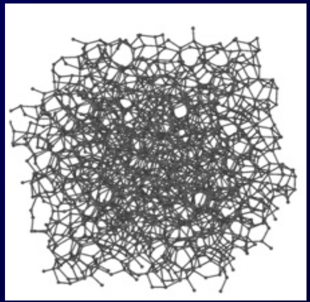
Fullerenes

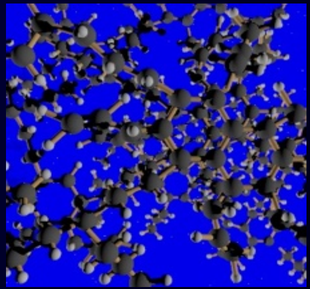


AIBs-PAHs :
Class A to C-D



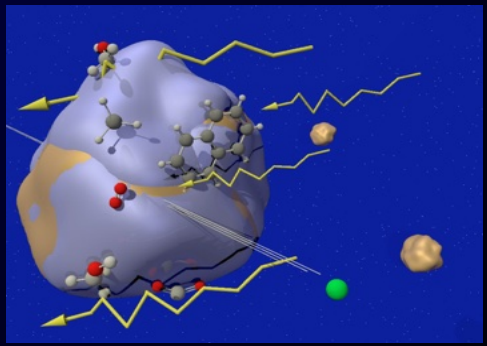
Amorphous carbon





Hydrogenated amorphous carbon

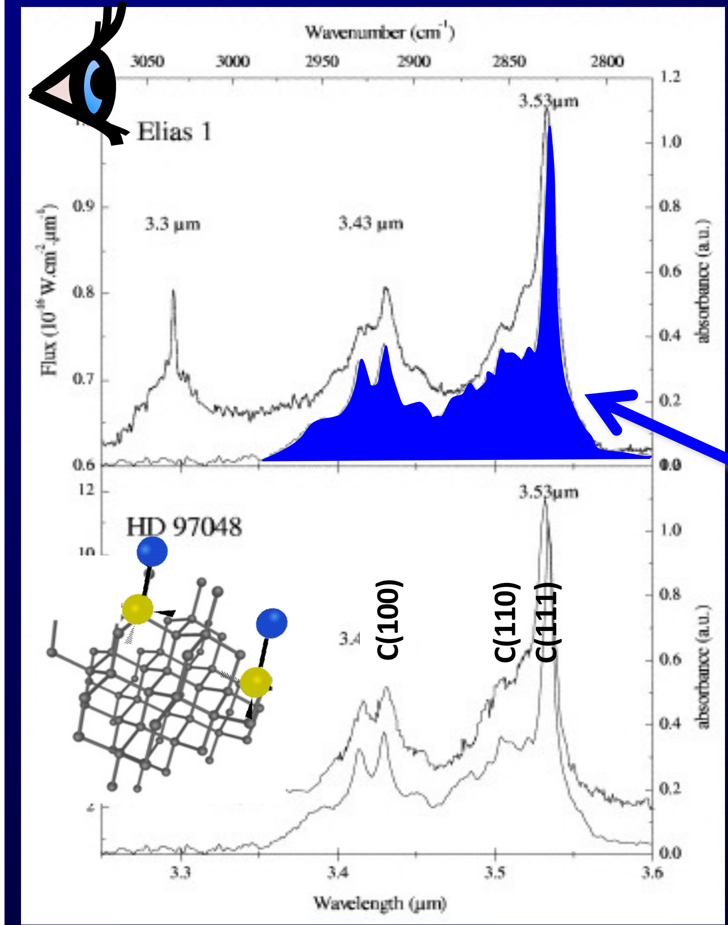
+ organic matter



Ice mantles residues

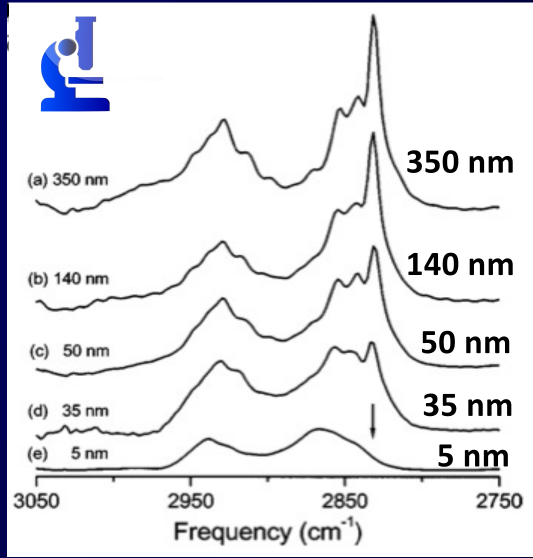
Nano-diamonds

Astrophysical Observations



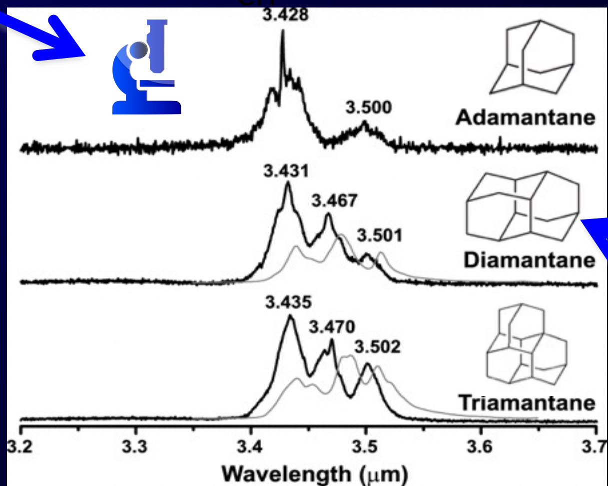
Guillois+1999, Chen+ 2003 Chang+ 1995

Lab Top down approach > 35nm

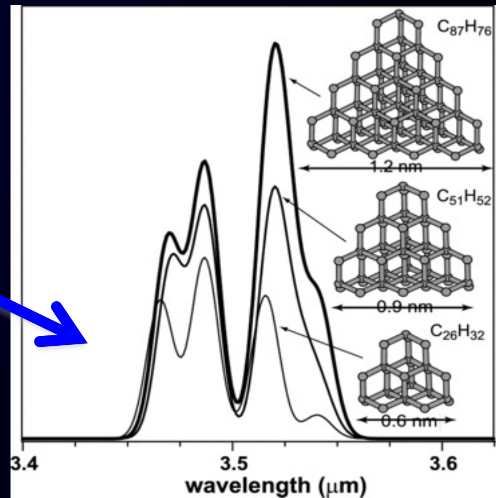


Chen+2003

size dependence



Pirali+ 2007



Lab Bottom up approach ~ 130 C

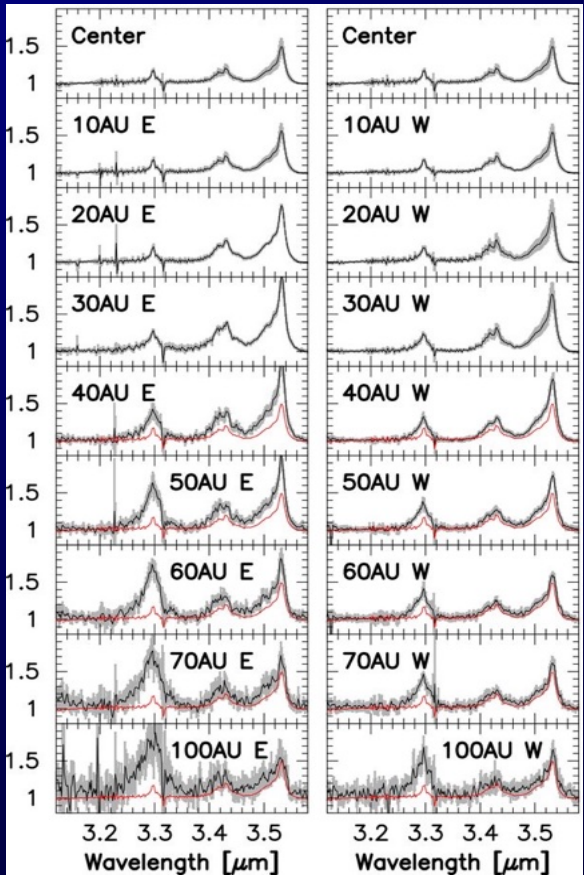
Jones & d'Hendecourt 2000; Van Kerckhoven+2002, Chen+2003, Jones+2004

Nanodiamond approach : Non relaxed surface for nanodiamonds < 35nm

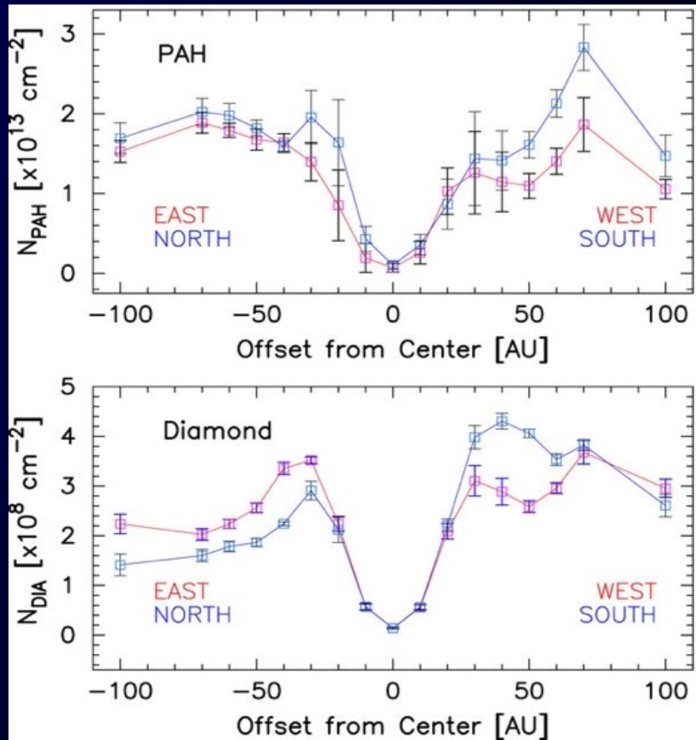
Molecular approach : Observed I(3.53µm/3.43µm) = analogues around 130 C atoms

Nano-diamonds: almost resolved observations

Observed close to the star



Elias 1



Goto et al. ApJ 2009

HD 97048

Habart et al. A&A 2004

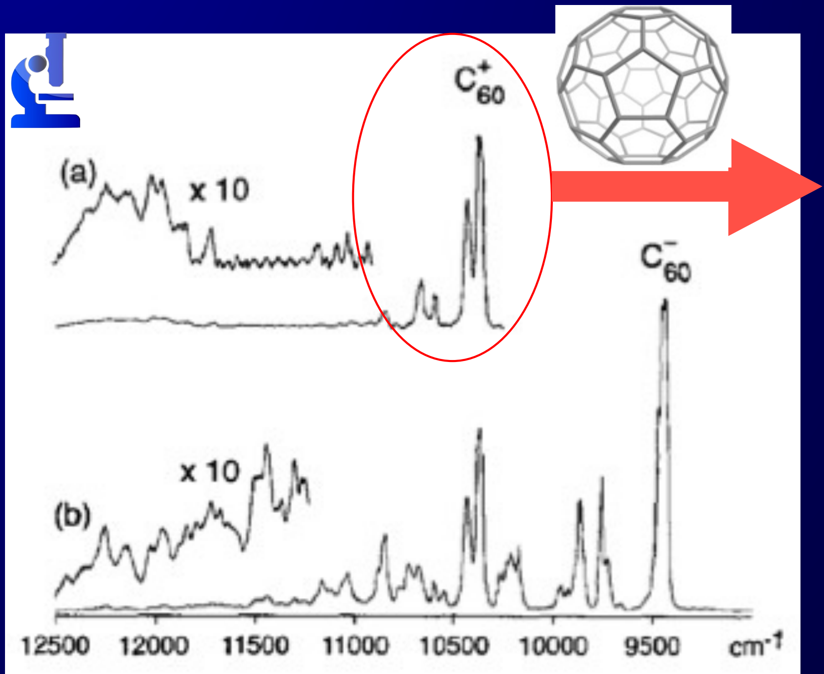
- Survey of 30 Herbig Ae/Be stars

Acke et al. A&A 2006

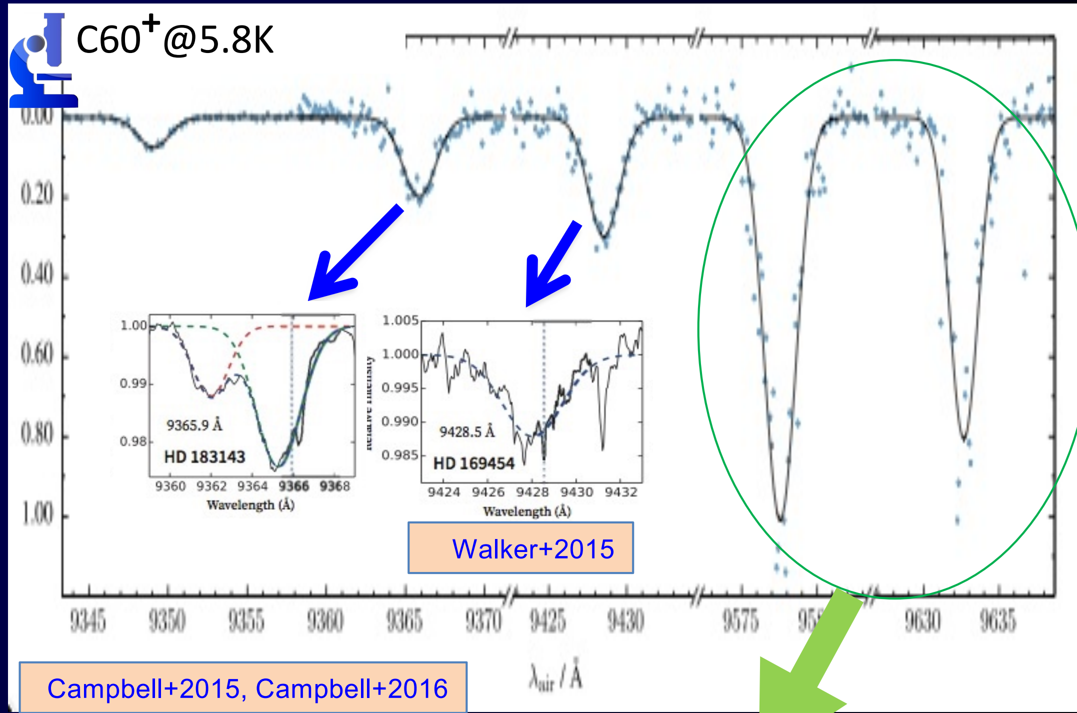
Jones+2022

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

Fullerenes in the DISM

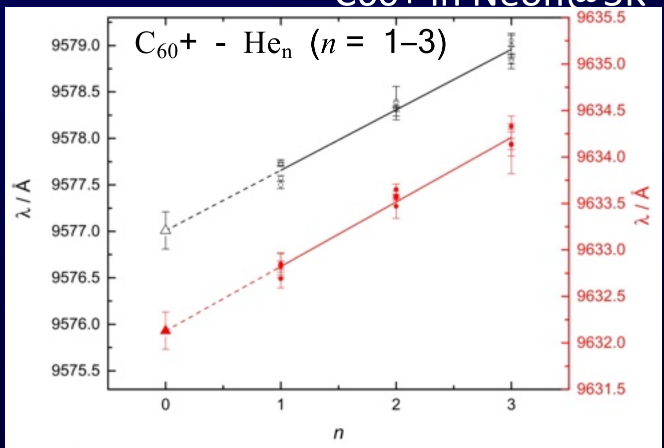


Fulara+1993



Campbell+2015, Campbell+2016

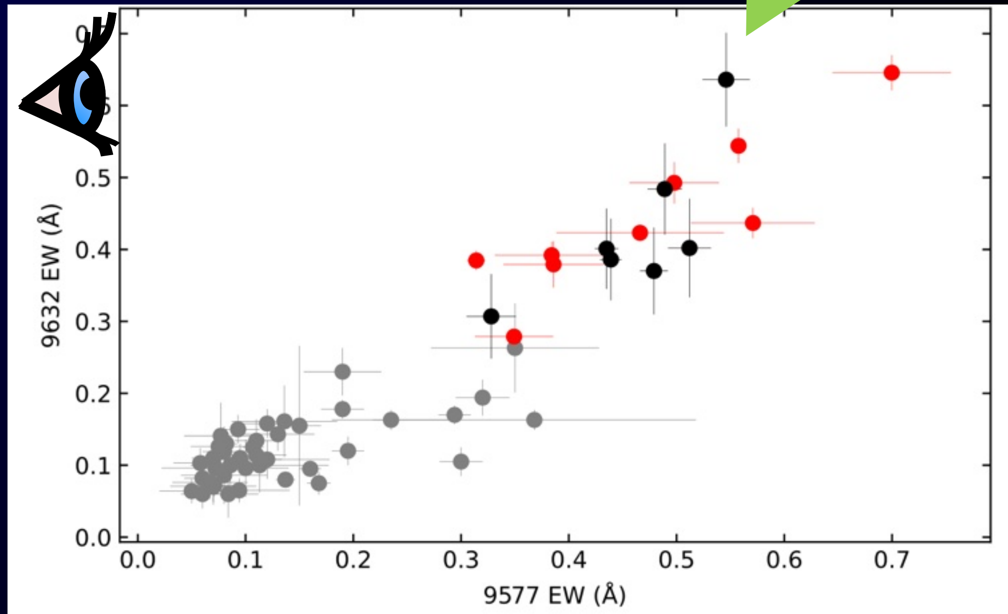
C60+ in Neon@5K



C60+ f value measured in Ne

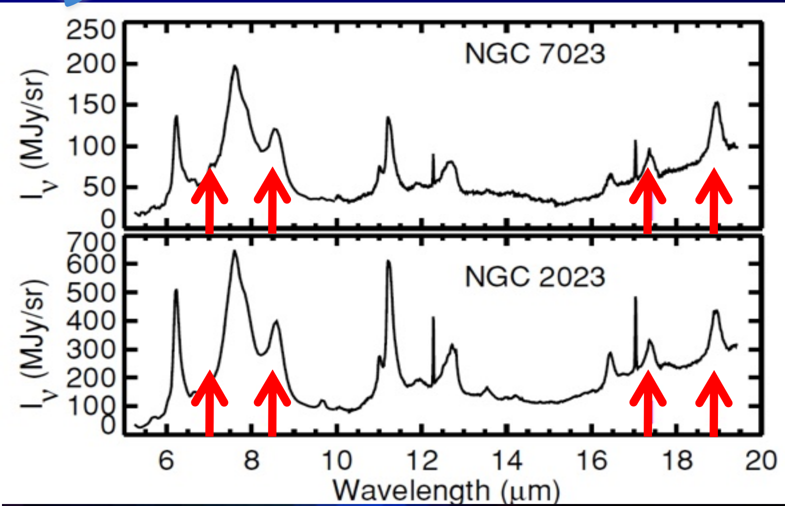
< X_C(C60+)> ≈ 0.04%

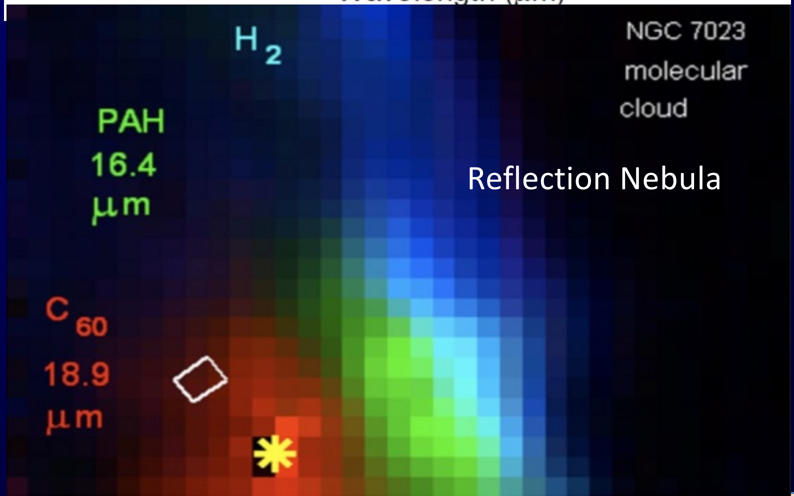
Strelnikov+2015



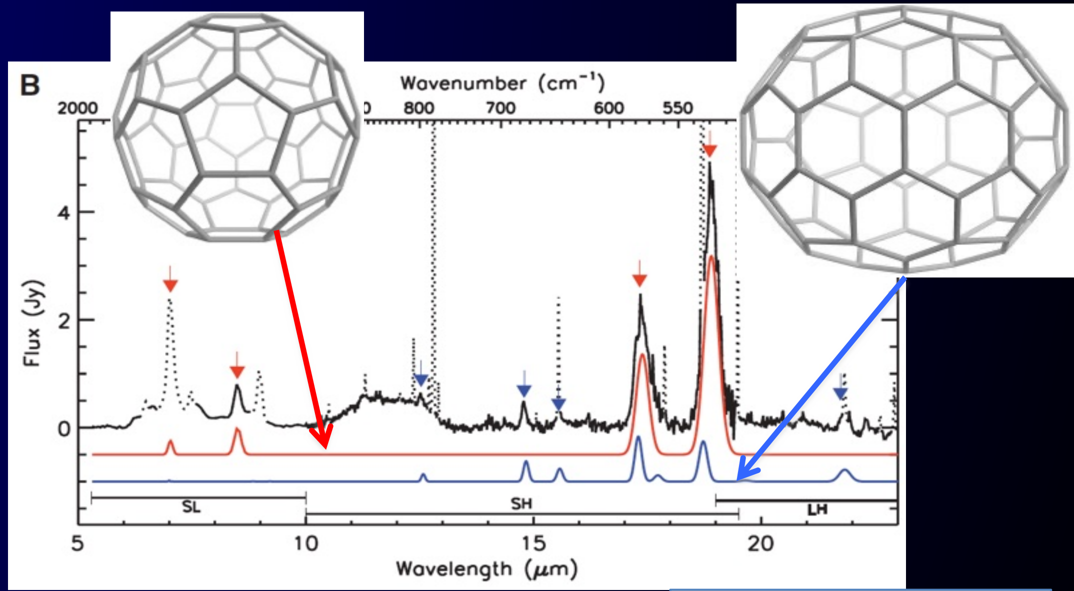
Majaess+2025

Space Fullerenes





Sellgren+2009, 2010



PN (white dwarf) with low H

Cami et al. Science 2010

A long search with upper limits: visible DIBs & IR

e.g. Foing & Ehrenfreund1994, Fulara+1993; Moutou+1999, Herbig 2000

Spatially resolved C_{60} in Reflection Nebulae

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

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

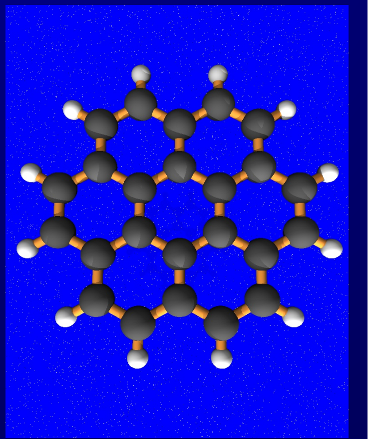
Cami+2010, García-Hernández+2010,2011,2012, Gielen+2011, Otsuka+2013, Zhang & Kwok 2011, Rubin+2011, Peeters+2012, Boersma+2012, Berné & Tielens 2012, Roberts+2012, Omont 2016, Arun+2023 García-Hernández+2023…

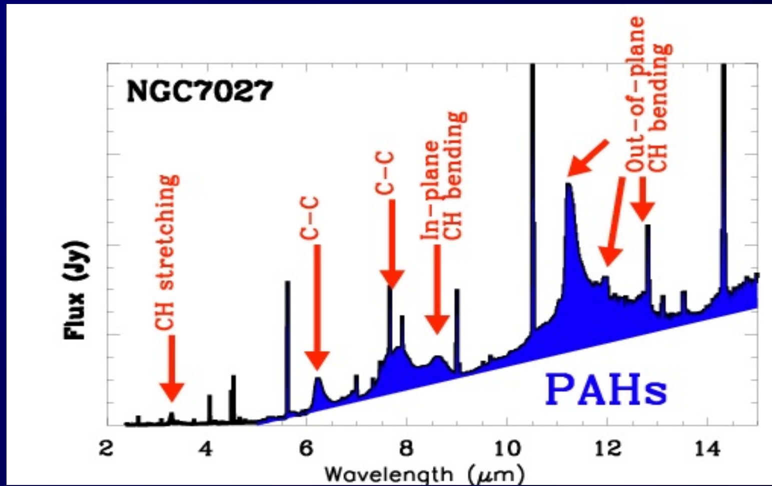
Low % of the cosmic C implied (~0.001-0.05 % of C) Formation route ?
only ~ 3% of all PNe observed in the Milky Way with Spitzer show evidence of the C60 mid-IR bands

Otsuka+2014

Aromatic Infrared Bands (AIBs)

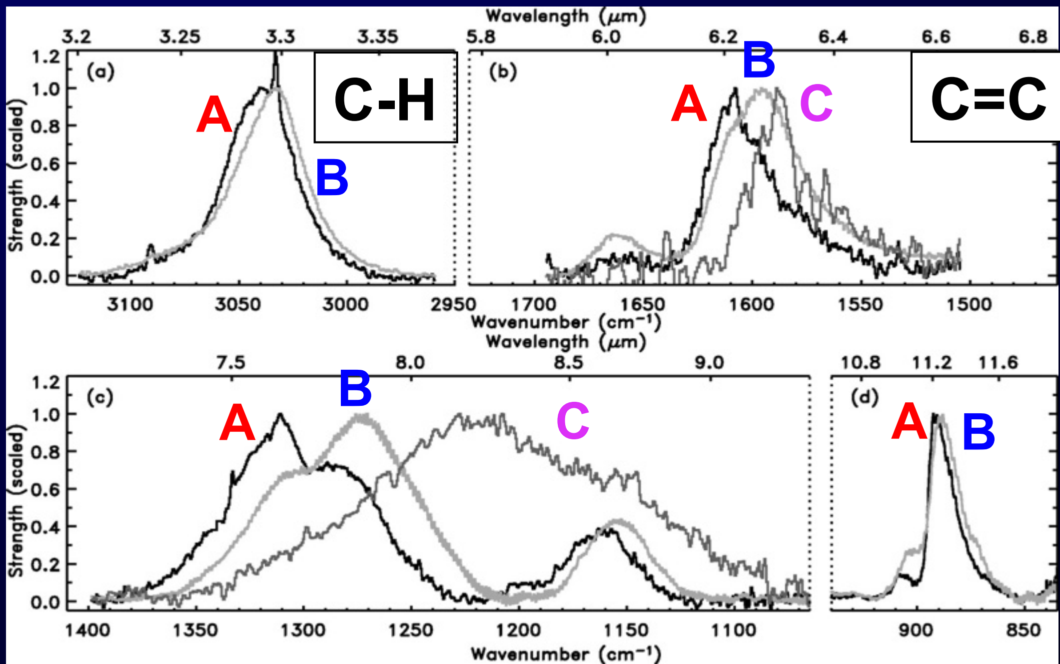
"Polycyclic Aromatic Hydrocarbons hypothesis"





ISO database

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

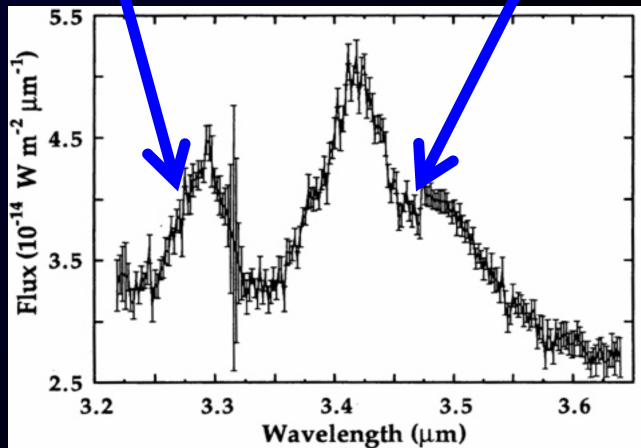


Van Diedenhoven+2004, Sloan+2014

Aliphatic/aromatics mixed in class C

Aromatic C-H

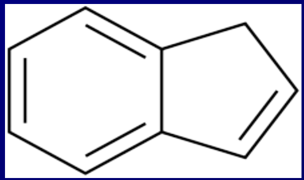
Aliphatic C-H



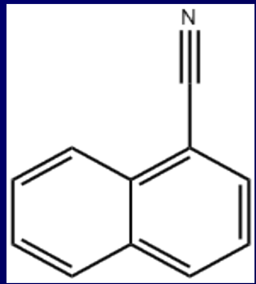
Joblin+1996

5-20% C

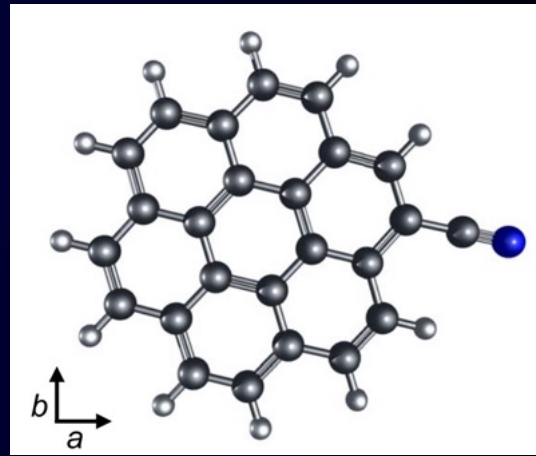
(Cyano-)PAHs detected in (sub-)mm in TMC1

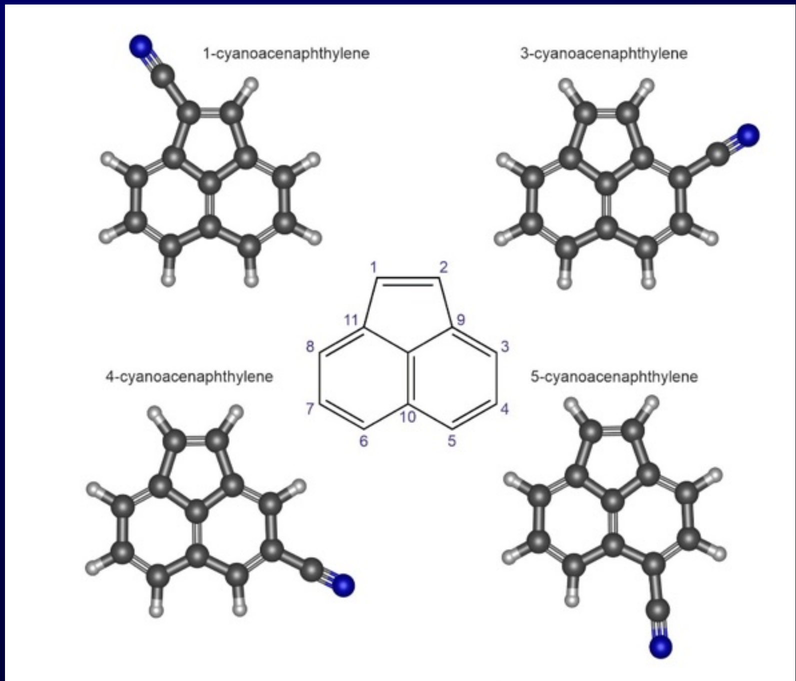


Cernicharo+ 2021

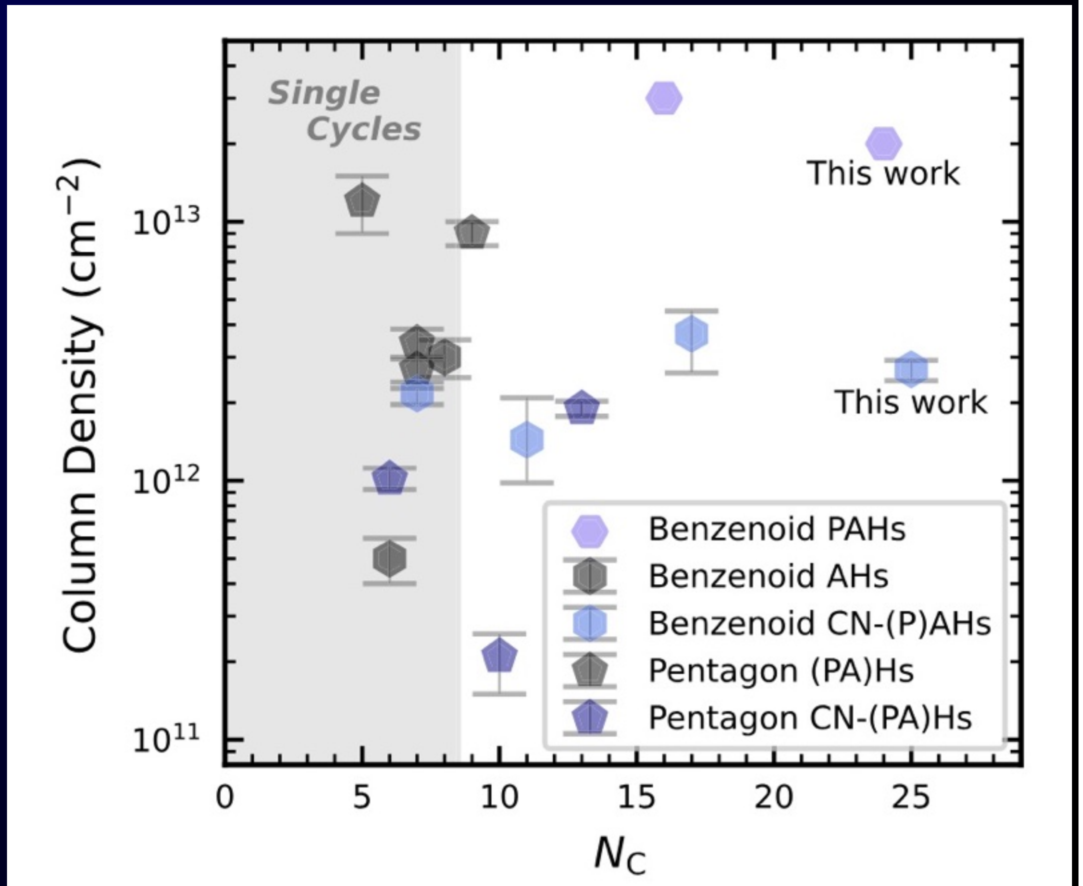


McGuire+ 2021





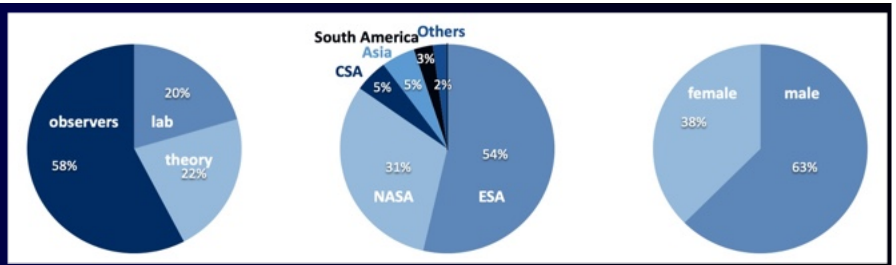
Cernicharo+ 2024

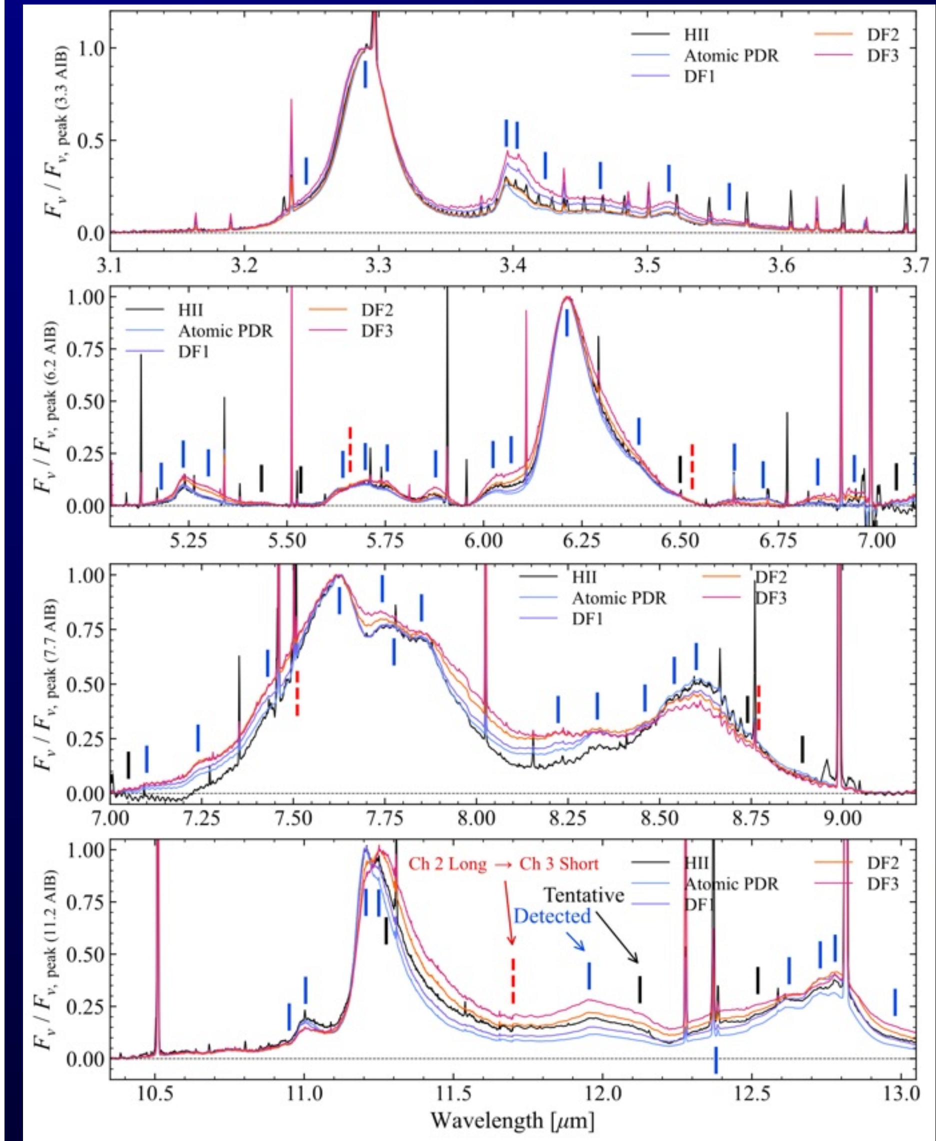


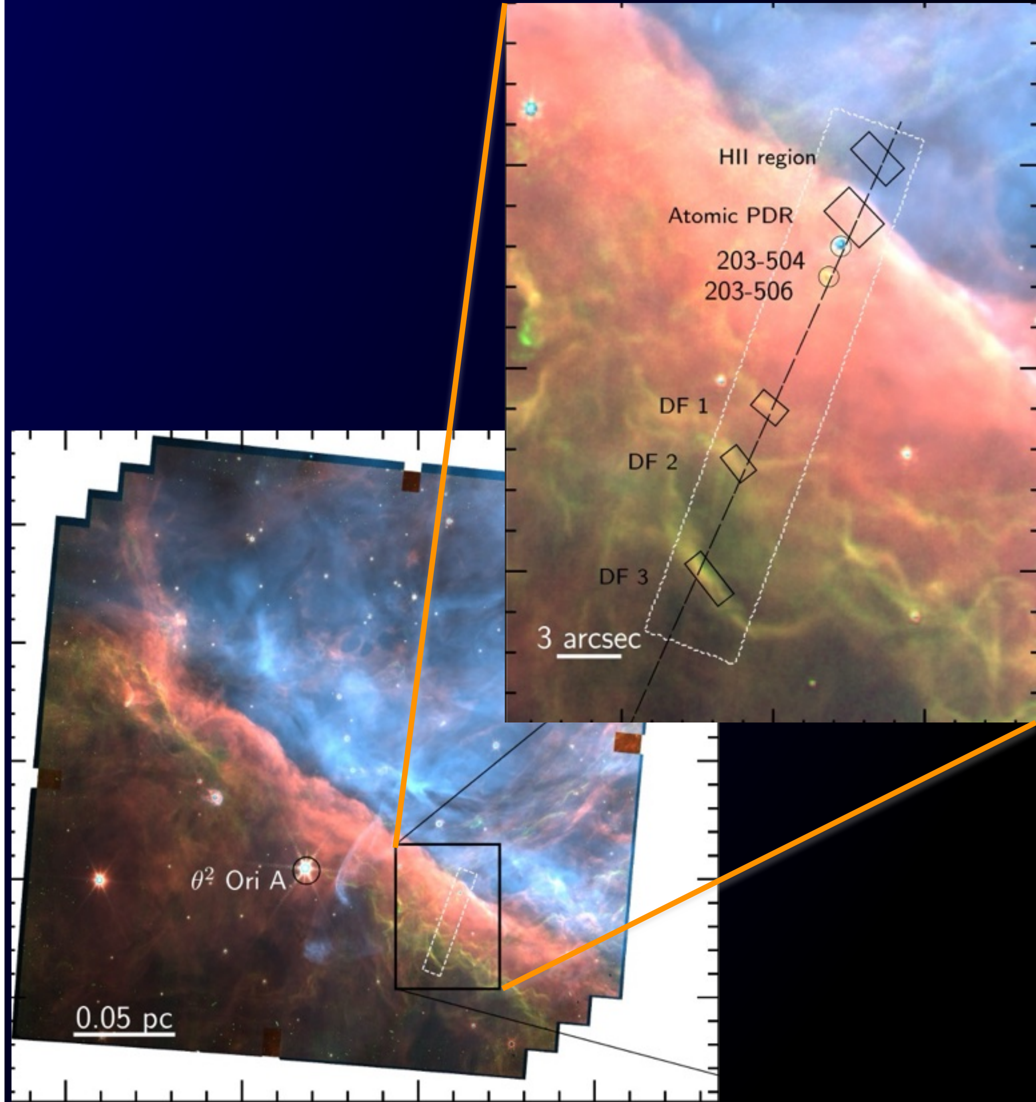
Wenzel+ 2025

PDRs4All ERS program

- PI Team : O. Berné (FR), E. Habart (FR), E. Peeters (CA)
- 122 scientists, from 18 countries
- Target : Orion Bar
- Instruments : 15.5h NIRspec / 22.5h MIRI / 2.7h NIRCam





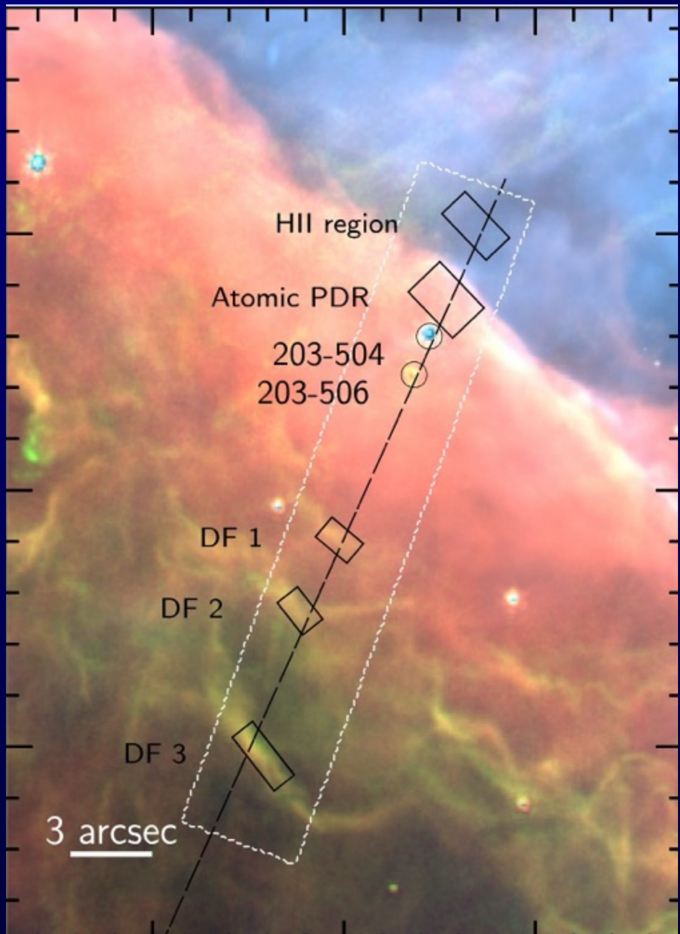


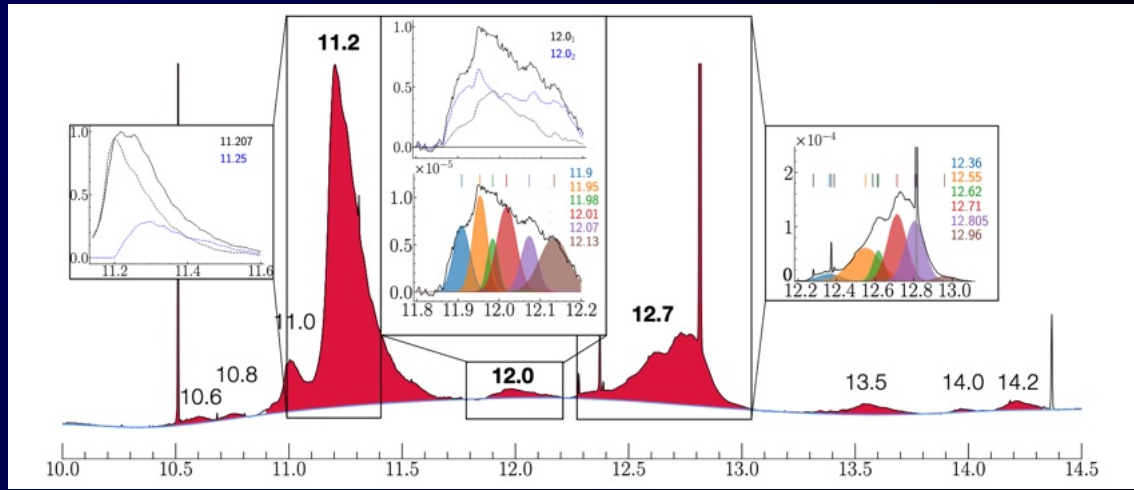
Chown+2024

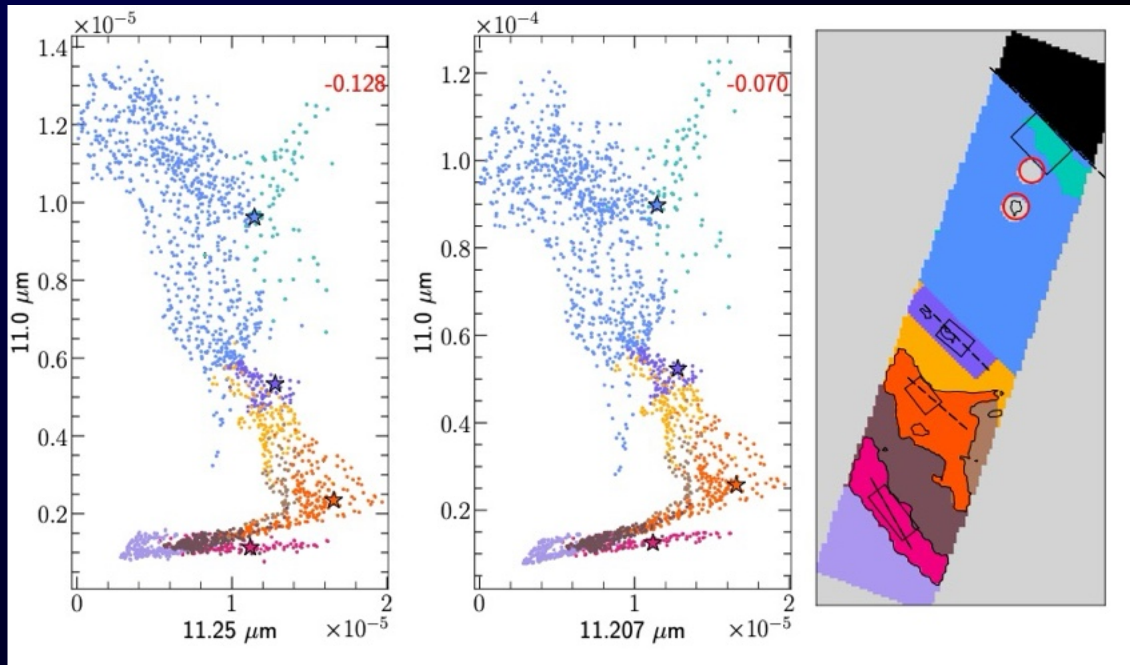
Habart+2024, Berné+2023, Peeters+2024,van de Putte+2025, many others…

Aromatic Infrared Bands (AIBs)

“Polycyclic Aromatic Hydrocarbons hypothesis”



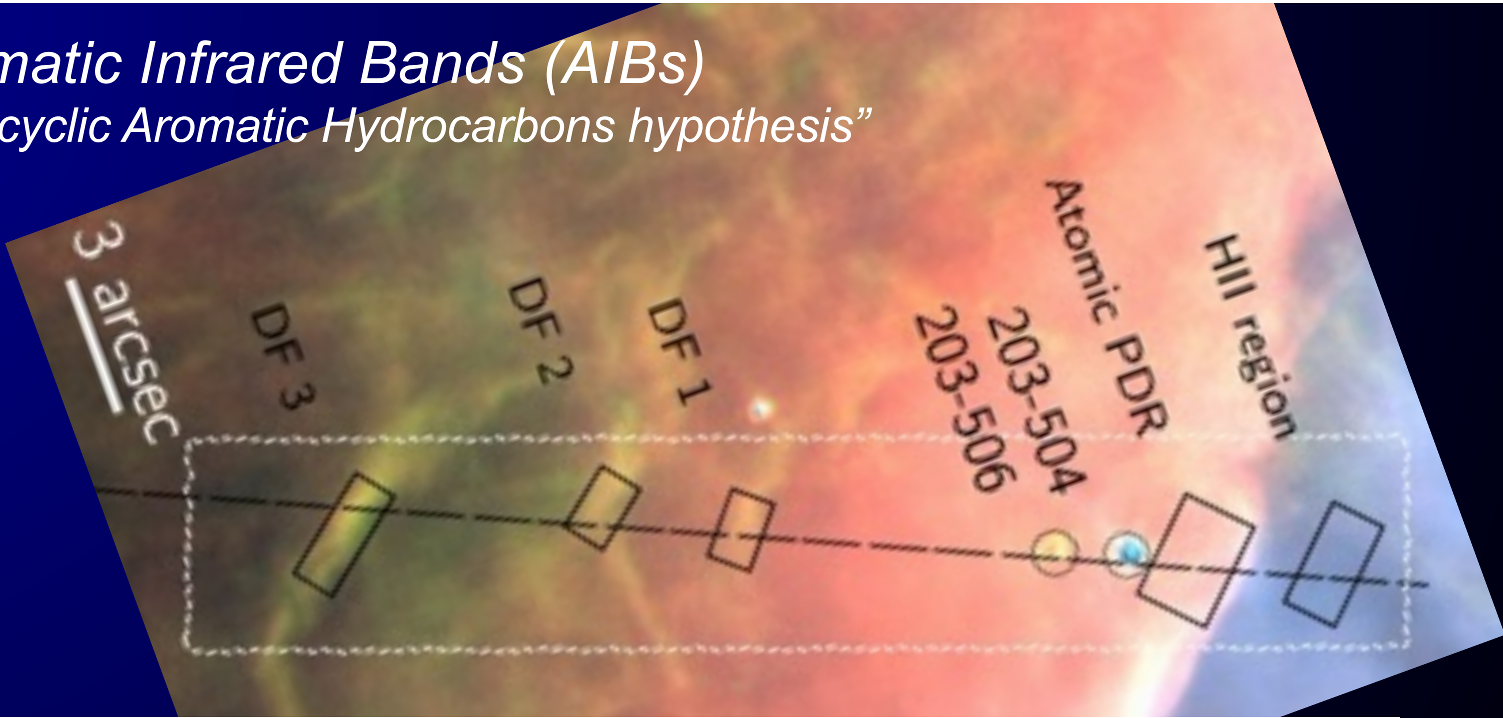


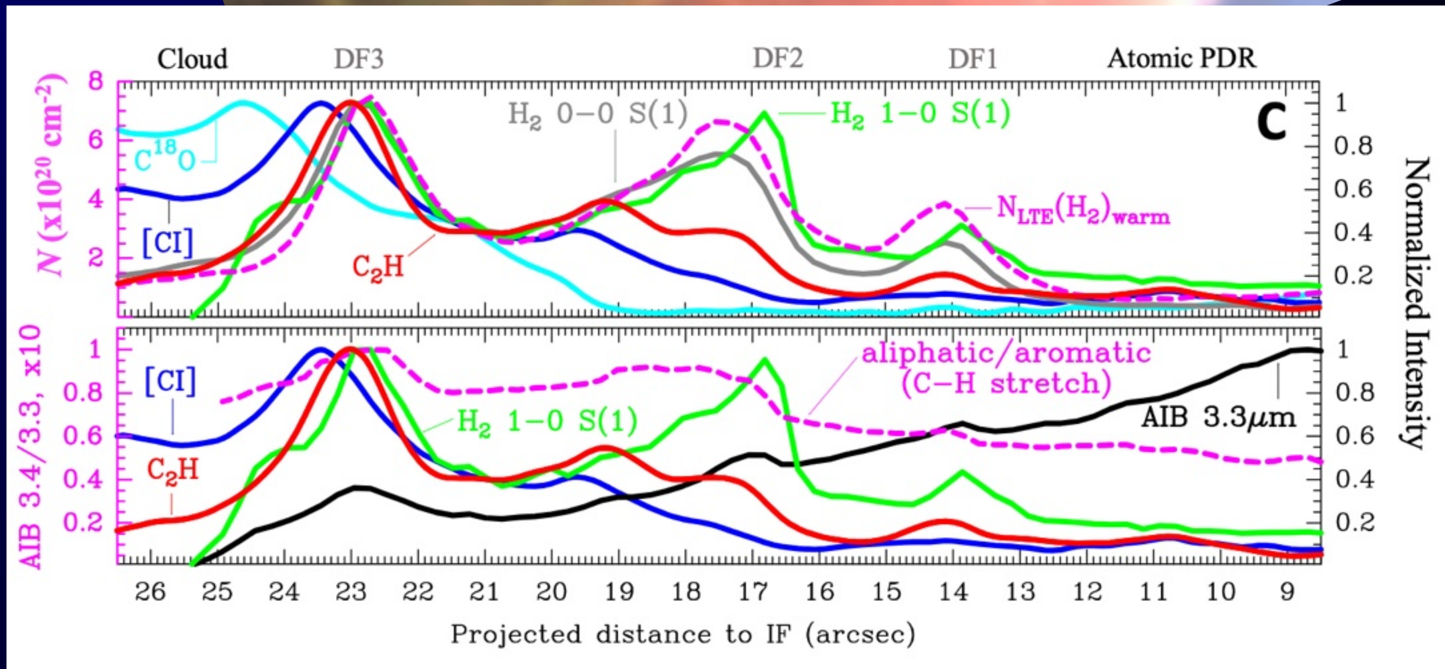


Khan+2025

Aromatic Infrared Bands (AIBs)

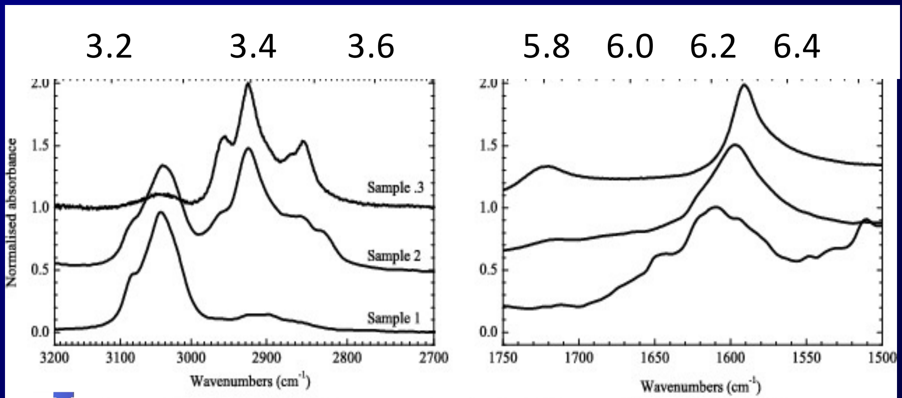
“Polycyclic Aromatic Hydrocarbons hypothesis”

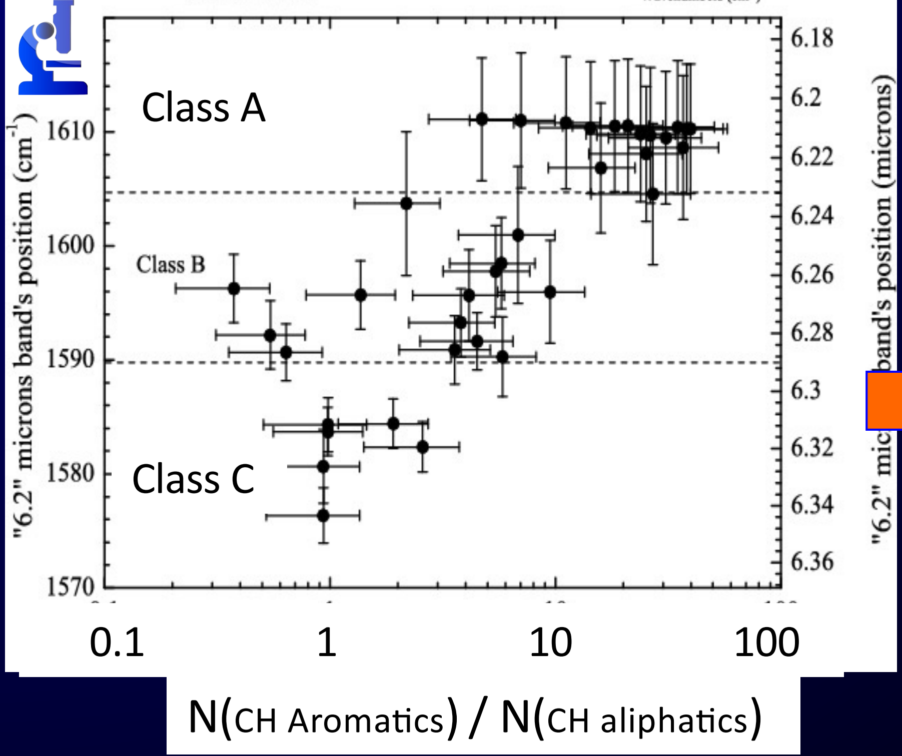


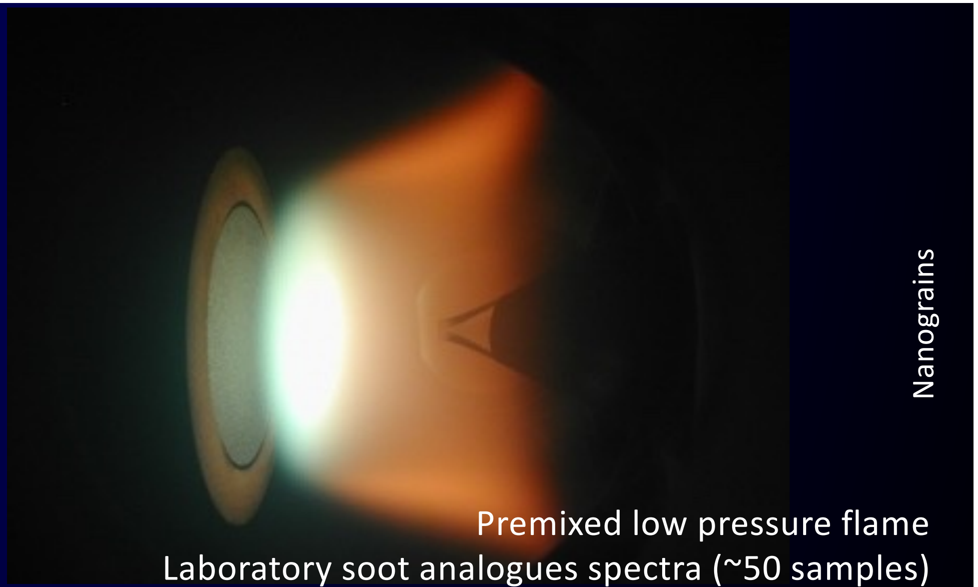


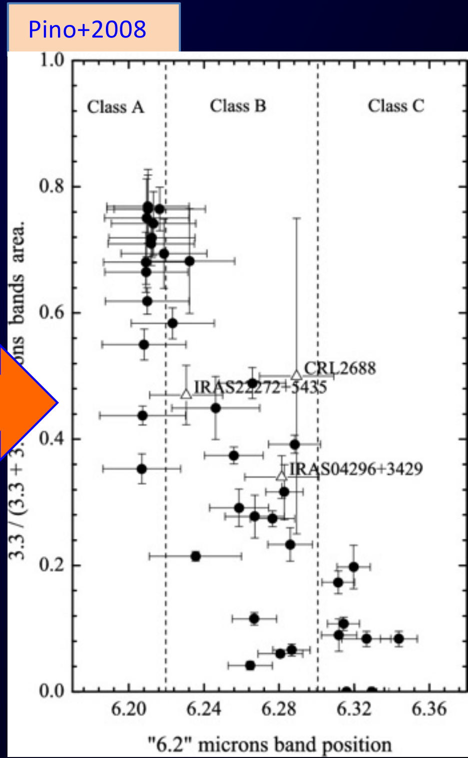
Goicoechea+2025

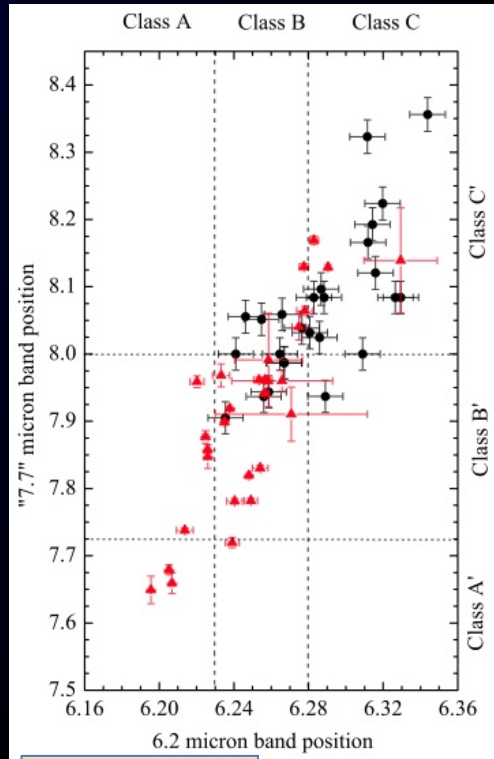
Class C-D spectral signatures reproduced with laboratory analogues





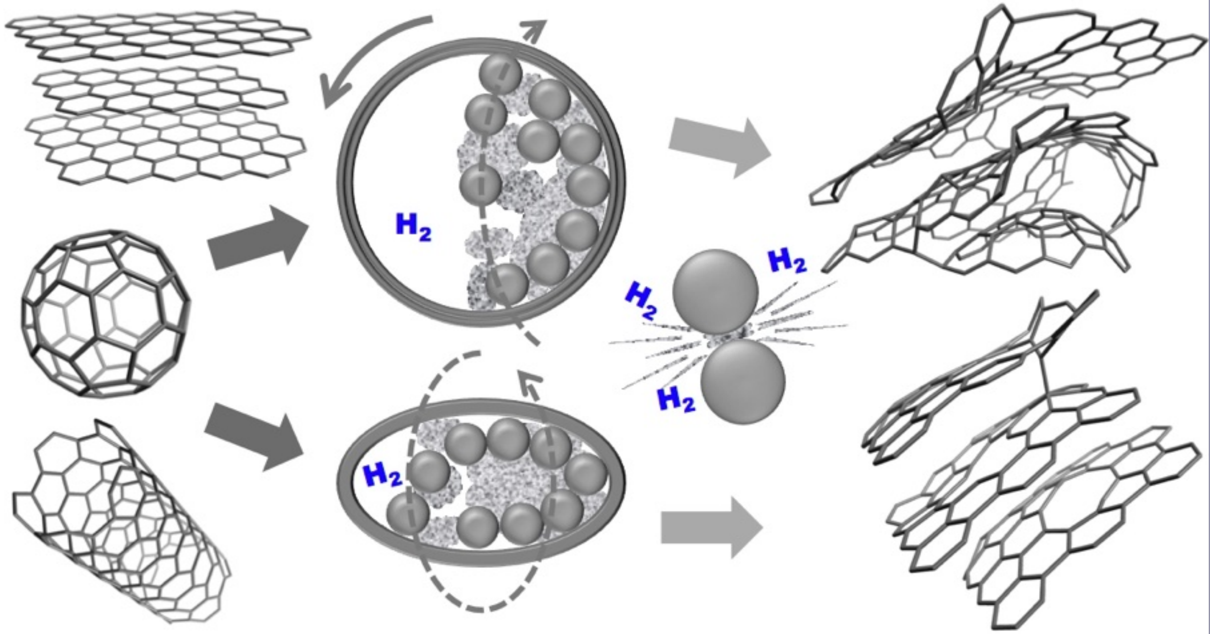


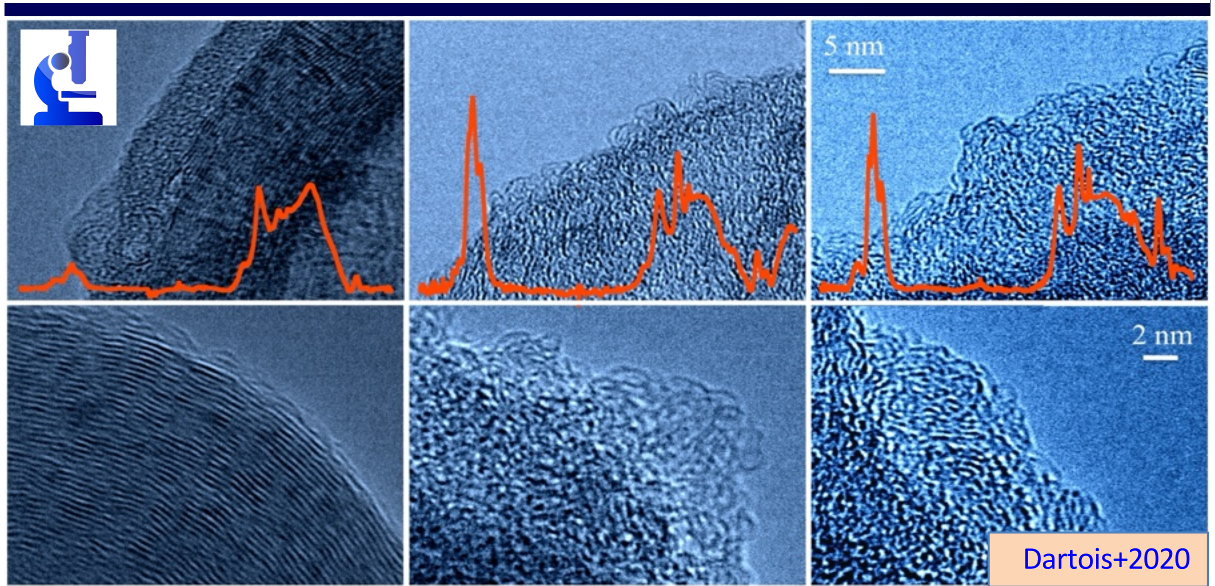


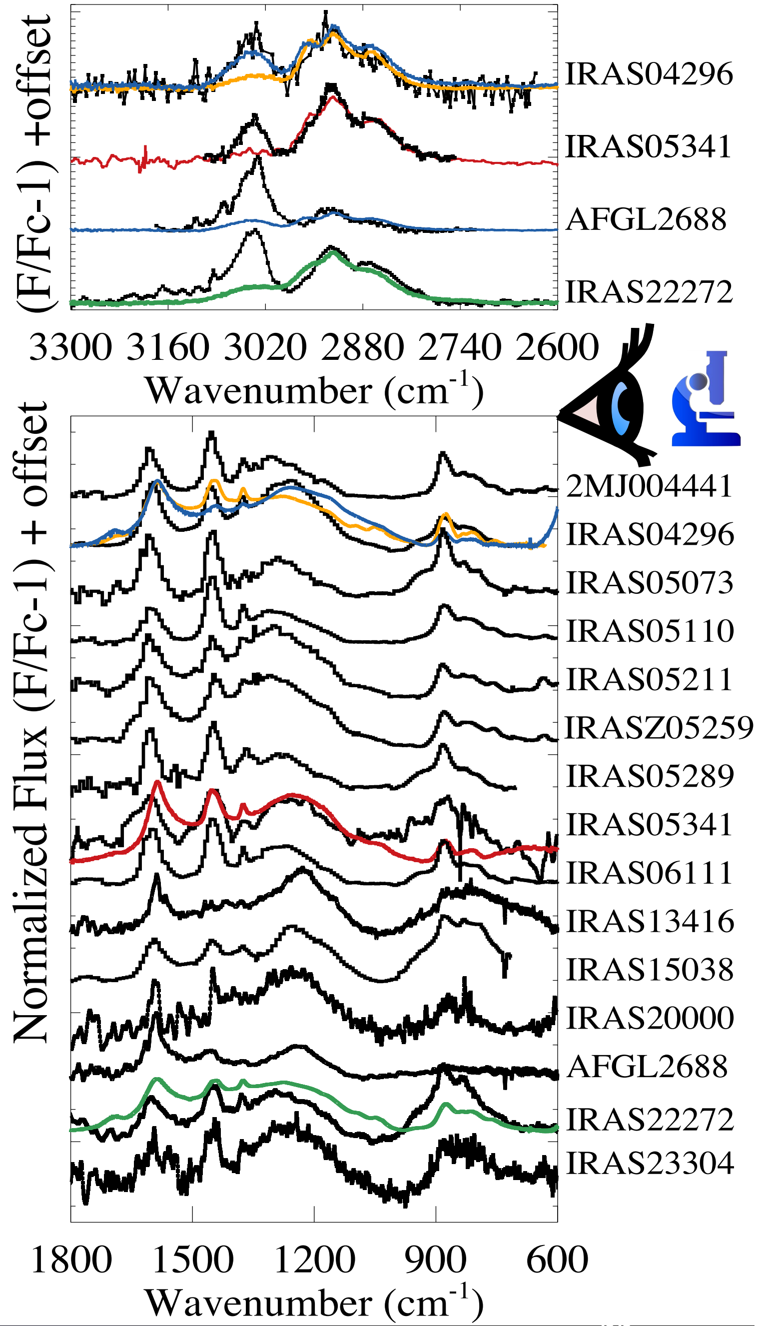


Aromatic C=C shift induced by aliphatics sp3 CH bonds ?

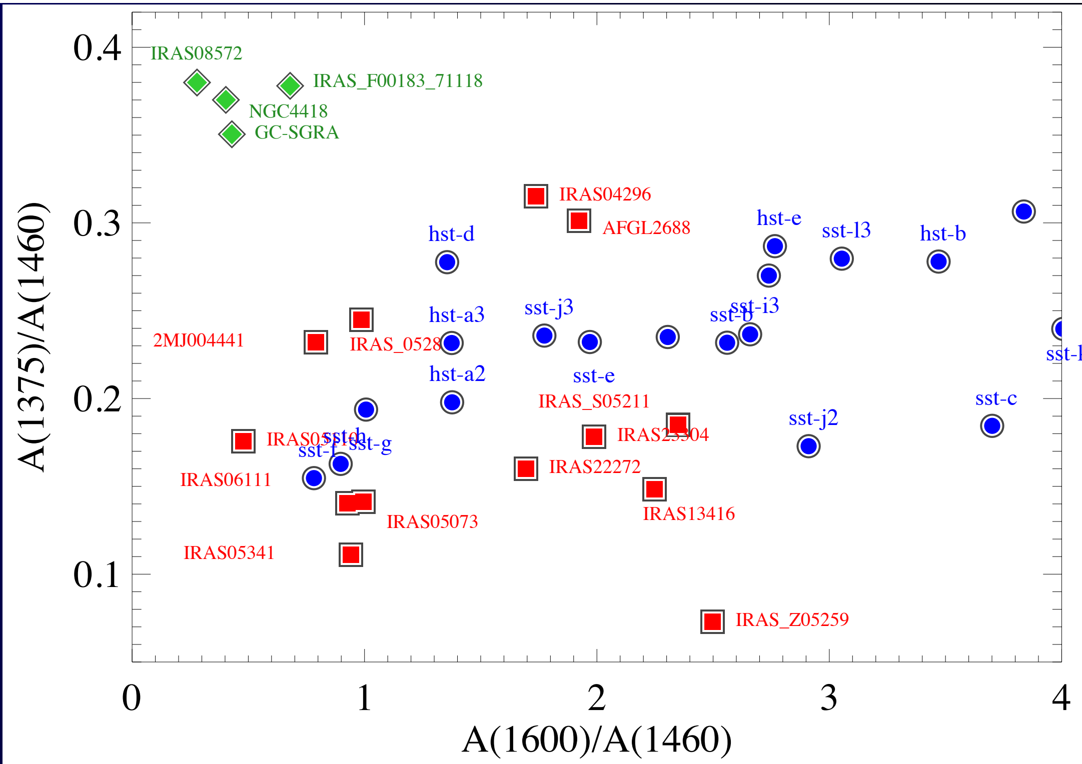
Class C-D spectral signatures reproduced with laboratory analogues

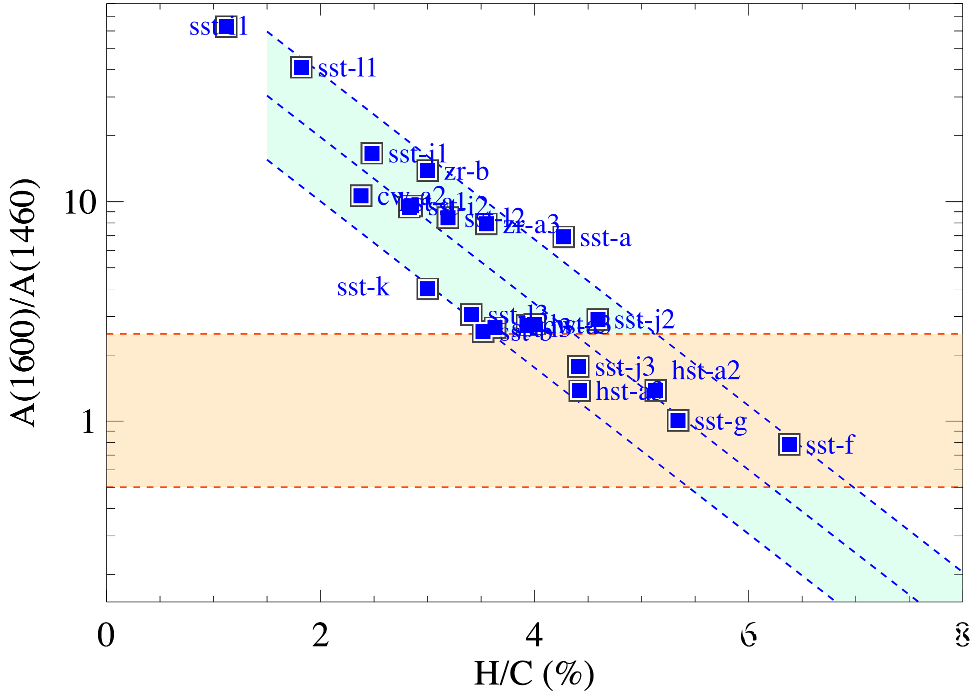


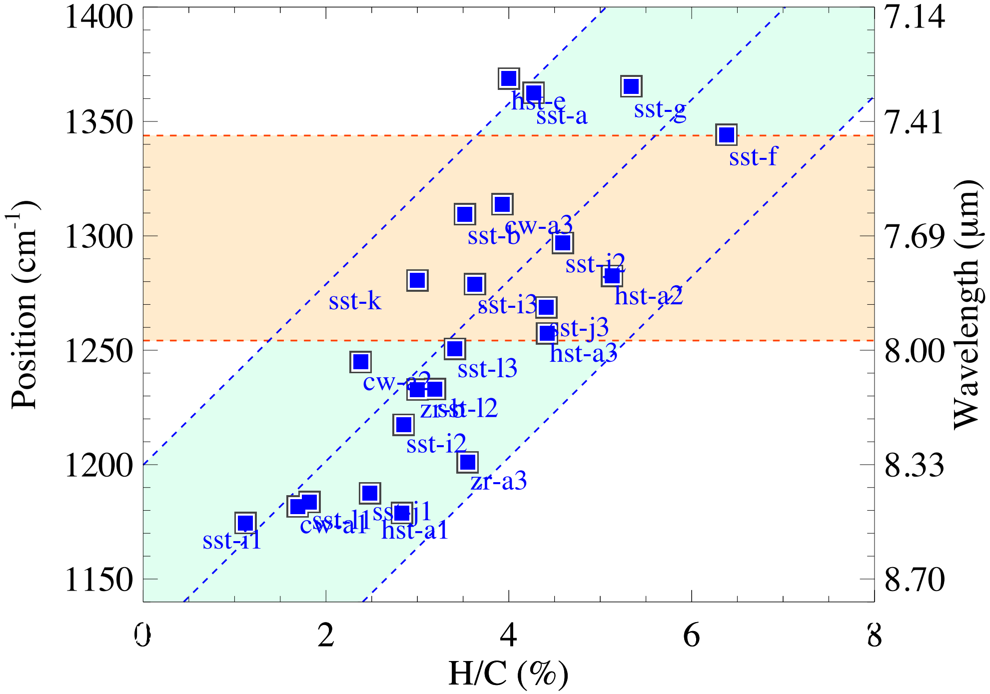




Laboratory analogues constrain astrophysical H/C from comparison to Class C-D spectral signatures

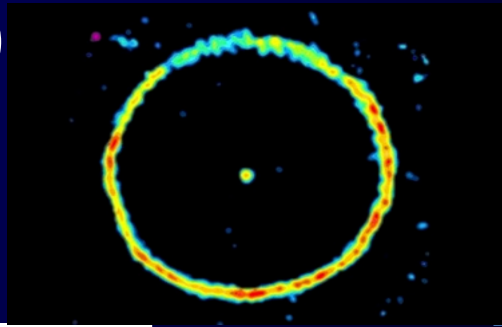




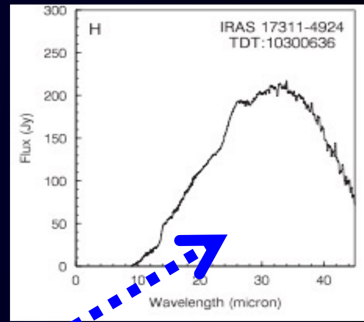


Amorphous carbon (a-C)

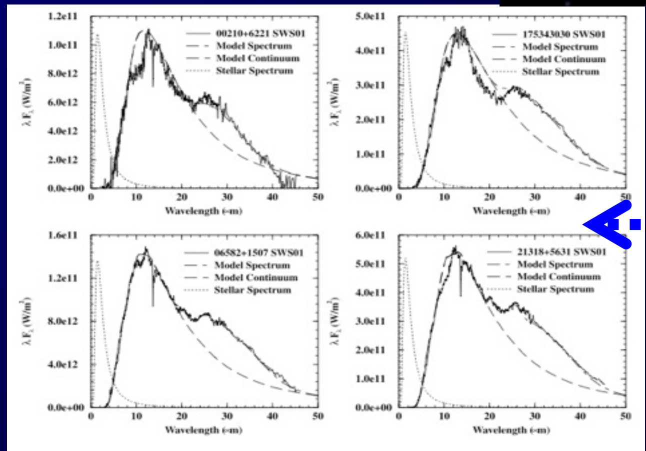
Carbon(-phase) stars

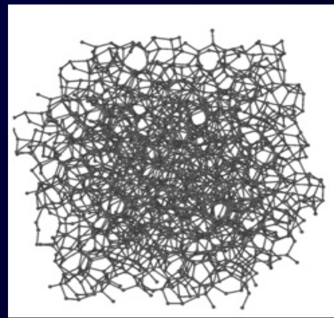


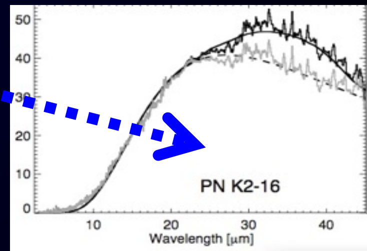
Etoile carbonée
TTCygni / IRAM



Chen et al.2010
Gauba 2004

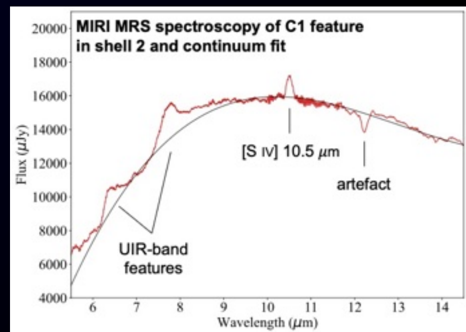






Hony et al.2002

Volk et al.2001



Lau+2022

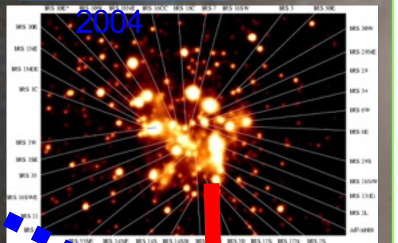
C rich PPNs progenitors like AFGL 2688 (class C) & PNs like NGC 7027

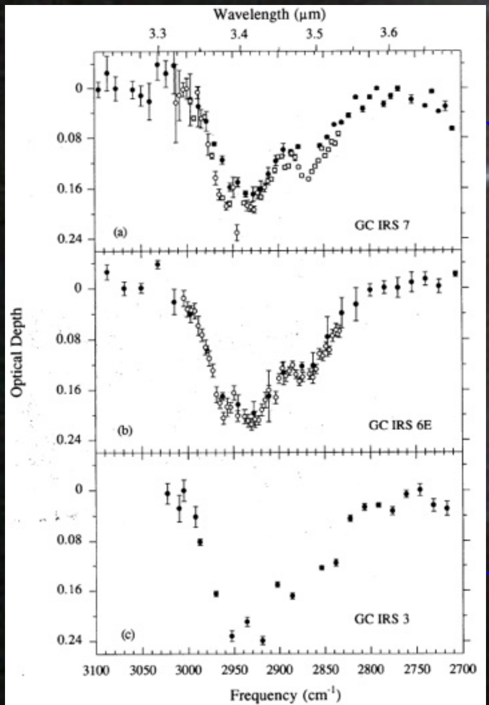
Hydrogenated amorphous carbons (a-C:H or HAC)

DISM

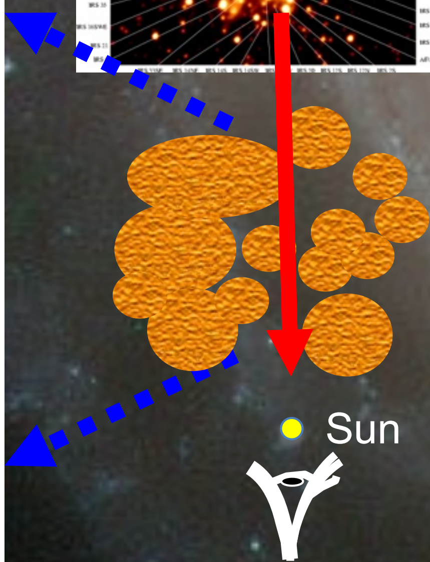
CH stretch abs. observed against IR bkgd sources

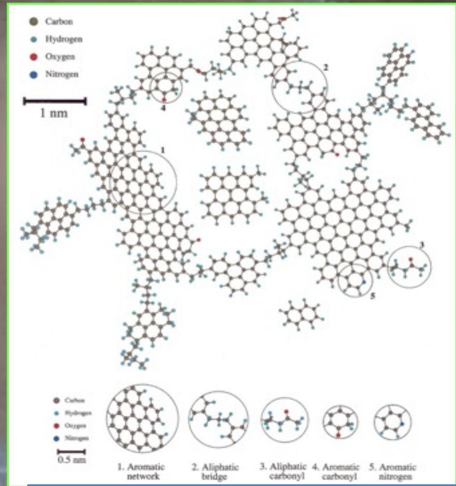
Viehmann+ 2004



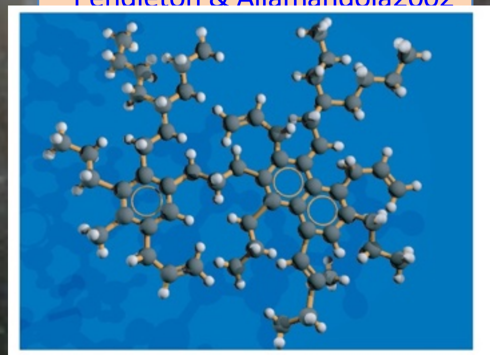


Pendleton+1994

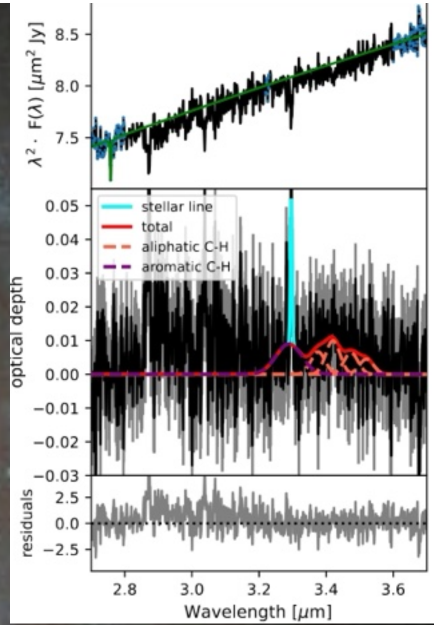


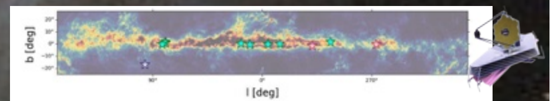


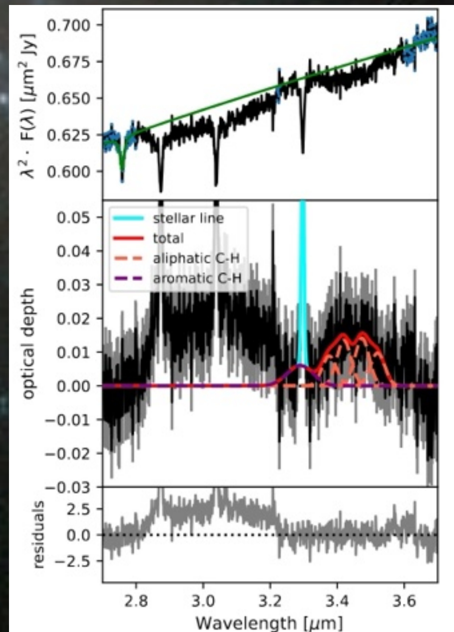
Pendleton & Allamandola2002



Dartois+2007



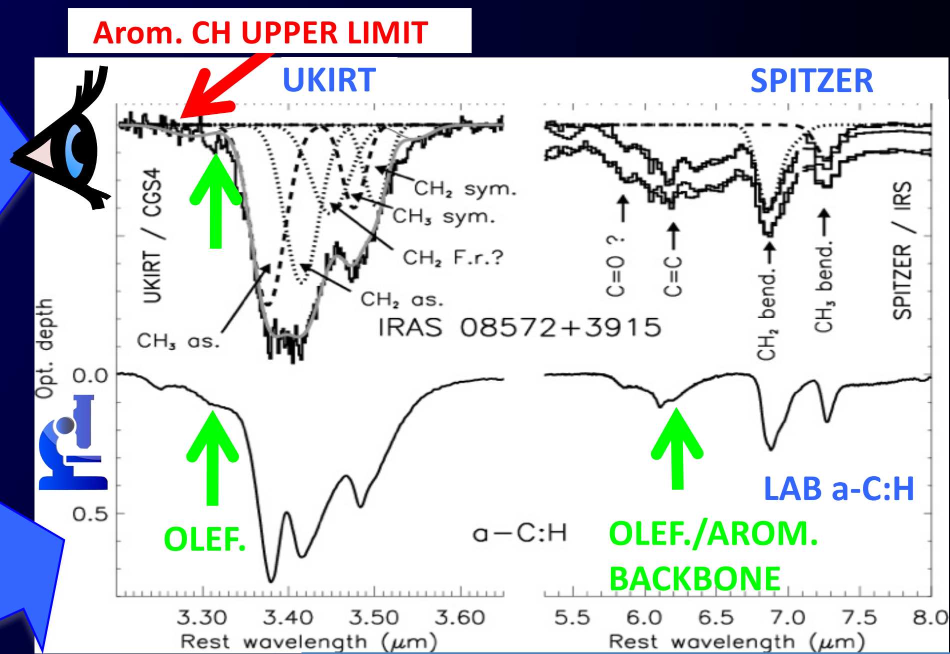




Zeegers+2025

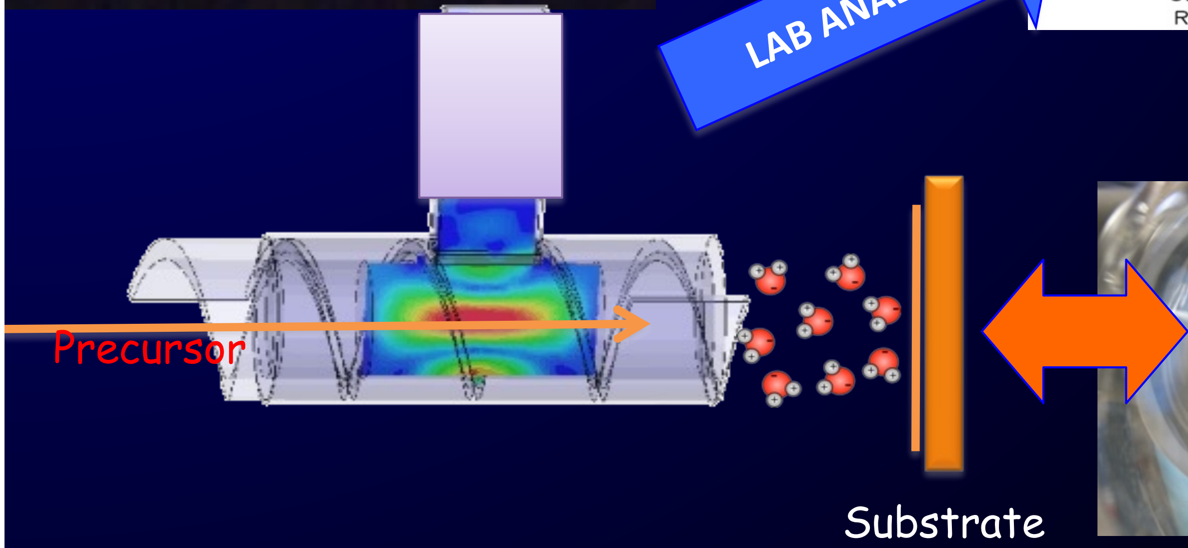
Sandford+1991; 1995, Pendleton+1994, Duley+1994, 1998, Dartois+1997; Godard+2013, …

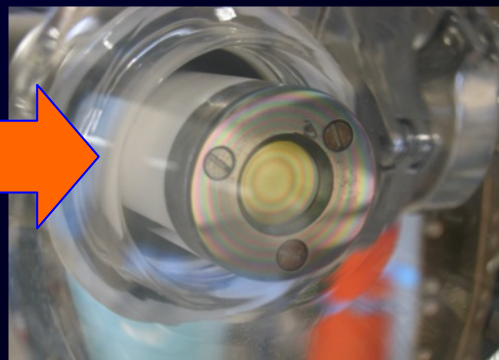
ISM (ext. galaxies)

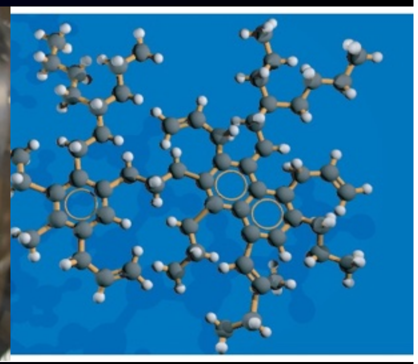


Godard et al. 2011; Dartois, Geballe, Pino et al. 2007

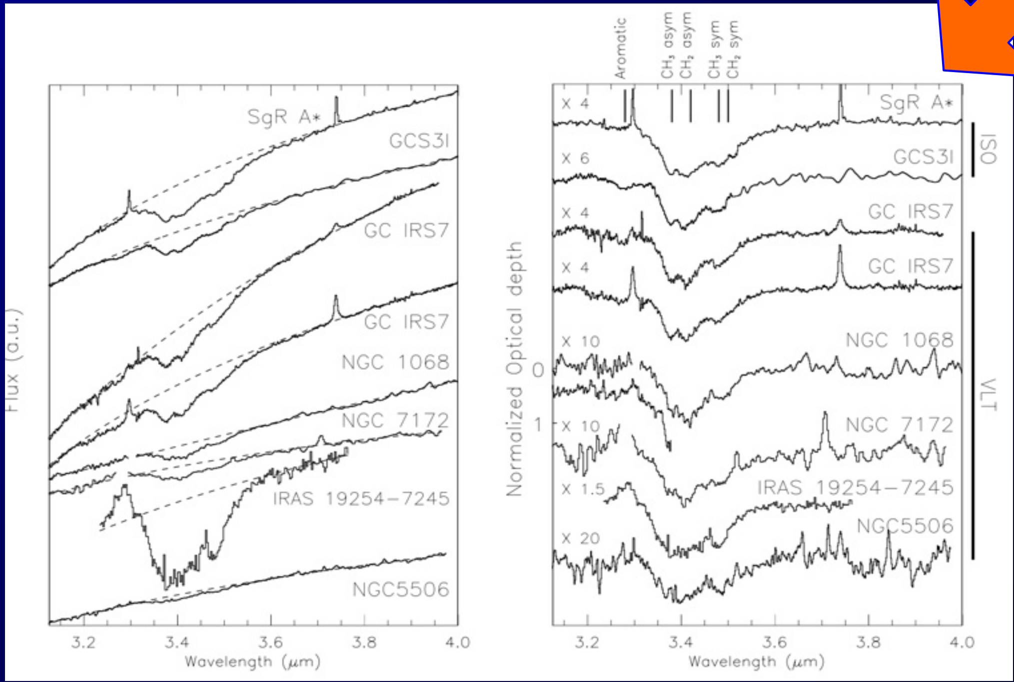
Mori+2022; Sakata+1984; Duley+1998

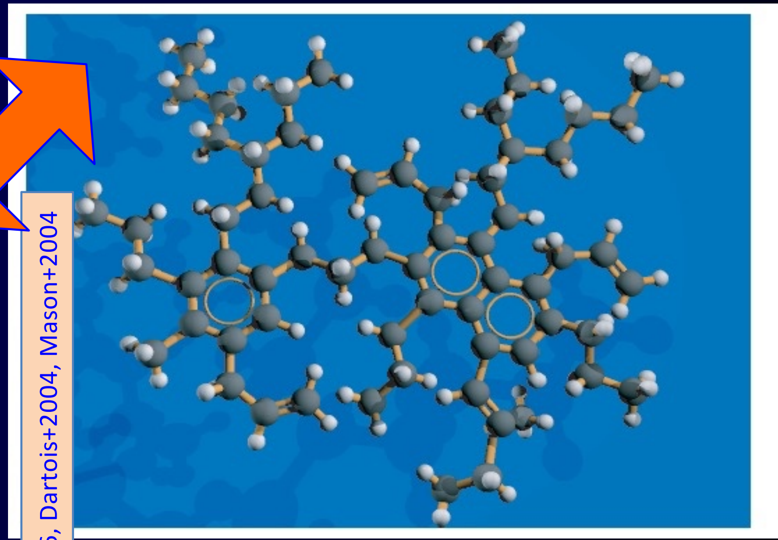






Extragalactic sources ISM observed with a-C:H

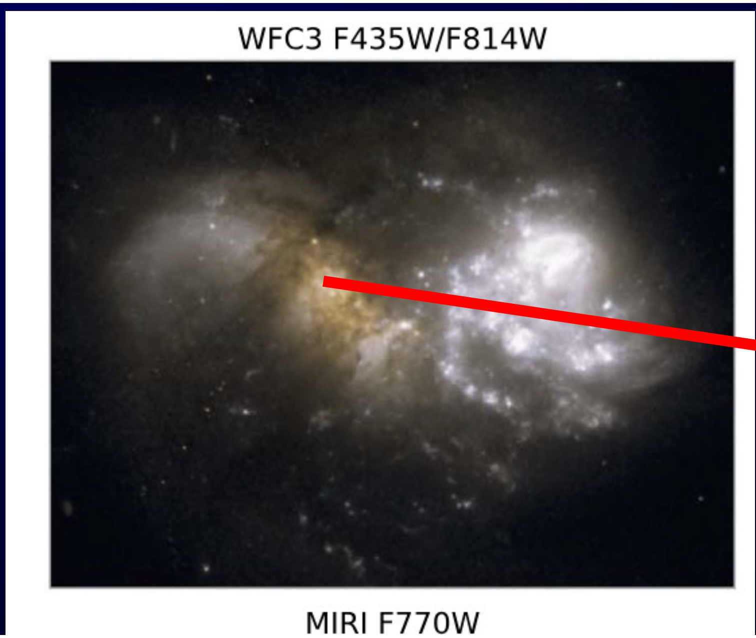


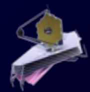


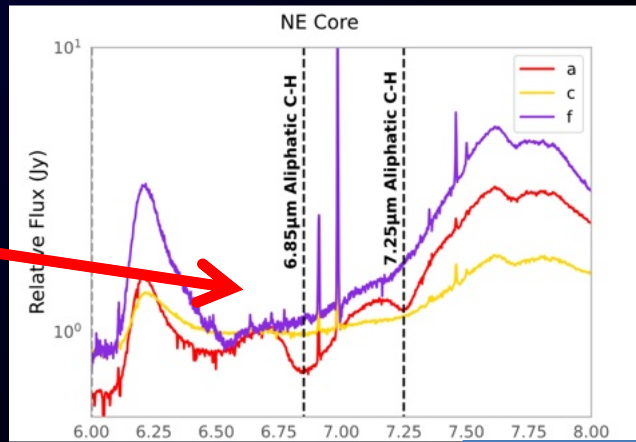
Imanishi+2010, Risaliti+2006, Dartois+2004, Mason+2004

5% to up to 40%

of cosmic C?

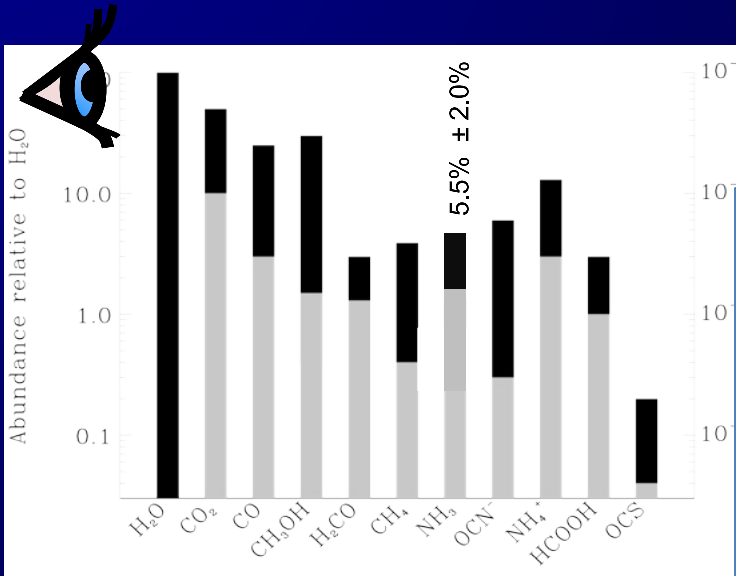






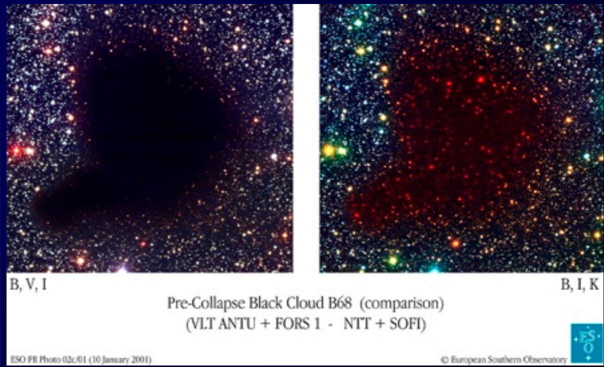
Rich+2023

Ice mantles irradiation + T increase -> organic residues

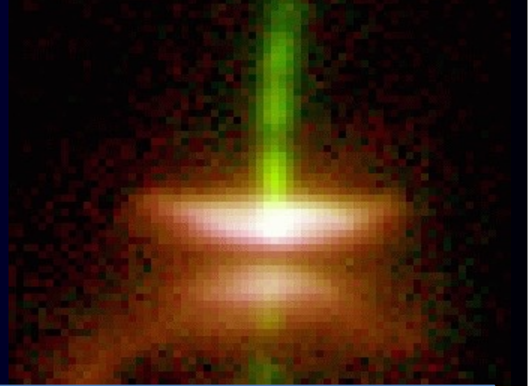


Dartois 2005, SSRv 119, 293

Field stars

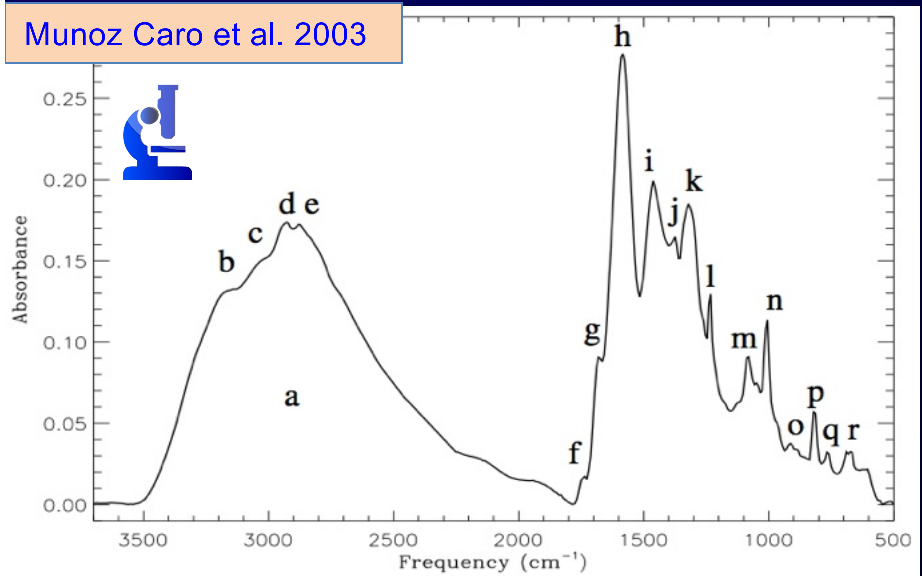


Protostars/Disks

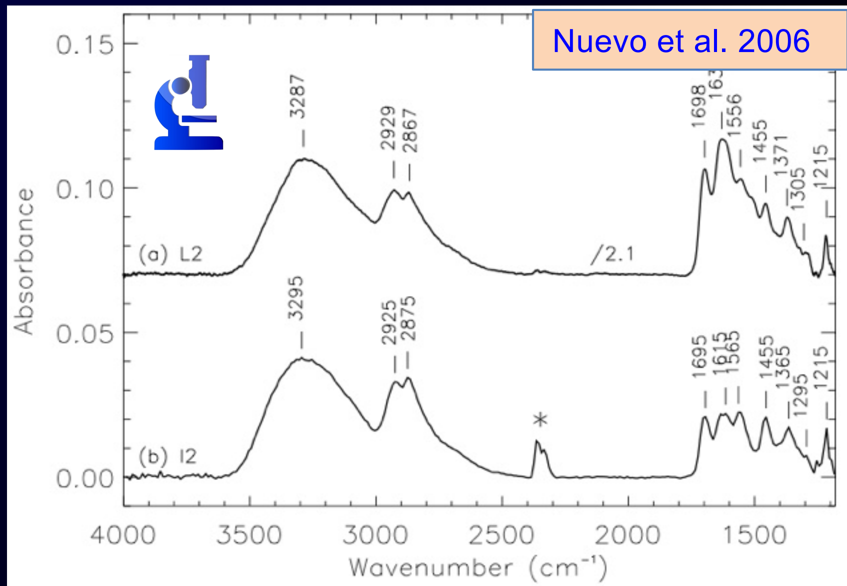


e.g. Bottinelli et al. 2010, Boogert et al. 2008; Pontoppidan et al. 2008; Oberg et al. 2008; Bergin et al 2005; Dartois et al. 2005; Van Dishoeck 2004; Boogert & Ehrenfreund 2004; Gibb et al. 2000.

Munoz Caro et al. 2003

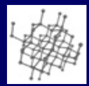


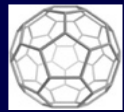
Nuevo et al. 2006



e.g. Danger+2021, 2016, de Marcellus+2017, Raunier+2004,…

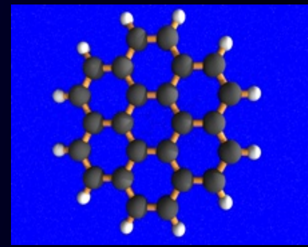
Which ISM carbonaceous solids ingredients ?

(nano-) Diamonds 

Fullerenes 

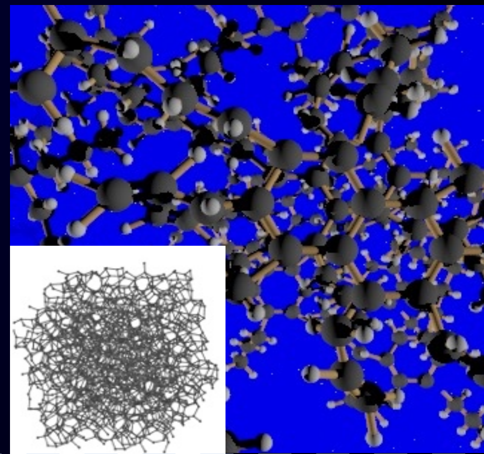
C_{60} C_{60}^{+} (C_{70}?)

AIBs-PAHs :
Class A to C

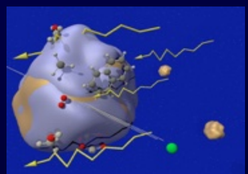


Hydrogenated
amorphous carbon

Amorphous
carbon



+ organic matter



Ice mantles
residues

Observational biases ?
Location along l.o.s. ?
μ–physics evolution ?
How are they mixed ?

Many additional laboratory astrophysics experimental simulations of energetic processes involving solids are needed to interpret observations, a few examples ...

Photon sources

VUV photolysis:
- ambient
- stellar
- CR induced

X-Rays

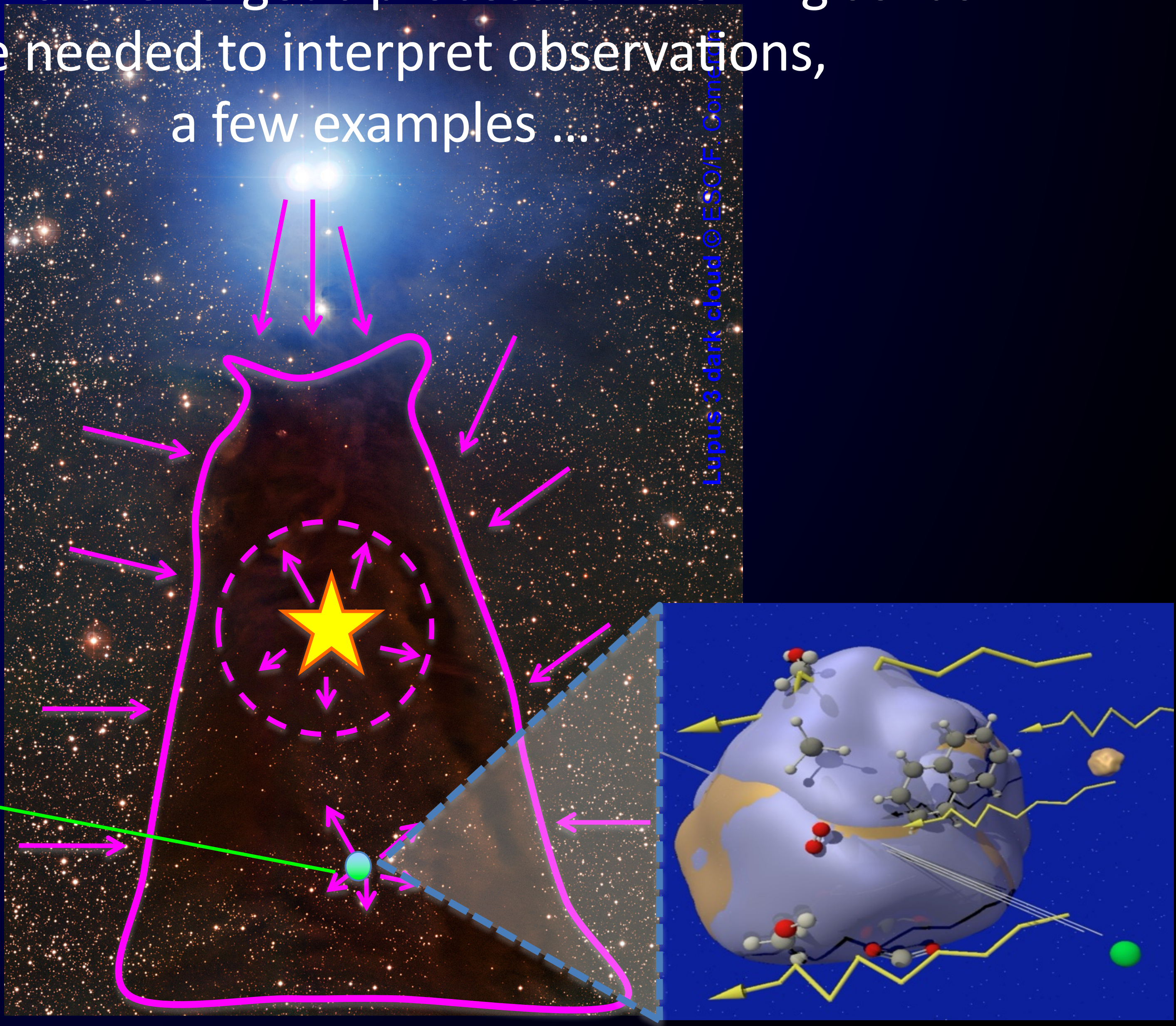
Particles sources

electrons

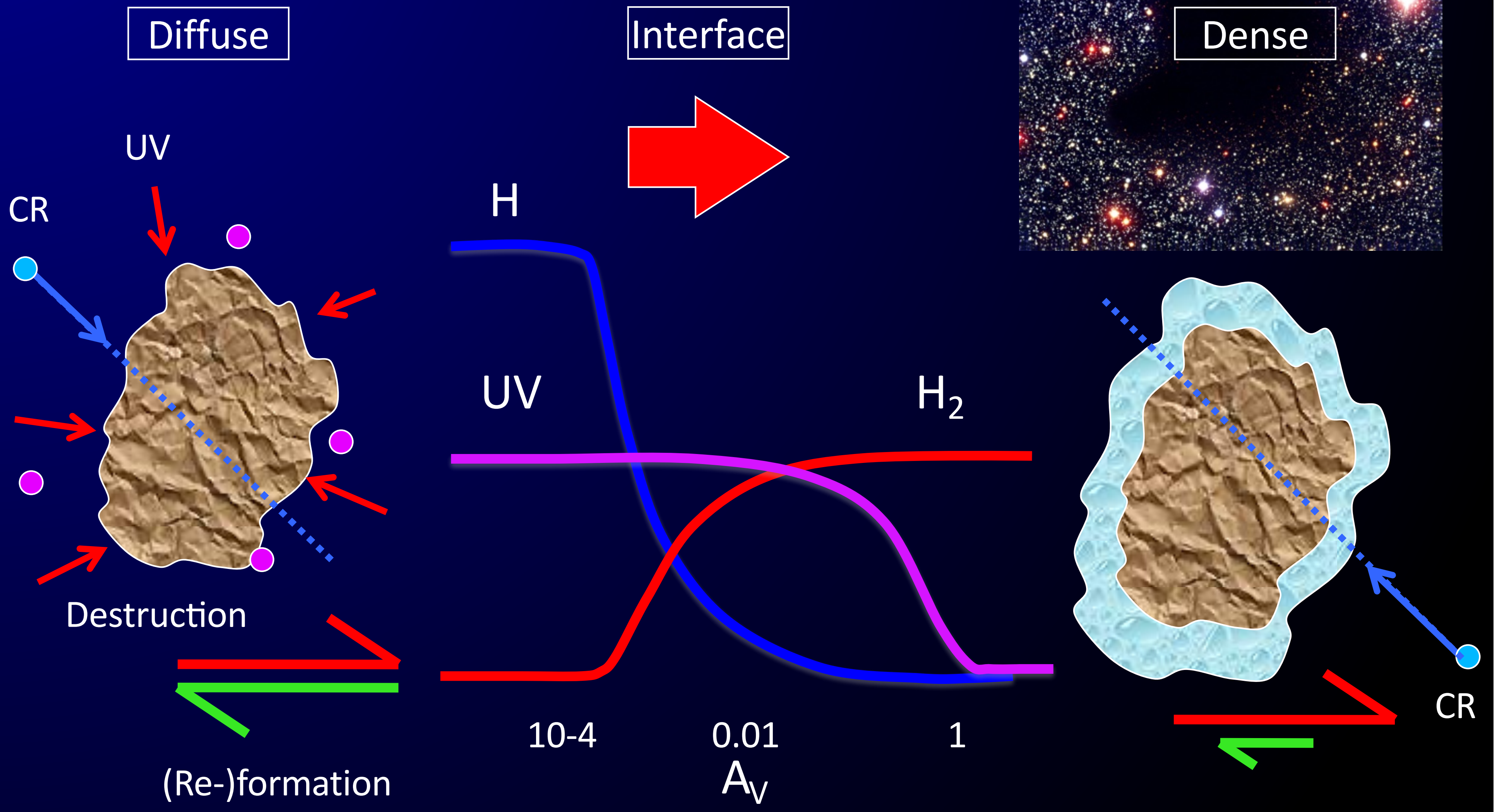
Cosmic rays

Thermal

Shocks (C,J,...)



Diffuse to dense ISM transition

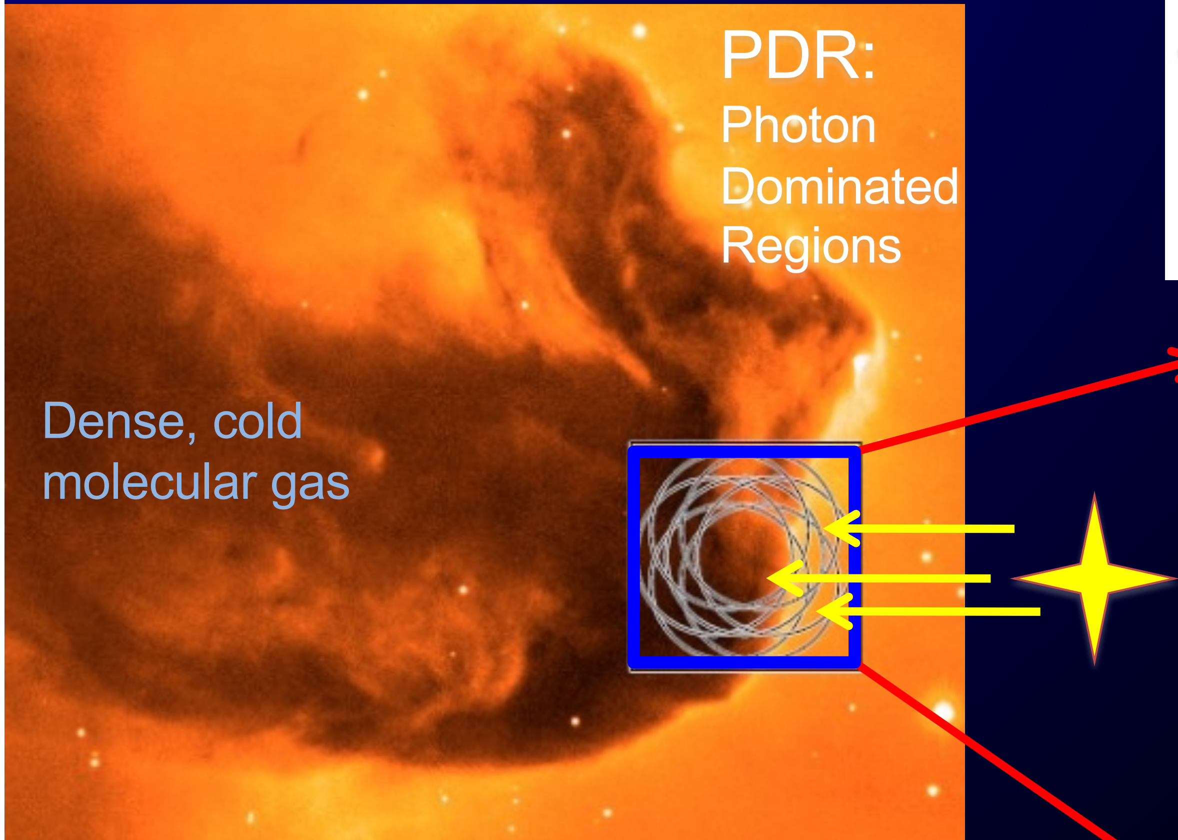


Evolution at the ISM interfaces & radiative env.

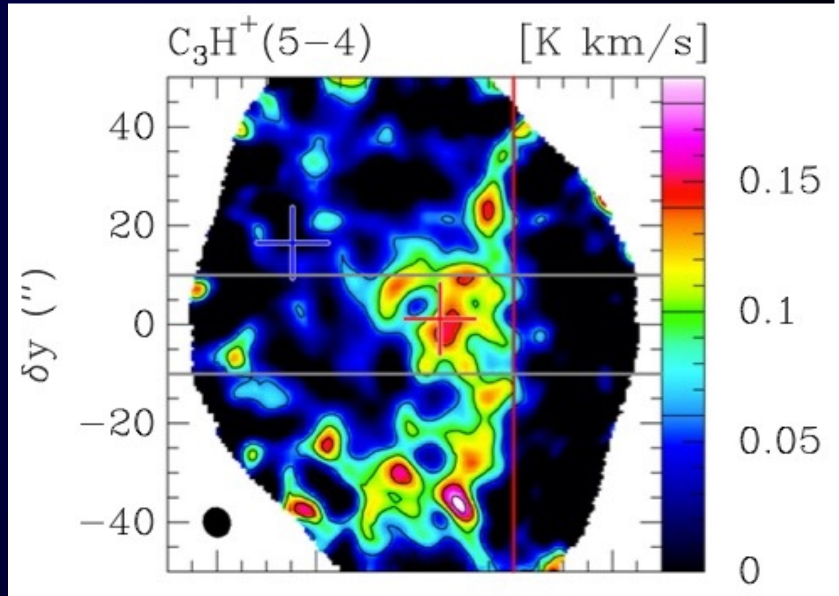
VUV

Hydrocarbons molecules detections

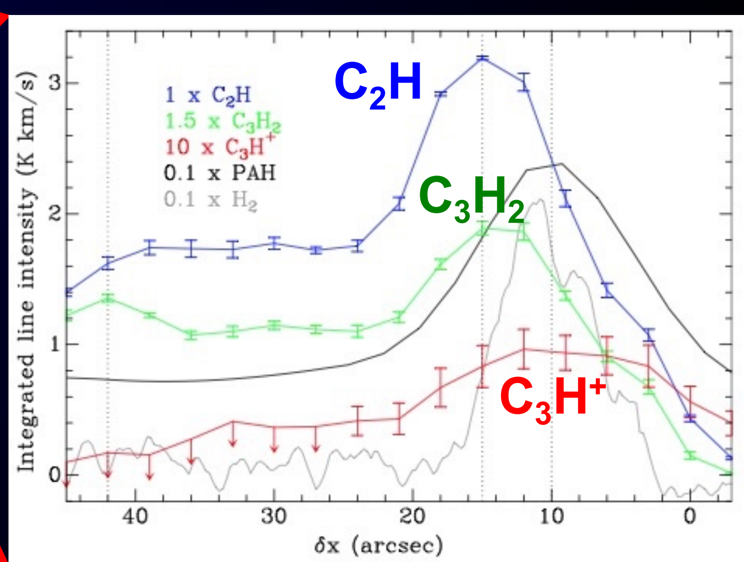
C_2, C_3, C_2H_2, CCH, c-C_3H_2, C_4H ….



Pety et al. 2005



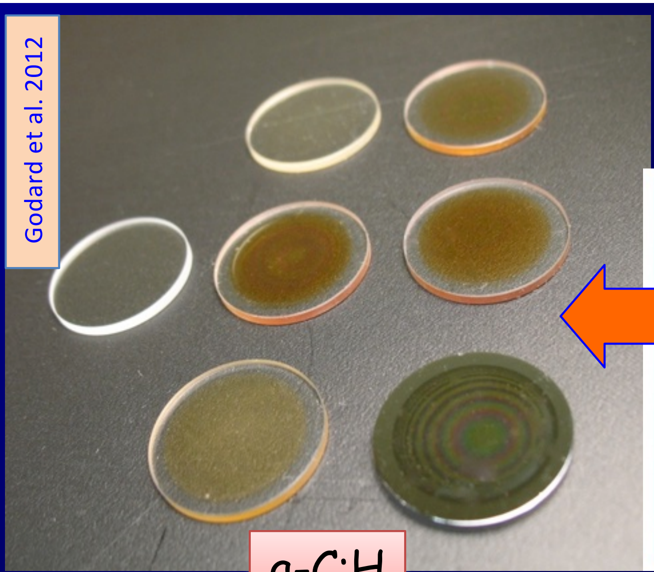
Top-down chemistry ?

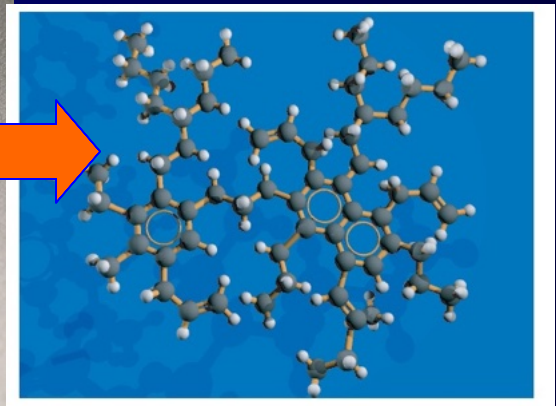


Guzman et al. 2015

One-dimensional Photo-Dissociation Region,
The Horsehead (PDR)

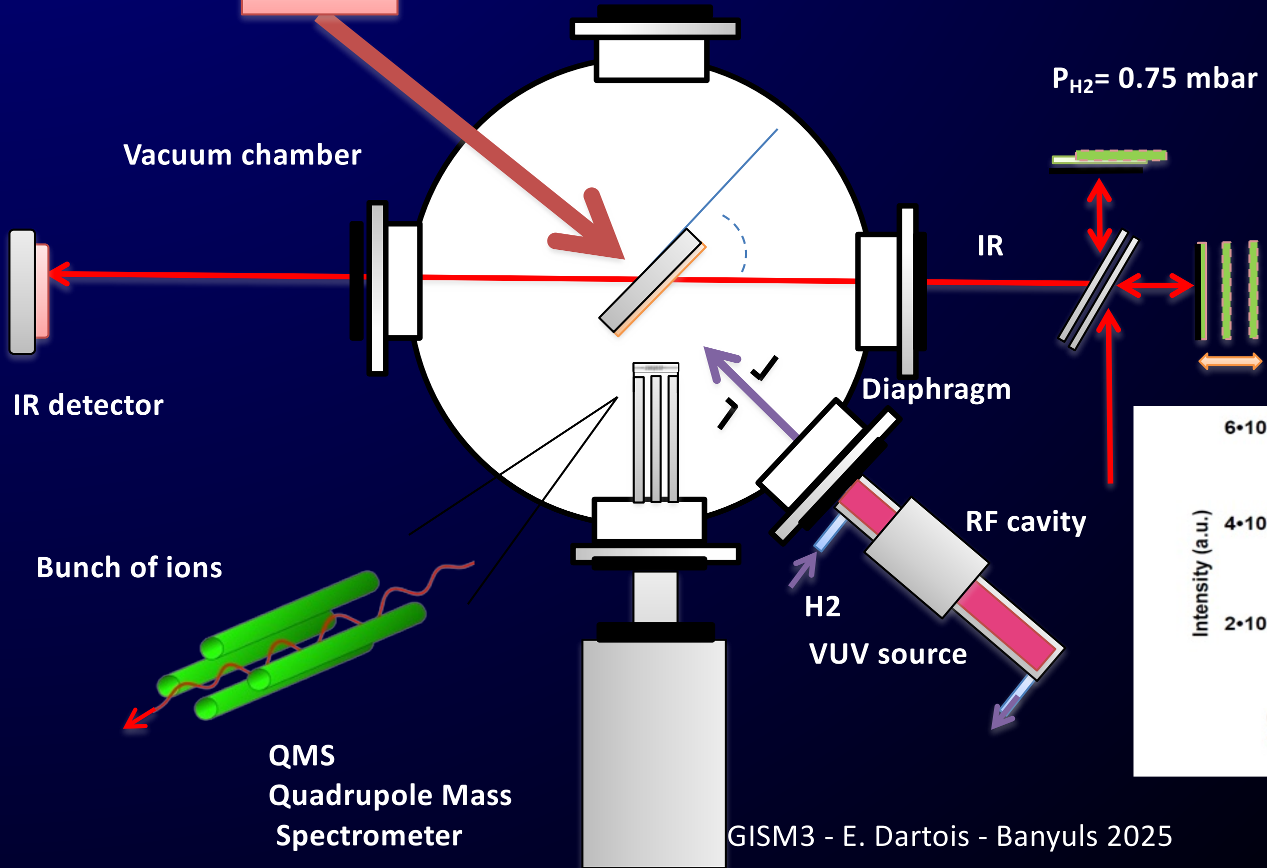
ISM UV irradiation experiments

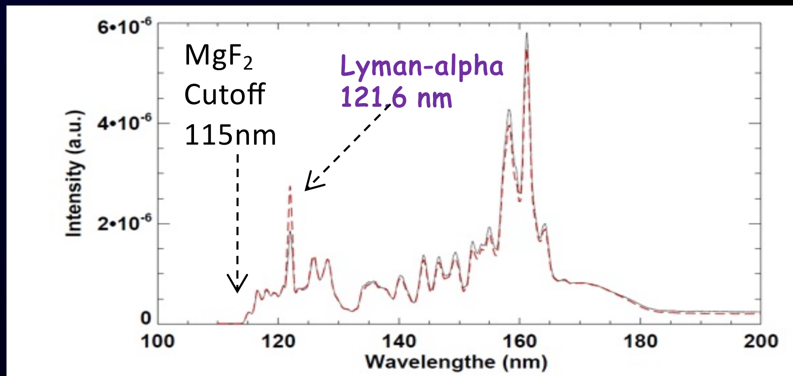




Irradiation @T=10 K

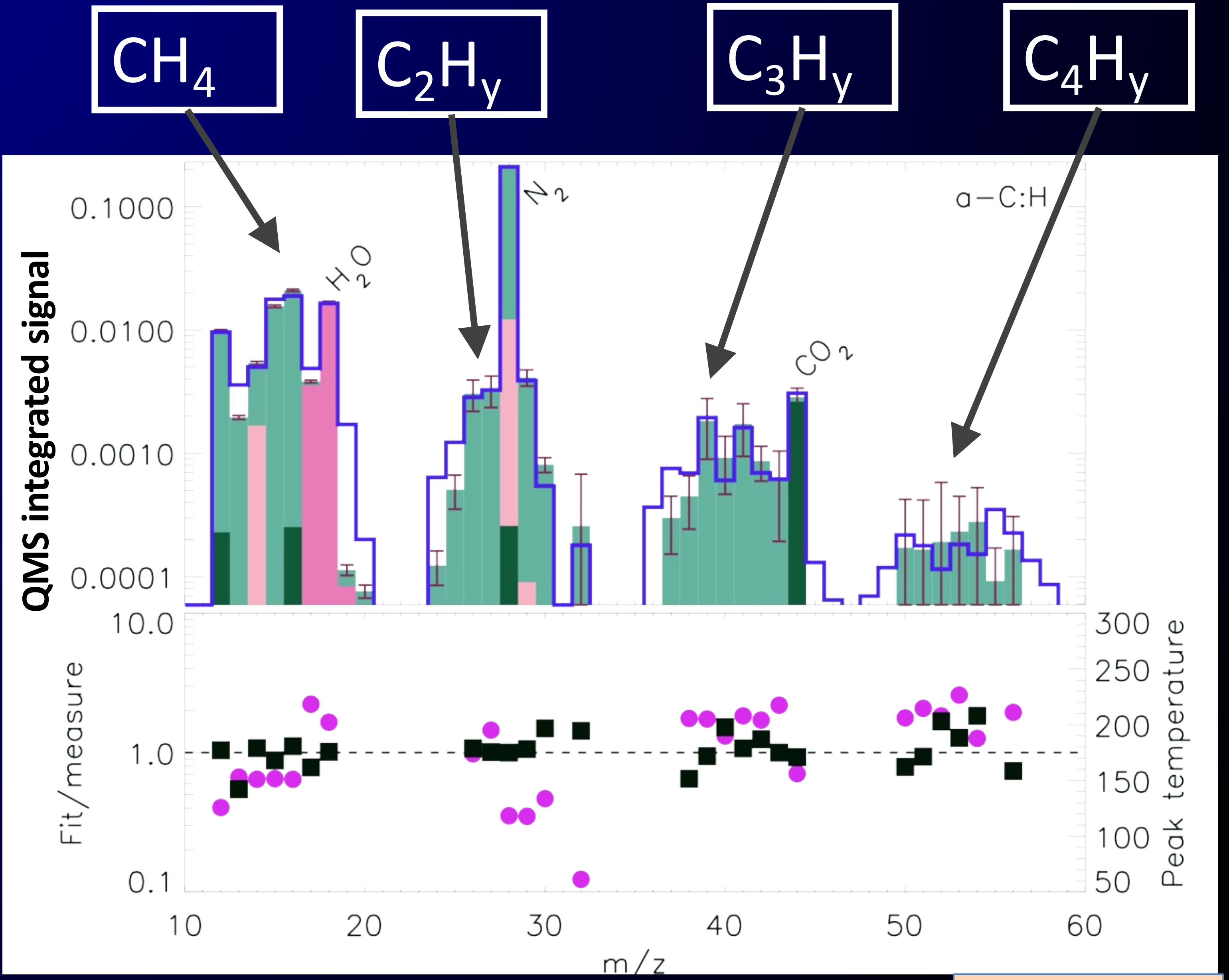
TPD 5K/min





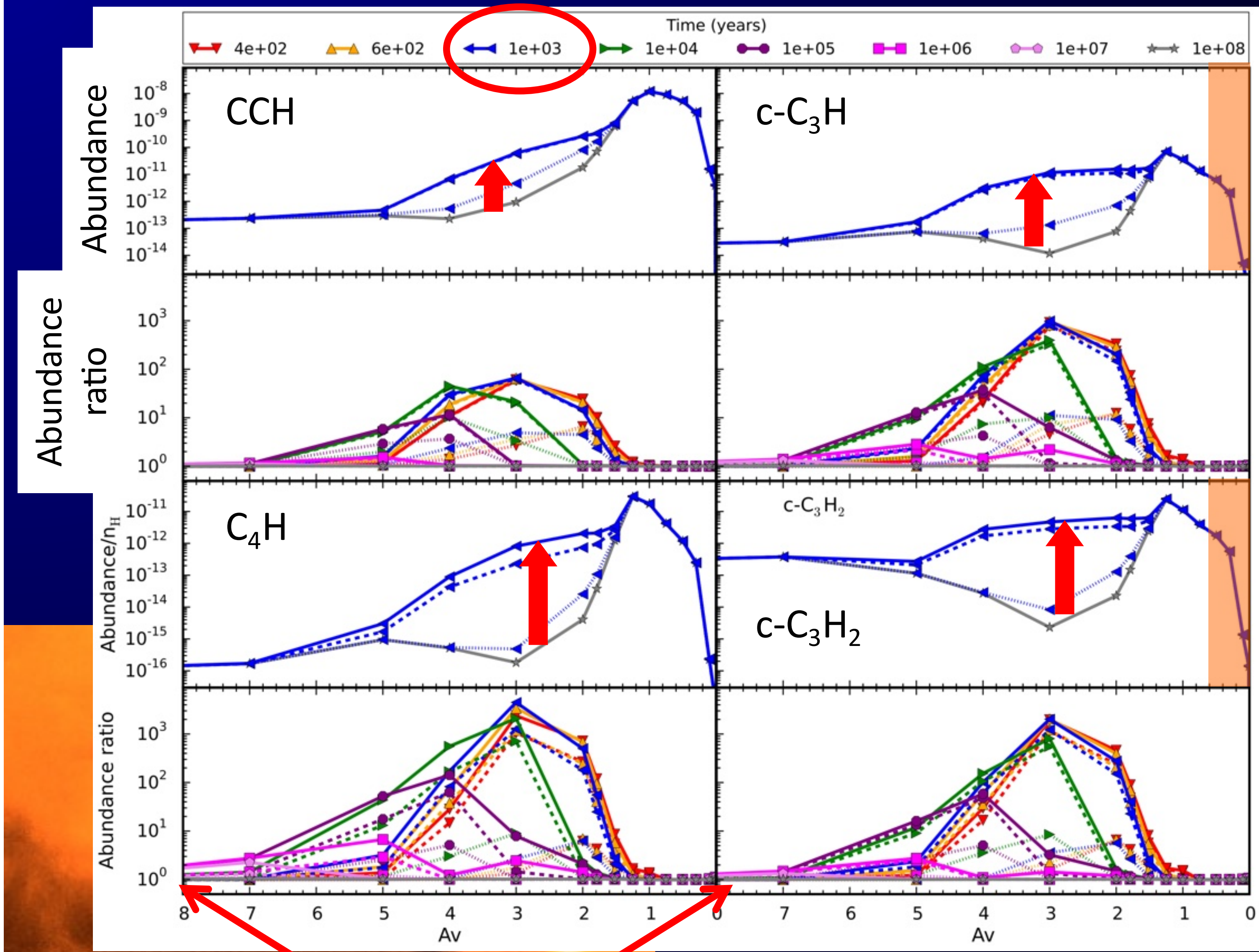
Chen et al. 2014; Cruz-Diaz et al. 2014

Photoproducts: H_2 and…



UHV

Alata, Jallat+ 2015



1st stage
Meudon PDR Code:

Le Petit et al. 2006

2nd stage
Code Nahoon:
Time dependent
Perturbation a-CH

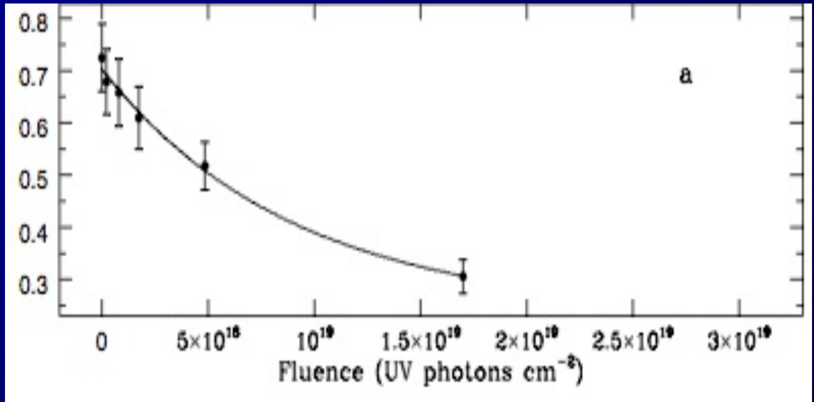
Wakelam 2006

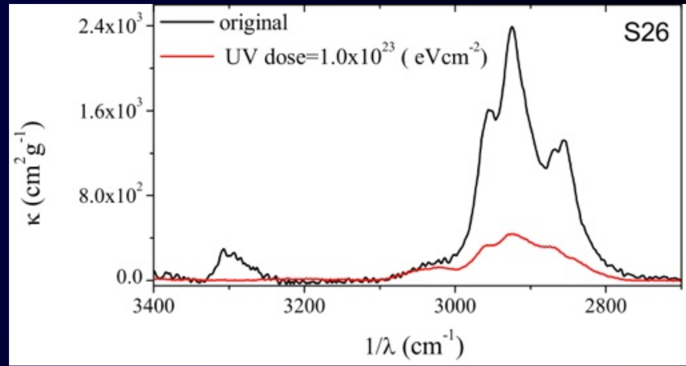
PDR speed of advective front : ~ 1 km/s

Jallat2015; Alata+2015

$d(0.5A_V) \sim 7.8 \times 10^{15}$ cm,
equivalent to $2.5\text{–}5 \times 10^3$ years

Laboratory VUV radiative environment simulations



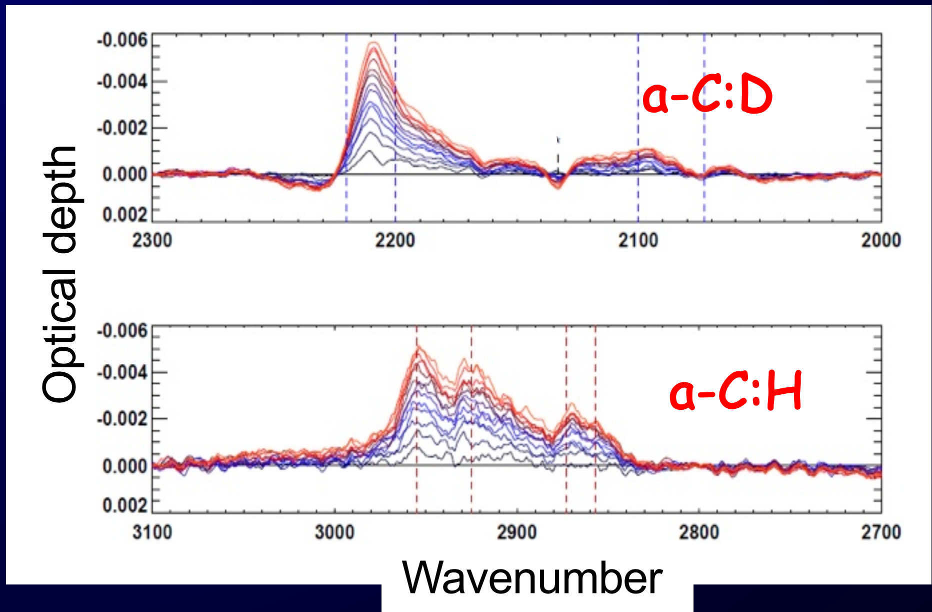


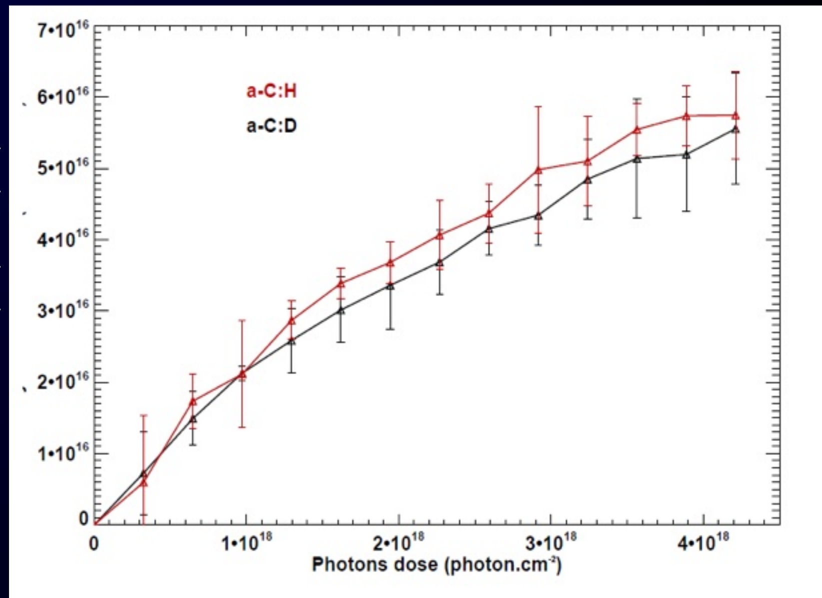
Mennella+1999, 2001 σ_{CH}(VUV) = 1 to 5 × 10^{-19} cm^2

σ_{CH}(VUV) ? Gadallah+2011,2013

HV

UHV





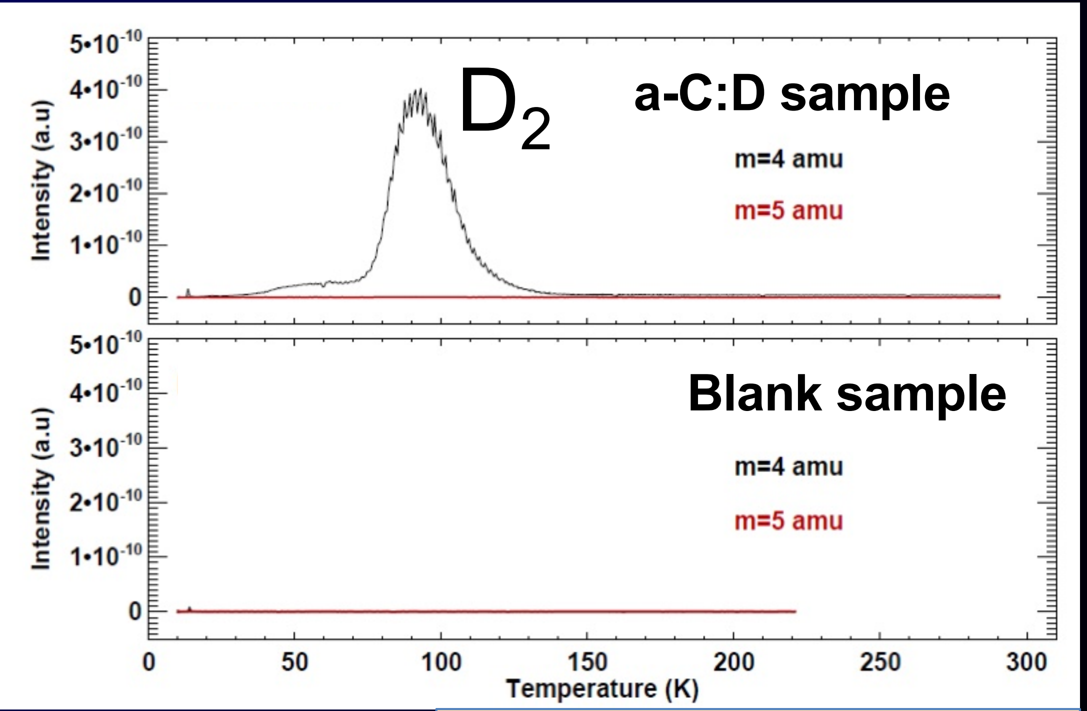
Alata+2014

destruction cross-section

σ_{CH}(VUV) = 3 ± 0.9 × 10^{-19} cm^2

Post irradiation TPD

5h irradiation then TPD 5K/min



Alata, Jallat+ 2015, Martín-Doménech +2016

Photolytic D_2 / H_2 formation rate

$$R_{\mathrm{f}}^{\mathrm{FUV}}[\mathrm{cm}^{-3}\,\mathrm{s}^{-1}] \approx \gamma_{\mathrm{H2}}\,\sigma_{\mathrm{CH}}^{\mathrm{des}}(\mathrm{FUV})\,\frac{n(\mathrm{CH})}{n_{\mathrm{tot}}}\,n_{\mathrm{tot}}\,\chi\,\phi^{\mathrm{ISRF}}(\mathrm{FUV})\,\mathrm{e}^{-\tau_{\mathrm{d}}}$$

CH abundance

extinction

Yield

Destruction cross-section

VUV photons flux

VUV Rate coefficient

$$R_{\mathrm{f}}^{\mathrm{FUV}}[\mathrm{cm}^{-3}\,\mathrm{s}^{-1}] = R_{\mathrm{c}}[\mathrm{cm}^{3}\,\mathrm{s}^{-1}]\;n(\mathrm{H})\;n_{\mathrm{tot}}.$$

VUV H_2 Rate coefficient

R_c [cm^{3}s^{-1}] ~ 10^{-14} $f(C)_{aCH}$ $\chi/n(H)$ $e^{-\tau_d}$

With 5-10% C locked into a-C:H &

PDR: $\chi/n(H)$ up to 0.25 → R_c up to 1.25-2.5 10^{-16} cm^{3}s^{-1}

Table 3. Temperatures of dust and gas and H_2 formation rates.

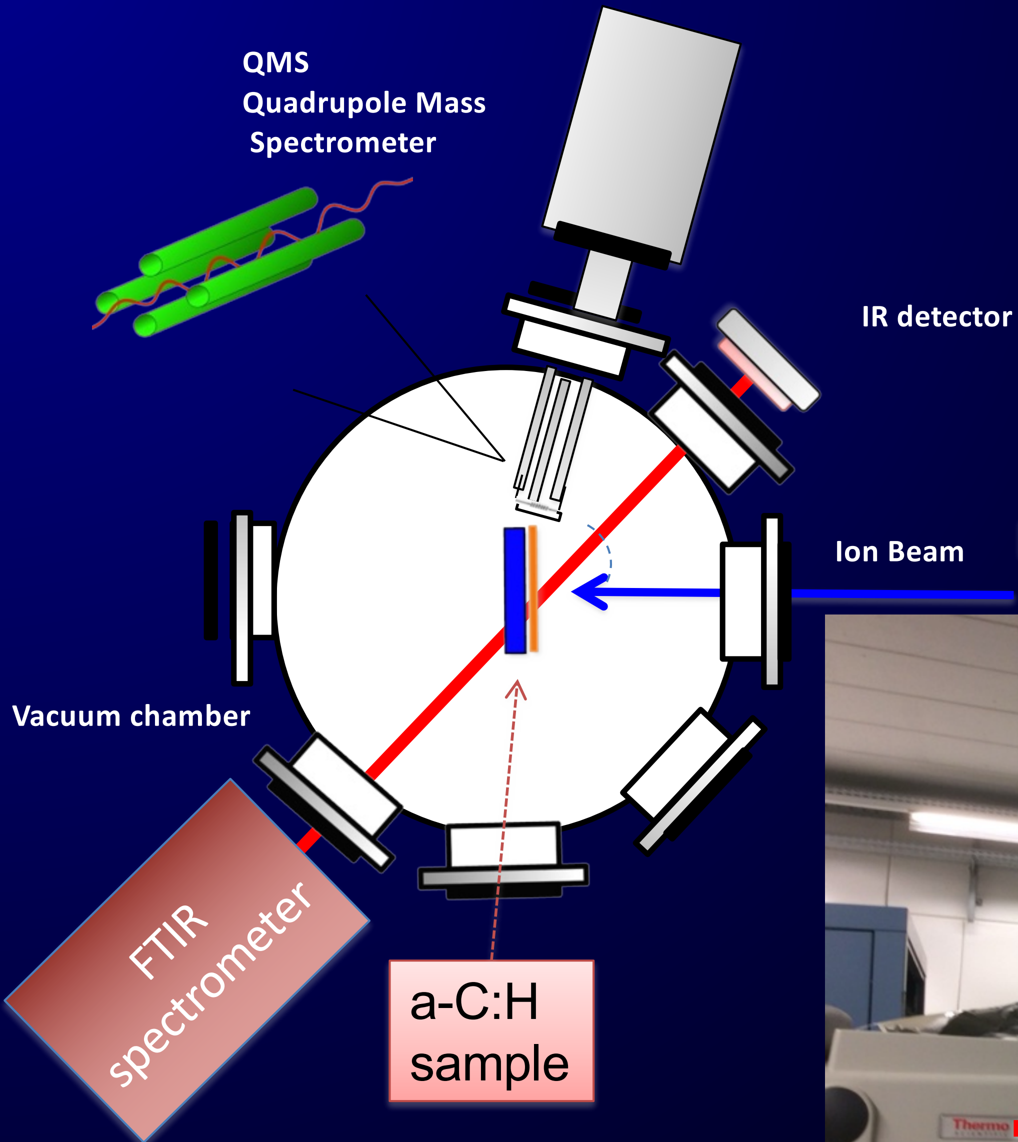
Region	T^a_{SGs} (K)	T^a_{BGs} (K)	T^b_{gas} (K)	R_f^c (cm^3 s^{-1})
Chamaeleon	>2.7	15	60	4×10^{-17}
Oph W	10	36	330	1.5×10^{-16}
S140	10	36	500	1.5×10^{-16}
IC 63	12	44	620	1.5×10^{-16}
NGC 2023	25	60	330	3×10^{-17}
Orion Bar	62	90	390	3×10^{-17}

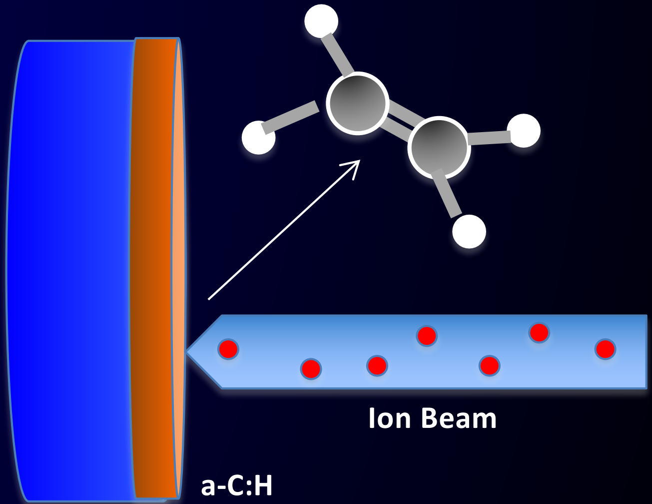
Habart+ 2004

No Langmuir–Hinshelwood
Low T limitation

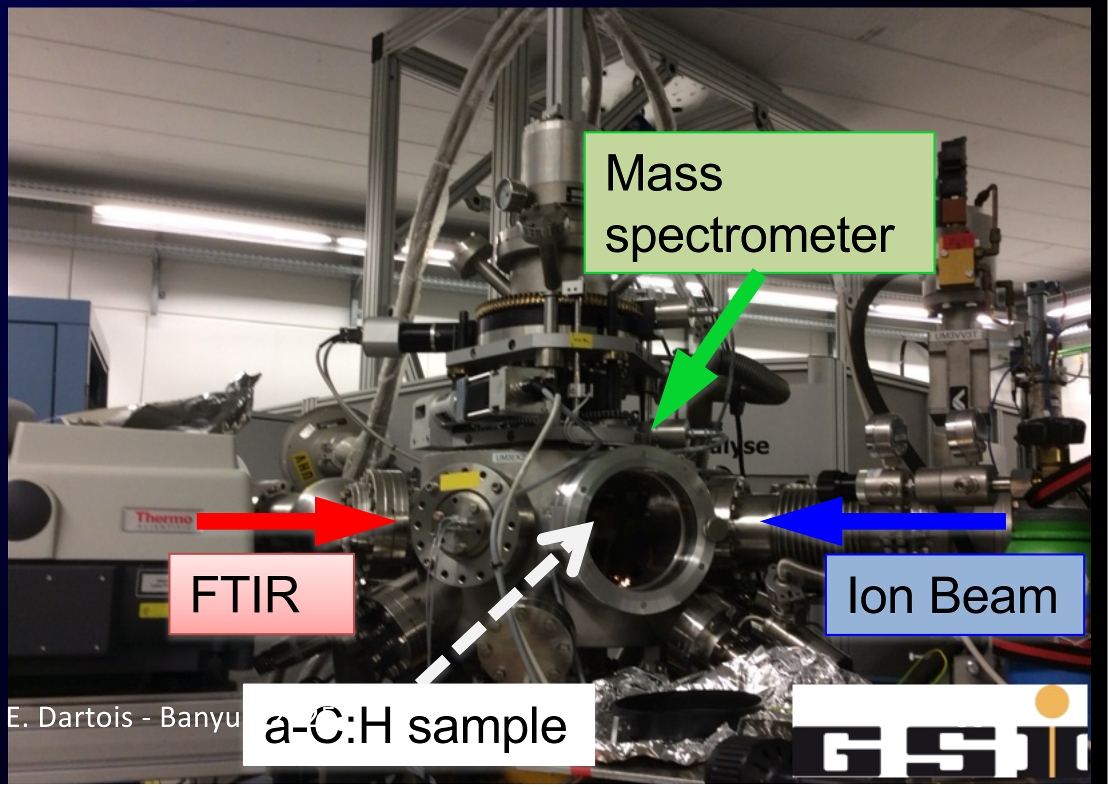
Provides high H_2 formation rates at low to high grain T, as long as a-C:H grains are present

Cosmic rays environment simulated in the laboratory



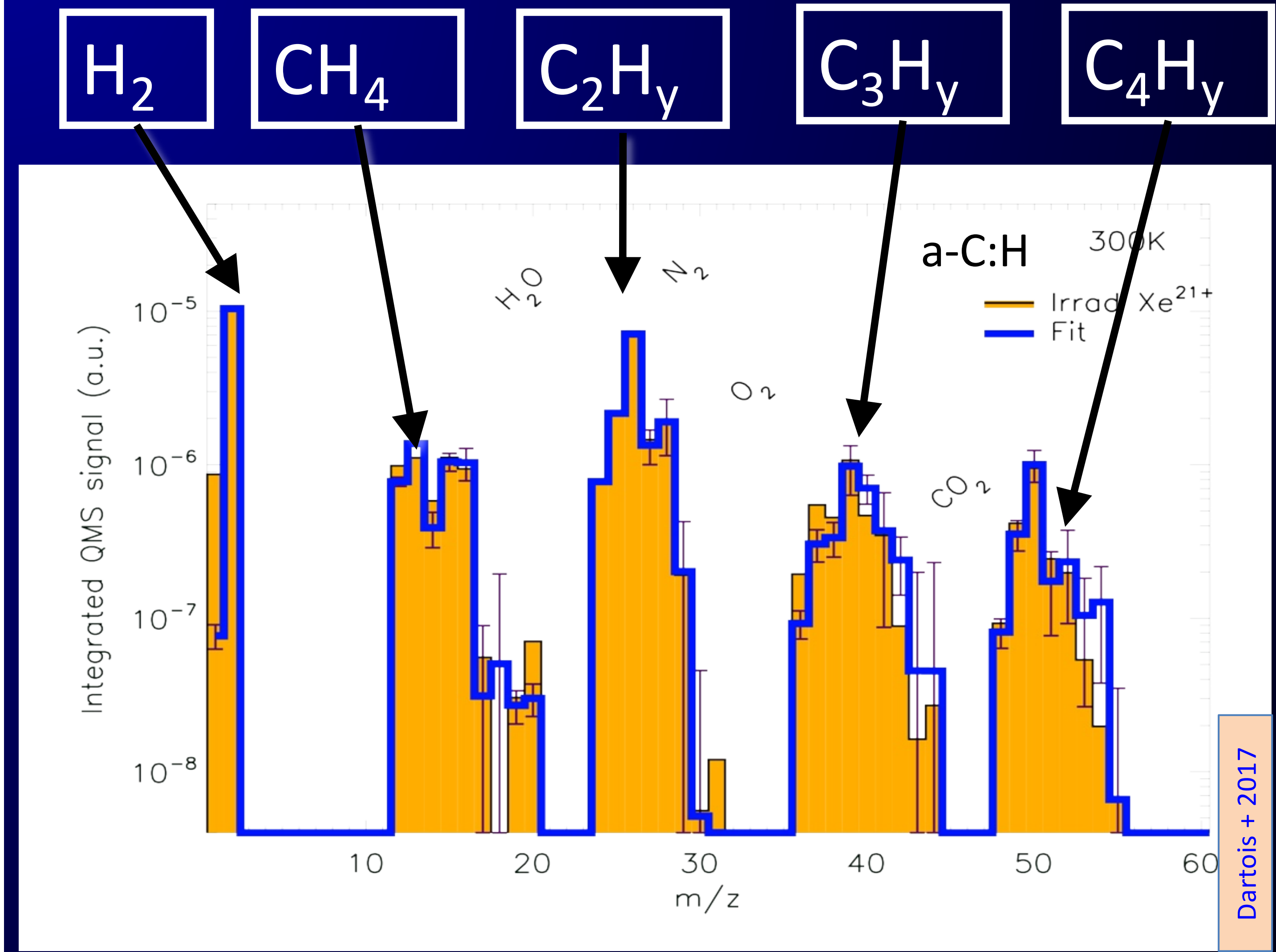


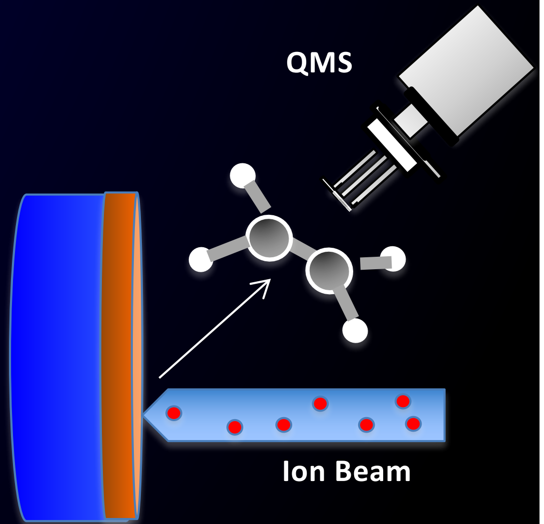
M-branch-3 @ GSI (Darmstadt)



Irradiation @ T=25-300 K

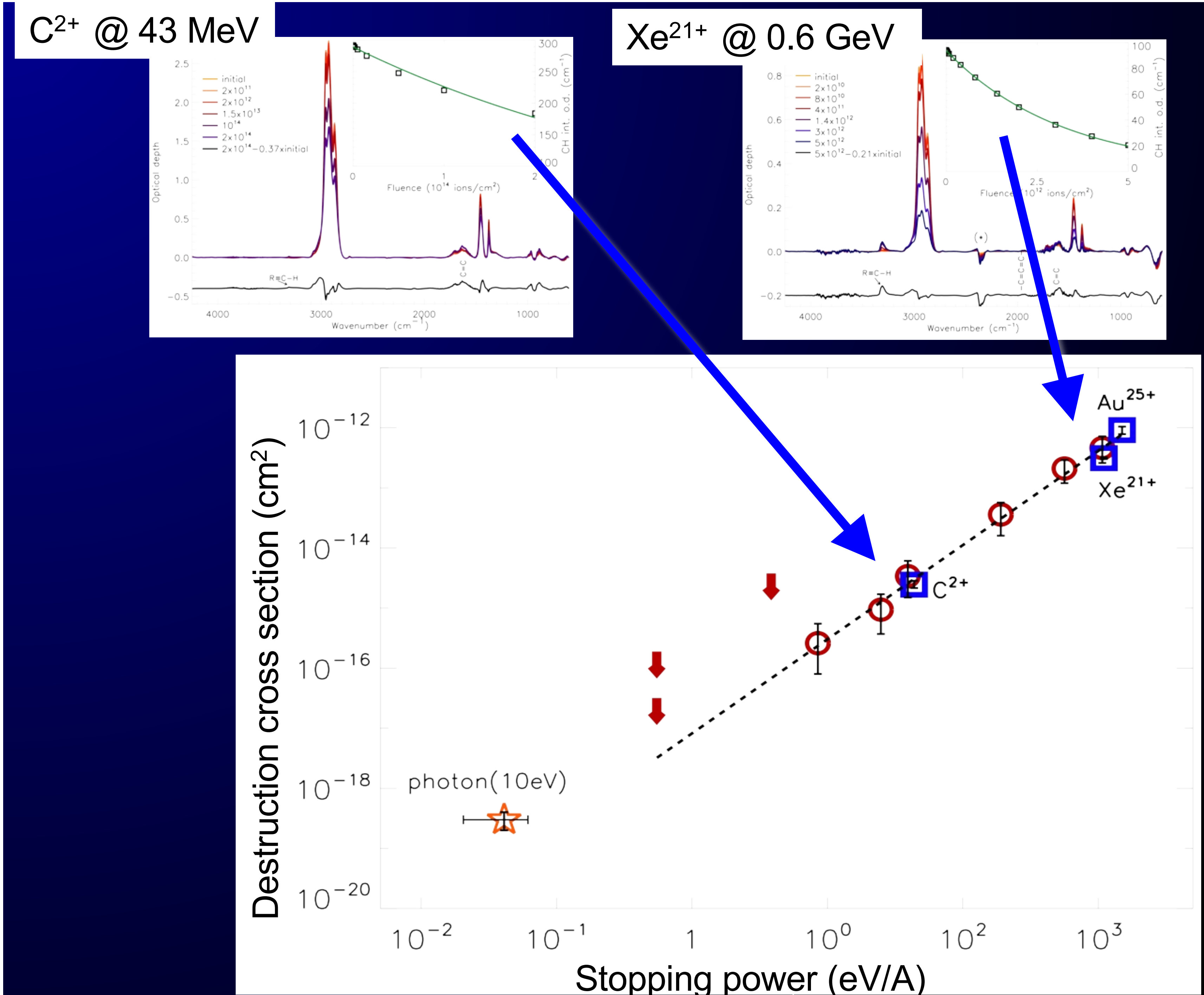
+ TPD 5K/min



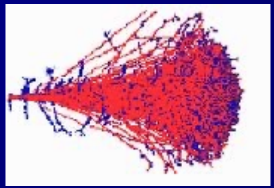


Species released by interaction with CRs

Interstellar chemistry « Top down » feeding the ladder of high C # species

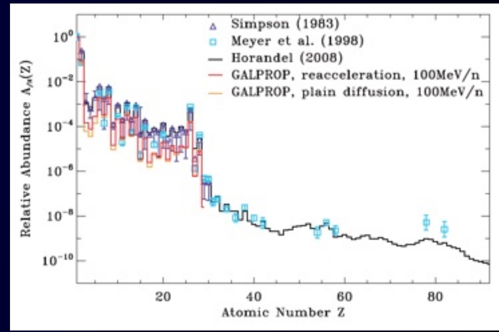

C2+ @ 43 MeV
Xe21+ @ 0.6 GeV
Destruction cross section (cm2)
Stopping power (eV/A)
photon(10eV)
Au25+
Xe21+
C2+

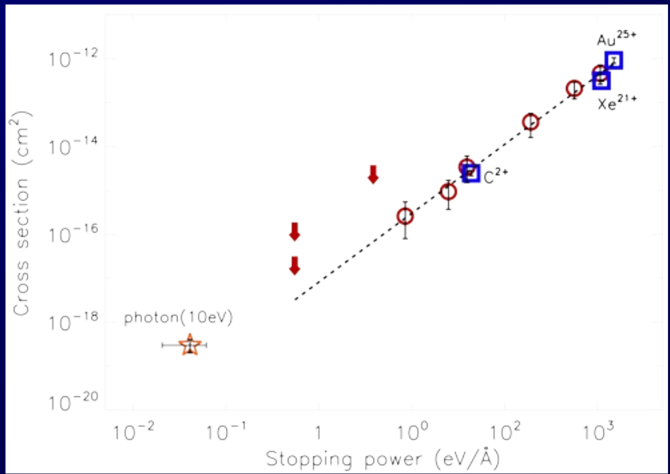
Implementation in astrophysical models



Se(Z,E)

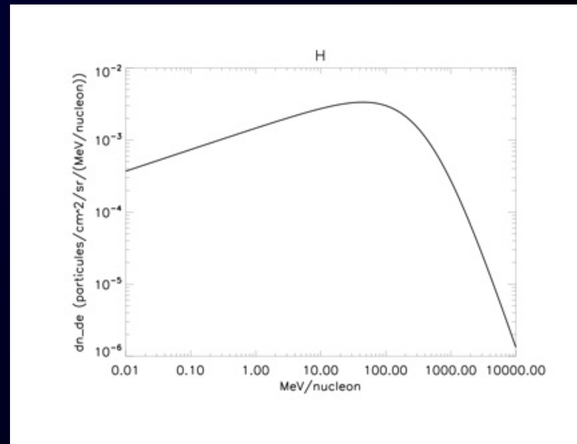
f (Z)





σ (Se)

Φ(Z,E)



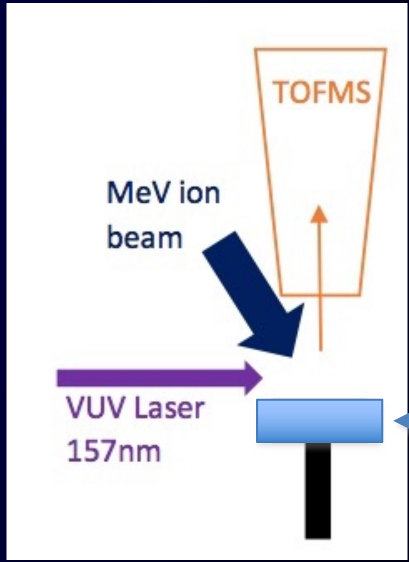
Destruction rate:

$$R_d^{GCR}[s^{-1}] = 4\pi \sum_{Z} \int_{E_A^{MIN}} \sigma_d^{CR}(E_A)\, f(Z)\, \Phi(E_A,Z)\, dE_A$$

Destruction time scales several tens to thousands My

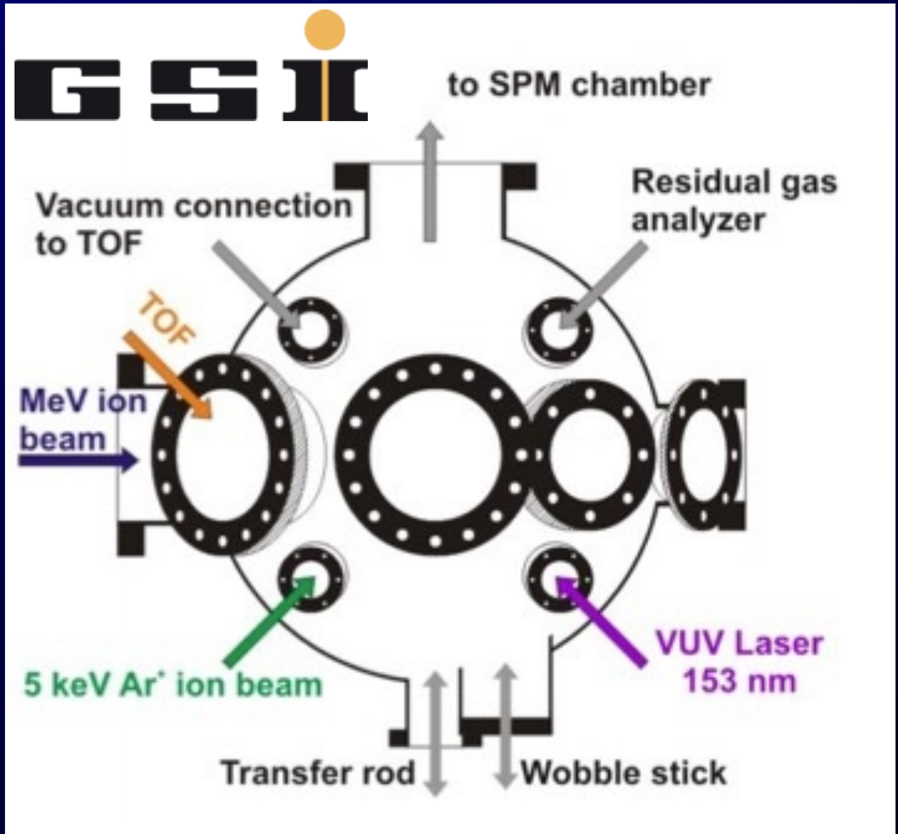
CRs simulated in laboratory

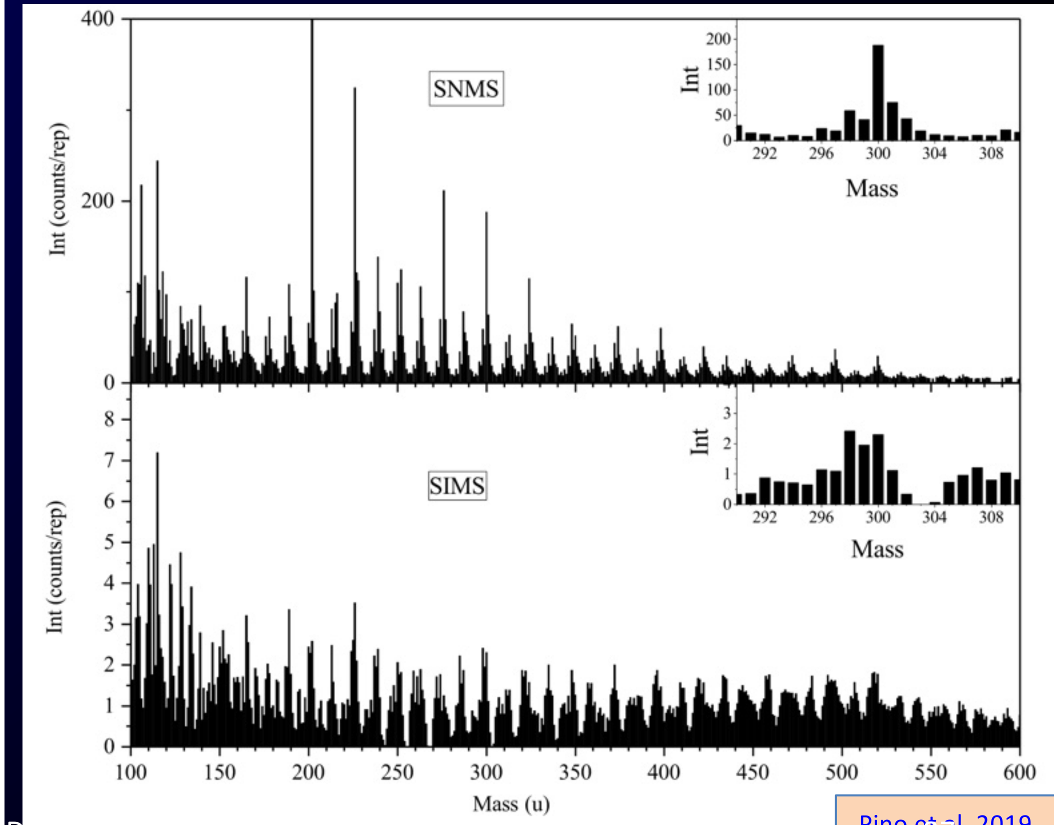
QMS do not see easily the reactive species
Detect reactive/unstable species and more complex (n_C>>5)



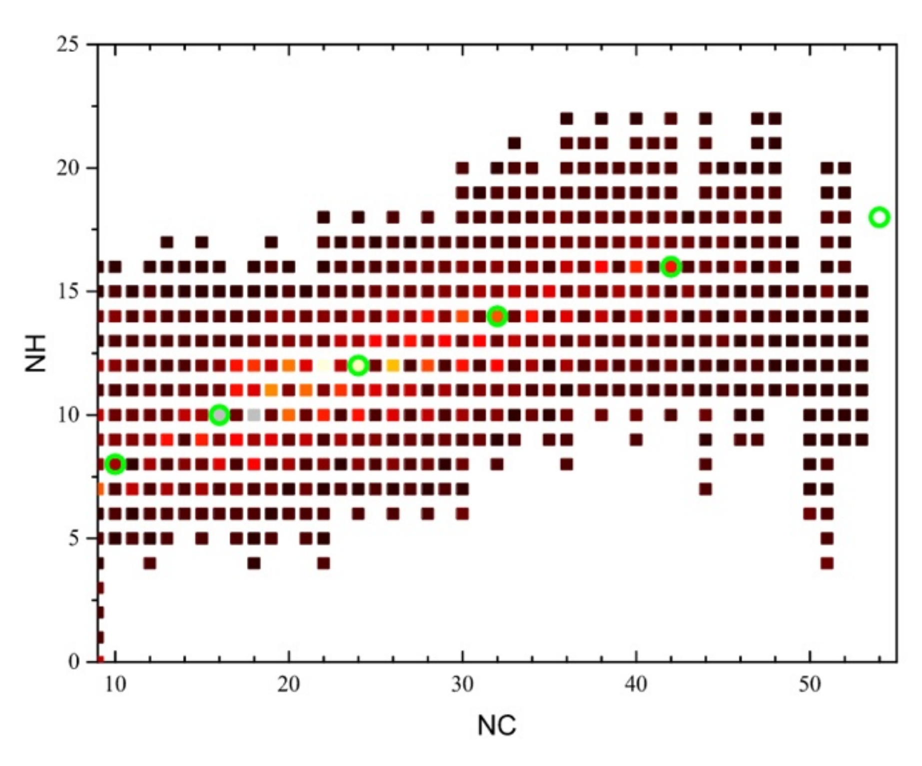
Analogue

Experiments @ GSI (Darmstadt)

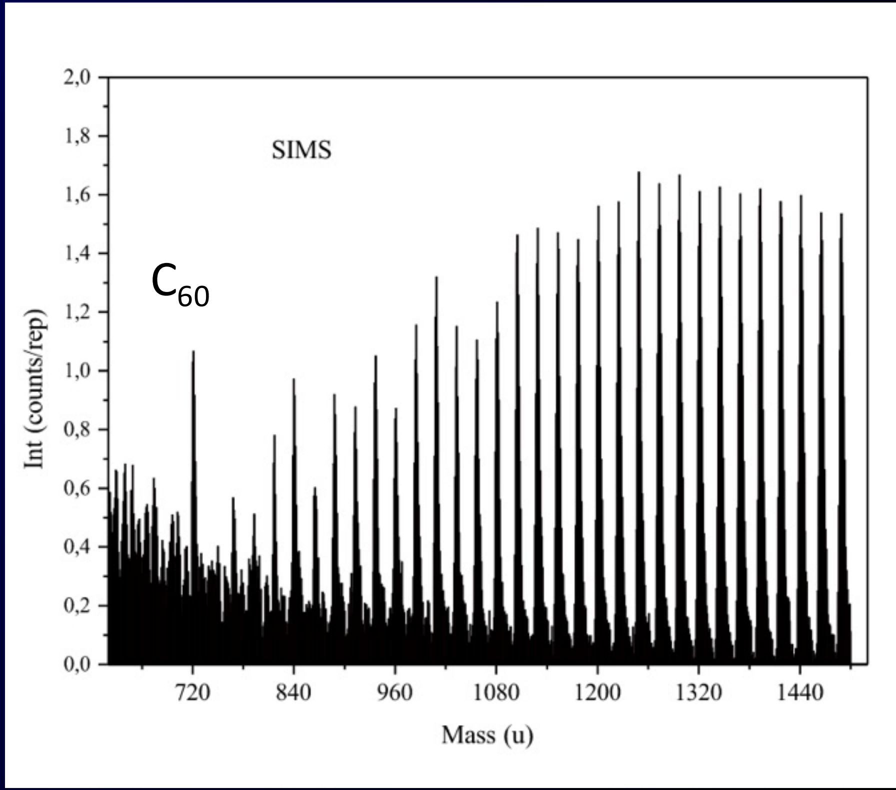




Pino et al. 2019



Neutral PAH mass range
open green circles = compact PAHs up to circumcoronene.
Lower H content = partially dehydrogenated fragments,
higher H probably less compact structures

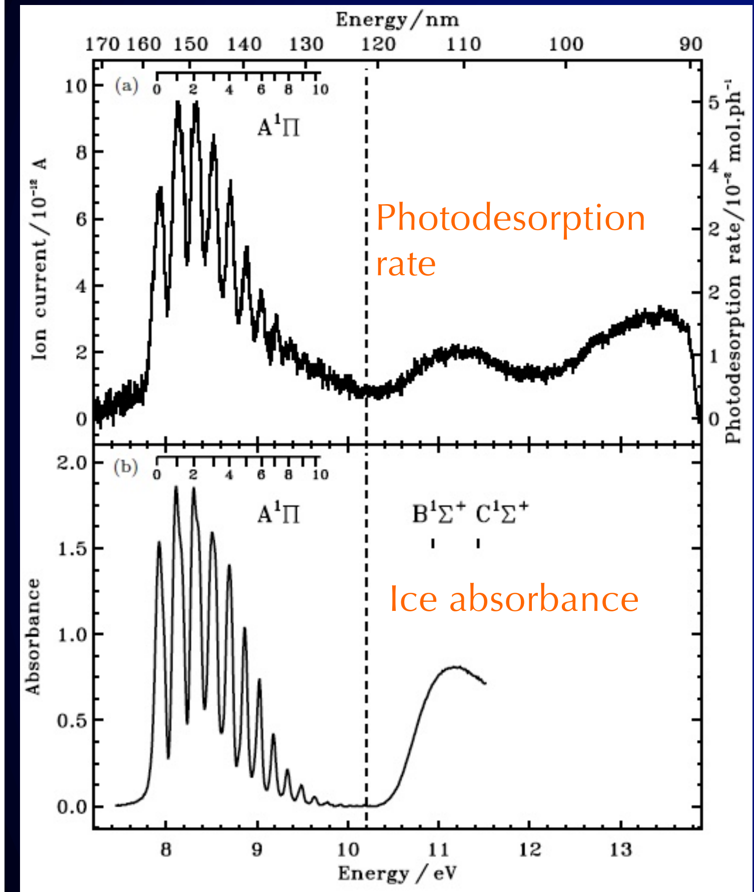


SIMS in the mass range above 620 u.

Pino et al. 2019

VUV photons desorption

Wavelength dependent measurements point that photodesorption is induced by electronic transitions



Fayolle et al. 2011

CO 8×10^{-2} to 10^{-3} per hν

Oberg+ 2007, Muñoz Caro+2010,2011, Fayolle+2011, Bertin+2012, Chen+2014

$CO, N_2, O_2, CO_2, H_2O, H_2CO, CH_3CN, CH_3OH$

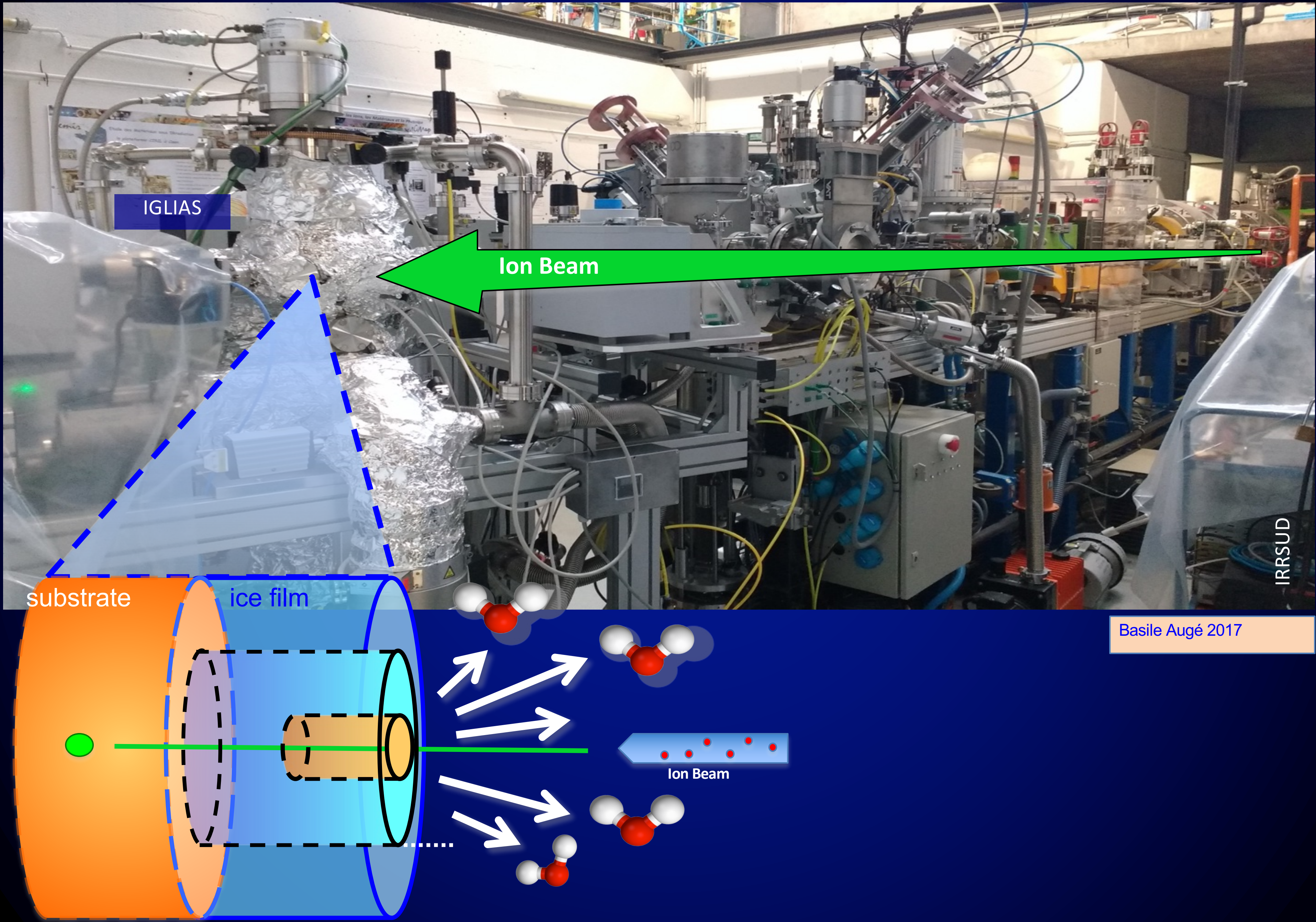
measured with efficiencies in the 10^{-2}-10^{-5} / impinging photon range

Féraud+2019, Cruz-Diaz+ 2018, Cruz Diaz+ 2016, Bertin+ 2016, Muñoz Caro+2016, Martín-Doménech+2015, Arasa+2015, Fillion+2014, Chen+2014, Andersson+2014, DeSimone+ 2013, Yuan+2013, Fayolle+2013, Zhen+2013, Bertin+2012, Bahr+2012, Fayolle+2011, Muñoz Caro+2010,2011, Oberg+ 2009, Westley+1995…

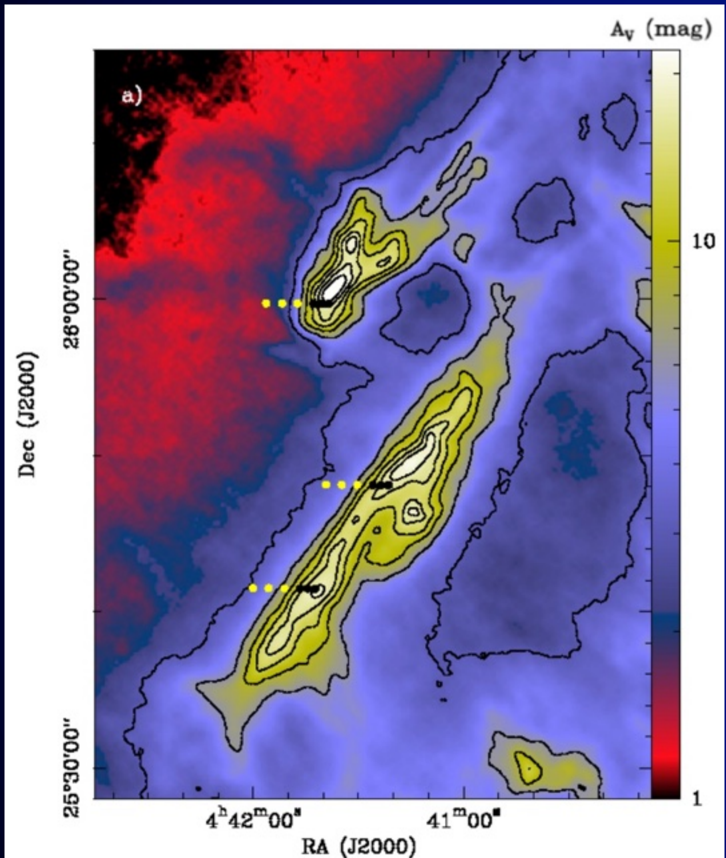
In YSOs envelopes, for 10^4 hν cm^{-2} s^{-1}
CO rate (10^{-3}) of ~10 molecules cm^{-2} s^{-1}
CH_3OH rate (~ 10^{-5}) of ~0.1 molecules cm^{-2} s^{-1}

Efficient at the border of clouds, inside provide a few per thousand/percent gas phase injection

Measuring CR sputtering with IR:



Taurus Molecular cloud (TMC-1)

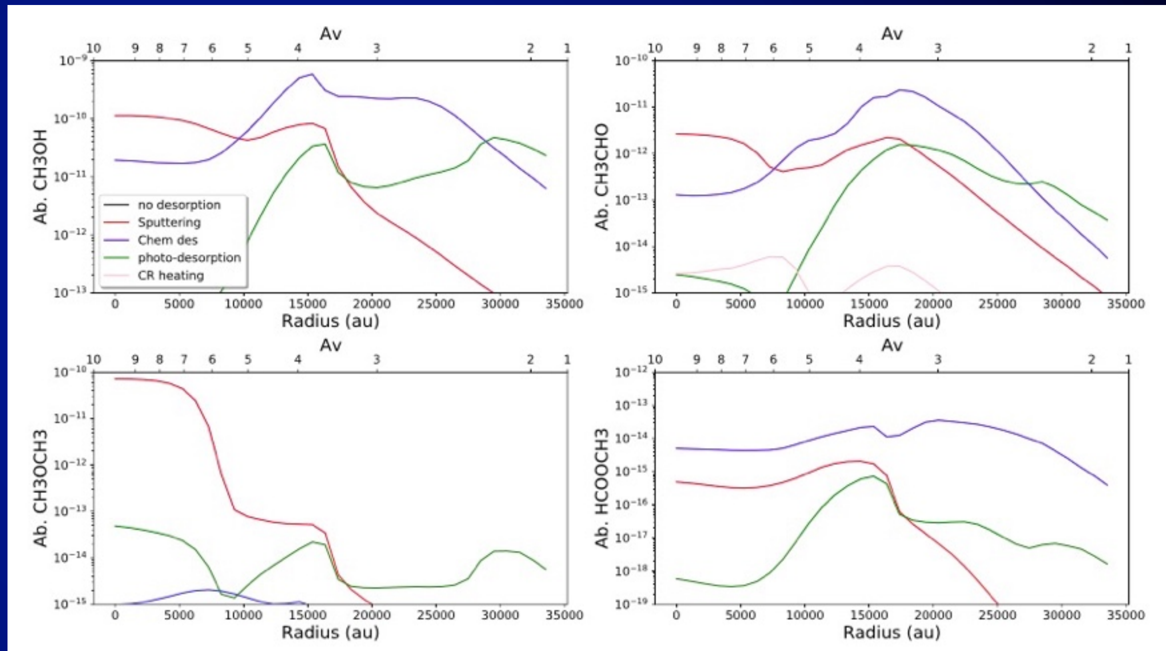


Rodriguez-Barras+2021

Abundance of COMs @ 6×10^5 yr

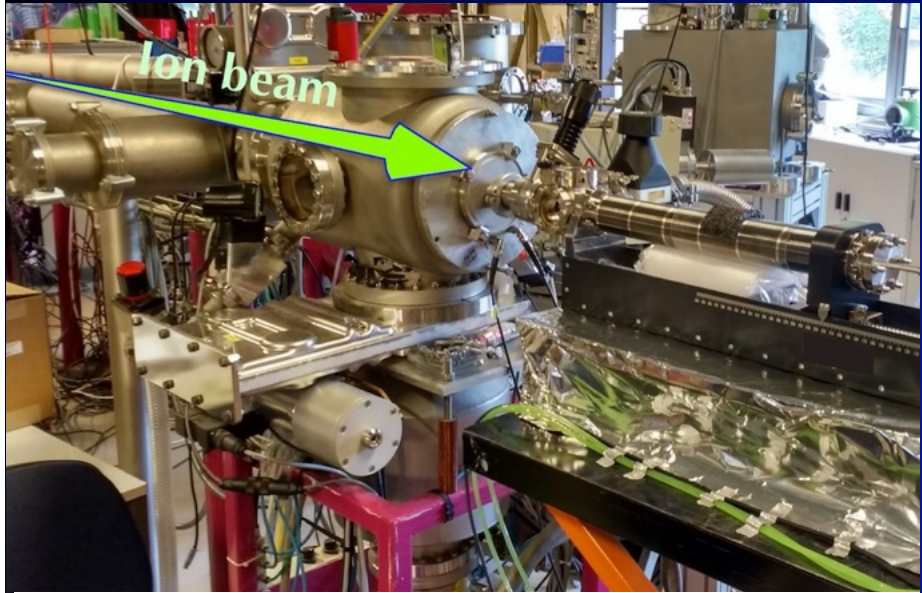
CH_3OH

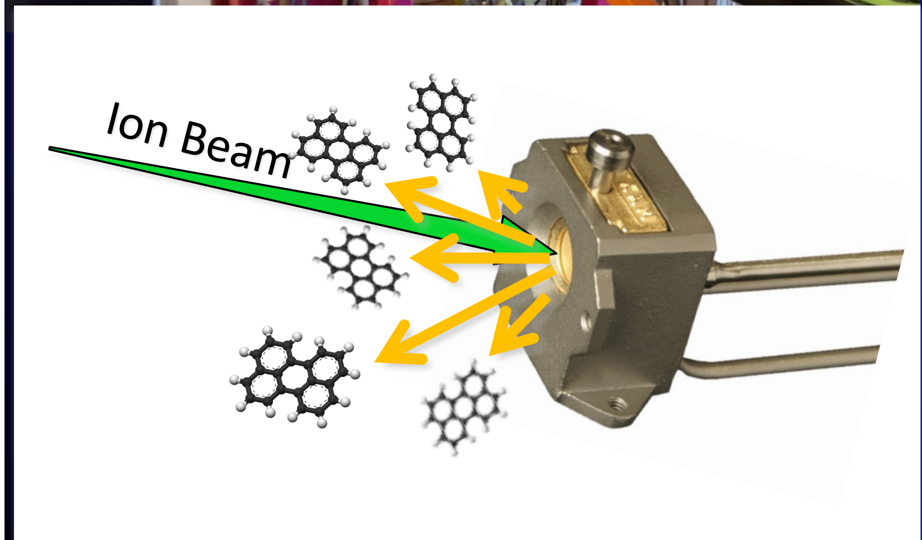
CH_3CHO



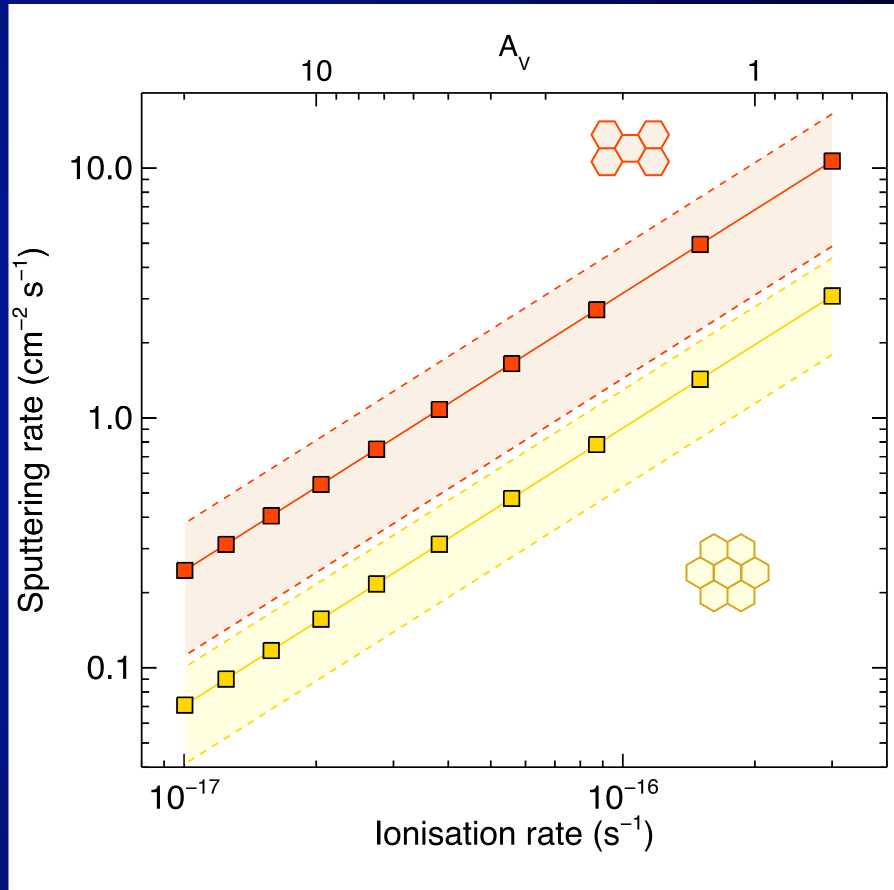
CH_3OCH_3

Wakelam+2021





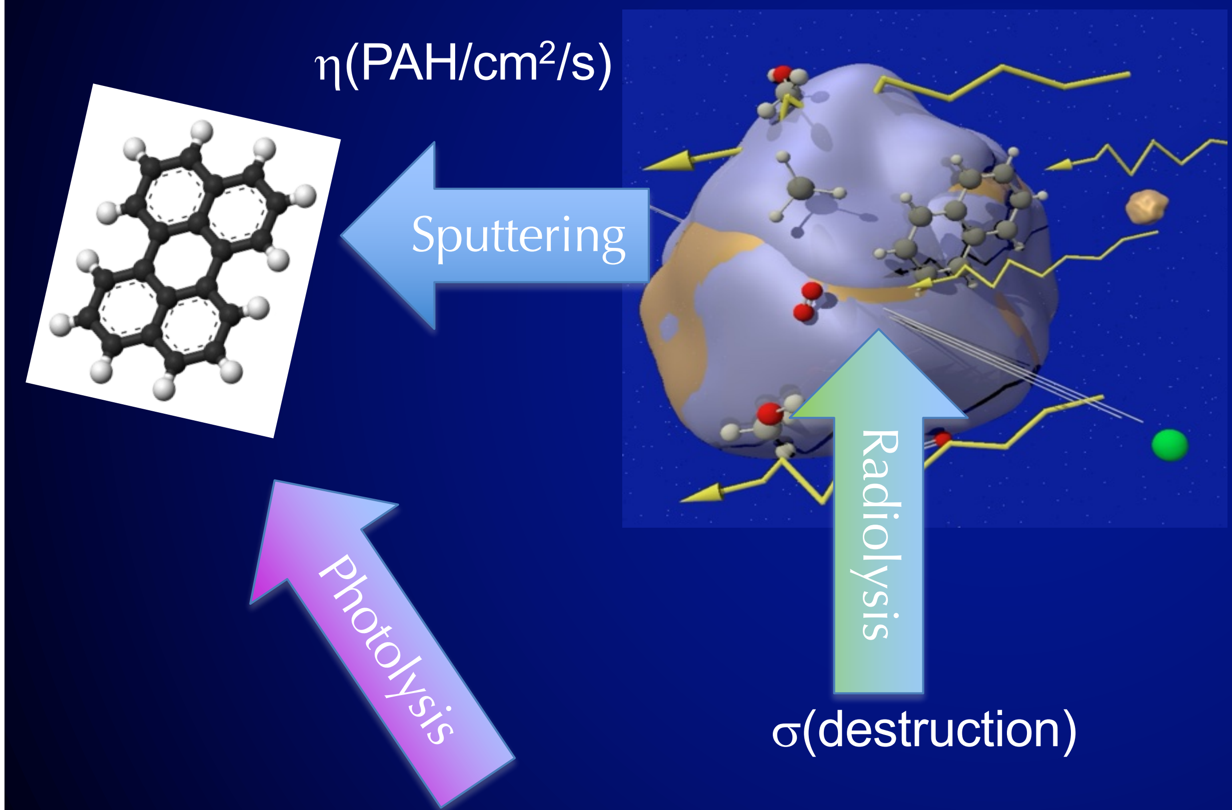
What about very large species ?



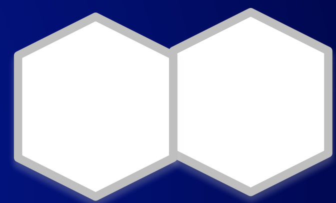
Dartois+2022

Which abundances are needed for observations?

Implementation in a simple astrophysical model

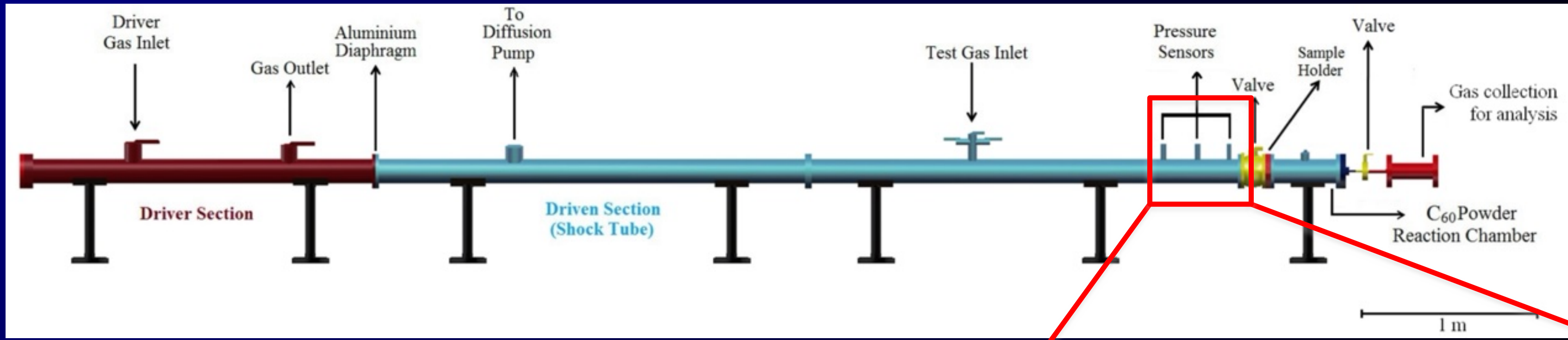


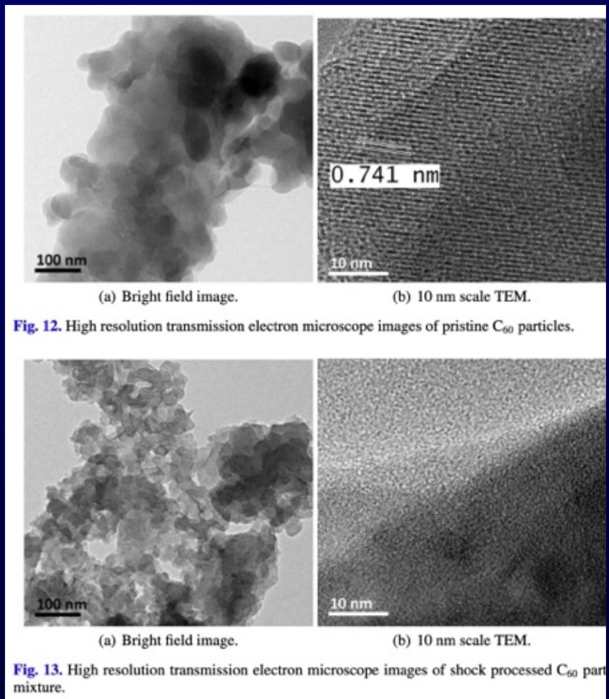
Extrapolated to

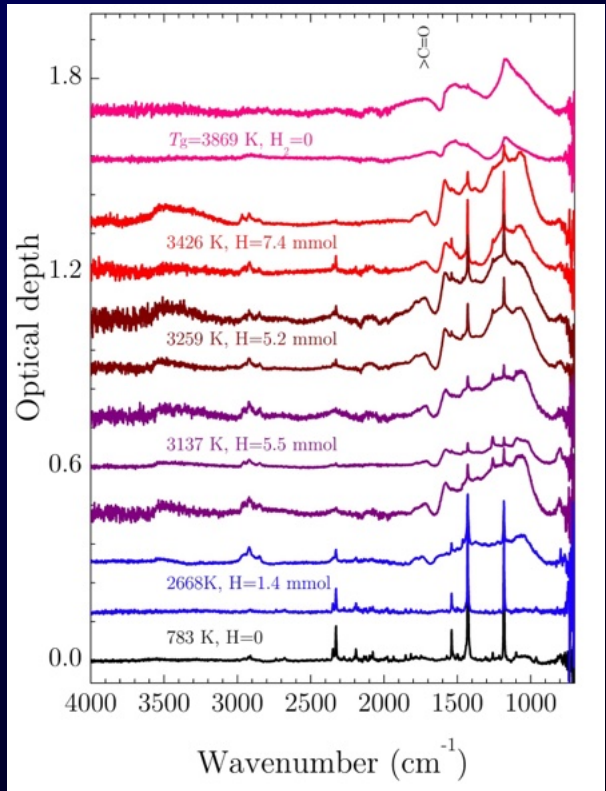


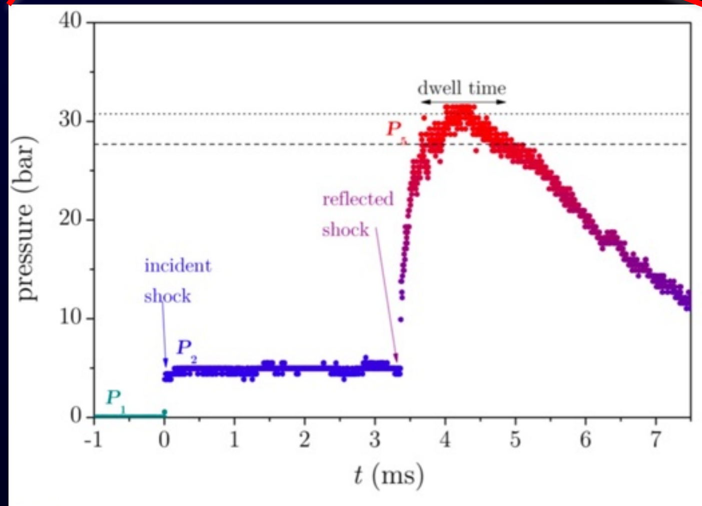
f_{gas}(naphthalene) = $1.9 - 3.2 \times 10^{-7}$ f_{solid}(naphthalene)

Shock processing of carbonaceous dust: e.g. C60







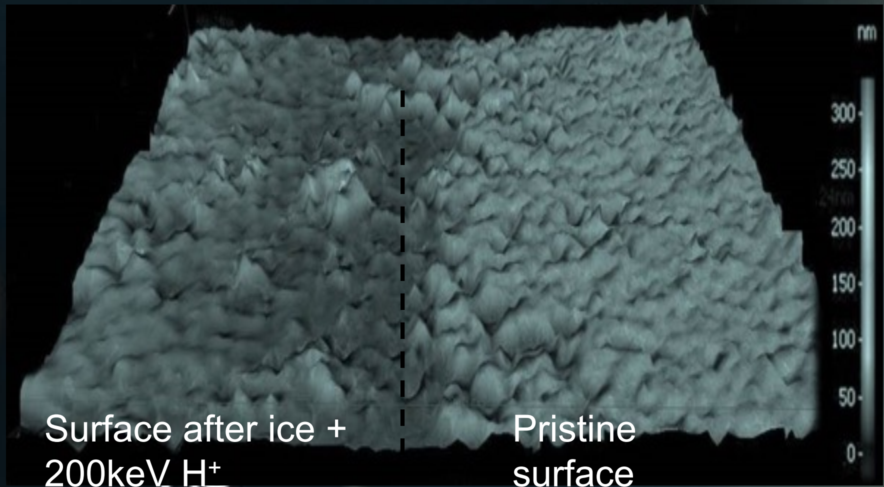


Biennier et al. 2017

Heliopause

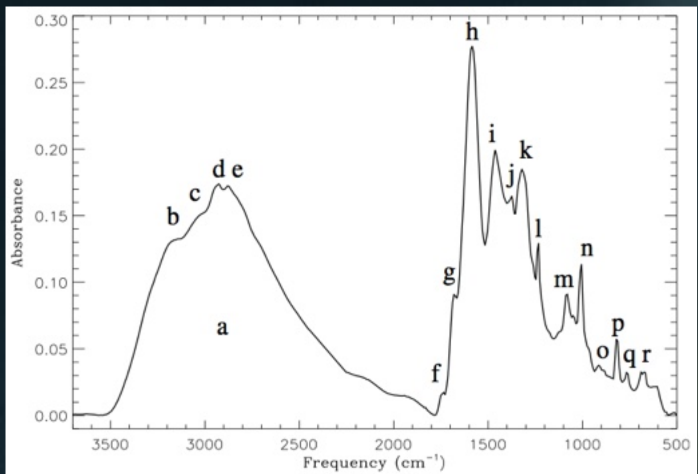
100

1000

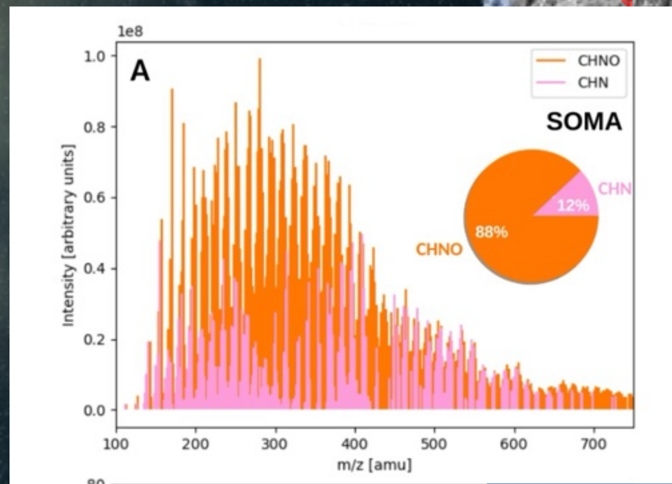


Sabri+2015, Jaeger+2020, Mennella+2003

Do chemistry in SFRs and UV-ions induce modifications of ice covered grains? Role of interfaces



Formation of macromolecular residues incorporated during the late stages of SF ? The PPD ?



Munoz Caro+ 2002, Greenberg+1995, Bernstein+1995, Munoz Caro+ 2003, Nuevo+ 2006+2008+2009, de Marcellus+2011, Cottin+2011, Ciesla+2012, Danger+2013+2016+2020, Theulé+2013, Meinert+2016

Danger+2022

Laboratory experiments for gas, grains, detections, interactions, energetic processes

Process		Constraints ?
(Identifications)		Spectroscopies (From VUV to mm)
Low T gas phase reactivity		Chemical diversity (models)
Excitation (collisions, UV pumping,…)		Direct/models
Surface reactions		UHV(lab), Indirect, composition evol
Cosmic rays	Radiolysis	Specific radicals, ions?
	Sputtering (CR desorption)	Indirect, gas chemistry?
VUV	Photolysis (*, ambiant, RC induced)	Ions?
	Photodesorption	Indirect, gas chemistry?
Radical Recombinaison		Release ?
	Chemical desorption	
Thermal evolution		Band profiles (solids)? Chemical diversity (gas)?