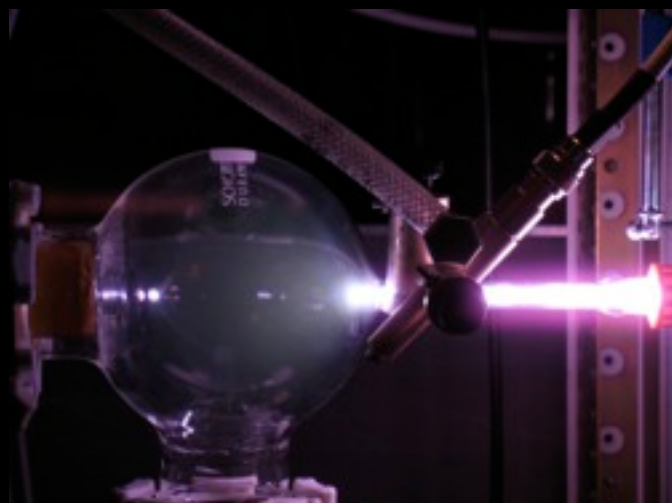
PCMI INSU

PHYSIQUE et CHIMIE du MILIEU INTERSTELLAIRE
Colloque général
19-21 novembre 2012
Paris

Colloque PCMI

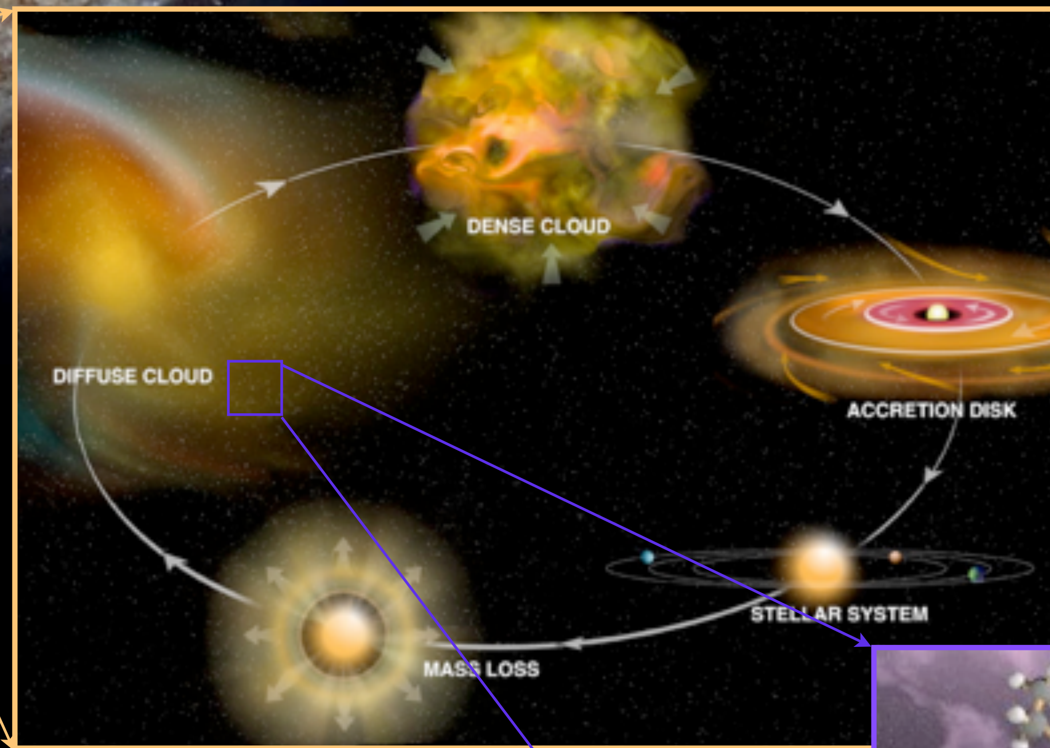
21 Novembre 2012

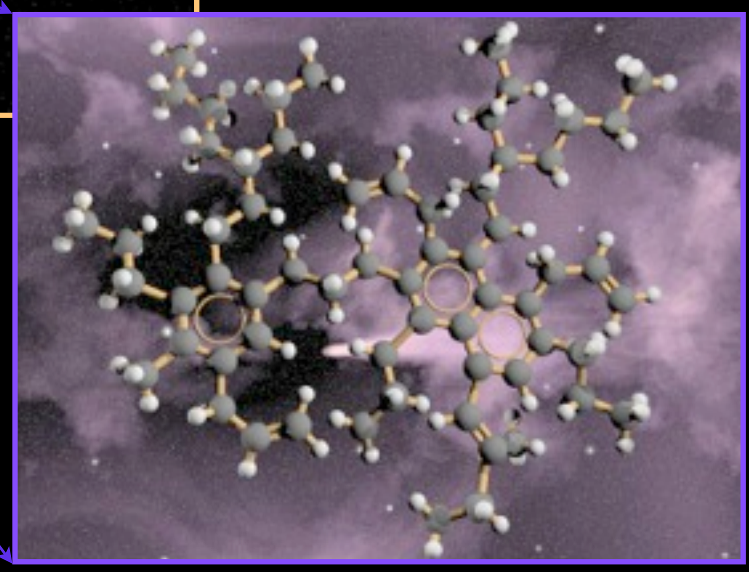
Effects of cosmic rays on hydrocarbon interstellar dust



Marie Godard, Géraldine Féraud, Marin Chabot, Yvain Carpentier, Thomas Pino, Rosario Brunetto, Jean Duprat, Cécile Engrand, Philippe Bréchignac, Louis d'Hendecourt, Emmanuel Dartois.

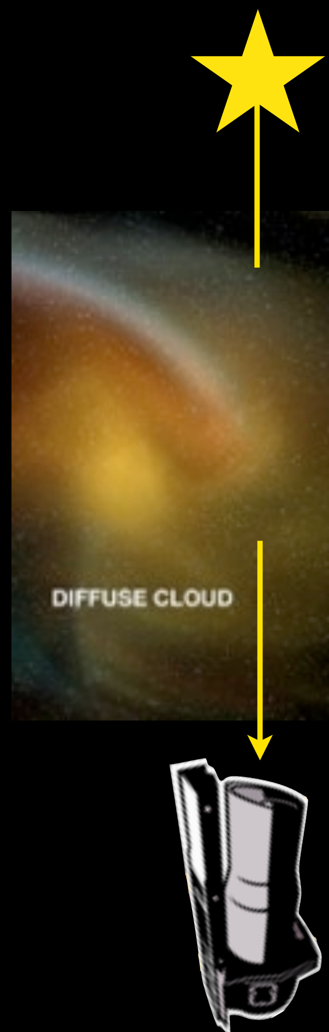
Goddard SPACE FLIGHT CENTER · NASA · IAS · ISMO · CSNSM · IPN Orsay

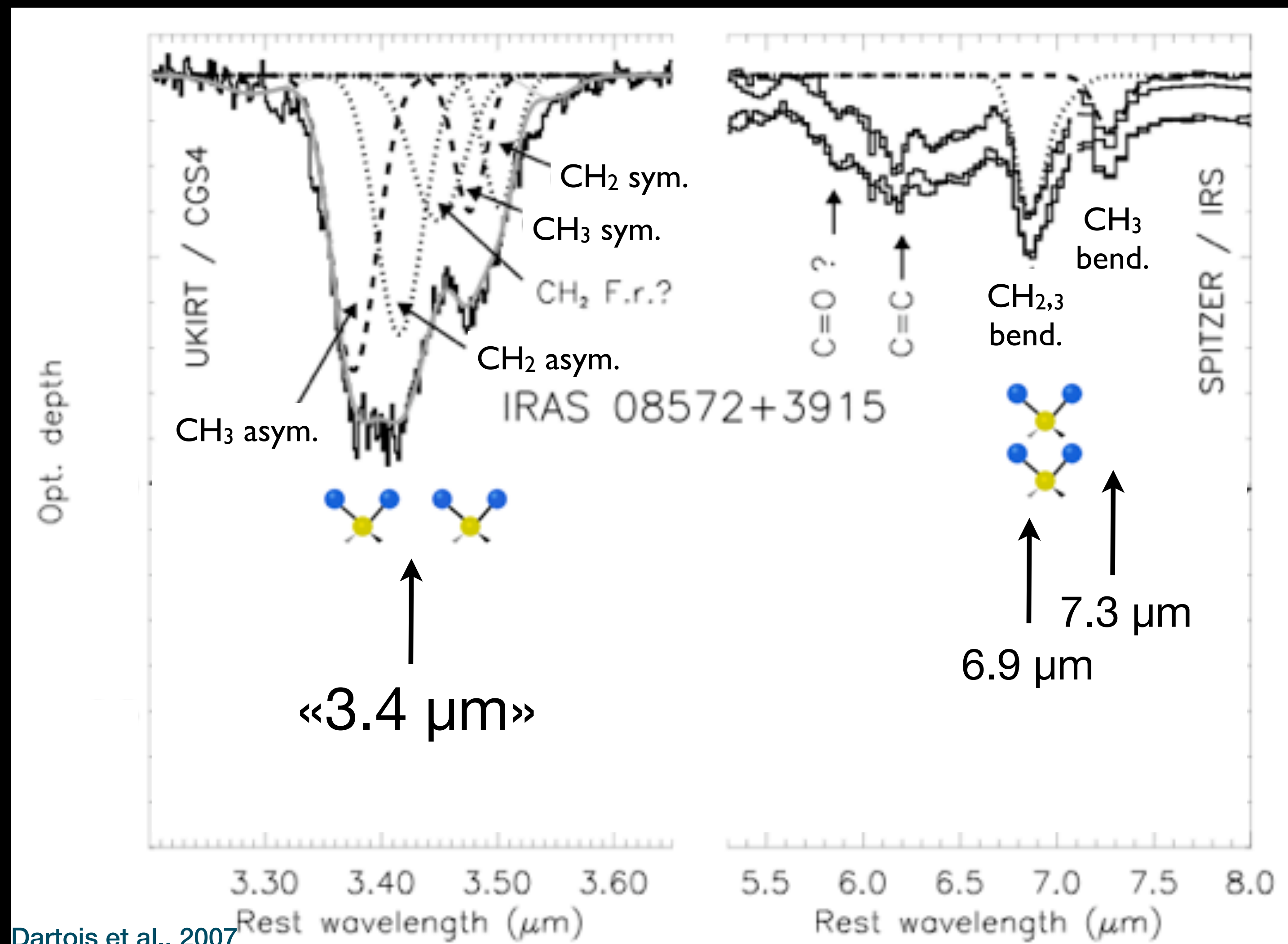




Hydrogenated amorphous carbons (**a-C:H** or **HAC**) :
➫ Important component of carbonaceous interstellar dust
➫ Observed in **diffuse interstellar medium**

Spectral signatures of interstellar a-C:H





Signature of **aliphatic C-H vibrations** of interstellar carbonaceous dust

Evolution of the 3.4 µm band carriers in the interstellar medium

Observation of the 3.4 µm band

3.4 µm band not observed

<u>Evolution of dust due to:</u>

UV irradiation

Hydrogen atoms exposure

Cosmic rays irradiation

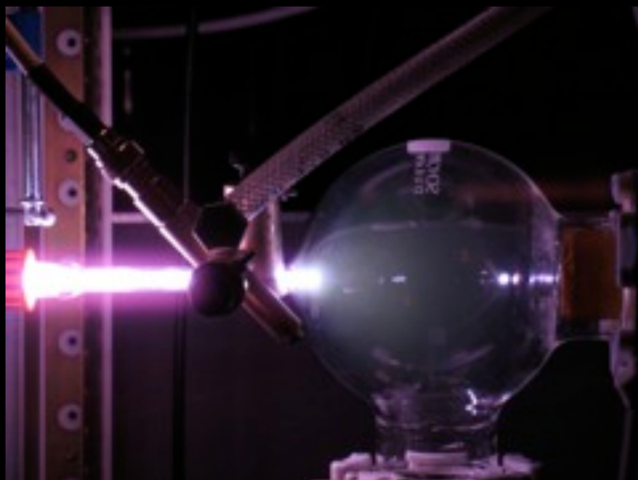
...

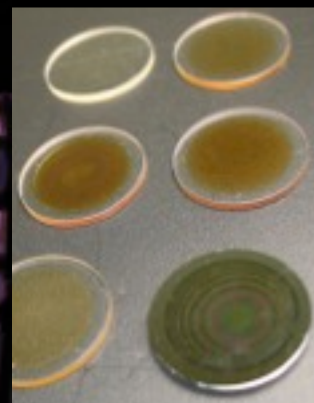
Aims :

⇨ Evaluate the processing of interstellar aCH and their spectral signatures by exposure to cosmic rays

Irradiated samples

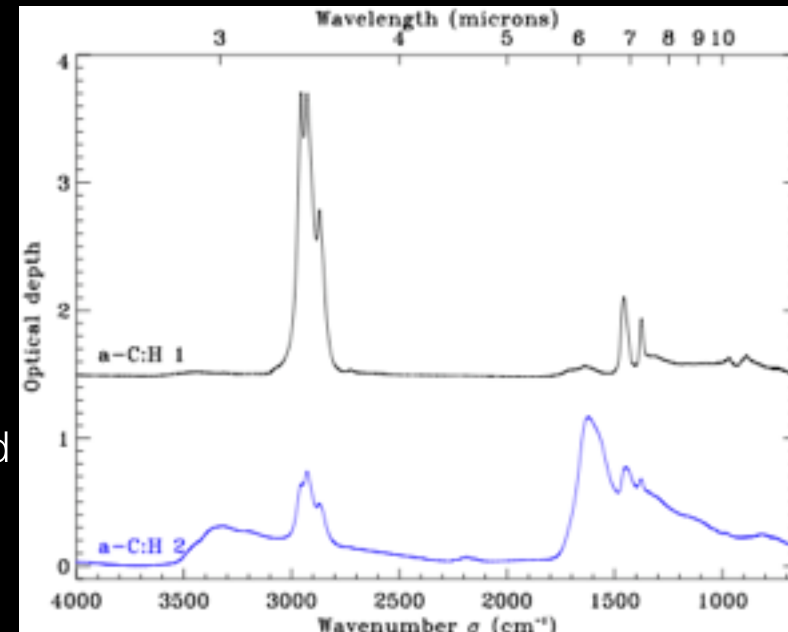
a-C:H



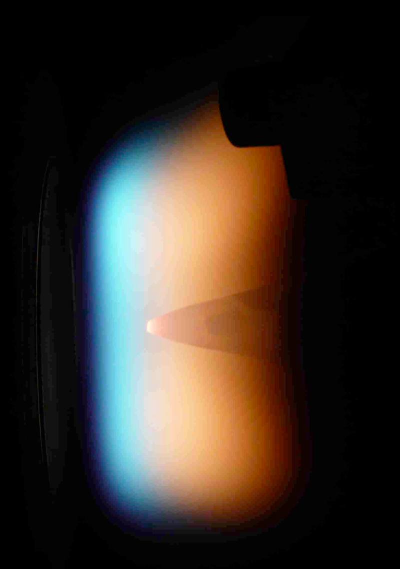


H/C ~ 1

Highly aliphatic, highly hydrogenated materials

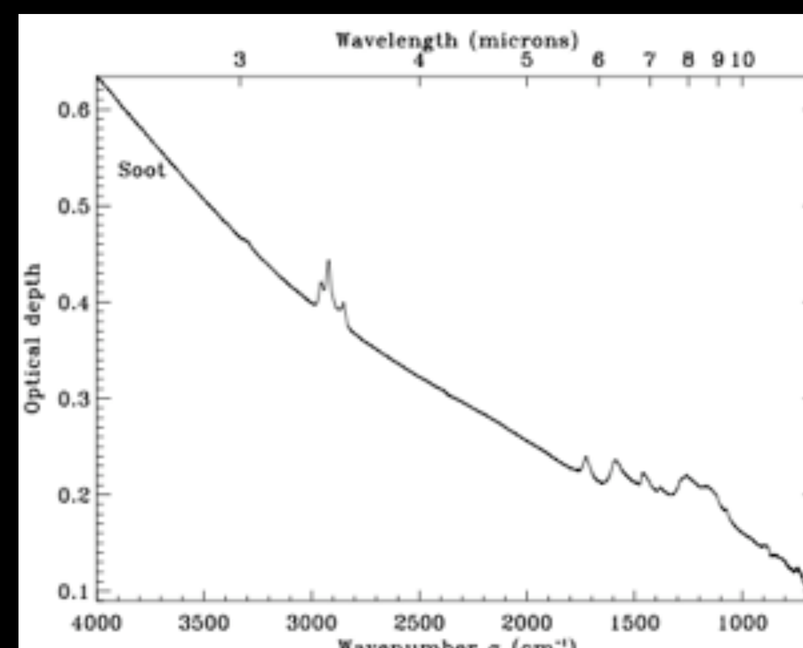


Soot



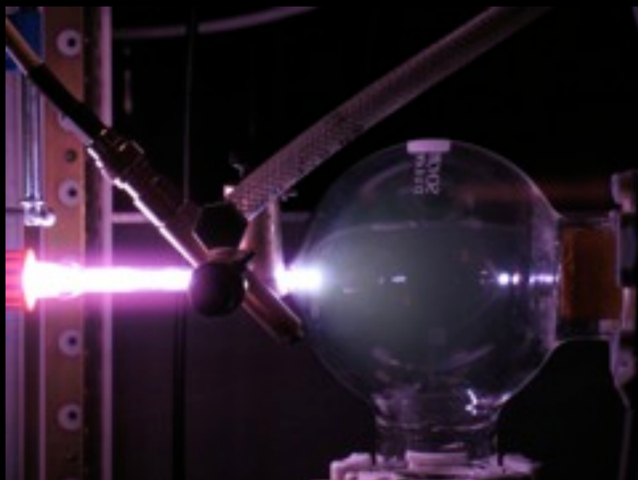
H/C ~ 10^{-2}

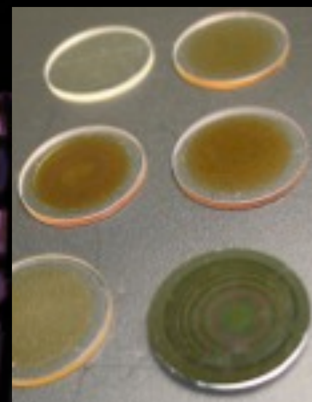
Polyaromatic units linked by aliphatic bridges



Irradiated samples

a-C:H





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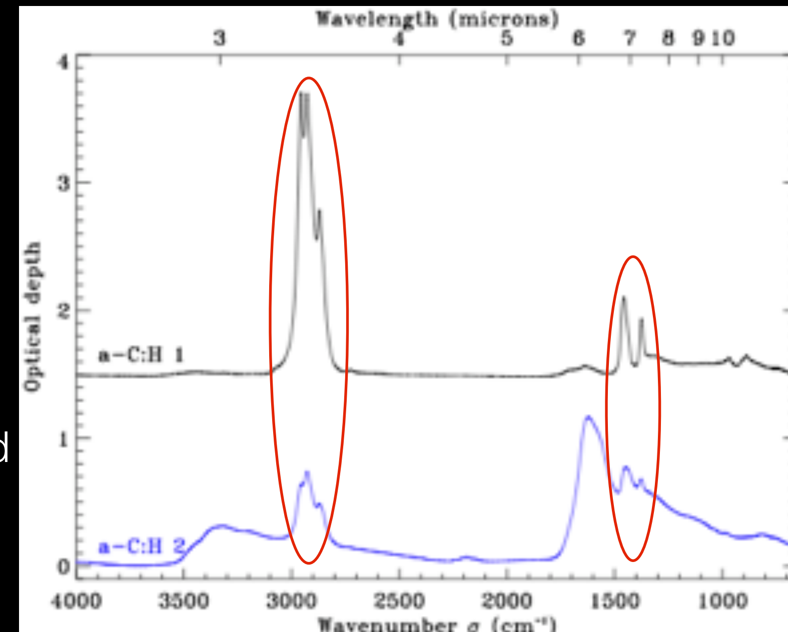

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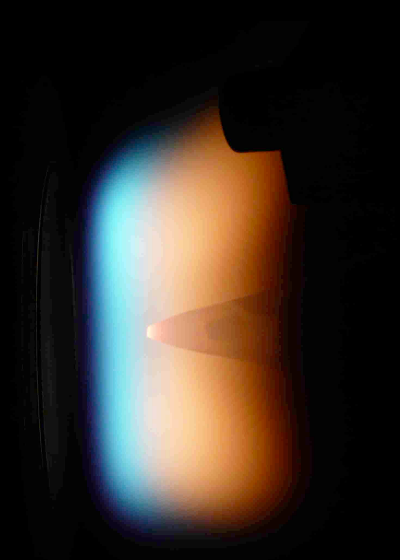

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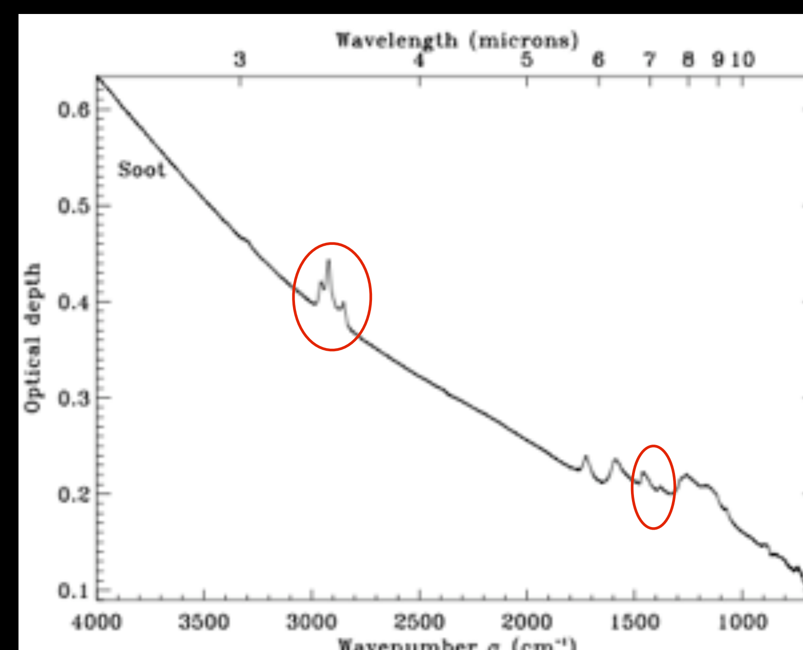
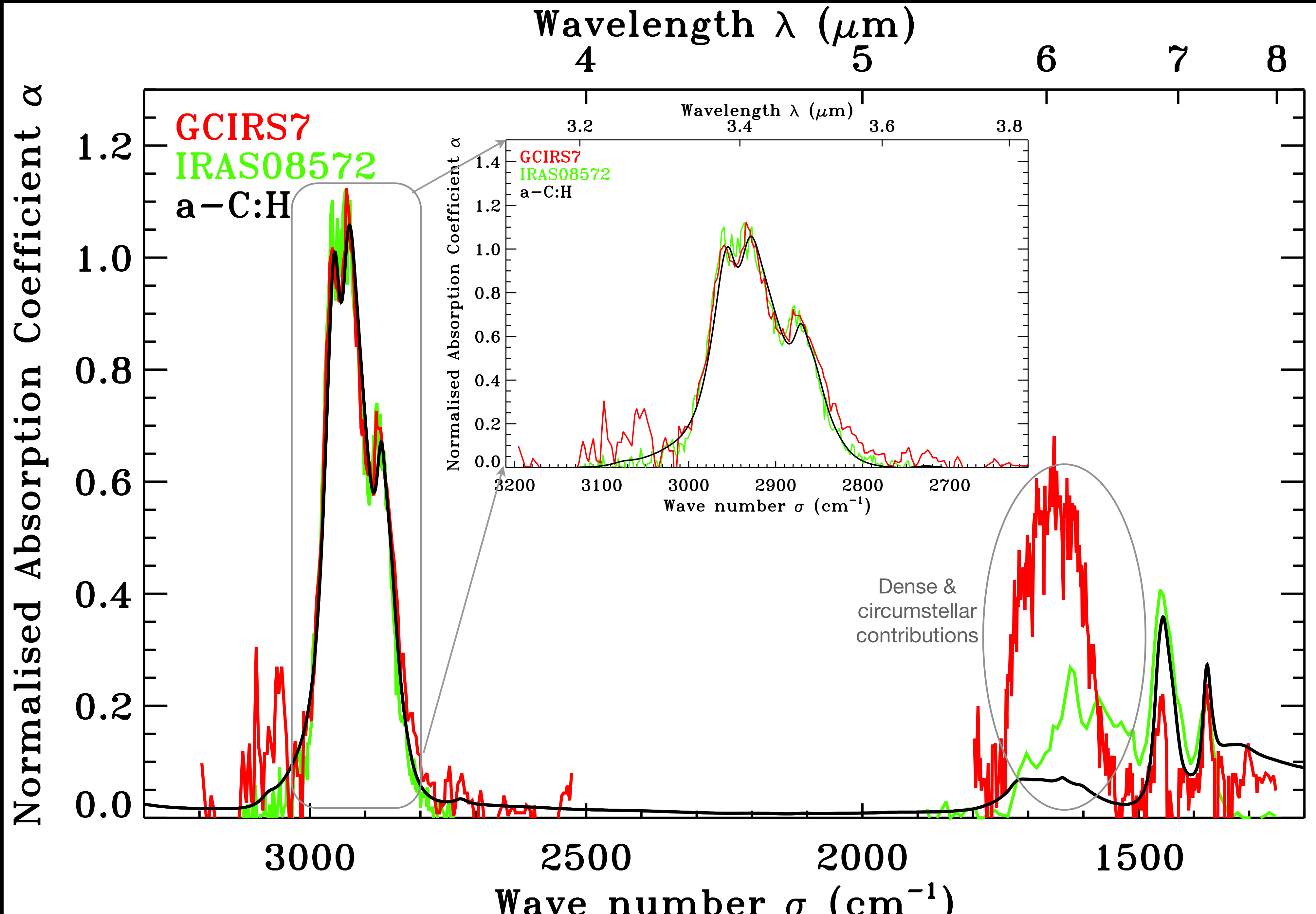


Laboratory vs observed IR spectra
➫ a-C:H are excellent analogs

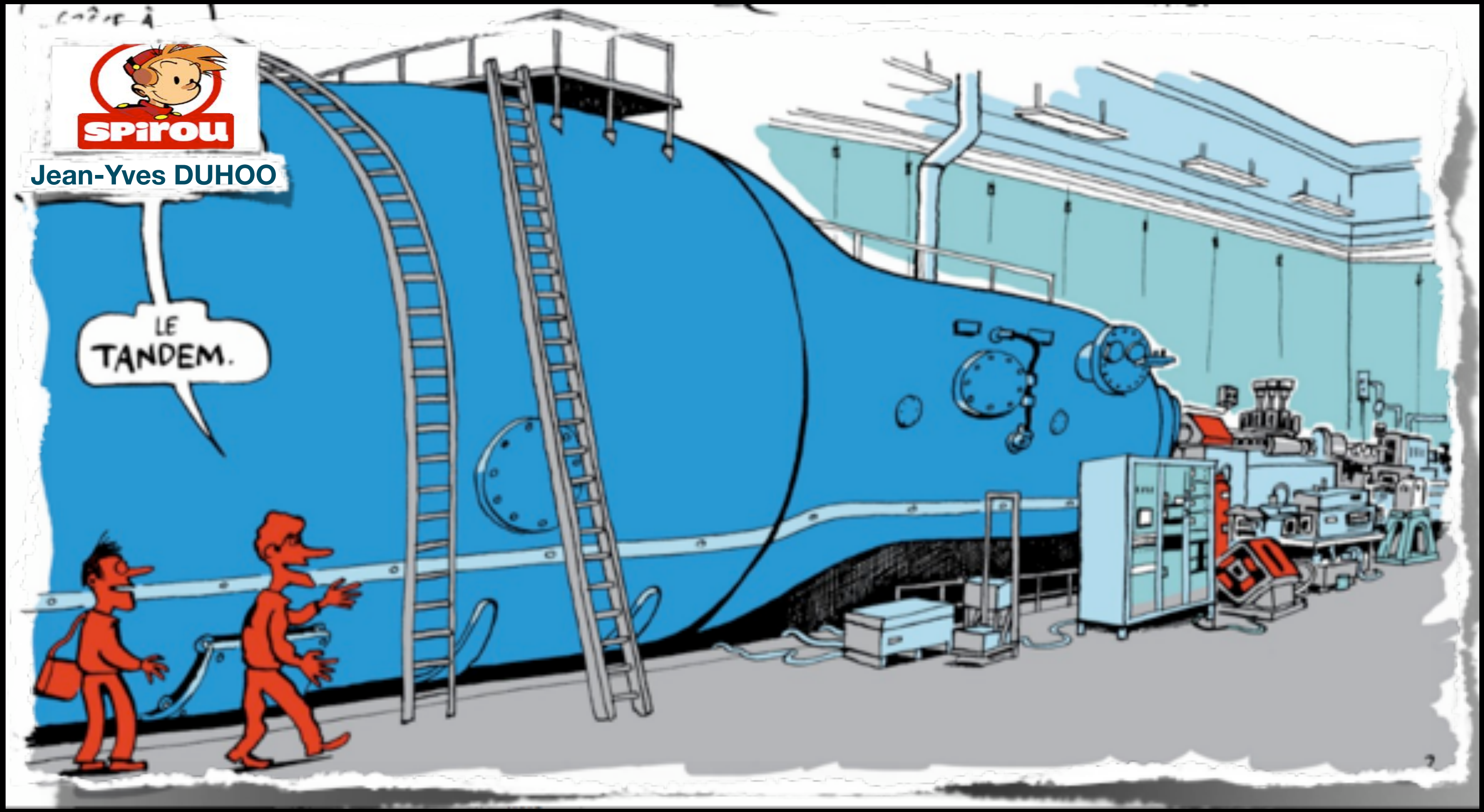


Irradiations by energetic ions

A large range of ≠ ions and energies were used:

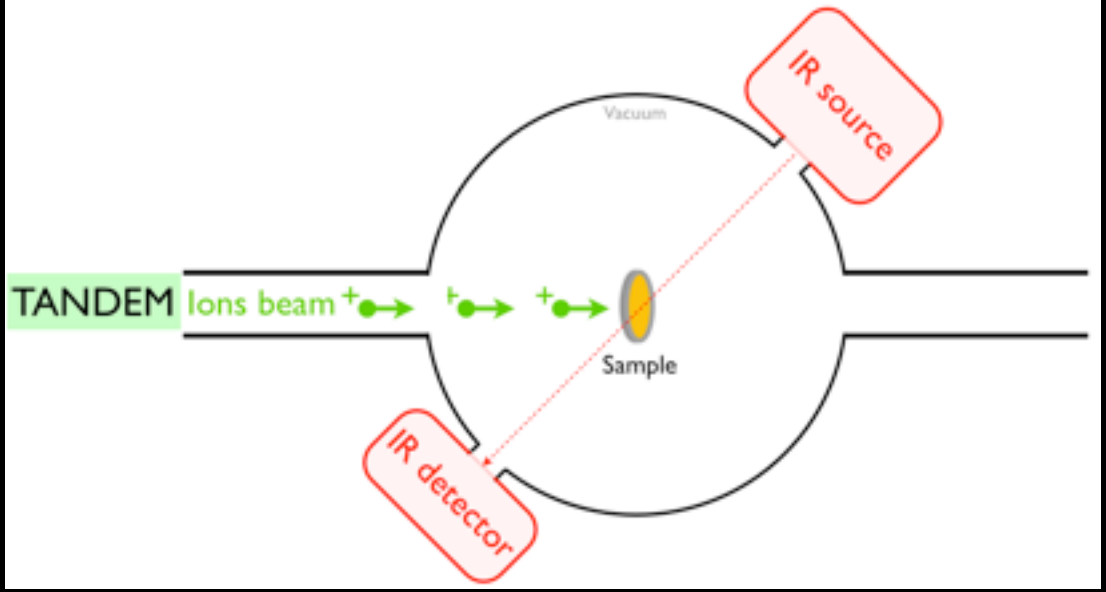
- **TANDEM** (IPN Orsay) in March 2009 & February 2010 (~ **10-100 MeV**)

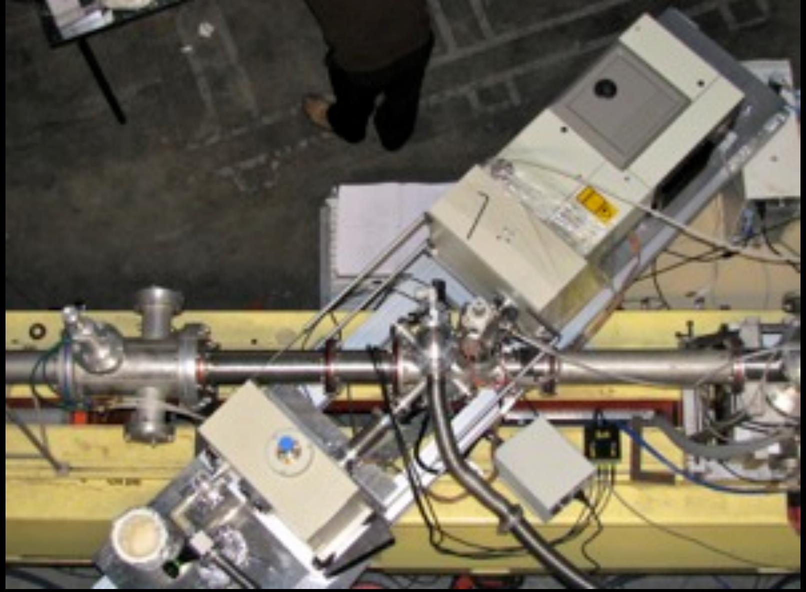
  H^+ 10 MeV He^{2+} 20 MeV C^{6+} 91 MeV C^{5+} 50 MeV
  Si^{7+} 85 MeV Ni^{9+} 100 MeV I^{12+} 160 MeV



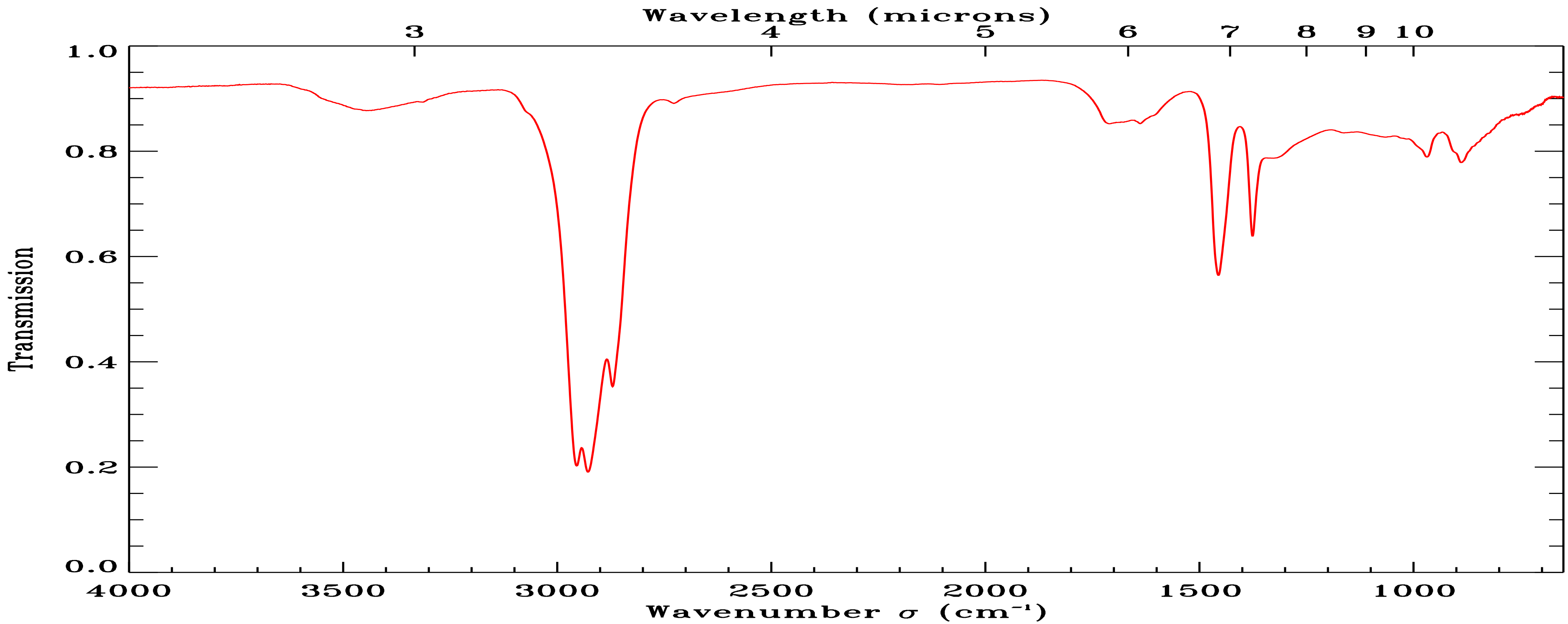
- in **Catania** (Laboratory for Experimental Astrophysics) in October 2007 & February 2009 (~ **100 keV**)

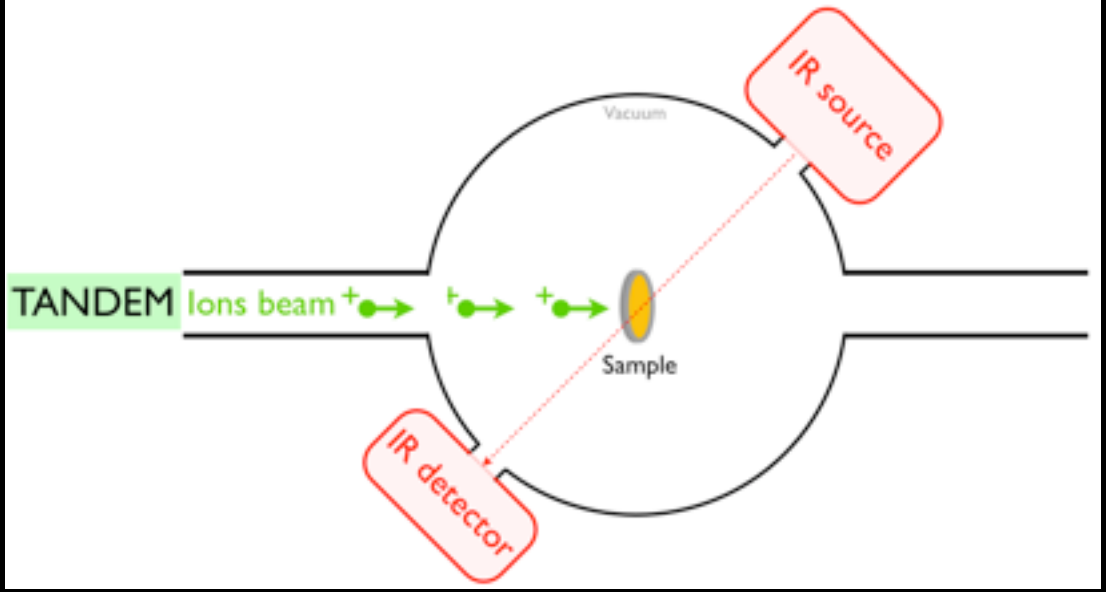
  H^+ 200 keV He^+ 200 keV Ar^{2+} 400 keV

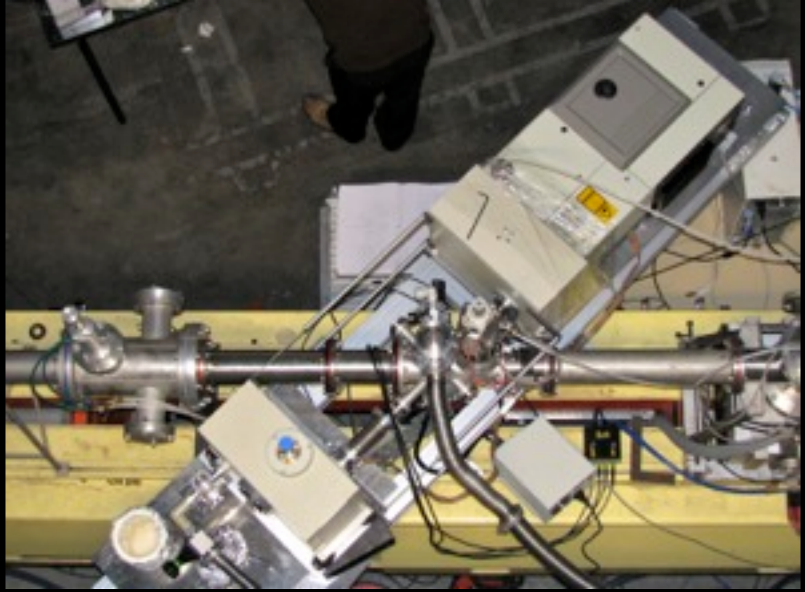




IR spectroscopy measured during the experiment to follow the evolution induced by irradiations.







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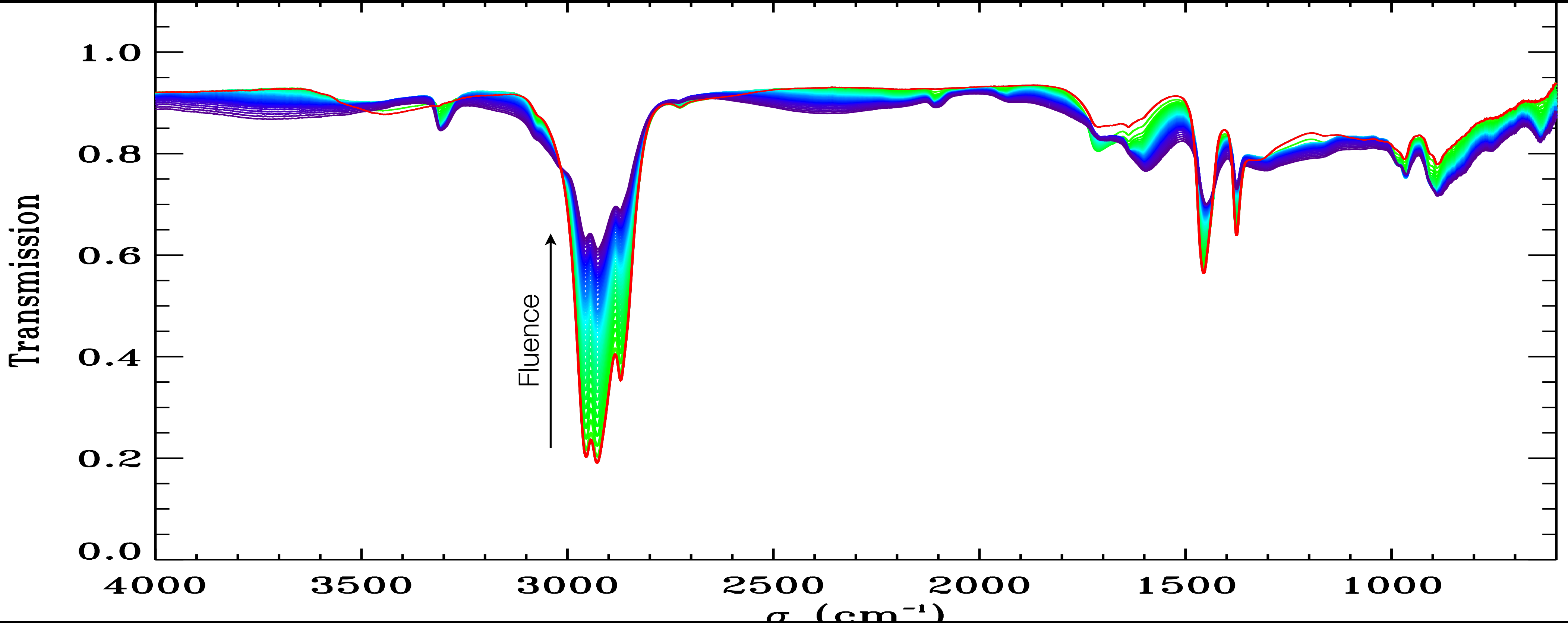

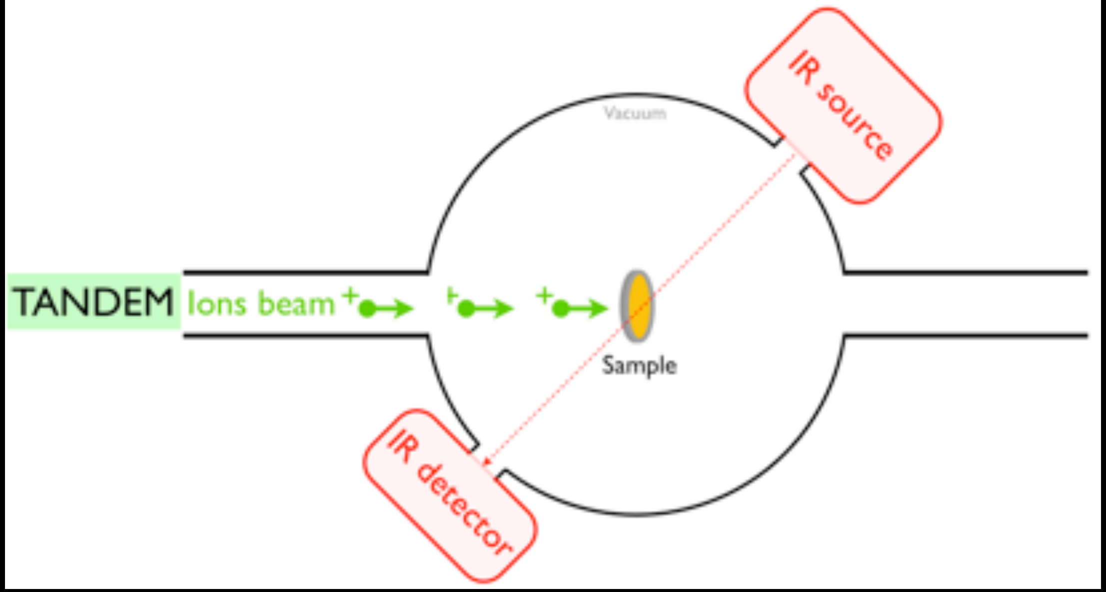

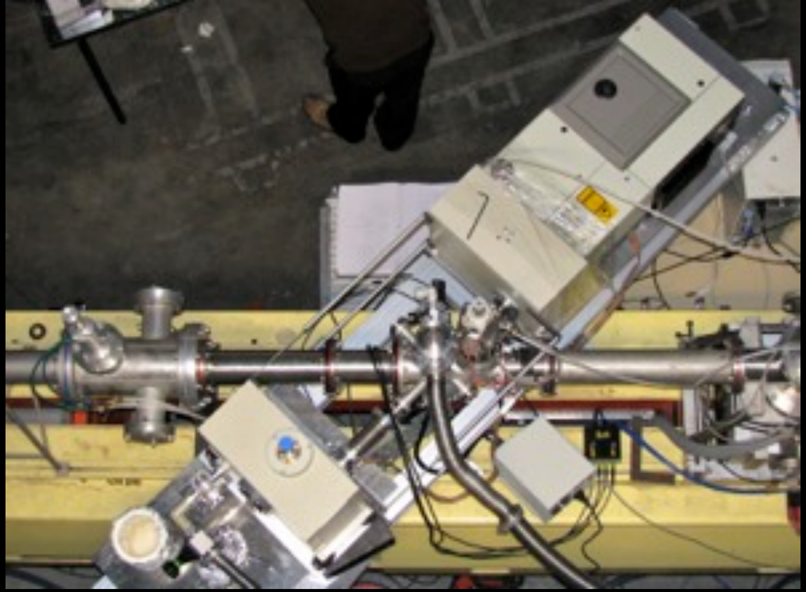

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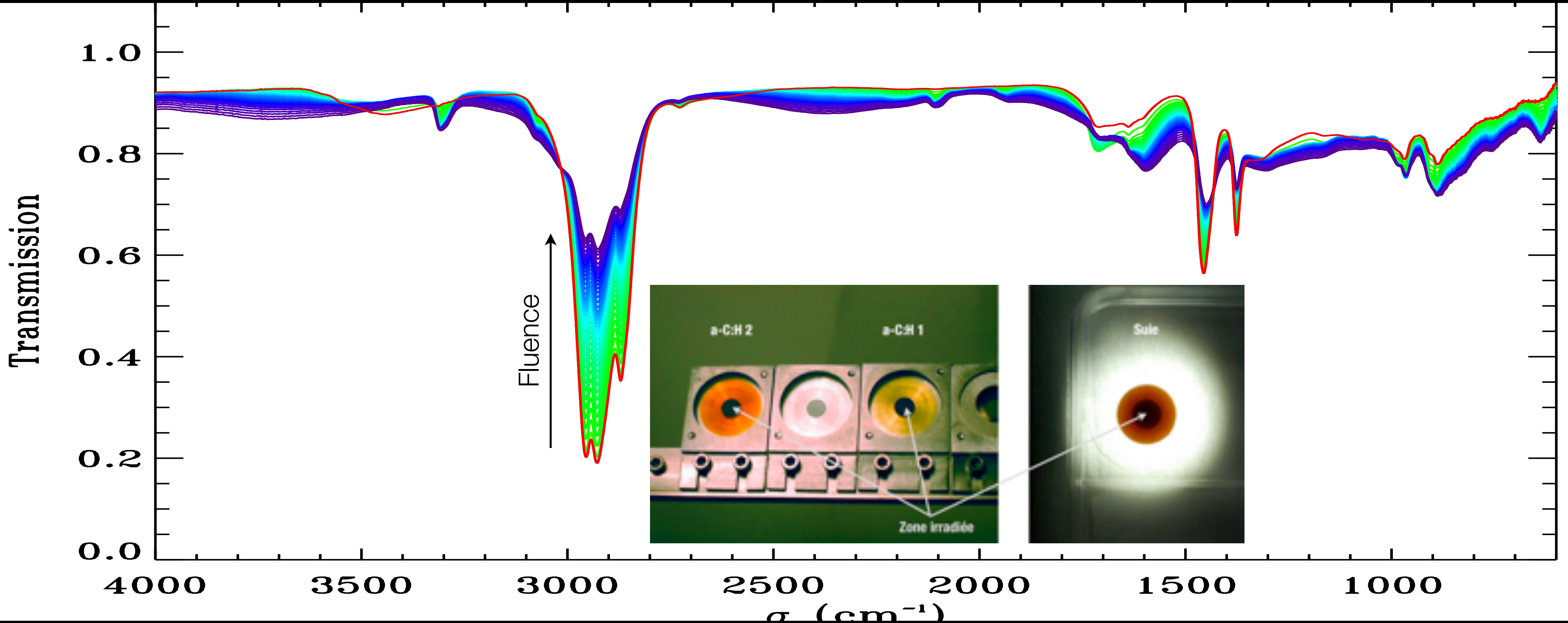
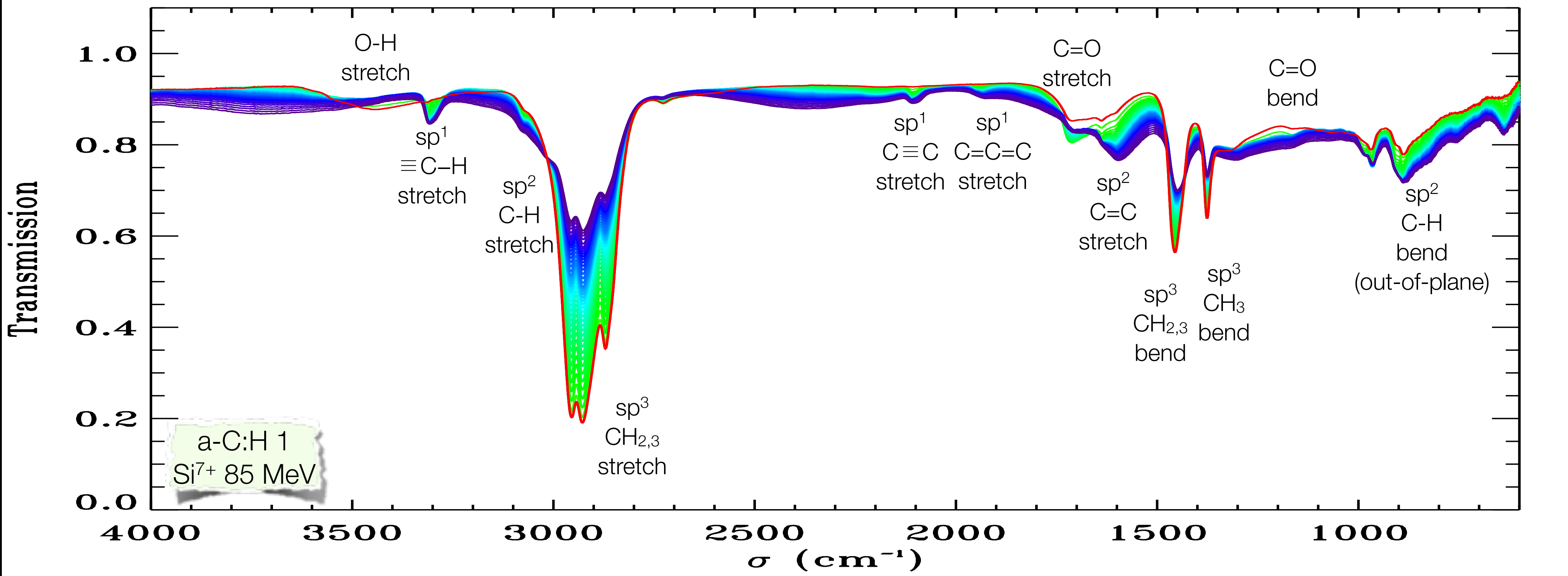
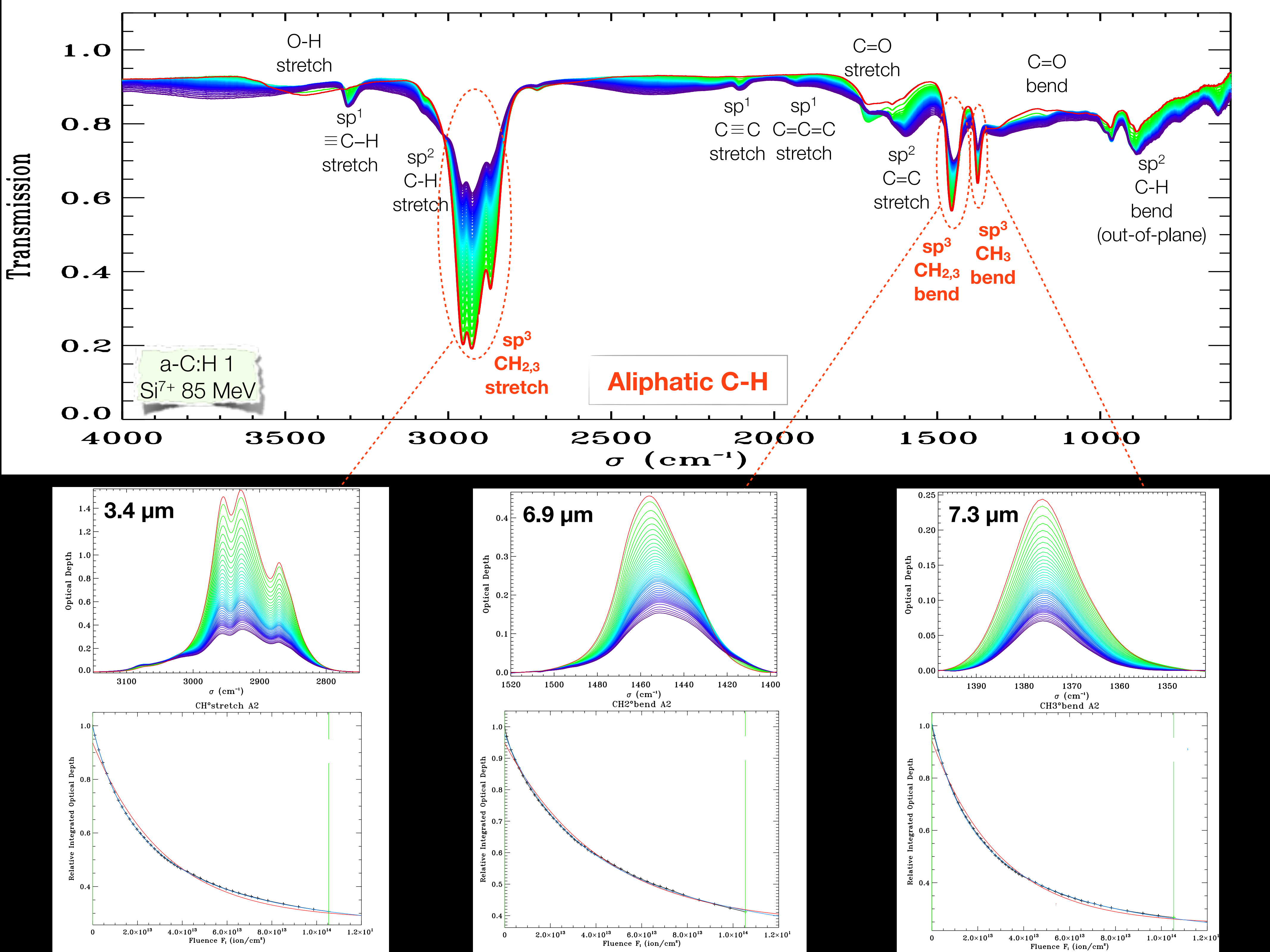



Transmission
1.0
0.8
0.6
0.4
0.2
0.0
4000
3500
3000
2500
2000
1500
1000
σ (cm⁻¹)
O-H stretch
sp1 ≡C–H stretch
sp2 C-H stretch
sp3 CH2,3 stretch
sp1 C≡C stretch
sp1 C=C=C stretch
C=O stretch
sp2 C=C stretch
sp3 CH2,3 bend
sp3 CH3 bend
C=O bend
sp2 C-H bend (out-of-plane)
a-C:H 1
Si7+ 85 MeV



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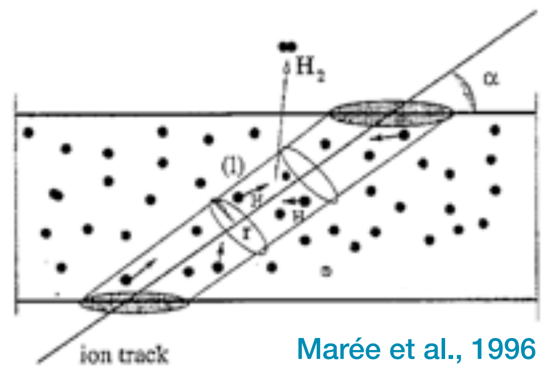
sp2 C=C stretch
sp3 CH2,3 bend
sp3 CH3 bend
C=O bend
sp2 C-H bend (out-of-plane)
a-C:H 1
Si7+ 85 MeV
Aliphatic C-H
3.4 µm
Optical Depth
σ (cm⁻¹)
CH°stretch A2
Relative Integrated Optical Depth
Fluence Fi (ion/cm²)
6.9 µm
CH2°bend A2
7.3 µm
CH3°bend A2

Recombination model



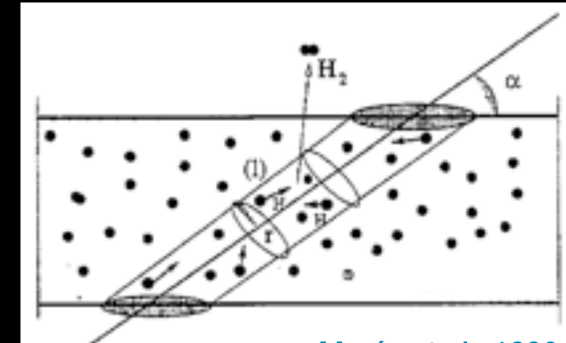
Marée et al., 1996

➯ **Hydrogen is lost in molecular form**

Model developed by Adel et al. (1989) and Marée et al. (1996)

- Electronic energy deposition ➯ **Breaking of C-H bonds** along the ion track
- If 2 free H atoms are close ➯ **Recombination in H_2** within the material bulk
- The H_2 molecule diffuses out of the bulk without interaction.
- The **hydrogen loss stops** when the H concentration ρ reaches the threshold when **H atoms are too far from each other** to recombine in H_2 ($V=1/\rho_f$)

Recombination model



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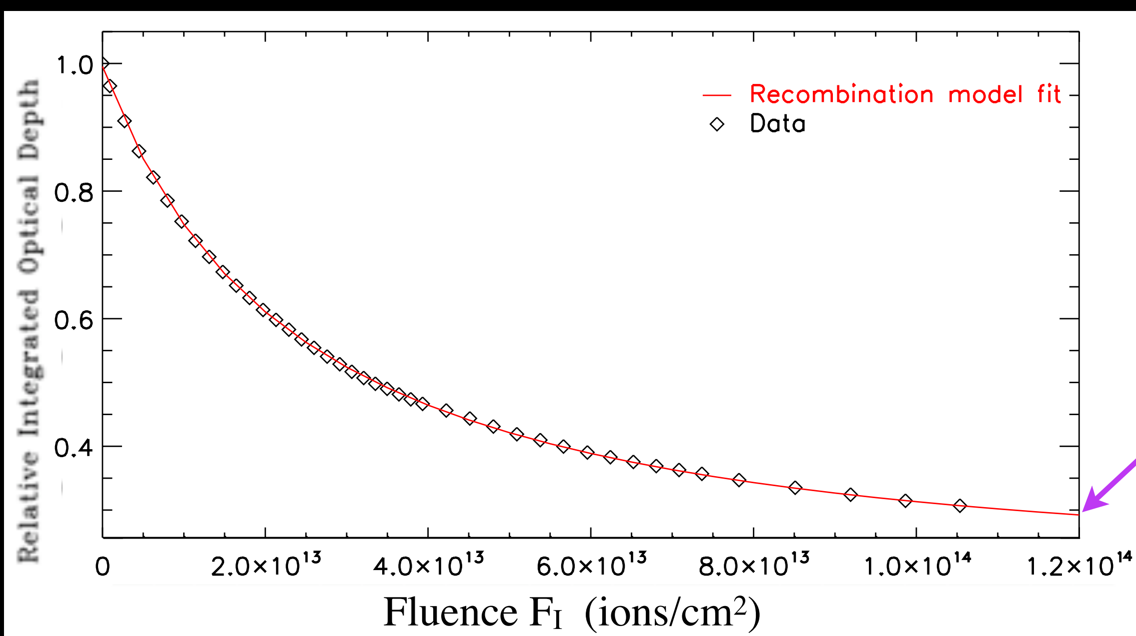
$$\frac{\rho}{\rho_i} = \frac{1}{\rho_i/\rho_f + (1-\rho_i/\rho_f)\ \exp(-\sigma_d\ F_I)}$$



For each irradiation experiment:

σ_d : the destruction cross section

ρ_f/ρ_i : the asymptotic value of the integrated optical depth at infinite fluence

Evolution of interstellar aliphatic C-H exposed to cosmic rays

Experiments with a large range of Z & E → Effect of each Cosmic Ray (Z,E)

Cosmic ray flux: Φ(Z,E)

→

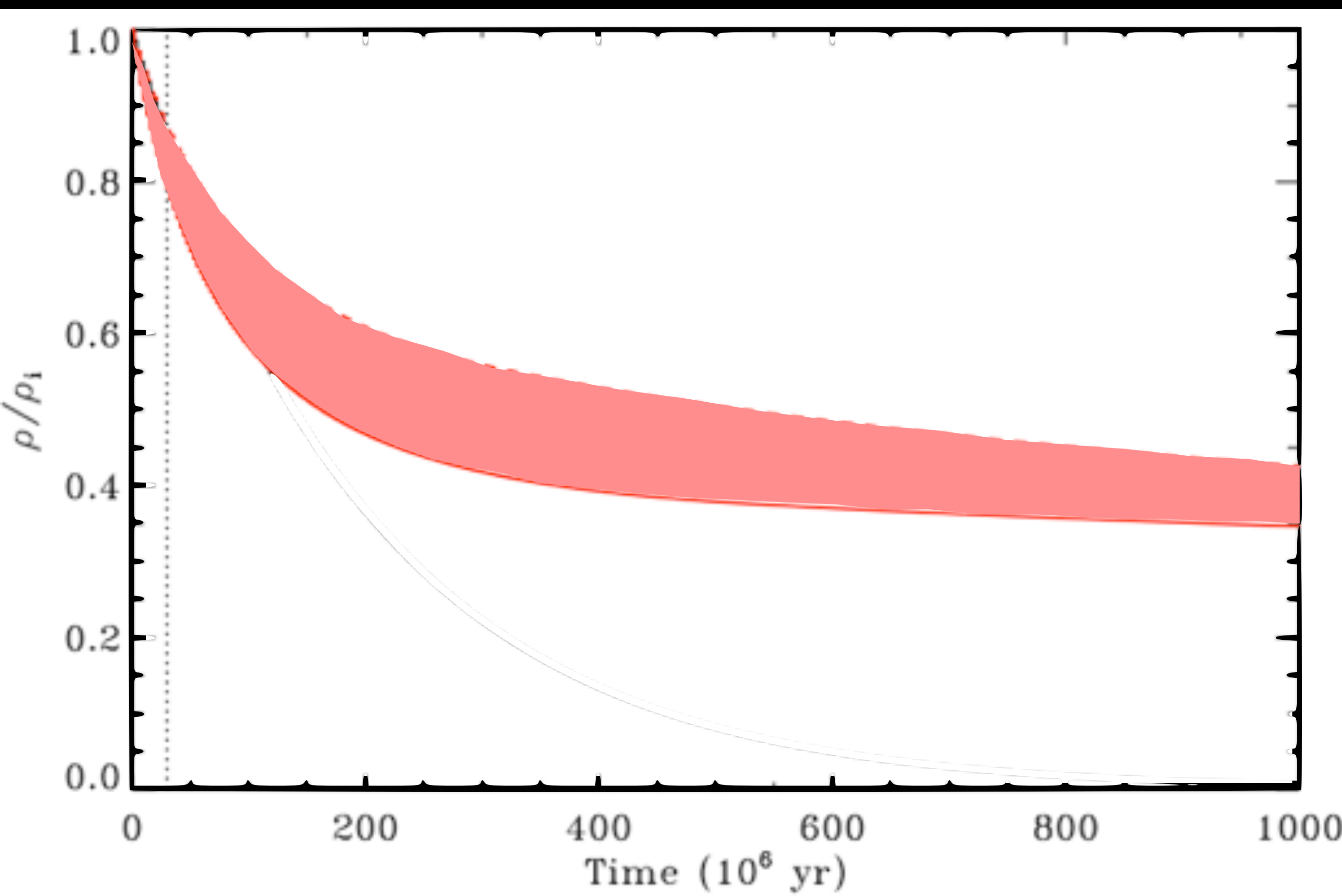
$$\sum_{Z} \int_{E} \text{Dehydrogenation by a CR(Z,E)}$$

Evolution of interstellar aliphatic C-H exposed to cosmic rays

Experiments with a large range of Z & E → Effect of each Cosmic Ray (Z,E)

Cosmic ray flux: $\Phi(Z,E)$

→ $\sum_{Z} \int_{E}$ Dehydrogenation by a CR(Z,E)



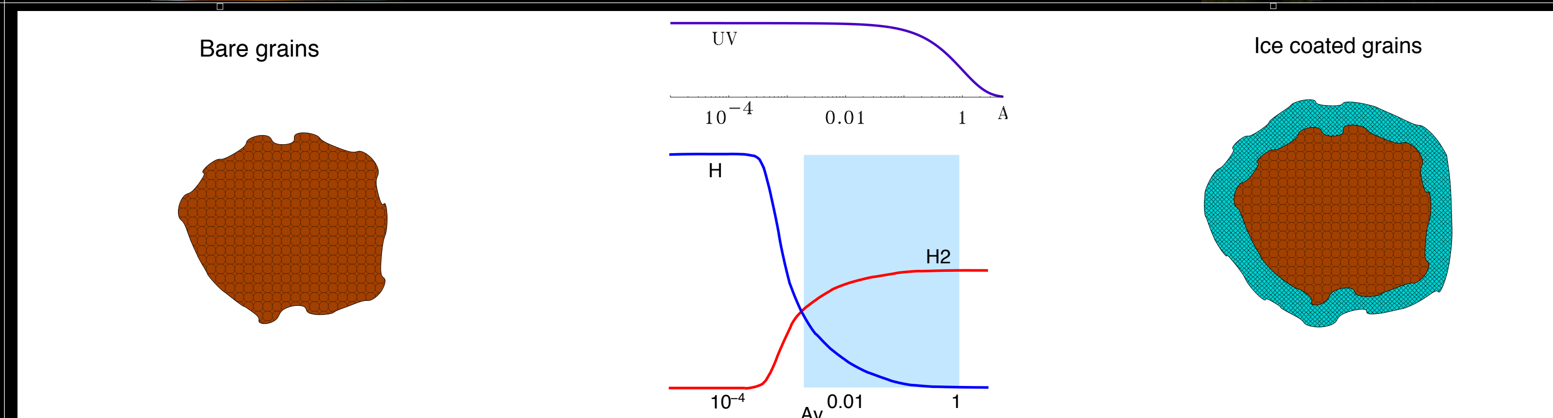
➩ **characteristic destruction time** of aliphatic C-H by cosmic rays: ~ a few **10^8 years**

>> 10^7 years : lifetime of an interstellar cloud

➩ Even in 10^8-10^9 years, or with higher cosmic ray flux, the **destruction by CR is not total**

Evolution of the 3.4 μm band in interstellar medium

	Diffuse ISM	Interface	Dense ISM



3.4 μm band	observed		Not observed
Destruction time by **cosmic ray**	10^8 years	10^8 years	10^8 years
Destruction time by **UV photons**	4 10^3 years	$\gtrsim 4.10^3 \exp(A_V)$ years	$\gtrsim$ 10^7 years
Formation time by **H atoms**	2 10^3 years		inefficient
Destruction/ Formation	Efficient formation	**Efficient destruction ?**	Slow destruction

Results of a-C:H exposure to cosmic rays: **H_2 formation**

$R_{H2,CR} \sim 10^{-11}$ molecules cm^{-3} yr^{-1}

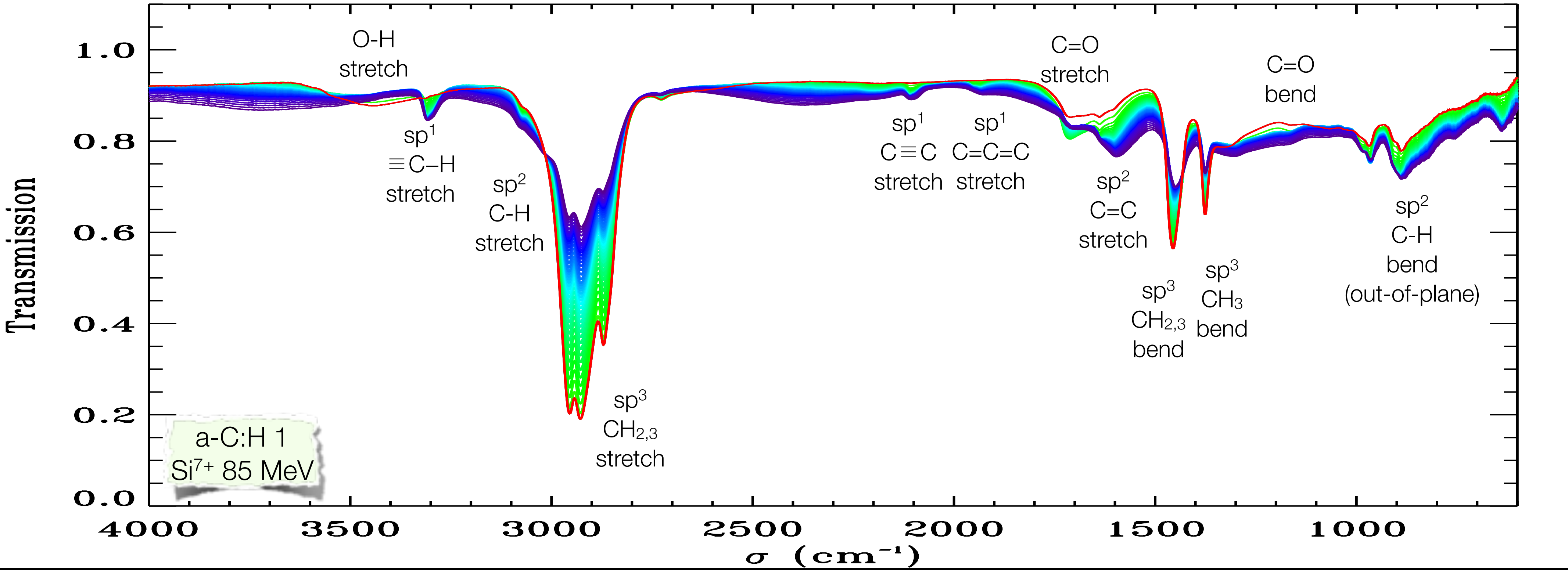
➩ Much lower than the "classical" H_2 formation rate on dust grains (~ 10^{-5} molecules cm^{-3} yr^{-1})

This process can produce H_2 from the whole bulk of interstellar a–C:H in all interstellar environments

$R_{H2,UV} \sim 10^{-7}$-10^{-6} molecules cm^{-3} yr^{-1} (Jones 2012)

H atoms ⟶ | a-C:H: Dehydrogenation by CR & UV / Rehydrogenation in diffuse ISM | ⟶ H_2 molecules

a–C:H grains can contribute to accelerate the $H \rightarrow H_2$ conversion and have a role of catalyst for the formation of H_2



Transmission
1.0
0.8
0.6
0.4
0.2
0.0
4000
3500
3000
2500
2000
1500
1000
σ (cm⁻¹)
O-H stretch
sp1 ≡C–H stretch
sp2 C-H stretch
sp3 CH2,3 stretch
sp1 C≡C stretch
sp1 C=C=C stretch
C=O stretch
sp2 C=C stretch
sp3 CH2,3 bend
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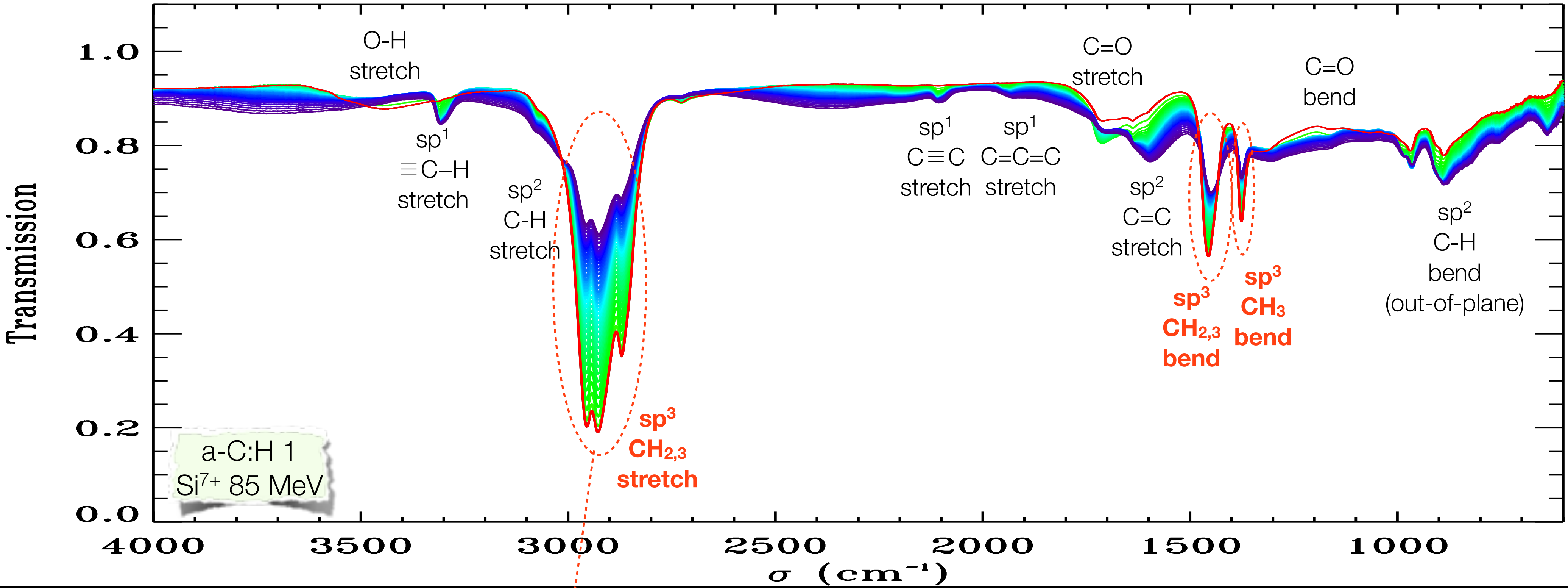
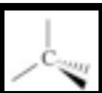
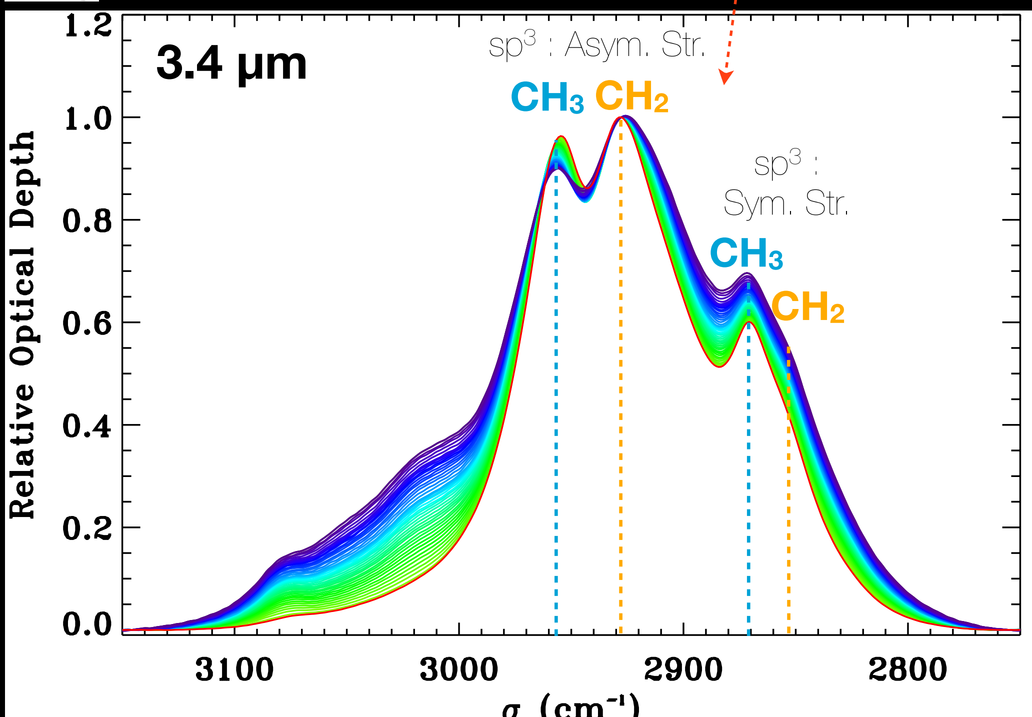
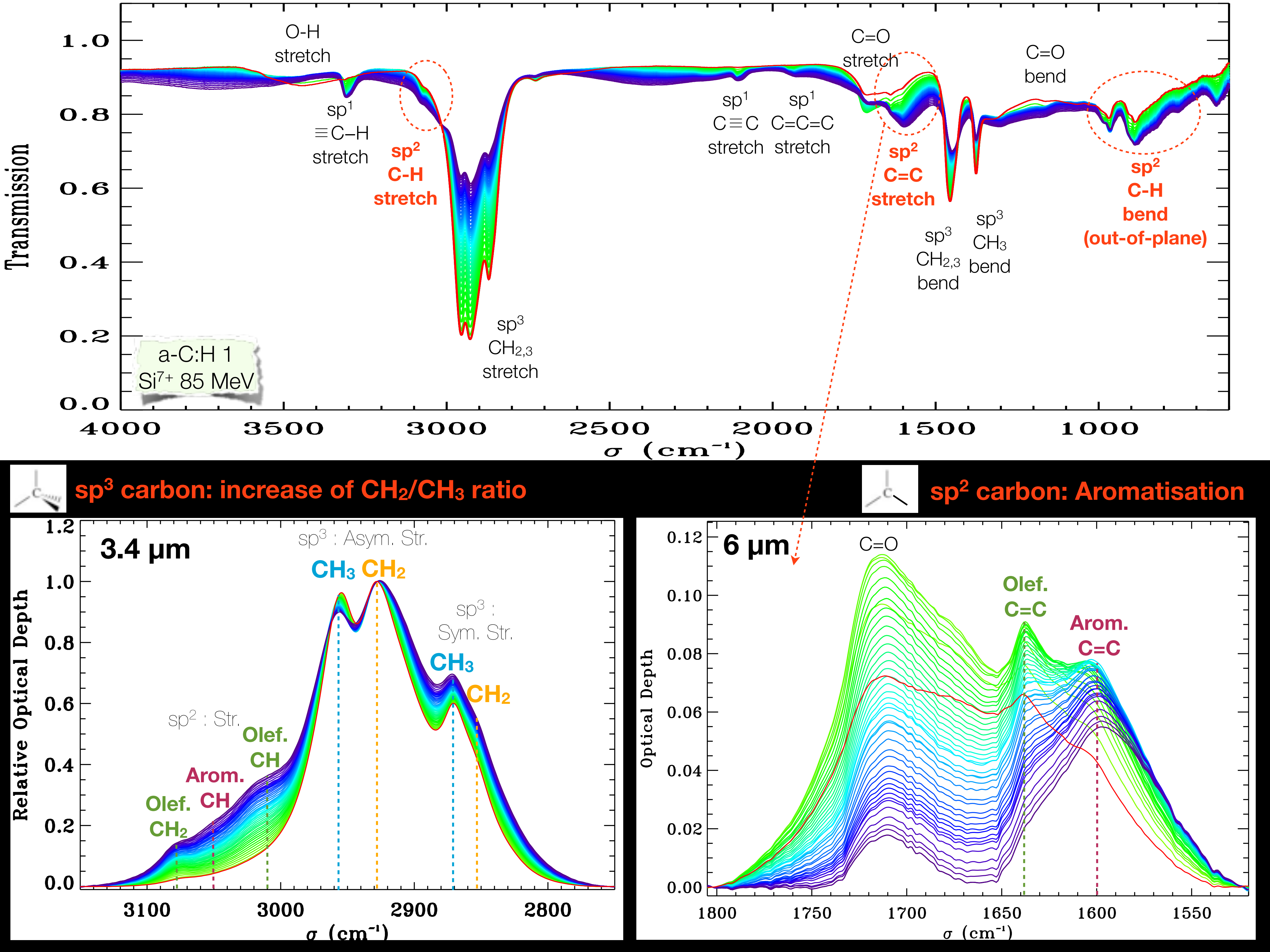
C=O bend
sp2 C-H bend (out-of-plane)
a-C:H 1
Si7+ 85 MeV



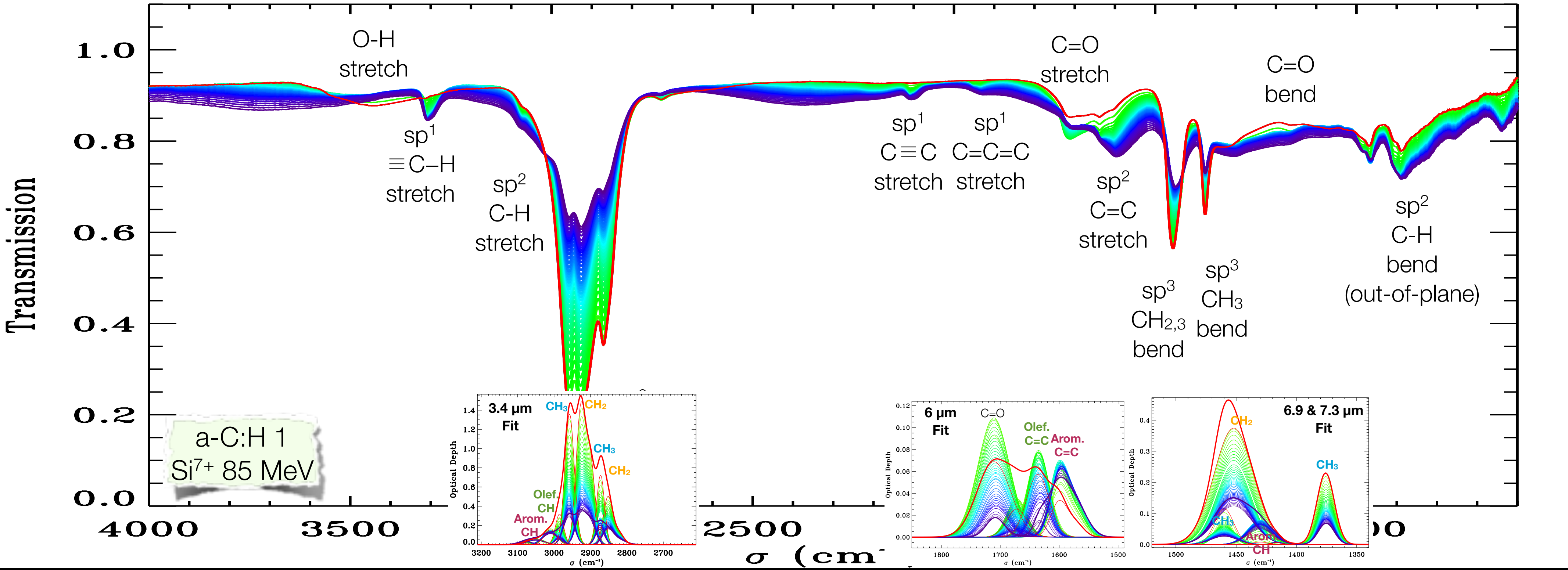


sp^3 carbon: increase of CH_2/CH_3 ratio

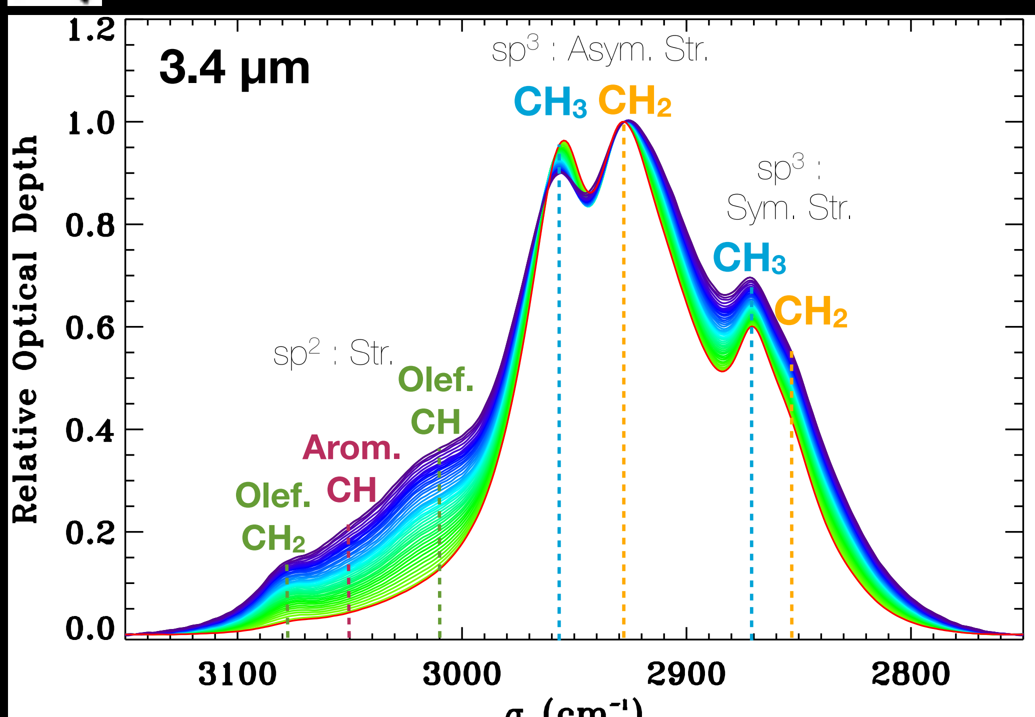




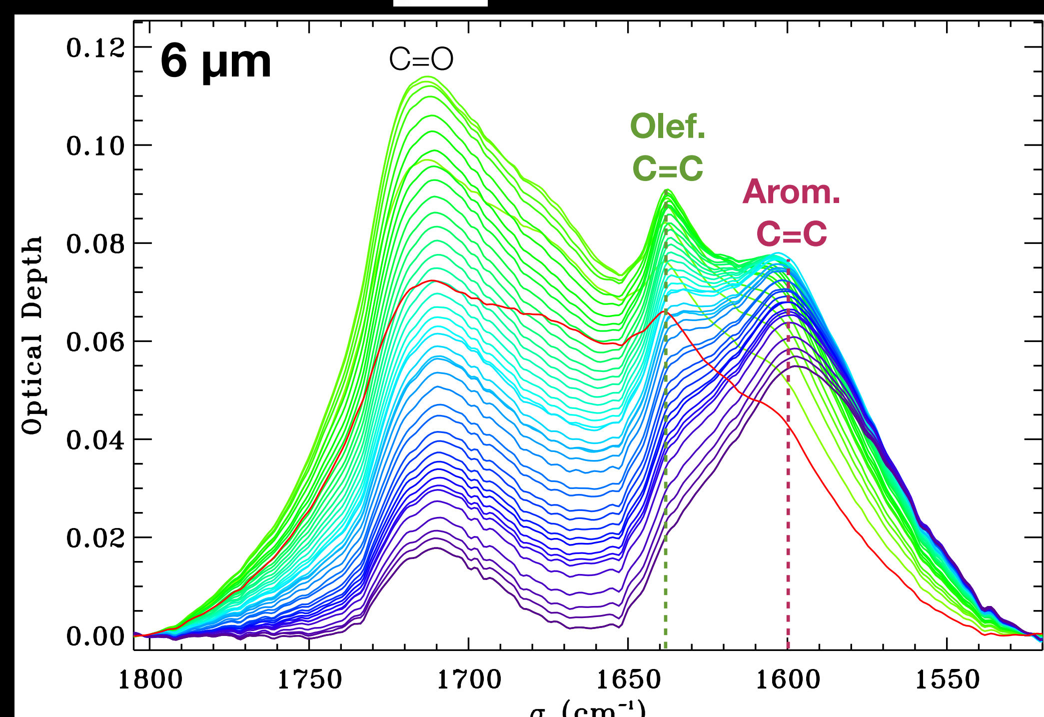
Transmission
O-H stretch
sp1 ≡C–H stretch
sp2 C-H stretch
sp3 CH2,3 stretch
sp1 C≡C stretch
sp1 C=C=C stretch
C=O stretch
sp2 C=C stretch
C=O bend
sp3 CH2,3 bend
sp3 CH3 bend
sp2 C-H bend (out-of-plane)
a-C:H 1
Si7+ 85 MeV
σ (cm⁻¹)
sp3 carbon: increase of CH2/CH3 ratio
sp2 carbon: Aromatisation
3.4 μm
Relative Optical Depth
sp3 : Asym. Str.
CH3 CH2
sp3 : Sym. Str.
CH3
CH2
sp2 : Str.
Olef. CH
Arom. CH
Olef. CH2
6 μm
Optical Depth
C=O
Olef. C=C
Arom. C=C

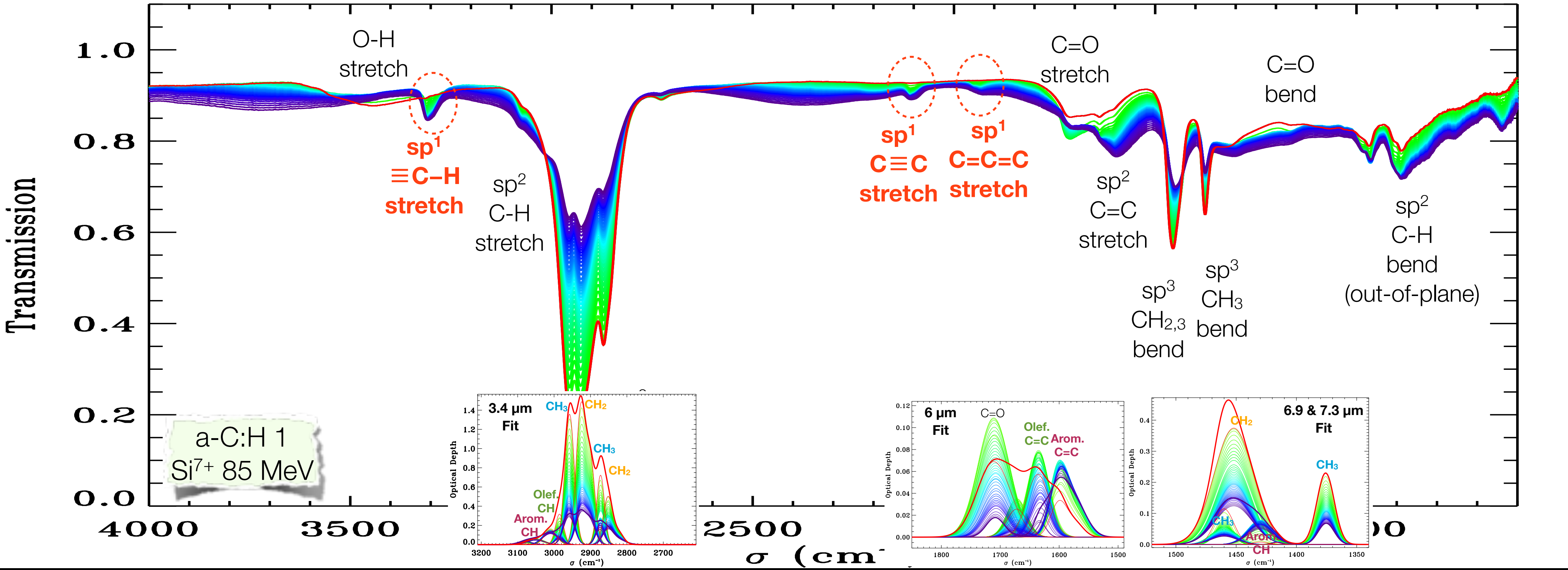


sp^3 carbon: increase of CH_2/CH_3 ratio

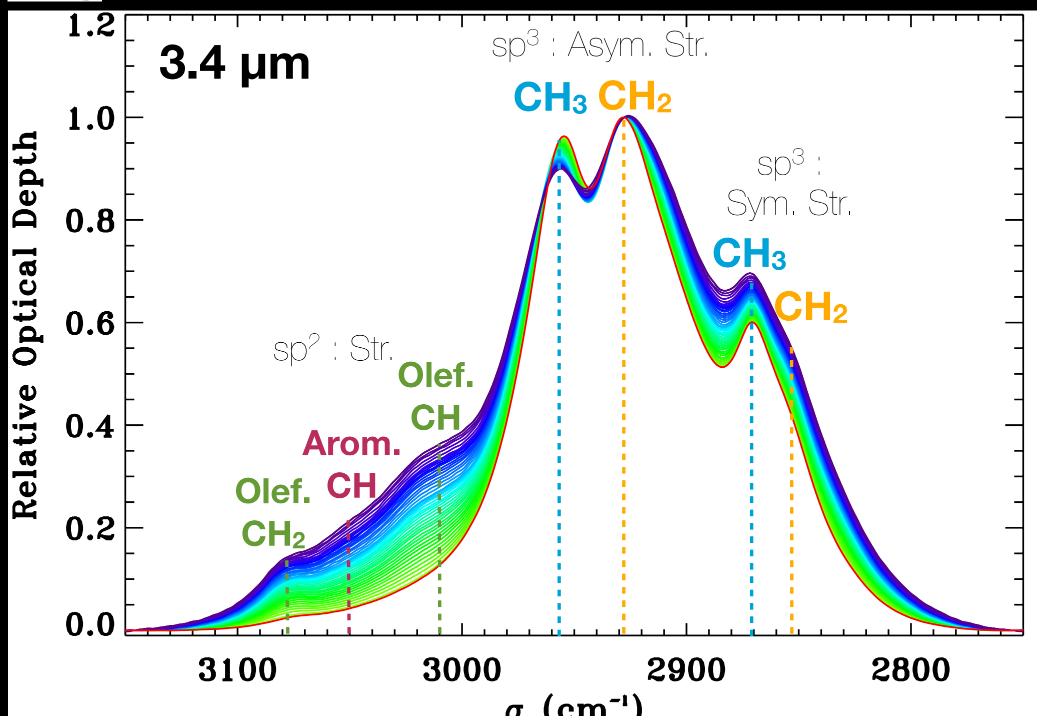


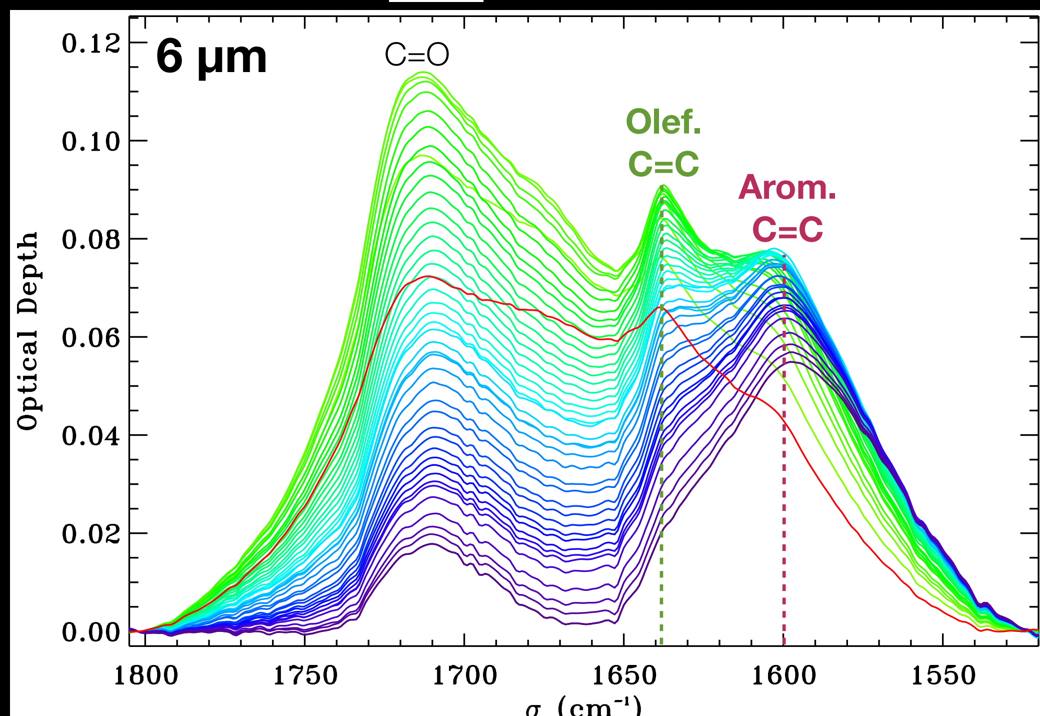
sp^2 carbon: Aromatisation



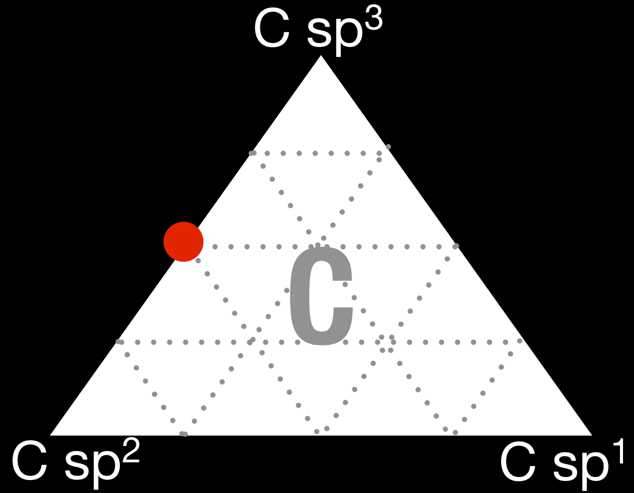


sp³ carbon: increase of CH_2/CH_3 ratio —C— ↗ **sp¹ carbon** **sp² carbon: Aromatisation**



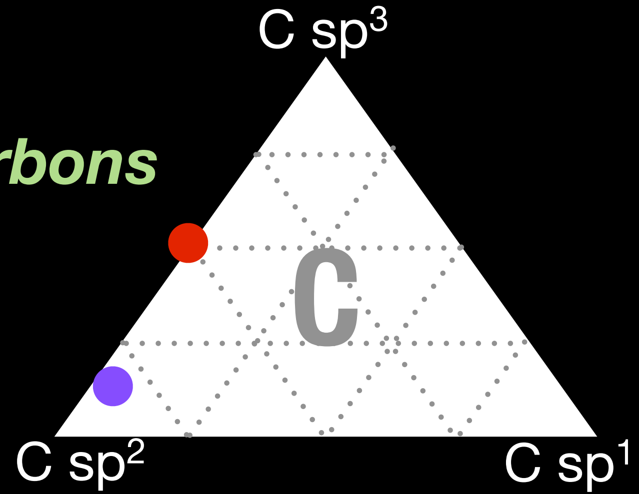


a-C:H before irradiation



Emergence of sp^1 & sp^2 carbons

sp^1 C	~ 0% of C	2-3% of C
sp^2 C	45-55% of C	80-90% of C



a-C:H before irradiation

Irradiated a-C:H (equivalent to ~10^8 years of CR exposure)

a-C:H before irradiation

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Emergence of sp^1 & sp^2 carbons

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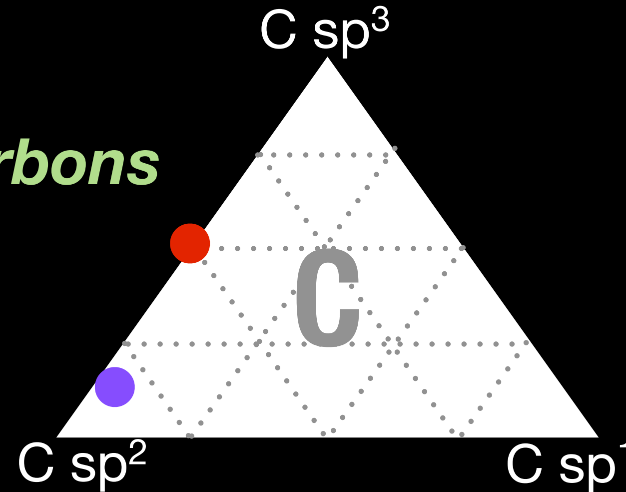
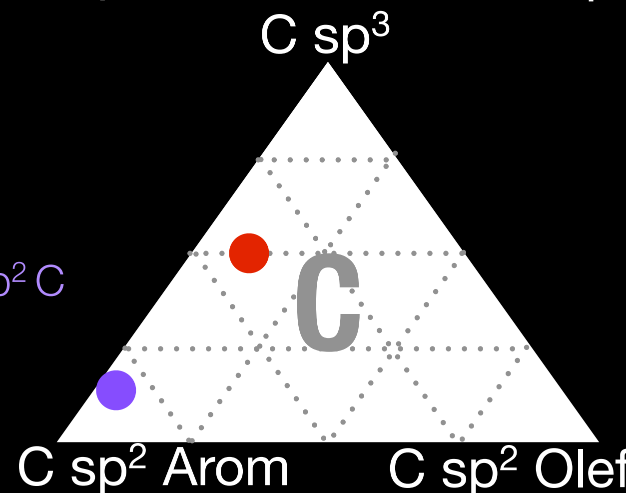


Aromatisation

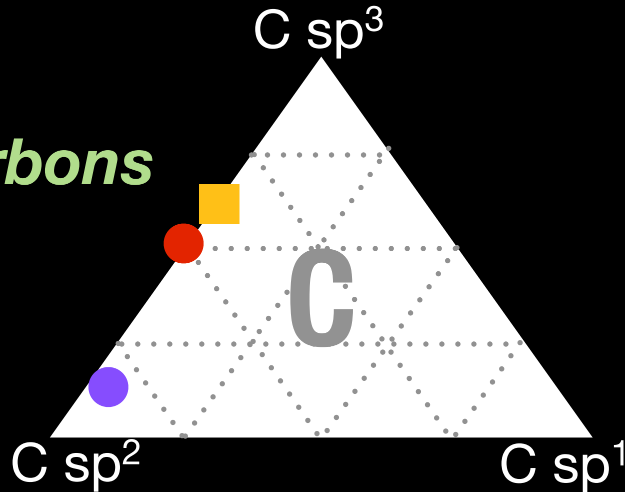
	a-C:H before irradiation	Irradiated a-C:H
Aromatic C	35-40% of C	70-90% of C
	75-85% of sp^2 C	90-95% of sp^2 C
Aromatic H	2-4% of H	10-13% of H



a-C:H before irradiation

Irradiated a-C:H (equivalent to ~10^8 years of CR exposure)

Emergence of sp^1 & sp^2 carbons



	a-C:H before irradiation	Irradiated a-C:H
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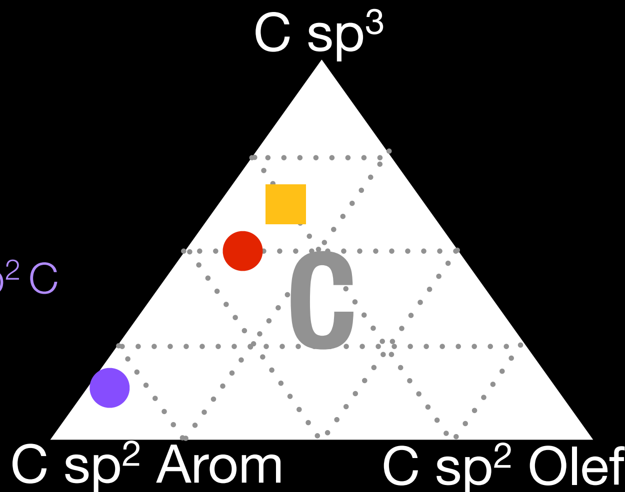
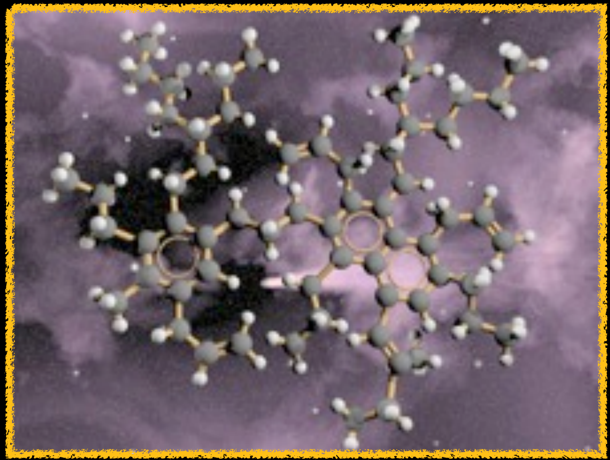
sp^2 C	45-55% of C	80-90% of C

Aromatisation



	a-C:H before irradiation	Irradiated a-C:H
Aromatic C	35-40% of C	70-90% of C
	75-85% of sp^2 C	90-95% of sp^2 C
Aromatic H	2-4% of H	10-13% of H

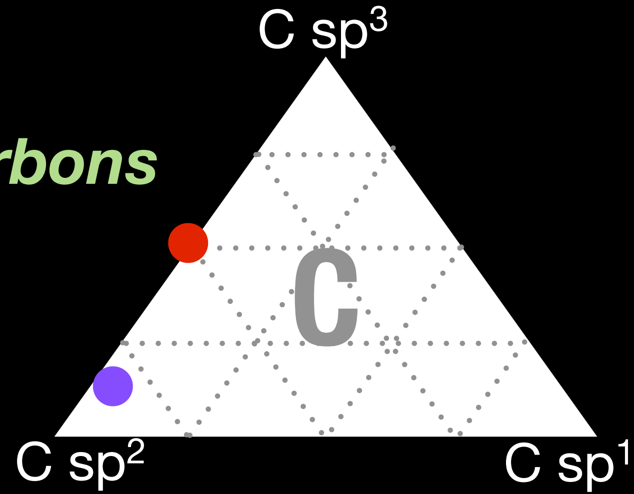


a-C:H before irradiation

Irradiated a-C:H (equivalent to ~10^8 years of CR exposure)

Emergence of sp^1 & sp^2 carbons

	a-C:H before irradiation	Irradiated a-C:H
sp^1 C	~ 0% of C	2-3% of C
sp^2 C	45-55% of C	80-90% of C



Aromatisation

	a-C:H before irradiation	Irradiated a-C:H
Aromatic C	35-40% of C	70-90% of C
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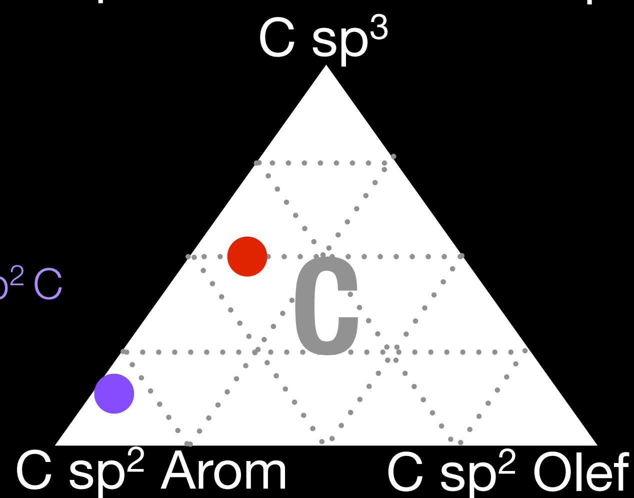
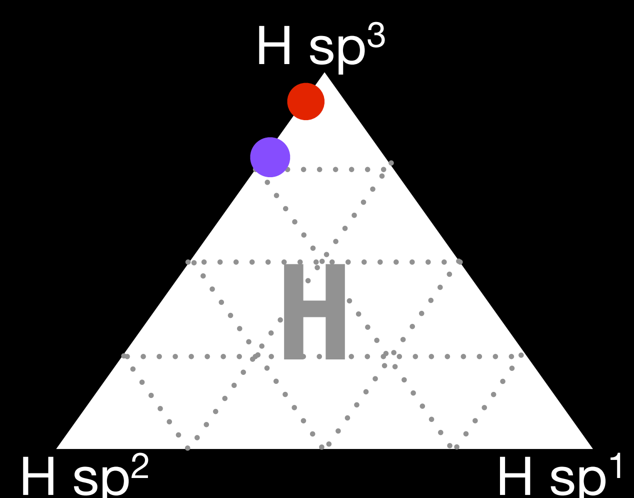


Dehydrogenation

	a-C:H before irradiation	Irradiated a-C:H
H/C	1.2-1.3	0.3-0.5
%H	55%	25-30%
CH_2/CH_3	1.9	2.3

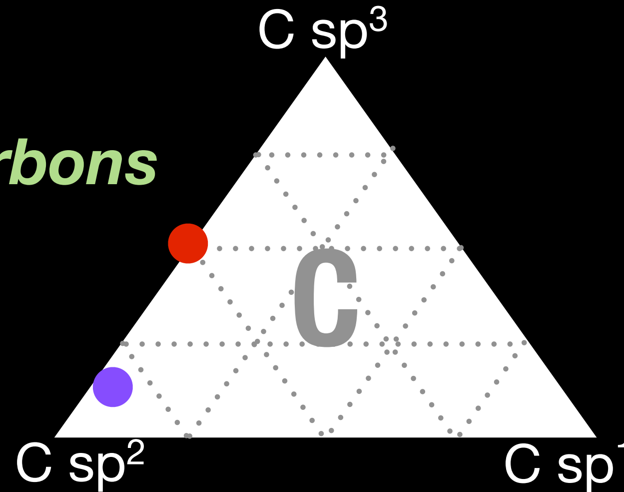


a-C:H before irradiation

Irradiated a-C:H
(equivalent to ~10^8 years
of CR exposure)

Emergence of sp¹ & sp² carbons

	a-C:H before irradiation	Irradiated a-C:H
sp^1 C	~ 0% of C	2-3% of C
sp^2 C	45-55% of C	80-90% of C



Aromatisation

	a-C:H before irradiation	Irradiated a-C:H
Aromatic C	35-40% of C	70-90% of C
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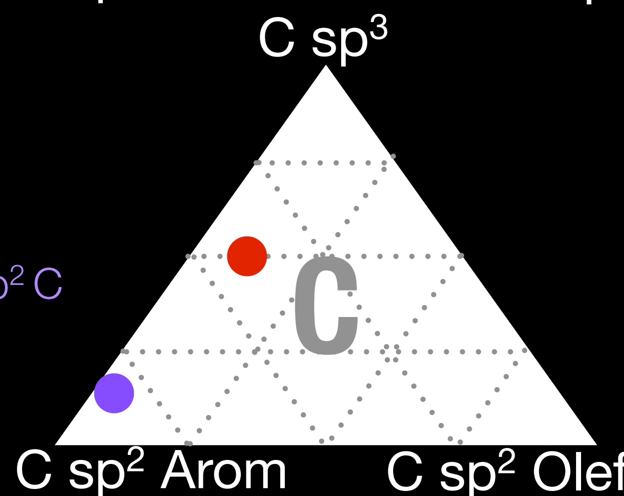

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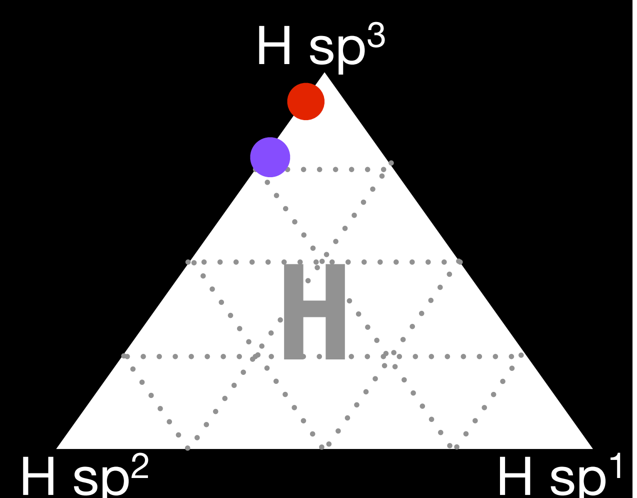

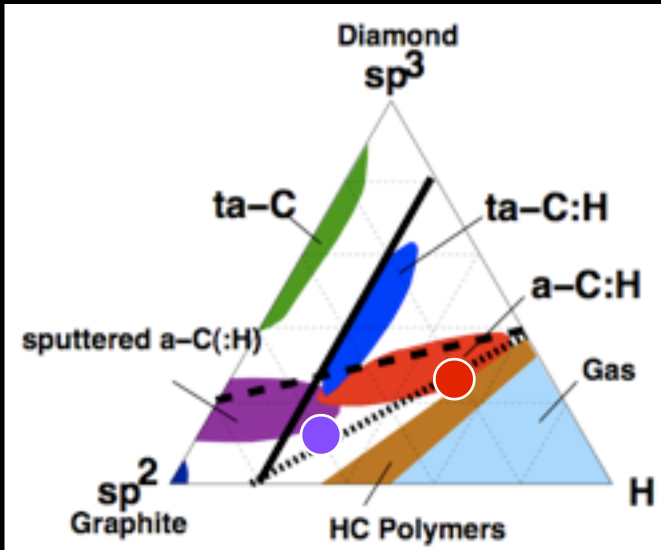

Conclusion

➯ **Characteristic destruction time of aliphatic C-H** by cosmic rays: ~ **10^8 years**

➯ Cosmic rays destroy a-C:H but don't seem to be efficient enough to explain the disappearance of the 3.4 µm band in dense ISM

➯ Interstellar a-C:H can be efficiently dehydrogenated in the **interfaces** between diffuse and dense regions

➯ **$R_{H2,CR}$** ~ **10^{-11} molecules cm^{-3} yr^{-1}**

➯ Cosmic ray irradiation induces **aromatisation** and **emergence of C≡C** in a-C:H

➯ **Heavy ions** play an important role in these destruction/modification
(Fe contributes between 5% and 40% of total dehydrogenation)