Dust nucleation in very-low pressure plasmas

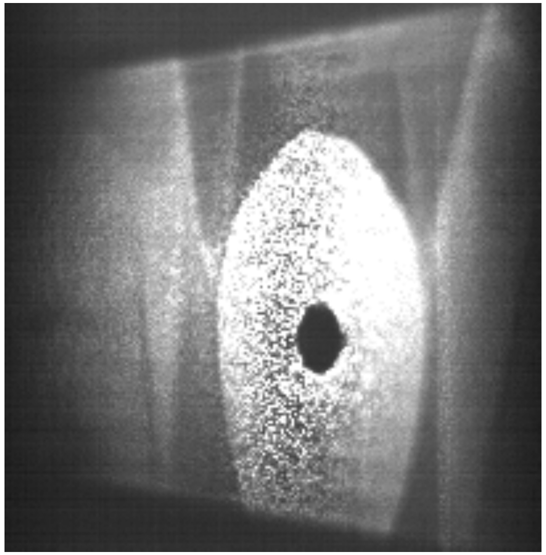
R. Clergereaux,

X. Glad, H. Sabbah, C. Joblin

M. Rojo, S. Dap

A. Perdrau, J. Philbrick

Outline



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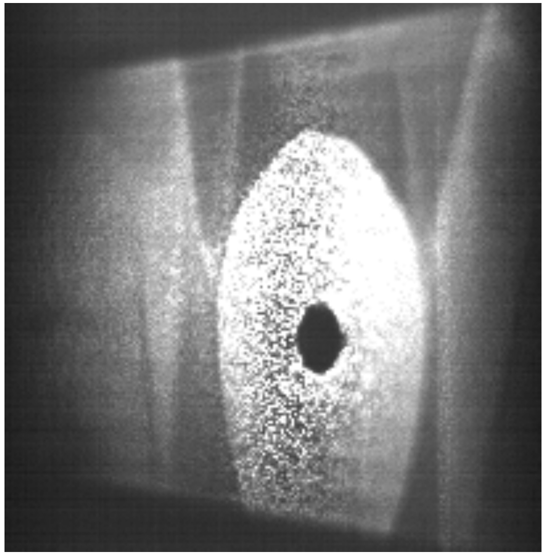

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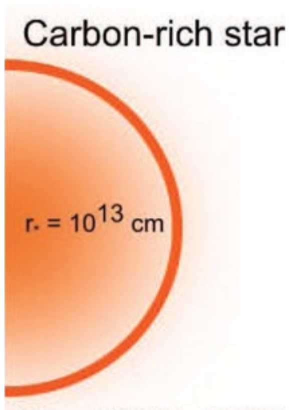

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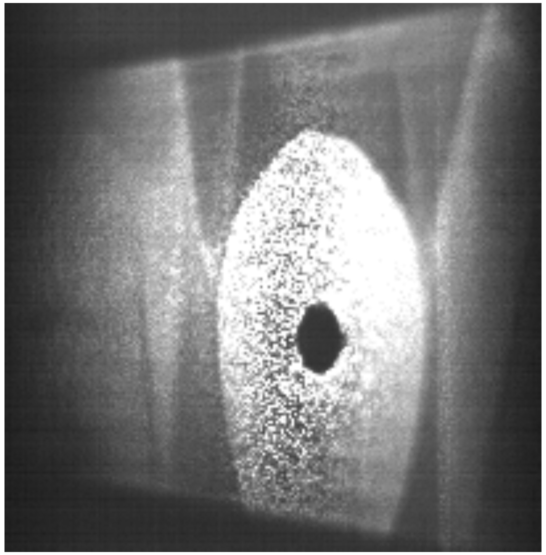

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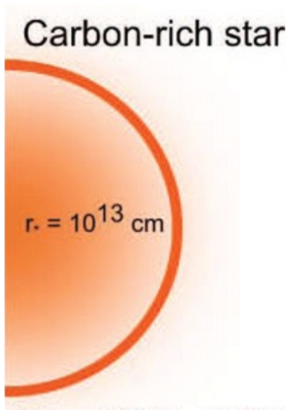

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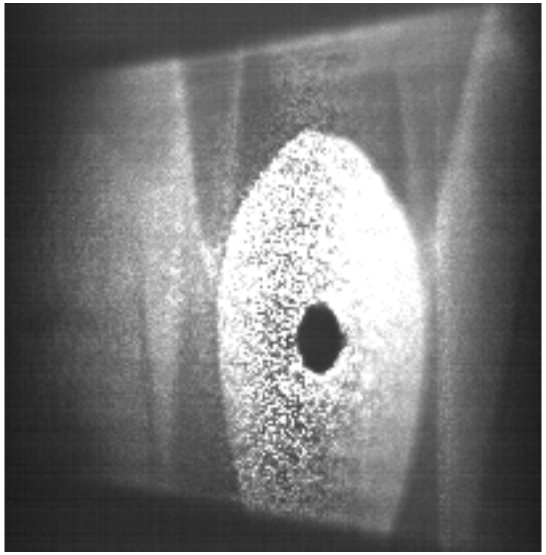

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➔ Formation of particles

NUCLEATION → COAGULATION → ACCRETION

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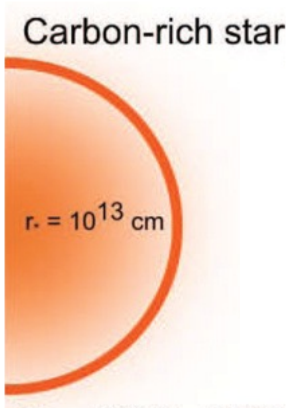

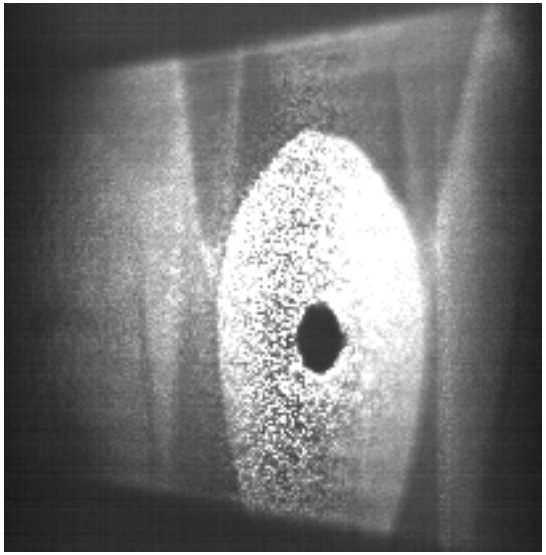

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Cosmic dusts

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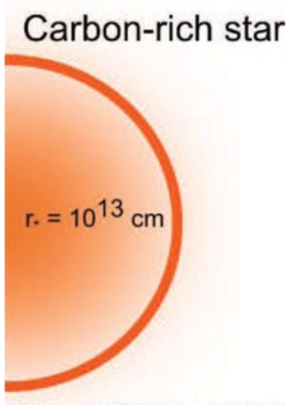

d = 10^{18} cm^{-3} d = 10^{9} cm^{-3} d = 10^{5} - 10^{3} cm^{-3}

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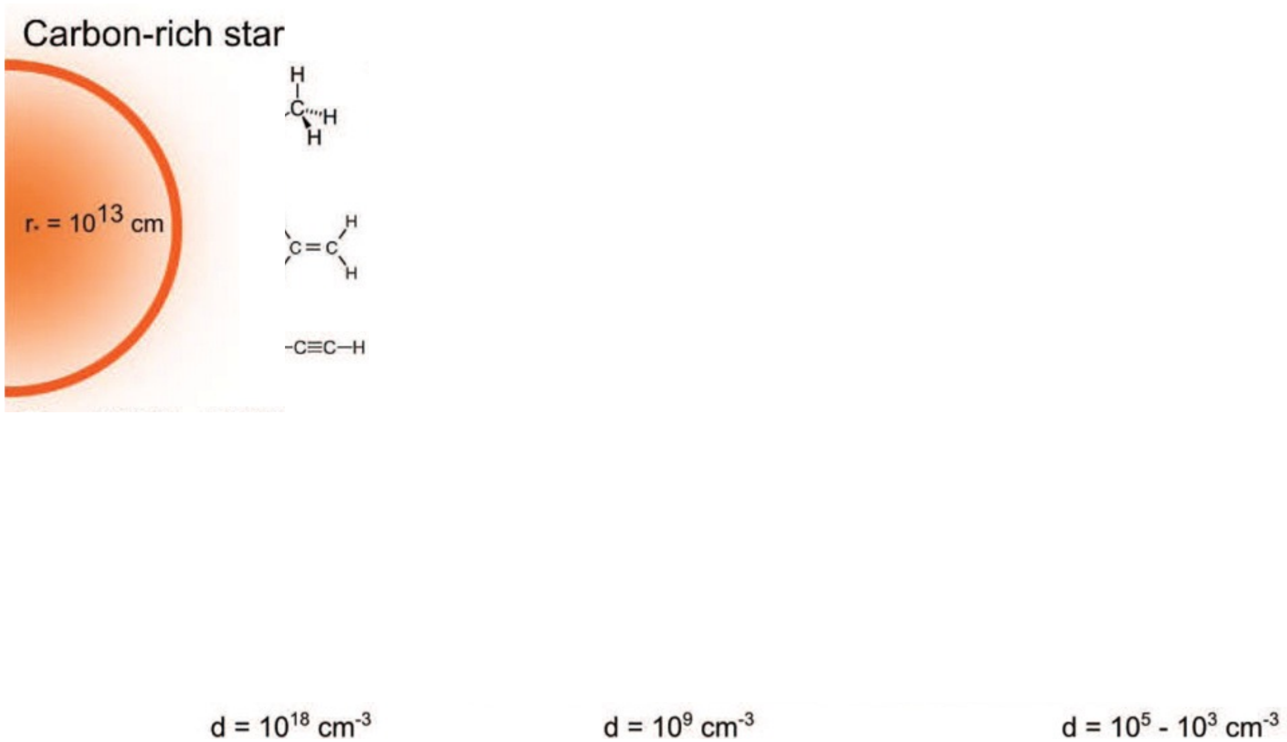
Contreras et al., *Laboratory investigations of polycyclic aromatic hydrocarbon formation and destruction in the circumstellar outflows of carbon stars*, ApJS (2013)



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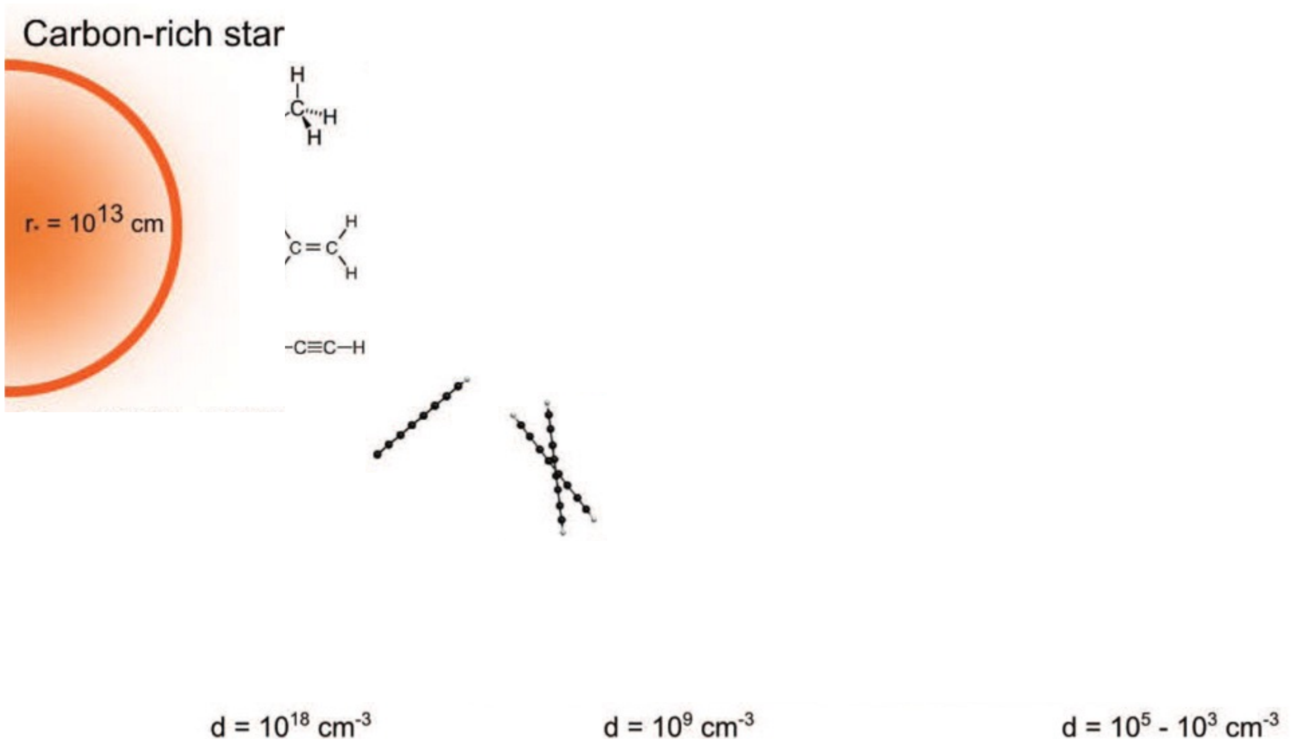

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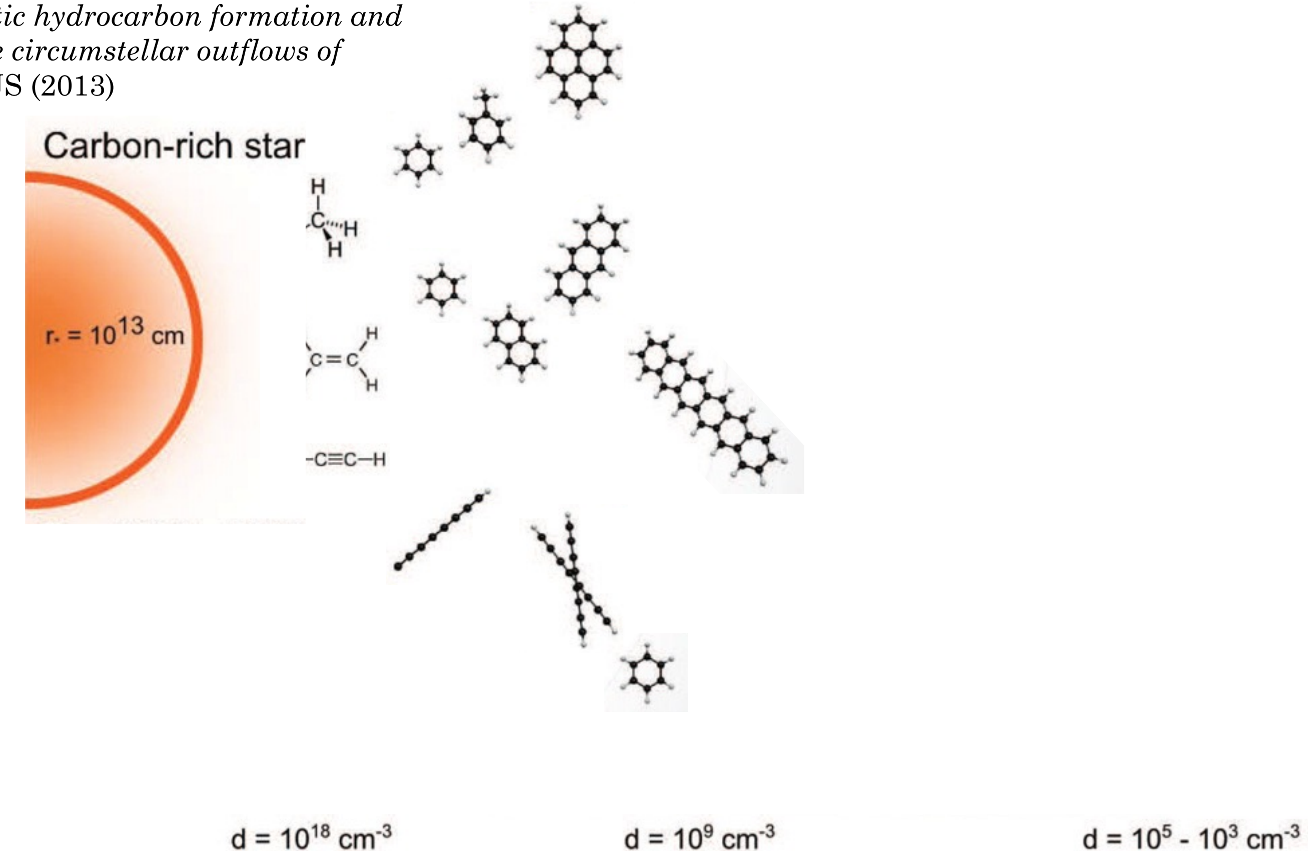

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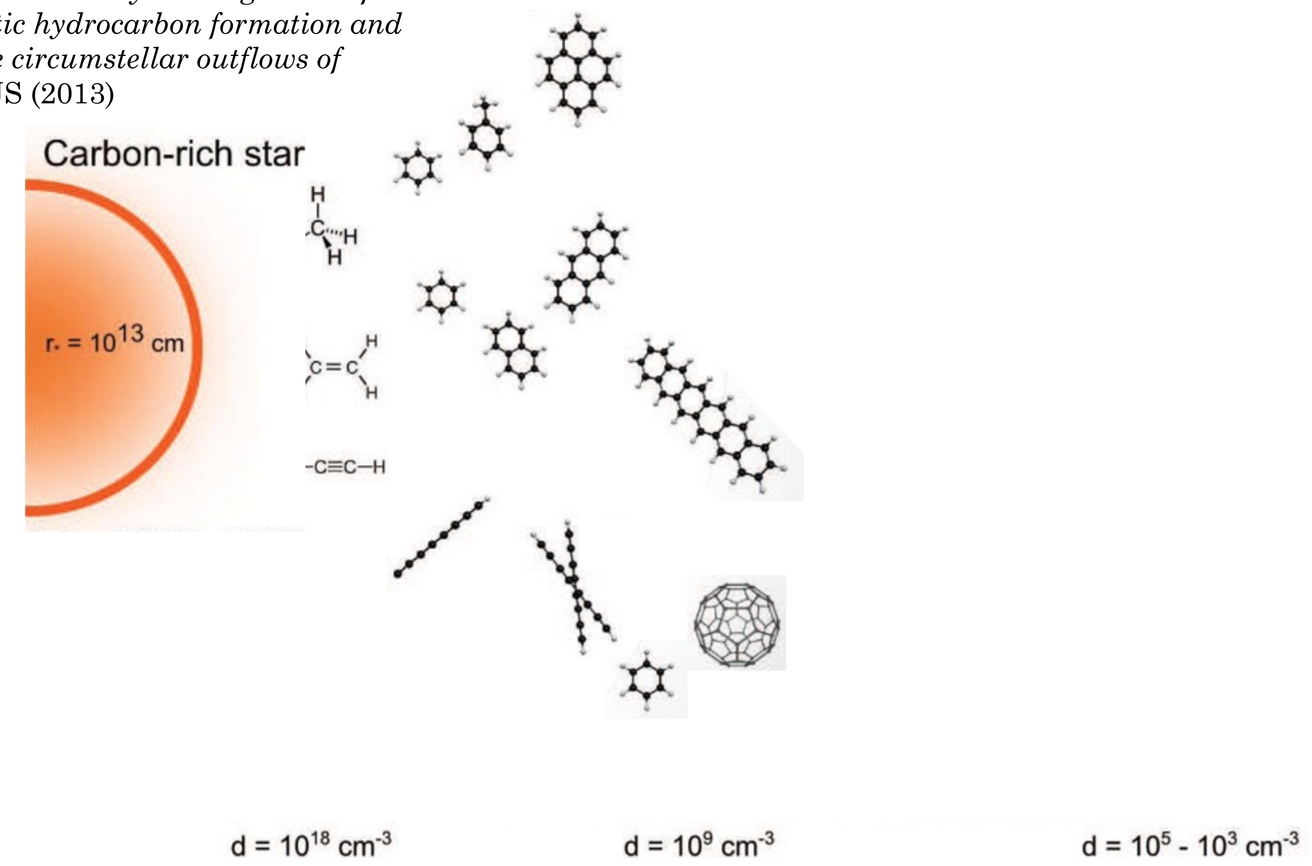

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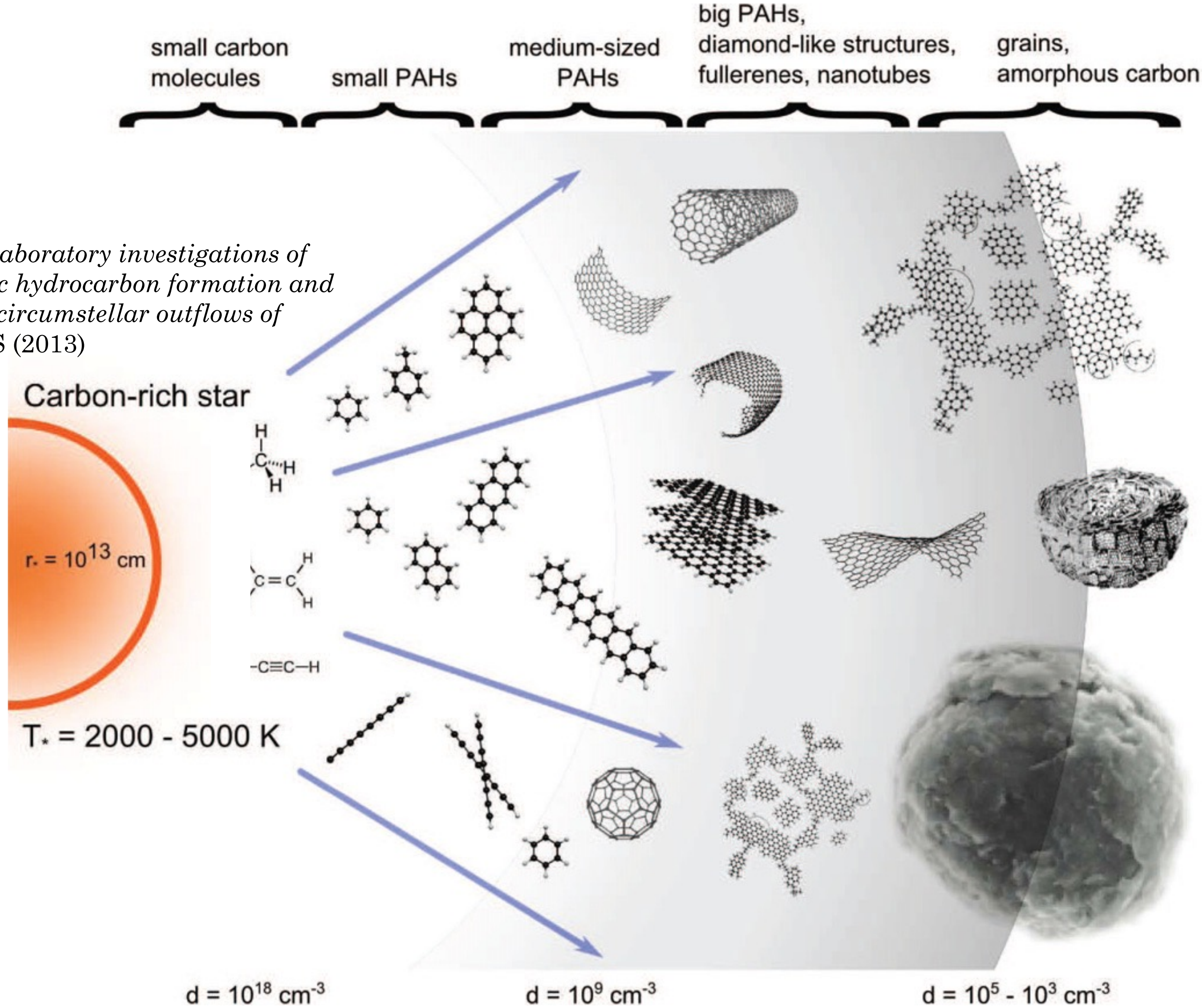
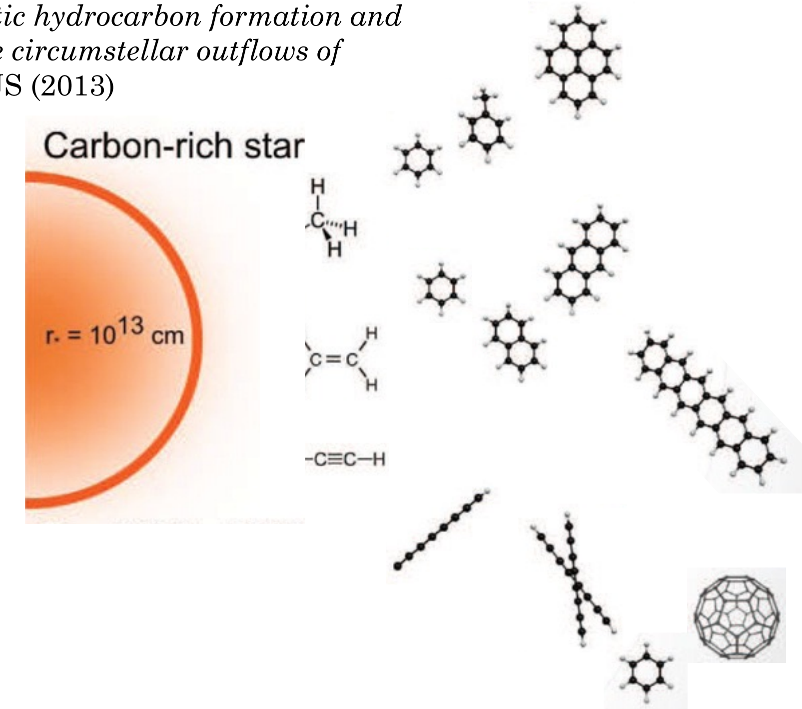


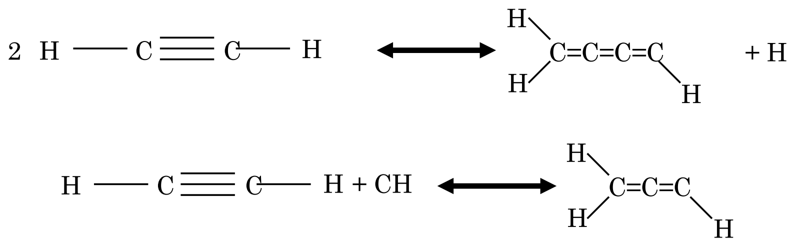
Cosmic dusts

Nucleation deduced from combustion

Contreras et al., *Laboratory investigations of polycyclic aromatic hydrocarbon formation and destruction in the circumstellar outflows of carbon stars*, ApJS (2013)



Formation of linear polyalkyne



Wang and Frenklach., *A detailed kinetic modeling study of aromatics formation in laminar premixed acetylene and ethylene flames*, Comb. Flame (1997)

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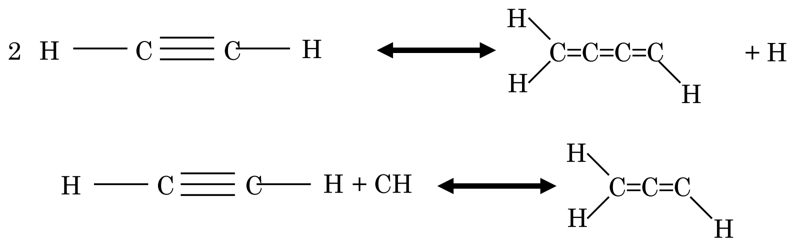
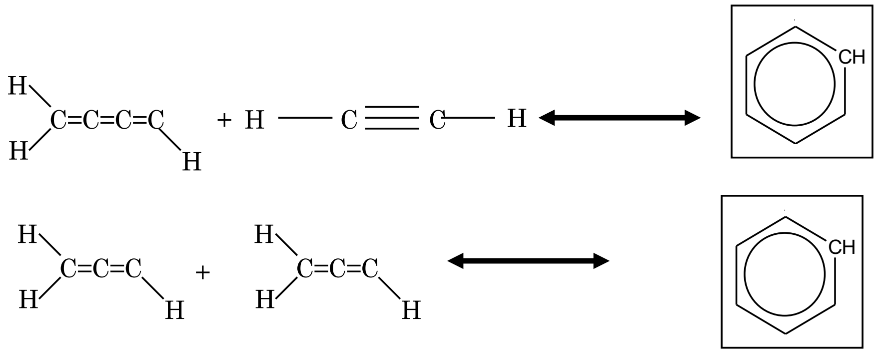


Formation of aromatic rings



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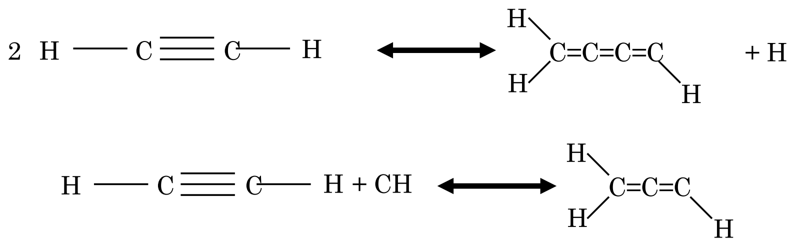

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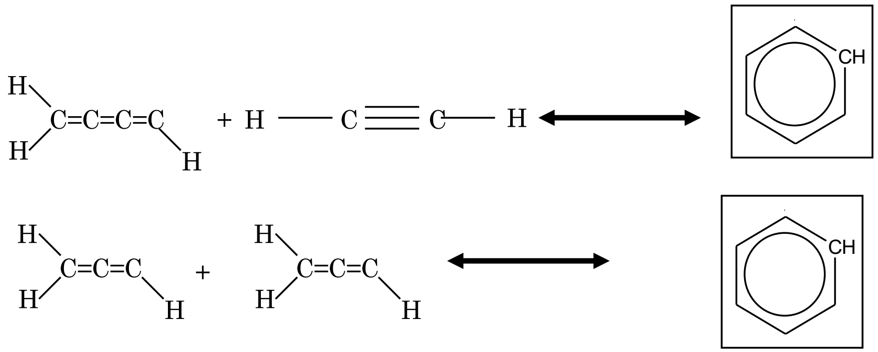
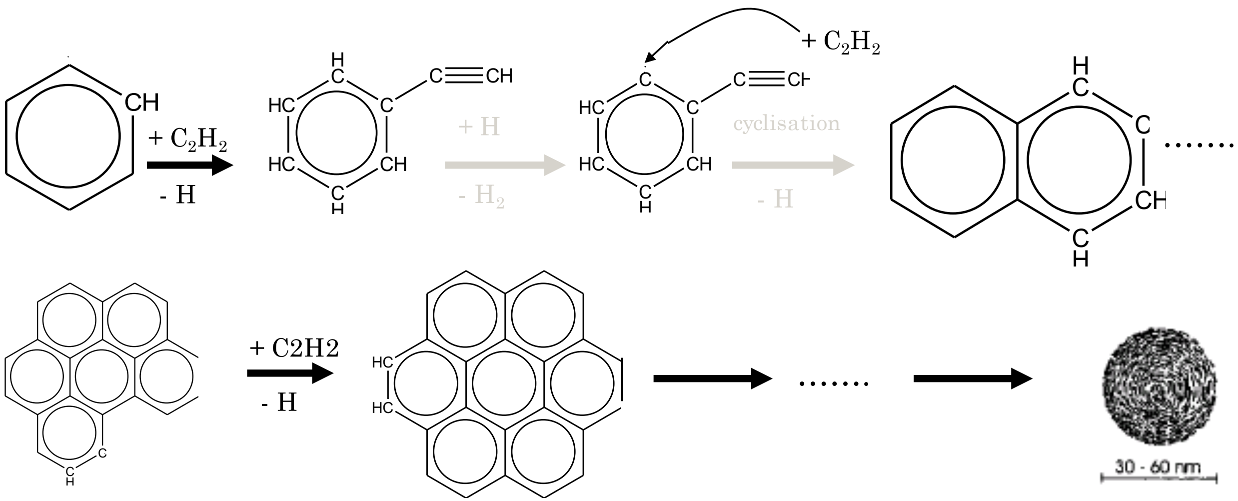


Hydrogen Abstraction Carbon Addition (HACA)



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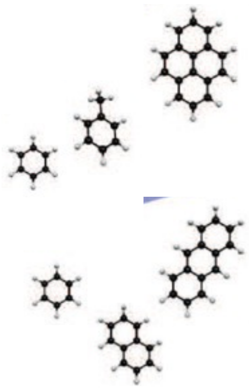
Nucleation?

PAHs formation / HACA shown in SOOTY FLAMES



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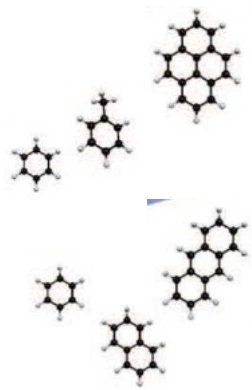


often used

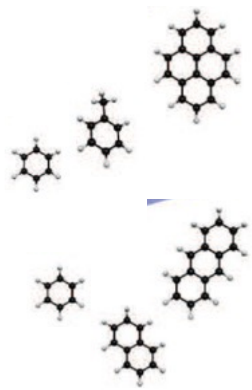
CARBON-RICH STARS

DUSTY PLASMAS

Nucleation?

PAHs formation / HACA shown in SOOTY FLAMES

$N_n = 5.10^{18}$ cm^{-3} / T = 1000-2000 K
$N_e > 10^{11}$ cm^{-3} / T_e = 0.2 eV



often used

CARBON-RICH STARS

$N_n = 5.10^{8}$ cm^{-3} / T = 2000-5000 K
$N_e \approx 2.10^{2}$ cm^{-3} / T_e = 0.1 eV

DUSTY PLASMAS

$N_n = 10^{14}$-10^{15} cm^{-3} / T = 300 K
$N_e = 10^{8}$-10^{9} cm^{-3} / T_e = 2-4 eV

Dust particle growth in plasmas

- In C_2H_2 dusty plasmas:

$$C_2H_2 \longmapsto \text{PAHs} \longmapsto \text{Dust particles}$$

De Bleecker et al., *Aromatic ring generation as a dust precursor in acetylene discharges*, APL (2006)

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MODELLING

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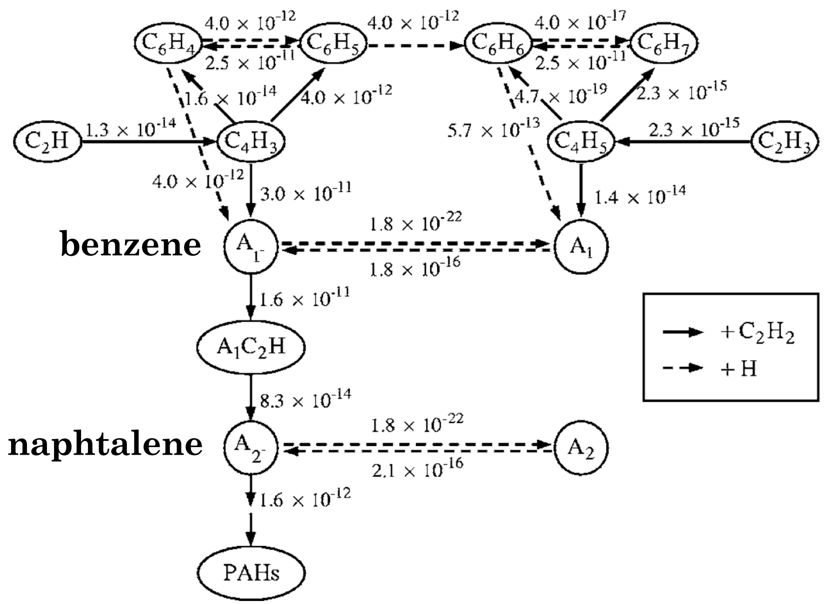

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EXPERIMENTS

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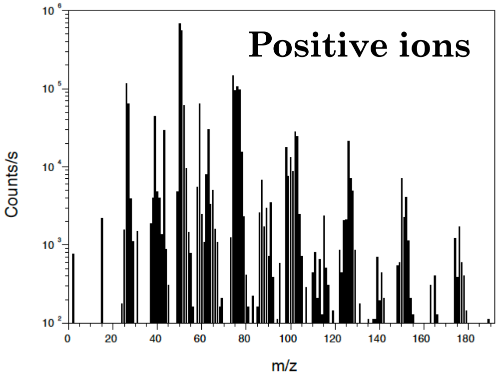

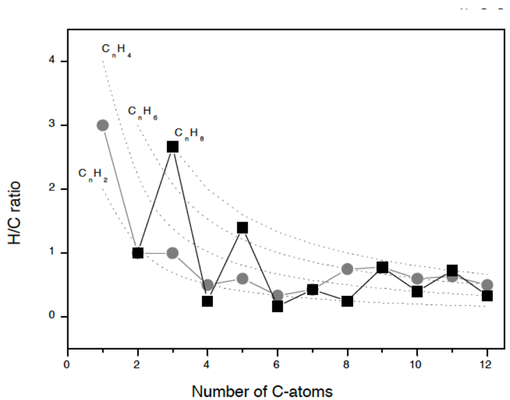

Linear polyalkynes ➔ Aromatic rings

Descheneaux et al., *Investigations of CH_4, C_2H_2 and C_2H_4 dusty RF plasmas by means of FTIR absorption spectroscopy and mass spectrometry*, JPD (1999)

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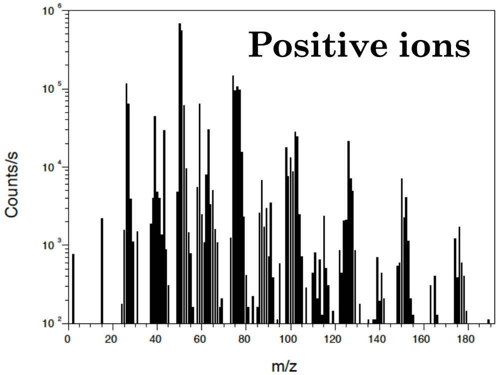

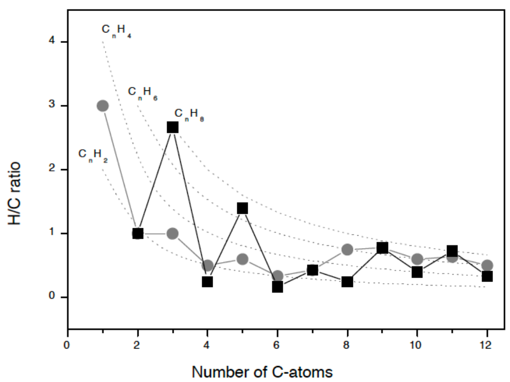

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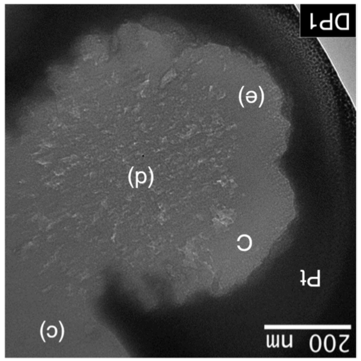
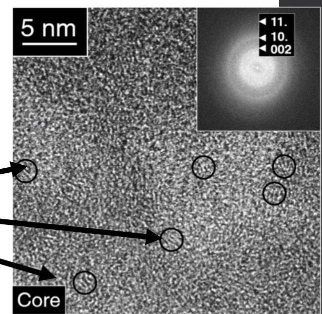
Microscopy



Very small grains

PAHs?



Al Makdessi et al., *Influence of a magnetic field on the formation of carbon dust particles in very low-pressure high-density plasmas*, JPD (2016)

No real evidence of PAHs

Dust particle growth in plasmas

- tricky under specific experimental conditions

  for example, with the working pressure

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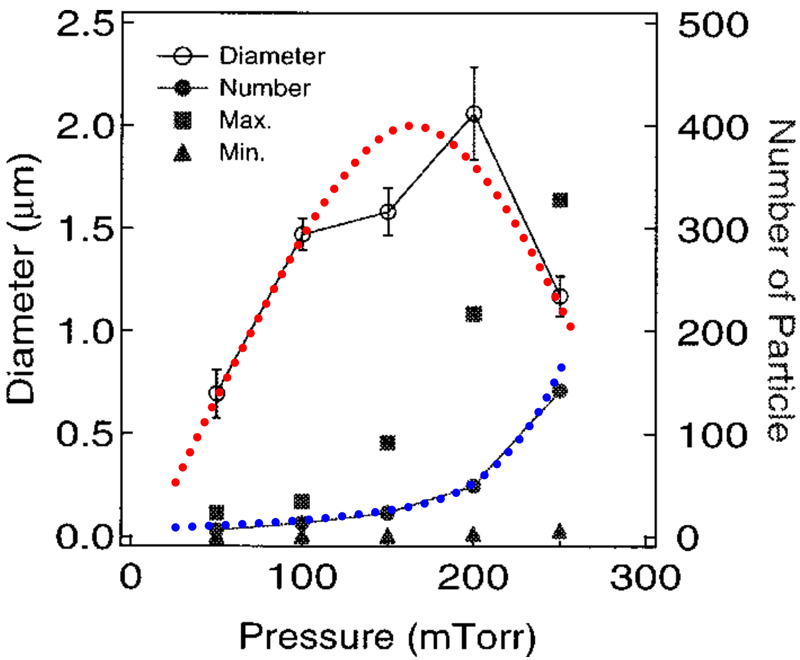


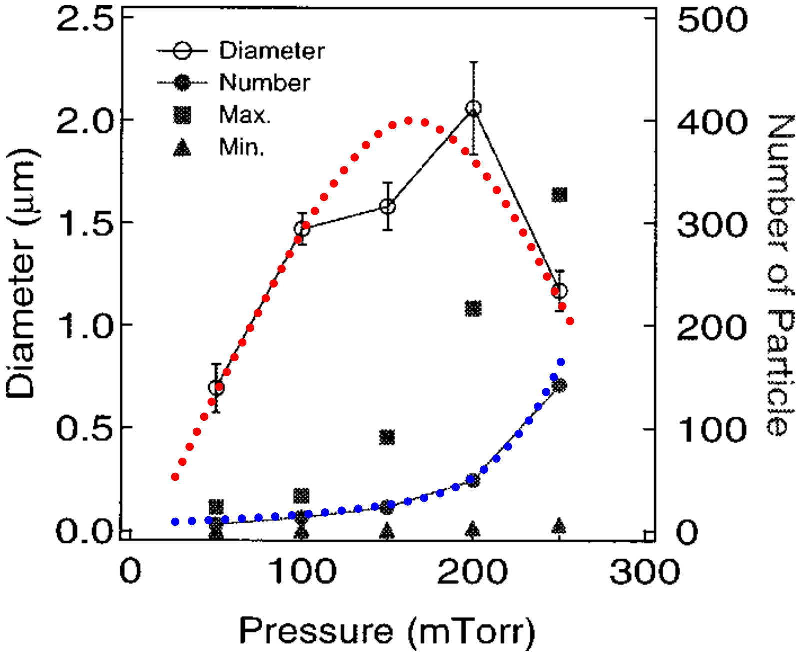
Takahashi et al., *Solid particle production in fluorocarbon plasmas. I. Correlation with polymer film deposition*, JVSTA (2001)

At low-pressure
➔ probability of recombination <<

Dust particle growth in plasmas

- tricky under specific experimental conditions

for example, with the working pressure



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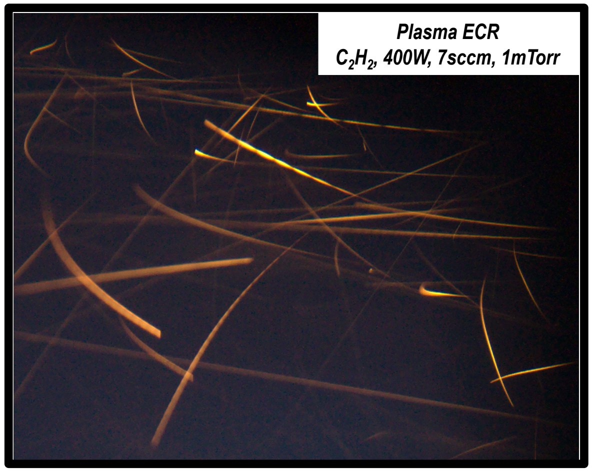
However…



Drenik et al., *Trajectories of dust particles in low-pressure magnetized plasma*, IEEETPS (2011)

No real evidence of PAHs

What's happening at really low-pressure?

Outline

ECR plasmas

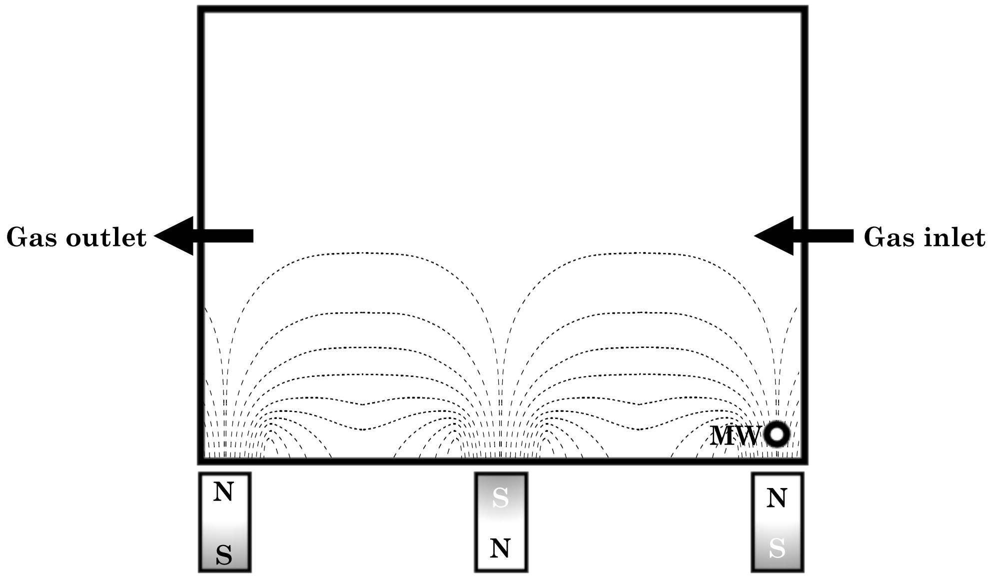
➔ static magnetic field

→ electron confinement

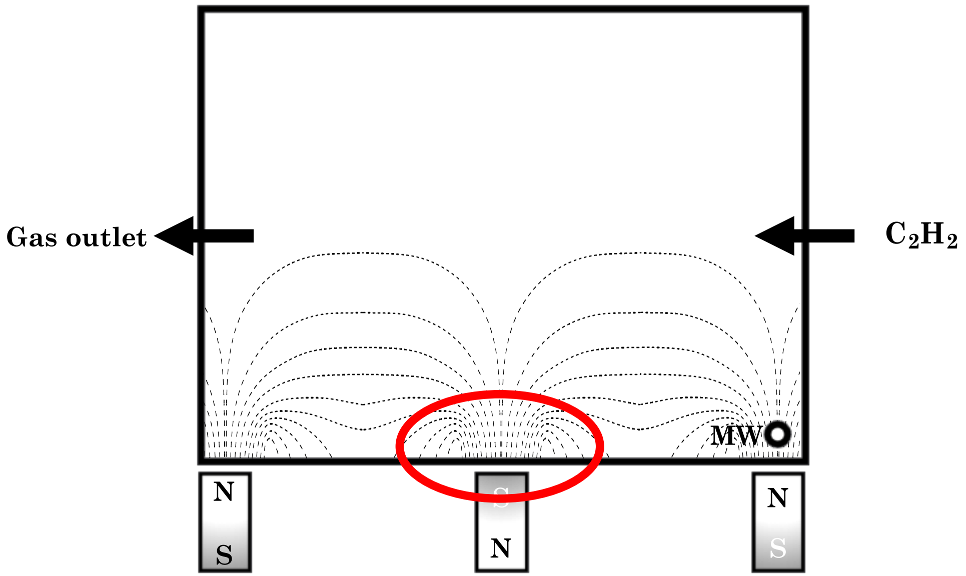
→ electron heating

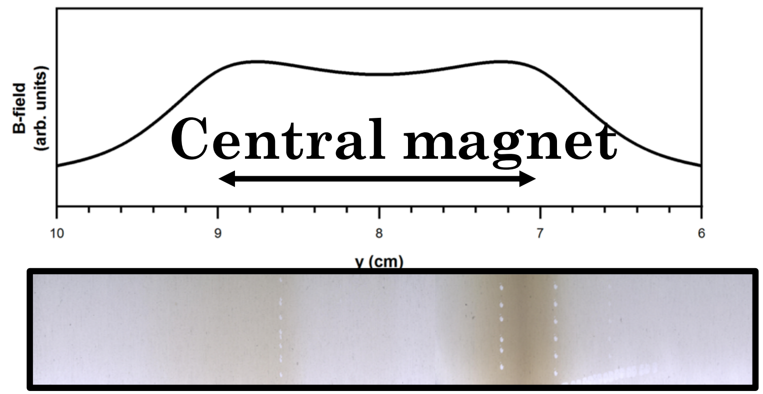
B=875 Gauss <=> microwave (2.45 GHz)

➔ really-low pressure regime – 0.1 Pa



ECR plasmas / C_2H_2





Deposition above the magnets / edges

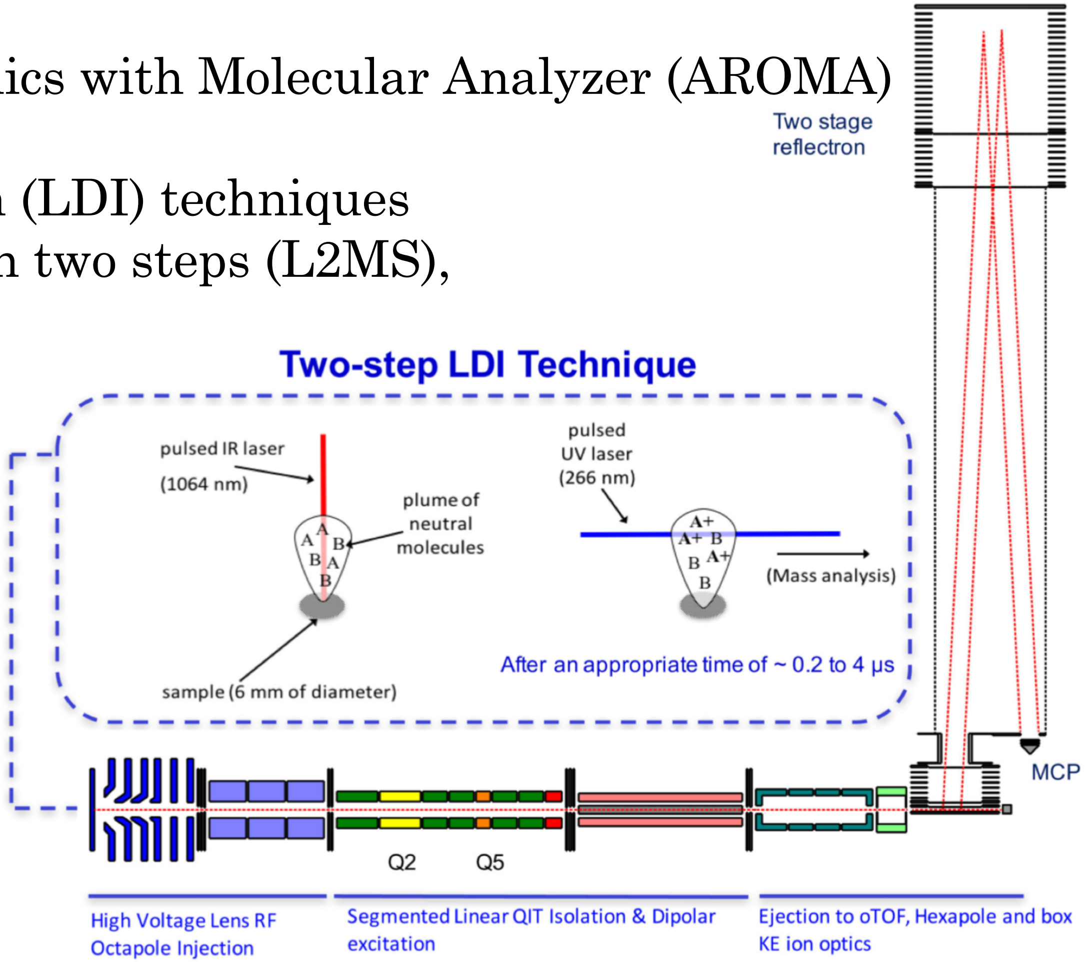
Ex-situ measurments

Microscopies (SEM / TEM)

Spectroscopies

Astrochemistry Research of Organics with Molecular Analyzer (AROMA)

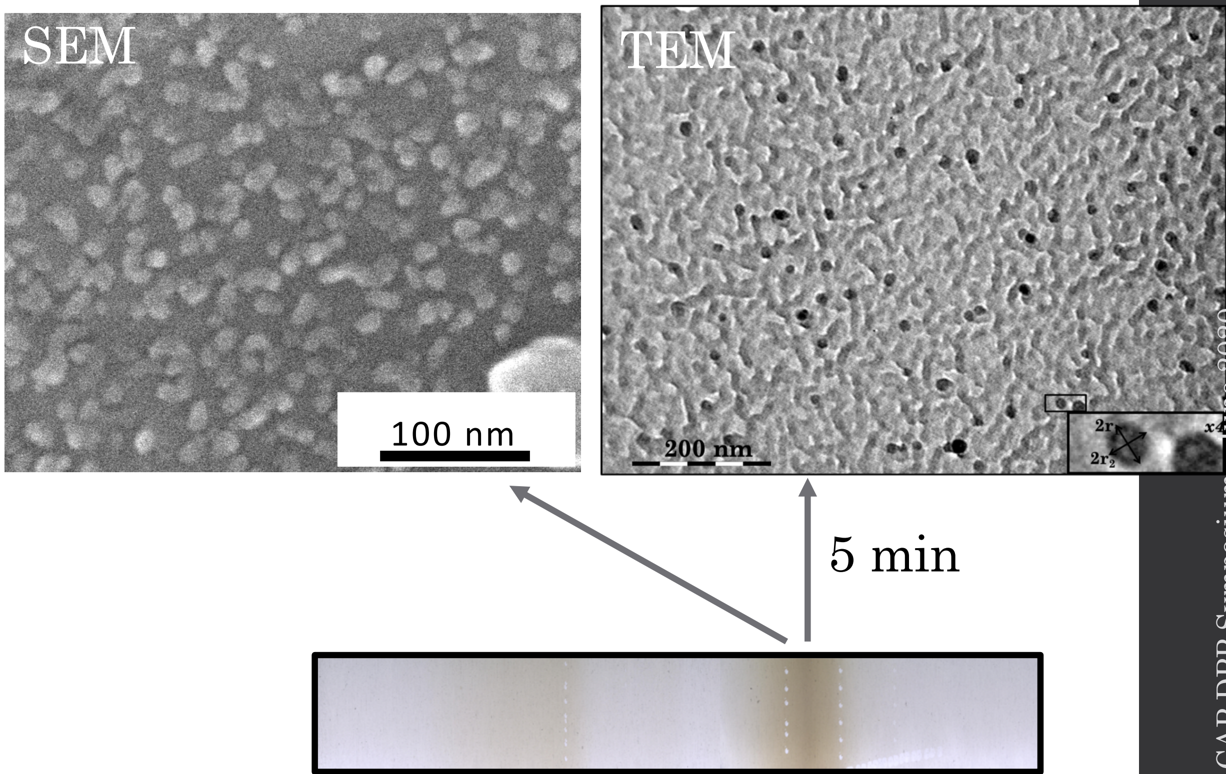
couples laser desorption/ionization (LDI) techniques
with ion trap mass spectrometry in two steps (L2MS),



Sabbah et al., *Identification of PAH Isomeric Structure in Cosmic Dust Analogues: the AROMA setup*, ApJ (2017)

Outline

ECR plasmas / C_2H_2



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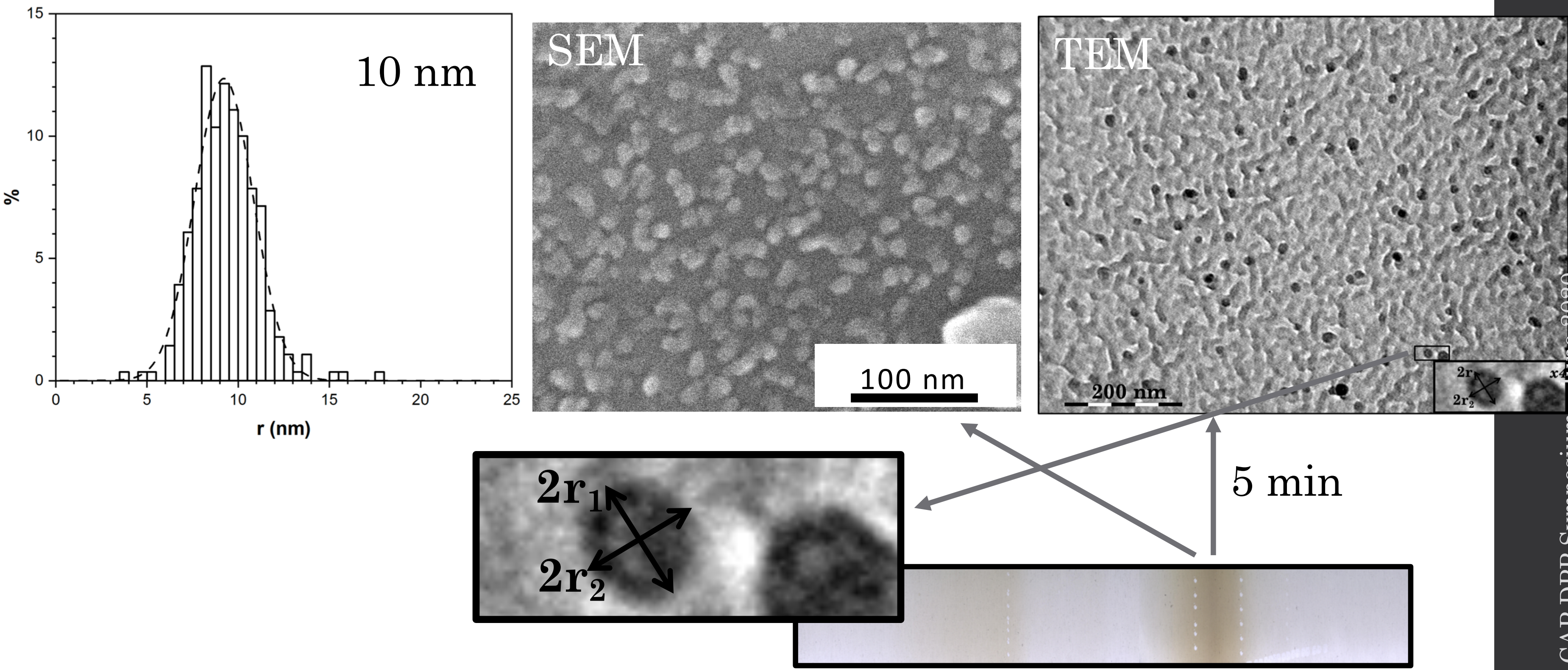

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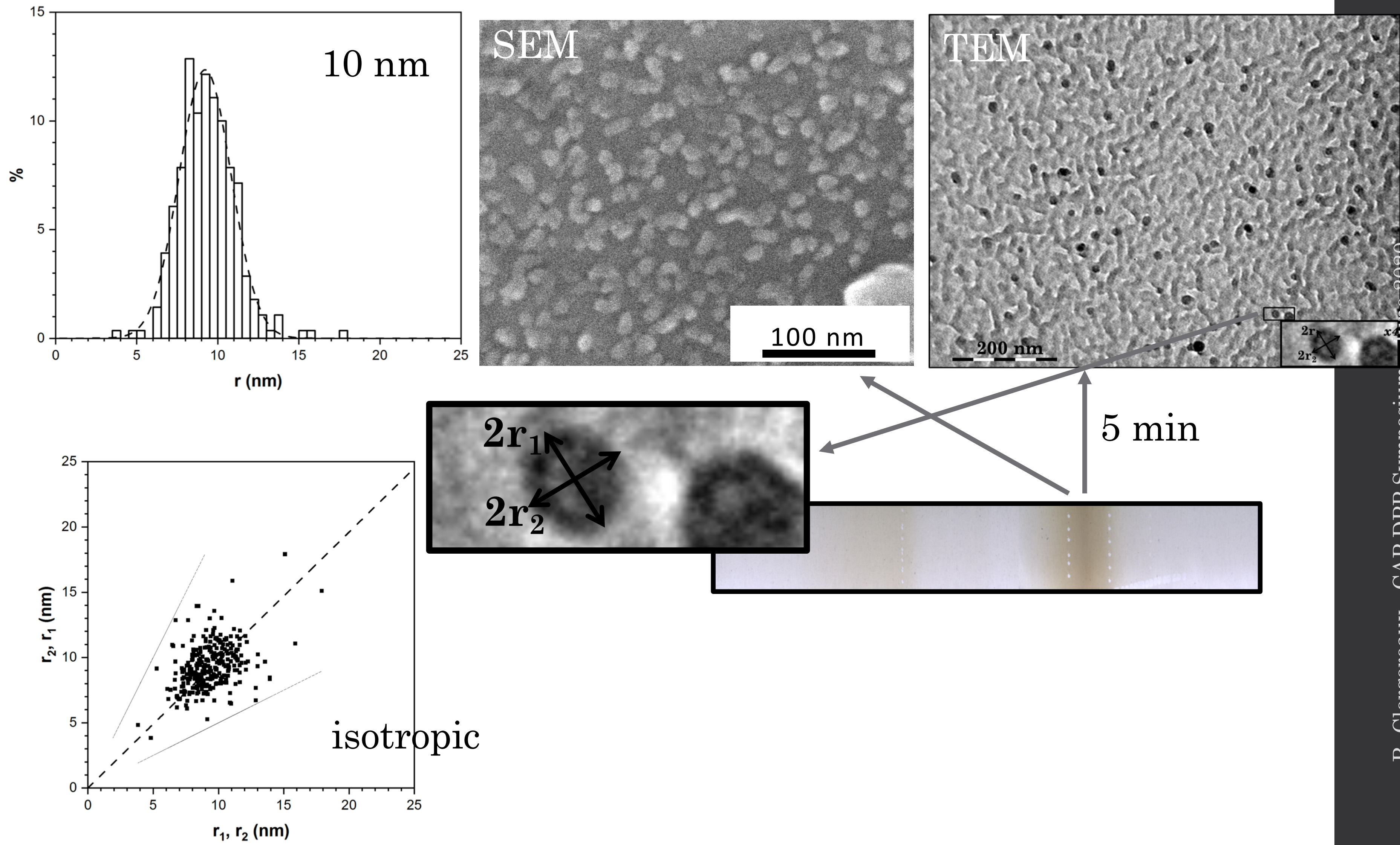
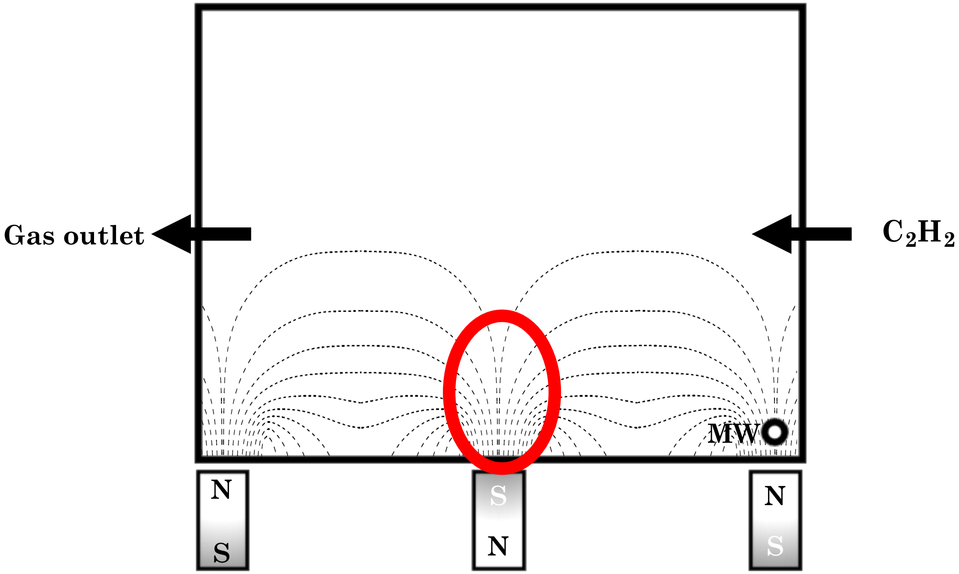
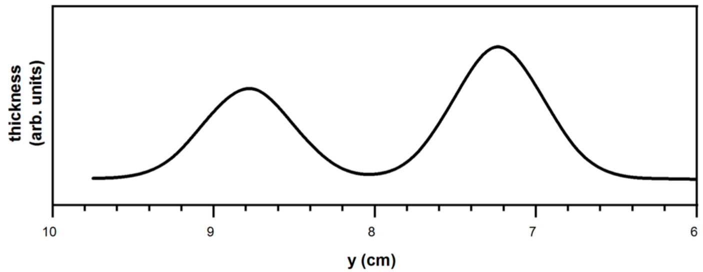
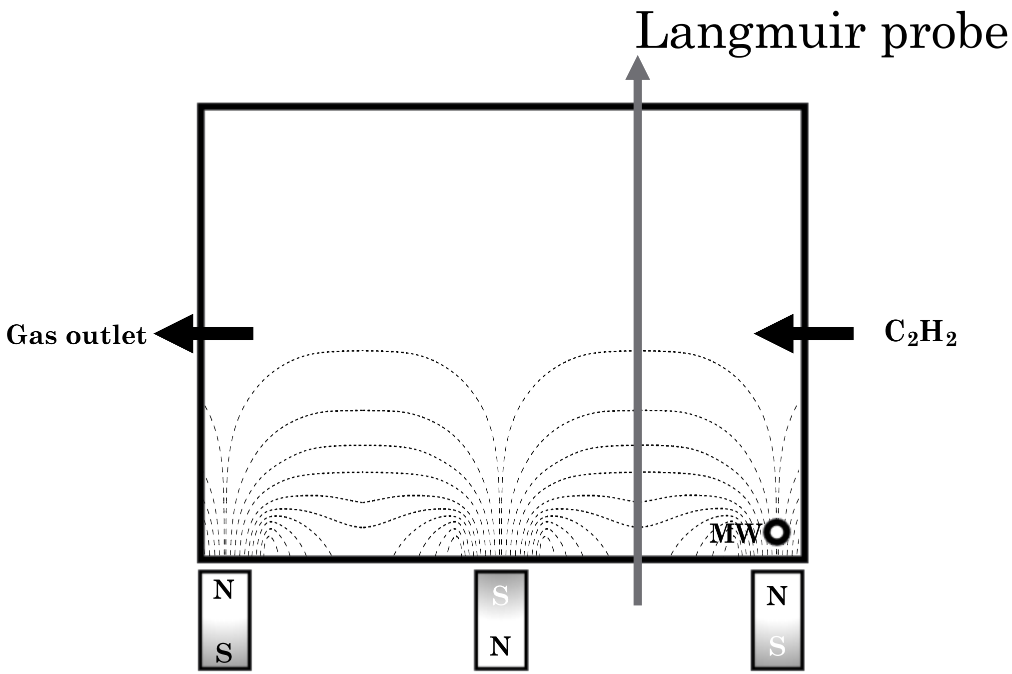






➔ Growth in the plasma volume

Growth processes?



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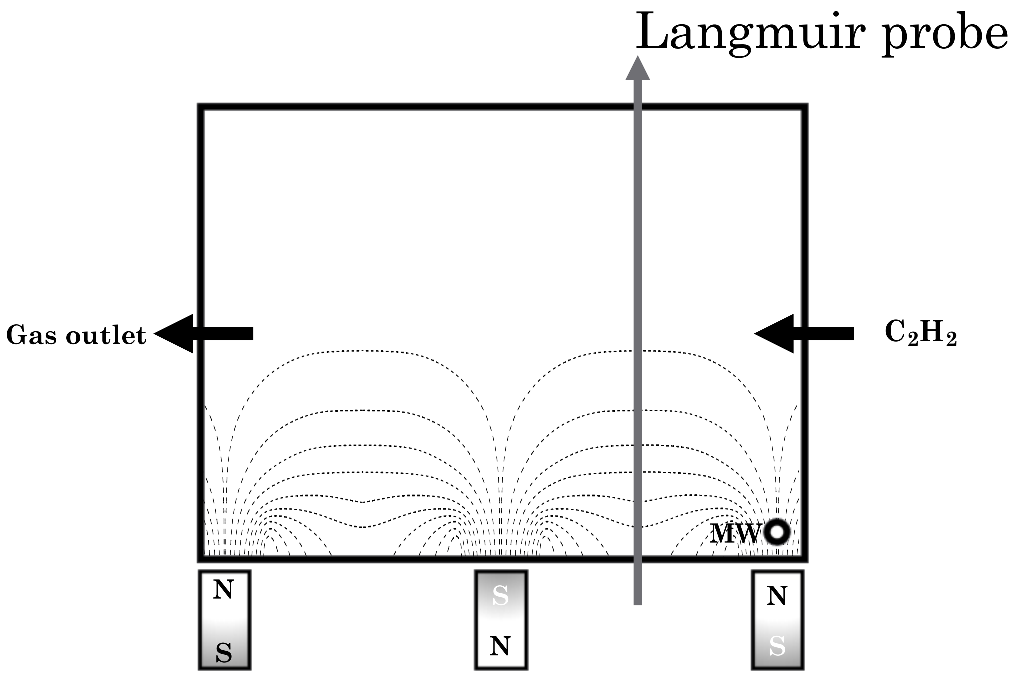

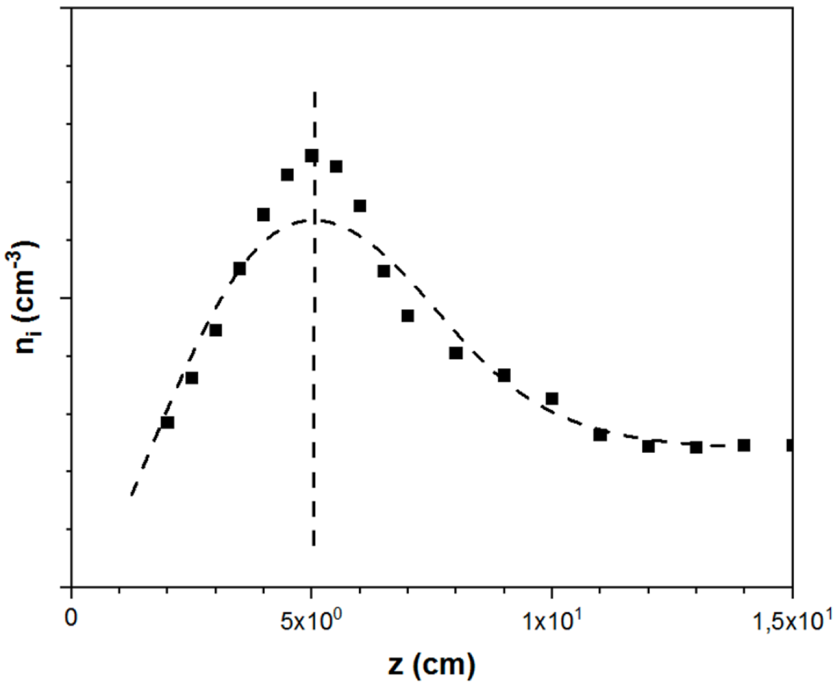

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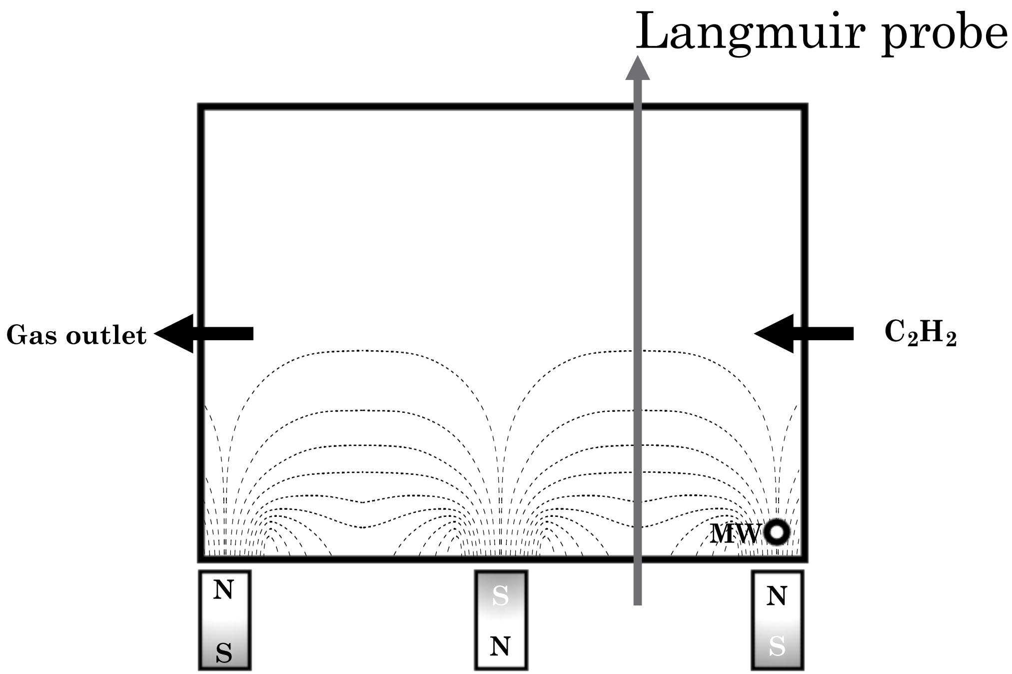

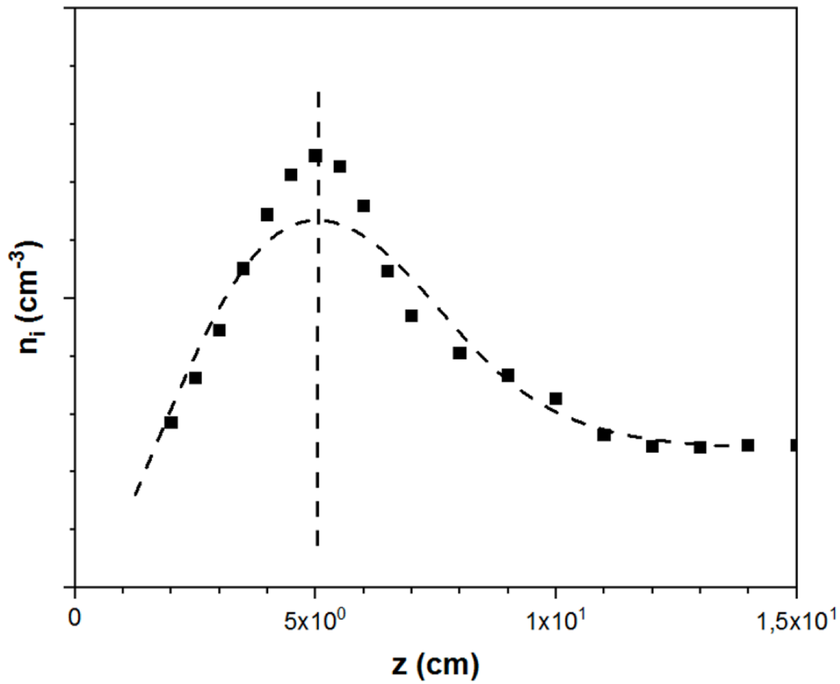

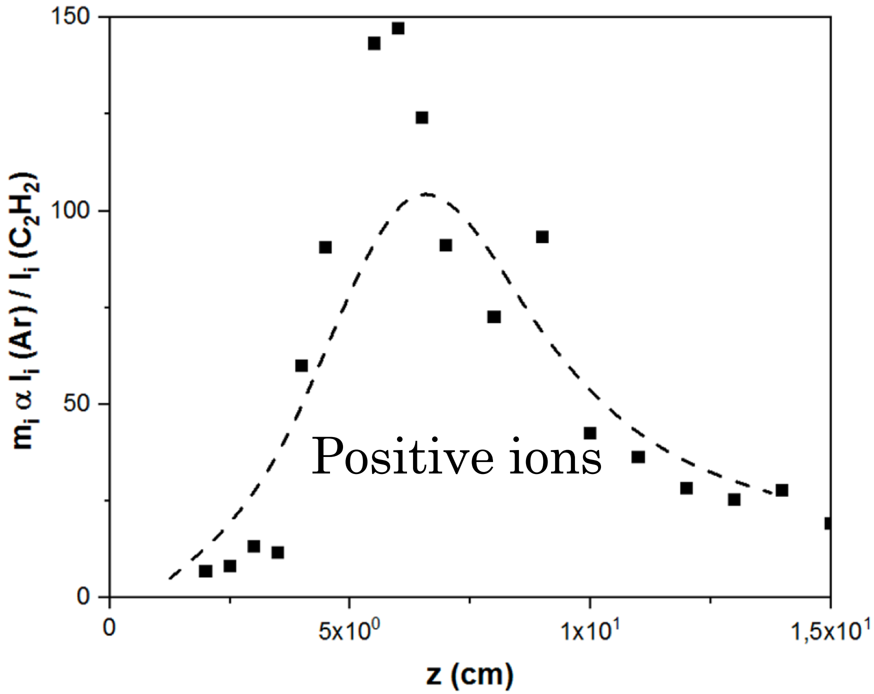

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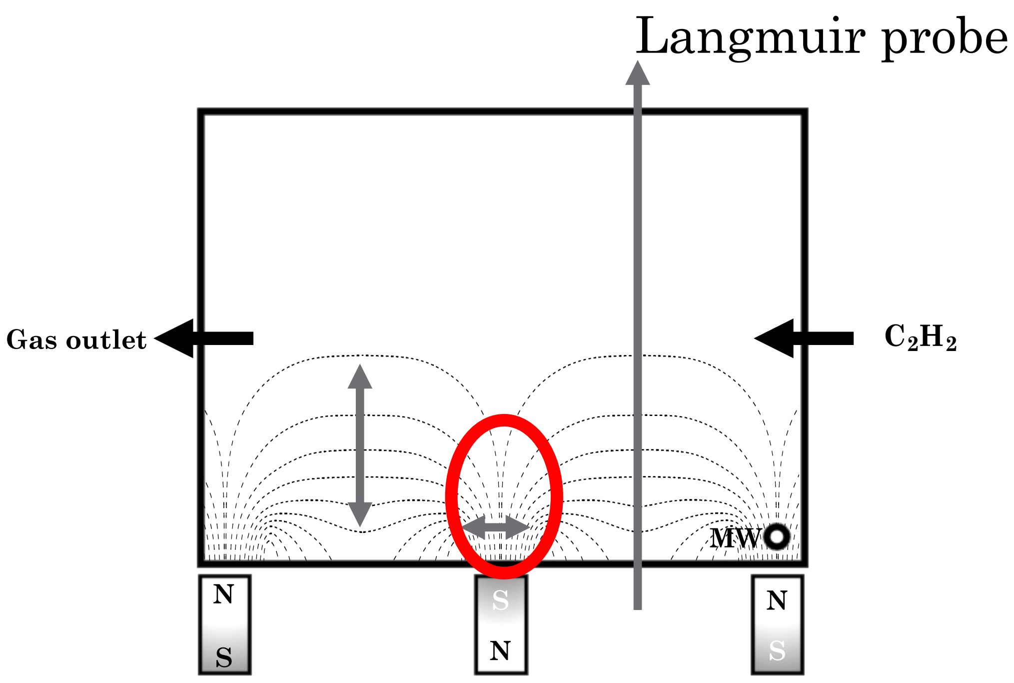
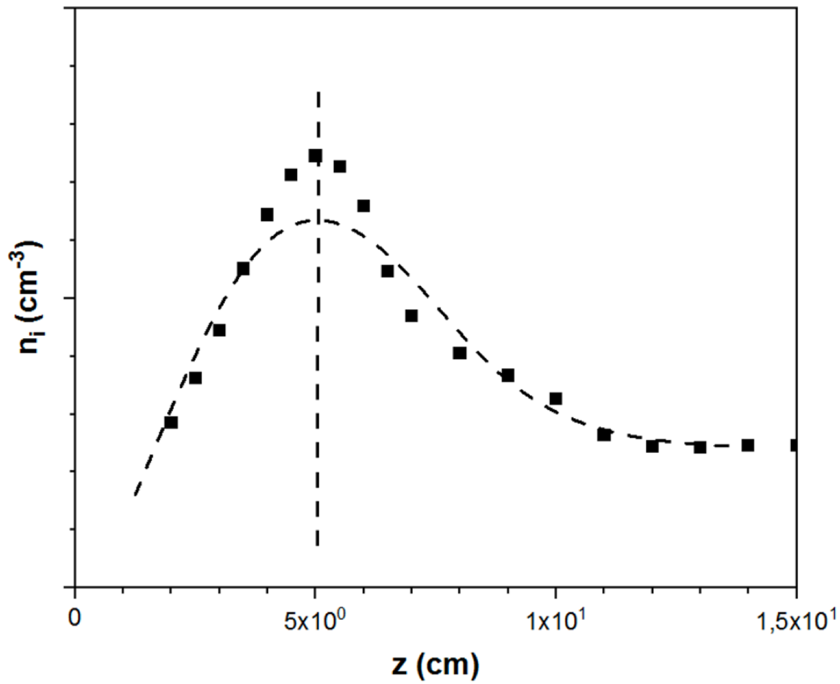
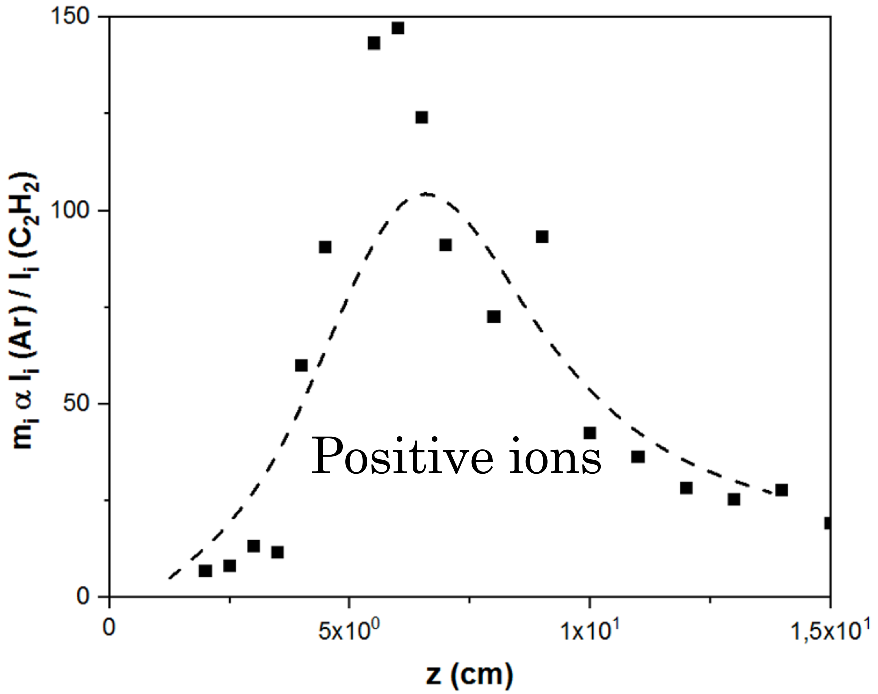
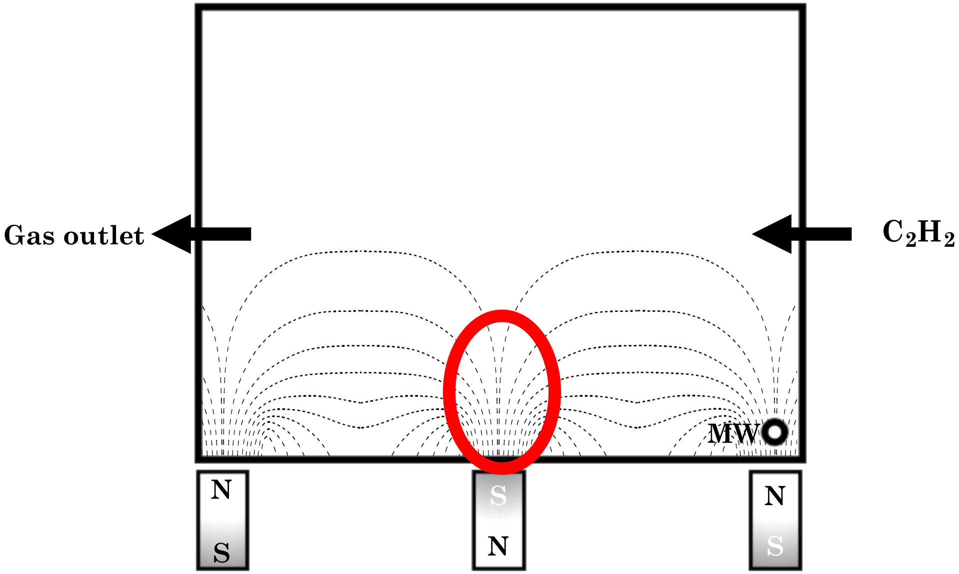
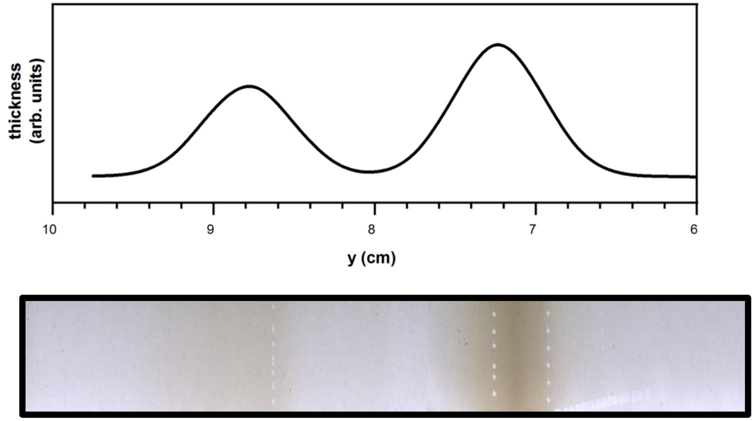




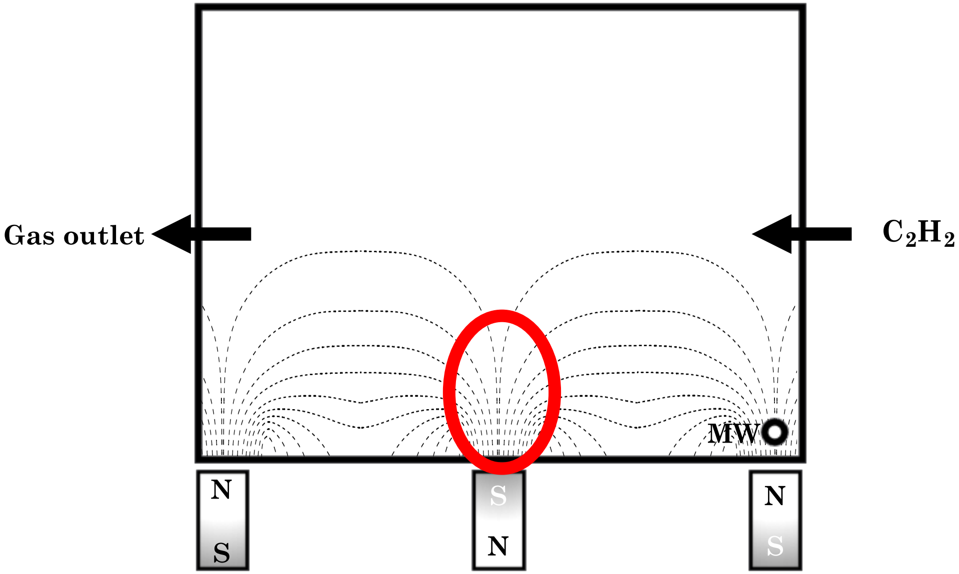


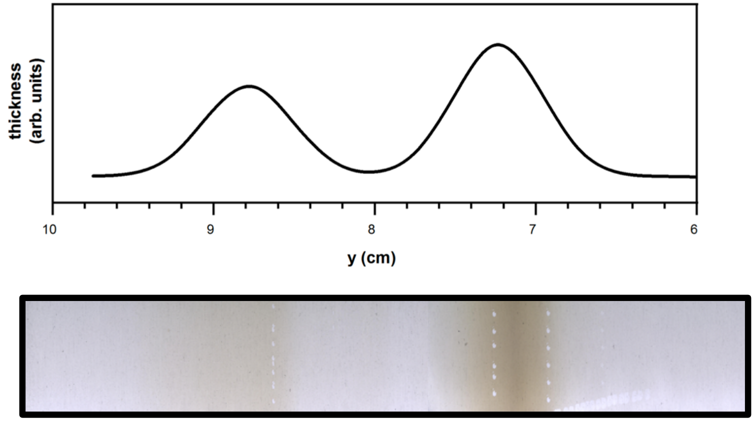




➔ Growth in the plasma volume

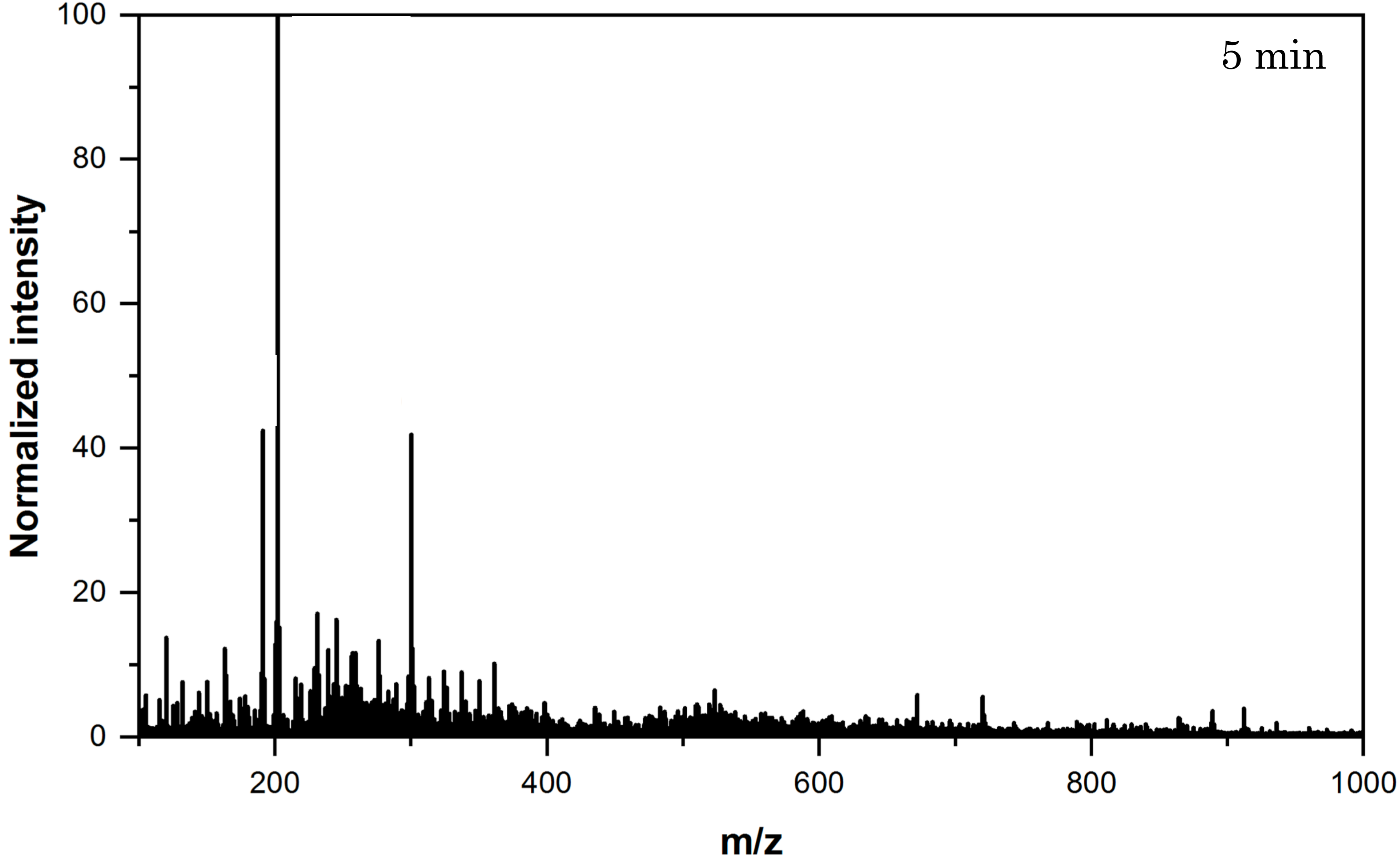
➔ Local growth



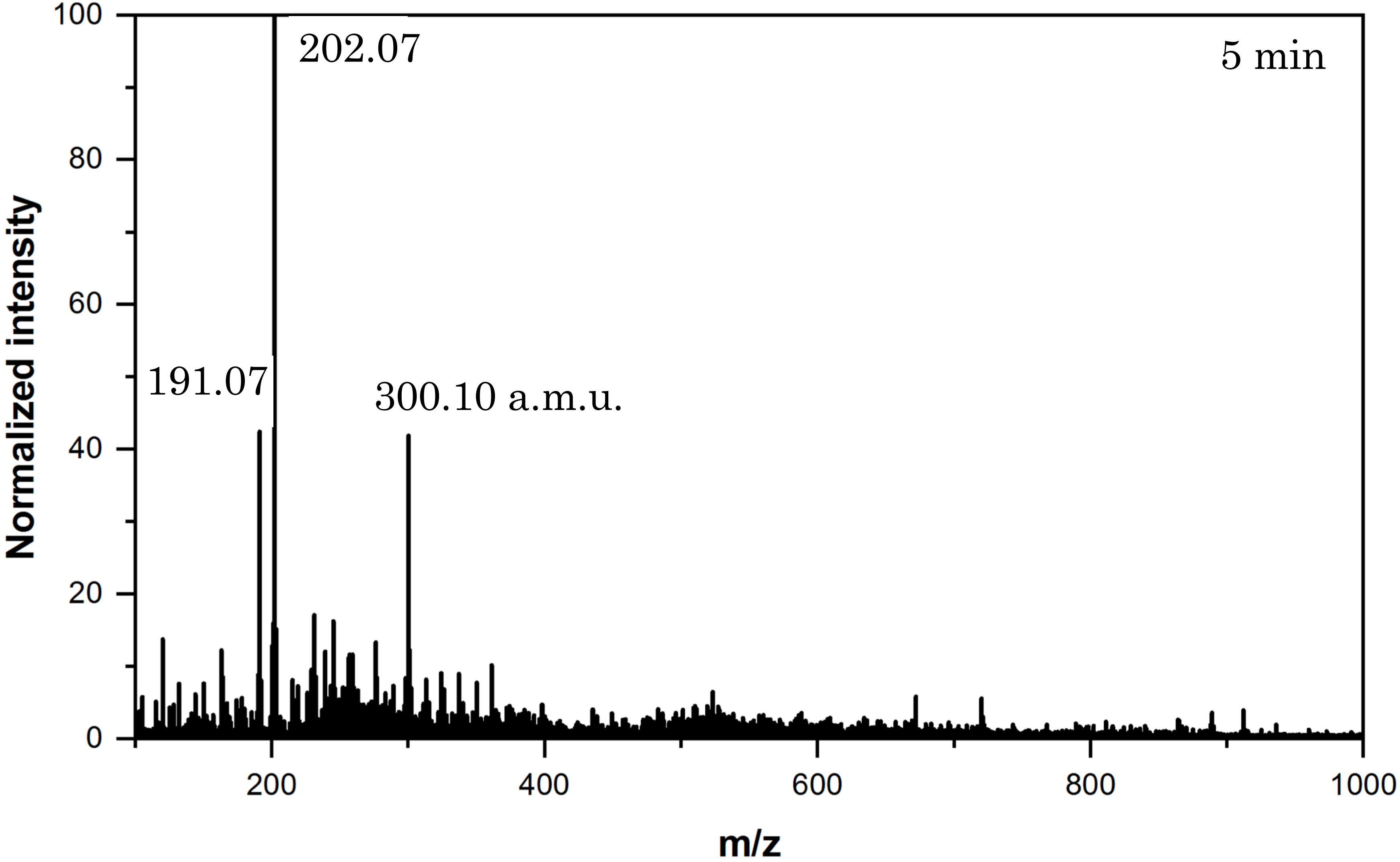


- ➔ Growth in the plasma volume
- ➔ Local growth
- ➔ Molecular composition?

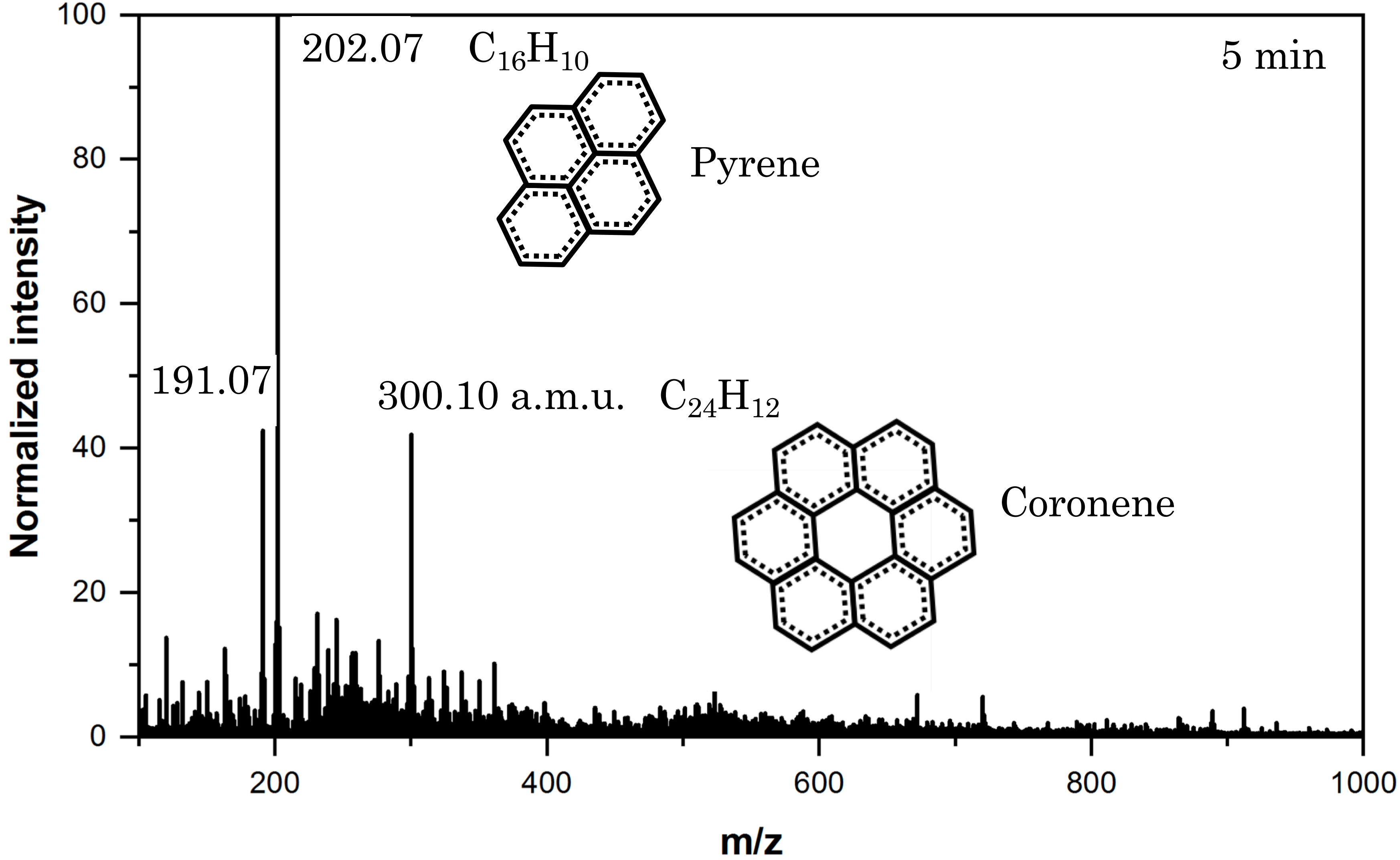
AROMA analyses



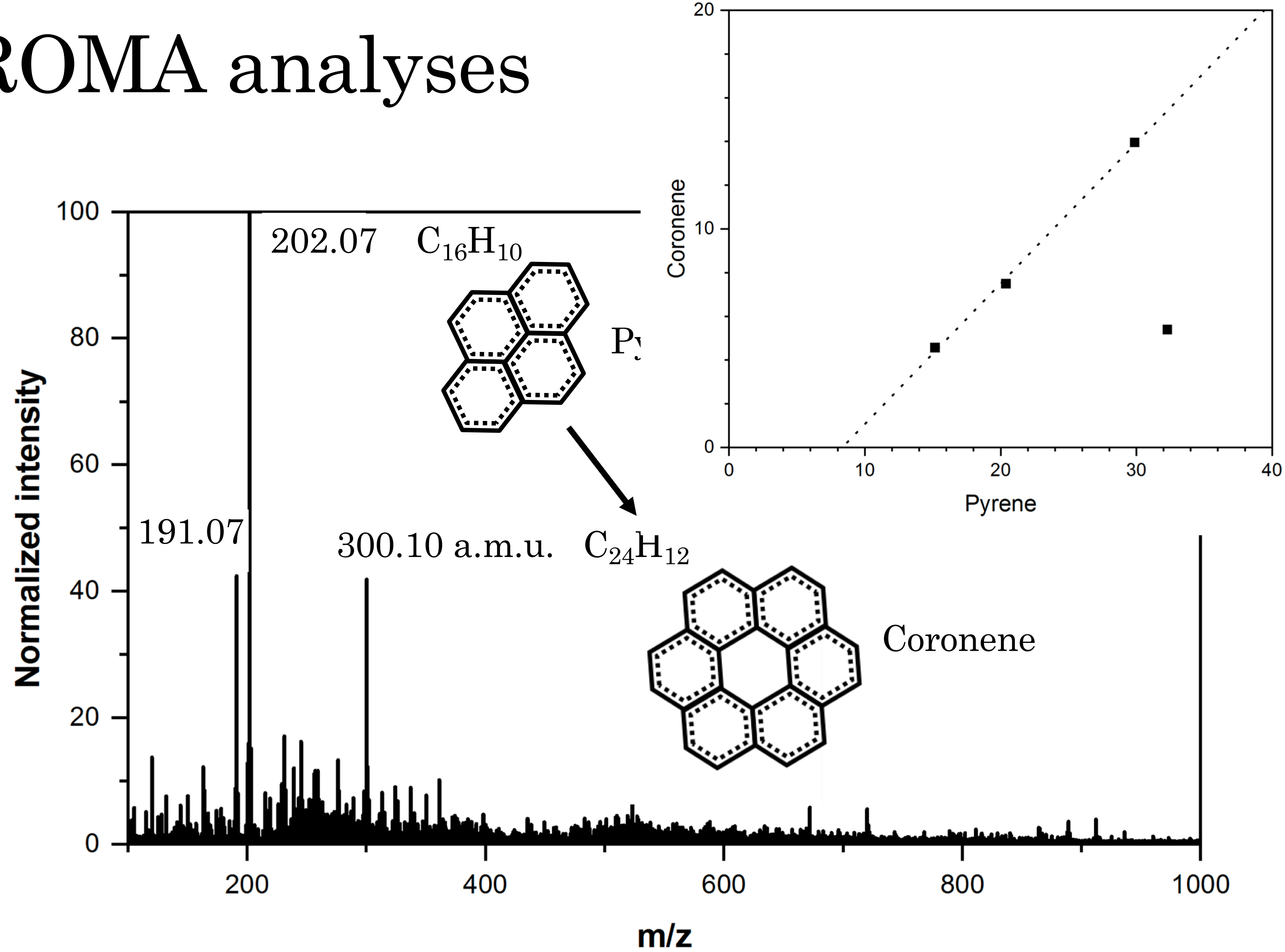
AROMA analyses



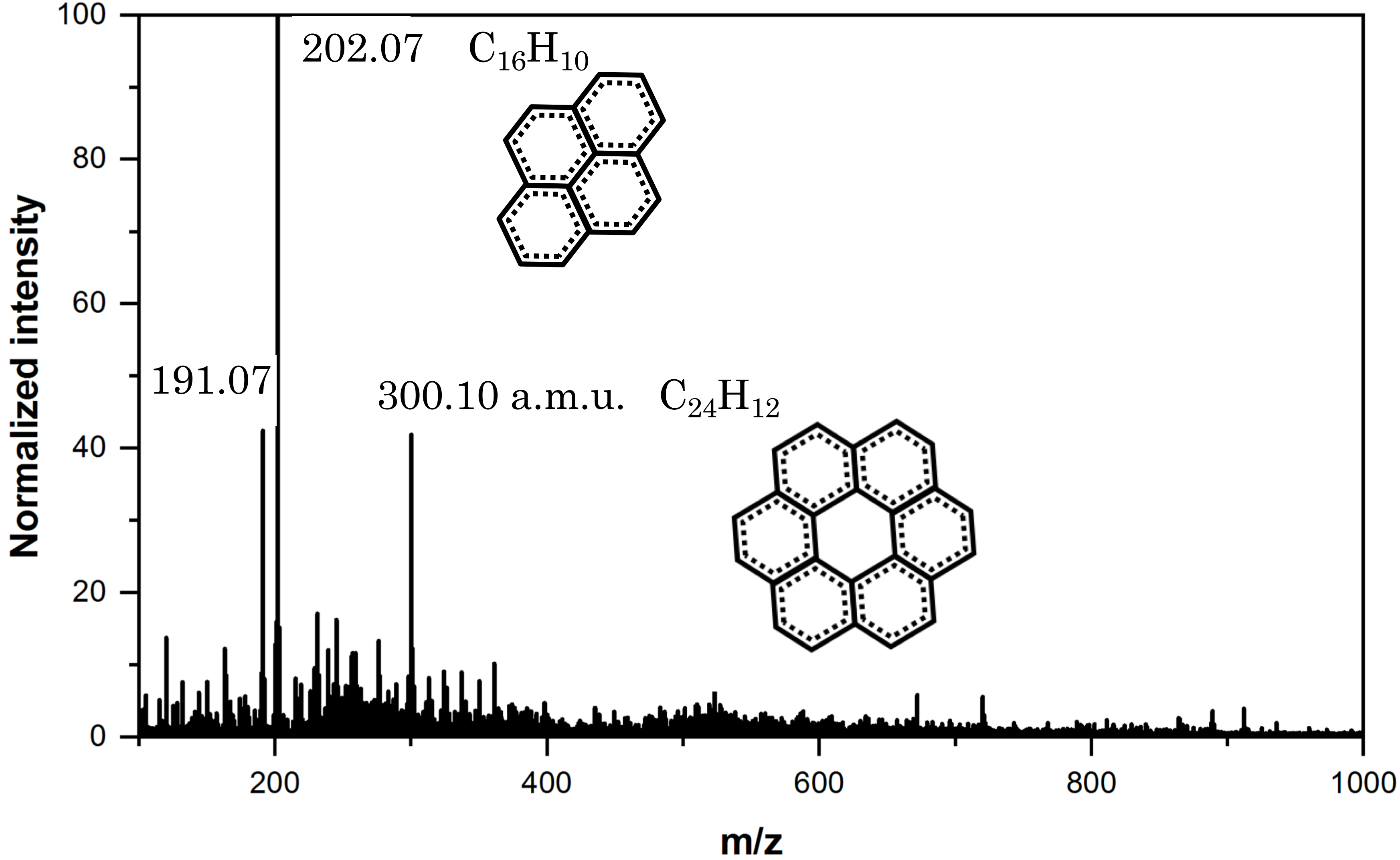
AROMA analyses



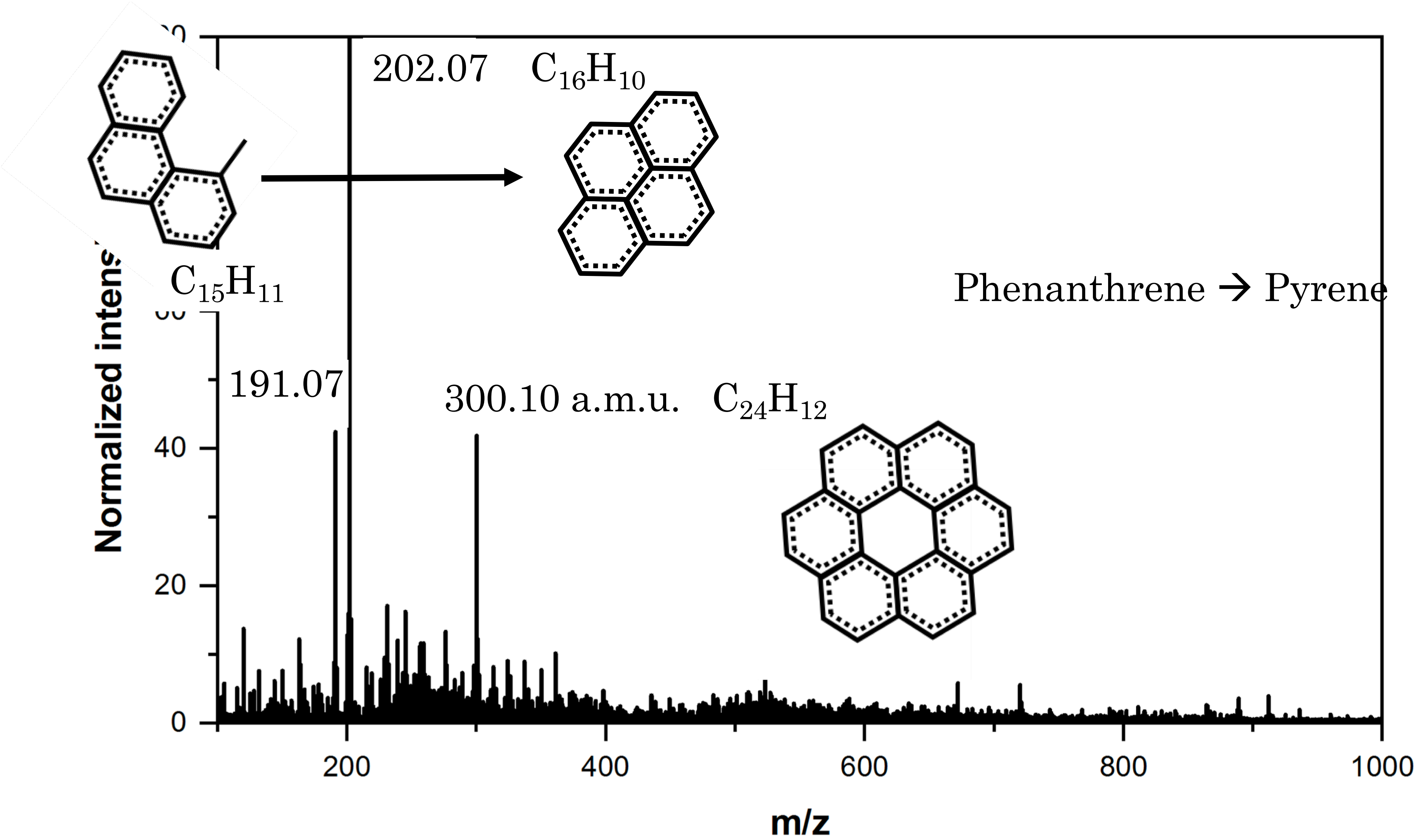
AROMA analyses



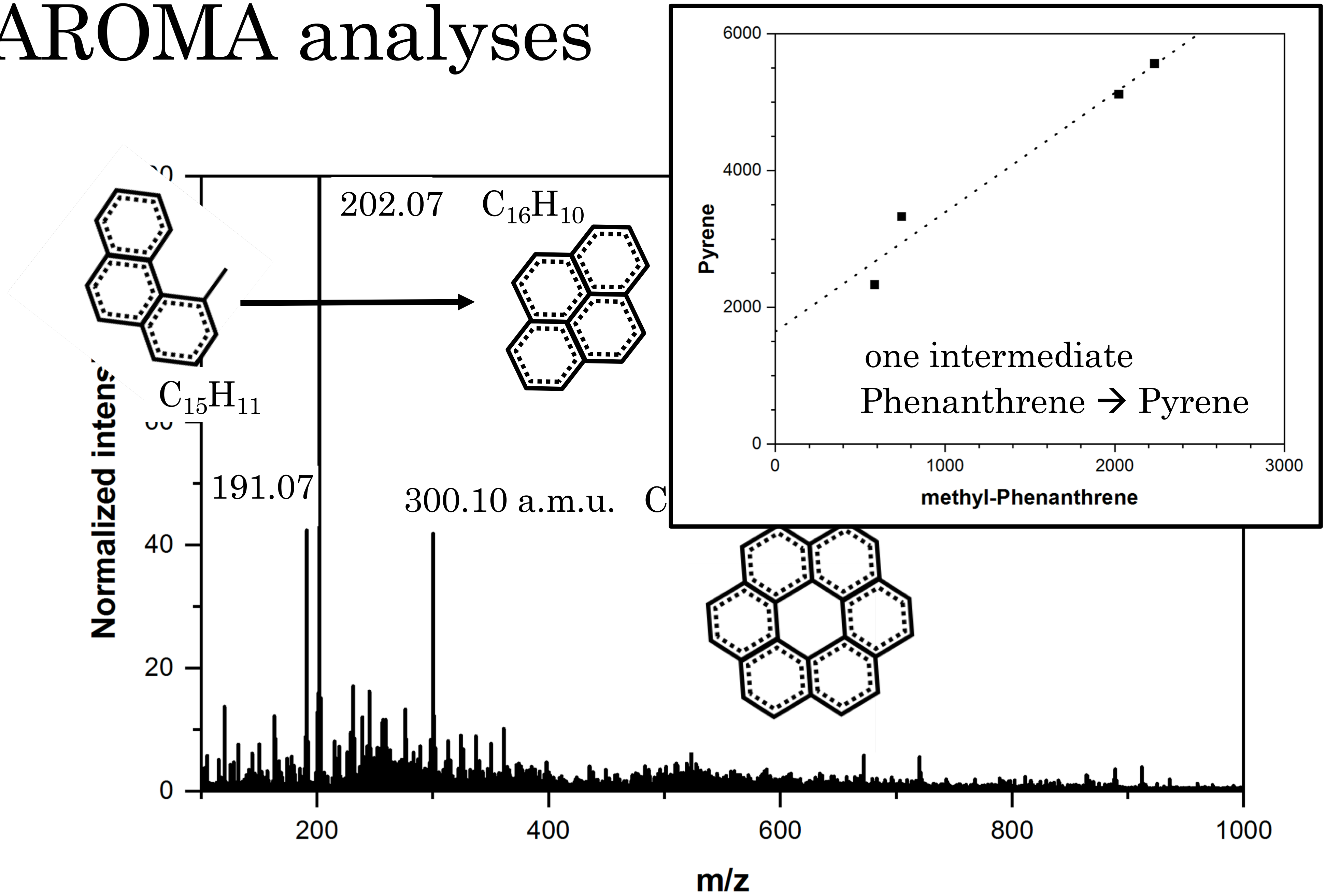
AROMA analyses



AROMA analyses

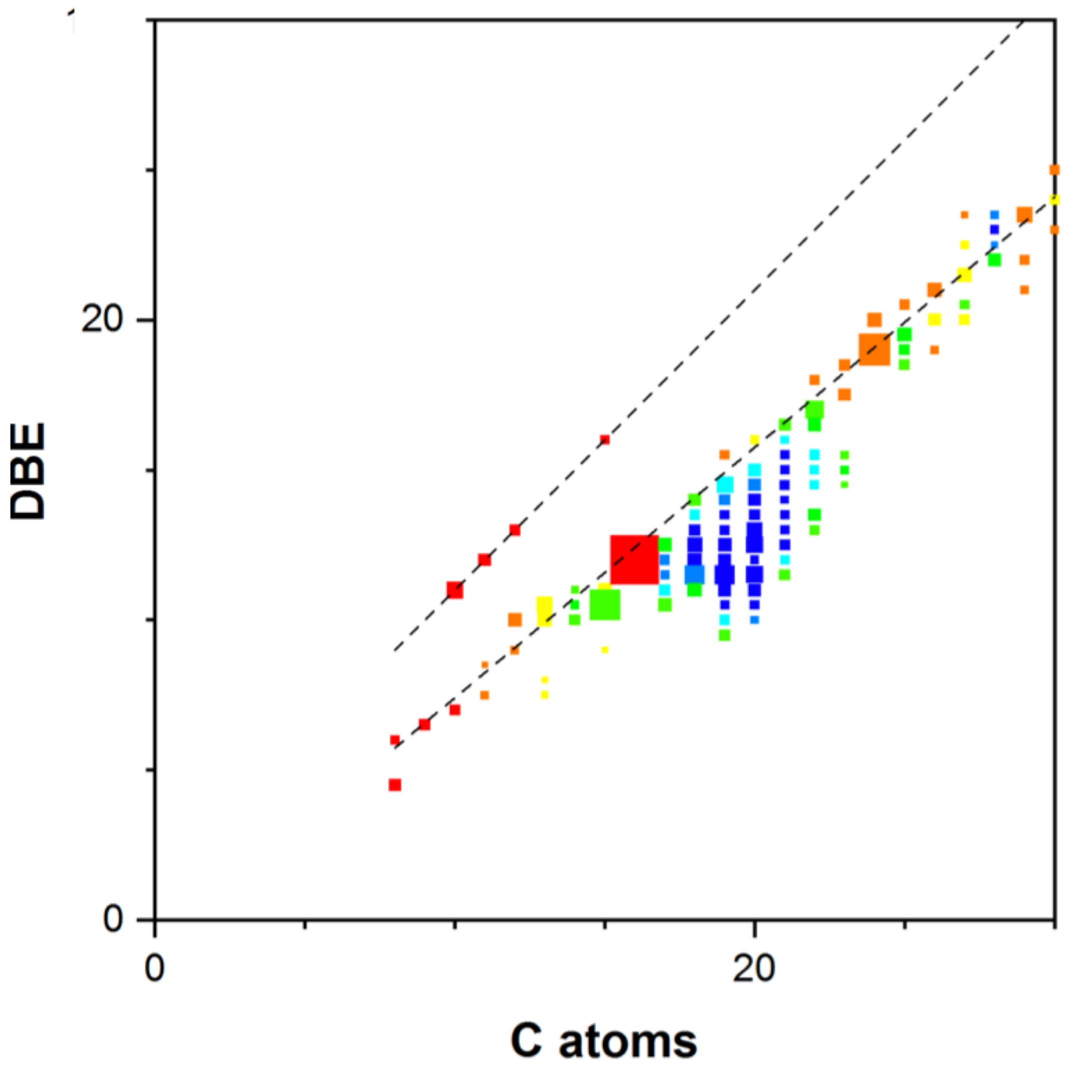


AROMA analyses



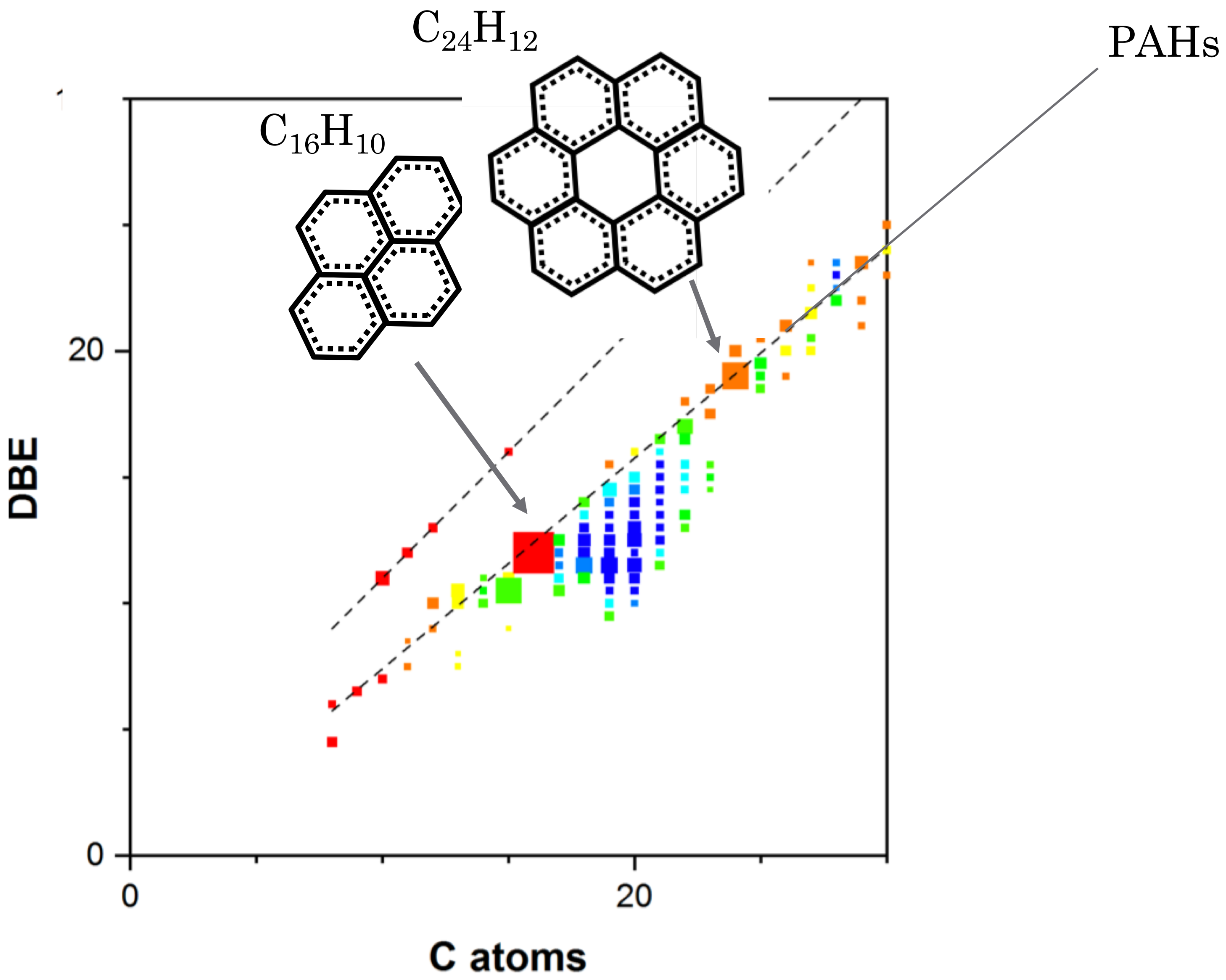
C_xH_y ➔ Double Band Equivalent (DBE)

$$DBE(C_xH_y) = x - y/2 + 1$$



C_xH_y ➔ Double Band Equivalent (DBE)

$$DBE(C_xH_y) = x - y/2 + 1$$



C_xH_y ➔ Double Band Equivalent (DBE)

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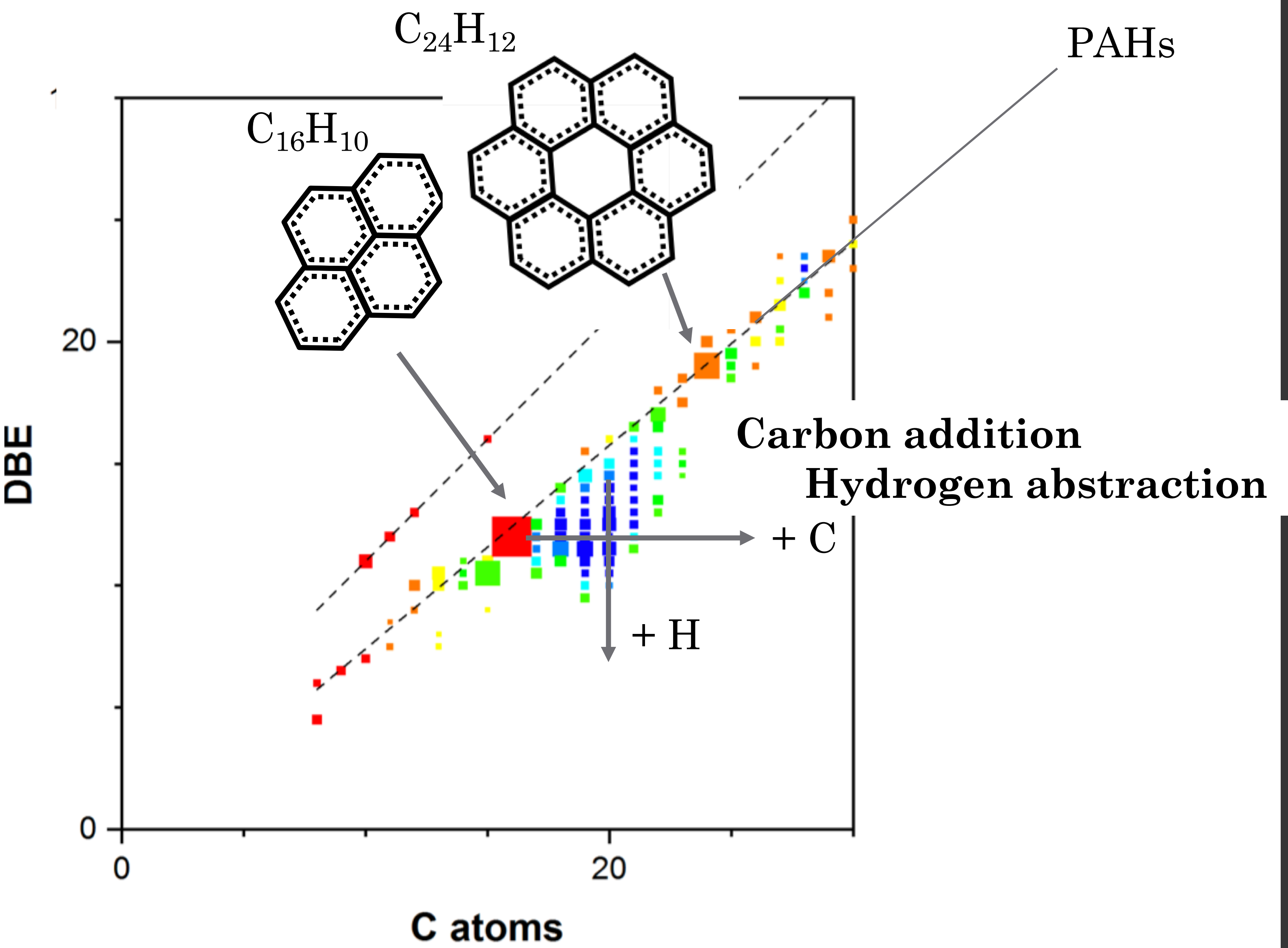
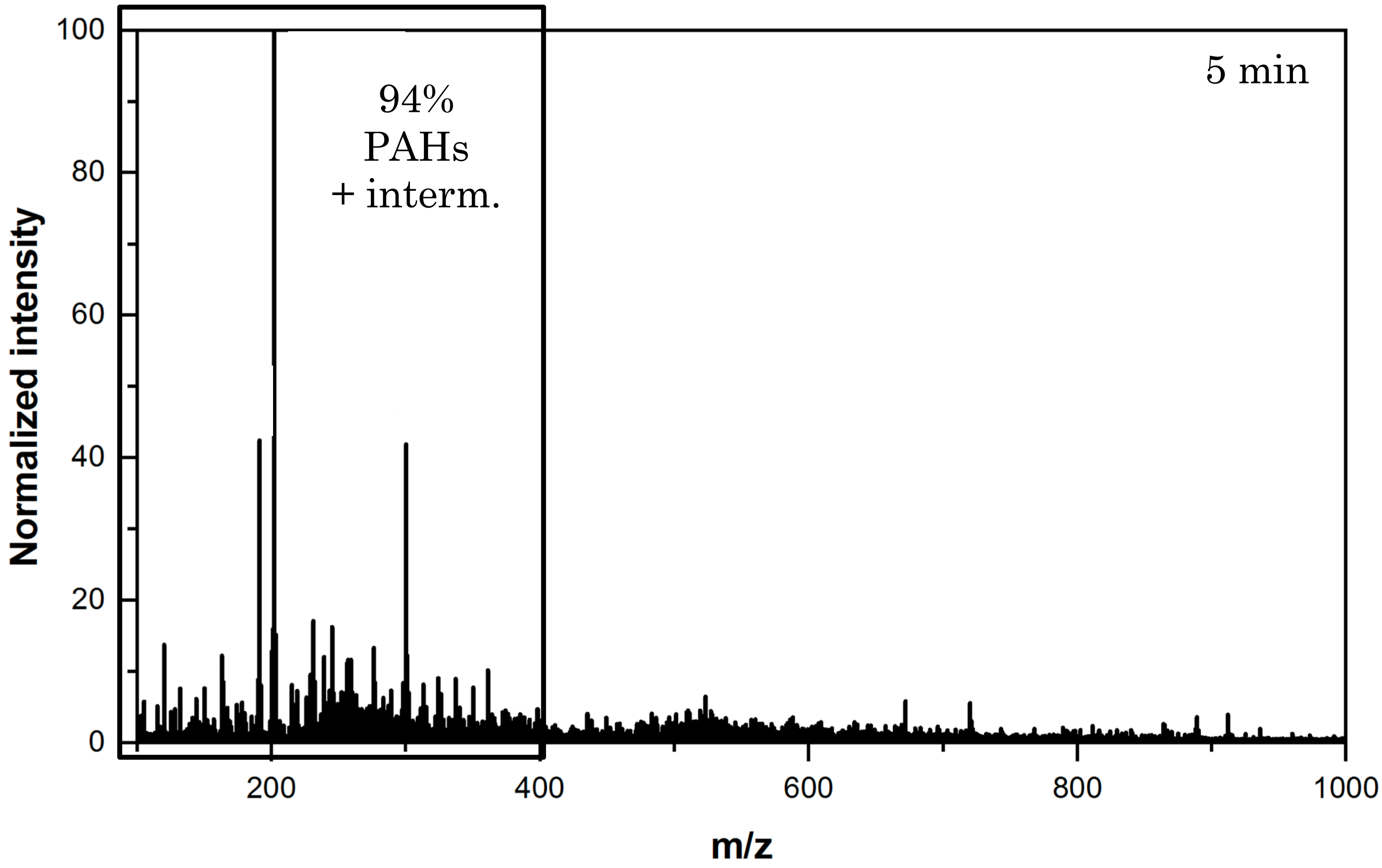


AROMA analyses



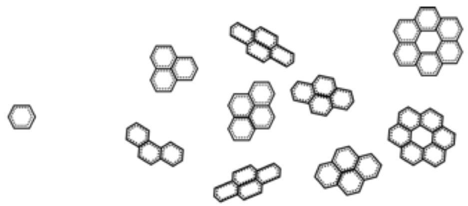
Above the magnets

$$C_2H_2 + e^- \longrightarrow C_xH_y^{\circ,+,-}$$

Above the magnets

Nucleation…

$C_2H_2 + e^- \longrightarrow C_xH_y^{\circ,+,-} \longrightarrow$ **PAHs**



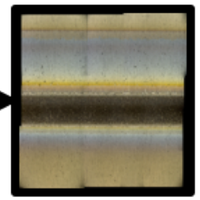
Carbon addition

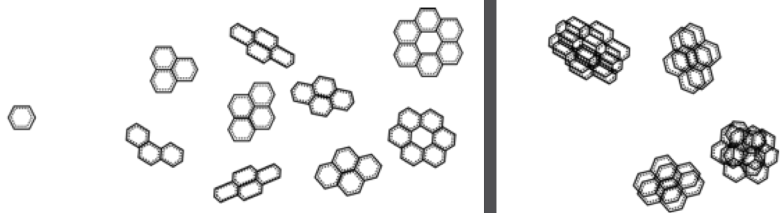
Hydrogen abstraction

Above the magnets

Nucleation… **…Growth** **➔ Deposition**

$C_2H_2 + e^- \longrightarrow C_xH_y^{\circ,+,-} \longrightarrow$ **PAHs** $\longrightarrow$ **dust** $\longrightarrow$

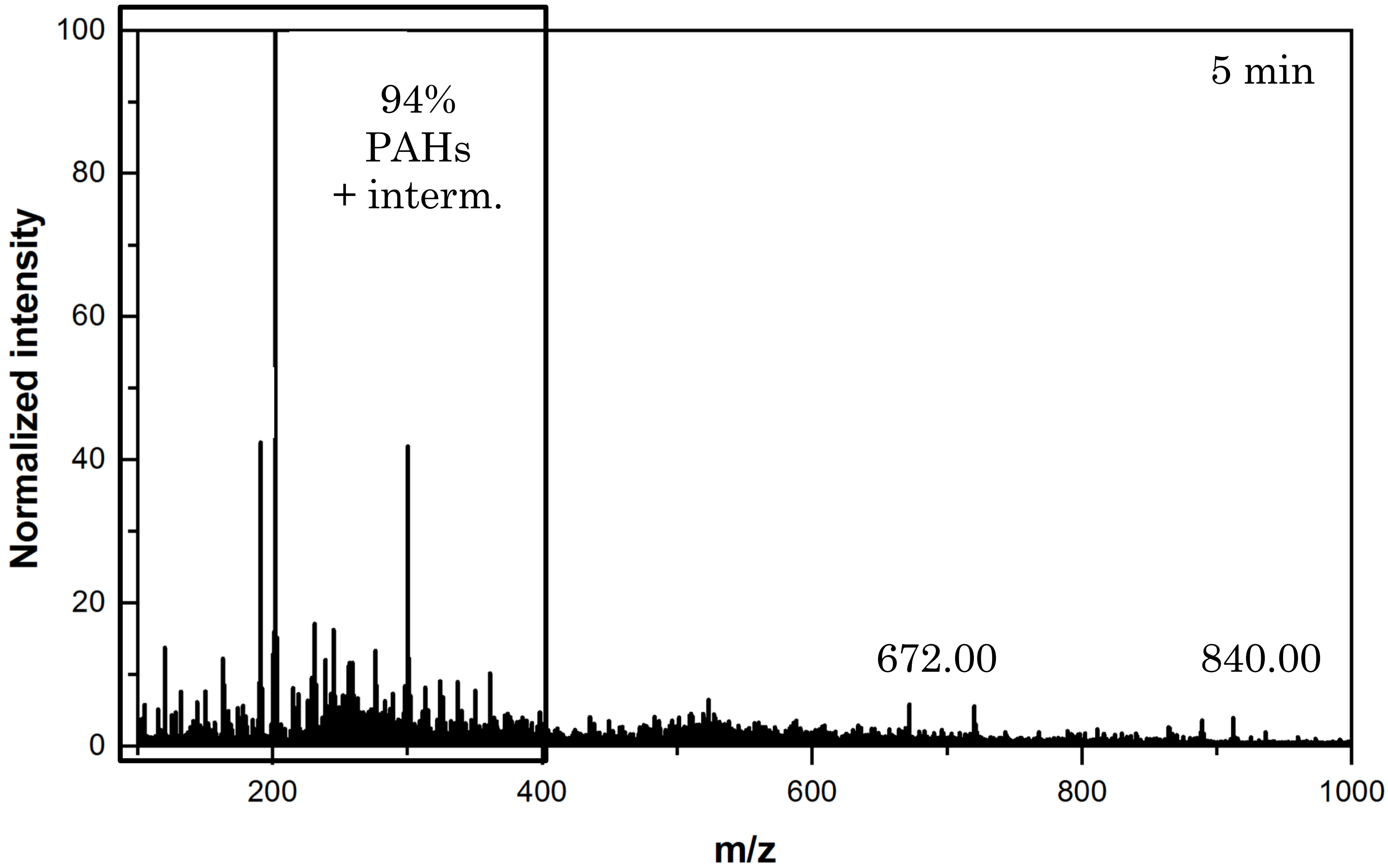




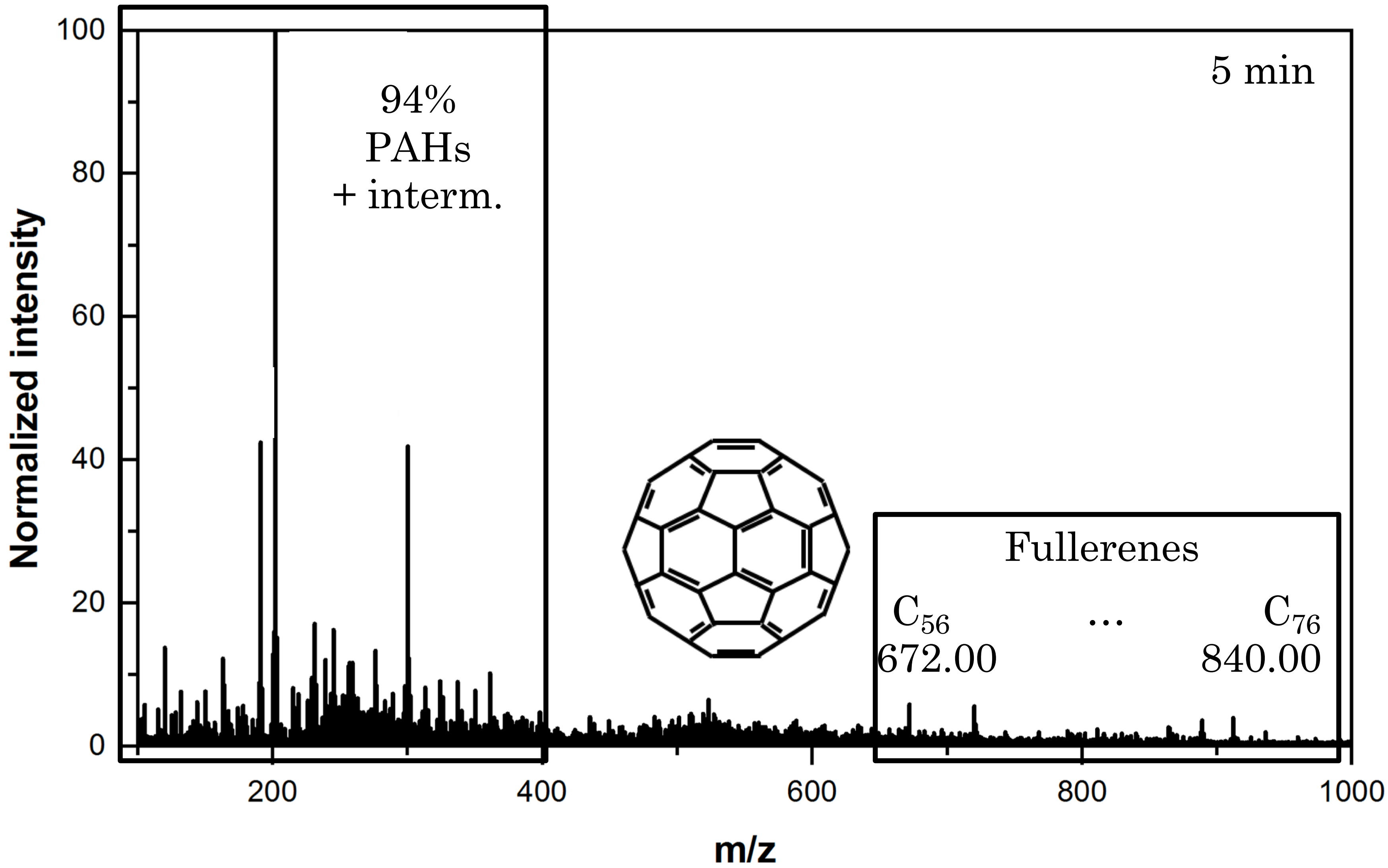
Carbon addition

Hydrogen abstraction

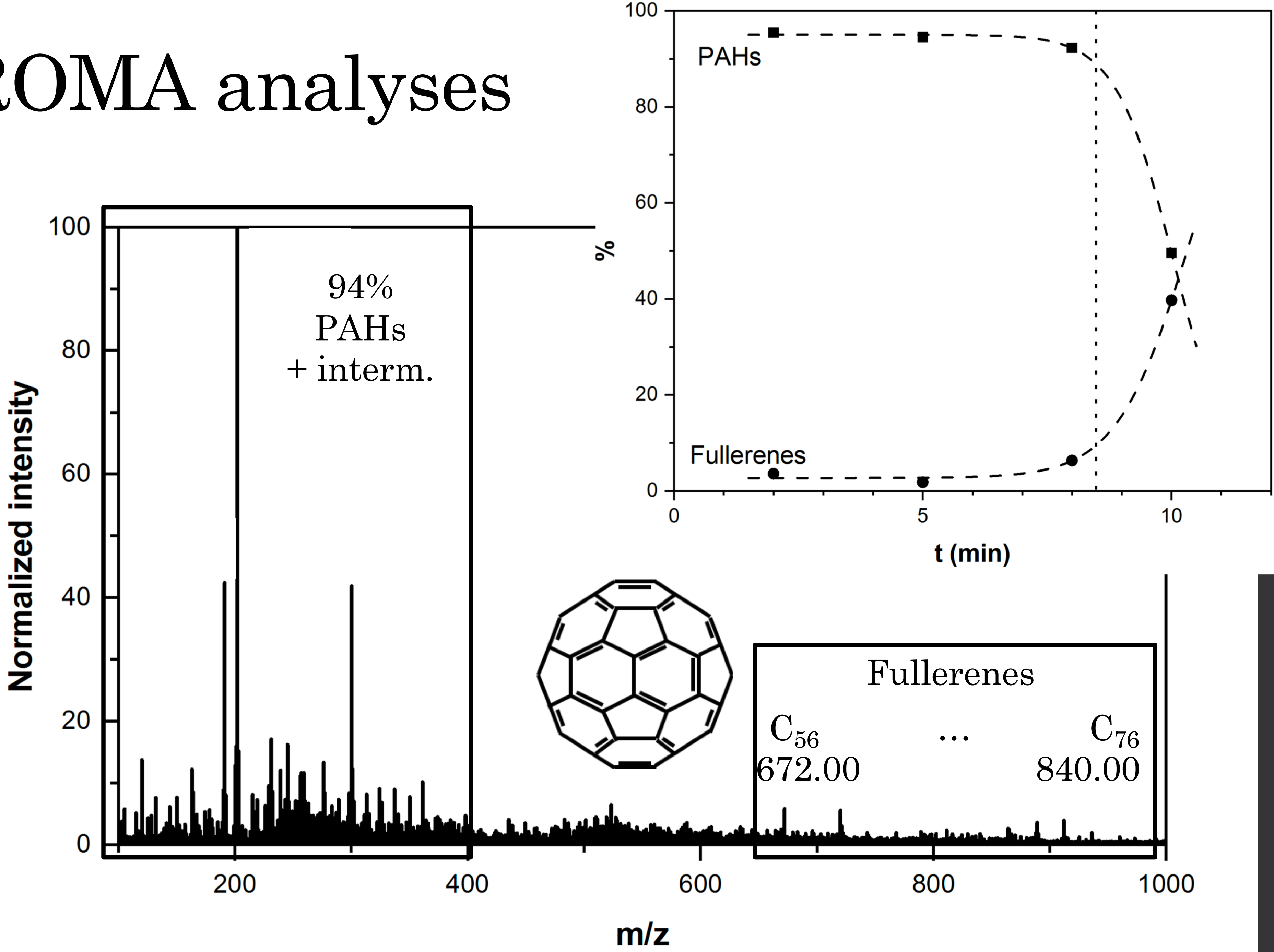
AROMA analyses



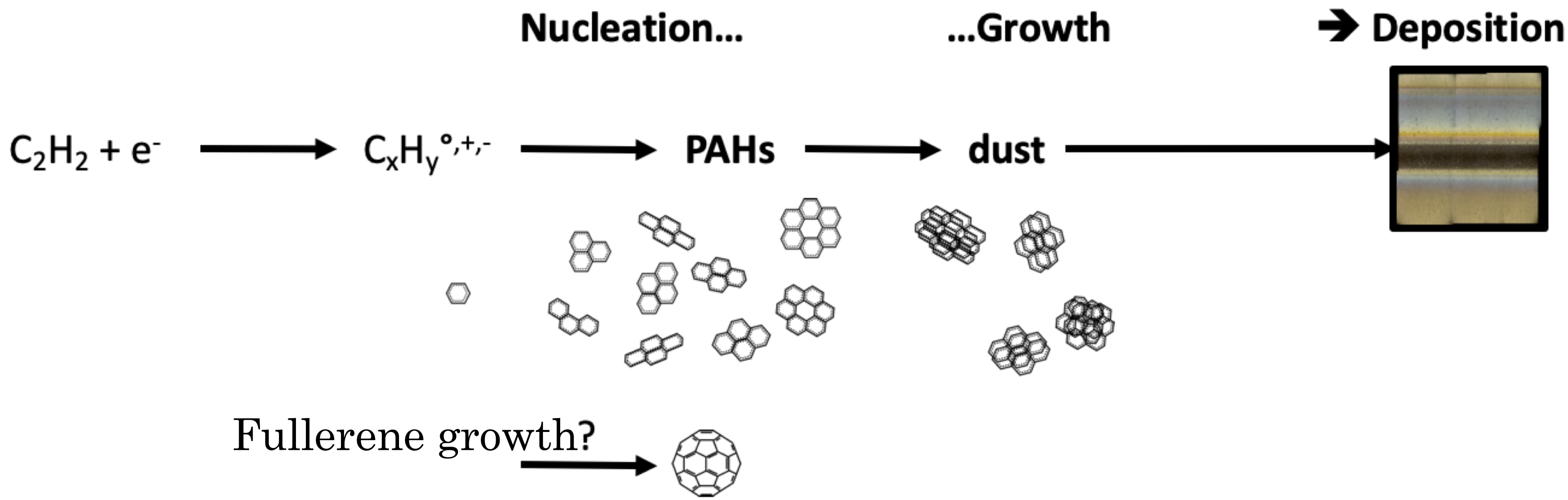
AROMA analyses



AROMA analyses



Above the magnets



Nucleation of Fullerenes?

Nucleation of Fullerenes?

Arc discharges

Ablation plume

Nucleation of Fullerenes?

Arc discharges

Ablation plume

➔ High electron density / $n_e > 10^{19}$ m^{-3}
➔ High pressure / $n_{radicals} > 10^{22}$ m^{-3}
➔ High temperature / T > 4000K

Nucleation of Fullerenes?

Arc discharges

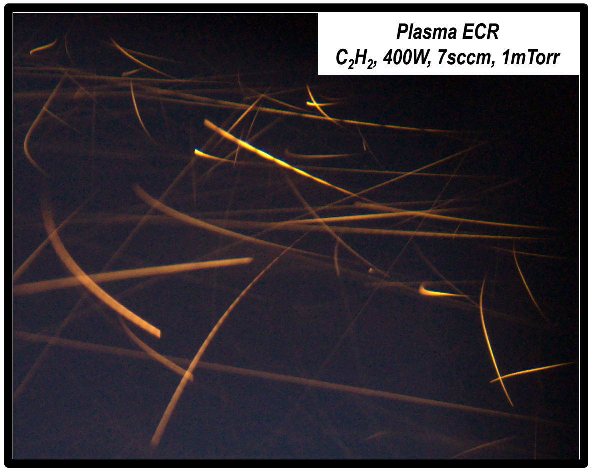
Ablation plume

➔ High electron density / $n_e > 10^{19}$ m^{-3}
➔ High pressure / $n_{radicals} > 10^{22}$ m^{-3}
➔ High temperature / T > 4000K

Obviously far from our conditions…

Formation of Fullerenes?

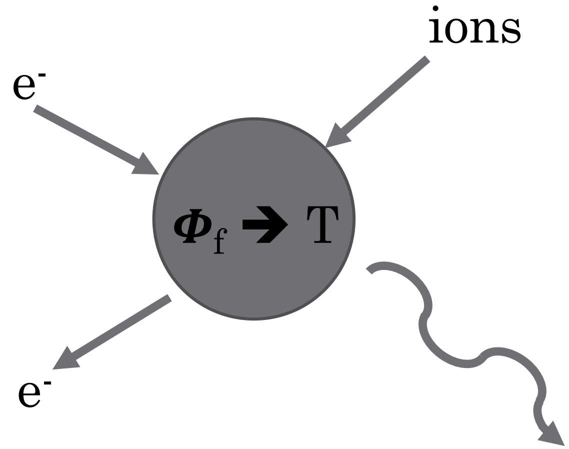
➔ Heating ?

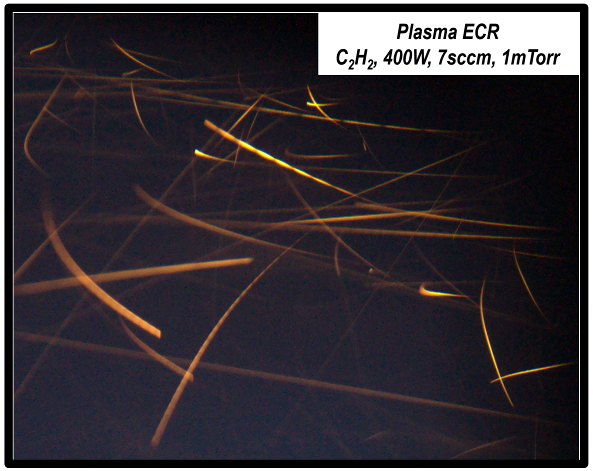


Drenik et al., *Trajectories of dust particles in low-pressure magnetized plasma*, IEEETPS (2011)

Formation of Fullerenes?

➔ Heating ?

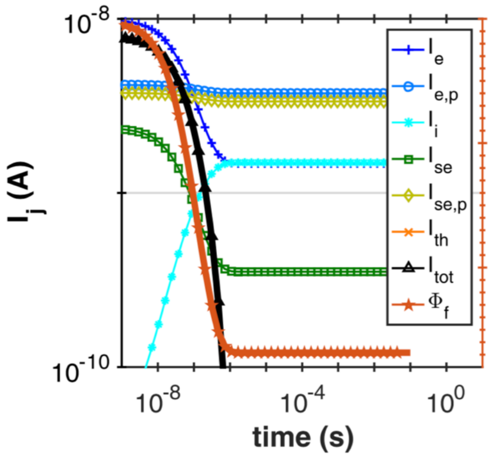


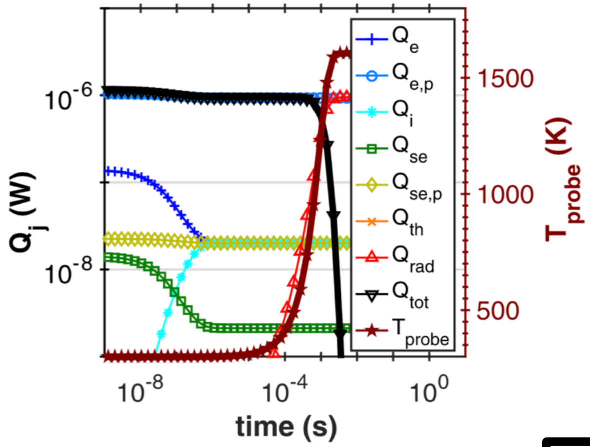


Drenik et al., *Trajectories of dust particles in low-pressure magnetized plasma*, IEEETPS (2011)

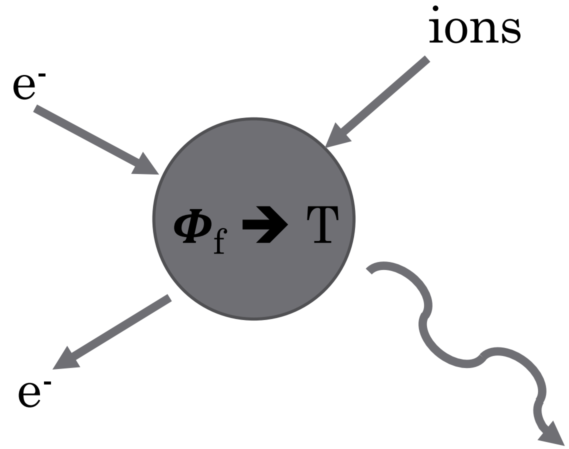
Formation of Fullerenes?

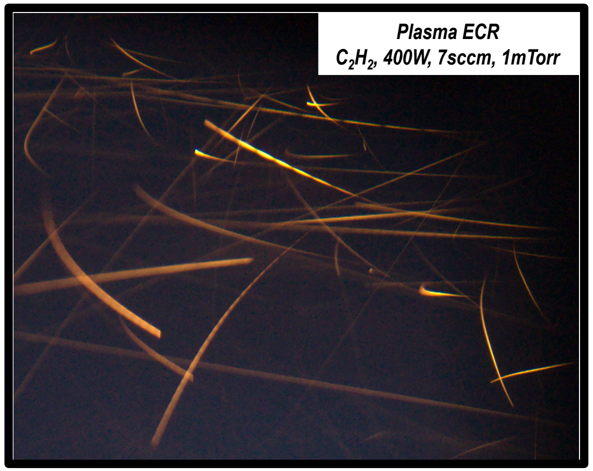
➔ Heating ?





Rojo et al., *Charging and heating processes of dust particles in an electron cyclotron resonance plasma*, PSST (2019)

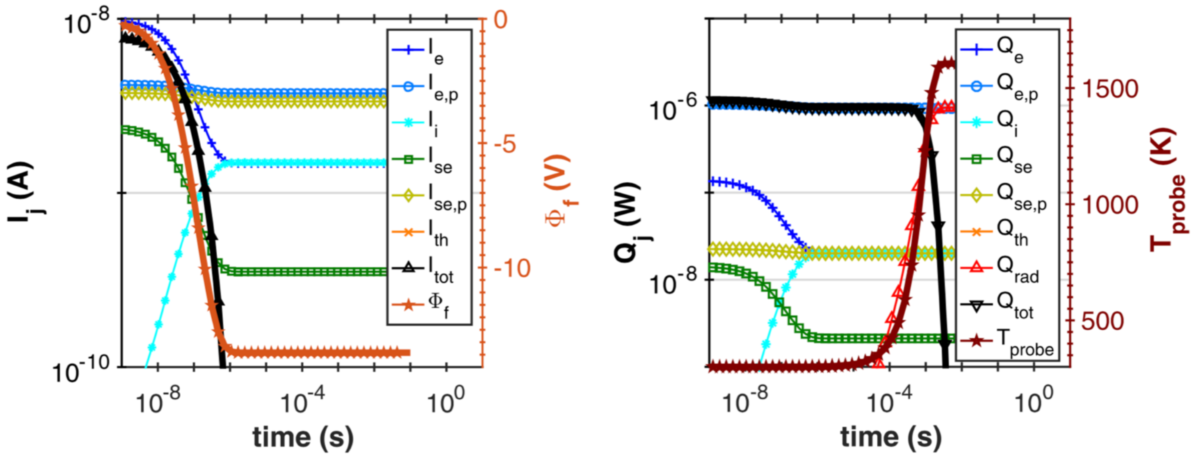




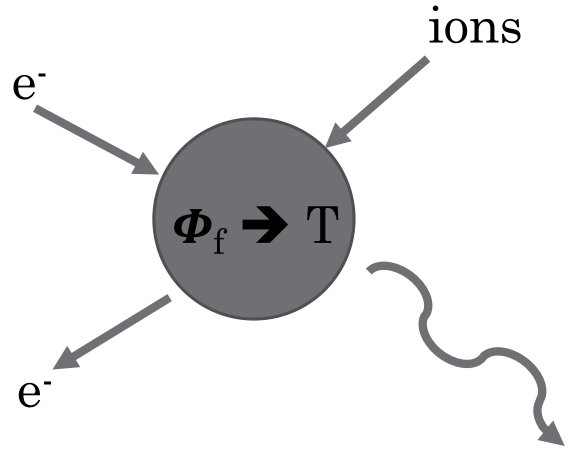
Drenik et al., *Trajectories of dust particles in low-pressure magnetized plasma*, IEEETPS (2011)

Formation of Fullerenes?

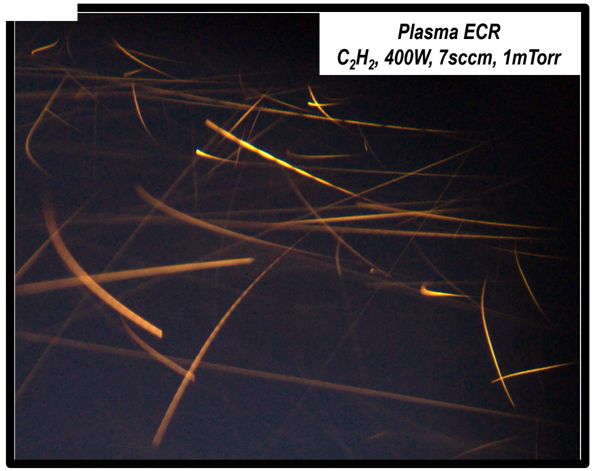
➔ Heating ?



Rojo et al., *Charging and heating processes of dust particles in an electron cyclotron resonance plasma*, PSST (2019)



➔ T<< to transform PAHs into fullerenes

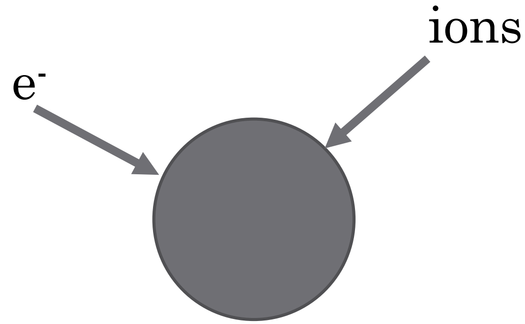


Drenik et al., *Trajectories of dust particles in low-pressure magnetized plasma*, IEEETPS (2011)

Formation of Fullerenes?

➔ Heating ?

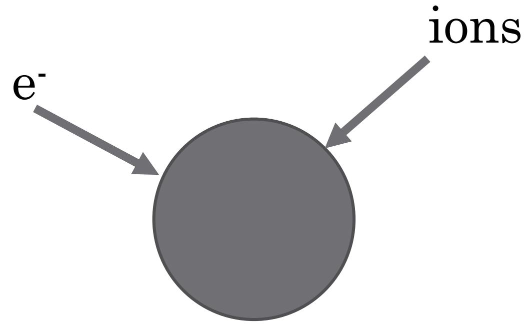
➔ Processing of PAHs on dust particles ?



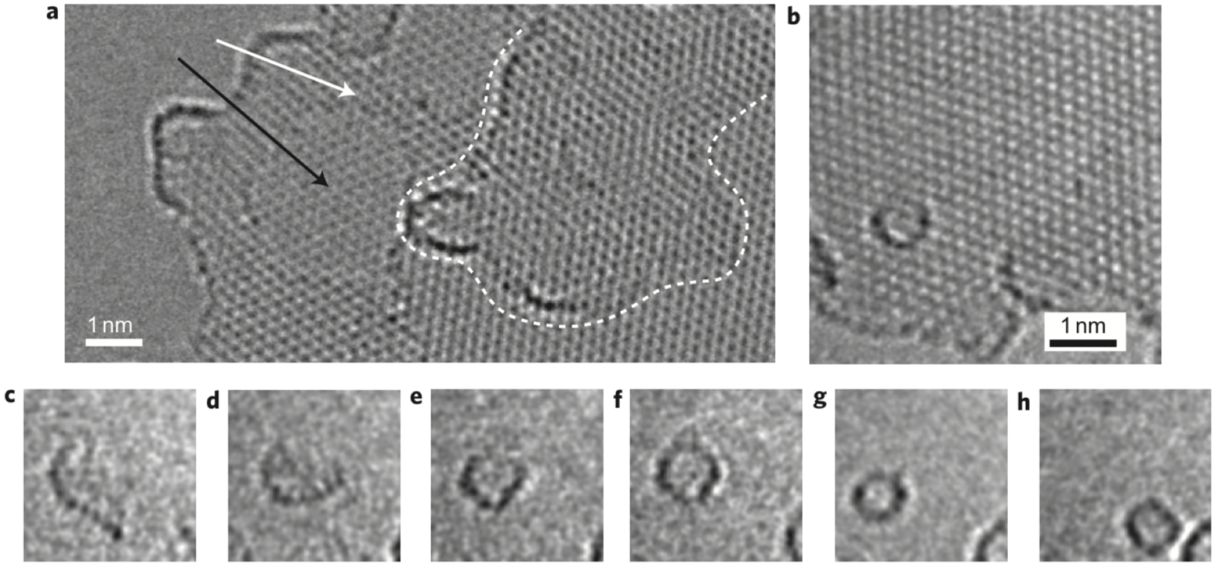
Formation of Fullerenes?

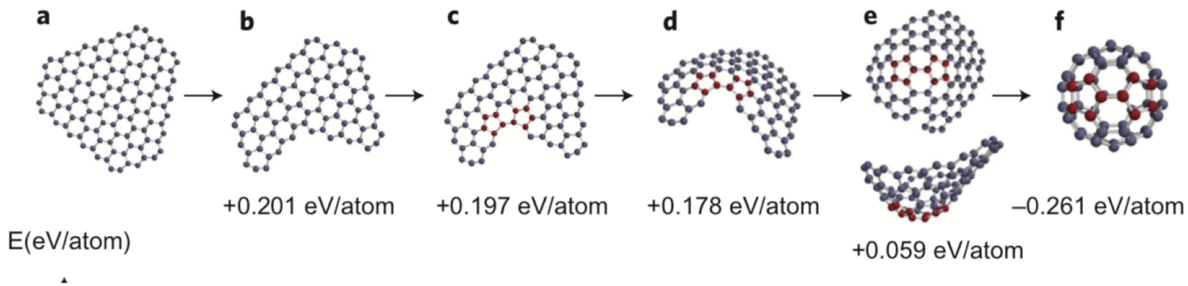
➔ Heating ?

➔ Processing of PAHs on dust particles ?

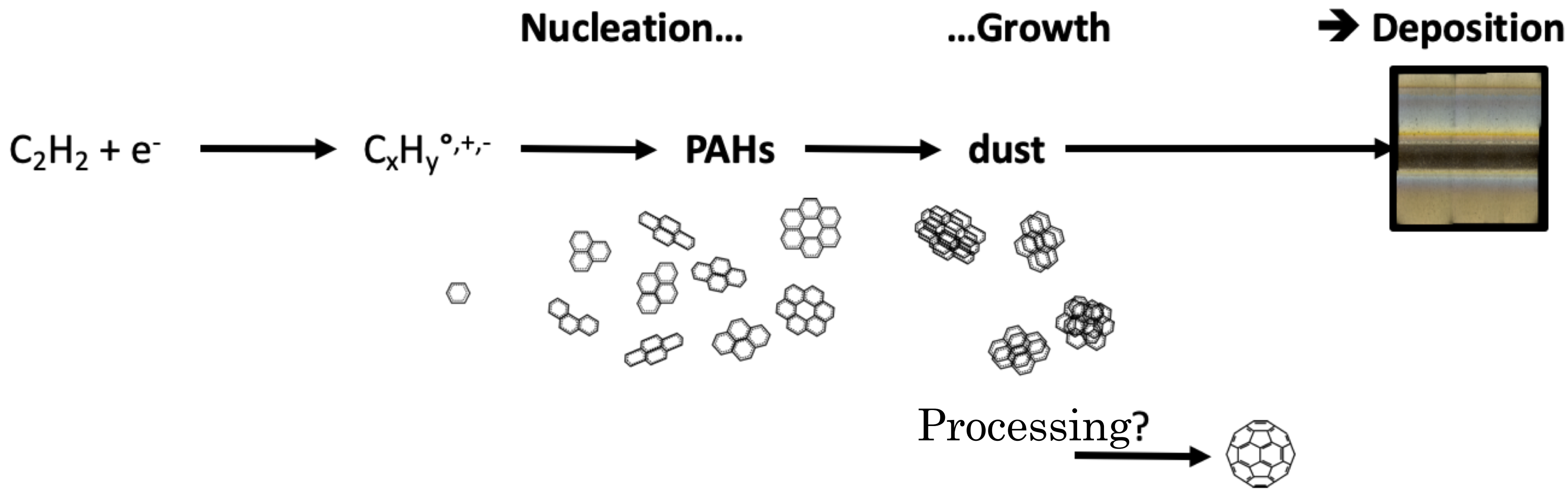


In TEM



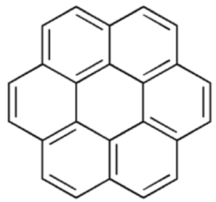


Above the magnets



Nucleation in ECR plasmas

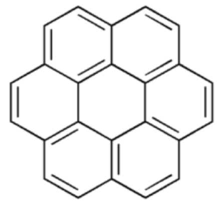
- in our conditions

$C_2H_2 \longrightarrow$ PAHs up to 

Carbon addition
Hydrogen abstraction

Nucleation in ECR plasmas

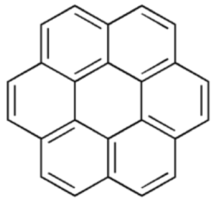
- in our conditions

$C_2H_2 \longrightarrow$ PAHs up to  $\longrightarrow$ Dust particles

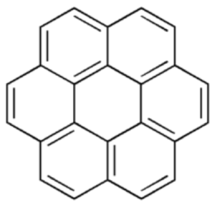
Carbon addition
Hydrogen abstraction

Nucleation in ECR plasmas

- in our conditions

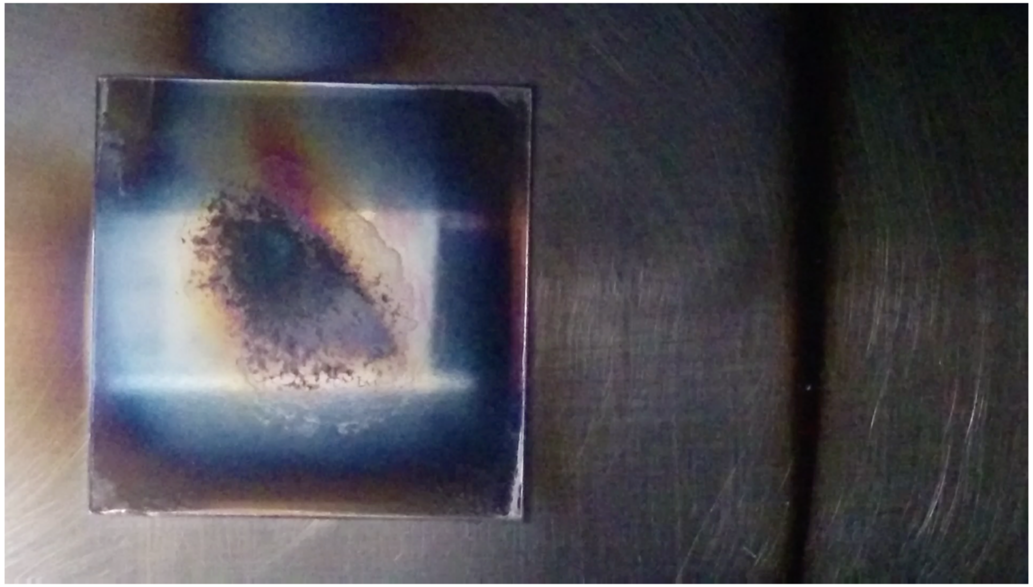
$C_2H_2 \longrightarrow$ PAHs up to  $\longrightarrow$ Dust particles

Carbon addition
Hydrogen abstraction

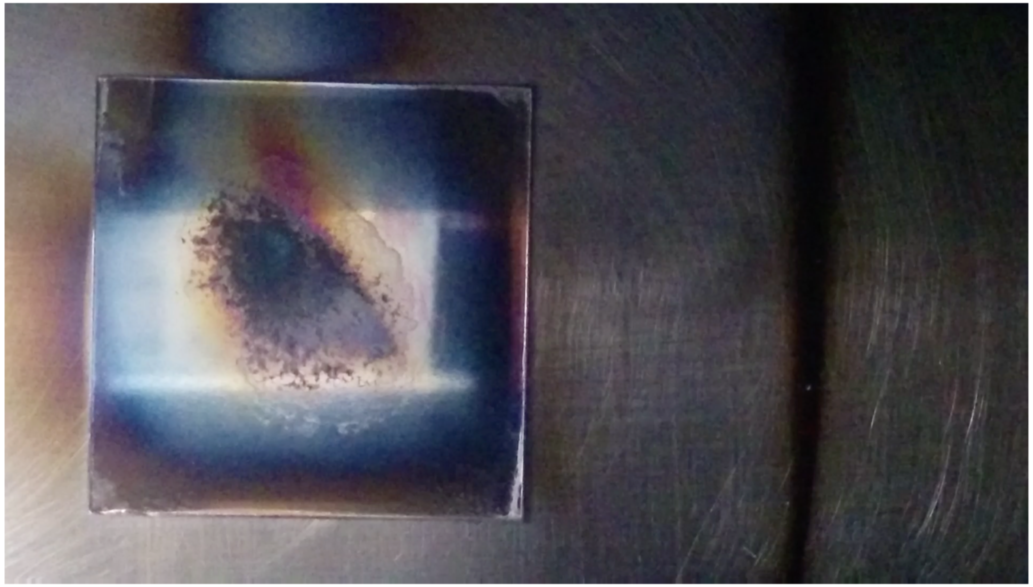
 $\xrightarrow{?}$ Dust particles

Outline

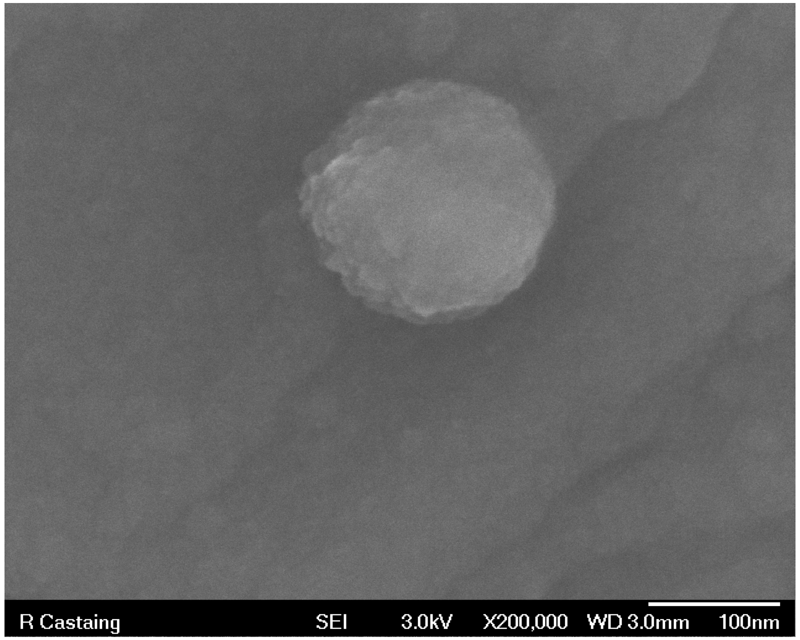
Plasmas seeded with PAHs



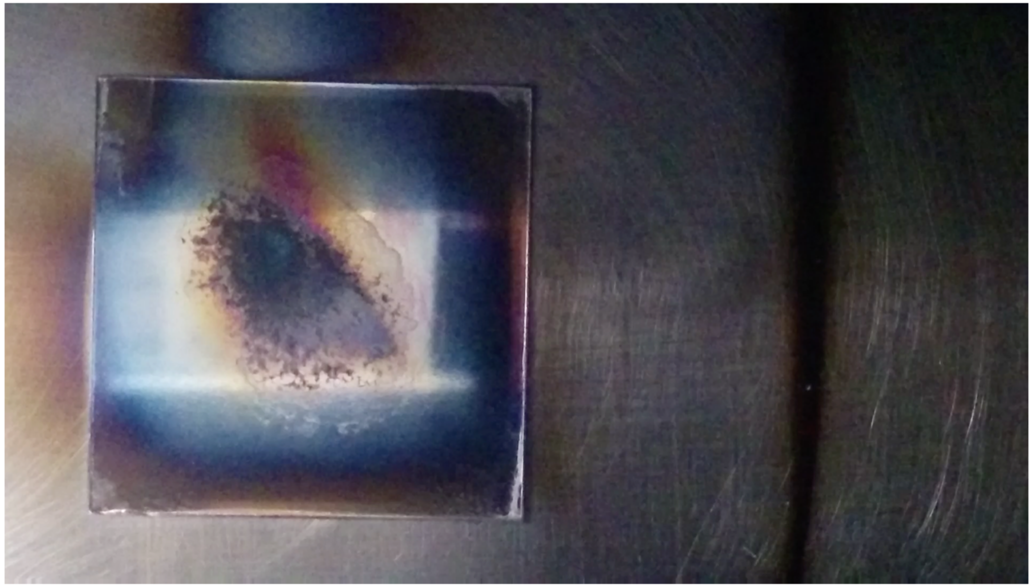
Plasmas seeded with PAHs



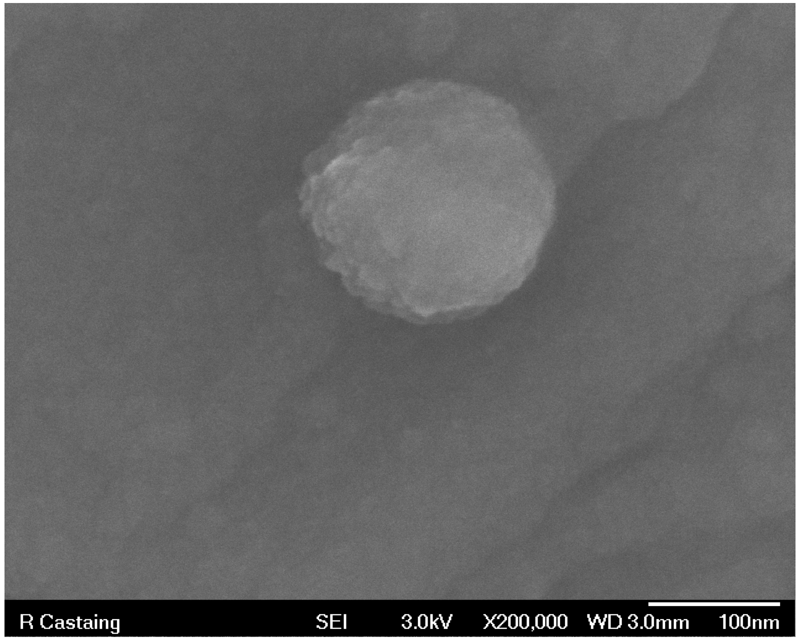
Anthracene
Perylene
Benzoperylene
Coronene



Plasmas seeded with PAHs

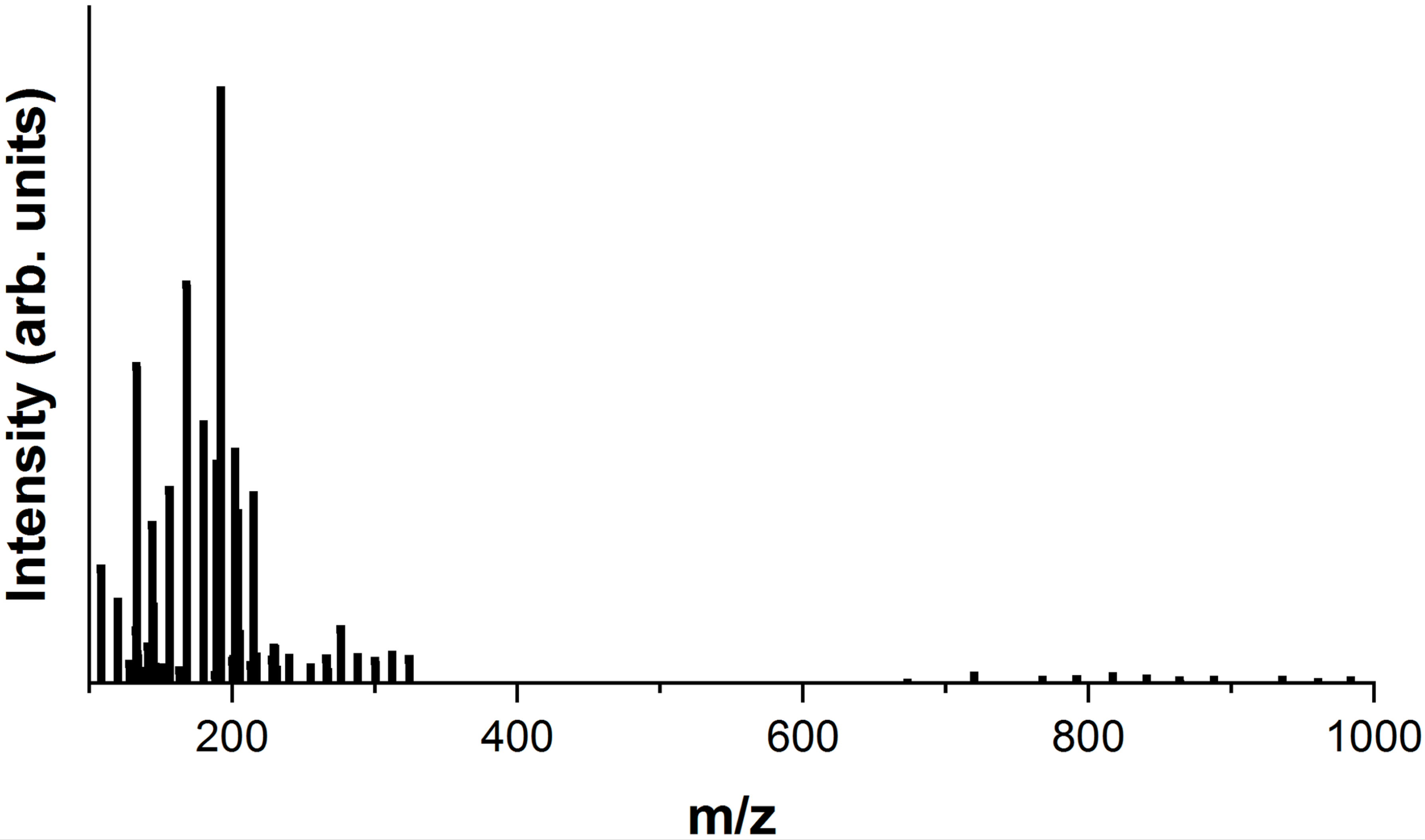


Anthracene
Perylene
Benzoperylene
Coronene

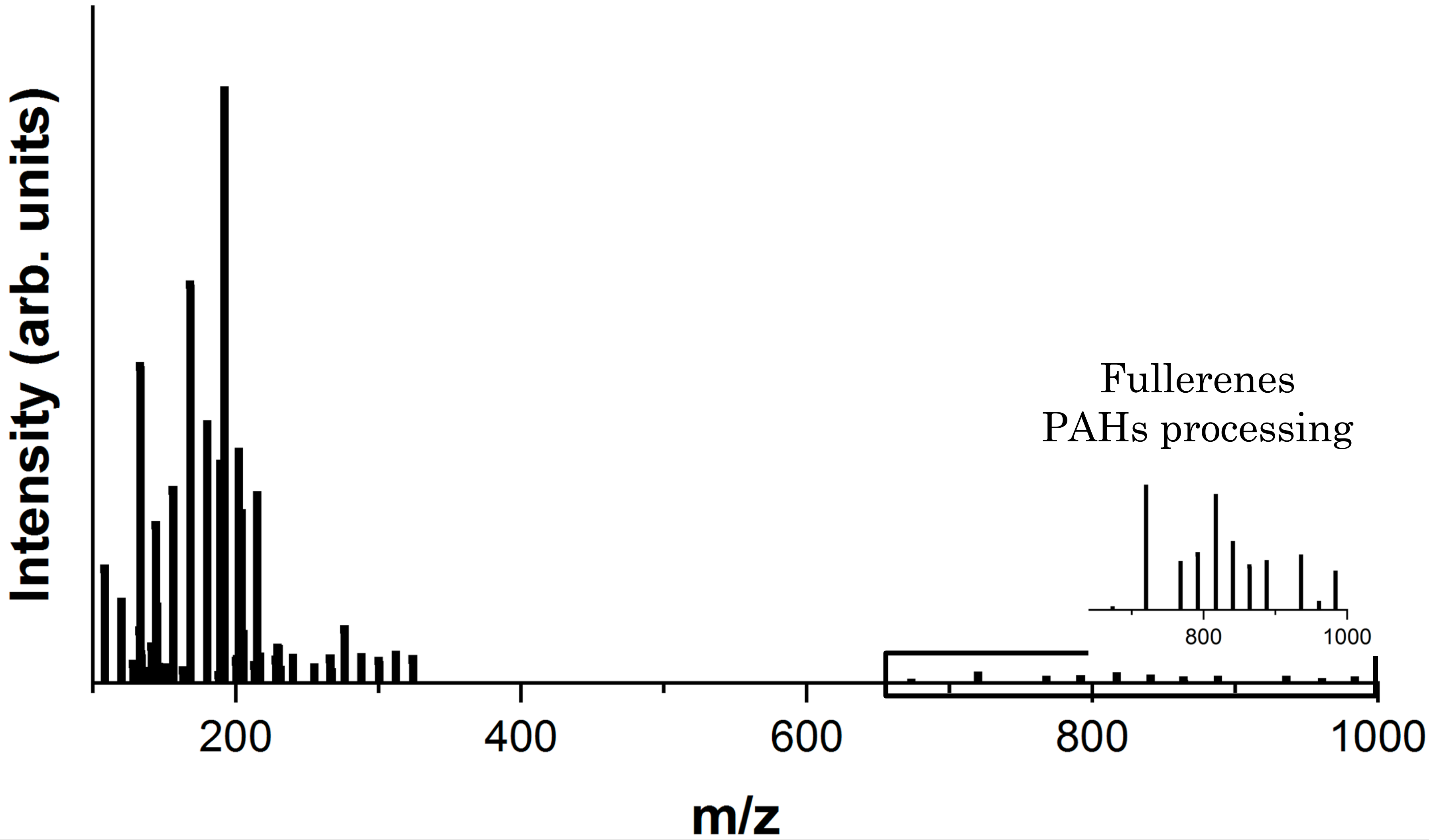


really larger than in C_2H_2 ECR plasmas

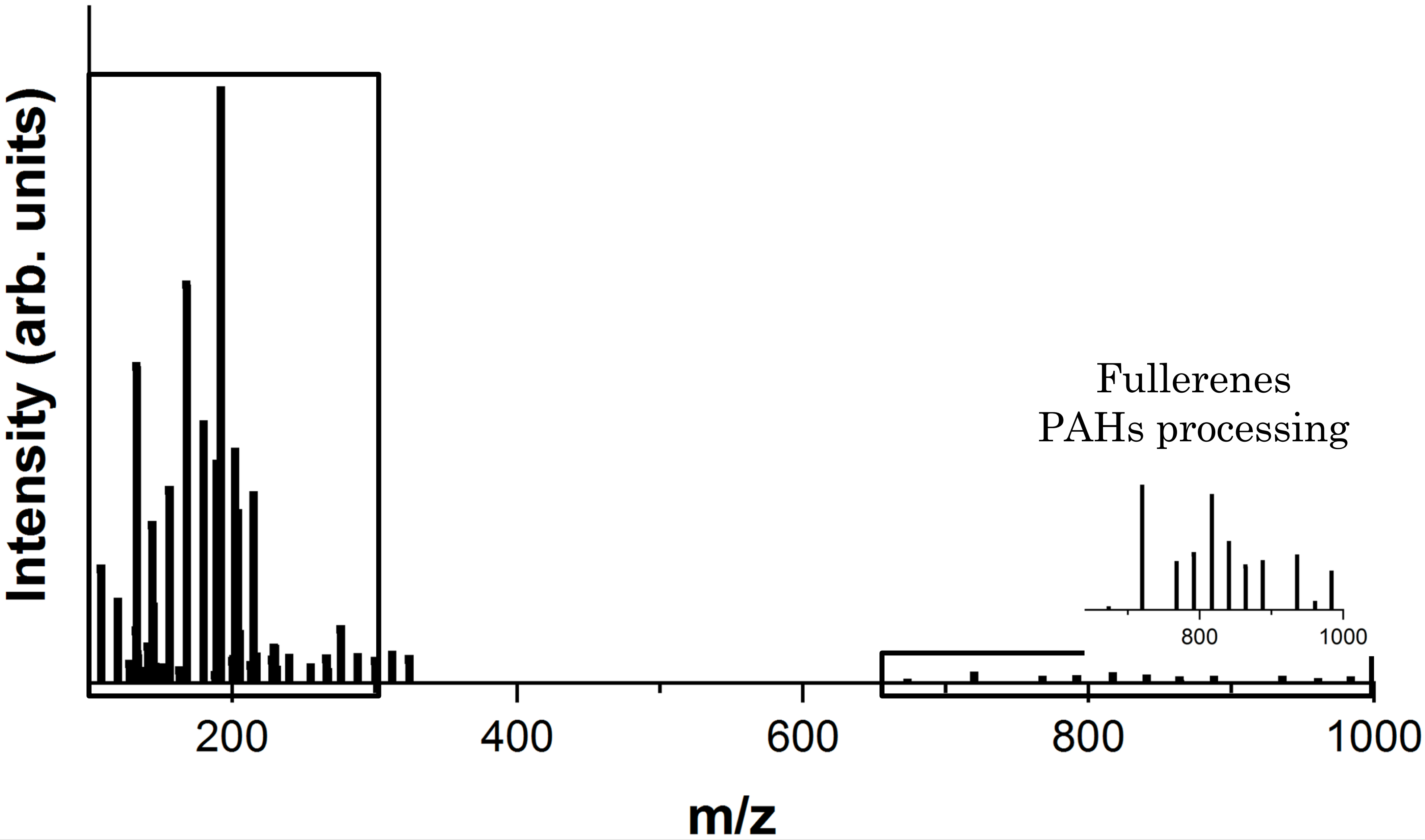
AROMA analyses



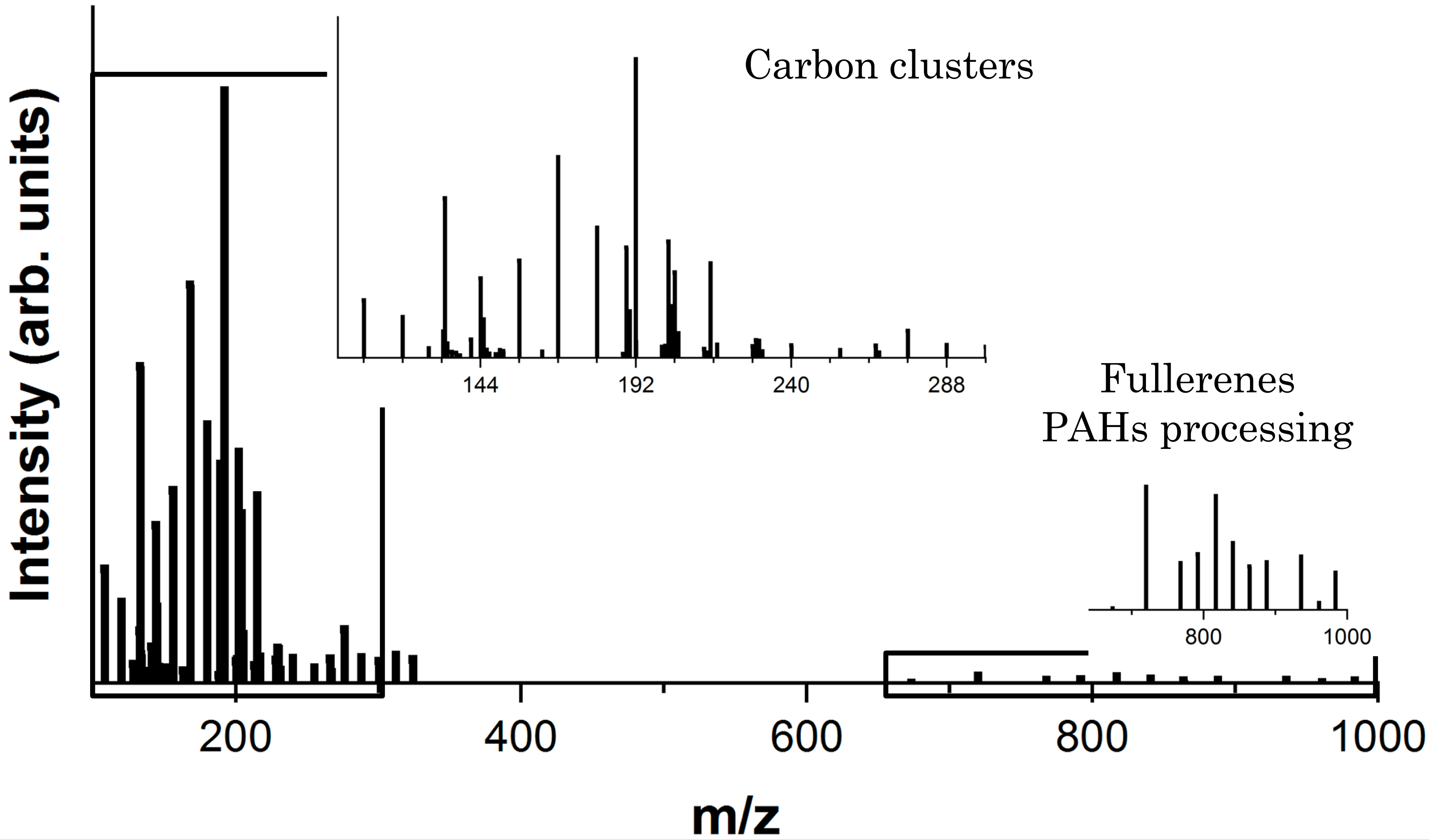
AROMA analyses

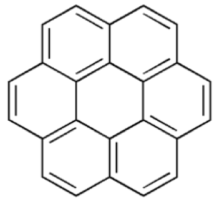


AROMA analyses

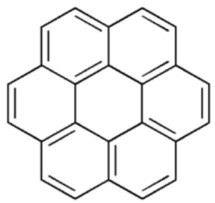


AROMA analyses

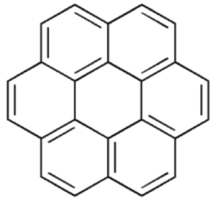


$C_2H_2 \longrightarrow$ PAHs up to  $\longrightarrow$ Dust particles

Carbon addition
Hydrogen abstraction

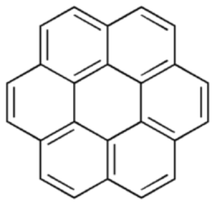
 $\longrightarrow$ Dust particles

PROCESSING

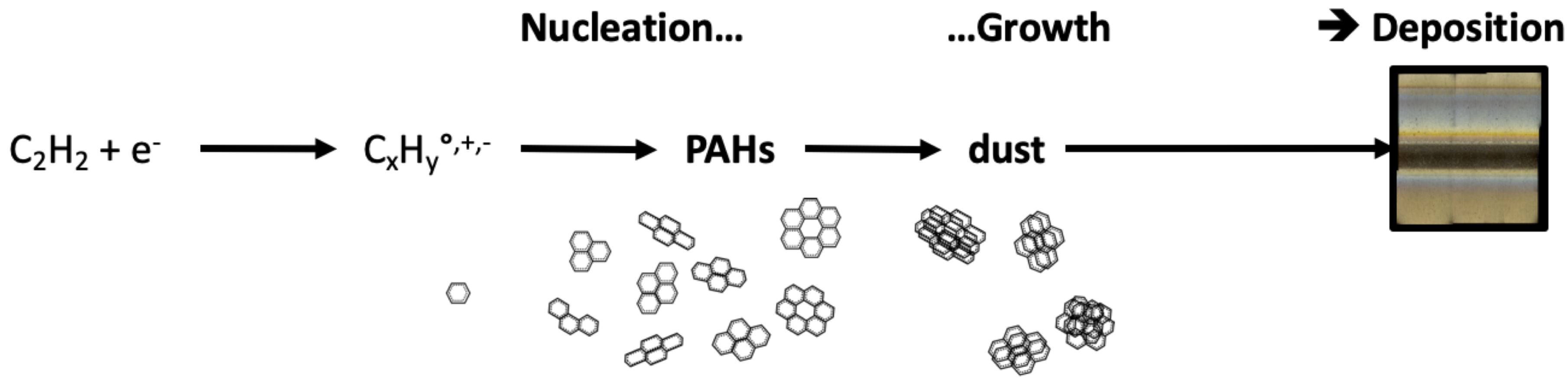
$C_2H_2 \longrightarrow$ PAHs up to  $\longrightarrow$ Dust particles

Carbon addition
Hydrogen abstraction

$\not\approx$

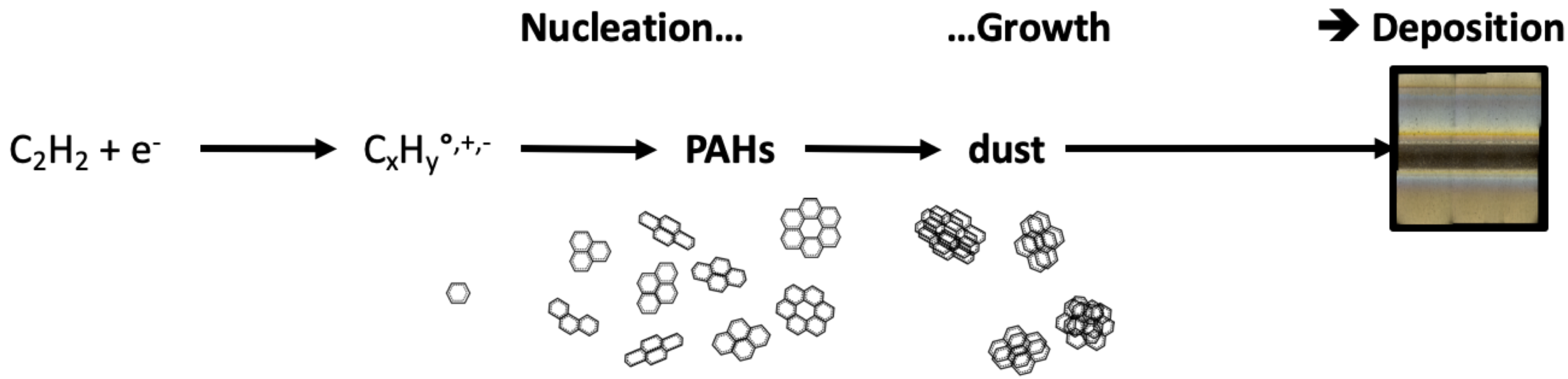
 $\longrightarrow$ Dust particles

Outline


Nucleation...
...Growth
Deposition
$C_2H_2 + e^-$
$C_xH_y^{°,+,-}$
PAHs
dust

Nucleation in C_2H_2 ECR plasmas involve the formation of PAHs

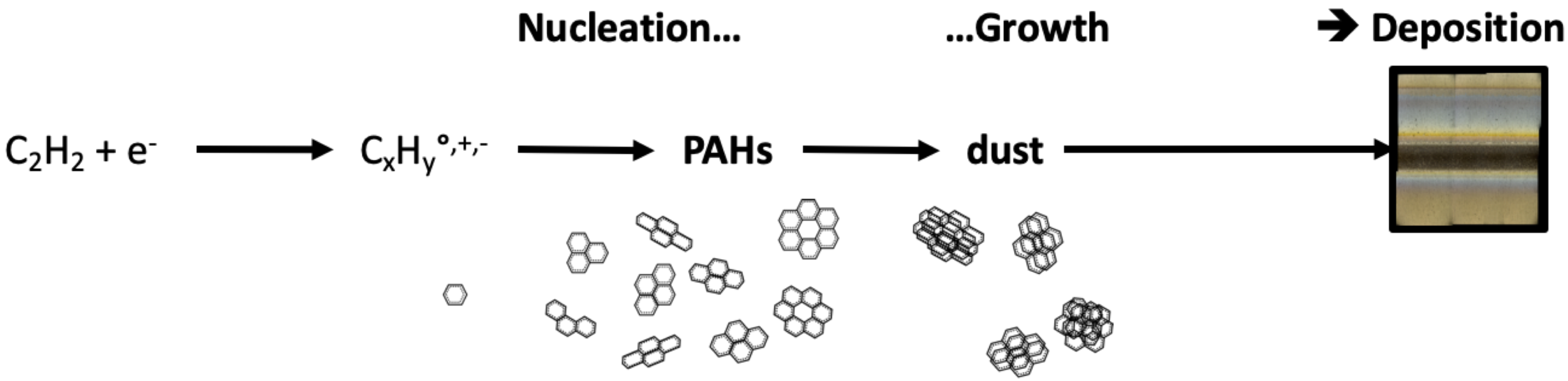
Through similar Hydrogen abstraction Carbon addition pathways as described in combustion



Nucleation in C_2H_2 ECR plasmas involve the formation of PAHs

Through similar Hydrogen abstraction Carbon addition pathways as described in combustion

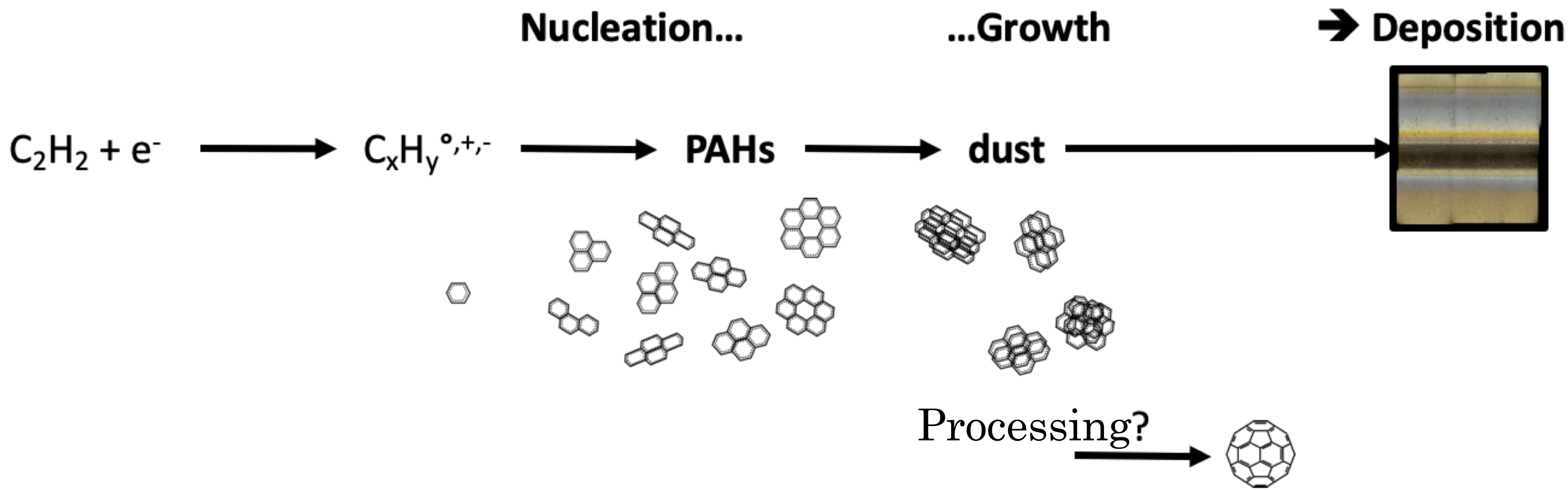
PAHs further stack into dust particles



Nucleation in C_2H_2 ECR plasmas involve the formation of PAHs

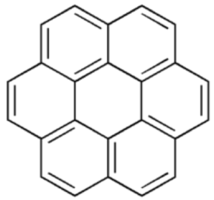
Through similar Hydrogen abstraction Carbon addition pathways as described in combustion

PAHs further stack into dust particles



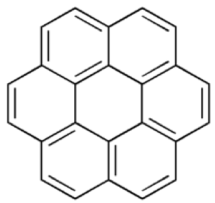
However, a lot of other mechanisms are also involved (thermal heating, electron bombardment, etc.)

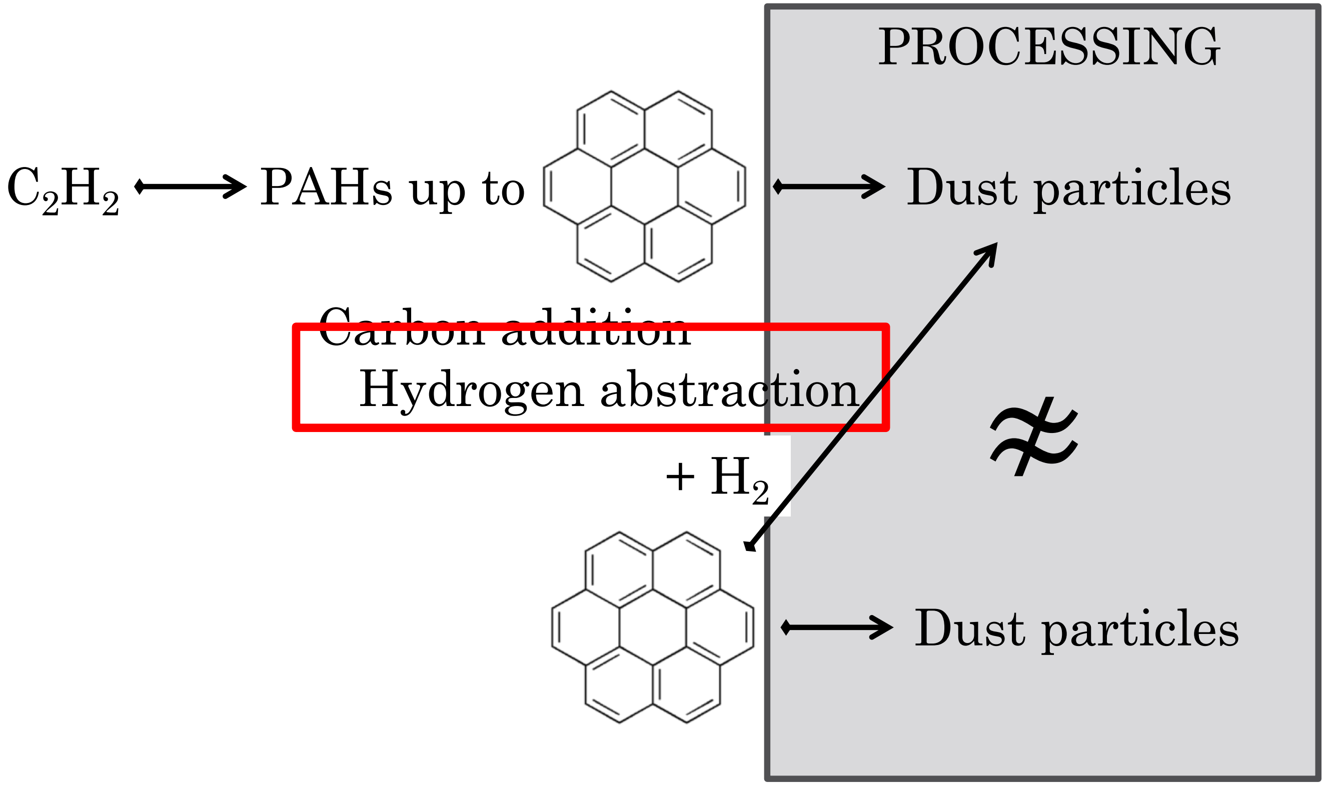
PROCESSING

$C_2H_2 \longrightarrow$ PAHs up to  $\longrightarrow$ Dust particles

Carbon addition
Hydrogen abstraction

$\not\approx$

 $\longrightarrow$ Dust particles


PROCESSING
C2H2
PAHs up to
Dust particles
Carbon addition
Hydrogen abstraction
+ H2
≉
Dust particles

nanocosmos

erc

European Research Council

Established by the European Commission

STAE TOULOUSE

X. Glad

H. Sabbah

C. Joblin

M. Rojo

A. Perdrau

J. Philbrick