Laboratoire Cobra

iC2MC INTERNATIONAL – COMPLEX MATRICES MOLECULAR CHARACTERIZATION

THE BEAUTIFUL FRIENDSHIP OF IMS AND FTICR MASS SPECTROMETRY FOR COMPLEX MIXTURES ANALYSIS

Carlos Afonso

cnrs INSA UNIVERSITE DE ROUEN

Context

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iC2MC INTERNATIONAL – COMPLEX MATRICES MOLECULAR CHARACTERIZATION

UNIVERSITÉ DE ROUEN NORMANDIE

UNIVERSITÉ DE PAU ET DES PAYS DE L'ADOUR

NATIONAL MAGLAB

TotalEnergies

Carlos AFONSO, Brice BOUYSSIERE, Ryan RODGERS, Pierre GIUSTI

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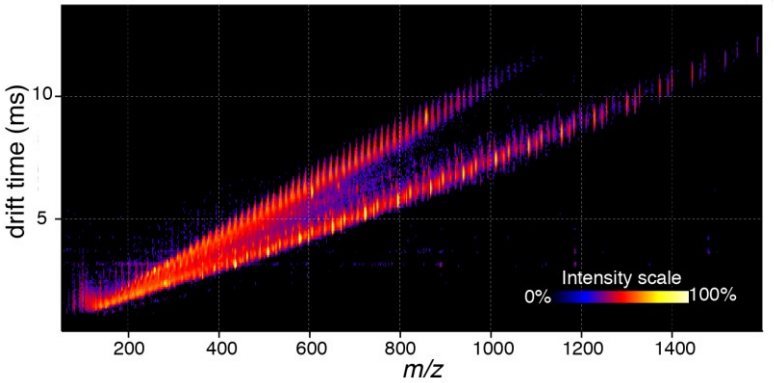
Highly Complex organic mixtures

- Complex mixture analysis
  - Requires high peak capacity
  - Post-ionization separation
    - 1 dimension: ultra-high resolution
    - 2 dimensions: ion mobility coupling

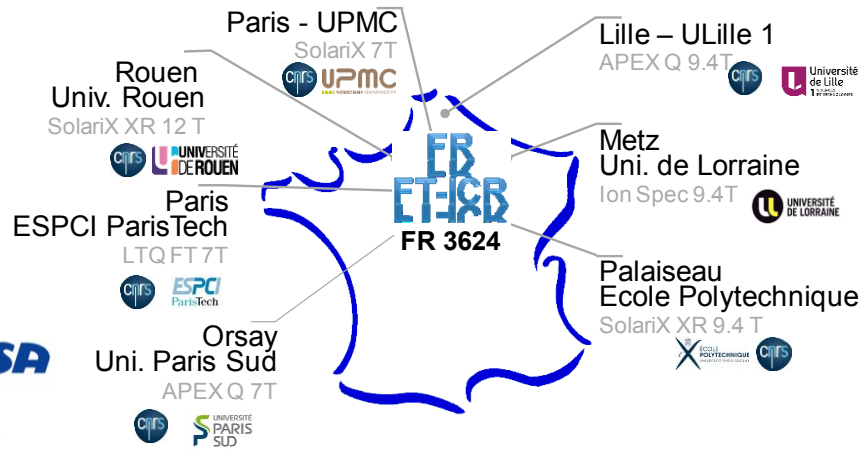
WATERS SYNAPT G2

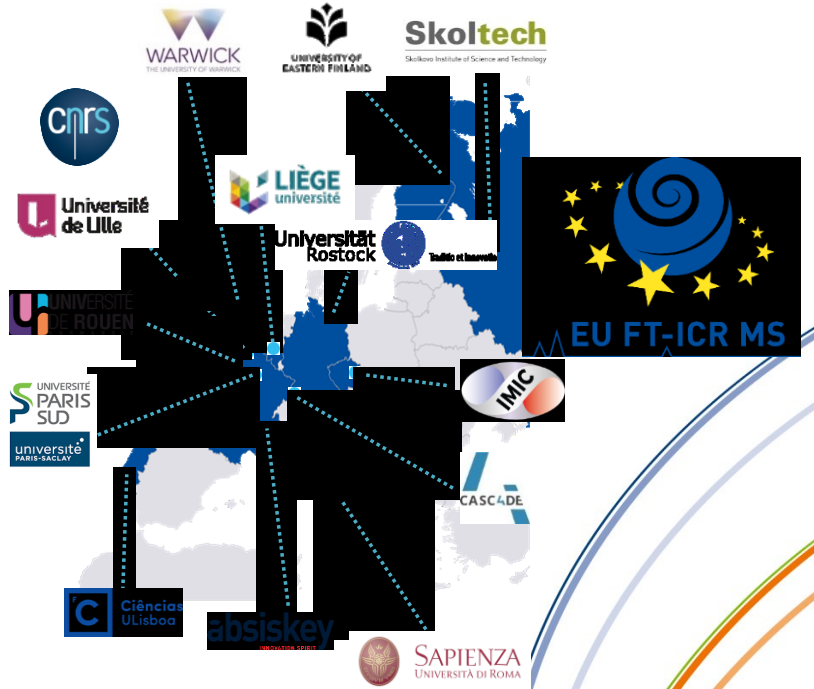
BRUKER 12T SOLARIX XR



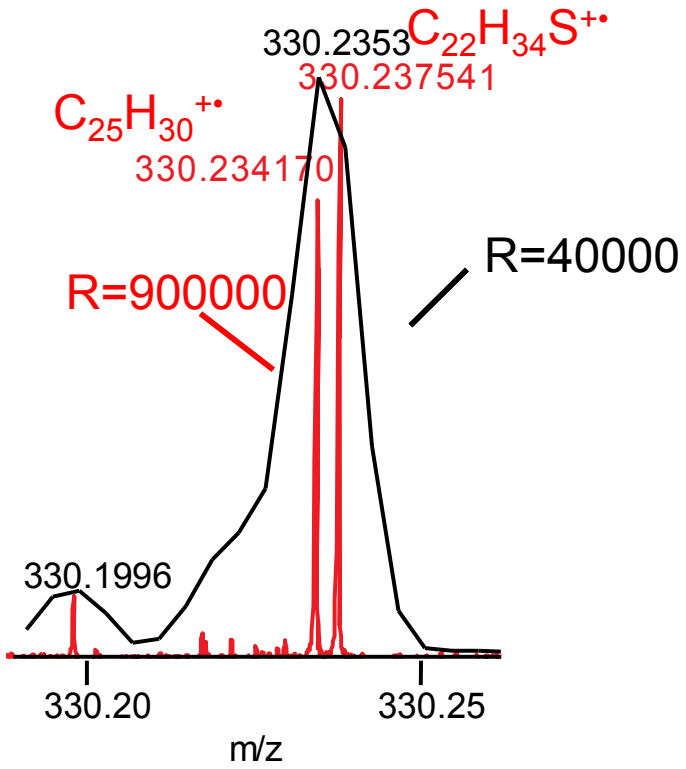
- 12 T Solarix XR
  - Highly Complex organic mixtures
  - Energy
  - Environment
  - Metabolomics

National and European infrastructure

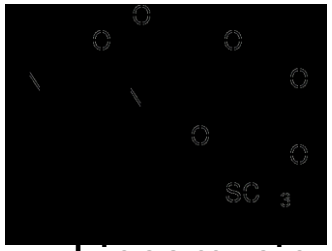




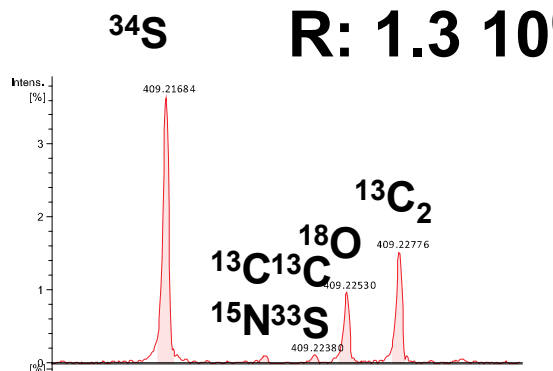
Complex mixture analysis and resolving power

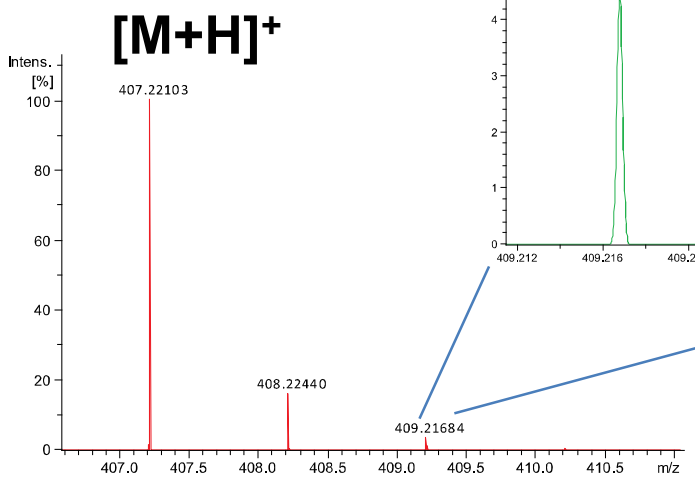


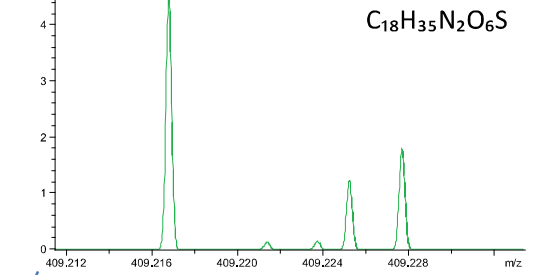
Isotopic Fine Structure



Lincomycin
($C_{18}H_{34}N_2OS$)







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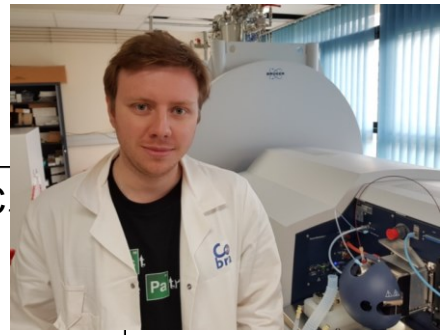
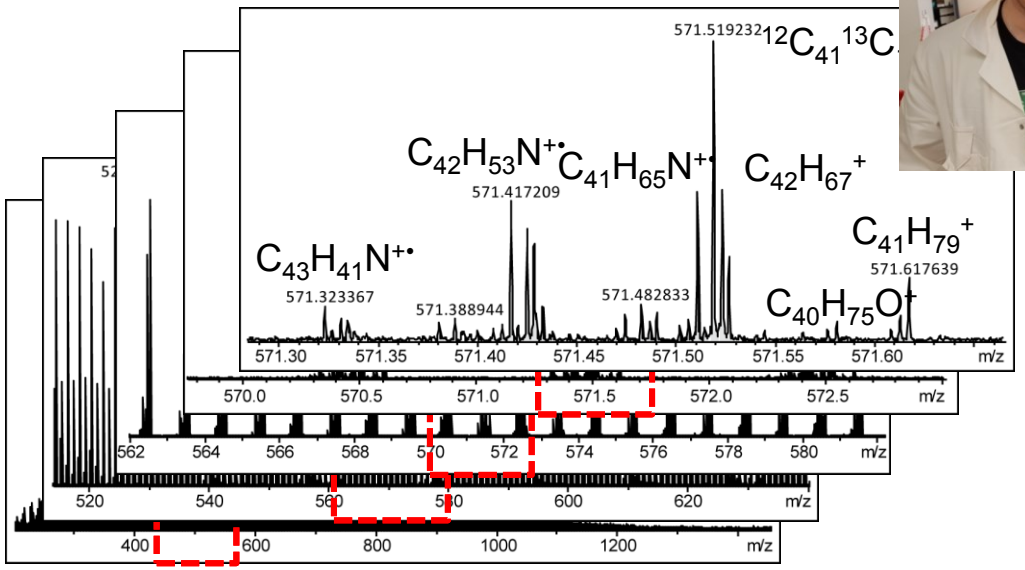
TotalEnergies

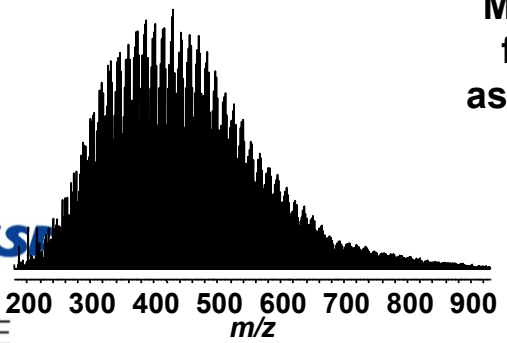
Johann Le Maitre

Crude oil analysis





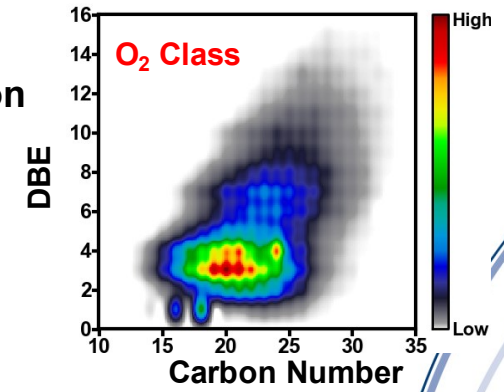
Crude Oil



Molecular formula assignment

Molecular Formula	Measured Mass	Calculated Mass	ppm error
$C_{29}H_{42}N_1$	404.3323	404.33227	0.16
$C_{30}H_{44}N_1$	418.348	418.34792	0.18
$C_{31}H_{46}N_1$	432.3638	432.36357	0.48
$C_{32}H_{50}N_1$	446.3793	446.37922	0.15
$C_{27}H_{47}O_2$	403.3582	403.35815	0.09
$C_{28}H_{49}O_2$	417.3738	417.37380	-0.13
$C_{29}H_{51}O_2$	431.3895	431.38945	0.18
$C_{30}H_{53}O_2$	445.4052	445.40510	0.12
$C_{31}H_{55}O_2$	459.4210	459.42075	0.49
$C_{32}H_{57}O_2$	473.4364	473.43640	-0.07

Data visualization



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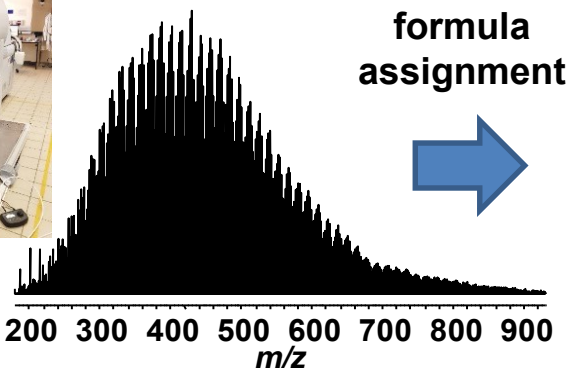
Data vizualization

Crude Oil



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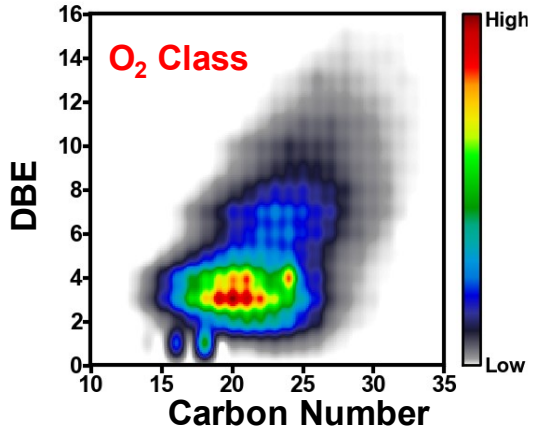
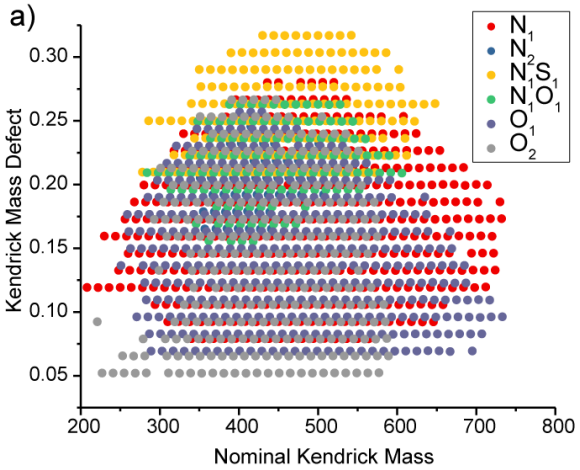
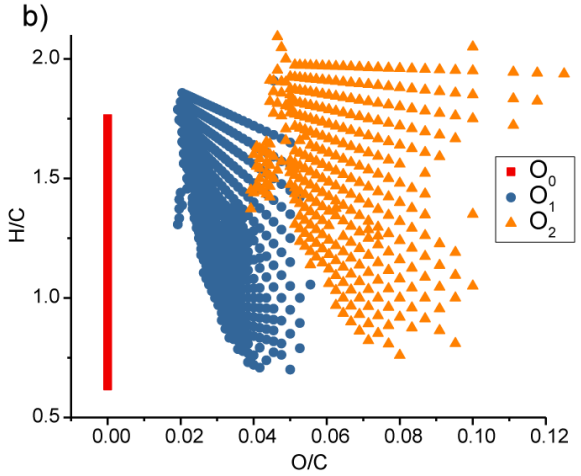
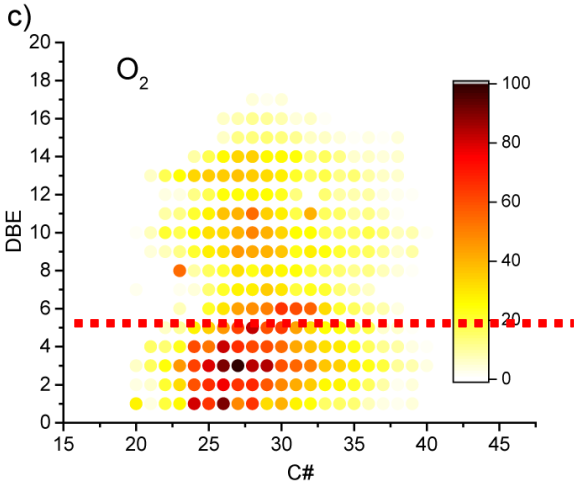




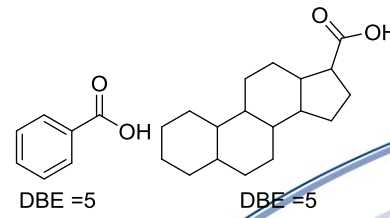
Kendrick Diagram



van Krevelen Diagram



DBE vs C#



S. Gutierrez Sama et al. *Energy Fuels* **2018**.

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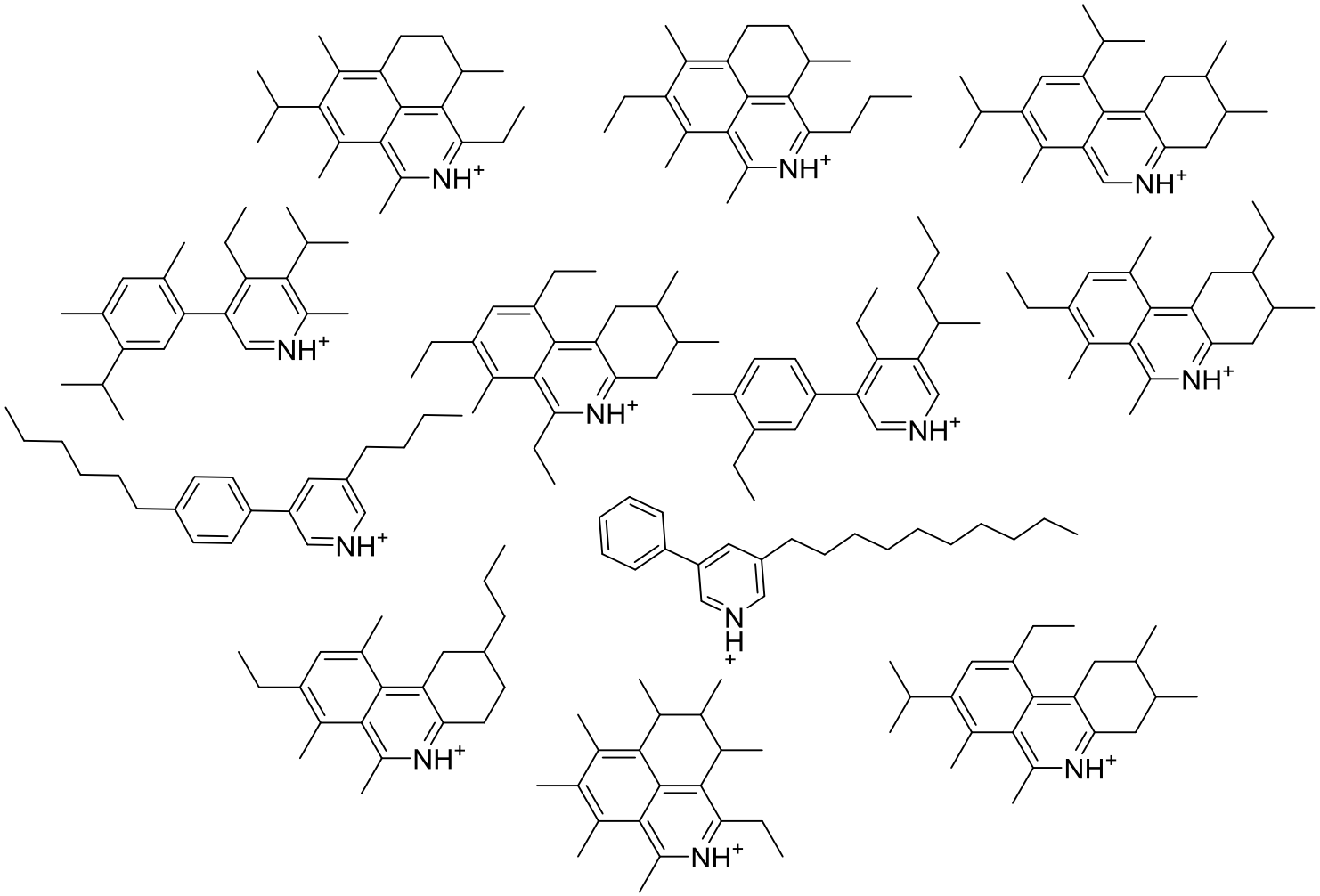
m/z 310.25293
Molecular Formula: $C_{22}H_{32}N^+$

Many structural formulas



Isomers

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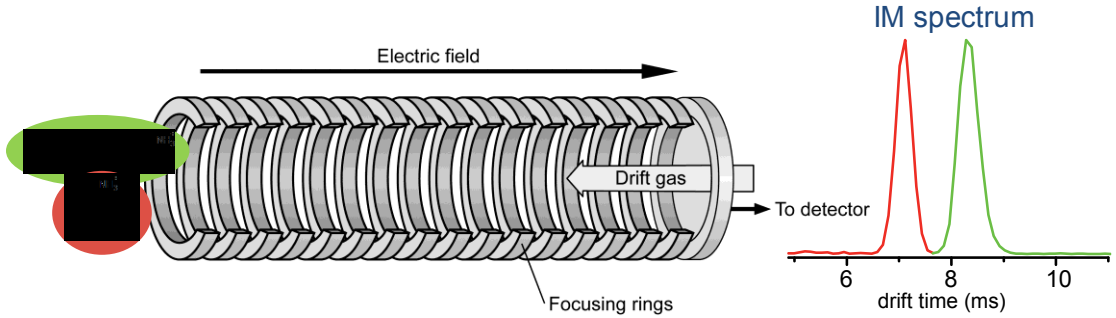
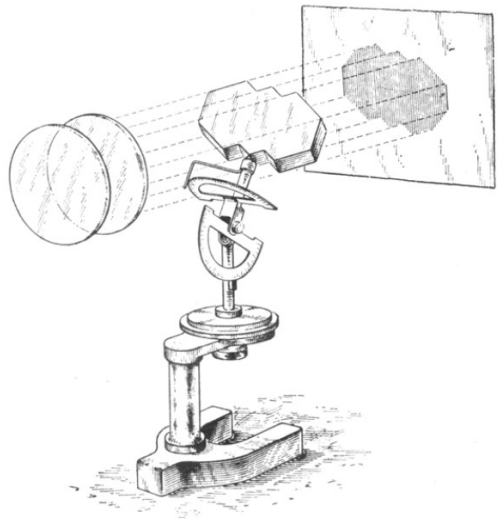
Structural information with IMS

- separation based on size and shape
  - drift time (1-30 ms)
  - access to collision cross section (CCS)
    - intrinsic property of the ion
    - predictable

- IMS-MS coupling
  - 2D separation
  - information on isomers
  - coupling with TOF
    (acquisition in µs range)



$$v_d = K \square E$$

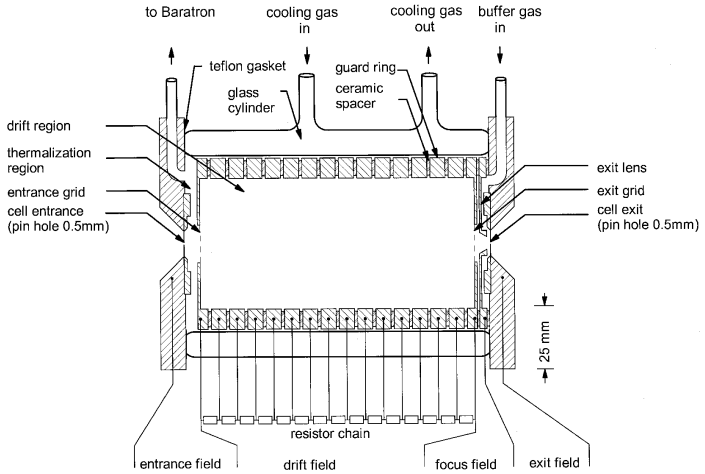


Edward Mack, Jr, *J. Am. Chem. Soc.* 1925, 47, 2468

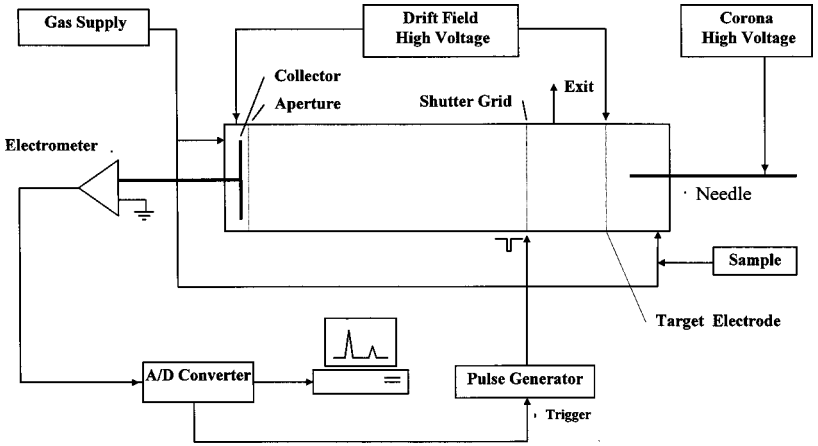
$$\frac{\Omega_{\exp}}{z} = \left(\frac{3}{16N}\right)\left(\frac{2\pi}{\mu kT}\right)^{\frac{1}{2}}\left(\frac{e}{K}\right)$$

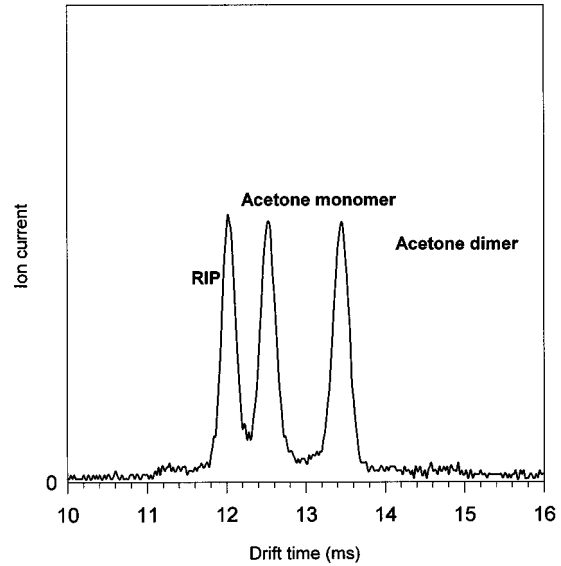
Drift tube IMS

- A very simple instrument
  - Uniform field
  - Atmospheric pressure
  - Cortana discharge ionization



P. Weis et al./Int. J. Mass Spectrom. 216 (2002) 59–73





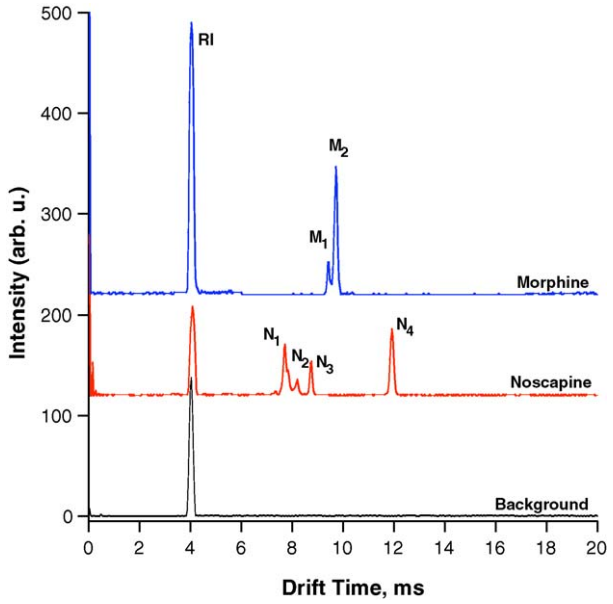
Rev. Sci. Instrum., Vol. 71, No. 6, June 2000

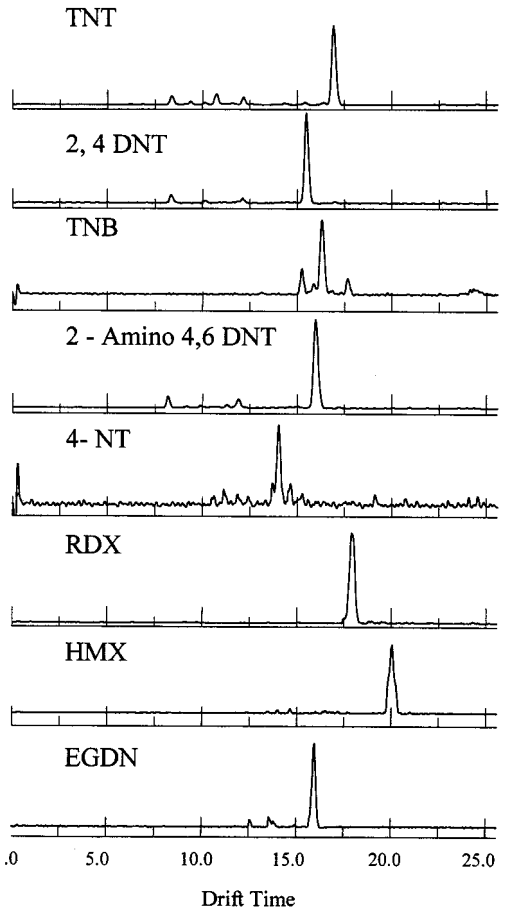
Portable IMS

Home land security

TR1000 Handheld Explosive Trace Detector

Smiths Detection (Ionscan 400B)





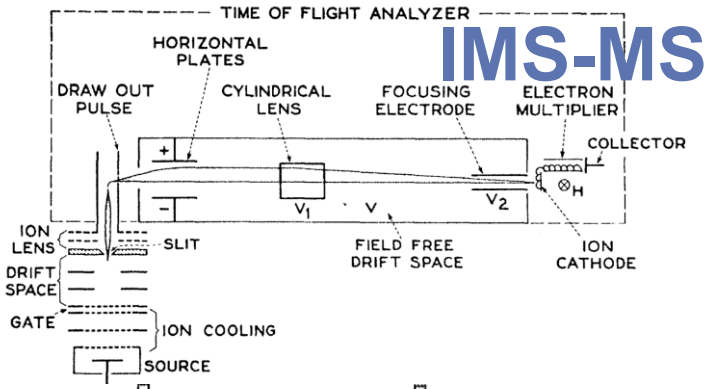
T. Khayamian et al. / Talanta 69 (2006) 795–799

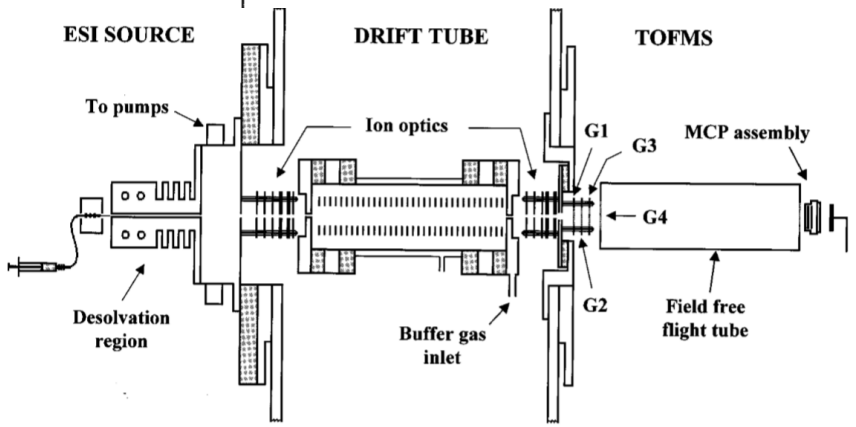
G. Reid Asbury et al. / Talanta 50 (2000) 1291–1298

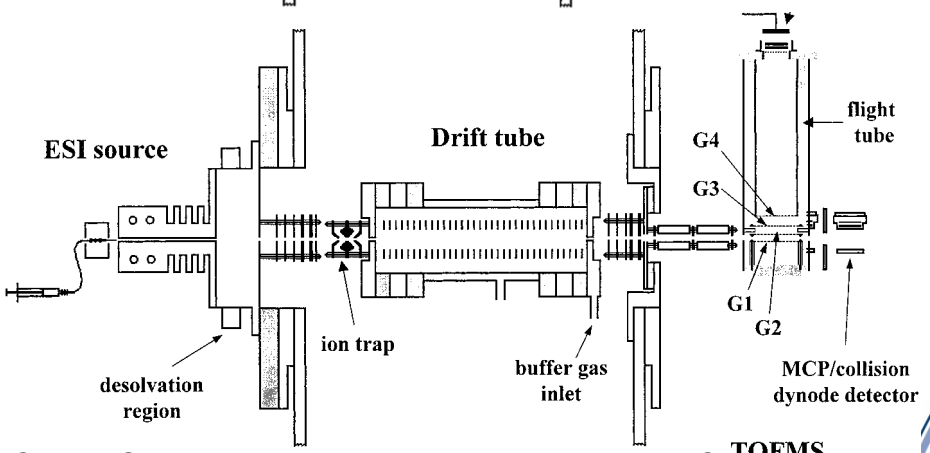
IMS-MS coupling

- IMS separation
  - <100 ms
- Fast mass analyzer
  - TOF
- First IM-MS
  - McKnight 1967
  - Ion/molecules reactions
  - Reintroduced in 1998-1999
    - David Clemmer

McKnight, Lee G., McAfee, Kenneth B., Jr. Sipler, D. P. Low-field drift velocities and reactions of nitrogen ions in nitrogen, Phys. Rev. 1067, 164, 62-70

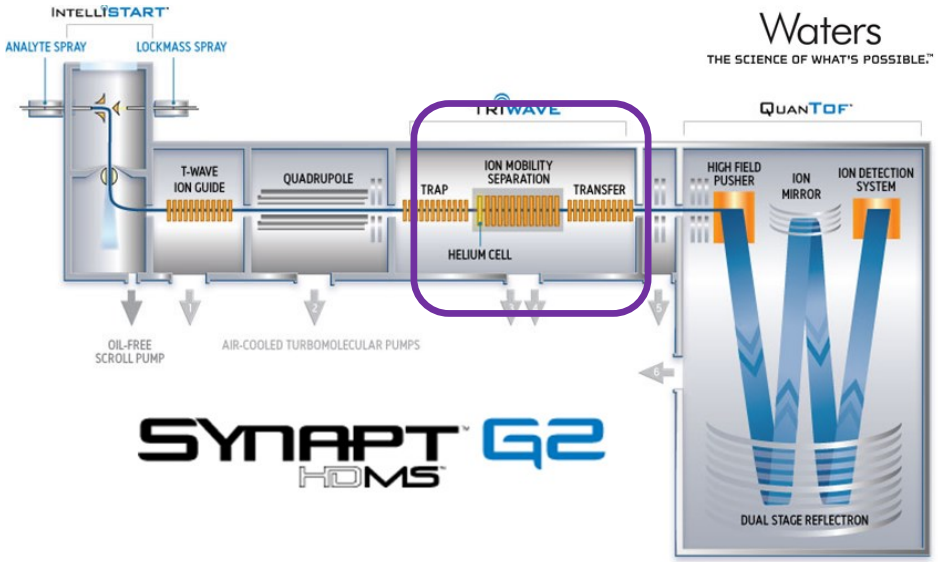


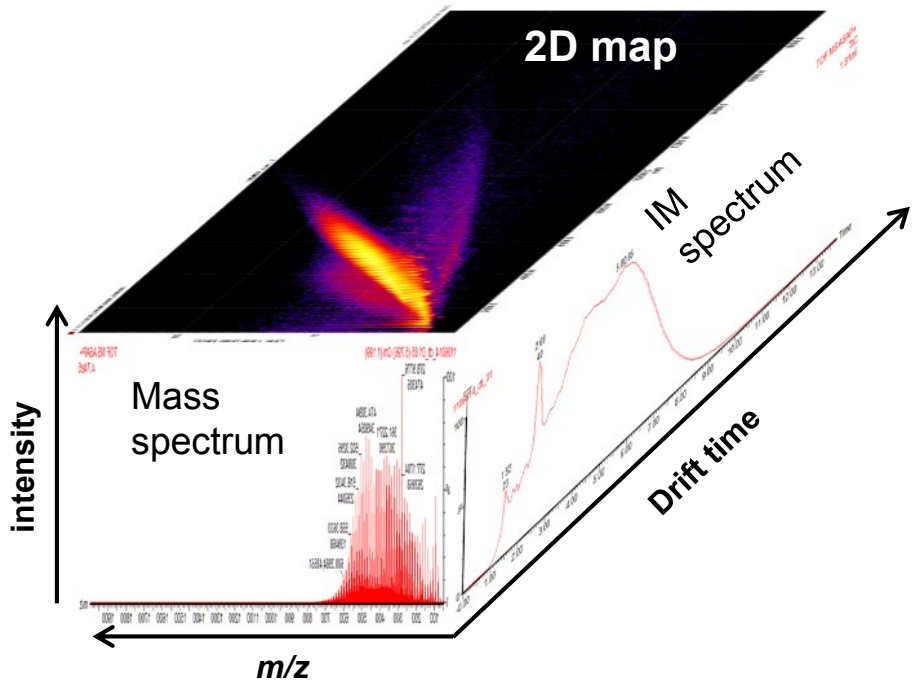




Cherokee S. Hoaglund, Stephen J. Valentine, C. Ray Sporleder, James P. Reilly, and David E. Clemmer Anal. Chem. 1998, 70, 2236-2242

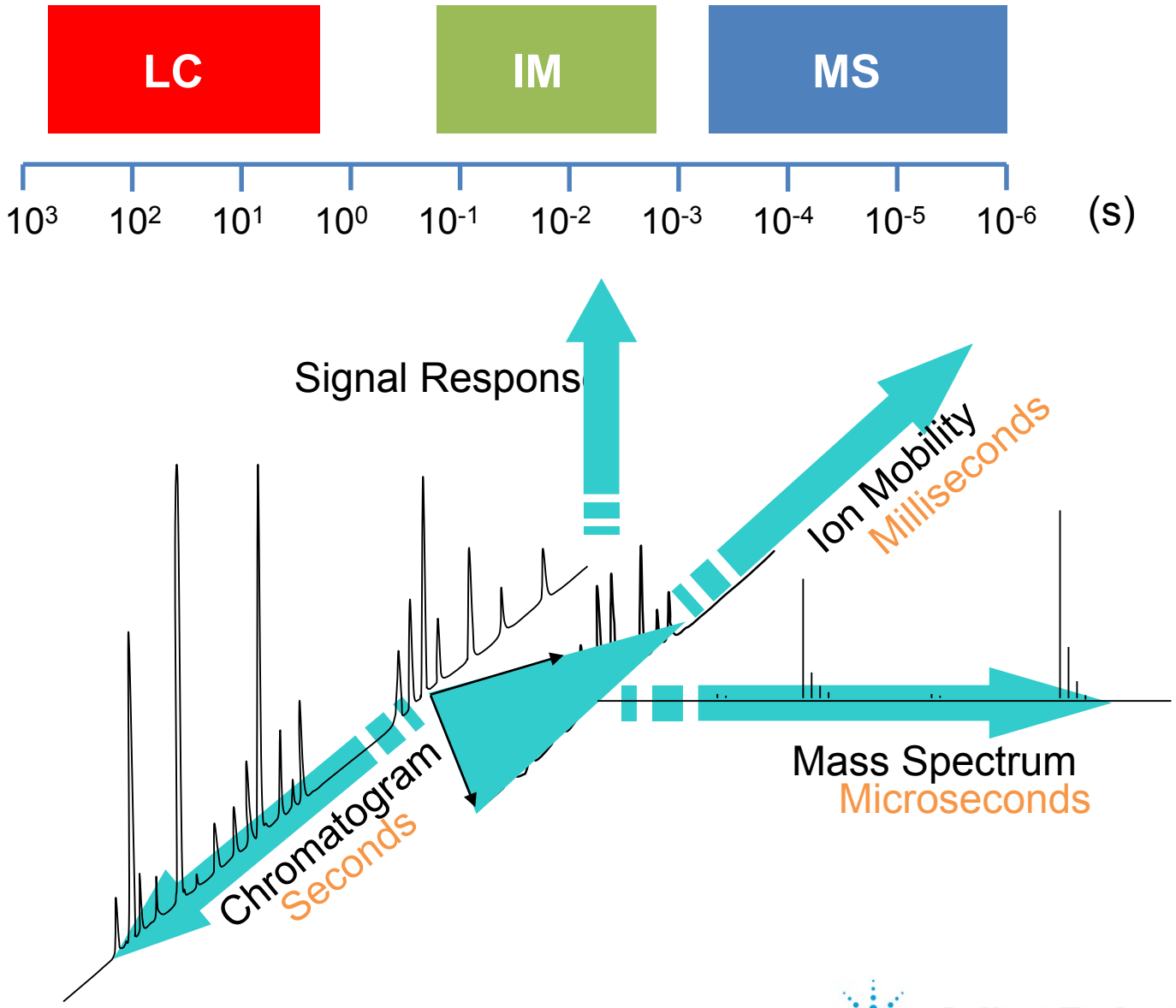
Ion Mobility-Mass spectrometry





- Ion coordinats = *m/z* + drift time + intensity

Timing



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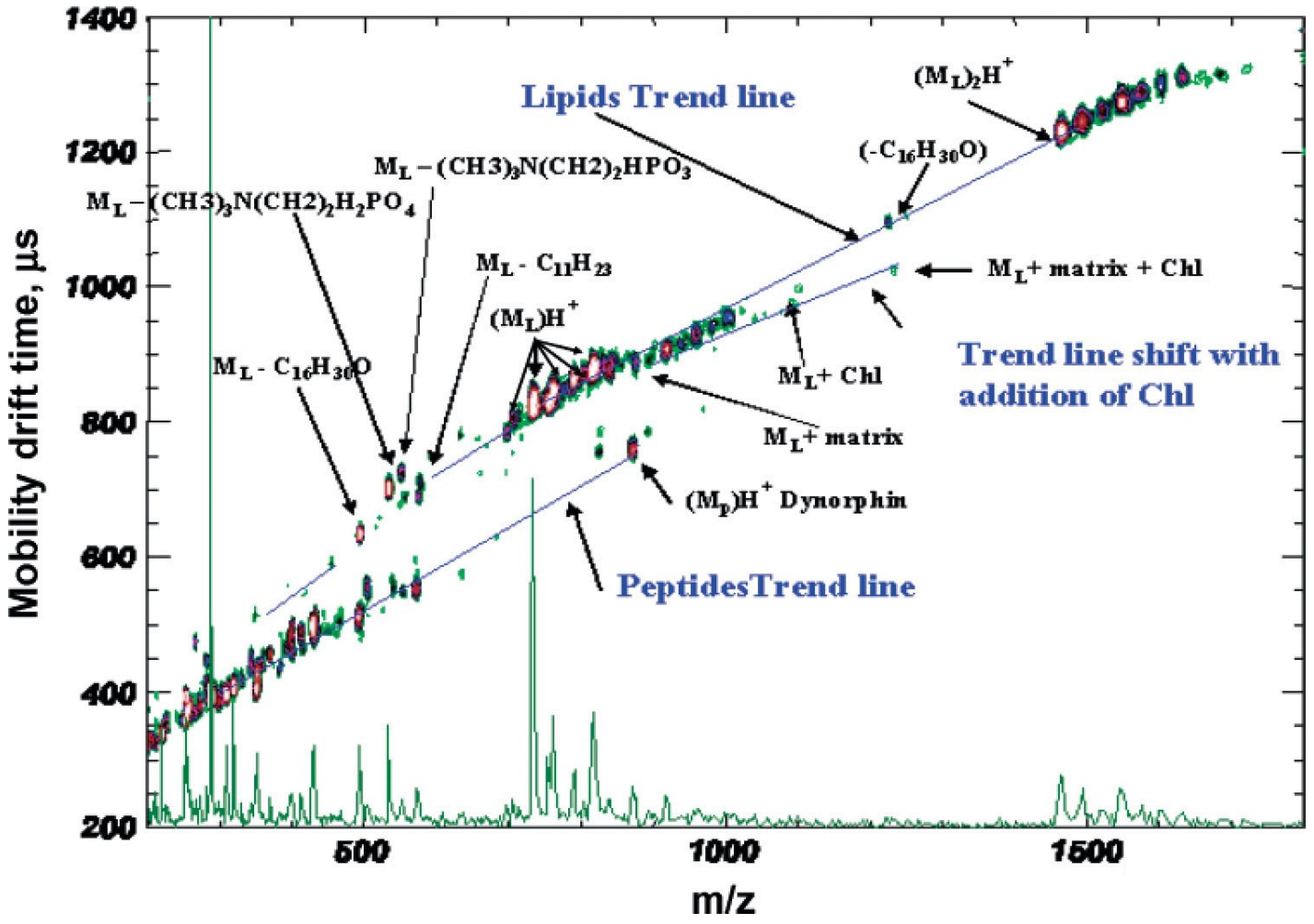
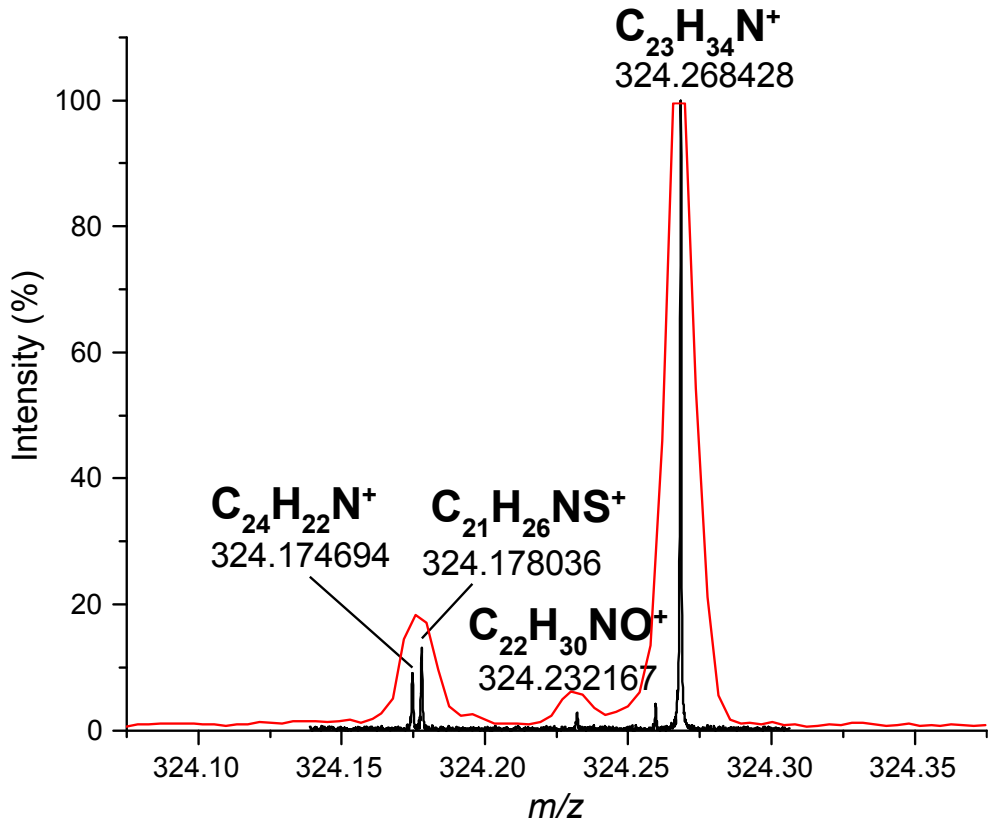
Agilent Technologies

2D Map



Woods A, Ugarov M, Egan T, Koomen J, Gillig KJ, Fuhrer K, Gonin M, Schultz JA. Lipid/peptide/nucleotide separation with MALDI-ion mobility-TOF MS. *Analytical Chemistry* 2004; 76: 2187–2195.

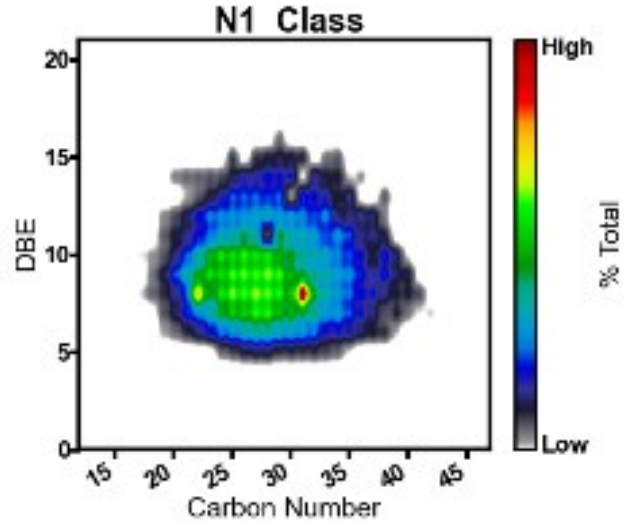
Complex mixture with TOF? Nitrogen speciation in Oil

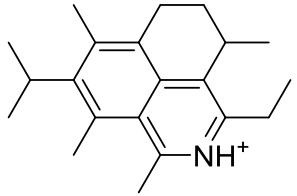


- isobaric interferences not resolvable (C_3 vs. SH_4) with the TOF but selected species can be investigated regarding IMS-profile
- UHRMS required for full molecular formula specification and proof for interferences

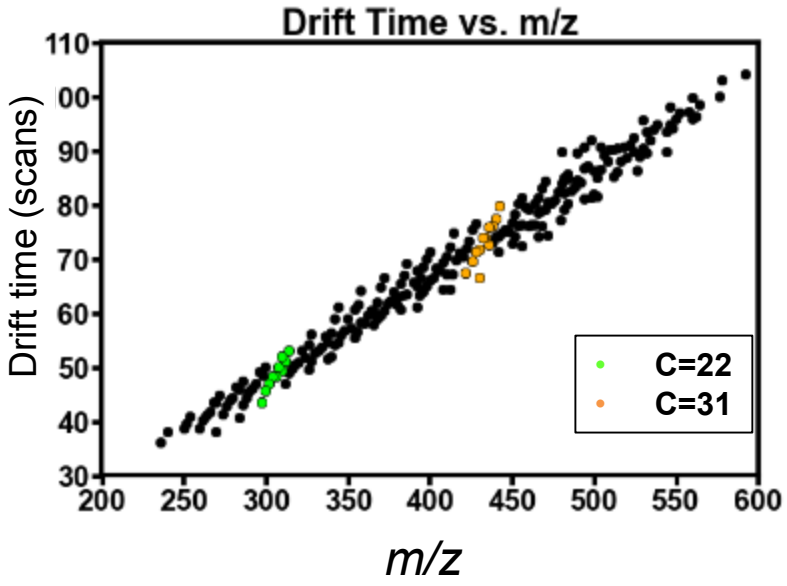
Application nitrogen speciation on a VGO

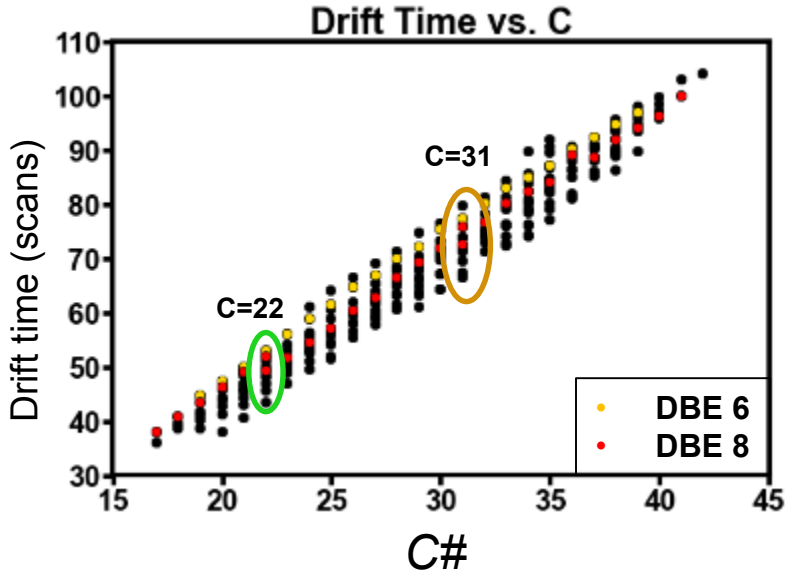
- ESI in positive mode:



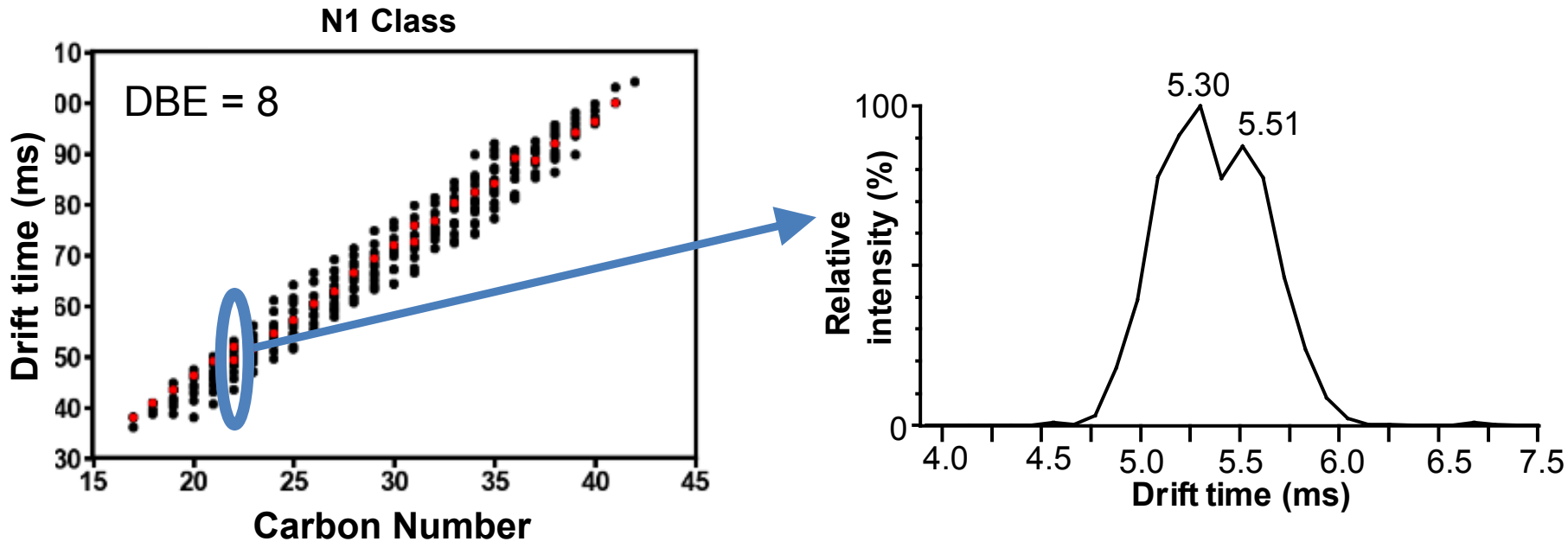


- Ion mobility display :



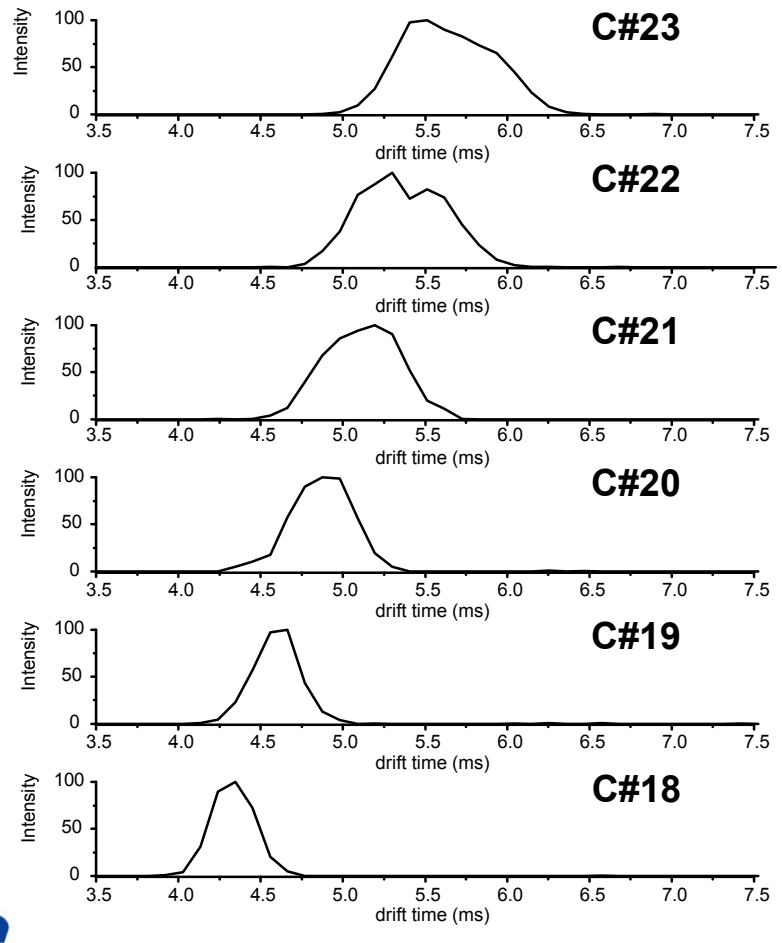


M. Farenc, Y. E. Corilo, P. M. Lalli, E. Riches, R. P. Rodgers, C. Afonso and P. Giusti, *Energy Fuels*, 2016, **30**, 8896-8903.

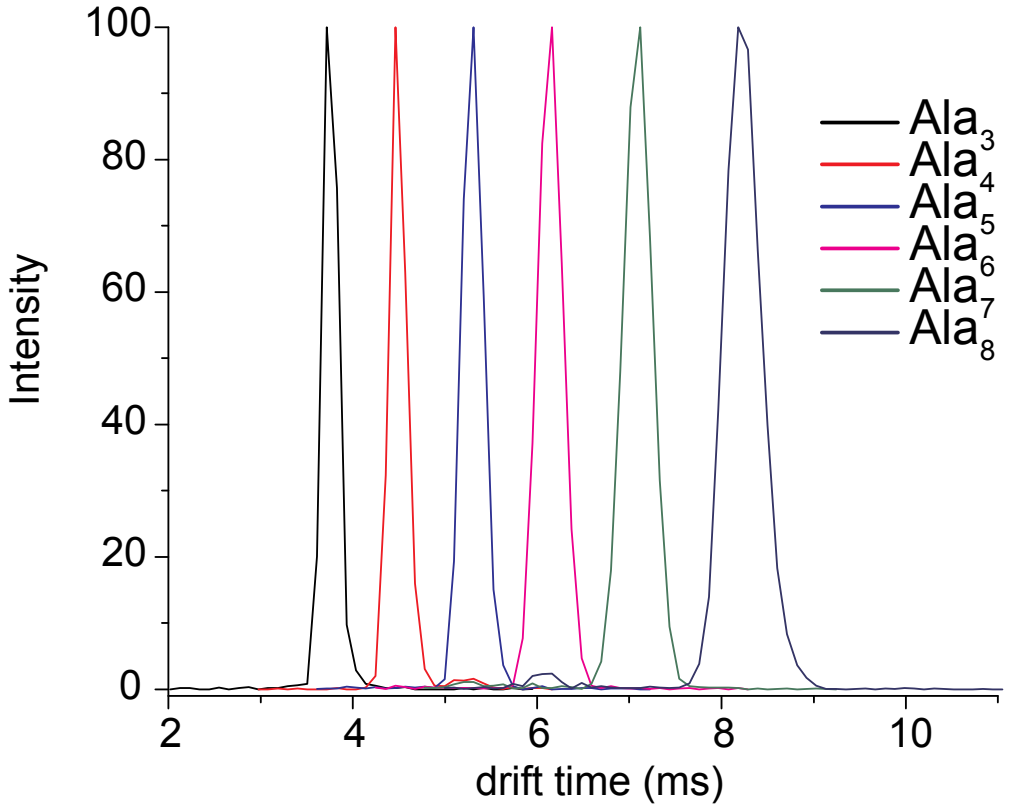

N1 Class
DBE = 8
Drift time (ms)
Carbon Number
10
00
90
80
70
60
50
40
30
15
20
25
30
35
40
45
5.30
5.51
100
0
Relative intensity (%)
4.0
4.5
5.0
5.5
6.0
6.5
7.5
Drift time (ms)

IMS profile

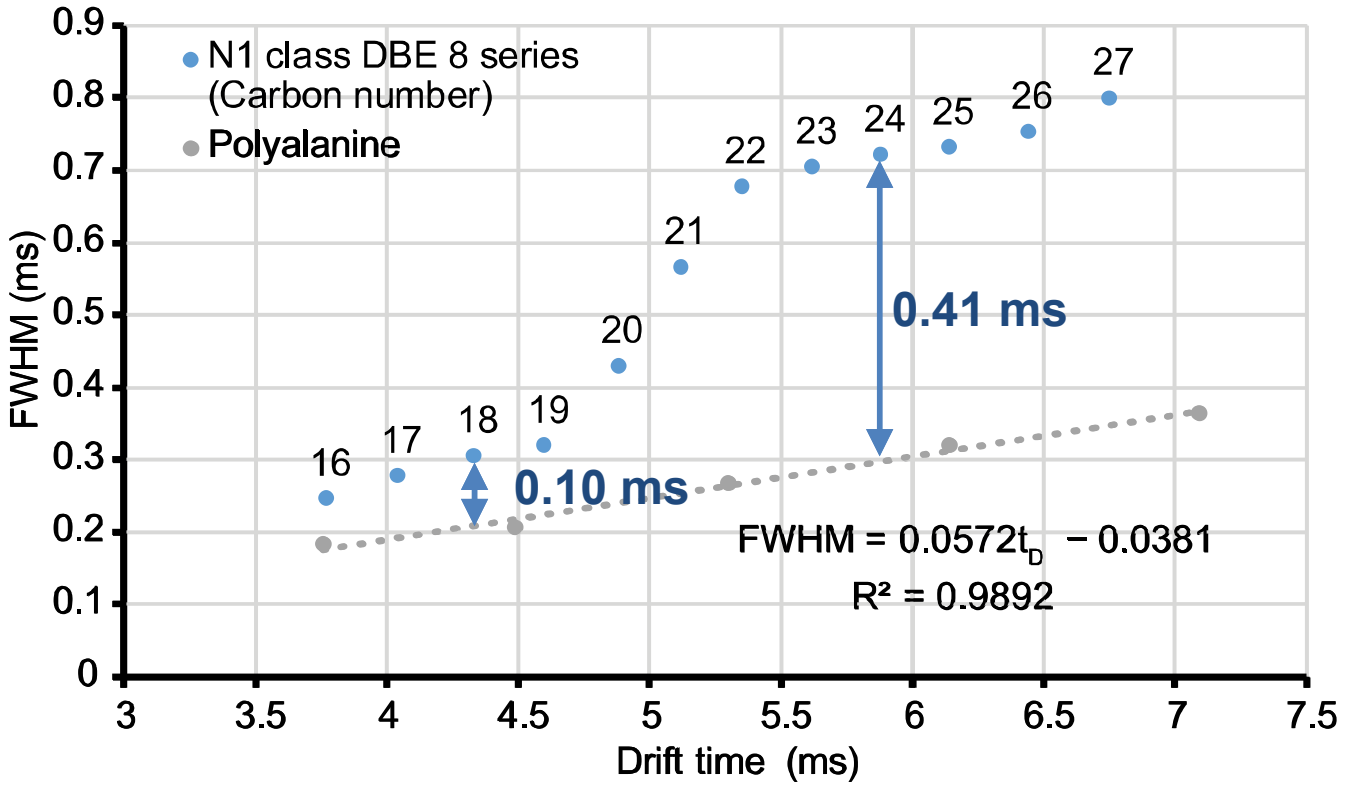
DBE8 N1 class



Polyalanine



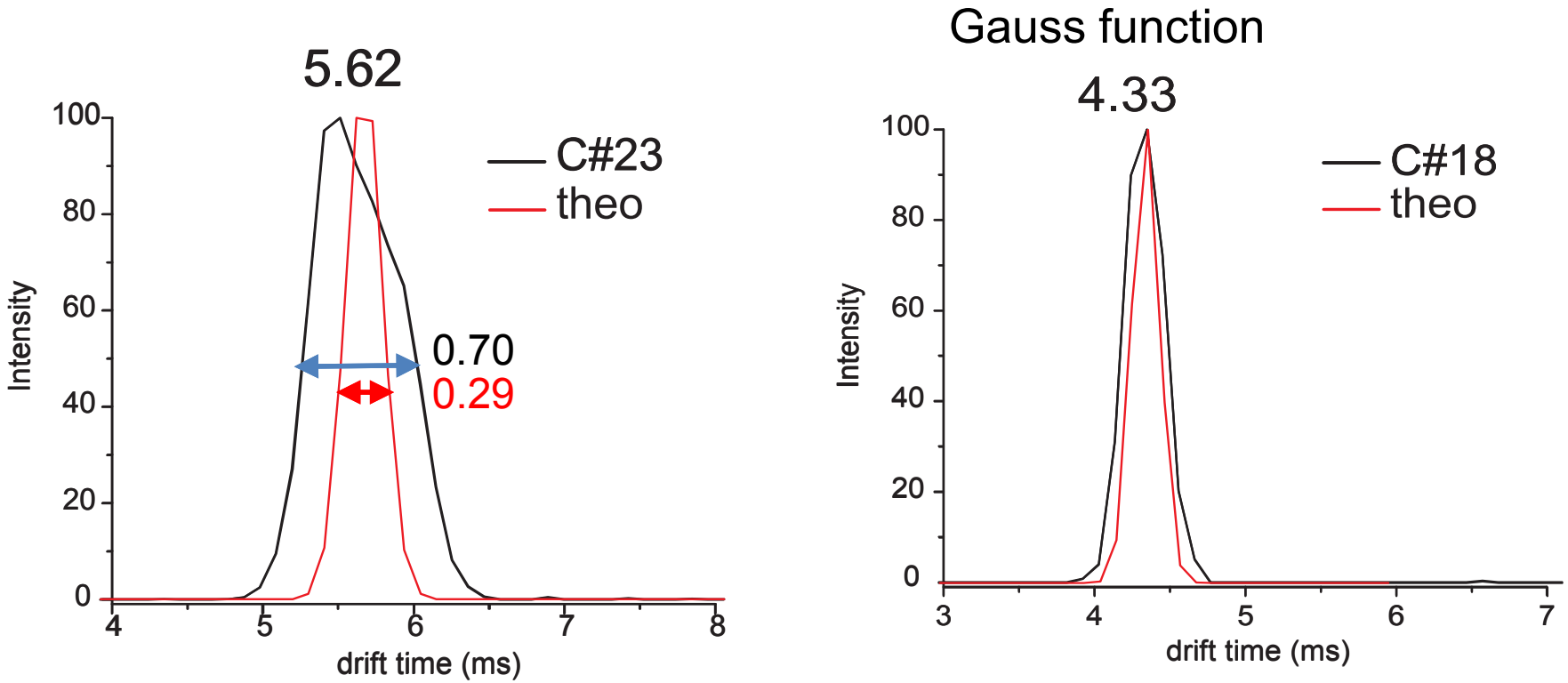
FWHM *vs* drift time



$$FWHM = 0.0572t_D - 0.0381$$

Prediction of peak width

FWHM = 0.0572t_D − 0.0381 ⇒ $f(x) = ae^{\frac{(x-b)^2}{2c^2}}$



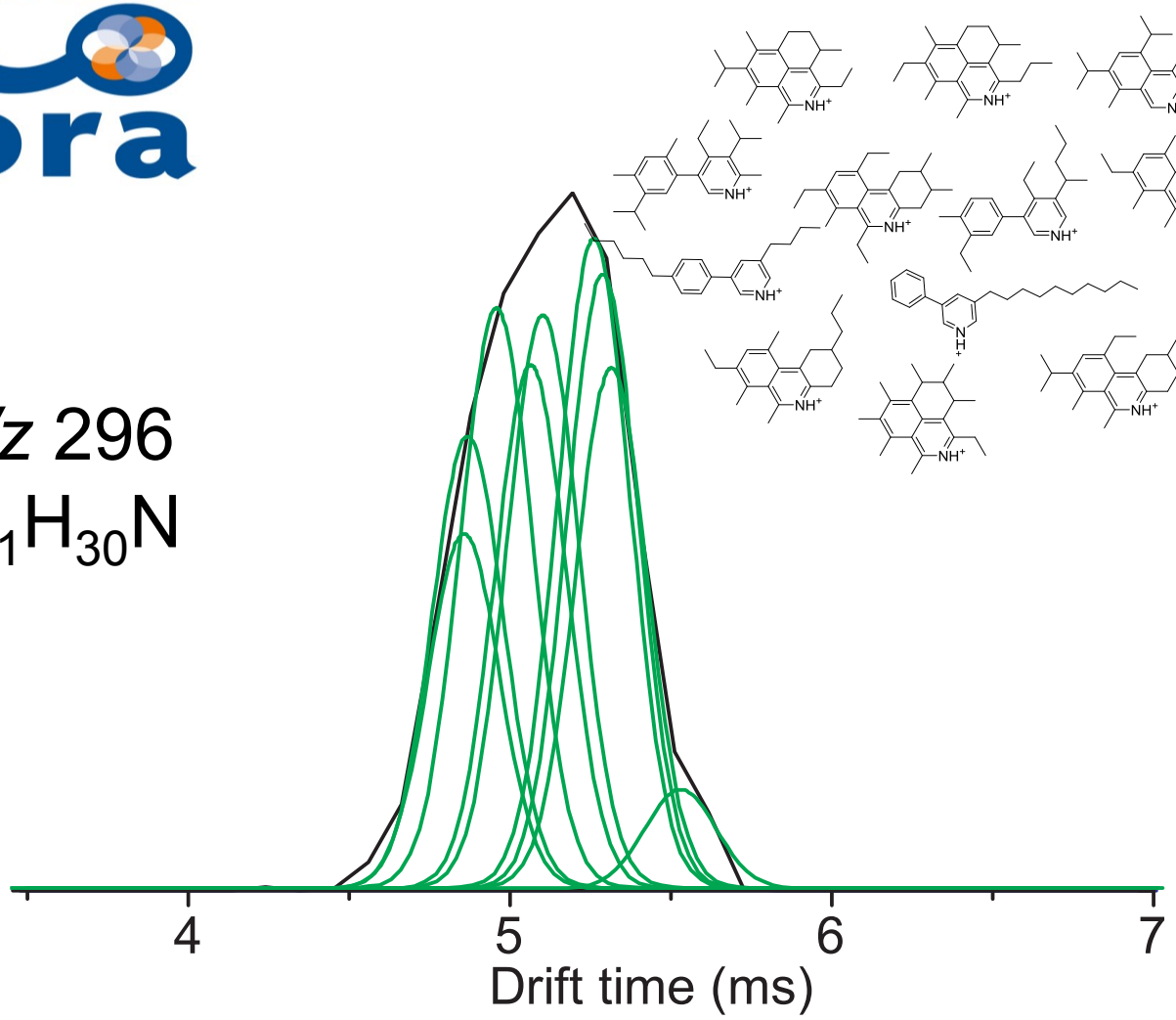
- Other way to obtain information on isomeric content?

Farenc, M., Paupy, B., Marceau, S. et al. J. Am. Soc. Mass Spectrom. (2017) 28: 2476. https://doi.org/10.1007/s13361-017-1749-1

Peak deconvolution ?

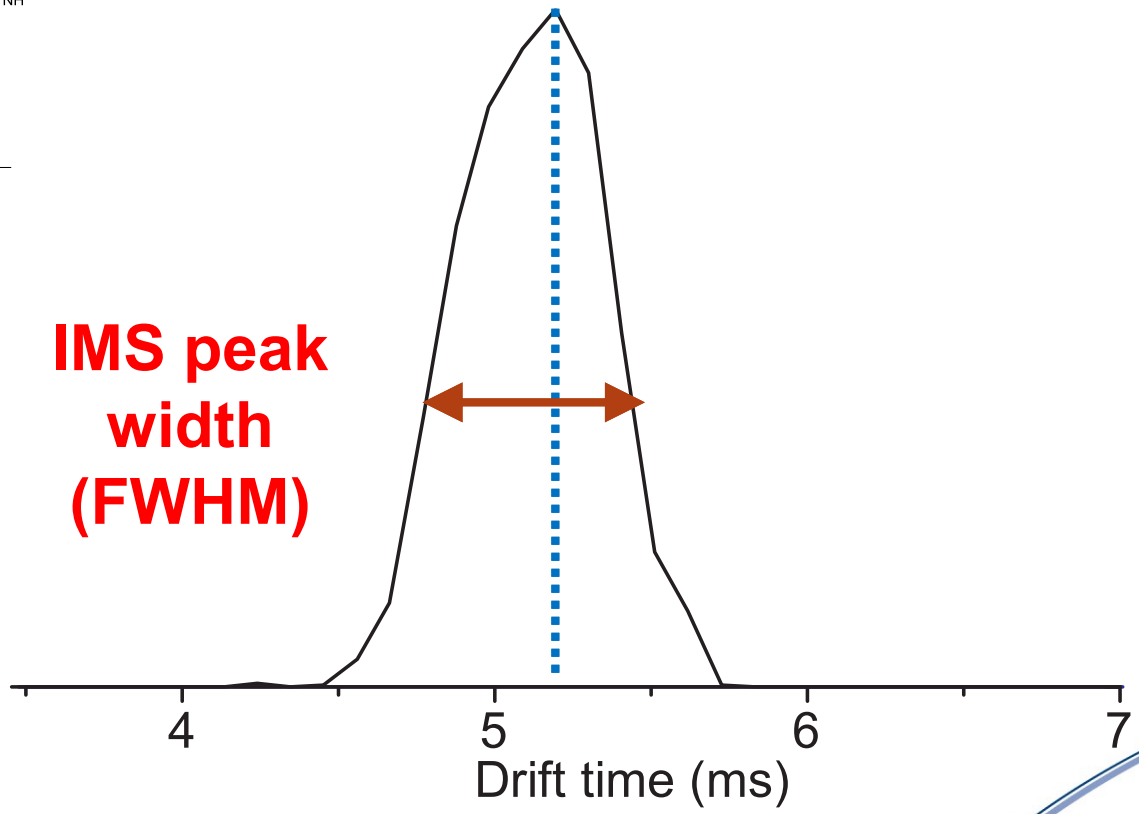
m/z 296

$C_{21}H_{30}N$



Drift time

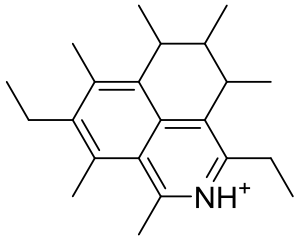
IMS peak width (FWHM)

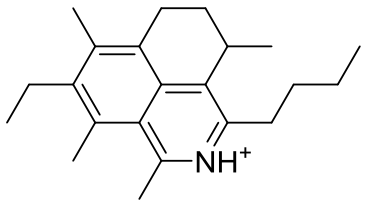


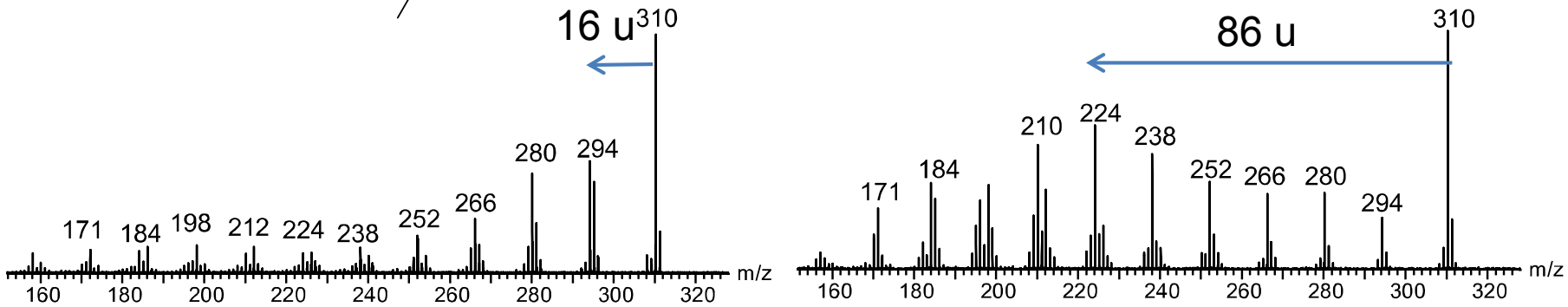
- Ion peak deconvolution on petroleum compounds not possible
- Continuum of isomeric species

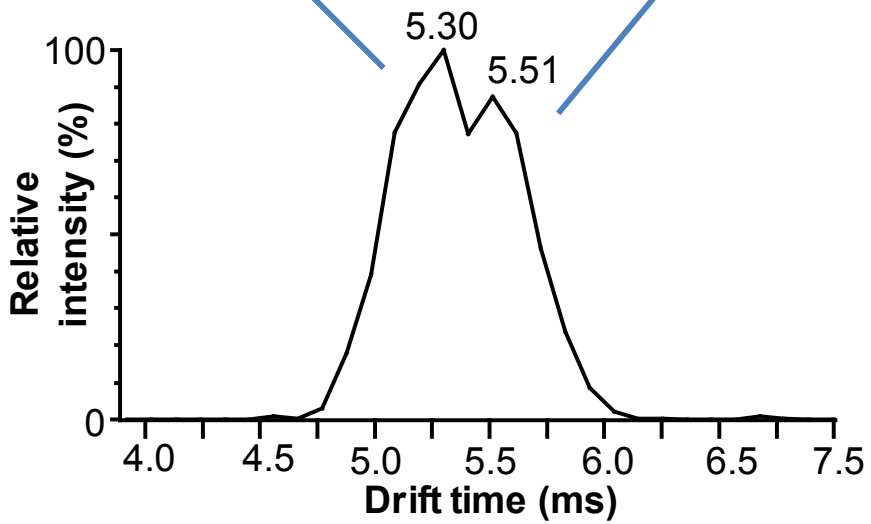
Laboratoire Cobra

Post IMS CID







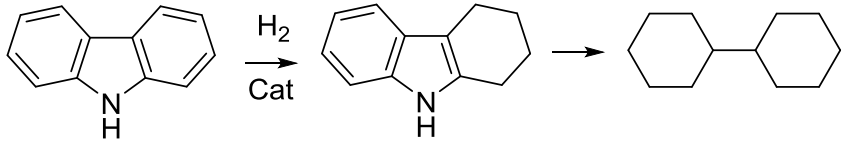


cnrs INSA UNIVERSITE DE ROUEN

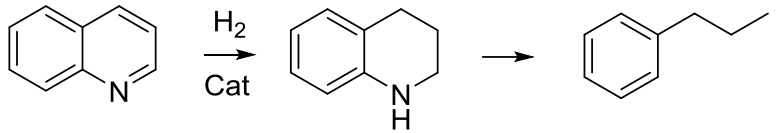
Molecules refractory to the HDN process

HYDRODENITROGENATION OF VGO

Neutral Nitrogen

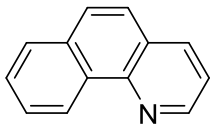


Basic Nitrogen

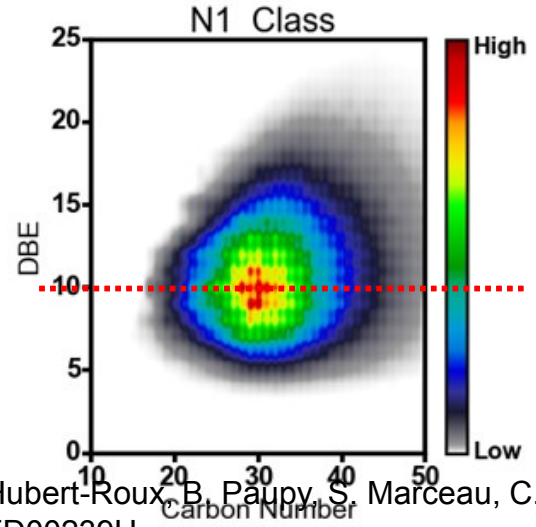


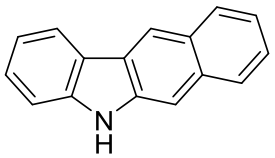
Basic Nitrogen
ESI(+)

Neutral Nitrogen
ESI(−)

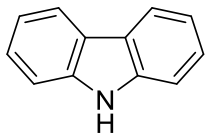


benzoquinoline
DBE=10

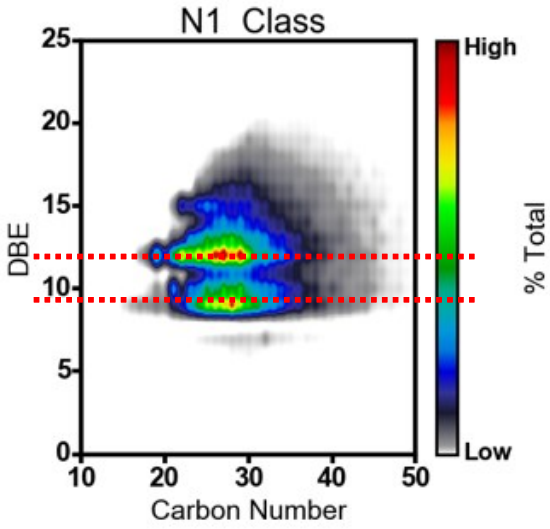




benzocarbazole
DBE=12



carbazole
DBE=9



J. Le Maître, M. Hubert-Roux, B. Paupy, S. Marceau, C. Rüger, C. Afonso, P. Giusti, *Faraday Discussions*, 2019, DOI:10.1039/C8FD00239H

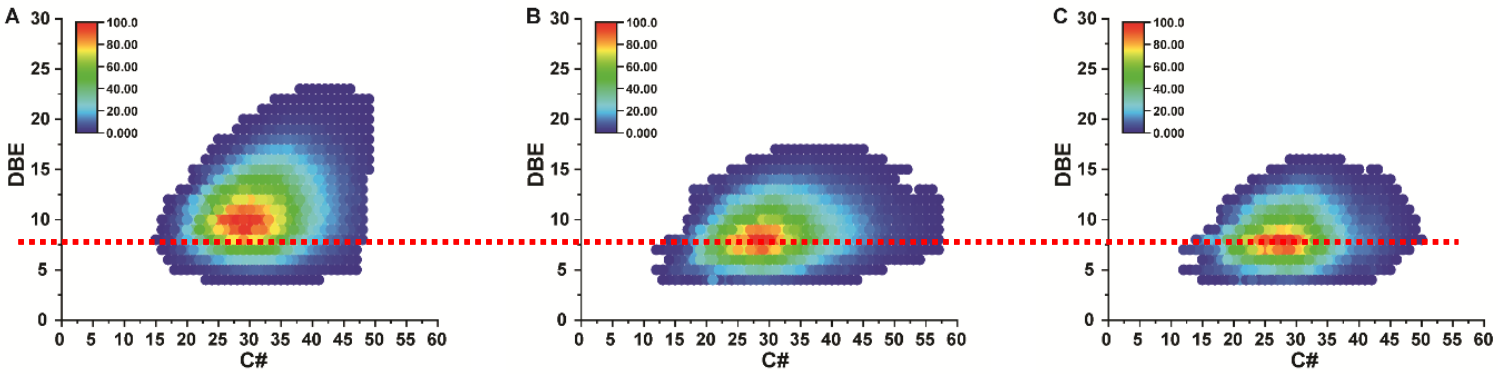
Faraday Discussion

Challenges in Analysis of Complex Natural Mixtures Faraday Discussion May 13, 2019 - May 15, 2019

Molecules refractory to the HDN process

Hydrodenitrogenation of VGO

(+)-ESI
12T FTICR



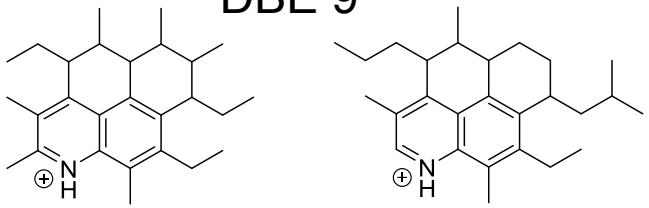
VGO **70 ppm** **10 ppm**

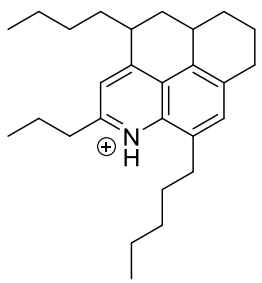
$DBE = c - h/2 + n/2 + 1$
(for $C_cH_hN_nO_oS_s$)

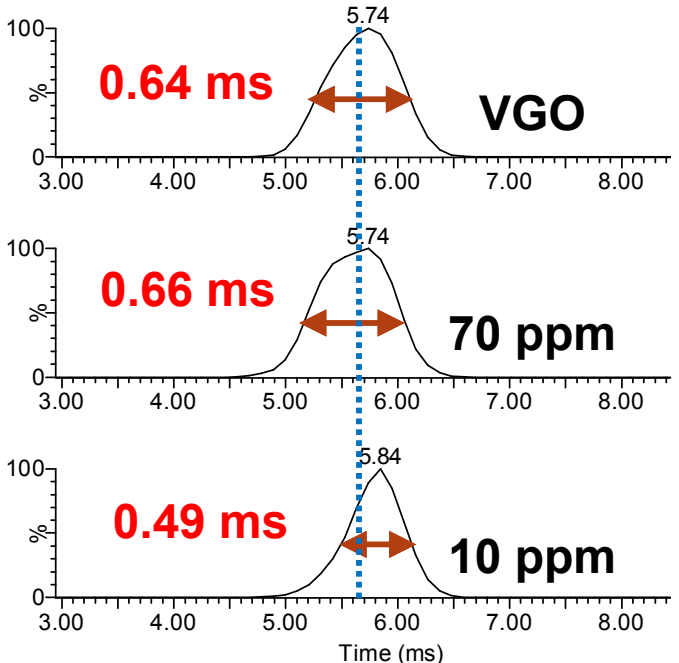
DBE 7-8-9 most refractory to HDN

(+)-ESI
IMS-QTOF

$C_{27}H_{40}N^+$ *m/z* 378.3155
DBE 9







137.5 Å²

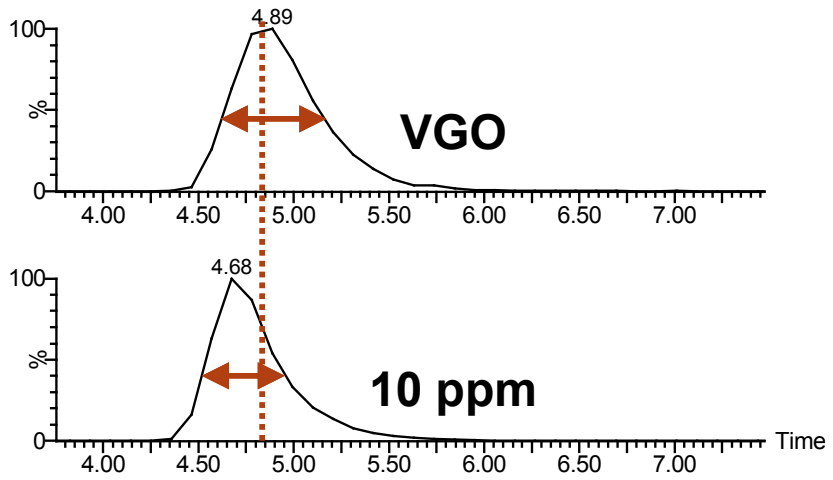
137.5 Å²

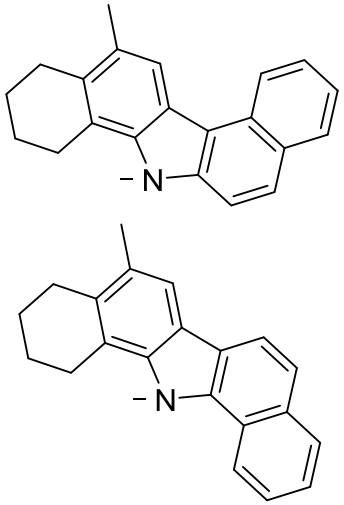
139.4 Å²

J. Le Maître, M. Hubert-Roux, B. Paupy, S. Marceau, C. Rüger, C. Afonso, P. Giusti, *Faraday Discussions*, 2019, 218 (0), 417-430.

IMS-HRTOF (-)-ESI

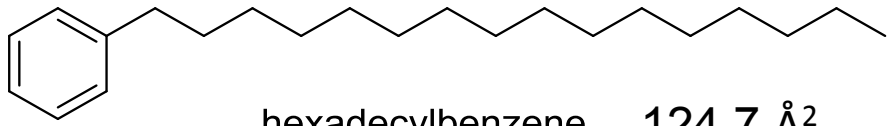
$C_{21}H_{18}N^-$
DBE 13





- significant shift in peak apex and FWHM also for (-)-ESI

CCS based structure prediction



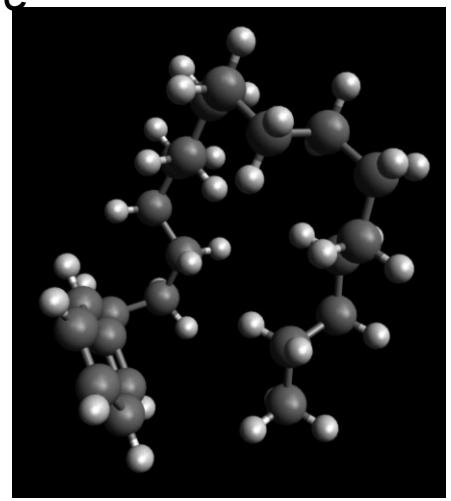
hexadecylbenzene 124.7 Å^2

- minimization using MMFF94 Force Field
- CCS determination of all structures using Mobcal

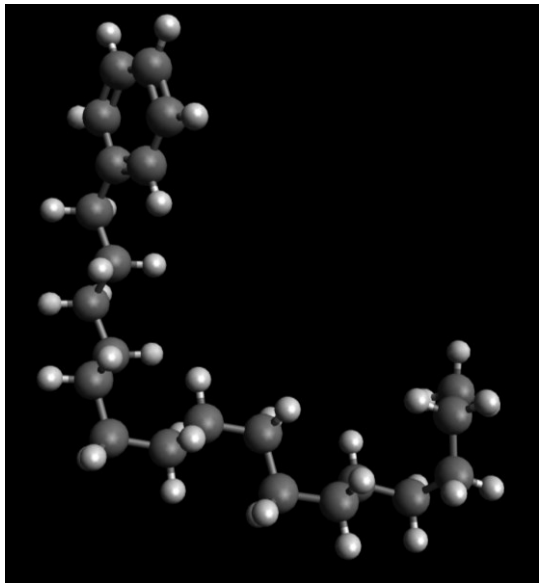
Simulation and modeling of CCS for structural elucidation…

Lowest energy structure

71.9 kJ/mol
119.6 Å^2

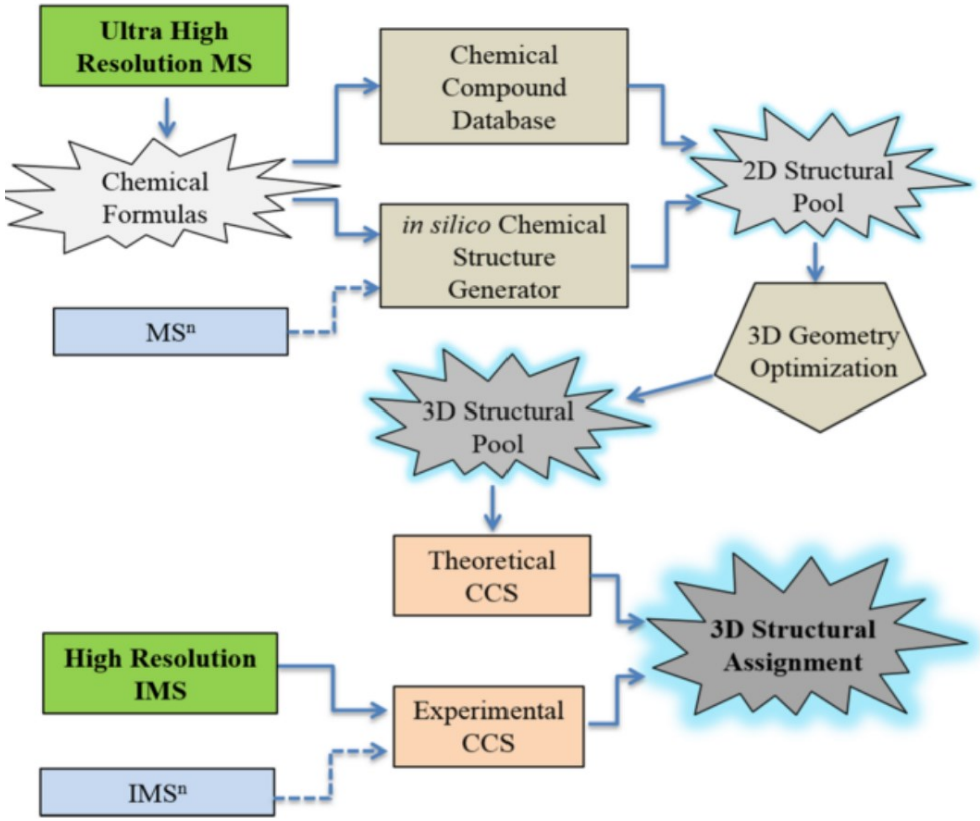


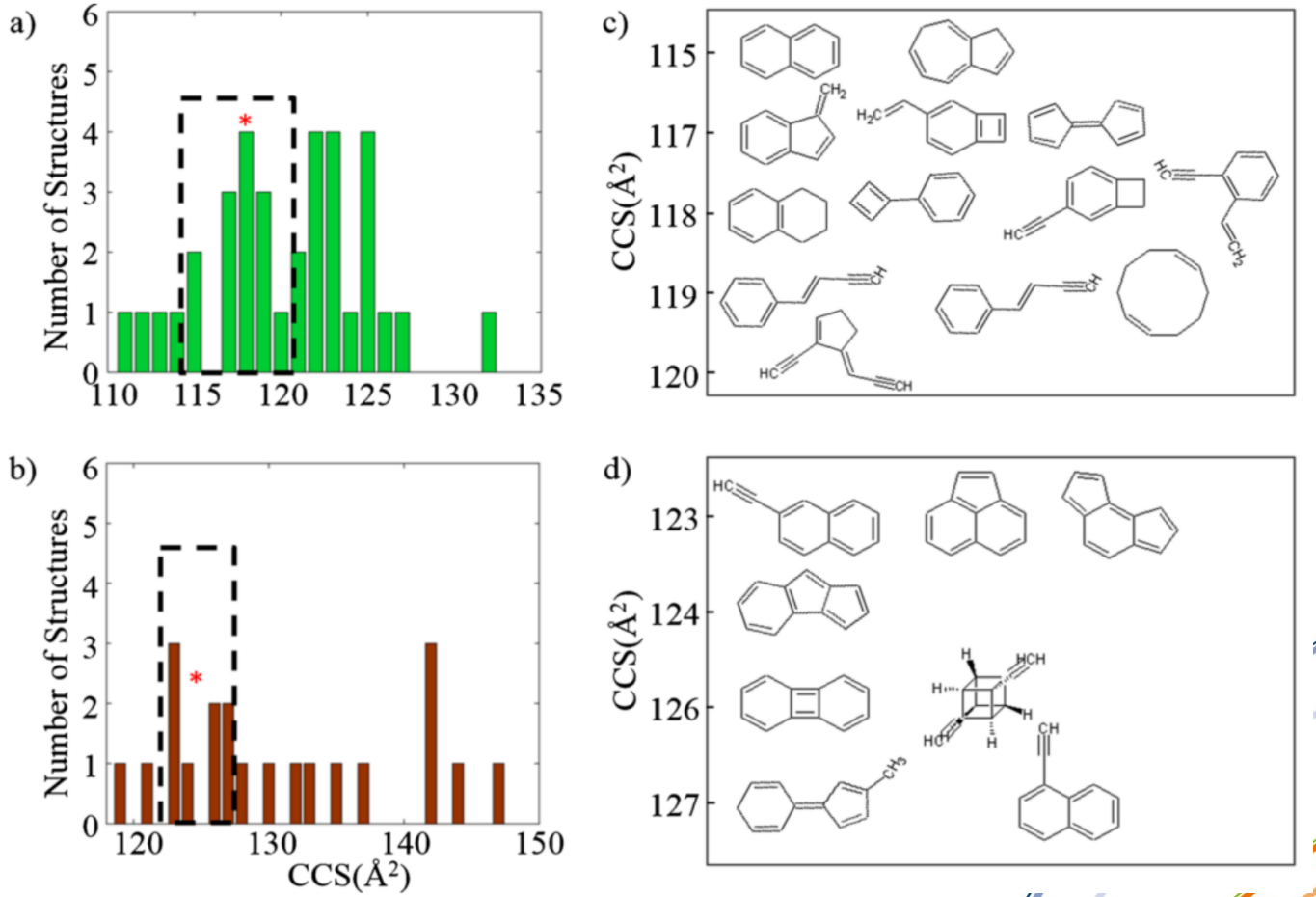
Highest energy structure



Structure prediction based on IMS-MS

Towards unsupervised polyaromatic hydrocarbons structural assignment from SA-TIMS-FTMS data



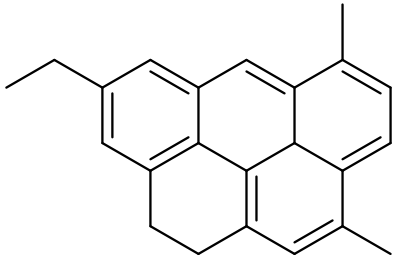


Complex mixture of polyaromatic hydocarbons coal tar in oil (SRM1597)

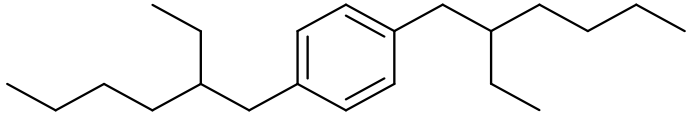
P. Benigni, R. Marin and F. Fernandez-Lima, *Int J Ion Mobil Spectrom*, 2015, **18**, 151-157.

CCS calculation from long alkyl chain molecules

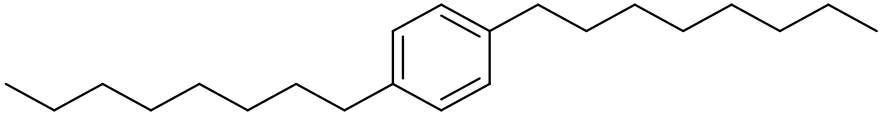
Rigid molecule



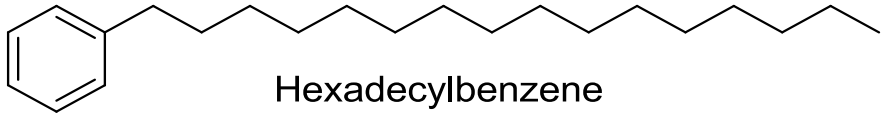
Highly floppy molecule



1,4-Bis(2-ethylhexyl)benzene

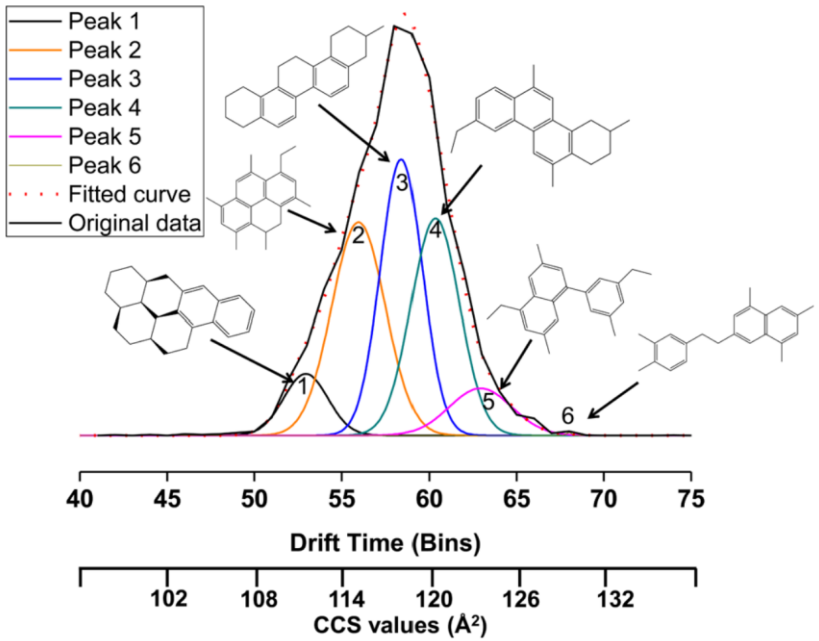


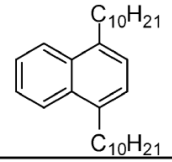
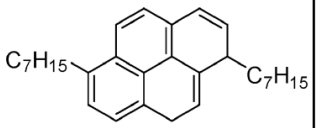
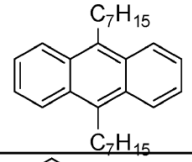
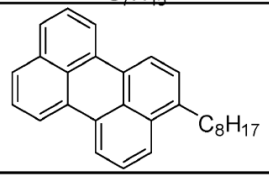
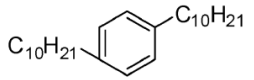
1,4-Dioctylbenzene



Hexadecylbenzene

Previous Work on CCS based structure prediction

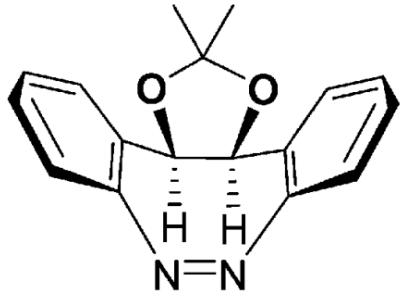


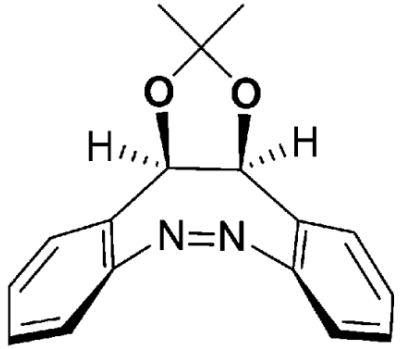
Standard compounds	Suggested structures	Experimental CCS values (Å²)	Theoretical CCS values (Å²)	ΔΩ (exp.- theo.)%
1,4-didecylnaphthalene		155.86	199.50	-28.0
1,6-diheptylpyrene		148.04	174.68	-18.0
9,10-diheptylanthracene		139.52	164.67	-18.0
3-octylperylene		128.68	147.48	-14.6
1,4-didecylbenzene		147.96	186.47	-26.0

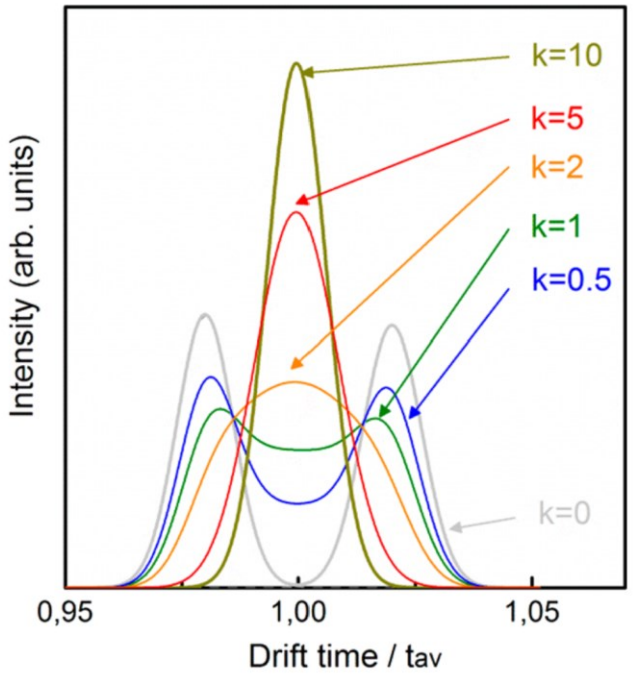
DFT using B3LYP/6-31G(d) base set

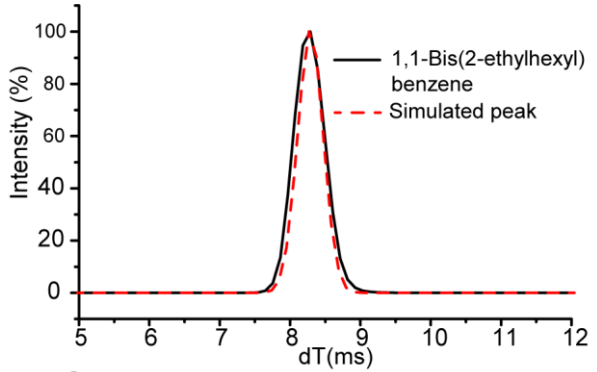
A. Ahmed, Y. Cho, K. Giles, E. Riches, J. W. Lee, H. I. Kim, C. H. Choi and S. Kim, *Anal. Chem.*, 2014, **86**, 3300-3307.

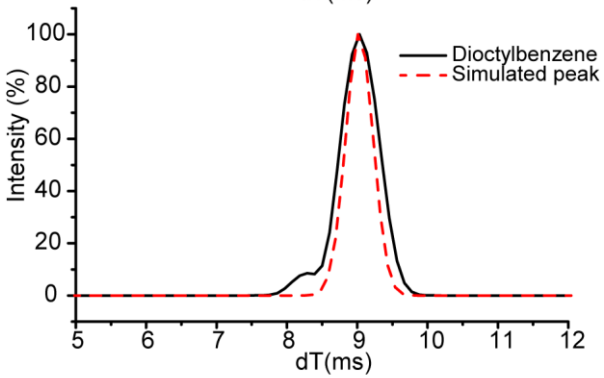
How floppy molecules fly in the IMS cell?

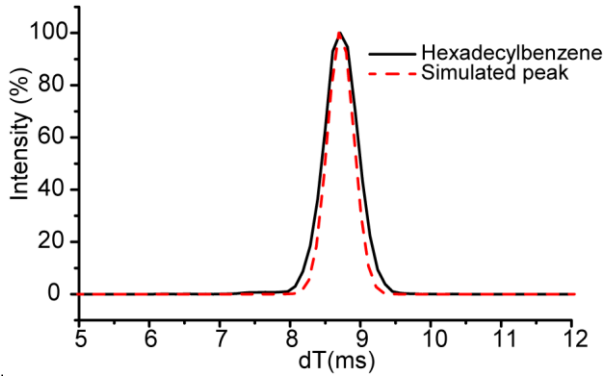












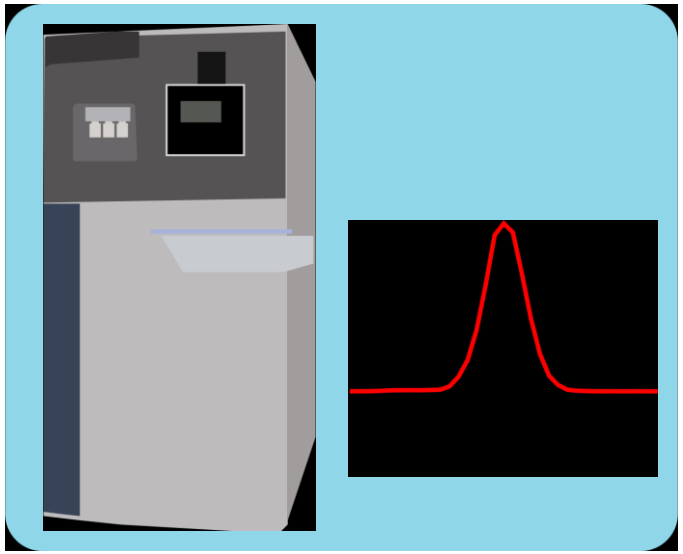
S. Poyer, C. Comby-Zerbino, C. M. Choi, L. MacAleese, C. Deo, N. Bogliotti, J. Xie, J. Y. Salpin, P. Dugourd and F. Chirot, *Anal. Chem.*, 2017, **89**, 4230-4237

CCS prediction Workflow

[redacted]

[redacted]

[redacted]



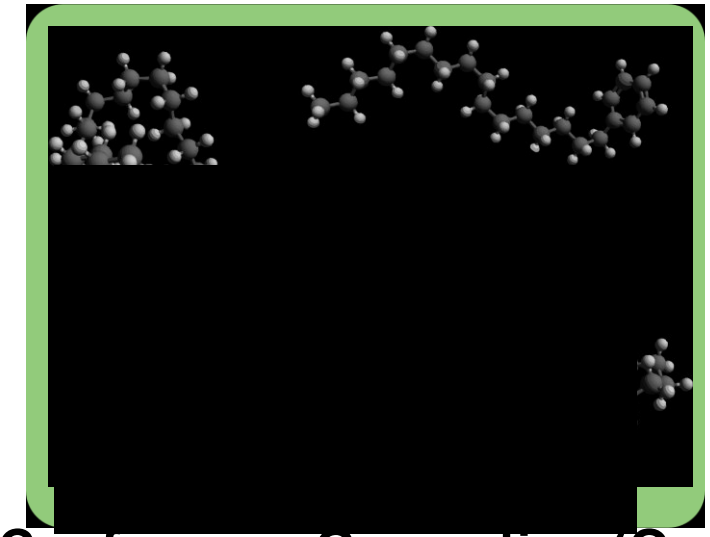
Measurement
CCS calibration

Theoretical

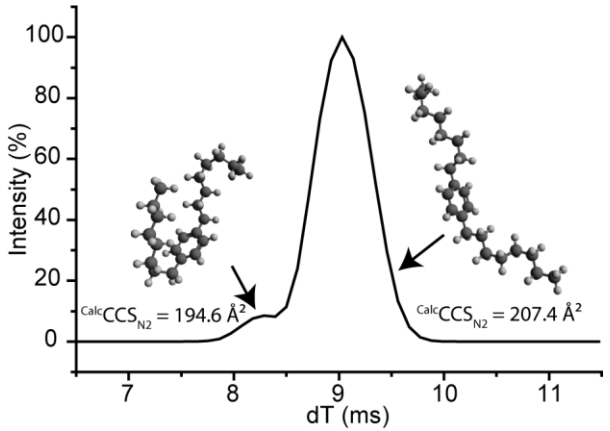
$^{calc}CCS_{N2}$: 201.9 Å²

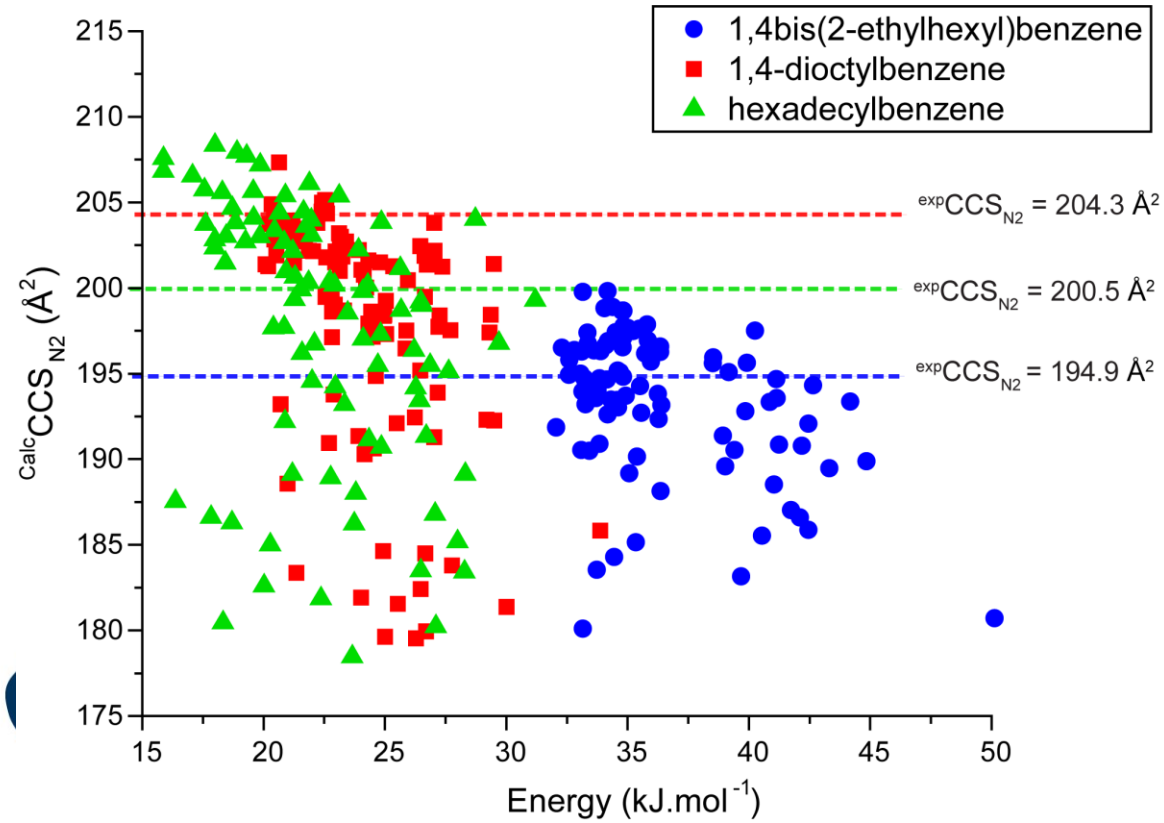
$^{exp}CCS_{N2}$: 200.5 Å²

Experimental



Conformers Generation (OpenBabel)
Minimization MMFF94

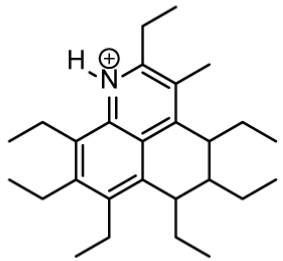




Name	1,4bis(2-ethylhexyl)benzene	1,4-dioctylbenzene	hexadecylbenzene	Average error (%)
$^{Exp}CCS_{N2}$	194.9	204.3	200.5	
1% Lowest energy (^{calc}CCS)	191.8 (1.59%)	201.4 (1.42%)	207.5 (-3.49%)	2.17
25% Lowest energy (^{calc}CCS)	193.3 (0.82%)	201.5 (1.37%)	203.9 (-1.69%)	1.29
50% Lowest energy (^{calc}CCS)	194.0 (0.46%)	200.5 (1.86%)	201.9 (-0.70%)	1.01
Average all $^{calc}CCS_{N2}$	193.3 (0.82%)	197.6 (3.28%)	198.7 (0.89%)	1.66

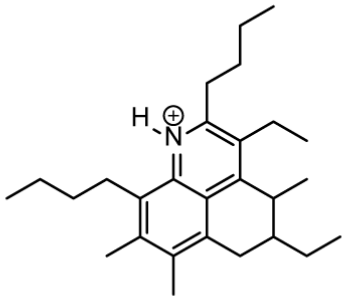
HDN VGO

$C_{27}H_{42}N^+$



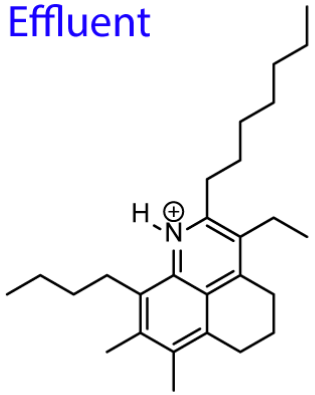
1
207.1 Å²

VGO

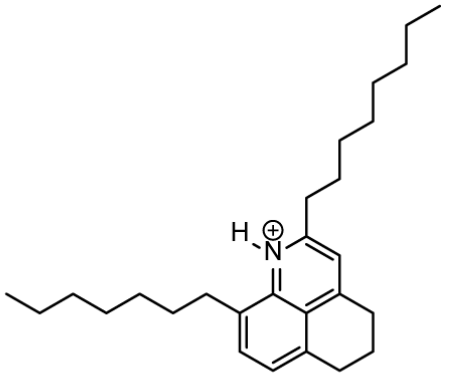


2
213.1 Å²

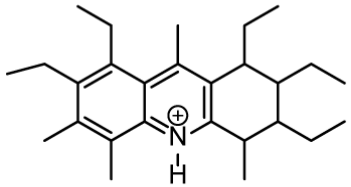
Effluent



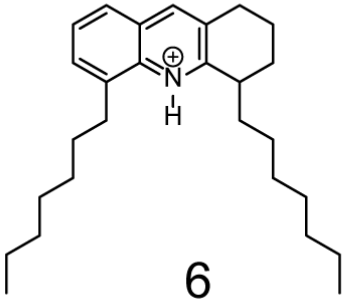
3
217.8 Å²



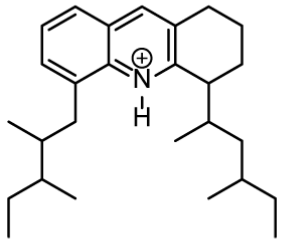
4
223.4 Å²



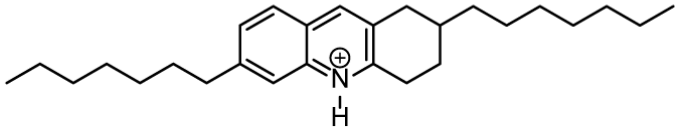
5
323.2 Å²



6
340.6 Å²

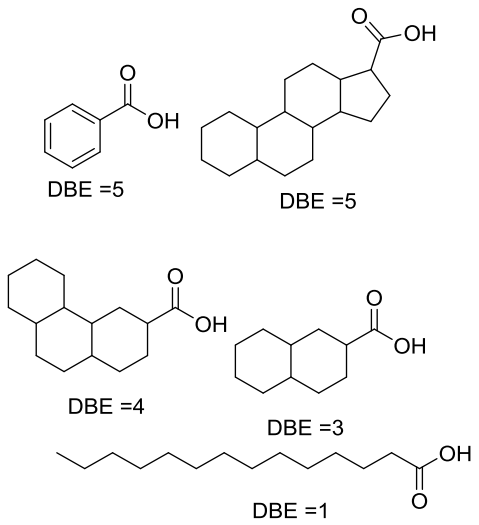


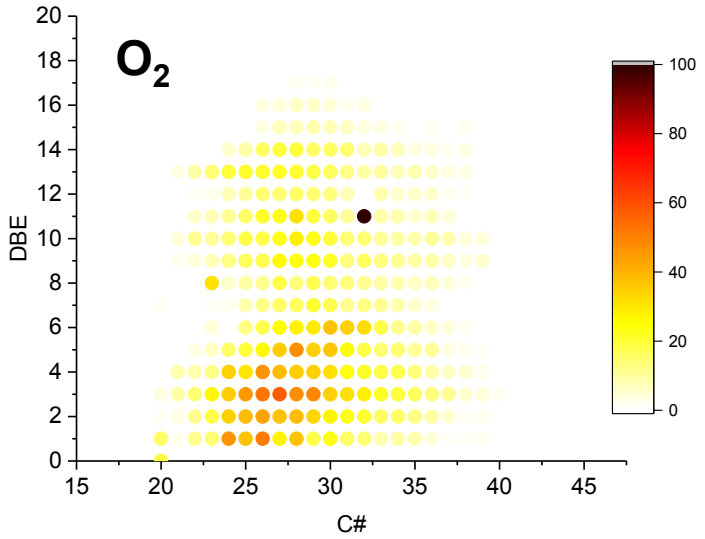
7
393.3 Å²



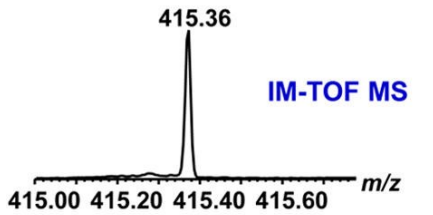
8
339.5 Å²

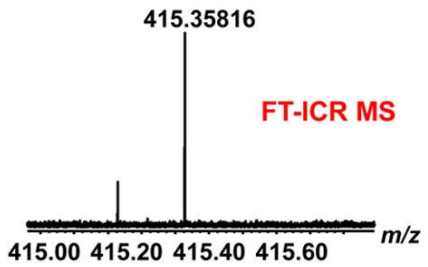
Structural Characterization of Acids in Petroleum by IMS-MS

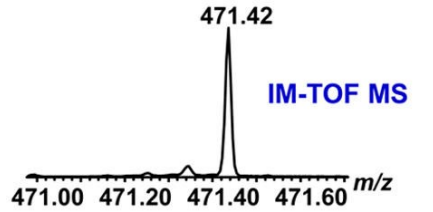


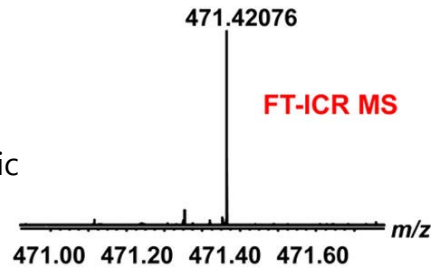


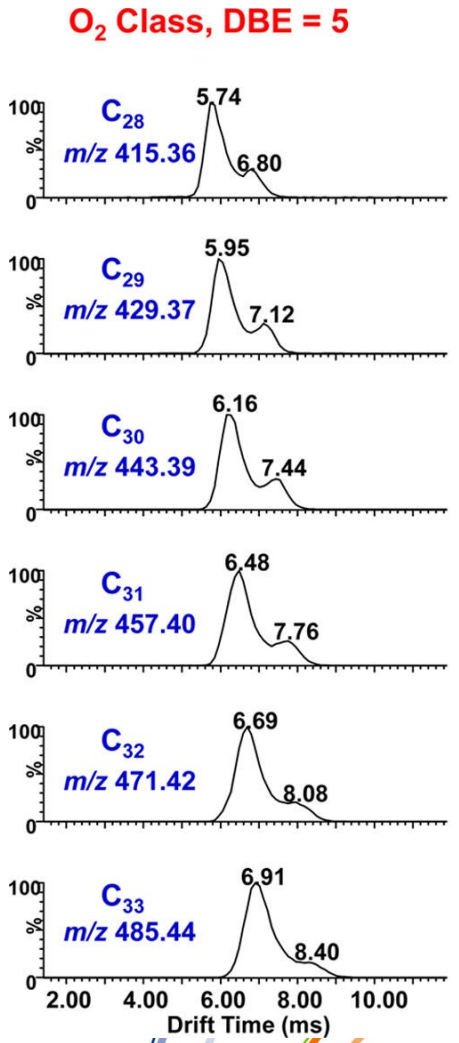
ESI(−)
O_2 Class, DBE=5





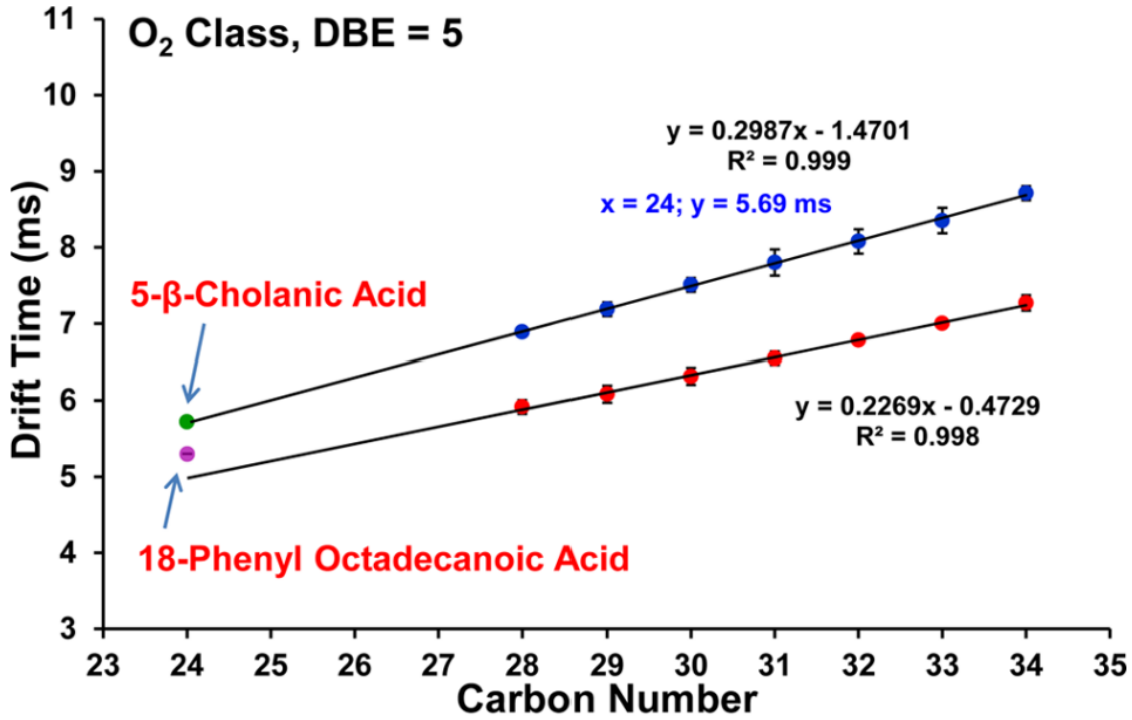




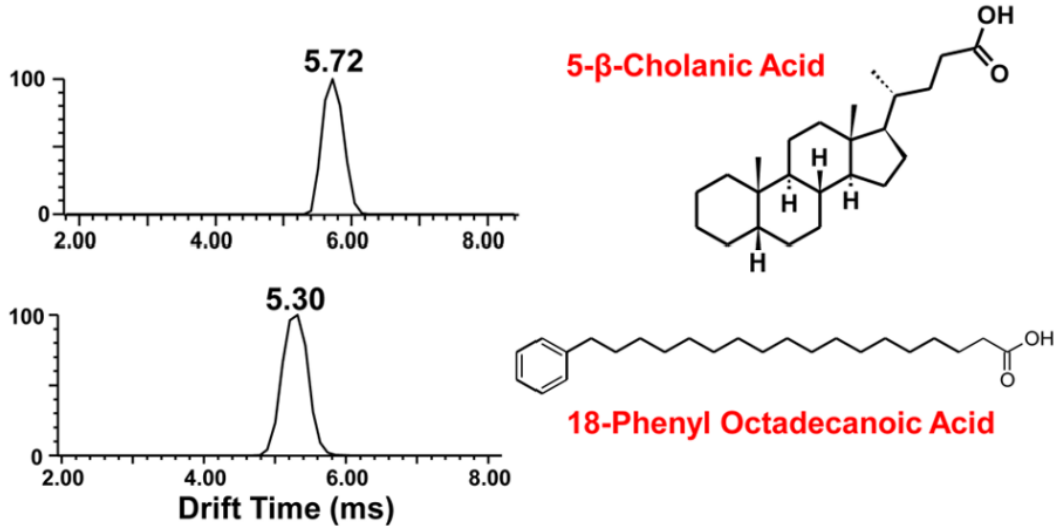


P. M. Lalli, Y. E. Corilo, S. M. Rowland, A. G. Marshall, R. P. Rodgers. Isomeric Separation and Structural Characterization of Acids in Petroleum by Ion Mobility Mass Spectrometry. *Energy Fuels* **2015**, *29*, 3626.

Comparison with standard compounds



Drift time vs carbon number for the O_2 class species of DBE = 5

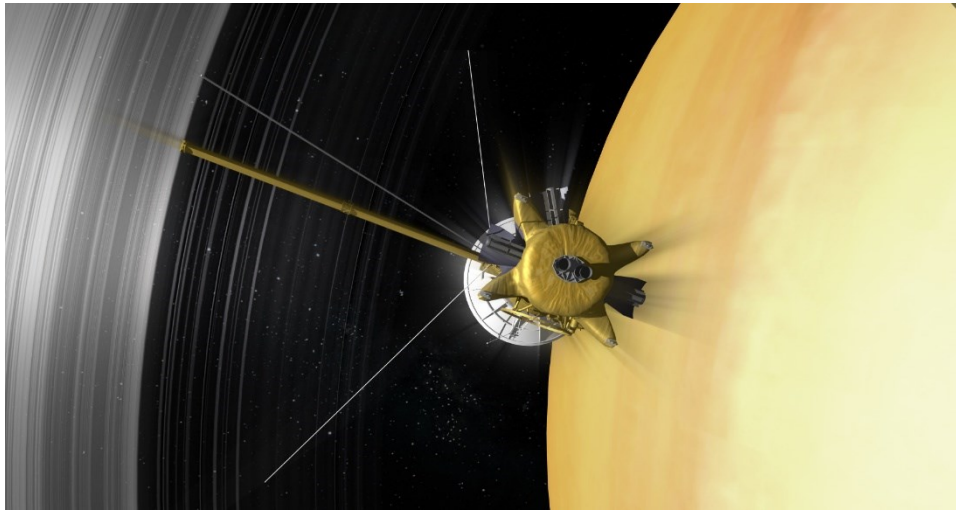


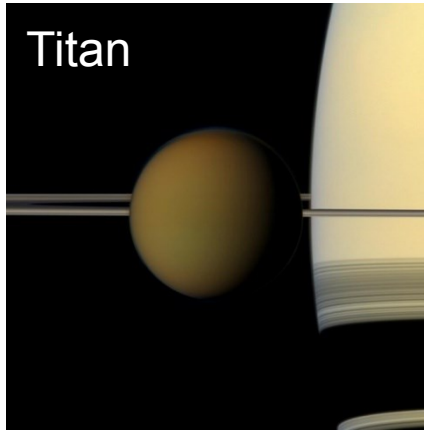
Experimental drift times for two standard compounds (both C24): 5-β-cholanic acid and 18-phenyl octadecanoic acid.

Tholins

Nathalie Carasco

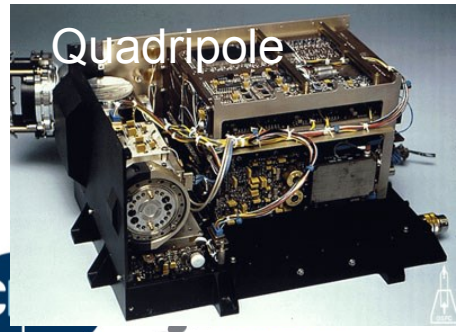
Cassini-Huygens Mission





erc

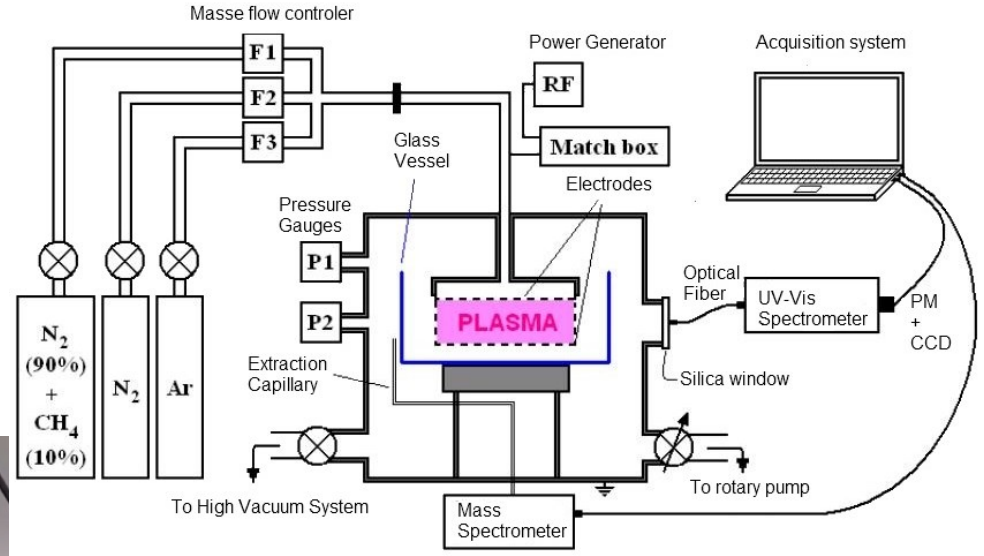
PhD of Julien Maillard

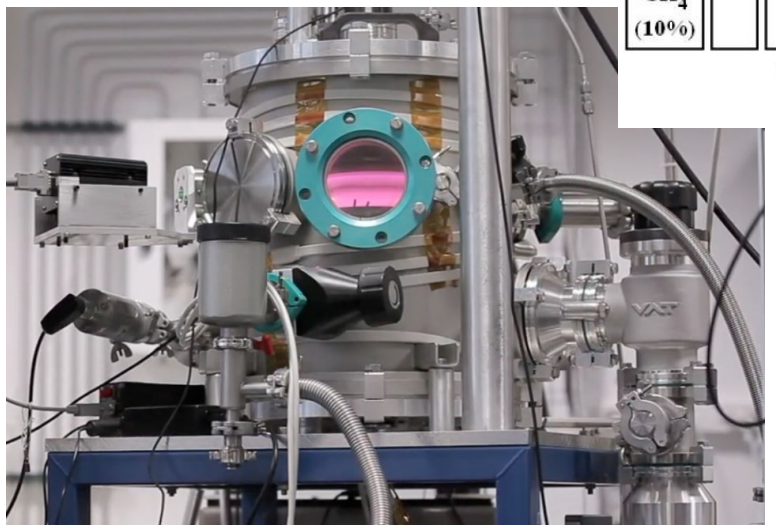


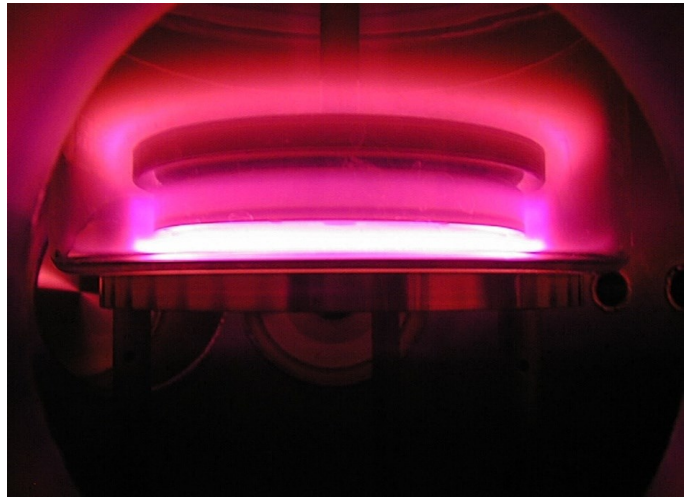
- 95 % N_2, 5 % CH_4
- Photochemistry reactions due to solar UV photons and Saturn charged particles (Khare et *al*. 1981)
  - Thick brown smog
  - Prebiotic chemistry

Earth. Planet. Sci. Lett., 2018, **495**, 185-191

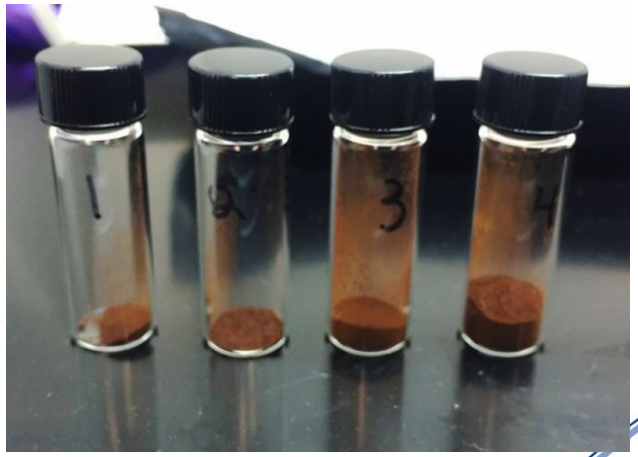
PAMPRE experiment







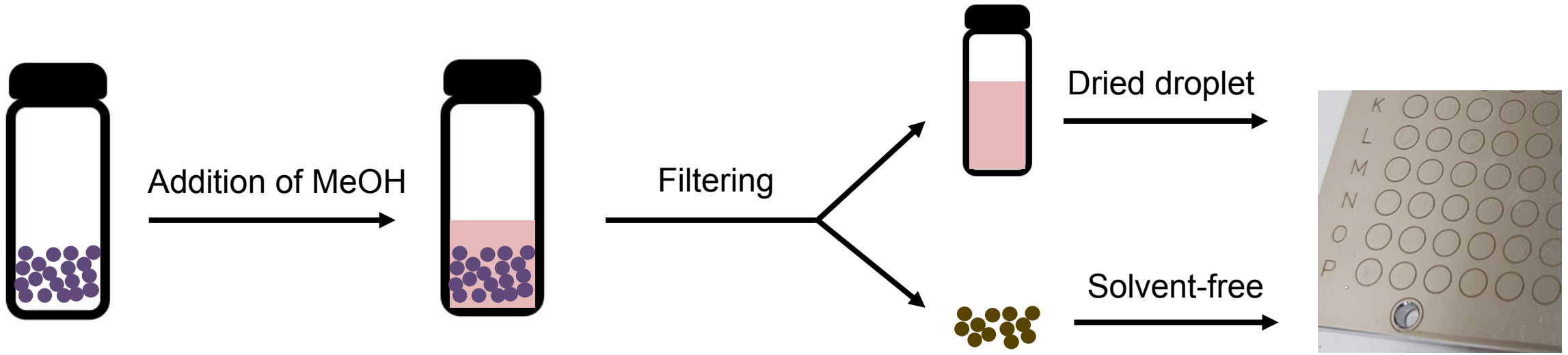
Tholins



PAMPRE experiment (Szopa et al 2006)
(**P**roduction d'**A**érosols en **M**icrogravité par **P**lasma **Re**actifs)

Highly complex organic matter

How to analyse the non soluble fraction ?

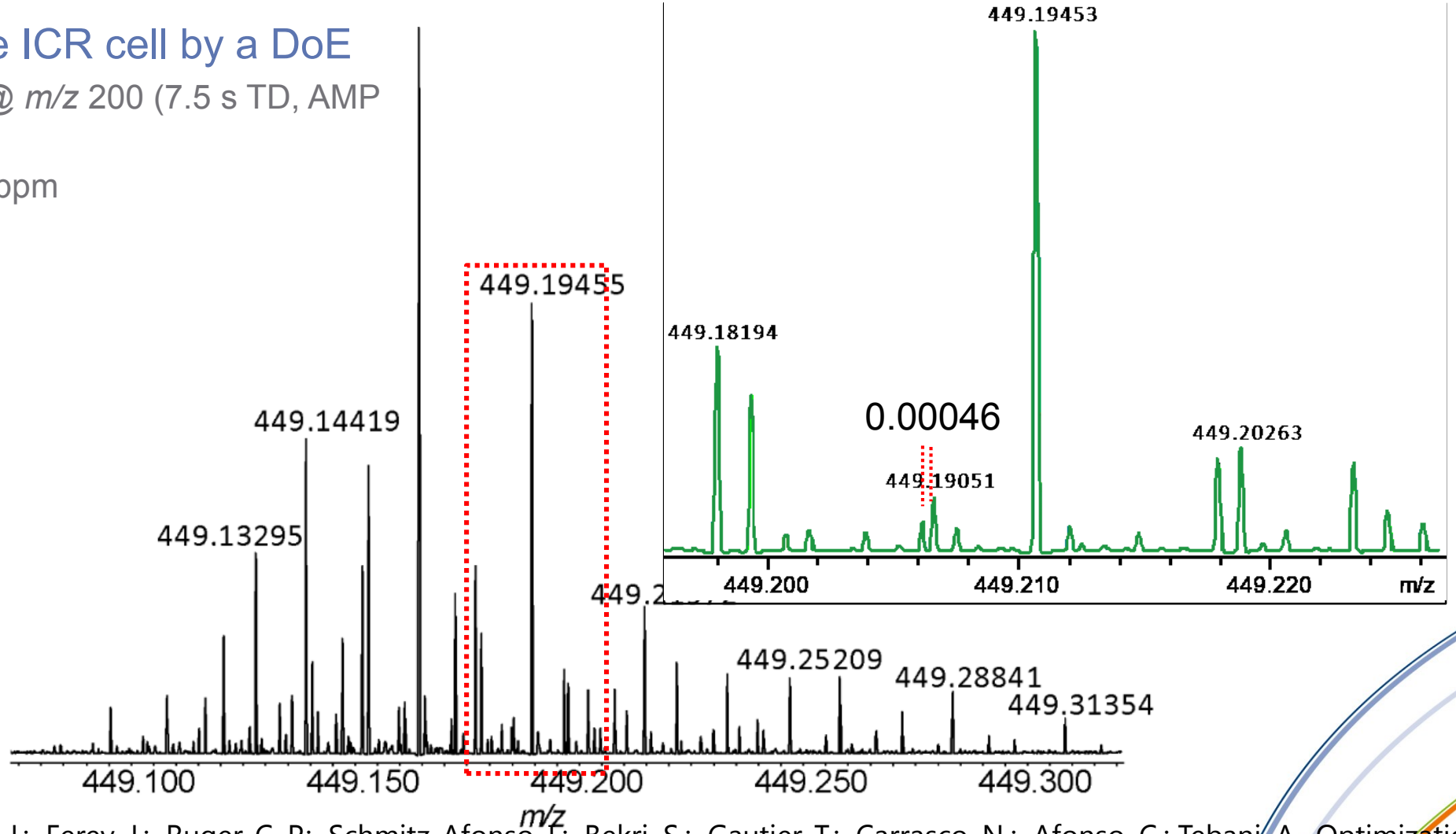


Analysis with a **Laser desorption ionisation source (LDI) coupled to a 12T FTICR**

* Barrere. C.. et *al.* (2012). "Solvent-based and solvent-free characterization of low solubility and low molecular weight polyamides by mass spectrometry: a complementary approach." Rapid Commun Mass Spectrom 26(11): 1347-1354.

Optimization for the best performances

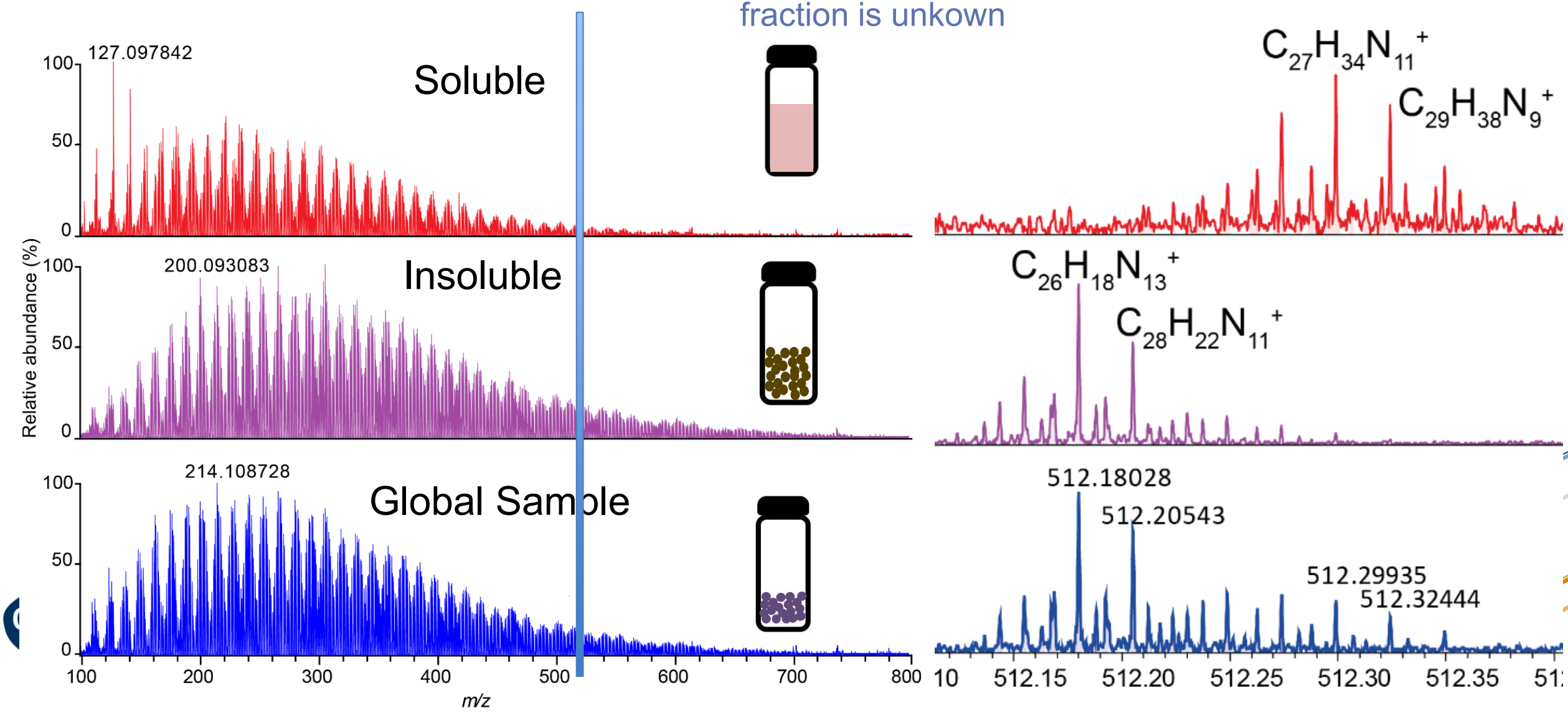
- Optimisation of the ICR cell by a DoE
  - Resolution 4.10^6 @ *m/z* 200 (7.5 s TD, AMP mode)
  - Mean error 0.050 ppm



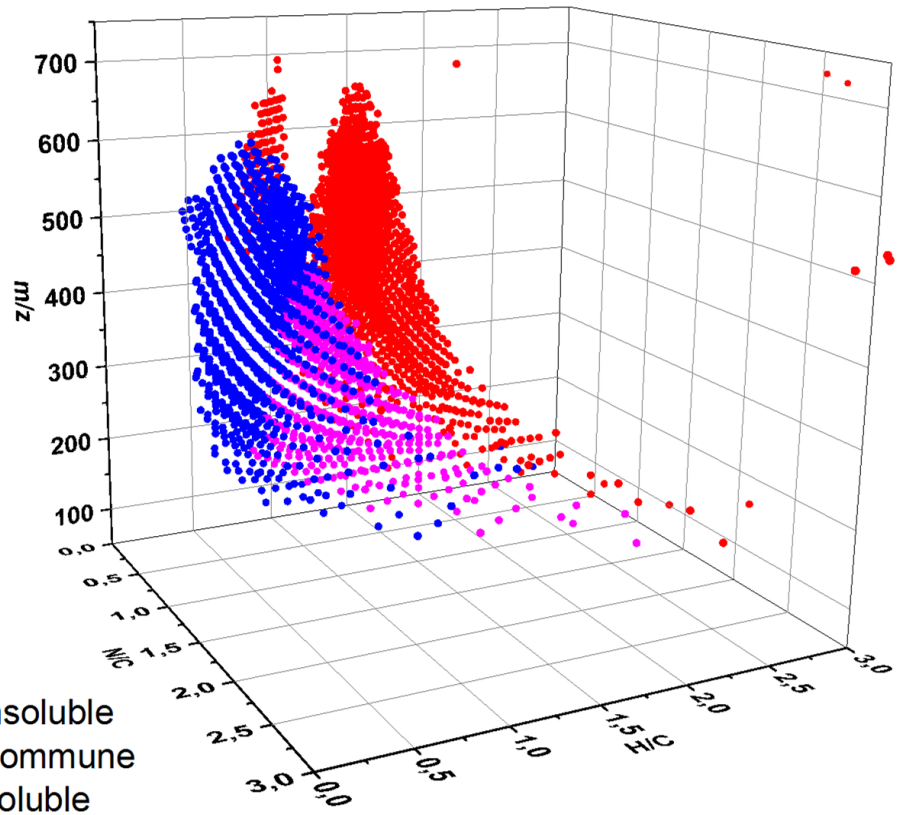
Maillard, J.; Ferey, J.; Ruger, C. P.; Schmitz-Afonso, I.; Bekri, S.; Gautier, T.; Carrasco, N.; Afonso, C.; Tebani, A., Optimization of ion trajectories in a dynamically harmonized Fourier-Transform Ion Cyclotron Resonance cell using a Design of Experiments strategy. *Rapid Commun. Mass Spectrom.* **2019**.

- Only 35 % of tholins are soluble in MeOH
- Structure of non soluble fraction is unkown

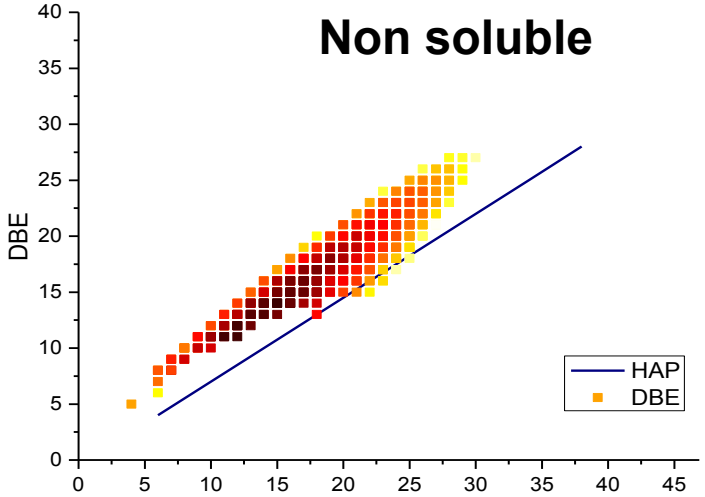
LDI-FTICR

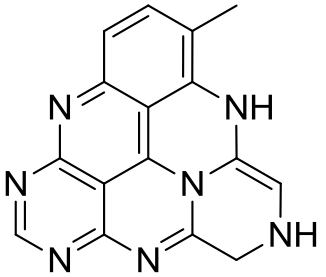


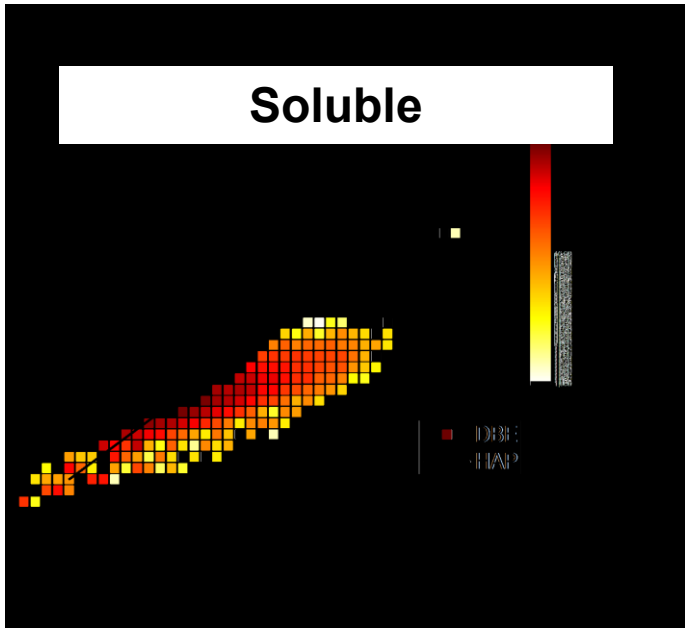
Molecular mapping: soluble and non soluble fractions

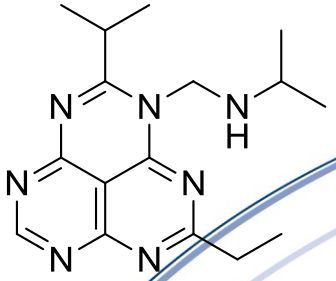


Van Krevelen diagram





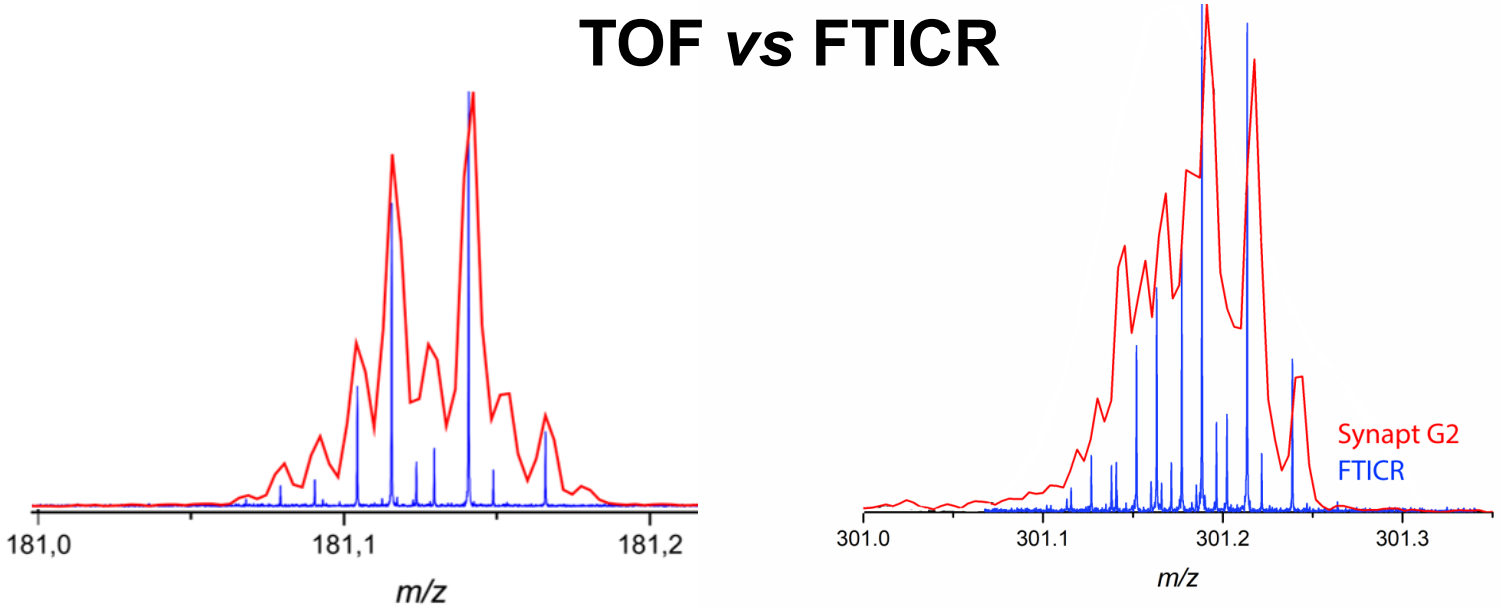




Maillard, J.; Carrasco, N.; Schmitz-Afonso, I.; Gautier, T.; Afonso, C., Comparison of soluble and insoluble organic matter in analogues of Titan's aerosols. *Earth and Planetary Science Letters* **2018,** *495*, 185-191.

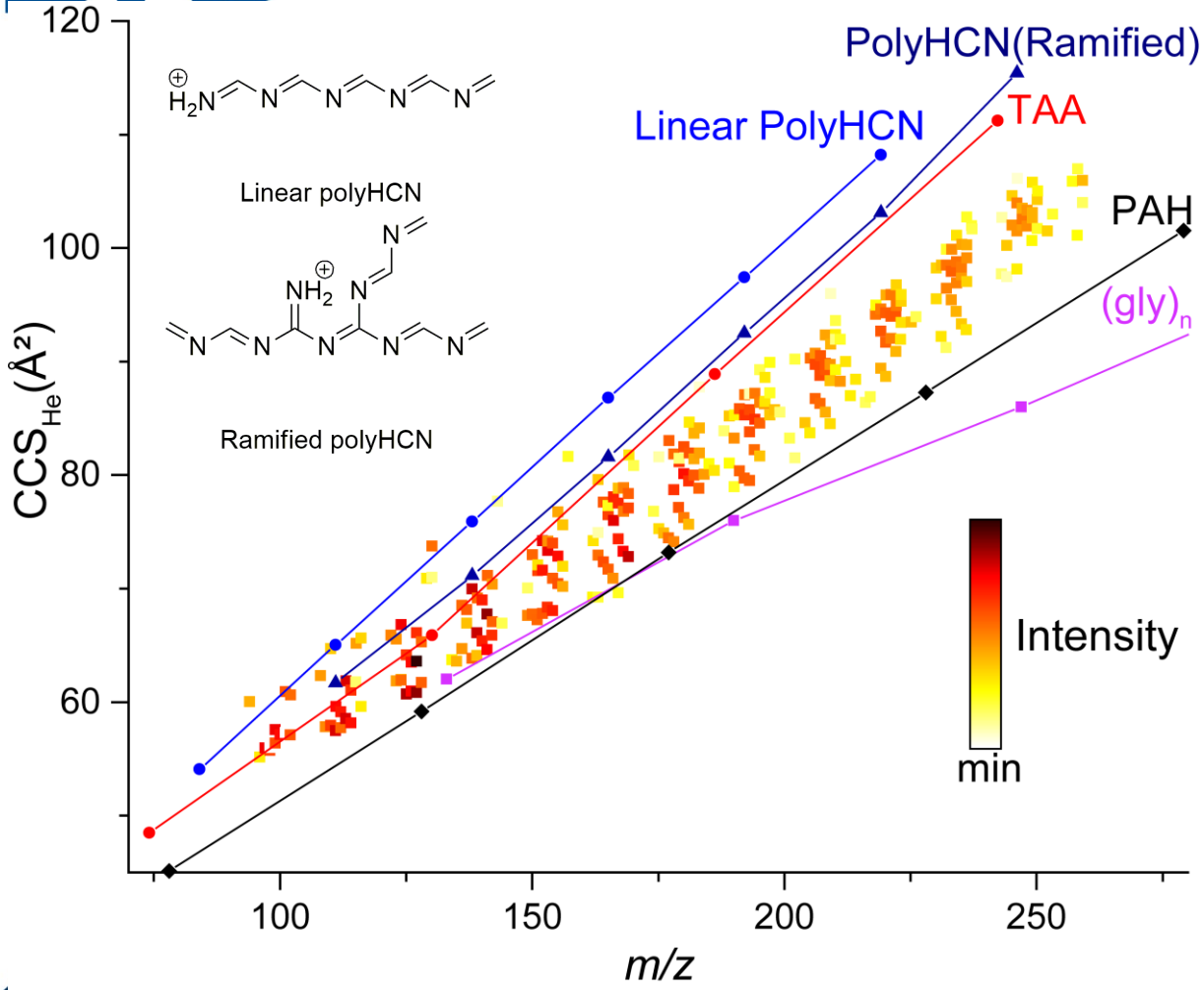
IMS of Tholins?

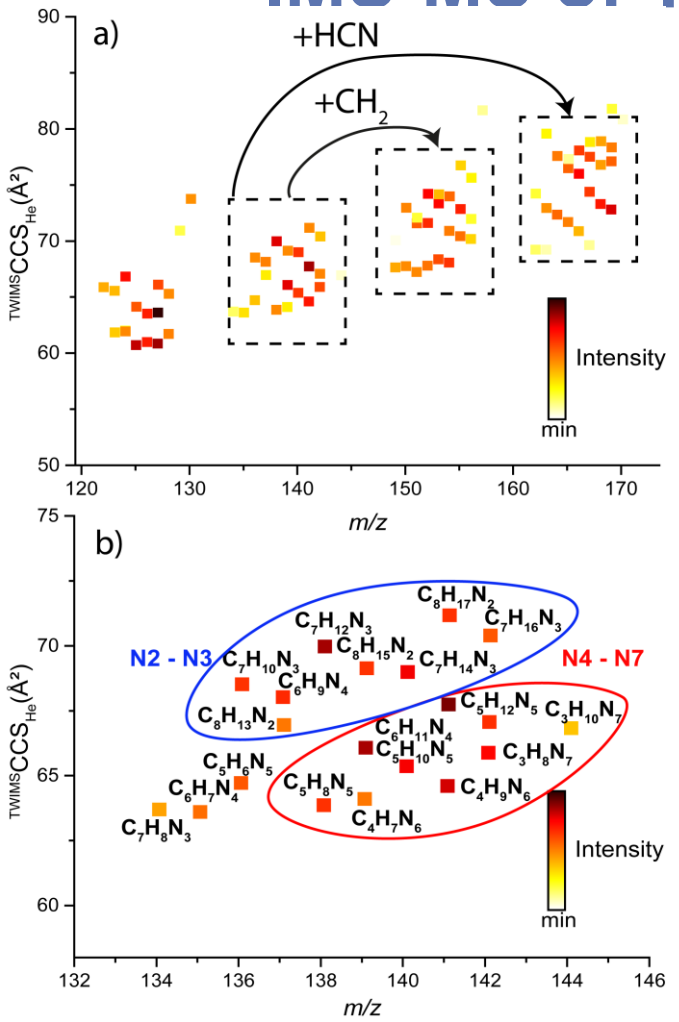
TOF *vs* FTICR



- Owing to the high complexity IMS-TOF analysis is very challenging and limited to low masses
- IMS with FTICR?
  - Drift tube IMS or TWIMS: ms time scale
  - FTICR second time scale
- Other IMS technique compatible with FTICR
  - FAIMS (High-field asymmetric waveform ion mobility spectrometry)
  - TIMS (tapped ion mobility spectrometry)
    - Low field access to

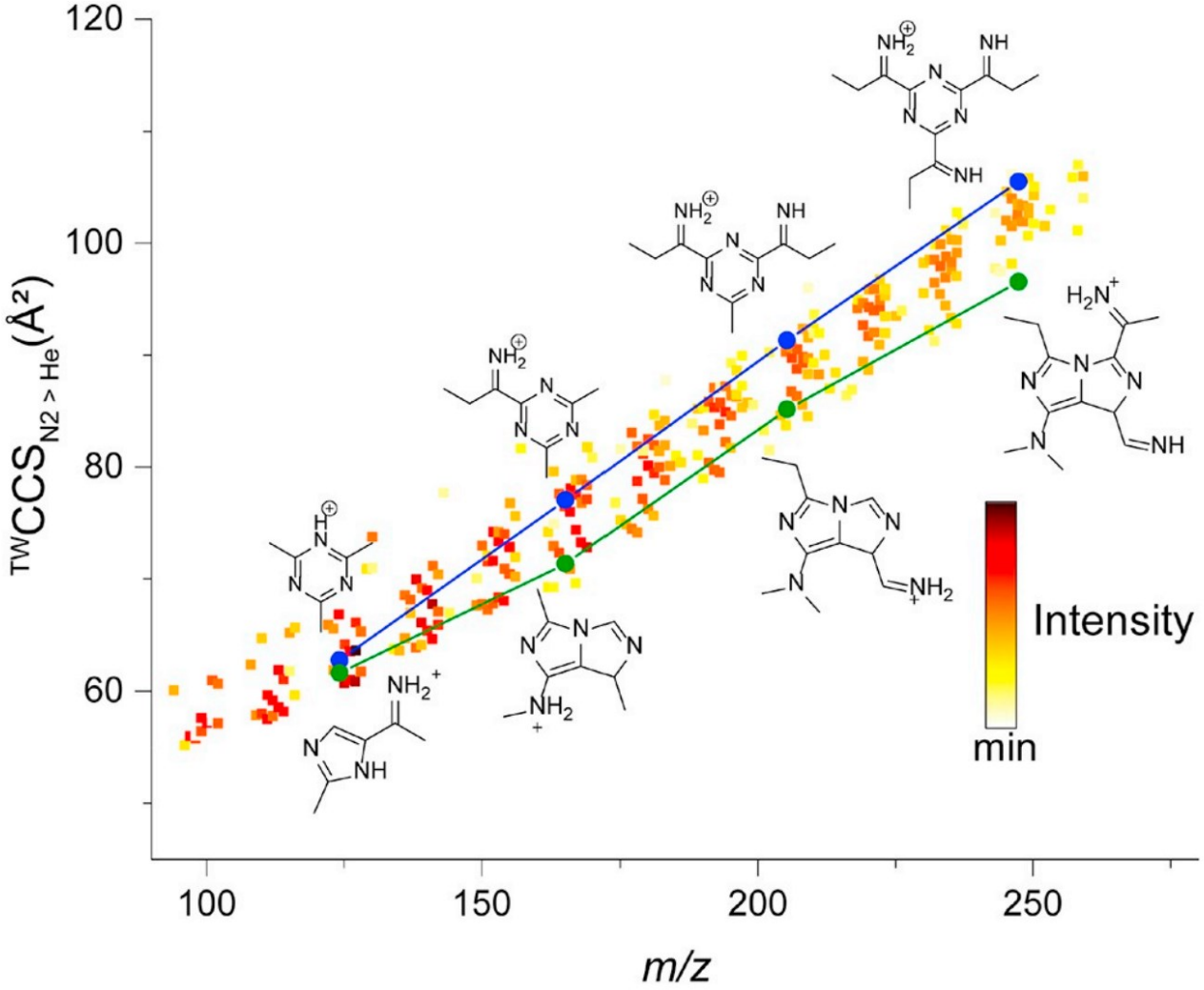
IMS-MS of Tholins

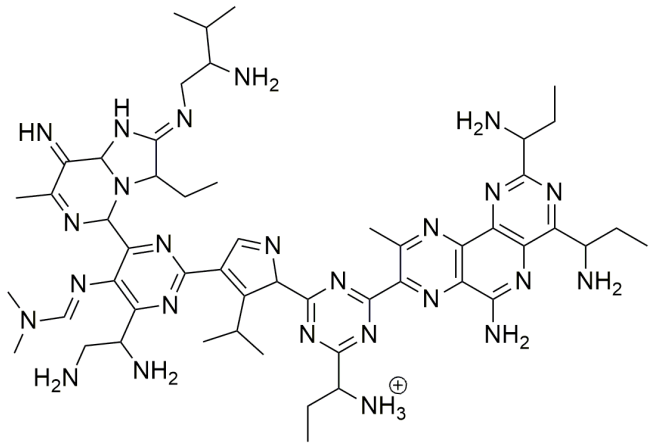




Comparison of collision cross section (A²) *vs m/z* of ions of tholins sample with polyHCN (blue), tetraalkylammonium salts (red), polyaromatics hydrocarbons (black) and polyglycan (purple).

IMS-MS of Tholins



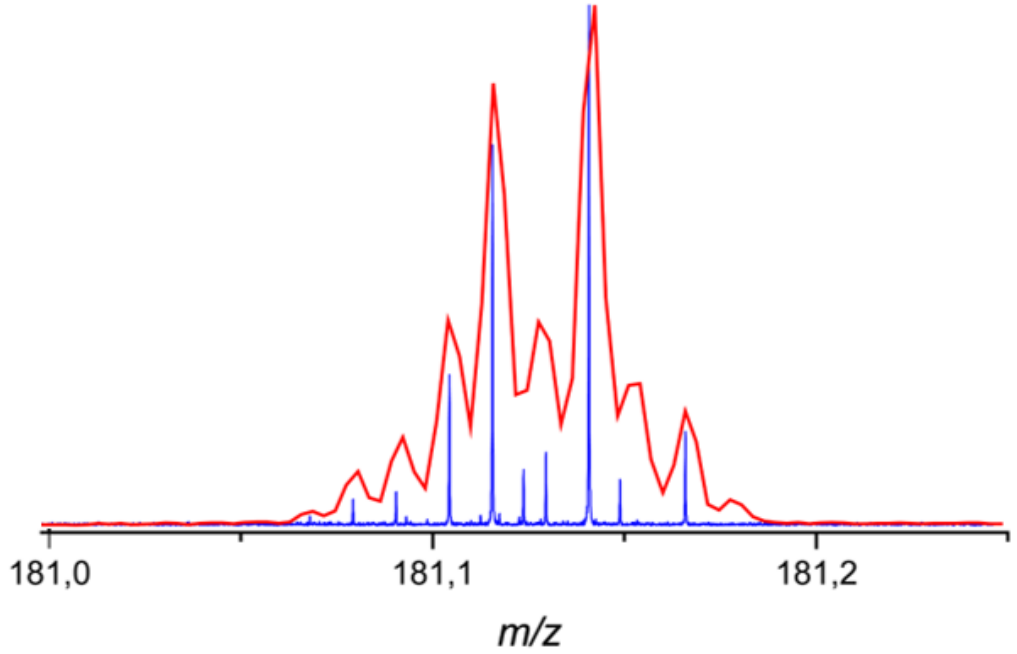


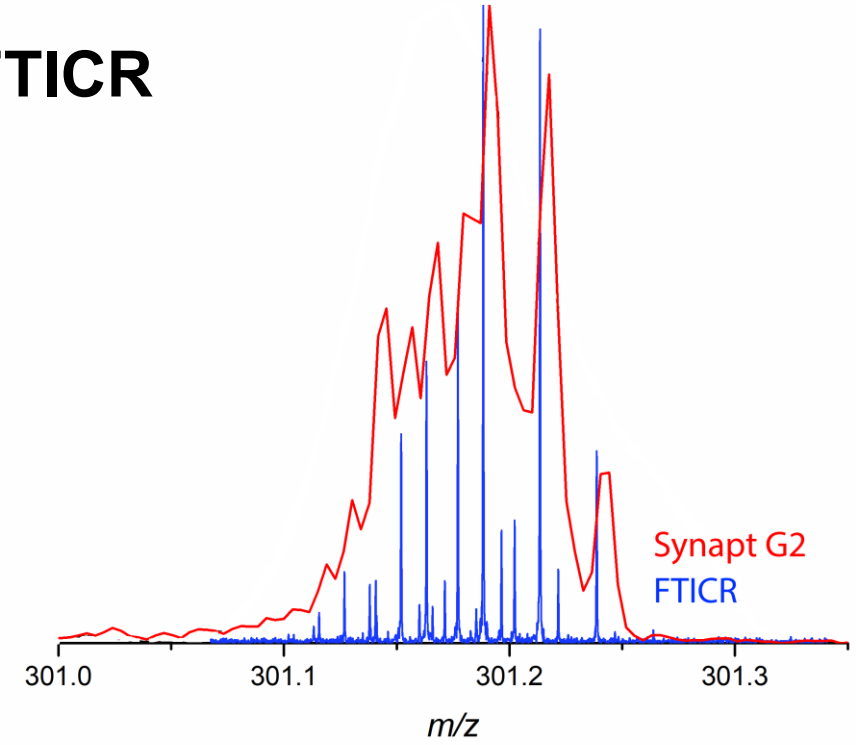
Comparison of CCS vs m/z with (blue) calculated CCS of triazine family (green) calculated CCS of pyrazole family

Maillard, J.; Hupin, S.; Carrasco, N.; Schmitz-Afonso, I.; Gautier, T.; Afonso, C., Structural elucidation of soluble organic matter: Application to Titan's haze. *Icarus* **2020**.

IMS with FTICR?

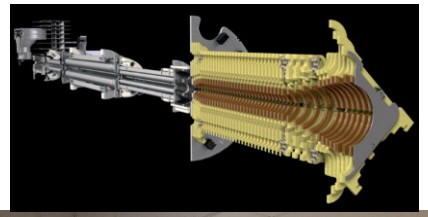
TOF *vs* FTICR

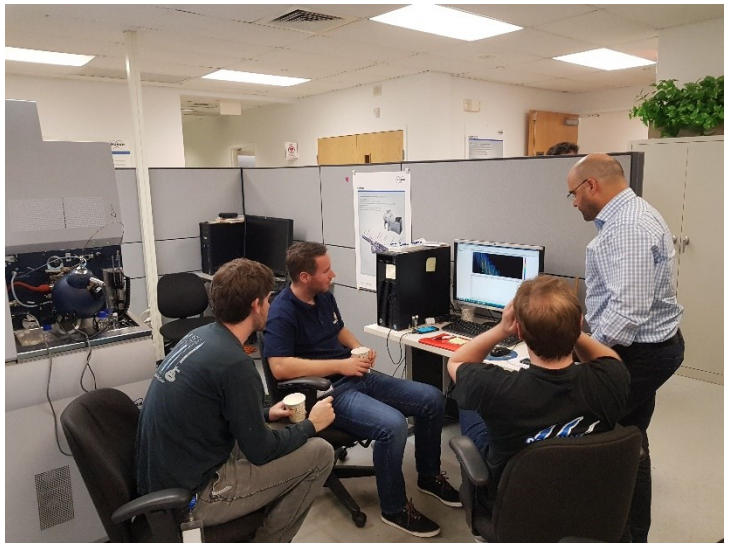




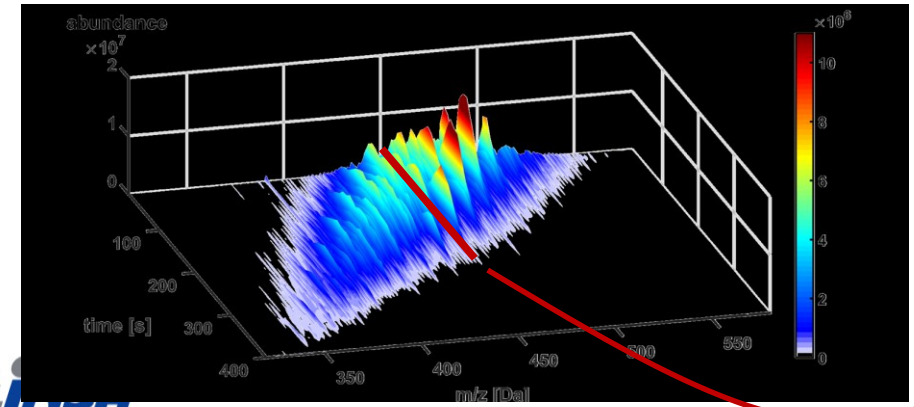
- Owing to the high complexity IMS-TOF analysis is very challenging and limited to low masses

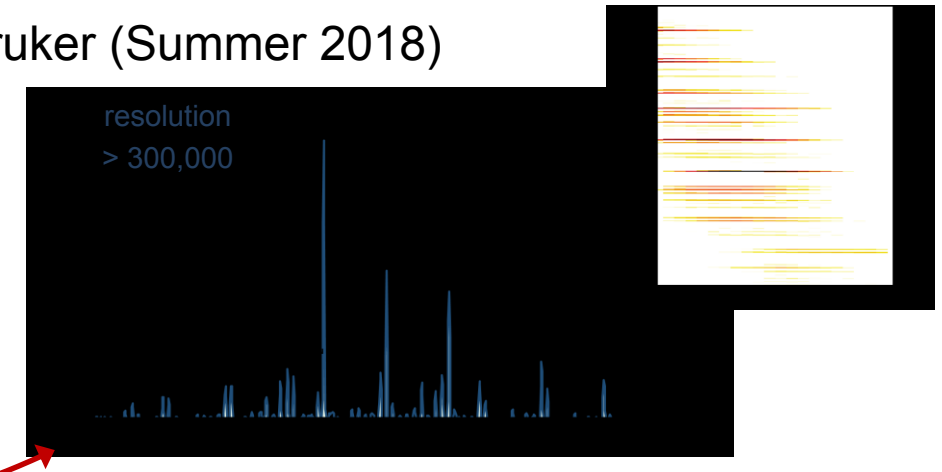
TIMS-FTICR





Experiments at Bruker (Summer 2018)



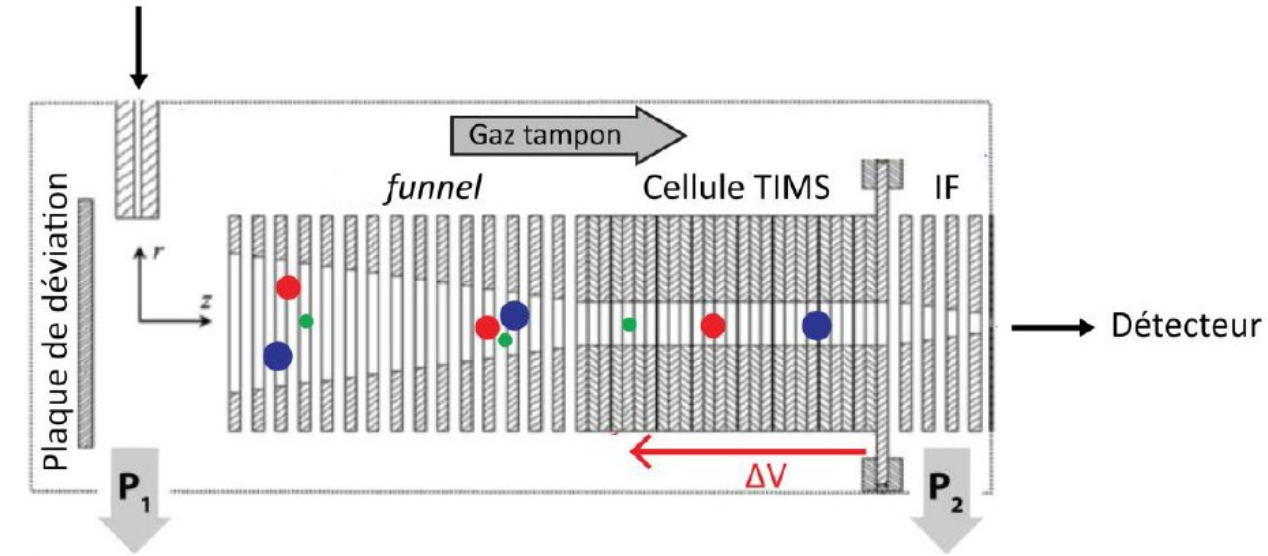


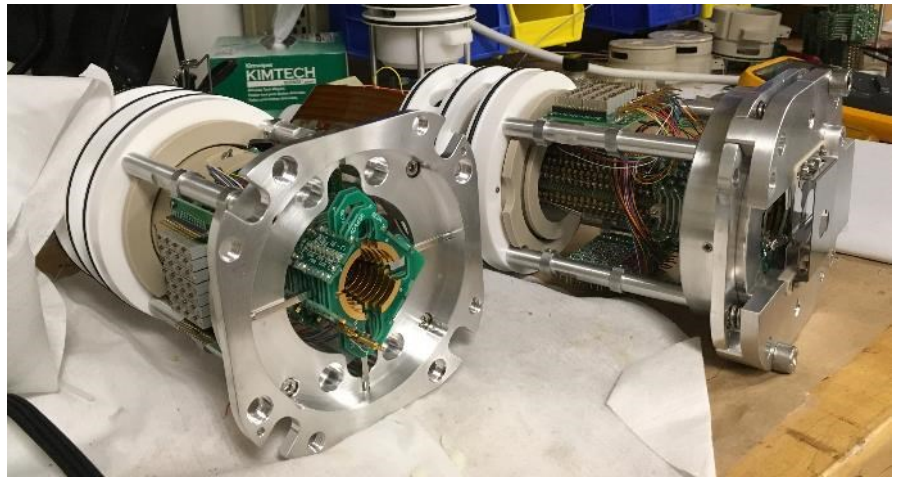
zoom-into 0.3 Da window → ultra-high resolving power needed

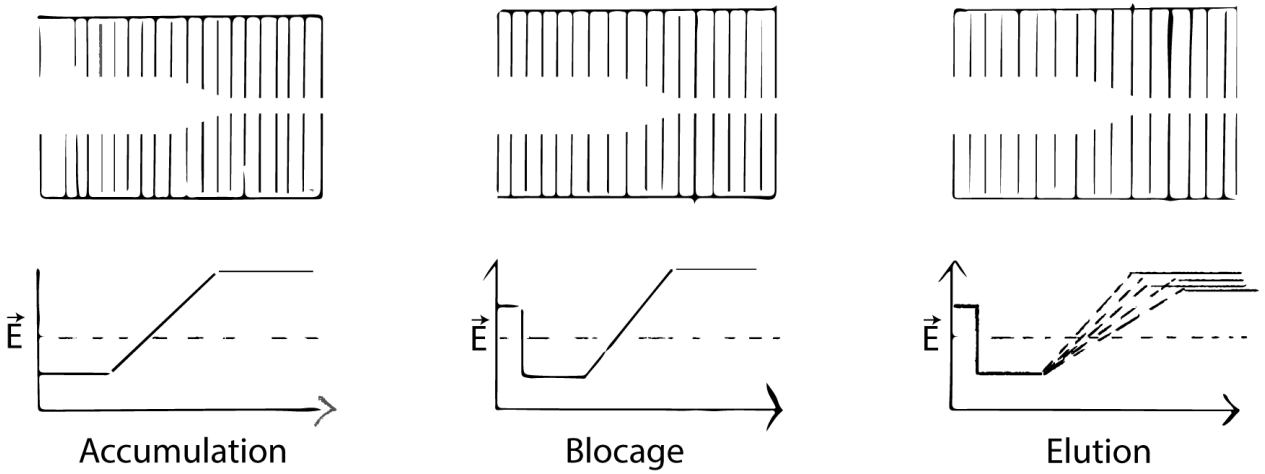
TIMS-FTICR

Ruger, C. P.; Maillard, J.; Le Maitre, J.; Ridgeway, M.; Thompson, C. J.; Schmitz-Afonso, I.; Gautier, T.; Carrasco, N.; Park, M. A.; Giusti, P.; Afonso, C.,. *J Am Soc Mass Spectrom* **2019,** *30* (7), 1169-1173.

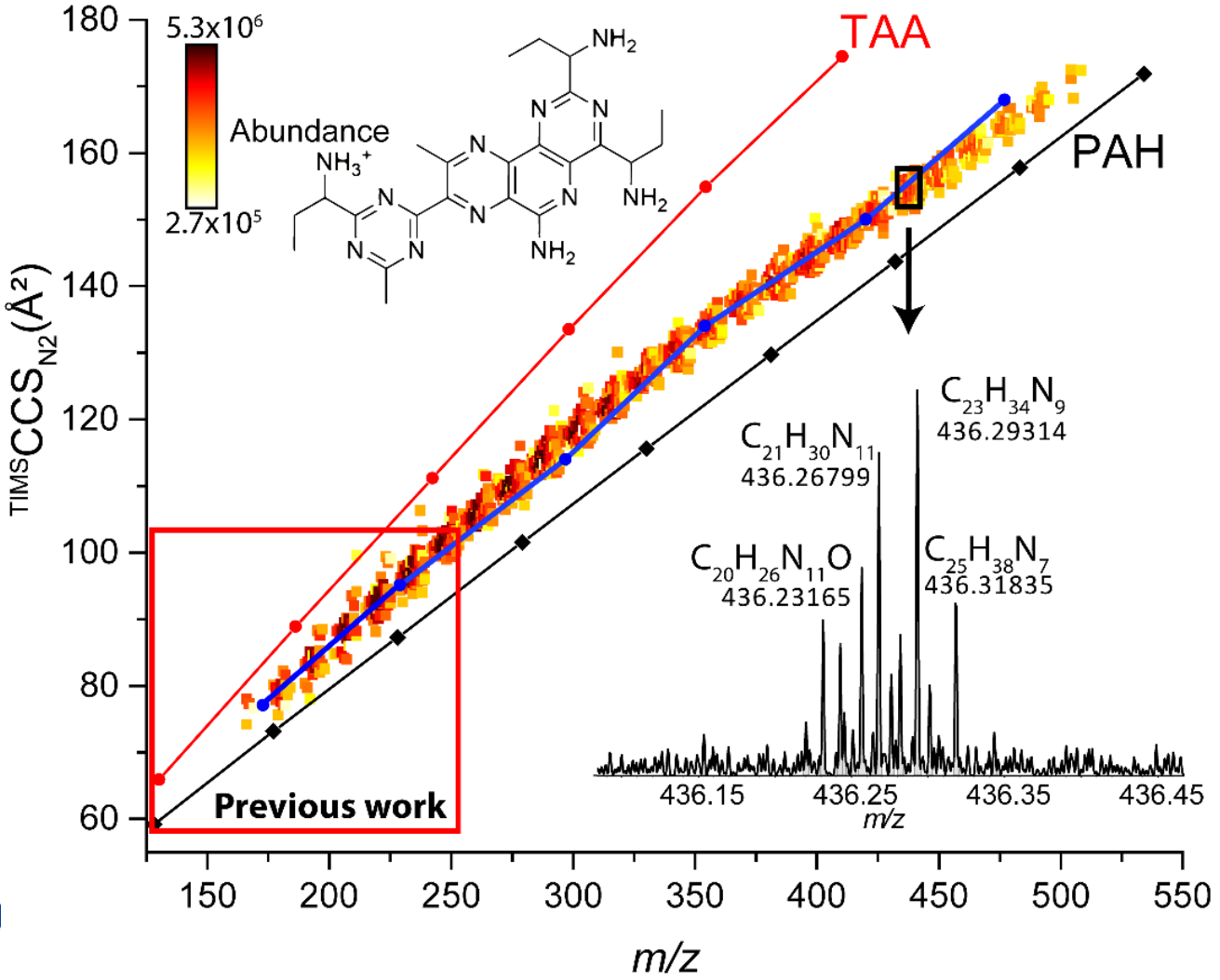
Trapped Ion Mobility Spectrometry (TIMS)

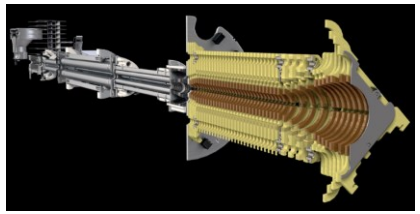






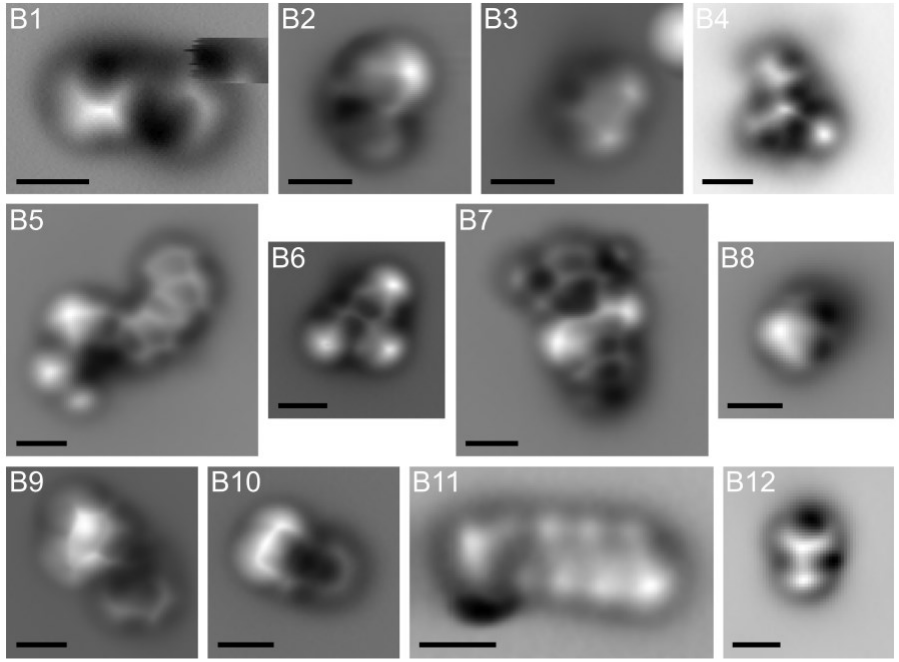
TIMS-FTICR of Tholins

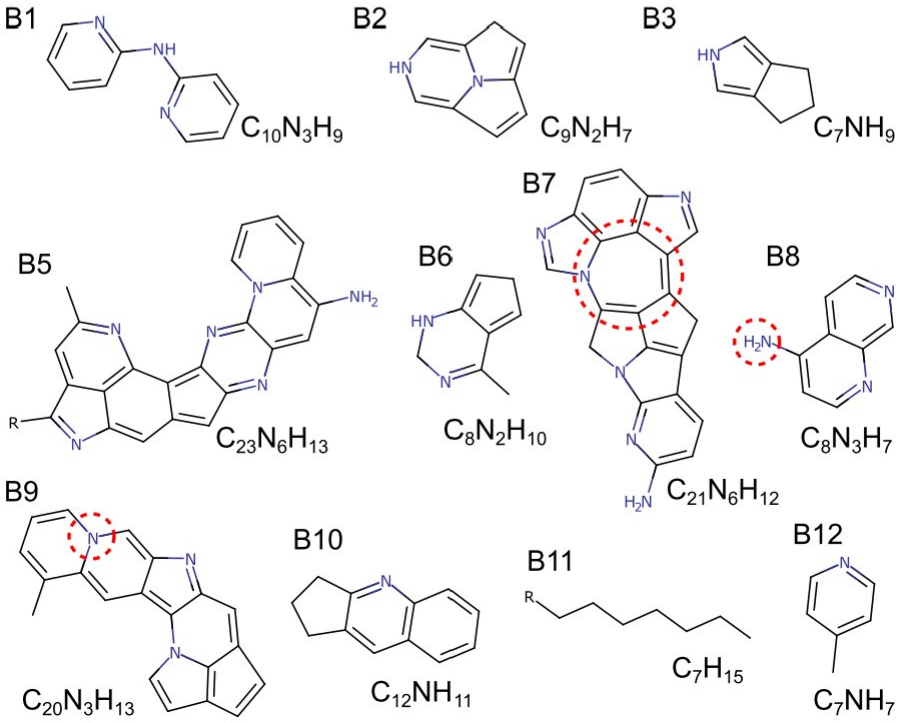


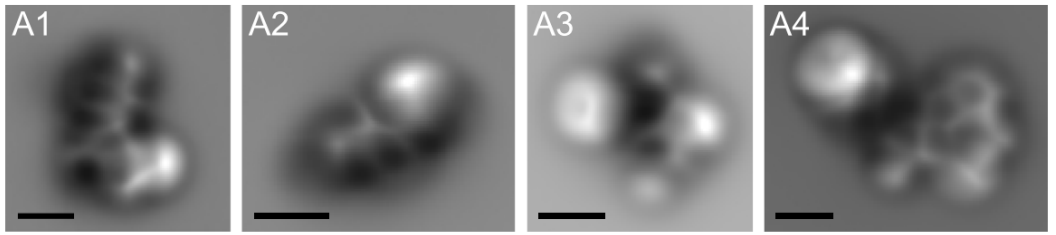


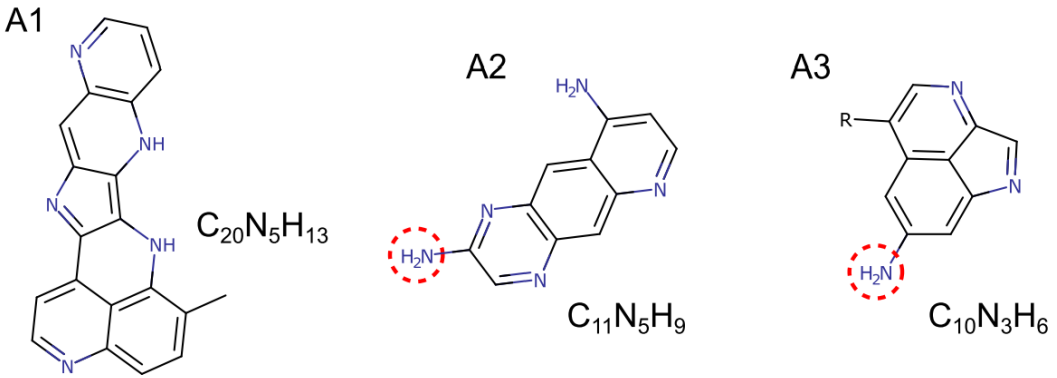
Ruger, C. P.; Maillard, J.; Le Maitre, J.; Ridgeway, M.; Thompson, C. J.; Schmitz-Afonso, I.; Gautier, T.; Carrasco, N.; Park, M. A.; Giusti, P.; Afonso, C.,. *J Am Soc Mass Spectrom* **2019,** *30* (7), 1169-1173.

AFM @ IBM









F. Schulz, J. Maillard, K. Kaiser, I. Schmitz-Afonso, T. Gautier, C. Afonso, N. Carrasco and L. Gross, The Astrophysical Journal Letters, 2021, 908.

TIMS FTICR of petrophyrins

Structural analysis

energy&fuels — Article
pubs.acs.org/EF

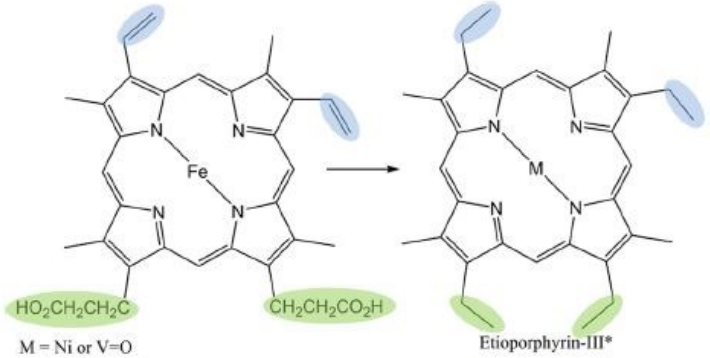
Analysis of Geologically Relevant Metal Porphyrins Using Trapped Ion Mobility Spectrometry–Mass Spectrometry and Theoretical Calculations

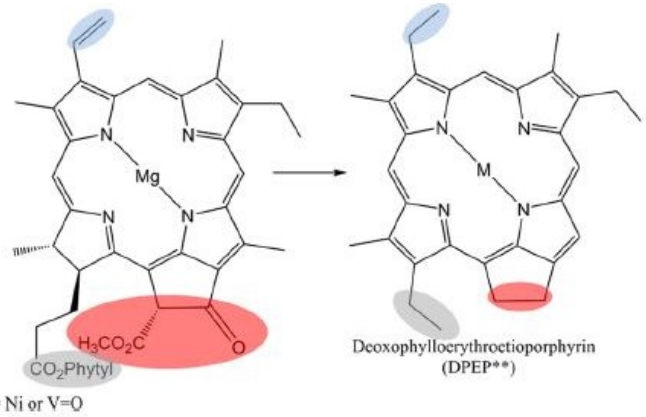
Paolo Benigni,[†] Carlos Bravo,[†] J. Martin E. Quirke,[†] John D. DeBord,[†] Alexander M. Mebel,[†] and Francisco Fernandez-Lima*[,†,‡]

[†]Department of Chemistry and Biochemistry and [‡]Biomolecular Sciences Institute, Florida International University, Miami, Florida 33199, United States

What about their structure in real sample?

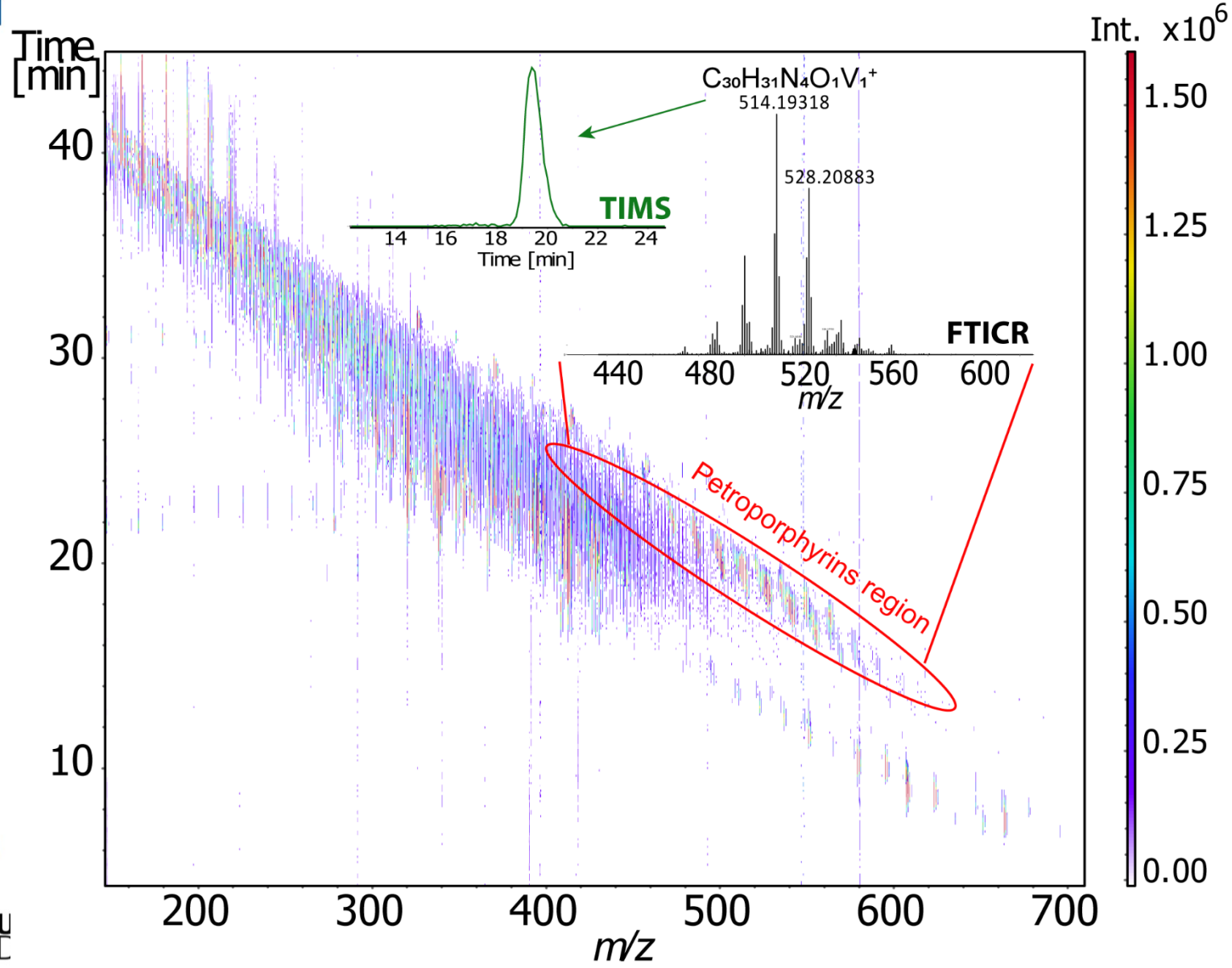
Scheme 1. Diagram Illustrating the Chemical Changes Outlined in the Treibs Hypothesis[a]

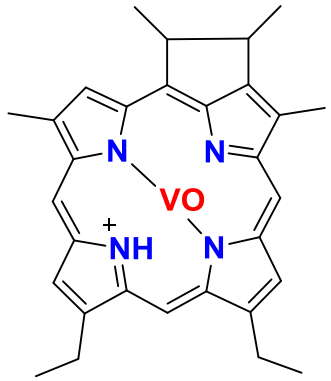




[a]Note the changes in the different functional groups observed.

APPI asphaltene fraction

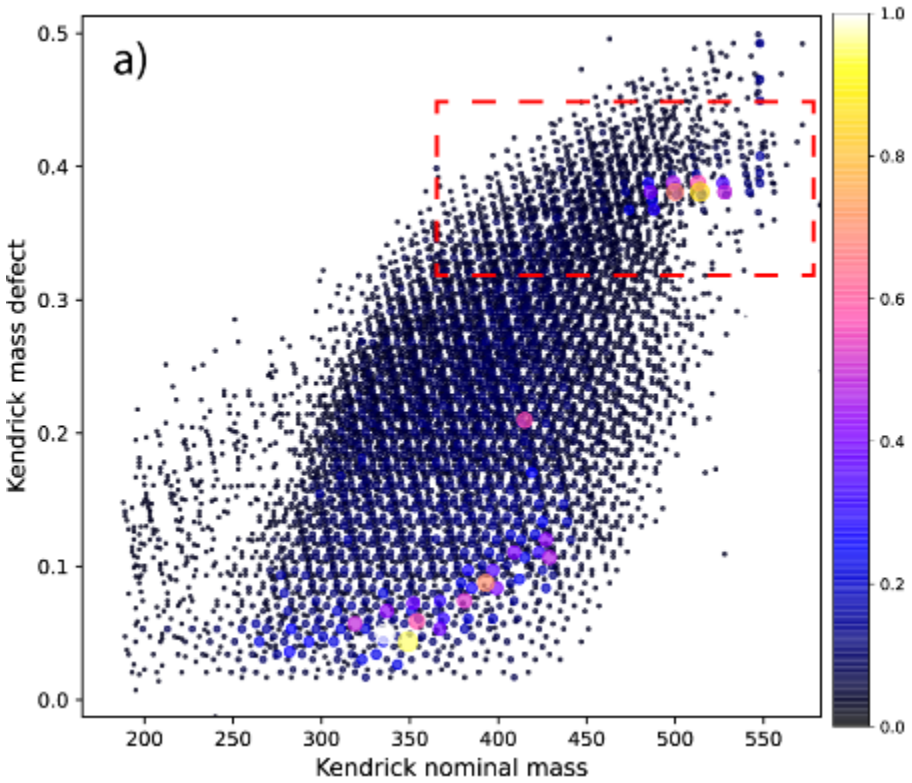




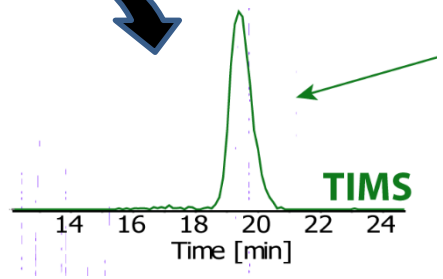
Chemical Formula: $C_{30}H_{31}N_4OV^+$

Exact Mass: 514,1932

Attribution and extraction of petroporphyrins signals



EIM generations

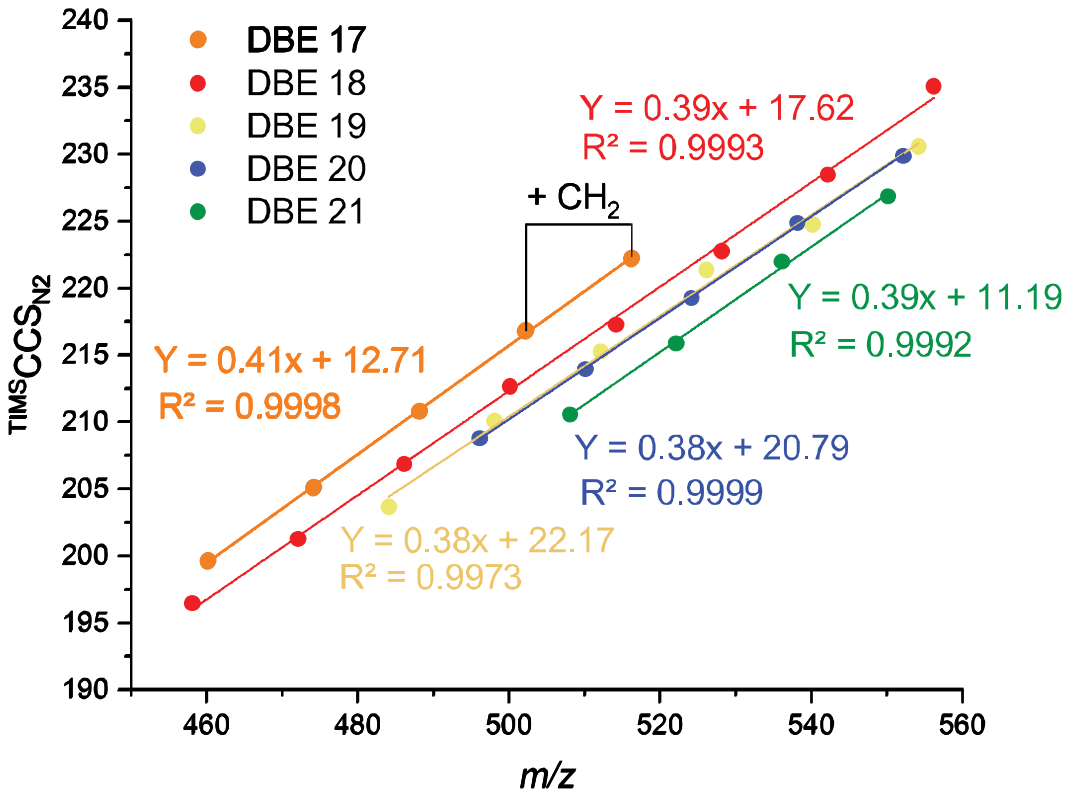


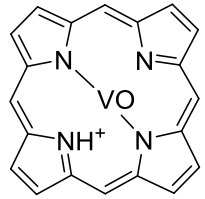
Recovering of the CCS

Attribution and extraction of petroporphyrins signals

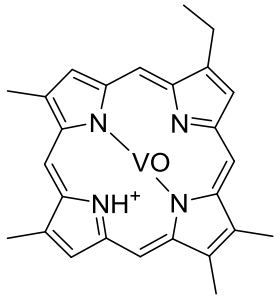
Molecular formula $[M+H]^+$	Calculated *m/z*	Experimental *m/z*	Error (ppm)	C#	DBE	$^{TIMS}CCS_{N2}$ (Å^2)	FWHM (s)
$C_{26}H_{25}N_4O_1V_1^+$	460.14625	460.14624	0.01	26	17	199.6	27
$C_{27}H_{27}N_4O_1V_1^+$	474.1619	474.16189	0.01	27	17	205.1	29
$C_{28}H_{29}N_4O_1V_1^+$	488.17755	488.17754	0.01	28	17	210.8	32
$C_{27}H_{25}N_4O_1V_1^+$	472.14625	472.14623	0.04	27	18	201.3	34
$C_{28}H_{27}N_4O_1V_1^+$	486.1619	486.1619	-0.01	28	18	206.9	38
$C_{29}H_{29}N_4O_1V_1^+$	500.17755	500.17754	0.01	29	18	212.7	35
$C_{30}H_{31}N_4O_1V_1^+$	514.1932	514.19319	0.01	30	18	217.3	35
$C_{31}H_{33}N_4O_1V_1^+$	528.20885	528.20885	-0.01	31	18	222.8	34
$C_{28}H_{25}N_4O_1V_1^+$	484.14624	484.14626	-0.02	28	19	203.7	38
$C_{29}H_{27}N_4O_1V_1^+$	498.1619	498.16184	0.1	29	19	210.1	38
$C_{30}H_{29}N_4O_1V_1^+$	512.17755	512.17751	0.07	30	19	215.3	41
$C_{29}H_{25}N_4O_1V_1^+$	496.14625	496.14628	-0.07	29	20	208.8	39
$C_{30}H_{27}N_4O_1V_1^+$	510.1619	510.16188	0.04	30	20	214	46
$C_{30}H_{25}N_4O_1V_1^+$	508.14625	508.14629	-0.09	30	21	210.6	37
$C_{31}H_{27}N_4O_1V_1$	522.1619	522.16191	-0.04	31	21	215.9	40
$C_{32}H_{29}N_4O_1V_1^+$	536.17755	536.17754	0.01	32	21	222	39
$C_{33}H_{31}N_4O_1V_1^+$	550.1932	550.19319	0.02	33	21	226.9	44
$C_{32}H_{27}N_4O_1V_1^+$	534.1619	534.16193	-0.06	32	22	218.5	43

Information recovered using the CCS vs m/z graphic

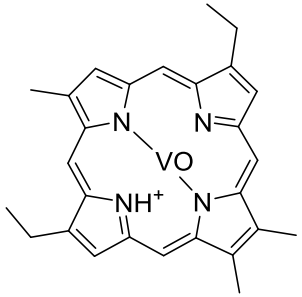




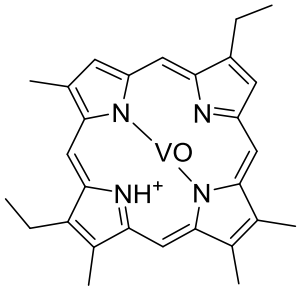
$C_{20}H_{13}N_4OV^+$
***m/z* 376.05235**



$C_{26}H_{25}N_4OV^+$
***m/z* 460.14625**
C6



$C_{27}H_{27}N_4OV^+$
***m/z* 474.16190**
C7

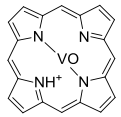


$C_{28}H_{29}N_4OV^+$
***m/z* 488.17755**
C8

Plot of the experimental $^{TIMS}CCS_{N2}$ (Å^2) of porphyrins by DBE (DBE 17 to 21) as a function of m/z. Linear regression is given for the different homolog rows.

Drawing of all possible core structures

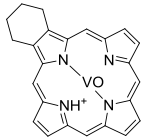
DBE 17



$C_{20}H_{13}N_4OV^+$
m/z 376.05235

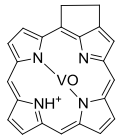
Core 1

DBE 18



$C_{24}H_{19}N_4OV^+$
m/z 430.09930

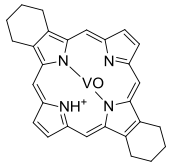
Core 2



$C_{22}H_{15}N_4OV^+$
m/z 402.06800

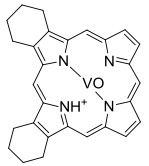
Core 3

DBE 19



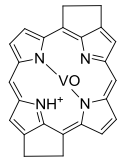
$C_{28}H_{25}N_4OV^+$
m/z 484.14625

Core 4



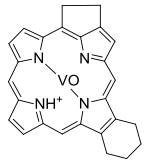
$C_{28}H_{25}N_4OV^+$
m/z 484.14625

Core 5



$C_{24}H_{17}N_4OV^+$
m/z 428.08365

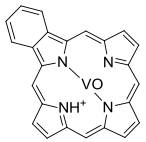
Core 6



$C_{26}H_{21}N_4OV^+$
m/z 456.11495

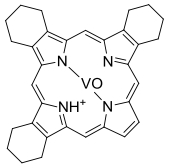
Core 7

DBE 20



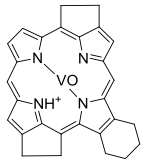
$C_{24}H_{15}N_4OV^+$
m/z 426.06800

Core 8



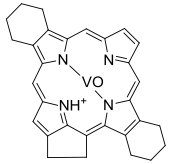
$C_{32}H_{31}N_4OV^+$
m/z 538.19320

Core 9



$C_{28}H_{23}N_4OV^+$
m/z 482.13060

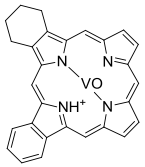
Core 10



$C_{30}H_{27}N_4OV^+$
m/z 510.16190

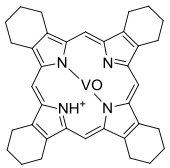
Core 11

DBE 21



$C_{28}H_{21}N_4OV^+$
m/z 480.11495

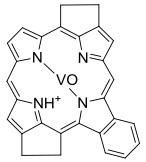
Core 12



$C_{36}H_{37}N_4OV^+$
m/z 592.24015

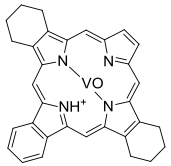
Core 13

DBE 22



$C_{28}H_{19}N_4OV^+$
m/z 478.09930

Core 14

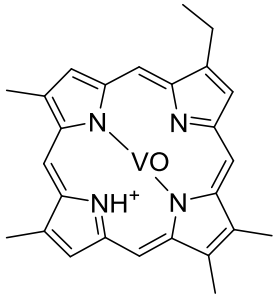


$C_{32}H_{27}N_4OV^+$
m/z 534.16190

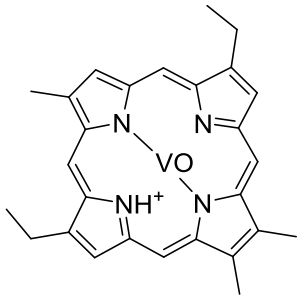
Core 15

To CCS Calculations

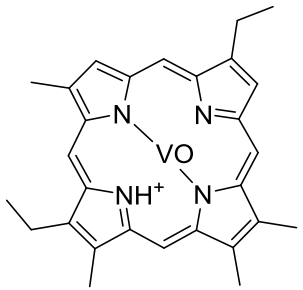
Calculation of CCS for proposed core structures



$C_{26}H_{25}N_4OV^+$
m/z 460.14625
C6



$C_{27}H_{27}N_4OV^+$
m/z 474.16190
C7

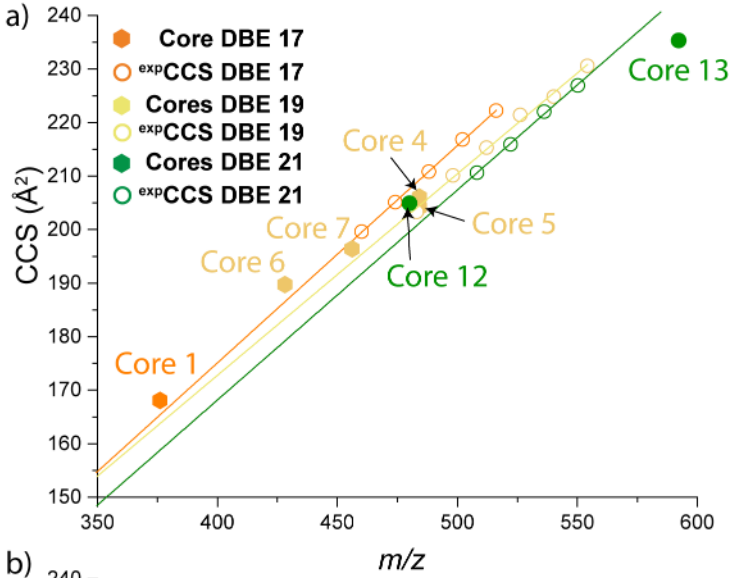


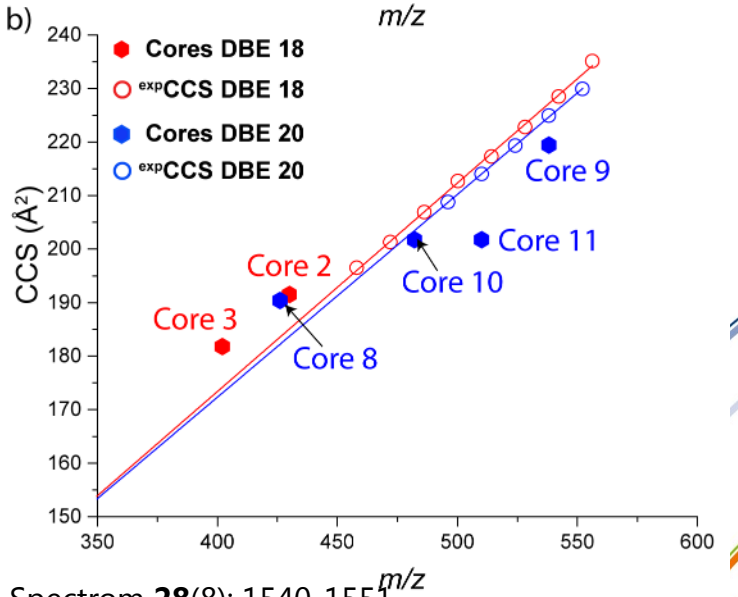
$C_{28}H_{29}N_4OV^+$
m/z 488.17755
C8

3D model of metal containing compounds

Use of DFT with Gaussian m062x/6-31g(d,p) level

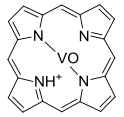
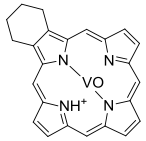
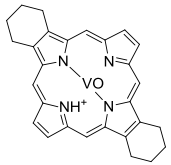
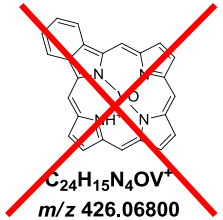
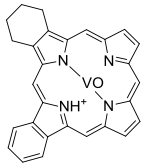
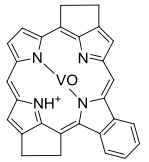
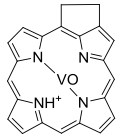
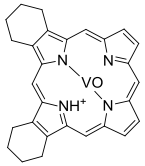
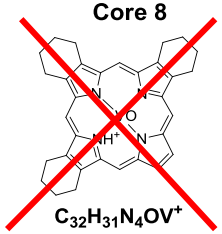
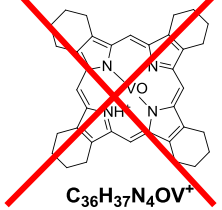
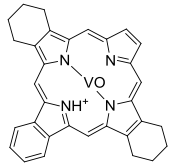
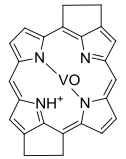
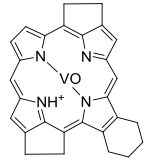
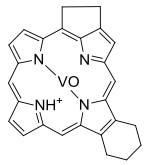
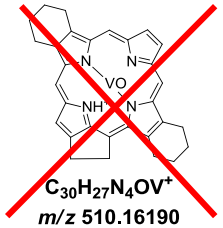
CCS calculations with IMOS



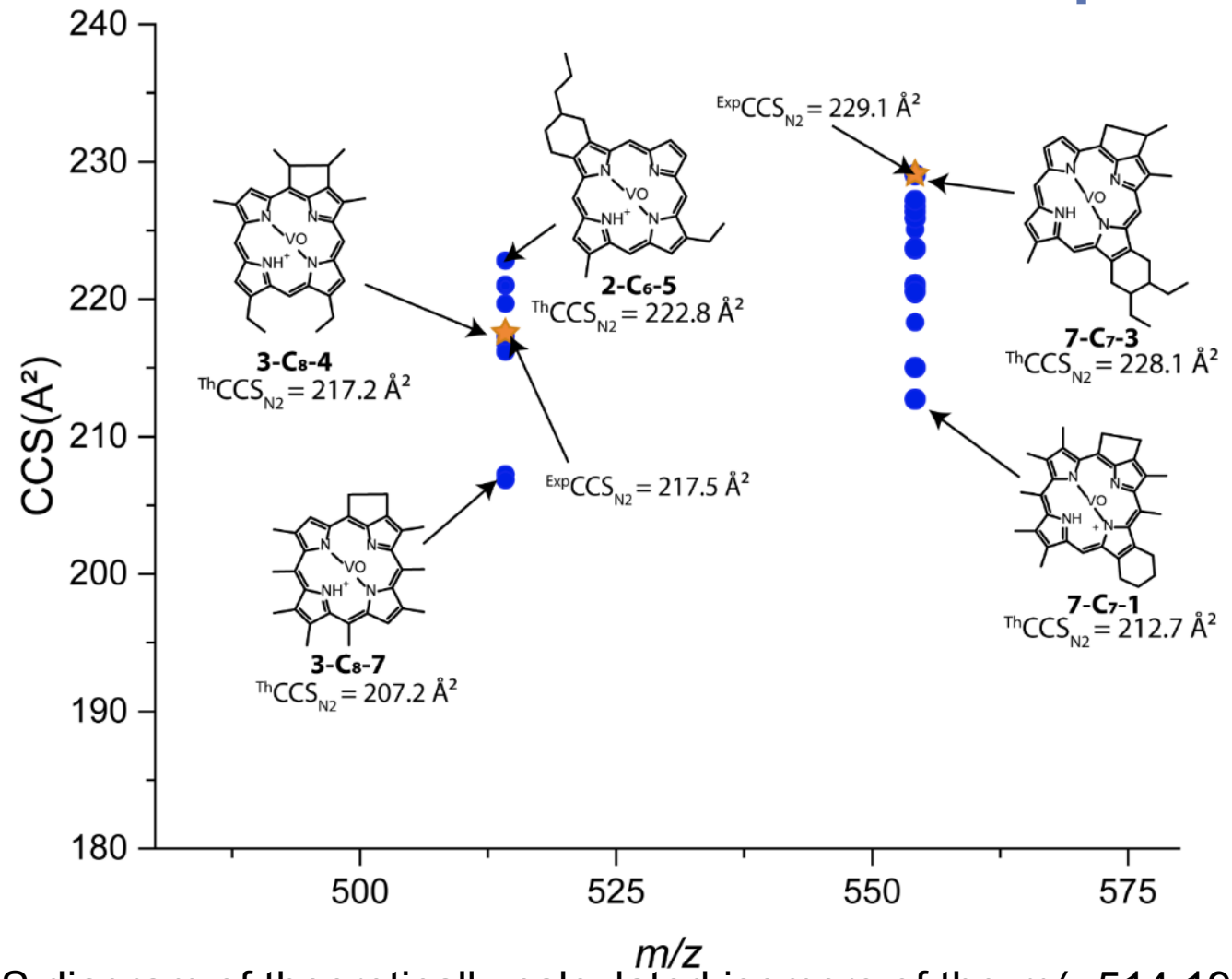


Shrivastav, V., M. Nahin, C. J. Hogan and C. Larriba-Andaluz (2017). J Am Soc Mass Spectrom **28**(8): 1540-1551.

Exclusion of several core structures

DBE 17	DBE 18	DBE 19	DBE 20	DBE 21	DBE 22
					
$C_{20}H_{13}N_4OV^+$	$C_{24}H_{19}N_4OV^+$	$C_{28}H_{25}N_4OV^+$	$C_{24}H_{15}N_4OV^+$	$C_{28}H_{21}N_4OV^+$	$C_{28}H_{19}N_4OV^+$
m/z 376.05235	*m/z* 430.09930	*m/z* 484.14625	*m/z* 426.06800	*m/z* 480.11495	*m/z* 478.09930
Core 1	Core 2	Core 4	Core 8	Core 12	Core 14
					
	$C_{22}H_{15}N_4OV^+$	$C_{28}H_{25}N_4OV^+$	$C_{32}H_{31}N_4OV^+$	$C_{36}H_{37}N_4OV^+$	$C_{32}H_{27}N_4OV^+$
	m/z 402.06800	*m/z* 484.14625	*m/z* 538.19320	*m/z* 592.24015	*m/z* 534.16190
	Core 3	Core 5	Core 9	Core 13	Core 15
					
		$C_{24}H_{17}N_4OV^+$	$C_{28}H_{23}N_4OV^+$		
		m/z 428.08365	*m/z* 482.13060		
		Core 6	Core 10		
					
		$C_{26}H_{21}N_4OV^+$	$C_{30}H_{27}N_4OV^+$		
		m/z 456.11495	*m/z* 510.16190		
		Core 7	Core 11		

Calculations of putative structures



IMS-MS diagram of theoretically calculated isomers of the *m/z* 514.19320 and 554.22450 (light blue dots) and the corresponding experimental measurement (orange star). Selected isomeric structure are included visualizing unlikely (high deviation) and likely (low deviation) structures.

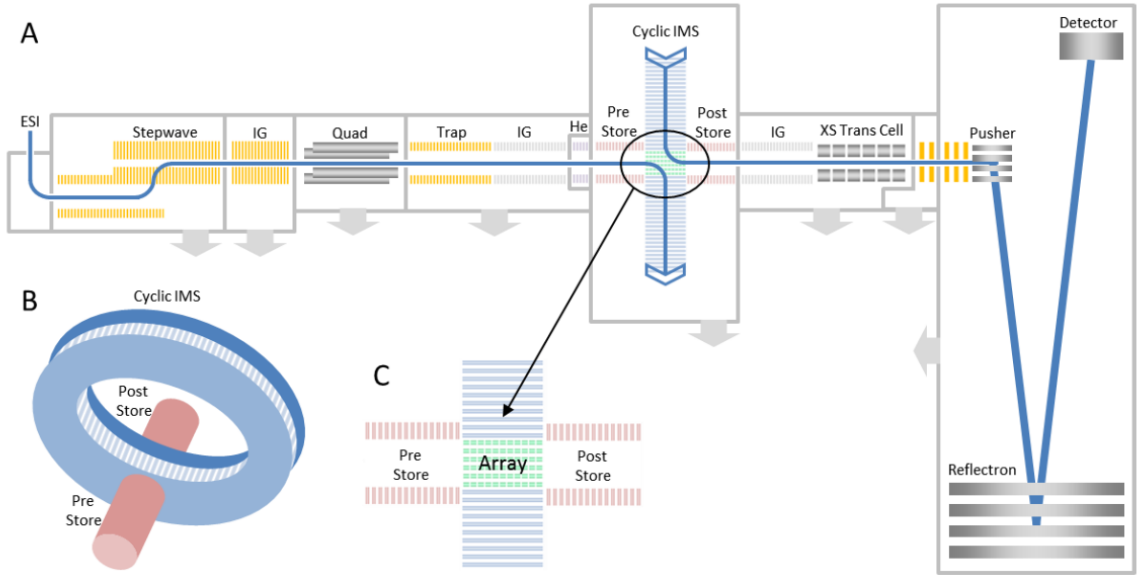
Conclusion

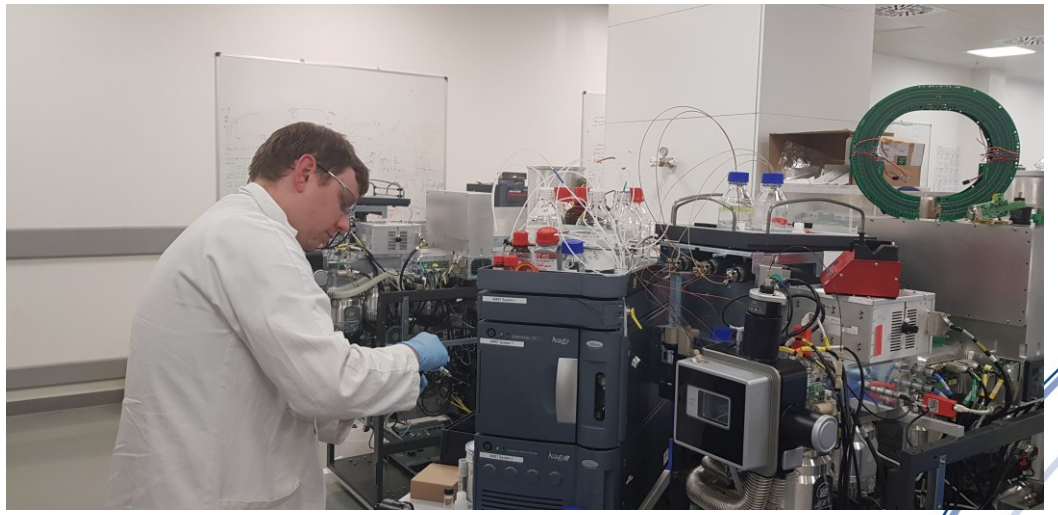
- Analysis of real petrophyrin by TIMS-FTICR
- Experimental CCS determination
- Theoretical CCS determination of petroporphyrin cores and akylated cores
- Comparison of experimental and theoretical data allowed to propose putative species with CCS in agreement with the experimental values.

cIMS Experiments in Manchester

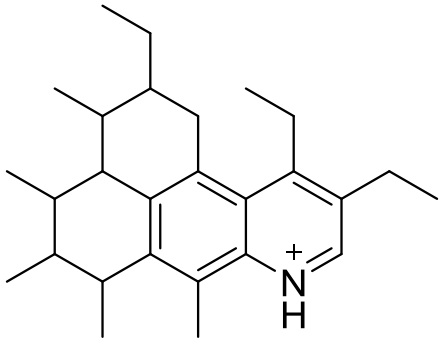
Johann Le Maitre
Christopher Ruger

Figures

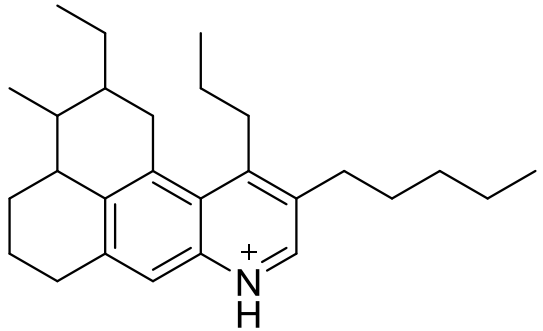




Separation of isomers

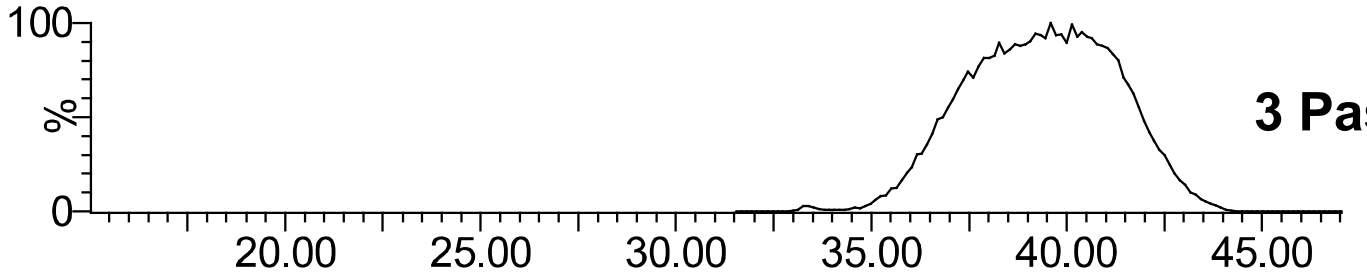


Chemical Formula: $C_{27}H_{40}N^+$
Exact Mass: 378.3155

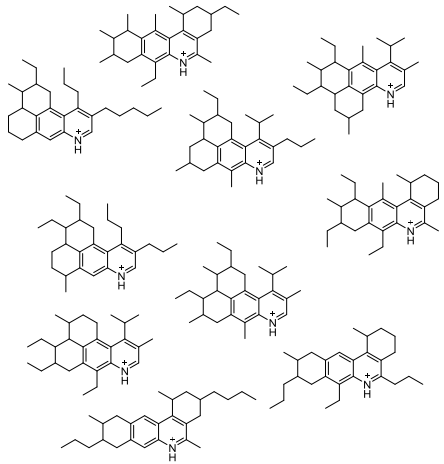


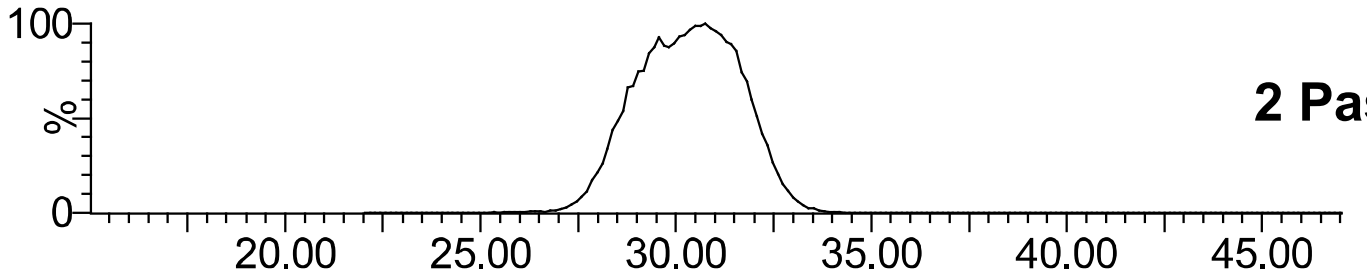
Chemical Formula: $C_{27}H_{40}N^+$
Exact Mass: 378.3155

Too many isomers !

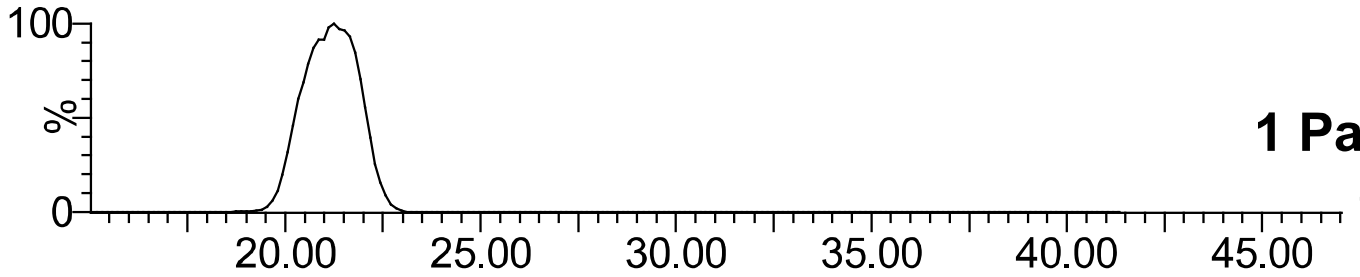


3 Pass



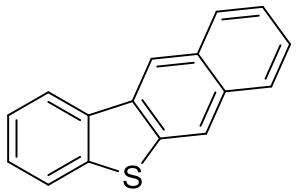


2 Pass

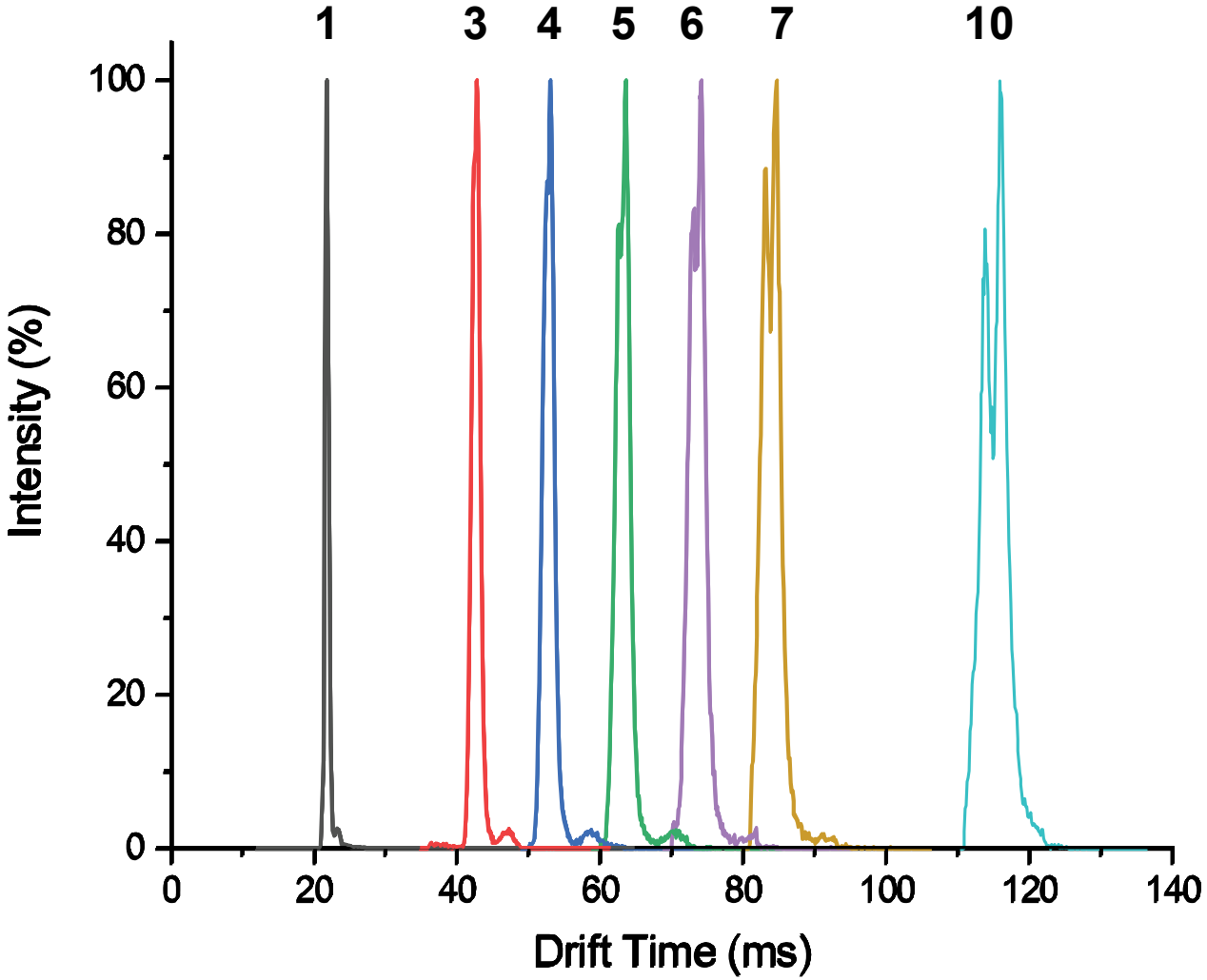


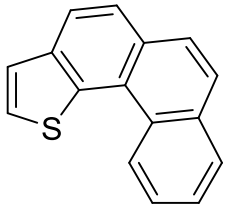
1 Pass

Core structure

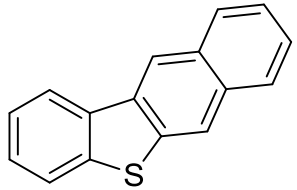


Chemical Formula: $C_{16}H_{10}S$
Exact Mass: 234.0503





Chemical Formula: $C_{16}H_{10}S$
Exact Mass: 234.0503



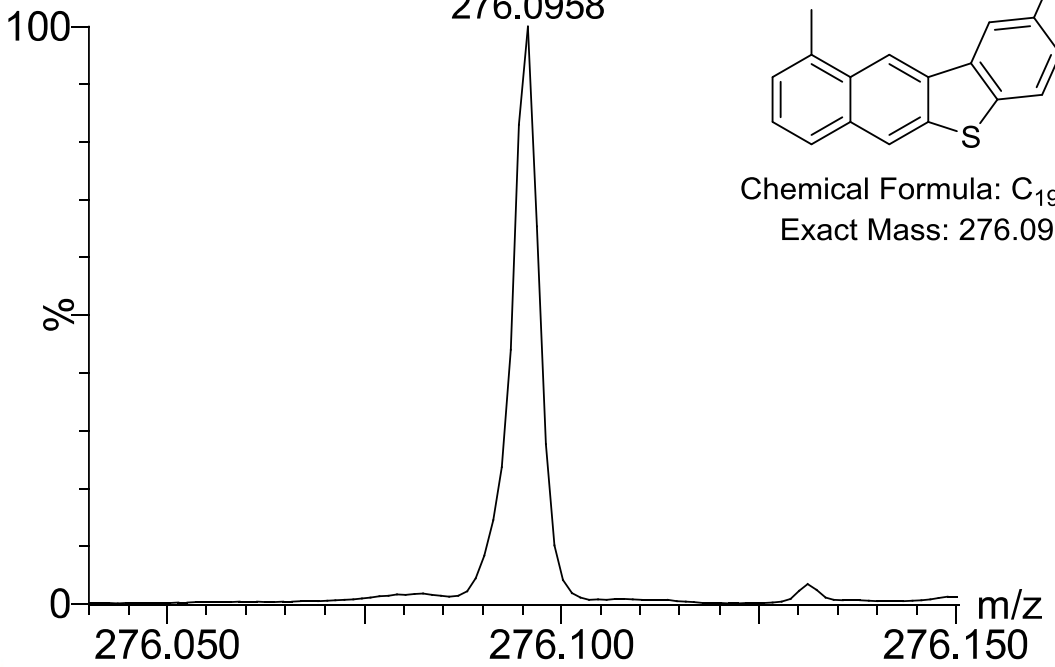
Chemical Formula: $C_{16}H_{10}S$
Exact Mass: 234.0503

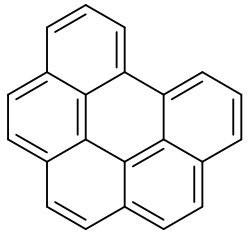
C_3-SH_4 split: VGO on the cIMS-MS

?

$C_{22}H_{12}^+$

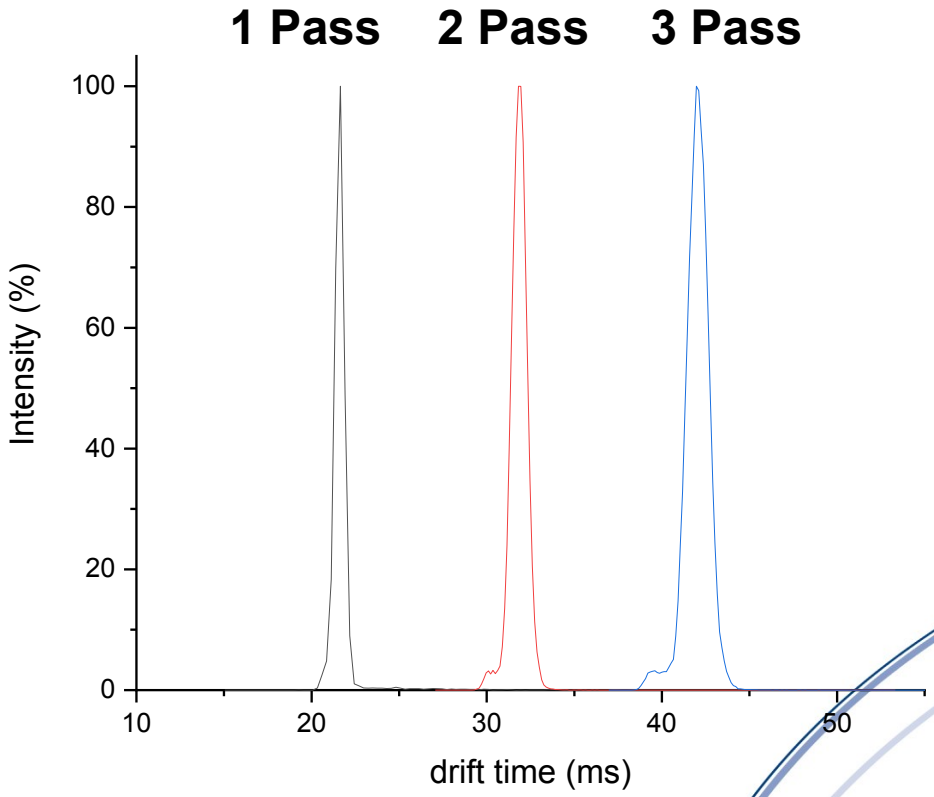
$C_{22}H_{16}S^+$



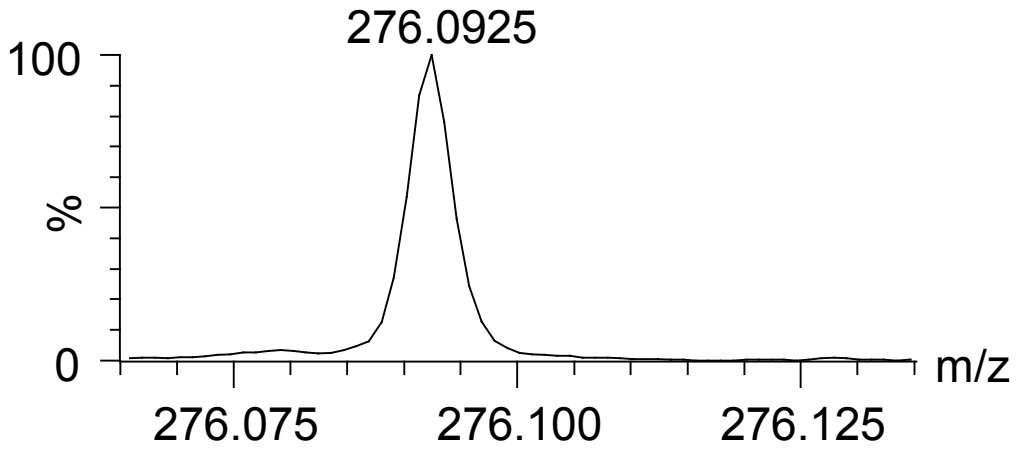


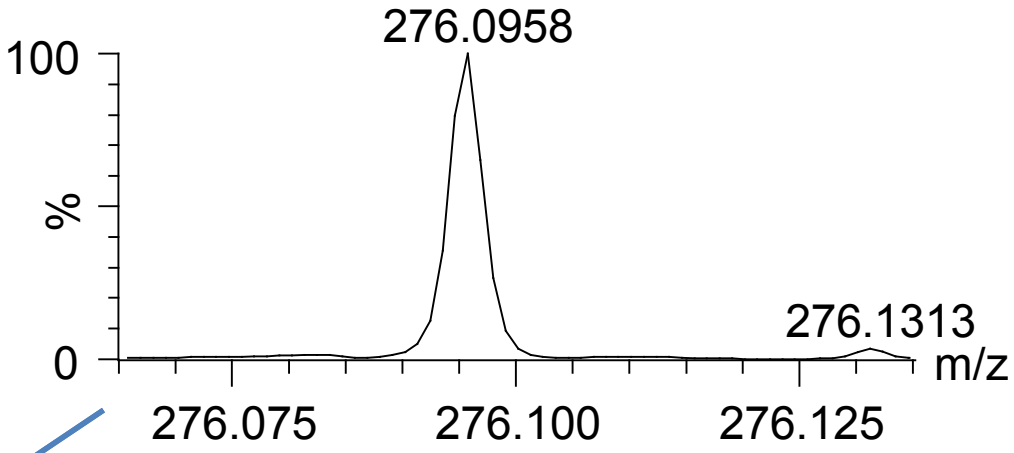
Chemical Formula: $C_{22}H_{12}$
Exact Mass: 276.0939

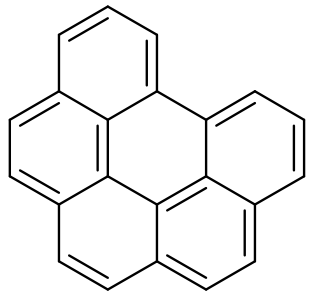
Chemical Formula: $C_{19}H_{16}S$
Exact Mass: 276.0973



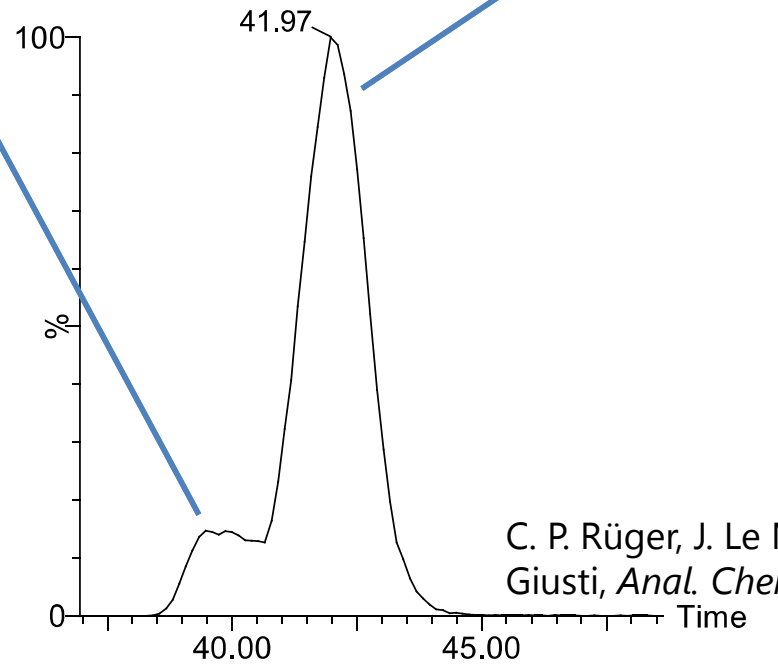
C_3-SH_4 split: VGO on the cIMS-MS

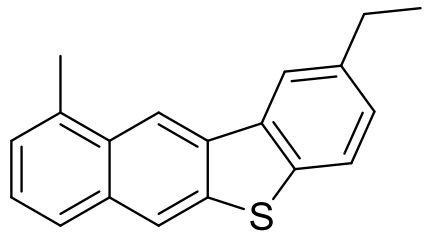






Chemical Formula: $C_{22}H_{12}$
Exact Mass: 276.0939





Chemical Formula: $C_{19}H_{16}S$
Exact Mass: 276.0973

C. P. Rüger, J. Le Maître, J. Maillard, E. Riches, M. Palmer, C. Afonso and P. Giusti, *Anal. Chem.*, 2021, **93**, 5872-5881.

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