Use of isotopes in metabolomics

Stephen Barnes, PhD

3-2-15

Synopsis

- Natural abundance isotopes
- Tracing a metabolic pathway
  - Labeling a precursor for qualitative analysis
  - 95% isotope/5% unlabeled and 5% unlabeled/95% isotope
- Following individual carbon atoms
- Quantitative analysis of metabolic flux
- Post-extraction isotopic labeling

Value of natural isotopes

- The natural abundance of isotopes enables the investigator to determine the charge state of an ion
  - The principal contribution to $[M+H]^+$ or $[M-H]^-$ isotope ions comes from ^{13}C (~1.1% of all carbon atoms)
  - The intensity of the ^{13}C isotope ion increases relative to the number of carbon atoms
  - There is often an observable $^{13}C_2$ isotope peak

Value of the [M+/-H+2] peak

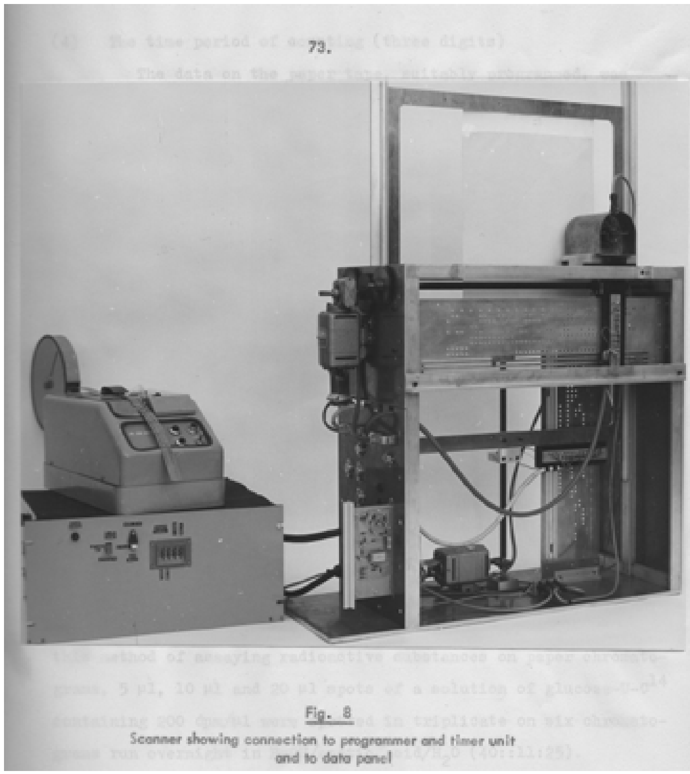
- The mass difference due to a nominal increase in mass of 2 contains a lot of information
  - These are isotopic mass differences for each of the common elements
    - $^{1}H_2/^{2}H_2$ 2 x 1.006277 = 2.012554 (0.012%)
    - $^{12}C_2/^{13}C_2$ 2 x 1.003355 = 2.006710 (1.078%)
    - $^{14}N_2/^{15}N_2$ 2 x 0.997035 = 1.994079 (0.364%)
    - $^{16}O_2/^{17}O_2$ 2 x 1.004217 = 2.008434 (0.038%)
    - $^{16}O_2/^{18}O_1$ 1 x 2.004246 = 2.004246 (0.205%)
    - $^{32}S_2/^{33}S_2$ 2 x 0.999387 = 1.998774 (0.752%)
    - $^{32}S_2/^{34}S_1$ 1 x 1.995796 = 1.995796 (4.252%)

Using isotopes to trace a pathway

- Early studies (1930s) used ^{2}H, ^{13}C and ^{15}N labeling to map pathways
  - Limited to 1-200 *m/z* mass range
- 1950s/60s ^{14}C-radiotracers
  - 2D-Paper or thin layer chromatography
  - Radio gas chromatography
    - labeling of specific carbon atoms

Origins of practical metabolomics

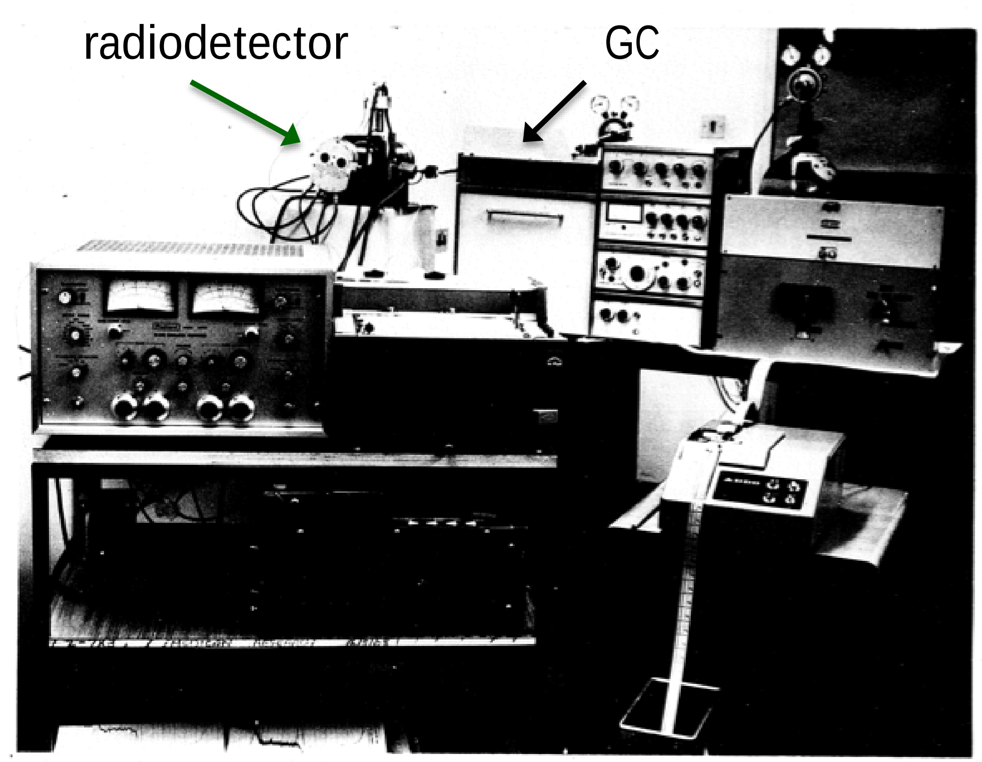
Imperial College 1967-1970



Radio 2D-paper chromatography scanner with digitization of collected data

The room had 20 of these scanners – data analyzed by a central computer (in 1968)

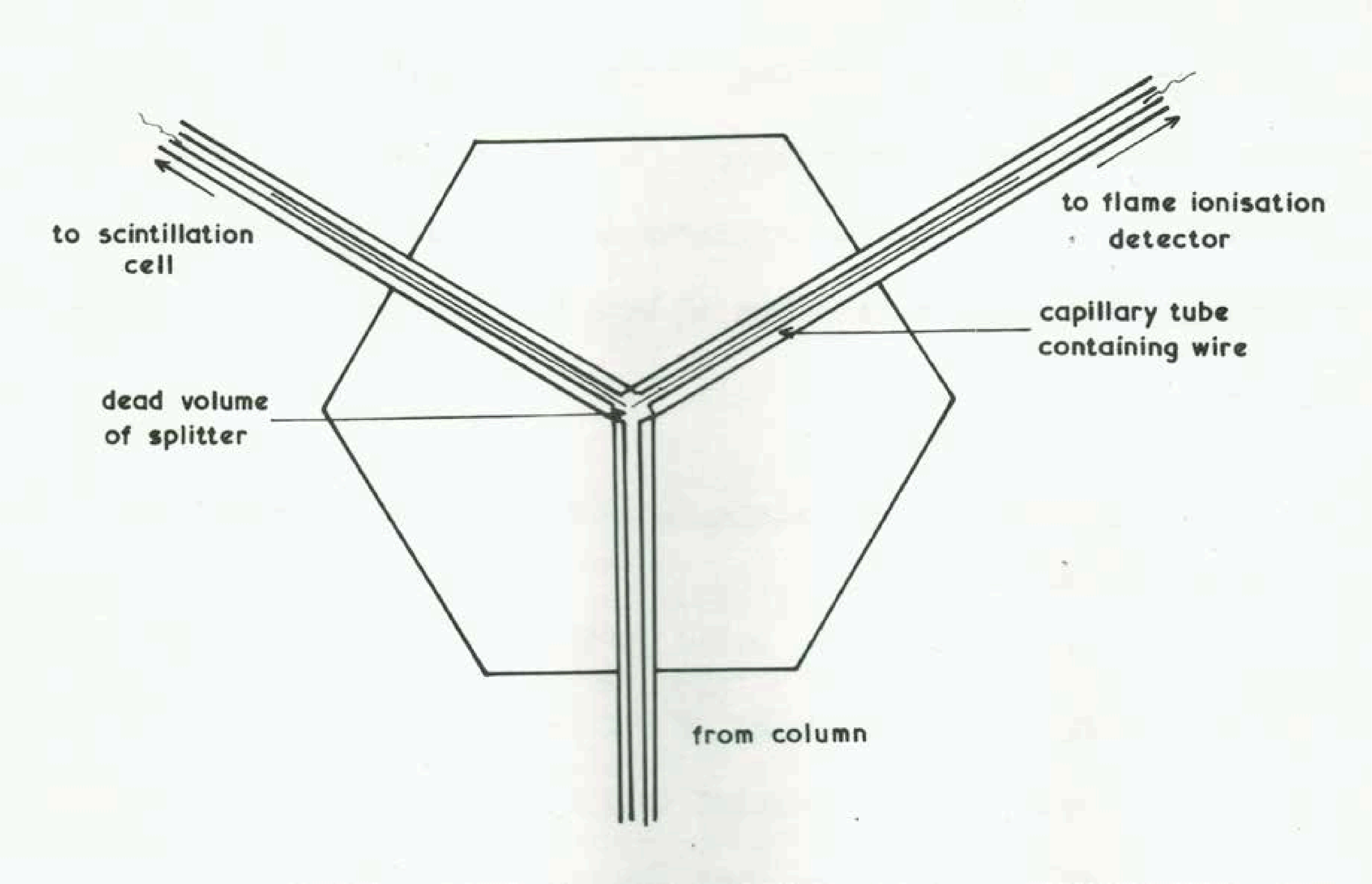
Courtesy of K.R. Mansford, PhD



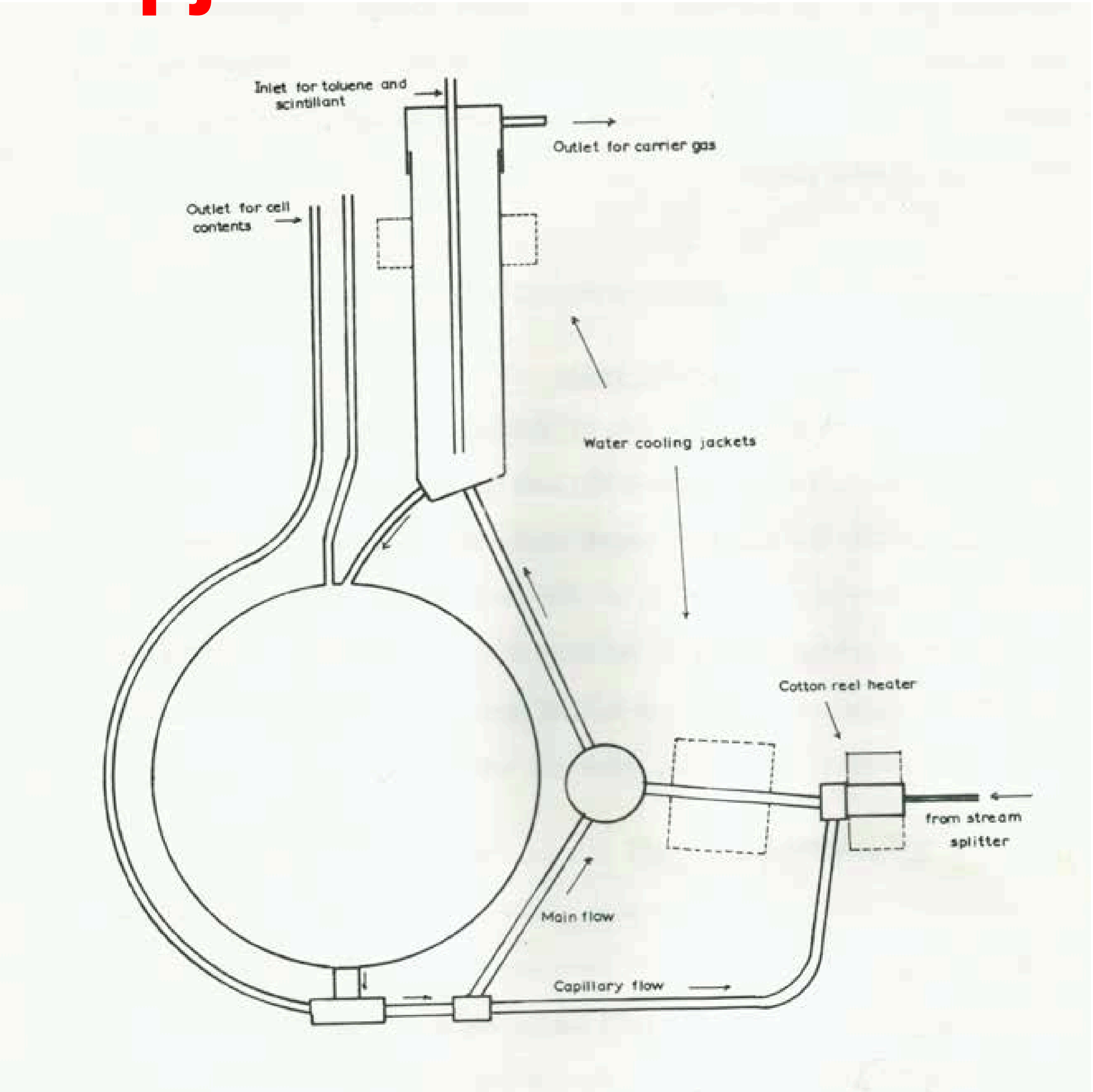
Radio gas-liquid chromatography with digitization of collected data

Developed this for my PhD work (1967-1970) to study glucose metabolism in acellular slime moulds

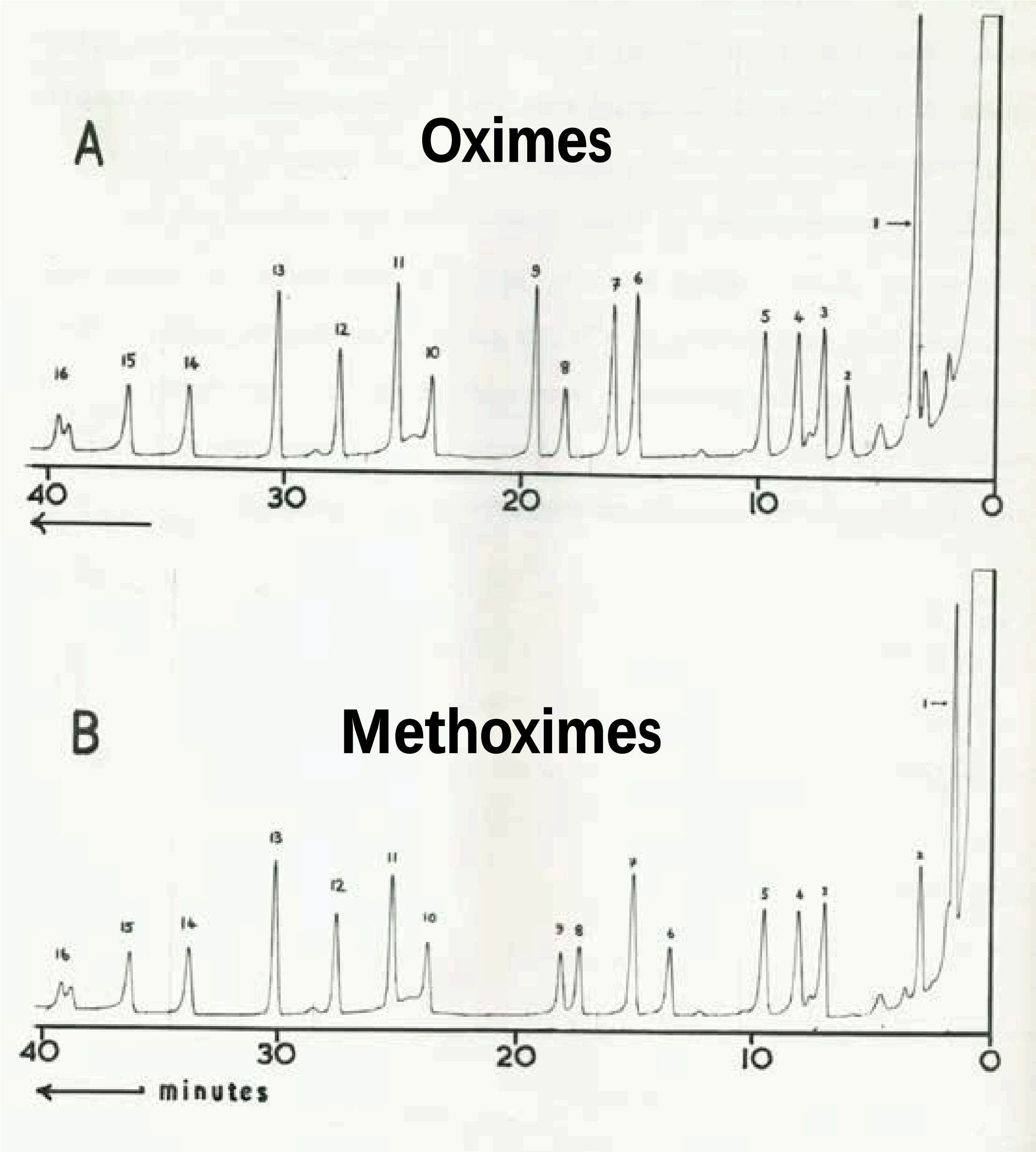
Stream splitter for radio GC



Popjak scintillation cell



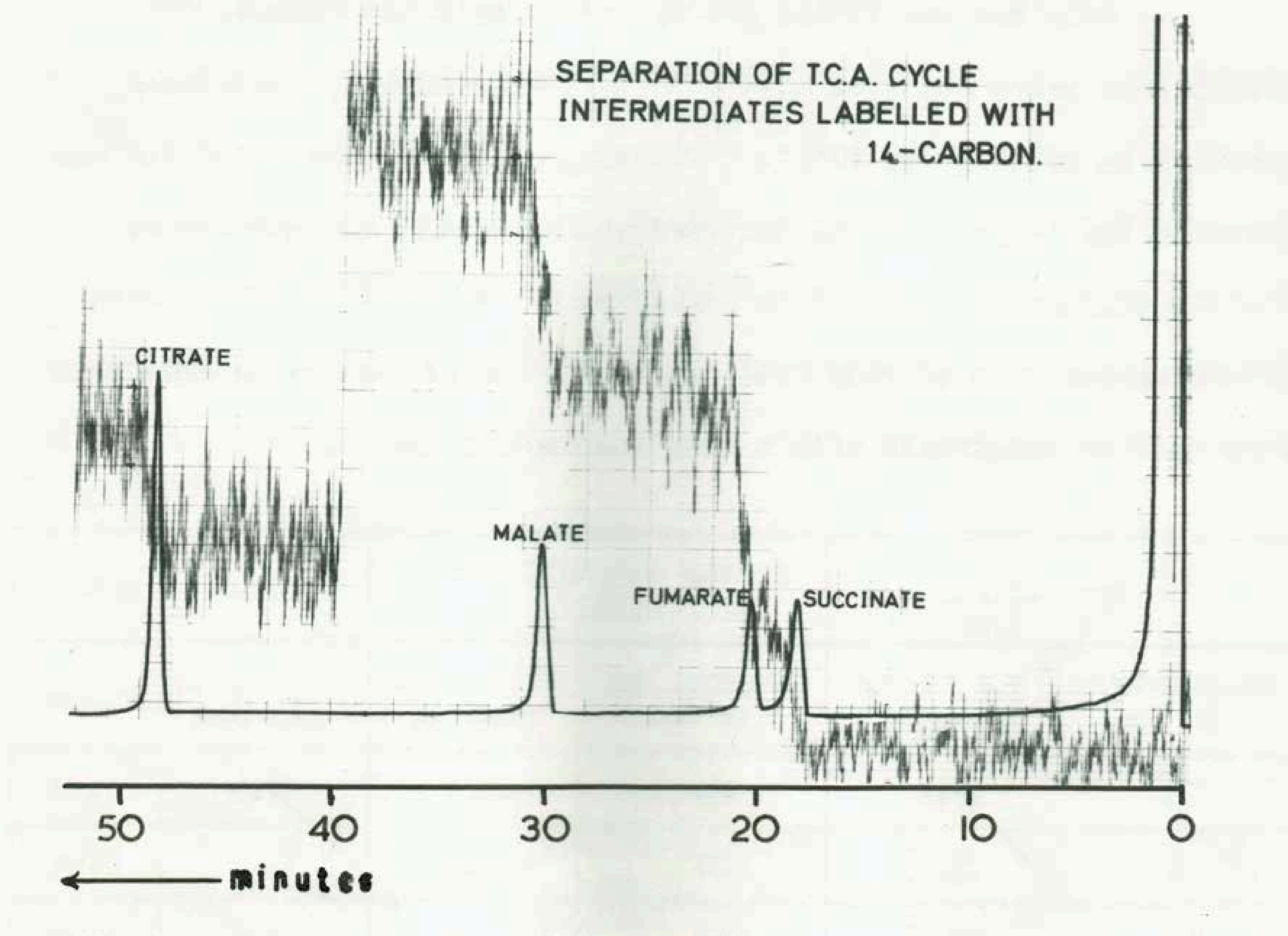
GC of glycolytic and Krebs cycle intermediates



Temperature programming of TMS ester/ethers on a 5' x ¼ inch packed column of Chromosorb W coated with OV-1 liquid phase

1= , 2= , 3= , 4= , 5= , 6= , 7= , 8= , 9= , 10= , 11= , 12= , 13= , 14= , 15= , 16=

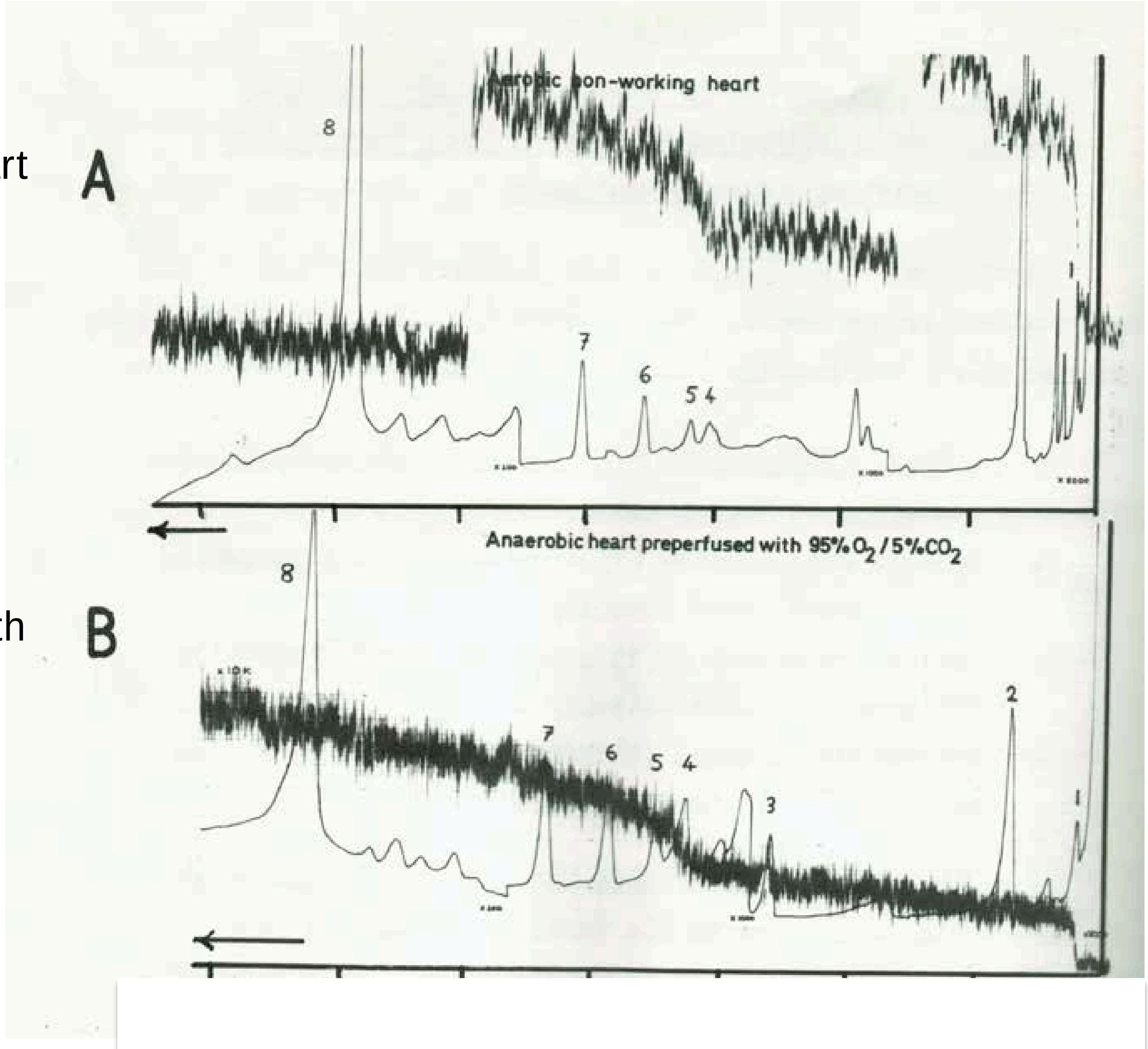
Radio-GC of Krebs Cycle intermediates



Radio GC analysis of beating heart

Aerobic beating heart

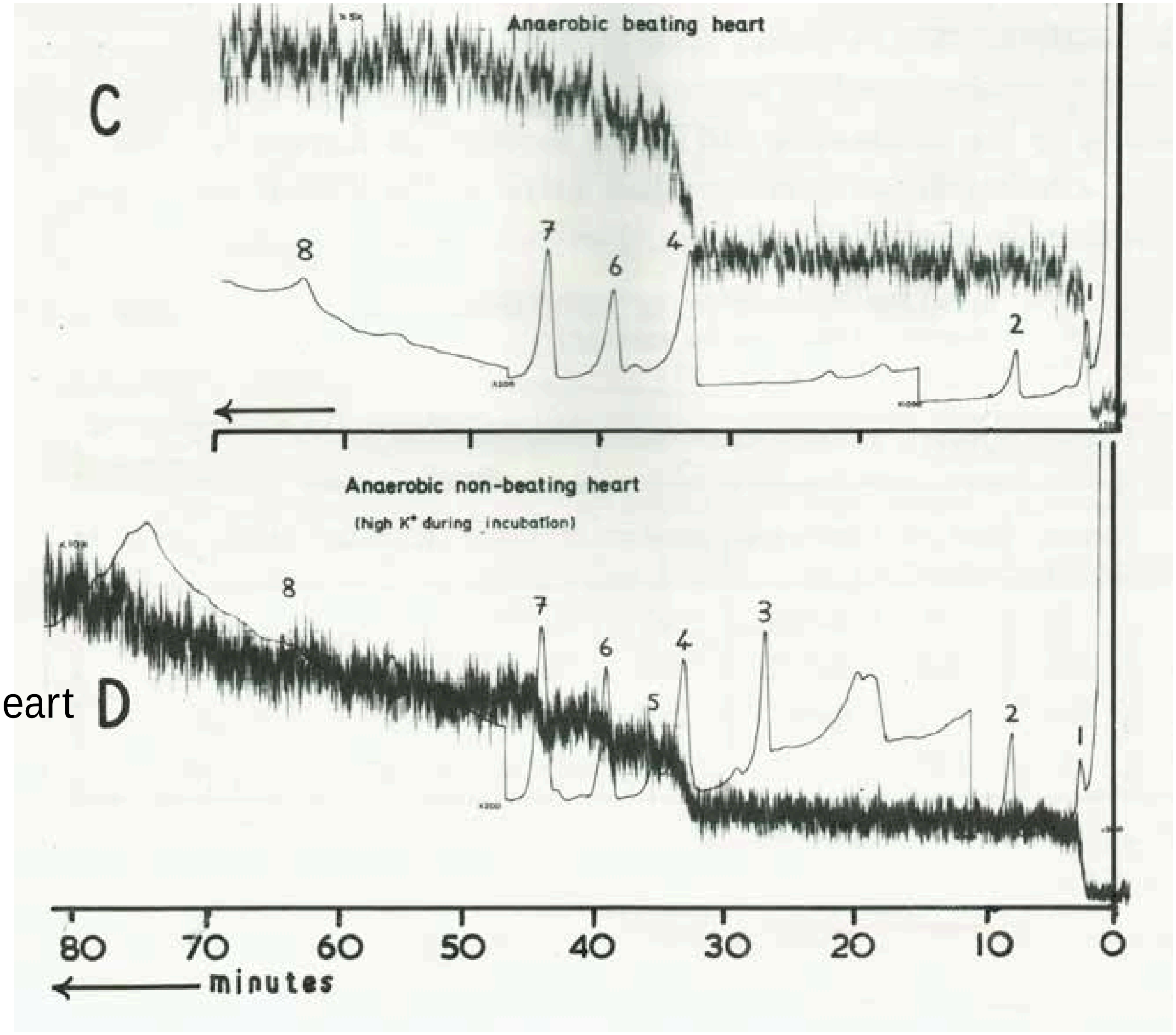
Anerobic beating heart perfused with 95% O_2/5% CO_2



Radio GC analysis of anerobic heart

Anerobic beating heart

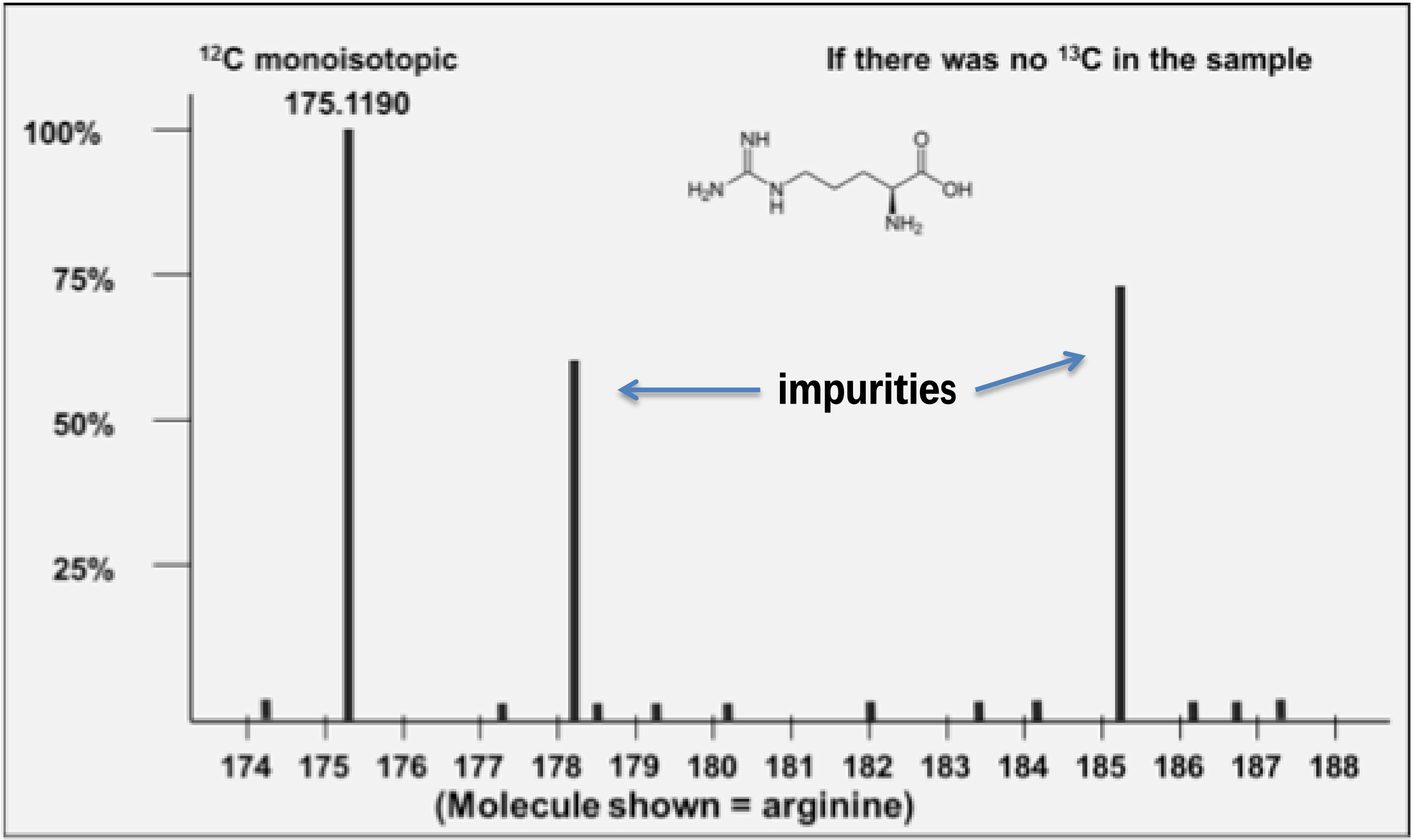
Anerobic non-beating heart



Tracking metabolites with IROA

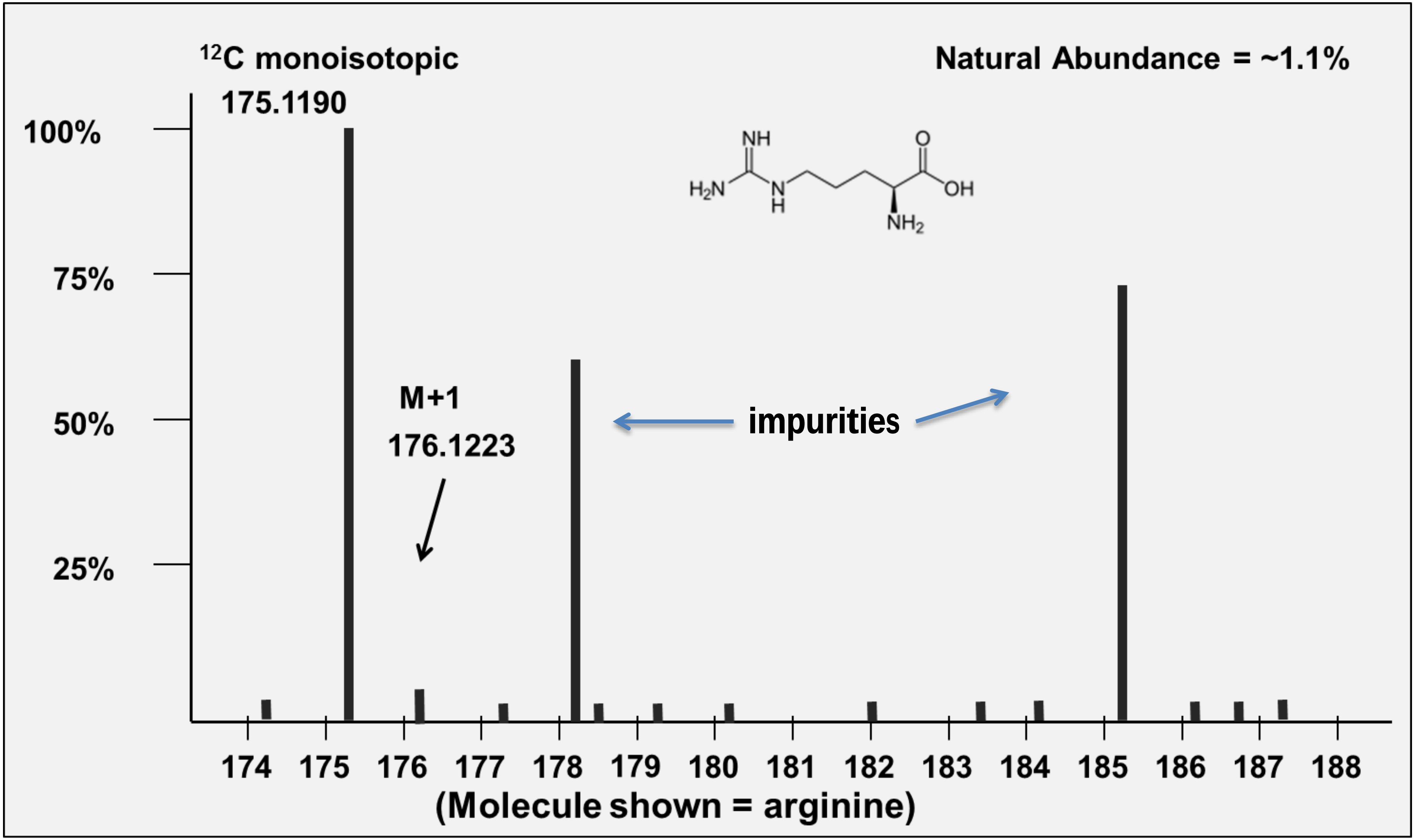
- Isotope ratio outlier analysis (IROA)
  - Not used for flux analysis, but rather to create a unique signal for metabolites
  - Used for LC-MS (and possibly GC-MS)
  - Designed to distinguish between metabolites of interest and background signals
  - Requires uniform labeling at the 95% and 5% ^{13}C-enrichment levels

All ^{12}C in arginine $[M+H]^+$



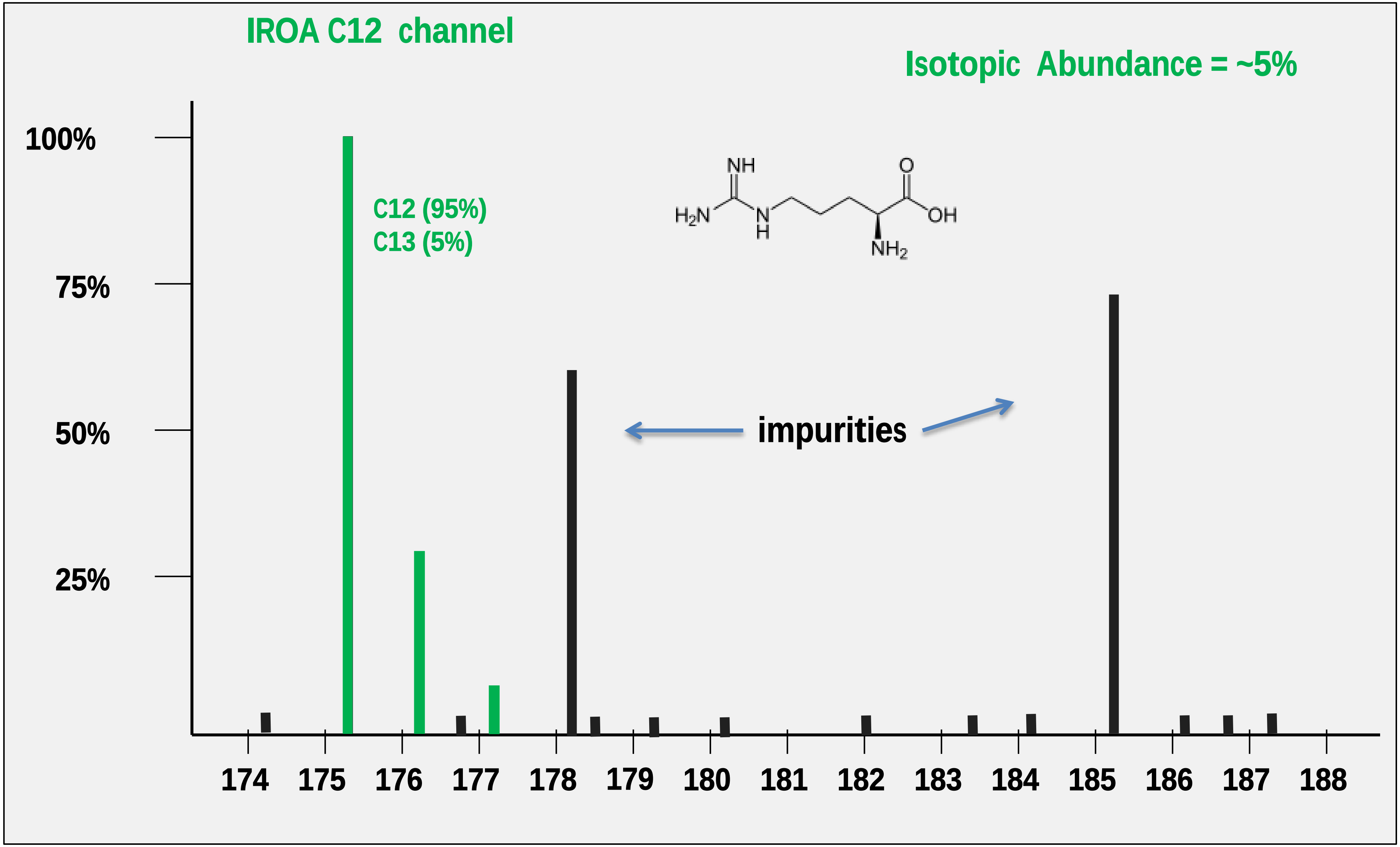
IROA Technologies

Natural abundance of ^{13}C in arginine



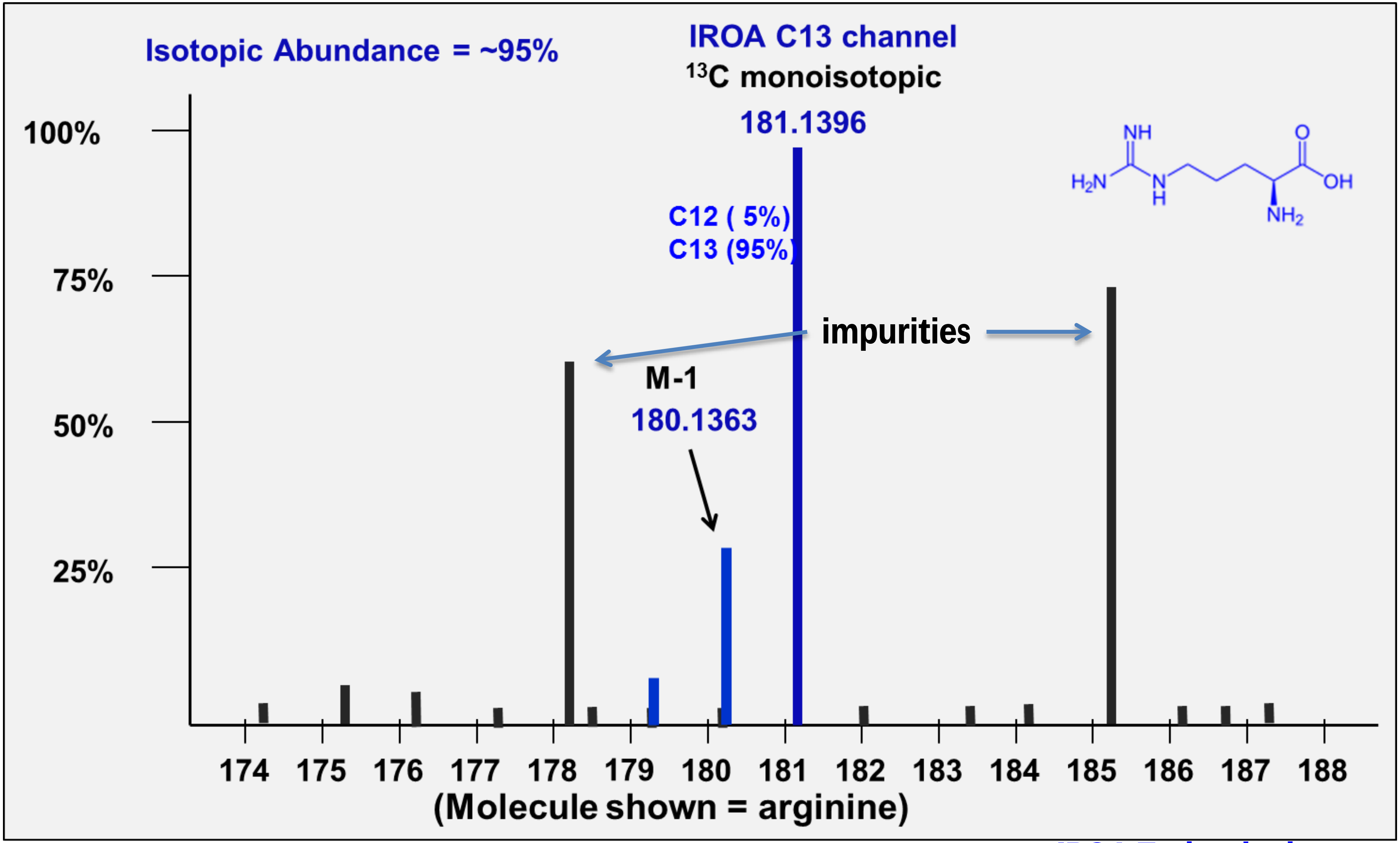
IROA Technologies

Making ^{13}C abundance = 5%



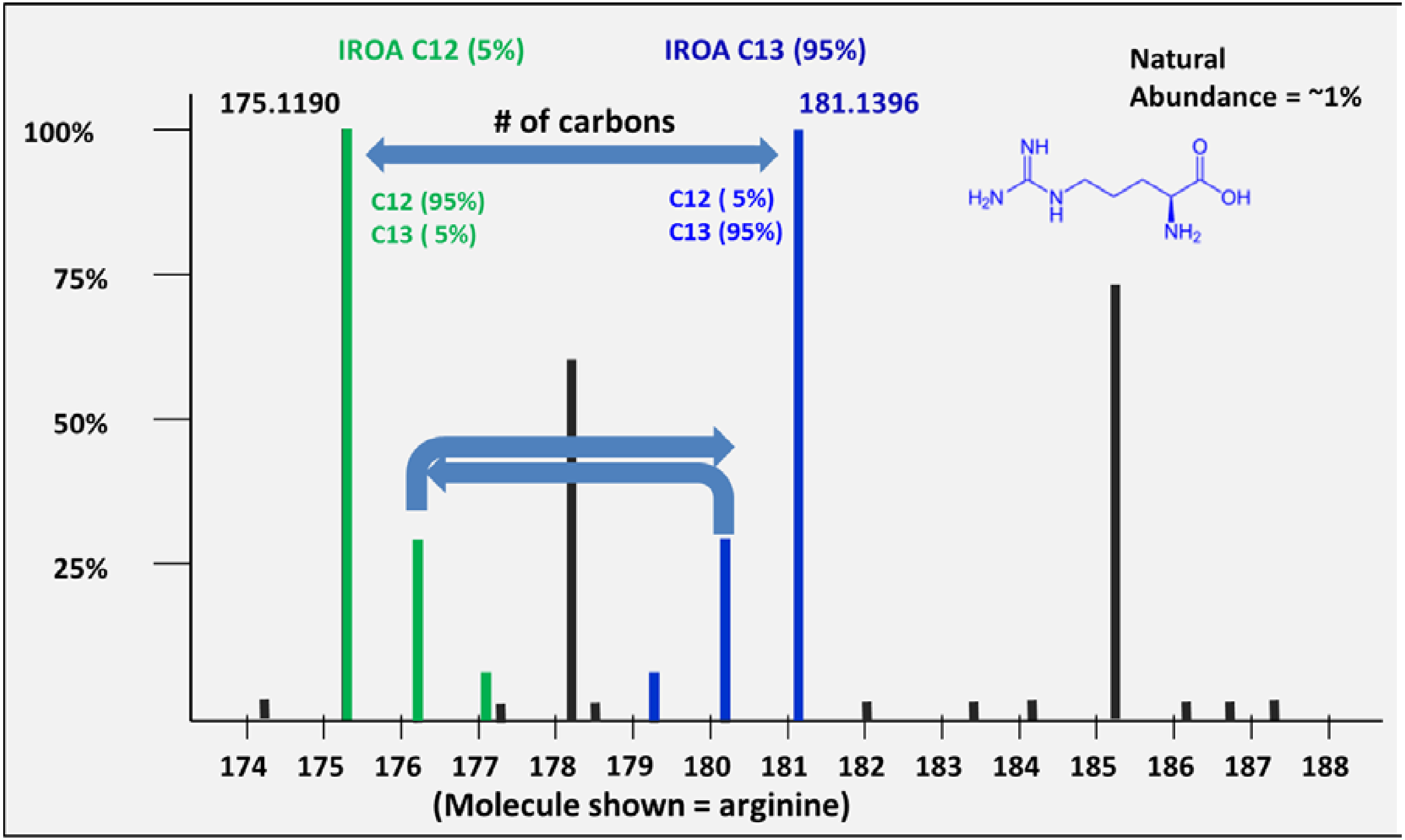
IROA Technologies

Making ^{13}C abundance = 95%



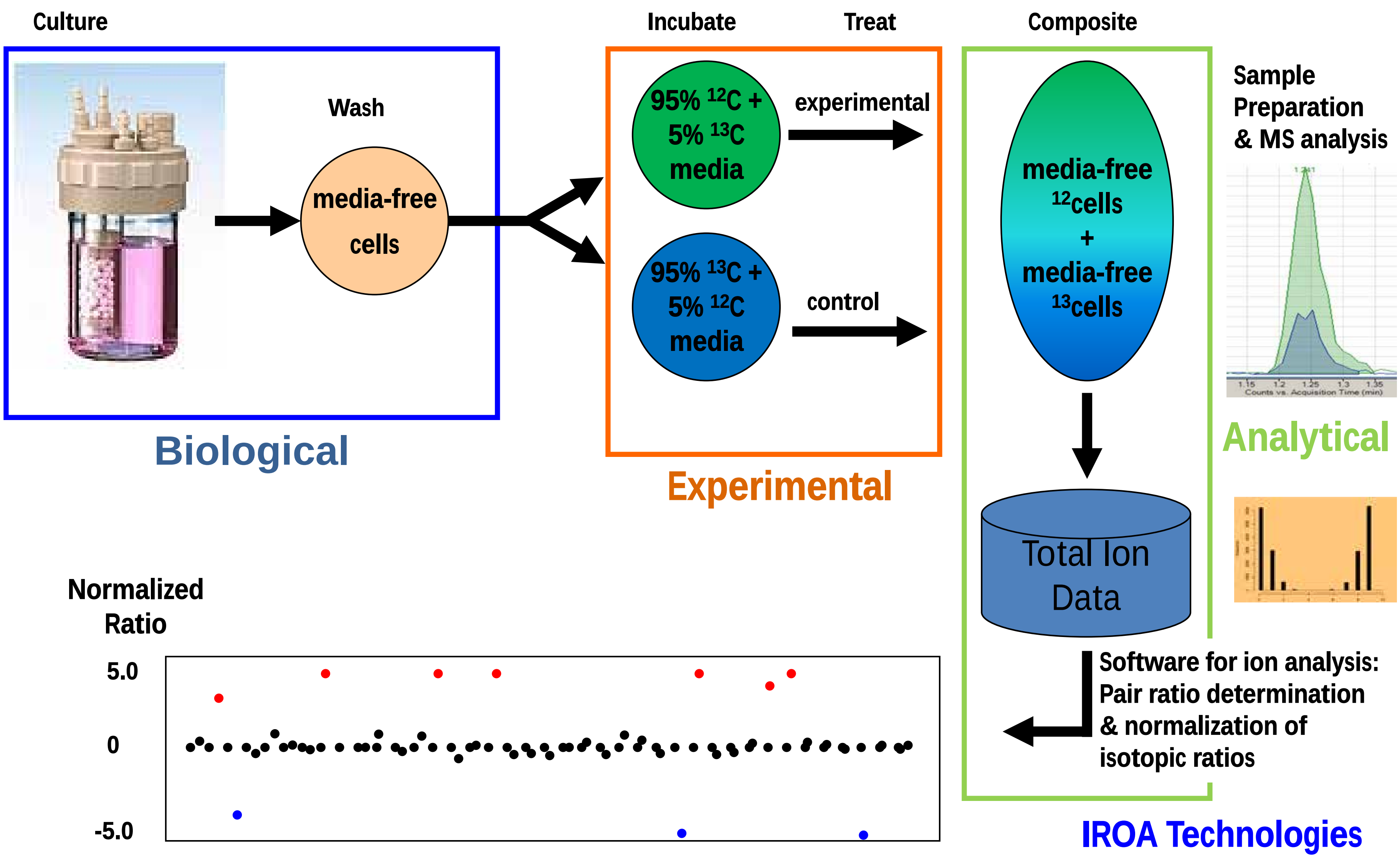
IROA Technologies

Pairing the 5% and 95% ^{13}C-labeling

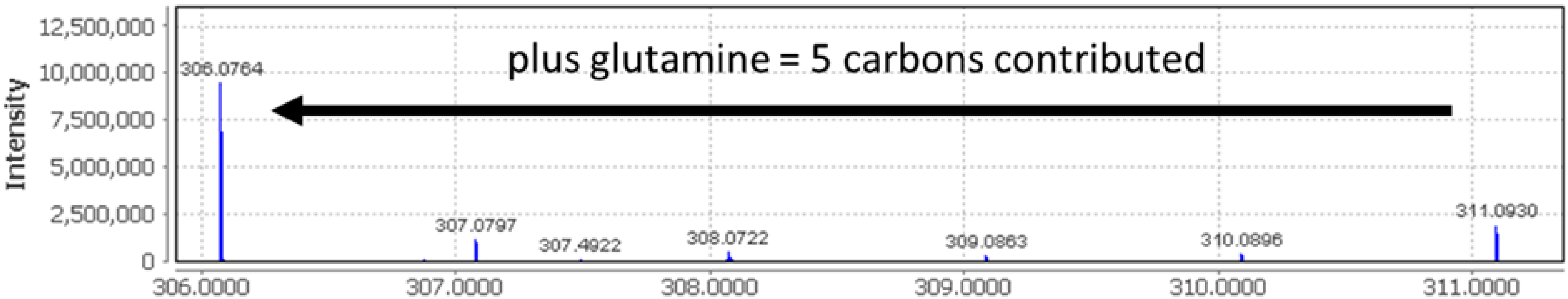


IROA Technologies

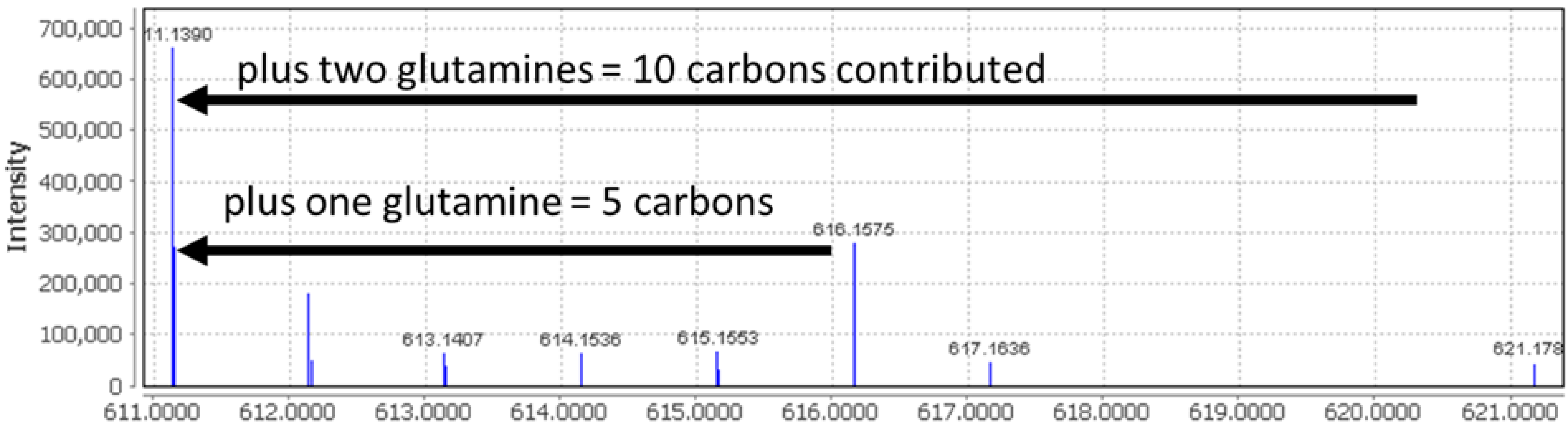
The IROA approach



The span of isotopes = # carbon atoms



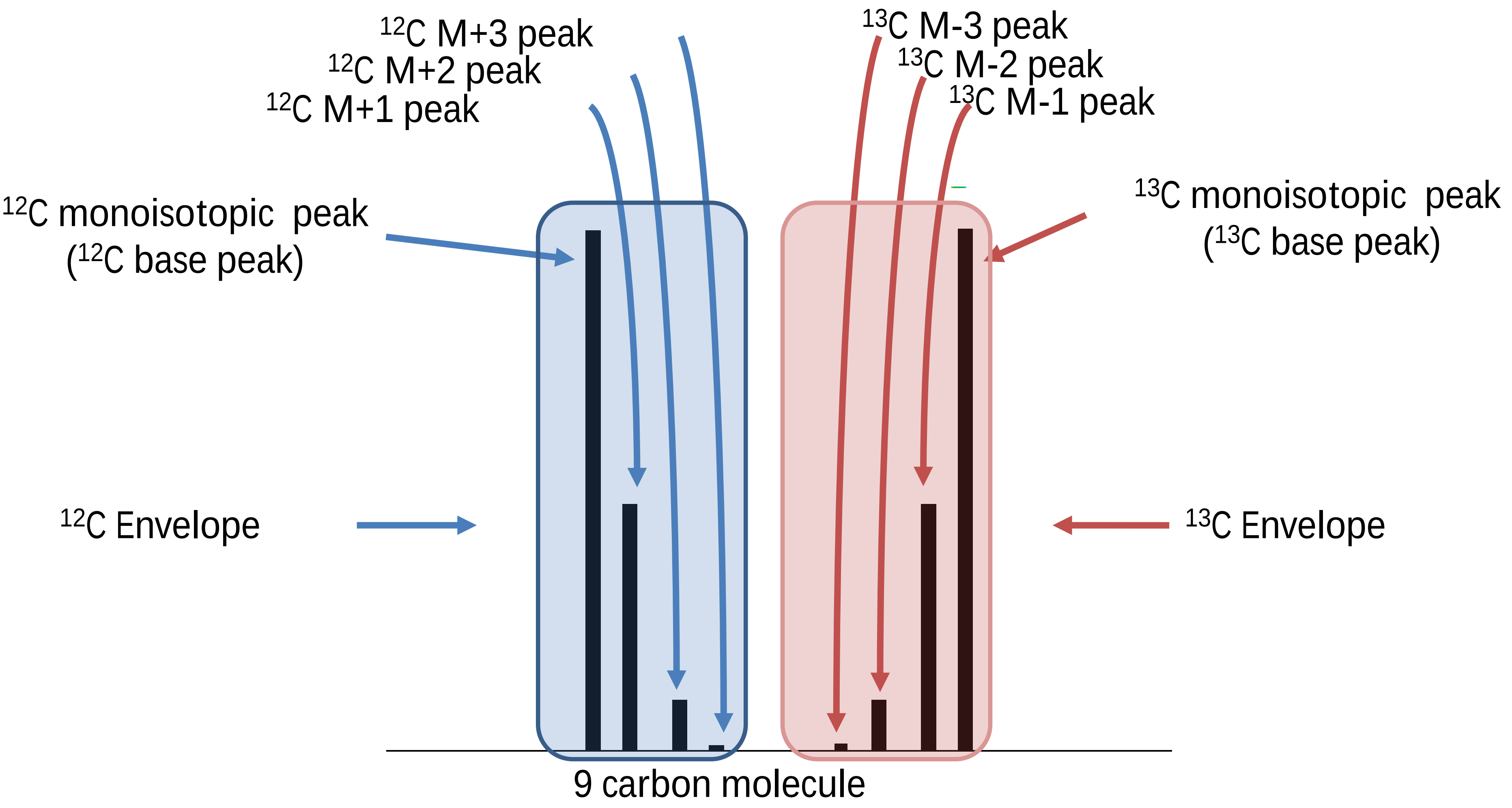
Glutathione shows the sizes of the non-labeled, and singly labeled species, which inherits a five carbon fragment from glutamine.



Oxidized glutathione shows the sizes of the non-labeled, singly labeled, and doubly labeled species. Each inheriting a five carbon fragment from glutamine.

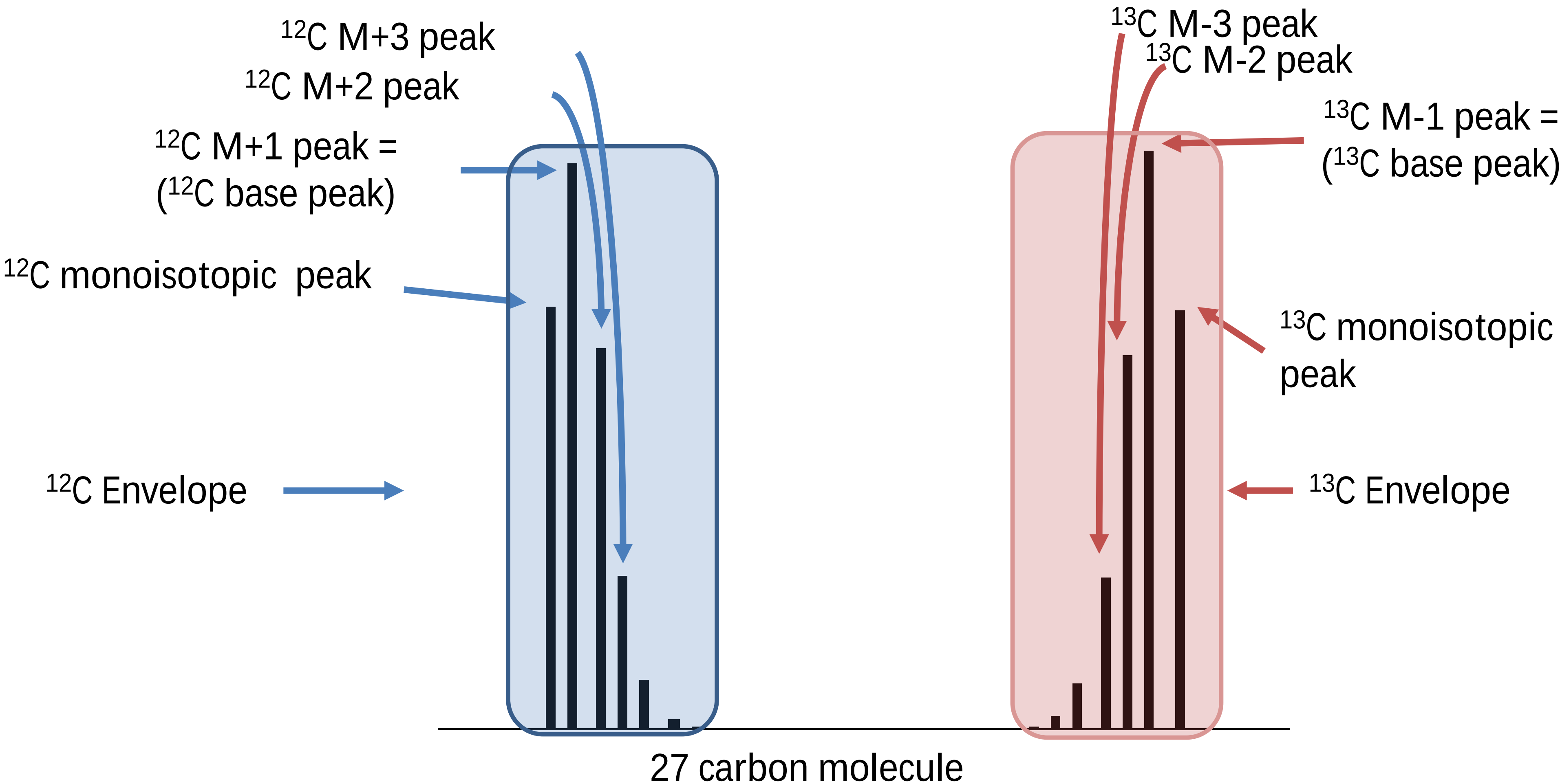
IROA Technologies

The IROA peak pattern



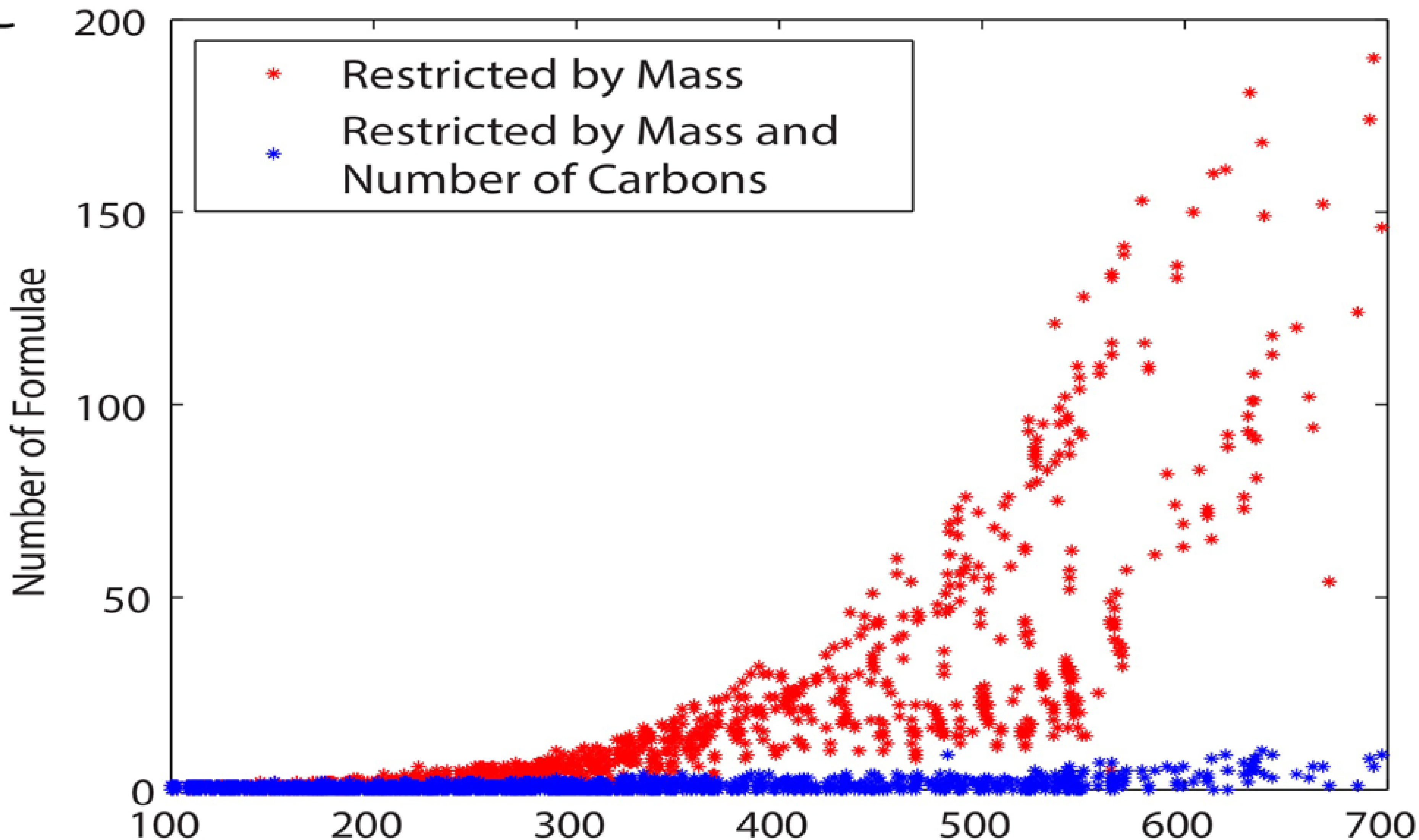
IROA Technologies

IROA profile of a bigger metabolite



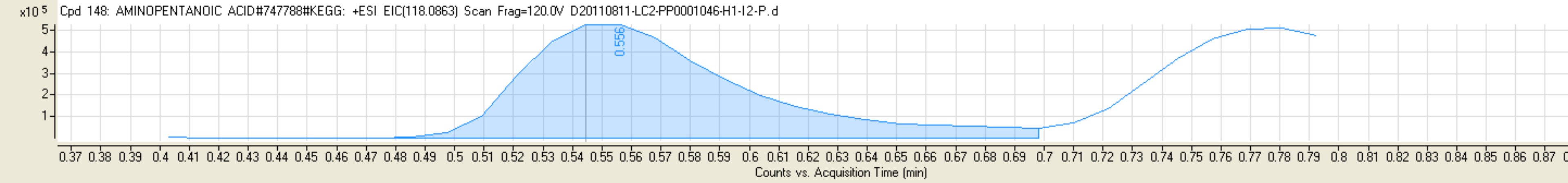
IROA Technologies

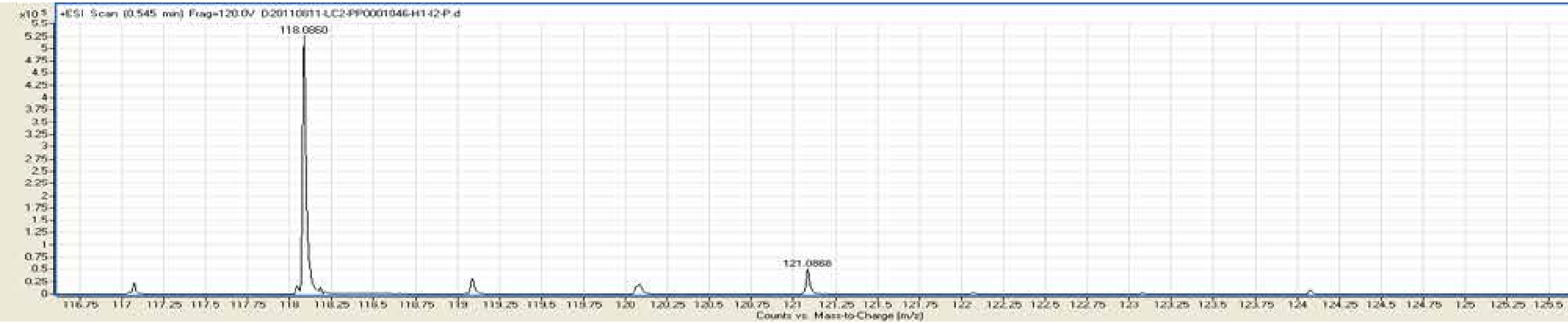
Value of knowing the carbon

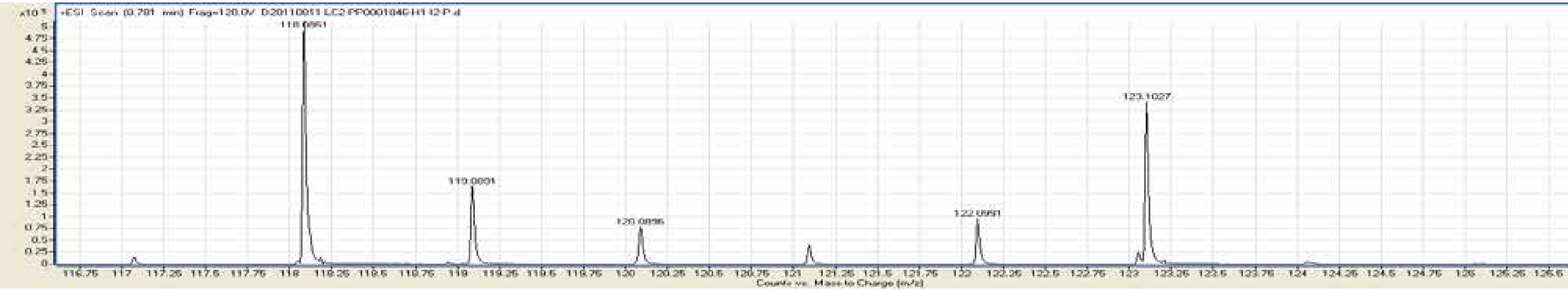


IROA Technologies

Avoiding metabolite artfacts with IROA

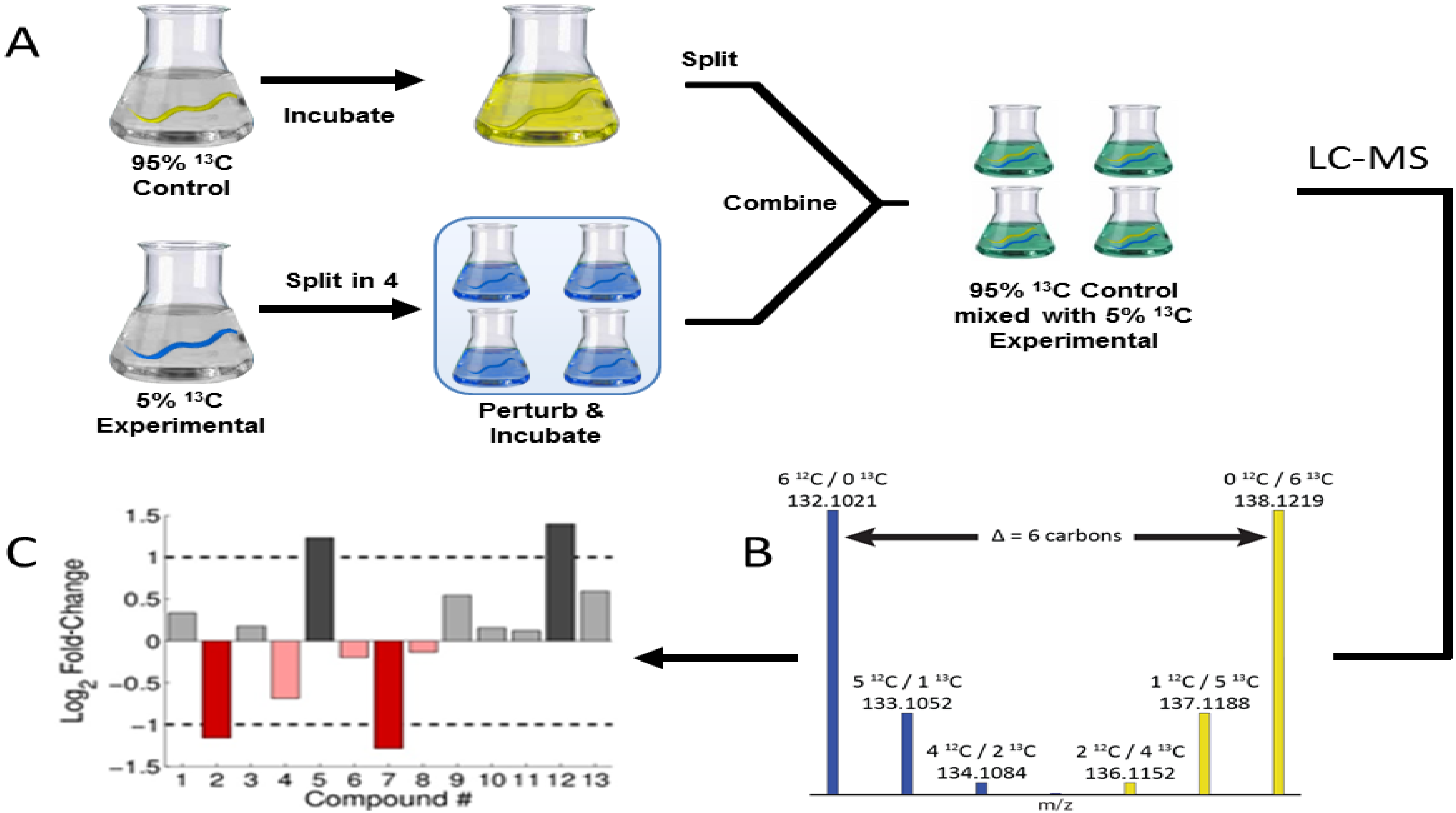






IROA Technologies

IROA with *C. elegans*



IROA Technologies

Effect of a toxin on *C. elegans*

- 742 strong IROA peak pairs were found
  - 314 named / 428 formula determined
  - Positive and negative mode LC
  - Thermo Orbi-trap @ 70K resolution

- Strong response signature determined
  - Basic statistics, PCA, Random Forest, NMF, SOM
  - 74 compounds were considered significant by at least 3 of these methods.

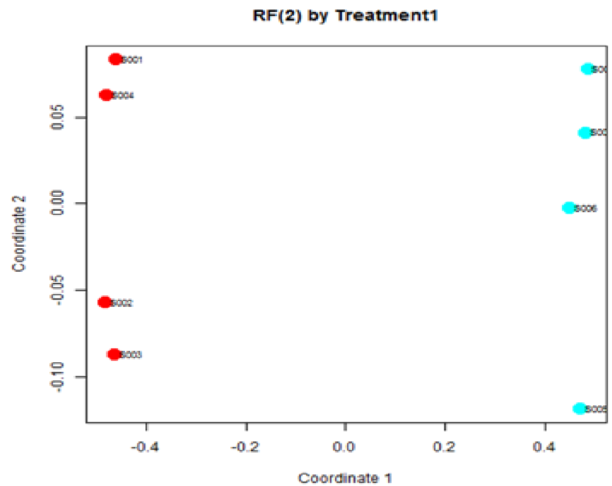
Ions significantly affected by the toxin

Name		p.value	F-Value treatment[2]
L-LYSINE	P000009	7.89E-05	89.71
Possibly $C_5H_7N_3O_9S$	P000018	3.06E-05	124.99
L-ARGININE	P000019	0.000131	74.84
Possibly $C_5H_9NO_{11}$	P000025	0.000182	66.63
UNK *m/z* 369.2215 RT 0.58	P000040	2.19E-05	140.24
SACCHAROPINE	P000046	7.23E-05	92.51
L-THREONINE	P000051	2.64E-05	131.52
L-GLUTAMIC ACID	P000053	1.09E-06	389.79
4-OXOPROLINE	P000054	1.74E-05	151.81
Possibly C_4H_5NO	P000058	1.8E-05	150.26
L-VALINE	P000060	0.000262	58.37
CITRULLINE	P000061	3.15E-05	123.67
4-METHYLENE-L-GLUTAMINE	P000062	0.000169	68.40
L-METHIONINE S-OXIDE	P000065	7.55E-06	202.32
L-PROLINAMIDE	P000085	0.000227	61.56
STACHYDRINE	P000102	4.75E-05	107.19
UNK *m/z* 206.0368 RT 0.71	P000114	0.000251	59.35
N-ACETYLPUTRESCINE	P000122	8.96E-07	417.06
EPSILON-CAPROLACTAM	P000123	1.29E-08	1731.72
2-AMINO-OCTANOIC ACID	P000131	0.000213	62.99
UNK m/z 345.1258 RT 0.97	P000141	0.000111	79.36
Possibly $C_{10}H_{19}N_2O_5P_2$	P000151	0.000154	70.78
CYS-GLY	P000152	0.000116	78.29
URATE	P000156	0.000222	62.02
Possibly $C_{13}H_{16}N_5OPS$	P000218	1.1E-05	177.82

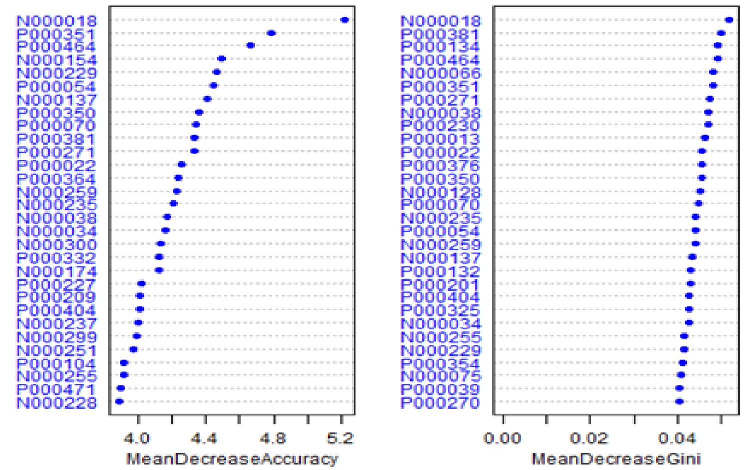
IROA Technologies

Multivariate statistics

A



B



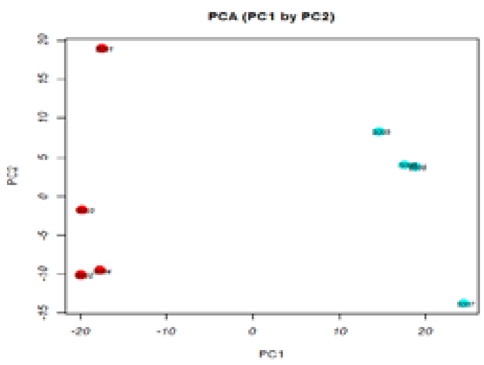
C

Name		X1.HP	heatShock	MeanDecreaseAccuracy	MeanDecreaseGini
Possibly C8H18N6PS2	N000018	5.165779	5.091283	5.219694	0.051833
UNK MZ 197.0968 RT 0.55	P000351	4.61306	4.651274	4.787018	0.047917
Possibly C11H14N3O6	P000464	4.527905	4.623332	4.660738	0.04925
Possibly C11H23N5PS	N000154	4.310867	4.345237	4.49079	0.038917
UNK MZ 373.1256 RT 0.60	N000229	4.384942	4.313313	4.461684	0.0415
4-OXOPROLINE	P000054	4.307818	4.380554	4.447013	0.044083
D-ALANYL-D-ALANINE	N000137	4.357447	4.298196	4.403362	0.043417
UNK MZ 160.0958 RT 0.55	P000350	4.194825	4.331486	4.35738	0.045333
S-ADENOSYLMETHIONINE	P000070	4.247356	4.247356	4.345614	0.04475
UNK MZ 224.1142 RT 0.78	P000381	4.245944	4.309512	4.333807	0.049917
Possibly C6H13N2S2	P000271	4.286066	4.238801	4.330957	0.047167
Possibly C5H10N4O5P	P000022	4.237845	4.104634	4.253873	0.045583
Possibly C14H29N11O3S	P000364	4.207787	4.123607	4.236865	0.036583
Possibly C18H18N11S3	N000259	4.115656	4.119522	4.230318	0.044
N-FORMIMINO-L-GLUTAMATE	N000235	4.115656	4.091016	4.208769	0.044167

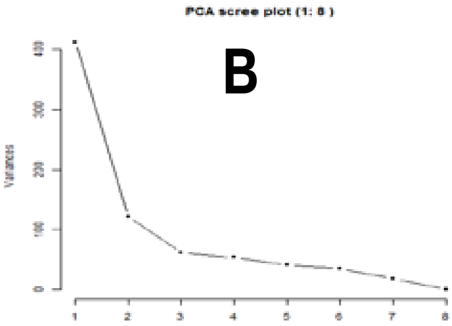
IROA Technologies

PCA analysis of toxin's effect

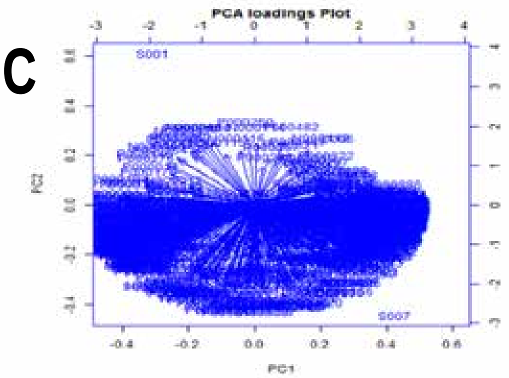
A



B



C



D

	PC1	PC2	PC3	PC4	PC5
P000123	-0.04867	-0.00122	-0.0028	0.002634	-0.00263
P000305	-0.04864	-0.01333	0.003947	-0.00022	0.000461
P000328	-0.04854	-0.01474	-0.00285	0.001186	0.002235
P000065	-0.04839	-0.01076	-0.00949	0.016892	0.002798
N000034	-0.04838	-0.00625	0.004756	-0.00207	-0.00469
P000268	-0.04834	-0.01365	0.013402	-0.00273	-0.00146
P000122	-0.04832	-0.00499	0.000535	0.0041	0.008176
P000485	-0.04814	-0.01292	0.013305	-0.00659	0.01036
N000006	-0.04792	-0.00964	-0.02169	0.005208	0.003092
N000068	-0.04775	-0.00849	0.026794	-0.00377	-0.00419
P000304	-0.04768	-0.02207	0.008128	-0.00055	0.004545
N000057	-0.04759	-0.00101	0.027516	-0.00376	-0.00763
N000174	-0.04753	0.005826	0.00295	0.003997	-0.0041
P000152	-0.04751	-0.01938	0.01513	-0.00054	0.003671
P000141	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

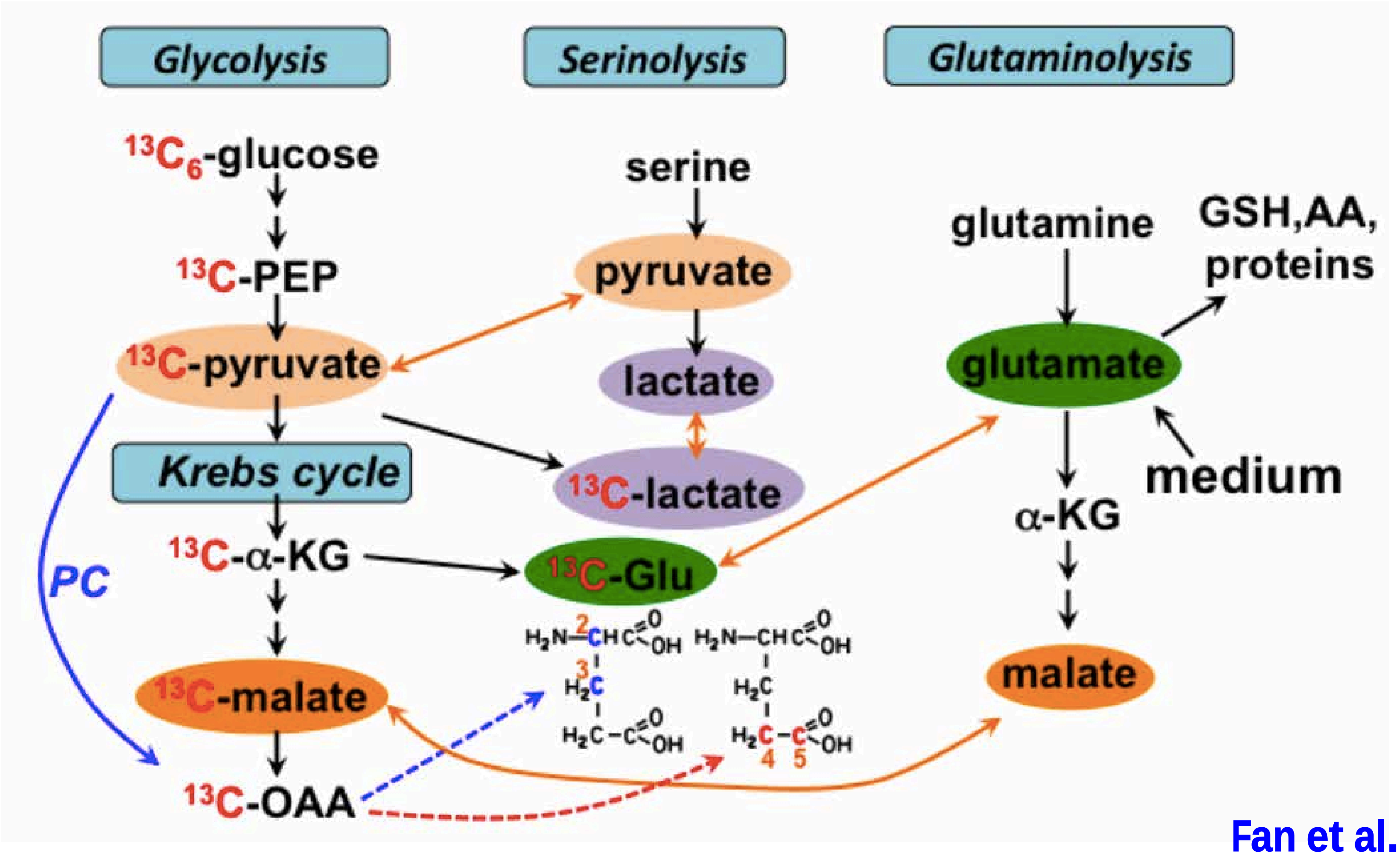
IROA Technologies

Summary of most likely metabolites

Name		Stats1	RFTop1	RFTop2	NMF3	NMF4	NMF5	NMF6	Count
UNK *m/z* 160.0958 RT 0.55	P000350	1	1	1	1	1	1	1	7
UNK *m/z* 197.0968 RT 0.55	P000351	1	1	1	1	1	1	1	7
UNK *m/z* 216.0852 RT 0.61	N000034	1	1	1	1	1	1	1	7
D-ALANYL-D-ALANINE	N000137	1	1	1	1	1	1	1	7
Possibly $C_{25}H_{34}N_4O_5$	N000174	1	1	1	1	1	1	1	7
UNK *m/z* 373.1256 RT 0.60	N000229	1	1	1	1	1	1	1	7
2-AMINO-OCTANOIC ACID	P000131	1	1	0	1	1	1	1	6
Possibly $C_6H_8N_4O_3$	P000354	1	1	0	1	1	1	1	6
UNK *m/z* 510.2122 RT 0.68	P000373	1	1	0	1	1	1	1	6
UNK *m/z* 224.1142 RT 0.78	P000381	0	1	1	1	1	1	1	6
Possibly $C_6H_9NO_6P$	P000410	1	1	0	1	1	1	1	6
Possibly $C_{11}H_{14}N_3O_6$	P000464	0	1	1	1	1	1	1	6
Possibly $C_6H_4N_2O_6P$	P000471	1	1	0	1	1	1	1	6
Possibly $C_5H_{12}N_2O_7PS$	N000006	1	1	0	1	1	1	1	6
Possibly $C_{11}H_{23}N_5PS$	N000154	1	1	1	0	1	1	1	6
D-GLUCOSE	N000228	1	1	0	1	1	1	1	6
UNK *m/z* 548.2037 RT 0.63	N000232	1	1	0	1	1	1	1	6
GLYCERATE	N000237	1	1	0	1	1	1	1	6

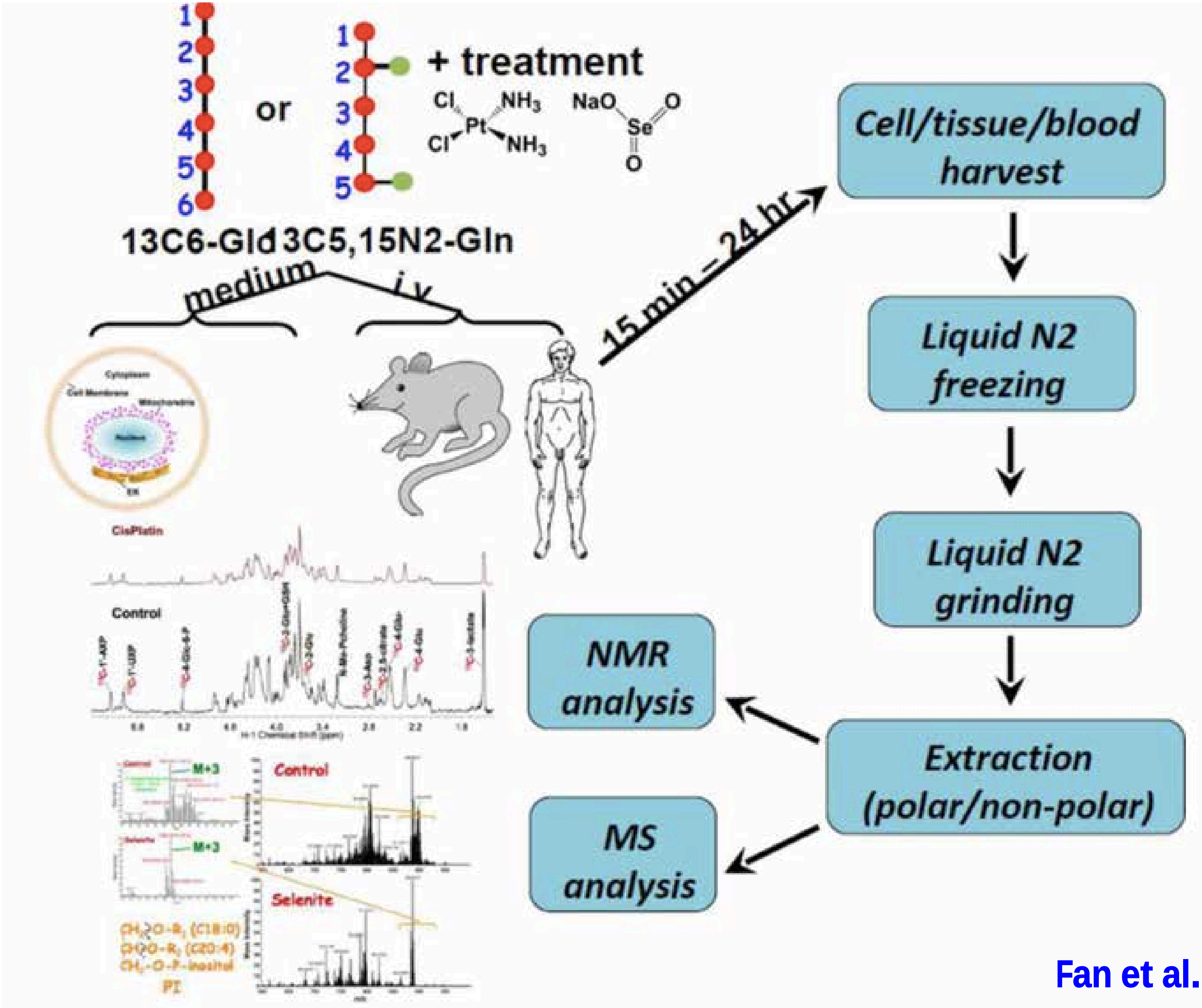
Fluxomics

- A feature of many metabolites is that they have multiple origins

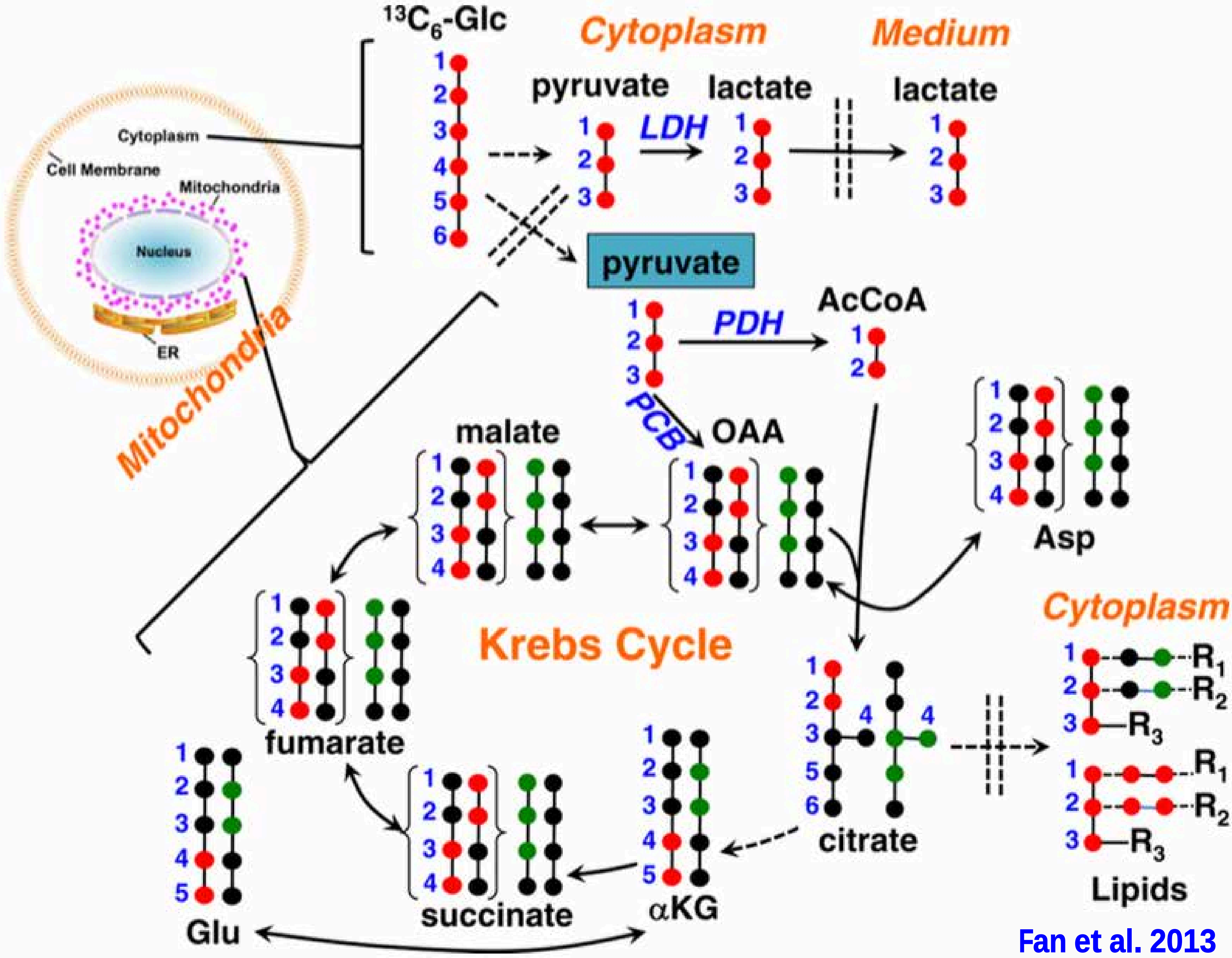


Fan et al. 2013

Stable isotope resolved metabolomics

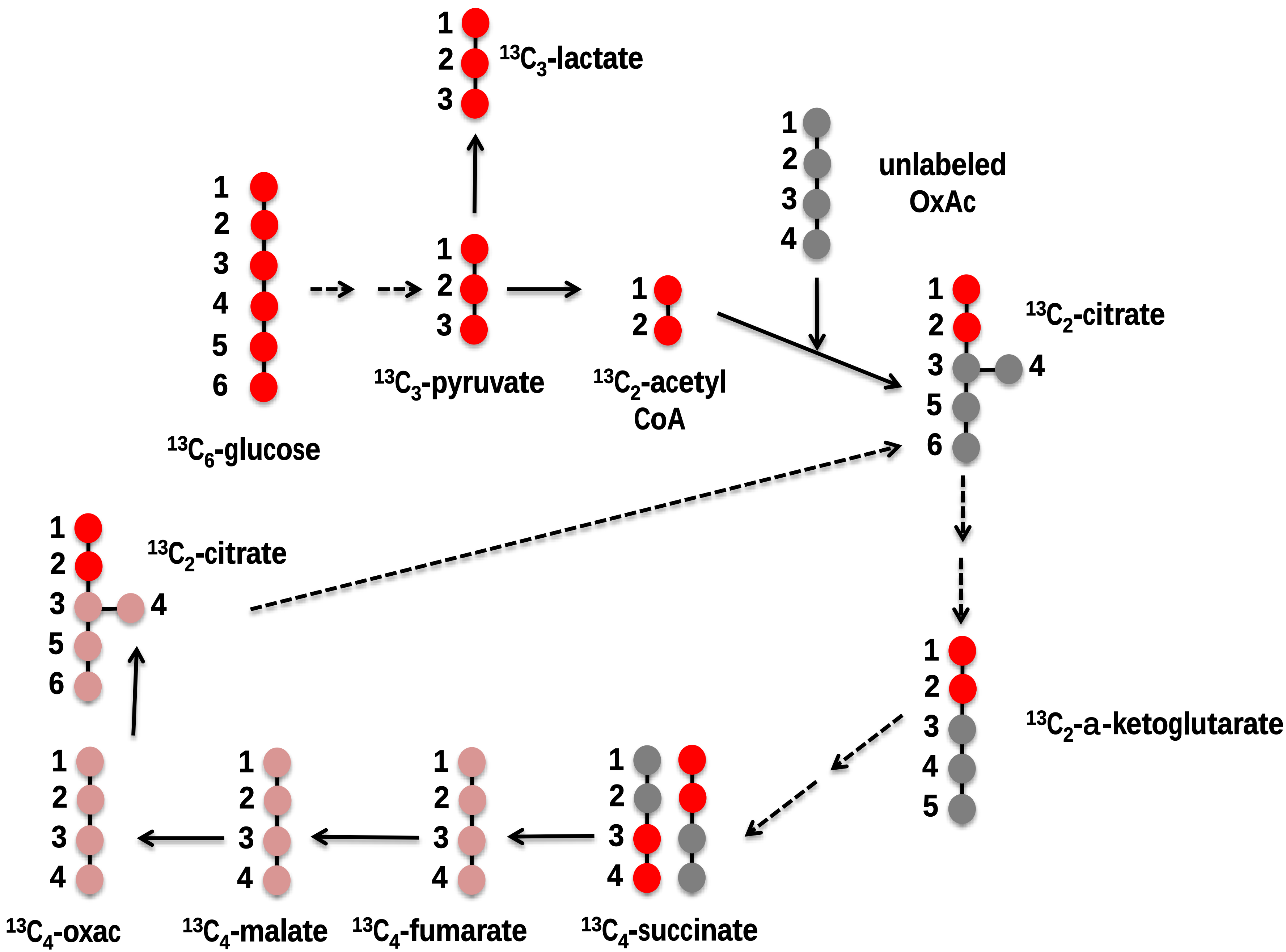


Fan et al. 2013

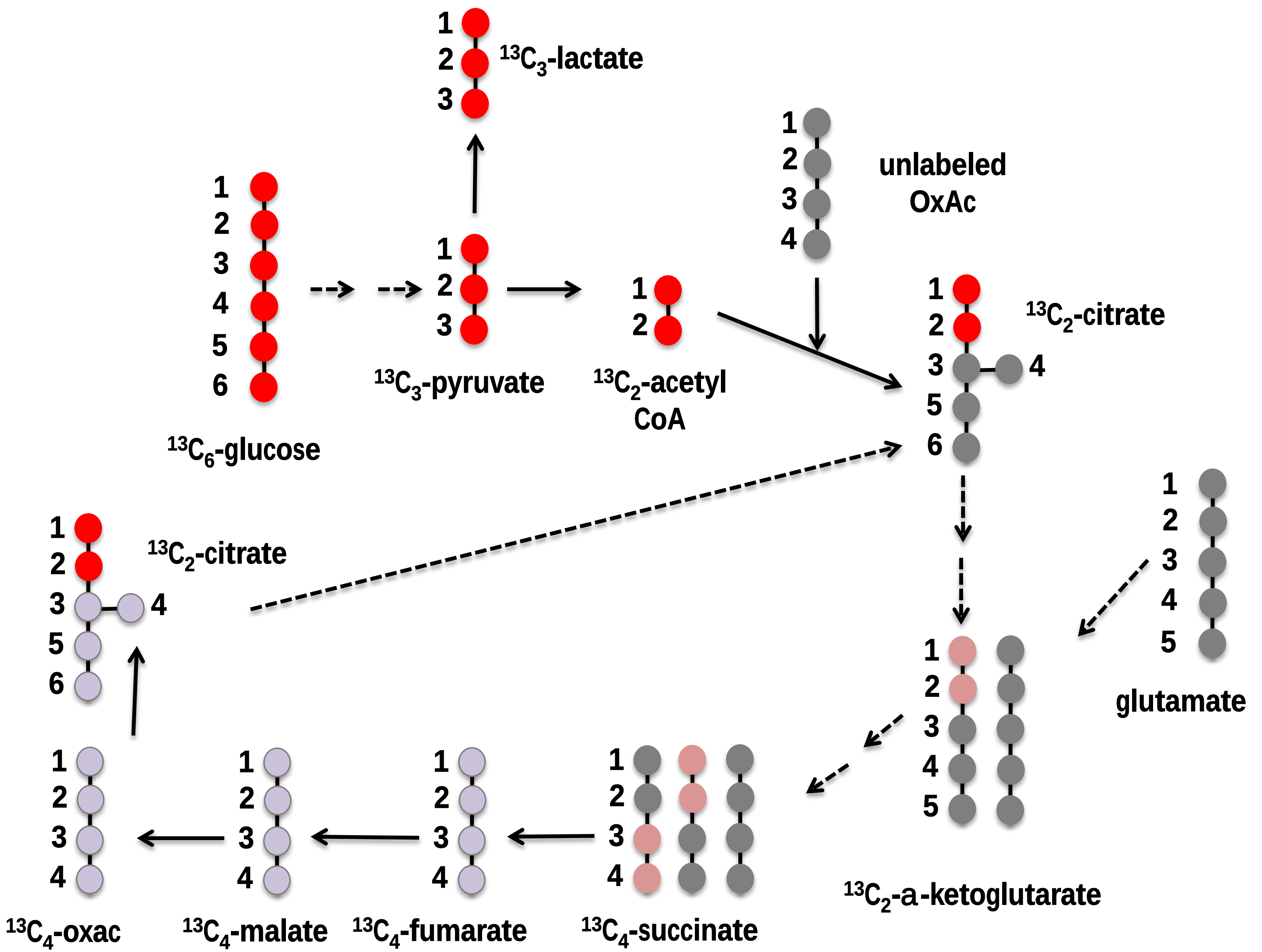


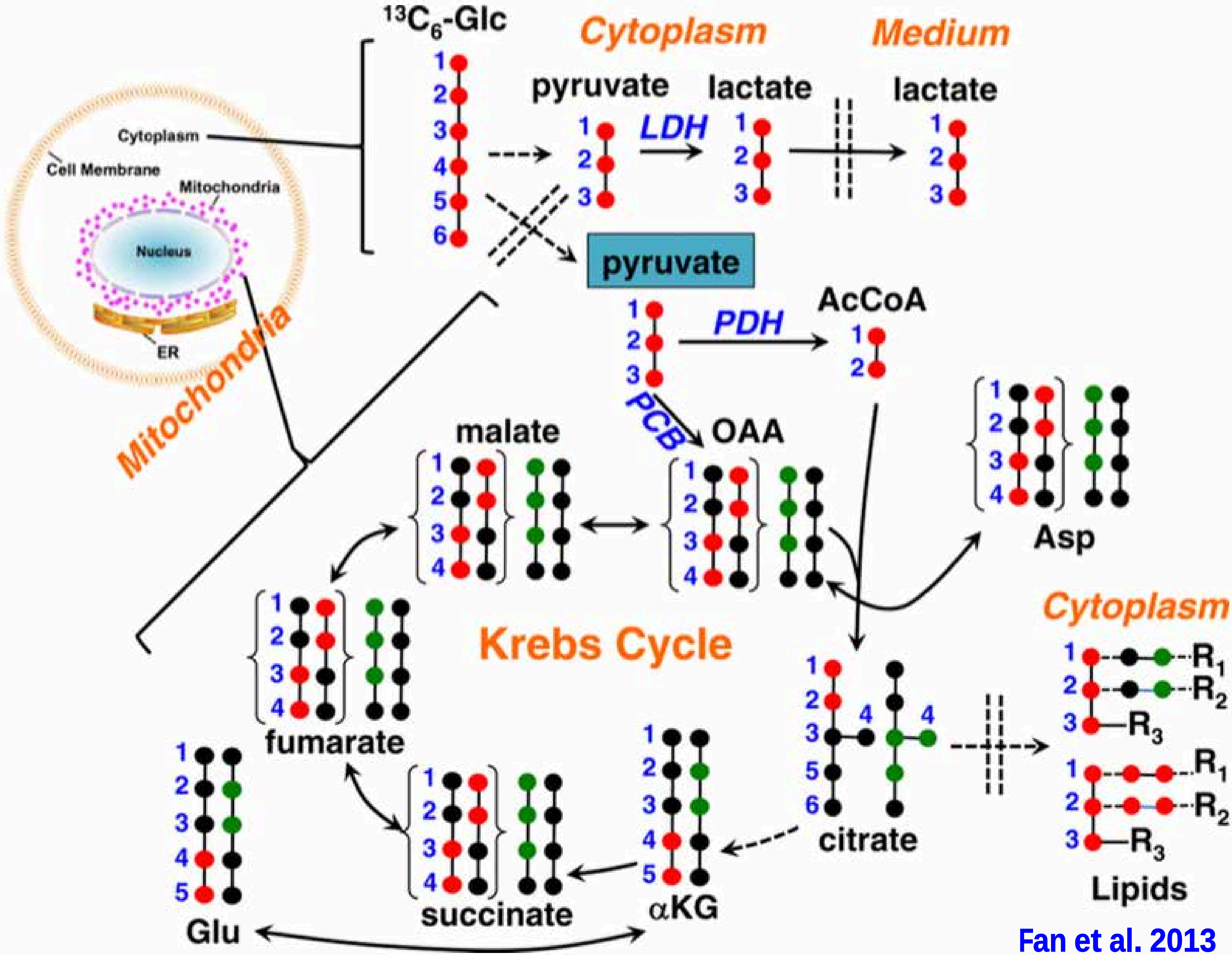
Fan et al. 2013

Ideal metabolism of glucose



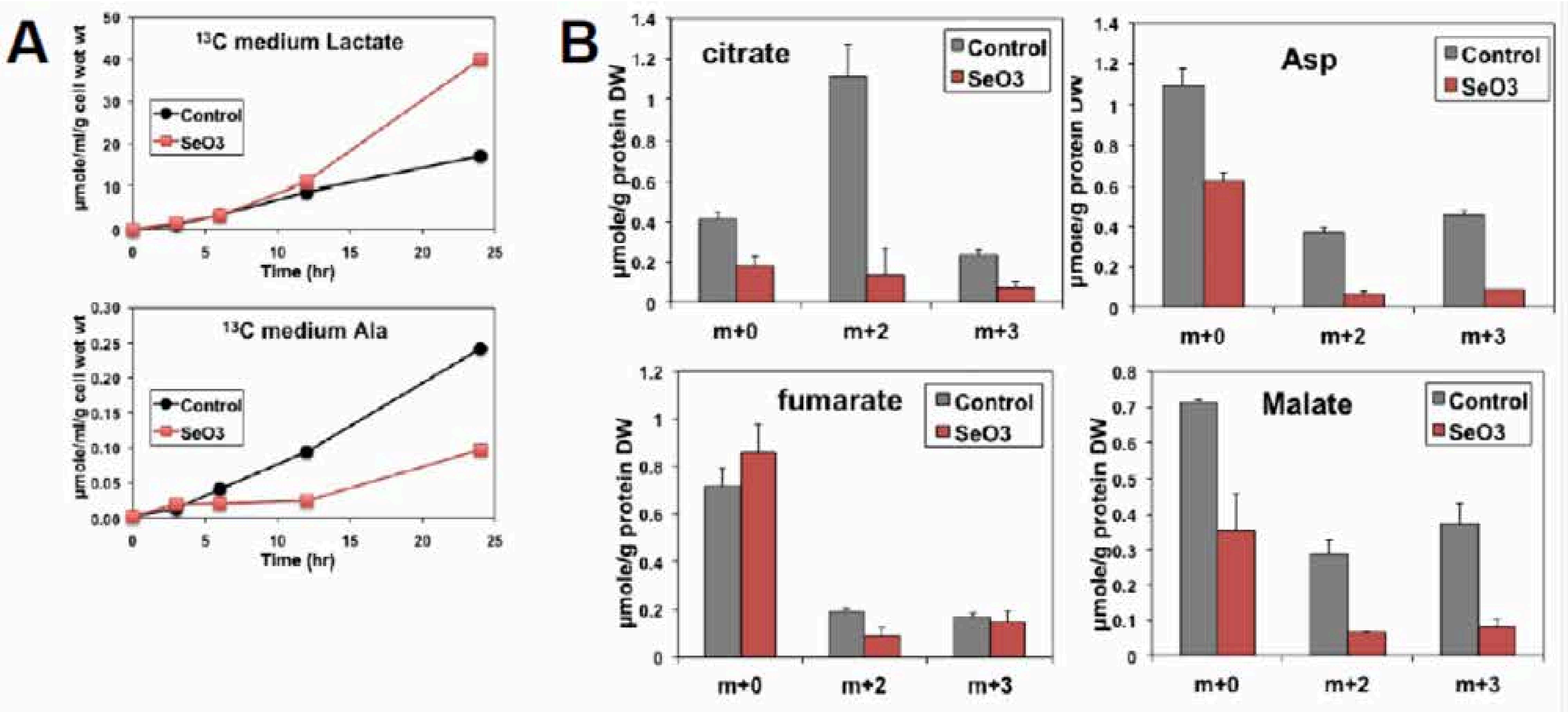
Effect of glutamate turnover





Fan et al. 2013

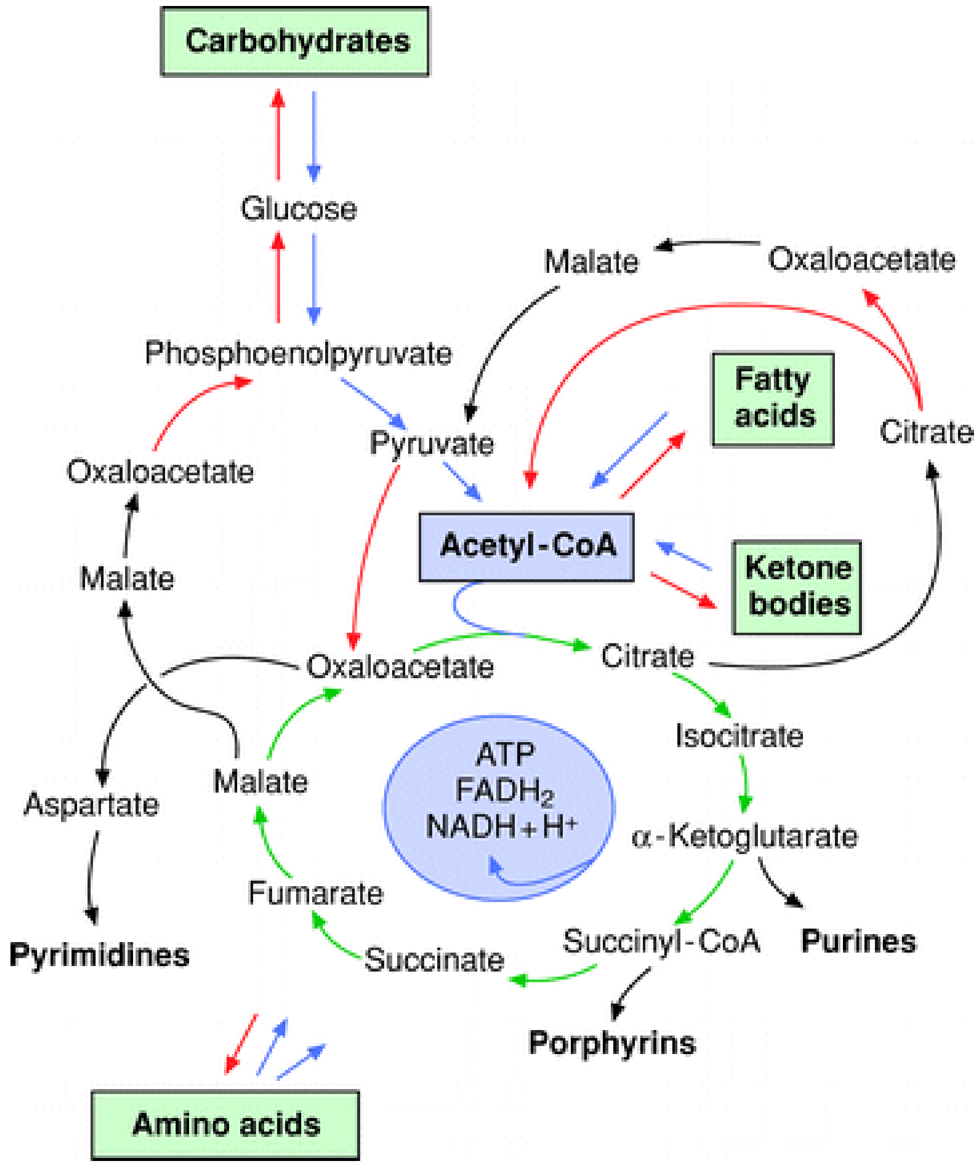
Effect of selenite on pools of intermediates



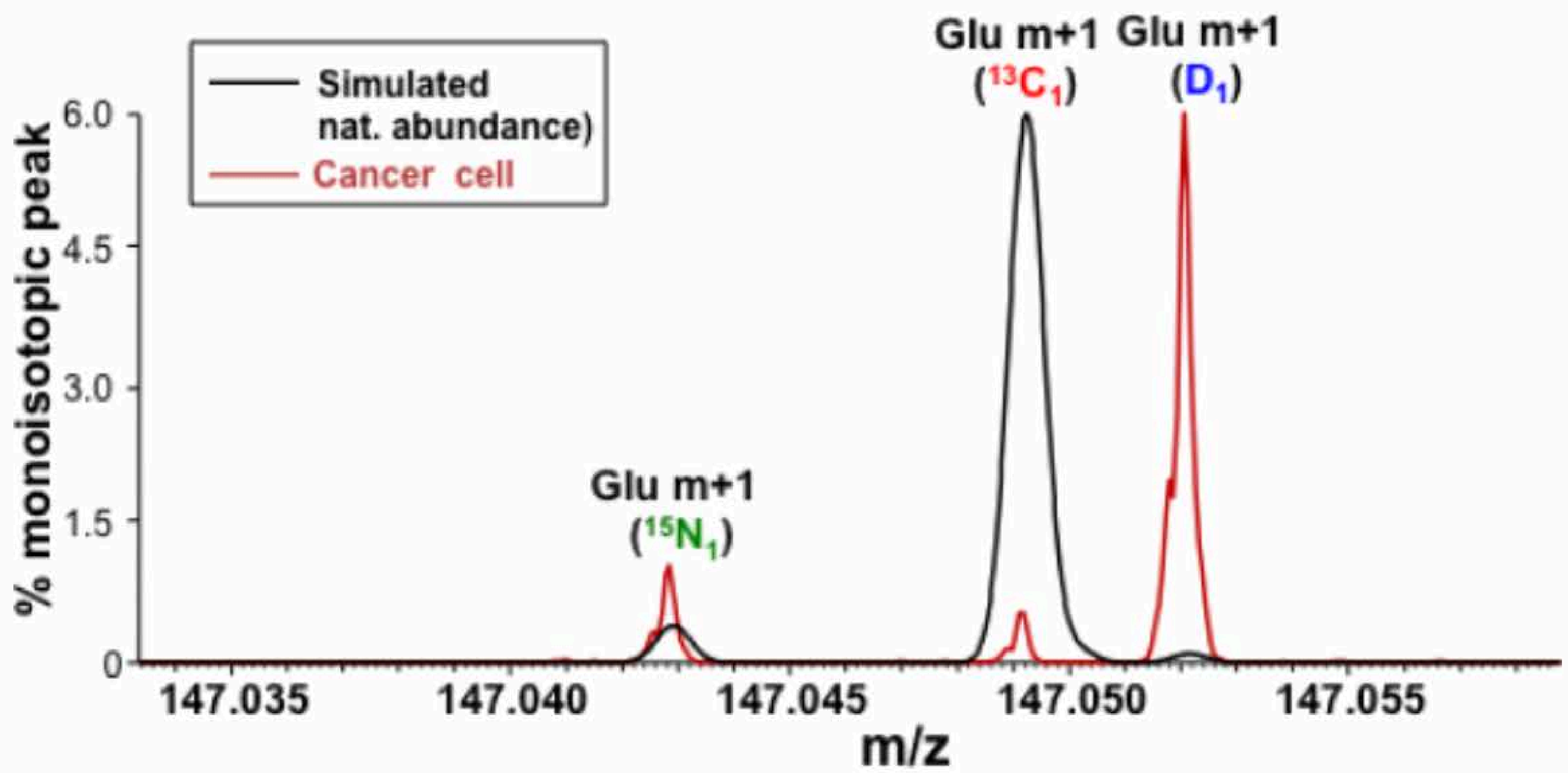
Pyruvate carboxylase converts pyruvate to oxaloacetate and by-passes the early steps in the Krebs cycle. Treatment of the cells with selenite blocks this step and the ^{13}C-content of citrate sharply decreases

Fan et al. 2013

Anaplerotic reactions

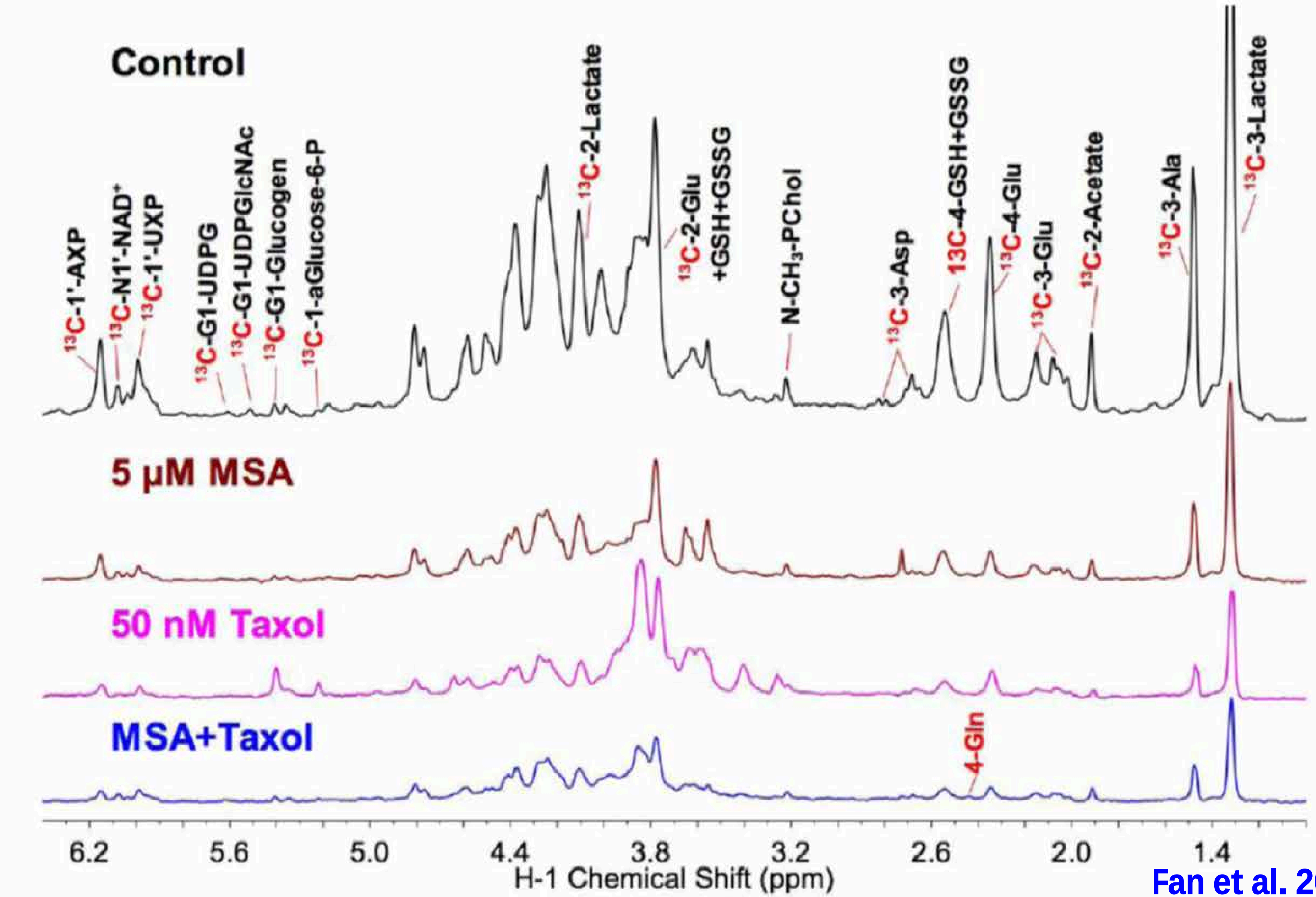


High resolution FT-ICR-MS



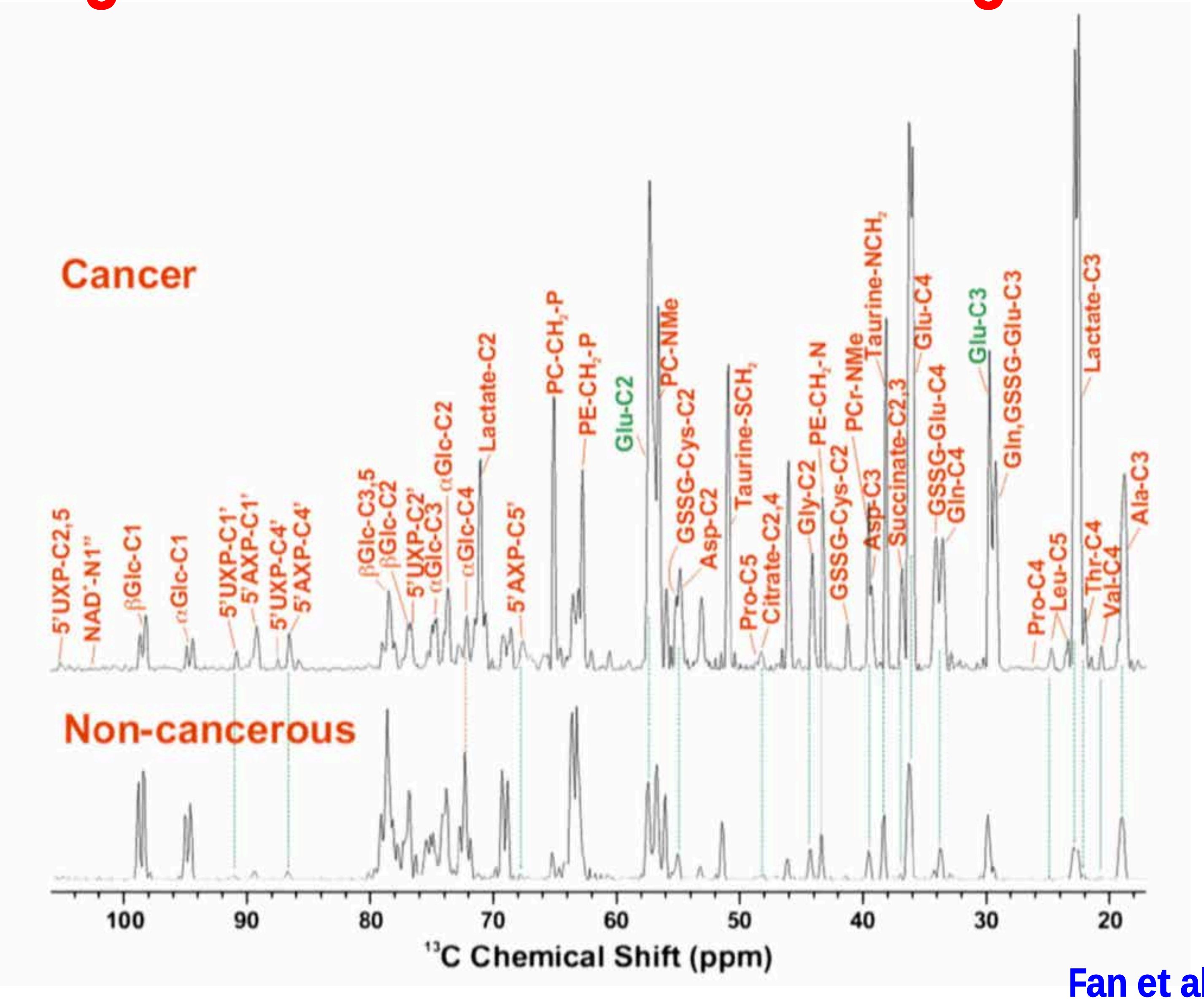
Fan et al. 2013

Use of ^{1}H-^{13}C-NMR



Fan et al. 2013

Changes in intermediates in lung cancer

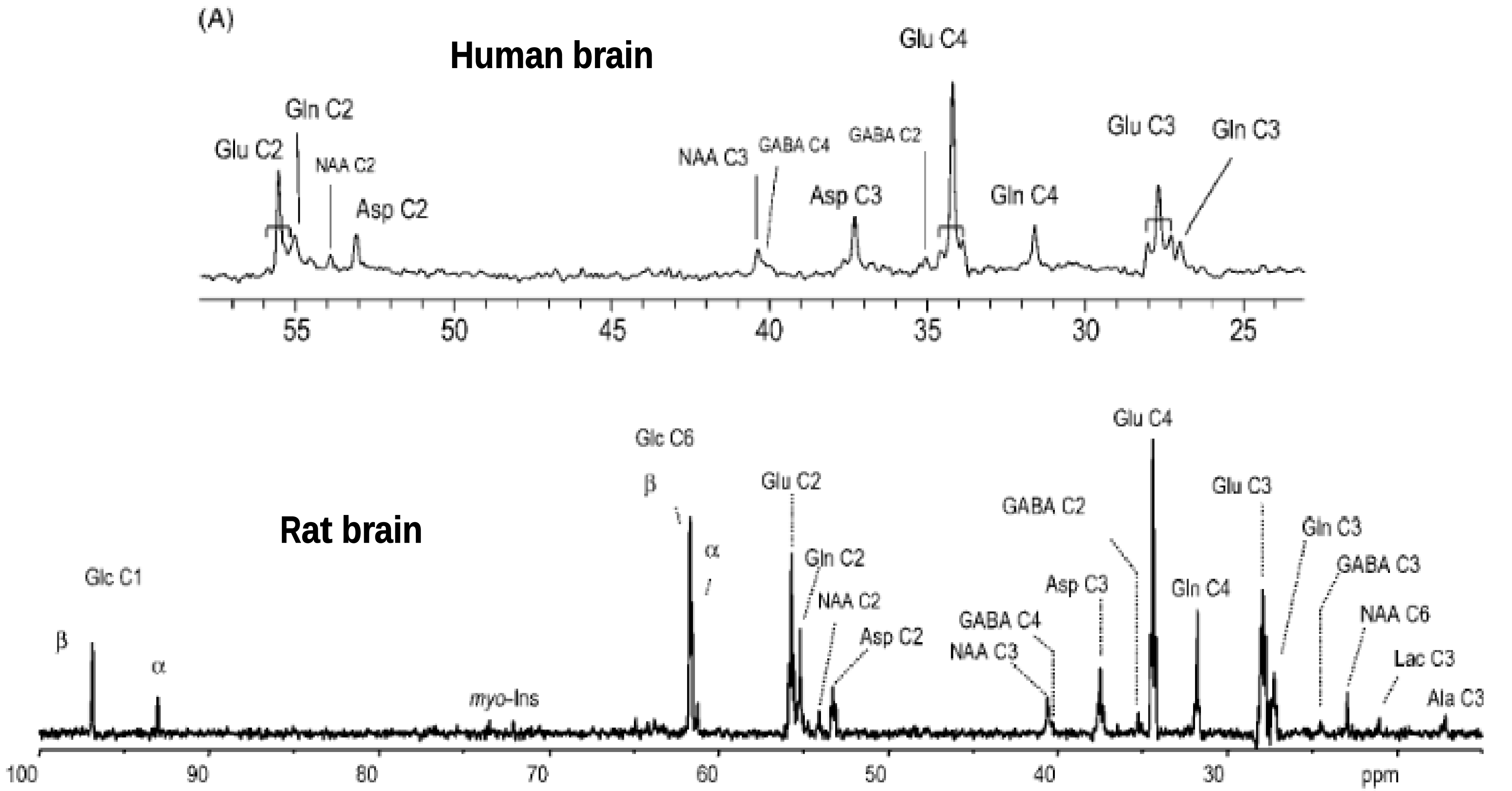


Fan et al. 2013

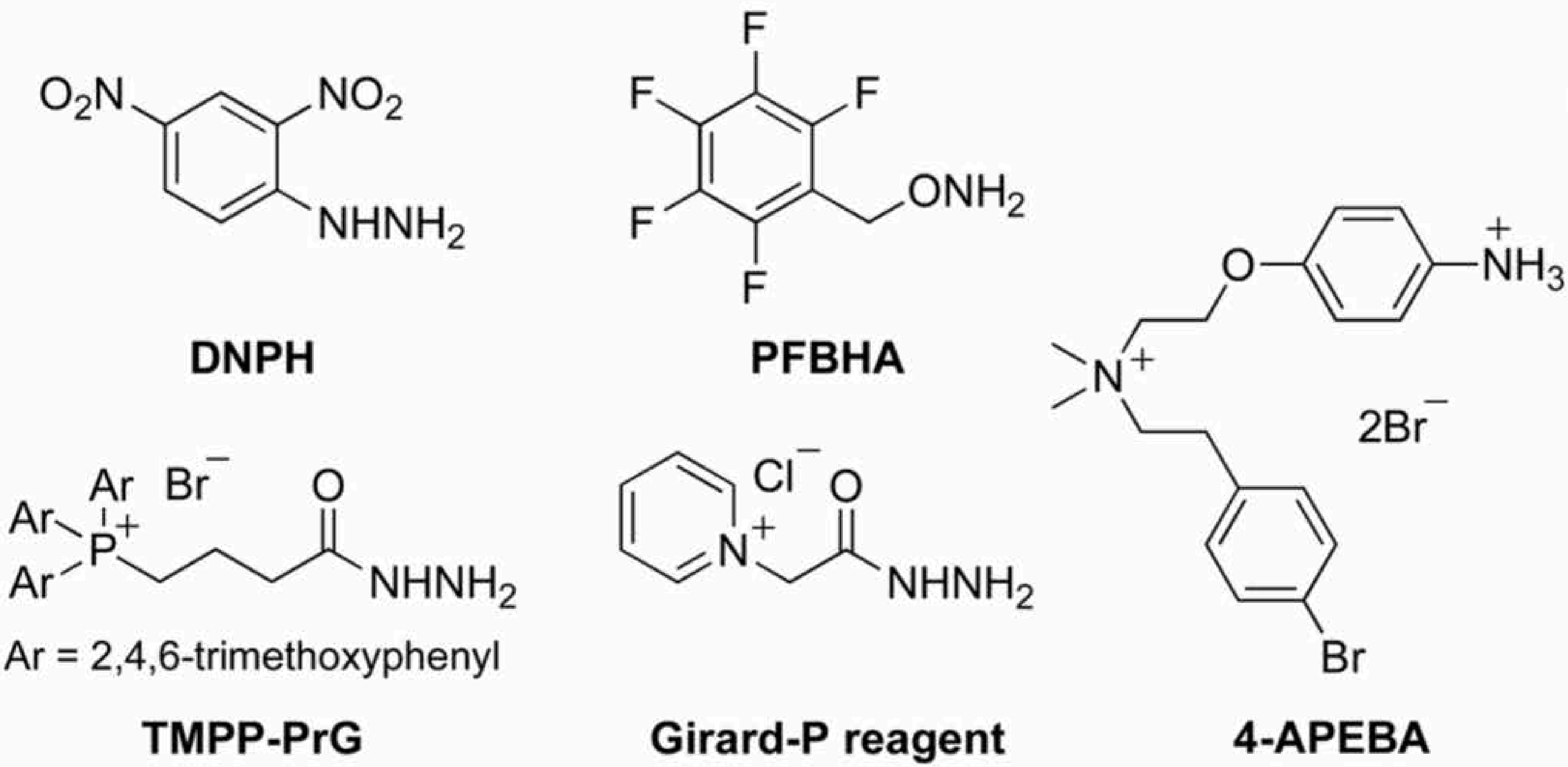
Biological NMR

- If ^{13}C-labeled precursors are used, there is a very much enhanced set of ^{13}C NMR resonances
- You have a choice between analysis of a biological extract (have all the time you need)
- And direct analysis in tissue:
  - Surface coil technology in the living animal
  - Magic Angle Spinning (see talk by Dr. Krishna) on a piece of tissue

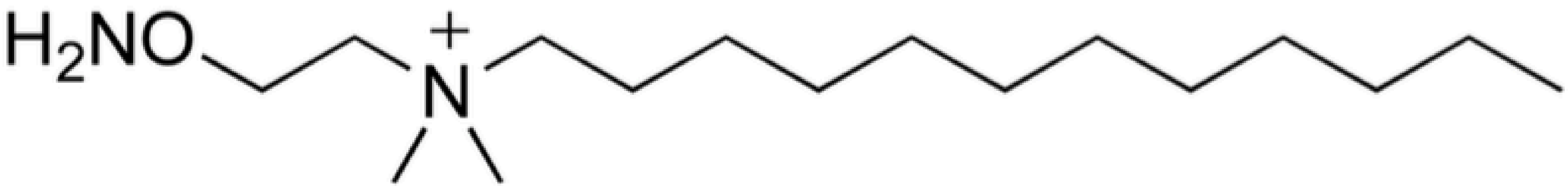
NMR analysis of metabolites from ^{13}C-labeled precursors using pulse sequences



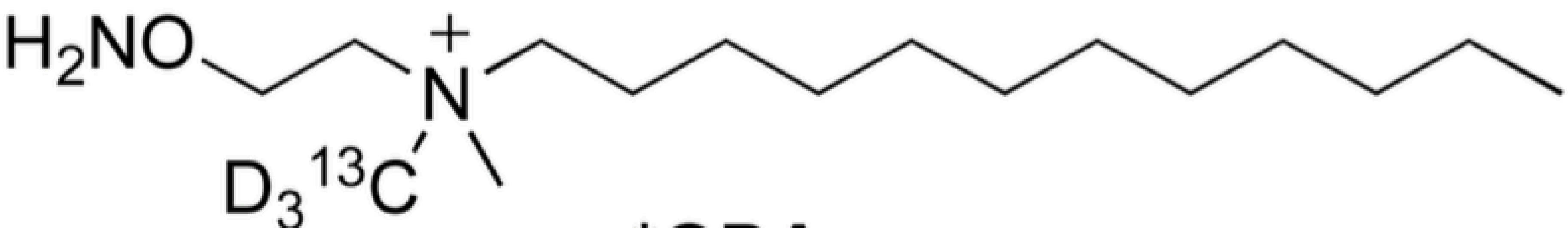
Carbonyl derivatization reagents



Isotopic carbonyl reagents

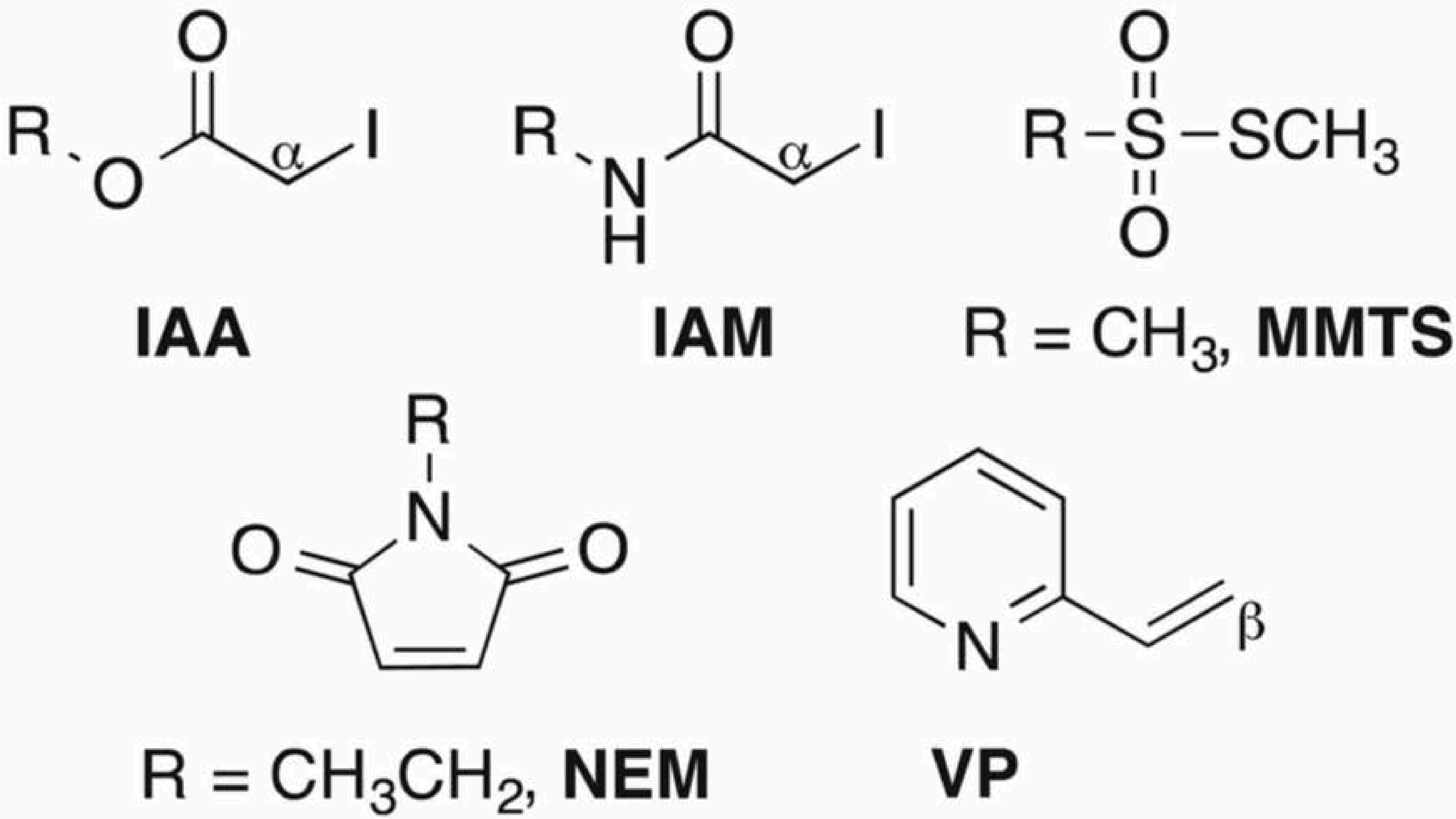


QDA

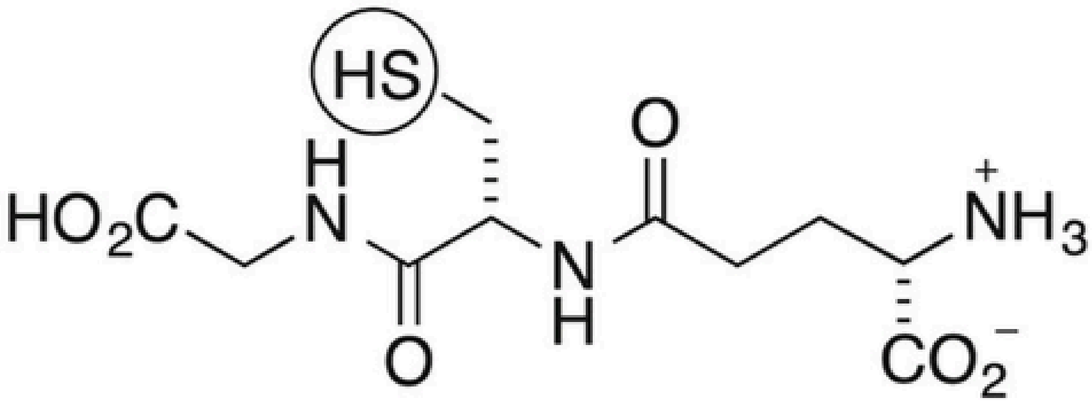


***QDA**

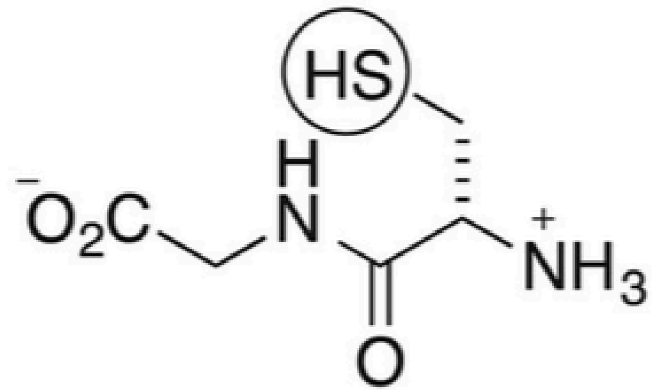
Thiol derivatization reagents



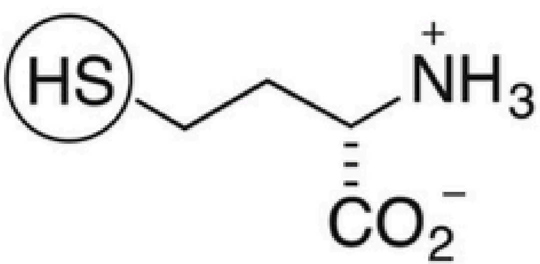
Detectable thio-metabolites



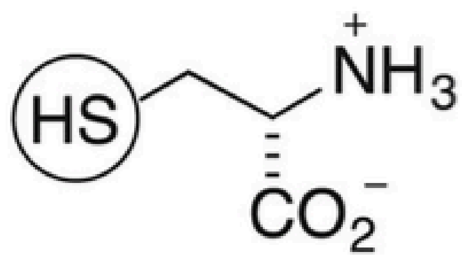
L-glutathione



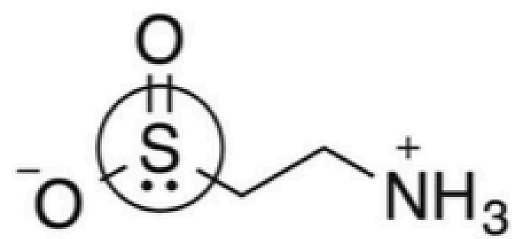
L-cysteinylglycine



L-homocysteine

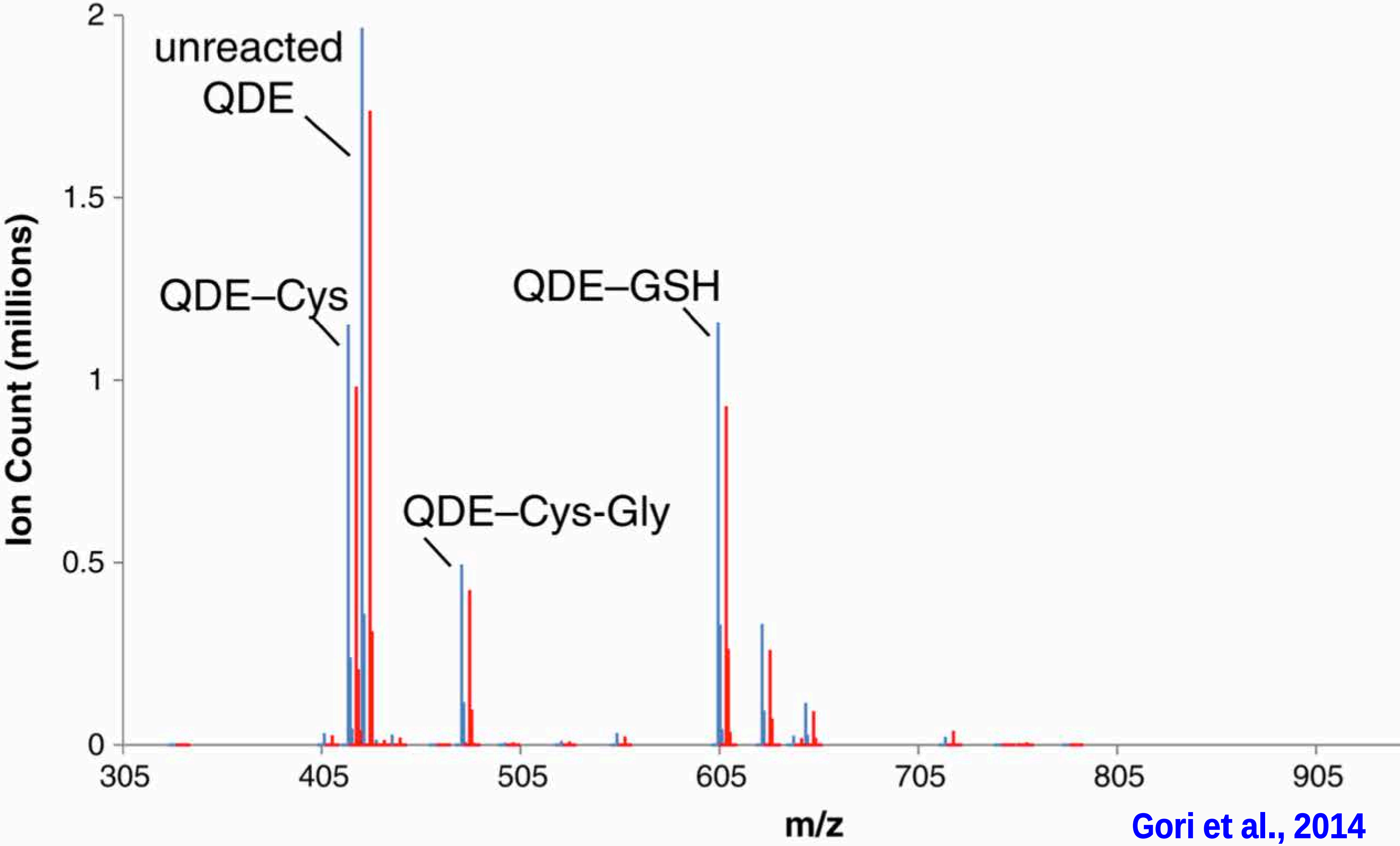


L-cysteine



hypotaurine

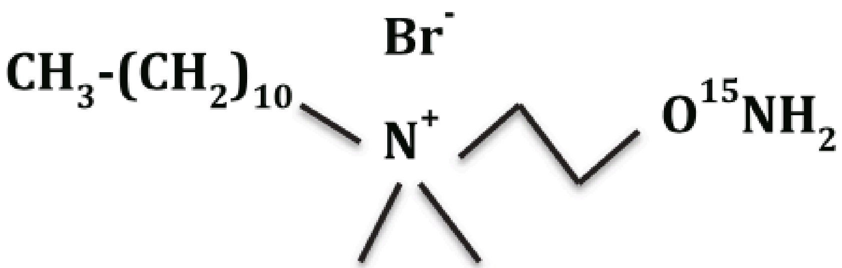
Thiol metabolites in A459 cell extract



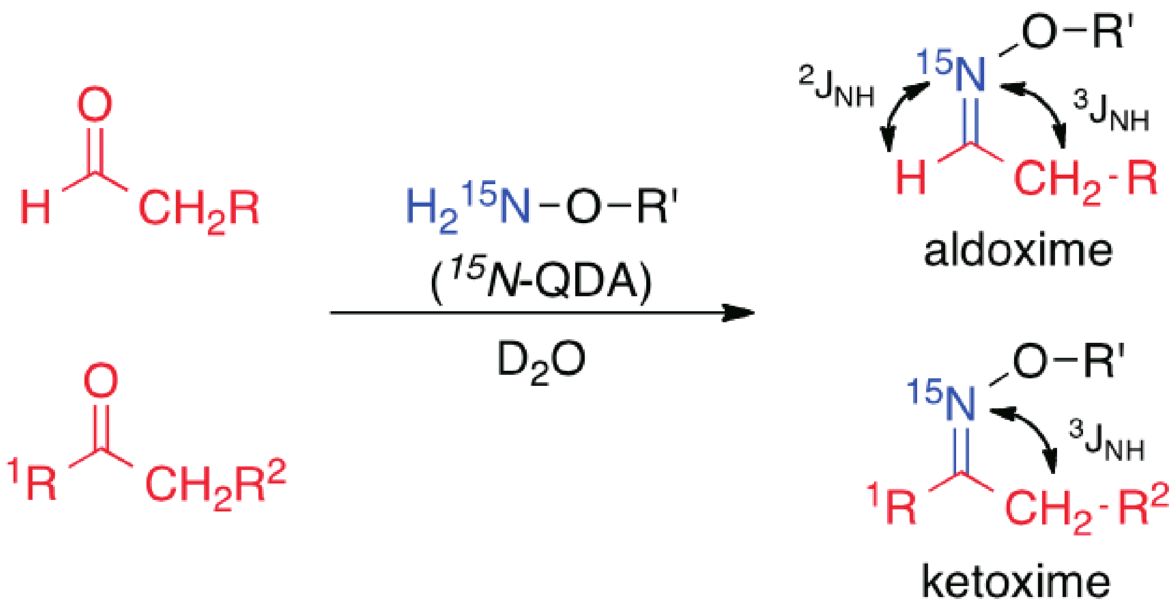
Gori et al., 2014

^{15}N-labeled derivatization reagent

A

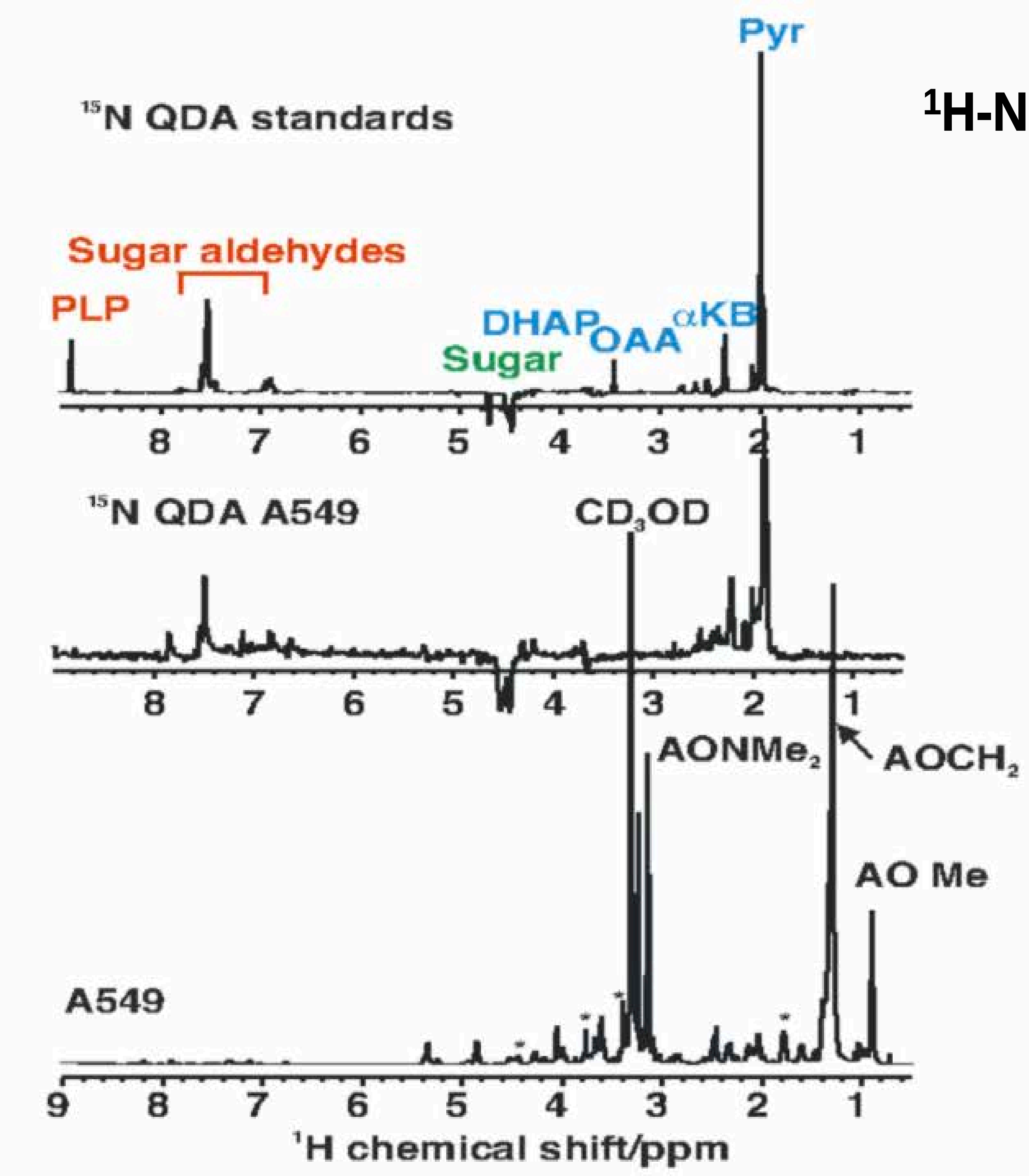


B



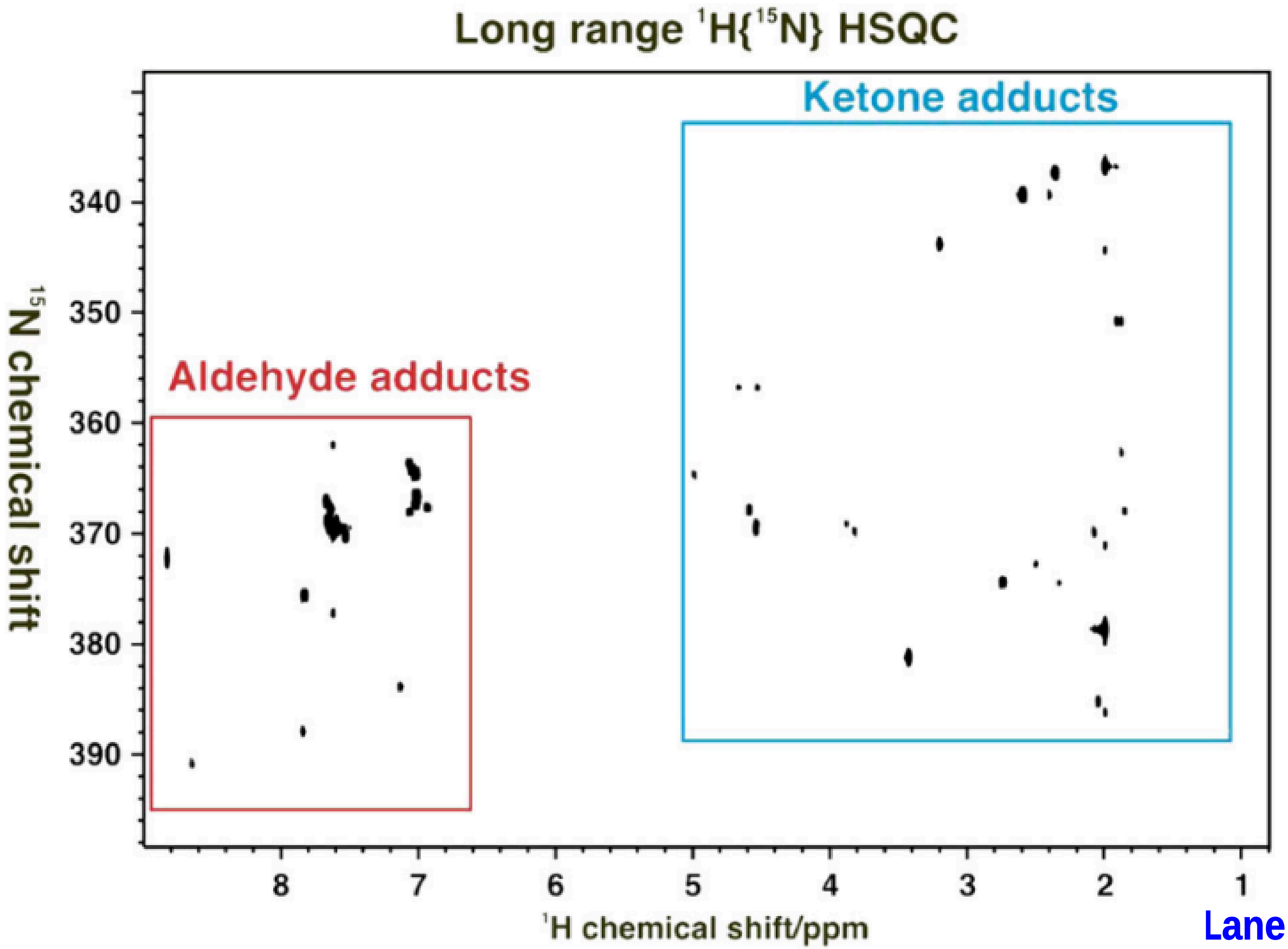
Lane et al., 2014

^{1}H-NMR of derivatized metabolites



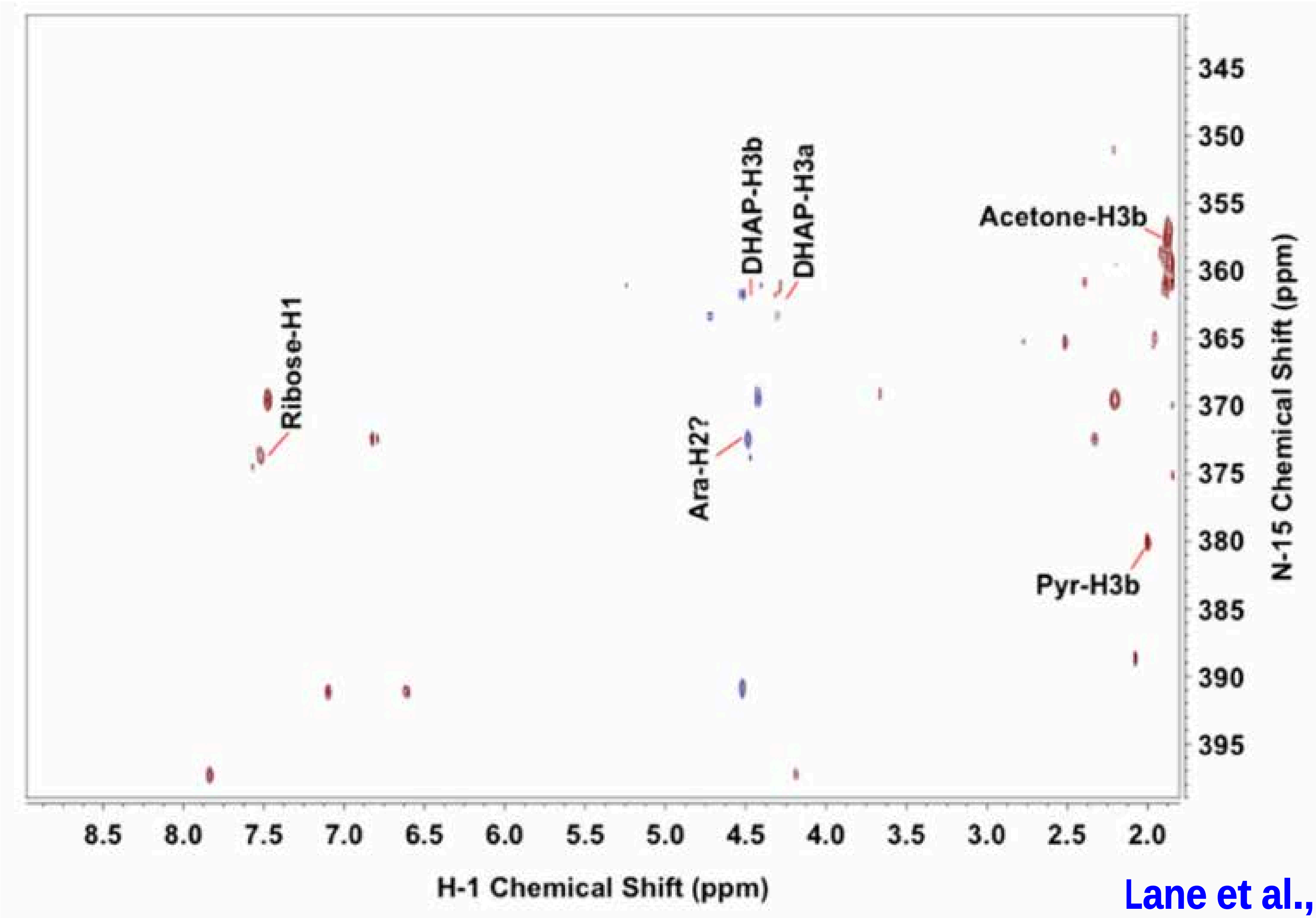
Lane et al., 2014

2D-^{1}H, ^{15}N-NMR of standards



Lane et al., 2014

2D-^{1}H, ^{15}N-NMR of A459 cell extract



Lane et al., 2014

References

- **Stupp GS, Clendinen CS, Ajredini R, Szewc MA, Garrett T, Menger RF, Yost RA, Beecher C, Edison AS. Isotopic ratio outlier analysis global metabolomics of *Caenorhabditis elegans*. Anal Chem. 2013 Dec 17;85(24):11858-65.**
- **Lane AN, Arumugam S, Lorkiewicz PK, Higashi RM, Laulhé S, Nantz MH, Moseley HN, Fan TW. Chemoselective detection and discrimination of carbonyl-containing compounds in metabolite mixtures by ^{1}H-detected ^{15}N nuclear magnetic resonance. Magn Reson Chem. 2015 Jan 23. doi: 10.1002/mrc.4199.**
- **Fan TW, Lorkiewicz PK, Sellers K, Moseley HN, Higashi RM, Lane AN. Stable isotope-resolved metabolomics and applications for drug development. Pharmacol Ther. 2012 Mar;133(3):366-91.**