Spontaneous Autocatalysis in a Prebiotic Broth

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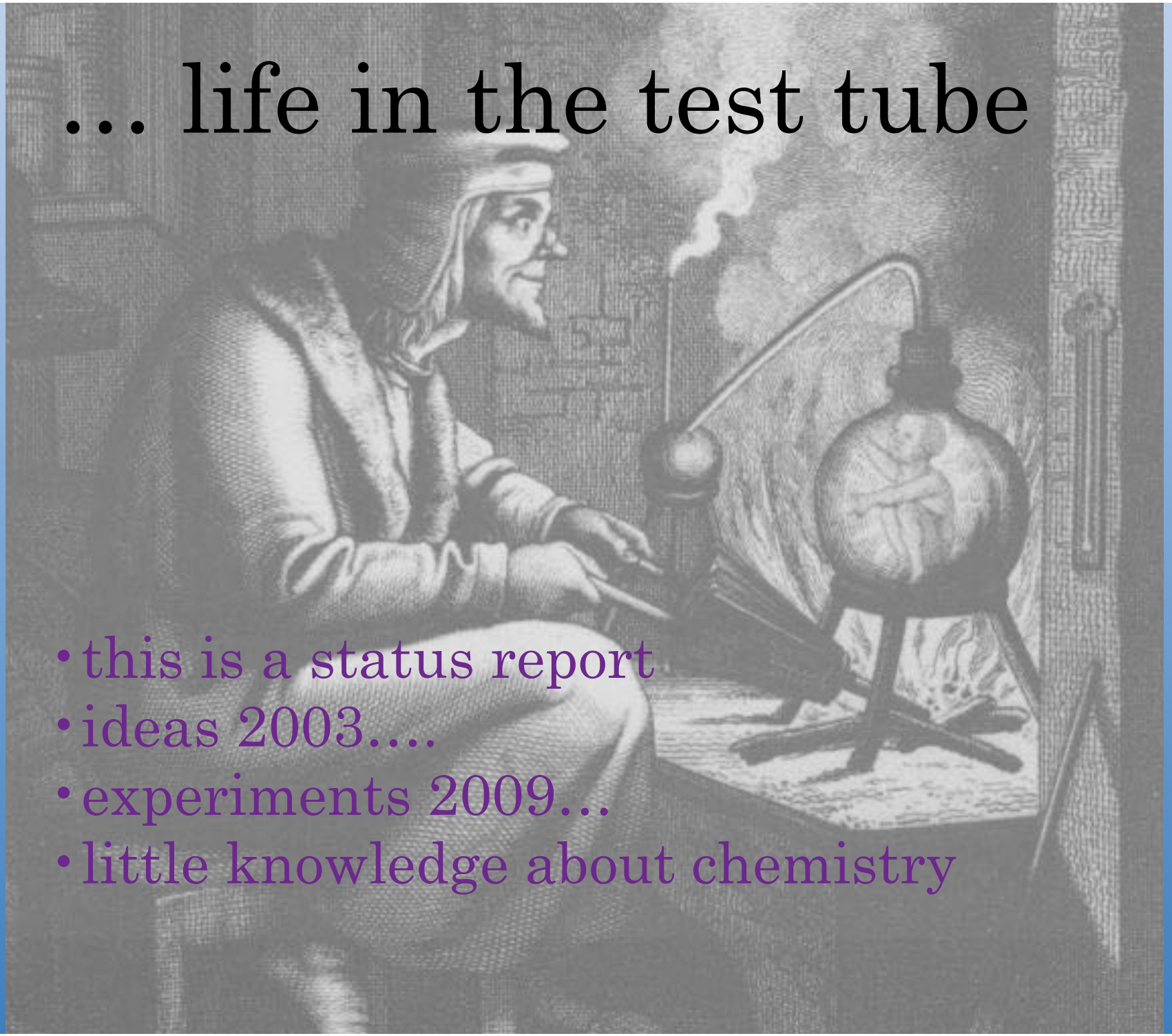
DES
SAARLANDES

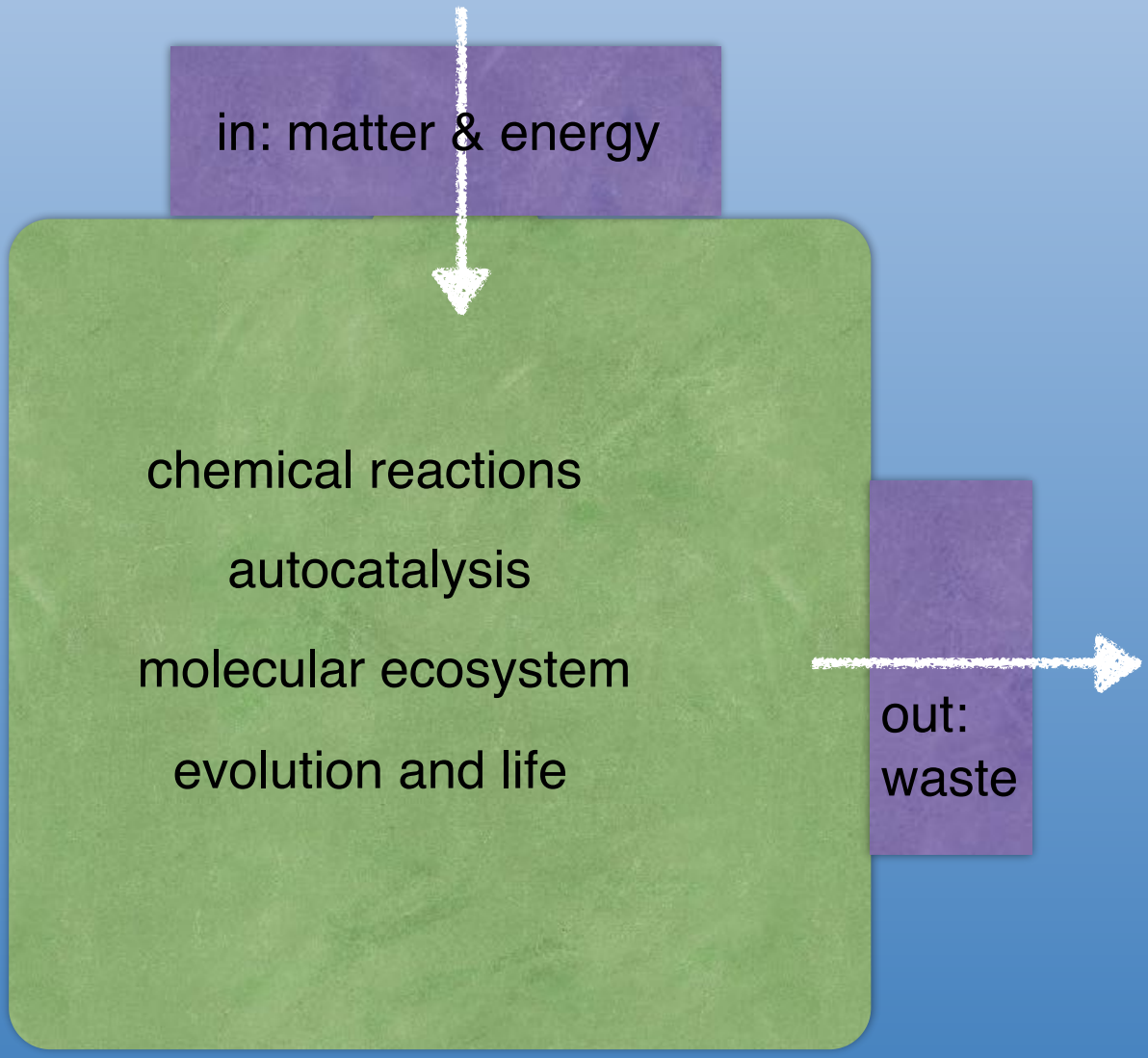
Biologische ExperimentalPhysik

… life in the test tube



- this is a status report
- ideas 2003….
- experiments 2009…
- little knowledge about chemistry

Artificial Life Reactor



Life is based on a complex form of autocatalysis

Living Beings + Food : more Living Beings

$$A + B \longrightarrow 2A + X$$

Life has evolved from primitive to complex

Ideas on how Life began

- Metabolism first hypothesis

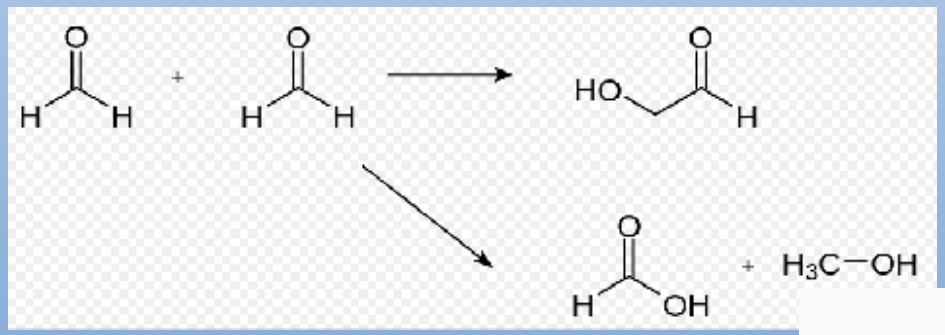
Chemical pathways emerged in gradients, somehow autocatalysis emerged later

- Autocatalysis first hypothesis

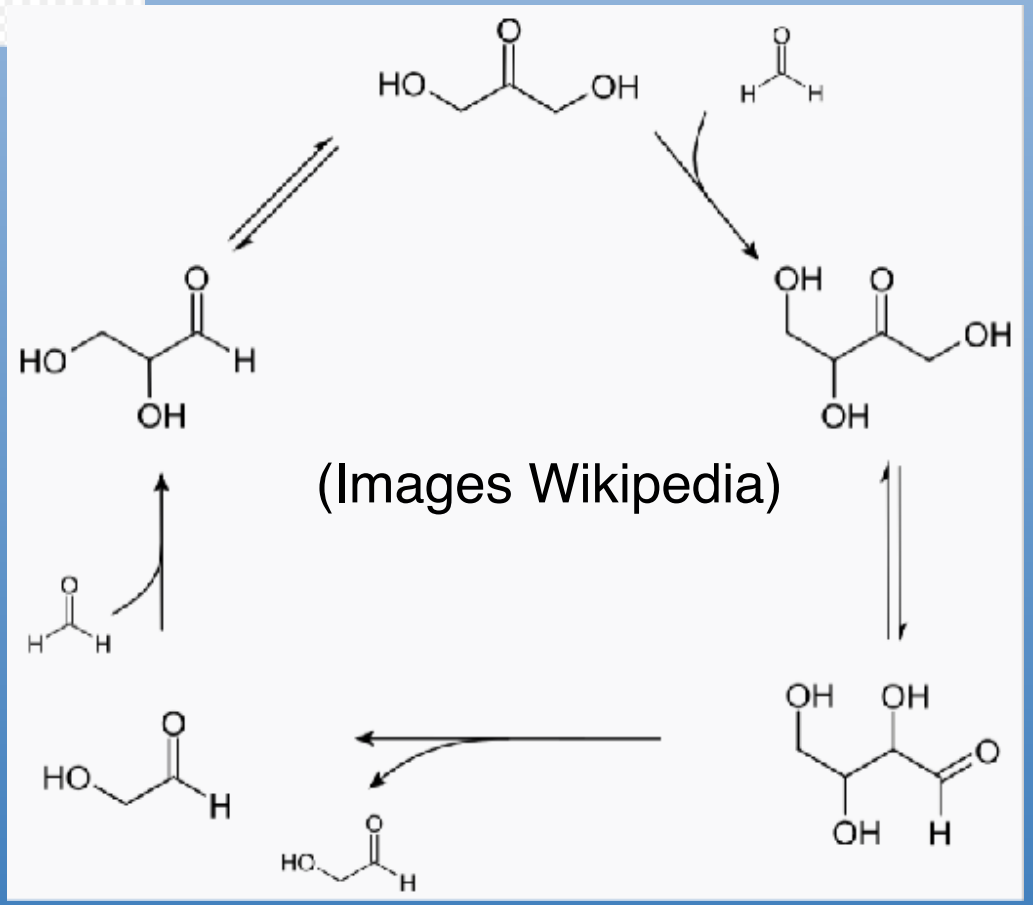
By chance autocatalytic networks arose. They made up a molecular ecosystem that evolved

Homochirality is in favor of a strong role of catalysis

Formose Cycle

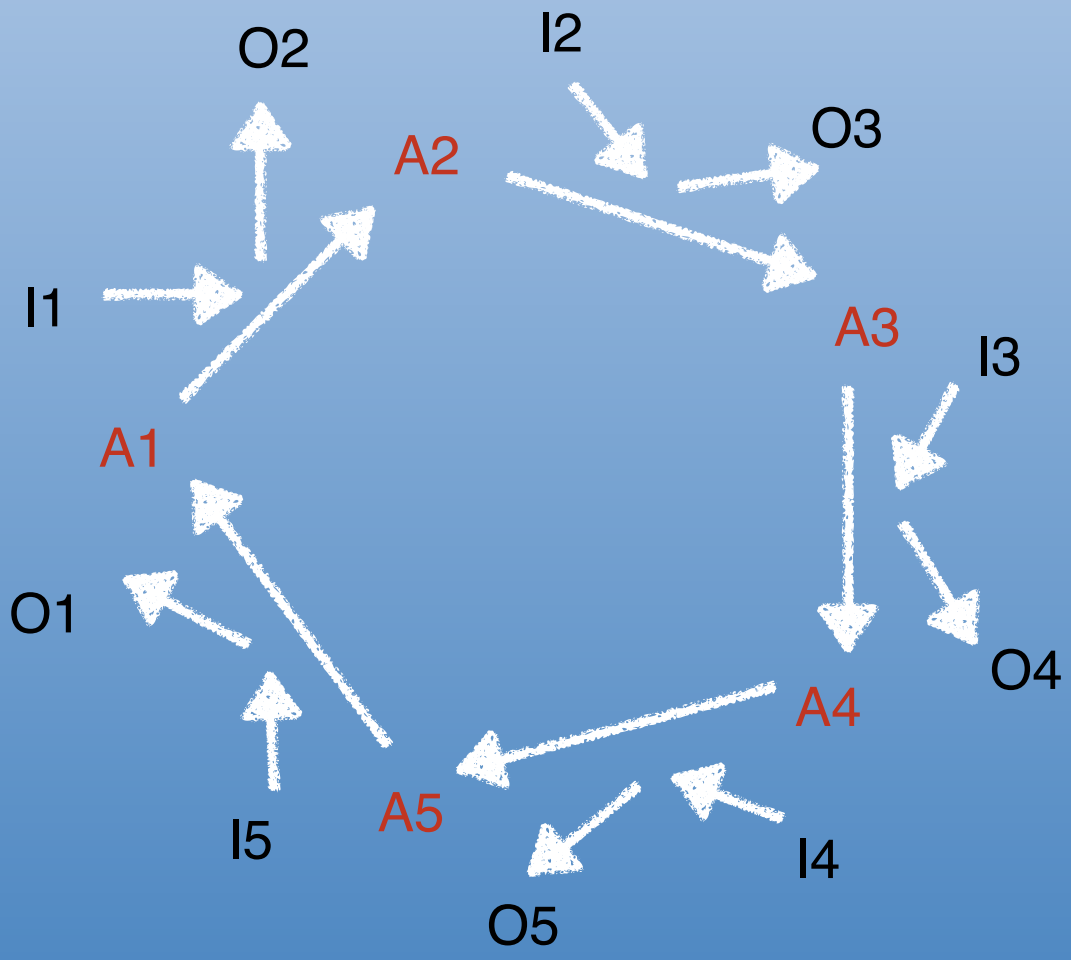


- not many other examples of autocatalysis
- Formose cycle not robust



(Images Wikipedia)

Autocatalytic Cycle



$P = (P_x)^n$

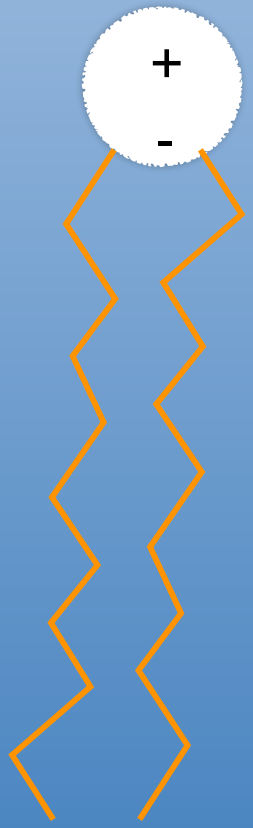
Unlikely !

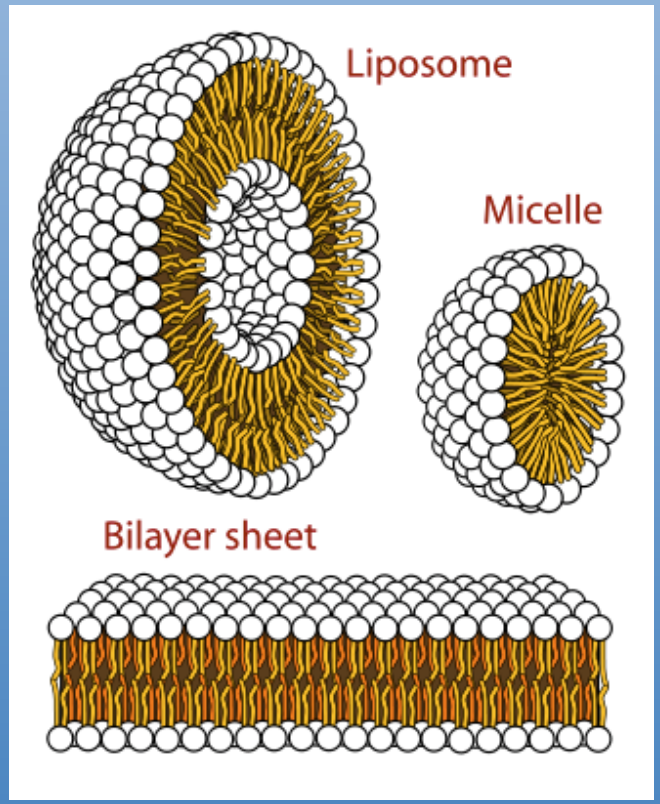
Membrane First Hypothesis

- membranes can have catalytic properties
- membrane acts as a hydrophobic container
- micelles easily multiply

Protocells

help to concentrate and select useful molecules

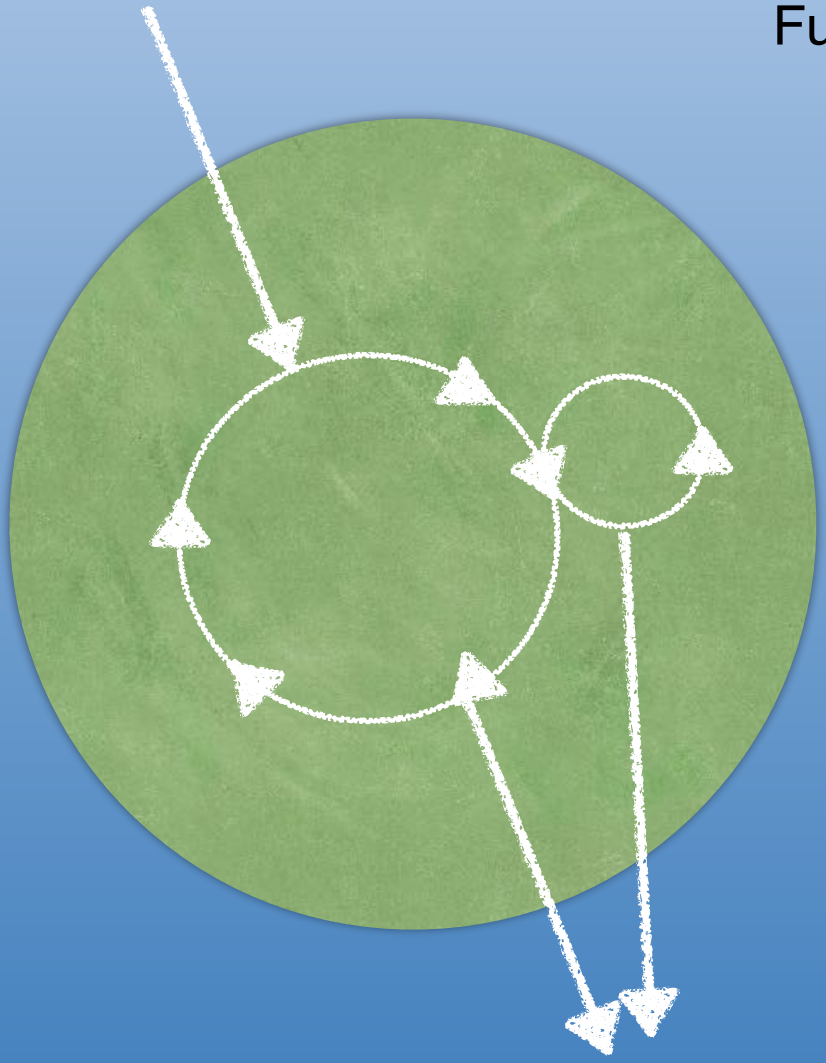




(Image Wikipedia)

Chemoton

Fundamental Unit of Life



Tibor Ganti

RNA World Hypothesis

- RNA carries information
- RNA can be subject to mutations - evolution !
- RNA can have enzymatic and catalytic properties
- RNA can act as a ligase for RNA
- Clay can act as a catalyst for RNA formation

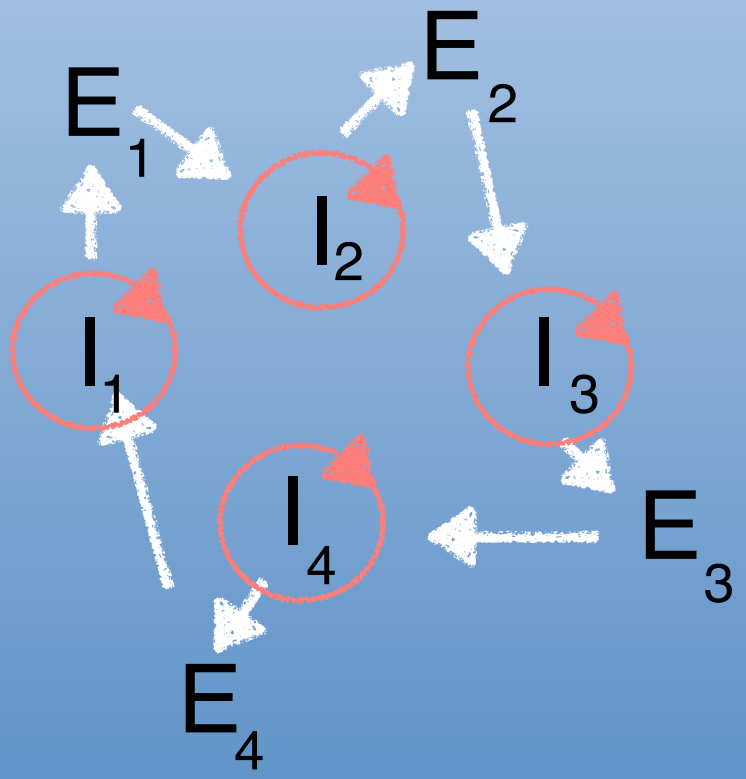
Ensembles of Reproducing RNAs

- Joyce and Tracey (2009)

RNA forms secondary structure
- can act a ligase recognizes shorter strands
- ligates them in an autocatalytic way

Ensembles of reproducing RNAs that compete
not robust - tend to simplify …

Hypercycles



- Eigen and Schuster
- information carriers I code for enzymes E that multiply information carriers to multiply enzymes …

Information carriers in competition do not evolve
- the largest hypercycle outcompetes all others

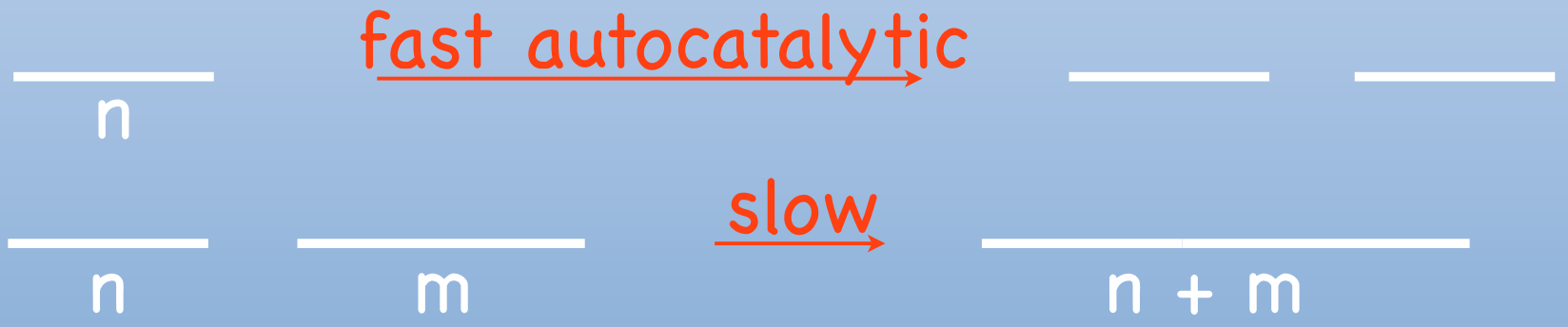
Molecular Darwinism

- how Darwinian evolution works remains poorly understood !

It is insufficient to just create a reproducing unit

In competition reproducers tend to simplify:
The best adapted wins - optimal solution to given constraints.

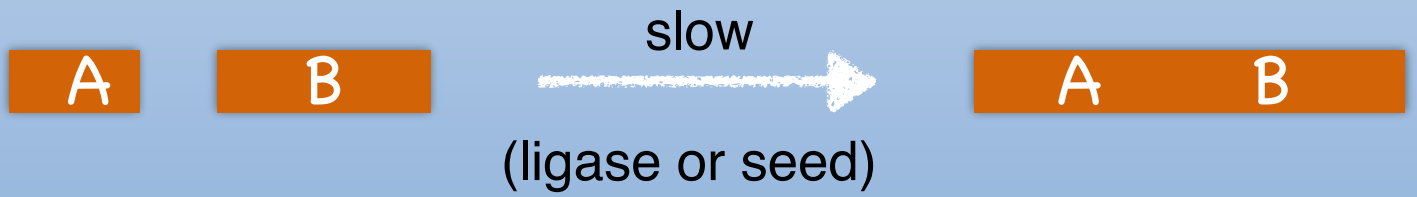
1 - D Objects



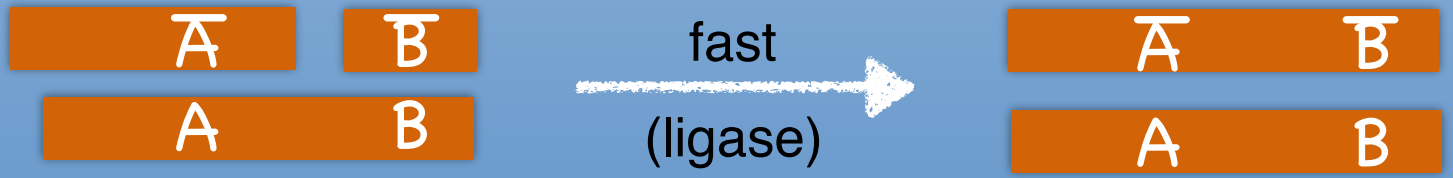
$$A_n + A_m \xrightarrow[r_c]{} A_{n+m}$$

$$r_c = \underbrace{\omega \cdot c_{A_{n+m}}}_{\text{template-driven}} + \underbrace{1}_{\text{spontaneous}}$$

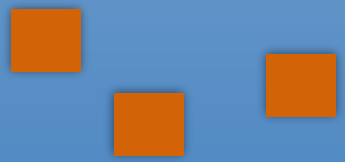
Fluctuation

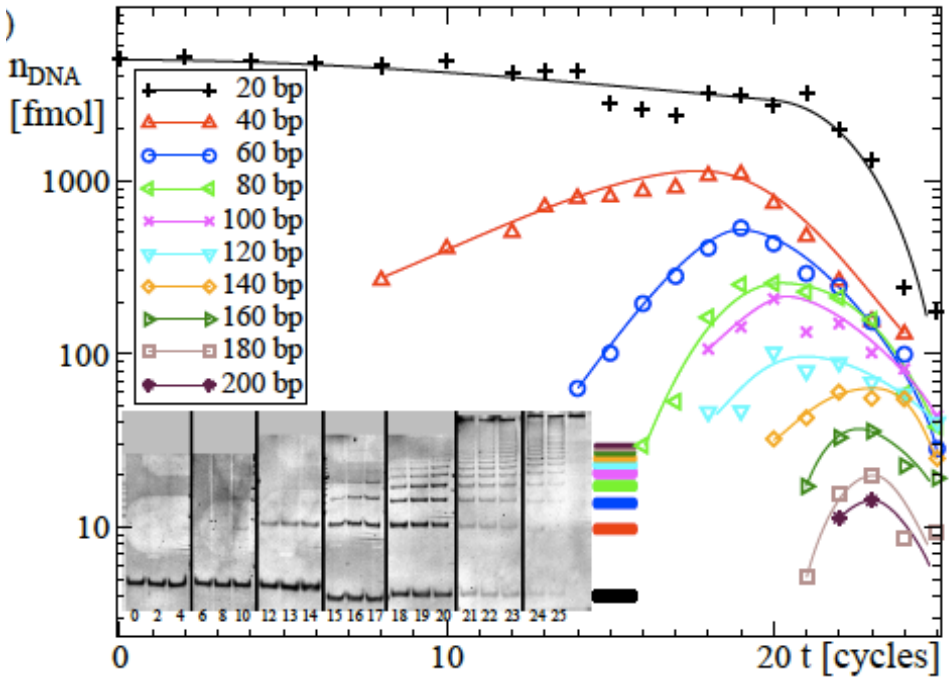


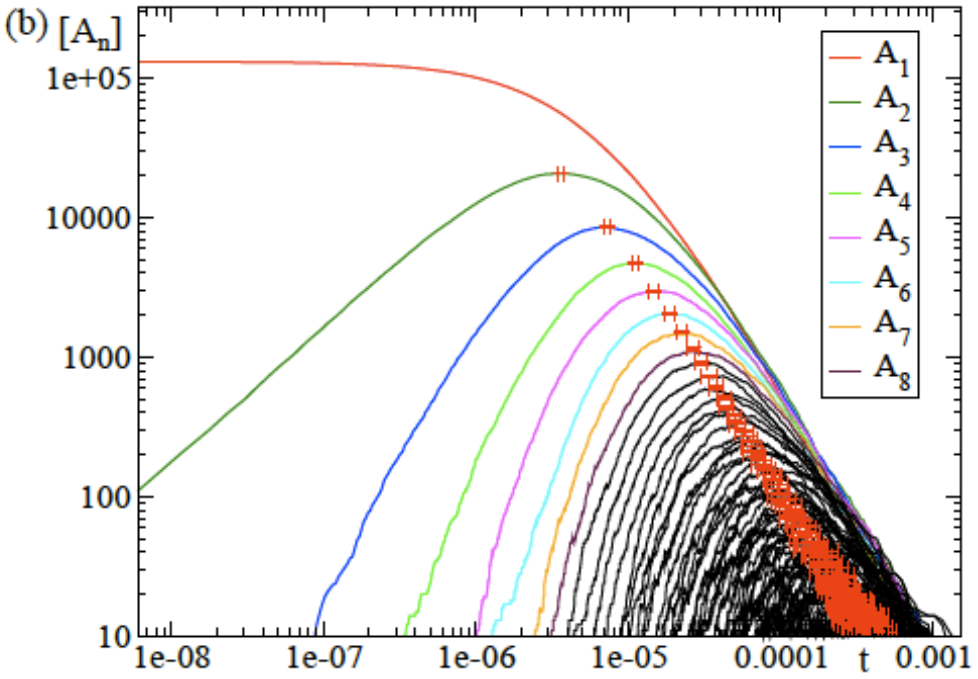
Reproduction



start with squares only….

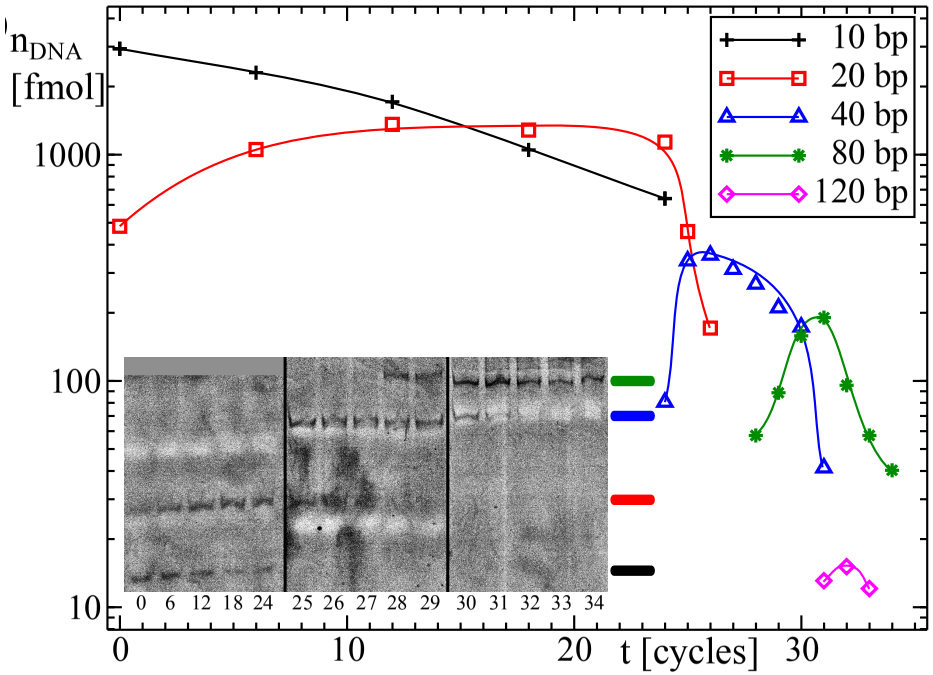


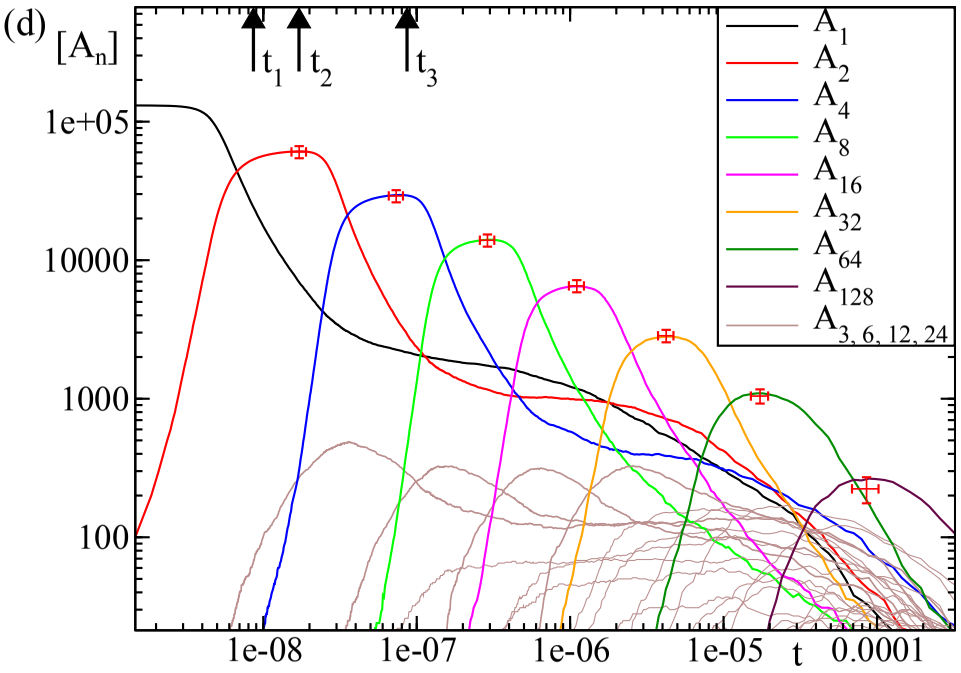




experiment in silico

undercritical reproduction rate - all possible lengths generated





experiment

in silico

Overcritical reproduction rate - length doubling

New generation feeds on the previous generation (niche)

Evolution

- Species formation requires supercritical reproduction
- Does evolution avoid dead ends by species feeding on each other ?
- Evolution is a strong constraint

Artificial Life

- a story of bright ideas that fail
- all bright ideas about Life have already been described: hopeless ?

Organic Chemistry

- heuristic rules, not really predictive
- reactions paths with many sideways
- no complete data on reactions available
- little knowledge beyond pairwise reactions

Chemical reactions in a prebiotic broth almost incomprehensible

I fear, we will never “synthesize” Life in a purposeful way…

Biomolecules may well have formed spontaneously on the early Earth ….

Nucleotides, Lipids, Amino-Acids may have formed simultaneously under similar conditions

mounts as small as 1 kilometer tall.

Smith's results were published online on 12 March in *Marine Geodesy* in advance of a special issue on the AltiKa instrument. Paul Wessel, a marine geophysicist at the University of Hawaii, Manoa, says the study is a good proof of principle showing how AltiKa can enable marine geologists to see more clearly. "It pushes the envelope a bit further," he says.

The scientific payoff extends beyond submarine navigation. For example, tsunami waves are sensitive to the roughness on the ocean floor; seamounts slow a passing tsunami, bending and deflecting its energy. A better map would improve tsunami predictions. Also sensitive to seafloor roughness are the internal waves in oceans that bring up deep, cold, nutrient-rich waters to the surface and carry dissolved atmospheric carbon dioxide to ocean depths. "Knowing the seafloor bathymetry better would definitely improve the mixing models that we use," says Steven Jayne, a physical oceanographer at Woods Hole Oceanographic Institution in Massachusetts.

Seamounts are also important for ecology, because they provide a rich habitat

BIOCHEMISTRY

Origin-of-life puzzle cracked

Study explains how three essential classes of molecules could have formed simultaneously

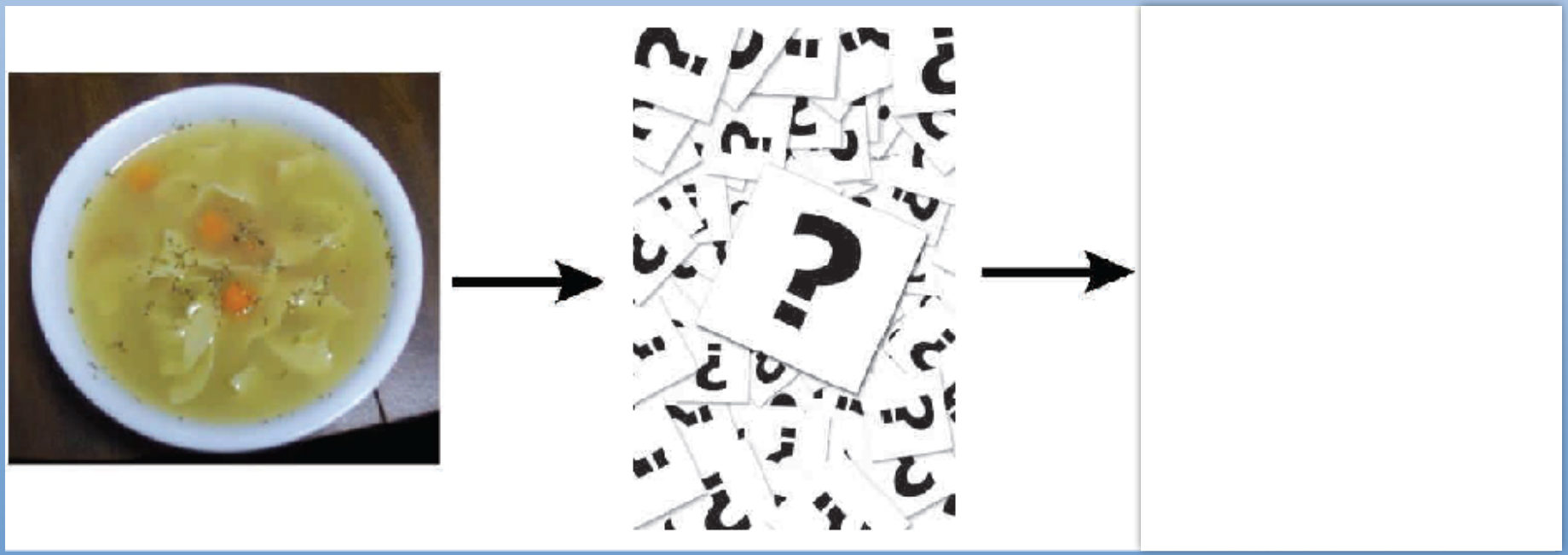
By **Robert F. Service**

The origin of life is a set of paradoxes. To get it started, there must have been a genetic molecule—something like DNA or RNA—capable of passing along blueprints for making proteins, the workhorse molecules of life. But modern cells cannot copy DNA and RNA without the help of proteins themselves. Worse, none of these molecules can do their jobs without fatty lipids, which provide the cell membranes needed to contain them. In yet another chicken-and-egg complication, protein-based enzymes (encoded by genetic molecules) are needed to synthesize lipids.

Now, researchers say they see a way out. A pair of simple compounds, which would have been abundant on early Earth, formaldehyde, could undergo a sequence of reactions to produce two of RNA's four nucleotide building blocks, showing a plausible route by which RNA could have formed on its own in the primordial soup. Critics, though, pointed out that acetylene and formaldehyde are still somewhat complex molecules themselves. That raised the question of where they came from.

So Sutherland and his colleagues set out to see if they could find a route to RNA from even simpler starting materials. They succeeded. Sutherland's team now reports that it created nucleic acid precursors starting with just hydrogen cyanide (HCN), hydrogen sulfide (H_2S), and ultraviolet (UV) light. What is more, Sutherland says, the same conditions also create the starting materials for amino acids and lipids.

We have a soup - what is next ?

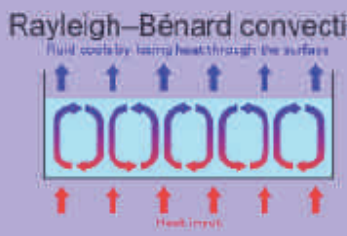


From the chicken soup …

… to the chicken ?

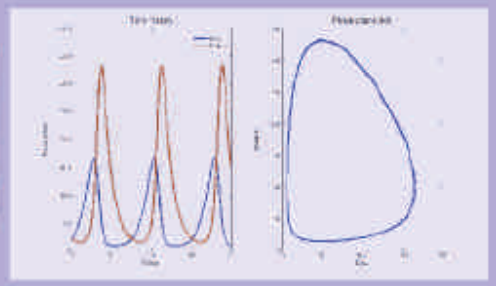
a highly non-linear, pattern forming system

Physics



Laser

Biology



Chemistry:

Belousov–Zhabotinsky reaction

Nonlinear Physics

- Driven (dissipating) non-linear systems create order ....

$$\dot{x}(t) = \alpha x_1 + \beta x_2 + \gamma x_3 + \delta x_4 + \ldots$$

$$\dot{x}(t) = \alpha (x_1)^2 + \beta (x_2)^5 + \gamma (x_3)^3 + \delta (x_3 * x_4) + \ldots$$

Nonlinear equations :
few solutions with $\dot{x}(t) = 0$

- Phase space contracts upon dissipation

Self-organizing molecular autocatalysis ?

Idea:

- a complex organic chemical mixture
- energy input
- self reproducing mode is the strongest and wins —
- careful: chemistry is not hydrodynamics…

Solution ?

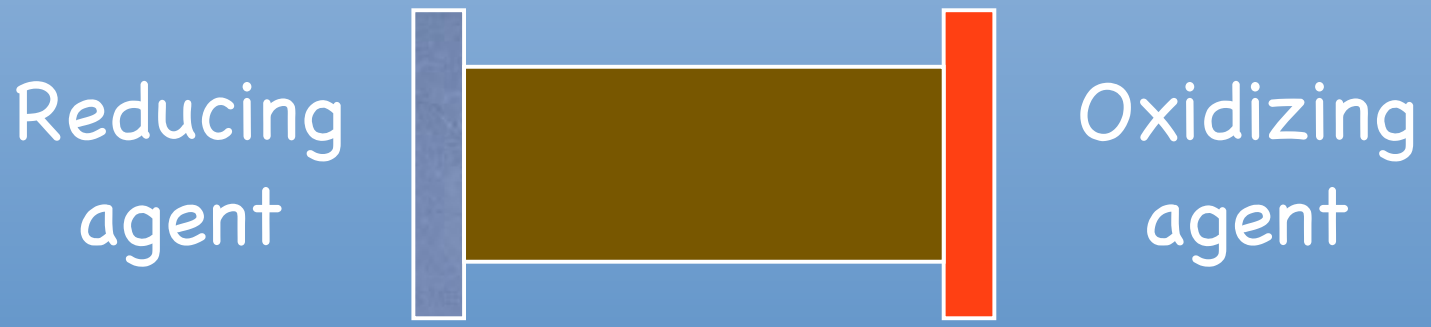
- The experiment is brighter that you.
- Work like an experimentalist ….
- Let the experiment guide you with the correct boundary conditions

Oxidizing and Reducing

- oxidation: electron uptake
- reduction : electron delivery
- careful: oxidative atmosphere does not create biomolecules

Idea :

- Oxidizing and reducing boundary
- Generate all oxidization states of all the molecules



The self reproducing mode should prevail…

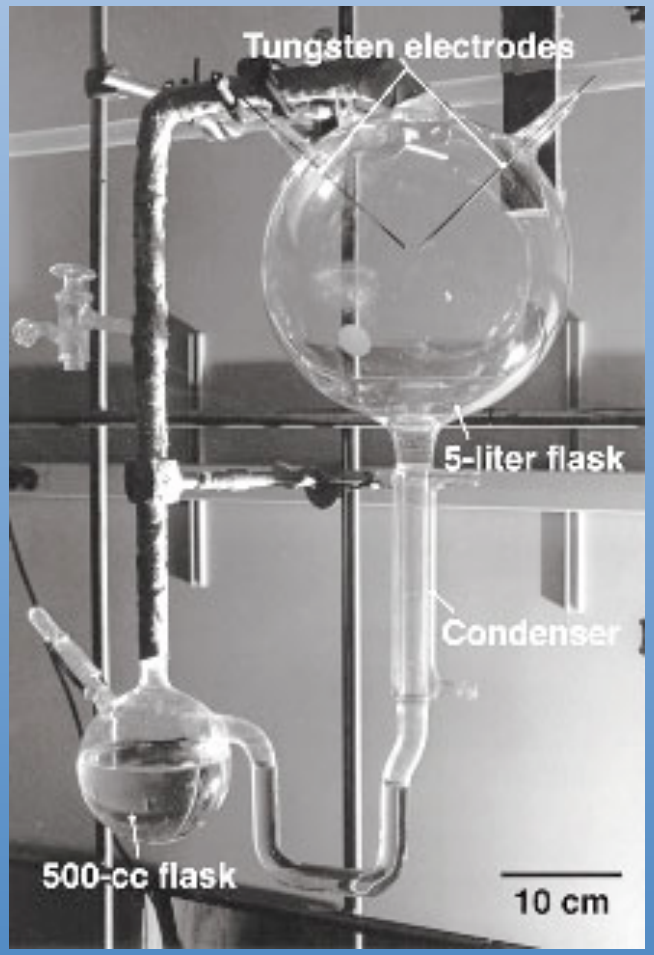
Origine of Life ? Physicist…

…. from a prebiotic soup : order from disorder !

@ first : simple, molecular form of autocatalysis ?

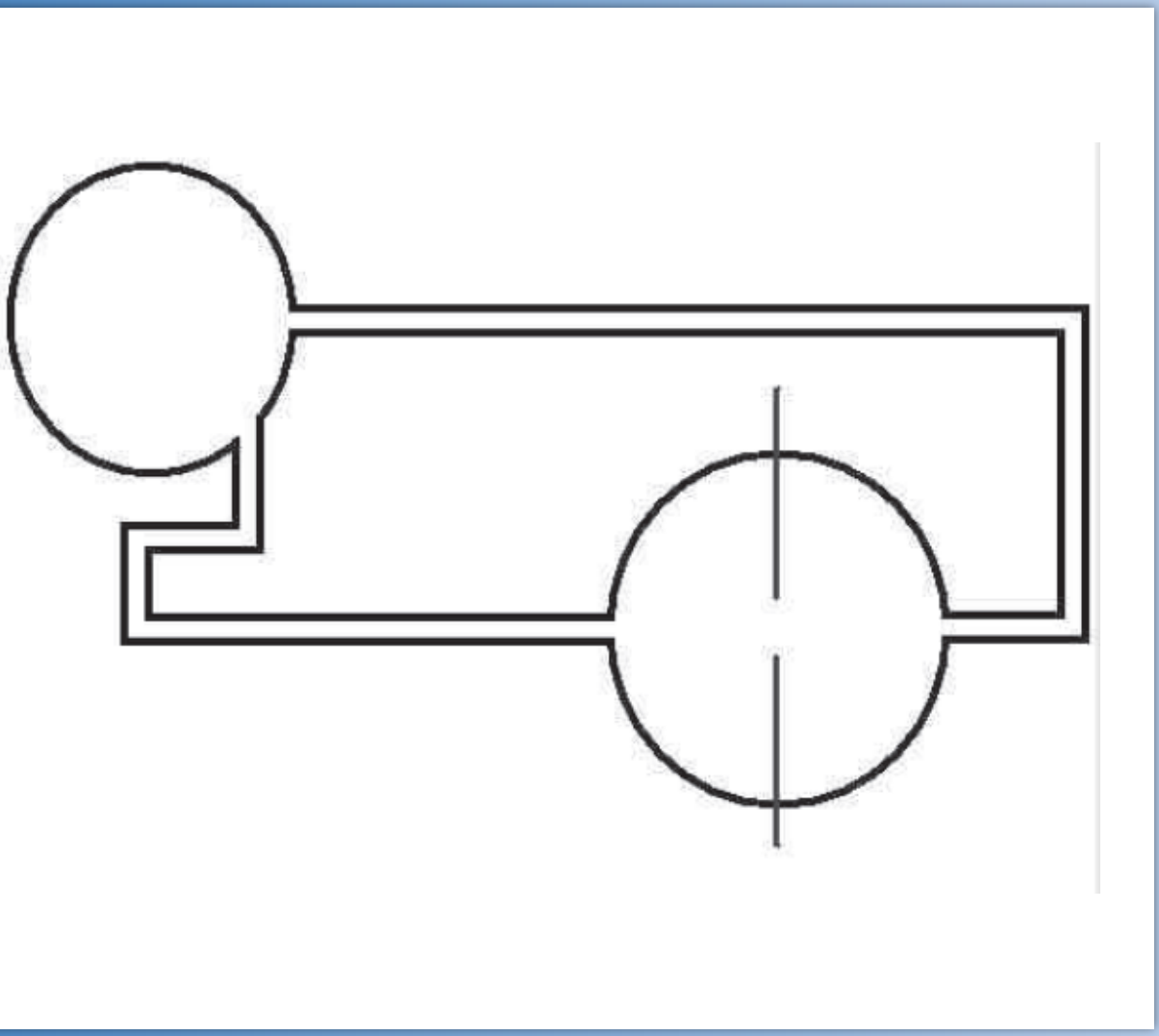
- single autocatalytic molecules ??
- sets of autocatalytic molecules ???

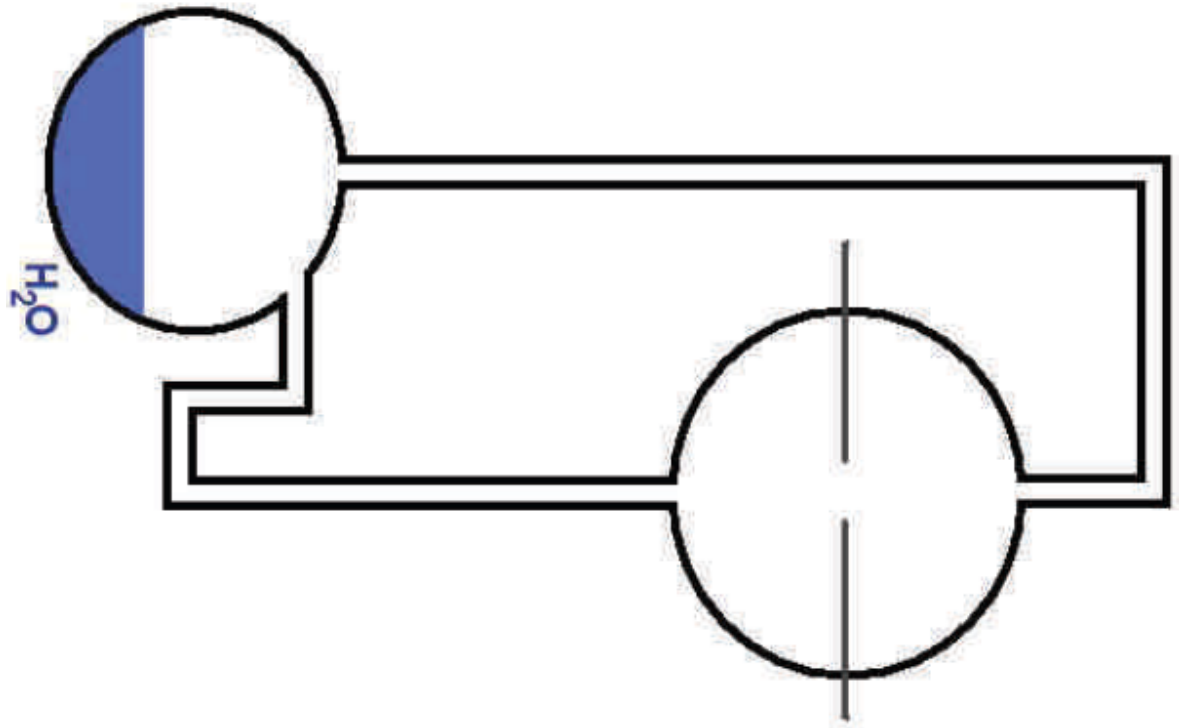
How to generate a complex ensemble of molecules ?

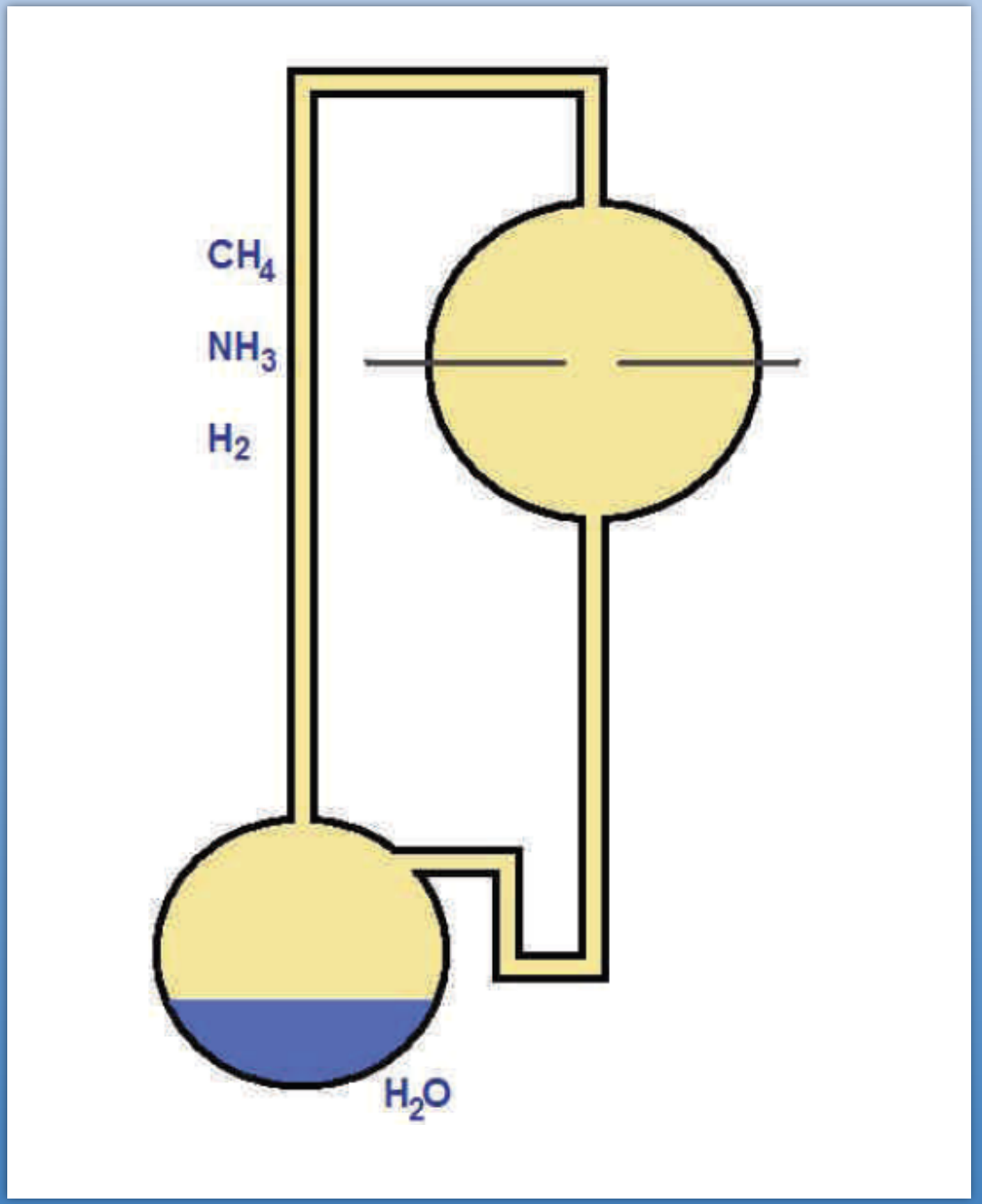


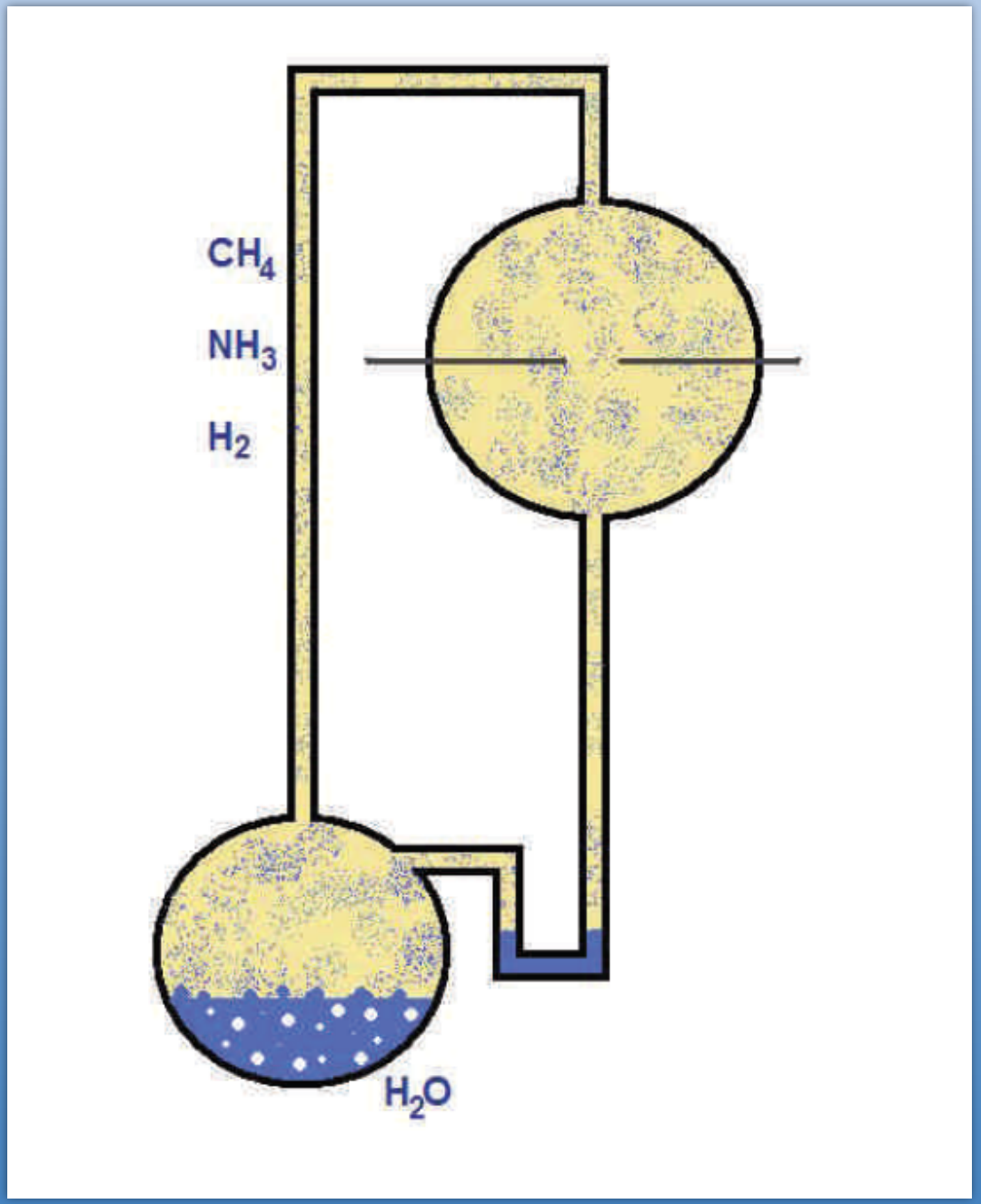
Miller-Urey Experiment

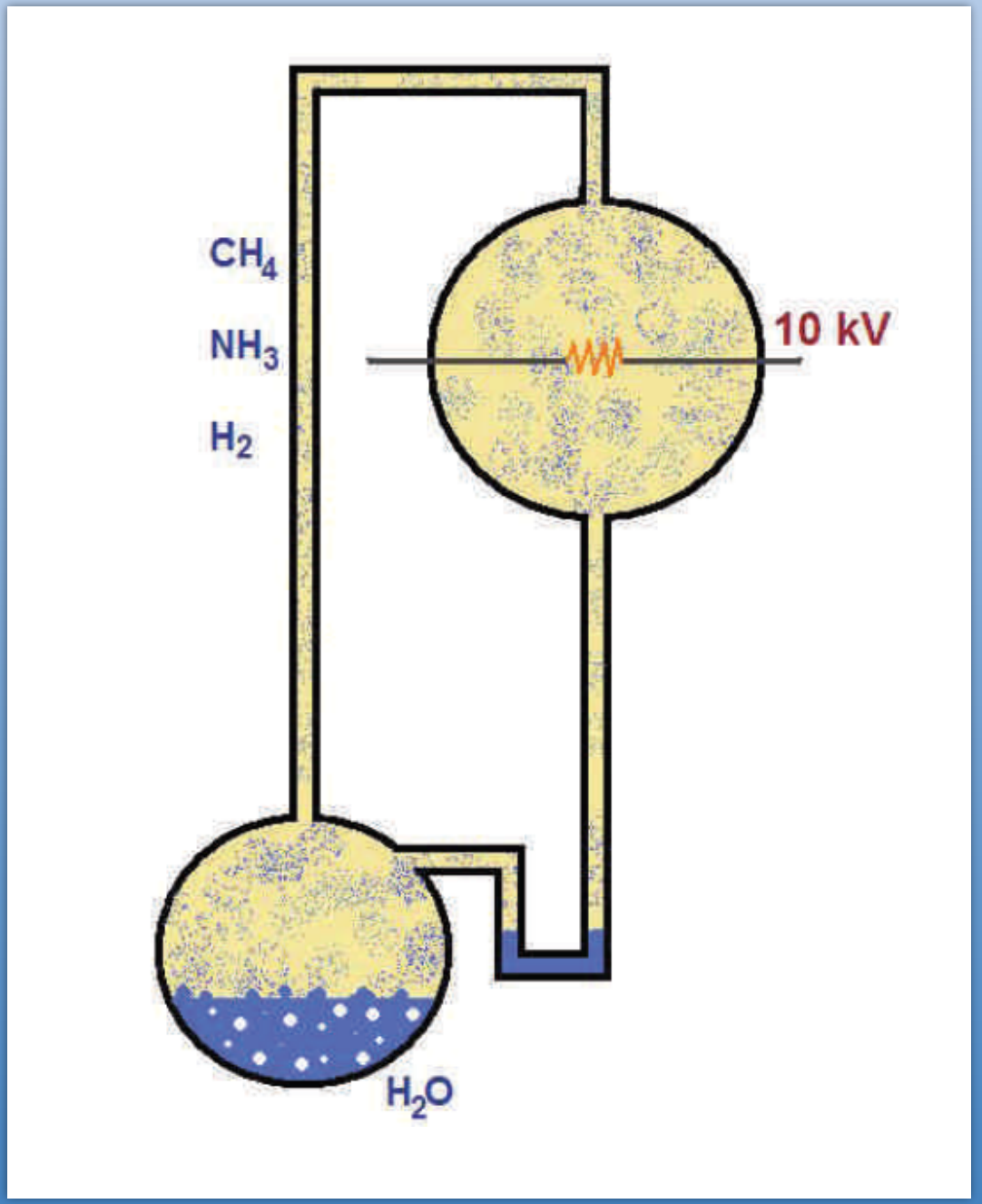
organic biomolecules may
have formed spontaneously
at the ORIGIN…

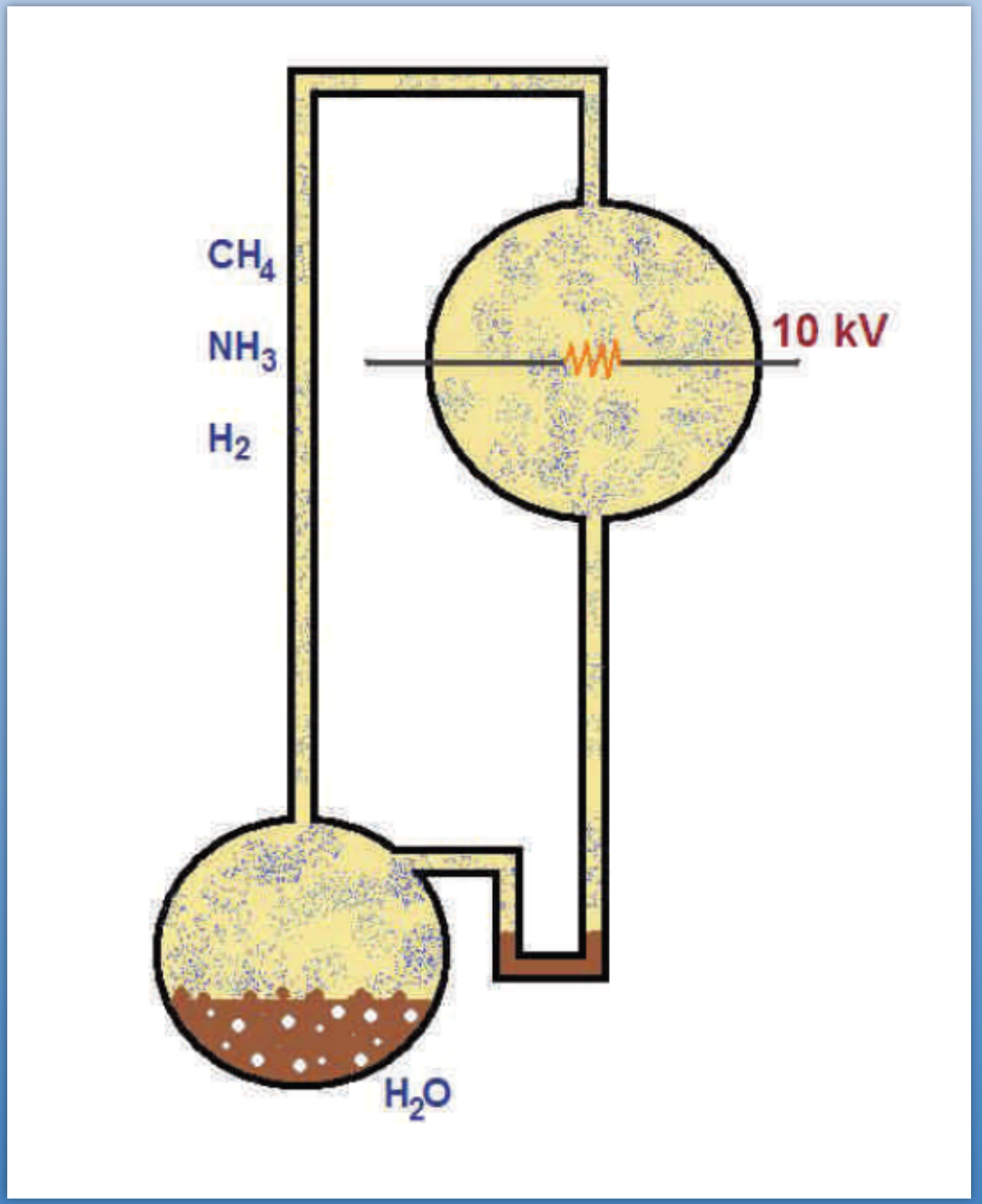


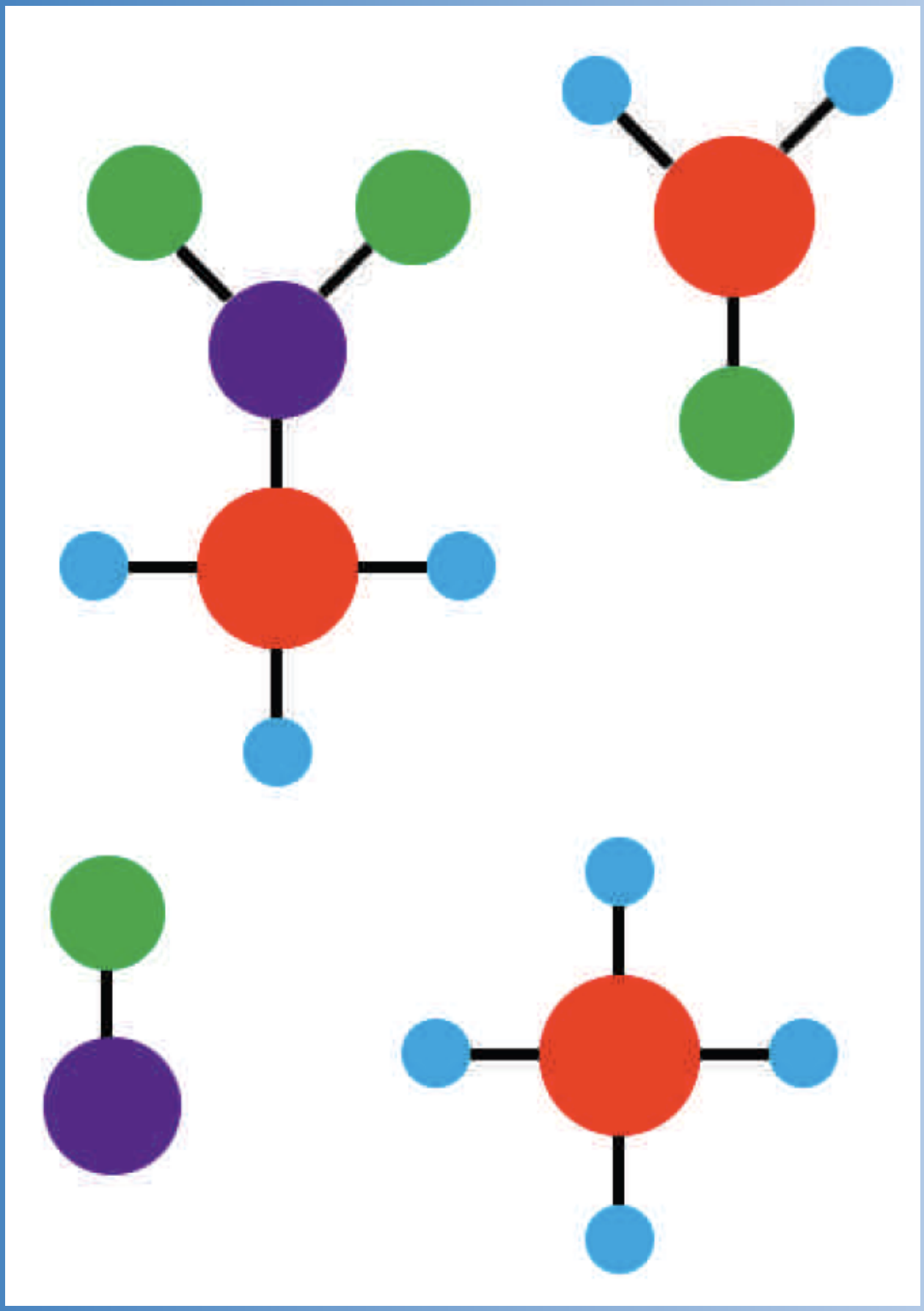

H_2O

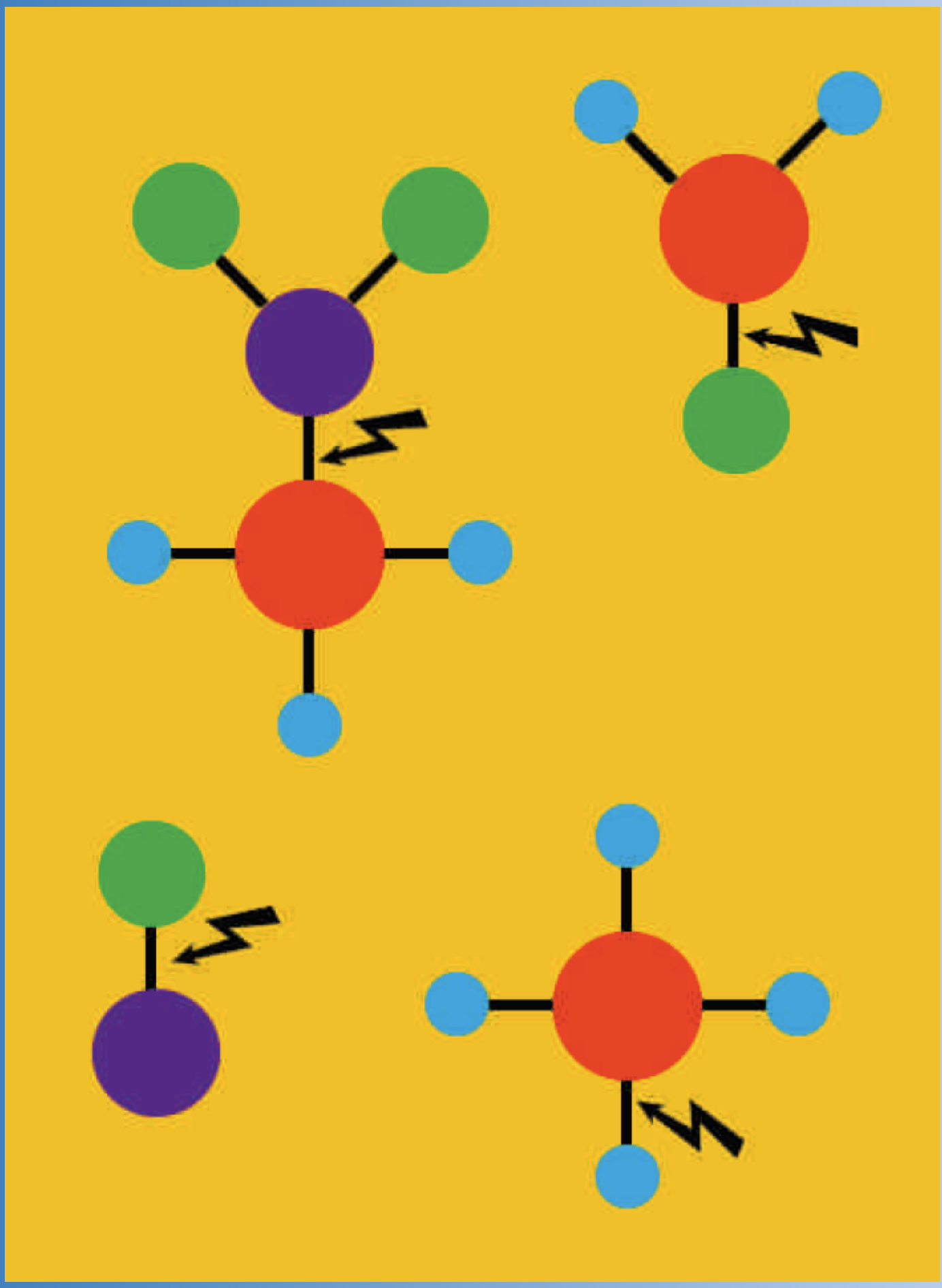

CH_4
NH_3
H_2
H_2O

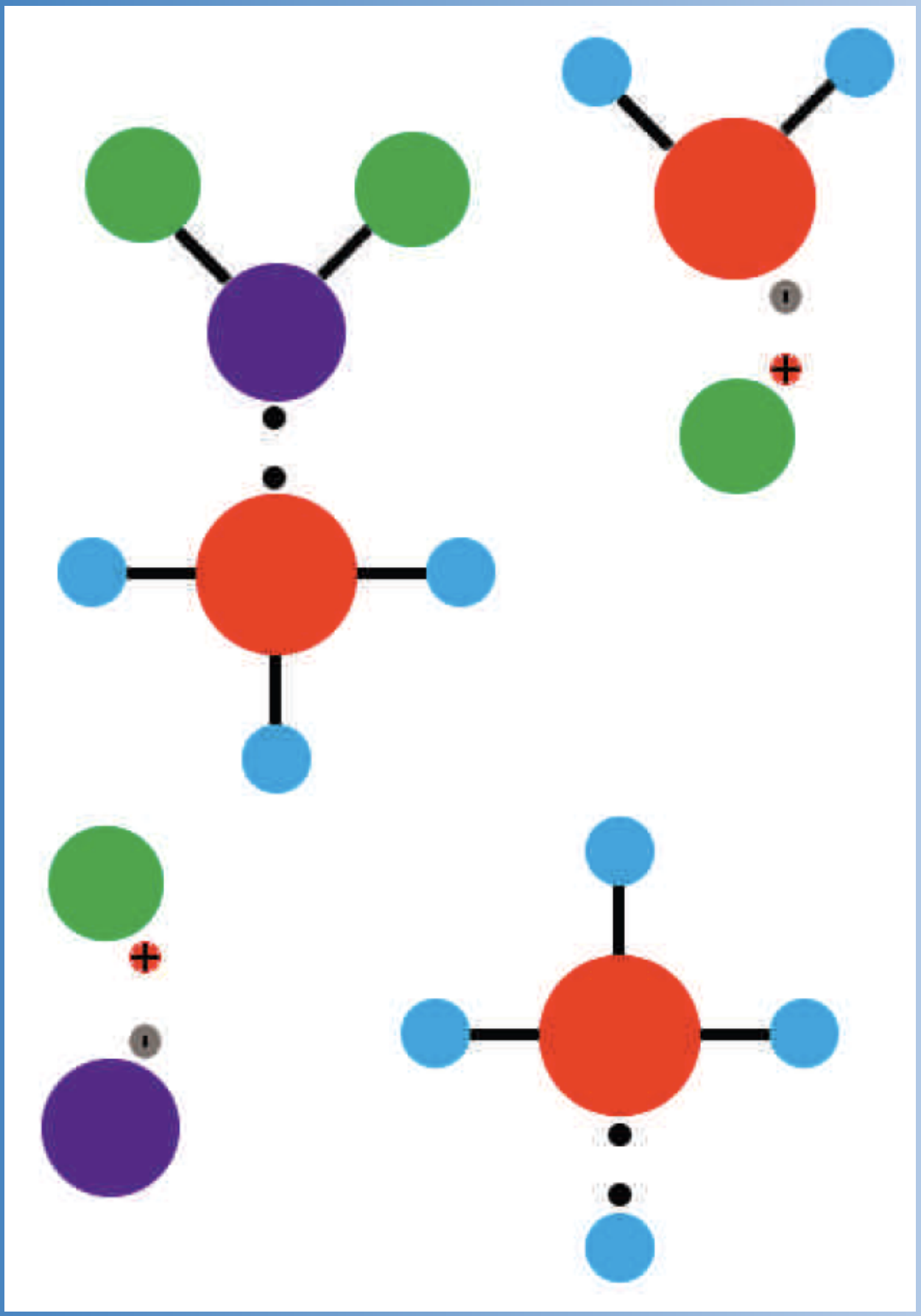

CH_4
NH_3
H_2
H_2O

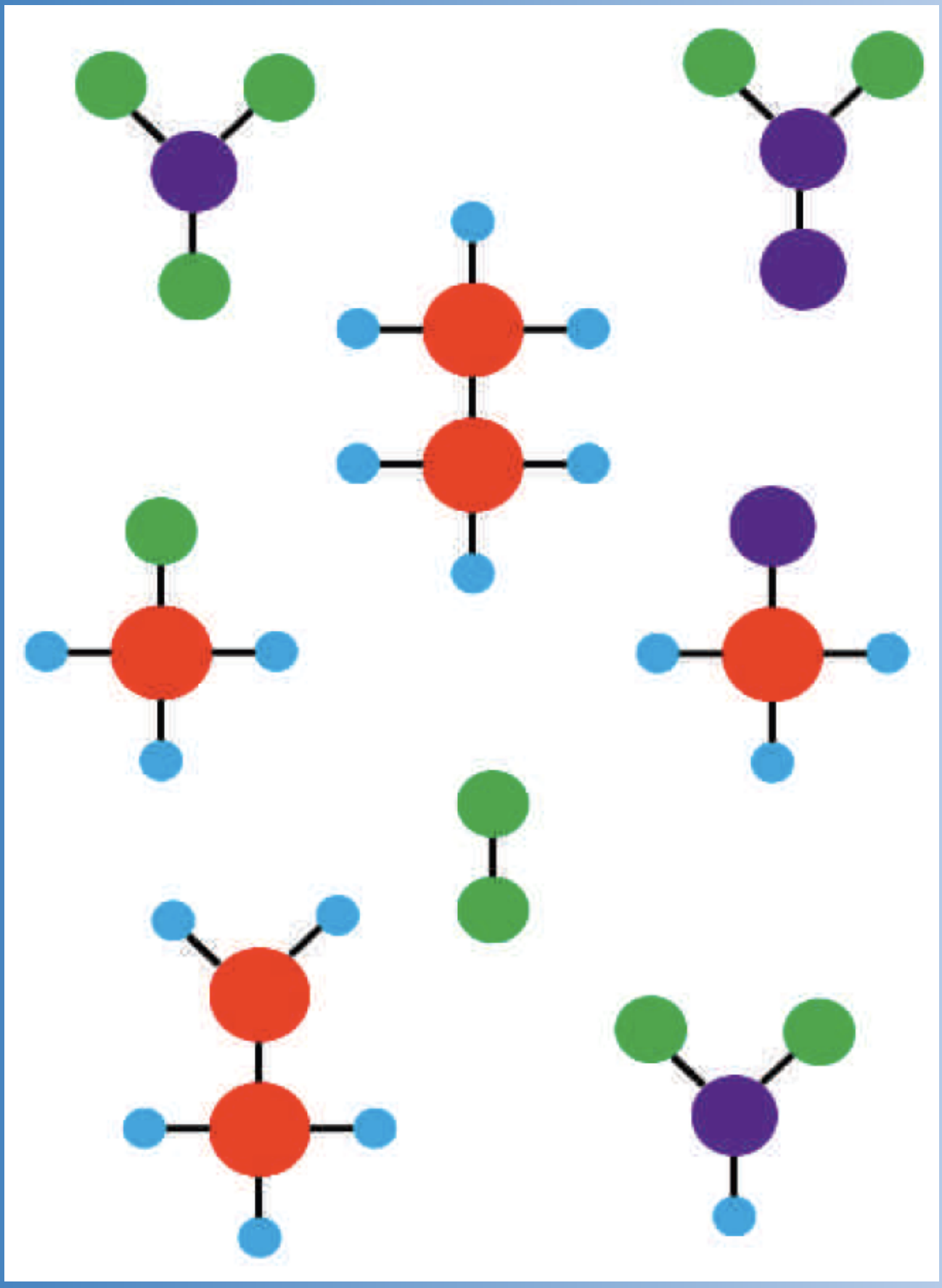

CH_4
NH_3
H_2
10 kV
H_2O

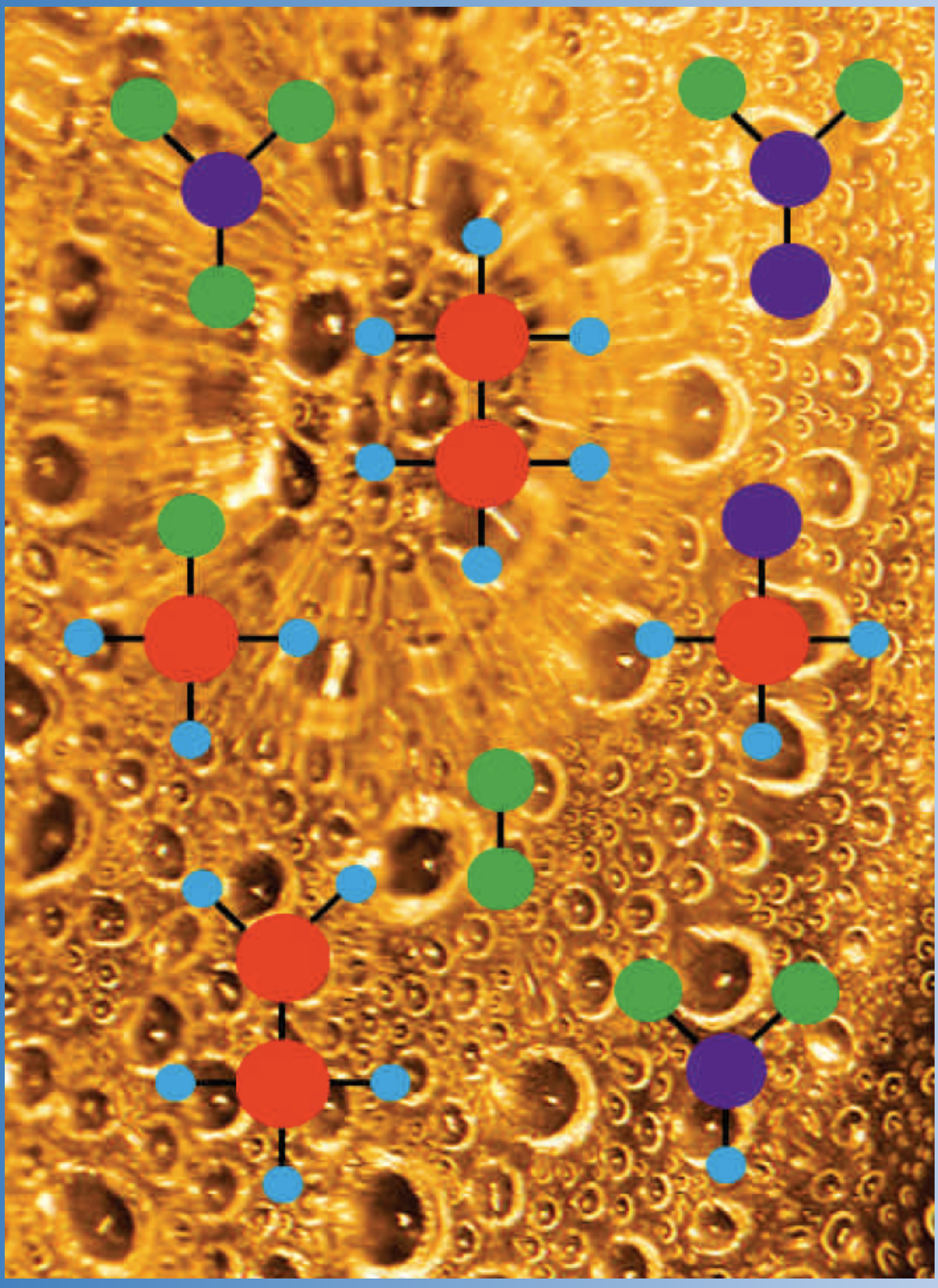

CH_4
NH_3
H_2
10 kV
H_2O











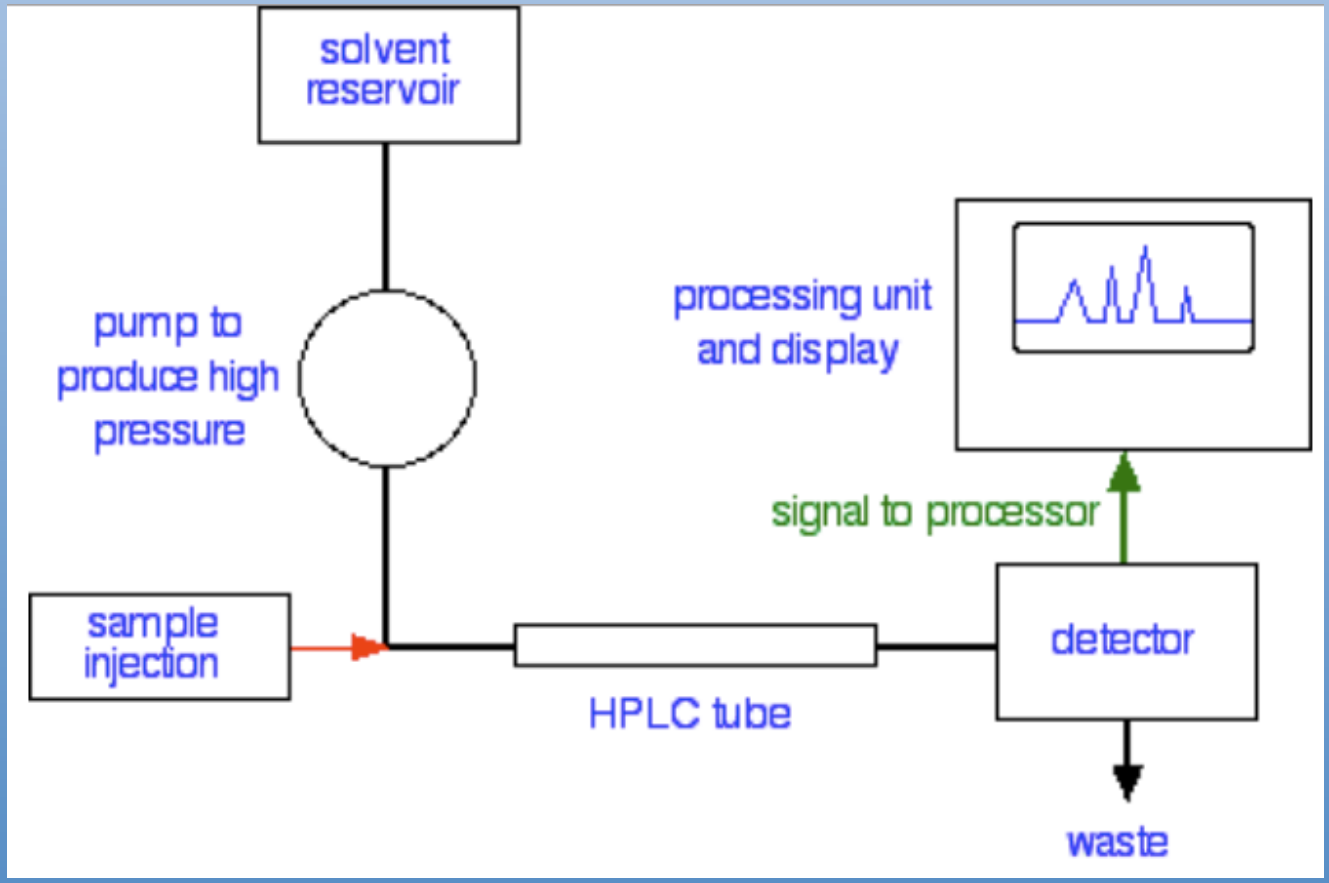
NH3, (H2), CH4 and H2O

Analysis ?

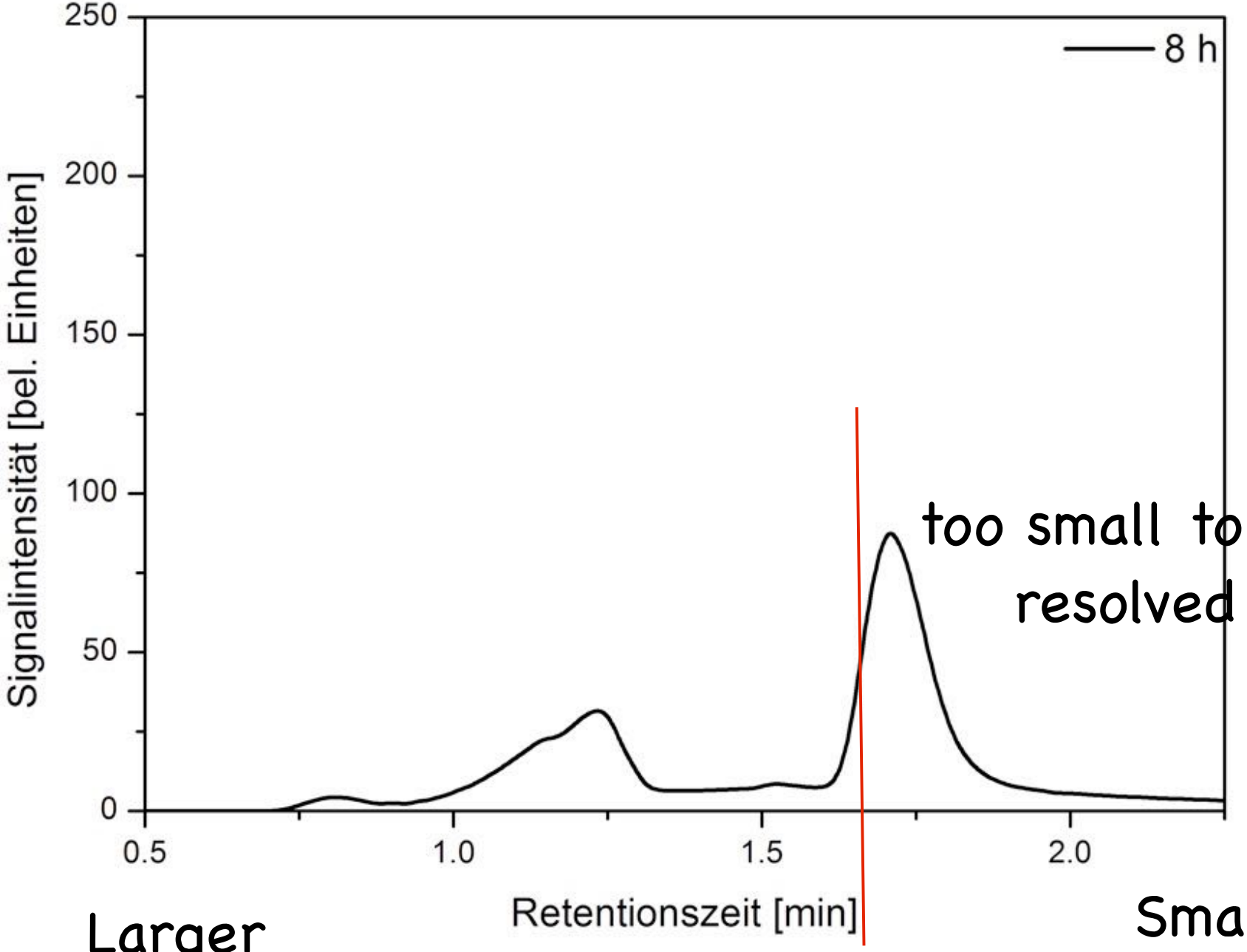
Chromatography : HPLC
- quantitative but low resolution

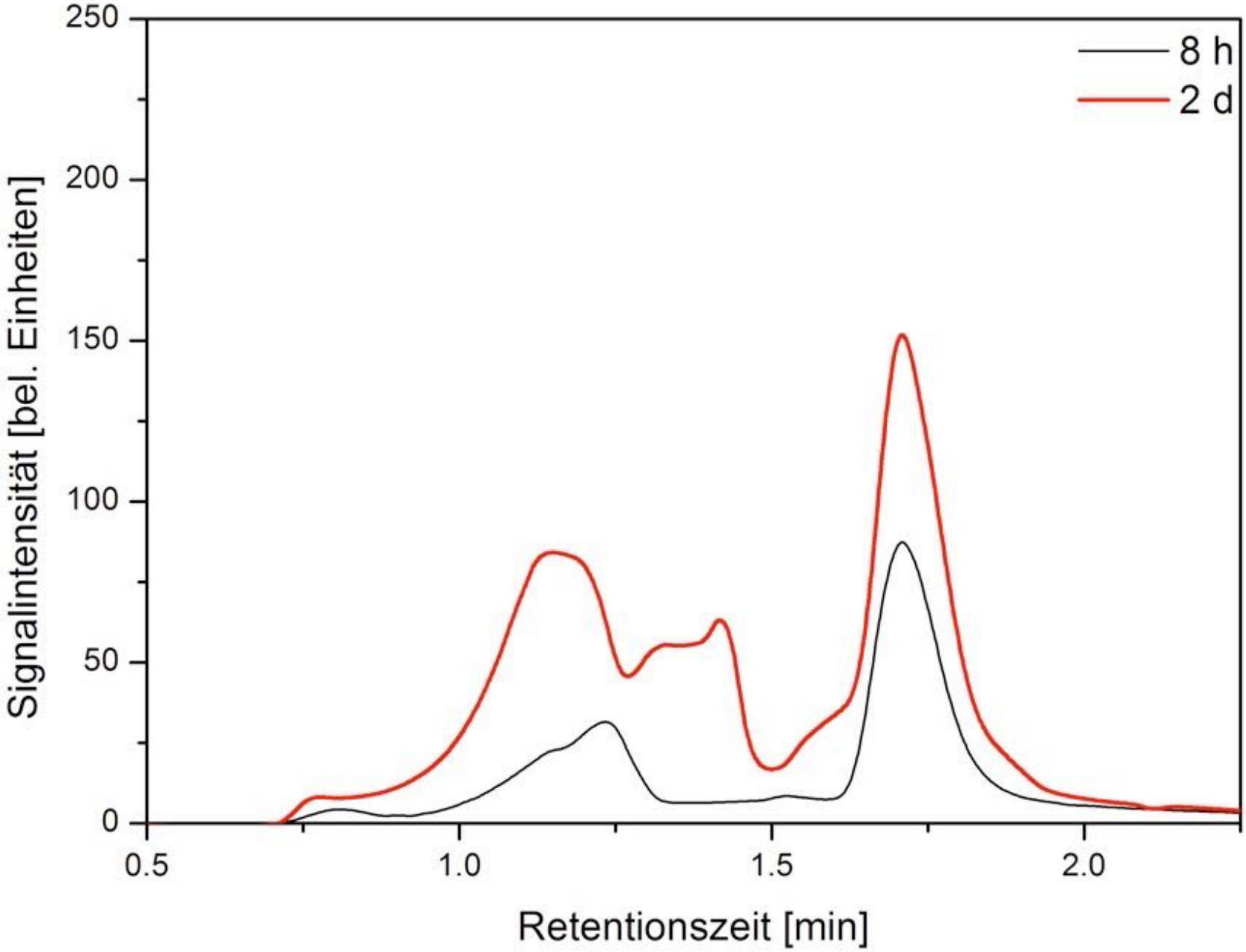
Mass spectroscopy : Q-Tof
- high res. but not quantitative
- too sensitive

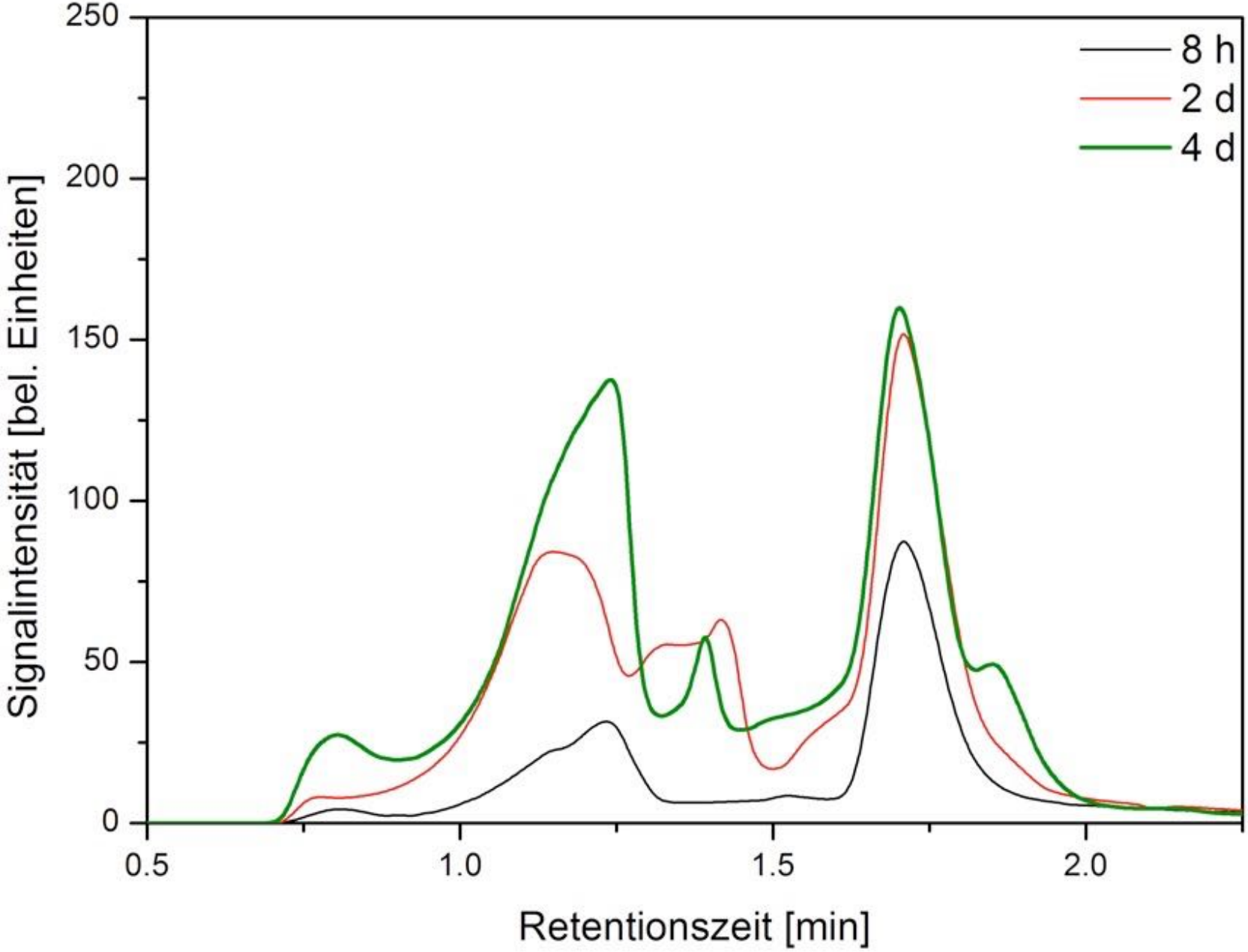
Analysis - High Pressure Liquid Chromatography

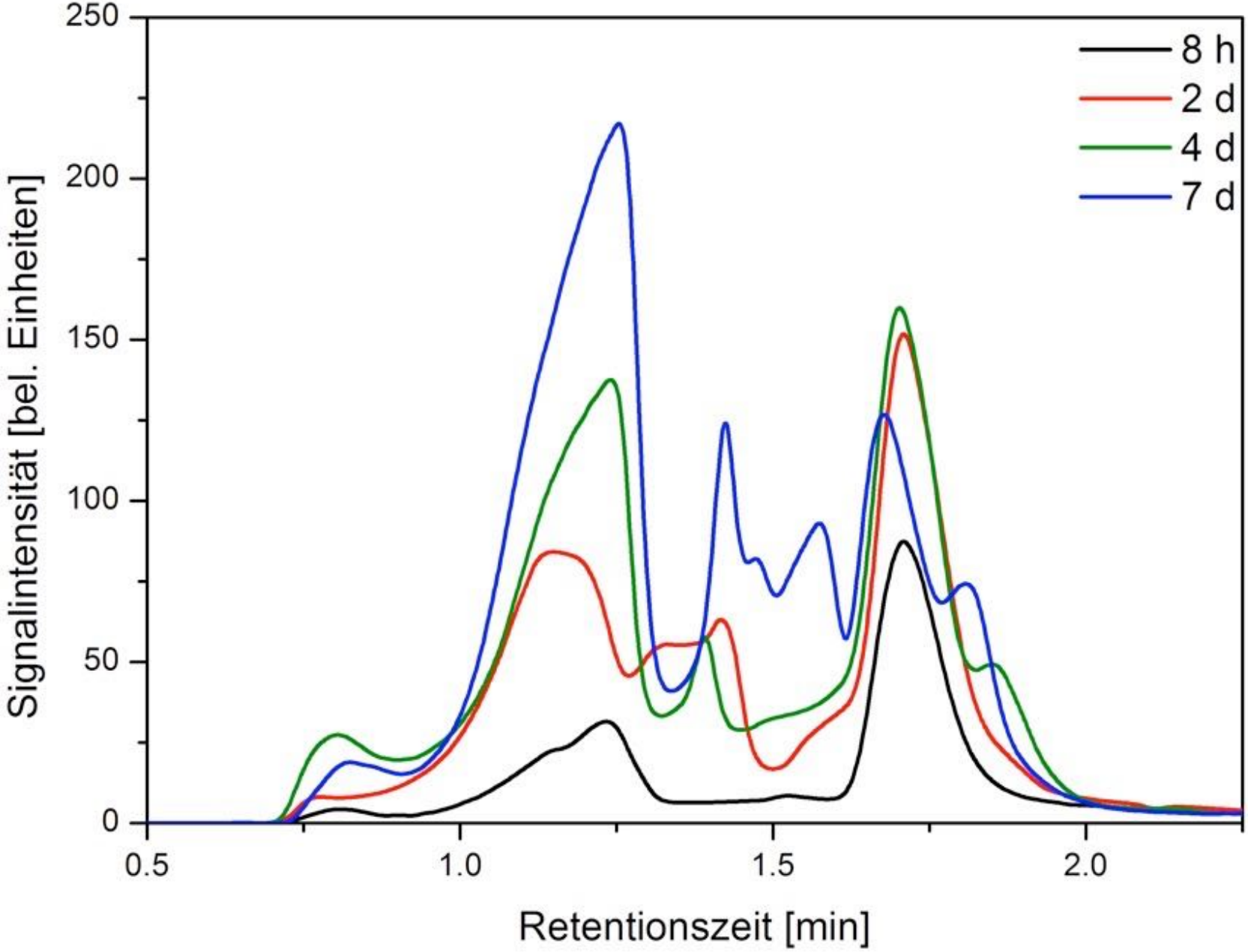


HPLC : Results, C13 column



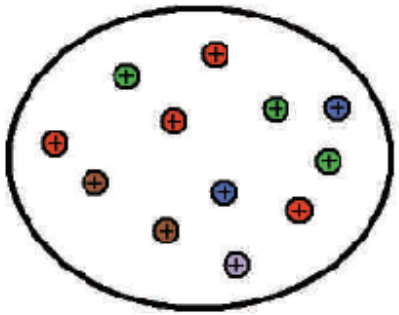

8 h
2 d
Signalintensität [bel. Einheiten]
Retentionszeit [min]
250
200
150
100
50
0
0.5
1.0
1.5
2.0


8 h
2 d
4 d
Signalintensität [bel. Einheiten]
Retentionszeit [min]
0
50
100
150
200
250
0.5
1.0
1.5
2.0


8 h
2 d
4 d
7 d
Signalintensität [bel. Einheiten]
250
200
150
100
50
0
0.5
1.0
1.5
2.0
Retentionszeit [min]

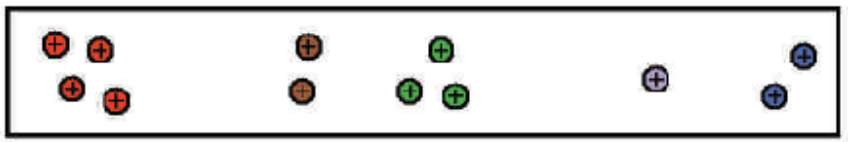
Analysis - Mass Spectroscopy

Ionisation



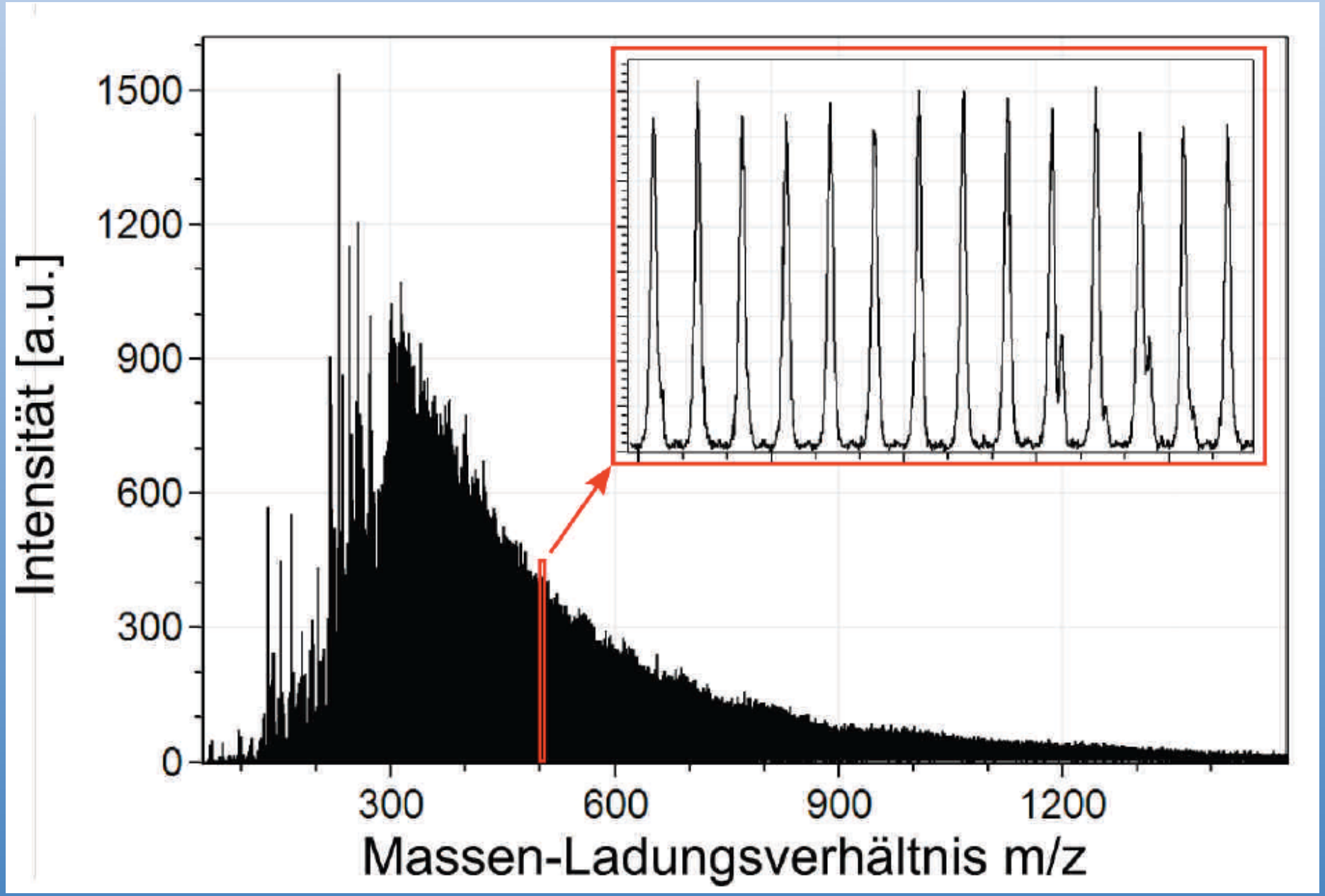
Acceleration

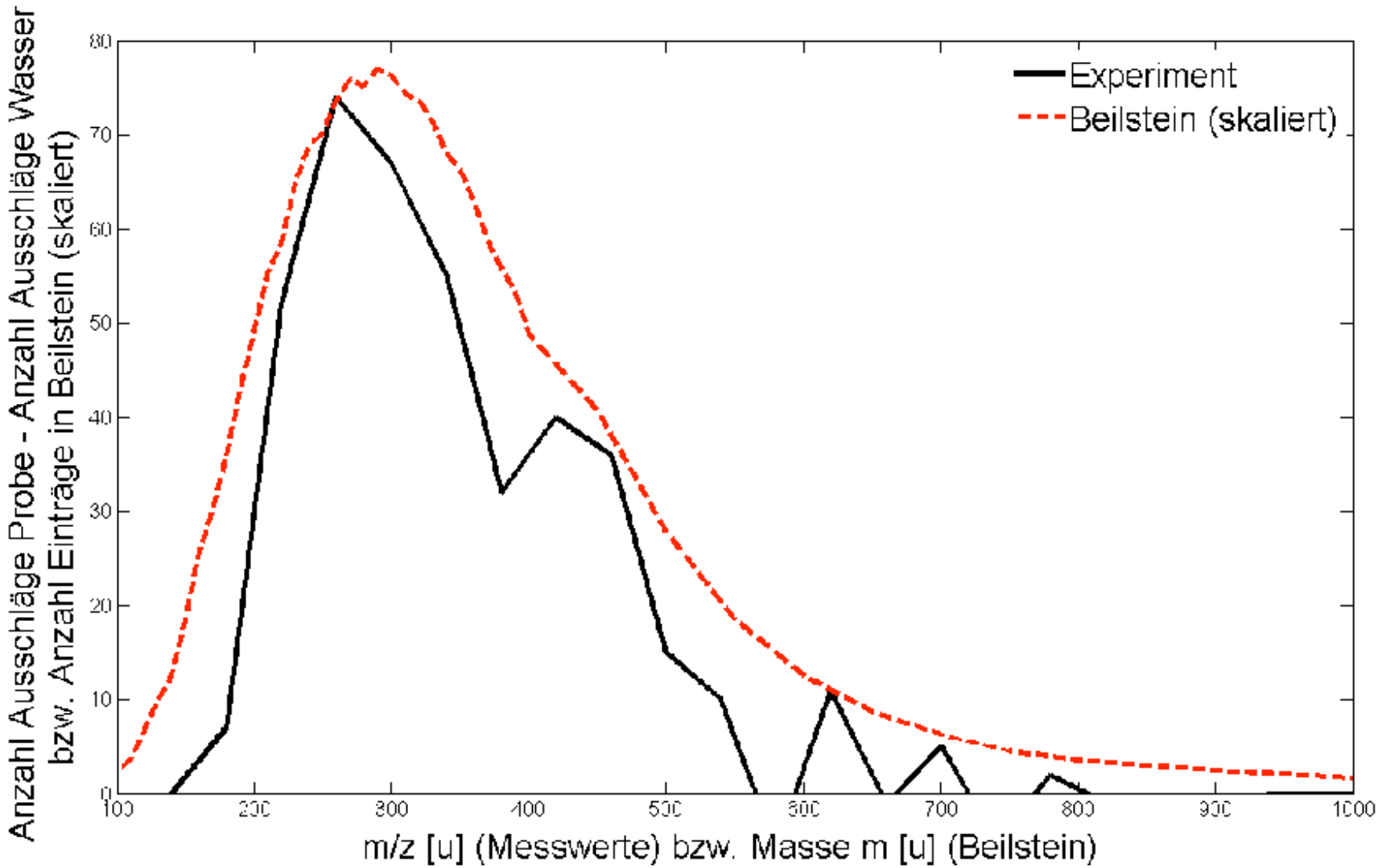
$F = q\,U$

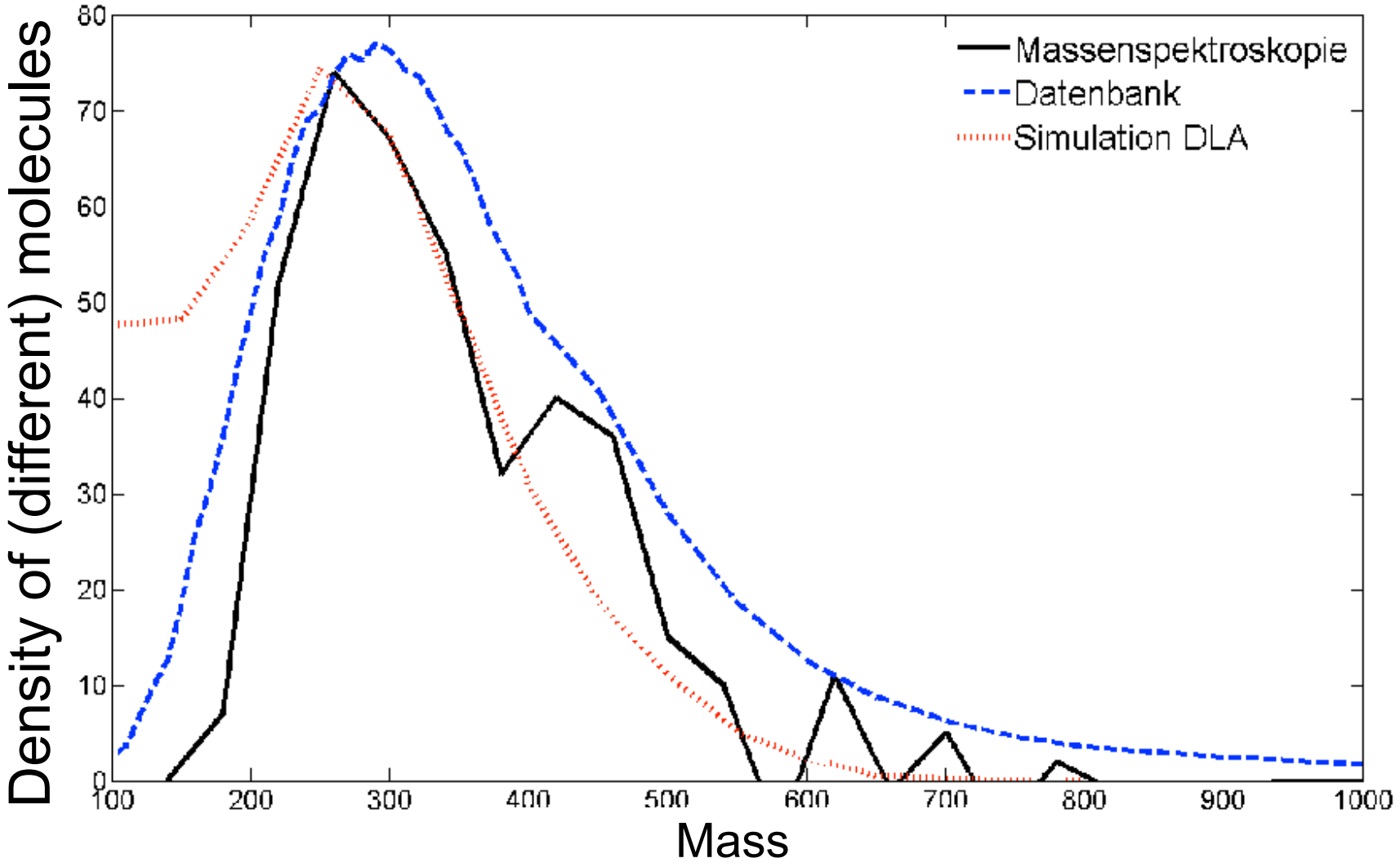


Separation by m/z

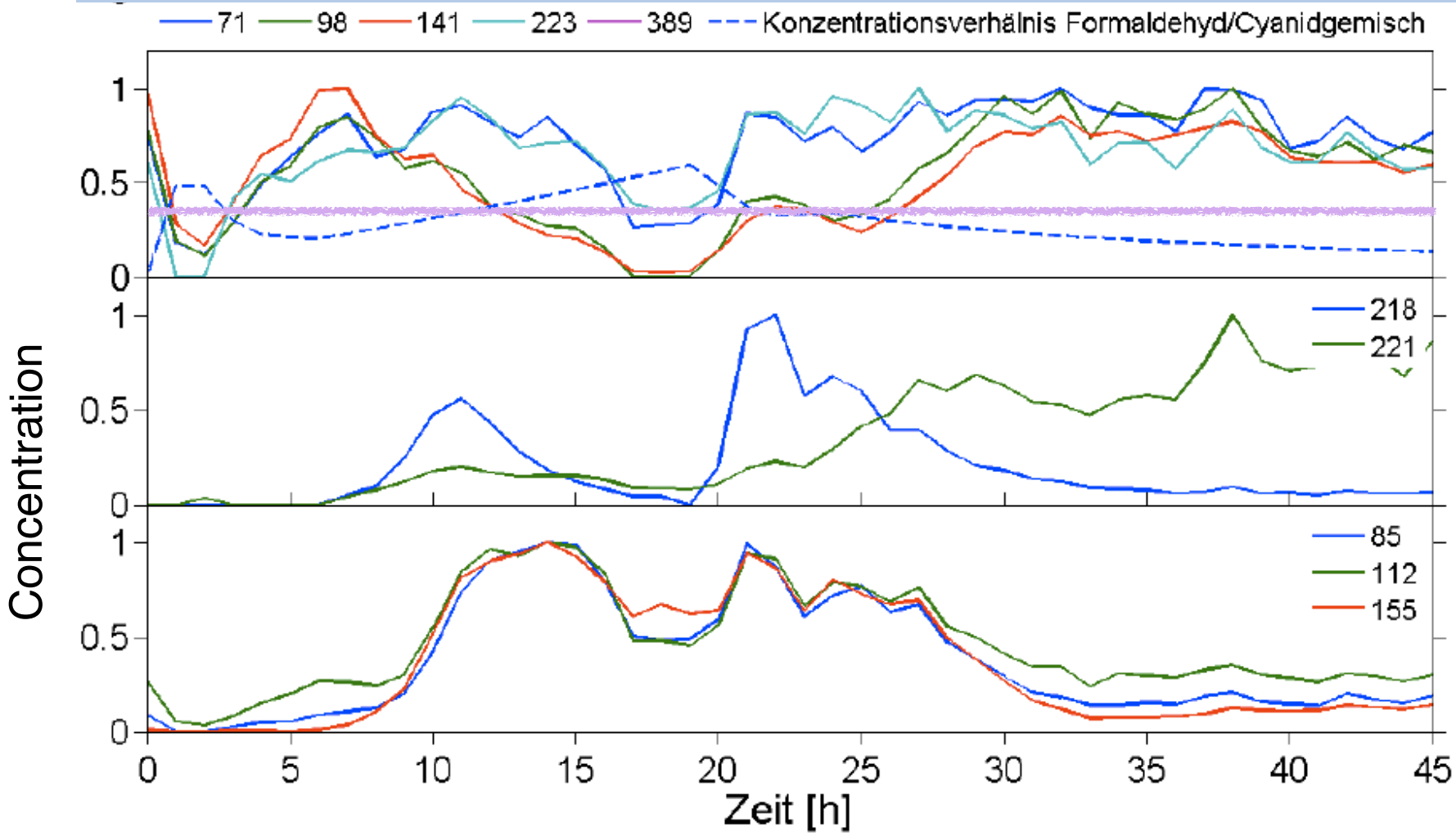
Time of flight measurement


Intensität [a.u.]
1500
1200
900
600
300
0
300
600
900
1200
Massen-Ladungsverhältnis m/z

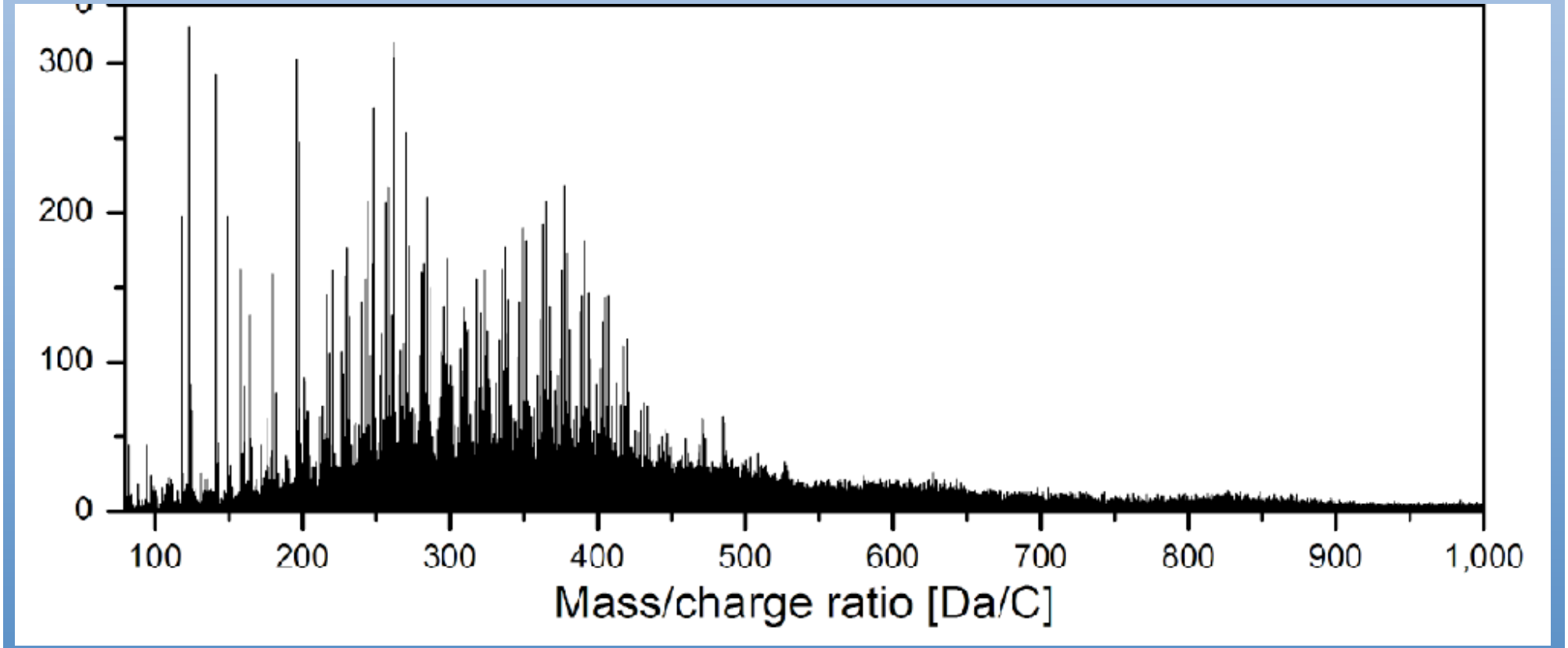

Anzahl Ausschläge Probe - Anzahl Ausschläge Wasser
bzw. Anzahl Einträge in Beilstein (skaliert)
Experiment
Beilstein (skaliert)
0
10
20
30
40
50
60
70
80
100
200
300
400
500
600
700
800
900
1000
m/z [u] (Messwerte) bzw. Masse m [u] (Beilstein)


Density of (different) molecules
Mass
Massenspektroskopie
Datenbank
Simulation DLA
0
10
20
30
40
50
60
70
80
100
200
300
400
500
600
700
800
900
1000

Non-linearity
formaldehyde - cyanide mixtures



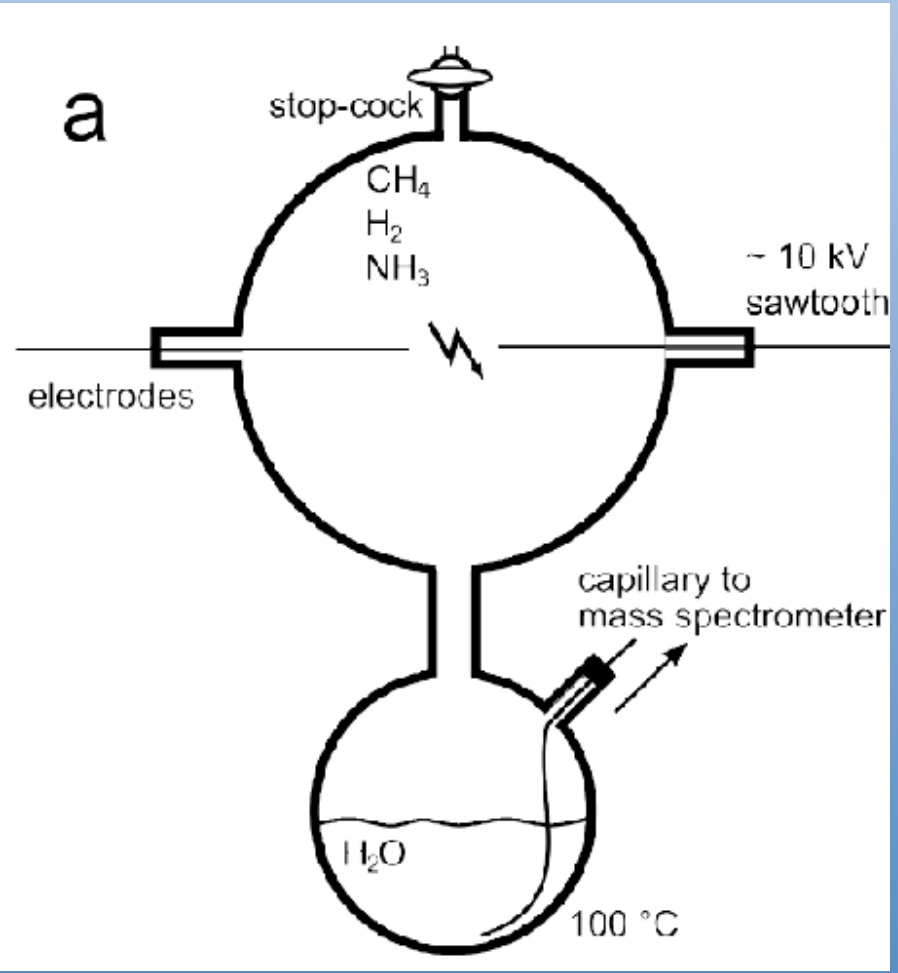
Electrical Potential: nothing....



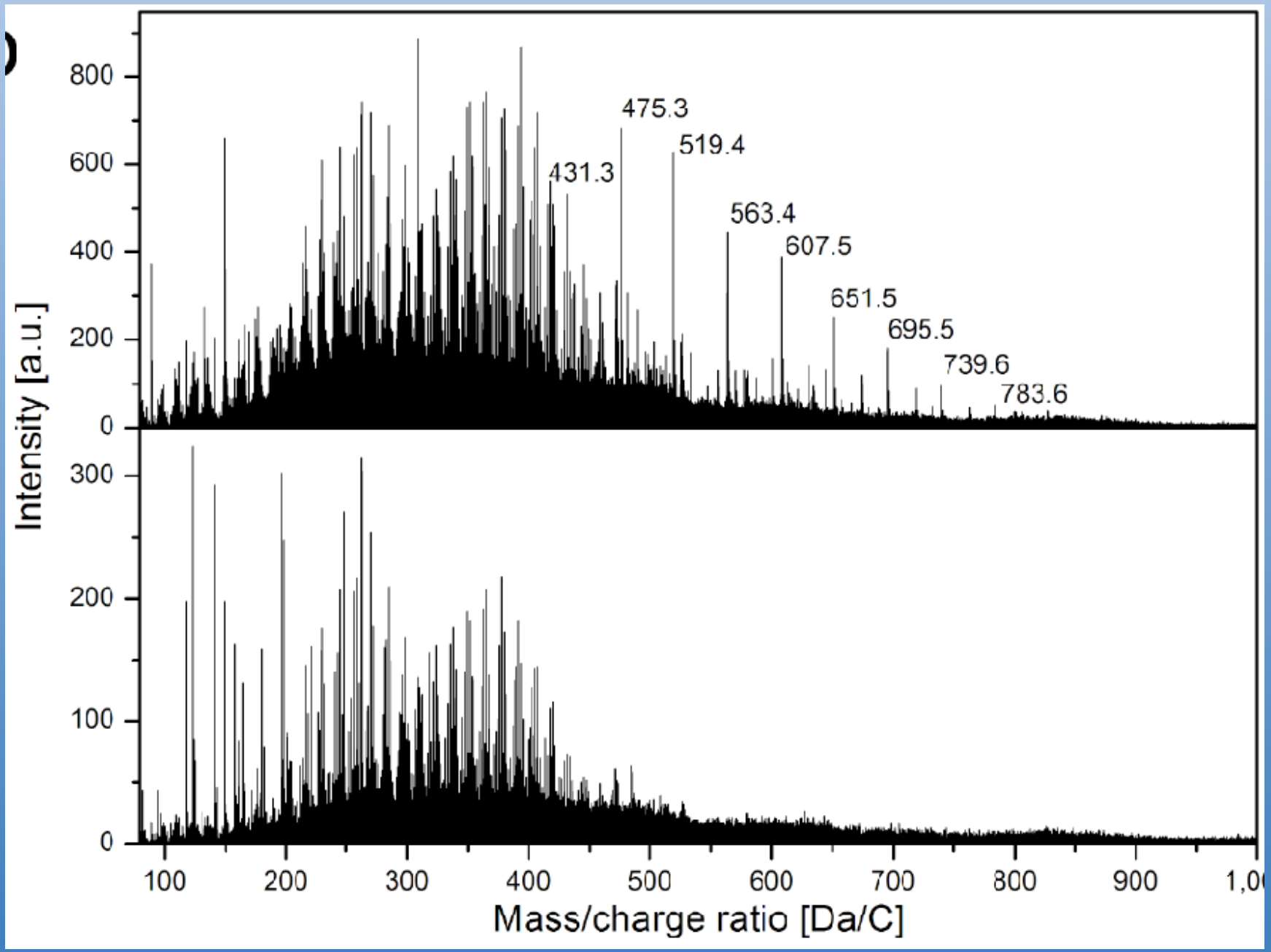
or a trivial answer ...

Energy Sources

- Iron-sulfur world hypothesis (Wächtershäuser): FeS, FeS_2 give energy and enable equivalent of the citric acid cycle
- Zn world hypothesis: Zn based minerals help in catalyzing polymerization
- Deep sea vent hypothesis: outflow of gases (also in lakes), reducing similar to Miller chemistry


a
stop-cock
CH_4
H_2
NH_3
~ 10 kV
sawtooth
electrodes
capillary to
mass spectrometer
H_2O
100 °C

Open Boundary: Miller Urey

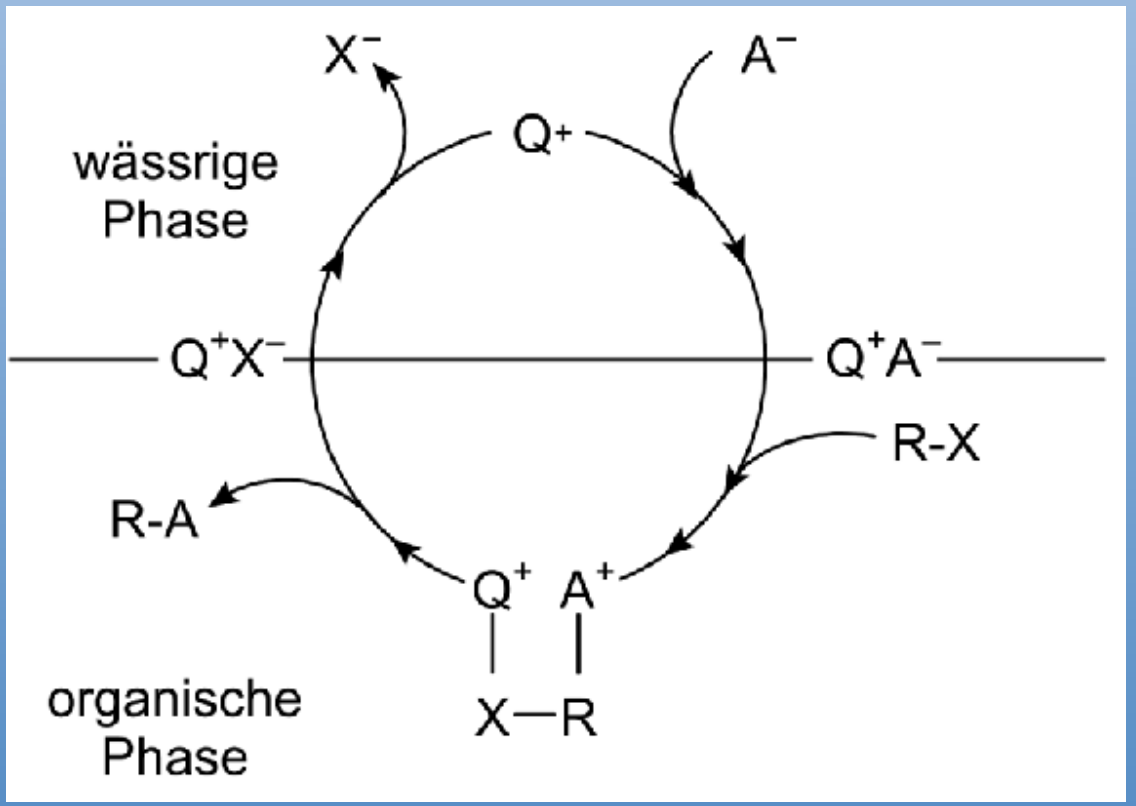


$\mathrm{H\text{-}(C_2H_4O)_{m=8..14}\text{-}OH}$
$\mathrm{H\text{-}(CH_2)_{10}\text{-}(C_2H_4O)_{m=4..9}\text{-}OH}$
$\mathrm{H\text{-}(CH_2)_{11}\text{-}(C_2H_4O)_{m=4..12}\text{-}OH}$
$\mathrm{H\text{-}(CH_2)_{12}\text{-}(C_2H_4O)_{m=3..10}\text{-}OH}$
$\mathrm{H\text{-}(CH_2)_{13}\text{-}(C_2H_4O)_{m=4..5}\text{-}OH}$
$\mathrm{(CH_2)_9\text{-}(C_2H_4O)_{m=6..7}}$
$\mathrm{H\text{-}(CHOHO)_5\text{-}CH_2O\text{-}(CH_2NH)_2\text{-}(C_2H_4O)_{m=4..5}\text{-}H}$

Amphiphilic Polyethyleneglycol

- Forms Micelles / Emulsifies with carbon tail

Phase Transfer Catalyst

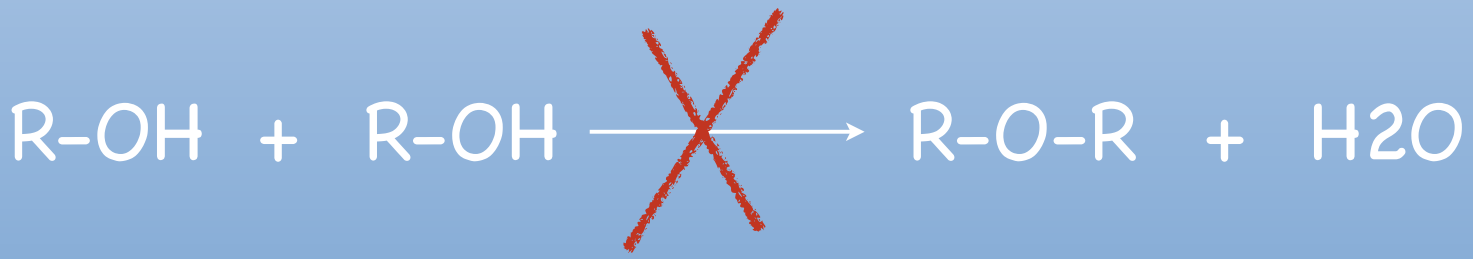


Here: NX4 and PEG ?

Phase Transfer Catalysis

- Many biomolecules could not form in pure water spontaneously
- PEG has been shown to produce DNA building blocks, peptides, … by PTC
  - avoids hydrolysis :

Polymerization

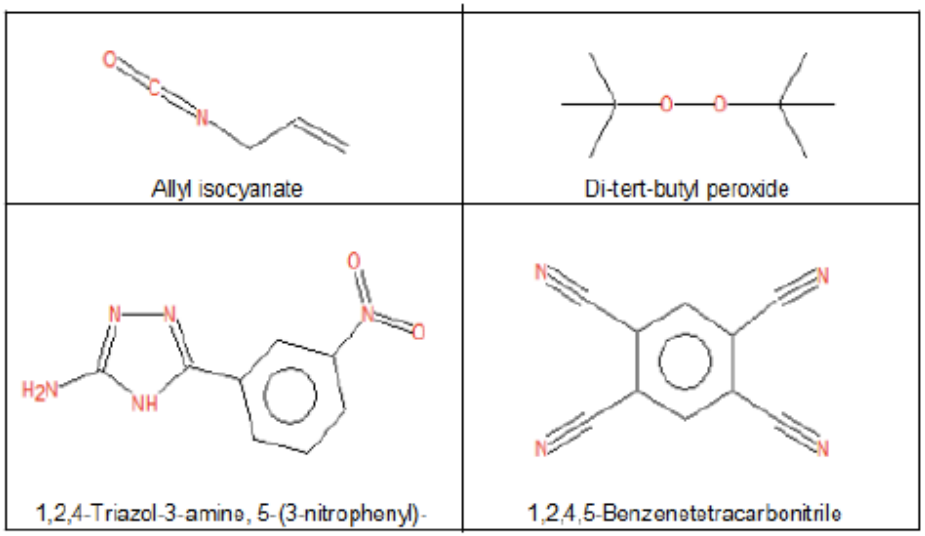


- in water nucleobases / amino acids do not polymerize (hydrolysis)
- @ interface this is possible (2011)
  charged lipids at surface + metal catalyst
- there is an oil layer on top of the broth !

Strong role of oxygen

- oxygen based surfactants in broth
- COOH group very likely to occur
- signature of oxygen incorporation in pairs
- peroxides are common - radical formation
- peroxide addition (H_2O_2) → PEG

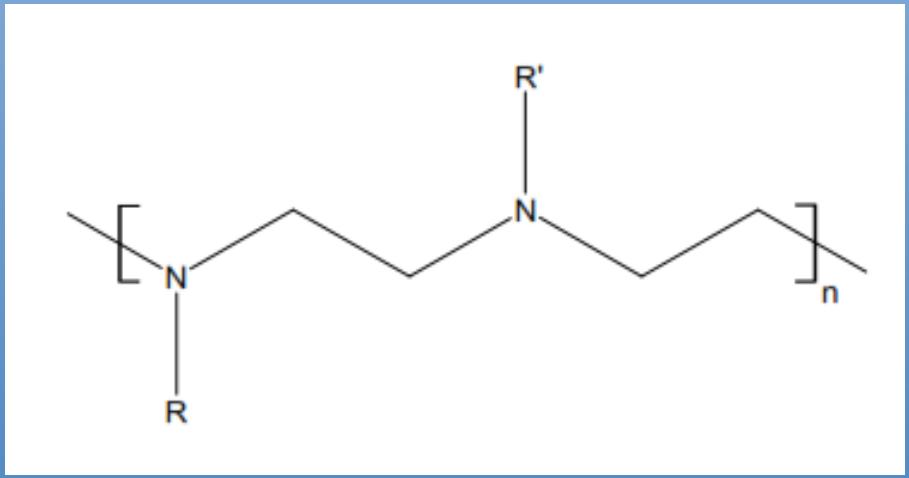
reactive molecules found in the organic phase by GC/MS



NMR

strong variations in broth composition

on polymers (chromatography purified)



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