

# Energy and matter at the origin of life

Nick Lane

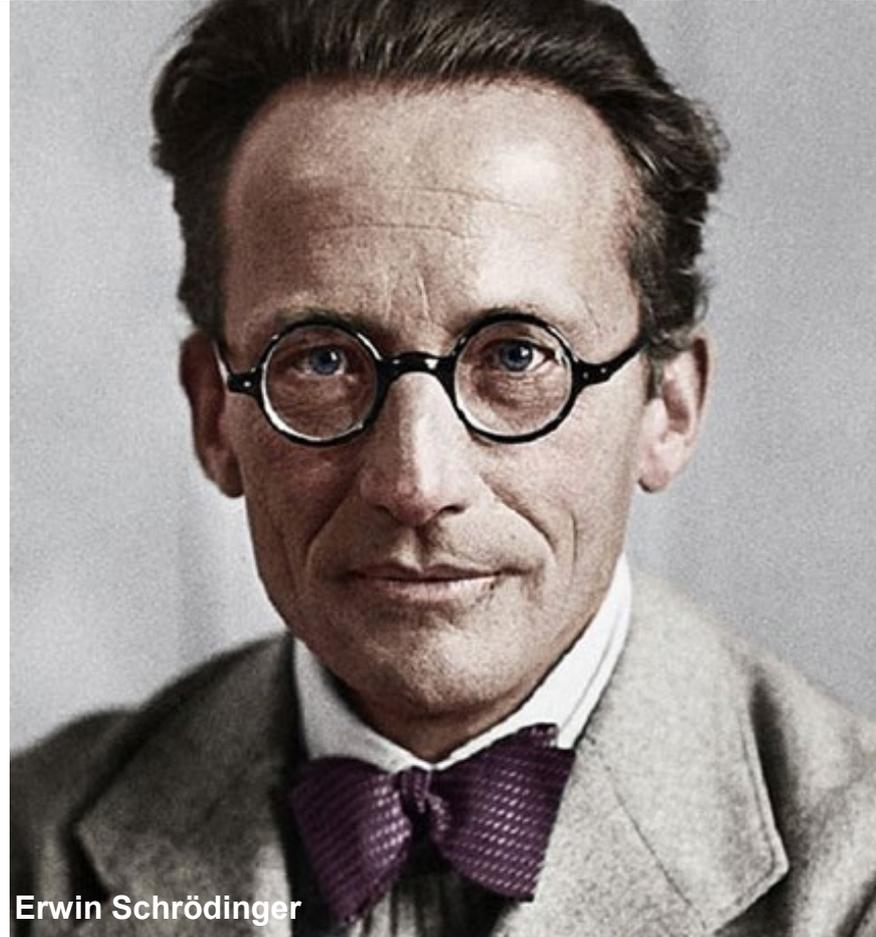
Professor of Evolutionary Biochemistry  
University College London

## Genes

“Chromosomes ... contain in some kind of **code-script** the entire pattern of the individual's future development and of its functioning in the mature state”

## Entropy

“Life feeds on negative entropy...The device by which an organism maintains itself stationary at a fairly high level of orderliness really consists in **continually sucking orderliness from its environment**”



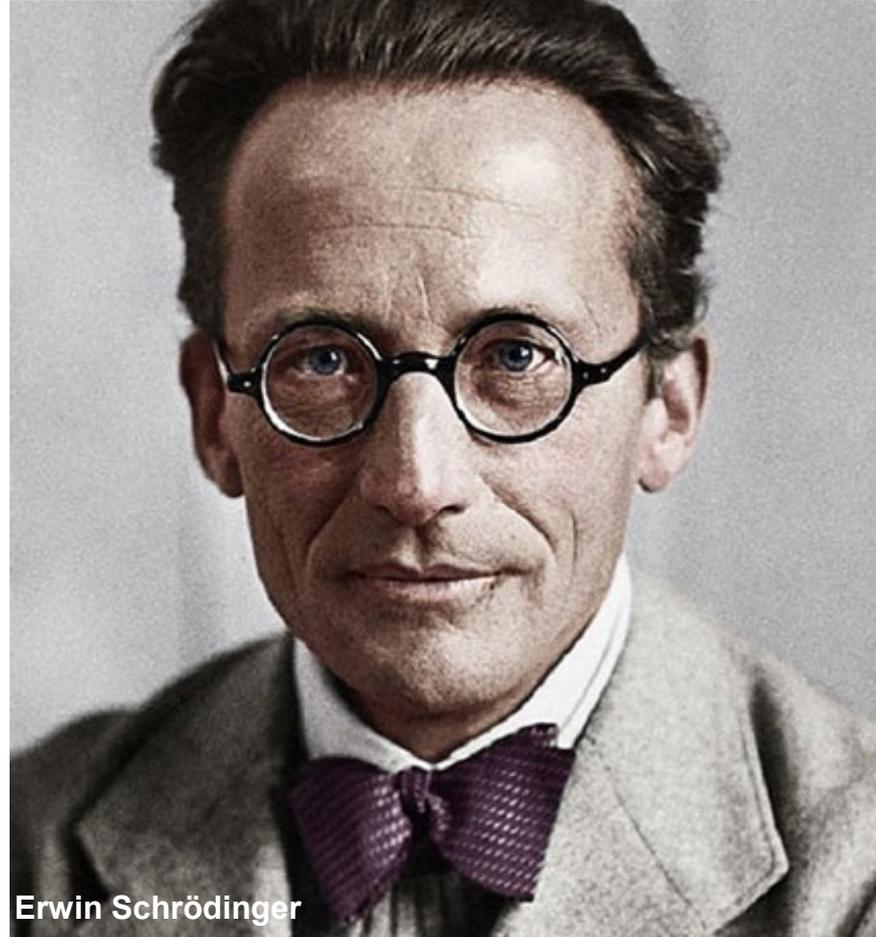
Erwin Schrödinger

## Genes

“Chromosomes ... contain in some kind of **code-script** the entire pattern of the individual's future development and of its functioning in the mature state”

## Energy

“If I had been catering for physicists alone I should have let the discussion turn on free energy instead.”



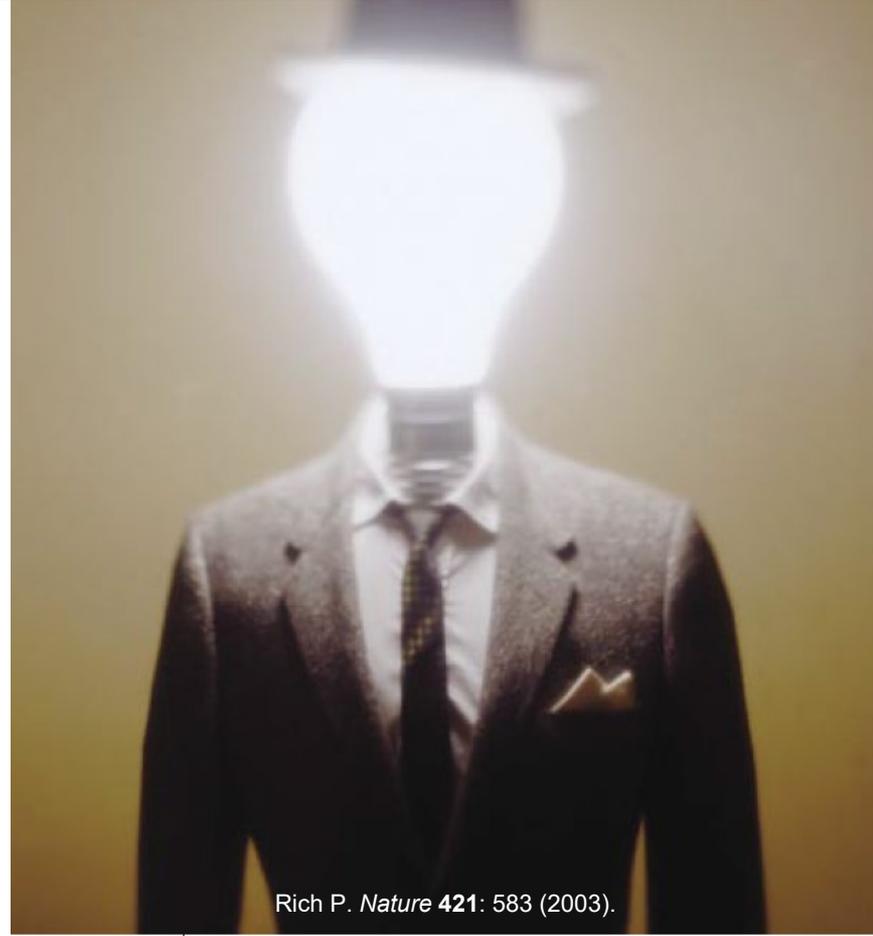
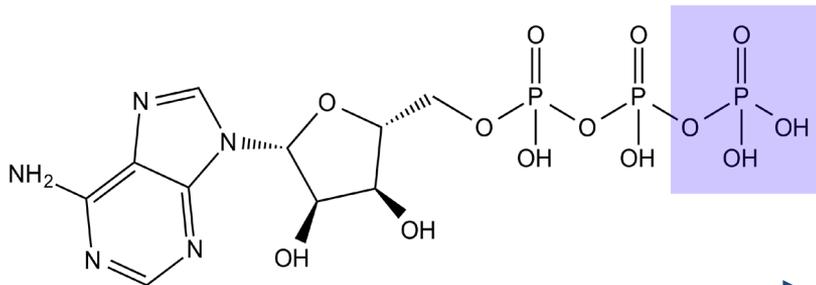
Erwin Schrödinger

# What is free energy?

Free energy is the energy available to power work e.g. muscle contraction

All our energy comes from burning food in oxygen – **cell respiration**

Respiration generates heat – entropy! –  
**but free energy is conserved as ATP**



# What is free energy?

Humans turnover >65 Kg ATP per day  
– our own bodyweight

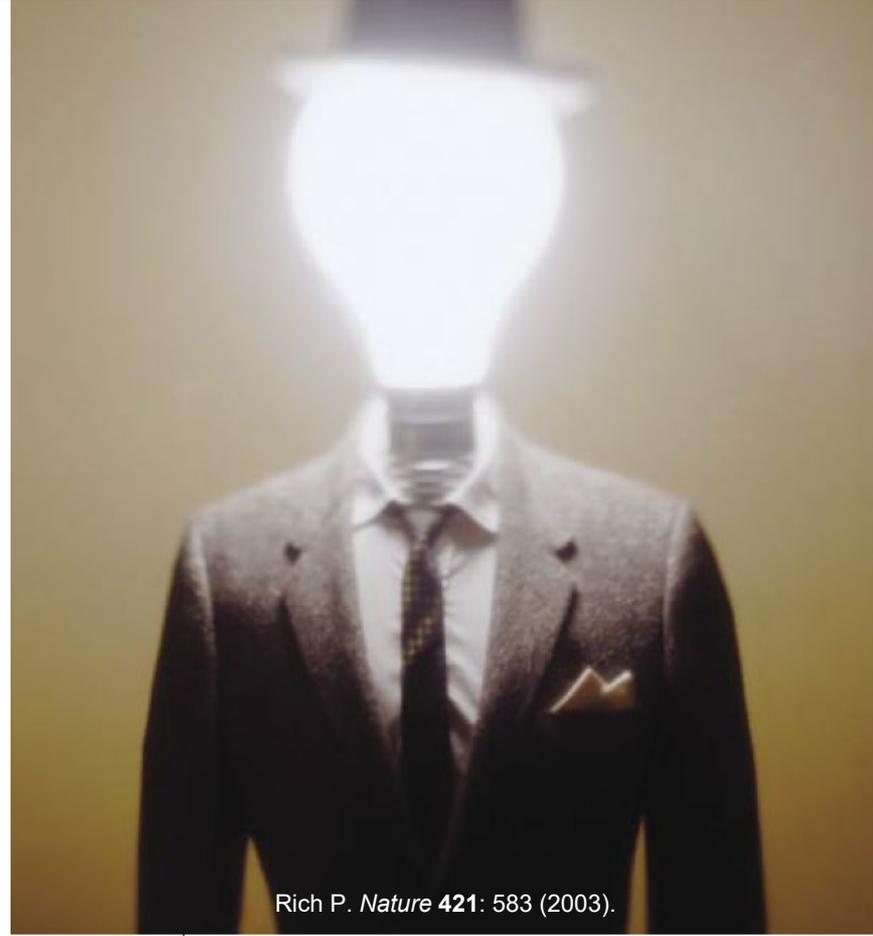
Ancient processes like methanogenesis



produce 16 grams of methane and 36 grams  
of water per 1.3 g cell

**40X the mass of excretion products  
as mass of cell**

Life is a **SIDE REACTION** of a  
main exothermic reaction

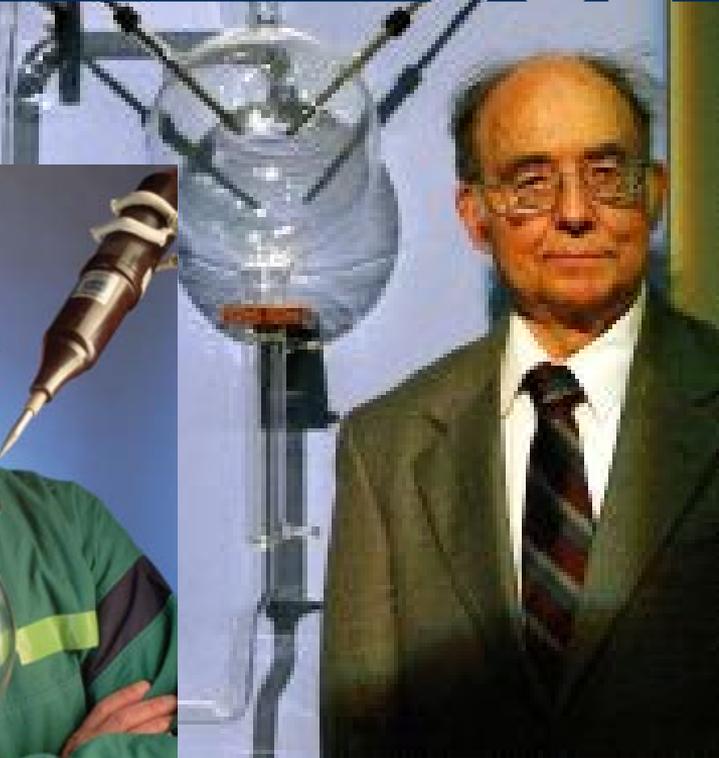
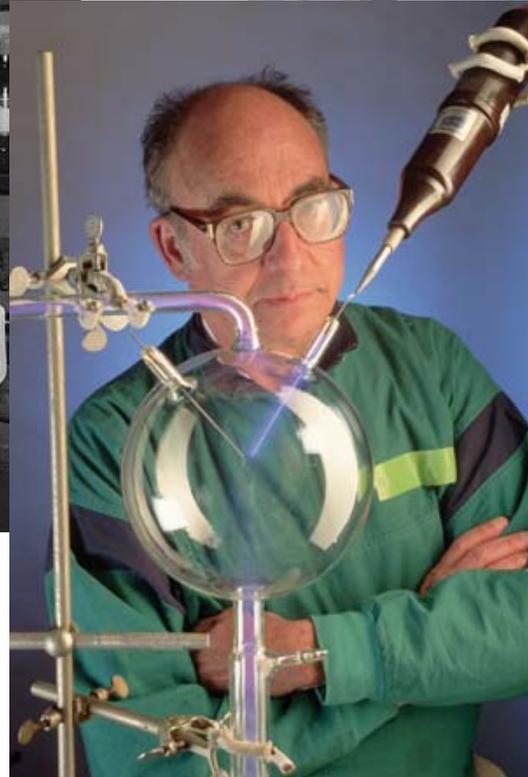


**At the origin of life, before the advent of evolutionarily refined enzymes**

**there must have been even greater flux through some main exothermic reaction to support doubling of organic matter**

**What was it?**

# Stanley Miller – from 1953



# Primordial soup



## QUICK & EASY DIRECTIONS

MIX SOUP + 1 OCEAN WATER

**RADIATION**: HEAT, UNCOVERED IN MICROWAVABLE OCEAN ON HIGH ABOUT 100 MILLION YEARS. CAREFULLY LEAVE IN OCEAN FOR 3 BILLION YEARS, ALLOWING OXYGEN TO ACCUMULATE.

**SMOKER**: HEAT, CIRCULATING OCCASIONALLY

REG. U.S. PAT. & TM. OFF.

# Campbell's®

CONDENSED

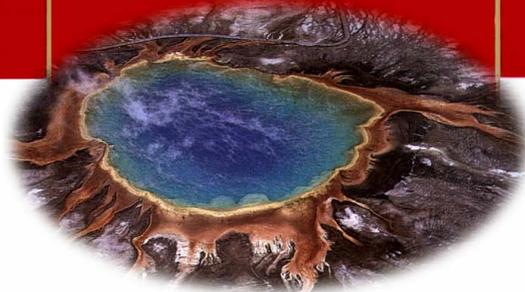


A QUICK MEAL IN 4.5 BILLION YEARS!

PRIMORDIAL SOUP; FOR THE PRIMITIVE...  
AND THE PRIMITIVE AT HEART!

A SIMPLE, SELF-ORGANIZING MEAL WITH EVERYTHING YOU NEED TO GET YOUR LIFE STARTED BEFORE THE ARCHAEOLOGICAL RECORD PASSES BY. GREAT FOR ALL WATERY PLANETS, SERVE HOT WITH LOTS OF REDUCING POWER AND A GOOD DOSE OF IONIZING RADIATION FOR THAT UNIQUE MICROBIAL FLAVOR!

PROMPTLY REFRIGERATE UNUSED PORTION ON A SEPARATE PLANET. RECOMMEND USE BY DATE ON END OF CAN. STORE UNOPENED CAN IN INTERSTELLAR SPACE.



Nutrition Facts	Amount/serving	%DV	Amount/serving	%DV
Protein	0%		Metal sulfides	100%
Fat	0%		Hydrogen	100%
Serv. Size 1 mole serves one planet	Carbohydrate	0%	Ammonia	100%
	Fiber	0%	Methane	100%
<b>Calories</b> 0.0	Vitamins	0%	Carbon monoxide	100%
Fat Calories 0.0	L-amino acids	1%	Formaldehyde	100%
Serving size based on a 99% chance of a successful Origin of Life.	D-amino acids	1%	High MW PAHs	100%
	Nucleic acid	0%	NP-40	100%

Rich in reducing power, low in toxic oxygen and reactive oxygen products. High in heavy and transition metals. Great for the hottest, most radioactive watery planets!

Satisfaction guaranteed. For questions or comments, please email arthur\_dent@zz9.plural.z.alpha Allow 5-6 x 10<sup>24</sup> years for refund or reply.

# Primordial



1251-108-10



WHERE ENZYMES AVAILABLE



# SOUP



NET WT.  
10 3/4 OZ.  
(305g)

INGREDIENTS: WATER, SILICA, IRON SULFIDE, HYDROGEN SULFIDE, CARBON DIOXIDE, HYDROGEN, POTASSIUM CYANIDE, POTASSIUM ACETATE, FORMALDEHYDE, ADENINE, PROLINE, ALANINE, METHANE, CARBON MONOXIDE, AMMONIA, SODIUM ARSENITE, GLYCEROL PHOSPHATE, ACETYLENE, ACETALDEHYDE, HIGH MOLECULAR-WEIGHT PAH'S, PYRENE, MAGNETITE, PHOSPHORIC ACID, WOLF'S TRACE MINERALS. AND NP-40.

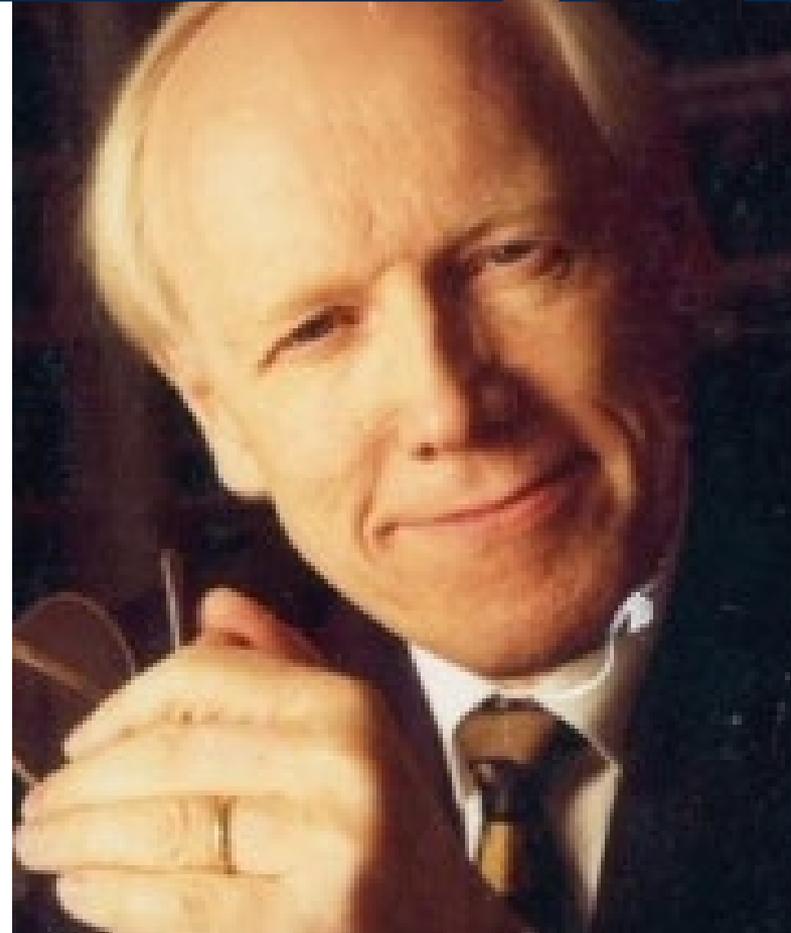
JWB MOCK SOUP COMPANY, RALEIGH, NORTH CAROLINA JAMES\_W\_BROWN@EARTHLINK.NET

No evidence it existed; nothing to contain the reactants; high entropy; no thermodynamic driving force

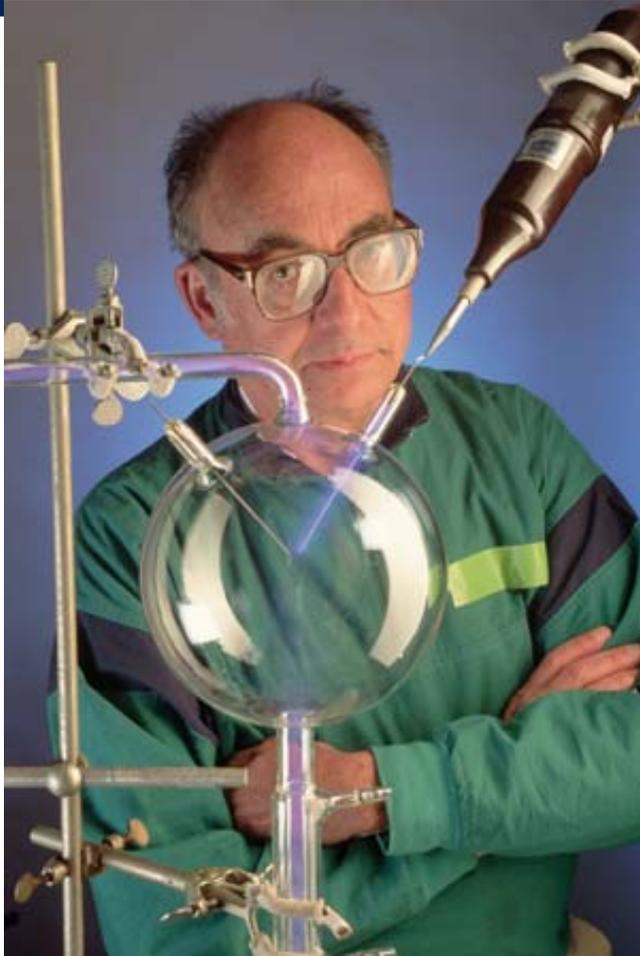
# No love lost

The prebiotic broth theory has received devastating criticism for being logically paradoxical, incompatible with thermodynamics, chemically and geochemically implausible, discontinuous with biology and biochemistry, and experimentally refuted.

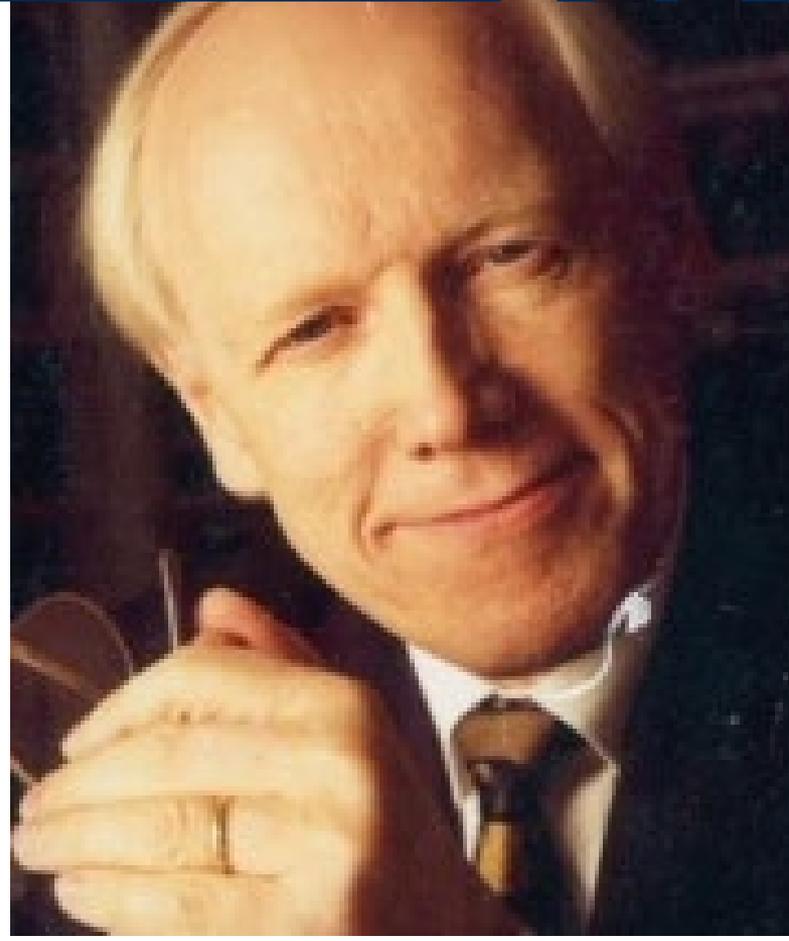
*Günter Wächtershäuser*



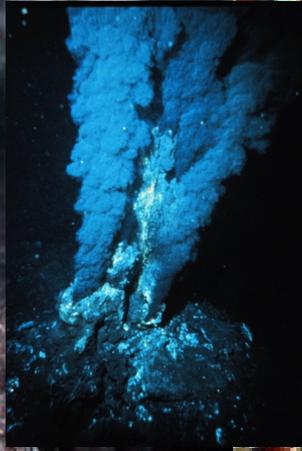
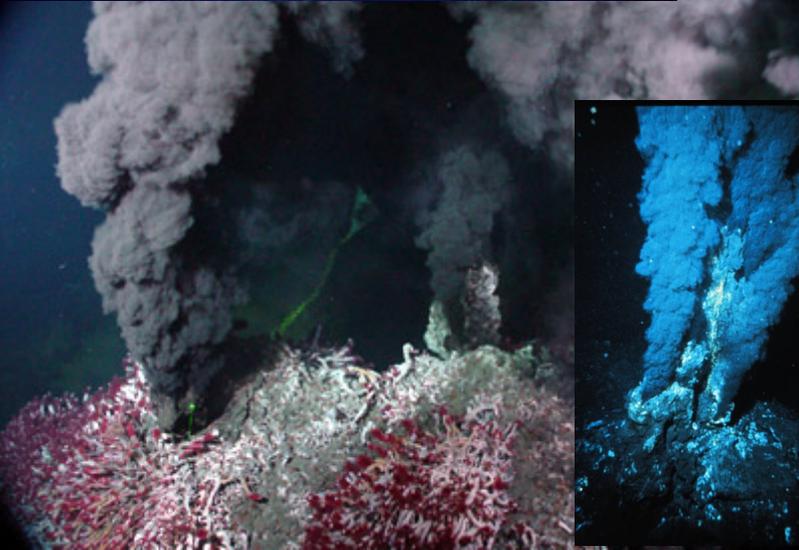
# No love lost



ory has  
criticism for  
ical,  
nodynamics,  
mically  
ous with  
ry, and



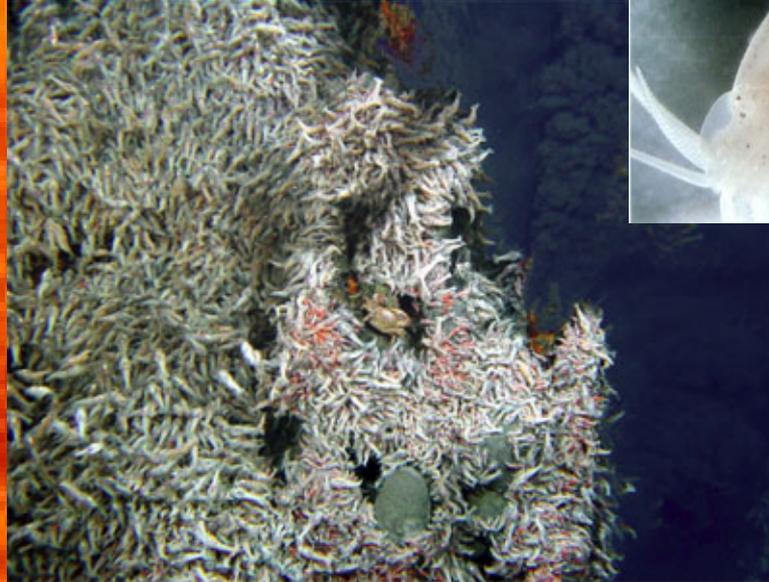
# Black smokers



# Life in black smokers depends on the sun



UCL



The energy in black smokers depends on the reaction of  $\text{H}_2\text{S}$  (or  $\text{H}_2$ ) with  $\text{O}_2$  – which derives from photosynthesis – the sun

# 'Life as we don't know it'

## The iron-sulfur world

Fool's gold ( $\text{FeS}_2$ )

Carbon monoxide ( $\text{CO}$ )

Sewer gas ( $\text{H}_2\text{S}$ )



# Cyanosulfidic protometabolism

Cyanide  
Cyanoacetylene  
Formamide  
UV radiation  
Zn sulphide  
Wet-dry cycles

# The unnatural origin of life?

## Frankenstein chemistry

No resemblance  
between prebiotic  
chemistry and  
biochemistry

Substrates – cyanide, cyanamide, formamide, PAHs (buckyballs from outer space!)

Solvents – formamide, silicate gels, supercritical water, wet-dry cycles

Catalysts – iron pyrites, borate, ZnS

Reaction pathways – cyanosulfidic protometabolism

Energy coupling – pyrites pulling, UV, heat, lightning, ZnS photosynthesis, radioactivity, proton radiation

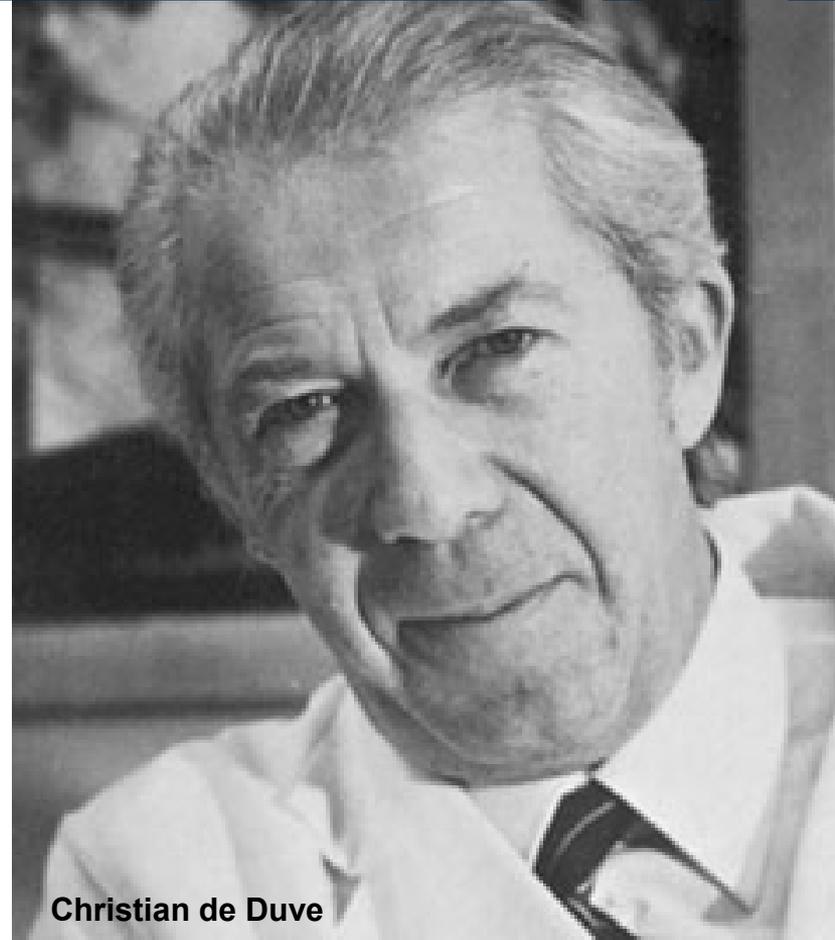
# Can life give insight into its own origins?

How did protometabolism come to be replaced by metabolism? The obvious answer to this question is that the appearance of catalysts, whether ribozymes, protein enzymes, or both, was responsible for the transition...

We have to ask how catalysts with appropriate properties came to appear...

**The only scientifically plausible explanation is that the catalysts arose through selection...**

**Enzymes are selected only if they fit into protometabolism**



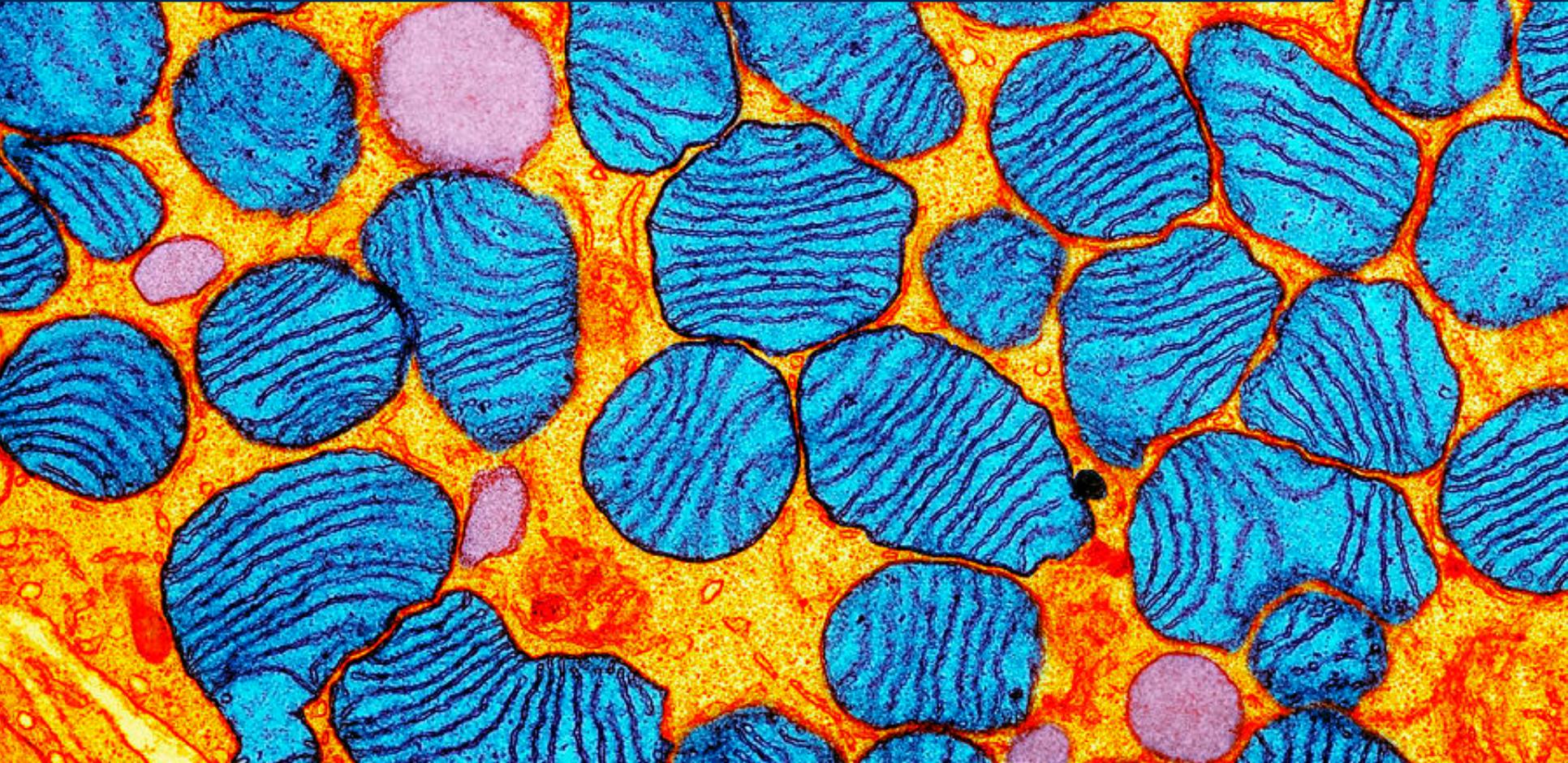
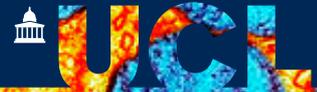
Christian de Duve

Is there a universal form of free energy conservation across all living things?

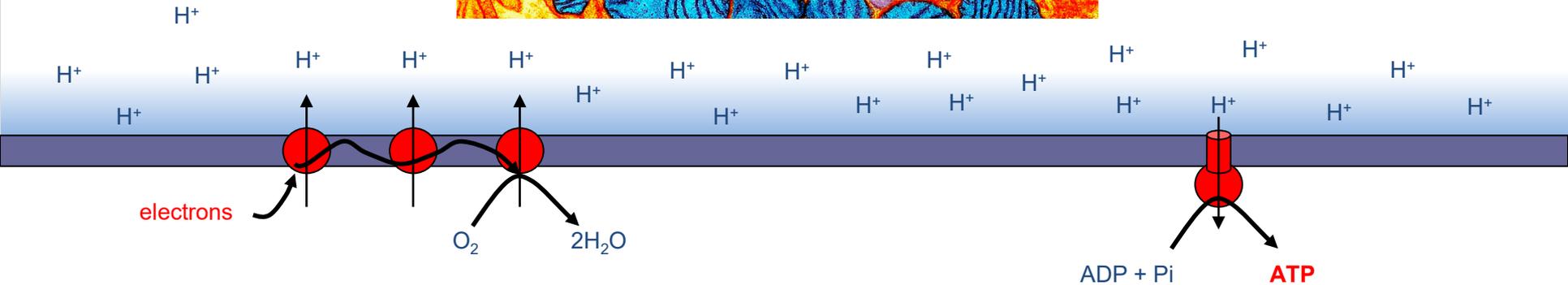
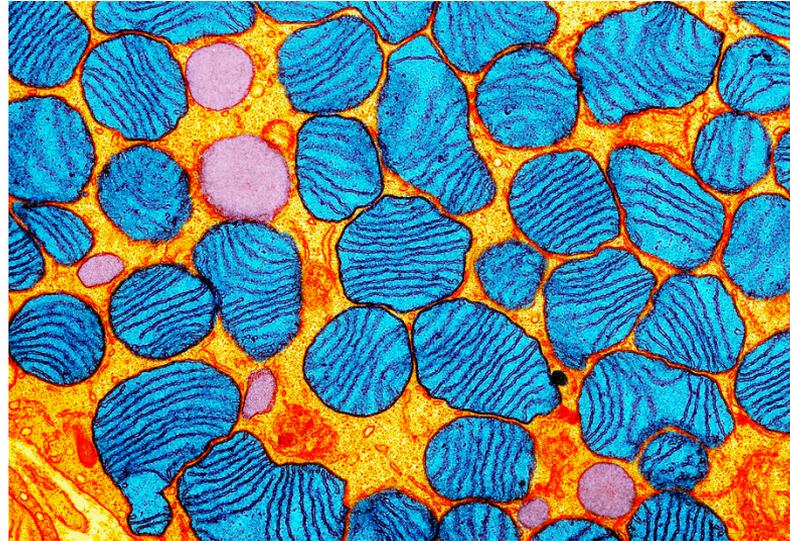
Yes: the use of ion gradients over membranes to power growth

**Proton gradients across membranes are as universal as the genetic code**

# What's happening in you right now

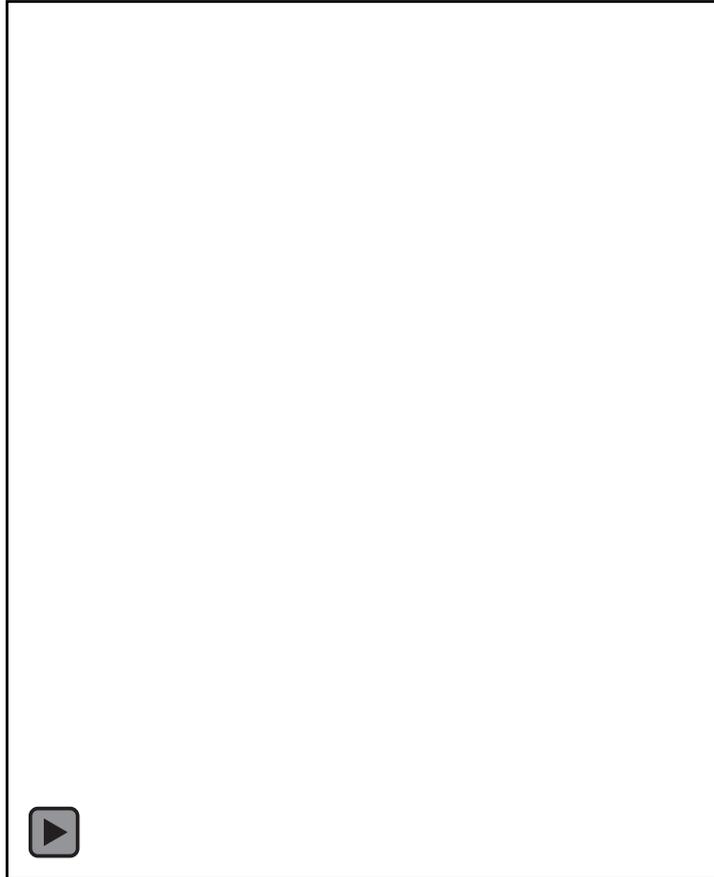


# What's happening in you right now





**ATP synthase  
is an amazing  
rotary motor  
set in the  
membrane –  
a turbine**



Sir John Walker

# Proton gradients are fundamental

“Not since Darwin has biology come up with an idea as counterintuitive as those of, say, Einstein, Heisenberg or Schrödinger...” Leslie Orgel

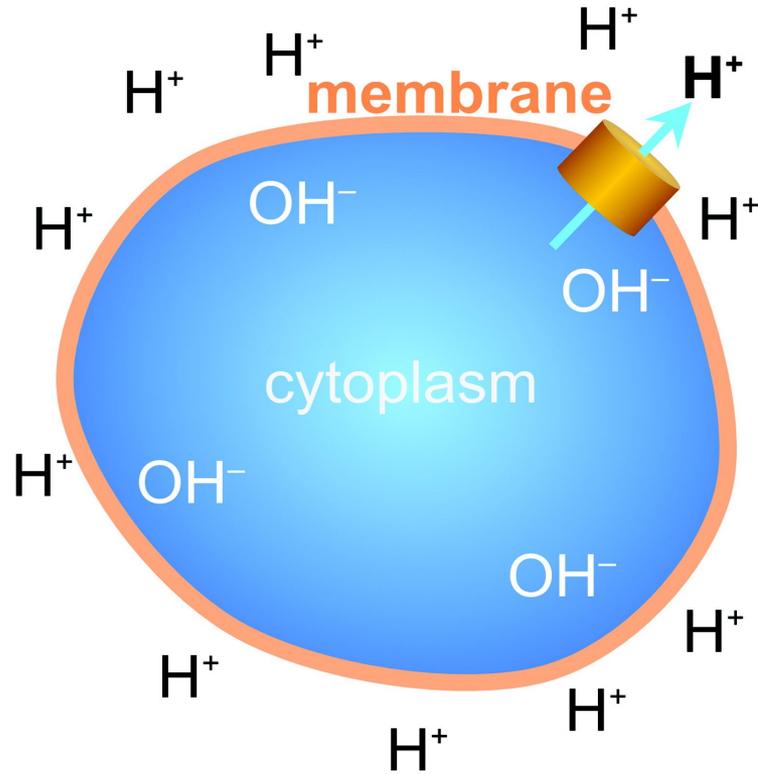


Jennifer Moyle and Peter Mitchell

**“I cannot consider the organism without its environment... from a formal point of view the two may be regarded as equivalent phases between which dynamic contact is maintained by the membranes that separate and link them.”**

**Peter Mitchell, 1957**

# How do bacteria keep the outside out?

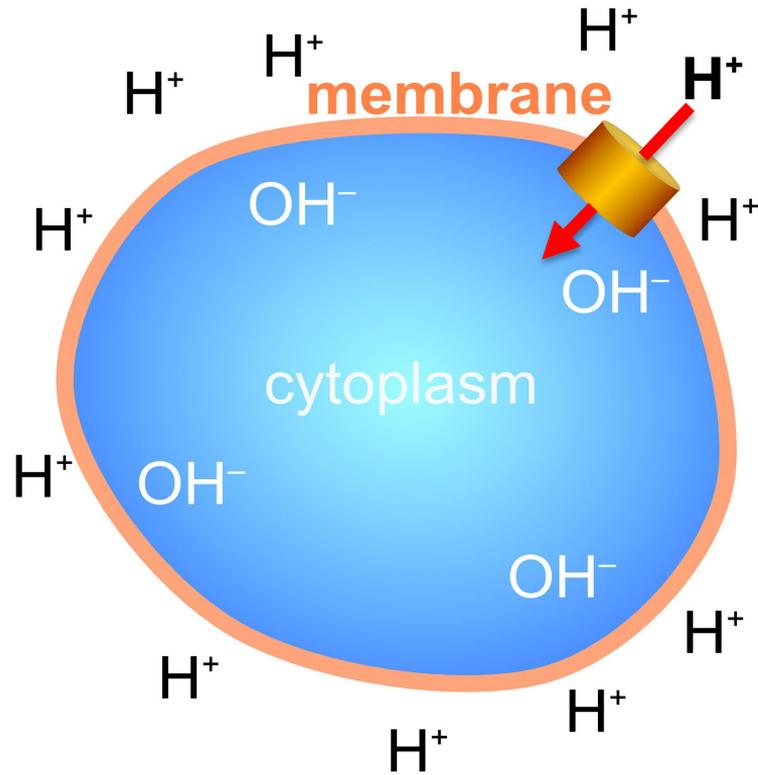


It costs energy to keep the outside out



Peter Mitchell

# How do bacteria keep the outside out?

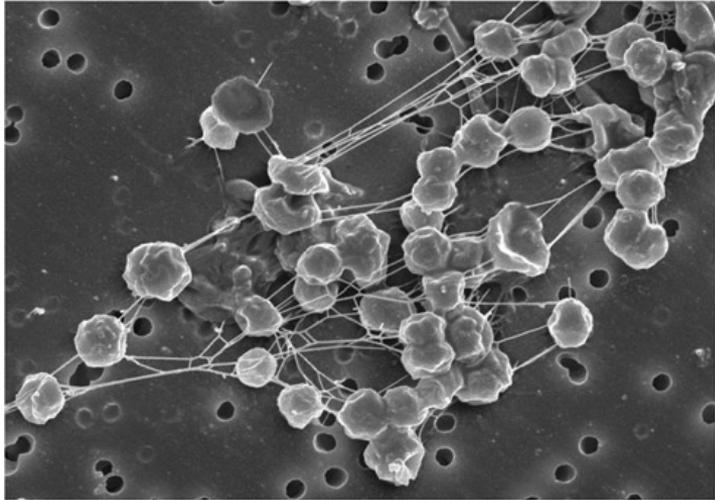


Energy is released by letting the outside in



Peter Mitchell

# Even very early cells used proton gradients

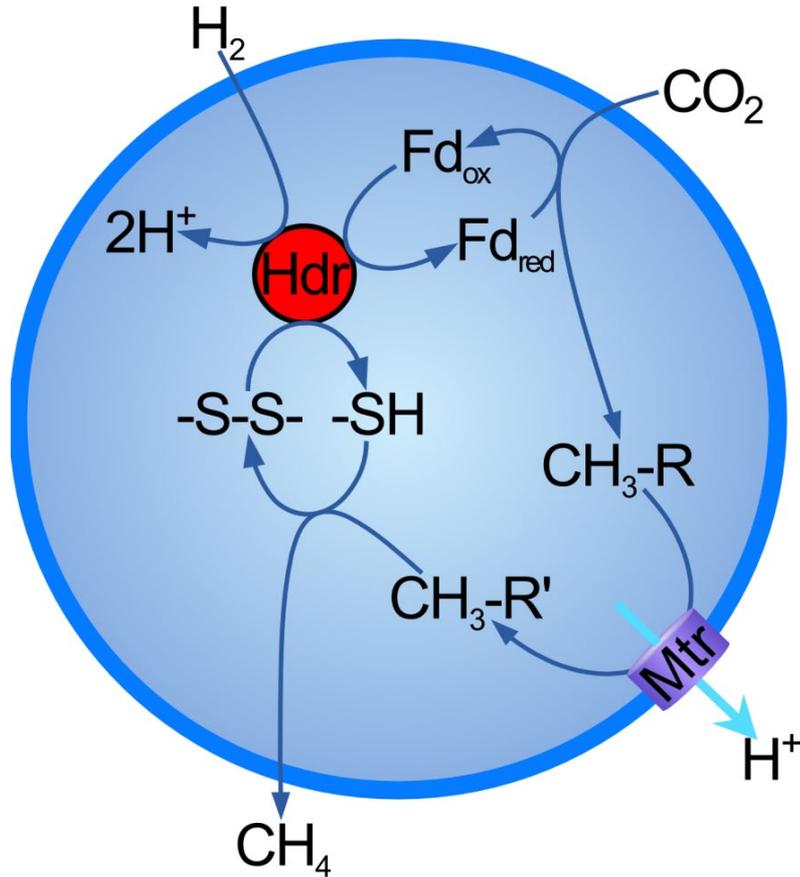


Methanogens – archaea



To drive the reaction between  $\text{H}_2$  and  $\text{CO}_2$  methanogens need a **proton gradient**

# Methanogenesis generates a proton gradient



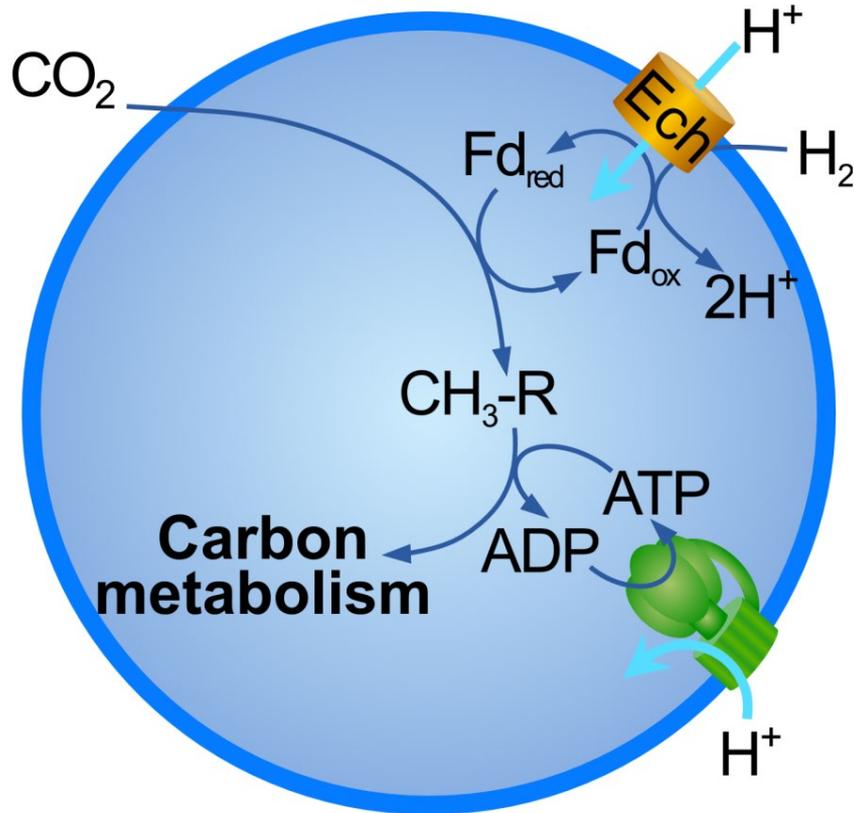
Wolfgang Buckel



Rolf Thauer

Methanogenesis generates an  $H^+/Na^+$  gradient via flavin-based electron bifurcation

# Proton gradient drives growth via Ech



The proton gradient drives  $\text{CO}_2$  fixation via a simple membrane protein: **Ech** or **Energy-converting hydrogenase**

**Could geological proton gradients have driven the growth of protocells at the origin of life?**

# Alkaline hydrothermal vents



UCL



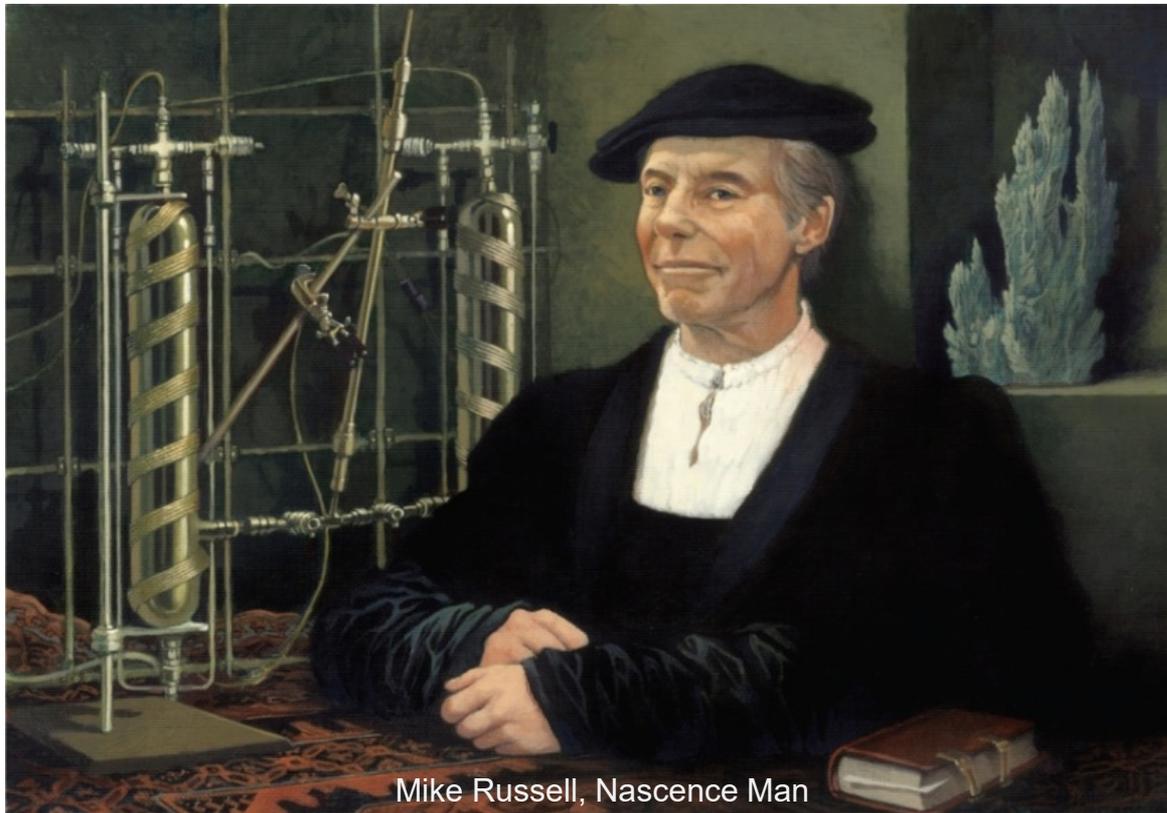
**Lost City vent field**



Deborah Kelley



# Electrochemical flow reactors



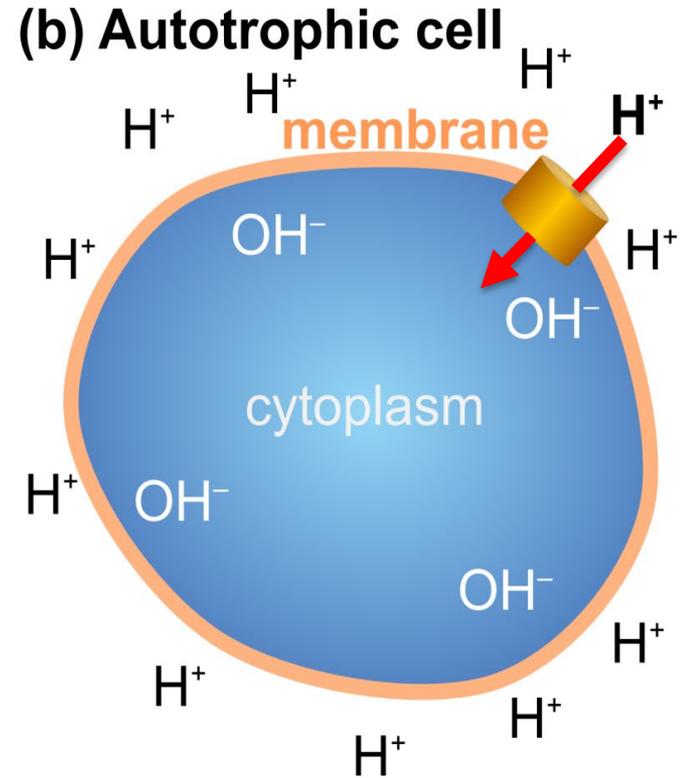
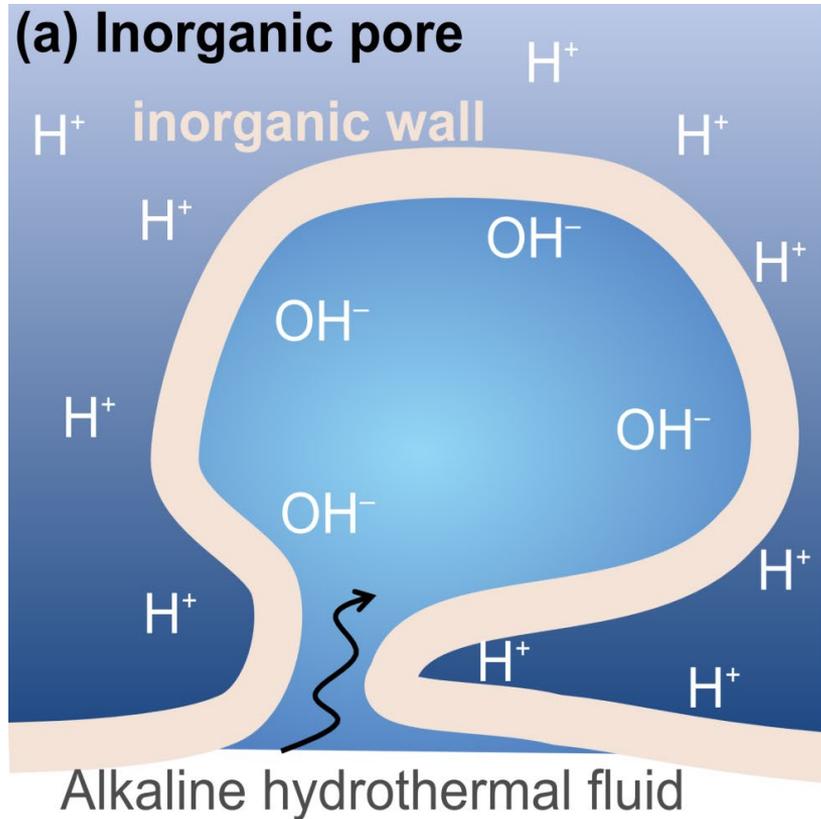
Mike Russell, Nascence Man

High concentrations of  $H_2$  and  $CO_2$   
**Proton gradients across catalytic FeS walls**



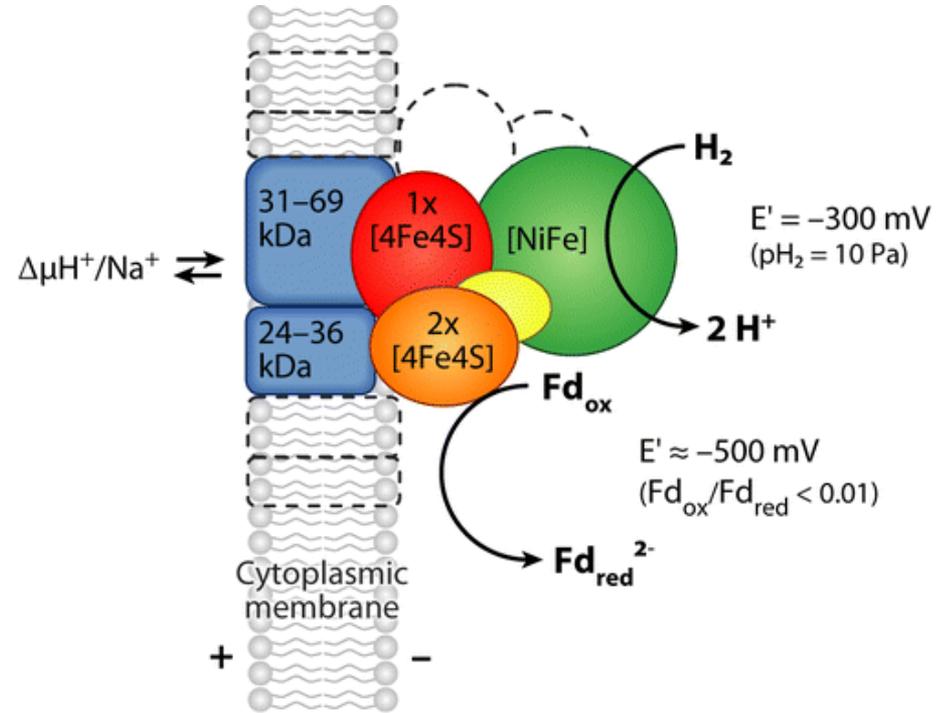
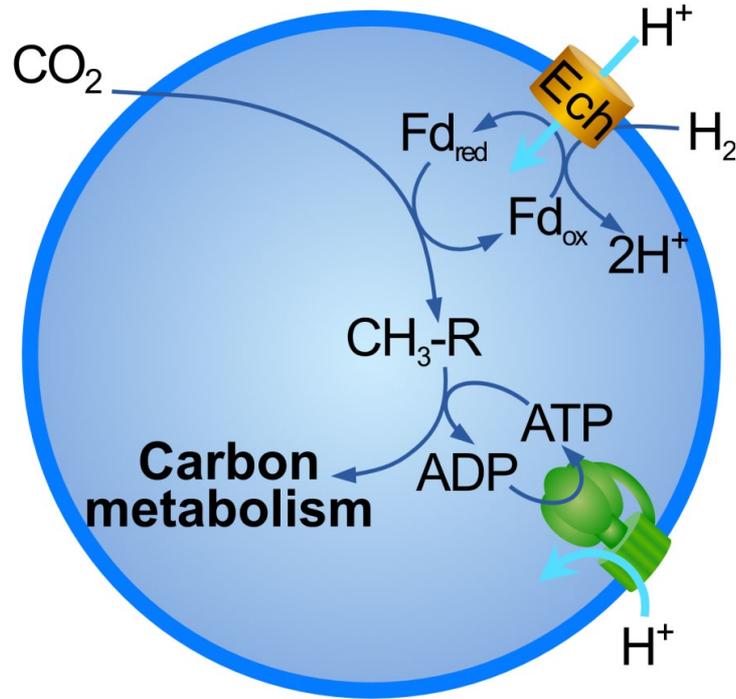
0.5 mm

# Vent pores are similar in topology to cells



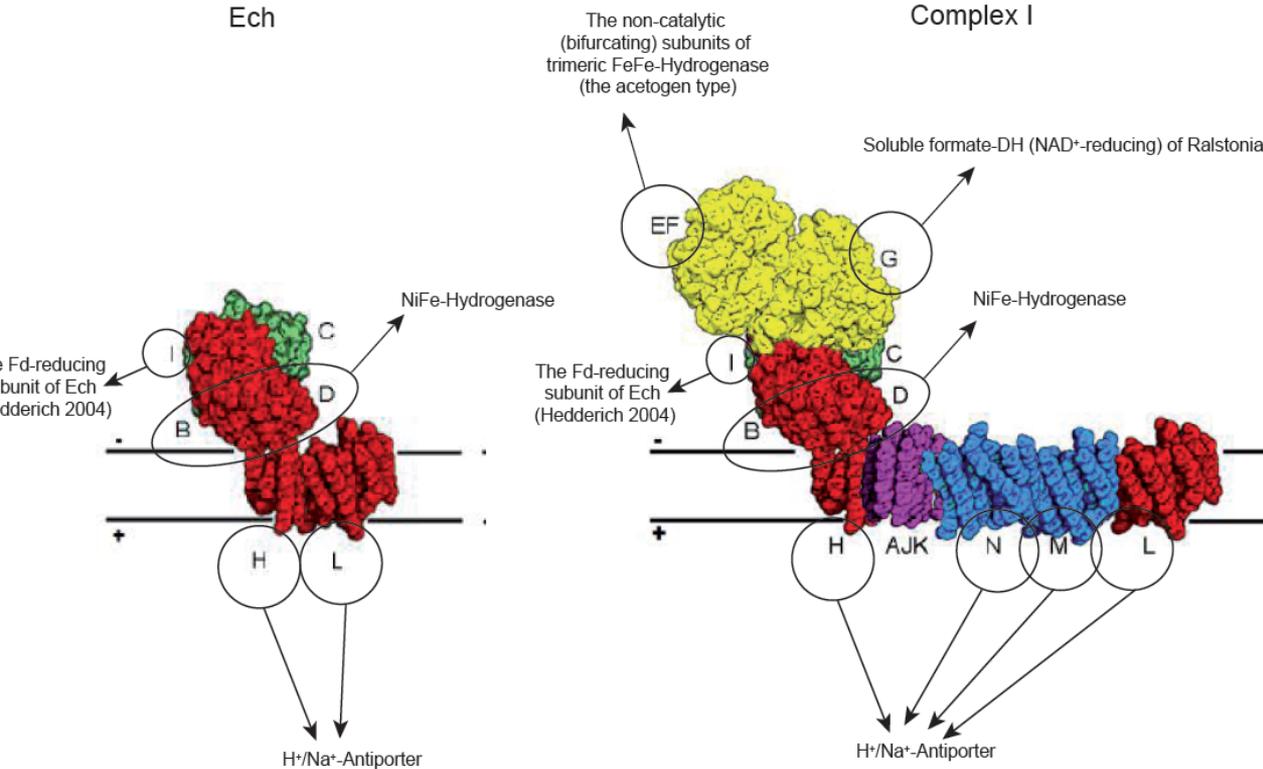
**But how could proton gradients across pores drive the evolution of cells?**

# Proton gradient drives growth via Ech



Ech uses the proton gradient to drive the difficult reduction of ferredoxin

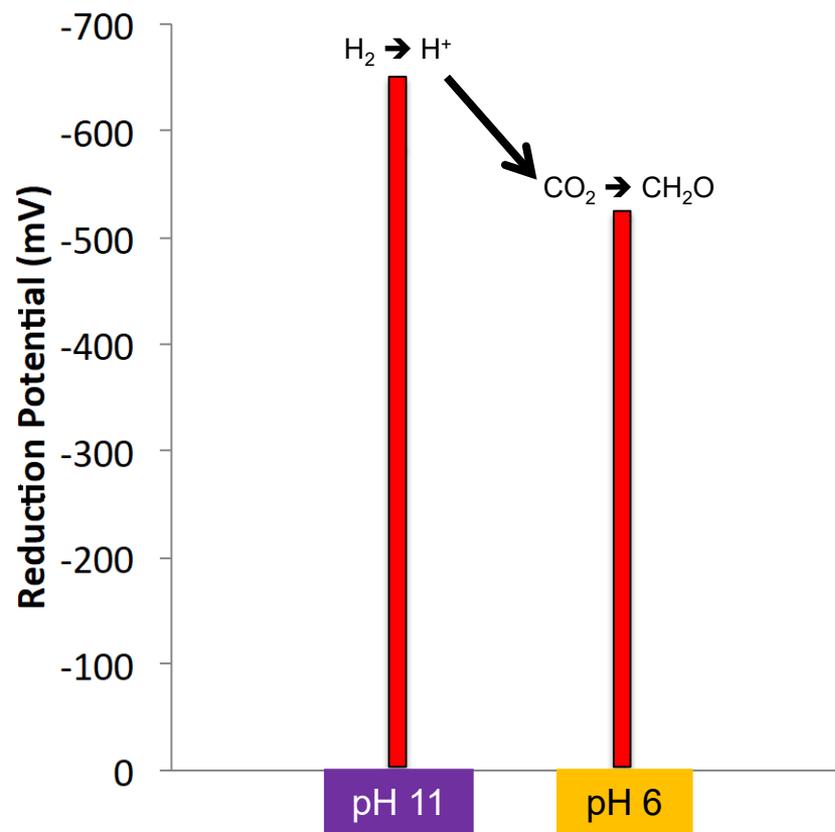
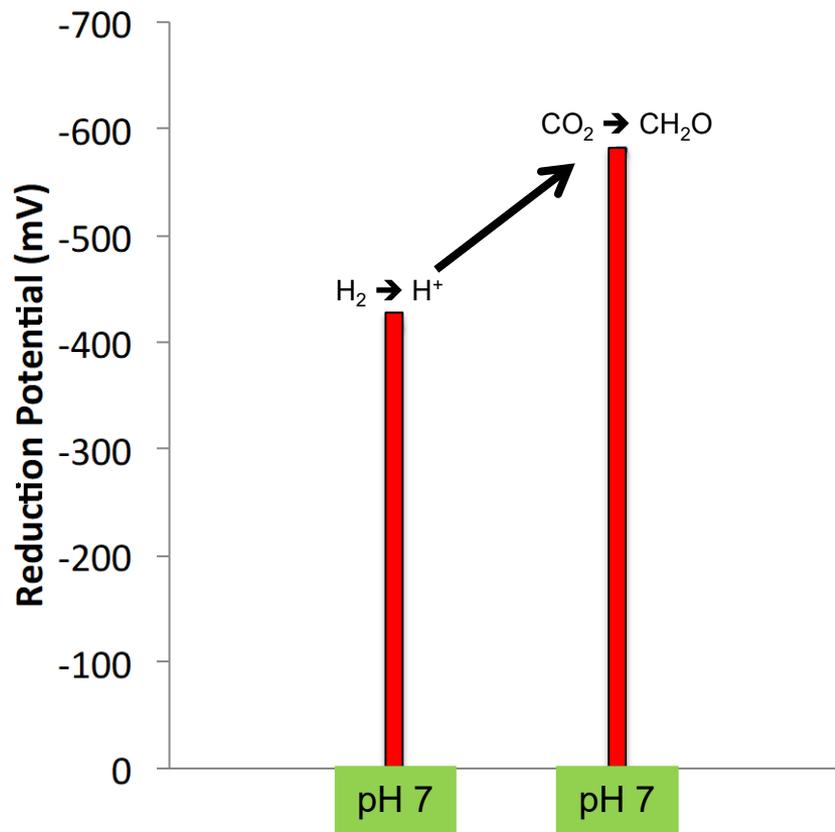
# Ech is still used in our own respiration



Manuela Pereira

**History is buried in molecular biology**

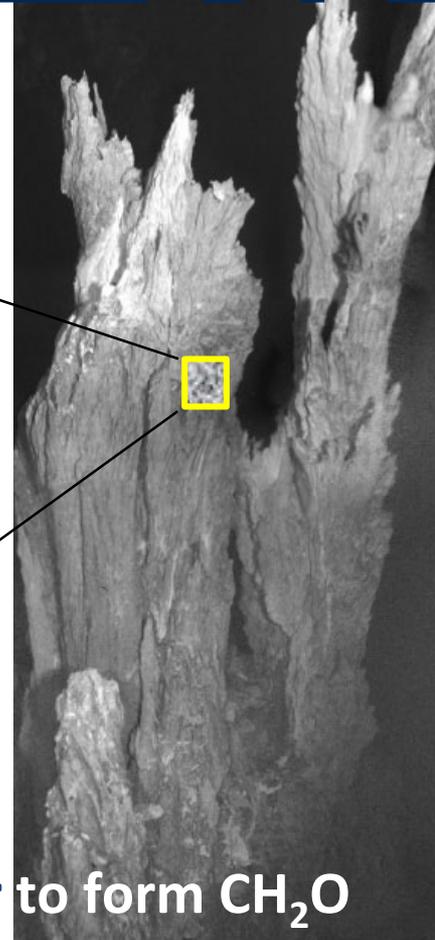
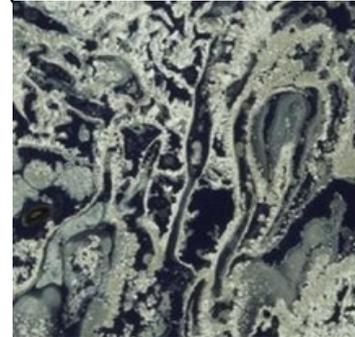
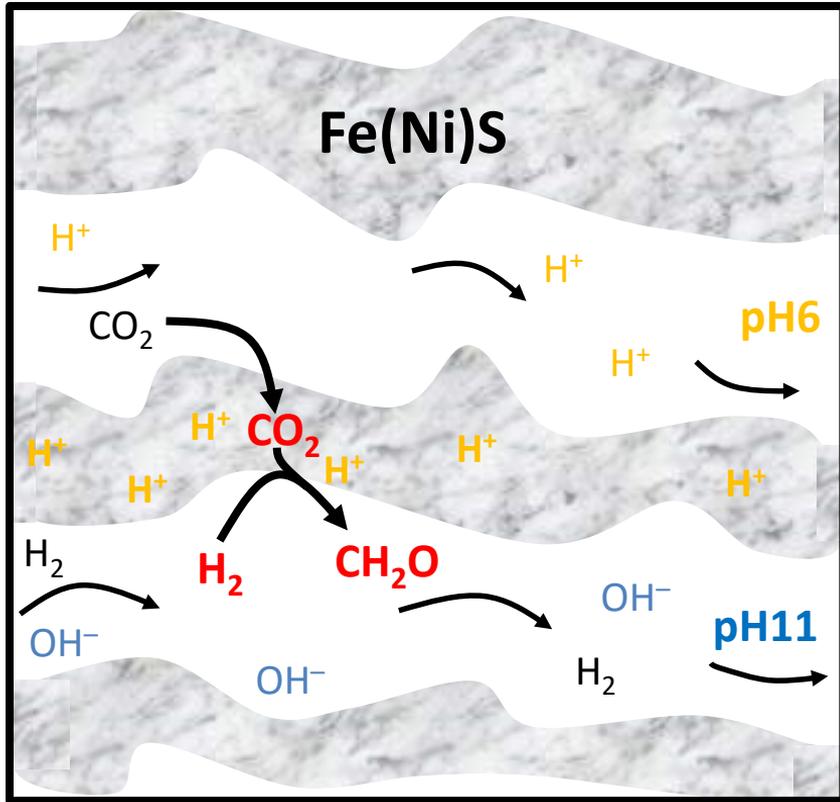
# Reactivity of $H_2$ and $CO_2$ depends on pH



# Gradients, structure & flow drives growth

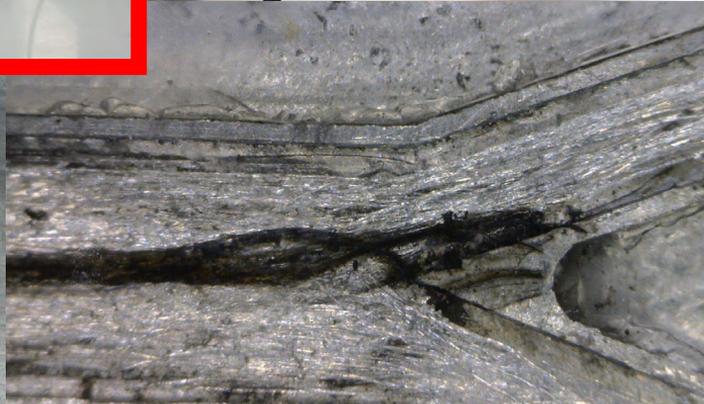
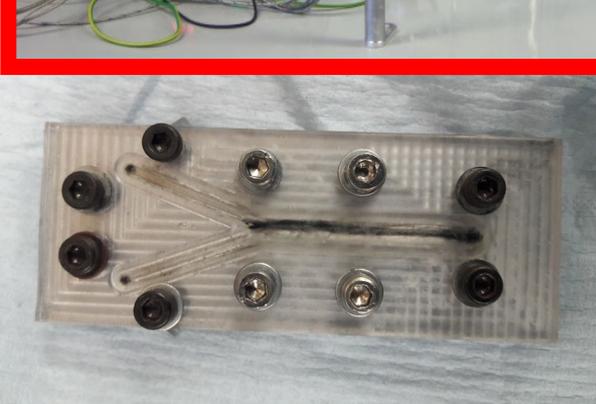
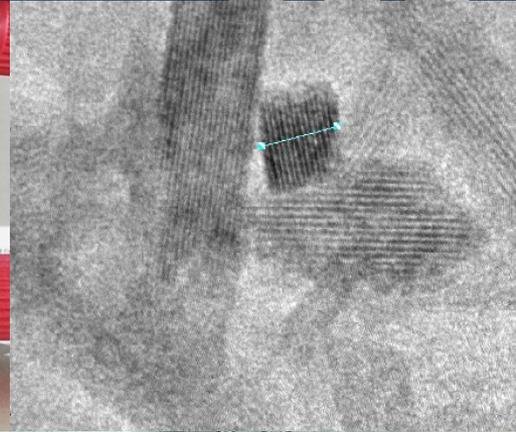


UCL



**$\text{H}_2$  should reduce  $\text{CO}_2$  across a semiconducting barrier to form  $\text{CH}_2\text{O}$**

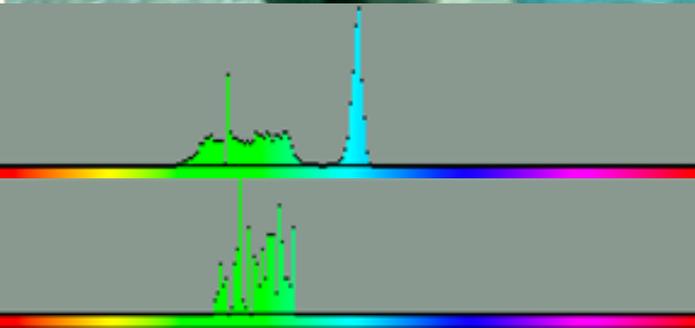
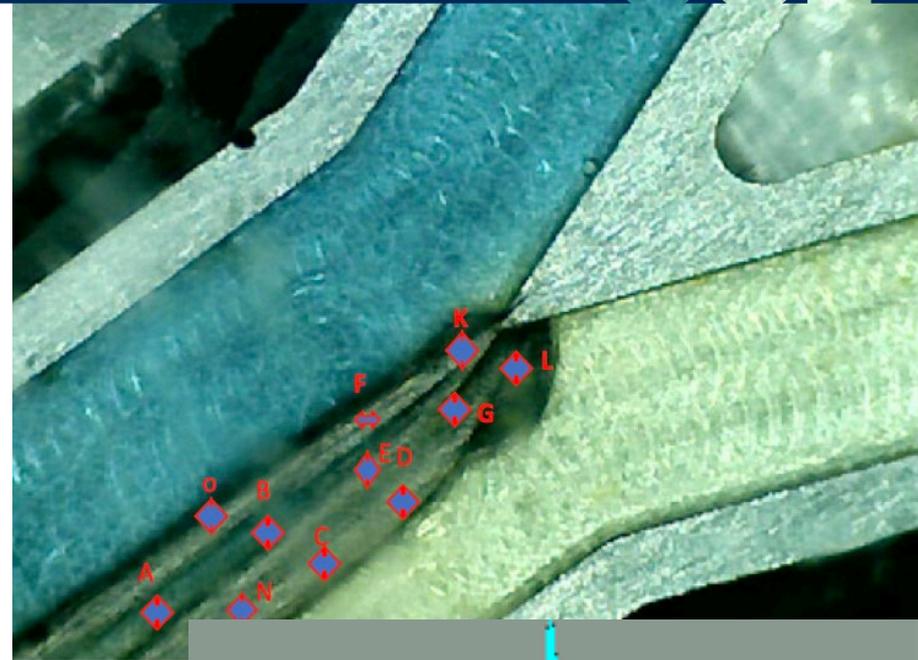
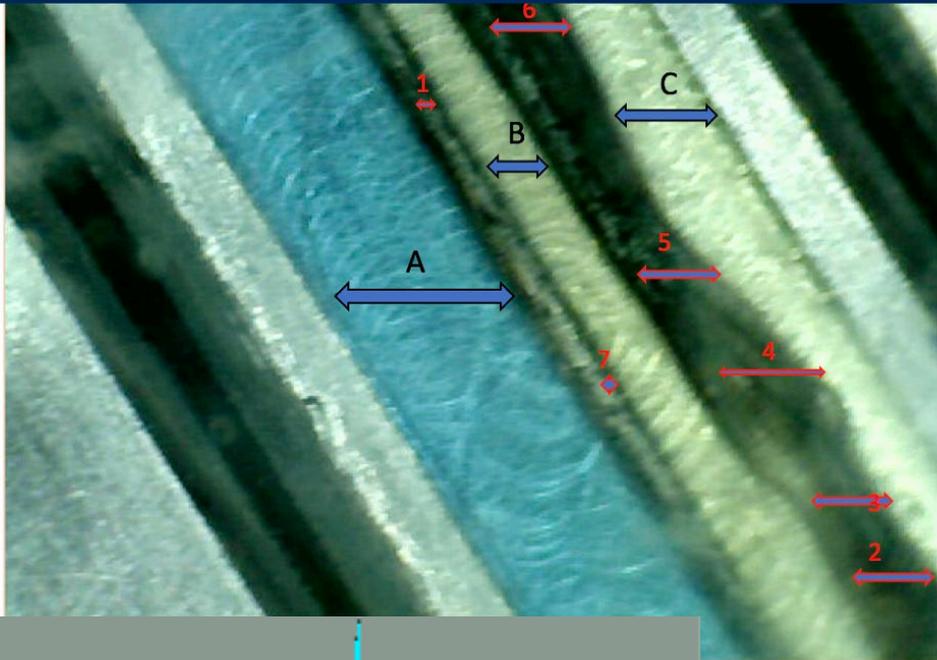
# An origin-of-life reactor to simulate vents



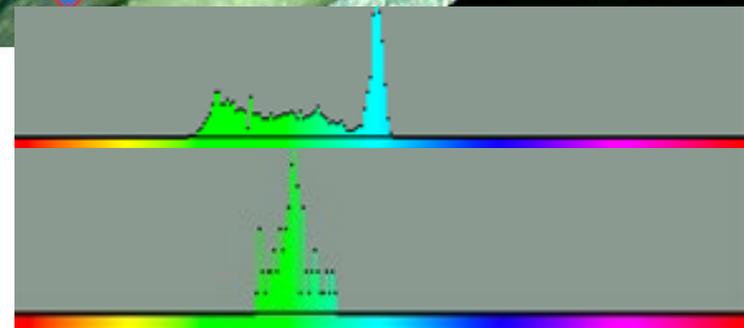
# Steep pH gradients across inorganic barrier



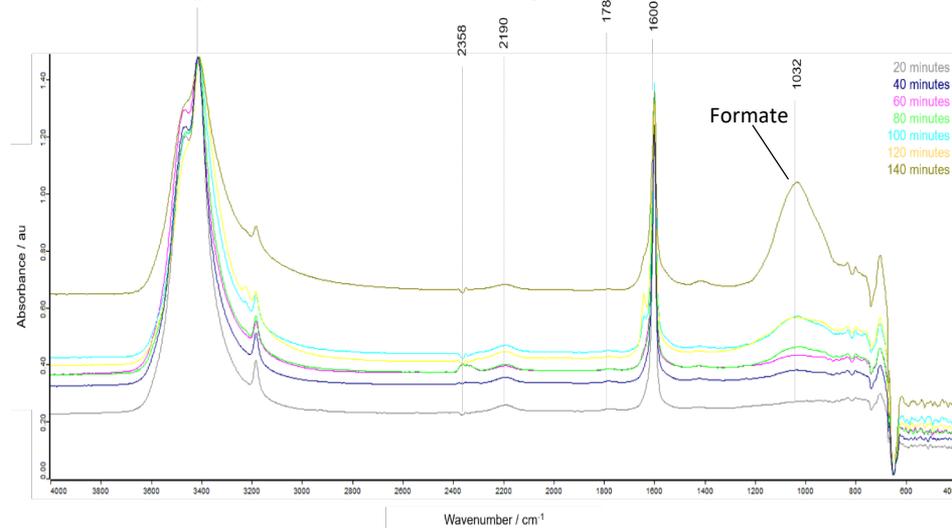
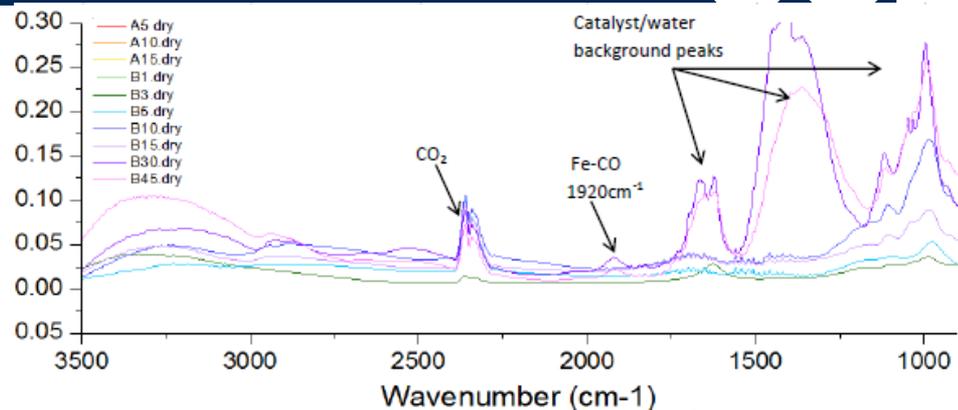
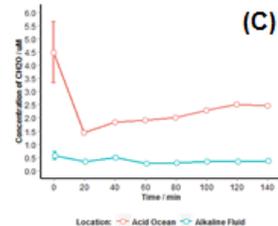
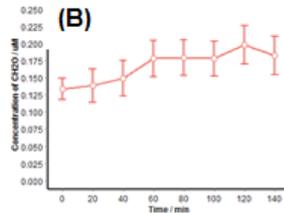
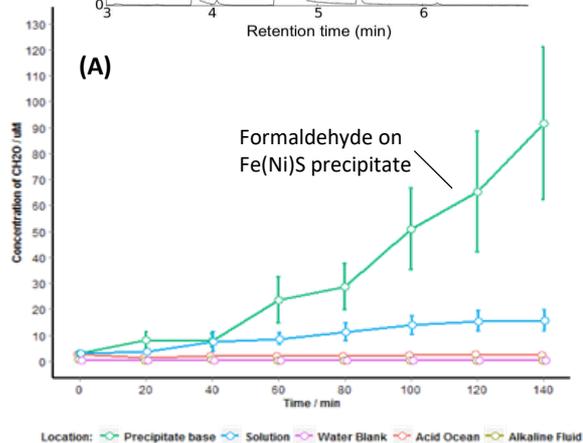
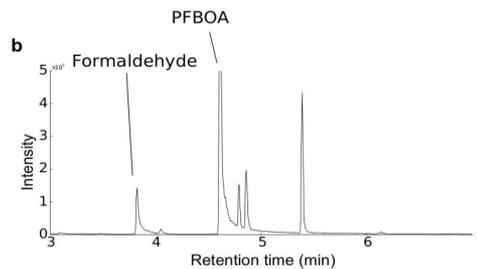
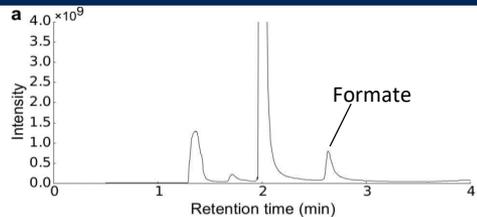
UCL



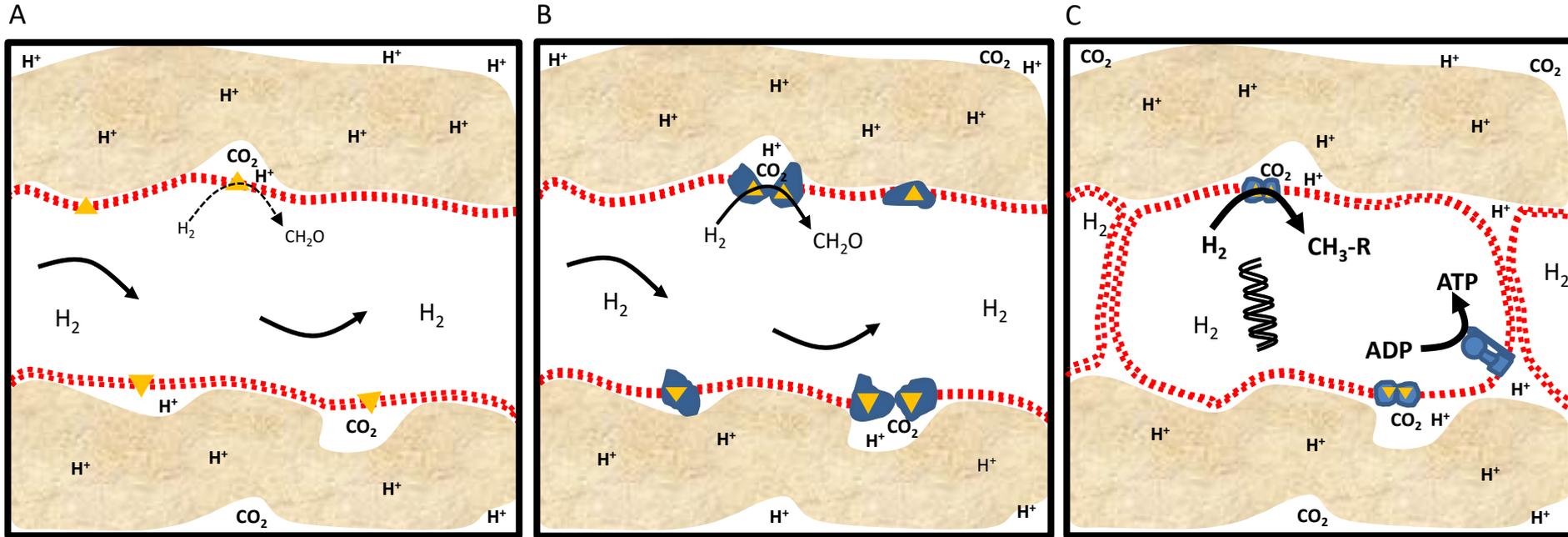
Can be 5 pH units  
across  $\sim 70 \mu\text{m}$



# Synthesis of CO, formate and formaldehyde



# Protocell evolution – topological equivalence

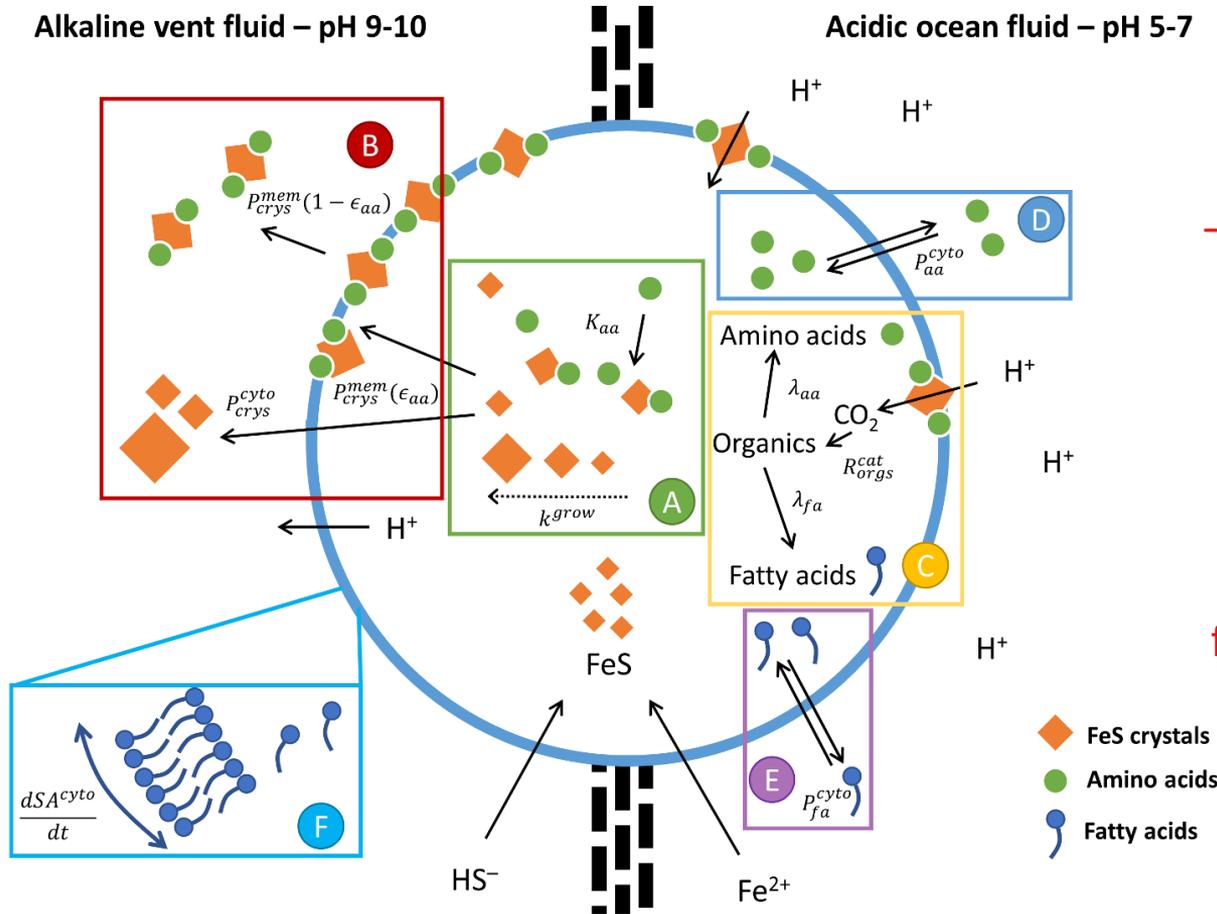


If organics form from  $\text{CO}_2$  driven by proton gradients there is continuity with biology at all stages of protocell evolution and development right up to genes and proteins

# Positive feedbacks drive growth in vents

Alkaline vent fluid – pH 9-10

Acidic ocean fluid – pH 5-7



## Computer simulation

Amino acids chelate FeS crystals – hinders growth giving more small crystals with larger surface area

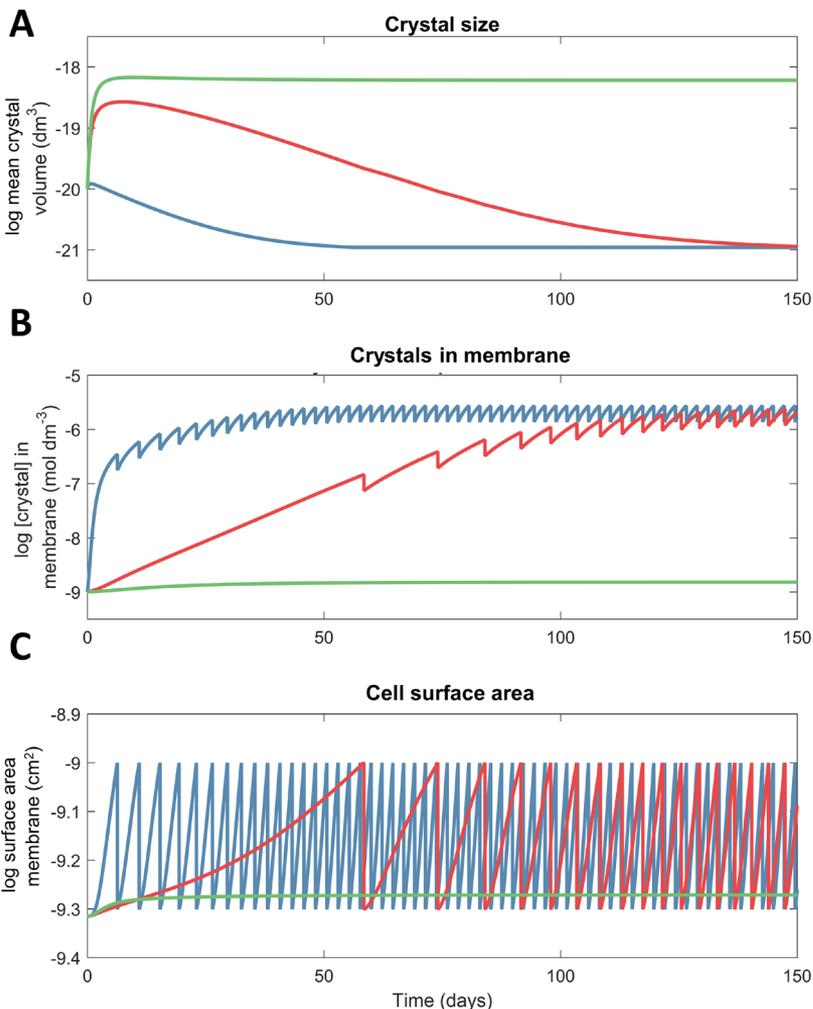
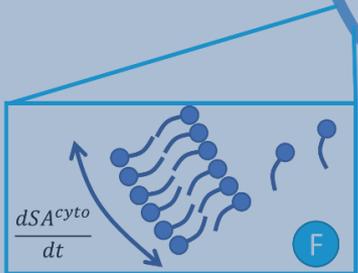
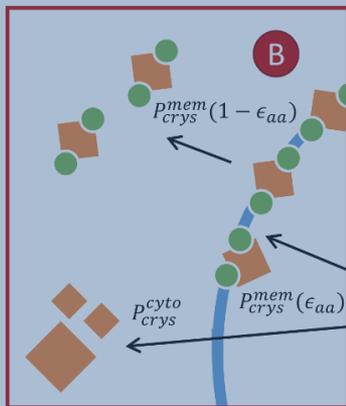
Chelation by amino acids partitions FeS crystals to membrane, giving ‘proto-Ech’

Natural proton gradients drive formation of new organics through proto-Ech – positive feedback

- ◆ FeS crystals
- Amino acids
- ⋈ Fatty acids

# Positive feedback

Alkaline vent fluid – pH 9-10



nts



## computer simulation

acids chelate FeS crystals  
 rs growth giving more small  
 ls with larger surface area

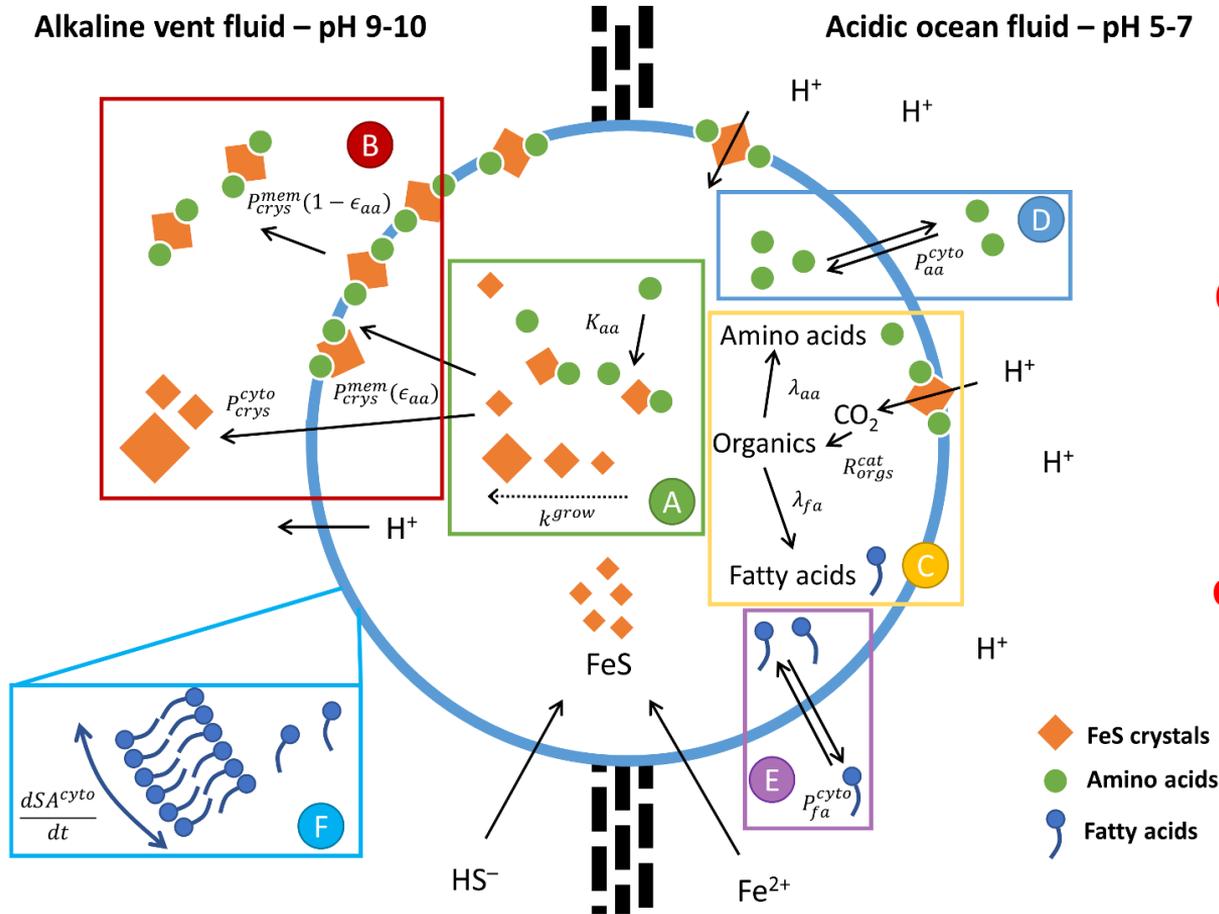
relation by amino acids  
 rtitions FeS crystals to  
 brane, giving 'proto-Ech'

ral proton gradients drive  
 on of new organics through  
 o-Ech – positive feedback

# Positive feedbacks drive growth in vents

Alkaline vent fluid – pH 9-10

Acidic ocean fluid – pH 5-7



Can we make fatty-acid vesicles under the correct range of pH?

Can we chelate FeS minerals with cysteine to form small 'biological' FeS clusters?

Can we associate the FeS clusters with the membrane?

Will the protocells fix  $CO_2$  driving growth?

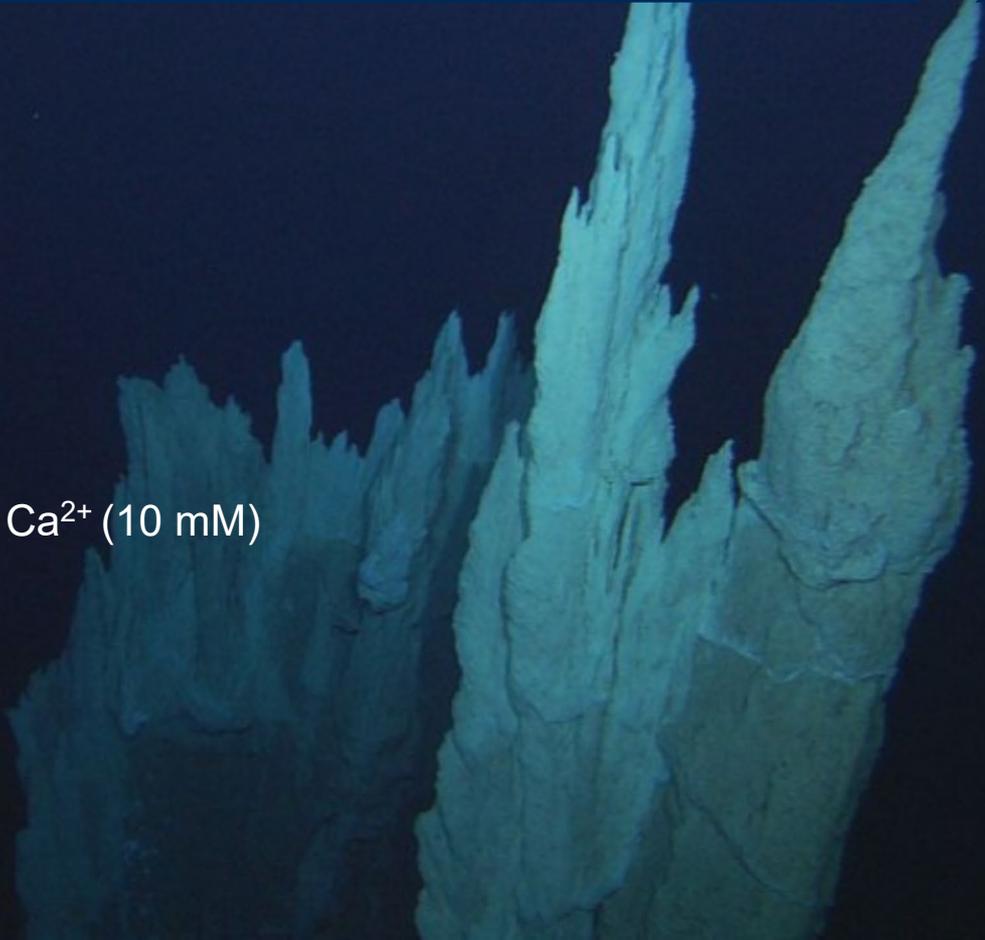
- ◆ FeS crystals
- Amino acids
- ⋈ Fatty acids

# Are vents too harsh for fatty acid vesicles?

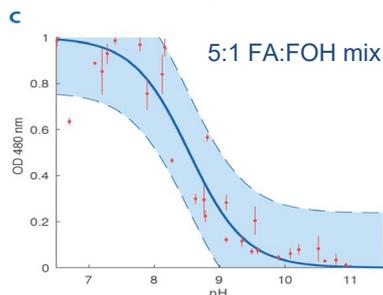
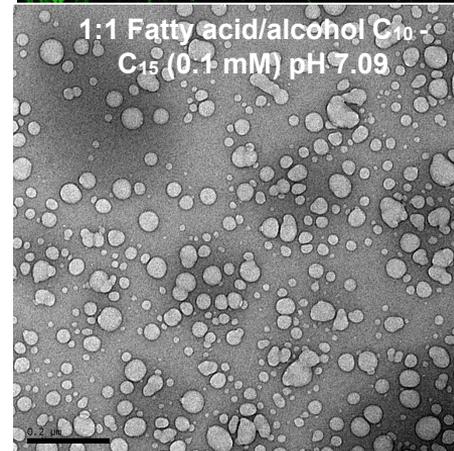
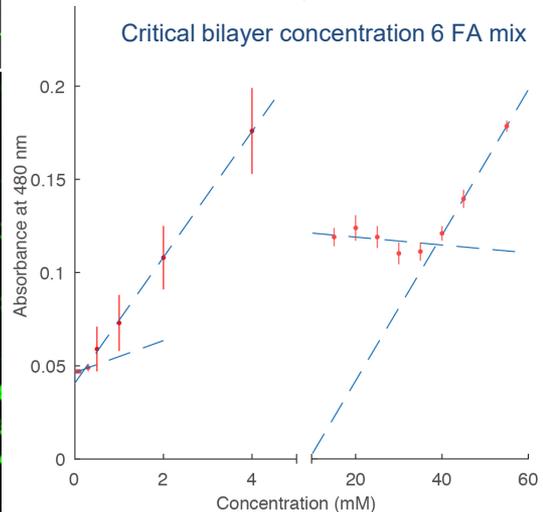
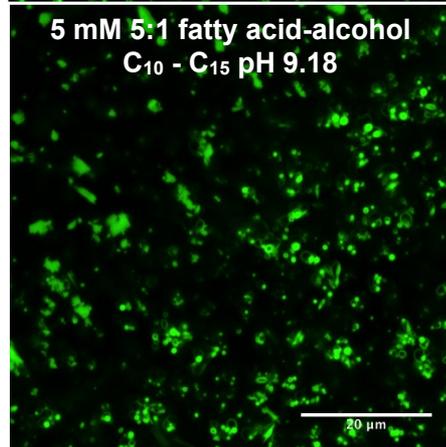
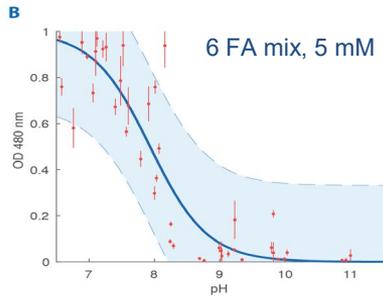
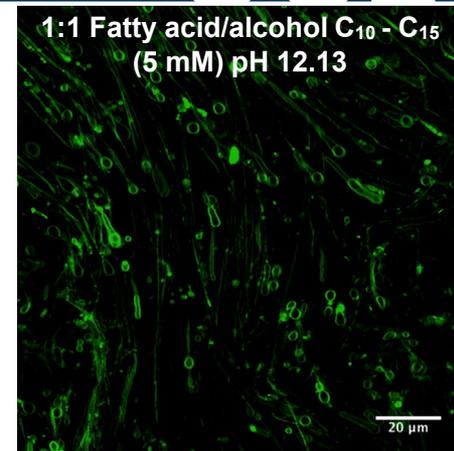
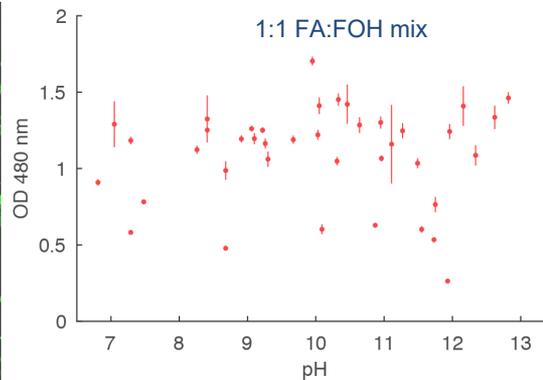
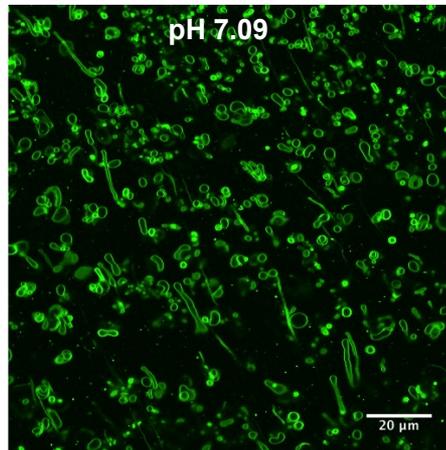
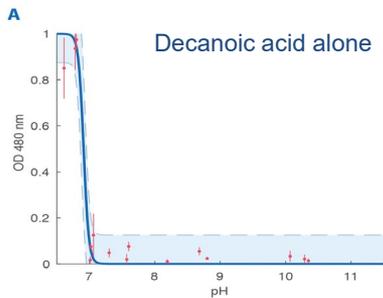


UCL

- pH - 5 -12
- Temperature - 50 to 100 °C
- Salinity - NaCl (600 mM)
- Divalent cations – Mg<sup>2+</sup> (50 mM), Ca<sup>2+</sup> (10 mM)

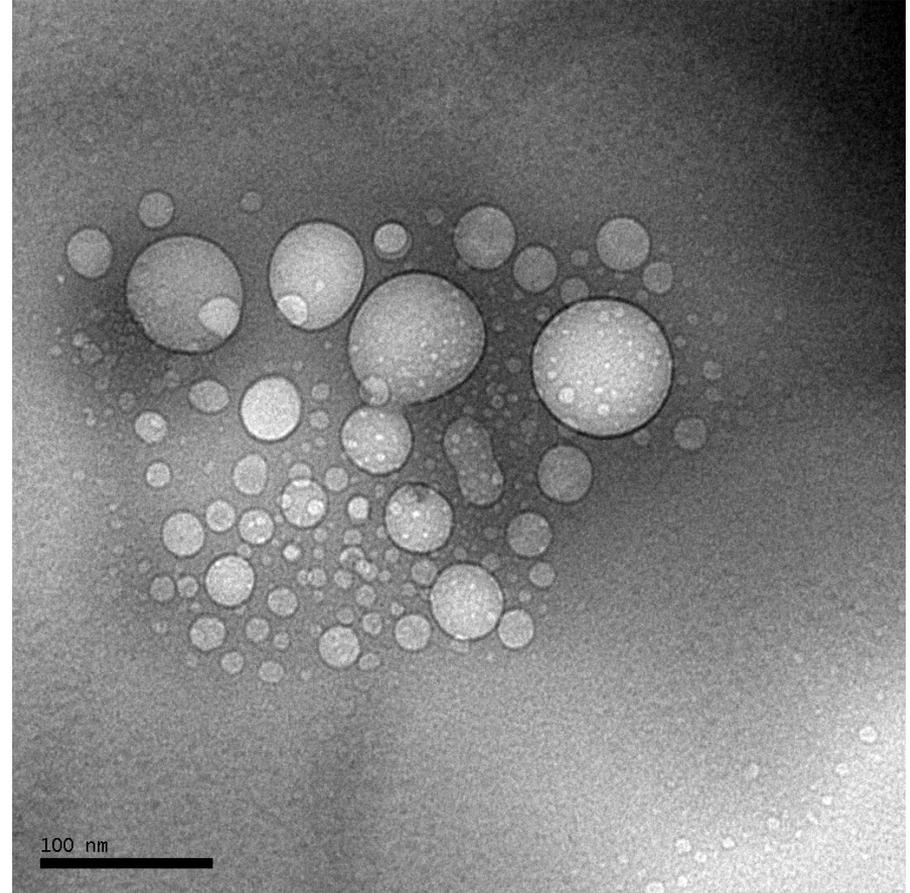
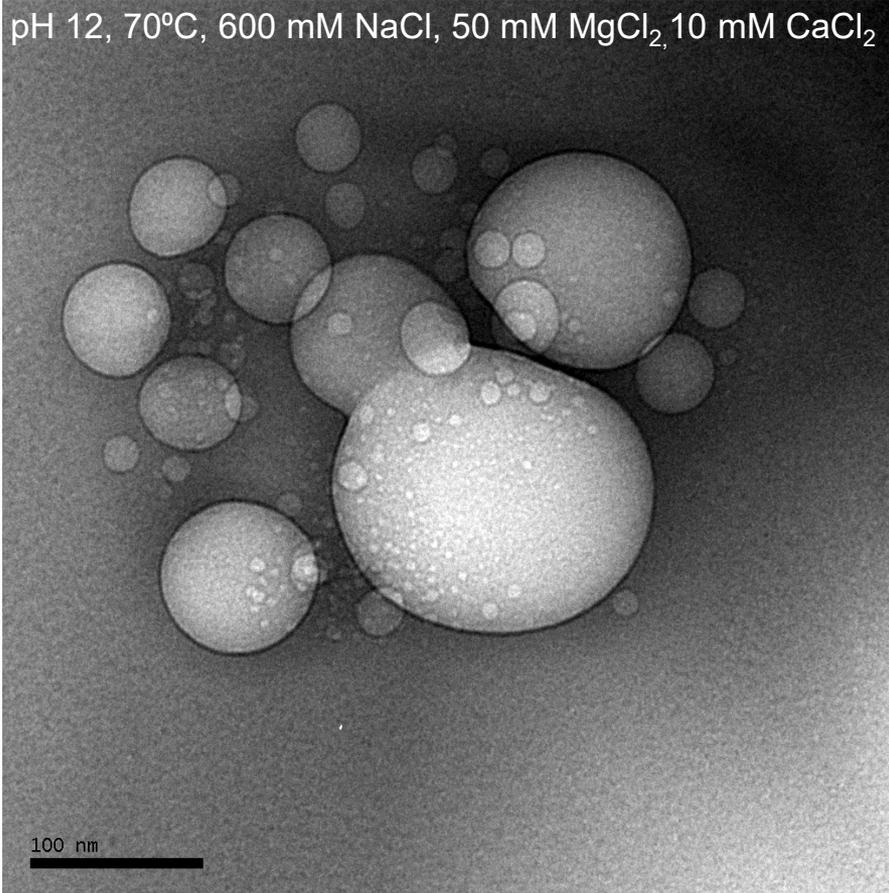


# Fatty acid + fatty alcohol protocells at 70 °C and pH 12

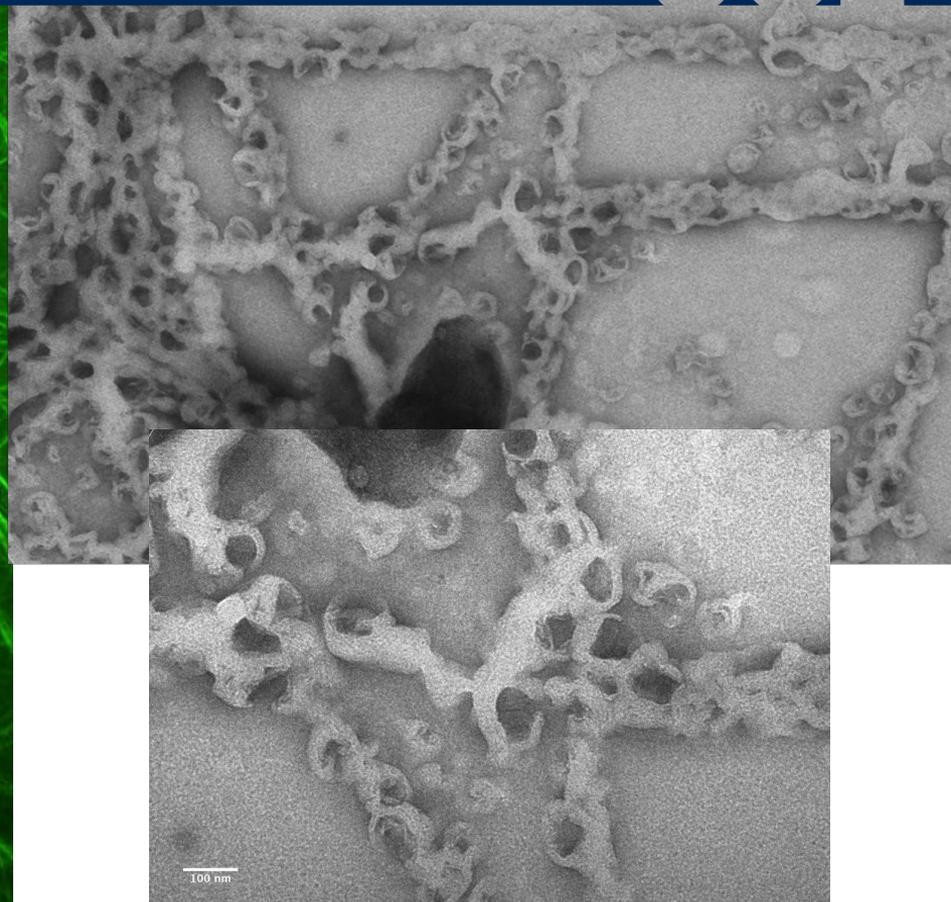
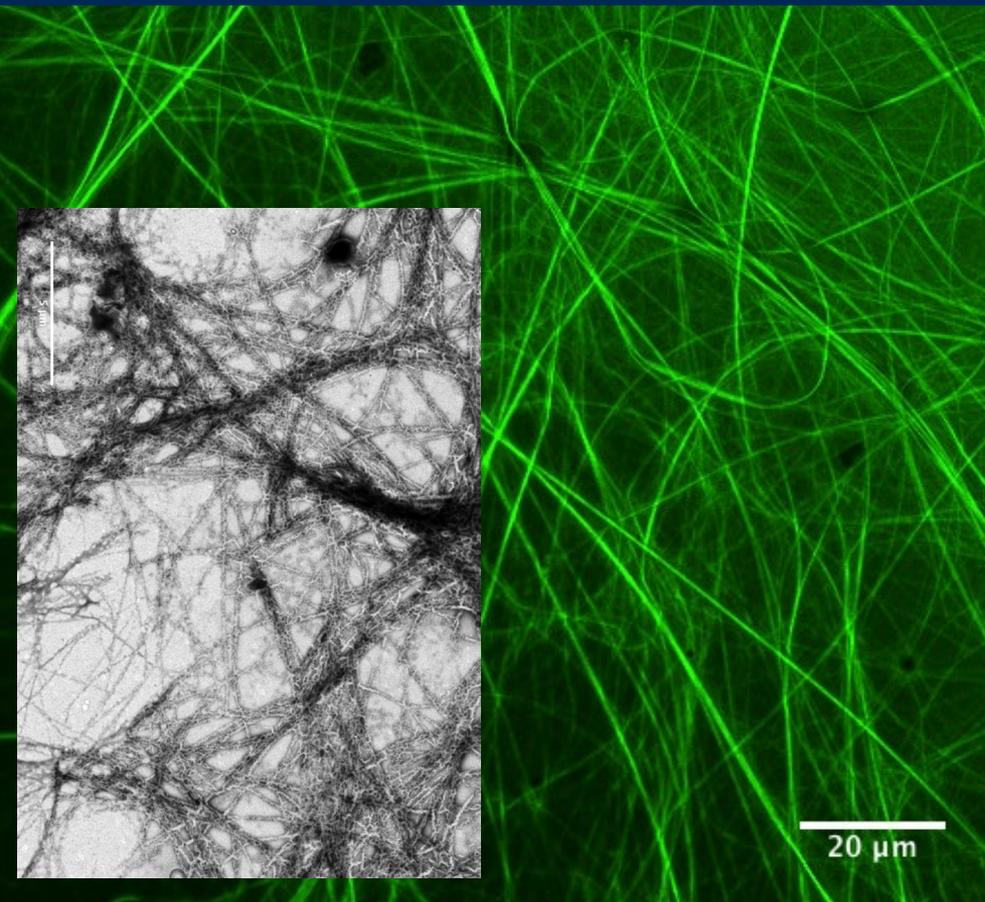


# Protocells at modern ocean salinity, $\text{Ca}^{2+}$ and $\text{Mg}^{2+}$

pH 12, 70°C, 600 mM NaCl, 50 mM  $\text{MgCl}_2$ , 10 mM  $\text{CaCl}_2$

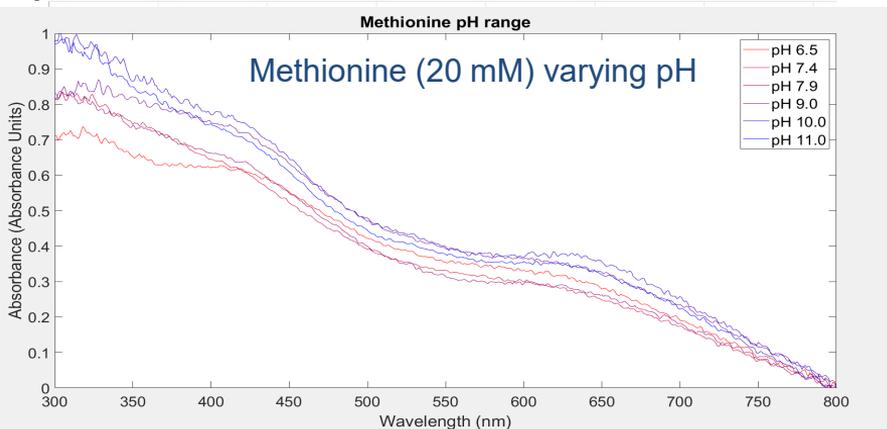
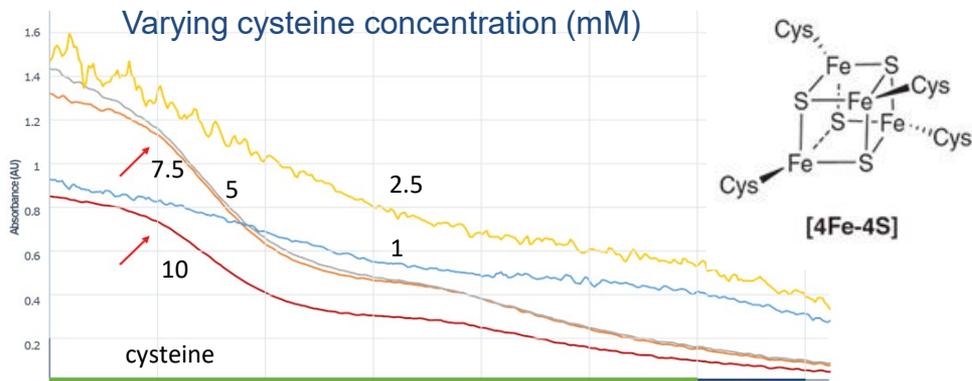


# Filamentous vesicles in salty solutions

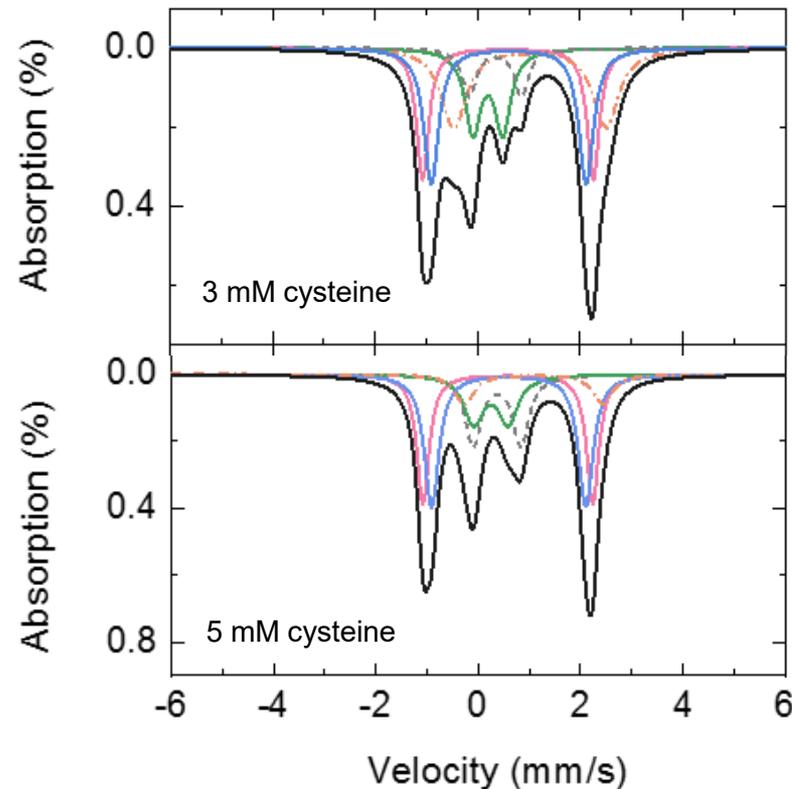


# Formation of FeS clusters by chelation with cysteine

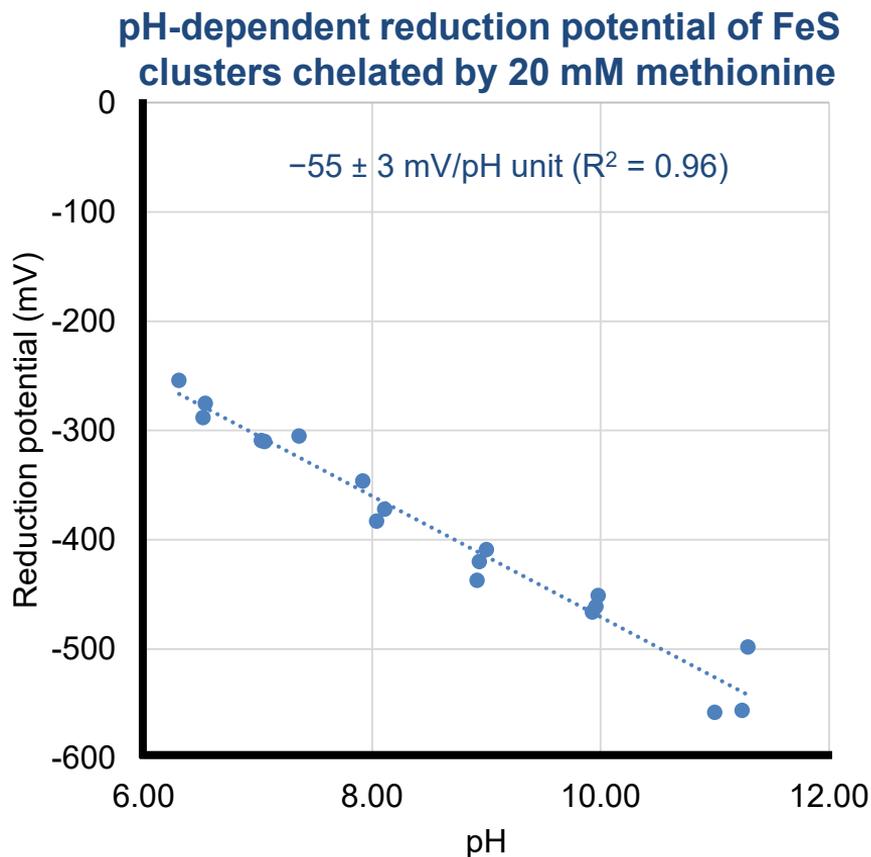
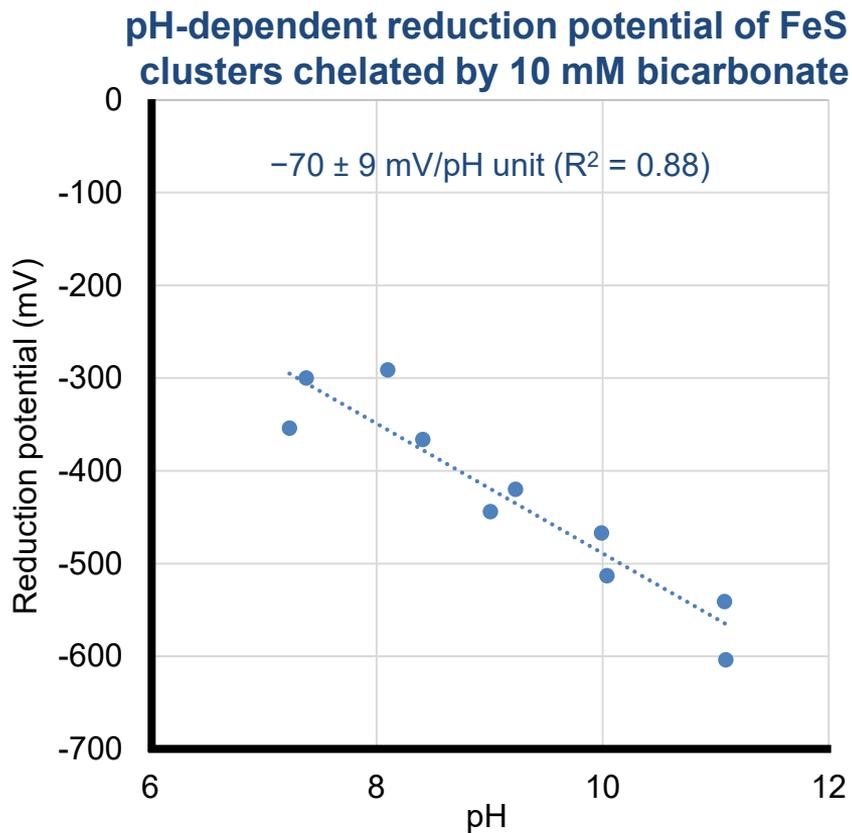
## UV-Vis spectroscopy of 4Fe-4S clusters



## Mossbauer spectroscopy: 4Fe-4S + 2Fe-2S clusters



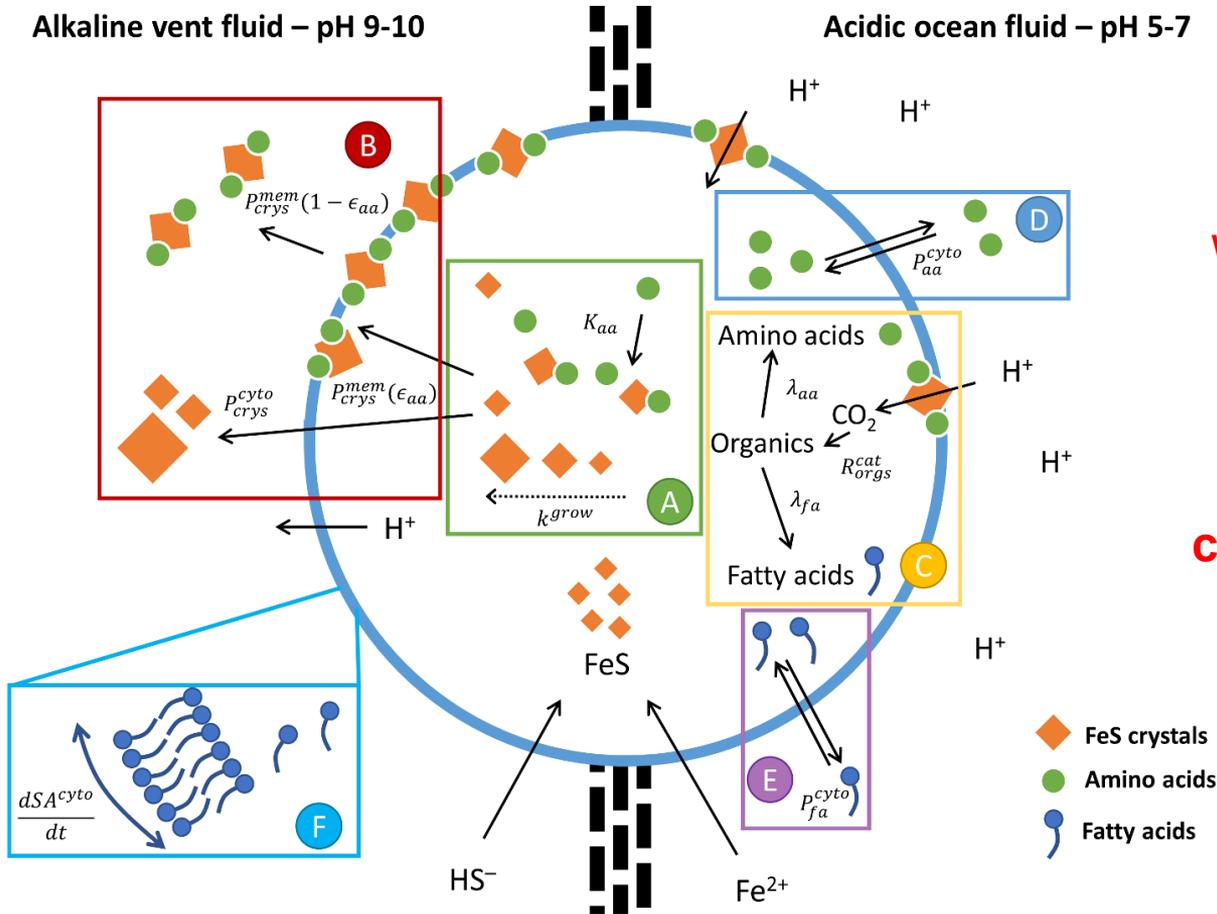
# Reactivity of FeS clusters is pH dependent



# Positive feedbacks drive growth in vents

Alkaline vent fluid – pH 9-10

Acidic ocean fluid – pH 5-7



We can make vesicles under the correct range of pH

We can chelate FeS minerals with cysteine at pH 9 to form  $4Fe_4S$  clusters

Can we associate the FeS clusters with the membrane?

Will the protocells fix  $CO_2$  driving growth?

# Mini natural disaster – protocells fleeing a bubble



# Thank you!



Thanks to the Leverhulme Trust, EPSRC and bgc3 for funding