# Dynamic Organic Reaction Networks And Where to find them

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*and also*: Marilyn Fogel, Dionysis Foustouskos, Penny Morrill, Barbara Sherwood-Lollar

A statement of the obvious: *Environments on Earth capable of the continuous synthesis of reactive organic molecules must have been a requirement for the emergence of life*

**Dynamic Organic Reaction Networks**

Not so obvious: *how and where could these naturally occur?*

# An interesting paper:
# *The Hadean-Archaean Environment*
# Norman Sleep (CSH Persp. Biol) 2010

"*Life probably originated and definitely evolved on the Early Earth*"

"*It is unproductive to precisely define when autocatalysis became life*" – **True, but what about exoplanets**?

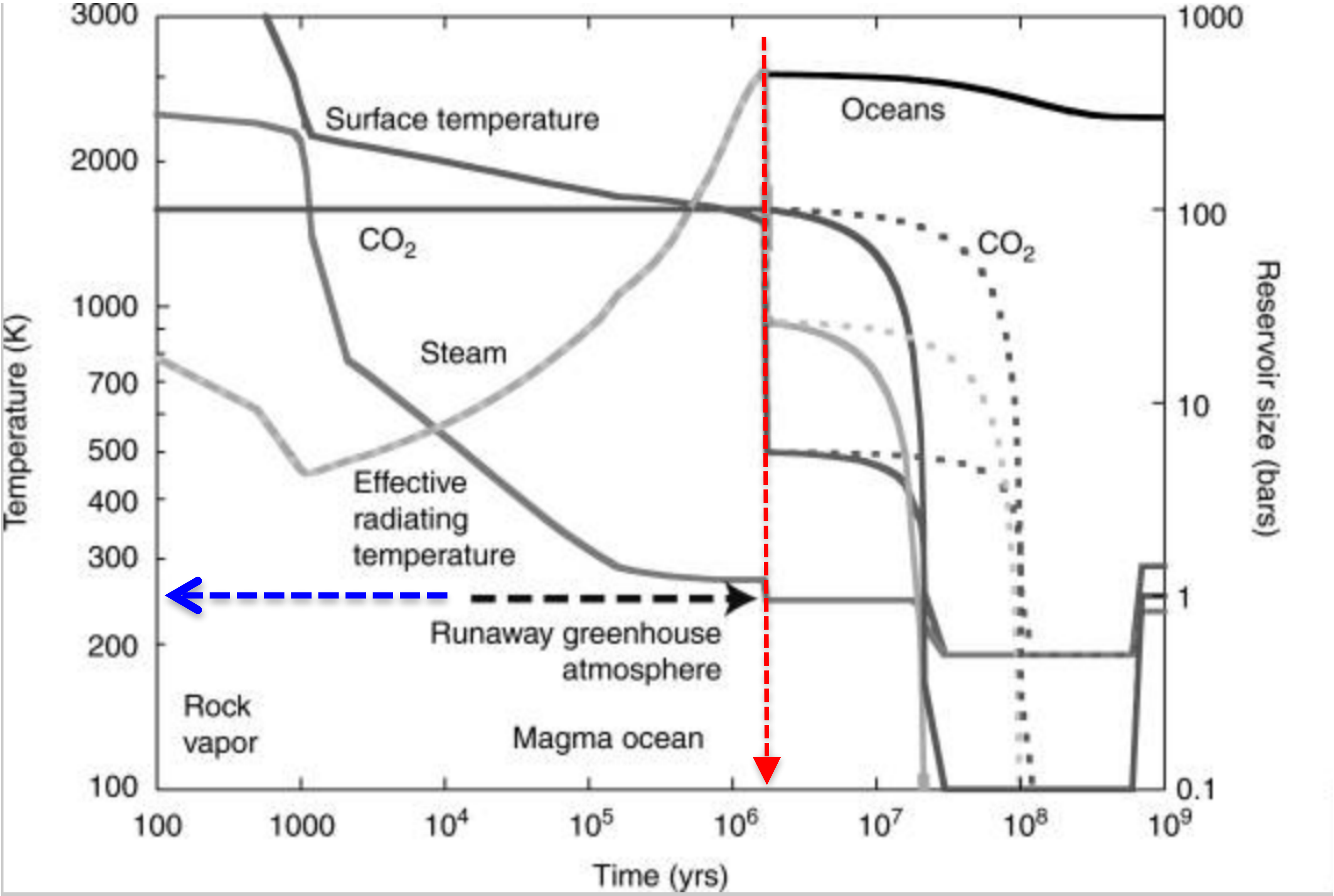
Sleep's Key requirements for life on Earth:

**Req 1**: Temperature T > solid $H_2O$, T < ~ 122 °C

**Req 2**: Energy "*There have always been hydrothermal systems to promote chemical disequilibrium*" **& then came phototrophism**

Both requirements seem reasonable to me!

# Early Earth Clement Atmosphere was likely Early
# Kevin Zahnle et al. (CSH persp. Biol.) 2010



# Hadean sources of "*fuel*" and "*oxidants*"- the engine for life's emergence…

**Fuel(?)** = $H_2$ [not likely interstellar… :) ]

$3Fe_2SiO_4 + 2H_2O \rightarrow 2Fe_3O_4 + 3SiO_2 + 2H_2$

Others = $CH_4$(?), $NH_3$(?), $H_2S$(?), …

**Oxidants(?)** = $CO_2$ and others?

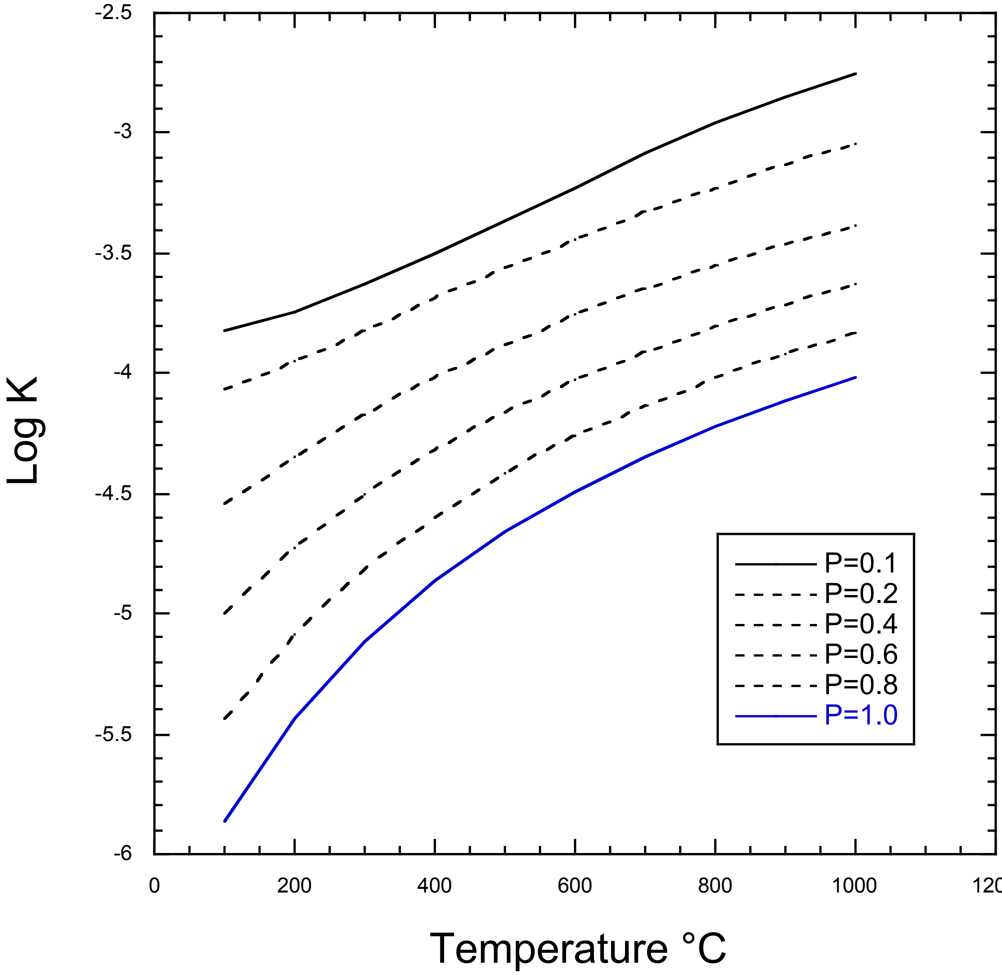
So $CO_2 + H_2$ is a good start for considering organo-synthesis…and life's origins

# SO WE BUILD STARTING FROM CO2 AND H2…

The bottom line starts with $CO_2$ reduction. $CO_2$ + $H_2$ can, thermodynamically, do two things… $CH_x$ formation **or** the WGR rxn

**Water Gas Shift Rxn**

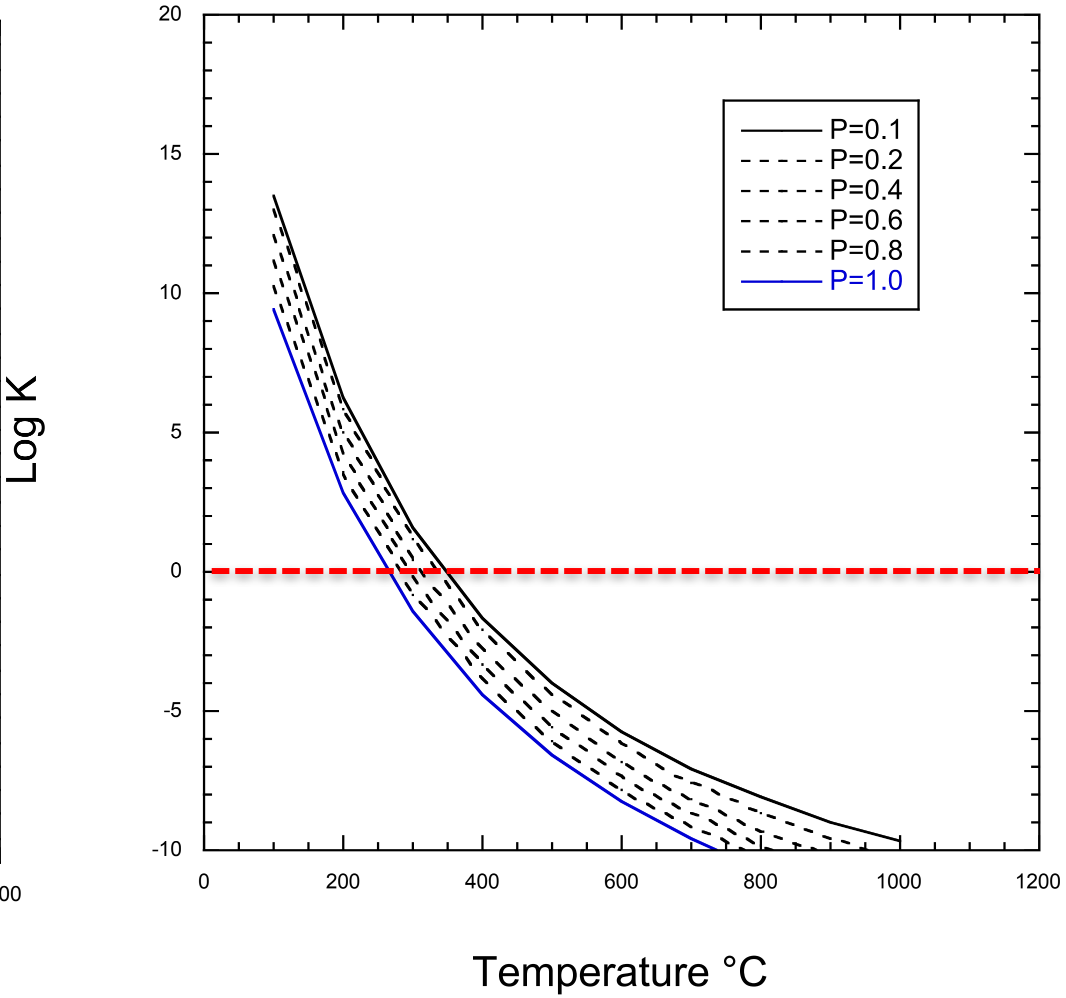
**CO2 + H2 <-> CO + H2O**



$CO_2$ + $H_2$ favored at low T

**Methanogenisis**

**CO2 + 4H2 <-> CH4 + 2H20**



$CH_4$ formation favored at low T

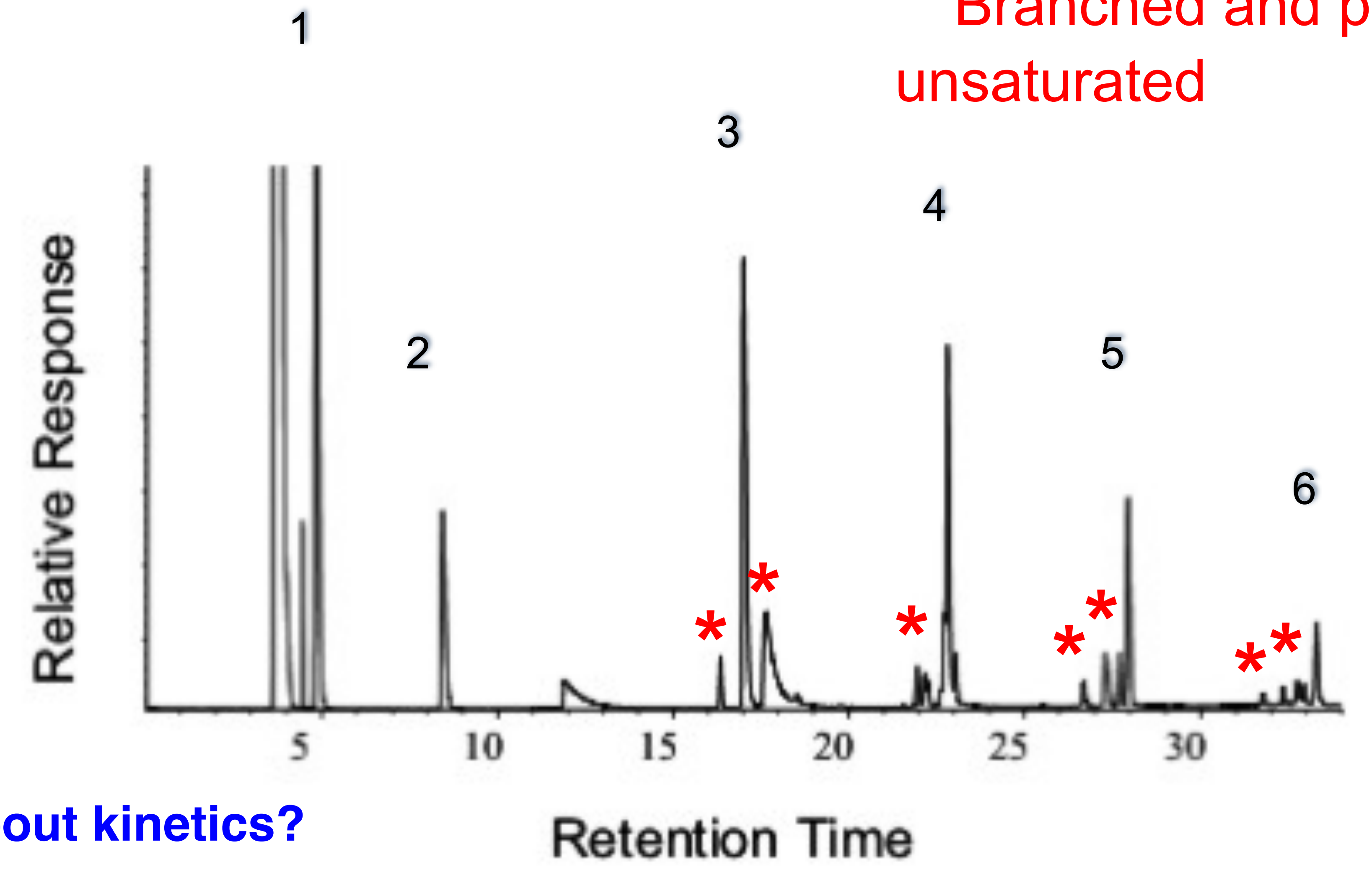
# Inhibition of methane formation has been observed many times

Cold Seal Reactor Experiments 250 °C, 200 MPa (w and w/o) Fe metal + aqueous Formic acid **(Penny Morril, Cody, Fogel, Sherwood-Lollar, Weinburger submitted)**

**<u>W/O</u> Fe-metal <u>no</u> methane is formed (any seen is due to metal contaminants in Au!)**

**<u>W</u> Fe metal Methane and HC synthesis extensive**

* Branched and partially unsaturated



**How about kinetics?**

**Theoretically:** At modest T & P, using formic acid as source of equiv. Conc. $CO_2 + H_2$, reaction stoich predicts 25 % $CH_4$

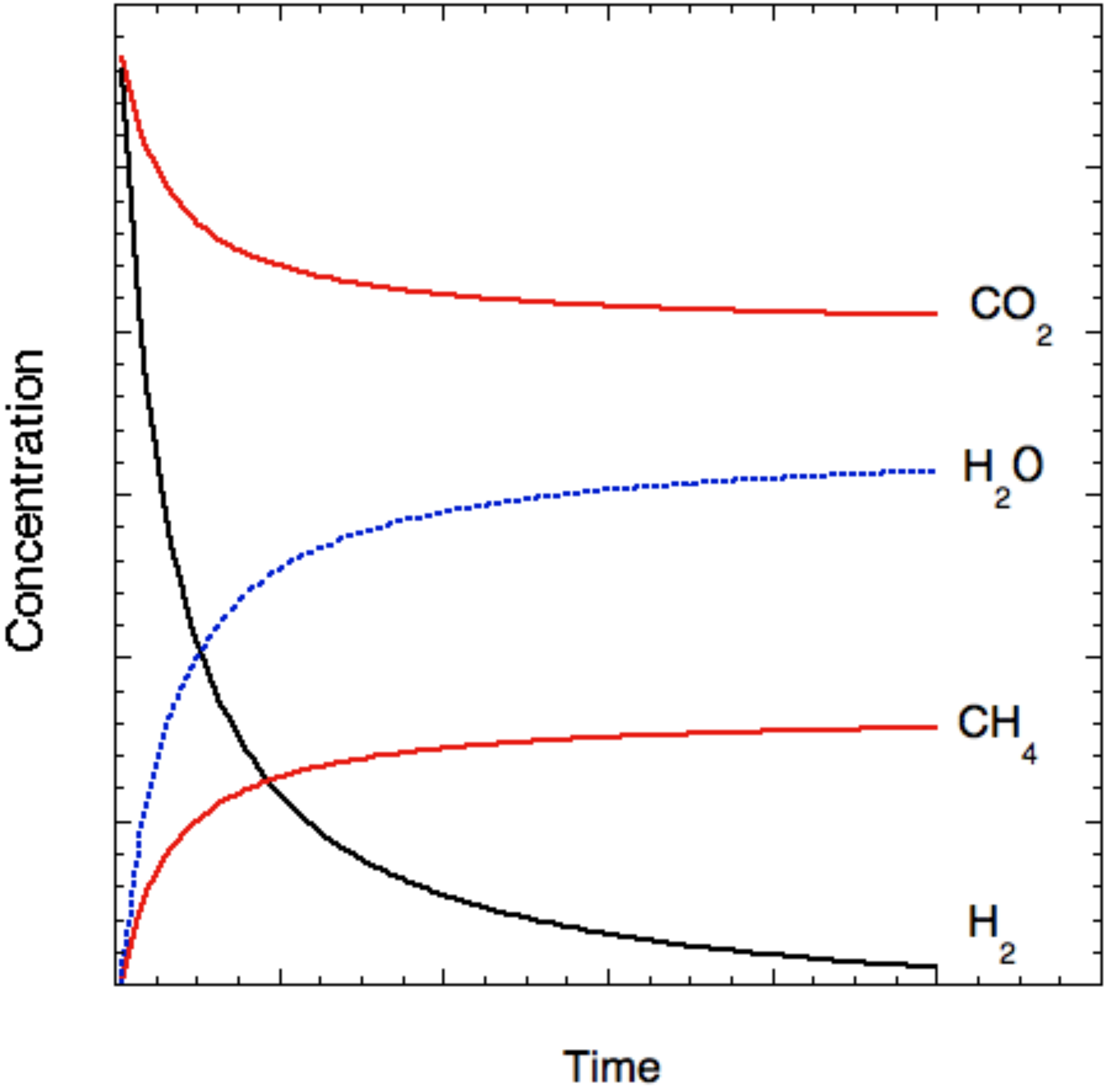
Homogeneous Kinetics expected to look like this…

A + B - > C + D

Classic 2nd order kinetics

**BUT we already stated that heterogeous catalysts are required**

**So don't expect these observed kinetics….**



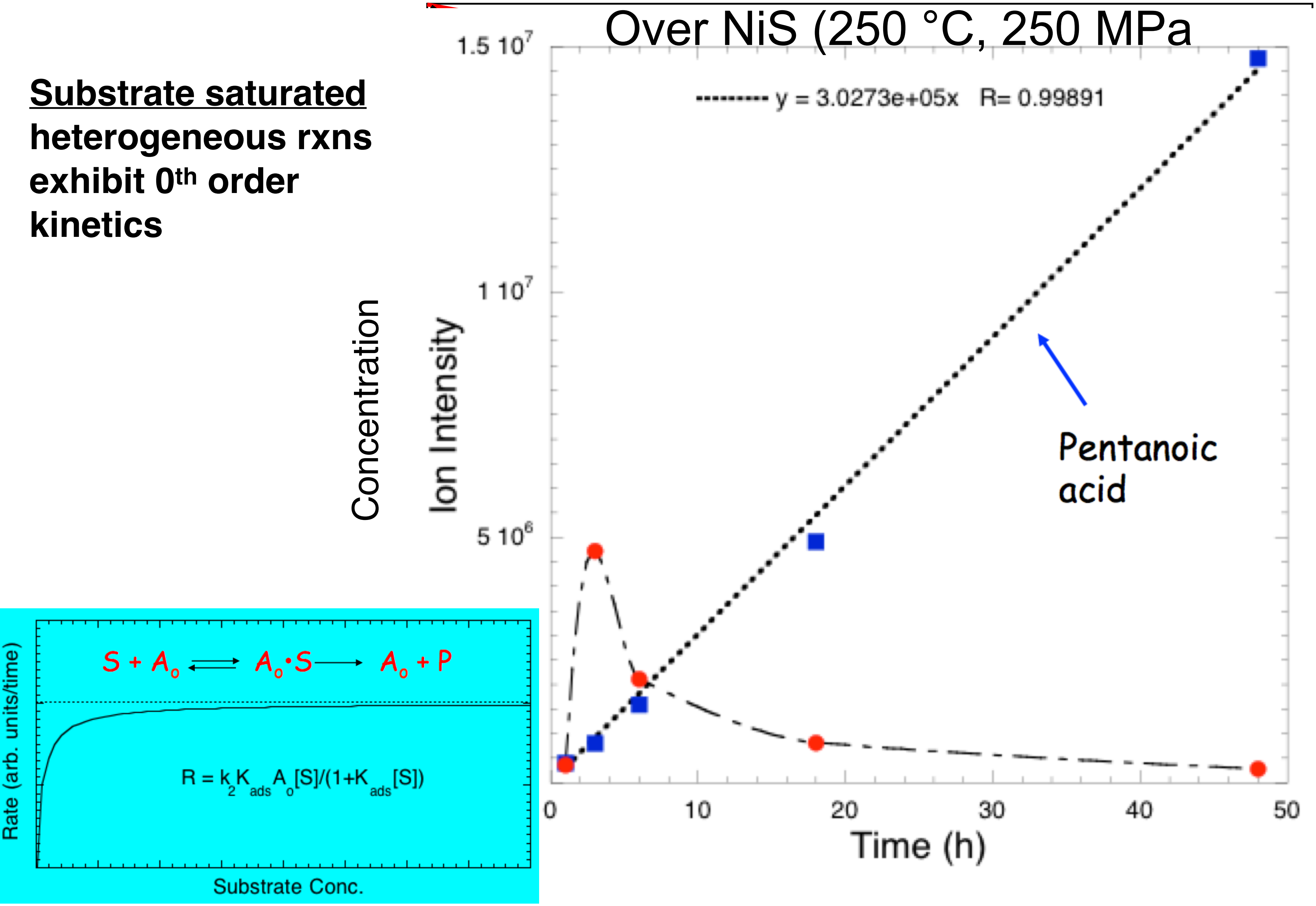
We know that with out a catalyst this RXN does not occur so with catalyst:

*Heterogeneous (surface catalyzed) Kinetics expected to look something like this…*

$CH_3(CH_2)_3SH + CO_2 + H_2$

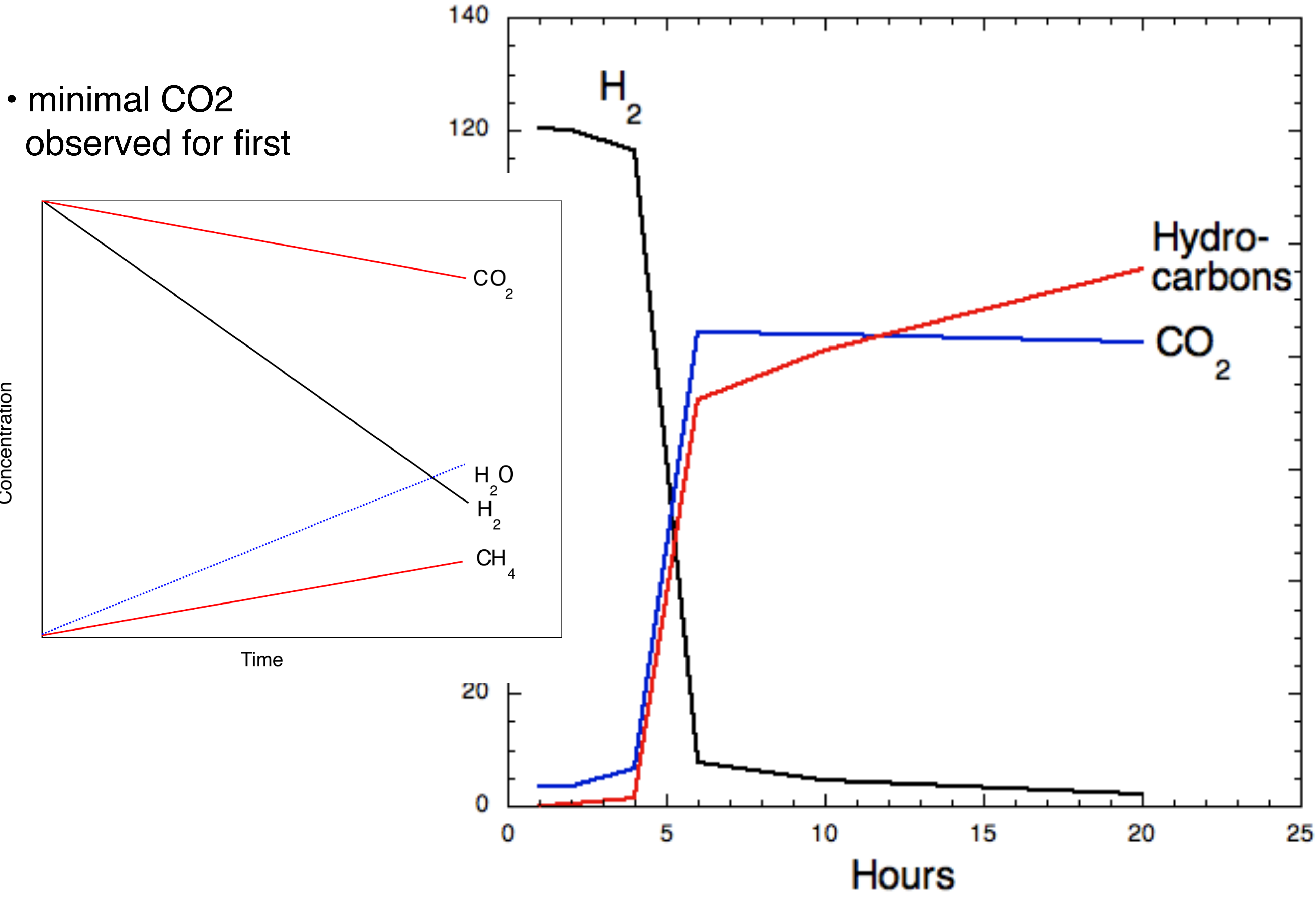
Over NiS (250 °C, 250 MPa

**<u>Substrate saturated</u> heterogeneous rxns exhibit 0th order kinetics**

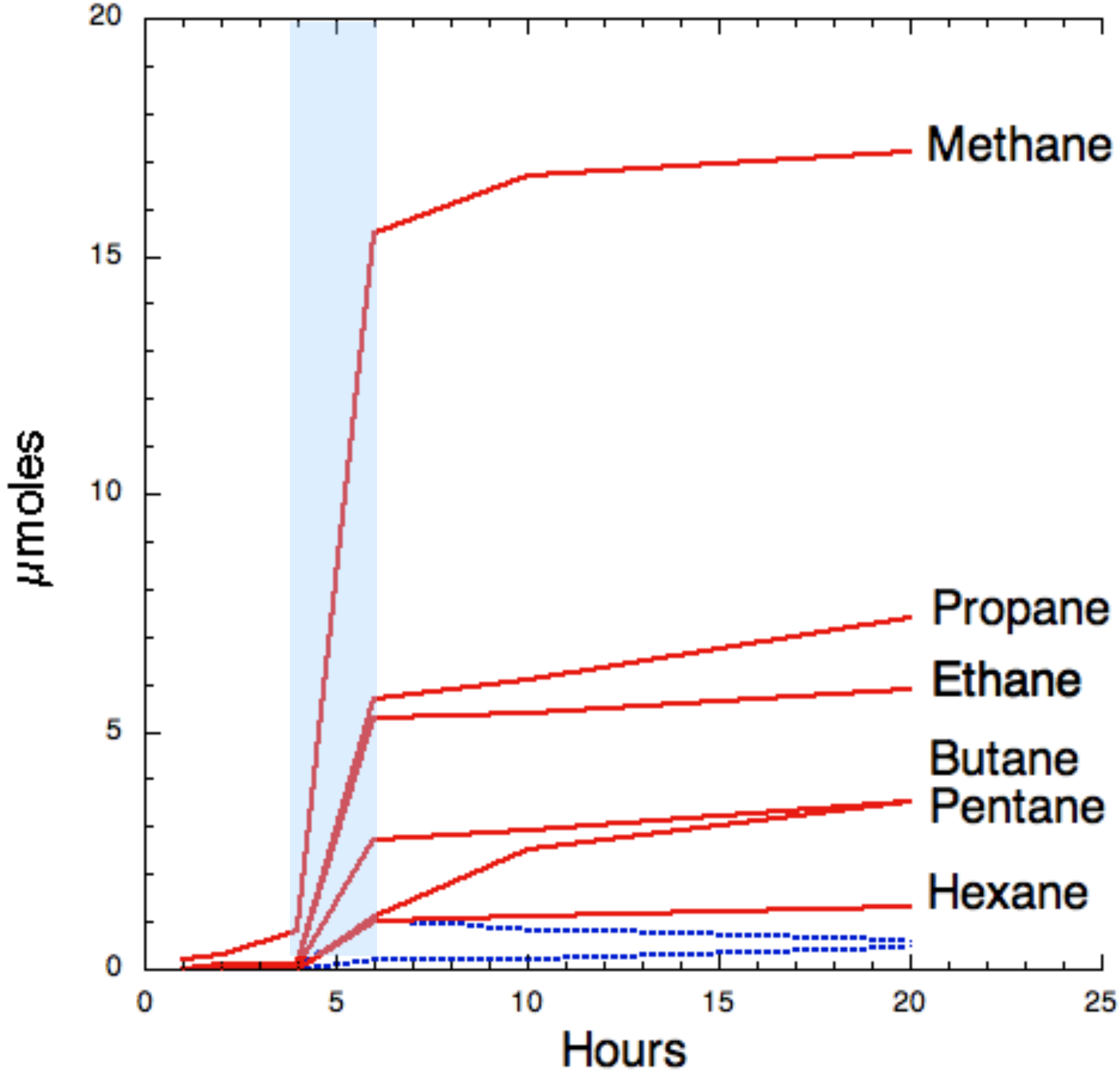


# What we observe is completely <u>unexpected</u> kinetic behavior…

- minimal CO2 observed for first

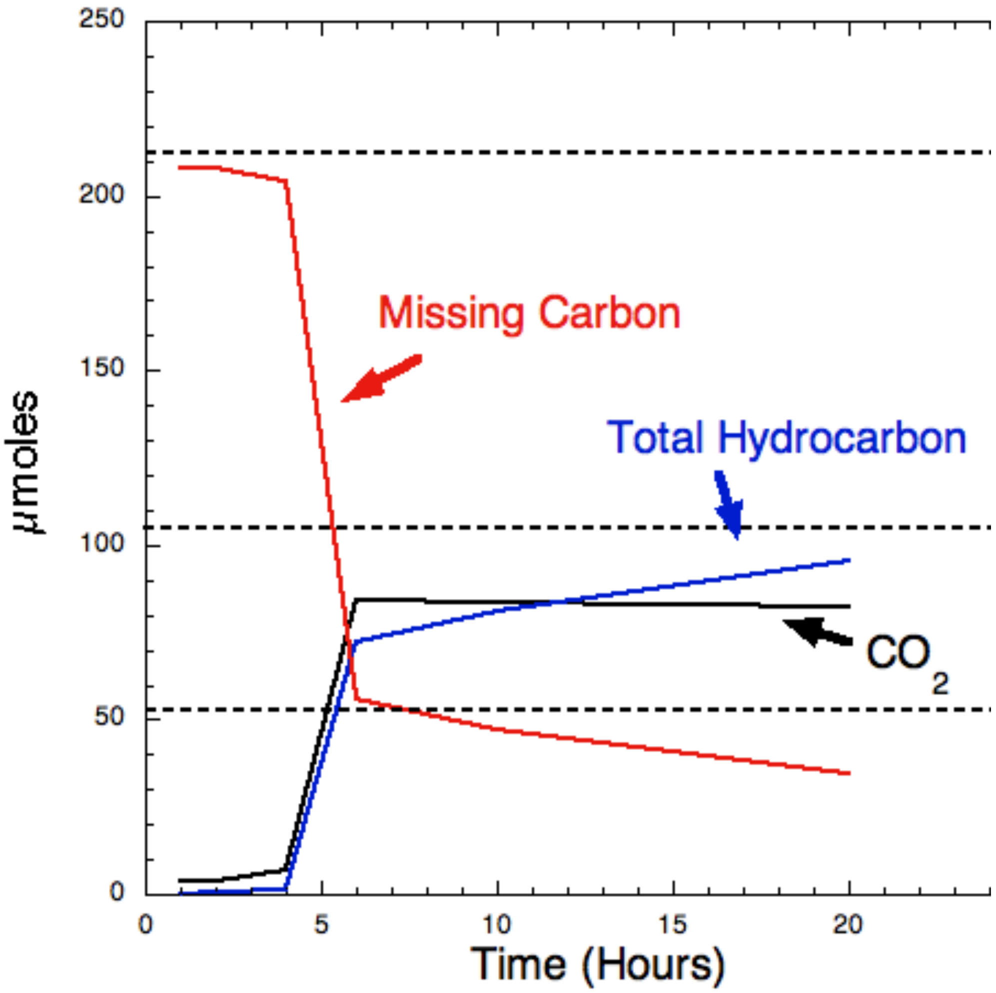


# HC products look classically FTT-like: note both normal and branched HC's



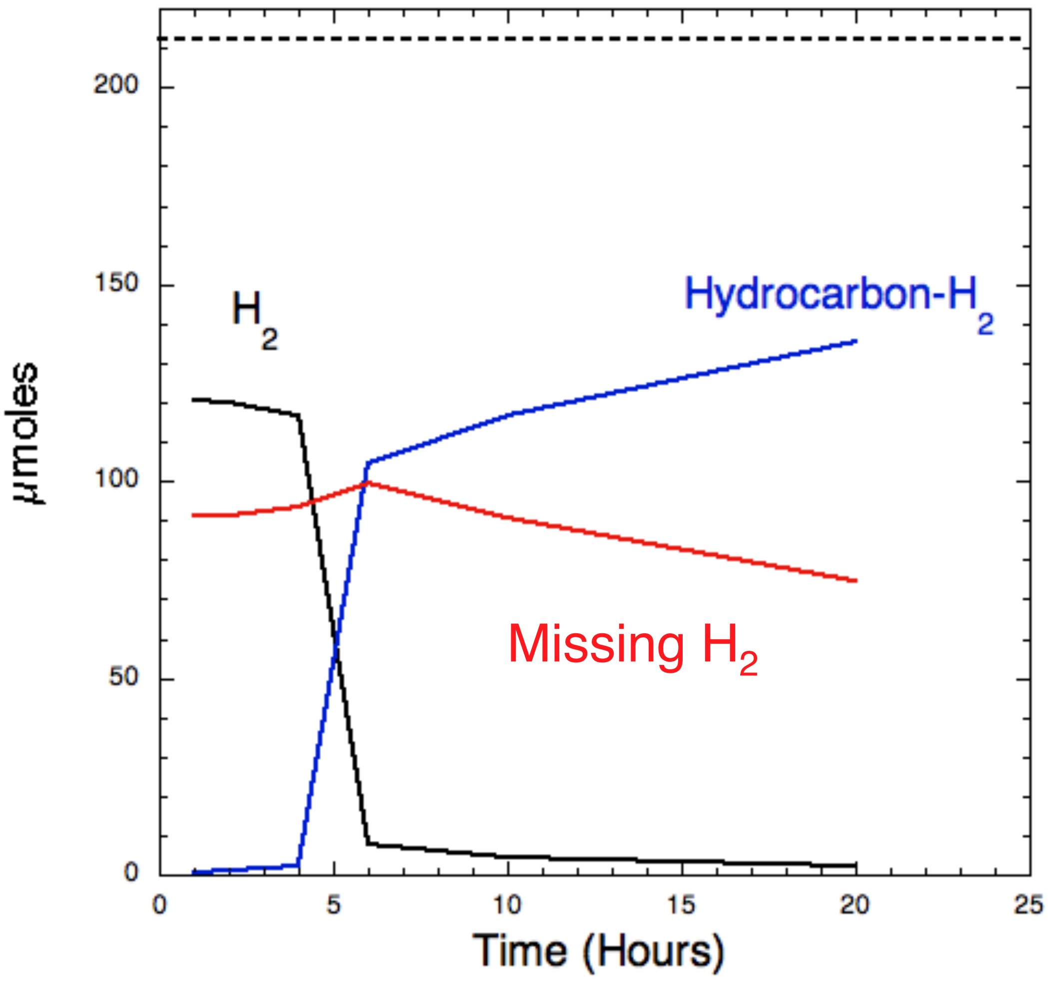
# We start with 212 μmoles $CO_2$ and $H_2$, each

**Carbon budget**



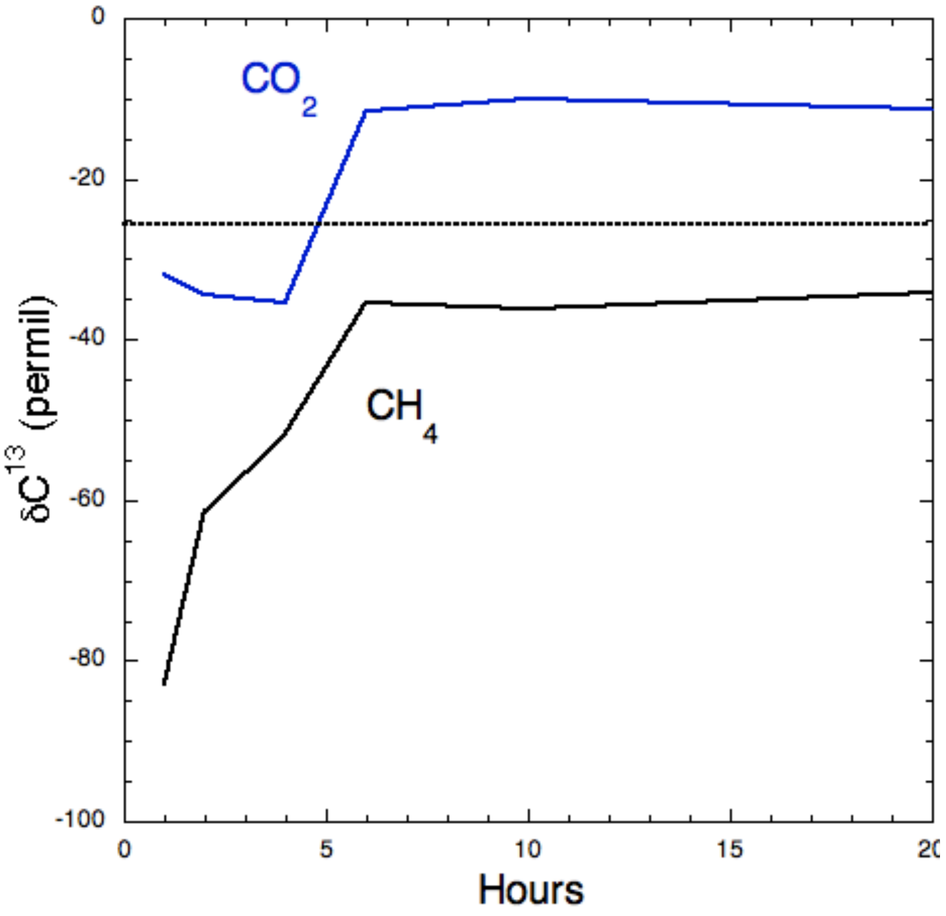
**During first 4 hours, ~ 100 % of carbon is unaccounted for.**

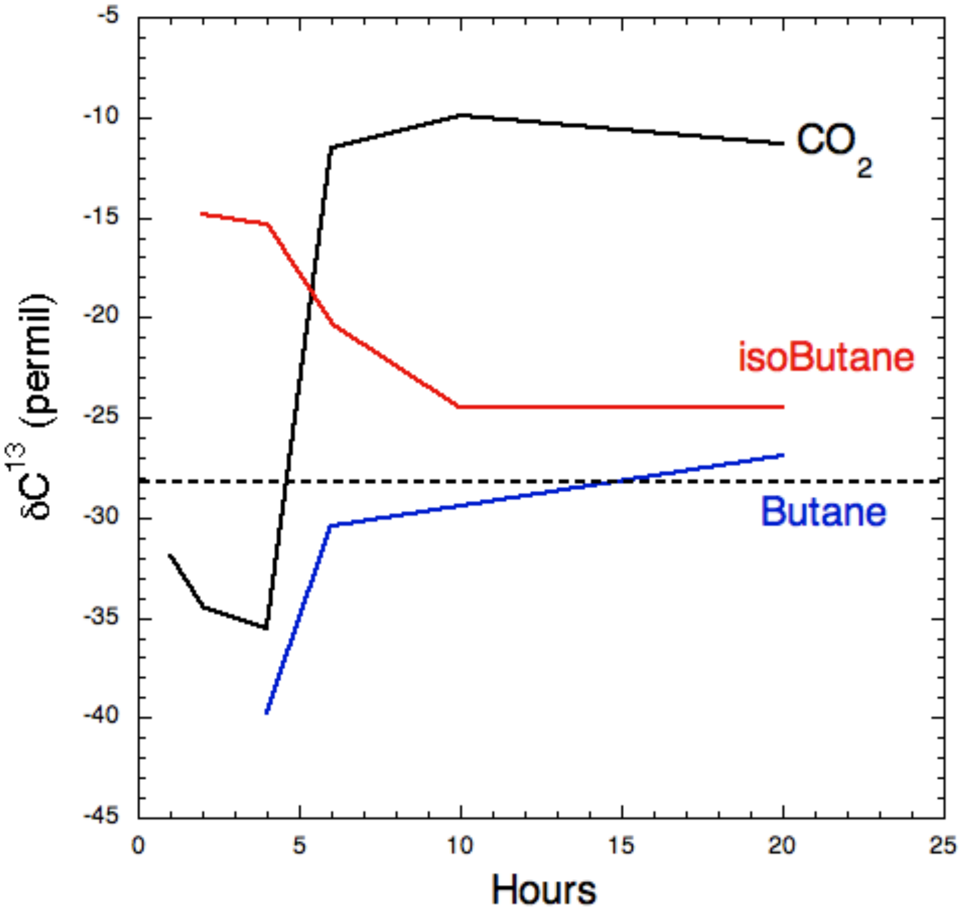
**Hydrogen budget**



**Throughout the experiment only ~ 50 % of the $H_2$ is accounted for.**

# Stable isotopes reveal hidden complexities; two carbon reservoirs





- As methane gets heavier, $CO_2$ gets lighter- C reservoir # 1
- early isobutane heavy, gets lighter- C reservoir # 2

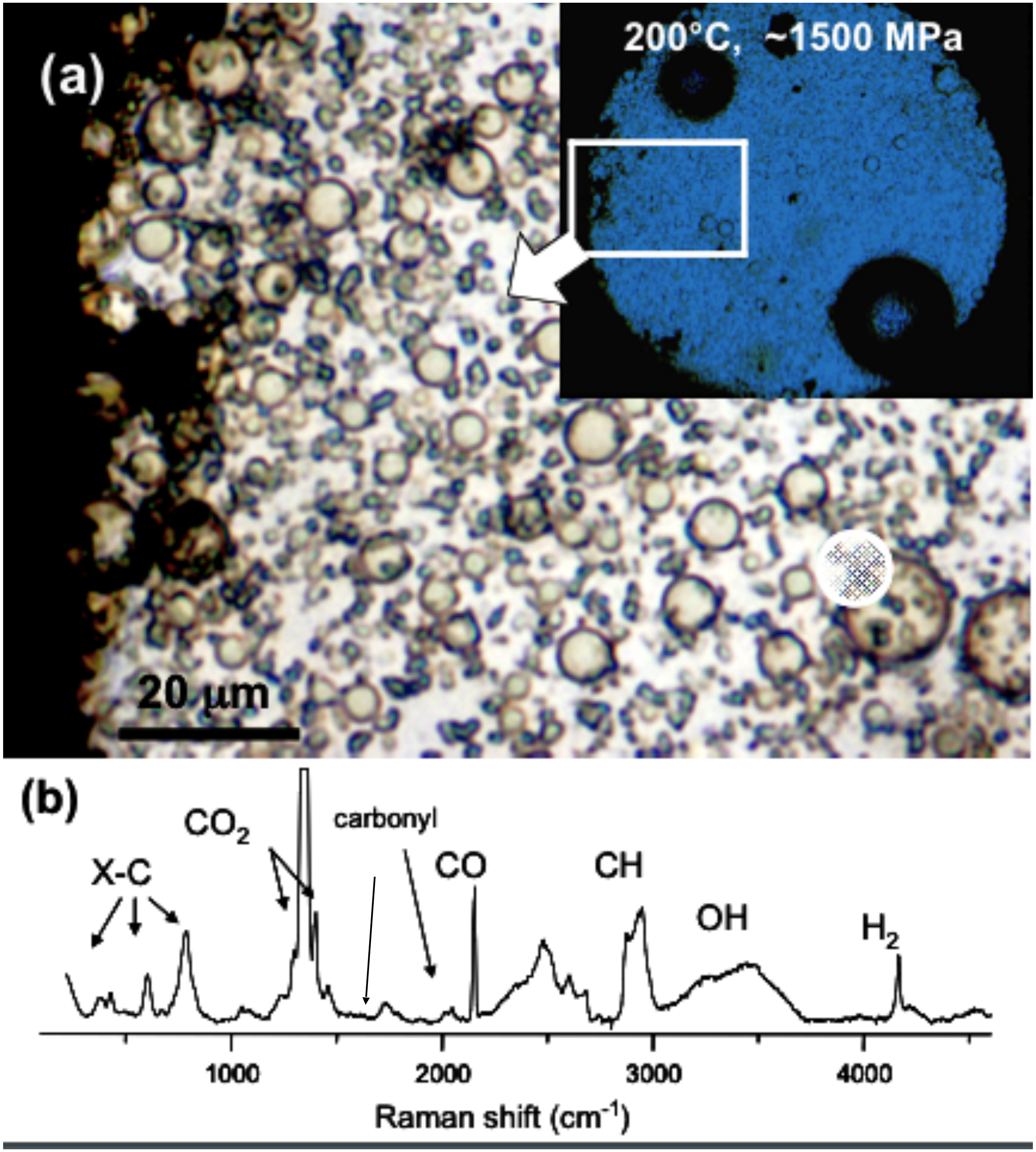
# What one observes via hydrothermal diamond anvil cell

Three phases clearly evident

1 crystalline
2 fluids-immissible

Transition metal carbonyls abundant

HC’s and CO abundant



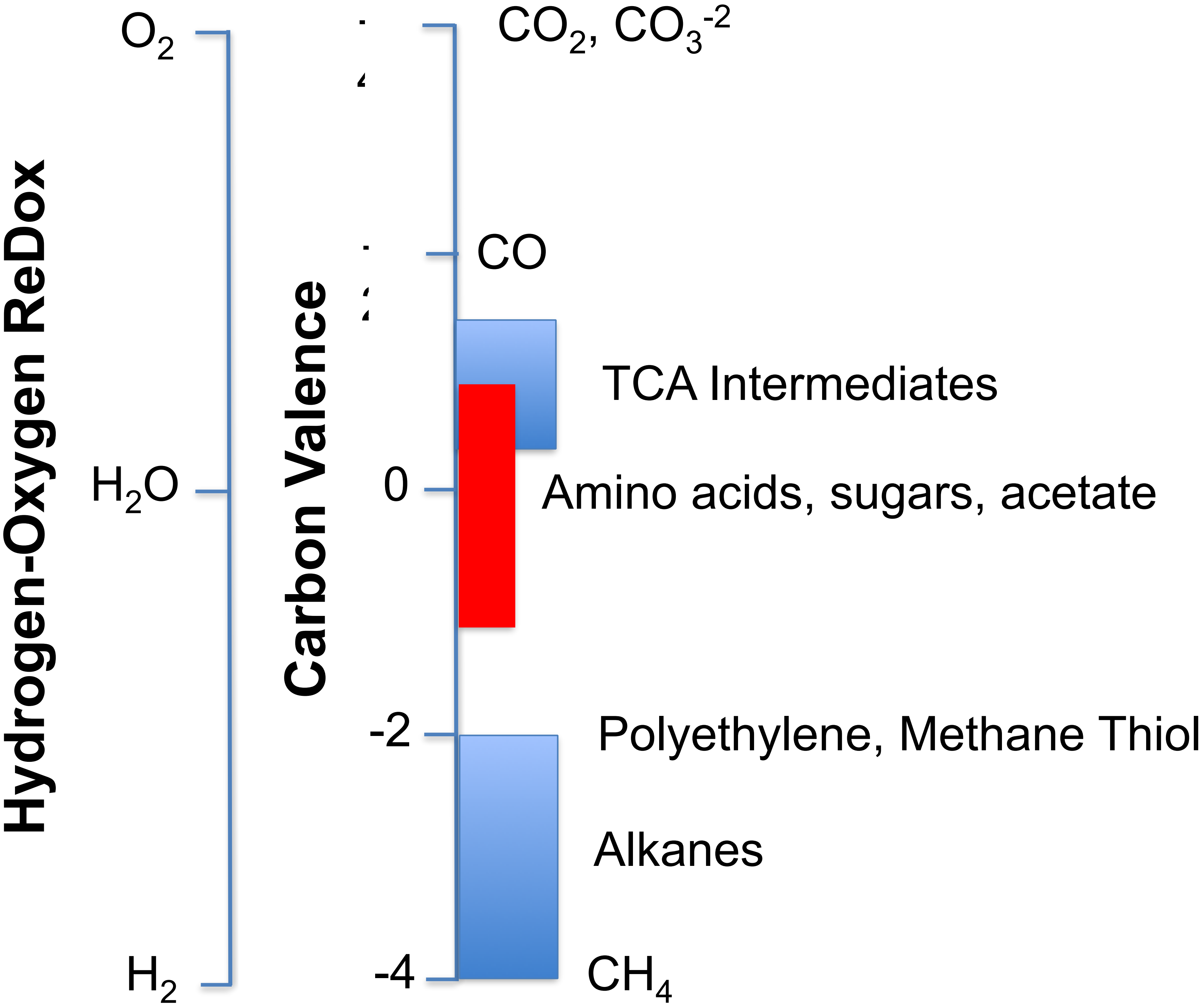
**Sharma et al. 2009**

**Organometallic complexes**, e.g. transition metal carbonyls might have played a significant role in organosynthesis given favorable geochemistry

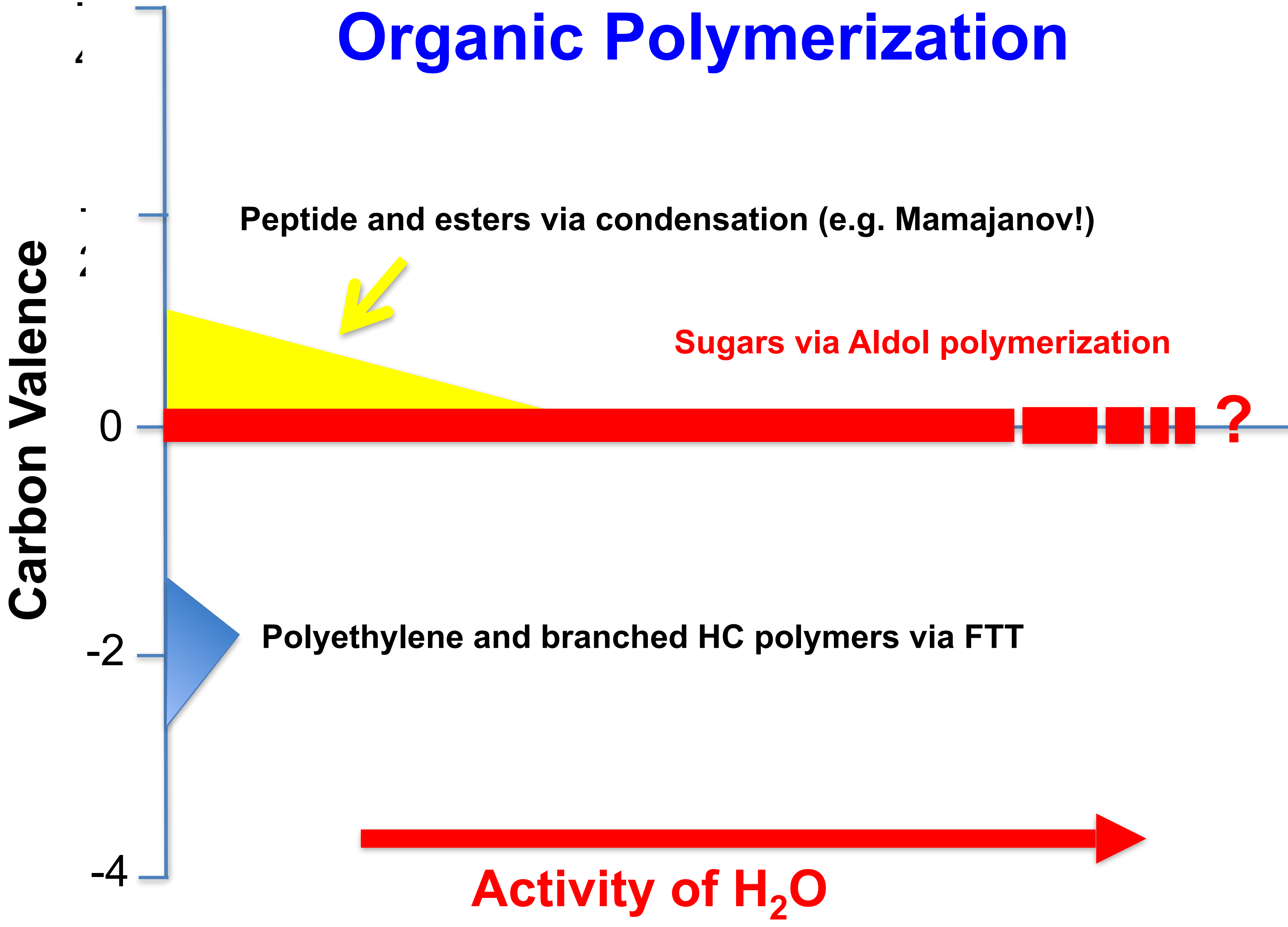
**Even "simple" experiments are rarely simple**…the hidden mineral chemistry drive the system towards rapid HC synthesis.

**Unusual kinetics- Explosive(?)- phase transition(?)**; our best het-catalyst 10 %/hr, this system yields ~ 80 %/hr (not likely heterogeneous catalysis).

*But either way!*… simple hydrocarbons are not reactive and **could not** sustain a *Dynamic Organic Reaction Network*. The formation of methane, ethane and propane are useless for OOL chemistry


Hydrogen-Oxygen ReDox
$O_2$
$H_2O$
$H_2$
Carbon Valence
0
-2
-4
$CO_2$, $CO_3^{-2}$
CO
TCA Intermediates
Amino acids, sugars, acetate
Polyethylene, Methane Thiol
Alkanes
$CH_4$

# Organic Polymerization



Peptide and esters via condensation (e.g. Mamajanov!)

Sugars via Aldol polymerization

Polyethylene and branched HC polymers via FTT

# A vital clue from the Natural World …..

**Carbonaceous chondrite parent body interiors**- an environment where prebiotic synthesis plausibility is known fact… and where apparently a Dynamic Organic Reaction Organic Network was sustained for 10's to 100 Million years

*Chondritic Planetesimal Interior Environment:*

***Warm*** (not hot)

***Wet***- not soaked

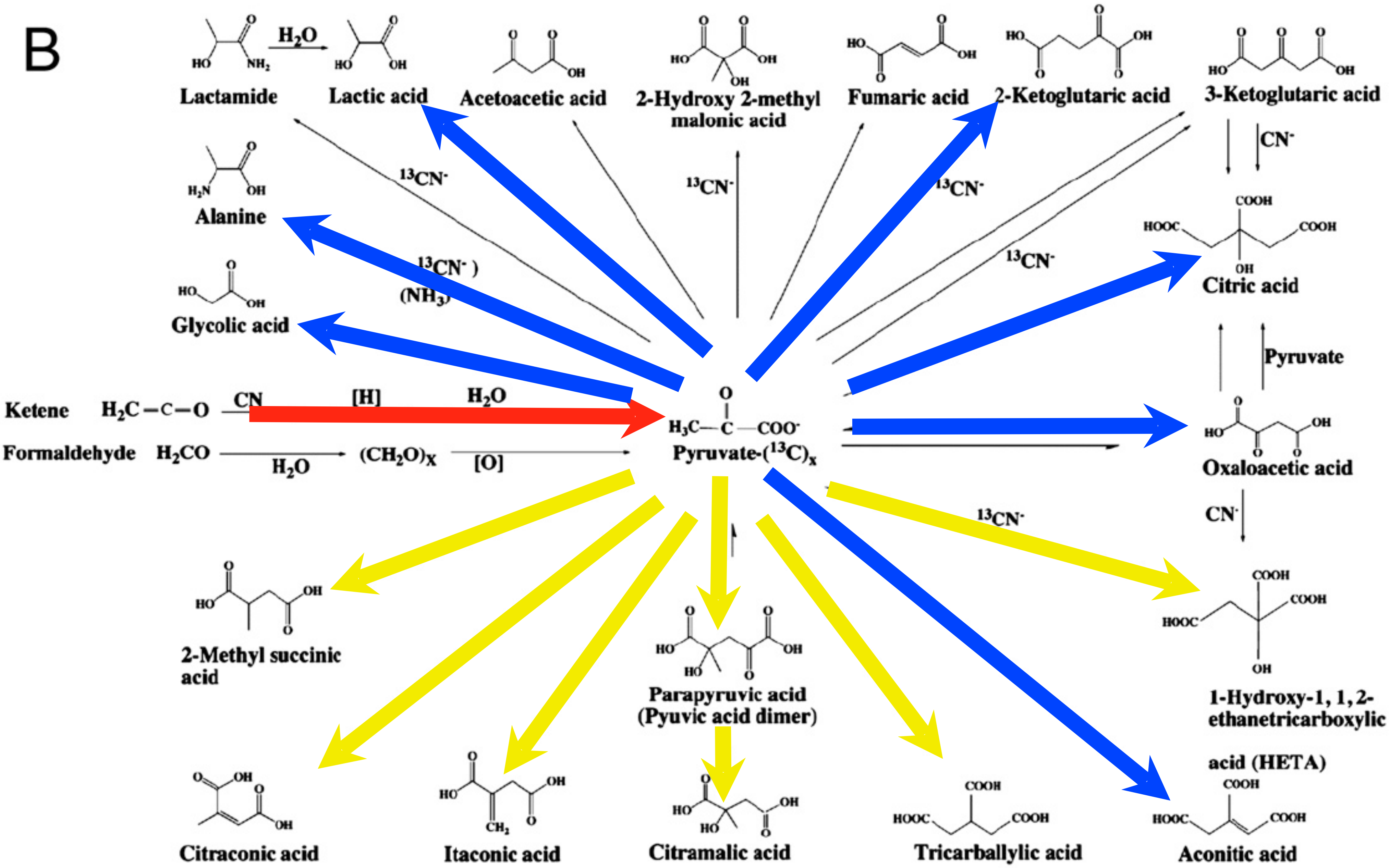
***Initially far from equilibrium*** (interstellar ice, metals, anhydrous Fe-bearing silicates)

***Initially rich in carbon*** (predominantly $CO_2$ and CO)

***Catalytic phases present-*** FeNi metal + FeS

*Potentially millions of years of mild hydrothermal reaction and (maybe) chemical evolution*- evidence not yet established

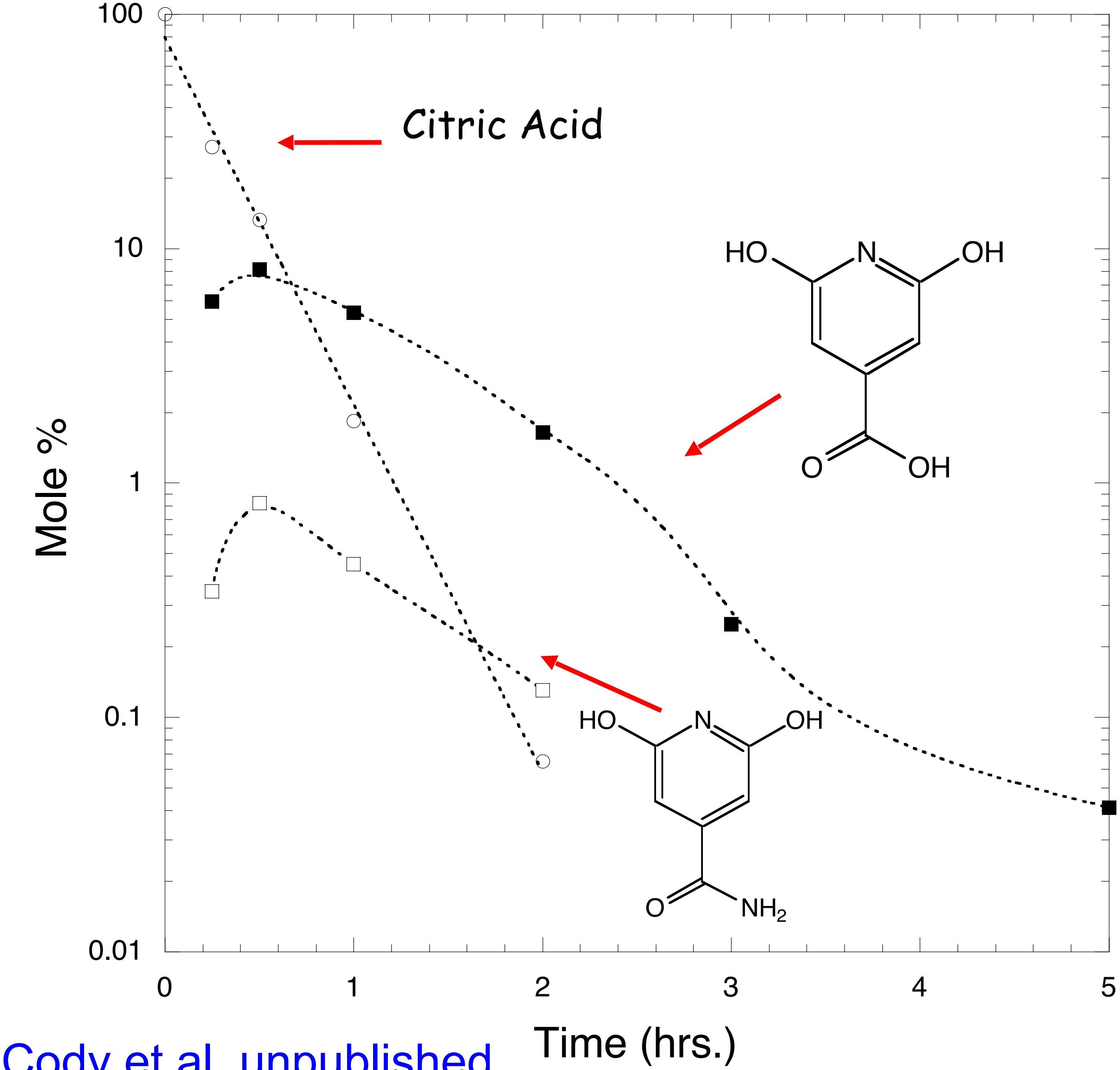
# Common metabolic intermediates present in Murchison...



Cooper et al. (2011) PNAS

And some non-metabolic “intermediates...”

# **But**, many of the compounds detected by Cooper et al 2011 are **not stable** in warm water for long periods of time



Cody et al. unpublished

~ fast decomposition in pure water to low molecular weight product.

Note that Citric acid is more robust than any alpha keto acid!

How could any of these survive $10^6$ years of aqueous alteration?

- None of the molecules identified in Cooper et al. (2011) formed prior to planetesimal accretion

- Many of these molecules are reactive in warm water and will not survive long.

- This would appear to require that reactive molecules are continuously regenerated.

Evidence of a natural **Dynamic Organic Reaction Network** operating in planetesimal interiors.

How did this start and how did it operate?

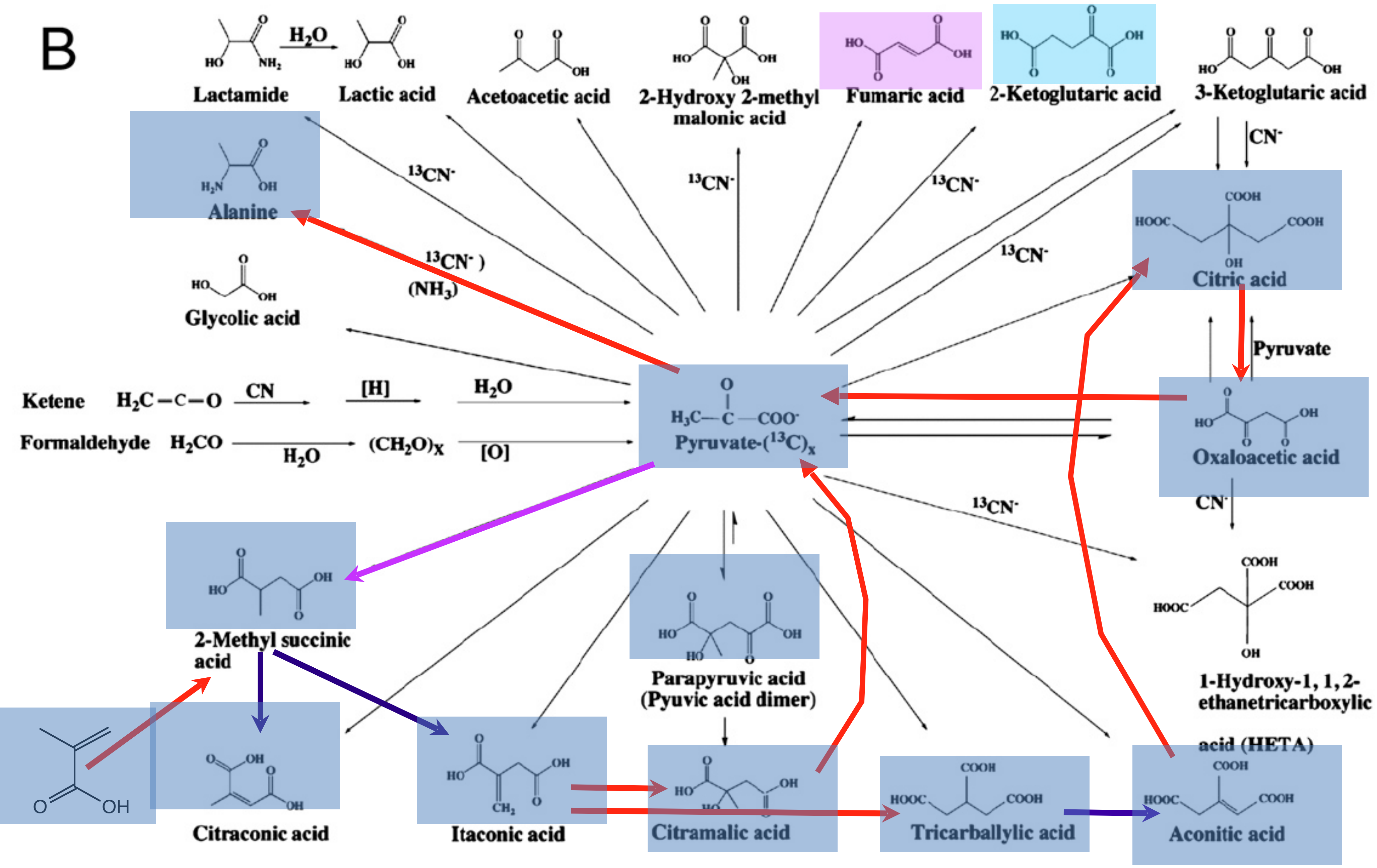
**Planetesimals accrete** from the rapid coalescence of ice covered interstellar silicate grains.

**Ice contains:** $H_2O > CO_2 \geq CO > MeOH \geq CH_2O \sim NH_3 \sim H_2S$, …

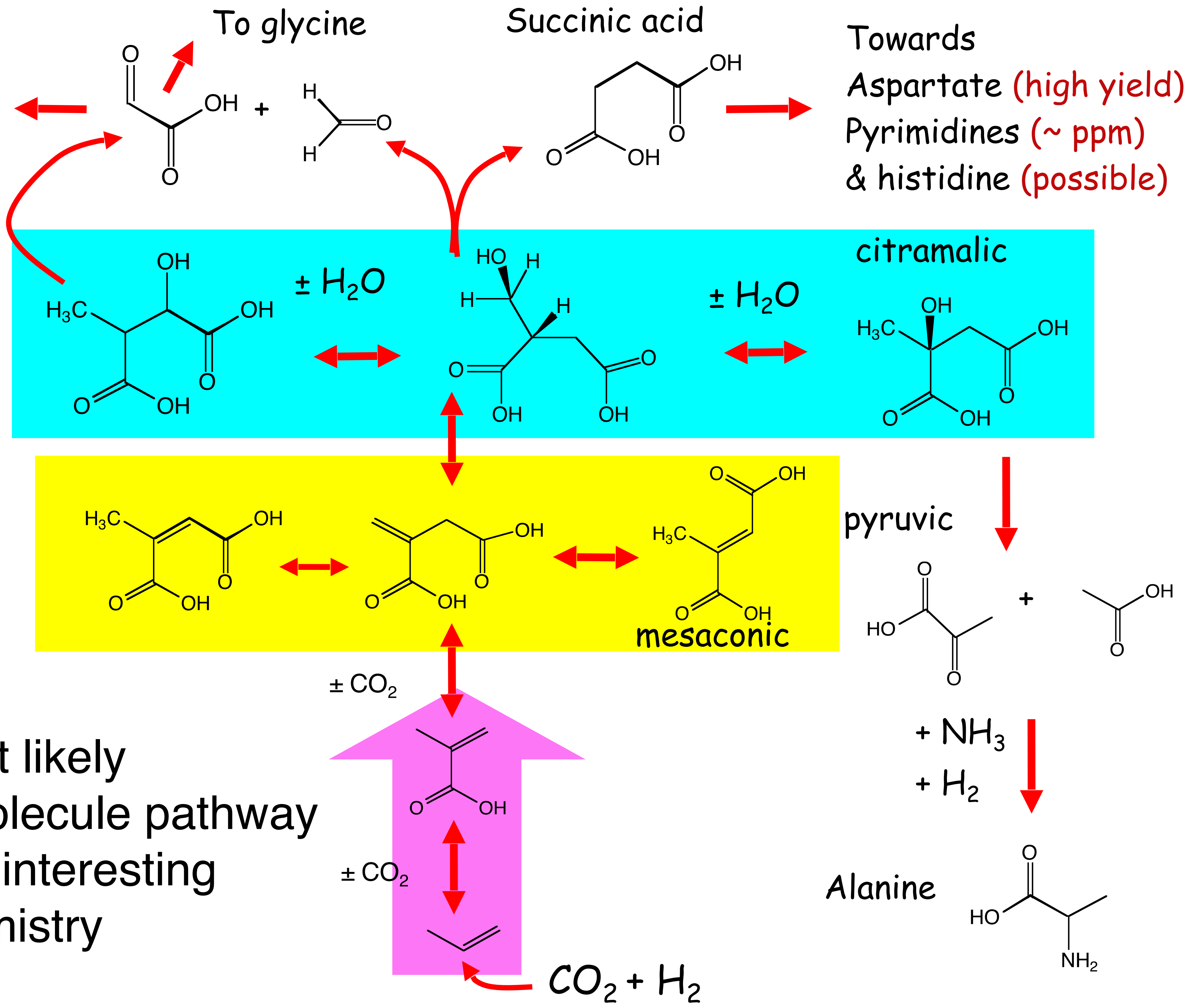
**Silicate includes** Anhydrous Fe-bearing silicates and amorphous glass.

**Radiogenic Elements:** creates heat- melts ice – alters silicates – generates $H_2$

Many of the molecules observed meteorite (Cooper 2011)



Were are are found **via exp.** by Cody et al 2001, 2004



Towards Serine & cysteine

To glycine

Succinic acid

Towards
Aspartate (high yield)
Pyrimidines (~ ppm)
& histidine (possible)

± $H_2O$

± $H_2O$

citramalic

pyruvic

mesaconic

± $CO_2$

± $CO_2$

+ $NH_3$
+ $H_2$

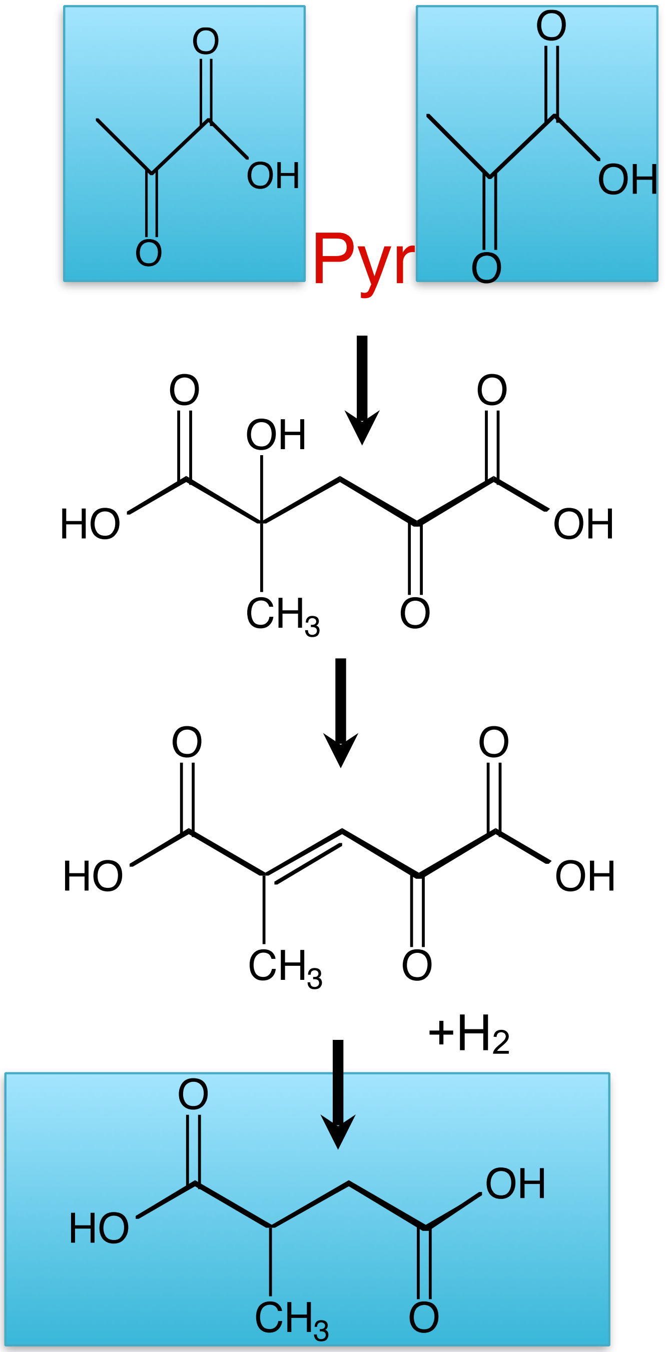
Alanine

$CO_2 + H_2$

# The most likely Small molecule pathway Towards interesting abiochemistry

Cody et al. Science 2000; Cody et al. GCA 2001, 2004

# Taming the “abio" Aldol rxn ?



Methylsuccinic (MS)

+ Formic Acid ($CO_2$ + $H_2$)

1) Acetate + $CO_2$ + $H_2$

2) Extreme molecular complexity, “Tar”

Interesting intermediates: on route to the DORN - interestingly the best pyruvate generator I have ever seen!

= Not very interesting molecule, but striking as a stable “<u>abio-marker</u>” of such chemistry in chondritic meteorites and other environments…

## **Harold's ideas lead to experiments**: Very Simple

React simple organic compounds capable of Aldol condensation in the presence of transition metal complexes

**Chlorides**: $FeCl_2$, $CoCl_2$, $NiCl_2$, $CuCl_2$, and $ZnCl_2$

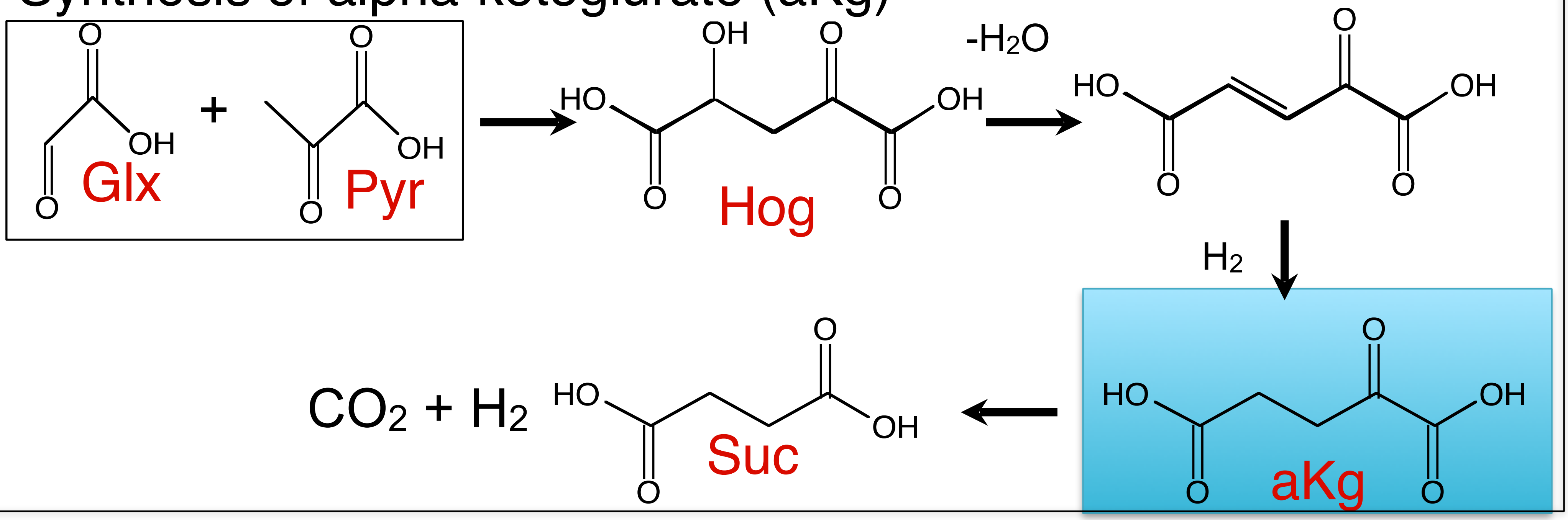
**Organic Compounds**: glyoxylate and pyruvate

**Conditions**: 80 °C, 24 hours, ambient P, run in triplicate- highly reproducible

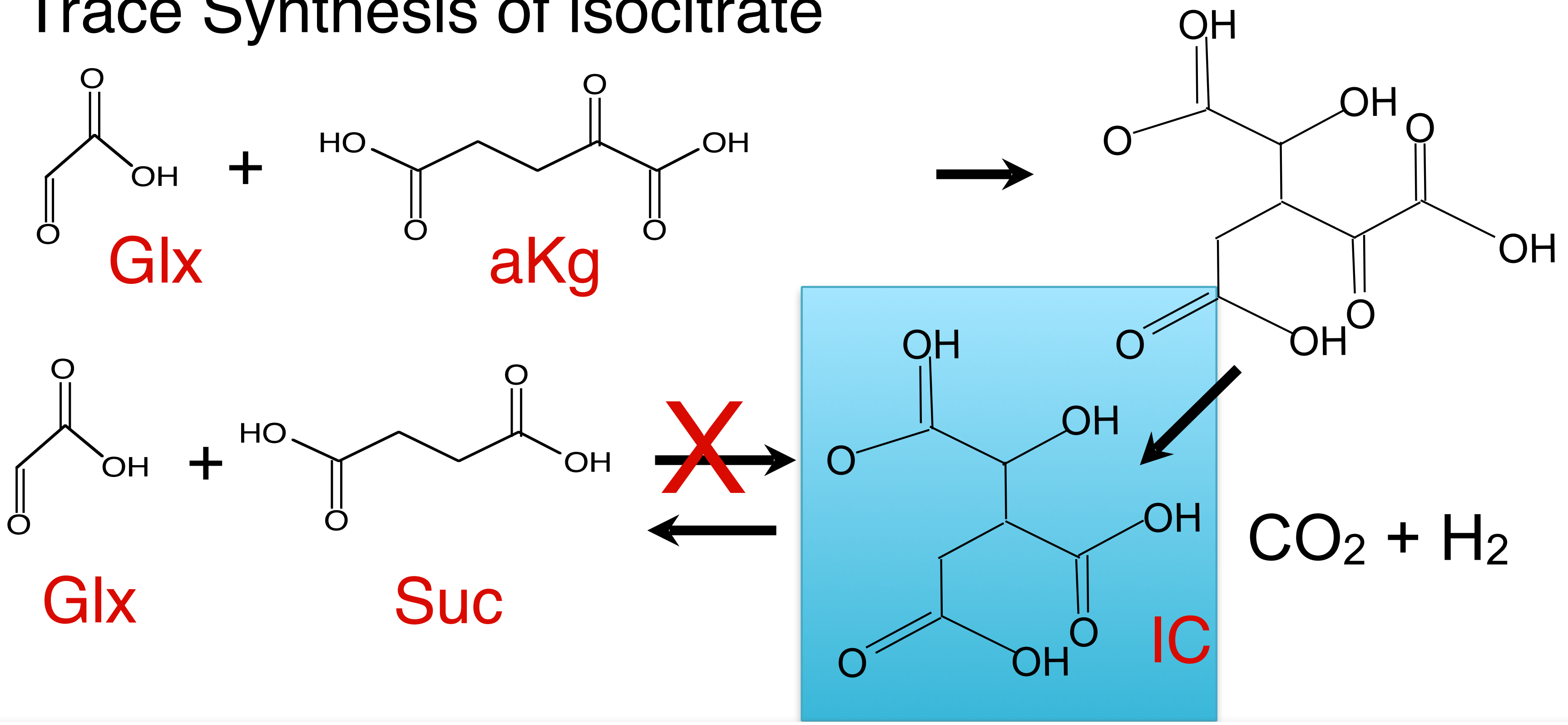
**Analysis**: LC-MS, quantitation with stds.

*Some really cool rxn pathways emerge!*

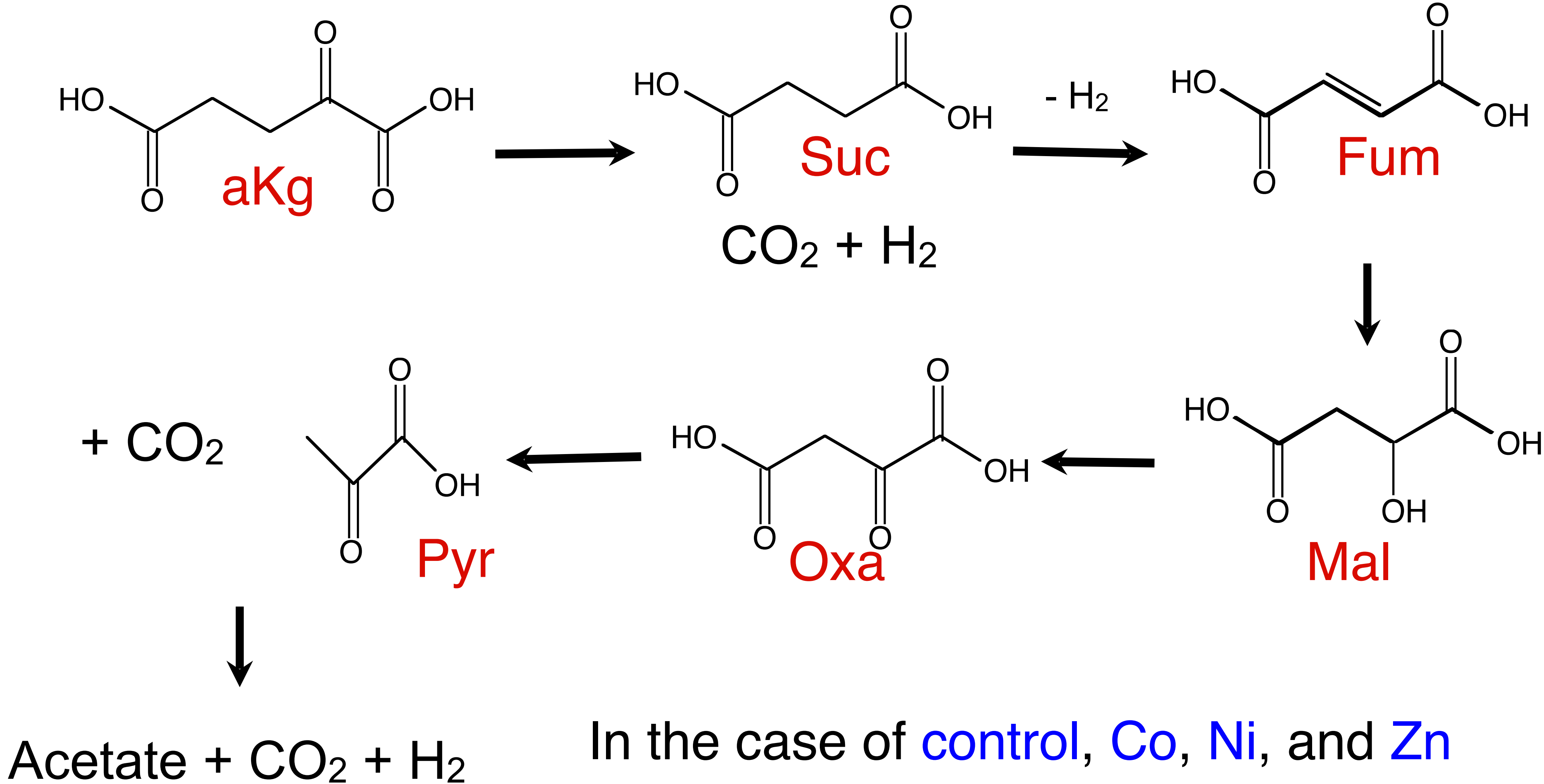
## Synthesis of alpha-ketoglurate (aKg)



## Trace Synthesis of isocitrate



Starting with aKG...



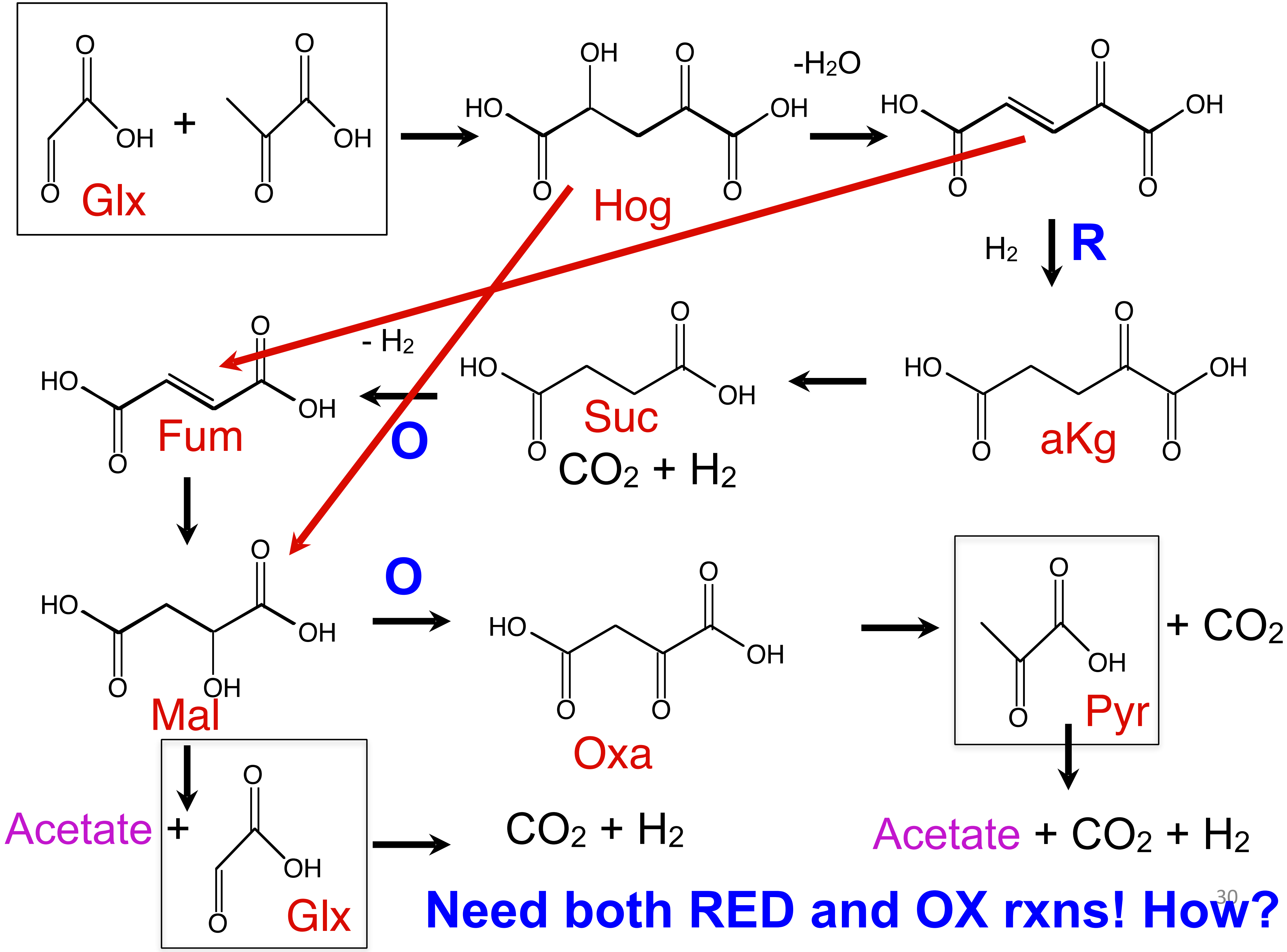
In the case of control, Co, Ni, and Zn **only Suc** was detected

## Total product recoveries are variable across transition metals and organic reactants

| Glx-Pyr | Rec % | aKg | Rec % | IC | Rec % |
|---|---|---|---|---|---|
| control | ~98.0 | control | 98.0 | control | 100.0 |
| Fe | 12.6 | Fe | 3.5 | Fe | 25.9 |
| Co | 83.3 | Co | 98.0 | Co | 90.0 |
| Ni | 78.2 | Ni | 98.0 | Ni | 98.0 |
| Cu | 17.4 | Cu | 0.4 | Cu | 0.1 |
| Zn | 52.7 | Zn | 98.0 | Zn | 98.0 |

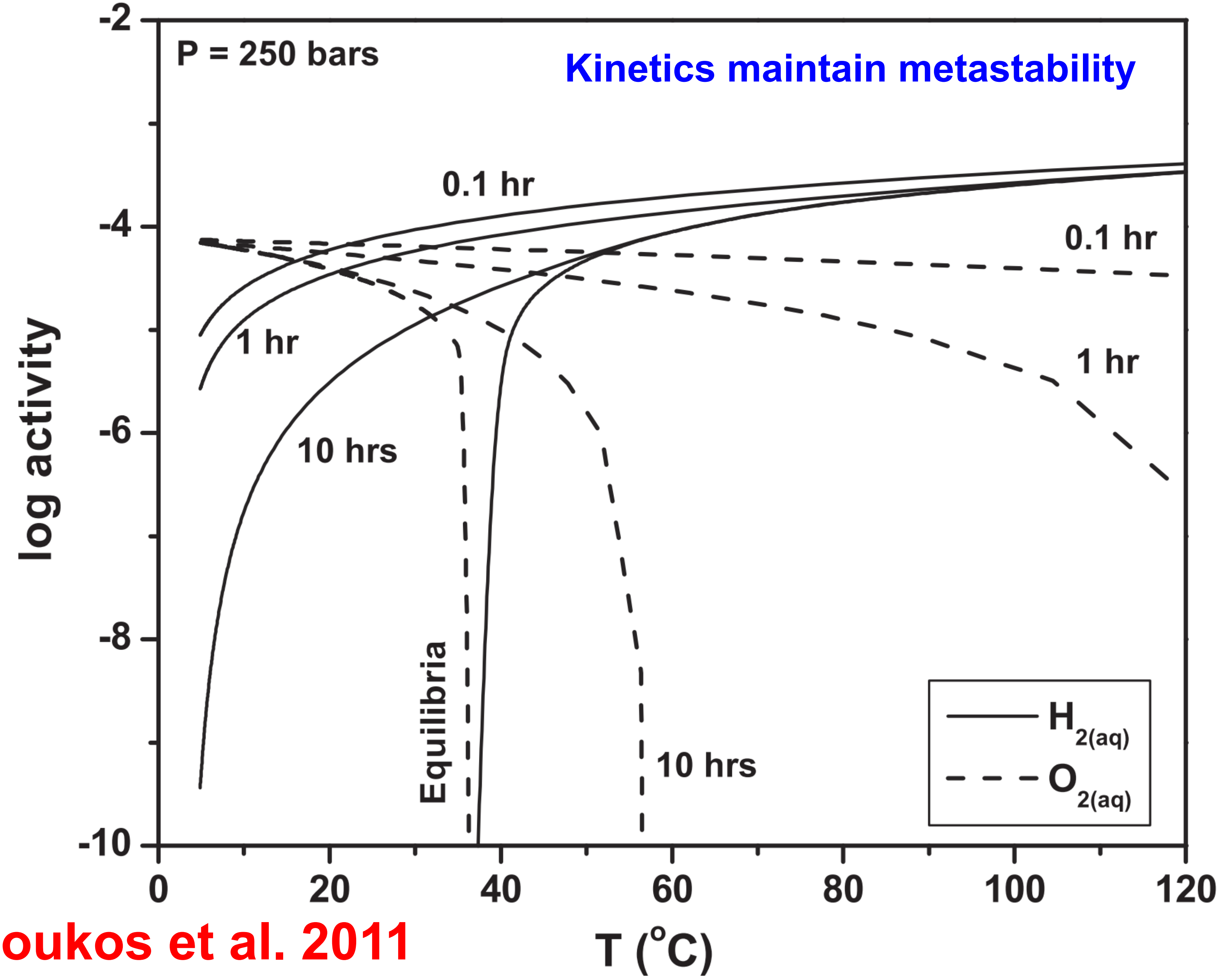
Individual transition metal cations work with different substrates in different ways. This chemical system is <u>hyper-complex</u>, and perhaps unknowable at the core level, but is a physico-chemical reality.

This is a <u>high loss</u> system! but it is **dynamic**!



**Need both RED and OX rxns! How?**

High Temperatures form $H_2$ and $O_2$ from $H_2O$, $H_2$ Oxidation kinetics is not instantaneous, **$H_2$** and **$O_2$** (plus **$H_2O_2$**) will persist beyond equilibrium… note: **radiolysis** of $H_2O$ will also produce oxidants **$H_2$** and **$O_2$** (plus **$H_2O_2$**)



Foustoukos et al. 2011

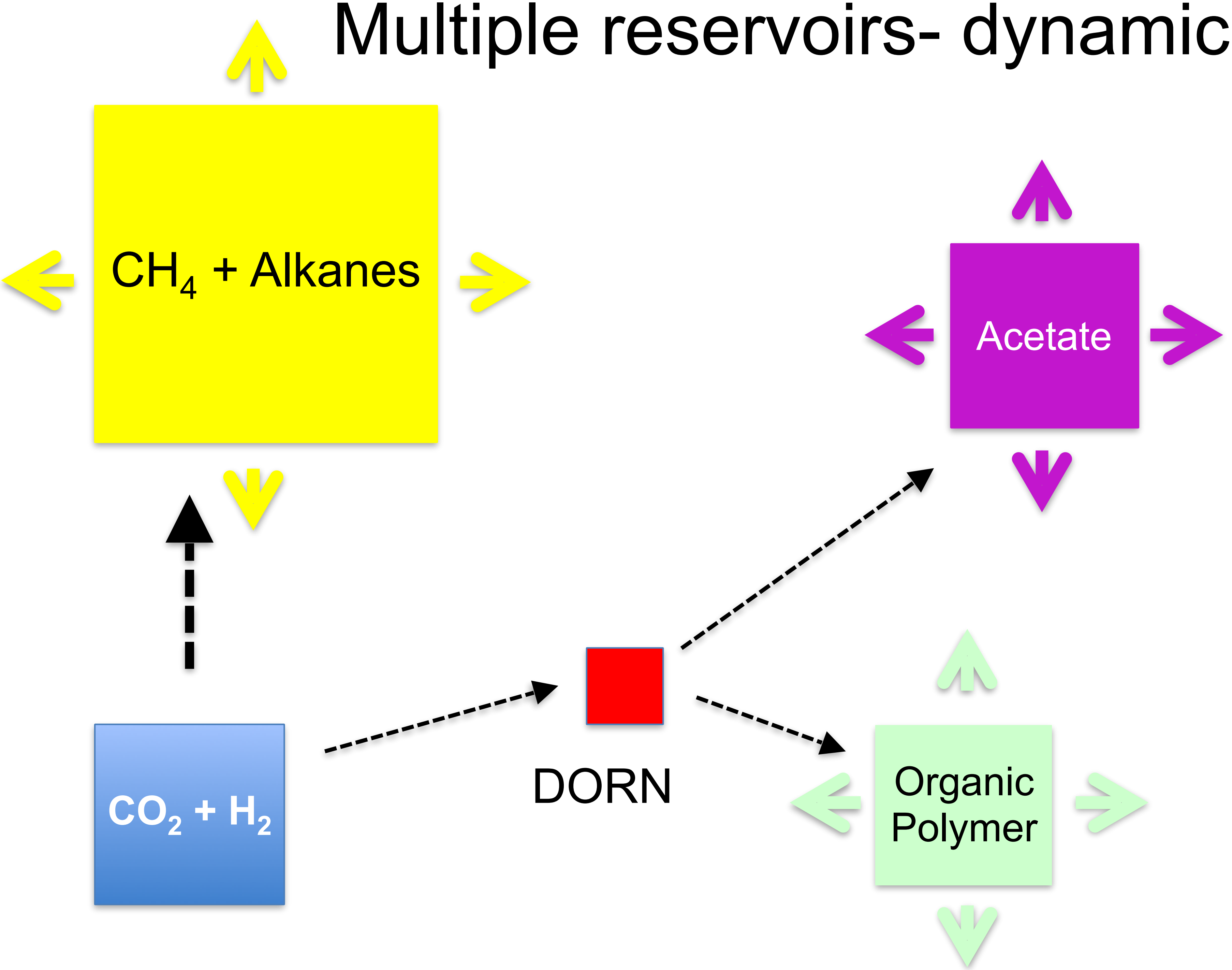
# With a functional *Dynamic Organic Reaction Network* a lot can form from a little...

**For example**: If you start with *butanoic acid* and *isobutanoic acid* and allow for following reactions...

carbonyl insertion √
partial oxidation √
Retro-Aldol cleavage √
Aldol condensation √
Amination and reductive amination √

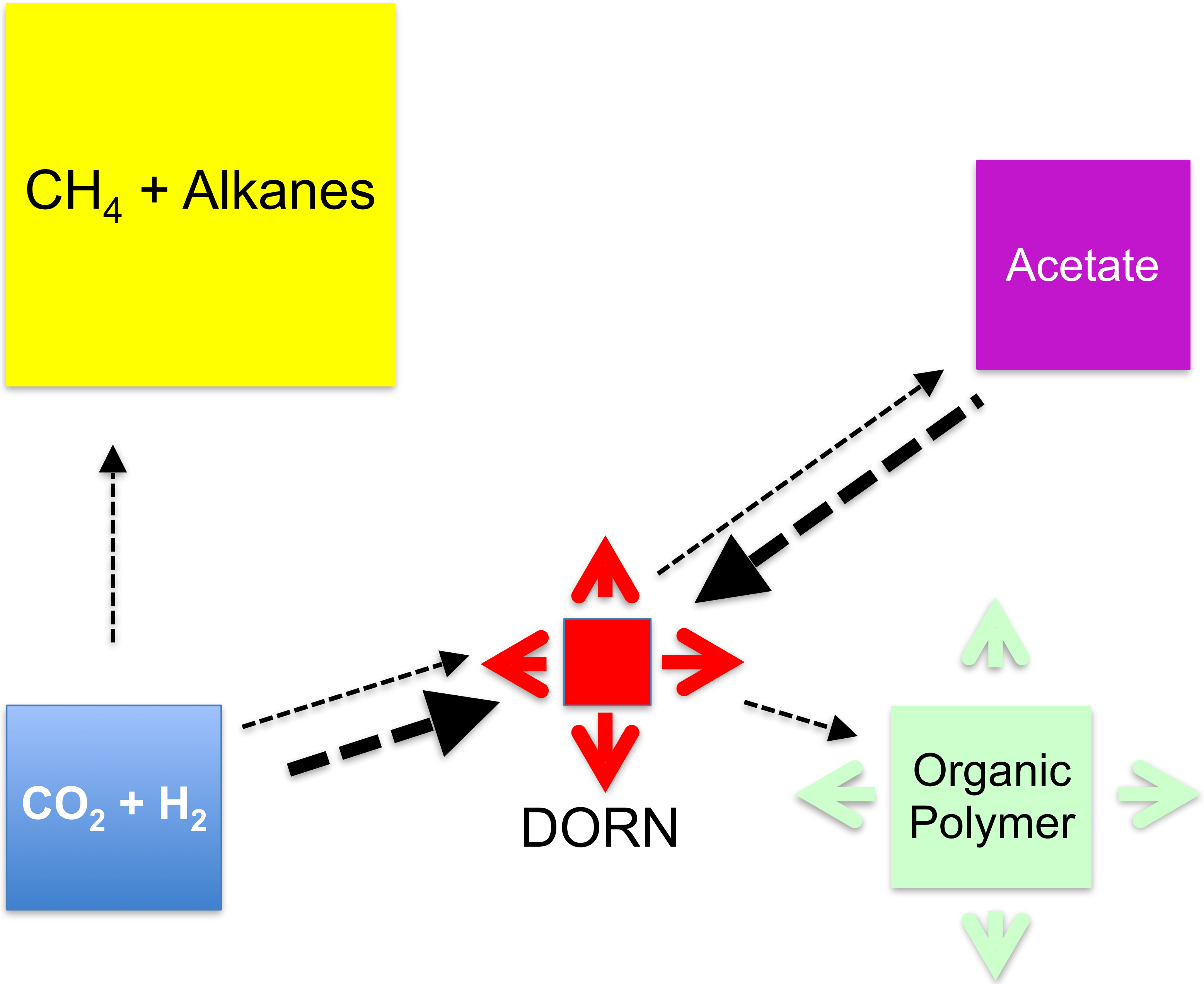
One easily generates (**on paper**) in excess of 350 molecules including saturated and olefinic polycarboxylic acids, amino-acids, keto acids, alcohol acids (*to get there one would need unusual controls*)

# Multiple reservoirs- dynamic!



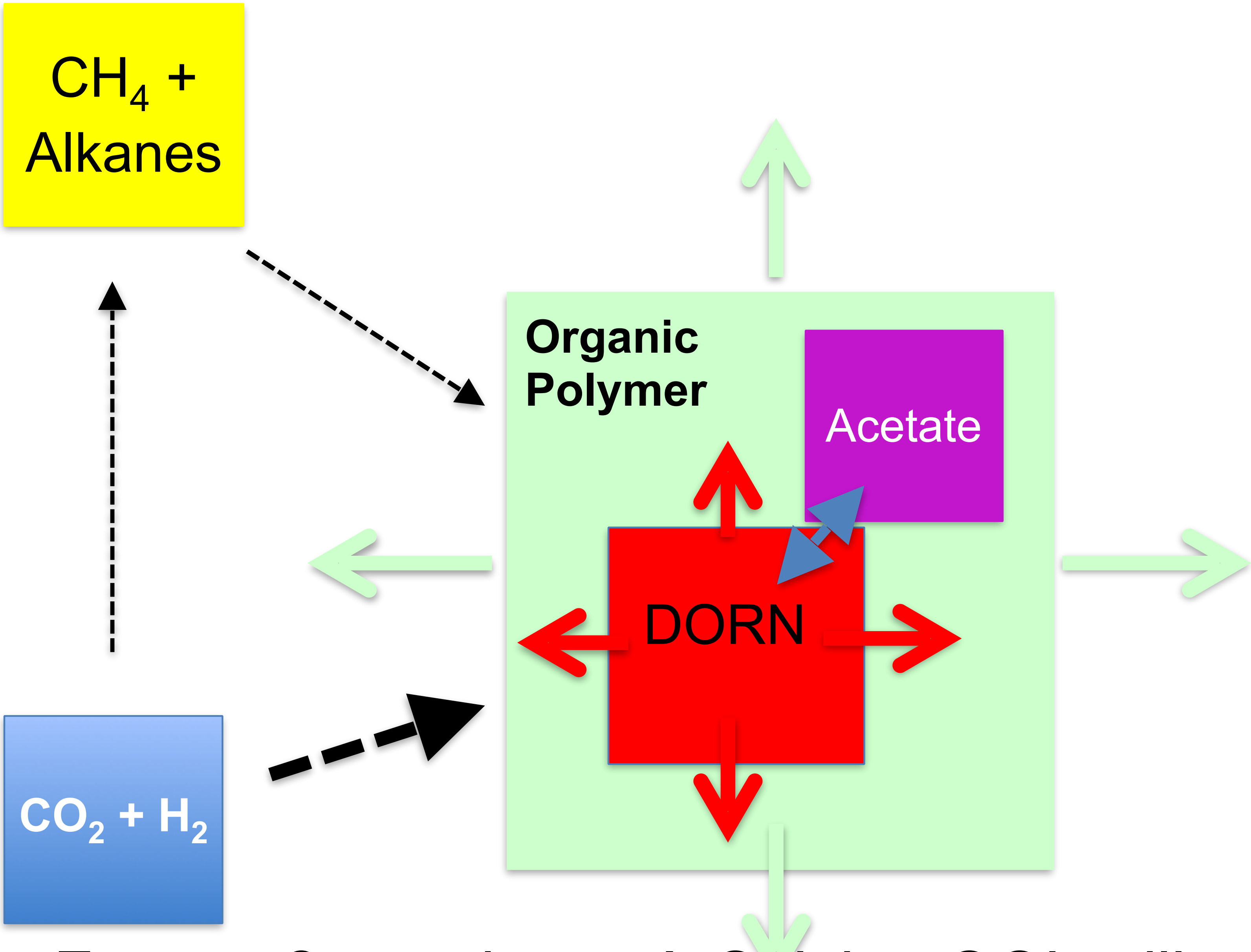
Everything that you <u>don't</u> want grows- DORN does not

# Multiple reservoirs- dynamic!



What you aim for is that DORN grows- How?

# How about Combining Reserviors?



$CH_4$ + Alkanes

**Organic Polymer**

Acetate

DORN

**$CO_2 + H_2$**

Pure Fantasy?- maybe not!  Solving OOL will require Creative thinking – AND – really Creative Chemistry

The “problem” of life’s origins is not a chemistry problem (the chemistry is not a problem-

The problem is understanding of “***special***” chemical environments that could somehow do the chemistry that “***is necessary***”.

**Four Important Examples**:

*Activation of Acetate (activation of phosphate)*- simplest way is phosphorylation

*Enhancement/Control of “$NH_3$” activity*- makes every nitrogenous compound easy- amino acids and nucleobases

*Control oxidative decarboxylation* – primary reductant- don’t waste it!

*Control partial oxidation* – critical to molecular complexity growth- but potentially very high loss

**Conclusions:** The requirement of a **Dynamic Organic Reaction Network** (DORN) remains obvious

The potential for at least a stable DORN is likely proven for chondritic planetesimals – it clearly happened and works!

Experimental evidence supports the potential chemical rxn topology for a DORN.

Both RED and OX chemistry must operate (*simultaneously*) to drive the DORN.

True Lab demo of DORN remains elusive…