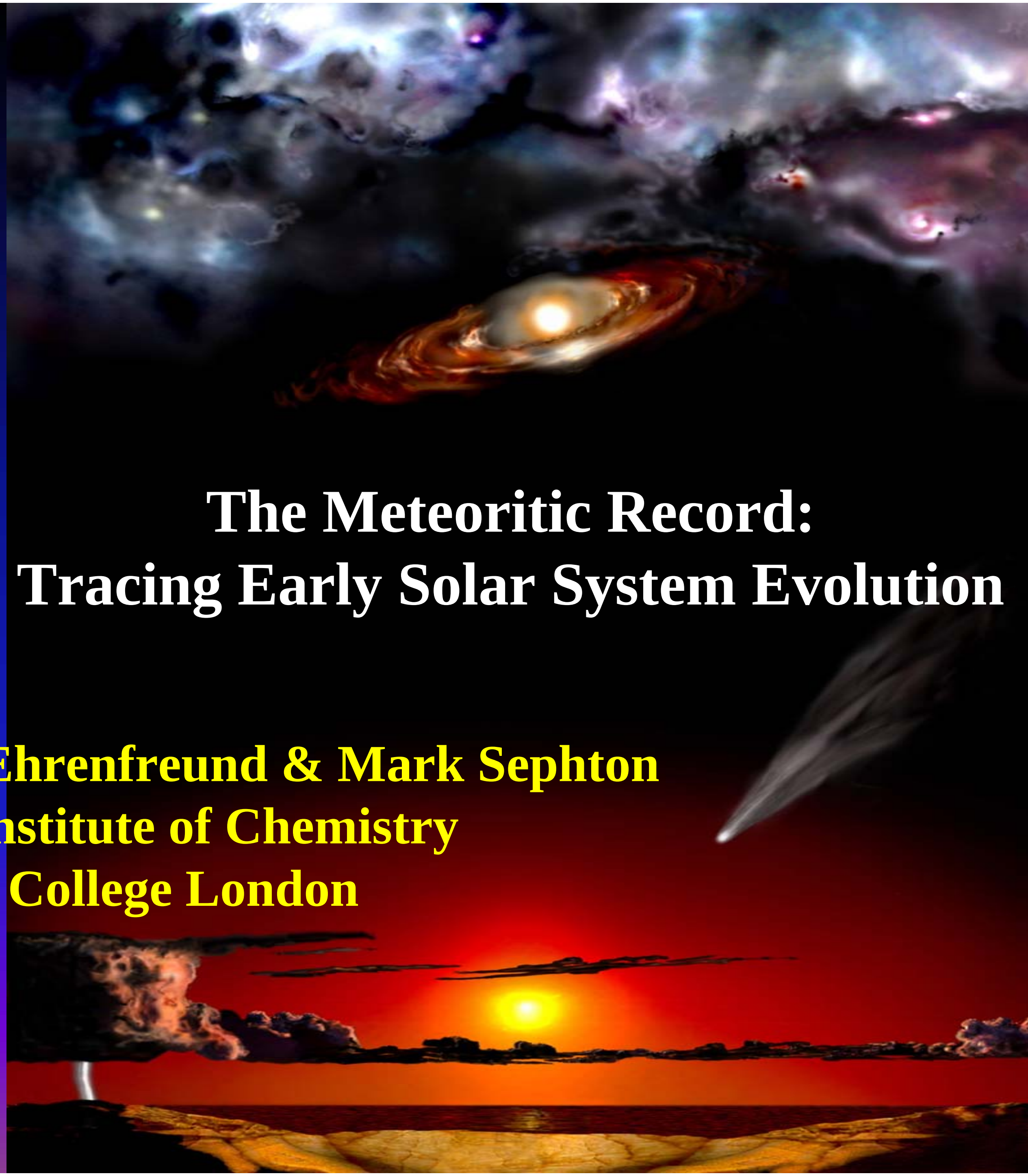

The Meteoritic Record: Tracing Early Solar System Evolution

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Meteorite analysis

- Asteroid fragments - "meteorites" are the only extraterrestrial material that can be investigated in the laboratory in substantial quantities

- The analyses of meteorites provide evidence that both volatile and refractory material has been substantially altered owing to thermal and aqueous processes within the solar system

- Chemical characterization and stable isotope measurements on individual molecules are revealing reaction mechanisms that preceded and coincided with the birth of the solar system

Solar nebula carbon chemistry

- **Infalling interstellar material experiences chemical alteration to varying degrees, depending upon the epoch and position of entry into the nebula**

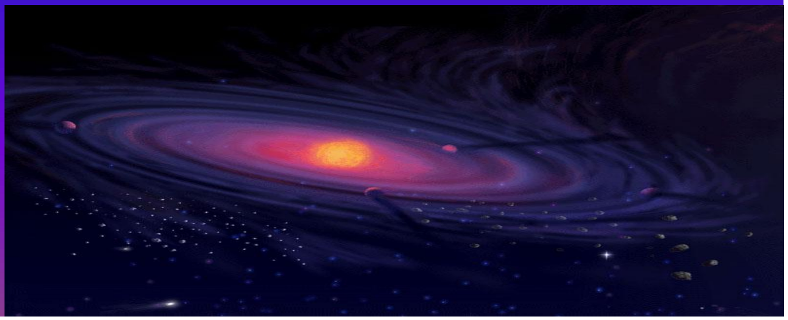
***Ionization source*: stellar X-rays, stellar UV, interstellar UV, cosmic rays ….**
***Heating:* viscous dissipation, stellar radiation**
***Transport:* radial mixing, diffusion**

- **Inner solar nebula: material is heavily processed, strong radiation, high temperature, dissociation of molecules**

- **Outer solar nebula: evaporation-recondensation of ices, similar chemistry as in dense clouds**

Solar System Inventory

- Some relative pristine material with a strong interstellar heritage
- Highly processed interstellar material that was exposed to high temperatures and radiation
- Material newly formed in the solar nebula or on solid solar system objects

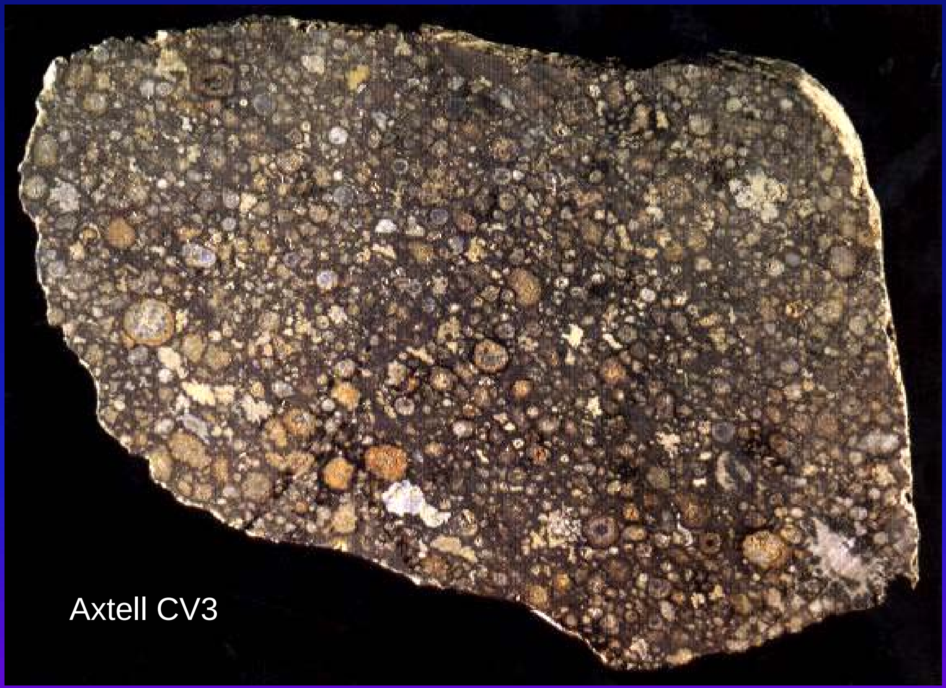


Minerals in meteorites

Chondrites

- Mineral components
  - chondrules
  - clays
  - carbonates

- Multiple proposed origins
  - circumstellar
    - carbonates
  - solar nebula
    - chondrules
    - clays
  - parent body
    - carbonates
    - clays



Lithium in meteorites

Lithium

• **Two isotopes**
- ^{6}Li, ^{7}Li

• **Action of water**
- ^{7}Li passes preferentially into solution

• **Reveals origins of minerals**
- chondrules (anhydrous)
  - ^{7}Li-poor
  - solar nebula
- clays
  - ^{7}Li-intermediate
  - some water on parent body
- carbonates
  - ^{7}Li-rich
  - lots of water on parent body

Lithium Isotopic Compositions of Bulk Murchison and Some of Its Constituent Parts

Sample	$^{7}Li/^{6}Li$	$\delta^{7}Li$[a]
Whole rock	12.0654	+3.78 ± 0.21
Carbonate-rich acetic acid–soluble phase[b]	12.1708	+12.55 ± 0.17
	12.1766	+13.03 ± 0.25
Phyllosilicate-rich matrix[c]	12.0940	+6.16 ± 0.78
	12.0901	+5.83 ± 0.61
Chondrule	11.9969	−1.92 ± 0.31

Sephton et al. 2004 ApJ 612, 588–591

Carbon in primitive meteorites

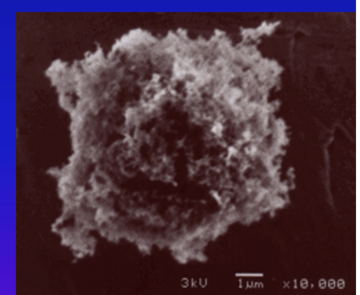
	Abundance (wt%)	$\delta^{13}C$ (‰)
Whole rock	-	0 to -25
Organic matter	2.0	-13 to -21
Carbonate	0.2	+20 to +80
Diamond	0.04	-38
Graphite	0.005	-50 to +340
Silicon carbide	0.009	+1200

Carbonaceous chondrites – most pristine!

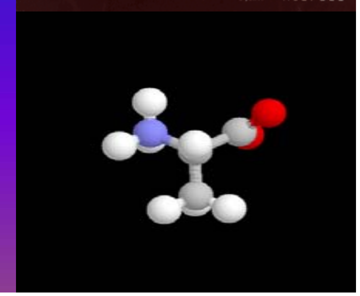
Murchison

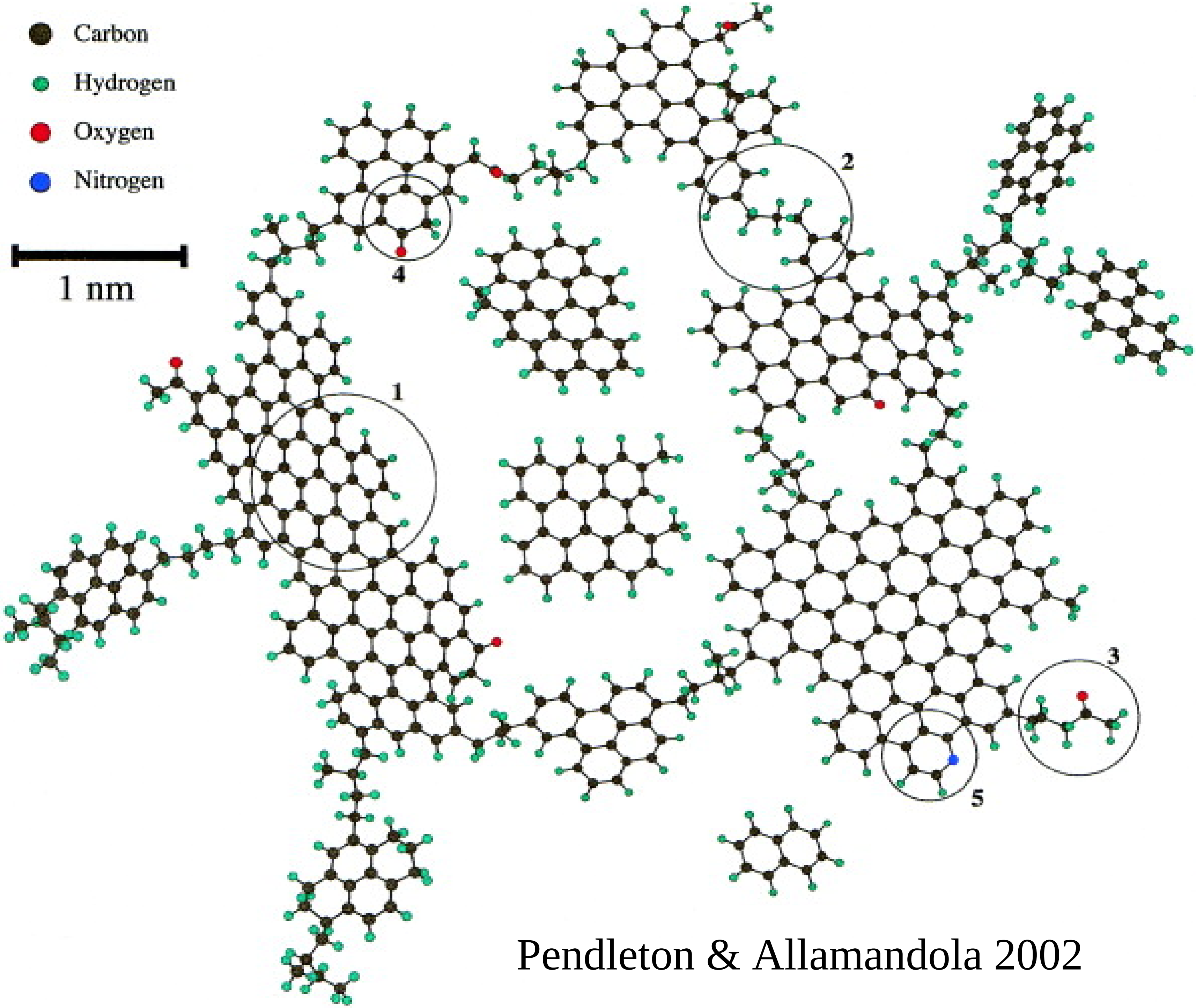
Insoluble Carbon-fraction:

60-80 % aromatic carbon
highly substituted small aromatic moieties branched by aliphatic chains



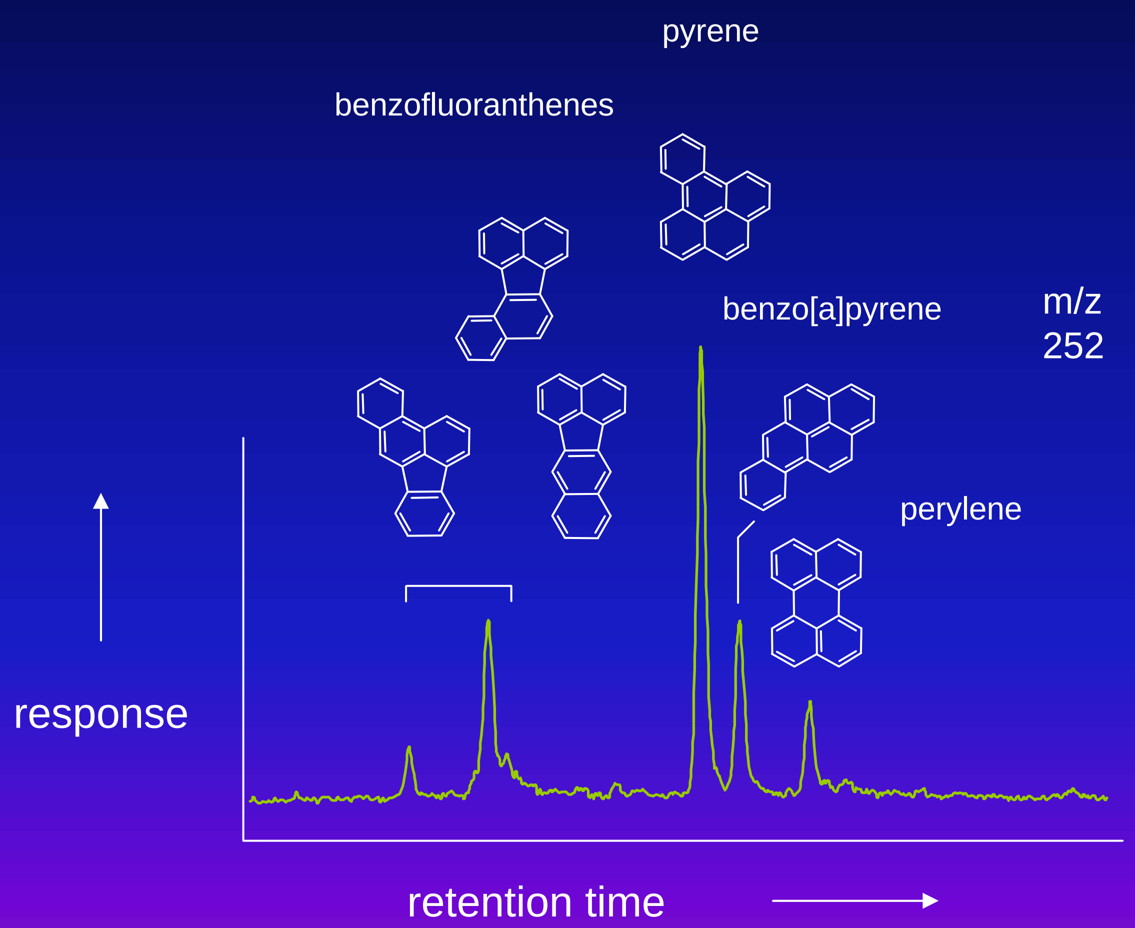
Volatile fraction:





Pendleton & Allamandola 2002

Origin of hydropyrolysate PAH



Ion chromatogram

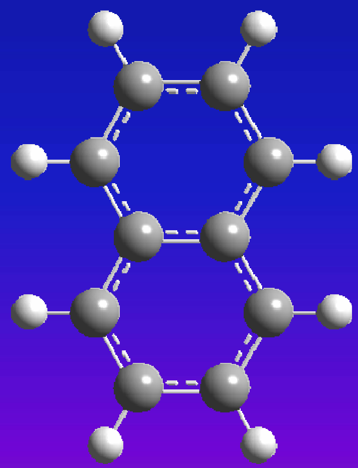
Parental PAH

- **poorly cross-linked units**
  - **short aliphatic chains**
  - **heteroatoms**
- **thermodynamics**
  - **unfavourable forms present**
- **pre-incorporation?**
  - **low temperature**
  - **isotopic heterogeneity**
- **interstellar?**

Sephton et al. 2004

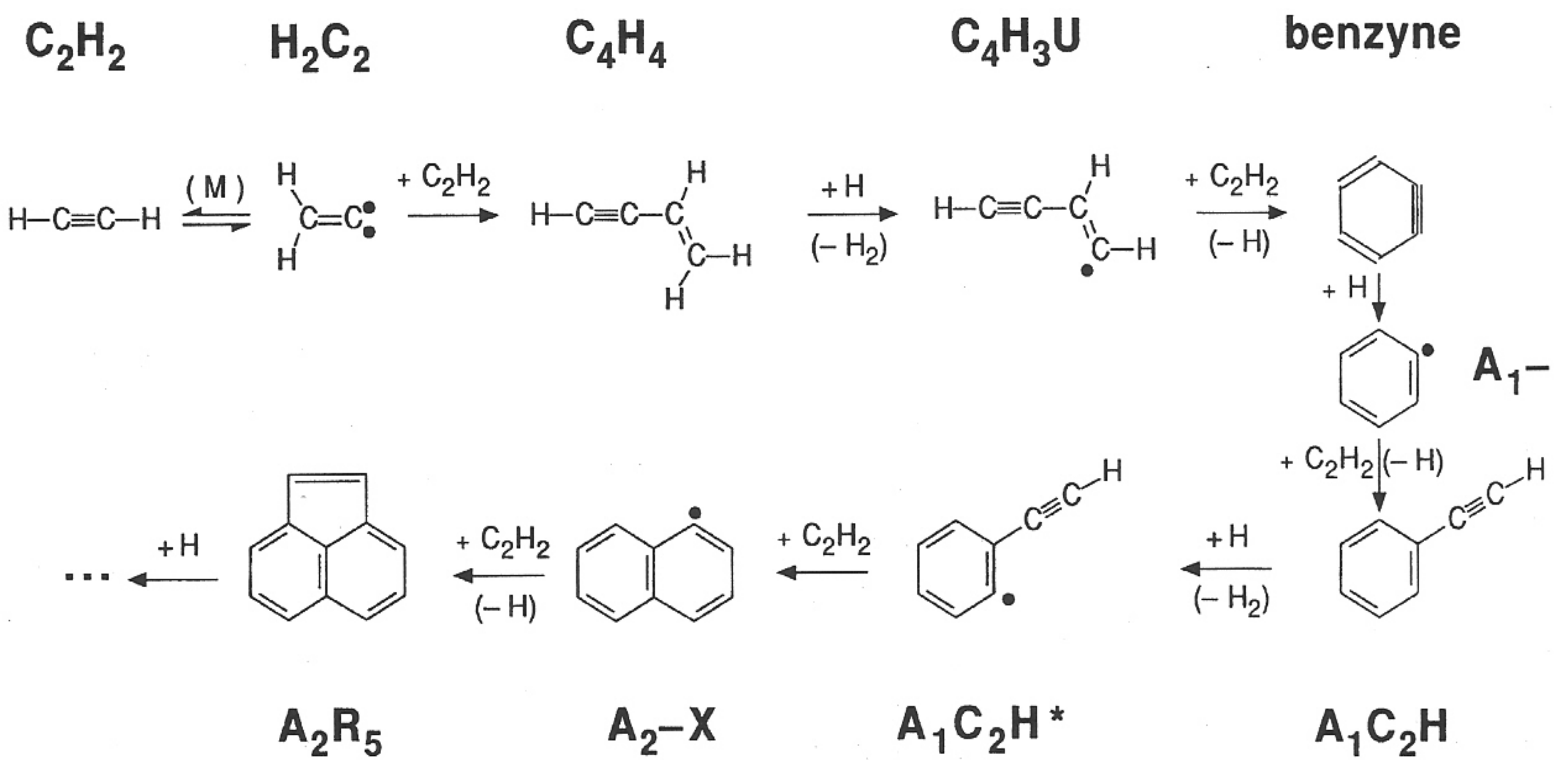
A hot or cold origin for aromatics ?

- **D-enrichment, hotspots ^{13}C, ^{15}N**
- **Increase in $\delta^{13}C$ and then decrease with increasing molecular size**
- **Large fractionation in C isotopes (in Murchison -13.1 and -5.9 ‰ for pyrene and fluoranthene respectively)**



The dominant reaction pathway of polycyclic aromatic hydrocarbons in circumstellar envelopes

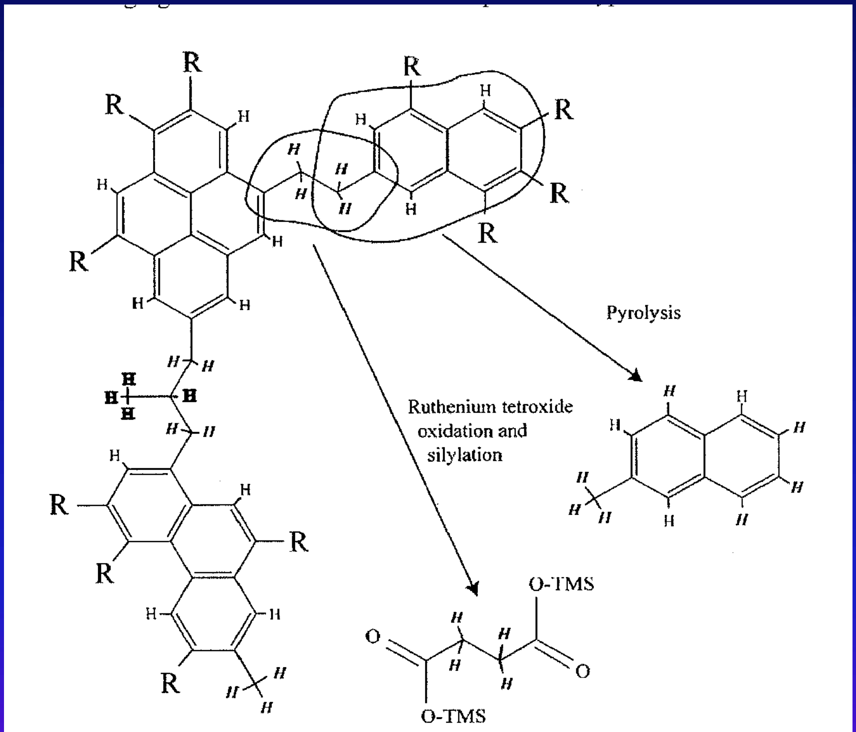
H abstraction, C_2H_2 addition, PAHs form at high T (900-1100 K)

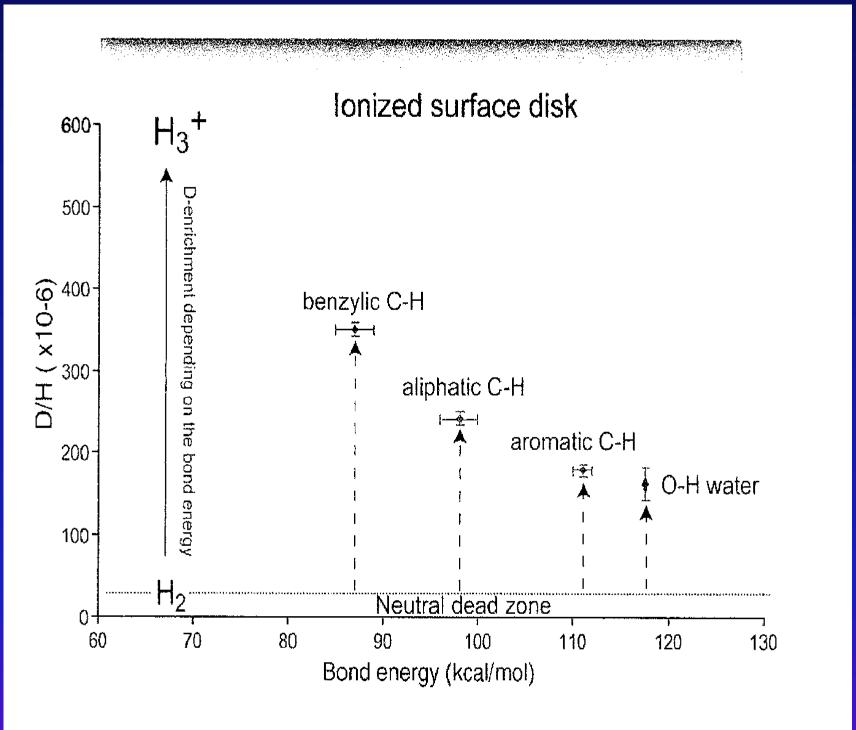


Frenklach & Feigelson 1989

A solar system origin for D-enrichment in organic matter

(Remusat et al. 2006)





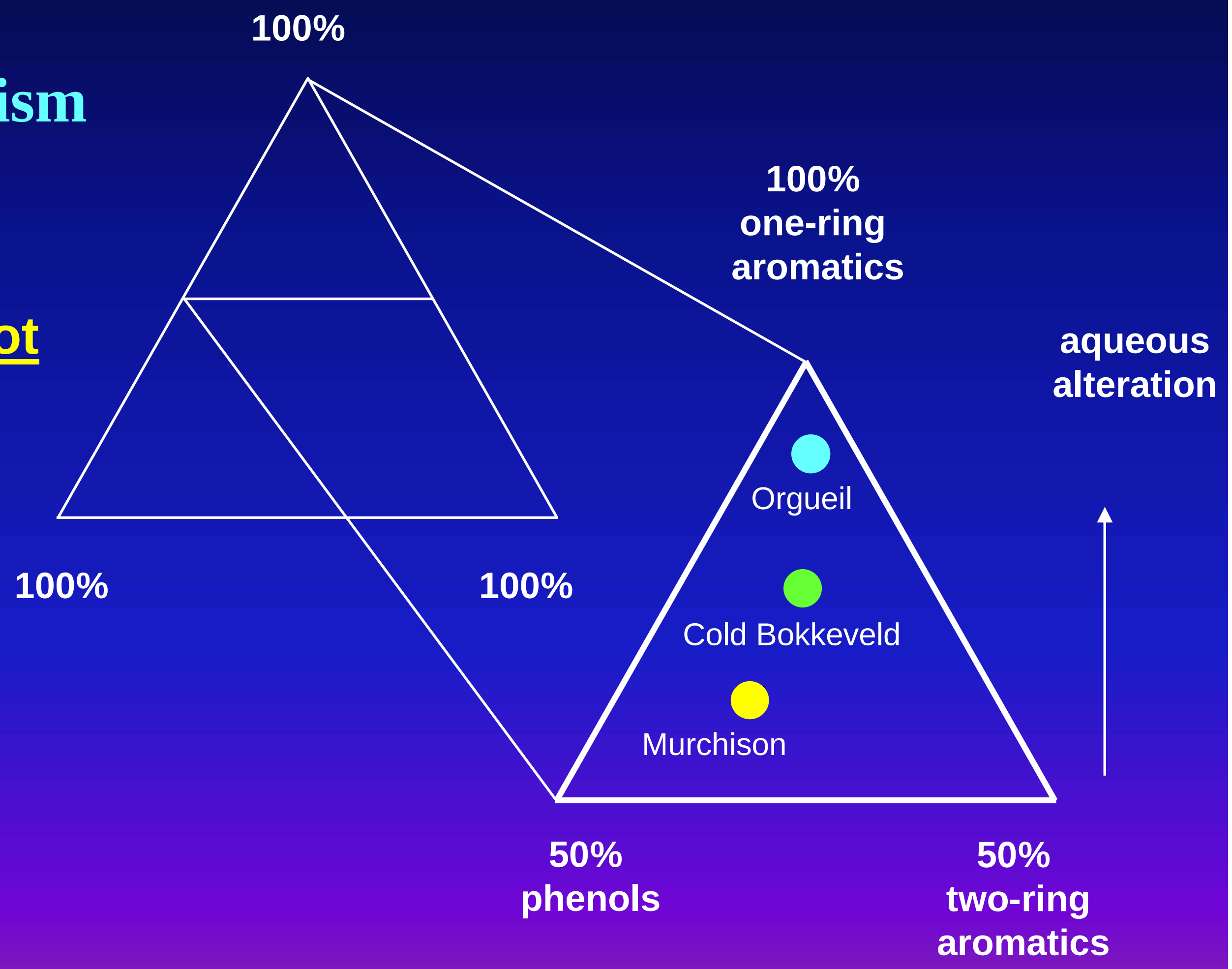
D/H ratio of benzylic, aliphatic and aromatic hydrogen and water as a function of the C-H bond energy. The water D/H indicates that this relation may illustrate a common process in the early solar system.

Quantitative relationships

Aqueous alteration
Oxidation
Thermal Metamorphism

Pyrolysates - ternary plot

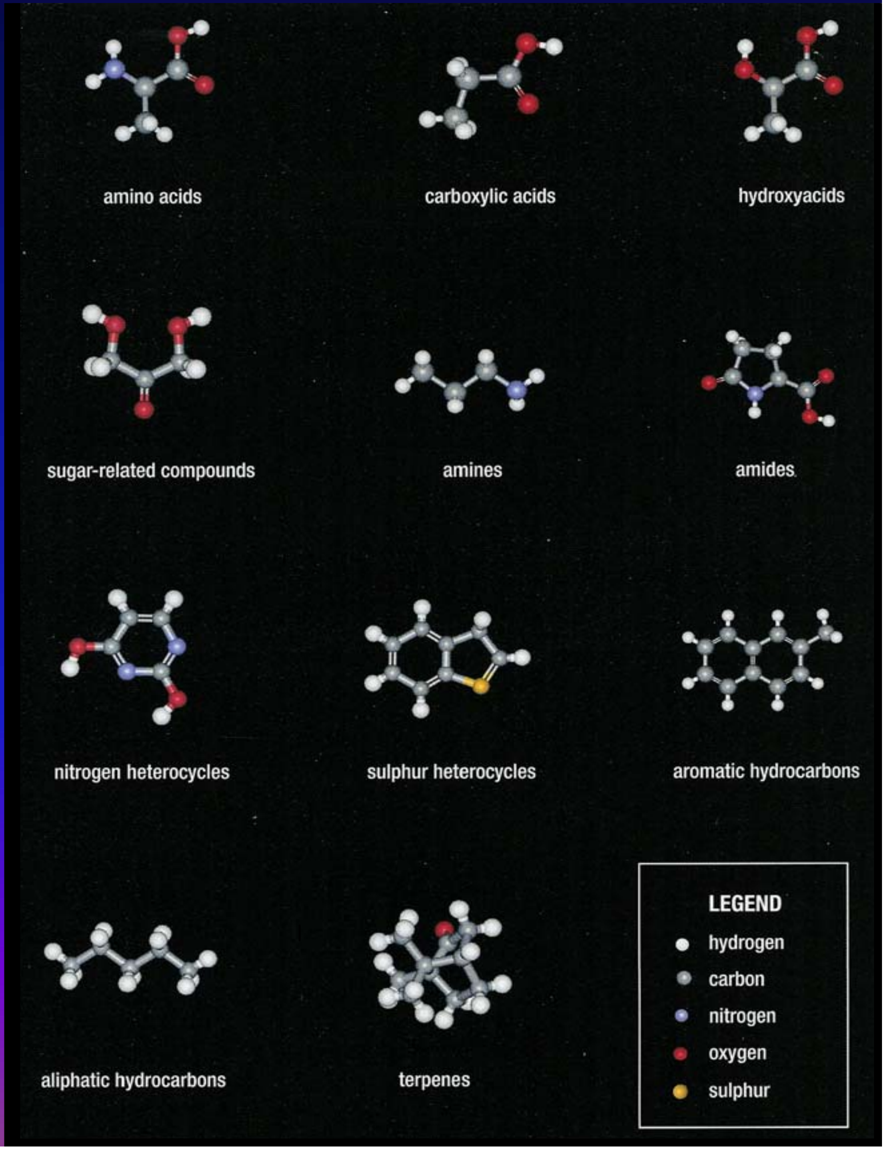
- quantitative differences
  - organic moieties
- one ring/two ring
  - degree of condensation
- hydrocarbons/phenols
  - oxygen content
- correlation
  - aqueous alteration



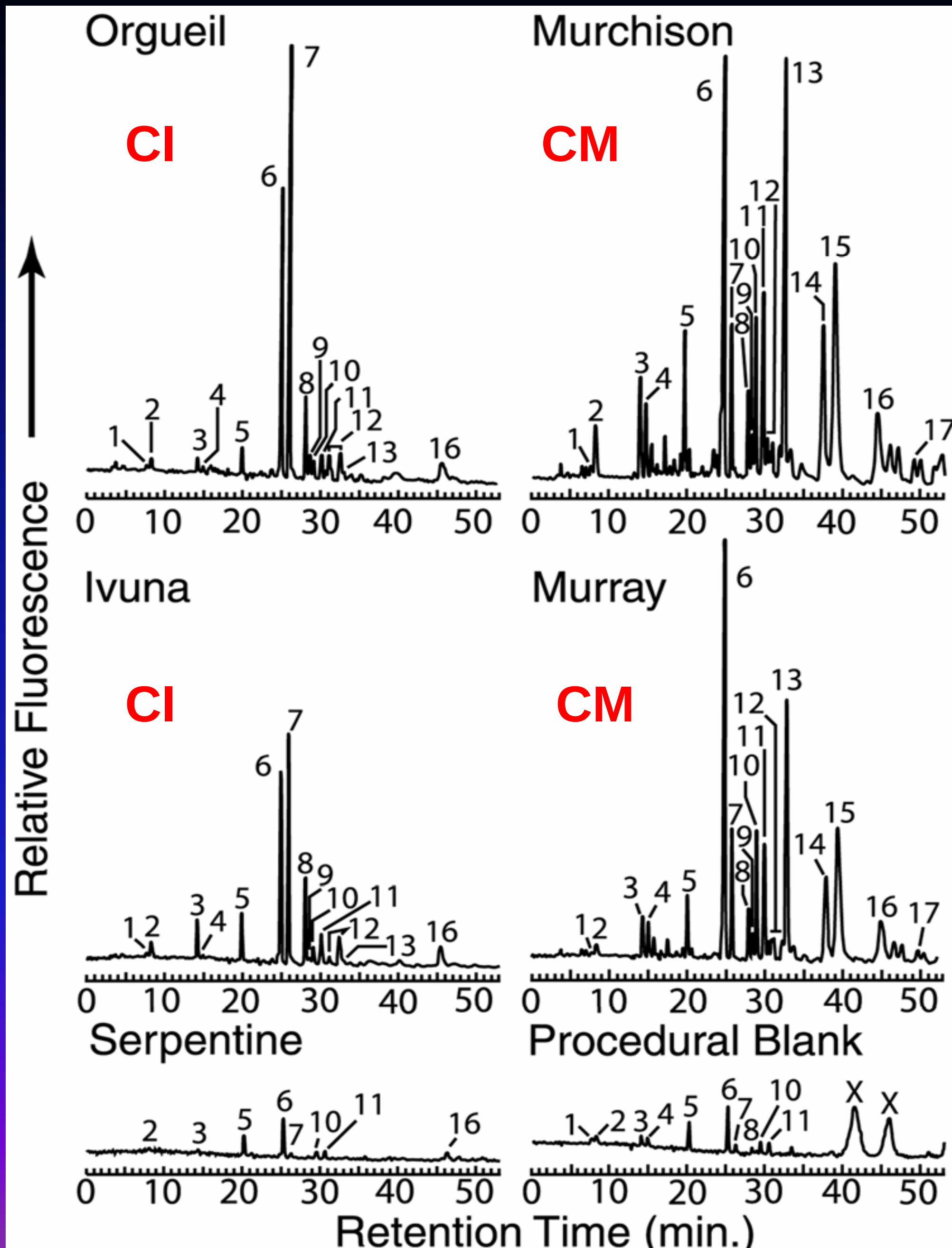
Organic compounds in the Murchison meteorite

Compound Class	Concentration(ppm)
CO_2	106
CO	0.06
CH_4	0.14
NH_3	19
Aliphatic hydrocarbons	12-35
Aromatic hydrocarbons	15-28
Amino Acids	60
Monocarboxylic acids	332
Dicarboxylic acids	26
α-hydroxycarboxylic acids	14
Polyols (sugar-related)	~24
Basic N-heterocycles	0.05-0.5
Purines	1.2
Pyrimidines	0.06
Amines	8
Urea	25
Benzothiophenes	0.3
Alcohols	11
Aldehydes	11
Ketones	16

Sephton 2002



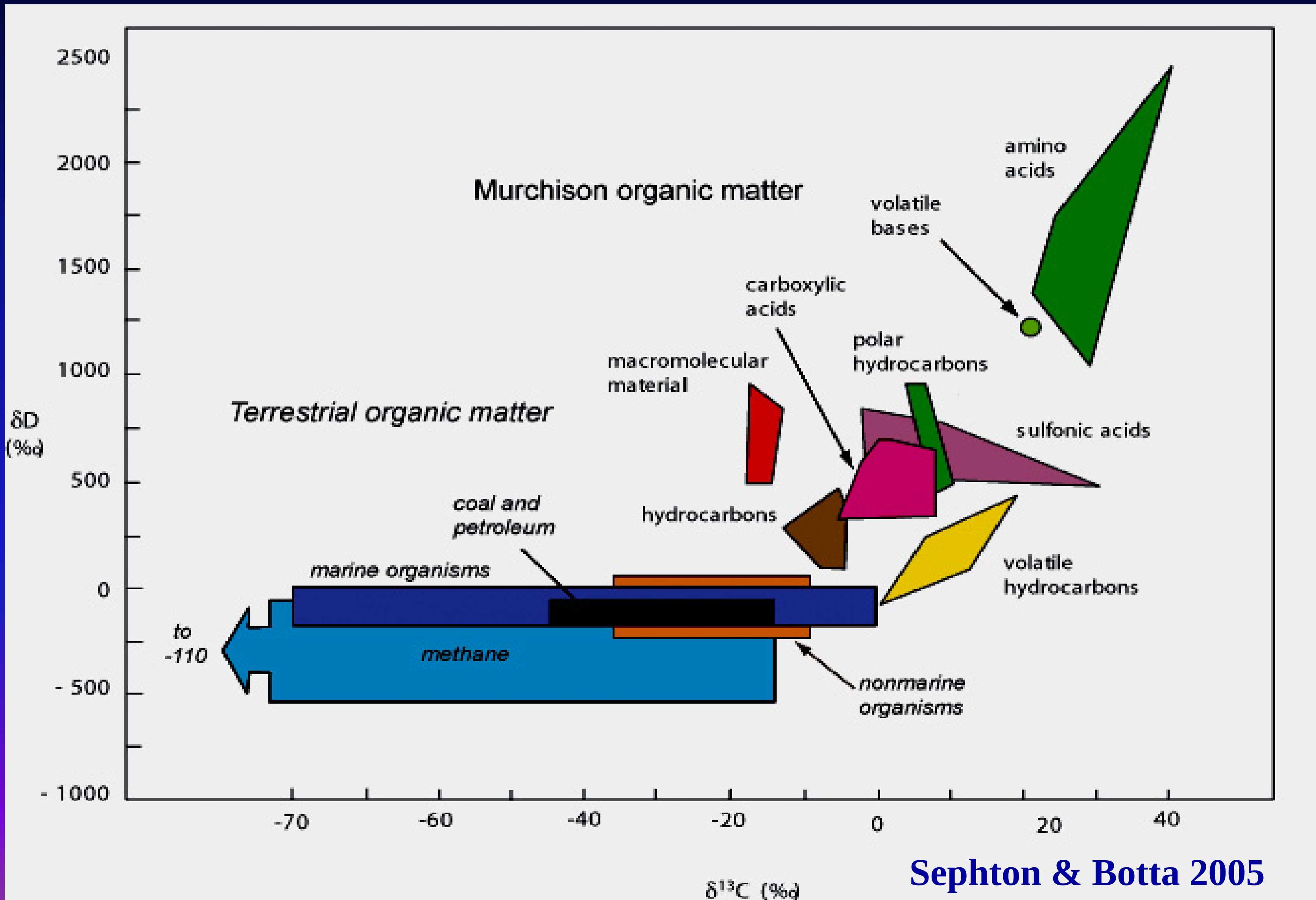
Amino Acids in Meteorite Extracts



1 D-Aspartic Acid
2 L-Aspartic Acid
3 L-Glutamic Acid
4 D-Glutamic Acid
5 D,L-Serine
6 Glycine
7 β-Alanine
8 γ-Amino-*n*-butyric Acid (γ-ABA)
9 D,L-β-Aminoisobutyric Acid (β-AIB)
10 D-Alanine
11 L-Alanine
12 D,L-β-Amino-*n*-butyric Acid (β-ABA)
13 α-Aminoisobutyric Acid (AIB)
14 D,L-α-Amino-*n*-butyric Acid (α-ABA)
15 D,L-Isovaline
16 L-Valine
17 D-Valine
X: unknown

Ehrenfreund et al. 2001

Distinction between stable carbon and hydrogen isotope ratios in Murchison and life



Sephton & Botta 2005

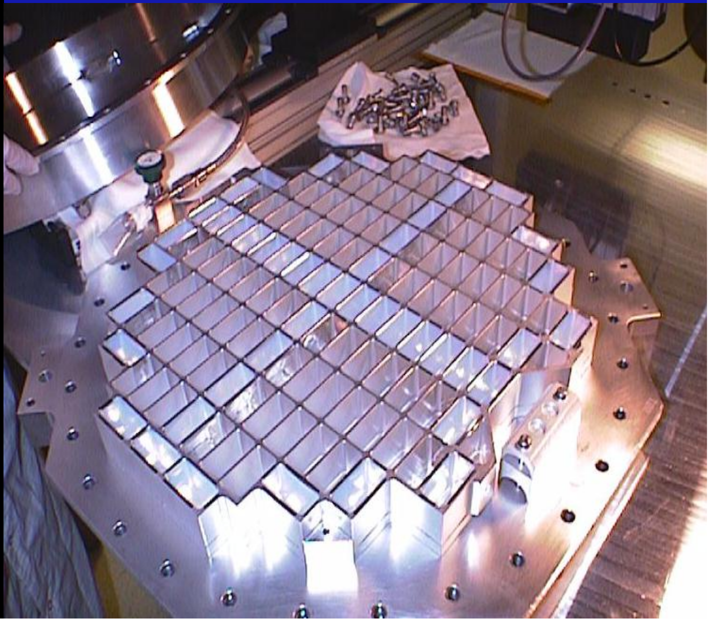
Molecule	Hale-Bopp	ISM
H_2O	100	100
CO	12-23	1-60
CO_2	6	15-40
CH_4	1.5	
C_2H_2	0.1-0.3	
C_2H_6	0.6	
CH_3OH	2.4	1-25
H_2CO	1.1	
$HCOOH$	0.09	
$HCOOCH_3$	0.08	
CH_3CHO	0.02	
NH_2CHO	0.015	
HCN	0.25	
$HNCO$	0.10	
HNC	0.04	
CH_3CN	0.02	
HC_3N	0.02	
OCS	0.4	
CS_2	0.2	
H_2CS	0.05	

Production rates relative to water of organic molecules in the coma of comet
C/1995 O1 Hale-Bopp

(Bockelee-Morvan et al. 2004, Ehrenfreund et al. 2004)

FLYBY Comet Wild 2

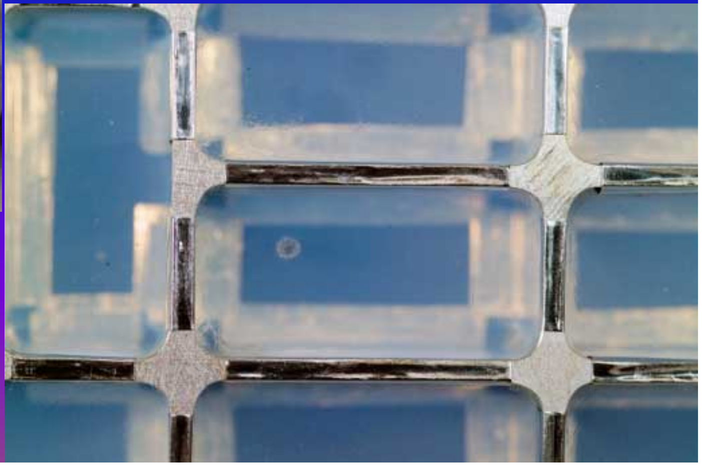
Capture of particles



Stardust touch down
15 January 2006 in Utah

Particles from a comet and interstellar dust have been returned to Earth

Silicon-based solid 1,000 times less dense than glass



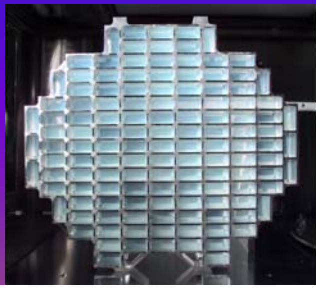
Thousands of impacts on the aerogel

Stardust clues…

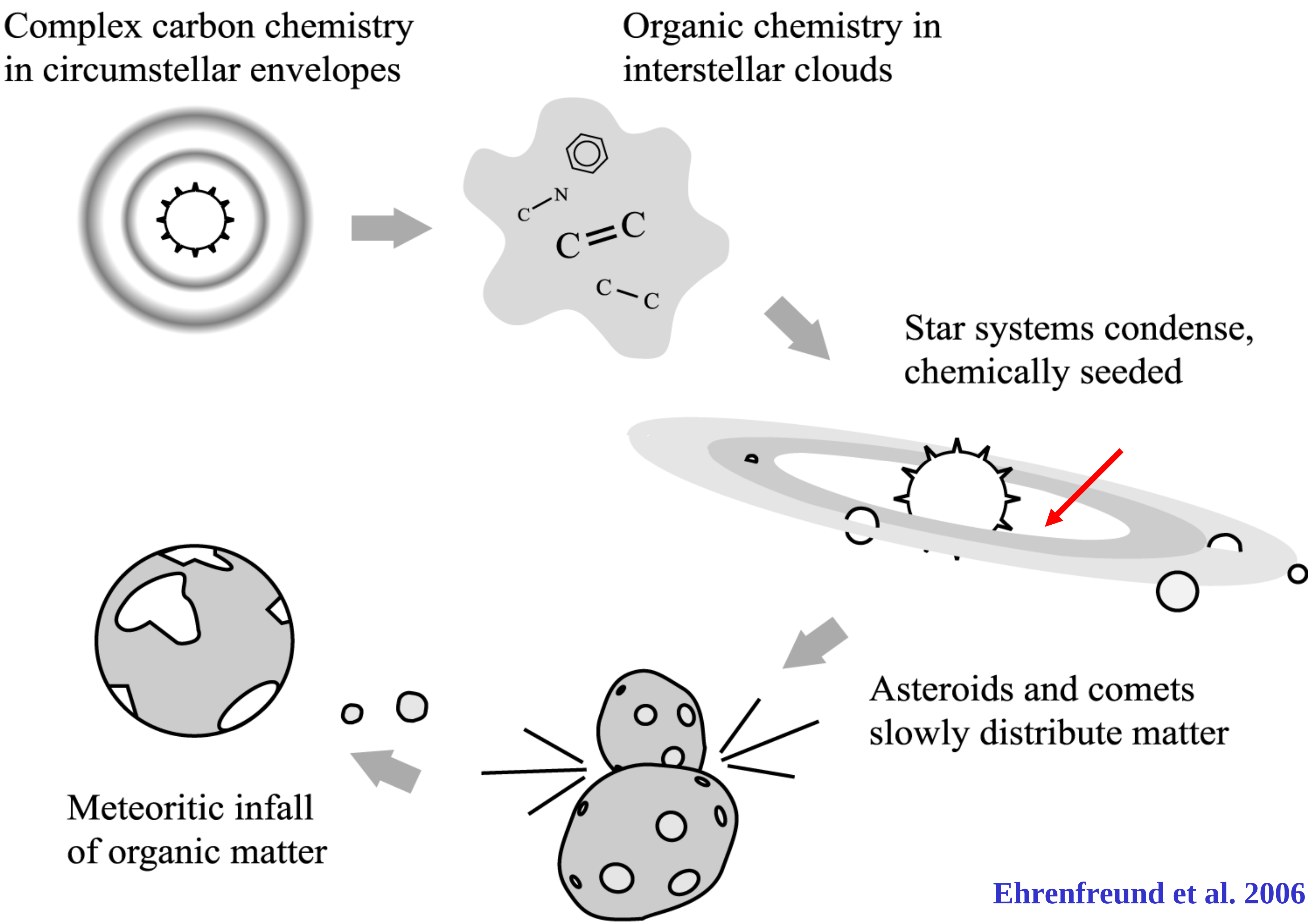
- **Comet Wild 2 dust was predominantly material from our solar nebula –**
  limited amount of preserved presolar material (isotopic O, McKeegan et al. 2006) – 1 CAI

- **Significant radial mixing in the early solar system**

- **Widely varying olivine and pyroxene compositions - wide range of formation conditions/locations, no aqueous alteration (Zolensky et al. 2006)**



Chemistry in space



Ehrenfreund et al. 2006

Summary

- **Meteorites deliver a protracted record of chemical evolution and links between interstellar and solar system material**

  → **constraints on the physical and dynamical properties of early solar system formation**

- **Extensive mixing in the solar nebula**

- **Active solar nebula chemistry**

- **Similar processes in extrasolar systems**