4. THE MESSAGE FROM COMETS AND METEORITES

1. Water and organics in comets
2. Water and organics in meteorites
3. Wrap-up: the threads

NOTE: This is NOT a review
=> references illustrative and NOT exhaustive

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PREFACE

Comets: bodies of a few km, formed by rocks and ice.

Asteroids: bodies of a few km, which orbit around the Sun, formed mainly by rocks.

Meteoroids: small bodies (<km) , which orbit around the Sun, formed mainly by rocks.

Meteors: meteoroids that penetrate into the terrestrial atmopshere.

Meteorites: meteoroids that arrive to the ground.

Parent body: comet or asteroid which the meteoroid or asteroid comes from.

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4.1 WATER AND ORGANICS IN COMETS

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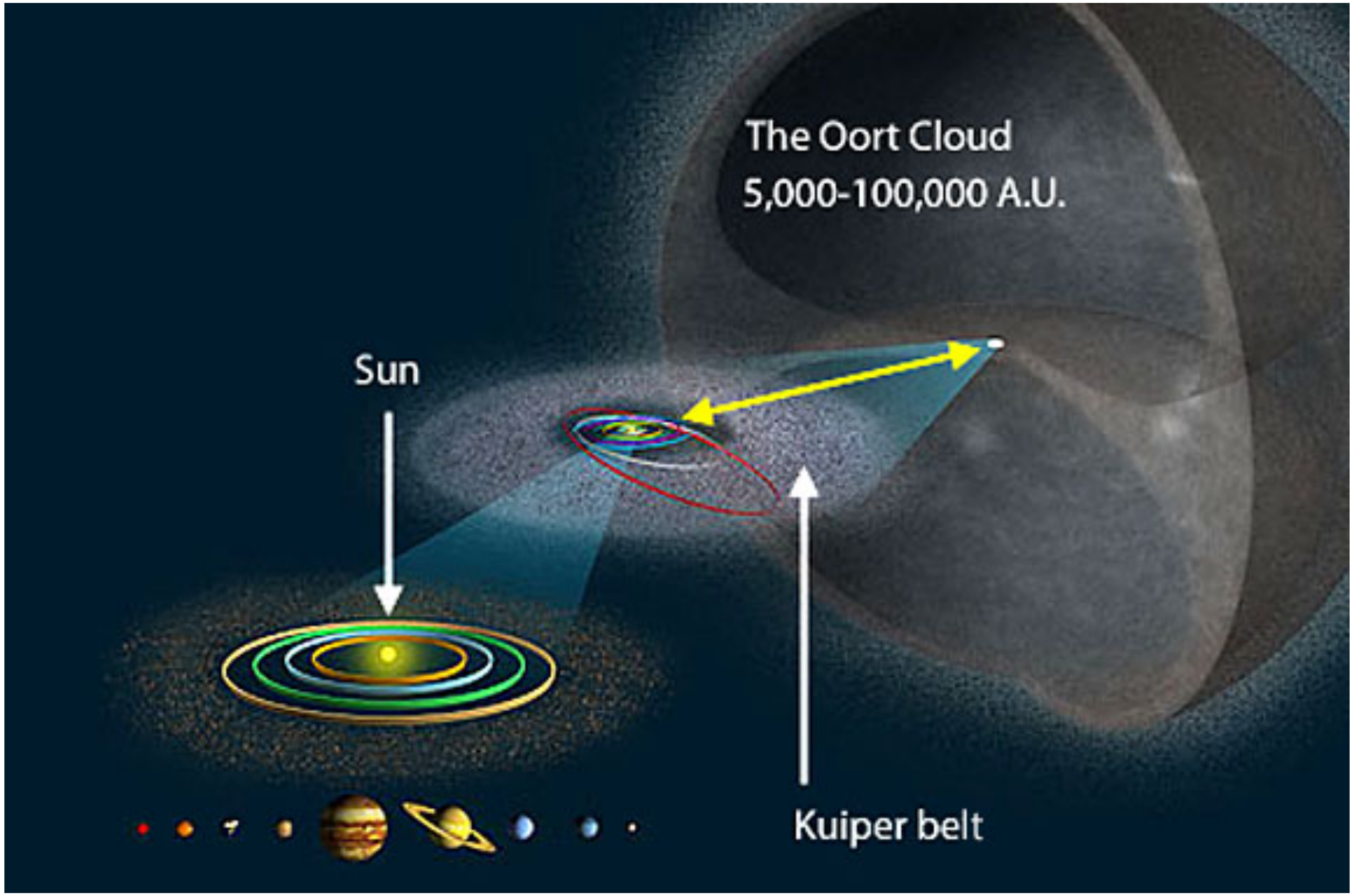
THE ORIGIN OF COMETS

The comets mainly originate from two regions:

1) The **Oort Cloud,** which envelopes the Solar System between 10,000 and 100,000 AU.
2) The **Kuiper Belt,** a disk beyond Neptune between 30 and 100 AU.



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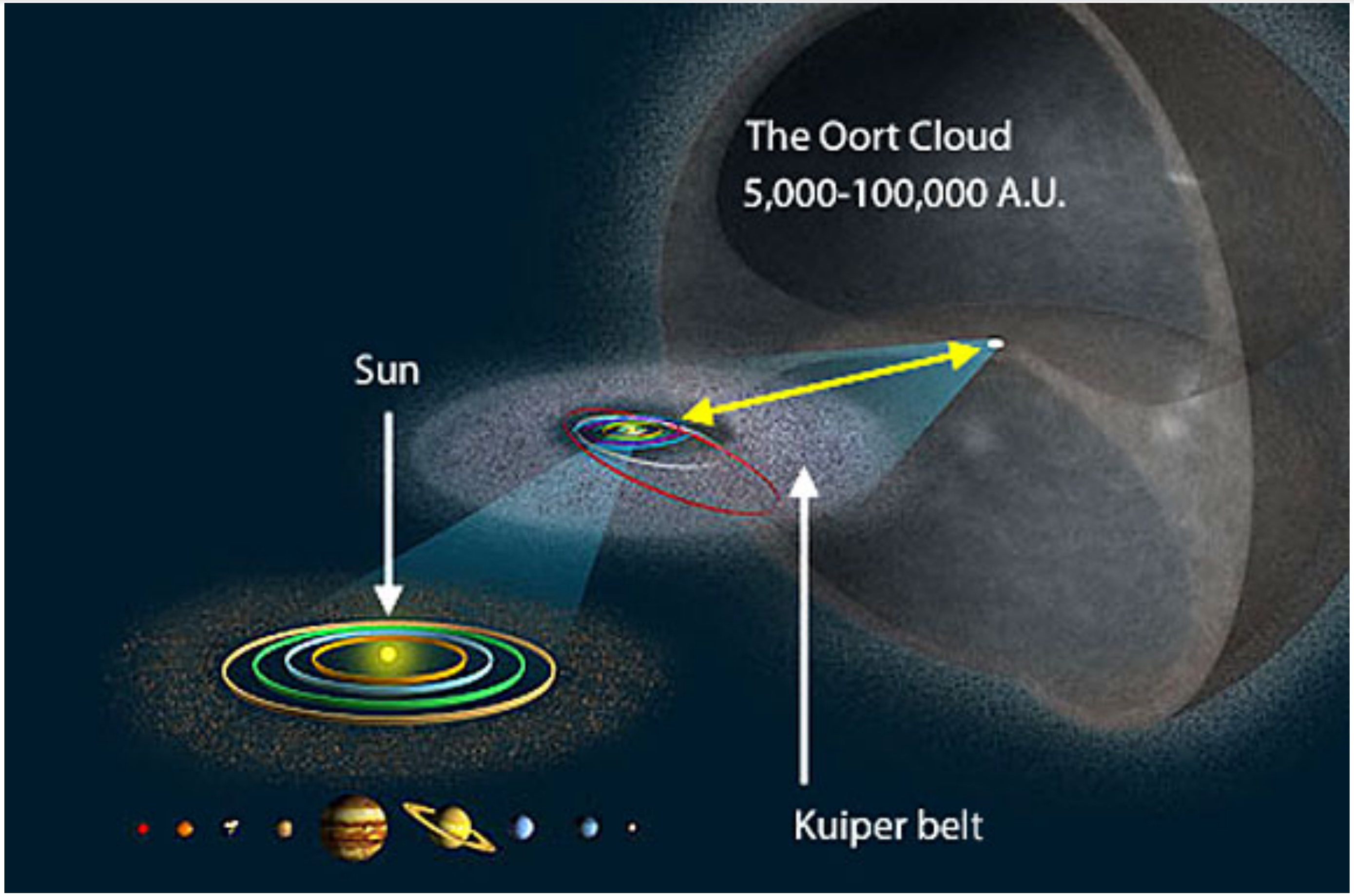
THE ORIGIN OF COMETS

BASED ON NUMERICAL SIMULATIONS: the Oort Cloud formed when the young Saturn migrating inward caused a resonance with the Jupiter orbit and expelled the bodies (the future comets) that were between 4 and 15 AU into the Oort Cloud.

THE OORT CLOUD COMETS WERE BORN IN A REGION CLOSER THAN THE KUIPER BELT



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WATER IN COMETS

WATER IS THE MAJOR VOLATILE COMPONENT AND THE MOST ABUNDANT GAS PHASE MOLECULE IN COMETS

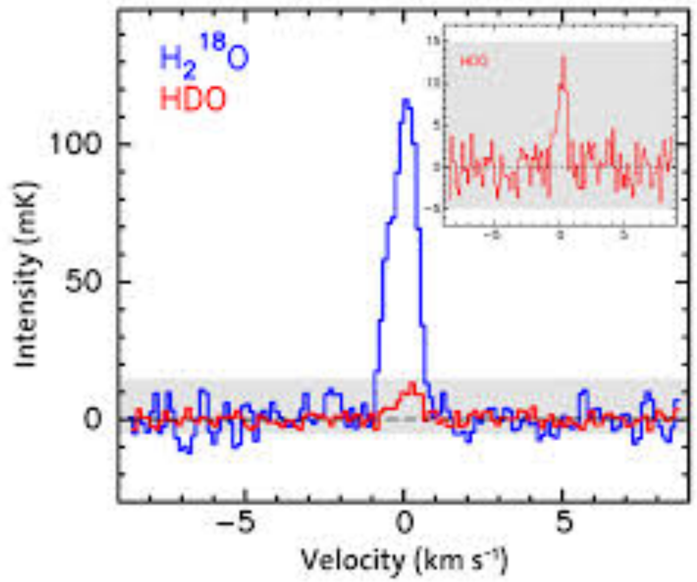
=> ICED WATER SUBLIMATED AT THE SUN APPROACH

=> WHEN WAS THIS WATER FORMED? THE HDO/H_2O CLUE

Comet	D/H	Type
Halley	$(3.1 \pm 0.5) \times 10^{-4}$	OCC
Hyakutake	$(2.9 \pm 1.0) \times 10^{-4}$	OCC
Hale-Bopp	$(3.3 \pm 0.8) \times 10^{-4}$	OCC
2002 T7	$(2.5 \pm 0.7) \times 10^{-4}$	OCC
Tuttle	$(4.1 \pm 1.5) \times 10^{-4}$	OCC
Ikeya-Zhang	$\leq 2.5 \times 10^{-4}$	OCC
2009 P1	$(2.06 \pm 0.22) \times 10^{-4}$	OCC
2001 Q4	$(4.6 \pm 1.4) \times 10^{-4}$	OCC
Hartley 2	$(1.61 \pm 0.24) \times 10^{-4}$	JFC
45P	$\leq 2.0 \times 10^{-4}$	JFC
Tchouri	$(5.3 \pm 0.7) \times 10^{-4}$	JFC

Ceccarelli et al. 2014, PP6; Altwegg et al. 2015

HERSCHEL OBSERVATIONS



Hartogh et al. 2011

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WATER IN COMETS

4.Comets & meteorites

4.1 Comets

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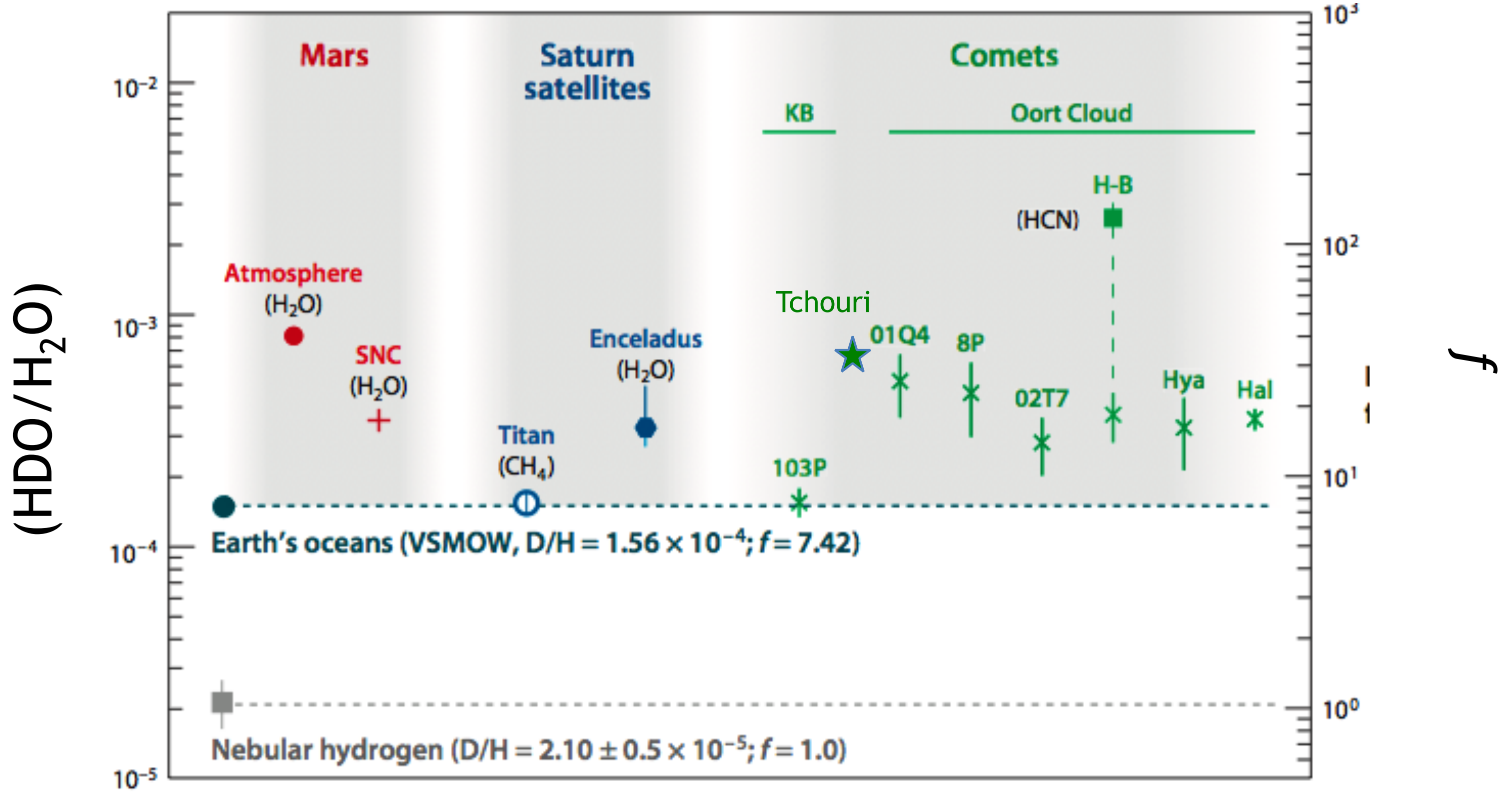
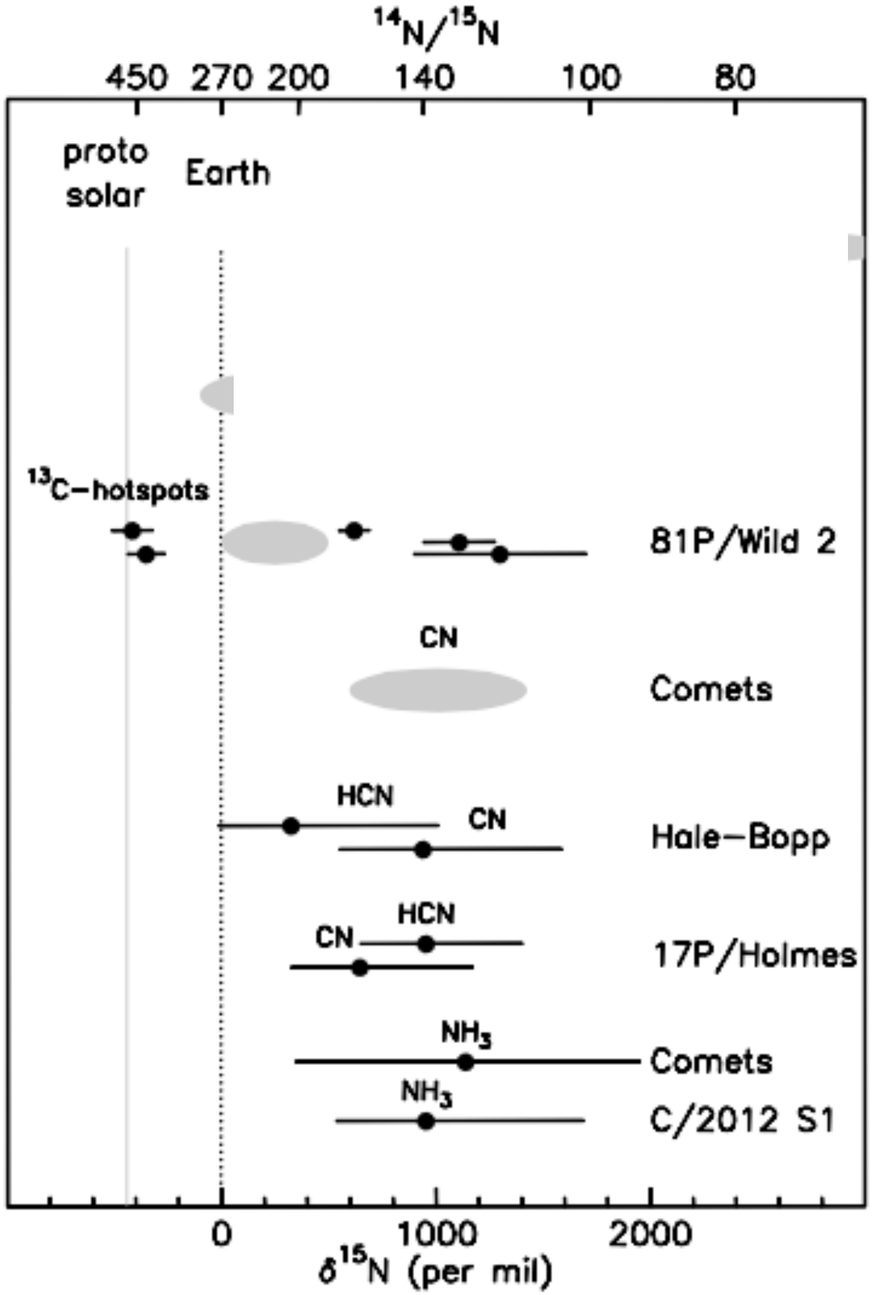


THE HDO/H$_2$O RATIO IS:

+ 10 x LARGER THAN THAT OF THE PROTO-SOLAR NEBULA
+ ABOUT A FACTOR 2 LARGER THAN THAT OF THE EARTH
+ IS NOT DIFFERENT IN KUIPER BELT AND OORT CLOUD COMETS => CHALLENGE TO THE THEORIES OF THEIR ORIGIN

NITROGEN FRACTIONATION IN COMETS



THE $^{14}N/^{15}N$ RATIO IS:

+ ABOUT 3 TIMES SMALLER THAN THAT OF THE PROTO-SOLAR NEBULA
+ ABOUT 3 TIMES SMALLER THAN THAT OF THE EARTH

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ORGANICS IN COMETS

4.Comets & meteorites

4.1 Comets

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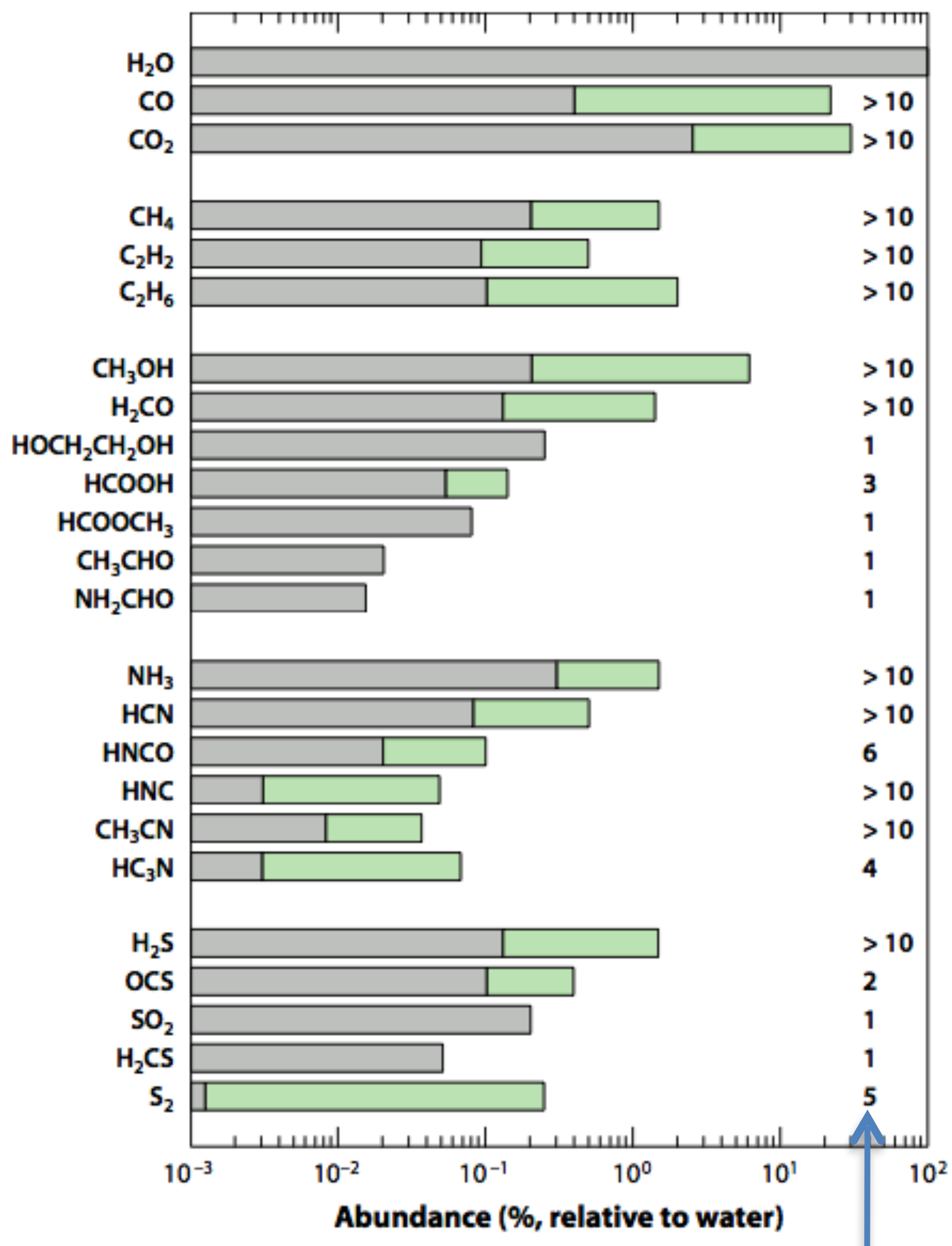
OBSERVATION OF ORGANICS ARE VERY DIFFICULT AND ARE LIMITED TO A FEW COMETS SO FAR

THE MOST ABUNDANT MOLECULES, AFTER WATER, ARE CO AND CO_2, FOLLOWED BY CH_3OH, H_2CO, CH_4, NH_3 et H_2S

=> THE COMPOSITION OF THE ICES FORMED DURING THE PRESTELLAR CORE PHASE



Number of comets

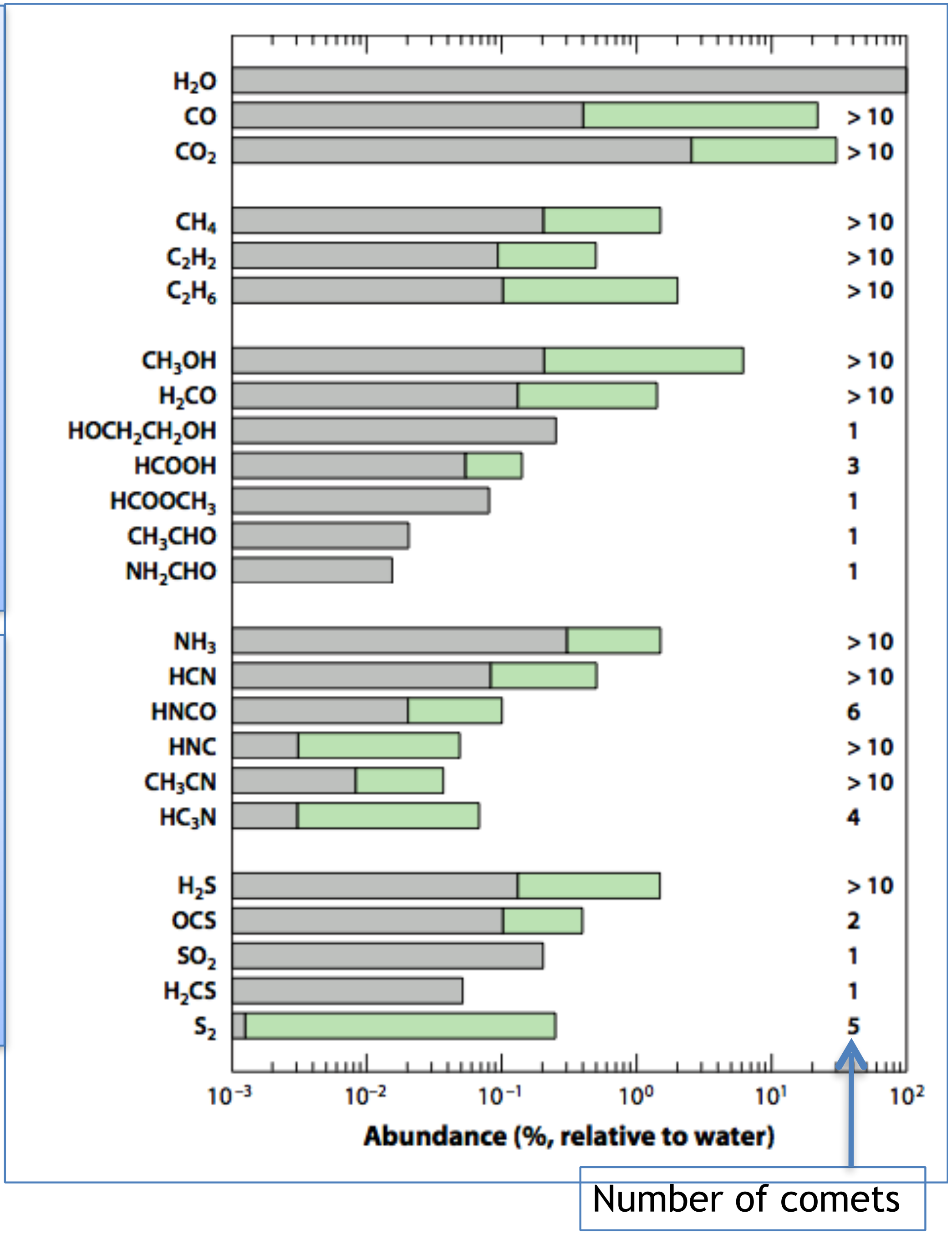
ORGANICS IN COMETS

THE MOST ABUNDANT MOLECULES, AFTER WATER, ARE CO AND CO_2, FOLLOWED BY CH_3OH, H_2CO, CH_4, NH_3 et H_2S

=> THE COMPOSITION OF THE ICES FORMED DURING THE PRESTELLAR CORE PHASE

PLUS SEVERAL ORGANIC MOLECULES - $HCOOH$, $HCOOCH_3$, NH_2CHO,HOCH2CH2OH…

ALL MOLECULES PRESENT IN THE HOT CORINOS



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ORGANICS IN COMETS

4.Comets & meteorites

4.1 Comets

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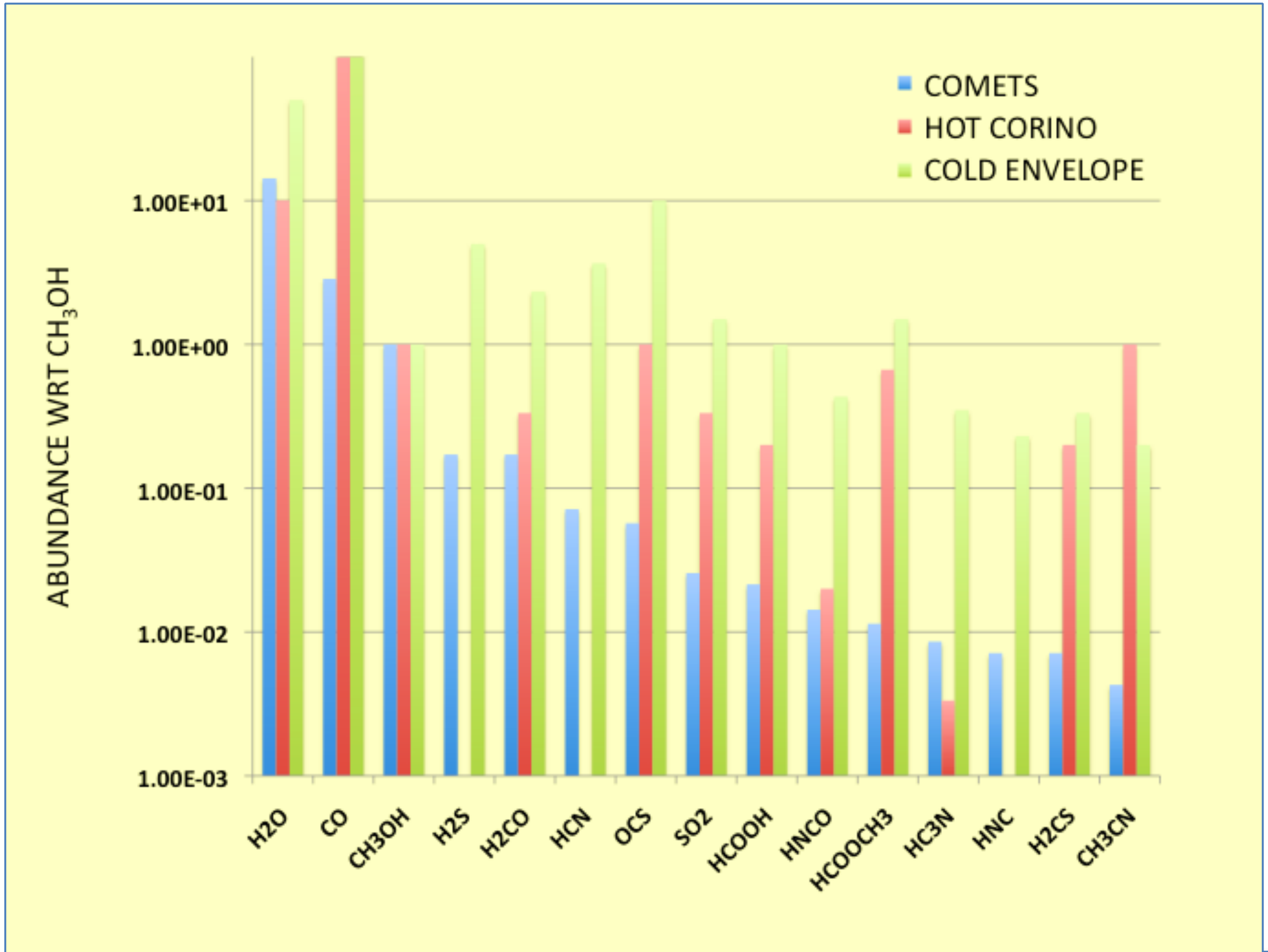

Caselli & Ceccarelli 2012

MOLECULES PRESENT IN COMETS AND HOT CORINOS

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ORGANICS IN COMETS

4.Comets & meteorites

4.1 Comets

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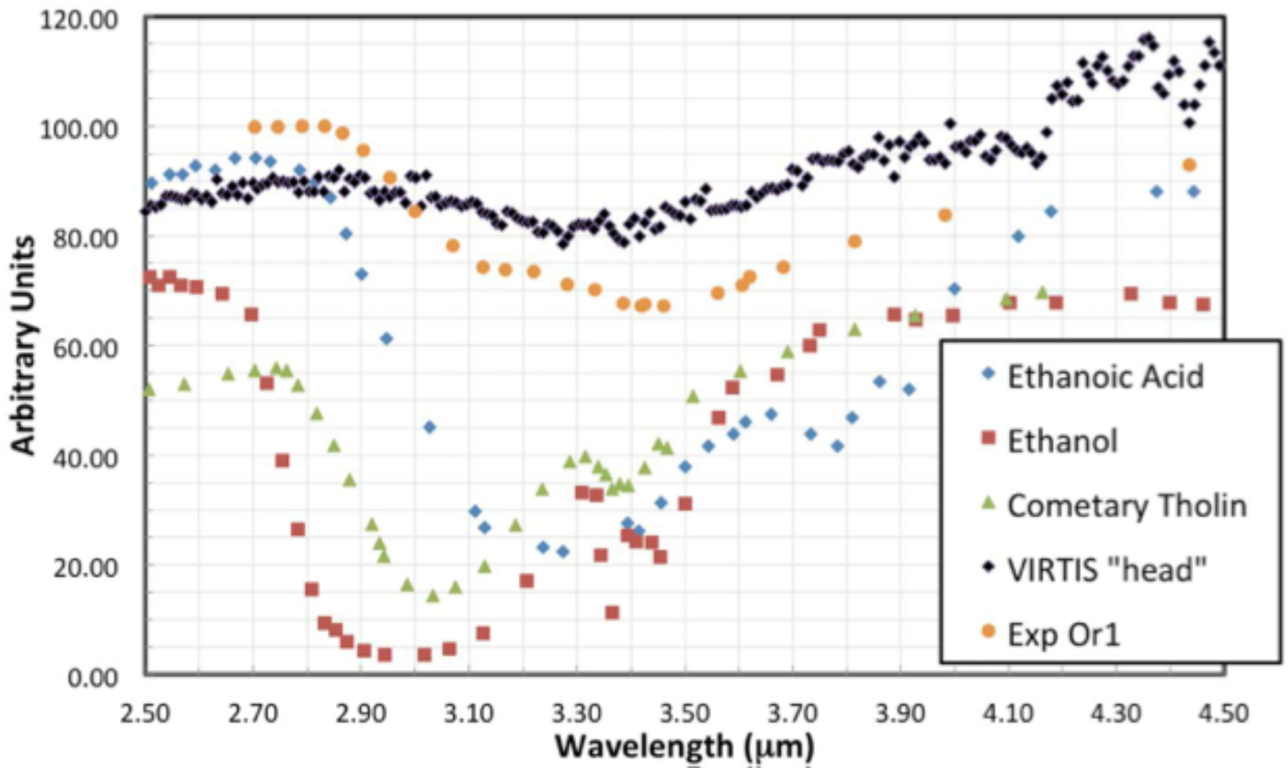

Fig. 4. The spectrum of the head in the spectral range 2.5 to 4.5 μm is compared to several other organic compounds described in the text. The VIRTIS spectrum is rescaled in arbitrary units to compare the X-H stretch region with ethanol and ethanoic (acetic) acid spectra (32), a cometary tholins (obtained after ion irradiation of a mixture of 80% H_2O, 16% CH_3OH, 3.2% CO_2, and 0.8% C_2H_6) (33), and a refractory residue (labeled "Exp Or1") obtained after UV irradiation of a mixture of H_2O:CH_3OH:NH_3:CO:CO_2 in the ratio 2:1:1:1:1 (34).

Capaccioni et al. 2015

SURFACE OF TCHOURI COVERED OF REFRACTORY ORGANICS

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GLYCINE IN COMETS

4.Comets & meteorites

4.1 Comets

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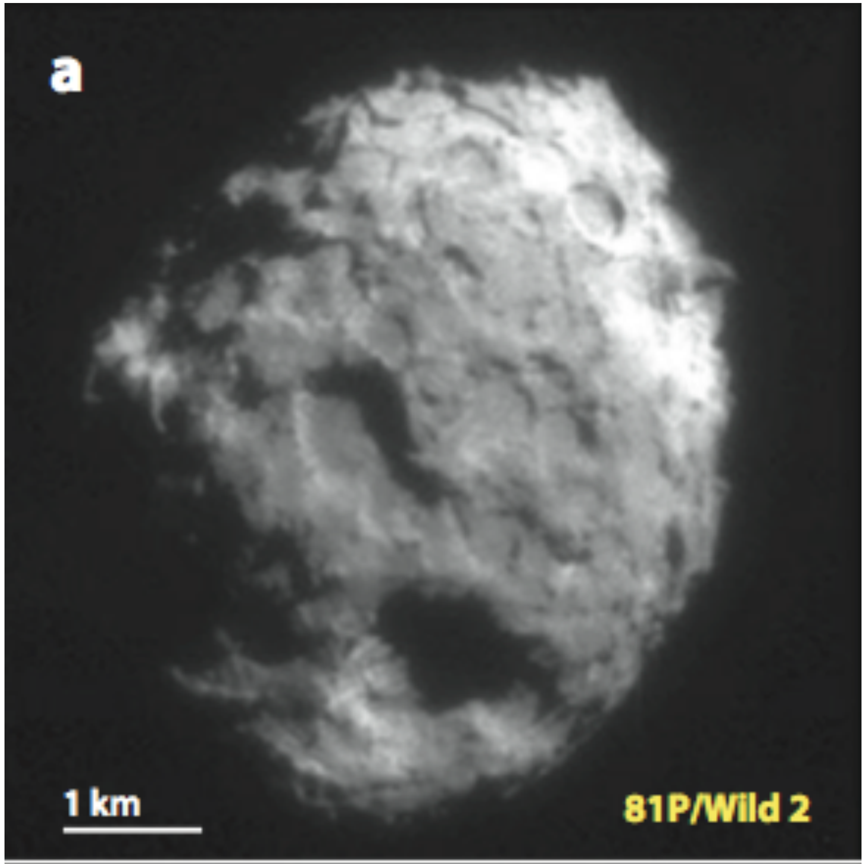

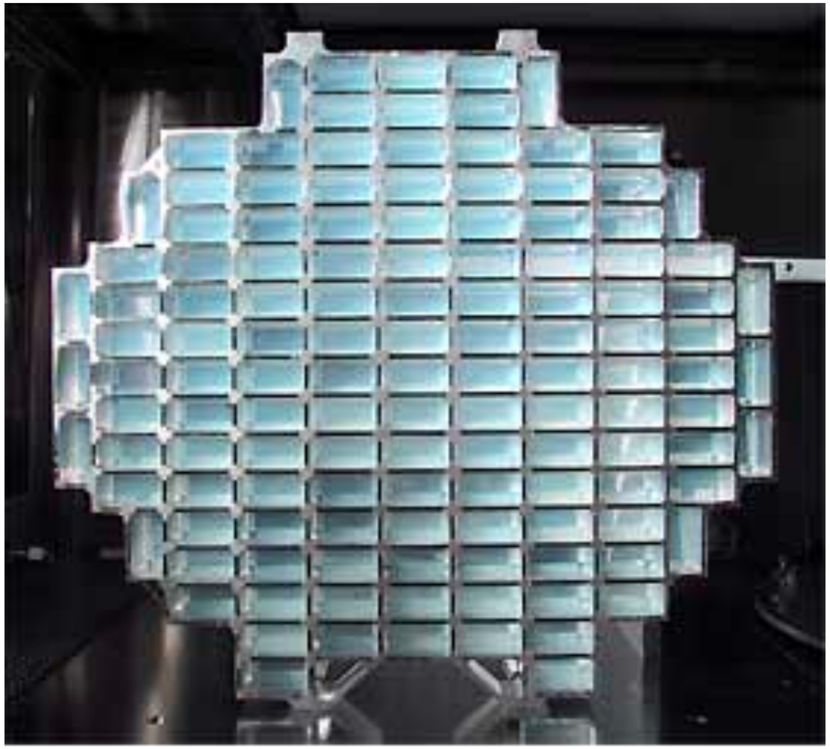

Elsila et al. 2009

STARDUST MISSION BROUGHT BACK MATERIAL ANALYSED IN THE TERRESTRIAL LABORATORIES => DETECTION OF GLYCINE

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4.2 WATER AND ORGANICS IN METEORITES

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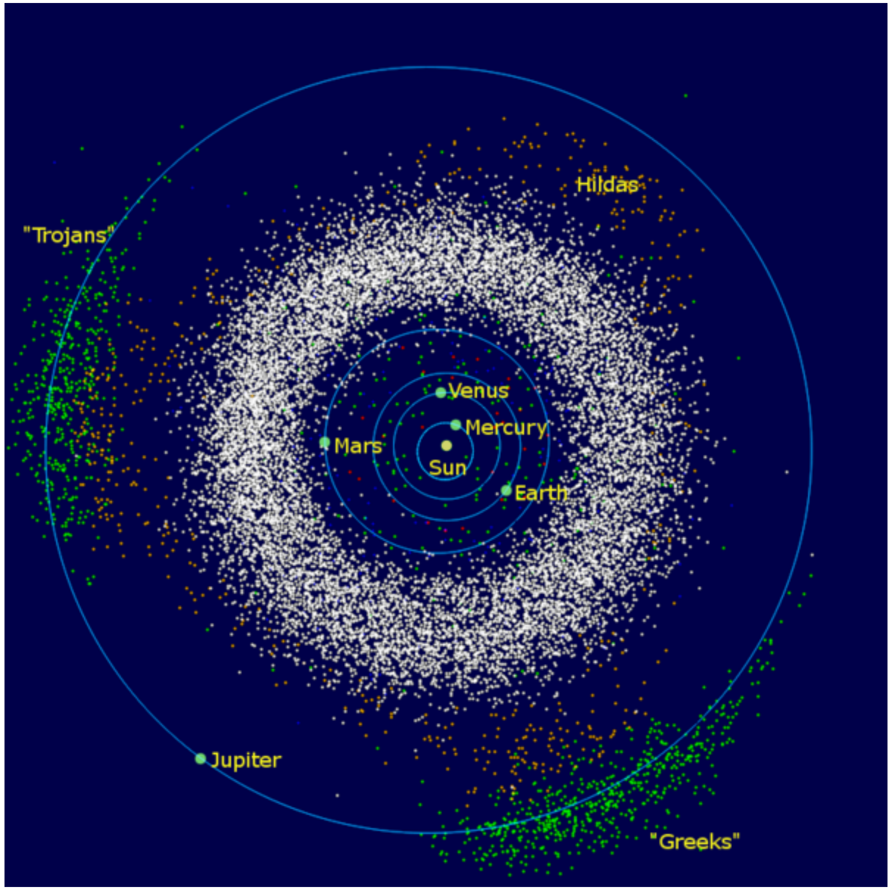
THE ORIGIN OF METEORITES

MAJOR RESERVOIR: THE ASTEROID BELT BETWEEN MARS AND JUPITER (2.5-3 AU).
MINOR RESERVOIRS: MOON, MARS, ASTEROIDES CROSSING THE EARTH ORBIT, FRAGMENTS OF COMETS



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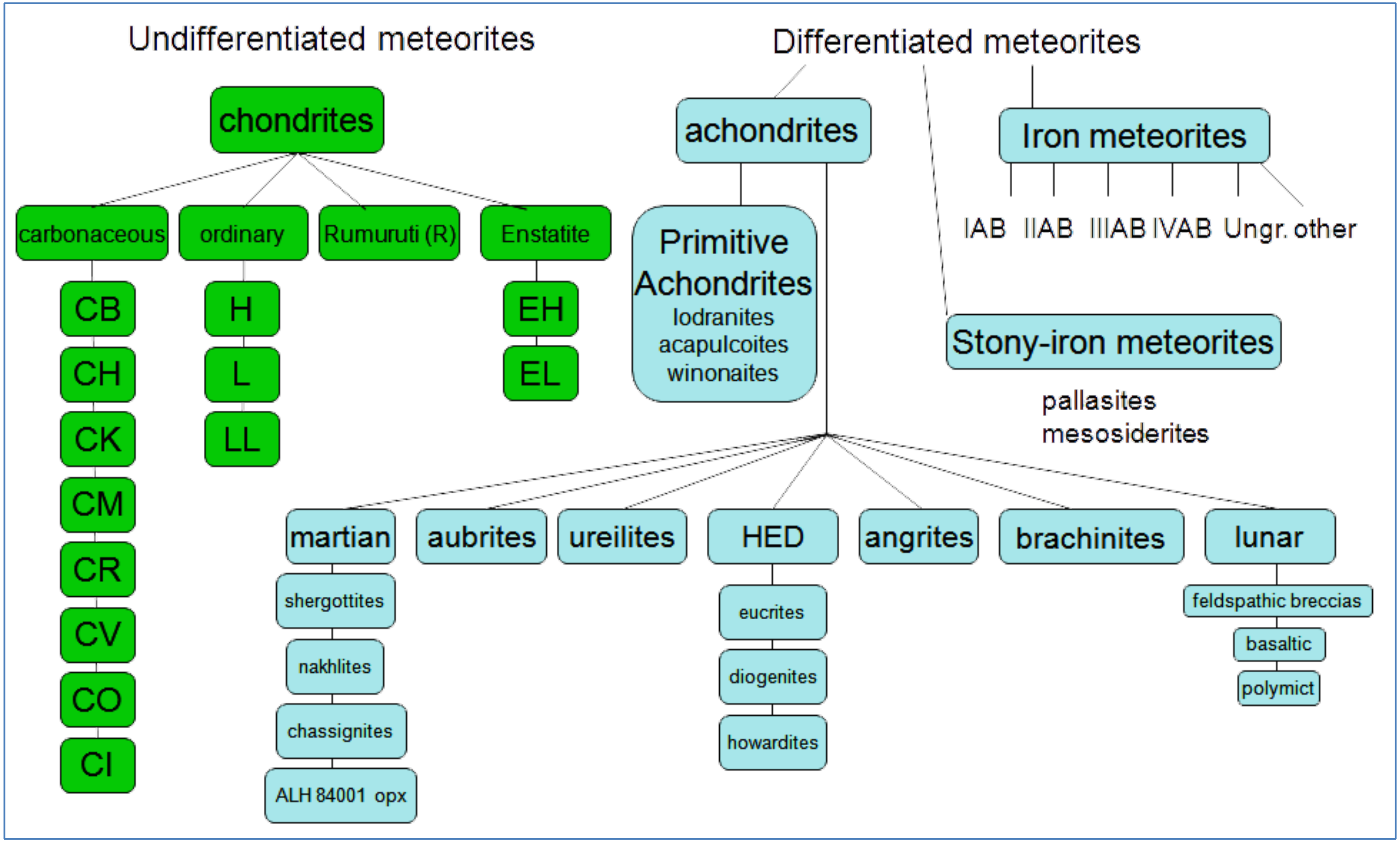
CLASSIFICATION OF METEORITES



4.Comets & meteorites

4.2 Meteorites

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CC = BRICKS OF EARTH

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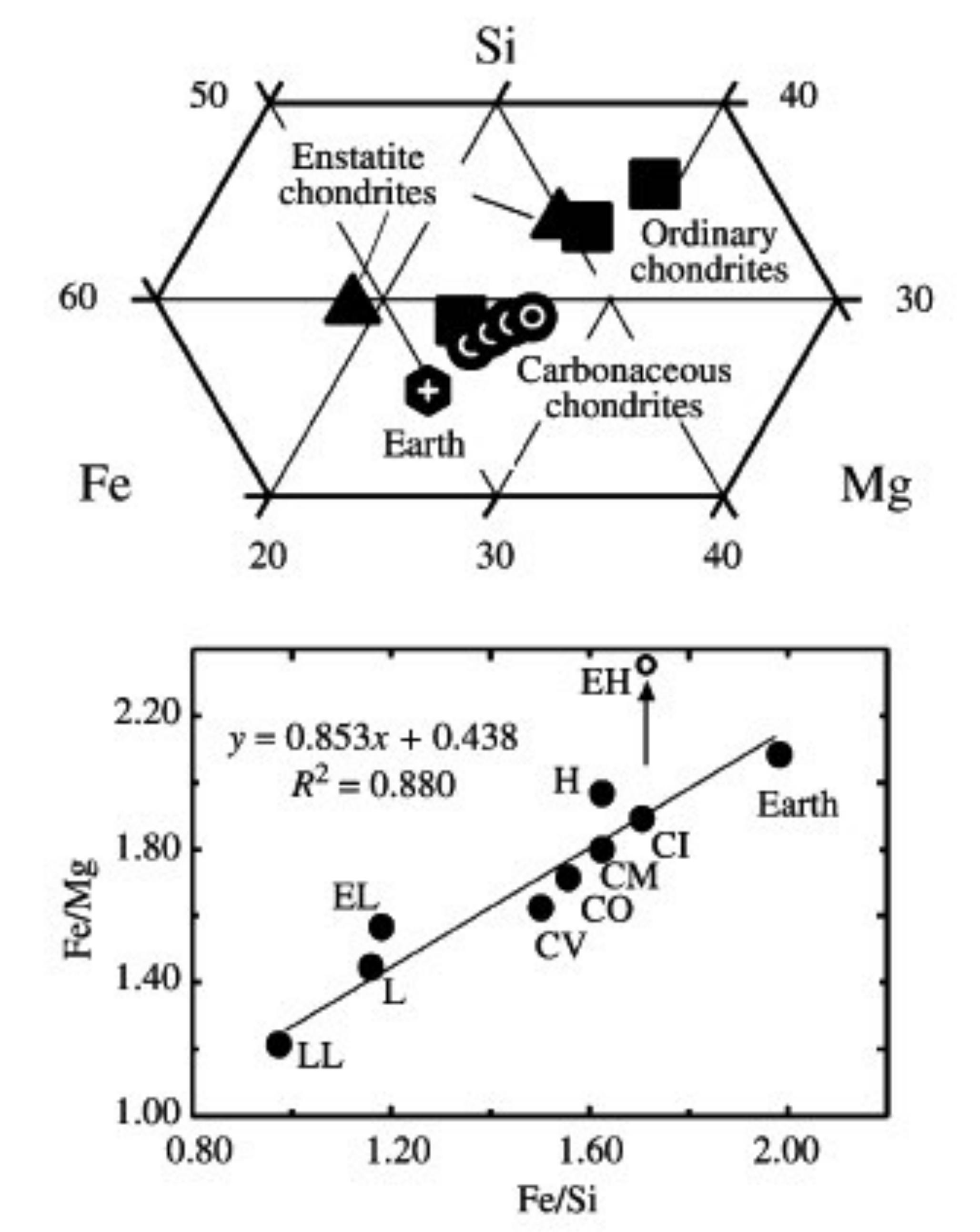
THE CARBONACEOUS CHONDRITES ARE THE MOST PRIMITIVE METEORITES AND THE MOST LIKELY BRICKS OF EARTH

ANY INHERITANCE FROM THE EARLY PHASES OF THE SOLAR SYSTEM FORMATION?



CC = BRICKS OF EARTH

4.Comets & meteorites

4.2 Meteorites

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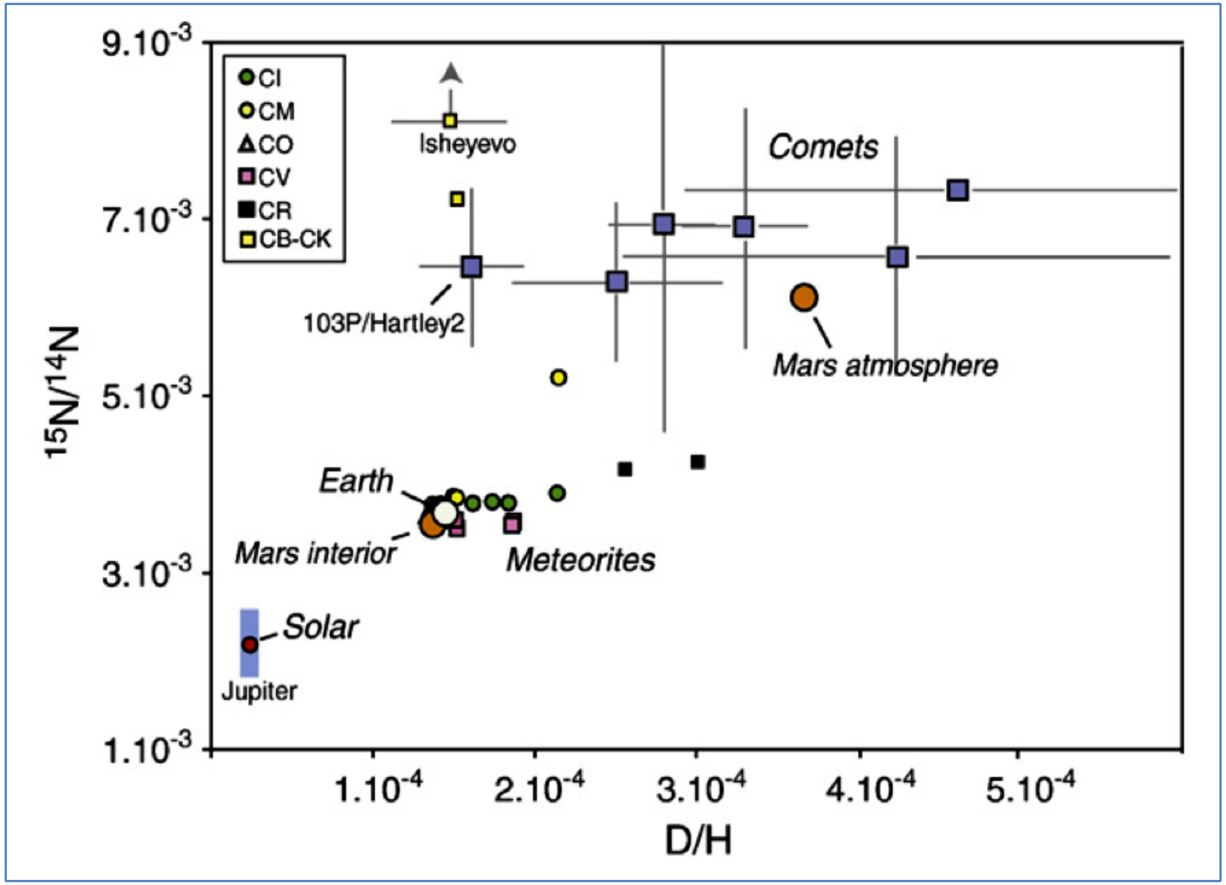


Marty 2012

ANY INHERITANCE FROM THE EARLY PHASES OF THE SOLAR SYSTEM FORMATION?

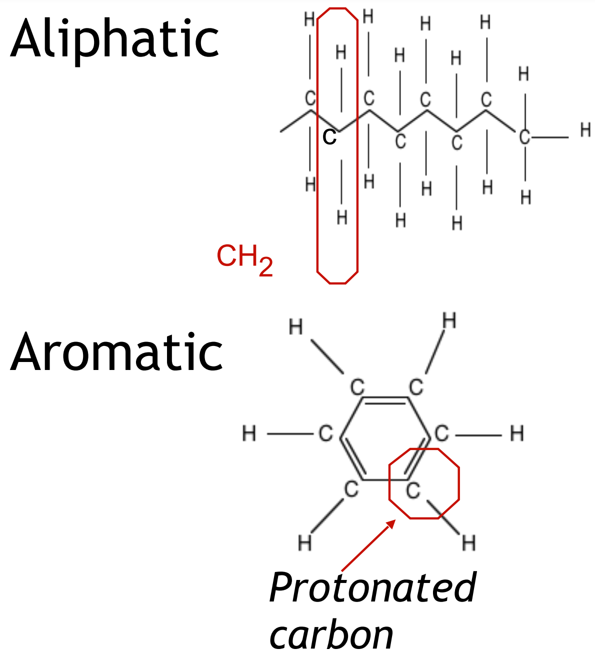
DEUTERIUM AND NITROGEN FRACTIONATION

ORGANICS IN CC METEORITES

MINERALS CONTAIN:

- **Clay minerals** (phyllosilicates);
- **Insoluble Organic Matter (IOM)** -> 70-90% of organics;
- **Soluble Organic Compounds (SOC**; sometime this is also referred as Soluble Organic Matter or **SOM)**.

The meteorites Allende, Yukon and Murchison, where organics are found.



4.Comets & meteorites

4.2 Meteorites

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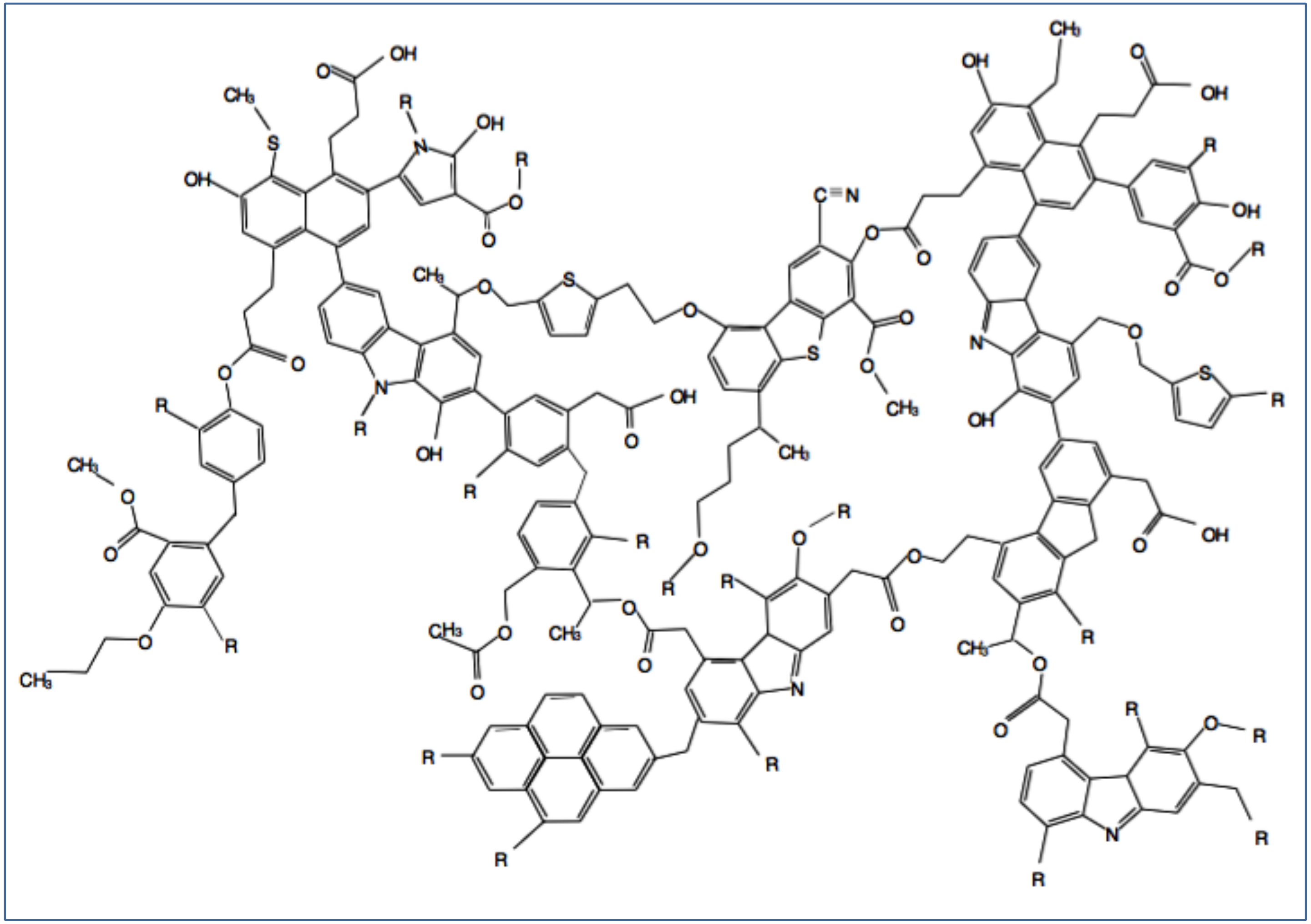
MOLECULAR STRUCTURE OF IOM



Remusat et al. 2005, Cody & Alexander 2005

COMPOSED BY CARBON RINGS AND CHAINS WITH H, O, N, S AND P ATOMS ATTACHED TO THEM

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ORIGIN OF IOM

4.Comets & meteorites

4.2 Meteorites

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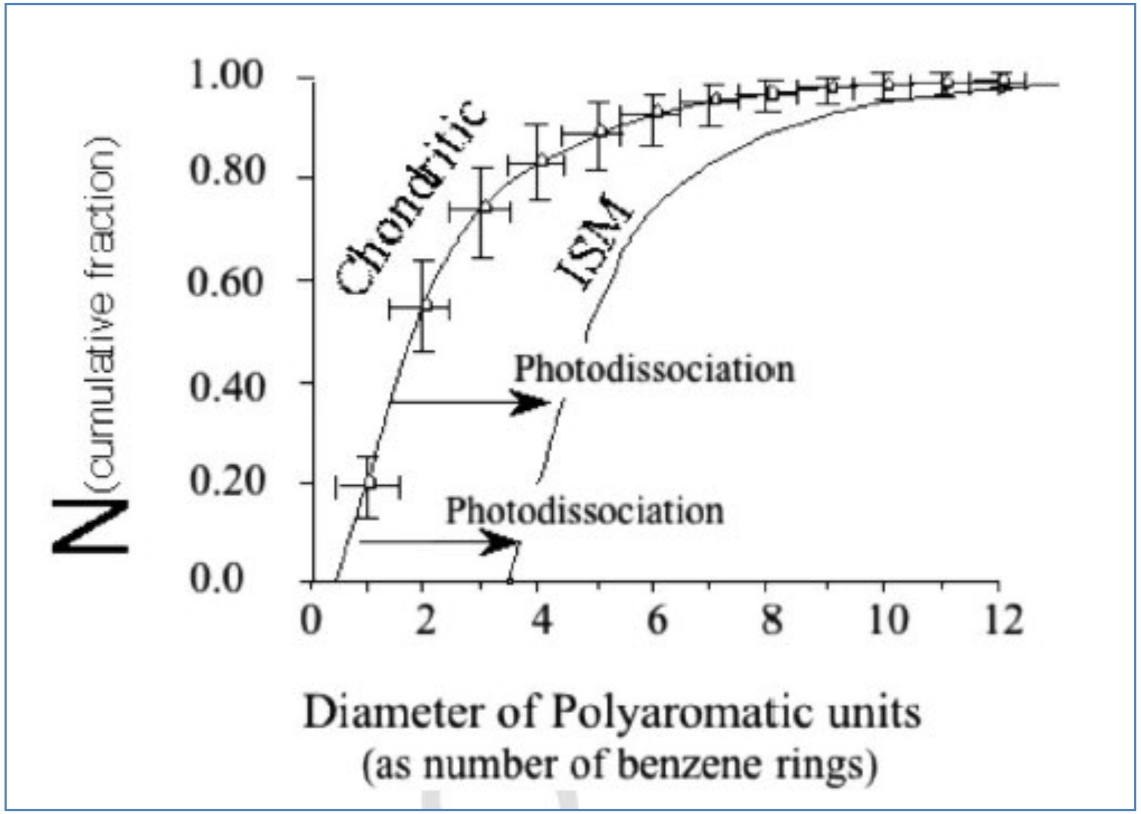
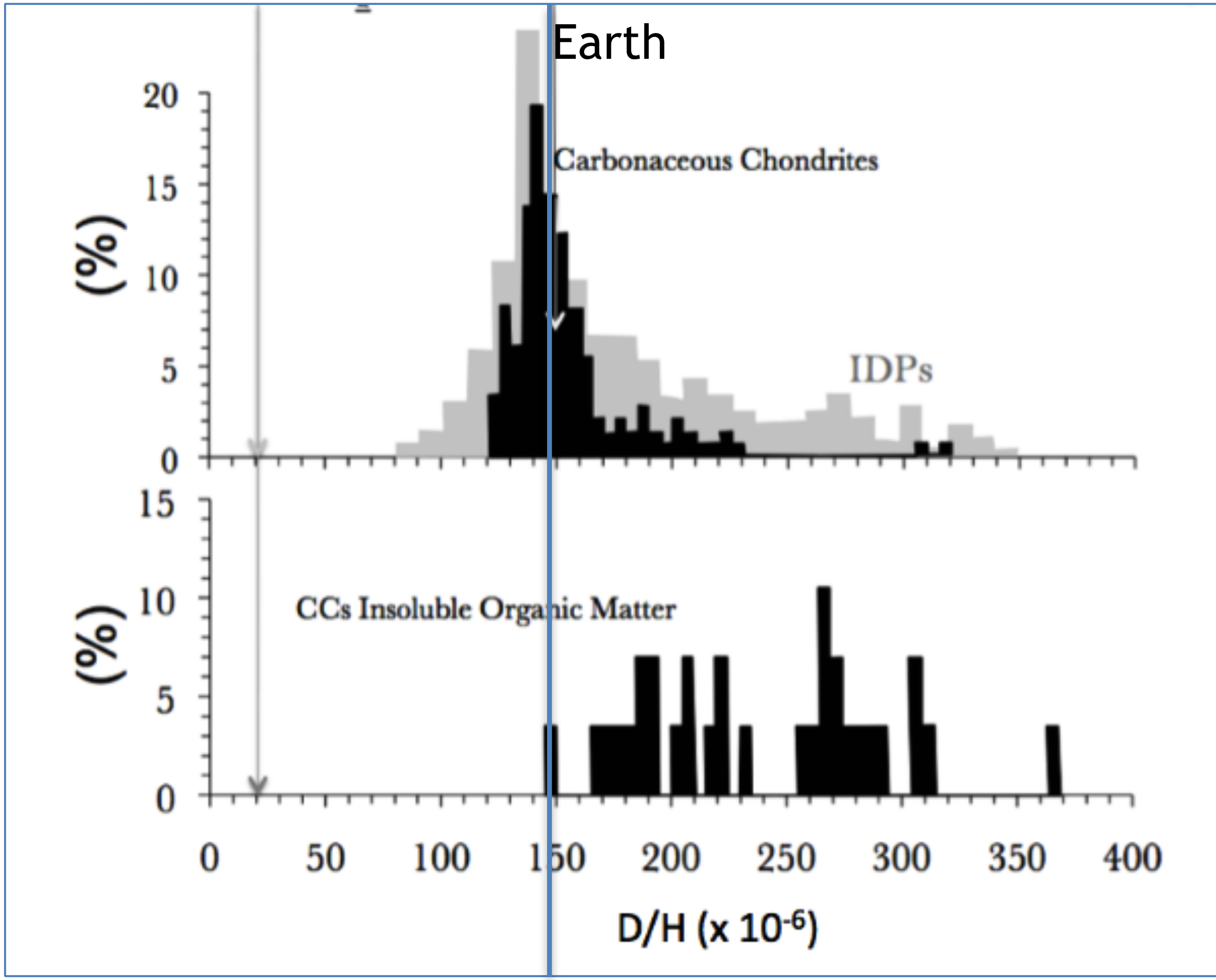


Remusat et al. 2005, Kwok et al. 2004

THE RELATION BETWEEN THE METEORITIC IOM AND THE ISM PAHs IS NOT CLEAR/OBVIOUS

DEUTERATION OF IOM



Ceccarelli et al. 2014, PP6: credit Robert

1- H/D RATIO IN CC WATER SIMILAR TO THAT ON EARTH
2- H/D RATIO IN IDPs SIMILAR TO THAT IN CC: WHY?
3- D/H IN IOM LARGER THAN IN WATER

MOLECULAR STRUCTURE OF SOM

4.Comets & meteorites

4.2 Meteorites

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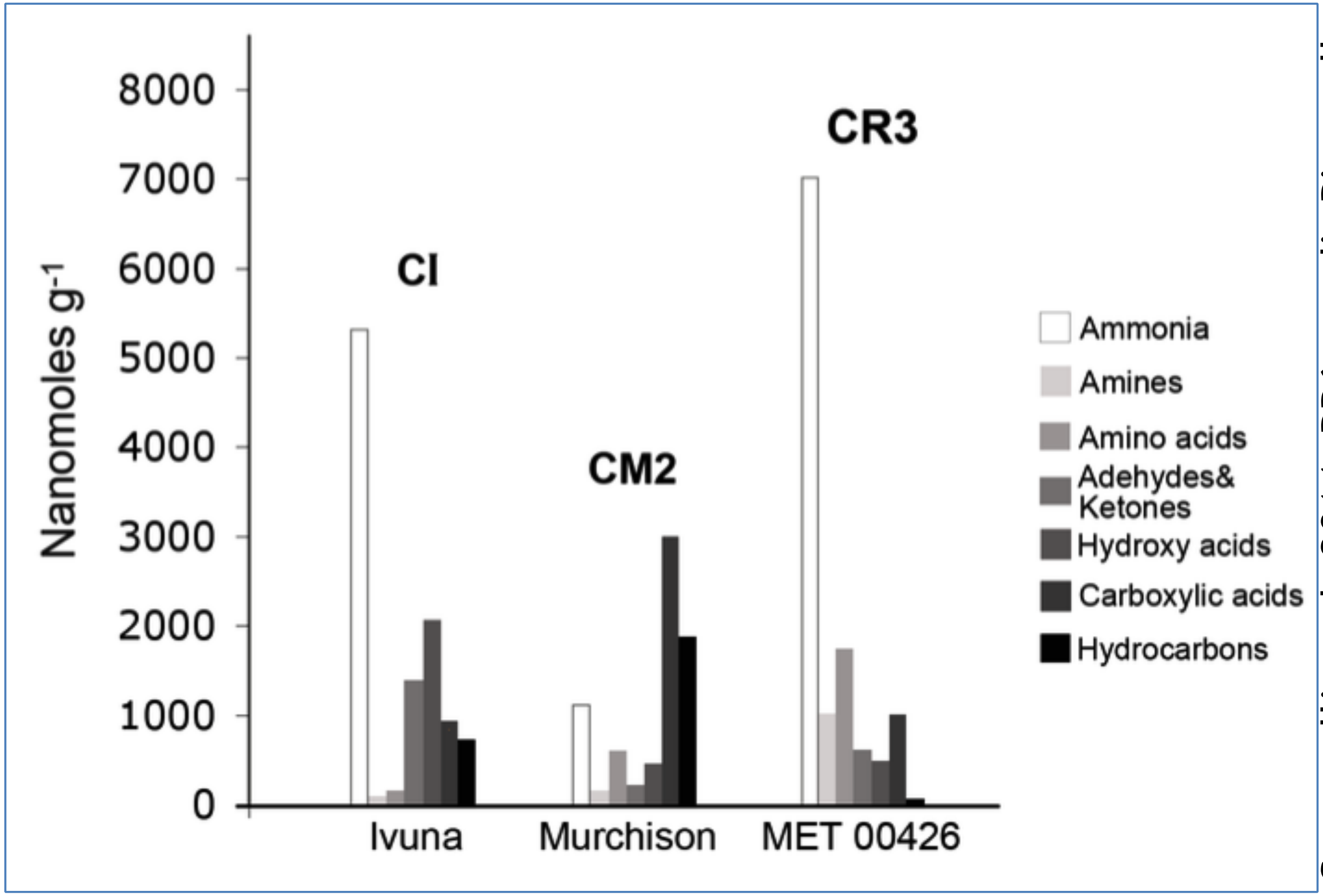


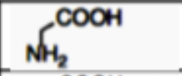
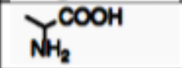
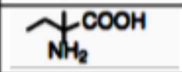
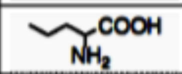
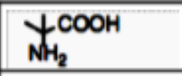
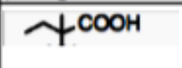
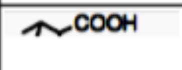
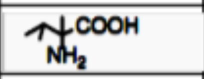
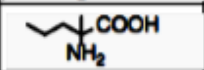
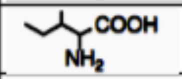
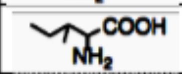
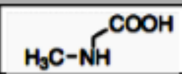
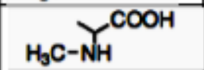
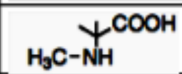
Ceccarelli et al. 2014, PP6: credit Pizzarello

A GREAT VARIETY OF MOLECULES, GREAT VARIETY OF COMPOSITION BETWEEN METEORITES.

- + amino acids in Renazzo-type (CR)
- + hydrocarbons in Mighei-type (CM) meteorites

AMINO ACIDS IN SOM

Ceccarelli et al. 2014, PP6: credit Pizzarello

AMINO ACID		CM2 (δD or D/H in 10^{-4})	CR2 (δD or D/H in 10^{-4})
Linear alkyl chain compounds			
glycine		366-399 or 2.12-2.17	868-1070 or 2.89-3.21
DL alanine		360-765 or 2.11-2.74	1159-1693 or 3.35-4.17
DL-2-a. butyric		1091-1634 or 3.24-4.08	1920-3409 or 4.53-6.63
norvaline		1505 or 3.88	nd
Branched chain compounds			
2-a. isobutyric		2362-3097 or 5.21-6.35	4303-7257 or 8.22-12.80
isovaline		2081-3419 or 4.78-6.85	3813-7050 or 7.46-12.48
DL-valine		1216-2432 or 3.43-5.32	2086-3307 or 4.78-6.68
2-a. 2,3 methylbutyric		3318-3604 or 6.69-7.14	nd
DL-2methylnorvaline		2686-3021 or 5.71-6.23	nd
DL-allo isoleucine		2206-2496 or 4.97-5.42	nd
L-leucine		1792-1846 or 4.33-4.41	nd
N-substituted amino acids			
Sarcosine		1274-1400 or 3.52-3.72	nd
DL-N-methylalanine		1224-1310 or 3.44-3.58	nd
N-methyl-2am. isobutyric		3431-3461 or 6.87-6.91	nd

LARGE D/H VALUES => EXTRATERRESTRIAL ORIGIN

4.Comets & meteorites

4.2 Meteorites

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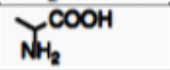
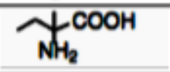
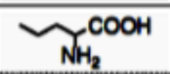
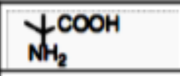
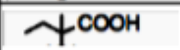
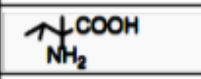
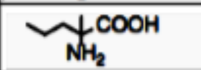
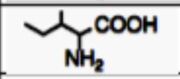
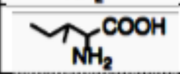
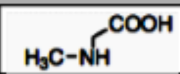
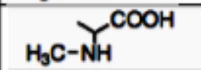
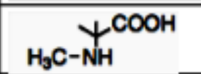
AMINO ACIDS DEUTERATION

Ceccarelli et al. 2014, PP6: credit Pizzarello

AMINO ACID		CM2 (δD or D/H in 10^{-4})	CR2 (δD or D/H in 10^{-4})
Linear alkyl chain compounds			
glycine		366-399 or 2.12-2.17	868-1070 or 2.89-3.21
DL alanine		360-765 or 2.11-2.74	1159-1693 or 3.35-4.17
DL-2-a. butyric		1091-1634 or 3.24-4.08	1920-3409 or 4.53-6.63
norvaline		1505 or 3.88	nd
Branched chain compounds			
2-a. isobutyric		2362-3097 or 5.21-6.35	4303-7257 or 8.22-12.80
isovaline		2081-3419 or 4.78-6.85	3813-7050 or 7.46-12.48
DL-valine		1216-2432 or 3.43-5.32	2086-3307 or 4.78-6.68
2-a. 2,3 methylbutyric		3318-3604 or 6.69-7.14	nd
DL-2methylnorvaline		2686-3021 or 5.71-6.23	nd
DL-allo isoleucine		2206-2496 or 4.97-5.42	nd
L-leucine		1792-1846 or 4.33-4.41	nd
N-substituted amino acids			
Sarcosine		1274-1400 or 3.52-3.72	nd
DL-N-methylalanine		1224-1310 or 3.44-3.58	nd
N-methyl-2am. isobutyric		3431-3461 or 6.87-6.91	nd

LARGEST D/H VALUES IN BRANCHED COMPONENTS

4.Comets & meteorites

4.2 Meteorites

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AMINO ACIDS ORIGIN

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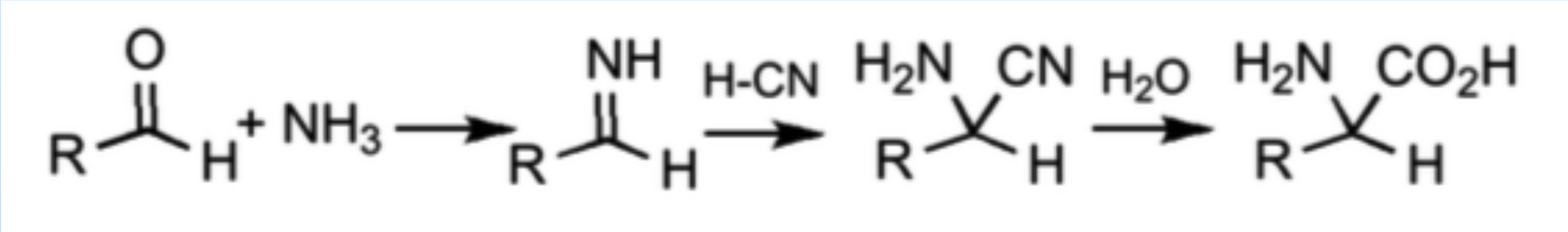
Ceccarelli et al. 2014, PP6: credit Pizzarello

PRECURSOR MOLECULES AND SYNTHESIS PATHWAYS STILL UNDER DEBATE

STRECKER-TYPE SYNTHESIS: ONE OF AND THE FIRST DISCUSSED SYNTHESIS PATH



IN PRESENCE OF LIQUID WATER (AQUEOUS ALTERATION OCCURRED ON THE PARENT BODY)

BUT SOME EVIDENCES POINT TO ACETALDEHYDE AS A PRECURSOR

=> NOT EVERYTHING IS UNDERSTOOD YET

4.3 WRAP-UP

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WATER AND ORGANICS

WATER IS THE MOST ABUNDANT MOLECULE PASSED FROM ONE PHASE TO THE OTHER OF THE SOLAR SYSTEM FORMATION PROCESS
=> BECAUSE IT IS FROZEN INTO THE GRAIN MANTLES

ORGANICS ARE ALSO PASSED: THEY UNDERGO SUBSTANTIAL CHANGES FROM THE PRESTELLAR CORE PHASE TO THE COMETS AND METEORITS
=> HOW AND WHY IS TOTALLY UNCLEAR, BUT FROZEN ORGANICS ARE CLEARLY A WAY

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MOLECULAR DEUTERATION

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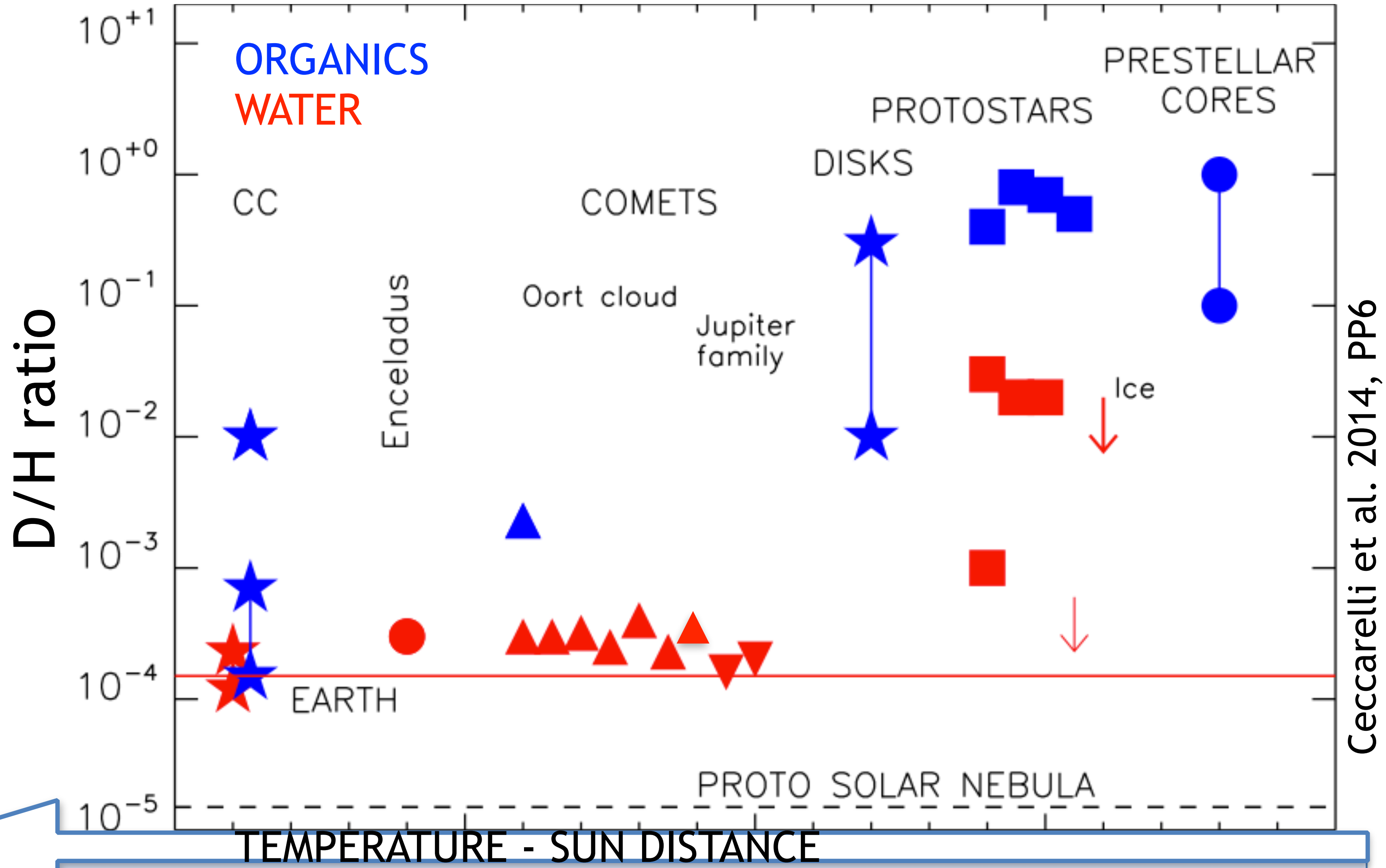
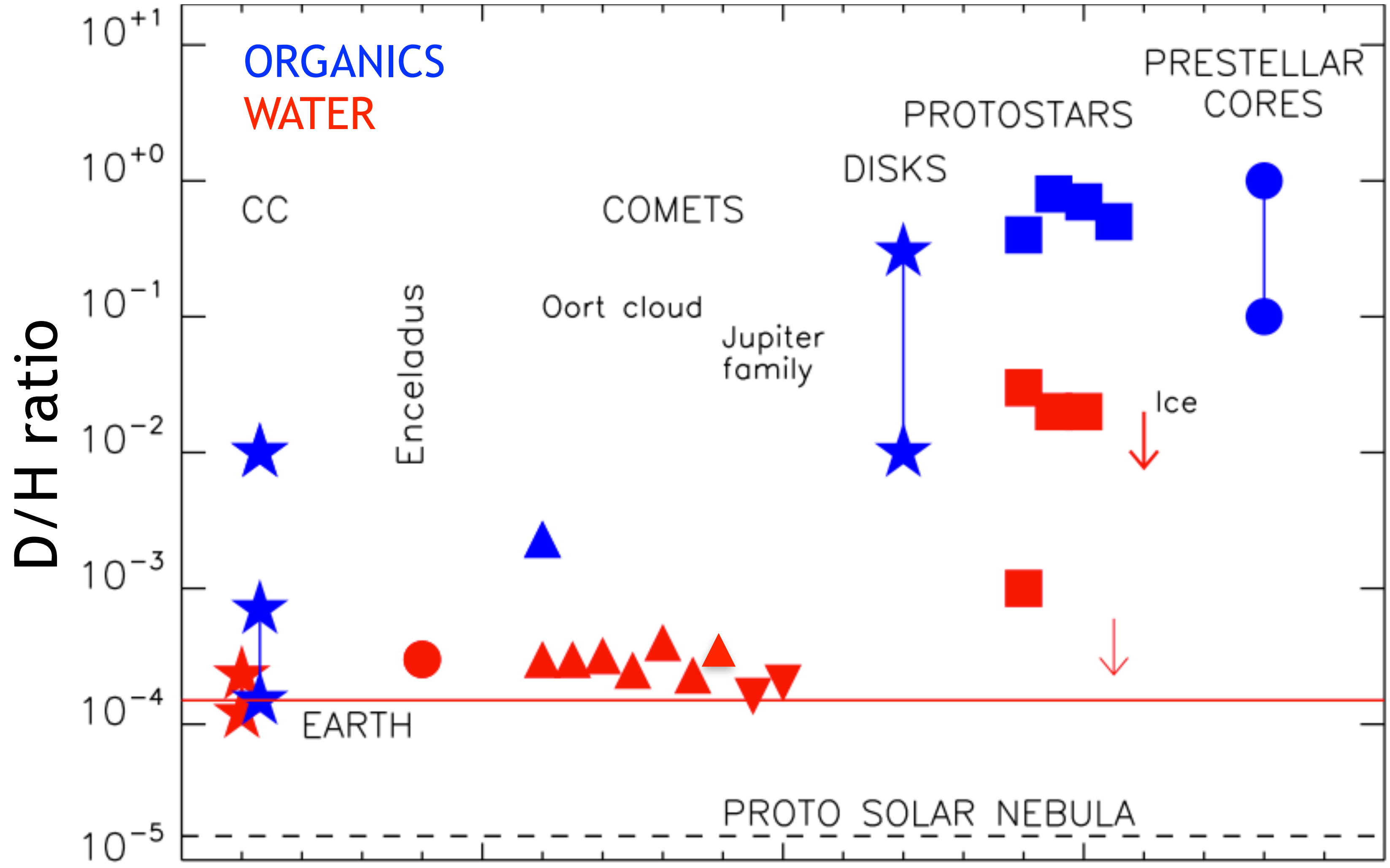


1- D/H SYSTEMATICALLY LARGER IN EARLIER PHASES

WHY? BECAUSE OF THE DIFFERENT LINEAR SCALE PROBED BY EACH CLASS OF OBJECT?

IF YES, NOT SUCH A LARGE MIXING IN THE PDISKS

MOLECULAR DEUTERATION



Ceccarelli et al. 2014, PP6

2- D/H SYSTEMATICALLY LARGER IN WATER THAN IN ORGANICS

WHY? WHEN DOES THE DIFFERENCE SET ON?

4.Comets & meteorites

4.3 Wrap-up

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HAZARD or COSMIC IMPERATIVE ?

	HAZARD	COSMIC IMPERATIVE
USE OF COSMIC ELEMENTS	0	1
EFFICENCY	0	1
WATER SYNTHESIS	0	1
ORGANIC SYNTHESIS	0	1

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