# Carbonaceous Meteorites & Asteroids: Clues to the Formation and Evolution of Our Solar System

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# Outline

1. Carbonaceous meteorites: reflectance spectra (chemical compounds & carbon-rich minerals)
2. Carbonaceous asteroids: ground- & space-based reflectance spectroscopy (chemical compounds & carbon-rich minerals)
3. Carbonaceous meteorites & asteroids linkage
4. Conclusions/future directions

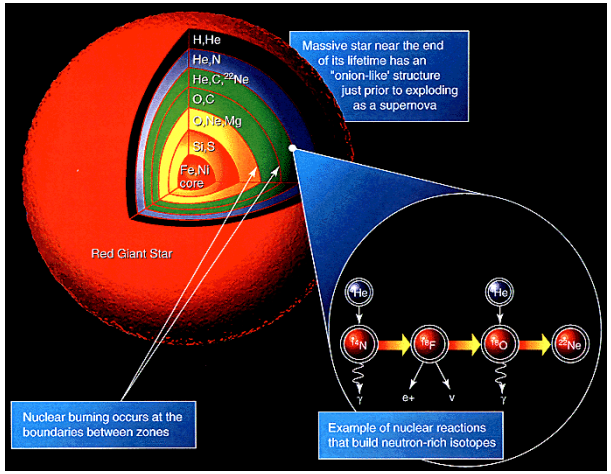
# Stellar Nucleosynthesis

- The current inventory of elements in the universe were produced by several processes
- H, He, Li were created in the Big Bang…then first stars, galaxies..
- Heavier elements than H and He, metals in astronomy, were produced in stars by processes stellar nucleosynthesis
- One of the most important reactions that involve carbon in stellar nucleosynthesis:

❑ The triple-alpha process

❑ Carbon-nitrogen-oxygen (CNO) cycle

❑ Carbon burning processes…




Credit: https://helios.gsfc.nasa.gov/nucleo.html

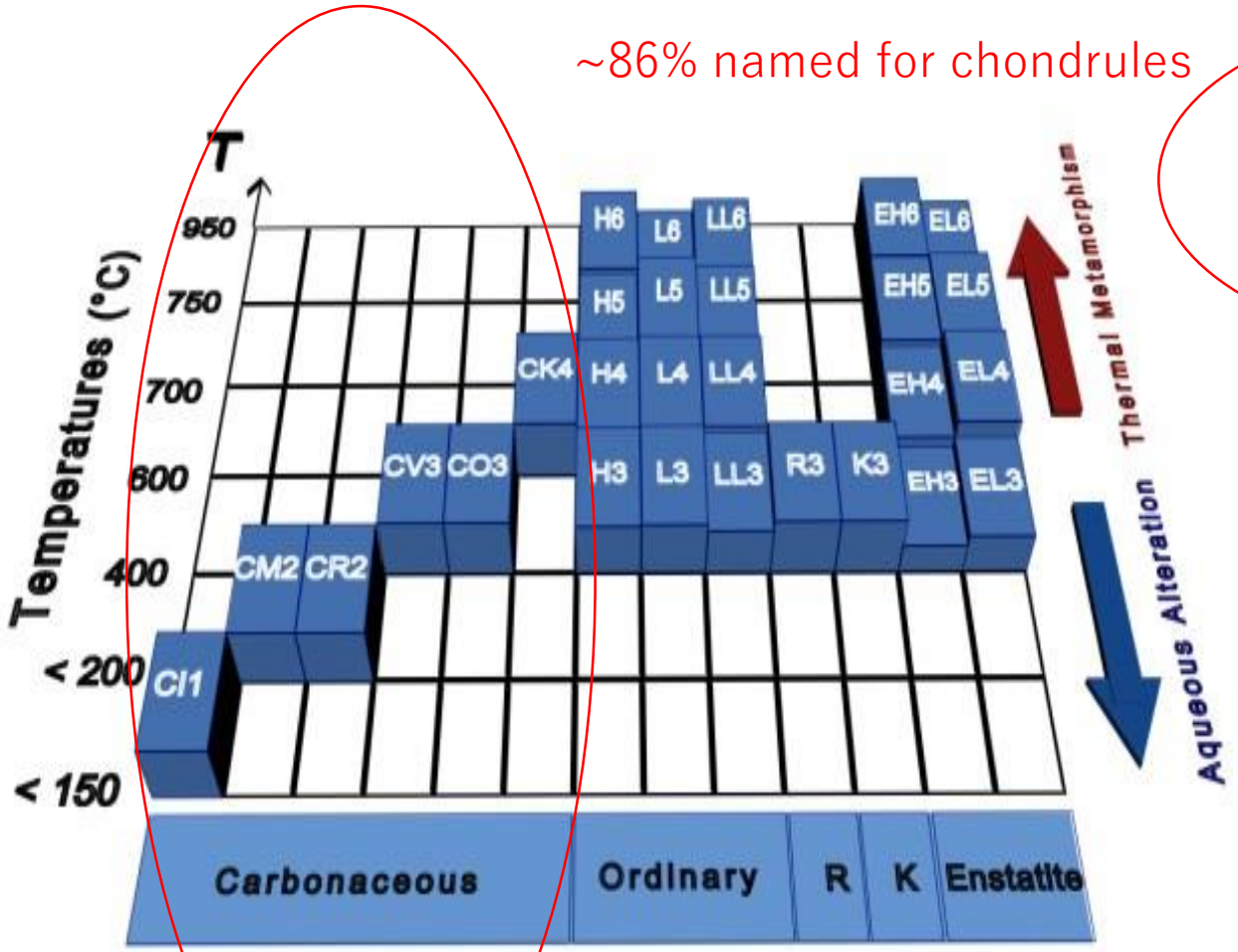
# Solar Nebula

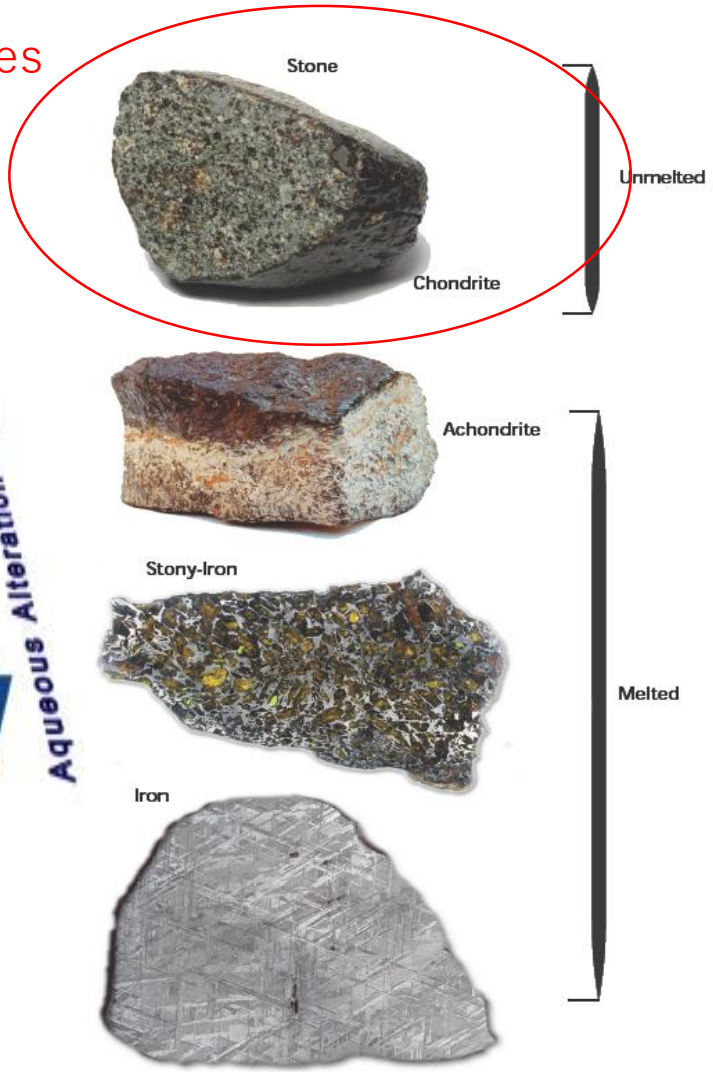

Credit: Dr. William K. Hartmann, Planetary Science Institute, Tucson, AZ

An artist's conception of the solar nebula, surrounding the violent young star

# Carbonaceous Meteorites

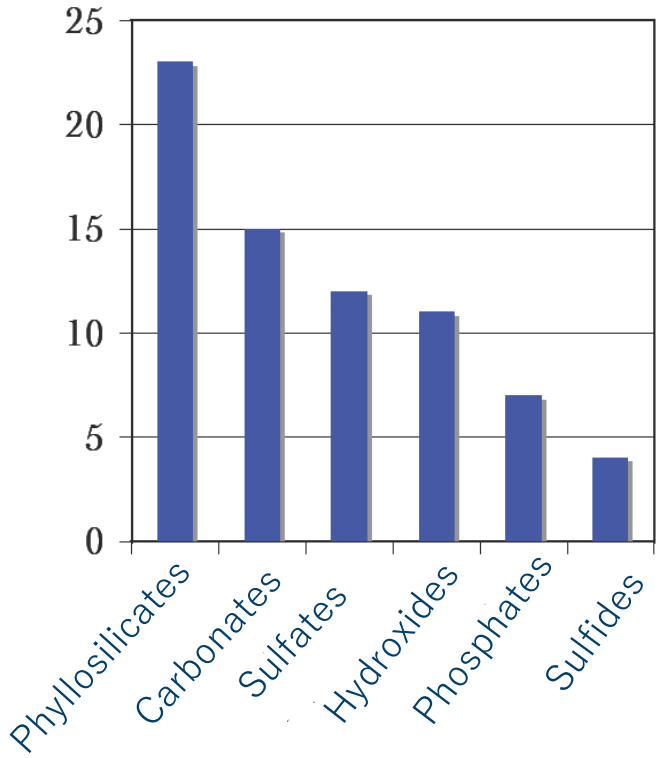
~86% named for chondrules



# Carbonates in Meteorites

- 275 different mineral species reported in meteorites
- 78 different hydrated minerals in meteorites
- 15 carbon-rich minerals (carbonates)




Graph courtesy of G.K. Benedix(NHM)

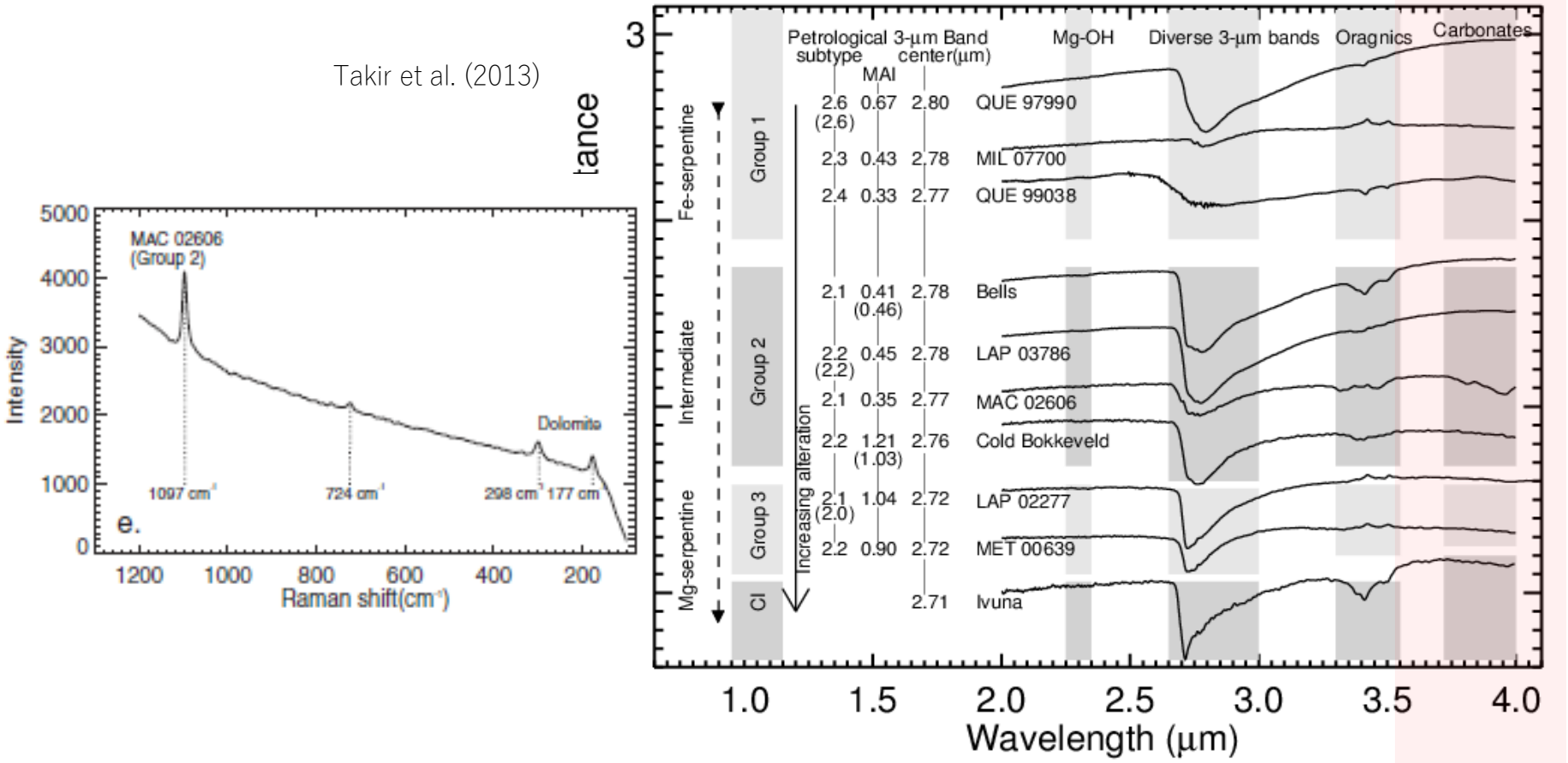
# Mineralogy of Carbonaceous Meteorites

Brearley (2006) & Zolensky (2011)

| CI | CM | CO | CV | CB/CH | CR | Tagish Lake |
|---|---|---|---|---|---|---|
| Serpentines<br>Saponite | Serpentines<br>Chlorite<br>Vermiculite<br>Garnets | Serpentine<br>Chlorite | Serpentines<br>Chlorite Micas<br>Amphiboles<br>Garnets<br>Fayalite<br>Hedenbergite | Serpentine | Serpentine<br>Saponite | Serpentine<br>Saponite |
| Calcite Dolomite<br>Breunnerite<br>Siderite | Calcite Dolomite<br>Aragonite | | | | Calcite | Calcite<br>Dolomite<br>Breunnerite<br>Siderite<br>Magnesite |
| Pyrrhotite<br>Pentlandite<br>Cubanite | Pyrrhotite<br>Pentlandite<br>Tochlinite | | Pyrrhotite<br>Pentlandite | | Pyrrhotite<br>Pentlandite | Pyrrhotite<br>Pentlandite |
| Sulfur | Awaruite | | | | | |
| Apatite Merrilite | | | | | | |
| Magnetite | Magnetite | | Magnetite | | Magnetite | Magnetite |
| | Brucite<br>Tochilinite | | | | | |
| | Halite | | | | | |
| Sulfates??? | Sulfates??? | | | | | NO SULFATES |

# Carbonates in Meteorites

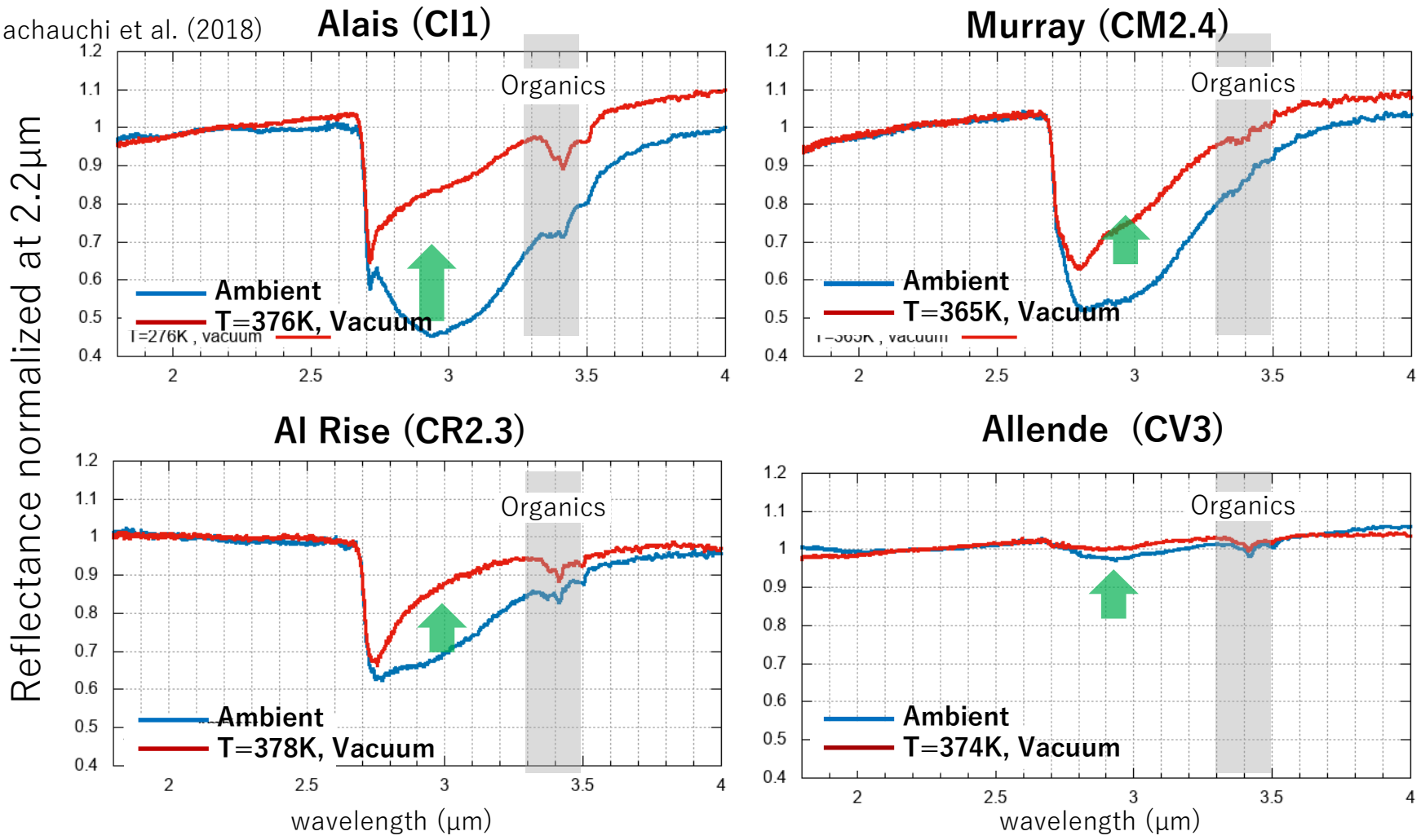
Takir et al. (2013)




Some CMs and CIs exhibit strong $CO_3$ absorptions in the 3.4–3.5 µm and 3.8–4.0 µm regions, attributed to carbonates (dolomite)

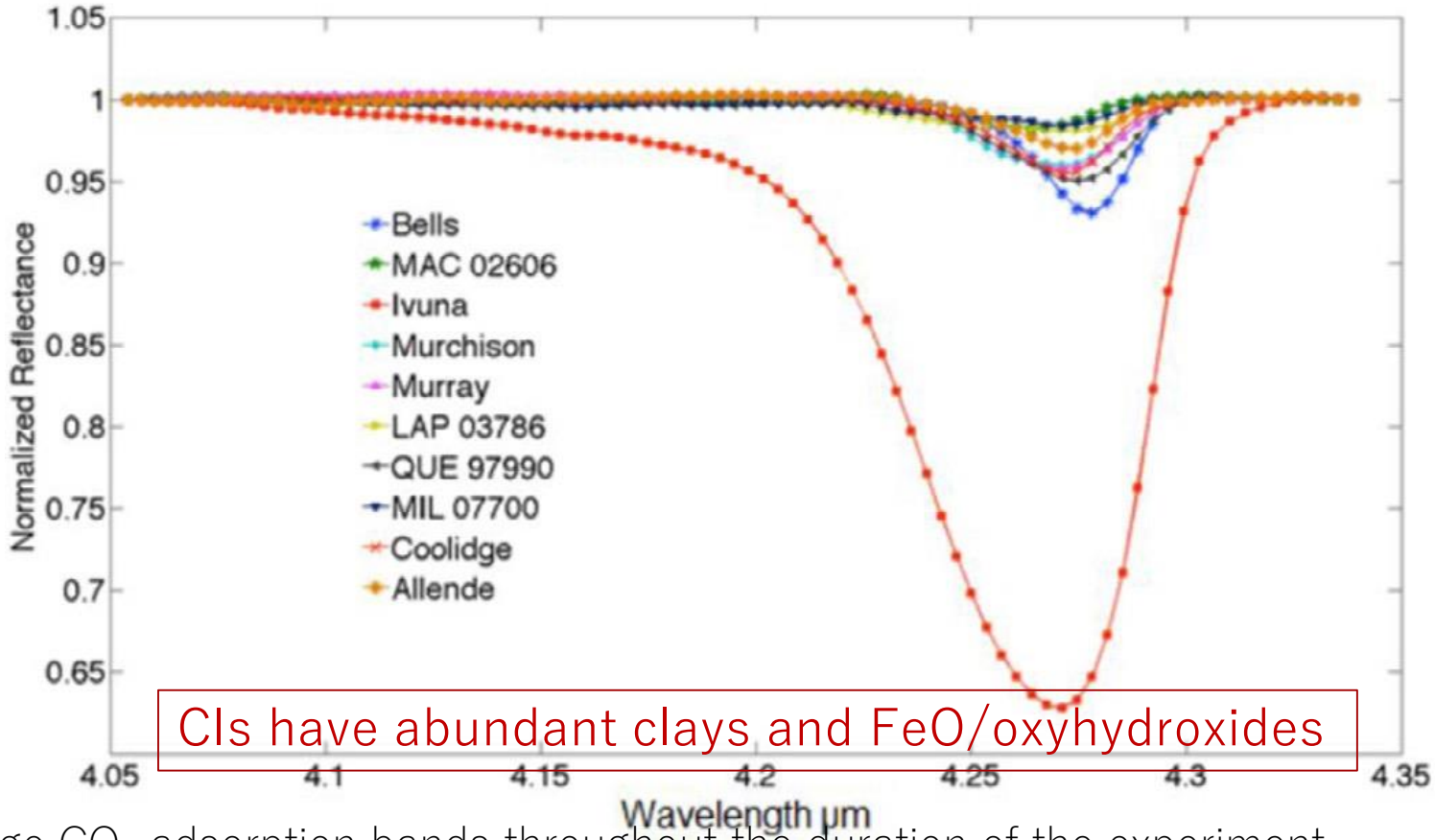
# Organics in Meteorites

Nachauchi et al. (2018)



# CIs have Adsorptive Surfaces

$CO_2$ gas adsorption experiments on carbonaceous chondrites:

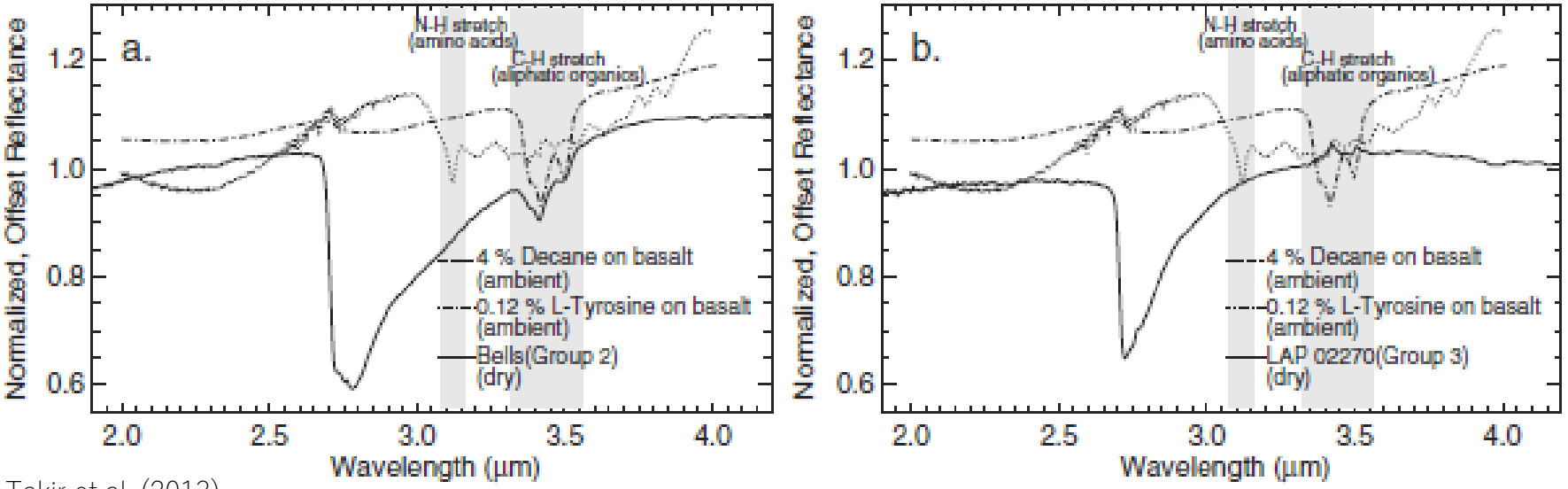



Average $CO_2$ adsorption bands throughout the duration of the experiment while maintaining 150 K. Ivuna (CI) displays the greatest CO2 adsorption

Berlanga et al. (2016)

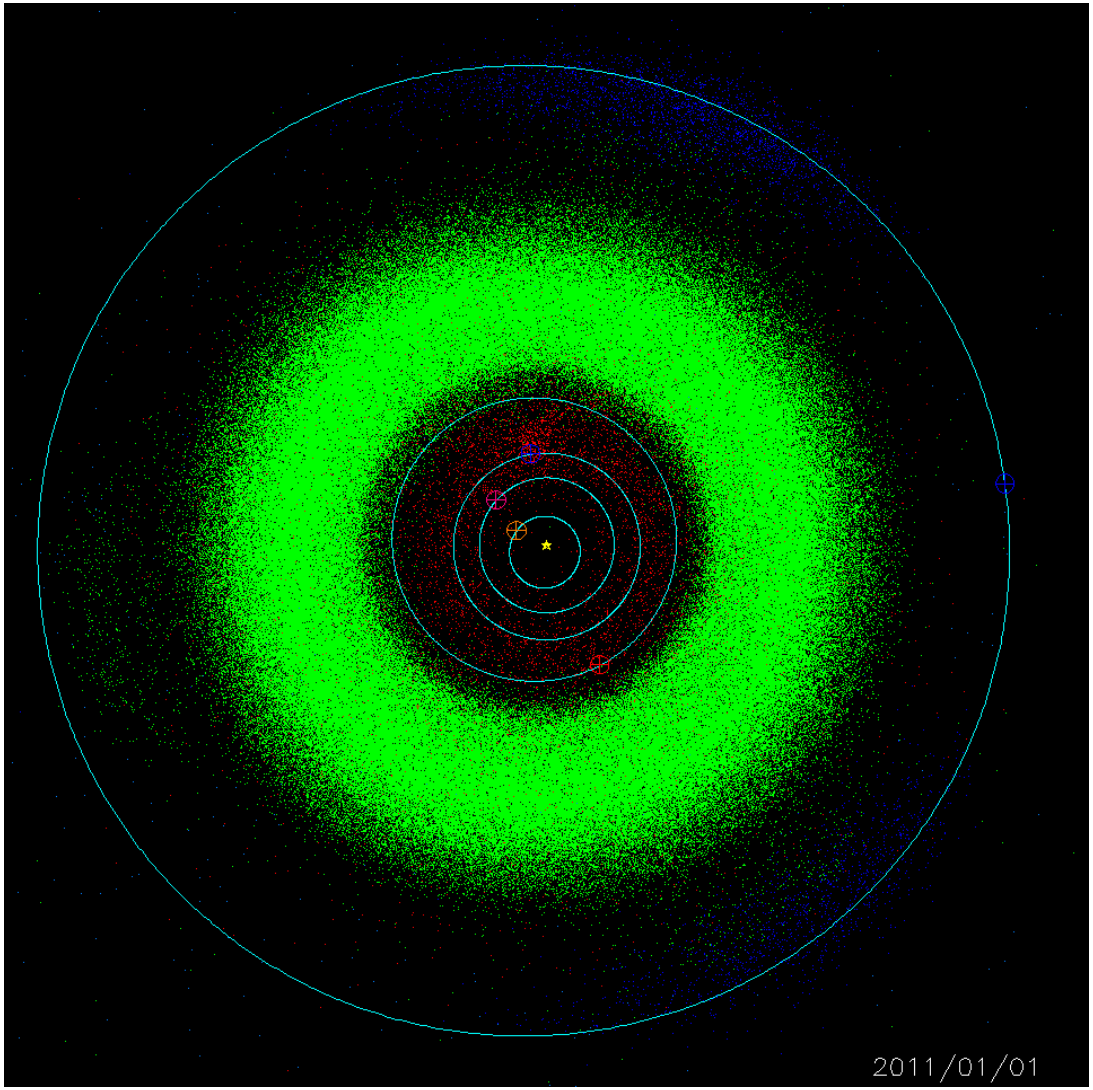
# Organics in CIs

- Adsorbed water masks organic features ✓
- Removal of adsorbed water compositionally alter the mix of organics
- New organics formed during heating
- Organics were deposited onto the sample




Takir et al. (2013)

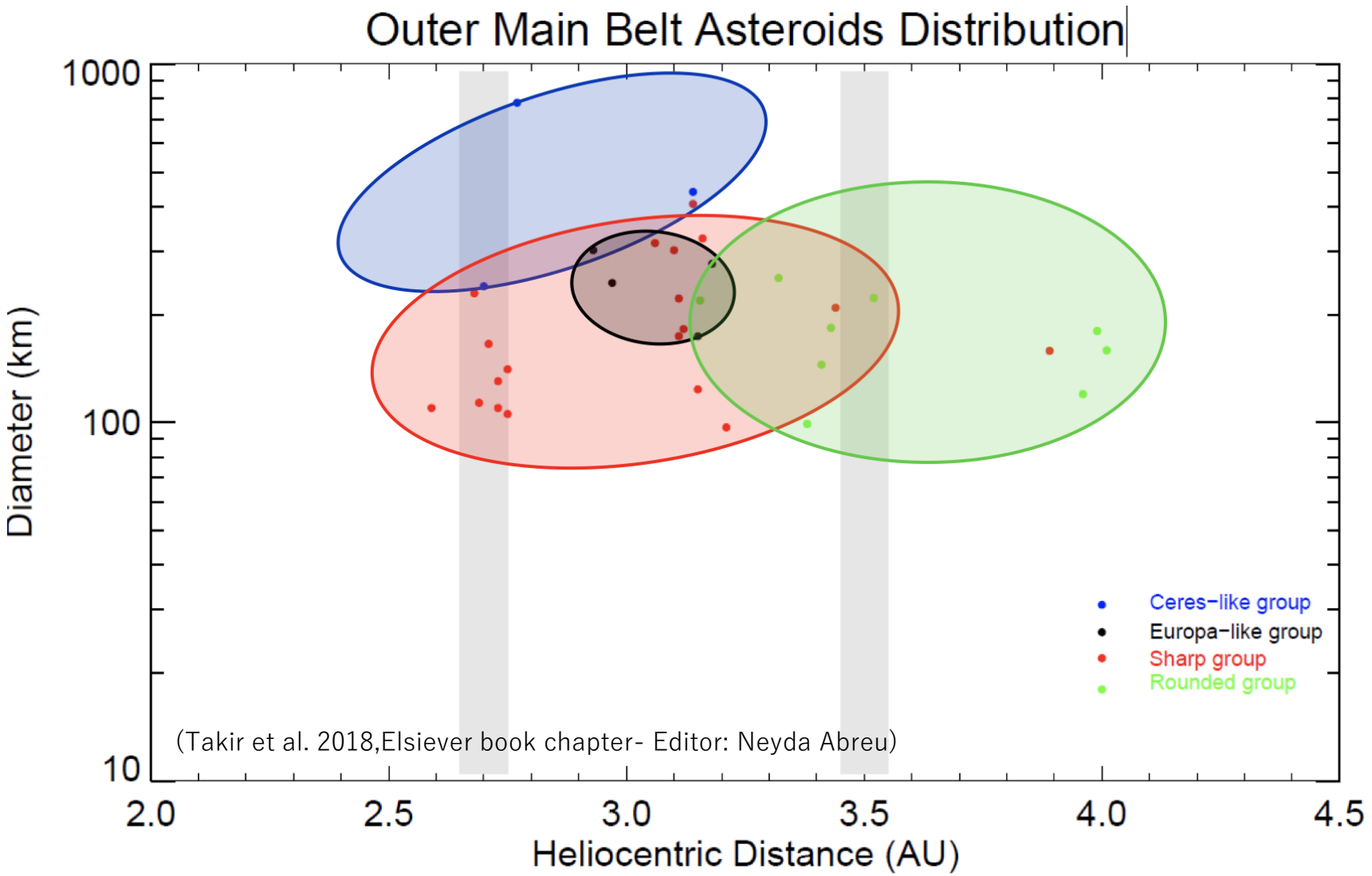
# Carbonaceous Asteroids





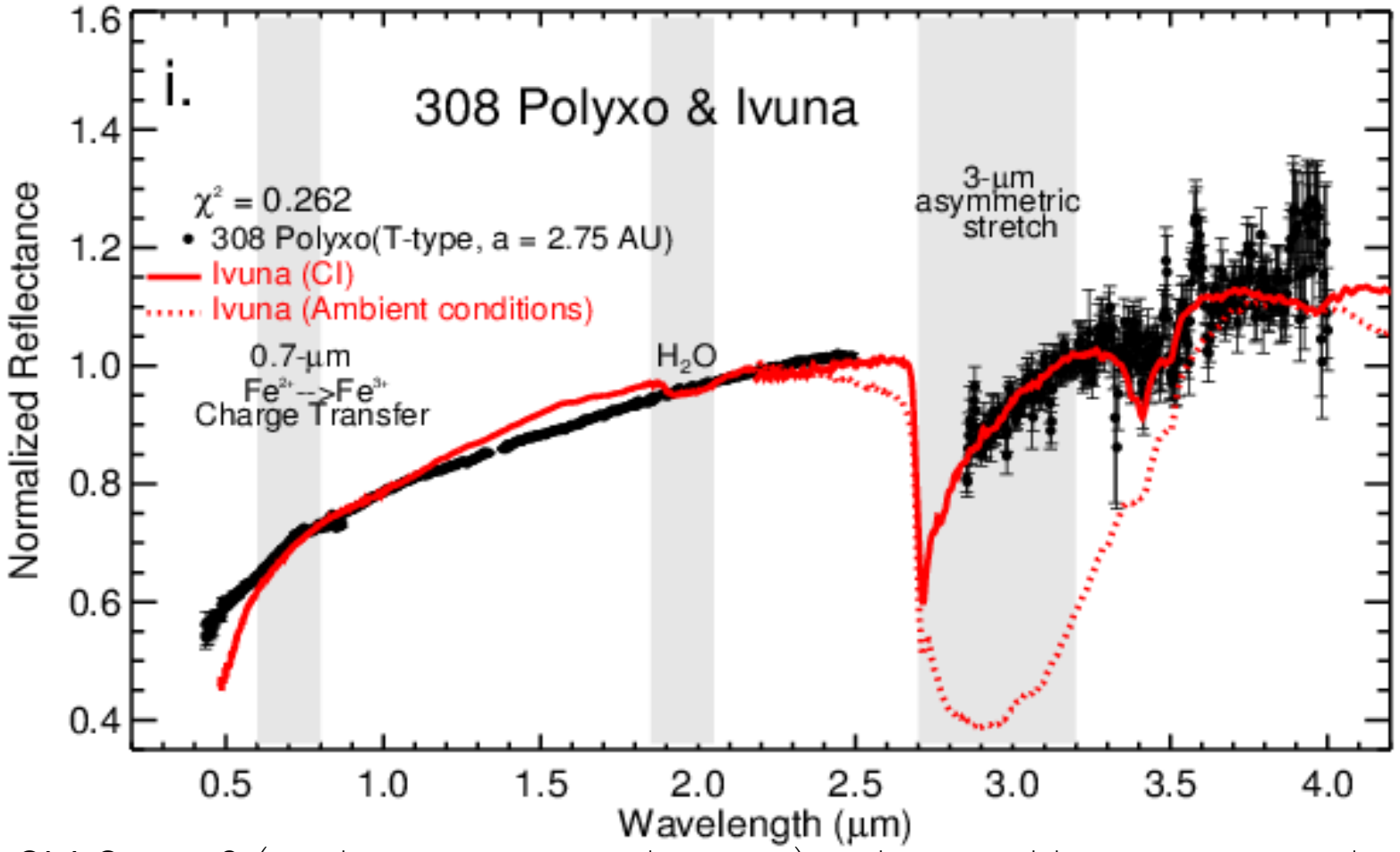

Credit: Minor Planet Center

# Orbital Distribution of Carbonaceous Asteroids



# Linking Carbonaceous Asteroids & Meteorites

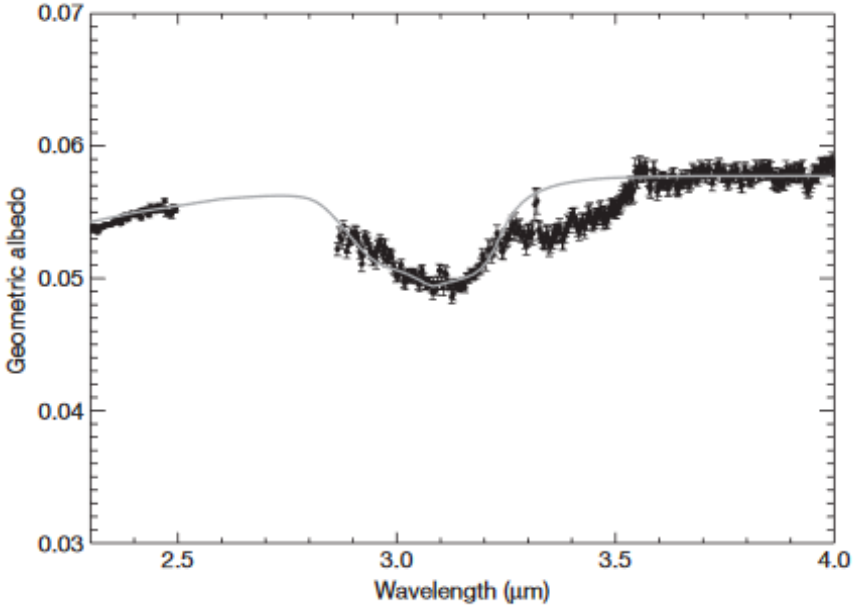
(Takir et al. 2015)

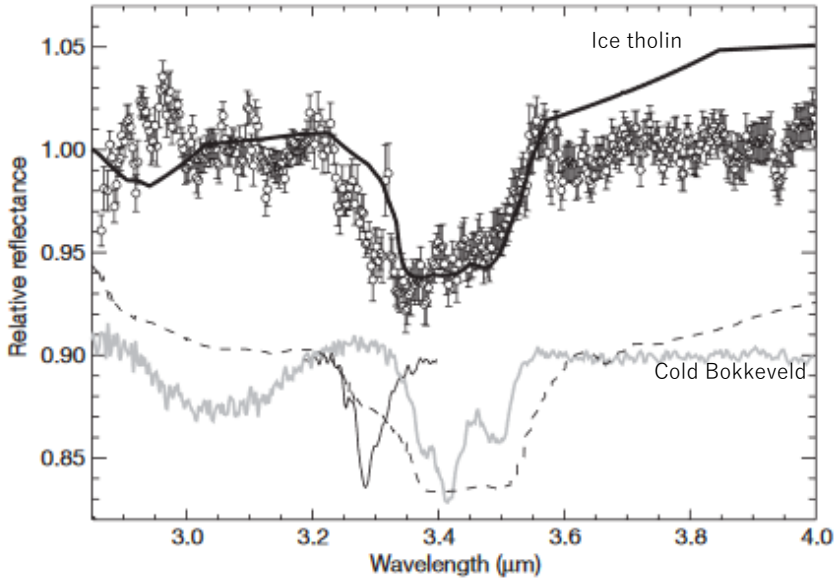



CM Group 2 (moderate aqueous alteration) is the possible meteorite analog for the sharp group ($2.5 < a < 3.3$ AU)

# Organics on Asteroids- ground-based

Organic material is present on the surface of 24 Themis (Rivkin & Emery 2010):

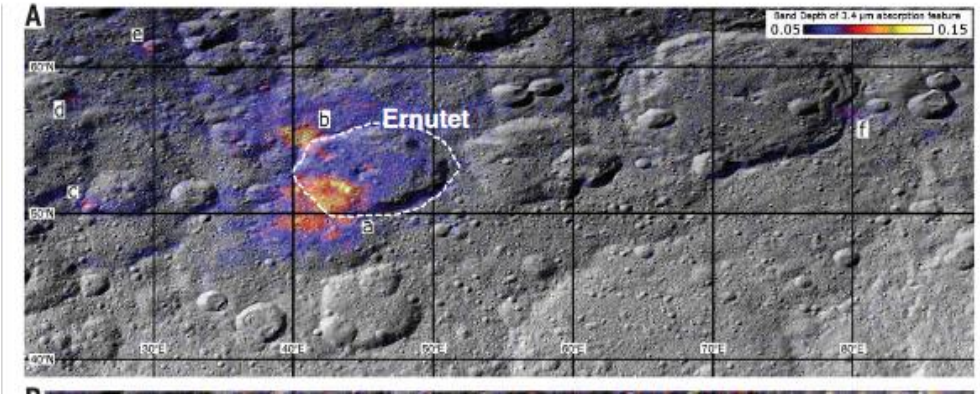


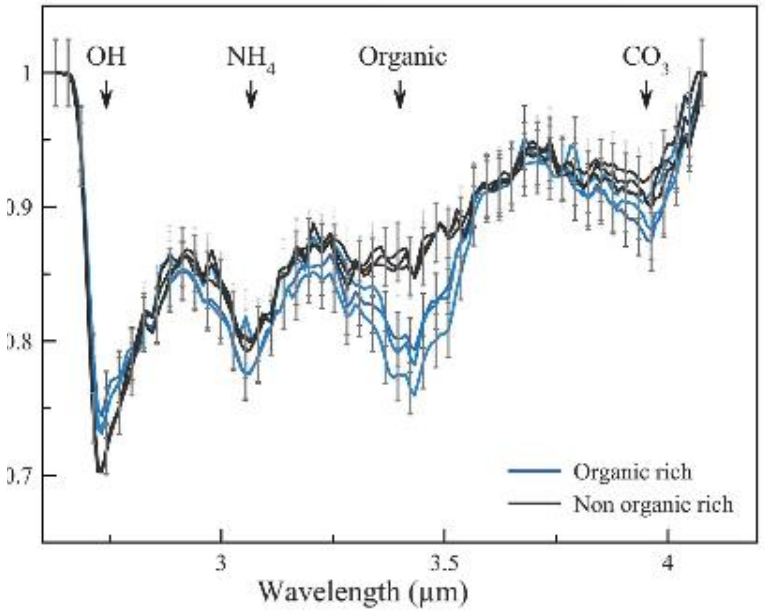

Absorption features in organic materials near 3.4 and 3.5 μm are typically $-CH_2$ and $-CH_3$ aliphatic stretch bands,

# Organics on Asteroids- spaced-based

Localized aliphatic organic material on the surface of Ceres (De Sanctis et al. 2017)




Distribution of the aliphatic organics- 3.4-μm band depth




Examples of organic-rich pixels (blue lines) taken from an area southeast of Ernutet)

# Conclusions- the ‘C’ diagram