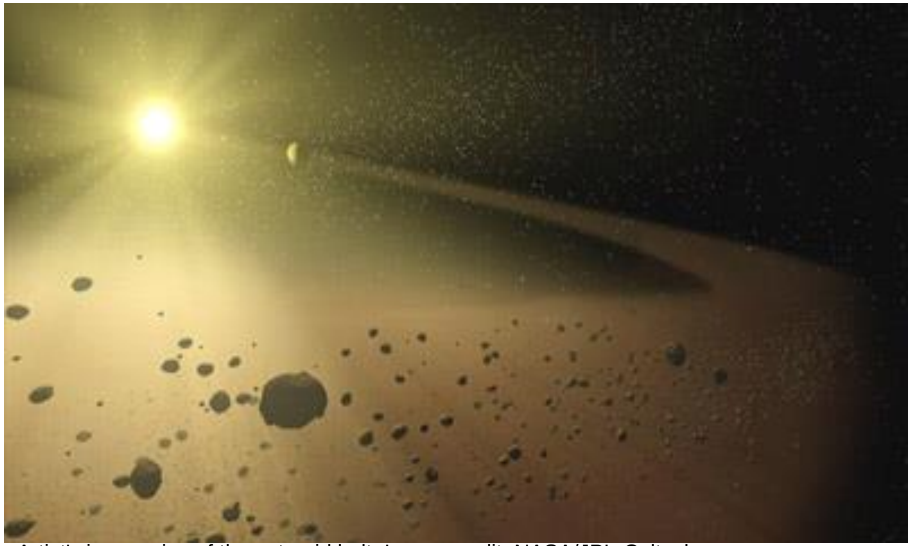
Primitive Asteroids: Insight into the Formation and Evolution of the Solar System



Artist's impression of the asteroid belt. Image credit: NASA/JPL-Caltech

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December 04, 2016

Kobe University, Center for Planetary Science

Outline

- Background about asteroid/meteorite science
- Ground-based astronomy of primitive asteroids
- Laboratory studies of primitive meteorites
- Linking primitive asteroid-meteorite science
- NASA's OSIRIS-REx mission to asteroid Bennu
- JAXA's Hayabusa2 mission to asteroid Ryugu

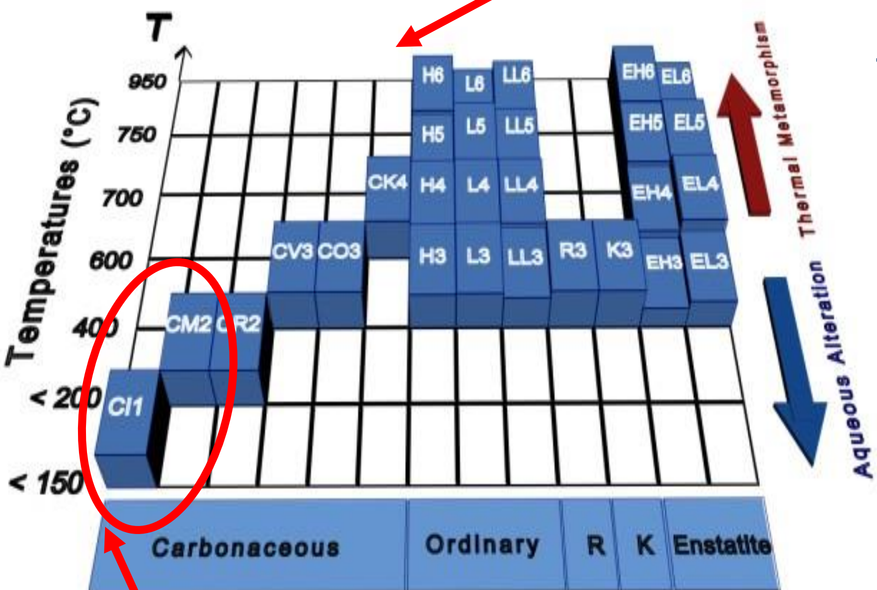
Solar Nebula

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

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

Meteorites: a record of nebular & Planetary processes

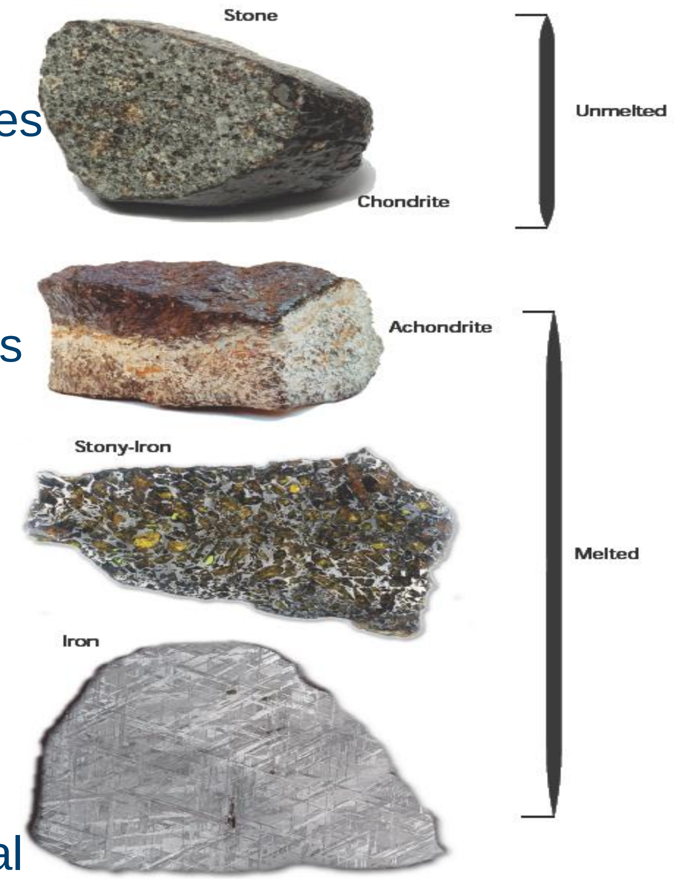
~86%
named for chondules



~6%
No chondules

~1%

~6%
Fe-Ni metal



Images courtesy of G.K Benedix (NHM)
https://physics.ucf.edu/~campins/paris2011/

CM: Carbonaceous Chondrites Mighei-like

CI: Carbonaceous Chondrites Ivuna-like

Chondrules

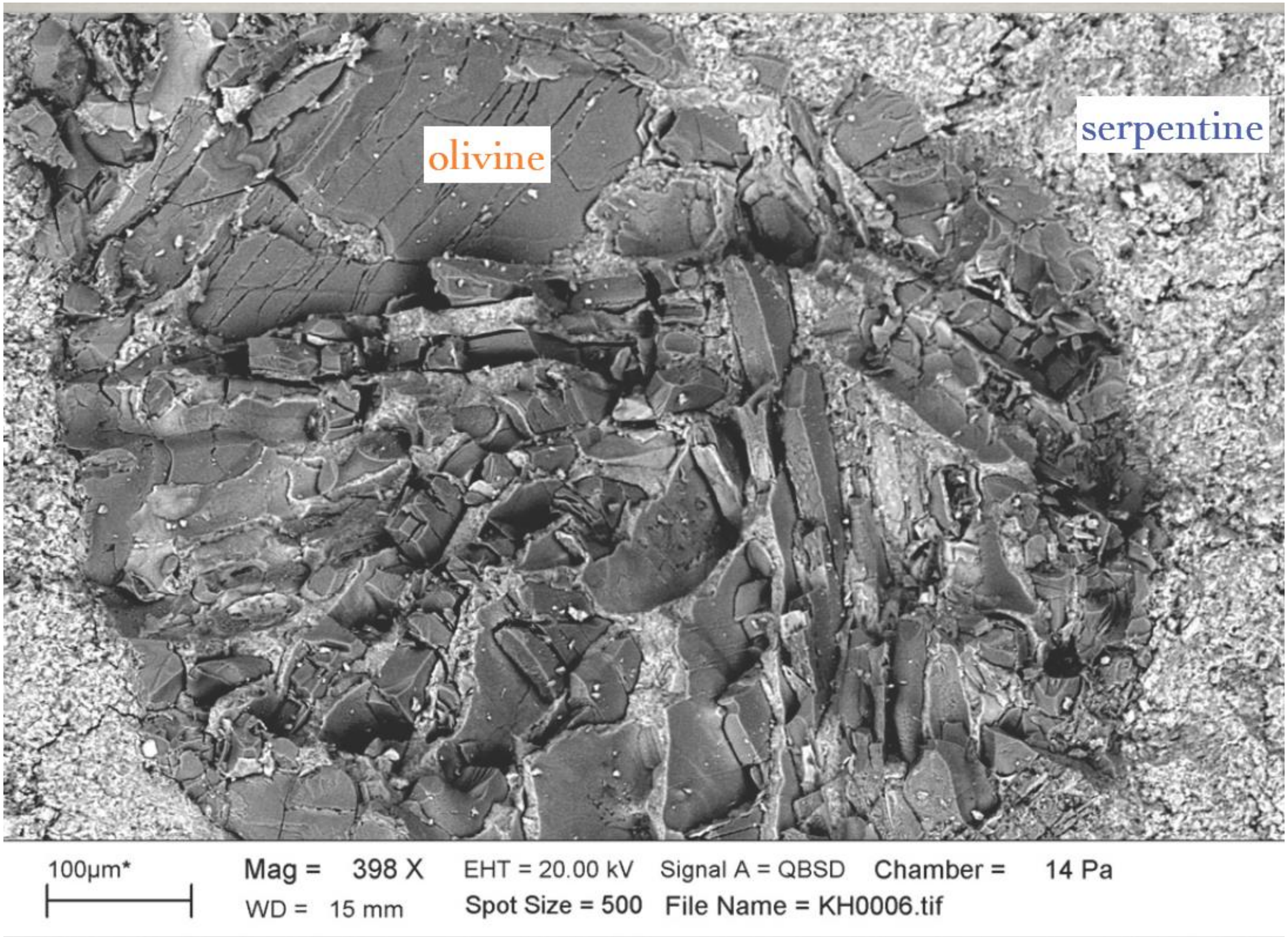
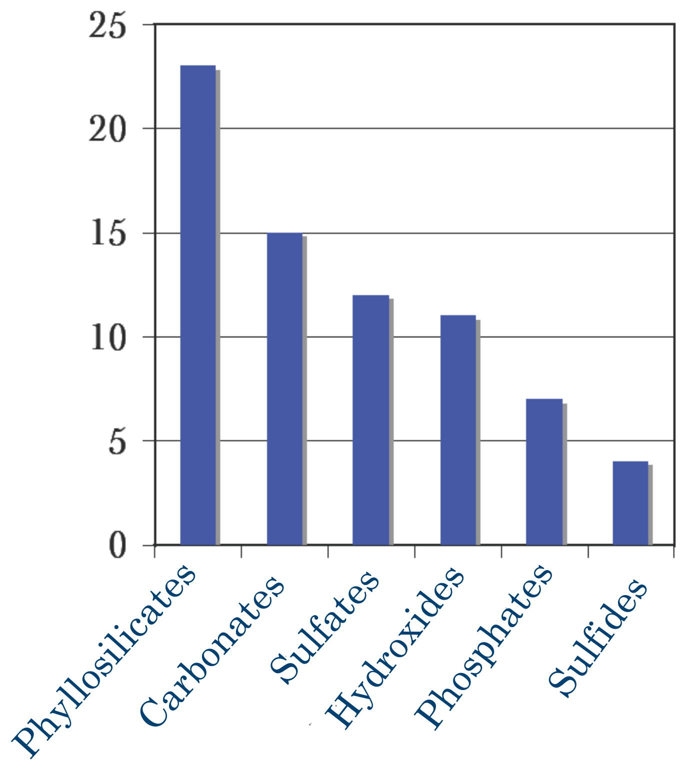


Image courtesy of G.K. Benedix (NHM)
https://physics.ucf.edu/~campins/paris2011/

Hydrated Minerals

- Hydrated minerals: any mineral tha contains structurally bound OH or H_2O
- 275 different mineral species reported in meteorites
- 78 different hydrated minerals in meteorites



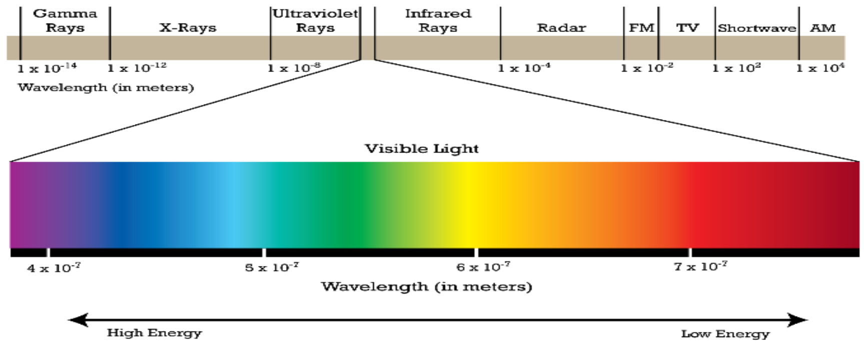
Graph courtesy of G.K. Benedix(NHM)
https://physics.ucf.edu/~campins/paris2011/

Hydrated Minerals

Brearley (2006) & Zolensky (2011)
https://physics.ucf.edu/~campins/paris2011/

	CI	CM	CO	CV	CB/CH	CR	Tagish Lake
Phyllosilicates	**Serpentines** **Saponite**	**Serpentines** **Chlorite** **Vermiculite** Garnets	**Serpentine** **Chlorite**	**Serpentines** **Chlorite** **Micas** Amphiboles Garnets Fayalite Hedenbergite	**Serpentine**	**Serpentine** **Saponite**	**Serpentine** **Saponite**
Carbonates	Calcite Dolomite Breunnerite Siderite	Calcite Dolomite Aragonite				Calcite	Calcite Dolomite Breunnerite Siderite Magnesite
Sulfides	Pyrrhotite Pentlandite Cubanite	Pyrrhotite Pentlandite Tochlinite		Pyrrhotite Pentlandite		Pyrrhotite Pentlandite	Pyrrhotite Pentlandite
	Sulfur	Awaruite					
Phosphates	Apatite Merrilite						
Oxides	Magnetite	Magnetite		Magnetite		Magnetite	Magnetite
Hydroxides		Brucite Tochilinite					
Halides		Halite					
	Sulfates???	Sulfates???					NO SULFATES

Asteroid Spectroscopy in VNIR



Credit: http://www.pion.cz/en/article/electromagnetic-spectrum

Credit: http://www.thewhitegoddess.co.uk/the_elements/the_planets/the_sun.asp

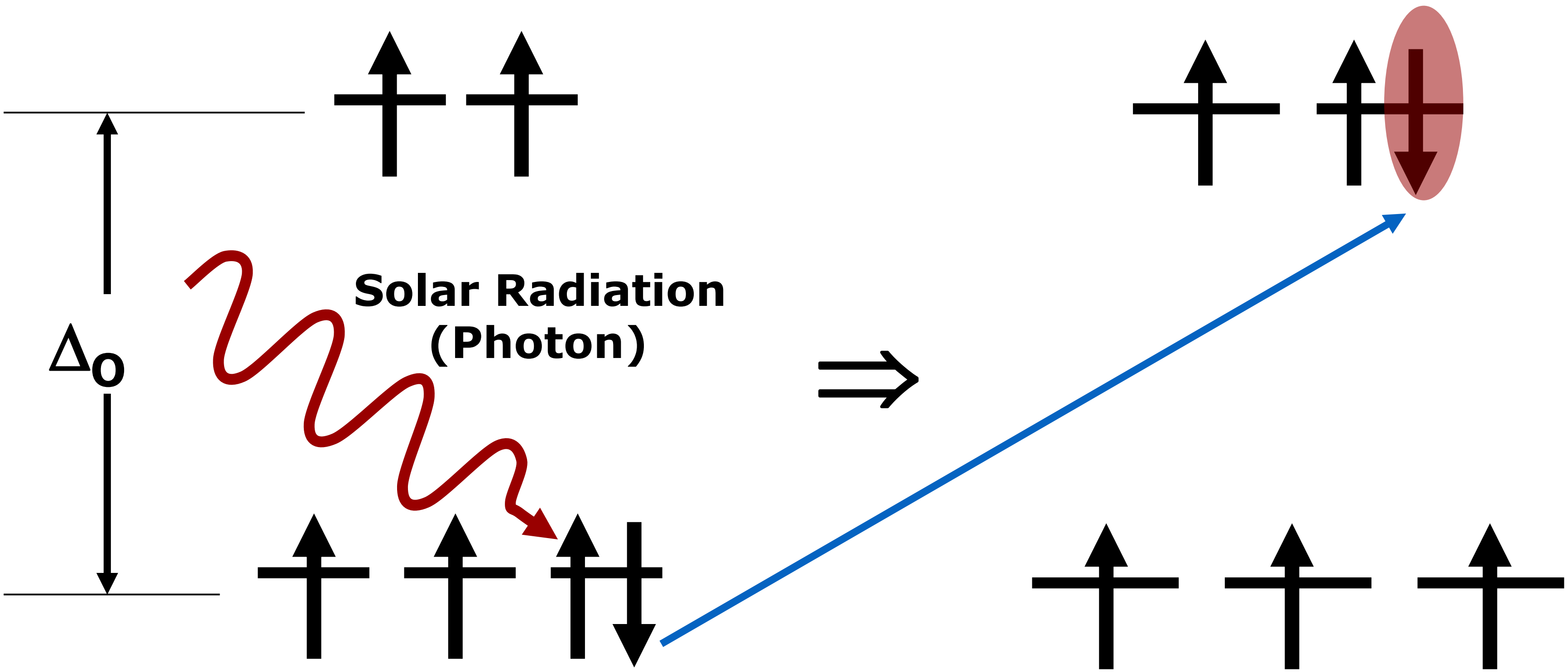
Solar Radiation (Photons)

Credit: NASA

Reflected Radiation

Remote Sensing: Crystal Field Theory

- Partially Filled d-orbital of Fe^{2+}:



Δ_O is the energy difference between the ground state and the upper state (excited)

Mineralogy & Remote Sensing

Early Solar System

1) H_2O + (Fe metal, sulfide) = Tochilinite

✓ $2[(Fe,Mg,Cr,Ni[\ ])S]\bullet 1.57\text{-}1.85[(Mg,Fe,Ni,Al,Ca)(OH)_2]$

3-µm asymmetric stretch

2) Solution + Silicates = Fe-rich phyllosilicates

✓ Cronstedtite- $Fe_2^{+2}Fe^{+3}(Si, Fe^{+3}O_5)(OH)_4$

0.7-µm charge transfer

3-µm asymmetric stretch

3) Mg-phyllosilicates are last to form

✓ Mg-serpentine(chrysotile/lizardite/antigorite)- $Mg_3Si_2O_5(OH)_4$

3-µm asymmetric stretch

✓ Saponite- $(Ca, Na)_{0.3}(Mg, Fe^{+2})_3(Si, Al)_4O_{10}(OH)_2\bullet 4H_2O$

3-µm symmetric stretch

✓ Vermiculate- $(Mg, Fe^{2+}, Al)_3(Al, Si)_4O_{10}(OH)_2\bullet 4H_2O$

2.2-µm OH-metal

3-µm symmetric stretch

Remote Sensing: Water Vibrations

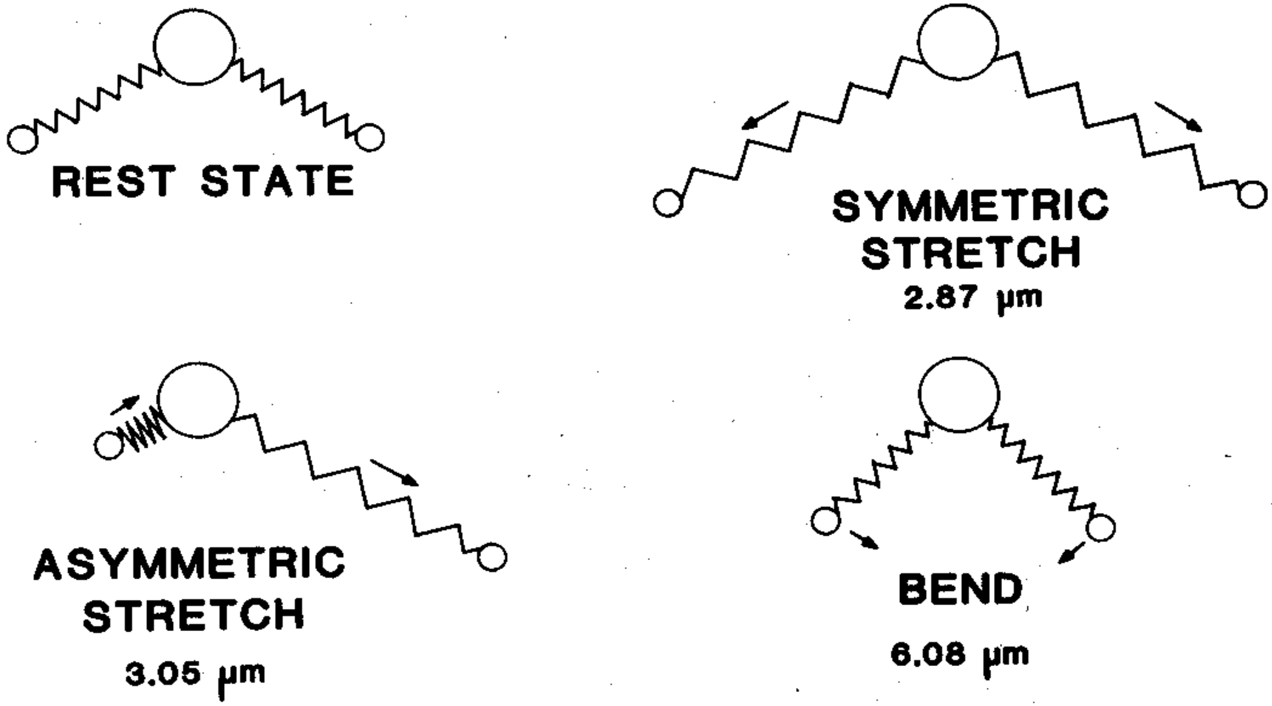
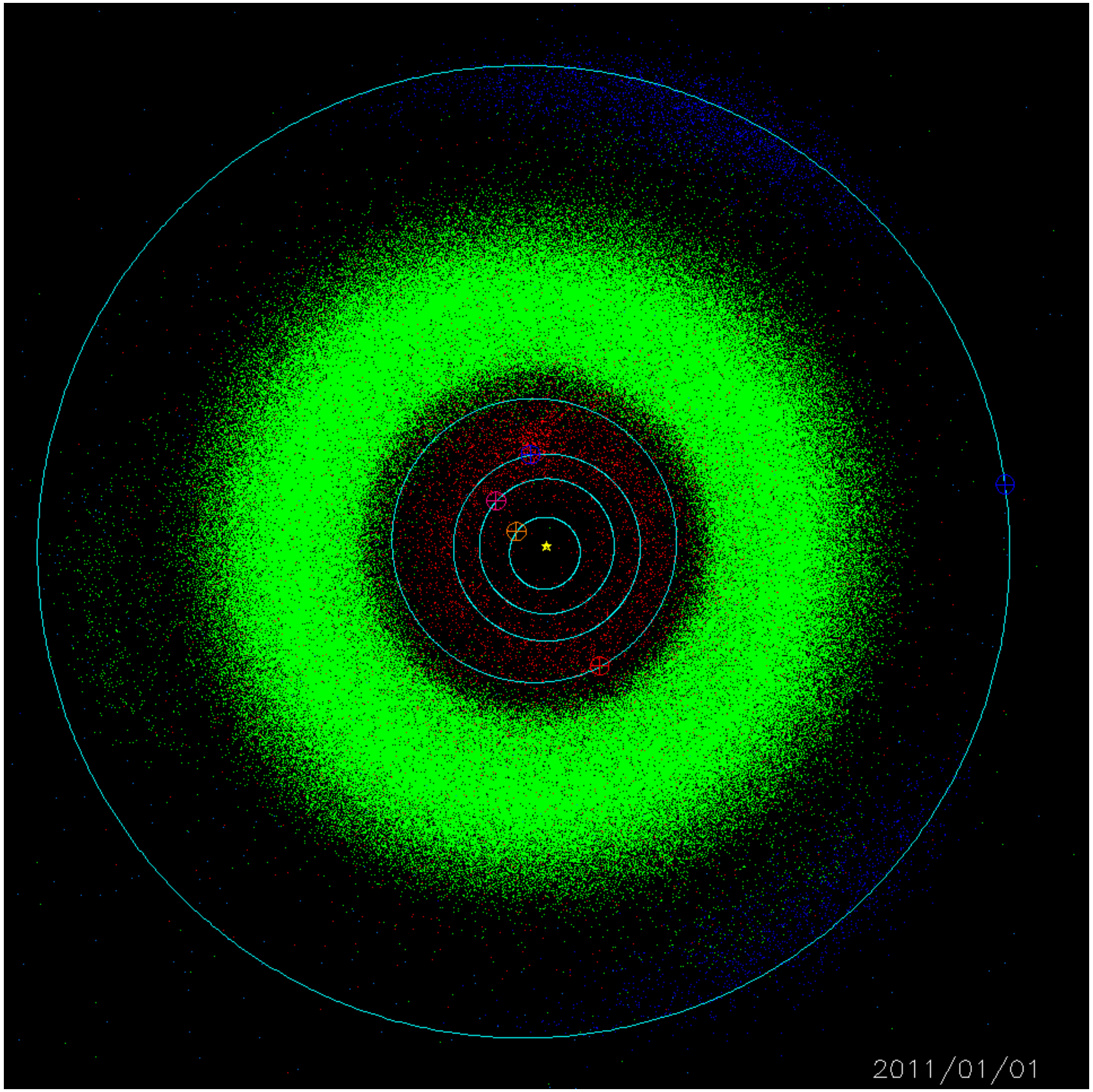


FIG. 2.—The fundamental internal vibrational modes of the free H_2O molecule. The O-H stretching mode of OH^- is the same as either of the stretching modes shown with one of the hydrogens removed.

S.J. Gaffey (1988)

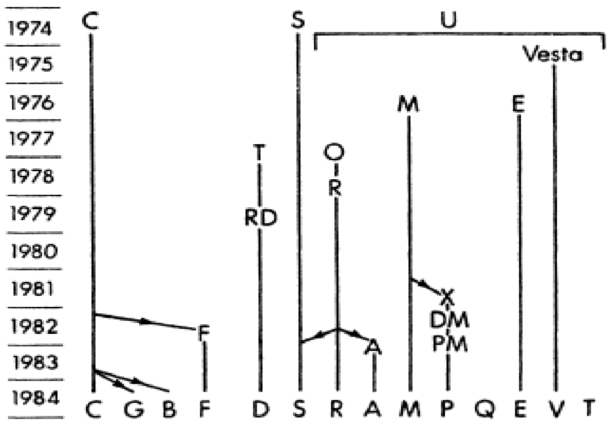
Molecular vibrations also produce spectral features

Main Asteroid Belt

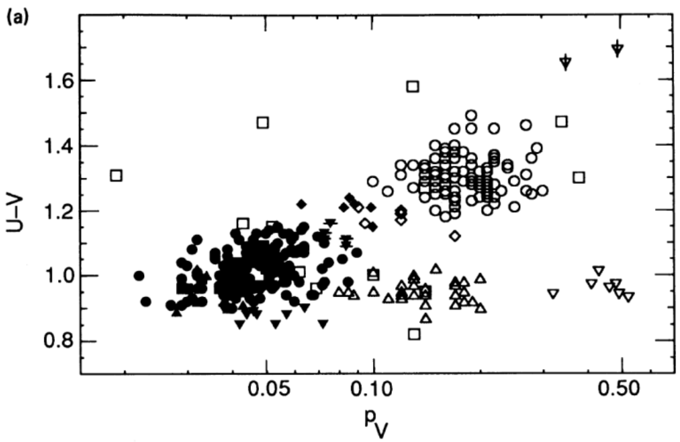


Credit: Minor Planet Center

Asteroid Taxonomies

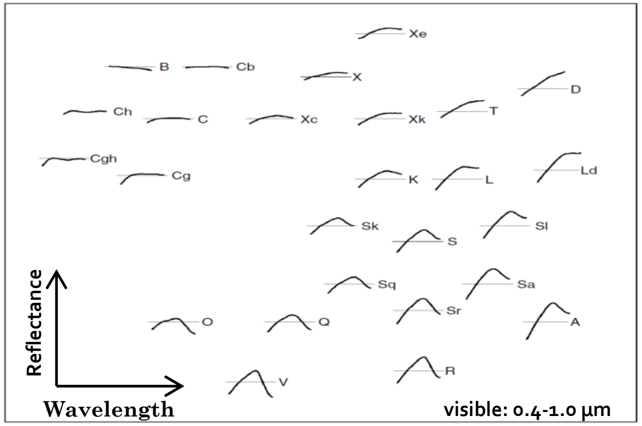


Tholen (1984)

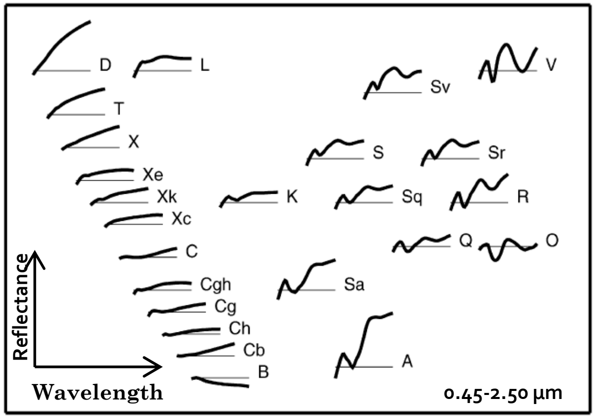


Tedesco et al. (1989)

Albedo and color



Bus and Binzel (2002)

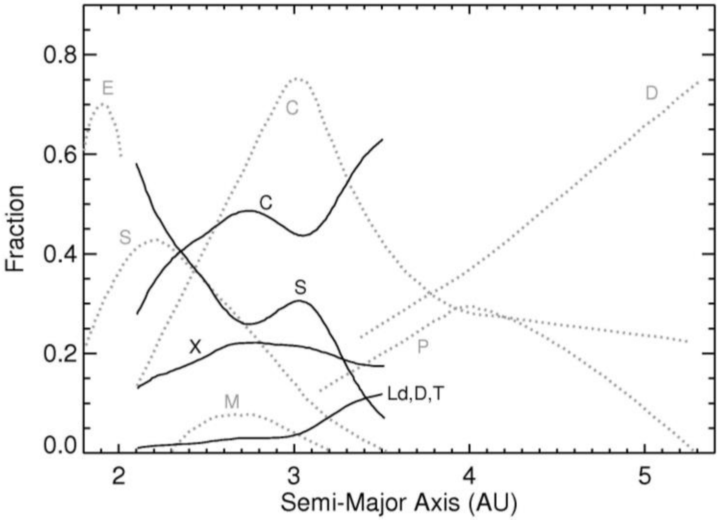


DeMeo et al. (2009)

Slope and spectral features

Main Belt Taxonomy (Classification)

- Main Belt is compositionally stratified



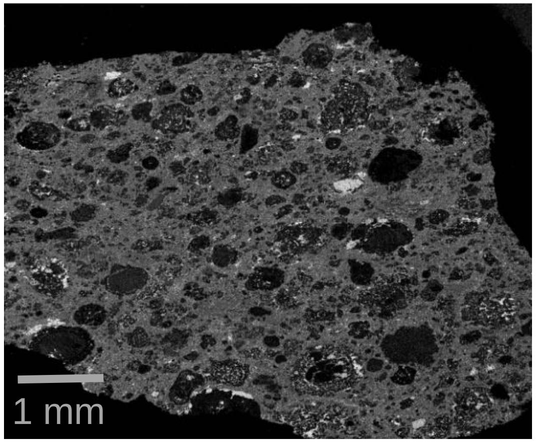
inner belt *E-type *high T, silicates
S-type *mod. T, silicates
C-type*low T, C-rich silicates
outer belt* P+D-type*lower T, more C-rich silicates

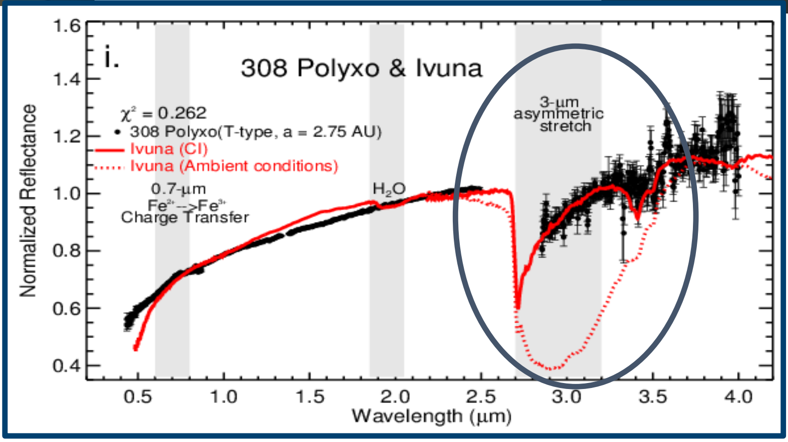
adapted from:
Gradie & Tedesco (1982); Bus & Binzel (2002)

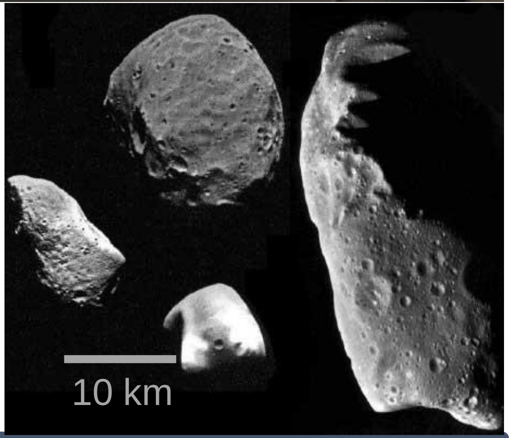
Open questions :

- The hydration state of these asteroids
- The nature of phyllosilicate mineralogy on the surface of these asteroids

Asteroid-Meteorite Research







Primitive Meteorite Petrology & Cosmochemistry

3-µm Reflectance Spectroscopy

Primitive Asteroid Astronomical Observations

Research's Goals & Motivation

The goal: is to apply the 3-μm spectral indicators (e.g., band center, band shape, band depth) in CM and CI chondrites to outer Main Belt asteroids (2.5 < a < 4.0 AU)

To better understand

Hydration state of these asteroids
Nature of phyllosilicate mineralogy on their surfaces

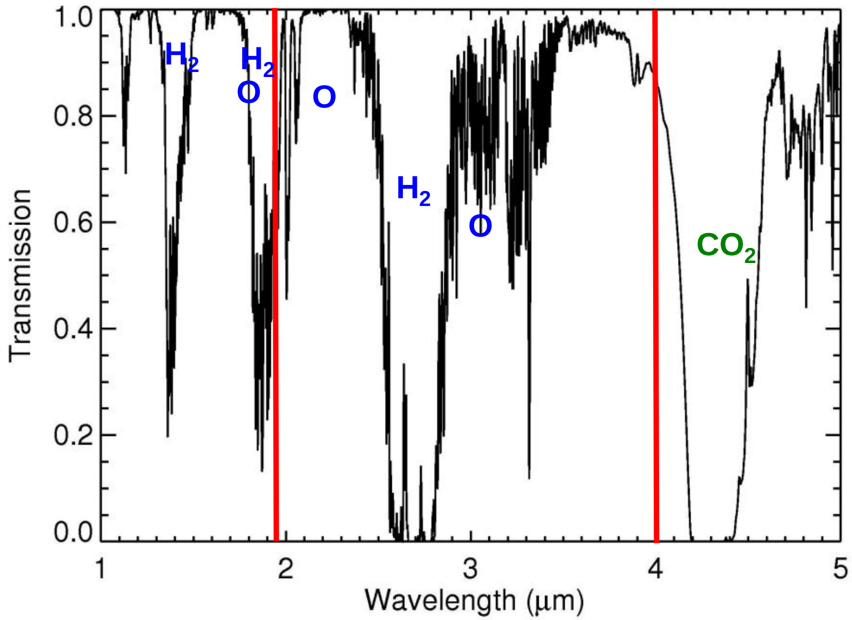
Broad implication

Address the question of the abundance and distribution of H_2O in the early Solar System and test current theories on the formation and evolution of the giant planets in the early Solar System.

Asteroid Observations

- Observations: 45 asteroids (2009-present)
  - ✓ NASA Infrared Telescope Facility (IRTF)
  - ✓ 3-m telescope on Mauna Kea, Hawai'i
  - ✓ SpeX: Prism (0.8-2.5-μm) and LXD (1.9-4.1-μm)
- Data reduction: IRTF Spextool & IDL custom routines
- We are observing 60 additional primitive asteroids in the next three years (IRTF & Gemini North)

Asteroid observations: Difficulties & Procedures

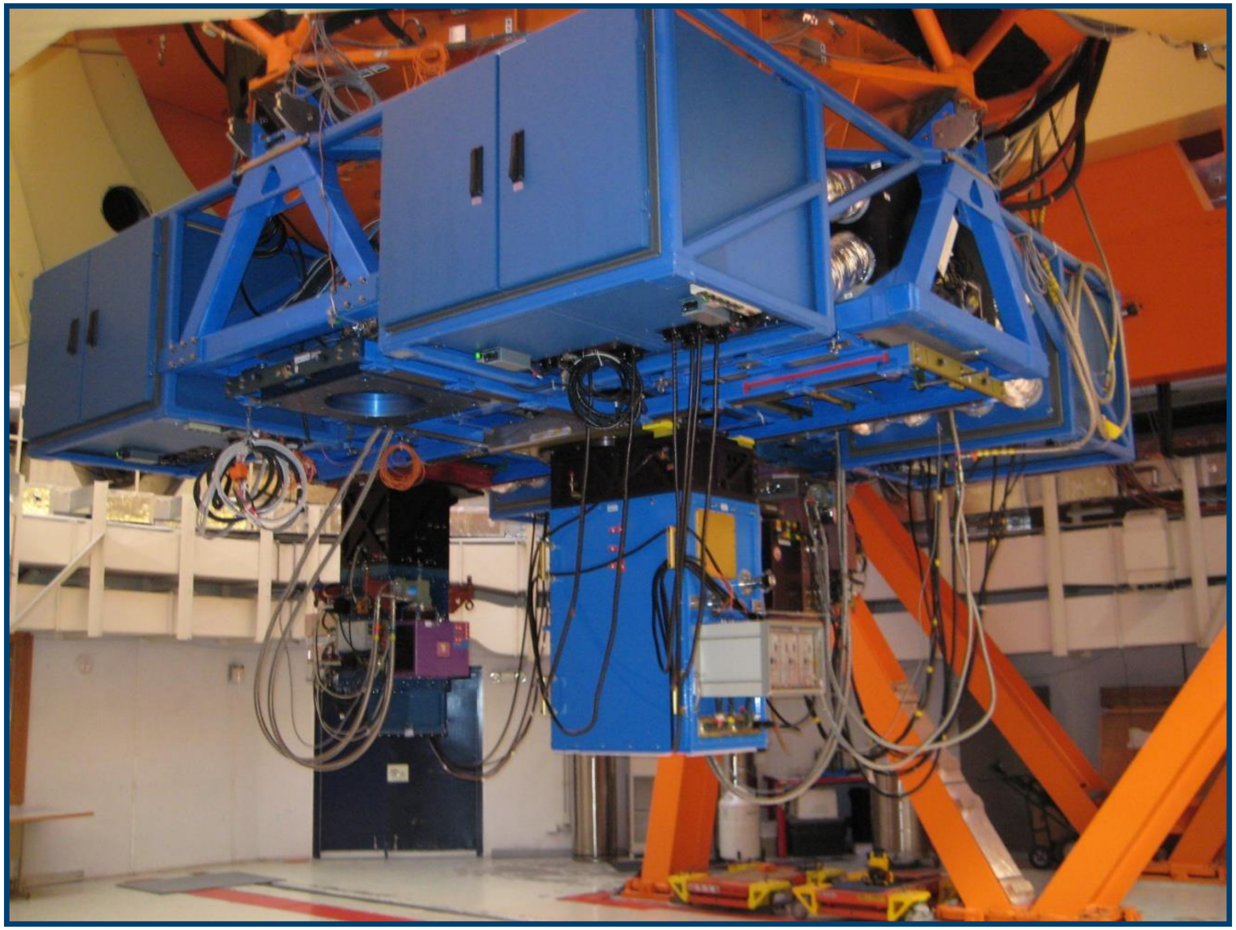


- Atmosphere not 100% transparent
  (the OH band at 2.7 μm is not observable from Earth)
- Thermal Excess(tail)

  (for most main-belt low-albedo asteroids the thermal contribution is 1–10% of the total flux at 3.1-3.5 μm)

- Observe object and nearby star (~few degrees)
- Subtract nearby (~10 arcsec) sky emission
- Divide object by star
  (remove transmission & solar spectral shape)
- Average all frames

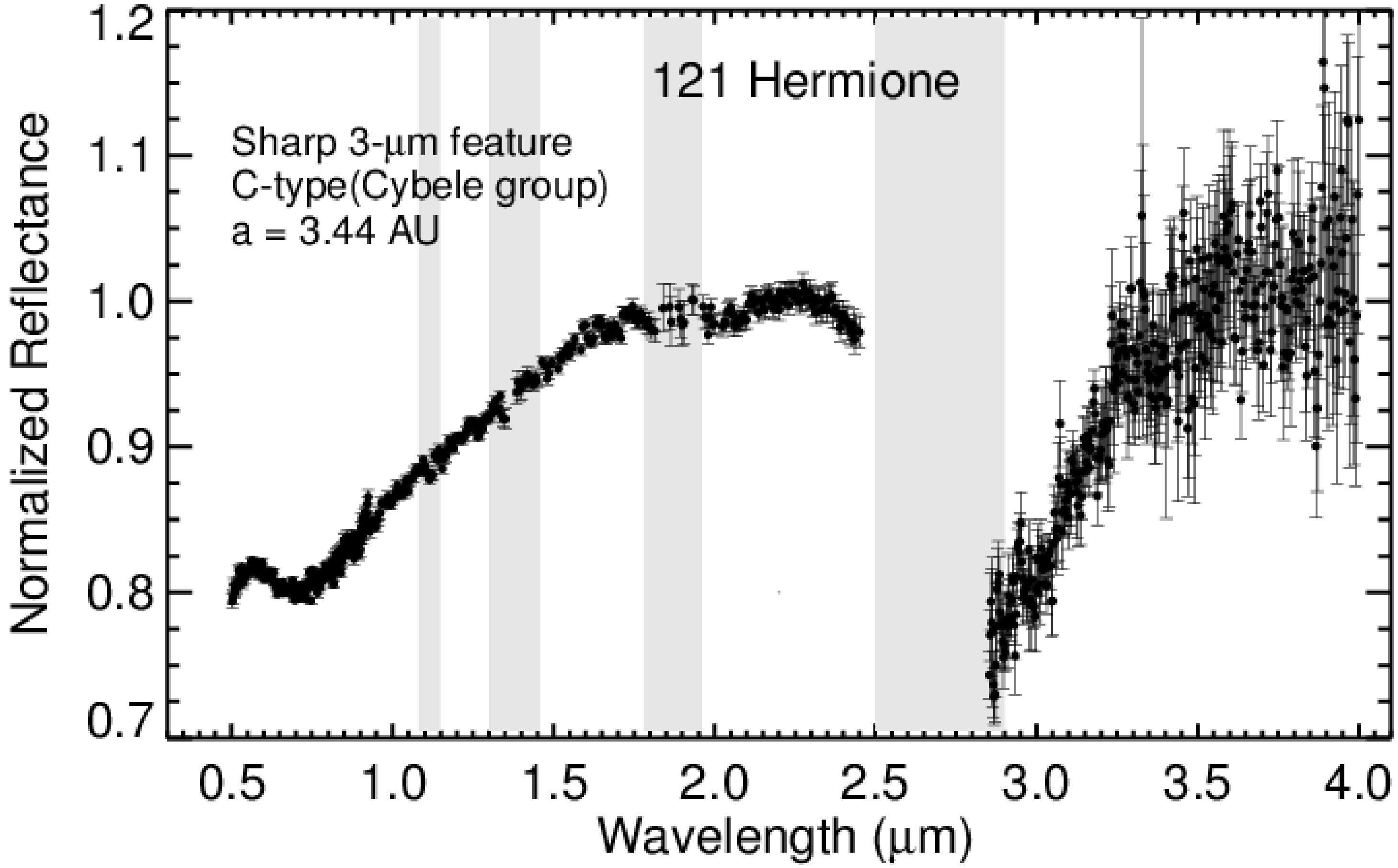
NASA IRTF Spectrometer



Asteroid observations: SpeX is used in the low-resolution mode (R~95) Prism (0.8-2.5-μm) and LXD (1.9-4.1-μm) mode

Four 3-μm spectral groups

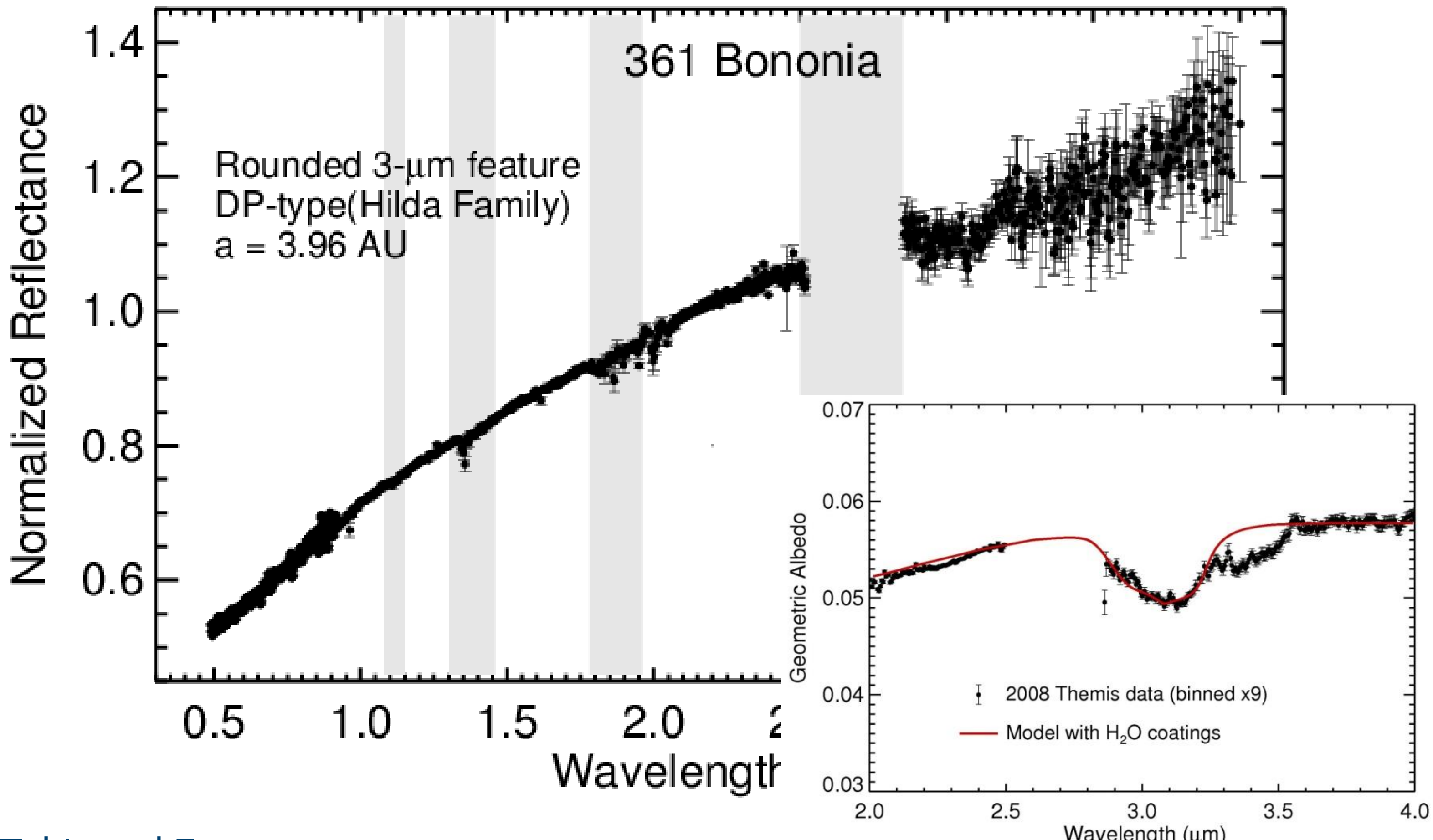
"Sharp" group: OH-stretching (phyllosilicates)



Takir & Emery(2012)

Four 3-μm spectral groups

"Rounded" group: H_2O ice

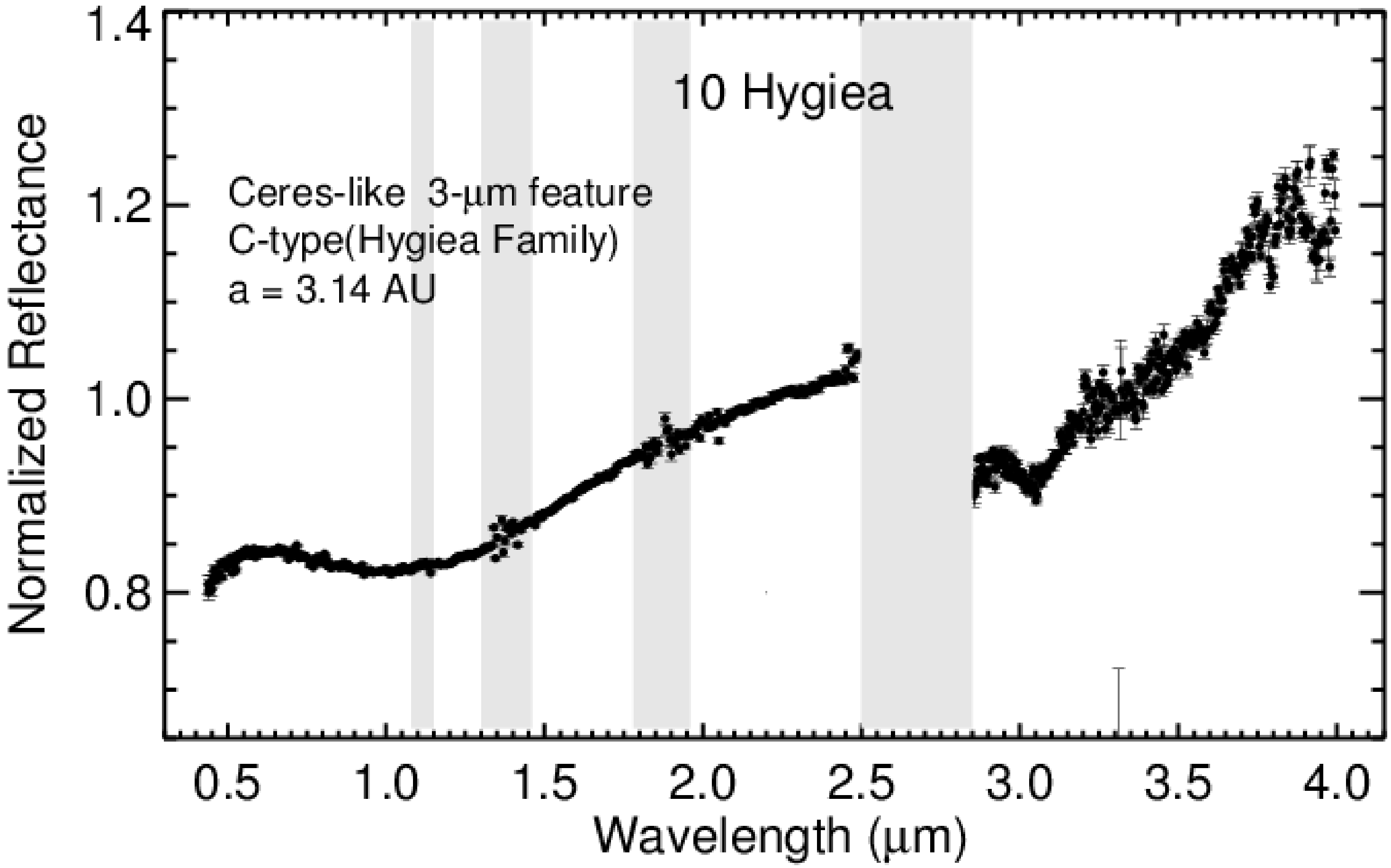


Takir and Emery 2012

Rivkin and Emery (2010)

Four 3-µm spectral groups

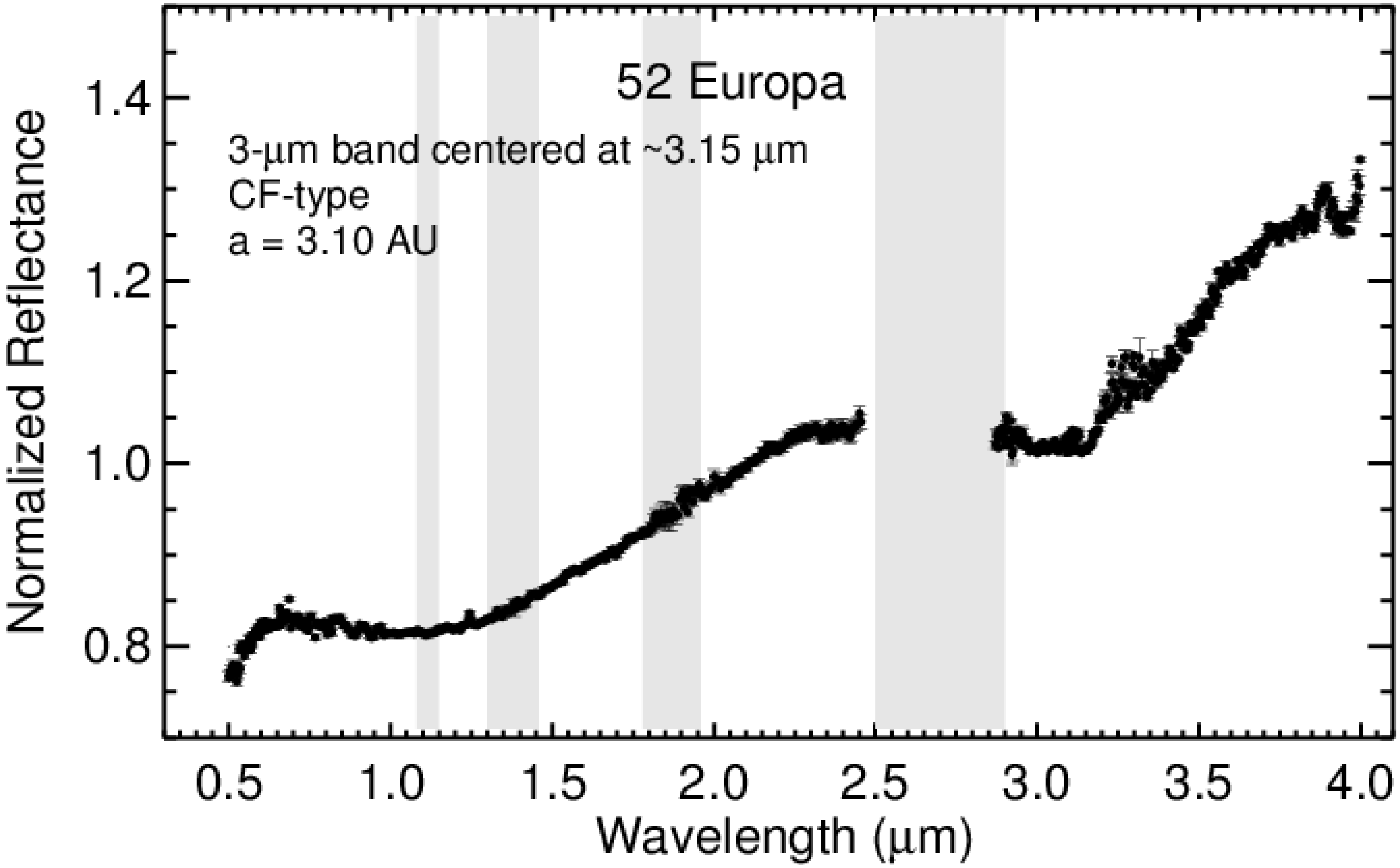
"Ceres-like" group: Ammoniated Phyllosilicates



Takir & Emery(2012)

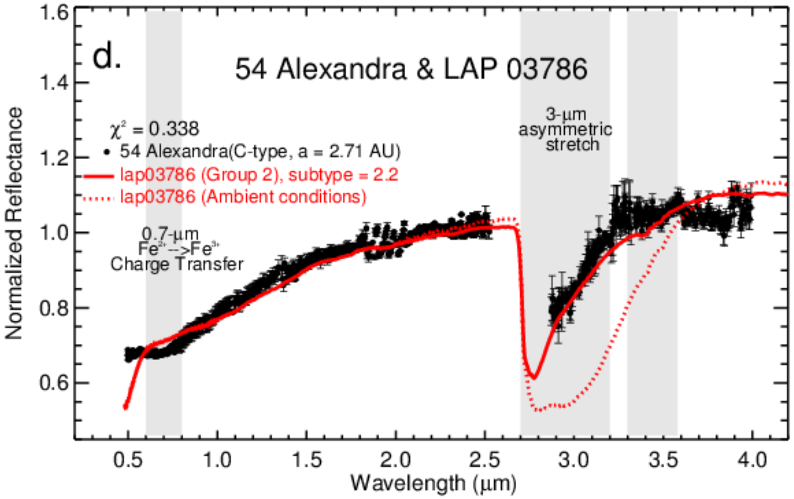
Four 3-μm spectral groups

"52 Europa-like" group: phyllosilicates (with interlayer H_2O)?

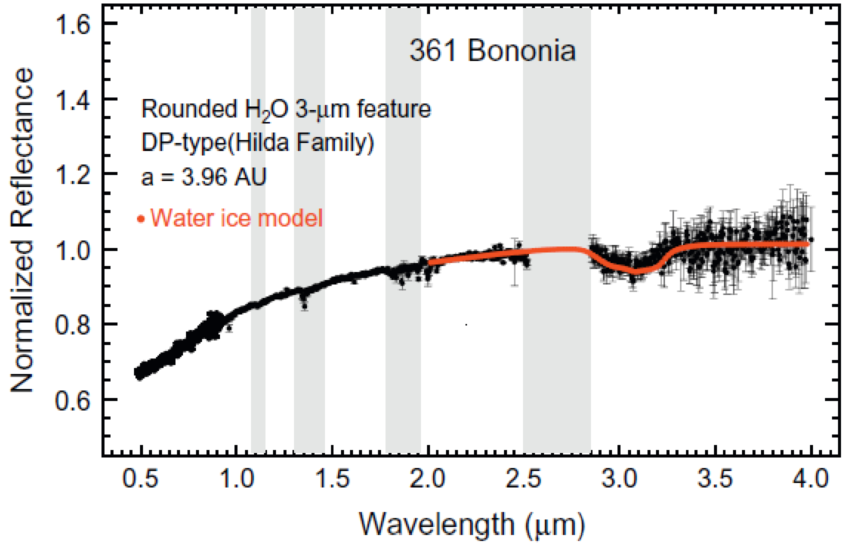


Takir & Emery(2012)

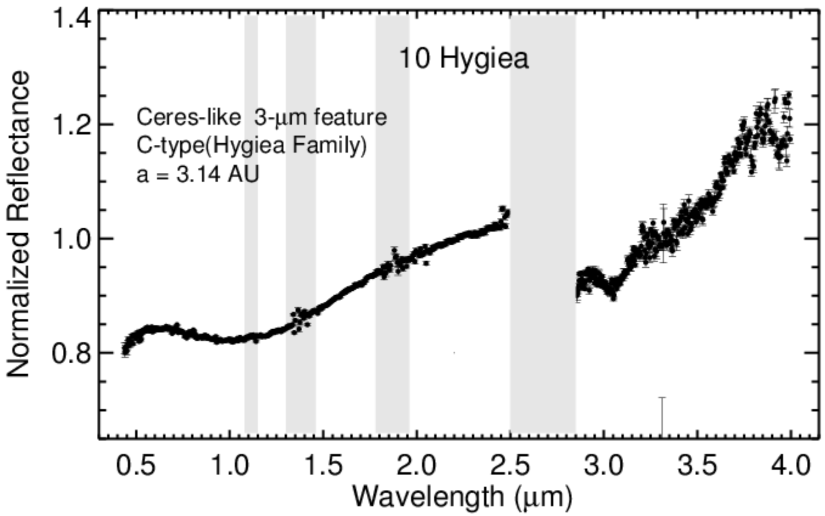
Diversity in the 3-µm band



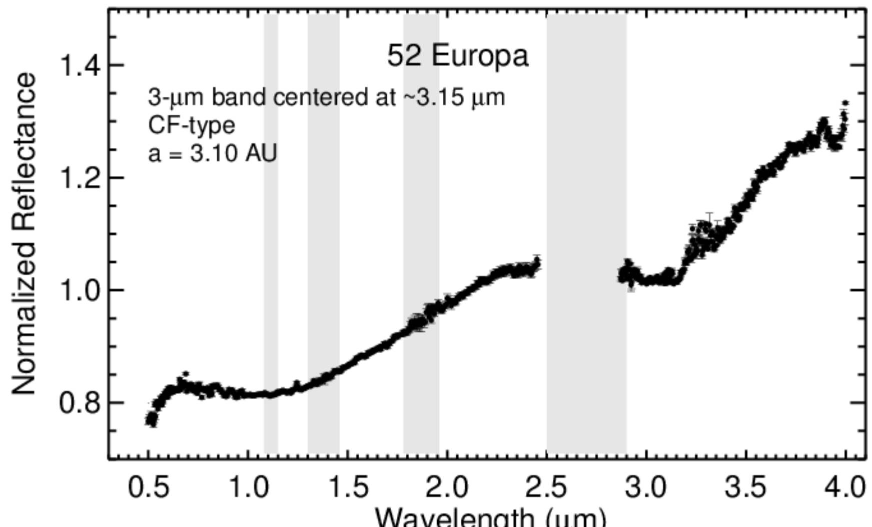
Sharp Group: OH-stretching (phyllosilicates)



Rounded Group: Possibly H_2O ice

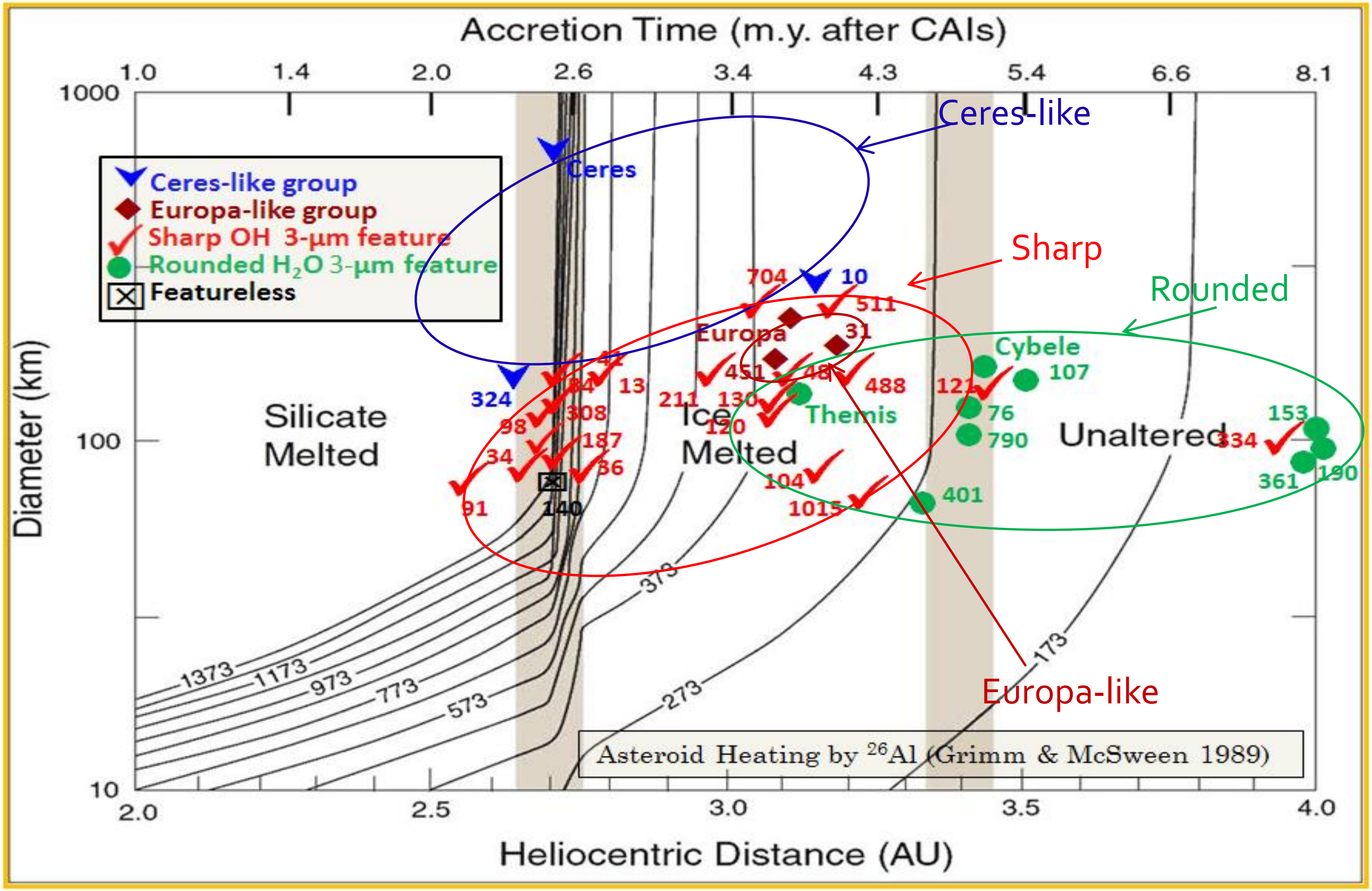


Ceres-like Group: Ammoniated phyllosilicates



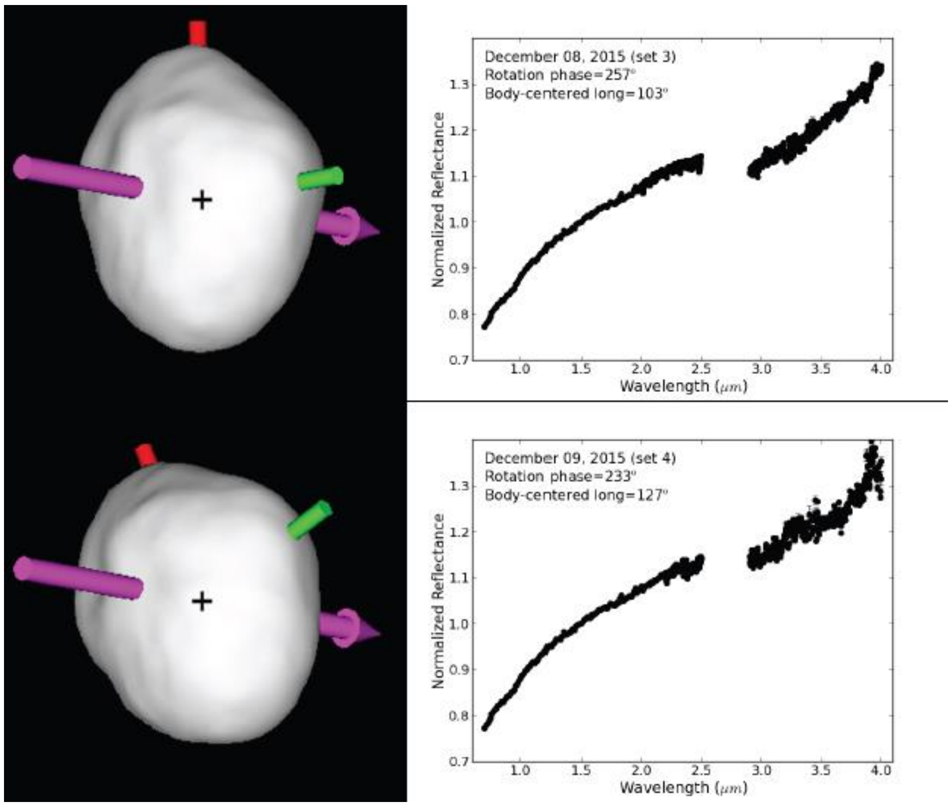
52 Europa-like Group: phyllosilicates (with interlayer H_2O)?

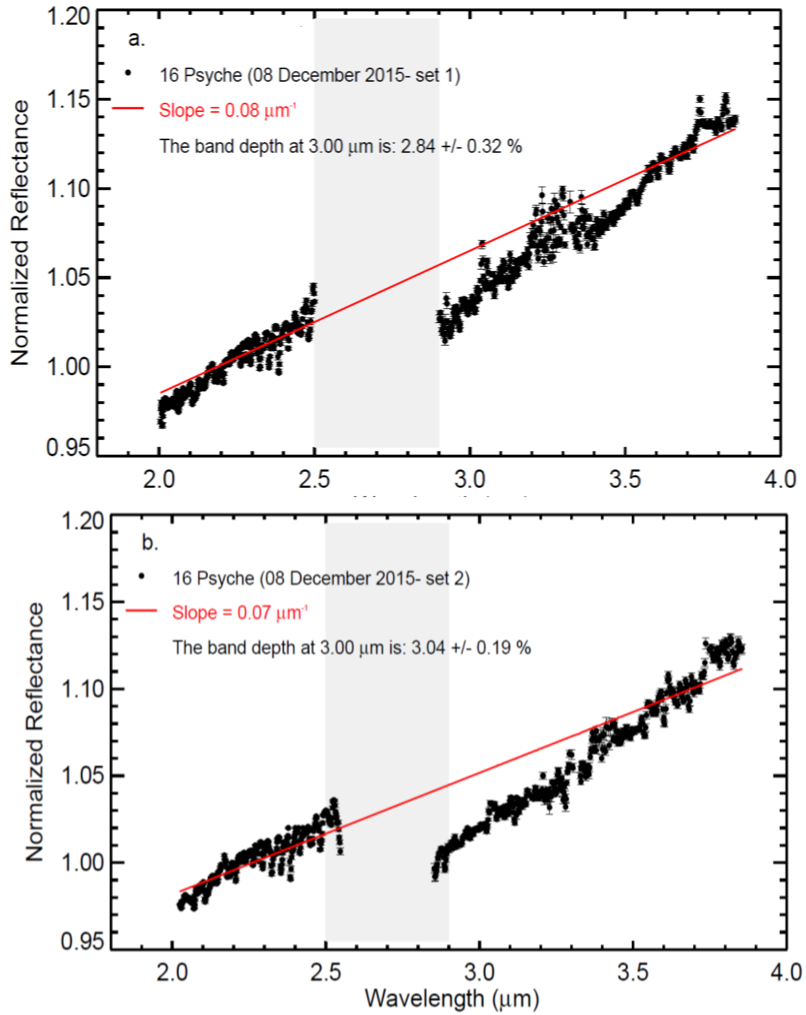
Intriguing Orbital Distribution



Takir & Emery(2012), Takir et al. (2015) + additional asteroids

Water Detected on largest Metallic Asteroid in Solar System: Psyche



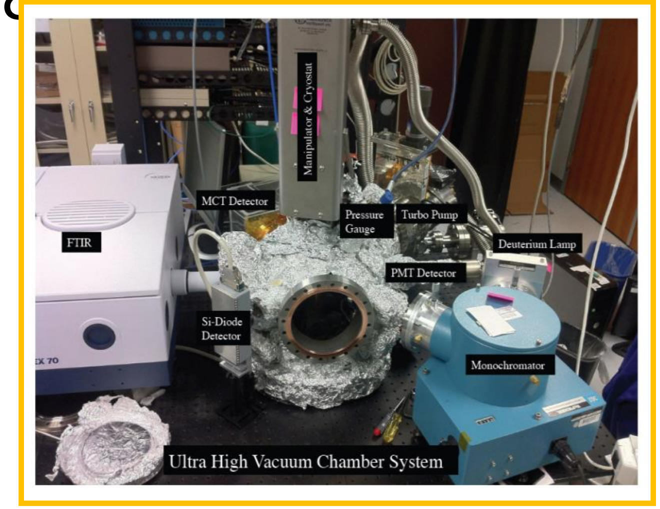


Takir et al. (2016)

Meteorite Petrology, Mineralogy, and Spectroscopy

Carbonaceous chondrites (powders & thin sections):

- Petrology & geochemistry (UTK)
- NIR reflectance spectroscopy (USGS & APL)
    - ✓ ASD spectrometer(0.35-2.5 µm)
    - ✓ Nicolet (FTIR: 1.3 to 15.5 µm)
    - ✓ Bruker Vertex-70 FTIR

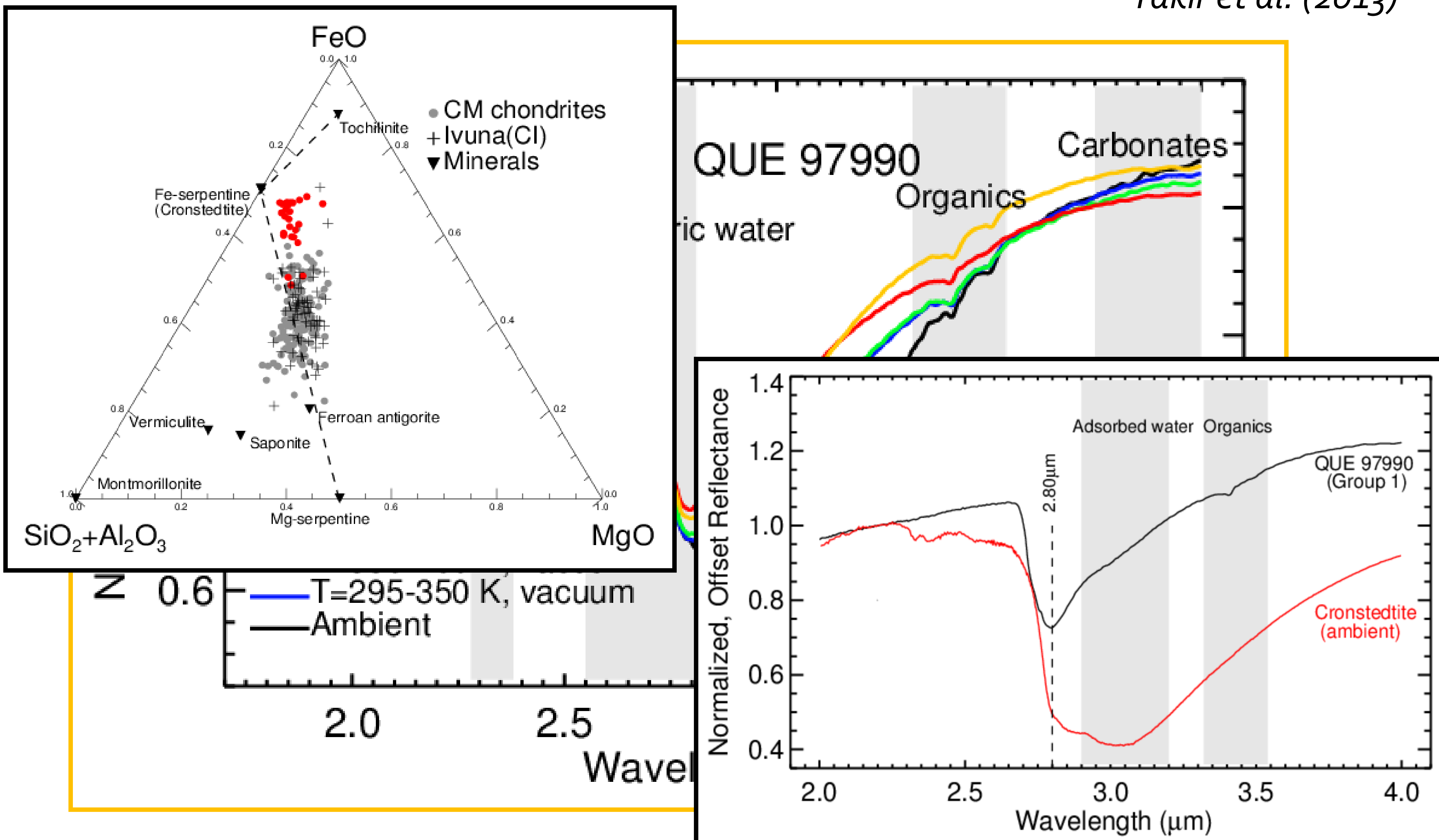


- Raman spectra (Wash U)
- High resolution SEM imaging (USGS)

Diversity in the 3-µm band

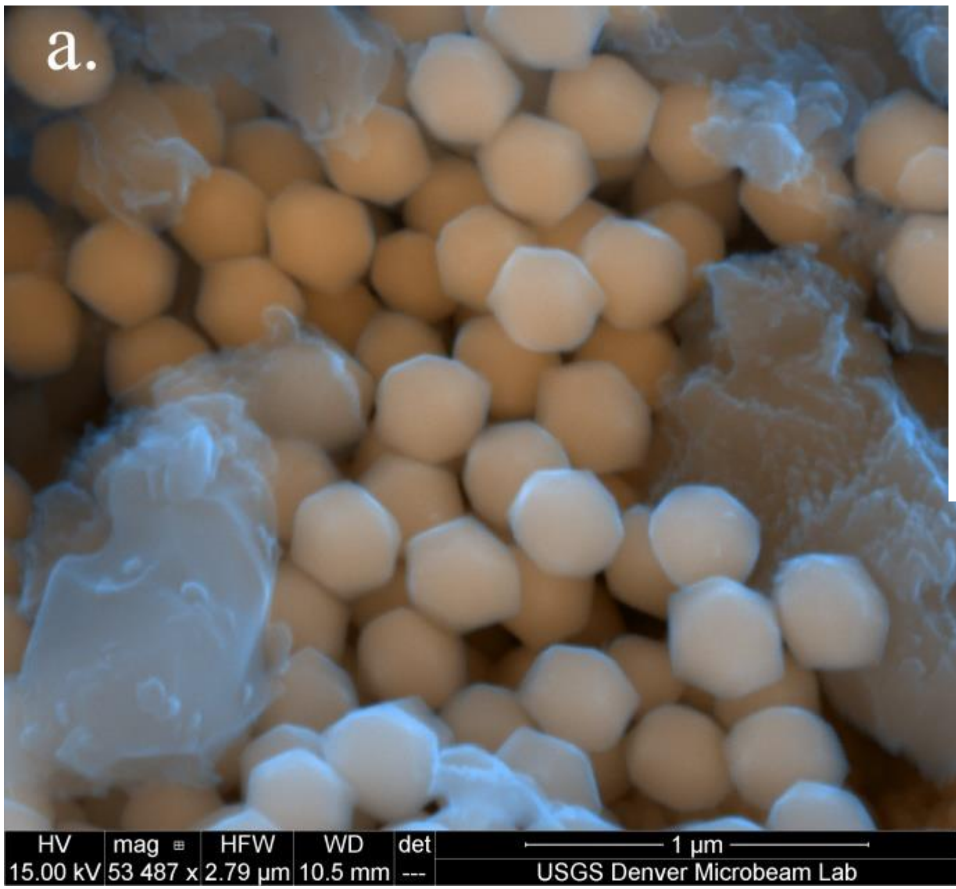
"CM Group 1": Fe-serpentine (cronstedtite) rich

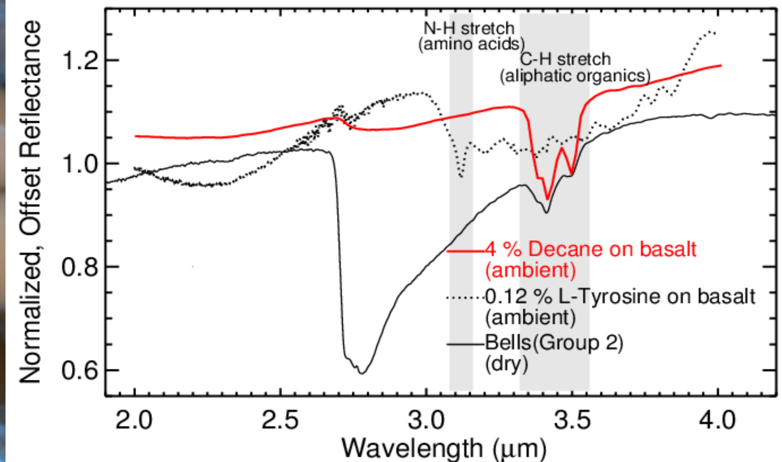
Takir et al. (2013)

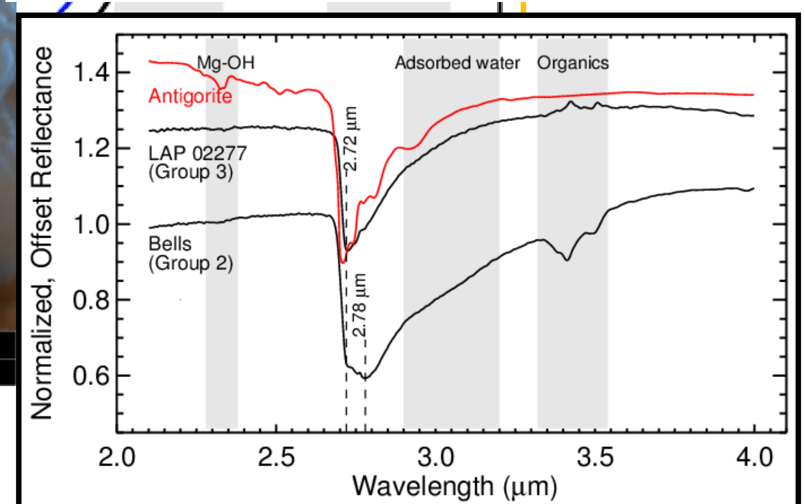


Diversity in the 3-μm band

"CM Group 2": Intermediate b/w Fe & Mg-serpentine *Takir et al. (2013)*



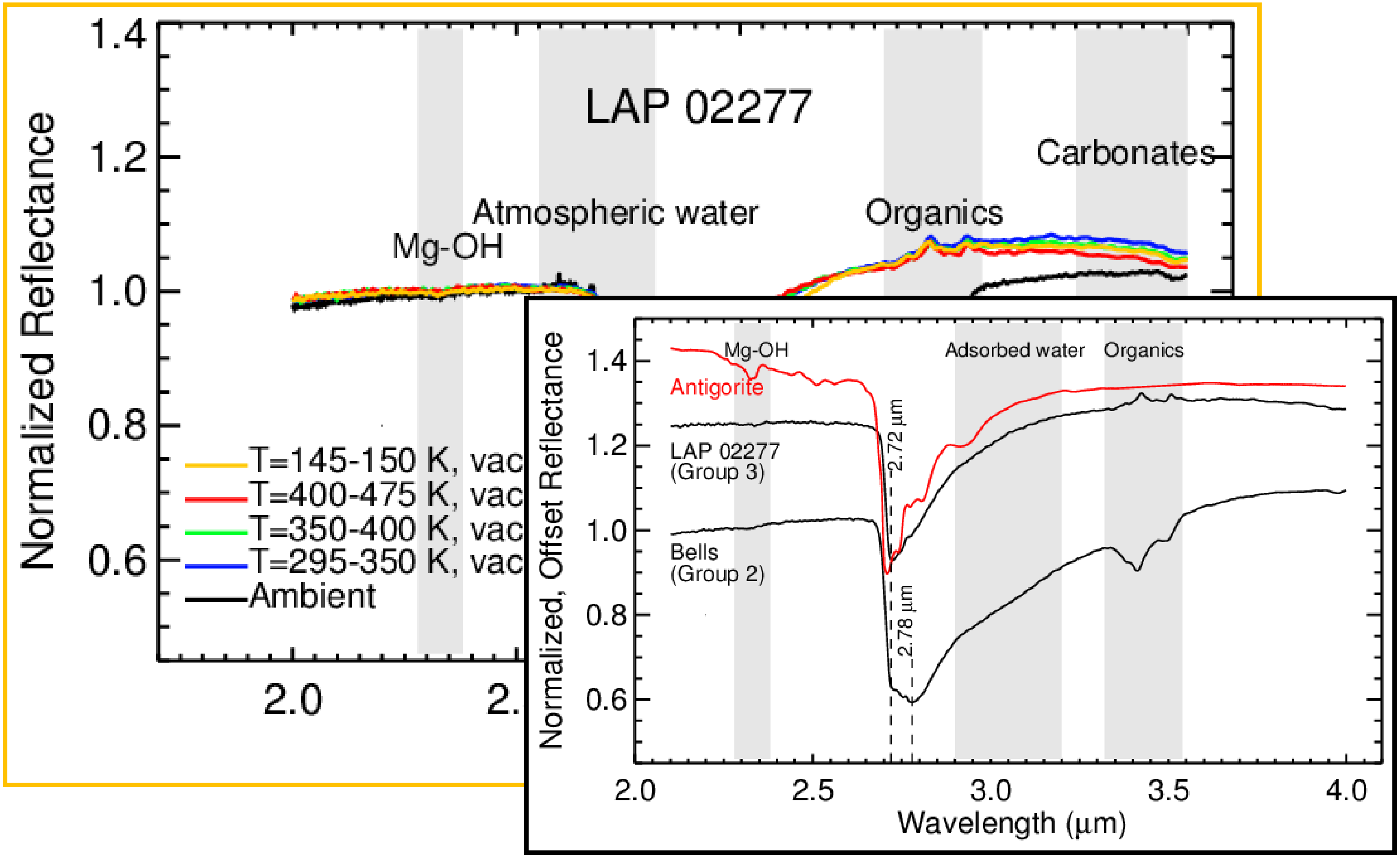




Diversity in the 3-µm band

"CM Group 3": Mg-serpentine-rich

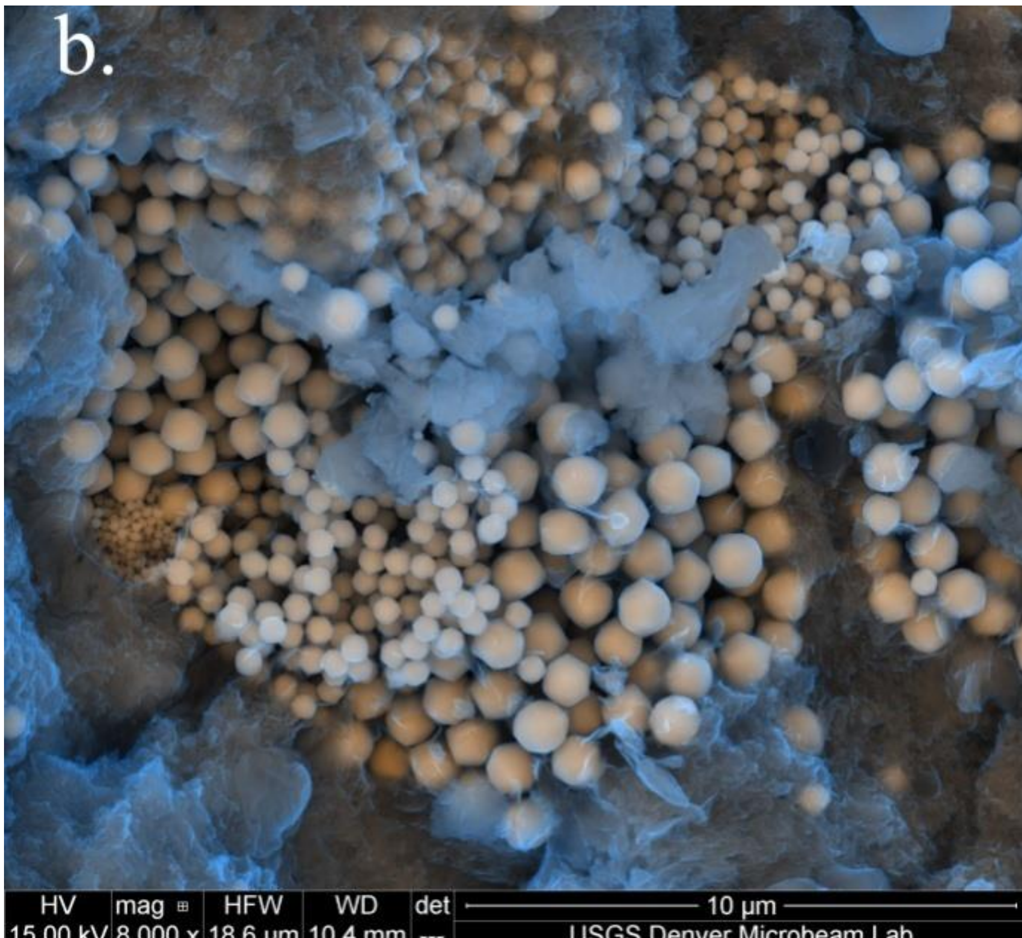
Takir et al. (2013)

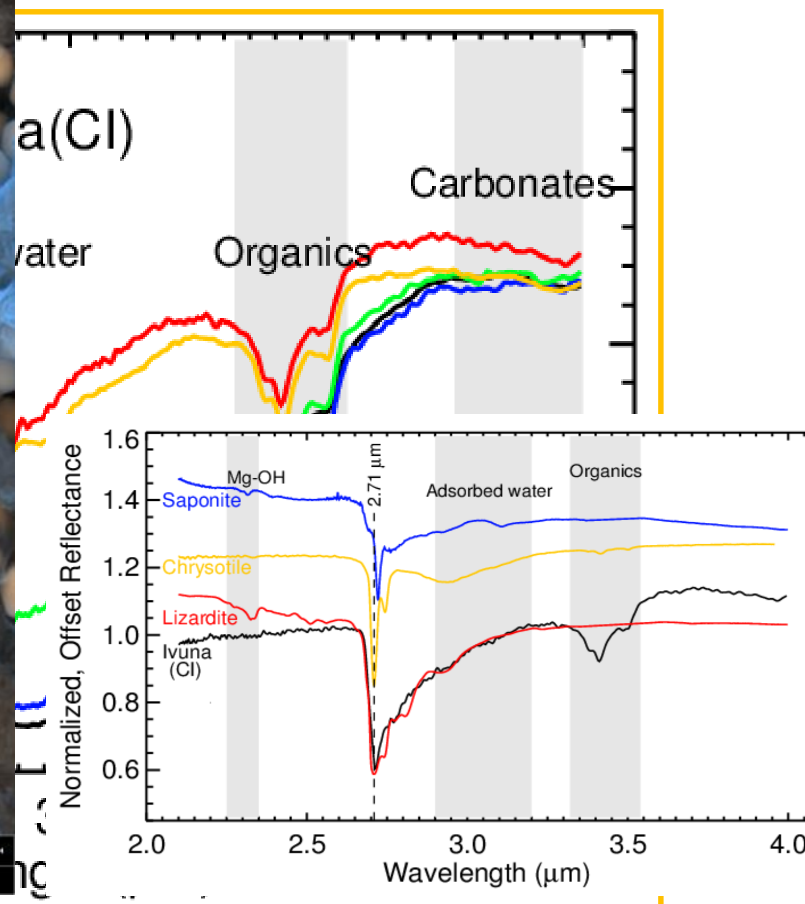


Diversity in the 3-µm band

"CI Ivuna": Mg-serpentine-rich

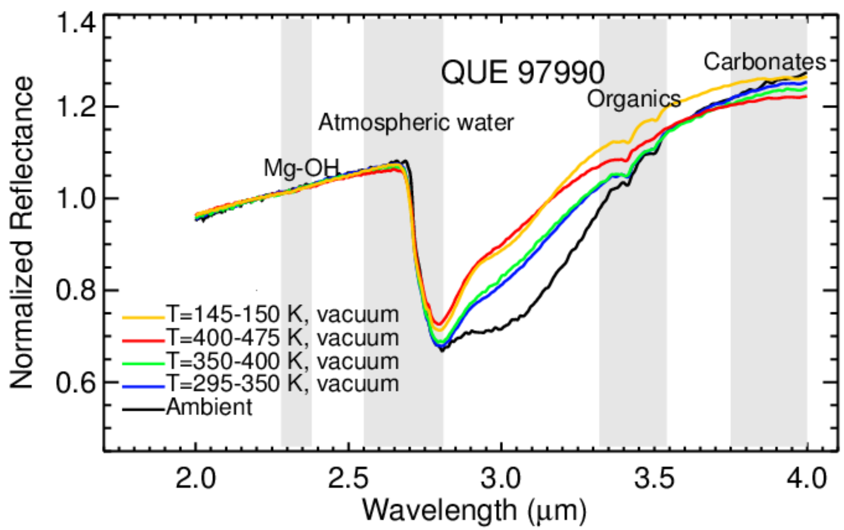
Takir et al. (2013)



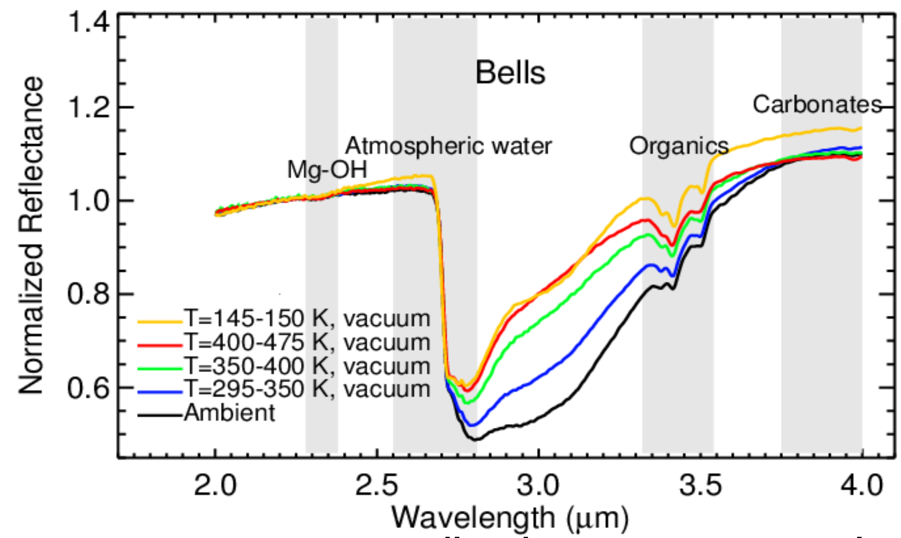


Diversity in the 3-µm band

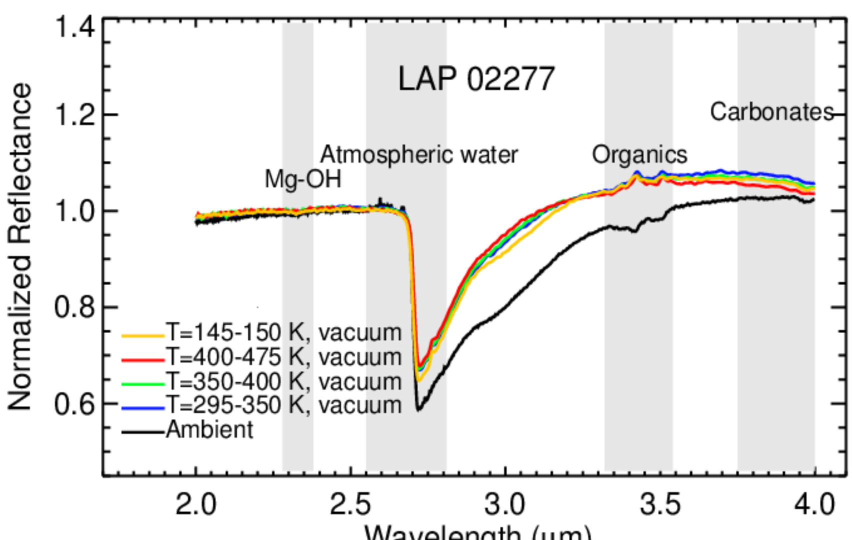
Takir et al. (2013)



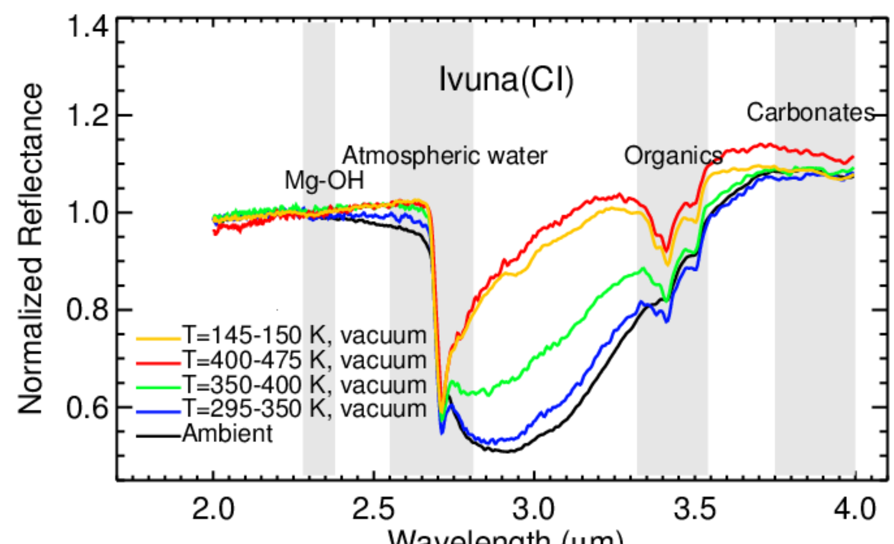
CM Group 1: Fe-serpentine (cronstedtite) rich



CM Group 2:Intermediate b/w Fe & Mg-serpentine



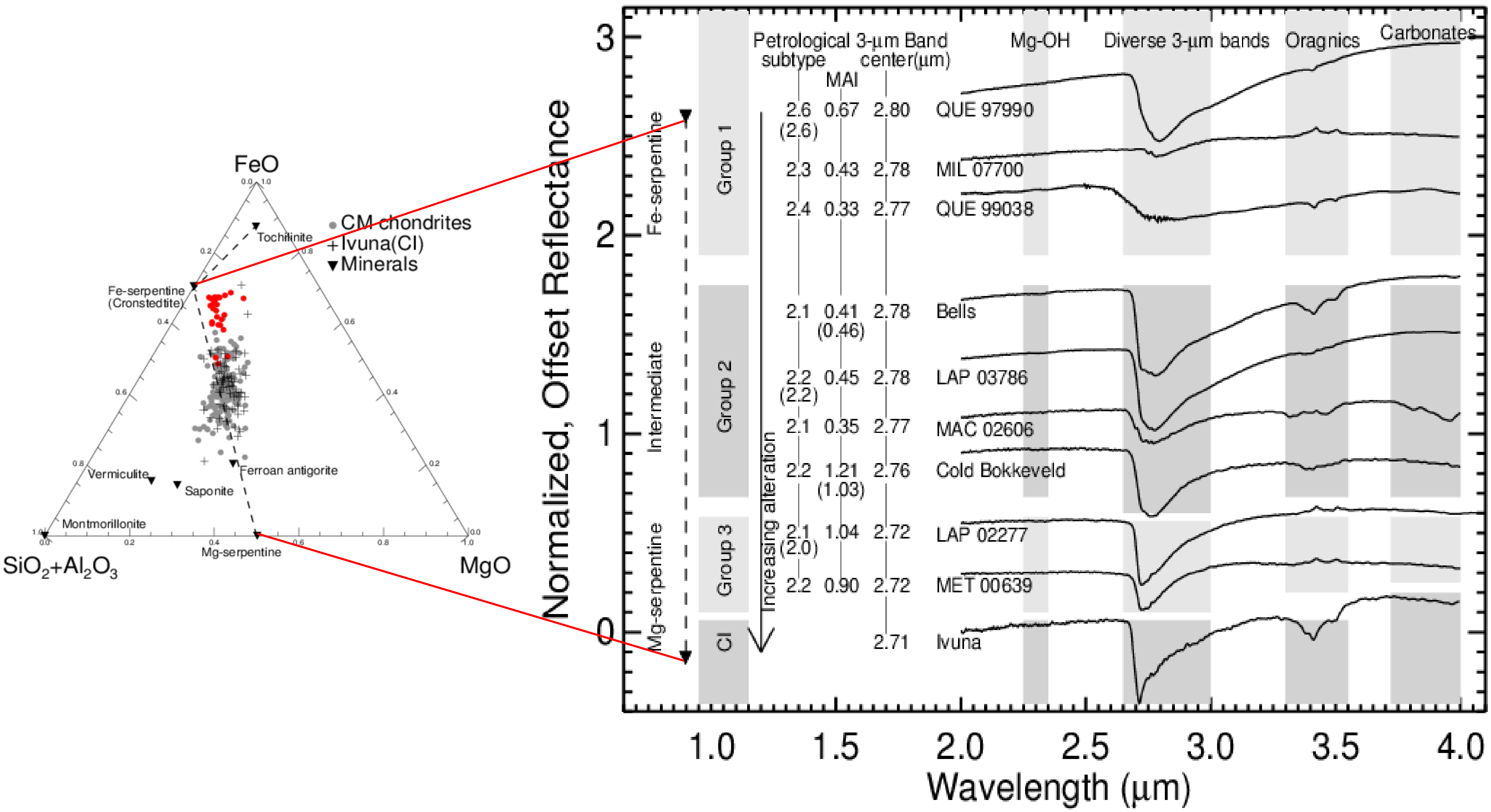
CM Group 3 : Mg-serpentine-rich



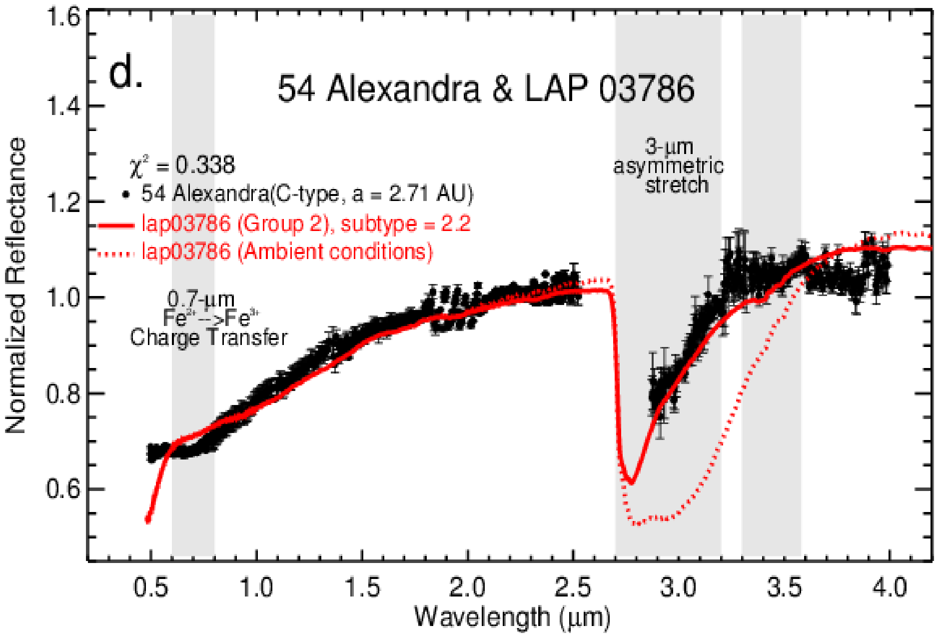
CI Ivuna: Mg-serpentine-rich

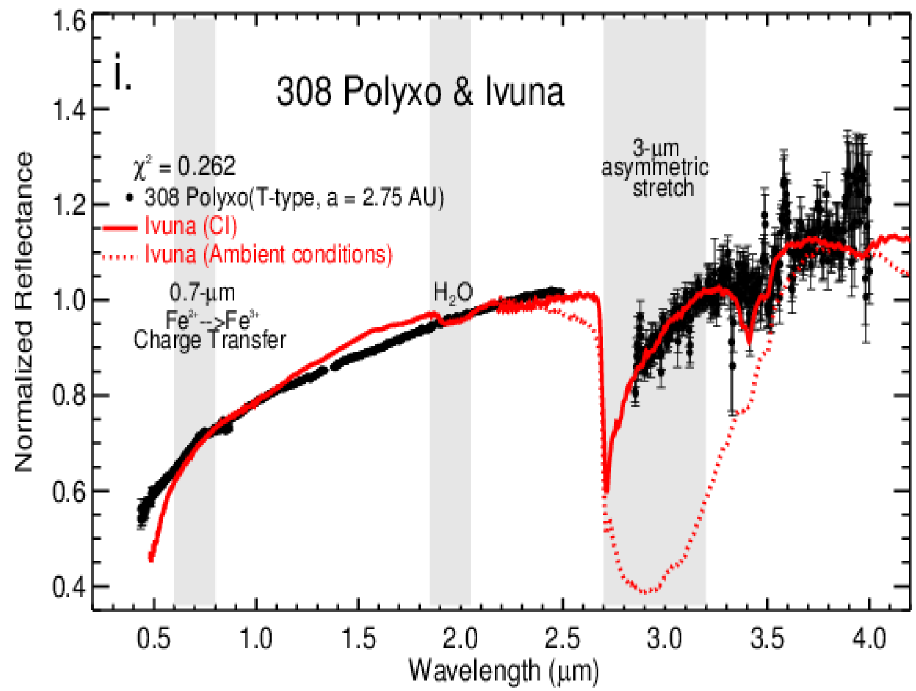
Degree of Aqueous Alteration & the 3-µm band

Takir et al. (2013)



Asteroid & Meteorite matches



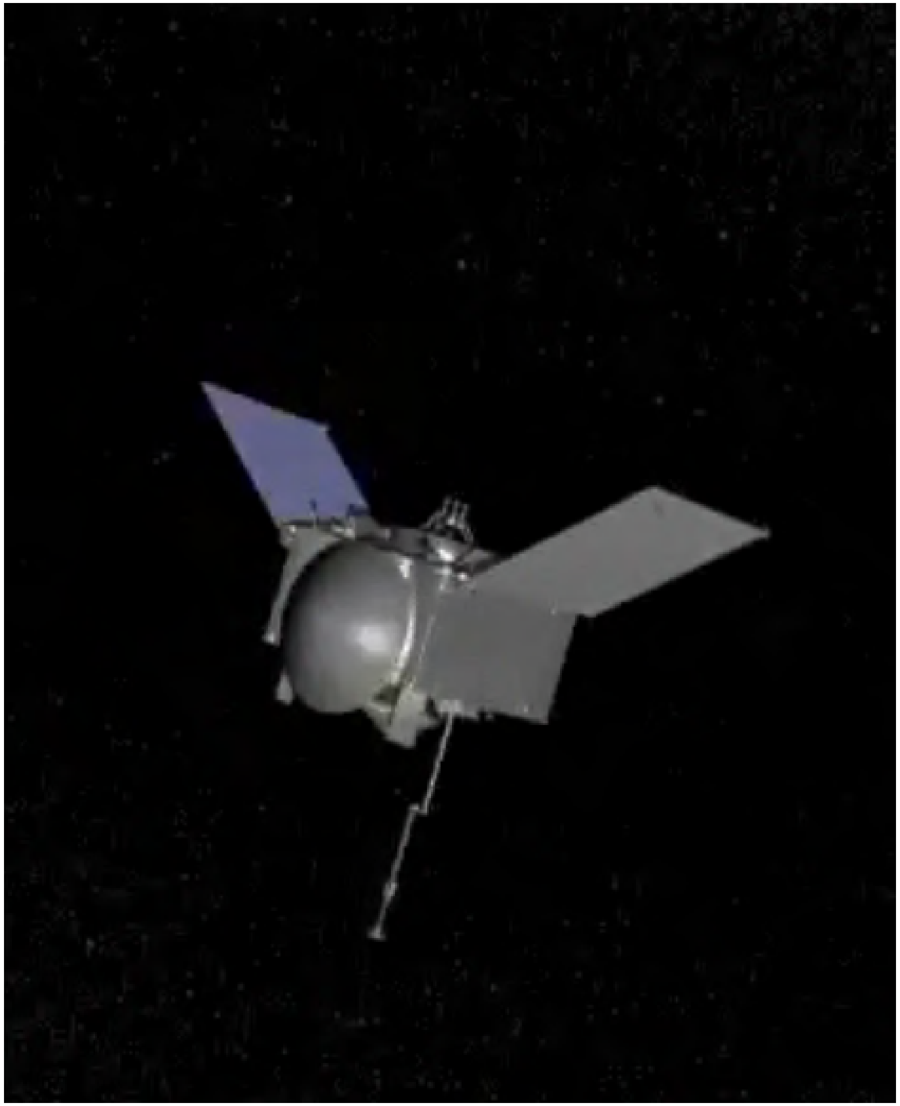


Takir et al. (2015)

NASA's OSIRIS-REx Mission to a Primitive Asteroid

Credit: http://www.lpi.usra.edu/sbag/meetings/

OSIRIS-REx Defined



- **O**rigins
  - Return and analyze a sample of pristine carbonaceous asteroid regolith
- **S**pectral **I**nterpretation
  - Provide ground truth for telescopic data of the entire asteroid population
- **R**esource **I**dentification
  - Map the chemistry and mineralogy of a primitive carbonaceous asteroid
- **S**ecurity
  - Measure the Yarkovsky effect on a potentially hazardous asteroid
- **R**egolith **Ex**plorer
  - Document the regolith at the sampling site at scales down to the sub-cm

Credit: http://www.lpi.usra.edu/sbag/meetings/

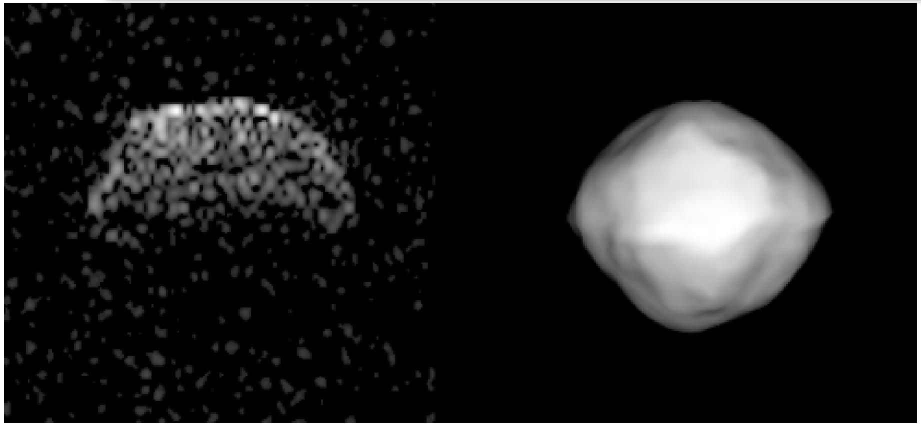
Asteroid (101955) Bennu

- Formally named 1999 RQ36
- Bennu is an Egyptian mythological bird that was born from the heart of Osiris
- It is associated with the Sun, creation, and renewal
- The name was selected in an international contest run by the Planetary Society

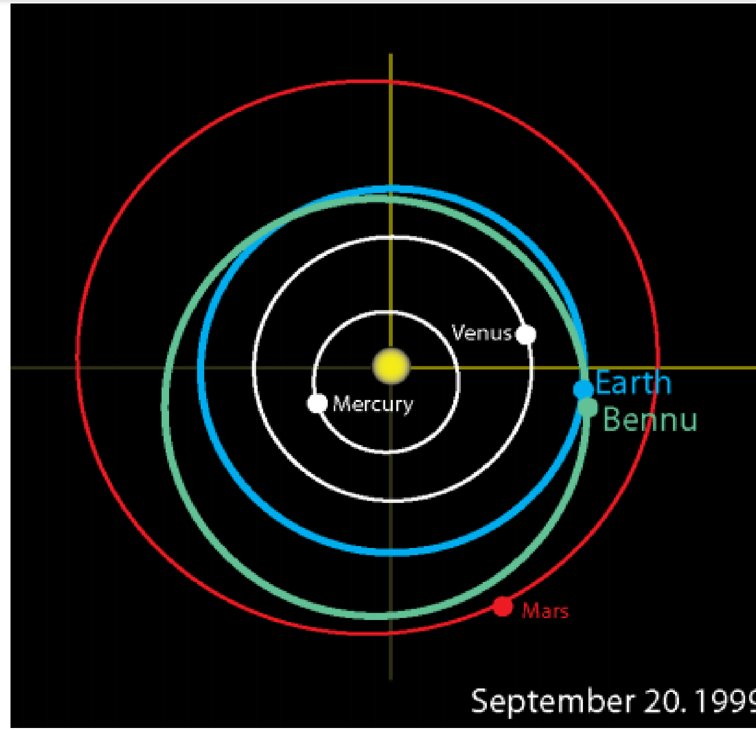
Image credit: http://www.touregypt.net

Credit: http://www.lpi.usra.edu/sbag/meetings/

Asteroid Bennu is well-characterized



- Images used to construct a geologically detailed three-dimensional model and define the rotation state
  - **Size =** 492-m (±20 m, mean diameter)
  - **Shape =** spheroidal “spinning top”
  - **Rotation state =** 4.3 hr period, 180° obliquity
- Radar also probed the near-surface bulk density and structure



Credit: http://www.lpi.usra.edu/sbag/meetings/

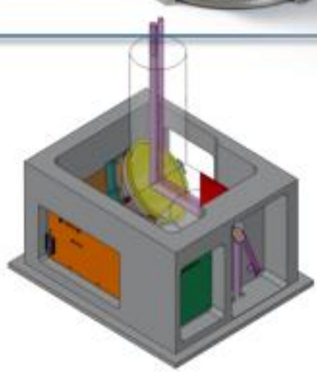
OSIRIS-REx Instruments

OCAMS (UA)

SamCam images the sample site, documents sample acquisition, and images TAGSAM to evaluate sampling success

MapCam provides landmark-tracking OpNav, performs filter photometry, maps the surface, and images the sample site

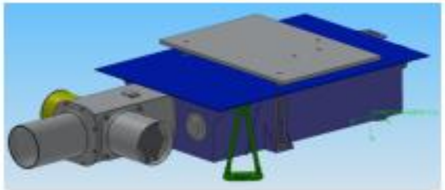
PolyCam acquires Bennu from >500K-km range, performs star-field OpNav, and performs high-resolution imaging of the surface



OLA (CSA) provides ranging data out to 7 km and maps the asteroid shape and surface topography

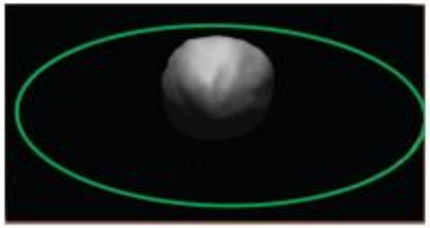
Credit: http://www.lpi.usra.edu/sbag/meetings/

OSIRIS-REx Instruments



OVIRS (GSFC) maps the reflectance albedo and spectral properties from 0.4 – 4.3 µm

OTES (ASU) maps the thermal flux and spectral properties from 4 – 50 µm

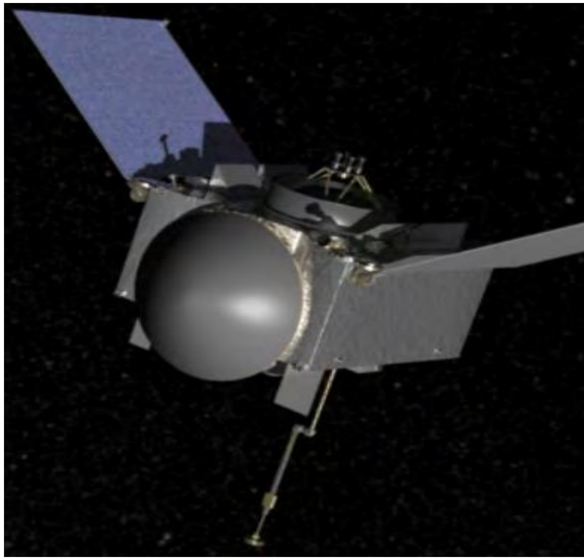


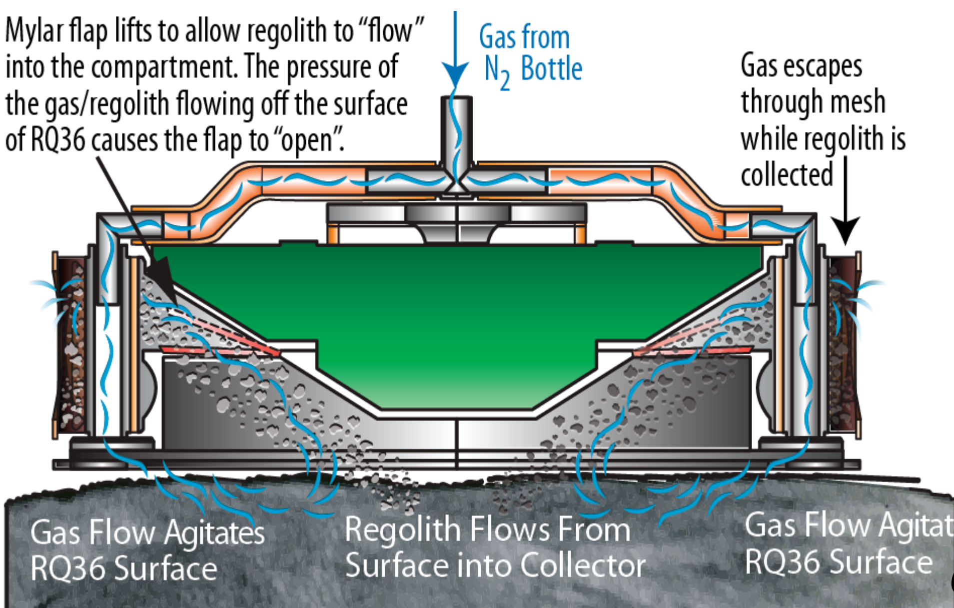
Radio Science (CU) reveals the mass, gravity field, internal structure, and surface acceleration distribution

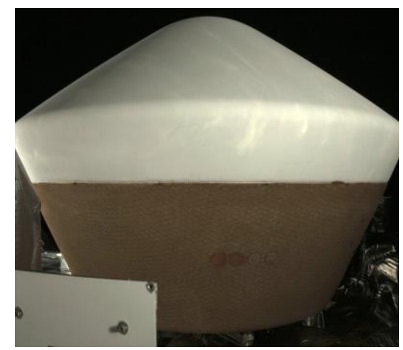
REXIS (MIT) is a Student Collaboration Experiment that trains the next generation of scientists and engineers and maps the elemental abundances of the asteroid surface

Credit: http://www.lpi.usra.edu/sbag/meetings/

Sample Collection System: TAGSAM







Sample Return Capsule

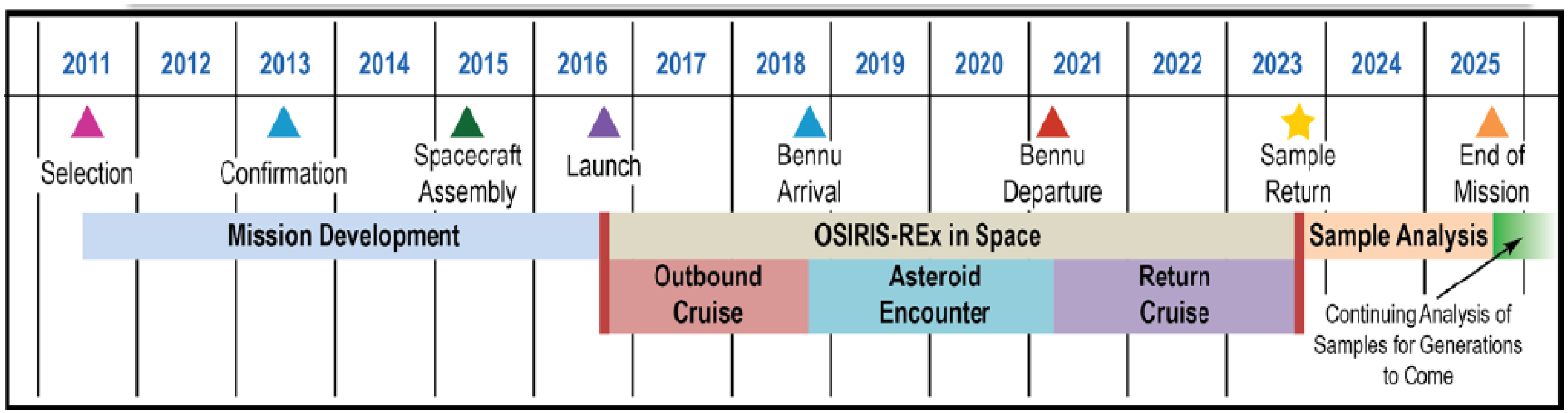
Credit: http://www.lpi.usra.edu/sbag/meetings/

Successful Launch of OSIRIS-REx a Few Weeks Ago

Credit: NASA & OSIRIS-REx

Cape Canaveral, FL
ULA's Atlas V rocket
September 8, 2016 ~7:05 pm EDT

OSIRIS-REx Timeline



- Selection: May 25, 2011
- Confirmation: April, 2013
- Spacecraft Assembly: February, 2015
- Launch: September, 2016
- Bennu Arrival: August, 2018
- Bennu Departure: March, 2021
- Sample Return: September, 2023
- End of Mission: September, 2025

Credit: http://www.lpi.usra.edu/sbag/meetings/

JAXA's Hayabusa2 Mission to a Primitive Asteroid

Credit: http://www.lpi.usra.edu/sbag/meetings/

Highlights of Hayabusa2 Mission

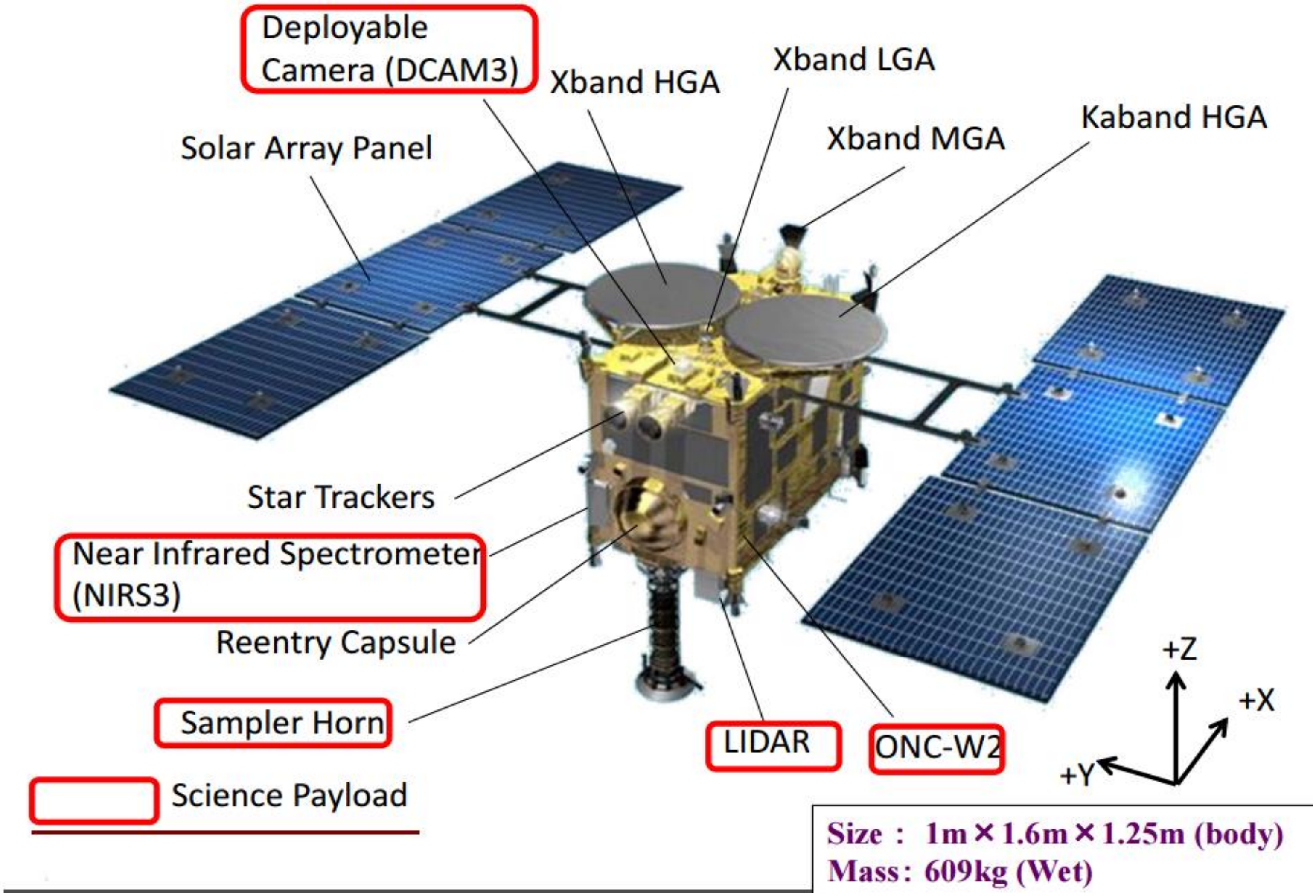
Hayabusa2 is the 2nd Japanese sample return mission to small body.

JAXA launched Hayabusa2 in 2014, which will explore the C-type asteroid *Ryugu (1999JU3)*, and will return back to the Earth in 2020.

- Round-trip mission
  - High specific impulse ion engine for continuous-thrust trajectory control.
- In-situ science at "Ryugu"
  - 1.5year proximity operation at "Ryugu"
  - Four landers, four remote science instruments.
- Touch down & sample collection
  - Two normal touch down, one pin-point touch down (to the artificial crater) are planned.
- Artificial crater generation
  - Kinetic impact on the asteroid surface to create a 2m-class crater.
  - Sub-surface structure of the asteroid can be acquired.

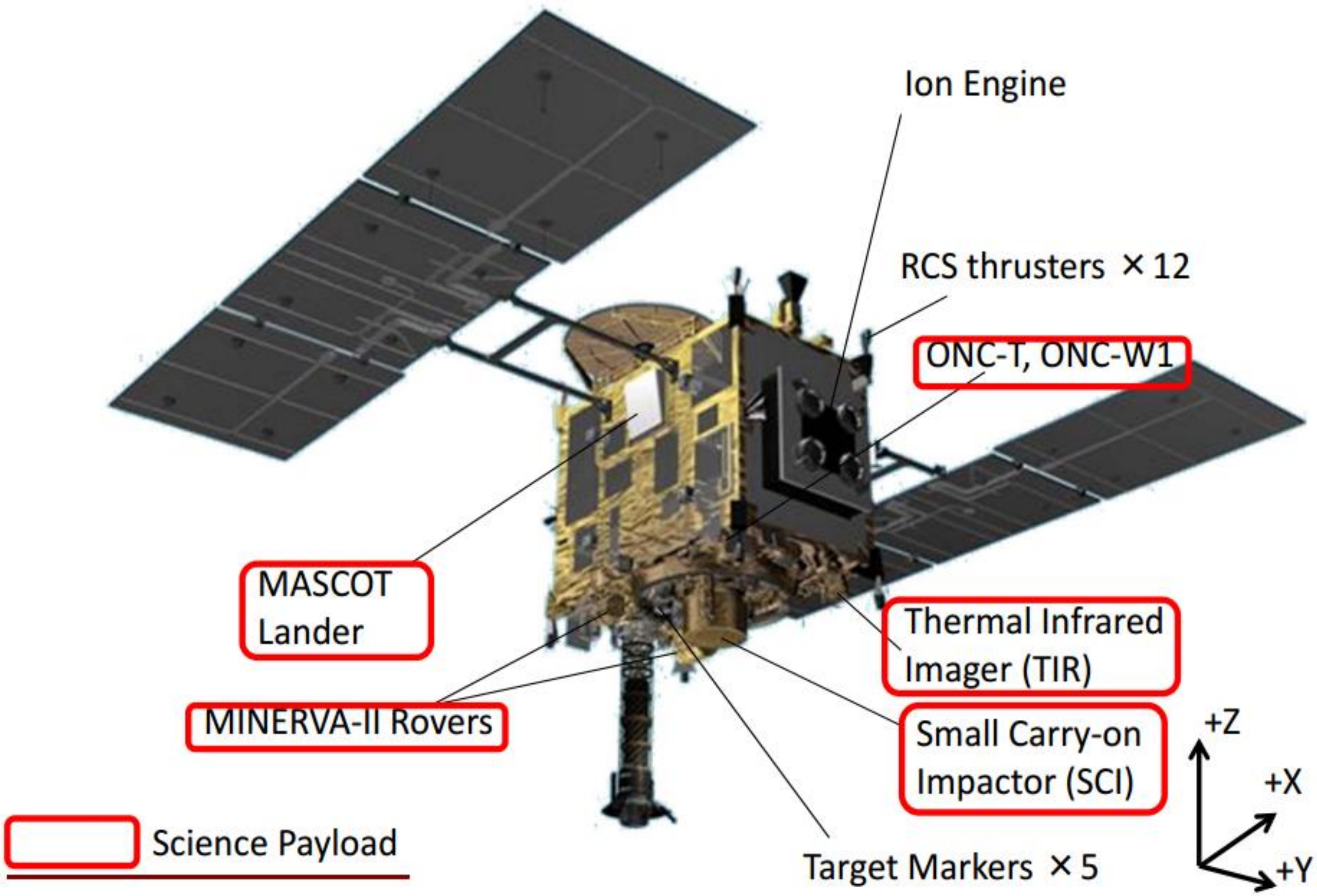
Credit: http://www.lpi.usra.edu/sbag/meetings/

Hayabusa2 Spacecraft (1/2)



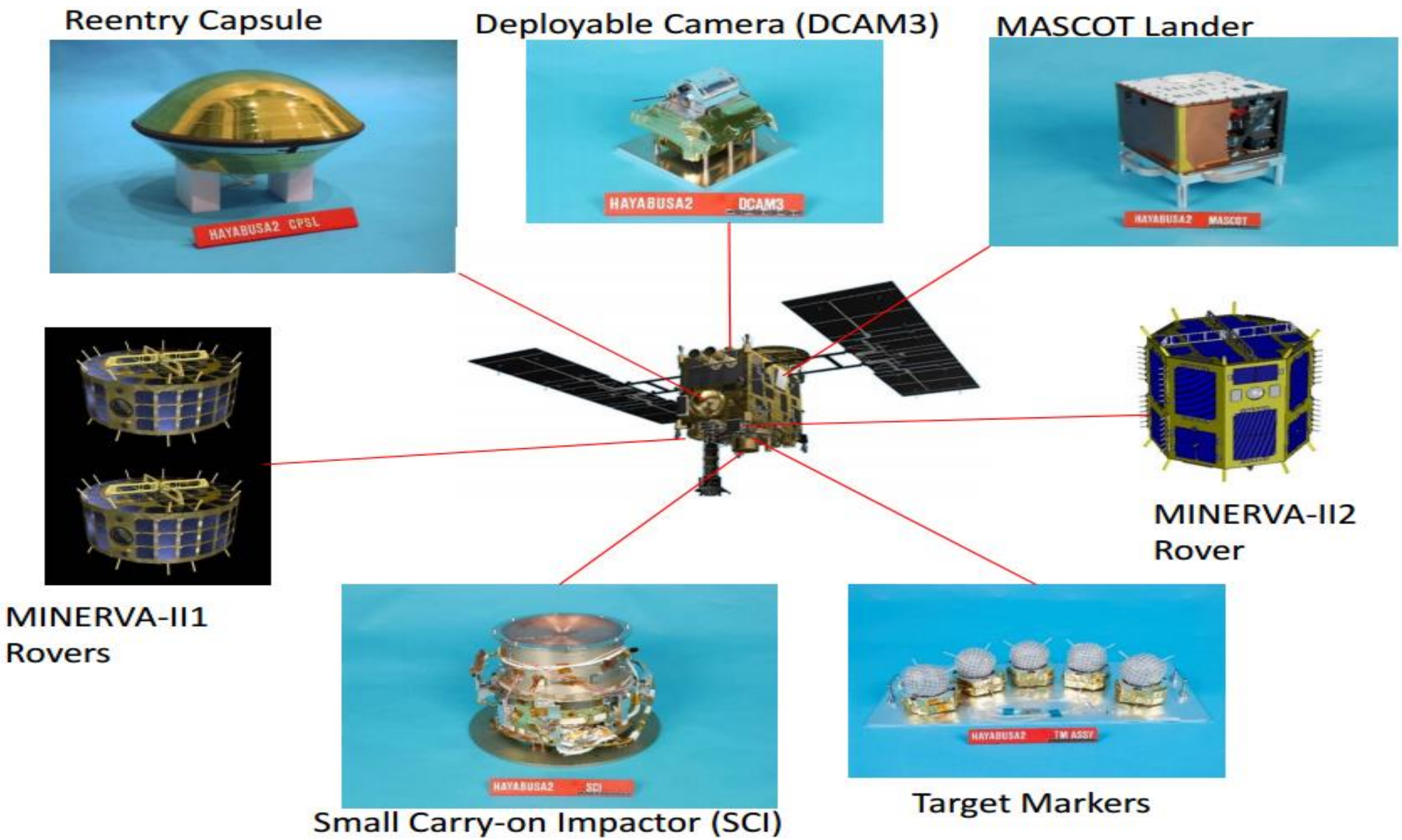
Credit: http://www.lpi.usra.edu/sbag/meetings/

Hayabusa2 Spacecraft (2/2)



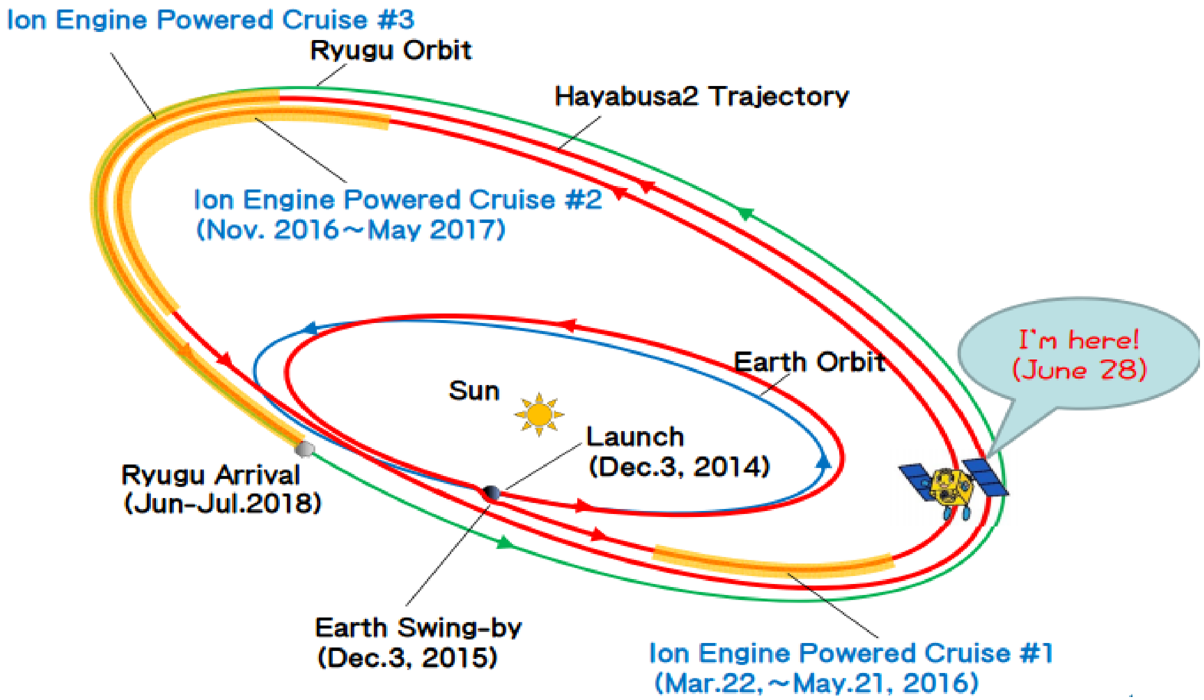
Credit: http://www.lpi.usra.edu/sbag/meetings/

Robotic Exploration with 12 Deployable "Robots"



Credit: http://www.lpi.usra.edu/sbag/meetings/

Hayabusa2 Timeline



Credit: http://www.lpi.usra.edu/sbag/meetings/

Solar Nebula

An artist's conception of the solar nebula, surrounding the violent young sun
Credit: Dr. William K. Hartmann, Planetary Science Institute, Tucson, AZ