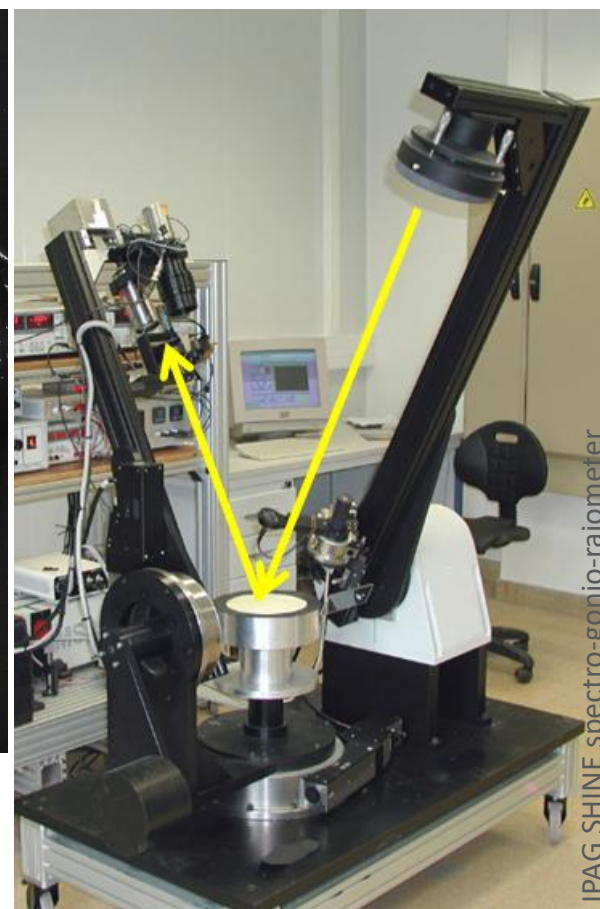


Laboratory experiments to understand the composition of small bodies

Olivier Poch

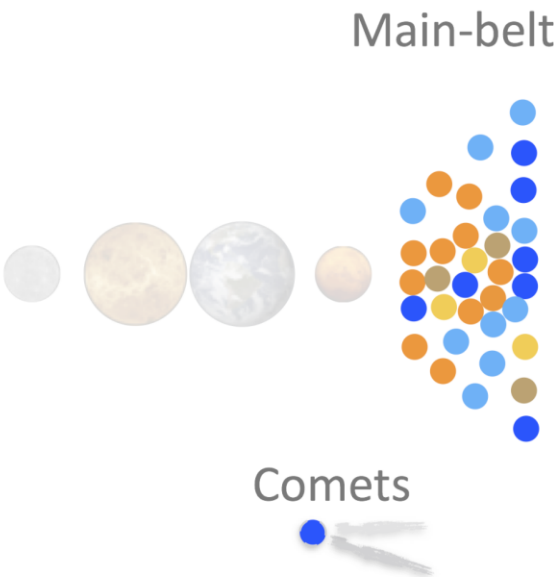
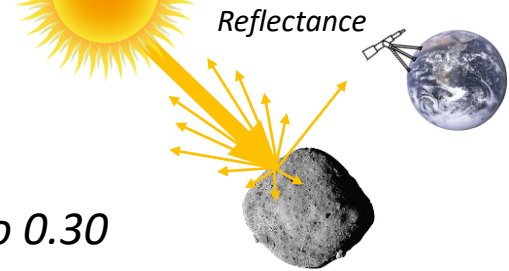
P. Beck, L. Bonal, J. Milli, E. Quirico, B. Schmitt, M. Bonduelle, E. Hénault, R. Sultana, L. Laize-Générat, J. Depoortere

Institut de Planétologie et d'Astrophysique de Grenoble (IPAG), CNRS, Univ. Grenoble Alpes



Solar System small bodies

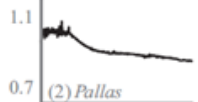
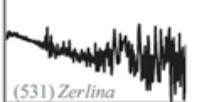
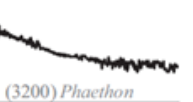
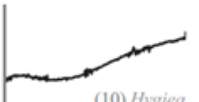
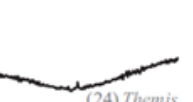
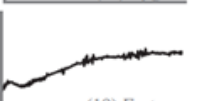
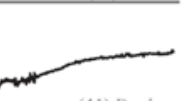
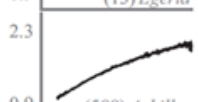
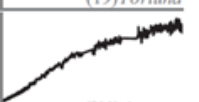
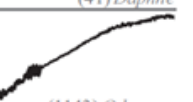
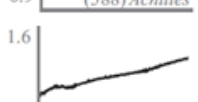
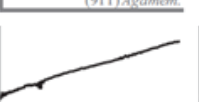
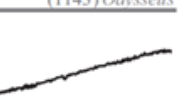
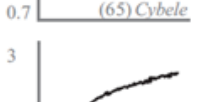
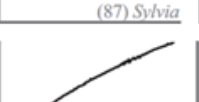
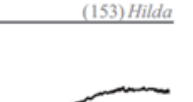
Albedos ranging from about 0.05 to 0.30
Various reflectance spectra from 0.5 to 2.5 μm
→ Spectral types/classes A, B, C, D etc.



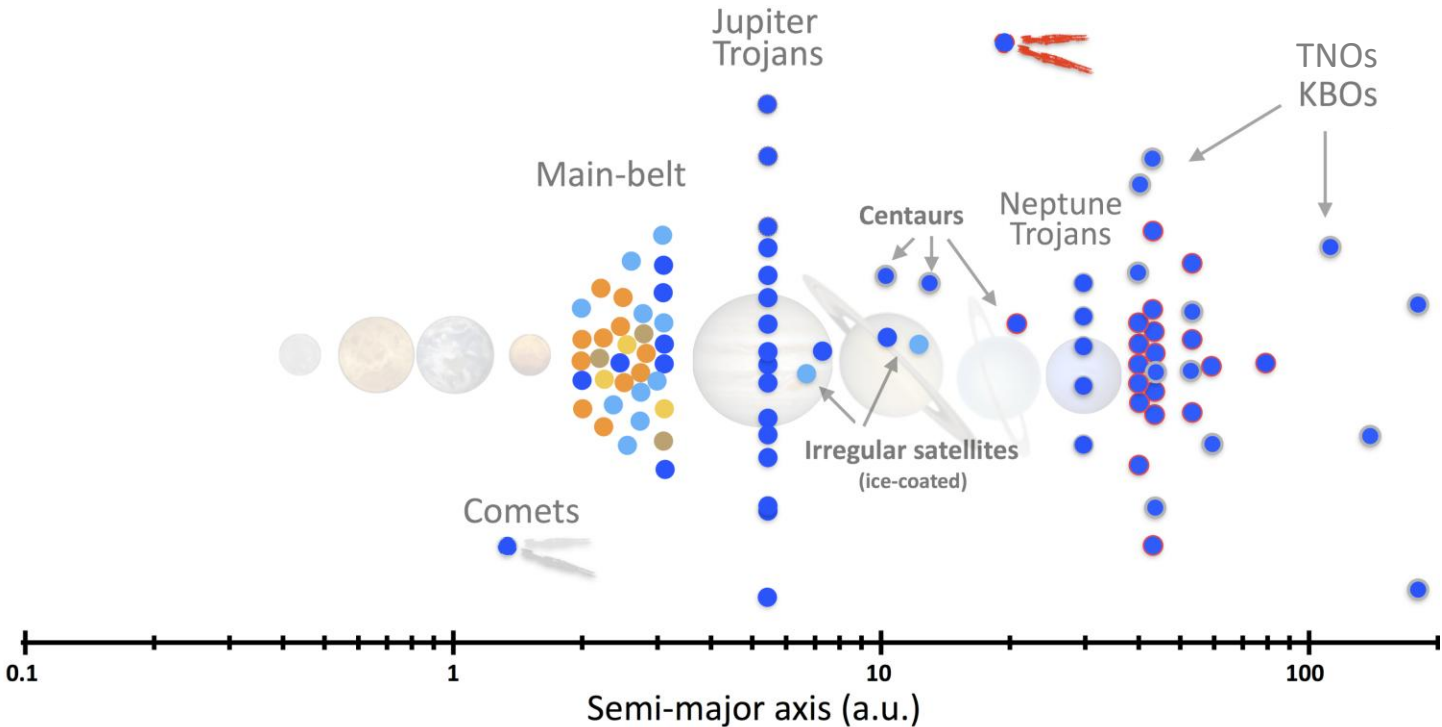
Class	Albedo	Reflectance spectra (0.5-2.5 μm)		
A	0.25 ^{+0.09} _{-0.07}			
B	0.06 ^{+0.05} _{-0.03}			
C	0.05 ^{+0.02} _{-0.01}			
Ch	0.05 ^{+0.02} _{-0.01}			
D	0.06 ^{+0.03} _{-0.02}			
E	0.57 ^{+0.15} _{-0.12}			
K	0.13 ^{+0.04} _{-0.03}			
L	0.18 ^{+0.07} _{-0.05}			
M	0.14 ^{+0.05} _{-0.04}			
O	0.26 ^{+0.02} _{-0.02}			
P	0.05 ^{+0.02} _{-0.01}			
Q	0.24 ^{+0.12} _{-0.08}			
R	0.30 ^{+0.05} _{-0.04}			
S	0.24 ^{+0.10} _{-0.07}			
V	0.29 ^{+0.11} _{-0.08}			
Z	0.07 ^{+0.04} _{-0.03}			

Solar System dark small bodies

Observational evidences for a continuum in composition between P/D/Z-type asteroids and Trans-Neptunian Objects (TNOs)/comets

Class	Albedo	Reflectance spectra (0.5-2.5 μm)		
B	0.06 ^{+0.05} _{-0.03}			
C	0.05 ^{+0.02} _{-0.01}			
Ch	0.05 ^{+0.02} _{-0.01}			
D	0.06 ^{+0.03} _{-0.02}			
P	0.05 ^{+0.02} _{-0.01}			
Z	0.07 ^{+0.04} _{-0.03}			

and they are all **very dark**



Solar System dark small bodies

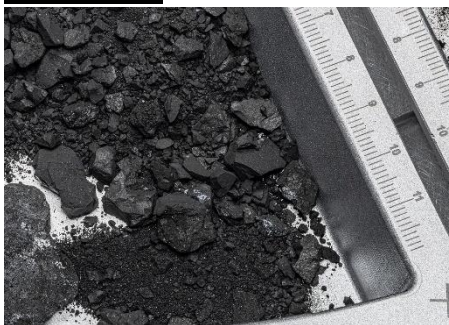
- Ryugu (C type)



JAXA Hayabusa2

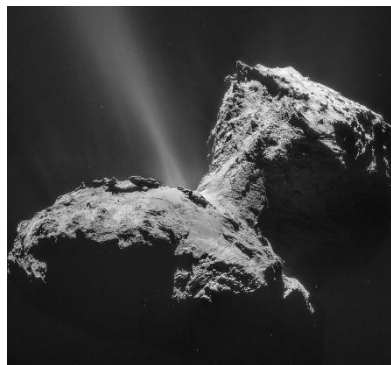


- Bennu (B type)



NASA/E. Blumenfeld/J. Abersold

- Comet 67P/C-G (P/D type)



ESA/Rosetta/Navcam

*Comets, P/D/C-type asteroids,
carbonaceous chondrites etc.
are dark... Why?*

Oued Chebeika 002 (CI chondrite)



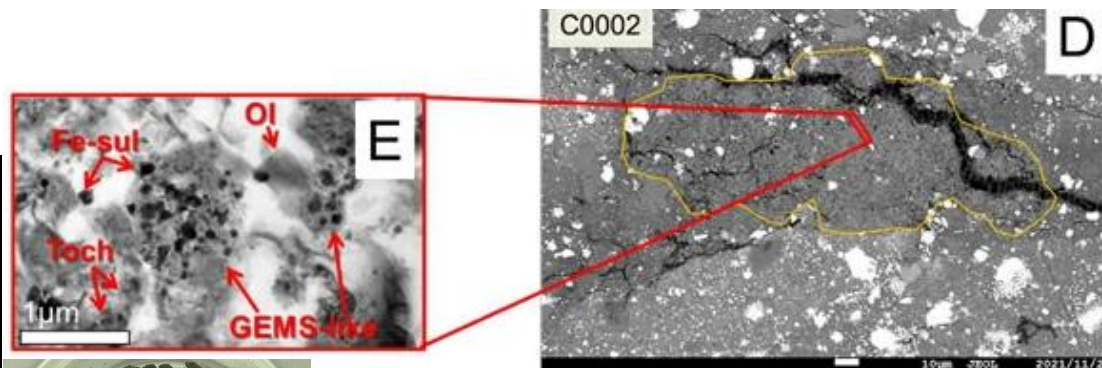
Jerome Gattacceca

Solar System dark small bodies

- Ryugu (C type)



JAXA Hayabusa2



Nakamura+ 2022

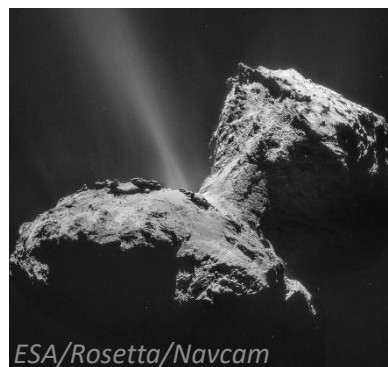


- Bennu (B type)

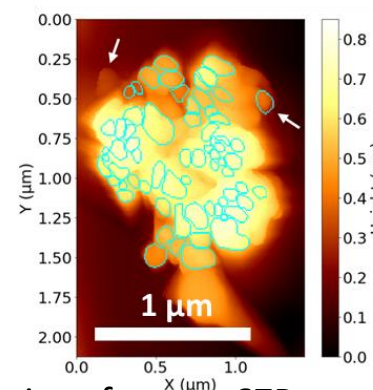


NASA/E. Blumenfeld/J. Aebersold

- Comet 67P/C-G (P/D type)



ESA/Rosetta/Navcam



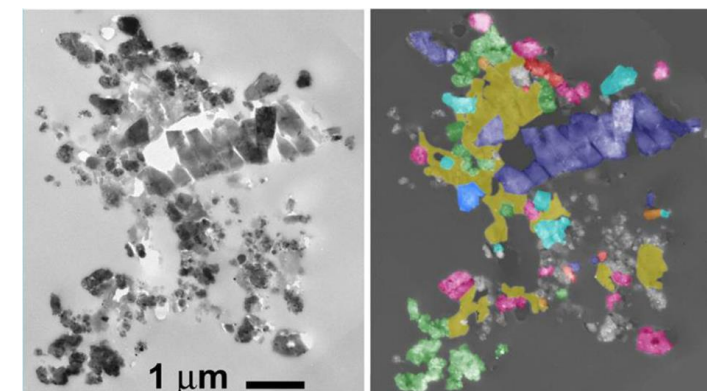
Aggregate of $\sim 0.1\text{-}\mu\text{m}$ grains of comet 67P
Rosetta/MIDAS, [Mannel+ 2019](#)

Oued Chebeika 002 (CI chondrite)



Jerome Gattacceca

33.5 g



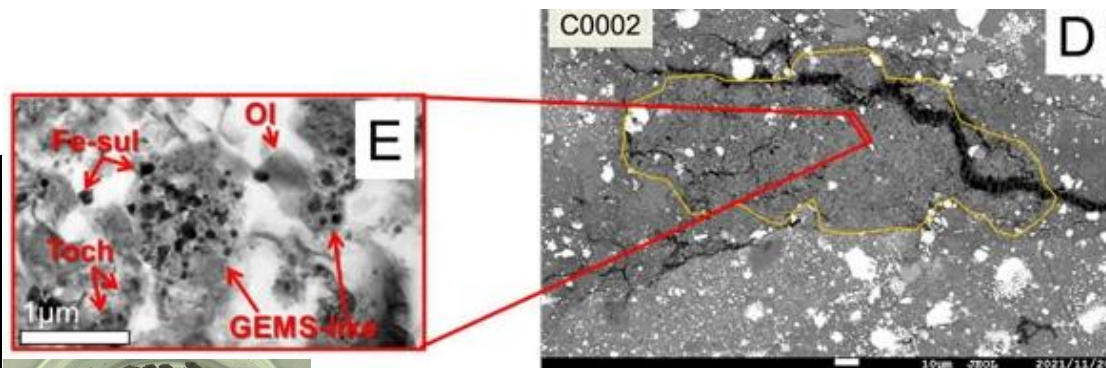
Chondritic Porous Interplanetary Dust Particle
(CP-IDP) [Messenger+ 2013](#)

Solar System dark small bodies

- Ryugu (C type)



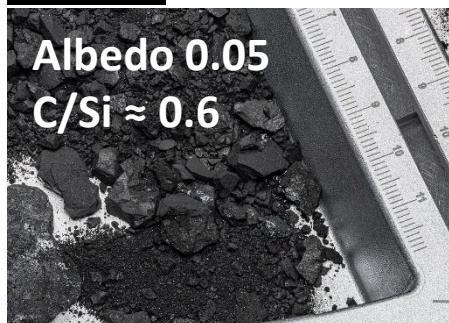
JAXA Hayabusa2



Nakamura+ 2022

*The darkness of the matrix
seems mainly due to opaque minerals,
not due to carbon* Beck+ 2025

- Bennu (B type)

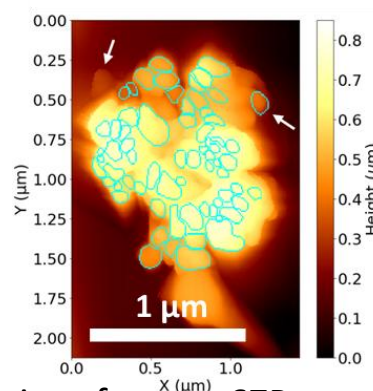


NASA/E. Blumenfeld/J. Aebbersold

- Comet 67P/C-G (P/D type)



ESA/Rosetta/Navcam

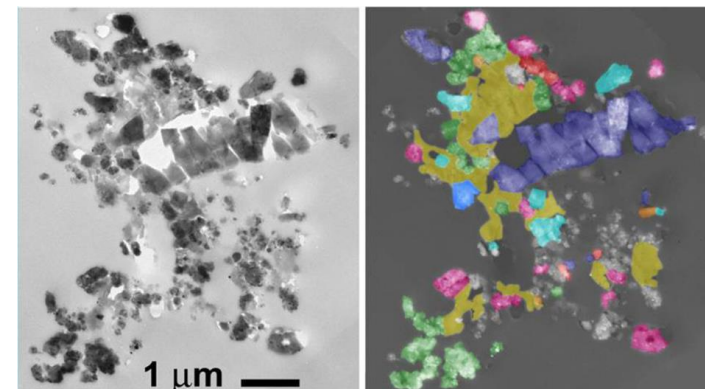


Aggregate of ~0.1-μm grains of comet 67P
Rosetta/MIDAS, Mannel+ 2019

Oued Chebeika 002 (CI chondrite)



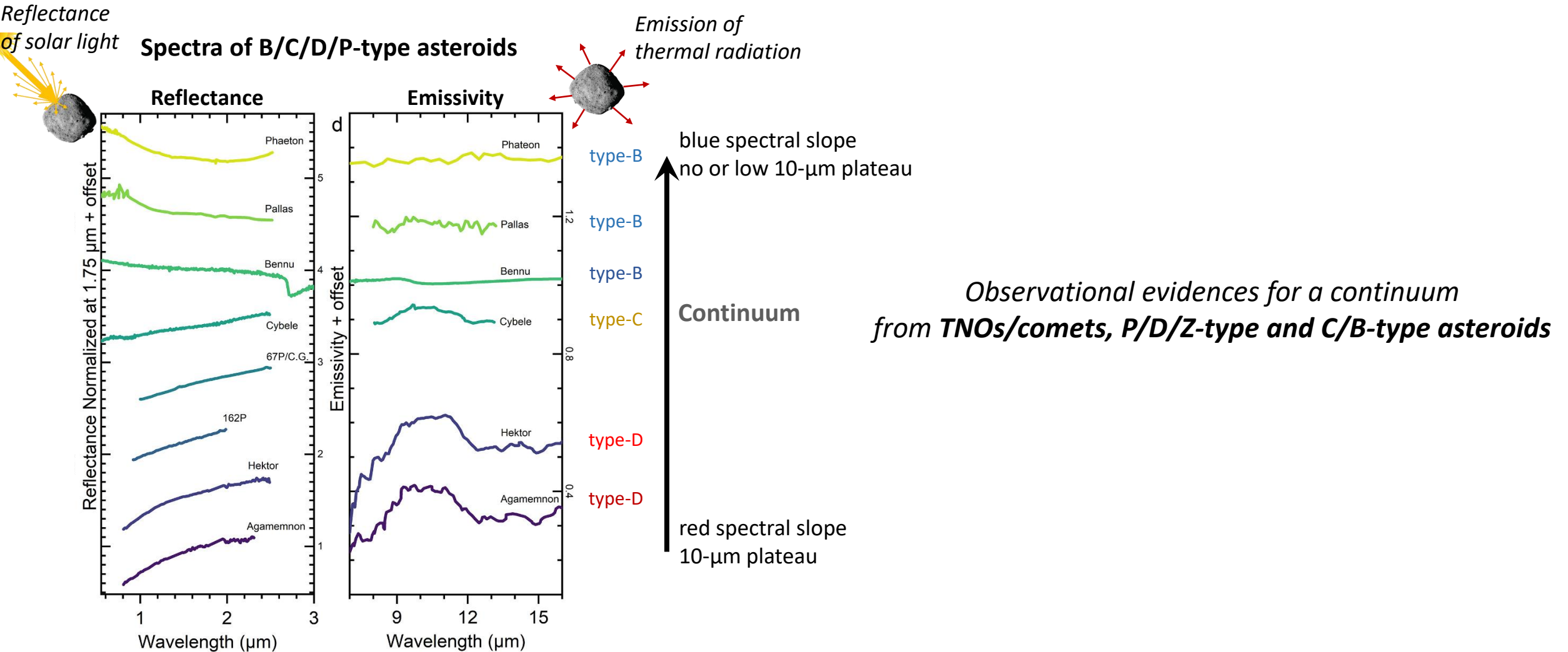
Jerome Gattacceca



Chondritic Porous Interplanetary Dust Particle
(CP-IDP) Messenger+ 2013

Optical properties of Solar system dark small bodies

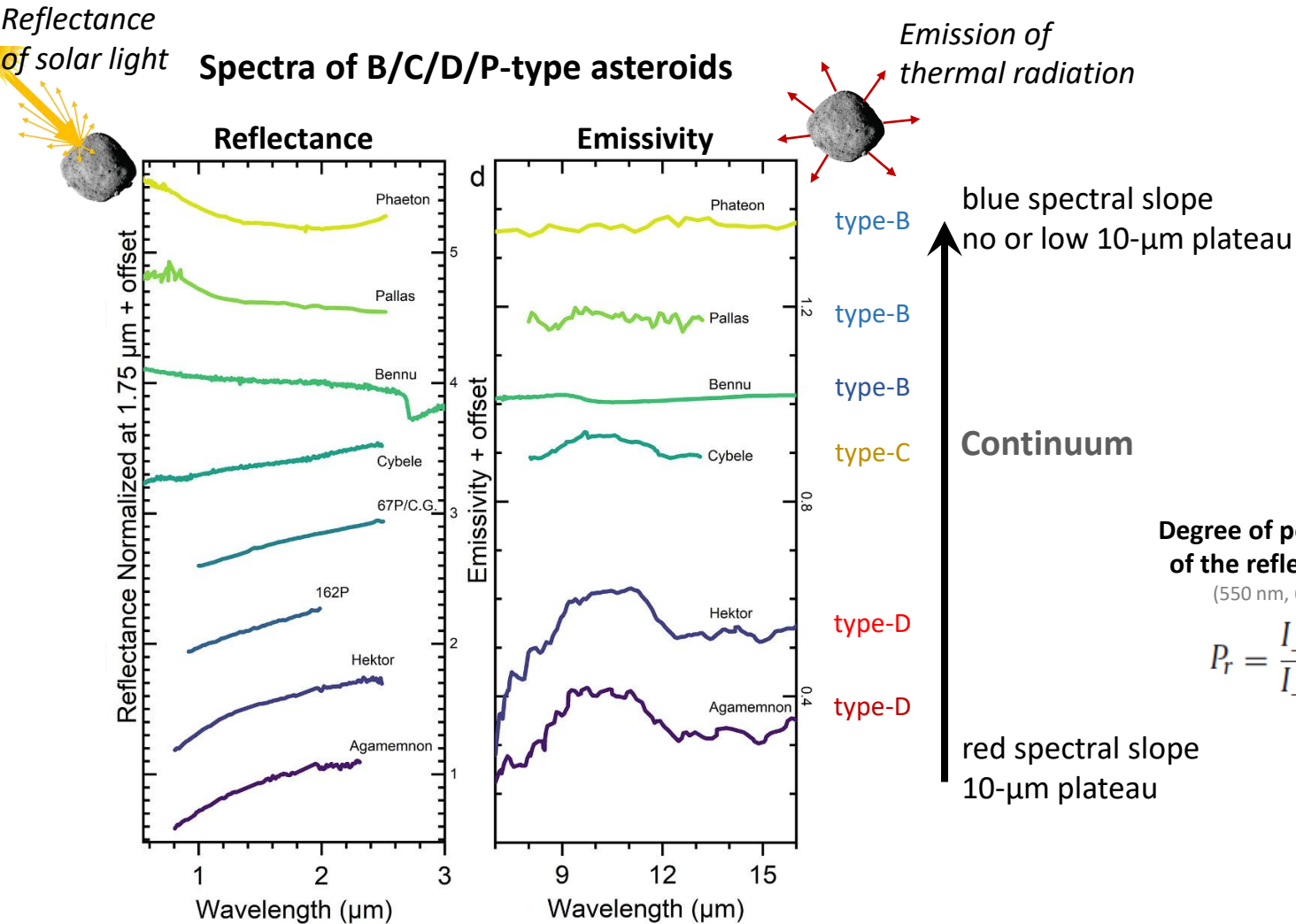
- Why do they exhibit diverse spectra?



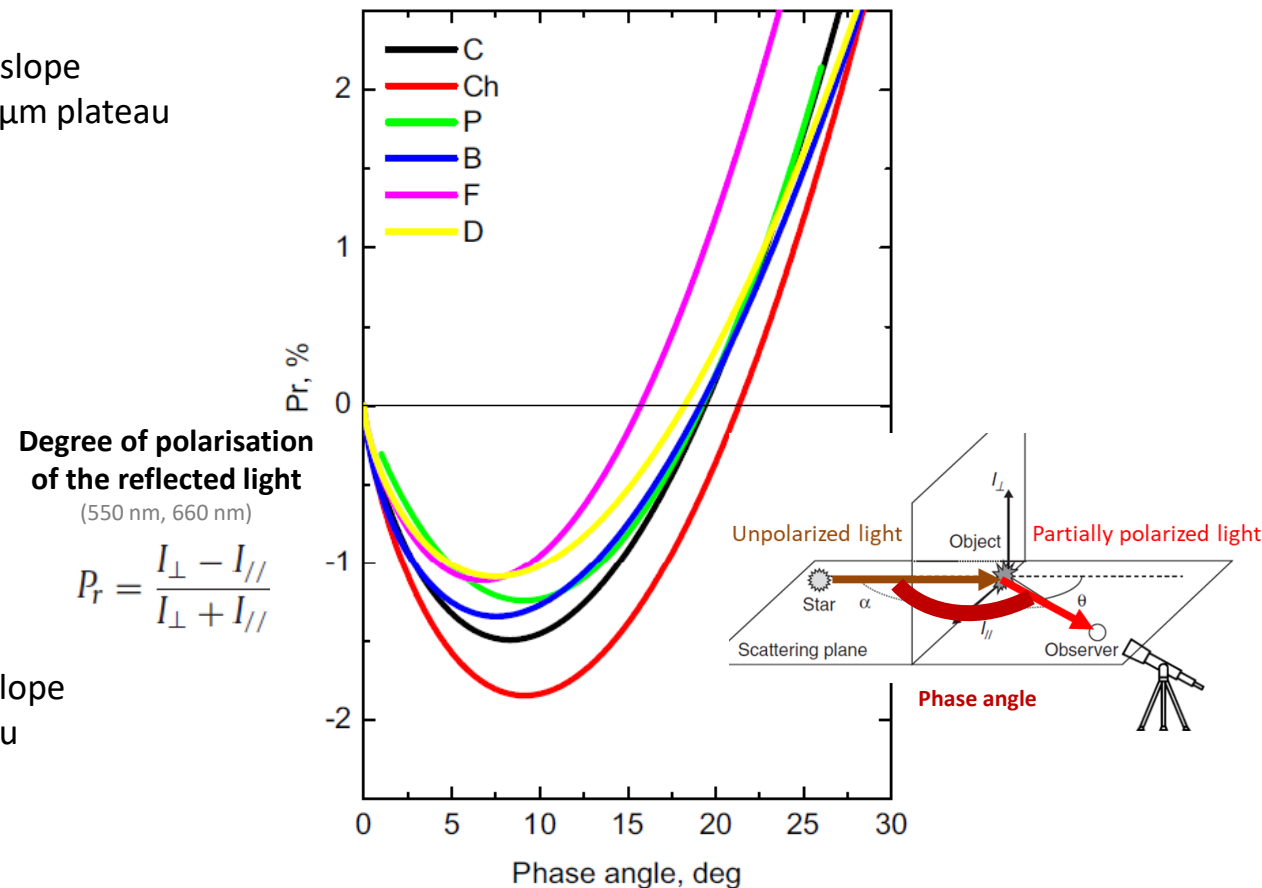
Optical properties of Solar system dark small bodies

- Why do they exhibit diverse spectra?

...and diverse polarimetric phase curves?



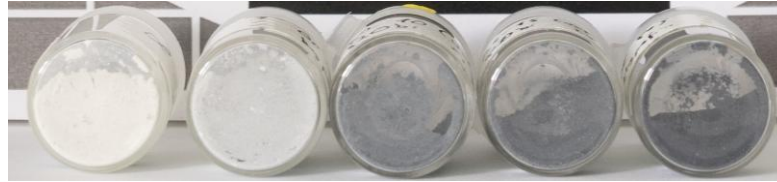
Polarimetric phase curves



Preparation of granular analogues of dark small bodies

① Samples of sub- μm grains and mixtures

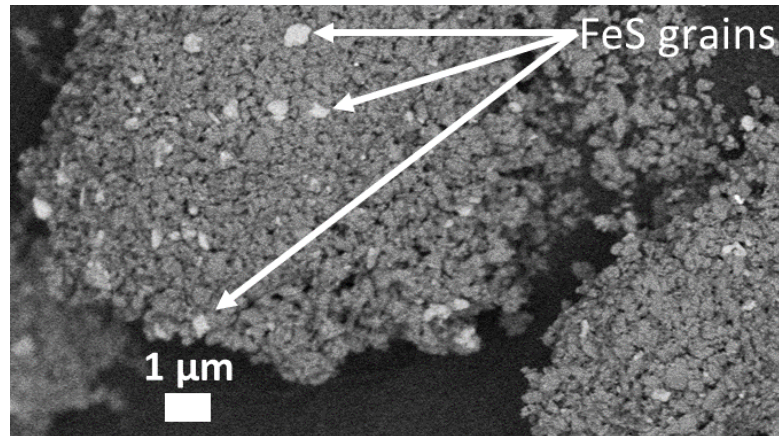
Series of dry and colloidal grindings of
Olivine (Mg_2SiO_4) + Iron sulfides (FeS)



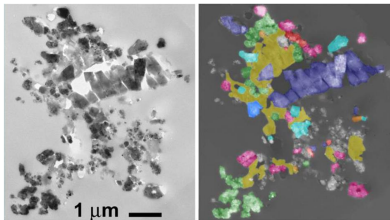
Olivine-FeS (vol. %) : 99-1 95-5 90-10 85-15 80-20



Analogue sample *Sultana+ 2023*

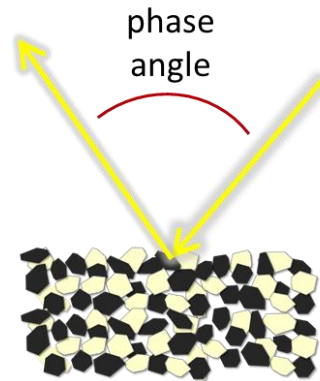
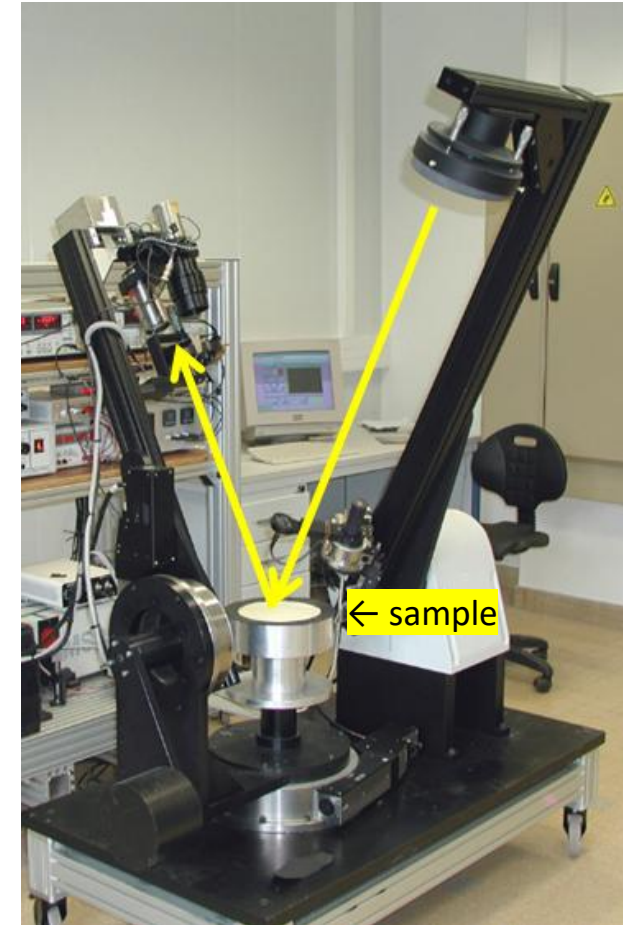


Chondritic Porous Interplanetary
Dust Particle (CP-IDP)
Messenger+ 2013



② Measurement of optical properties

Spectro-gonio-radiometer to measure reflectance spectra

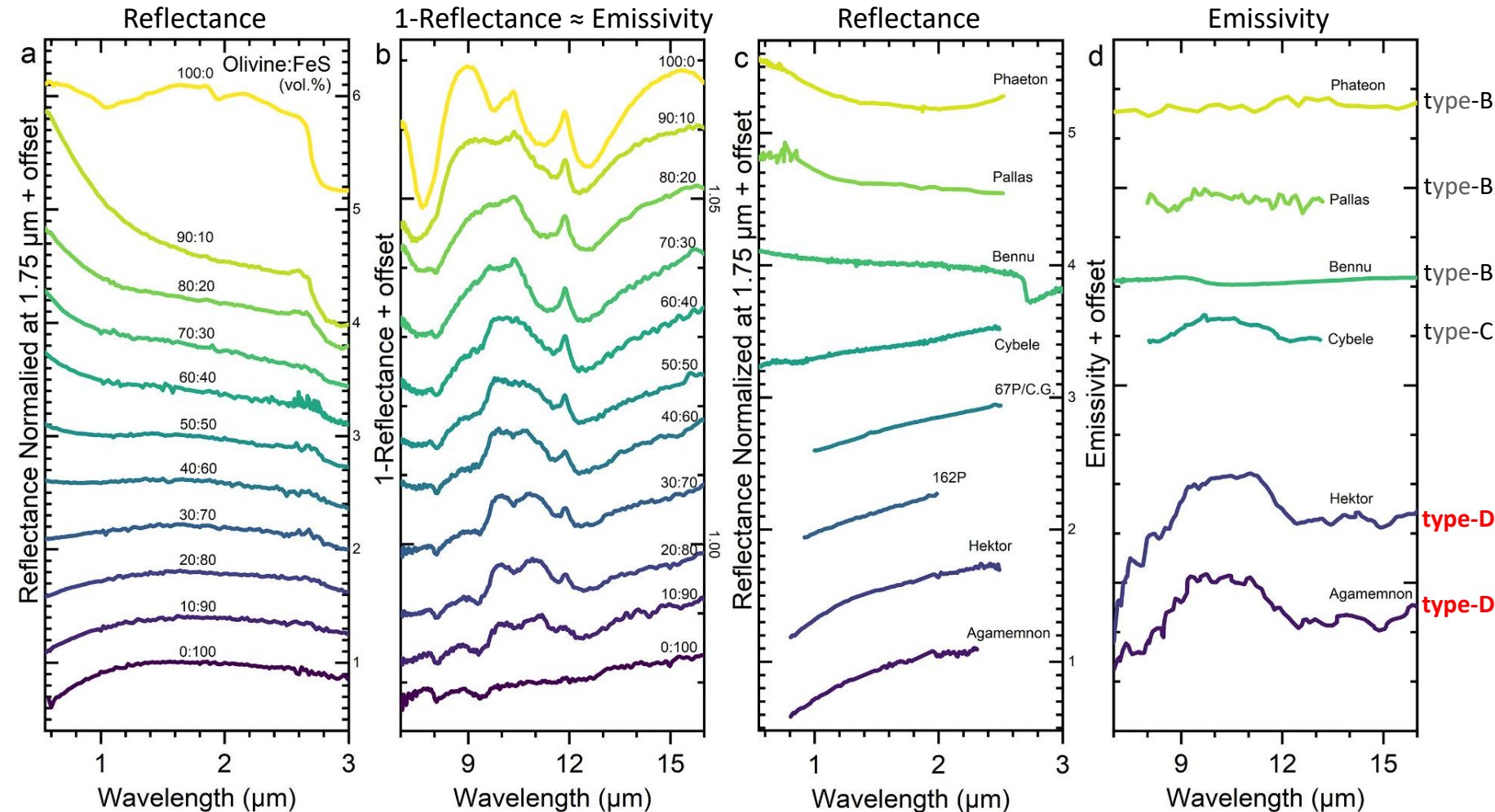


Interpretation of dark small bodies optical properties

- Comparison of laboratory measurements with astronomical observations:

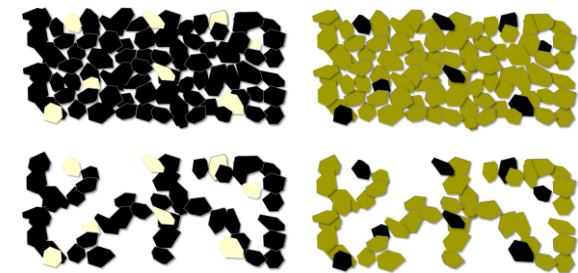
Spectra of mixtures Olivine + FeS (< 1 μm)

Spectra of B/C/X/D/P-types



aggregated FeS-like grains
and isolated silicate grains

in Near-IR : in Mid-IR :



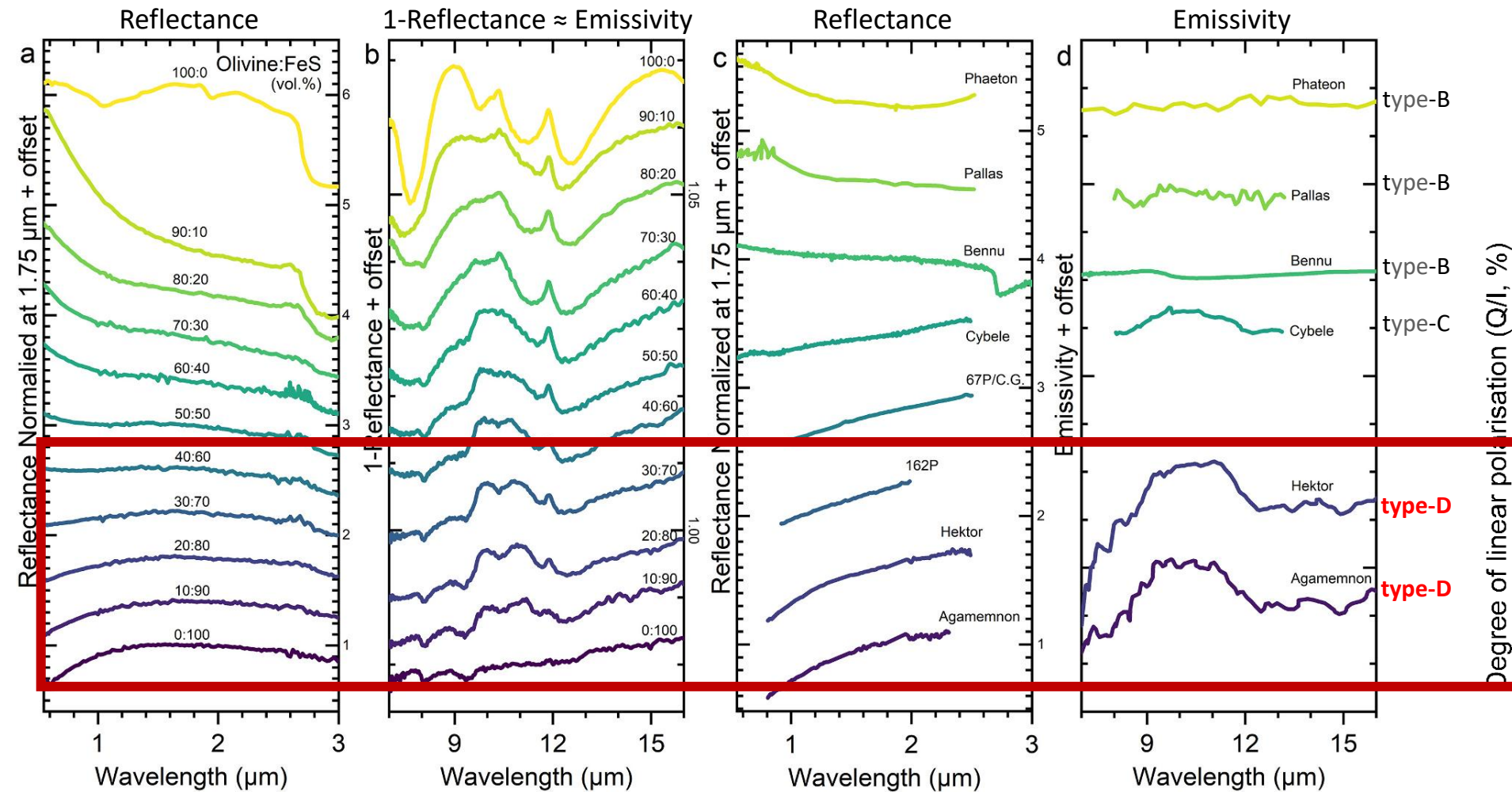
➡ The degree of isolation/aggregation of sub- μm grains controls the Vis-NIR spectral slopes and the 10 μm plateau contrast

Interpretation of dark small bodies optical properties

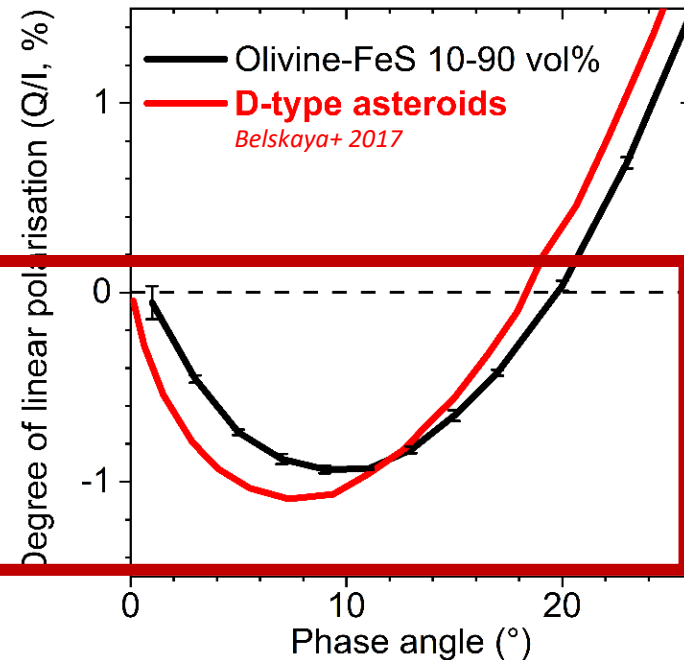
- Comparison of laboratory measurements with astronomical observations:

Spectra of mixtures Olivine + FeS (< 1 μm)

Spectra of B/C/X/D/P-types



Polarimetric phase curves

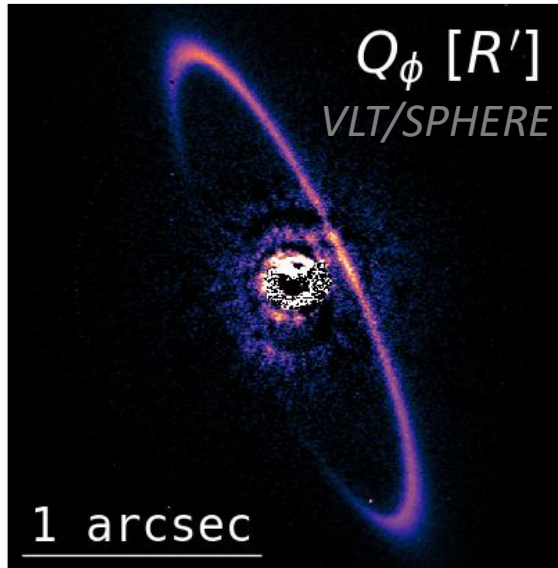


➡ The degree of isolation/aggregation of sub- μm grains controls the spectral and polarimetric properties of dark small bodies

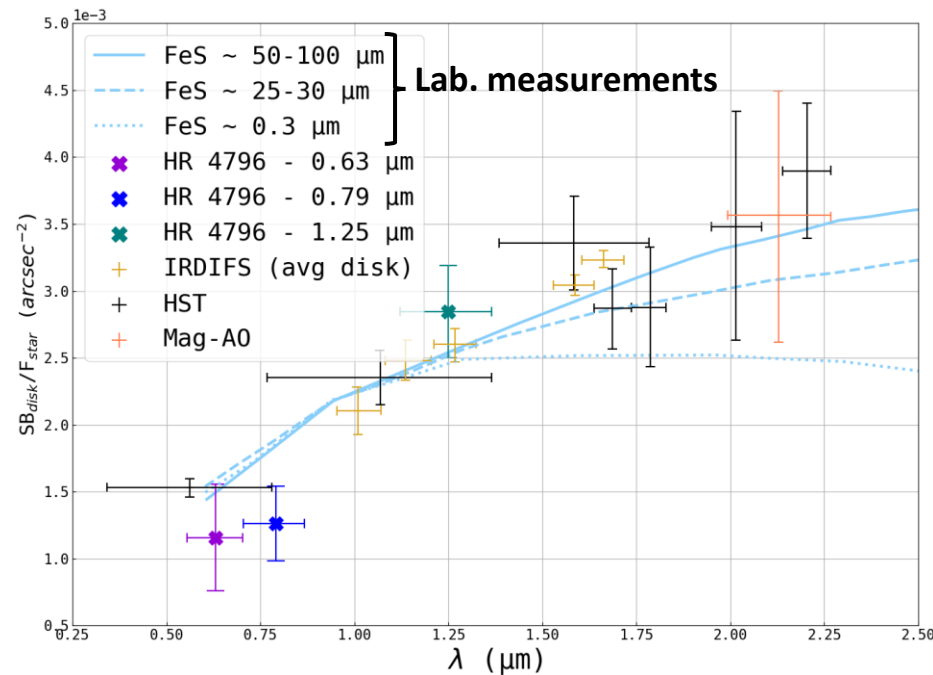
Interpretation of debris disks optical properties

- Comparison of laboratory measurements with astronomical observations:

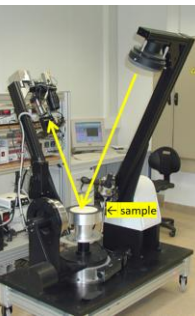
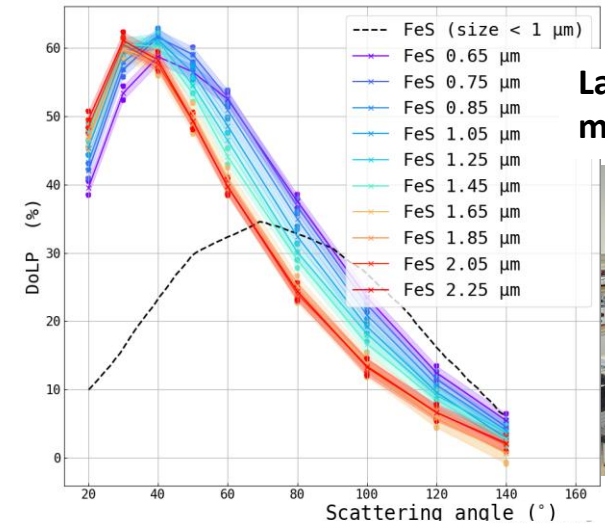
HR 4796 debris disk



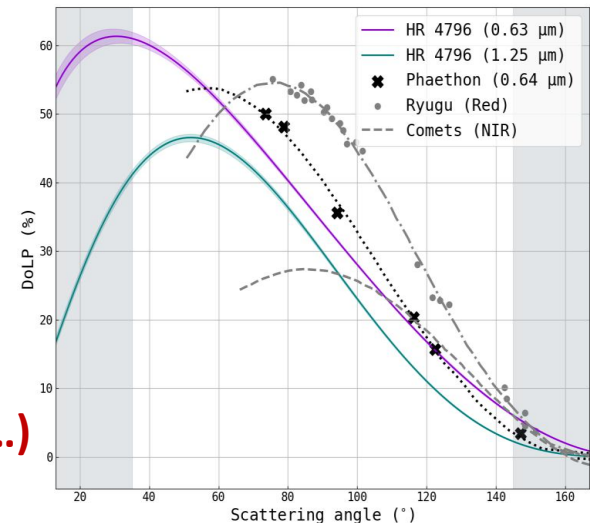
Reflectance spectra HR 4796 and iron sulfide (FeS) particles



Polarimetric phase curves



Observations



➡ HR 4796 optical properties similar to
➔ 50-100 μm opaque mineral particles
➔ space-weathered small bodies (Phaethon, Ryugu...)

Solar System dark small bodies

- Ryugu (C type)

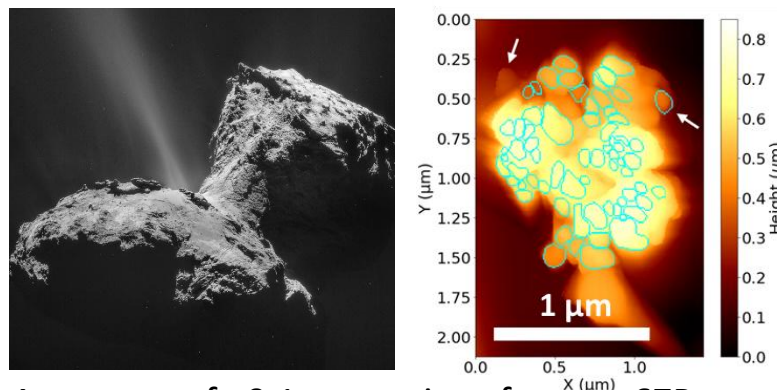


What is the composition of this dark matrix, remnant of a primordial dust?

- Bennu (B type)

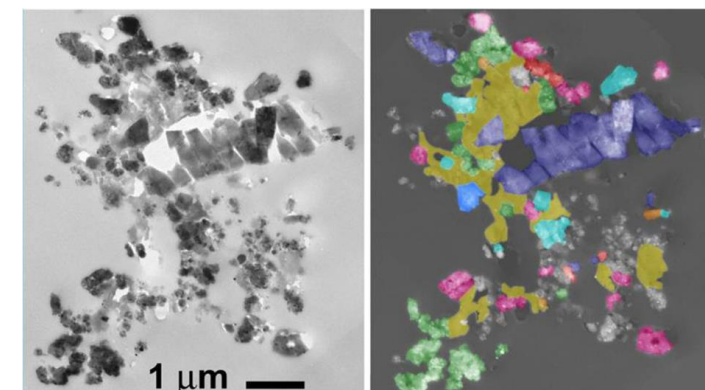


- Comet 67P/C-G (P/D type)



Aggregate of ~0.1-μm grains of comet 67P
Rosetta/MIDAS, [Mannel+ 2019](#)

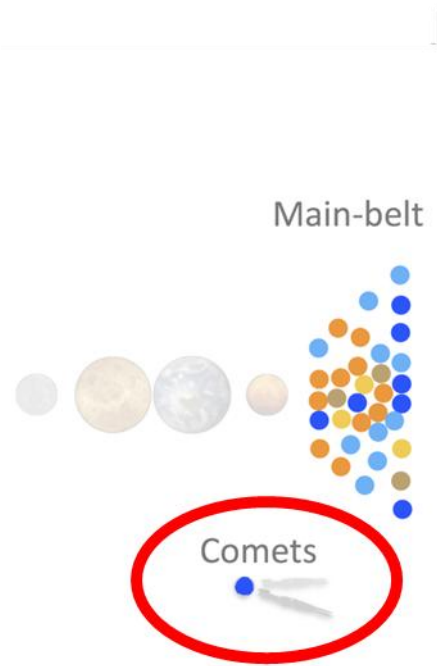
CI chondrite Oued Chebeika 002



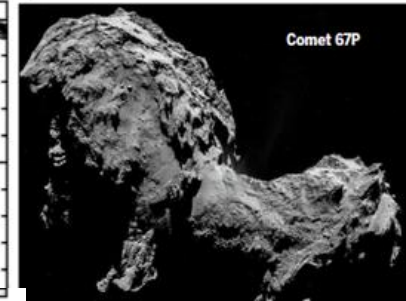
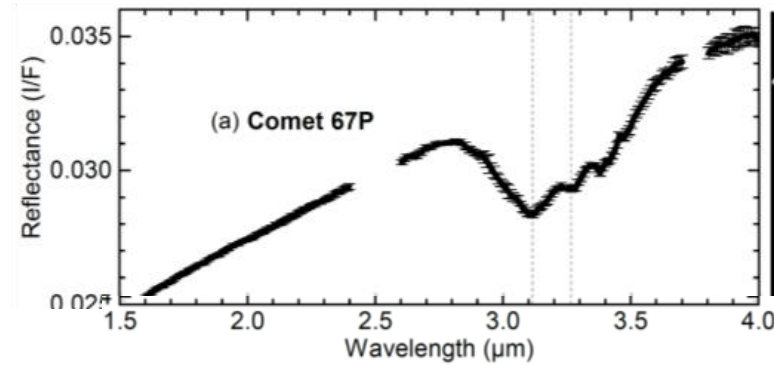
Chondritic Porous Interplanetary Dust Particle (CP-IDP) [Messenger+ 2013](#)

Compositional studies of Solar system dark small bodies

2014: the Rosetta space mission (ESA)



Reflectance spectrum from comet 67P/Churyumov-Gerasimenko



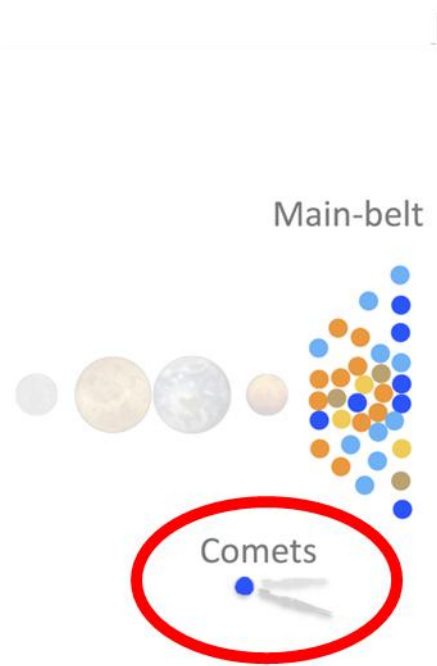
Rosetta/VIRTIS



Vernazza, Beck (2017)

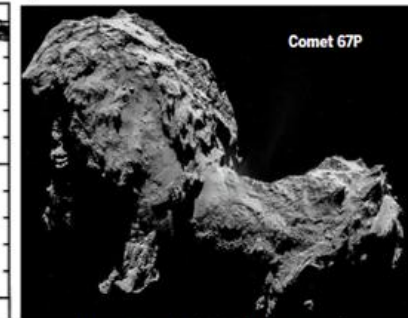
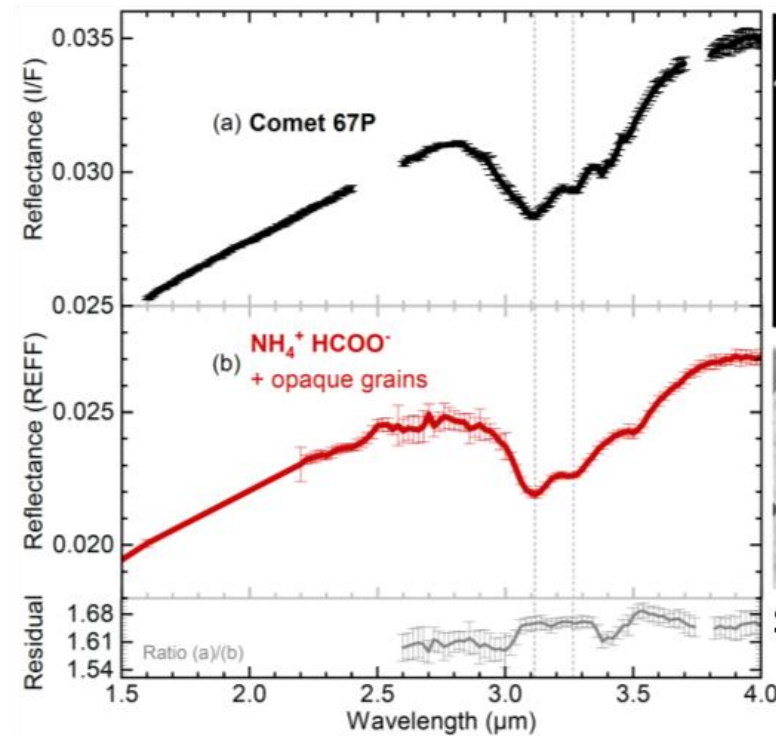
Compositional studies of Solar system dark small bodies

2014: the Rosetta space mission (ESA)

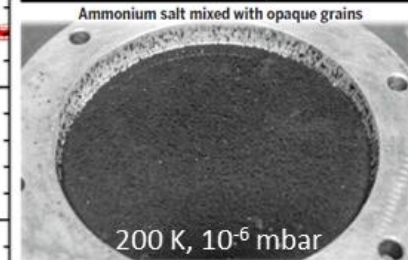


Vernazza, Beck (2017)

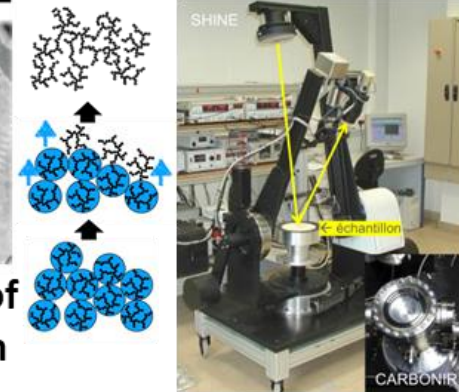
Reflectance spectrum from comet 67P/Churyumov-Gerasimenko



Rosetta/VIRTIS



Sublimation residue of NH_4^+ salts mixed with opaque grains

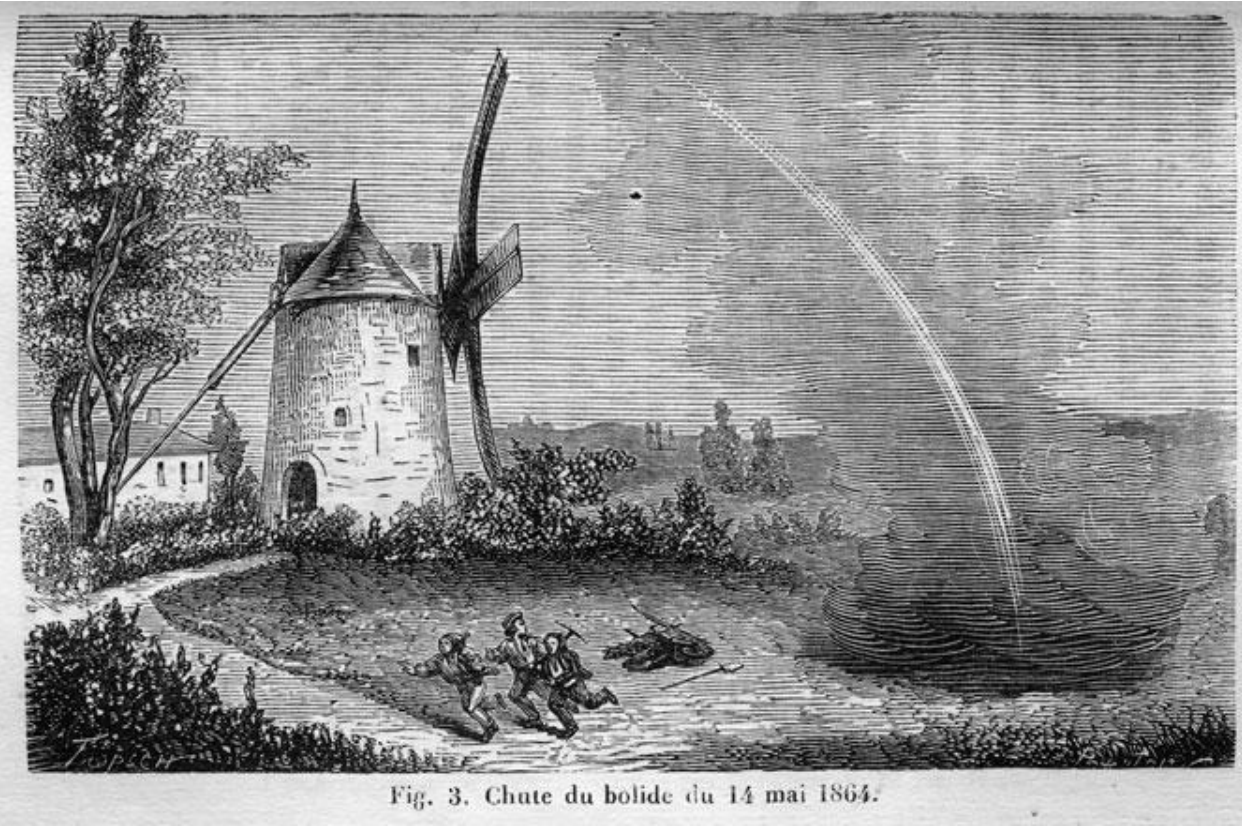


➡ Identification of ammonium NH_4^+ salts on a comet

Poch+ 2020; Altwegg+ 2020

Compositional studies of Solar system dark small bodies

1864: the Orgueil meteorite fall (May 14th)



Louis-Dominique Bayle

Chemical composition of the
Orgueil meteorite
(Cloëz, *Comptes Rendus de l'Académie des
Sciences Paris*, July 4th, 1864)

	Météorite à l'état naturel.	Météorite desséchée à 110°.
Eau hygroscopique.....	5,975	"
Acide silicique.....	24,475	26,0310
Acide sulfurique.....	2,195	2,3345
Soufre.....	4,369	4,6466
Chlore.....	0,073	0,0776
Phosphore.....	traces	traces
Alumine.....	1,175	1,2498
Oxyde de chrome.....	0,225	0,2392
Peroxyde de fer.....	13,324	14,2360
Protoxyde de fer.....	17,924	19,0630
Oxyde de nickel...	2,450	2,6057
Oxyde de cobalt.....	0,085	0,0904
Oxyde de manganèse.....	1,815	1,9302
Magnésie.....	8,163	8,6711
Chaux.....	2,183	2,3220
Soude.....	1,244	1,3230
Potasse.....	0,307	0,3265
Ammoniaque.....	0,098	0,1042
Substance humique.....	6,027	6,4100
Eau combinée.....	7,345	7,8120
	96,442	99,472

We remembered the 160 years old analysis of the Orgueil meteorite

NH₄⁺ salts
& organic matter

Ammoniaque..... 0,098 0,1042

Substance humique..... 6,027 6,4100

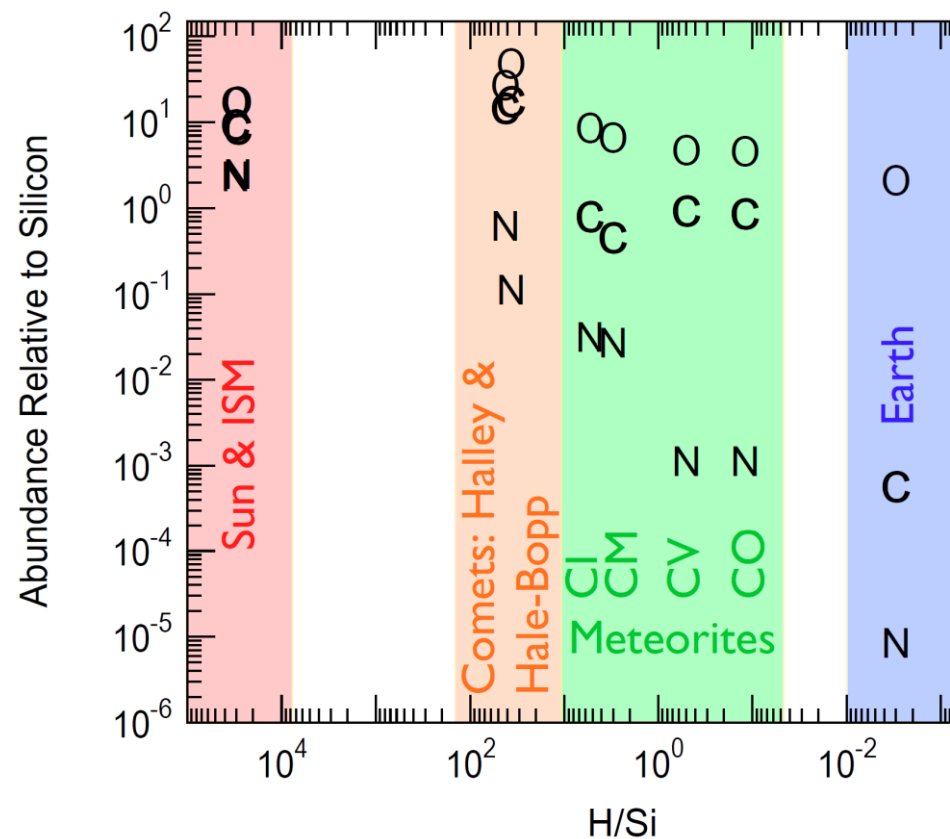
Eau combinée..... 7,345 7,8120

96,442 99,472

Compositional studies of Solar system dark small bodies

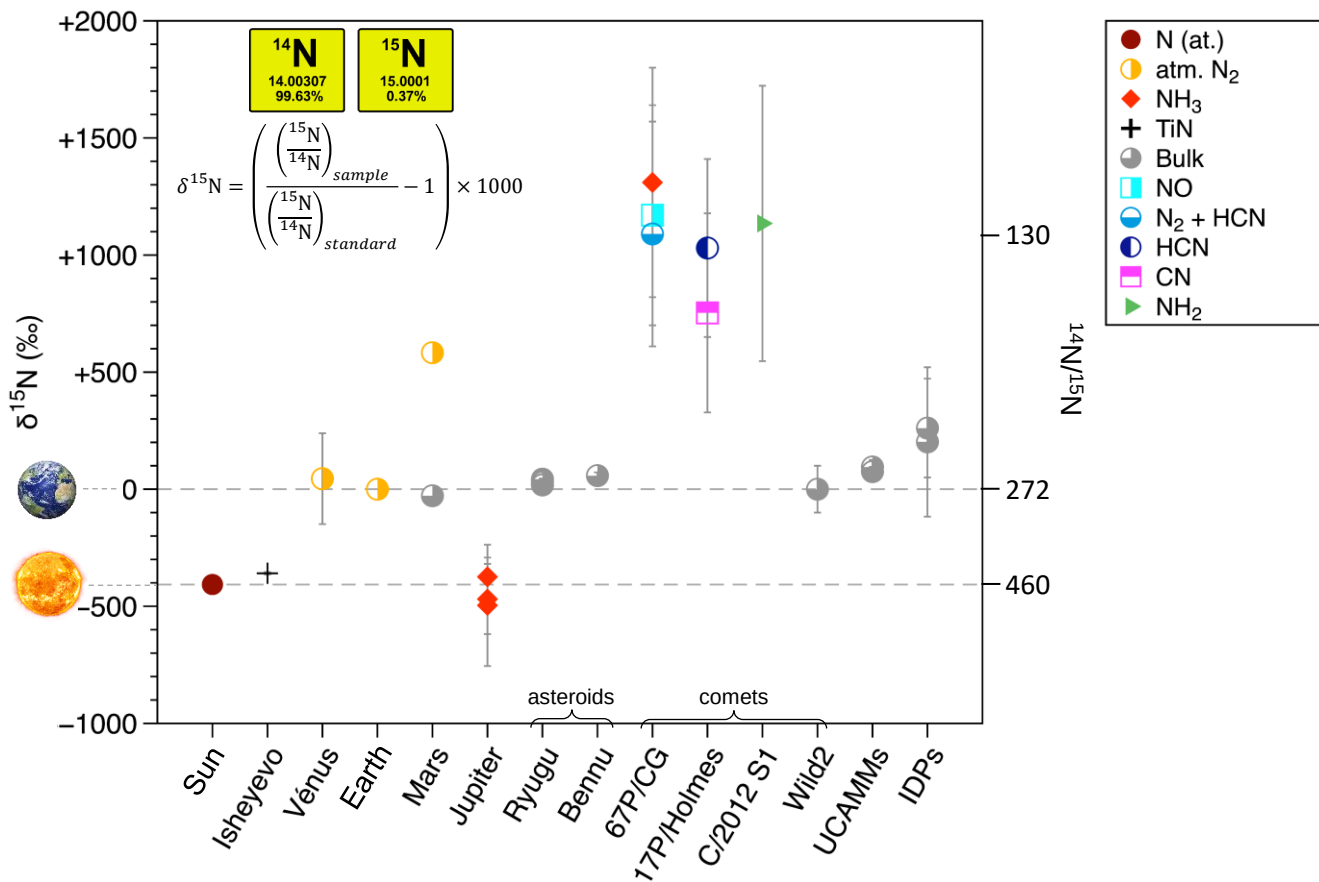
- Nitrogen (N) is a unique tracer of processes occurring at each step of planet formation

Abundance of N varies a lot between objects



Pontoppidan+ 2014, Lee+ 2010, Geiss 1987

$\delta^{15}\text{N}$ varies a lot between objects and carrier phases



Thesis Laize-G  n  rat 2024, F  ri and Marty 2015, Marty+ 2011, Nier 1950, Fouchet+ 2000, Owen+ 2001, Fletcher+ 2014, Meibom+ 2007, Broadley+ 2023, Grady+ 2023, 2024, Shinnaka+ 2014, Altwegg+ 2019, Hoppe+ 2023, Bockel  e-Morvan+ 2008, McKeegan+ 2006, Dartois+ 2013, Thesis N. Bardin, Stadermann+ 1989, Floss+ 2006

Compositional studies of Solar system dark small bodies



Does the Orgueil meteorite still contain NH_4^+ today?

If yes, is this NH_4^+ extra-terrestrial?

→ we need to measure N isotopic composition

Analyses of nitrogen in the Orgueil meteorite

PNP OAZAN project
Laize-Générat+ 2024



Bulk Sample



Acid digestion HF



Insoluble Organic Matter (IOM)

Elemental & isotopic analyses

- $N_{\text{IOM}} = 0.07 \pm 0.01 \text{ wt\%}$
- $\delta^{15}N_{\text{IOM}} = +32 \pm 1 \text{ ‰}$



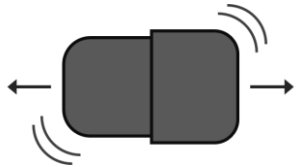
at IPAG

Meteorite ~ 150 mg
Grinding balls 2 Ø15 mm

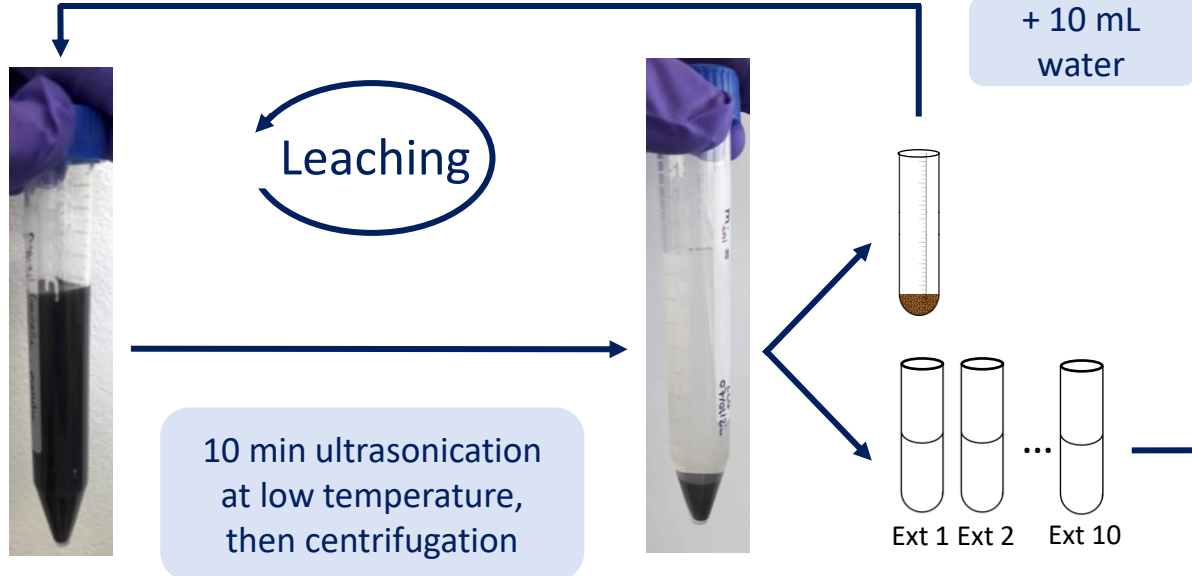


10 mL of pure water ice

6 min

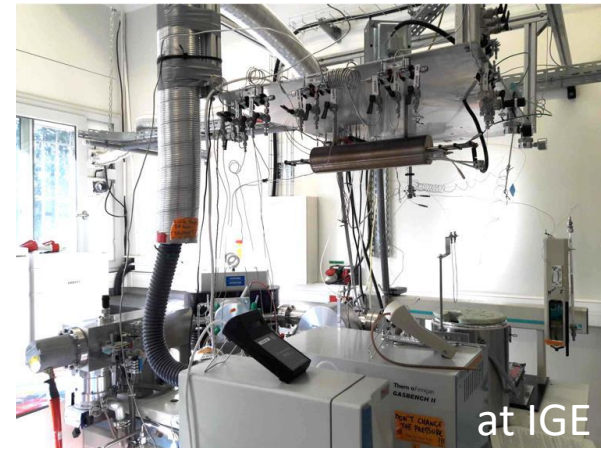


Cryogenic grinding
with water ice



Ion chromatography & isotopic analyses

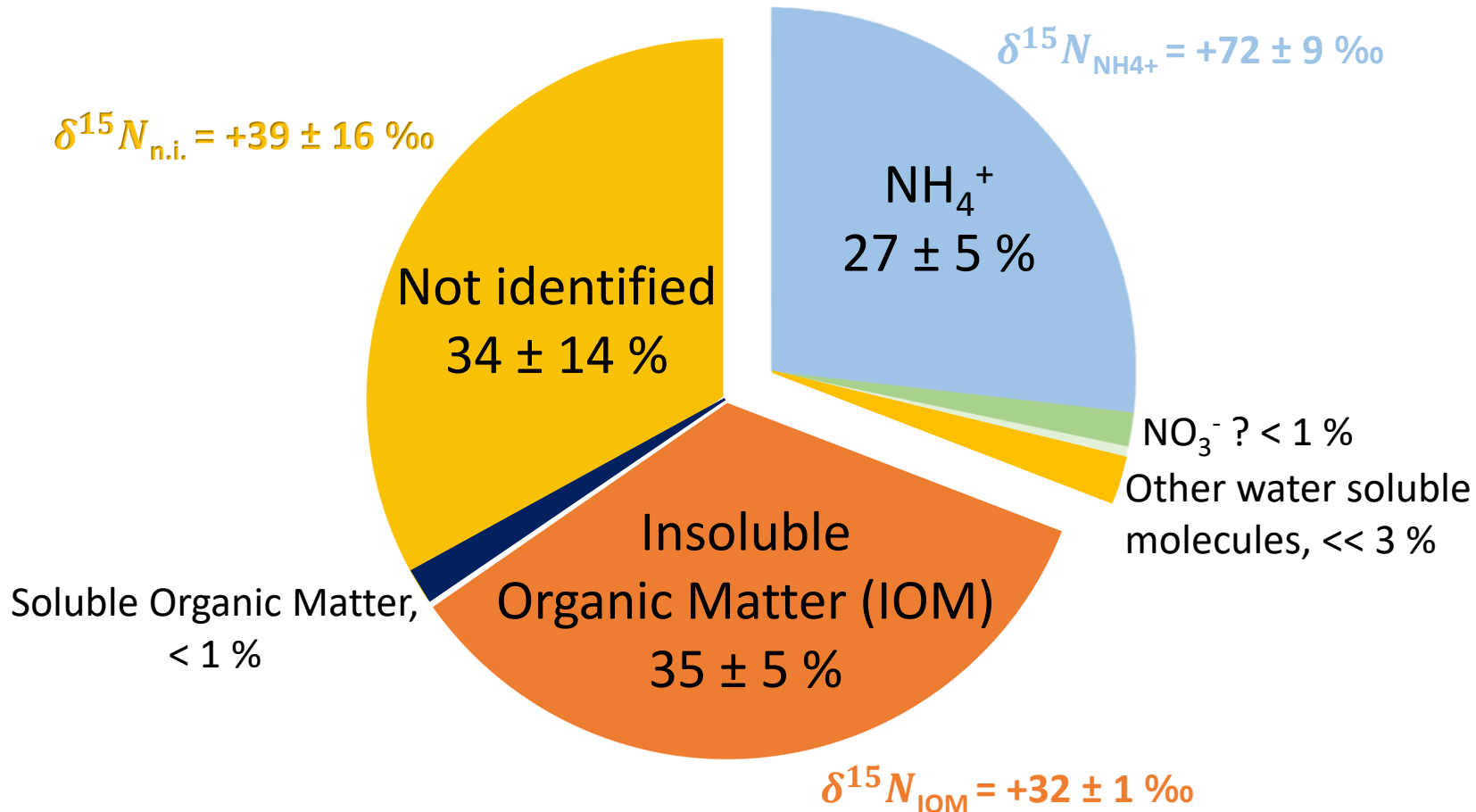
- $N_{\text{NH}_4^+} = 0.07 \pm 0.01 \text{ wt\%}$
- $\delta^{15}N_{\text{NH}_4^+} = +72 \pm 9 \text{ ‰}$



at IGE

Analyses of nitrogen in the Orgueil meteorite

Average distribution of the **nitrogen**
among **N-carrier phases** in Orgueil

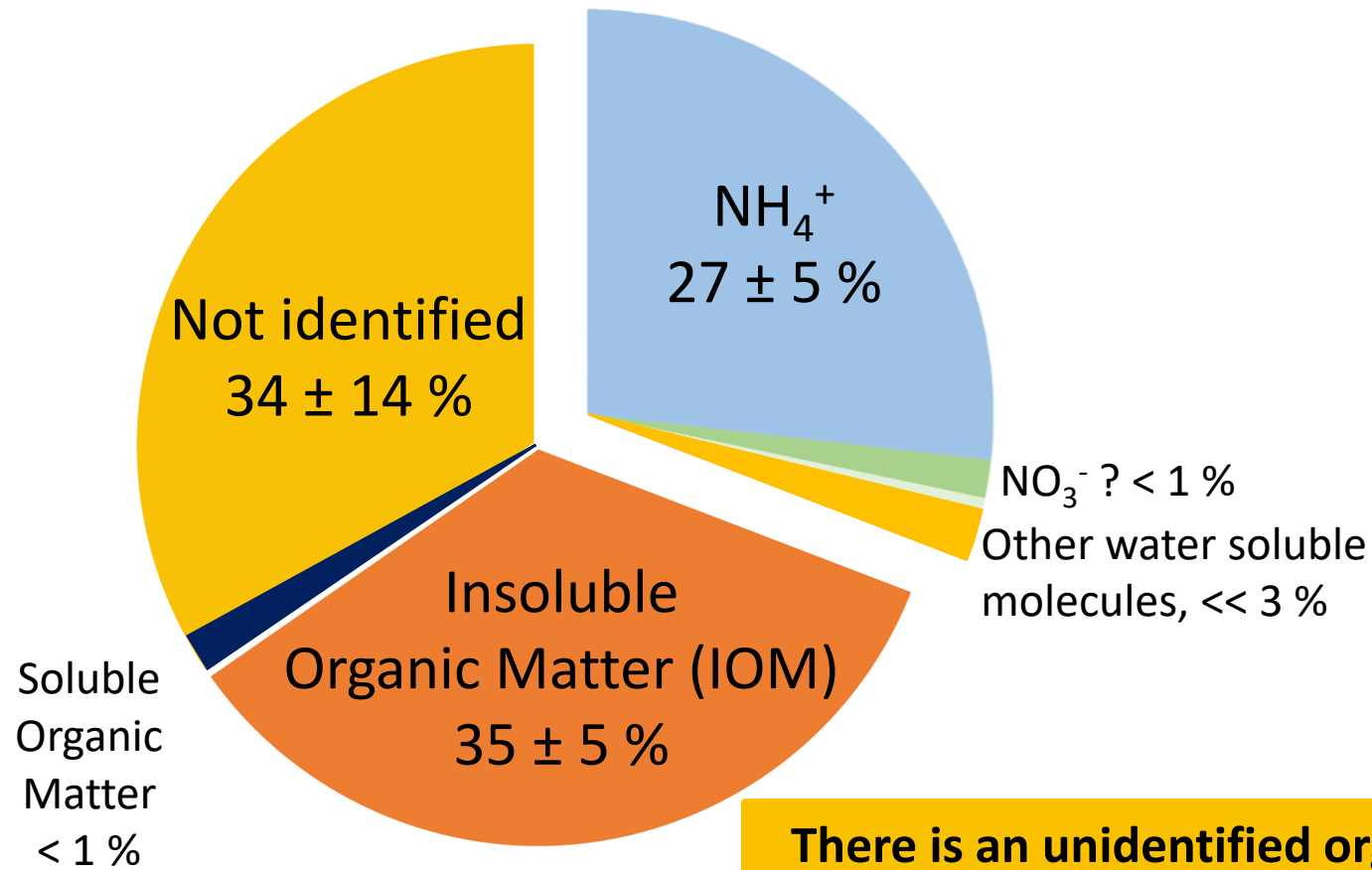


- NH_4^+ is a significant reservoir of N in Orgueil :
~ 1/4 of the total N
- NH_4^+ is extra-terrestrial
- IOM is not the main carrier of N
- Most of the non-identified N is in an organic matter, possibly soluble in acids

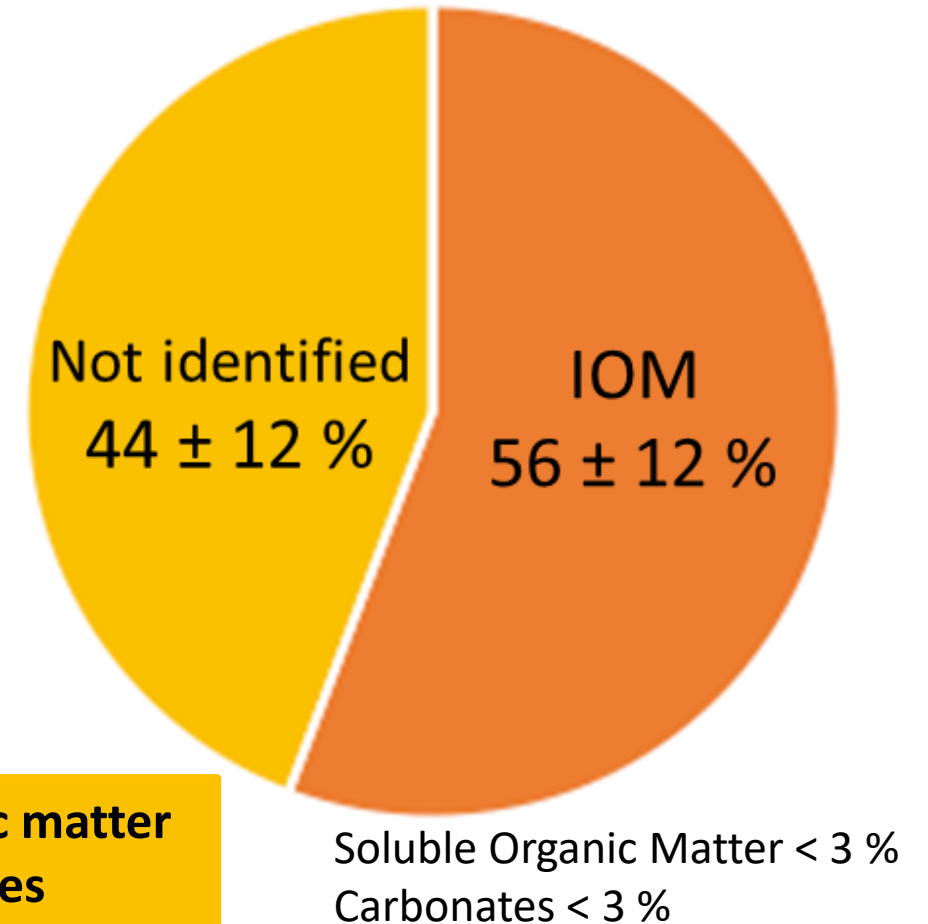
NH_4^+ and IOM
have distinct isotopic compositions

Analyses of nitrogen and carbon in the Orgueil meteorite

Distribution of the **nitrogen**



Distribution of the **carbon**



**There is an unidentified organic matter
in carbonaceous chondrites**
Acid Soluble Organic Matter?

Conclusions *Perspectives*

Darkness and colour of dark small bodies

- Comets, and dark asteroids have low albedo probably not because of organic-carbon, but because of **Fe-bearing opaque minerals** (FeS, Fe_{1-x}S, Fe-Ni...). *Quirico+ 2016; Beck+ 2025*
- **The degree of optical isolation/aggregation of sub-μm grains** controls dark small bodies optical properties. Optical properties depend **non-linearly on silicates and opaques proportions**. *Sultana+ 2023*
→ Origins of the diversity of optical properties of small bodies & debris disks?

Composition of dark small bodies

- **Elemental budgets of nitrogen and carbon** to elucidate small bodies history.
- **30-50 % of the carbon and nitrogen** in the Orgueil meteorite is in a yet **unidentified organic matter**!
- **Ammonium NH₄⁺ is a significant carrier of nitrogen** in CI chondrites (> 25% of total N). It may trace accretion and/or later deposit of **NH₃ ice, NH₃ hydrates, and/or NH₄⁺ salts** on parent bodies. *Laize-Générat+ 2024*
→ Measure Bennu asteroid sample return... and prepare future cometary sample return?