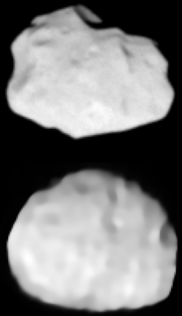
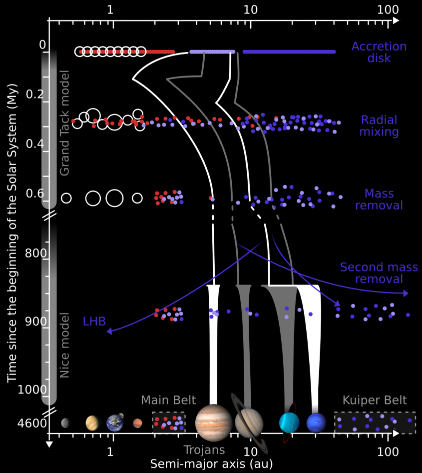
# Exploring the asteroid belt from the ground with VLT/SPHERE



**Benoit Carry**

Lagrange, Observatoire de la Côte d'Azur

# Solar system history




DeMeo & Carry 2014

## A. Stratified accretion disk

- Gas & dust & Volatiles

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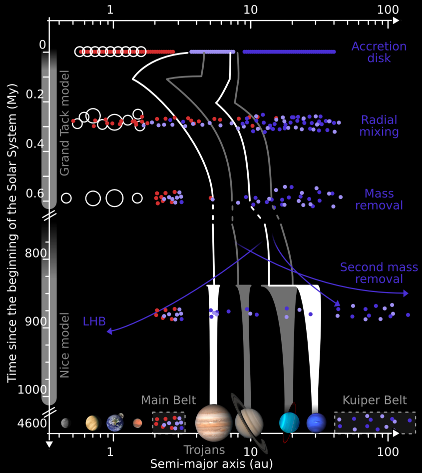


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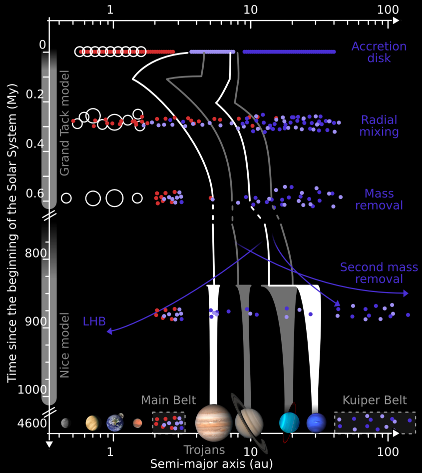


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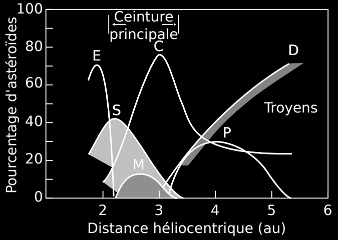
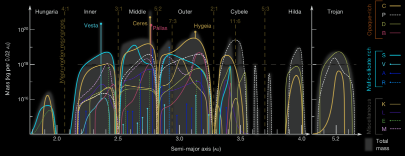



Gradie & Tedesco 1982

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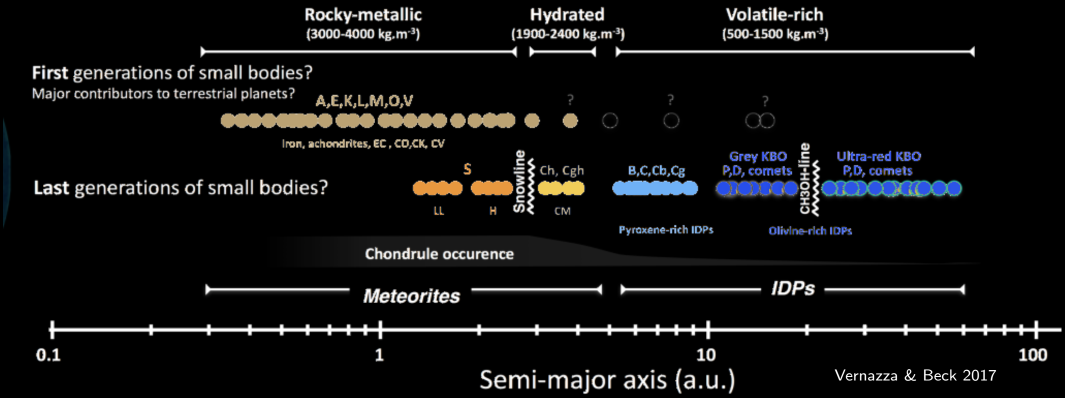
▶ **Asteroid main belt** = mix of everything

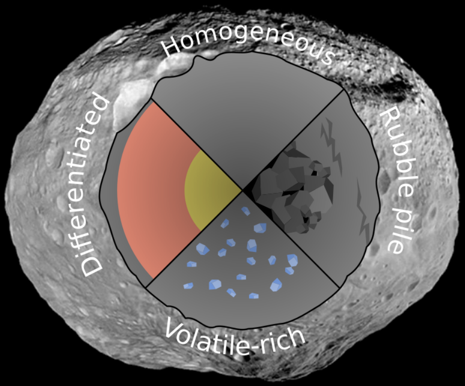
# Origin of asteroids




Vernazza & Beck 2017

- Meteorites & Interplanetary Dust Particles (IDPs) as reference
- Try to constrain formation model with locations and timeline

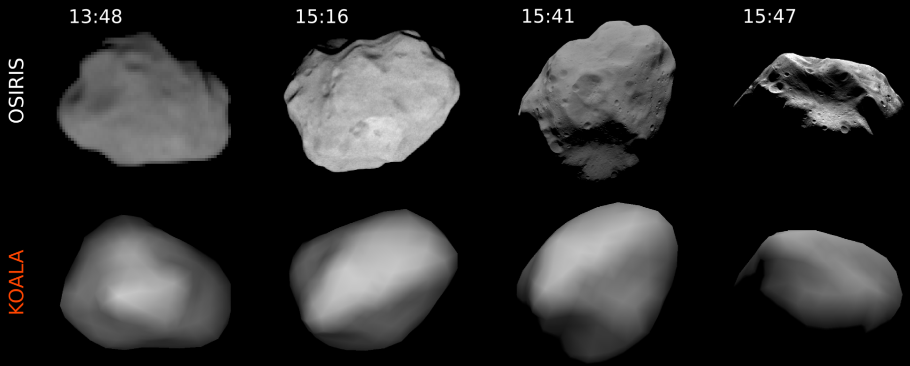
# Internal structure




- Rock *vs* rock-ice → **Location** of formation
- Differentiation → Thermal history → **Time** of formation
- Collisions → Craters, cracks, and porosity

**Extremely complex to determine**

# A new perspective with adaptive optics



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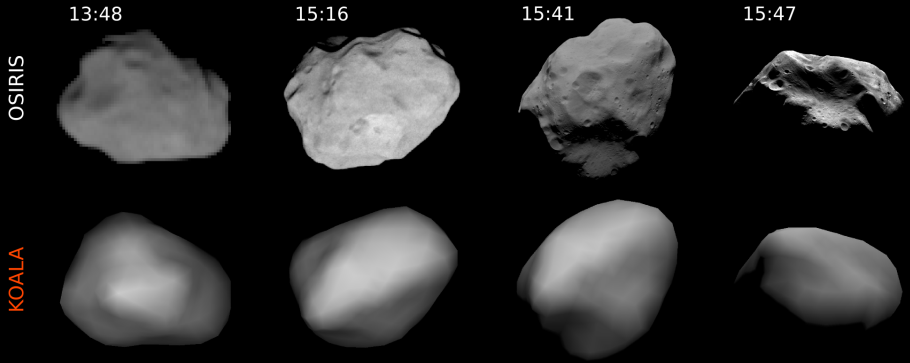
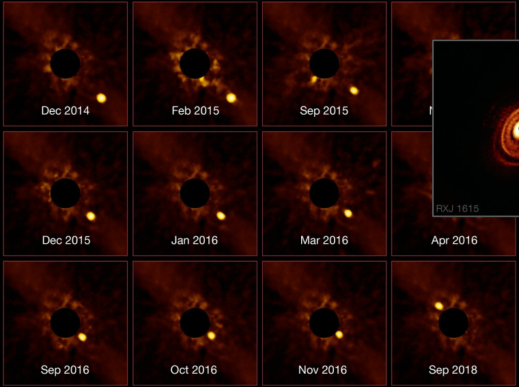


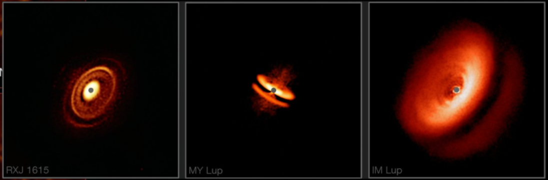

**Pre-flyby model**
KOALA
300 000 000 km

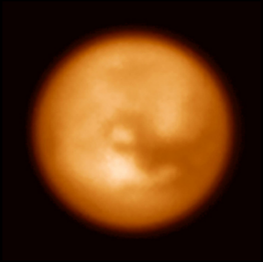
**vs. Rosetta**
Shape RMS **2** km
3 000 km

**Accuracy**
**Diameter @ 2–5%**
Carry et al. 2010b, 2012

# SPHERE @ ESO VLT



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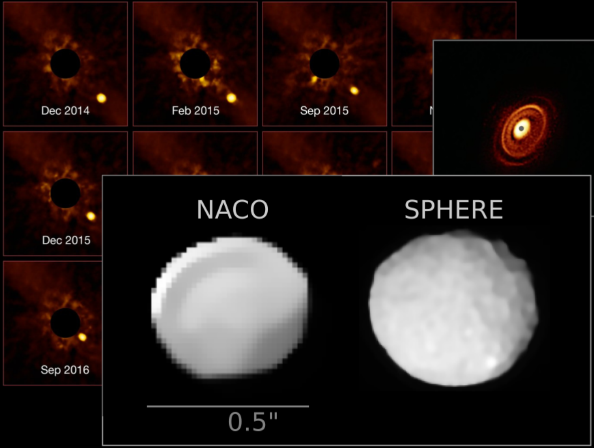
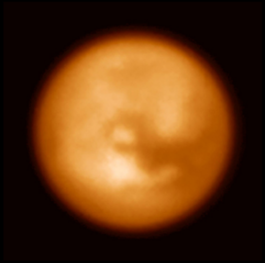






# ESO Large Program: HARISSA

- ESO Large Program
  - 152 h with SPHERE
  - 4+1 semesters
  - SPHERE/ZIMPOL: 3.5 mas/pix

  PI: Vernazza

- Asteroid sample
  - 35 targets
  - All compositional groups
  - Multiple systems

- Building 3D models
  - 6 epochs per target
  - Combining LC+Occ+AO
  - `ADAM` algorithm

  Viikinkoski+2015

- Dynamics of satellites
  - LOCI processing
  - Archives of large telescopes
  - `Genoid` algorithm

  Vachier+2012

# HARISSA is a Tour of the asteroid belt

(21) Lutetia

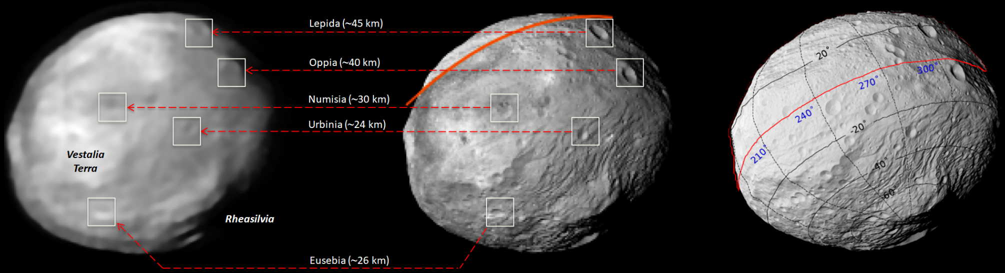
ESA Rosetta

(7) Iris

VLT SPHERE

| Distance | 70,000 km | 135,000,000 km |
| --- | --- | --- |

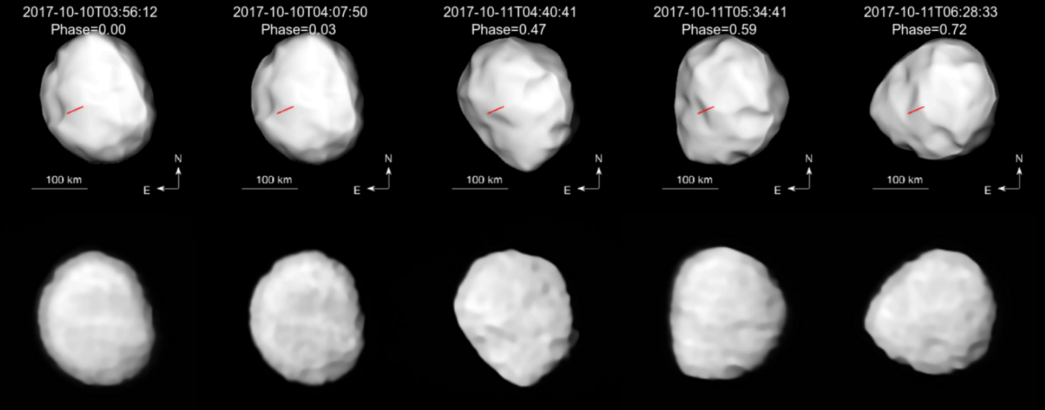
# What to expect from HARISSA?




Fetick+2019

- (4) Vesta
  - NASA Dawn
  - Diameter ≈0.6″
- Size measurement
  - RMS 0.93 pixel
  - Diameter @ 1%
- Feature recognition
  - Above ∼30 km
  - 80% detection rate

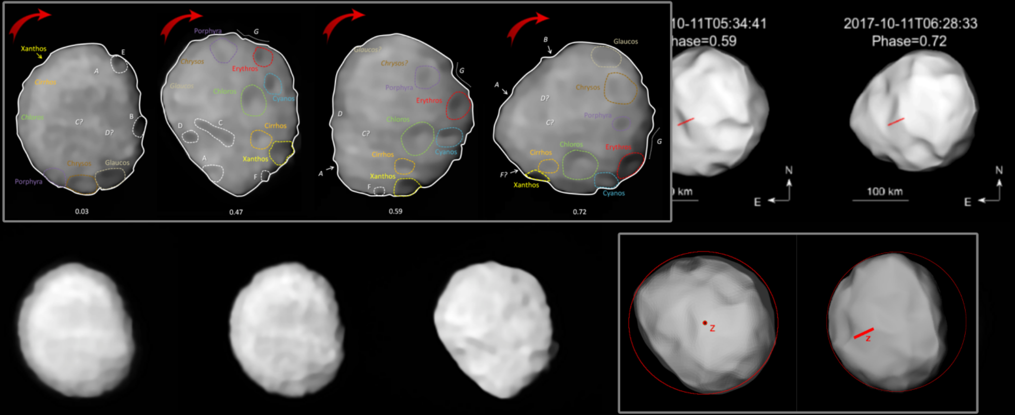
# (7) Iris and the impact rate among asteroids




Hanus+2018

# (7) Iris and the impact rate among asteroids

20-40 km craters




Giant basin?

Hanus+2018

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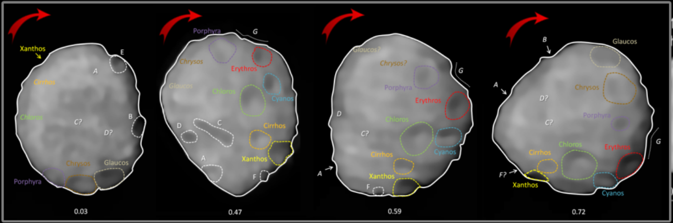


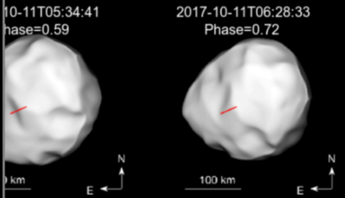


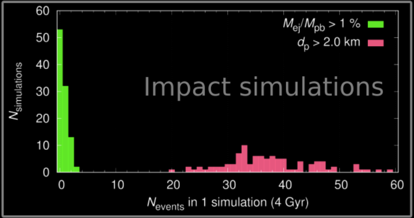


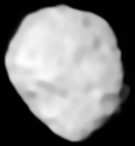

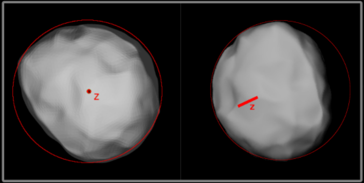

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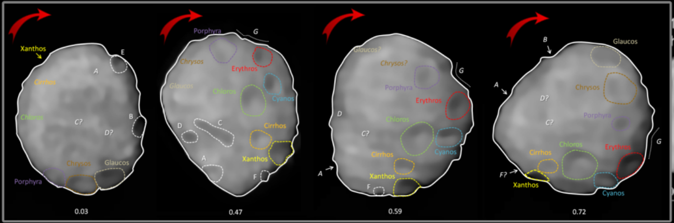
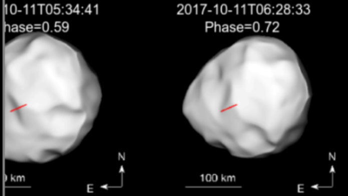
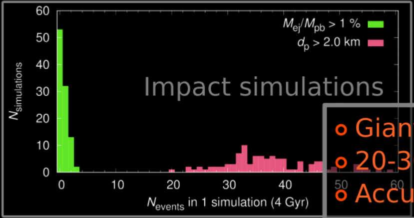
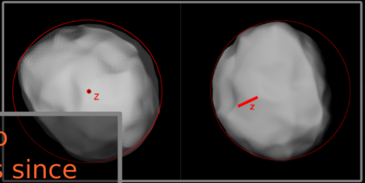


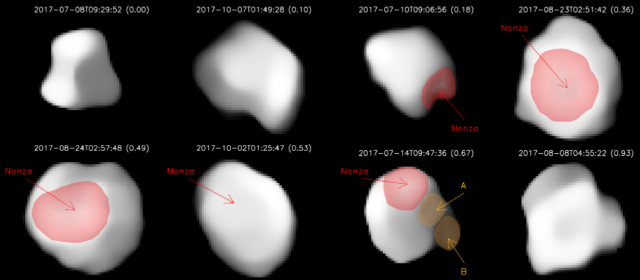



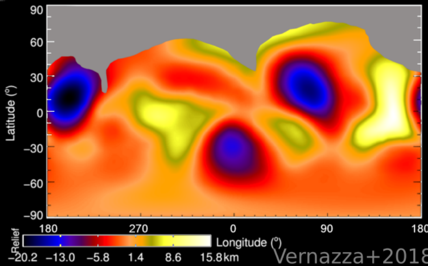




- Giant impact 3 Gy ago
- 20-30 regular impacts since
- Accurate models of population

Hanus+2018

# The impact at the origin of (89) Julia's family




Vernazza+2018

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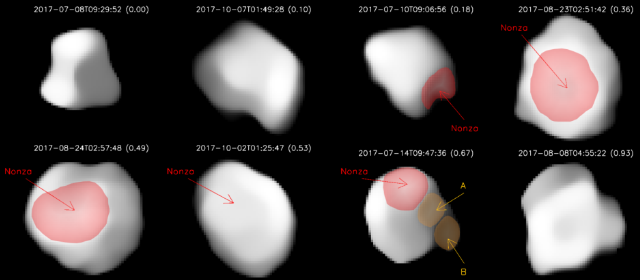
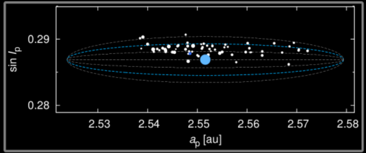
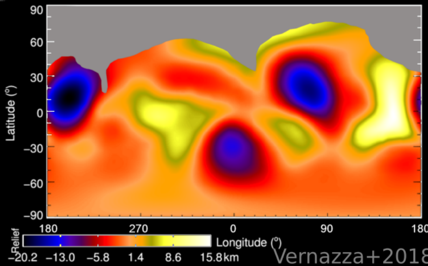



Small but peculiar family




Vernazza+2018

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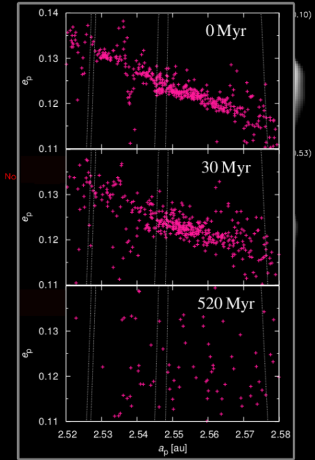
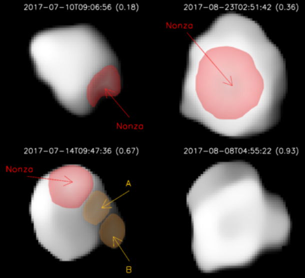



Dynamical evolution

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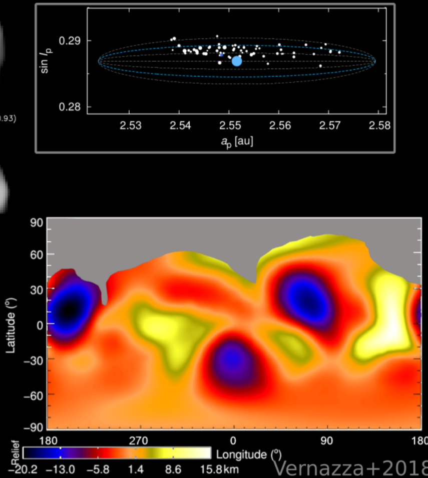


Vernazza+2018

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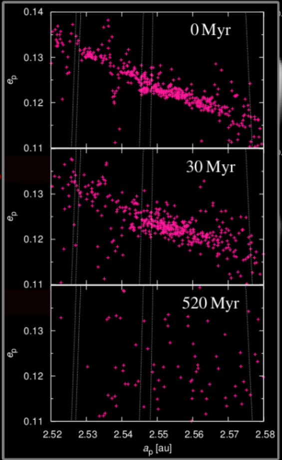
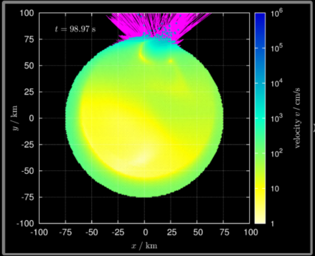



Dynamical evolution

Impact simulations

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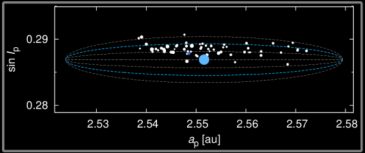


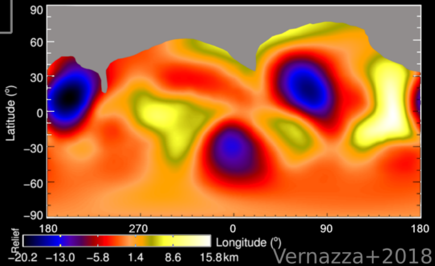


Vernazza+2018

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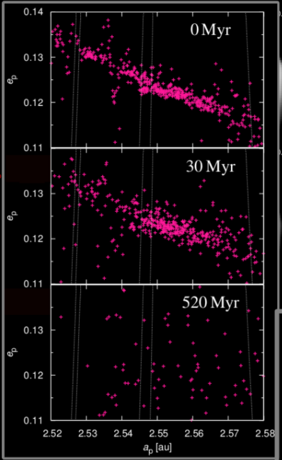


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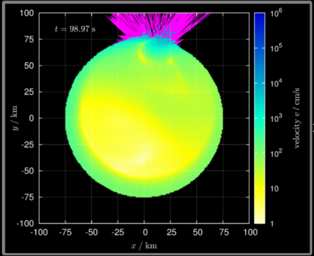


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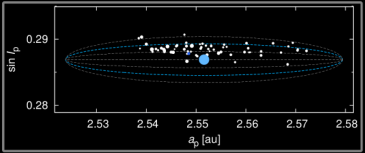
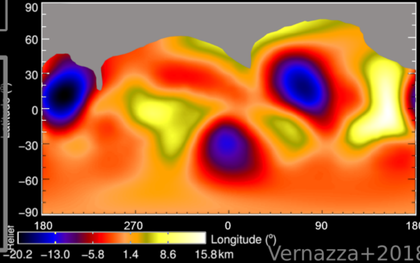
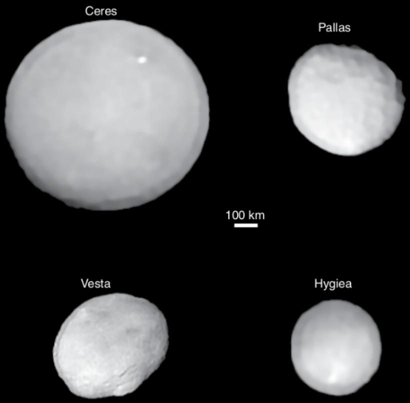



- Family 30-120 My
- Nonza: 75 km crater (half the size of Julia)
- 8 km impactor
- Link crater to family




Vernazza+2018

# Major impact at (10) Hygeia




Vernazza+2019

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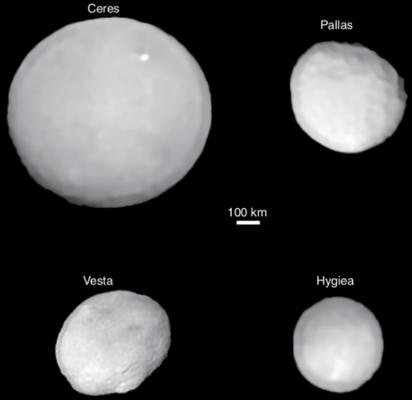
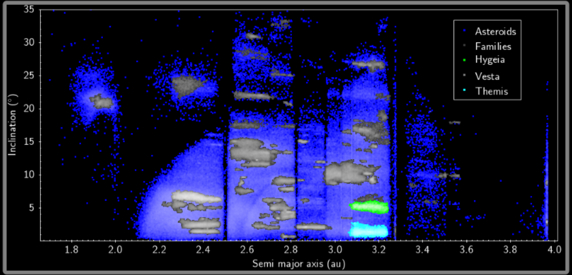



Second largest family in the asteroid belt




Vernazza+2019

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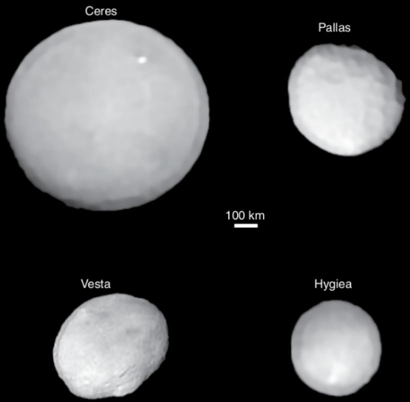


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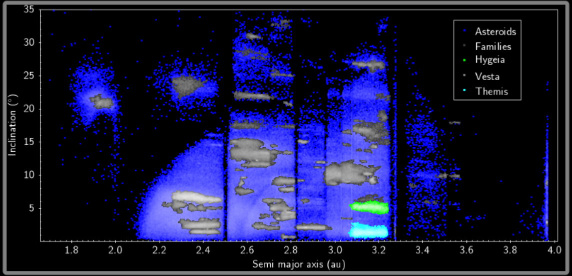


Vernazza+2019

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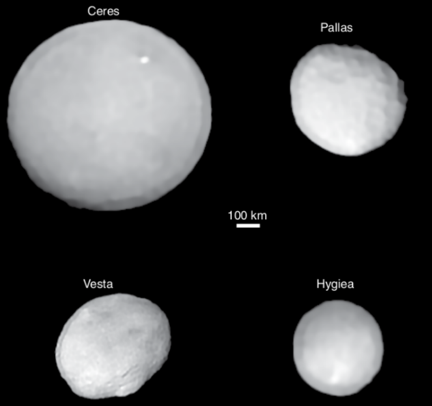


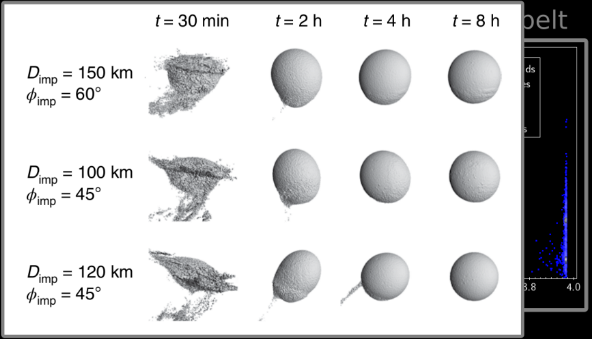


Impact simulations

Vernazza+2019

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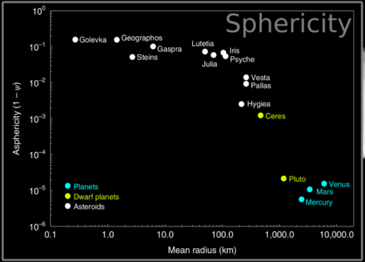
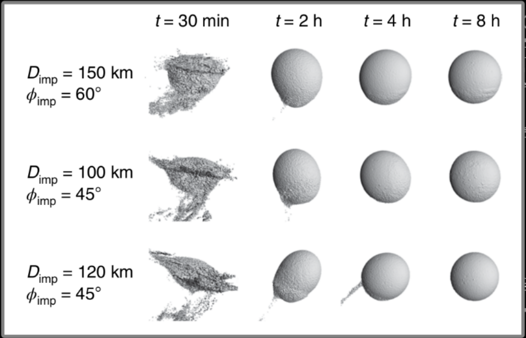



Vesta Hygeia

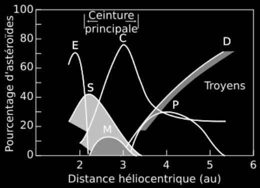
- Prominent old family
- Absence of basin! (vs Vesta)
- 75-150 km impactor
- Complete breaking of Hygeia
- A new dwarf planet?

Impact simulations

Vernazza+2019

# Rogues from the Outer Solar System?

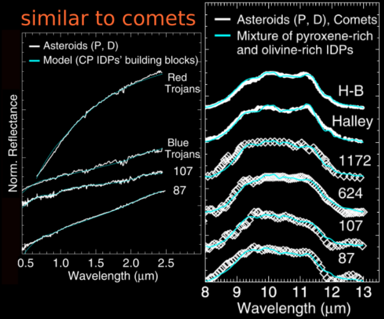
C/P/D asteroids dominate the outer belt




Gradie & Tedesco 1982

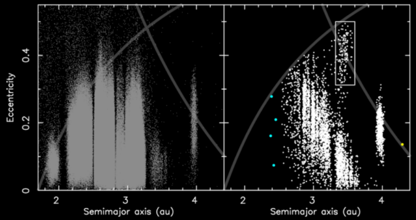
Absent from meteorite record

Compositionnally similar to comets



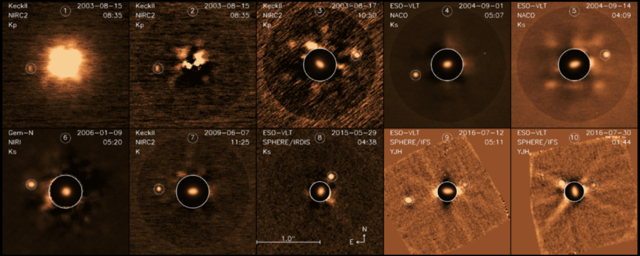

Vernazza+2015

Vokrouhlický+2016




C/P/D are KBOs injected into the asteroid belt

# Satellites and density




Pajuelo+2018

Focus on binary systems

- Challenge: $\Delta m > 5$ @ 0.5"
- Data processing ~ exoplanet
- Most archival data not published (!)

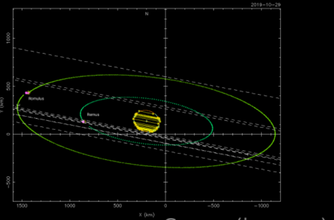
SPHERE & HARISSA

- A new binary: (31) Euphrosyne
- Second satellites to (107) Camilla & (130) Elektra

Yang+2014, Marsset+2017, Vernazza+2019

Orbits of satellites

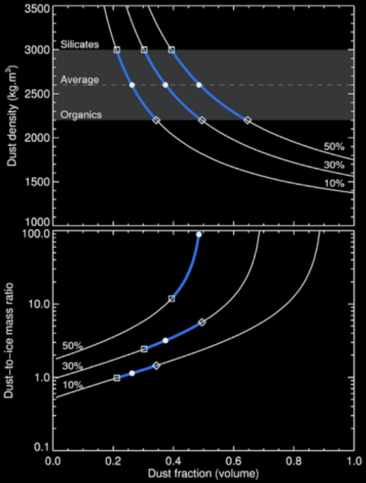
- Sub-pixel accuracy
- Masses of components
- Ephemerides to occultations




Carry+(in prep.)

Density

# Ice to rock ratio

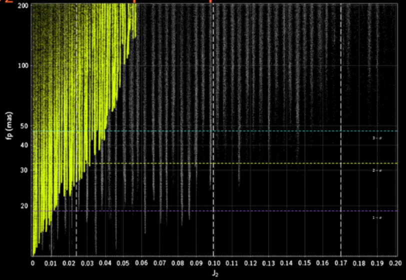


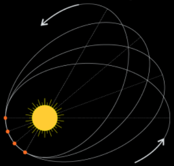

Pajuelo+2018

1. **Density of P/D asteroids is LOW**
   - Camilla: $1280 \pm 260\,\mathrm{kg{\cdot}m^{-3}}$ Pajuelo+2018
   - Sylvia: $1365 \pm 75\,\mathrm{kg{\cdot}m^{-3}}$ Carry+(in prep)
   - Patroclus: $800 \pm 150\,\mathrm{kg{\cdot}m^{-3}}$ Marchis+2005
   - Consistent with KBOs Carry2012
2. **P/D made of rock+ice+void**
   - Rocks: 2200 to 3000 (StarDust) Brownlee+2006
   - Ice: $900\,\mathrm{kg{\cdot}m^{-3}}$
   - Porosity from cracks/fractures
   - a.k.a. **big** 67P/C-G
3. **Infered internal structure**
   - Ice-to-rock ratio 4:1 (C-G like)
   - Porosity 30%
   - Rocky interior and outer ice-rich shell?

# Probing the internal structure

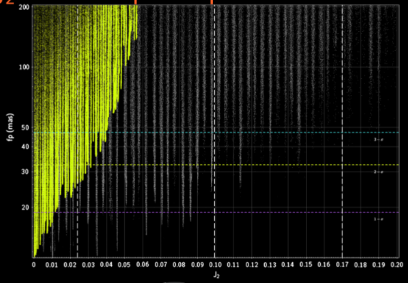
## $J_2$ induce apside precession

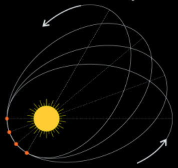


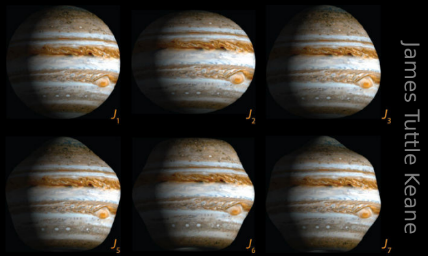



# Probing the internal structure

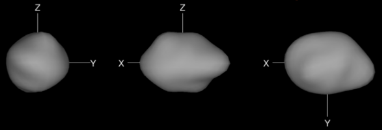
## $J_2$ induce apside precession








## $J_2$ measured from the shape



Berthier+2014

# Probing the internal structure

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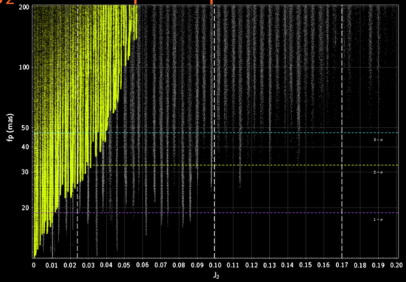
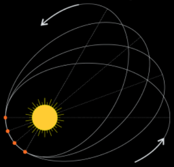
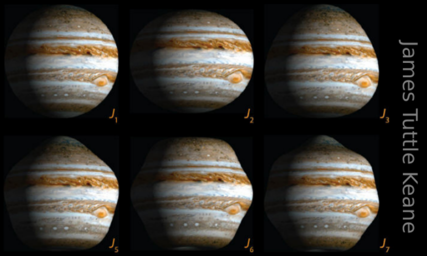


- $J_2$ (shape) > $J_2$ (dynamics)
- Mass is more concentrated (and less oblate)
- P/D = mixture of rock & ice from the outer solar system

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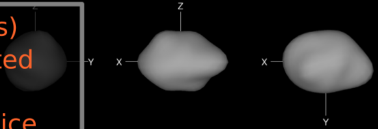
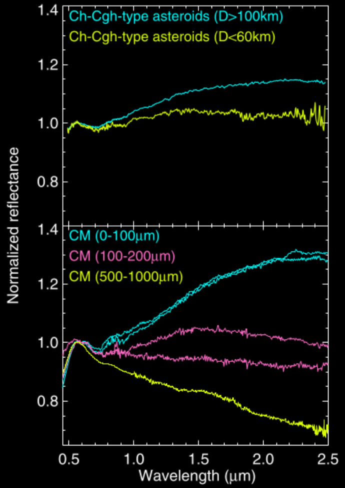



Berthier+2014

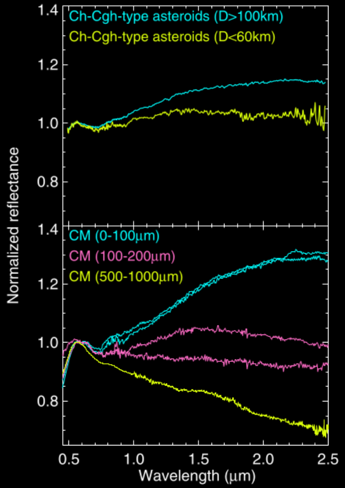
# Giant Mud Balls in the Solar System?




Vernazza+2016

1. **CM carbonaceous chondrites**
   - Primitive composition
   - Extensive hydration
   - Low peak T: ≤120-150° C
2. **Linked with Ch/Cgh asteroids**
   - 10% of all asteroids by mass
   - Hydration signatures
   - Homogeneous composition
   - Vernazza+2016
3. **Giant Mud Balls Hypothesis**
   - Body-wide convection
   - Homogeneous parent bodies
   - Strong implication on structure
   - Bland & Travis 2017

# Giant Mud Balls in the Solar System?

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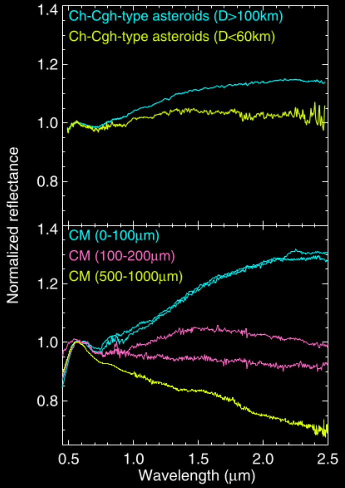


Vernazza+2016

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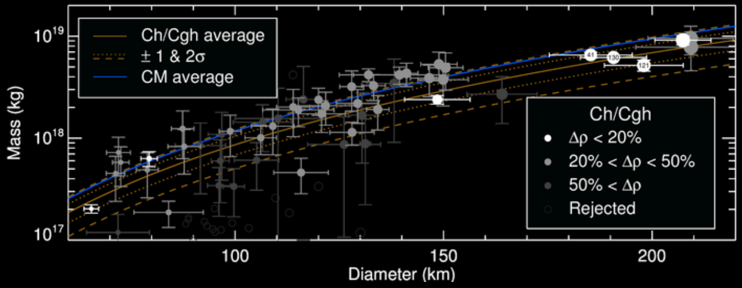
# Homogeneous structure of Daphne supports it!

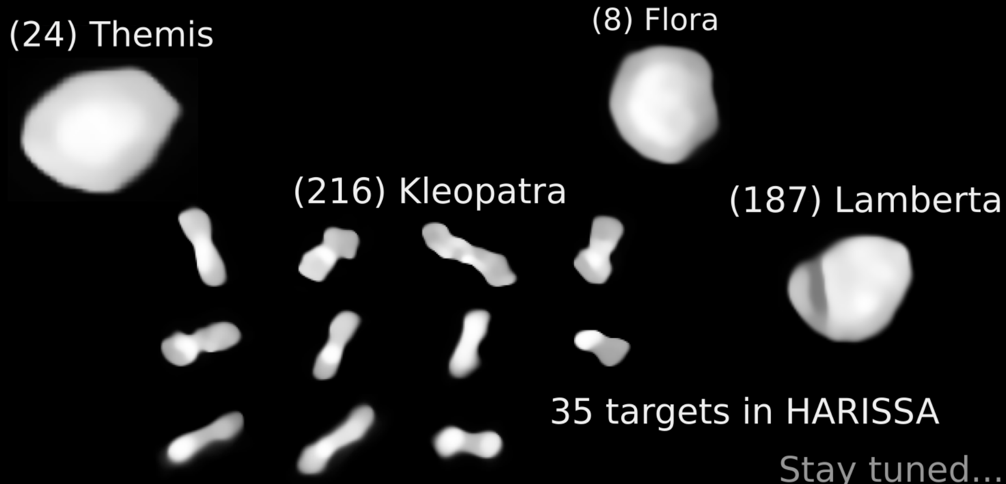



Carry+2019

- (41) Daphne
  - Shape → volume
  - Satellite → masse
- Compiled 77 Ch/Cgh
  - $\rho \lesssim$ CM
  - Homogeneous structure
- Formation (from CM)
  - Farther than Jupiter
  - 3.5-4.5 My after CAI

# HARISSA visits the Asteroid Main Belt

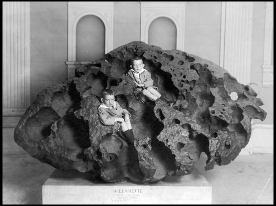
- Extreme AO offers a new window for asteroid study
  - VLT/SPHERE resolves angularly 100+ km asteroids
  - Equivalent to distant flyby
  - ELT/TMT? Not at first light. Then 5x better!
- Count craters and collisions among asteroids
  - Large crater statistics from the ground!
  - Trace impact to family to meteorites
  - Material strength to shocks
- Peer into internal structure and origins
  - Density and structure from 3D and satellite
  - Reveal formation location & timing
  - Push further Solar System formation models




35 targets in HARISSA

Stay tuned...

# (16) Psyche




American Museum of Natural History

www.elabarts.com

- **Evidence for asteroid differentiation**
  - Ni-Fe meteorites (*80+ parent bodies*)
  - Asteroids with high radar albedo
  - But where is the *mantle* material?

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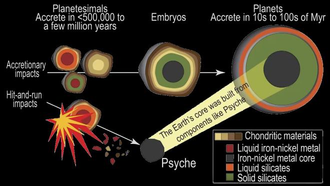


NASA

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  - Ni-Fe meteorites (*80+ parent bodies*)
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  - ▷ But where is the *mantle* material?
- **NASA Psyche Discovery mission**
  - Orbiter to Psyche [2022-2026-2028]
  - Remnant of iron core
  - ▷ Challenged by density & silicate detection

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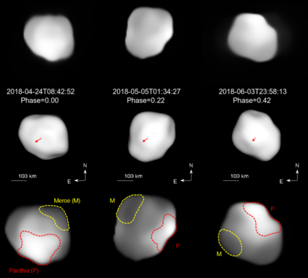


Viikinkoski+2018

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  - Remnant of iron core
  - ▷ Challenged by density & silicate detection
- **HARISSA meets Psyche**
  - Density $= 3{,}990 \pm 260\,\mathrm{kg{\cdot}m^{-3}} \ll$ iron
  - Meso-siderite parent body?
  - ▷ Expect surprises with Psyche