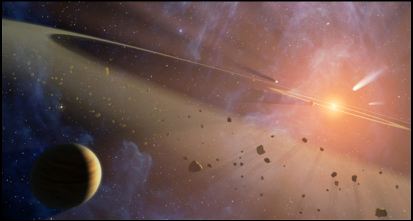
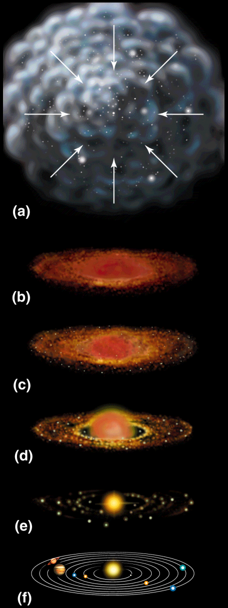
The asteroids and the early Solar System



B. Carry
European Space Agency

Resume of planetary formation



Step-by-step

a. Gas & dust cloud contracts
b. Disk forms
c. Rotation, accumulation @ center
d. A star is born
e. Accretion within the disk
f. Planetary system

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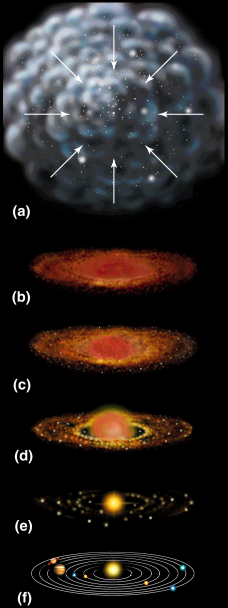

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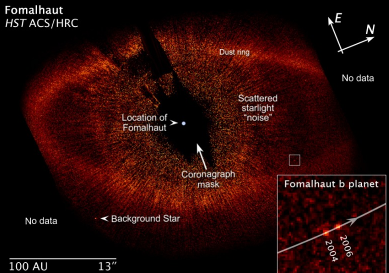

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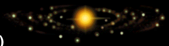
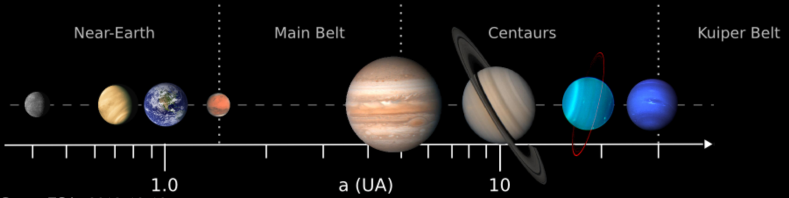

(e)

Interest of asteroids

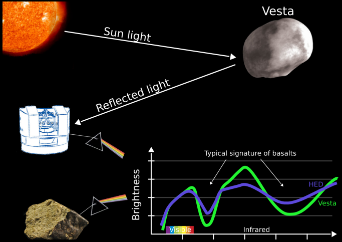
1. Large population
   - 600 000 objects (*several millions*)
   - Sample the whole Solar System [1–100 AU]
   - Sample all the compositions [rocks → ices]
2. Primitive population
   - Small objects [km]
   - Internal energy ≈ null
   - No endogenous activity

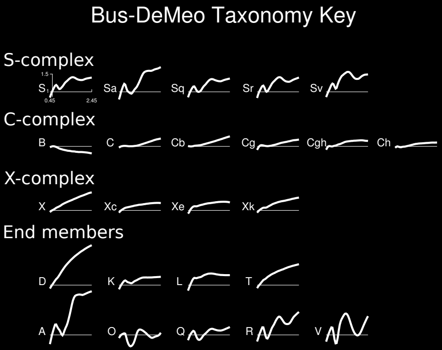
▷ Direct witnesses of the early Solar System



The 1982's view

1. Asteroid **taxonomy**
   - Reflectance
   - Albedo
   - 24 classes
2. Strong **gradient** in **1 AU**
   - X : Iron cores
   - V,A : Crust & Mantle
   - S : Melted silicates
   - C : Most primitive
   - D,T : Comet nucleus ?
3. **Paradigm** from 1982
   - Survey of 800 asteroids
   - Visible spectrometry
   - ▶ **In-situ formation**





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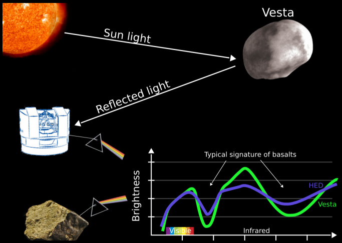
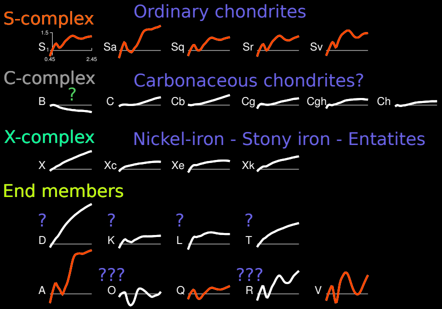


Bus-DeMeo Taxonomy Key



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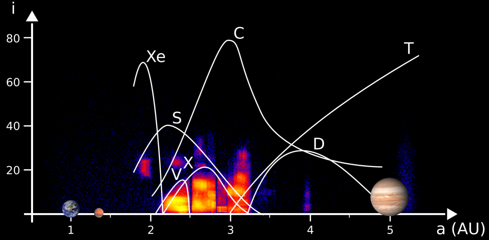
Relative fractions of classes



Adapted from Gradie and Tedesco, 1982

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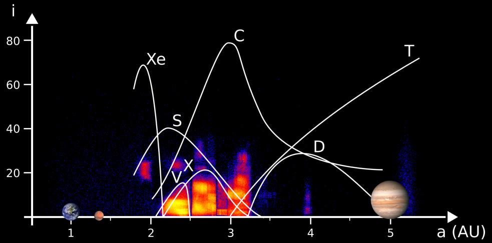

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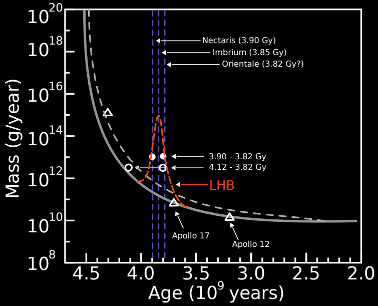
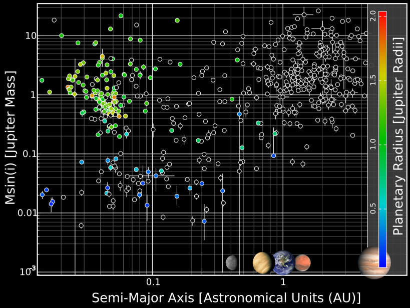
Some open questions





- Late Heavy Bombardment •

Excess cratering @ 3.8 Gy

Thick disk for accretion

Tiny fraction remains

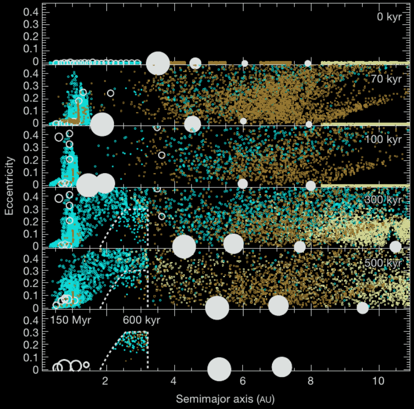
- Planetary migration •

Hot Jupiters

Migration within disk

Solar System ?

The Grand Tack & Nice model



Walsh et al. 2011

A. Grand Tack – **100 kyr**

- Jupiter inward migration
- Stopped by Saturn
- **Inner** Solar System

B. The Nice Model – **700 Myr**

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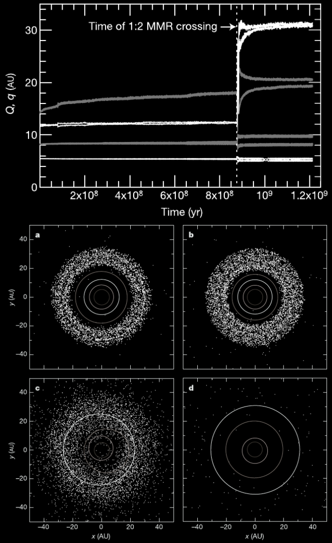
Overall result

- Complete mixing
- Removal of 99% mass

The Grand Tack & Nice model



Gomes et al. 2005

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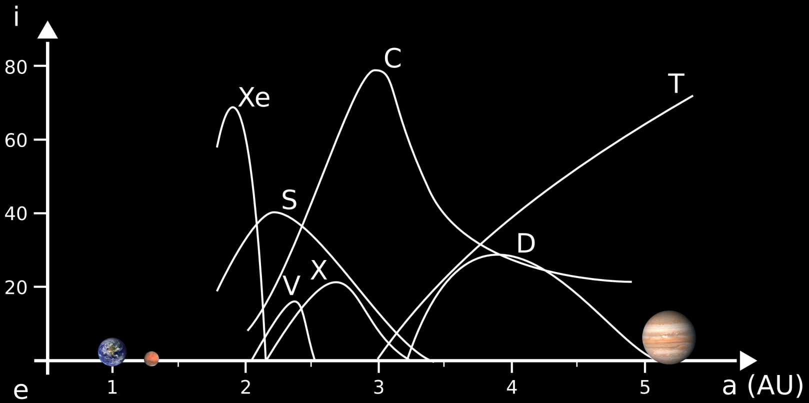

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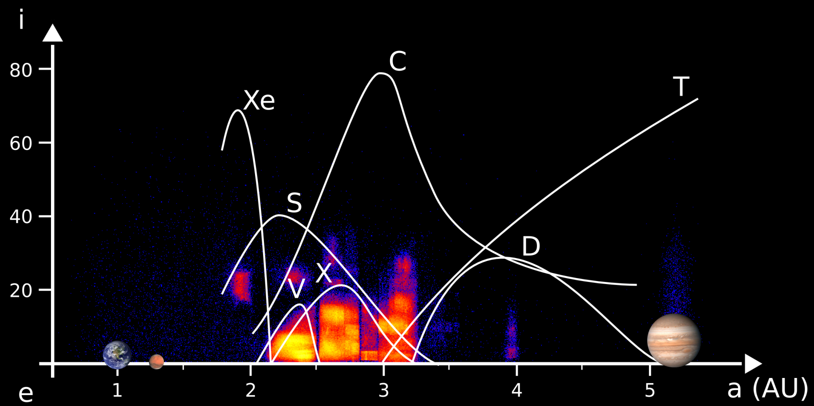

Adapted from Gradie and Tedesco, 1982

In-situ formation ?

Number instead of **mass** – Only **largest** asteroids

The era of all-sky surveys

1. Number of discoveries sky-rocketed in 30 years
   - 10,000 in 1982 ... 600,000 in 2012
   - **Completeness** vastly improved (2–5 km)
   - **Dynamic** models

2. Compositional information available for thousands of asteroids
   - **SDSS** : visible colours for 100,000 asteroids (*vs* 800)
   - **WISE** : albedo for 150,000 asteroids (*vs* 2000)
   - Large-scale taxonomy

3. **Density** is needed to convert numbers in **mass**
   - **Limiting factor**
   - How do we measure density ?

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How do we measure density ?

$$\rho = \frac{\mathcal{M}}{\mathcal{V}}$$

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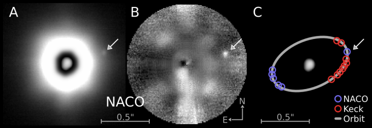
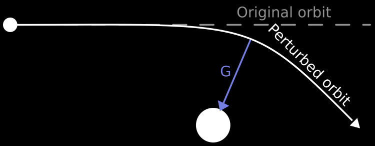
Mass measurements

Gravitational interaction





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   - Asteroid - Probe
   - **Precise** but rare
2. **Satellites**
   - Asteroid - Satellite
   - Precise and about common
3. **Deflection**
   - Asteroid - Asteroid
   - Low precision but common
4. **Ephemeris**
   - Asteroid - Everything
   - **Low** precision but **common**

Mass measurements

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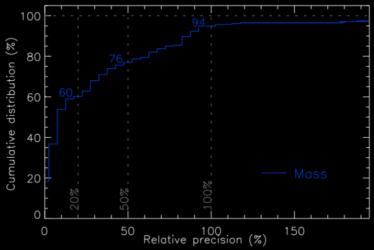

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Volume measurements

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- Masses : **287**
- Diameters :
  - IRAS : **2228**
  - AKARI : **10 000**
  - WISE : **150 000**
  - Gaia : **10 000**

Volume measurements

$$\rho = \frac{\mathcal{M}}{\mathcal{V}}$$

$$\frac{\delta\rho}{\rho} = \sqrt{\left(\frac{\delta\mathcal{M}}{\mathcal{M}}\right)^2 + \left(\frac{\delta\mathcal{V}}{\mathcal{V}}\right)^2} = \sqrt{\left(\frac{\delta\mathcal{M}}{\mathcal{M}}\right)^2 + 9\left(\frac{\delta\mathcal{R}}{\mathcal{R}}\right)^2}$$

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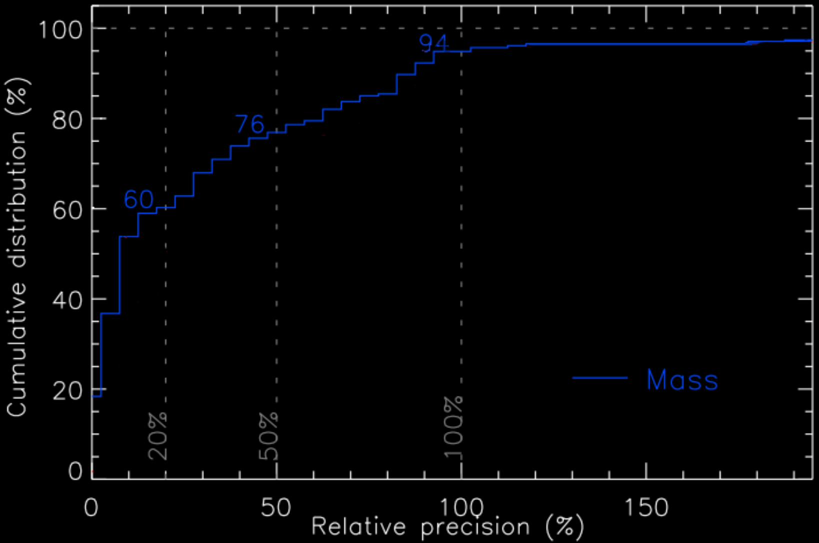
The **Volume** is (easily) the **Limiting Factor**

Summary of accuracy



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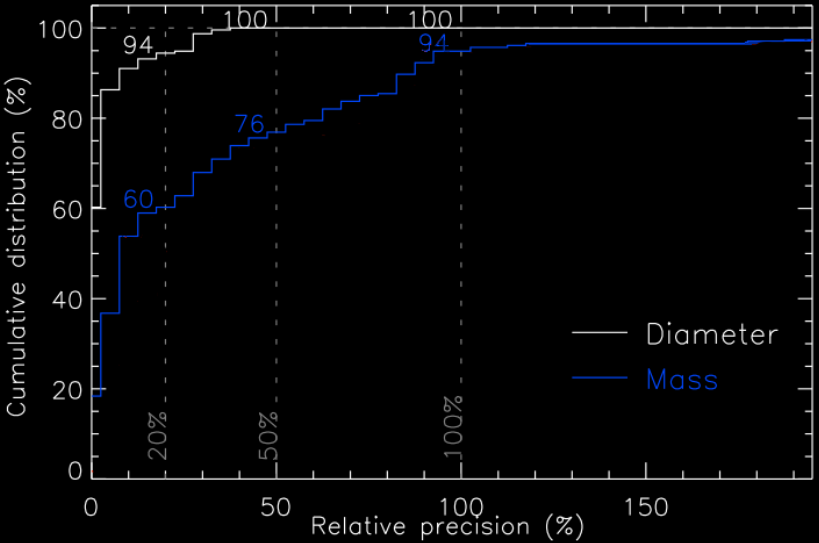

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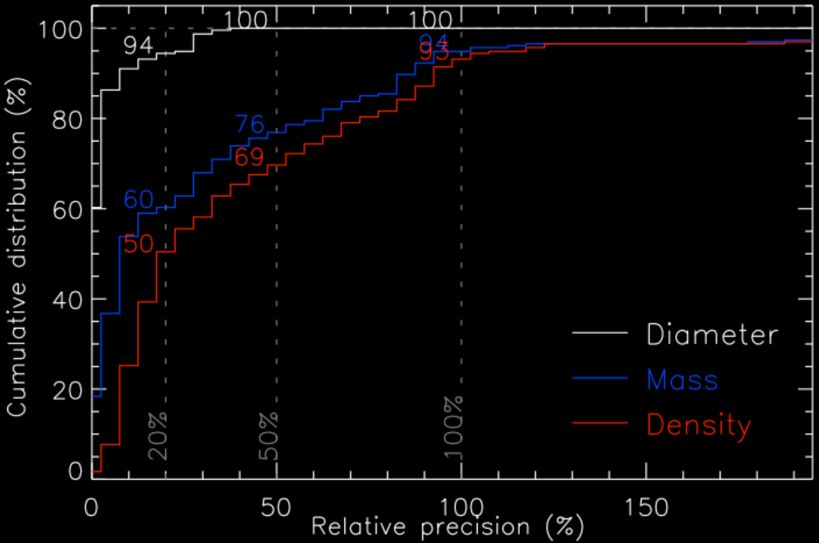
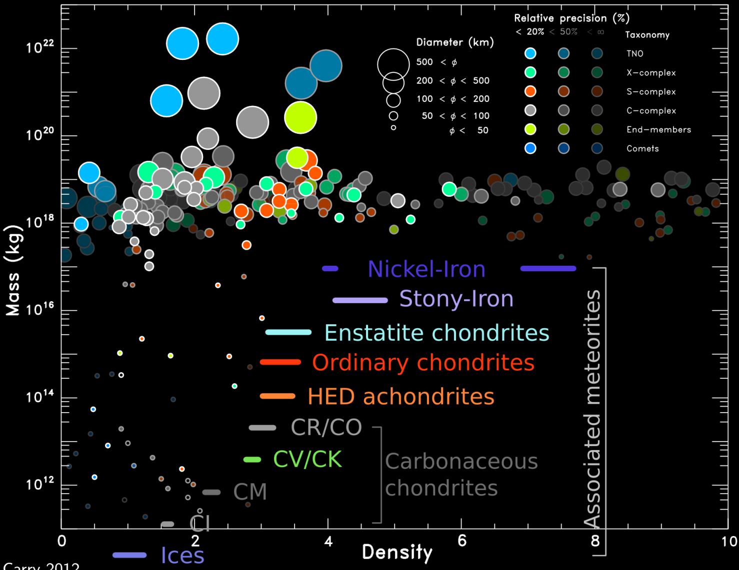
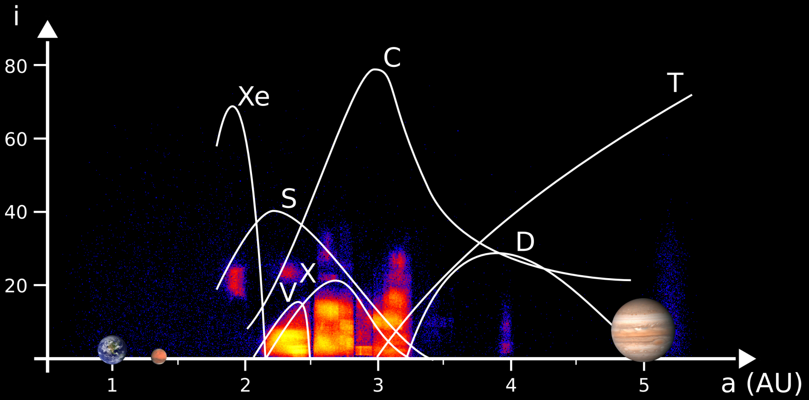


Current knowledge on density



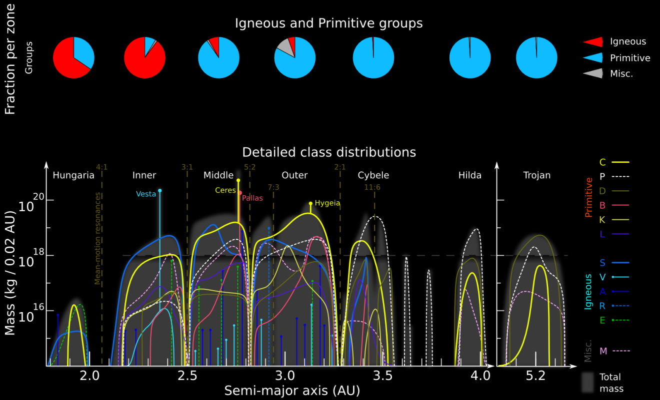
Carry 2012

Compositional distribution



Adapted from Gradie and Tedesco, 1982

Compositional distribution revised

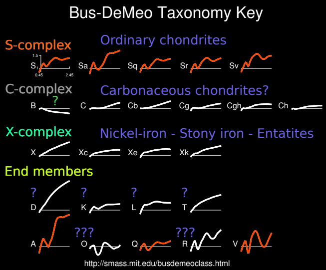


DeMeo & Carry

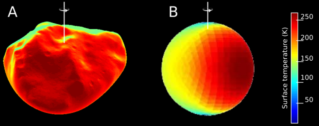
Composition distribution revisited is radically different !

- Almost complete **mix** everywhere
- **Absence** of mixing in Hilda & Trojan
  - ▶ Evidences for Grand Tack and Nice models

Open questions



No interpretation for 50%



Albedo biased

- **Meteorite & asteroid spectroscopy**
  - Now based on 0.5–2.5 μm
  - Wider spectral range : 3–5 & 5–40 μm
  - Albedo & thermal inertia
- **More asteroid analogs**
  - Laboratory experiments
  - Recovery campaigns
- **Density determinations**
  - Binary systems (now $\sim$50/200)
  - Accurate volume determination

Accurate volume determination

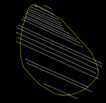
1. **Direct measurements**
   - **WYSIWYG** $\neq$ model-dependent
   - Disk-resolved imaging
   - Stellar occultations

2. **Realistic 3-D shape**
   - Assumptions $\Rightarrow$ Biases
   - Concavity $\Leftrightarrow$ Volume
   - Lightcurves (dense & sparse)

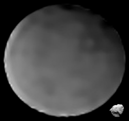
3. **Geometry completeness**
   - Extensive approach
   - Mid-IR radiometry
   - Interferometry
   - Radar echoes

(21) Lutetia

(135) Hertha



(1) Ceres



=

100 pesos

@ 2km

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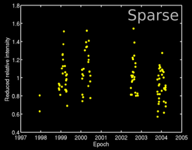

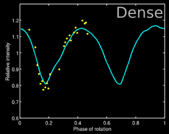

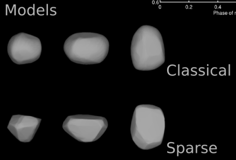

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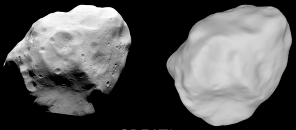
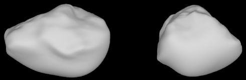
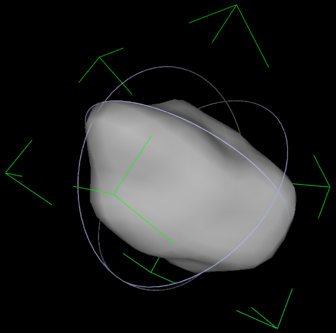


GREAT!



Not so great....

The concept of KOALA



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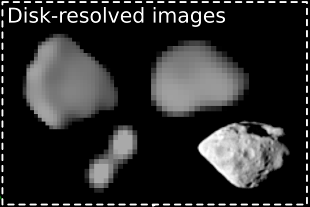
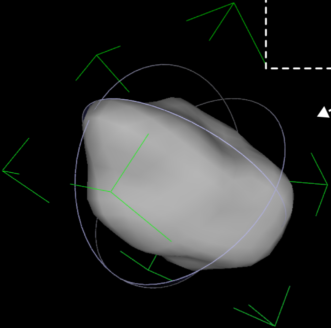
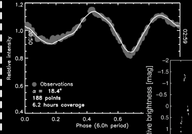


Direct Size
Direct Shape
Indirect Spin

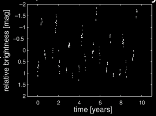


The concept of KOALA

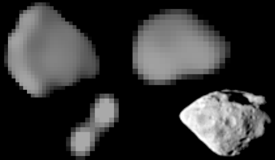
Lightcurves

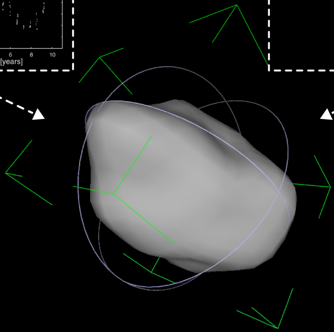


Sparse Photometry



Disk-resolved images

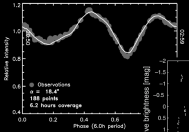




Direct	Spin
Indirect	Shape

The concept of KOALA

Lightcurves



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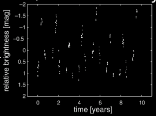
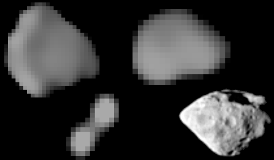
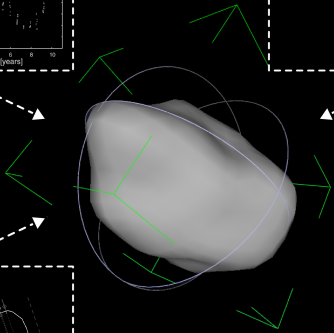


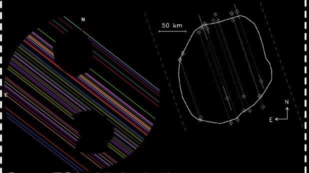
Disk-resolved images





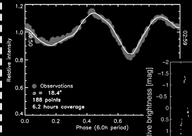
Direct Size
Direct Shape

Stellar occultations

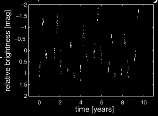


The concept of KOALA

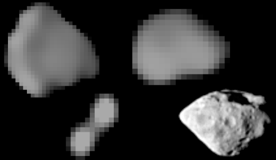
Lightcurves

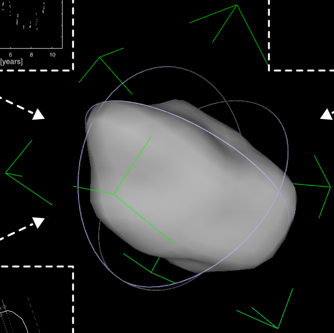


Sparse Photometry



Disk-resolved images

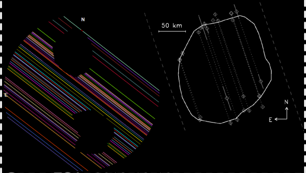




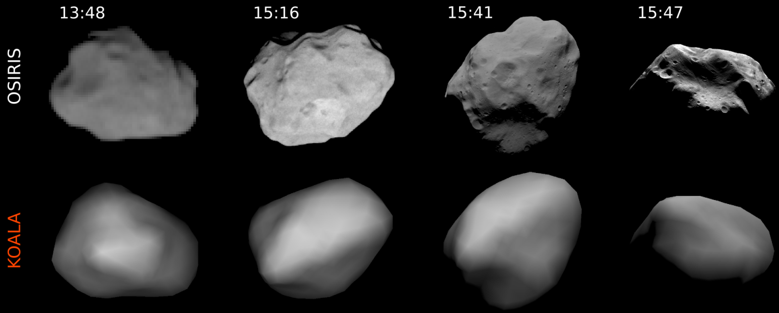
Knitted
Occultation,
Adaptive-optics, and
Lightcurve
Analysis

Carry *et al.*, Icarus 2010
Kaasalainen, IPI 2011
Carry *et al.*, P&SS 2012

Stellar occultations



Accuracy of KOALA

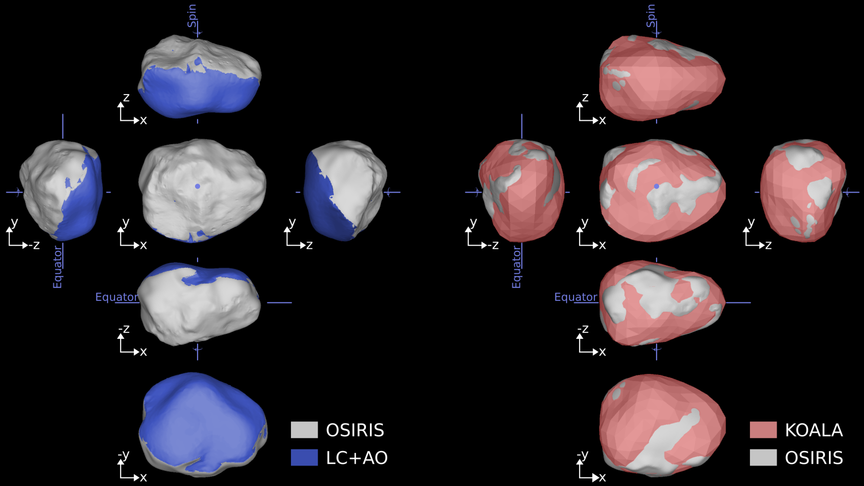


Pre-flyby model
KOALA
Carry et al. 2010

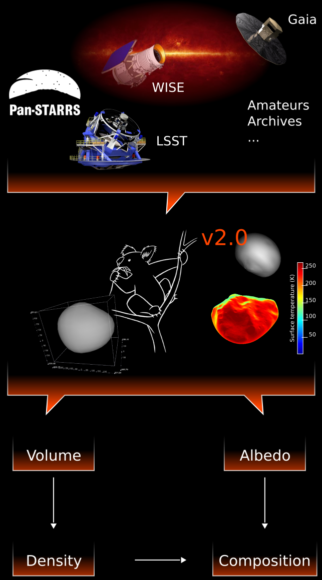
vs. Rosetta
Shape : **2** km RMS
Carry et al. 2012

Accuracy
Diameter $\sim$ 2%
Volume $\leq$ 15%

Accuracy of KOALA

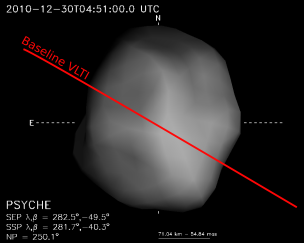


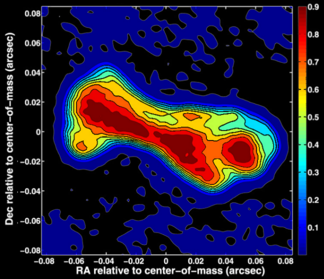
On-going research...



1. **Lightcurves & Stellar occultations**
   - Interactions with amateur community
   - Now 200 *convex* shape models available
   - Size determination for 25%
2. **Disk-resolved imaging**
   - AO camera on VLT, Keck, Gemini
   - **KOALA** shape modeling
   - Working on $\sim$30 objects
3. **Adding data modes in KOALA**
   - Mid-infrared (thermal) radiometry
   - Interferometry fringes
   - Radar echoes
   - Getting ready for **massive** inputs

On-going research...





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... up to 2020

- Spin
  - 10^5 objects
  - **Accretion epoch**
  - **YORP**, **Yarkovsky** (non $\vec{\mathcal{G}}$)
- Shape & Size
  - $10^4 - 10^5$ objects
  - Size-freq. distribution
  - **Dynamics** & **Collisions**
- Surface properties
  - $10^4 - 10^5$ objects
  - Albedo, reflectance
  - Link with **meteorites**
- Density
  - $10^2 - 10^3$ objects
  - **Composition**
  - **Internal structure**

Summary

- **Asteroids are remnants from the early Solar System**
  - Distribution of composition → initial conditions
  - Evidences for planetary migration like many exoplanets

- **Asteroid composition remains elusive in many cases**
  - Half of the classification lacks compositional interpretation
  - Still a lot of observational constraints needed

- **Surface and physical properties mostly unknown**
  - Albedo, thermal inertia, density → Composition
  - Period, spin, shape → YORP & Yarkovsky