Solar System Science Before and After Gaia

Shape models and densities of asteroids

THE POST-GAIA ERA

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with
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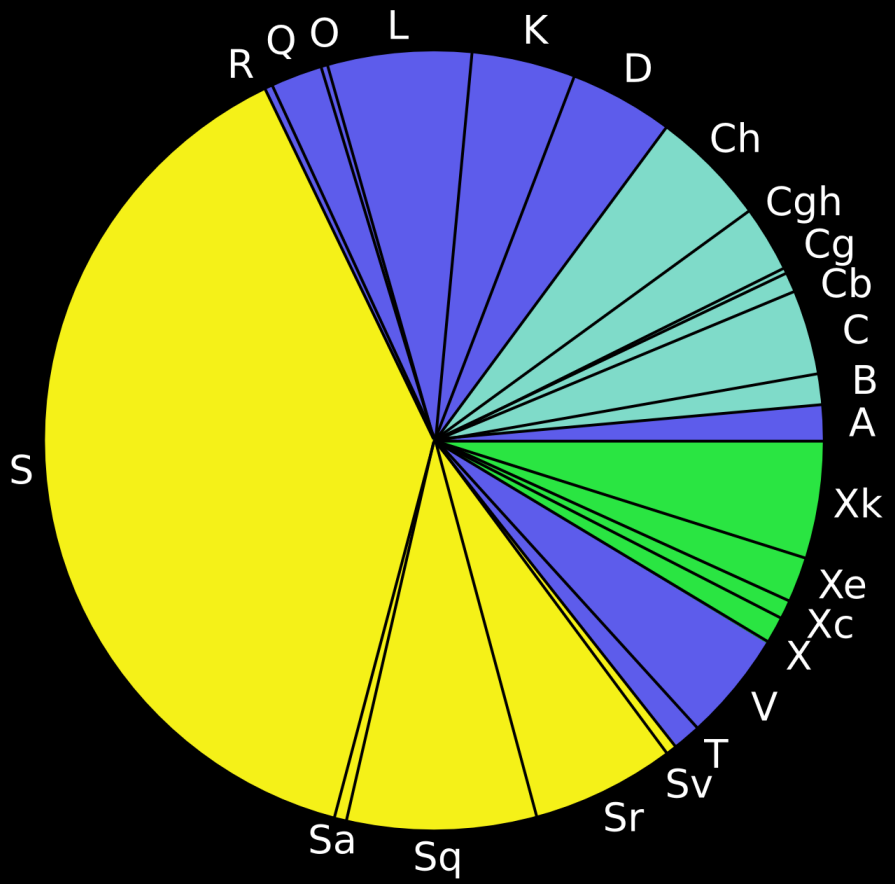
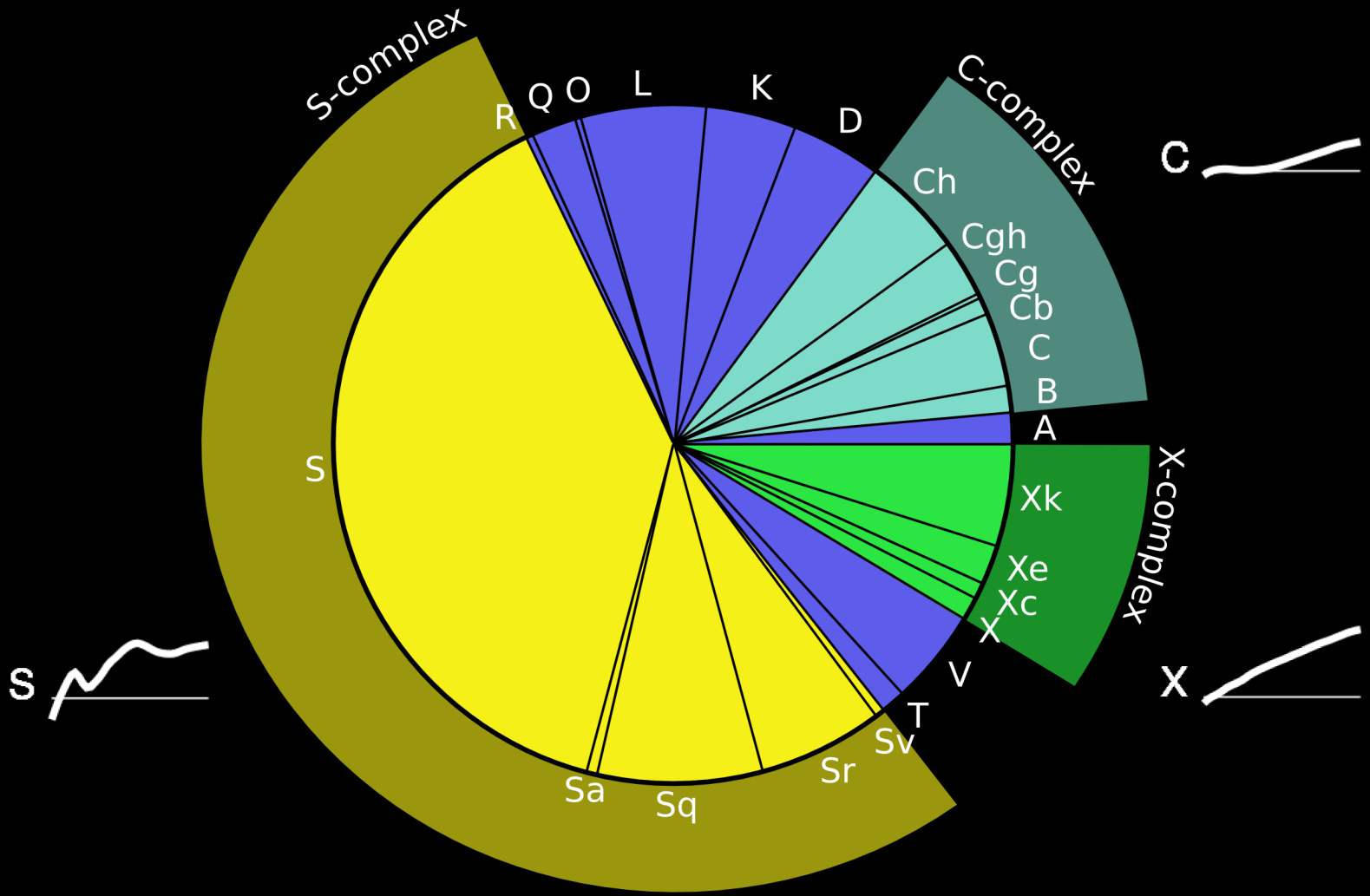
Density & Composition



based on DeMeo et al. 2009

Density & Composition



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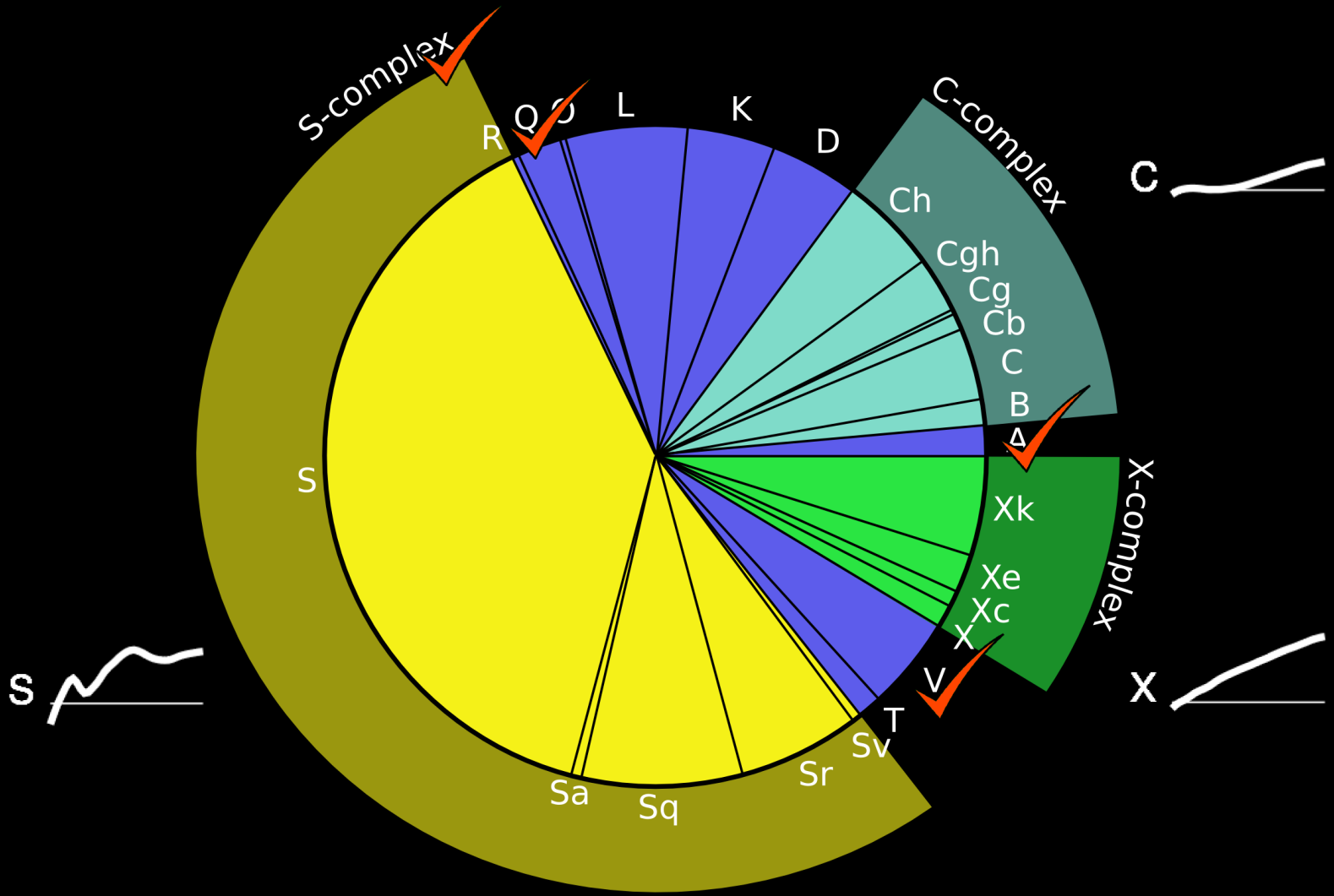

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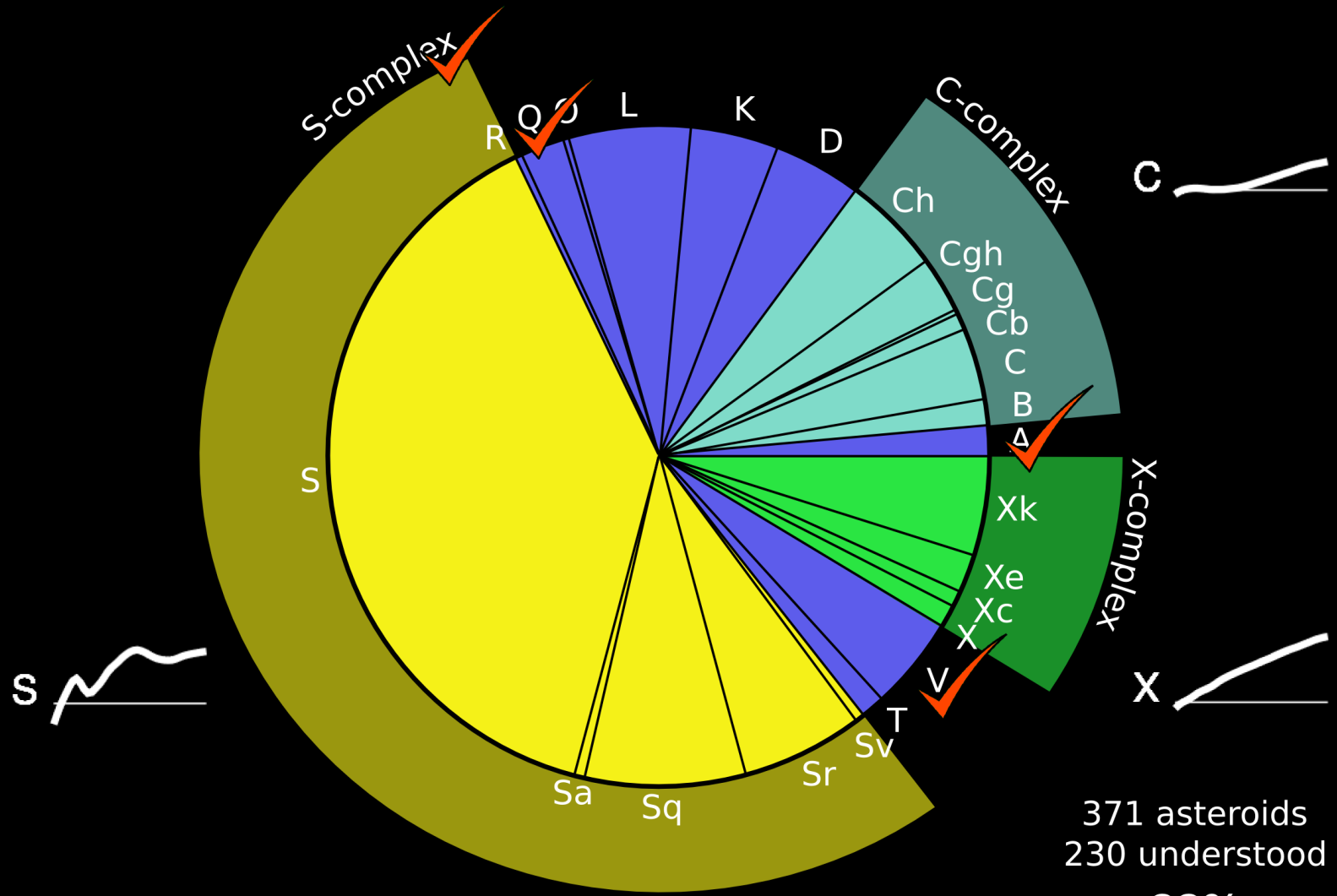

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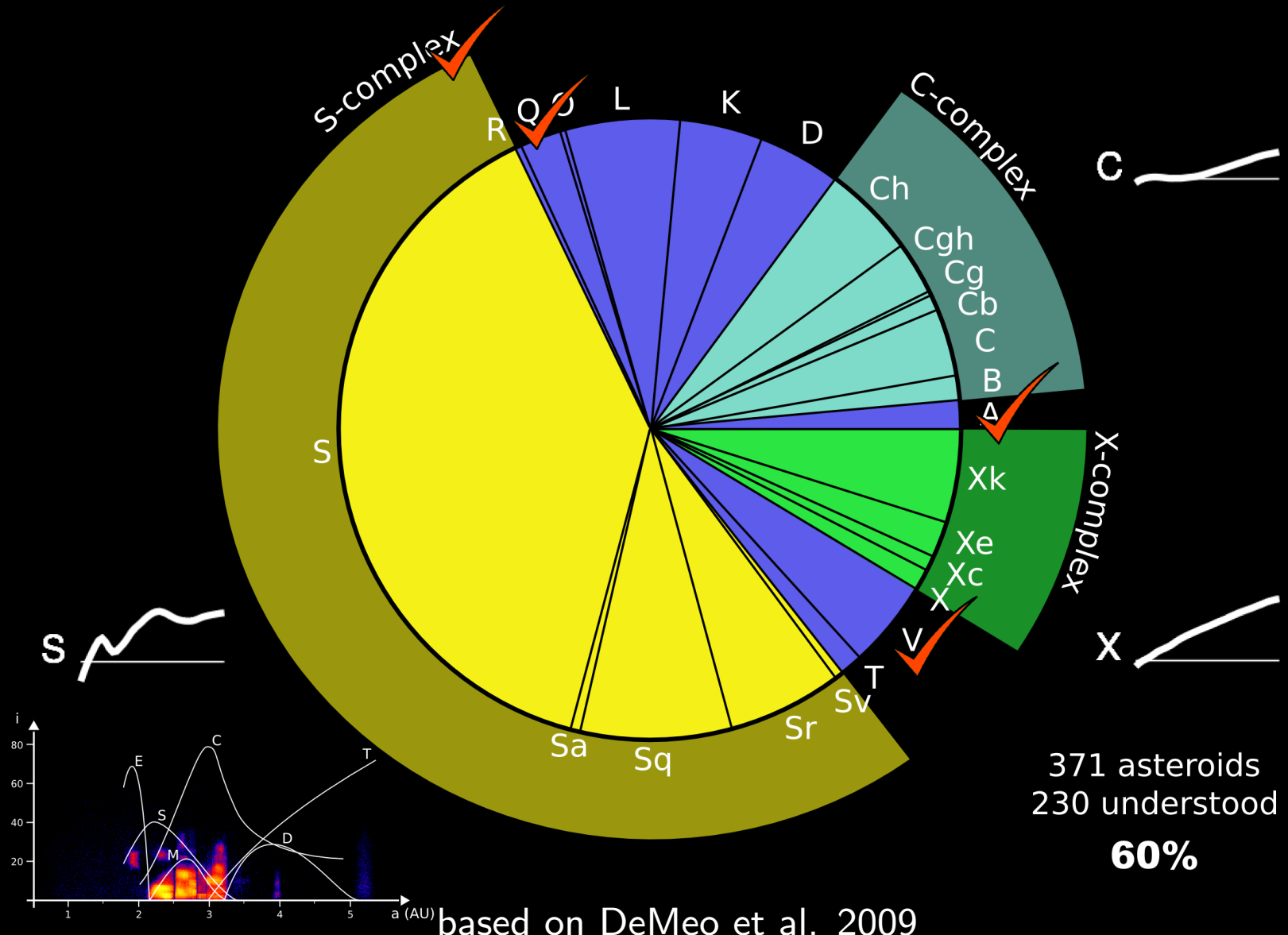
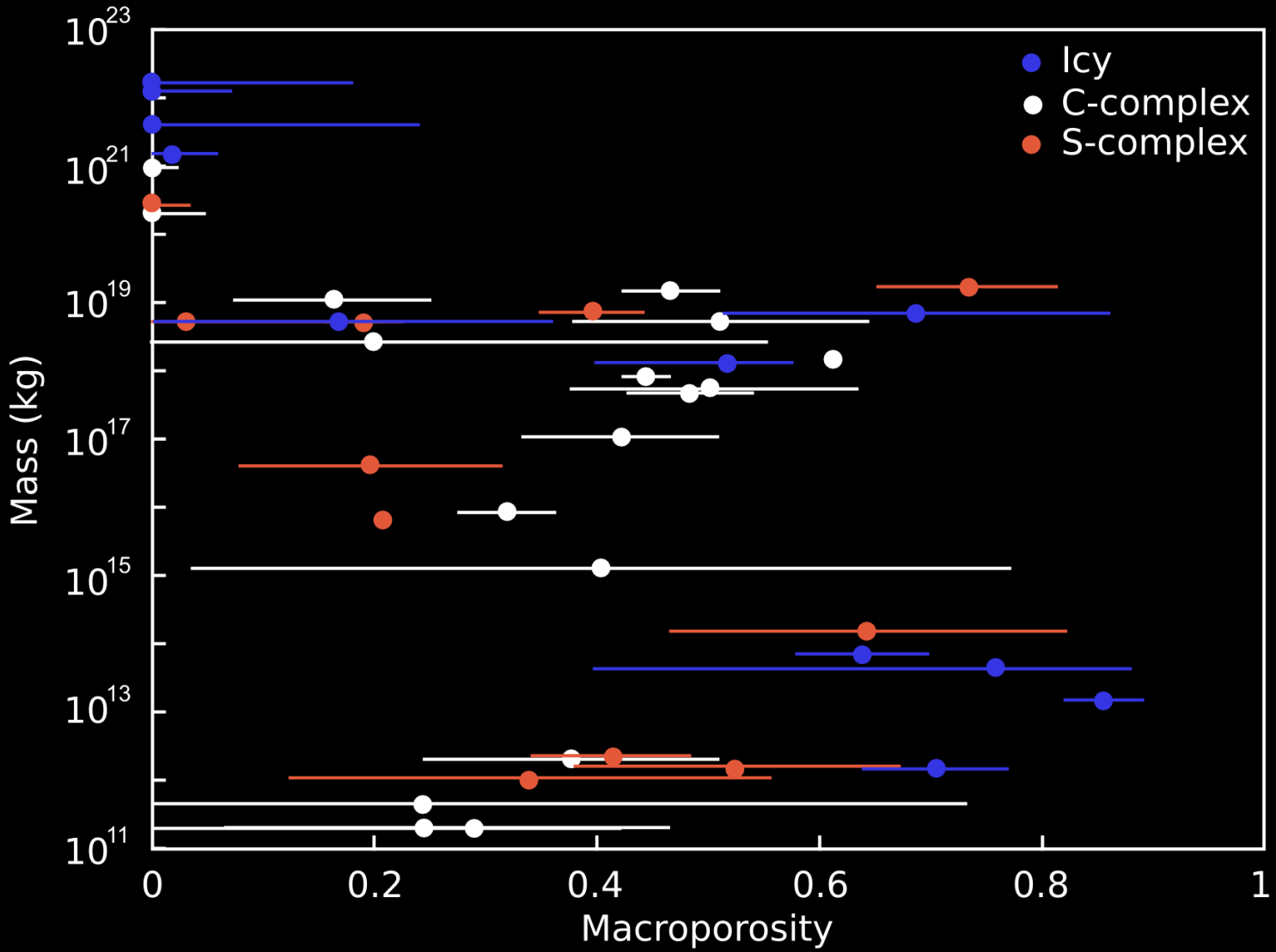
Density & Composition



371 asteroids
230 understood
60%

based on DeMeo et al. 2009

Density & Structure



adapted from Britt et al. 2006

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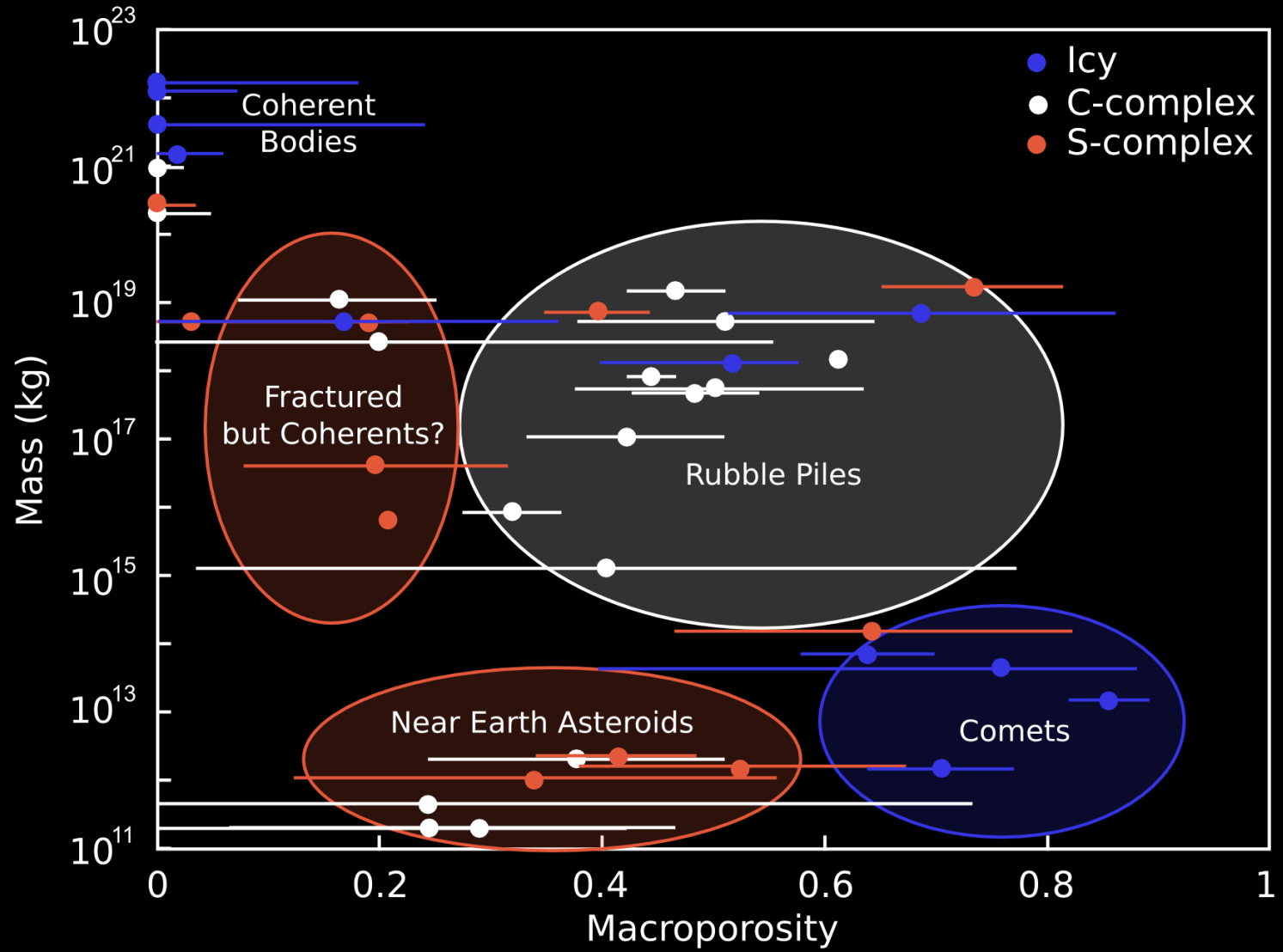

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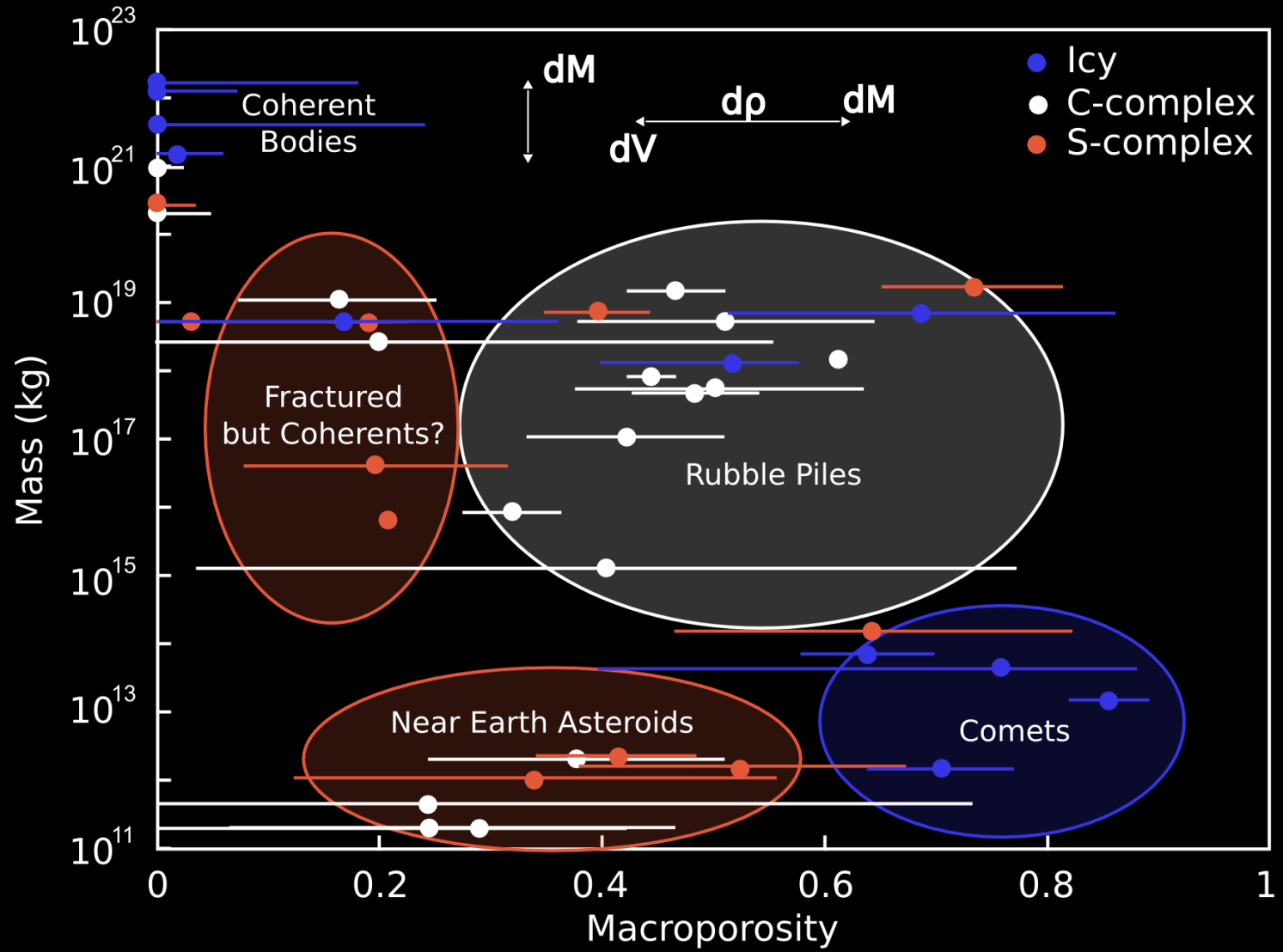

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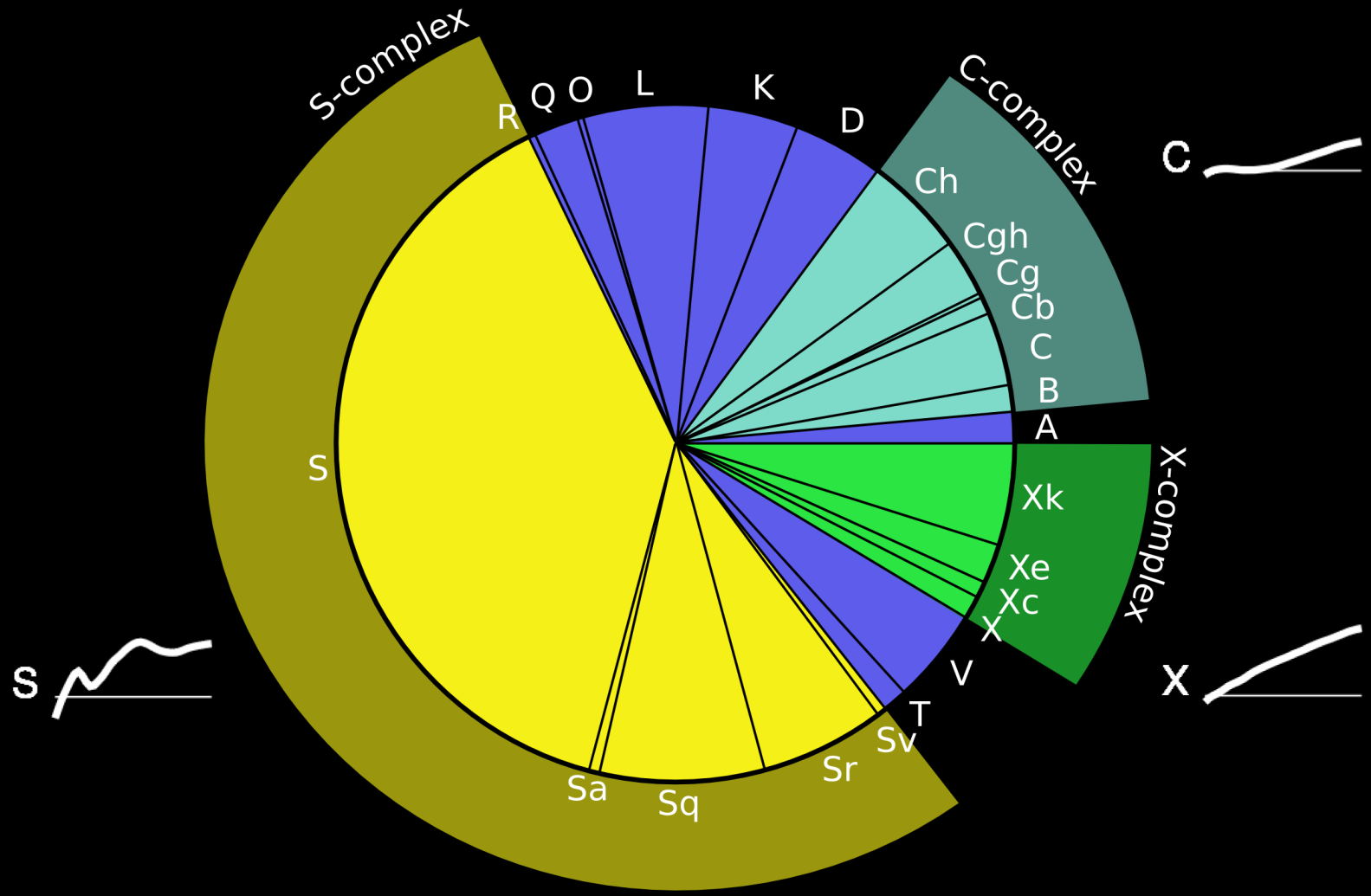
Density & Troubles

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

Mass measurements

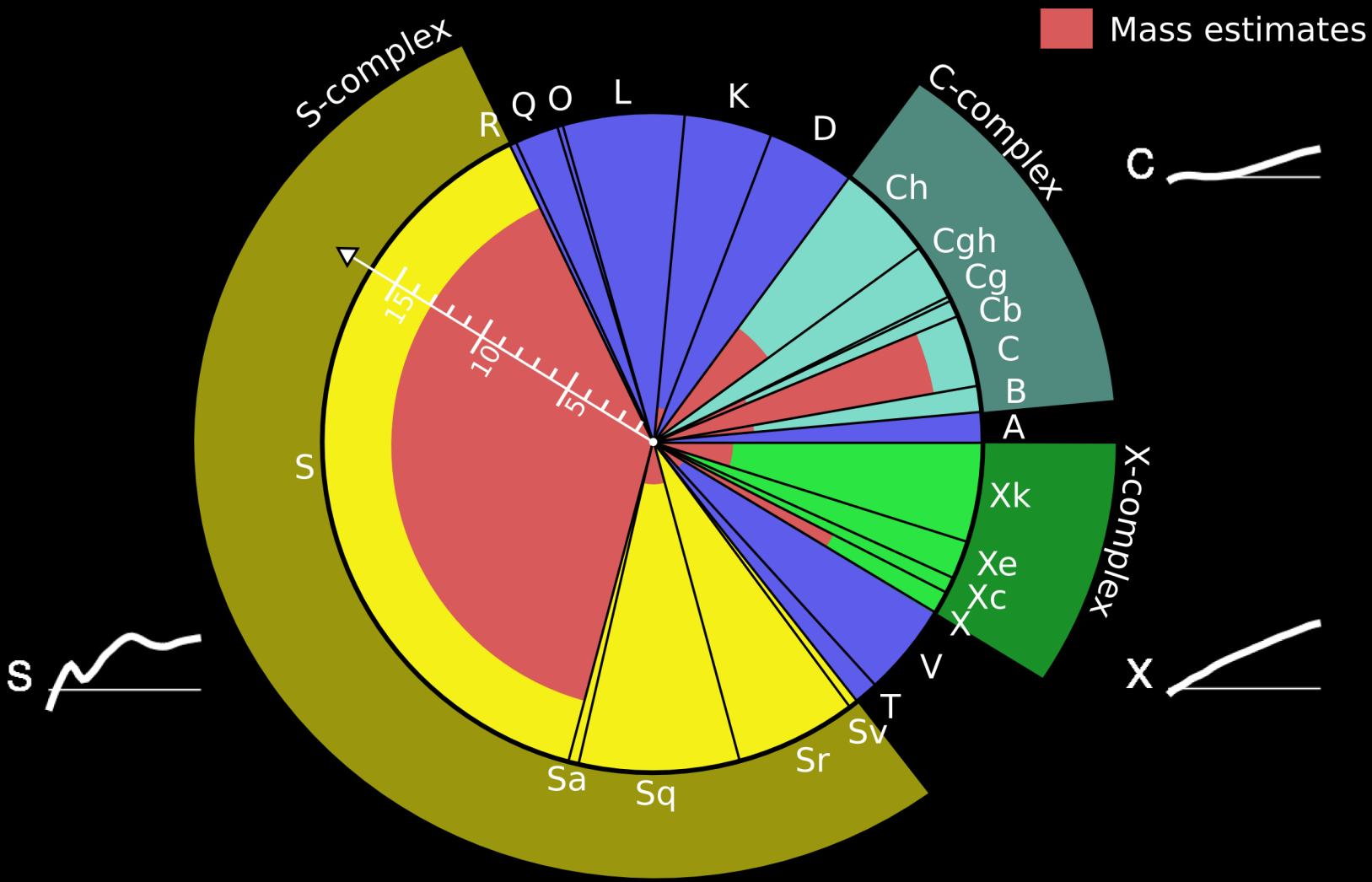
$$\rho = \frac{\mathcal{M}}{\mathcal{V}}$$

Mass & Taxonomy



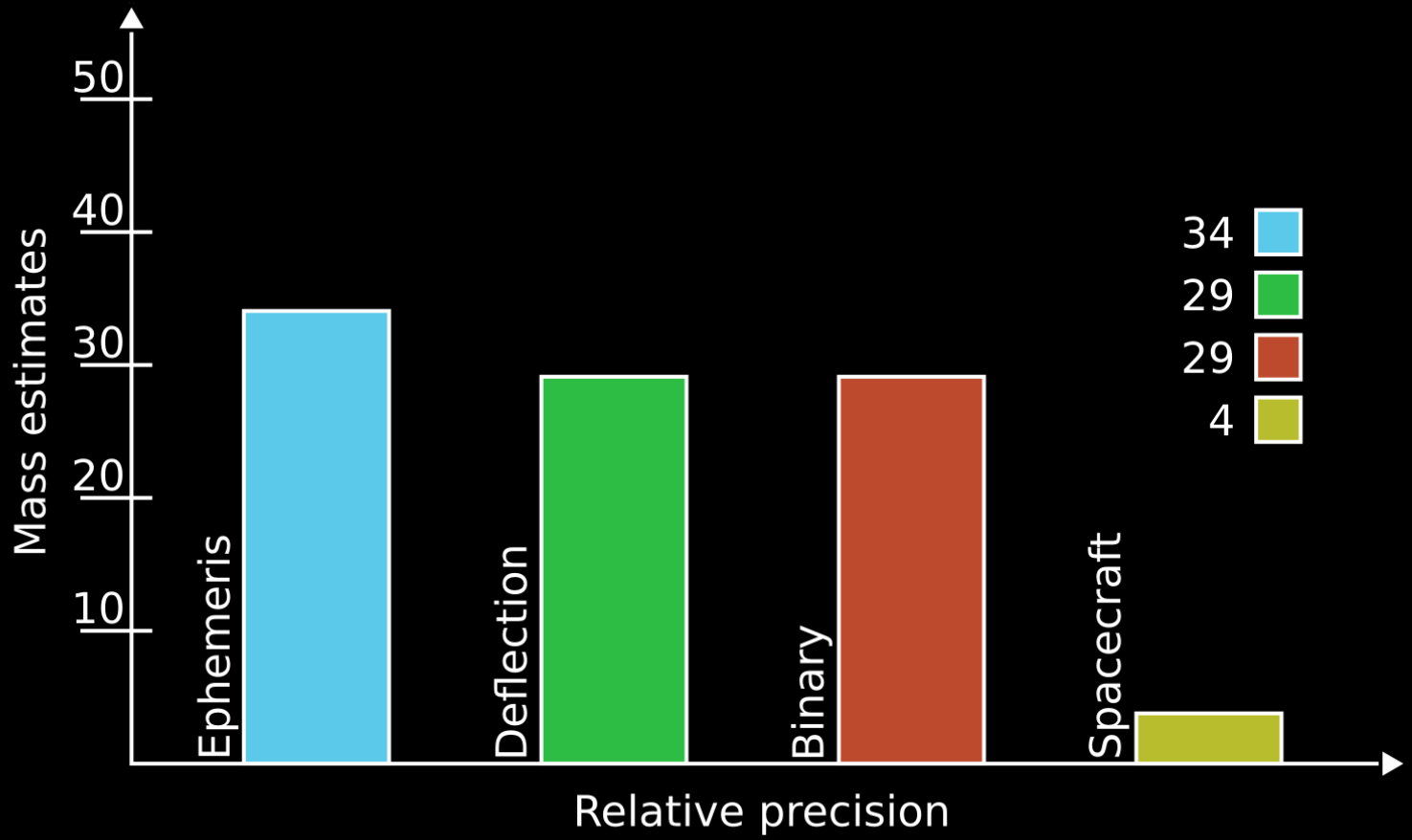
based on DeMeo et al. 2009

Mass & Taxonomy

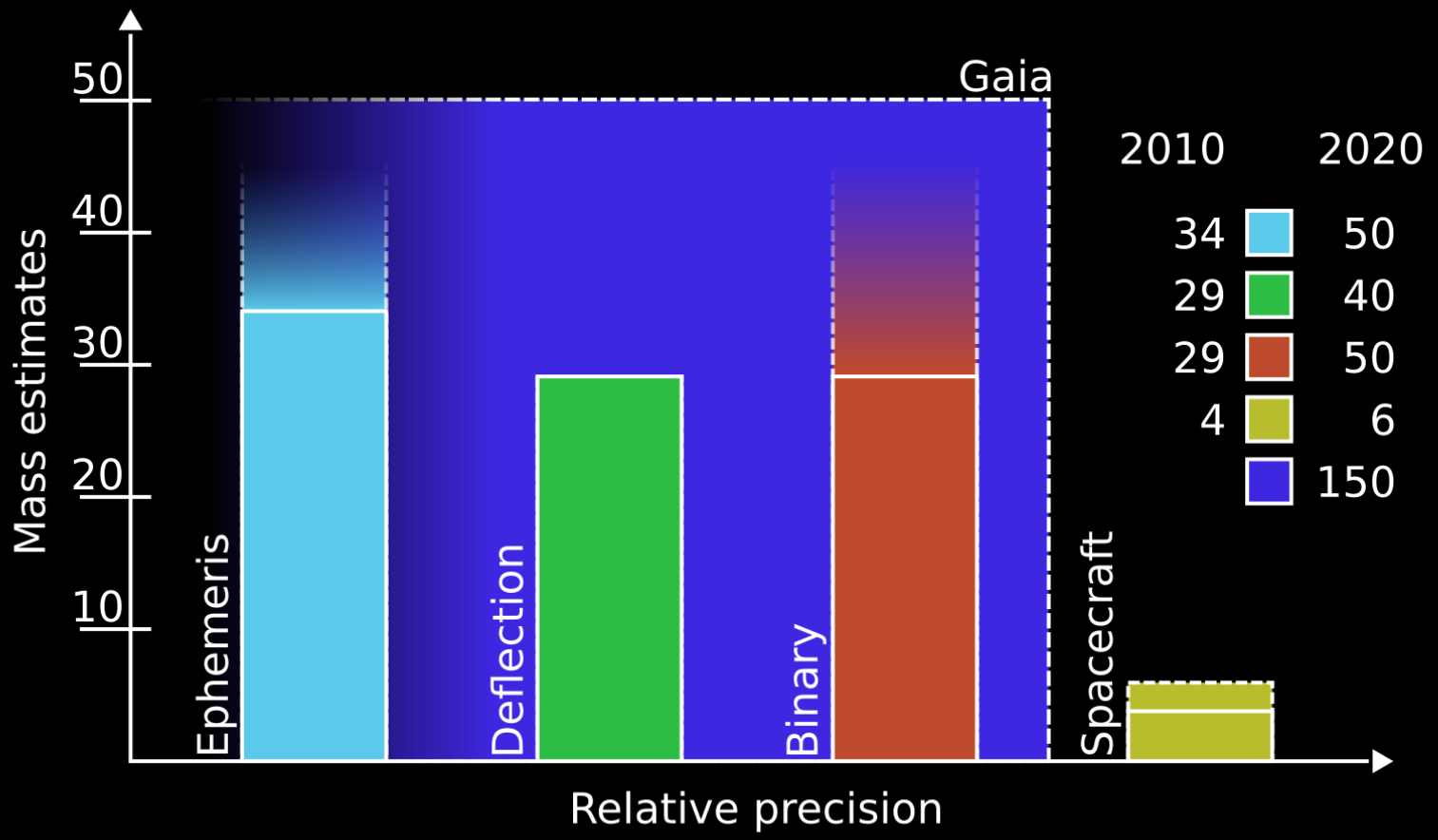


based on DeMeo et al. 2009 & Baer et al. 2011

Mass & Uncertainty



Mass & Gaia


Mass estimates
50
40
30
20
10
Ephemeris
Deflection
Binary
Spacecraft
Gaia
2010
2020
34
50
29
40
29
50
4
6
150
Relative precision

Mass & Gaia

- Breakthrough in mass estimates
- **Deflection** & Binary
- About **200-300** masses
- Coherent set
- Span taxonomy

Volume estimates

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

Volume & Troubles

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

- **100-300** masses
- **2228** diameters IRAS
- **10 000** diameters Spitzer
- **100 000** diameters WISE
- **10 000** diameters Gaia

Volume & Troubles

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

$$\frac{d\rho}{\rho} = \frac{d\mathcal{M}}{\mathcal{M}} + \frac{d\mathcal{V}}{\mathcal{V}} = \frac{d\mathcal{M}}{\mathcal{M}} + 3\frac{d\mathcal{R}}{\mathcal{R}}$$

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- **100 000** diameters WISE
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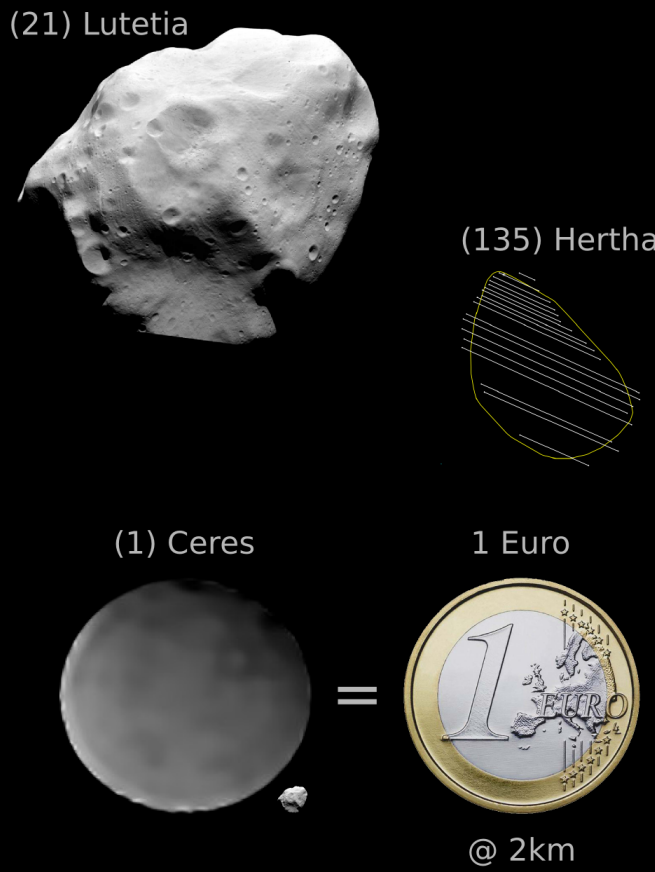
Size is the **Limiting Factor**

Accurate Volumes

1. **Direct measurements**
   - **WYSIWYG** $\neq$ model-dependant
   - Disk-resolved imaging
   - Stellar occultations
2. **Realistic 3-D shapes**
   - Assumptions $\Rightarrow$ bias
   - Concavity $\Rightarrow$ Volume
   - Lightcurves (dense & sparse)
3. **Completeness of geometries**
   - Extensive approach
   - Thermal radiometry
   - Interferometry
   - Radar echo



Tanga & Delbò 2007
Carry et al. 2008
Ďurech et al. 2011

Accurate Volumes

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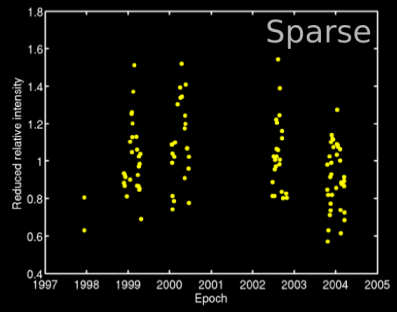
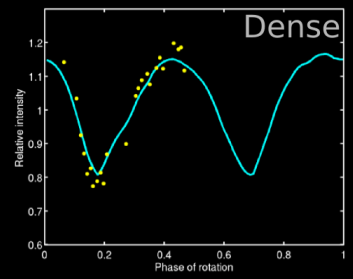
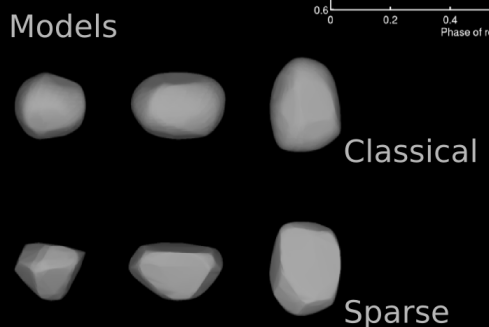
2. **Realistic 3-D shapes**
   - Assumptions $\Rightarrow$ **bias**
   - Concavity $\Leftrightarrow$ Volume
   - Lightcurves (dense & sparse)

3. **Completeness of geometries**
   - Flyby/rendezvous approach
   - Thermal radiometry
   - Interferometry
   - Radar echo







Kaasalainen & Ďurech
Hanuš et al. 2011

$\Rightarrow$ Cellino, Hanuš, Carbognani

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   - **Extensive** approach
   - Thermal radiometry
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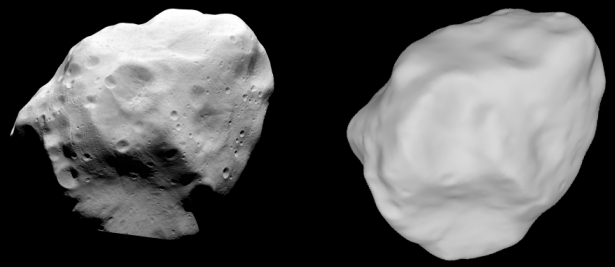
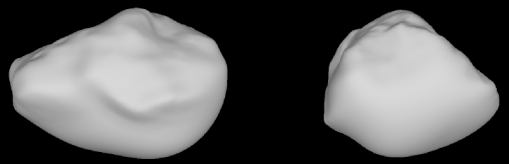
   - Radar echo

(21) Lutetia



GREAT!

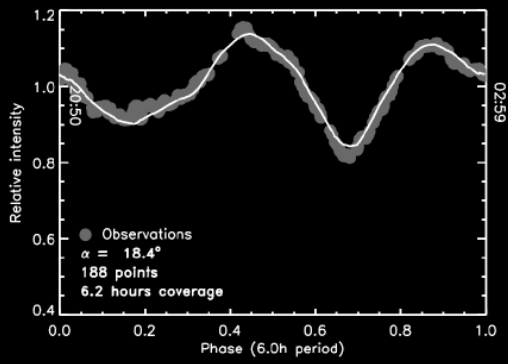


Not so great....

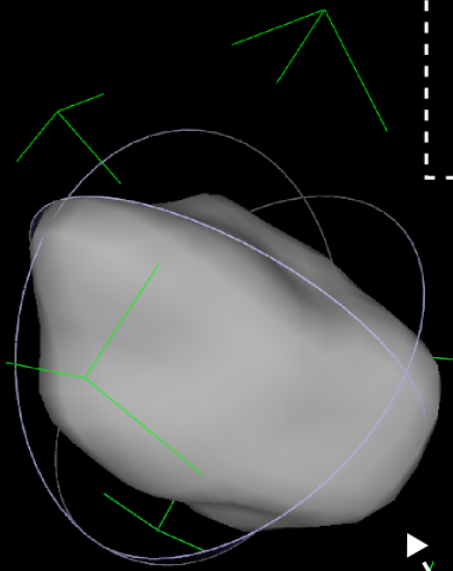
Tanga et al. 2003
Busch et al. 2009
Delbò et al. 2009

Volume with KOALA

Light-curves



Disk-resolved images

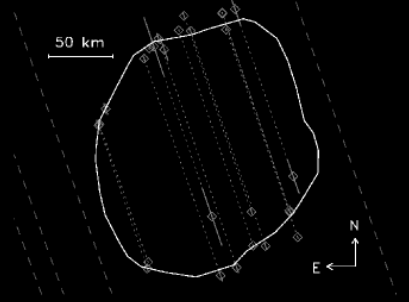


Indirect measurement
- Shape
- Spin

Direct measurement
- Size
- Shape

Knitted
Occultation
Adaptive optics
Light-curve
Analysis

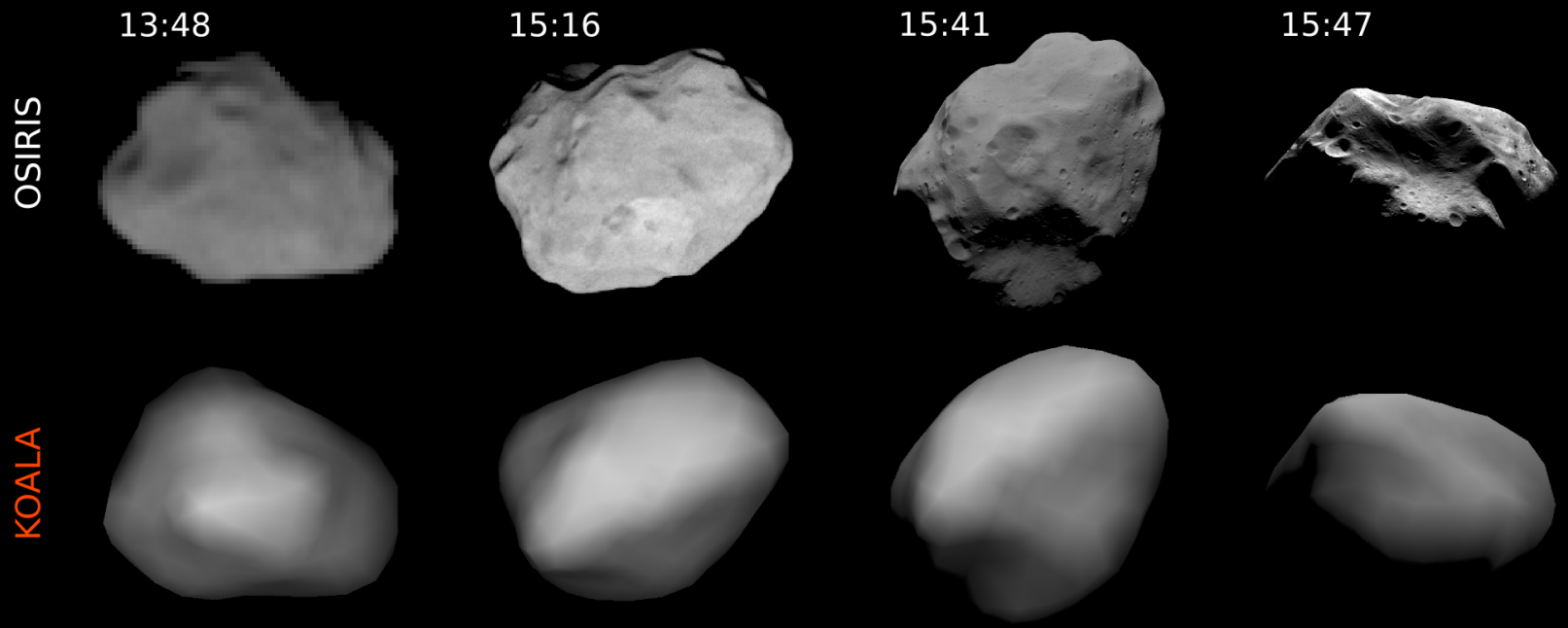
Kaasalainen, IPI 2011



Stellar occultations

Direct measurement
- Size
- Shape

Volume with KOALA



Pre-Flyby model
KOALA
Carry et al. 2010

vs. Rosetta
Shape: **2** km
Carry et al. 2011

Accuracy
Volume: 15%

KOALA Development

- **KOALA 1.0:** Kaasalainen, Ďurech & Carry
  - Lightcurves (dense & sparse)
  - Disk-resolved imaging
  - Stellar occultations
  - Code being cleaned for release
- **KOALA 1.x:** Current development
  - Interferometry (optical): *FGS on HST, JWST*
  - Thermal radiometry: *IRAS, Spitzer, WISE*
  - Kaasalainen, Ďurech, Delbò, Carry
- **KOALA 2.0:** Planned development
  - Interferometry (thermal): *VLTI, LBT*
  - Radar: *Arecibo, LOFAR+EISCAT3d*

Gaia's Contribution

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

Gaia's Contribution

- **Ultra-high precision astrometry**
  - Mass determination: Deflection & Binary
  - **150 estimates** – spanning taxonomy
  - Ground-based support — Colas
  - Ephemeris (*e.g* INPOP) — Fienga
  - **N extra estimates?**

- **Very-high precision photometry**
  - 3-D shape reconstruction — Cellino, Hanuš, Carbognani
  - Minor contribution for volume

- **Ground-based support**
  - **Lightcurves** (dense) campaigns
  - Dedicated **imaging** on large telescopes
  - Stellar **occultations** — Tanga, Delbò