# The Solar System at mas *and μas* accuracy

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# Summary: implications of a Gaia-like NIR-extended mission

- Taxonomy and composition
- Epoch photometry
- Astrometric accuracy

# Why we need asteroid spectra?

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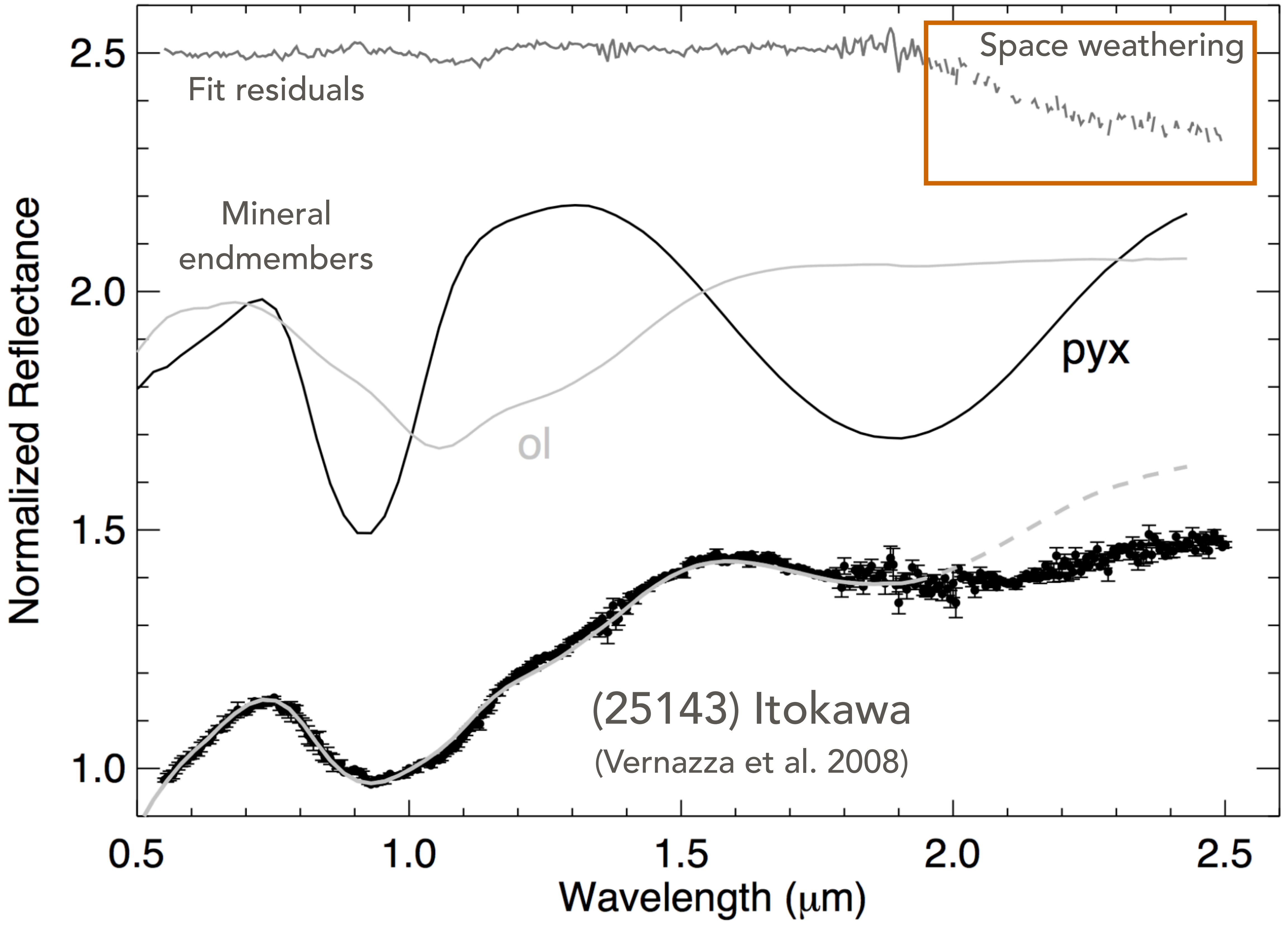
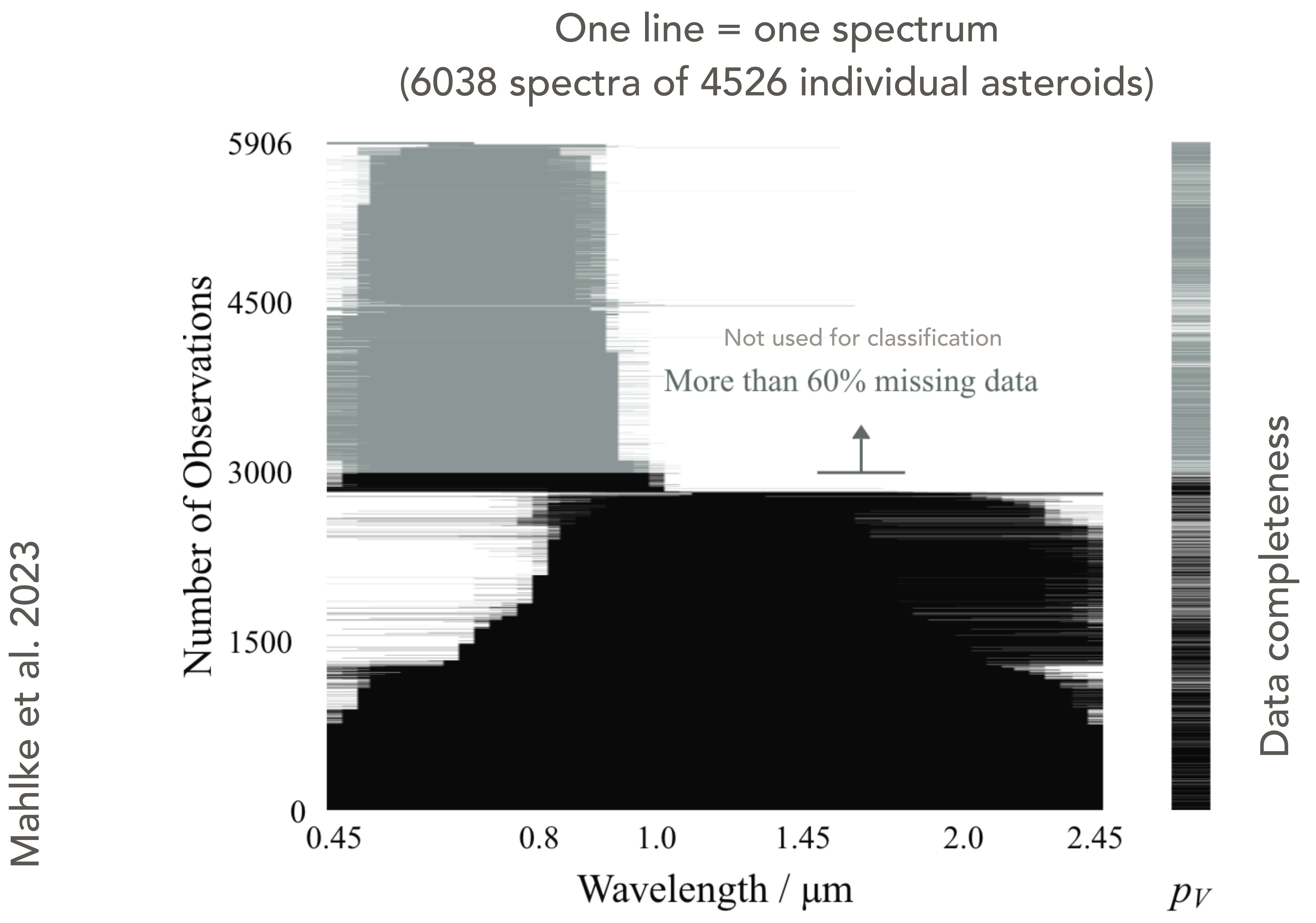
  - Depends on the collisional evolution
- Composition —> origin
  - Hydrated asteroids - formed far from the Sun, bringing water to Earth
  - “Primitive types”, unaltered since formation (?)
  - Family members —> composition of the parent body…
  - Near Earth Asteroids —> source regions / mitigation strategies
  - etc.

# Asteroid spectrum from vis to NIR - an example

- Reflectance spectra: fit to laboratory spectra of different minerals
- Note the important bands at 1 and 2 $\mu$m



# Sample available for classification (pre-DR3)




- Spectra in literature, used by Manlike et al. 2023 to build new taxonomy (with new classes!)
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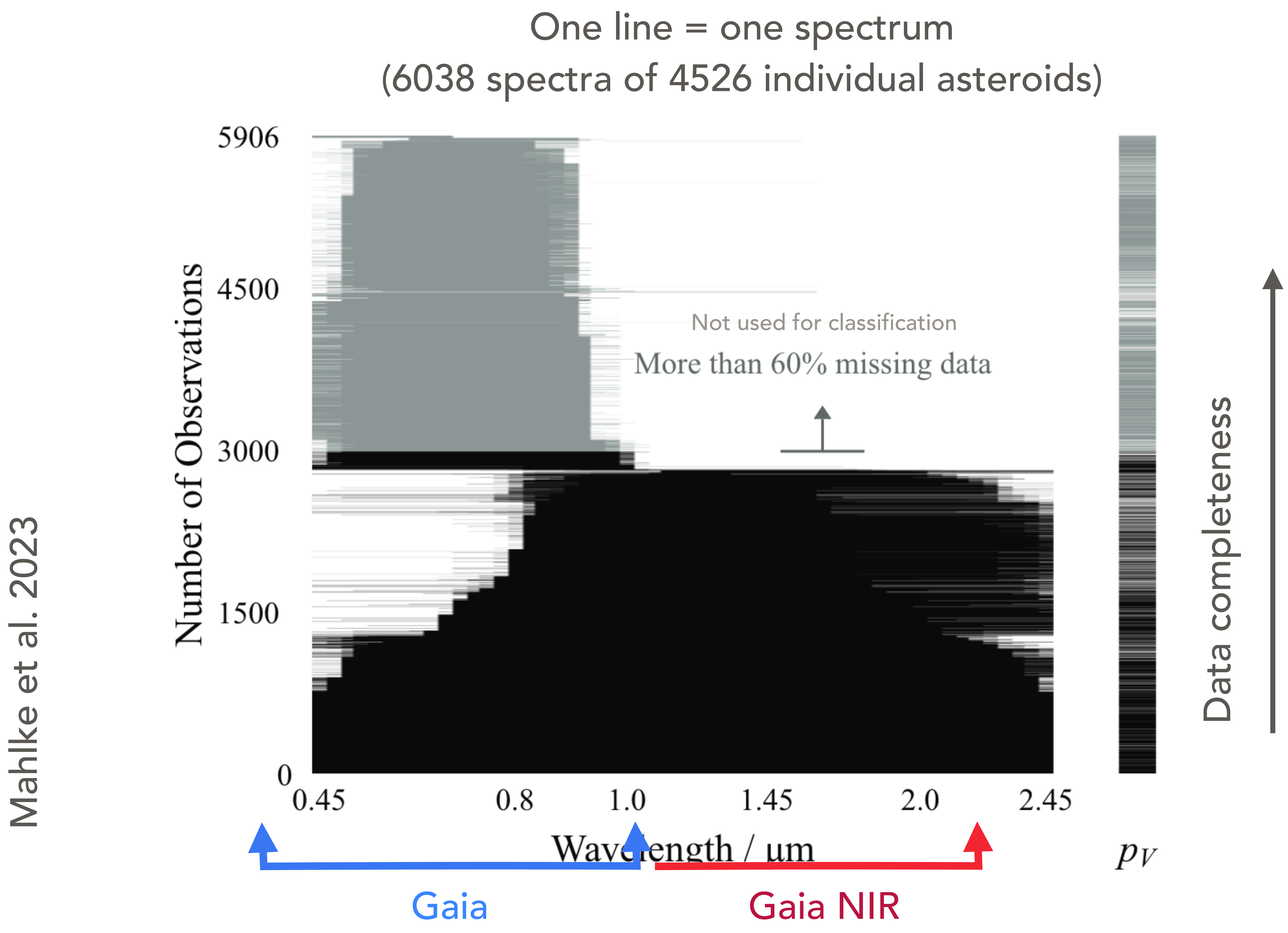


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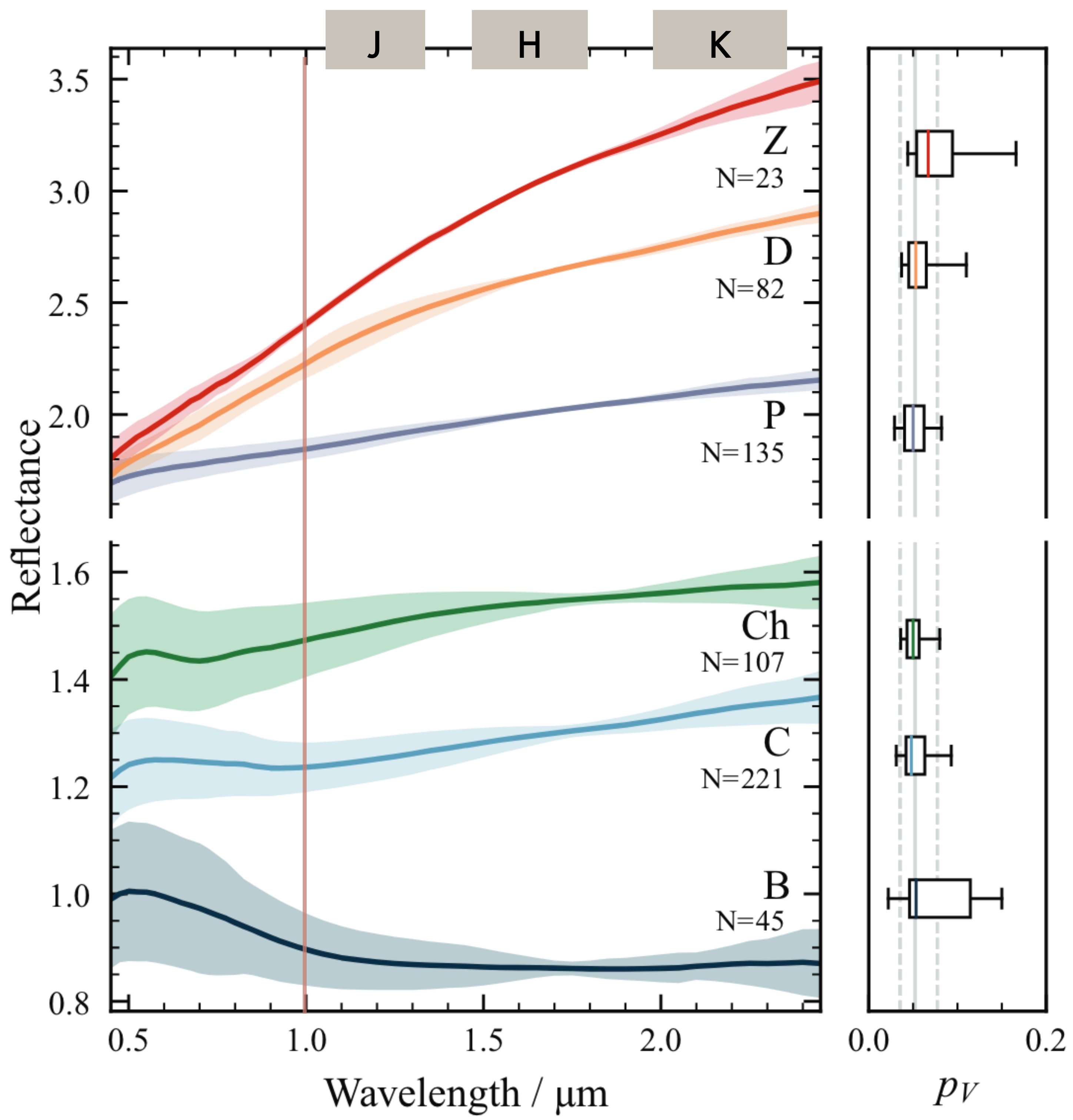
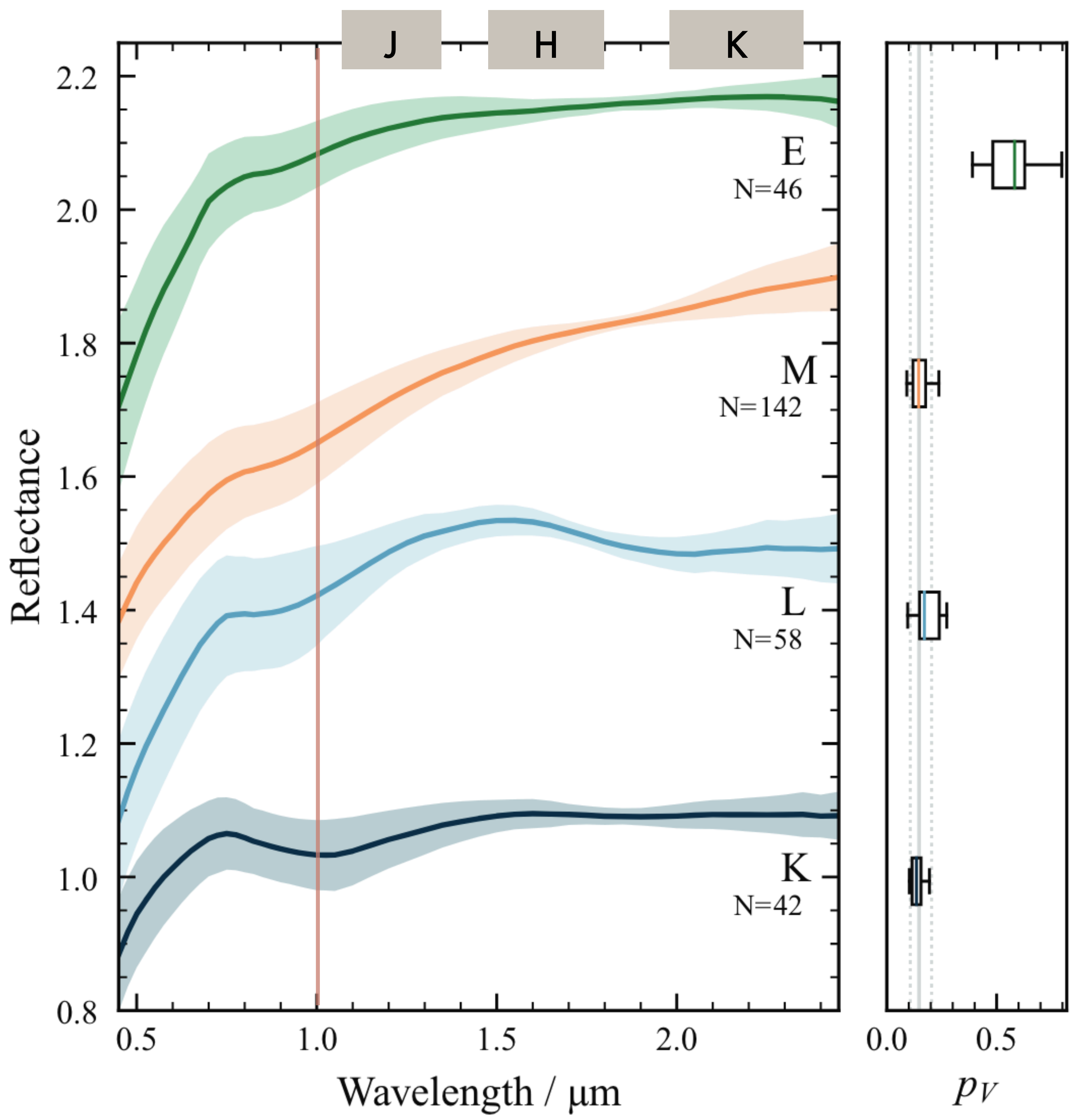
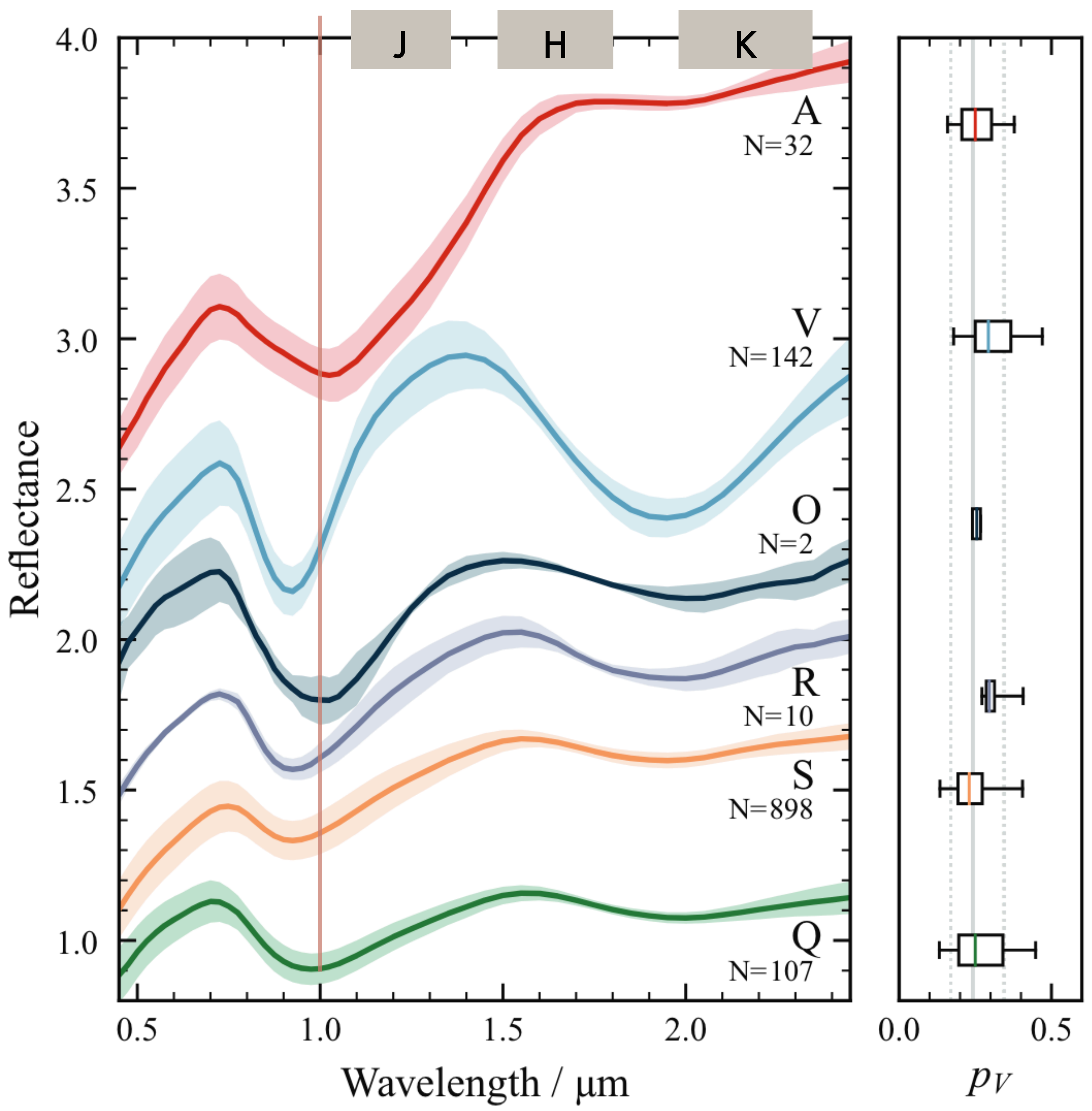



Some degeneracy in the NIR (B, C, Ch)




Mainly distinguished from the varying ratio between the two bands

Mahlke et al. 2023

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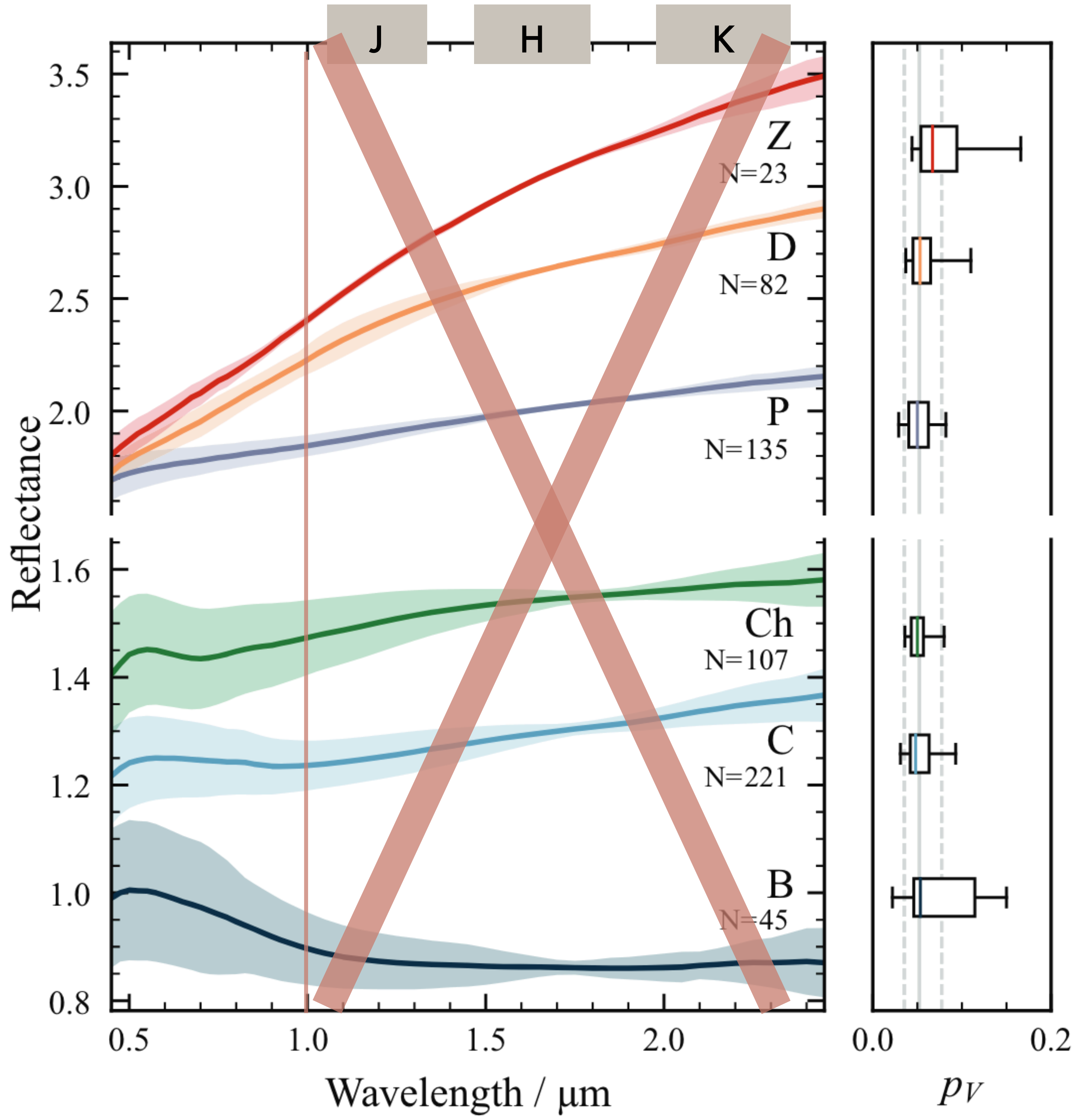


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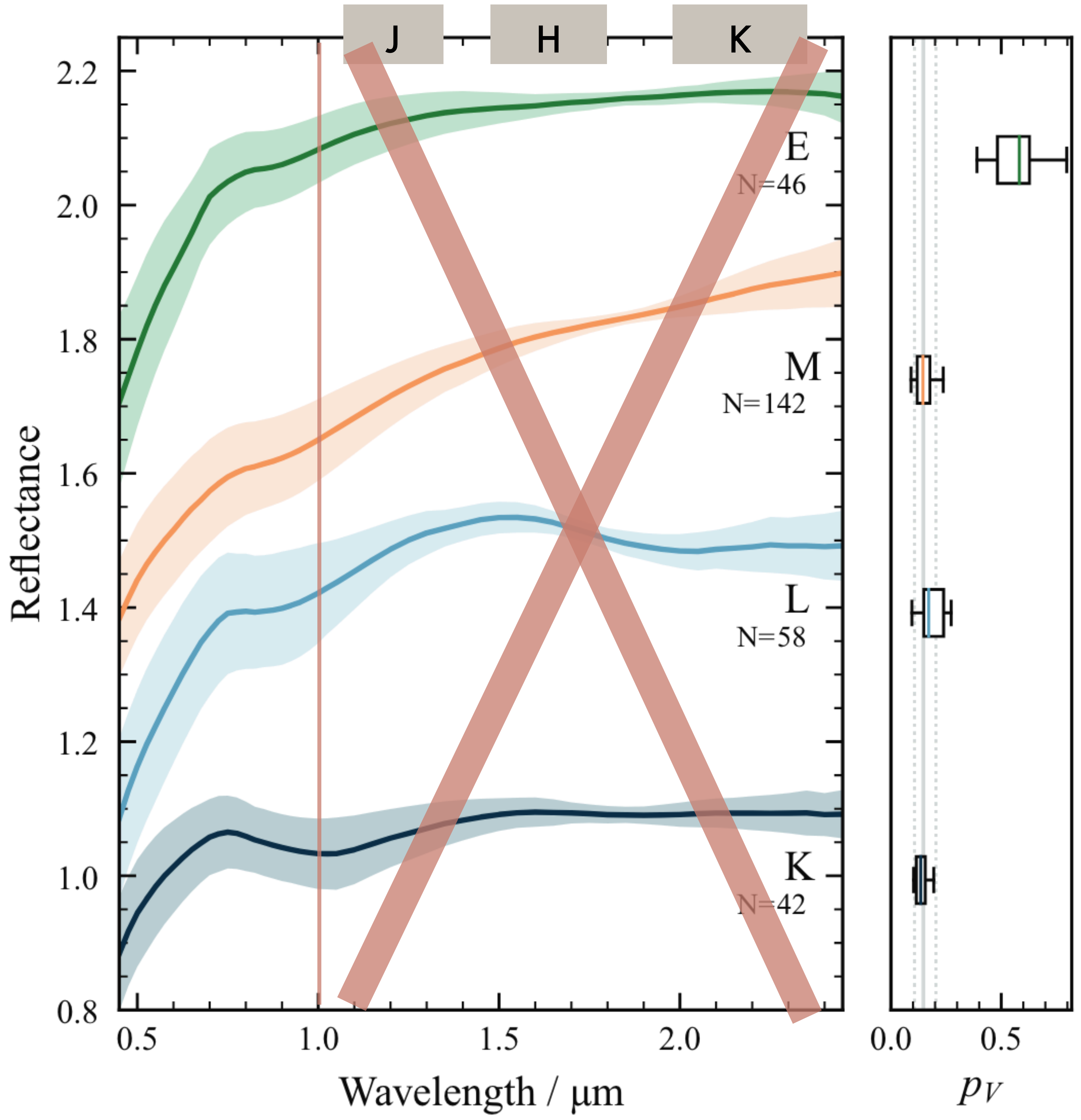
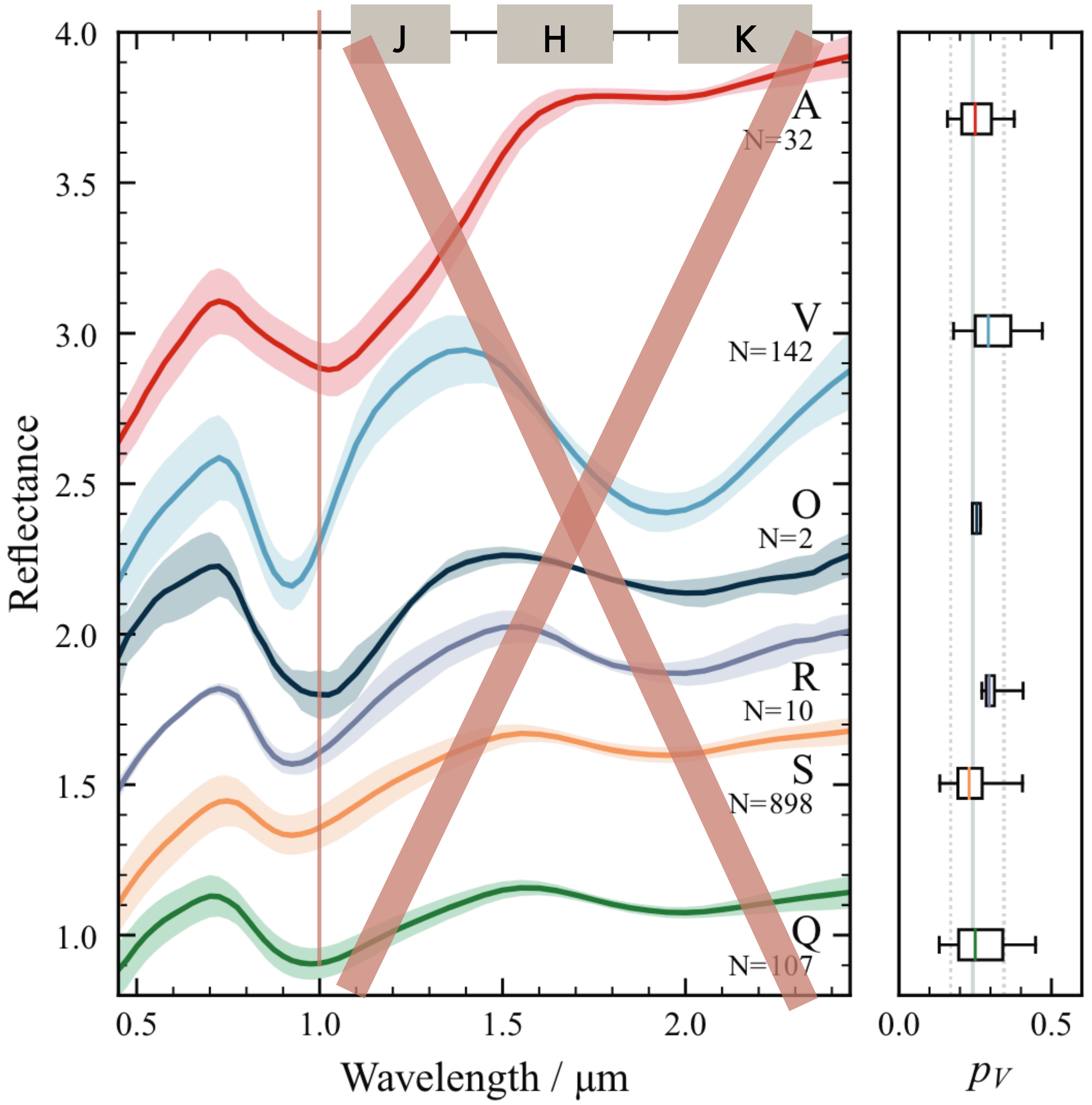



(M) K-L degeneracy in the Vis



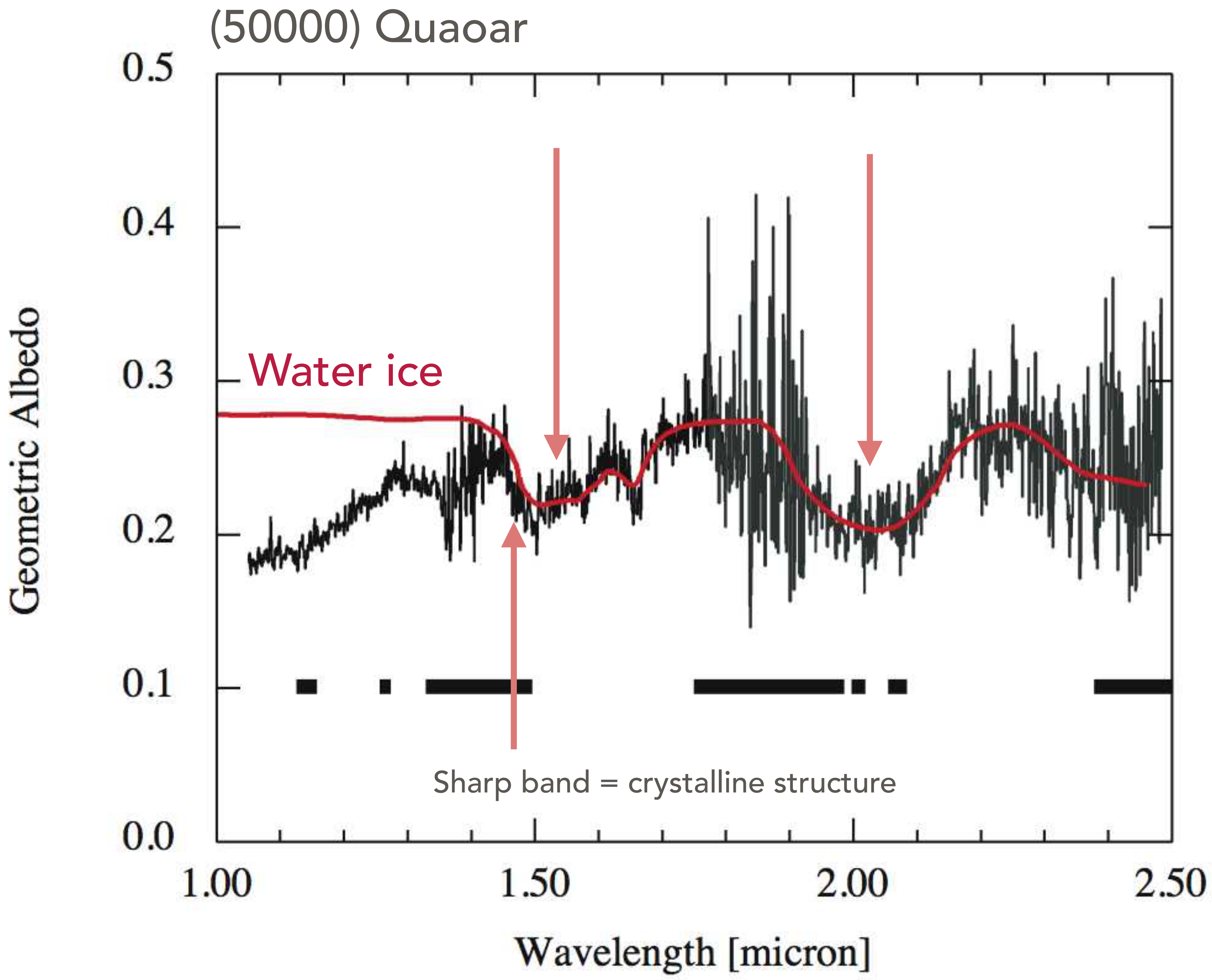

Mainly distinguished from the varying ratio between the two bands

E-M-P degeneracy in the Vis

Mahlke et al. 2023

# More distant objects - the Kuiper Belt and the comets

- Signatures of water ice
    - Broad features compatible with filter photometry (low spectral resolution) but band details are not accessible
    - Similar for comets
        - Most chemicals have specific signatures in the IR (> 3 $\mu$m)



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- LSST data (Vis) will be abundant in coming years (for “faint” asteroids)
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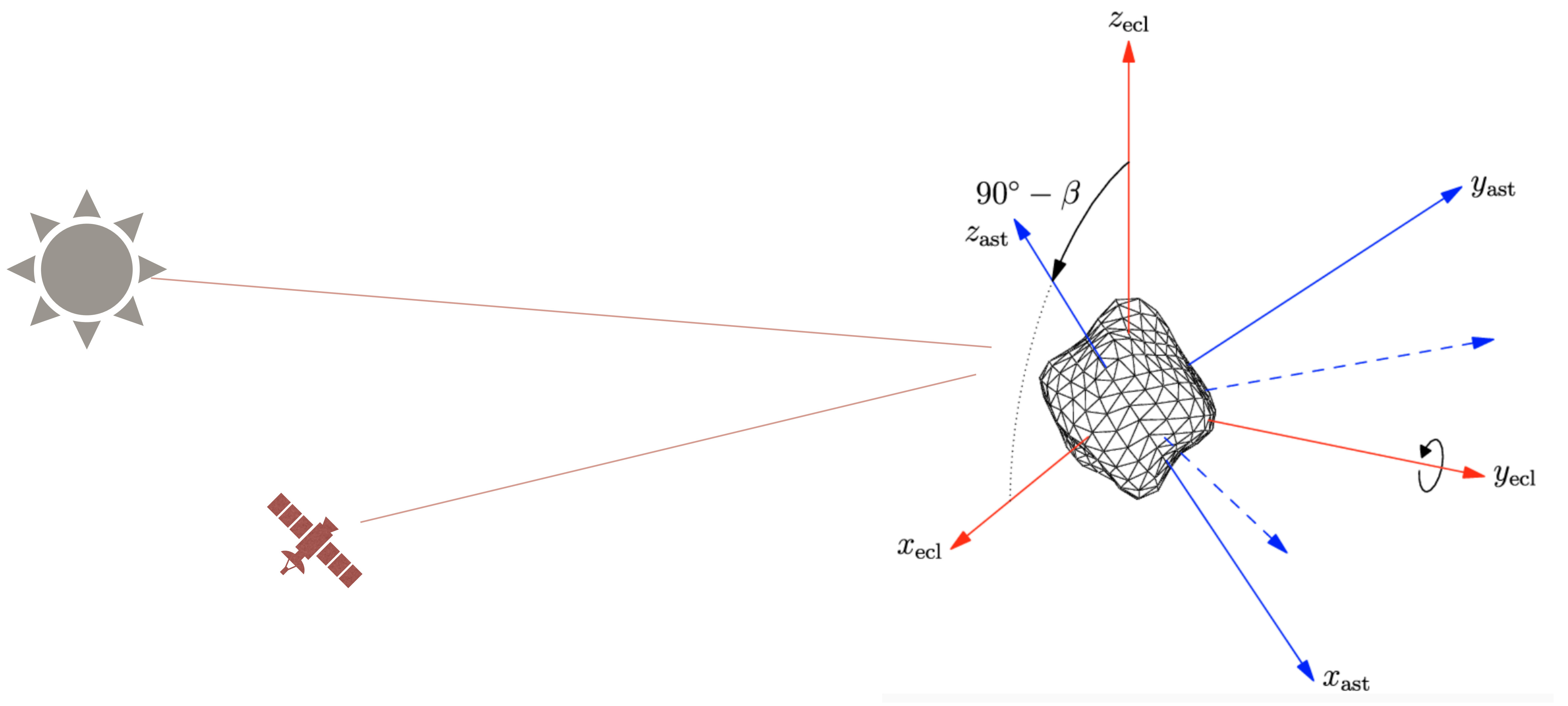
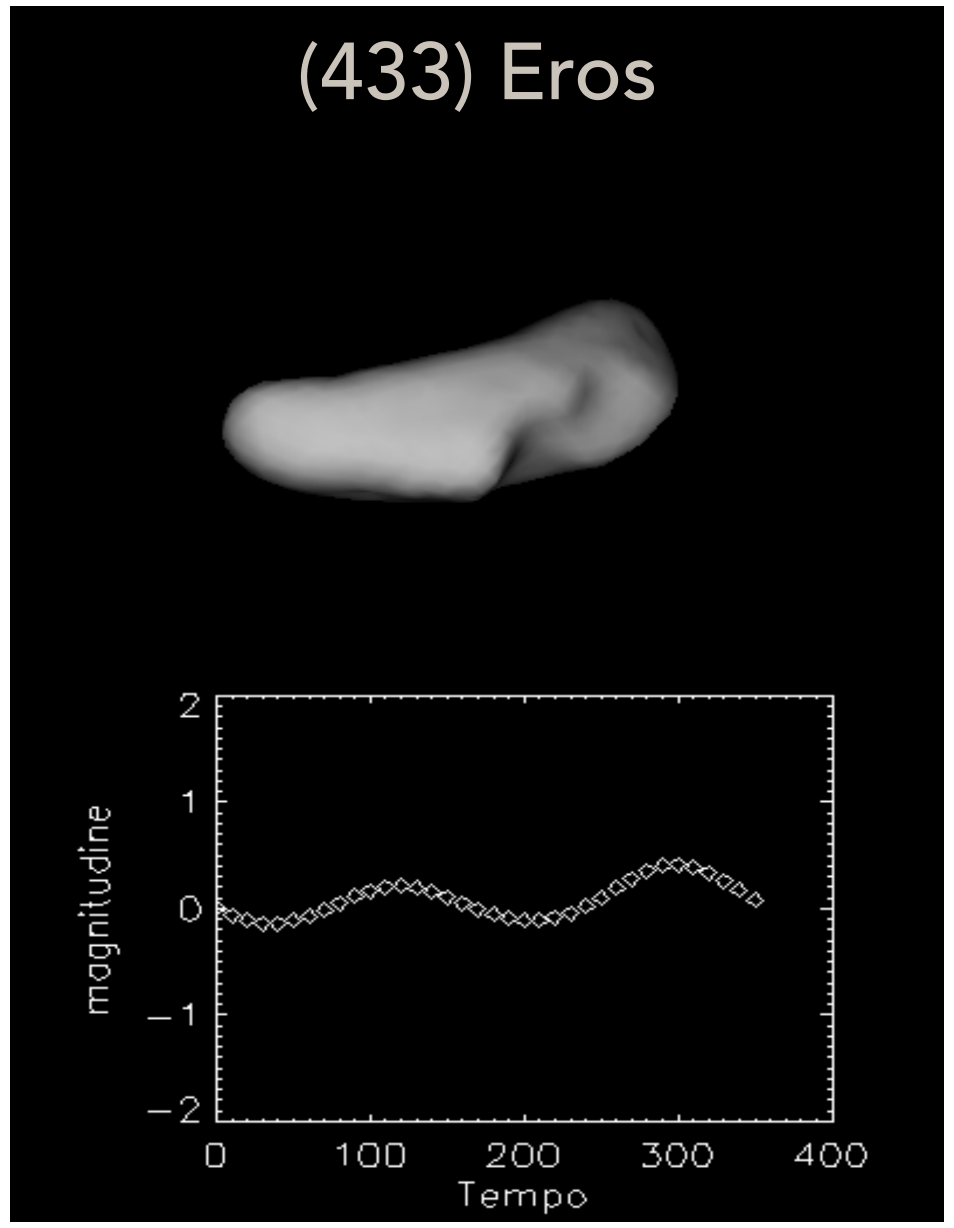
  - …provided that calibration and some physical effects (different epochs / rotation effects) can be dealt with
- **No large scale survey exists in the NIR - but essential to have a complete picture of the composition**

# Inversion of epoch photometry



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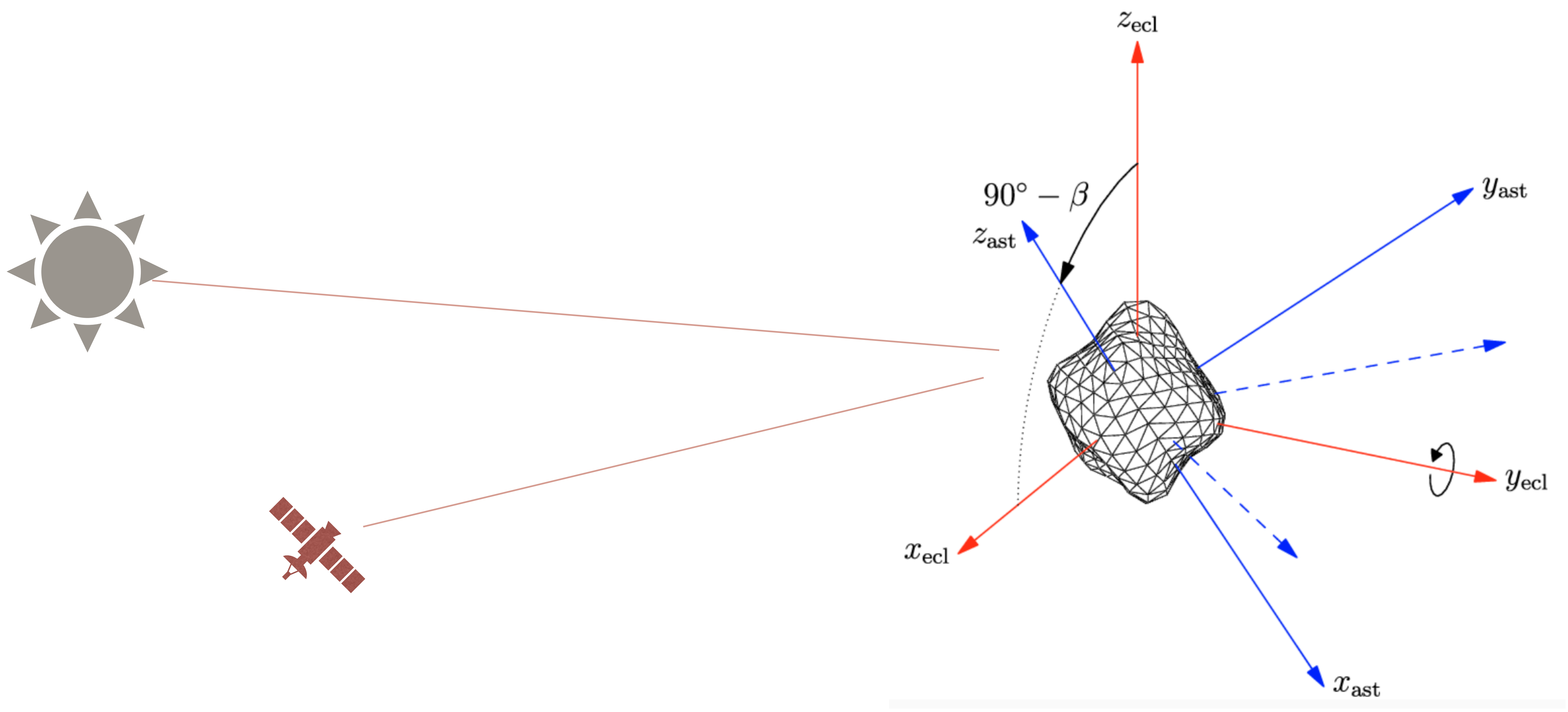


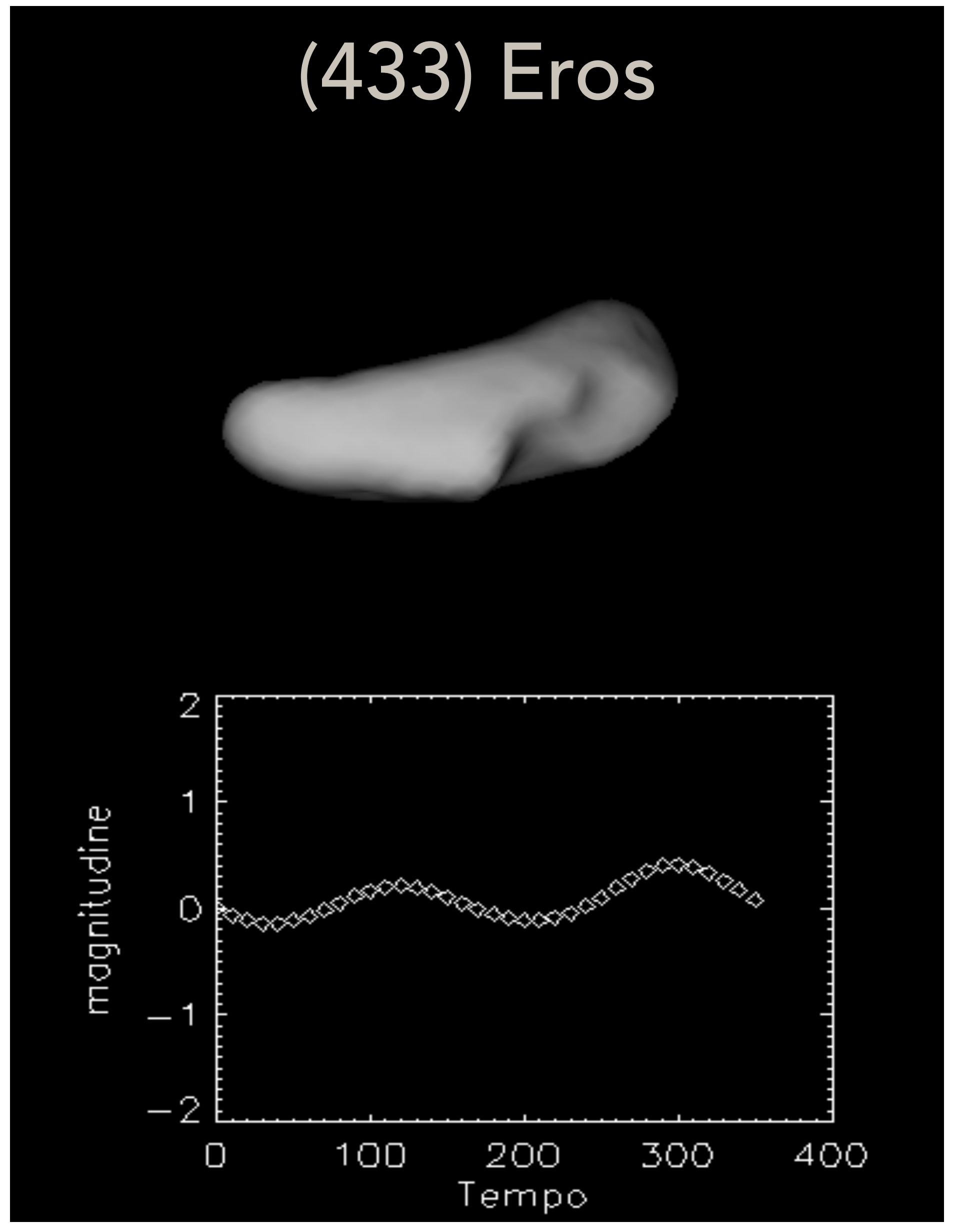

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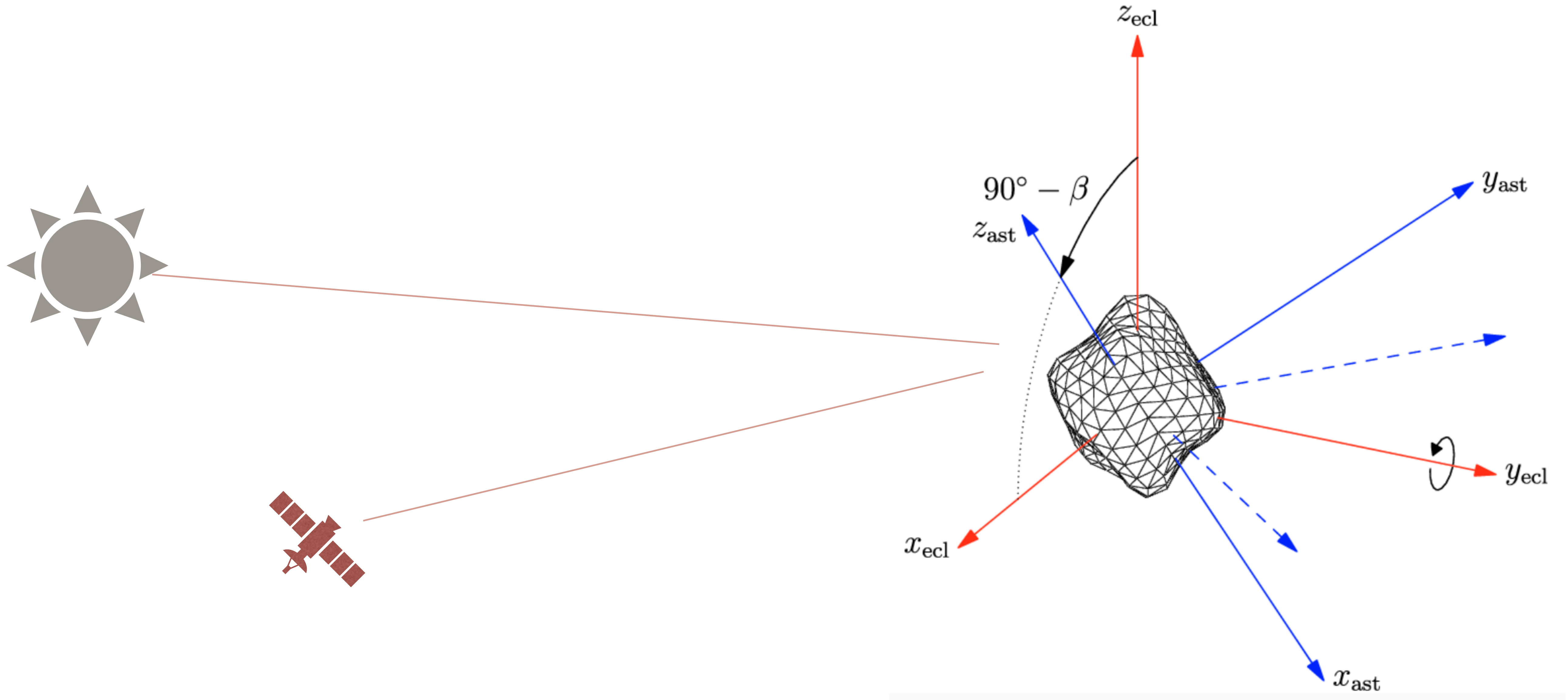


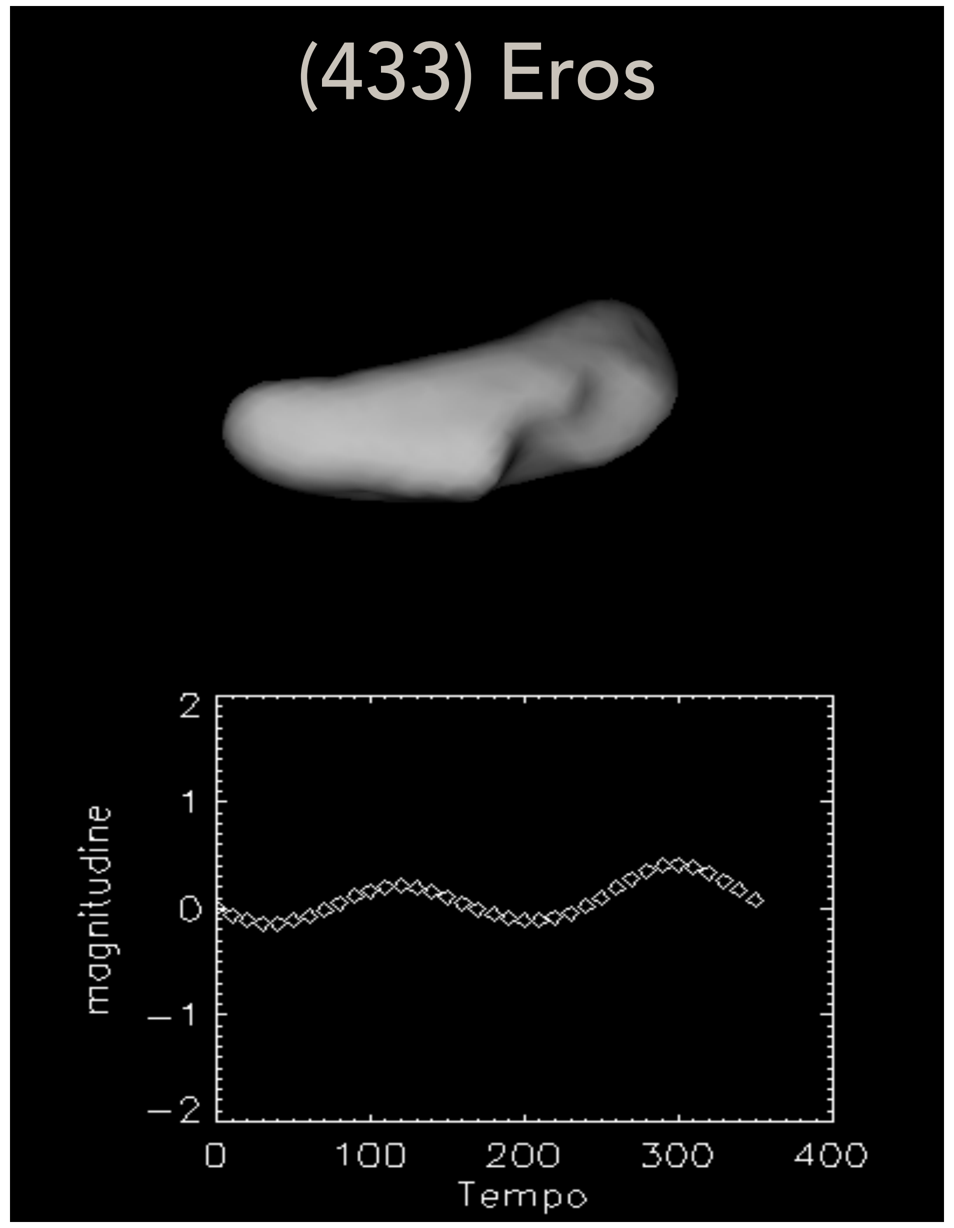

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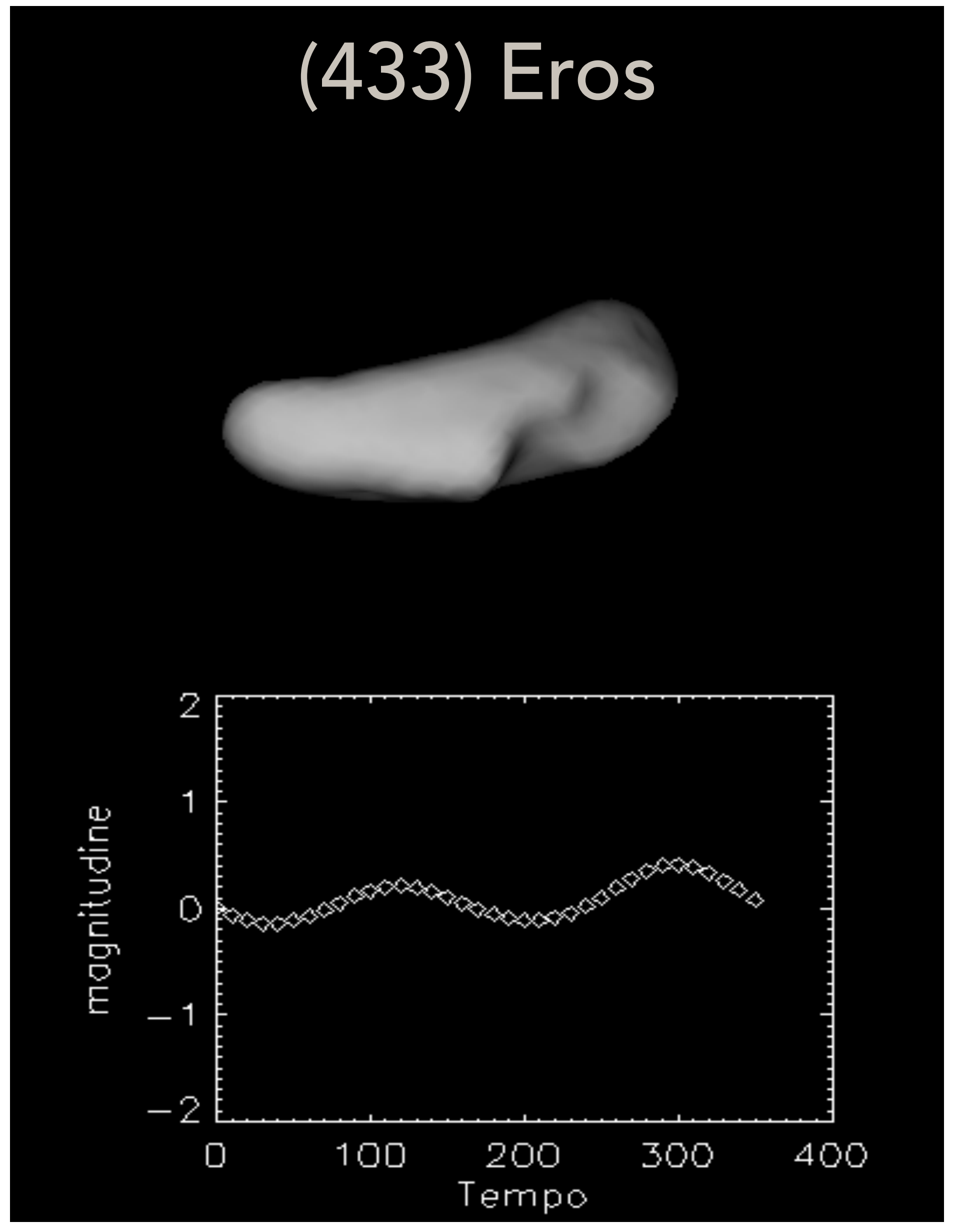
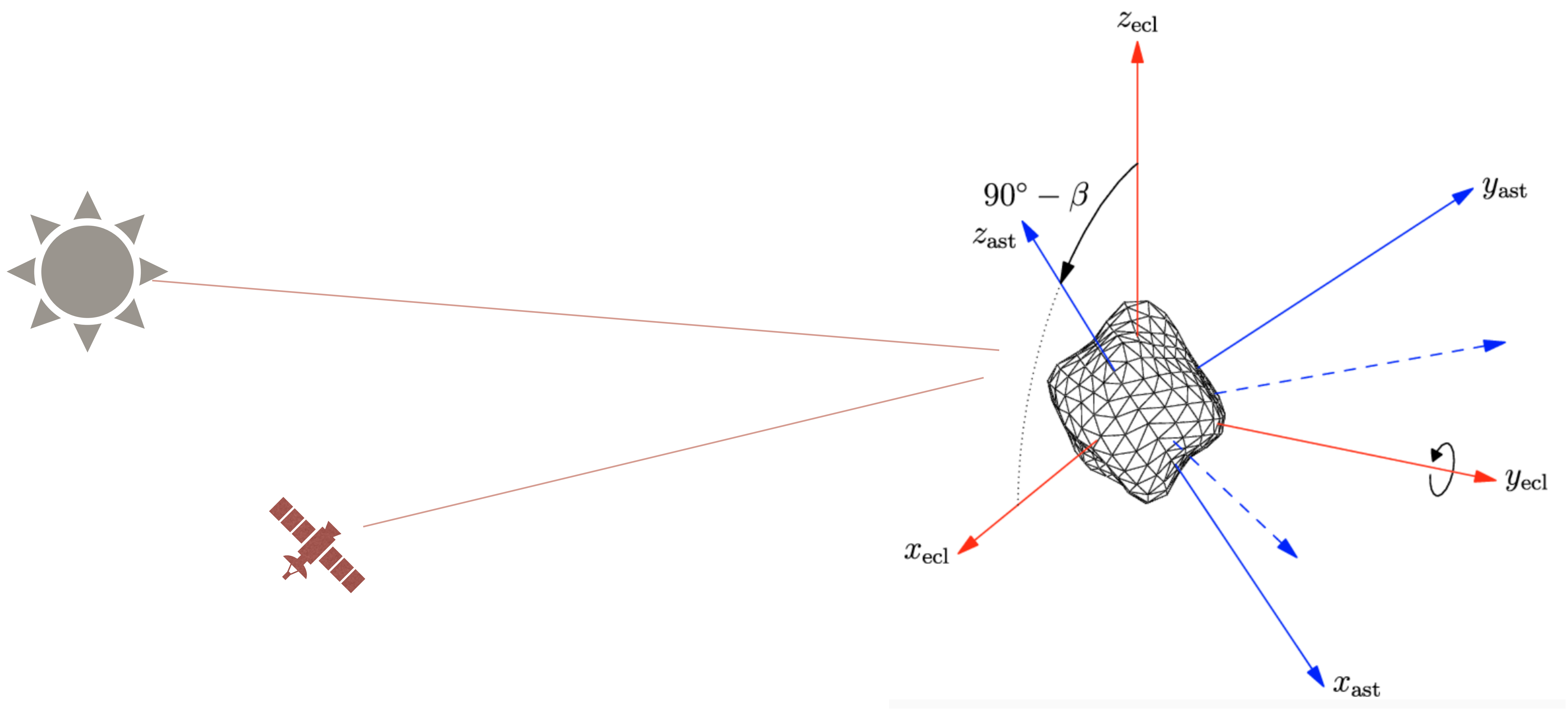
- The success of the inversion depends on:
    - Photometric accuracy
    - A good coverage of the different aspects of the asteroid wrt the observer, changing with:

        1 - Rotation around its axis (~ hours)

        2 - Relative Sun - Observer - Target geometry (~ years)

    - Sparse photometry poorly samples (1)
    - …but algorithms can still converge if enough data are corrected (articles by Cellino et al., CU4)



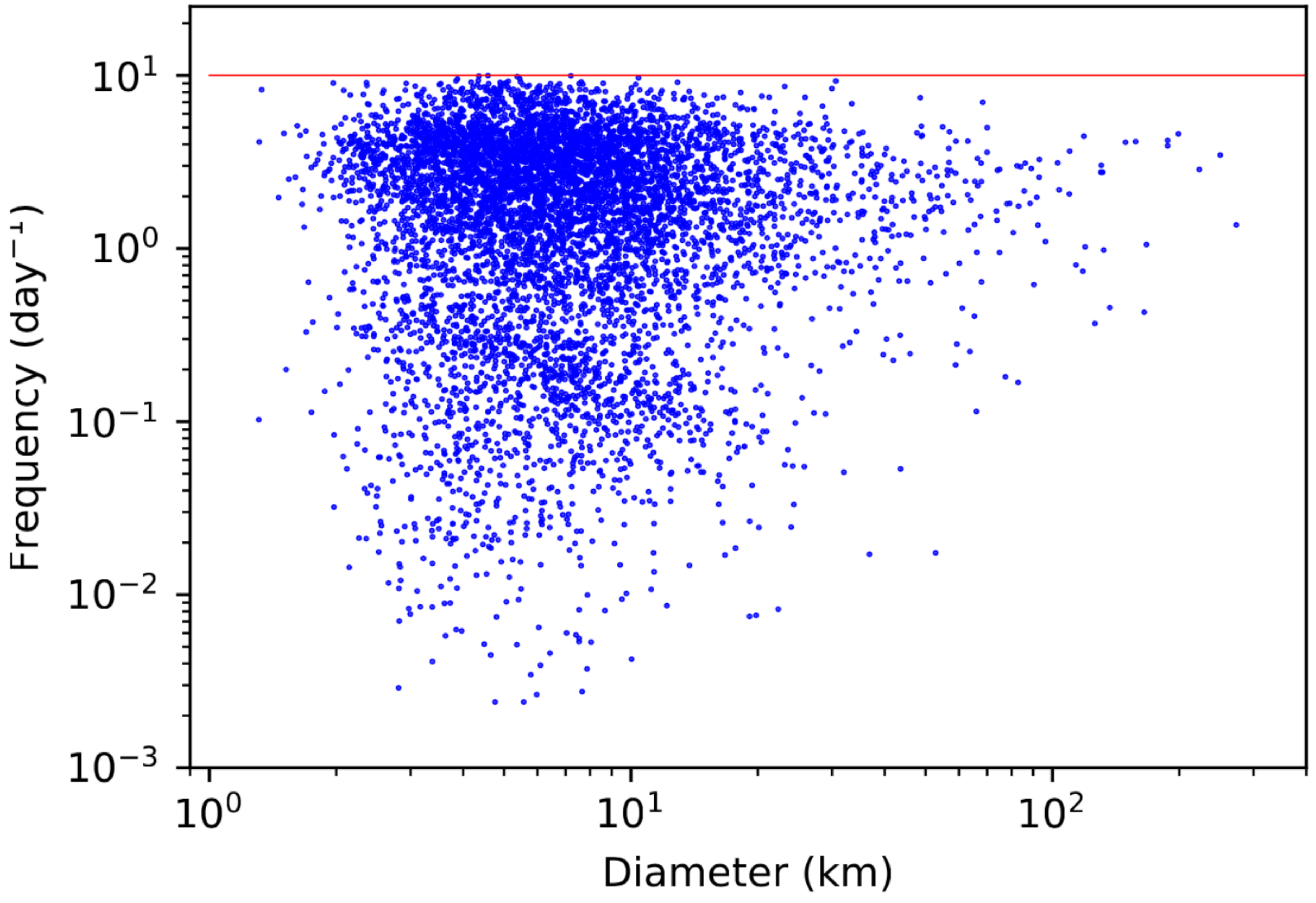



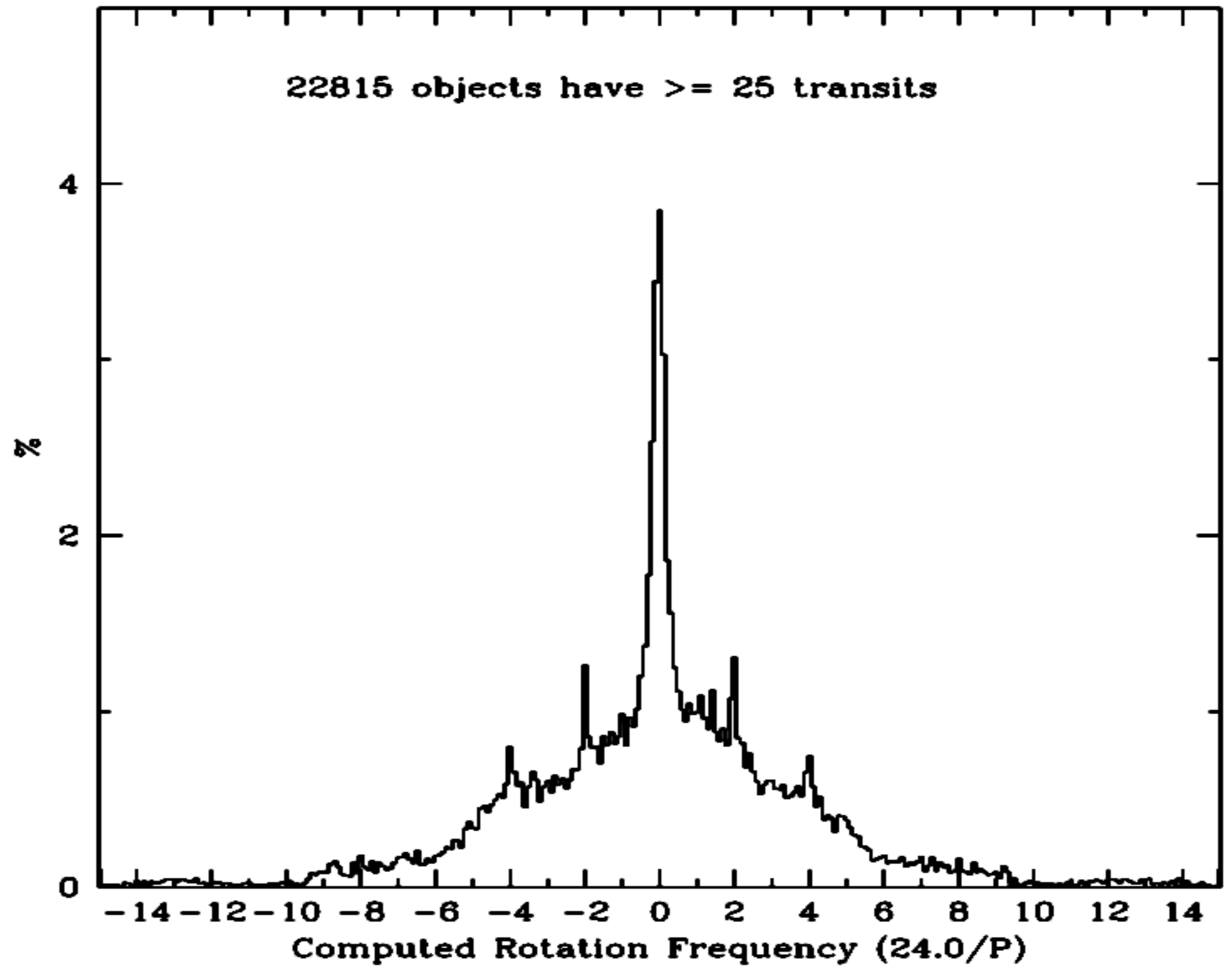
# Inversion of epoch photometry: the experience on Gaia DR3

- ~8600 rotation and shape parameters from two independent inversions
  - Durech & Hanus A&A 2023
  - Cellino et al. 2023, in preparation

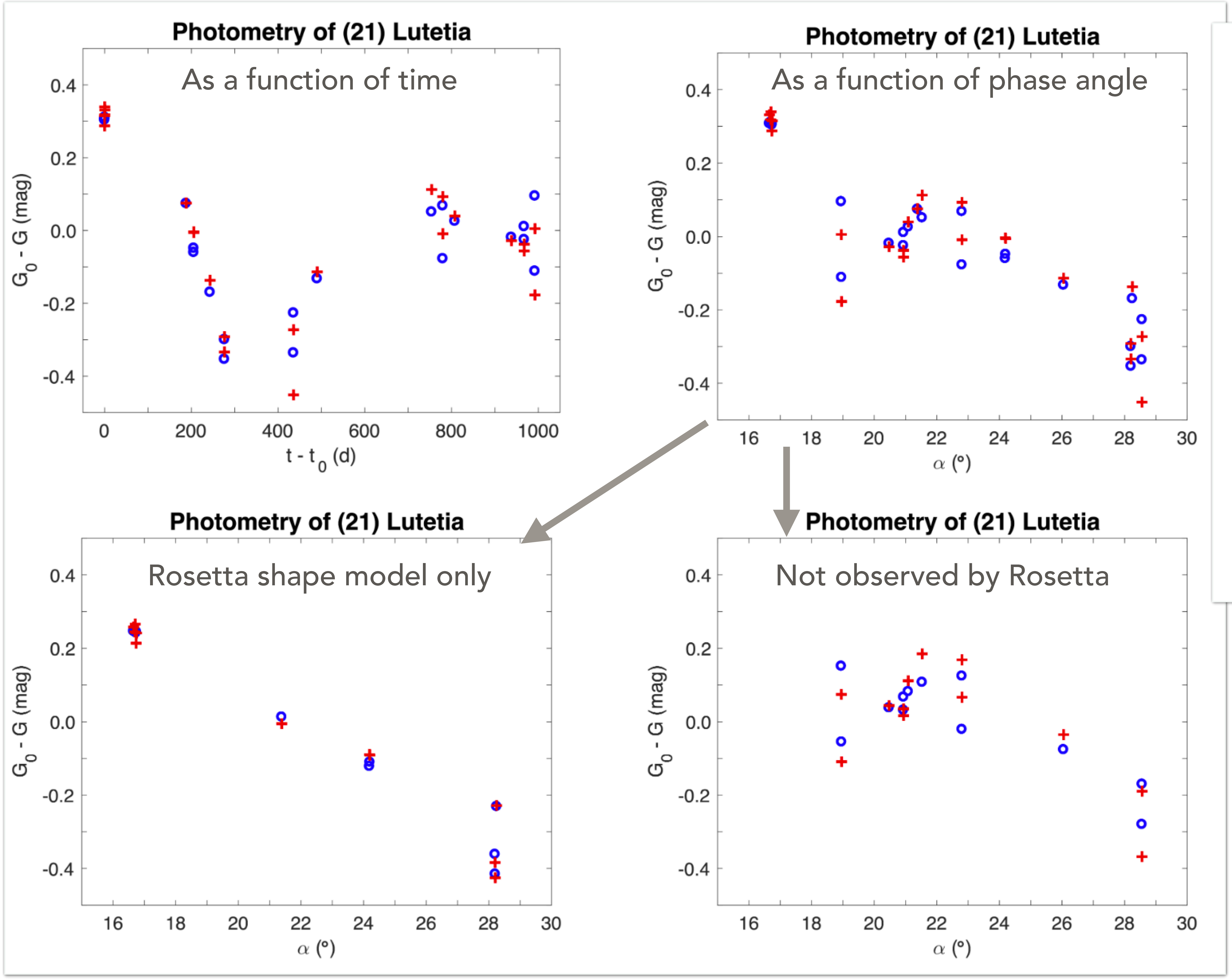
- Important amount of slow rotators
  - Possible population of tumblers

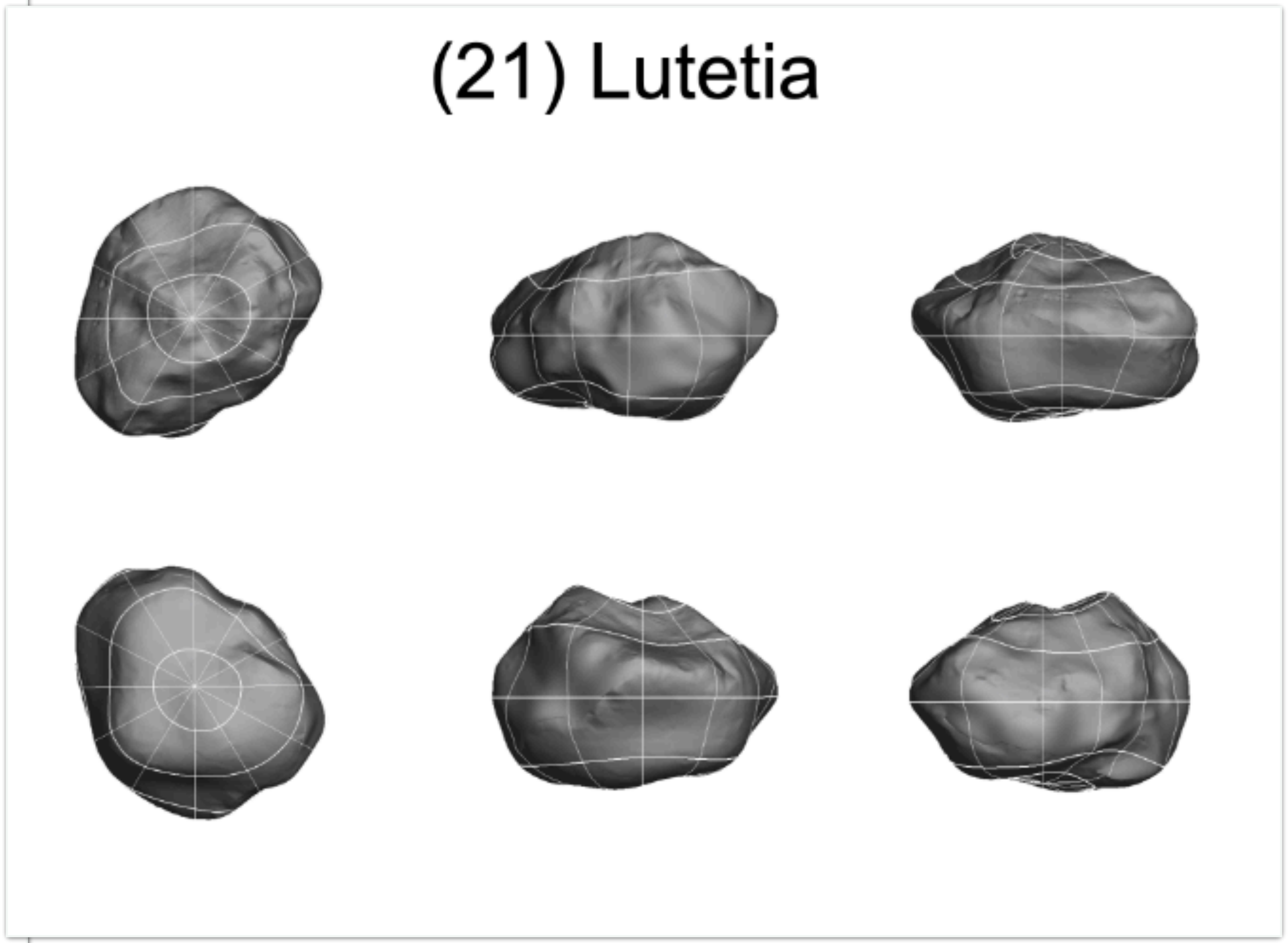
- Important filtering to get rid of spurious periods



# A glimpse into photometric performance (DR3)




Modelling limited by the knowledge of scattering properties.
Not possible to asses accuracy below ~0.01 mag

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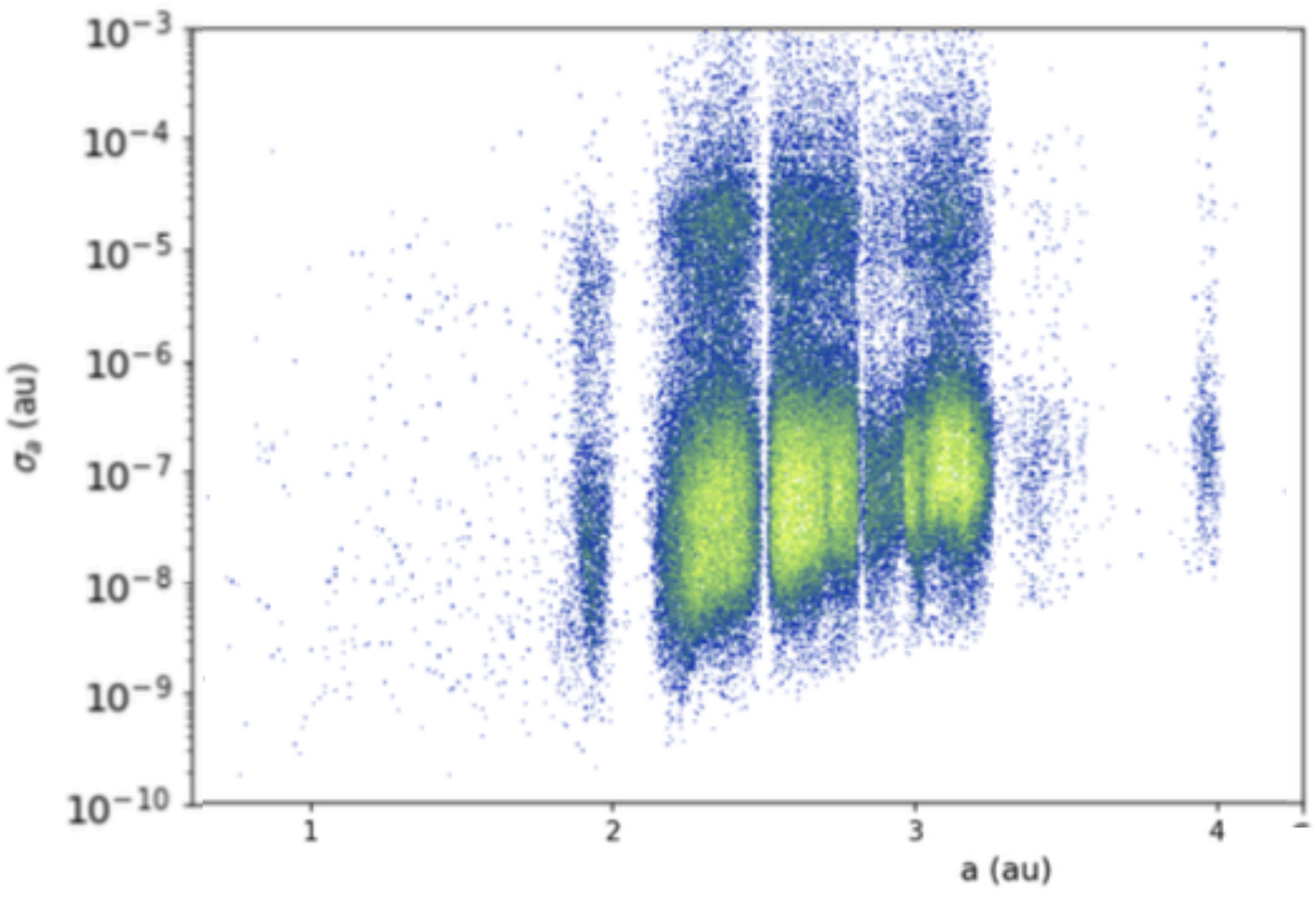
  - …however, Vis + NIR photometry opens a new perspective of investigation
- Vis (Gaia 1) + NIR (Gaia 2): very useful to increase the sample of size/shapes
- Different scanning law periods between the two missions —> mitigation of spurious periods
  - This would be useful for ALL epoch data

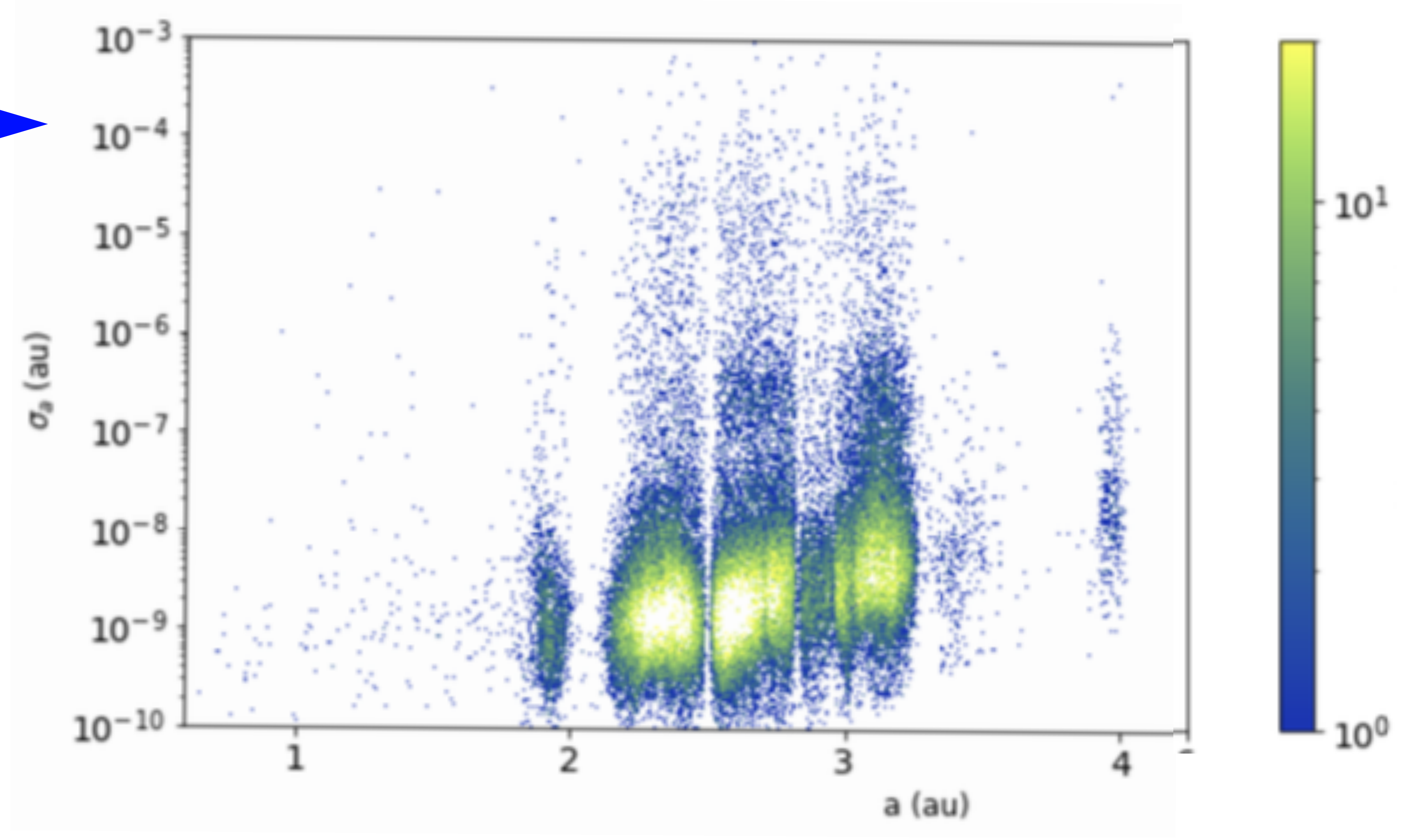
# Astrometry: gain on orbit accuracy

Strongly non linear and large gain when time span ~ orbit period

DR3 (34 months)




FPR (66 months)




- Increased arc length : 20 X improvement with respect to DR3
- Impact on:
  - Mass determination
  - Prediction of stellar occultations

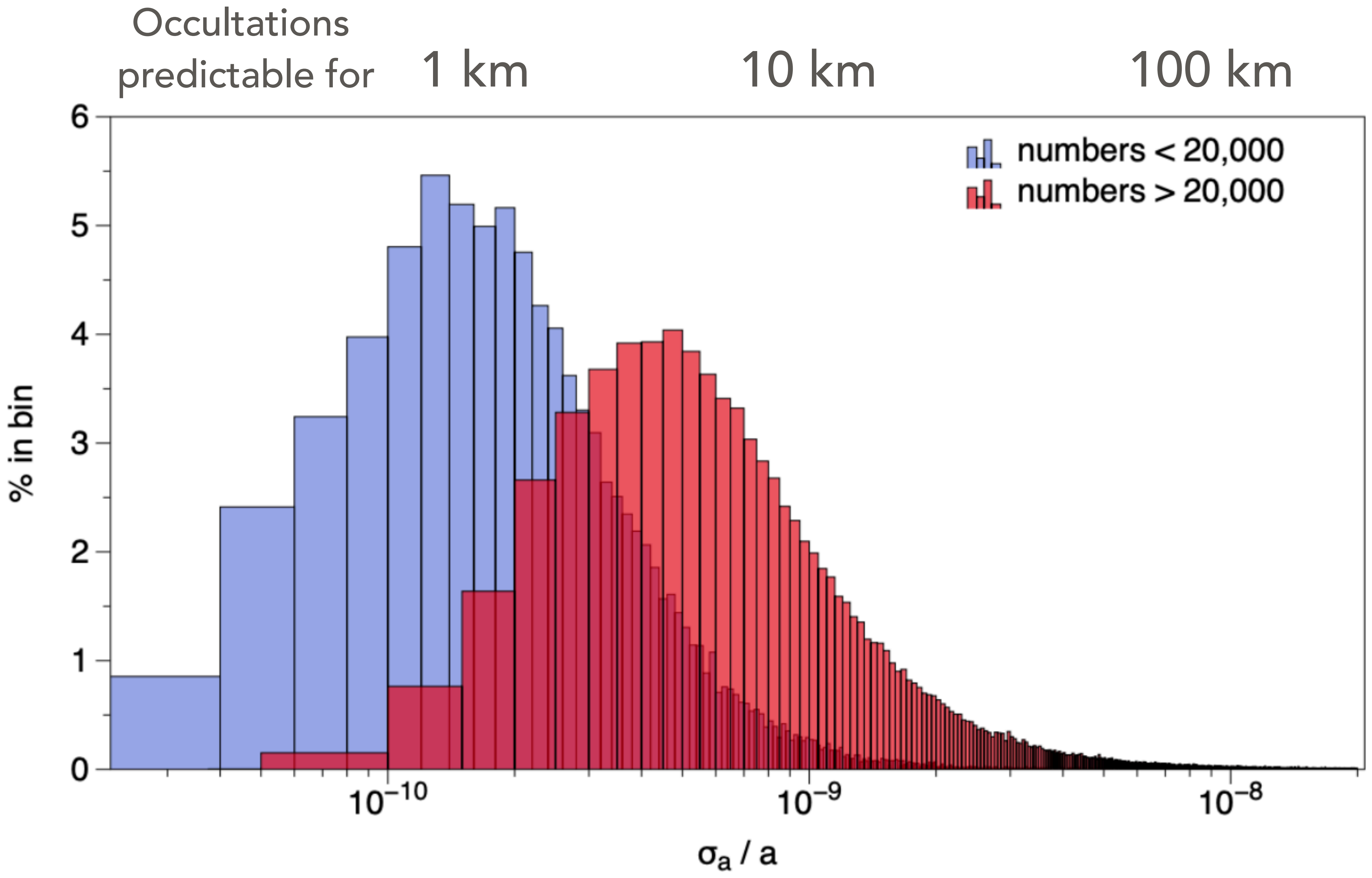
David et al., FPR article, A&A 2023, submitted

# Orbit accuracy, which perspectives by Gaia NIR?

- Strong gain on orbits whose period is similar (or <) to the time gap between the missions
  - Situation analogue to what is observed between DR3 and FPR:
    - 66 months —> 3 au
    - 20-30 years —> 7.4 - 10 au
  - Strong gain also for the exterior of the Solar System (inner KBOs)
- Orbits of shorter period: incremental gain
  - Which are the limits?

# Orbit accuracy: can we do better…?

FPR: formal orbit uncertainties



# Orbit accuracy: can we do better…?

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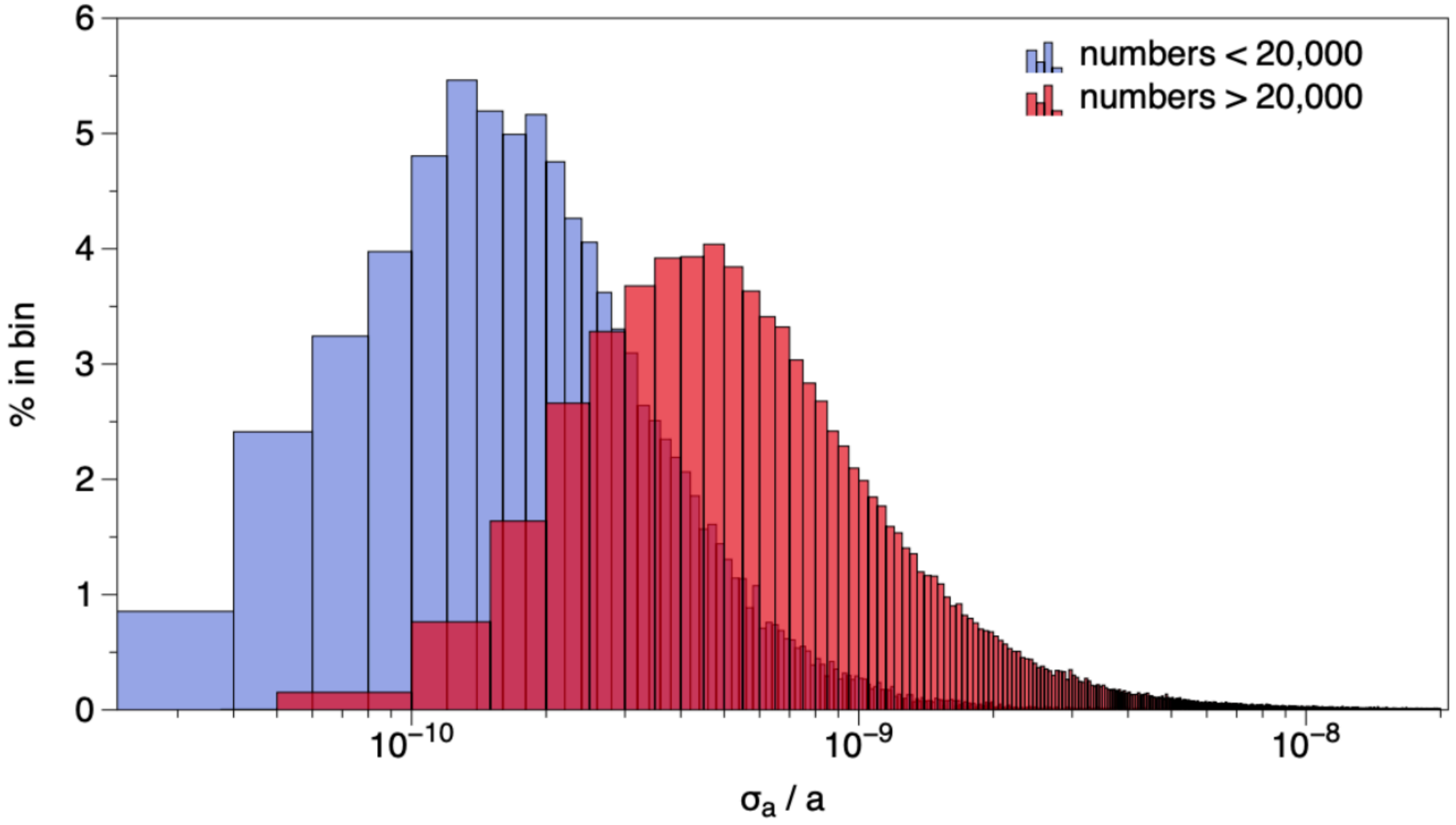
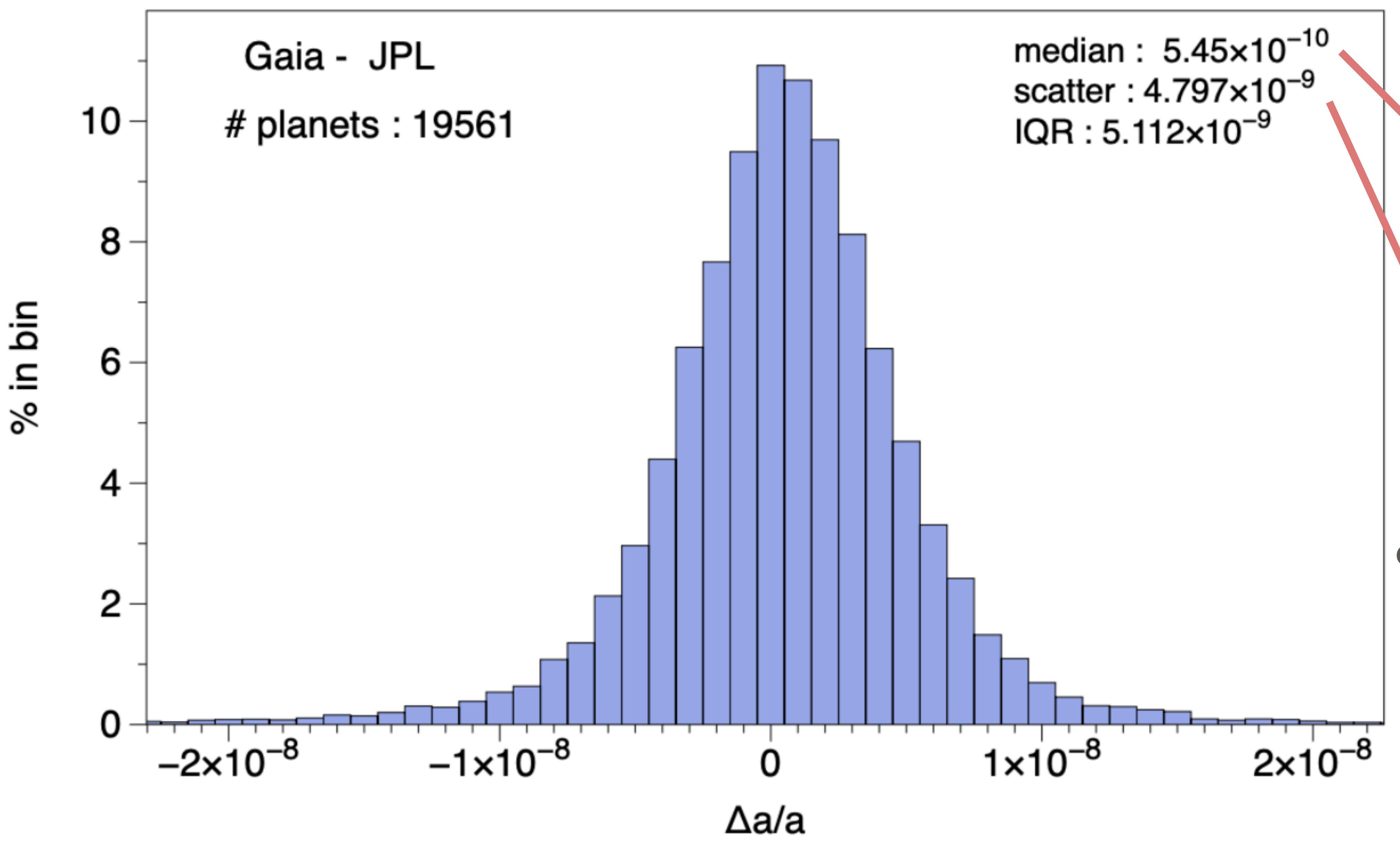
Occultations predictable for 1 km 10 km 100 km




FPR: comparison to JPL

1000s observations per objects over 10s-100s yr !!




Very good agreement!

Comparable to catalogue accuracy

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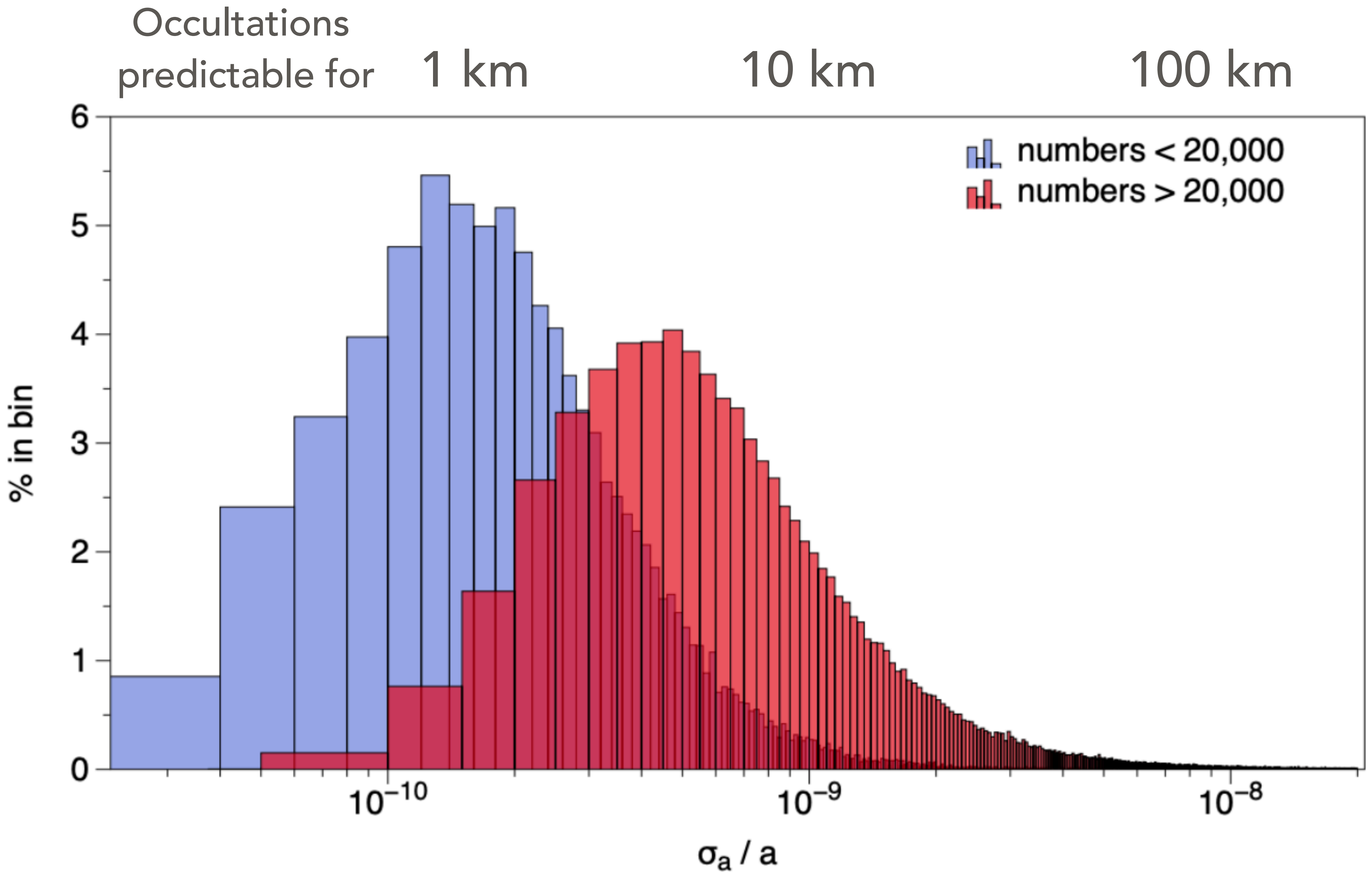


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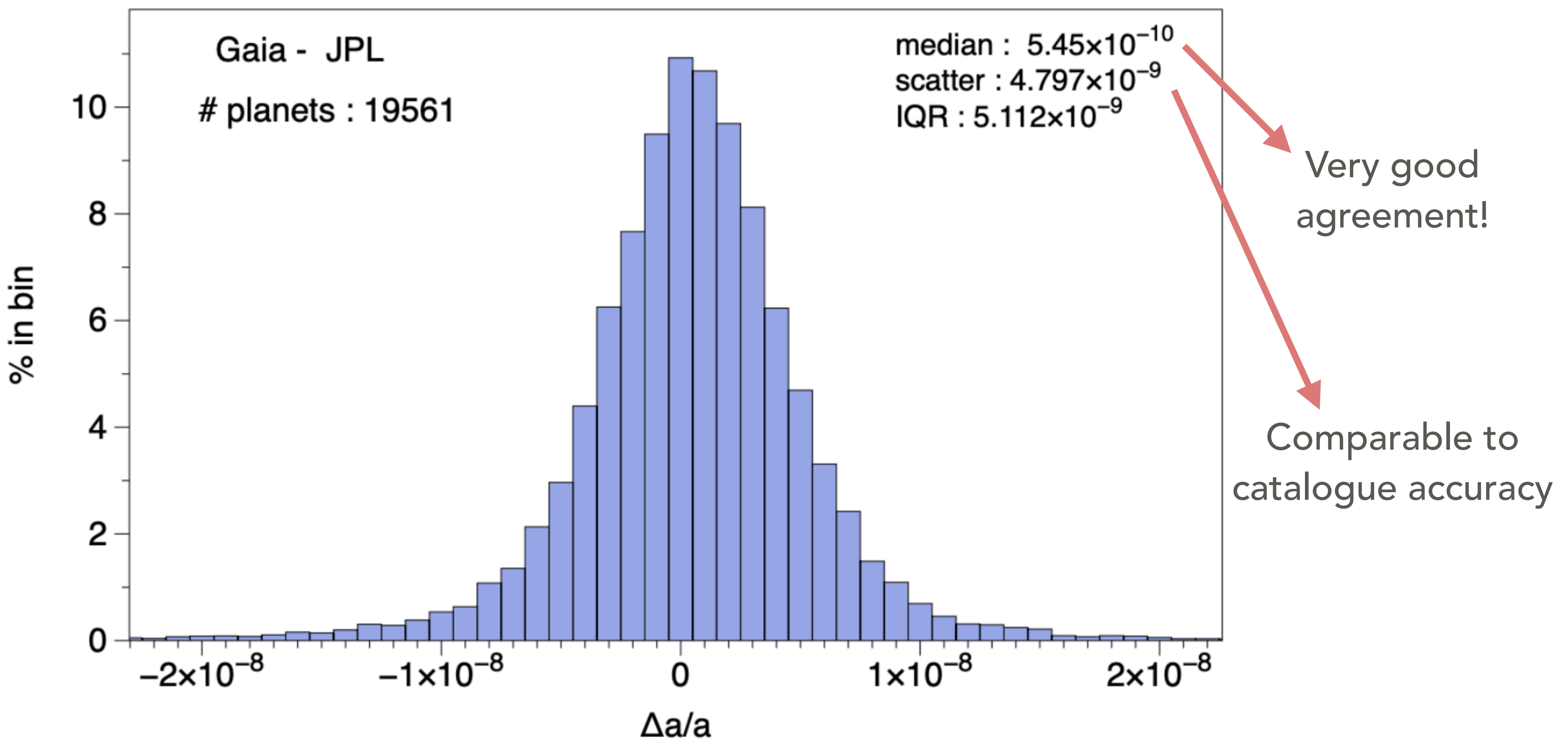


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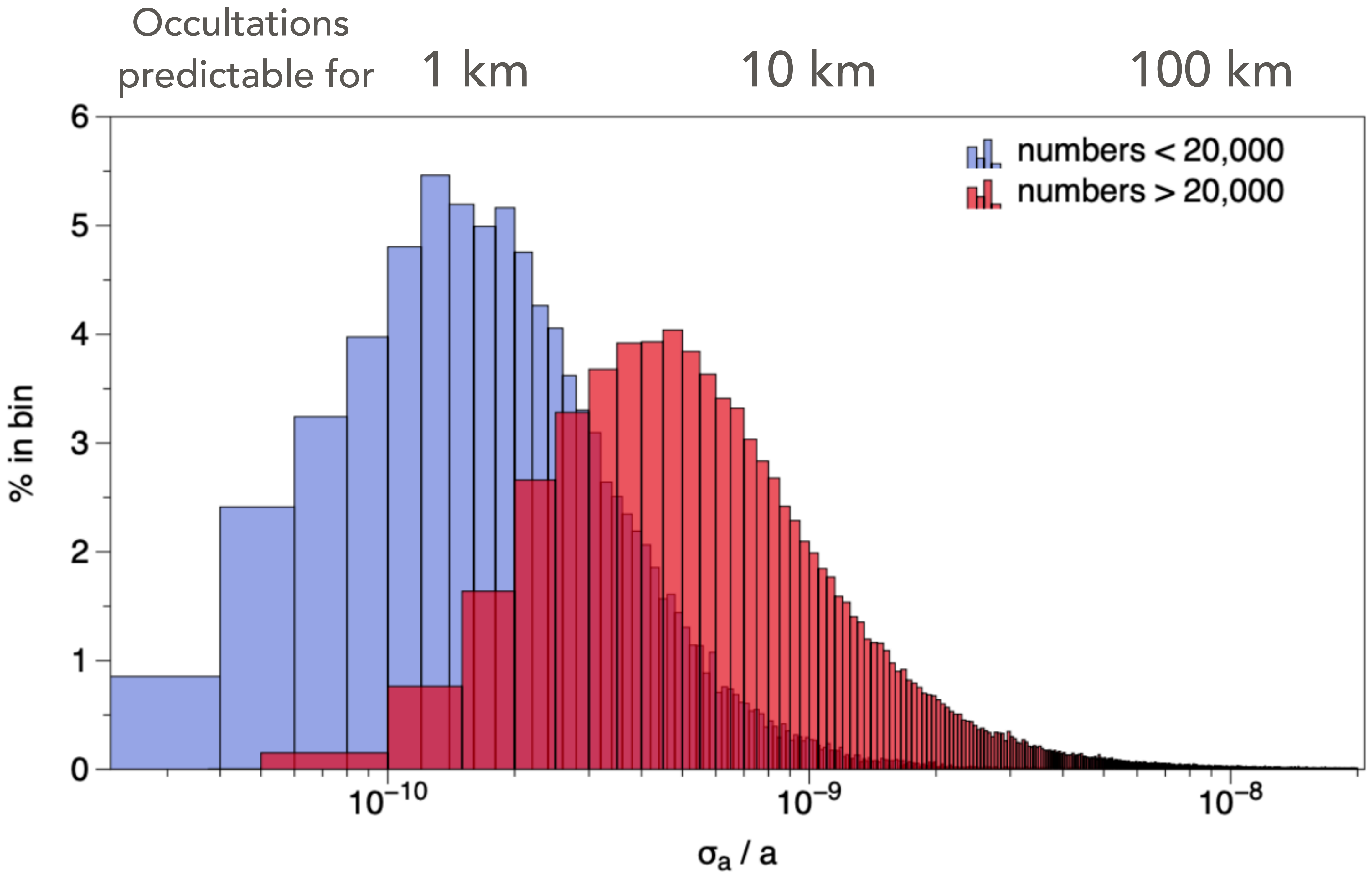


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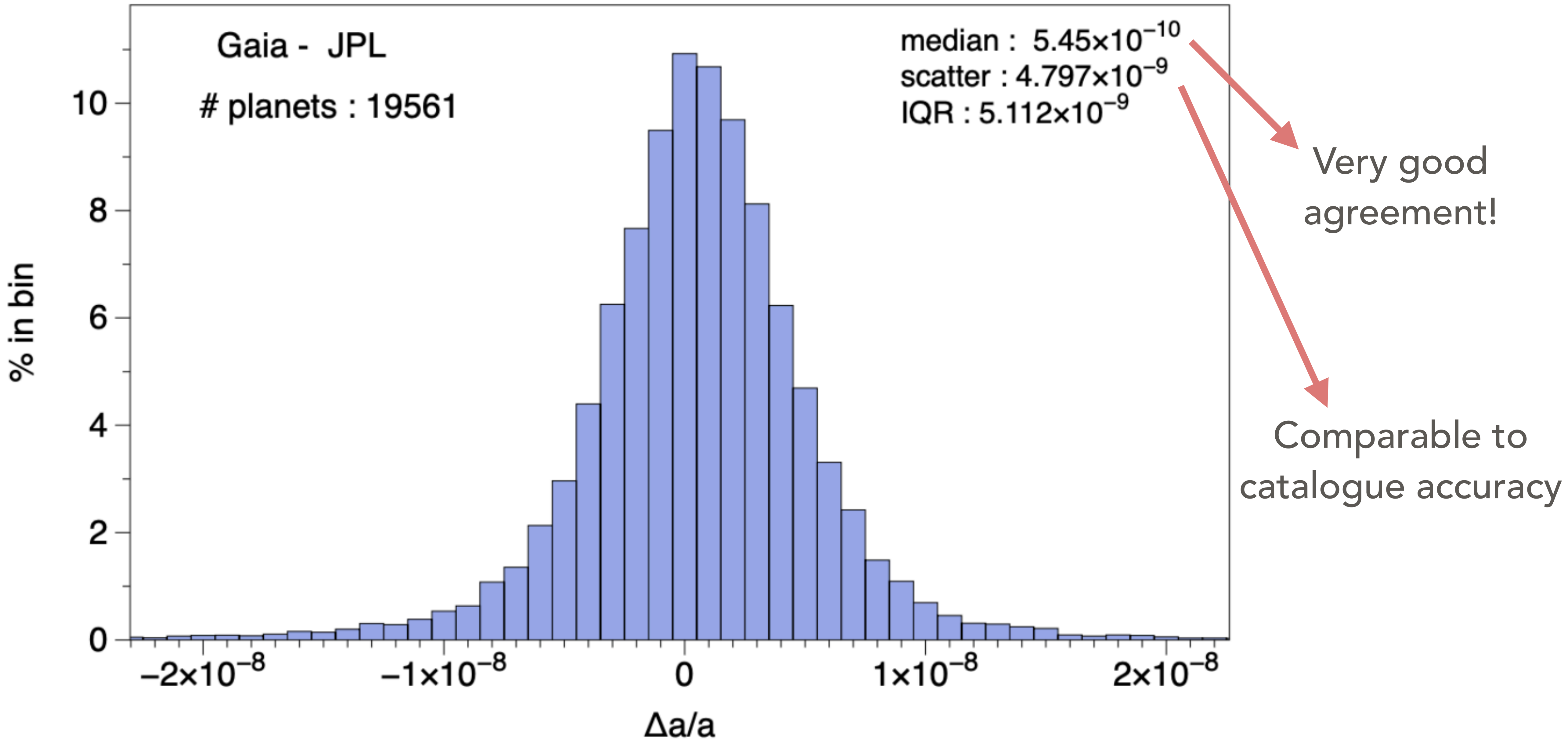
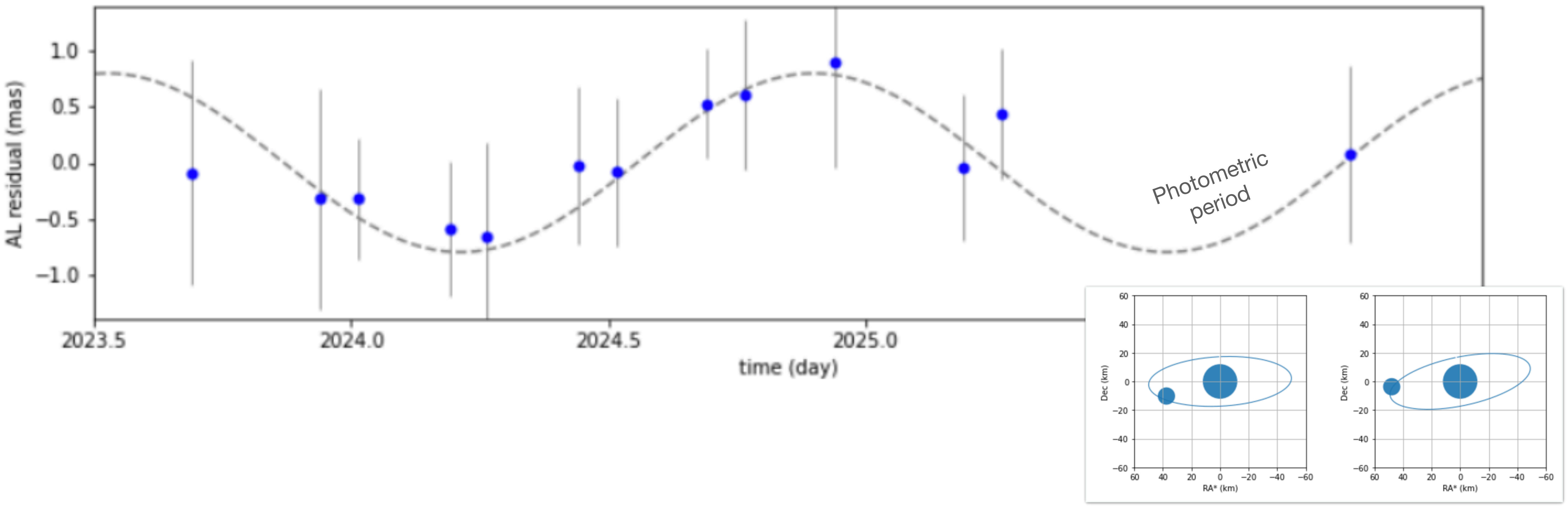



- Answer: yes, for faint objects whose accuracy has margins of improvement
- …and, no, for the best sample: if the dynamical model is not improved at the same time
  - Going below 1e-10 requires a careful evaluation of the masses of perturbers, the treatment of J2 for the largest planets, the Earth-Moon model, etc. —> a better dynamical model

# Added complexity at mas level: physical properties and astrometry

- Satellite-induced wobble in DR3 astrometry of (4337) Arecibo




Tanga et al. A&A special issue 2022

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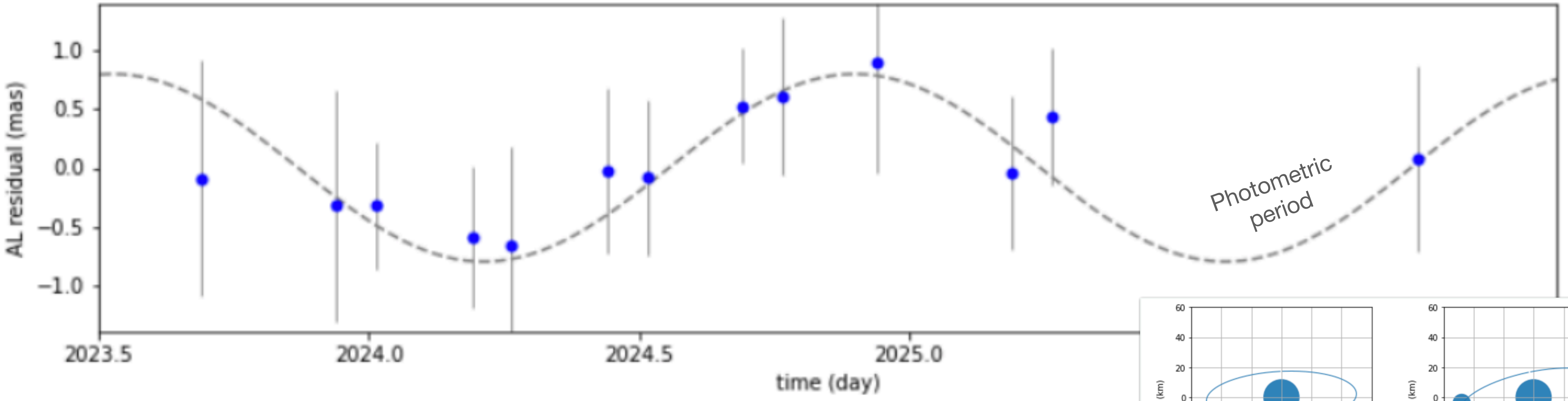
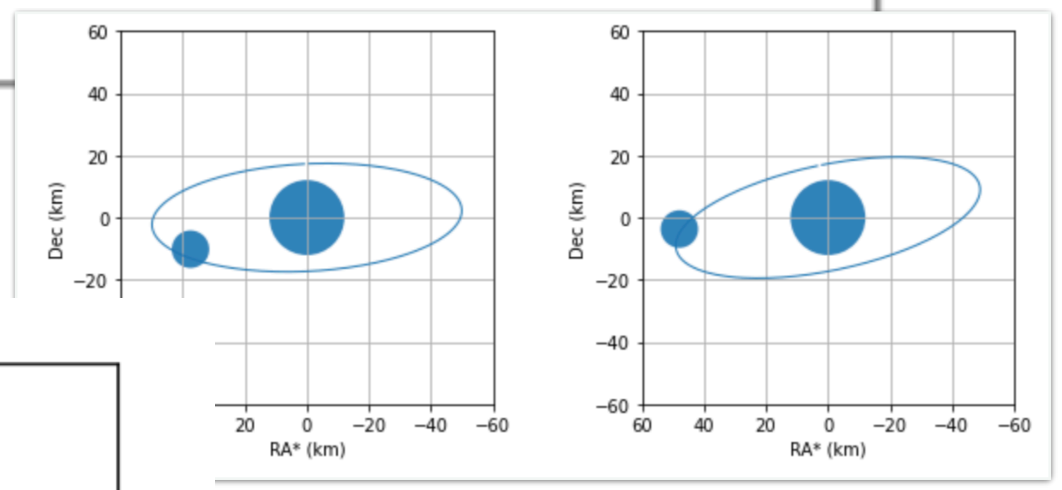
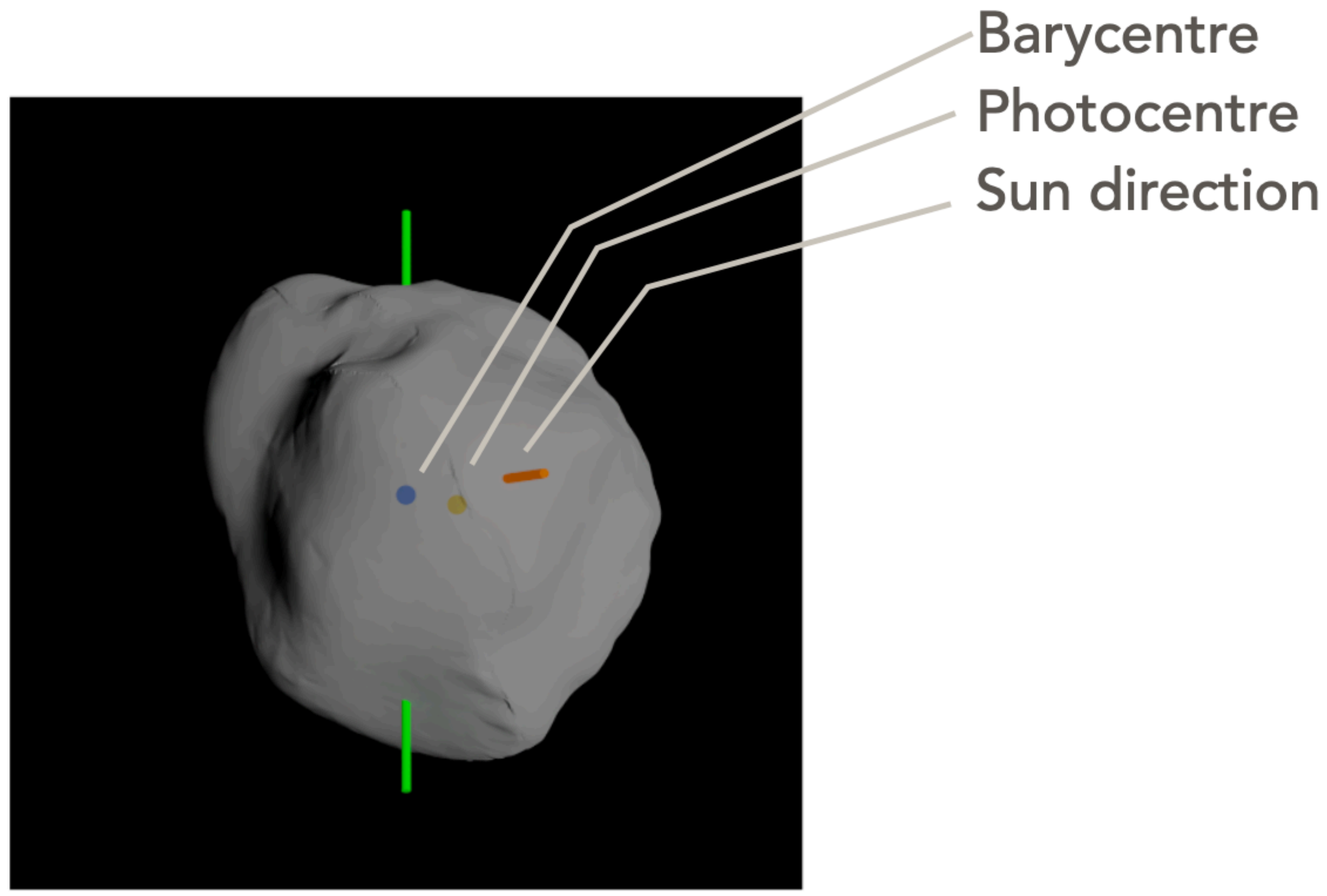
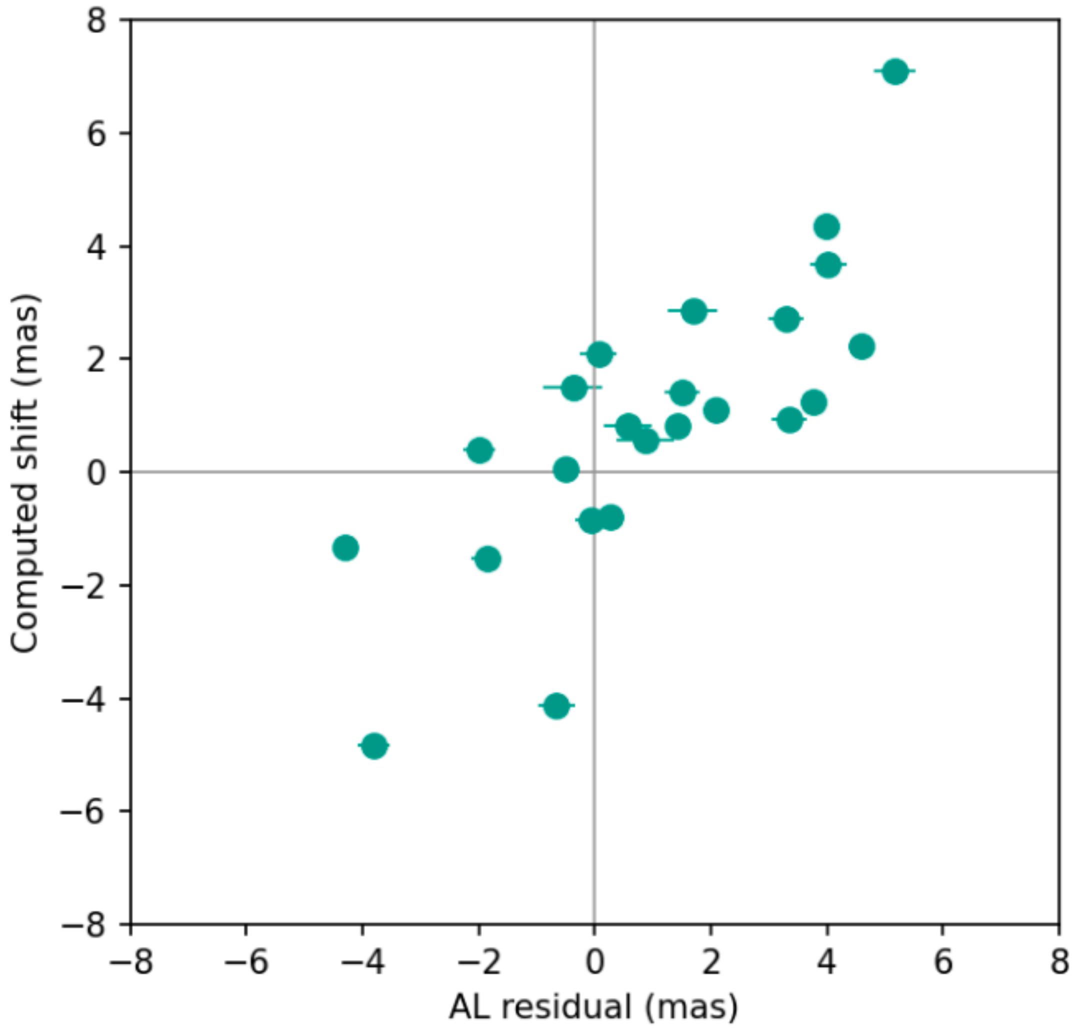


- Photocenter - barycenter difference: modelling surface properties by astrometry

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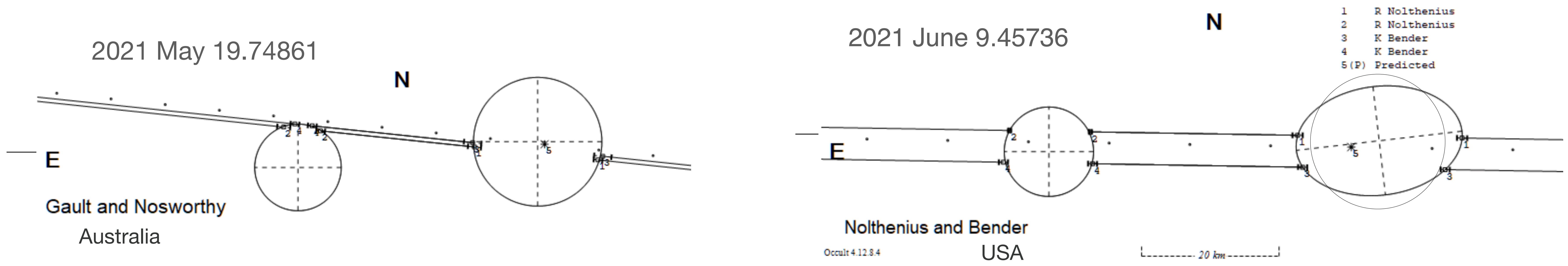
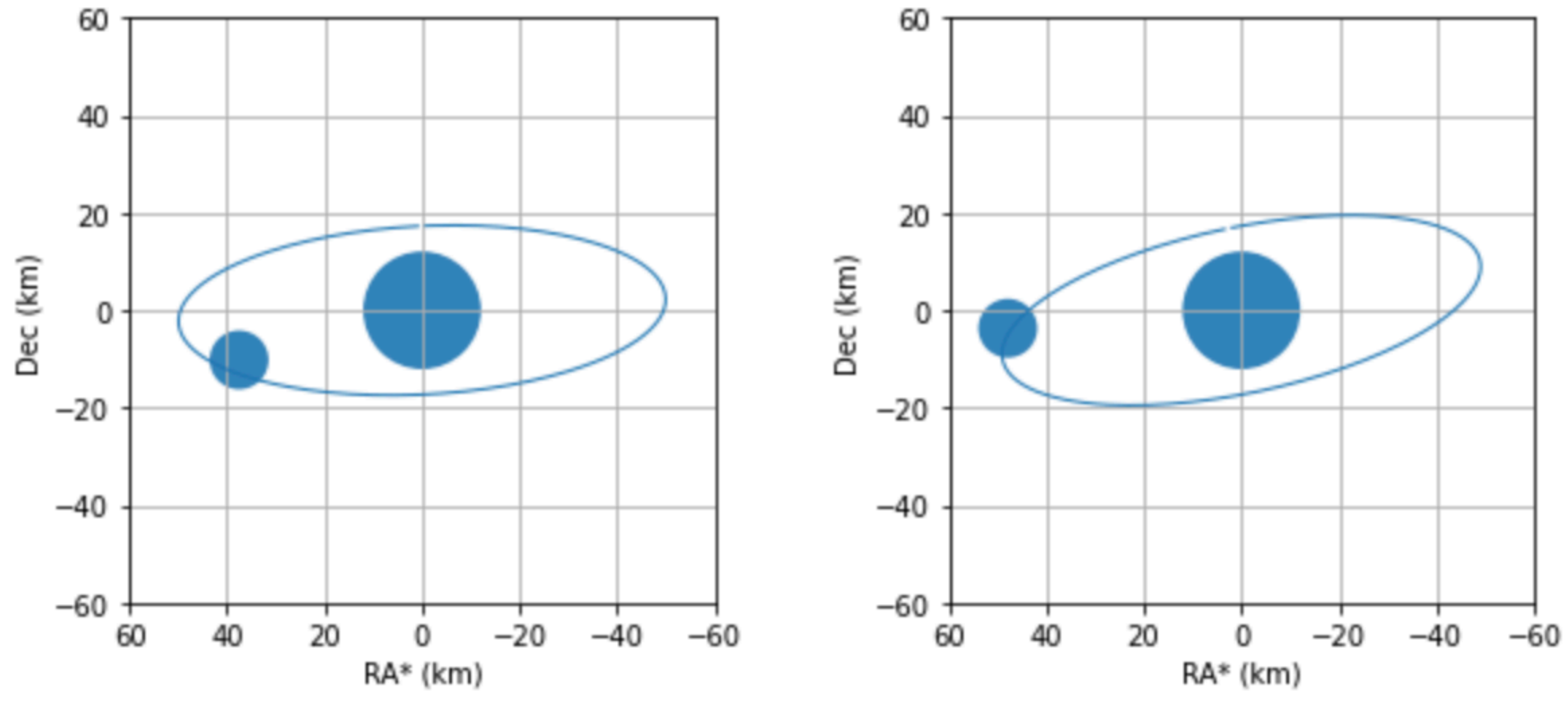
# 4337 Arecibo

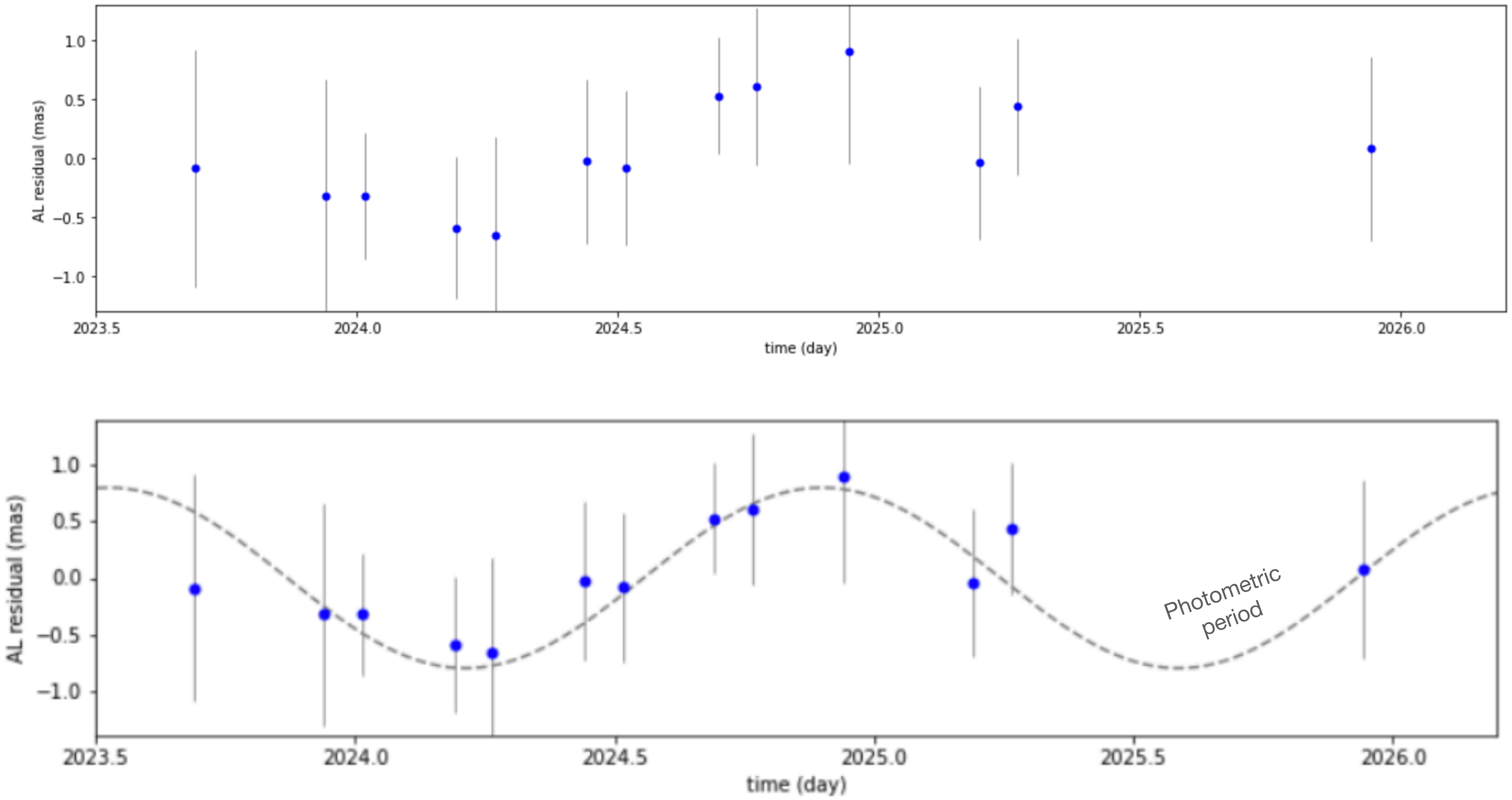
Binary discovered by two stellar occultations - independent observers



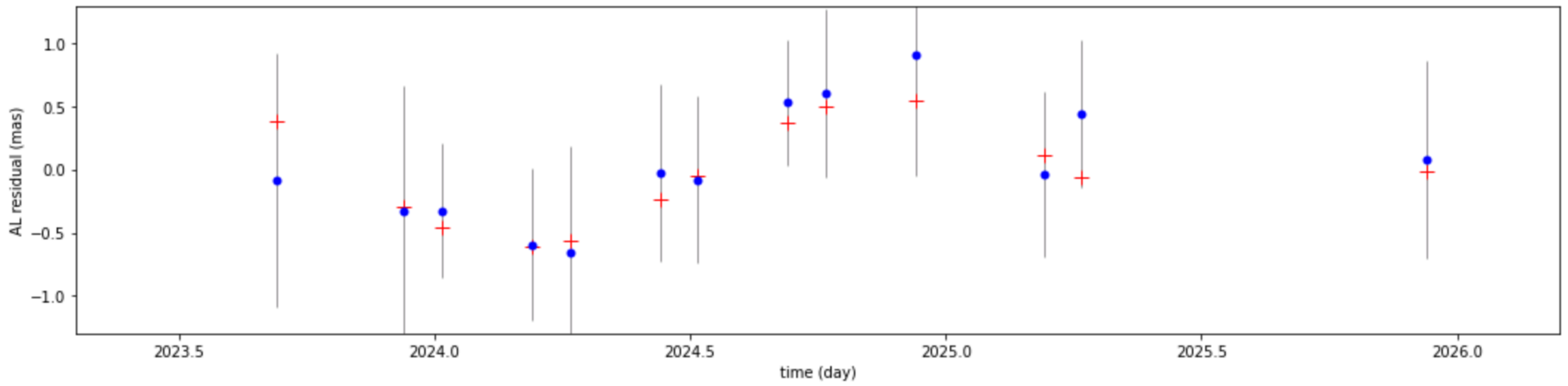



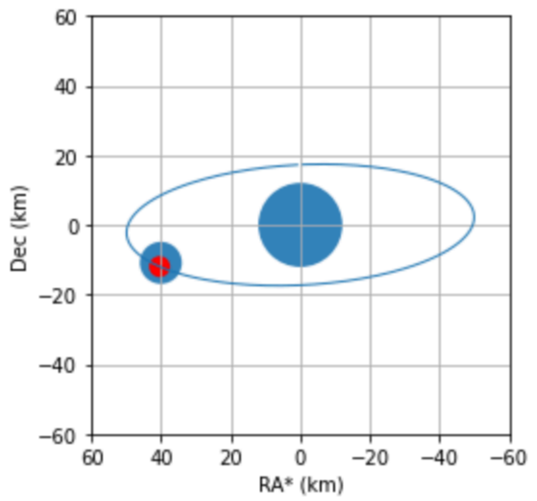

Two accurate relative positions
Size ratio k ~ 0.55

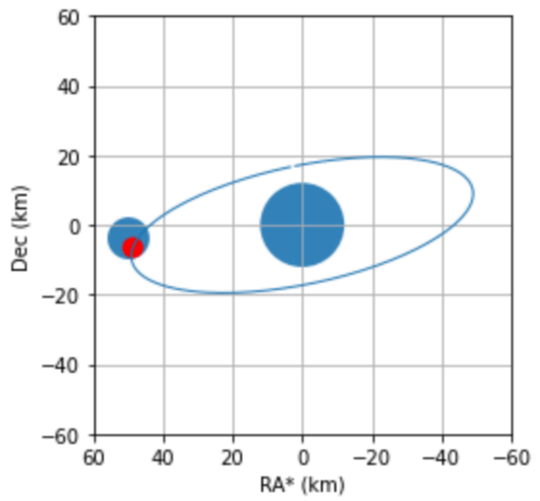
# Post-fit residuals - Gaia observations of (4337) Arecibo



# A complete solution for (4337) Arecibo



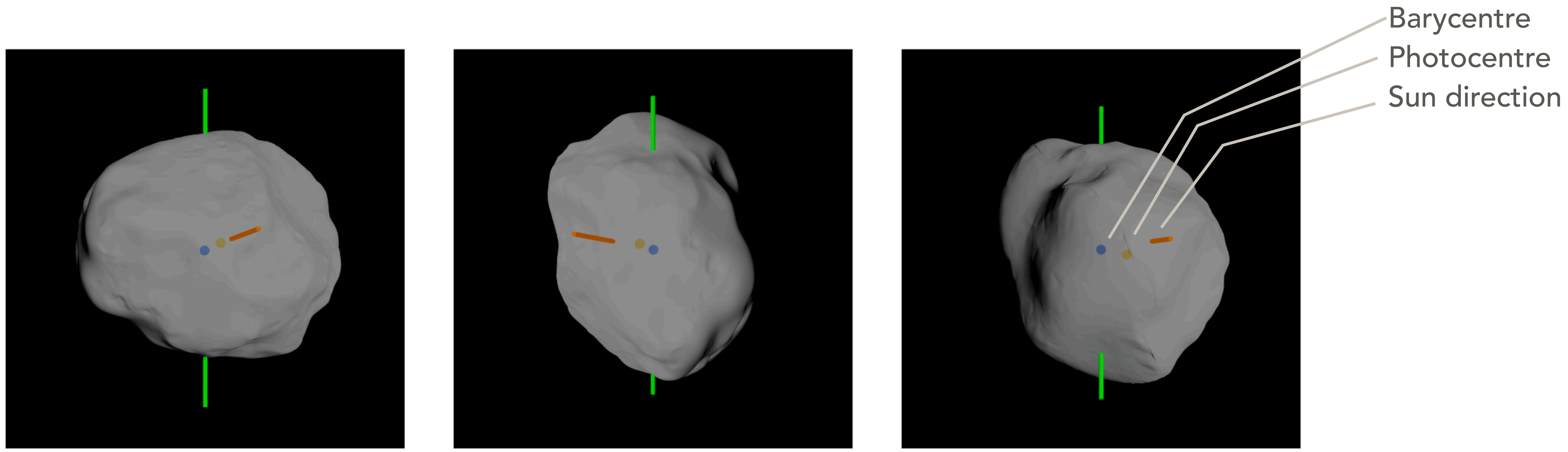



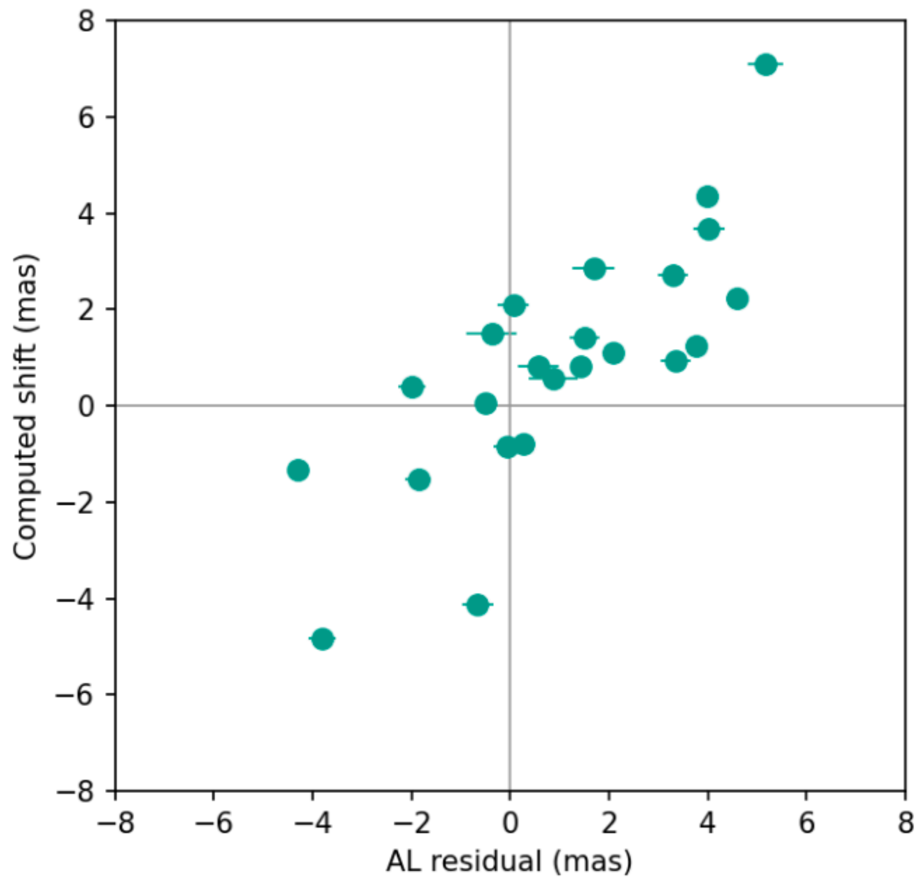



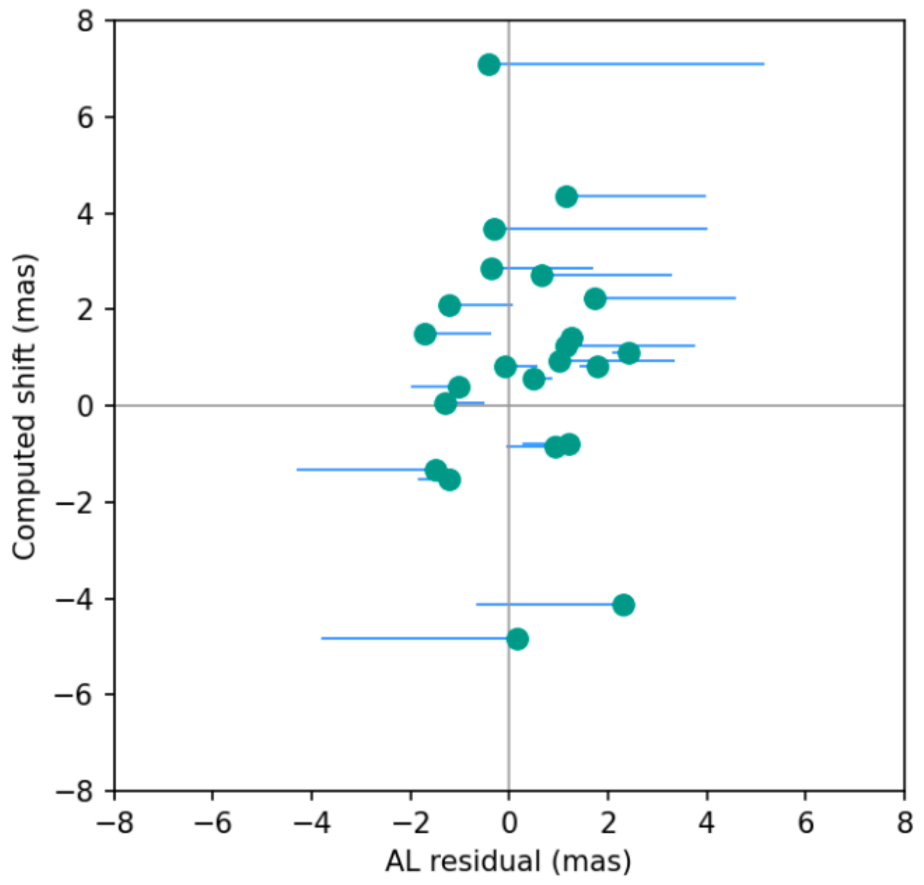

- From photometry:
  - T = 32.972823 h
- Parameter optimisation:
  - Pole coordinates ($\lambda$, $\beta$), rotation origin, separation
  - Size ratio 0.35 (smaller than obtained by the occultations)
    - Probable flattened shape of the 2 components
- Through Kepler's law: bulk density = 1.0 $g/cm^3$
  - In agreement with Themis family (< 1.3 $g/cm^3$) !

# Application of astrometry: shape effects

Example of 21 Lutetia



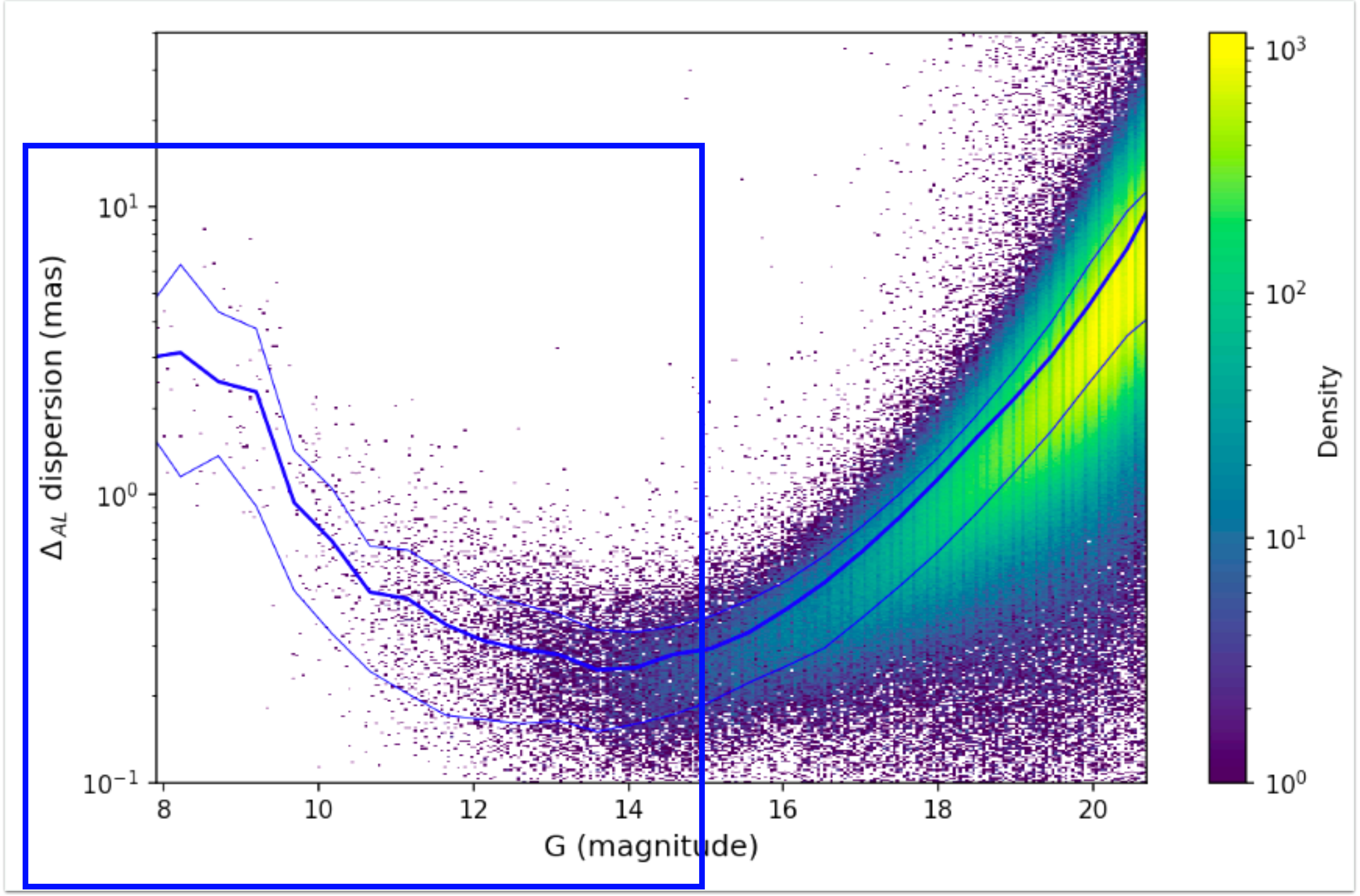




Residuals corrected for the shape model and the illumination geometry

# DR3, astrometric accuracy: post- orbital fit residuals

- Shape probably affecting asteroid astrometry for objects >10-15 km
    - > 10.000 objects
- Even larger sample affected with more precise orbits




Tanga et al. A&A DR3 special issue, 2022

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  - Useful if the scanning law permits longer sequences of consecutive data on Main Belt asteroids, to better sample rotational variations / satellites
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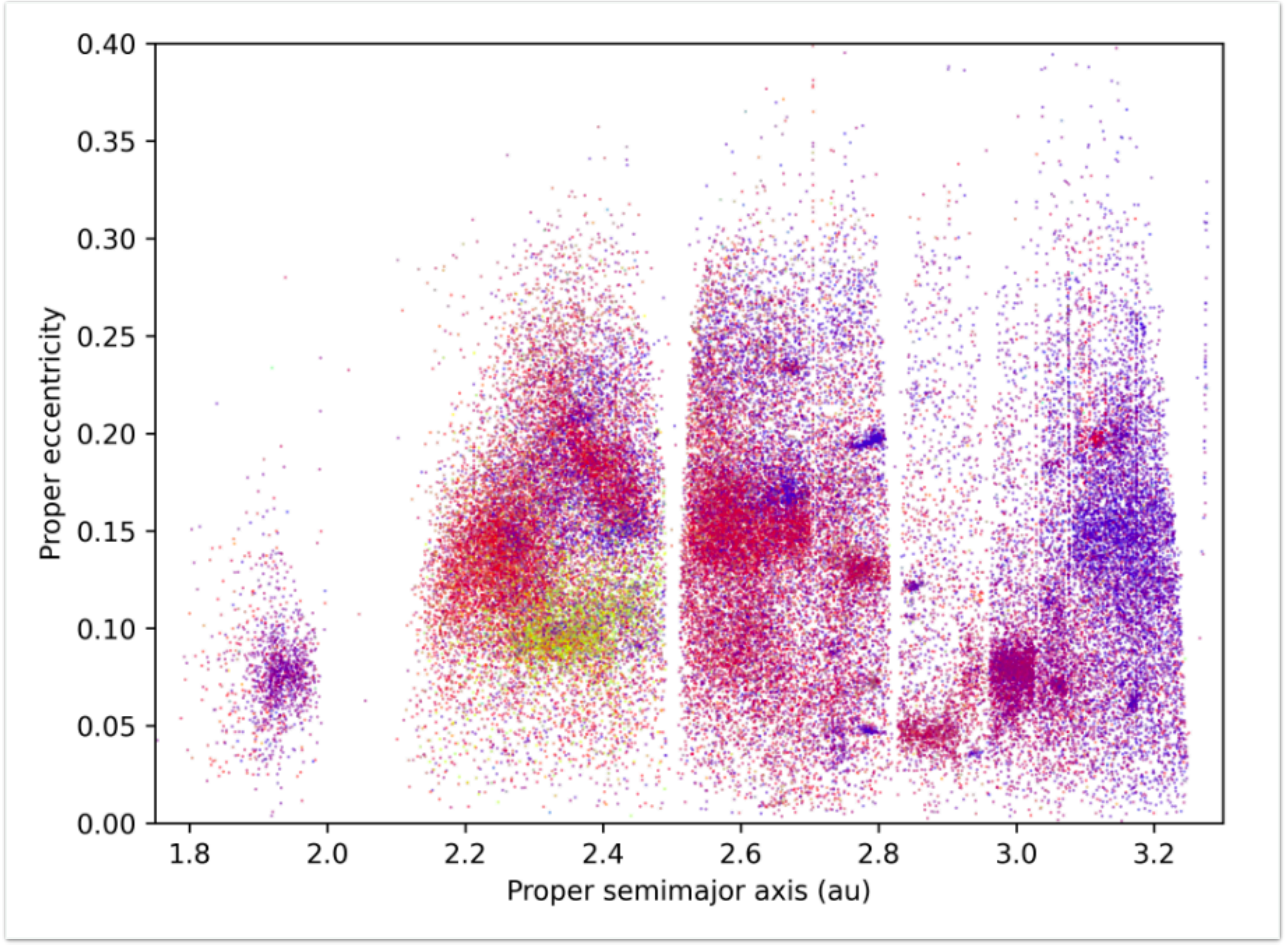
  - But for NEOs in general: a better treatment of fast movers would be highly desirable
- Epoch astrometry
  - Further increase in accuracy based on the Gaia + Gaia NIR
  - Physical and dynamical properties to be modelled at the same time for a larger number of objects
  - Would trigger improvement in the dynamical model of the Solar System (more perturber masses…. )

# Thank you !




Galluccio et al. A&A DR3 special issue (2022)