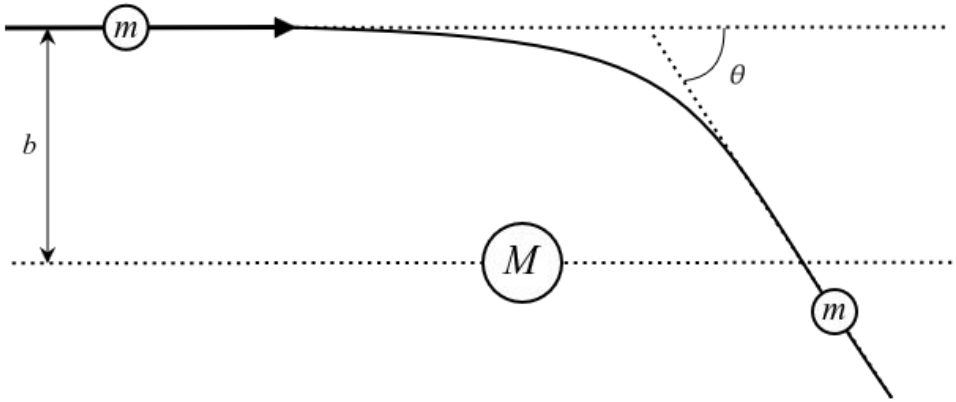
Asteroid mass estimation in the Gaia era

Elo Tuominen (they/them/theirs)
Mikael Granvik, Karri Muinonen
Nordic-Baltic Astronomy Days 2026, Turku, Finland

Asteroid mass estimation based on close encounters

Close encounters between asteroids cause orbital changes, which can be analyzed to estimate the mass of the perturbing asteroid. The changes are constrained with astrometric observations.



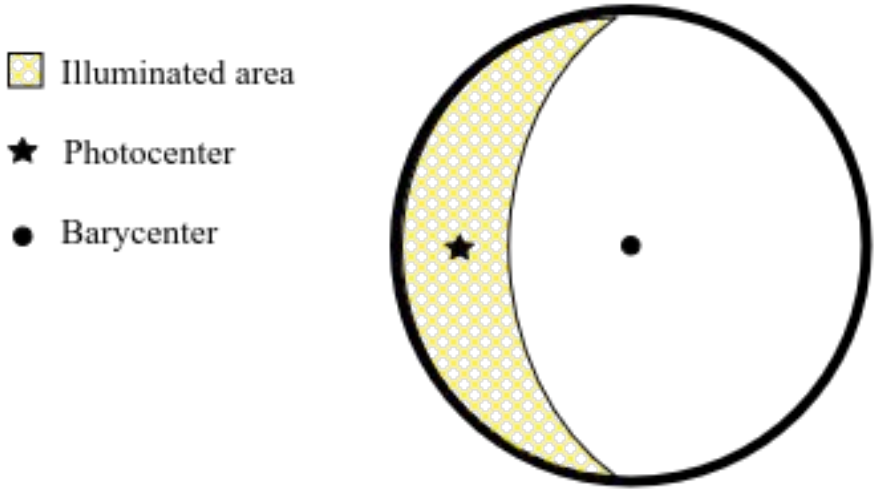
Gaia space telescope

- Operated until January 15, 2025
- Data releases (DRs) still coming, latest releases were DR3 (34 months of data) and Focused Product Release (FPR, 66 months of data)
- Astrometry with sub-milliarcsecond accuracy
    - Accuracy decreases for larger asteroids

Image credit: ESA

Photocenter-barycenter offset

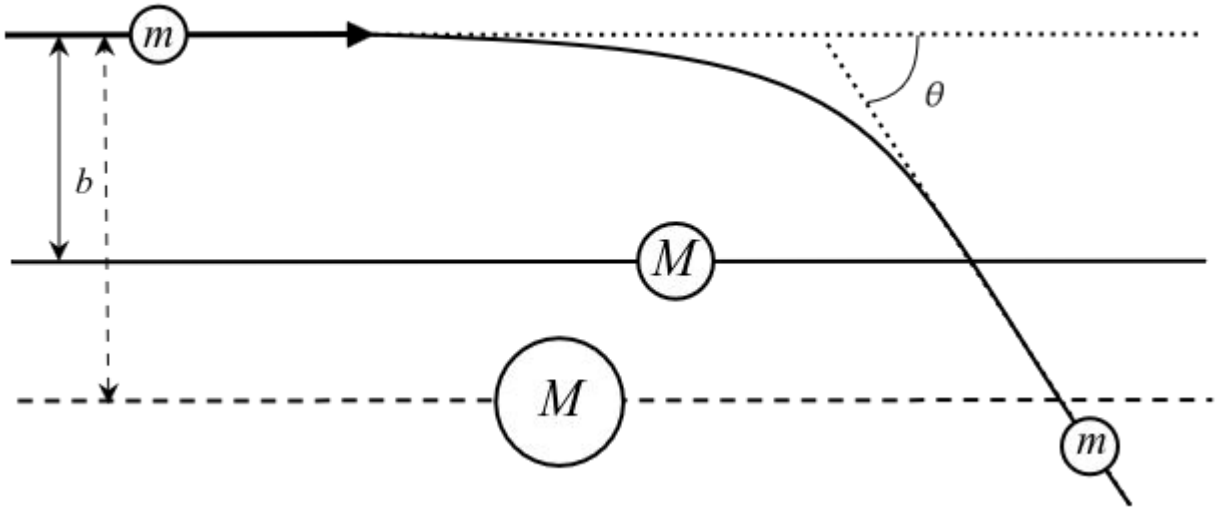
i.e., the misalignment of the center of light and the center of mass of the asteroid



Previous studies show improvement in, e.g., orbital fitting residuals when the offset is corrected for (Gaia Collaboration, Tanga et al. 2023; Fuentes-Muñoz et al. 2024)

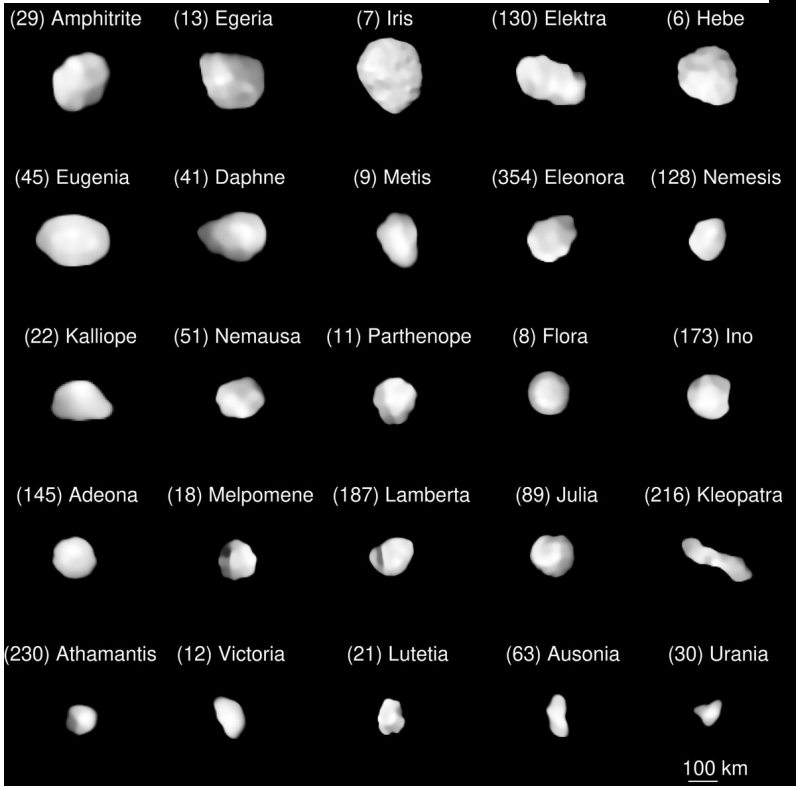
The significance of the offset for mass estimation

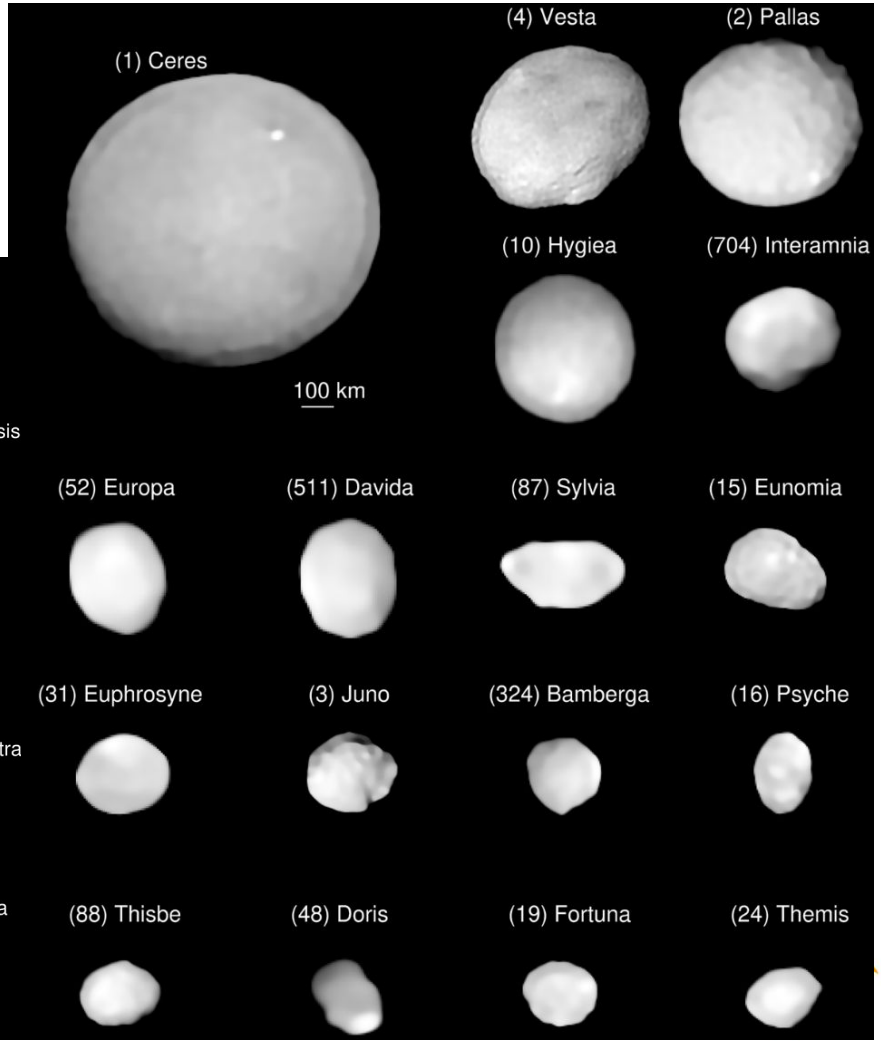
Orbits (are supposed to) track the barycenter!



Asteroid shapes

Adaptive optics images from Vernazza et al. 2021





Photocenter offset computation and correction

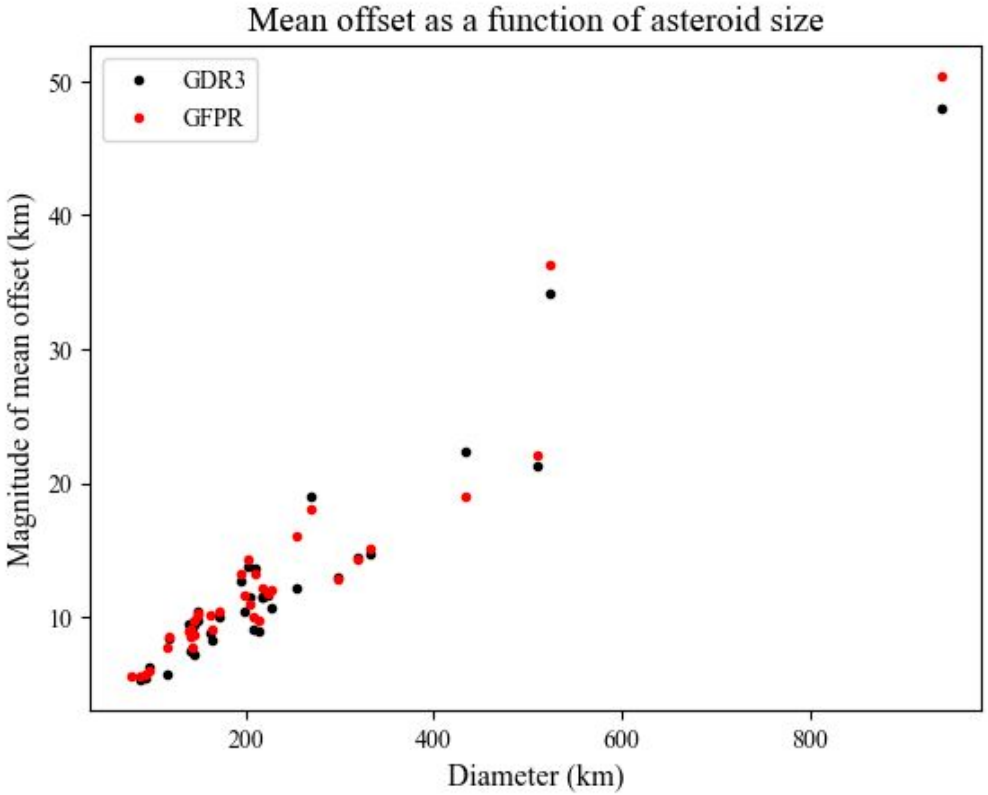
Step 1: Compute the offset.

- Computation based on Muinonen & Lumme 2015, assuming a general shape (shape model) and using the fractional Brownian motion Particulate Medium (fBm-PM) scattering model (Björn et al. 2024)

Step 2: Correct astrometric observations by subtracting the offset.

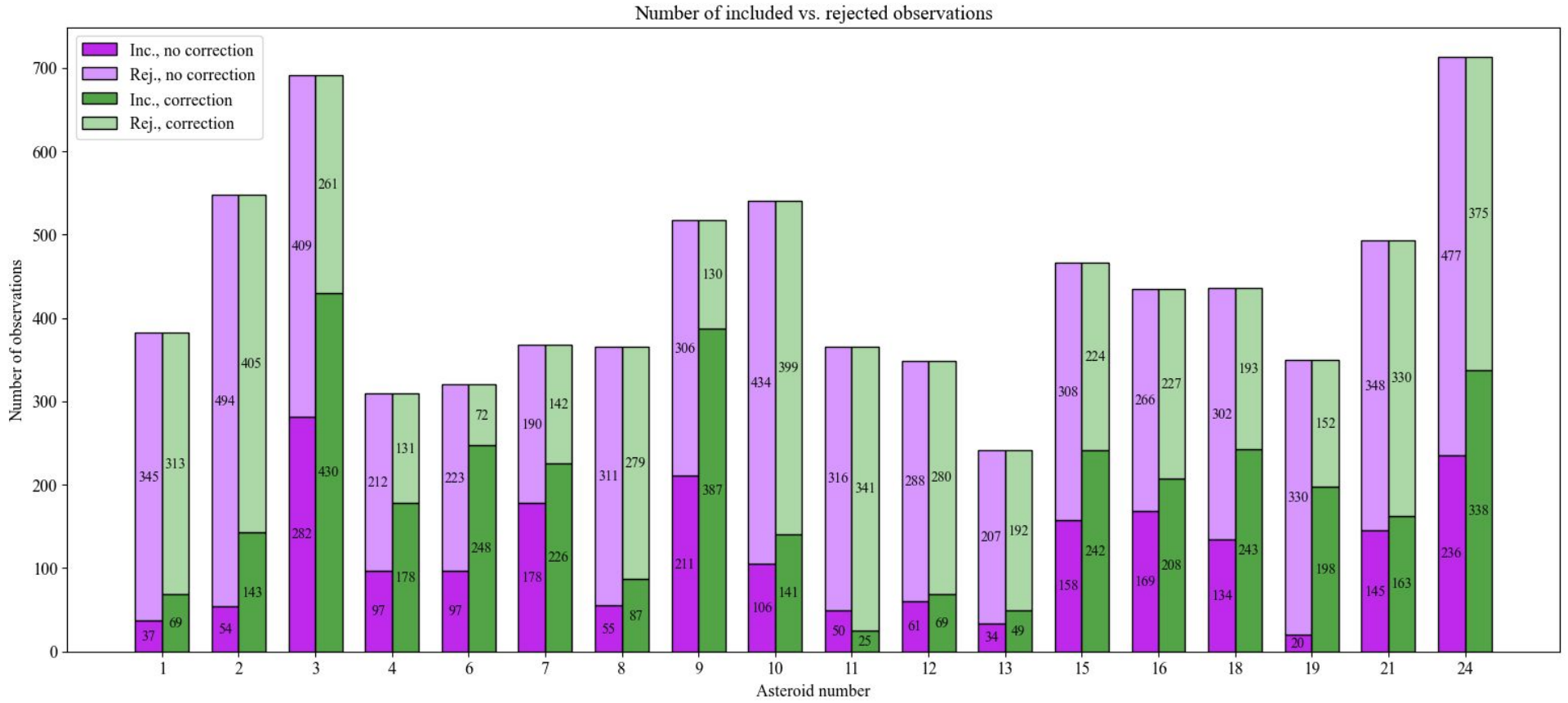
- Asteroid can rotate between observations: compute and subtract offsets accordingly!

Magnitude of mean photocenter offsets with Gaia FPR

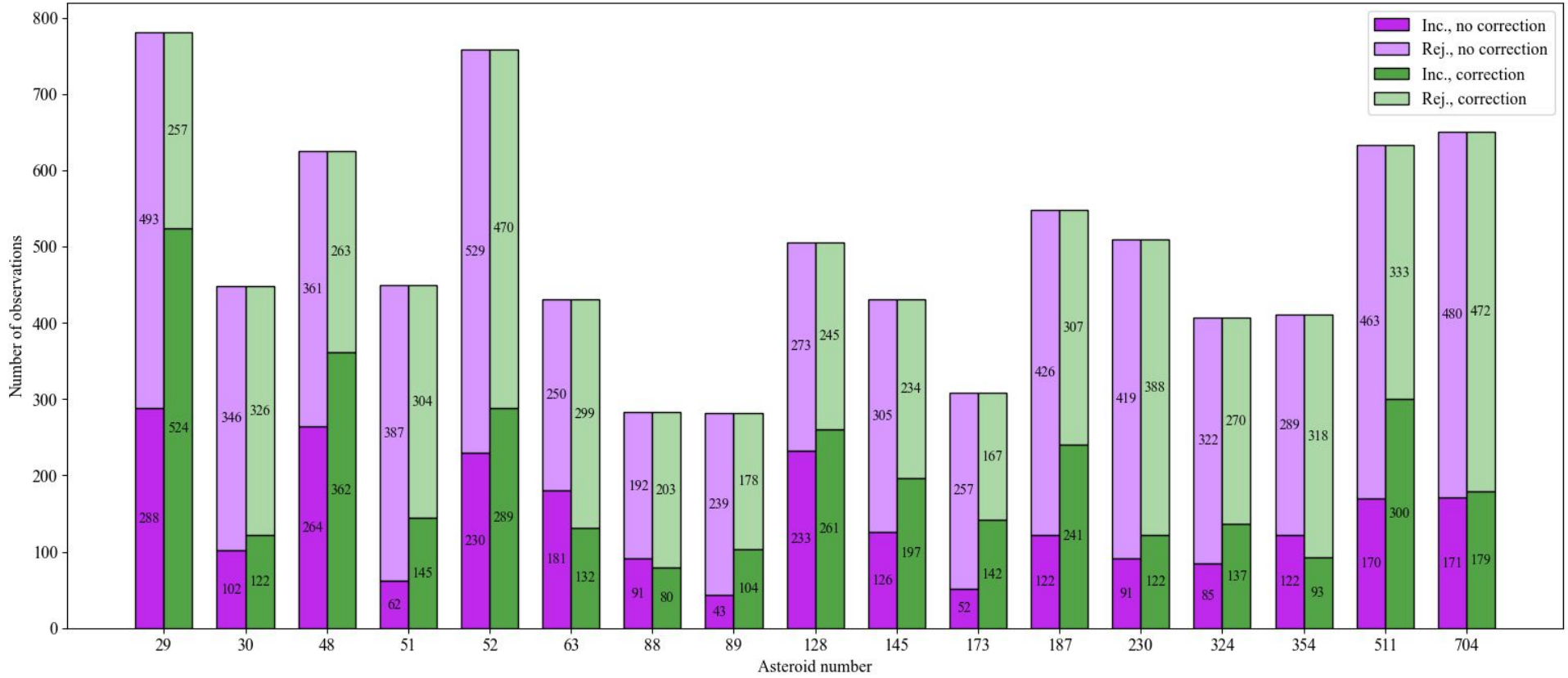


Offsets typically correspond to some milliarcseconds in angular diameter.

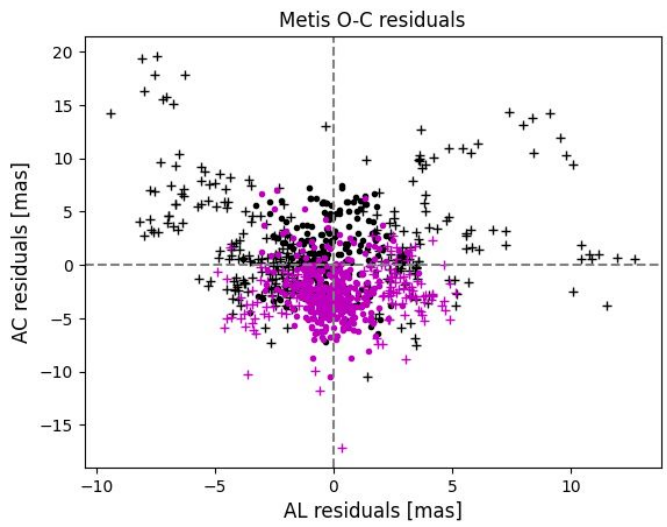
Here GDR3 offsets computed with Lommel-Seeliger scattering and GFPR with the fBm-PM model.

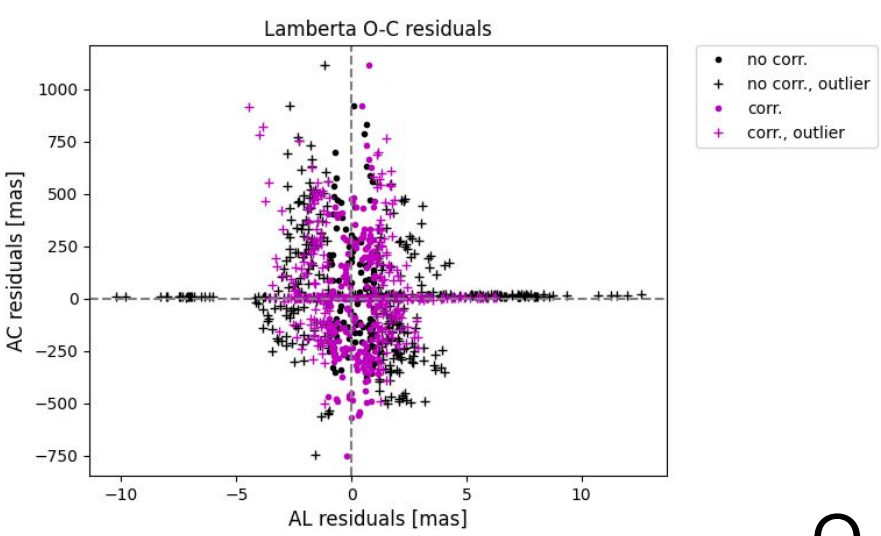


Number of included vs. rejected GFPR observations from orbital solutions before and after applying a photocenter offset correction

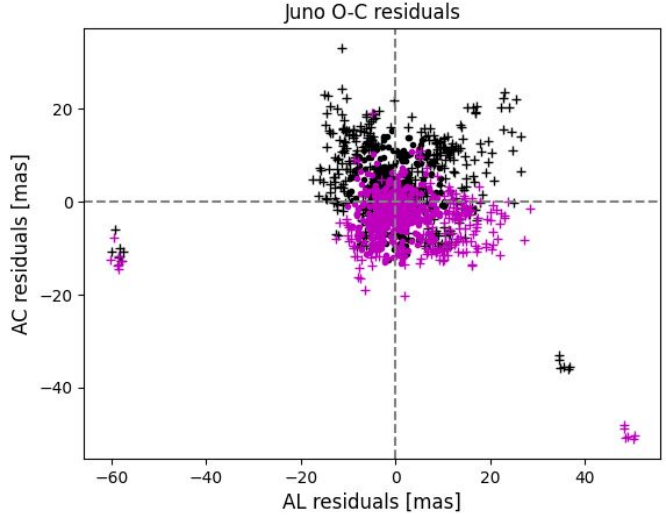


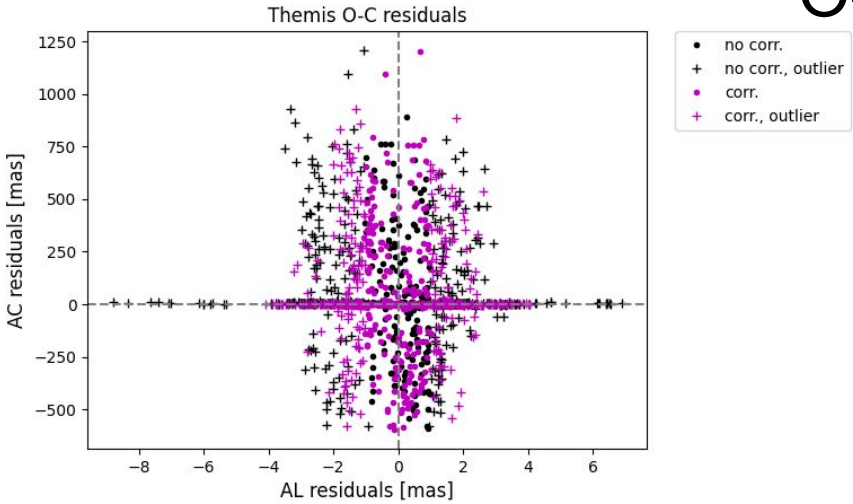
Number of included vs. rejected GFPR observations from orbital solutions before and after applying a photocenter offset correction





O-C residuals

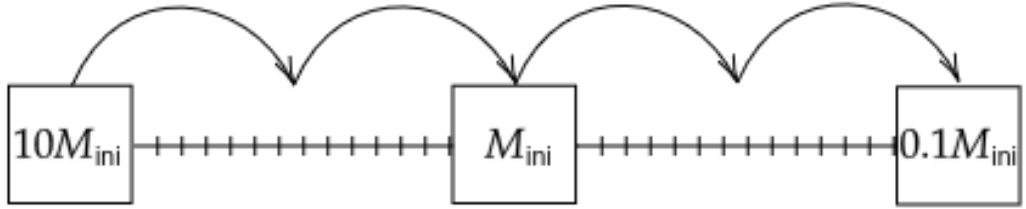




Mass marching inverse method

Initial least-squares orbits for perturber asteroid and test asteroid(s)

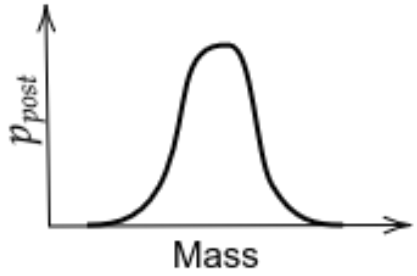
Evenly spaced perturber asteroid mass interval

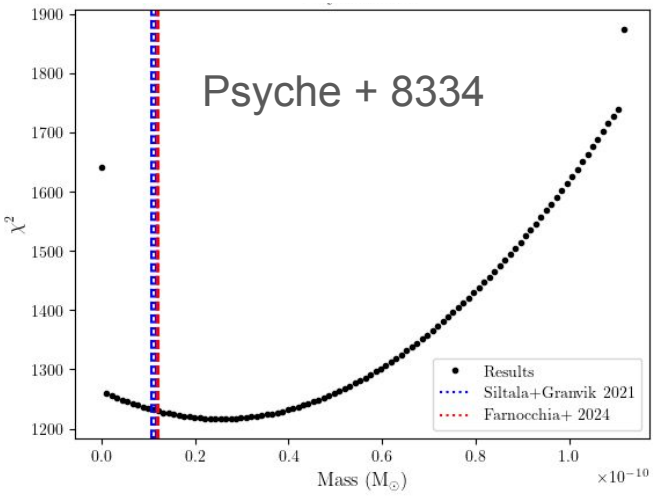


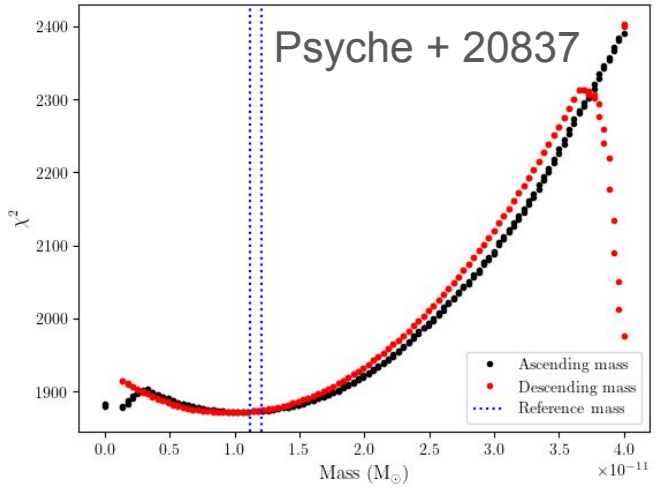
Orbit(s) of the test asteroid(s) and the chi2 value recomputed at each mass

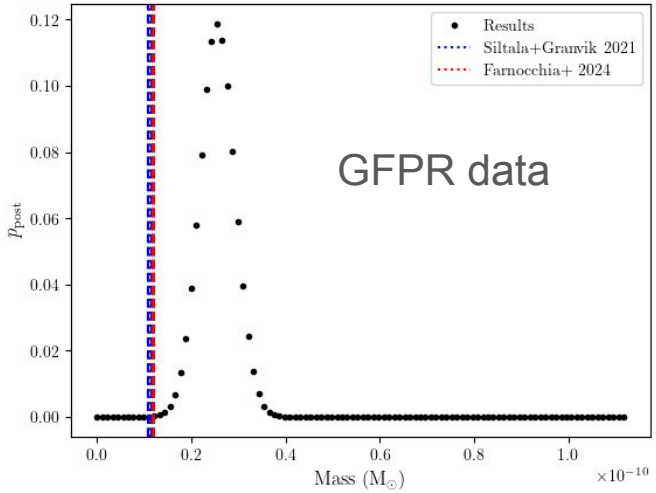
When moving to the next mass use the updated orbit

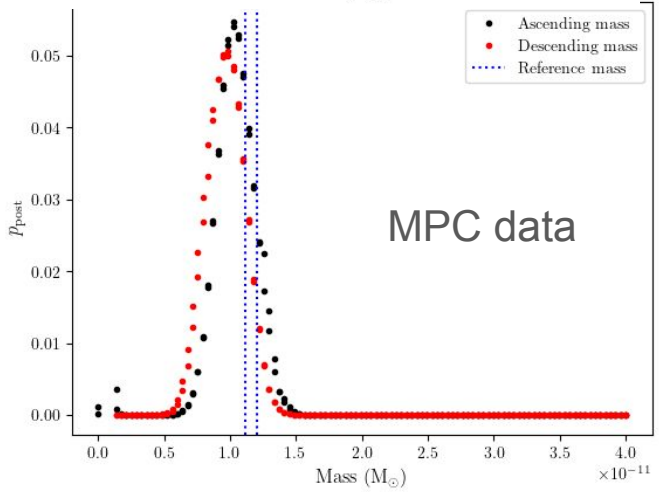
$$p_{post}(M) \propto \sqrt{det\Sigma(M)}exp\left(-\frac{1}{2}\chi^2(M)\right)$$




Psyche + 8334
Results
Siltala+Granvik 2021
Farnocchia+ 2024
χ^2
Mass ($M_\odot$)
$\times 10^{-10}$


Psyche + 20837
Ascending mass
Descending mass
Reference mass
χ^2
Mass ($M_\odot$)
$\times 10^{-11}$


GFPR data
Results
Siltala+Granvik 2021
Farnocchia+ 2024
p_{post}
Mass ($M_\odot$)
$\times 10^{-10}$


MPC data
Ascending mass
Descending mass
Reference mass
p_{post}
Mass ($M_\odot$)
$\times 10^{-11}$

MMI results

Conclusions

- Photocenter offsets are significant at Gaia's accuracy
- No drastic change in photocenter offsets with GFPR + fBm-PM compared to GDR3 + Lommel-Seeliger
- Mass estimates are a work in progress

Thank