ASTEROID MASSES WITH ESA/GAIA

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CONTENTS

- Asteroid masses: why and how?
- Observing asteroids with Gaia
- Photocenter-barycenter offset
- Mass estimation with mass marching and Markov chain Monte Carlo
- Tentative results

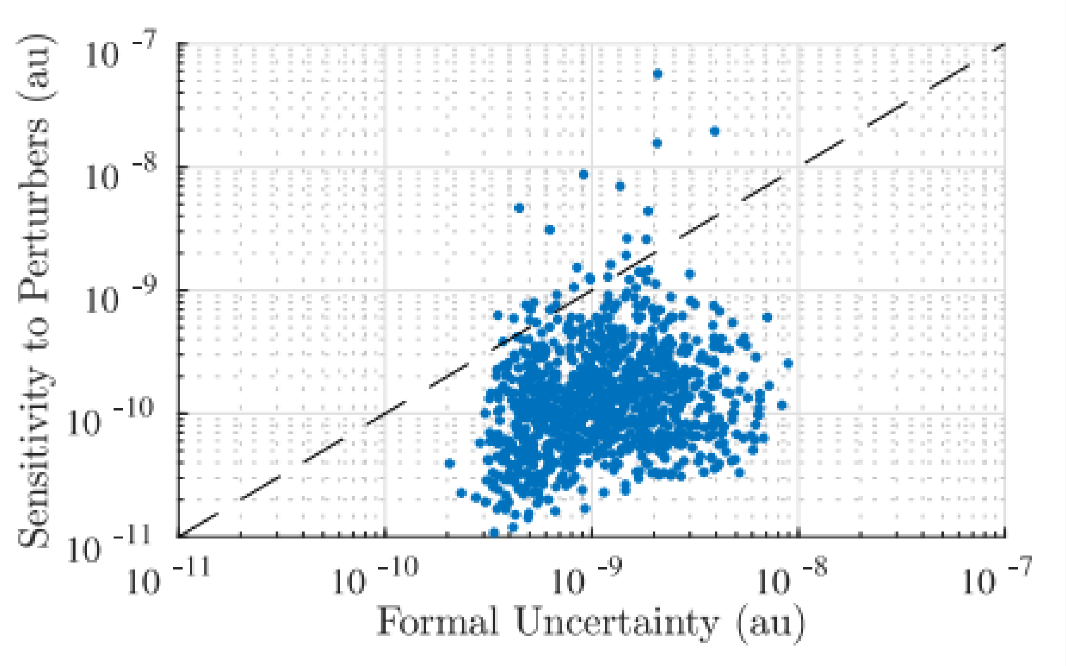
ASTEROIDS IN GENERAL

- Asteroids are key to understanding formation/evolution of the Solar System
- Composition/structure can reveal where in Solar System asteroid was formed, and its collisional evolution
- Dynamical processes during the evolution of the Solar System

ASTEROID MASSES: WHY?

- Asteroid perturbation effects on the dynamics of the solar system
    - For example, explaining motion of space probes around Mars requires including over 200 asteroids in dynamical models (Somenzi et al., 2010)

- Uncertainty in asteroid perturber masses
    - For example, altering perturber masses can cause changes in orbits that are larger than their formal uncertainties (Fuentes-Muñoz et al., 2024) -->



ASTEROID MASSES: WHY?

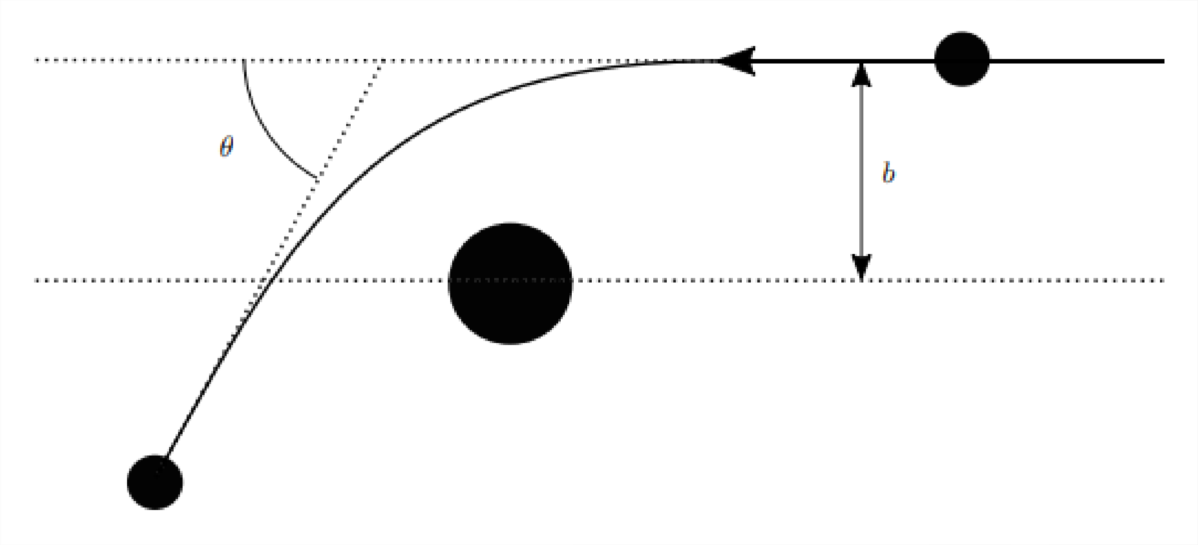
- Bulk density = Mass / Volume
- Constrains interior composition and structure
- Density estimates often poor (review article by Carry 2012)

Asteroid	Density
(33) Polyhymnia	75.28 ± 9.71
(72) Feronia	10.71 ± 27.44
(152) Atala	47.92 ± 13.10

Some unphysical density estimates listed in Carry 2012, density normalized to liquid water 1000 kg/m^3

ASTEROID MASSES: HOW?

- Gravity based methods
  - Perturbations on planets
  - Asteroid-spacecraft close encounters
  - Binary systems
  - **Asteroid-asteroid close encounters**



Two-body ballistic approximation of a close encounter (Siltala 2021, PhD thesis)

ASTEROID MASSES: HOW?

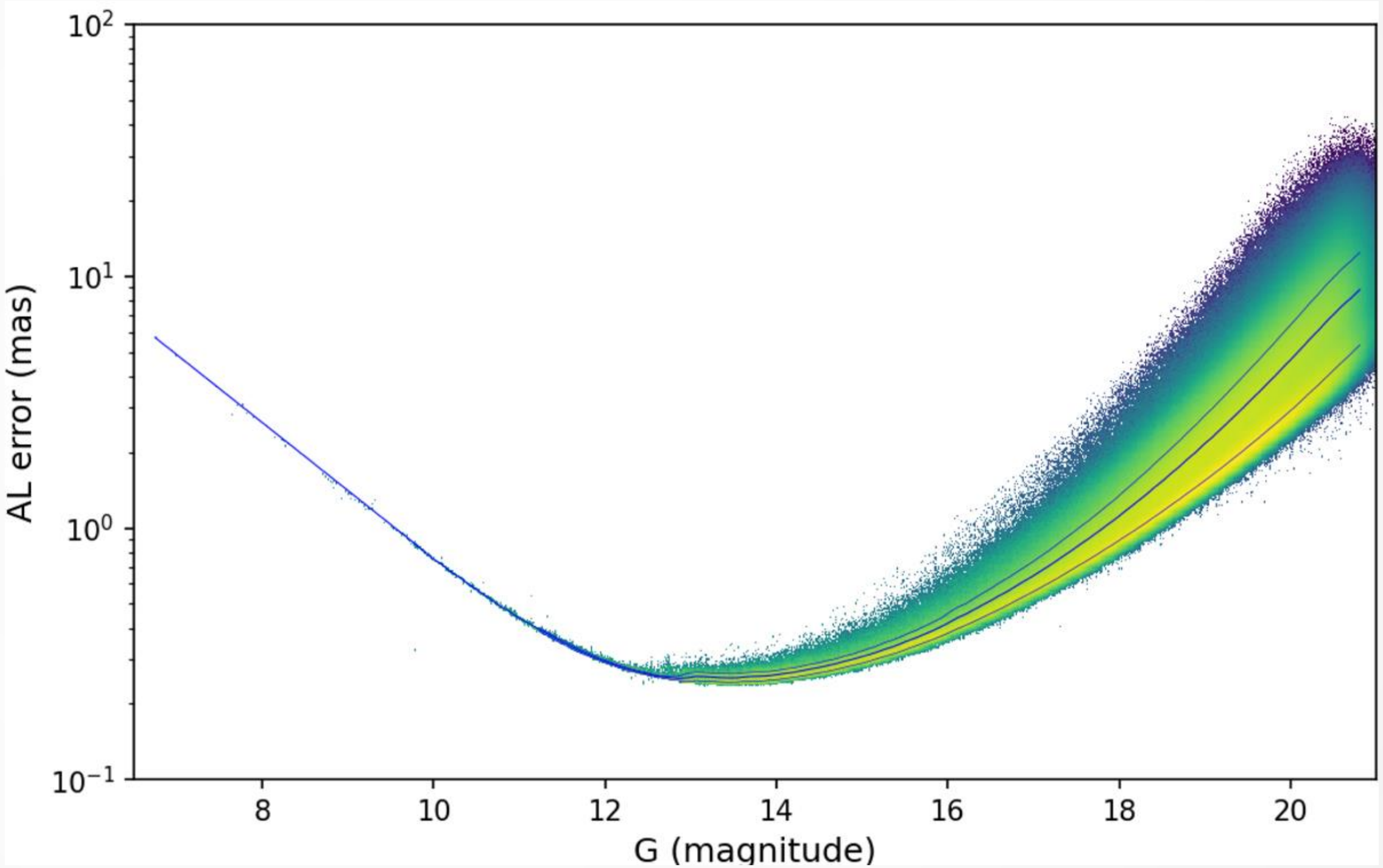
- Starting point: astrometric observations
- In practice: solving a multidimensional inverse problem
- Approaches: least-squares methods, mass marching, Markov chain Monte Carlo...

GAIA SPACE TELESCOPE

- Gaia provides milliarcsecond accuracy astrometry
- Main scientific goals focused on stars & galaxies
  - Luckily, asteroids are adequately point-like and bright
- Data releases (DRs): DR2 14 099 asteroids, DR3 ~160 000 asteroids, Focused Product Release (FPR) same asteroids as in DR3, but with longer time coverage

GAIA ERROR/UNCERTAINTY

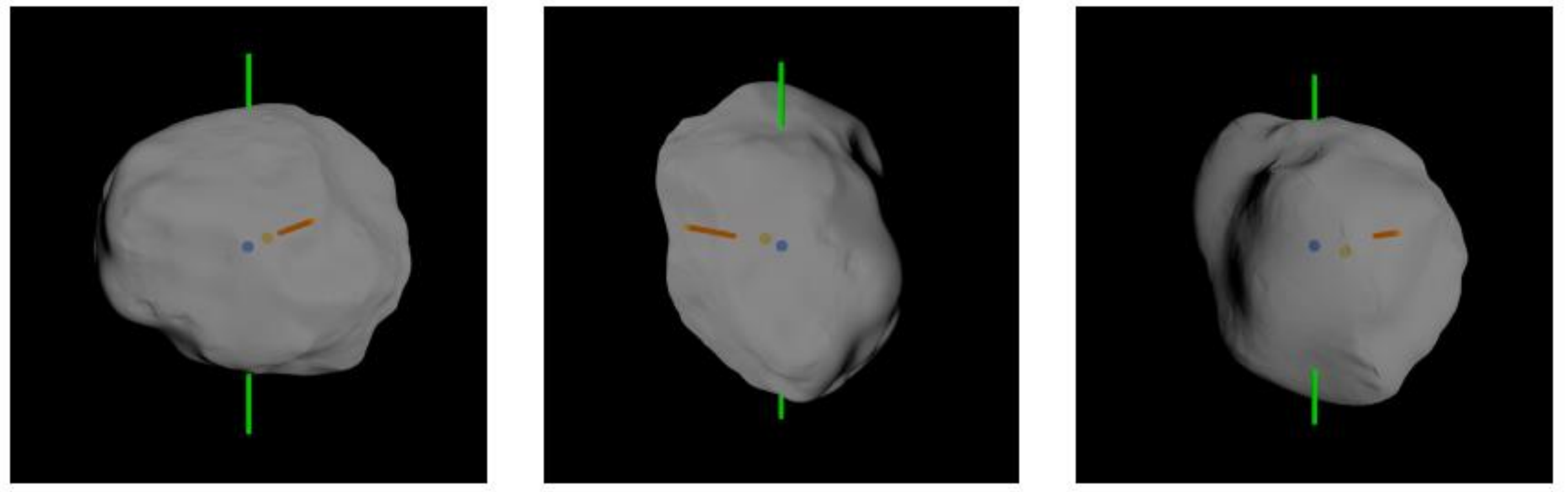
- Gaia observes in Along-scan (AL)-Across-scan (AC) plane
  - True precision only achieved in AL
  - Strong correlations in standard RA & Dec
- Quality decreases for brighter objects



Gaia DR3 error model in the AL direction (Gaia collaboration, Tanga et al., 2023)

PHOTOCENTER-BARYCENTER OFFSET

- When the observed photocenter does not align with the center of mass of an object

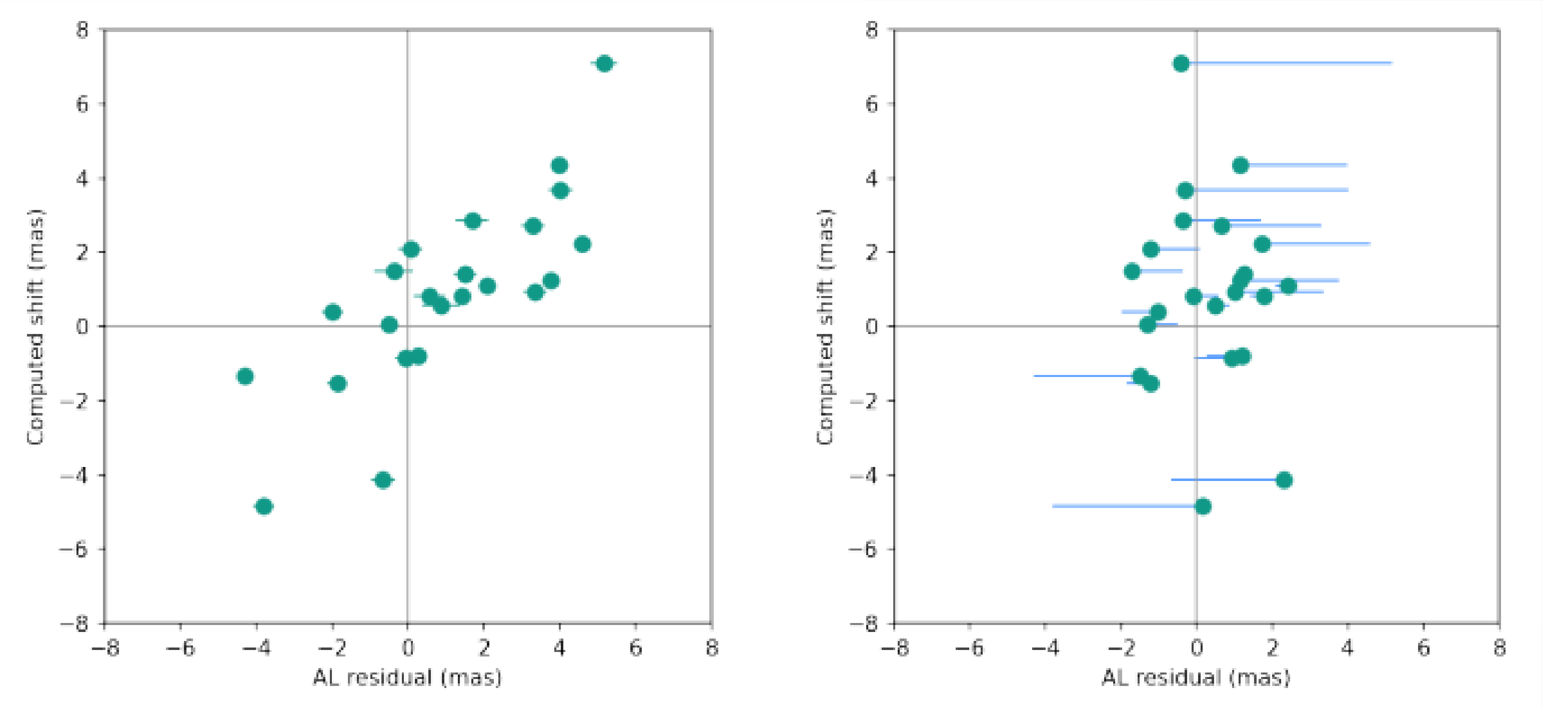


Offset at 3 epochs for (21) Lutetia (Gaia collaboration, Tanga et al., 2023)

- Computing the offset requires assuming a shape for the asteroid: simple spherical models or highly accurate shape models?

EXAMPLE: (21) LUTETIA

- Offsets were some kilometers
- = angular offsets of some milliarcseconds
- Distribution of residuals of orbit fitting more compact



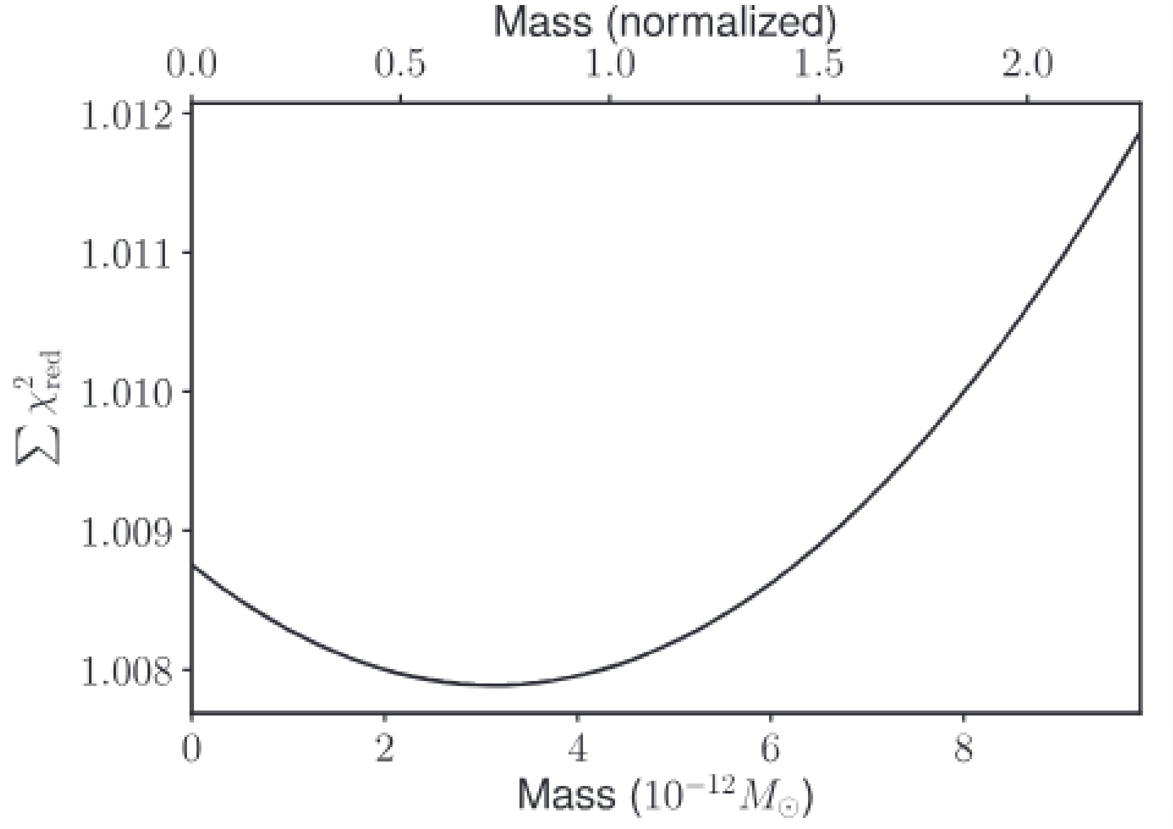
Residuals before and after correcting for offset (Gaia collaboration, Tanga et al., 2023)

MASS MARCHING ALGORITHM

- Initial mass estimate based on observed magnitude
- Range of masses around initial estimate tested against initial orbits and observations
- For each mass, χ^2 -value is computed: smaller value, better fit

EXAMPLE: (19) FORTUNA

Mass marching finds result that is roughly 75% of reference mass ($0.433 \pm 0.073 \times 10^{-11}$ solar masses)

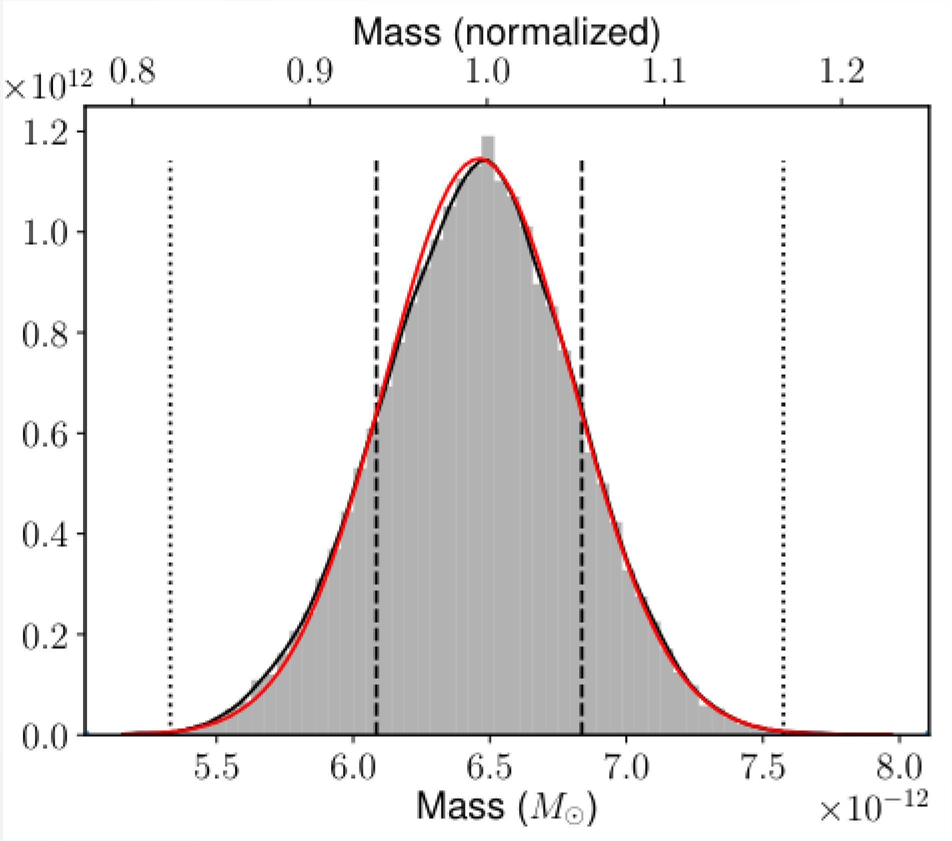


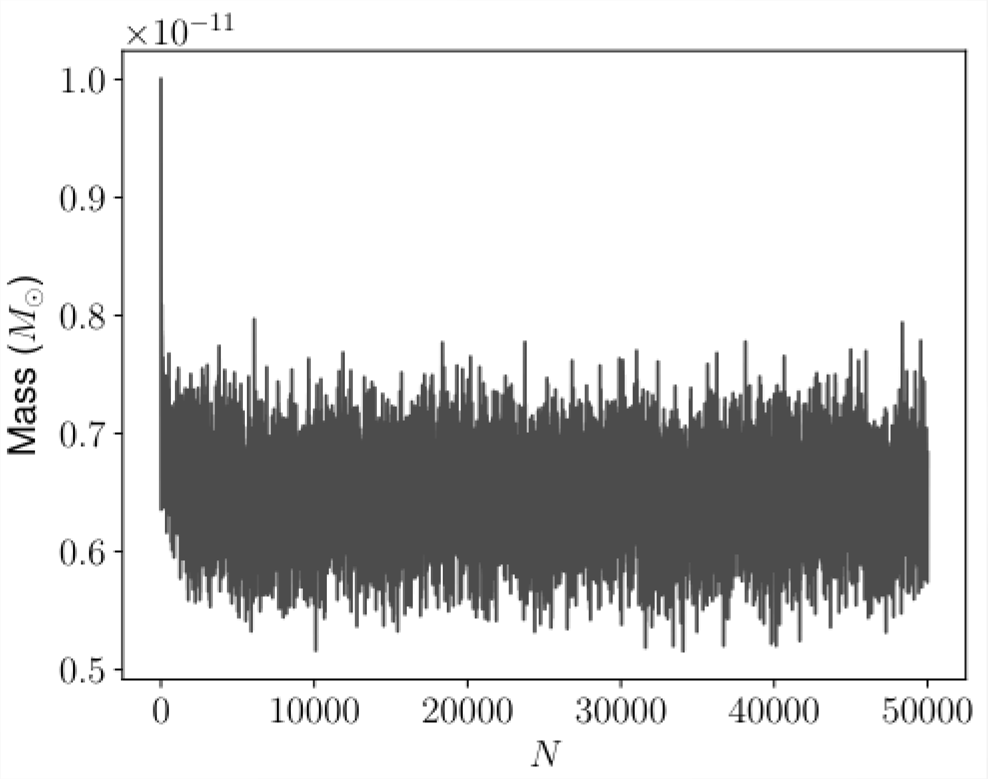
Mass marching result for [19;3486] encounter (Siltala & Granvik 2017)

MARKOV CHAIN MONTE CARLO FOR MASS ESTIMATION

- Markov chain = series of elements where each element is derived from the one preceding it
- Monte Carlo = random sampling
- Sampling a probability-density distribution of orbits and perturber mass, providing a mapping of the parameters and uncertainty

EXAMPLE: (7) IRIS

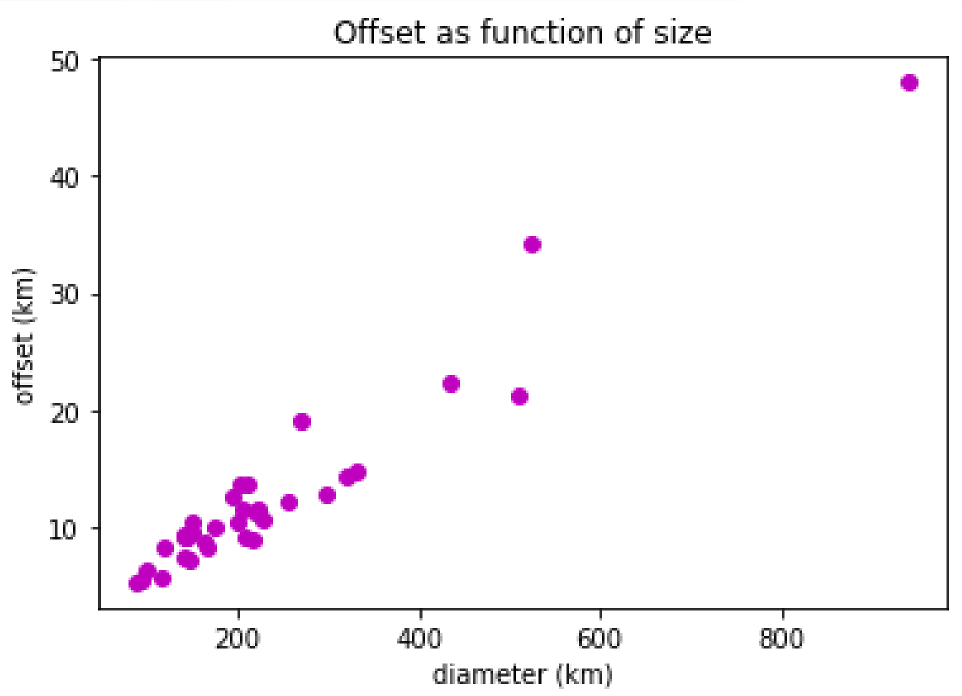


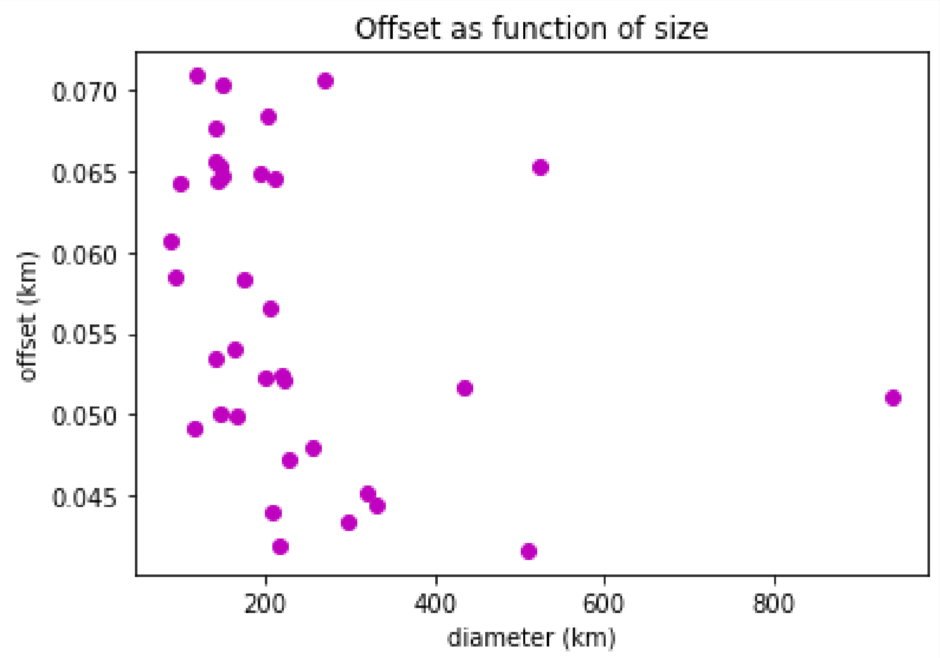


Histogram and trace of MCMC chain for (7) synthetic data of Iris (Siltala & Granvik 2020)

RESULTS

RESULTS: OFFSETS



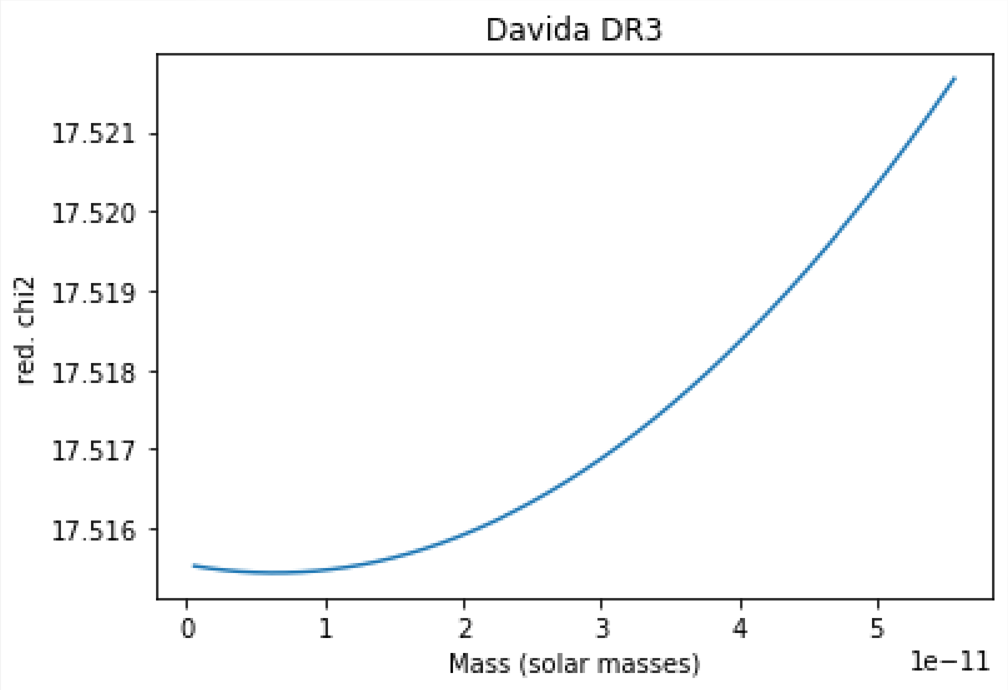


Magnitude of offset for 35 large main-belt asteroids as a function of size and magnitude normalized by size of asteroid

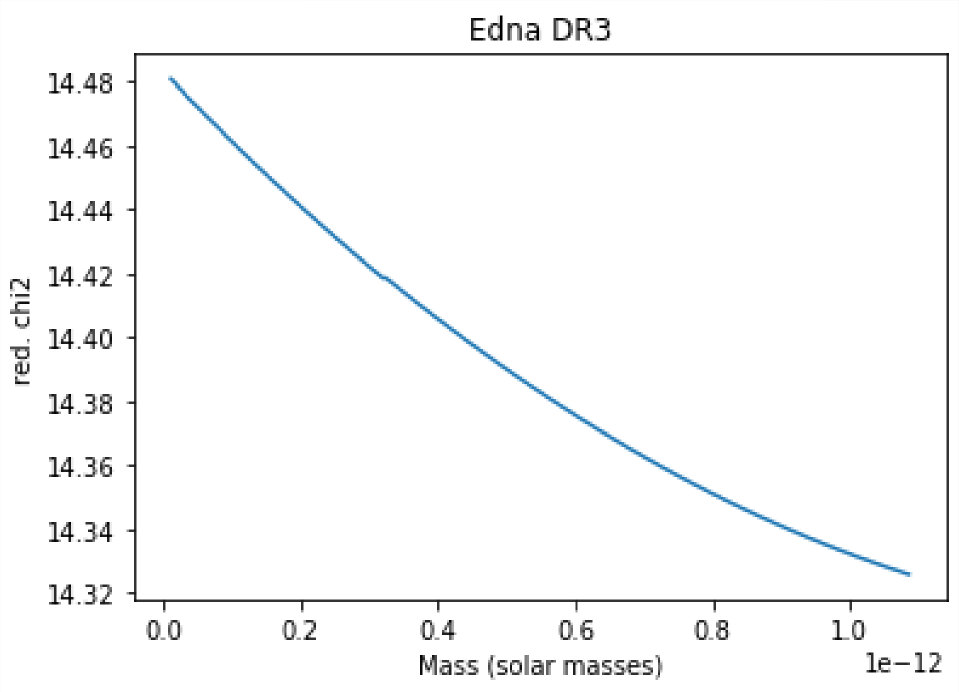
RESULTS: OFFSET CORRECTIONS

- (21) Lutetia's orbital fitting seemed better when offset was subtracted
- (511) Davida's orbital fitting seemed better when offset was added...
- Better orbital fitting: less observations rejected as outliers and smaller residuals

RESULTS: MASS MARCHING

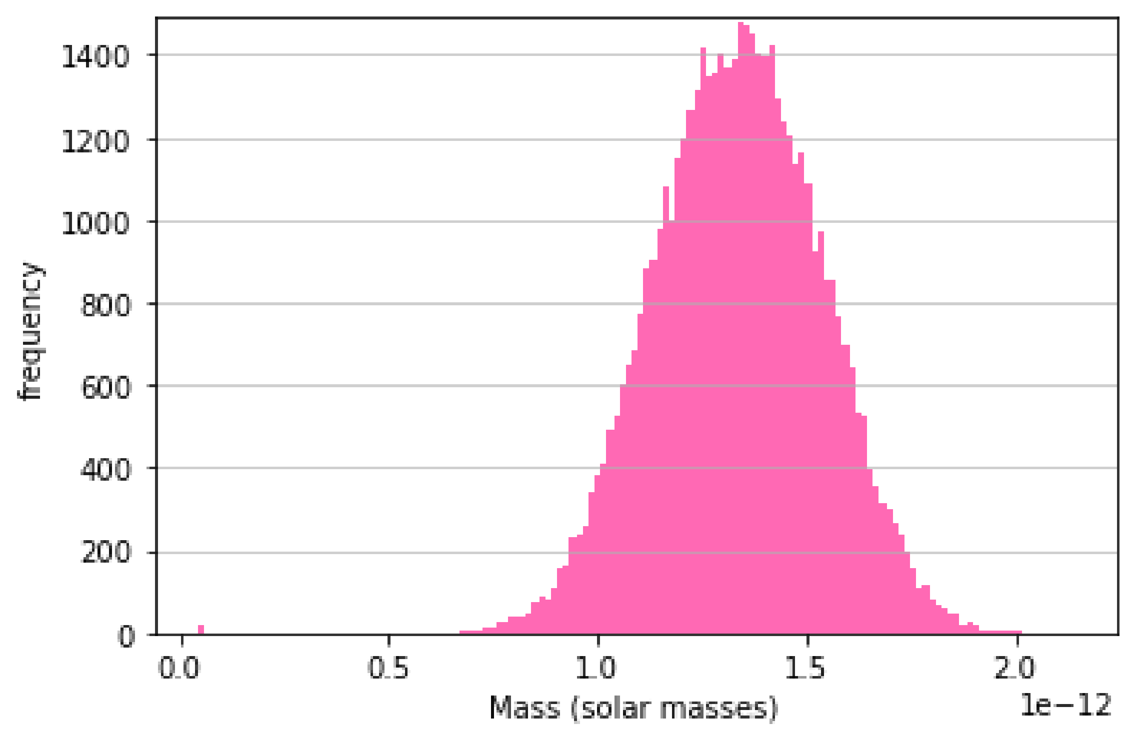


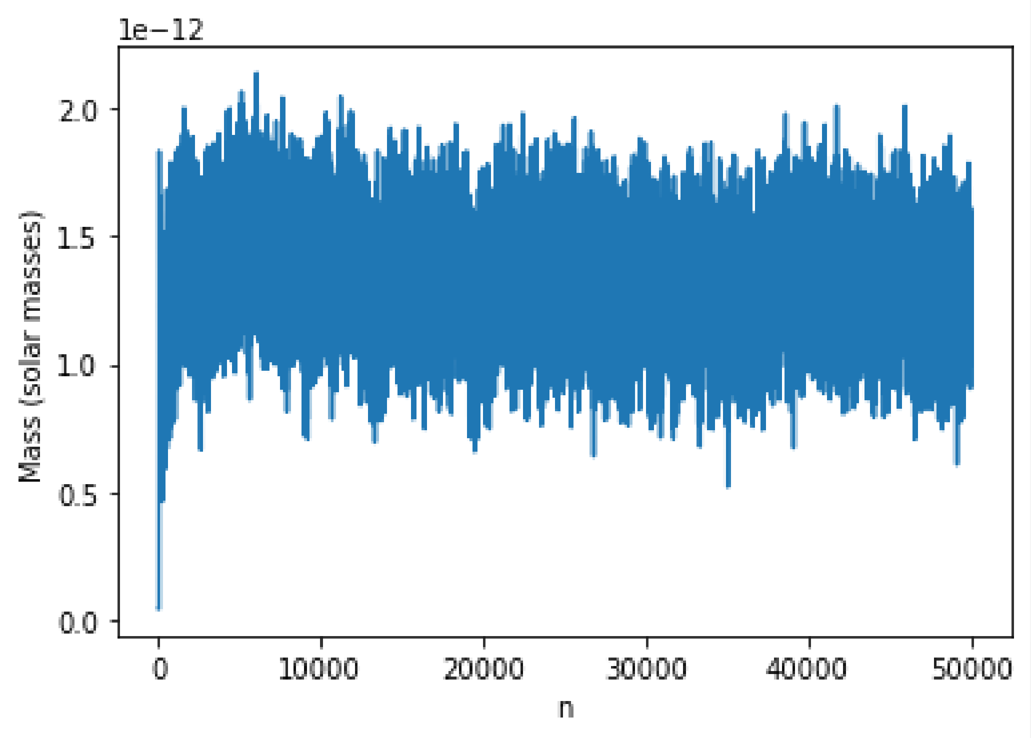
Davida mass marching result. Reference mass 1.338×10^{-11} solar masses (Vernazza et al., 2021)



Edna mass marching result. Reference mass 1.791×10^{-13} solar masses (Siltala & Granvik 2022)

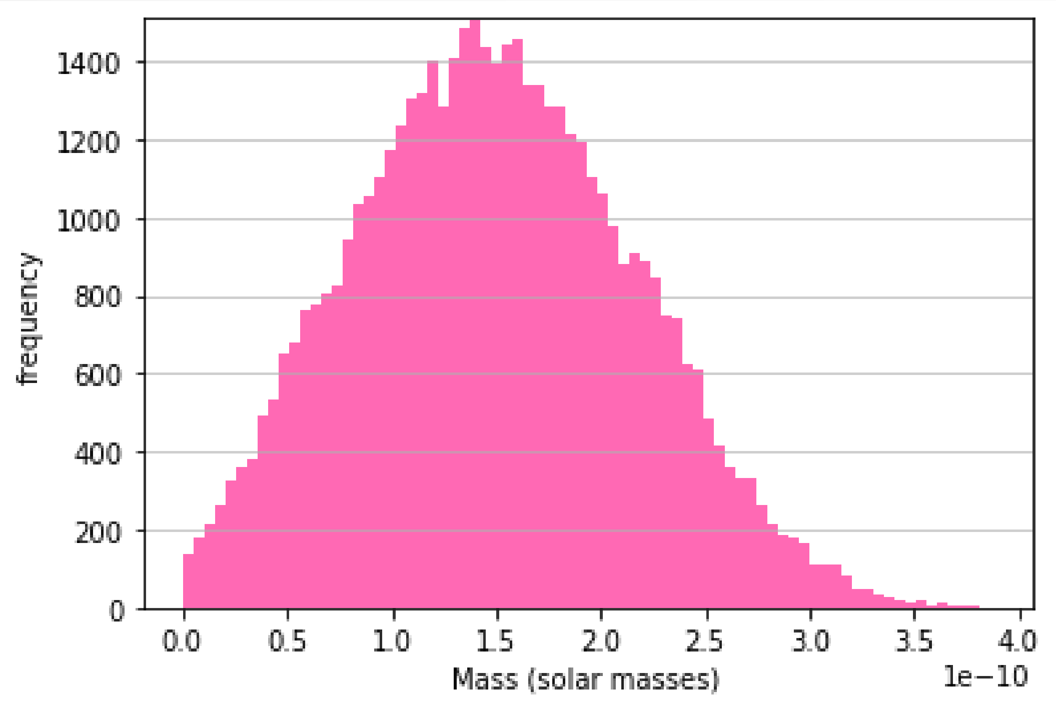
RESULTS: MASSES WITH MCMC

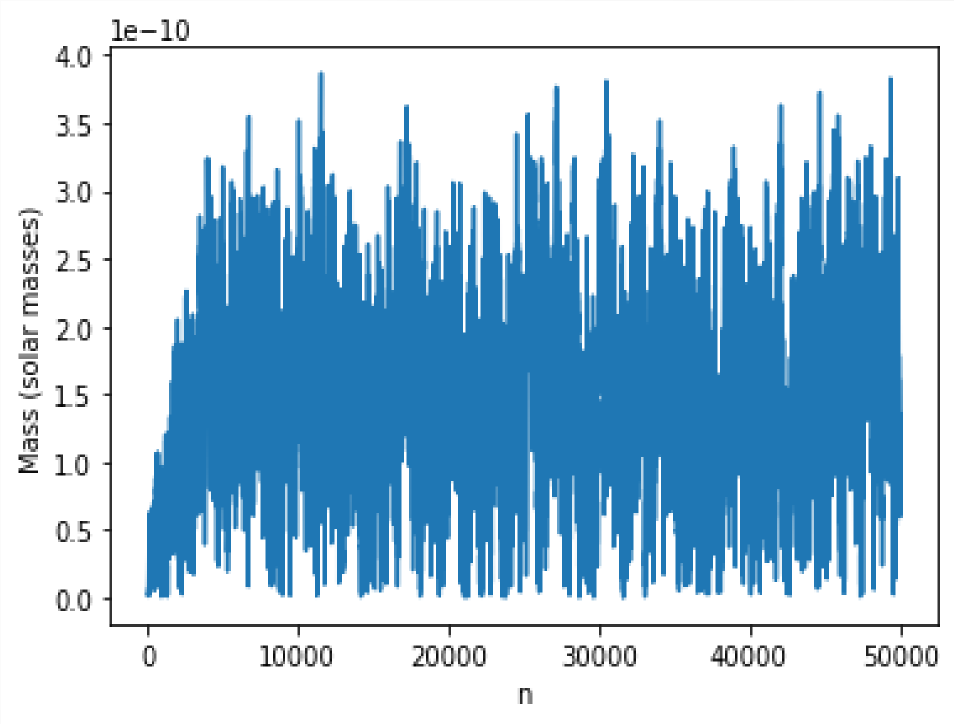




MCMC results for (445) Edna. Reference mass 1.791 × 10^{-13} solar masses

RESULTS: MASSES WITH MCMC





MCMC results for (511) Davida. Reference mass 1.338×10^{-11} solar masses

WHAT COULD BE GOING WRONG?

- Photocenter-barycenter offset correction
- Relativistic light deflection
- Error model
- Something else entirely?

SUMMARY

- Asteroid masses are important for constraining composition, structure, and Solar System dynamics.
- There are different approaches for estimating asteroid masses, such as MCMC and mass marching.
- My results are still a bit whacky :)

THANK YOU FOR LISTENING!
QUESTIONS?

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