From raw images to shape models: Photometric reduction and physical characterization of asteroids

Josef Hanuš

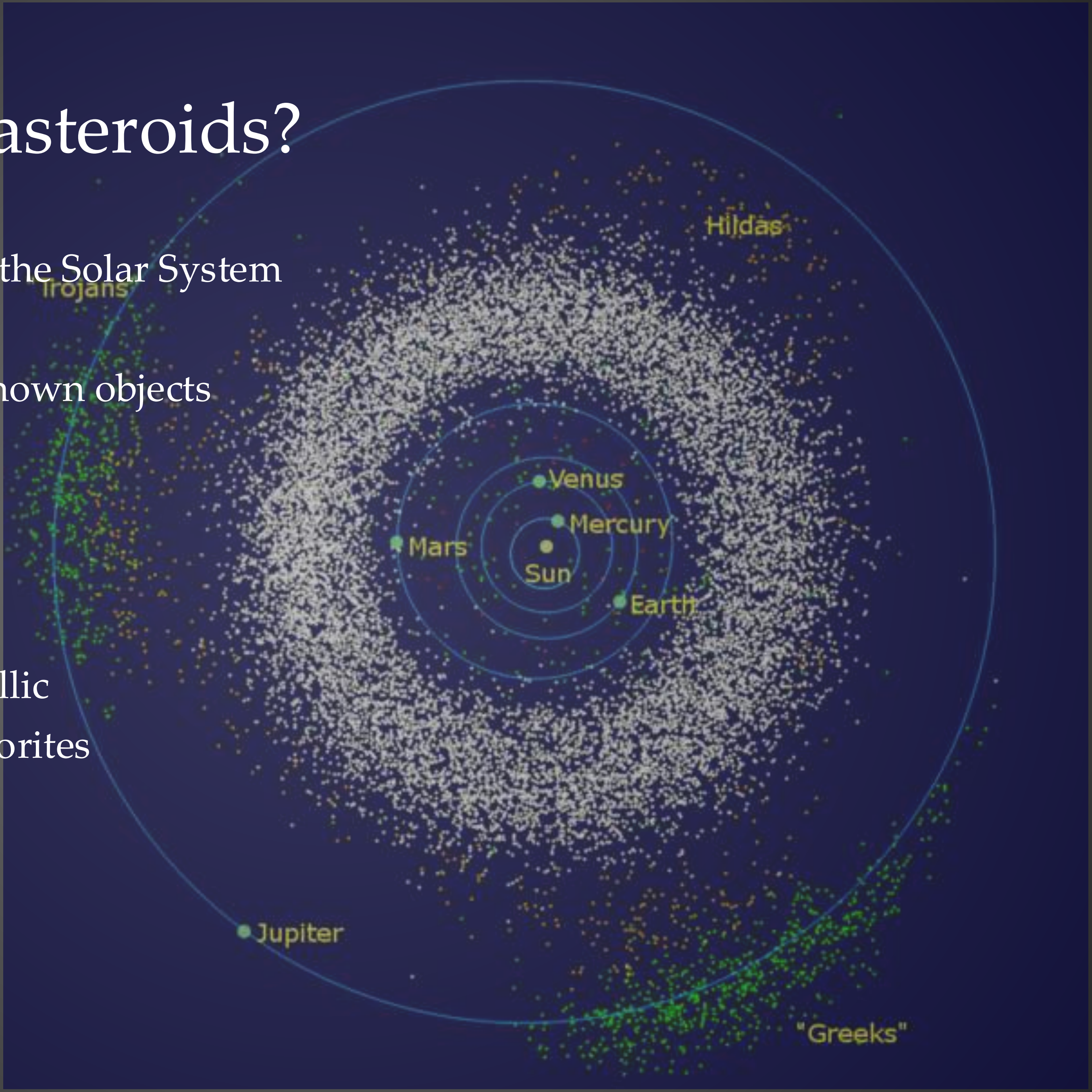
Charles University, Faculty of Mathematics and Physics, Institute of Astronomy, Prague, Czech Republic

Outline

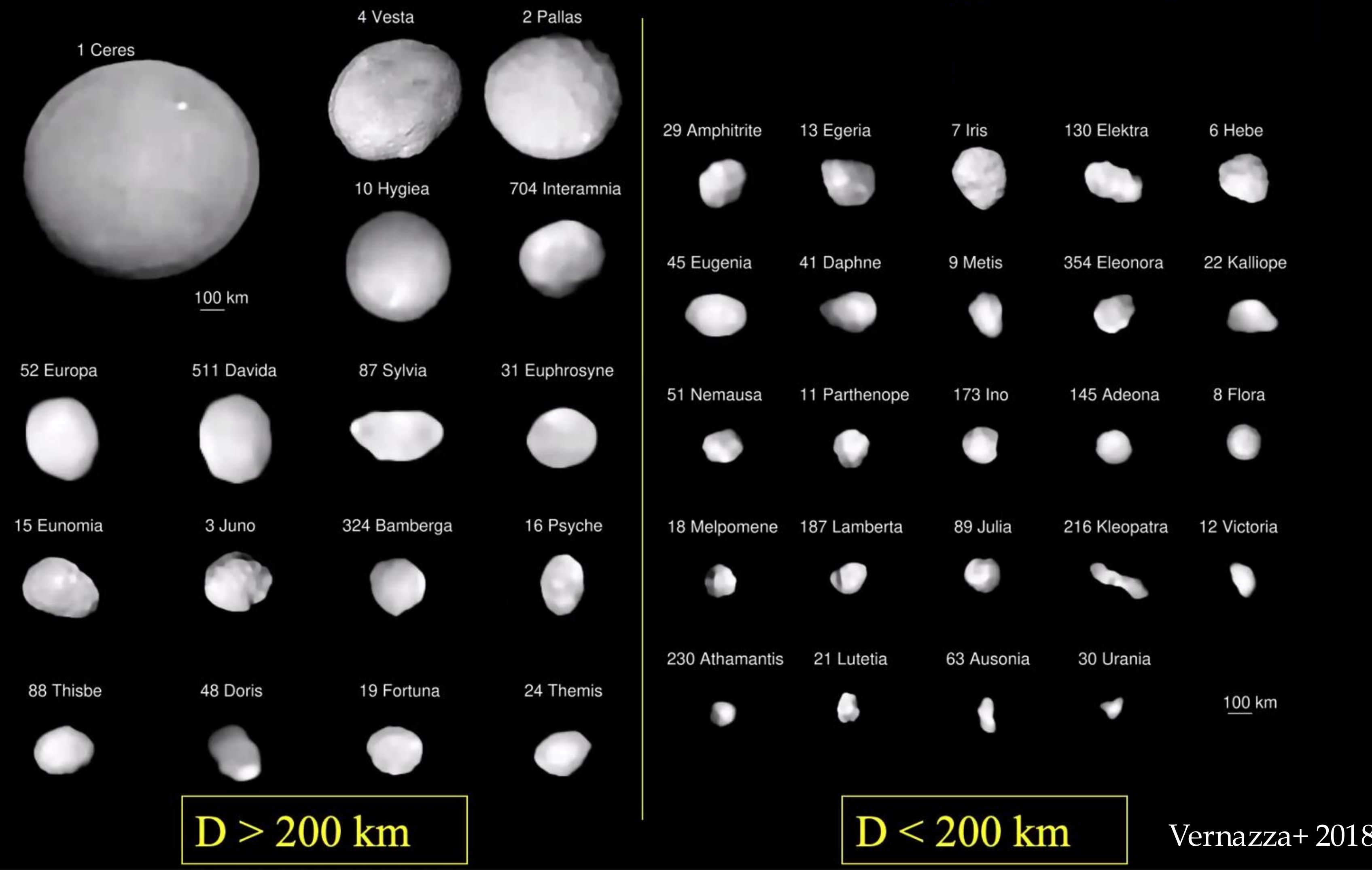
- Why asteroid photometry matters
- What we measure
- How we observe
- Reduction basics
- Lightcurves -> rotation -> shape models
- Scientific results
- How students can get involved

What are asteroids?

- Small bodies in the Solar System
- NEAs
- MBAs – most known objects
- Trojans
- Centaurs
- TNOs
- KBOs
- Rocky, icy, metallic
- Sources of meteorites



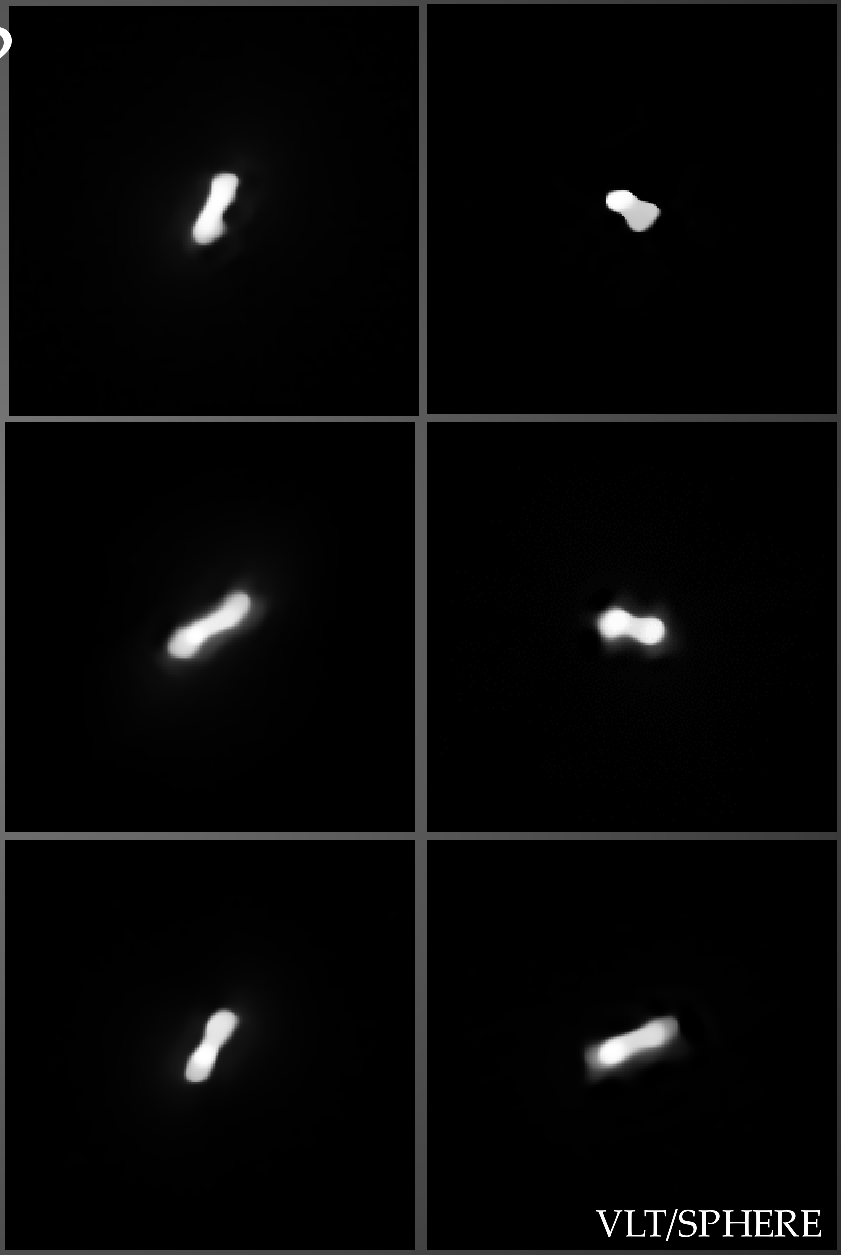
Large asteroids



Vernazza+ 2018

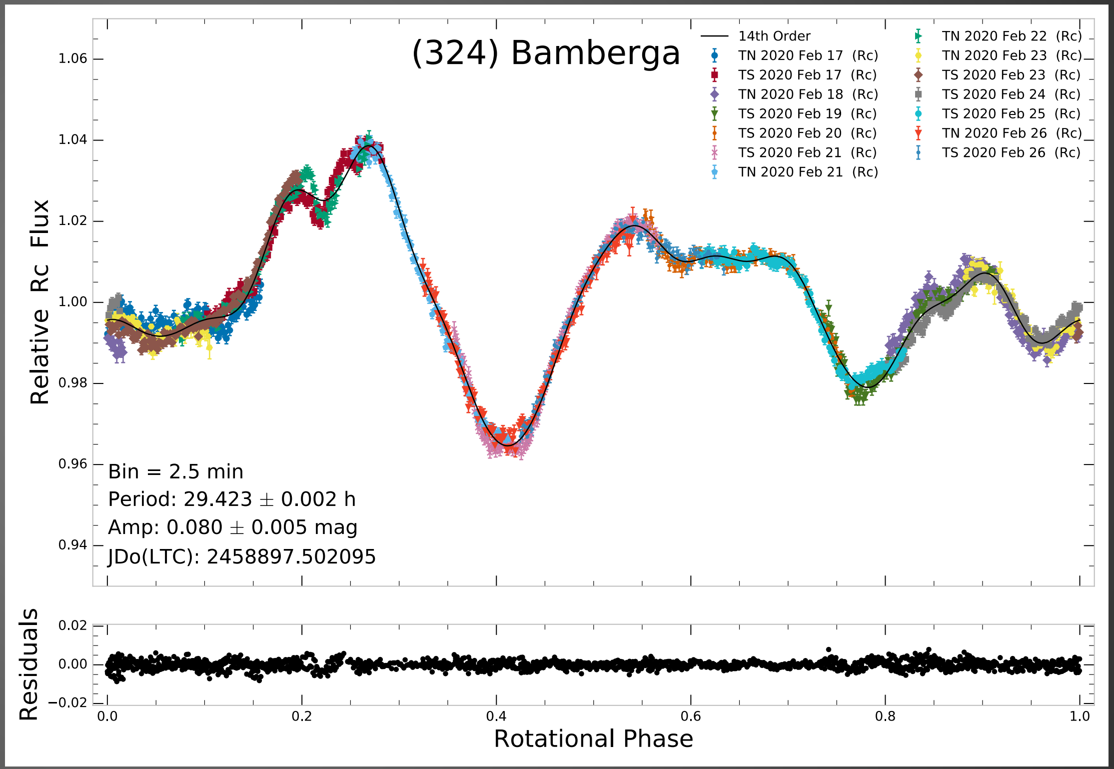
Why Study Asteroids?

- Primitive Solar System material
- Clues to planet formation (remnant from the early solar system, building blocks of planets)
- NEA hazard monitoring -> main driver
  - Surveys optimized to detect NEAs
  - Other objects in the surveys are mostly by-products (e.g., MBAs)
- Space mission targets (Lucy, Psyche, Destiny+, etc.)
- Techniques -> physical properties:
  - Photometry (reflected, thermal IR)
  - Spectroscopy
  - Imaging
  - Radar
  - Stellar occultations
  - Space probes (Dawn, Rosetta, Hayabusa, etc.)
  - Polarimetry



Asteroid Photometry?

- Asteroids reflected sunlight
- Measurement of brightness as a function of time
- Uses CCD or CMOS cameras
- Sensitive to
  - Rotation
  - Shape
  - Albedo, surface features
  - Binary systems
  - Activity or outbursts
  - Phase curves → albedo, surface texture



Observational Workflow

- Target selection
- Planning and ephemerides
- Image acquisition
- Calibration frames
- Astrometric check
- Differential photometry
- Lightcurve construction
- Period analysis
- Shape/spin modeling

Klet Observatory, asteroid 2000 UG11

Choosing a Target

- Brightness & observability
- Sky position and altitude
- Phase angle (avoid very small/very large extremes)
- Rotation period (fast/slow, too slow? unknown)
- Science interest:
  - NEAs (rapid rotators, hazard, close flybys, even a few meter objects can be bright enough)
  - Main-belt asteroids (spin states and shapes, collisional families)
  - Space mission targets
  - Binarity
  - Activity

Project	Asteroid	Maximum Observing Duration (h)	Minimum Ap. Mag. (V)	P (h)
Young Families	702 Alauda (A910 OA)	4	12.977	16.7072
Young Families	26382 Charlieduke (1999 LT32)	8	15.91	7.784
Young Families	5394 Jurgens (1986 EZ1)	8	15.915	6.073
Young Families	1051 Merope (1925 SA)	4	15.977	13.71
Young Families	2775 Odishaw (1953 TX2)	10	16.087	NaN
Young Families	4988 Chushuho (1980 VU1)	10	16.168	3.17
Young Families	29595 (1998 HL14)	10	16.196	6.418

Tools for Target Selection

- We need the on-sky coordinates – RA and Dec
  - JPL Horizons
  - MPC ephemerides
- Periods
  - Lightcurve Database (LCDB, Brian Warner)
- Physical properties
  - Minor Planet Lightcurve Photometry Catalogs
  - MP3C database
  - Other literature

```
05394              [H=13.80]
Date       UT      R.A. (J2000) Decl.     Delta      r     El.    Ph.    V       Sky Motion       Object     Sun    Moon
           h m s                                                                 "/min    P.A.    Azi. Alt.  Alt.   Phase Dist. Alt.
... Suppressed ...
2025 12 04 180000 07 24 03.7 +23 11 20   1.147   2.024  143.2  17.0  16.5      0.17    271.9    238  +04   -28    1.00   040  +34
2025 12 04 190000 07 24 03.0 +23 11 20   1.146   2.024  143.3  16.9  16.5      0.18    272.0    249  +13   -38    1.00   039  +43
2025 12 04 200000 07 24 02.2 +23 11 21   1.146   2.024  143.3  16.9  16.5      0.19    272.0    260  +22   -47    1.00   039  +52
2025 12 04 210000 07 24 01.4 +23 11 21   1.146   2.024  143.4  16.9  16.5      0.19    271.8    271  +32   -55    1.00   038  +60
2025 12 04 220000 07 24 00.5 +23 11 21   1.145   2.024  143.4  16.9  16.5      0.20    271.4    284  +42   -61    1.00   037  +66
2025 12 04 230000 07 23 59.6 +23 11 22   1.145   2.024  143.4  16.9  16.5      0.20    271.0    299  +51   -63    1.00   037  +67
2025 12 05 000000 07 23 58.7 +23 11 22   1.145   2.024  143.5  16.8  16.5      0.21    270.4    319  +58   -59    1.00   036  +63
2025 12 05 010000 07 23 57.8 +23 11 22   1.144   2.024  143.5  16.8  16.5      0.21    269.9    346  +63   -53    1.00   036  +56
2025 12 05 020000 07 23 56.9 +23 11 22   1.144   2.024  143.6  16.8  16.5      0.21    269.3    016  +63   -44    1.00   035  +48
2025 12 05 030000 07 23 56.0 +23 11 21   1.144   2.024  143.6  16.8  16.5      0.21    268.7    043  +58   -34    1.00   034  +39
```

Telescope and Camera Requirements

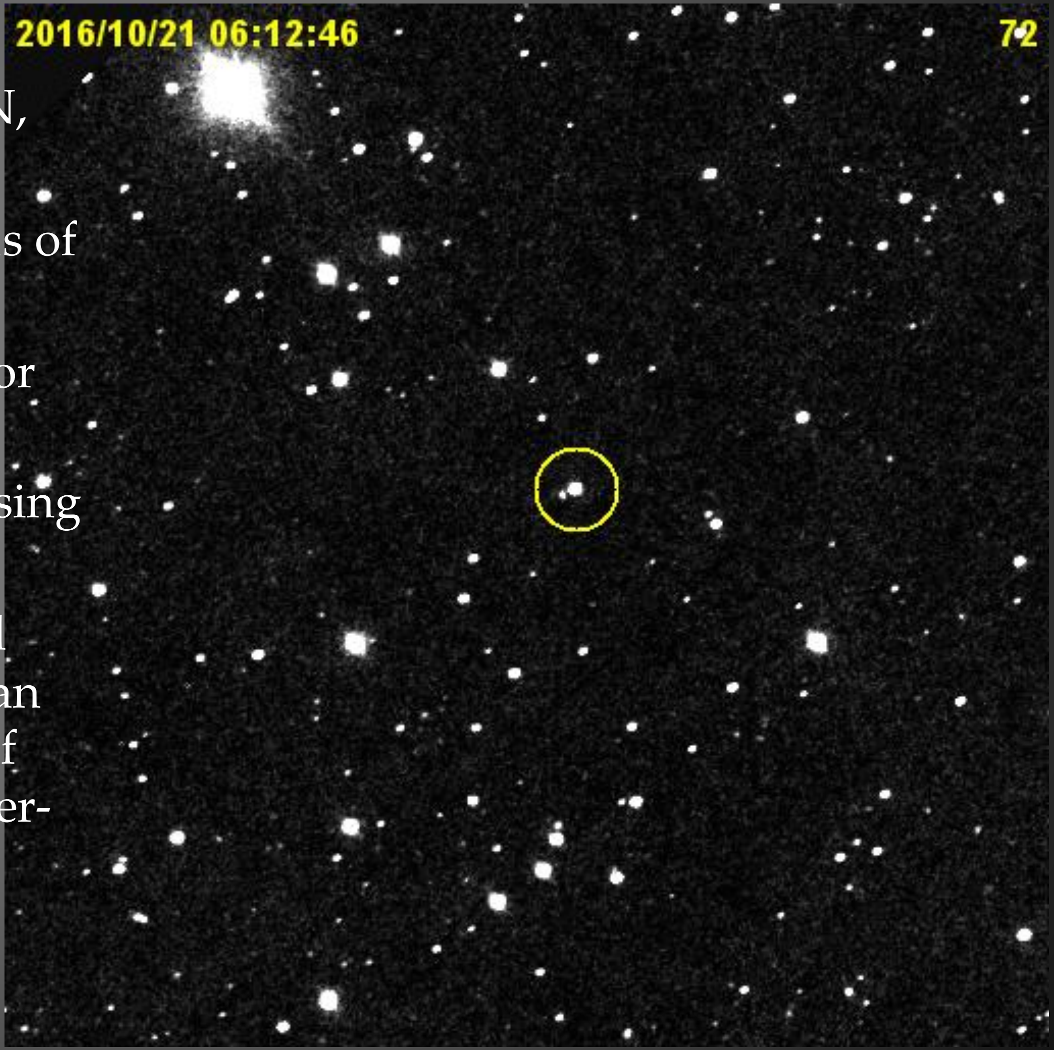
- Aperture: 20–40 cm is enough for many targets
- Camera: cooled CCD/CMOS
- Good tracking (but not necessarily autoguiding), usually half sidereal
- Filters: R or unfiltered for S/N; V for standard photometry, Sloan filters
- Field of view: must include good comparison stars


BlueEye600 telescope in Ondřejov, Czechia.

Small 11cm eVscope smart telescope.

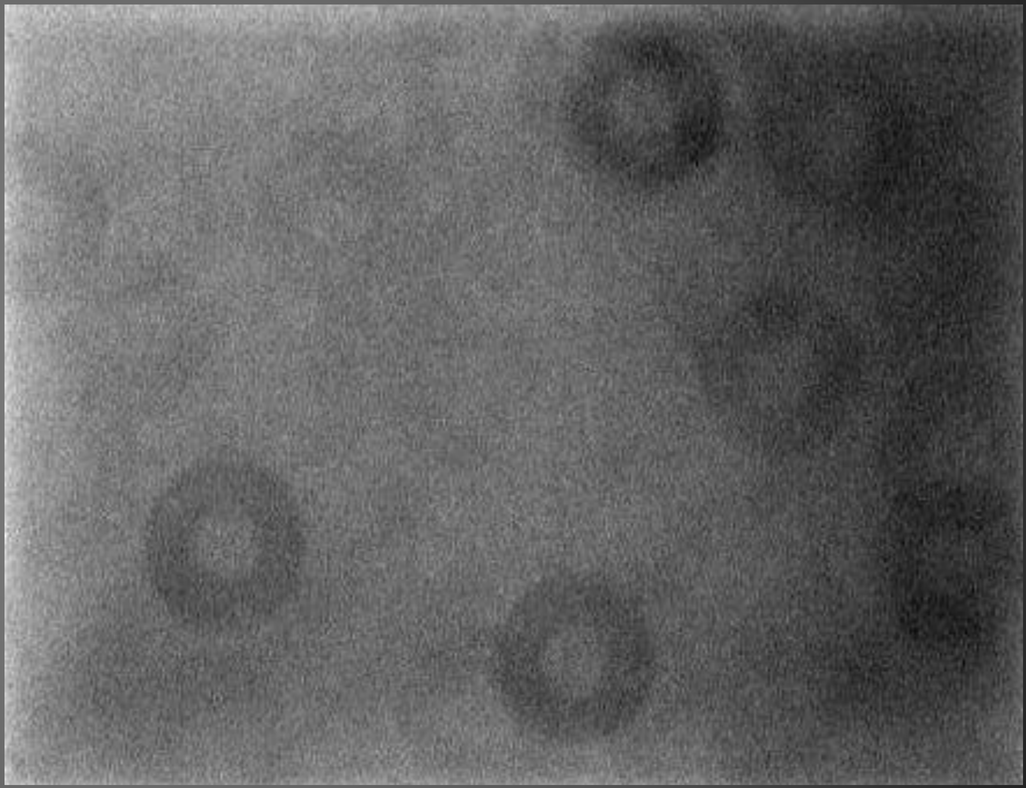
Raw Image Acquisition

- Exposure time: maximize S/N, avoid trailing
- Use series of tens to hundreds of images
- Maintain constant pointing for differential photometry
- Check for saturation (defocusing to allow longer exposures)
- Typical exposures are several minutes, significantly less than the typical rotation periods of asteroids, exceptions are super-fast rotators (NEAs)



Calibration Frames

- Bias frames: readout noise – short (zero time) exposures with telescope capped
- Dark frames: thermal noise – longer exposures (same as science data) with telescope capped
- Flat fields: pixel sensitivity & vignetting
- Collect each observing night or regularly with stable setup
- Removes instrumental signatures
- Reduces scatter in photometry
- Ensures stability across night(s)
- Essential for combining multi-night lightcurves



Data Reduction Summary

- Subtract bias
- Subtract dark
- Divide by flat
- Inspect image quality (tracking, clouds, seeing)
- Align images if needed
- Extract photometry

Differential Photometry

- Comparison stars:
  - Similar brightness as asteroid
  - Not saturated
  - Non-variable (choose multiple)
  - Good S/N
  - Preferably similar color
- Measure target + comparison stars (signals in small circles, instrumental flux)
- Compute Δm = m_target – m_comp

Differential Photometry - software

- AstroImageJ
- MaximDL
- MPO Canopus (now free, many citizen astronomers in Europe)
- Photometrypipeline (Python package), usually professionals
- Some professionals have developed their own dedicated software/pipelines (e.g., Petr Pravec)

MPO Canopus v12 Initial Release Available

Download the version 12 installer.

Download the v10 to v12 data converter.

More than 150,000 asteroid photometry measurements producing more than 2,500 lightcurves published in more than 200 papers. More than two dozen binary asteroid discoveries. More than 2,500 double star measurements. More than 50,000 variable star observations. All these were done by just one person using *MPO Canopus* since its first release in 1999. There are untold numbers more when including the work of hundreds of *MPO Canopus* over the years.

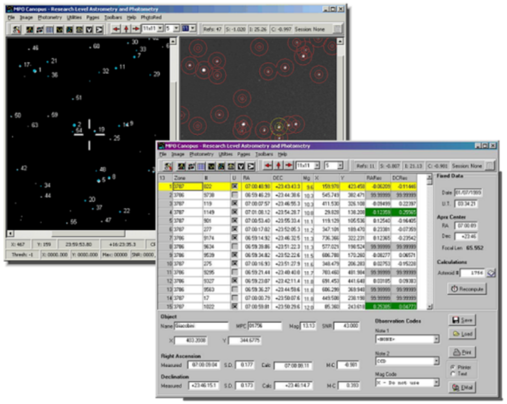
MPO Canopus/PhotoRed is a complete package for astrometry and photometry. With it you can easily measure the positions of asteroids or other targets and perform photometry on just about any variable object. Combined with the supplemental program, PhotoRed (Photometric Reductions), you can transform raw instrumental magnitudes taken through one or more filters to standard magnitudes. This makes combining your data from night to night with that of other observers much easier.

MPO Canopus is a tried and true research-level tool for amateurs, small colleges, and even professionals.

Quick and Accurate Astrometry

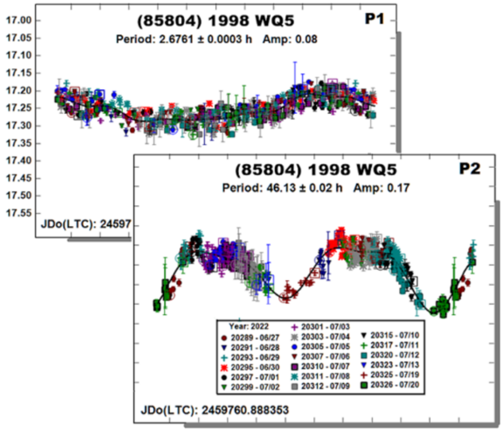
Supports ATLAS, APASS, UCAC4, CMC-15

Gaia DR3 coming



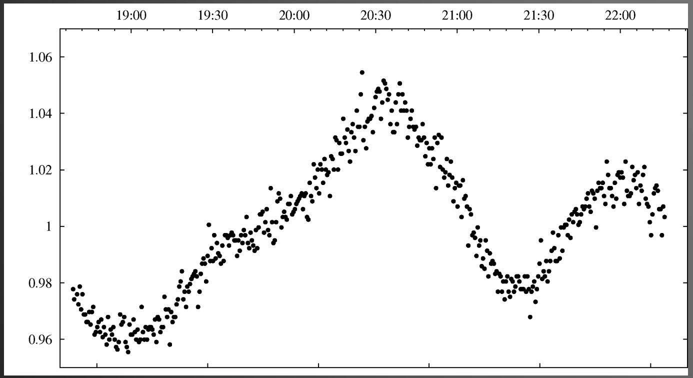
Fourier Period Analysis

Solves up to three simultaneous additive periods

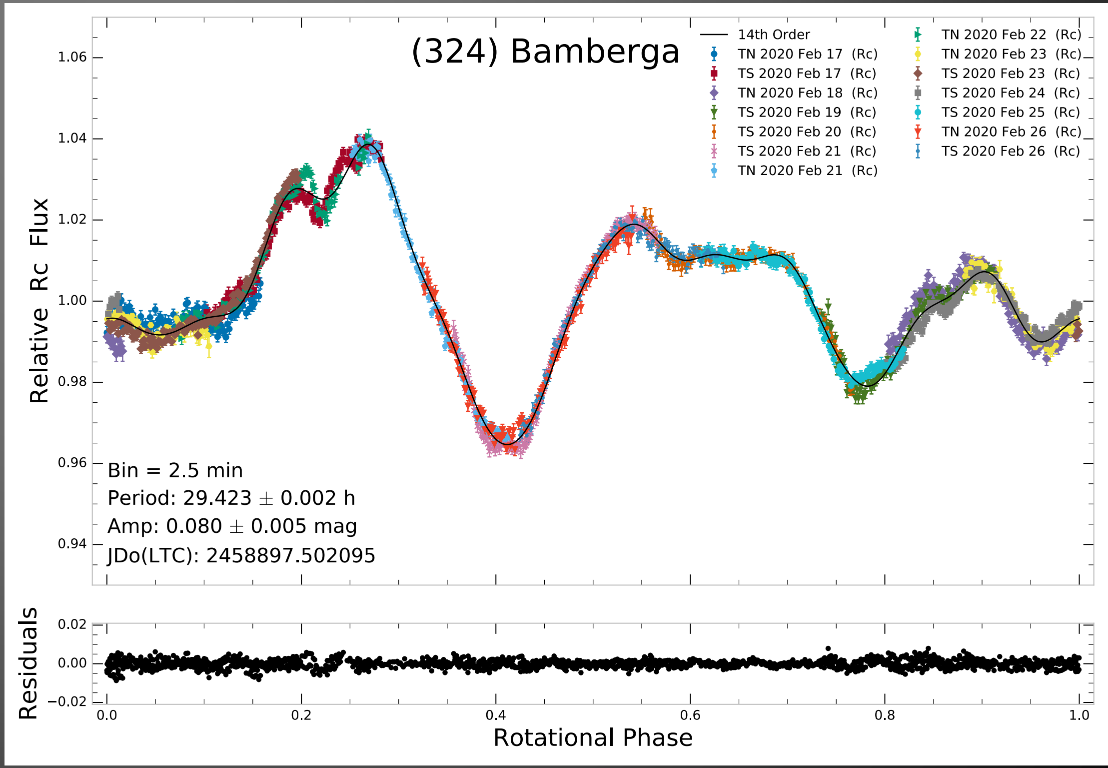


Creating a lightcurve

- Convert instrumental flux to relative magnitudes
- Plot brightness vs. time
- Remove outliers (clouds, guiding jumps)
- Merge nights

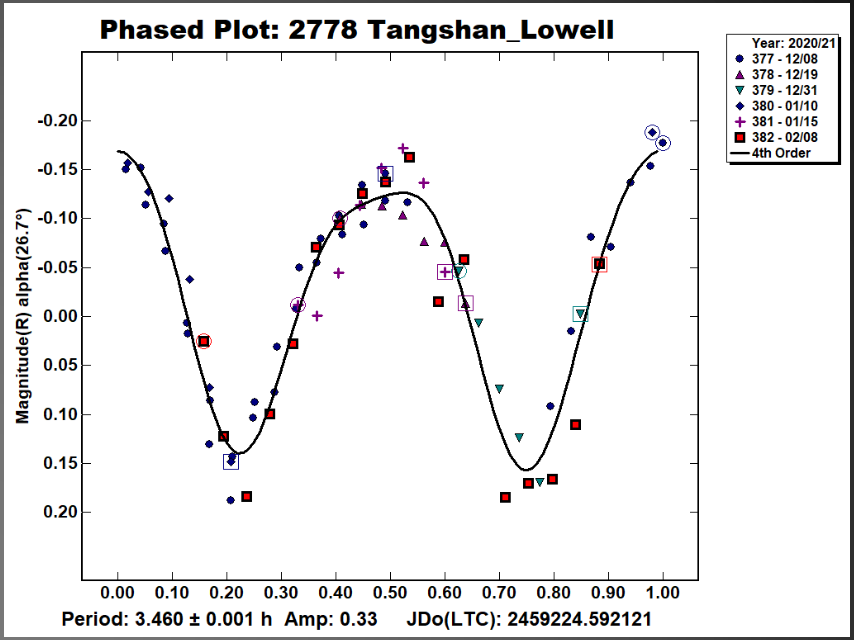


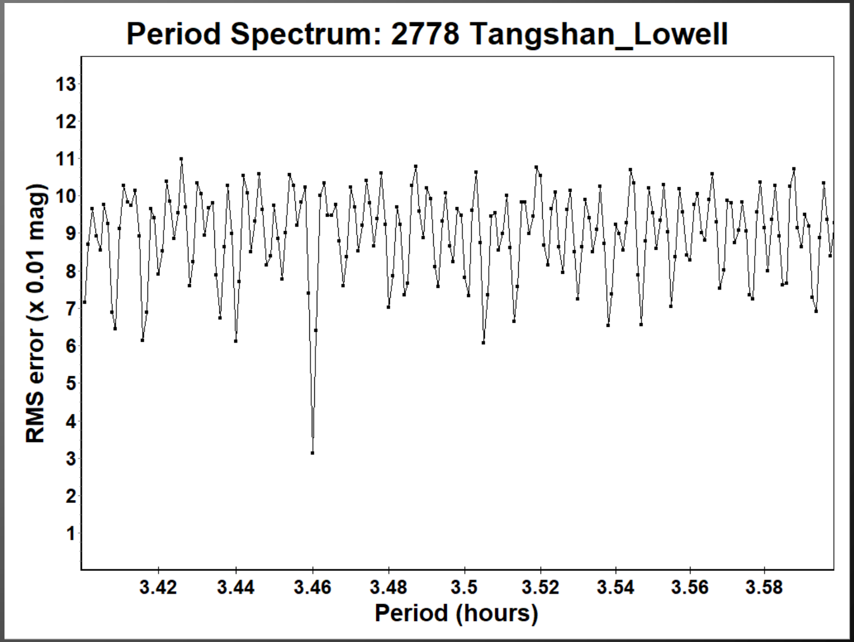
Top: Lightcurve of asteroid 51 Nemausa obtained by the 65cm telescope in Ondřejov. Right: Composite lightcurve from TRAPPIST telescopes.



Period determination

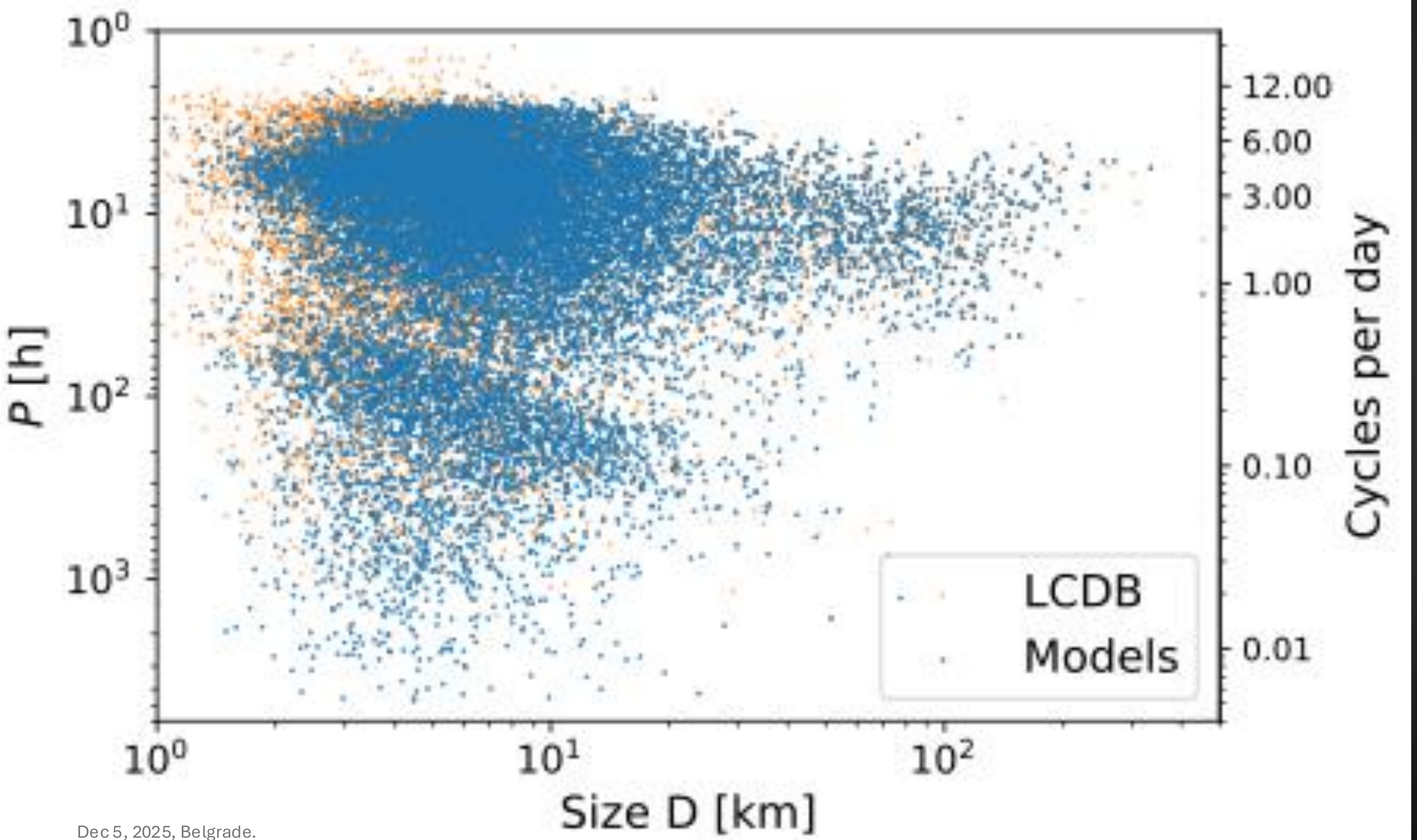
- Methods:
  - Lomb–Scargle periodogram
  - Fourier series fit
  - Phase Dispersion Minimization (PDM)
- Look for repeating patterns
- Ambiguities:
  - 2- or 1/2-fold aliases common
  - 24h alias
  - Issues with partial lightcurves, slow rotators, low amplitudes





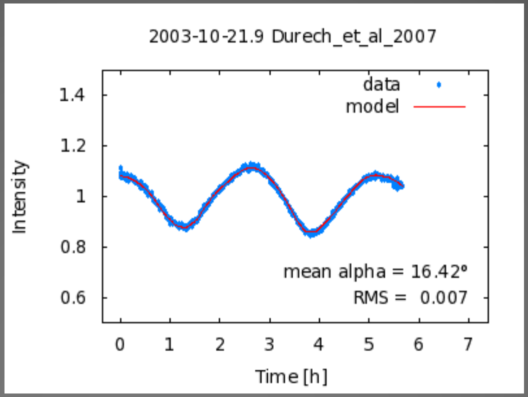
Top: Lightcurve of 2778 Tangshan observed by Roberto Bonamico.
Bottom: Fourier series period spectrum.

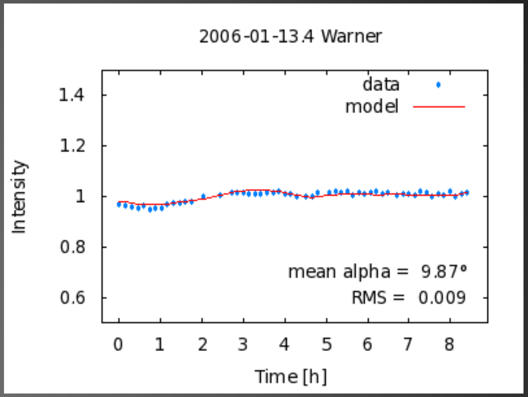
Rotation periods

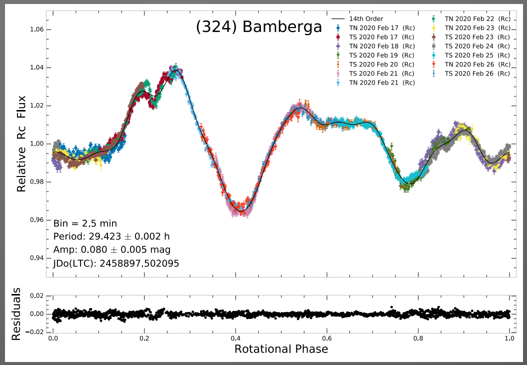


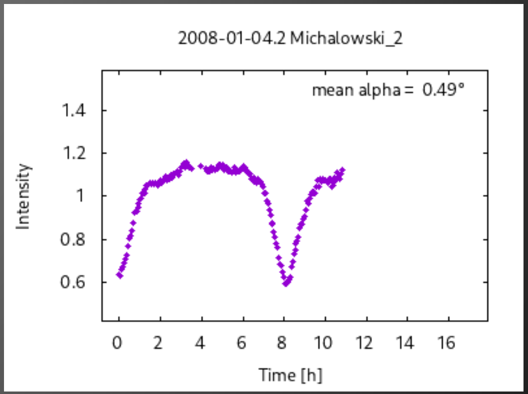
Understanding Lightcurve Shapes

- Amplitude → shape elongation
- Two maxima → typical elongated body
- Unequal maxima → irregularities
- Very large amplitude → contact binary candidate
- Flat → spherical or pole-on geometry
- Occultation pattern



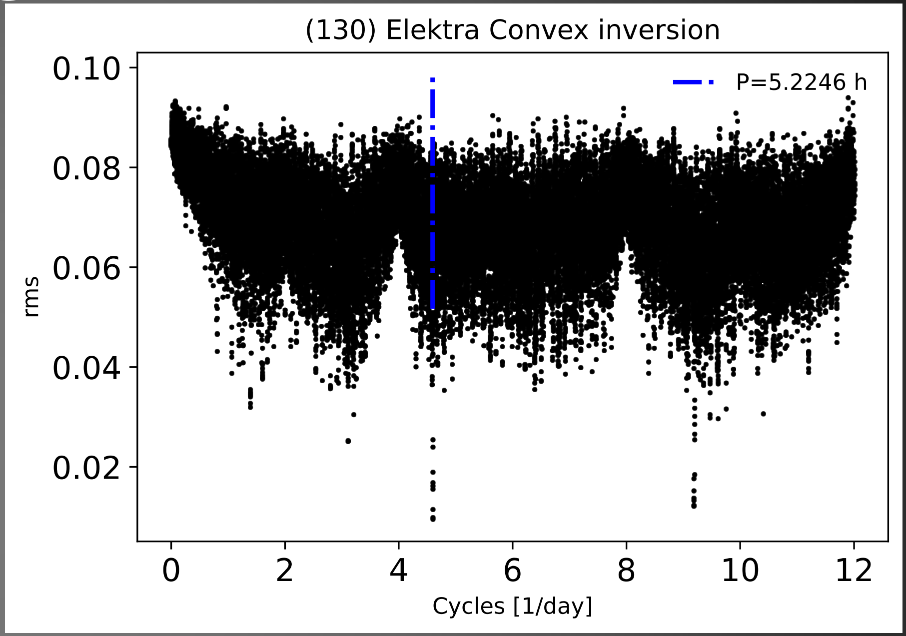




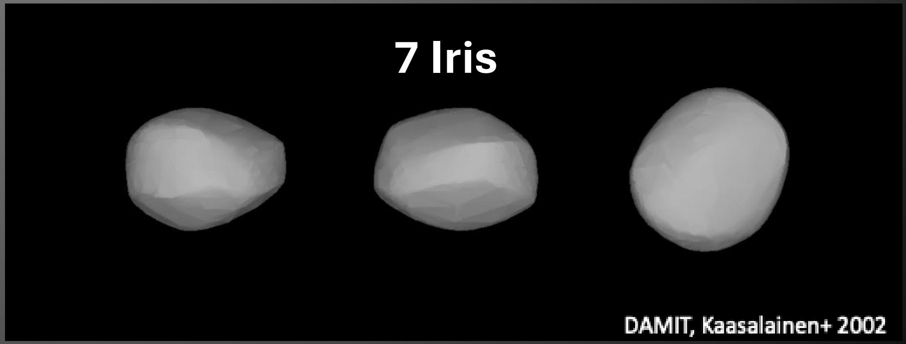


Shape modeling by lightcurve inversion

- Convex inversion of Kaasalainen et al. (2001) and Kaasalainen & Torppa (2001)
- Approach of Ďurech and Hanuš (2023)
- Physical model (CI):
  - Sidereal rotation period P
  - Orientation of the spin axis – ecliptic longitude and latitude
  - Shape – convex polyhedron
  - Parameters of the phase function (exp-linear model)
- We search the parameter space for the global minimum
- ~26,000 solutions

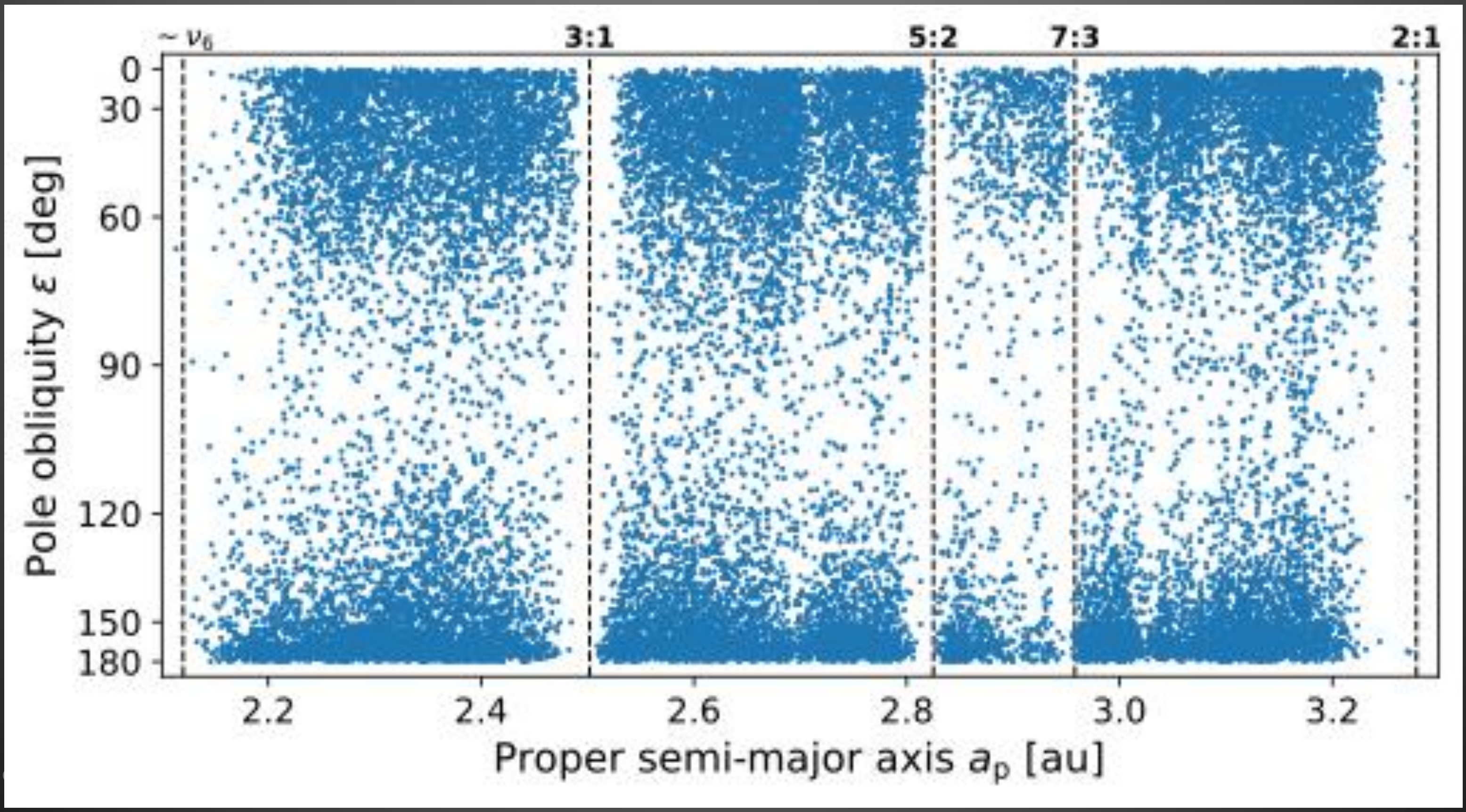


Periodogram based on convex inversion with indicated best-fitting period (blue).



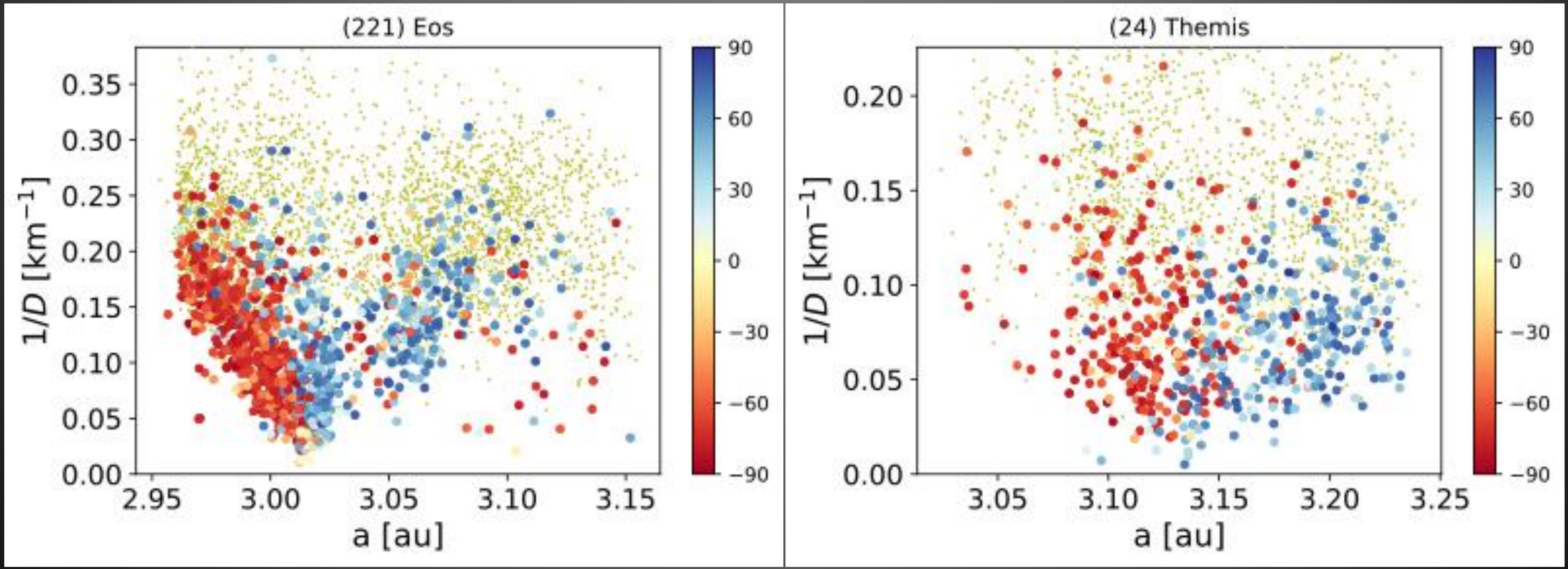
Spin vectors of asteroids

- Evolved by YORP -> bimodality, spin vectors are mostly perpendicular to the orbital plane, for sizes D < 30 km
- Evolved by Yarkovsky -> asymmetry near resonances
- Collisional evolution can reset the spin state



Spin vectors in families

- We have large dataset to study individual families
- Evolved by Yarkovsky and YORP
- Spin sense is well separated, only little contamination
- Some minor mixture in the center (more apparent for Themis)



What Students Can Actually Do

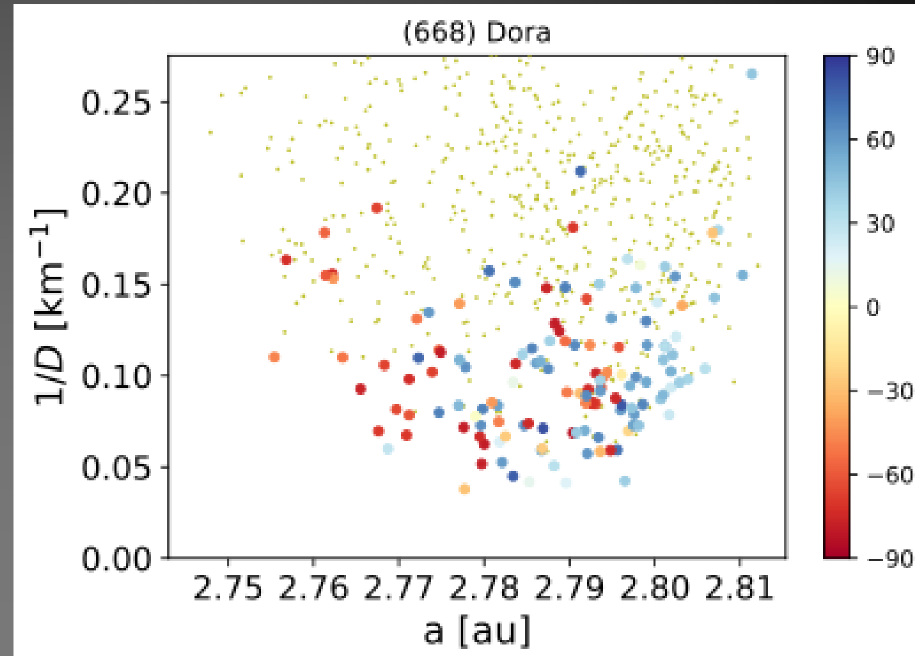
- Photometry with 20–30 cm telescope – connect with institutes
- Contribute to LCDB – rotation periods, amplitudes, binarity, etc.
- Detect rotation period (new estimates)
- Participate in coordinated campaigns – young families, NEAs, etc.
- Analyze archival survey photometry (ZTF, ATLAS, Gaia DR3)
- Contribute to shape-model databases – free version of the lightcurve inversion code on DAMIT
- Analyze the physical properties available in databases (e.g., DAMIT)

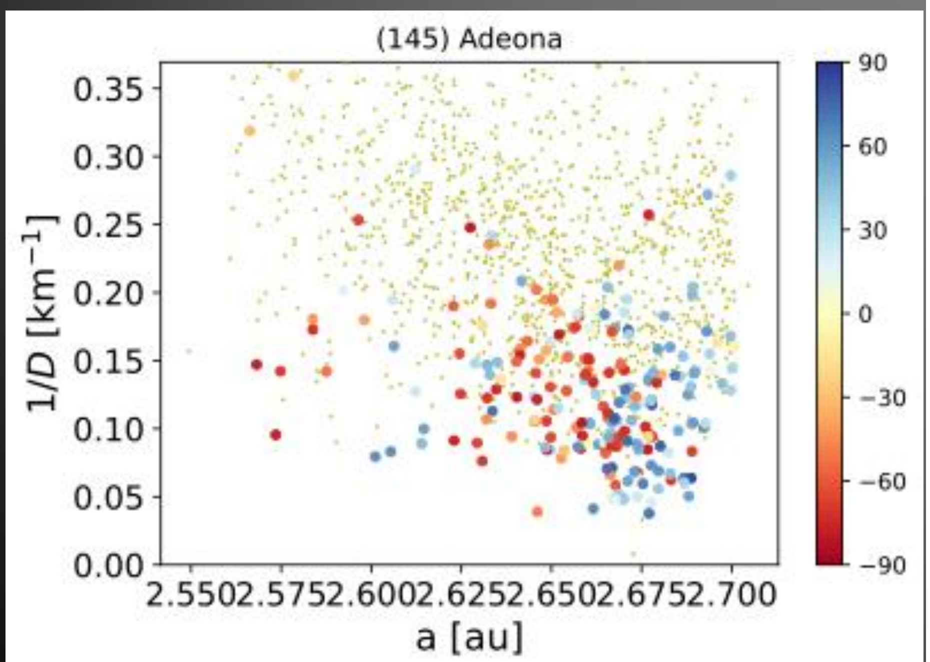
Summary

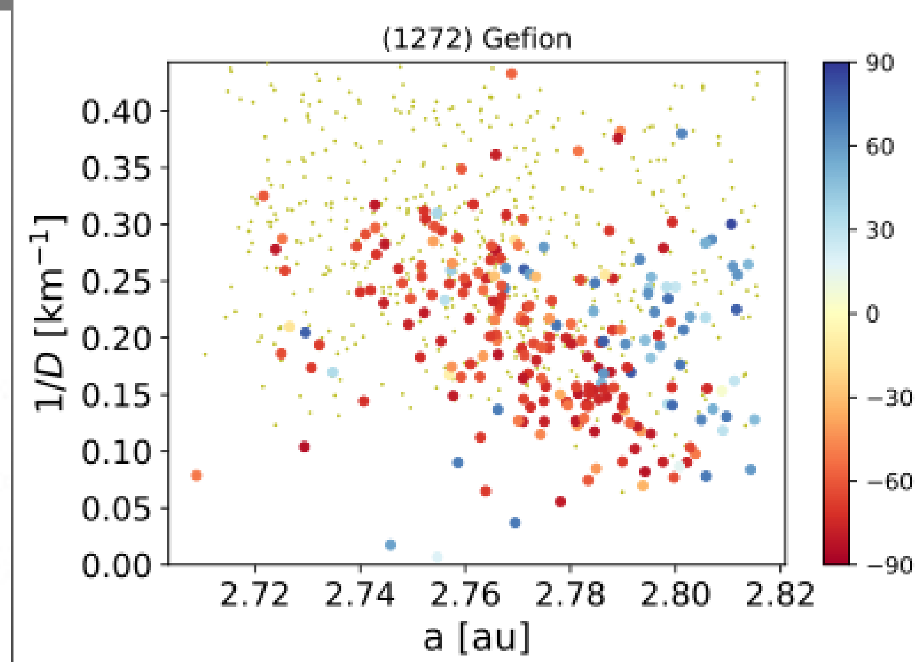
- Photometry is powerful & accessible
- Astrometry – orbits, new discoveries
- Lightcurves → rotation, shape, pole
- Workflow: target → data → reduction → lightcurve → physical properties
- Combining techniques improves physical constraints
  - Direct imaging (AO)
  - Stellar occultations
  - Thermal IR data
  - Delay-Dopler images
- Students can meaningfully contribute to asteroid science

Families with ages of several 100 Myr

- Adeona and Gefion (400-700 Myr, Carruba2013, Nesvorny+2009)
- Dora, age 500 Myr, Brož+2013
- Spin vectors are pretty much evolved for Gefion and Adeona, but not for Dora

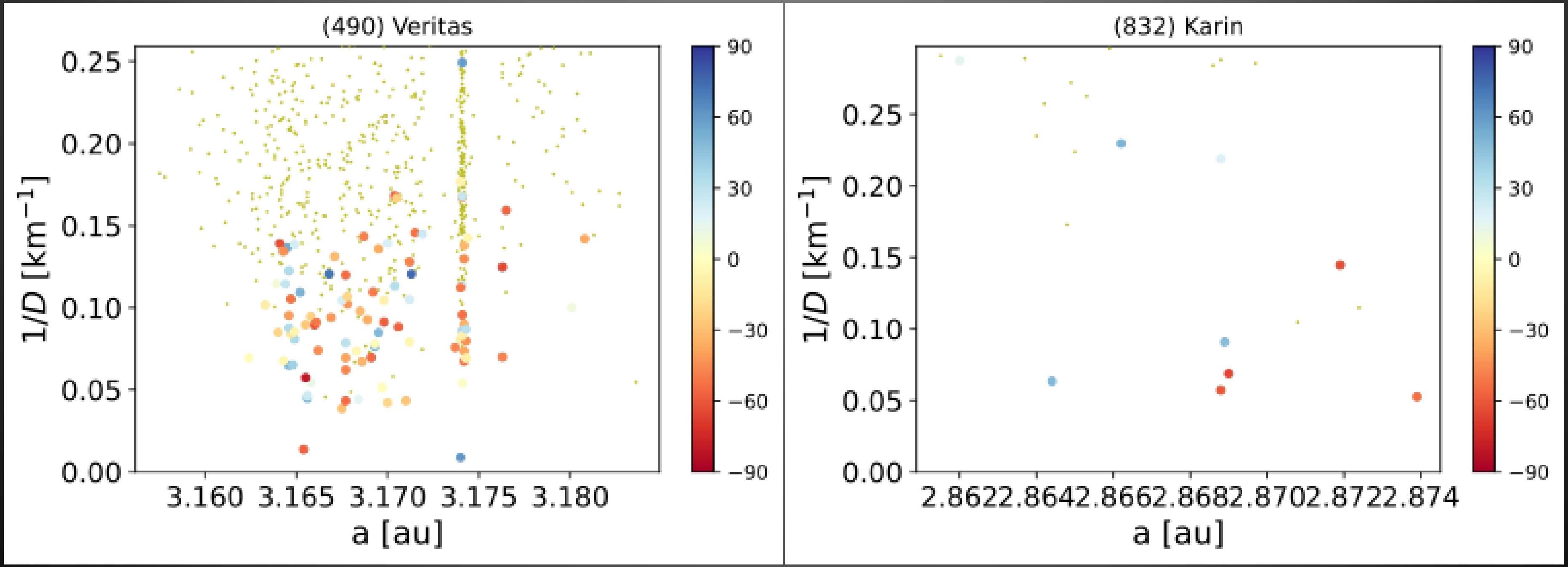






Young families

- Issue – young families are small clusters, with small bodies
  - Usually not many members with spin states (e.g., Karin, age 5.8 Myr, Nesvorny+2002)
  - A single exception is Veritas (age 8.3 Myr, Nesvorny+2003)
  - We are conducting an observational campaign with our colleagues from Greece (Athanasopoulos+2024) to increase the statistics
  - And waiting for LSST and Gaia
- Spin vectors are isotropic in Veritas – collisionally dominated, still close to the initial distribution, this is also valid for rotation periods



Young families – rotation periods

- Rotation periods in Veritas – almost no fast or slow rotators
- Comparison with the old Maria family, where the rotation period distribution is more extended