



Abstract: We present results from an EU Horizon2020-funded benchmark study (2016-2019) that addresses critical points in reconstructing physical and thermal properties of near-Earth, main-belt, and trans-Neptunian objects. The combination of the visual and thermal data from the ground and from astrophysics space missions is key to improving the scientific understanding of these objects. The development of new tools is crucial for the interpretation of much larger data sets, but also for the operations and scientific exploitation of interplanetary missions. We combine different methods and techniques to get full information on selected bodies: lightcurve inversion, stellar occultations, thermophysical modeling, radiometric methods, radar ranging and adaptive optics imaging. The applications to objects with ground-truth information from interplanetary missions Hayabusa1/2, NEAR-Shoemaker, Rosetta, and DAWN allow us to advance the techniques beyond the current state-of-the-art and to assess the limitations of each method. We present our recently developed tools, services, products, deliverables, and list important SBNF publications.

Results I: Tools & Services

- **ISAM service** (<http://isam.astro.amu.edu.pl/>) contains shape models for more than 900 asteroids. It allows to (i) display an asteroid orientation as seen from Earth at any date; (ii) to generate lightcurves; (iii) to animate the rotation; (iv) to produce 3D views; and (v) to investigate viewing & illumination geometries.
- **Gaia-GOSA** (<http://www.gaiagosa.eu/>): an interactive tool which supports observers in planning photometric observations of asteroids. The asteroid prediction tool is based on the Gaia orbit and scanning law (ESA) and SSO ephemerides (MPC).
- **Asteroid IR database:** a database for thermal IR/submm/mm observations of small bodies (NEAs, MBAs, Trojans, Centaurs, TNOs). The database includes measurements from ground (MIR, submm, mm instruments), airborne (SOFIA), and space projects (IRAS, MSX, AKARI, ISO, Spitzer, WISE, Herschel, Planck). The public release for the database was in February 2019 (TherMoPS III meeting).

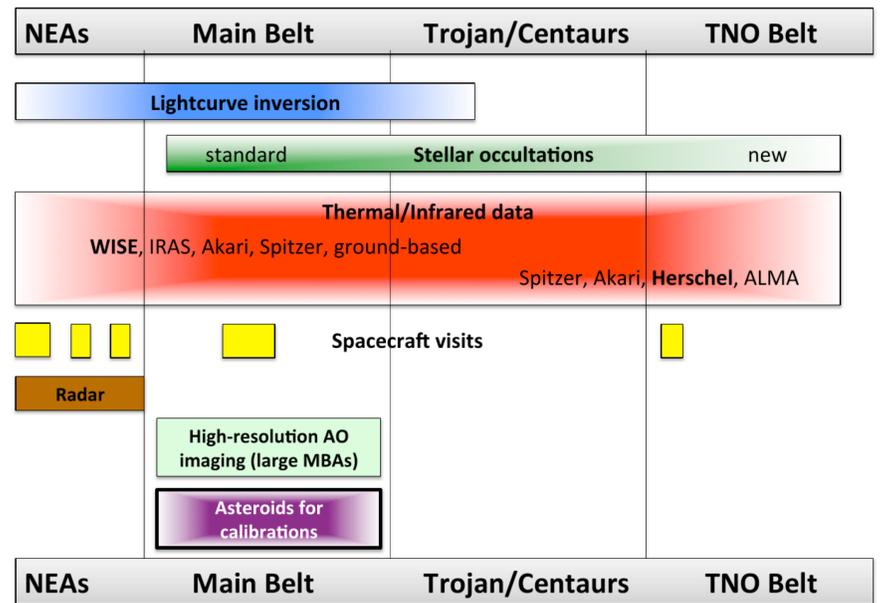
Results II: Products & Deliverables

- **Occultation predictions:** MBA events in 2017/18/19; long- and short-term planning/calculations for TNO events
- **NEAs, MBAs, and Centaurs/TNOs images and fluxes** derived from **Herschel photometric measurements** for an upload to the Herschel Science Archive Talk by Szakáts
- **Asteroid-related calibration:** highly accurate FIR/submm/mm model predictions for selected asteroids for Herschel, ALMA, APEX, SOFIA, ISO, AKARI, IRAM, etc. **calibration work** Talk by Müller Talk by Santos-Sanz
- **Deliverables:** "Ground truth" shape models; **Occultation vs. thermal tools vs. AO imaging**; Shape/spin solutions for large MBAs; Volume determination; ...

goo.gl/29Zwip or <http://www.mpe.mpg.de/~tmueller/sbnaf>
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Selected Key Publications & Synergies

Visible and thermal photometric studies (shape, size, spin & thermal properties)

- Thermal properties of slowly rotating asteroids – Results from targeted survey, Marciniak et al. 2019, A&A, subm. Talk by Marciniak
- Photometric survey, modelling, and scaling of long-period and low-amplitude asteroids, Marciniak et al. 2018, A&A 610, A7
- Hayabusa-2 Mission Target Asteroid Ryugu: Searching for the Object's Spin-Axis Orientation, Müller et al. 2017, A&A 599, A103 Talk by Müller
- Large Halloween Asteroid at Lunar Distance, Müller et al. 2017, A&A 598, A63
- 2008 OG₁₀: a highly elongated Trans-Neptunian object, Fernandez-Valenzuela et al. 2016, MNRAS 456, 2354
- Physical properties of centaur (54598) Bienor from photometry, Fernandez-Valenzuela et al. 2016, MNRAS 466, 4147
- Thermal light curves of Haumea, 2003 VS₂ and 2003 AZ₈₄ with Herschel-PACS, Santos-Sanz et al. 2017, A&A 604, A95

Occultations, partly combined with thermal measurements (Herschel & Spitzer)

- Haumea's thermal emission revisited in the light of the occultation results, Müller et al. 2019, Icarus, in press, arXiv:1811.09476.
- The size, shape, density and ring of the dwarf planet Haumea from a stellar occultation, Ortiz et al. 2017, **Nature** 550, 219 Talk by Santos-Sanz
- Results from a triple chord stellar occultation and FIR photometry of TNO (229762) 2007 UK₁₂₆₇, Schindler et al. 2016, A&A 600, A12
- The Eris-Dysnomia system as seen with the synergy of occultation and thermal emission measurements, Kiss et al., A&A, in prep.
- JWST Observations of Stellar Occultations by Solar System Bodies and Rings, Santos-Sanz et al. 2016, PASP 128, 8011
- Study of the Plutino Object (208996) 2003 AZ₈₄ from Stellar Occultations: Size, Shape, and Topographic Features, Dias-Oliveira et al. 2017, AJ 154, 22D

Kepler-K2 lightcurves combined with thermal data

- K2 light curves of ten Centaurs, Kiss et al. 2019, MNRAS, subm.
- Large Size and Slow Rotation of the TNO (225088) 2007 OR₁₀ Discovered from Herschel and K2 Observations, Pál et al. 2016, AJ 151, 117
- Nereid from space: rotation, size and shape analysis from K2, Herschel and Spitzer observations, Kiss et al. 2016, MNRAS 457, 2908
- The heart of the swarm: K2 photometry and rotational characteristics of 56 Jovian Trojan asteroids, Szabó et al. 2017, A&A 599, 44
- Uninterrupted optical light curves of main-belt asteroids from the K2 Mission, Szabó et al. 2016, A&A 596, 40
- Properties of the irregular satellite system around Uranus inferred from K2, Herschel and Spitzer observations, Farkas-Takács et al. 2017, AJ 154, 119

Herschel, HST, WISE, Catalogues, and Others

- The mass and density of the dwarf planet (225088) 2007 OR₁₀, Kiss et al. 2019, resubm.
- TNOs are Cool. XIII. Size/albedo characterization of the Haumea family observed with Herschel and Spitzer, Vilenius et al. 2018, A&A 618, A136
- The AKARI IRC Asteroid Flux Catalogue: updated diameters and albedos, Alí-Lagoa et al. 2018, A&A 612, A85
- Discovery of a satellite of the large trans-Neptunian object (225088) 2007 OR₁₀, Kiss et al. 2017, ApJL 838, L1
- Sizes and albedos of Mars-crossing asteroids from WISE/NEOWISE data, Alí-Lagoa et al. 2017, A&A 603, 55A
- Assessment of different formation scenarios for the ring system of (10199) Chariklo, Melita et al. 2017, A&A 602, A27
- Characterization of multiple trans-Neptunian objects observed with Herschel Space Observatory, Kovalenko et al. 2017, A&A 608, A19
- Several catalogue papers for small body thermal observations are in preparation/submitted (Herschel, AKARI, WISE)

Shape and spin determination

- Volume uncertainty assessment method of asteroid models from disk-integrated visual photometry, Bartczak & Dudziński 2019, MNRAS, in press
- Shape Models and Physical Properties of Asteroids, Santana-Ros et al. 2017, ASSP, Vol 46
- A new non-convex model of the binary asteroid (809) Lundia obtained with the SAGE modelling technique, Bartczak et al. 2017, MNRAS 471, 941
- Statistical analysis of the ambiguities in the asteroid period determinations, Butkiewicz-Bąk et al. 2017, MNRAS 470, 1314
- Shaping Asteroid Models Using Genetic Evolution (SAGE), Bartczak & Dudziński 2018, MNRAS 473, 5050B

General papers

- Small Bodies Near and Far (SBNF): a benchmark study on physical and thermal properties of small bodies in the Solar System, Müller et al. 2018, Advances in Space Research 62, 2326, arXiv:1710.09161

The Trans-Neptunian Solar System, D. Prrialnik, A. Barucci & L. Young (eds.), Elsevier (in preparation):

- TNOs and Centaurs at thermal wavelengths, Müller, Lellouch & Fornasier 2019, accepted Talk by T. Müller
- Stellar occultations by Trans-Neptunian Objects: from predictions to observations and prospects for the future, Ortiz et al. 2019, accepted

