Stellar occultations by NEAs, challenges and opportunities

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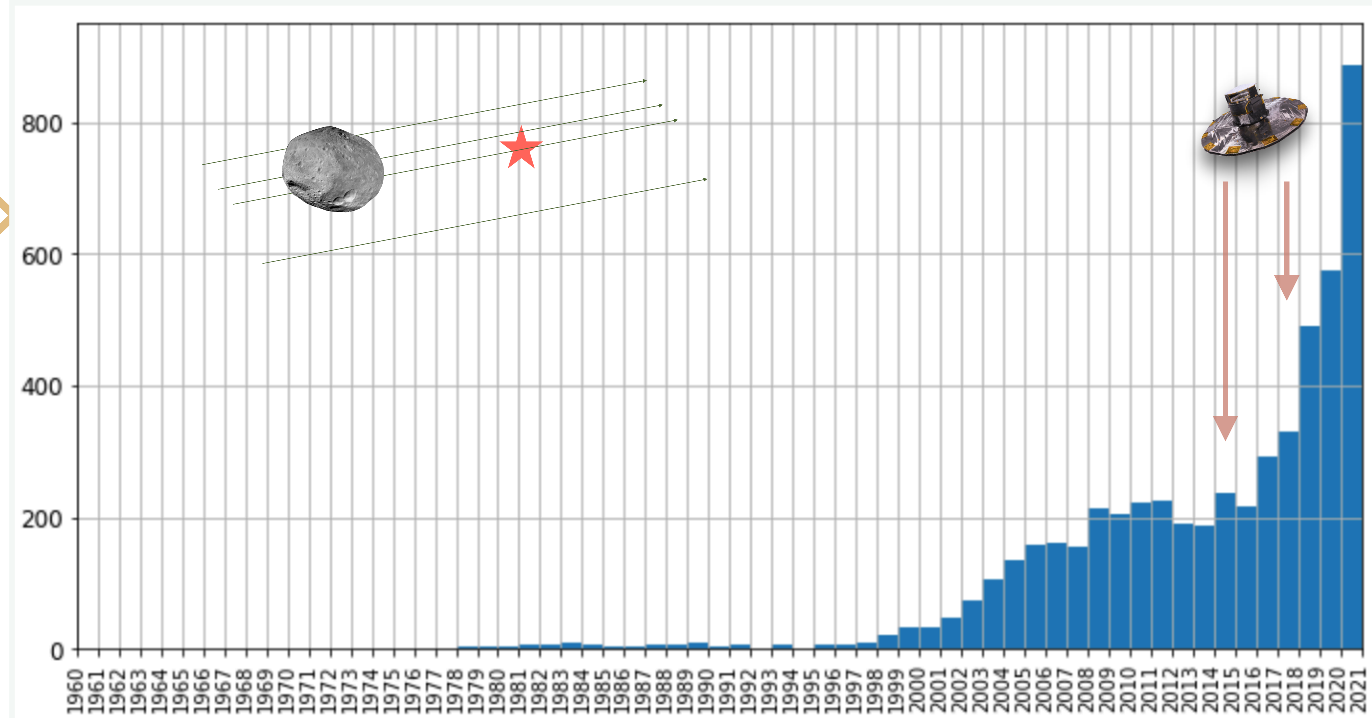
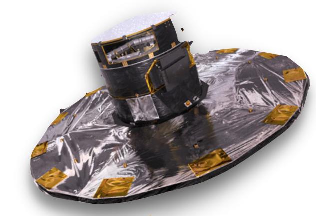
The evolving landscape of stellar occultations

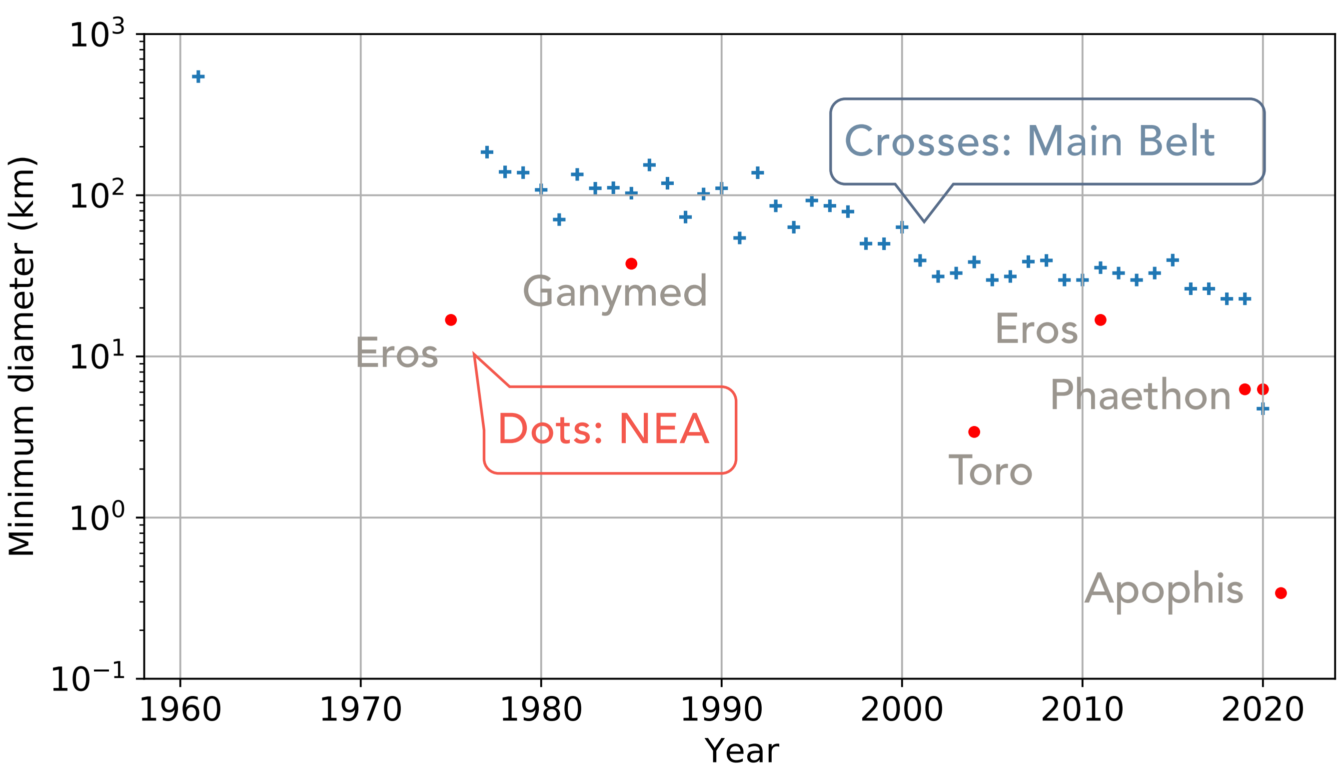
The number of astrometric measurements obtained by occultations: increasing dramatically thanks to stellar astrometry by Gaia (DR1 in 2016, and DR2 in 2018) + use in the **orbital solutions** of Gaia astrometry of asteroids.





ESA/Gaia has published the astrometry of 1.8 billion stars (magnitude G<20.5) in EDR3.

14.099 minor bodies are present in DR2. 10 times more will be released in DR3 (early 2022).



The diameter of the smallest asteroid that resulted in a positive observed event, per year.

It decreases, due to orbit improvement.

It makes a big jump with Gaia DR2 and reaches very small NEAs recently!

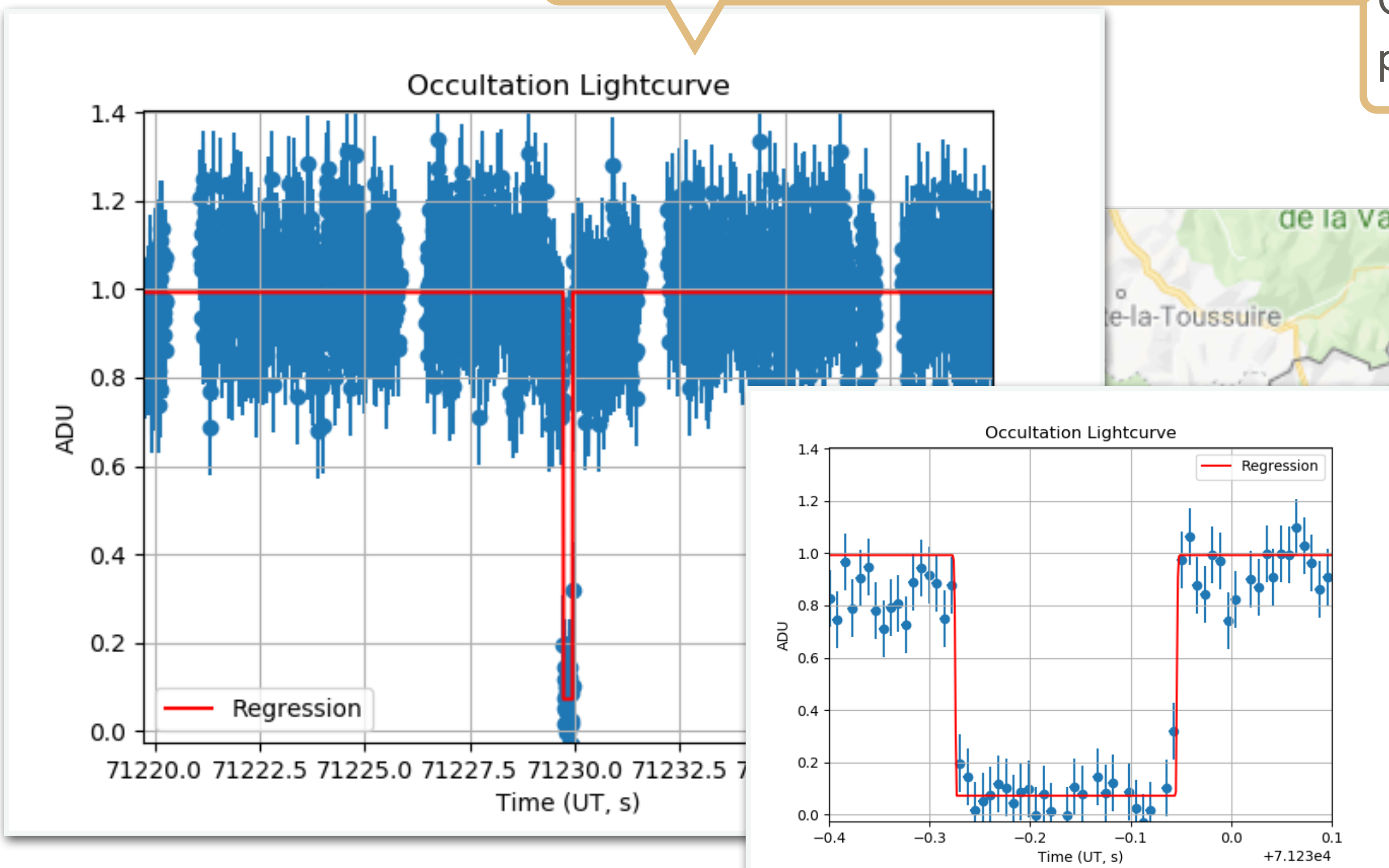
The Gaia role is essential in the improvement: Increased accuracy on stars and on asteroids directly measured + new, dense reference frame for ground-based optical astrometry.

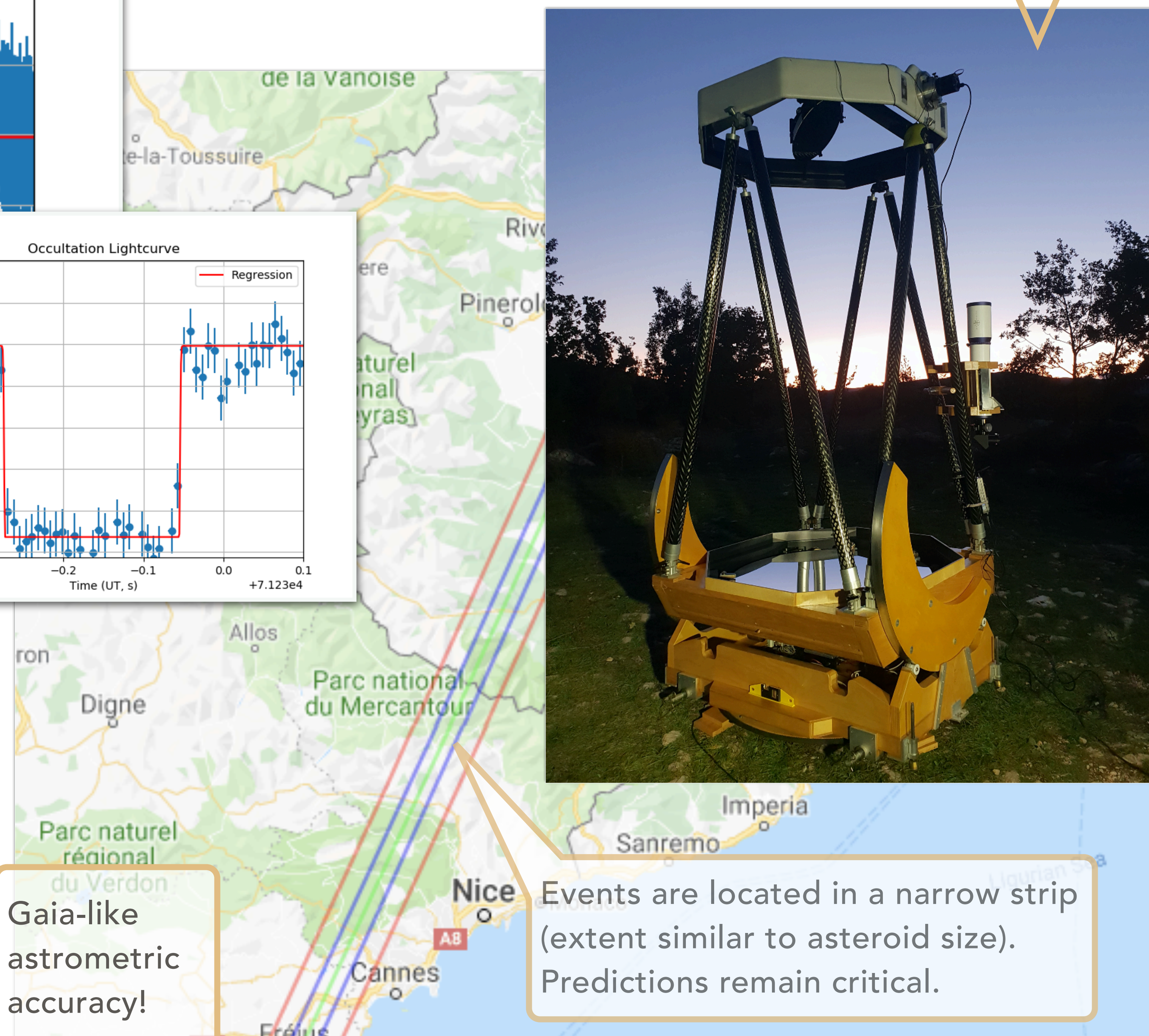
Radar astrometry has proved essential for the prediction of occultations by Phaethon and Apophis.

The challenge. Example: Phaethon Oct. 15, 2019

Events for NEA are SHORT (typ. <0.1 s)

Consequence: large telescopes required for fast photometry (here a 1 m "portable" instrument).





Disappearance (UTC)	19:47:09.7270	+/-	0.0015
Reappearance	19:27:09.9496	+/-	0.0015

Duration : 0.218 +/- 0.002 s

Velocity: 23.30078 km/s —> chord length 5.09 km
Error ~1% —> 45 m ! (= 67 μas)

Total error budget (with star + shape uncertainty):
RMS(RA*) = 1.6 mas / RMS(Dec) = 2.8 mas

Gaia-like astrometric accuracy!

Events are located in a narrow strip (extent similar to asteroid size). Predictions remain critical.

The best NEA candidates for occultations

Some indicative (and approximate) statistics about the number of events that can be expected, for **a sample of NEAs with the best orbit uncertainty** (σ_a).
(Eros, Phaethon and Apophis are excluded as already well observed by occultations)

σ_a has been computed from the **orbital fit** of the available observations, including **radar** and **Gaia DR2**.

The columns "Events" report the number of predicted occultations in 1 year on the Earth ("global") and the European continent, to give a feeling about the amount of potentially interesting opportunities, involving stars G<14.

The "dt" columns represent the **minimum/ maximum of the max. expected duration** among all the events of a given asteroid.

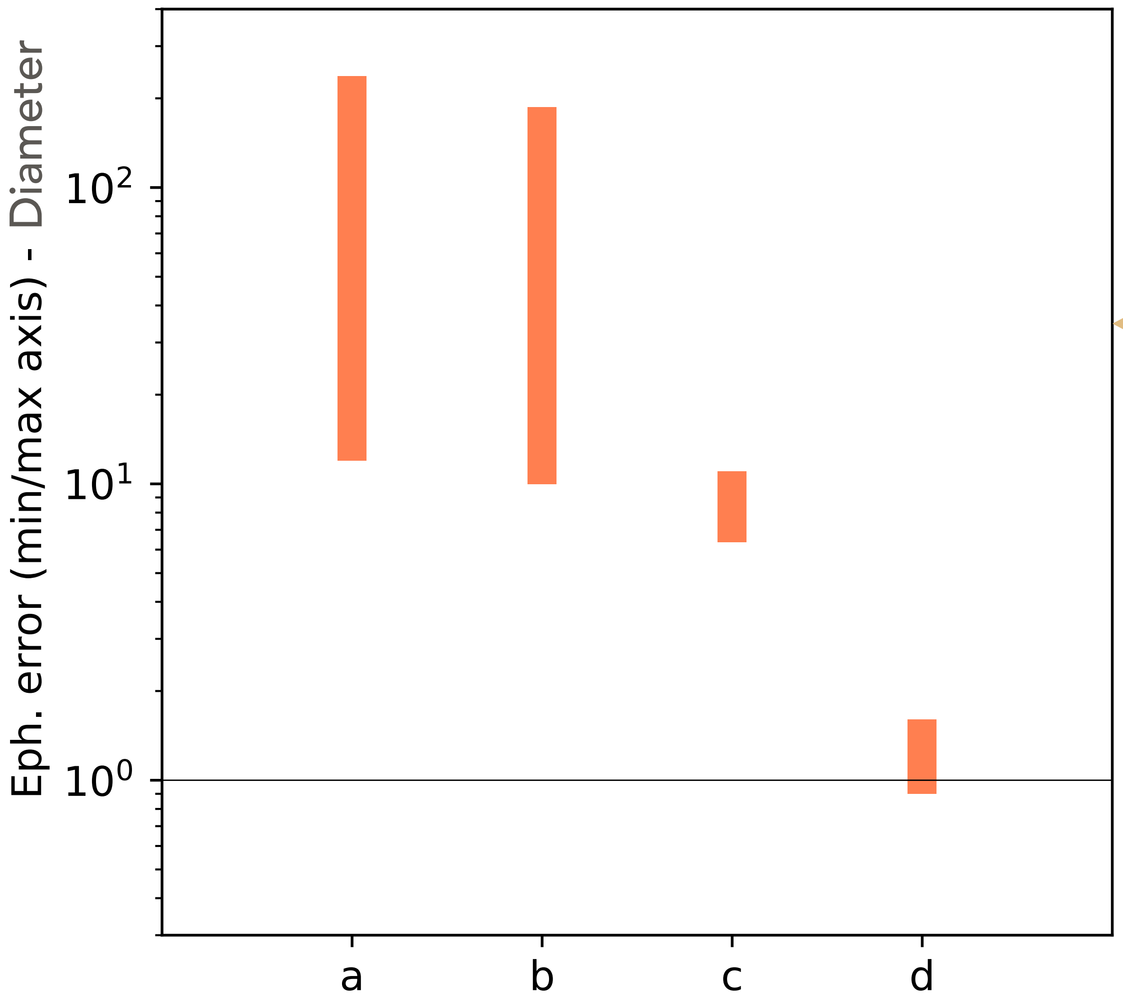
#	Designation	σ_a (au)	D (km)	Events (global)	Events (Europe)	dt min (s)	dt max (s)
68 950	2002 QF15	3.8E-11	1.10	334	10	0.02	0.08
1 620	Geographos	5.4E-11	1.87	862	19	0.04	0.69
1 566	Icarus	6.5E-11	1.42	272	1	0.02	0.25
4 179	Toutatis	1.0E-10	2.70	35	3	0.07	0.18
2 063	Bacchus	1.1E-10	1.10	616	32	0.03	0.58
2 100	Ra-Shalom	1.1E-10	2.00	464	13	0.03	0.23
90403	2003 YE45	1.1E-10	1.04	452	8	0.02	0.10
1 627	Ivar	1.3E-10	8.37	144	17	0.15	2.40
65 803	Didymos	1.4E-10	0.78	156	5	0.02	0.23
1 685	Toro	1.6E-10	3.81	190	6	0.06	0.68
144 411	2004 EW9	1.7E-10	1.84	52	2	0.04	0.23
29 075	1950 DA	2.1E-10	2.00	60	5	0.05	0.61
1 580	Betulia	2.2E-10	8.55	254	8	0.09	0.19

Some of the data in this table have been produced by *Orbfit* and *Occult*.

Improving predictions for (65803) Didymos

(65803) Didymos is an outstanding occultation target, as it will be visited by the NASA/DART and ESA/Hera missions.

(65803) Didymos: ephemeris uncertainty on Apr. 9, 2021 using different astrometric data sets. The uncertainty is given in units of the average diameter of Didymos (taken as 780 m). The bar extend from the smallest to the large axis of the ellipse of uncertainty (1-sigma).



a: all optical observations available at the date of the close encounter with Earth in 2003-2004

b: the same + radar data obtained in 2003

c: all optical data available + radar of 2003

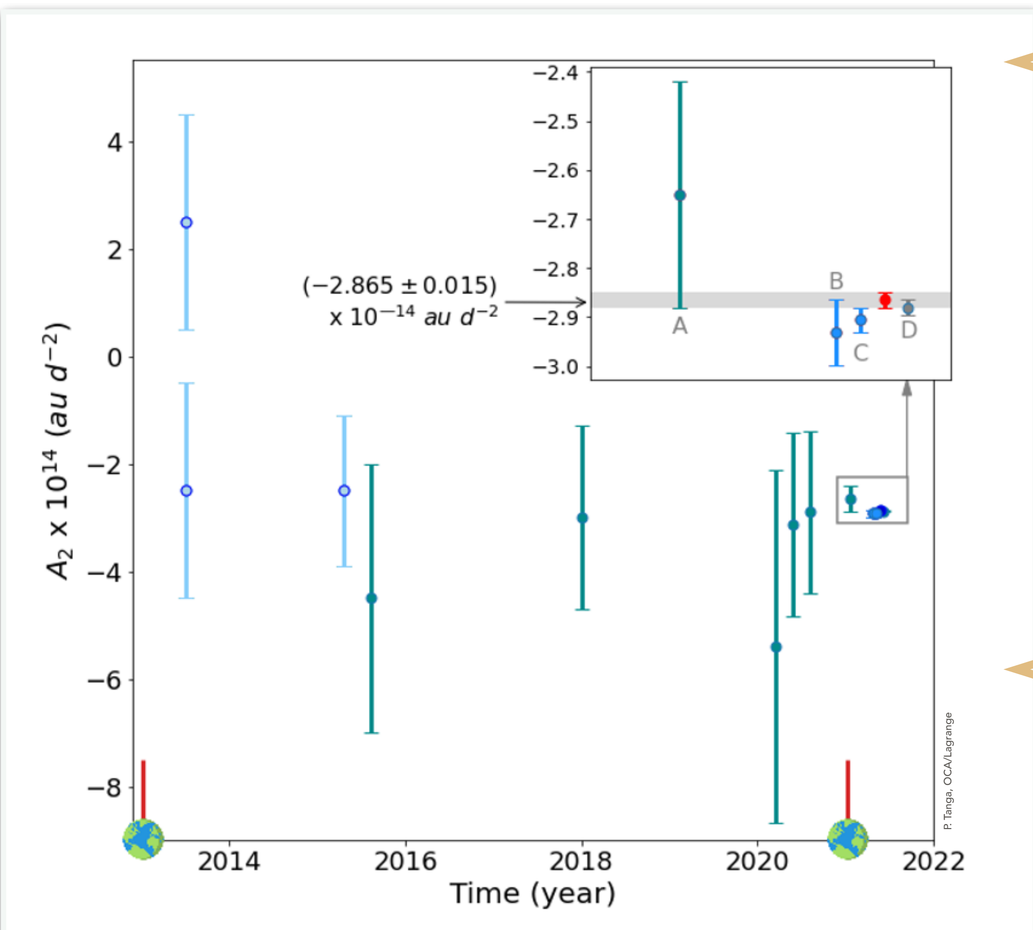
d: with additional optical observations obtained in the frame of the **DART/Hera Working Group** dedicated to collect remote observations (mostly 2015-2021).

The line represent the diameter of Didymos. At this level the predictability of the occultations becomes good.

NEA occultation successes, attempts, implications

- (3200) Phaethon
  - Several occultations observed in 2019-2020.
  - See talk by D. Dunham - session 6b, April 27, 2021
- (99942) Apophis
  - Success on March 7, 22, April 4, 11 2021. More events to come. The event on March 7 is "problematic" (possible errors on the star astrometry).
- (65803) Didymos
  - First attempt on April 9, 2021 in Greece in the frame of the ESA/Hera observation activities. Occultations not detected yet.

Current campaigns are strongly impacted by travel restrictions due to covid-19 pandemics.



Evolution in time of our **knowledge of the Yarkovsky acceleration** for Apophis. Light blue: theoretical estimates from models (sign unknown for the first). Other data: from orbital fits including optical and radar astrometry. Inset: last estimates. In red: from all the observations available on March 15, including the occultation on March 7, 2021. The other values: the best measurements available in January (A), with adding of optical data during the close encounter (B), plus radar (C). The (D) solution: same data used for our red point, but computed independently by JPL.

For Apophis (no Gaia astrometry available), **radar** was essential to the prediction of the first occultation, however the occultation (1) still improves the Yarkovsky value by a significant factor and (2) enables a better prediction of future events.

https://www.cosmos.esa.int/web/gaia/image-of-the-week

Take away messages

- Gaia stellar astrometry + asteroid astrometry:
  - Increasing number of positive events on “general” Main Belt asteroids, and new categories becoming possible: NEAs ~100s m in size!
  - The presence of radar and/or Gaia astrometry of the NEA itself strongly enhances the orbit and the prediction of the first event of an object (once a positive event is observed, subsequent ones are easier to predict).
- Implications for planetary defense:
  - Occultations reach Gaia-like or radar-like accuracies on NEA positions, providing a non-negligible contribution to the improvement of NEA orbits.
- Challenges
  - Events are visible from a very restricted strip on Earth. Movable telescopes are strongly favoured.
  - Events are rapid and those involving bright stars, rare. Large telescopes favoured, but lucky exceptions exist.
  - Complementary, accurate astrometry in epochs close to the targeted events is important to increase the chances.
- Perspectives
  - Several NEA orbits are close to provide reasonable success probabilities for future.
  - (65803) Didymos represents an outstanding target due to its relevance for planetary defense, brought by the NASA/DART and ESA/Hera mission.
  - Ground based optical astrometry, appropriately performed, can allow to reach the accuracy required to predictions.