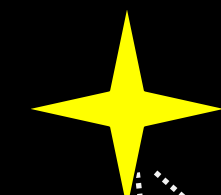


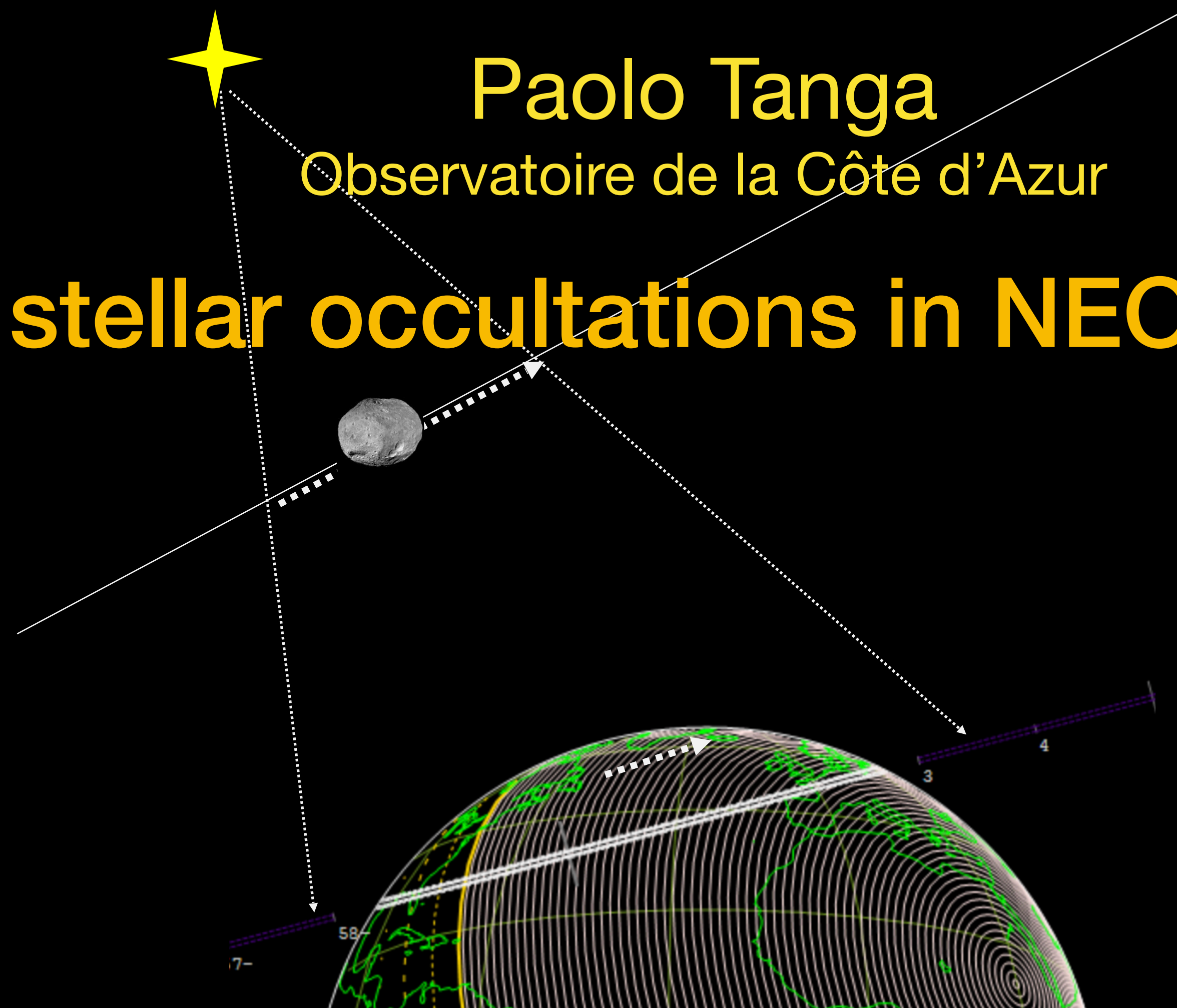


EU-ESA Workshop on Astrometric and
Radar Observations of NEOs



Paolo Tanga
Observatoire de la Côte d'Azur

The role of stellar occultations in NEO astrometry



Large asteroids vs. small NEOs, many challenges

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- **Prediction**

- Extremely accurate ephemeris required.
 - Typ. semi-major axis uncertainty for a first occultation 10^{-9} - 10^{-10} au.
- A first positive occultation shrinks the uncertainty to ~asteroid size
- Subtle effects to take into account: Earth topography, differential relativistic light bending etc. play a role at ~100 m level accuracy

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- Narrow occultation tracks! Fixed stations out of the game, in general.
- Short duration (0.01-0.1 s): fast photometry. “Bright” star events ($V < 13$) are very rare..
- Coordinated campaigns, largest portable telescopes required.

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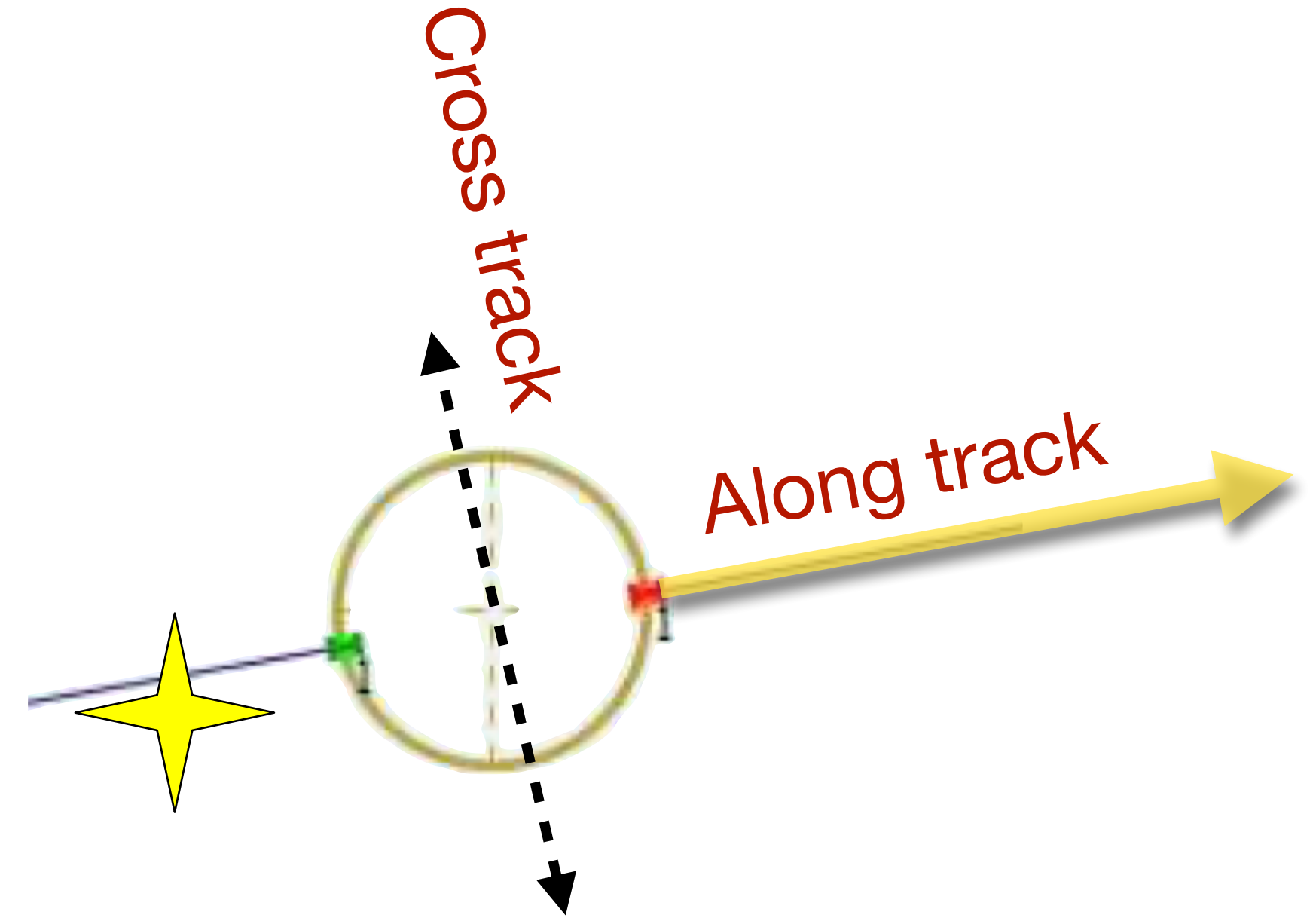
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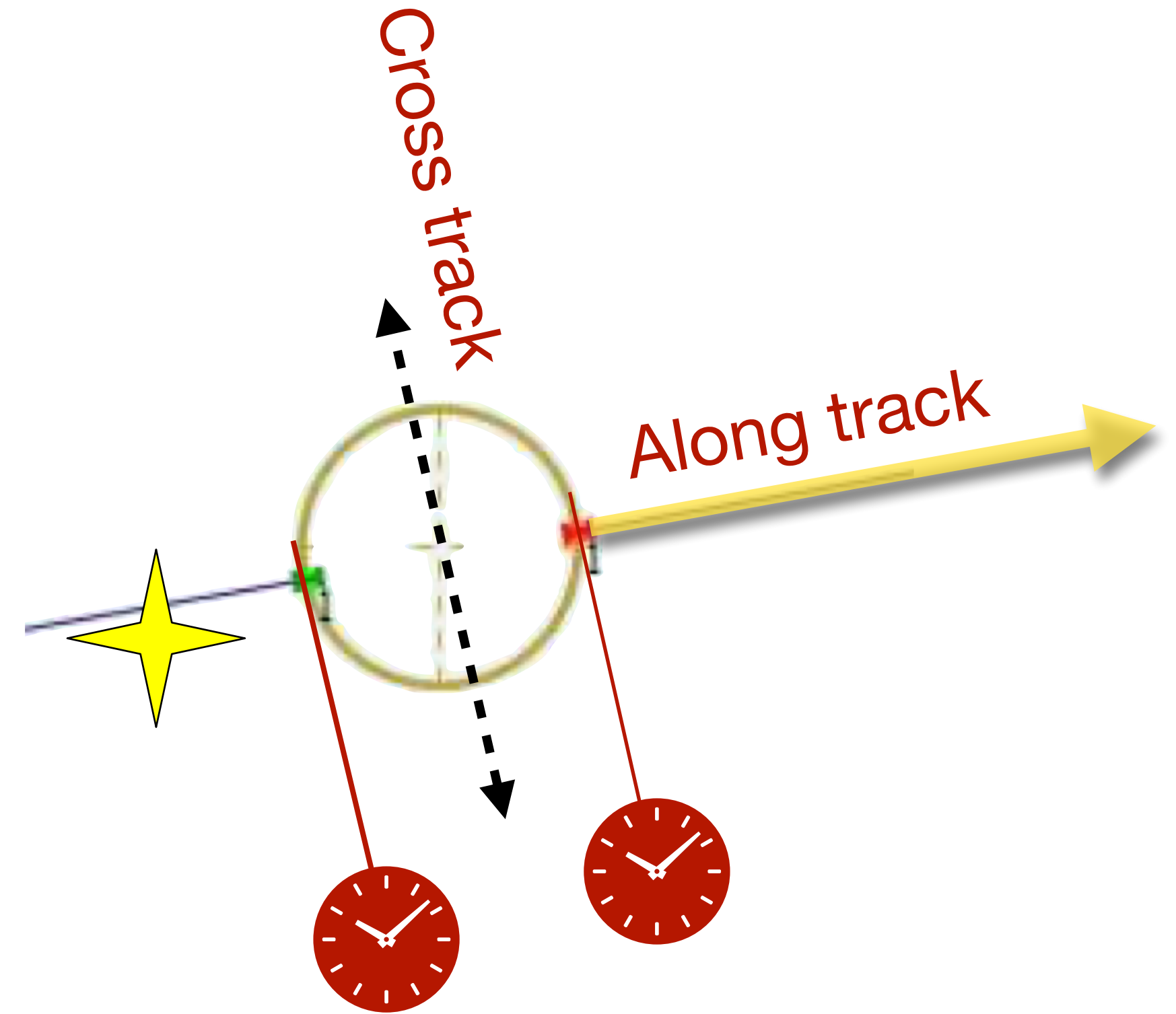
- **Astrometric reduction and exploitation**

- Astrometry at ~mas level not easy to exploit (esp. jointly to other data).
- The huge weight strongly drive the orbital solution

Essential properties of occultation astrometry

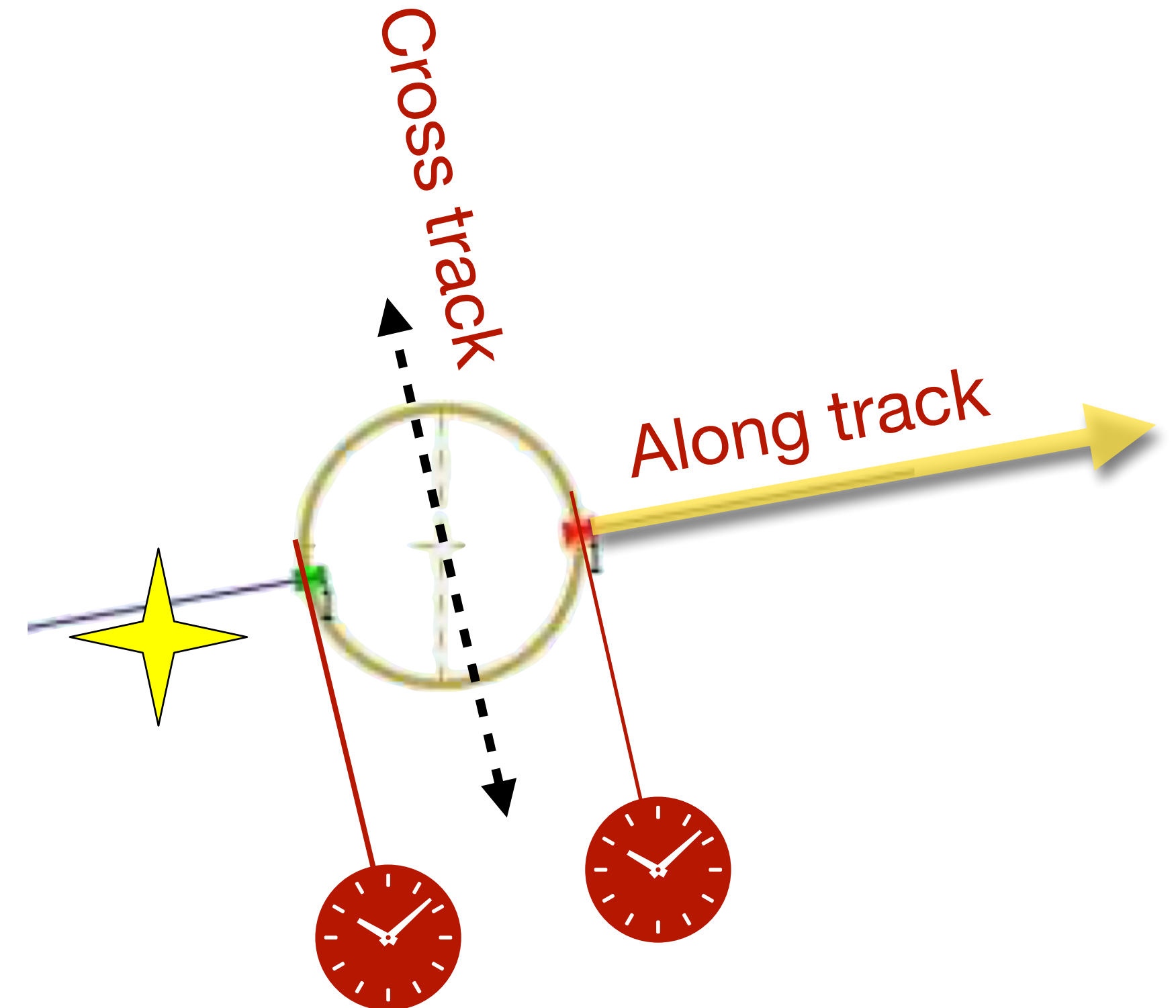


Essential properties of occultation astrometry



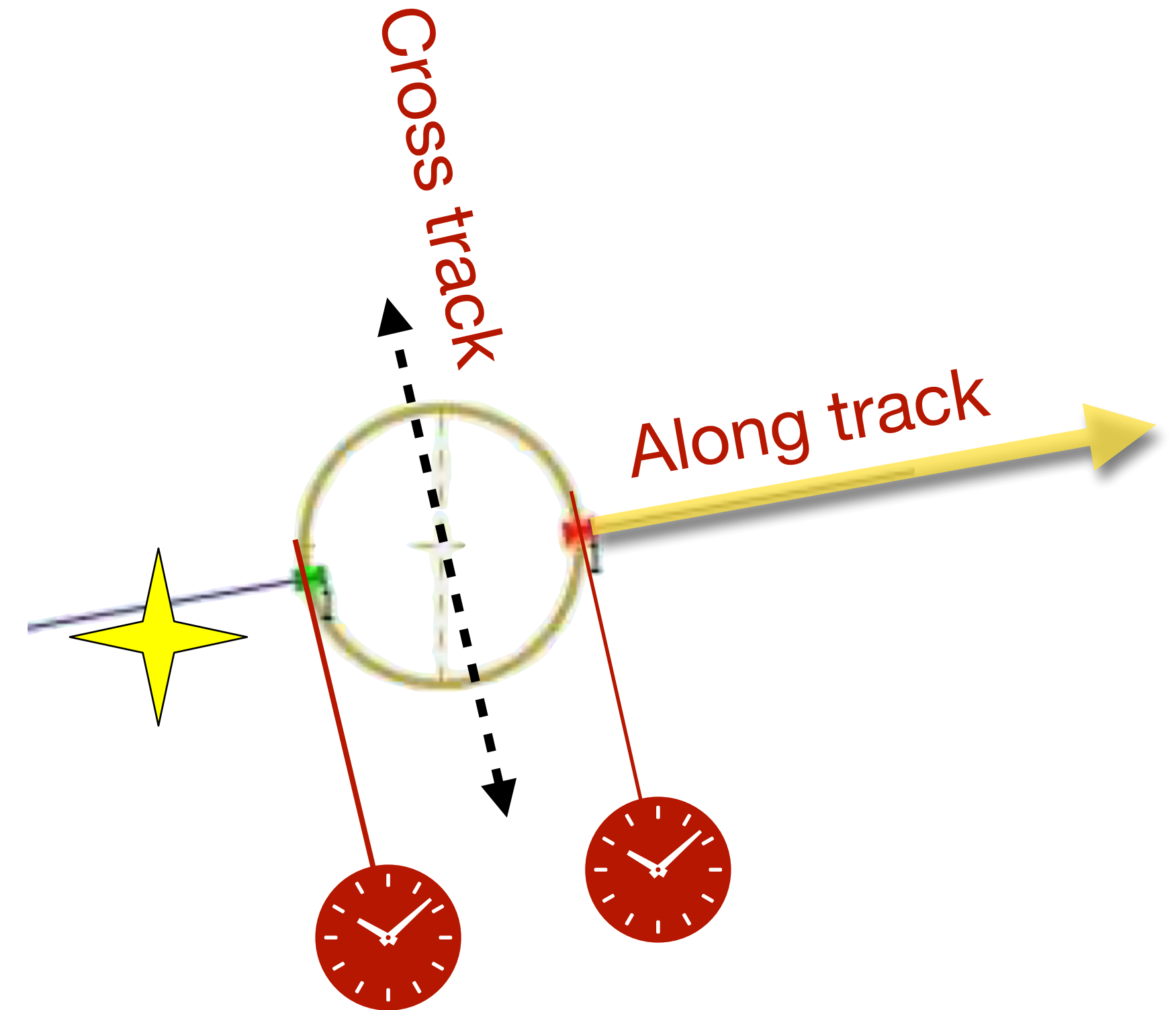
Essential properties of occultation astrometry

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 - Absolute UTC timing of an observed epoch associated to the event
 - Typical target accuracy ~1 ms: all problems mentioned yesterday are present (CMOS readout delays, rolling shutter, GPS time sync etc)



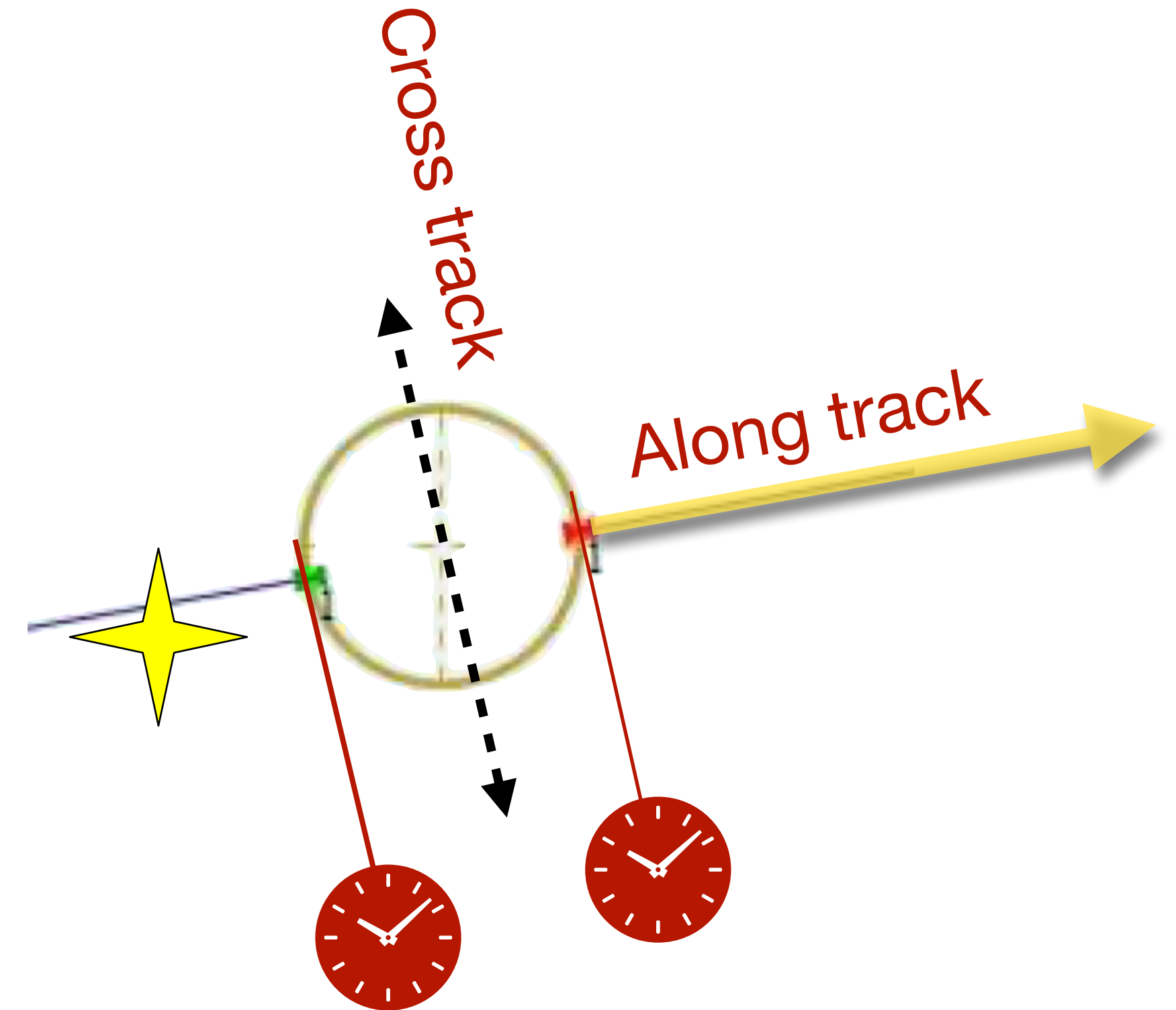
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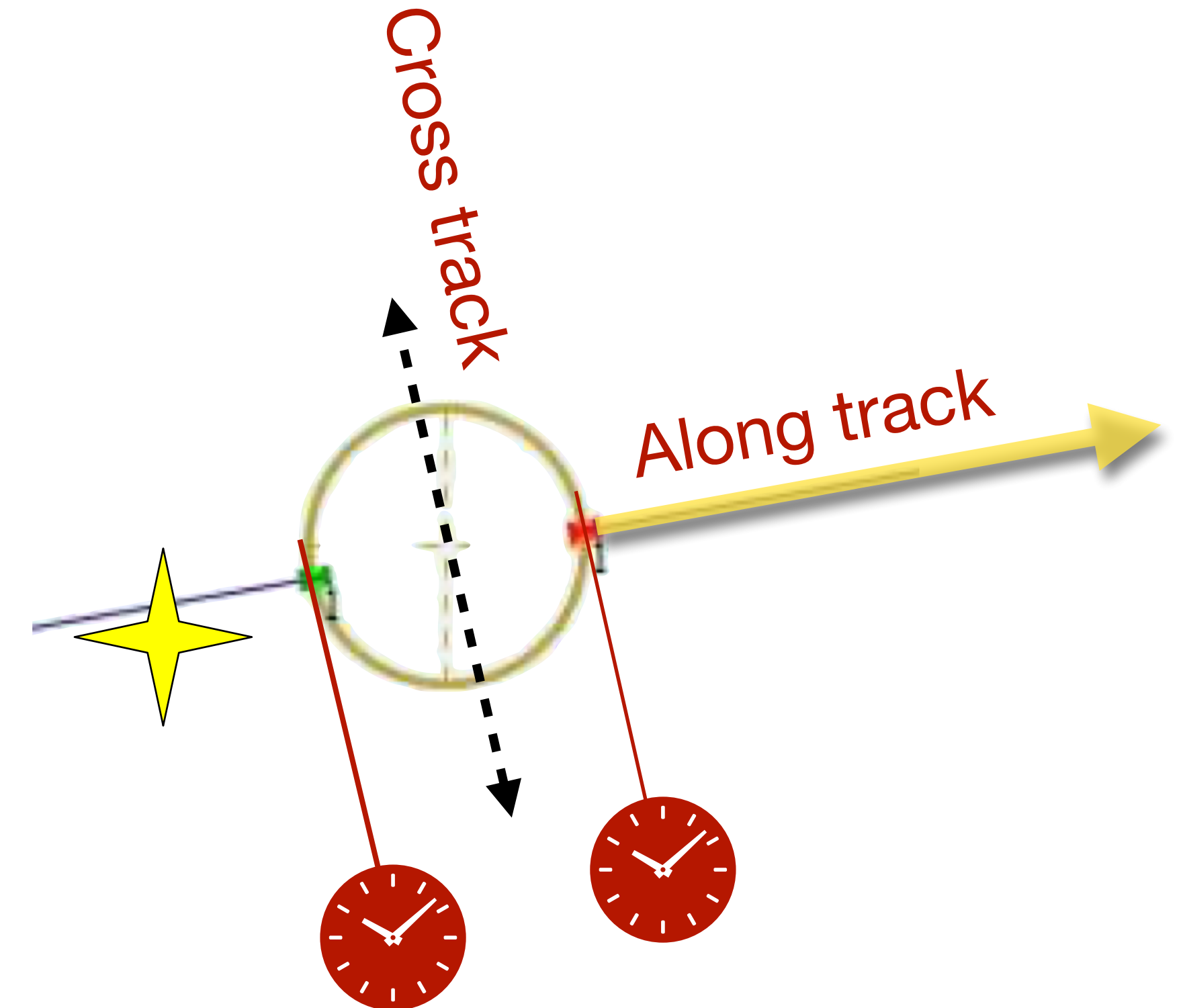
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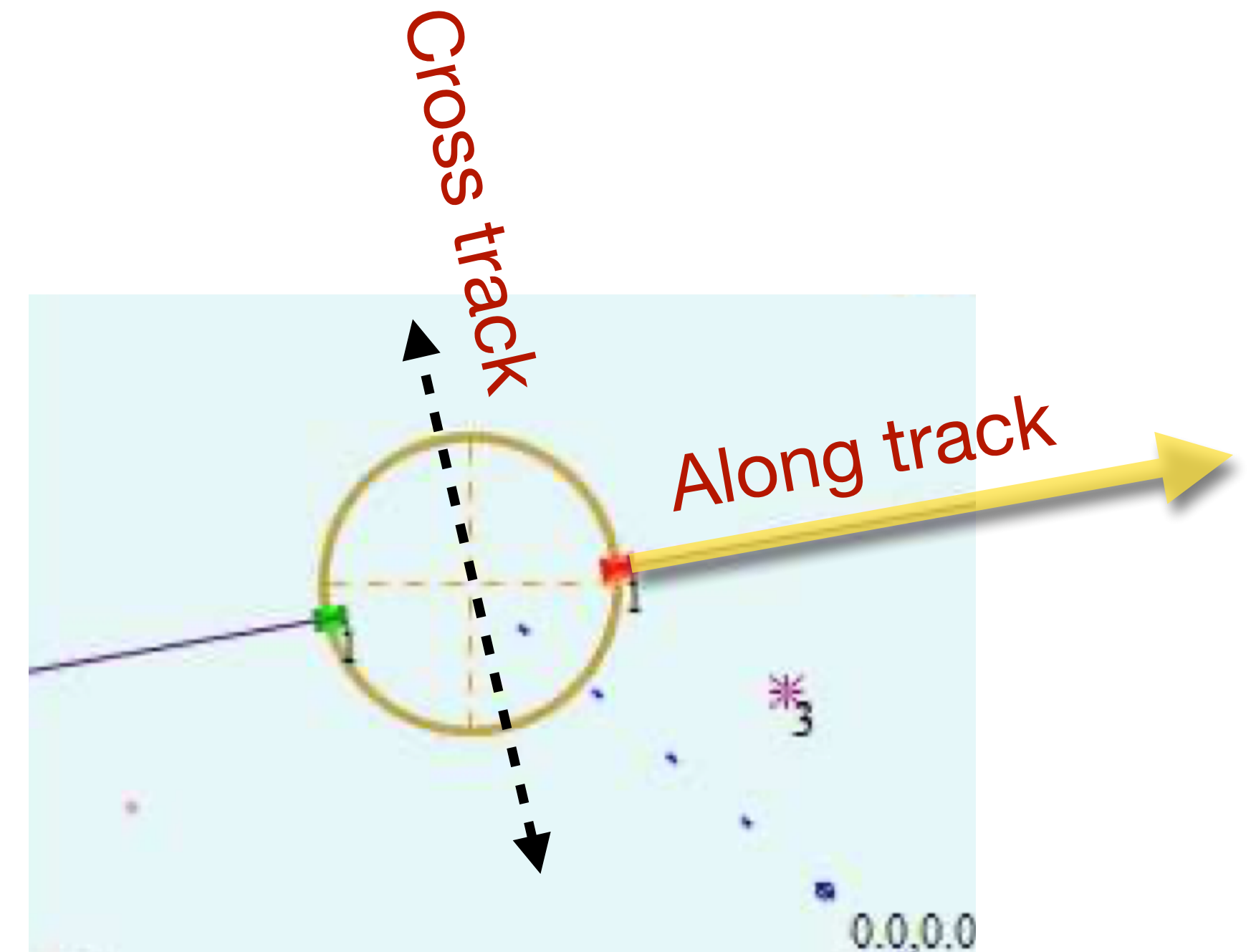
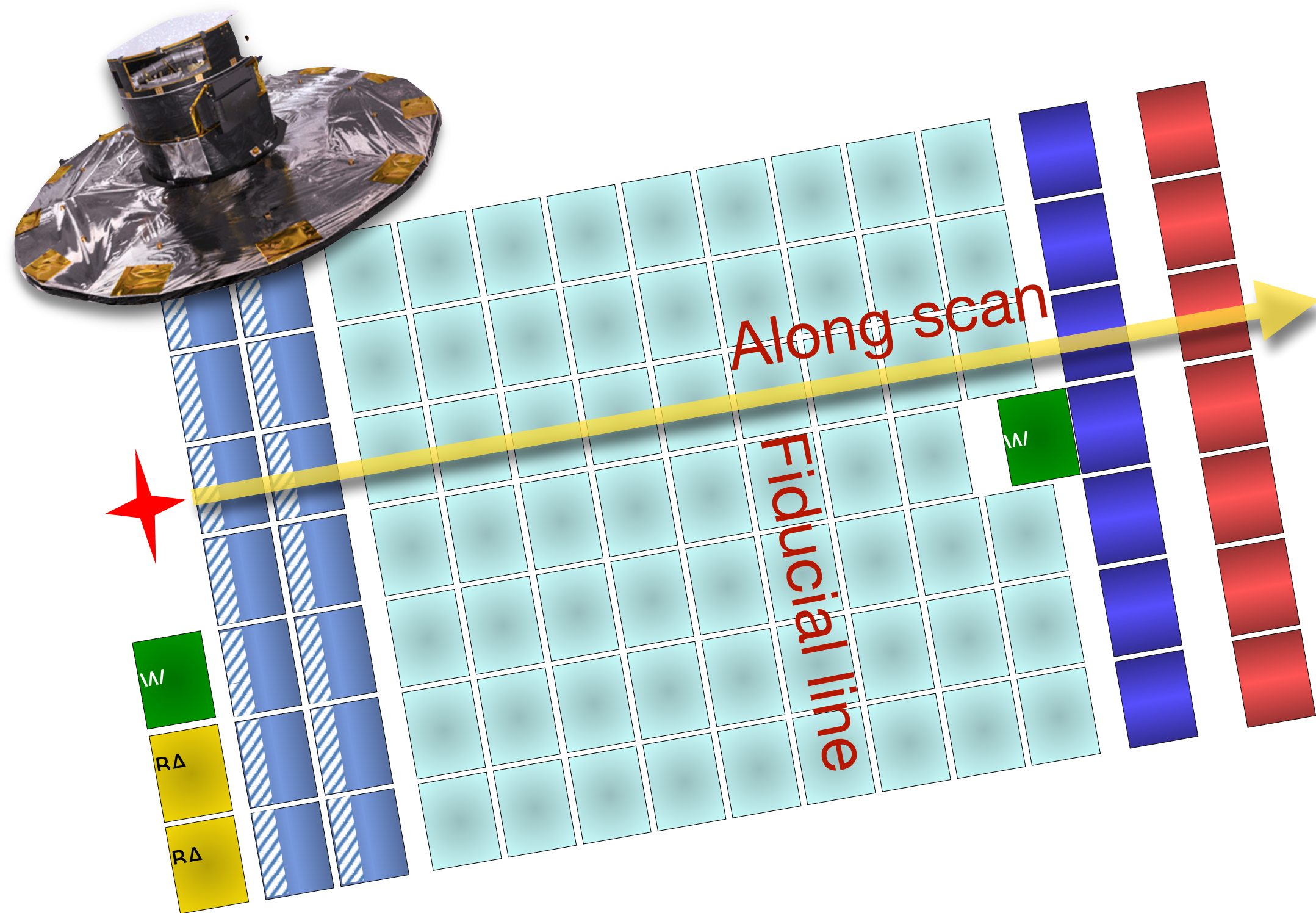


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- Strength: astrometric errors (relative to the star) cannot be larger than the (*real* !) asteroid radius (cross track) and the timing uncertainty (along track)
 - Even with a single occultation chord !!!
 - Some complexity related to non-spherical shapes, unknown orientation on the sky...

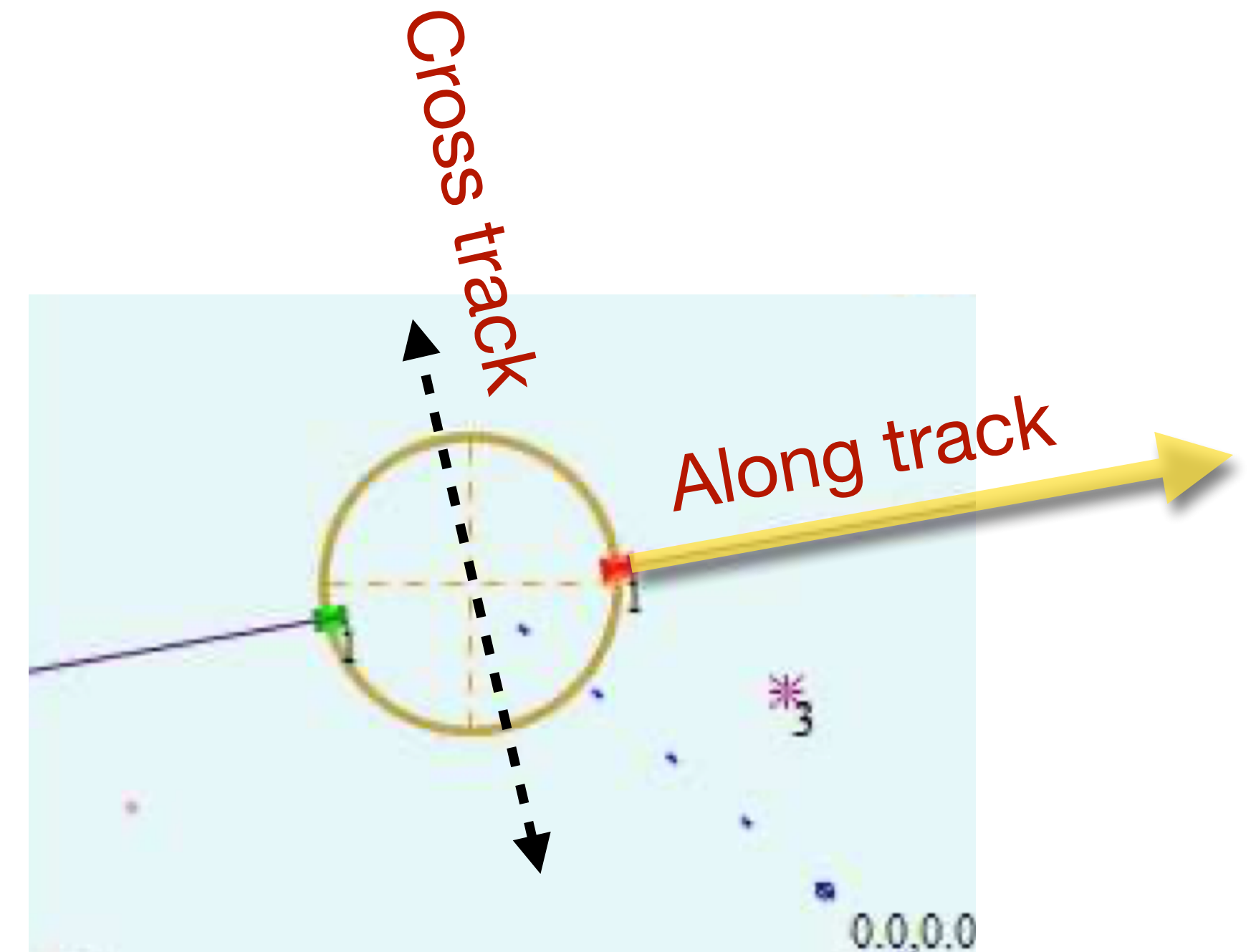
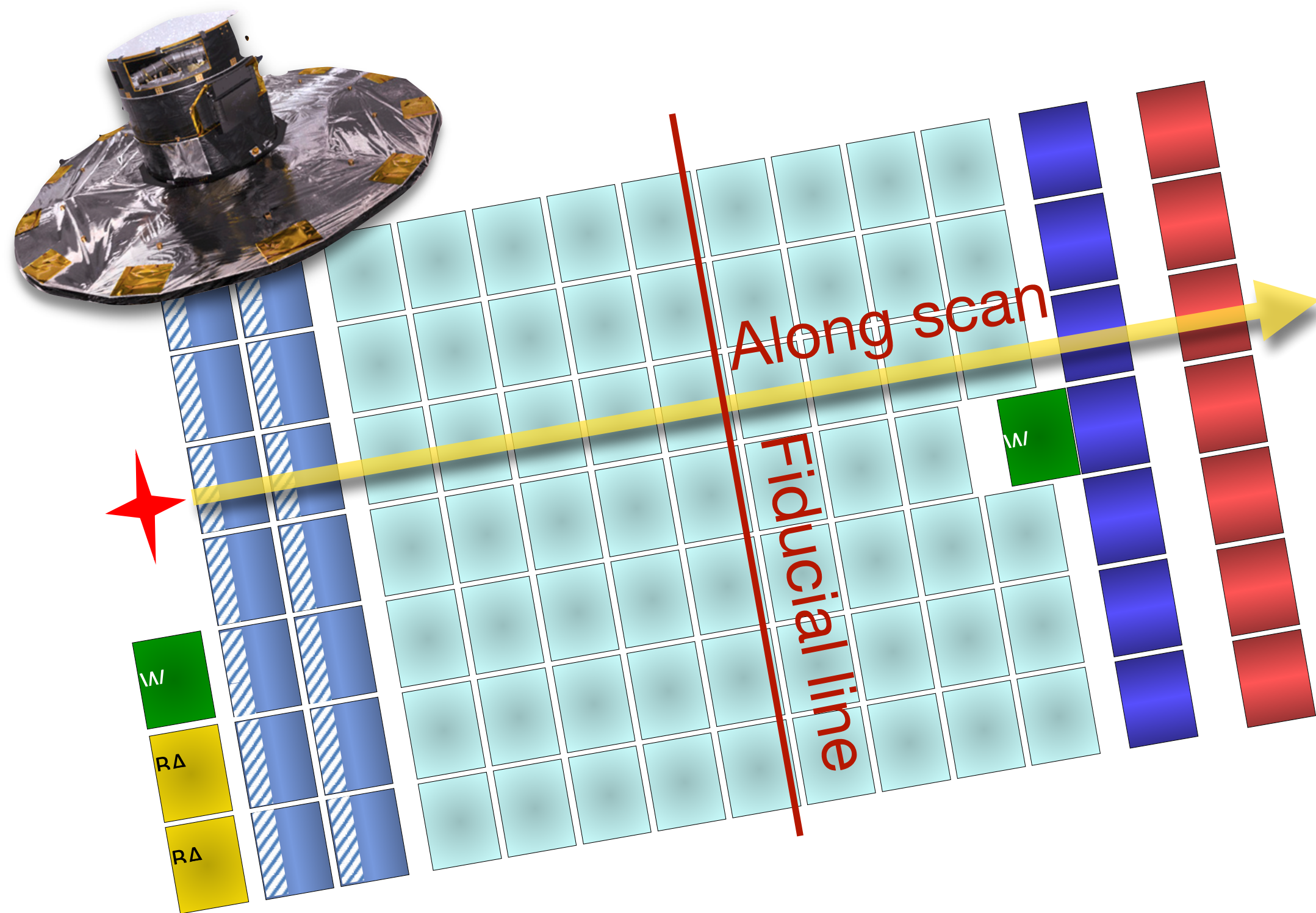


Comparing Gaia and stellar occultations



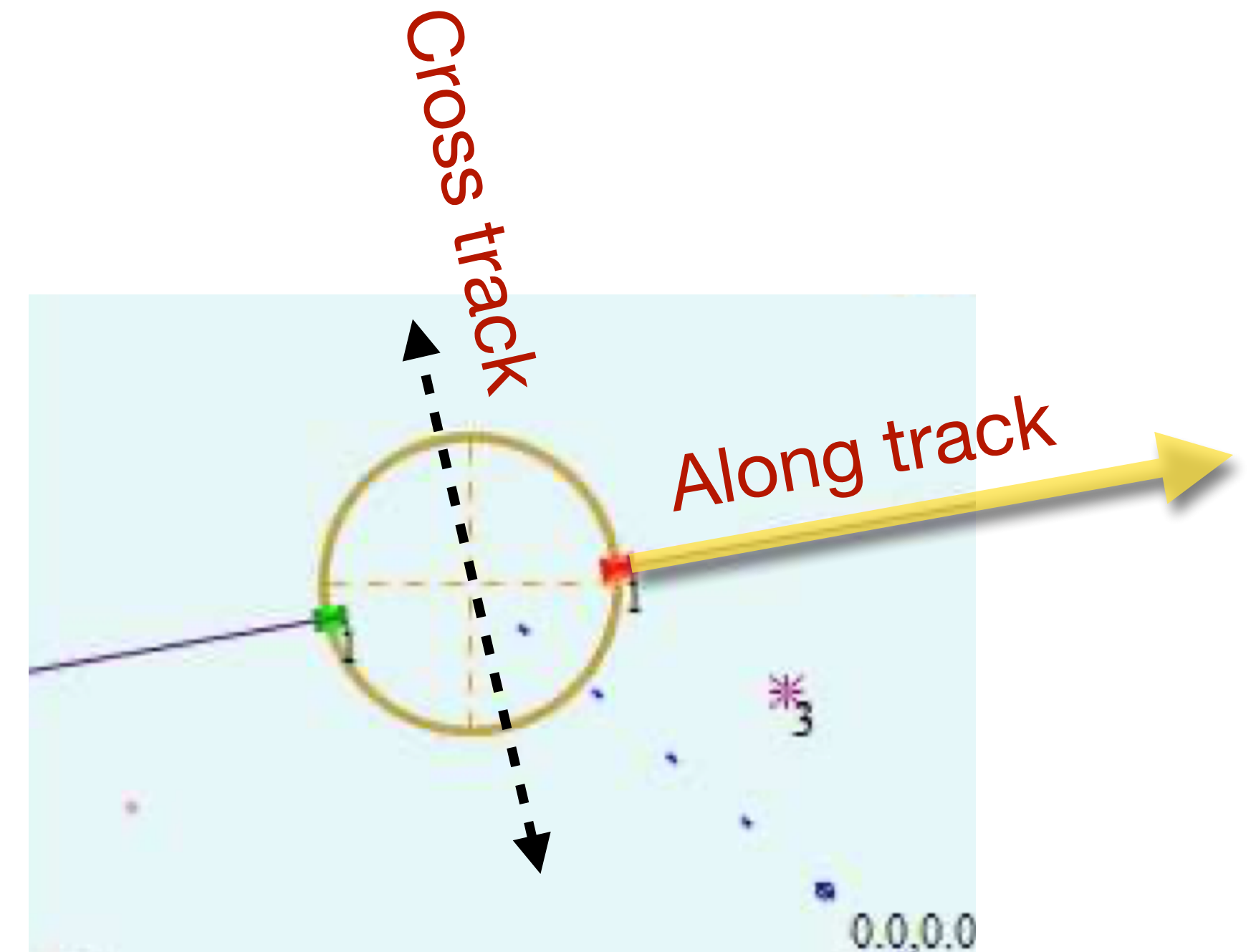
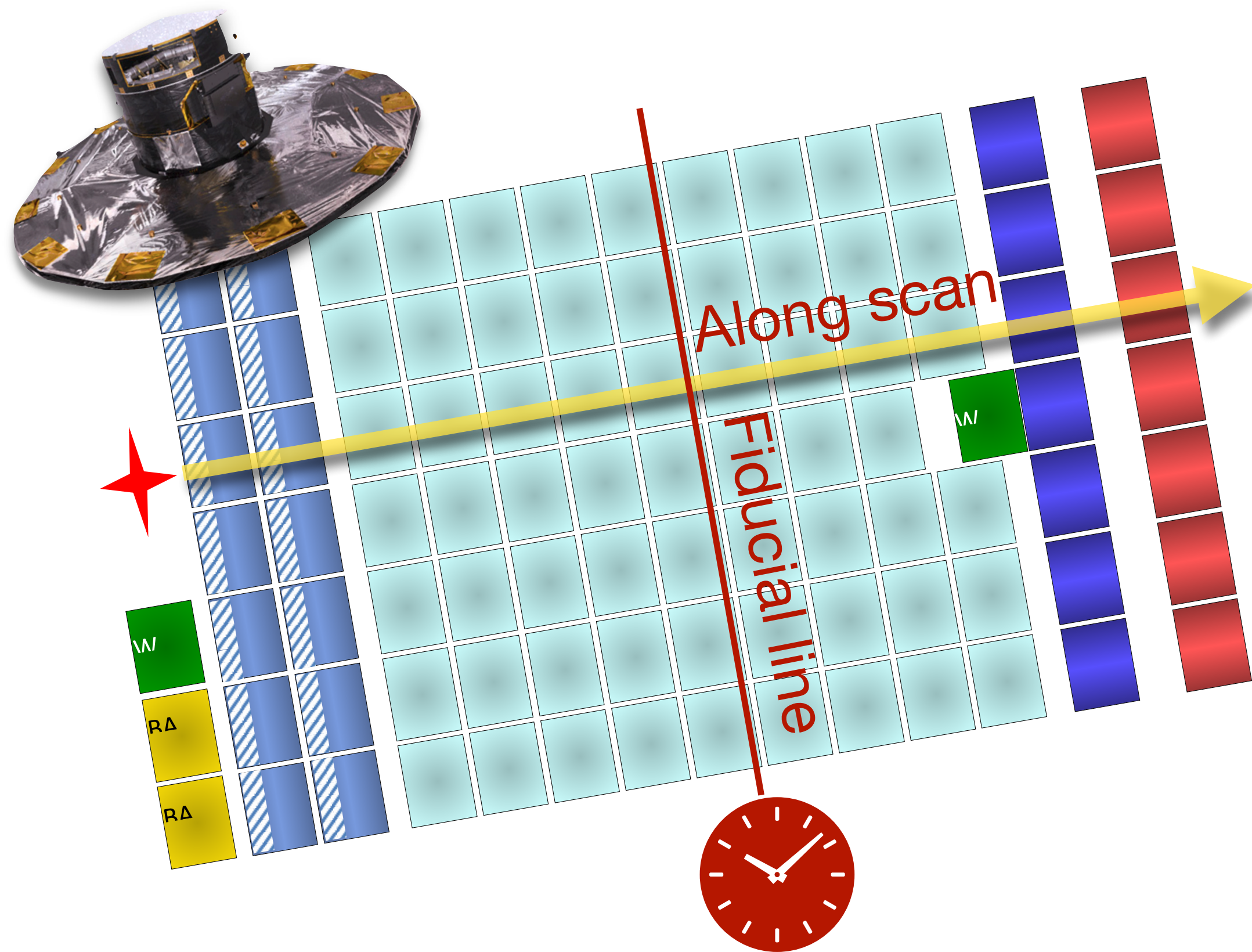
= High accuracy in the along-track (or along-scan) direction
Correlated uncertainty

Comparing Gaia and stellar occultations



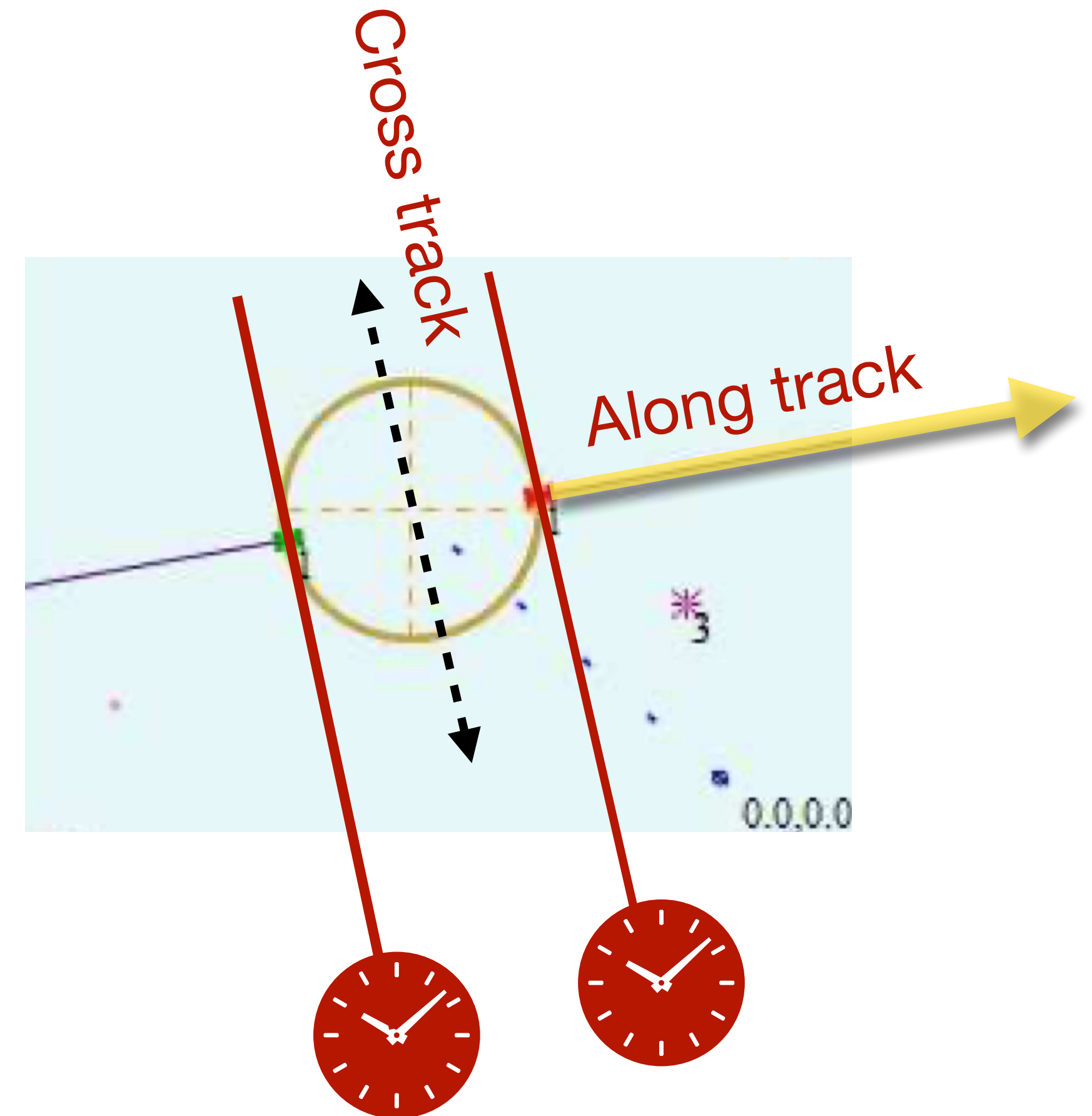
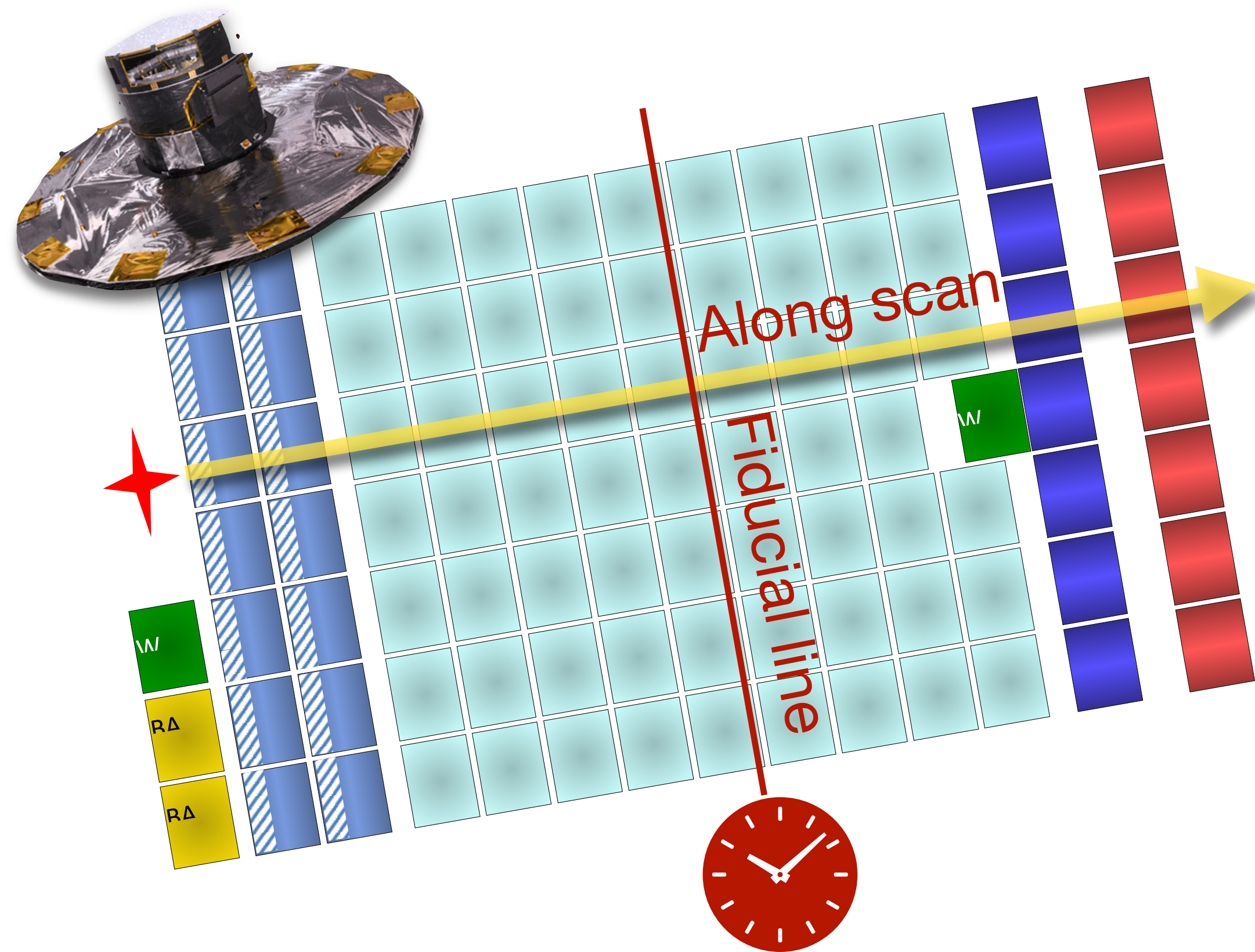
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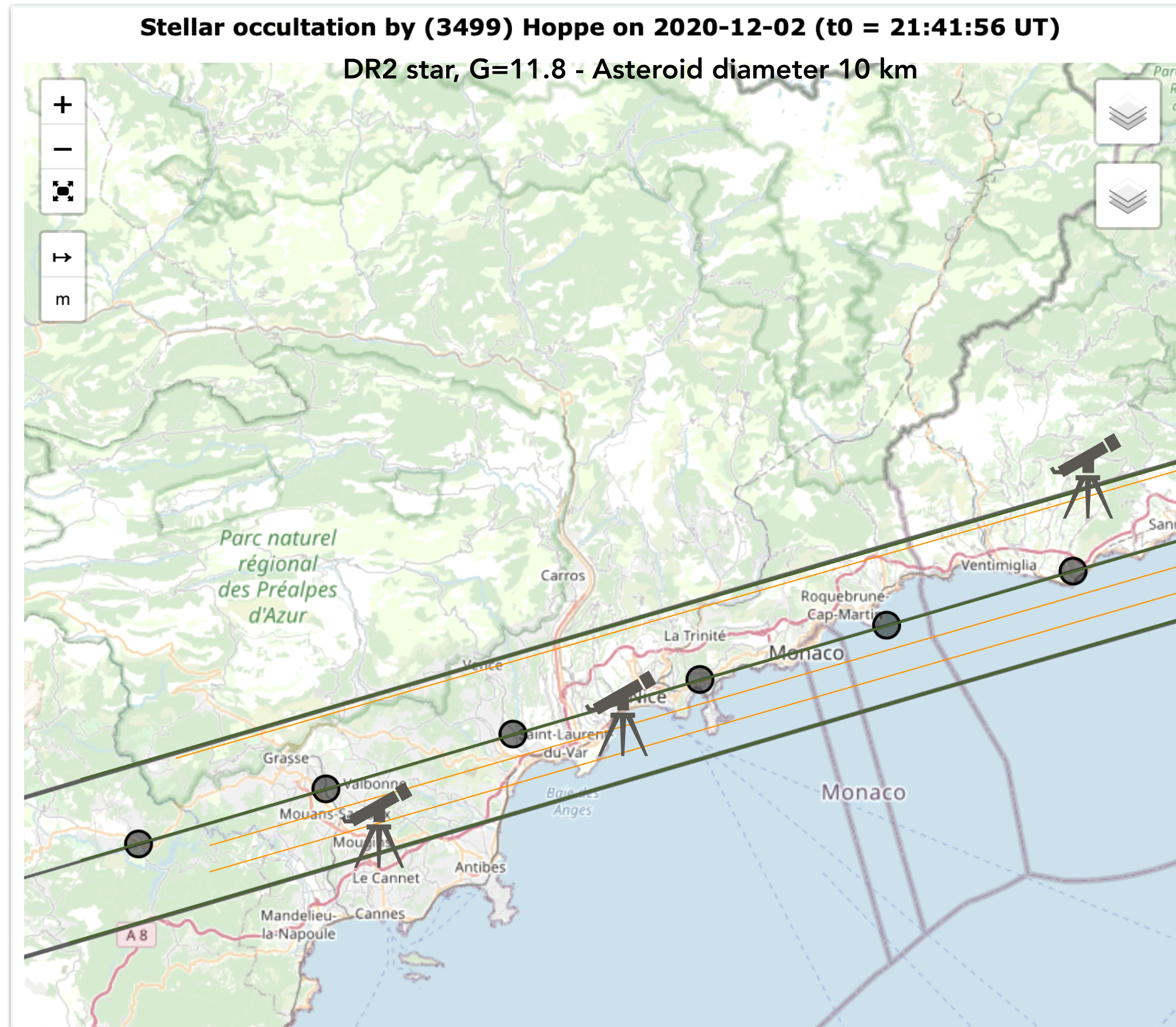
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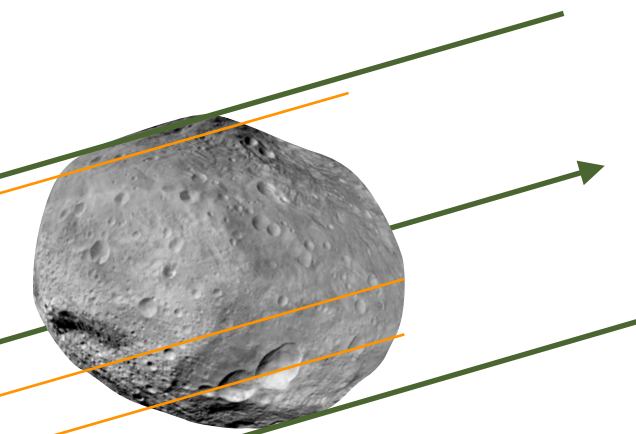


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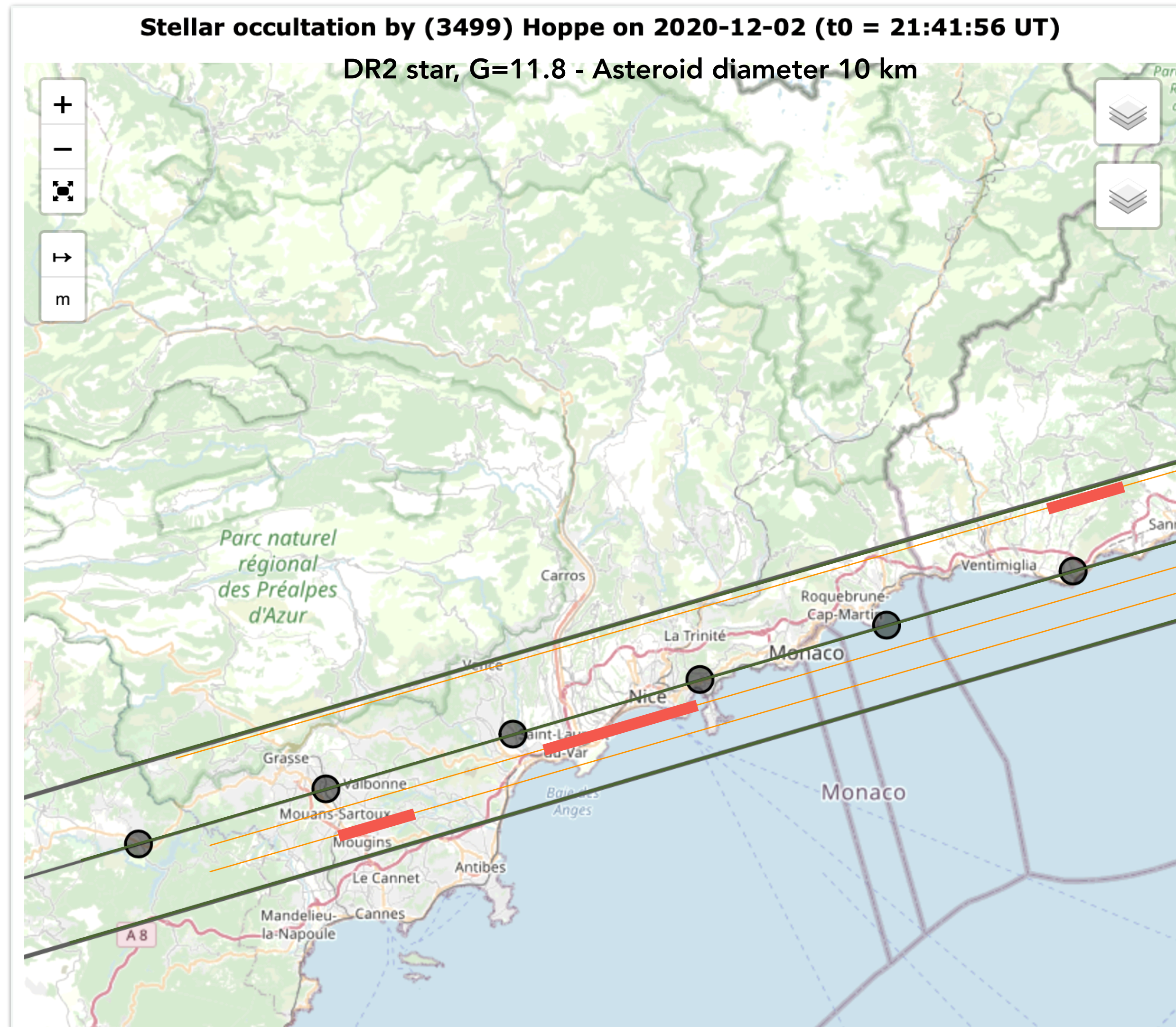
From timing to astrometry



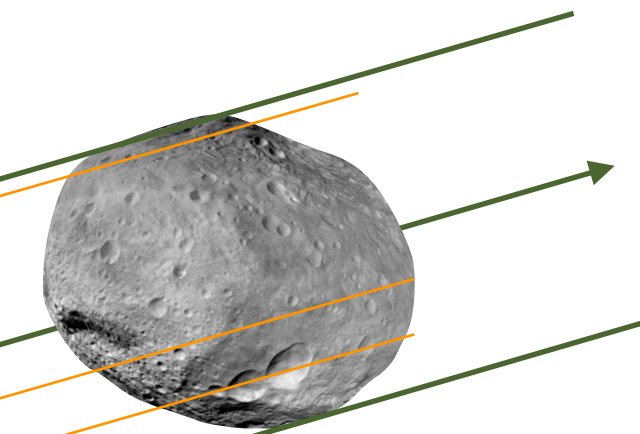
View from the
star



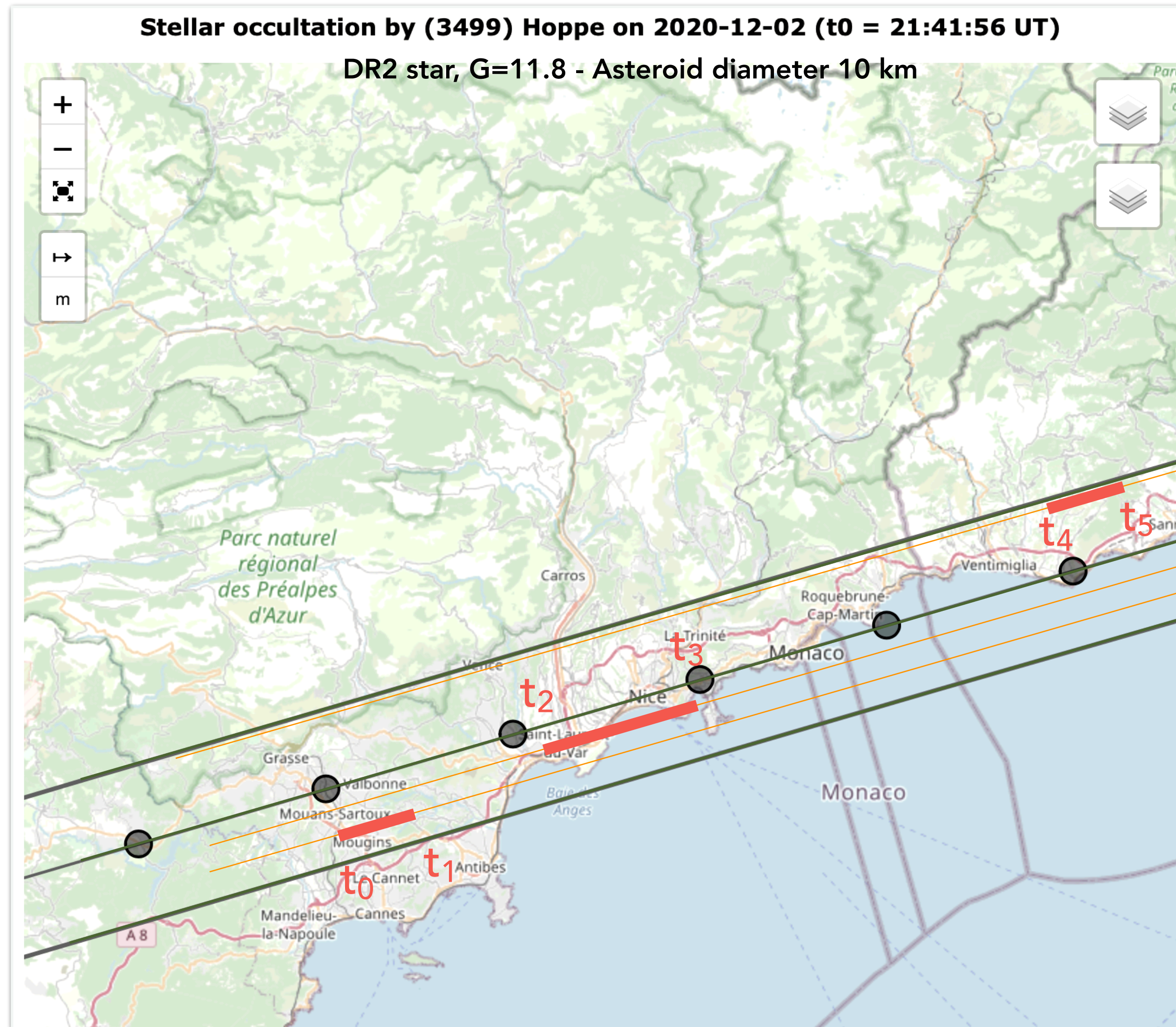
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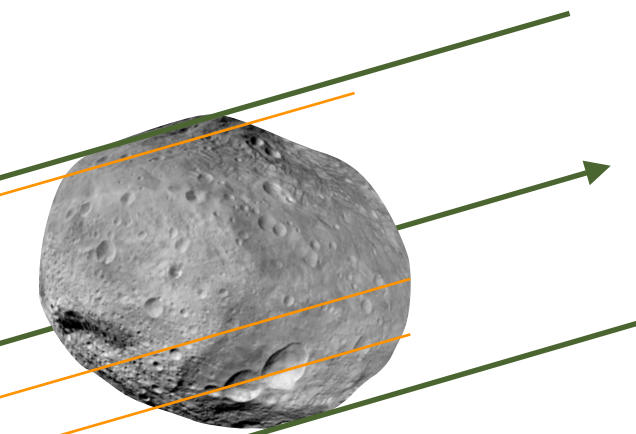
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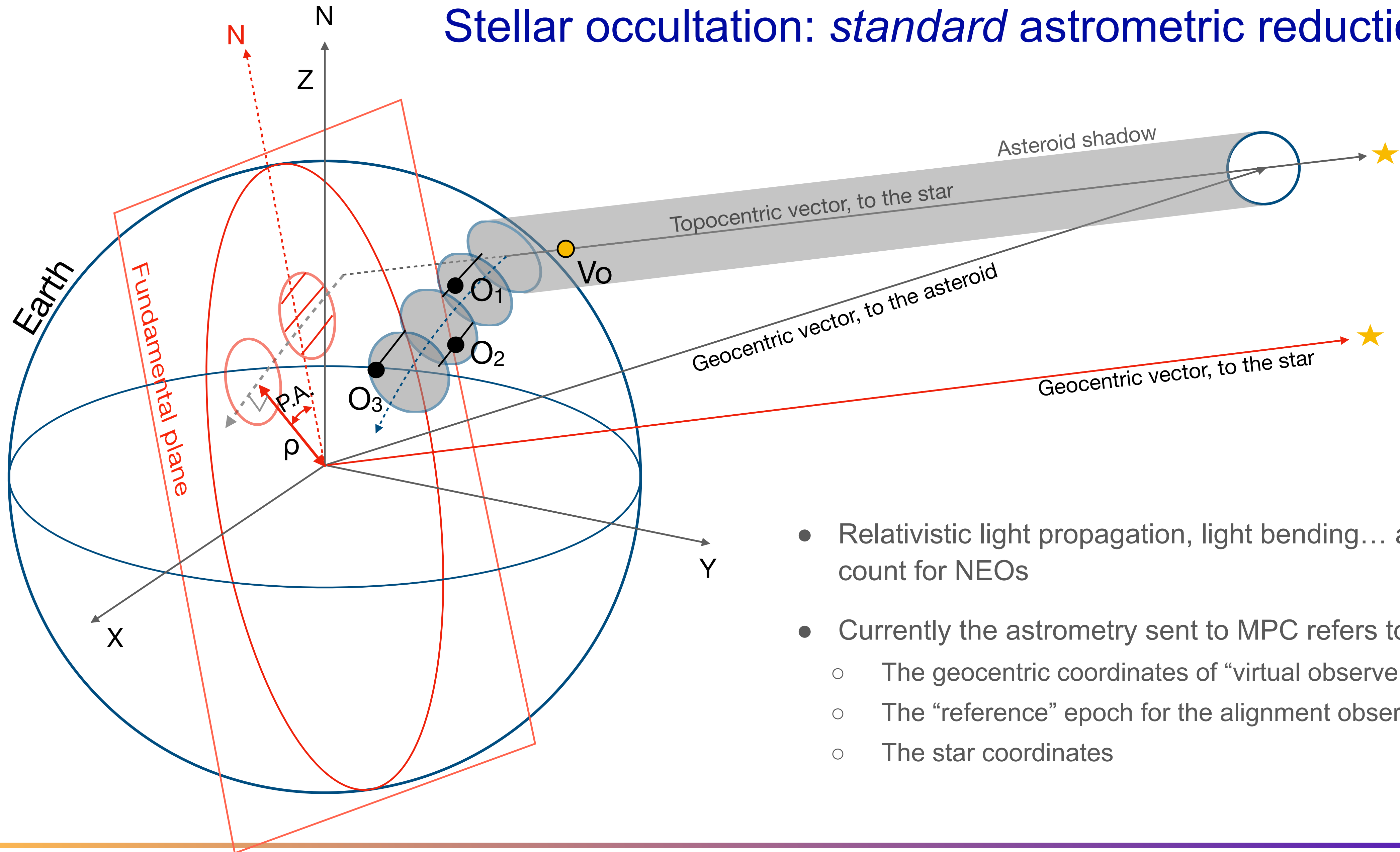
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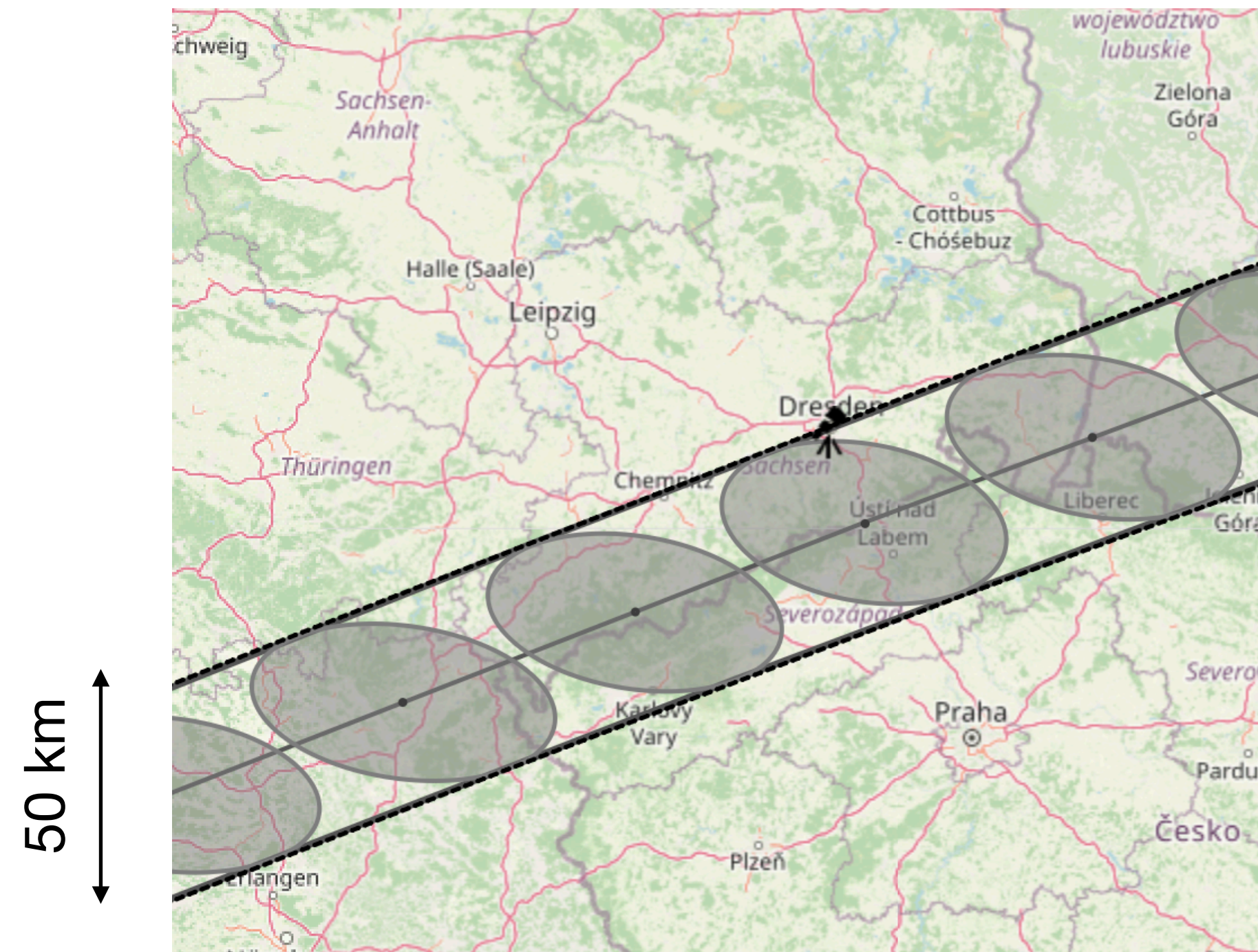
Stellar occultation: *standard* astrometric reduction



- Relativistic light propagation, light bending... all the details count for NEOs
- Currently the astrometry sent to MPC refers to:
 - The geocentric coordinates of “virtual observer”
 - The “reference” epoch for the alignment observer-asteroid-star
 - The star coordinates

Large asteroids vs. small NEAs, not the same challenge

Stellar Occultation by (3754) Kathleen on 2025-09-11 (01:35:45 UT)



(65803) Didymos - S Sardinia, Italy - April 16, 2026



Some common problems with predictions

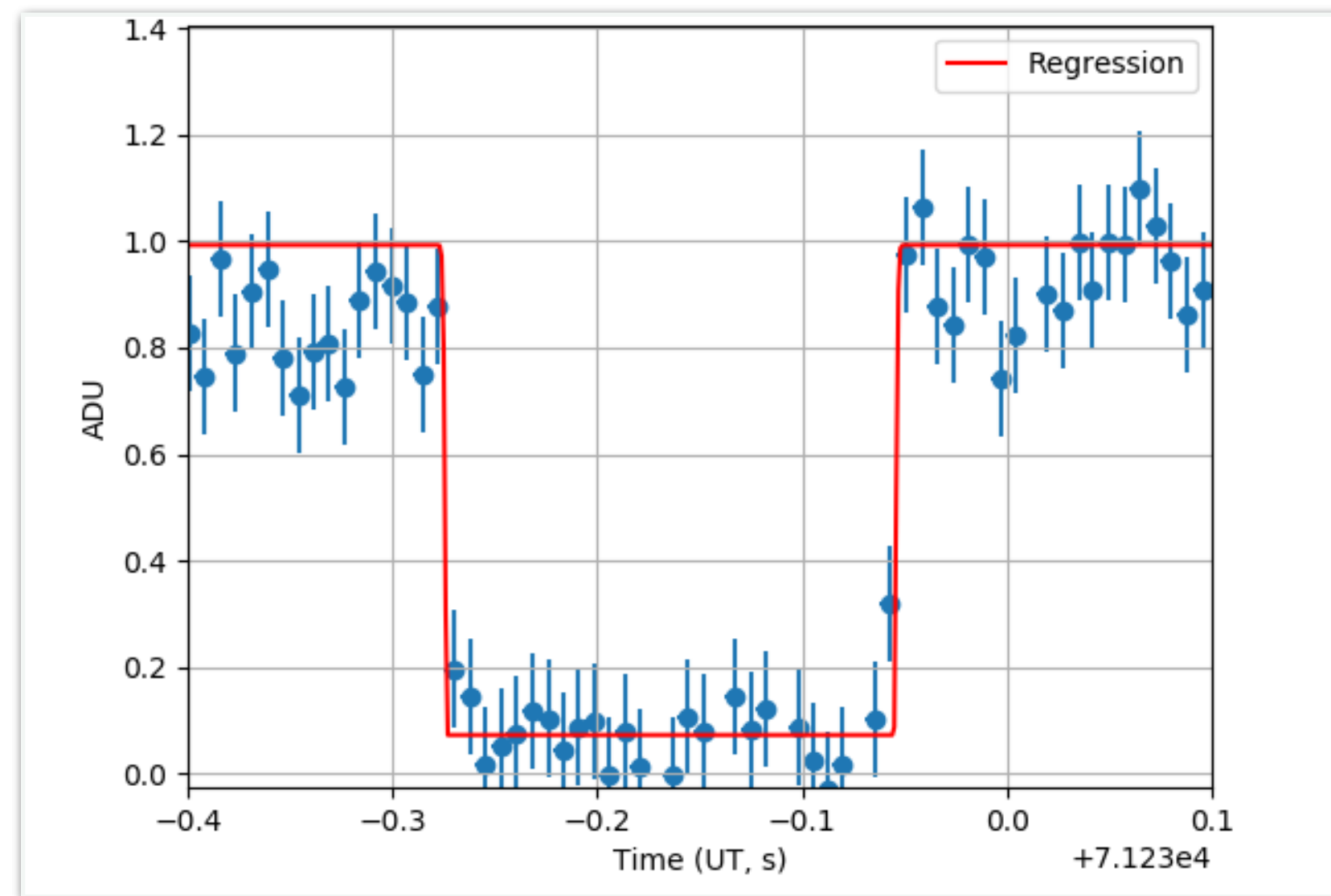
- The uncertainty on the ephemeris is critical
- The dynamical model and all transformations are critical
 - Perturbing masses
 - J2 of the Earth (for close encounters)
 - Relativistic terms
 - Relativistic light propagation
- Still.... Systematic errors not represented by the nominal uncertainty easily show up at few $\sim$ mas level and can unpredictably shift the path (especially for a first event)

ACROSS FOR CITIZEN SCIENTISTS

Asteroid Collaborative Research vis Occultation Systematic Survey



Single chord performance: example event (3200) Phaethon, Oct 15, 2019

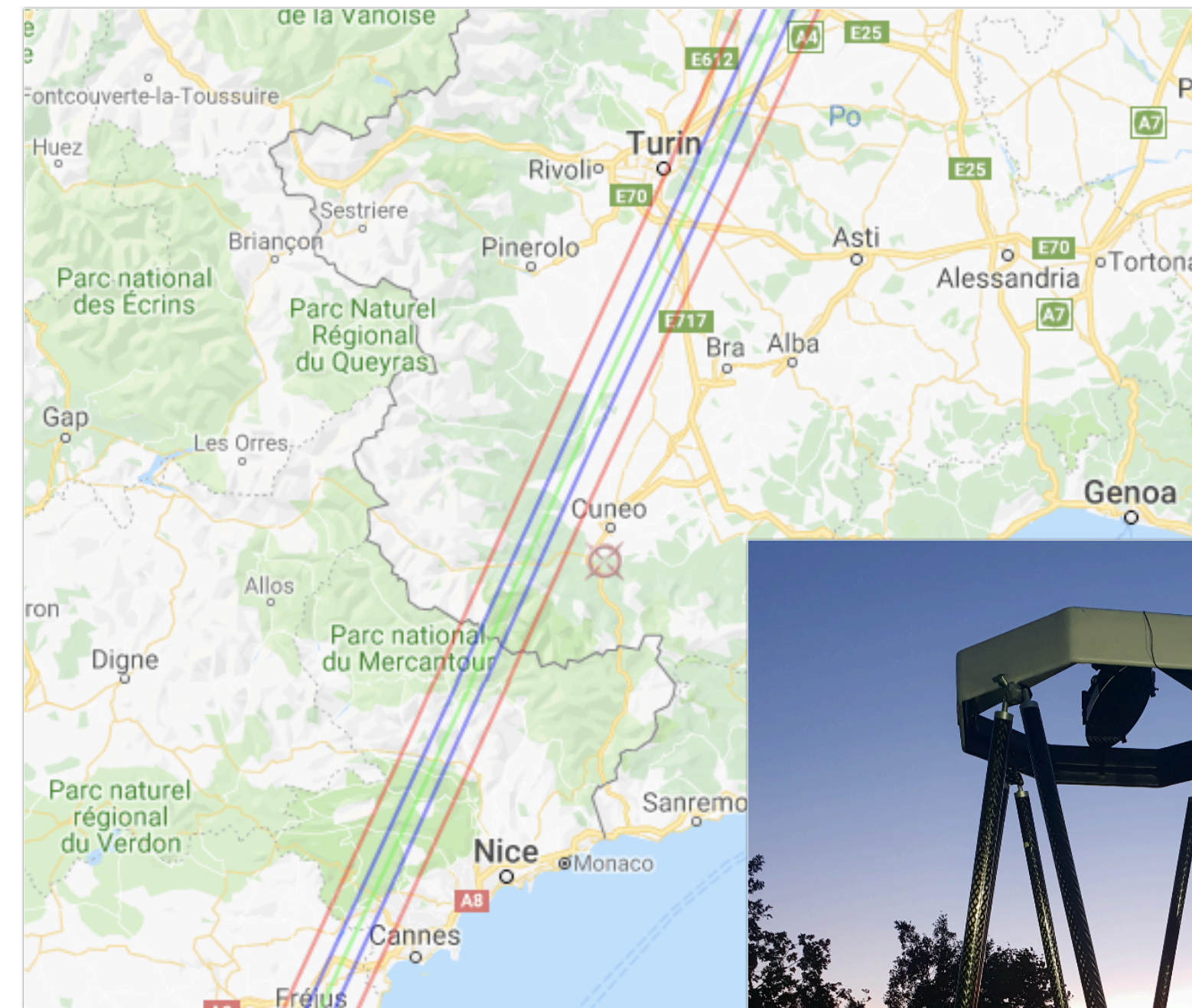


Disappearance (UTC) 19:47:09.7270 +/- 0.0015
Reappearance 19:27:09.9496 +/- 0.0015

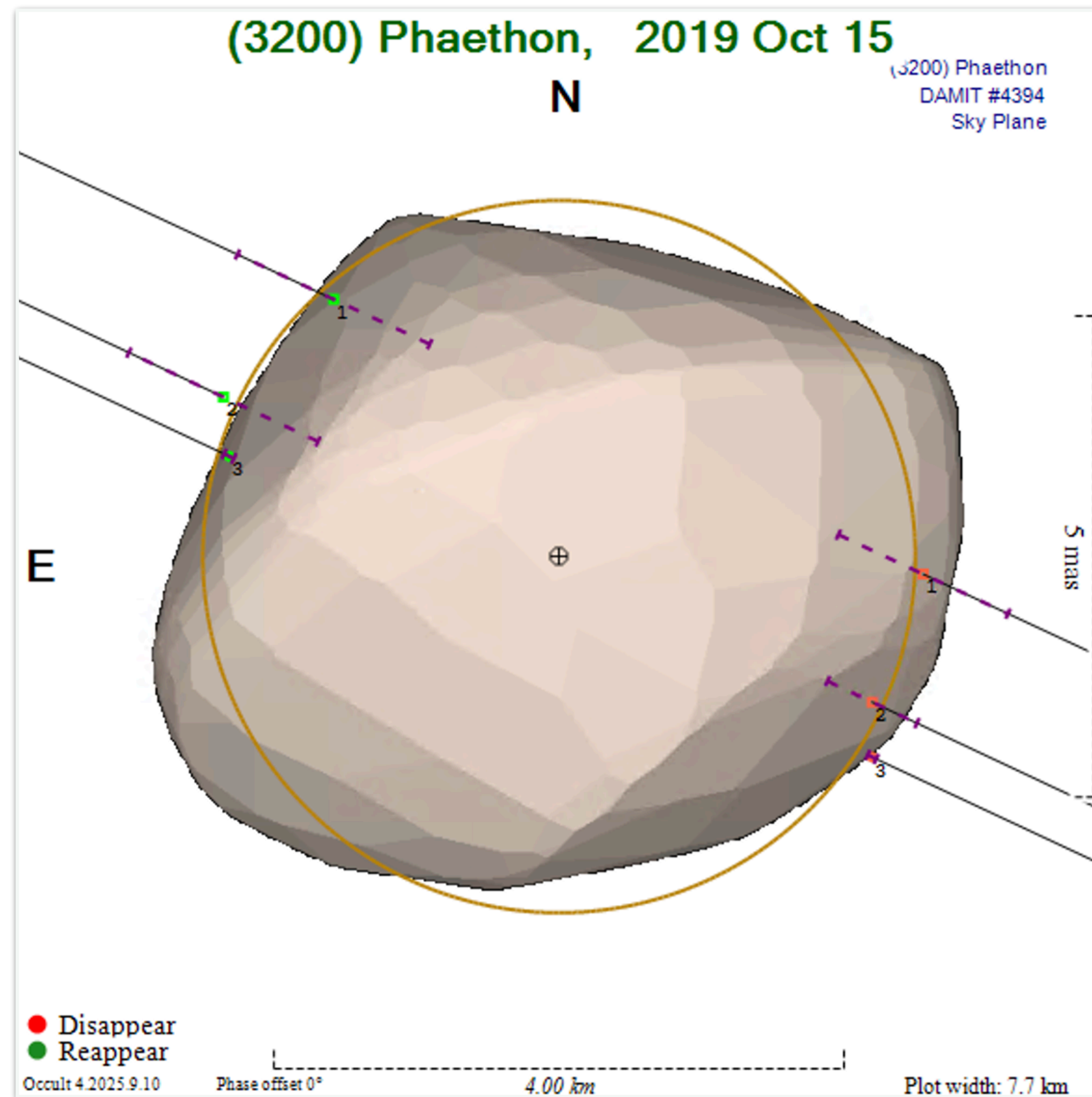
Duration : 0.218 +/- 0.002 s

Velocity: 23.3 km/s —> chord length 5.09 km
Error ~1% —> 45 m !

In apparent angles —> 67 μ as !

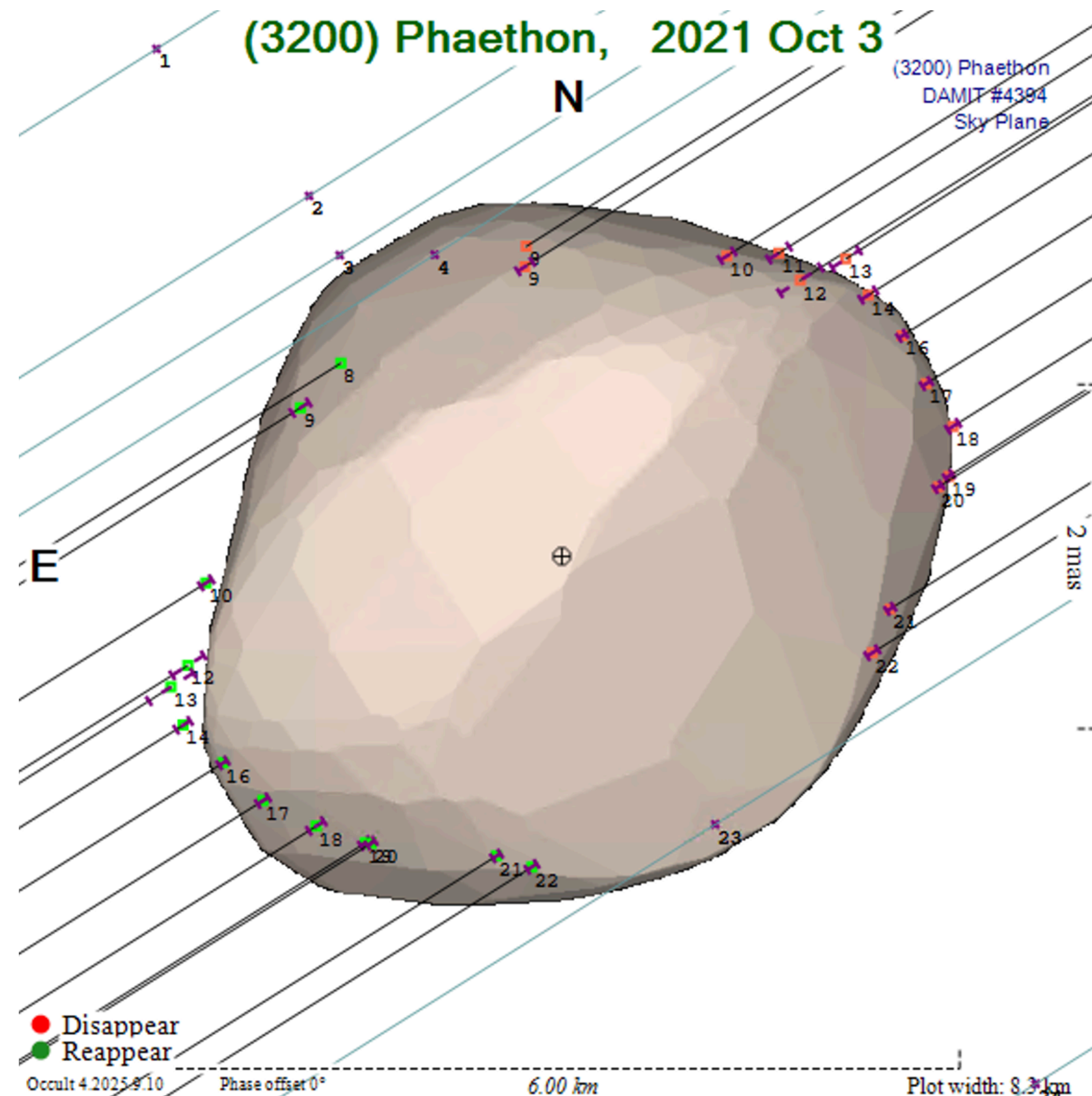


Final astrometry (poorly constrained)



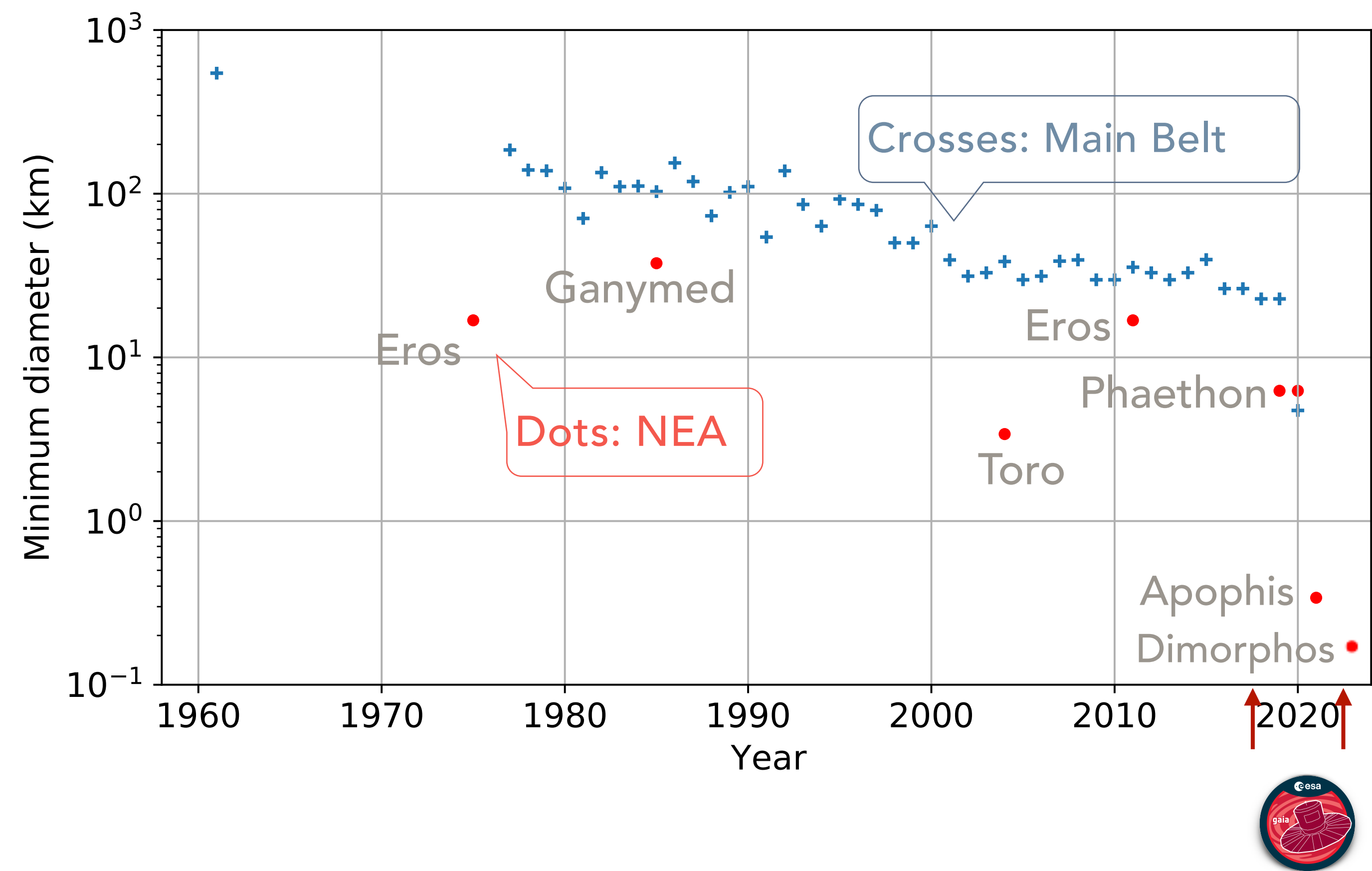
- Propagated uncertainty on the star position (Gaia):
 - RA: 0.7 mas Dec: 0.8
 - (Problematic compact binary)
- Uncertainty on shape fit (apparent diameter ~ 7.4 mas):
 - RA: 1.4 mas Dec: 2.7 mas
- Final uncertainty:
 - RA: 1.6 mas Dec: 2.8 mas
 - At object distance 1.2 - 2.1 km

A better (ideal?) example



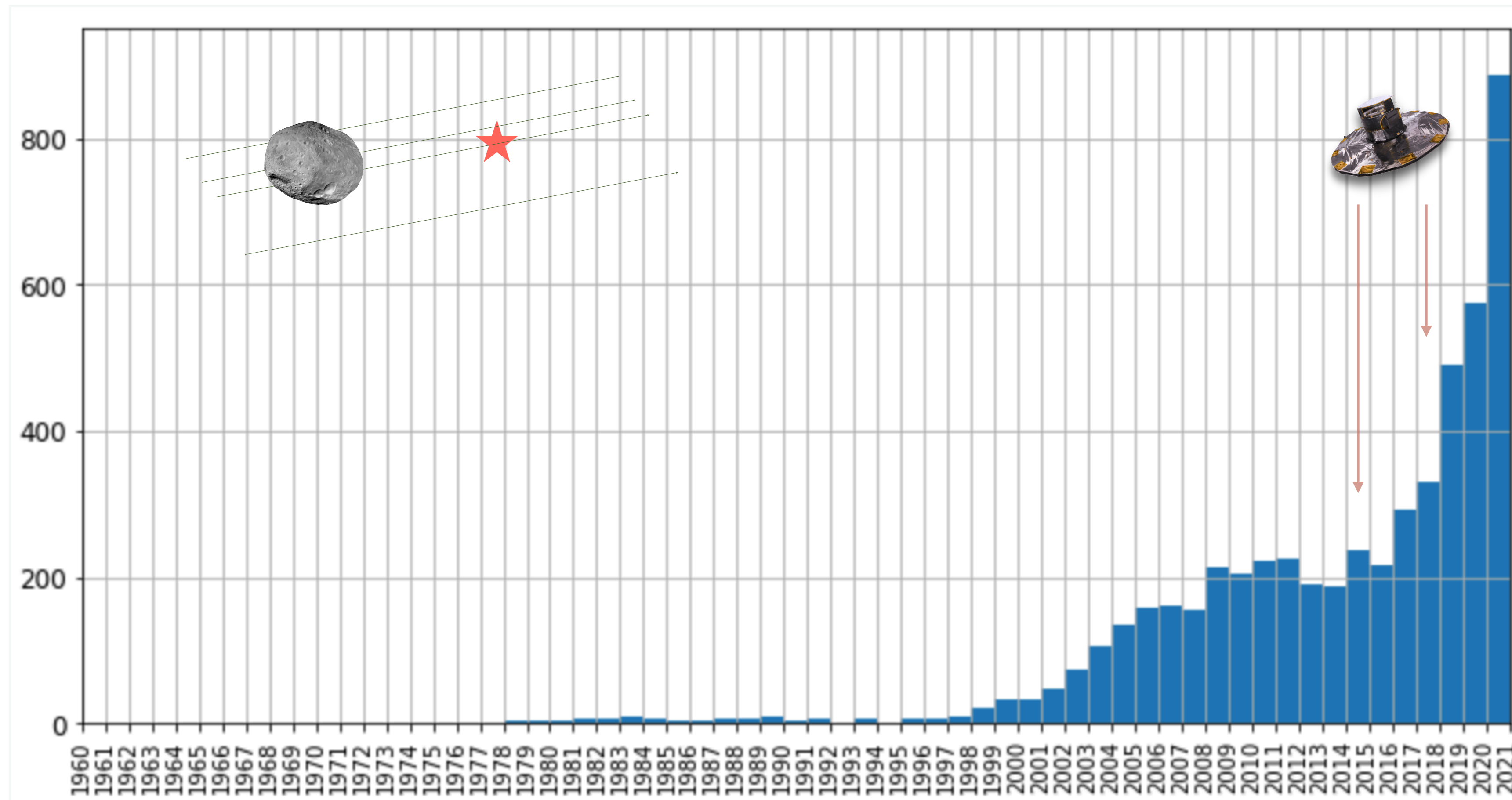
- 25 observed chords, 16 positives
- Final astrometric uncertainty (reported to MPC)
 - RA, Dec : 0.3 mas, correl. 0.59
- Limitations (for astrometry)
 - None of the available shape models (from radar or photometry) matches well occultation profiles (especially the N hemisphere)
 - Shape fitting limits in practice the astrometric accuracy

Gaia astrometry: enormous enhancement of prediction capabilities



Interval	Positive events by diameter range (km)					
	<3km	3-10km	10-20km	20-50km	50-100km	>100km
2023 - 2025	108	1639	1089	1219	922	615
2018 - 2020	0	69	123	399	721	679

Number of positive events per year



How many stellar occultations by NEOs ?

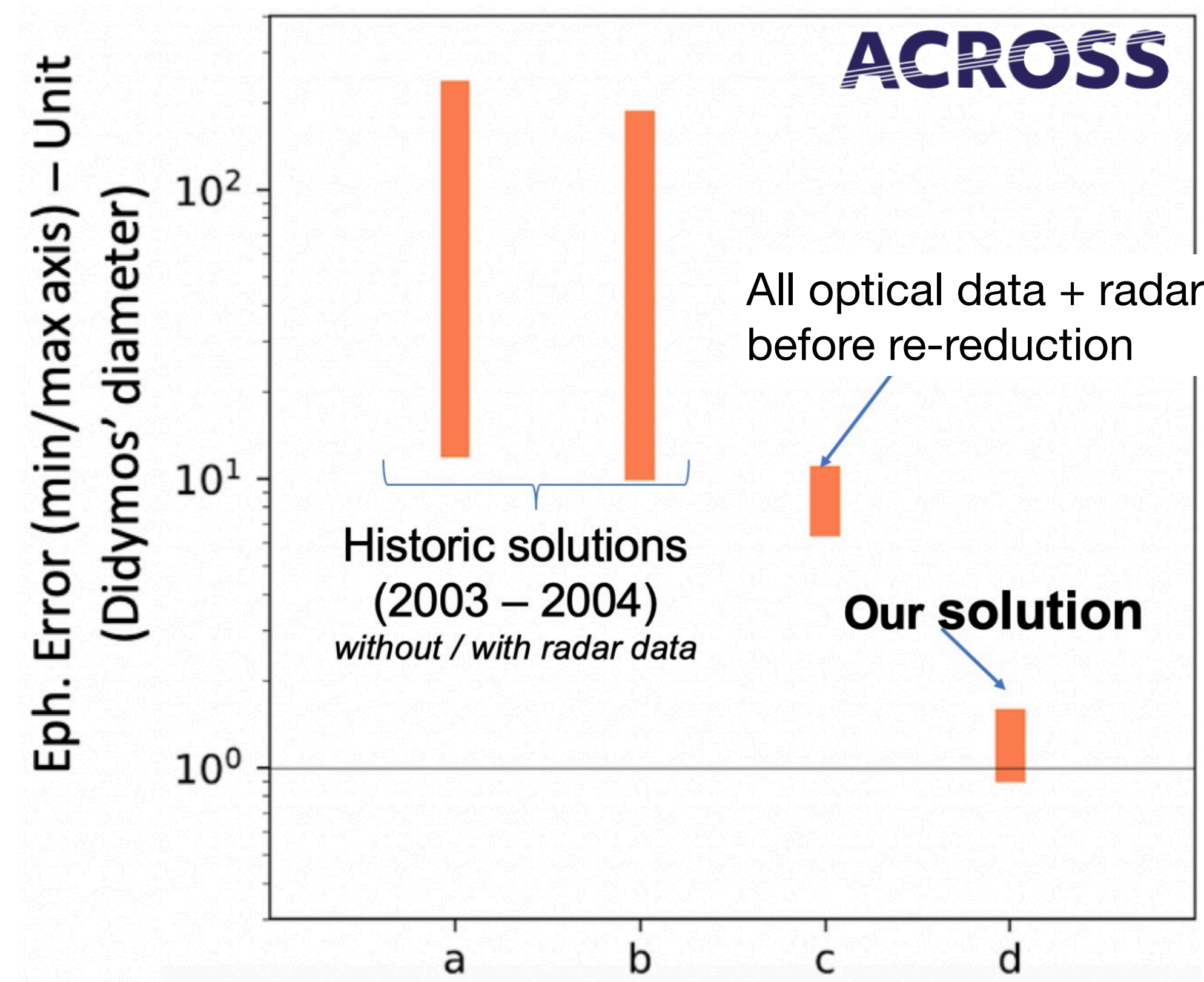
79 observations for 17 NEOs - Last updated Sept 1st 2025

ID	Denomination	N occultations	1st observed
433	Eros	8	Jan 24, 1975
887	Alinda	1	Jan 17, 2025
1036	Ganymed	10	Aug 22, 1985
1685	Toro	3	Aug 10, 2004
1866	Sisyphus	1	Nov 26, 2022
2102	Tantalus	1	Jul 29, 2019
3122	Florence	1	Sep 20, 2024
3200	Phaethon	13	Jul 19, 2019
4954	Eric	1	Nov 25, 2024
5332	Davidaguilar	2	Jan 1, 2025
16960	1998 QS52	1	Jun 22, 2025
65803	Didymos	24	Oct 15, 2022
98943	Torifune	1	Mar 5, 2023
99942	Apophis	7	Mar 7, 2021
137170	199 HF1	1	Apr 1, 2025
137805	1999 YK5	1	Jan 7, 2025
163899	2003 SD220	1	Dec 10, 2024
385186	1994 AW1	3	Aug 5, 2022
		80	

This represents a small fraction of the occultation astrometry delivered to MPC by IOTA in ADES format
~1,000++ measurements / year now - ~10,000 in total

Reaching the goal: the case of (65803) Didymos

Ephemeris uncertainty at the start of the occultation campaign
(Apr. 4, 2021)



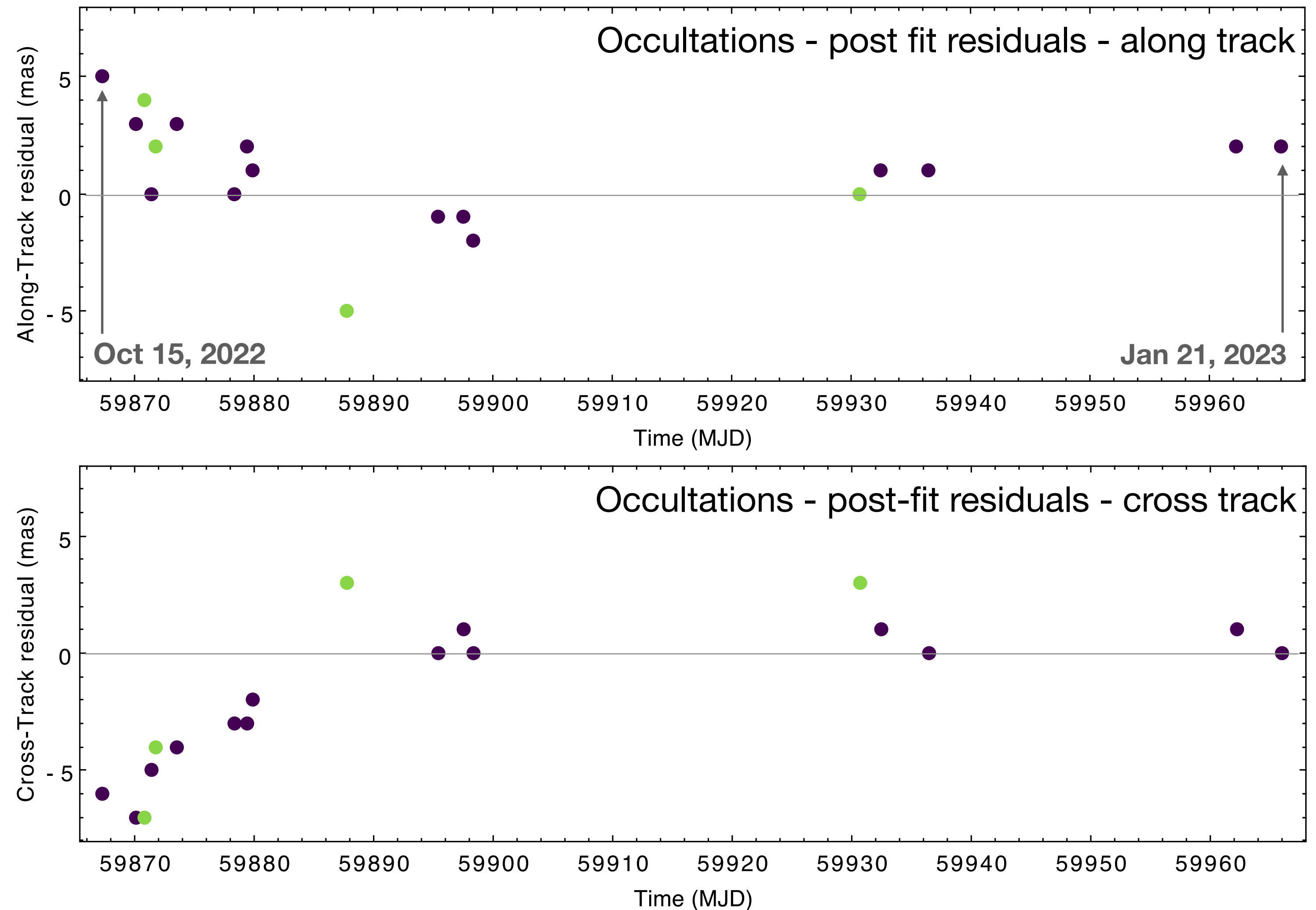
- *Re-reduction* of hundreds of observations obtained by the DART ground-based photometry campaign.
- Differential refraction correction (Stone 1996, using Gaia “colors” and known color index of Didymos) - *GARP pipeline Bouquillon et al. 2017*

Observatory Code	Location	# of data points	Dates
269	New Horizons KBO Search-Magellan	186	2022/07/02
309	Cerro Paranal	399	2019/04/05-07
493	Calar Alto	15	2022/08/09
557	Ondrejov	32	2003/11/20-12/18
568	Maunakea	66	2021/01/14
696	Whipple Observatory	248	2017/02/25-03/02
829	Complejo Astronomico El Leoncito	27	2022/08/02
G37	Lowell Discovery Telescope	614	2015/04/12-2022/07/07
I33	SOAR, Cerro Pachon	204	2022/07/05
J13	La Palma-Liverpool Telescope	69	2022/08/16-22
K91	Sutherland-LCO A	21	2022/06/25-27
L10	Kryoneri Observatory	209	2022/07/22-08/05
Q63	Siding Spring-LCO A	24	2022/06/25-07/29
V37, V39	McDonald Observatory-LCO ELP	20	2020/09/16-10/18
W74	Danish Telescope, La Silla	7	2022/05/29
W85, W87	Cerro Tololo-LCO A and C	11	2022/06/26-07/28
Z18	Gran Telescopio Canarias	33	2017/02/25
Z19	La Palma-TNG	231	2021/01/20-2022/07/01

Number	Name	Observatory Code	Location	# of data points	Dates
1 620	Geographos	L10	Kryoneri Observatory	60	2022/08/03-05
2 100	Ra-Shalom	Z19	La Palma-TNG	77	2022/07/02-05
3 200	Phaethon	244	Occultations	10	2019/07/29-2022/10/22
29 886	Randytung	J13	La Palma-Liverpool Telescope	10	2022/07/07
95 802	Francismuir	J13	La Palma-Liverpool Telescope	4	2022/07/13
137 170	1999 HF ₁	J13	La Palma-Liverpool Telescope	46	2022/07/14-25
137 199	1999 KX ₄	Z19	La Palma-TNG	18	2022/07/01
385 186	1994 AW ₁	L10	Kryoneri Observatory	80	2022/08/02-04

Didymos occultation astrometry - all data

- **All the available astrometry**
(Apr 1996 - Feb 2025)
- Radar 2003 and 2022
- DART navigation “in situ” pre-impact astrometry (Sept 24-26, 2022)
- **18 occultations (2022-2023)** *there are 4 more at present (2024-25) not reported here*
- Clear systematic deviation up to ~30 days after the impact. 4 data points are rejected.



Occultations by Didymos

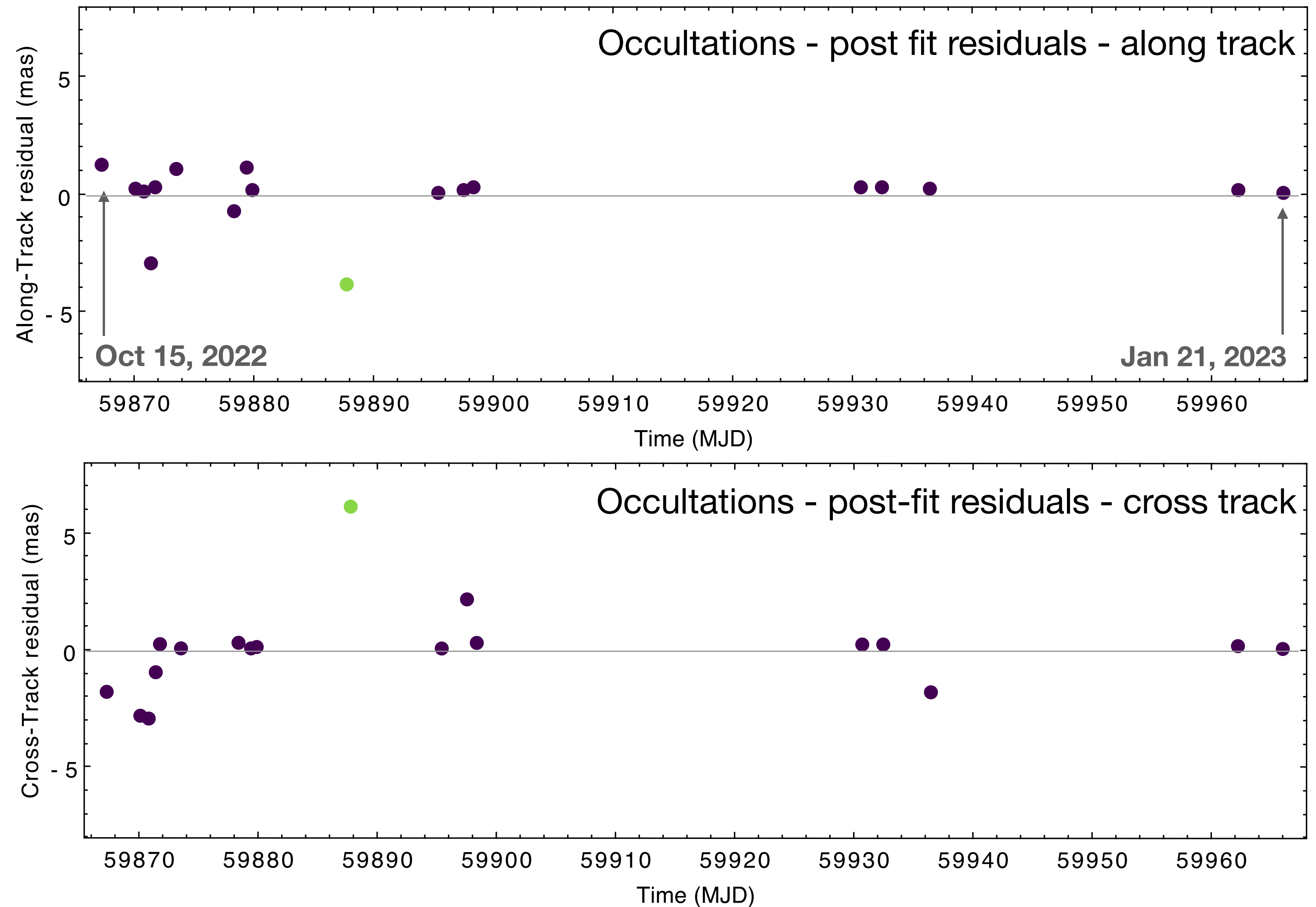
Only positive detections in the table

Campaigns with negative results: 6 before the 1st success, 4 after

Time [UTC]	α [deg]	δ [deg]	σ_α [mas]	σ_δ [mas]	
2022-10-15 07:03:31.42	97.1041455	-11.0346223	6.2	6.0	
2022-10-18 01:17:38.09	101.5510585	-7.5427614	3.5	4.2	
2022-10-18 17:56:52.70	102.5657452	-6.7124245	1.9	2.1	
2022-10-19 08:19:57.53	103.4219904	-6.0093145	3.6	4.1	
2022-10-19 17:02:14.52	103.9292382	-5.5934691	0.7	0.6	
2022-10-21 11:35:38.56	106.2559304	-3.6321584	4.1	4.4	
2022-10-26 06:48:48.50	111.6241512	1.0639910	1.2	1.2	
2022-10-27 09:47:04.85	112.6897403	2.0416663	1.7	1.8	
2022-10-27 19:07:02.46	113.0441130	2.3712576	1.8	1.9	
2022-11-12 10:08:27.04	122.8098608	12.5080567	1.4	1.2	
2022-11-14 10:51:24.79	123.5309687	13.5150630	2.7	1.9	
2022-11-15 08:50:22.17	123.8426617	13.9522922	1.0	1.1	
2022-12-17 17:50:13.62	121.9657045	26.1740939	0.9	0.8	
2022-12-19 10:31:06.53	121.3261161	26.6496702	1.4	1.6	
2022-12-23 11:27:00.02	119.6945635	27.6902112	1.2	1.6	
2023-01-18 06:43:02.36	109.8460358	30.8253237	1.4	0.8	
2023-01-21 23:29:17.42	109.0118486	30.8469606	0.3	0.2	
2024-05-05 15:13:09.38	285.2062425	-23.1264033	0.2	0.3	
2024-09-22 02:22:35.36	269.6924187	-29.2163833	0.6	0.4	
2025-03-11 12:35:52.01	77.5835568	26.5572911	0.2	0.1	

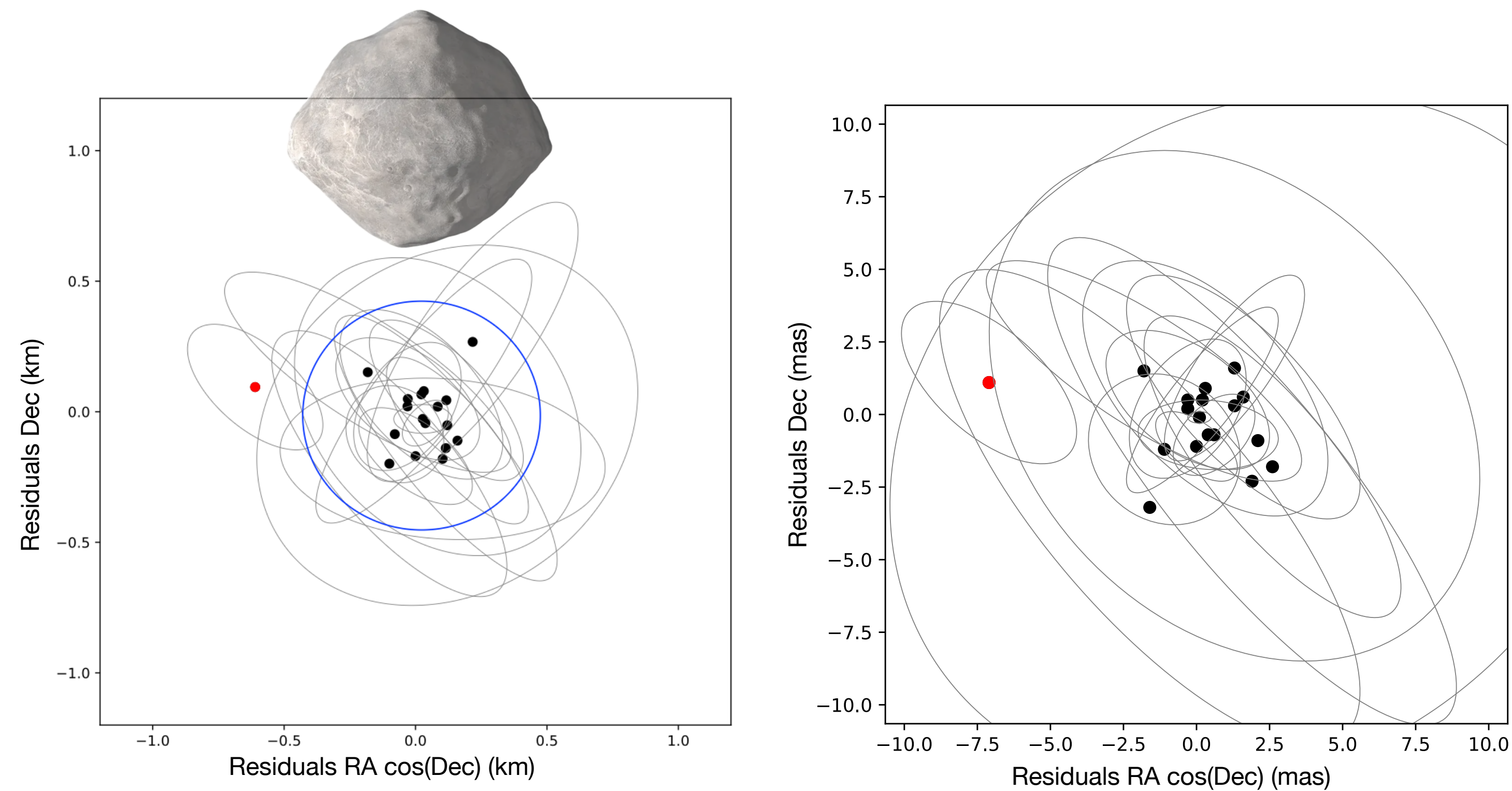
Didymos occultation astrometry - post-DART impact only

- **Only post-impact astrometry**
(Apr 1996 - Feb 2025)
- Radar: 2022 only
- DART navigation “in situ” pre-impact astrometry (Sept 24-26, 2022)
- Same **18 occultations** (2022-2023)
- Systematic trend suppressed. A single problematic occultation rejected.
- **Stellar occultations detect the heliocentric orbit change after the DART impact**

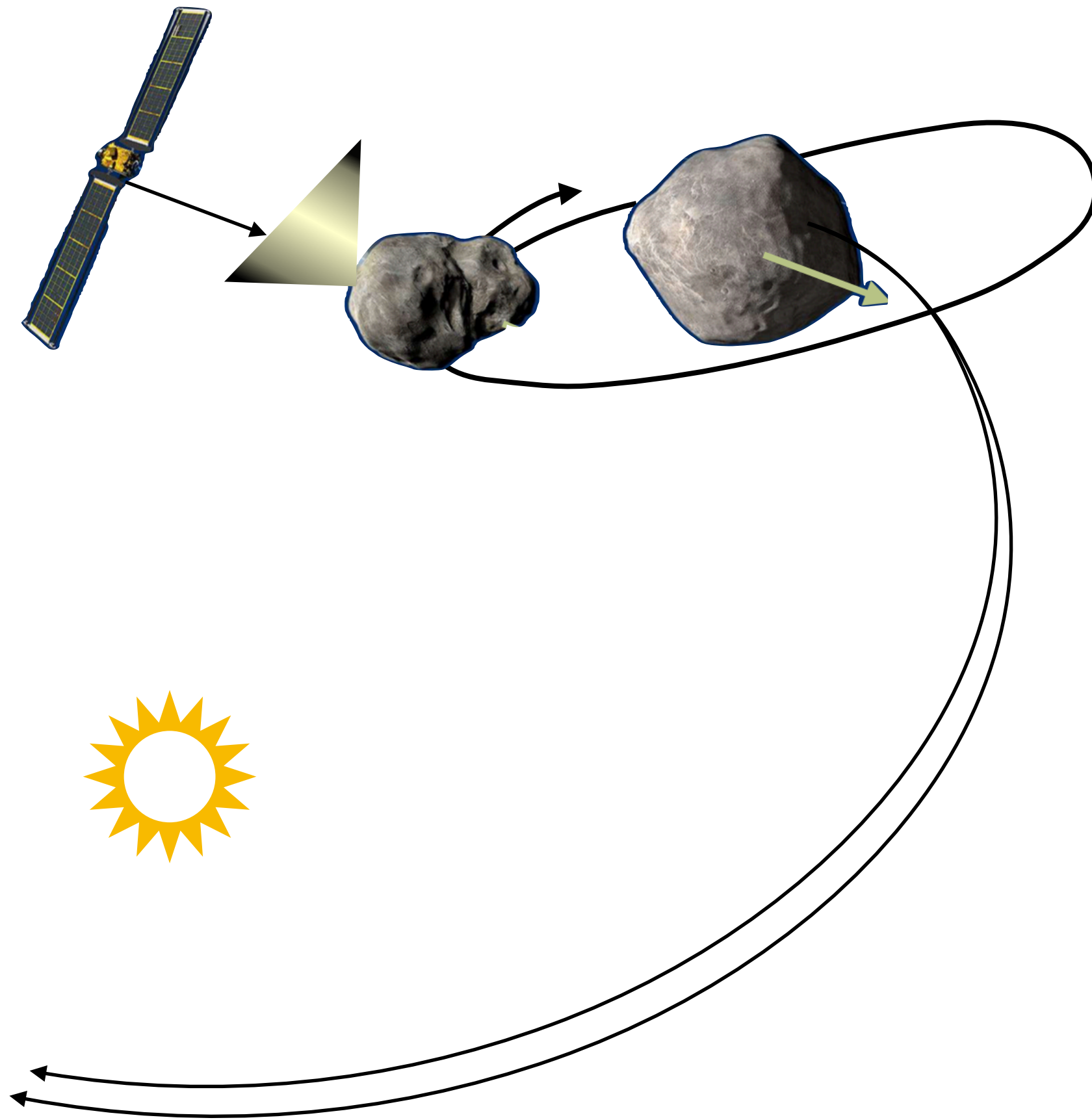


Residuals on the sky plane - absolute and apparent (observed)

Post-fit residuals all within 220 m (Dec) and 300 m (RA)



The heliocentric deviation of Didymos (Makadia et al., submitted)



Change in orbital velocity due to a kinetic impact.

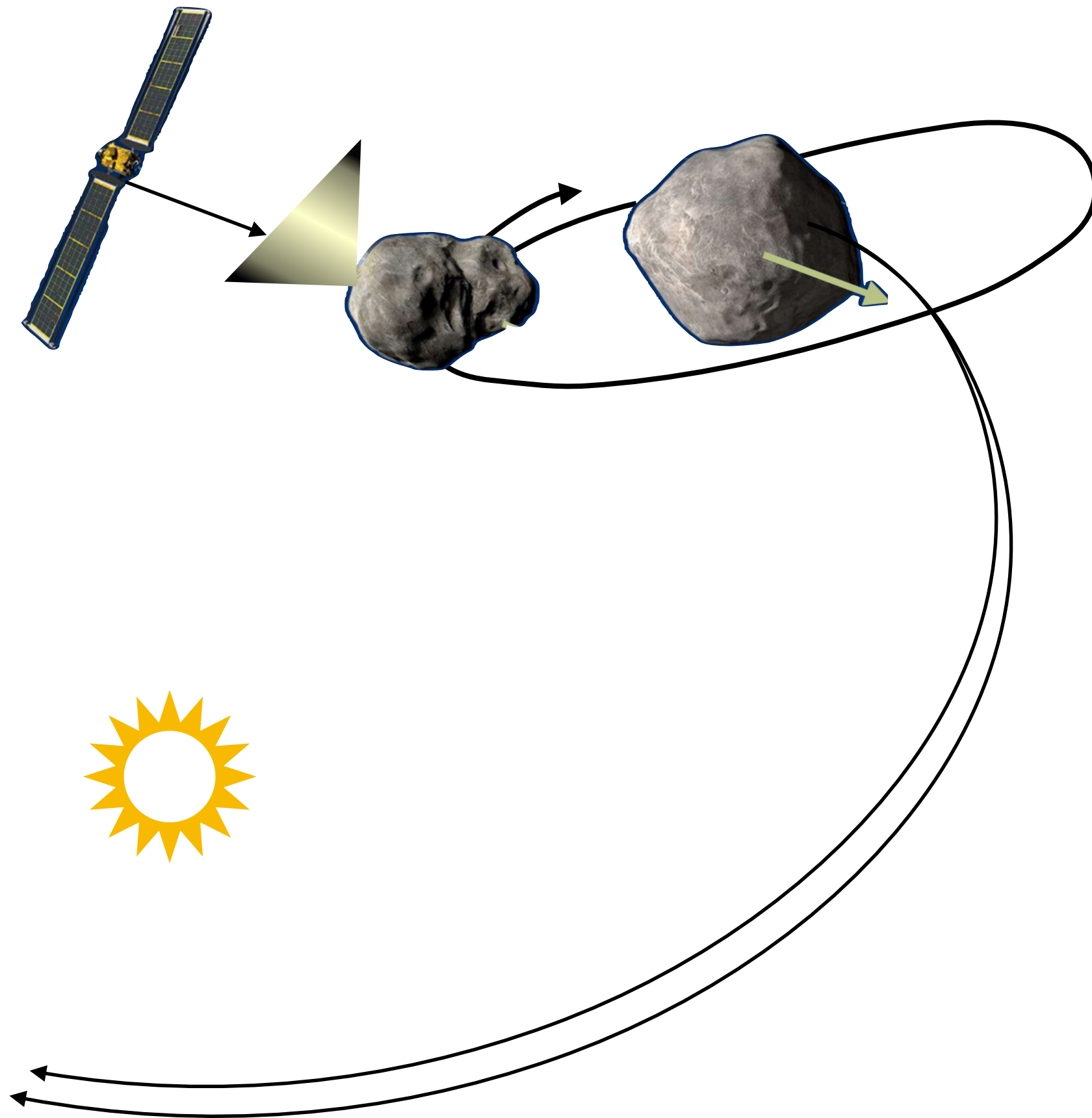
β = momentum enhancement factor relative to spacecraft impact alone

$$\Delta \vec{V}_{\odot} = \frac{m_{DART}}{m_{sys}} \left[\underbrace{\vec{V}_{\infty}}_{\text{impact velocity}} + (\beta_{\odot} - 1) \left(\vec{V}_{\infty} \cdot \underbrace{\hat{e}_*}_{\text{direction of ejecta}} \right) \underbrace{\hat{e}_*}_{\text{direction of ejecta}} \right].$$

Makadia et al., 2025, under review



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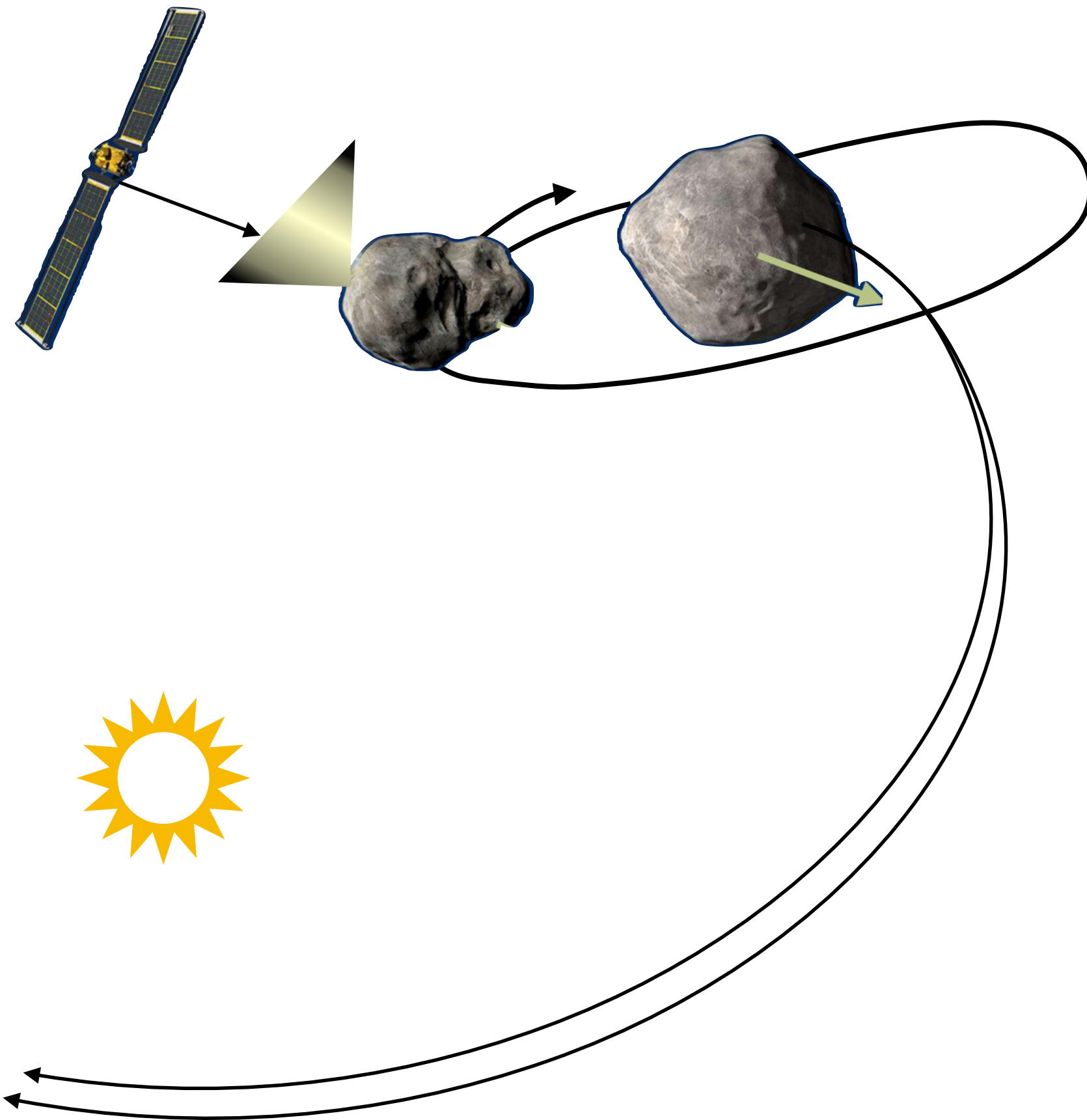
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$$\frac{\text{Heliocentric deflection}}{\text{Dimorphos deflection}} \sim \frac{-13 \mu\text{m s}^{-1}}{-2600 \mu\text{m s}^{-1}} \sim \frac{m_{Dimorphos}}{m_{Didymos}} \sim \frac{1}{200}$$

Makadia et al., 2025, under review



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Orbit model fitting including radar (9), DART navigation astrometry (3), stellar occultations (22)

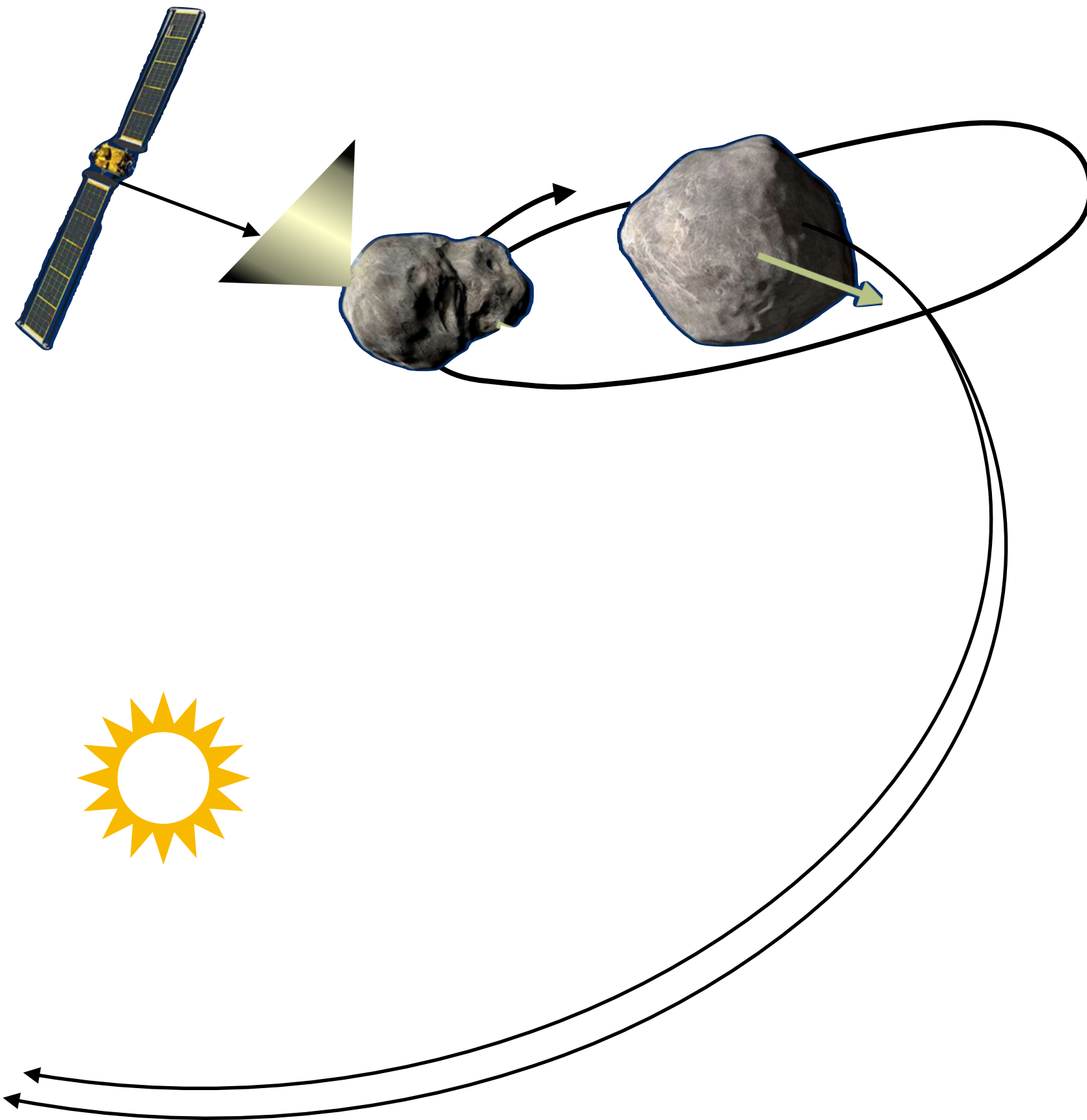
$$\beta_{p,\odot} \sim 2.3 \pm 0.4 \text{ (SNR} \sim 7\text{)}$$

Corresponding to -360 ± 40 m on semi-major axis, -150 ± 20 ms on orbital period

Makadia et al., 2025, under review



The heliocentric deviation of Didymos (Makadia et al., submitted)



Change in orbital velocity due to a kinetic impact.

β = momentum enhancement factor relative to spacecraft impact alone

$$\Delta \vec{V}_{\odot} = \frac{m_{DART}}{m_{sys}} \left[\underbrace{\vec{V}_{\infty}}_{\text{impact velocity}} + (\beta_{\odot} - 1) \left(\vec{V}_{\infty} \cdot \underbrace{\hat{e}_*}_{\text{direction of ejecta}} \right) \hat{e}_* \right].$$

$$\frac{\text{Heliocentric deflection}}{\text{Dimorphos deflection}} \sim \frac{-13 \mu\text{m s}^{-1}}{-2600 \mu\text{m s}^{-1}} \sim \frac{m_{Dimorphos}}{m_{Didymos}} \sim \frac{1}{200}$$

Orbit model fitting including radar (9), DART navigation astrometry (3), stellar occultations (22)

$$\beta_{p,\odot} \sim 2.3 \pm 0.4 \text{ (SNR} \sim 7\text{)}$$

Corresponding to -360 ± 40 m on semi-major axis, -150 ± 20 ms on orbital period

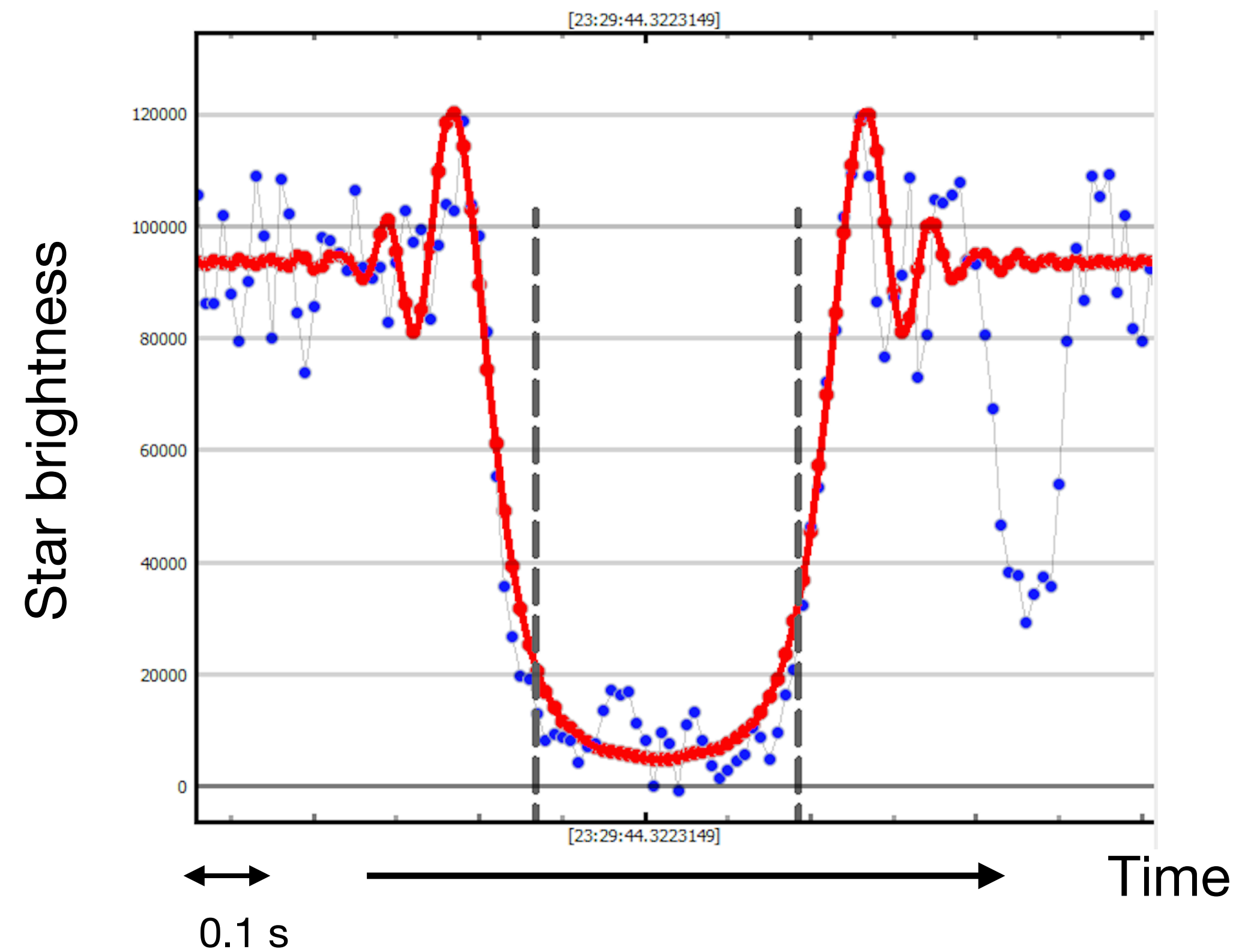
Makadia et al., 2025, under review



Without occultations the error increases by a factor ~ 10

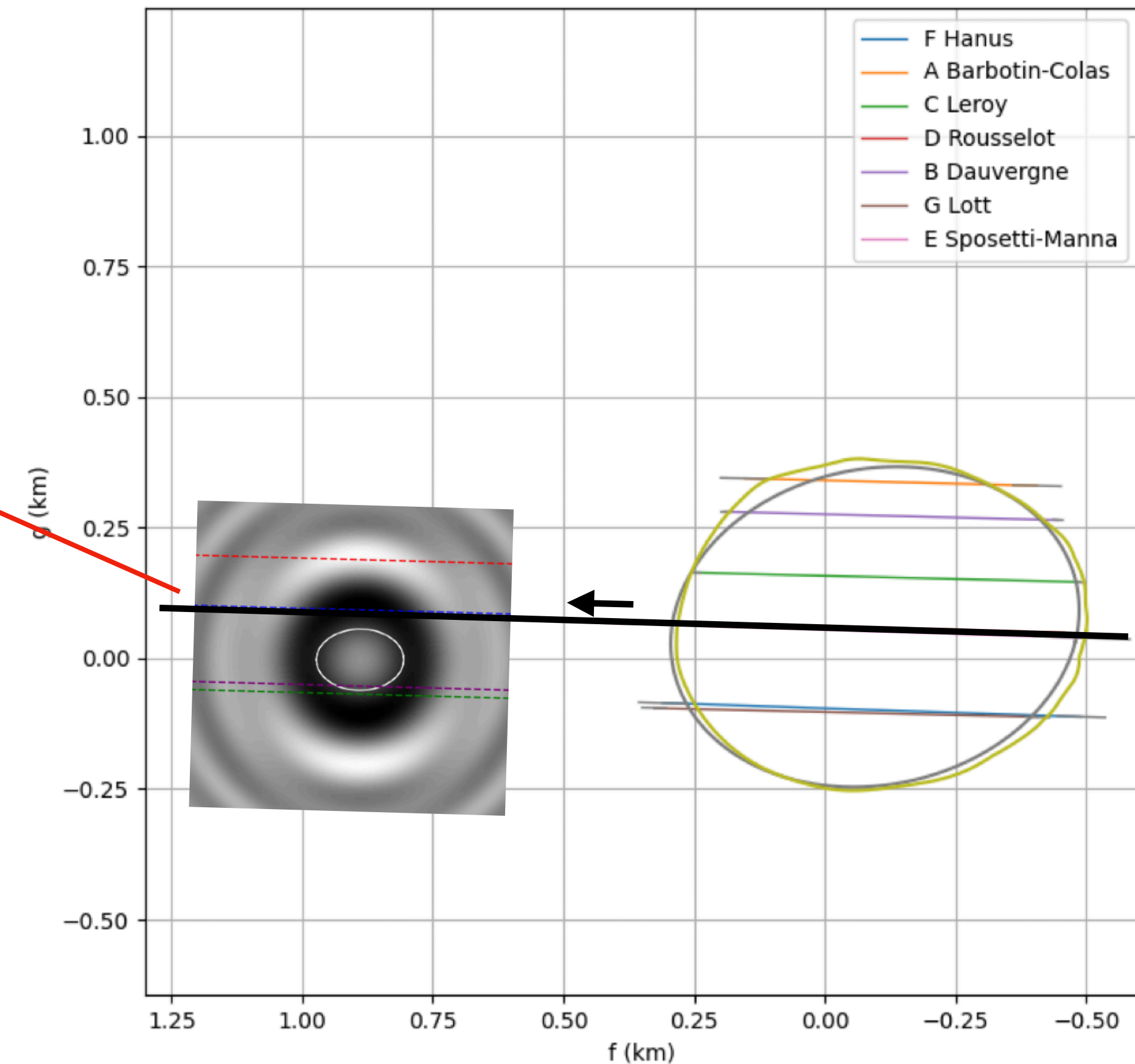
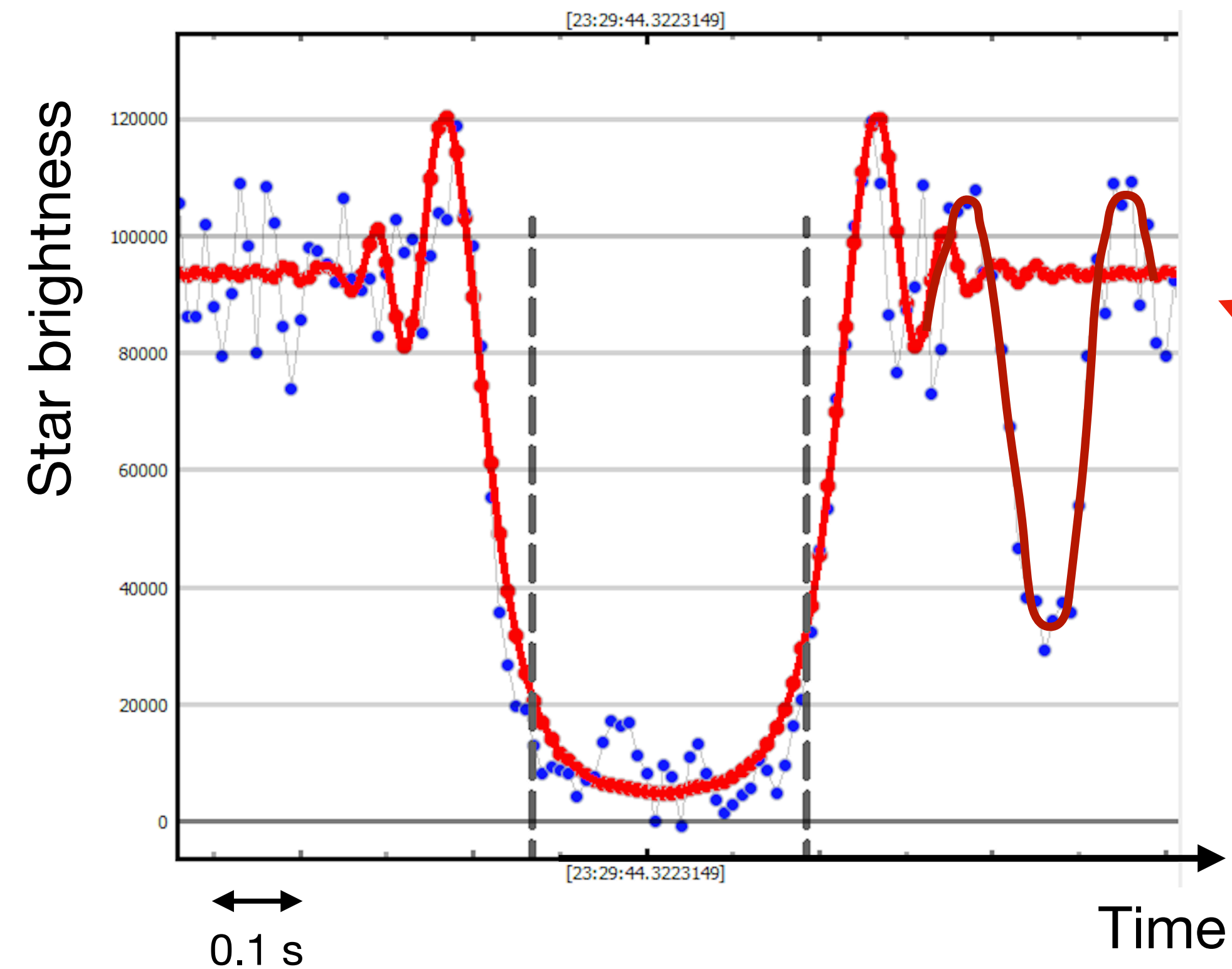
(65803) Didymos and Dimorphos, January 21, 2023

Lionel Russelot (January 21, 2023)
Duration 0.42 s



(65803) Didymos and Dimorphos, January 21, 2023

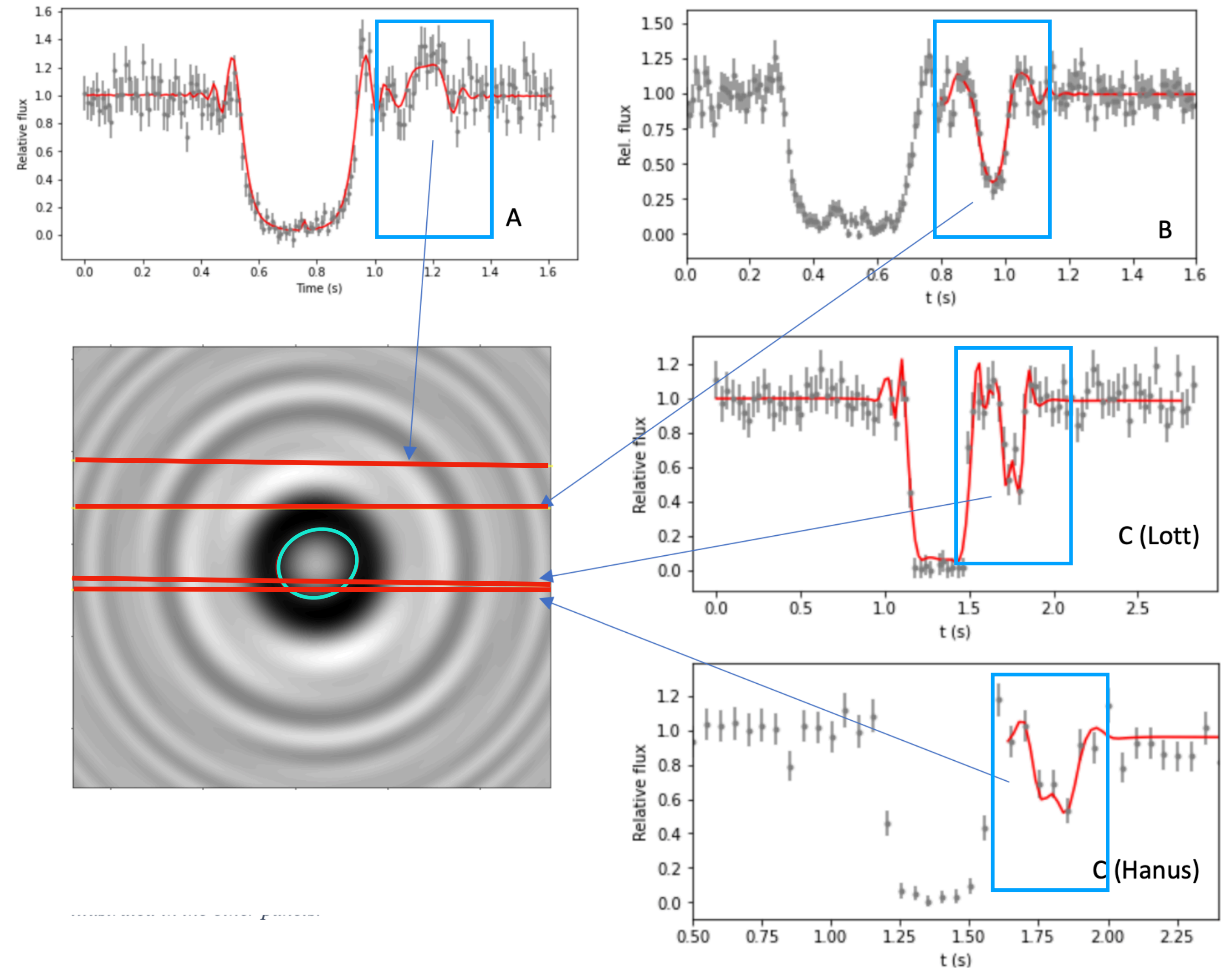
Lionel Russelot (January 21, 2023)
Duration 0.42 s



- Diffraction provides orientations and size of Dimorphos (post-DART impact)

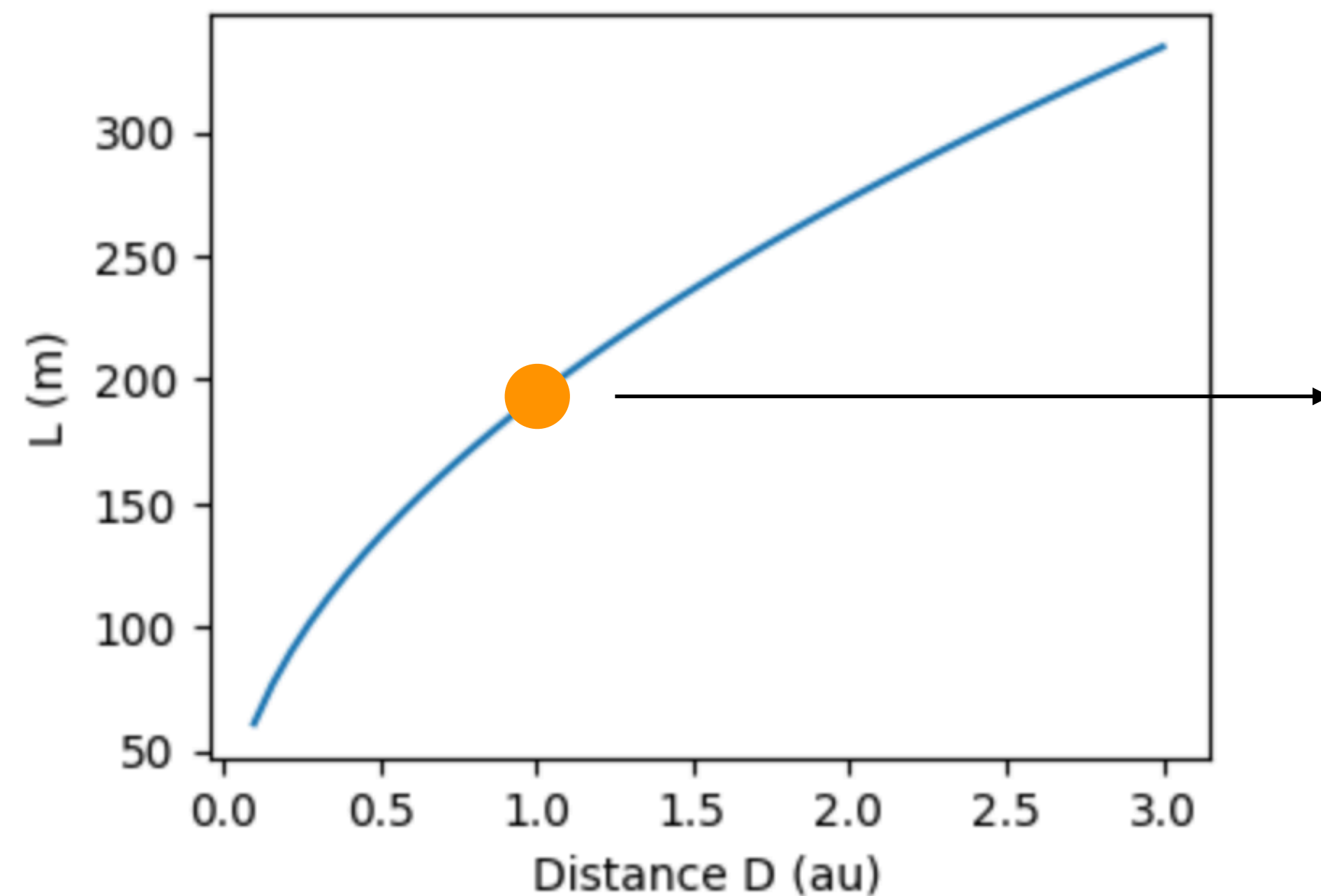
The complete picture

- The position of Didymos is shifted with respect to the nominal one
- Only the two lower chords correspond to geometric occultations
- But useful signal is present in all the four chords!

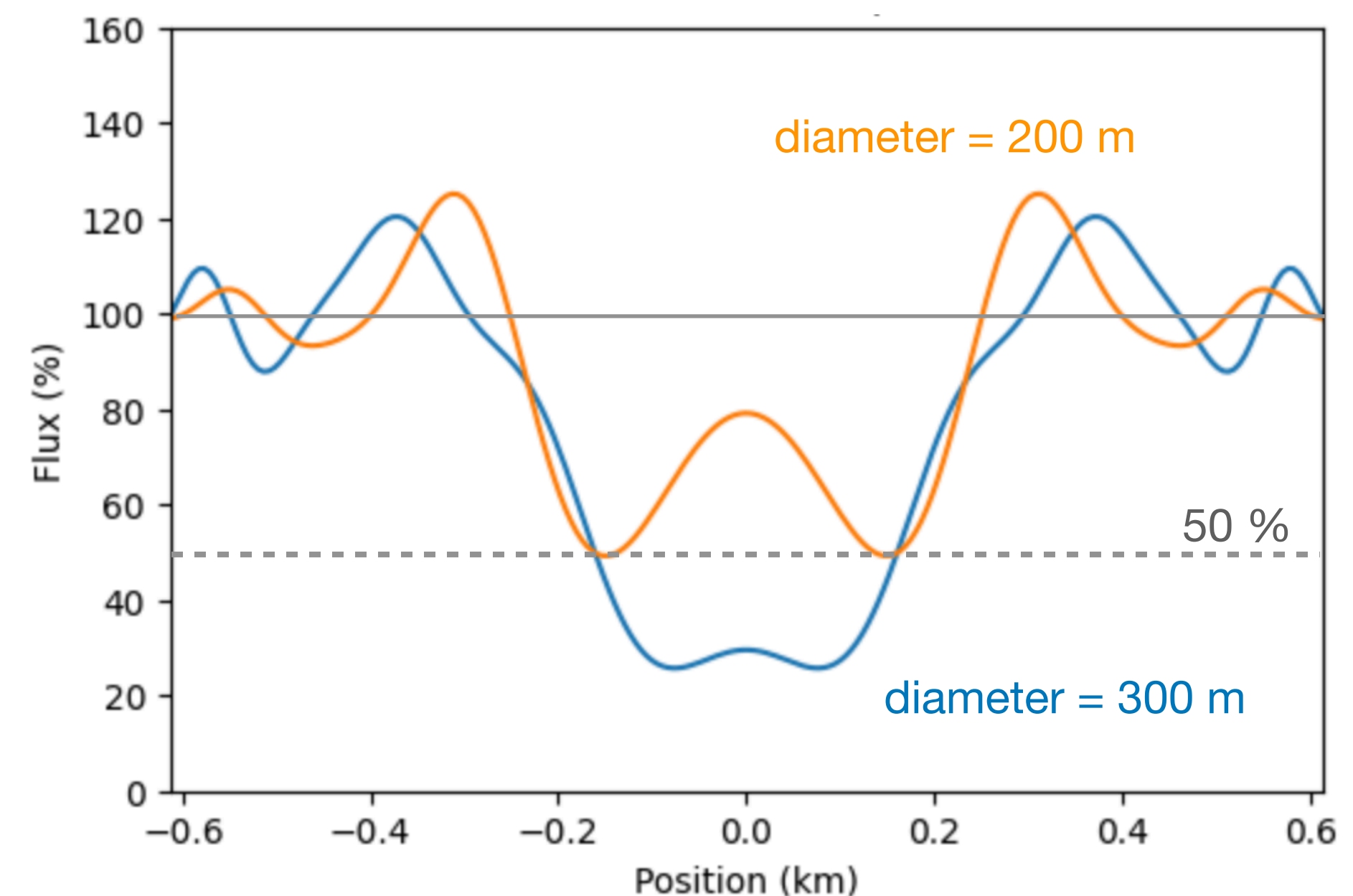


How far can we push to small diameters? Physical and practical limits

- Diffraction reduces the depth of the flux drop
- Fresnel length $L = \sqrt{\lambda D/2}$



Nearly central chord for
a spherical object at ~1 au



In practice: diffraction + short duration (coarse sampling) affect detection capabilities (binned signal may not reach 50% drop...). It gets worse for larger distances / smaller objects.

Conclusions

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- Short-arc potentially impacting orbits not sufficiently precise
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 - A systematic activity must be granted appropriate funding
 - Very rewarding activity for high-school / university students - citizen science aspect



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 - Very rewarding activity for high-school / university students - citizen science aspect
- Interesting physical properties accessible



Will ESA build ~30 of these ?

ESA / Nissan Navara “dark sky” concept telescope (with a PlaneWave telescope).
Where is it hidden?



