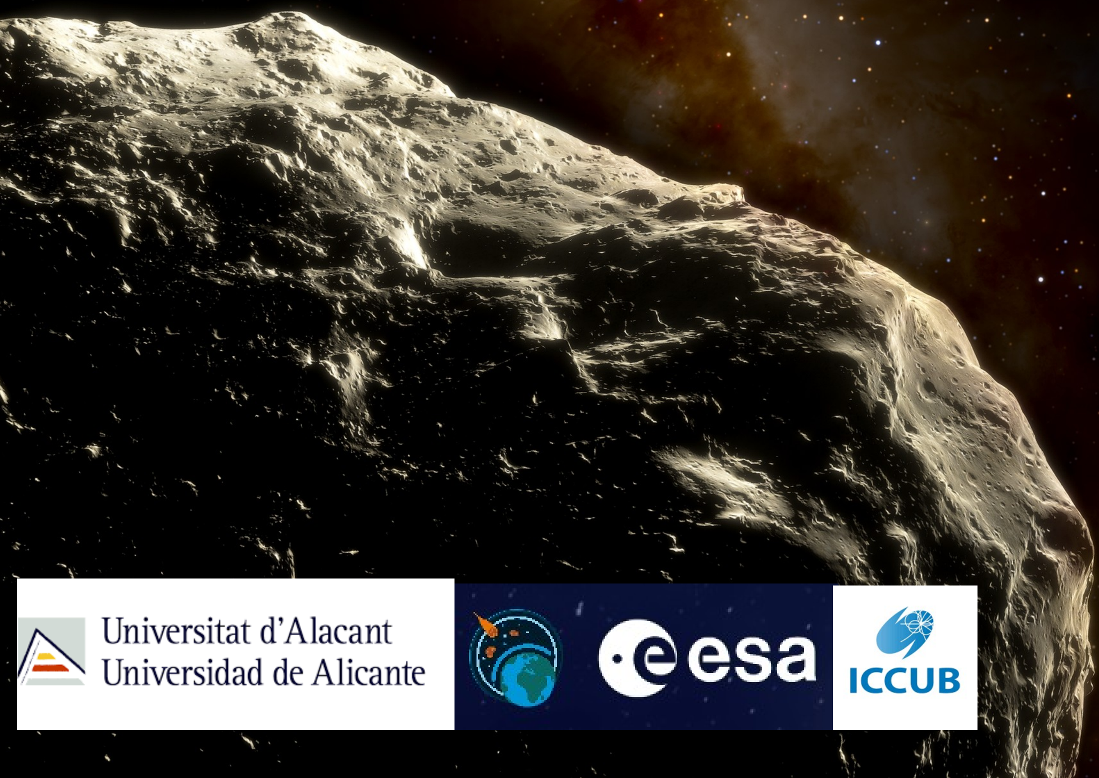
Investigating the interior secrets of the Solar System



T. Santana-Ros

XXXVIII Trobades de la Mediterrània

Life in the Universe, Formation and Evolution of the Solar System and Exoplanets

Maó, 7 November 2023

Universitat d'Alacant
Universidad de Alicante
esa
ICCUB

TROJANS, ATIRAS AND RISKY ASTEROIDS

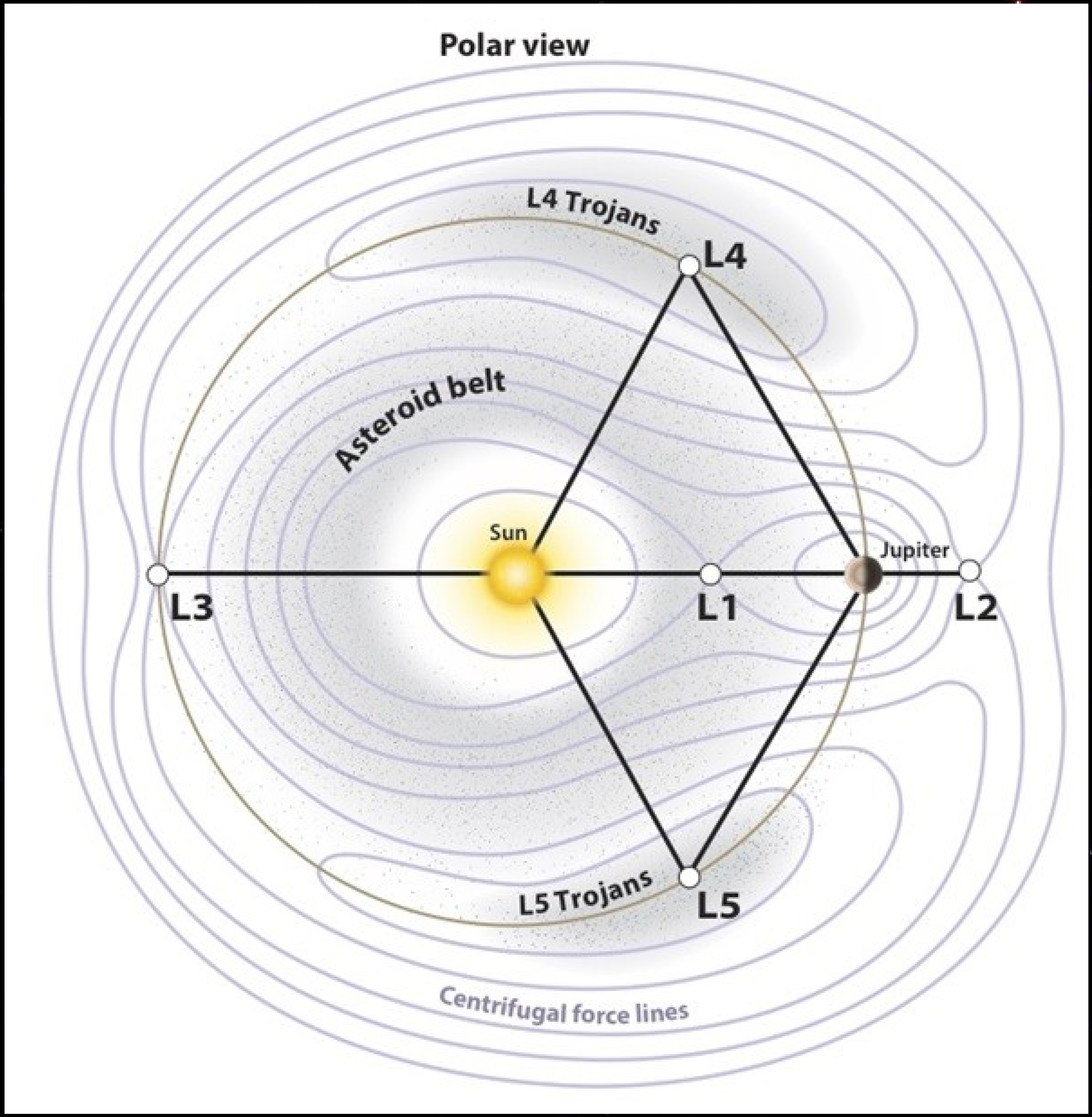
CHAPTER 1
TROJANS

CHAPTER 2
ATIRAS

CHAPTER 3
RISKY

CHAPTER 1: Trojan Asteroids

BUT FIRST OF ALL... WHAT IS A TROJAN ASTEROID?



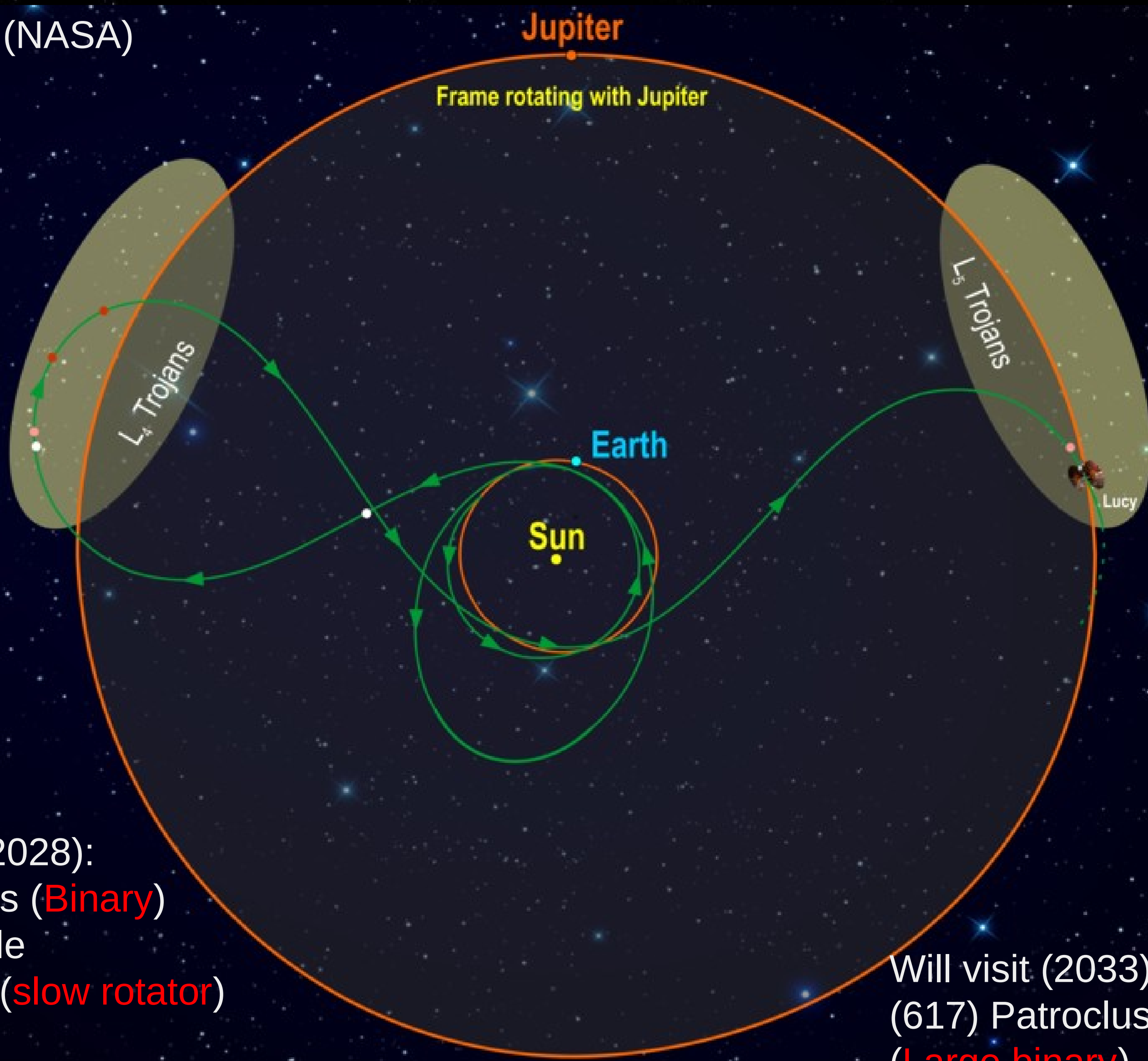
JUPITER TROJAN ASTEROIDS

Max Wolf, the discoverer in 1906 of the first trojan asteroid (588) Achilles

YEAR	NUMBER OF KNOWN JUPITER TROJANS
1907	3
1938	11
1961	14
2000	257
2003	1600
2022	~7500

JUPITER TROJANS: A TRENDY TOPIC

Lucy mission (NASA)
Launched
October 2021

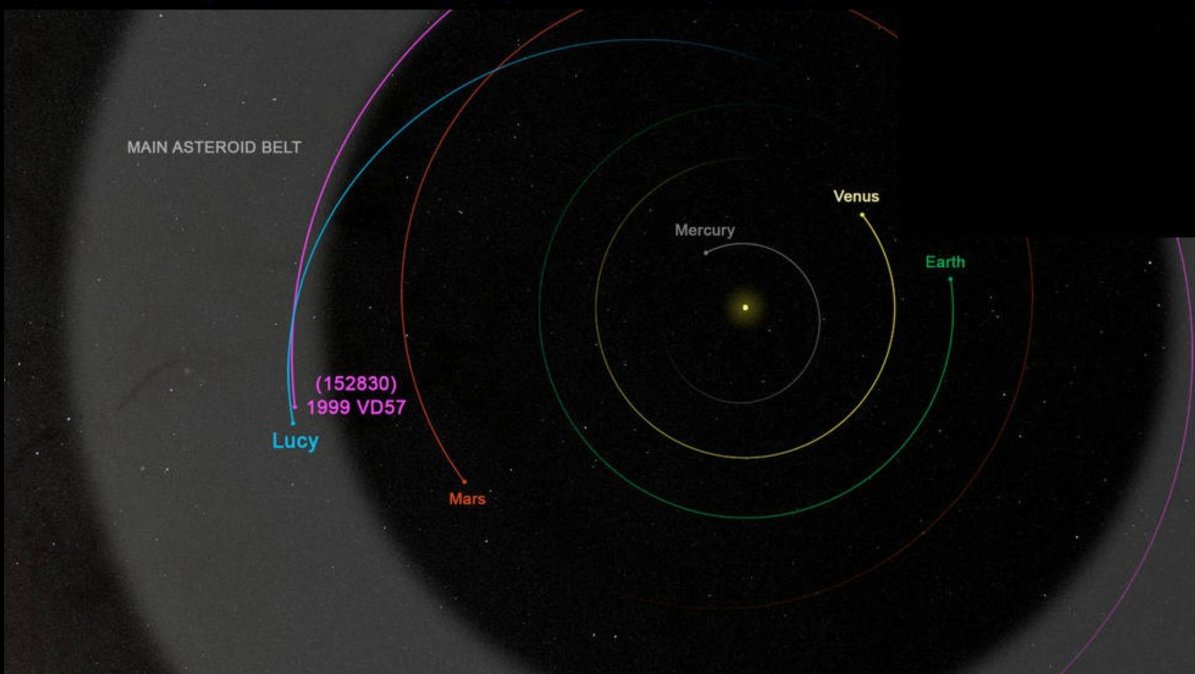


Will visit (2027-2028):
(3548) Eurybates (Binary)
(15094) Polymele
(11351) Leucus (slow rotator)
(21900) Orus

Will visit (2033):
(617) Patroclus-Menoetius
(Large binary)

JUPITER TROJANS: A TRENDY TOPIC

(152830) Dinkinesh fly-by
1 Nov 2023



WHY DO WE CARE ABOUT JUPITER TROJANS?

...time capsules from the birth of our Solar System more than 4 billion years ago, the swarms of Trojan asteroids associated with Jupiter are thought to be remnants of the primordial material that formed the outer planets.

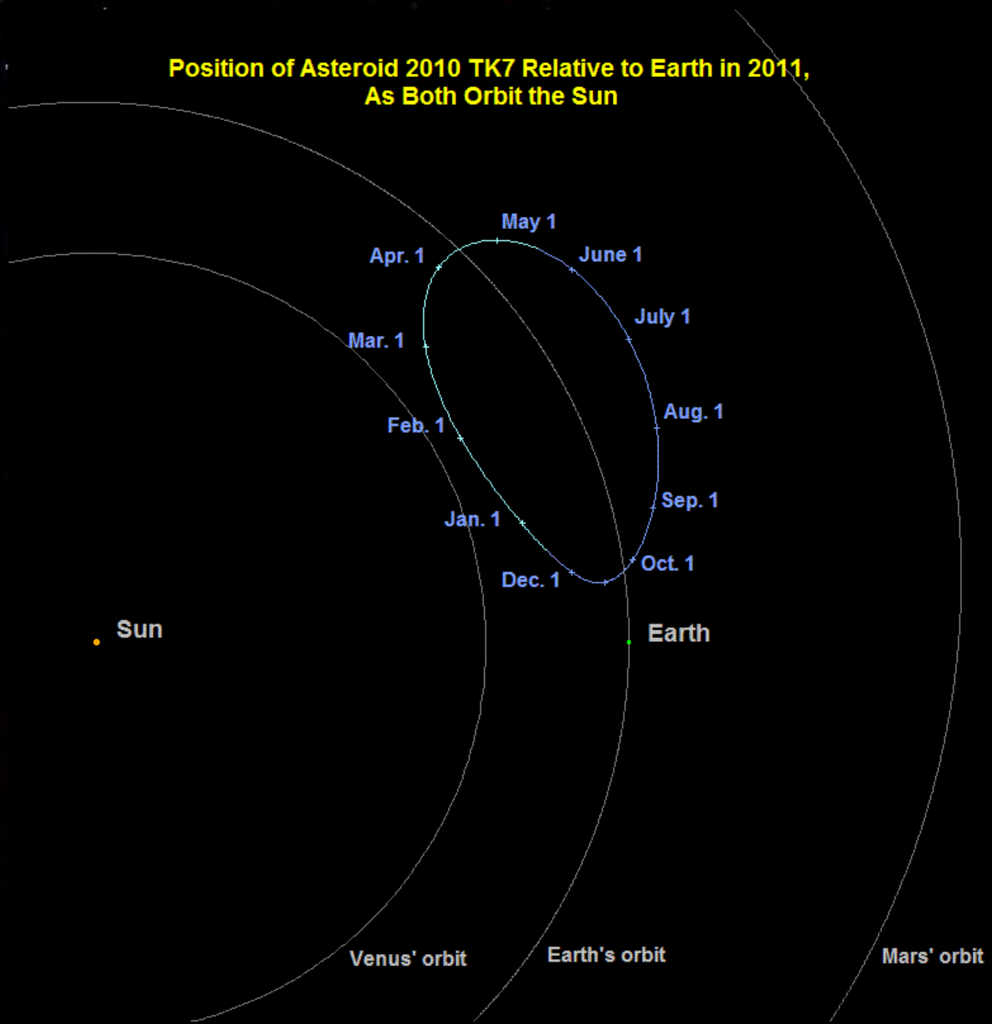
Credit: NASA

IS JUPITER THE ONLY HOST OF TROJANS?

PLANET	NUMBER OF KNOWN TROJANS
VENUS	1
MARS	4
URANUS	2
NEPTUNE	28

AND WHAT ABOUT THE EARTH?

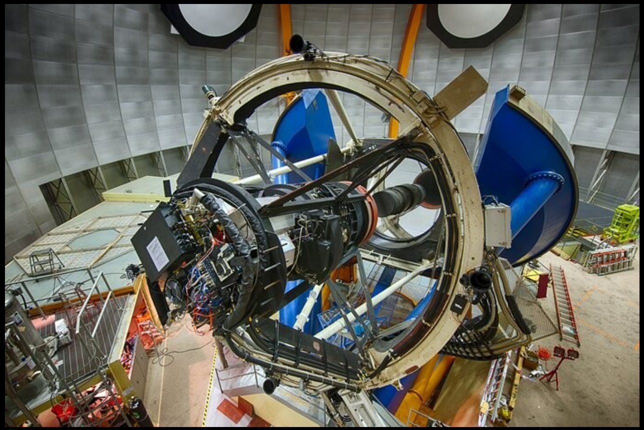
2010 TK7 was confirmed as the first Earth Trojan known
(Connors, Wiegert & Veillet, 2011, Nature)



But it was shown to be a captured Trojan (i.e. not primordial), with a stability time-scale of ~15k years

IS 2010 TK7 THE ONLY EARTH TROJAN?

Some dedicated surveys failed...



Cambioni et al. 2018
Markwardt, L. et al. 2020
Lifset et a. 2021

Even in-situ observation of spacecrafts produced no results

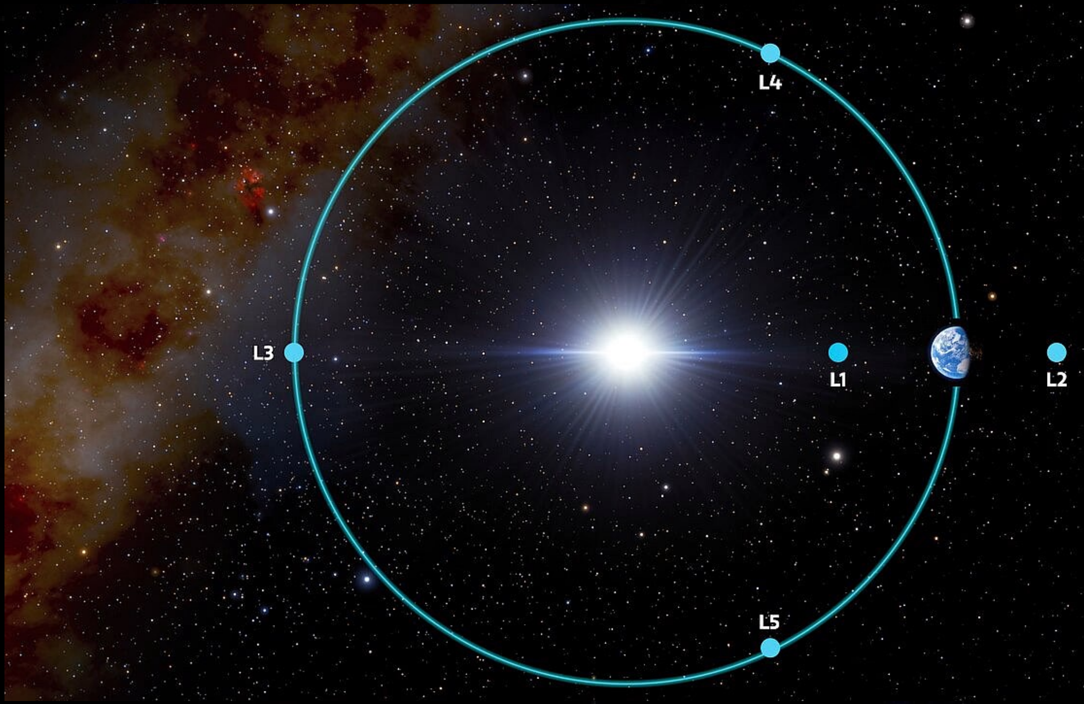
OSIRIS-REx spacecraft within the L4 region

Hayabusa2 spacecraft within the L5 region

A NEW CANDIDATE

On 12 December 2020, Pan-STARRS1 discovers P11aRcq later designated as 2020 XL5

After some follow-up observations gathered during the next few days, it is suggested that 2020 XL5's nominal orbit seems to be librating around L4. But its short arc makes it impossible to confirm it (de la Fuente Marcos & de la Fuente Marcos 2021)

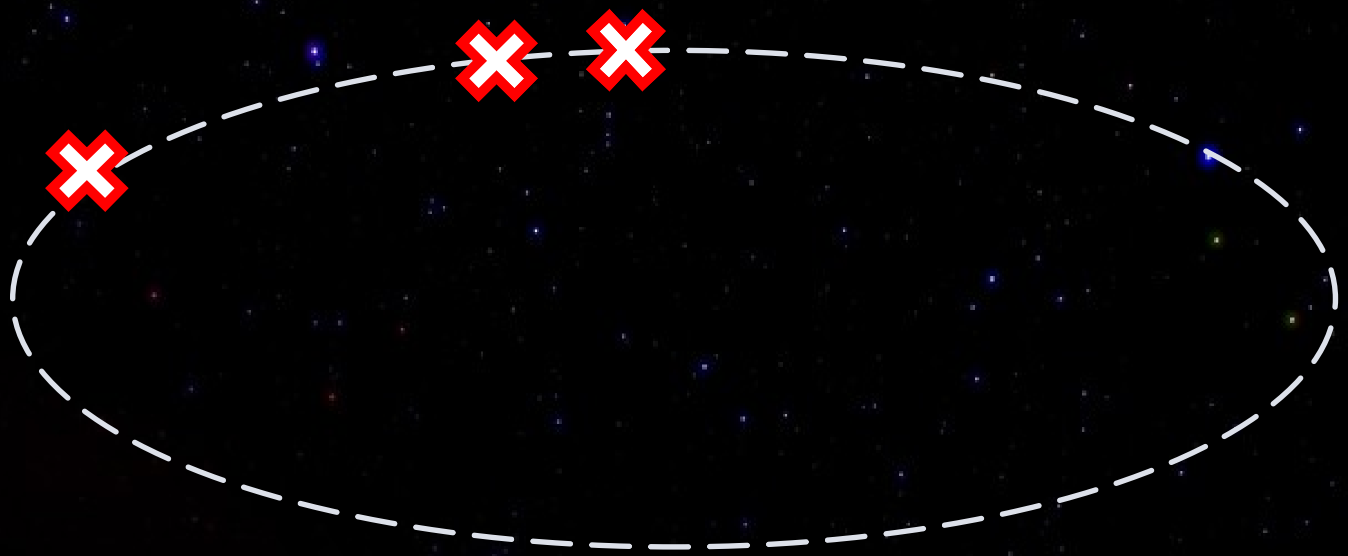


ORBIT DETERMINATION

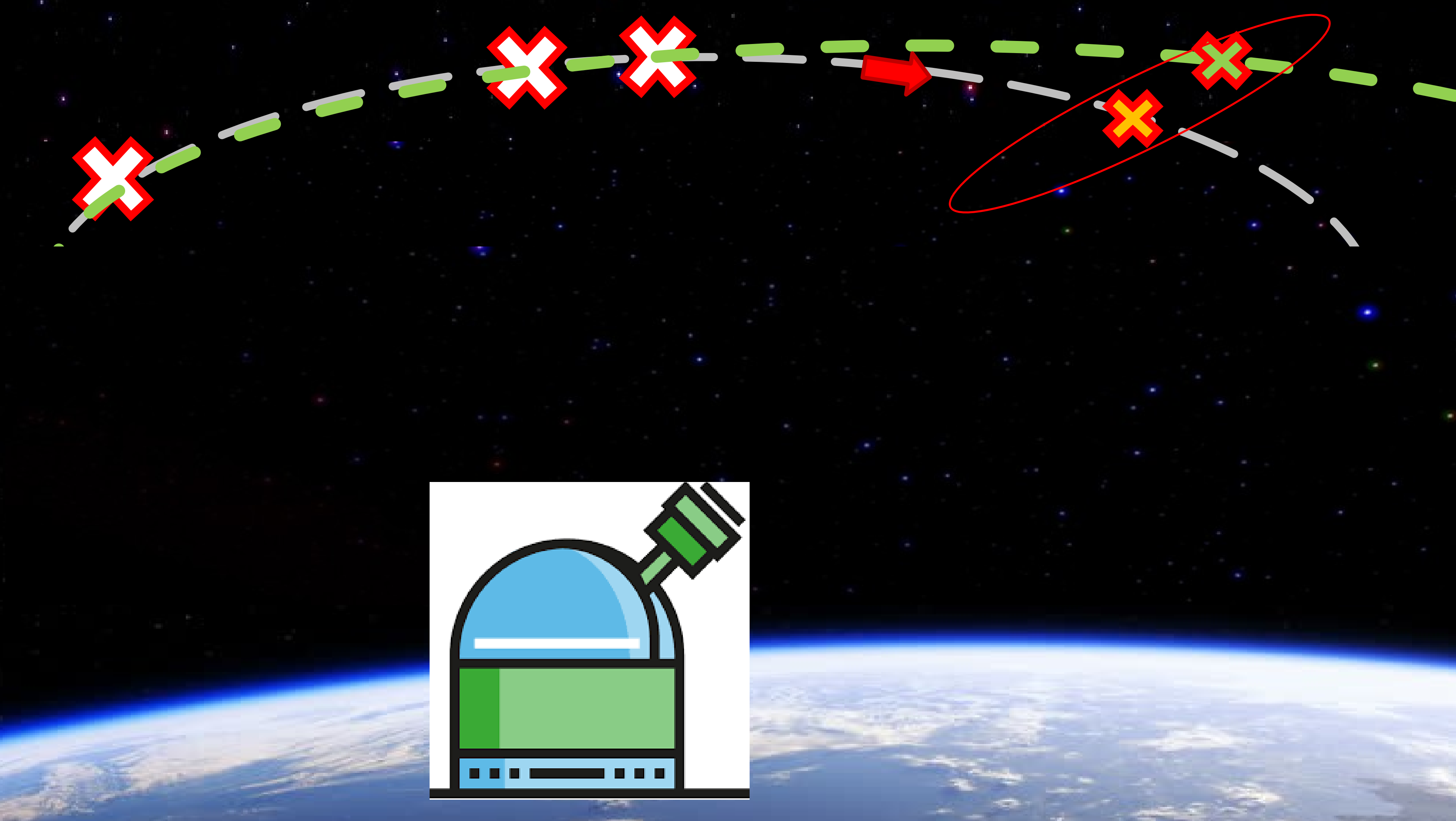
Observation arc:

Let's assume we obtained 3 observations of an asteroid

We want to predict its position for a given future time



ORBIT DETERMINATION



EASY-PEASY! LET'S GATHER SOME MORE DATA!

Wait... what was its magnitude again? Aha... 21.8...

And how long can we observe?
Less than 30 minutes... lower than 20 degrees above horizon... right before twilight...

And the object's motion limits our exposure time to 30 s...

And where is it now? Oh, really? Crossing the Galactic plane... (January 2021)

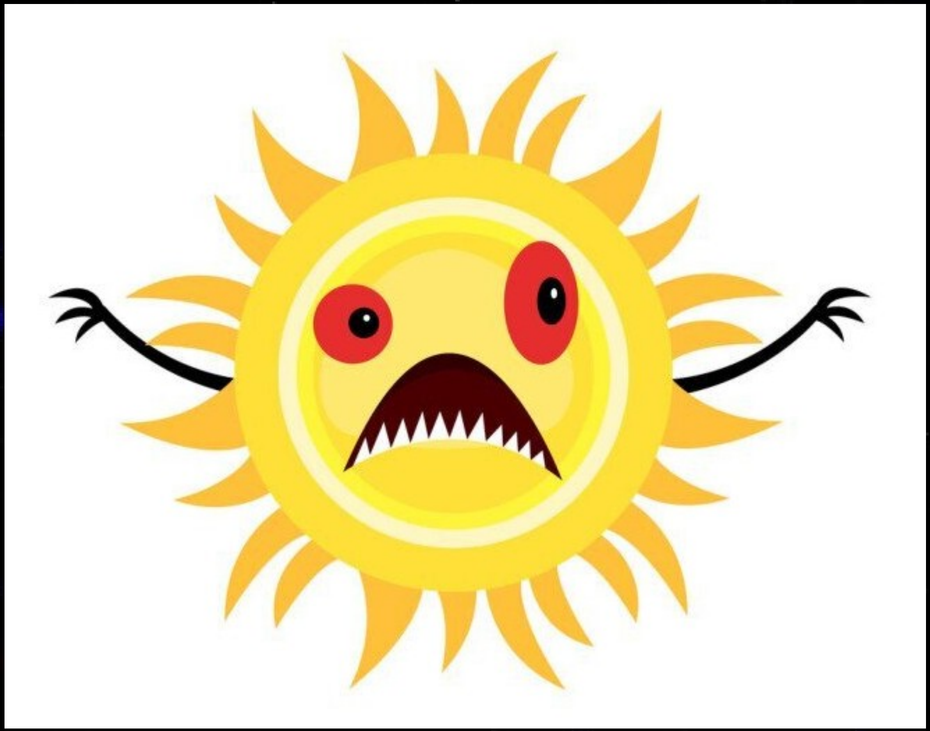
TRIUMPH IS FOR OPTIMISTS

In February 2021, we requested DDT time in the TJO (0.8 m) and CAHA (2.2 m).

Background was higher than 15k counts → NO DETECTION

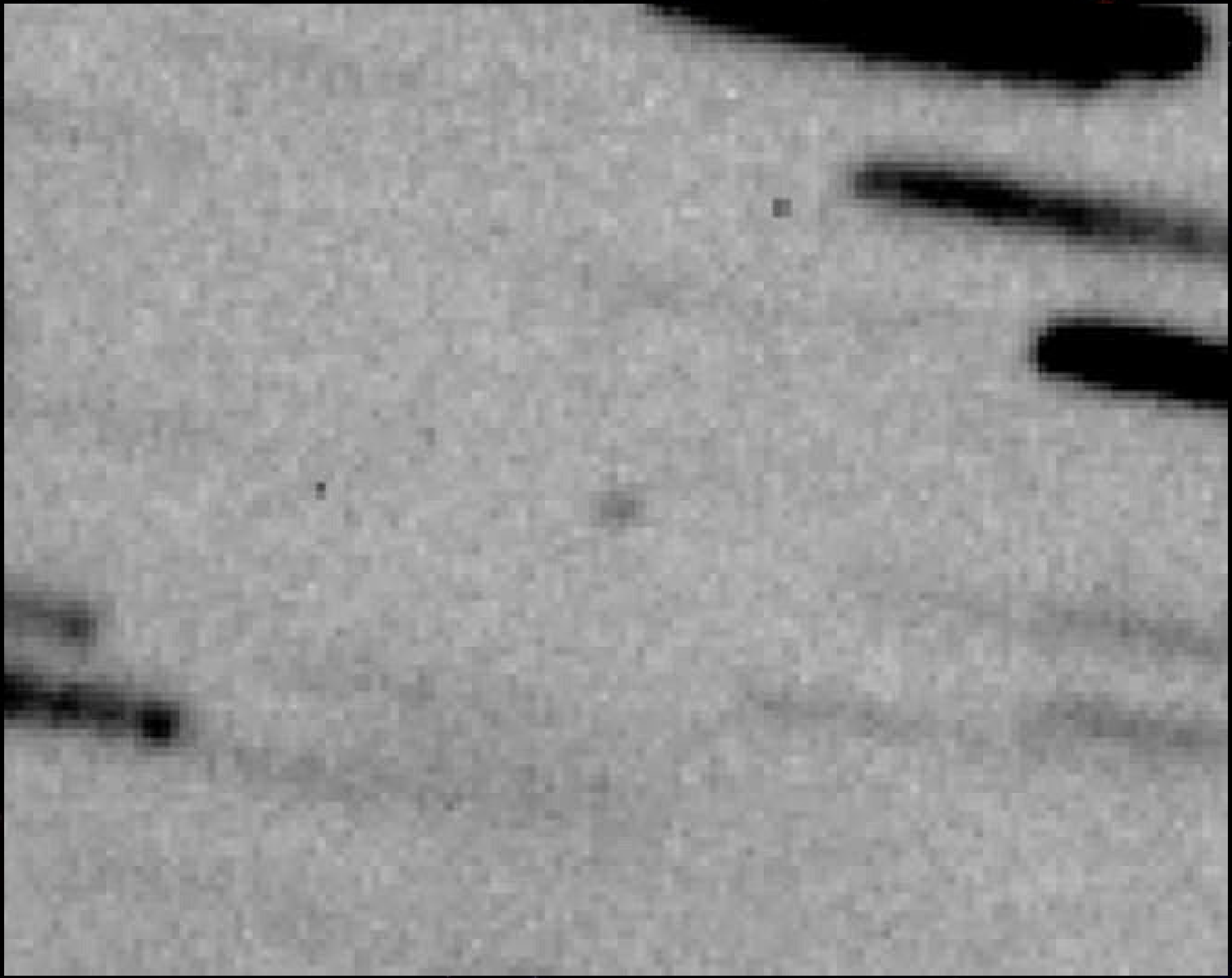
AND OUR TARGET WAS ALREADY 40 DEG AWAY FROM THE SUN...

And approaching!



We only had a few weeks left before
we would lose our candidate for a
few months until September

AND THEN...



We caught it with the 4.3 m Lowell Discovery Telescope!
At only 13 deg above horizon
(22 February 2021)

AN IMPORTANT STEP FORWARD

With LDT data, combined with the existing observations from December 2020 we covered 3 months of arc and we gained a factor of 20 in orbital accuracy...

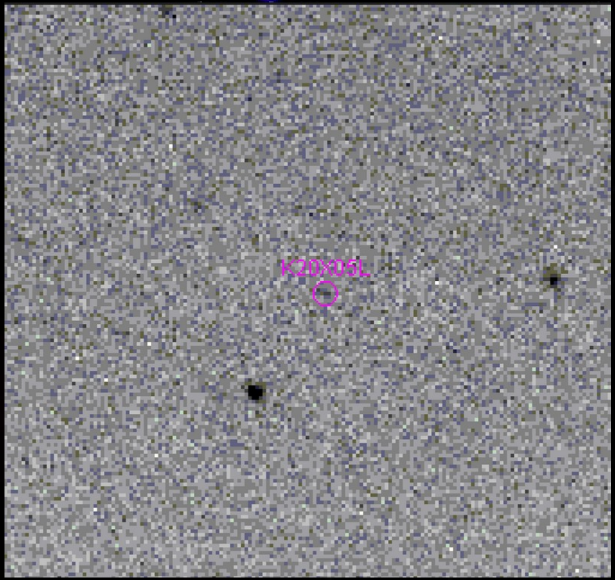
But this was still not enough for a long term orbit analysis.

A FEW NEW DETECTIONS!

We optimized our observing strategy to get the highest SNR during a short time window with high airmasses.

We obtained 3 new detections using the 4.1 m SOAR telescope.

Date	α (°)	r'	i'	g'	V	MPC Code
2021 March 9	64	21.26 ± 0.42	20.99 ± 0.34	20.84 ± 0.42		I33
2021 March 14	58	20.85 ± 0.31				I33
2021 March 16	56	20.63 ± 0.43	20.22 ± 0.50	20.77 ± 0.98		I33



AND NOW... WHY NOT TO LOOK BACK?

With the new orbit improved by another factor of 20, we looked for ancillary data. We found 14 precoveries spanning from 2012 to 2019!

Catalina Sky Survey, DECam and Pan-STARRS

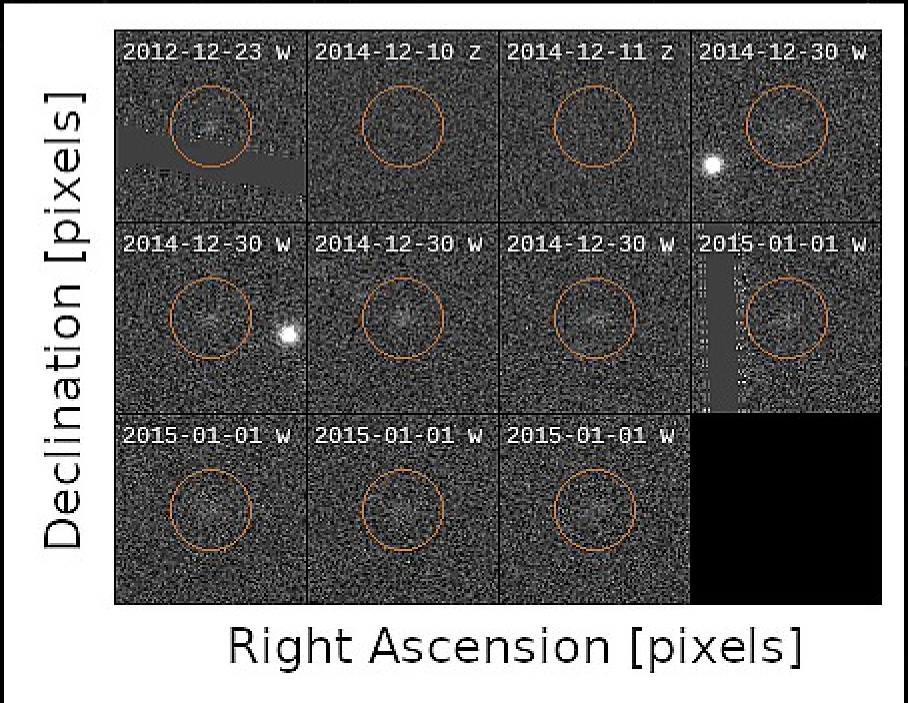
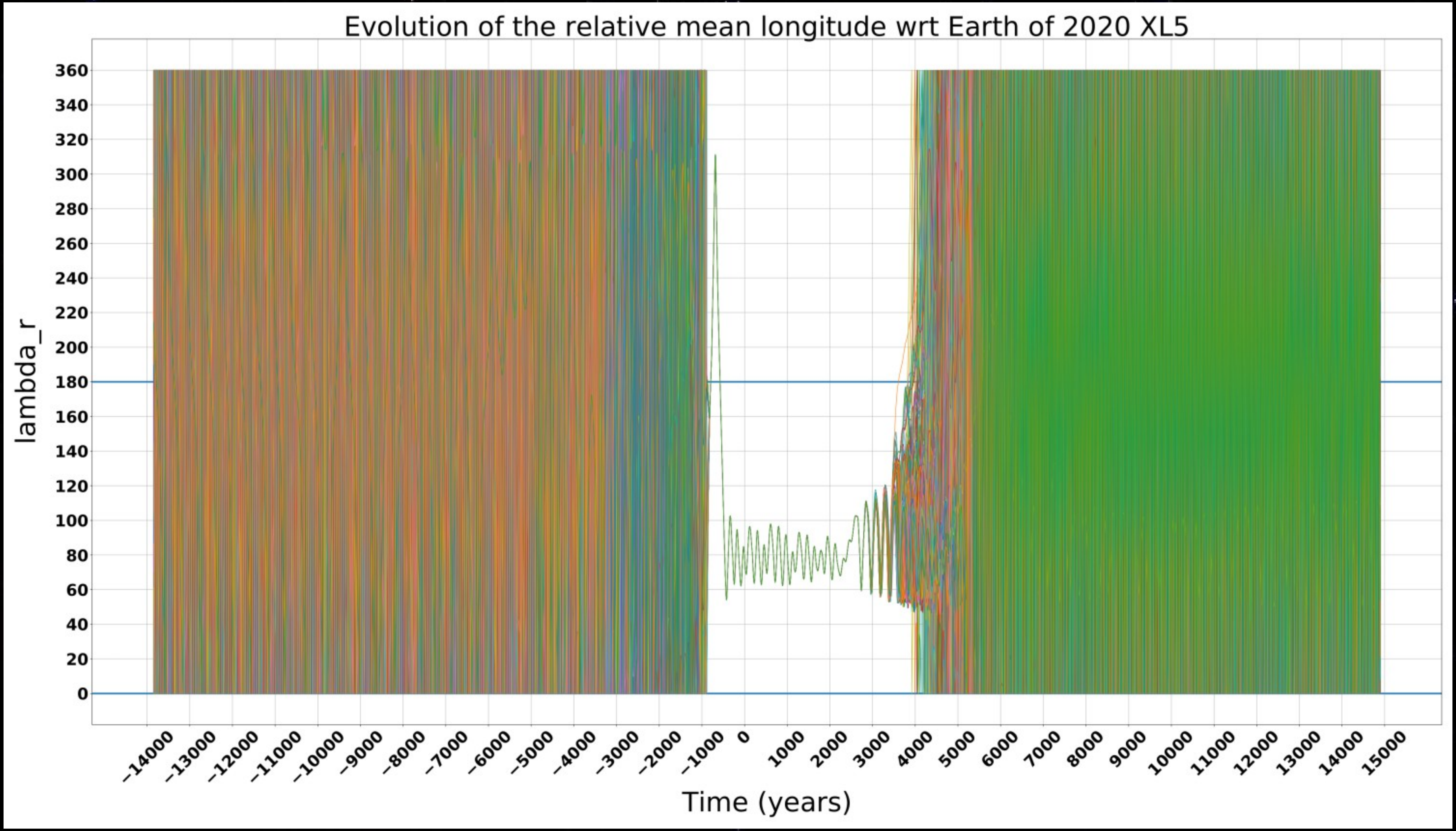


Table 1 Orbital elements.

Element	Value	1σ uncertainty	Unit
a	1.00070559767	5.61×10^{-9}	au
e	0.387220870	1.56×10^{-7}	
i	13.8458718	1.58×10^{-5}	deg
Ω	153.6128174	5.03×10^{-5}	deg
ω	87.9797957	4.25×10^{-5}	deg
M	258.3840814	2.25×10^{-5}	deg

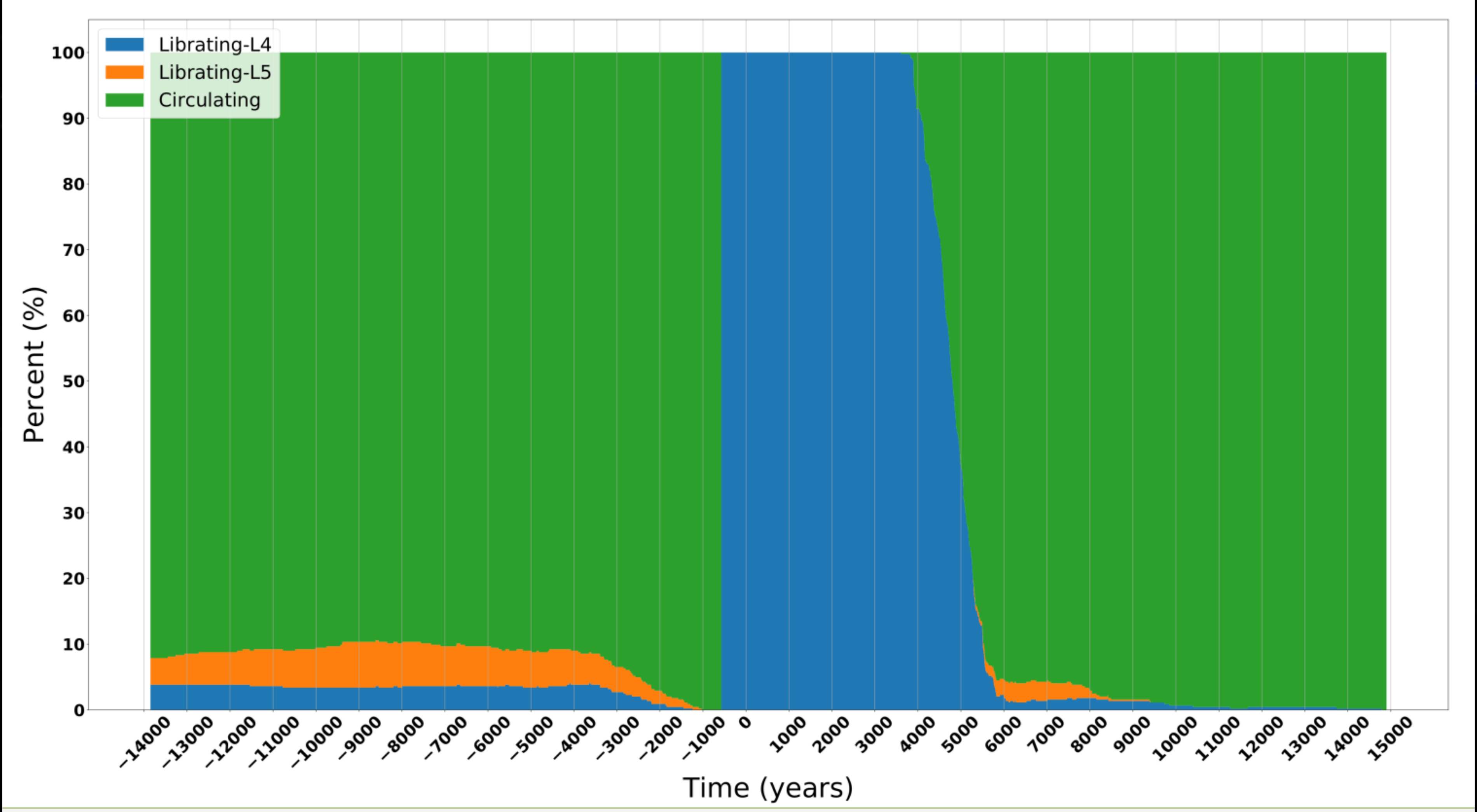
Keplerian orbital elements of 2020 XL_5 and their uncertainties, at the epoch MJD = 58444.1, computed with the European Space Agency's (ESA) AstOD orbit determination software[19,20], based on the methods described in the literature[21], taking as input the full observations dataset described in the observation sections of Methods.

ORBIT LONG-TERM CHARACTERIZATION



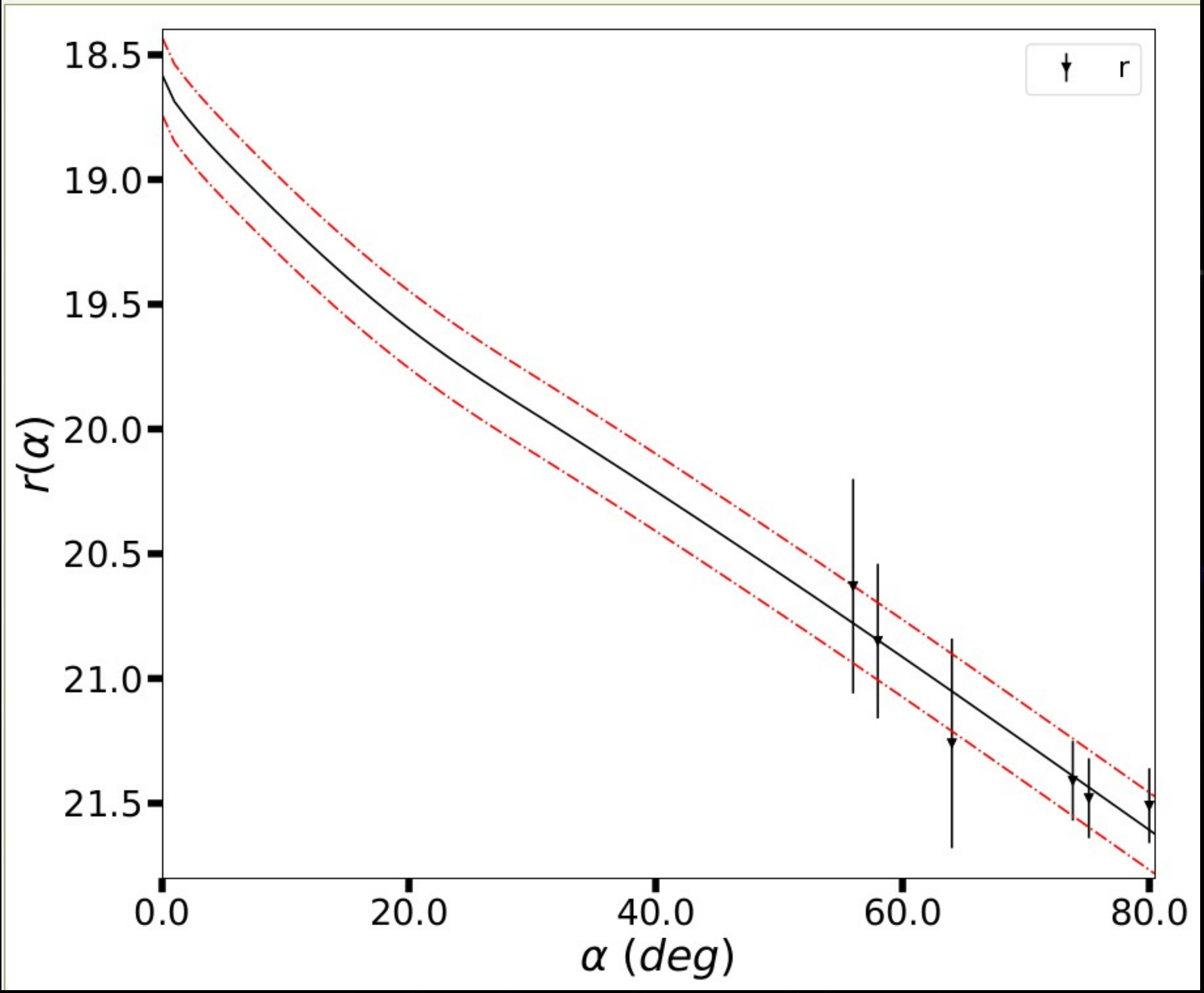
Santana-Ros et al. 2022, Nature Communications

WE HAD A NEW EARTH TROJAN!



But we confirm it is a transient Trojan (like 2010 TK7), so no primordial ETs yet...

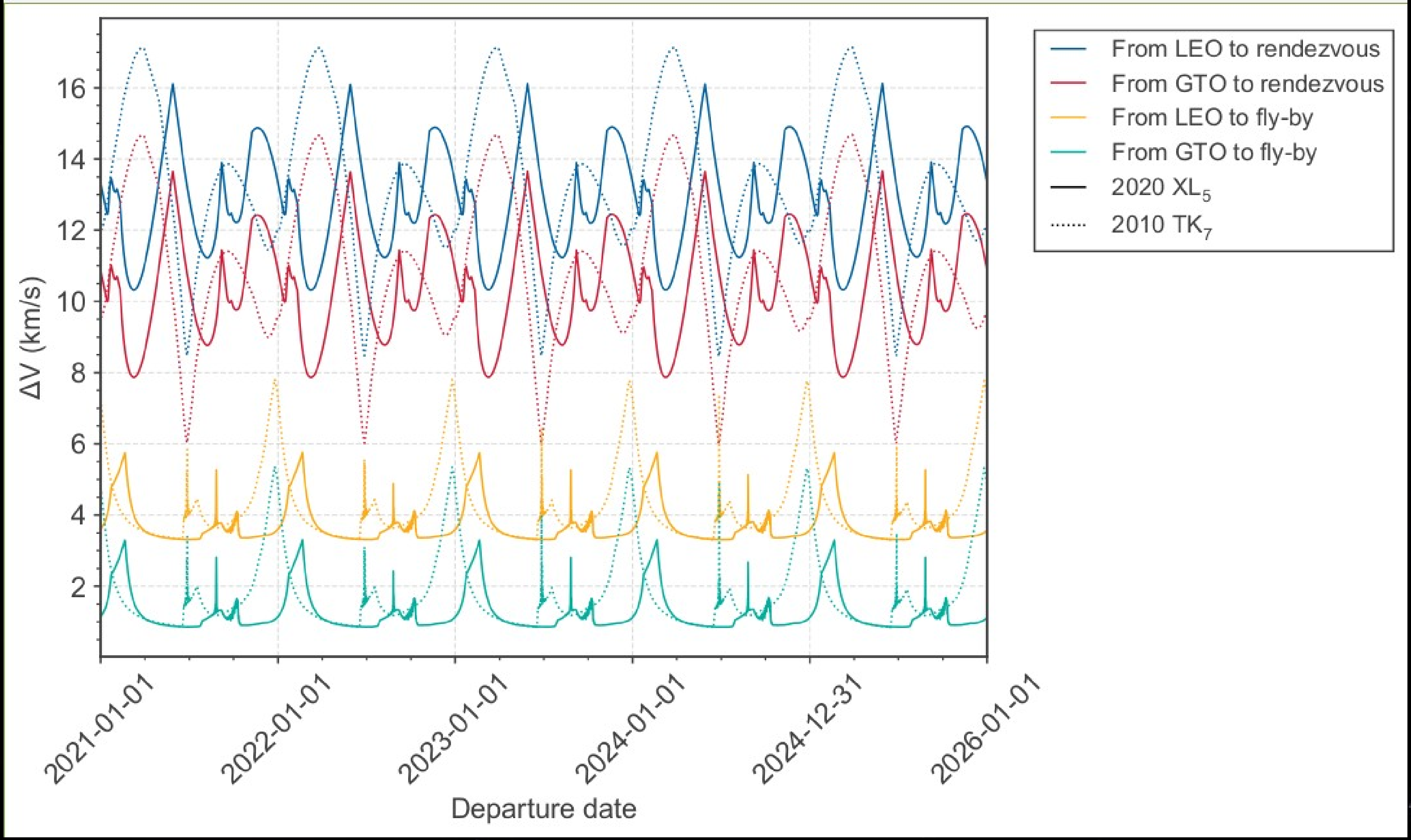
CHARACTERIZATION OF 2020 XL5



H = 18.58 ± 0.16, Size = 1.18 ± 0.08 km
(assuming an albedo of 0.06 ± 0.03)

DELTA-V BUDGET

Earth Trojans can be good candidates for a space mission, since they share Earth's orbit!



But not this one...

CHAPTER 2: ATIRA ASTEROIDS

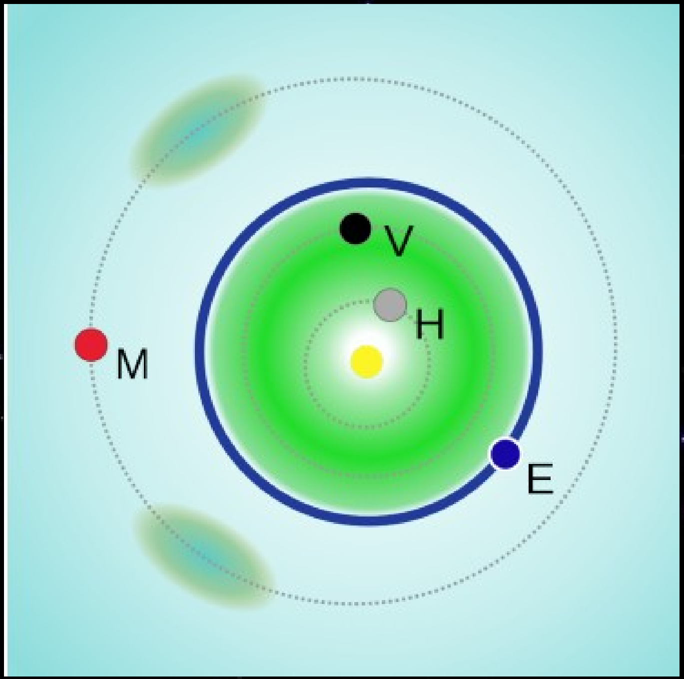
ATIRAS (AKA INTERIOR-EARTH OBJECTS)

- Atiras are objects which stay always **within the Earth's perihelion**

- They have frequent close encounters with Mercury and Venus
- which **could eventually push an Atira-orbit into an Earth-crossing orbit**

- Only **31 objects** have been discovered to date (source JPL)

- Very **challenging** from an **observational point of view**

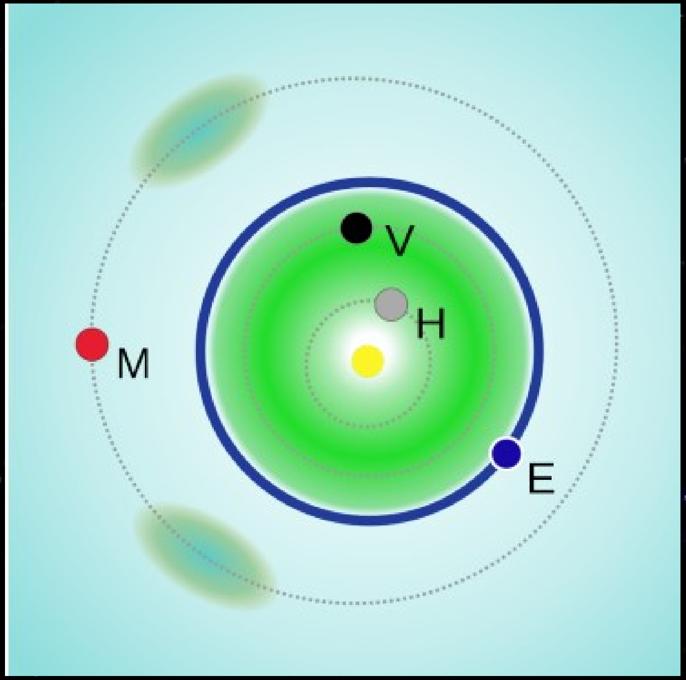


The Atira objects represent a part of our Solar System which is poorly known

ATIRAS (AKA INTERIOR-EARTH OBJECTS)

They are interesting because:

- They are regularly heated at temperatures between 500 K and 1000 K
- Non-gravitational forces (YORP, Yarkovsky)
- Relativistic orbit effects
- Only 31 discovered so far, but we estimate a population of a few hundreds larger than 100 m

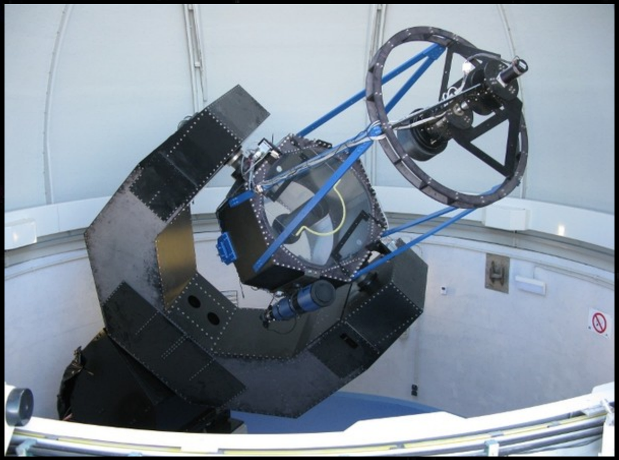


DISCOVERING NEW ATIRAS IS NOT EASY

FEATURE	ISSUE
Only observable during twilight	Limited time window (<1 hour)
Low elevations (<20 deg)	High airmass / extinction
Exposure time limited by their proper motion	Time lost during readouts
Unknown orbit	Need for follow-up!

SURVEYING THE EARTH-INTERIOR REGION

TELESCOPI JOAN ORÓ



- Located at the Catalan Pyrenees
- 0.8 m robotic telescope
- 4k x 4k back-illuminated CCD
- FoV of 30'
- Elevation limit 5°
- 200 hours granted (p485)

TELESCOPI FABRA-ROA

- Located at the Catalan Pyrenees
- 0.5 m telescope
- 4k x 4k back-illuminated CMOS
- FoV of 4.4°
- Elevation limit 5°
- 100 hours granted (p531)

SPRINGBOK

- Located in Namibia
- 0.4 m robotic telescope
- CMOS
- FoV of 157.2' x 105.2'
- Elevation limit 5°

SURVEYING THE EARTH-INTERIOR REGION

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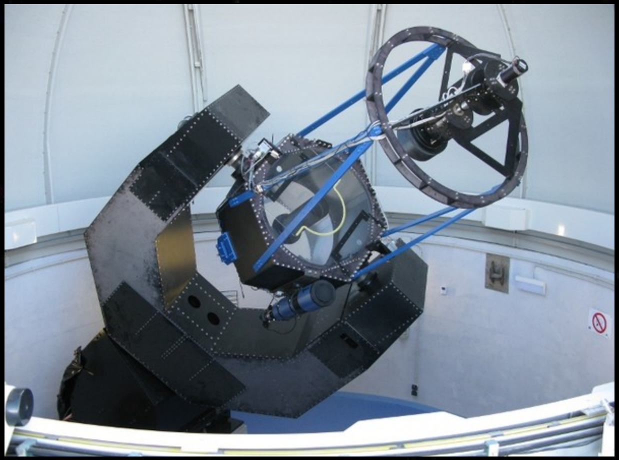

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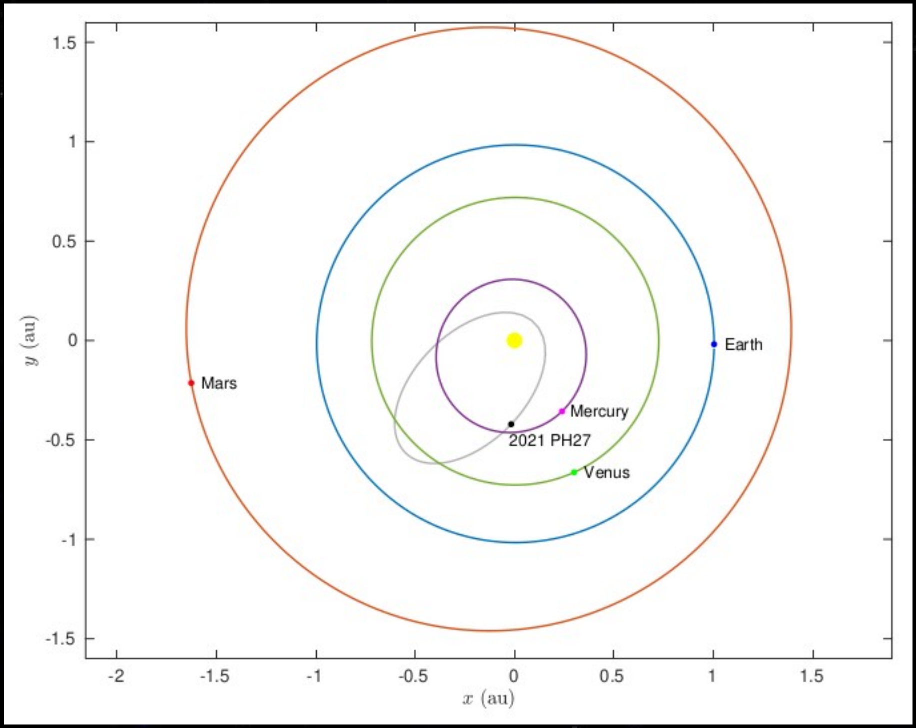
Do you know of a 1 meter class telescope (or larger) with a large FoV, able to point at low elevations (<20 deg) and with a fast-readout camera? Contact me!

THE MOST EXTREME ATIRA KNOWN: 2021 PH27

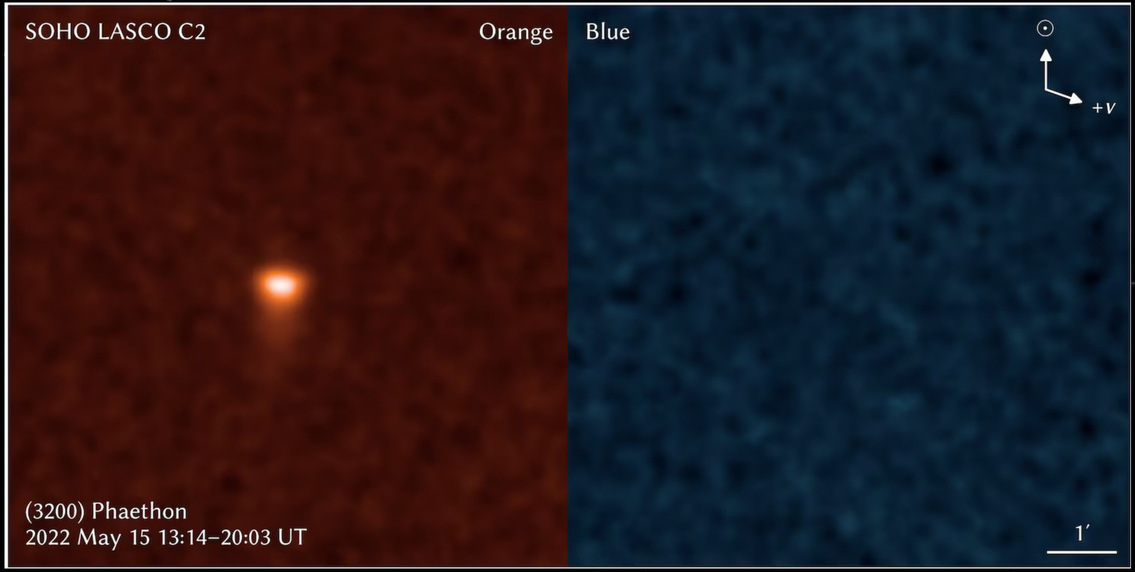
2021 PH27 has...

- The **smaller semi-major axis** known (0.46 au)
- A **perihelion distance at only 0.13 au** from the Sun
- Extreme **temperatures of 1000 K** at perihelion
- 106 km/s at perihelion with
- a relativistic perihelion shift of 42.9’’/century, 1.6 times that of Mercury



2021 PH27: A LOW-Q ACTIVE ASTEROID?

(3200) Phaethon is a low-q asteroid known to have activity near perihelion due to the extreme thermal fatigue at 0.14 au

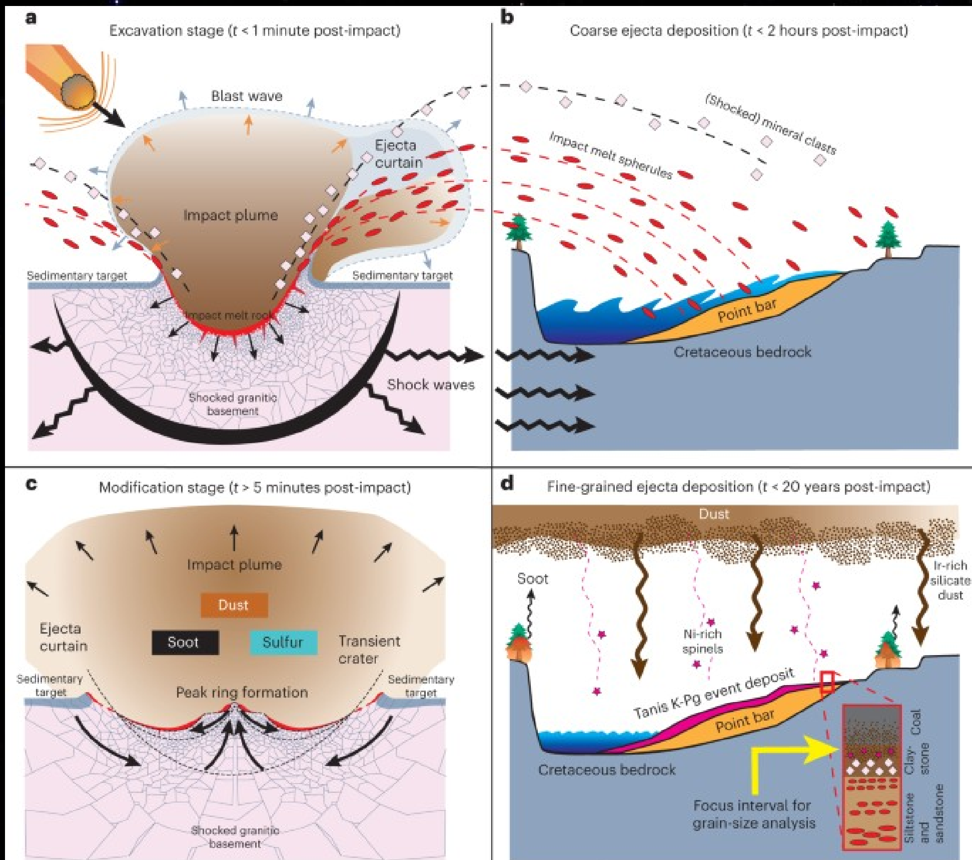


Credit: U.S. Naval Research Laboratory

CHAPTER 3: The danger from asteroids: what can we do?

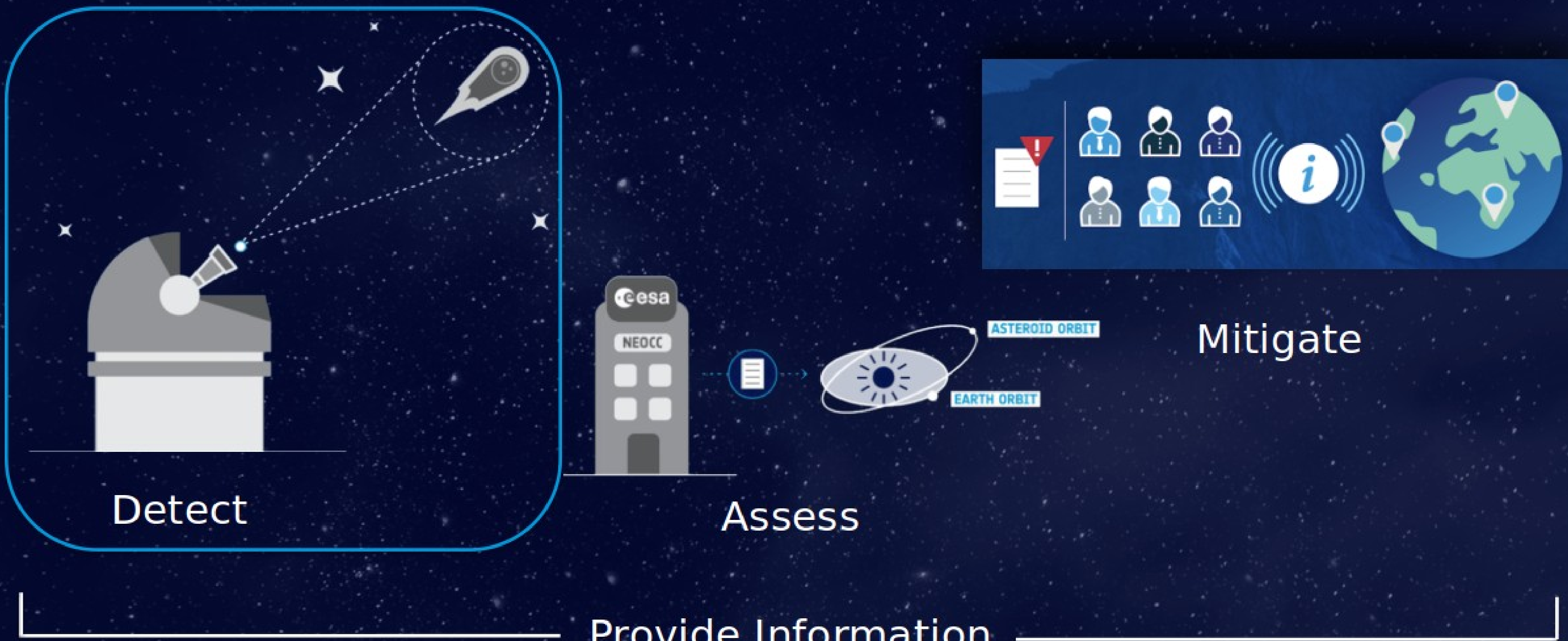
ESA Planetary Defence Office, NEO Coordination Centre

LIFE CAN BE CREATED... BUT ALSO EXTINCTED



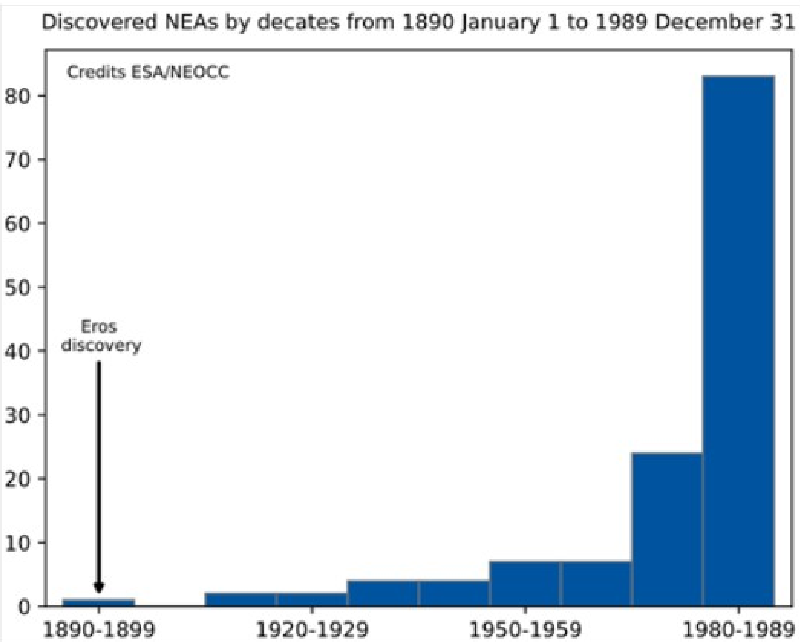
Chicxulub impact winter sustained by fine silicate dust,
Berk Senel et al. 2023, Nature Geoscience

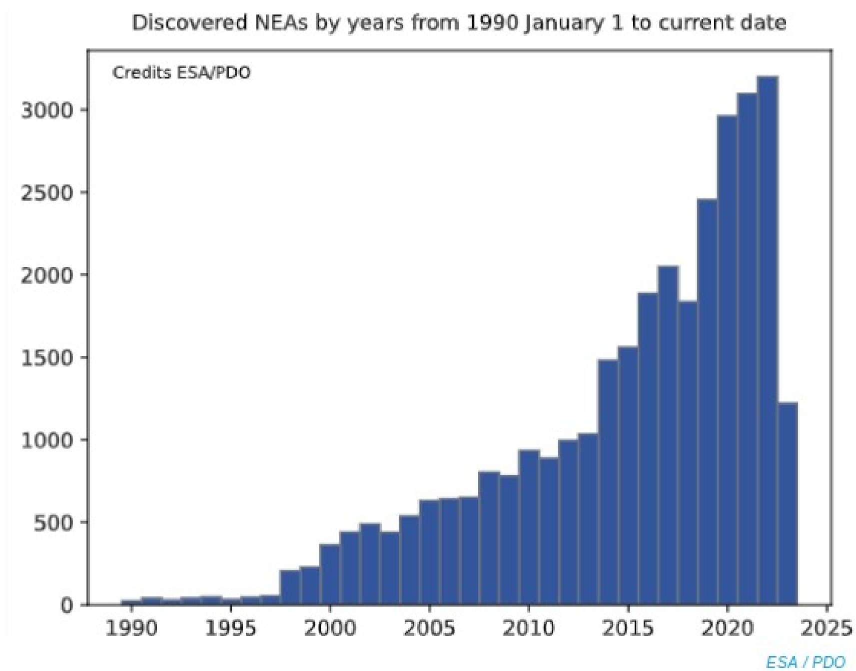
The Three Pillars Of Planetary Defence



Discovering asteroids: how is it going?

The discovery rate has been improving, significantly, during the last few years.





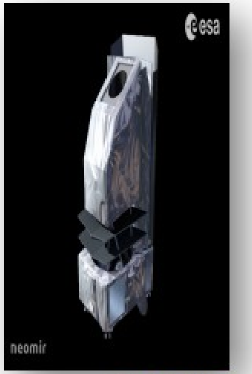
Surveys: present and future

The first step to improve the situation is discovering unknown asteroids.

Pan-STARRS

LSST

ESA / QHB



ESA / NEOMIR

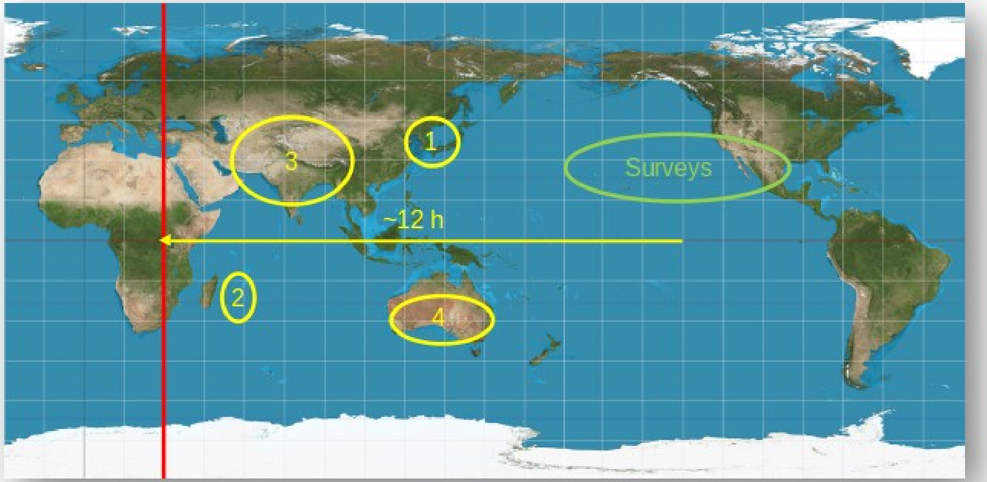
Right now, they are mostly medium-sized ground-based telescopes.

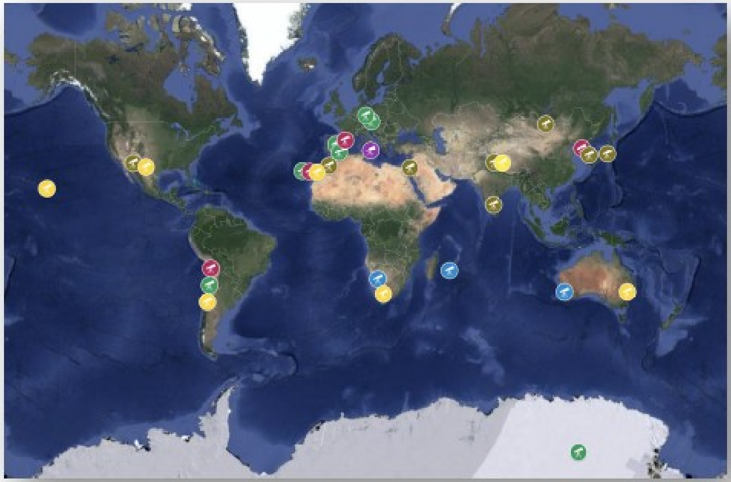
In the future:

- Larger telescopes.
- Faster coverage of the sky.
- Space, to get closer to the sun.

Discovery is not enough: the role of follow-up

Newly discovered asteroids need to be followed up, often immediately!





ESA PDO

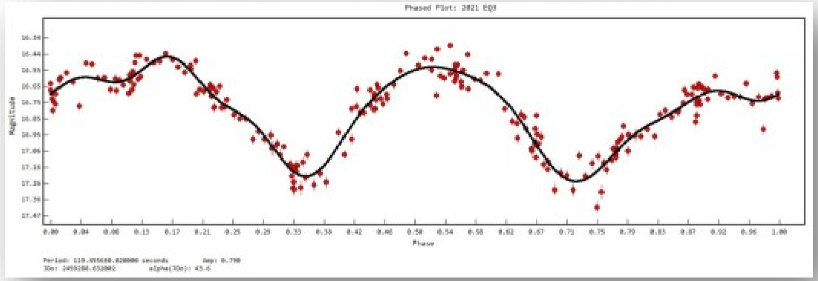
This global nature of the follow-up effort requires:

- Coordination between different teams.
- International cooperation to access the right facility at the right time.

Physical characterization

If an object is about to collide with our planet, we need to know its physical properties too.

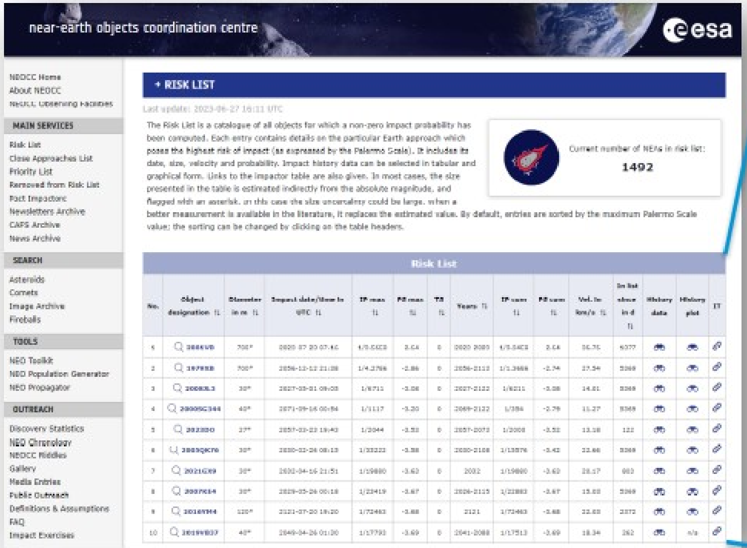
- Compositional/taxonomical information, provide direct evidence of the compositional properties of a possible impactor, and can indirectly constrain key parameters, such as density, that are essential to predict ground effects.
- Rotational lightcurves and period determination provide shape information, binary nature, and indirectly help constrain the internal strength of the object.
- Infrared measurements and polarimetry can measure size of an object, possibly the most important observable quantity to assess its impact threat.



Calar Alto Observatory / ESA PDO

The goal: a risk list

The main end goal of the NEO discovery process for planetary defence purposes is the assessment of the impact threat posed by each known NEO.

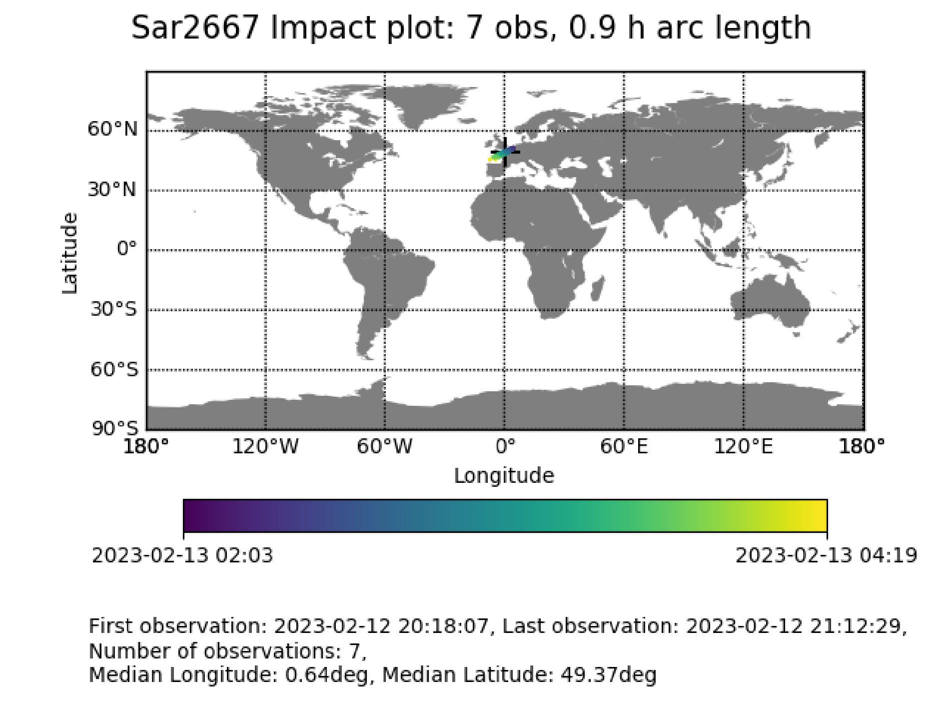


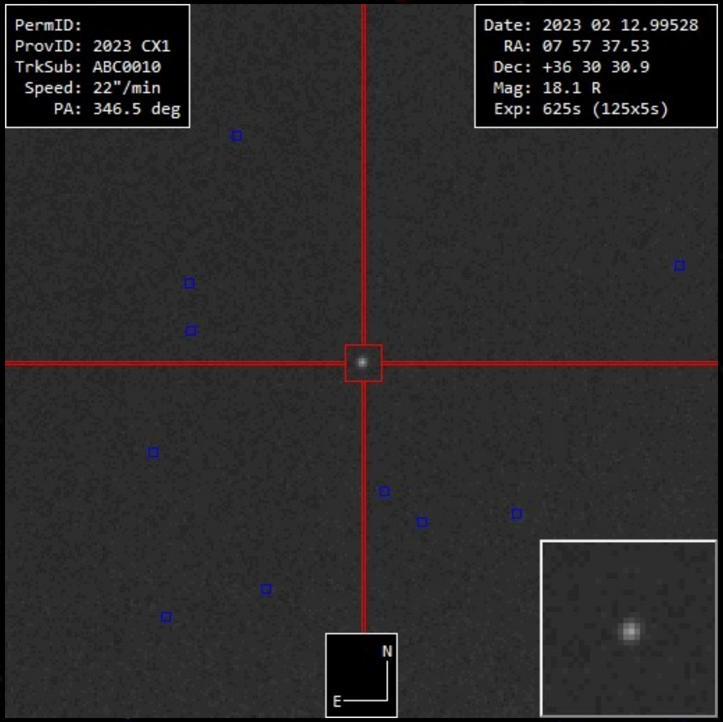
ESA / PDO / NEOCC

No.	Object designation ⇅	Diameter in m ⇅	Impact date/time in UTC ⇅	IP max ⇅	PS max ⇅	TS ⇅	Years ⇅	IP cum ⇅	PS cum ⇅	Vel. in km/s ⇅	In list since in d ⇅	History data	History plot	IT
1	2001VB	700*	2023-07-23 07:16	1/3.56E8	-2.64	0	2023-2089	1/3.34E8	-2.64	36.76	1377			
2	1979XB	700*	2056-12-12 21:38	1/4.27E6	-2.86	0	2056-2113	1/1.36E6	-2.74	27.54	5369			
3	2008JL3	30*	2027-05-01 09:05	1/6711	-3.08	0	2027-2122	1/6211	-3.08	14.01	5369			
4	2000SG344	40*	2071-09-16 00:54	1/1117	-3.20	0	2069-2122	1/354	-2.79	11.27	5369			
5	2023DO	27*	2057-03-23 19:43	1/2044	-3.53	0	2057-2073	1/2000	-3.52	13.18	122			
6	2005QK76	30*	2030-02-26 08:15	1/33222	-3.58	0	2030-2108	1/15576	-3.42	22.66	5369			
7	2021GX9	30*	2032-04-16 21:51	1/19880	-3.63	0	2032	1/19880	-3.63	20.17	803			
8	2007KE4	30*	2029-05-26 00:18	1/23419	-3.67	0	2026-2115	1/22883	-3.67	15.03	5369			
9	2016YM4	120*	2121-07-20 19:20	1/72463	-3.68	0	2121	1/72463	-3.68	22.03	2372			
10	2019VB37	40*	2049-04-26 01:30	1/17793	-3.69	0	2041-2088	1/17513	-3.69	18.34	262		n/a	

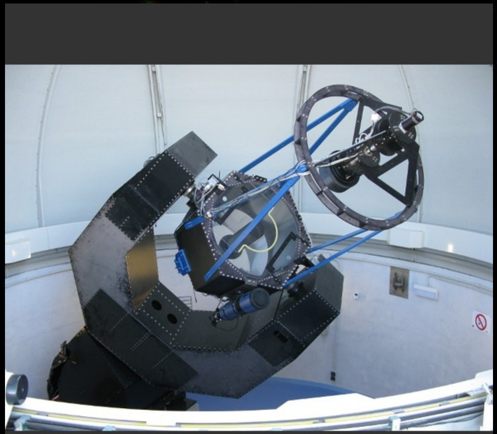
The end-result is the publication of "risk lists" of objects with a non-zero impact probability.

A RECENT REAL CASE: 2023 CX1



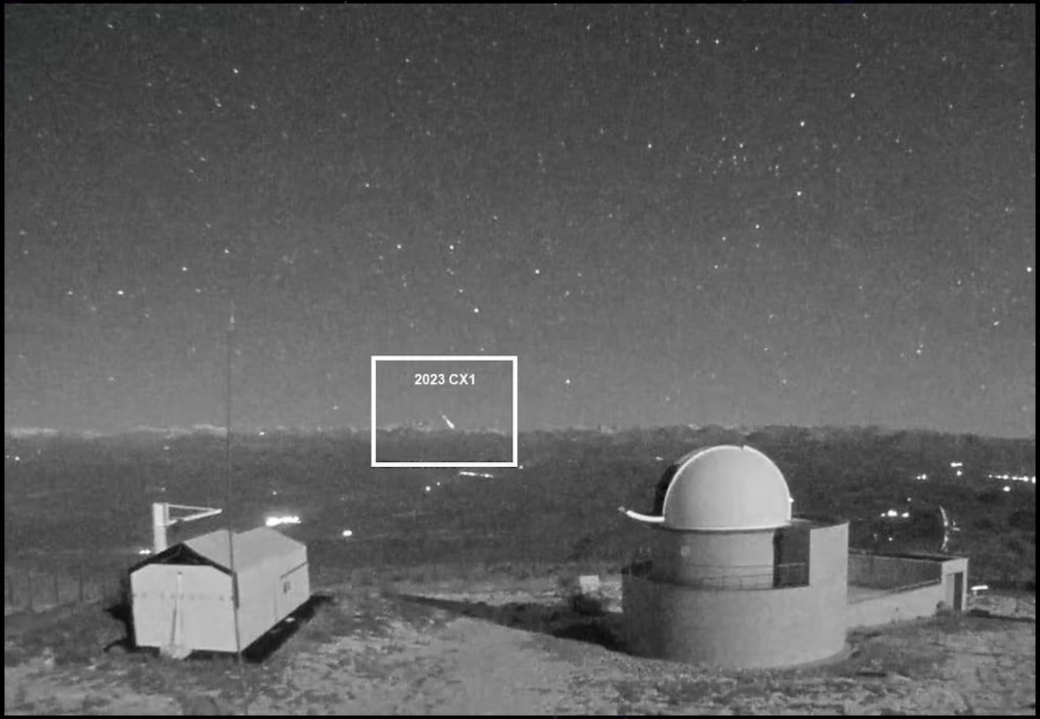


OBSERVATORI DEL MONTSEC



A RECENT REAL CASE: 2023 CX1

13 FEBRUARY 2023, 03:59 UTC



A RECENT REAL CASE: 2023 CX1

15 FEBRUARY 2023

Investigating the interior secrets of the Solar System

T. Santana-Ros
XXXVIII Trobades de la Mediterrània
Life in the Universe, Formation and Evolution of the Solar System and Exoplanets
Maó, 7 November 2023

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