NEOMIR: ESA's space-based infrared mission for NEO detection and early warning

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Approaches to planetary defence

US congress mandate to NASA:

- Discover 90% NEOs >140 m by 2020
  - ➡ Focus on larger objects
- According to models, we are below 50% - and would require other 30 years using current observational facilities

ESA’s Planetary Defence Office mandate on NEO detection:

- Discover all asteroids of $mag_V \leq 21.5$ in any given night
  - ➡ Equivalent to > 40 m at ~3 weeks distance
  - ➡ Focus on smaller objects

NEOs in the IR

Current NEO surveys are carried out from the ground in the optical domain

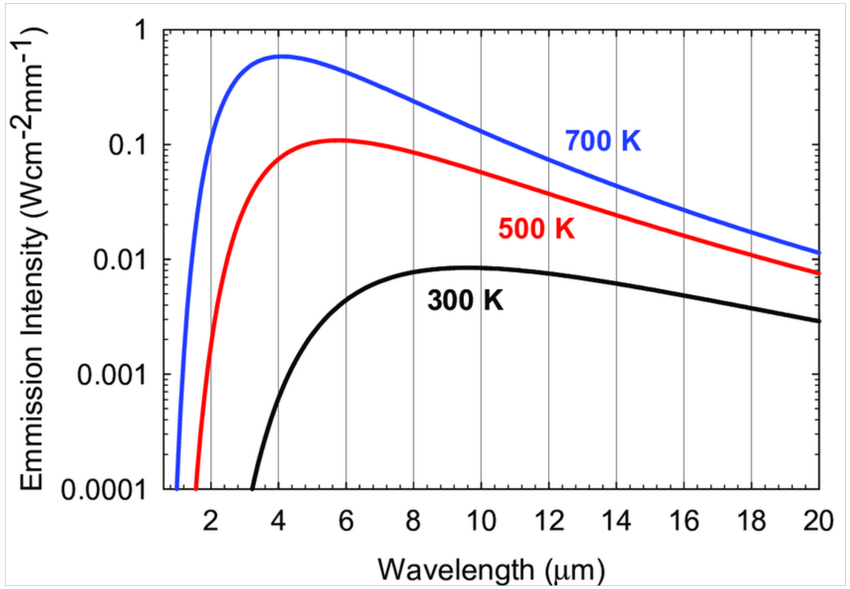
Main drawback: we can't observe objects at small solar aspect angle (Sun direction)

- Small portion of NEO surface to reflect sunlight
- Rayleigh scattering in atmosphere increases the sky background

One solution: go to space and observe the NEO thermal emission.

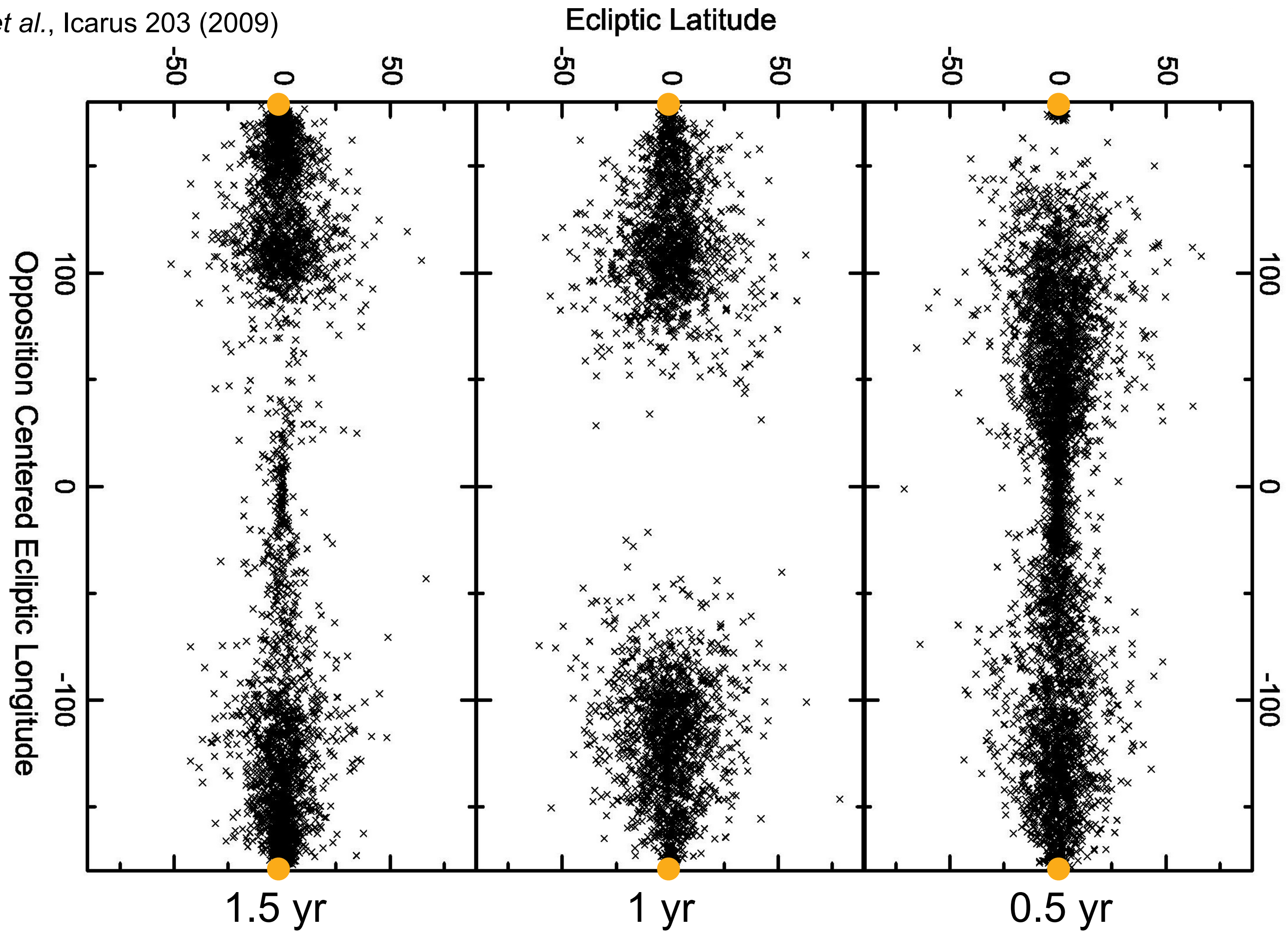
- Typical temperature: 200-400 K; peak between 6 and 9 µm
- Plus, less confusion from background stars & galaxies

However this requires more complex instrumentation, data handling, calibration, data processing, etc.



Impactor distribution - 1

Veres *et al.*, Icarus 203 (2009)



Distribution of impactors as a function of days to the impact.

As we get closer in time (and distance), the distribution is more uniform.

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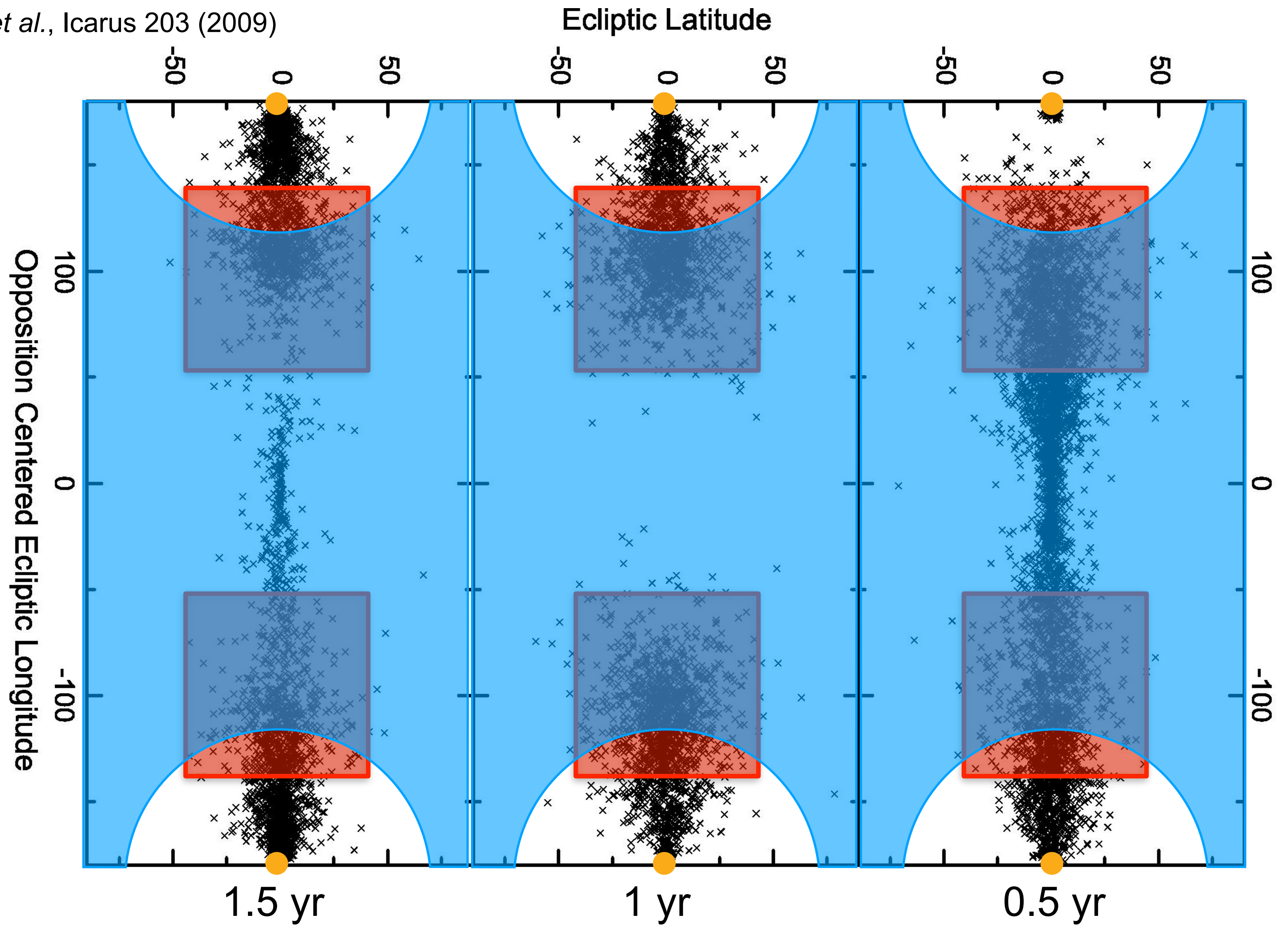

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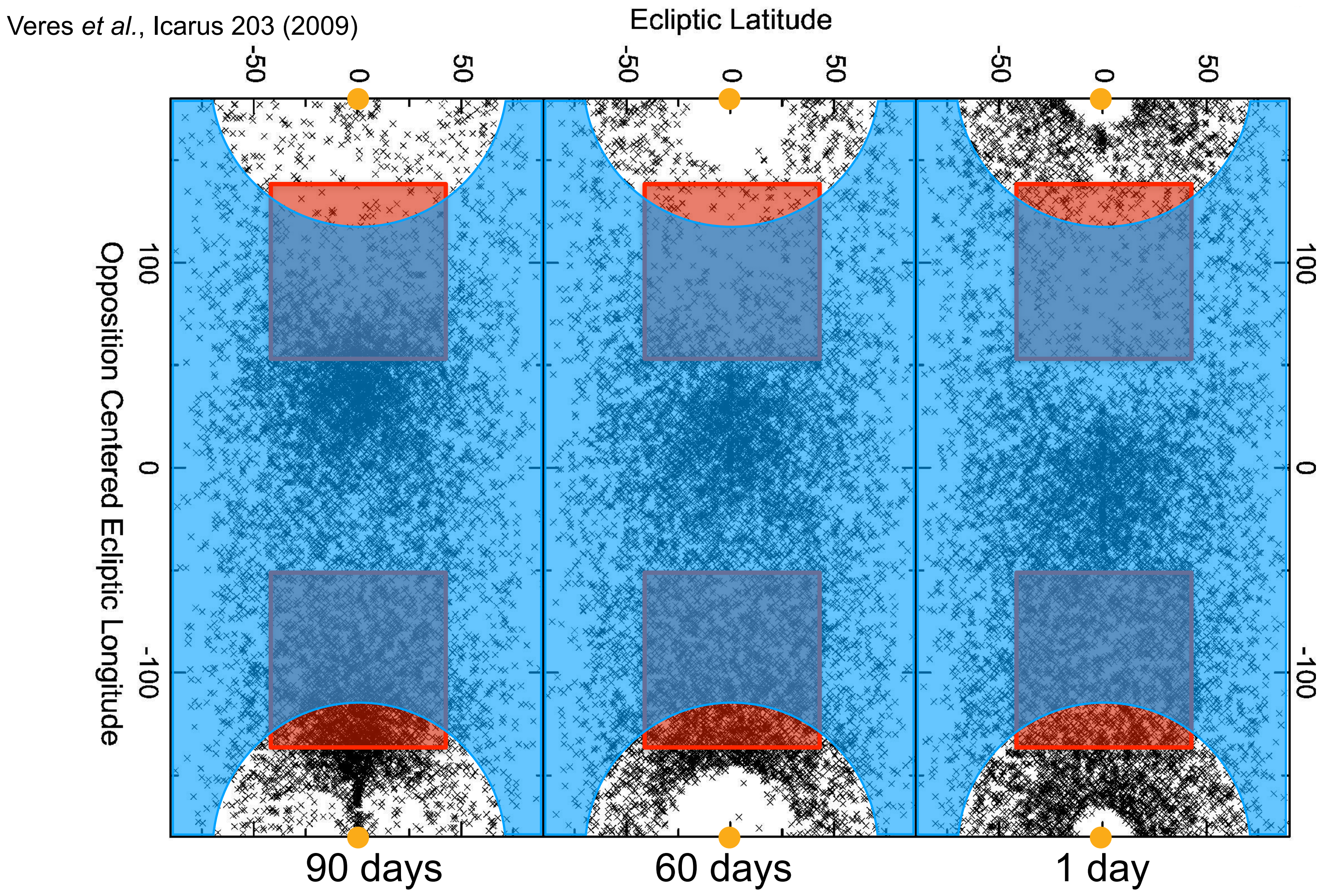
NEOSM Coverage

Ground Coverage

Impactor distribution - 2



NASA's NEOSM aims at finding NEOs when they are *distant*.

However, due to survey strategy revisit time, it may miss the *smaller* ones (below 100 m) - only observable when *closer*, thus *faster*.

NEOSM Coverage

Ground Coverage

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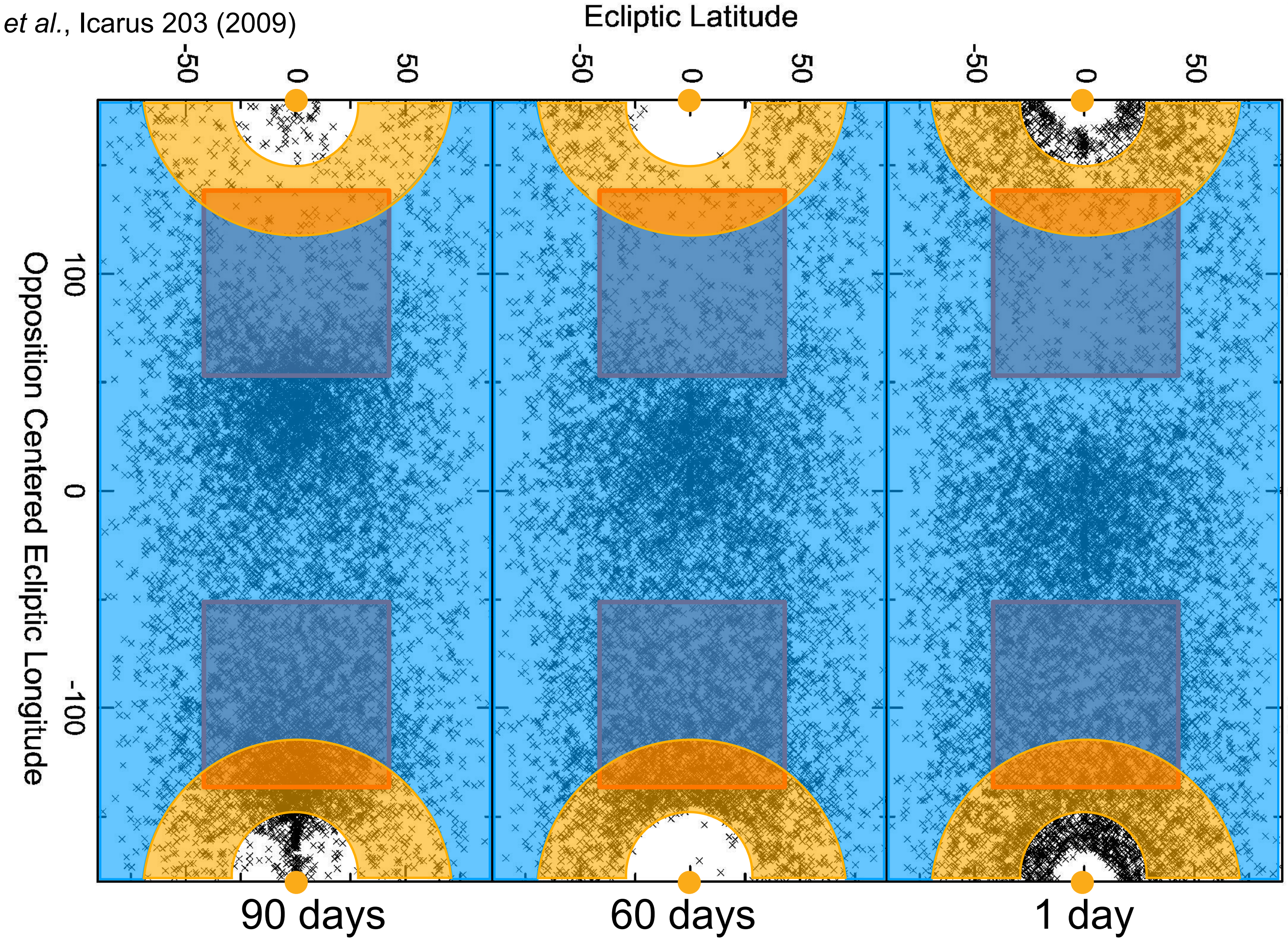

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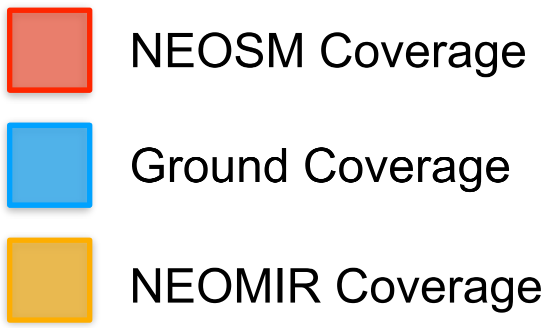


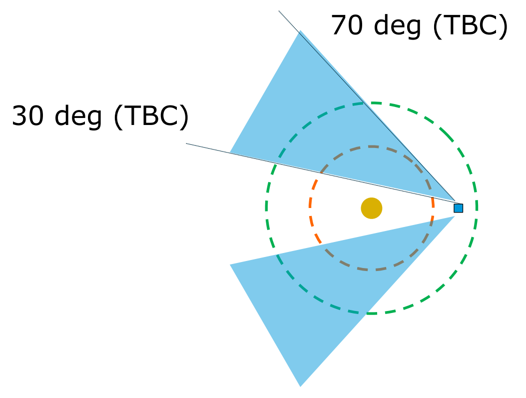
NEOMIR in a nutshell: mission design

2021: first study in ESA’s Concurrent Design Facility (phase 0)
2023: first studies by European industries (phase A1)
2024: started second round of studies (phase A2)

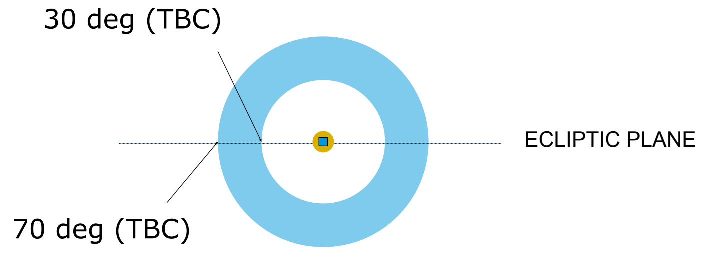
Out come of the studies regarding the mission design:

- Observatory at L1
- Spacecraft field of regard: 30º - 70º in solar elongation
- Multi-daily downlink; high data volume (similar to Euclid: up to 1.4 Gbit / day)
- Launch wet mass: ~2000 kg
- Launch with Ariane 6-2
- Launch possible in the early 2030s

View onto ecliptic plane



View through ecliptic plane



NEOMIR in a nutshell: payload design

Optics

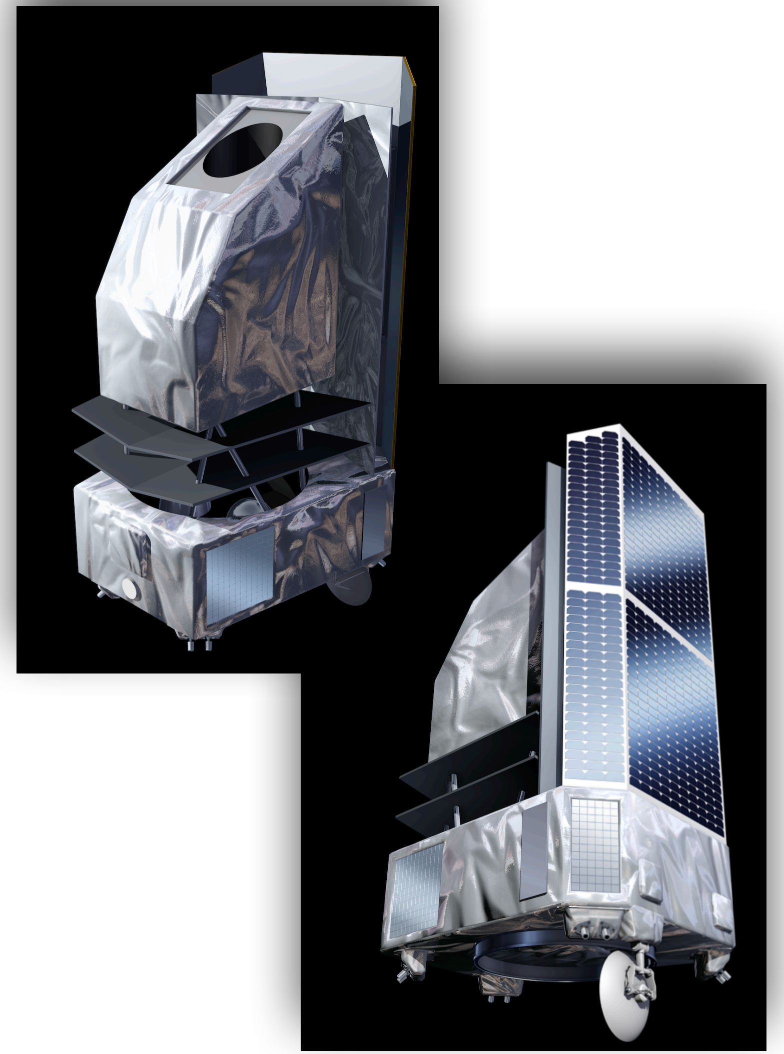
- Three-mirror anastigmat; M1 diameter is 50-60 cm
- Field of view: 1.7º x 7º
- PSF FWHM: 3”

Detectors

- 4 2k x 2k HgCdTe detectors covering one passbands: 6 - 10 μm
- Develop IR sensor capability in Europe
- Alternatively, use Teledyne HxRG

Thermal

- All payload (including telescope) passively cool down to ~55 K
- Detectors’ operating temperature: 40 K
- Trade-off being carried out for active vs passive cooling



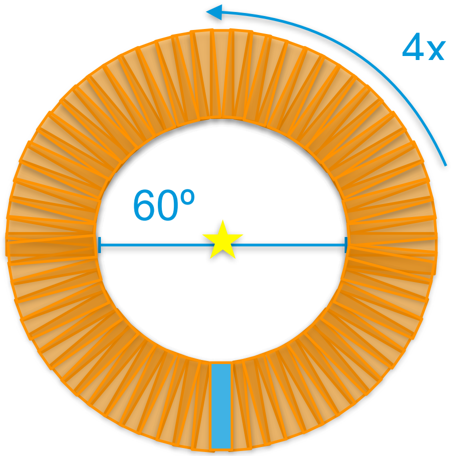
Classic observing strategy

In order to "intersect" as many potential impactors as possible, NEOMIR baseline survey strategy is to observe rings around the Sun at a fixed elongation (constant solar aspect angle).

In a classic observing strategy, each field (and thus ring) shall be observed at least 4 times to build a tracklet.

Pros: proven concept; much less data generated as exposures last typically 40-60 s each

Cons: NEO must be detectable in every exposure; plus if moving fast, it will trail: less flux per pixel, and more difficult to extract precise astrometry



Ring Band	Number of fields	Time required for 4 visits [h]
30º - 37º	127	11.3
37º - 44º	147	13.1
44º - 51º	165	14.6
51º - 58º	180	16.0
58º - 65º	192	17.1

Synthetic tracking

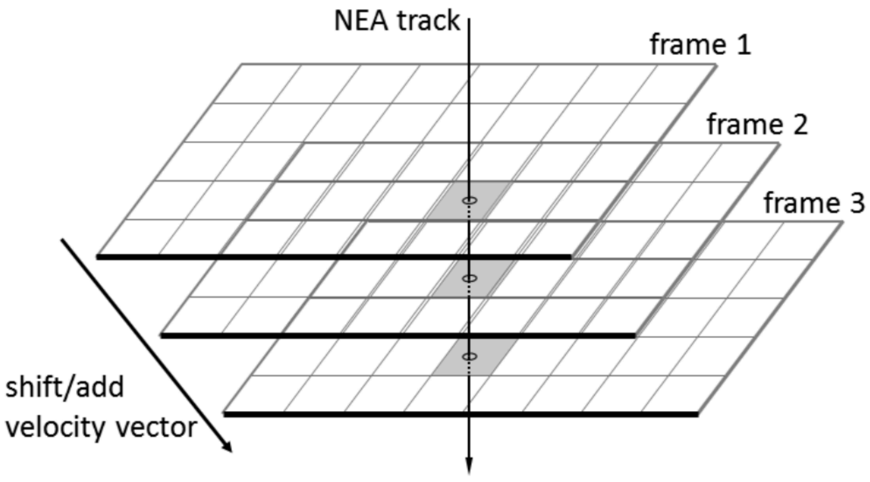
In this novel technique, many short exposures are taken. Then, all images are stack together via software trying many motion vectors. When the vector matches the NEO motion, this will look round-ish and easy to be detected.

Pros:

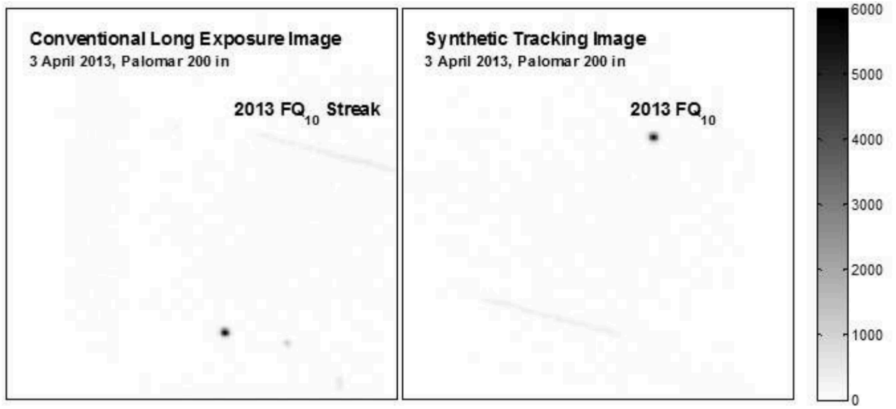
- gain up to a factor of 2 in SNR (assuming equal T_{exp})
- recover faster objects as exposures are shorter (5-10 s)
- potentially less S/C overhead as it is not needed to revisit a field 4 times (4x longer single visit)

Cons:

- readout overhead (for CCDs)
- much higher data volume
- need powerful GPUs to speed-up processing



Shao *et al.*, ApJ 782 (2014)



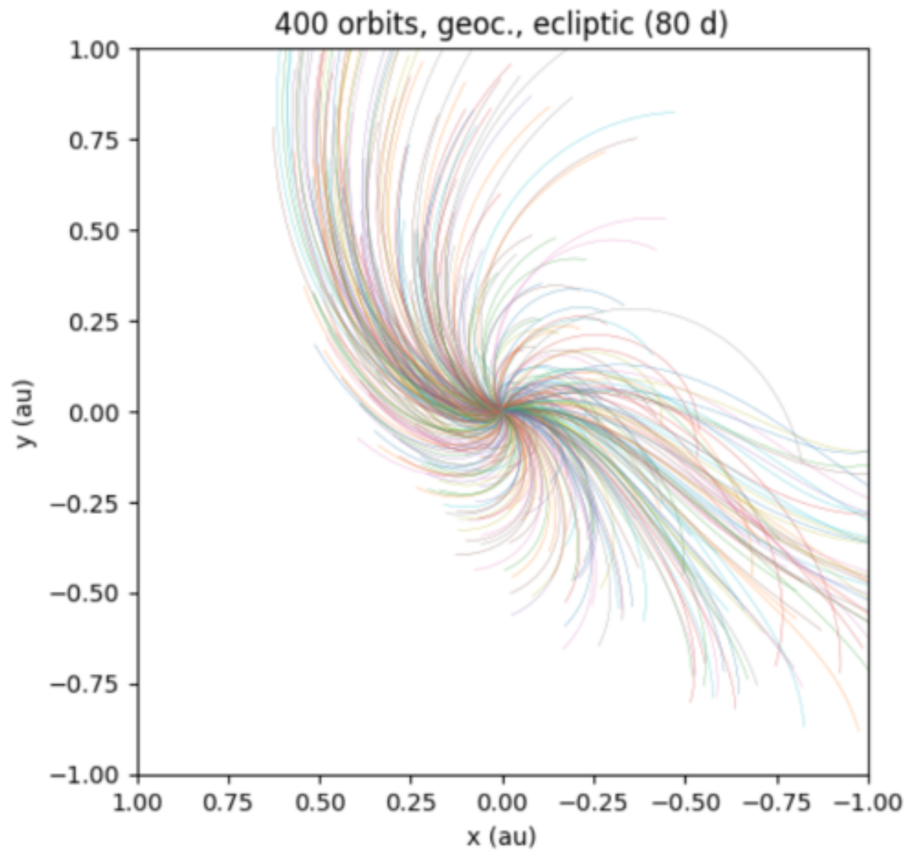
Simulating impactors detection

To assess NEOMIR detection capabilities, we used a list of 3000 impactors (see Chesley *et al.*, IEEE Aerospace Conference 2019)

- The list is representative in terms of orbit "distribution", not in frequency of the events
- We assume all objects to have same diameters, testing 2 values: 35 m and 15 m

We generated ephemerides for 60 days before impact in steps of 1 hour and selected all impactors that crossed NEOMIR's field of regard (30º ≤ SAA ≤ 70º).

Of the 3000 impactors, 1081 passed the criteria.



Synthetic impactors orbit in Earth reference frame

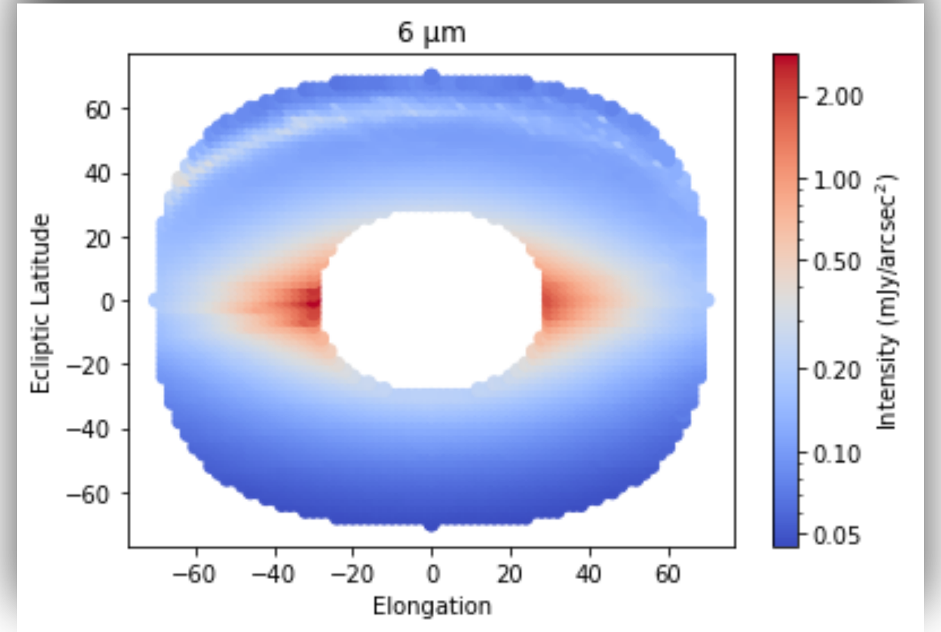
Signal & noise estimation

Signal estimation:

- Use thermo-physical model to estimate IR flux emitted by the asteroid
- Use orbital information to scale with distance
- Use a simplified instrument model to convert flux to photons

Noise estimation - Main components:

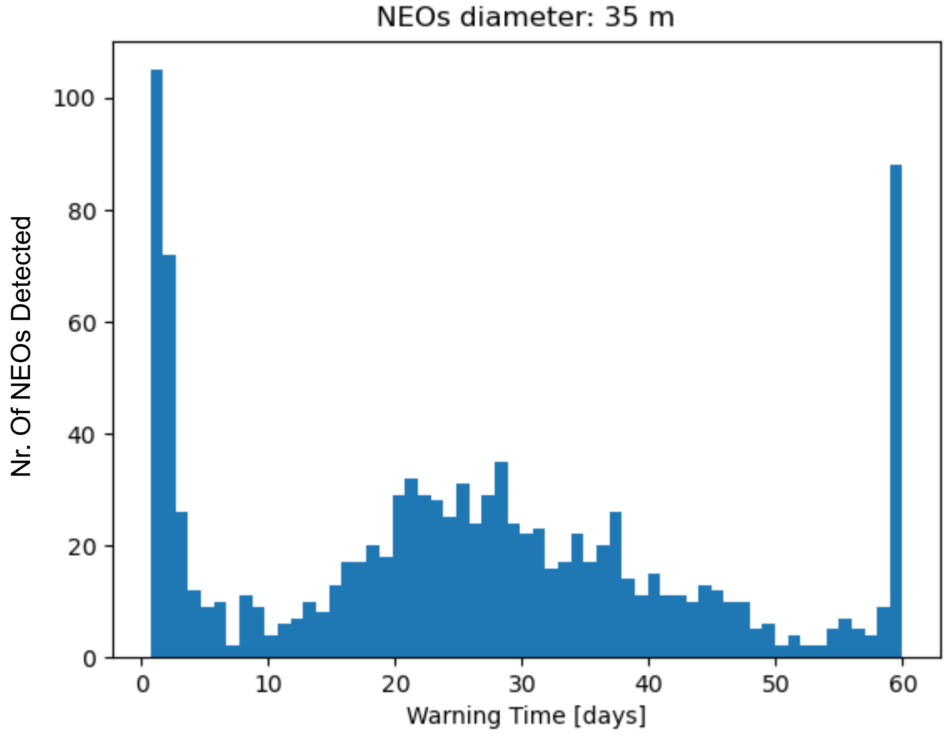
- Sky background (especially zodiacal light)
- Detector dark current
- Thermal and stray-light contribution

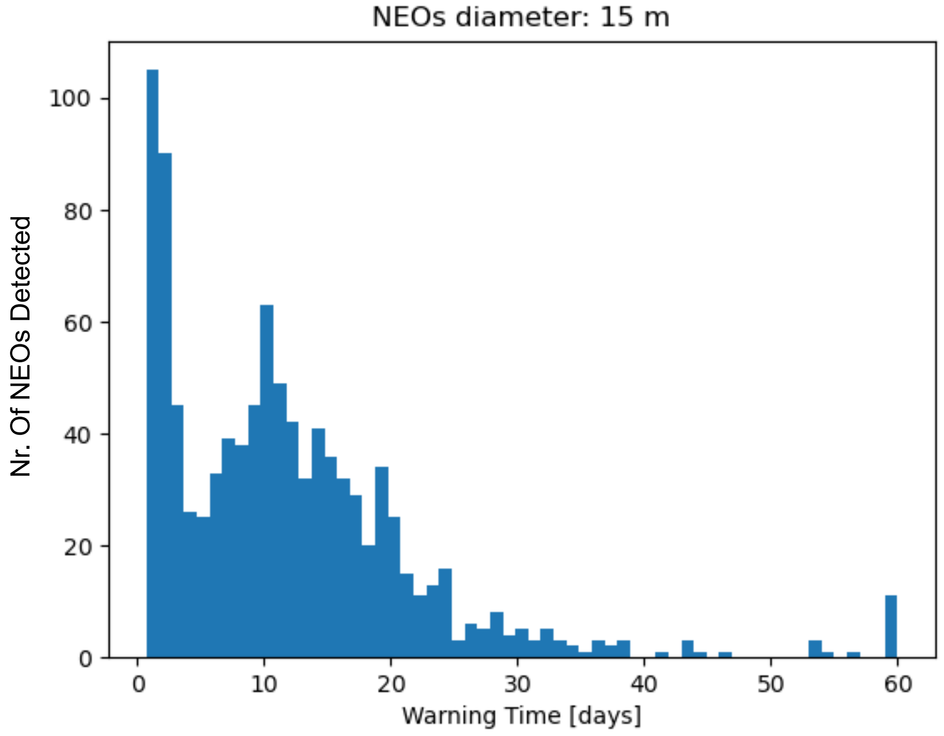


Overall sky background (Sun-centred)

Results

We assume that an object is detected if it has SNR > 5 while being in NEOMIR field of regard.



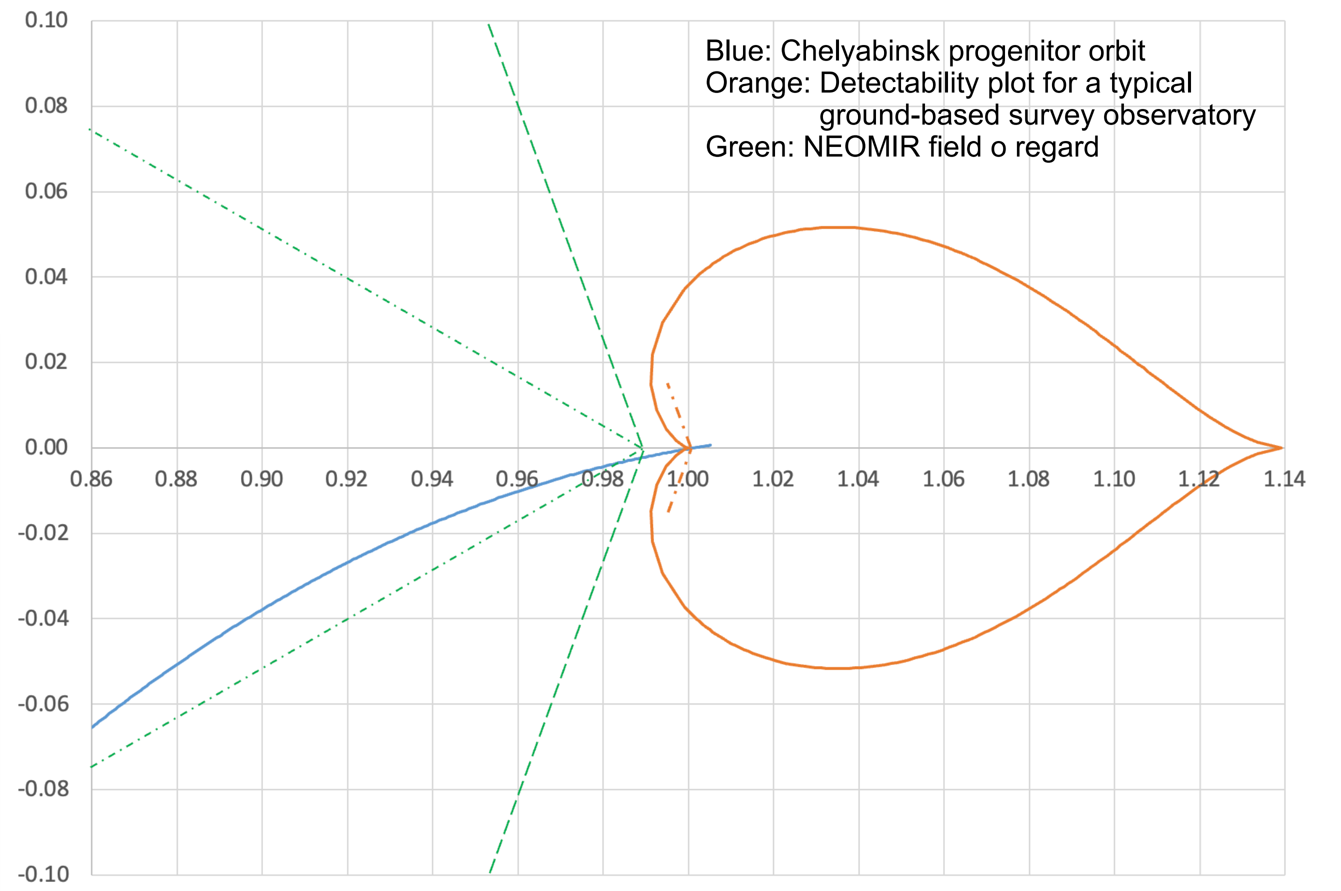


Assuming 35 m diameter, NEOMIR can detect 992 NEOs out to 1082 (92% success rate). ~180 are discovered ≤ 2 days before impact.

Assuming 15 m diameter, NEOMIR can detect 890 NEOs out to 1082 (82% success rate). ~200 are discovered ≤ 2 days before impact.

Could we detect Chelyabinsk?

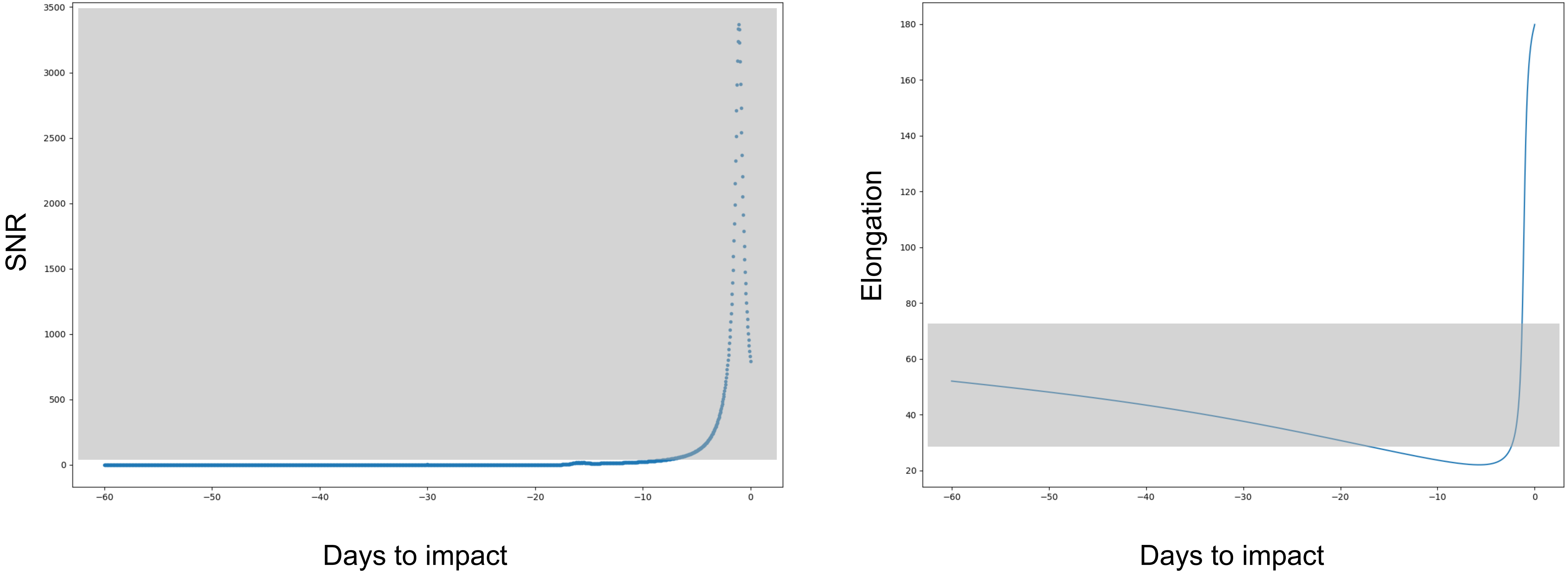
Finally, we used the same methods to verify if NEOMIR could have detected the Chelyabinsk progenitor, had it been operational in 2013.



Chelyabinsk progenitor orbit in Earth reference frame

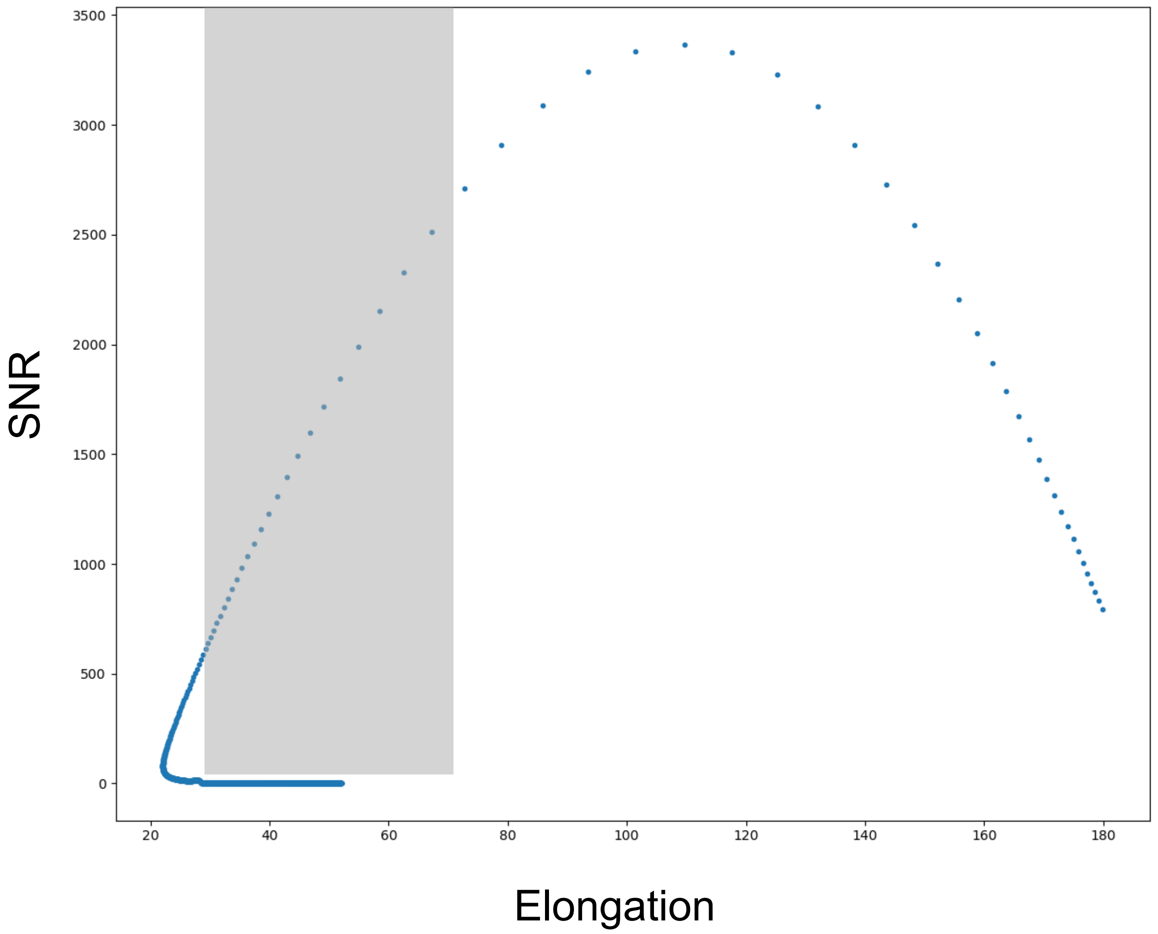
Chelyabinsk - SNR & Elongation

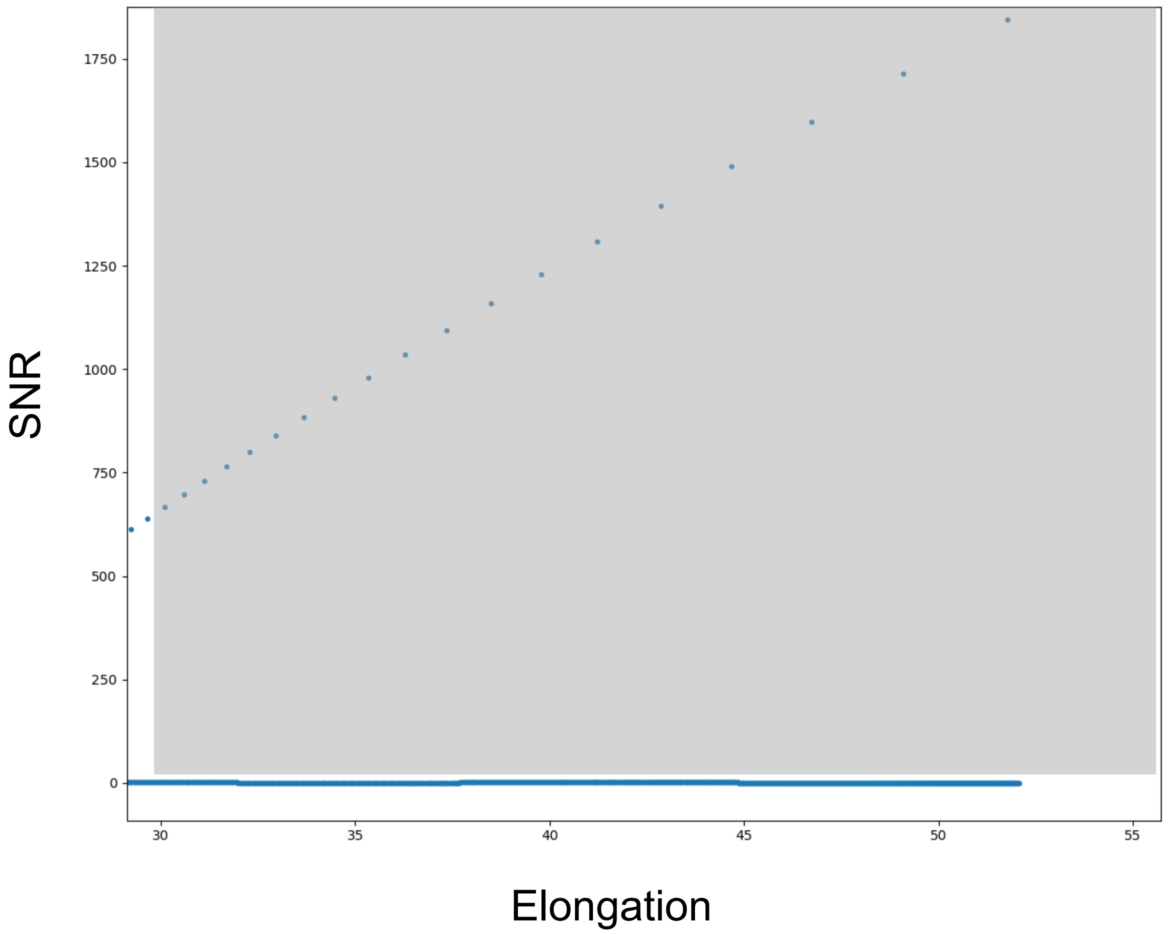
Shaded area: NEOMIR “visibility” zone



Chelyabinsk - Elongation vs SNR

Shaded area: NEOMIR "visibility" zone





Astrometric accuracy

Then we asked ourselves:

- Assuming NEOMIR detects an object, could we recognise it is an (impacting) NEO?
- Can we carry out ground-based follow-ups?
- Is the foreseen astrometric accuracy (0.3 arcsec) sufficient?

To answers these questions, we used the NEOMIR detected impactors and:

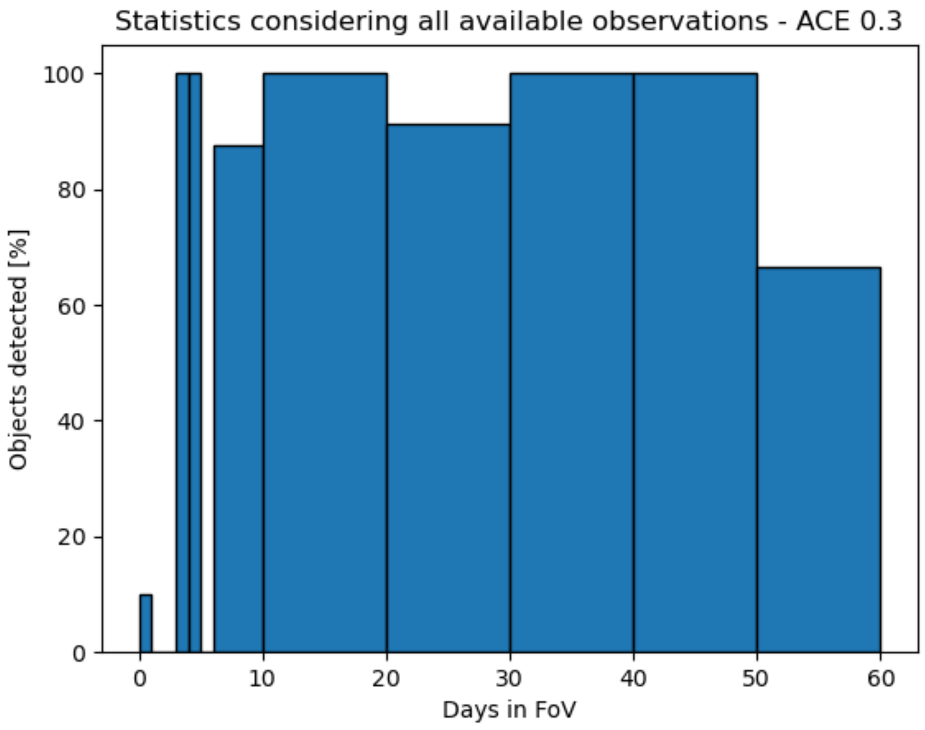
1. Query JPL Horizons to get their ephemerides from ACE or NEO Surveyor (both S/C in L1)
2. Add Gaussian noise (0.3 arcsec) to the observations
3. Fit orbit through *find_orb* program
4. Run a Monte Carlo to explore the uncertainty region and define the impact probability
5. Generate geocentric ephemerides to determine the possibility of re-observing from Earth

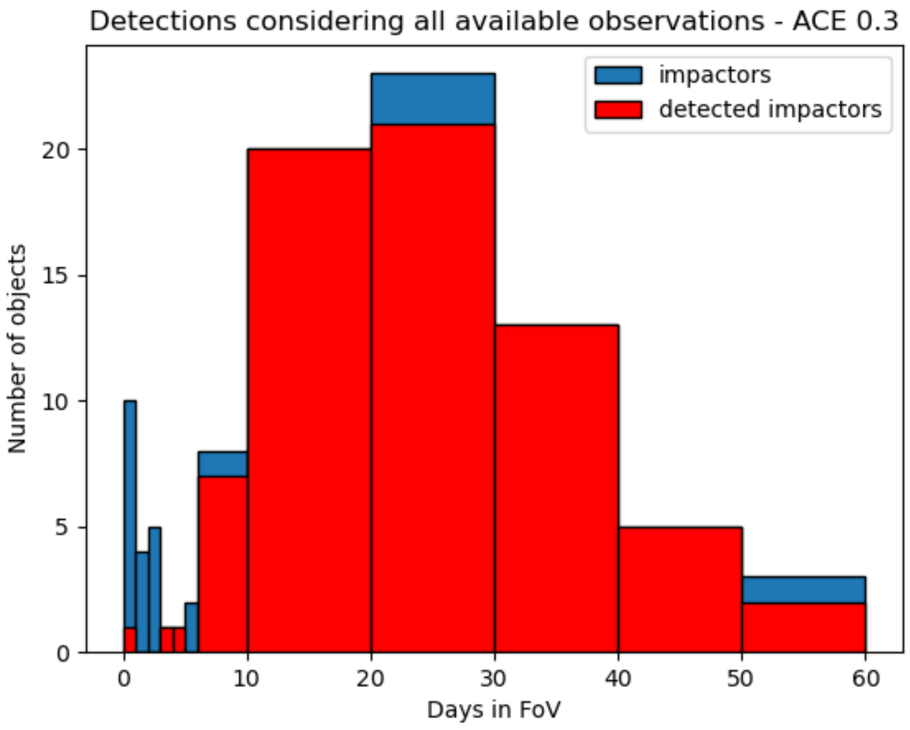
Time dependency of orbit convergence

Orbit fitting using the entire temporal arc for which the object remains observable by NEOMIR

Sample of 100 objects – 23 of these have an arc between 0 and 5 days

Object considered “detected” if its impact probability is > 0%

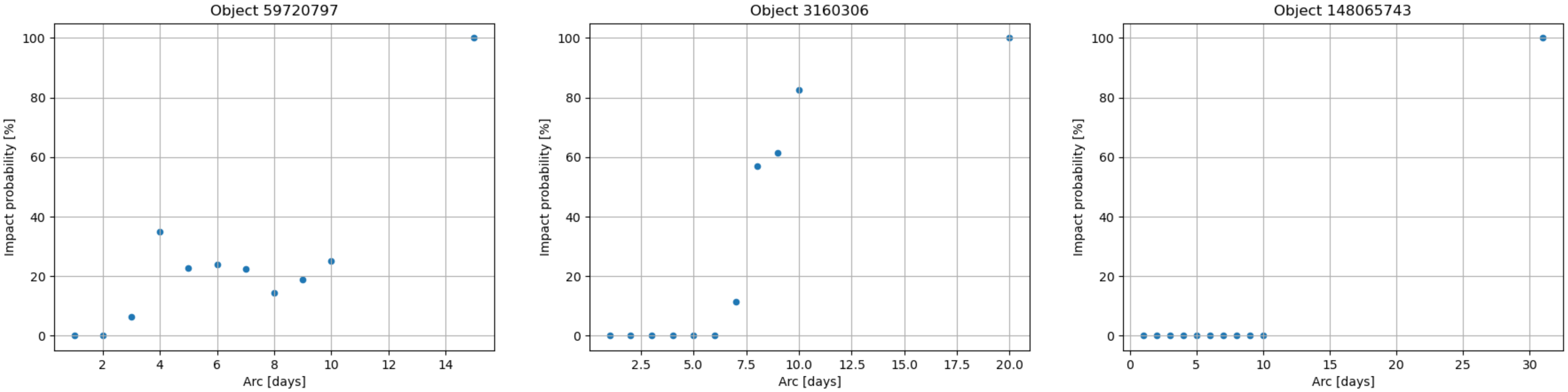




Evolution of the impact probability

How the impact probability evolves if a longer arc length is used

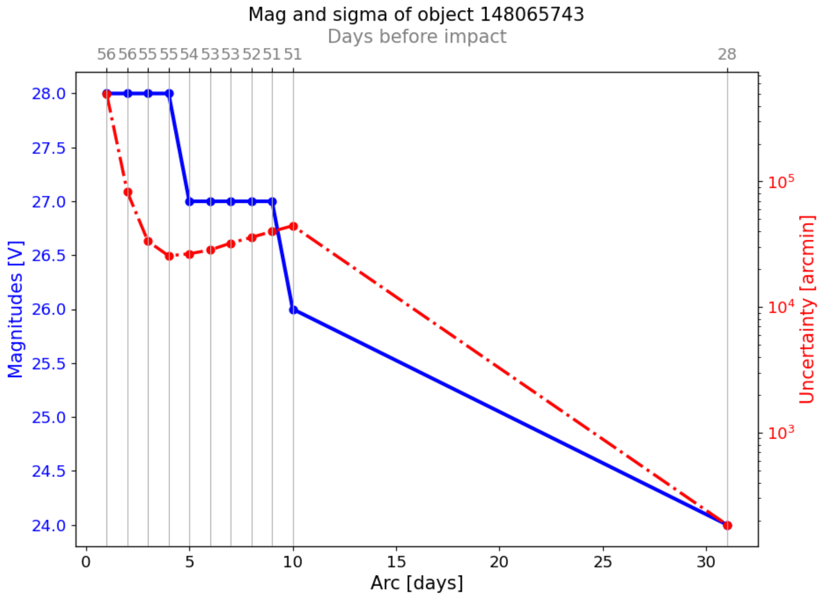
How many days of observations are necessary to categorise the object as impactor?

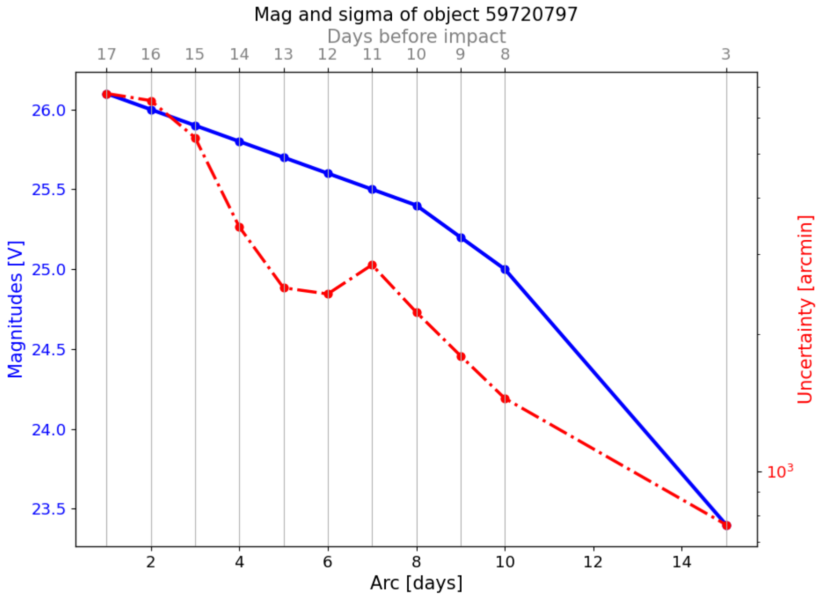


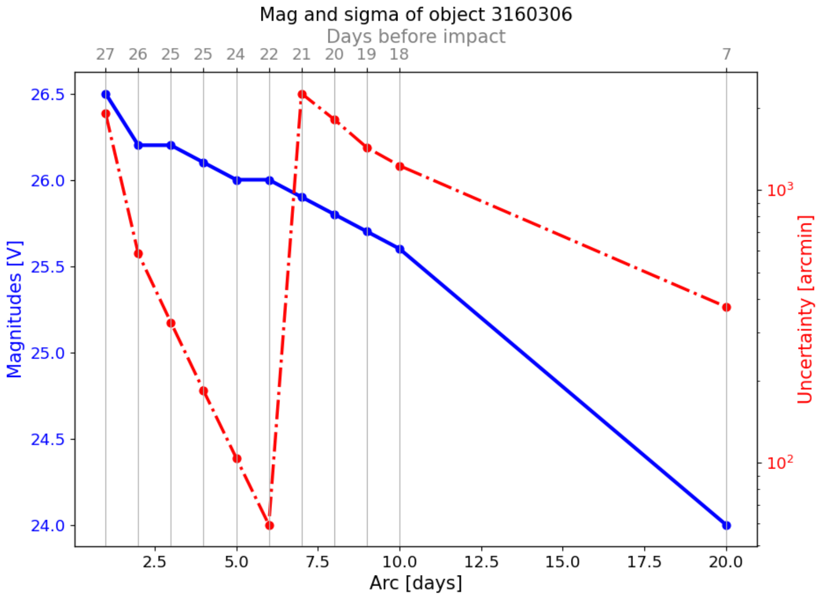
Observing from Earth

Evolution of magnitude and uncertainty of geocentric ephemerides (calculated from the obtained orbital fit) reported for the last day for which NEOMIR observed the object.

Is the object going to be observable from Earth? And if so, how many days before impact?



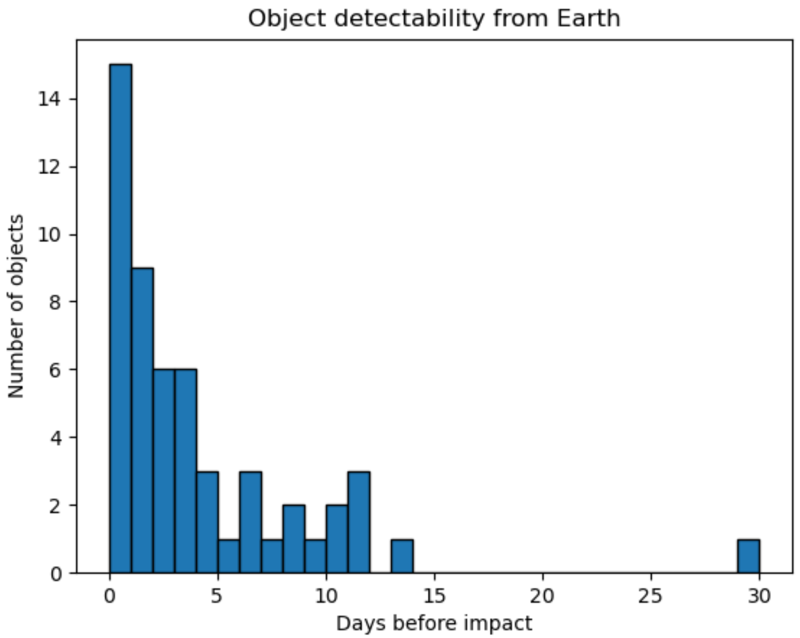


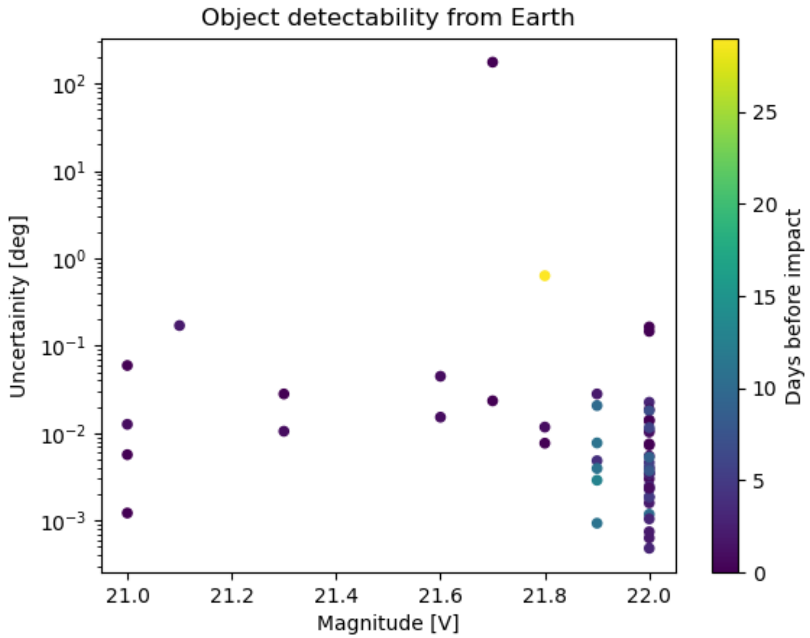


Detectability from Earth

Main challenge for Earth observation is the magnitude rather than the uncertainty

- Magnitude and ephemerides uncertainty obtained using the entire available arc
  - ➡ Uncertainties are much higher (up to tens of deg) using shorter arcs
- In this preliminary analysis, we assumed detectability only for $mag_V \leq 22$
  - ➡ 57% objects can be observed from Earth

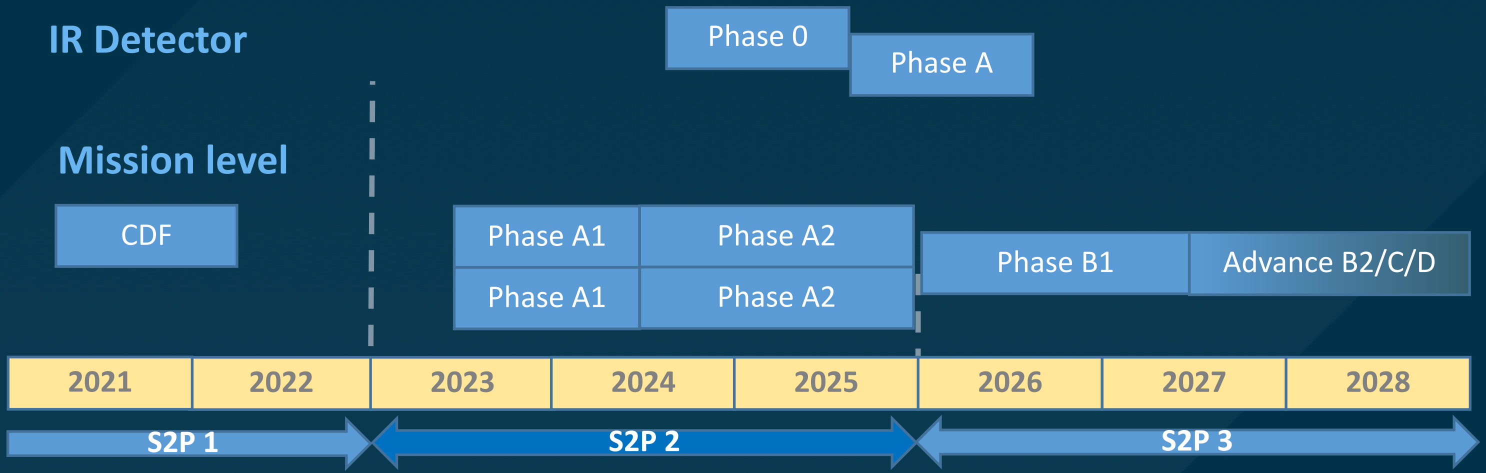




NEOMIR Roadmap

IR Detector development:

- Q2/2024: started Phase 0 study
- 2025/2026: start Phase A



Mission level studies (funds secured until B1 included):

- 2021: ESA internal study
- 2023: 2x Phase A1 studies + SAG creation
- 2024: 2x Phase A2 studies on-going + SAG support continuation
- 2026: start of Phase B1 study ("mission definition" phase)
- 2027+: B2/C/D/E (mission adoption, operations, etc.)

Conclusions

ESA is continuing the study for a space-based infrared mission for NEO detection, characterisation and early warning: NEOMIR. It is a cryogenic mission working in thermal infrared (6-10 μm) focused on detecting smaller potential impactors. Funds are secured for up to phase B1.

Preliminary sims show that:

- it has ~92% probability of detecting impactors of 35 m diameter coming from the Sun direction, allowing on average 3 weeks' warning time.
- If the diameter is 15 m, it can detect ~82% of the objects with 10 days' warning time, on average.
- Of these, it can determine the orbit of ~75% of the detected ones, without any follow-up needed.
- Follow-up can be carried out for 57% of the objects, assuming a pessimistic limiting magnitude of 22

Further analyses are required, especially w.r.t.:

- IR detector development is required for a fully European S/C
- Survey and observing strategies