SMPAG Meeting February 2020: Mapping of threat scenarios to mission types

Prepared by	**Michael Fruehauf**
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Table of contents:

1 INTRODUCTION

This work is creating a set of reference deflection missions for potentially impacting NEOs, which can be used as basis for decision-making in case of an upcoming impact event. With the current developments for the AIDA mission [1], a Kinetic Impactor is the most realistic, non-nuclear, available deflection options. Hence we concentrate on objects for Kinetic Impactor missions, based on Figure 1 [2] and using NEOs from ESA's risk list[1] (29 January 2020). Therefore we analyse humankinds current deflection possibilities for real threat scenarios.

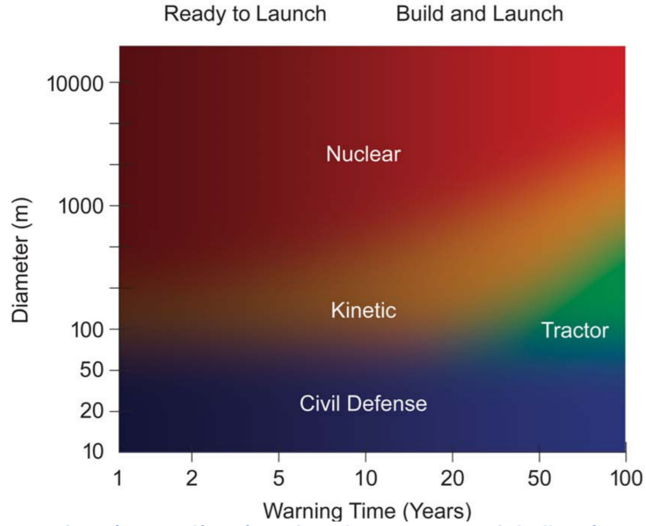

Figure 1: Rough regimes of main application for three types of deflection, depending on the NEO diameter and warning time. [2]

2 METHOD

2.1 Miss distance

For each potentially impacting NEO of ESA's risk list, we use the orbital elements of the associated virtual impactor from NEODyS[2] with the highest impact probability, since may objects have multiple potential impacts. Hence, whenever a NEO is mentioned below, we speak about the specific virtual impactor and not about the object defined by the MPC Orbit Database[3]. The velocity of the NEO is modified to obtained a central impact on Earth with a distance of closest approach to Earth's centre $DCA < 0.09R_{\oplus}$, where $R_{\oplus}$ is the radius of Earth (detailed numbers in Table 5). This procedure is required due to differences in the propagator tools. As a result we rule out comparatively easy situations of grazing impacts and providing roughly similar conditions for deflections to any direction.

[1] http://neo.ssa.esa.int/risk-page
[2] https://newton.spacedys.com/neodys/
[3] https://minorplanetcenter.net/db_search

We solve Lambert's problem to derive the hyperbolic excess speeds of Earth $v_{\infty,\oplus}$ and the NEO $v_{\infty,NEO}$. Assuming a Ariane 5G+ as launch vehicle, launching from Guiana Space Centre (CGS), we can compute the payload mass m_p (Kinetic Impactor) by using $v_{\infty,\oplus}$. The performance of the Ariane 5G+ is shown in Figure 2 . Combining $v_{\infty,NEO}$ and m_p leads to the momentum of the Kinetic Impactor. We do not assume an additional velocity gain by the gravitational attraction of the NEO. The mass m_{NEO} of the NEO (simplified as a sphere) is derived by the expected diameter, listed in ESA's risk list, and a homogeneous density of $\rho_{NEO} = 2700\frac{kg}{m^3}$ [3]. Due to momentum conservation, the new velocity of the NEO is derived by using $m_{NEO}\Delta v = \beta m_p v_{\infty,NEO}$, where Δv is the velocity change of the NEO [4]. In the simulation, we use specific $\beta \in [1,2,3,4,5,8,10,15,20,25,30,40,50]$ as momentum enhancement factors. Finally, the "deflected" object is propagated, using the gravity of all planets and the Moon, and tested for an impact on Earth. If no impact occurs, the distance to Earth's surface, which we call the miss distance d, is computed. This is done for a range of departure and arrival dates, starting on 1 January 2021, with 14 days steps size. The result is a porkchop plot showing the miss distances for departure and arrival dates, depending on the assumed β.

For all β, we extract the best launch date to a achieve the maximum miss distance d_{max}. Yet, huge miss distances are not necessarily needed, but even a smaller d might be enough to save Earth. We set the minimum needed miss distance to save Earth to $d = 1R_\oplus$. Now we can extract the latest launch date to obtain at least one Earth radius miss distance. Using this data for various β, we can estimate the minimum required β_{req} to deflect the NEO by $1R_\oplus$.

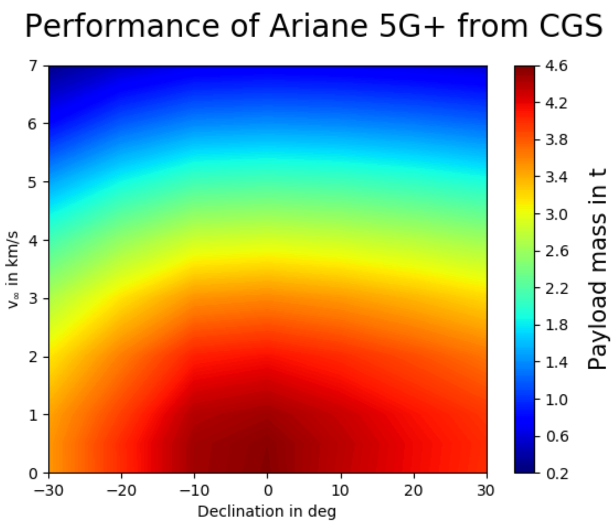

Figure 2: Performance of Ariane 5G+, launched from Guiana Space Centre (CGS). The Payload mass in tons depends on the Declination and required v_∞.

2.2 Telescope observation possibilities

The telescope observation possibilities are derived with the absolute magnitude of the virtual impactor, given by NEODyS. The visual magnitude is computed for a hypothetical station at the centre of the Earth and set to a limit of 27 mag. The object is set to non-visible if the solar elongation is smaller than 40 degree [5]. The earliest observation is set to 1 January 2020. Using the latest launch dates for specific β, we can determine the latest telescope observation possibilities, after which we cannot get more information without using in-situ observation missions.

3 RESULTS

3.1 Detailed example 2019AF14

An example for a porkchop plot can be seen in Figure 3 for the NEO 2019AF14 with a potential impact on 10 June 2028. The plots differ by the enhancement factors $\beta \in [1,5,10,20]$. One can see the different islands for effective deflections. Due to the orbit condition of the NEO, they are arranged in lines of arrival years. Larger β lead to larger miss distances and later arrival years result in lower miss distances. The white cross marks the largest miss distance d_{max}, which can be achieved for the used β. In this case, the maximum miss distance would be approximately $d_{max} \approx 6R_{\oplus}$ and would require a launch in early-2021 and an arrival in early-2023. As $6R_{\oplus}$ miss distance might not be required, but even less is sufficient to save Earth, we mark the latest launch date to obtain at least $1R_{\oplus}$ miss distance with a white X. This date is changing with β and is in this example we get for $\beta = 20$ mid-2024 and $\beta = 10$ mid-2020. Lower plotted β do not achieve $d > R_{\oplus}$.

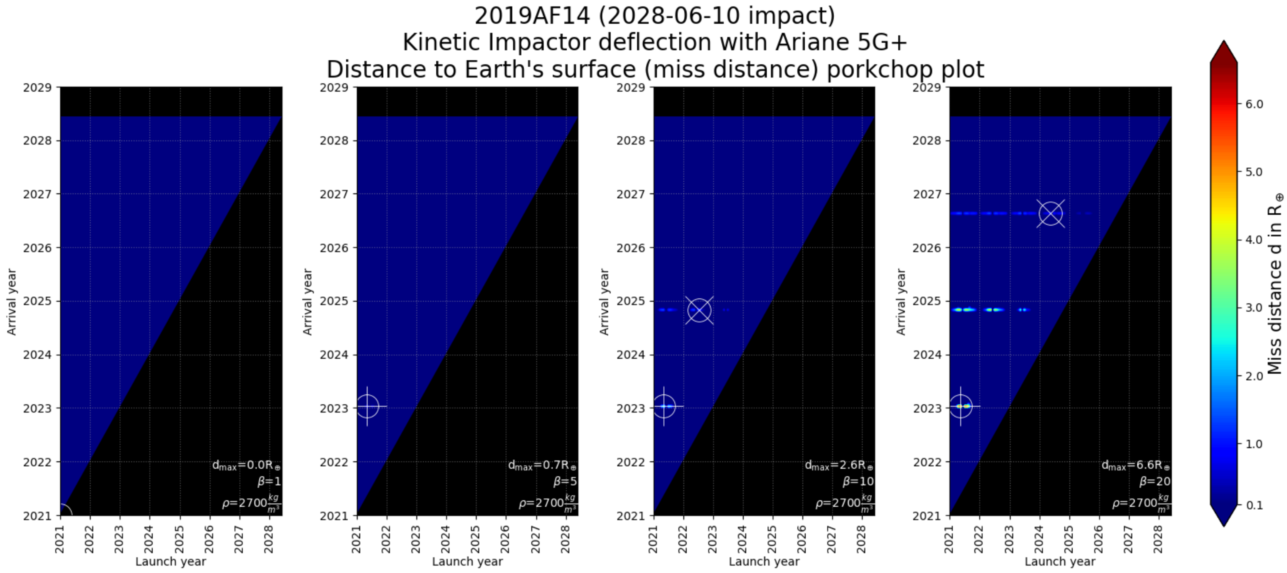

Figure 3: The figure shows porkchop plots for various momentum enhancement factors β of the virtual impactor of 2019AF14 for an impact on 10 June 2028. The density of the spherically approximated NEO is set to $\rho_{NEO} = 2700\frac{kg}{m^3}$. The black area marks physically unreasonable solutions. Other colours show the miss distance d (distance to Earth's surface) in Earth radii $R_{\oplus}$. The white cross shows the largest miss distance and the white X the last launch option to achieve $1R_{\oplus}$ miss distance.

The best miss distance for each momentum enhancement factor β, obtained from the simulations, are plotted in Figure 4 as blue dots for 2019AF14. The red dashed line shows a linear interpolation of the non-zero miss distance data points. Hence, in this example we exclude the data points for the lowest 3 β values for the fit. We can approximate the minimum required beta β_{req} to achieve $d = 1R_{\oplus}$. In this example we get $\beta_{req} \approx 6$.

The observation windows of 2019AF14 are shown in Figure 5. The blue curve indicates the apparent magnitude, while the black area marks the time after the impact on Earth. The grey lines (solid, dashed, dash-dotted, dotted) mark the latest launch dates to achieve $d = 1R_{\oplus}$ for the associated momentum enhancement factors $\beta \in [1,5,10,20]$, computed above. If $\beta = 20$ can be reached for a deflection mission, the last observation possibility before the launch starts about one year before and reaches almost to the launch date in early-2024. In contrast, $\beta = 10$ does have a gap of roughly half a year between the latest observation possibility and the launch in mid-2022. Only in-situ observation missions could generate more information in between to rule out the impact on Earth and make the deflection mission unnecessary.

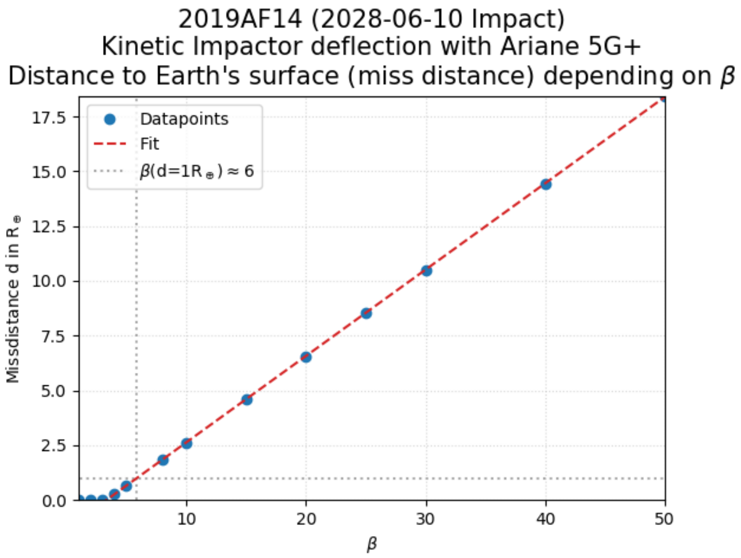

Figure 4: The plot shows the maximum miss distances d in Earth radii $R_{\oplus}$ for certain momentum enhancement factors β of 2019AF14 for an impact on 10 June 2028. The blue dots mark the data derived from the simulations. The red dashed line shows a linear fit through data points of non-zero miss distances. We can approximate the minimum required β_{req} to obtain $1R_{\oplus}$ miss distance. For this example we get $\beta_{req} \approx 6$.

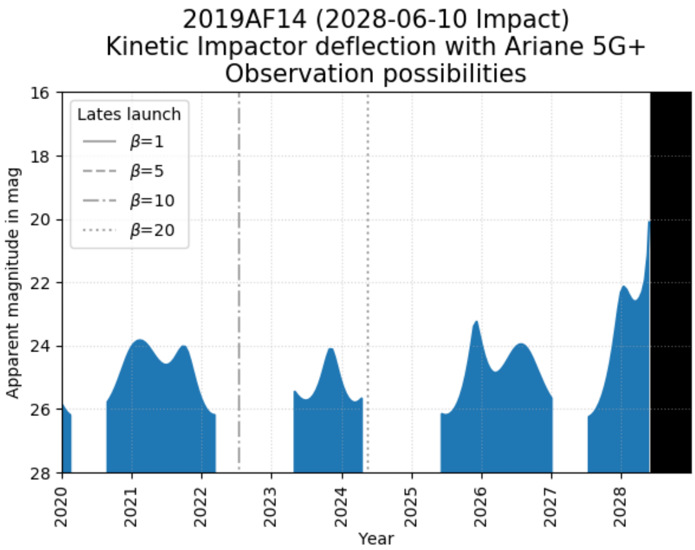

Figure 5: The plot shows the apparent magnitude of 2019AF14 for an impact on 10 June 2028, depending on the observation date. The black area marks the time after the impact on Earth. The grey lines (solid, dashed, dash-dotted, dotted) indicate the last launch dates for the associated momentum enhancement factors β.

3.2 All results

Table 1 shows the solutions for all NEOs in ESAs risk list (29 January 2020) which fit to the Kinetic Impactor regime of Figure 1. It lists the Designation of the NEO, its estimated diameter, the potential impact date and the required momentum enhancement factor β_{req}. For the computed β, which is closed to the β_{req}, the latest launch date, the Kinetic Impactor mass m_p, the hyperbolic excess speed for the launch at Earth $v_{\infty,\oplus}$ and arrival at the NEO $v_{\infty,NEO}$ and the last observation date are given. The white NEOs have not been computed and the "-" indicates that no data could be computed with the used computation setup. In total, we analysed 27 out of 35 objects. All objects are categorized in 3 groups, depending on their β_{req}, with green $\beta_{req} \leq 3$, yellow $3 < \beta_{req} \leq 10$, red $10 < \beta_{req} \leq 50$ and grey $\beta_{req} > 50$.

Risk-list NEOs of the gravity tractor regime are listed in Table 2 and of the nuclear detonation regime in Table 3, without further analysis.

Table 4 shows an analysis about the latest launch dates of Table 1, where we use the categories from above and the information for each NEO of the computed $\beta \in [1,2,3,4,5,8,10,15,20,25,30,40,50]$ closest to the derived β_{req}. 30% (8 NEOs) of the scenarios require momentum enhancement factors smaller or equal 3. 4 NEOs (50%) of the $\beta_{req} \leq 3$ have their latest launch date in the year 2032 or later. In contrast, 22% (6 NEOs) of the full set are in the category $10 < \beta_{req} \leq 50$ and 4 (66%) of them have their latest launch year before 2024. The largest group is the $\beta_{req} > 50$ with 9 NEOs (33%). For those objects no detailed information could be derived, since no computation was done for $\beta > 50$ for this work.

Object Designation	Diameter in m	Pot. Impact Date	β_{req} ($1R_{\oplus}$)	Closest to β_{req} ($1R_{\oplus}$)					
				β	Latest Launch Date	m_p in t	$v_{\infty,\oplus}$ in km/s	$v_{\infty,NEO}$ in km/s	Last Obs. Date
1979XB	700	2113-12-14							
2001CA21	600	2045-10-12	5.4	8	Jun. 2031	3.3	3.4	41.0	Apr. 2031
2006CD	290	2032-07-04	17.3	20	Oct. 2022	2.9	3.9	15.8	Oct. 2022
2007FT3	300	2024-10-02	>50	-	-	-	-	-	-
2007VH189	80	2042-06-05	1.0	1	Jun. 2038	1.4	6.0	19.2	Jan. 2036
2008KN11	90	2045-06-20							
2010CR5	300	2062-01-01							
2010DG77	315	2059-01-08	1.5	2	Mar. 2036	3.7	2.3	15.4	Jul. 2031
2010MA113	903	2068-08-02	7.4	8	Nov. 2036	4.1	1.7	30.0	Mar. 2031
2010MY112	372	2030-12-23	20.9	25	May 2022	4.0	2.1	22.4	May 2022
2010XB73	150	2037-06-01	4.7	5	Aug. 2021	3.2	3.4	9.9	< 2020
2011BT59	240	2052-04-10	1.0	1	Jul. 2043	3.3	3.4	47.6	Mar. 2042
2012CR	160	2025-05-20	>50	-	-	-	-	-	-
2014HN197	400	2031-01-04	55.9	-	-	-	-	-	-
2014JU79	110	2041-10-03	1.5	2	Sept. 2028	3.3	3.3	7.0	Aug. 2027
2015HV182	230	2045-09-04							
2015ME131	400	2027-08-18	>50	-	-	-	-	-	-
2016JR38	150	2022-11-11	>50	-	-	-	-	-	-
2016NL56	600	2078-02-14							
2016PR66	80	2026-05-11	1.0	1	May 2021	2.2	4.7	5.7	May. 2021
2016RP41	110	2022-12-22	>50	-	-	-	-	-	-
2016WN55	400	2032-09-12	>50	-	-	-	-	-	-
2017DA120	300	2024-09-13	>50	-	-	-	-	-	-
2017MA9	150	2042-11-23	1.0	1	Feb. 2036	2.0	5.1	15.8	Feb. 2036
2017QC36	190	2024-02-20	14.4	15	May 2021	3.5	3.0	32.5	Nov. 2020
2017RZ17	300	2029-11-26	10.8	15	Mar. 2024	3.1	3.7	27.2	Feb. 2024
2017SC33	120	2029-03-03	1.0	1	Jul. 2021	3.0	3.6	23.8	Jul. 2021
2017SD33	400	2085-07-21							
2017UG52	400	2047-06-19	12.9	15	Jun. 2028	3.9	2.4	17.0	Aug. 2027
2018LF16	290	2023-08-07	>50	-	-	-	-	-	-
2018LH16	220	2025-12-06	24.4	25	Dec. 2021	4.1	2.0	8.1	Dec. 2021
2018YH2	90	2038-07-14	1.0	1	Sept. 2029	3.0	3.7	13.1	Jul. 2027
2019AF14	200	2028-06-10	5.9	8	Aug. 2021	2.9	4.1	13.4	Aug. 2021
2020BC8	400	2085-01-25							
99942	375	2068-04-12							

Table 1: The table lists all results for NEOs in ESA's risk list (2020-01-29) in the Kinetic Impactor regime. Non-computed objects are white. "-" indicates that no data could be derived with the used computation setup.

Object Designation	Diameter in m	Pot. Impact Date	Object Designation	Diameter in m	Pot. Impact Date
1999RZ31	70	2056-09-05	2009BR5	130	2078-07-19
2001SB170	100	2095-03-17	2010GM23	341	2105-04-15
2001UD5	120	2107-10-10	2010HS20	70	2071-07-01
2002GM5	130	2064-10-03	2010HV20	465	2116-05-05
2002RB182	70	2110-09-27	2010RA91	80	2104-03-24
2004GE2	160	2106-05-03	2011VG9	110	2086-11-01
2005CC37	100	2117-01-13	2011XC2	80	2056-12-02
2006CM10	150	2092-08-12	2012QD8	90	2047-03-08
2006WM3	70	2113-12-20	2013NH6	80	2060-06-29
2007KO4	80	2046-11-23	2014MO68	70	2108-08-07
2007PR25	130	2094-08-18	2014UX34	110	2084-10-18
2007TC14	140	2082-10-22	2014XM7	90	2115-12-27
2007WP3	80	2105-11-12	2016AF9	130	2083-12-23
2008EX5	90	2083-10-09	2016JT38	300	2103-10-22
2008FF5	90	2060-03-27	2016WG	80	2076-06-23
2008PK9	80	2057-08-10			

Table 2: The table lists all results for NEOs in ESA's risk list (2020-01-29) in the gravity tractor regime.

Object Designation	Diameter in m	Pot. Impact Date	Object Designation	Diameter in m	Pot. Impact Date
2001VB	700	2023-07-23	2017SH33	700	2026-04-30
2010JA43	478	2023-01-07	2017SM33	600	2021-03-18

Table 3: The table lists all results for NEOs in ESA's risk list (2020-01-29) in the nuclear detonation regime.

In addition, Table 4 shows an analysis about the latest observation possibilities. We investigate the latest observation dates with respect to the latest launch dates. We consider the case that both dates are in the same month, having half a year or less difference and having 2 years or less difference. Among the analysed NEOs, the group of $10 < \beta_{req} \leq 50$ has with 83% (5 NEOs) the best conditions for doing observations within 2 years before the latest launch date and 50% (3 NEOs) within the same month.

All objects can be placed in a modified plot of Figure 1, which is shown as Figure 6. The marker sizes indicate the impact probability IP of the NEO. As before, the colours show the β_{req} for each object in the four categories. The dotted line marks the borders used to categorize the samples in the different regimes. Among the analysed cases, one can see that the objects within 5 years of warning time need high momentum enhancement factors of $\beta_{req} > 10$ and hence might not be deflectable. For warning times larger 5 years, the success of deflection missions get more likely, in particular for NEOs below roughly 150m.

	All	$\beta_{req} \leq 3$	$3 < \beta_{req} \leq 10$	$10 < \beta_{req} \leq 50$	$\beta_{req} > 50$
Analysed NEOs	27	8	4	6	9
Percentage of analysed NEOs	100%	30%	15%	22%	33%
Latest launch date ≥ 2024	-	6	2	2	-
Percentage of latest launch date ≥ 2024 within group	-	75%	50%	33%	-
Latest launch date ≥ 2028	-	6	2	1	-
Percentage of latest launch date ≥ 2028 within group	-	75%	50%	17%	-
Latest launch date ≥ 2032	-	4	1	0	-
Percentage of latest launch date ≥ 2032 within group	-	50%	25%	0%	-
Latest observation in same month as latest launch date	-	3	1	3	-
Percentage of same month	-	38%	25%	50%	-
Difference between latest observation date and latest launch date < 0.5 years	-	3	2	4	-
Percentage of difference < 0.5 years	-	38%	50%	66%	-
Difference between latest observation date and latest launch date < 2 year [4]	-	5	2	5	-
Percentage of difference < 2 year	-	62%	50%	83%	-

Table 4: The table investigates the launch dates and the observation possibilities, depending on the momentum enhancement factor groups. "-" indicates that no data could be derived with the used computation setup.

[4] Excluding 2010XB73, with its latest launch date in Aug. 2021 and its latest observation date <2020. Hence it cannot be observed before the latest launch date anymore.

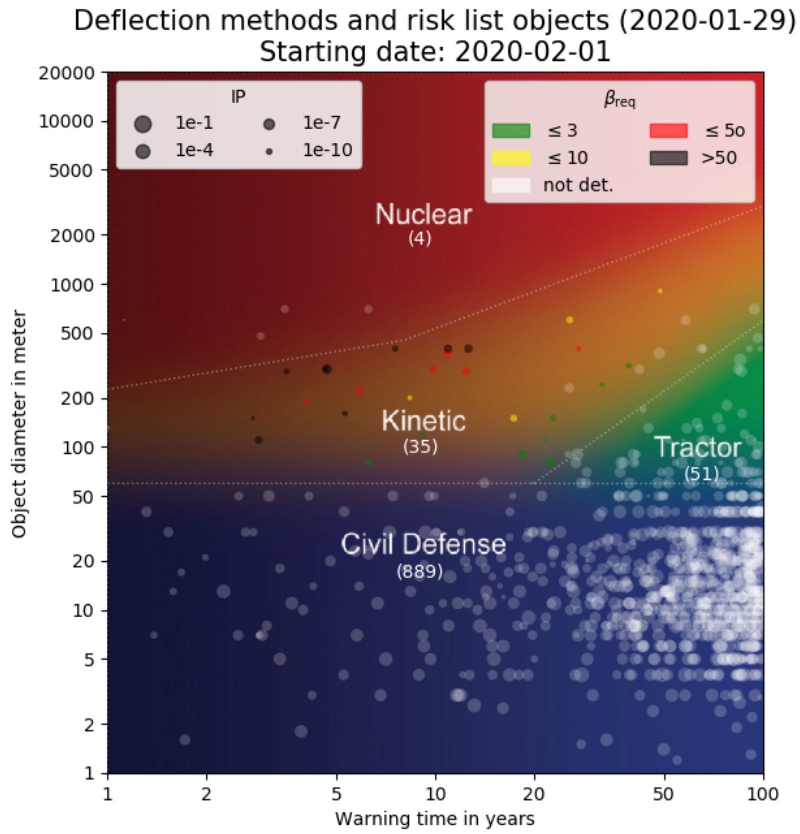

Figure 6: This plot is a modified version of Figure 1, showing all objects of ESA's risk list (29 January 2020) with their estimated diameter and warning time. The plot uses 1 February 2020 as warning time. The marker size indicate the impact probability IP for the associated impact event. The marker color represent the computed required enhancement factors β_{req}. The dashed lines show the limits of the regimes.

4 DISCUSSION

By using a high density and central impacts, we tweak the study cases to pessimistic scenarios, why lower densities or grazing impacts could increase the chances of a deflection success. In addition, we only consider simple Kinetic Impactor orbits without any fly-by manoeuvre, which could increase $v_{\infty,NEO}$ and hence the miss distance and achievable β.

Even though we use distinct boundaries for categorizing the NEOs in this work, the boundaries are not strict. This is already indicated by the colour transition in Figure 1. For NEOs in a transition region, all appropriate options need to be checked.

The analysis in Table 4 is mostly based on only a few samples, especially making the percentage values vague. Using the missing 9 objects and some objects from the transition region could increase the number of samples. In addition, the risk list is changing frequently, why continuously more and more objects can be studied, leading to better statistics.

5 REFERENCES

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[5] D. Farnocchia, F. Bernardi and G. B. Valsecchi, "Efficiency of a wide-area survey in achieving short-and long-term warning for small impactors," *Icarus,* vol. 219, no. 1, pp. 41-47, 2012.

6 APPENDIX

6.1 Undeflected DCAs of NEOs to centre of Earth

Designation	DCA to Earth's centre in $R_\oplus$	Designation	DCA to Earth's centre in $R_\oplus$
2001CA21	0.06	2016PR66	0.06
2006CD	0.04	2016RP41	0.08
2007FT3	0.04	2016WN55	0.04
2007VH189	0.07	2017DA120	0.02
2010DG77	0.04	2017MA9	0.08
2010MA113	0.05	2017QC36	0.04
2010MY112	0.04	2017RZ17	0.04
2010XB73	0.03	2017SC33	0.02
2011BT59	0.05	2017UG52	0.08
2012CR	0.02	2018LF16	0.04
2014HN197	0.04	2018LH16	0.04
2014JU79	0.04	2018YH2	0.03
2015ME131	0.03	2019AF14	0.04
2016JR38	0.05		

Table 5: The table shows the distances of closest approach DCA of the undeflected NEOs to the center of Earth after modifying the initial velocities of the virtual impactors to ensure a roughly central impacts on Earth.