# Very short reaction time, low ΔV, non-nuclear mitigation of some NEOs: a case study

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**[Abstract] This paper proposes a new strategy for kinetic impact of NEOs that possess resonant returns and therefore pass though a "keyhole" near Earth. Interception of the NEO at the time it passes through the keyhole, and its deflection there, will cause at least the first subsequent resonant return to miss the Earth, and probably many others as well. Since the intercept is very close to the Earth the interceptor can be a simple propulsive stage which grapples a dead communications satellite in GEO to form the collision mass, is either stored in GEO at the ready or is launched to GEO on alert, and propulsively transfers to the keyhole at the right time. Using Apophis (2004MN$_4$) as an example it is shown that a 300 kg dry weight stage with 2875 kg of hydrazine propellant, and grappling a 2,000 kg dead communications satellite in GEO, can transfer from GEO to the 2029 Apophis keyhole with only a few days of launch lead time. Interception is accomplished by targeting a point in space (the 0.5 km keyhole) at an instant in time (the time of passage of Apophis through the keyhole). Apophis is deflected by 1 cm/s, sufficient to avoid at least the 2035 resonant return, and probably others as well. The energy per unit mass imparted to Apophis is sufficiently small so as to probably avoid fragmenting it, though if it did fragment the fragments would likely disperse greatly and be harmless in the future. This new strategy thus does not need decades of warning to fly out to meet a NEO far from Earth. Though very promising for NEOs with keyholes and resonant returns the strategy does not apply to those lacking those attributes.**

## 1. A new strategy

Some NEOs that miss the Earth in a close approach nonetheless pass through a so-called "keyhole"--an imaginary area in space--with the result that interaction with the Earth's gravity alters the NEO orbit so that its period comes to be resonant with the Earth's period around the Sun. The result is that the NEO will have a set of future close approaches with the earth at a number of times given by the resonance ratios, any of which could in principle present an impact risk. Conventional approaches for mitigating impact risk entail intercepting the NEO as far before the impact as possible and deflecting it by a variety of means,, changing its velocity sufficiently to cause at least a one Earth radius miss. This strategy minimizes the required ΔV by maximizing the time before impact, and requires preferably decades of warning time to attain, as the ΔV becomes impractically large as the time becomes shorter. In such missions the ΔV imparted to the NEO can be exceedingly small if it aims only to cause the NEO to miss the keyhole, which can be in the order of 1 km in size, but must nonetheless be applied many years or decades before closest approach. The ΔV required for missing the Earth grows by many orders of magnitude if the NEO is not deflected out of the keyhole. If the time before impact becomes even shorter not even nuclear deflection is sufficient to avoid an impact.

This paper presents a new concept and strategy for intercepting such a NEO. Rather than fly out to meet the NEO far from Earth, which requires decades to assure that a low ΔV will be effective, we should intercept the NEO at its passage through the keyhole near Earth and collide with it there. The resultant modest ΔV modifies the NEO orbit so as to cause an Earth miss at least at the first subsequent resonant return and probably further into future resonant returns, requires only days of flight time, and can use existing spacecraft in GEO as payloads for the intercept. The advantages of such a strategy are manifold and listed in Figure 1.

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- **Very little warning time is needed**
  - **just enough to refine the NEO orbit to predict location and dimensions of a keyhole**
- **The total reaction time from launch to intercept can be small--days-weeks, not decades**
- **The interceptor can be stored on the ground or in GEO.**
- **Most of the intercept mass is provided "free" by a dead communications satellite which is already in GEO and mostly out of the Earth's gravity well**
- **The interception ΔV can be very small: the interceptor only transfers from GEO to keyhole**
- **The interceptor uses current bus and propulsion technologies**
- **The only new technology is the grappling mechanism to grab the dead satcom**
  - **Many studies have defined and simulated such arms--they are not difficult to develop**
- **The intercept mass required is independent of the time between detection and intercept**
- **The perturbed NEO orbit misses the Earth o at least the first resonant return and possibly many others later as well**
- **Even if the NEO is fragmented the fragments will generally disperse even more widely**
- **Nuclear explosives are not needed to attain this fast yet effective response**

**Figure 1. Advantages of intercepting in the keyhole**

## 2. A case study as an example

In order to illustrate this new strategy an example was analyzed as a case study by using the asteroid Apophis ($2004MN_4$),which is of the right type and for which good data exists. All the following numbers are approximate and used to illustrate the technique, though the actual numbers may vary a little from those used when precise calculations are made. Apophis will pass some 56,000 km from the Earth on April 13, 2029, and the keyhole is fairly well defined and about 0.5 km across. After passing through the keyhole Apophis will enter a resonance with the Earth's orbit and return to many potential impacts every 7-19 years starting with 2034. The closeness of the 2029 approach is illustrated roughly to scale in Figure 2, though the keyhole is notionally placed and not necessarily to scale.

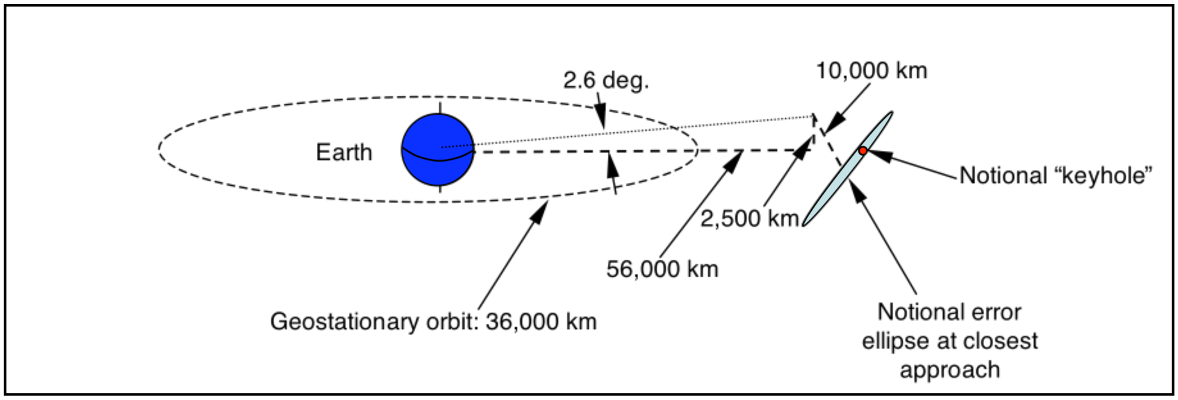
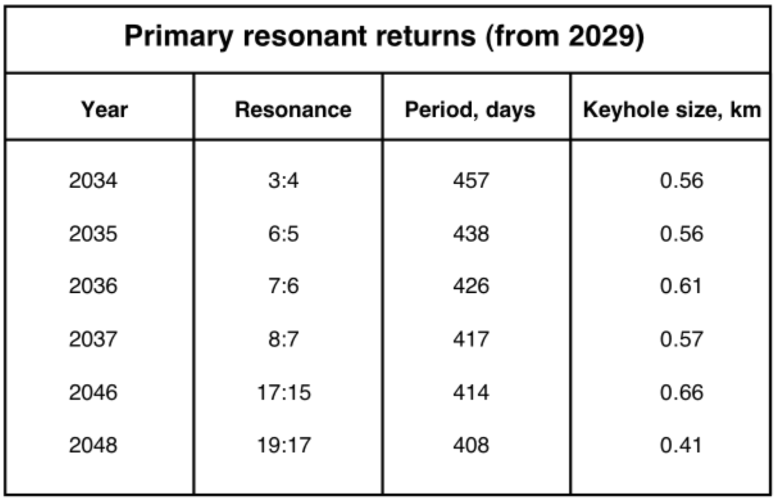


**Figure 2. Apophis keyhole and close Earth pass of 4/13/2029**

The nominal keyhole is located approximately 56,000 km radially and 10,000 km tangentially from the Earth, and 2,500 km out of the equatorial plane, which translates to about 2.6 degrees inclination difference. While the error ellipse can be very large, the keyhole itself can be very small, as shown in Table 1.



| Primary resonant returns (from 2029) | | | |
|---|---|---|---|
| Year | Resonance | Period, days | Keyhole size, km |
| 2034 | 3:4 | 457 | 0.56 |
| 2035 | 6:5 | 438 | 0.56 |
| 2036 | 7:6 | 426 | 0.61 |
| 2037 | 8:7 | 417 | 0.57 |
| 2046 | 17:15 | 414 | 0.66 |
| 2048 | 19:17 | 408 | 0.41 |

**Table 1. Keyholes of Apophis resonant potential impacts**[i]

The interceptor can be stored on the ground and launched on warning to GEO, or it can be stored in GEO waiting for a command. The interceptor would consist of a propulsive stage fitted with grapple arms or mechanisms, and the necessary guidance and control. It would be placed into GEO by a launch vehicle, where it would slowly transfer to rendezvous with a dead satellite such as a communications satellite. It would rendezvous with the dead satellite and then grapple it or attach itself to it via any number of schemes and equipment choices. This technology is essentially developed with the ATV and the Orbital Express vehicles, and the grapples have been defined many times though not yet developed and flown. It would then wait for the command to transfer to intercept Apophis.

The launch from GEO would occur using refined orbit ephemeredes for Apophis, which can be very accurate since radar can be used due to the close approach and the short time needed before impact. The launch would use an explicit guidance system into which was input the location of the point in space and the instant in time when it should arrive at the keyhole, and would automatically transfer into the correct plane for the trajectory. Terminal guidance seekers such as those developed and tested for kinetic kill missile defense could also be used, though may not be necessary if sufficient accuracy can be attained in a predictive mode. Such guidance systems are state of the art and have been used in a number of missile and space intercepts to date to effect the intercept. The interceptor would then arrive at the desired location in space at the same time as Apophis and a collision would occur, resulting in a kinetic deflection. This sequence of the mission profile is illustrated in Figure 3.

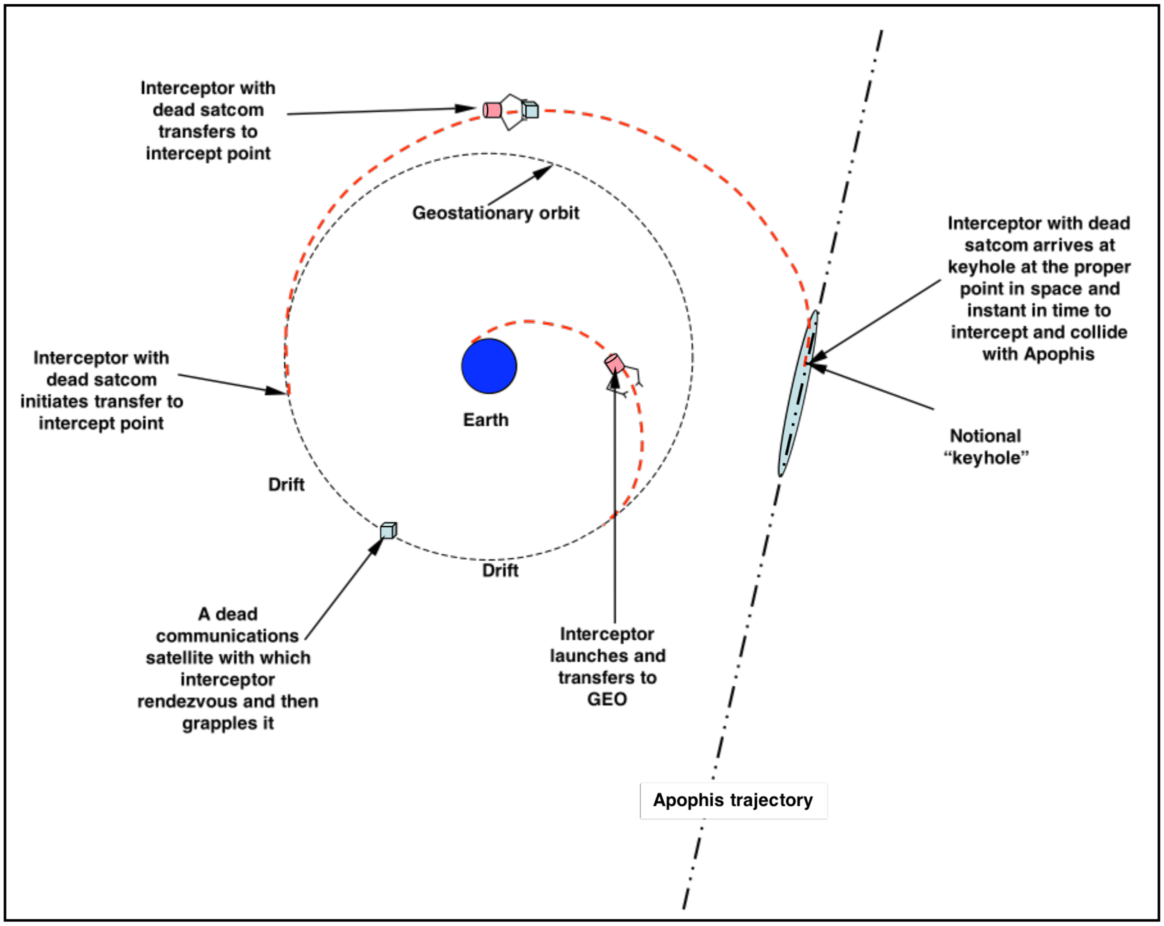
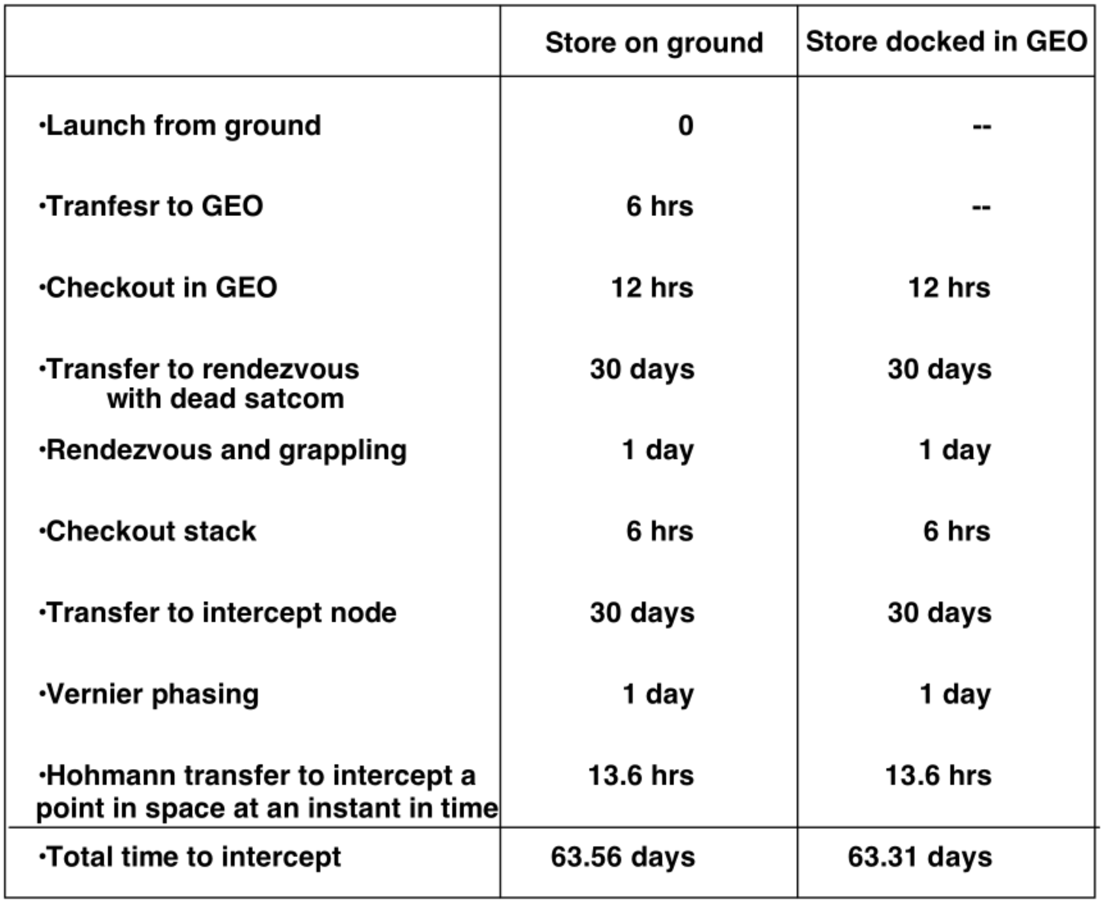


**Figure 3. Apophis keyhole intercept mission profile**

An approximate timeline for the sequence of events is shown in Figure 4, in which it is seen that the total time from interceptor launch to kinetic impact with Apophis can be in the order of 2 months. But this figure includes two 30 day periods allowed for slow transfer to an arbitrary longitude on the geostationary arc, which could easily be reduced to 1-20 days with a little more propulsion depending on the phasing of the various spacecraft concerned, so that the timeline could be reduced to perhaps 2 weeks or less if the circumstances were right. But even 2 months is a wonderfully short timeline compared to the decades required to impart the same impact ΔV if the interceptor has to fly all the way to meet the NEO decades before passing through the keyhole.



| | Store on ground | Store docked in GEO |
|---|---|---|
| •Launch from ground | 0 | -- |
| •Tranfesr to GEO | 6 hrs | -- |
| •Checkout in GEO | 12 hrs | 12 hrs |
| •Transfer to rendezvous with dead satcom | 30 days | 30 days |
| •Rendezvous and grappling | 1 day | 1 day |
| •Checkout stack | 6 hrs | 6 hrs |
| •Transfer to intercept node | 30 days | 30 days |
| •Vernier phasing | 1 day | 1 day |
| •Hohmann transfer to intercept a point in space at an instant in time | 13.6 hrs | 13.6 hrs |
| •Total time to intercept | 63.56 days | 63.31 days |

**Figure 4. Approximate timeline for Apophis intercept in the keyhole**

## 3. System calculations

The ΔV required to deflect Apophis sufficiently to miss Earth in the next resonant return, which is 6 years after 2029, is small. A ΔV of 1 cm/sec will suffice to deflect the trajectory more than 1 Earth radius given that Apophis is 250 m diameter and the velocity at impact will be about 5-7 km/sec. Using nominal Apophis ephemeris data the transfer from a circular orbit at 36,000 km altitude to one with 56,000 km apogee is a Hohmann transfer that requires 345 m/s using a hydrazine propulsion system. The plane change of 2.6 degrees would require an additional 167 m/s ΔV, but we will double that to allow for the random location of the ascending node of the earth's equator at the time of the epoch. Thus the total ΔV required will be 334 + 345 = 679 m/s. Using the rocket equation we determine that the ratio of initial to final mass must be 1.25 to attain this ΔV with a hydrazine propulsion system. If we take the mass of the dead communications satellite to be 2,000 kg and the mass of the dry propulsion stage to be 300 kg then the stage needs to have a fully fueled mass of 2,300x1.25 or 2,875 kg, which means the propellant load need be only 575 kg. The total mass to be boosted from the ground will be 2,875 kg, which is well within the mass capability of today's medium sized launch vehicles. This is illustrated in Figure 5.

- **ΔV needed**
    - **Transfer from 36,000 km orbit to 56,000 km apogee requires 345 m/s**
    - **Plane change of 2.6 degrees at GEO altitude requires 167 m/s**
    - **Double that to account for the ascending node being nonoptimum at epoch = 334 m/s**
    - **Total ΔV needed = 334 + 345 = 679 m/s**
- **Mass required**
    - **Dead communications satellite is 2000 kg**
    - **Interceptor bus = 300 kg dry mass. Hydrazine propulsion system**
    - **Rocket equation dictates Initial/Final mass = 1.25 for Hohmann transfer to 56,000 km**
    - **The total propellant load required is 575 kg of hydrazine**
    - **Thus the interceptor must weigh 2,875 kg fully fueled**
    - **This is well within capability of current launch vehicles**

**Figure 5. Interceptor mass and propellant required**

This is adequate to attain the 1 cm/s deflection of the 250 m diameter Apophis at a closing velocity of 5-7 km/s which is illustrated in Holsapple's calculations[ii], shown as Figure 6.

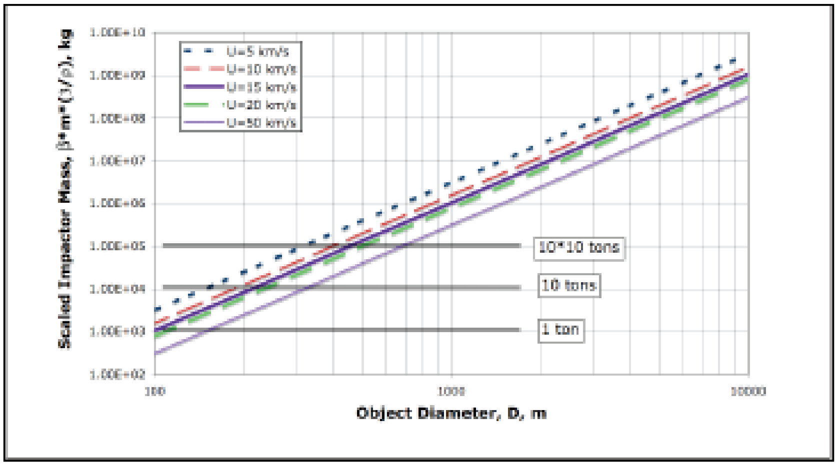


**Figure 6. Mass required to attain the 1 cm/s V**

## 4. Deflect of fragment?

The kinetic impact can cause a deflection or a fragmentation. While deflection is preferable the fragmentation is also a satisfactory result, as discussed by Holsapple in the same reference. Calculating the energy per unit mass imparted by the collision it is seen, from Figure 7, that for the conditions of this intercept the NEO is unlikely to fragment regardless of its composition. Nonetheless the consequences of fragmentation are benign, since most of the fragments will have velocities comparable to the escape velocity of Apophis, and thus will disperse over great distances before the 2035 conjunction. We therefore conclude that fragmentation is as good and as effective as deflection for the case considered.

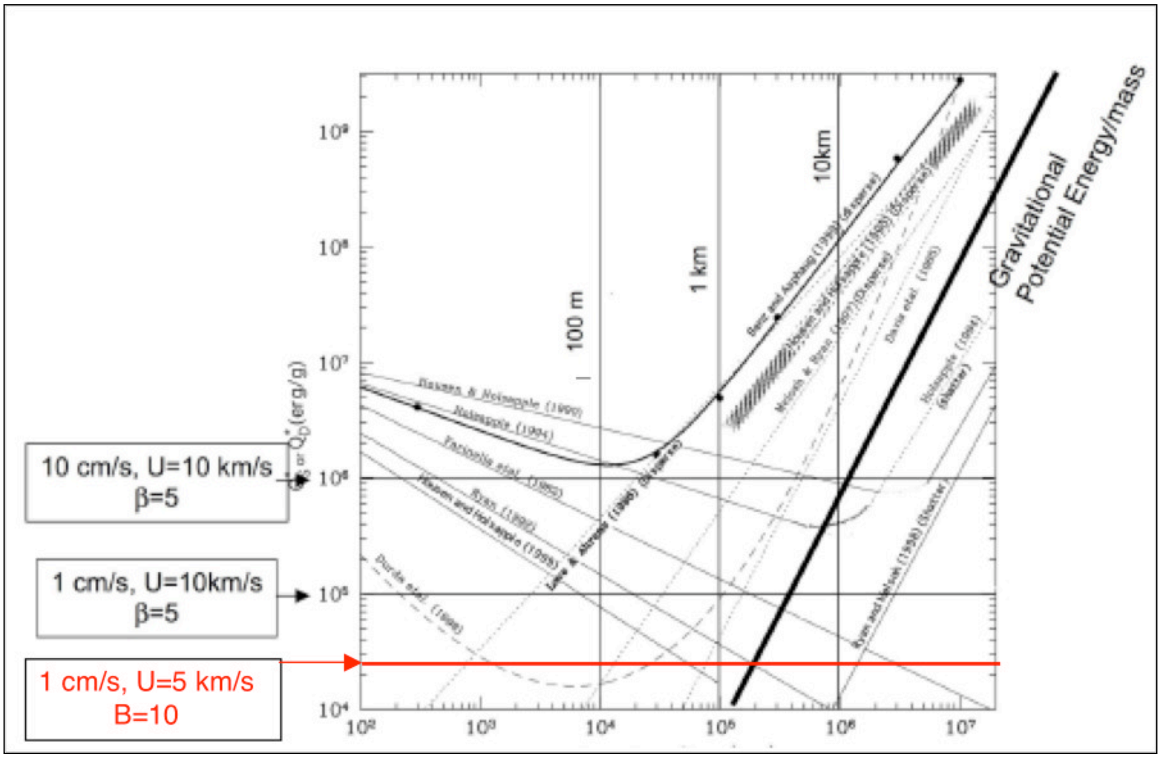


Figure 7. Energy/mass and likelihood of fragmentation

## 5. Conclusions

This cursory study shows that kinetic interception in the keyhole of a NEO that has resonant returns requires little mass, can be attained with only a few weeks of lead time to the interceptor, and can be attained using mostly current technology in a non-nuclear manner. This has great advantages over conventional concepts of interception of NEOS which require decades of warning in order for the mass and V requirements to be reasonable, or require nuclear devices, neither of which is desirable.

This new strategy applies only to NEOs that have resonant returns and thus possess a keyhole fairly near Earth. NEOs that do not possess these characteristics must, unfortunately, still be intercepted very early.

### Acknowledgments

I would like to thank Keith Holsapple for his seminal paper, referenced below, from which I have borrowed figures and calculations. I also would like to acknowledge Steve Chesley's fine paper on Apophis, which so well describes the resonant returns and the keyholes of Apophis.

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[i] Steven R. Chesley, "Potential Impact Detection For Near Earth Asteroids: The Case Of 99942 Apophis ($2004MN_4$), *Proceedings IAU Symposium,* #229, 2005. S. Ferraz-Mello and D. Lazarro, Eds.

[ii] Keith A. Holsapple, "Existing methods of asteroid deflections will work: Impacts and Nuclear Bombs", *White Paper prepared for NASA NEO Detection, Characterization and Threat Mitigation Workshop*, Vail, Colorado, June, 2006.