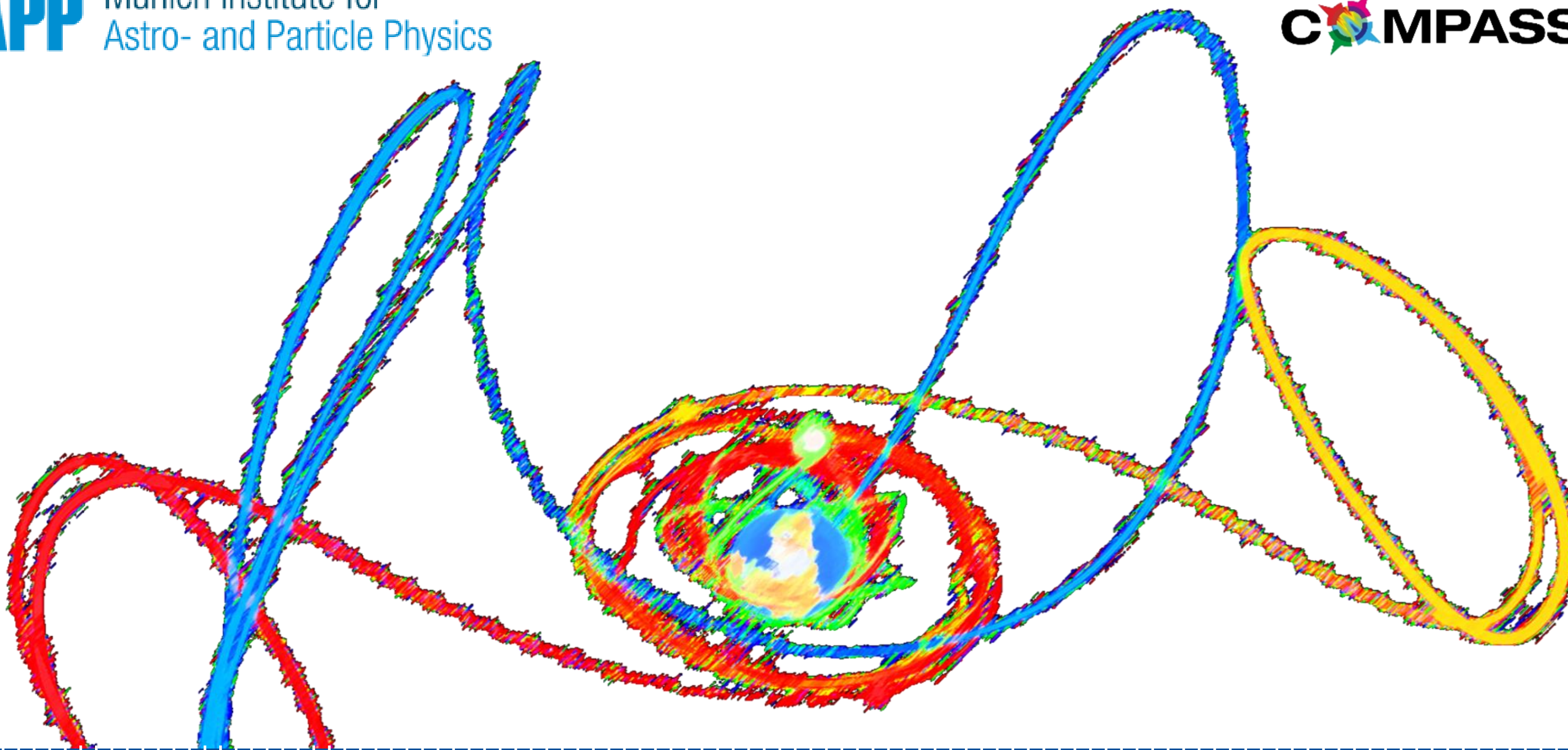


Asteroid deflection

Camilla Colombo, Robert Jedicke, Detlef Koschny, Richard Wainscoat, Andreas Burkert

Near-Earth Objects: Properties, Detection, Resources, Impacts and Defending Earth

14 May - 8 June 2018, Munich Institute for Astro- and Particle Physics (MIAPP)

Some questions…

- What types of missions are needed for asteroid deflection?
- How do we prepare for the multitude of options?
- What is the appropriate time frame for each option being ready given its application?

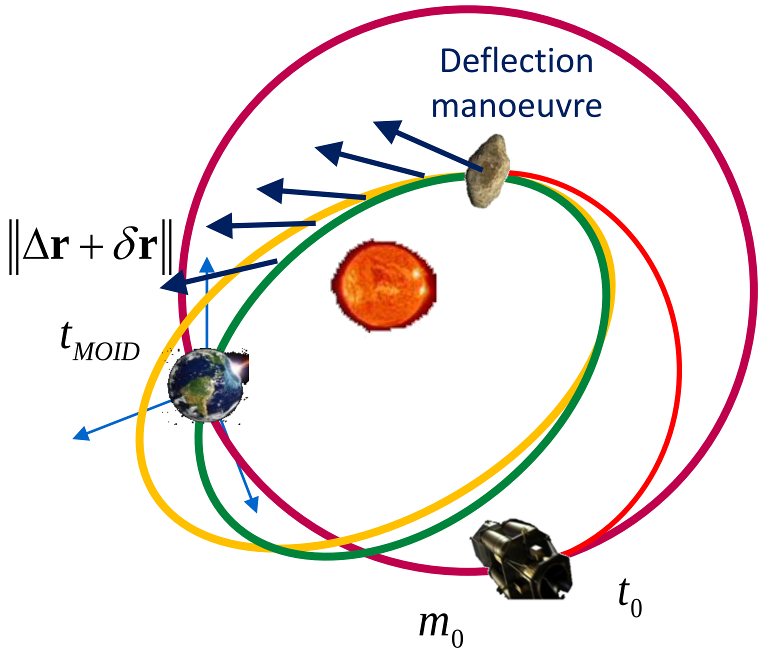
- Which physical properties are relevant and how do we measure them?

- Who should pay for deflection?

- How do we avoid future resonant encounters?
- Do we need to worry about misapplication of deflection techniques?

What types of missions are needed?

- Integrated design of interception phase and asteroid deviation phase
- How many criteria to select the strategy?
  - Mass into space (=cost)
  - Warning time till collision
  - Total deviation at MOID
  - Technology readiness level of strategy
  - Time required to perform required observation
  - Type of asteroid
  - Characteristics of asteroid
  - Etc…



What types of missions are needed?

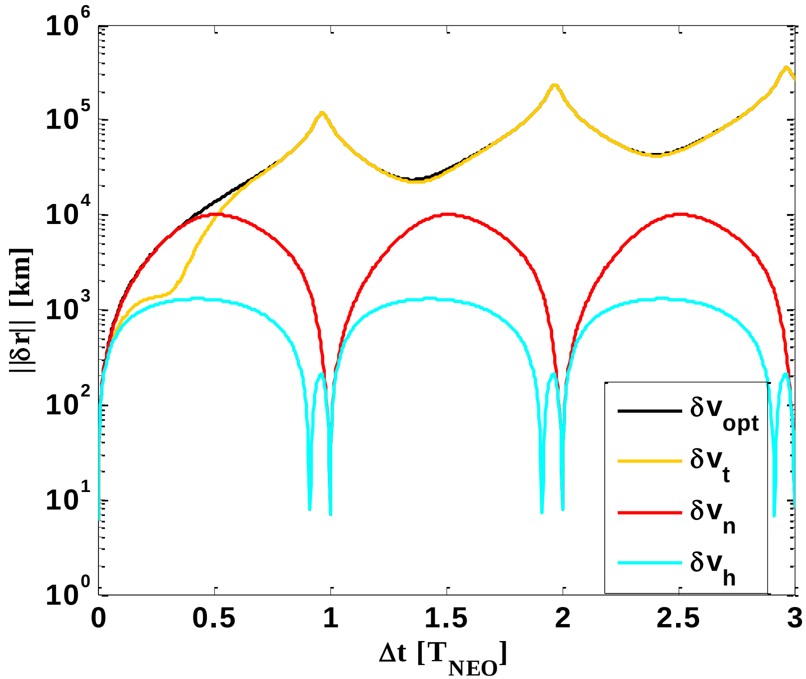
Deflection techniques

- High thrust
  - Kinetic impactor
  - Nuclear interceptor/explosion
  - …
- Low-thrust push
  - Laser ablation
  - Solar concentrator
  - Ion beaming
  - Gravity tug
  - Anchored low-thrust propulsion
  - …

How to deflect an asteroid

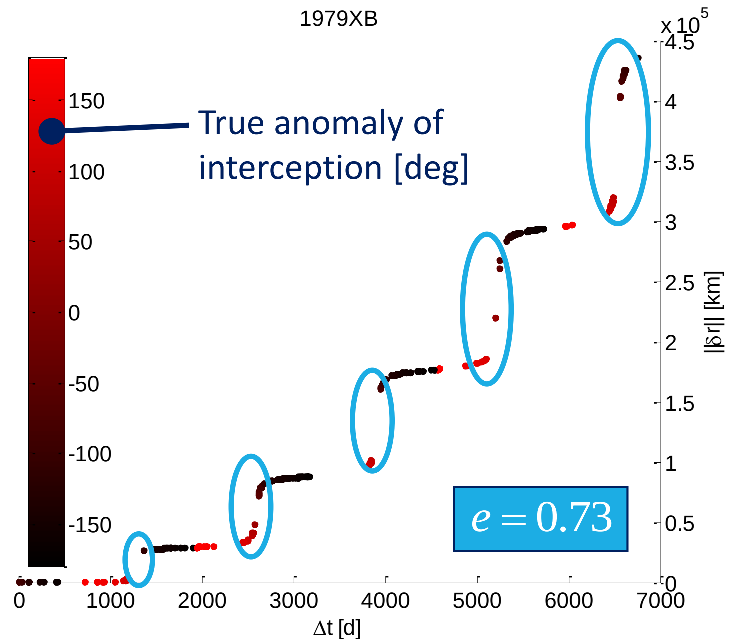
Deflection action versus lead time

Dependence of the optimal direction of the deflection manoeuvre on the lead time between manoeuvre and time at MOID (NEO 1979XB)



➢ *Vasile M., Colombo C., "Optimal Impact Strategies for Asteroid Deflection", Journal of Guidance, Control, and Dynamics, 2008.*

But interception trajectory matters… deflection strategy: 100 m solar collector strategy (NEO 1979XB)



➢ *Colombo C., Vasile M., Radice G., "Semi-Analytical Solution for the Optimal Low-Thrust Deflection of Near-Earth Objects", Journal of Guidance, Control, and Dynamics, 2009.*

What types of missions are needed?

Comparison among mitigation strategies for dangerous NEOs

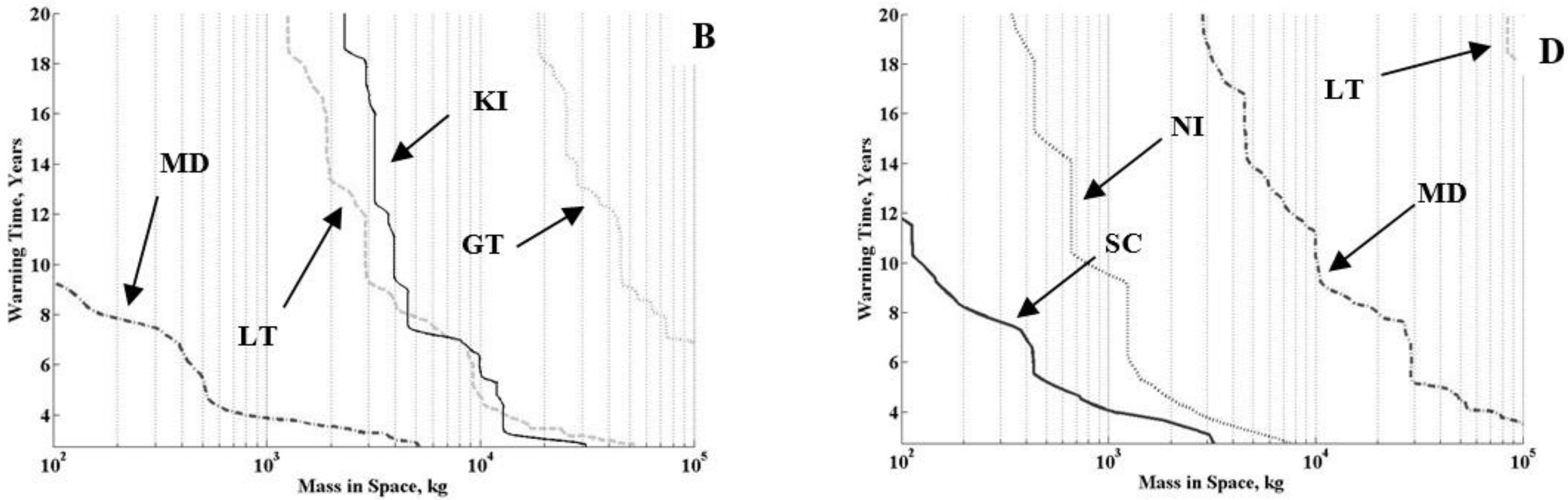
	a (AU)	e	i (deg)	Ω (deg)	ω (deg)	M (deg)	Epoch (MJD)	t_{MOID} (MJD)
Aten-case	0.88	0.31	7.83	260	50.7	97.2	62481.0	**62481.0**
Apollo-case	1.71	0.52	10.7	267	121	18.1	62488.0	**62488.0**

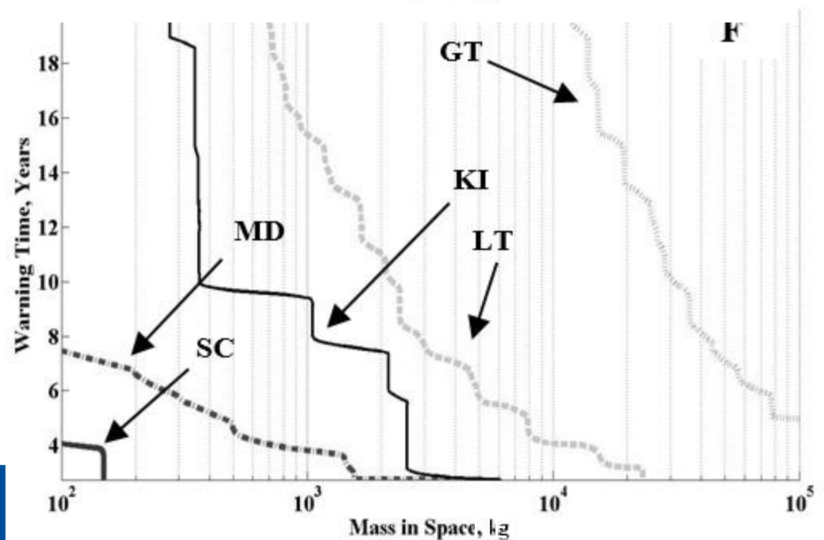
	M_a (kg)	Density (kg/m³)	Diameter (m)	Estimated Impact Frequency	Rotation (hours)
Aten-1	5.0×10^8	2500	73	1 every 1,000 years	**4.33**
Aten-3	5.0×10^{10}	2500	337	1 every 100,000 years	**4.33**
Apollo-1	5.0×10^8	2500	73	1 every 1,000 years	**4.33**
Apollo-3	5.0×10^{10}	2500	337	1 every 100,000 years	**4.33**

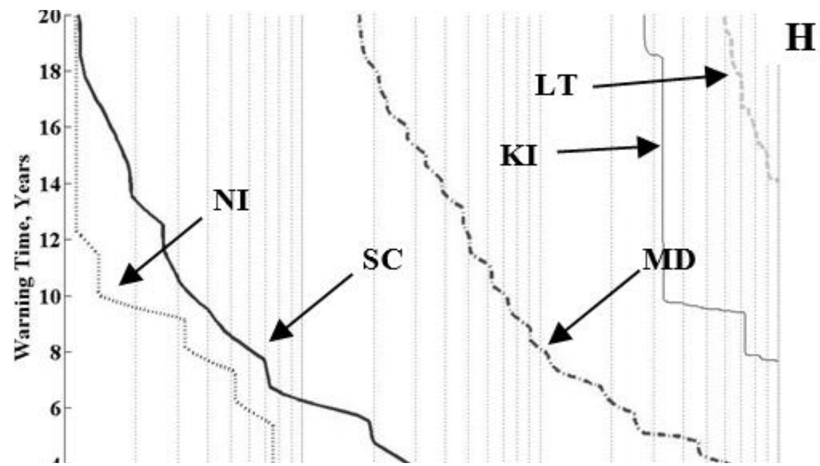
- *Sanchez J. P., Colombo C., Vasile M., Radice G., "Multicriteria Comparison Among Several Mitigation Strategies for Dangerous Near-Earth Objects", Journal of Guidance, Control, and Dynamics, 2009.*

What types of missions are needed?

Strategy isolines for a deviation of 13720km for different deviation methods B) Aten-1 case, D) Aten-3 case, F) Apollo-1 case, H) Apollo-3 case



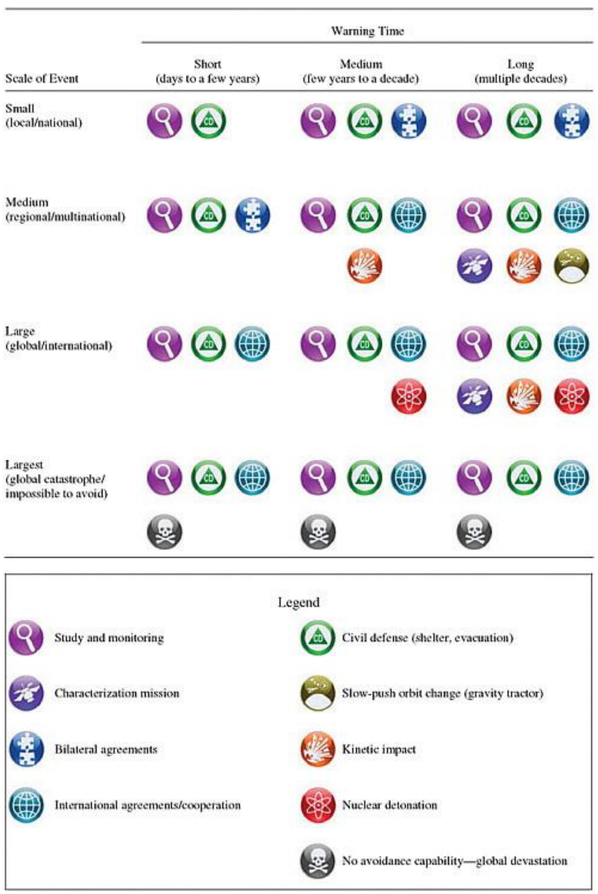


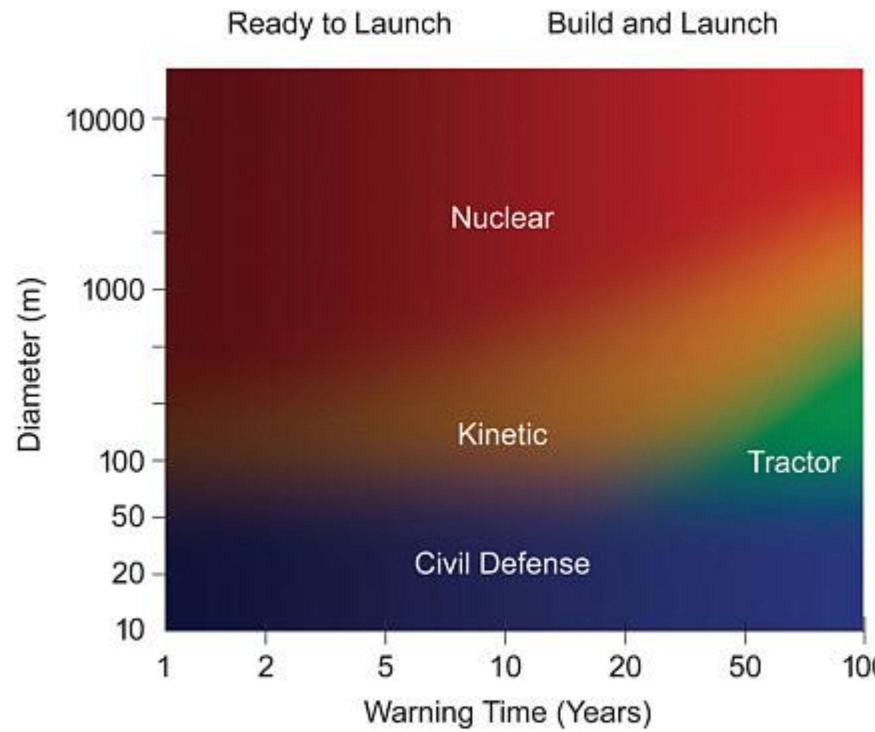


SC = solar collector, LT = low thrust, MD = mass driver, NI = nuclear interceptor, KI = kinetic impactor, GT = gravity tug

What types of missions are needed?

Summary of the Implementation of Primary Strategies for Mitigating the Effects of Potential NEO Impacts





Approximate outline of the regimes of primary applicability of the four types of mitigation
(see Ref below for the many caveats associated with this figure).

- *Defending Planet Earth: Near-Earth-Object Surveys and Hazard Mitigation Strategies (2010)*

How do we prepare for the multitude of options?

- Goal: Determine capability of a kinetic impactor system to provide protection against any, realistic impact threats

- Find quantitative measure of the ability of the deflection system to mitigate possible Earth-impacting object
  - estimate the probability of succeeding in deflecting to a safe Earth distance a randomly generated realistic impact threat
  - obtain a statistically meaningful sample of deflection scenarios.

- **Ready to go**: The threatening object is known, the kinetic impactor can be deployed as soon as is ready to be launched
- **Not yet detected:** Need for surveying campaign

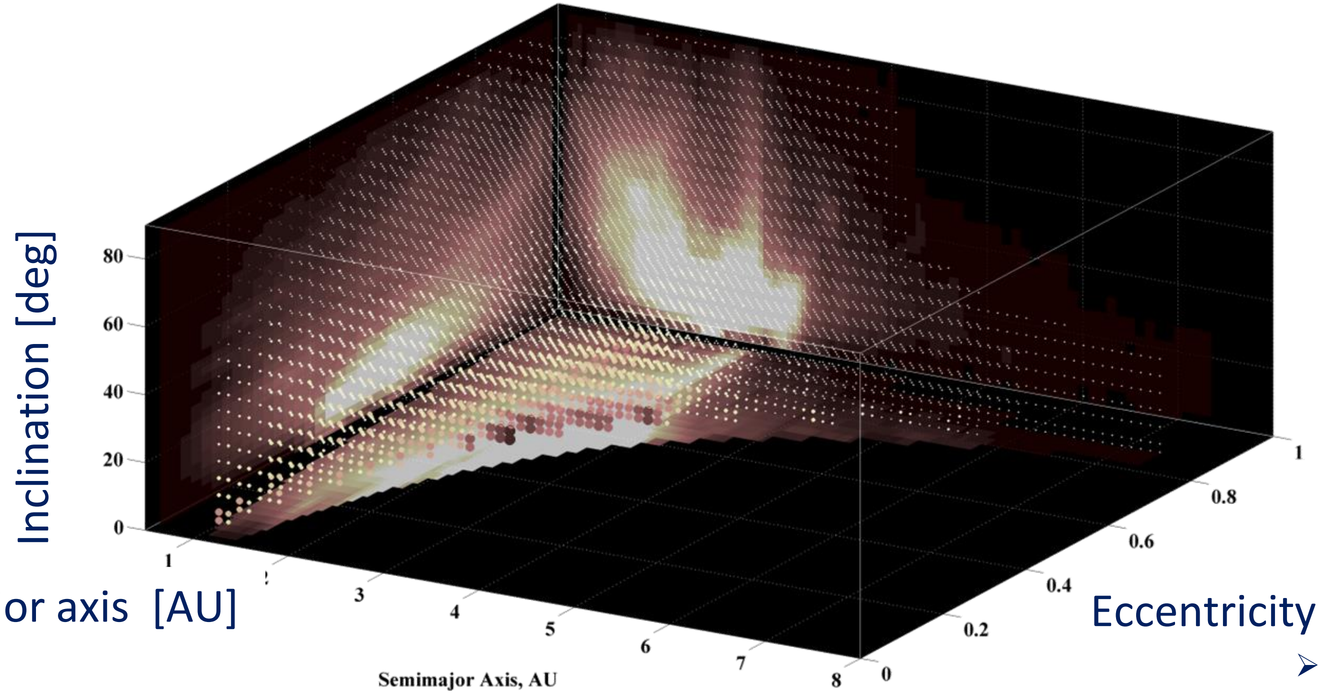
➢ *Sanchez J. P., Colombo C., "Impact hazard protection efficiency by a small kinetic impactor", Journal of Spacecraft and Rockets, 2013*

How do we prepare for the multitude of options?

Virtual impactors

Total of 18,000 Earth-impacting orbits as set of impact hazard scenarios

- Grid in semi-major axis, eccentricity, inclination
- Determine ascending node and perigee required for an impact with Earth (all at same epoch)
- Determine relative frequency of each virtual impactor (NEO density distribution, collisional probability)



➢ *Bottke W. F. et al., 2006*

How do we prepare for the multitude of options?

Probability of a deflection system to deflect a generic impact threat

Impact hazard categories

Type of event	Approximate range of impact energies (MT)	Approximate range size of impactor	Relative event frequency
Airburst	1 to 10 MT	15 to 75 m	~177,000 of 200,000
Local Scale	10 to 100 MT	30 to 170 m	~20,000 of 200,000
Regional Scale	100 to 1,000 MT	70 to 360 m	~2400 of 200,000
Continental Scale	1,000 MT to 20,000 MT	150 m to 1 km	~600 of 200,000
Global	20,000 MT to 10,000,000 MT	400 m to 8 km	~100 of 200,000
Mass Extinction	Above 10,000,000 MT	>3.5 km	~1 of 200,000

Planetary defense of previously detected Earth-impacting objects

Type of event	Warning time				
	20 year	15 years	10 years	5 years	2.5 years
Airburst	99.4%	99.0%	98.1%	88.8%	26.9%
Local Damage	92.5%	88.3%	80.7%	51.4%	9%
Regional Damage	43.0%	31.7%	22.8%	9.5%	0.6%
Continental Damage	3.9%	1.8%	0.6%	0.03%	0%
Global Damage	0%	0%	0%	0%	0%

How do we prepare for the multitude of options?

Fraction of the impact threat discovered with the corresponding warning time. Hence, with 5, 10, 15, 20 or 22.5 years of survey time

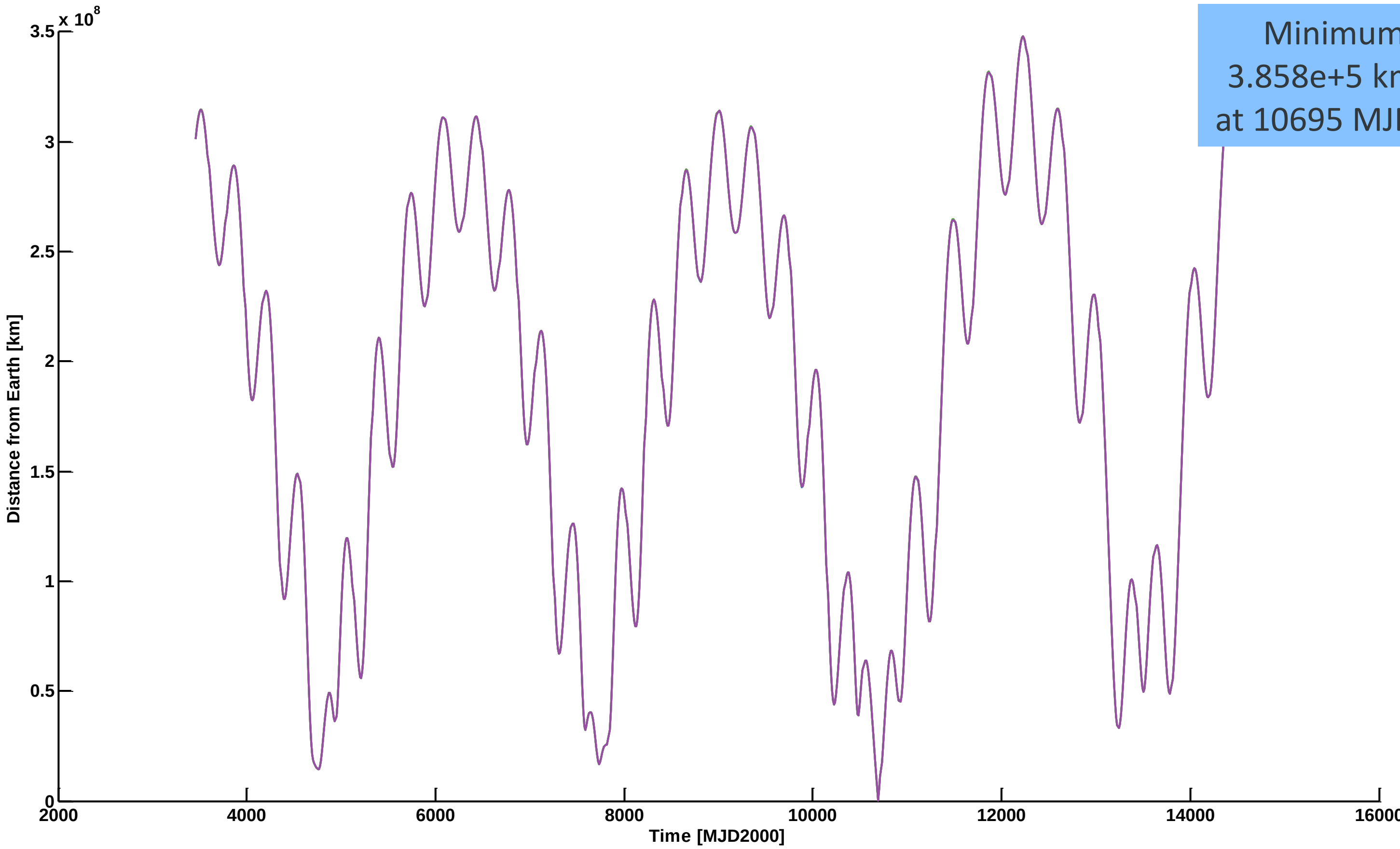
Type of event	Warning time/Survey time-span				
	20/5 year	15/10 years	10/15 years	5/20 years	2.5/22.5 years
Airburst	11.2%	20.8%	27.5%	34%	35.1%
Local Damage	19.3%	35.6%	47.8%	55.9%	62.6%
Regional Damage	41.4%	64.1%	73.6%	84.7%	92.7%
Continental Damage	81%	92.9%	98.8%	99.6%	99.8%
Global Damage	98.7%	99.8%	100%	100%	100%

Planetary defense on the detection-required scenario

Type of event	Warning time/Survey time-span				
	20/5 year	15/10 years	10/15 years	5/20 years	2.5/22.5 years
Airburst	10.8%	20.4%	26.4%	32.3%	32.7%
Local Damage	15.8%	29.8%	38.6%	42.9%	43.1%
Regional Damage	15.8%	23.4%	25.9%	27.1%	27.1%
Continental Damage	2%	2.5%	2.6%	2.6%	2.6%
Global Damage	0%	0%	0%	0%	0%

- *Sanchez J. P., Colombo C., "Impact hazard protection efficiency by a small kinetic impactor", Journal of Spacecraft and Rockets, 2013*

How do we avoid future resonant encounters?



Minimum distance:
3.858e+5 km (0.003 AU)
at 10695 MJD2000 (2029)

Some questions…

- What types of missions are needed for asteroid deflection?
- How do we prepare for the multitude of options?
- What is the appropriate time frame for each option being ready given its application?
- Which physical properties are relevant and how do we measure them?
- Who should pay for deflection?
- How do we avoid future resonant encounters?
- Do we need to worry about misapplication of deflection techniques?