



Asteroid Impact Risk: The Uncertain Outcome of Deflection Missions

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University of Arizona



Outline

- **Background**
 - Asteroid Impacts
 - Asteroid Deflection Missions
 - Predictability
 - Temporal
 - Spatial
 - Consequences
- **Building Blocks**
 - Uncertainty
 - Physical
 - Beta factor
 - Orbit
 - Deflection Analysis Setup
- **Application**
 - 2019 PDC Case Study

Asteroid Impacts

Asteroid Impacts - Examples

Barringer Crater
USA
50 000 yrs



https://commons.wikimedia.org/wiki/File:Barringer_Crater_aerial_photo_by_USGS.jpg

Chelyabinsk
Russia
2013



https://commons.wikimedia.org/wiki/File:Chelyabinsk_meteor_trace_15-02-2013.jpg

Tunguska, Russia, 1908



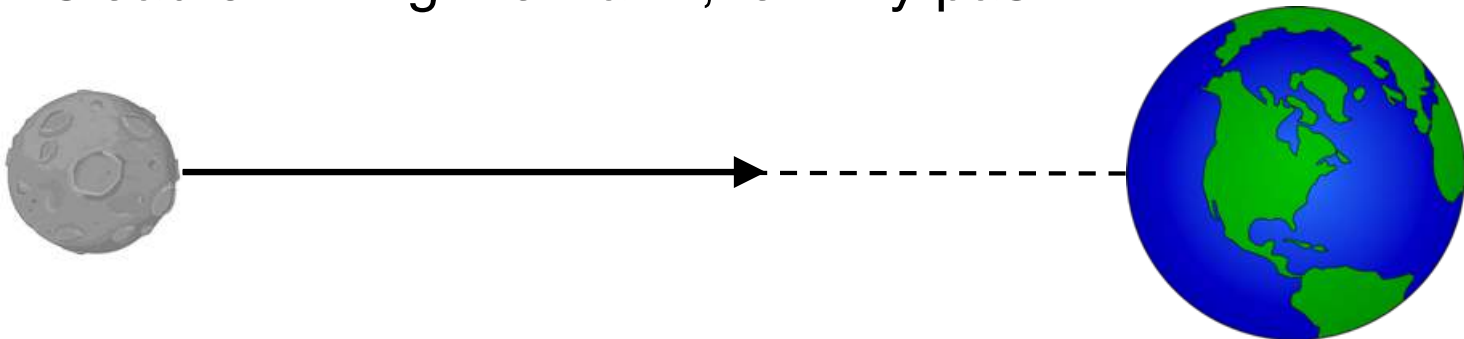
https://commons.wikimedia.org/wiki/File:Tunguska_Ereignis.jpg

Deflection Missions

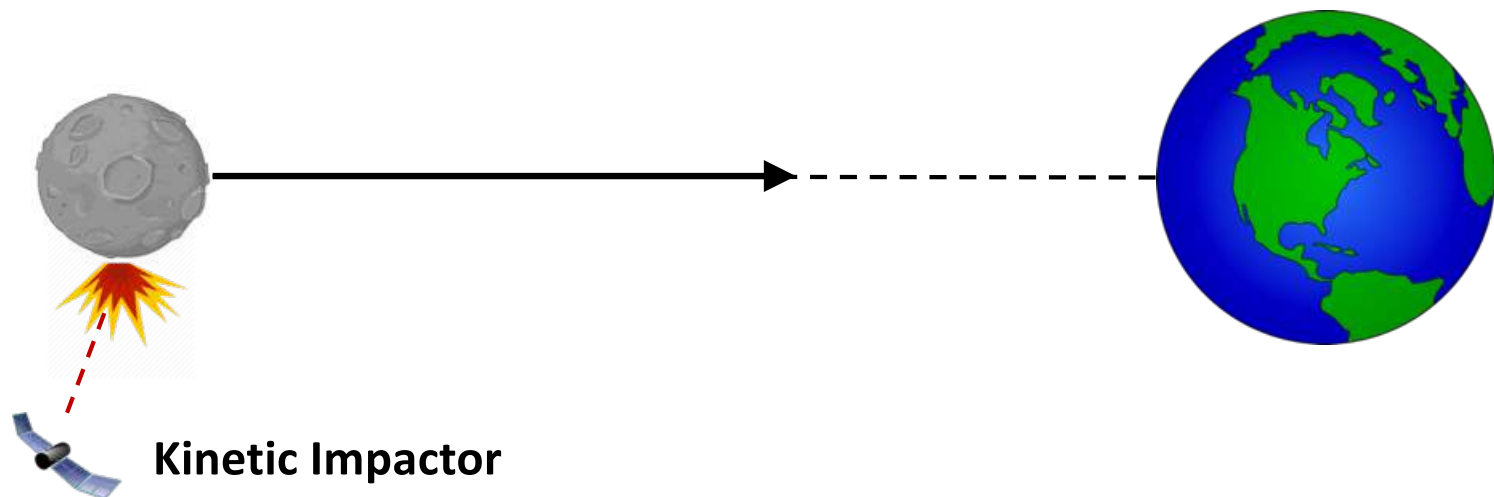
- Mechanics
- Heritage

Deflection Scenario

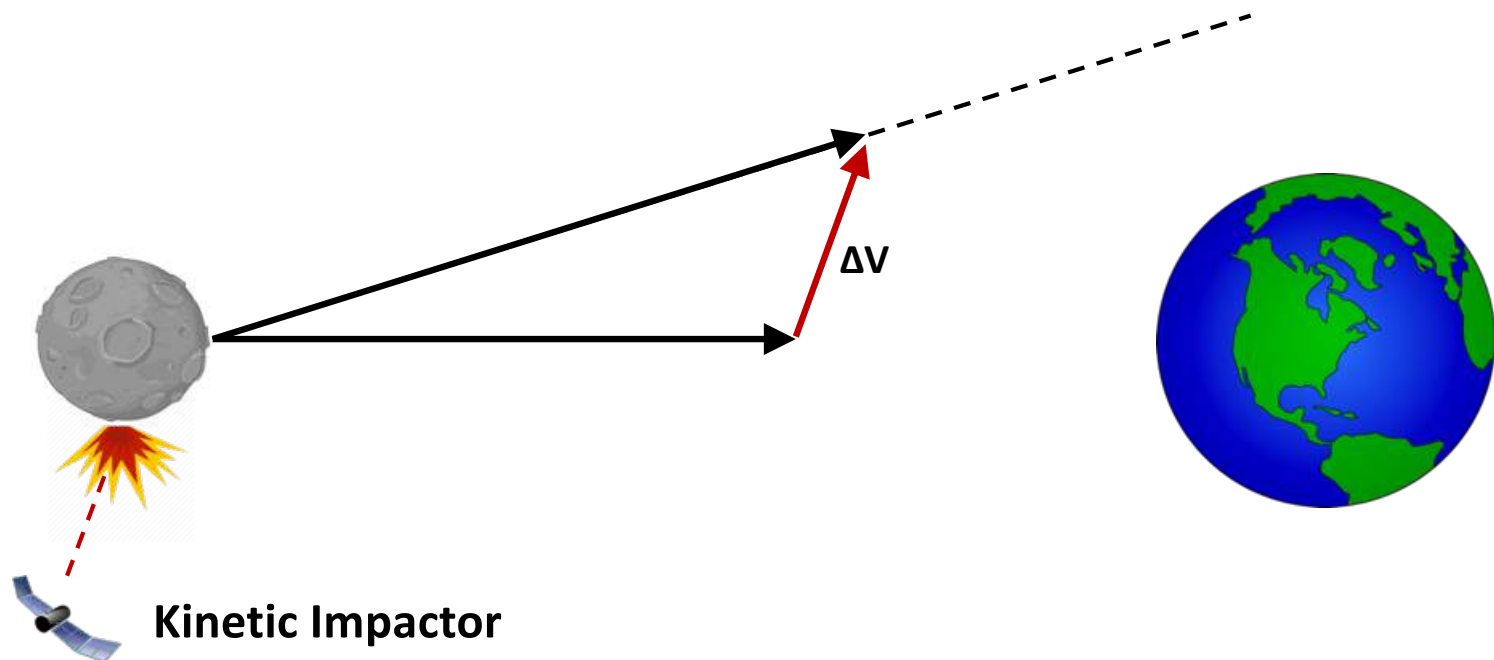
- An asteroid is on a collision course with Earth
- It's possible to change the orbit of asteroids.
- Goal: Instead of hitting the Earth, let it fly past



Deflection Scenario



Deflection Scenario

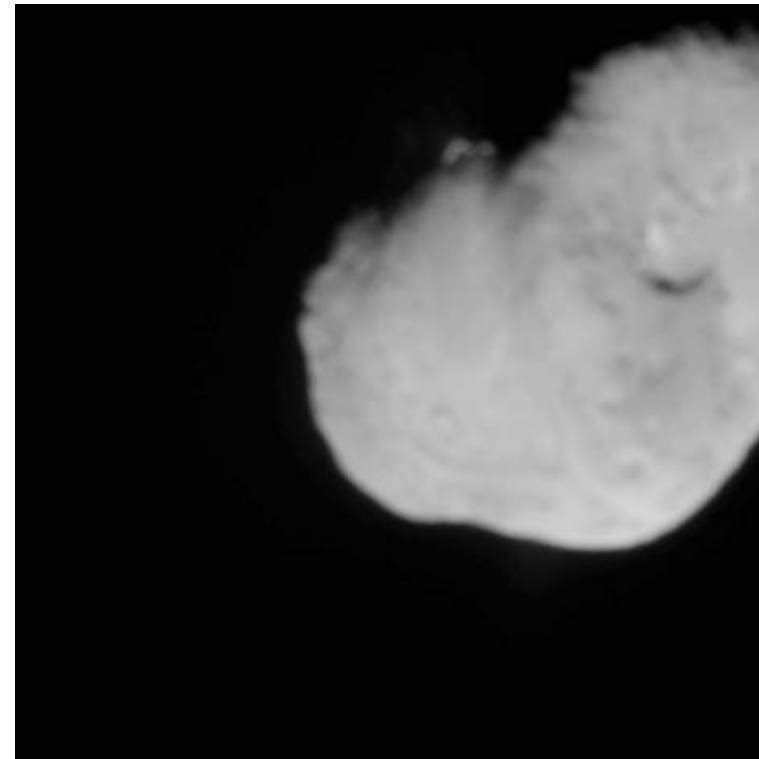


Deflection Missions

- Mechanics
- **Heritage**

Deep Impact 2005

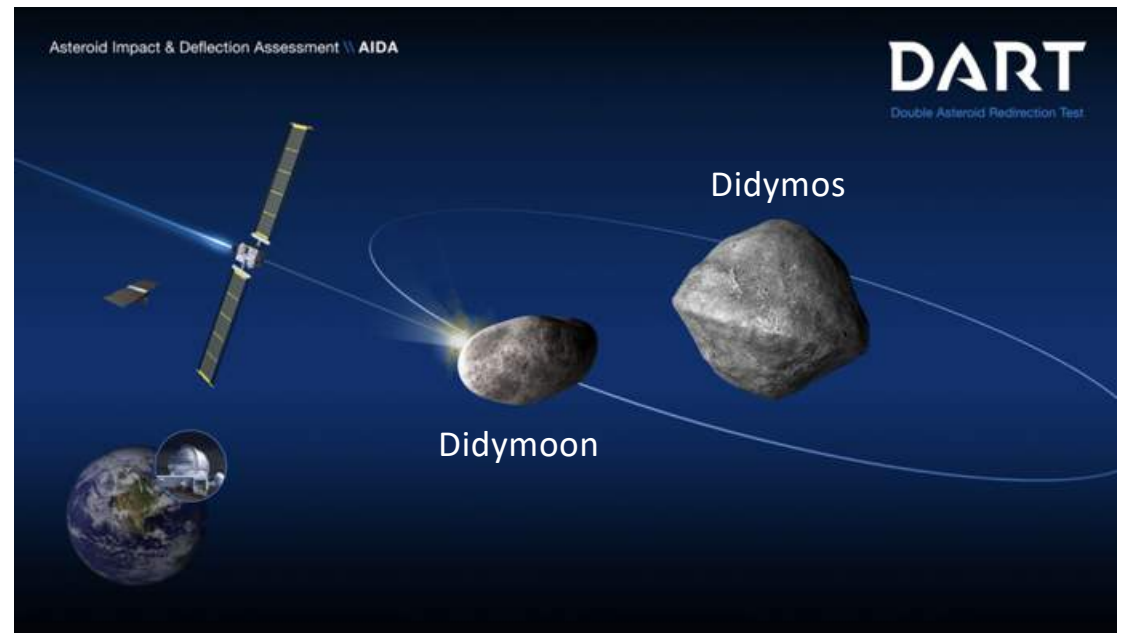
- Scientific mission by NASA in 2005
- Excavate sub-surface material by impact
- Evaluate sub-surface material using spectroscopy
- Equivalent to kinetic impactor
- **But:**
 - Target was large: $\cong 5$ km
 - No measurements on trajectory change



https://commons.wikimedia.org/wiki/File:HRIV_Impact.gif

NASA DART

- Launch on July 22nd 2021
- Dedicated planetary defense mission
- Change orbit of “Didymoon”
- Target size: $\cong 170$ m
- Measure orbit change
- Measure **momentum enhancement factor β**



<https://www.nasa.gov/planetarydefense/dart>



Deflection Mission Caveat



- The impact point "moves" over the surface of the Earth before being fully deflected
- The outcome of a deflection mission is uncertain because many of the problem's properties are uncertain
 - Orbit uncertainty
 - Physical uncertainty

Predictability

- Temporal
- Spatial
- Consequences

Asteroid Impacts - JPL Risk Page

Object Designation	Year Range	Potential Impacts	Impact Probability (cumulative)	V_{∞} (km/s)	H (mag)	Estimated Diameter (km)	Palermo Scale (cum.)	Palermo Scale (max.)	Torino Scale (max.)
29075 (1950 DA)	2880-2880	1	1.2e-4	14.10	17.6	1.300	-1.42	-1.42	
101955 Bennu (1999 RQ36)	2175-2199	78	3.7e-4	5.99	20.2	0.490	-1.71	-2.32	
99942 Apophis (2004 MN4)	2060-2105	12	8.9e-6	5.85	19.1	0.370	-2.83	-2.93	0
(2000 SG344)	2069-2113	101	2.6e-3	1.36	24.8	0.037	-2.86	-3.23	0
(2008 JL3)	2027-2119	27	1.6e-4	8.42	25.3	0.029	-3.27	-3.27	0
(2009 JF1)	2022-2022	1	2.6e-4	23.92	27.1	0.013	-3.28	-3.28	0
(2010 RF12)	2095-2117	73	5.3e-2	5.10	28.4	0.007	-3.27	-3.30	0
(2019 DS1)	2082-2108	5	1.4e-3	10.48	25.6	0.025	-3.29	-3.30	0
(1994 GK)	2051-2067	5	6.9e-5	14.87	24.2	0.048	-3.65	-3.66	0
(2005 QK76)	2030-2107	9	6.8e-5	19.67	25.2	0.031	-3.55	-3.70	0
(2007 FT3)	2024-2116	164	1.4e-6	17.06	20.0	0.340	-3.07	-3.73	0
(2018 VP1)	2020-2025	3	4.1e-3	9.53	30.9	0.002	-3.86	-3.86	0
(2005 ED224)	2023-2064	5	2.6e-6	24.96	24.0	0.054	-3.90	-3.93	0

<https://cneos.jpl.nasa.gov/sentry/>

Example Risk Page

2005 ED224 -- Earth Impact Risk Summary [\(orbit details\)](#)

Torino Scale (maximum)	0
Palermo Scale (maximum)	-3.93
Palermo Scale (cumulative)	-3.90
Impact Probability (cumulative)	2.6e-6
Number of Potential Impacts	5
Impact Search Technique	LOV

V_{Impact}	27.33 km/s
V_{Infinity}	24.96 km/s
H	24.0
Diameter	0.054 km
Mass	2.2e+8 kg
Energy	1.9e+1 Mt
All above are mean values weighted by impact probability	

Analysis based on 11 observations spanning 3.1215 days
(2005-Mar-13.26326 to 2005-Mar-16.38477)

Show 10 entries

Showing 1 to 5 of 5 entries

Impact Table (these results were computed on 2017-Apr-07)

Date (yyyy-mm-dd.dd)	Distance (r _{Earth})	Width (r _{Earth})	Sigma Impact	Sigma LOV	Stretch LOV (r _{Earth})	Impact Probability	Impact Energy (Mt)	Palermo Scale	Torino Scale
2023-03-11.35	0.66	8.33e-3	0.000	-0.21306	2.86e+5	2.0e-6	1.805e+01	-3.93	0
2028-03-10.54	0.48	7.01e-3	0.000	-3.45386	1.97e+5	8.6e-9	1.048e+01	-6.76	0
2029-03-10.79	0.25	6.44e-3	0.000	-4.02246	1.91e+5	1.2e-9	9.583e+00	-7.71	0
2030-03-11.19	0.10	1.44e-2	0.000	1.96176	6.12e+5	1.9e-7	2.706e+01	-5.17	0
2064-03-10.38	0.59	3.51e-2	0.000	0.81899	1.23e+6	3.7e-7	2.175e+01	-5.51	0

Print CSV Excel

<https://cneos.jpl.nasa.gov/sentry/details.html#?des=2005%20ED224>

Predictability

- Temporal
- **Spatial**
- Consequences

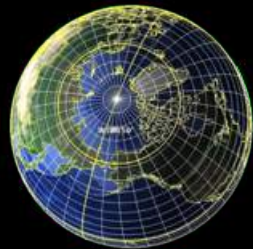
Impact Corridors



Presented during
Planetary Defense
Conference 2019 by Paul
Chodas of JPL



EXERCISE



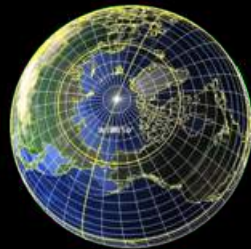
EXERCISE ONLY!!



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EXERCISE



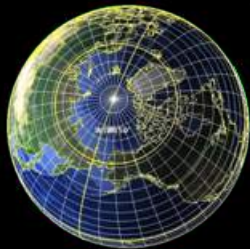
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EXERCISE



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EXERCISE ONLY!!

2019 PDC Impact Corridor

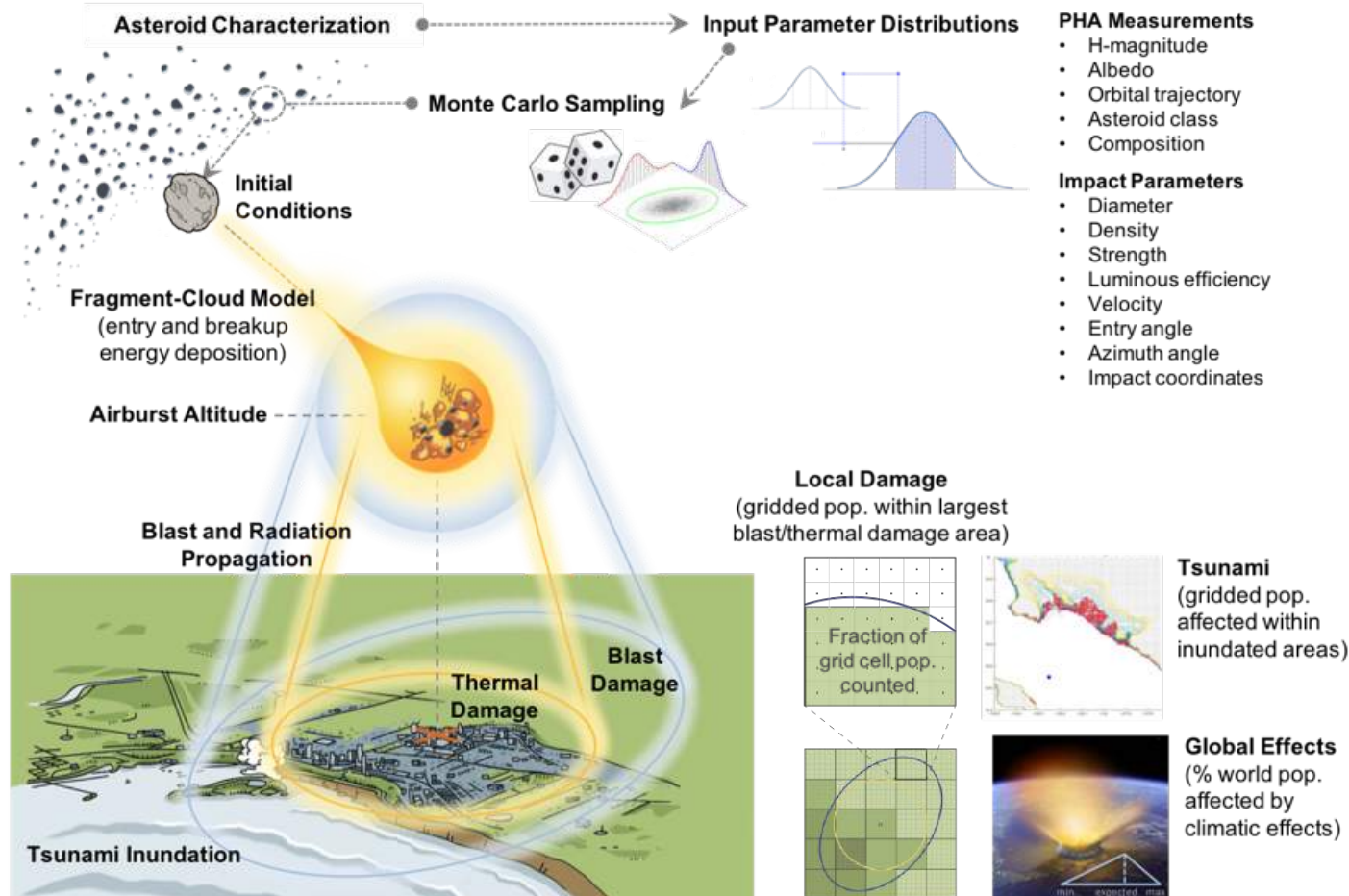
- Potential impact locations
 - Which regions might be affected?
 - Which are not?
- Impact conditions
 - Speed
 - Angle
- Enables further analysis



Predictability

- Temporal
- Spatial
- **Consequences**

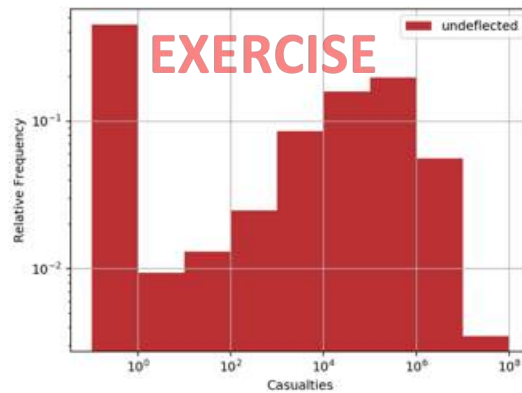
PAIR - Probabilistic Asteroid Impact Risk



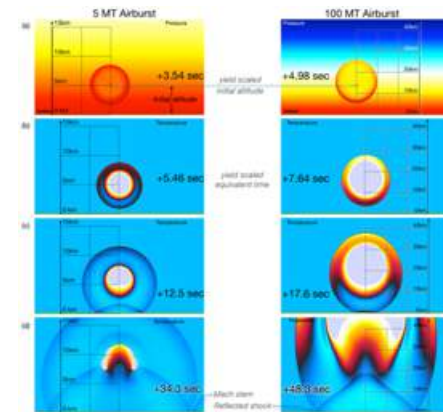
Mathias, D. L., Wheeler, L. F., & Dotson, J. L. (2017). A Probabilistic Asteroid Impact Risk Model: Assessment of Sub-300 m Impacts. *Icarus*, 289, 106–119.

Impact Consequences

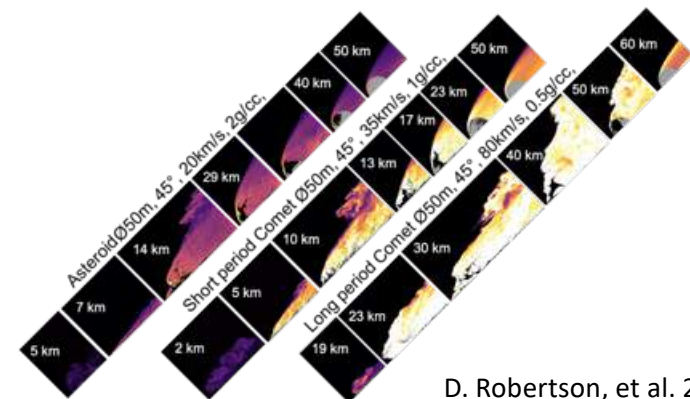
PAIR Consequence Predictions



High Fidelity Simulations



M. Aftosmis, et al. 2019



D. Robertson, et al. 2019

Uncertainty

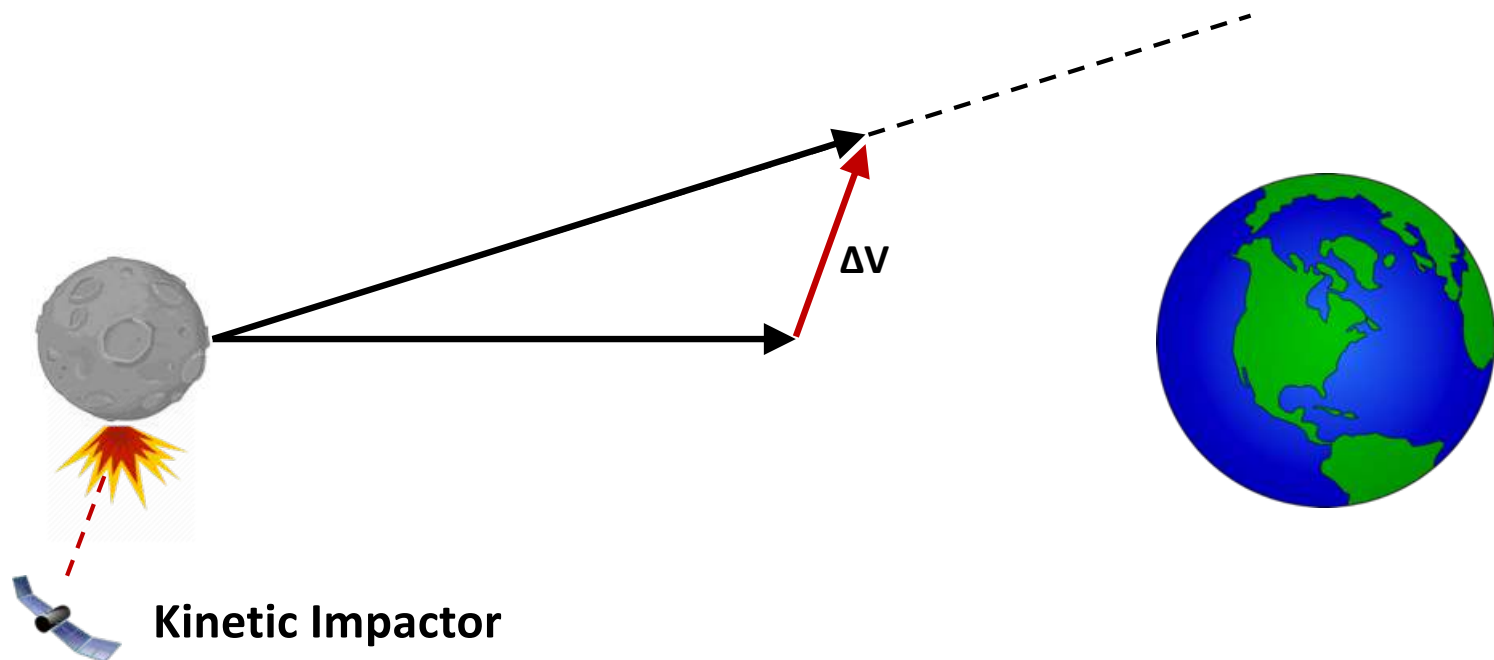
- Physical
- Orbital



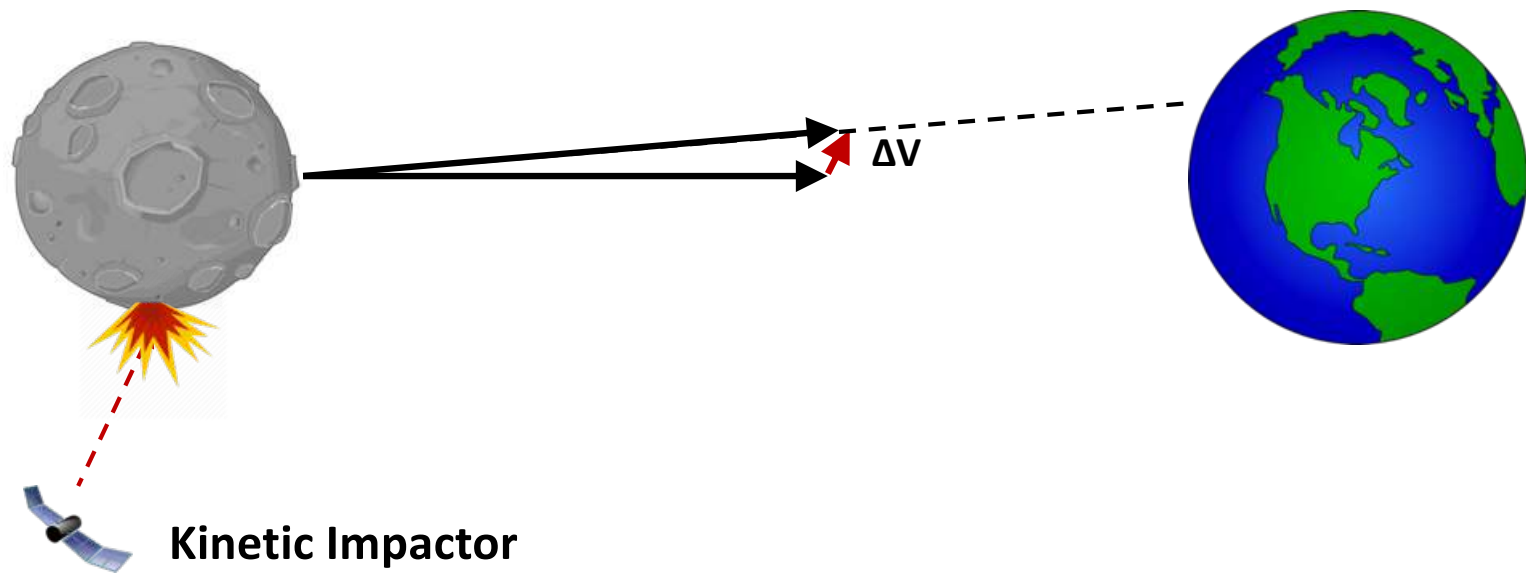
Physical Uncertainty

- The effect of a deflection mission is highly dependent on physical properties of the asteroid
- Conservation of Momentum (size, density uncertainty of asteroid)
- Physical properties drive momentum enhancement factor β

Deflection Scenario



Deflection Scenario



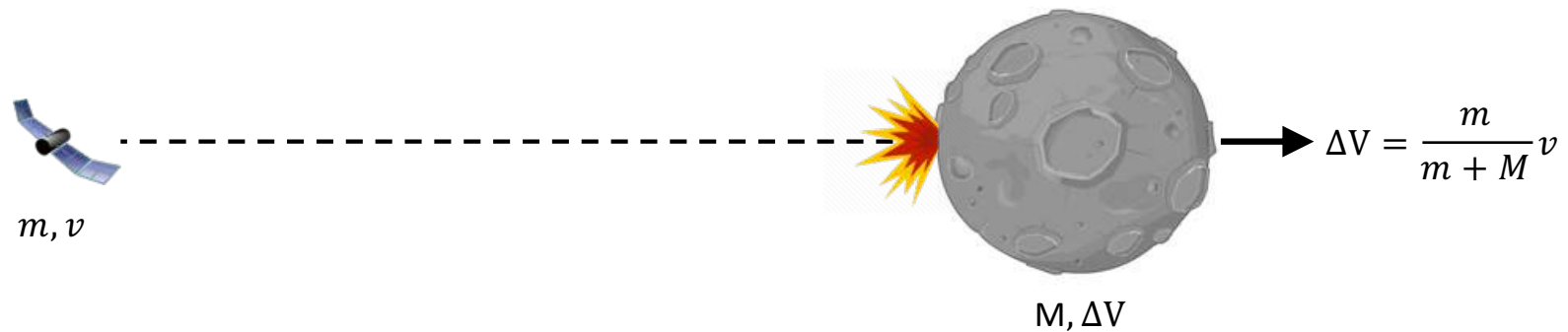


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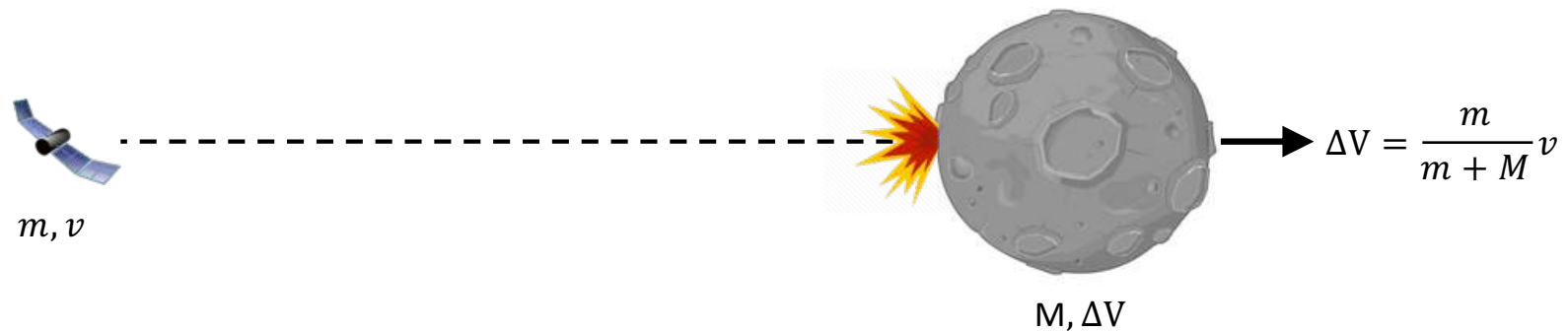
Beta factor explanation

- Beta factor is an important concept for kinetic impactor deflection
- Depends on physical properties such as strength and porosity



Beta factor explanation

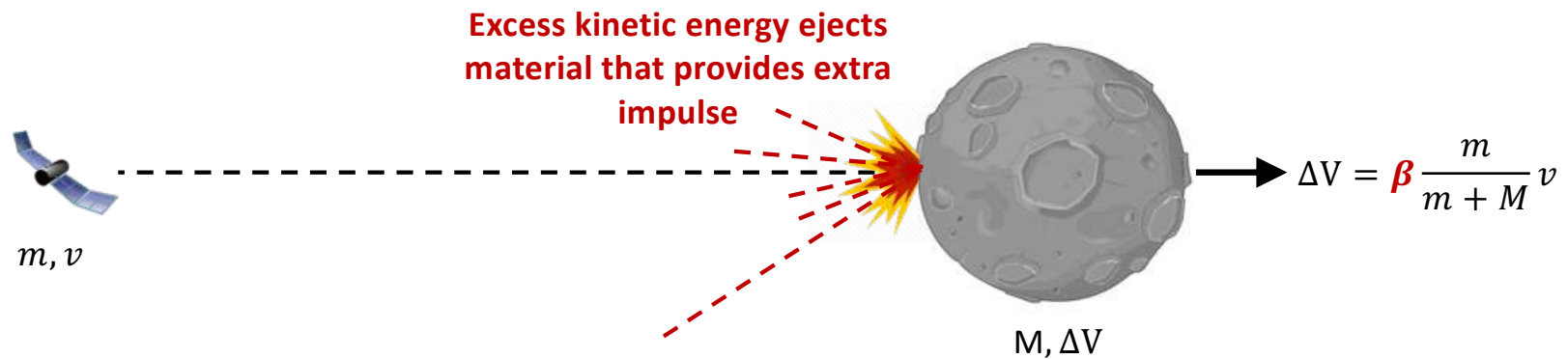
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BUT

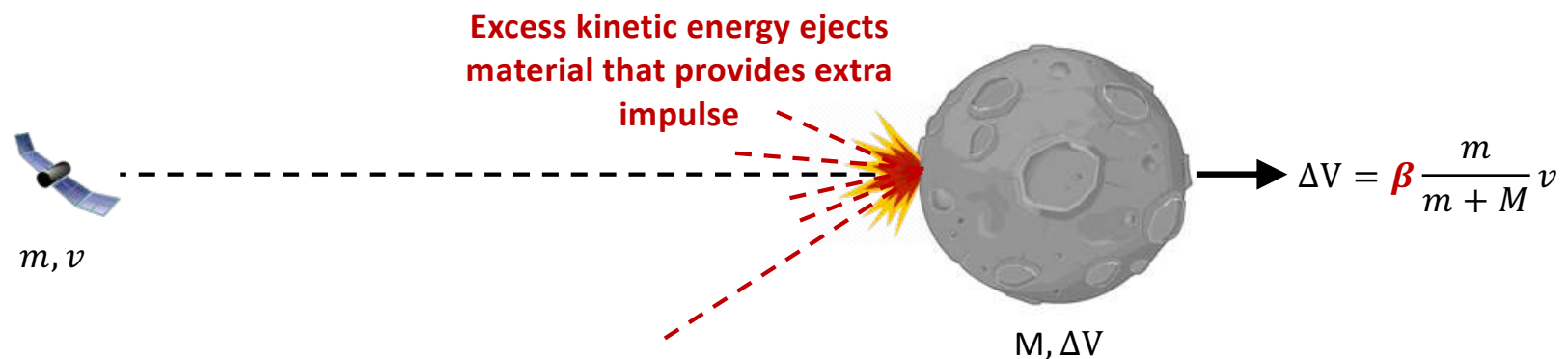
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Beta factor explanation

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Current estimates of β are in the range [1,10]

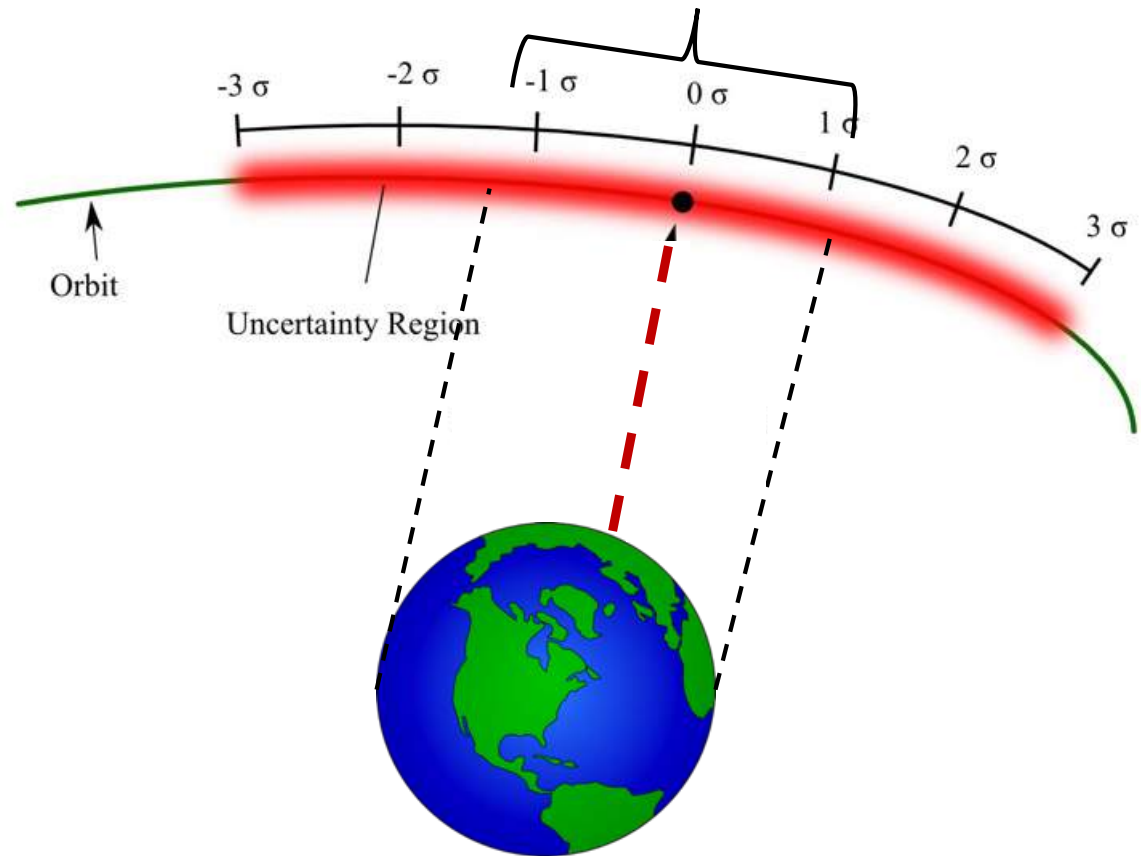
We used a semi-empirical equation from Lawrence Livermore Labs based on hydrocode impact simulations

Uncertainty

- Physical
- **Orbital**

Orbit uncertainty

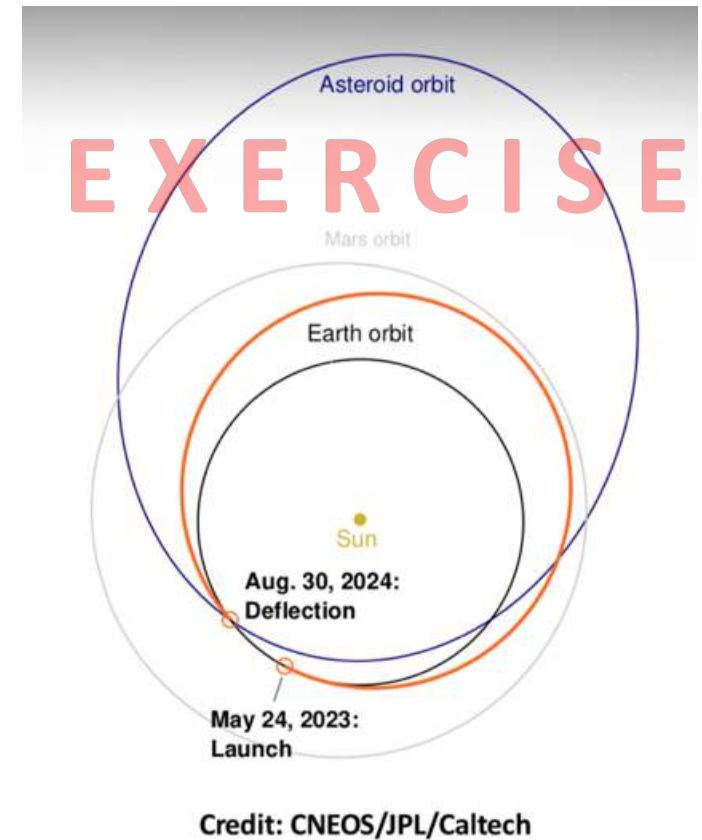
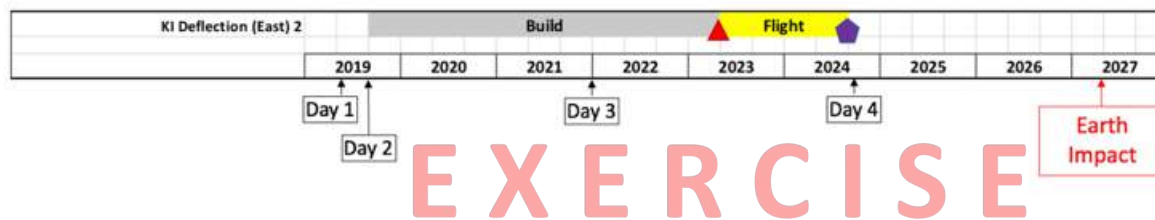
- "Envelopes" the possible "positions" (states) of the the asteroid at a given time
- Real asteroid is only in one location corresponding to one impact location within impact corridor
- Real location determines new impact location due to a given deflection mission



Deflection Analysis Setup

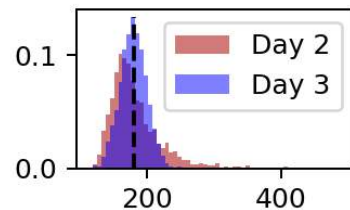
Deflection Mission

- Design ΔV : 27.3 mm/s
- ΔV -vector = $[-1.43407e+01, -1.62387e+01, 1.66142e+01]$ mm/s
- Mass: 13 214 kg
- Deflection date: JD 2460552.50
- Time Before Impact: 972.17 days

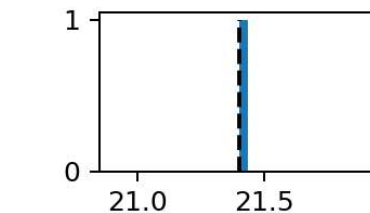


https://cneos.jpl.nasa.gov/pd/cs/pdc19/pdc19_briefing2.pdf

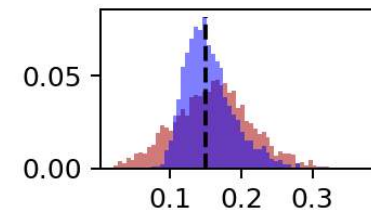
Asteroid Properties



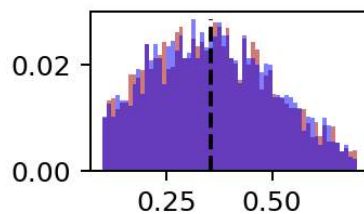
Diameter: median=180.2 m



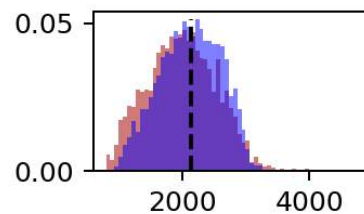
Abs. Magnitude [-]: median=21.4



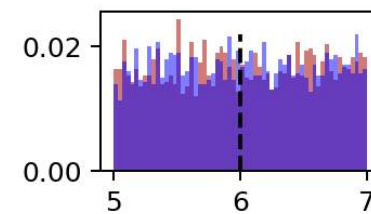
Albedo [-]: median=0.150



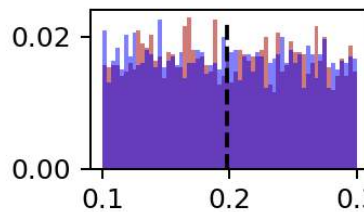
Porosity [-]: median=0.355



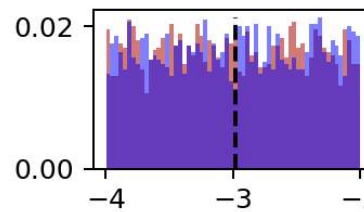
Density: median=2136.5 $\frac{kg}{m^3}$



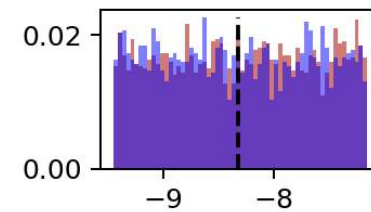
$\log_{10}(\text{Strength})$
median=1.0e+06 MPa



Alpha [-]: median=0.2

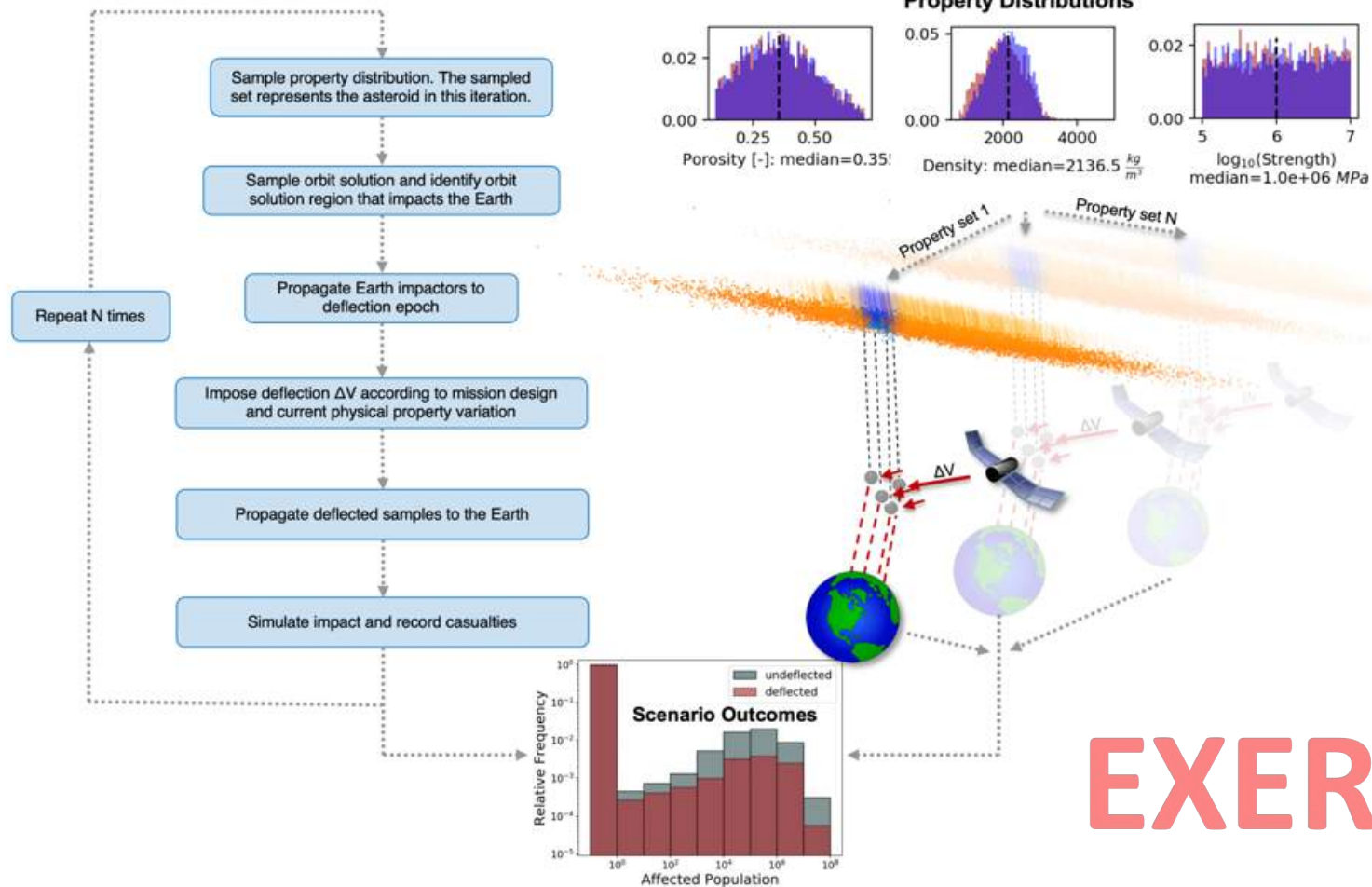


$\log_{10}(\text{Luminous Efficiency})$ [-]
median=1.0e-03



$\log_{10}(\text{Ablation Coefficient})$ [-]
median=4.7e-09

Deflection Analysis Process



Impact Risk

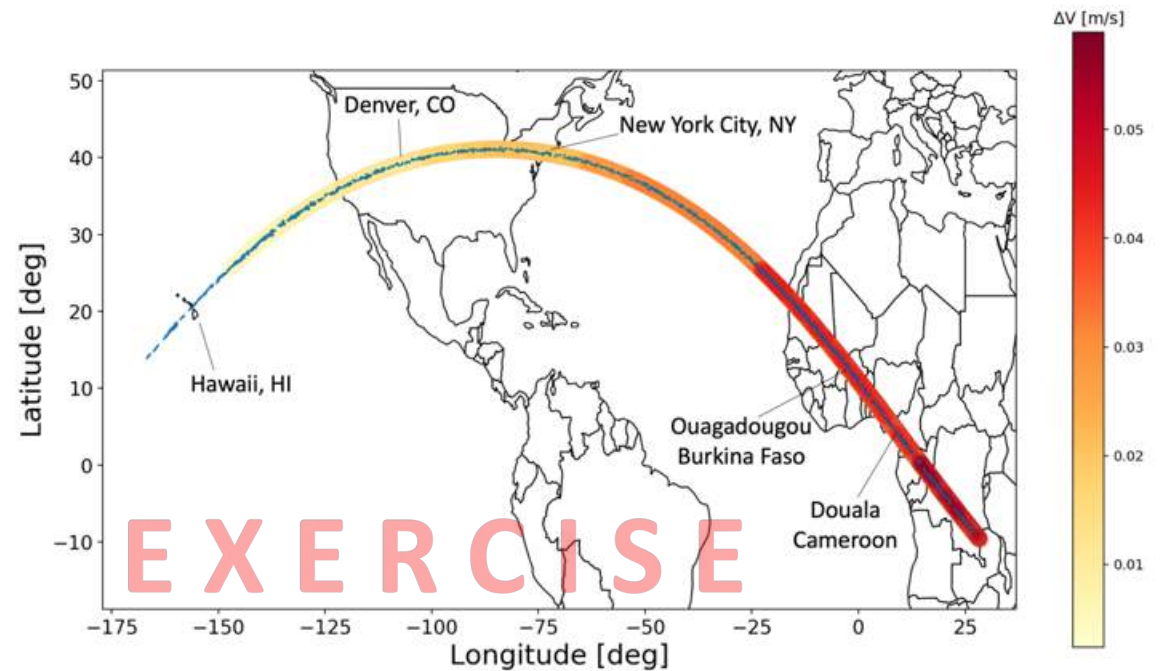
$$\mathbf{Risk} = (N_{\mathbf{Casualties}} | \mathbf{Impact}) \times \mathbf{Impact\ Probability}$$

- Metric to capture risk level
- Combines nicely the consequences of a potential impact with the probability of it happening
- Unit is “number of Casualties”

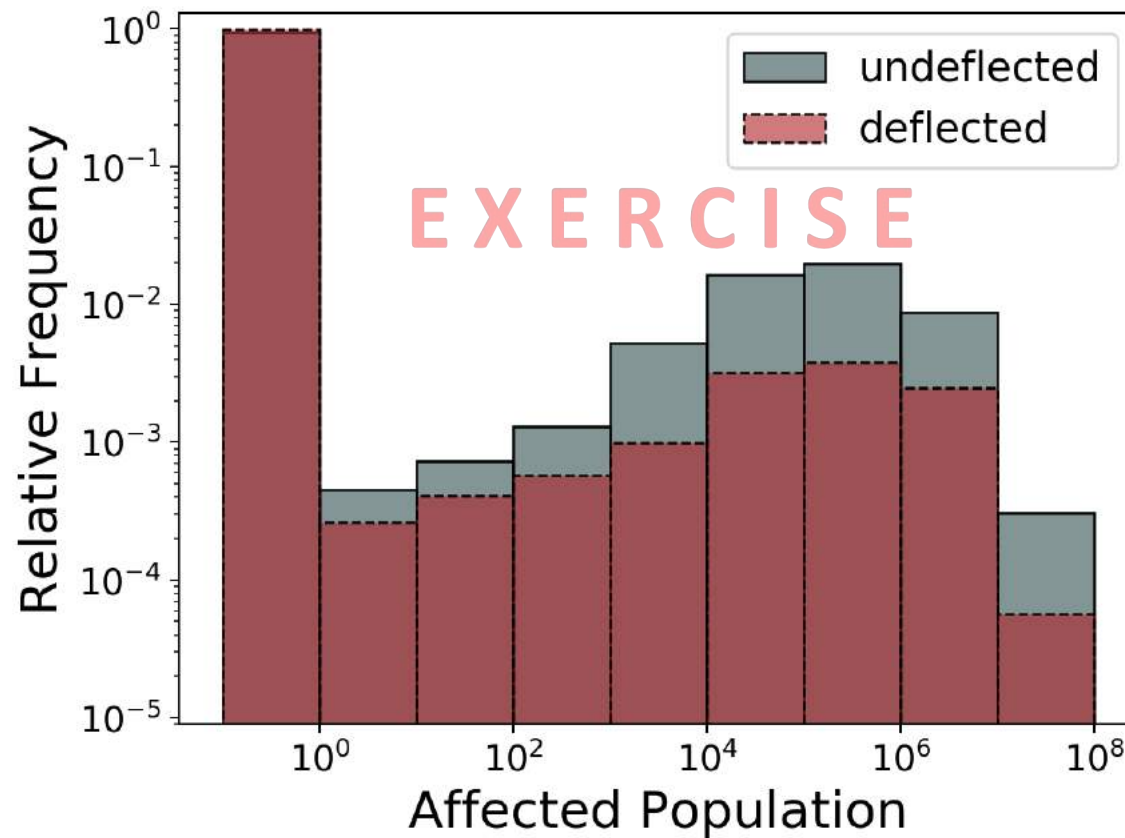
2019 PDC Results

Day 2 Deflected Corridor

Deflection	Impact Probability [%]	Risk [affected people]
Without	10.7	35 k
With	1.7	10 k

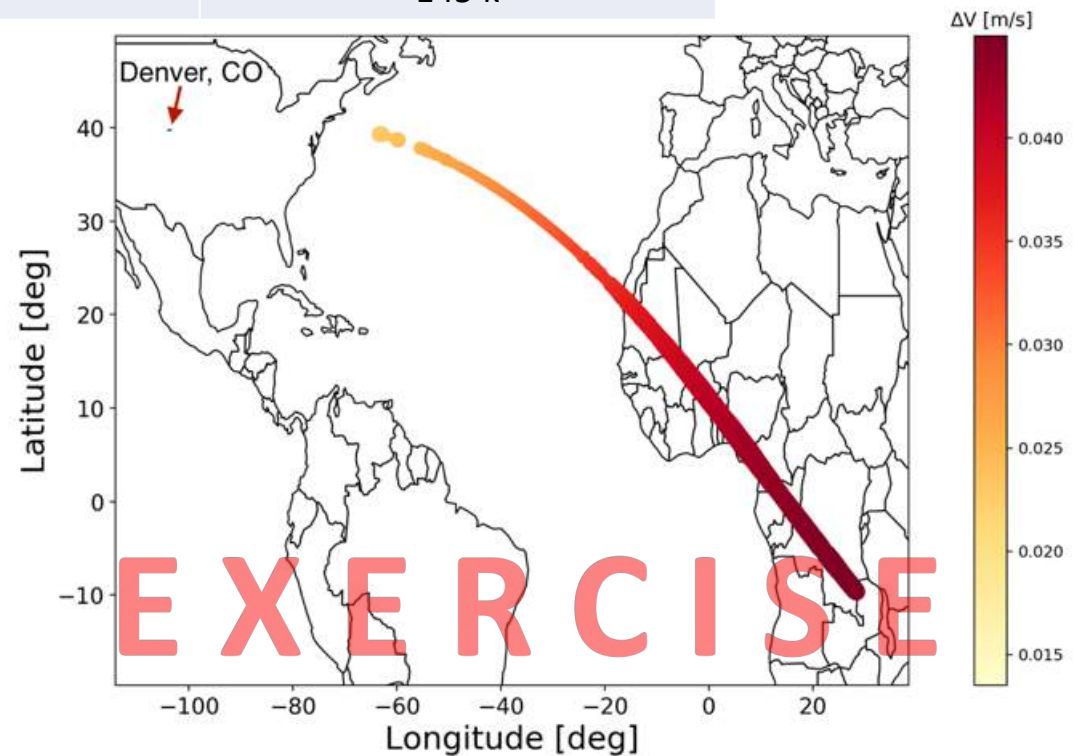


Day 2 Casualty Histogram



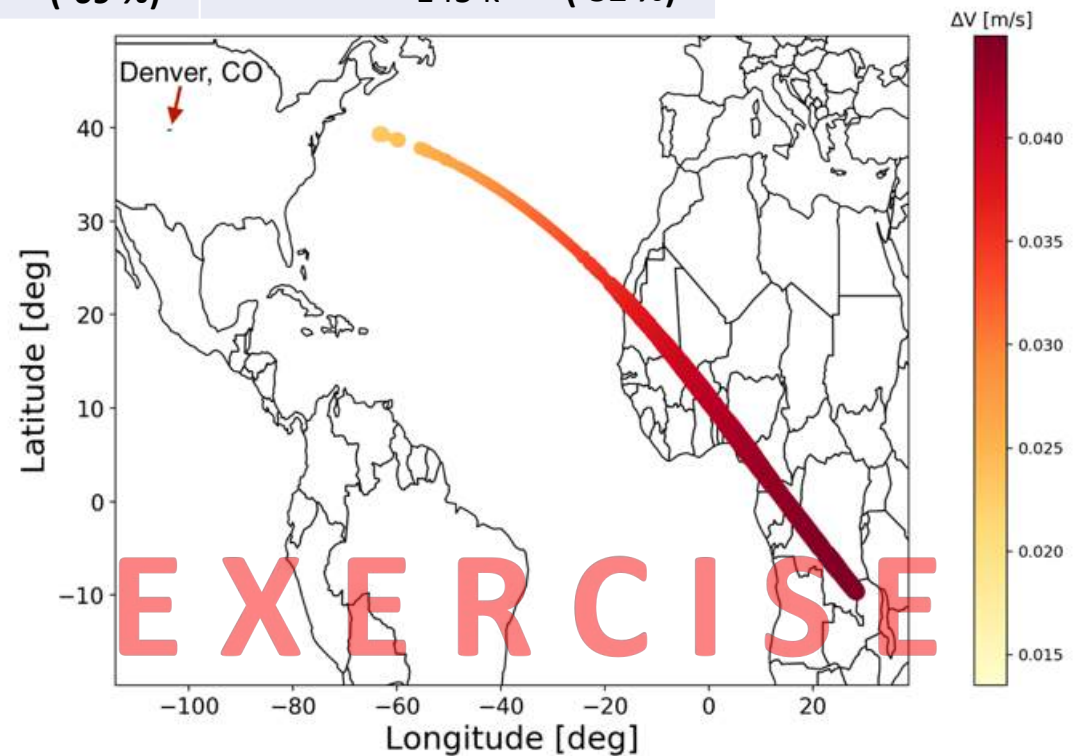
Day 3 Deflected Corridor

Deflection	Impact Probability [%]	Risk [affected people]
Without	100	302 k
With	30.7	145 k

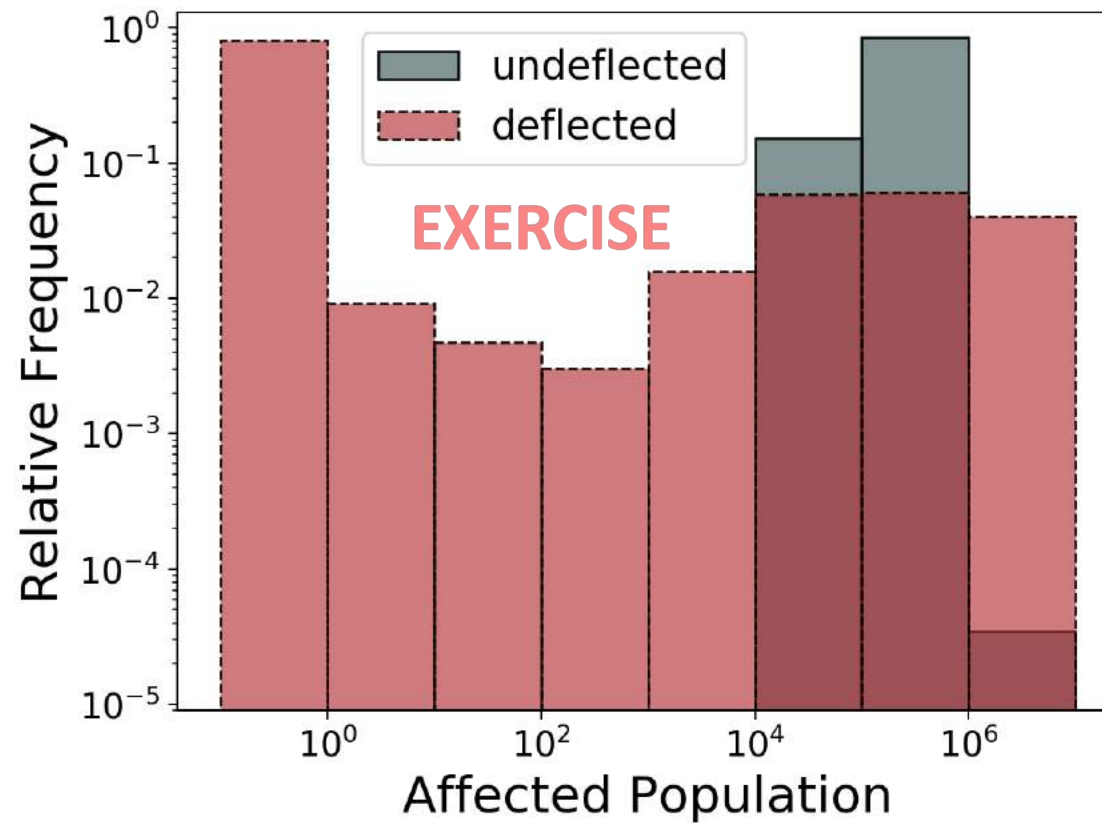


Day 3 Deflected Corridor

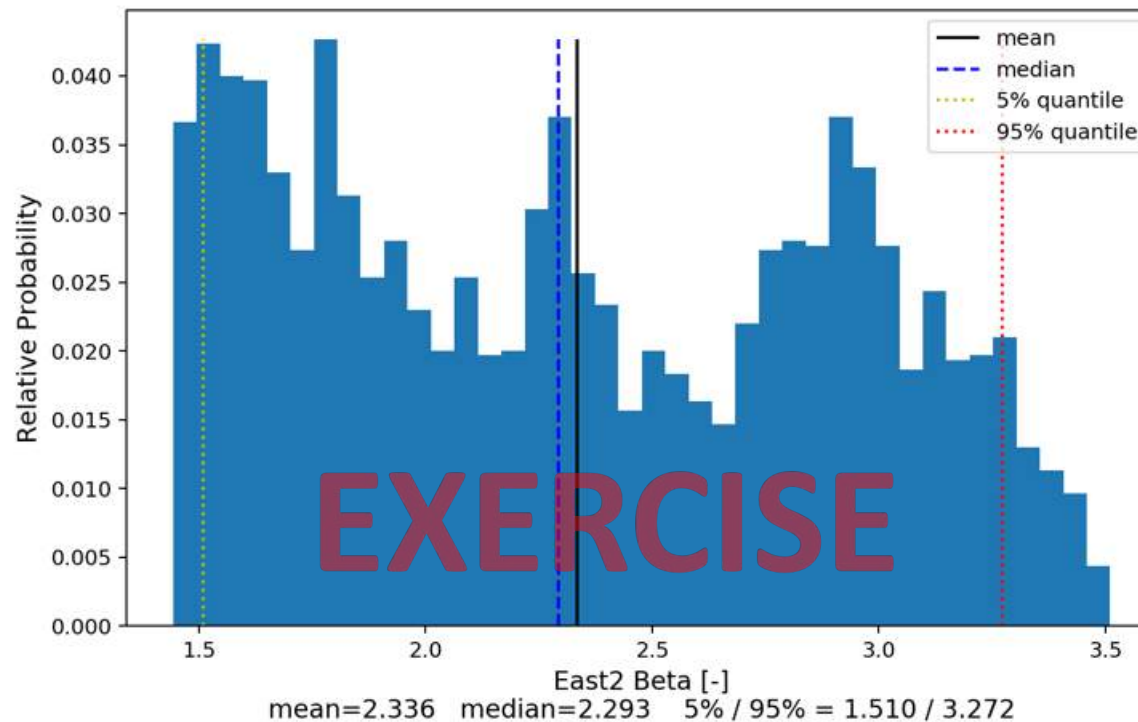
Deflection	Impact Probability [%]		Risk [affected people]	
Without	100		302 k	
With	30.7	(-69 %)	145 k	(-52 %)



Day 3 Casualty Histogram



Realized Beta Values

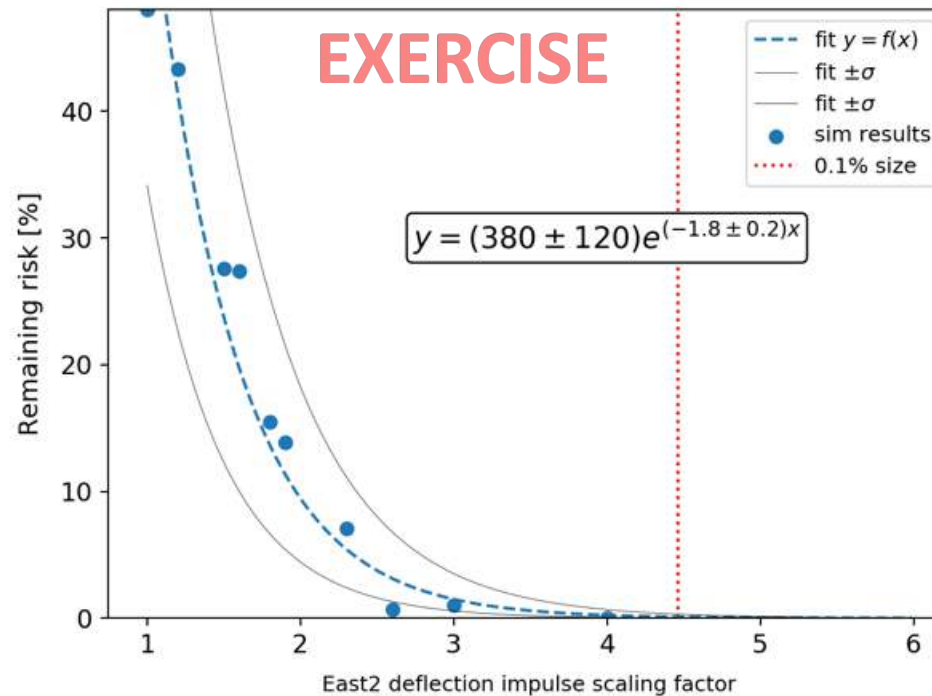


β was in range $\cong [1.5, 3.3]$ in this study

Deflection Mission Scaling

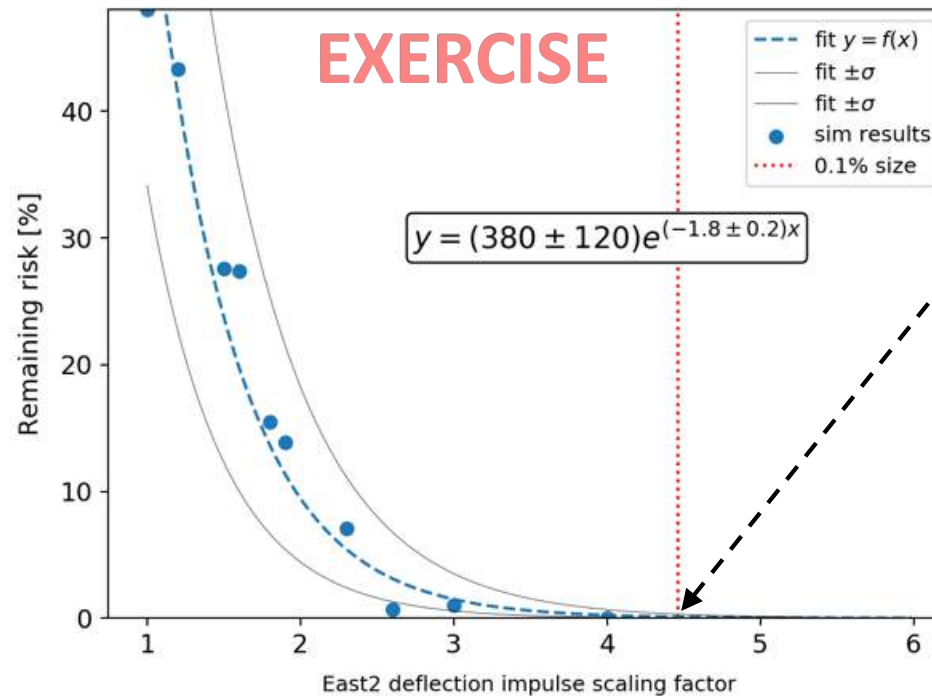
Scaling Deflection Missions for Success

- How to achieve “successful” deflection in uncertain environment?
- One approach: Define a risk reduction level you are comfortable with
- For example 99.9 % risk reduction



Scaling Deflection Missions for Success

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- 99.9 % risk reduction achieved with $\cong 4.5$ scaling
- Could be achieved with 4.5 times heavier deflection spacecraft
- Or by sending 5 of the original deflection spacecraft

Summary

- Asteroid impacts are special natural disasters due to their
 - Predictability (time, location, consequences)
 - Preventability (deflection missions)
- Introduction to deflection missions
- Uncertainties let deflection outcomes vary
- Results show that deflection missions might be unsuccessful and only move impact location
 - Could make situation worse
- Considering uncertainties allows to determine deflection scaling factor to increase success probability to comfortable levels



Thank You

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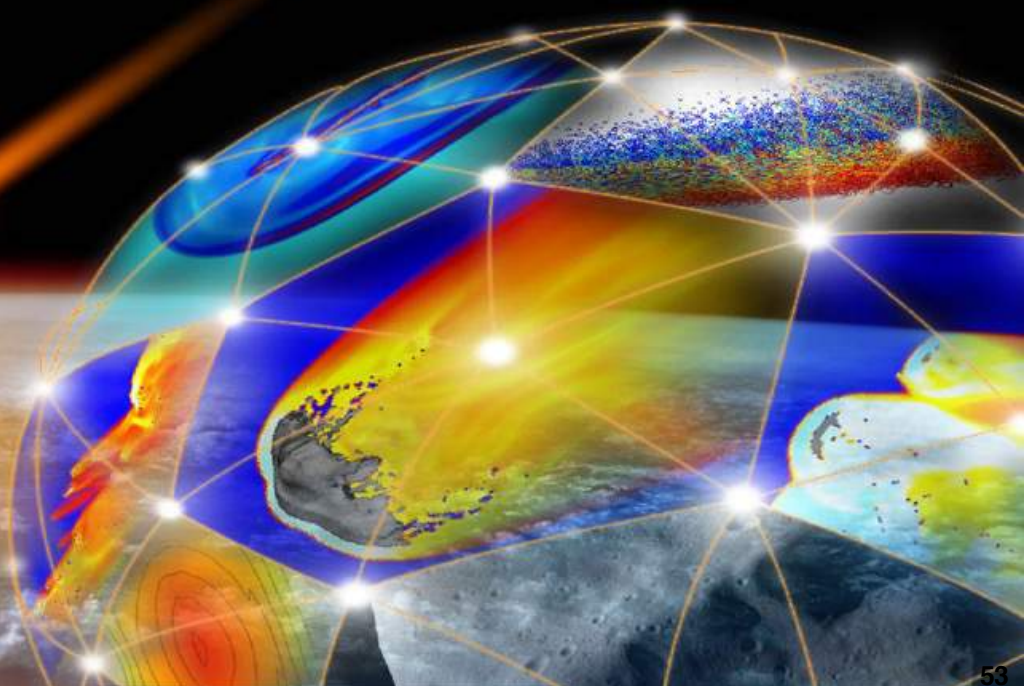
Acknowledgements:

The ATAP team for collaborative work

NASA Advanced Supercomputing Facility for computational resources

NASA Postdoctoral Program for funding part of this work

JPL and NASA GSFC for contributions to this work



Day 3 Risk and achieved ΔV

