Asteroid Impact Risk: The Uncertain Outcome of Deflection Missions

Clemens Rumpf
ATAP Team

AMS Seminar, Nov 5th 2019

NASA ARC

Outline

- **Background**
  - Asteroid Impacts
  - Predictability
    - Temporal
    - Spatial
    - Consequences
- **Building Blocks**
  - Deflection Missions
  - Uncertainty
    - Physical (Beta factor)
    - Orbit
- **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

Predictability

- **Temporal**
- Spatial
- Consequences

Asteroid Impacts - JPL Risk Page

Object Designation	Year Range	Potential Impacts	Impact Probability (cumulative)	$V_{infinity}$ (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

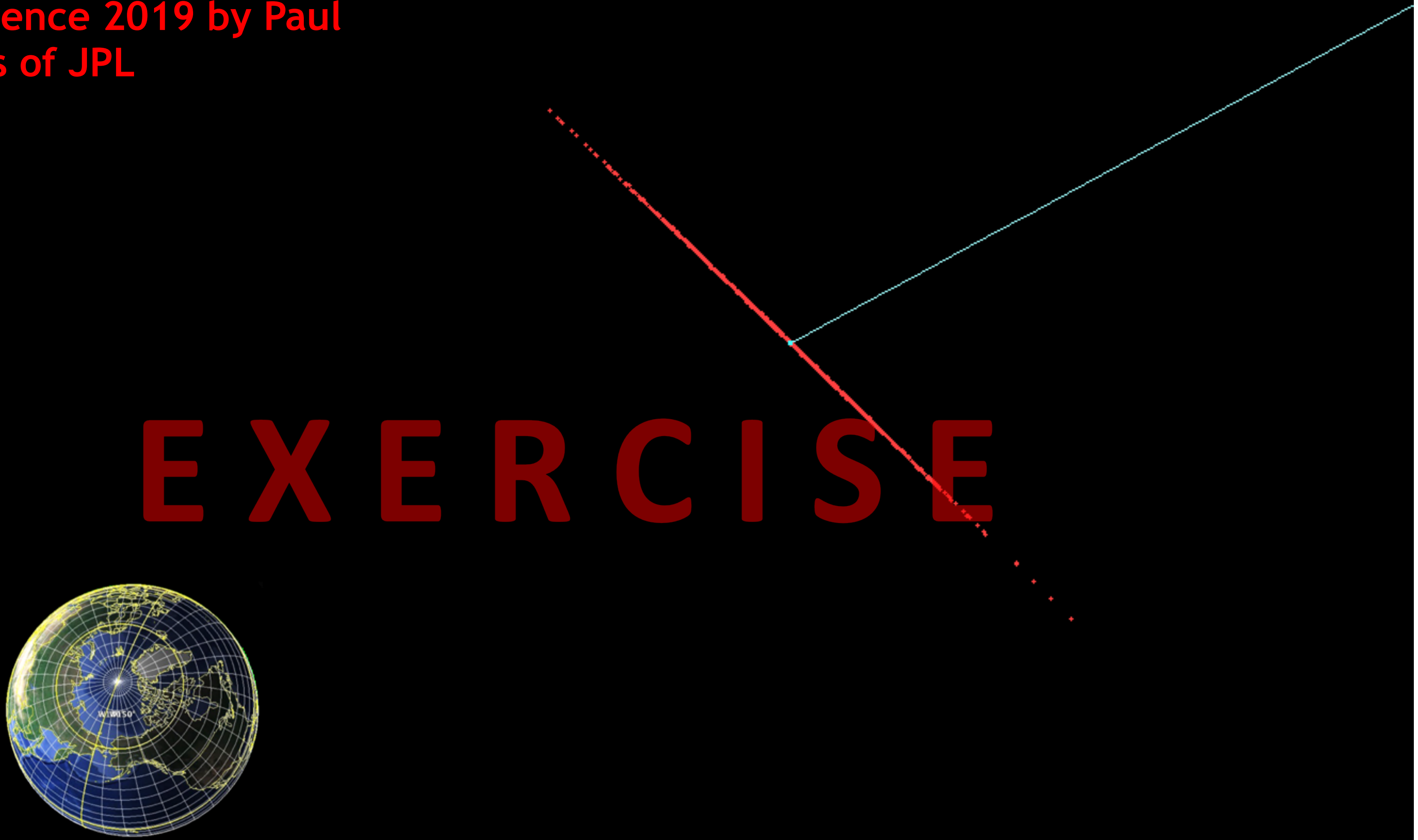
Impact Corridors

Presented during Planetary Defense Conference 2019 by Paul Chodas of JPL

E X E R C I S E

EXERCISE ONLY!!

Presented during Planetary Defense Conference 2019 by Paul Chodas of JPL



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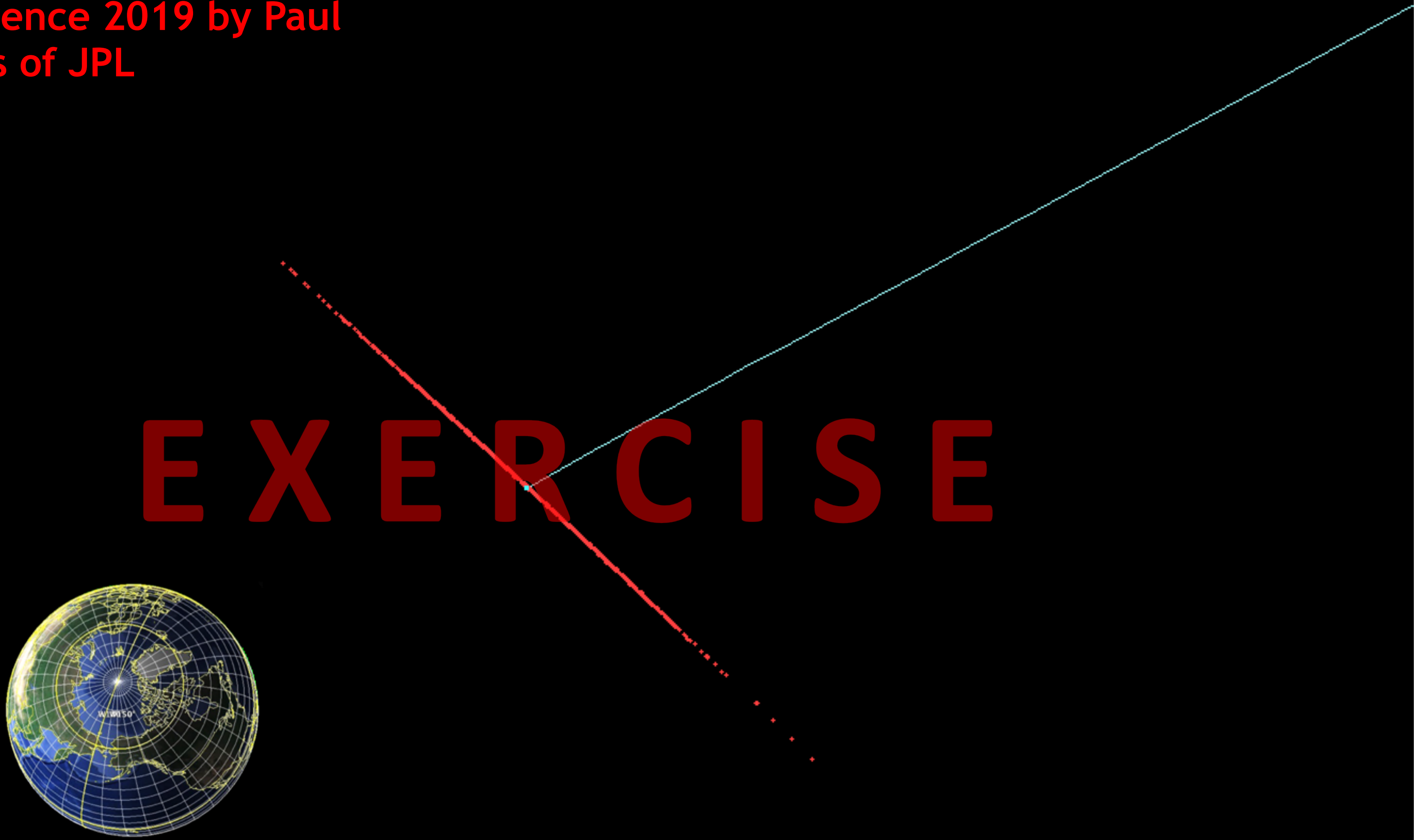

EXERCISE

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EXERCISE ONLY!!

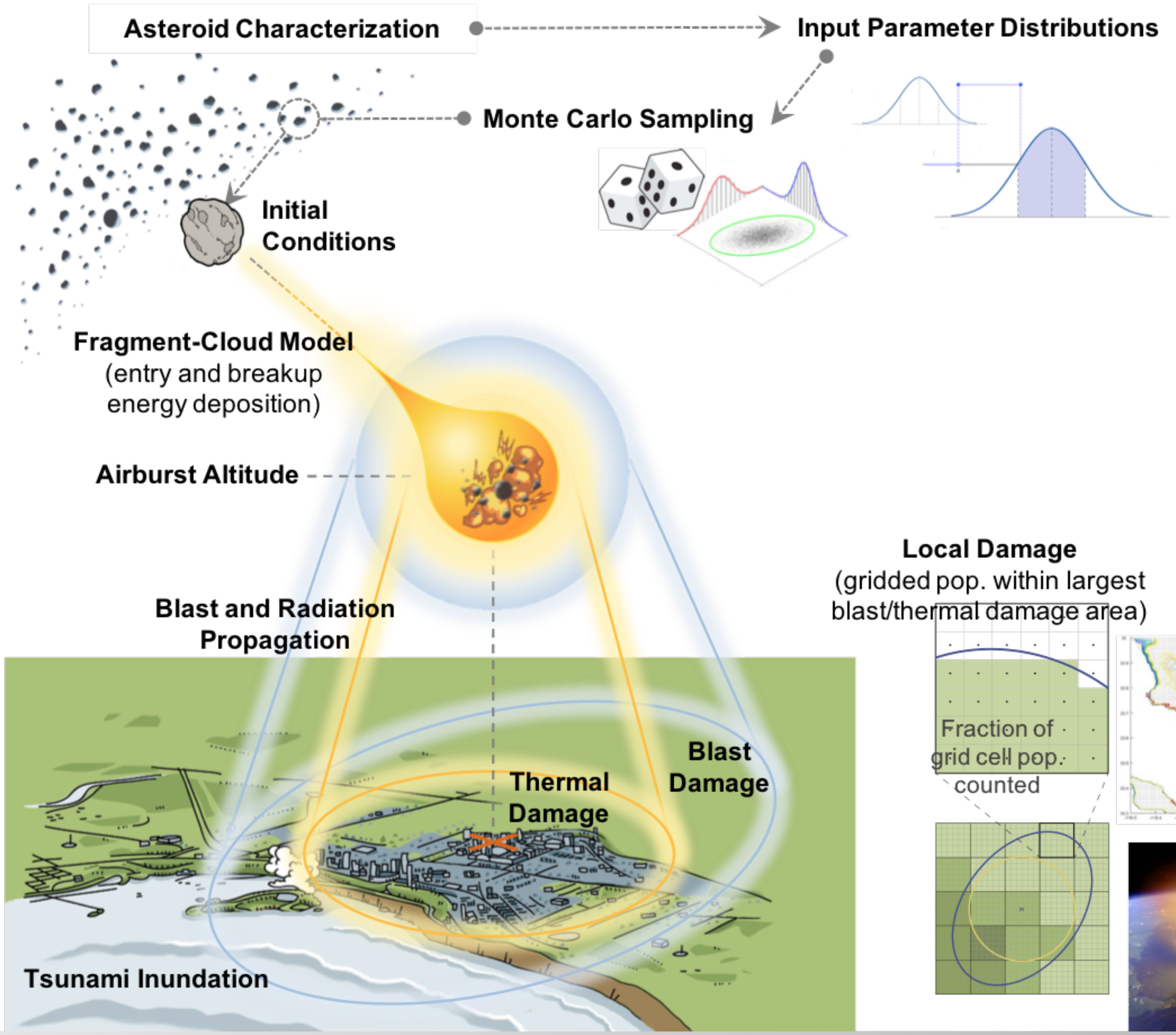
2019 PDC Impact Corridor

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

Predictability

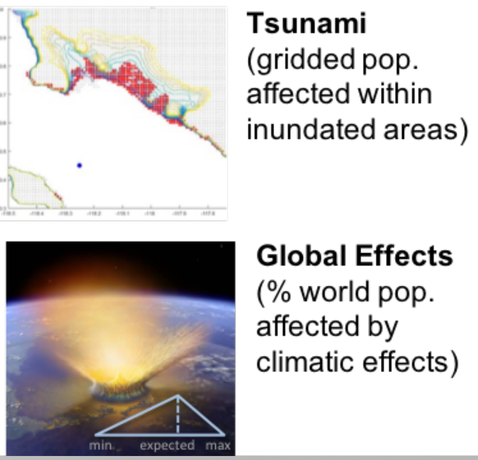
- Temporal
- Spatial
- **Consequences**

PAIR - Probabilistic Asteroid Impact Risk



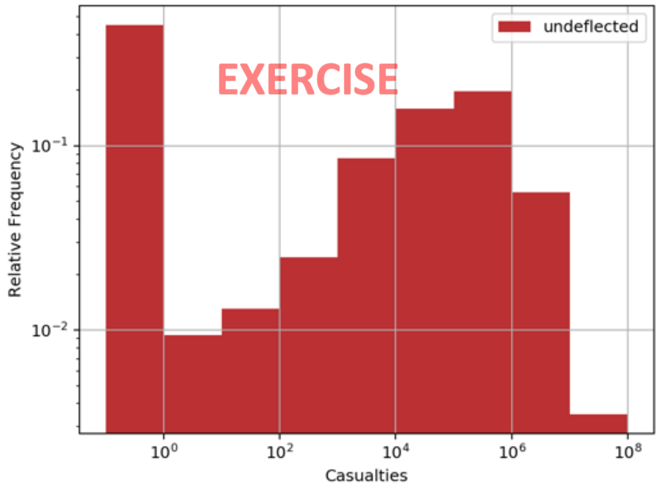
PHA Measurements
- H-magnitude
- Albedo
- Orbital trajectory
- Asteroid class
- Composition

Impact Parameters
- Diameter
- Density
- Strength
- Luminous efficiency
- Velocity
- Entry angle
- Azimuth angle
- Impact coordinates

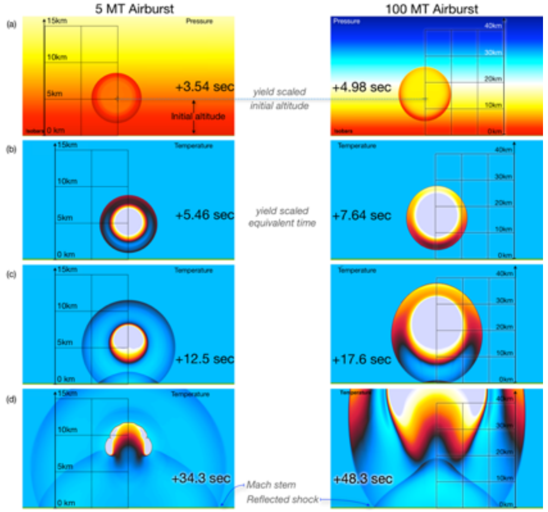


Impact Consequences

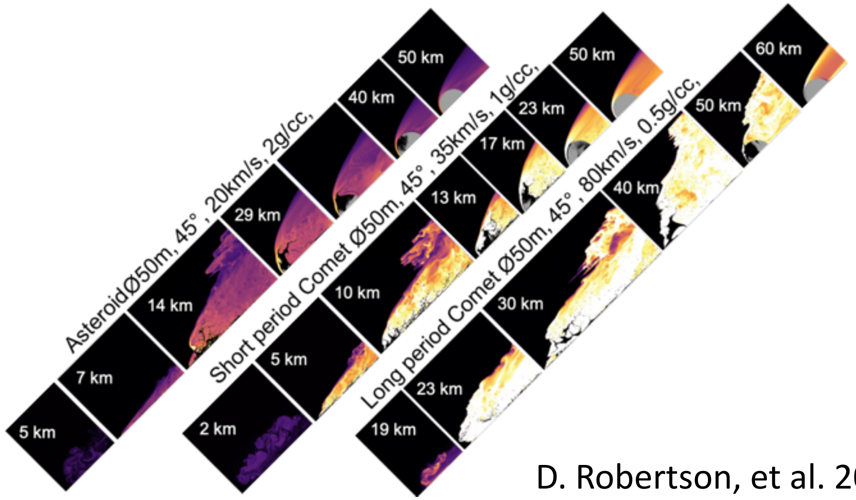
PAIR Consequence Predictions



High Fidelity Simulations



M. Aftosmis, et al. 2019



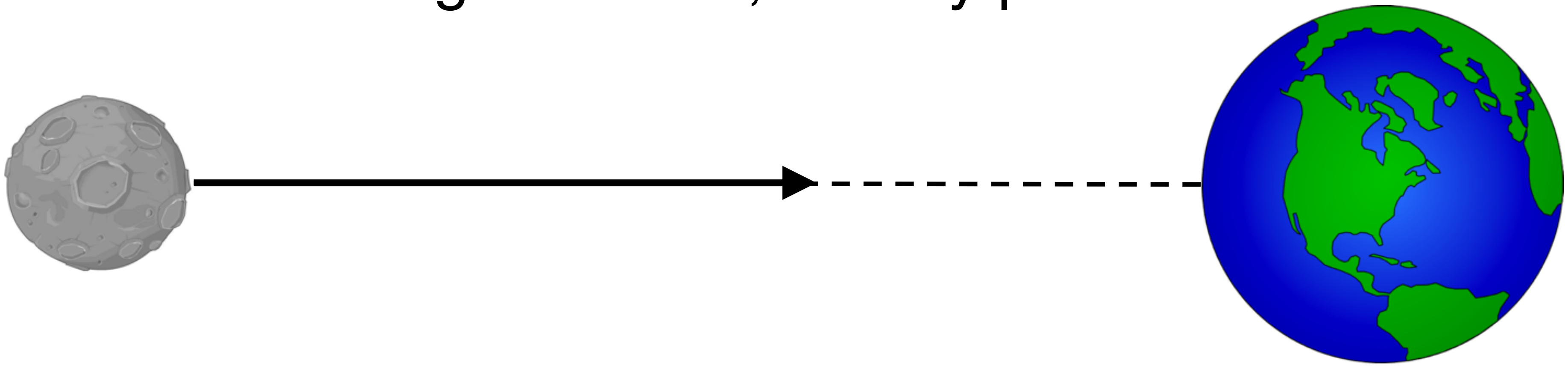
D. Robertson, et al. 2019

Deflection Mission

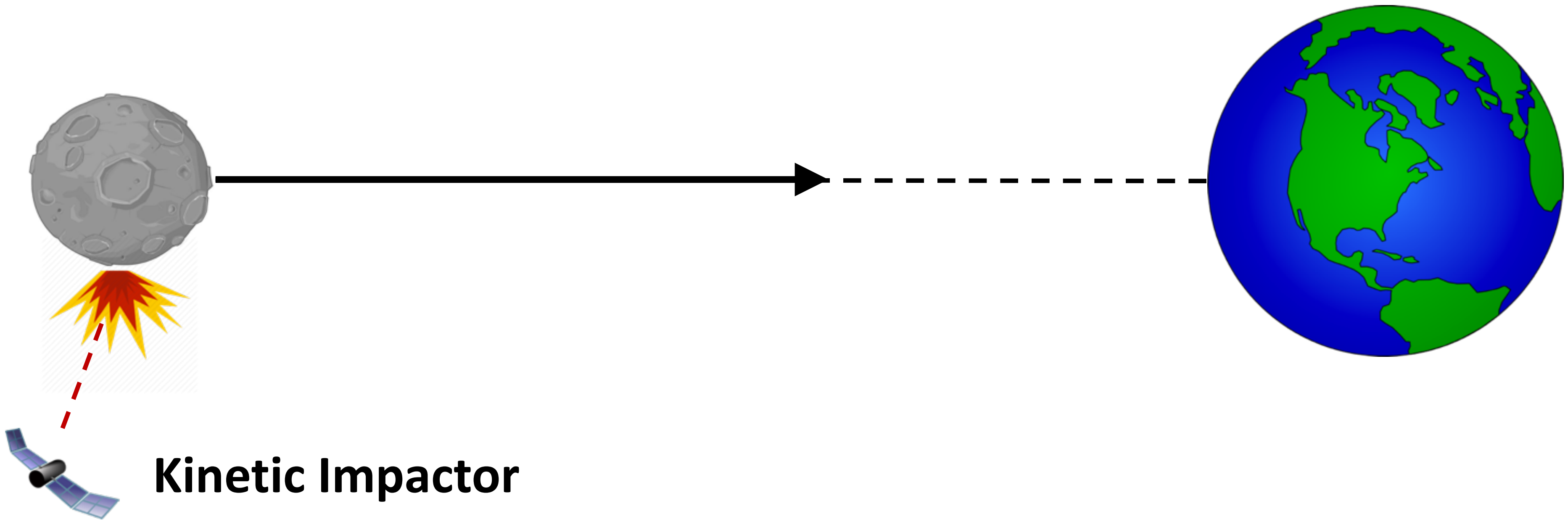
- **Mechanics**
- Heritage

Deflection Scenario

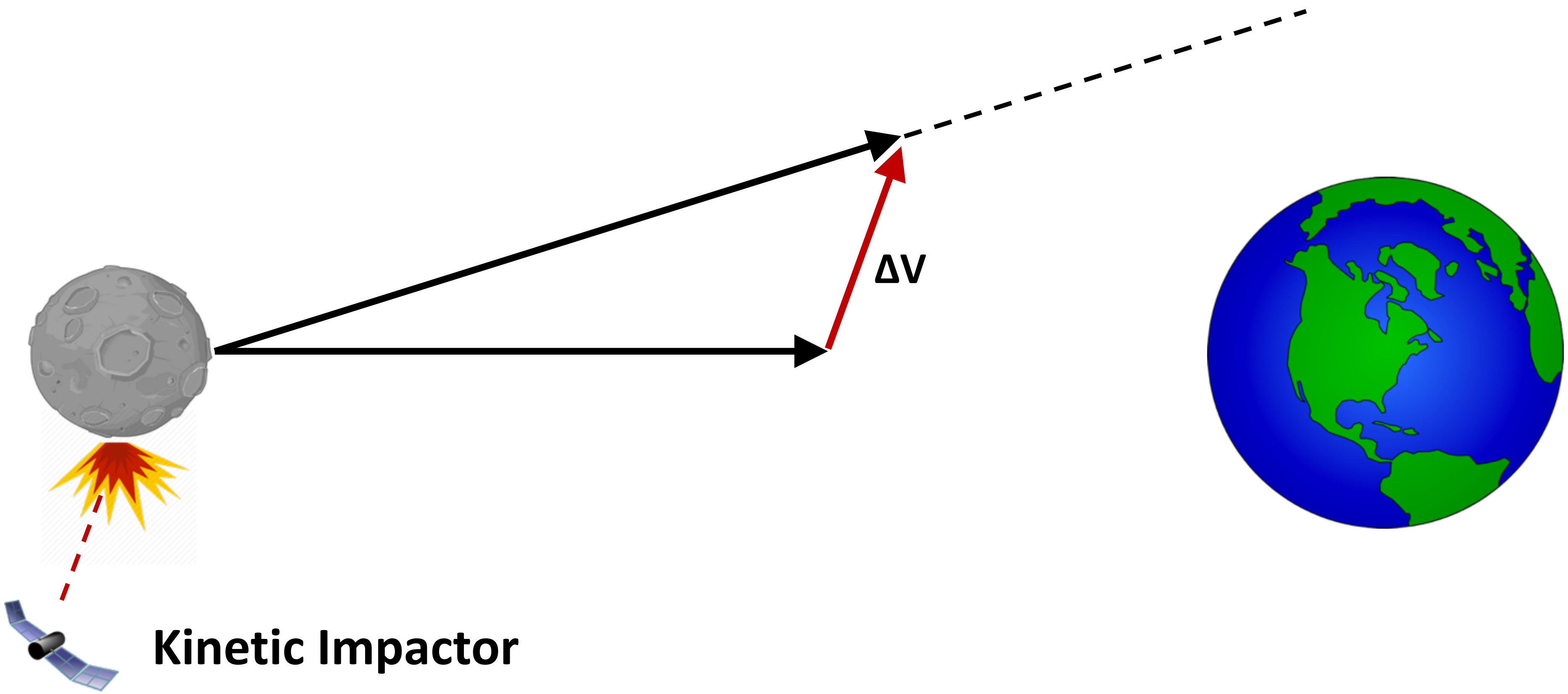
- An asteroid is on a collision course with Earth
- It’s possible to change the orbit of asteroids.
- Goal: Instead of hitting the Earth, let it fly past



Deflection Scenario



Deflection Scenario



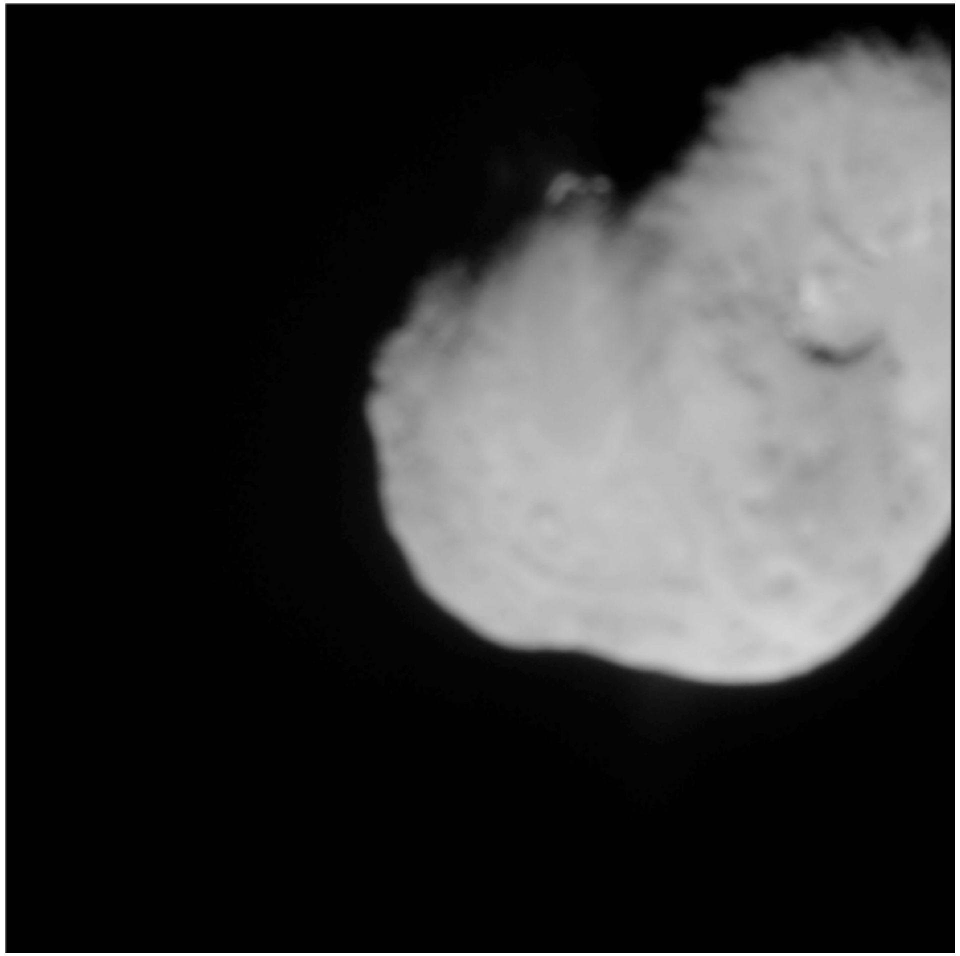
Ames Research Center

Deflection Mission

- Mechanics
- **Heritage**

Deep Impact 2005

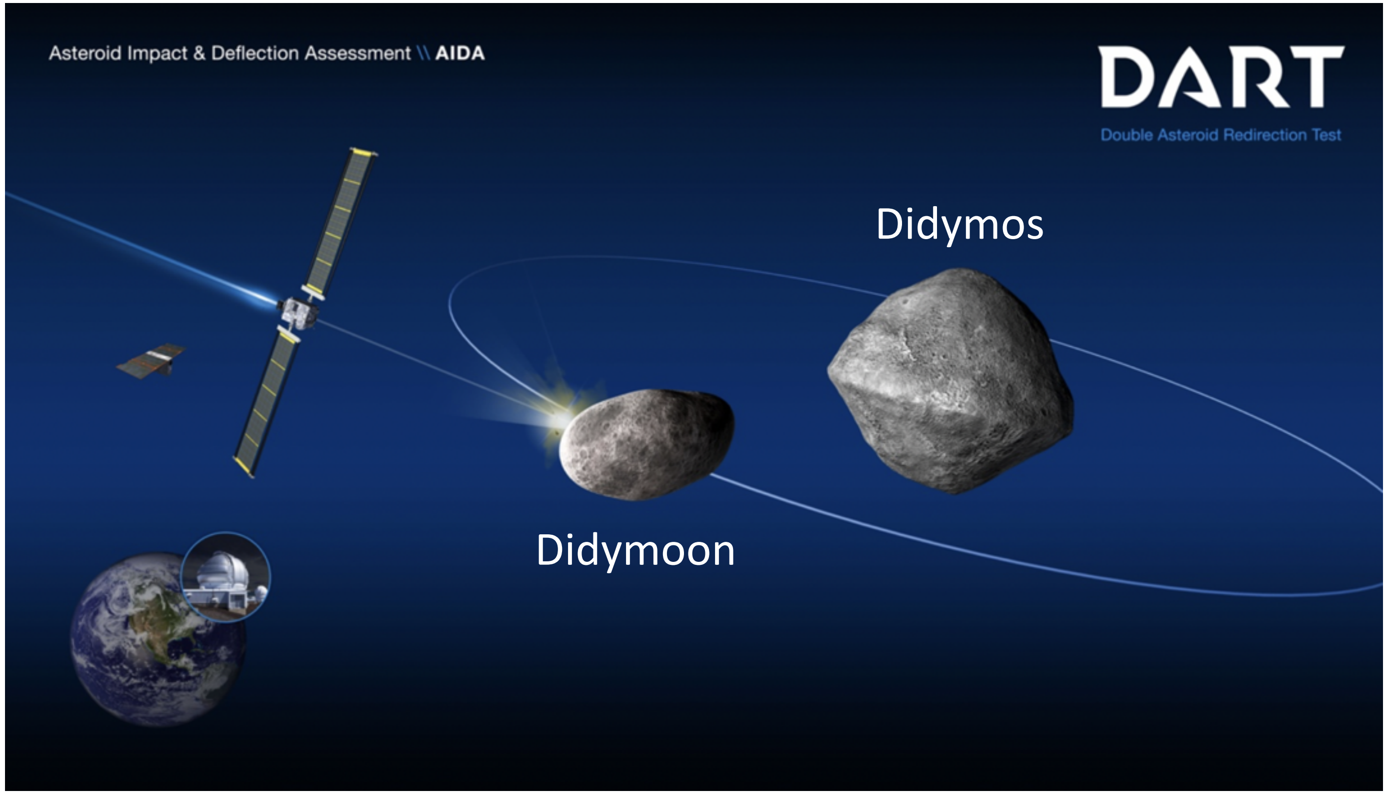
- Scientific mission by NASA in 2005
- Excavate sub-surface material by impact
- Evaluate sub-surface material using spectroscopy
- Equivalent to kinetic impactor
- **But**:
    - Target was large: ≅ 5 km
    - No measurements on trajectory change



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: ≅ 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

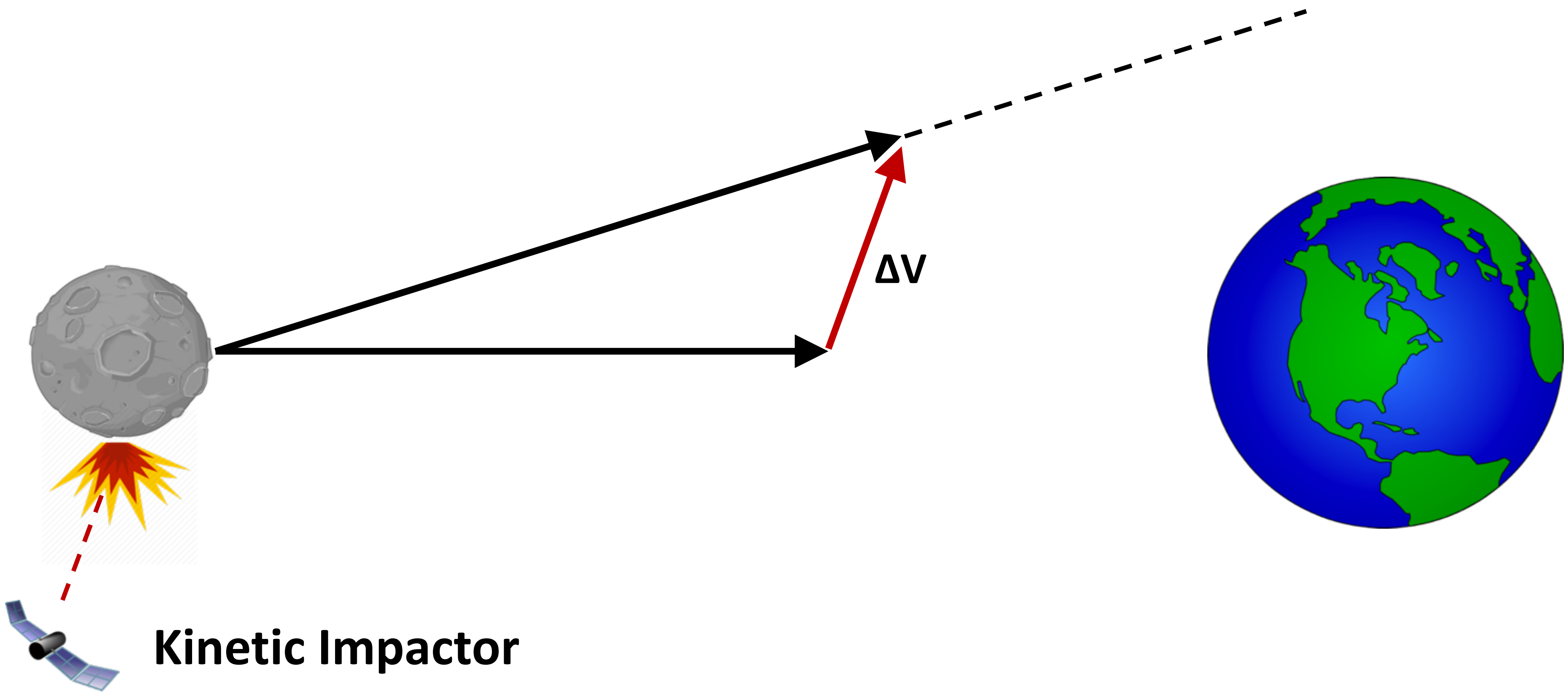
Uncertainty

- **Physical**
- Orbital

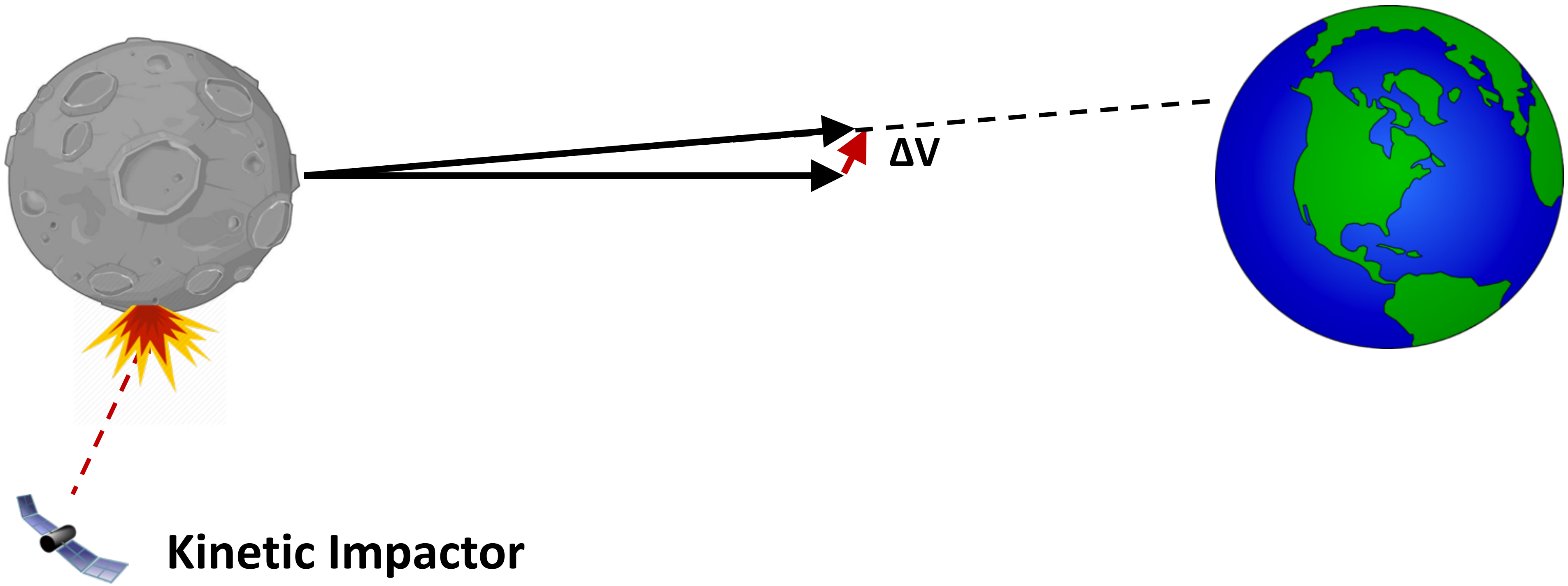
Physical Uncertainty

- 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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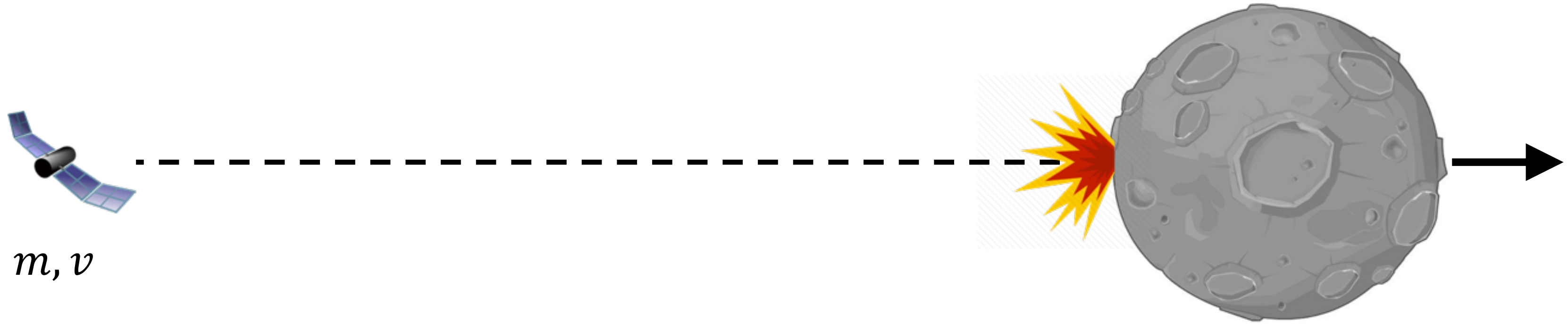
Beta factor explanation

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



$$\Delta V = \frac{m}{m + M} v$$

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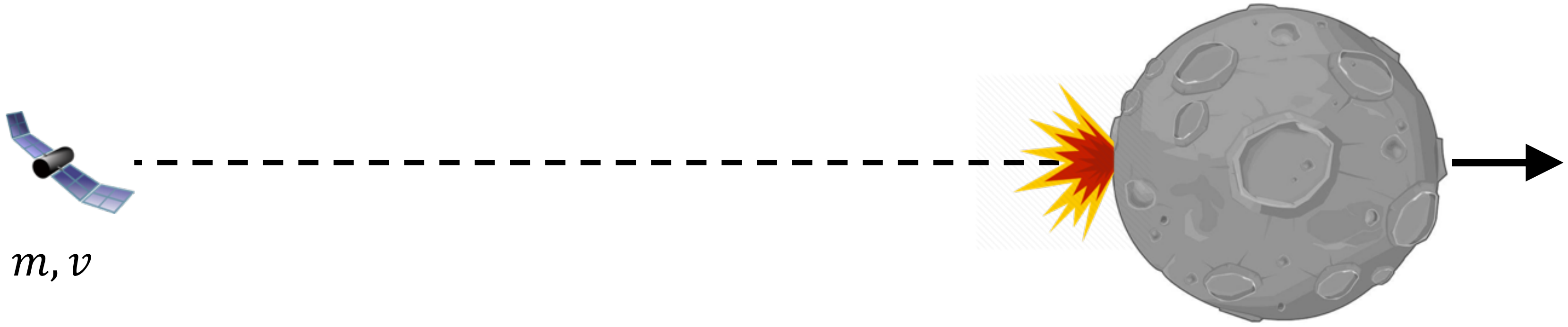

m, v

$M, \Delta V$

$$\Delta V = \frac{m}{m + M} v$$

BUT

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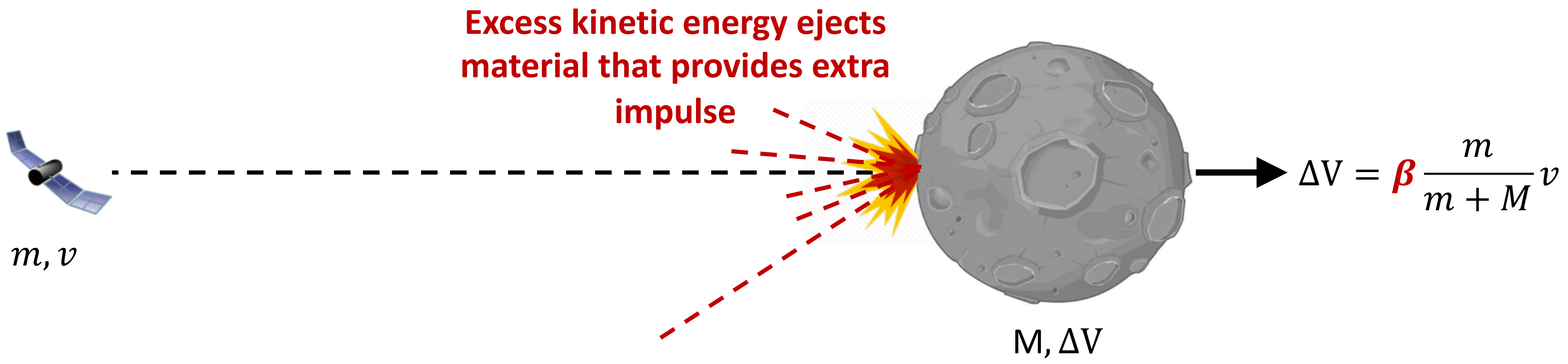

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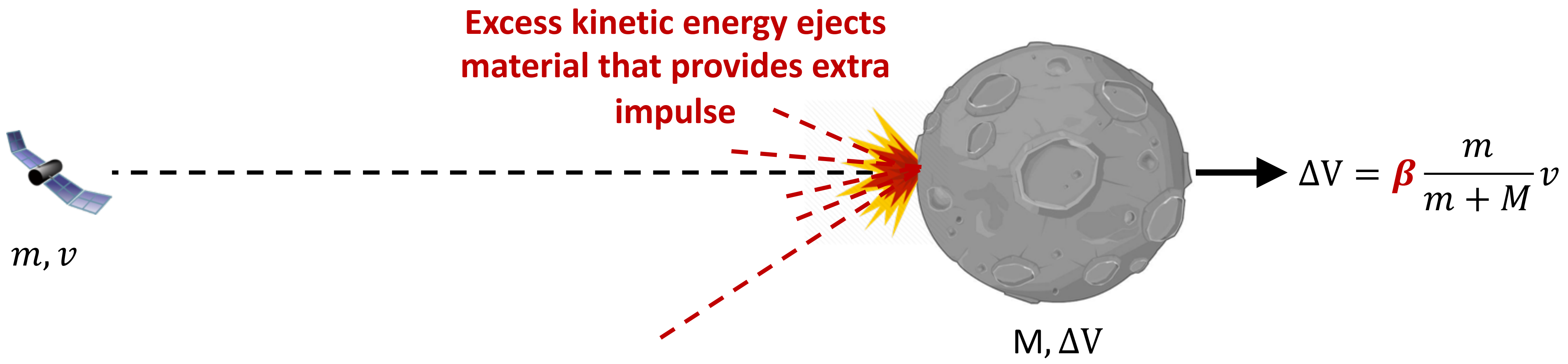


Current estimates of β are in the range [1,10]

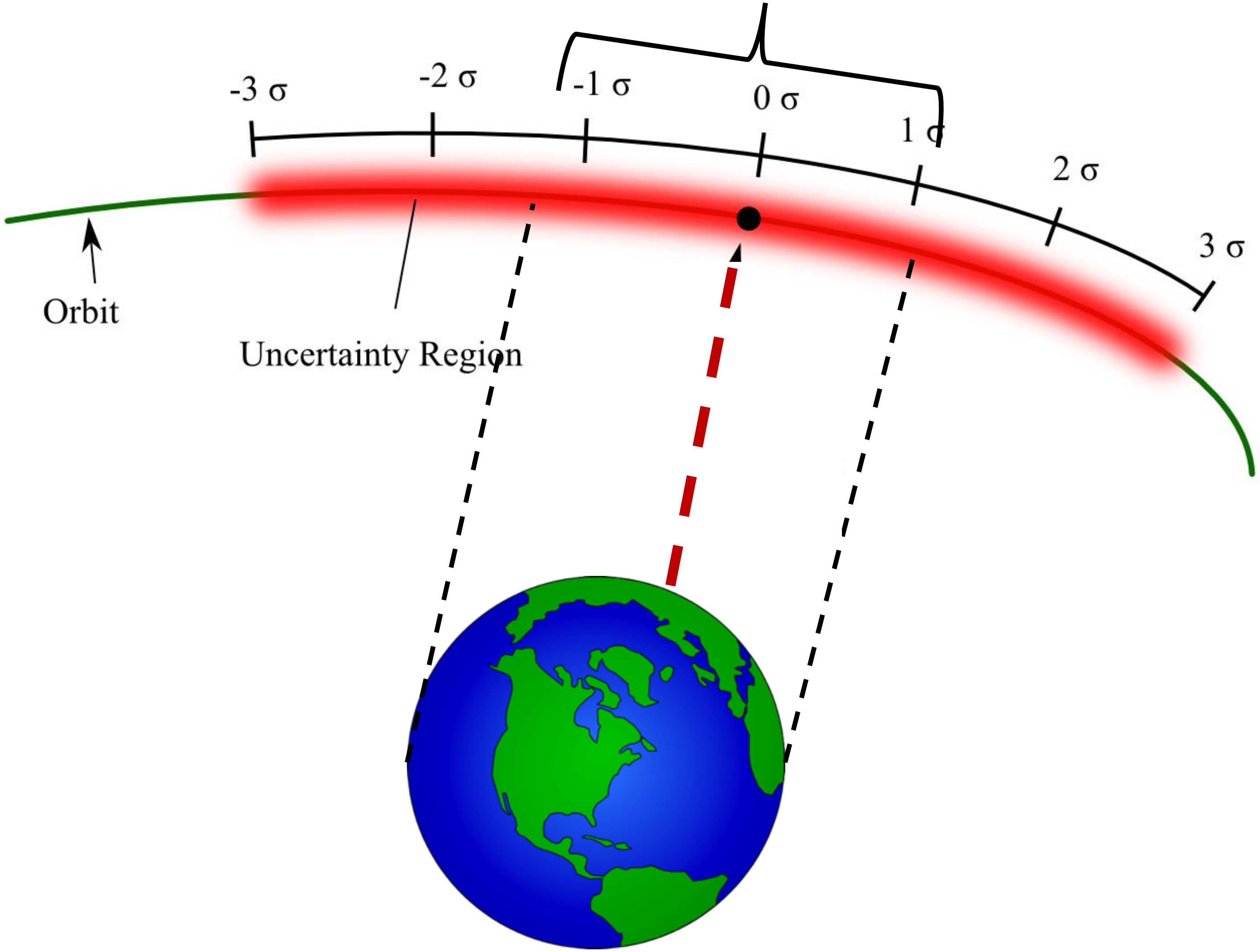
We used a semi-empirical equation from Lawrence Livermore Labs based on hydrocode impact simulations

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



2019 PDC Deflection Study

- Simulation setup
- Impact Risk
- Results

Deflection Analysis Process

Draw a sample from physical property distributions based on current knowledge state

Sample orbit solution and identify orbit solution region that impacts the Earth

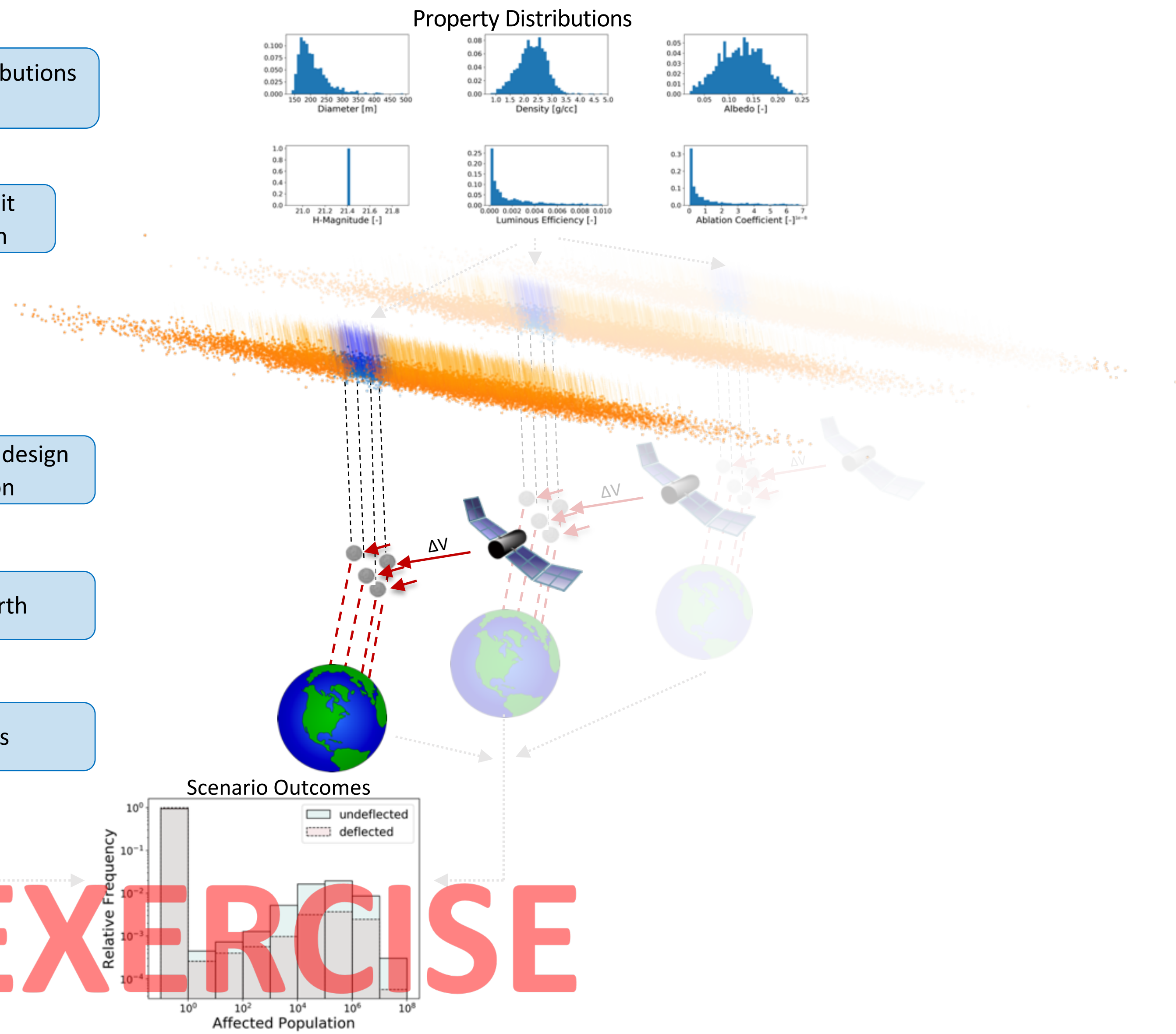
Propagate Earth impactors to deflection epoch

Impose deflection ΔV according to mission design and current physical property variation

Propagate deflected samples to the Earth

Simulate impact and record casualties

Repeat N times



Impact Risk

Risk = (Casualty # | *Impact*) × Impact Probability

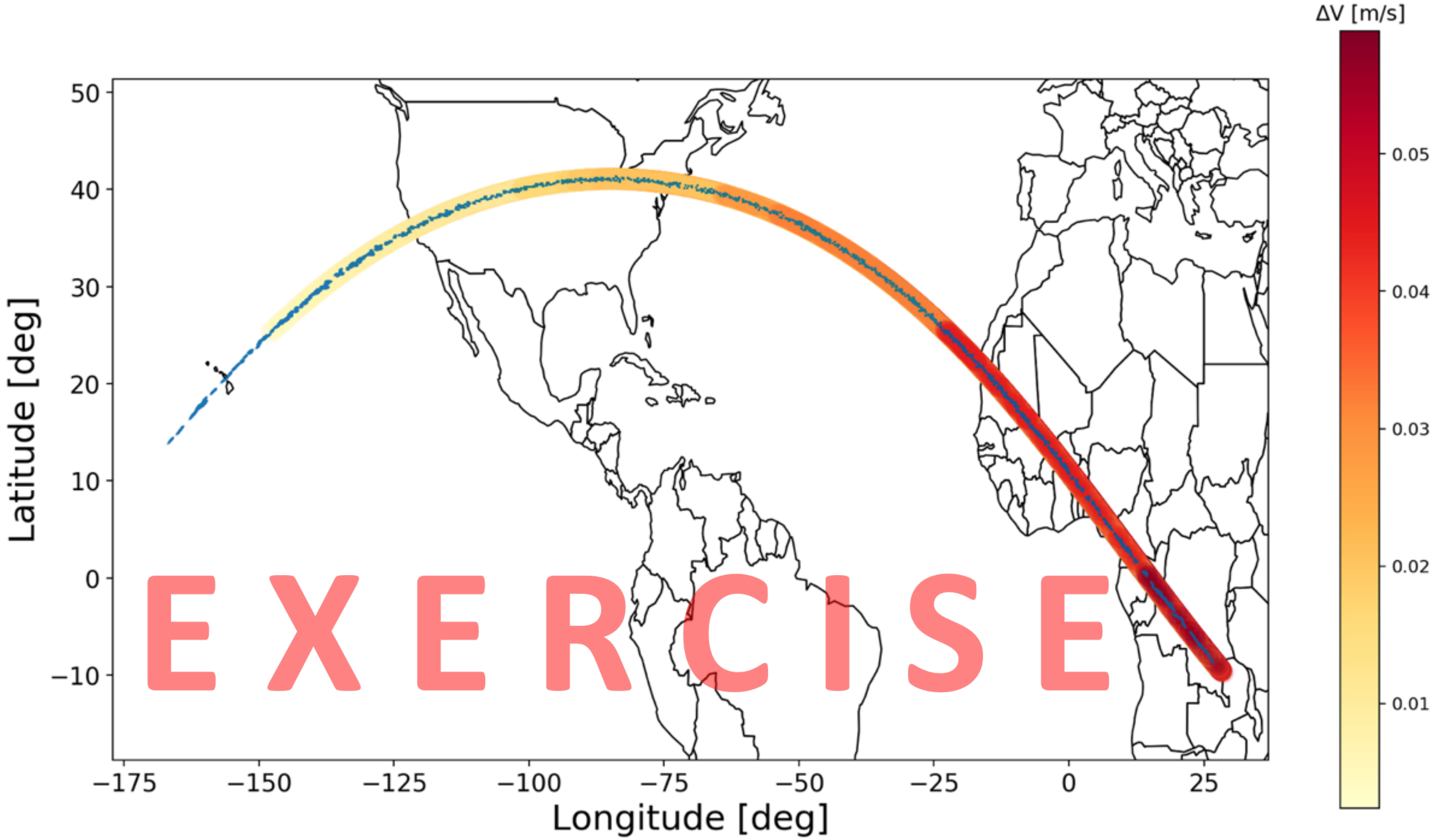
- Metric to capture risk level

- Combines nicely the consequences of a potential impact with the probability of it happening

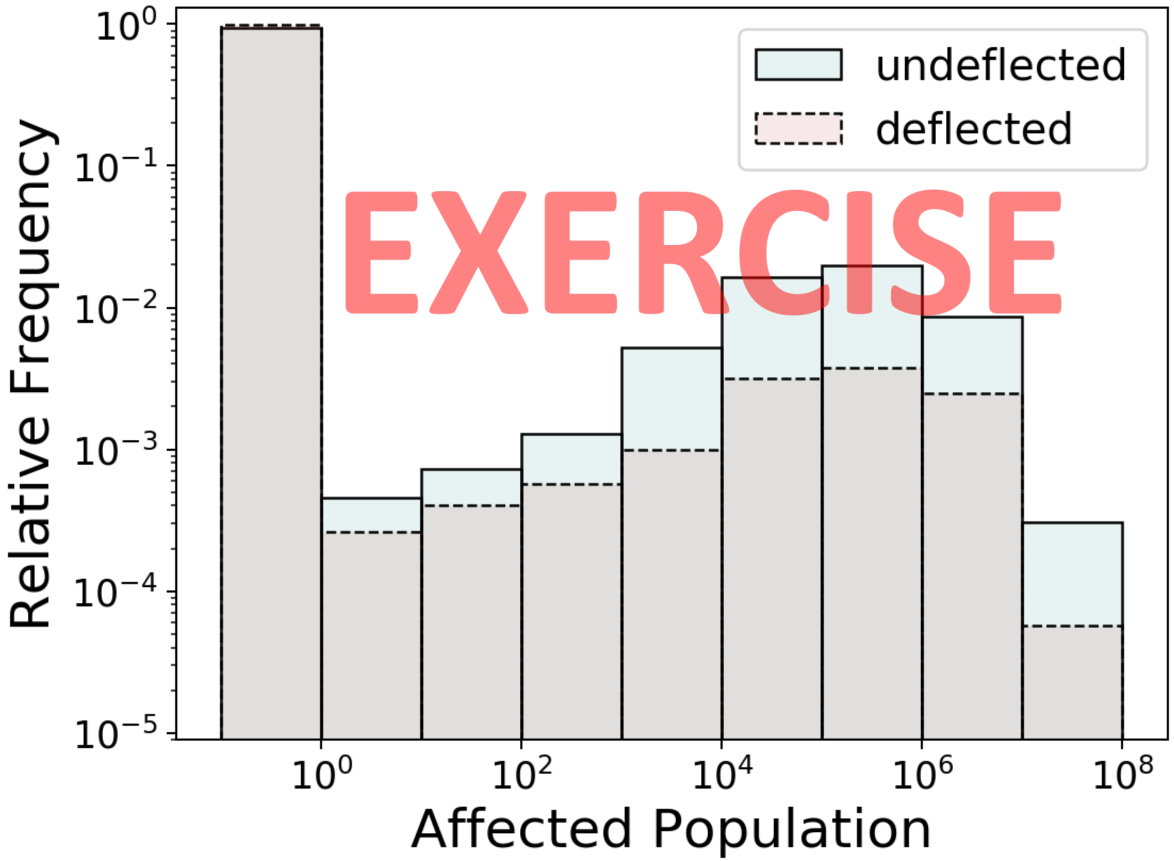
- Unit is “number of affected people”

Day 2 Deflected Corridor

Deflection	Impact Probability [%]	Risk [affected people]
Without	10.7	35 k
With	1.7 (-84 %)	10 k (-72 %)

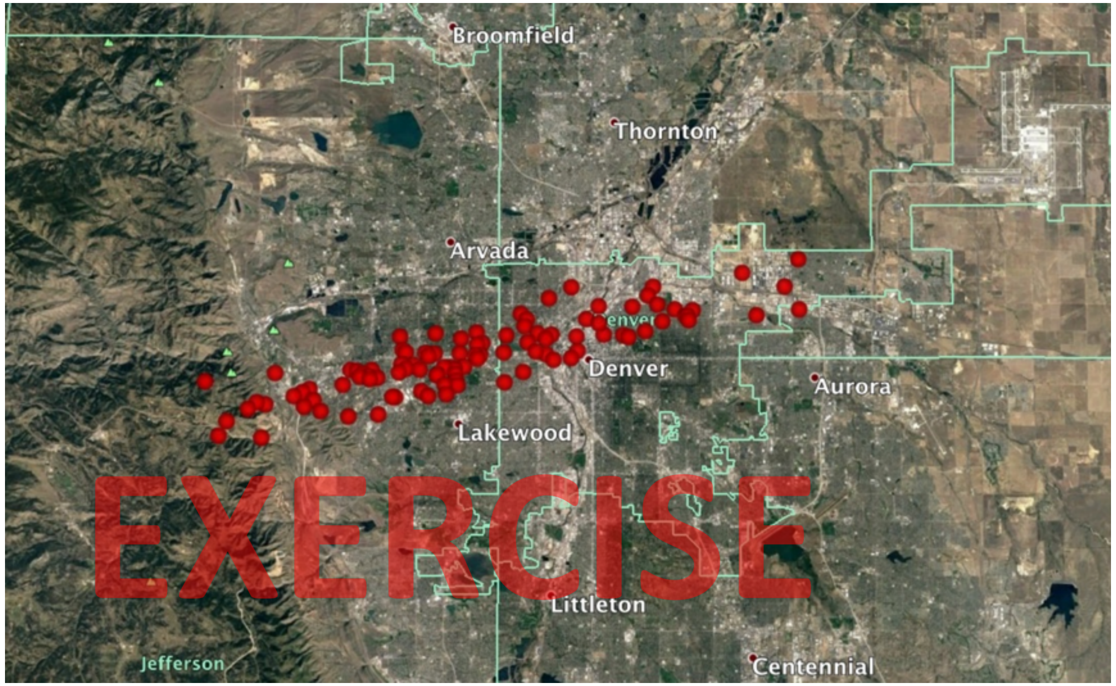


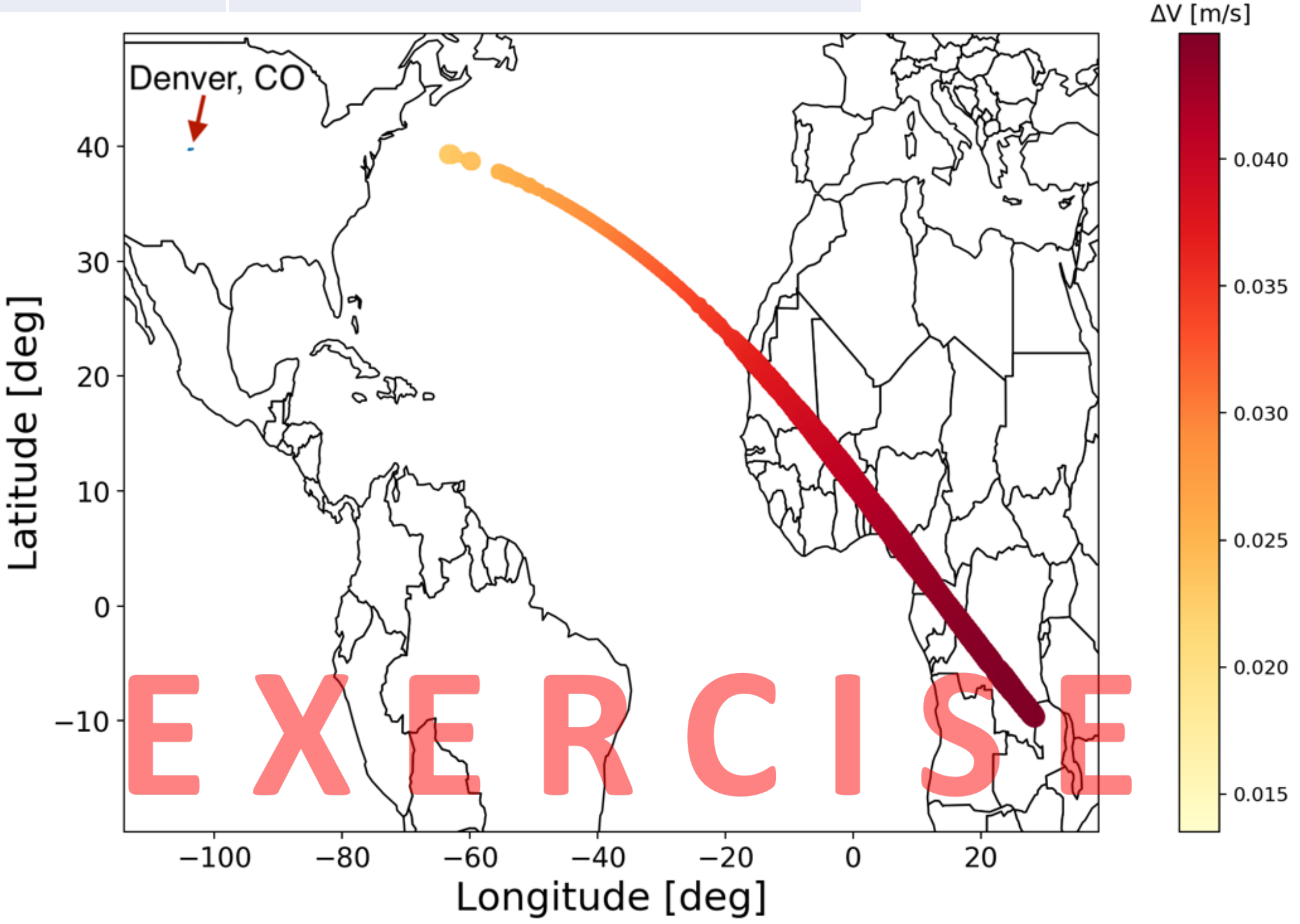
Day 2 Casualty Histogram



Day 3 Deflected Corridor

Deflection	Impact Probability [%]	Risk [affected people]
Without	100	302 k
With	30.7 (-69.3 %)	145 k (-52 %)





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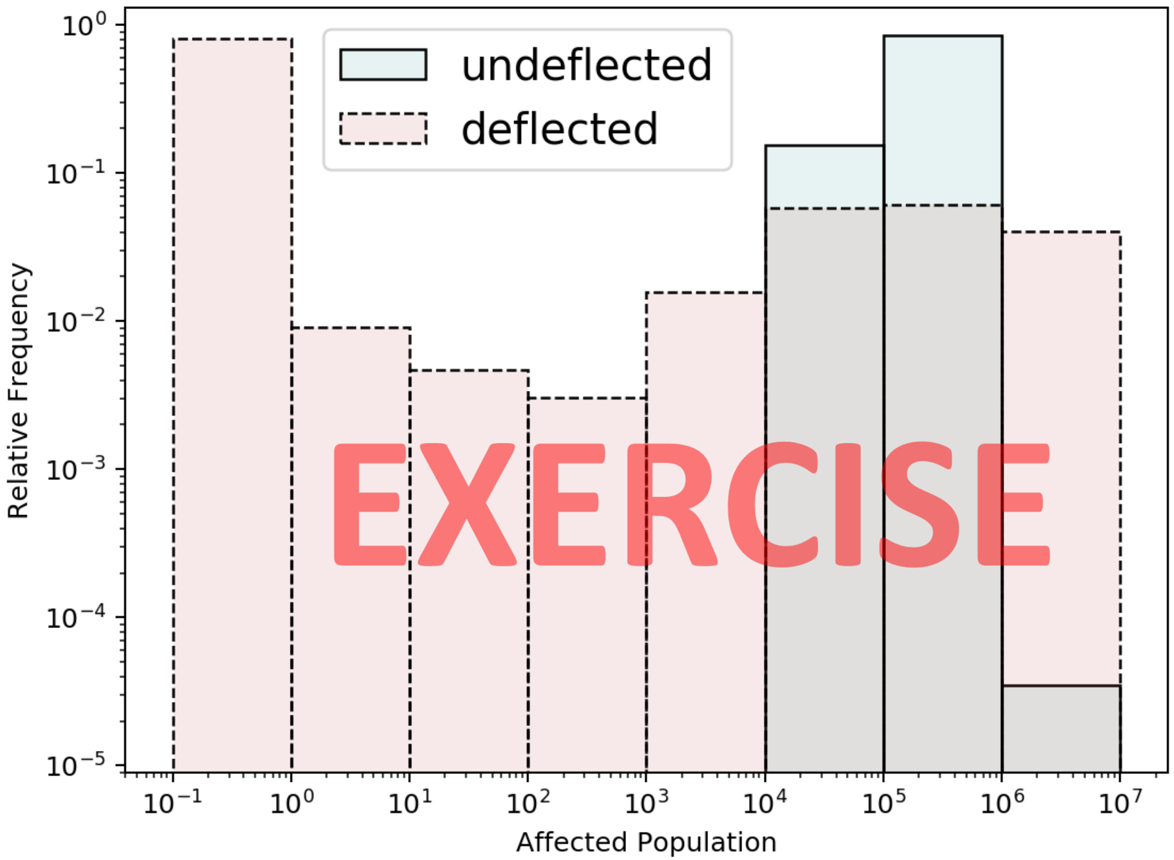
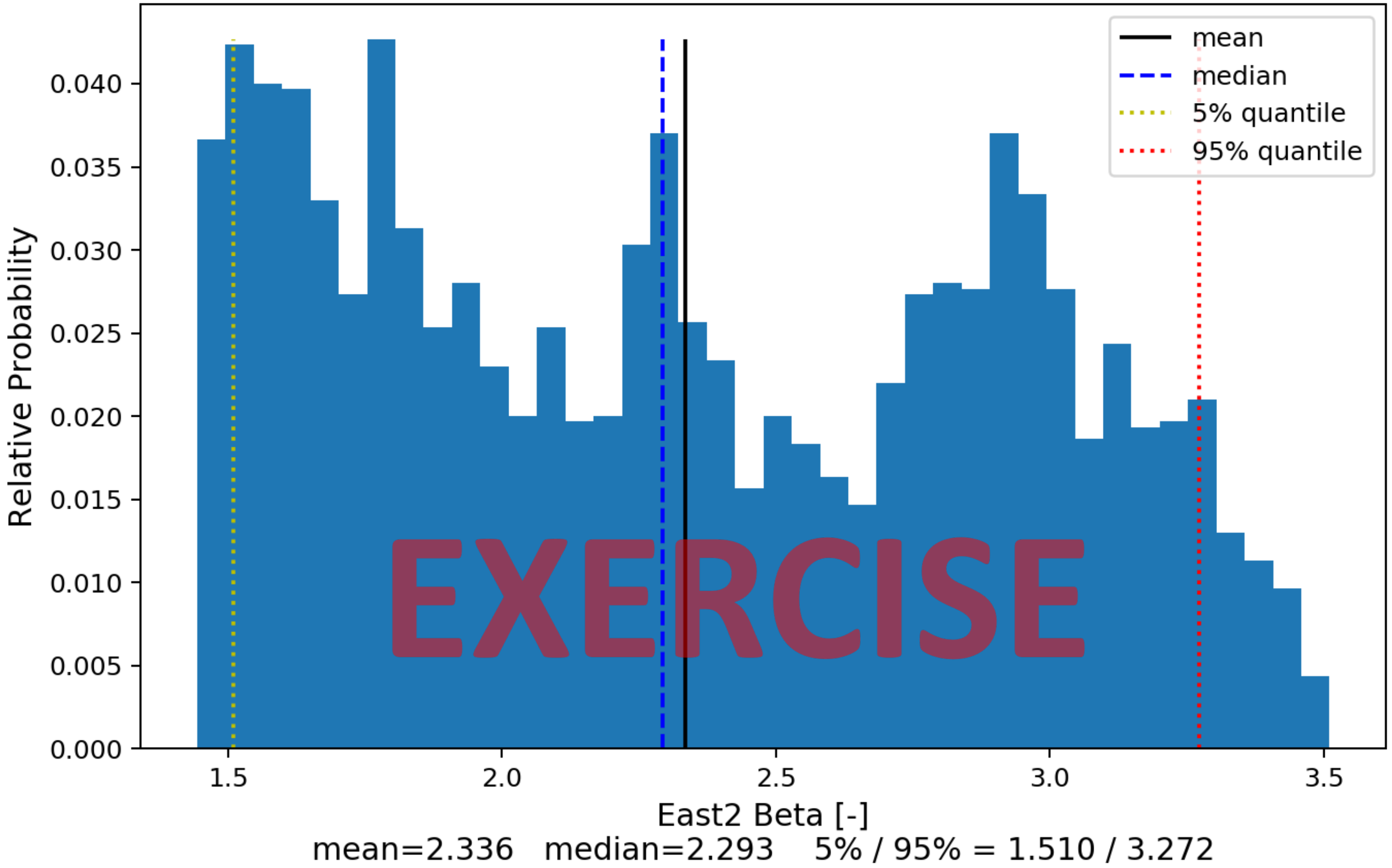


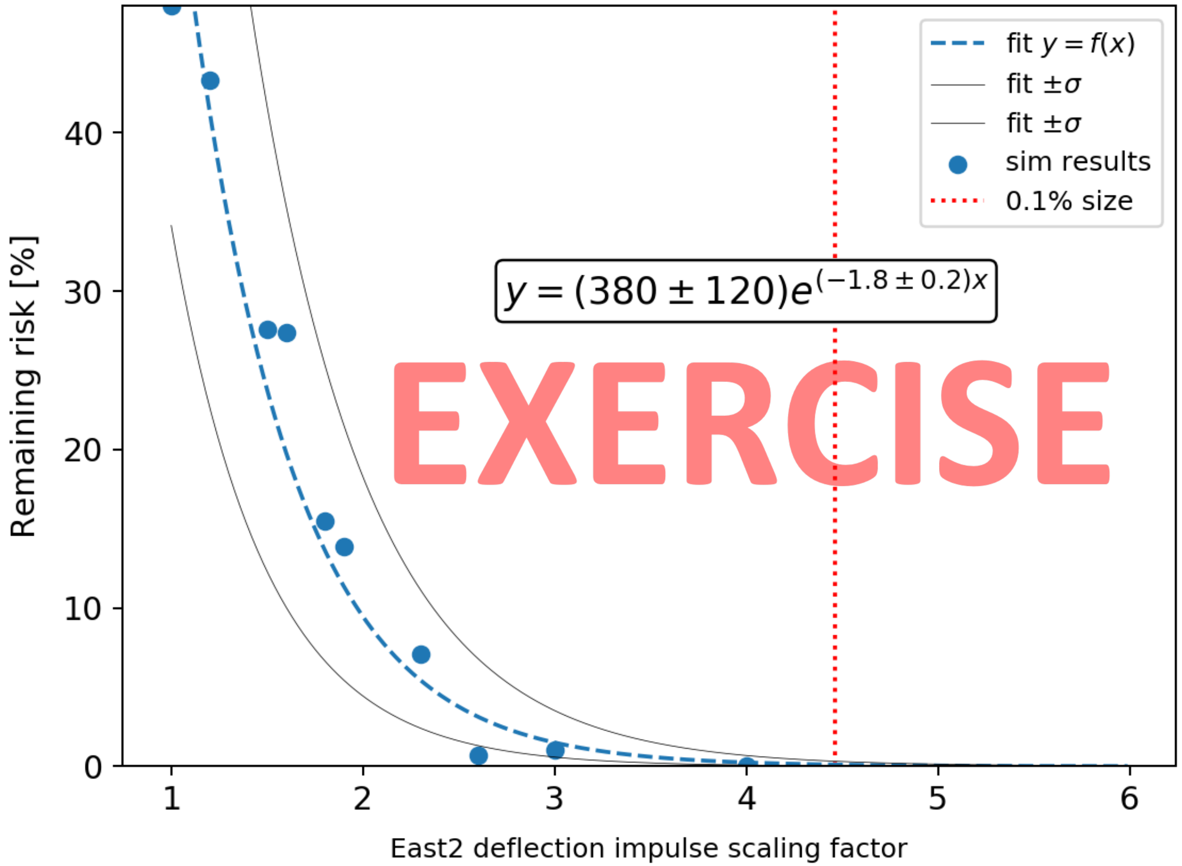
Realized Beta Values



β was in range ≅ [1.5, 3.3] in this study (for what it is worth)

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



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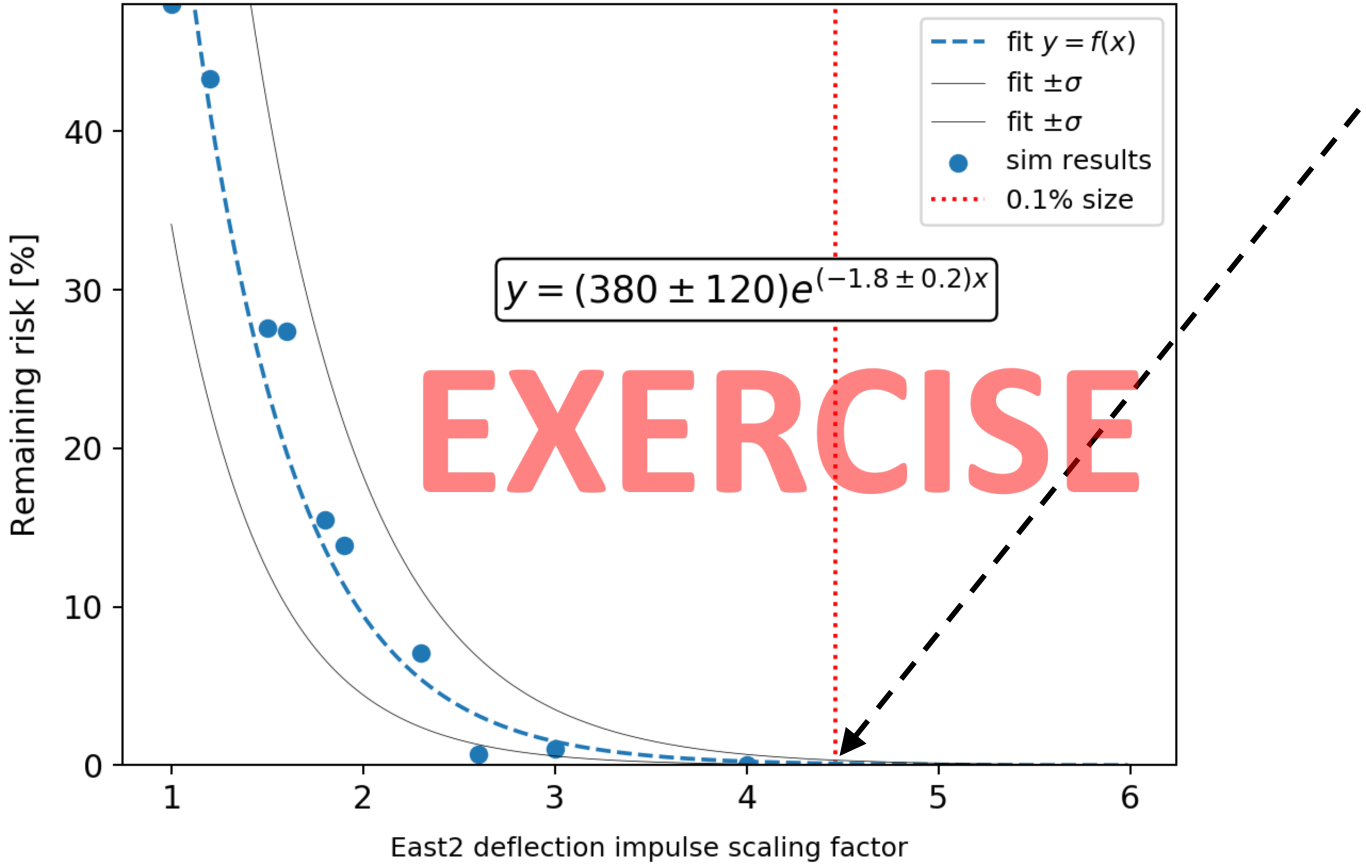

- 99.9 % risk reduction achieved with ≅ 4.5 scaling
- Could be achieved with 4.5 times heaver deflection spacecraft
- Or by sending 5 of the original deflection spacecraft

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

Clemens Rumpf
Clemens.rumpf@nasa.gov