Considering Deflection Missions for Asteroid Impact Risk

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Orlando, FL

Outline

- **Background**
  - Asteroid Impacts
  - Deflection Missions
- **Building Blocks**
  - Impact Corridor
  - Uncertainty
    - Orbit
    - Physical (Beta factor)
- **Application**
  - 2019 PDC Case Study

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

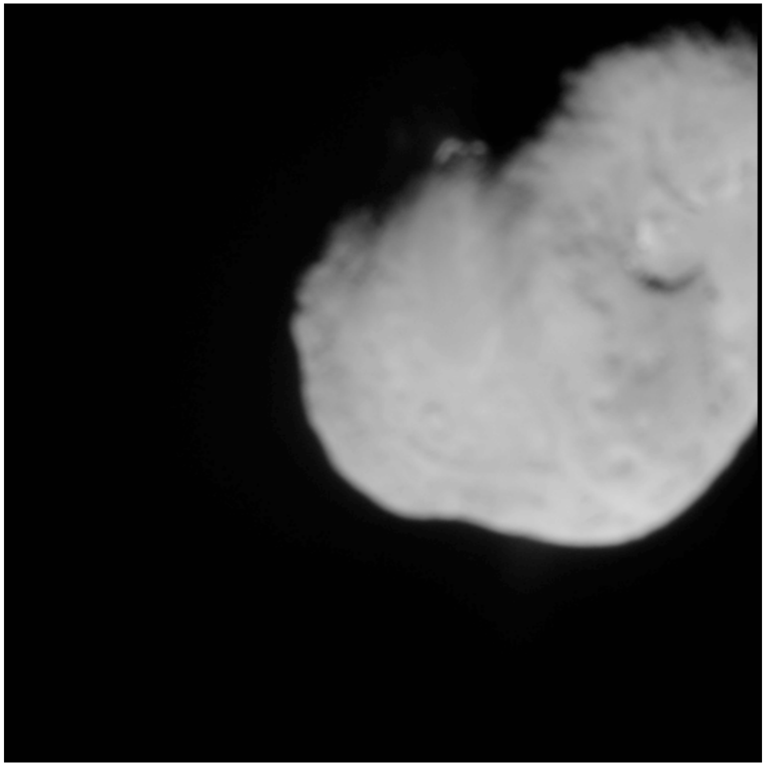
https://commons.wikimedia.org/wiki/File:Chelyabinsk_meteor_trace_15-02-2013.jpg

Tunguska, Russia, 1908

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

Deep Impact 2005

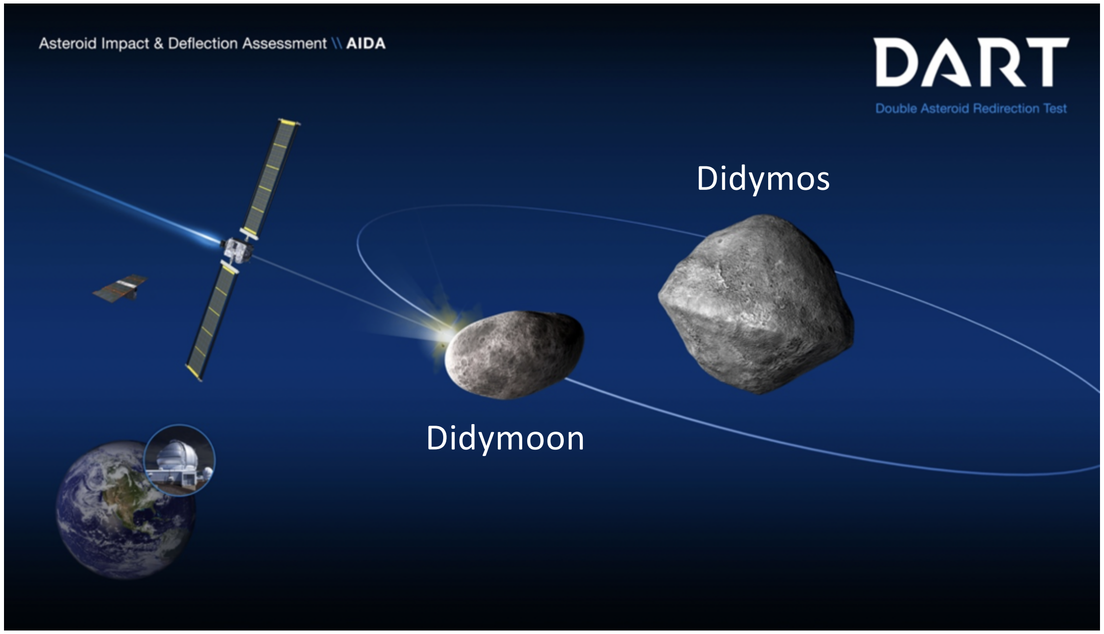
- Scientific mission by NASA in 2005
- Excavate sub-surface material by impact
- Evaluate sub-surface material using spectroscopy
- Equivalent to kinetic impactor
- **But**:
  - Target was large: ≅ 5 km
  - No measurements on trajectory change



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

NASA DART and ESA HERA

- 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

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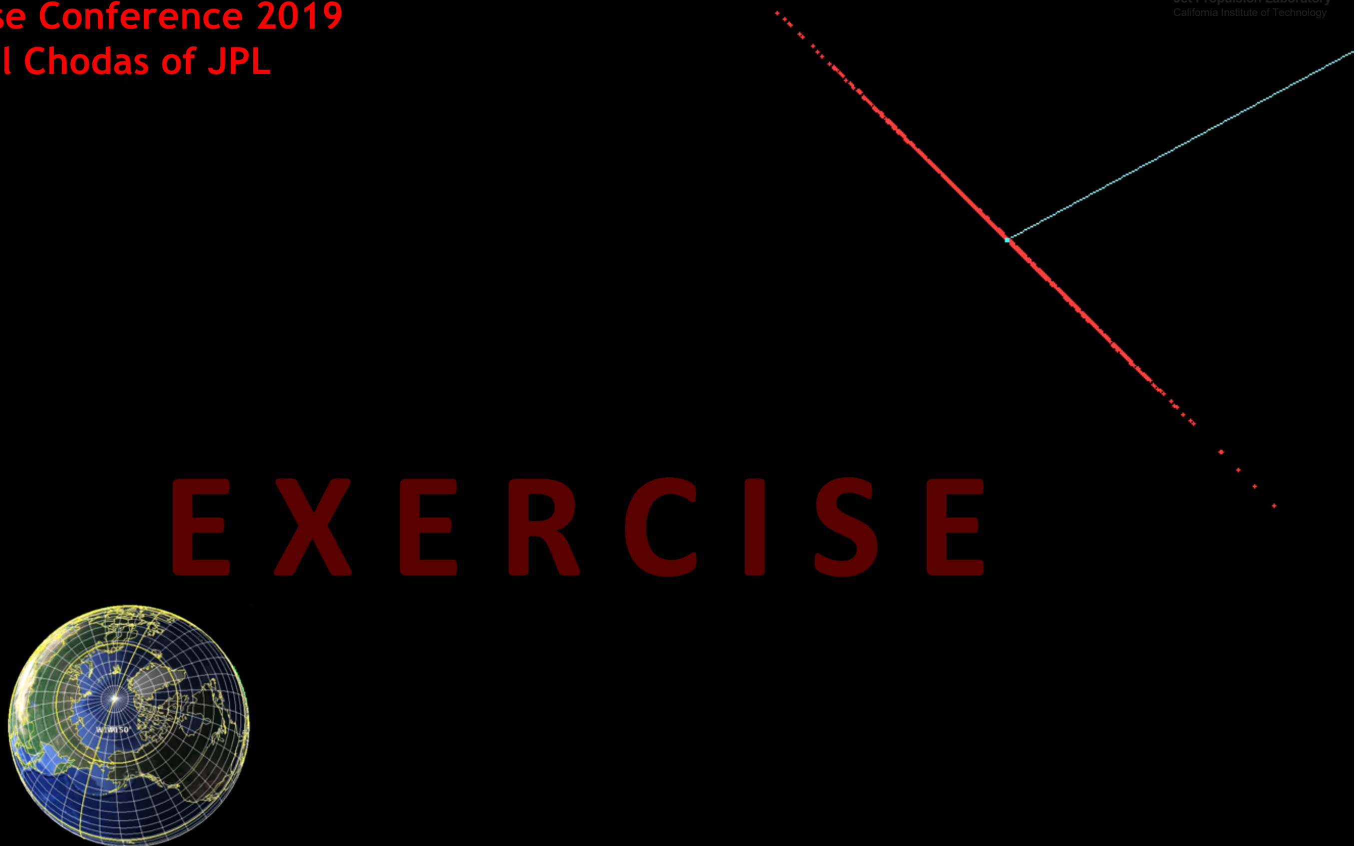
Impact Corridors

Presented during Planetary Defense Conference 2019 by Paul Chodas of JPL



EXERCISE

EXERCISE ONLY!!

Presented during Planetary Defense Conference 2019 by Paul Chodas of JPL

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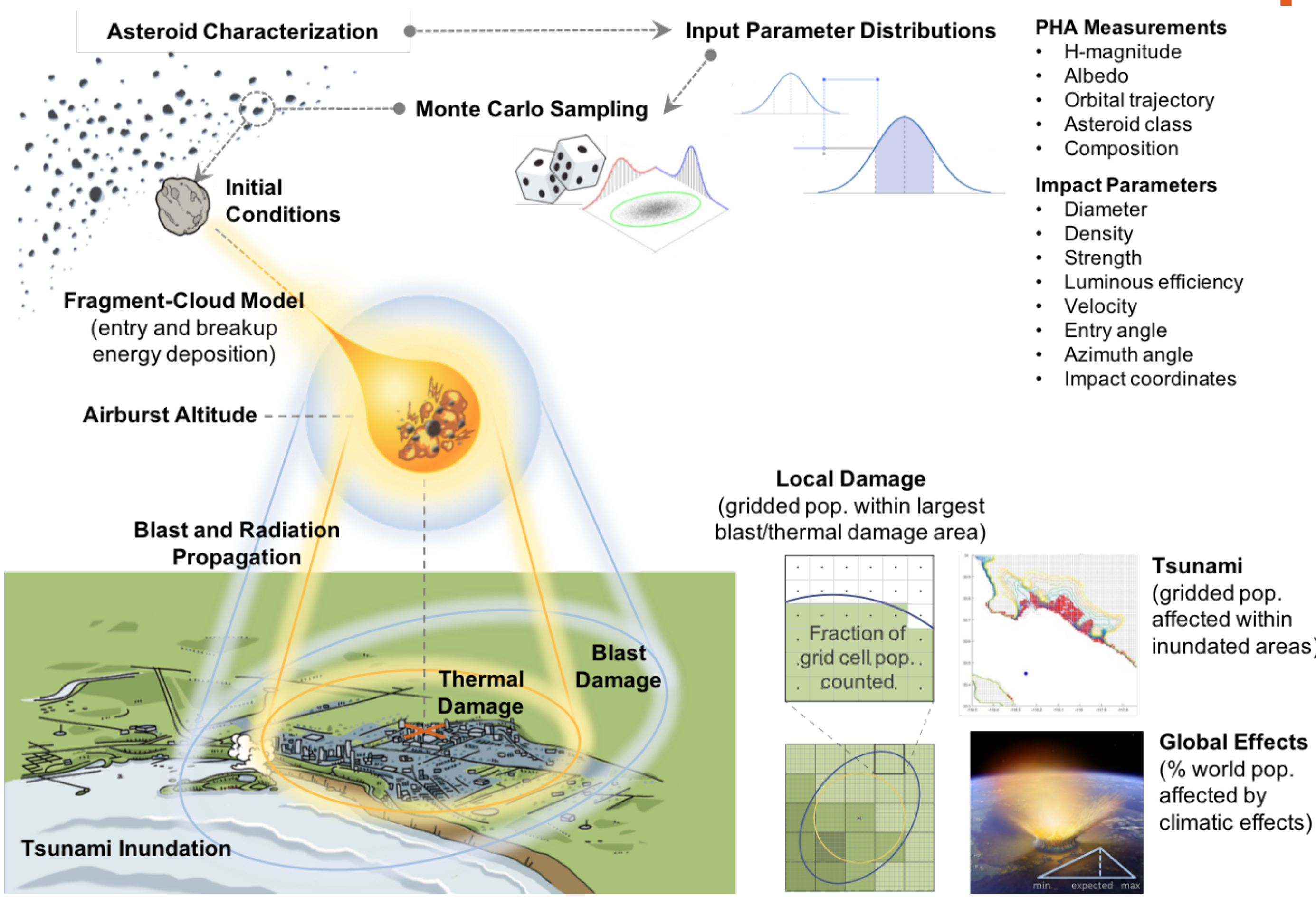
EXERCISE

2019 PDC Impact Corridor

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

PAIR - Probabilistic Asteroid Impact Risk



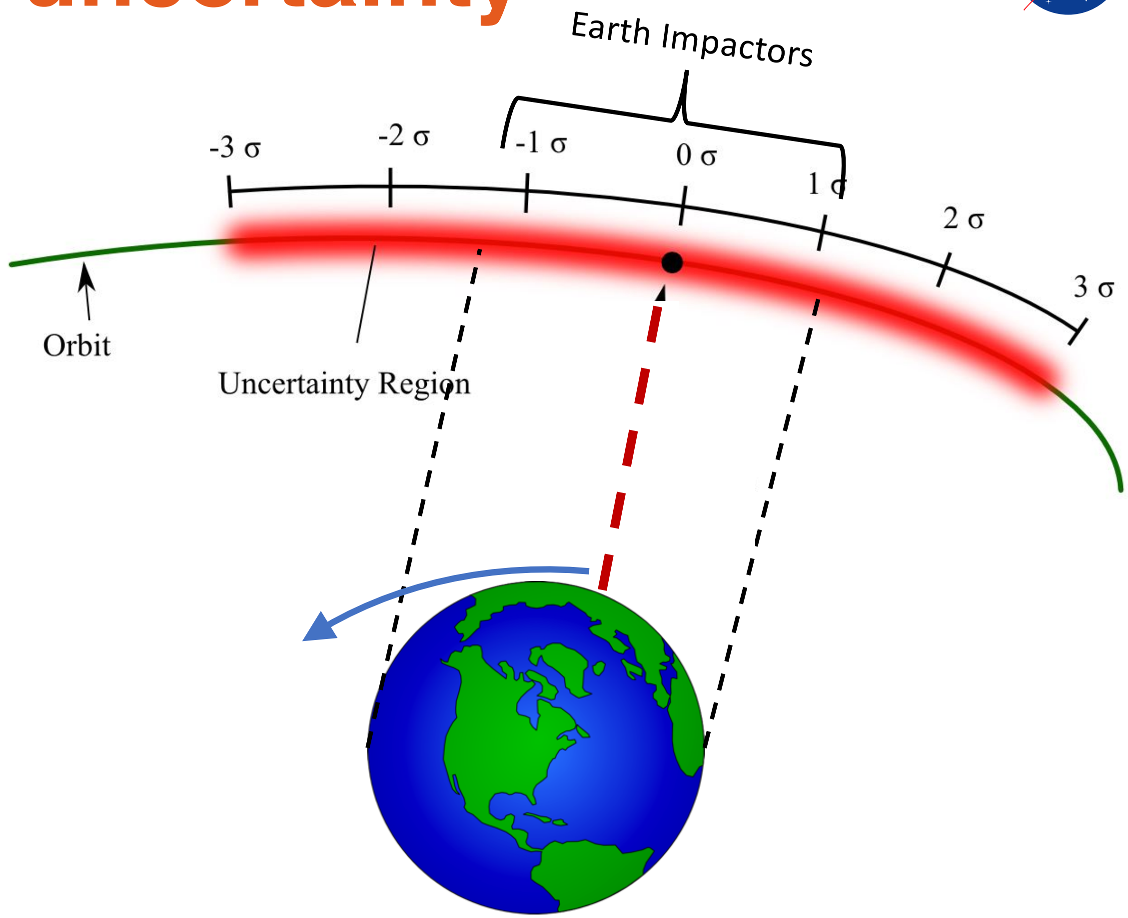
Mathias, D. L., Wheeler, L. F., & Dotson, J. L. (2017). A Probabilistic Asteroid Impact Risk Model: Assessment of Sub-300 m Impacts. *Icarus*, *289*, 106–119.

Uncertainty

- Orbital
- Physical

Orbit uncertainty

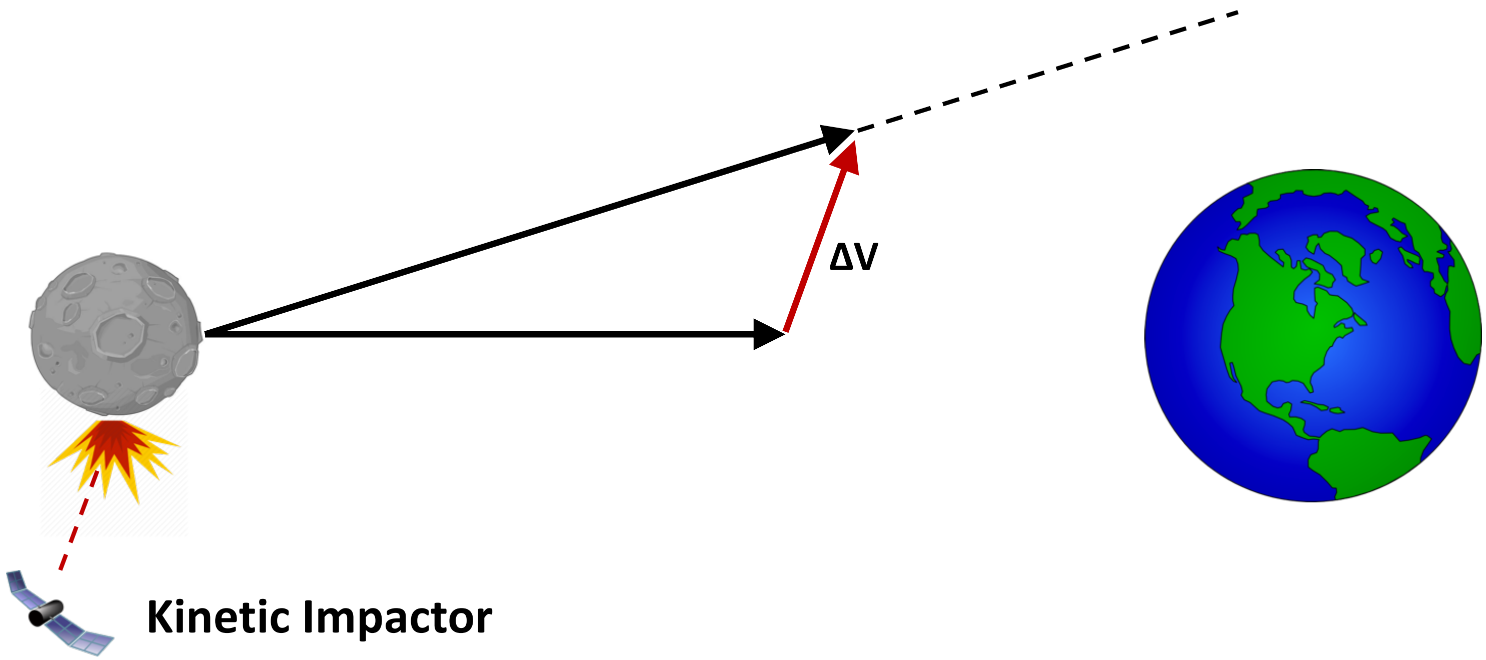
- ”Envelopes” the possible “positions” of the the asteroid at a given time
- Real asteroid is only in one location corresponding to one impact location within impact corridor
- Real location determines new impact location due to a given deflection mission



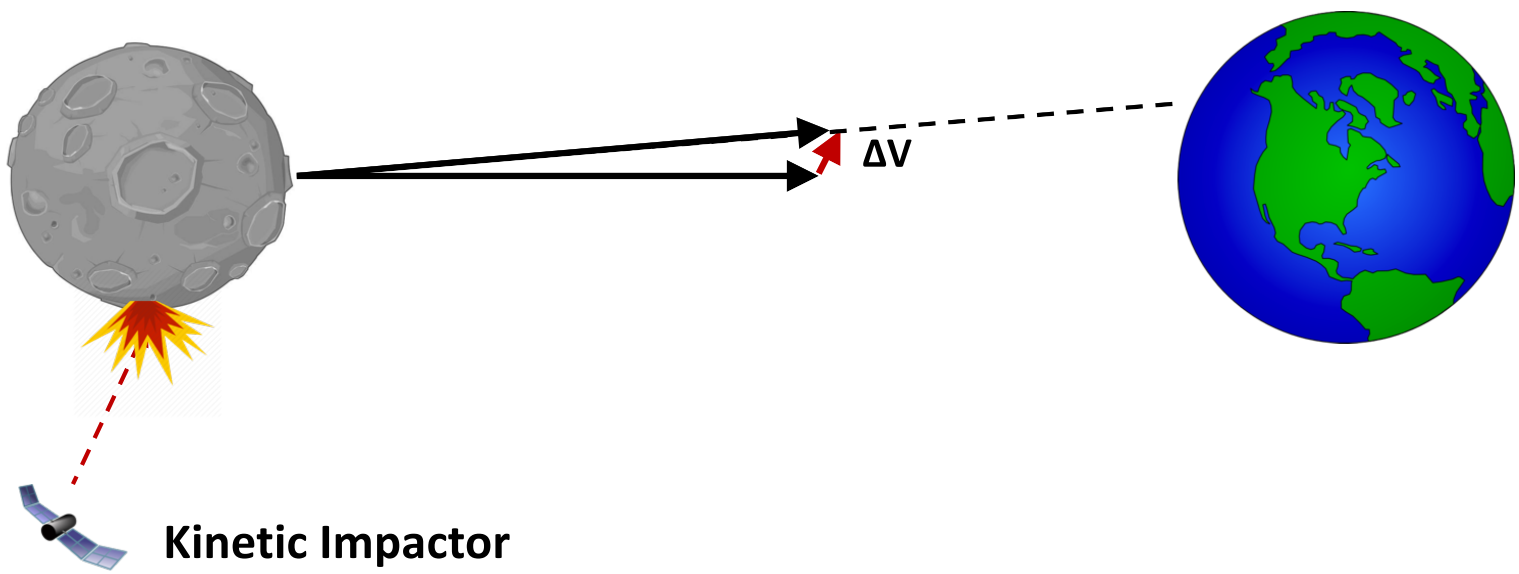
Physical Uncertainty

- 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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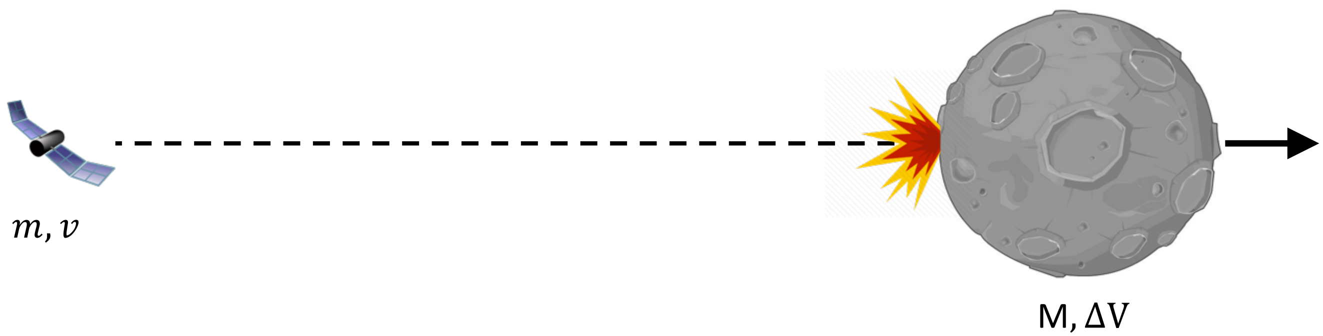
Beta factor explanation

- 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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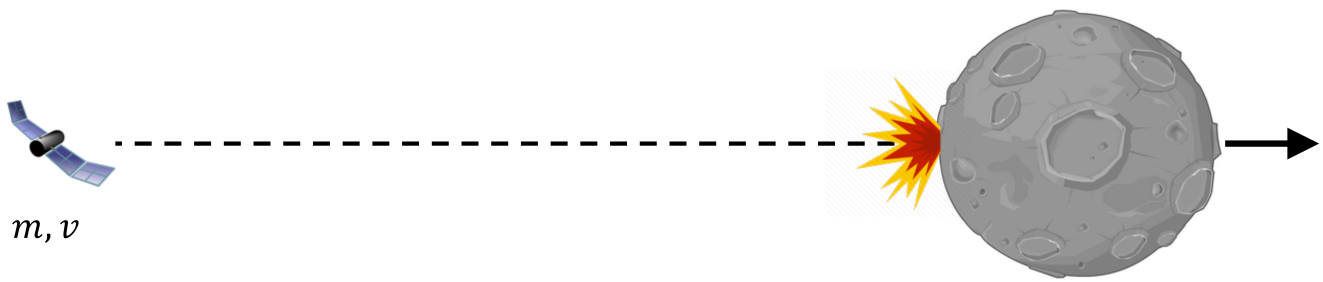

$$\Delta V = \frac{m}{m + M} v$$

BUT

Beta factor explanation

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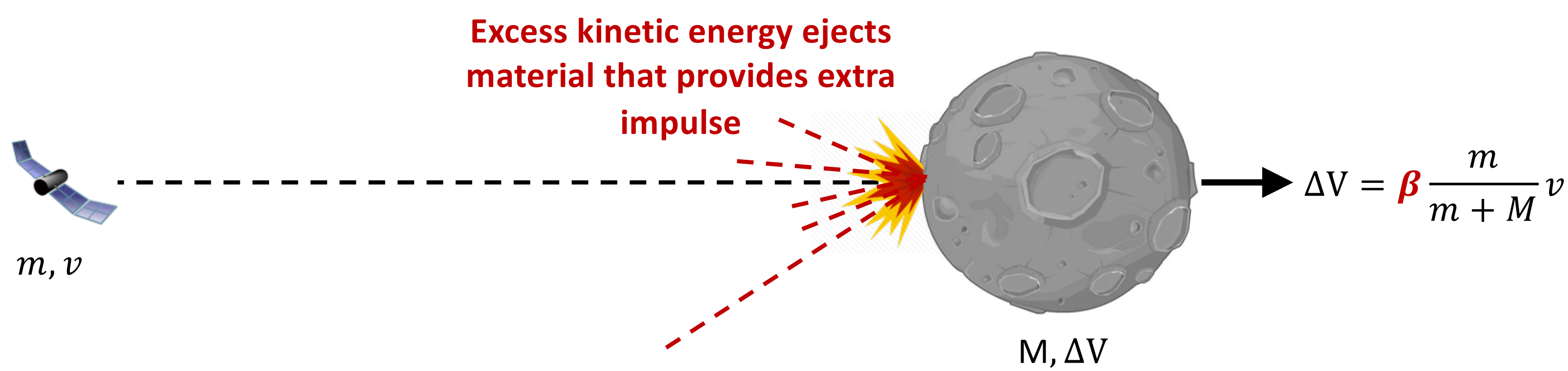

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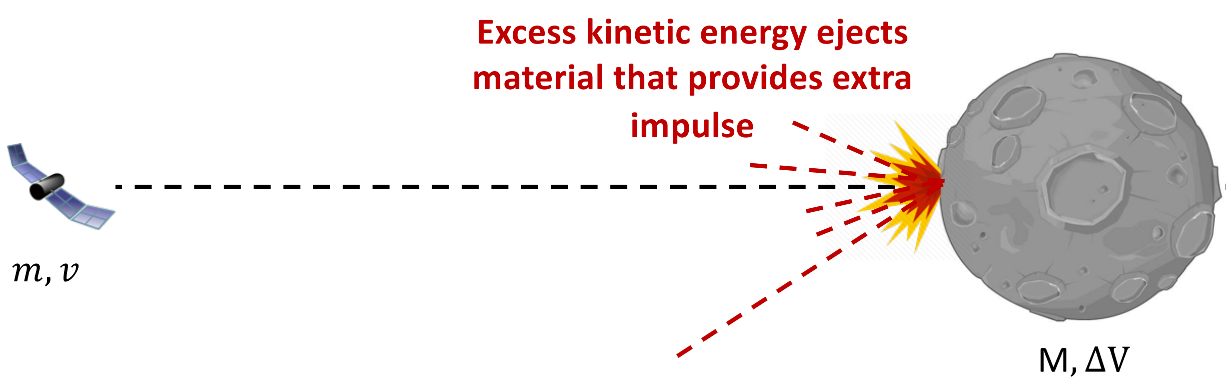


$$\Delta V = \boldsymbol{\beta} \frac{m}{m+M} v$$

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

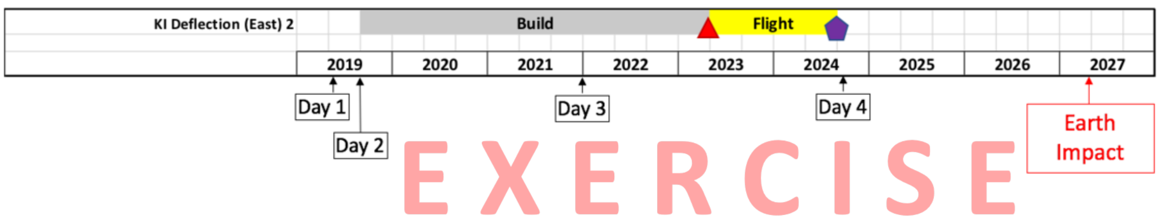
We used a semi-empirical equation from Lawrence Livermore Labs based on hydrocode impact simulations

Dearborn, D. S. P., Bruck Syal, M., Barbee, B. W., Gisler, G., Greenaugh, K., Howley, K. M., … Zebenay, M. (2020). Options and uncertainties in planetary defense: Impulse-dependent response and the physical properties of asteroids. *Acta Astronautica*, *166*(December 2018), 290–305. https://doi.org/10.1016/j.actaastro.2019.10.026

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**

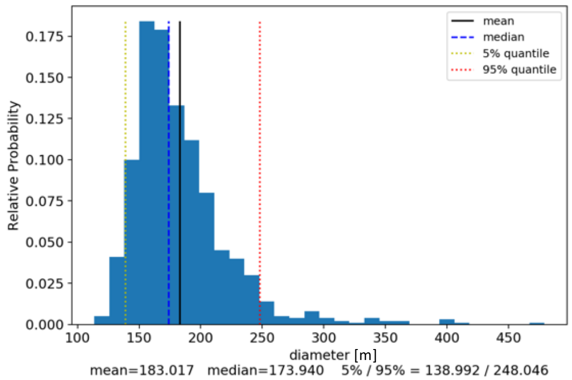


Credit: CNEOS/JPL/Caltech

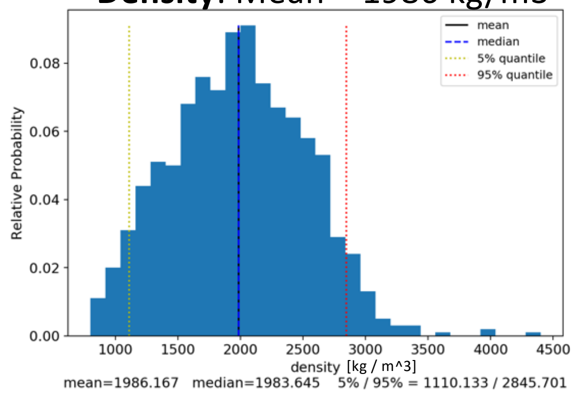
https://cneos.jpl.nasa.gov/pd/cs/pdc19/pdc19_briefing2.pdf

Asteroid Properties

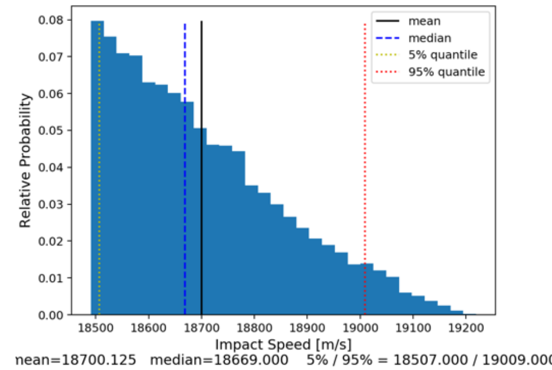
Diameter: Mean = 183 m



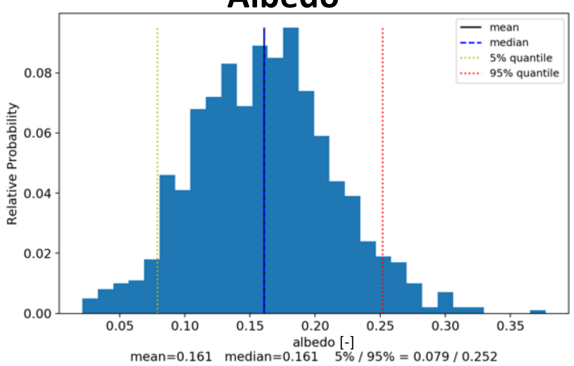
Density: Mean = 1986 kg/m3



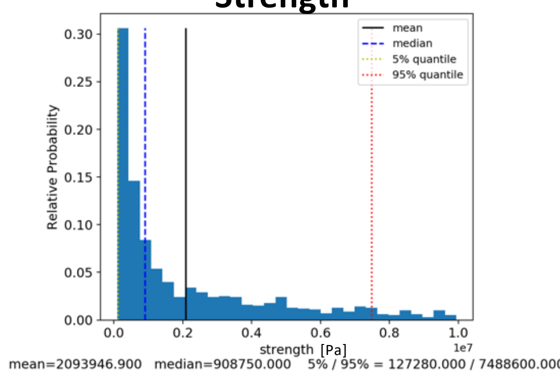
Impact Speed: Mean = 18.7 km/s



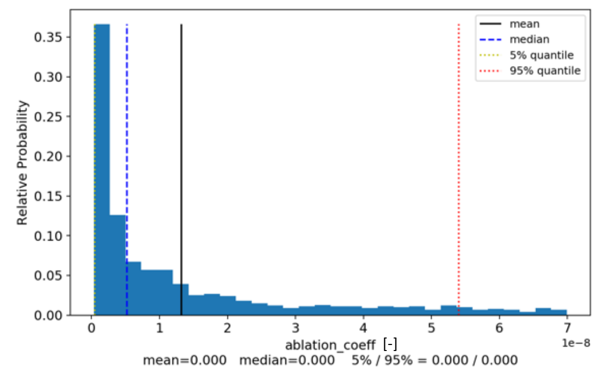
Albedo



Strength



Ablation Coefficient



- Absolute magnitude: 21.4
- Also considered: Alpha (Strength Scaling), Luminous Efficiency, Asteroid Classes

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

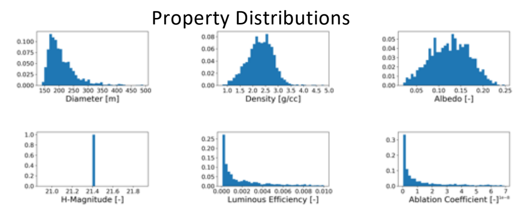
Propagate Earth impactors to deflection epoch

Repeat N times

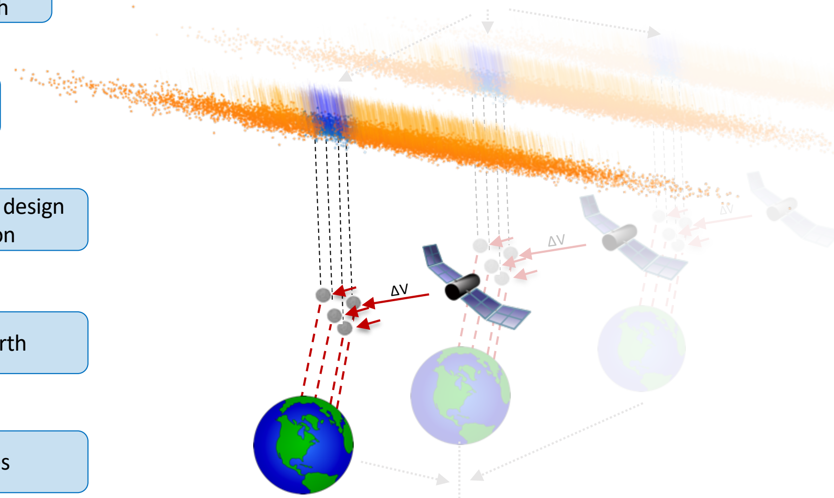
Impose deflection ΔV according to mission design and current physical property variation

Propagate deflected samples to the Earth

Simulate impact and record casualties



1000 X



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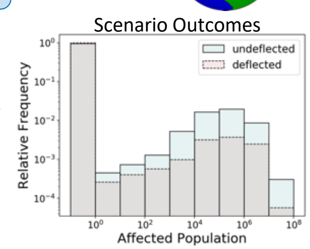

EXERCISE

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”

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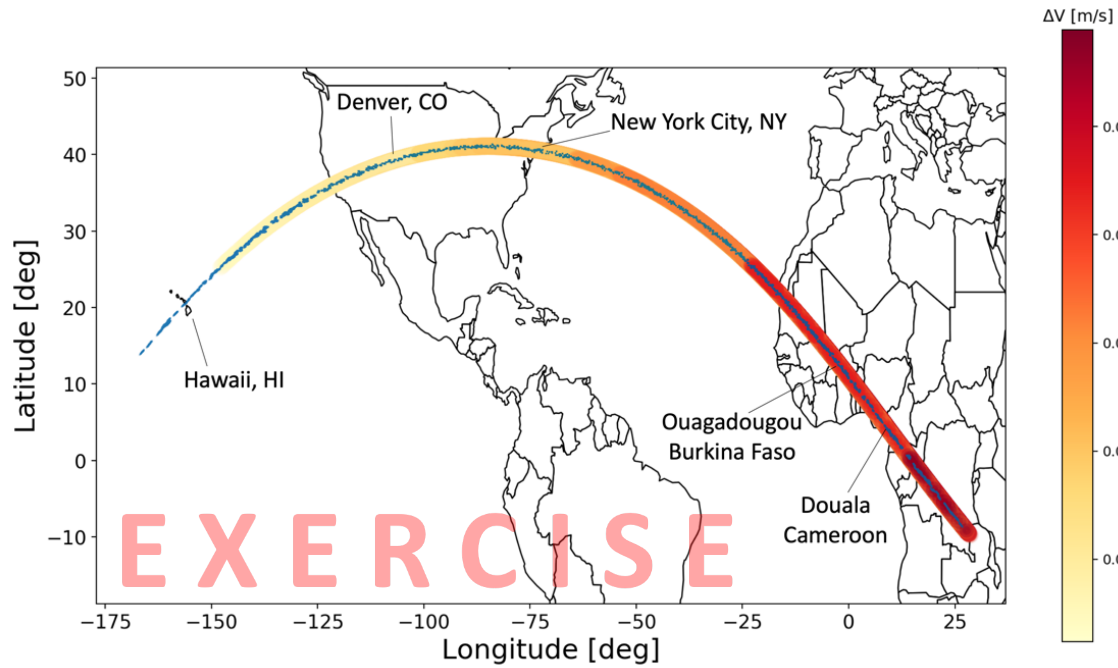
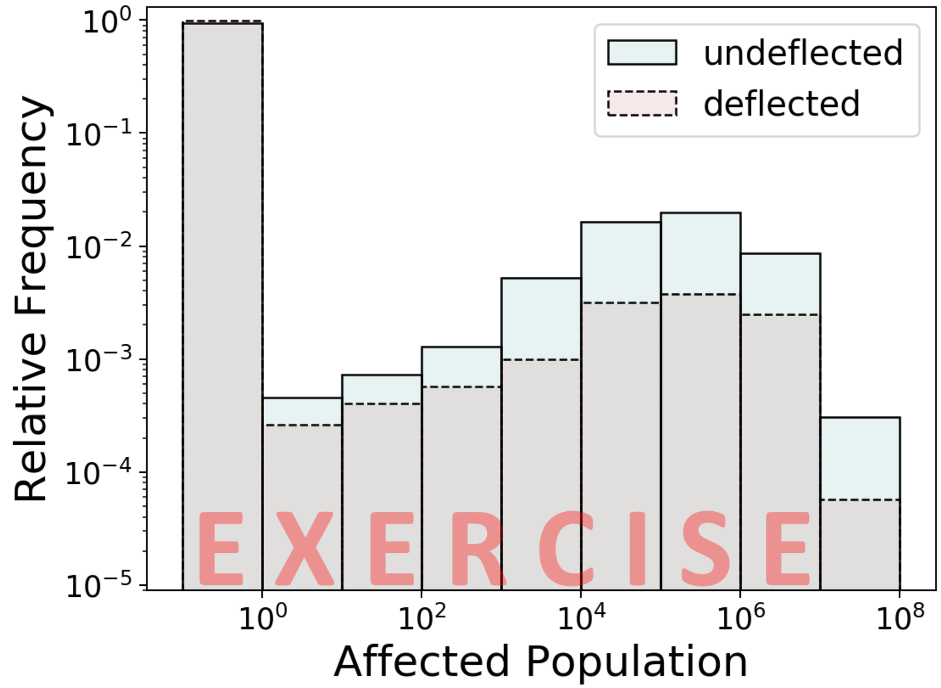
2019 PDC Results

Day 2 Deflected Corridor

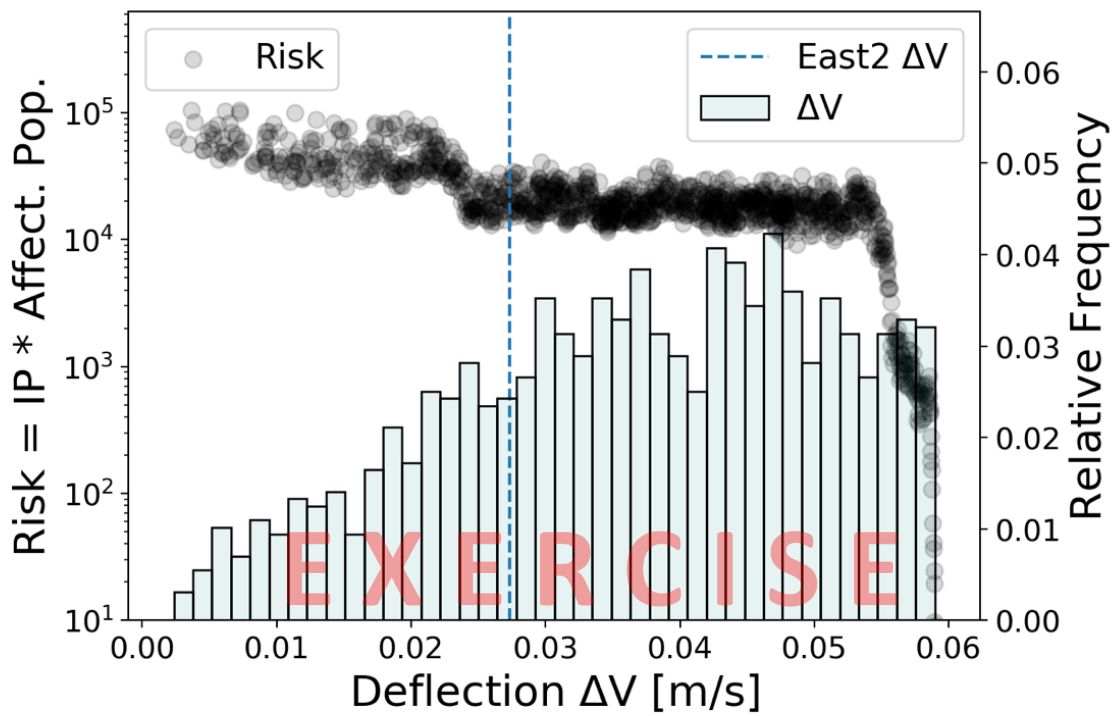
Deflection	Impact Probability [%]	Risk [affected people]
Without	10.7	35 k
With	1.7 (-84 %)	10 k (-72 %)



Day 2 Casualty Histogram



Day 2 Risk vs Observed ΔV



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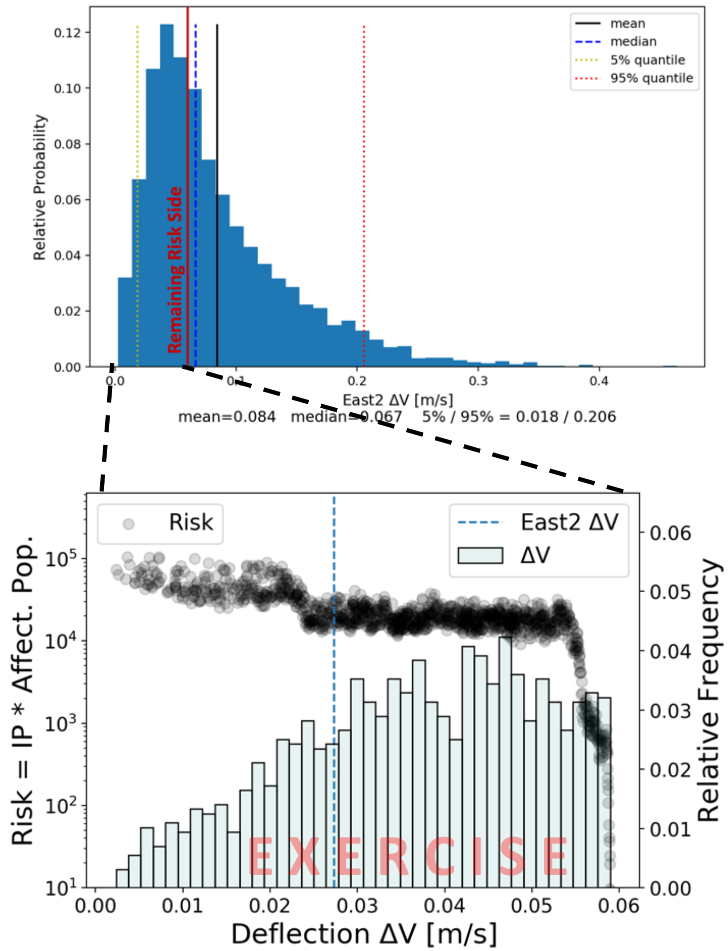
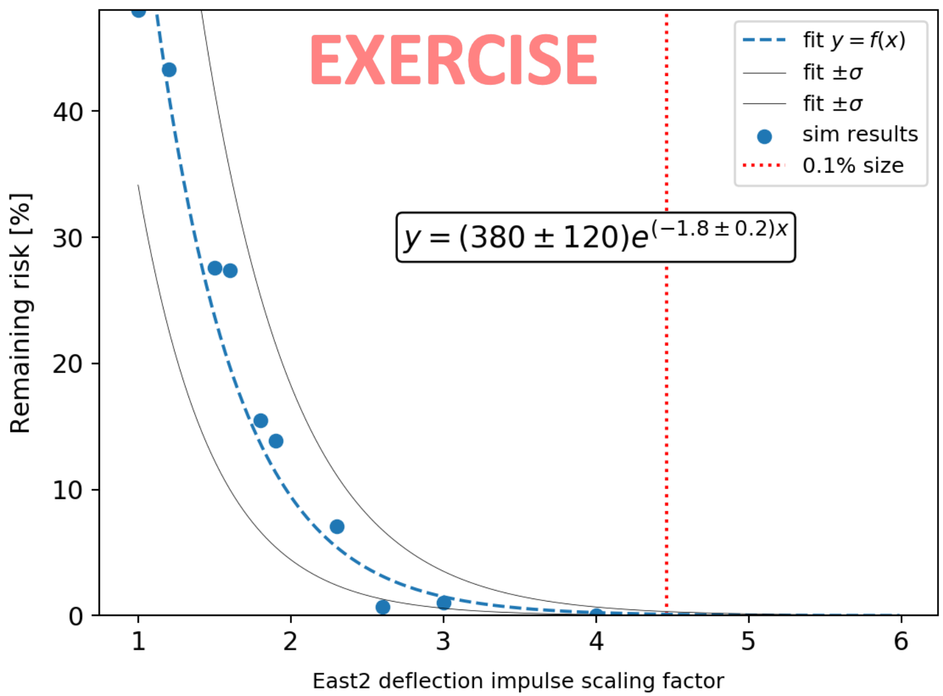


Deflection Mission Scaling

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



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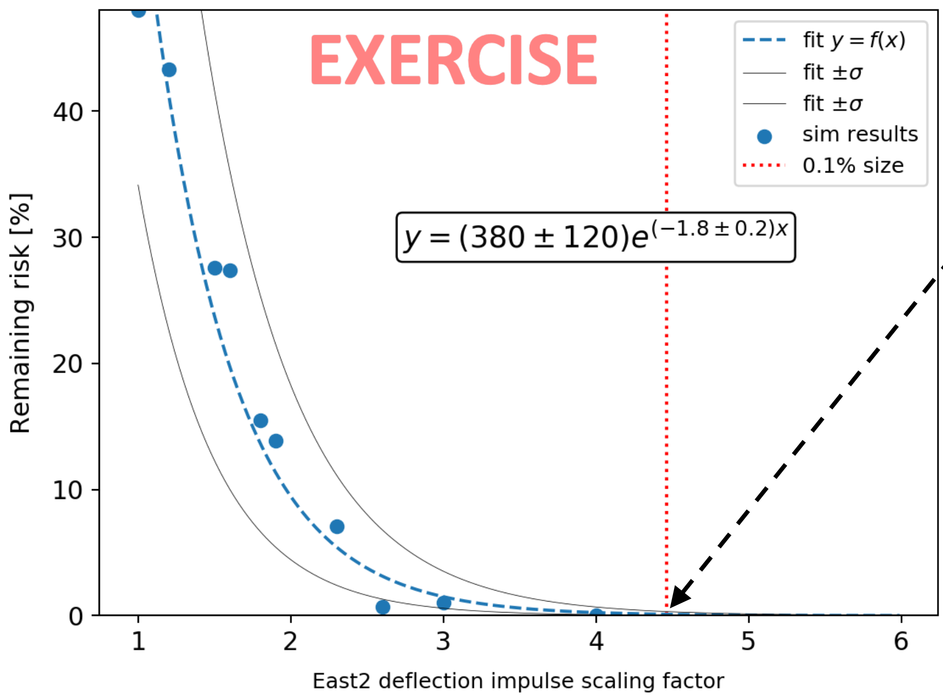

- 99.9 % risk reduction achieved with ≅ 4.5 scaling
- Could be achieved with 4.5 times heaver deflection spacecraft
- Or by sending 5 of the original deflection spacecraft

Challenges

- Multidisciplinary work
  - Orbit mechanics
  - Mission analysis
  - Impact effect simulation
  - Risk analysis
- Coordinate transformation of covariance matrix from comet elements to cartesian coordinates
  - Adopted finite difference approach
- Finding adequate figures and metrics to present results

Future Work

- Port code to supercomputing facility to enable quicker execution and larger scale simulations
- Stabilize code base
- Implement options for deflection analysis using non-KI options (e.g. nuclear)
- Explore options to practically feed into deflection mission design work

Summary

- 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
- Scaling the deflection mission mass increases robustness against uncertainties

Thank You

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Co-Authors: D. Mathias, L. Wheeler, J.Dotson

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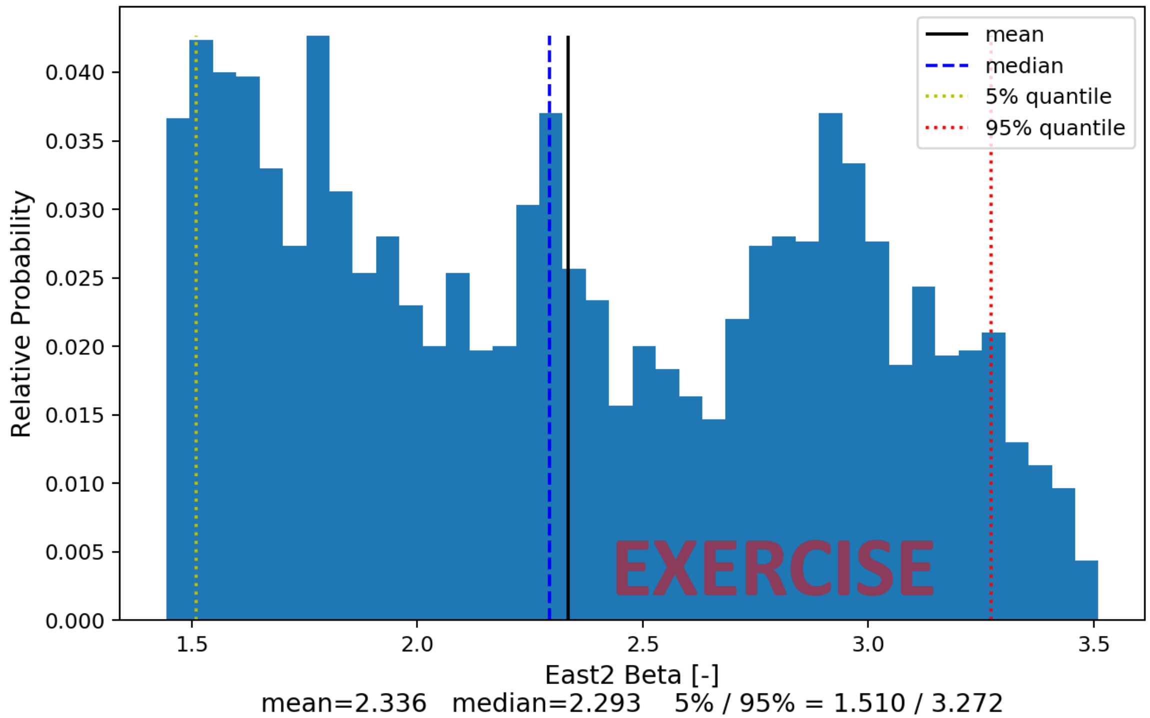
- NASA supercomputing facilities: NAS Pleiades,
- JPL
- GSFC

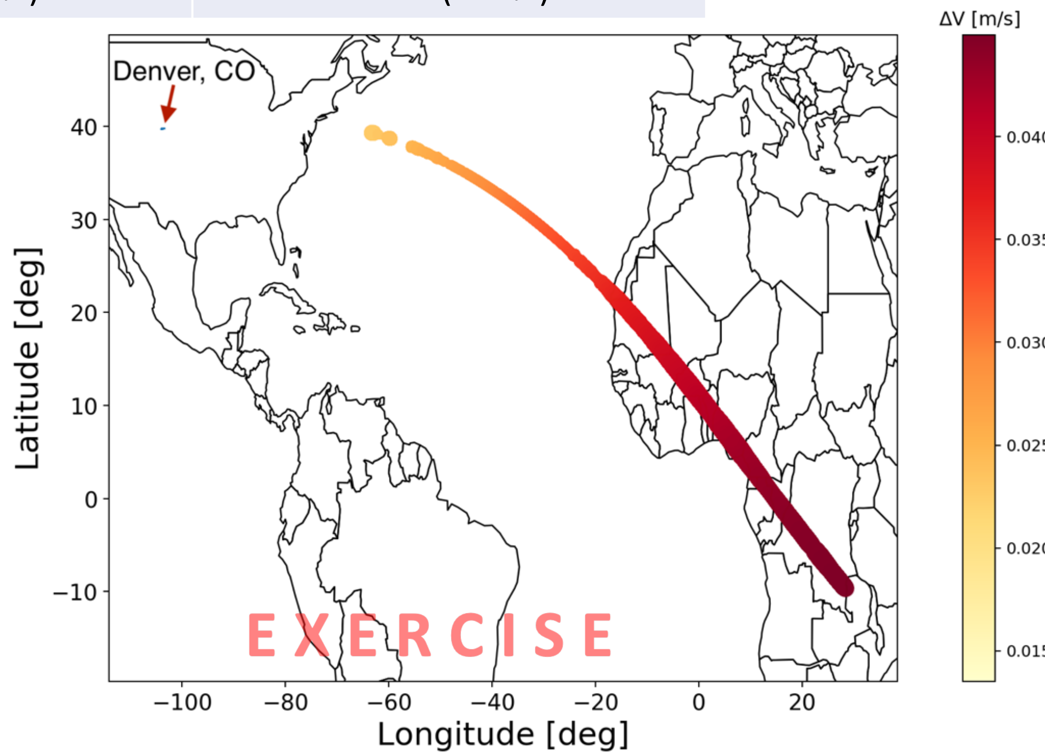
Realized Beta Values



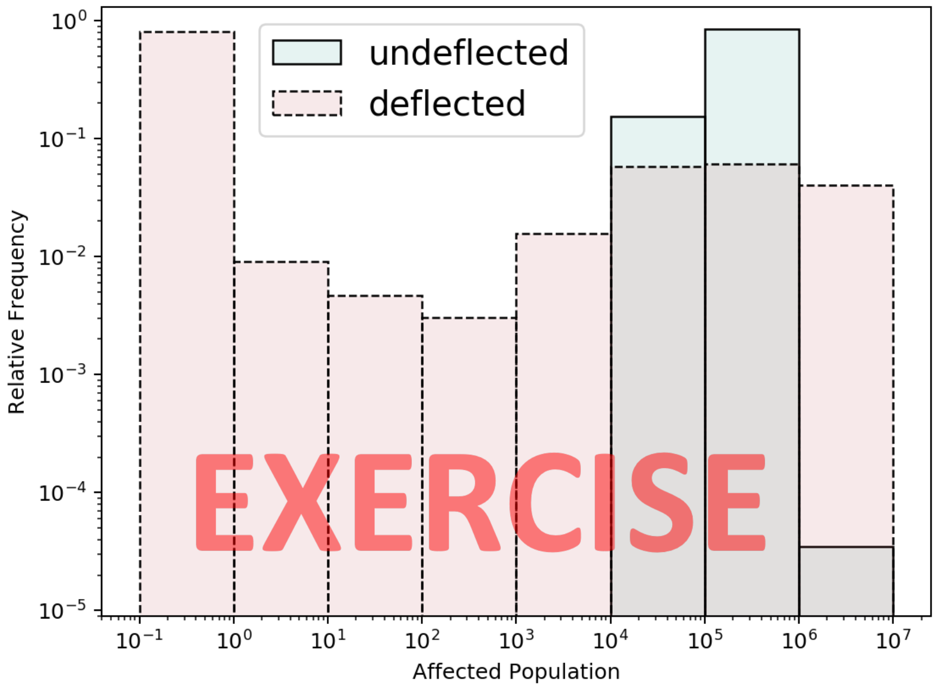
β was in range ≅ [1.5, 3.3] in this study.

Day 3 Deflected Corridor

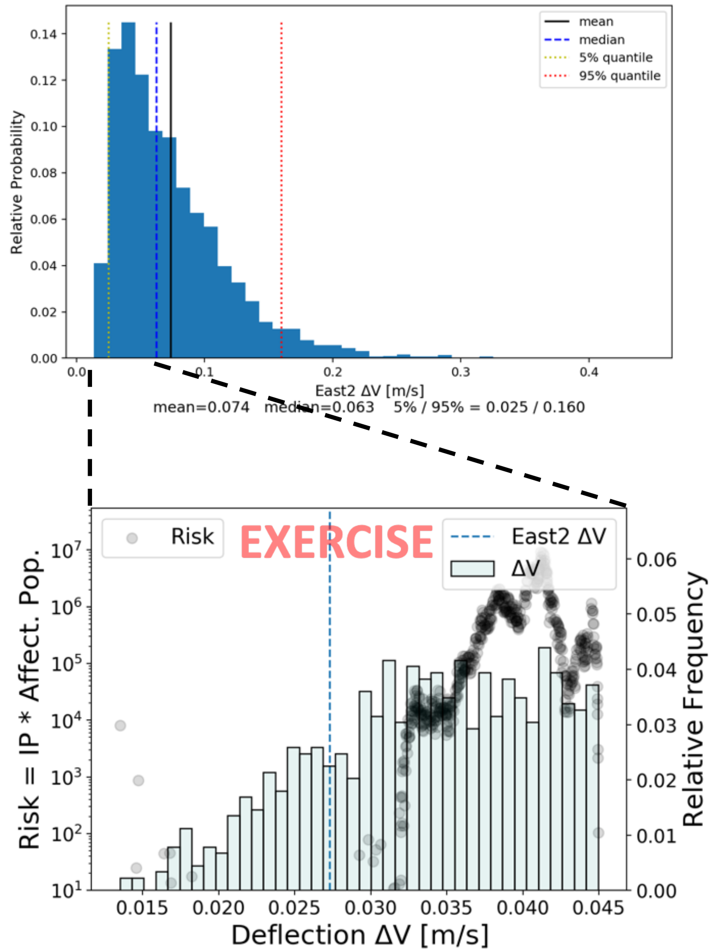
Deflection	Impact Probability [%]	Risk [affected people]
Without	100	302 k
With	30.7 (-69.3 %)	145 k (-52 %)



Day 3 Casualty Histogram

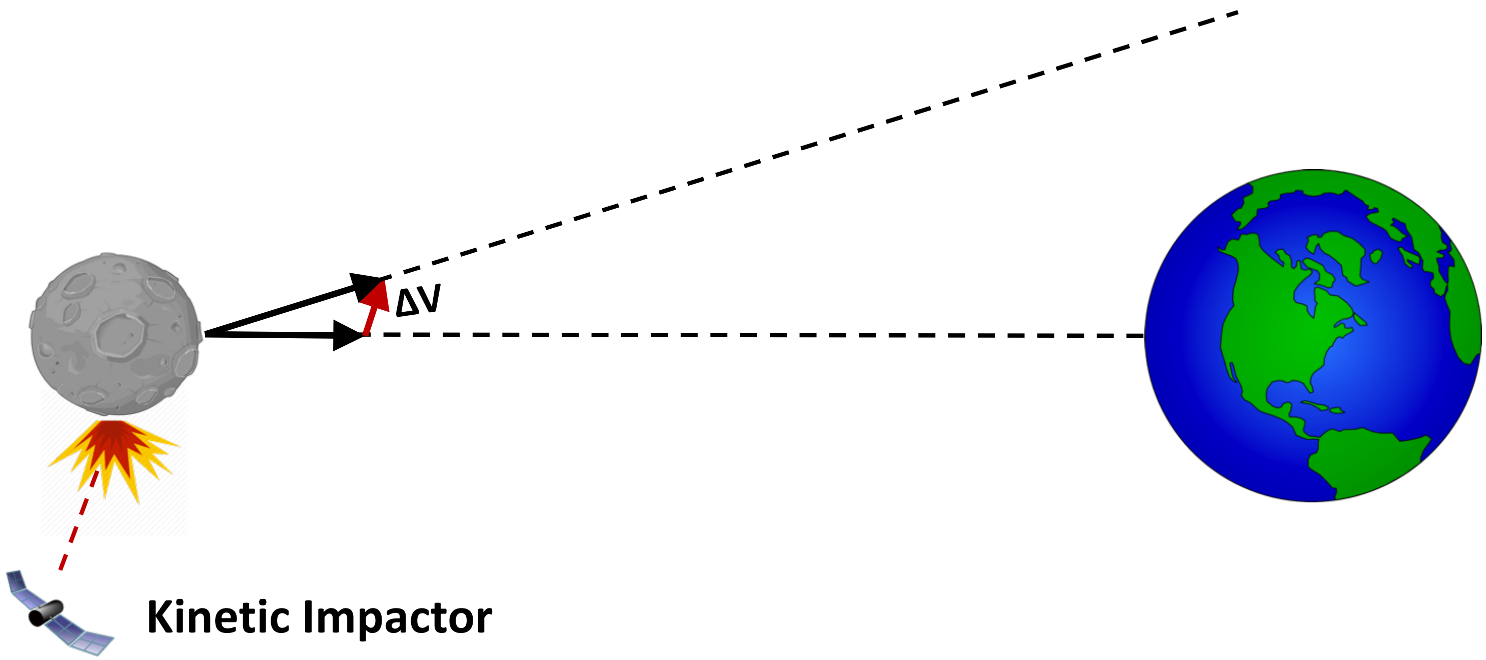


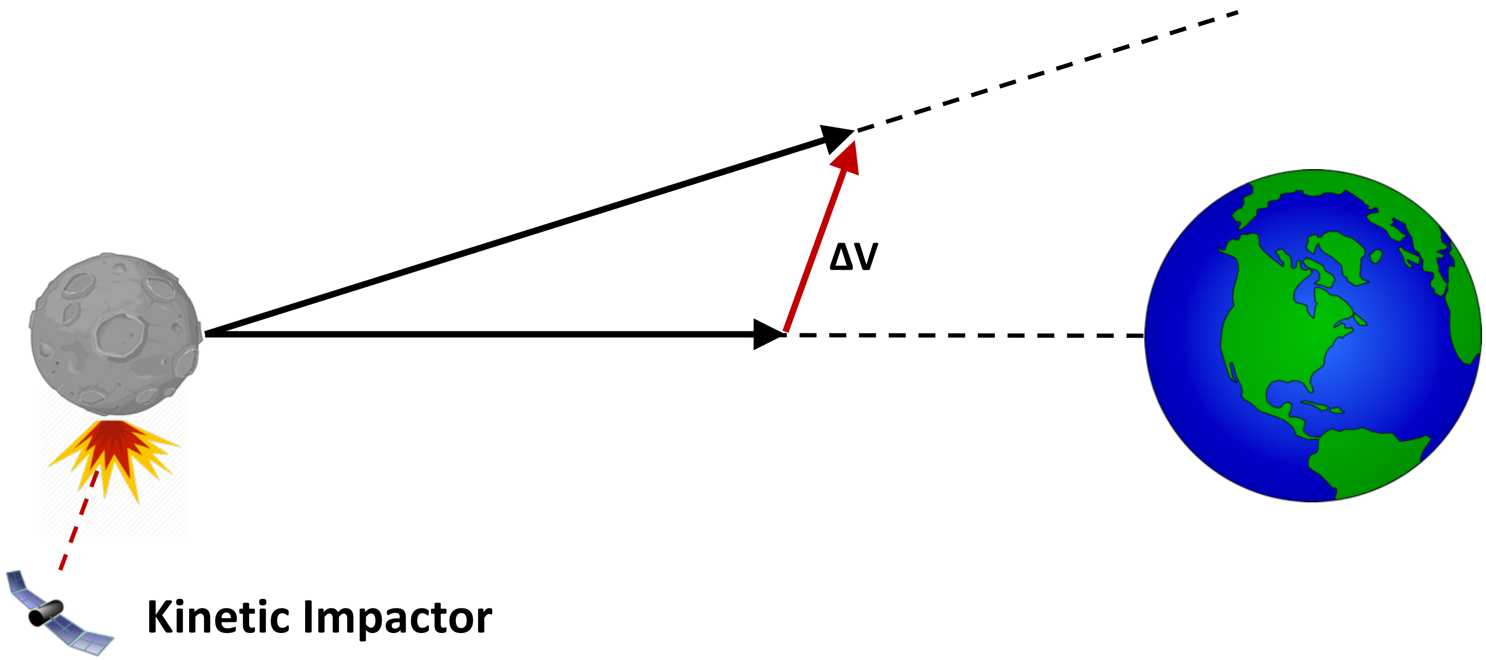
Day 3 Risk and achieved ΔV



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


ΔV
Kinetic Impactor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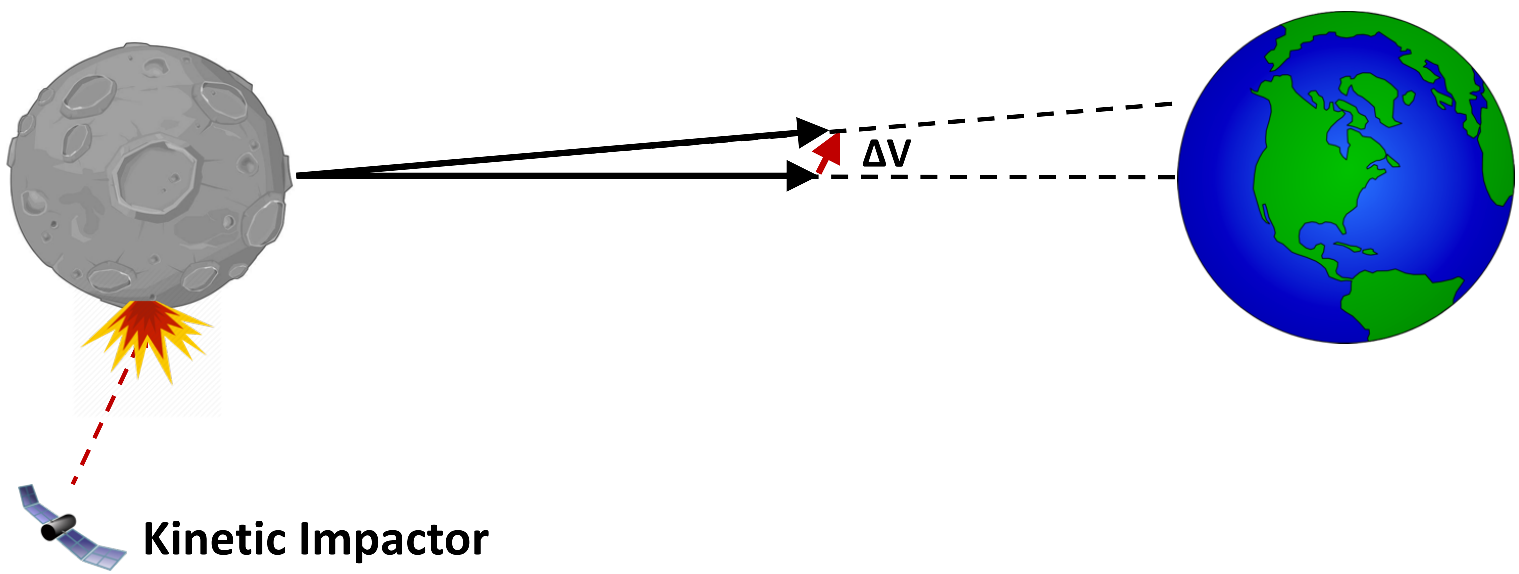
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