7th IAA Planetary Defense Conference
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Session 7a: Deflection & Disruption Testing
Chairs: Patrick Michel | Angela Stickle | Megan Syal

Presenters: S. Raducan | R. Luther | R. Nakano |
P. King | N. Gentile

Cratering processes on rubble-pile asteroids: insights from laboratory experiments and numerical models

S.D. Raducan[1], J. Ormö[2], M.I. Herreros[2], K. Wünnemann[3,4], Y. Zhang[6], R. Luther[3], C. Hamann[3], G.S. Collins[5], P. Michel[6] and M. Jutzi[1]

[1] Space Research and Planetary Sciences, Physikalisches Institut, University of Bern, Switzerland; [2] Centro de Astrobiologia (INTA-CSIC), Torrejon de Ardoz, Spain; [3] Museum für Naturkunde Berlin, Leibniz Institute for Evolution and Biodiversity Science, Germany; [4] Freie Universität Berlin, Germany; [5] Impacts and Astromaterials Research Centre, Department of Earth Science and Engineering, Imperial College London, UK; [6] Université Côte d'Azur, Observatoire de la Côte d'Azur, Laboratoire Lagrange, France.

26-30 April 2021
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DART is a kinetic impactor test

DART = Double Asteroid Redirection Test

- S-type double asteroid system
- YORP asteroids $\implies$ low cohesion and high porosity
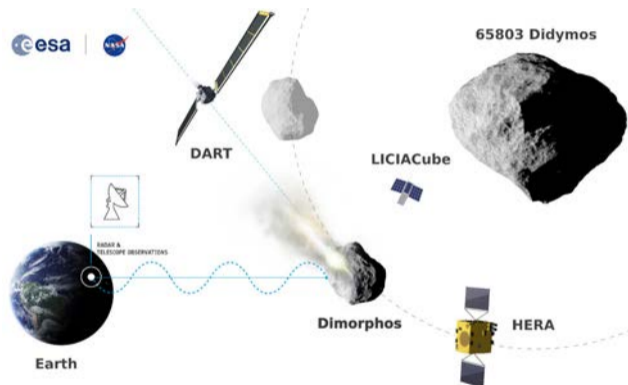- Diameter of the secondary: 150–180 m

Figure 1: DART mission concept, at the point of impact. Source: ESA.

What do we know about the impact conditions and what is the main driver for β?

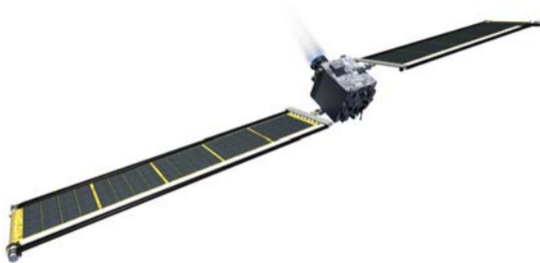**Target properties**

Figure 2: Dimorphos. Source: ESA.

- ■ Cohesive strength – not known
- ■ Bulk density/porosity – not known
- ■ Internal structure – not known

Impact conditions

Figure 3: DART spacecraft. Source: NASA.

- ■ Impact velocity – known
- ■ Impact angle – not known
- ■ Impactor mass/shape – known

Previous work quantifies the effects of various target properties and simple structures ($Y_0 > 100$ Pa)

The DART impact into different targets can produce the same β, but different craters. Both β and crater size/morphology together can be diagnostic of target properties (Raducan et al., 2020).
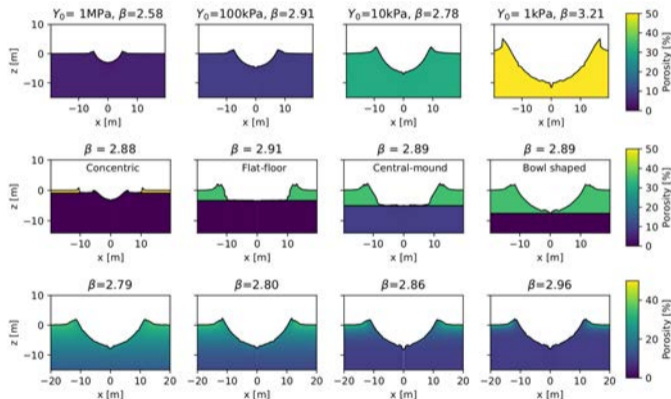

Figure 4: Crater profiles from iSALE-2D simulations of various targets.

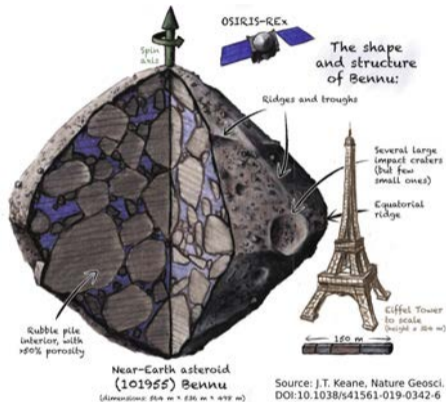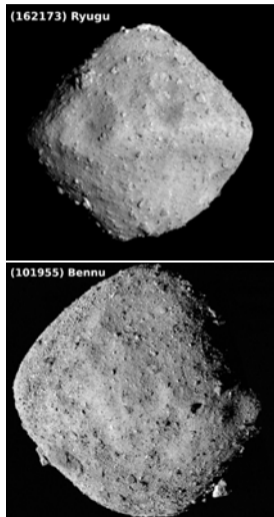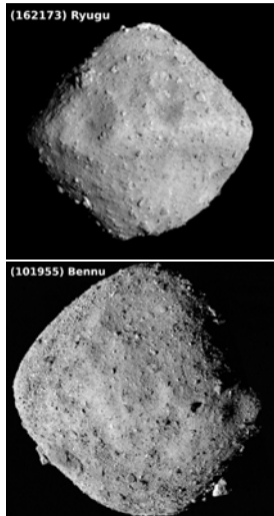## Ryugu, Bennu – both rubble-pile asteroids. Dimorphos also a rubble-pile?

Figure 5: Sketch of asteroid Bennu interior. Source: James Tuttle Keane, Nat. Geosci. vol. 12 (226).

Ryugu, Bennu – both rubble-pile asteroids. Dimorphos also a rubble-pile?

We need to validate our numerical models against laboratory experiments!
We need laboratory experiments purposely designed to mimic asteroid surfaces!

Experimental Projectile Impact Chamber (EPIC) - Quarter space experiments into heterogeneous targets

Projectile:

- Delrin (disrupts upon impact), 2 cm diameter, m_p = 5.7 g
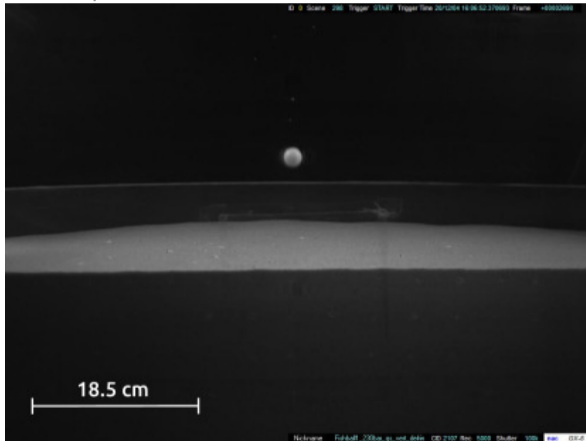- Velocity: $\approx$ 400 m/s

Target:

- 4 layers of porous ceramic balls embedded in dry beach sand matrix;
- Sand: ρ = 1.8 g/cm^3;
- Ball: d = 2.25 cm, m = 5.7 g, $\approx$50% porosity.

Projectile ~ 2 cm

Ball ~ 2.25 cm
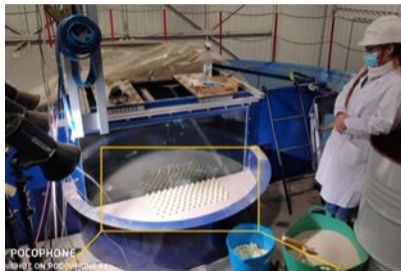
We used SPH to model the EPIC experiment

T = 0 ms
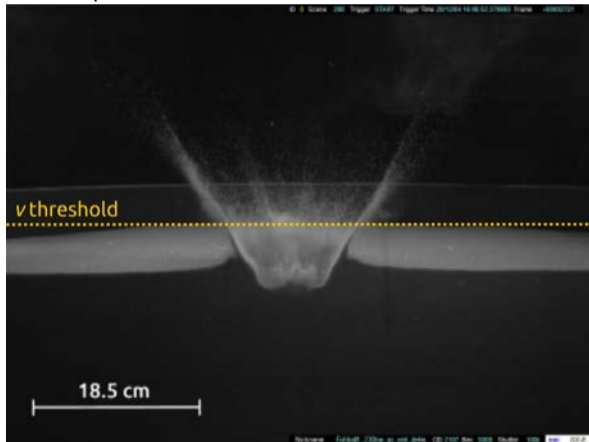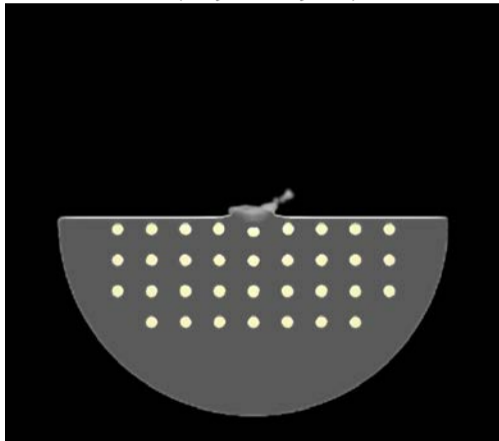
EPIC experiment

SPH simulation (only slow ejecta)

18.5 cm

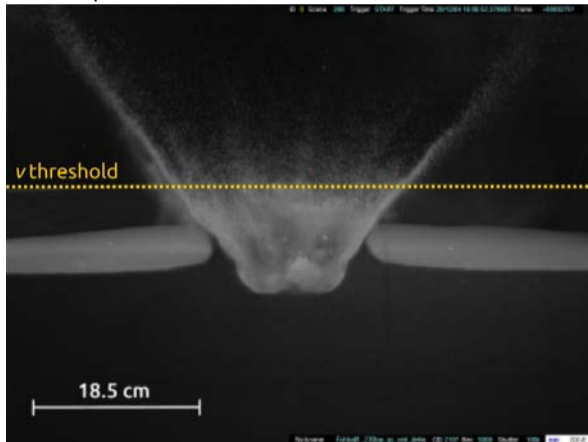## We used SPH to model the EPIC experiment

$T = 4\,\mathrm{ms}$

EPIC experiment

SPH simulation (only slow ejecta)

v threshold

18.5 cm

We used SPH to model the EPIC experiment

$T = 10\,\text{ms}$

EPIC experiment

SPH simulation (only slow ejecta)

v threshold

18.5 cm

We used SPH to model the EPIC experiment

T = 20 ms

EPIC experiment

SPH simulation (only slow ejecta)
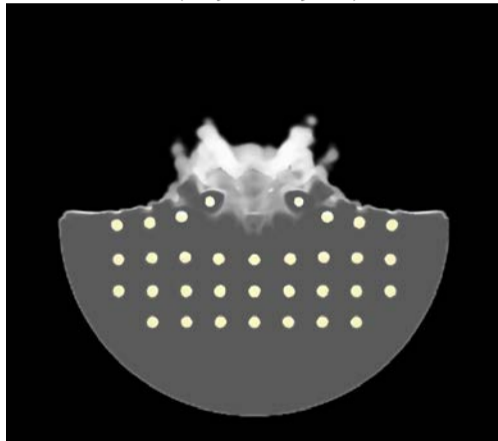

v threshold

18.5 cm

We used SPH to model the EPIC experiment

$T = 35\,\text{ms}$

EPIC experiment

SPH simulation (only slow ejecta)
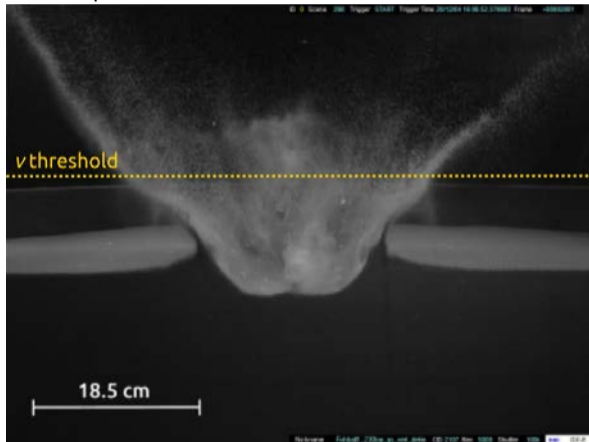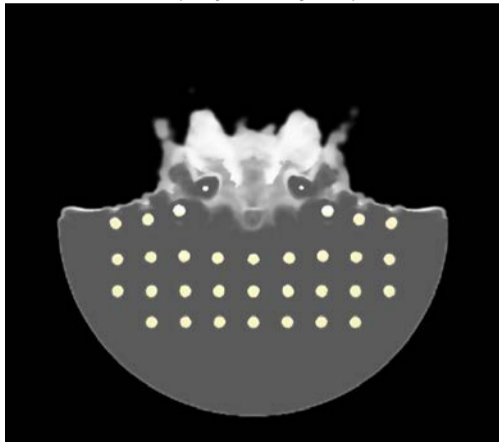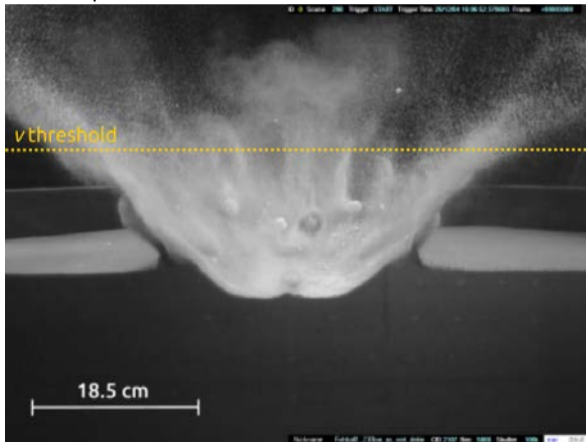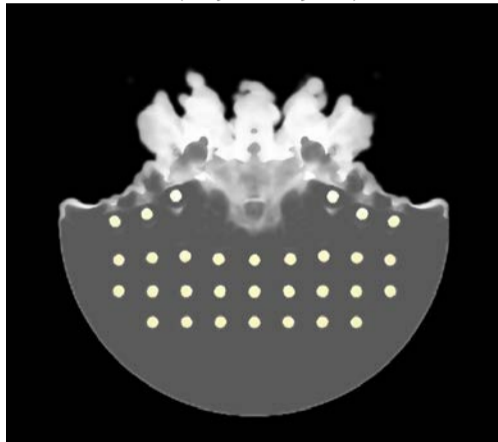
We used SPH to model the EPIC experiment

Final crater - good match with the experiment

Crater dimensions
Pre-impact level diameter: 20.2 cm
Rim diameter: 28.2 cm
Depth: 2.9 cm
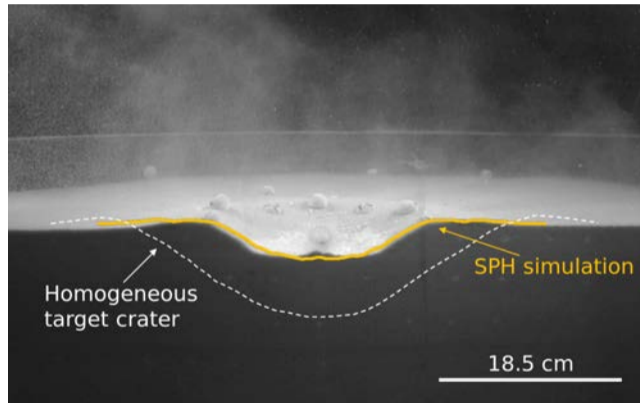
Figure 6: Final crater morphology (T $\approx$ 0.8 s).

We used SPH to model the EPIC experiment

Boulder distribution - good match with the experiment

Experiment

SPH simulation
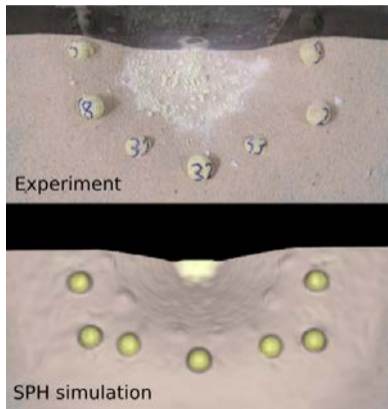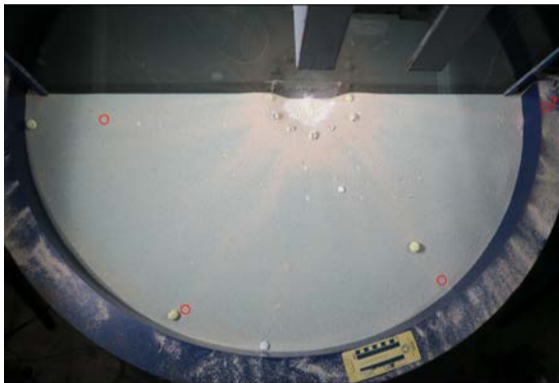
Figure 7: Boulder distribution.

We used SPH to model DART-like impacts on spherical homogeneous asteroid
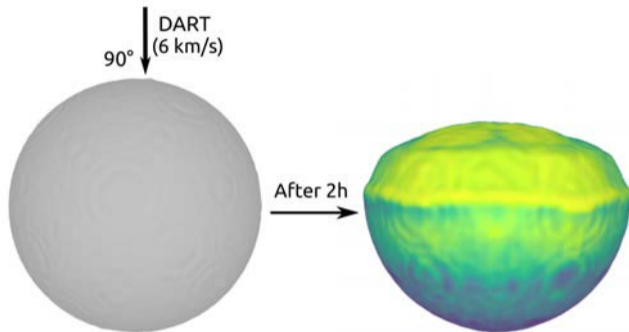
	Impactor			Target	
radius	mass	velocity	strength	friction	density
a	m	U	Y_0	f	ρ
(m)	(kg)	(km/s)	(Pa)		(kg/m^3)
0.5	500	6.0	0	0.6	1620

We modelled DART-like impacts on spherical rubble-pile asteroids - initial

a) Grid-like distribution of 2.5 m boulders;
b) Random distribution of 2.5 m boulders;
c) Random distribution of boulders
   between 2 and 10 m.
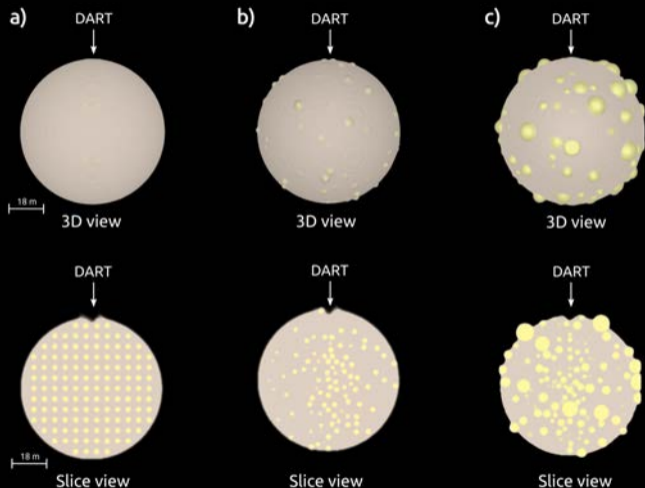
DART-like impacts on spherical rubble-pile asteroids – after $\approx 2\,h$

a) Grid-like distribution of 2.5 m boulders;
b) Random distribution of 2.5 m boulders;
c) Random distribution of boulders
   between 2 and 10 m.
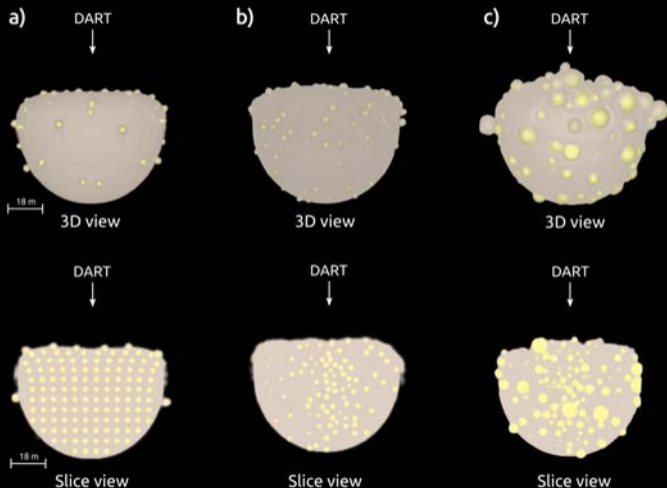
DART-like impacts on spherical rubble-pile asteroids – after $\approx 2\,$h

Homogeneous target
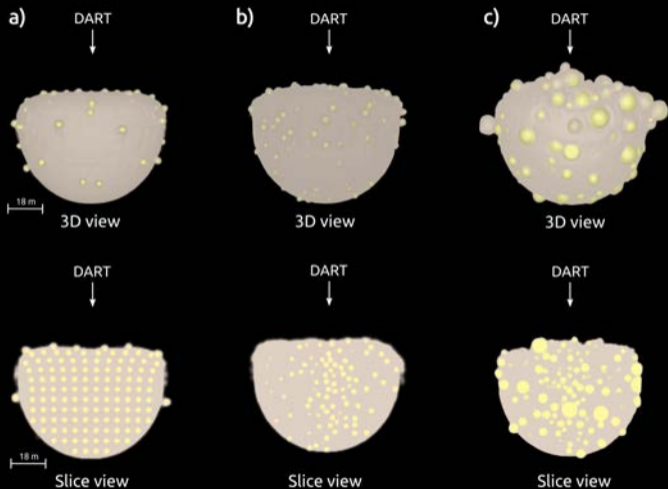
The boulder size-distribution influences the deflection efficiency, β
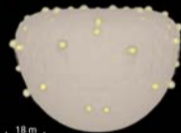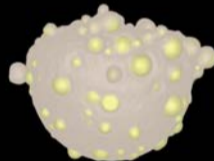
Conclusions

- The DART mission may impact a rubble-pile asteroid. We need laboratory experiments purposely designed to mimic asteroid surfaces;
- SPH simulations of impacts into heterogeneous targets show great agreement with laboratory experiment results;
- The DART impact on cohesionless spherical bodies is likely to produce morphologies that are dissimilar to cratering and change the global morphology of the asteroid;
- DART-like impact simulations on rubble-pile asteroids show that both the target morphology and the momentum transfer are affected by the distribution of surface boulders.

Acknowledgements

Kinetic Impactor Technique: Benchmark and Validation Studies with iSALE and SPH

Near Earth Object
Modelling And Payloads
for Protection

R. Luther, S.D. Raducan, M. Jutzi, K. Wünnemann, P. Michel,
Y. Zhang, D. Koschny, T.M. Davison, G.S. Collins
28.04.2021

Image: ESA

iSALE (grid-based code)

SPH (particle code)
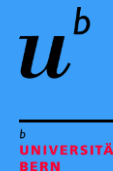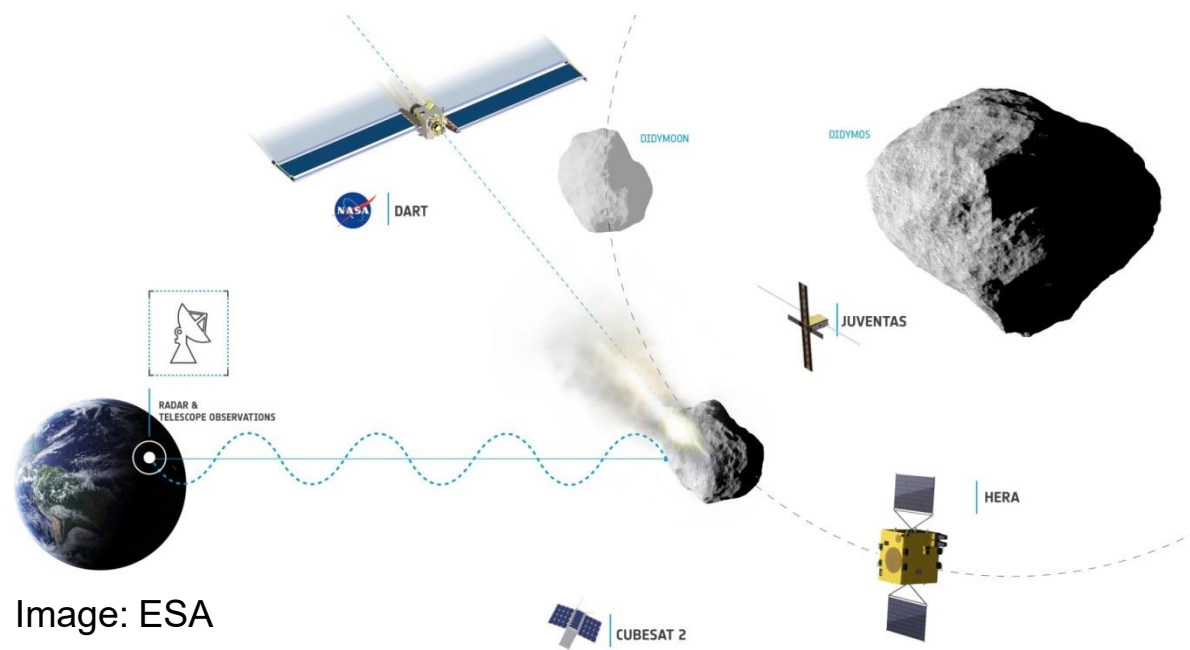
- **Objective:** relate observed orbital change with momentum enhancement and crater morphology for given material properties (low strength regime)
- Shock physics codes simulate different materials; prove accuracy by:
  → validation against experiments
  → benchmarking codes (iSALE & SPH)

Electro-thermal accelerator

Blue/hatched: Mounting structure

Muzzle plasma shield

Projectile (4 mm dia, ~25 mg mass)

Capacitor bank

High-speed camera

Diffusor

Flash illuminator

Target container on springs
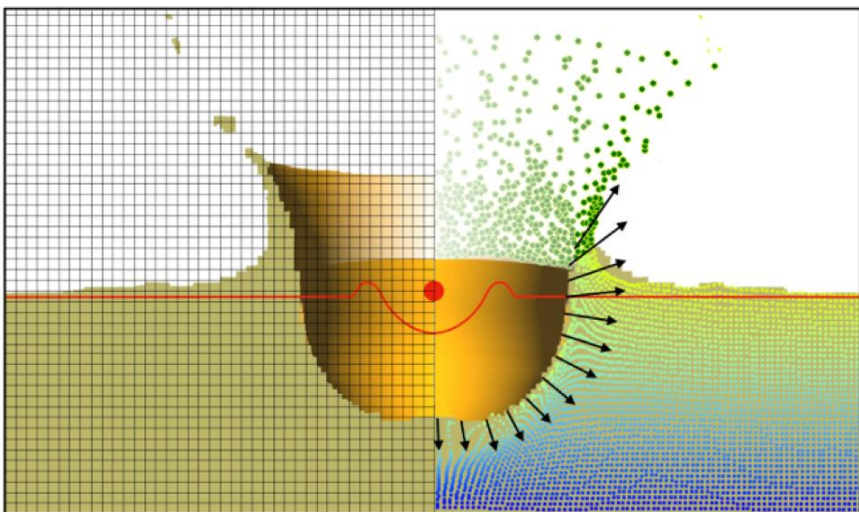
Laser distance measurement device

ESA-MRG-DR-118/1.1, 04 Jan 2019
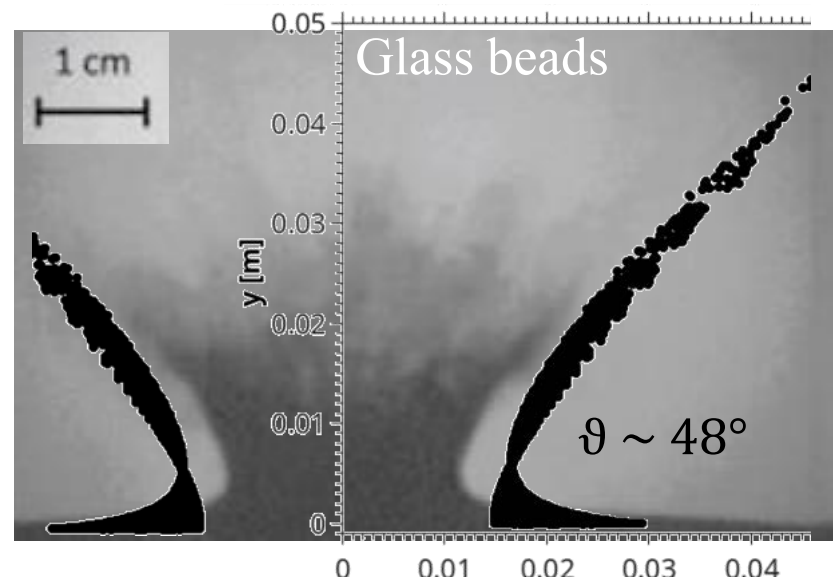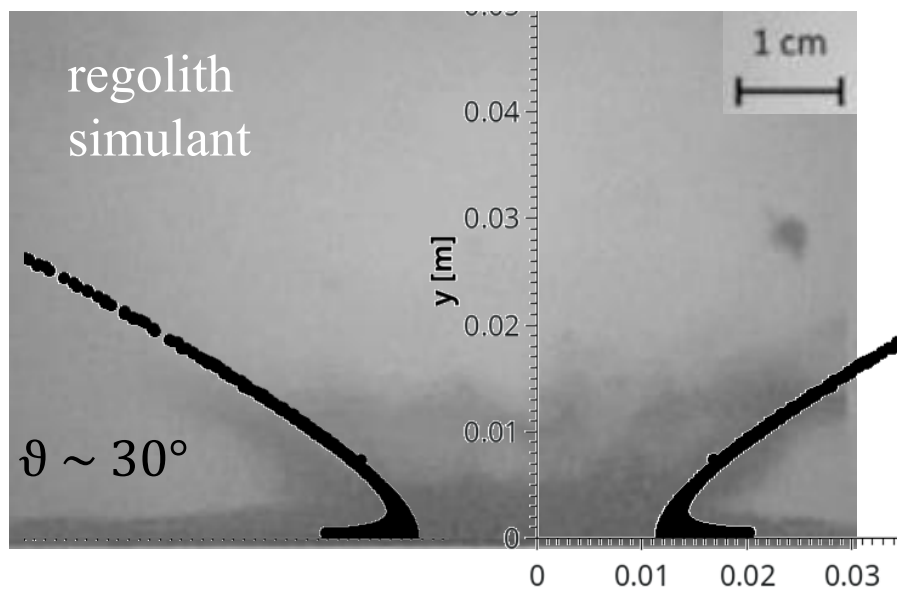
Experimental Setup:
- Chourey et al. 2020, PSS:
  - v~1-3 km/s
  - target materials:
    - glass beads
    - quartz sand
    - regolith simulant
  - formation of ejecta curtain
  - crater size
  - momentum enhancement

3

regolith simulant

$\vartheta \sim 30°$

1 cm

Glass beads

$\vartheta \sim 48°$

Experimental Setup:
- Chourey et al. 2020, PSS:
  - v~1-3 km/s
  - target materials:
    - glass beads
    - quartz sand
    - regolith simulant
  - formation of ejecta curtain
  - crater size
  - momentum enhancement

- similar material models & parameters for iSALE-2D and SPH
- both codes agree with experimental data
- some deviation towards faster impact velocity between codes

v = 2.2 km/s, m = 24 mg (PVC), regolith simulant (experiment: Chourey et al. 2020, PSS)

Strength model	Lundborg, Y_0=1.4 kPa, f=0.77
Porosity model Φ=42%	ε-α-model (iSALE), κ=0.96
	P-α-model (SPH), P_e=100 Pa, P_s=1.5 GPa

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	P-α-model (SPH), P_e=100 Pa, P_s=1.5 GPa

$$\beta = \Delta p / p_i$$

- similar material models & parameters for iSALE-2D and SPH
- both codes agree with experimental data
- results from both codes agree with each other

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Porosity model Φ=42%	ε-α-model (iSALE), κ=0.96
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- Similar material models for iSALE-2D and SPH
- results from both codes agree with each other for a range of material parameters
- some deviations occur for small porosities (Y_0=1 kPa & 100 kPa) and at 50% (Y_0=10 kPa)

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Effect of impact angle?
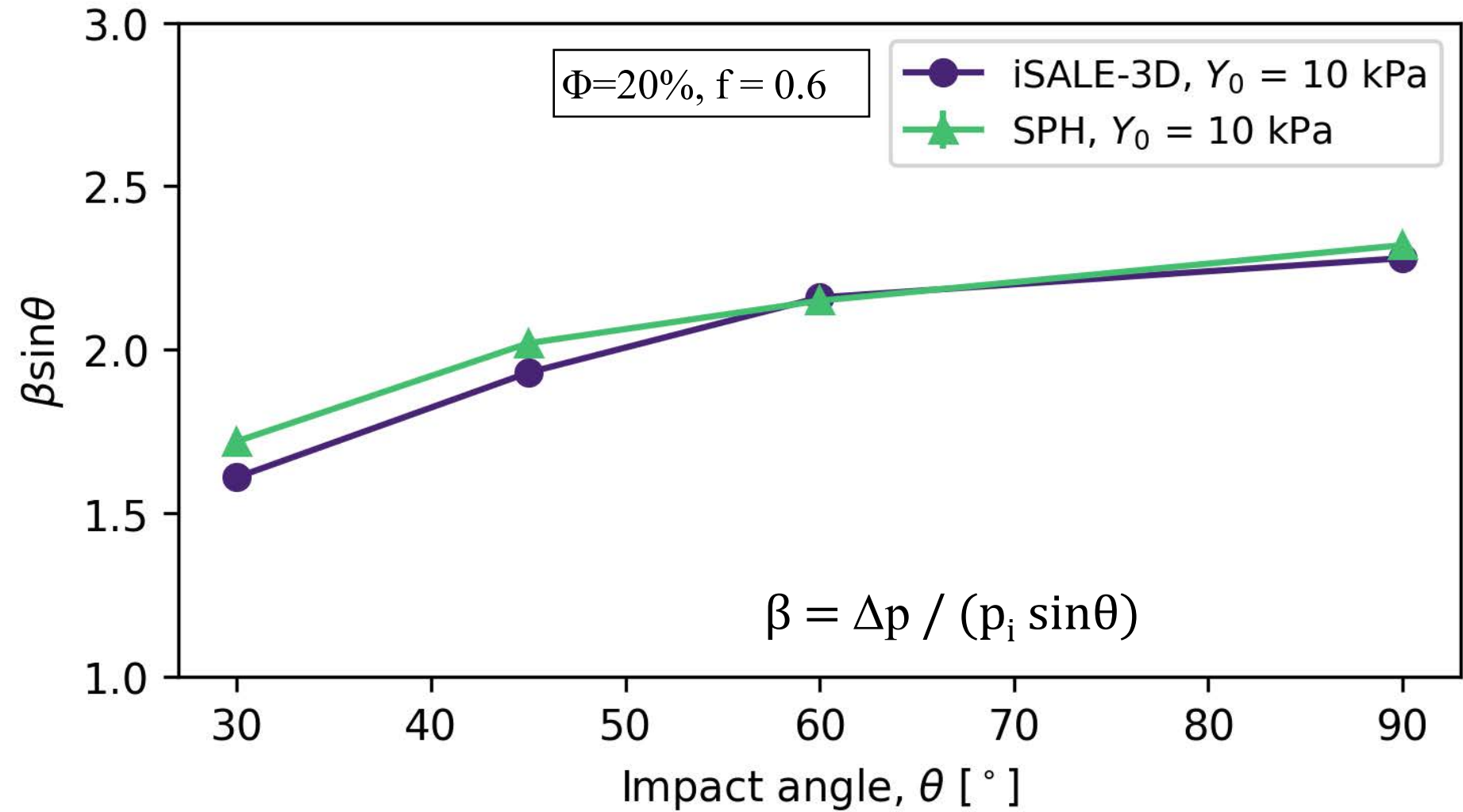
$\Phi = 20\%, f = 0.6$

iSALE-3D, $Y_0 = 10$ kPa

SPH, $Y_0 = 10$ kPa

$$\beta = \Delta p / (p_i \sin\theta)$$

- same material models & parameters for iSALE-3D and SPH
- results from both codes agree with each other for all impact angles

$\Phi=20\%$, $f = 0.6$

Legend:
- iSALE-3D, $Y_0 = 10$ kPa
- SPH, $Y_0 = 10$ kPa

-25%

$$\beta = \Delta p / (p_i \sin\theta)$$

y-axis: $\beta\sin\theta$
x-axis: Impact angle, θ [°]

- same material models & parameters for iSALE-3D and SPH
- results from both codes agree with each other for all impact angles

Φ=20%, f = 0.6

iSALE-3D, $Y_0 = 10$ kPa
SPH, $Y_0 = 10$ kPa

-25%

+9%

$$\beta = \Delta p / (p_i \sin\theta)$$
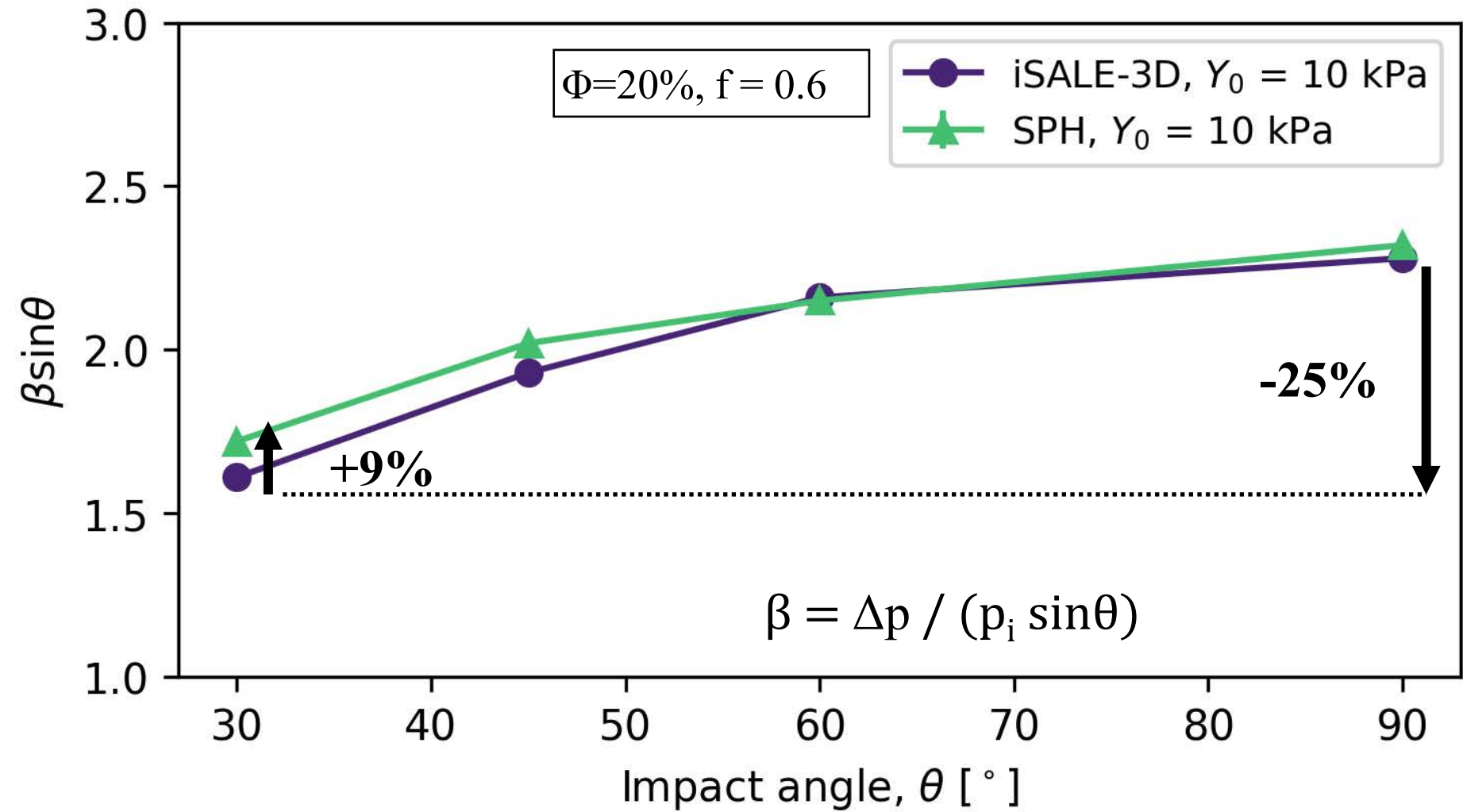
- same material models & parameters for iSALE-3D and SPH
- results from both codes agree with each other for all impact angles

Thank you.

Conclusion

- We have run **validation** tests in the Hera-relevant low strength regime for iSALE & SPH against experimental results for regolith simulant, **including measured values of β**
  → **both codes agree** with independent experimental data in terms of diameter, ejection behaviour and momentum enhancement

- Expanding the **benchmark** to **further materials** (Y_0=1, 10, 100 kPa, Φ=20-50%) shows **good agreement** between the codes (<23% deviation in β, in agreement to Stickle et al. 2020)

- Deviations for the impact angle scaled momentum between both codes for different **impact angle** are below 9%

- We plan further validations with other materials

Thank you.

Near Earth Object
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NASA/Double Asteroid Redirection Test: Orbital perturbation by the ejecta-collision driven reshaping of Didymos after the impact event

Ryota Nakano and Masatoshi Hirabayashi

STAR Lab, Auburn University

IAA Planetary Defense Conference

26 – 30 April 2021

Didymos is spinning at close to its spin limit.

- Didymos is a ~780 m dia. top-shaped asteroid, spinning at 2.26 hr.

- May be structurally sensitive to reshaping

  → Even <u>small perturbations</u> may trigger reshaping.

  - Ejecta cloud hitting on Didymos (delivers kinetic energy)
  - Seismic shaking attenuation due to the DART impact

Understanding the orbital perturbation due to reshaping is important to determine the momentum transfer coefficient and
to assess the DART deflection capability.

Statistically determine the effect of asymmetric reshaping.

How Didymos' reshaping affects the orbital period after the DART impact?

- While the reshaping magnitude is unknown, we have knowledge of possible reshaping processes of top-shaped asteroids.

- Ejecta will distribute heterogeneously on Didymos, which will lead to asymmetric reshaping.

→ We developed a shape model generator to create "reshaped" shape models.

6,000 asymmetric reshaped cases are prepared.

- We characterize the reshaping with 4 parameters: α_{+x}, α_{-x}, α_{+y}, and α_{-y}.

- Each represents the ratio of the $\pm x$ or $\pm y$ axis for the reshaped body to that of the original body.

- We randomly define a value for each, <u>in a range from 1 to α_{max}.</u> (= maximum reshaping magnitude).

- α for z axis is uniquely determined by keeping the volume constant regardless of the shape.

Ex: $\alpha_{max} = 1.1 \quad \approx 40\,m$

$\alpha_{+x} = 1.099 \quad \approx 38\,m$
$\alpha_{-x} = 1.085 \quad \approx 33\,m$
$\alpha_{+y} = 1.021 \quad \approx 8\,m$
$\alpha_{-y} = 1.049 \quad \approx 19\,m$
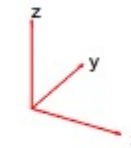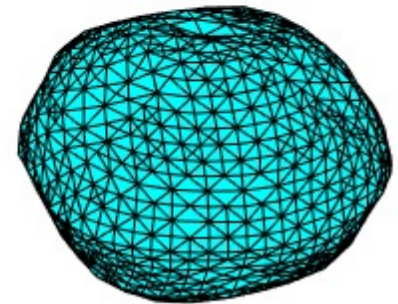
12 different α_{max},

    500 cases for each α_{max}

   → 6,000 simulation cases in total

Dimorphos' orbital period change after 180 days from the impact

$\alpha_{max} = 1.05$

$\rightarrow$ less than 20 m of reshaping

$\alpha_{max} = 1.001$

$\rightarrow$ less than 1 m of reshaping
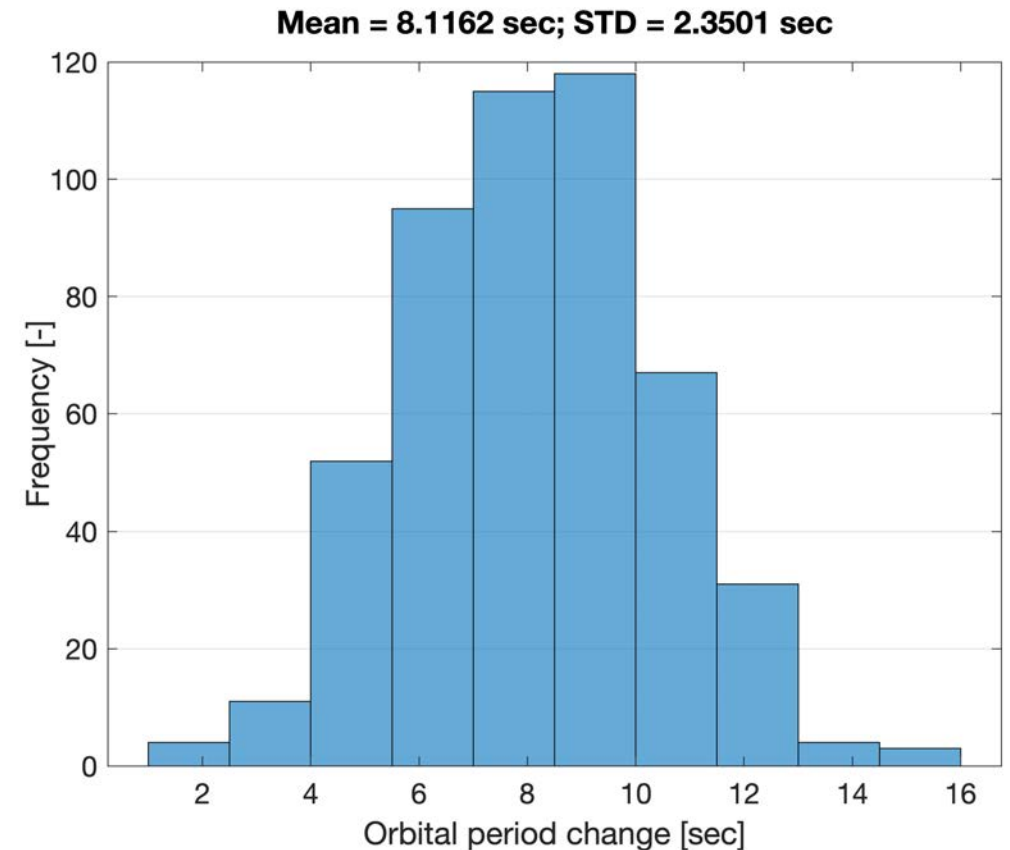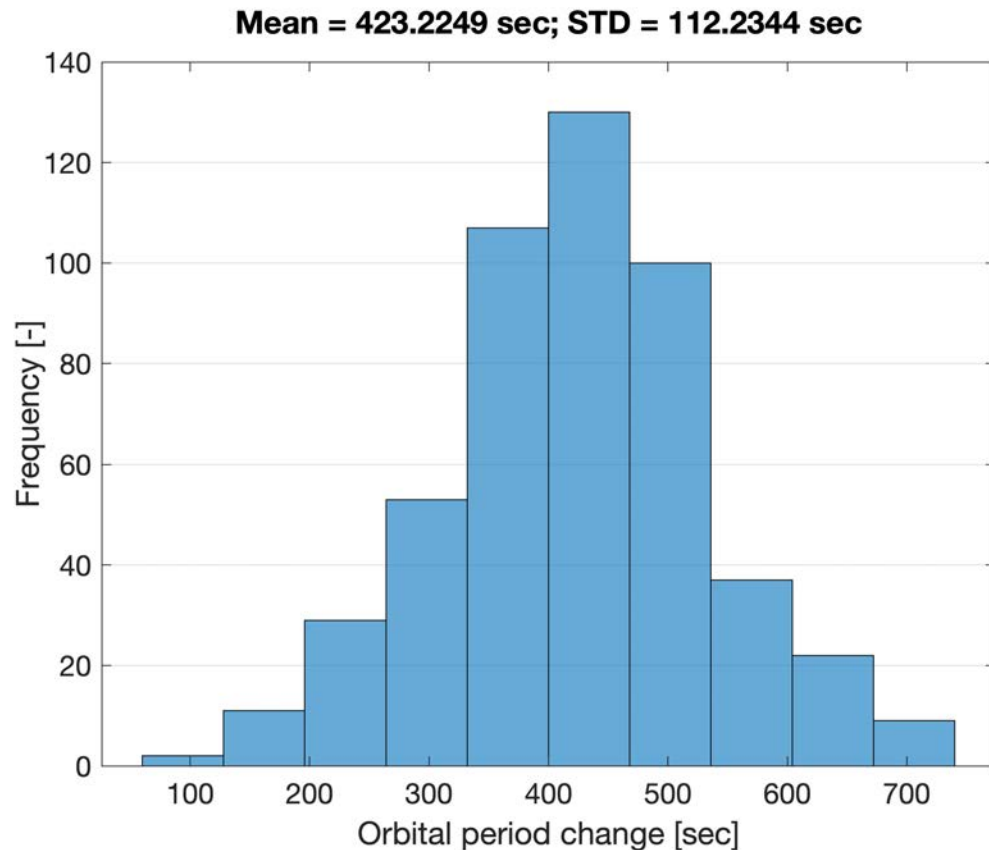
Reshaping magnitude can be constrained with the spin period change.

Didymos' angular momentum should be conserved.

$\rightarrow$ The spin period changes during the reshaping event.

α_{max}	(Reshaping scale)	$\Delta \bar{P}_{spin}$ [sec]
1.1	(≈ 40 m)	840.57
1.05	(≈ 20 m)	415.09
1.01	(≈ 4 m)	82.684
1.009	(≈ 3.5 m)	74.192
⋮		⋮
1.002	(≈ 0.8 m)	15.701
1.001	(≈ 0.4 m)	8.0486

$y = -0.9831x - 3.905$

Orbital period change [sec] vs Spin period change [sec]
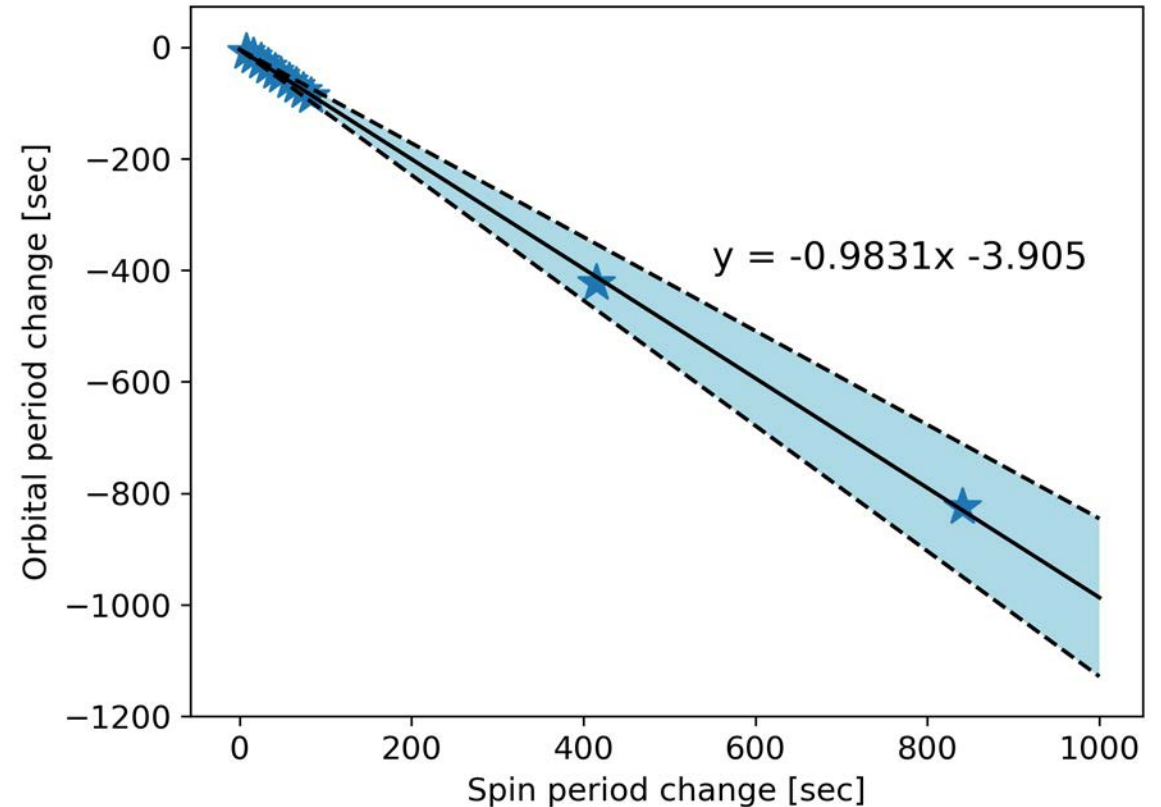
The orbital period linearly decreases as reshaping mag. increases.

From the statistical investigation, we found:

- For <u>a shape change of less than 40 m</u>, the reshaping-driven orbital period change is characterized to be <u>linear</u>.

- We predict the relationship: $\Delta P_{orb} = -0.9831\ \Delta P_{spin} - 3.905$

- The orbital period should always become <u>shorter</u> than the original period, for the head-on DART impact scenario.

- Detailed observation of Didymos' spin period change can constrain the magnitude of reshaping,

- from which we can decouple the reshaping-driven orbital period change and can accurately determine the momentum transfer efficiency.

Thank you!

12 different α_{max}, 500 cases for each α_{max}, 6,000 simulation sets

α_{max}	$\Delta\overline{P}_{spin}$	$\Delta\overline{P}_{orb}$
1.1	840.57	824.47
1.05	415.09	423.22
1.01	82.684	87.354
1.009	74.192	78.527
1.008	65.933	69.719
1.007	57.823	61.155
1.006	47.863	51.004
1.005	40.937	43.781

α_{max}	$\Delta\overline{P}_{spin}$	$\Delta\overline{P}_{orb}$
1.004	32.844	34.983
1.003	24.762	26.054
1.002	15.701	16.078
1.001	8.0486	8.1162

$\Delta\overline{P}_{spin}$: Mean spin period change

$\Delta\overline{P}_{orb}$: Mean orbital period change

Relative phase angle evolution 180 days after the DART impact

$\alpha_{max} = 1.1 \rightarrow$ less than 40 m of reshaping in each axis
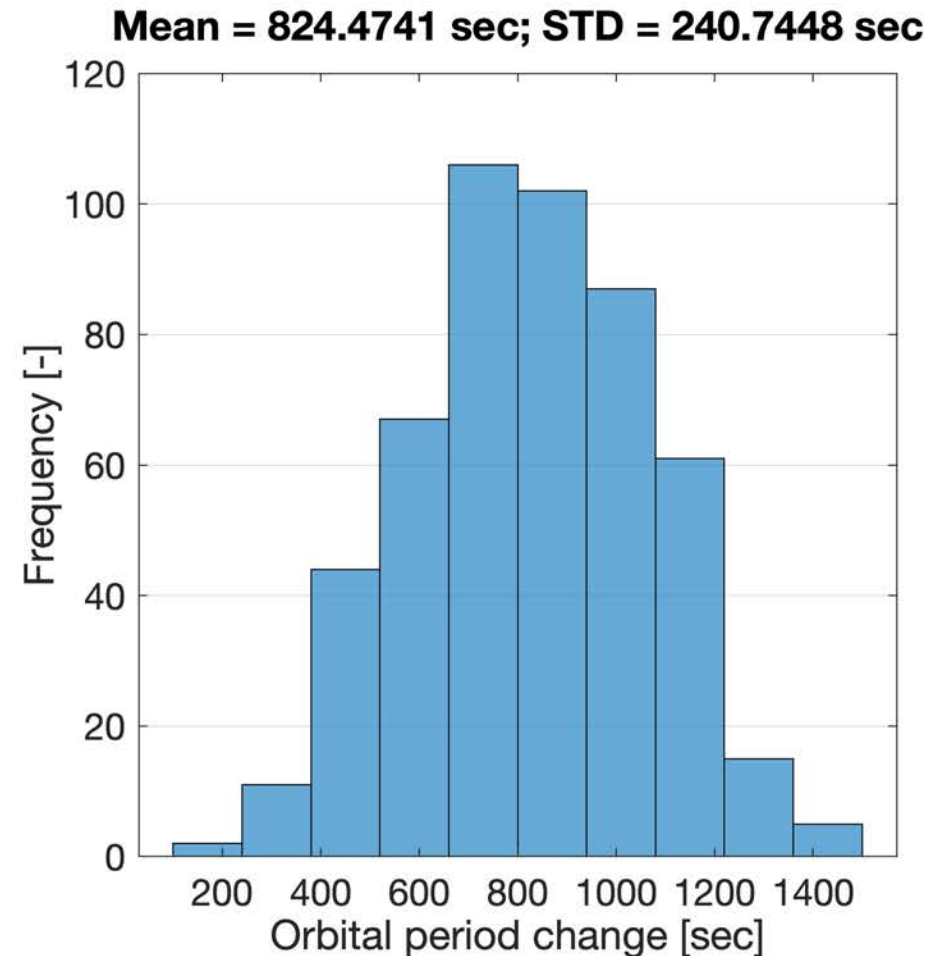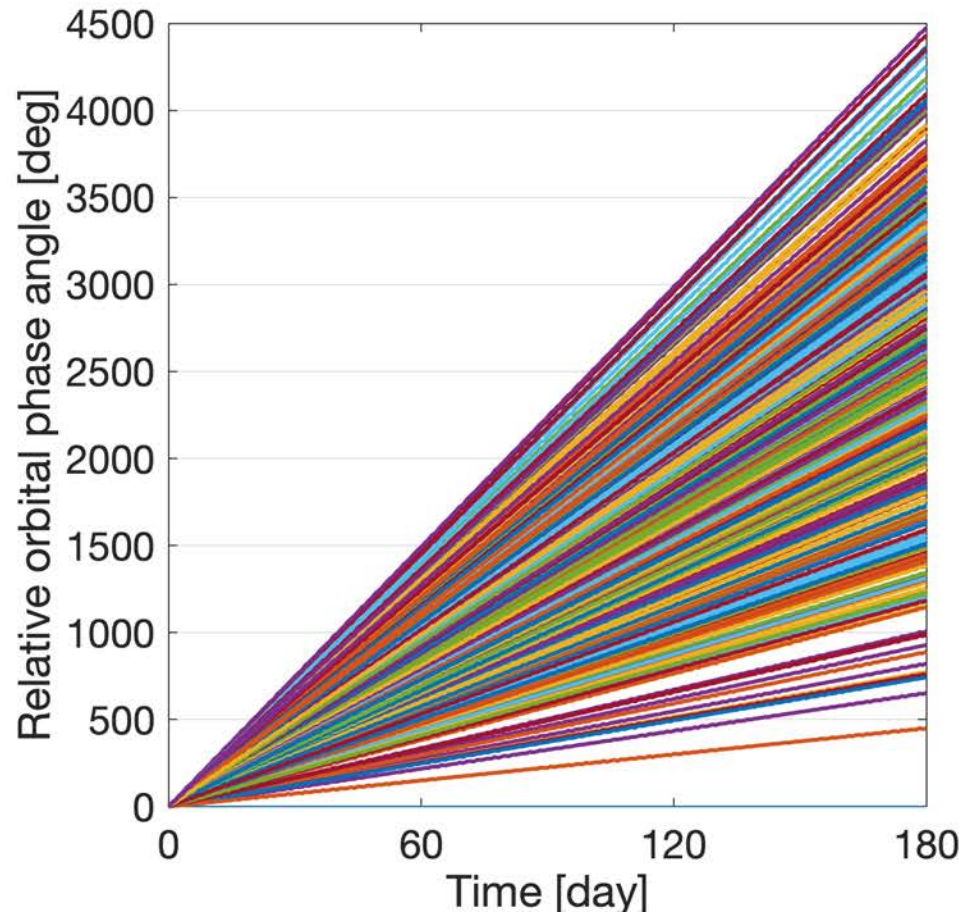
Relative phase angle evolution 180 days after the DART impact

$\alpha_{max} = 1.05 \rightarrow$ less than 20 m of reshaping in each axis
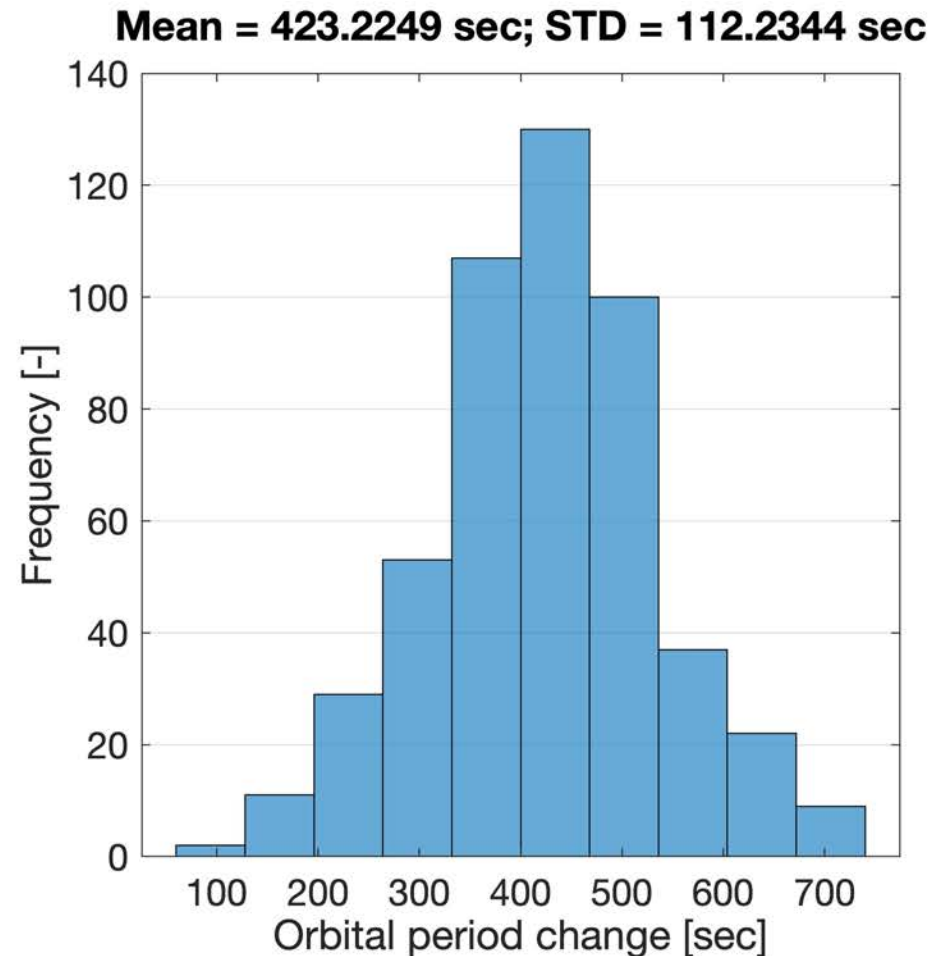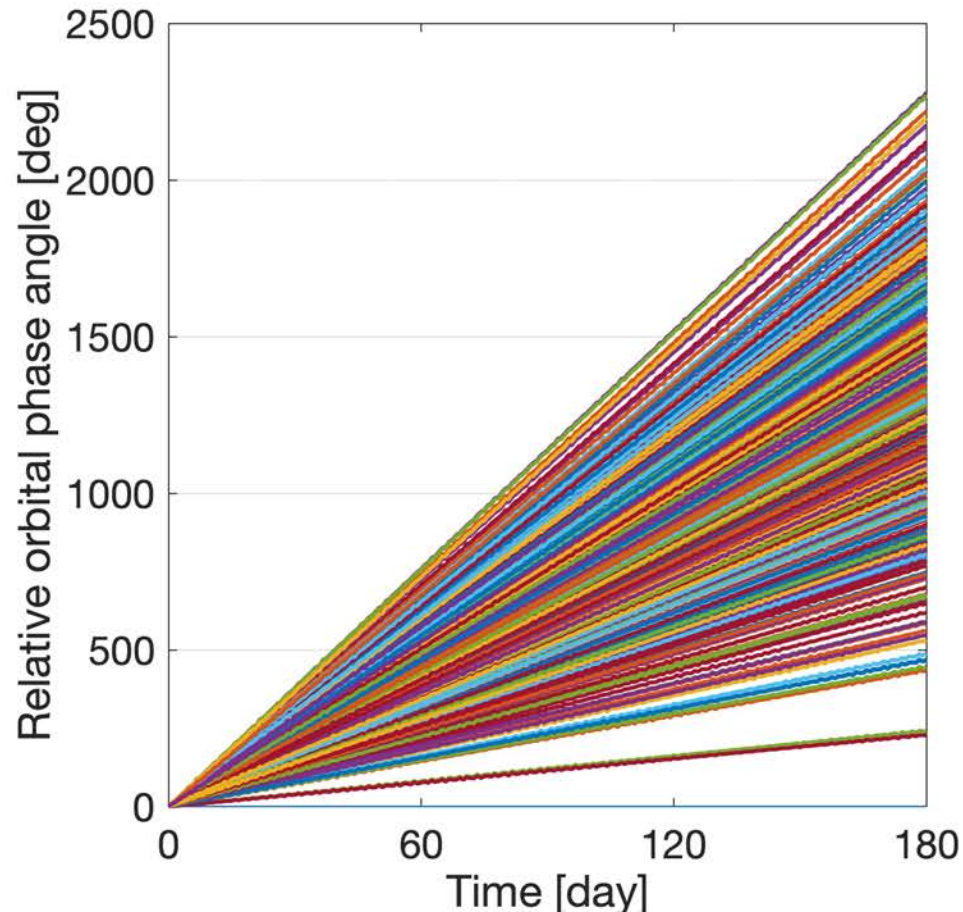
Relative phase angle evolution 180 days after the DART impact

$\alpha_{max} = 1.001 \rightarrow$ less than 1 m of reshaping in each axis
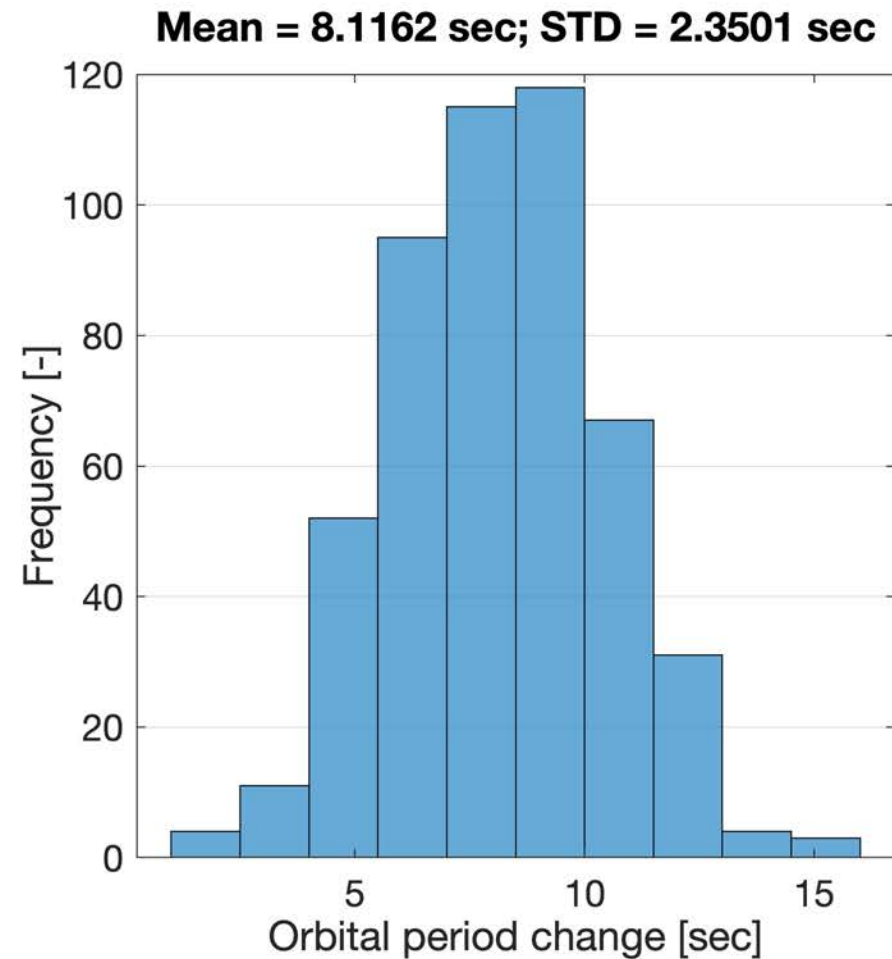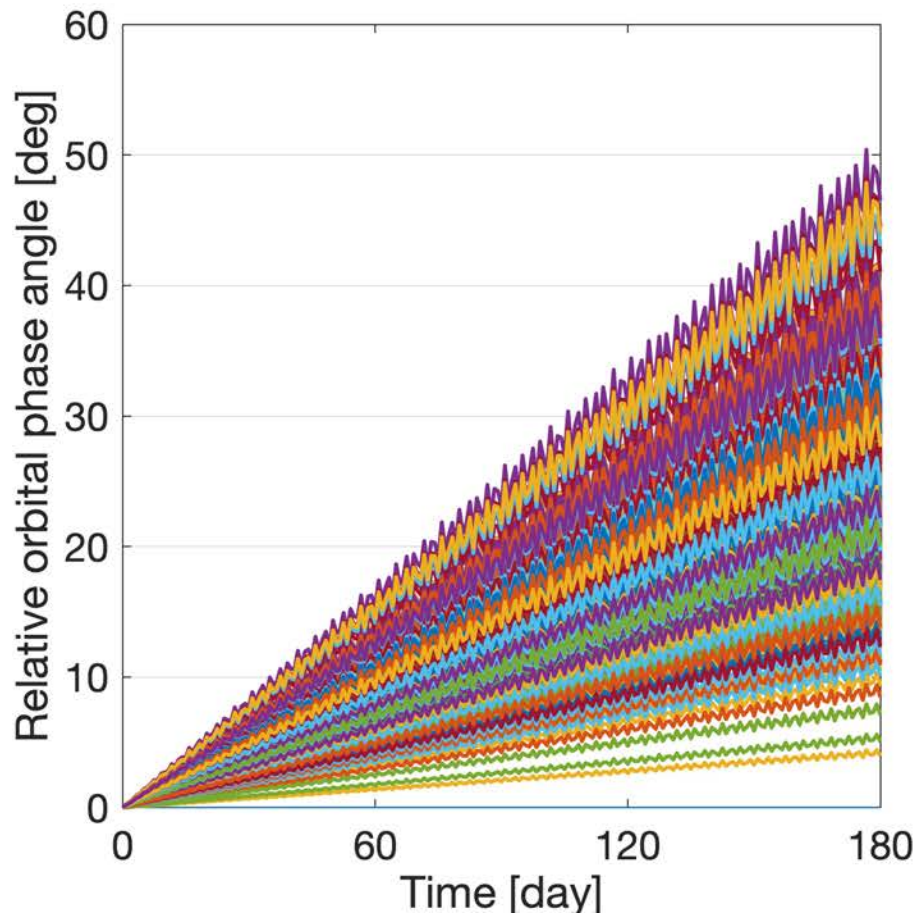
Late-time Nuclear Disruption in the PDC 2021 Scenario

Patrick King[1], Megan Bruck Syal[2], David S.P. Dearborn[2], Robert Managan[2], J. Michael Owen[2], and Cody Raskin[2]

Session 7a: Deflection & Disruption Modeling and Testing   Paper 151   04/28/21

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Overview

- Nuclear Disruption of a Fiducial Small Body

- N-Body Methodology

- Results for the PDC 2021 Scenario

Nuclear Disruption of a Fiducial Small Body

- Simulation conducted with Spheral hydrocode

- 20% scaled model of 101255 Bennu (corresponds to 100 meter diameter)

- Modeled as uniform granite with 25% microporosity; Collins strength model with Tillotson EOS

- Uniform bulk linear resolution (~1.6 meter linear resolution) with ratioed zoning deposition zone for source

- 1 MT device at 15 meter height-of-burst (65 meters from center) at equator

- Consistent with simulation scheme described in Dearborn et al. 2020
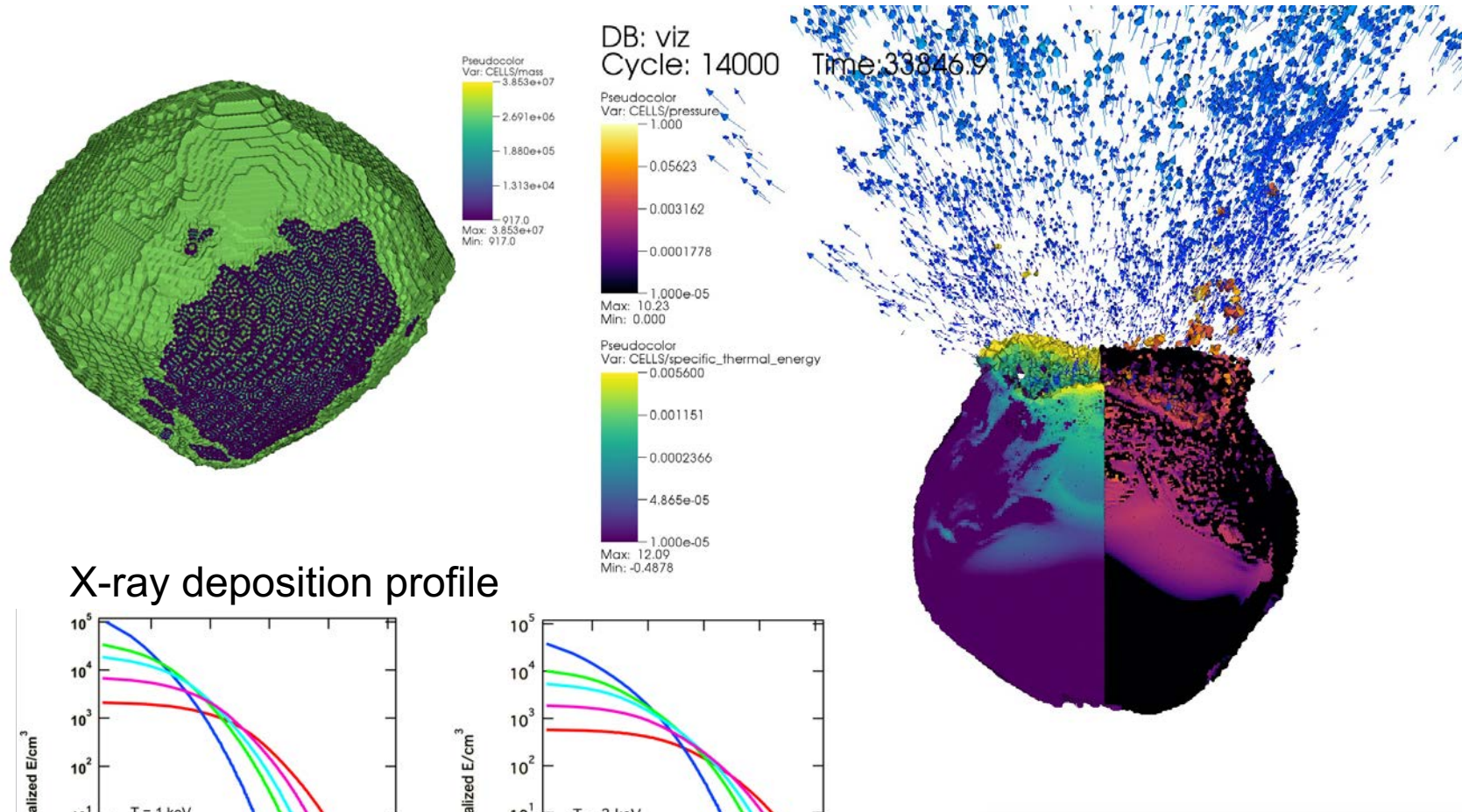
X-ray deposition profile
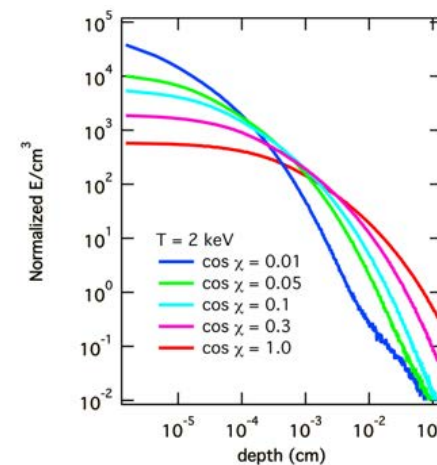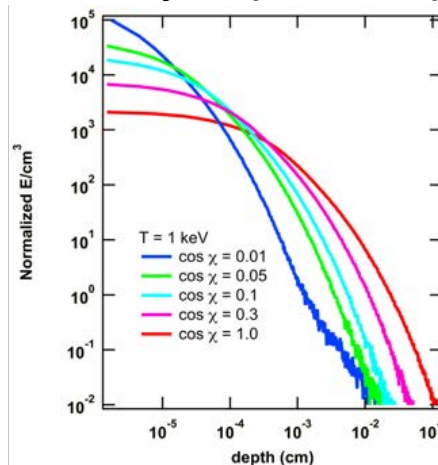
Nuclear Disruption of a Fiducial Small Body

- Simplified treatment of fragmentation: using bulk particles as estimate of disrupted debris field

- Delivered about 60 kT of yield to the target; about 4 kT of this was debris field kinetic energy (~0.35% KE yield efficiency)

- Kinetic Energy/Mass of ~17000 J/kg (much greater than Q^*_D)

- Center of mass velocity (a deflection) of 46.96 m/s

- COM frame expansion velocity (disruption) of 48.89 m/s

- Expansion field in COM frame is nearly uniform and radial

- Details to appear in King et al., submitted to Acta Astronautica
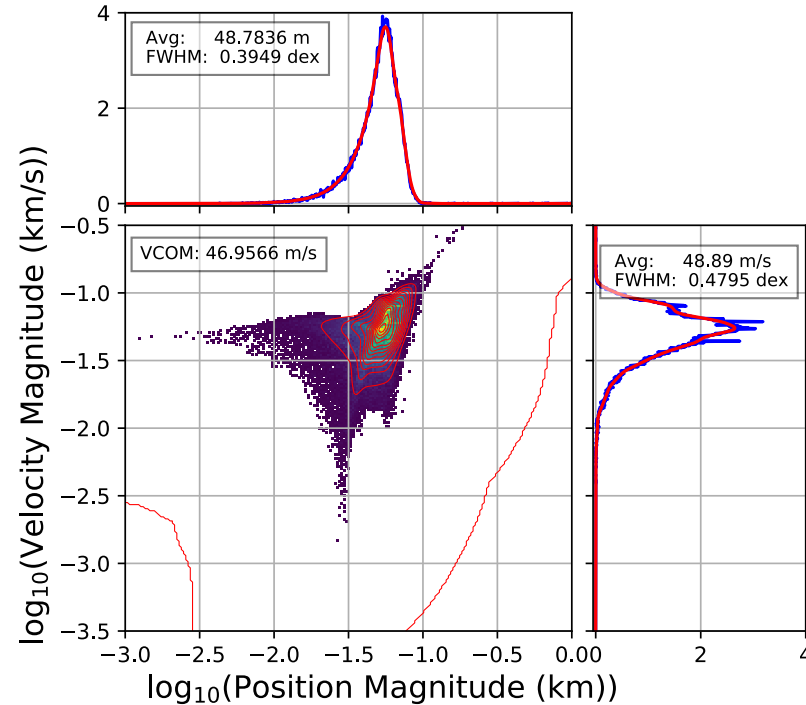
Calculated Deflection: 46.96 m/s
Calculated Disruption: 48.89 m/s
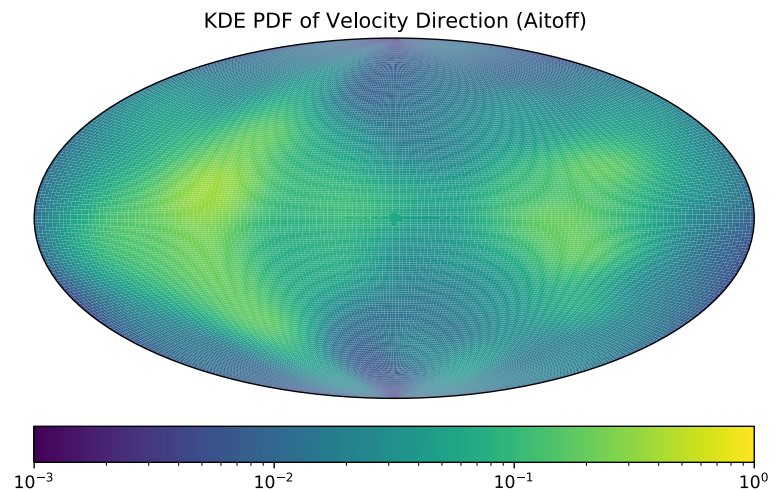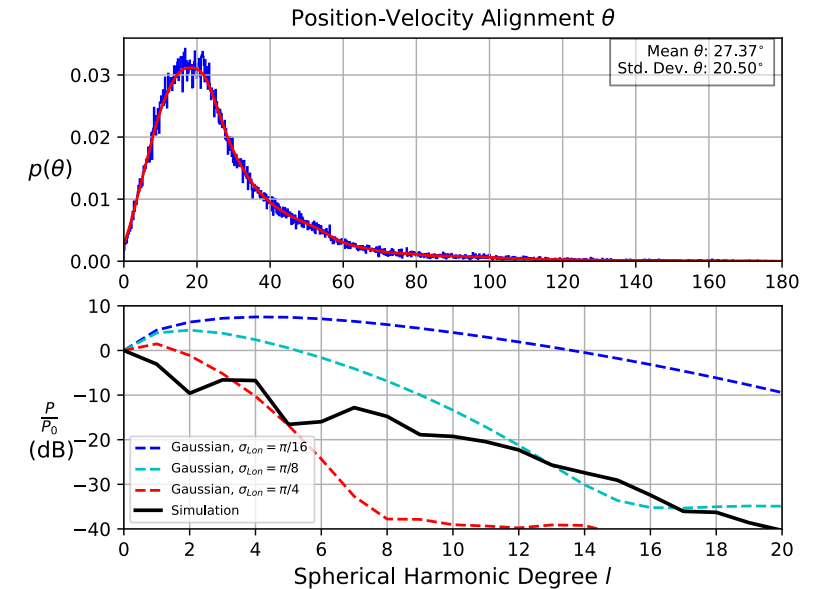
N-Body Methodology

- Approach is to insert an approximate fragment field directly into a realistic N-body model of the solar system and evolve fragment orbits

- Fragment field based on disruption simulation and consists of deflection and disruption components

- Softening is employed to ensure stability and speed; carefully controlled for accuracy bounds

- Care is taken to ensure the initial trajectory results in an impact

- Effects such as gravitational focusing included to orbital evolution accuracy

- Fragment-fragment gravity is included
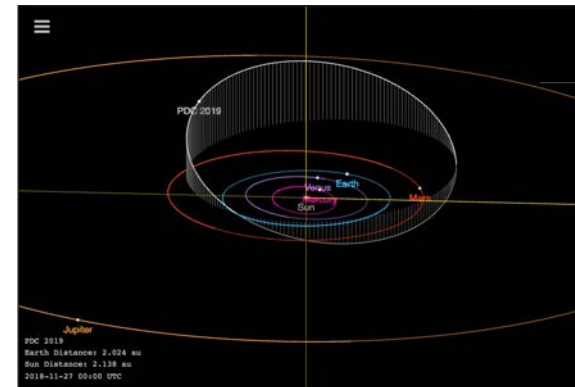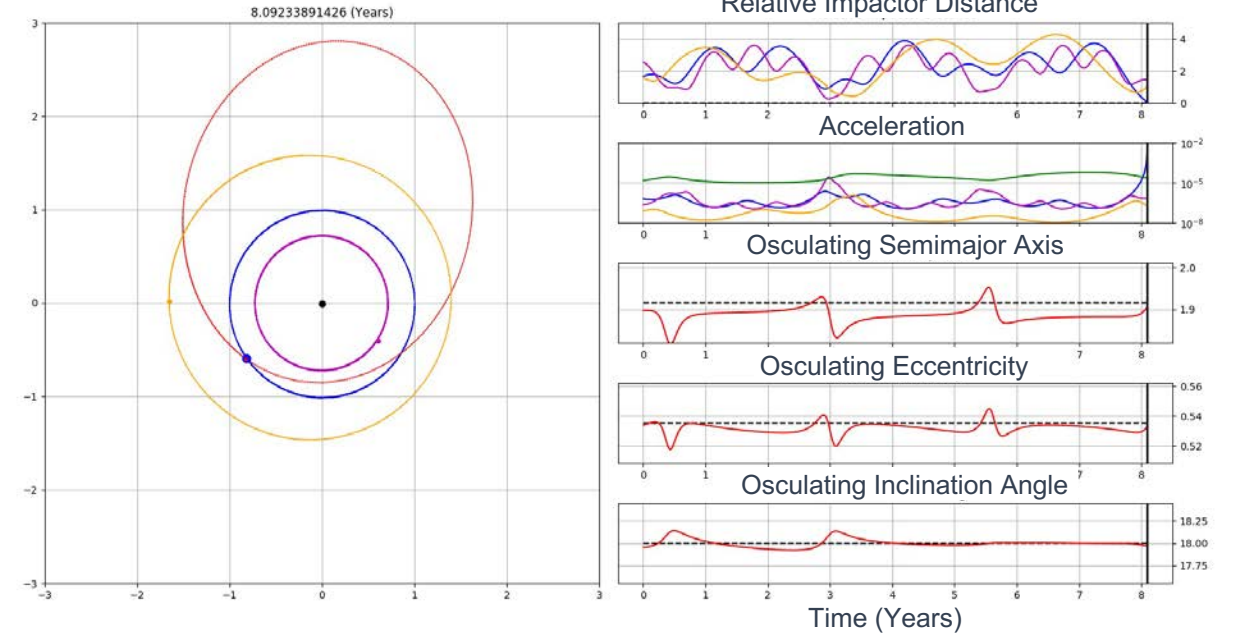
Example based on the 2019 PDC Scenario
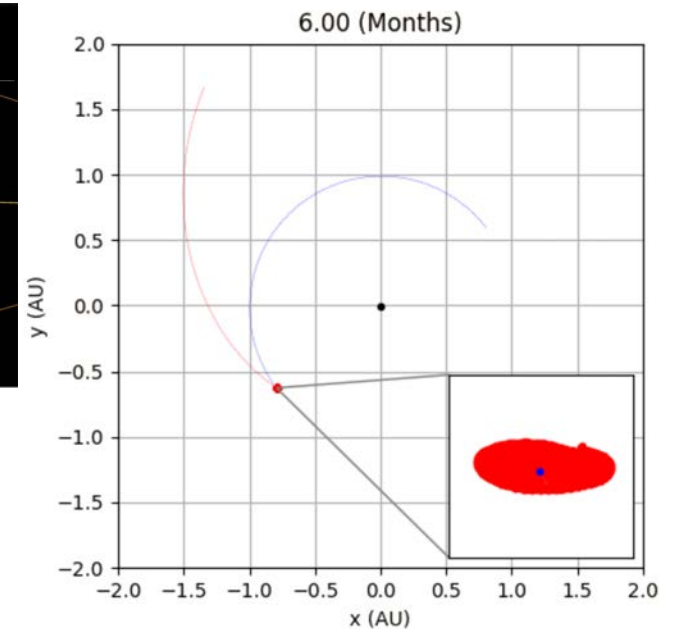
N-Body Methodology

- Can apply a naïve yield scaling to accommodate either different yields or uncertainty in target size

$$\frac{v_{scaled}}{v_{nominal}} = \left(\frac{Y}{1\ MT\ TNT}\right)^{1/2} \left(\frac{D}{100\ m}\right)^{-3/2}$$

- Study should be repeated with dedicated high-fidelity disruption simulation using best available target data

- Primary metric is the *impact fraction* (quantity of impacting mass relative to total mass)

- This study has been conducted for the PDC 2019 scenario and several other reasonable scenarios and is to appear in King et al., submitted to Acta Astronautica
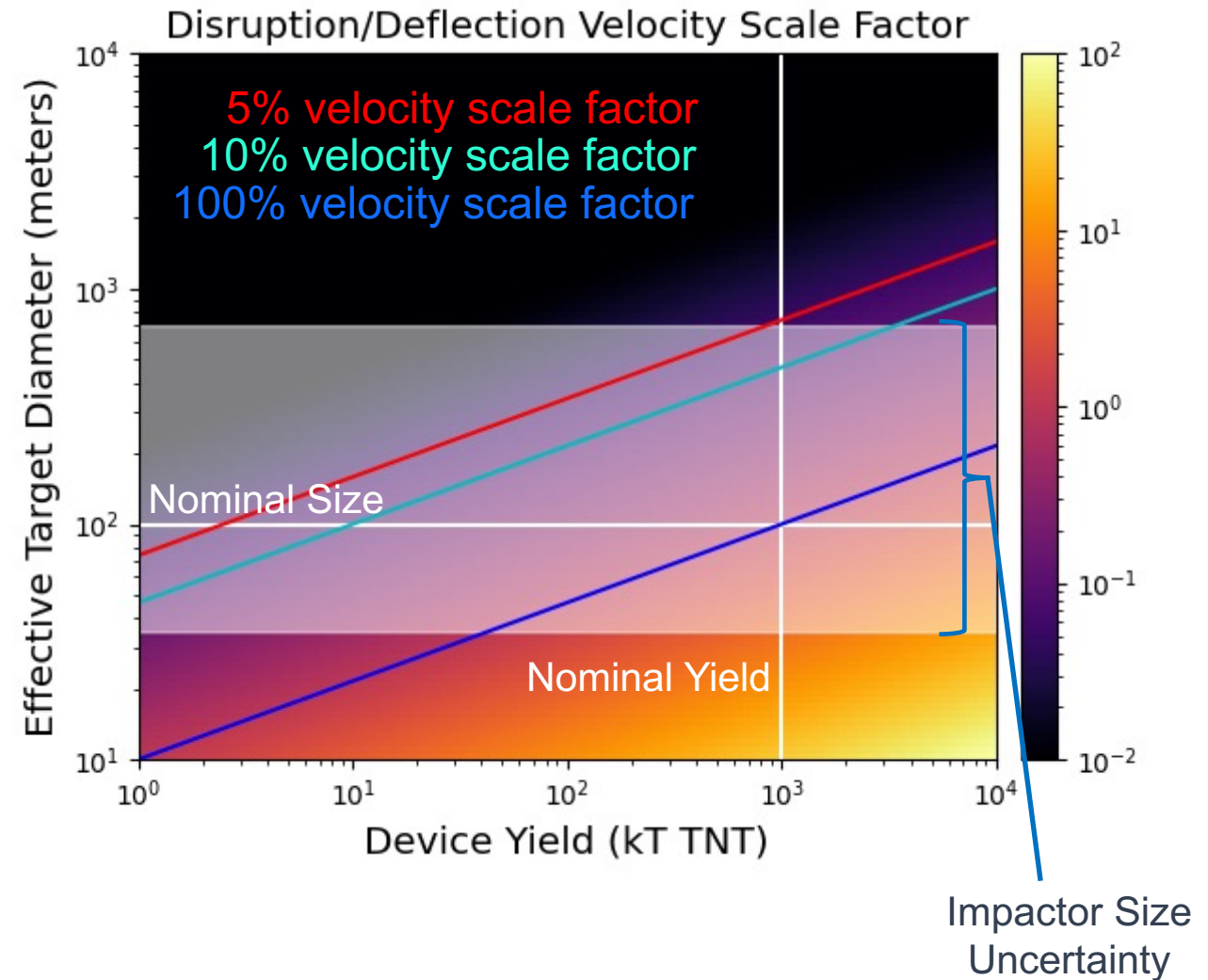
Results for the PDC 2021 Scenario

- The nominal disruption model can disrupt the impactor efficiently enough to result in only 1% impacting mass by two weeks
  - By 2 months the nominal disruption has likely achieved 0.1% impact fraction, but this estimate is limited by the fragment resolution of our simulations

- The less efficient disruptions require more time before impact to work effectively
  - The 10% scaled disruption achieves impact fraction of 10% by 2 months; 5% scaled disruption requires 3.5 months

- Deflection direction appears to have a modest effect; the strongest performing direction is the radial direction and the weakest is the ecliptic direction
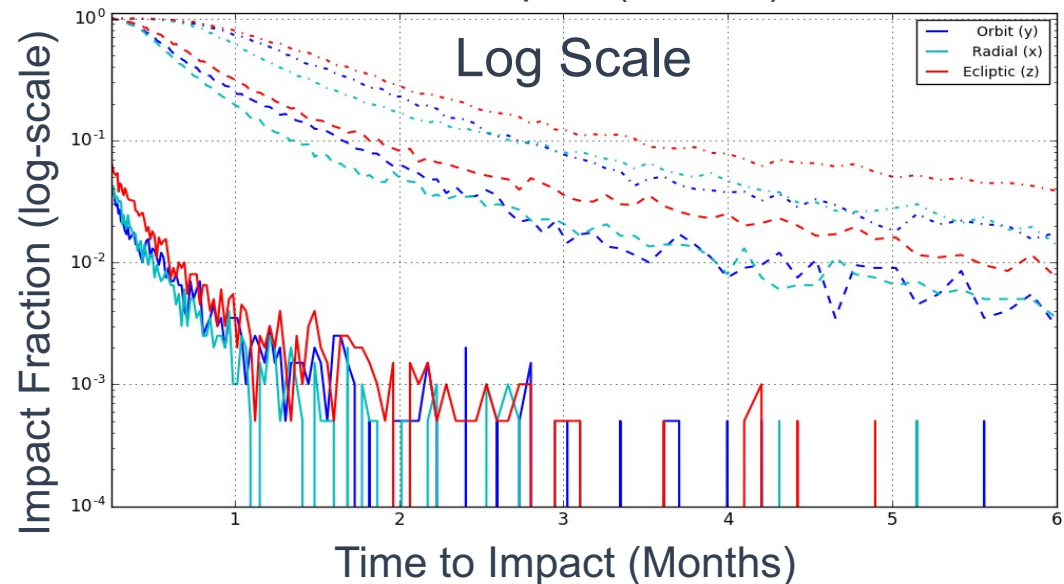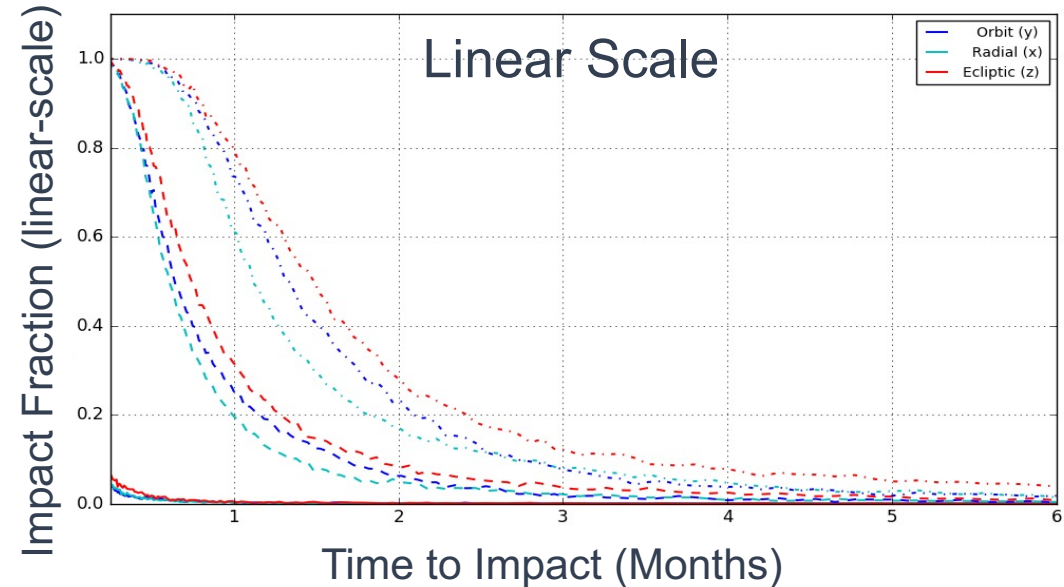
An Overview of Numerical Radiation Transport Techniques in Asteroid Deflection Modeling

Planetary Defense Conference 2021

April 28, 2021
Vienna, Austria

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Photon transport is necessary to accurately model deflection scenarios using x-ray deposition

- Inertial confinement fusion (ICF) and asteroid simulations share some commonalities and challenges
  - Both have large length, density, and opacity scales

  - Both model round things suspended in vacuum hit by x-rays
  - We can use the same code for both

- ICF codes discretize in space and time
  — Zones have ρ, T, P, radiation intensity, etc.
  — Energy deposition done by a radiation transport method
  — Hydrodynamic motion and shocks handled by a hydro method
  — Radiation and matter are coupled by thermal emission from material and electron and ion conduction

- Transport dominates the simulation run time
  - We face tradeoffs in the radiation methods between speed and accuracy

The transport equation describes the motion of photons including interactions with moving matter

Absorption (Doppler-shifted)

Thermal emission Doppler-shifted

$$\frac{1}{c}\frac{\partial I(\nu,\Omega)}{\partial t} + \Omega \cdot \nabla I(\nu,\Omega) = -\gamma D \sigma_a I(\nu,\Omega) + \sigma_a \frac{B[\nu,T]}{[\gamma D(\Omega)]^2}$$

Photons move in straight lines at speed c

In-scattering

$$+ \int_0^\infty d\nu' \int_{4\pi} d\Omega' \frac{\nu}{\nu'} \sigma_s(\nu' \to \nu, \Omega' \to \Omega) I(\nu',\Omega') \left[1 + \frac{c^2 I(\nu,\Omega)}{2h\nu^3}\right]$$

Out-scattering

$$- \int_0^\infty d\nu' \int_{4\pi} d\Omega' \sigma_s(\nu \to \nu', \Omega \to \Omega') I(\nu,\Omega) \left[1 + \frac{c^2 I(\nu',\Omega')}{2h\nu'^3}\right]$$

Stimulated scattering

with $\gamma \equiv \left(1 - \frac{v^2}{c^2}\right)^{-\frac{1}{2}}$ and $D \equiv 1 - \Omega \cdot \frac{v}{c}$ arising from material motion and $B(\nu,T) = \frac{2h\nu^3}{c^2}\left[\exp\left(\frac{h\nu}{kT}\right) - 1\right]^{-1}$ the Planck function describing thermal emission in Local Thermodynamic Equilibrium

- This is the Boltzmann equation written in terms of Intensity
  - *I* has units of Energy/(Length²-Time-Steradian)

- Material motion corrections (MMC) need to be included
  - Emission isn't isotropic, absorption is angle dependent
  - There are many O(v/c) MMC approximations; also many numerical simplifications are employed, some inaccurate

- Radiation exchanges energy and momentum with matter

The two common numerical methods for transport simulations are IMC and S_N

- Implicit Monte Carlo (IMC) simulates radiation by computational particles with randomly selected emission positions and directions
  - Emit, scatter, track, and absorb "fake" photons
  - "implicit" refers to a numerical extrapolation in time of the matter temperature used in emission
  - Allows accurate simulation of scattering and Doppler shifts
    — Energy-angle correlation in Compton scattering can be simulated
  - Use of random numbers causes statistical noise ~ $N_{particles}^{-1/2}$ in the results
    — Reducing the slowly-declining noise leads to long simulation times
    — Discretization errors in thermal emission, both temperature and emission location, require small Δx and Δt
    — Stimulated Compton is approximated or ignored

- S_N or Discrete Ordinates represents I at fixed angles using finite element basis functions in each zone
  - The discrete angles are selected to enable Gauss integration of spherical harmonics
  - Faster than IMC (>10x in opaque problems)
  - Fully implicit in emission temperature; smaller spatial discretization error
  - Can simulate stimulated Compton
  - The use of discrete angles makes anisotropic scattering approximate and can lead to simulation artifacts

Computational artifacts of IMC and S_N

- IMC simulation of radiation flux in an illuminated asteroid shows statistical noise

- The electron and ion conduction flux also shows noise, seeded by the IMC through its effect on the electron temperature
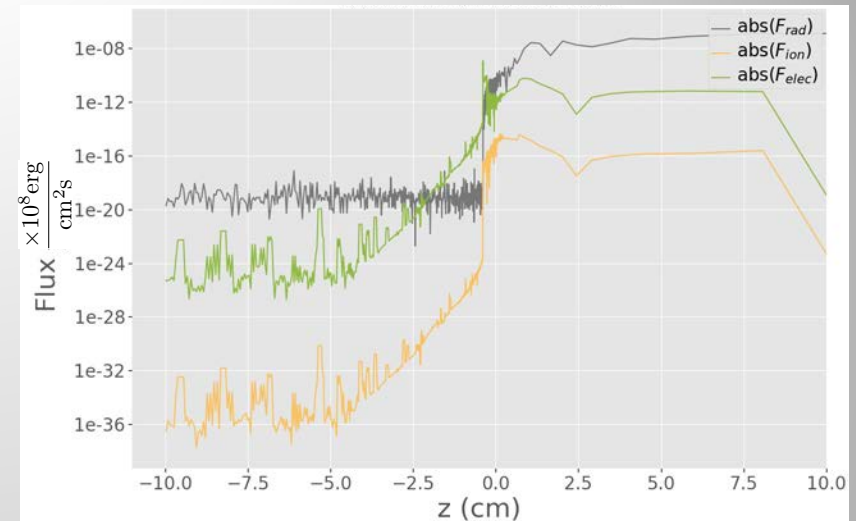
Simulation with an isotropic point source in an absorbing non-scattering medium

- IMC simulation (top) shows statistical noise

- S_N simulation shows ray effects
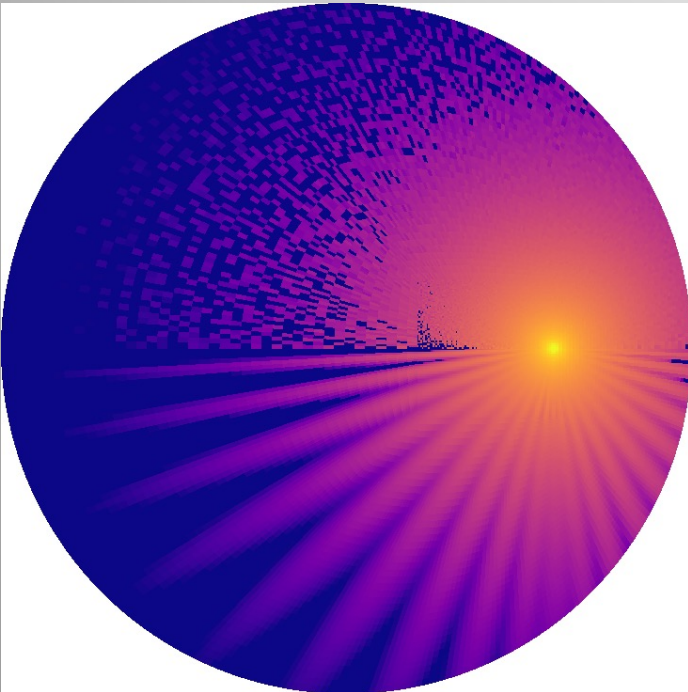
Flux-limited Diffusion is a quick but very approximate transport simulation technique

- Averaging the transport equation over angle plus an ansatz for the flux results in diffusion equation

Material motion correction terms

$$\frac{\partial E}{\partial t} + \nabla \cdot [-\mathcal{L}F] + \frac{4}{3}\nabla \cdot (Ev) + \frac{1}{3}v \cdot \nabla E = c\sigma aT^4 - c\sigma_a E$$

Here $E = -\frac{1}{c}\int_{4\pi} d\Omega I$ is the radiation energy density (Energy/Length^3) and

$$F = -\frac{c}{3(\sigma_a + \sigma_s)}\nabla E$$ is the radiation flux (Energy/Length^2-Time)

- This expression for F is <u>an approximation</u>

- Diffusion can't model angular information – no shadows

- Diffusion is accurate when radiation is isotropic AND gradients in E are small

  - Ad hoc flux limiter $\mathcal{L}$ in [0,1] needed to suppress superluminal energy flow (F > c ΔE) when σ is small

- For heat conduction in electrons and ions, which typically have small flux, a similar diffusion approximation is accurate

The Multigroup approximation is used to express frequency dependence of σ and I (or E)

- We pick O(10)-(100) fixed values of ν; each range is called a "group"
  - Group bounds are constant in time and space in a simulation
  - We solve one transport or diffusion equation per group
  - Scattering and absorption-reemission couple the groups and the per-group equations
    - This requires iteration in S_N and FLD

SiO_2 opacity $\rho = 2.65 \frac{g}{cm^3}$, $T = 1.723 \times 10^{-5}$

Lines can be represented with enough groups

Compton scattering > absorption at high ν
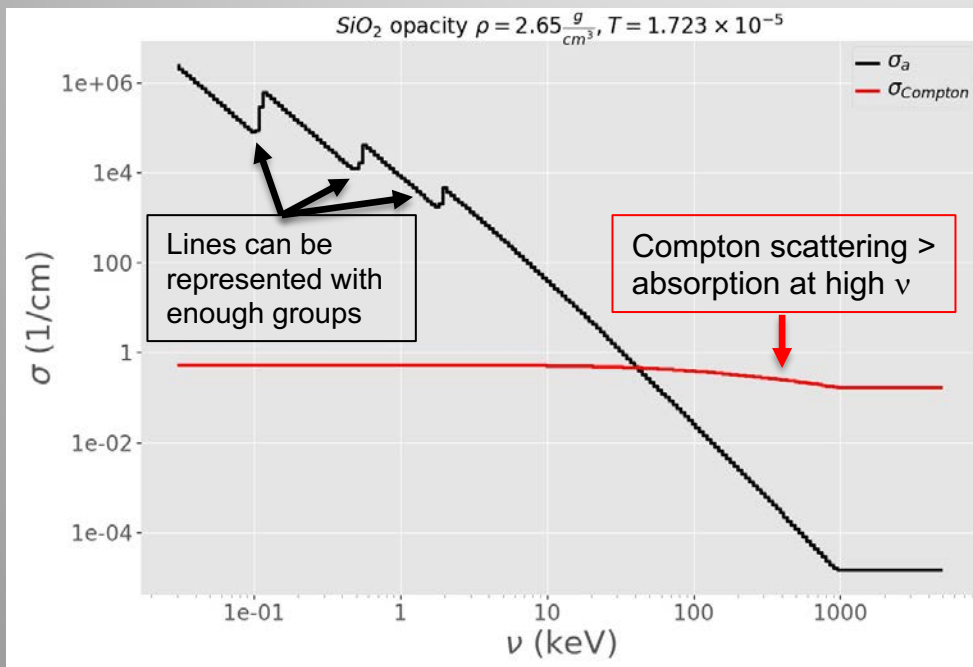
- Opacities are constant in each group during a time step
  - Recalculated in each group at the beginning of the time step to account for changes in ρ and T

We are using IMC in our deflection calculations because they contain vacuum and point sources

- ## Diffusion has poor accuracy in vacuum
  - It also can't simulate the directionality of a point source

- ## S_N suffers from ray effects in vacuum
  - Can't accurately model strongly peaked scattering like Compton

- ## IMC can simulate point and ray sources
  - We have to incur and mitigate the drawbacks:
    — Statistical noise
    — Long runtimes
    — Use lots of zones and time steps

We must use lots of particles and processors

1D simulations simulate surface absorption, reemission, and momentum transfer

- 1 sq. cm chunk ~ 60 cm deep
- Source equivalent to 1 kiloton 85 m away
  - Spectrum = 1 keV Planckian
- 200 groups in [3 x 10^{-3}, 1000] keV log-spaced
- Run to ~ 1e-4 sec
  - Δt in [10^{-16}, 10^{-9}] sec
- 2000 zones with Δx in [10^{-5},.4] cm
- 10^6 computational photons
- Materials = SiO2, Fe, H_2O, Fosterite
- Simulations take ~ 1 Day on 144 2.1 MHz procs
- Hydrodynamics is Lagrangian
  - Mesh moves with the material

Finely zoned asteroid material

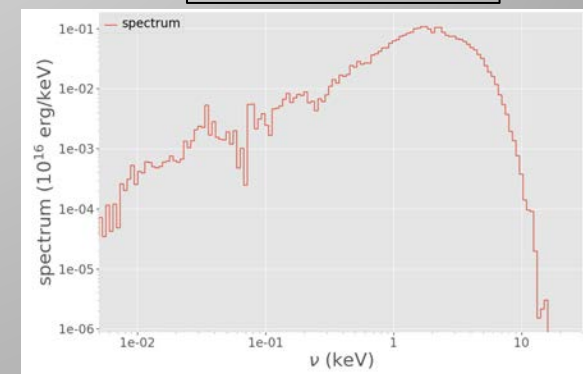Computational photons are created moving parallel on vacuum face
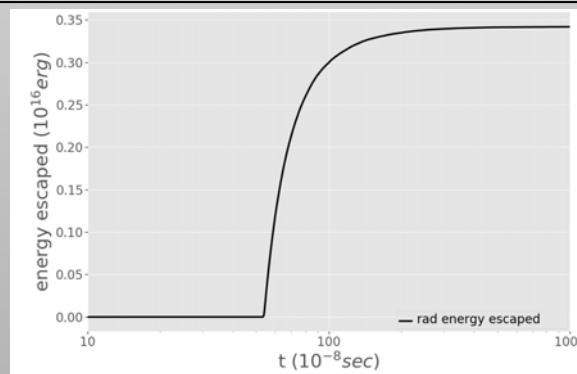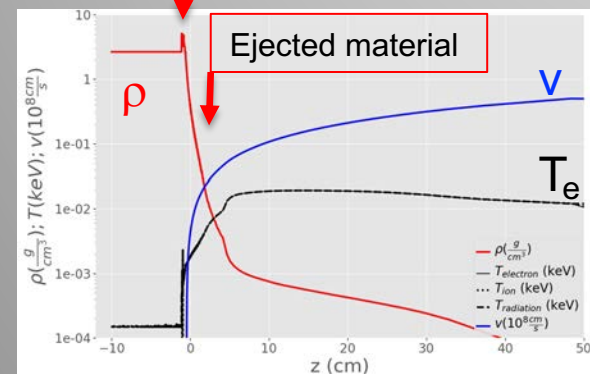
1 large vacuum zone
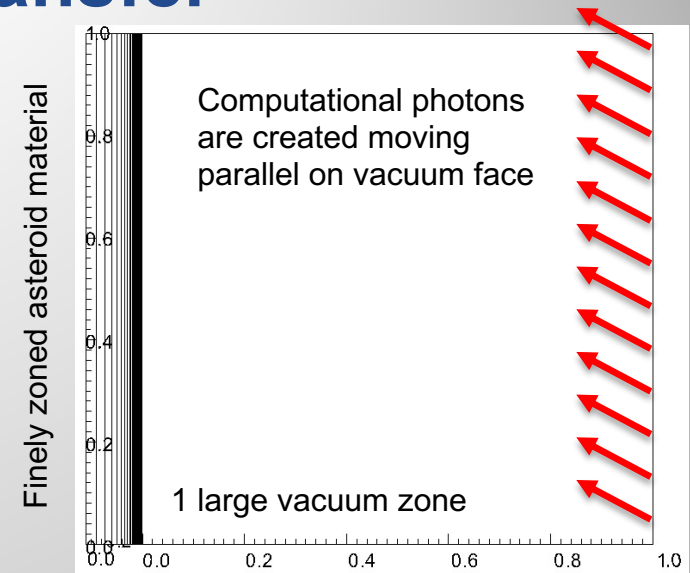
Ingoing shock

Ejected material

Energy escaping through asteroid surface

Escaping spectrum

2D simulations provide more realistic exploration of deposition as a function of angle

T_r showing reradiated photons

T_e of matter in asteroid surface

Source photons
- The computational photons have exact positions on a spherical shell
- The jaggedness is an artifact of the coarse vacuum zoning

Reradiated photons From asteroid
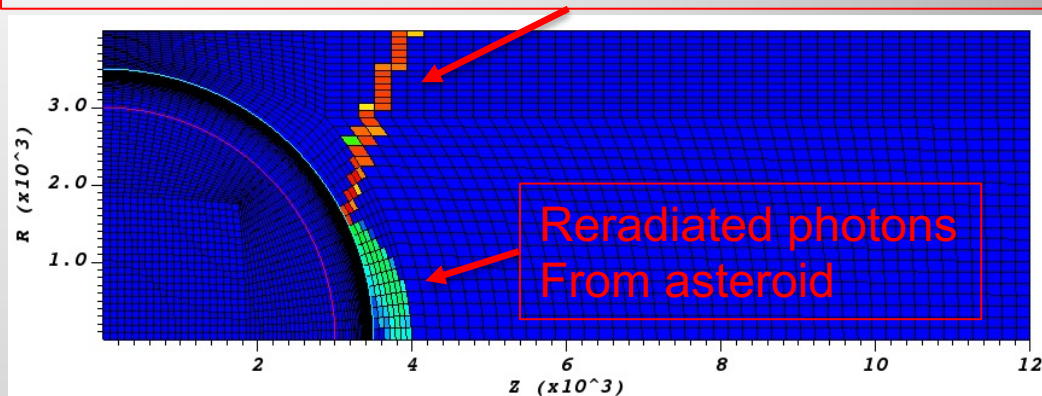
- ½ of 35 m asteroid on an axisymmetric mesh
- Source is 1 kiloton, 85 m from surface
  - Spectrum = 1 keV Planckian
- 200 groups in [3 x 10^{-3}, 1000] keV log-spaced
- 20719 zones; sizes in [10^{-6}, 100] cm
- 10^8 computational photons
- Materials = SiO2, Fe, H_2O, Forsterite
- Simulations take ~ 1 Week on 144 2.1 MHz procs
- Hydrodynamics is Lagrangian
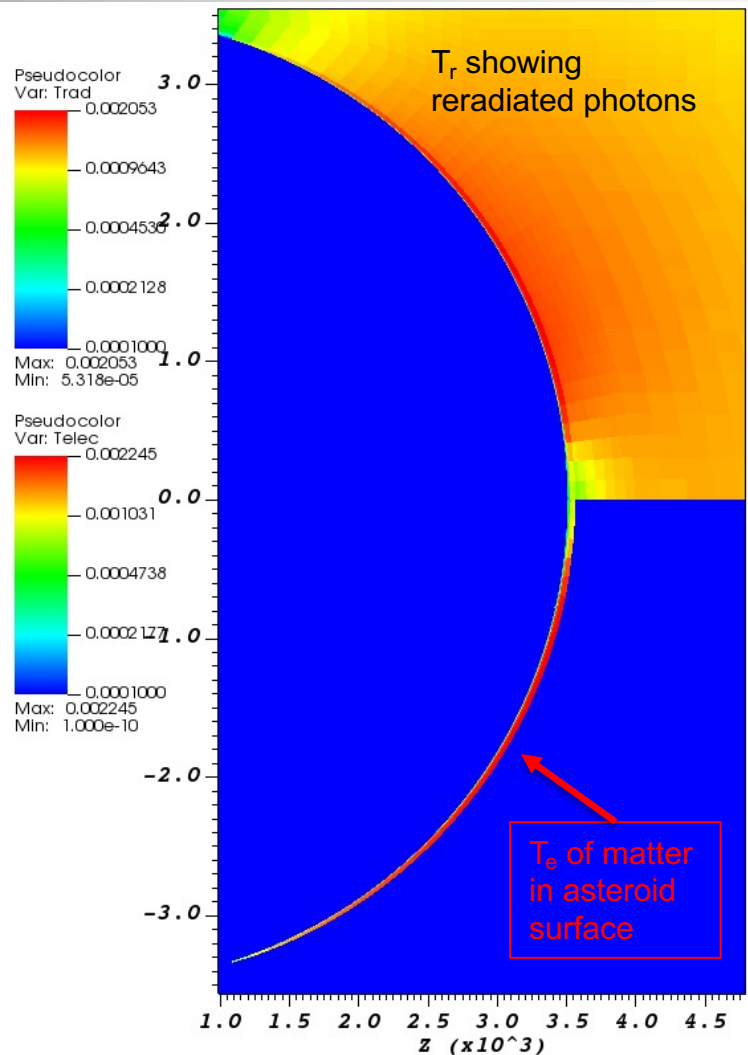 - Mesh moves with the material

Radiation hydrodynamics simulations using IMC will contribute to asteroid deflection modeling

- We are currently running radiation hydrodynamics calculations in 1 and 2D

  - These expensive calculations model absorption and reemission, shock physics, and asteroid momentum

- These simulations allow us to characterize energy deposition with relevant physics

- We are investigating whether we can use that deposition in hydro-only calculations and still obtain accurate results for momentum coupling

  - These simulations ignore radiation transport but are much faster

A derivation of FLD with MMC

1) $\dfrac{\partial E_L}{\partial t} + \dfrac{\partial F_{L,i}}{\partial x_i} = c\sigma_a a T^4 - c\sigma_a E_F - \sigma_t \dfrac{v_i}{c} F_{F,i}$

Energy conservation in lab frame: $\nabla_a T^{a0}_{rad} = g^0_L$ with $g^0_L = g^0_F + v_i g^i_F$, $g^0_F = c\sigma_a a T^4 - c\sigma_a E_F$ and $g^i_F = -\frac{1}{c}\sigma_t F^i_F$ [See [2], Eqs.(6.31)—(6.38)]

2) $E_L = E_F + 2\dfrac{v_i}{c^2} F_{F,i} \approx E_F$ since we will drop $\frac{1}{c}\frac{\partial F_F}{\partial t}$

$F_{L,i} = F_{F,i} + v_i E_F + v_j P_{F,ij} + O(\dfrac{v}{c})$

Express lab frame radiation quantities in fluid frame to O(v/c) via Lorentz transformation [2] Eq.(6.30)

3) $P_{F\ ij} \equiv \dfrac{1}{c}\displaystyle\int_{4\pi} I_F \Omega_i \Omega_j\, d\Omega \approx \dfrac{1}{3} E_F \delta_{ij}$ assuming $I_F = \dfrac{1}{4\pi}\left(cE_F + \Omega_F \cdot F_F\right)$ I_F is weakly anisotropic

4) $F_F = -\mathcal{L}c\dfrac{1}{3\sigma_t}\dfrac{\partial E_F}{\partial x_{F,i}} \approx -\mathcal{L}c\dfrac{1}{3\sigma_t}\dfrac{\partial E_F}{\partial x_i}$

Flux ansatz in fluid frame and $\frac{\partial}{\partial x_{F,i}} = \frac{\partial}{\partial x_i} + \frac{v_i}{c^2}\frac{\partial}{\partial t}$ with $\mathcal{L} \in [0,1]$ the flux limiter, used in $\frac{\partial F_{L,i}}{\partial x_i}$ term

5) $F_{F,i} = -c\dfrac{1}{3\sigma}\dfrac{\partial E}{\partial x_i}$

Inconsistent !

Flux ansatz in fluid frame without the flux limiter, used in $\sigma_t \dfrac{v_i}{c} F_{F,i}$ term

Steps 1-5 finally yield the standard form of the diffusion equation with MMC

$$\dfrac{DE}{Dt} - \dfrac{\partial}{\partial x_i}\mathcal{L}\dfrac{1}{3\sigma_t}\dfrac{\partial E}{\partial x_i} + \dfrac{4}{3}E\dfrac{\partial v_i}{\partial x_i} = c\sigma a T^4 - c\sigma_a E$$

Eq.(11.9) in [2], Eq.(7.18) in [6]

References

- [1] G.C. Pomraning, *Equations of Radiation Hydrodynamics*, in: D. ter Harr (Ed.), International Series of Monographs in Natural Philosophy, vol. 54, Pergamon, New York, 1973.

- [2] J.I. Castor, *Radiation Hydrodynamics*, Cambridge University Press, New York, 2007

- [3] Mihalas and Weibel-Mihalas, *Foundations of Radiation Hydrodynamics*, Oxford University Press, Oxford, 1984.

- [4] J. R. Buchler, Radiation Transfer in the Fluid Frame, JQSRT 30 No.5 (1983) 395–407.

- [5] R. B. Lowrie, D. Mihalas, J. E. Morel, Comoving-frame radiation transport for nonrelativistic fluid velocities, JQSRT 69 (2001) 291–304.

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Q&A

Session 7a: Deflection & Disruption Testing