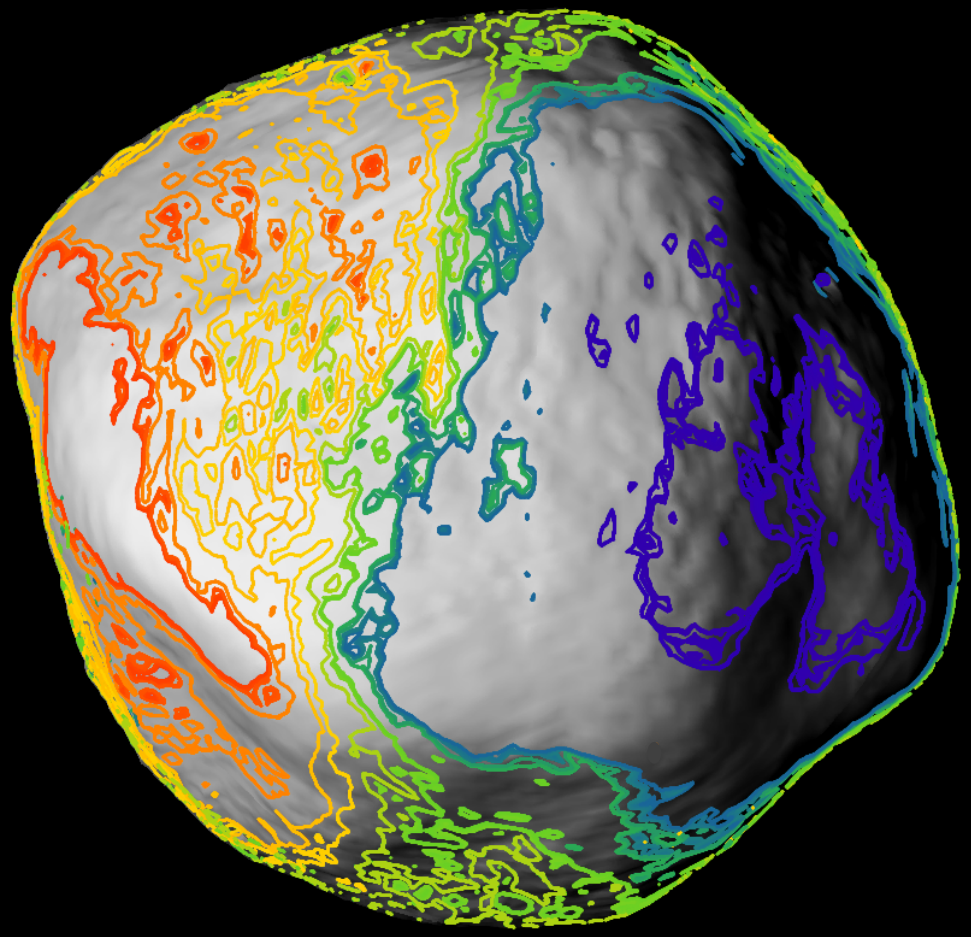


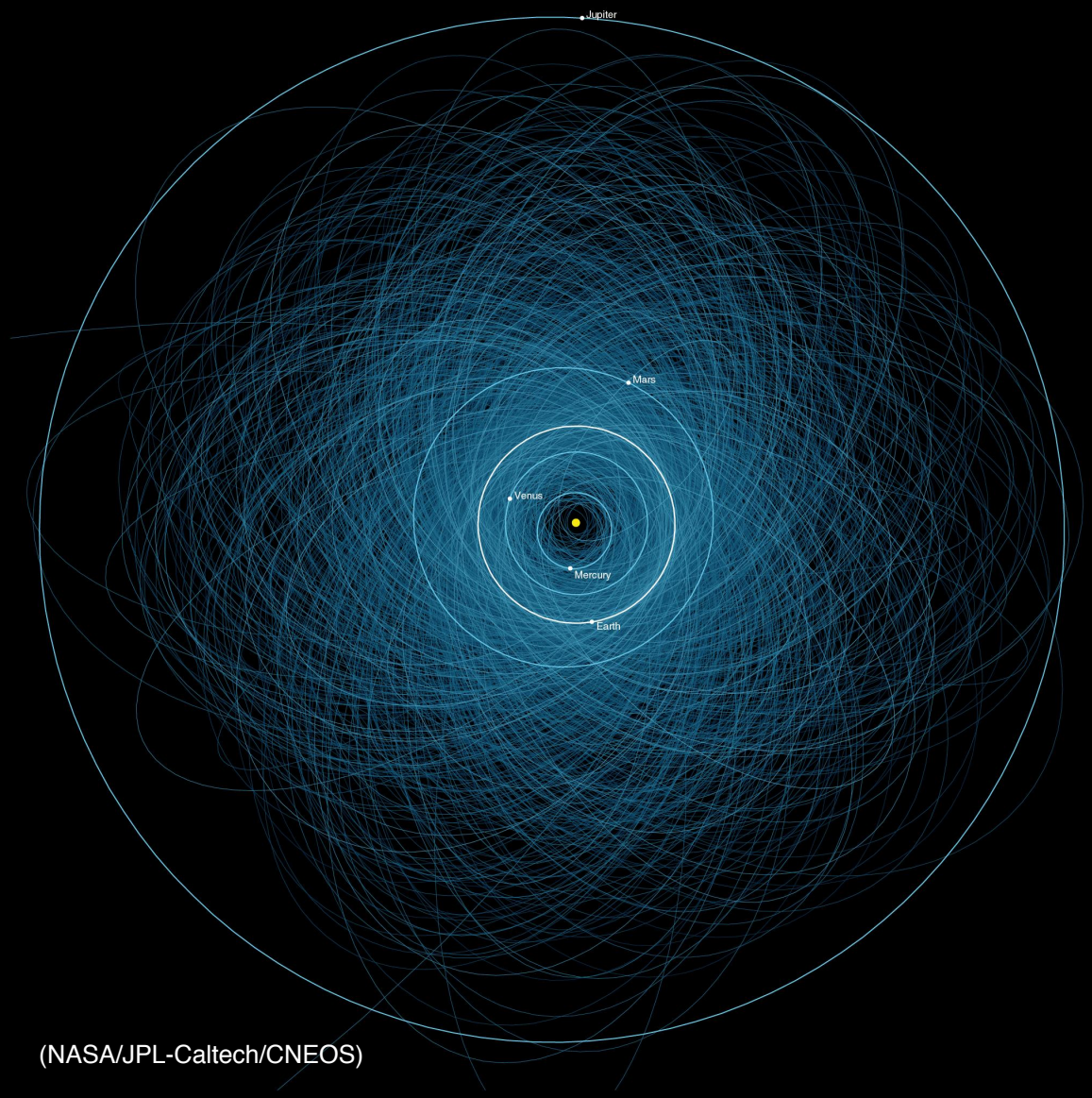
Avoiding Armageddon:

Long Term Asteroid Orbit Deflection Optimization

Siegfried Eggl, Davide Farnocchia,
Steven R. Chesley and Paul Chodas

Jet Propulsion Laboratory
California Institute of Technology

near-Earth asteroids



(NASA/JPL-Caltech/CNEOS)

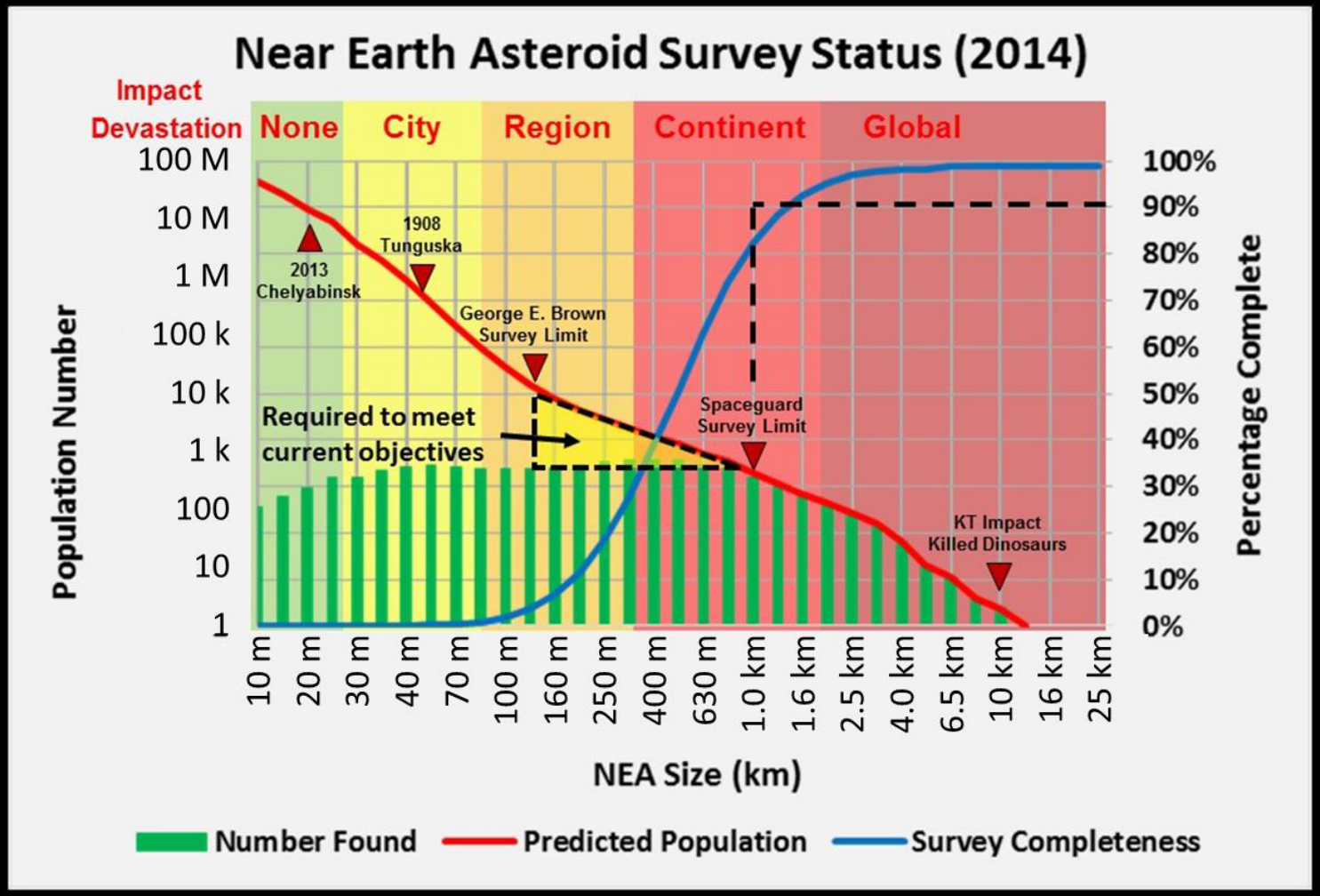
16983 NEAs

7883 > 140m

1845 PHAs

as of 10/29/2017

http://cneos.jpl.nasa.gov



(NATIONAL NEAR-EARTH OBJECT PREPAREDNESS STRATEGY, DAMIEN, 2016)

Sentry: Earth Impact Monitoring

http://CNEOS.JPL.NASA.GOV

Introduction | Object Table | VI Table | FAQ | Operational Notes | Removed Objects

Impact Risk Data

The following table summarizes by object the potential future Earth impact events that the JPL Sentry System has detected based on currently available observations. Click on the object designation to go to a page with full details on that object.

Sentry is a highly automated collision monitoring system that continually scans the most current asteroid catalog for possibilities of future impact with Earth over the next 100 years. Whenever a potential impact is detected it will be analyzed and the results immediately published here, except in unusual cases where we seek independent confirmation. It is normal that, as additional observations become available, objects will disappear from this table whenever there are no longer any potential impact detections. For this reason we maintain a list of removed objects with the date of removal.

Table Settings: [Use Unconstrained Settings] [Use Defaults]

Observed anytime | Any Impact probability | Palermo scale >= -6 | H <= 24

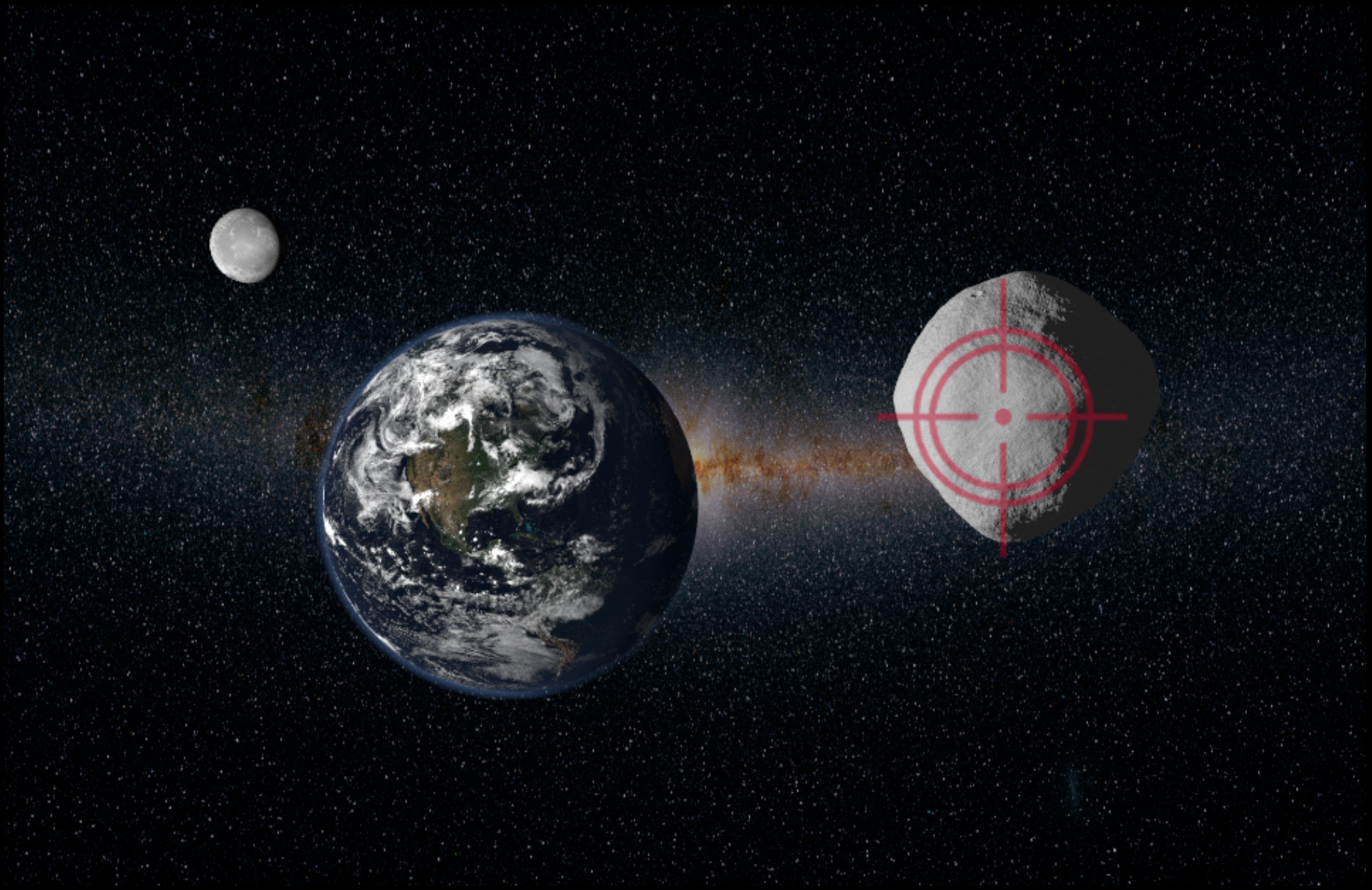
Show 100 entries

Showing 1 to 73 of 73 entries

Search: Object Designation

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.)
410777 (2009 FD)	2185-2198	7	1.6e-3	15.87	22.1	0.160	-1.78	-1.83	
101955 Bennu (1999 RQ36)	2175-2199	78	3.7e-4	5.99	20.2	0.490	-1.71	-2.32	
29075 (1950 DA)	2880-2880	1	1.2e-4	14.10	17.6	1.300	-1.42	-1.42	
(2008 EX5)	2061-2090	16	4.7e-5	9.92	23.8	0.059	-3.88	-4.16	0
(2008 UB7)	2044-2100	33	3.5e-5	18.51	23.9	0.058	-3.71	-4.31	0
(2017 PL26)	2083-2114	54	2.6e-5	8.70	22.2	0.120	-3.58	-4.37	0
(2015 RN35)	2065-2116	11	1.4e-5	5.72	23.0	0.085	-4.17	-4.38	0
99942 Apophis (2004 MN4)	2060-2105	12	8.9e-6	5.85	19.1	0.370	-2.83	-2.93	0
(2007 WP3)	2098-2114	17	7.7e-6	13.03	23.5	0.067	-4.62	-4.99	0

What if…?



What if…?

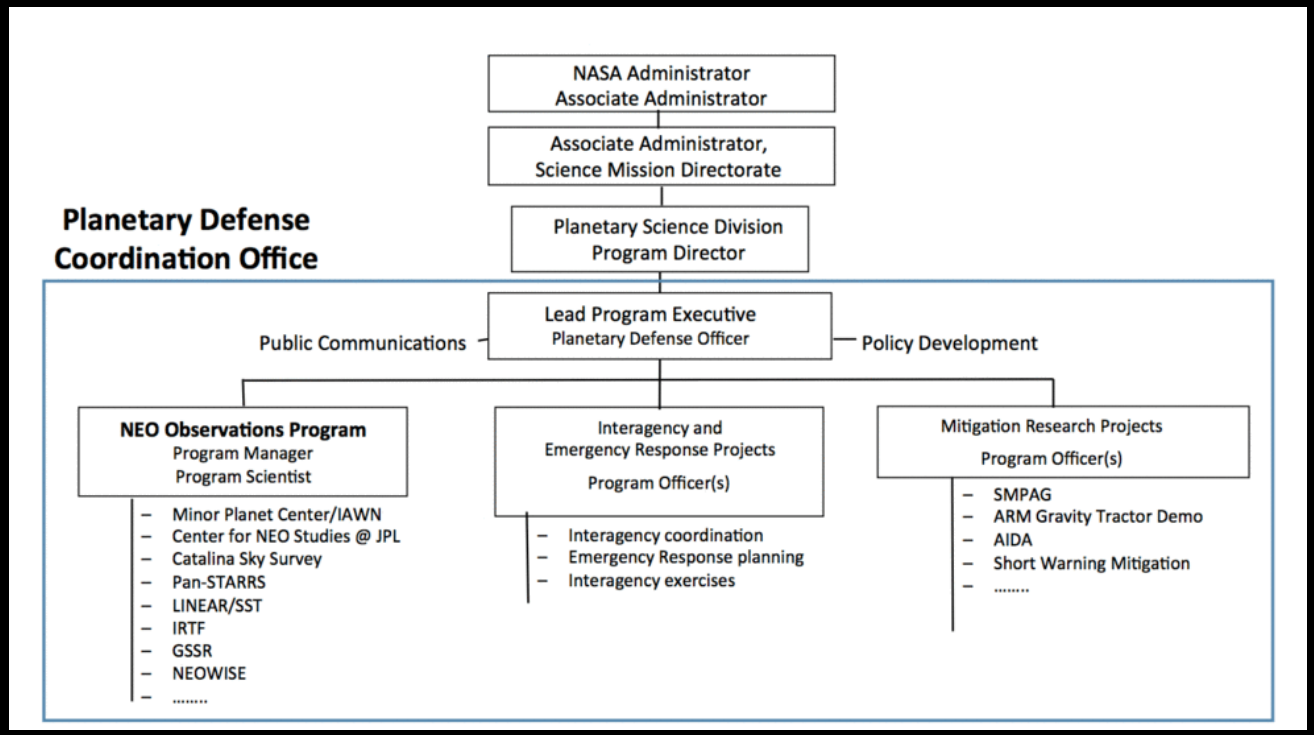
international

UNITED NATIONS

IAWN
International Asteroid Warning Network

SMPAG
Space Mission Planning Advisory group

national



NEO deflection strategies

NEO size

m

km

- Gravity tractor
- Laser ablation
- Ion beam shepherds
- Kinetic Impactors
- Nuclear ablation

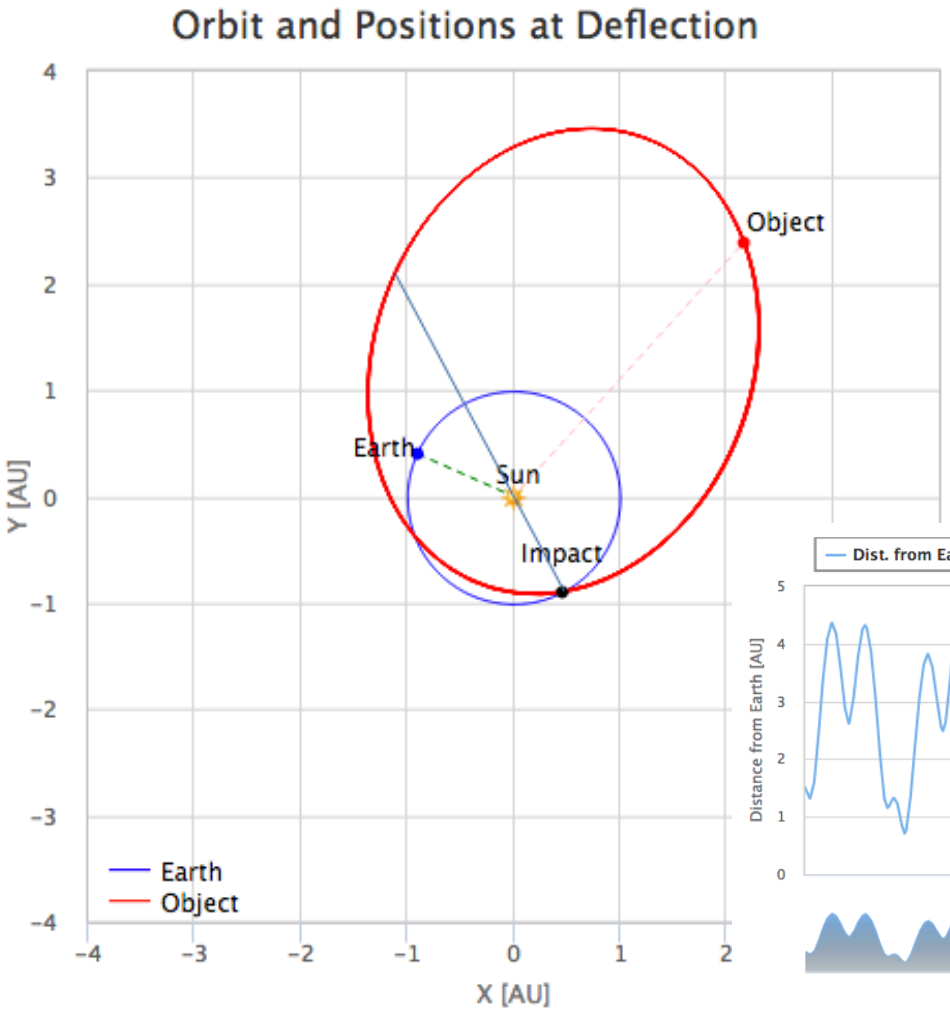
Warning Time

NEO deflection strategies

- Gravity tractor
- Laser ablation
- Ion beam shepherds
- Kinetic Impactors
- Nuclear ablation

(e.g. Thiry & Vasile 2017)

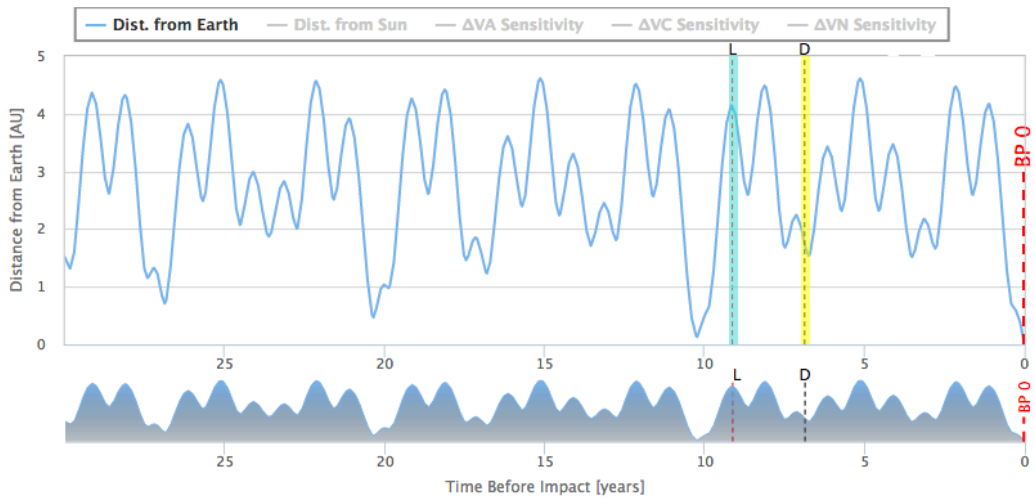
NEO deflection strategies



NASA/JPL NEO Deflection App

(https://cneos.jpl.nasa.gov/nda/nda.html)

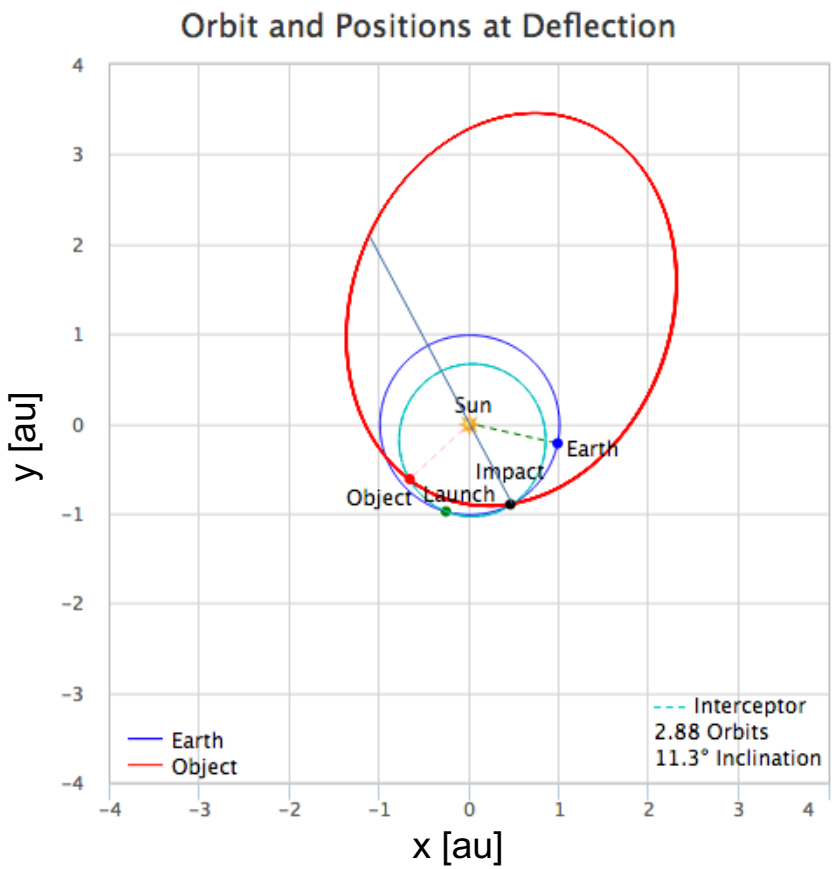
hypothetical Earth-impacting asteroid

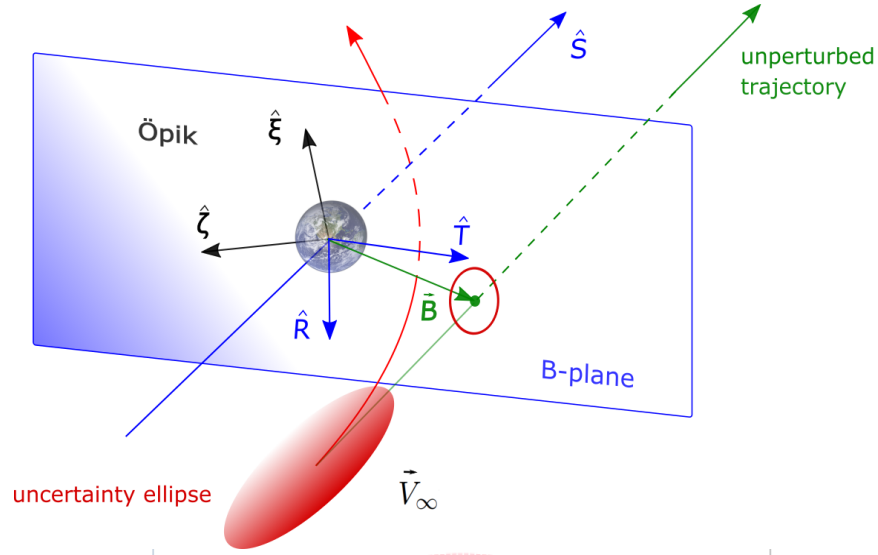


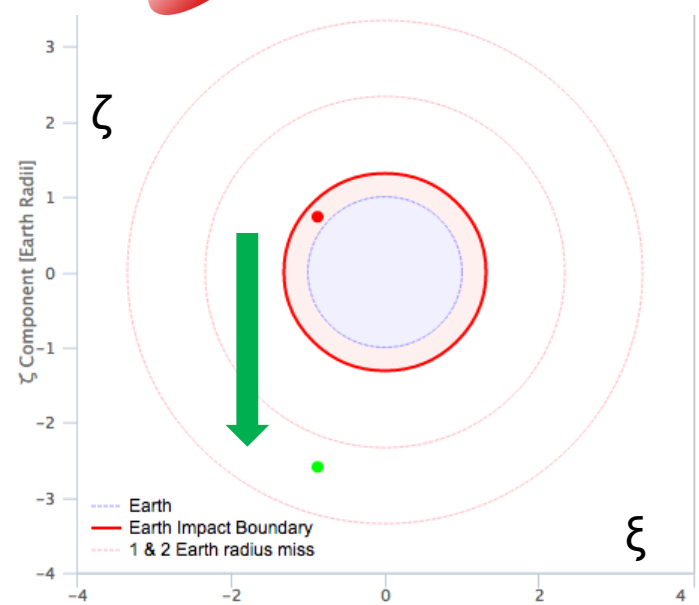
NEO deflection strategies

hypothetical Earth-impacting asteroid

(https://cneos.jpl.nasa.gov/)







Uncertainties…

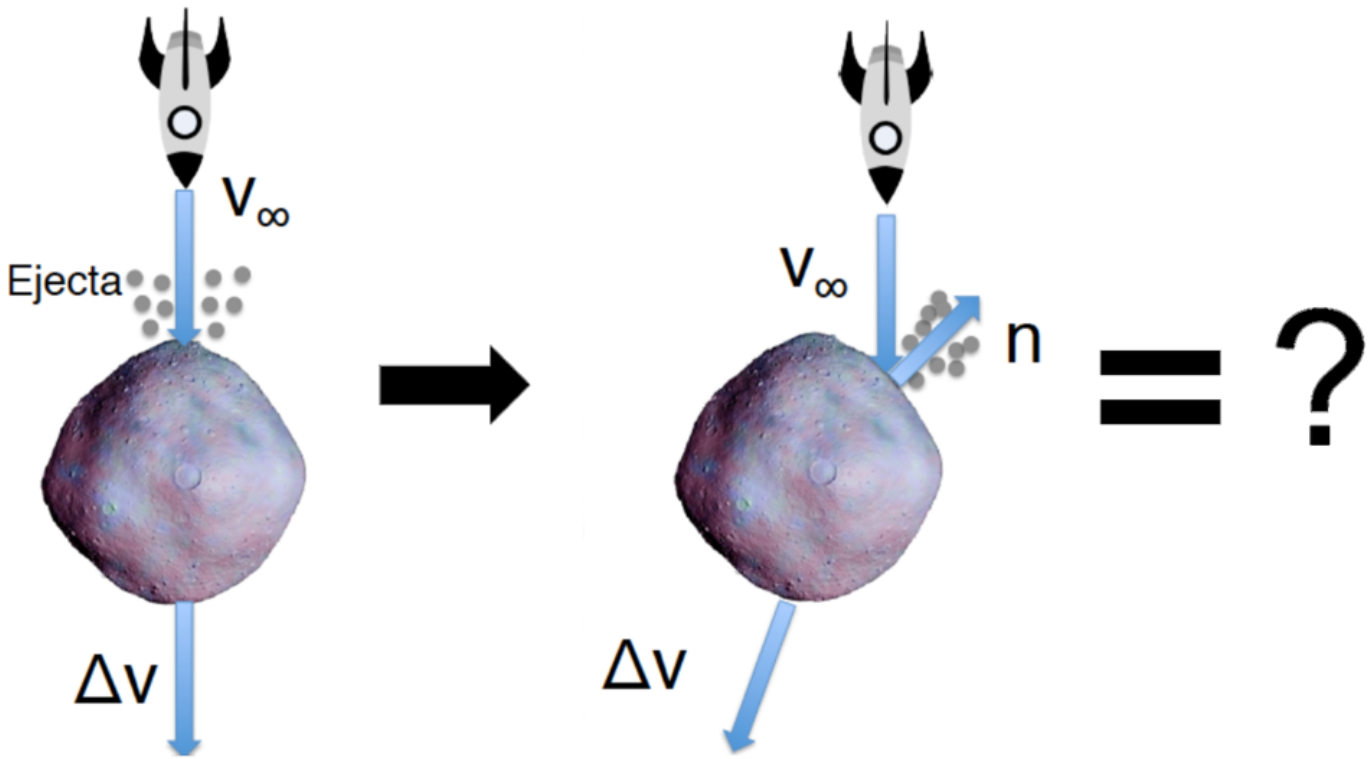
a) NEO properties (mass, shape, spin, β, orbit)

b) mission related (e.g. stand off distance, GNC)

c) modeling (deflection prediction, ephemeris)

Probabilistic description of asteroid deflection
(e.g. Eggl et al. 2015)

Orbit Deflection Uncertainties



$$\Delta\vec{V} \approx \frac{m}{M}\left[\vec{v}_\infty + \vec{\beta}\right], \qquad \vec{\beta} = (\beta - 1)\,(\vec{n}\cdot\vec{v}_\infty)\,\vec{n}$$

Orbit Deflection Uncertainties

$$\Delta\vec{V} \approx \frac{m}{M}[\mathcal{I} - (\beta - 1)\hat{n}\hat{n}]\Delta\vec{v}$$

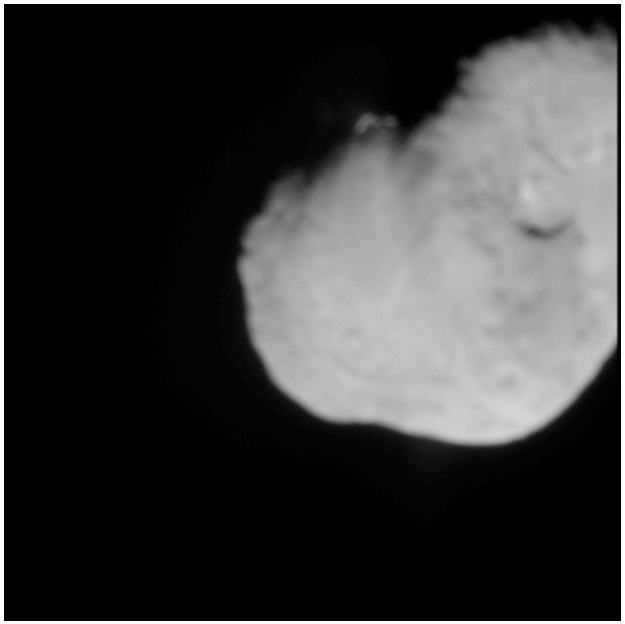
10% 100% ?

uncertain parameters

$$\beta = 1 + p_{ej}/(M_p v_p)$$

Momentum enhancement
Jutzi & Michel (2014)

$$1 \leqq \beta \leqq 3$$



(Image: Deep impact mission, NASA)

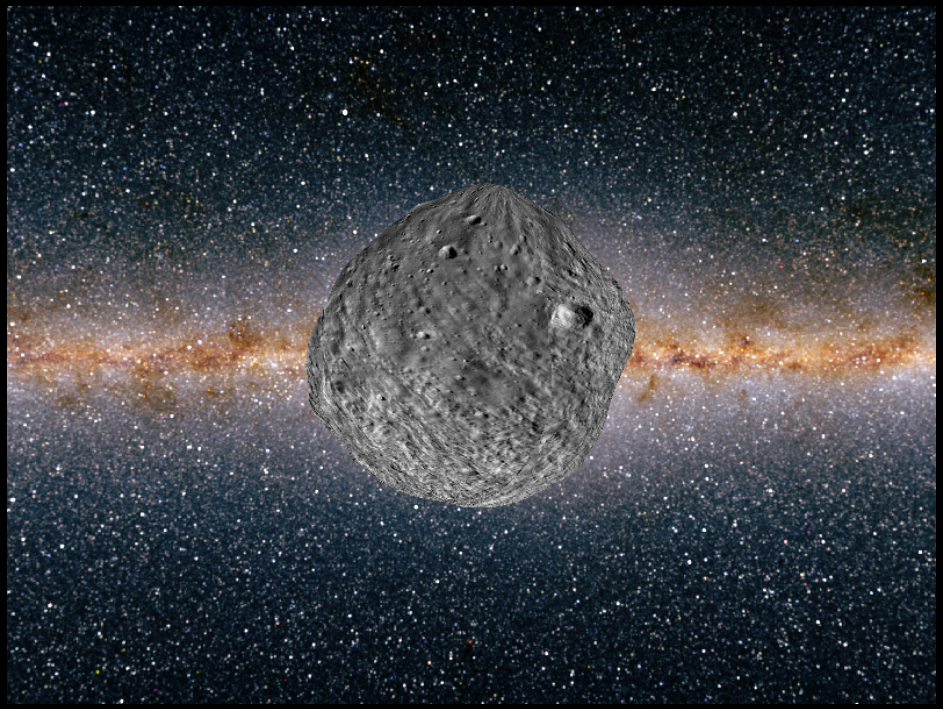
Uncertainties…

- need to be accounted for in orbit deflection
- weaken post deflection orbit predictions

⬇

Post Deflection Impact Risk Assessment

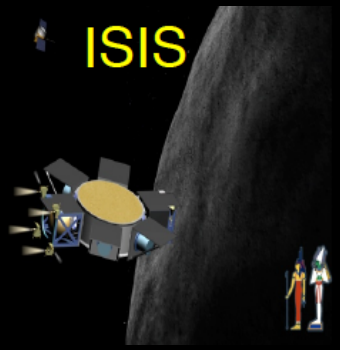
(101955) Bennu



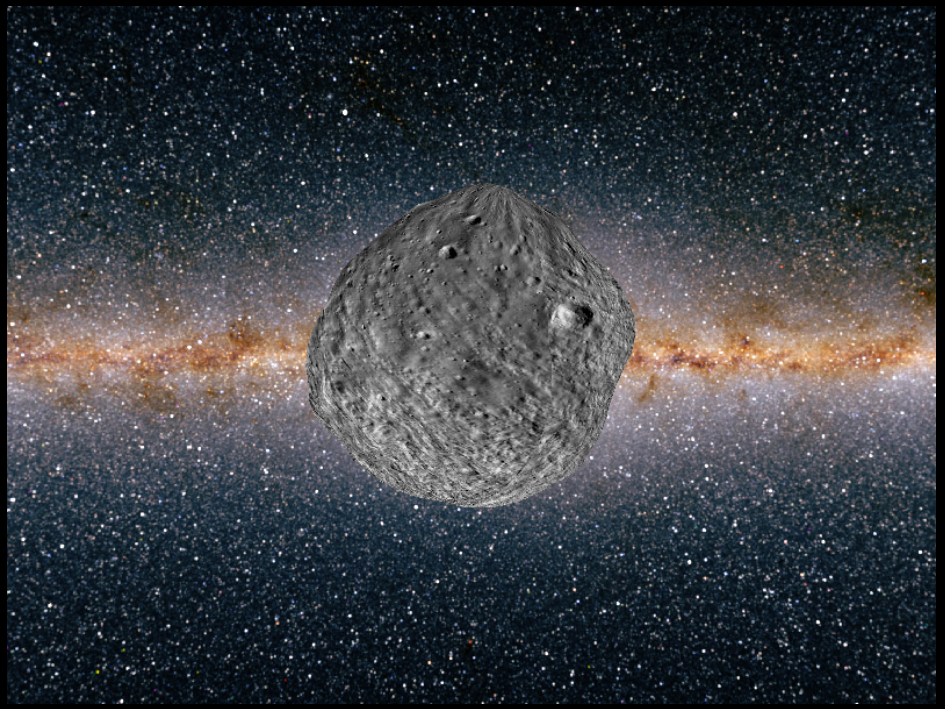
Near Earth Object (Apollo)

D ~	490 m
H ~	20 mag
P_{rot} ~	4.3 h
ρ ~	1.3 g/cm^3

Kinetic Impactor concept



(101955) Bennu



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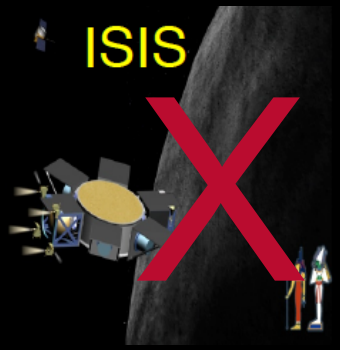
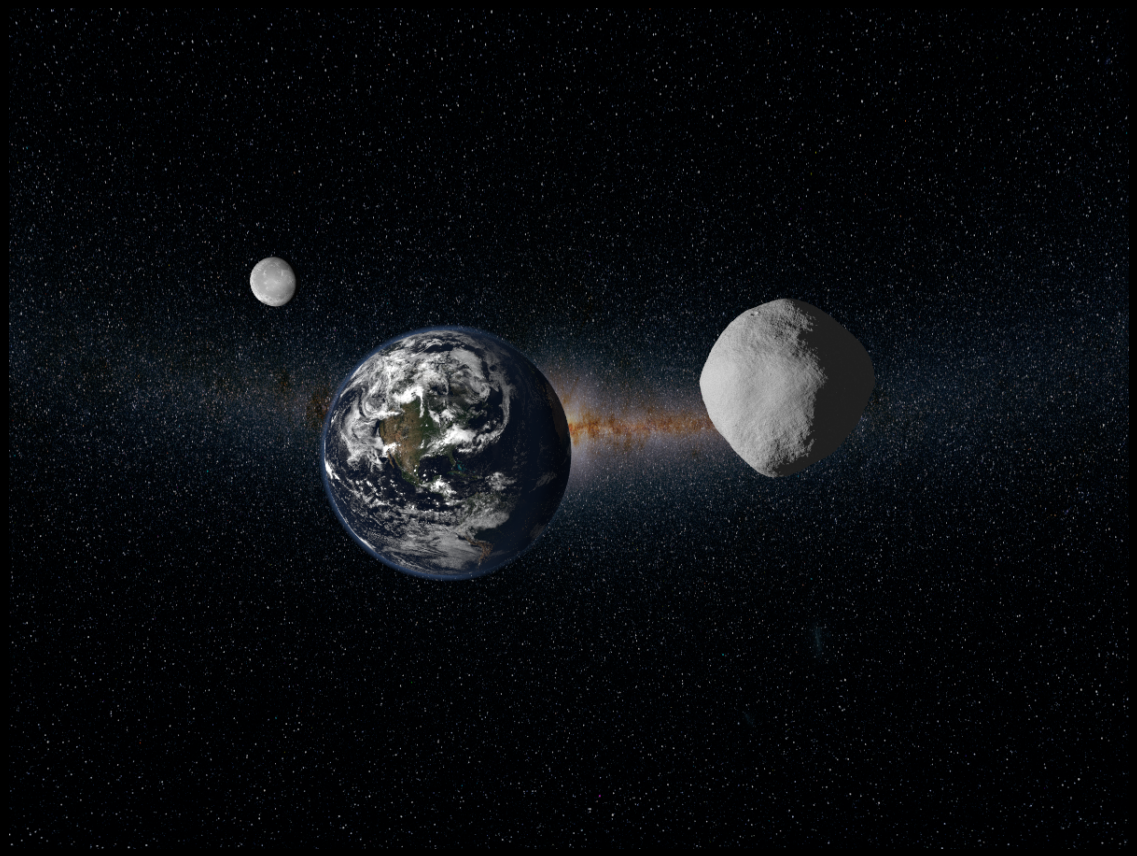


Close Approaches to the Earth and Keyholes

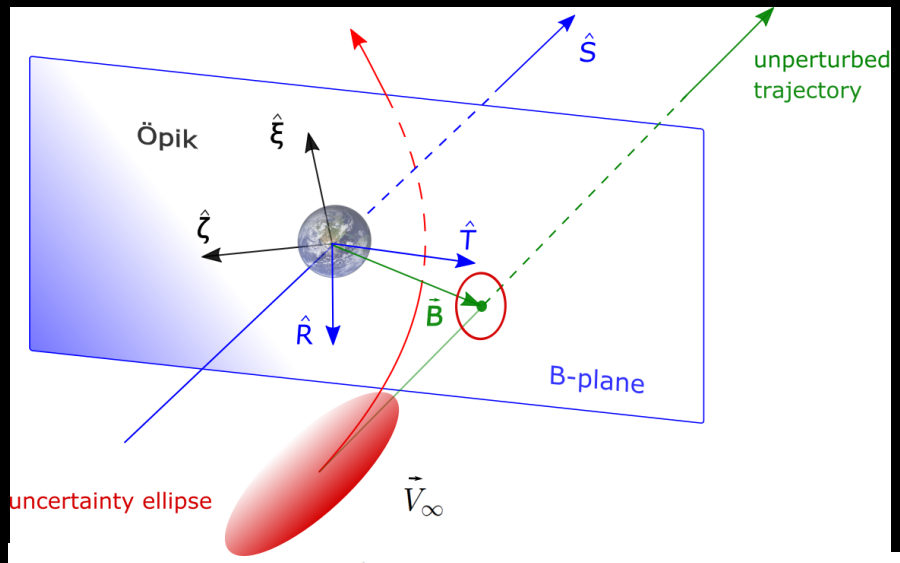


(101955) Bennu close approaches to the Earth and the Moon:

2060-Sep-23 ~ 120 R_E
2135-Sep-25 ~ 65 R_E

Farnocchia et al. (2014)

Close Approaches to the Earth and Keyholes



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2060-Sep-23 ~ 120 R_E
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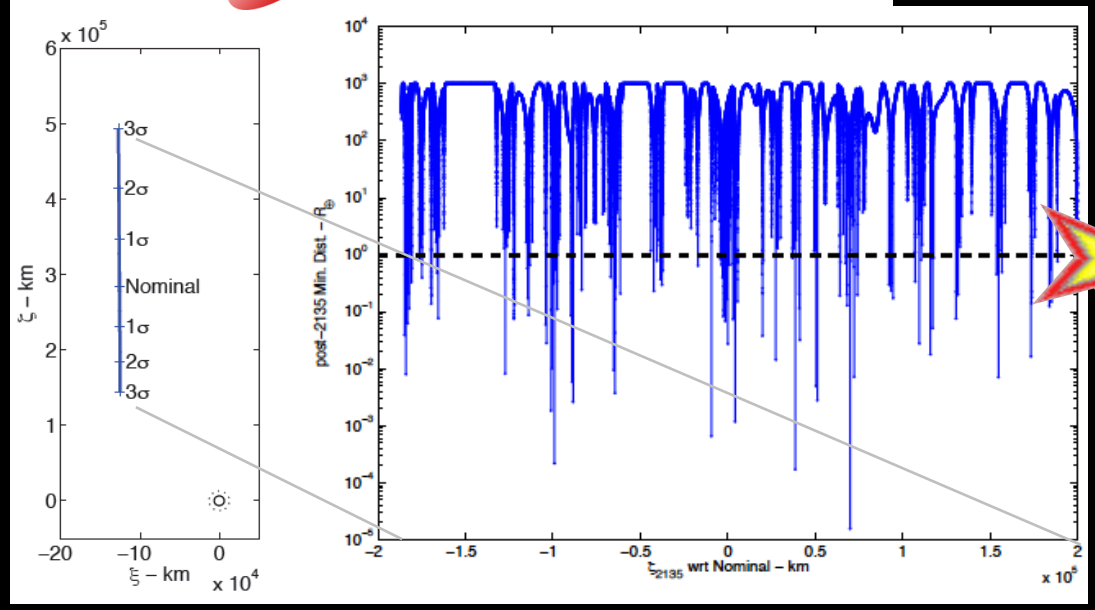
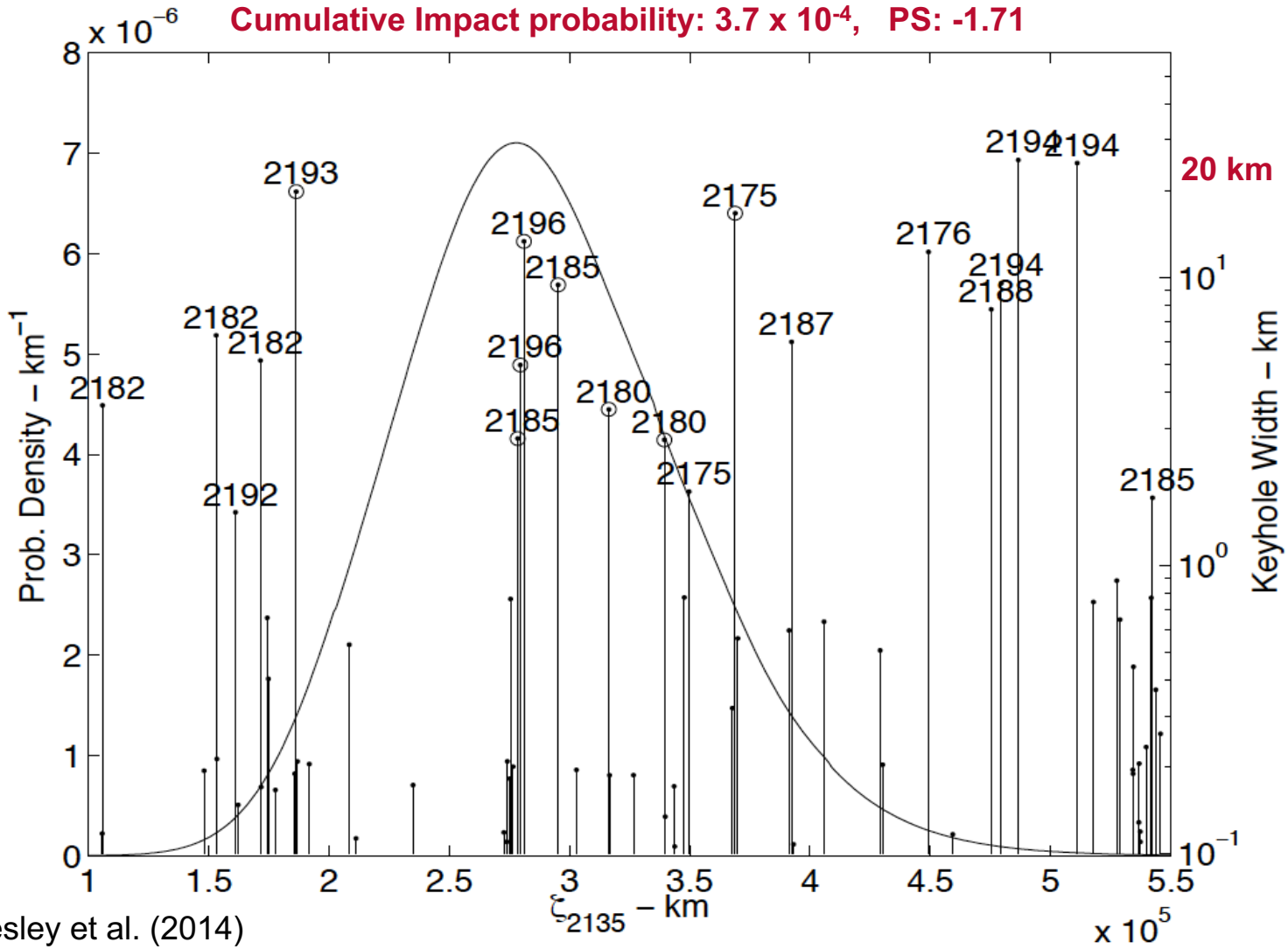


beyond 2135...
statistical predictions

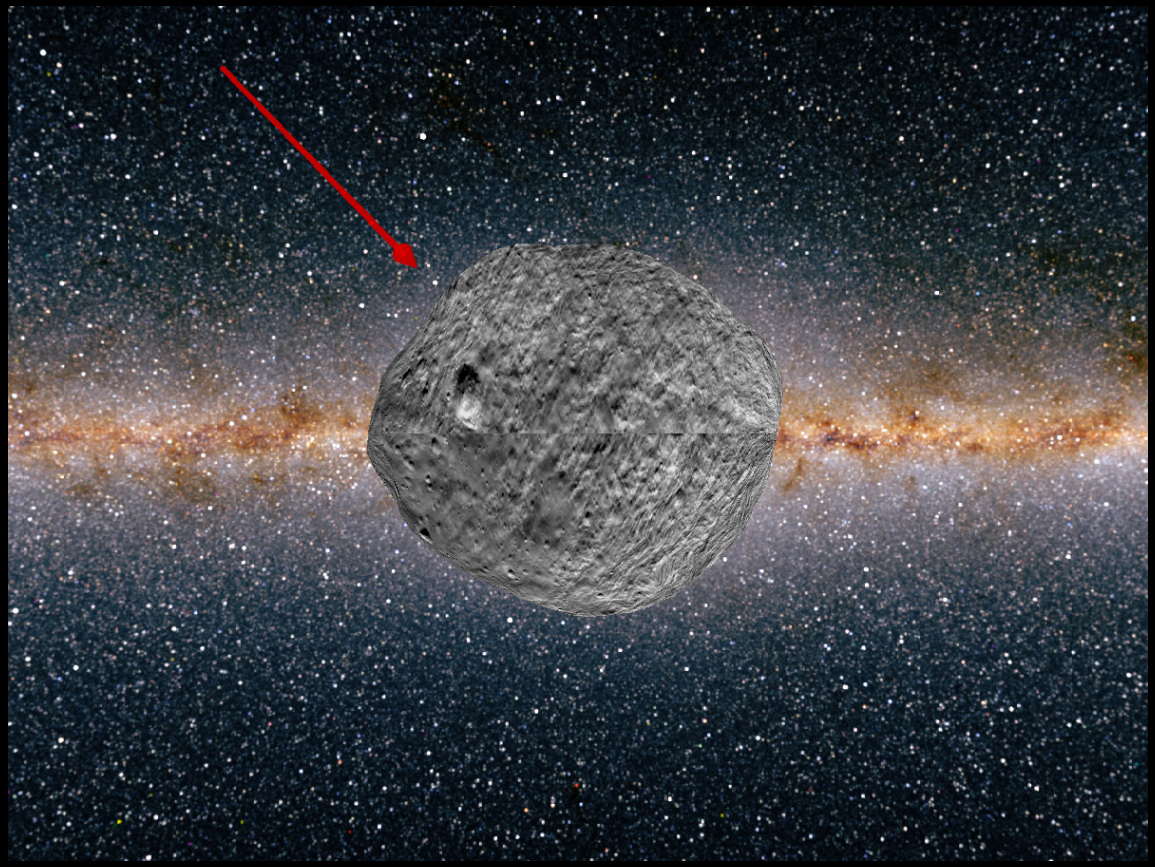
Farnocchia et al. (2014)

Risk assessment

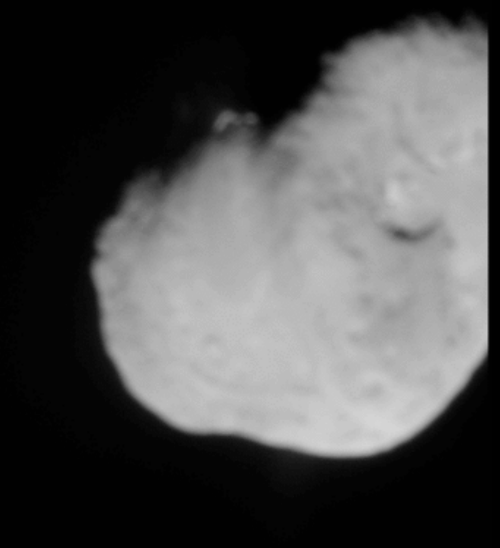


Chesley et al. (2014)

Hitting Bennu… where?



KI Deflection Experiment on Bennu



NASA: Deep Impact Mission

Impact: 03/10/2021

v_{inf} ~ 14,9 km/s

m = 420 kg

M = 6 x 10^{10} kg

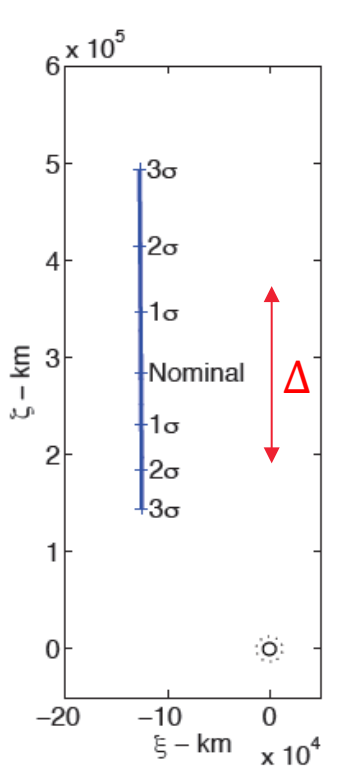
$1 \leqq \beta \leqq 3$

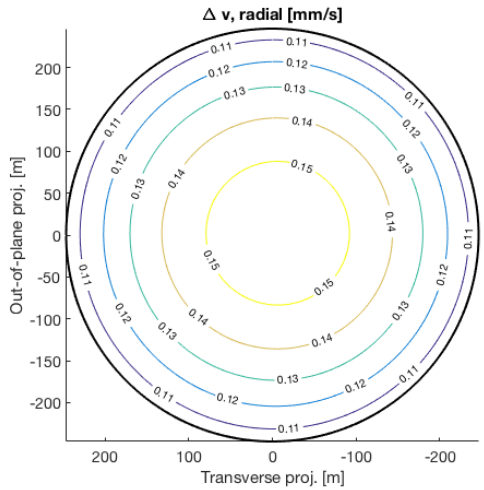
$$\Delta\vec{V} = \frac{m}{M}\left(\hat{I} + (\beta - 1)\hat{n}\hat{n}\right)\vec{v}_{inf}$$

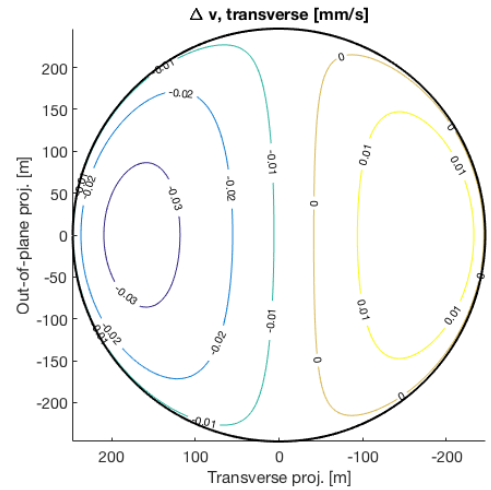
Scheeres et al. (2015)

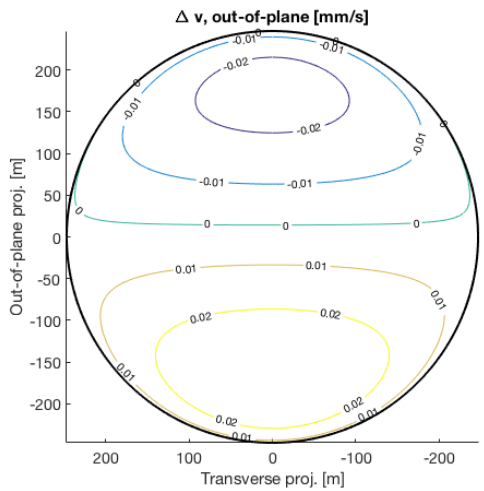
Chesley et al. (2014)

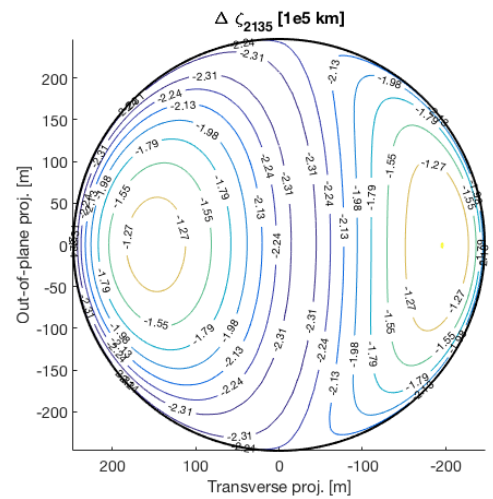
Map 1: $\Delta\vec{V} \rightarrow \Delta\zeta_{2135}$



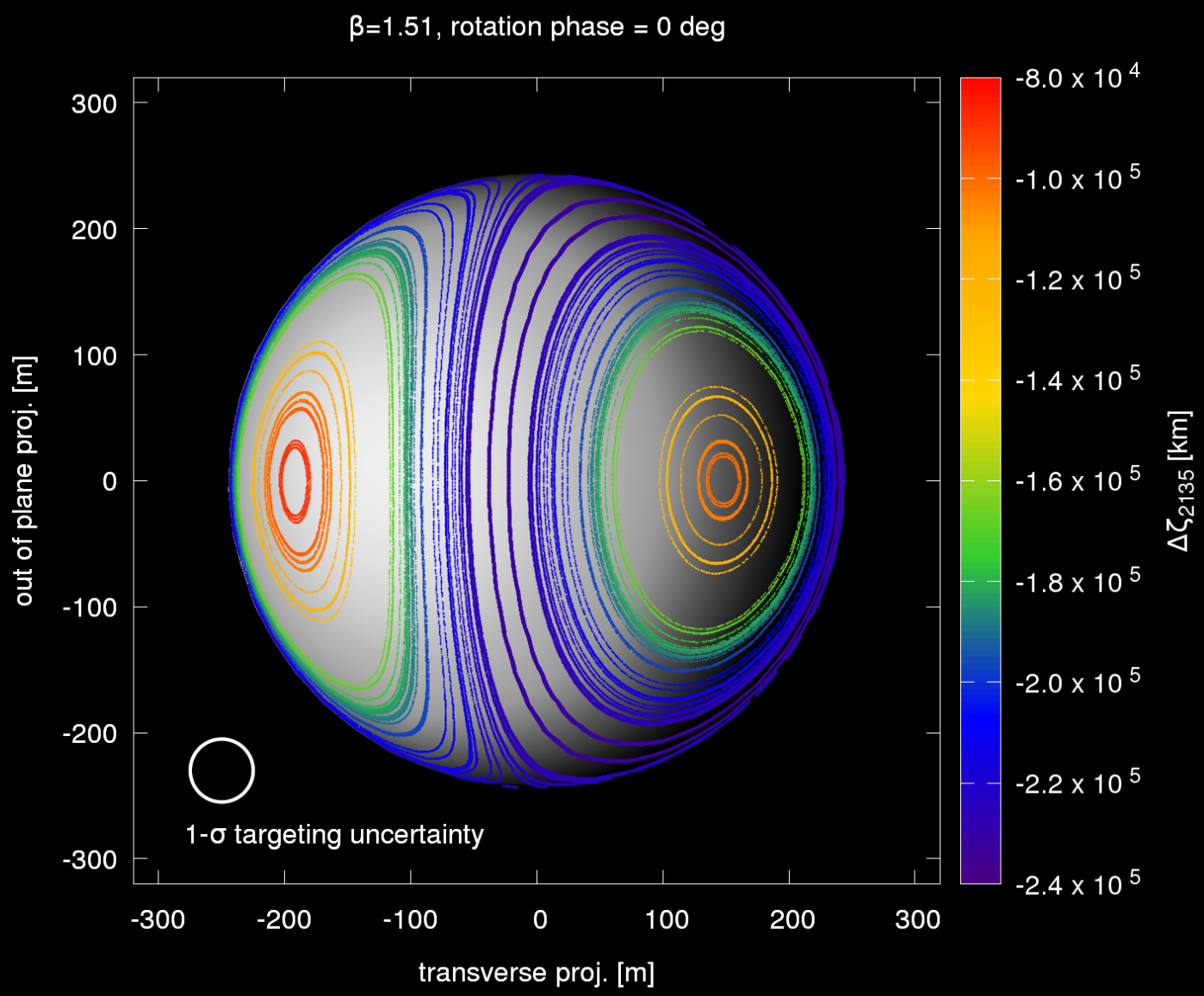








Map 2: $\Delta\zeta_{2135} \rightarrow Keyholes$



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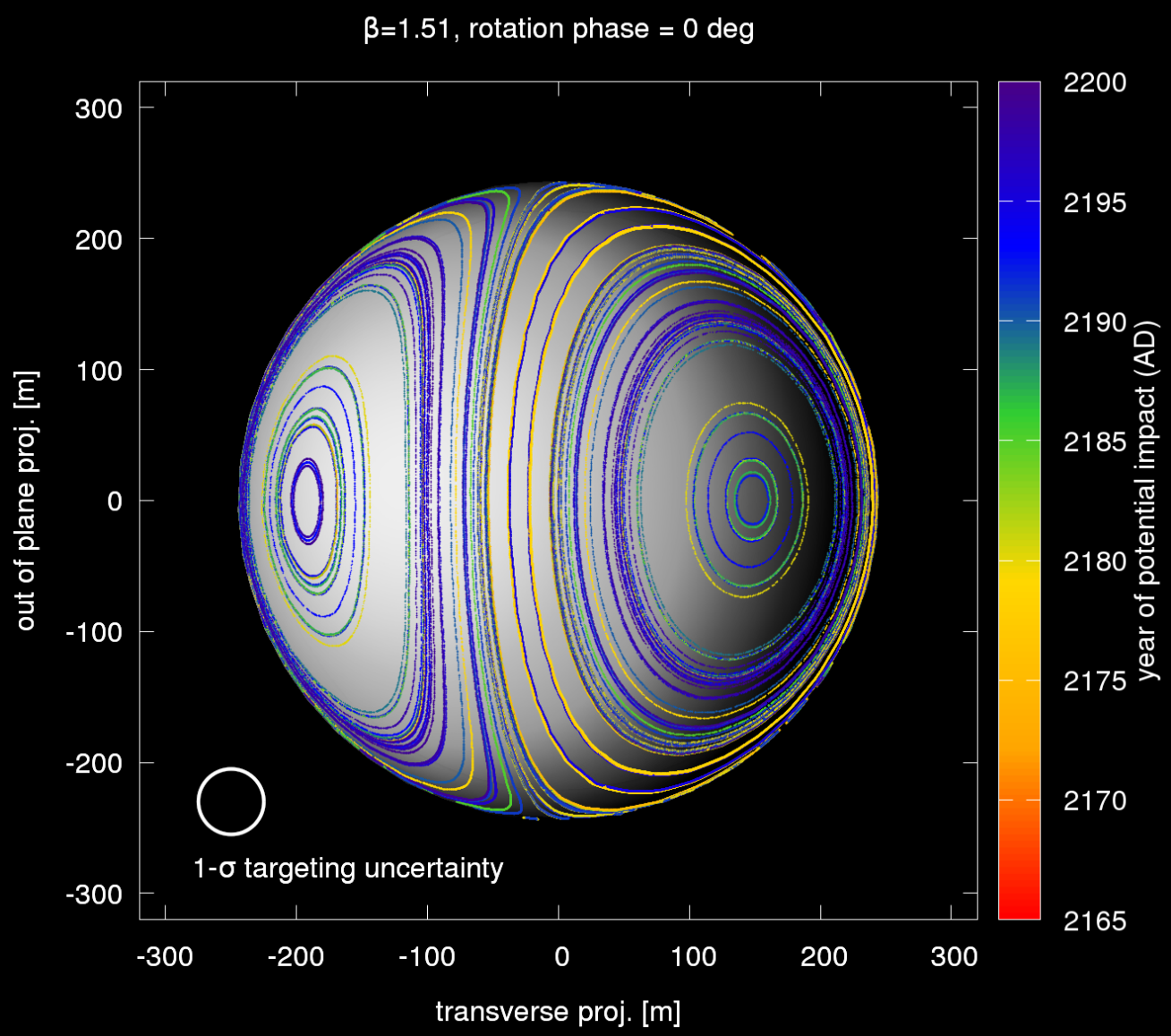
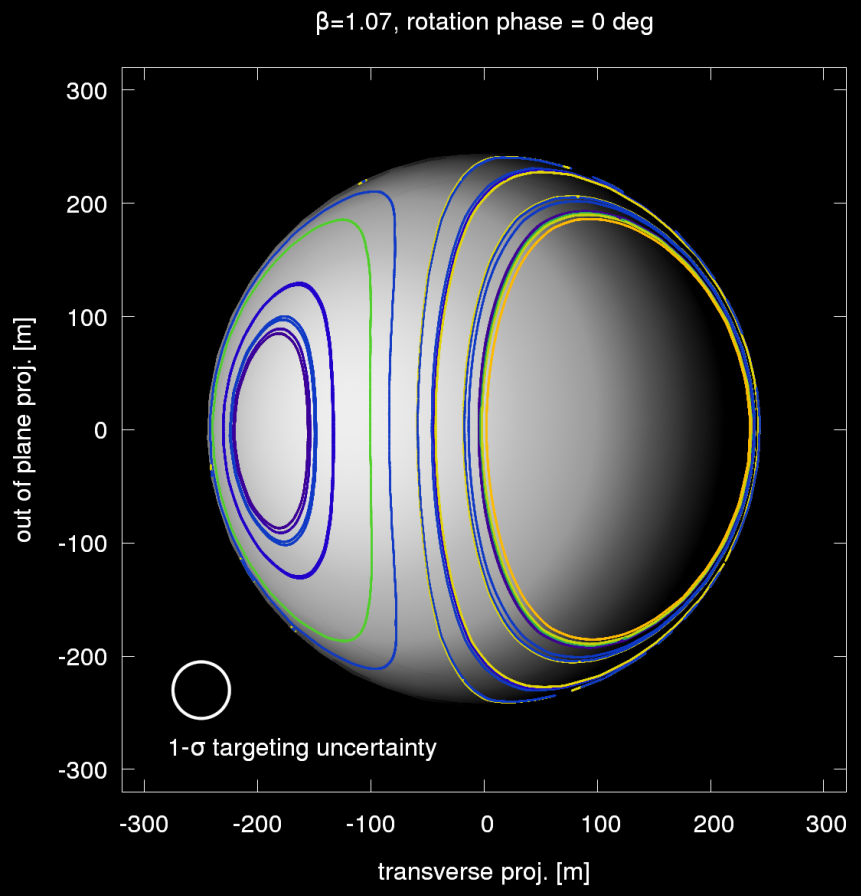
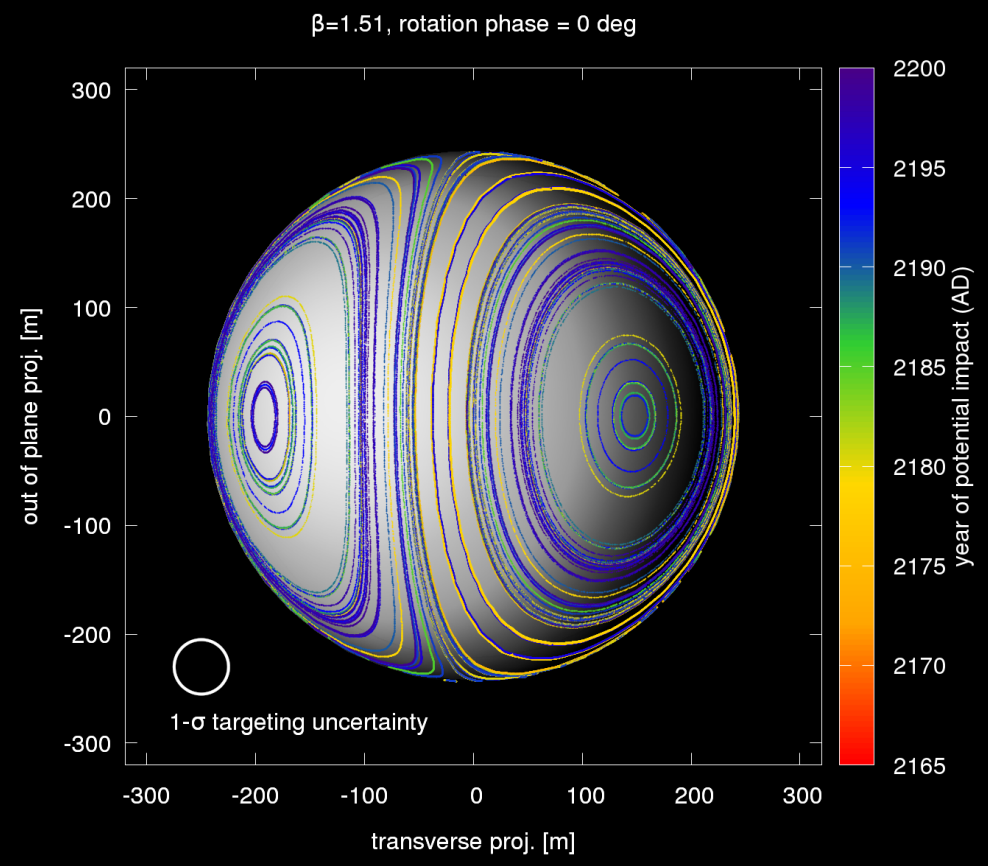
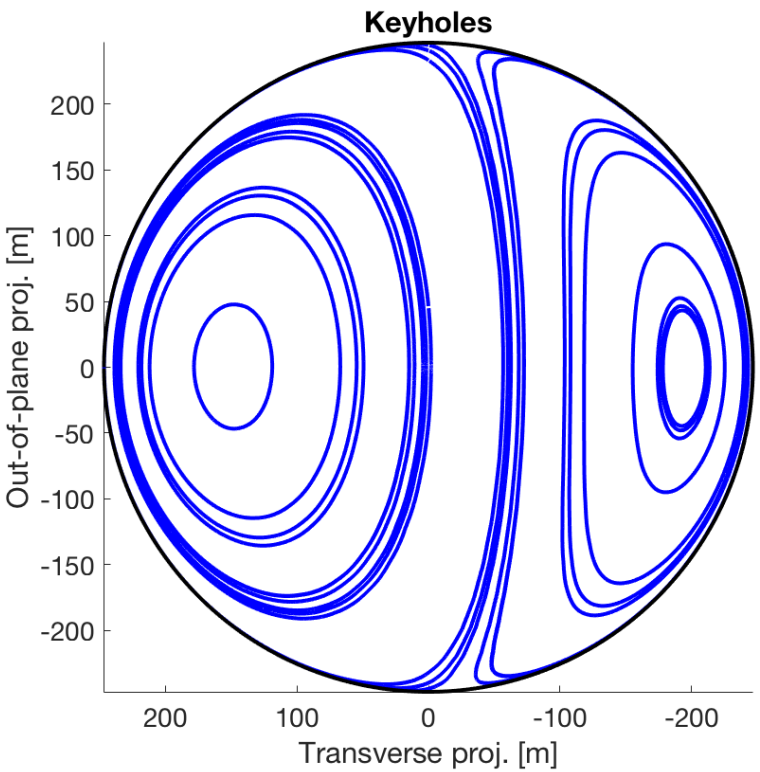


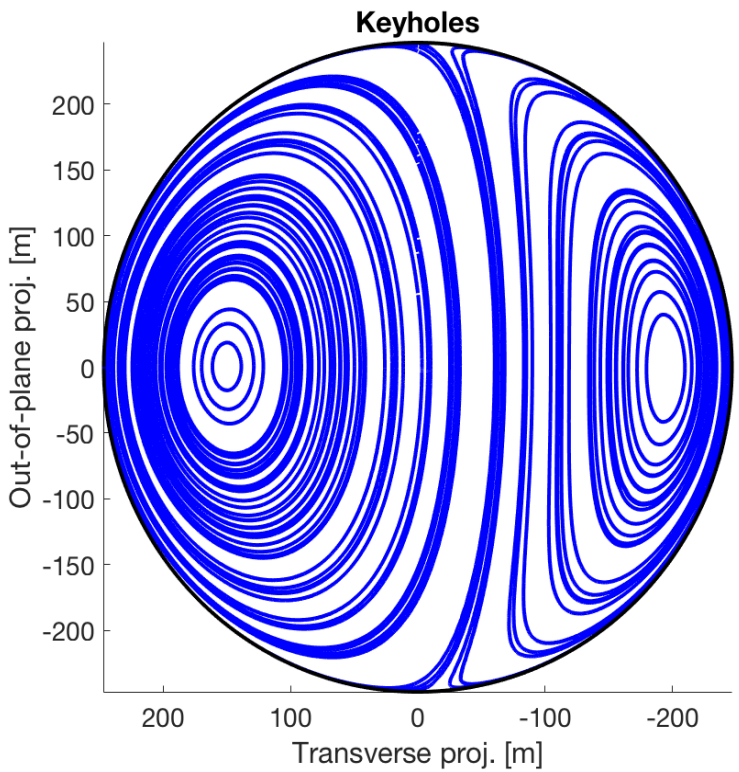
Maps depend on *β!*





Maps depend on β!

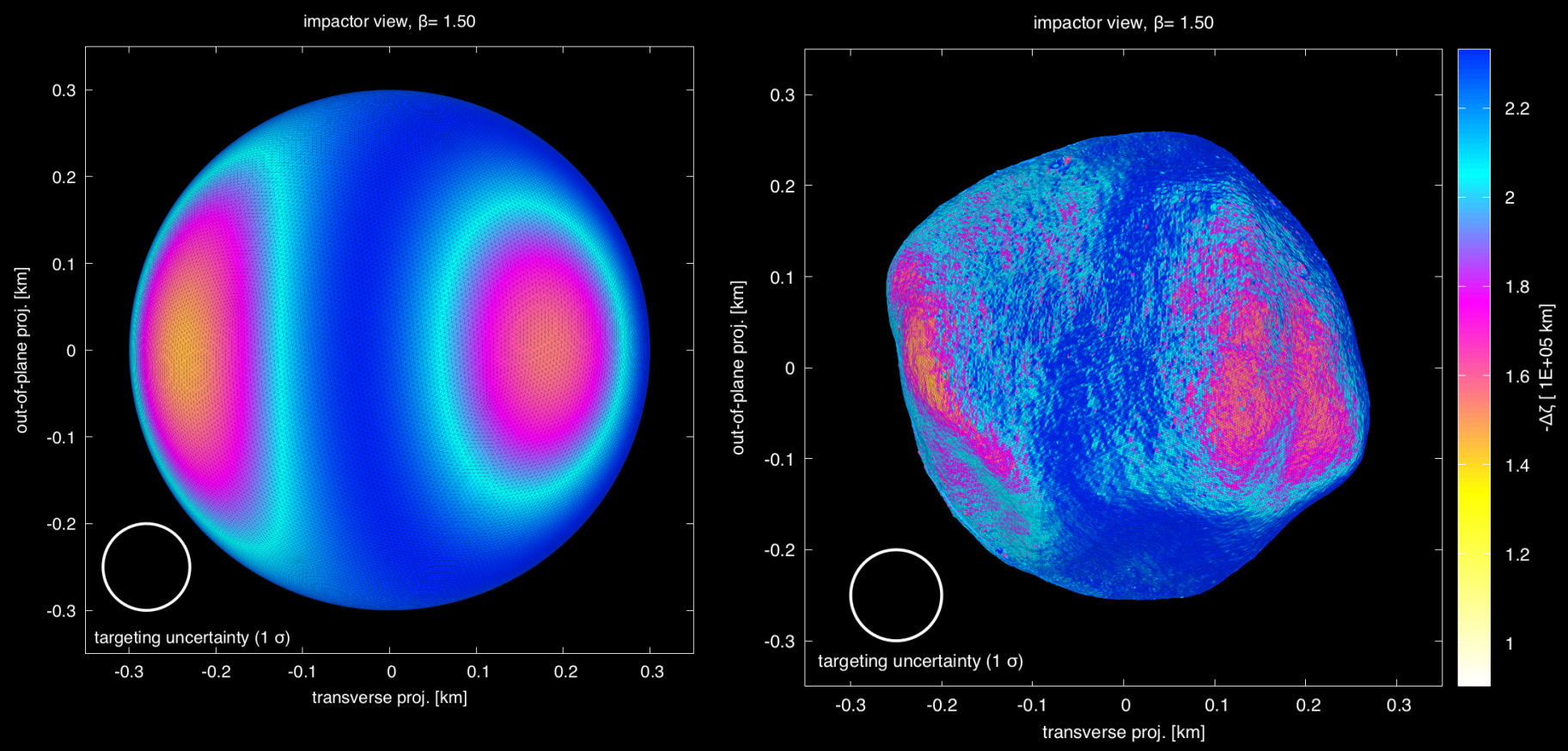




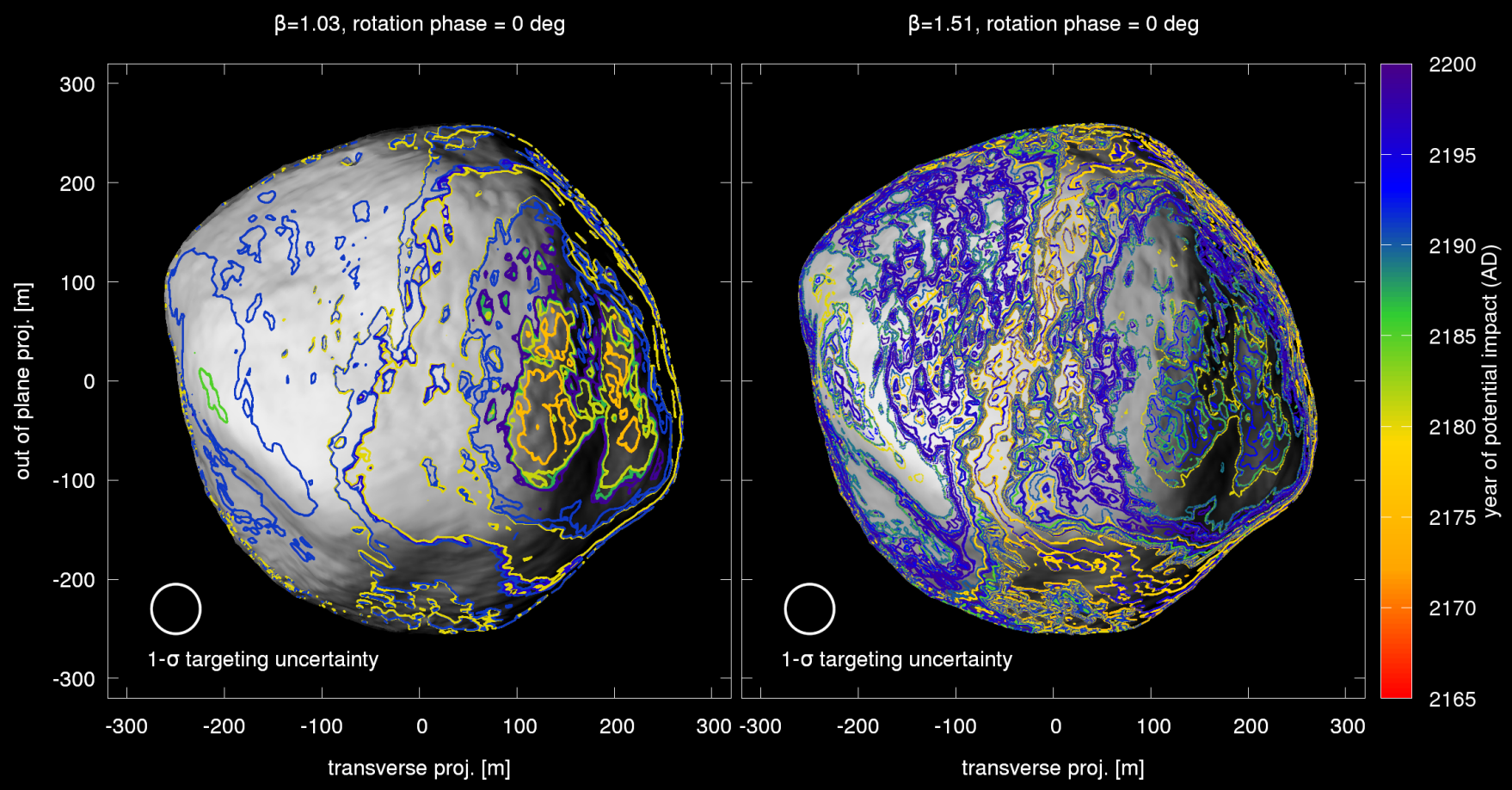
β =1.5

β =2

Bennu shape: $\Delta\vec{V} \rightarrow \Delta\zeta_{2135}$



Bennu shape : $\Delta\zeta_{2135} \rightarrow Keyholes$

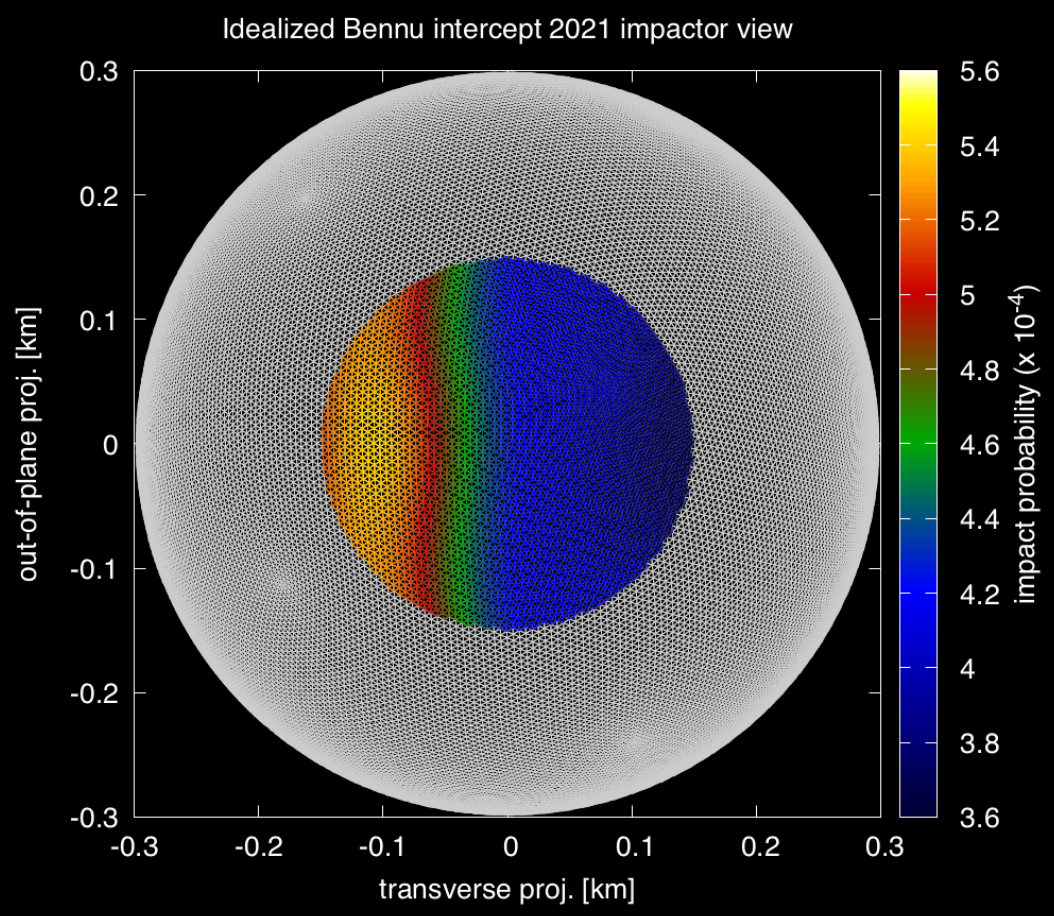


β =1.03

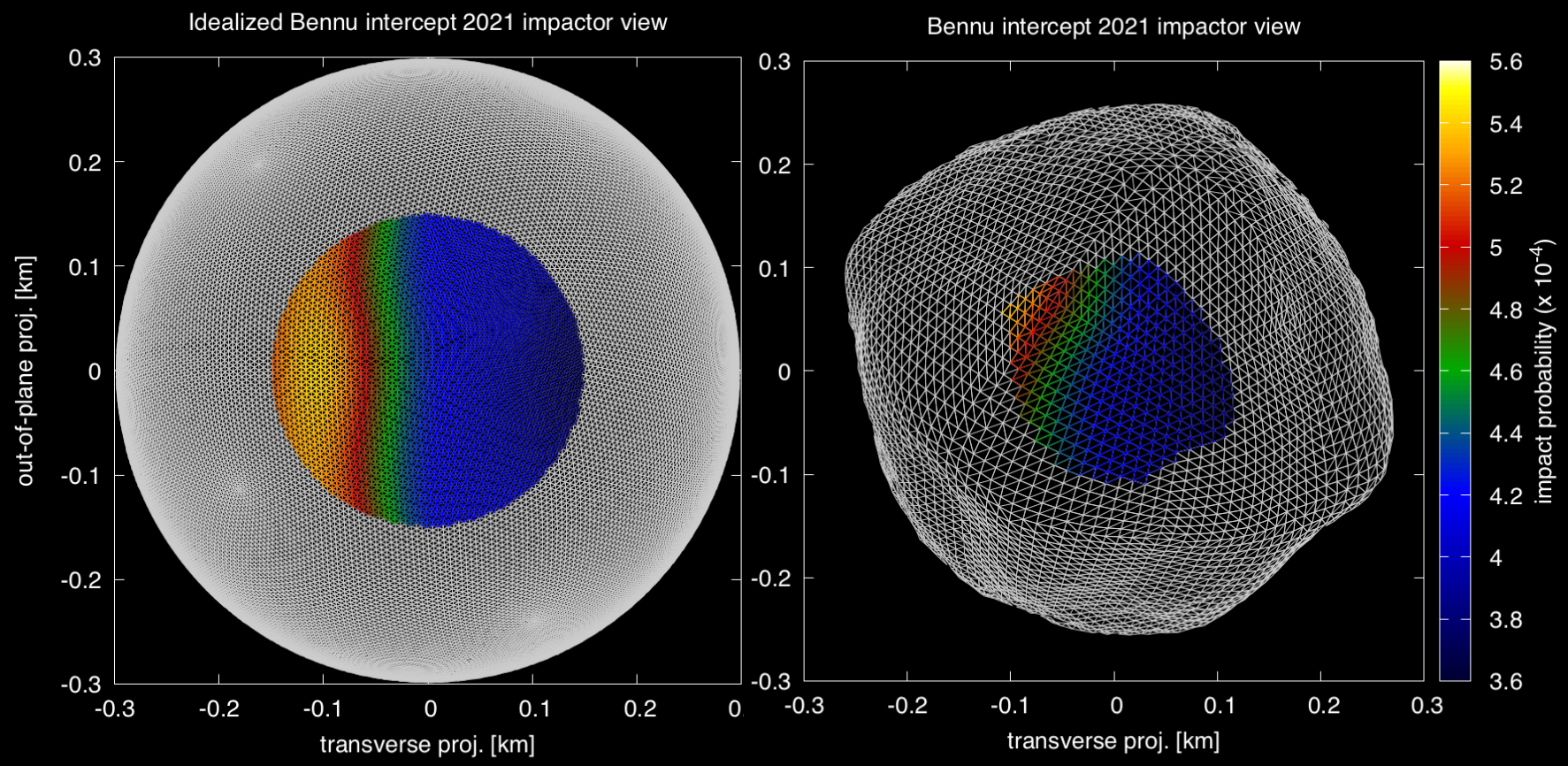
β =1.51

Statistically best impact point: MC

- draw β from distribution
- calculate impact probability for each facette by evaluating how often a keyhole is hit
- weighs according to visible facette surface

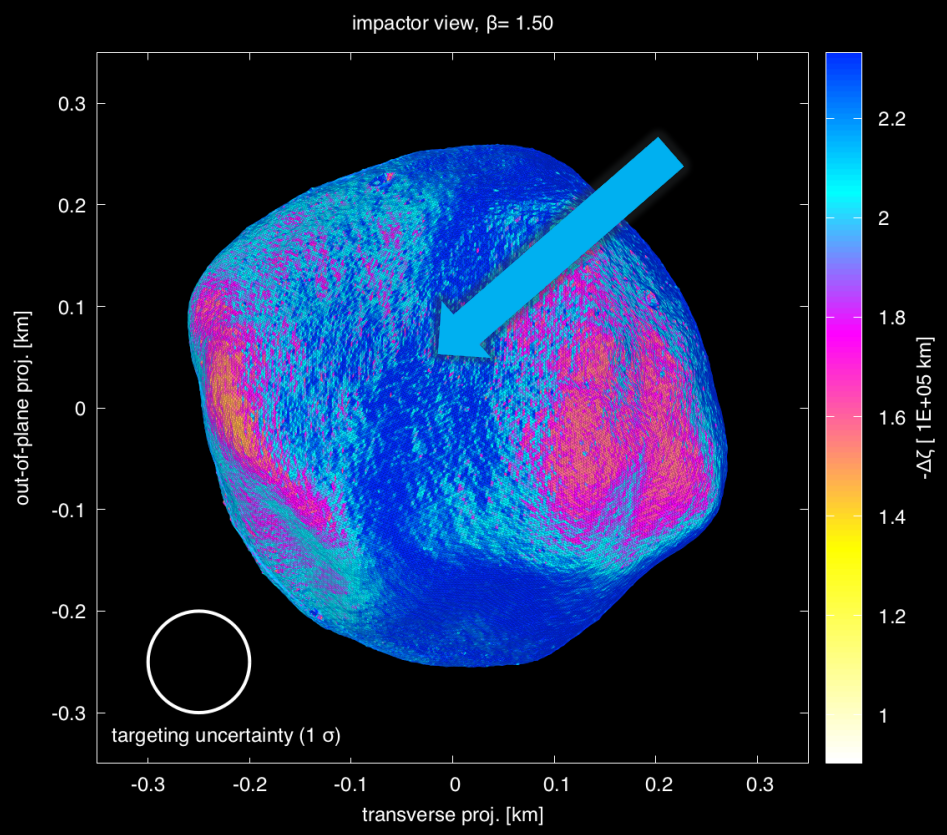


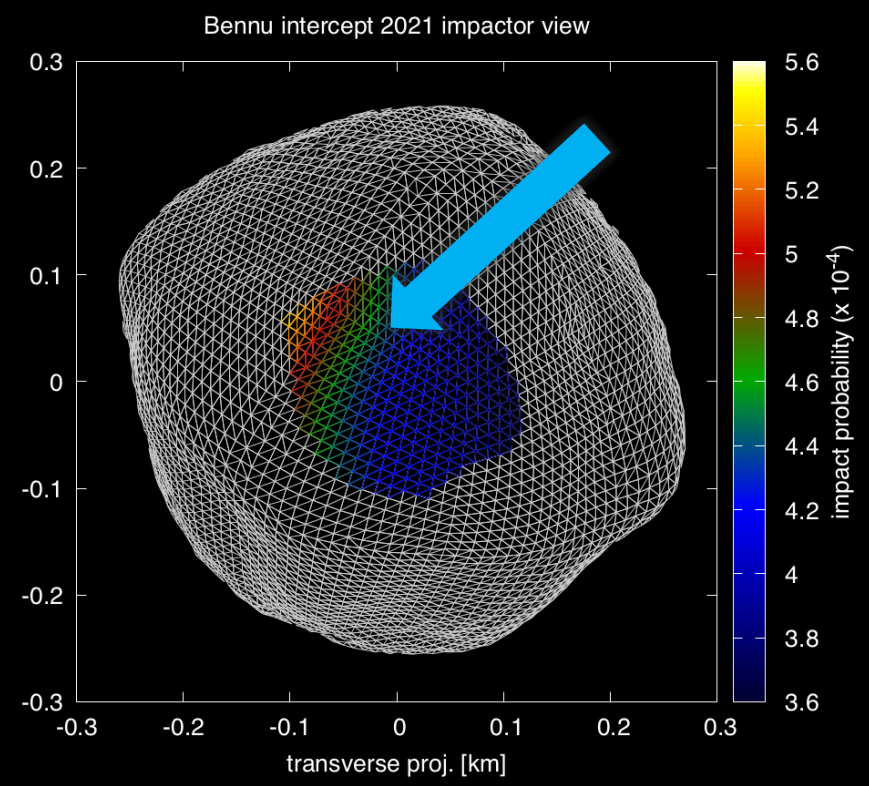
Statistically best impact point: MC



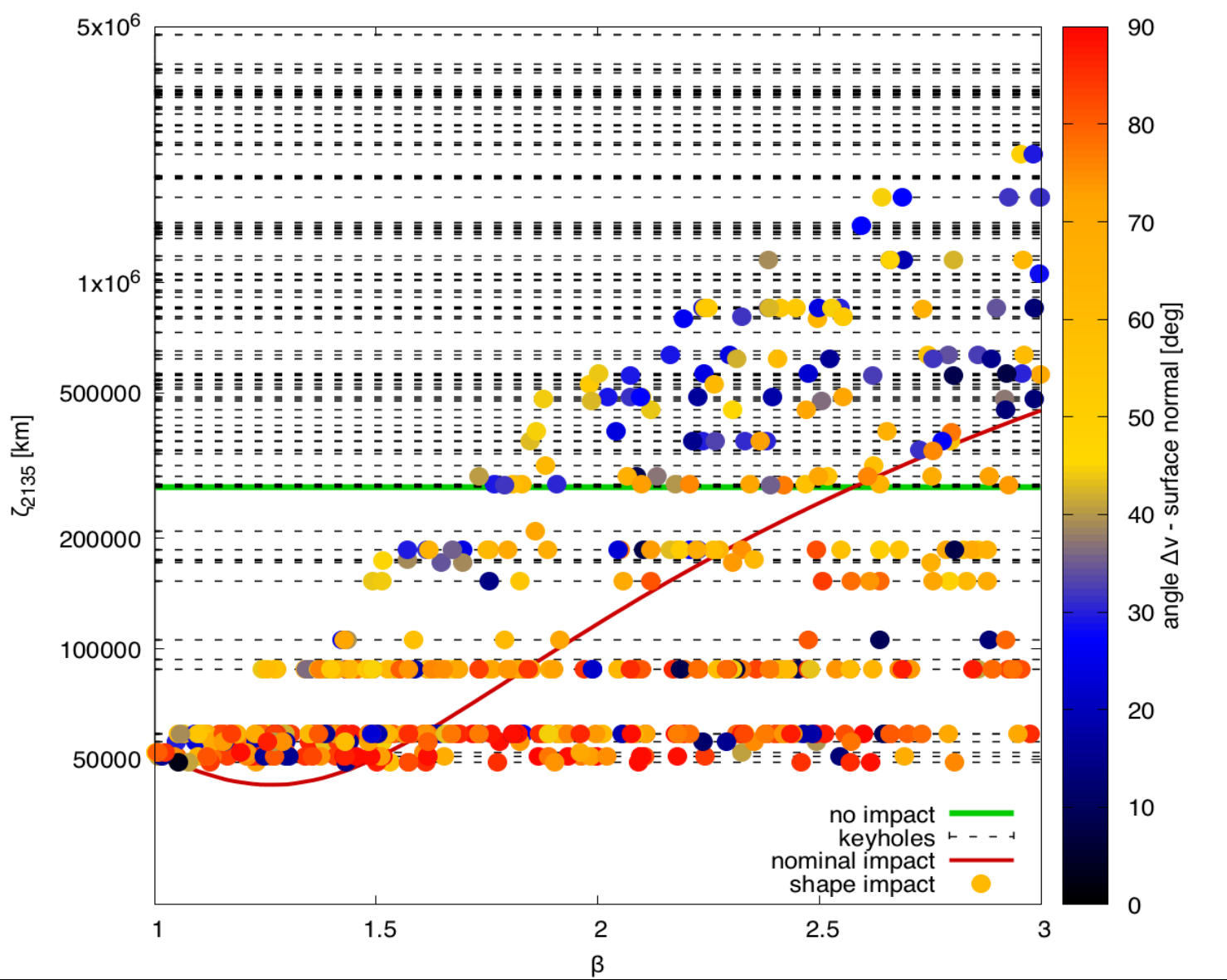
Aiming for the center may not always be the best approach…

Uncertainty in β + shape = More accessible keyholes!

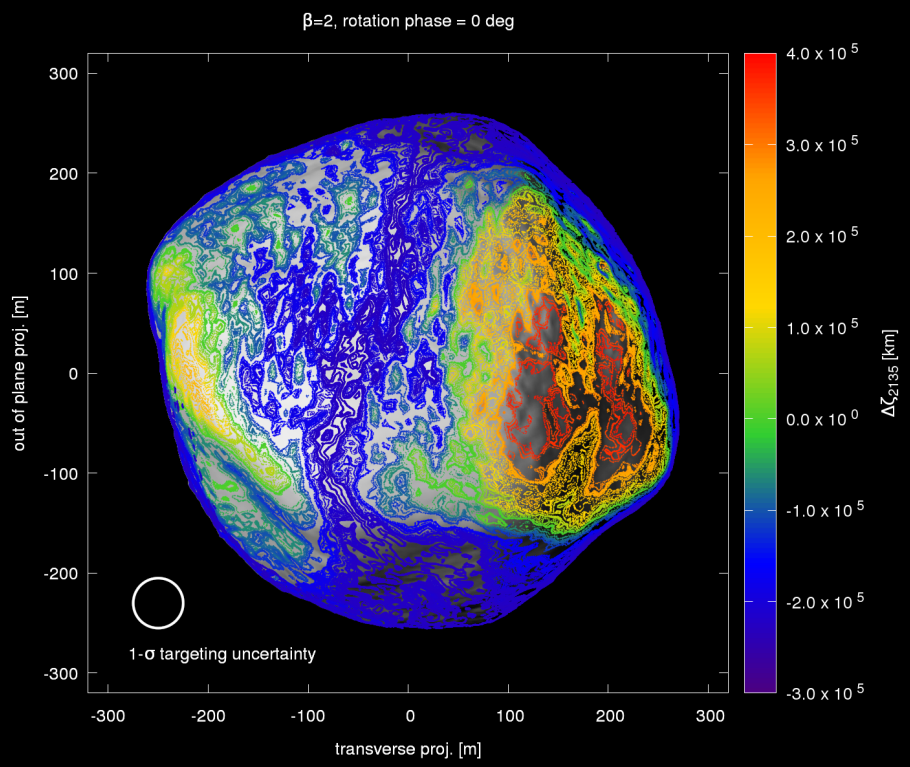




β: Keyhole accessibility

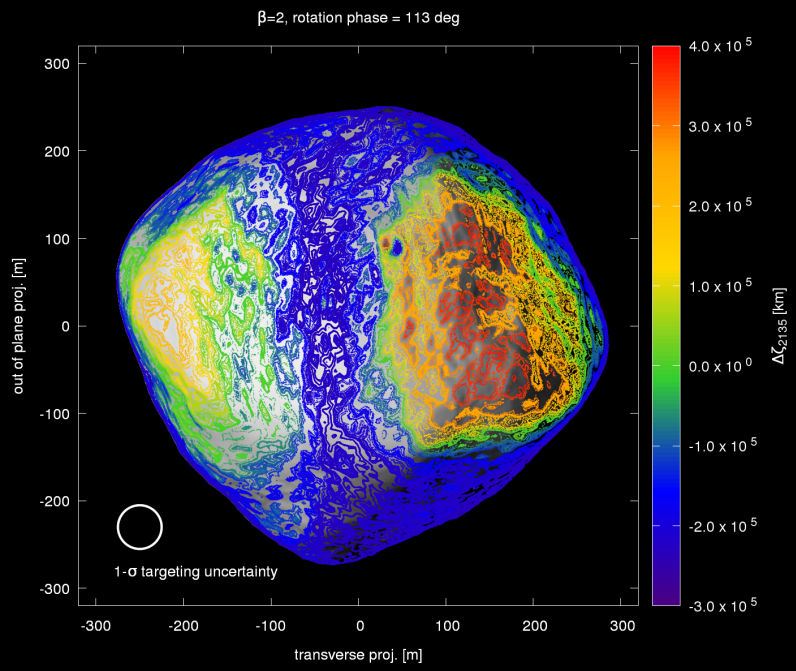


The target spins!

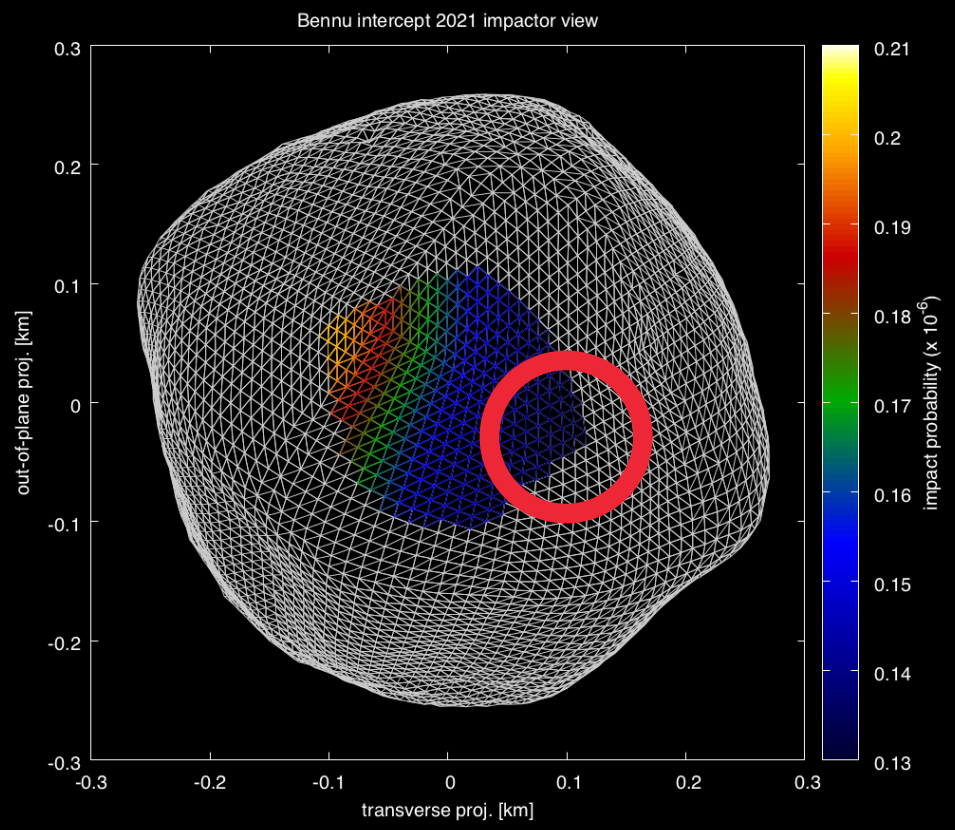


Rotation: φ=0 deg

Rotation: φ=113 deg

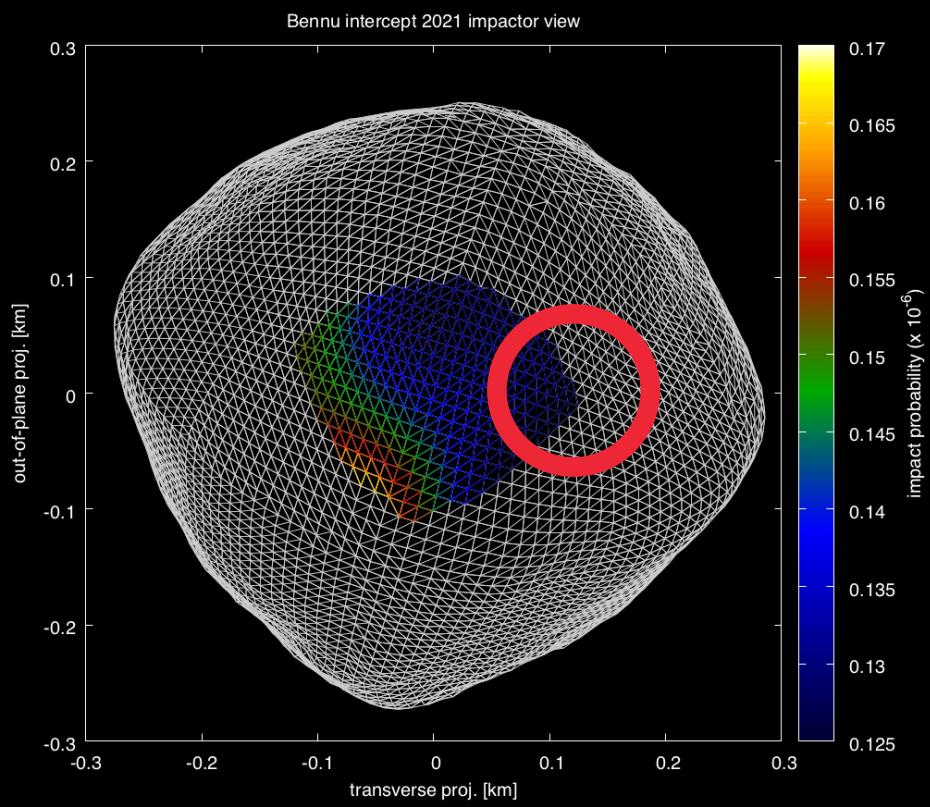


Targeting Maps can change with spin!



Rotation: φ=0 deg

Rotation: φ=113 deg

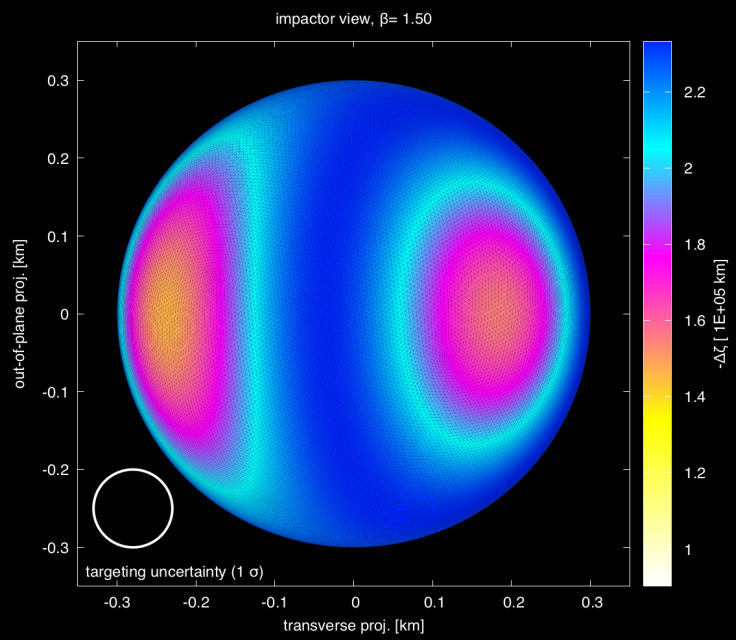


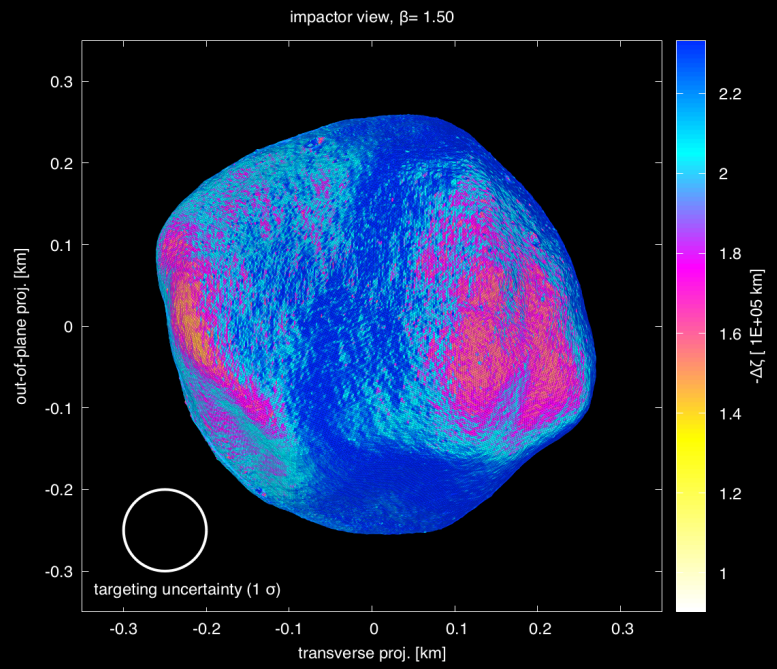
Shape based impactor trajectory optimization

$$\Delta\zeta \propto \beta\, t\, \vec{V}.\Delta\vec{V}$$

e.g. Izzo (2007)

For a given $\Delta\zeta$ necessary to deflect and asteroid, the impact point on the target surface can be optimized wrt. the S/C $\Delta\vec{v}$.





Key concepts

- post deflection impact risk assessment
- keyhole-to-surface targeting maps

Conclusions

- Knowledge of physical and spin properties is vital for a controlled KI based deflection of potentially hazardous near-Earth asteroids.
- Large uncertainties in β in combination with realistic shapes necessitate a careful evaluation of the safest impact location!
- Impulsive deflection missions can take advantage of a target's shape to avoid keyhole passages and optimize impactor trajectories.

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