



Optimizing Trajectories in Asteroid Defense Missions: Potential Gains from Eccentric Collision Approaches

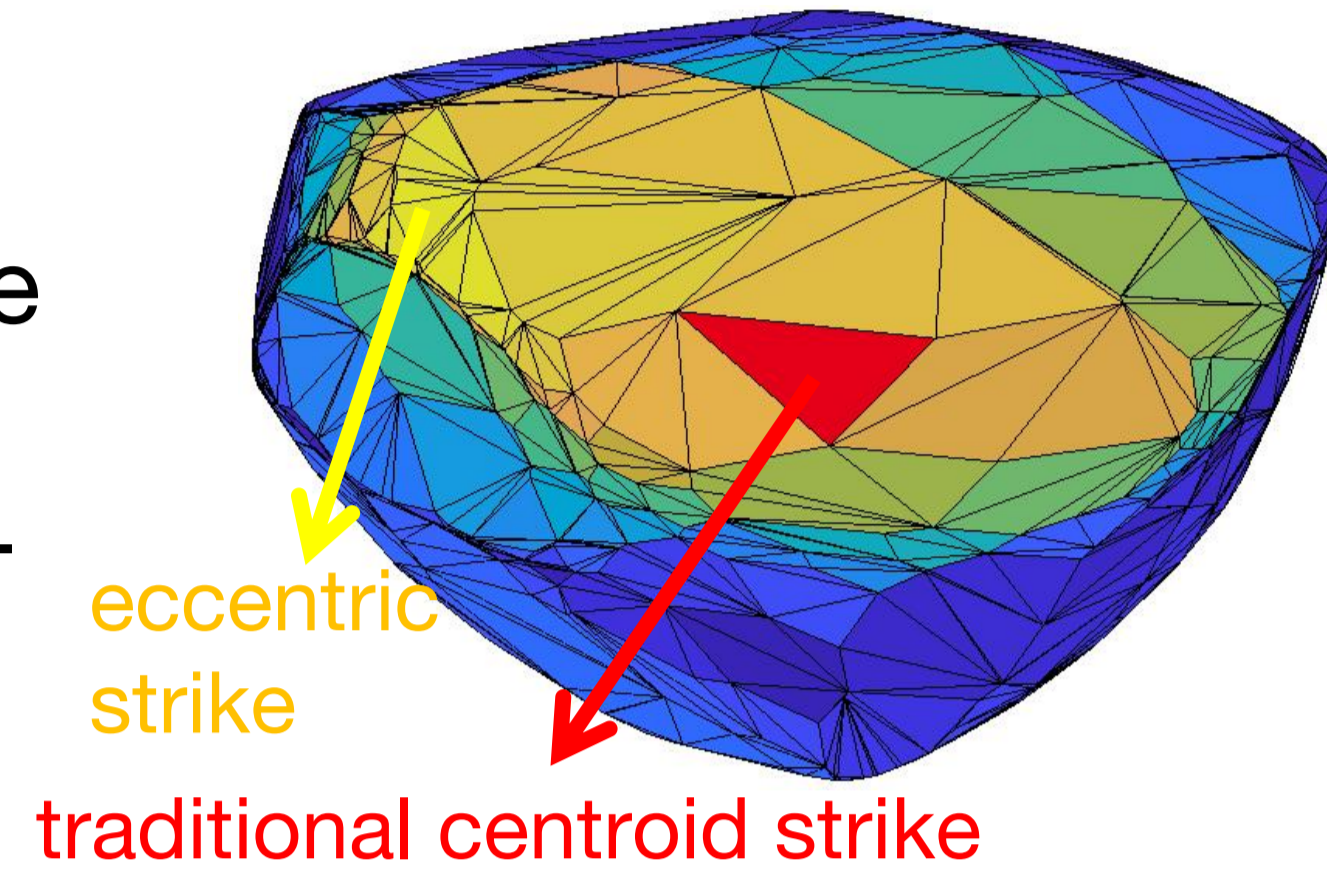
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Introduction

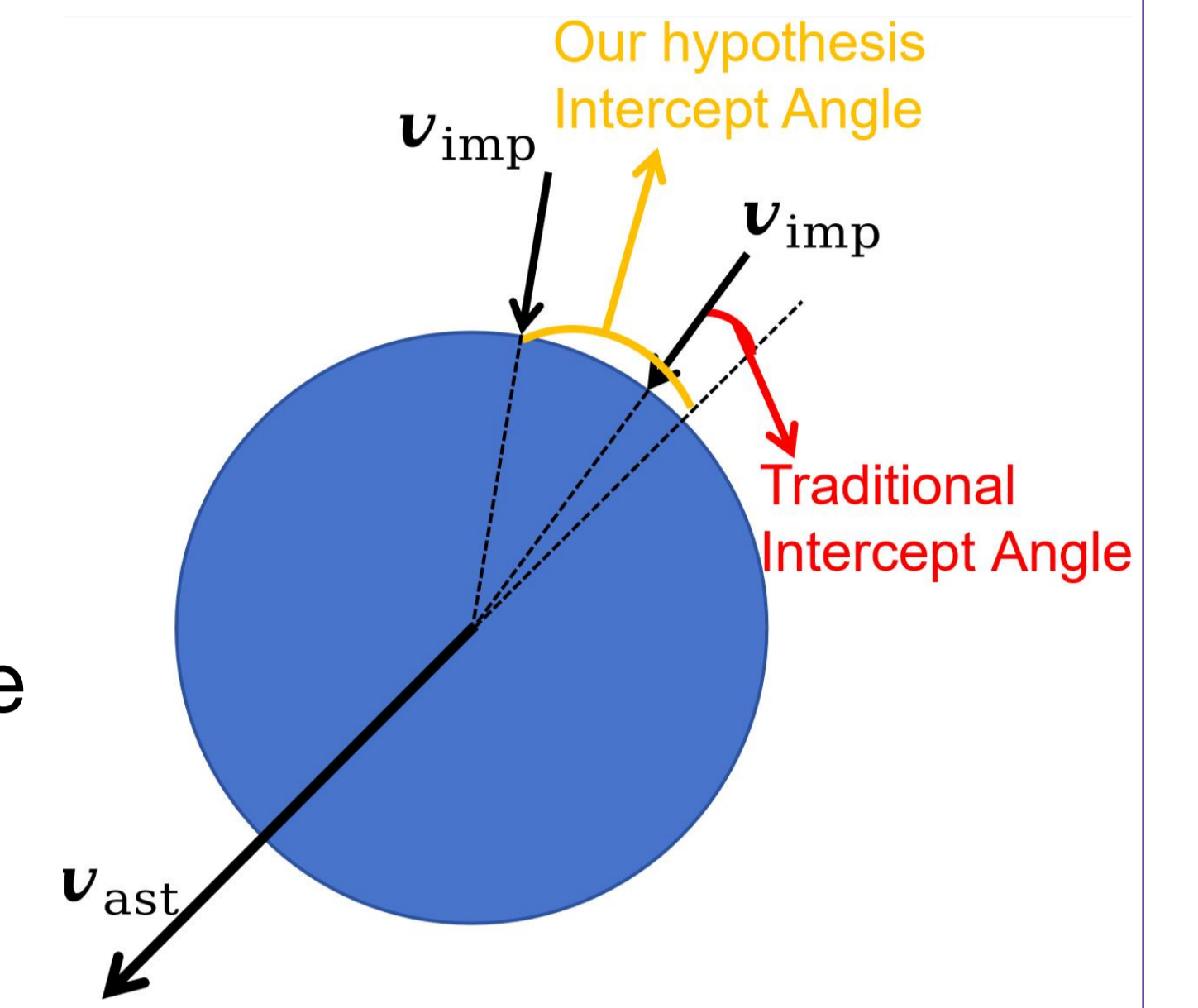
In asteroid deflection missions, the presence of ejecta leads to a phenomenon where the system's momentum appears to be "amplified."

- By utilizing an **eccentric strike** strategy, the deflection distance can be further magnified compared to a direct center-of-geometry collision.



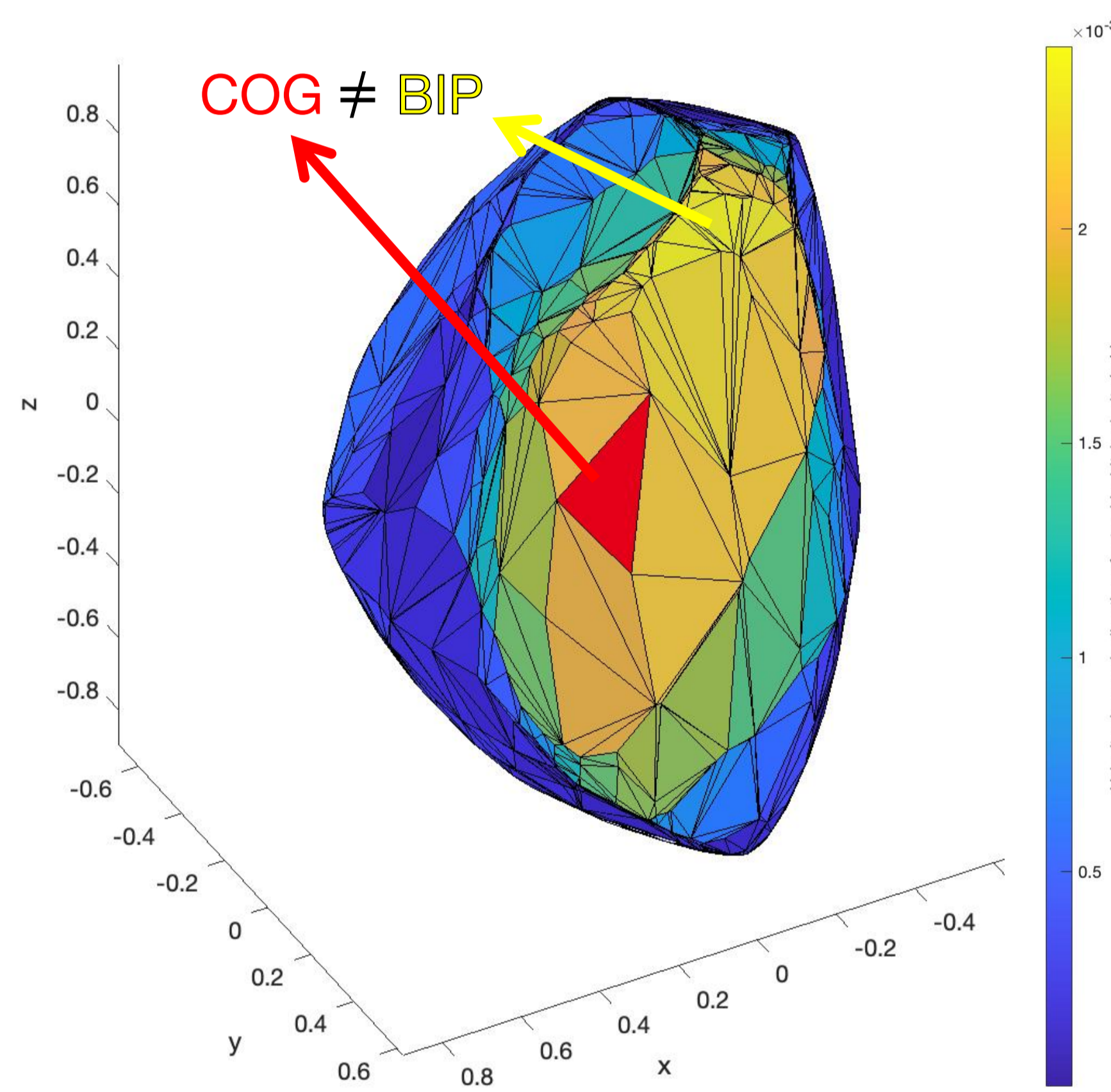
Our Hypothesis

- In traditional optimization, the optimal transfer trajectory usually ends with the interception angle is as close to 0/180 as possible.
- We predicts that eccentric strike could allows the optimizer to explores a trajectory with larger intercept angles



Theory

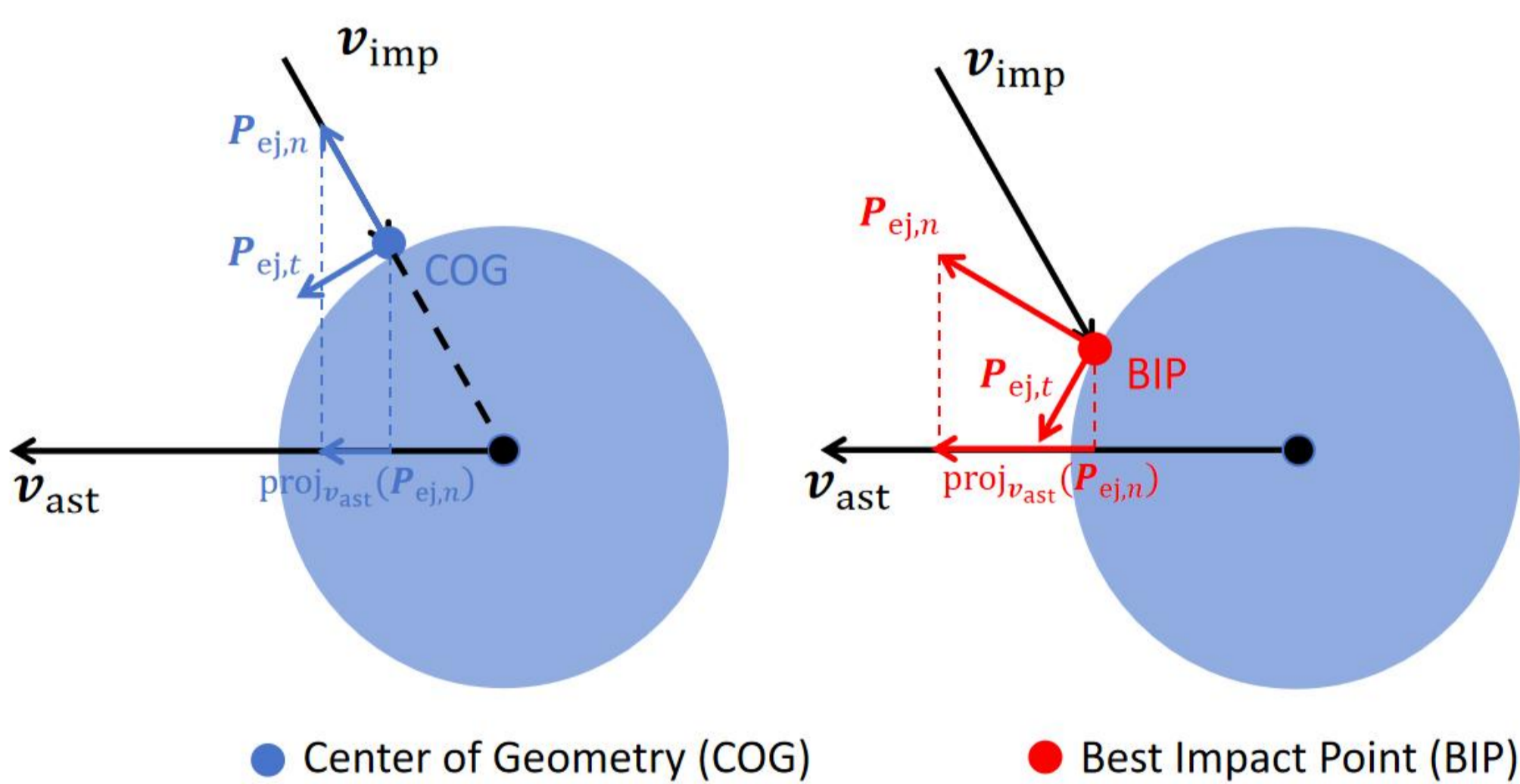
- The schmatic diagrams are shown below, the eccentric strike strategy (red, BIP) produce larger projection of normal ejecta momentum, $\mathbf{P}_{ej,n}$ onto asteroid's velocity, $\text{proj}_{\mathbf{v}_{ast}}(\mathbf{P}_{ej,n})$, than striking the Center of Geometry (blue, COG). Thus we predict that eccentric collision strategy will produce larger deflection distance.
- If exclude the ejecta, This phenomenon is **quite similar to playing snooker**.



Contour map of striking Apophis with an interception angle of 5°

To verify our hypothesis, we conducted deflection simulations on 32 Potentially Hazardous Asteroids (PHAs). Using impulsive-low-thrust combined transfer trajectory, optimized by two different optimizers:

- ❖ The Center of Geometry impact strategy (COG).
- ❖ The Eccentric impact strategy (BIP).



Schmatic diagrams of outcomes produced by Center of Geometry (blue) and Eccentric (red)

Deflecting 1994 OX4

Based on a condition of a 10-year warning period, the optimal deflection trajectory found by both the COG and BIP strategies are shown below. For BIP strategy, the impulse is approximately 11 km/s higher and the low-thrust transfer duration is extended by about 230 days, resulting in a reduction of the spacecraft's mass at impact by roughly 2400 kg compared to the COG strategy. Despite consuming significantly more fuel, BIP strategy achieves a larger interception angle, with 22.56° versus 6.81° for the COG strategy, ultimately producing a deflection distance of 418 km, an improvement of 70.61 % over the 245 km achieved by the COG strategy.

Optimal intercept trajectory for 1998 OX4 found by optimizers through COG and BIP strategies

| | Center of Geometry (COG) | Best Impact Point (BIP) |
|---------------------|--------------------------|-------------------------|
| Launch Date | 13th Nov 2139 08:59 | 4th Jan 2139 02:38 |
| Impact Date | 18th Jun 2141 19:33 | 24th Mar 2141 11:48 |
| Flight Duration | 583.44 days | 810.38 days |
| Impulse ΔV | 5.50 kms^{-1} | 16.70 kms^{-1} |
| Mass at Impact | 6165.55 kg | 3768.81 kg |
| Interception Error | 0.3227 m | 0.0376 m |
| Intercept Angle | 6.81° | 22.56° |
| Deflection Distance | 245.57 km | 418.85 km |

Simulation on 32 PHAs

- The deflection distances achieved by the BIP strategy are all higher than those obtained with the COG strategy, with an average relative increase of 38.61 % and a maximum increase of 177 %.
- Among these PHAs, 87 % exhibited transfer trajectories under the BIP strategy with larger interception angles than those from the COG strategy, which validates our initial prediction.

Conclusion

- This study demonstrates that a larger interception angle and eccentric impacts could increase the efficiency of asteroid deflection mission. Provides an important theoretical support and technical reserves for future asteroid defense strategies.

Optimal intercept trajectories for 1998 OX4 Center of Geometry (red, COG) and Eccentric (orange, BIP)

