Accessibility of Earth Impactors for Planetary Defense Rendezvous Missions

Planetary Defense
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Objective

- Examine the accessibility of rendezvous planetary defense (PD) missions given the high degree of variation in impactor orbital elements and the time constraints associated with warning time
- Compare mission performance with chemical propulsion versus solar electric propulsion (SEP)

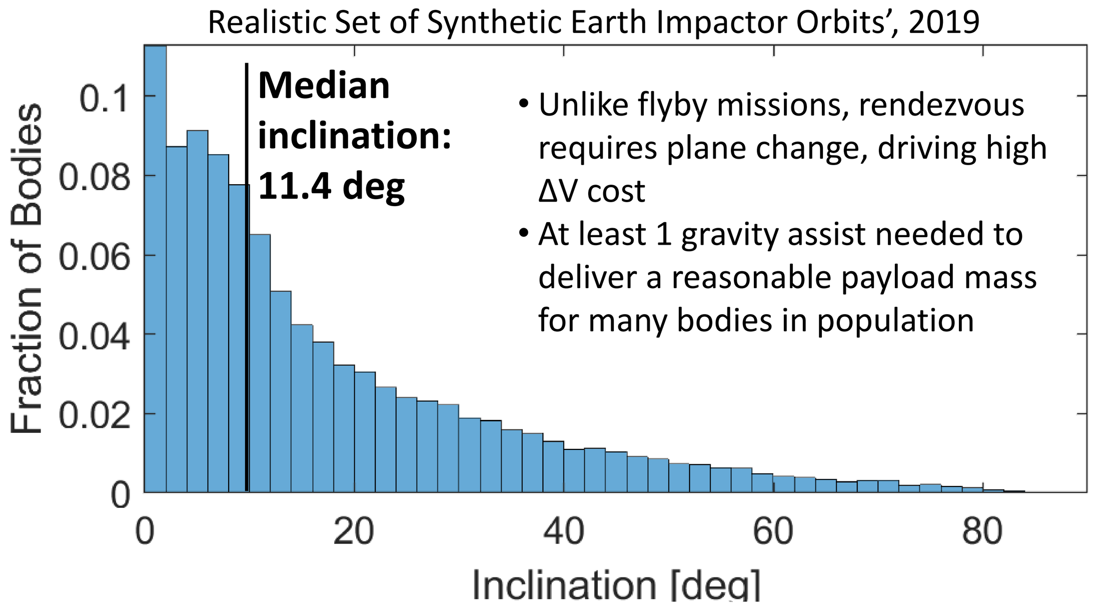
Background

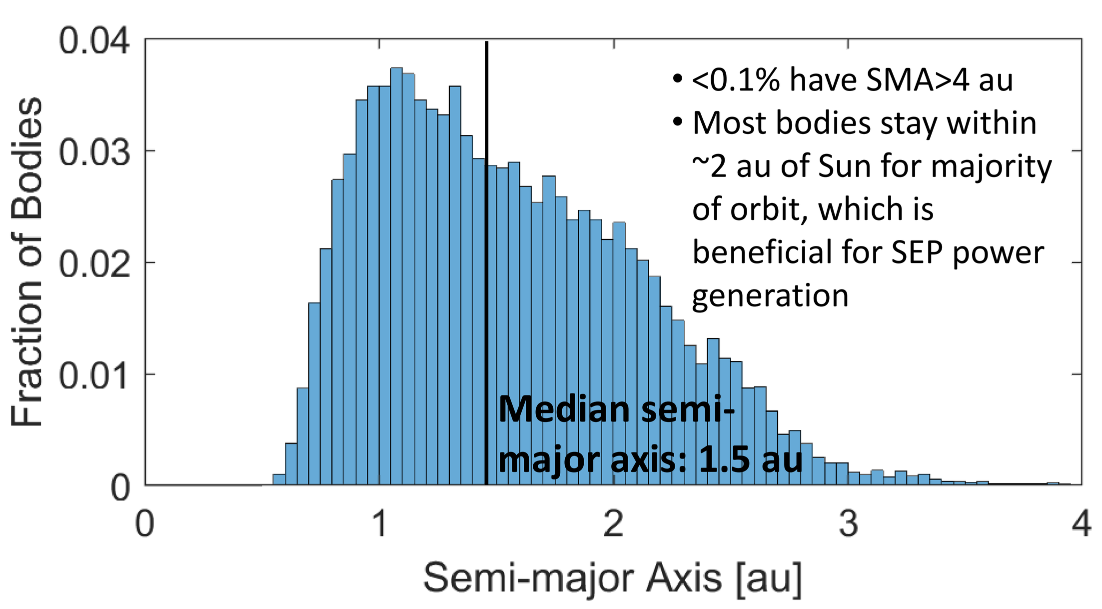
PD scenarios present unique mission design challenges compared to typical space missions:

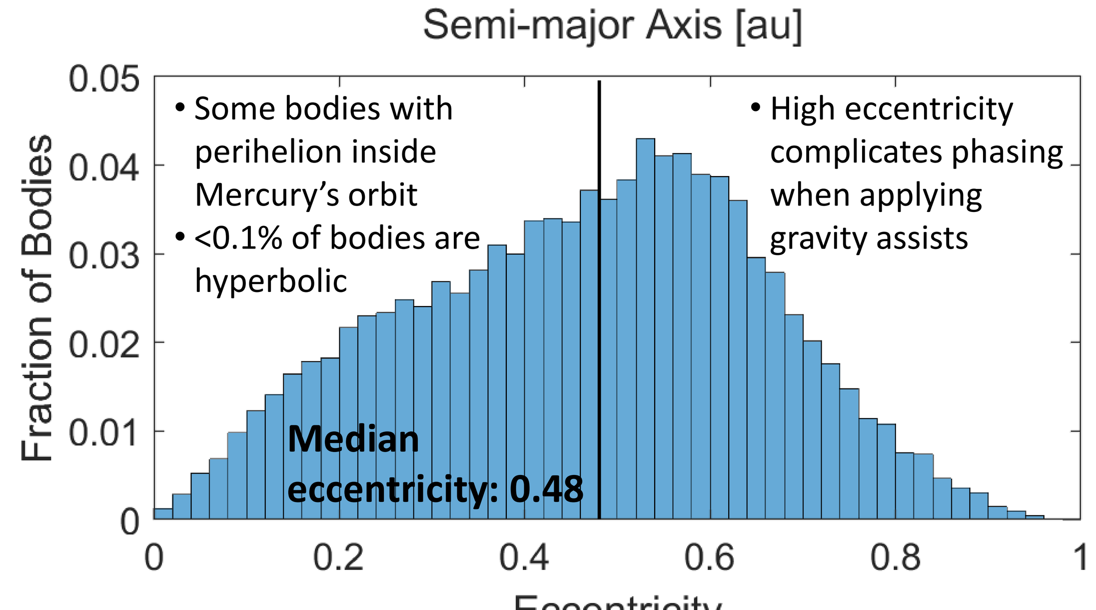
- Target body cannot be selected to conform to predefined science or tech. demo. objectives
- Orbit of the body strongly influences difficulty & complexity of an impact prevention campaign
- The semi-major axis (SMA), eccentricity, & inclination of impacting orbits vary widely and drive the ΔV requirements of space missions for reconnaissance and Earth impact prevention space missions

Histogram of orbital elements of simulated Earth-impacting bodies

based on pool of bodies from Chesley et al., 'Development of a Realistic Set of Synthetic Earth Impactor Orbits', 2019

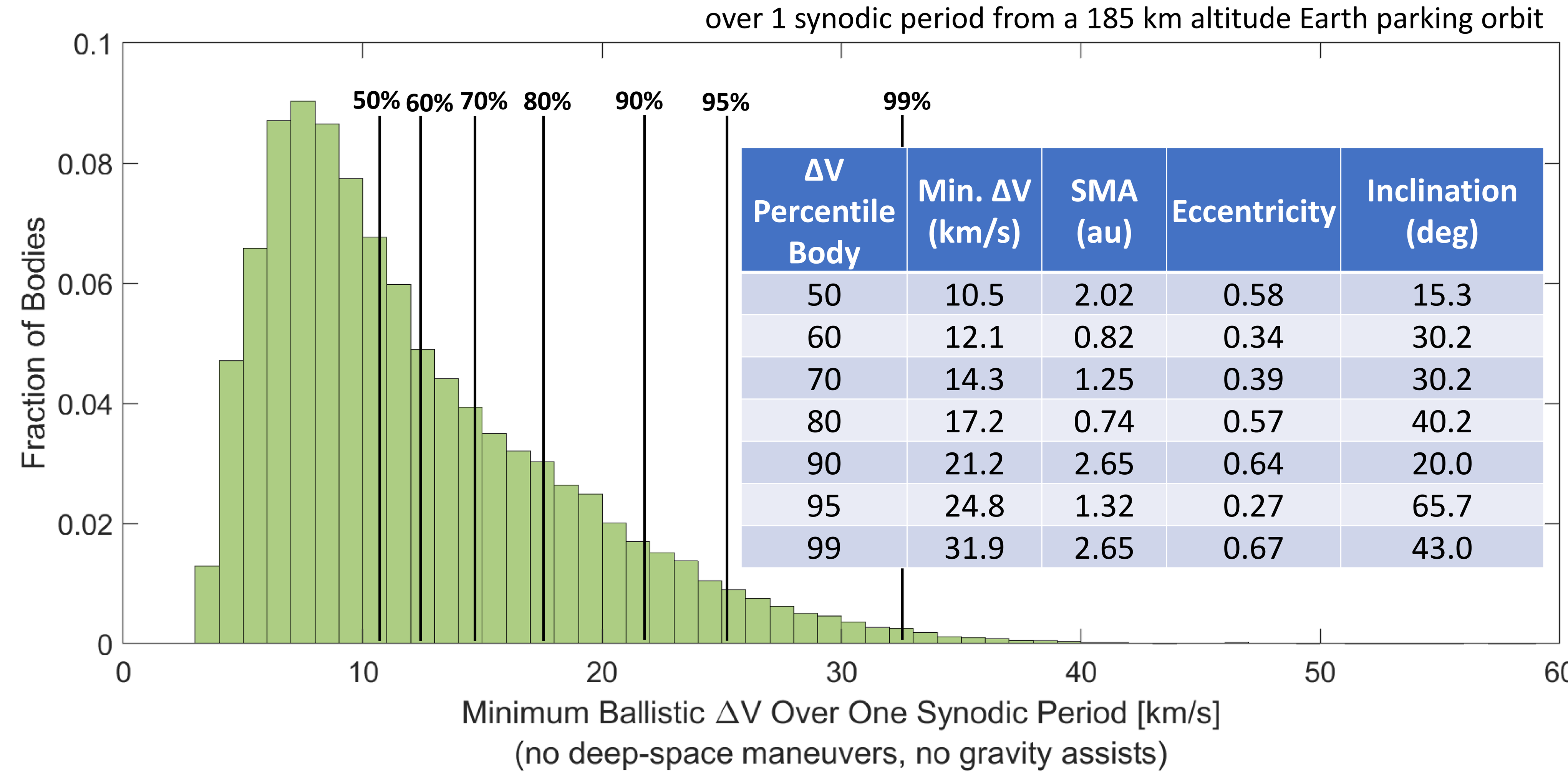






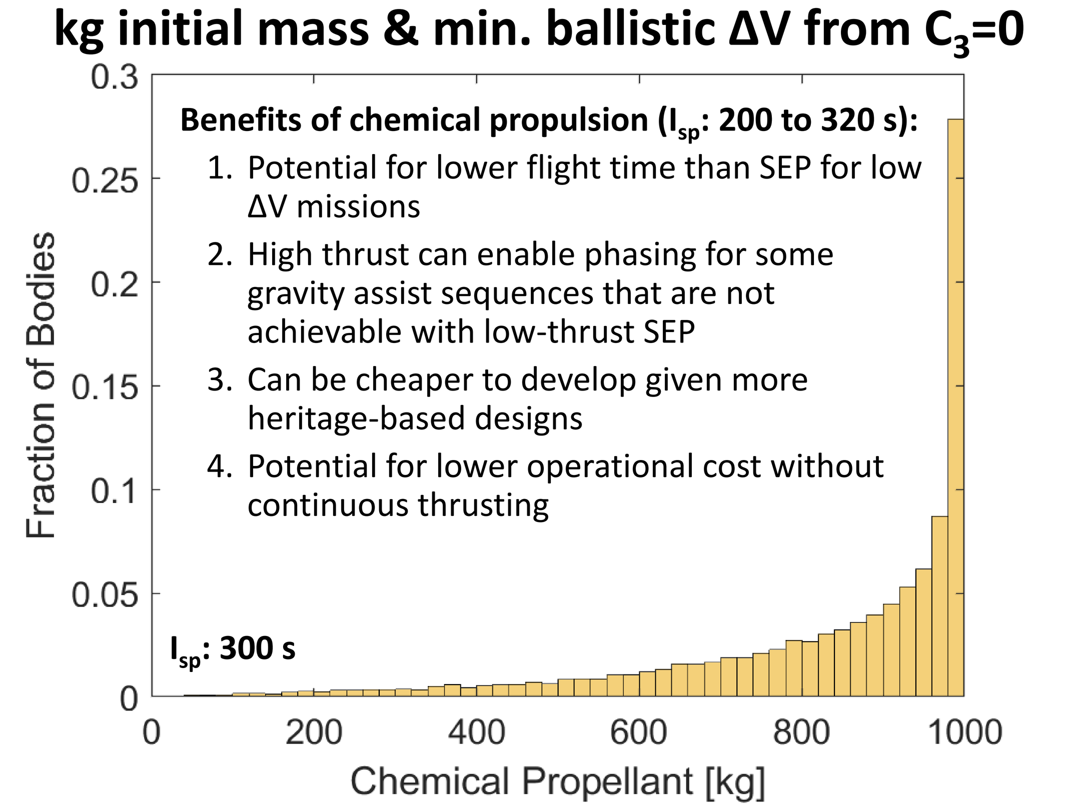
Minimum Ballistic ΔV

Minimum ΔV for direct, ballistic rendezvous is determined based on a Lambert grid scan of all ~27,000 simulated impacting bodies over 1 synodic period from a 185 km altitude Earth parking orbit

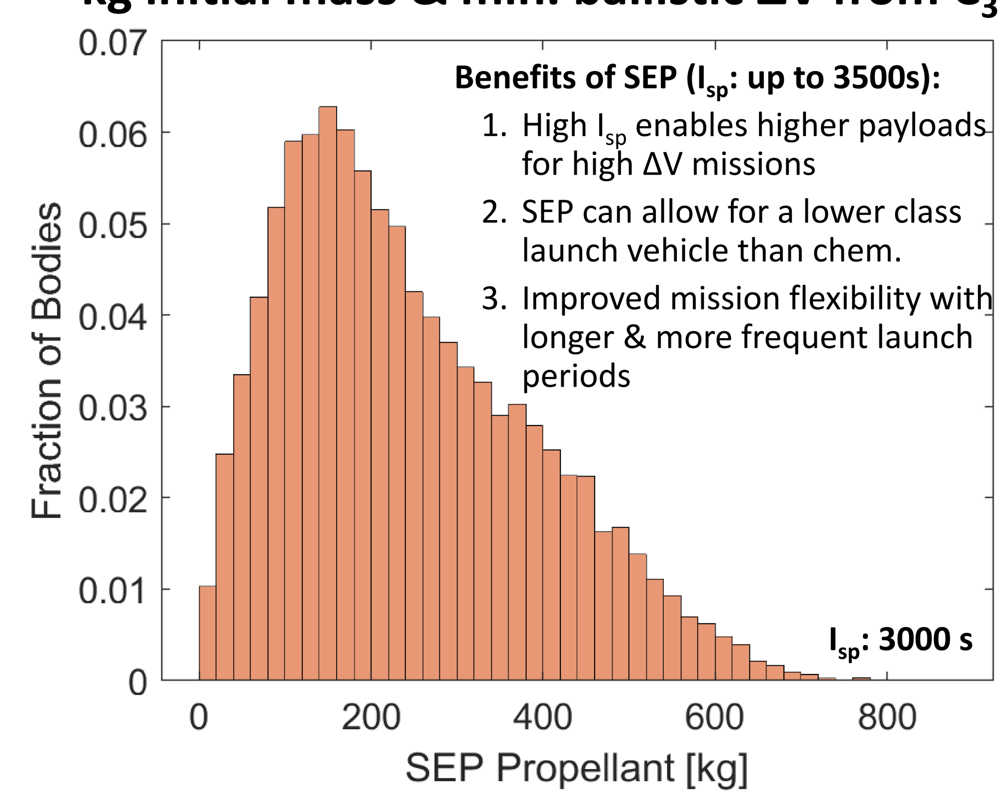


ΔV Percentile Body	Min. ΔV (km/s)	SMA (au)	Eccentricity	Inclination (deg)
50	10.5	2.02	0.58	15.3
60	12.1	0.82	0.34	30.2
70	14.3	1.25	0.39	30.2
80	17.2	0.74	0.57	40.2
90	21.2	2.65	0.64	20.0
95	24.8	1.32	0.27	65.7
99	31.9	2.65	0.67	43.0

Chemical propellant for rendezvous given a 1000 kg initial mass & min. ballistic ΔV from C_3=0



SEP propellant for rendezvous given a 1000 kg initial mass & min. ballistic ΔV from C_3=0



Optimal Delivered Mass Performance with Gravity Assists & Maneuvers

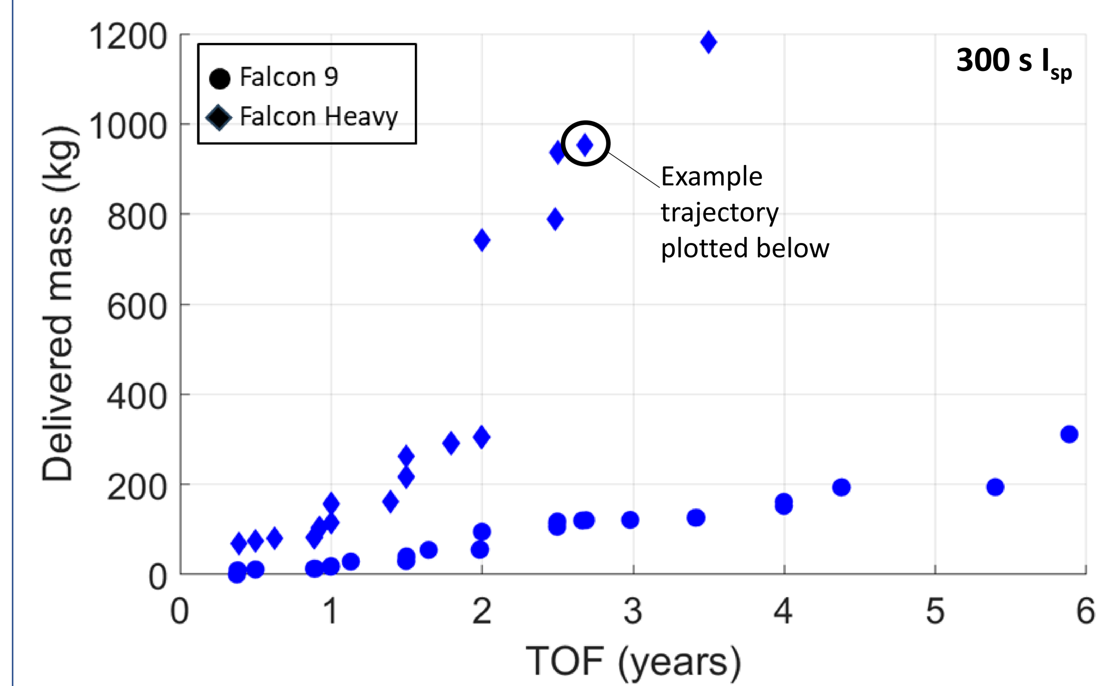
- Time of flight ≤ 3 years
- Chemical propulsion I_{sp}: 300 s
- Variety of SEP engines evaluated

ΔV Percentile Body	Falcon 9 Launch Vehicle: Chemical	Falcon 9 Launch Vehicle: 10-kW SEP	Falcon 9 Launch Vehicle: 20-kW SEP	Falcon Heavy Expendable Launch Vehicle: Chemical	Falcon Heavy Expendable Launch Vehicle: 20-kW SEP	Falcon Heavy Expendable Launch Vehicle: 45-kW SEP
50th	320 kg (GA:VE, PMF: 0.85)	1230 kg (direct)	2000 kg (direct)	1980 kg (GA:E, PMF: 0.78)	2780 kg (direct)	4660 kg (direct)
60th	150 kg (GA:EE, PMF: 0.94)	1620 kg (GA:E)	1900 kg (GA:E)	1100 kg (GA:EE, PMF: 0.87)	4630 kg (GA:E)	5290 kg (GA:E)
70th	120 kg (GA:VE, PMF: 0.94)	1200 kg (GA:E)	1850 kg (GA:E)	950 kg (GA:VE, PMF: 0.89)	2330 kg (GA:E)	4510 kg (GA:E)
80th	20 kg (GA:VEE, PMF: 0.99)	860 kg (direct)	1280 kg (GA:E)	130 kg (GA:VEE, PMF: 0.87)	2490 kg (direct)	4240 kg (direct)
90th	170 kg (GA:MV, PMF: 0.92)	810 kg (direct)	1700 kg (GA:E)	1210 kg (GA:VE, PMF: 0.88)	1940 kg (direct)	3160 kg (direct)
95th	<5 kg (GA:VEE, PMF: 0.99)	310 kg (direct)	530 kg (GA:V)	20 kg (GA:VEE, PMF: 0.99)	750 kg (GA:E)	1240 kg (direct)

PMF: propellant mass fraction; GA: gravity assist; Gravity assist body sequence shorthand: V=Venus, E=Earth, M=Mars

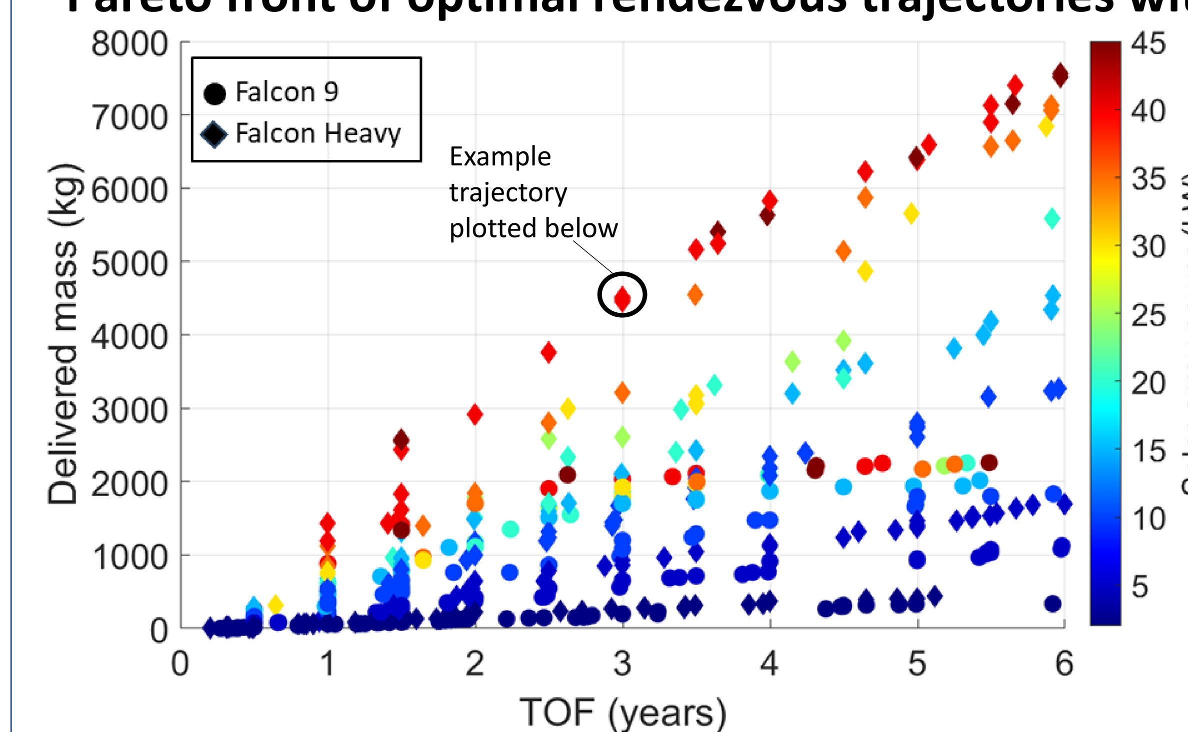
Example Solution Space: 70th Perc. ΔV Body

Pareto front of optimal rendezvous trajectories with chemical propulsion



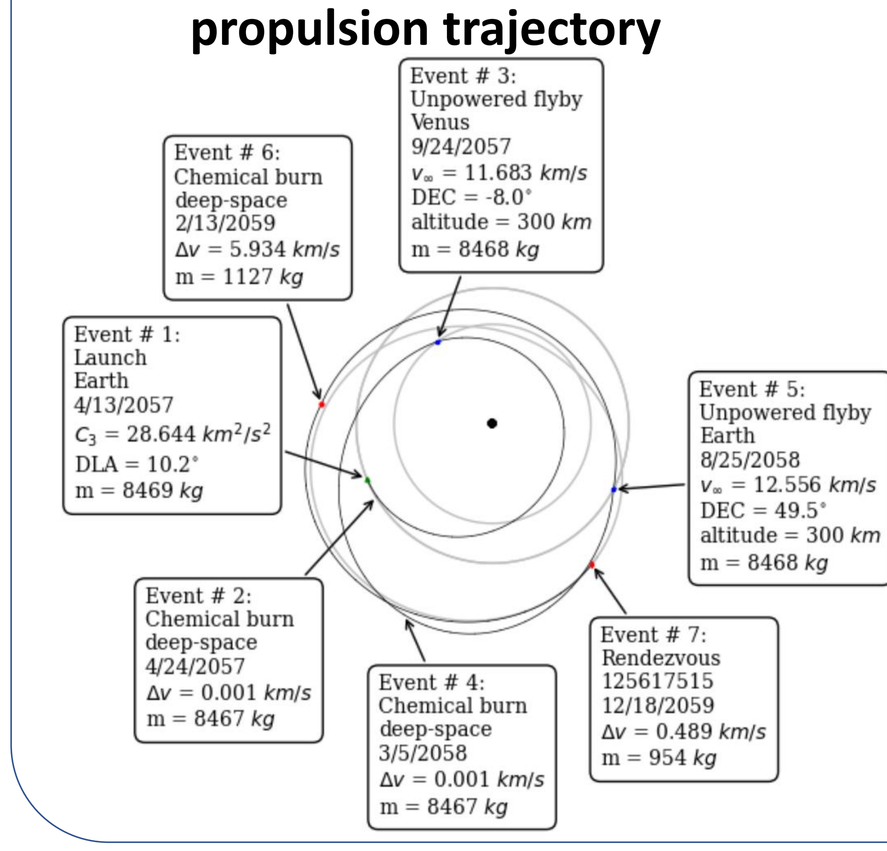
- Any combination of up to 3 flybys (Earth, Venus, Mars)
- Launch date: as early as 10 years before impact
- Time of flight (TOF): 0 – 6 years,
- Launch vehicles (LV): Falcon Heavy Recovery (FHR), Falcon Heavy Expendable (FHE)
- Optimization objectives: maximize (max.) delivered mass, minimize (min.) TOF, min. LV class (i.e., prefer Falcon 9 over Falcon Heavy

Pareto front of optimal rendezvous trajectories with SEP (0 to 45 kW)

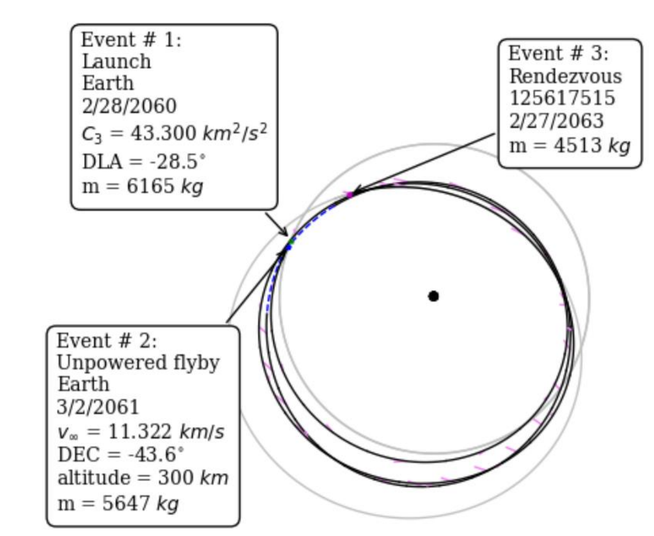


- Power: 2 to 45 kW
- Thrusters traded: NEXT-C, AEPS, XIPS-25, XR5
- Number of thrusters: 1 to 4
- Any combination of up to 3 flybys (Earth, Venus, Mars)
- Launch date: as early as 10 years before impact
- TOF: 0 – 6 years
- LVs: FHR or FHE
- Objectives: max. delivered mass, min. TOF, minimize power, min. number of thrusters, min. LV class

Example 3-year TOF chemical propulsion trajectory



Example 3-year TOF SEP trajectory with 45-kW power



Summary

- Gravity assists are necessary for rendezvous with most impactors if using chemical propulsion
- Propellant mass fractions for chemical rendezvous may be too high for over half of impacting bodies unless flight times >3 years are viable
- Falcon Heavy like capability is needed for most chemical propulsion based missions, even when exploiting gravity assists & deep-space maneuvers
- SEP is highly advantageous for rendezvous given the high ΔV & low solar ranges associated with most impacting bodies
- High-power SEP (>20 kW) & heavy-lift launch vehicle needed for the most challenging impactor orbits (e.g., >90th percentile Lambert ΔV bodies)