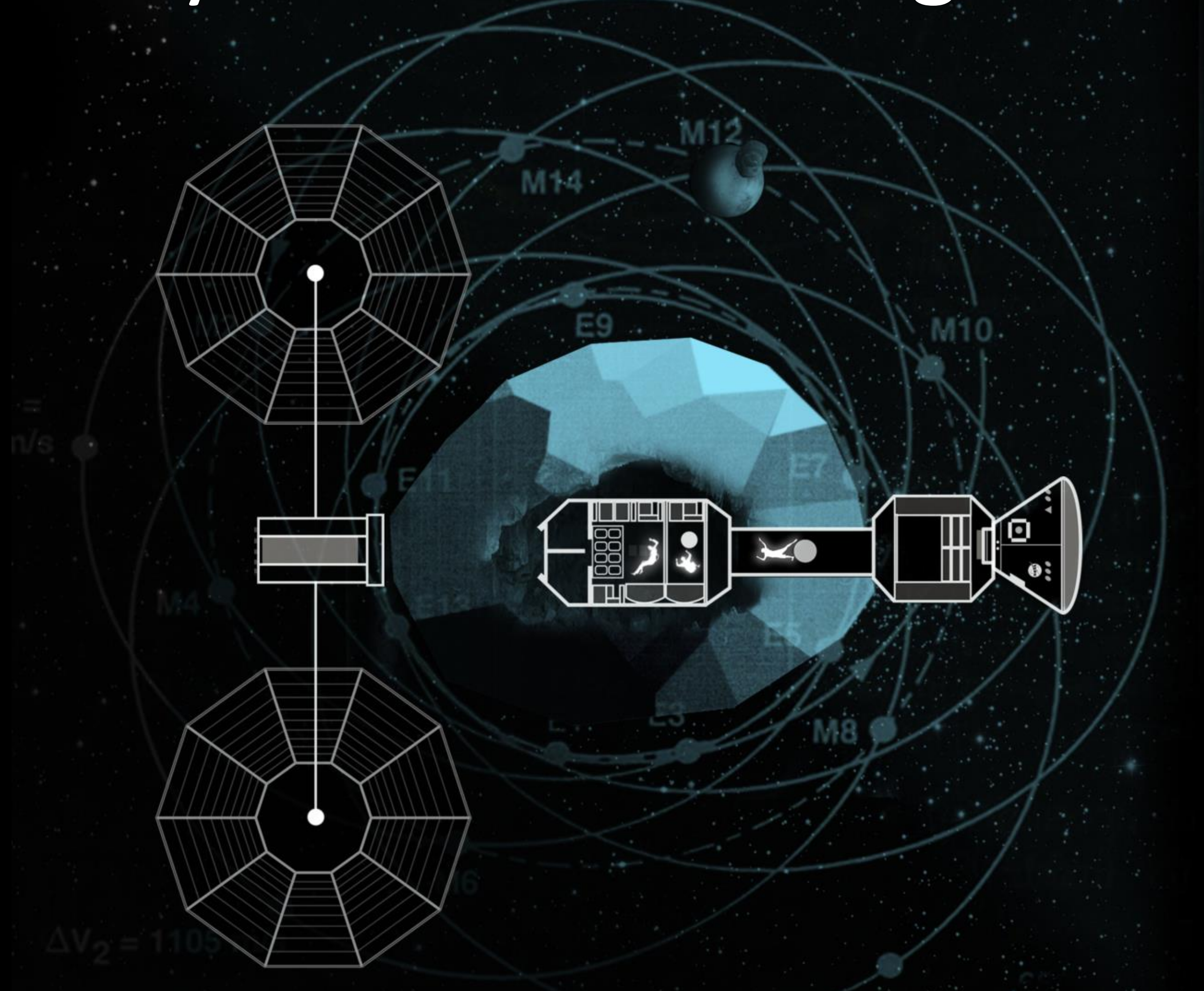
Astrodynamics of Moving Asteroids



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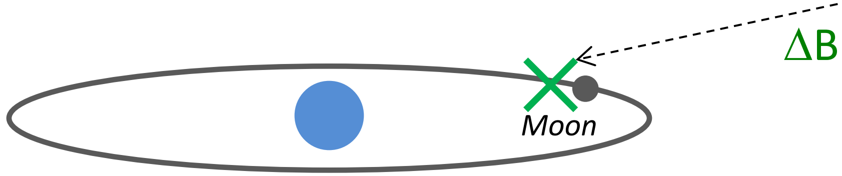
NASA-JPL/CalTech

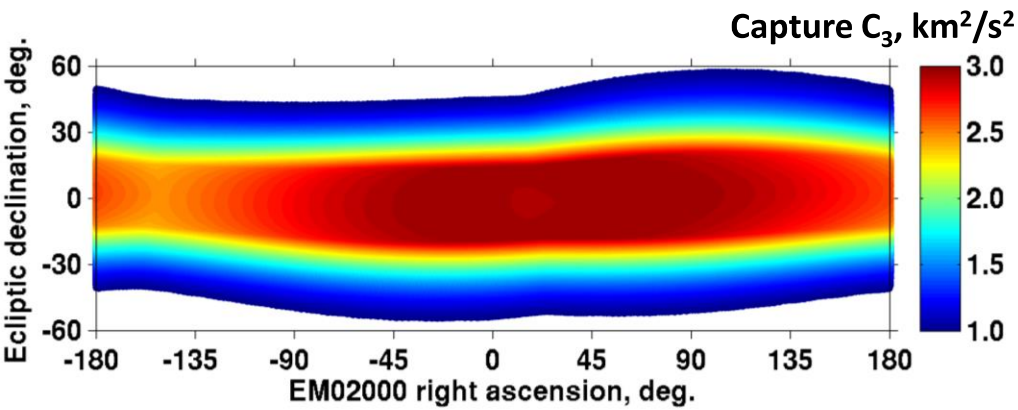
Capture a NEA into Earth orbit

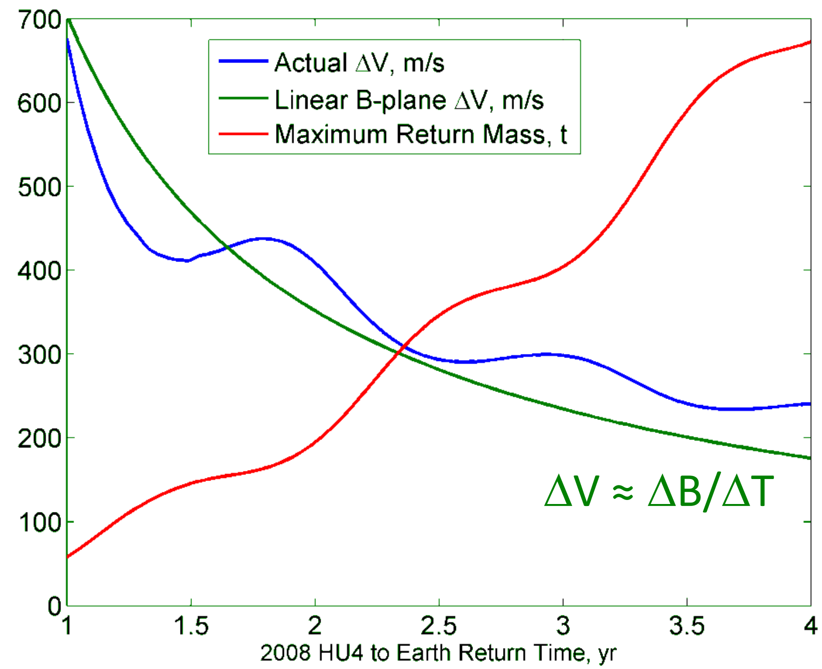
Redirect asteroid for a close approach of the Moon

Most of the ΔV is to speed up/slow down the NEA to encounter Earth near their MOID (typically a node)



Lunar gravity assist captures NEA during Earth flyby

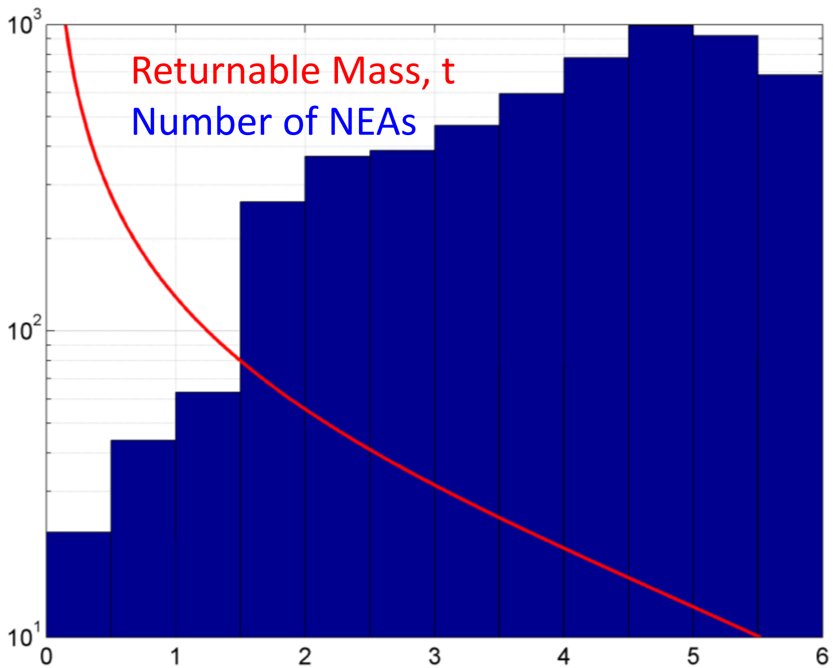




Single flyby captures objects from up to ~3 km^2/s^2 C_3
Double flyby up to ~5 km^2/s^2, depends on declination

2008 HU4 example, return leg only
Natural approach of 0.15 AU, 1.3 km^2/s^2

Asteroids and ΔV and Mass (oh my!)



Minimum ΔV (km/s) between NEA & Lunar Flyby
Deimos is ~7 km/s, Phobos is ~8 km/s

Returnable mass from (10,776) currently known NEAs

Returnable Mass, t	Earth-Sun Lagrange Pts C_3 <1 km^2/s^2	Lunar Flyby C_3 <2.5	Earth flybys & "backflips" C_3 <25
10–50	653 NEAs	2564	4067
50–150	62	207	827
150–300	10	16	190
300–500	6	10	75
500–1000	4	8	40
1000+	0*	0*	10

Phase-free, circular Earth orbit, 6 t Xe, 5 t SEP, 2000 s Isp*

**circular Earth orbit → up to 300 m/s ΔV errors*
2006 RH120 is the known exception for 1000+ t to Lagrange Pts and 2000 SG344 > 1000 t for Lunar flyby

Close approaches no longer factor into the equation for high-ΔV NEAs

Potential Return Opportunities, 2020s

- Atlas 551 Launch to 200 x 11k km alt., Launch ~1.5 yr before escape
- 40 kW array
- 3000 s Isp, 60 % eff.
- 60 days at NEA
  - 4 d Rendezvous (200 km)
  - 13 d Characterization
  - 4 d Bag deployment
  - 0.5 d Capture
  - 1.5 d De-spin/de-tumble
  - 1.5 d Checkout
  - Double & round up for margin

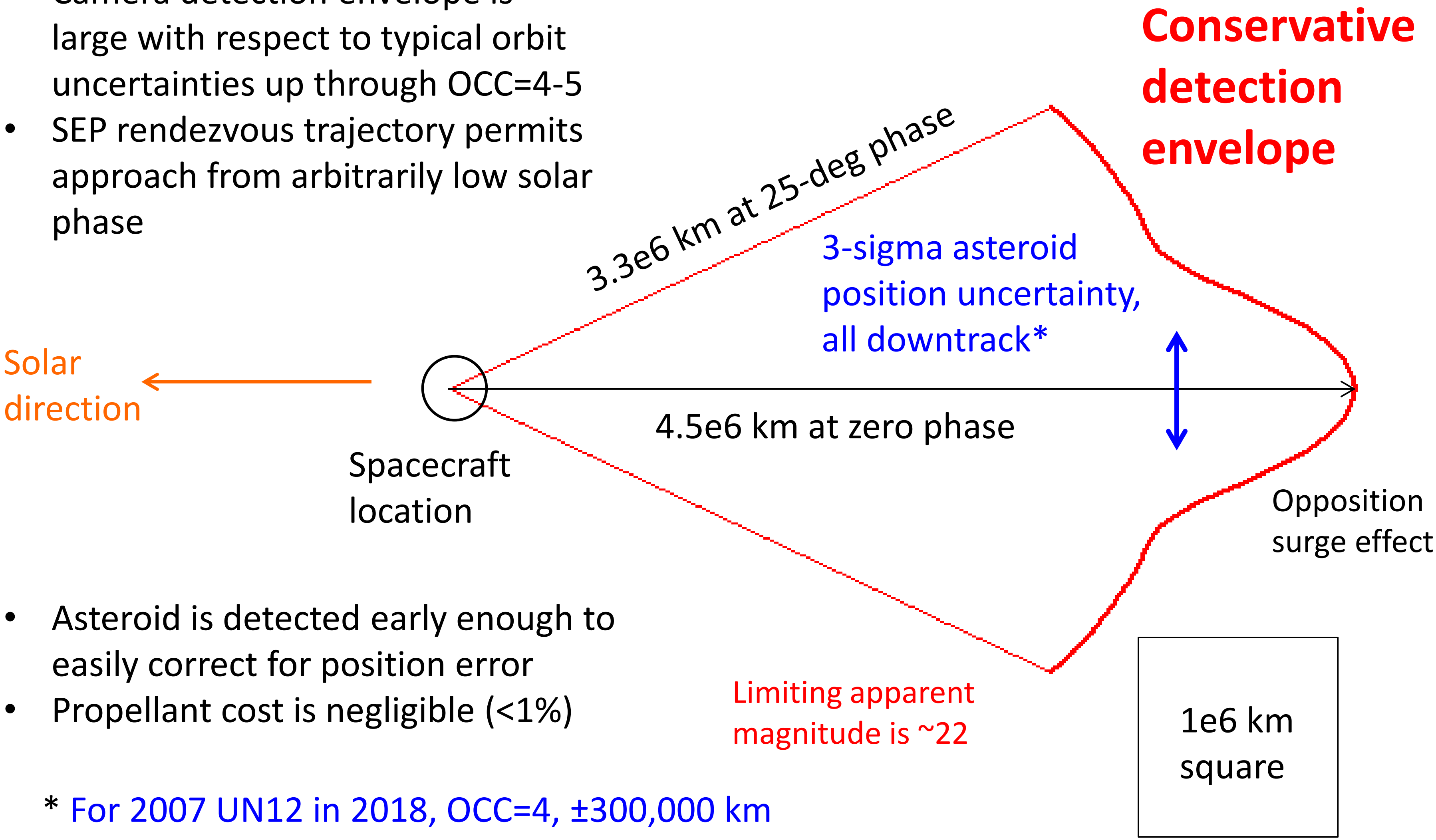
Abbreviated List

Asteroid	Asteroid Diameter	Return C_3	Max Return Capability	Earth Escape	Return Date
2007 UN12	4–11 m	2.2 km^2/s^2	500 t	Jun '17	Sep '20
2009 BD	5–13	1.7	900	Jun '17	Jun '23
2009 BD	5–13	1.7	500	Jan '19	Jun '23
2010 UE51	5–13	0.9	500	Jun '18	Nov '23
2011 MD	6–14	2.1	800	Jun '18	Jun '25
2011 MD	6–14	2.1	450	Jan '20	Jun '25
2008 HU4	6–14	1.6	500	Apr '20	Apr '26
2013 GH66	6–14	5.3	800	Jan '23	Apr '27
2000 SG344	27–65	1.6	1000	Feb '24	Sep '28
2006 RH120	3–7	0.3	400	Jul '24	Nov '28
2000 SG344	27–65	2.1	3000	Mar '27	Sep '29

Diameter assumes 5–30 % albedo range

Finding the target is easy with a good camera and SEP

- Camera detection envelope is large with respect to typical orbit uncertainties up through OCC=4-5
- SEP rendezvous trajectory permits approach from arbitrarily low solar phase

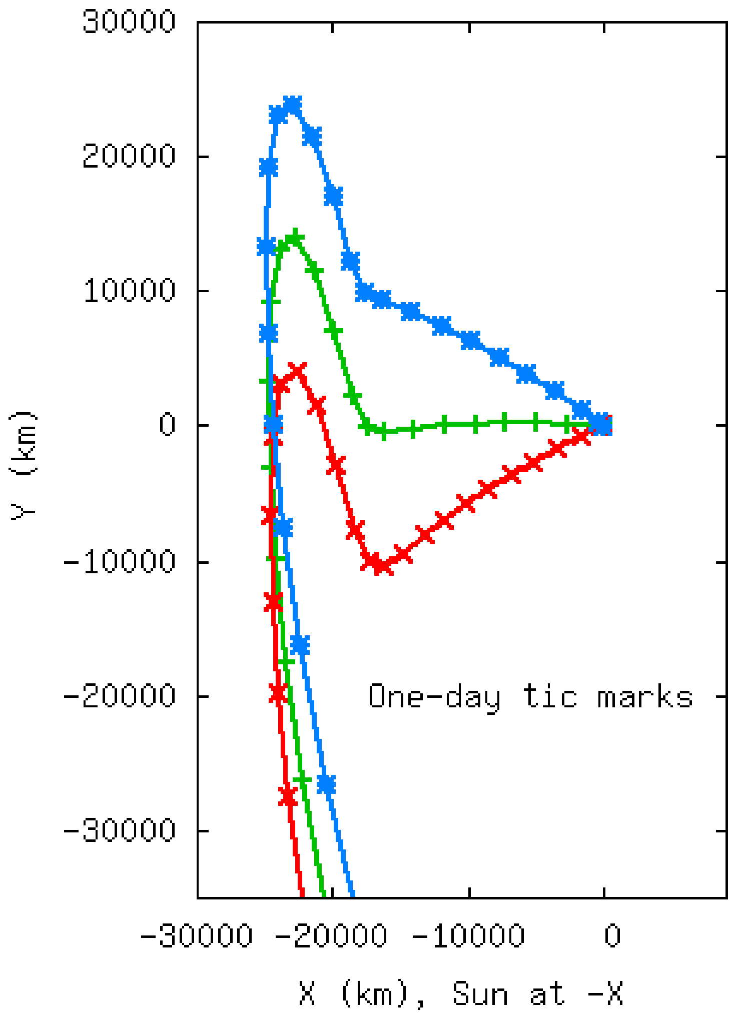


- Asteroid is detected early enough to easily correct for position error
- Propellant cost is negligible (<1%)

* For 2007 UN12 in 2018, OCC=4, ±300,000 km

Example Anti-Sunward Approach Trajectory
10k–100k km error

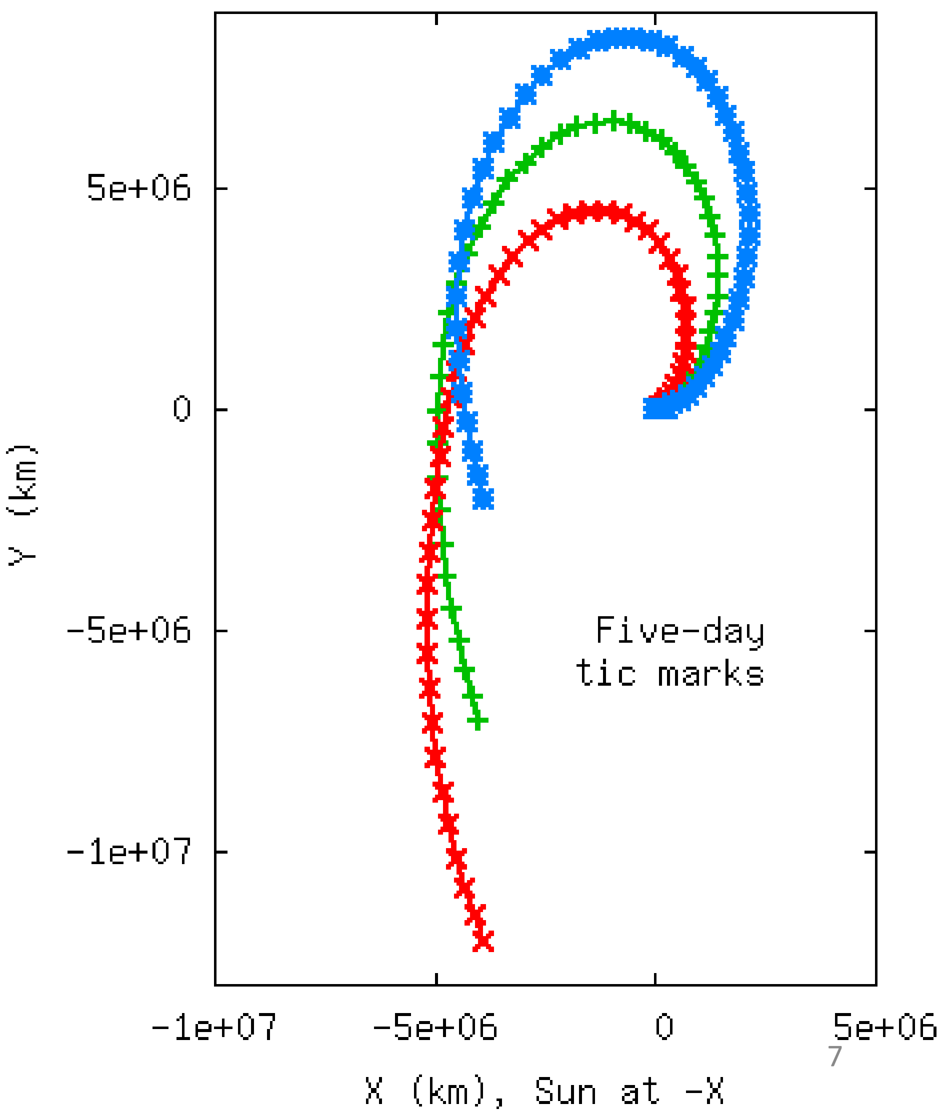
- Example trajectory, in Sun-asteroid rotating frame, asteroid-centered, Sun at the left
  - Trajectories all the same inertially up to 15,000 km sunward
    - Approach forced through a sunward point
    - Assumes only minimal MRO ONC performance
  - Trajectories are offset in asteroid relative frame due to ephemeris error
    - Nominal, plus 10K, minus 10K
  - All trajectories reach (0,0) at rendezvous by definition
- Propellant cost is only ~1% total prop for 300,000 km error
  - 2009 BD error is only 2,500 km
  - Larger error is applicable to 2010 UE51, 2011 MD, 2007 UN12
  - Result not optimized, can do better



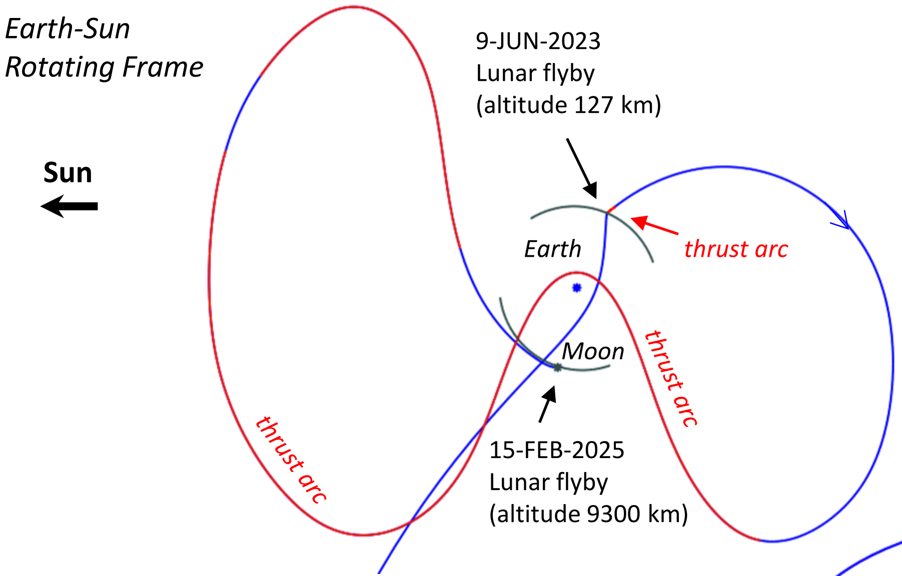
Example Anti-Sunward Approach Trajectory

5M km error

- 2008 UA202 example, in Sun-asteroid rotating frame, asteroid-centered
  - Trajectories start out the same inertially
    - Plan includes forced coast, covering ±5 million km of downtrack, at up to 5 million km sunwards
  - Thrusting starts again as soon as trajectory passes sunward of actual asteroid location
  - Trajectories are offset in asteroid relative frame due to ephemeris error
    - Nominal, plus 5 million, minus 5 million
  - Post-detection thrusting corrects error, achieves rendezvous
- Time cost is 10.5 months, for essentially no propellant
  - Result not optimized, can perhaps do better
  - Time cost will remain significant

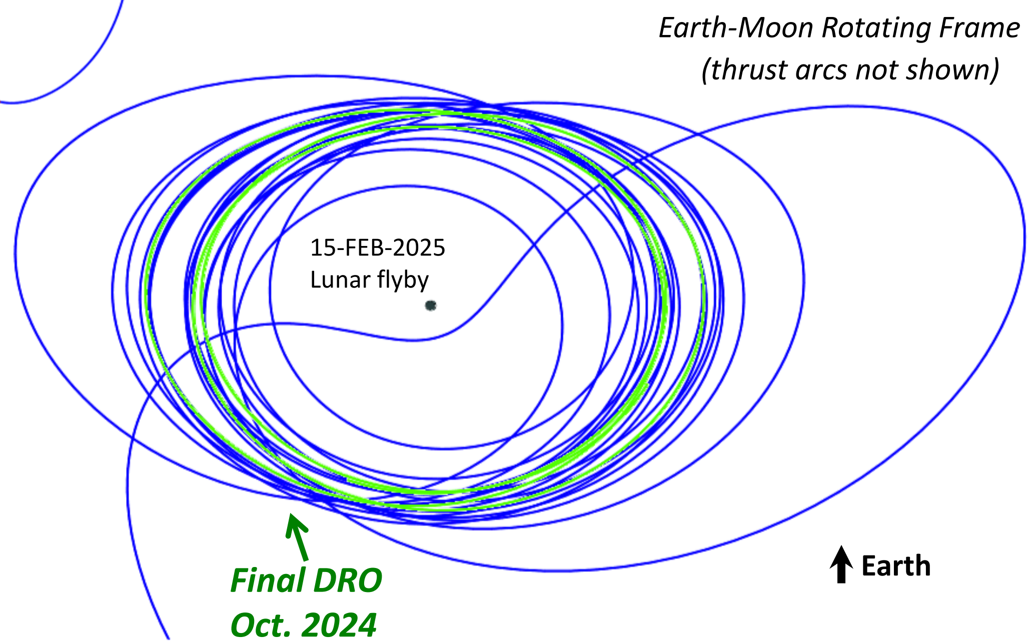


Earth-Moon System Trajectory



Trajectory to Storage Orbit
DV = 10–35 m/s
TOF = 251 days (0.7 yr)

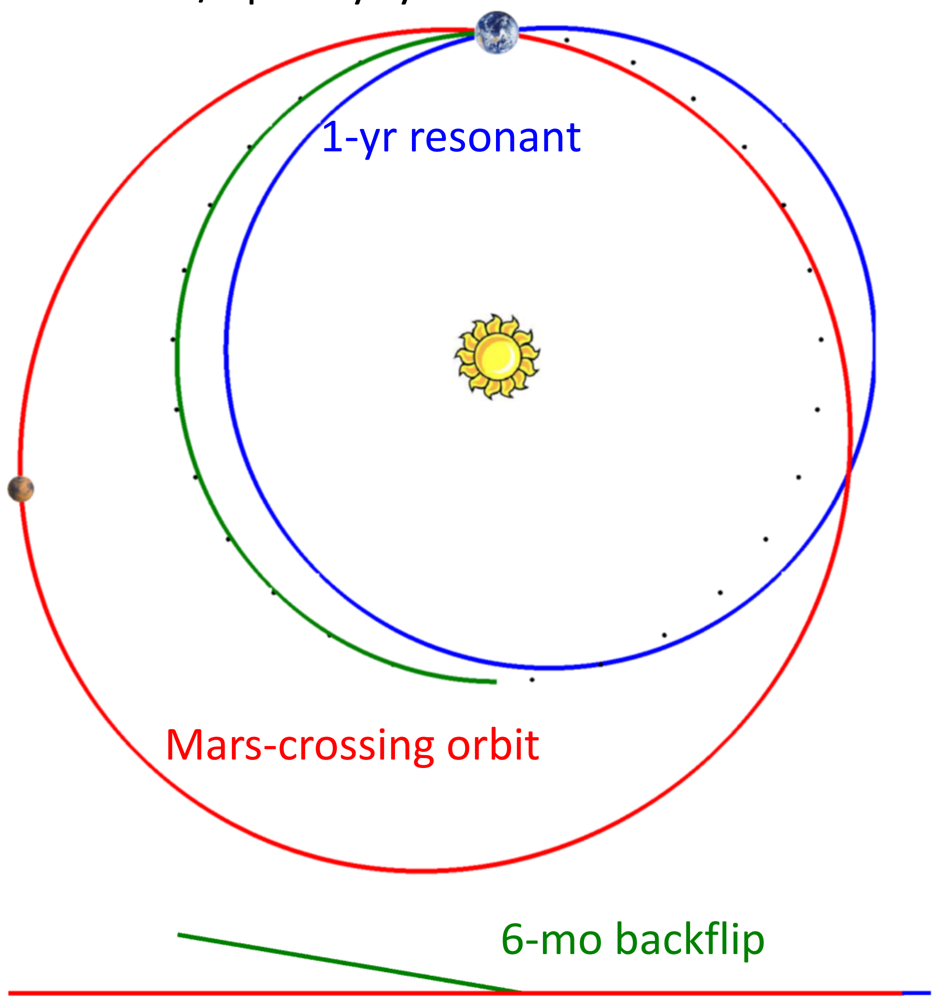
Use Moon to burn off energy wrt Earth
Use Sun to burn off energy wrt Moon



Orbit Trim Maneuvers
(for long term stability)
DV = 25 m/s
TOF = 257 days (0.7 yr)

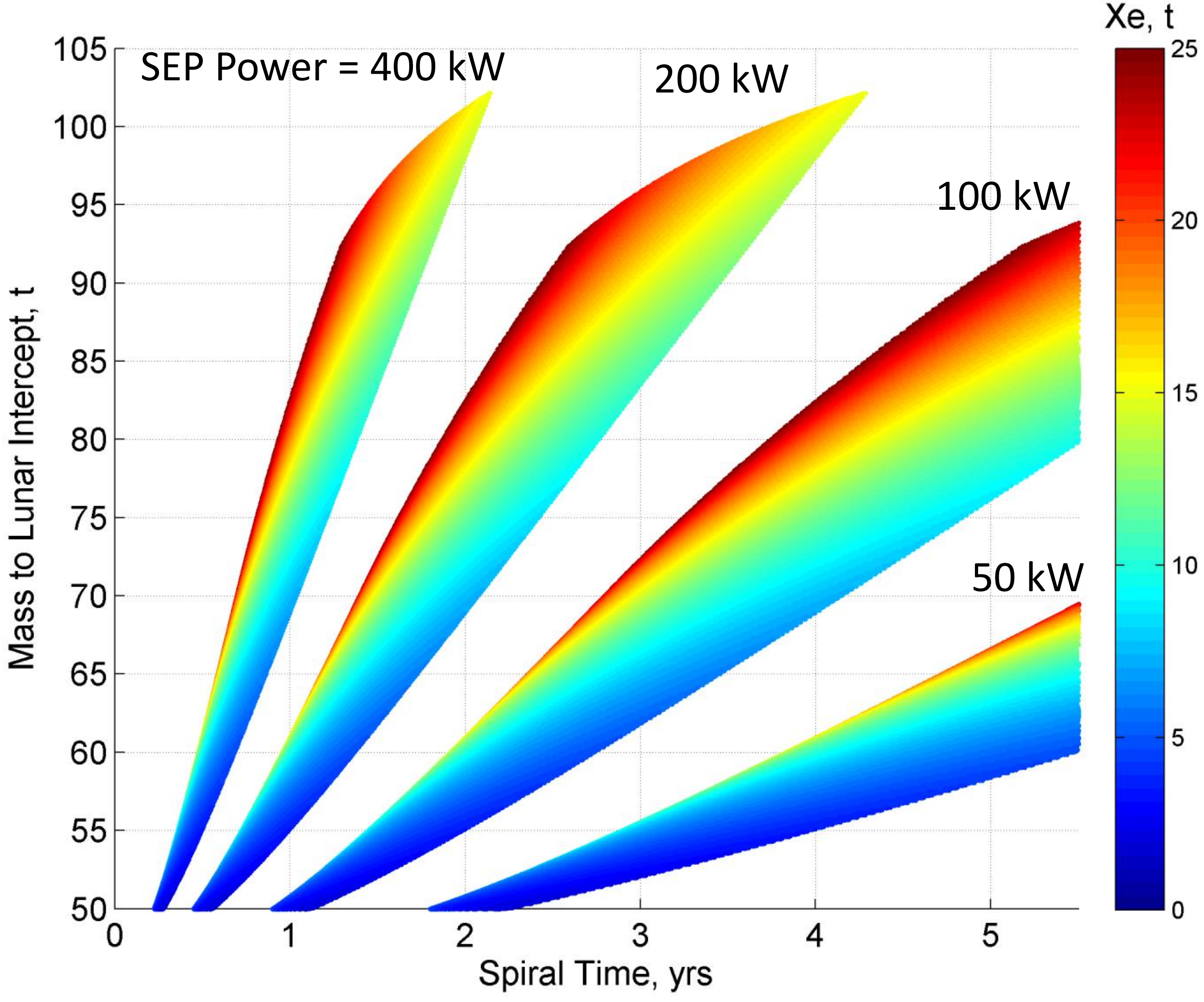
Earth Flybys Provide a Range of Orbits

Flyby $C_3 = 25\ km^2/s^2$
1–10 m/s per flyby



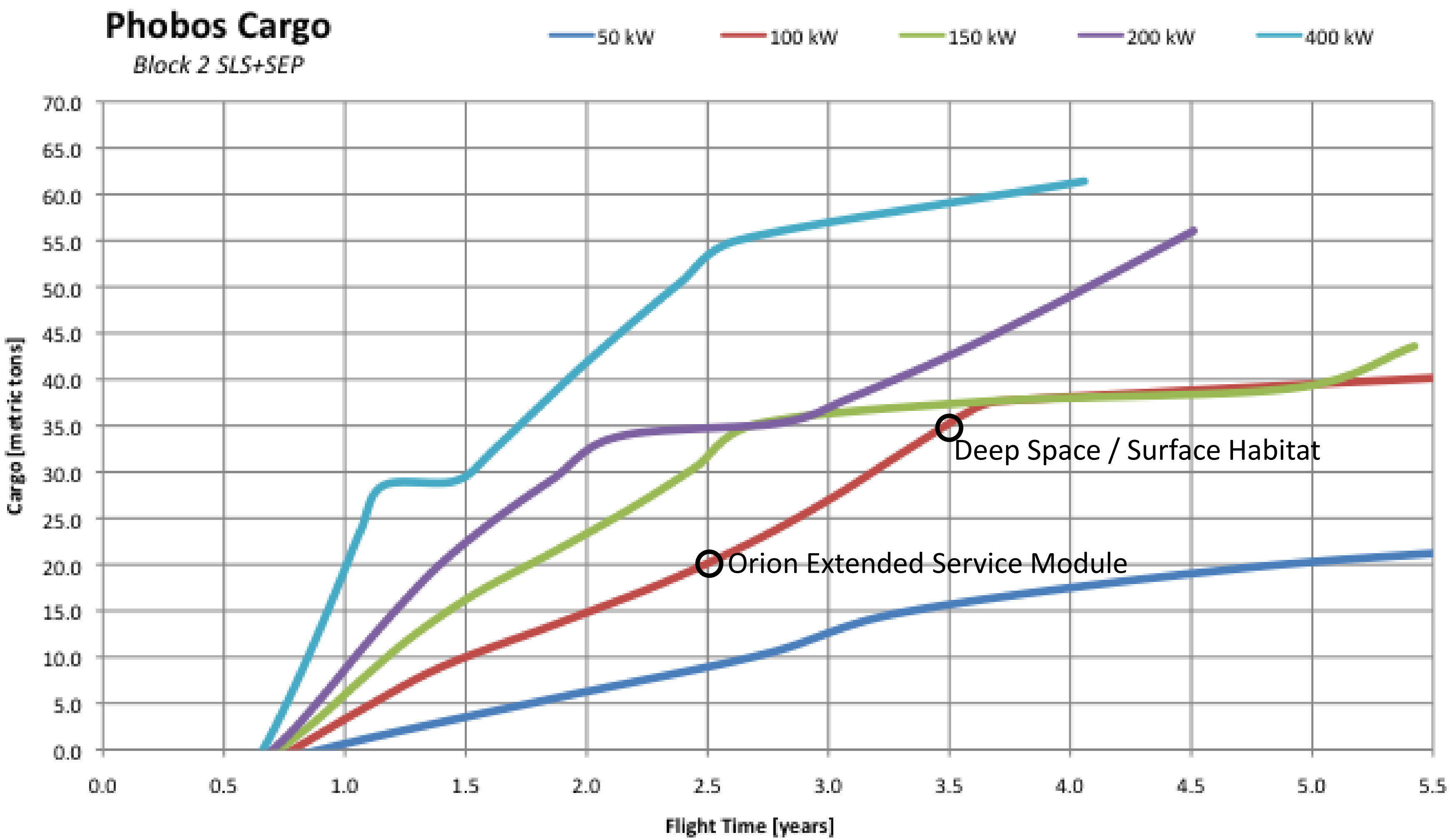
- 180° "backflip" transfers enable low ΔV, 6-month missions.
- 1-year transfers also available. Shorter transfers with modest ΔV.
- Potential precursors to longer duration NEA and Mars missions.

Single SLS Earth Cargo Spirals



47 t direct to Lunar Flyby with Block 2 (25 t with Block 1a)

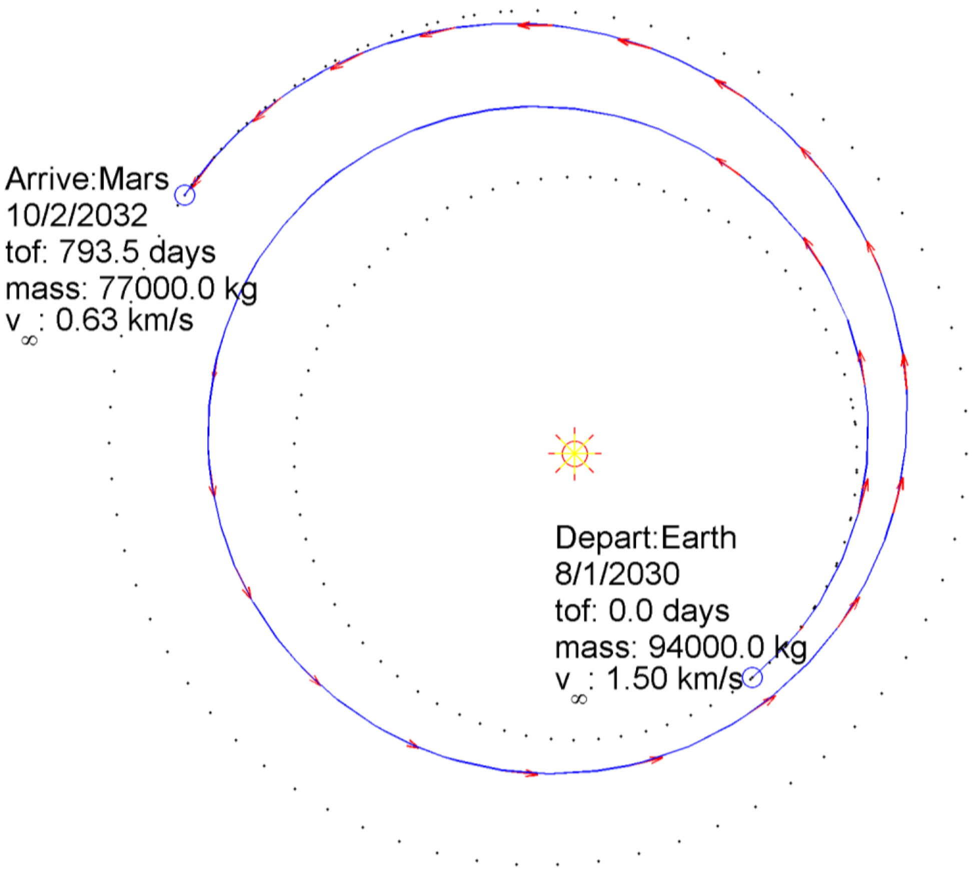
Single SLS Mars Cargo Trajectories



Power provides largest lever on Flight Time.
Additional Xe (above 15 t) enables additional Cargo, or SEP transfers at Mars.

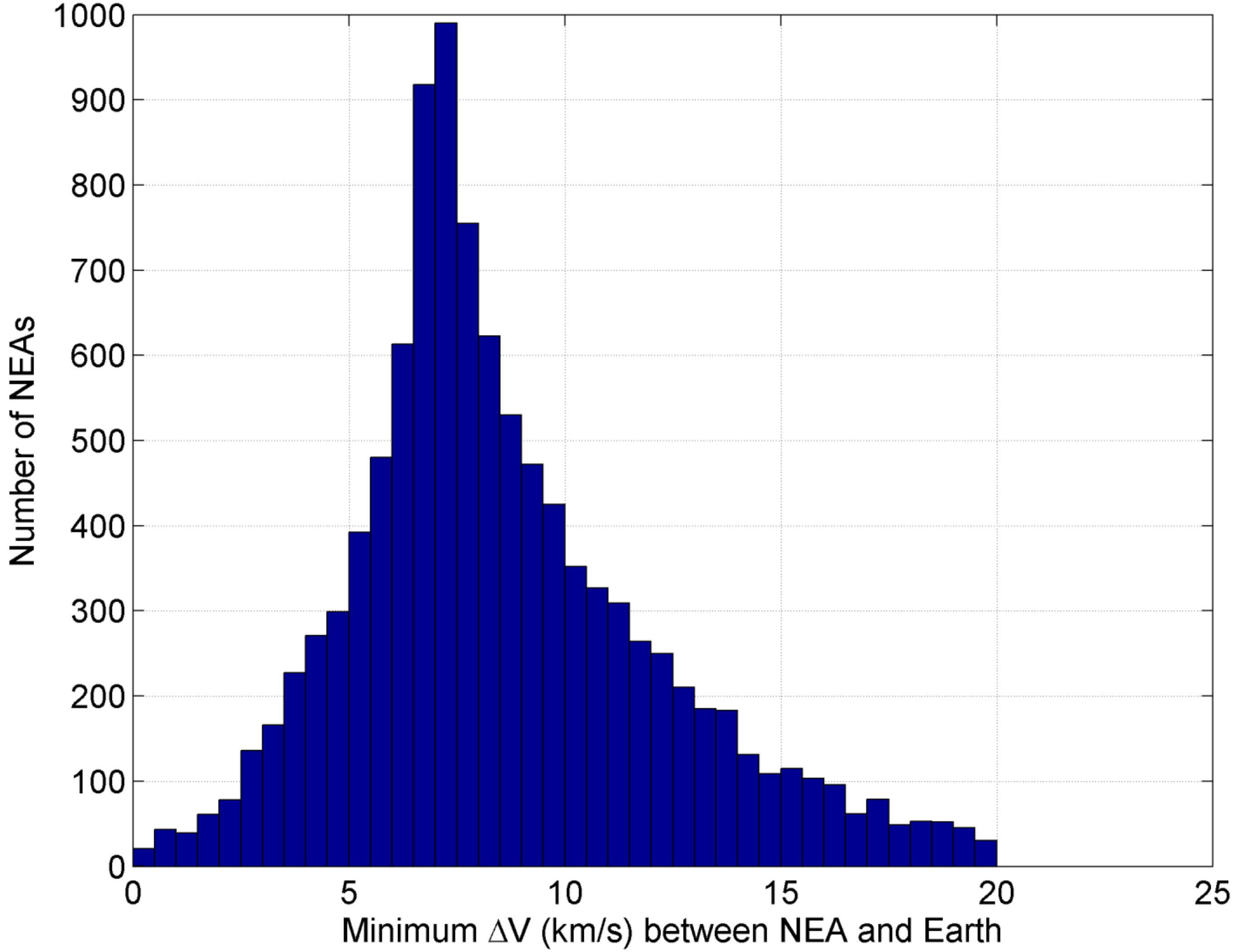
70 t to 1-sol Mars Orbit with Single SLS

- 270 kW SEP, 3200 s Isp
- Additional payload requires more spiraling at Earth
- High-thrust capture with bi-prop eliminates Mars spiral time
- Takes 4.5 years to deliver to Mars orbit (860 d spiral, 791 d to Mars), and 32.2 t Xe (22.0 t spiral, 10.2 to Mars)



Takeaways

- Lunar gravity assist significantly expands the range of NEAs retrievable to Earth orbit.
- Lower return mass (i.e. a boulder) opens the door to a lot of high ΔV (several km/s) NEAs.
- Even more targets could be accessed in Earth resonant orbits for stepping-stone duration ($\leq$ 1 yr) missions.
- ARV-derived SEP systems can roughly double cargo payloads delivered to HEO, Lunar DRO, HMO, Phobos, and Deimos.


1000
900
800
700
600
500
400
300
200
100
0
Number of NEAs
0
5
10
15
20
25
Minimum ΔV (km/s) between NEA and Earth

Assumptions for 70 t Payload to Mars

- Single SLS launch
  - Begin in 241 km alt orbit
  - 140.8 t in LEO, 23.6 t of which is inert upper stage
  - 462 s Isp
- Lunar-assisted escape
- 323 s Isp for chemical capture
- Deliver 77 t to 250 km alt x 24 hr Mars orbit