Comet Hitchhiker

FY15 NIAC Phase I Study

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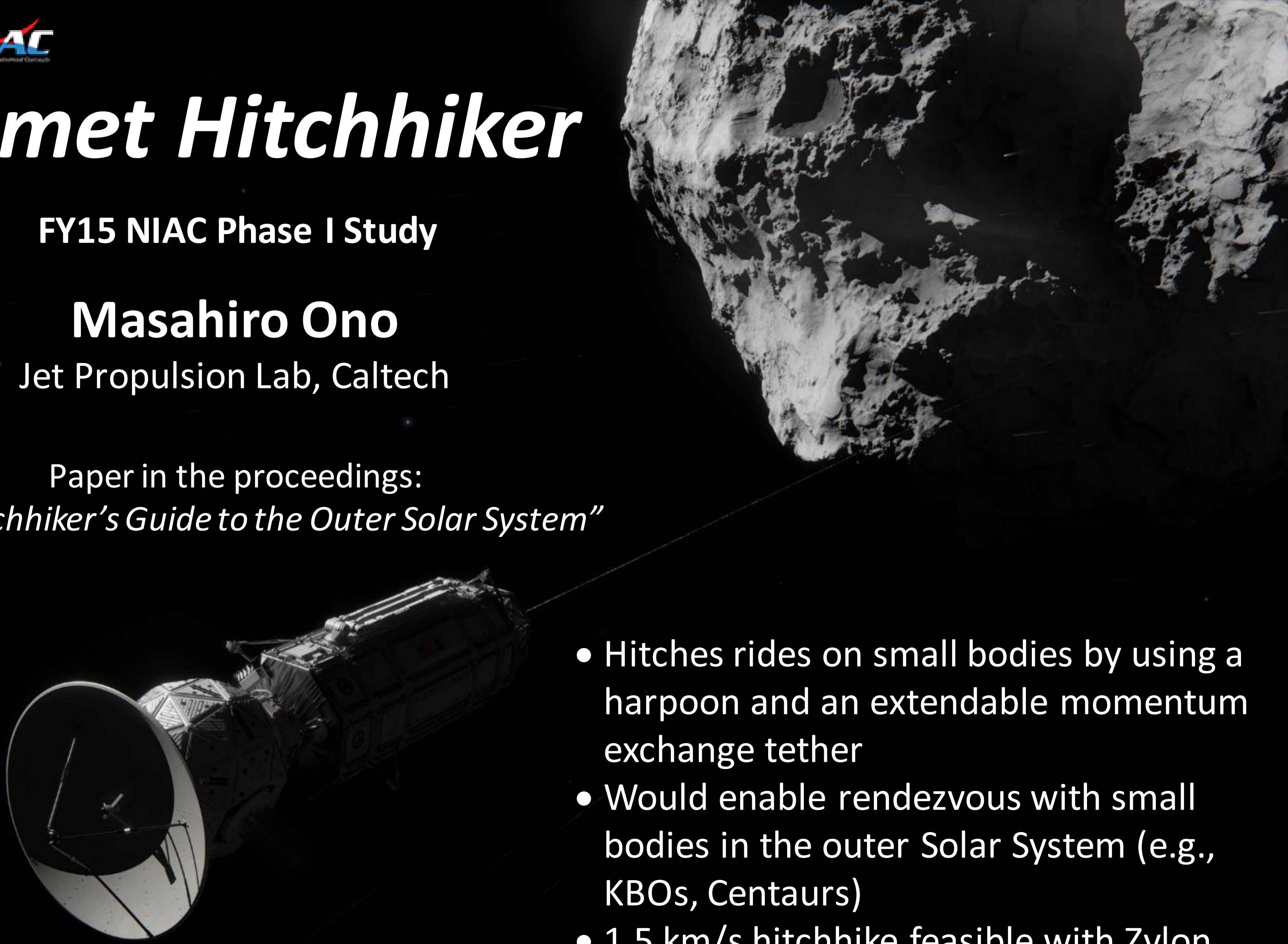
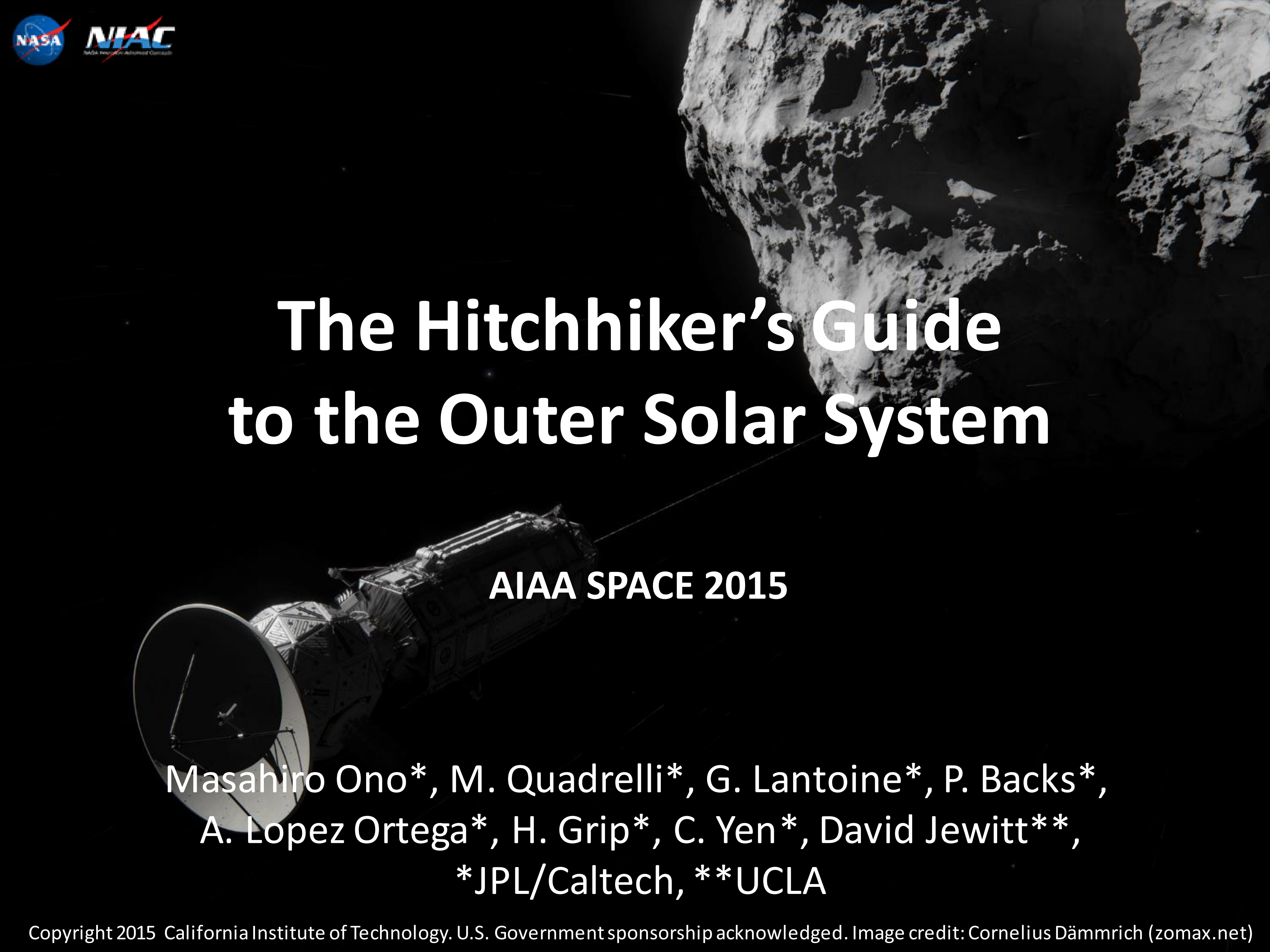
Paper in the proceedings:
"The Hitchhiker's Guide to the Outer Solar System"



- Hitches rides on small bodies by using a harpoon and an extendable momentum exchange tether
- Would enable rendezvous with small bodies in the outer Solar System (e.g., KBOs, Centaurs)
- 1.5 km/s hitchhike feasible with Zylon tether; 10 km/s enabled by CNT tether



The Hitchhiker's Guide to the Outer Solar System

AIAA SPACE 2015

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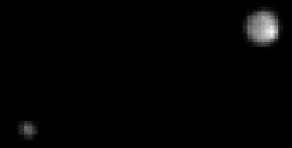
 Image credit: Cornelius Dämmrich (zomax.net)

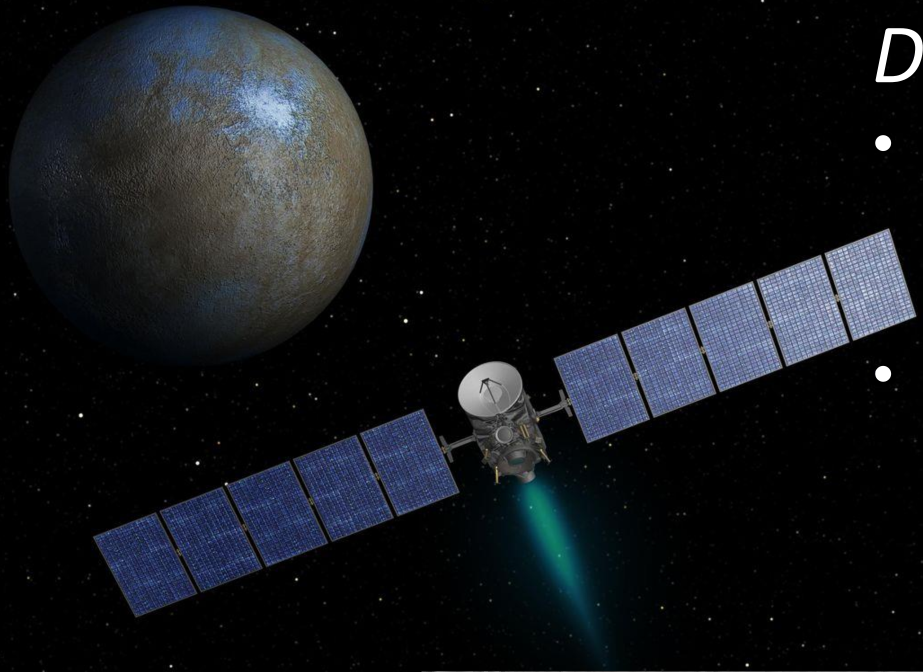
New Horizons

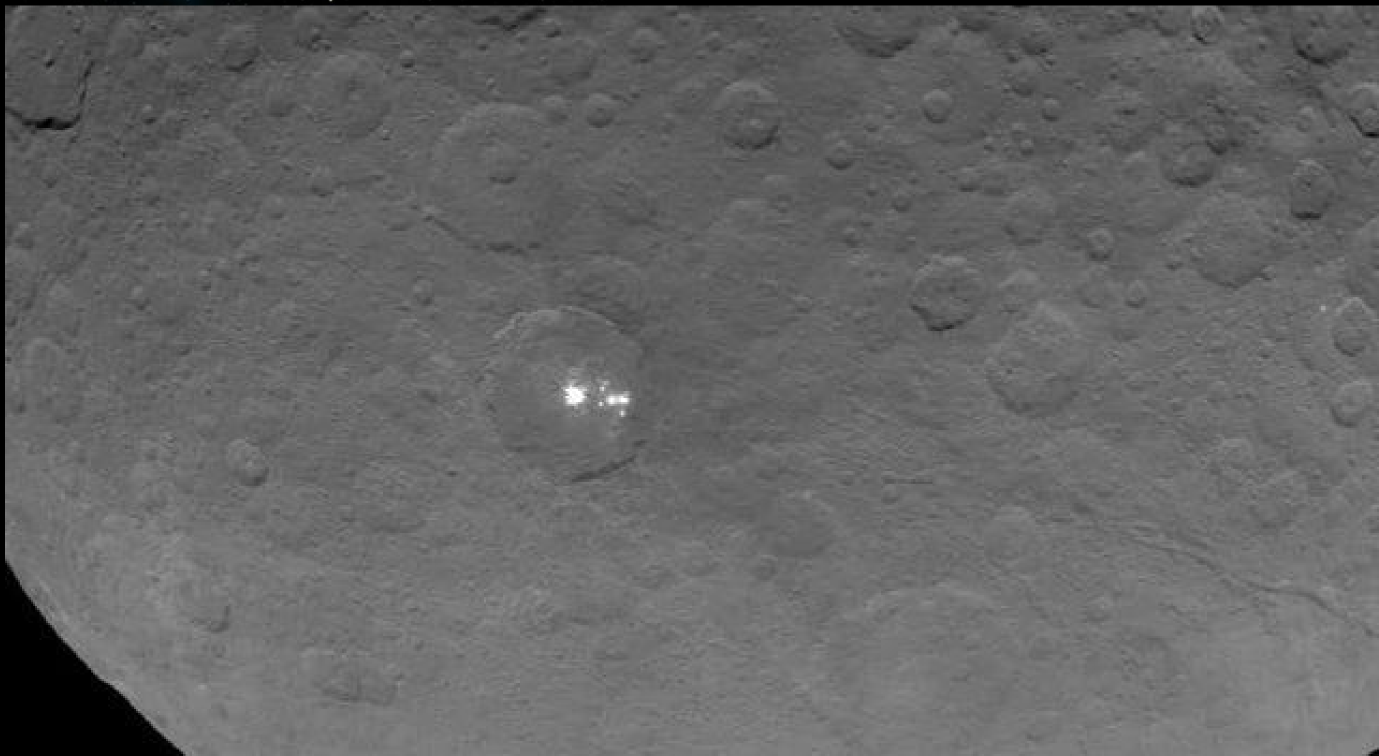
- The first spacecraft encounter with KBO
- Launched in 2006
- Pluto fly-by on July 14, 2015
- Closest distance: 10,000 km
- Relative velocity: 13.78 km/s (~50,000 km/hr)



Dawn

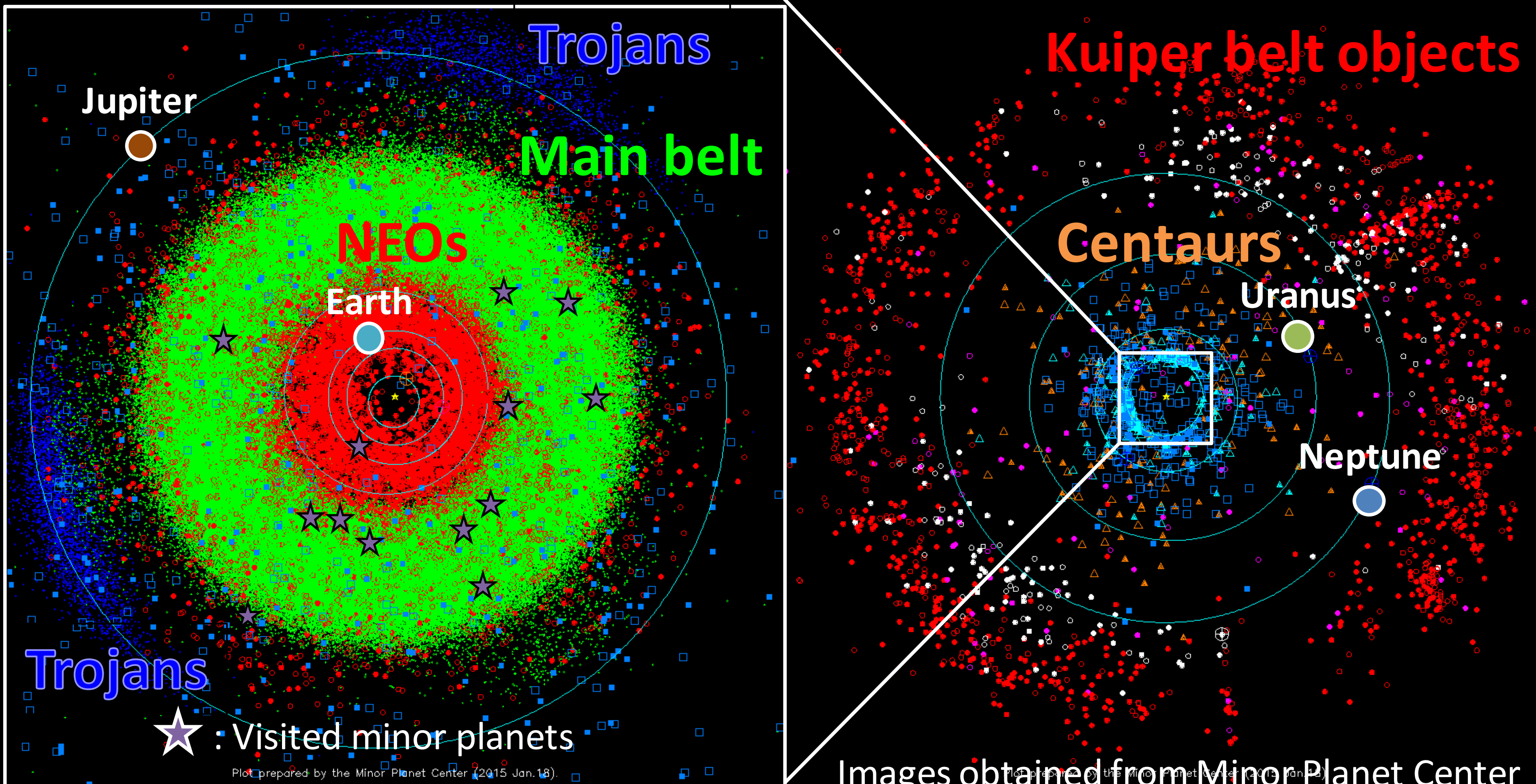
- Vesta rendezvous in 2011
  - 14 months in orbit
  - Closest distance: 210 km
- Ceres rendezvous in 2015
  - Expected closest distance: 375 km





Only a *very* small fraction of minor bodies has been visited

Minor body exploration is a key to ascertain the content, origin and evolution of the Solar System

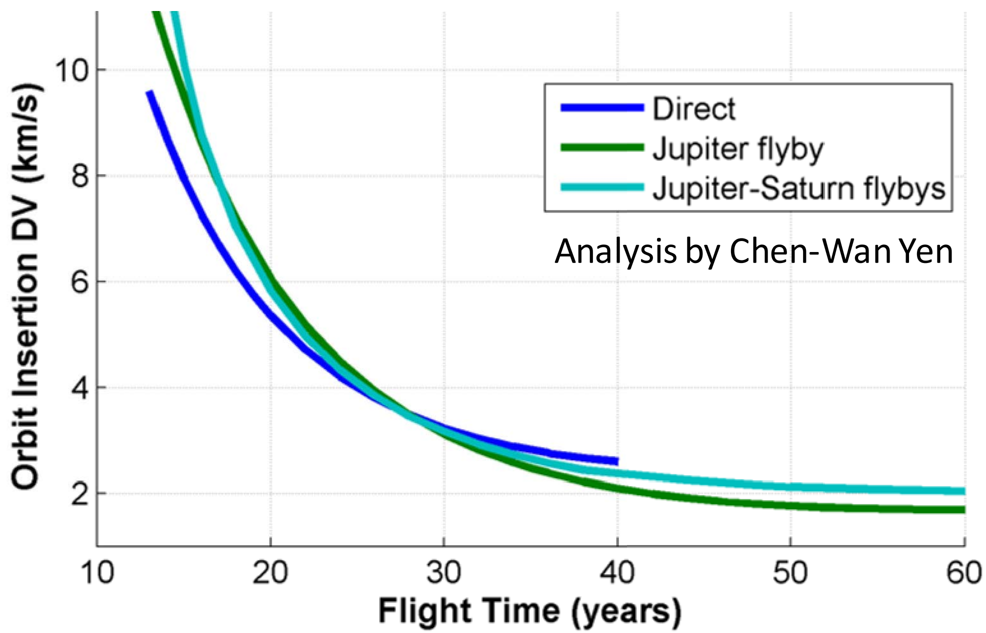


	Found	Visited	Orbited/landed
Asteroids	670,444	13	4
Comets	3,830	8	1

Why Rendezvous with Minor Bodies in the Outer Solar System is difficult?

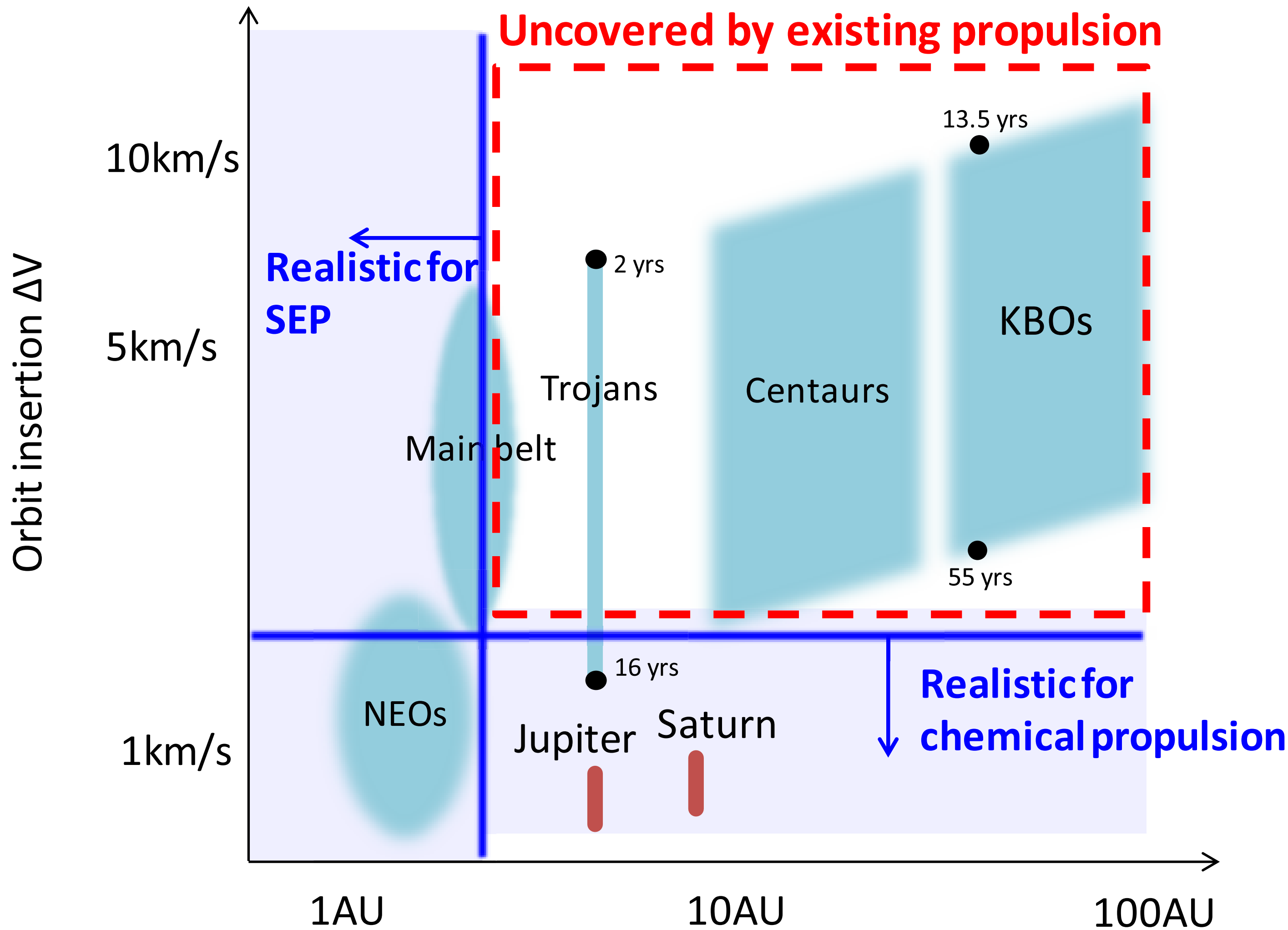
1. Orbit insertion ΔV is too high for chemical propulsion
2. Sunlight is too dim for Solar electric propulsion (SEP)
3. Gravity is too weak to be helpful
4. Flight time too long

Pluto orbit insertion ΔV v.s. flight time



- A faster flight time can only be achieved with a cost of greater orbit insertion ΔV
- 10 km/s @ 16 yrs, 1.7 km/s @ 60 yrs

Limitations of existing propulsion methods



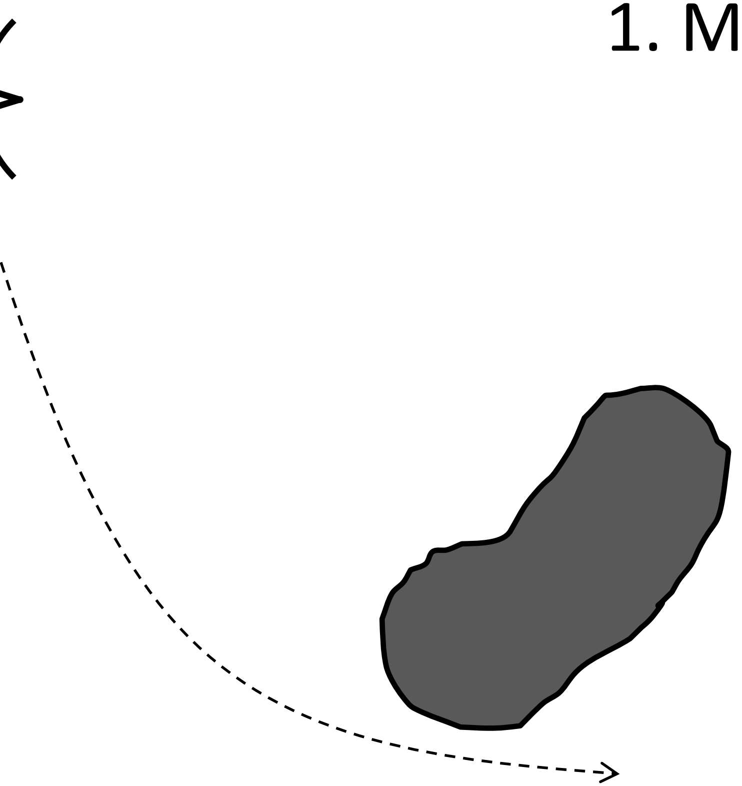
- Radioisotope electric propulsion: 7-10 We/kg specific power required for outer Solar System rendezvous*
- GSHS RTG: ~5 We/kg, MMRTG: 2.8 We/kg

*S. Oleson et at. Radioisotope electric propulsion for fast outer planetary orbiters, 2002

Idea: hitchhike using a tether!

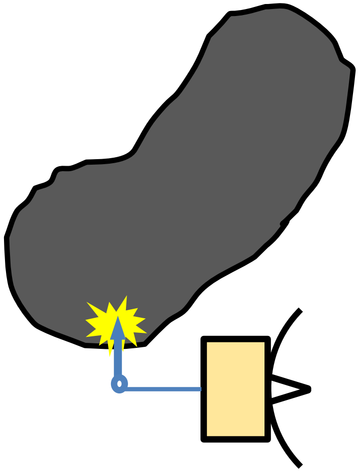
Planetary Hitchhike 101

1. Make a close flyby



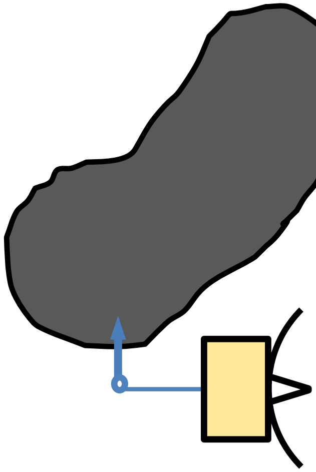
Planetary Hitchhike 101

2. Harpoon a target and attach a tether

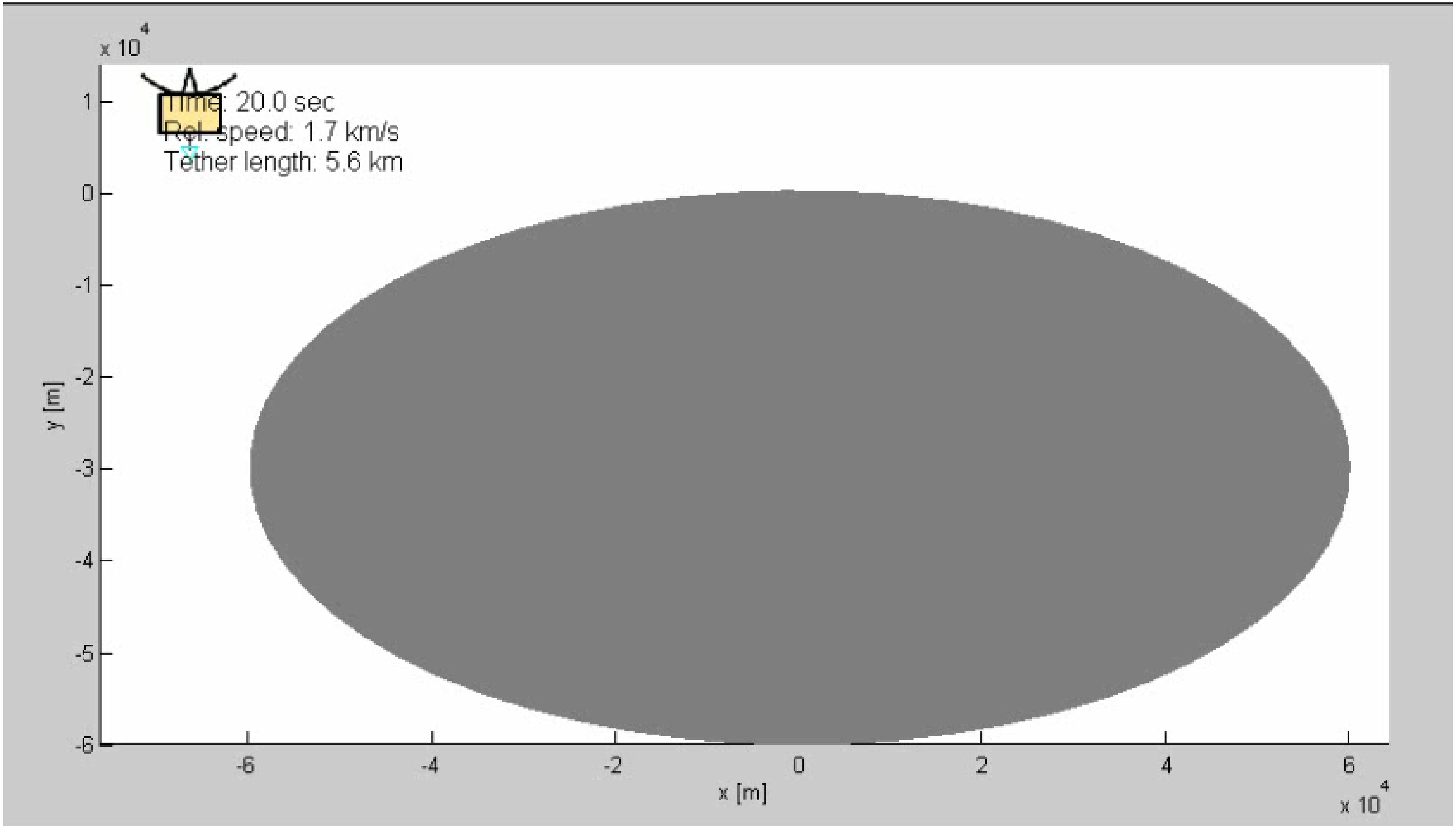


Planetary Hitchhike 101

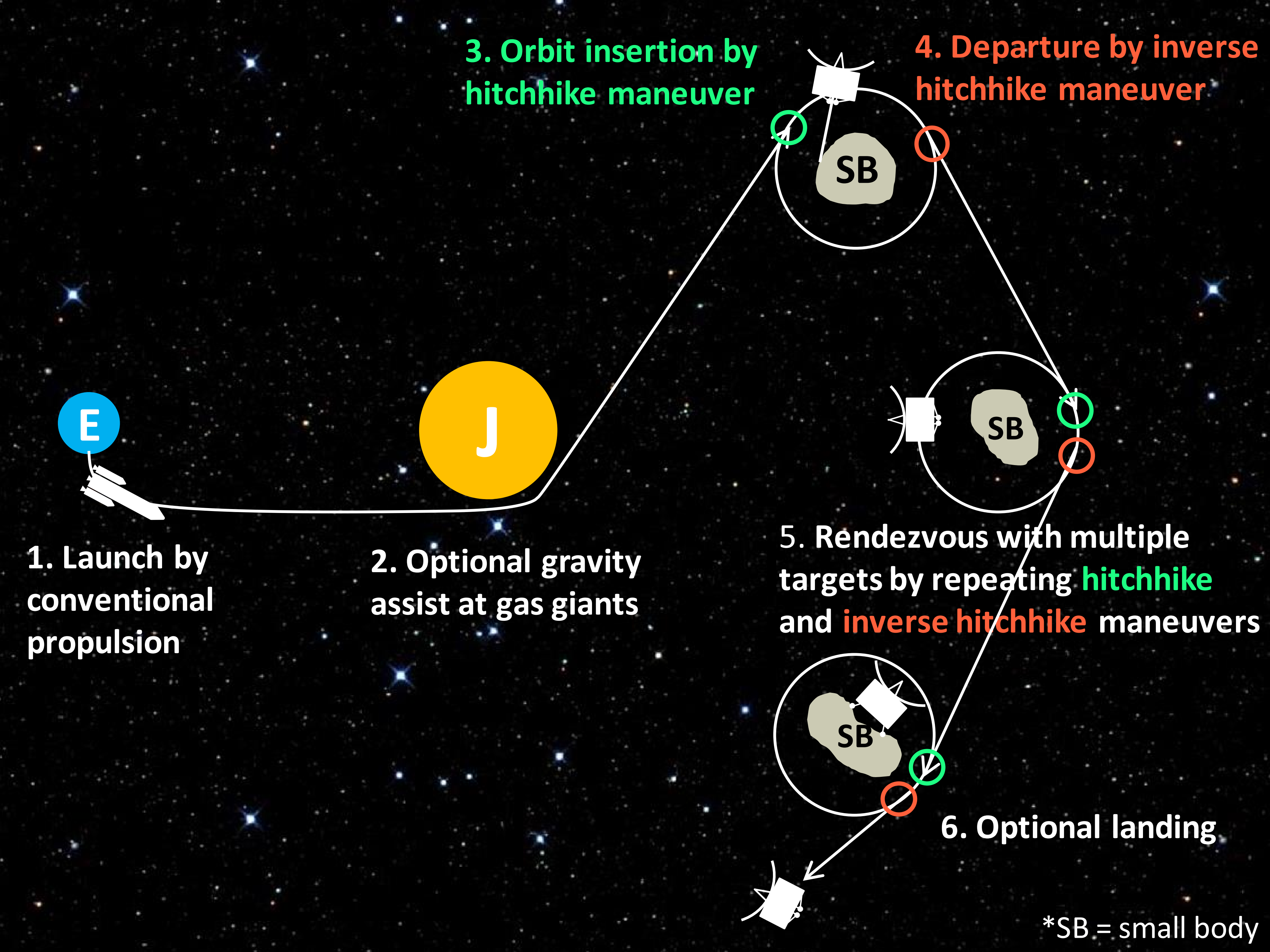
3. Reel out the tether while applying tension until the relative velocity becomes sufficiently low



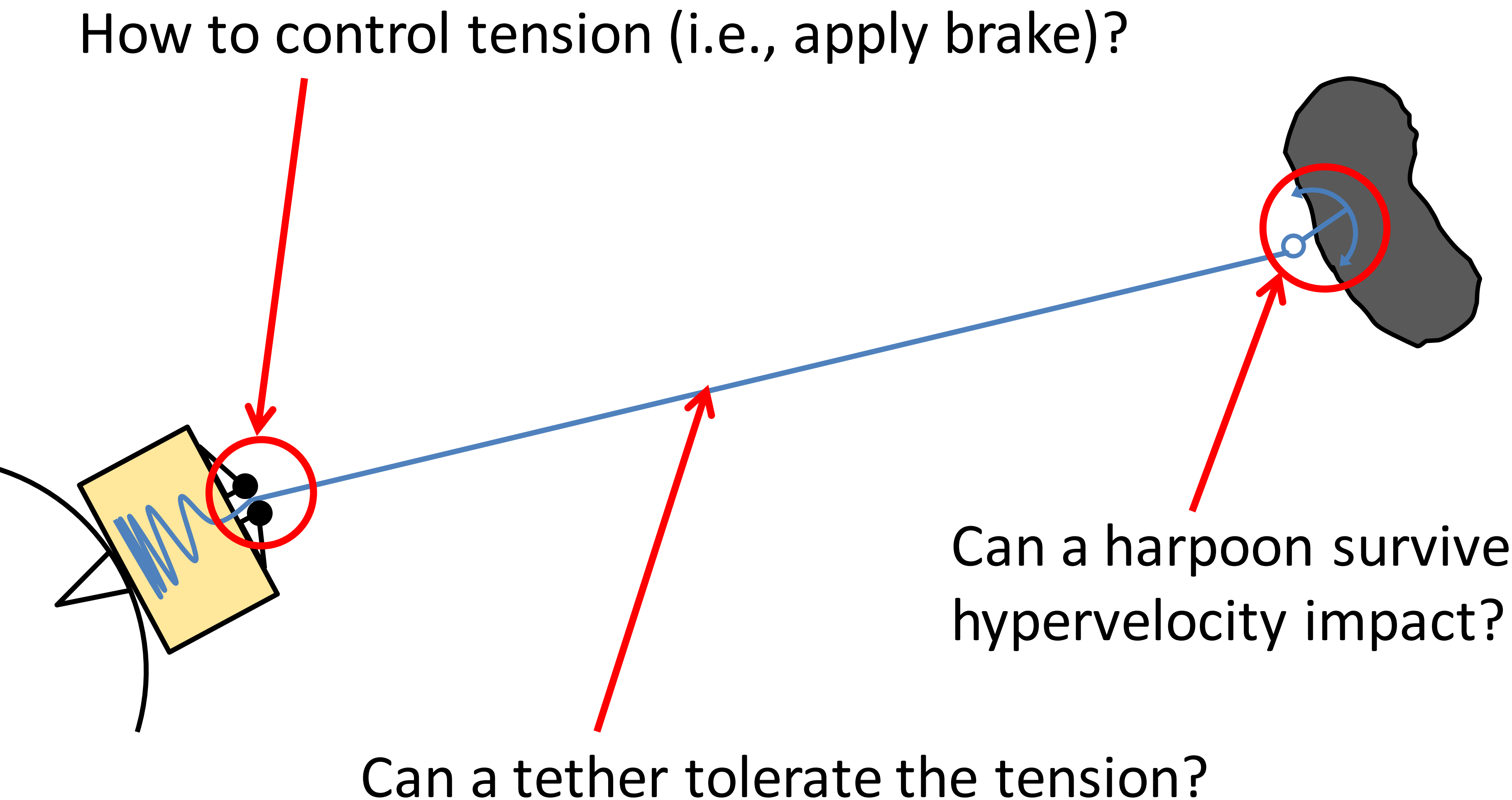
Hitchhike Maneuver



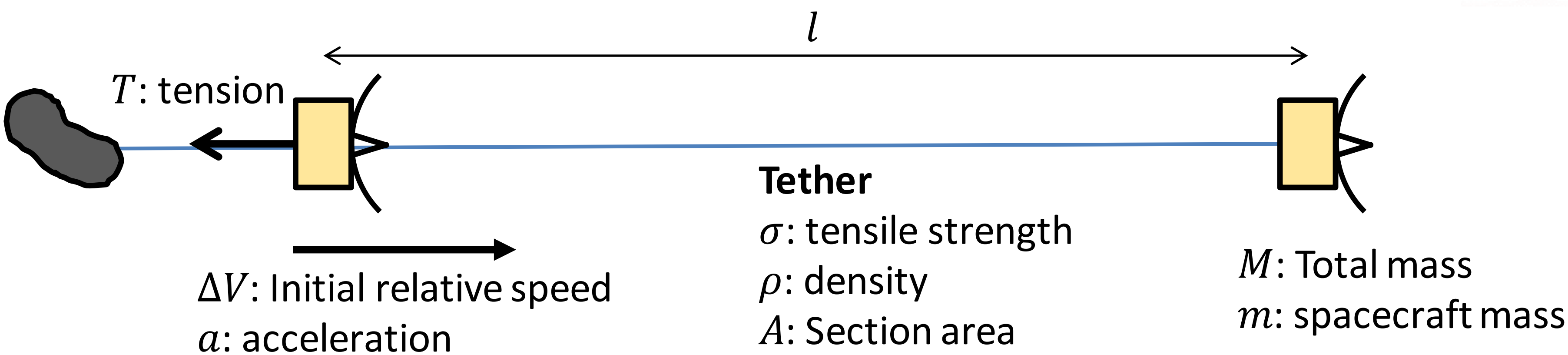
Size of spacecraft is exaggerated for visualization purpose


3. Orbit insertion by hitchhike maneuver
4. Departure by inverse hitchhike maneuver
SB
E
J
SB
1. Launch by conventional propulsion
2. Optional gravity assist at gas giants
5. Rendezvous with multiple targets by repeating hitchhike and inverse hitchhike maneuvers
SB
6. Optional landing
*SB = small body

Technical Challenges



Tether Feasibility



- Tether goes out from spacecraft (S/C)
- Applying tension slows down S/C
- Tension is upper bounded by tensile strength
- Hitchhike is successful if relative velocity is killed before tether is all gone

$$T = -\frac{\mathrm{d}v}{\mathrm{d}t} m - \frac{\mathrm{d}m}{\mathrm{d}t} v$$

Total tension = Tension to accelerate S/C
+ Tension to accelerate tether

$$\frac{\mathrm{d}m}{\mathrm{d}t} = -A\rho v$$

Rate of change of the S/C's mass
= mass of tether deployed in a unit time

$$T_{\max} = A\sigma$$

Max tension = tensile strength x area

Basic Equation for Hitchhiker

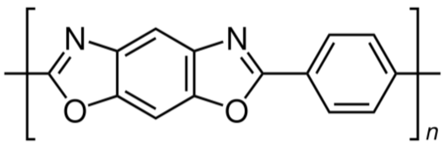
Space Hitchhike Equation (SHE): $\Delta V_{\max} = \sqrt{\frac{\sigma}{\rho}\left\{1 - \left(\frac{m}{M}\right)^2\right\}}$

σ: Tensile strength of tether
ρ: Density of tether
m: Payload mass
M: Spacecraft mass (including fuel/tether)

- Key parameter: σ/ρ (specific strength: tensile strength / density)
  - Intuitively, a stronger and lighter tether can give a greater ΔV

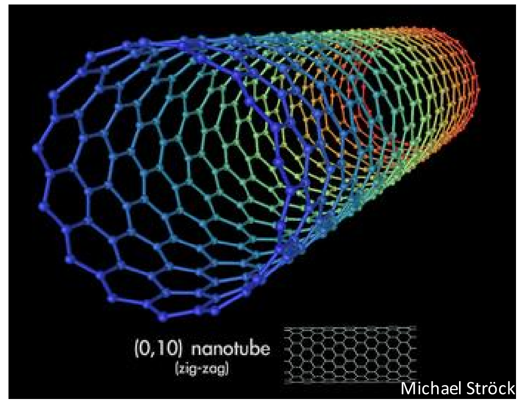
Potential Tether Materials

Zylon



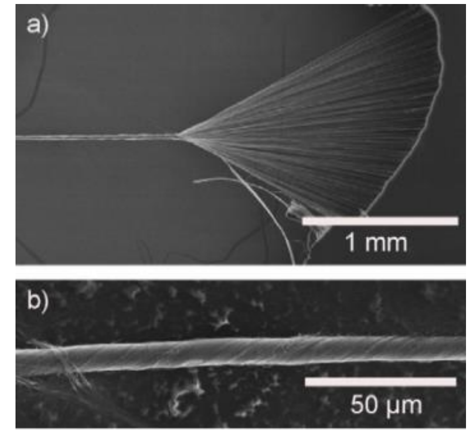
- One of the strongest materials in practical use
  - $\sigma = 5.8$ GPa
  - $\rho = 1560$ kg/m^3
- High thermal stability
  - Decomposition temperature = 650 C^o
- Flight validated in MER

Carbon nanotube (CNT)



- The strongest known material in terms of tensile strength
  - $\sigma = > 150$ GPa
  - $\rho = 1400$ kg/m^3
- Manufacturing a long CNT fiber is an active area of research
  - Longest fiber: ~50 cm[1]

CNT yarn

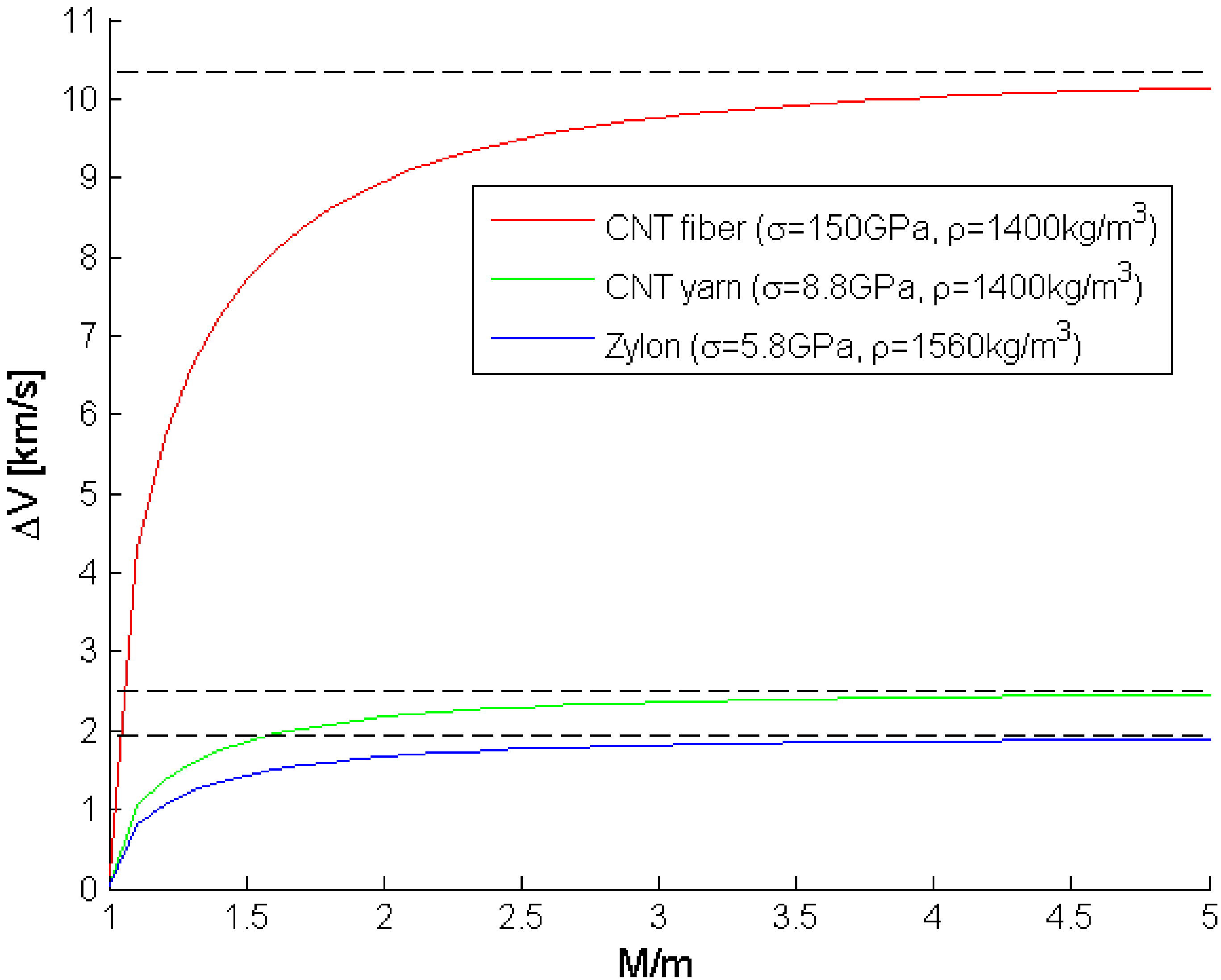


From Zhao et al., 2010

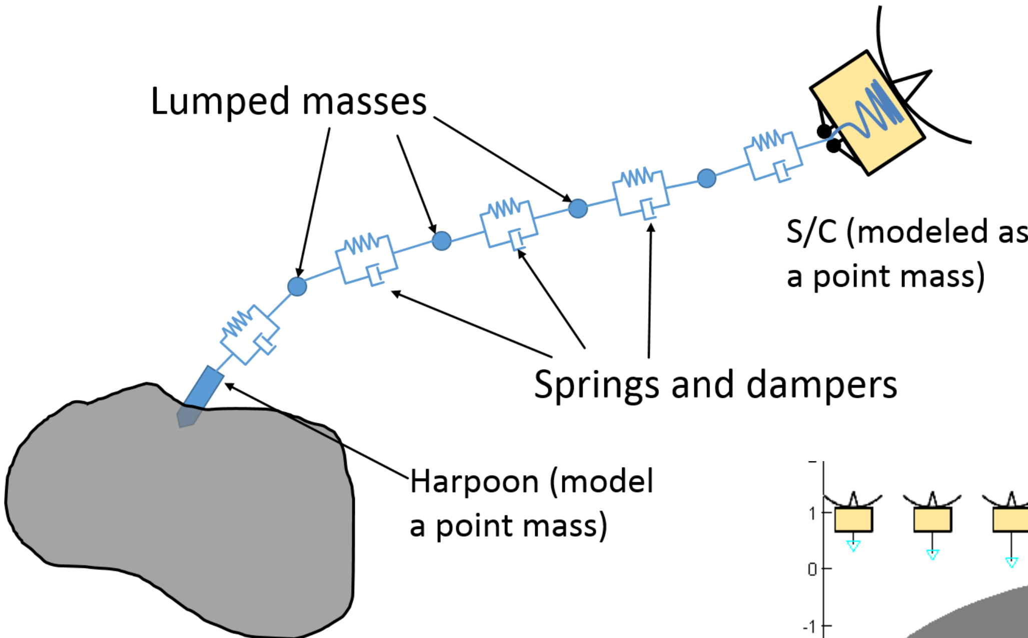
- A tether made of multitudes of short CNT fibers
- To date, the best tensile strength that has been achieved is 8.8 GPa[2]
- >1km long yarn available
- CNT yarns is also a very active topic of research

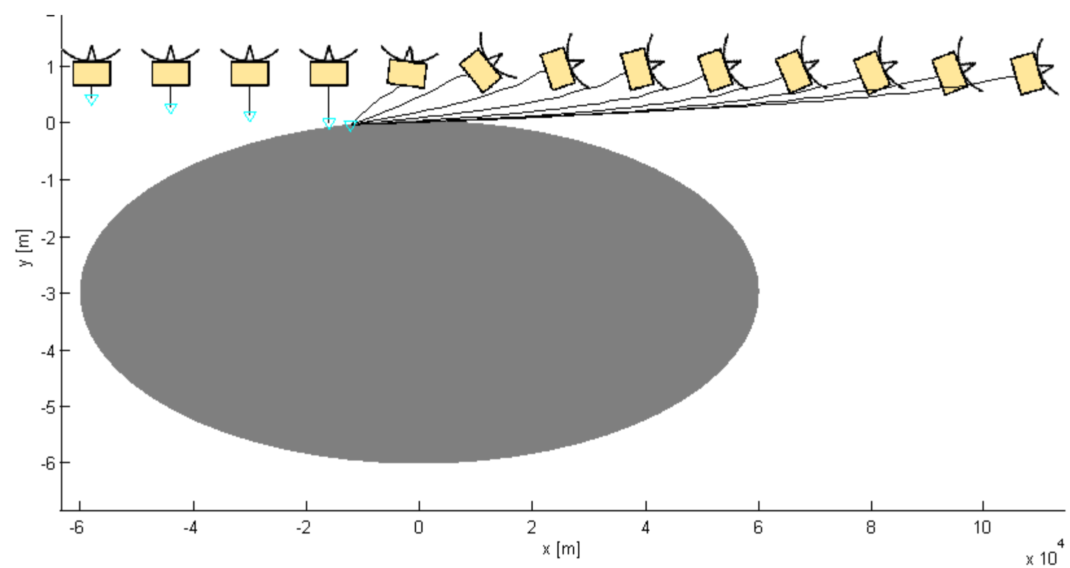
[1] Growth of Half-Meter Long Carbon Nanotubes Based on Schulz–Flory Distribution. Rufan Zhang et al. *ACS Nano* 2013
[2] Key Factors Limiting Carbon Nanotube Yarn Strength: Exploring Processing-Structure-Property Relationships. Allison M. Beese et al. *ACS Nano*, 2014
[3] J. Park and K. Lee, "Carbon Nanotube Yarns," *Korean Journal of Chemical Engineering*, 2012.

Achievable DV



Tether dynamics simulation

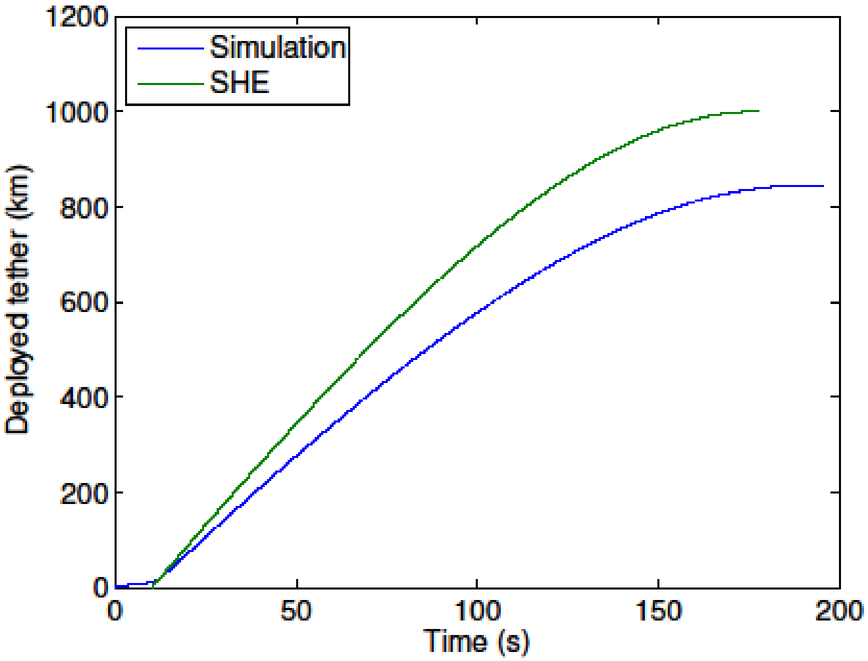


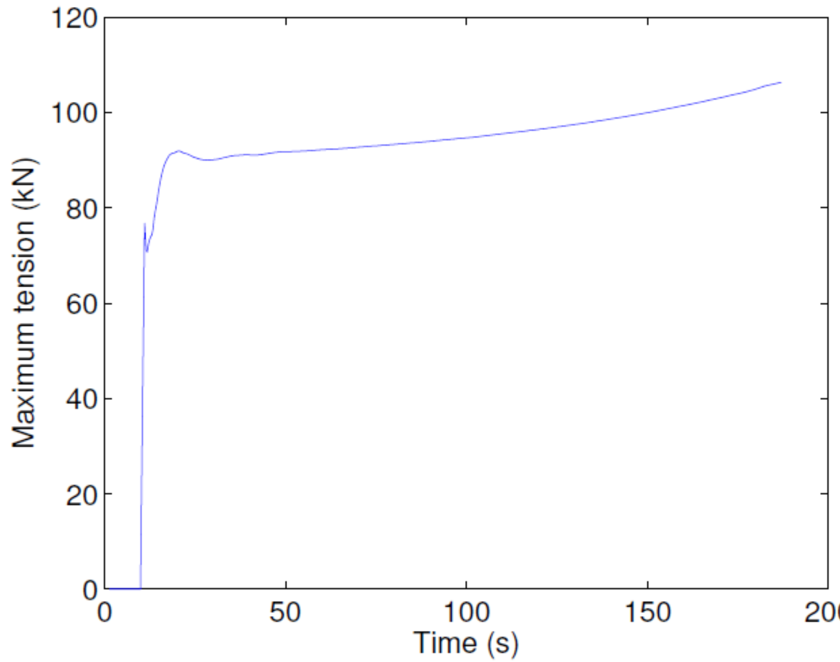


- Tethers are modeled by lumped masses connected by springs and dampers

Tether Simulation Results

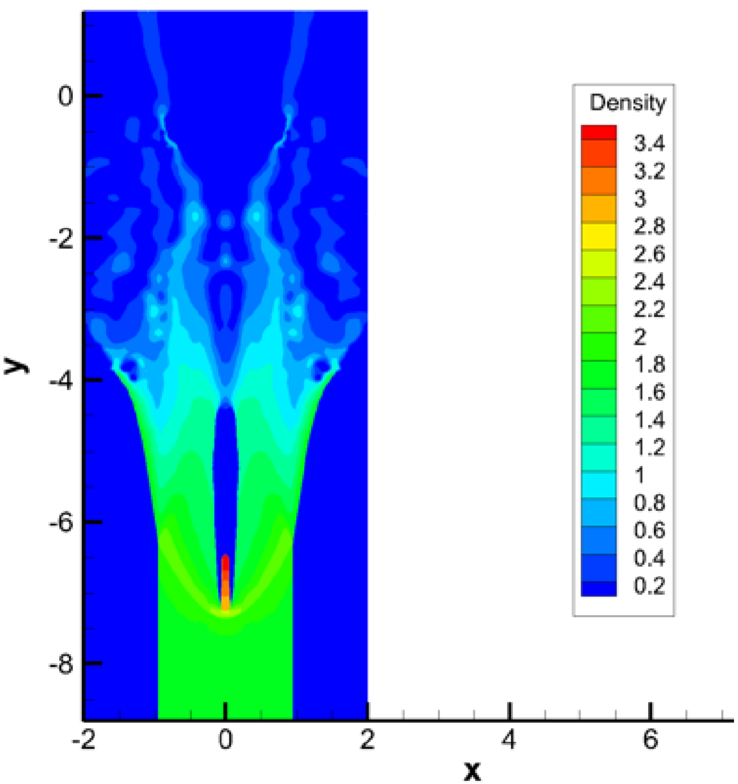
Initial relative velocity: 9.0 km/s, CNT tether





- Tested with 1) 1.5 km/s hitchhiker with Zylon and 2) 9.0 km/s with CNT
- Jerk observed but tension can be controlled within the tensile strength
  - Lower damping results in greater spike in tension
- SHE assumes a perfectly stiff tether
- An extensible tether can achieve the same ΔV with a less mass ratio

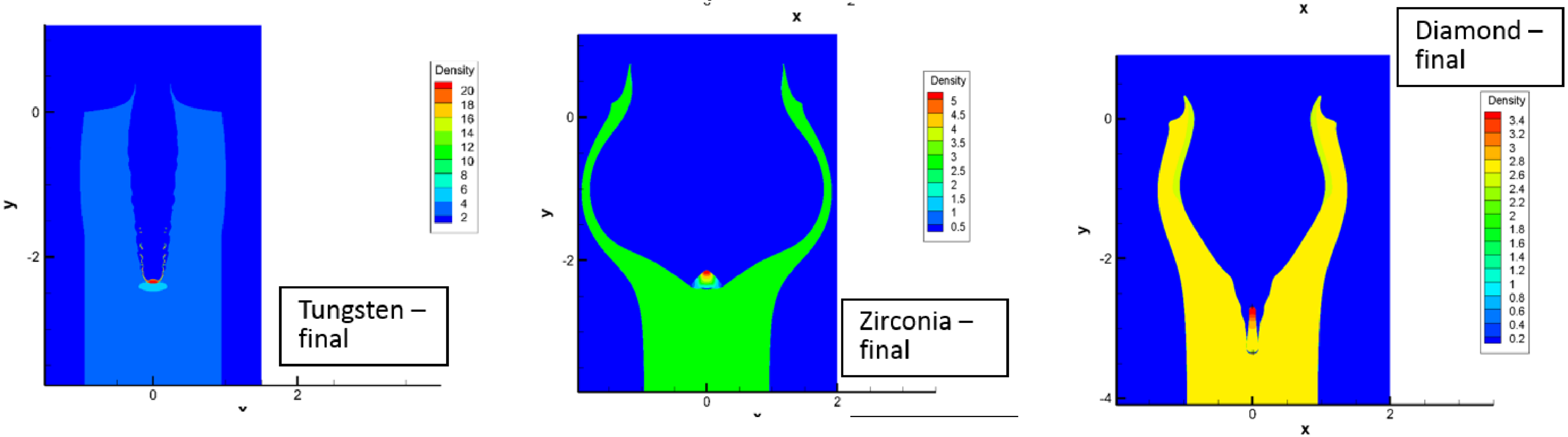
Supercomputer Simulation of Harpoon Impact



- Used the Adaptive Mesh Refinement Objected-oriented C++ (AMROC) algorithm
- Three harpoon materials (elastic limit):
  - Tungsten (3.8 GPa)
  - Zirconia ceramic (39 GPa)
  - Diamond (68 GPa)
- Two target materials:
  - Hard rock (0.1 GPa)
  - Soft soil (0.00025 GPa)
- Two impact speed:
  - 1.5 km/s
  - 10 km/s

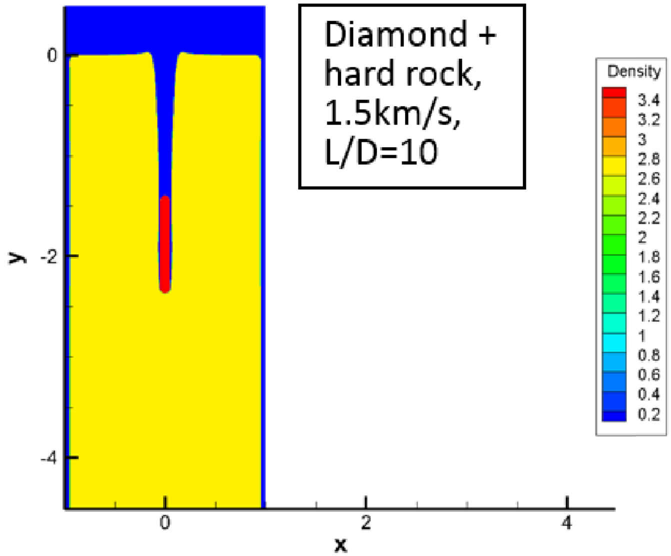
Harpoon Survivability

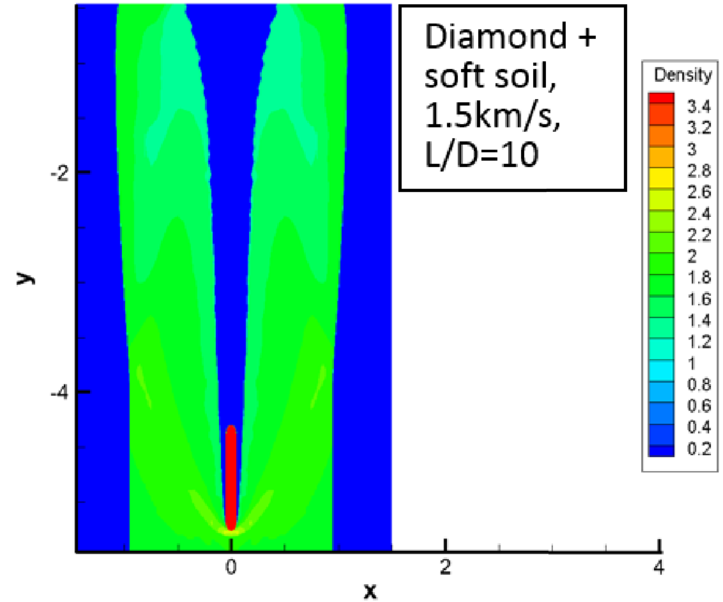
10 km/s impact simulation



- Tungsten, zirconia, and diamond can tolerate 1.5 km/s impact
- Only diamond can tolerate 10 km/s impact
  - Tungsten is completely eroded
  - Zirconia ceramic creates a huge crater

Low Sensitivity to Target Material

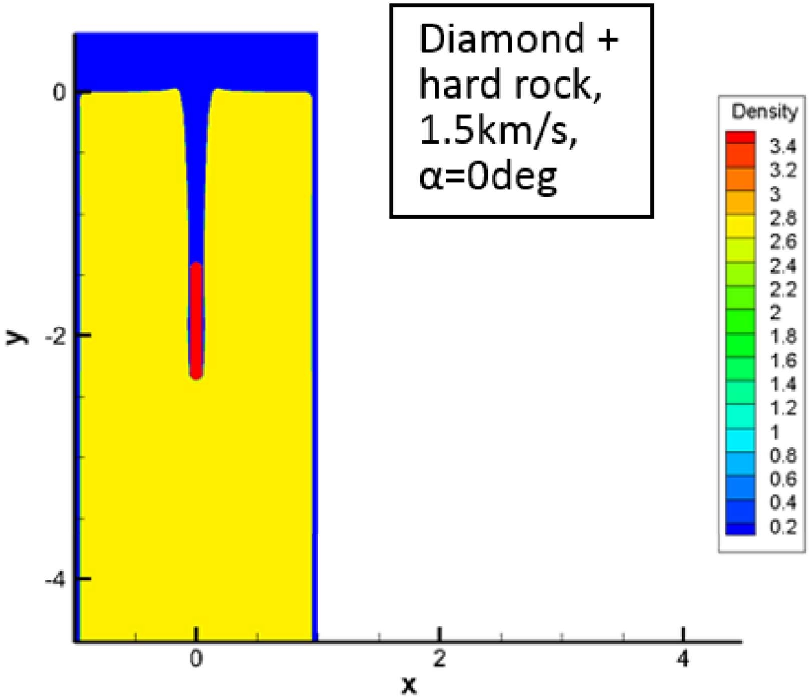


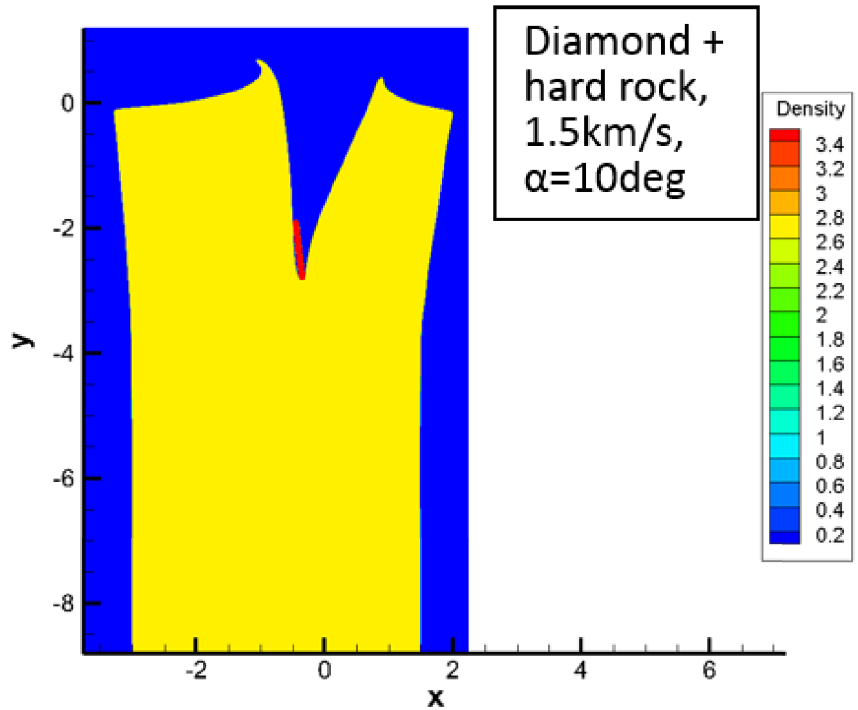


Penetration depth at 1.5 km/s impact (in relative to the projectile length)

Target (elastic limit)	Tungsten	Zirconia Ceramic	Diamond
Hard rock (100 MPa)	8.80	5.92	2.38
Soft soil (0.25 MPa)	8.80	8.80	5.29

Sensitivity to Angle of Attack

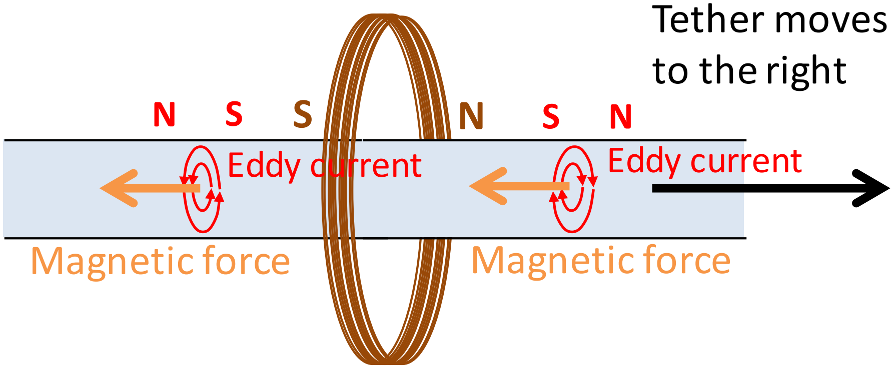




- An oblique impact results in a wide crater

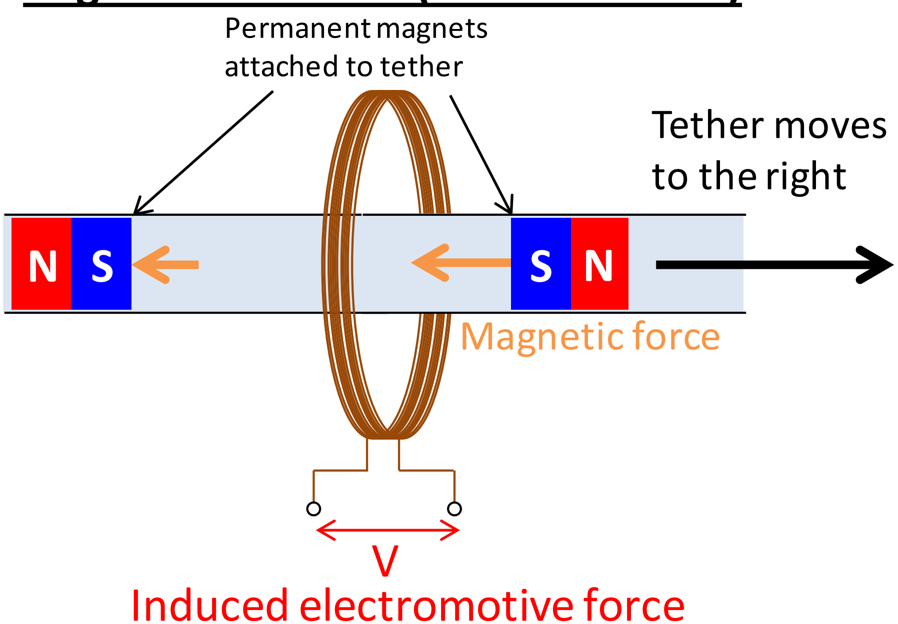
Contactless Brakes for Hitchhikers

Linear eddy current brake



- Conductive tether goes through electromagnetic coils (DC)
  - Can be donut-shaped permanent magnets but tension is not controllable
- Kinetic energy is dissipated solely as heat
- **No electricity generated**

Regenerative brake (& linear motor)



- Permanent magnets attached to the tether go through coils
- Electromotive force is induced in the coils
- A part of kinetic energy is turned to electric energy
- **No heating of tether**
- By injecting energy, the same mechanism can be used to accelerate the tether (i.e., linear motor)

Analysis Summary

- A hitchhike maneuver at 1.5 km/s relative velocity is feasible with existing technologies
  - A Zylon tether can support up to 1.9 km/s
  - A tungsten harpoon does not experience plastic deformation
- A hitchhike maneuver at ~10 km/s is possible, but requires future advancements in tether material
  - A CNT tether can support up to 10.4 km/s, but the technology to produce sufficiently long CNT fiber currently does not exist
  - A diamond harpoon does experience plastic deformation, but 70% and 83% of the projectile will remain uneroded for hard rock and soft soil targets, respectively

Conclussion

- Innovations are needed to enable rendezvous with small bodies in the outer Solar System
  - E.g., Pluto rendezvous with 1.7 km/s ΔV_{OI} and 60 yr flight time, or 10 km/s ΔV_{OI} and 16 yr flight time
- The hitchhiker concept is a potential enabler
  - 1.5 km/s ΔV with existing materials
  - 10 km/s ΔV with a CNT tether and a diamond harpoon
- Don't forget to bring a towel!

Announcement:
Forum 360
Interactive NIAC and Emerging Technology Exchange
2pm in Ballroom C

ono@jpl.nasa.gov

***Mission Concept**