National Aeronautics and Space Administration

Keck Workshop: Applications of Asteroid Redirection Technology
ARM Mission Design and Solar Electric Propulsion

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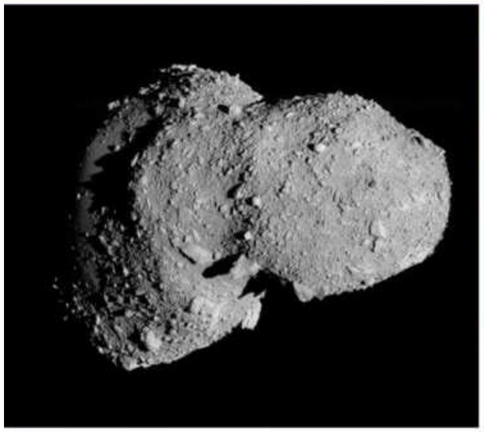
Asteroid Redirect Mission Concept Team

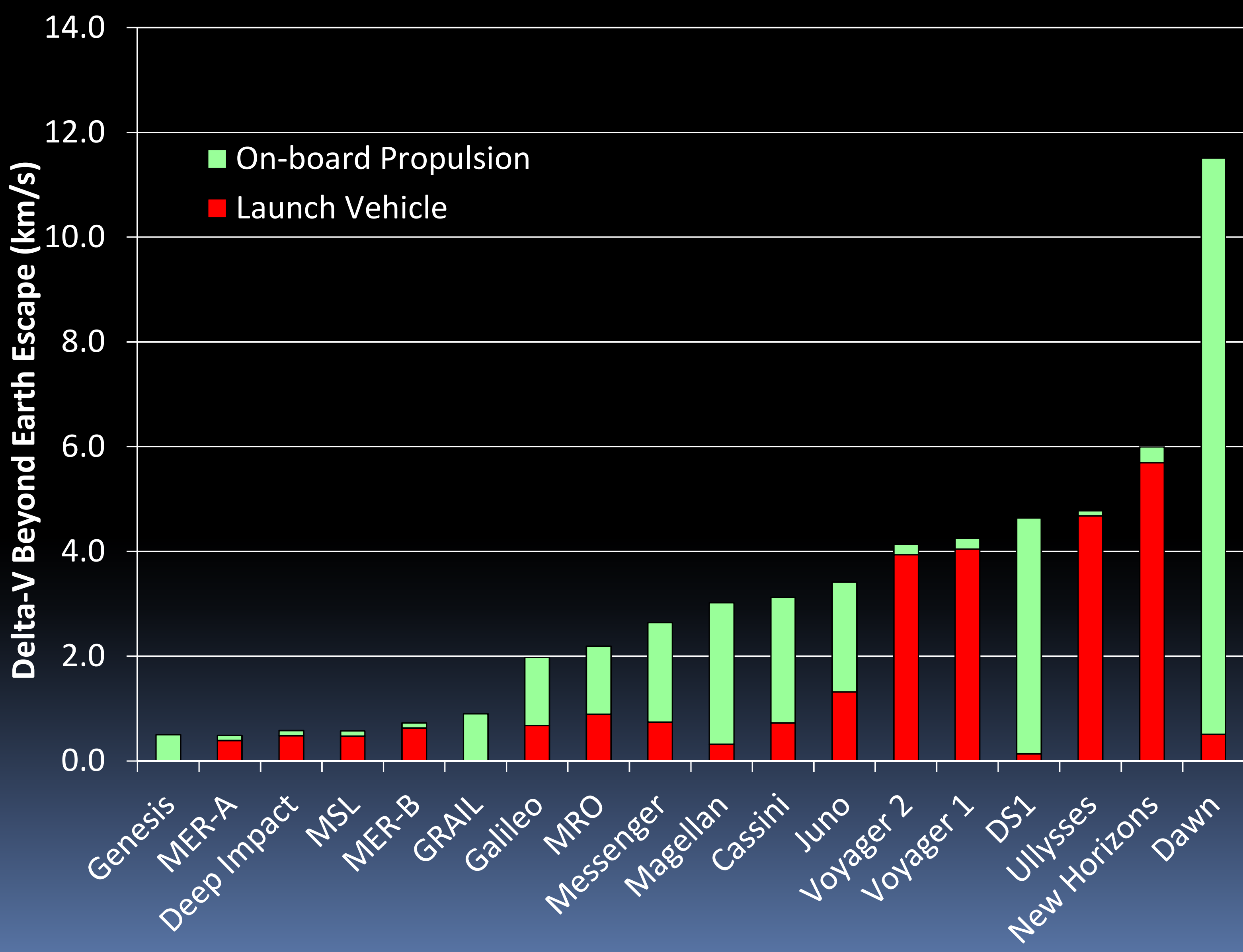
April 7, 2014




Solar Electric Propulsion (SEP) Benefits

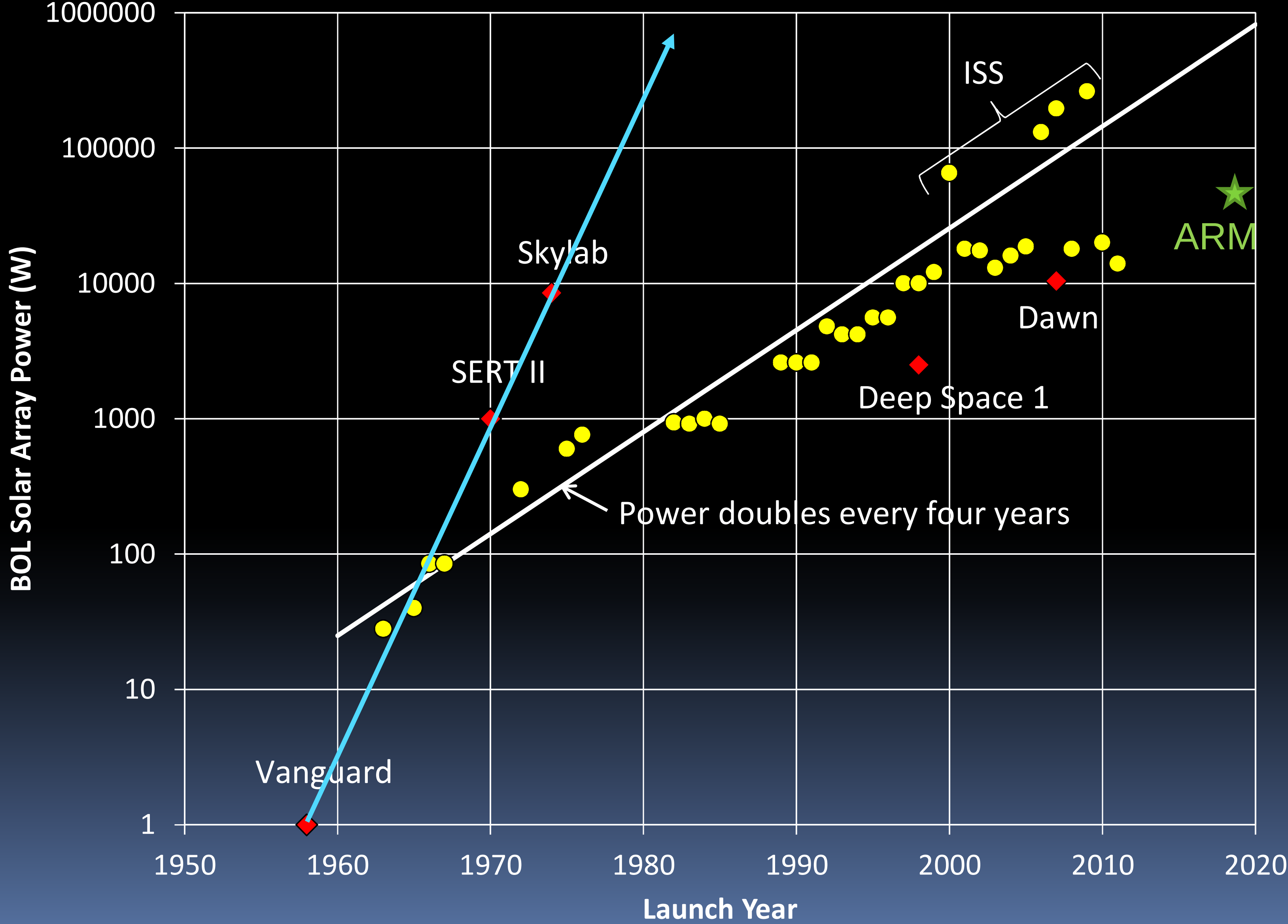
- High-power SEP provides the highest ΔV capability of any near-term, in-space propulsion technology
- It offers real time mission flexibility (e.g. launch date, trajectory)
- ARM SEP component and system technologies are extensible to multiple future applications
  - Commercial communication satellites
  - Deep space cargo, including for Mars
  - Deep space science

SEP Enables High ΔV Missions

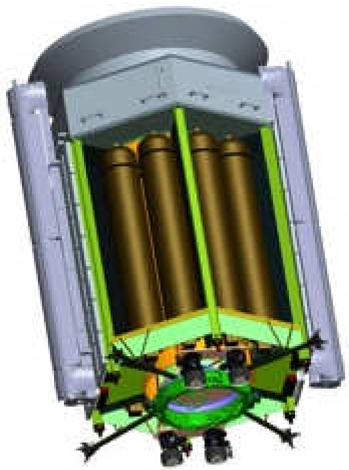


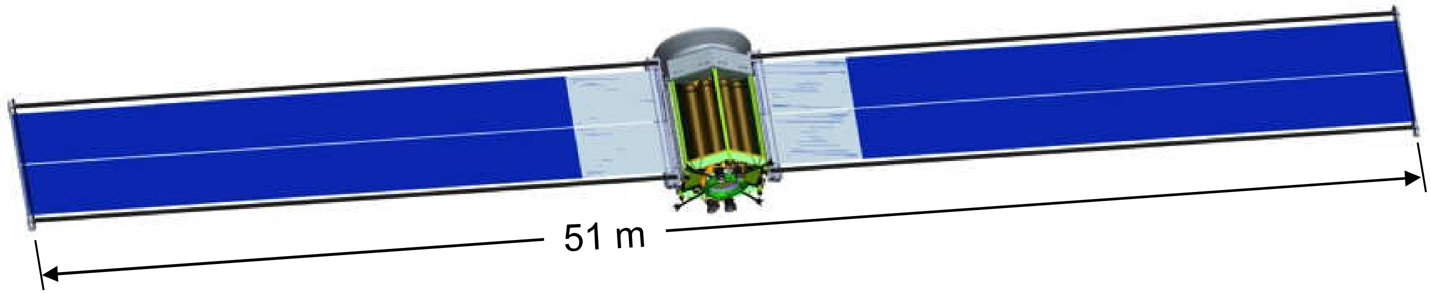
It's All About Power

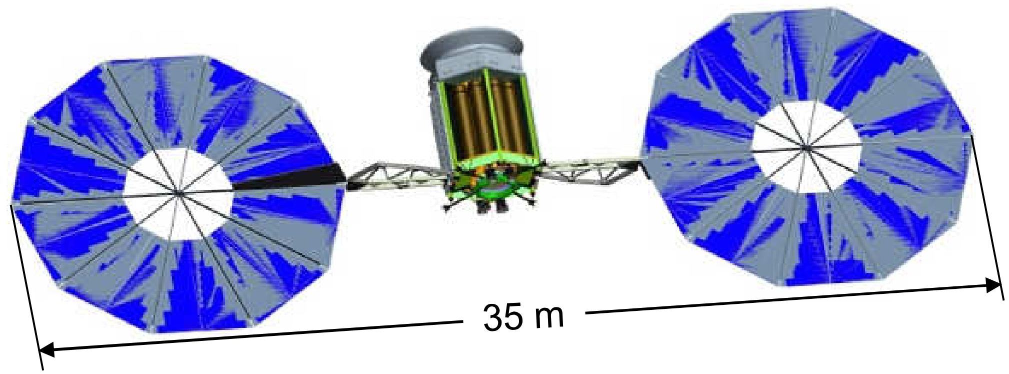
Space Solar Power History



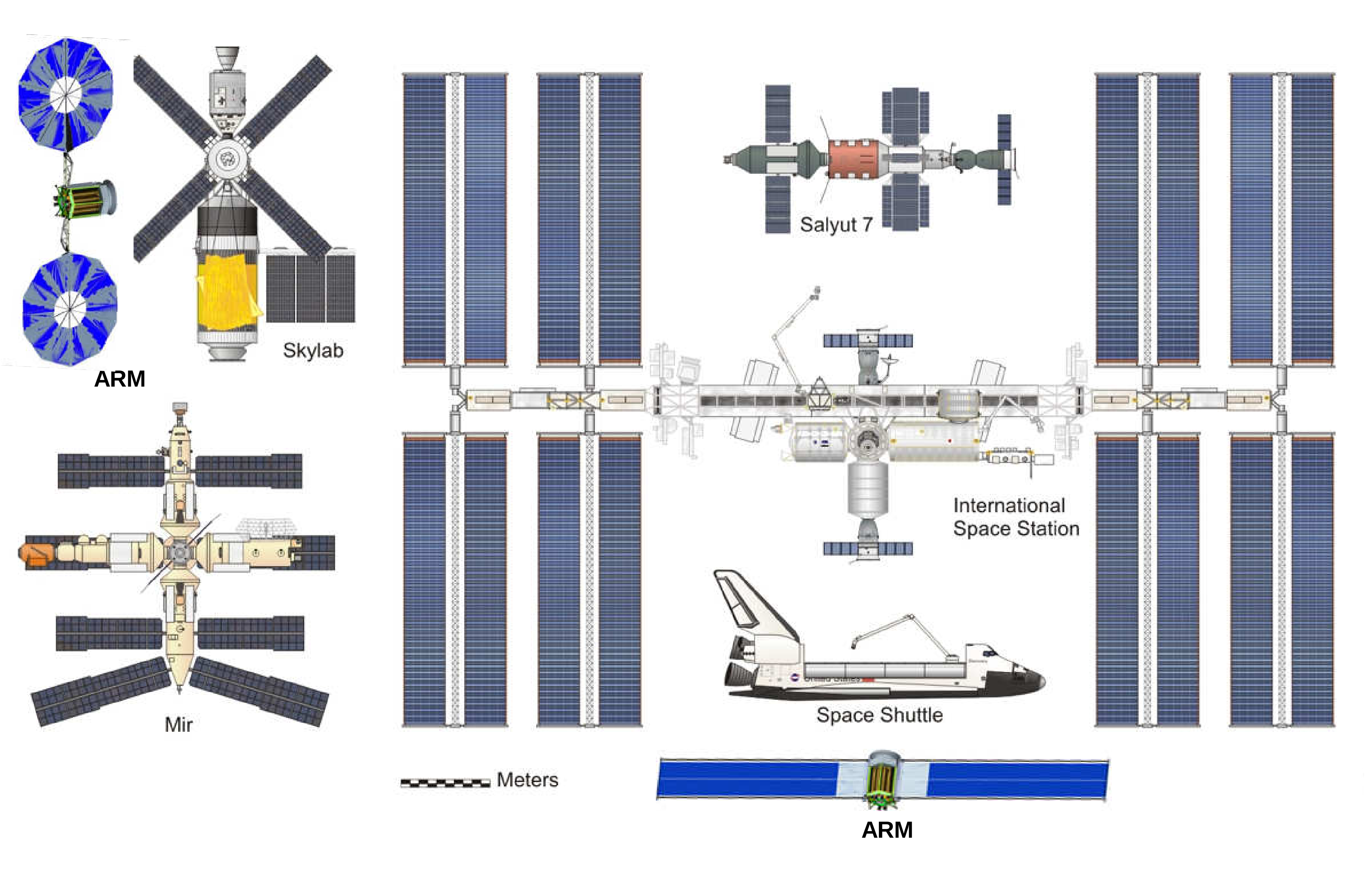
Representative Flight System Deployed Configurations



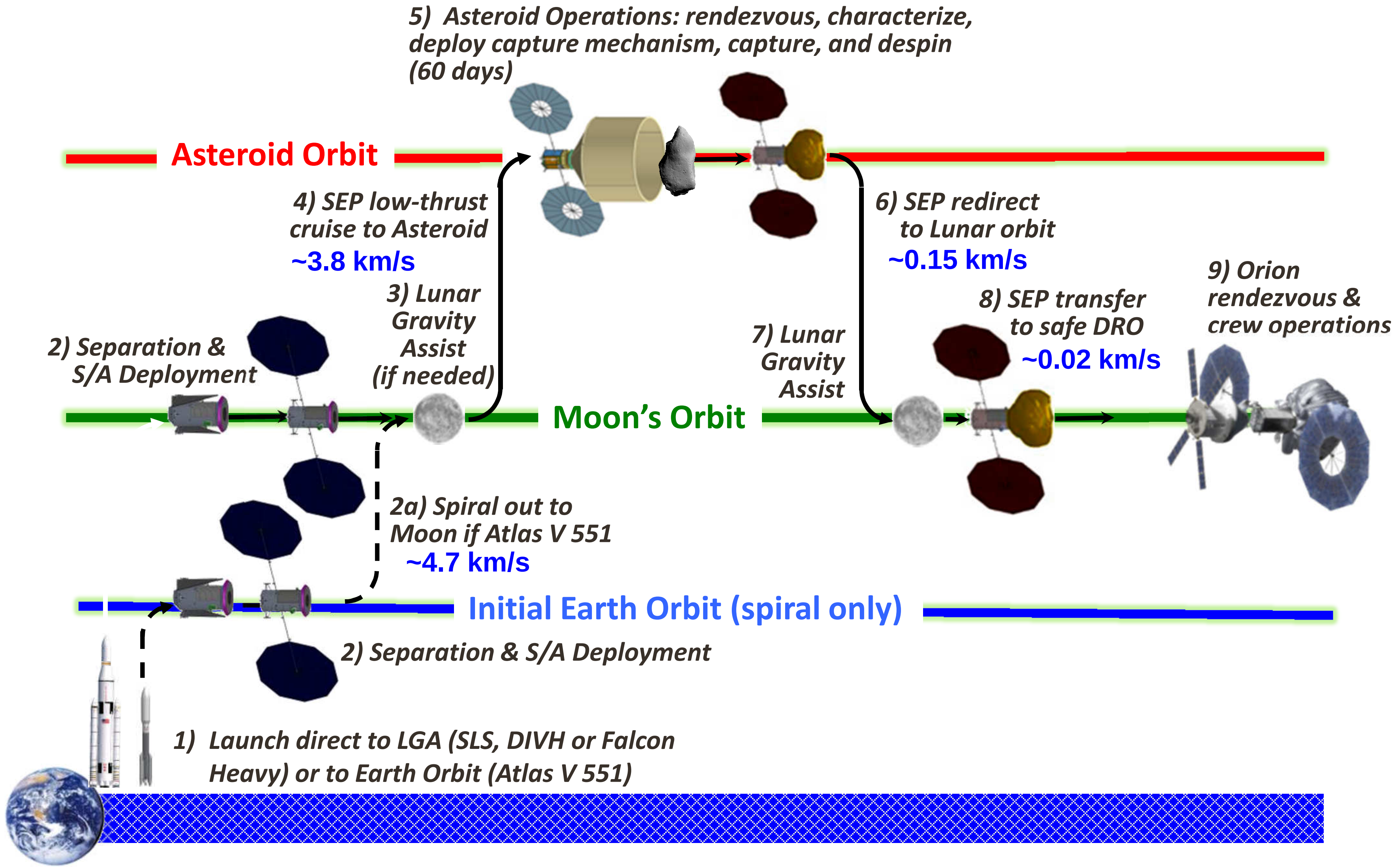




ARV Size Comparison



Mission Option A Overview



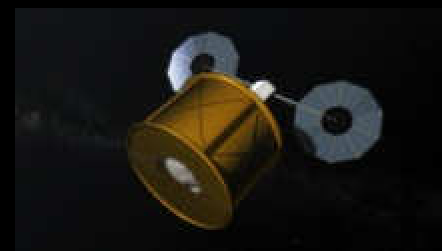
Option A: Proximity Operations Overview

Orbit Refinement and Rendezvous
(Radio and Optical)

Pre-Capture
Capture System Deploy

Final Approach

Capture



Capture Bag Retraction

Characterize, Spin down, and Detumble

Option B: Mission Timeline

Day 0 | Day 14 | Day 51

1. Approach (14 Days)
1,000 km to 100 km. Refine shape model, acquire landmarks, and update spin state.

2. Characterization (37 days)
Four fly-bys (~7.5 days each) with a week reserved for processing and gathering additional images as needed

3-4. Dry-Runs and Boulder Collection (18 days)
Dry-Runs (x2): ~5.3 days each. ~6 hours to complete dry-run with 5 days of coast in-between for downlink and processing.

Boulder Collection Attempt: ~7.4 days with ~0.5 day for collection and 7 days for ascent and coast to allow for downlink and processing

Day 69 | Day 120

3-4. Contingency Dry-Run and Boulder Collection Attempts (51 days)
Reserve for complete dry-run sequences at two additional sites and four additional boulder collection attempts between the three sites to protect against failed collection due to boulder properties, system anomalies or other contingencies.

5. Orbit Determination (21 Days)
Hold for precise orbit determination prior to gravity tractor demonstration.

Day 141 | Day 231 | Day 360 | Day 381 | Day 400

6. Gravity Tractor (90 Days)
Maintain orbit for at least 90 days. Resources reserved for 180 days.

6. Hold for Alignment (129 days)
Hold for to allow deflection to propagate and to achieve favorable orbital alignment for deflection verification.

7. Deflection Verification (21 Days)
Hold for precise orbit determination to verify orbit deflection.

Margin (19 days)
Unused margin in the 400 day stay-time allocation.

Operations heritage to prior robotic missions

Mission unique operations

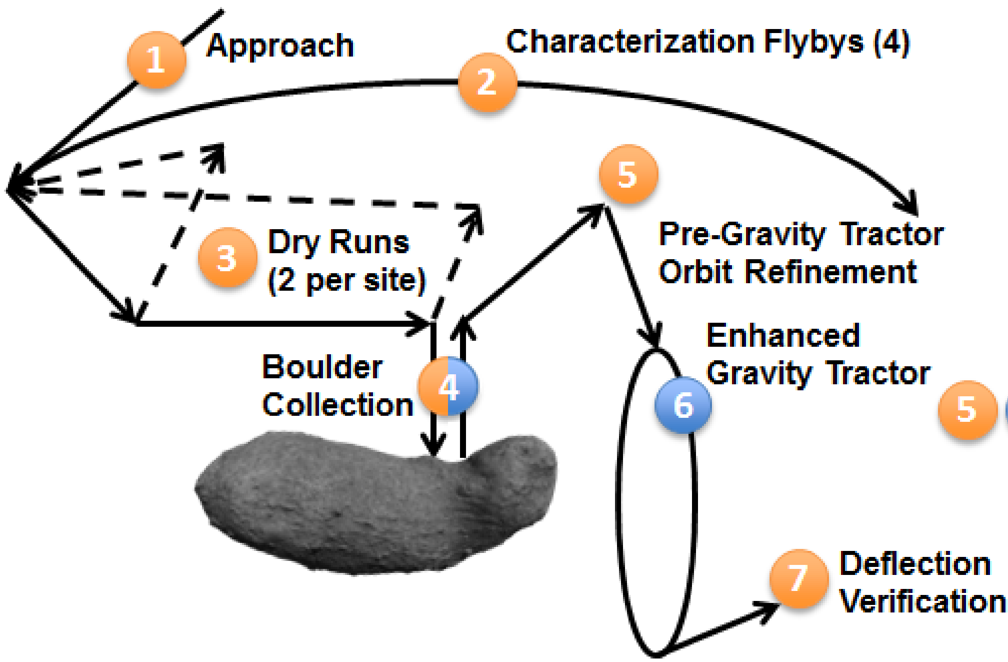
Option B: Proximity Operations Overview

Proximity Operations Timeline (400 days)

1	2	3	4	Reserve (3 & 4)	5	6	Reserve (6) & Wait	7	Margin

(#) Operations heritage to prior robotic missions

(#) Mission unique operations



Proximity operations having a high heritage, along with a conservative operations strategy.

(1) (2) **Approach, Flybys, & Characterization:** 37 days to verify and refine shape, spin, and gravity models, and obtain ~cm imagery for majority of the surface.

(3) **Dry Runs:** 2 dry runs at up to 3 sites refine local gravity, provide sub-cm imagery, and verify navigation performance.

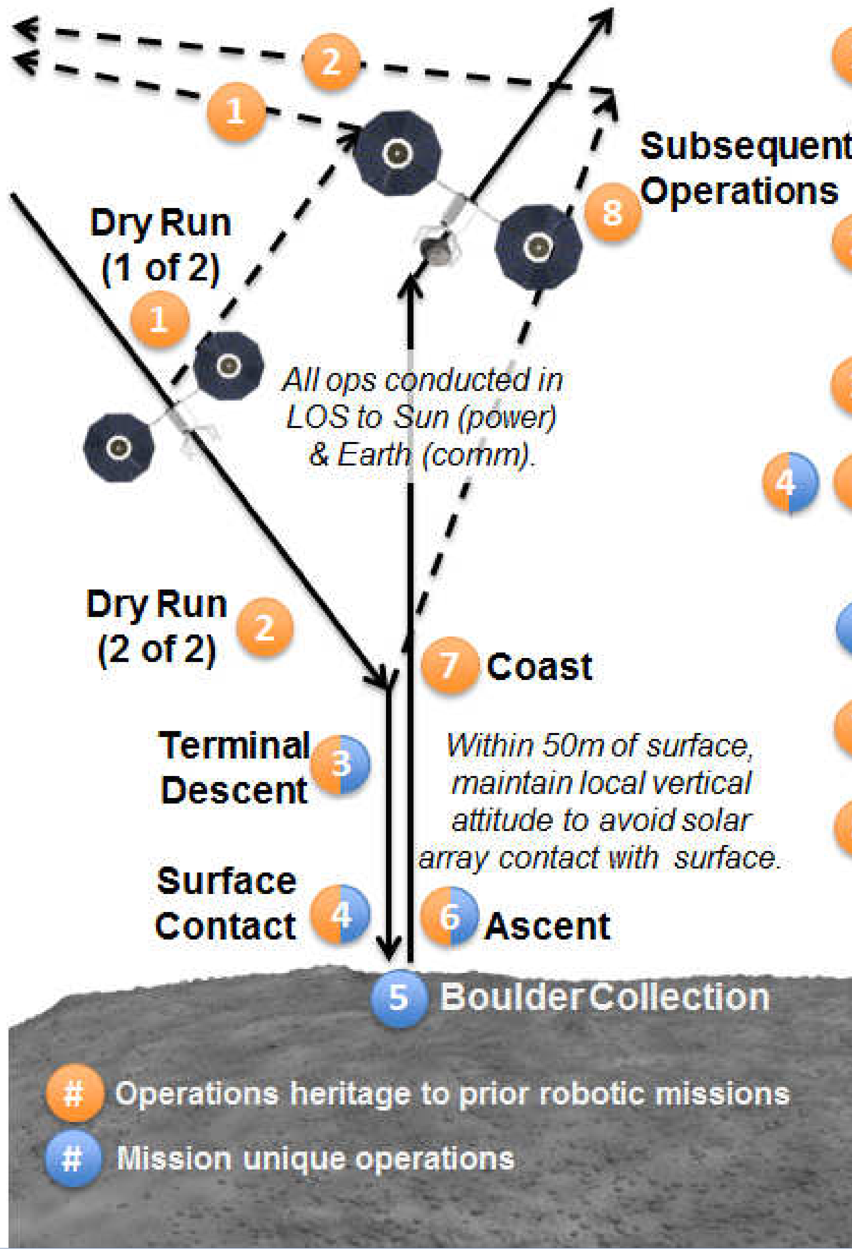
(4) **Boulder Collection:** Reserving for up to 5 boulder collection attempts provides contingency against surface and boulder anomalies.

(5) (6) (7) **Enhanced GT Demonstration:** 260 days allows for operations and proper Earth-Itokawa alignment to verify deflection.

(6) **Enhanced Gravity Tractor (EGT):** 180 days reserved for EGT operations, 60 days required for measurable deflection.

Operations Margin: In addition to conservative operations profile, 19 days of unencumbered operations schedule reserve is provided in mission plan.

Option B: Boulder Collection



1. **Dry Run (1 of 2):** *Refine local gravity* and increase *boulder characterization* while in *passively safe* trajectory. Sufficient time allocated between dry runs to downlink data, process data, and update spacecraft.
2. **Dry Run (2 of 2):** System verifies *closed-loop* Terrain Relative Navigation acquisition of landmarks for descent navigation by while in *passively safe* trajectory.
3. **Terminal Descent:** No nominal thrusting toward asteroid to *limit debris*.

4 6 **Surface Contact/Ascent:** Contact arms allow *controlled contact/ascent*, provide stability, and limit debris. Thrusters provide attitude control and contingency ascent.

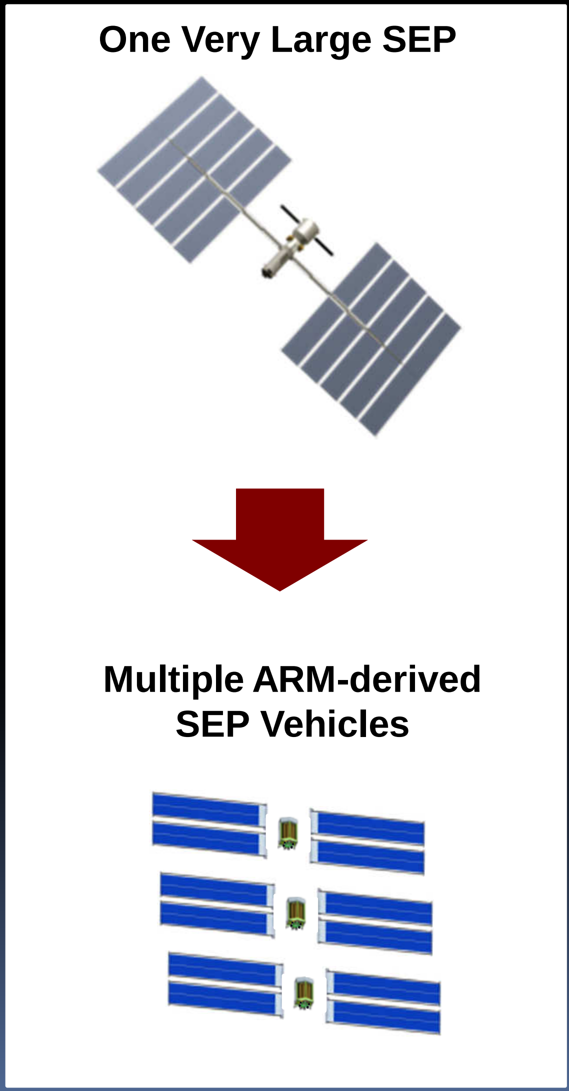
5. **Boulder Collection:** *Conservative* 120 minutes reserved, nominal ops estimated at 30 minutes.
7. **Coast:** Slow drift escape provides time to *establish mass properties* of the combined spacecraft/boulder system.
8. **Subsequent Operations:** As appropriate, transition to performing gravity tractor or subsequent capture attempt.

Conservative, high-heritage operations mitigate risks during boulder collection operations to increase probability of successful boulder capture.

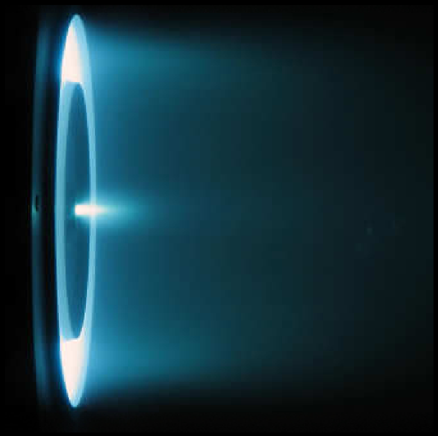
Future Use of ARM Robotic Spacecraft and Solar Electric Propulsion

- Some assessments have shown that human Mars missions utilizing a single round-trip monolithic habitat + Orion requires a very high power SEP vehicle
  - Approaches 1 MW total power
  - An engineering and operational challenge

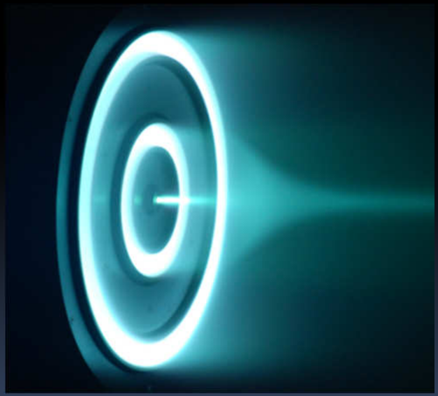
- Alternate architecture concepts enable ARM derived SEP to be used. As an example:
  - Pre-deploy crew mission assets to Mars utilizing high efficient SEP, such as
    - Orbit habitats: Supports crew while at Mars
    - Return Propulsion Stages or return habitats
    - Exploration equipment: Unique systems required for exploration at Mars.
  - High thrust chemical propulsion for crew
    - Low-thrust SEP too slow for crew missions
    - Crew travels on faster-transit, minimum energy missions: 1000-day class round-trip (all zero-g)



High-Power Hall Thrusters



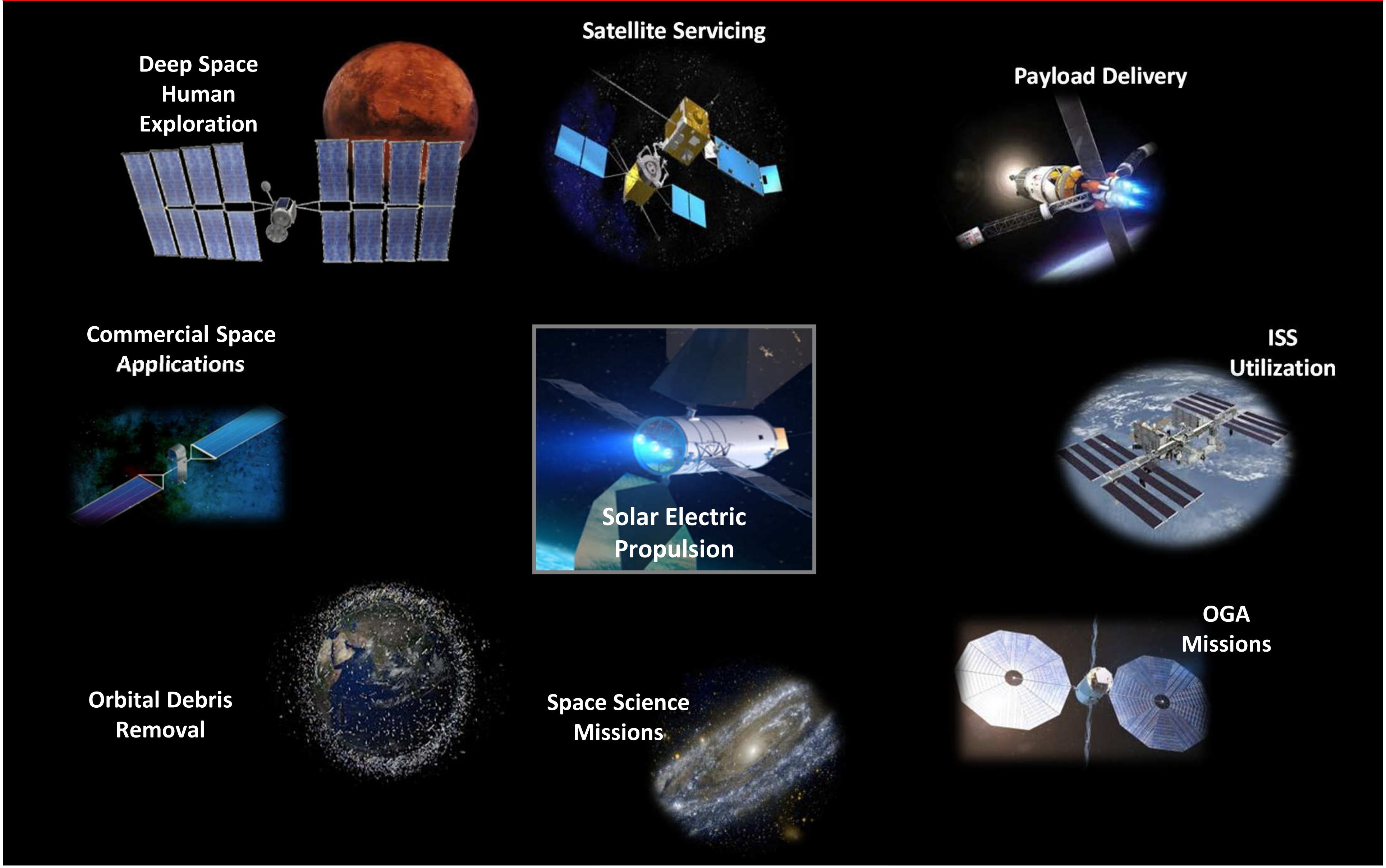
Hall Thruster

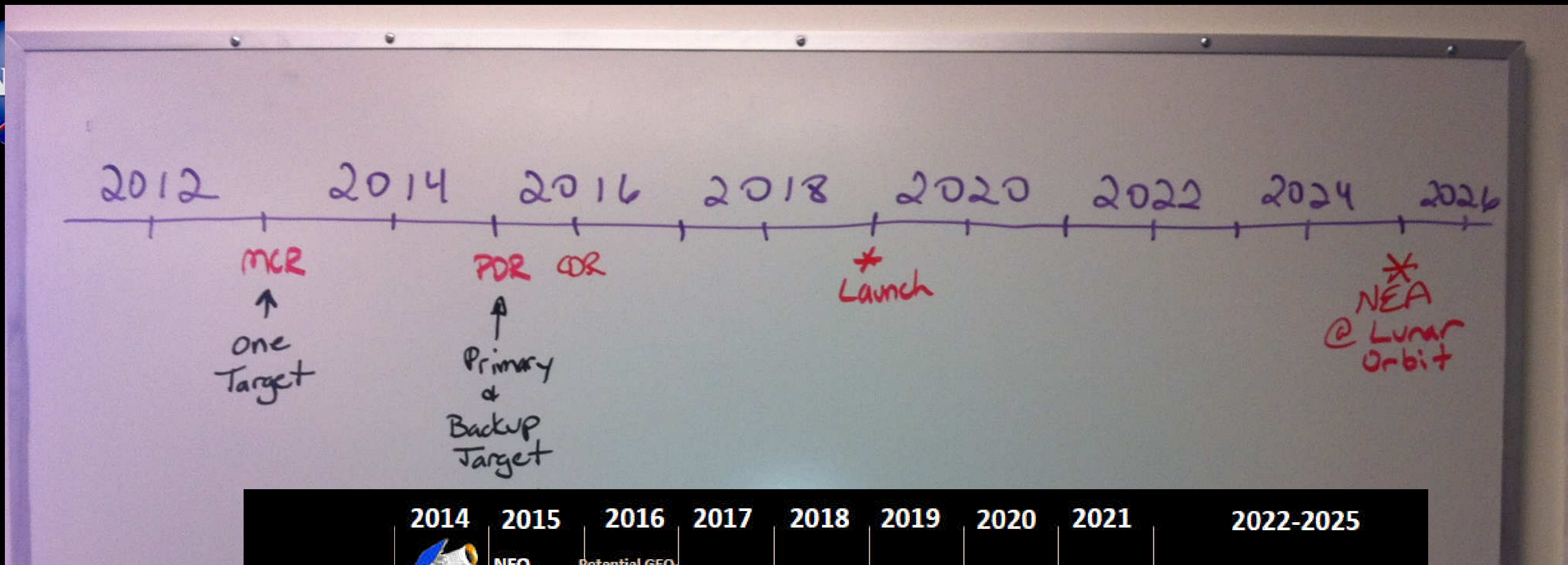


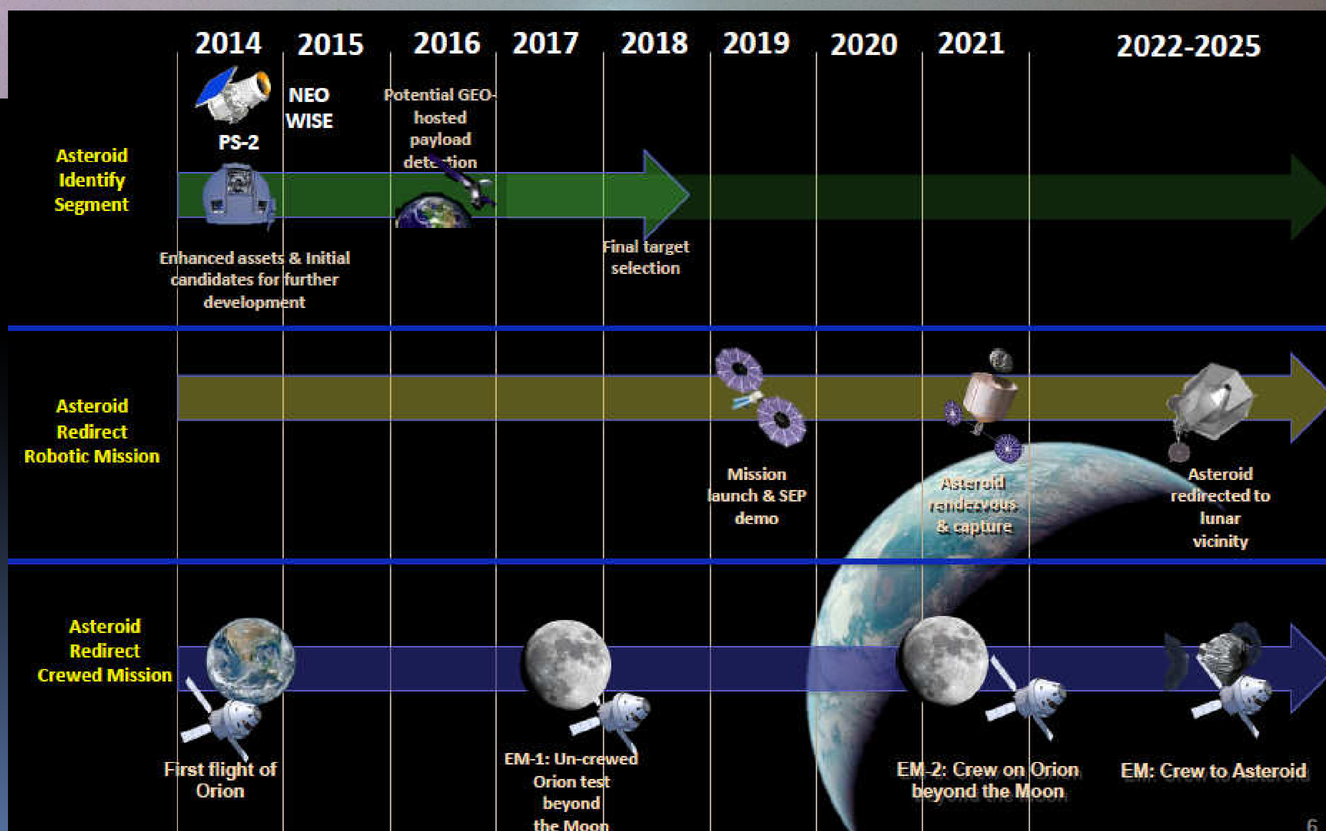
Nested Hall Thruster

- Hall thrusters have extraordinary performance and are extremely scalable
  - Isp's from 1000 to 8000 s
  - Power levels from 200 W to >100 kW
- Magnetic shielding enables huge advances in the technology
- Nested Hall Thrusters may facilitate high-power operation and a very large throttle dynamic range

High-powered SEP Enables Multiple Applications




2012
2014
2016
2018
2020
2022
2024
2026
MCR
One Target
PDR
CDR
Primary & Backup Target
* Launch
* NEA @ Lunar Orbit


2014
2015
2016
2017
2018
2019
2020
2021
2022-2025
Asteroid Identify Segment
PS-2
NEO WISE
Potential GEO-hosted payload detection
Enhanced assets & Initial candidates for further development
Final target selection
Asteroid Redirect Robotic Mission
Mission launch & SEP demo
Asteroid rendezvous & capture
Asteroid redirected to lunar vicinity
Asteroid Redirect Crewed Mission
First flight of Orion
EM-1: Un-crewed Orion test beyond the Moon
EM-2: Crew on Orion beyond the Moon
EM: Crew to Asteroid
6


A DEEPER VISION, A BOLDER MISSION, ONE STEP AT A TIME
Step One:
2014