Applications of Droplet Streams in Space

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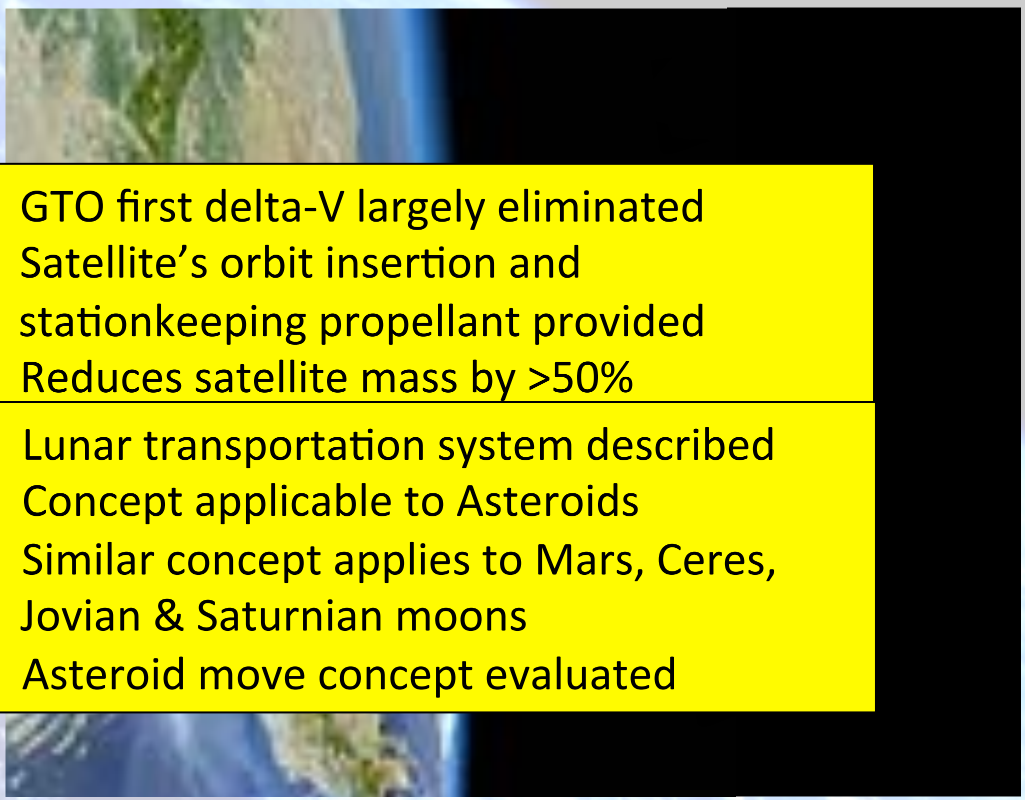
Droplet Stream Applications

- Side-by-side formation
- Orbital debris remediation
- GTO boost/refuel
- Interplanetary propulsion



- GTO first delta-V largely eliminated
- Satellite's orbit insertion and stationkeeping propellant provided
- Reduces satellite mass by >50%

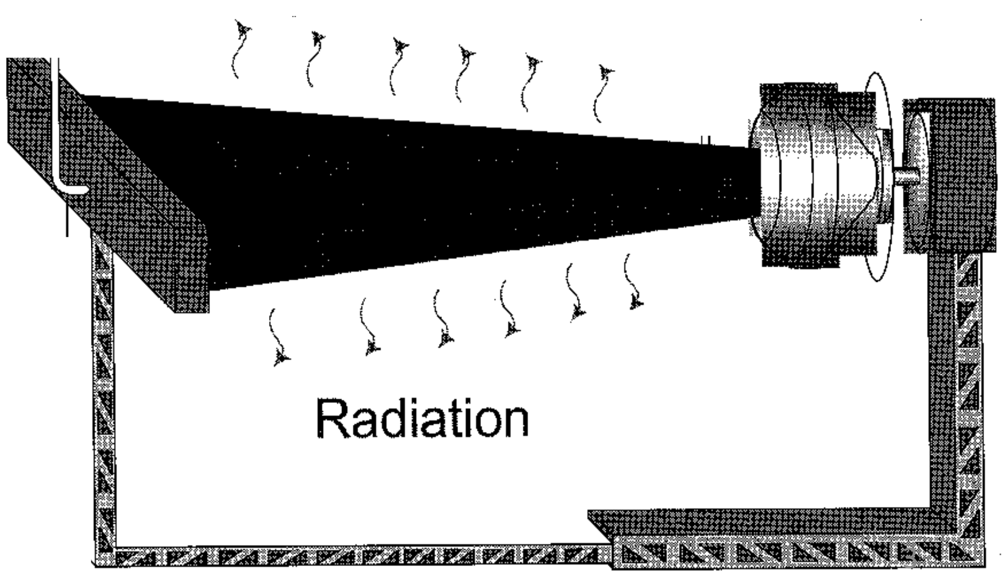
- Lunar transportation system described
- Concept applicable to Asteroids
- Similar concept applies to Mars, Ceres, Jovian & Saturnian moons
- Asteroid move concept evaluated

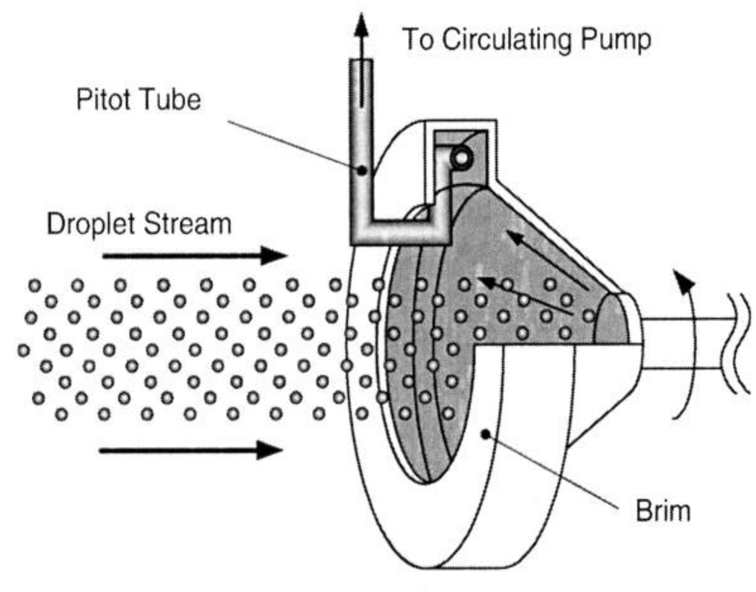
- Enabling technology
- Sparse aperture communication
- Interferometric SAR
- Active cooling

- 1-2 kg liquid de-orbits 1000kg object
- Single spacecraft targets dozens of large objects
- No plane change or rendezvous required
- Missing droplets evaporate
- Object is not fractured

Projection/Collection Technology

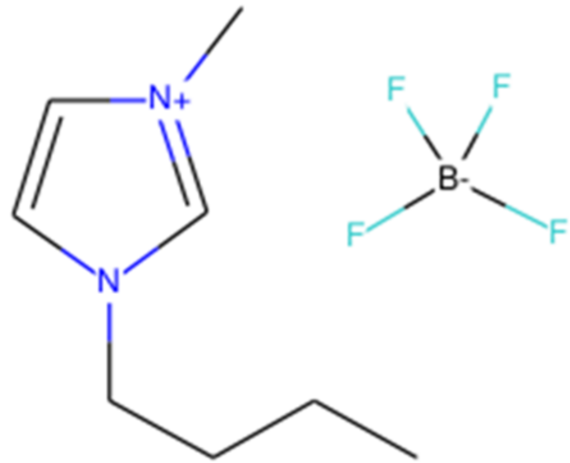
- Feasibility est. in 1980s for Liquid Droplet Radiator
  - Mass-efficient replacement for conventional radiators
  - Droplet generation & collection tested in vacuum & free-fall (NASA Lewis, Hokkaido Univ.)
  - Stream pointing accuracy 1 micro-radian (USC)

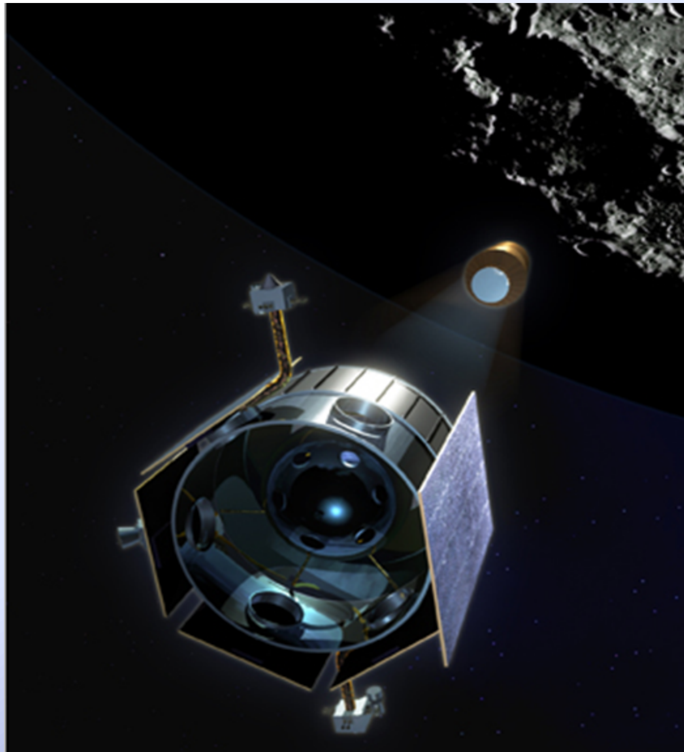




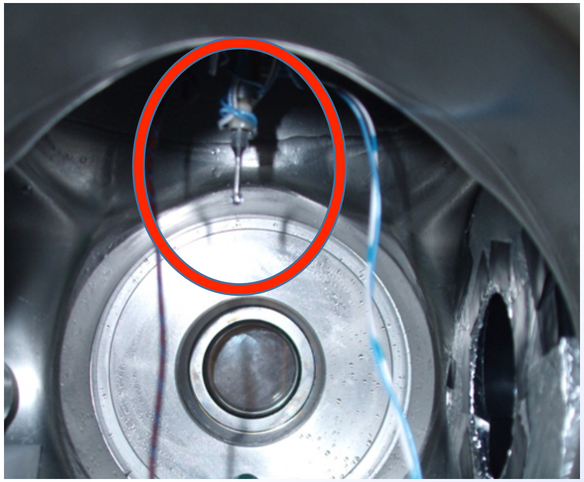
Ionic Liquids

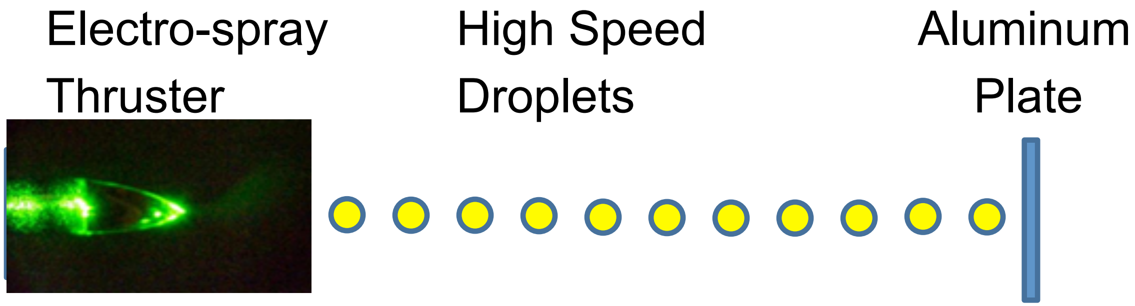
- Stable Mixture Anions & Cations
  - Low vapor pressure
  - Low glass transition: 185K
  - High decomposition: 653K
  - High conductivity
  - Dual mode IL propellants
    - Electrospray (~HET)
    - Monoprop (~Hydrazine)
    - Hypergolic (~N2H4/ Hydrazine)



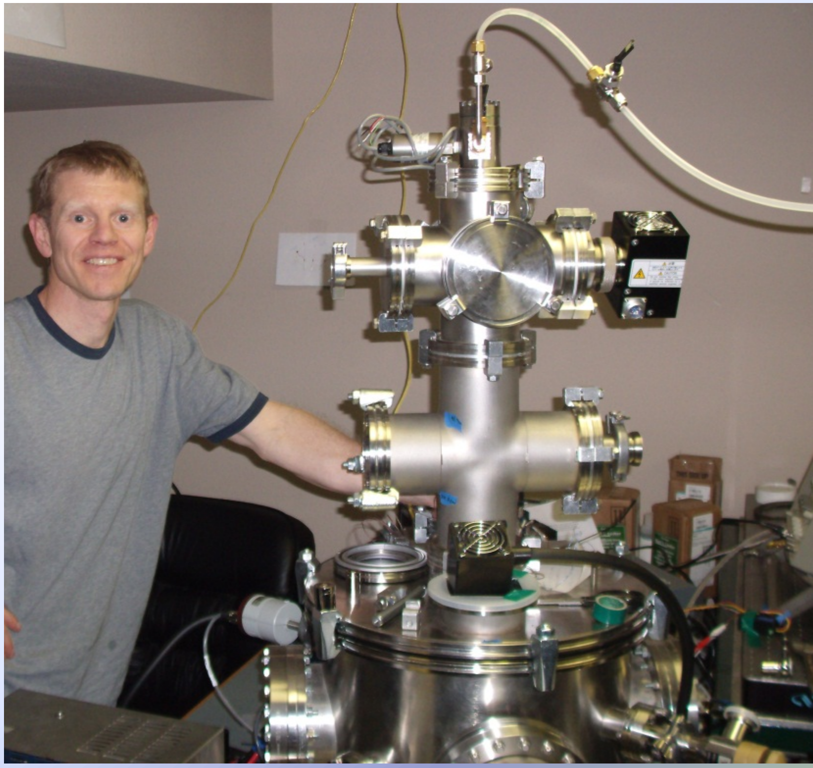


Recent Droplet Experiments



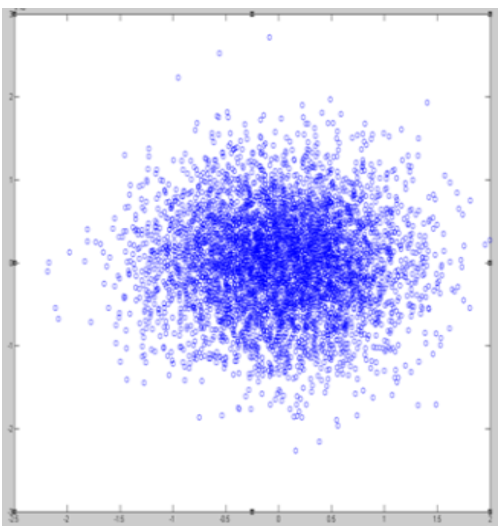


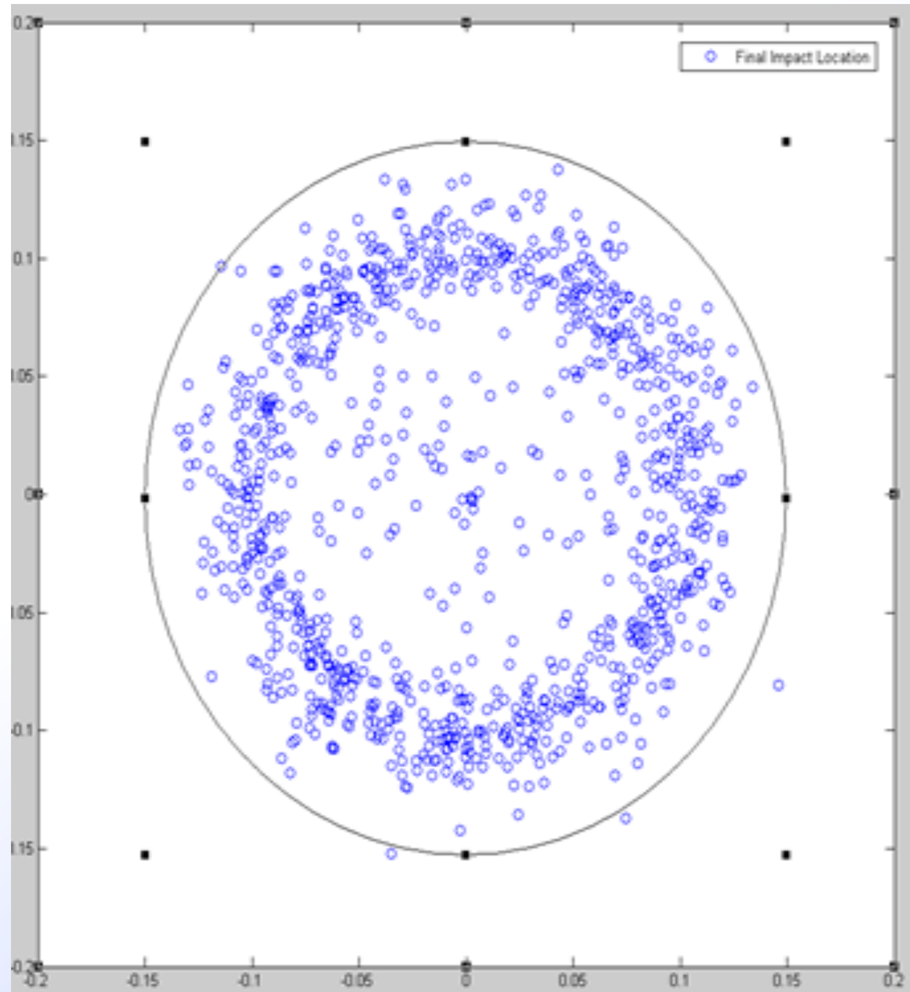
- Collision with Al plate
- RGA used to ID molecules
  - >1500 m/s no vaporization
  - No spalling of plate
- Microsolenoid droplet production
- Predictive charge model validation



Sources of Stream Projection Error

- Coulomb forces increase impact area
- Droplet charging modeled
- Model validated

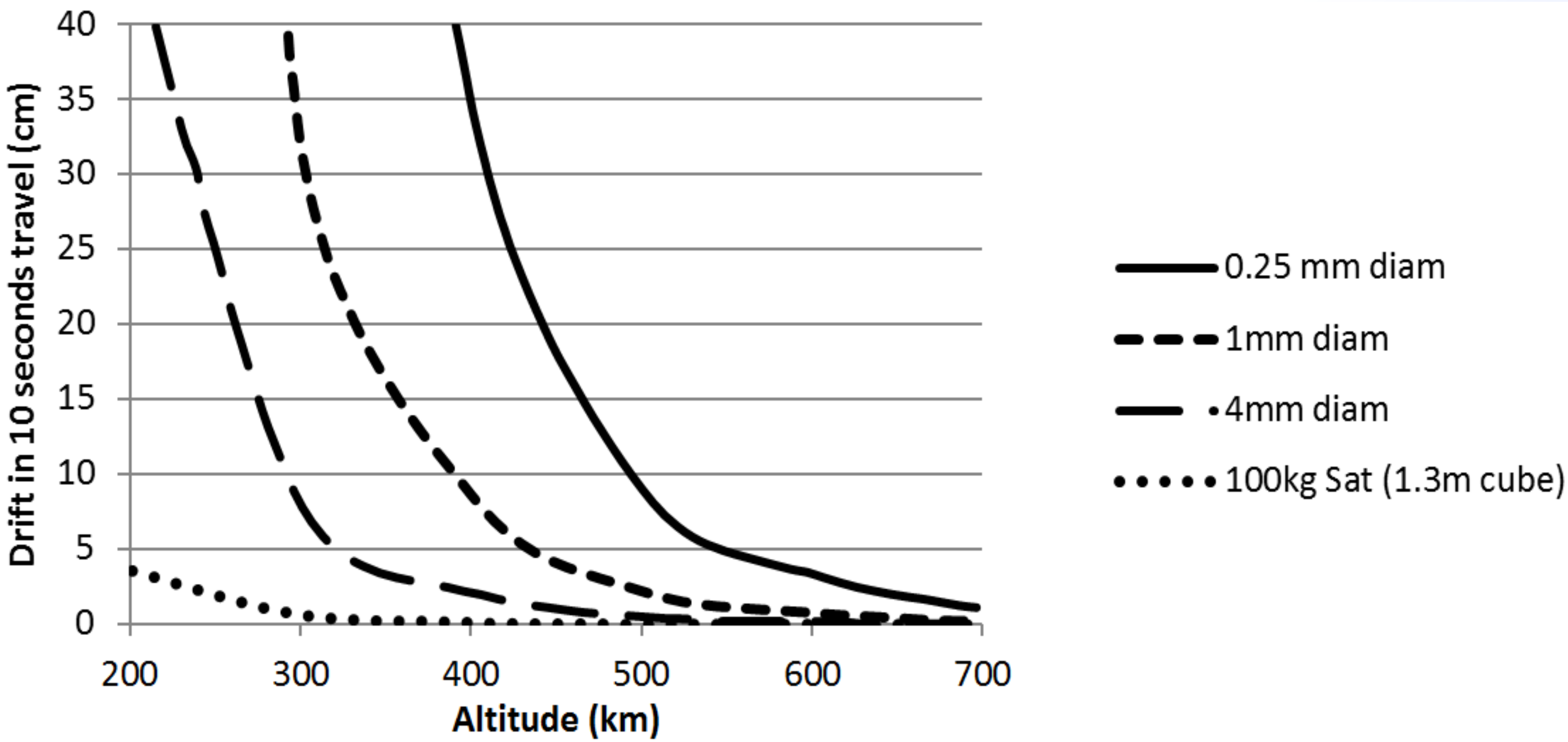




1 droplet diameter spacing (right)
4 diameter spacing (left)

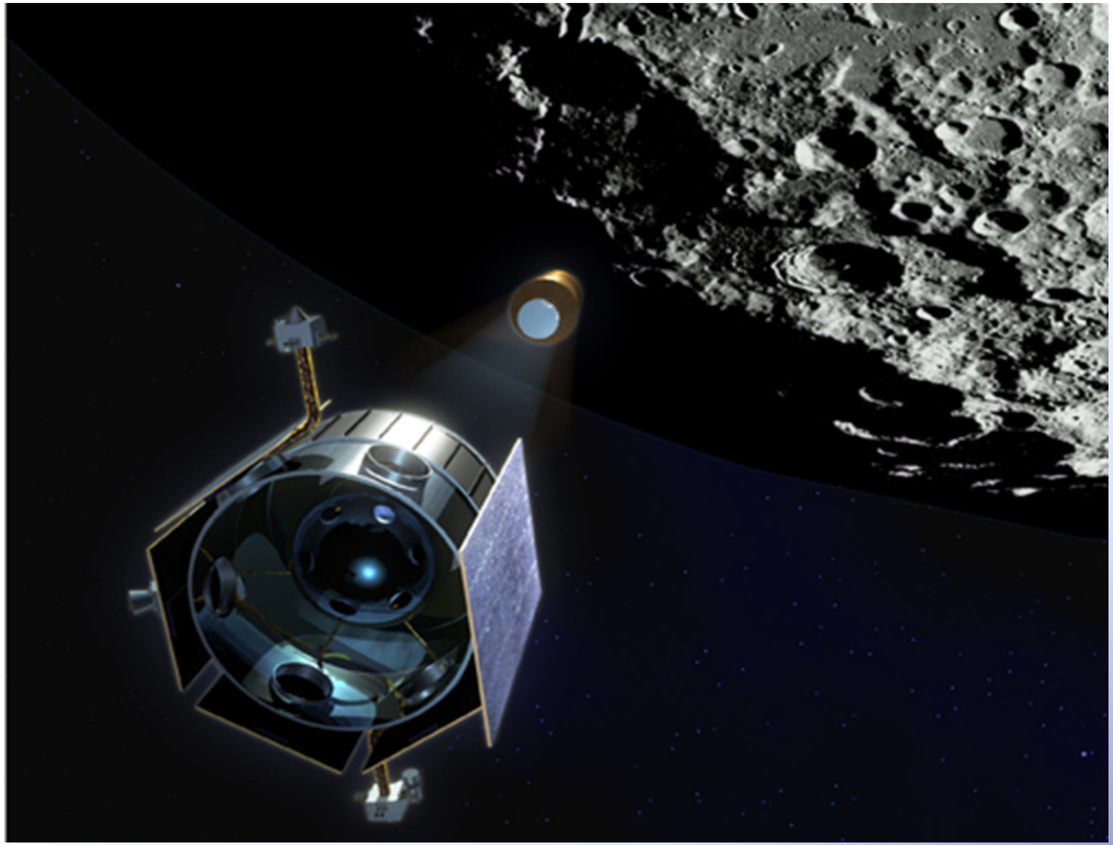
Drag Effects on Stream Projection

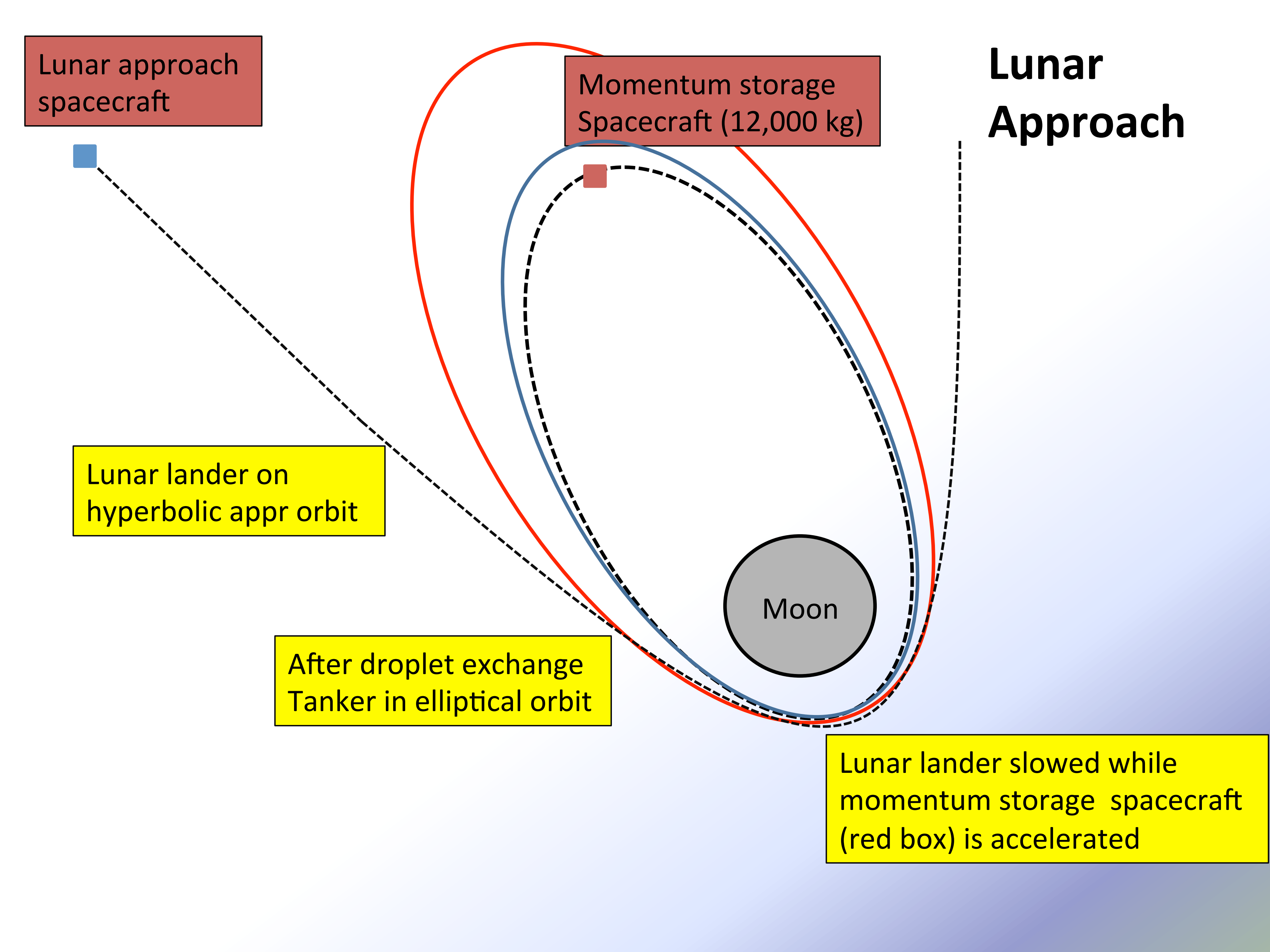
- Droplets modeled as solid spheres
  - Drag induced displacement after 10 sec shown



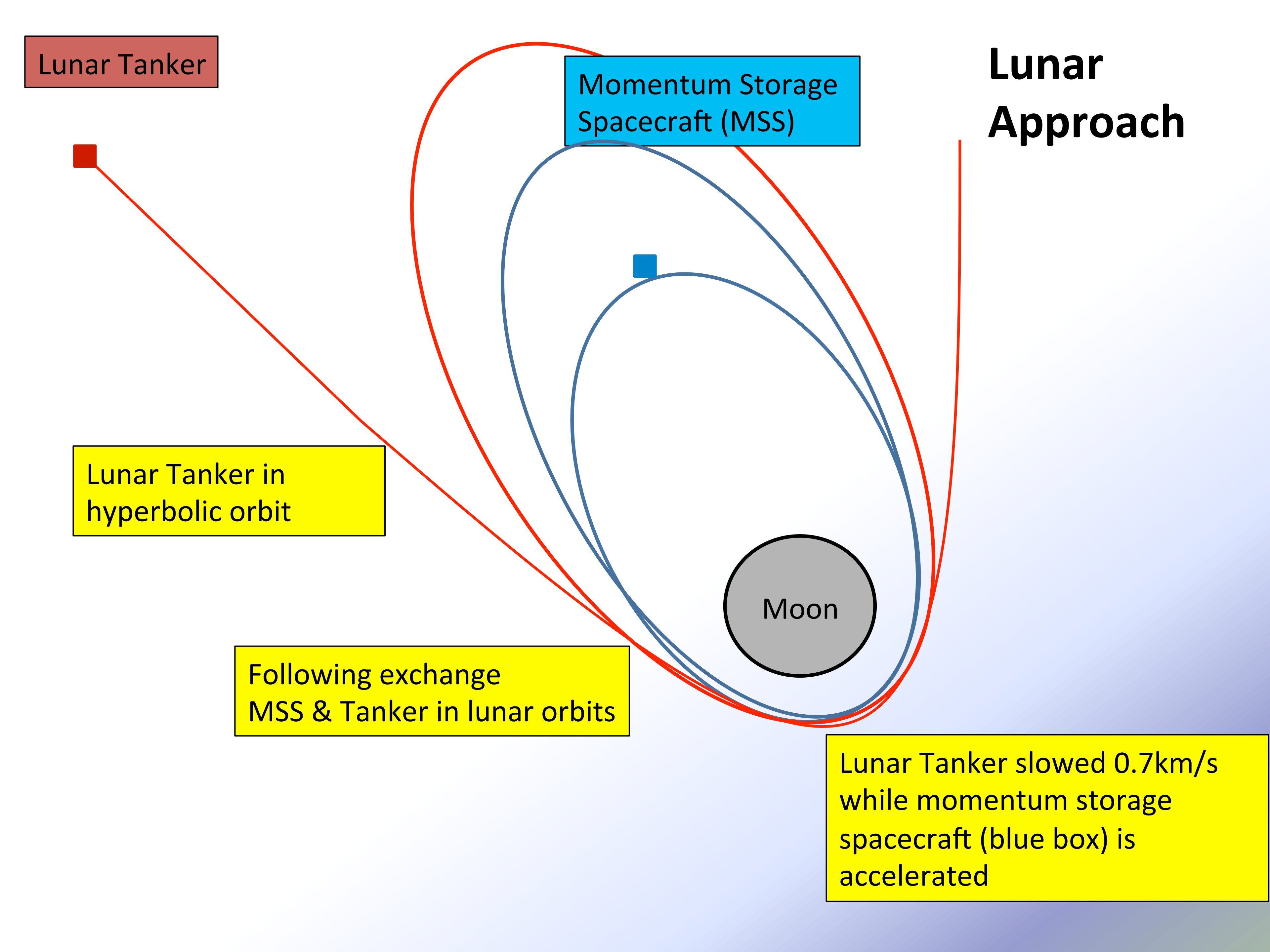
Droplet Stream Lunar & Interplanetary Propulsion Architecture

- To bring Ionic Liquids (and other resources) from Asteroids or moons to Earth orbit for various economically viable applications



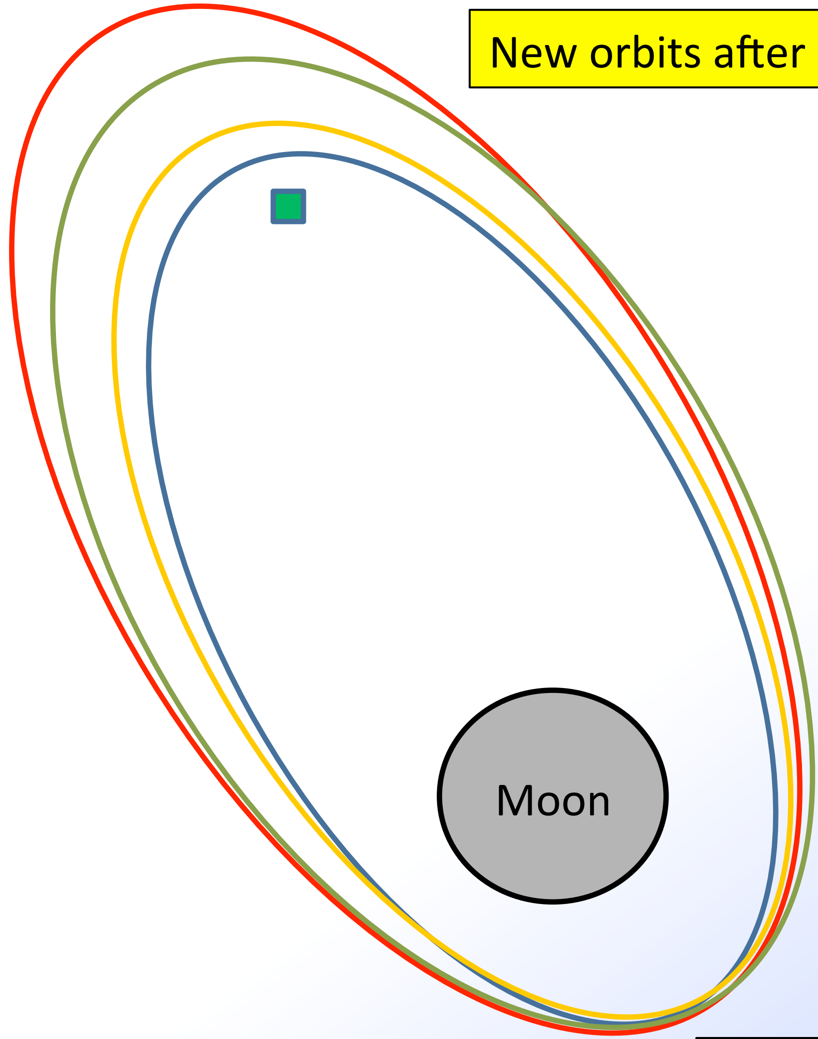


Lunar Approach
Lunar approach spacecraft
Momentum storage Spacecraft (12,000 kg)
Lunar lander on hyperbolic appr orbit
After droplet exchange Tanker in elliptical orbit
Moon
Lunar lander slowed while momentum storage spacecraft (red box) is accelerated


Lunar Tanker
Momentum Storage Spacecraft (MSS)
Lunar Approach
Lunar Tanker in hyperbolic orbit
Moon
Following exchange
MSS & Tanker in lunar orbits
Lunar Tanker slowed 0.7km/s while momentum storage spacecraft (blue box) is accelerated

Lunar Approach

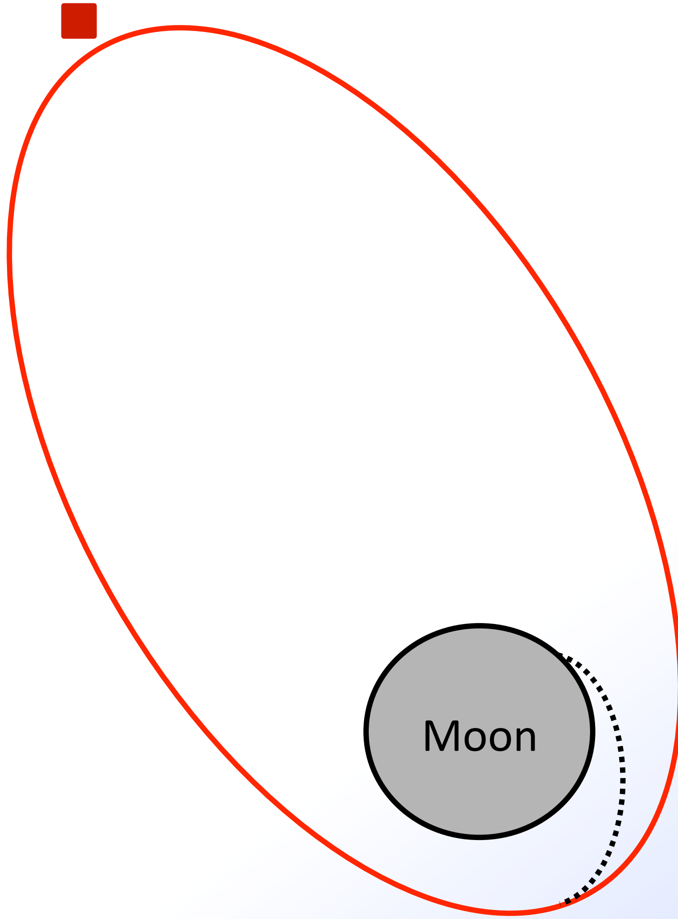
New orbits after 2nd droplet exchange



Lunar spacecraft transfers ionic fluid back to momentum transfer spacecraft

2nd Droplet exchange occurs

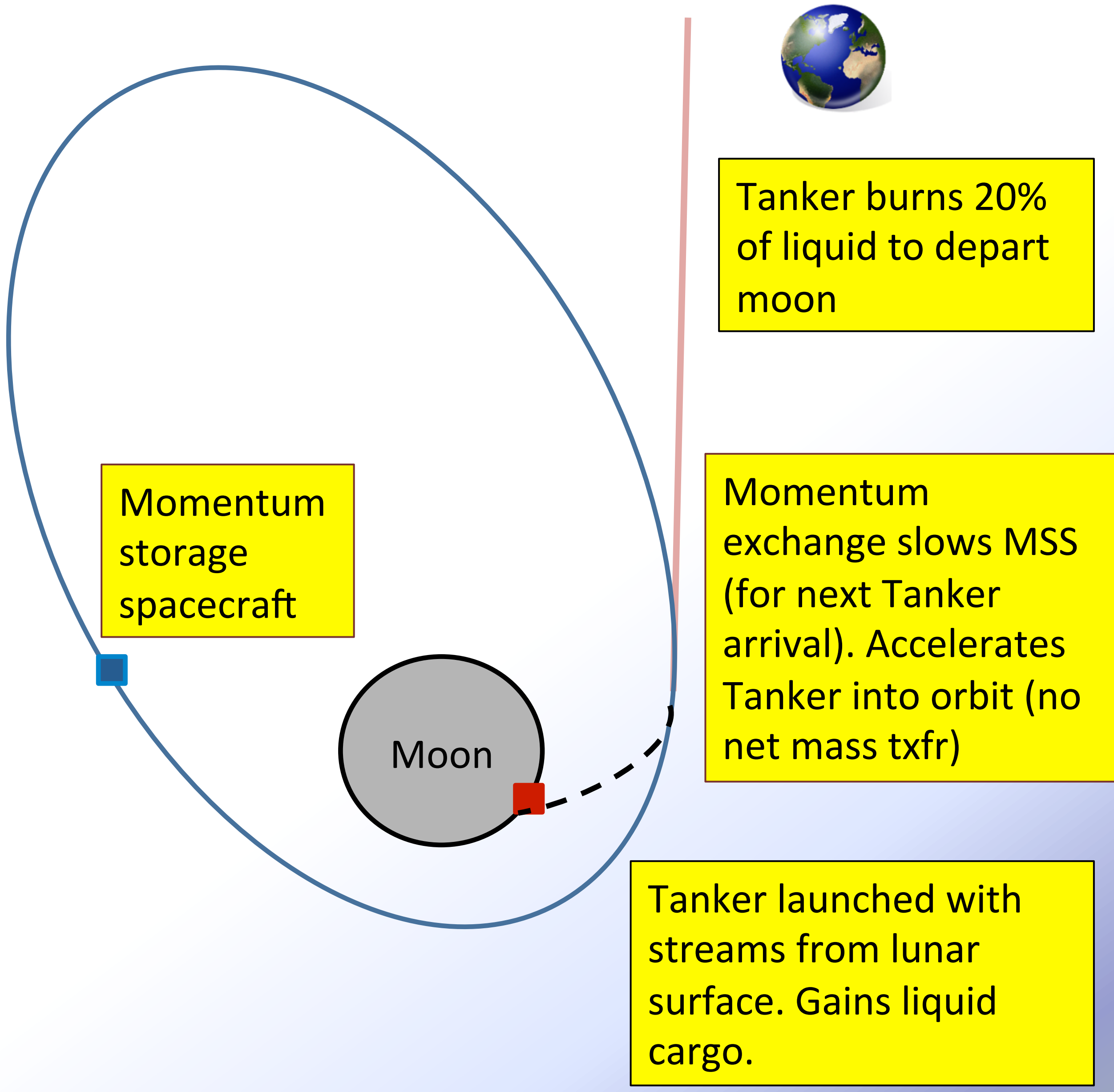
Lunar Landing



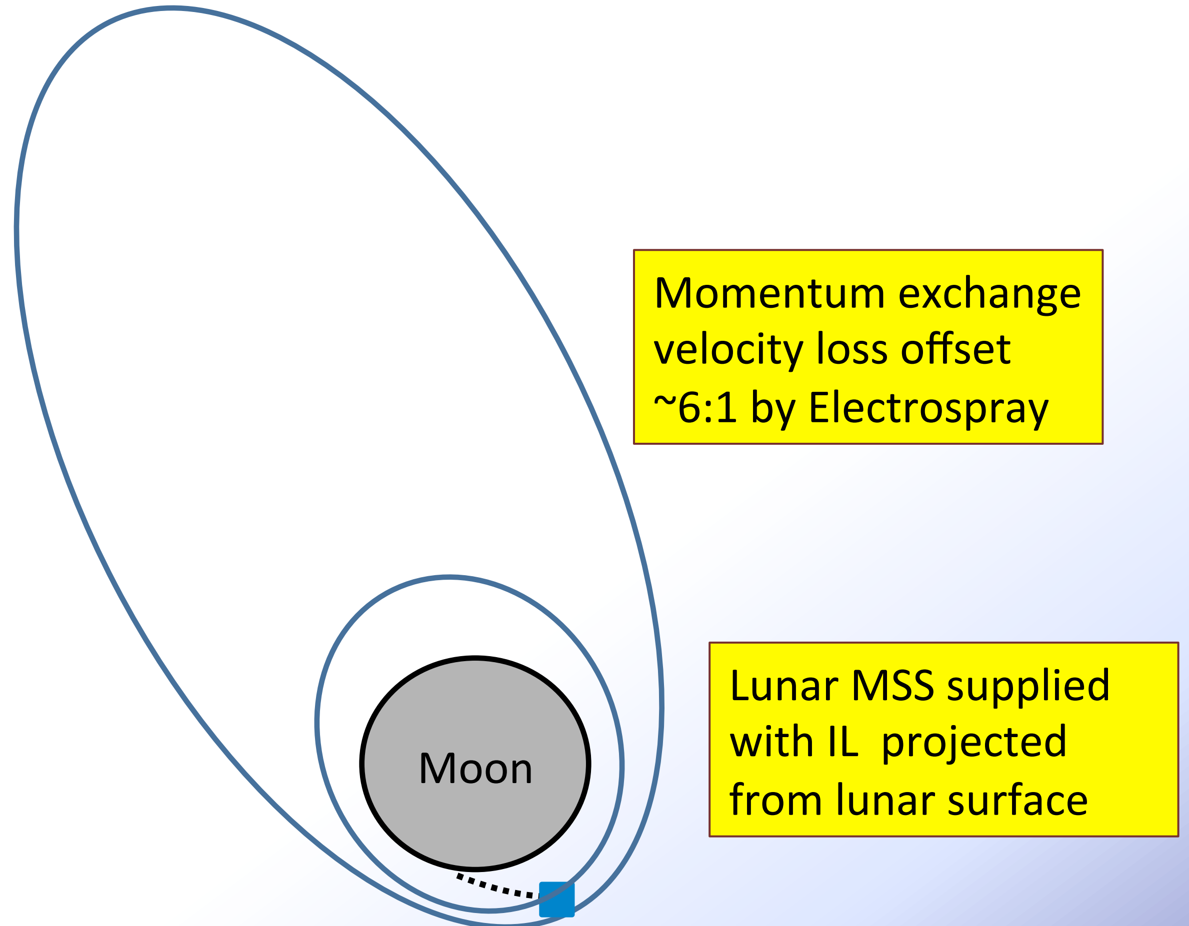
Droplet streams projected from surface (and back) slow Tanker for landing

Droplet Stream Landing/Launch

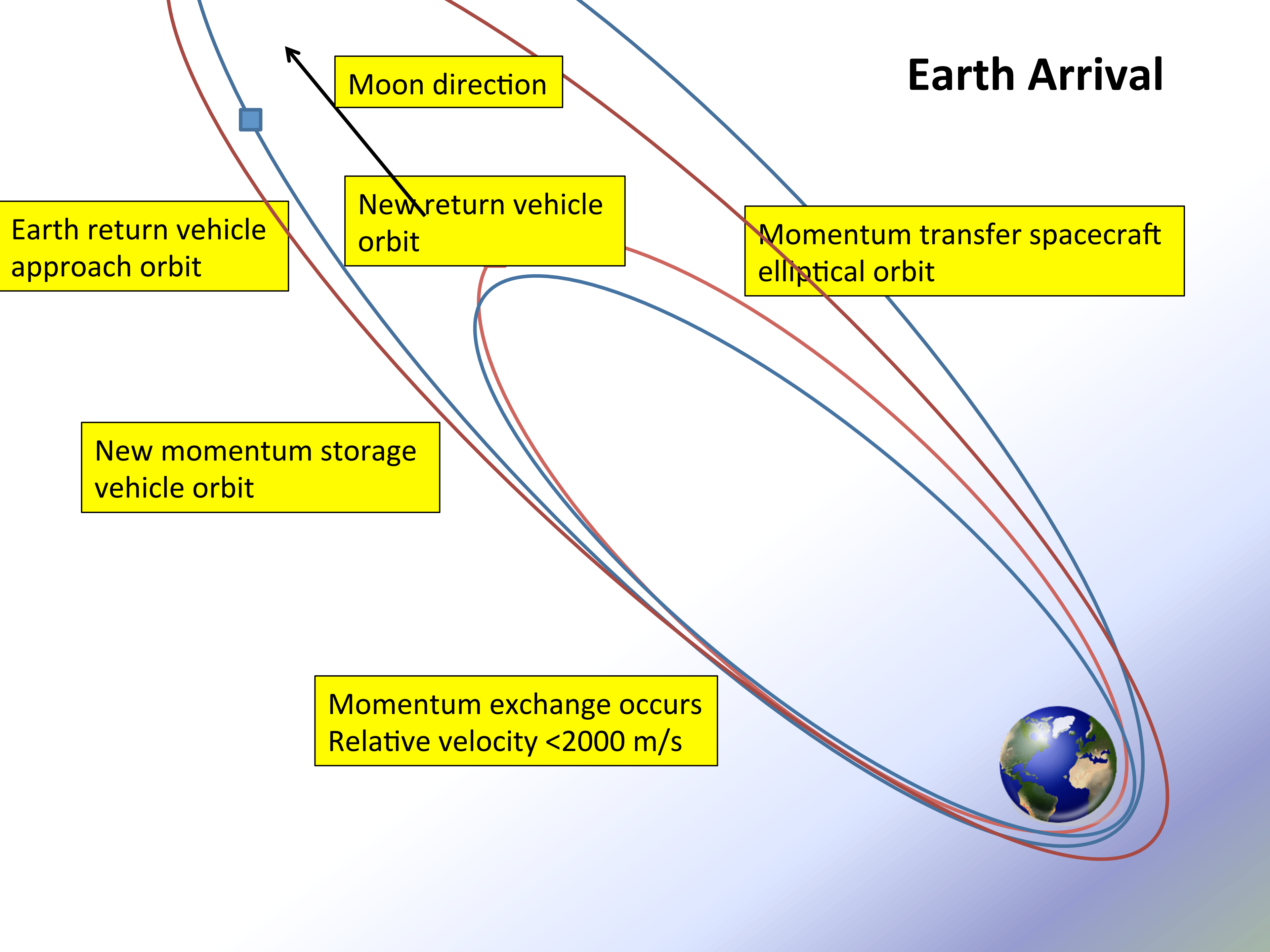
Moon Departure



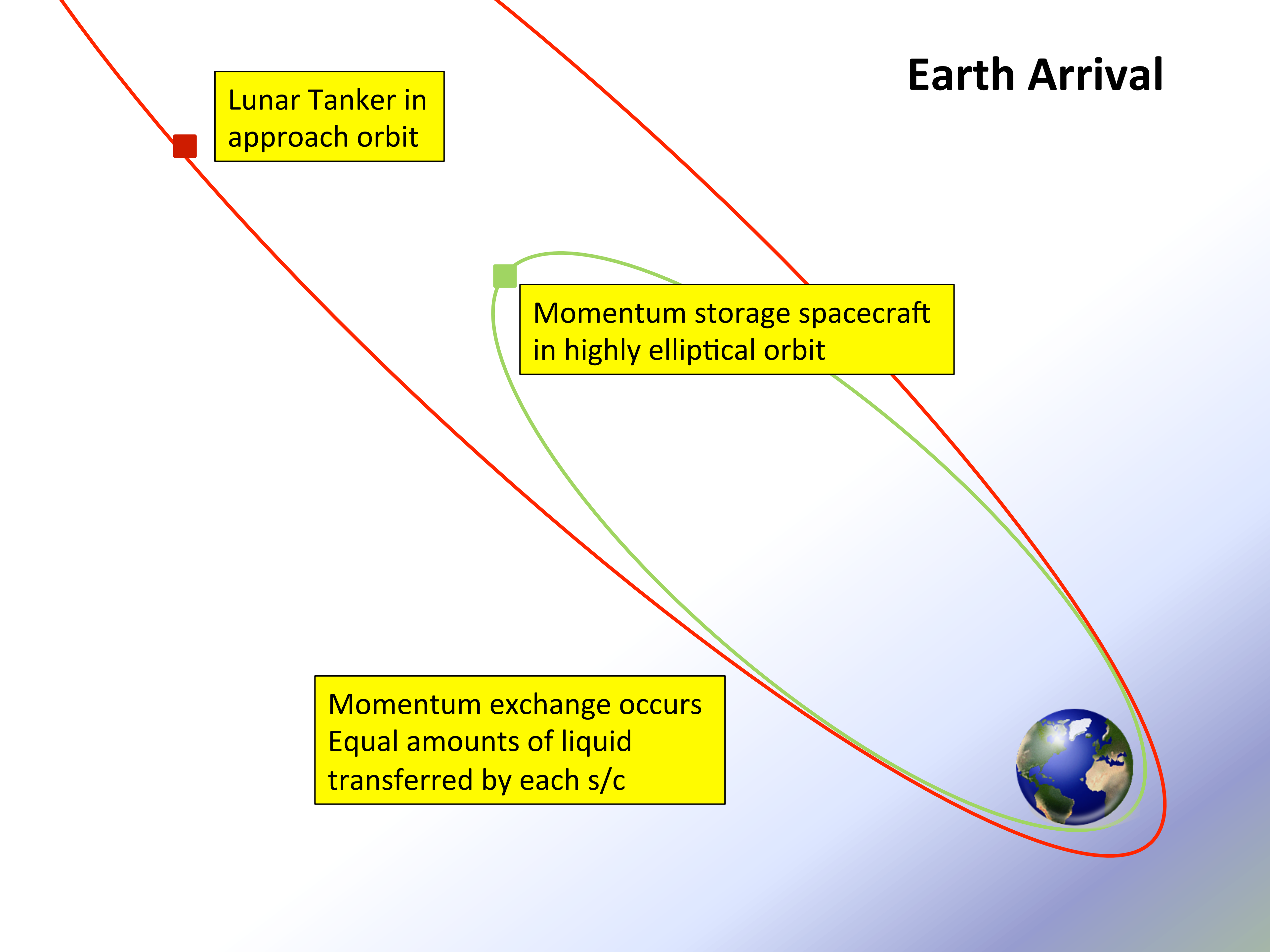
Mass Storage Spacecraft Refueling



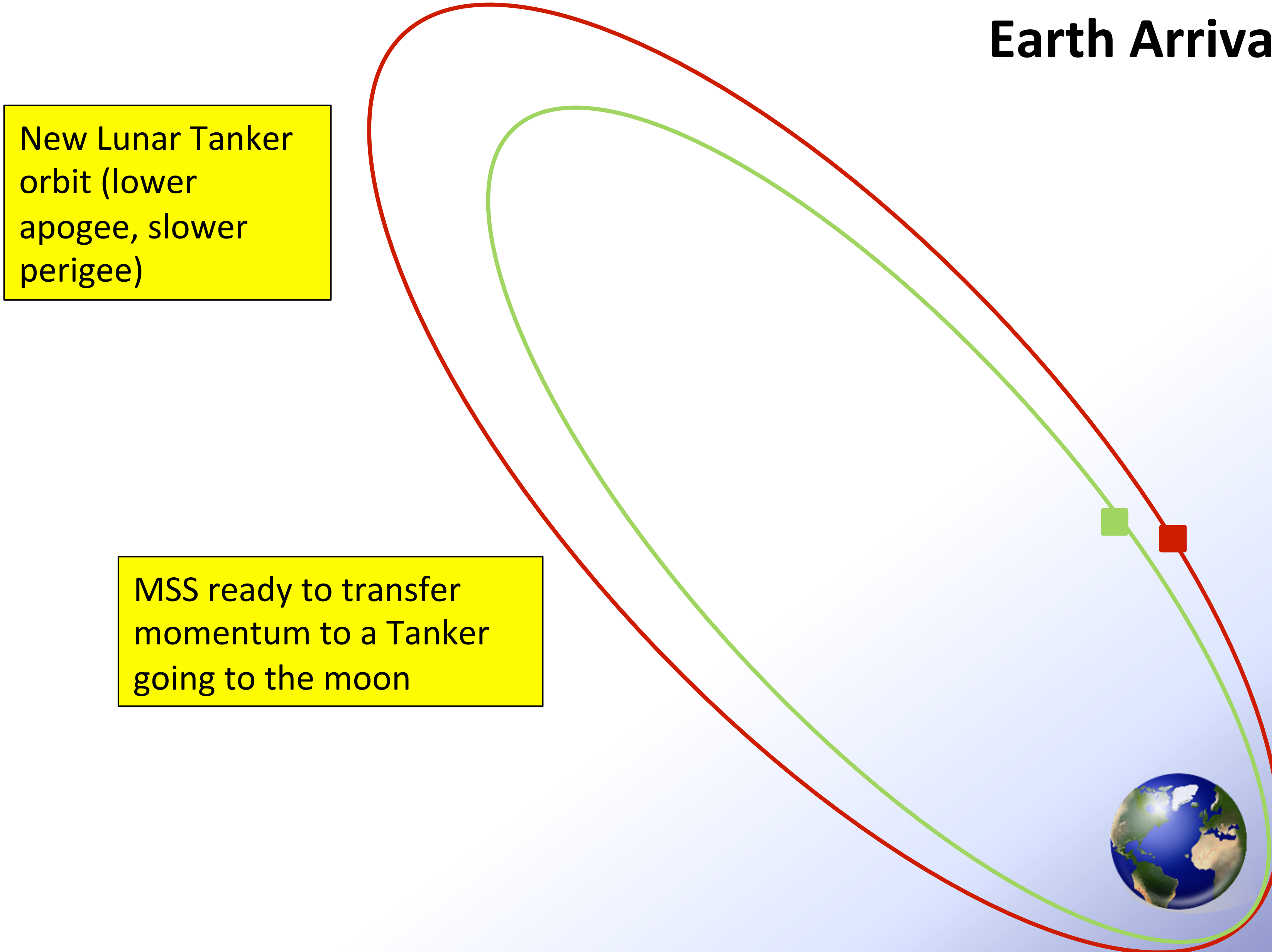
Earth Arrival

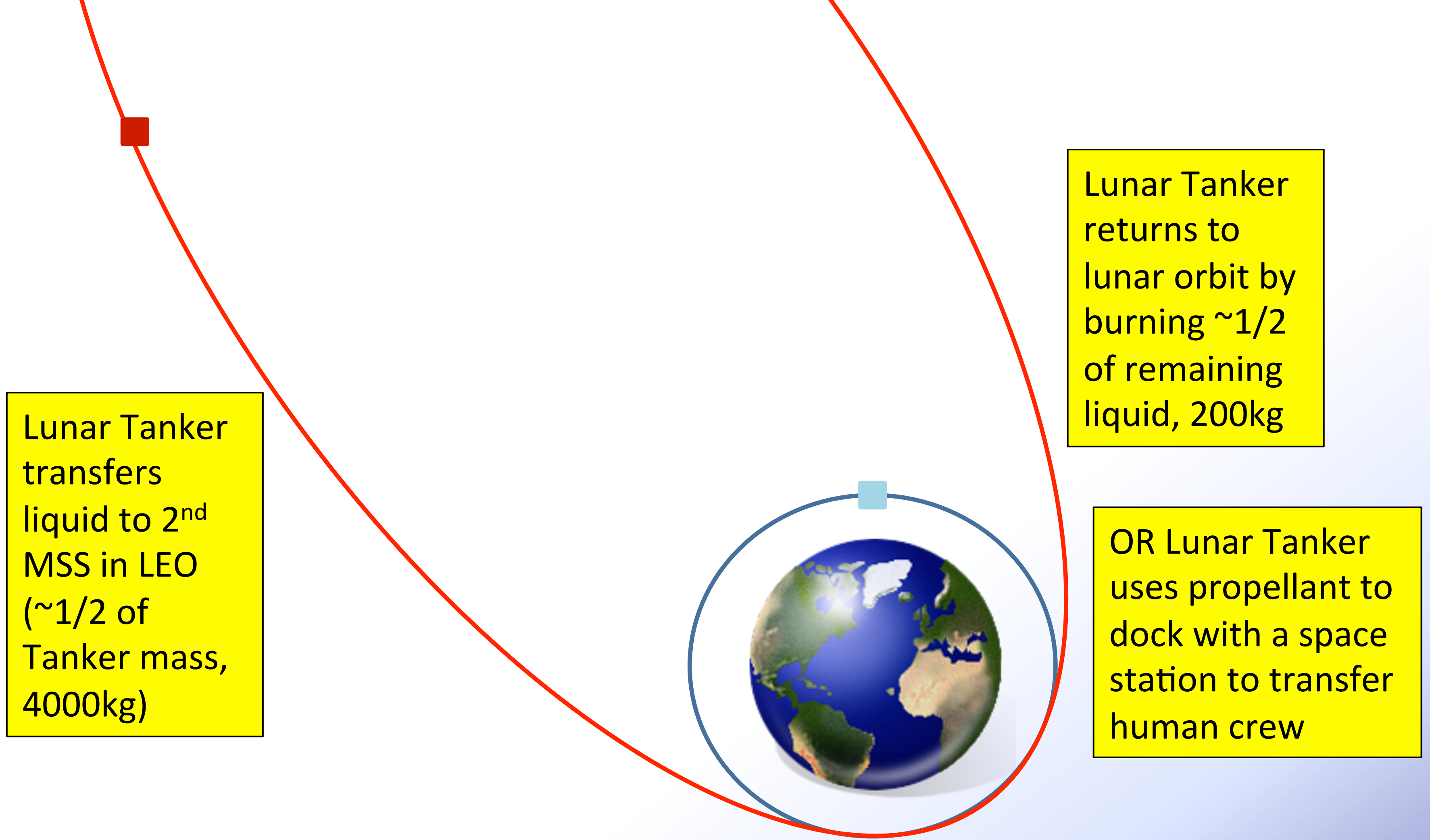


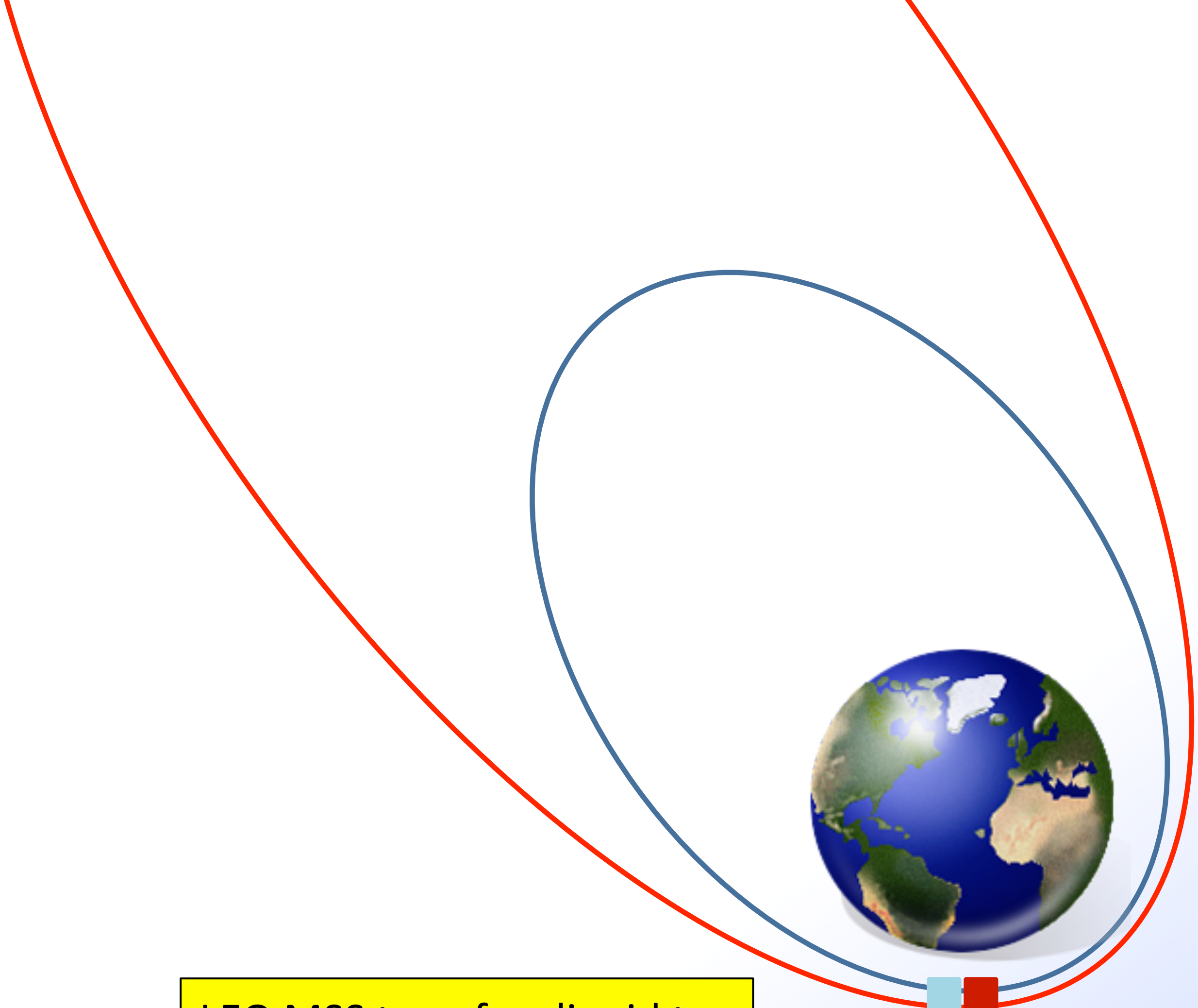
Earth Arrival



Earth Arrival




Lunar Tanker returns to lunar orbit by burning ~1/2 of remaining liquid, 200kg
Lunar Tanker transfers liquid to 2nd MSS in LEO (~1/2 of Tanker mass, 4000kg)
OR Lunar Tanker uses propellant to dock with a space station to transfer human crew



LEO MSS transfers liquid to various spacecraft at various altitudes for profit

Conventional vs. Momentum Exchange Lunar Missions

	Payload to Moon (kg)	Payload from Moon (kg)	Propellant Mass in LEO (kg)
Conventional N2H4/Hydrazine	5k (unmanned)	1k (unmanned)	**184k**
Droplet Stream Propulsion	5k (unmanned)	1k (unmanned)	**8.5k**

- Estimated Infrastructure Cost:$6B
  - 1 Lunar, 2 Earth-orbiting MSS, each 16,000 kg
  - 20 tons ionic liquid on lunar surface + 500 kg battery
  - 5 Falcon or Vulcan Heavy launches
    - Or 2 Heavies and one unmanned SLS launch

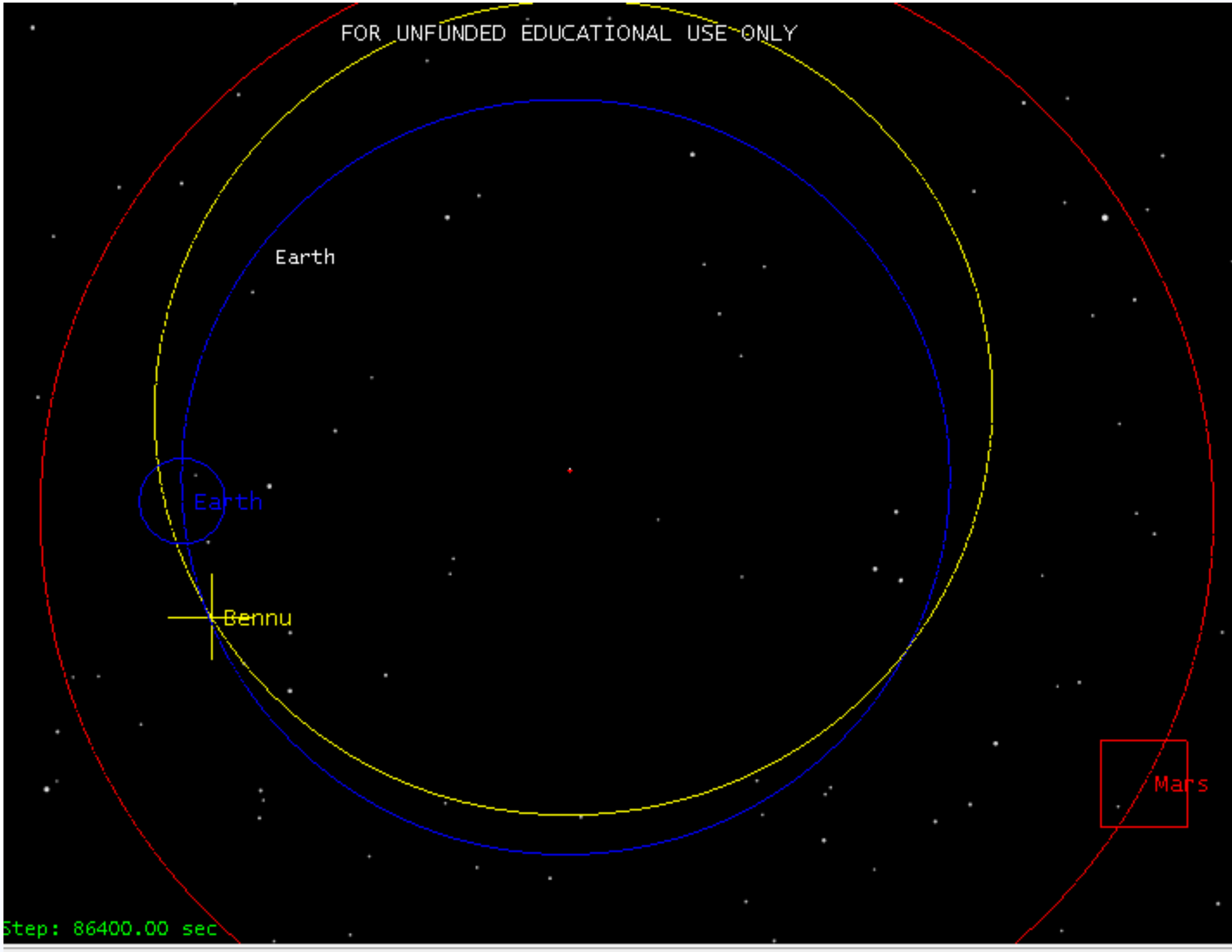
Conventional vs. Momentum Exchange (with in situ propellant from Earth's moon)

Performance with infrastructure in-place	Vehicle Mass On Moon (kg)	Propellant Mass (kg)	LEO Mass (kg)	Propellant Savings (kg/mission)
Conventional Rocket Thrusters (Apollo style)	16k	184k	200k	**175,500 (cargo)** **124,000 (humans)**
Droplet Stream Momentum Transfer	16k	8.5k (cargo) 60k (humans)	24.5k 76k	

- Estimated Infrastructure Cost:$2.5B
  - 1 Lunar, 2 Earth-orbiting MSS, each 16,000 kg
  - 20 tons ionic liquid on lunar surface + 500 kg battery
  - 5 Falcon or Vulcan Heavy launches
    - Or 2 Heavies and one unmanned SLS launch

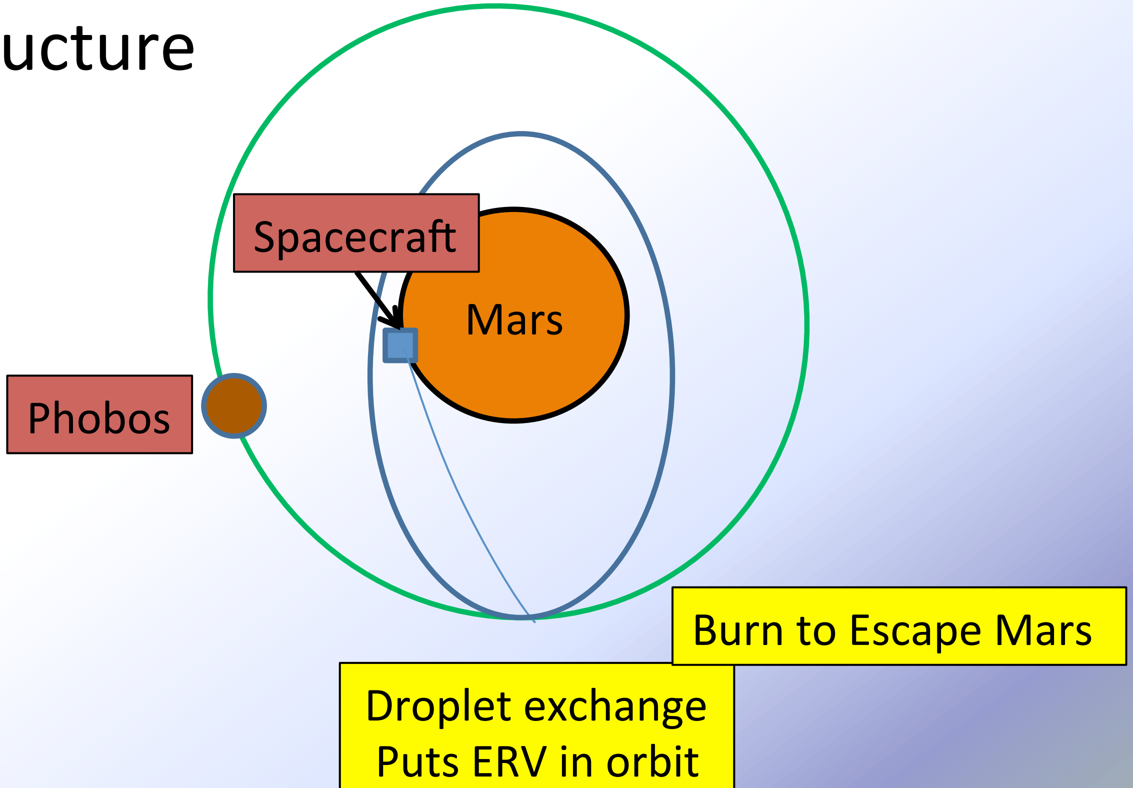
Asteroid Momentum Tranfers

- NEO Asteroids like Bennu as liquid depots
- Single exch allows Mars txfr



Mars Mission

- Same system for departing/arriving at Earth used at Mars
- Arrival aero-braking & Phobos momentum exchange
- Departure with Phobos momentum exch and thrusters
- 60% propellant reduction leaving Earth
- Reusable infrastructure



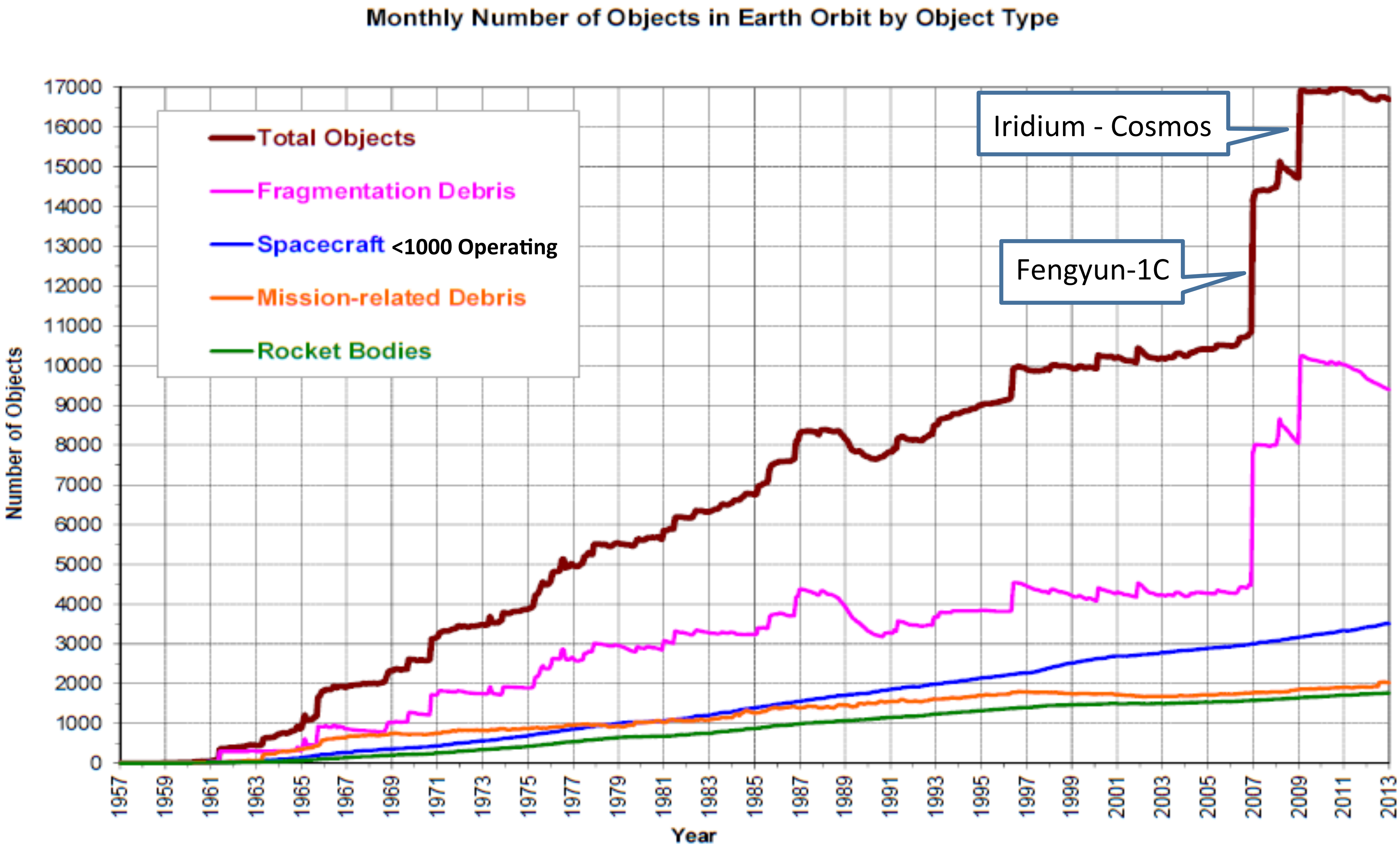
Creating Ionic Liquid In-situ

- Ionic liquids >50% Carbon by mass
- Phobos orbit good for momentum transfer
- m_{prop} leaving Earth reduced by >75%

Propellant Savings: Mars Mission

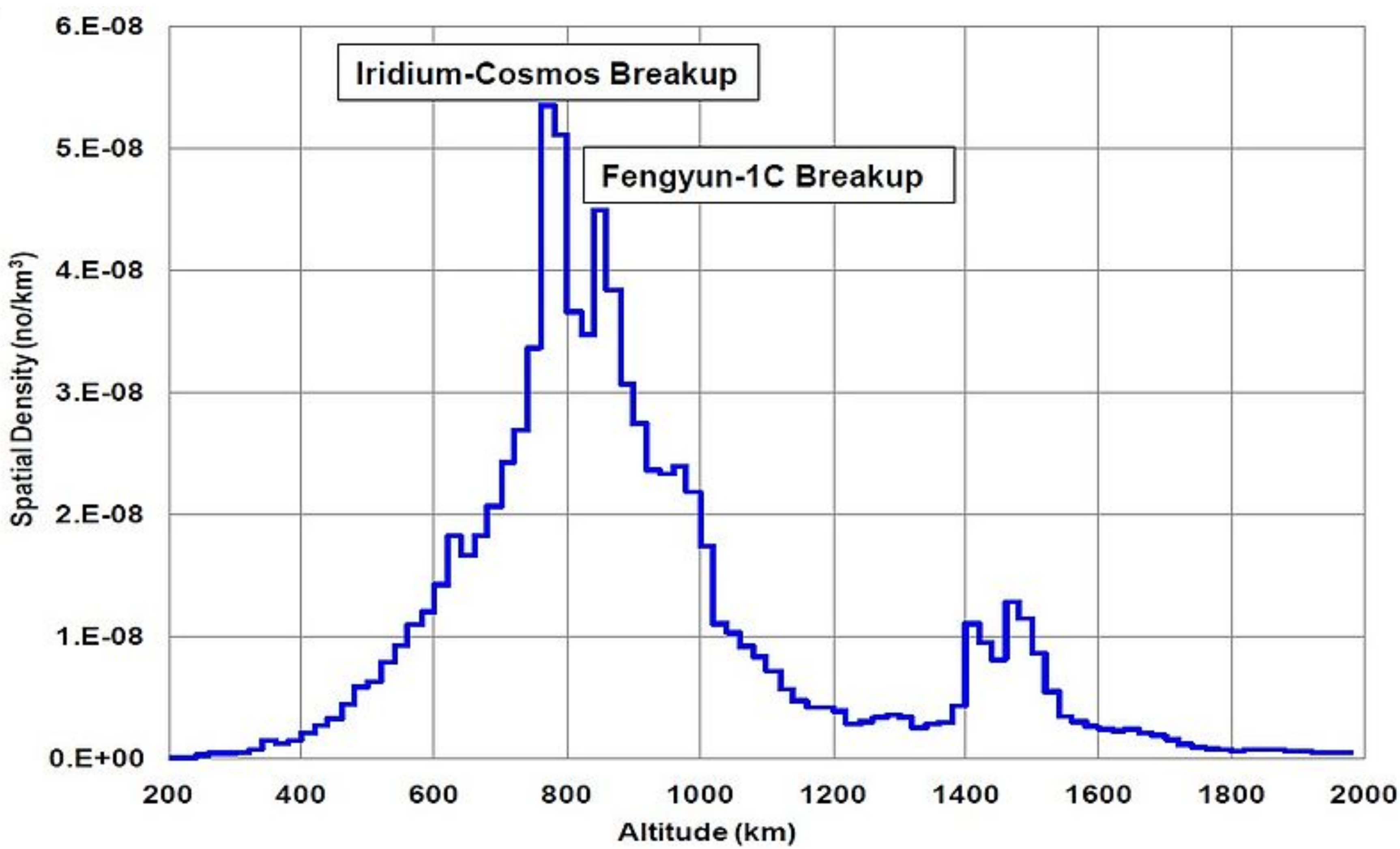
	Leaving Earth	Leaving Mars	Total Propellant	Propellant Saved	% Saved
325s Isp Rockets Only	1,806 mt	38.4 mt	1,645 mt	-	-
Droplet Streams plus Rockets	905 mt	28.8 mt	743 mt	328 mt	60%
Propellant Produced on Phobos	324.0 mt	28.8 mt	352 mt	1,292 mt	79%

Tracked Orbital Debris by Year



Source: NASA Johnson Space Center, Orbital Debris Office

Altitude of Orbital Debris

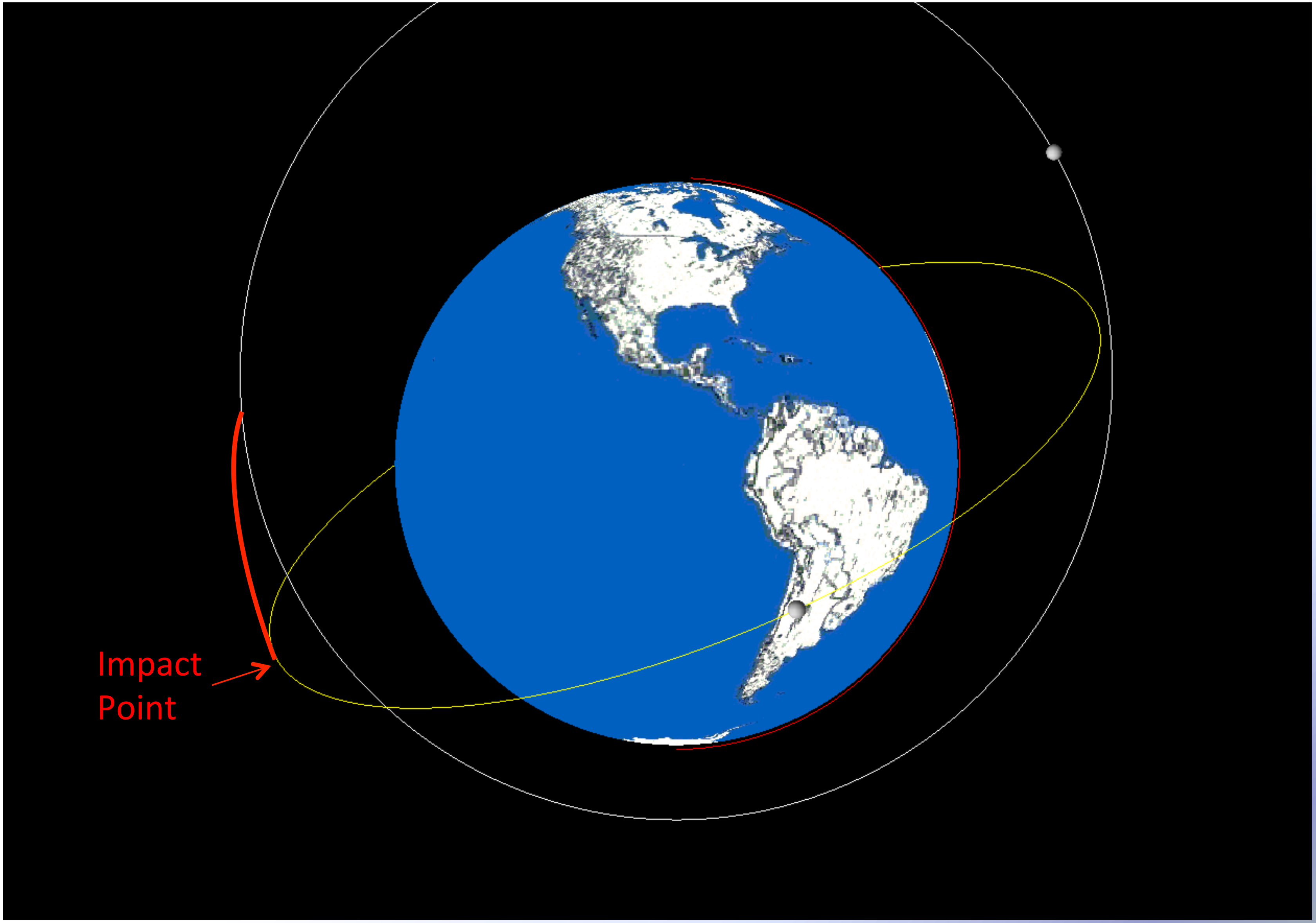


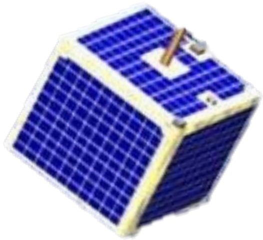
Source: NASA 2011 Report to the United Nations Office for Outer Space Affairs

Active Debris Removal

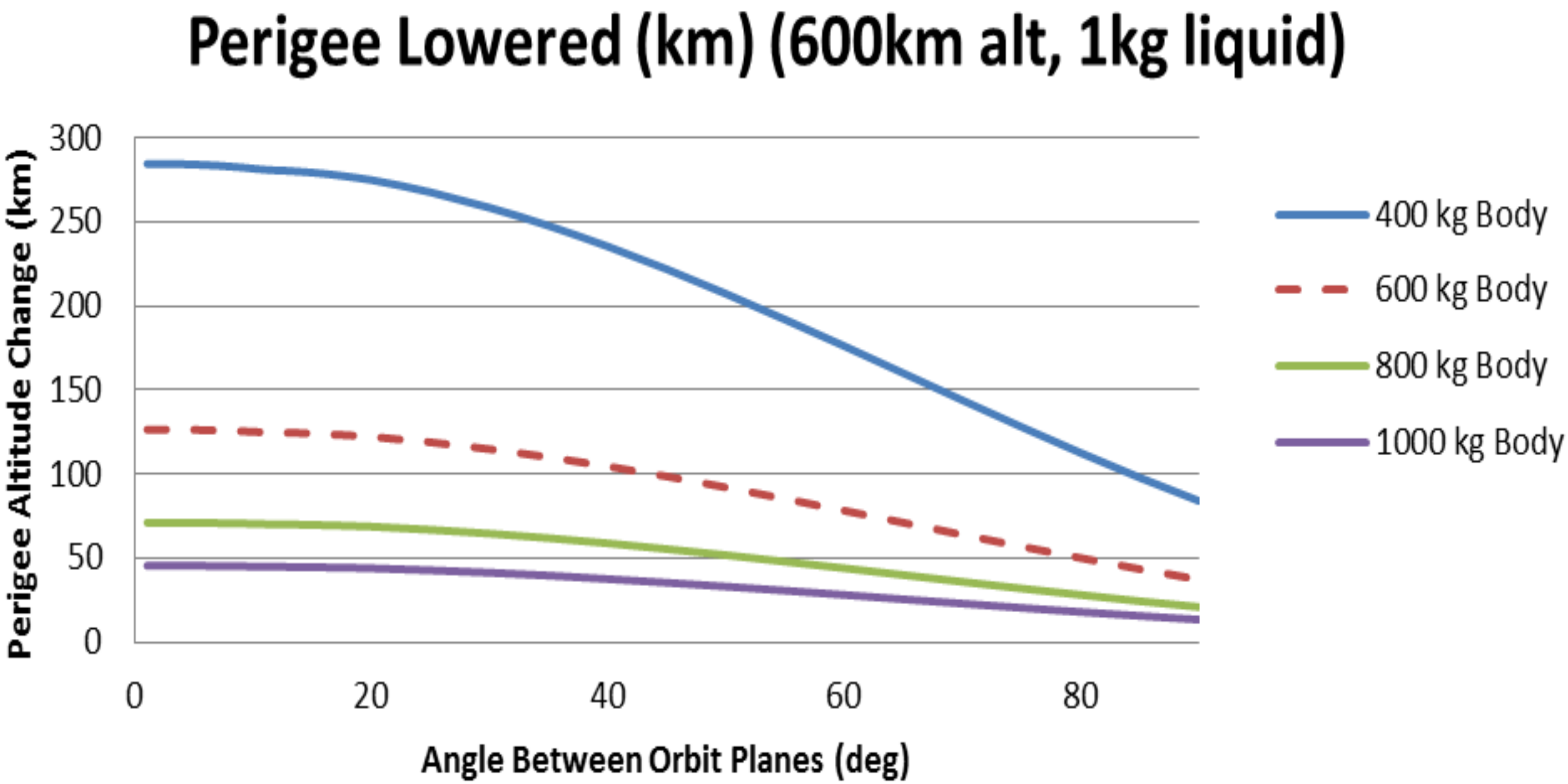
- Most proposals capture & lower (difficult & inefficient)

Droplet Orbit Dynamics: Out of plane





Resulting Object Altitude Loss



Tandem Flight for InSAR and Comm

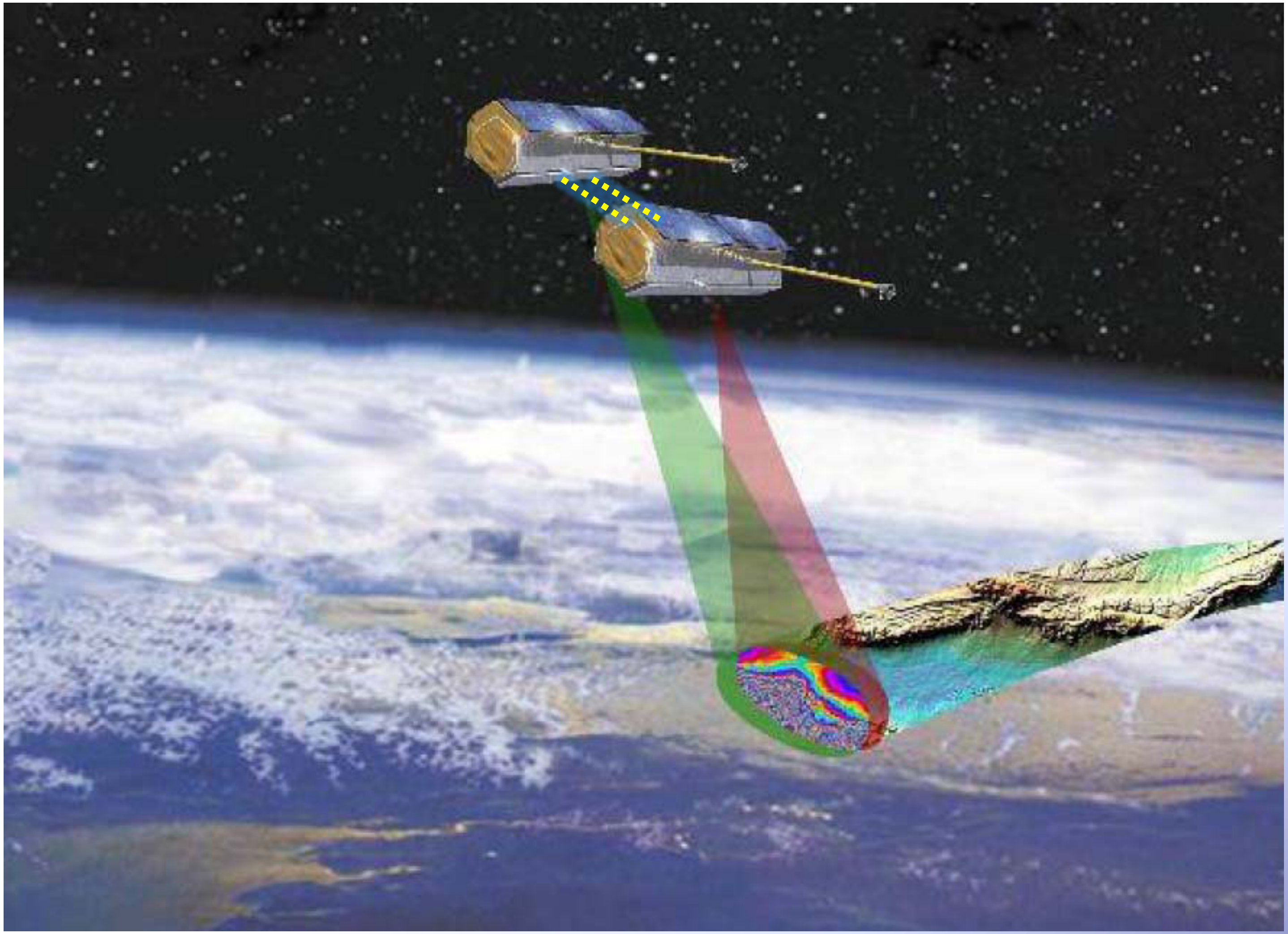
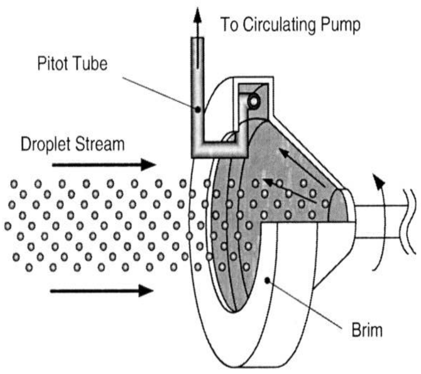
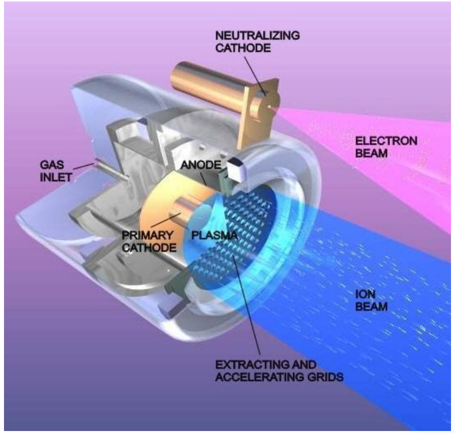


Photo Courtesy of ESA

Droplet Stream vs. Electric Propulsion (10-yr mission)

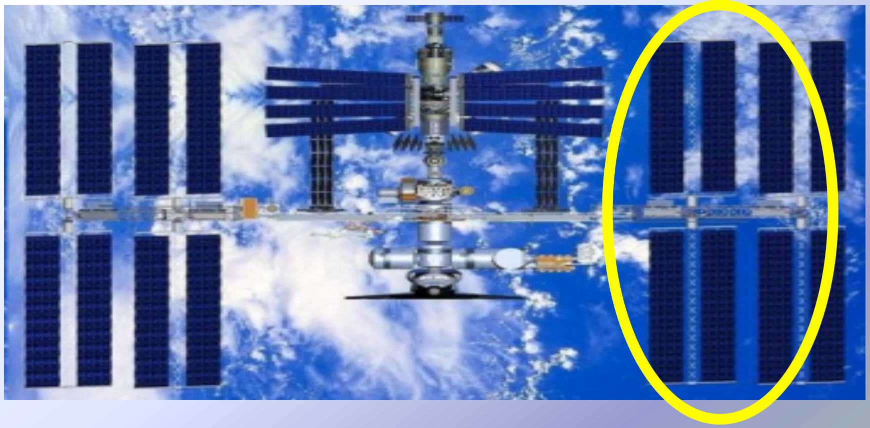




Ion Engines

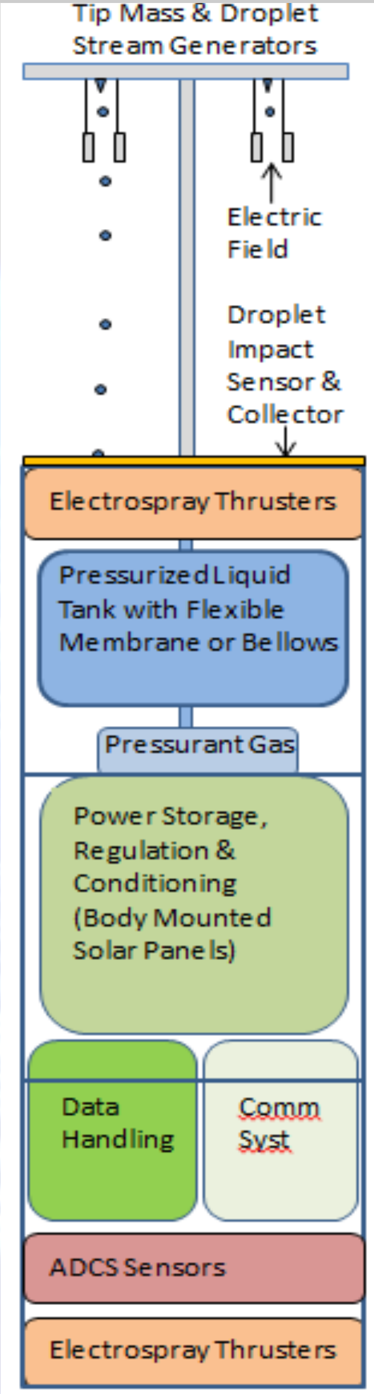
Droplet streams: 50W, 44kg

Electric Propulsion: 30kW
Chemical thrusters: 12000+ kg



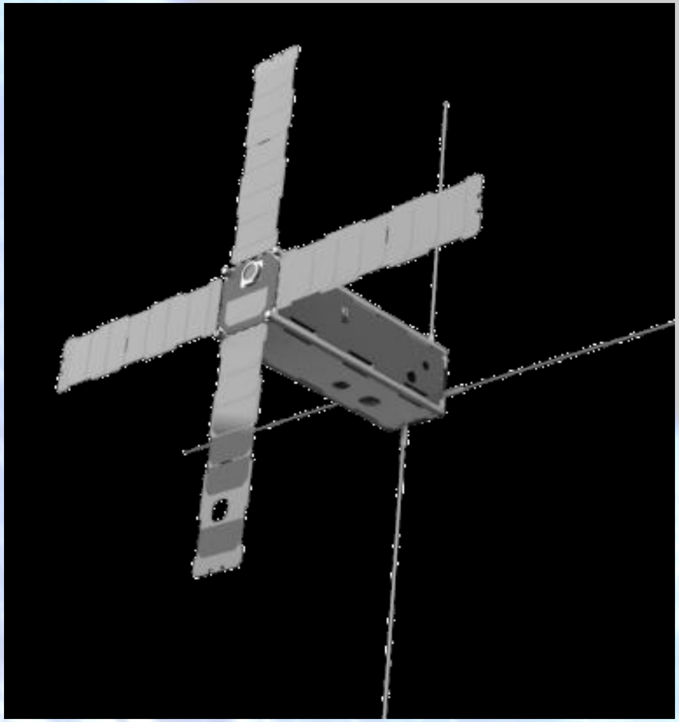
Asteroid Redirect Mission

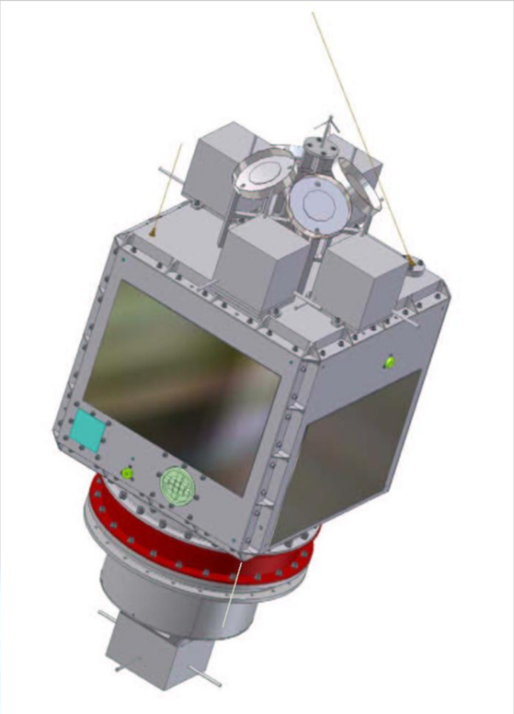
- 100kg liquid can redirect known NEOs
- Heliocentric retrograde orbit: 46km/s closure
- Split asteroid could be moved to Earth orbit
  - Second split allows parking at Lagrangian point



Next Steps

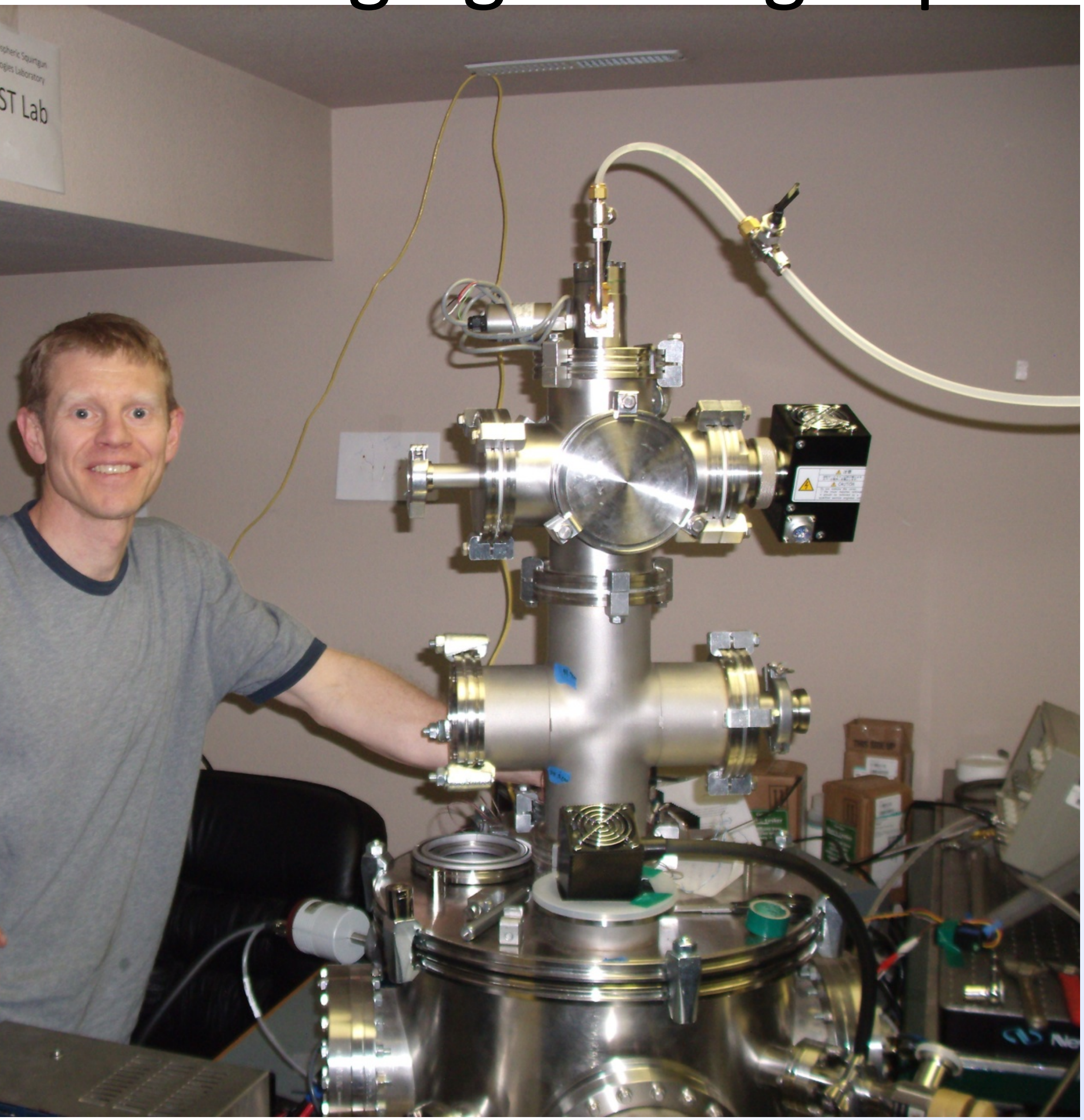
- BMIM-BF4 Droplet charging analysis & testing
- Debris position accuracy knowledge analysis
- Relative attitude determination sensor development
- Flight experiment to measure charge & demo intcpt

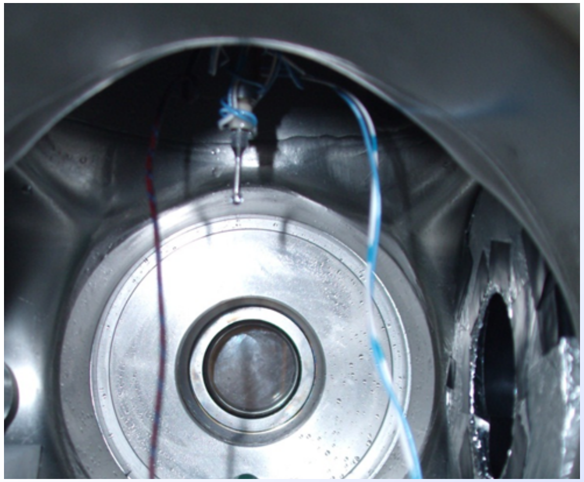




Any Questions?

Charging and high speed droplet testing



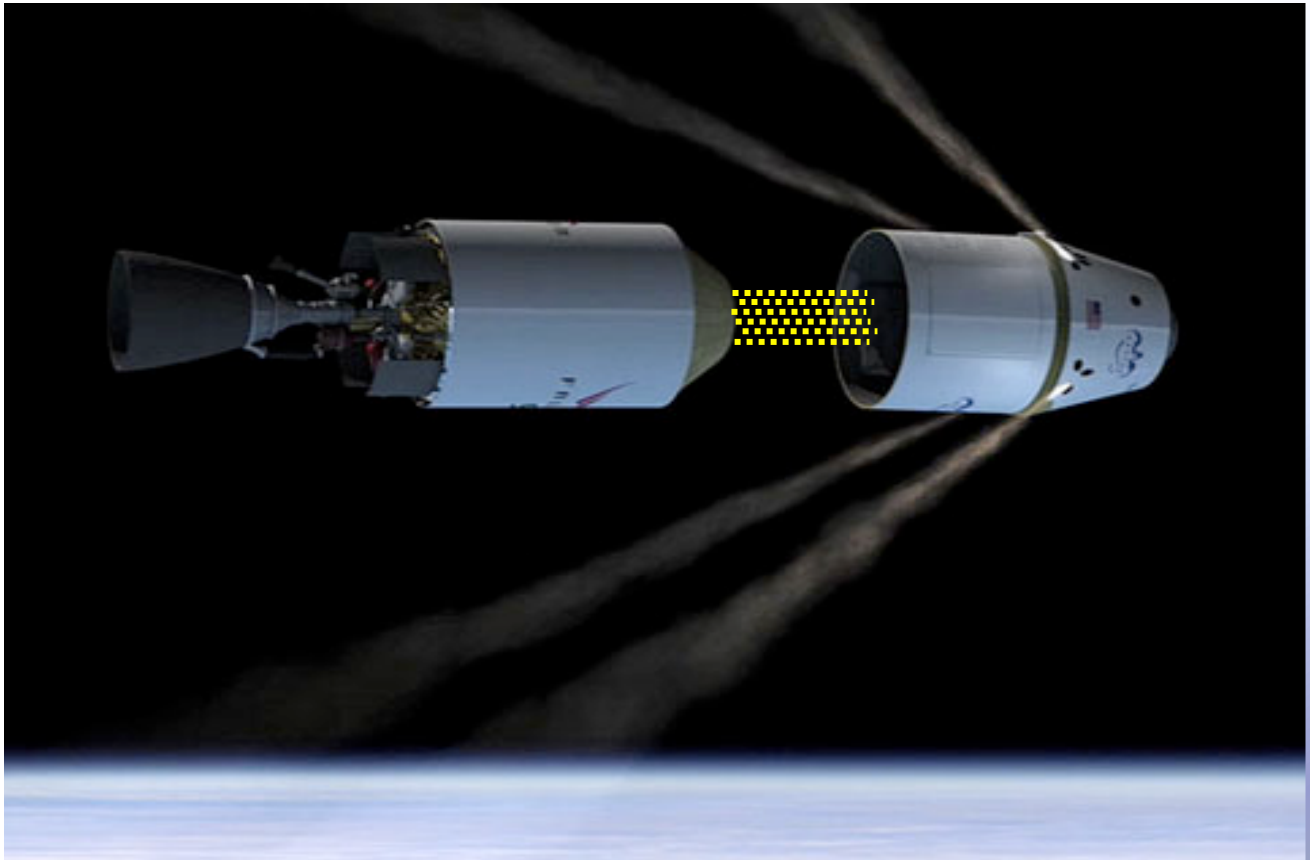



Questions?
TY

Backup Slides

Upper Stage Momentum Exchange

- Reduces liftoff mass several thousand lbs
- Cost savings: $0.9M per Falcon 9/Dragon



Momentum Exchange for Rendezvous

- Reduces rendezvous & reentry propellant ~200 kg
- More mass/drag efficient radiator

Catalogued Objects by Country

Country/ Organization	Payloads	Rocket Bodies & Debris	Total
CHINA	155	3609	3764
CIS	1439	4737	6176
ESA	46	45	91
FRANCE	58	442	500
INDIA	53	119	172
JAPAN	124	82	206
USA	1174	3787	4961
OTHER	666	119	785
TOTAL	3715	12940	16655

US satellite destroyed by Aegis Cruiser missile 2008. Debris lasted 18 months.

Data as of 1 January 2014, cataloged by U.S. Space Surveillance Network

Momentum Transfer Equation

Nearly Instantaneous deceleration of object

$F = ma$

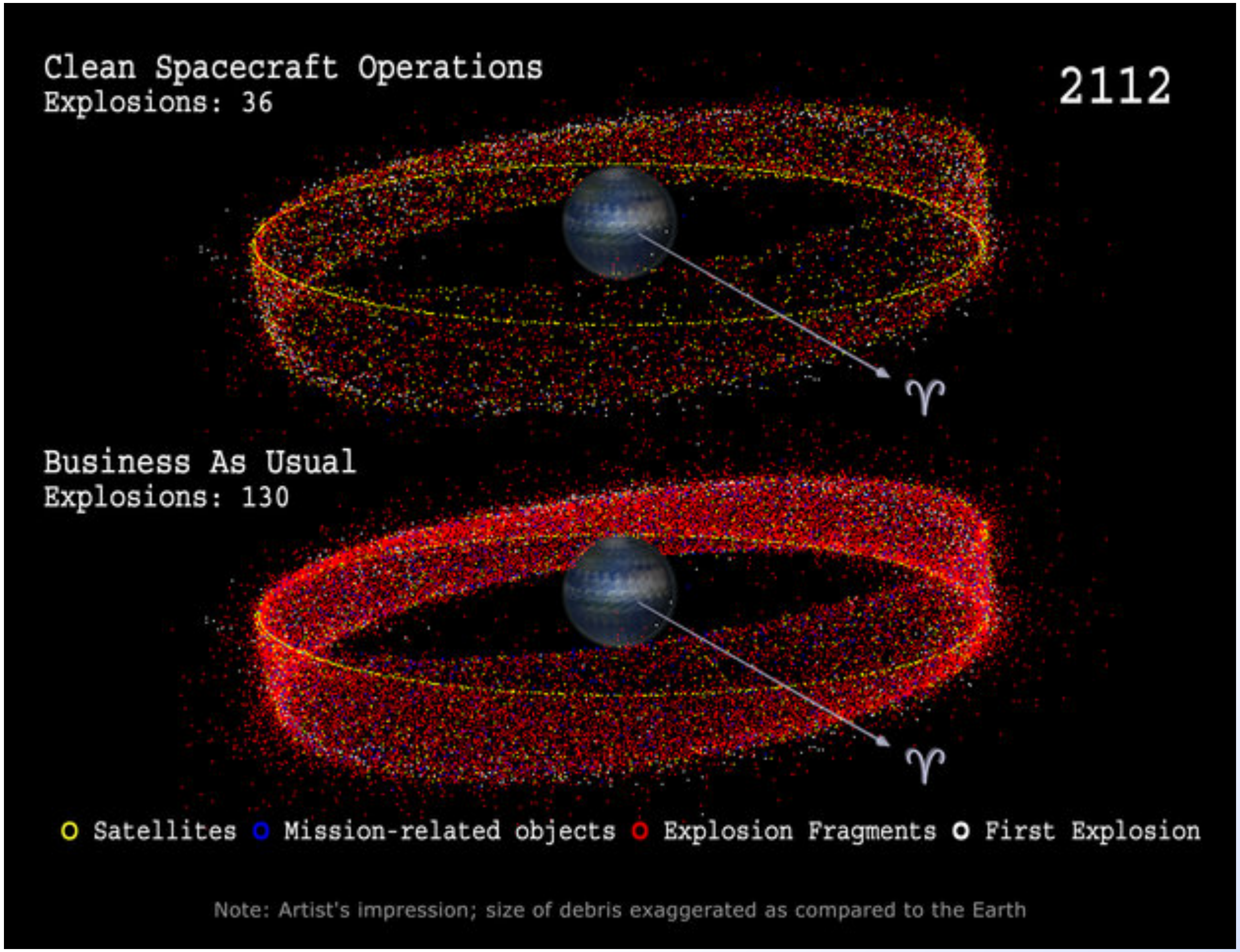
$F_{\text{object}} = m_{\text{liquid}} (v_{\text{liquid}} - v_{\text{object}})$

Change in momentum (*P*) of object

$\Delta P\ object = (mobject\ v\ body) - (m_{\text{liquid}}\ v_{\text{liquid}})$

$\Delta v\ body = \Delta P \downarrow body\ /mbody$

Geosynchronous Debris



- Population density low but growing
- Most nations now super-synch at EOL
- Single s/c can super-synch objects
- Retrograde StreamSat could lower objects
- Trans-GEO orbit could slow s/c

Source: European Space Agency official website

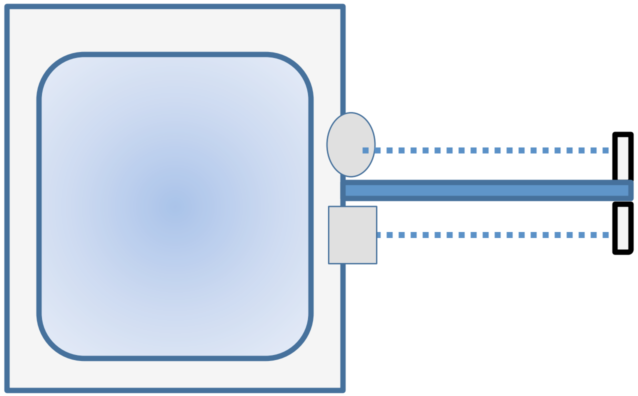
Mission Proposal

Single Demonstrator

- Validates droplet stream production/collection
- Quantifies environmental effects on stream
- Compares different collector designs

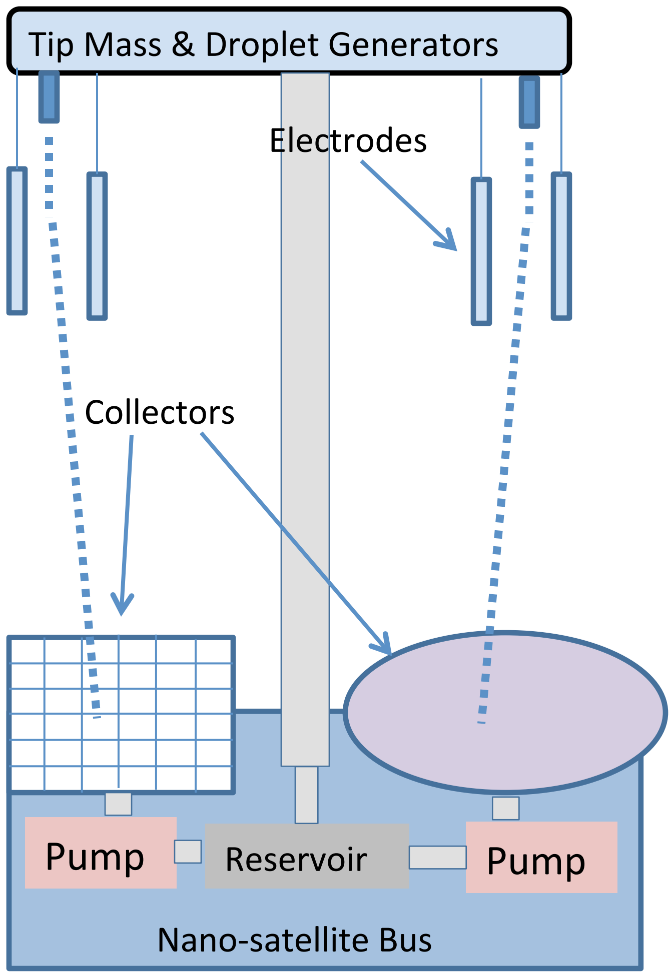
Tandem Pair

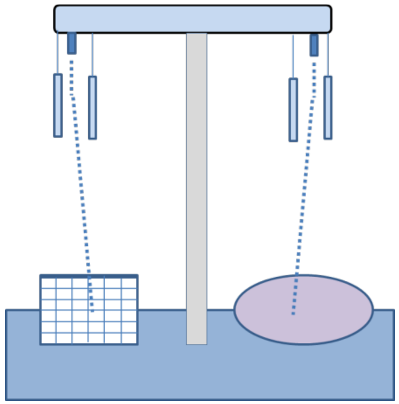
- Separating/maintaining baseline distance
- Uses best collector tested
- Demonstrates pointing system methods



Demonstration Satellite

- Use of electrodes to determine charging





- Thermal coupling array
- Droplet location and deviation