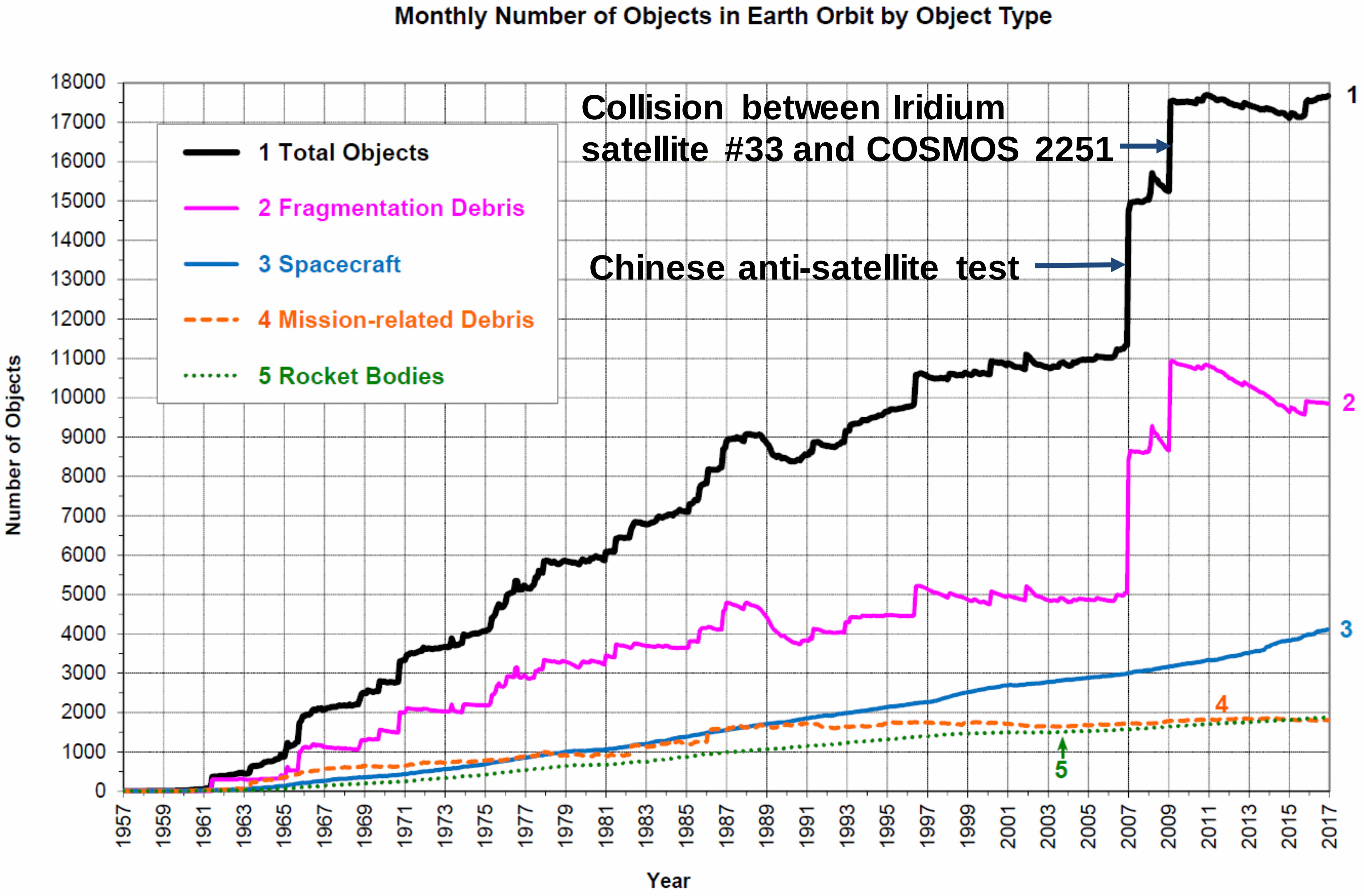
Brane Craft: Phase II

Dr. Siegfried W. Janson
Senior Scientist, The Aerospace Corporation

NIAC Symposium, September 27, 2017

The Growth of Orbital Debris:



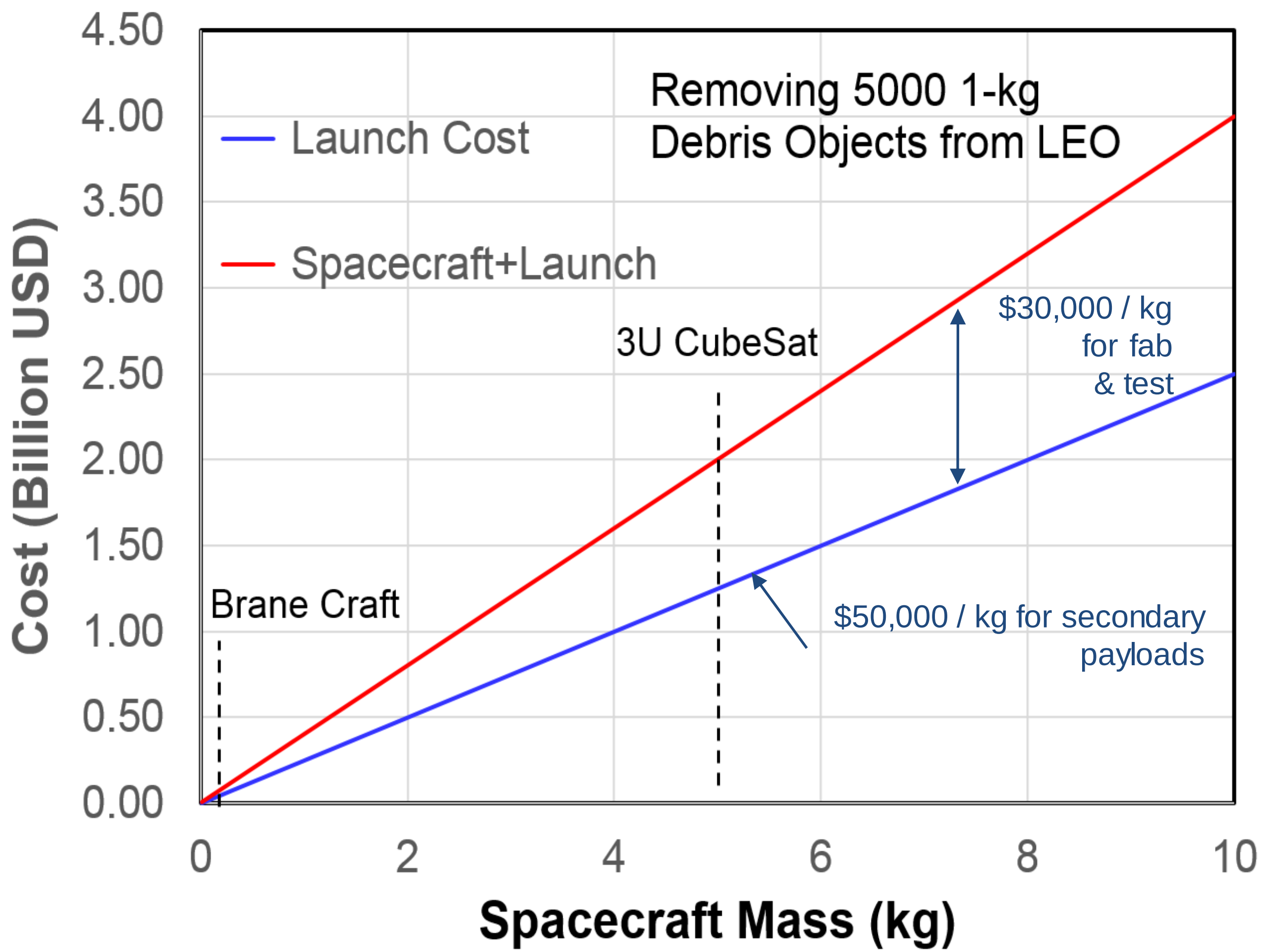
Reference: National Aeronautics and Space Administration, "Orbital Debris Quarterly News," **21**, #1, p. 12, February 2017.

These are just the tracked objects. The population of objects smaller than ~10 cm is much greater. Note satellite collision.

Cost of Removing 5,000 1-kg-class Debris Objects from LEO:

- **Cost using conventional tech:**
  - *~$2 billion U.S. Ouch!!!*
- **Cost using Brane Craft:**
  - *~$30 million U.S. + R&D costs*
- **You could spend $1.5 billion US on Brane Craft R&D and still save money!!!**

LEO: 200 to 2000 km altitude



The non-recurring R&D up to $1.5 billion would be wisely spent. This technology could be applied to many other missions.

Brane Craft: Removing Orbital Debris on a Budget

- **Reduce Spacecraft Launch Cost to a Minimum: Go Thin!!!**
  - *Typical launch costs are $5,000 to $10,000 per pound to LEO (low Earth orbit)*
  - *Secondary payloads like CubeSats cost ~$50,000 per kilogram (~$23,000 per pound)*
  - *Go ultra-thin (~50 microns thick) using10-micron thick Kapton® sheets as the main structure*
  - *Thin-film solar cells, electronics, sensors, actuators, and electrospray thrusters*
  - *82 gram mass vs. multi-kilogram mass for conventional approaches*
  - *Max acceleration: 0.1 m/s^2 (Huge for electric propulsion!)*
  - *Shape-changing ability (required!)*

- **Reduce Spacecraft Fabrication Cost to a Minimum: Use Mass-Production**
  - *Design for mass-production at 1,000 unit, or larger, lots*
  - *Print thin-film systems where possible*
  - *Use inexpensive, ~1-micron photolithography elsewhere*

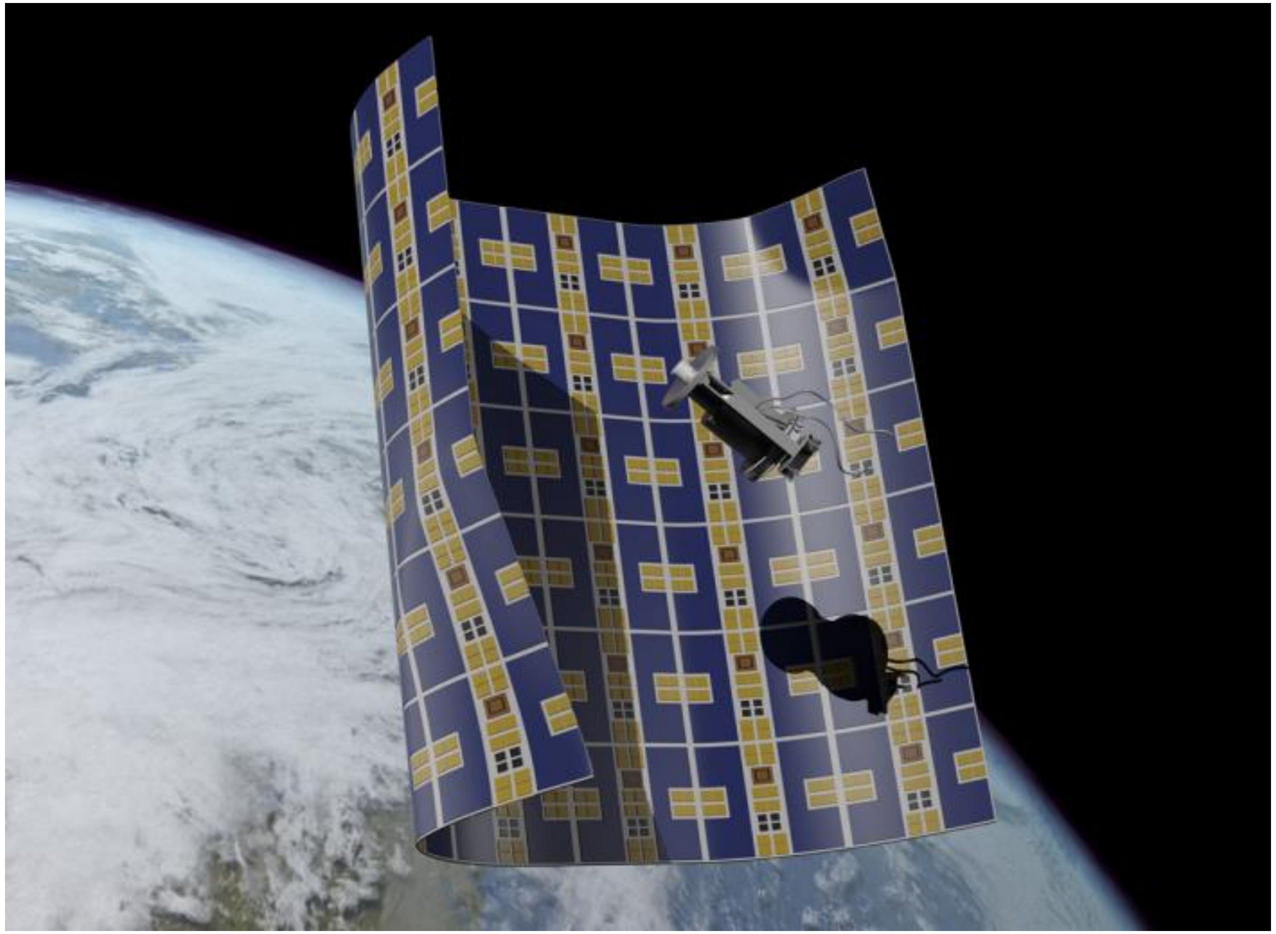
This is a radically new way to build and fly spacecraft.

Brane Craft for Active Orbital Debris Removal

- **Start from an ISS orbit**
- **Move to target's orbit**
  - Major Thrusting
- **Rendezvous with target**
  - Minor thrusting
- **Wrap around target**
  - Shape change
- **Lower altitude to ~200km**
  - Major thrusting

If propellant is still available:

- **Open up**
  - Shape change
- **Release target object**
- **Boost to higher altitude**
  - Major thrusting
- **Go after another target**

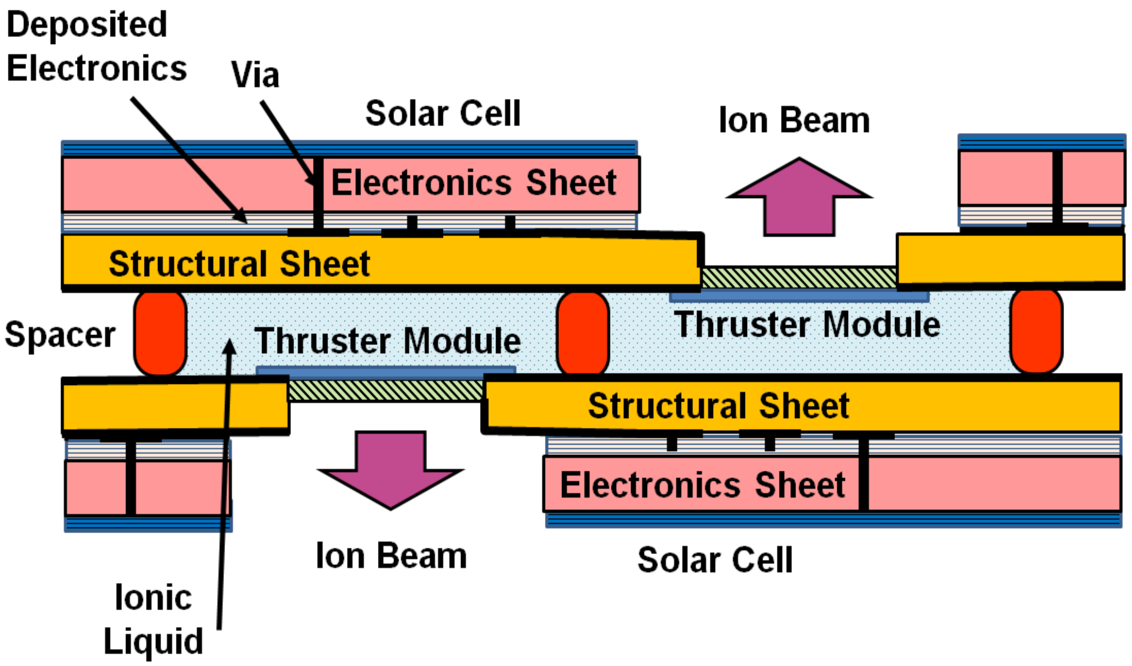


(Graphic: Joseph Hidalgo, The Aerospace Corporation)

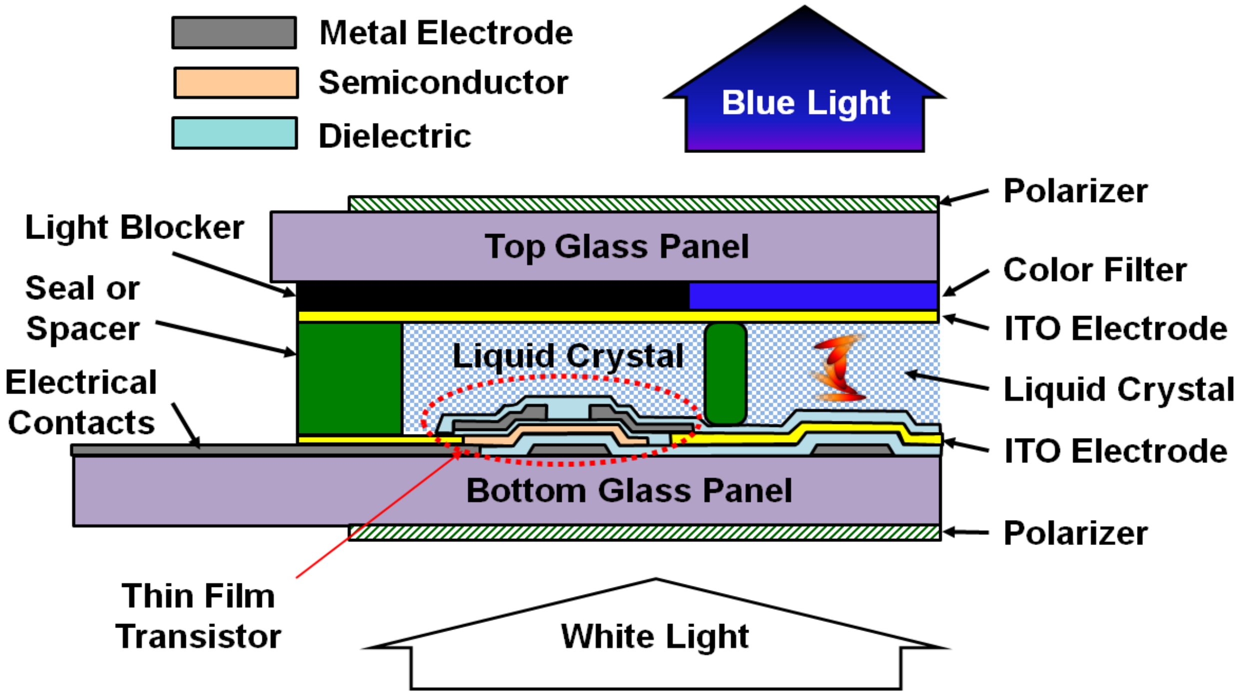
A Brane Craft has enough delta-V (ability to change velocity) to deorbit multiple space debris objects in different orbits.

Brane Craft Design at End of Phase I:

Brane Craft Cross Section



Flat Panel Display Cross Section



~25 million, 5-micron minimum feature size, thin film carbon nanotube transistors required

~25 million, 30-micron minimum feature size, thin film silicon transistors on glass for a 4K screen

The Brane Craft cross section is similar to that of a modern high-resolution display. It's much thinner, flexible, and designed for a much harder radiation environment. Delta-V is still 15.7 km/s.

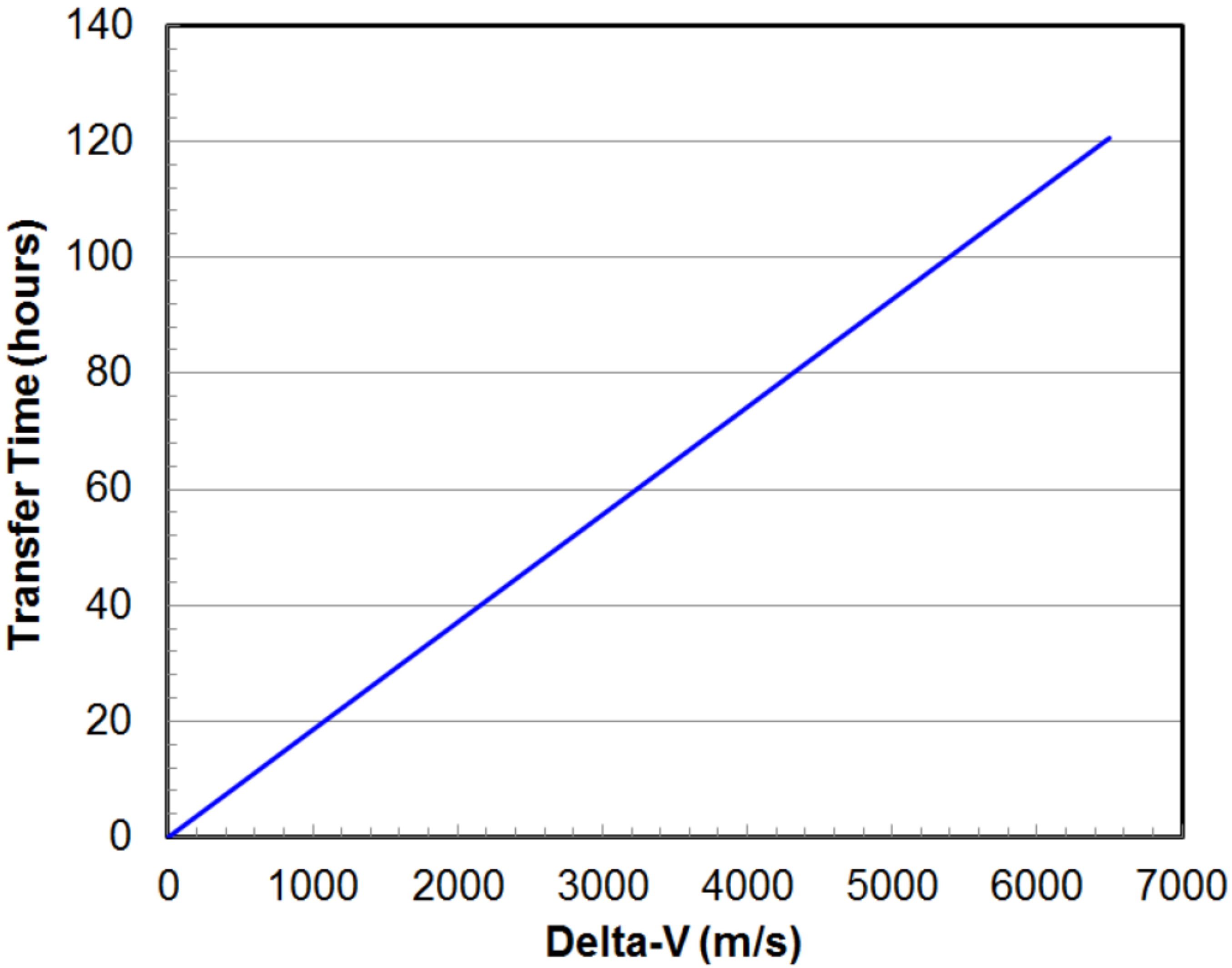
Brane Craft Analysis: “Up” Transfer Time for LEO Targets

Delta-V Used for the “Up” leg:

- *>800 m/s if no inclination change*
- *~1300 m/s for 10º inc. change*
- *~2600 m/s for 20º inc. change*
- *~3800 m/s for 30º inc. change*
- *~5100 m/s for 40º inc. change*
- *~6200 m/s for 50º inc. change*

Assumptions:

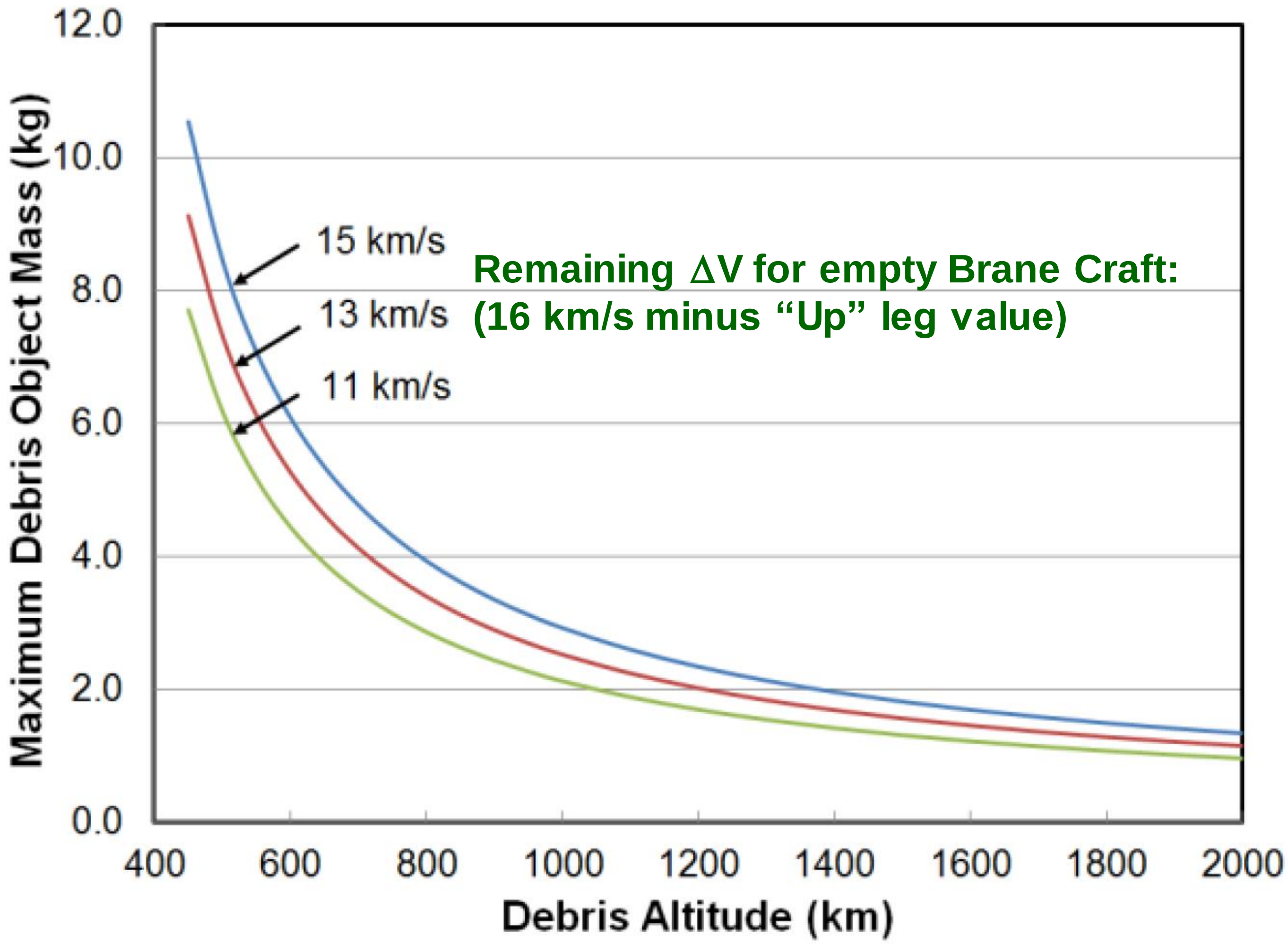
- *Starting from ISS altitude*
- *Maximum eclipse fraction*
- *Symmetric thrusting about the Earth-Sun line to minimize growth of orbit eccentricity*



A maximum of 5 days are required to go from the ISS starting orbit to any orbit from 0º inclination to sun-synchronous within LEO.

Brane Craft Analysis: How Much Mass Can it Drag Down?

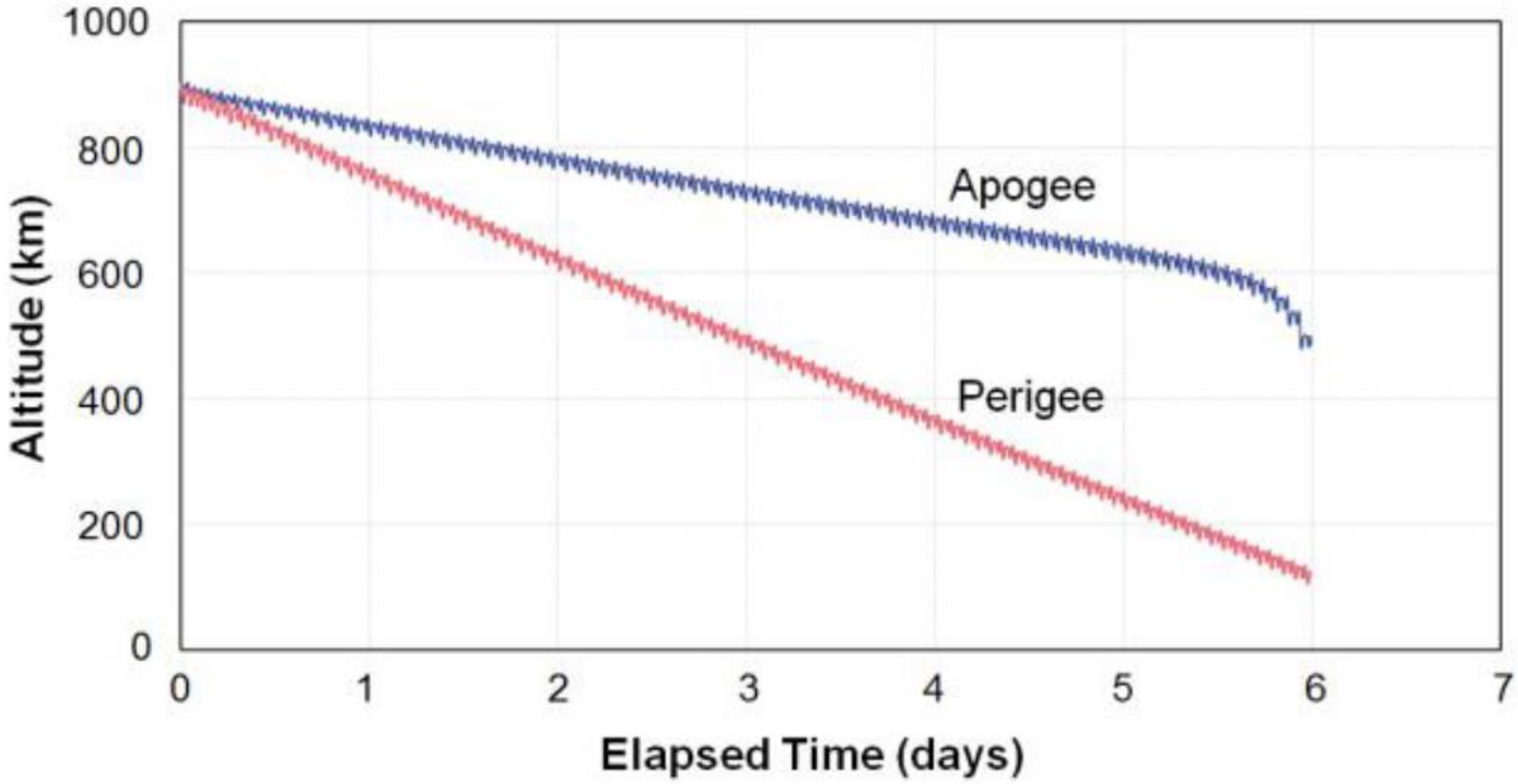
- **Remaining delta-V is a function of debris orbit altitude and inclination**
- **No inclination change required for deorbit**
- **0.9 kg can be removed under worst-case condition (debris in 2000-km sun-sync orbit, starting from the ISS)**
- **2.2 kg can be removed from a 900-km sun-sync orbit, starting from ISS**



A Brane Craft can remove a debris object that is more than order-of-magnitude heavier than the nominal 82-gram starting mass.

Brane Craft Analysis: Inbound Orbit Simulation

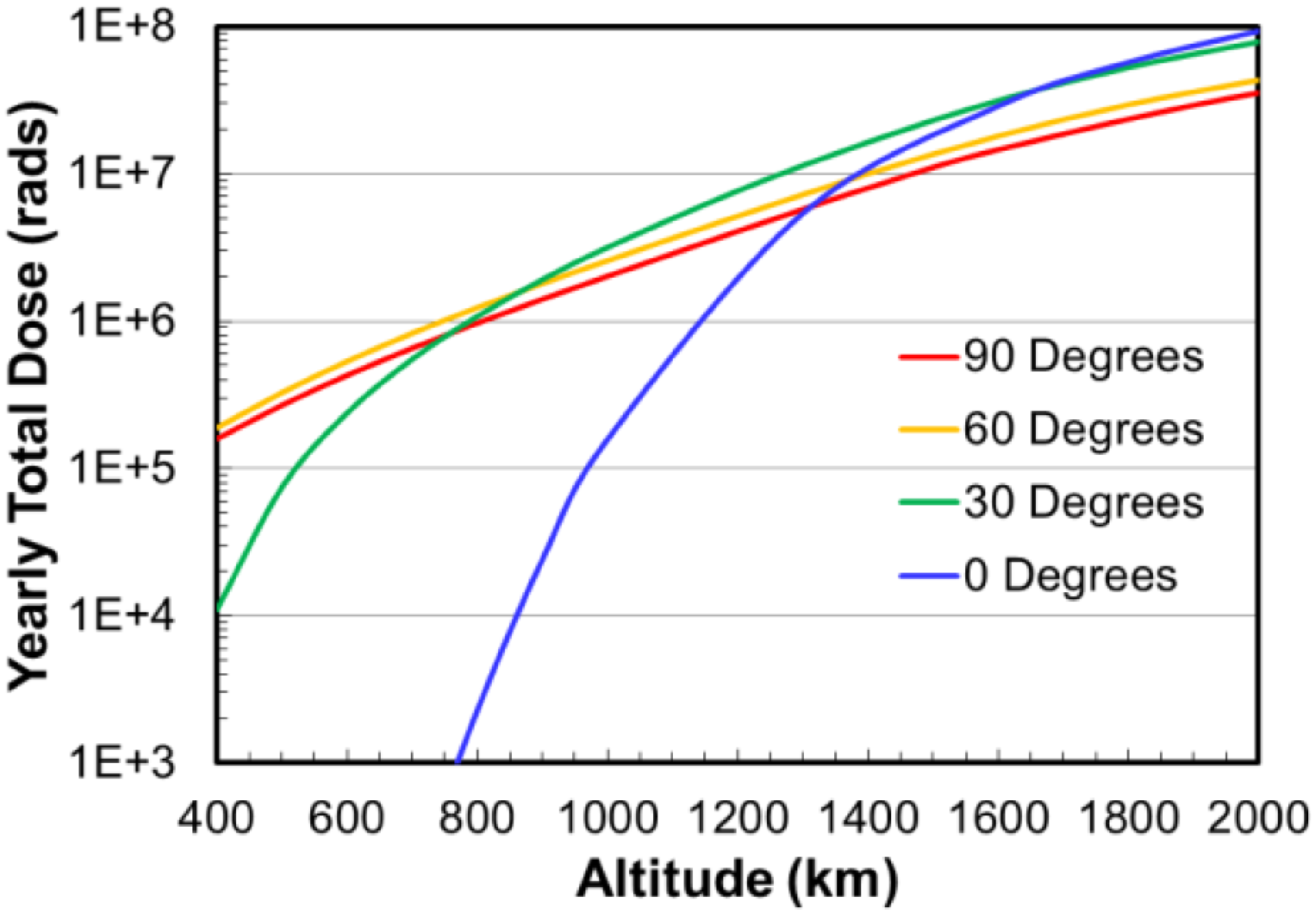
- ***Initial 900-km, sun-synchronous debris object orbit***
- ***Maximum debris object mass of 2.2 kg for this orbit***
- ***Thrusting only during sunlit periods with real eclipses***
- ***Orbit eccentricity allowed to grow***



In this case, 6 days are required to go from the debris object orbit to a burnup orbit. Maximum time for maximum mass in any LEO orbit is 10 days.

Brane Craft Analysis: General Radiation Environment

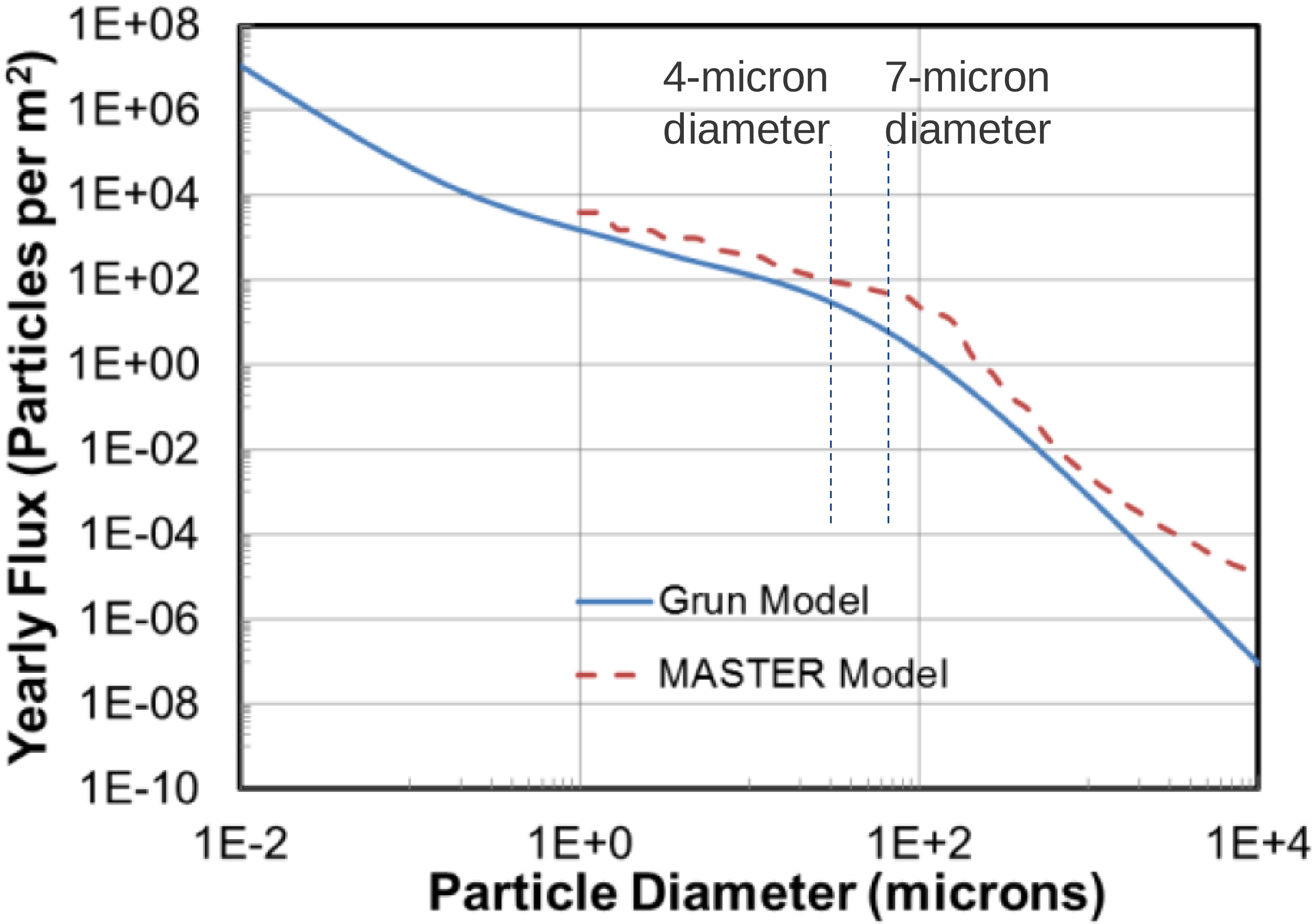
- **Circular orbits**
- **Yearly dose rate in silicon**
- **10-microns of Kapton® shielding on top, 30 microns below**
- **Most debris objects orbit at inclinations greater than 60º.**
- **Maximum deorbit time in LEO:**
  - *5 days to reach orbit*
  - *8 days for orbit rephasing*
  - *2 days for rendezvous and wrapping*
  - *10 days to deorbit*



Brane Craft will need electronics with a total dose limit of at least 5 Megarads for a worst-case 1-month mission in LEO.

Brane Craft Analysis: Micrometeoroid Environment

- **1,200-km altitude circular orbit**
- **Grün model is for natural objects**
- **MASTER model includes man-made debris**
- **10-microns of Kapton® shielding on top, 30 microns below**
- **Most debris objects orbit at inclinations greater than 60º.**
- **7-μ particles pierce 10-μ of Kapton @ 5 km/s.**
- **4-μ particles pierce 10-μ of Kapton @ 10 km/s.**



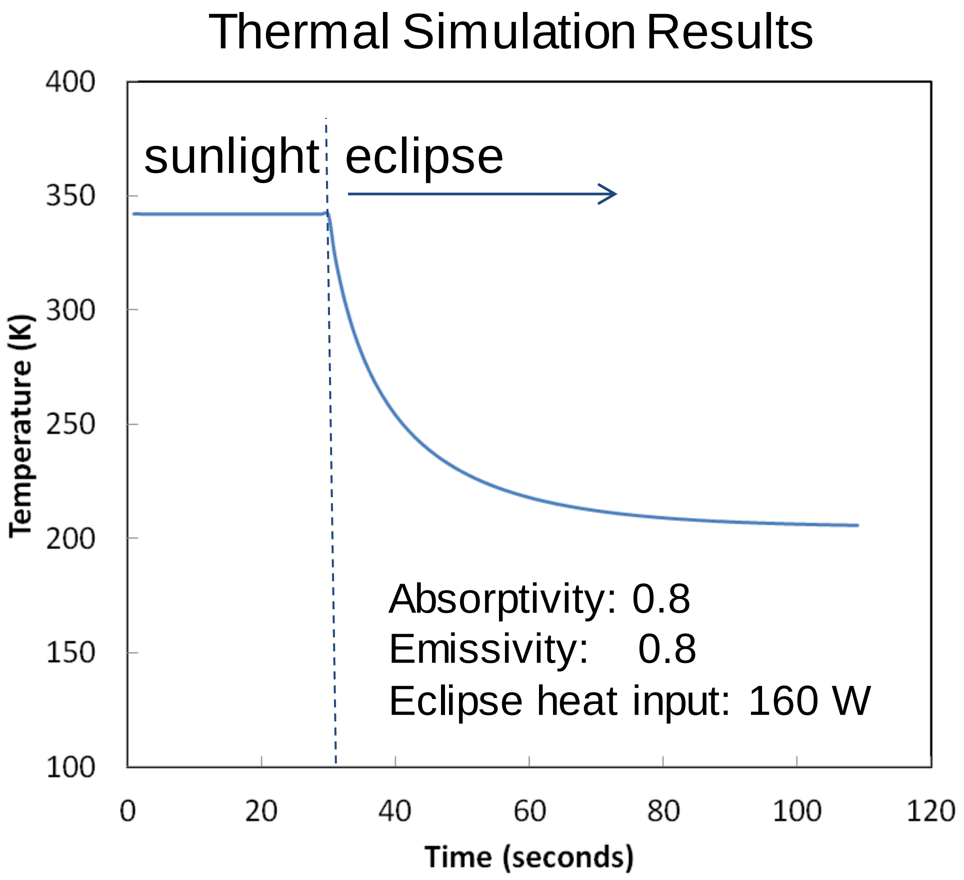
- *The on-orbit flux of micron-scale micrometeoroids is surprisingly high. Data from the European Space Agency's SPENVIS program.*

Thermal Environment

- **Almost no thermal mass**
  - *- Kapton® specific heat: 1.09 J/gram-K*
  - *- EMI-BF4 specific heat: 1.9 J/gram-K*
  - *- 1350 W thermal input in full sun*
  - *- 200 W max in eclipse*
  - *- Temp range: 206 to 342 K (-67 °C to +69 °C)*

- **Propellant freezing**
  - *- Standard propellant, EMI-BF4, freezes at 15 °C (298 K)*
  - *- Need to find other propellants with lower freezing point, or*
  - *- Live with fixed shape during eclipse*

EMI-BF4 = 1-Ethyl-3-methylimidazolium tetrafluoroborate

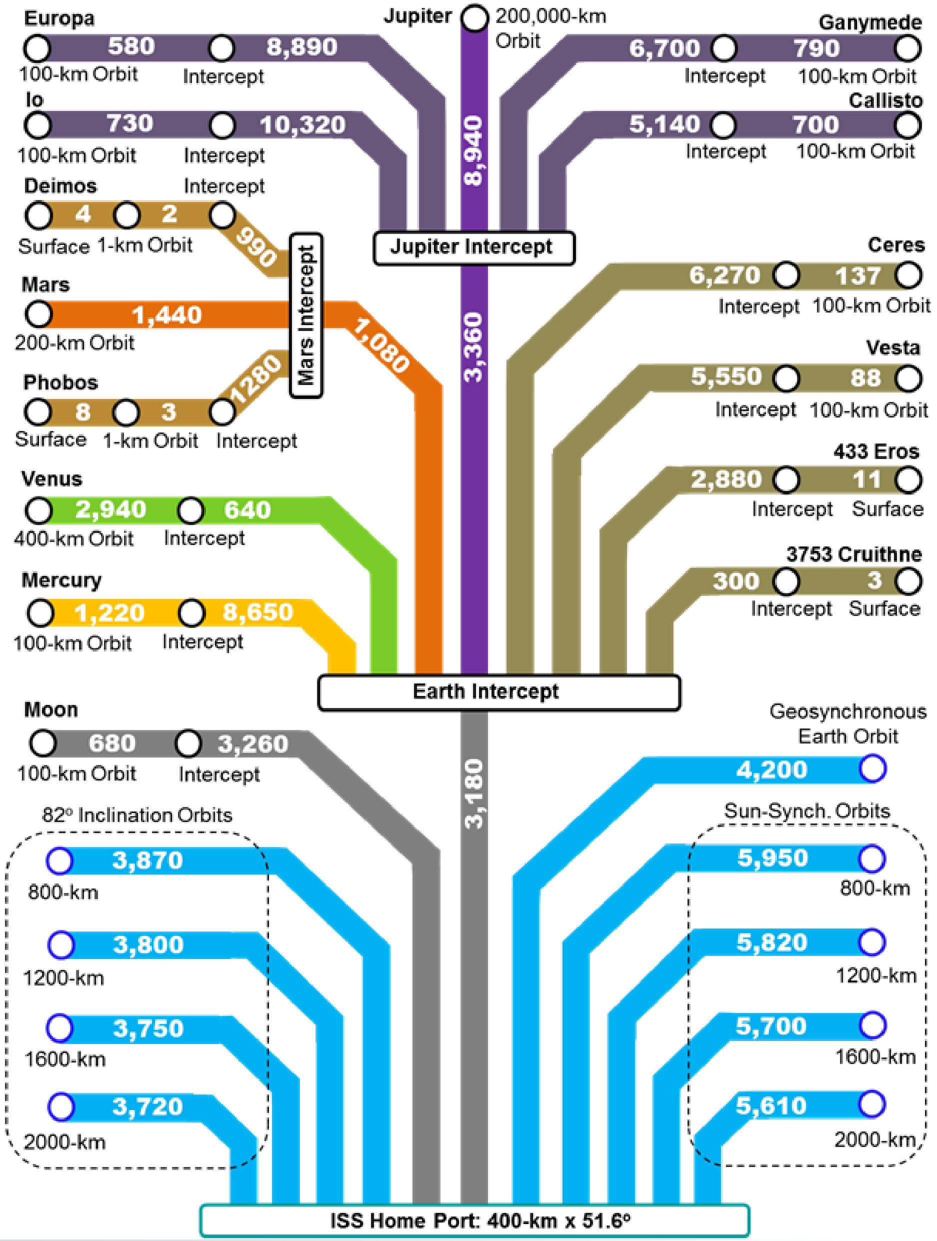


Thermal control is a big issue. May need to leave the Brane Craft frozen during eclipse; no power for thrusting anyway.

Where can Brane Craft Go?:

- **Nominal Brane Craft have a 16 km/s delta-V capability:**
  - *- ISS to 100-km low Lunar orbit (LLO), and back to ISS; twice*
  - *- ISS to Phobos or Deimos, land, and return to ISS*
  - *- ISS to 400-km Venus orbit, and back*
  - *- ISS to 100-km Mercury orbit*
  - *- ISS to orbit about any main-belt asteroid*
  - *- ISS to land on any main-belt asteroid with a surface gravity less than 0.1 m/s²*

- **Extended Range Brane Craft could have a 32 km/s delta-V capability:**
  - *- Visit any object in this chart and return; potentially multiple times*
  - *- Return to LEO with data or samples*
  - *- Millions of potential main belt asteroids*



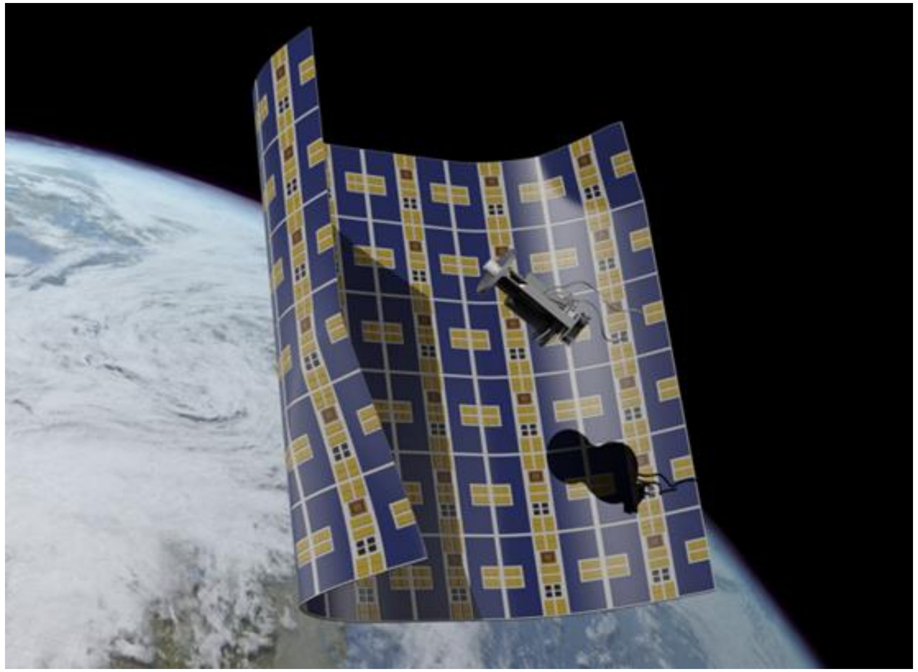
Solar System "Subway Map"; Delta-V for each leg in m/s

Brane Craft could explore most of the bodies in our solar system out to Jupiter; solar power limits the range.

What Are We Doing in Phase II?:

- **Fabricating and radiation testing carbon nanotube logic gates for a 5 megarad total dose**

- **Developing radiation-hard photosensors**
    - *Carbon nanotubes or copper indium gallium selenide*
    - *Sun and image sensors*
    - *Infrared and Earth sensors*



- **Designing and testing thin-film muscles**
    - *TiNi Muscle wire already demonstrated*
    - *Polymer matrix metal composites*

- **Evaluating thin film frequency references for communications systems**

- **Developing a fault-tolerant "bullet-proof" computer architecture**
    - *Multi-processor monitoring with power and data re-routing*

- **Evaluating other applications:**
    - *Asteroid and moon inspectors*

Thank you NIAC!

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Brane Craft appear to be possible, but will require ~10 years of further development.