Solar System Escape Architecture for Revolutionary Science March 2013 Conference

NIAC Phase 1: 2012-2013

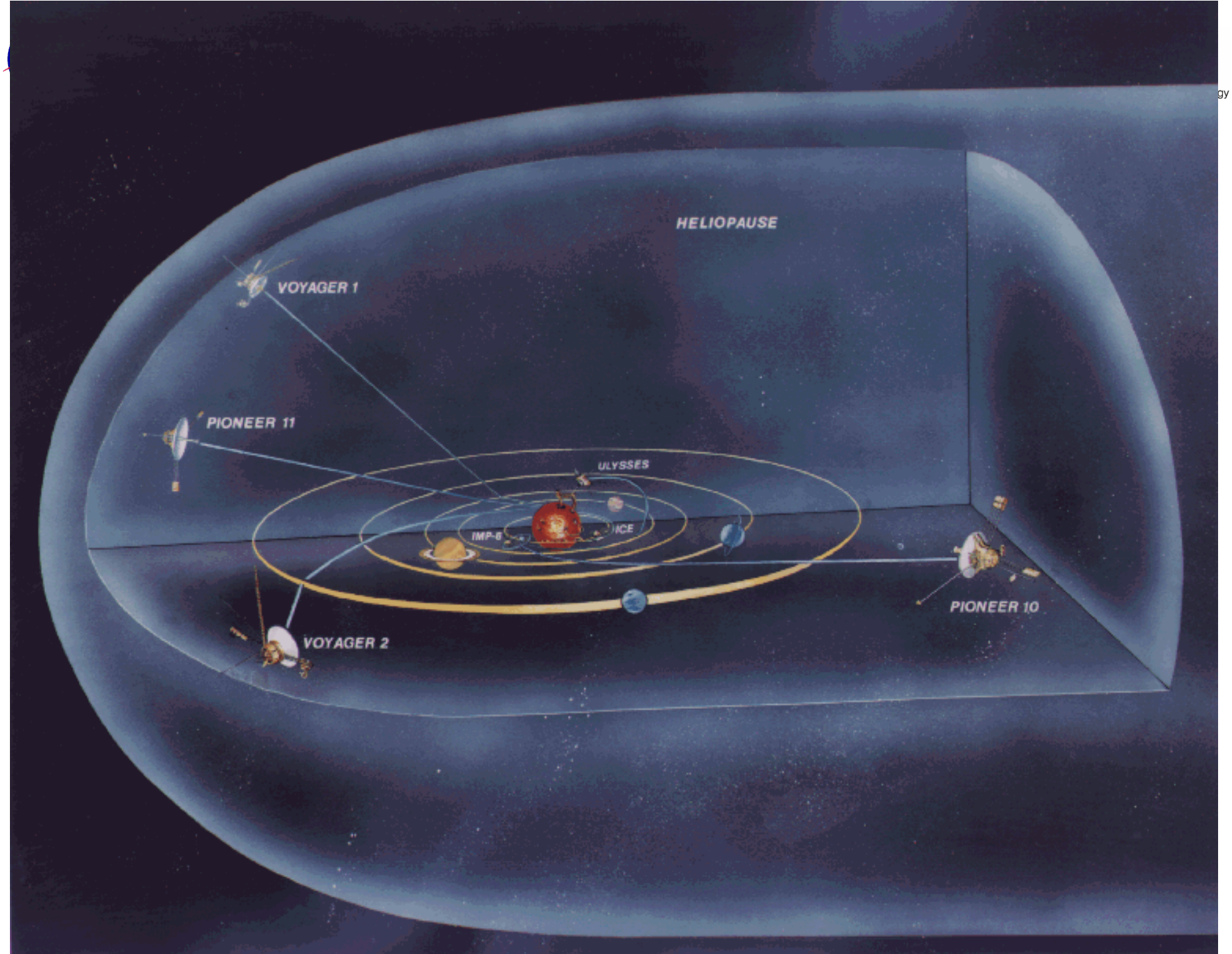
PI: Jeff Nosanov

Co-Is: Dr. Daniel Grebow, Dr. Brian Trease, John West, Dr. Henry Garrett

Summary

- Spacecraft velocities of 10-12 AU/year, which is the 3-4x Voyager solar system escape velocities are feasible with solar sails and modern materials (with future materials in the works)
- Desirable instrument suite for heliopause study can be accommodated on such a spacecraft
- Identified variables in real life terms that will affect architecture (perihelion distance, sail thickness, boom architecture, etc)

Jet Propulsion Laboratory
California Institute of Technology

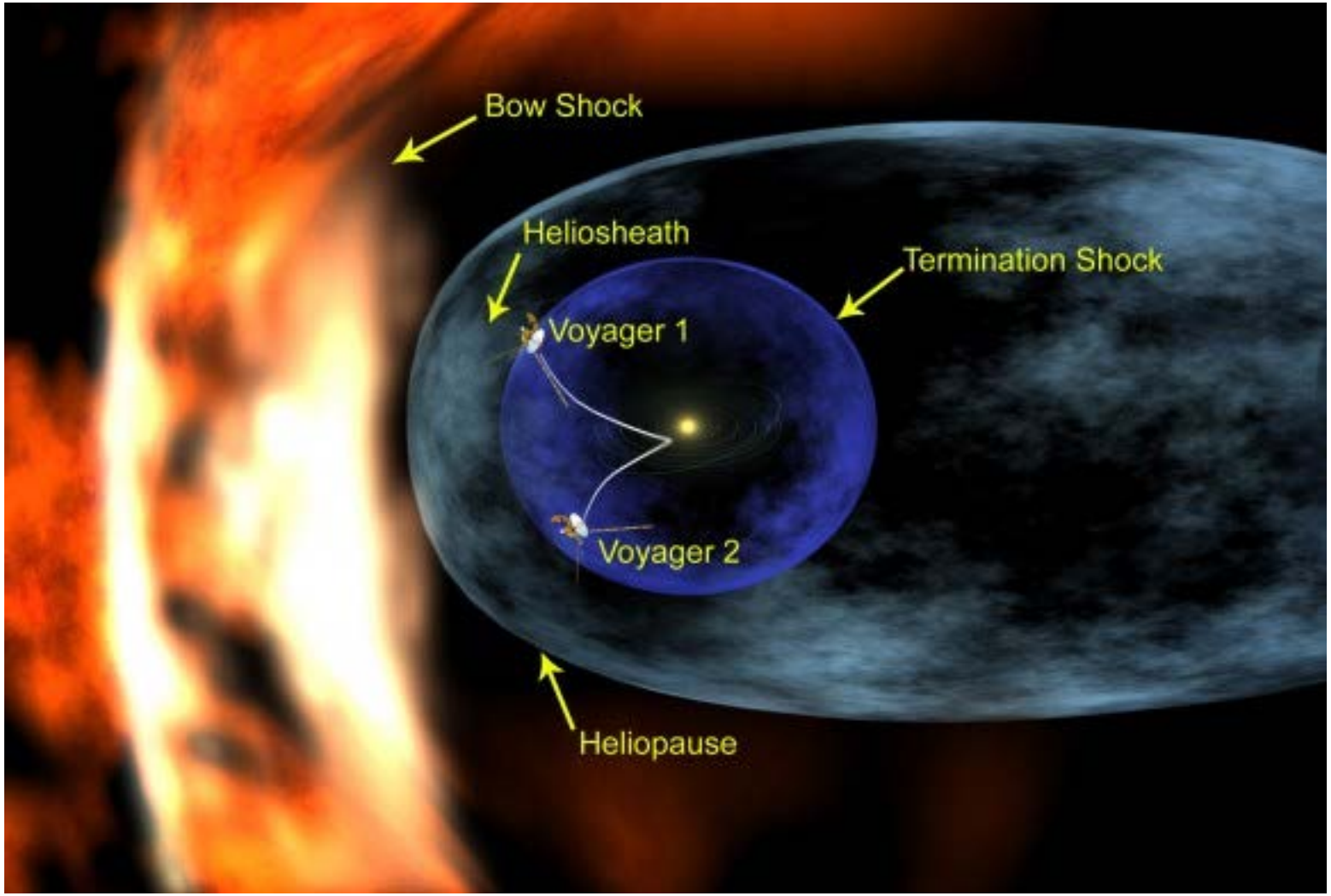

HELIOPAUSE
VOYAGER 1
PIONEER 11
ULYSSES
IMP-8
ICE
PIONEER 10
VOYAGER 2

Inspiration – Who?

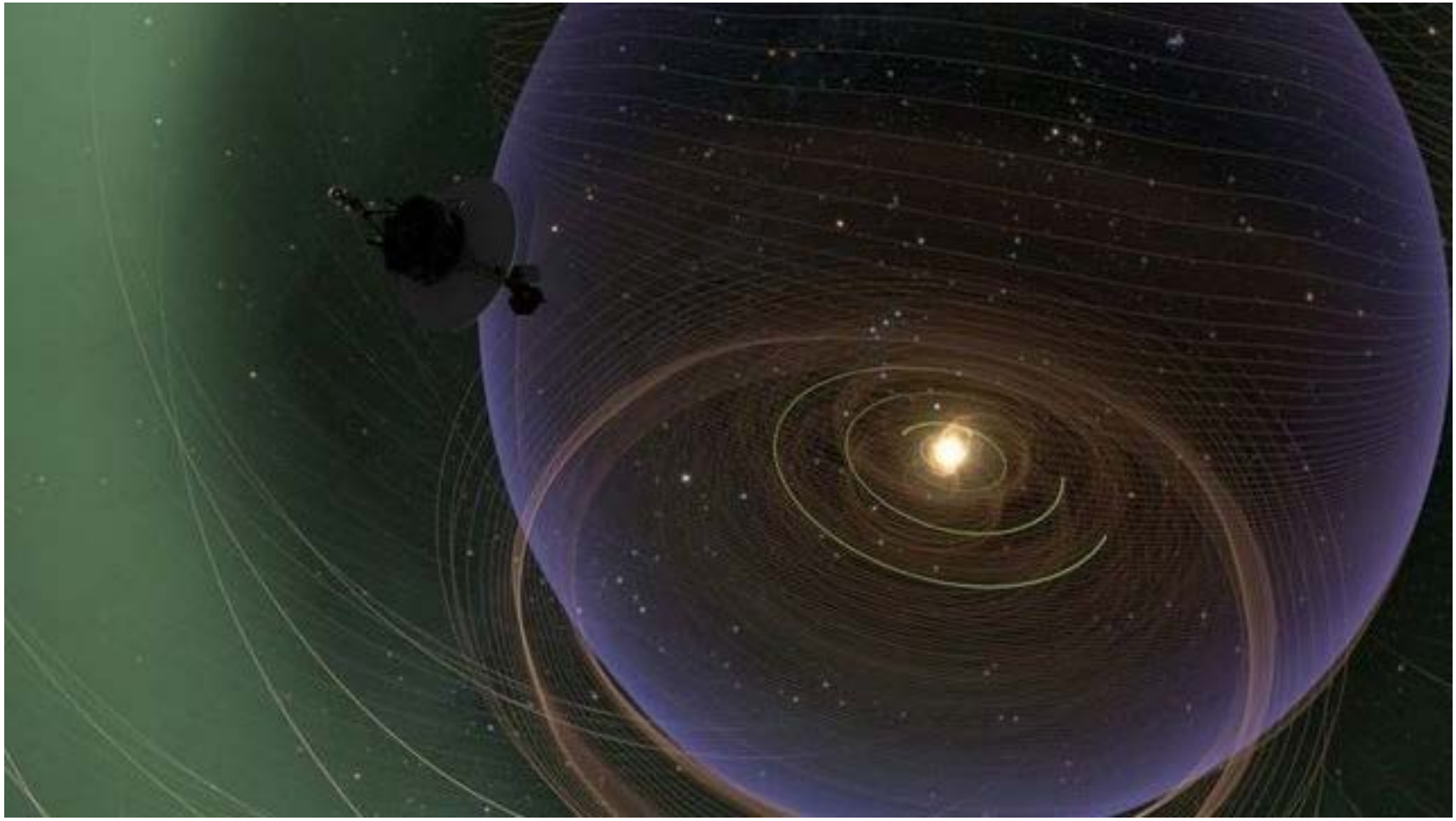
- Conversation with Ed Stone, Voyager Project Scientist
- Q: “What would you do to continue Voyager Science?”
- A: “Return to Heliopause and beyond, in multiple directions, with a fleet of spacecraft.”

- Let’s figure out how to do it.

Heliopause

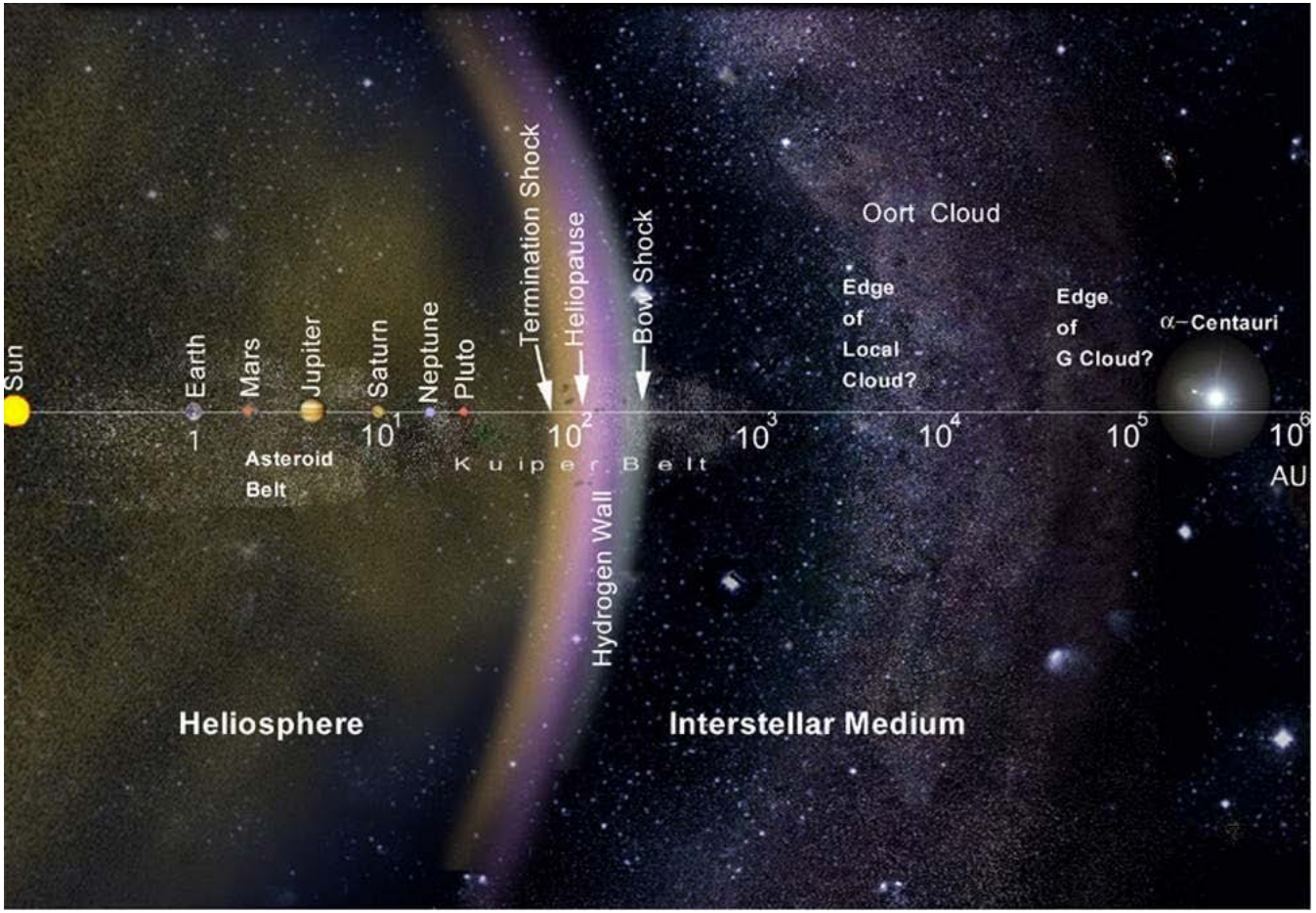

Bow Shock
Heliosheath
Termination Shock
Voyager 1
Voyager 2
Heliopause

Moving and revolving reference frames



“How fast can we go?” – What?

- Voyager took 35 years to reach the heliopause.

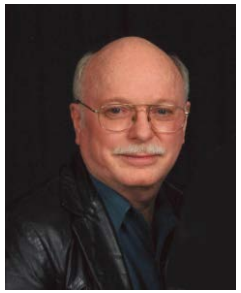


Phase 1 Goals

1. NIAC program asks “What will we be able to do in 10-20 years?”
2. Identify science destination “directions/regions” (done)
3. Develop trajectory modeling tool (done)
4. Determine current material performance limitations (done)
5. Project material trends to ~2030 (done)
6. Identify/design concept spacecraft for scaling estimates/modeling
7. Determine mission parameters for 2030 mission assuming current development trends (end of phase 1)
8. Propose for follow-up funds for further development (May- June)

Team – Who (part 2)?

- *Dr. Hank Garret*
  - Astrophysics, Instruments



- *John West*
  - Spacecraft and mission design

- *Dr. Daniel Grebow*
  - Trajectory Analysis

- *Dr. Brian Trease*
  - Mechanical Engineering

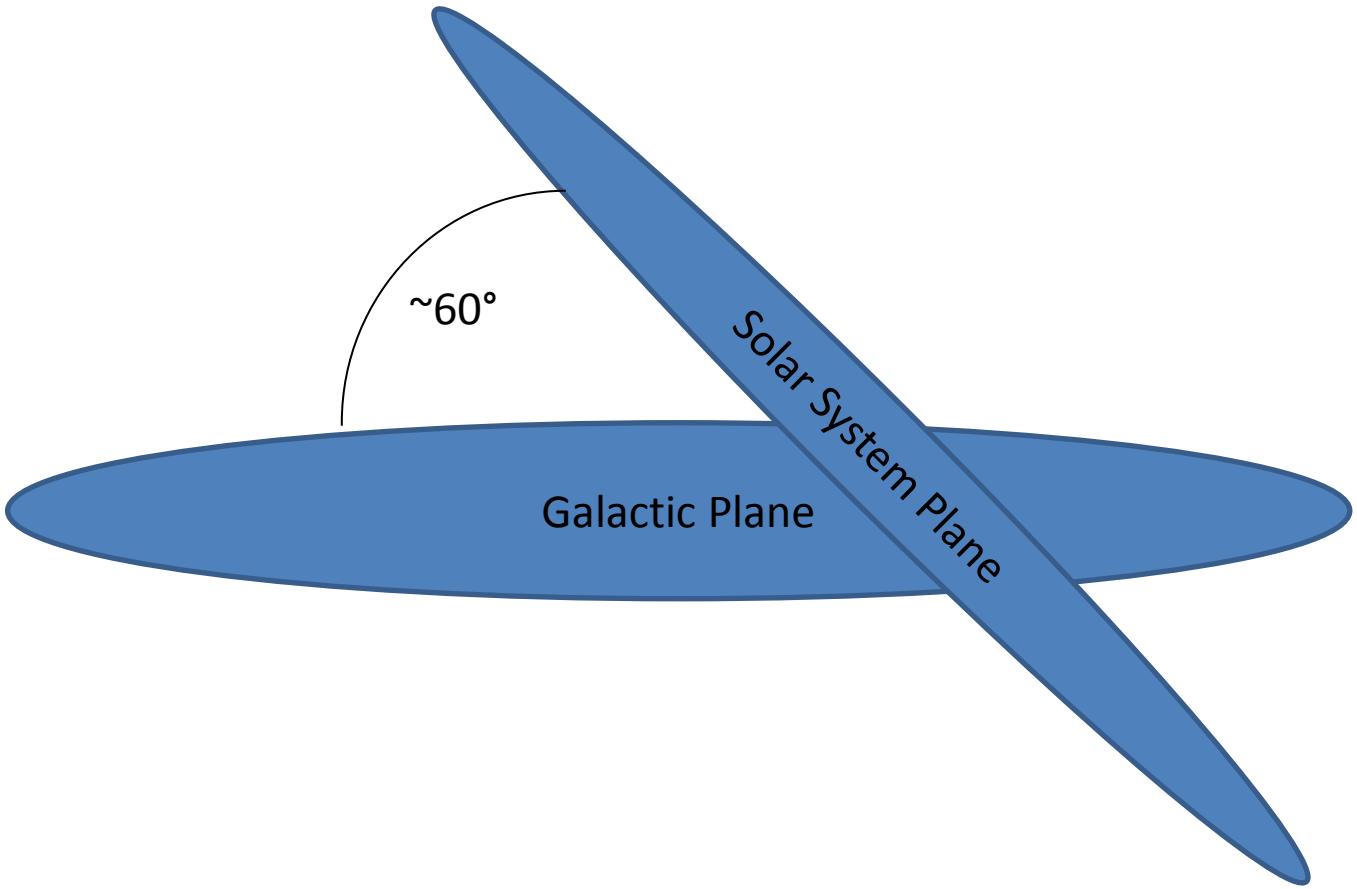
Science Goals - Why?

- **Science Mission Directorate**:
  - Interstellar medium (IM) and implications for origin and evolution of matter
  - Influence of IM on heliosphere
  - Influence of Heliosphere on IM as an example
  - Heliosphere/Solar System coupling as a model for other planetary systems
- **Human Exploration/Operations Mission Directorate**:
  - reduce human radiation risk by 2/3, possibly *enable* interplanetary human travel

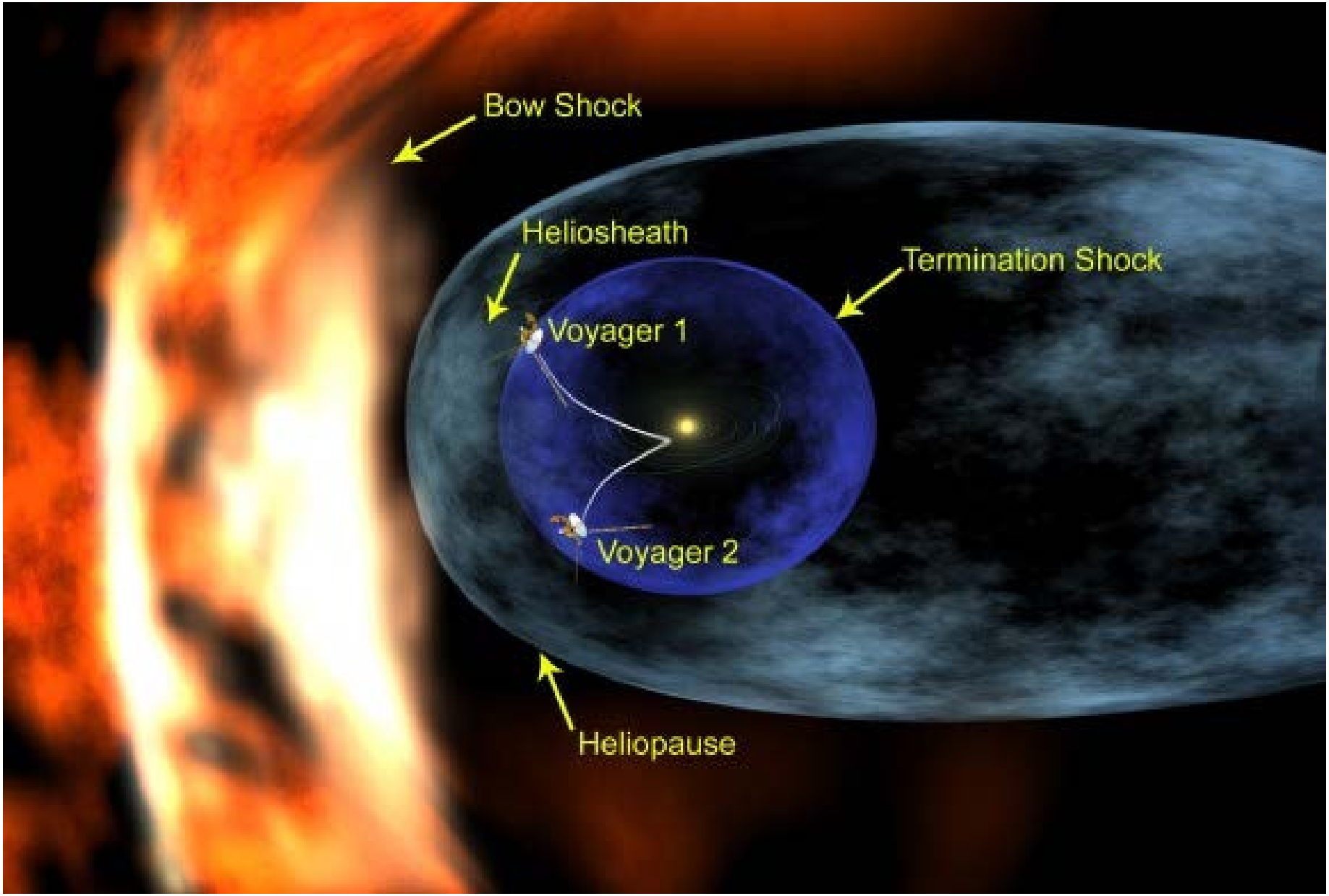
Heliophysics Decadal

- Direct, in-situ investigation of 2 of the 4 goals of the 2012 Heliophysics Decadal Survey:
  - #3. Determine the interaction of the sun with the solar system and the interstellar medium:
  - #4. Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.

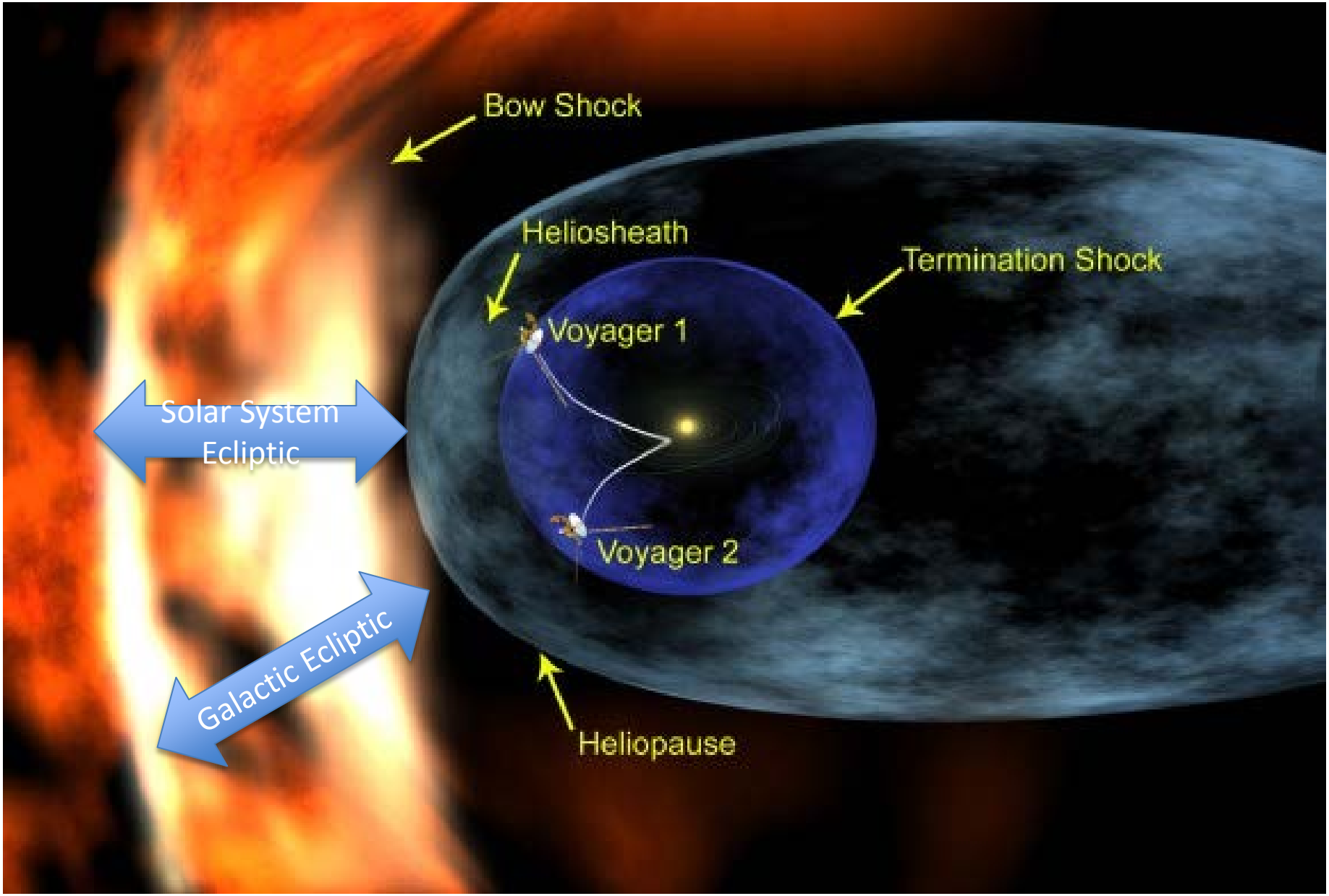
Solar System is inclined ~60° to the galactic plane



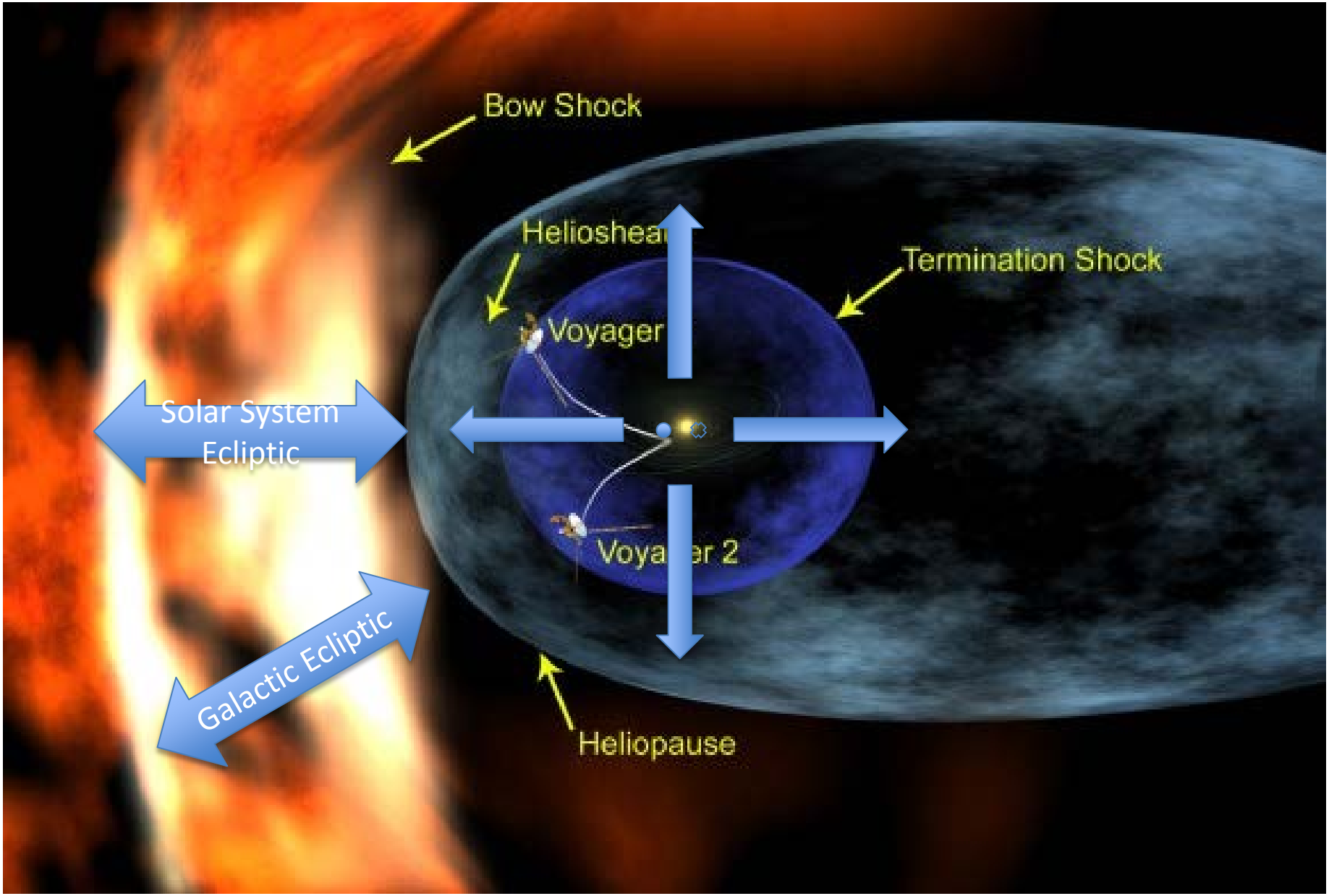
Which directions?



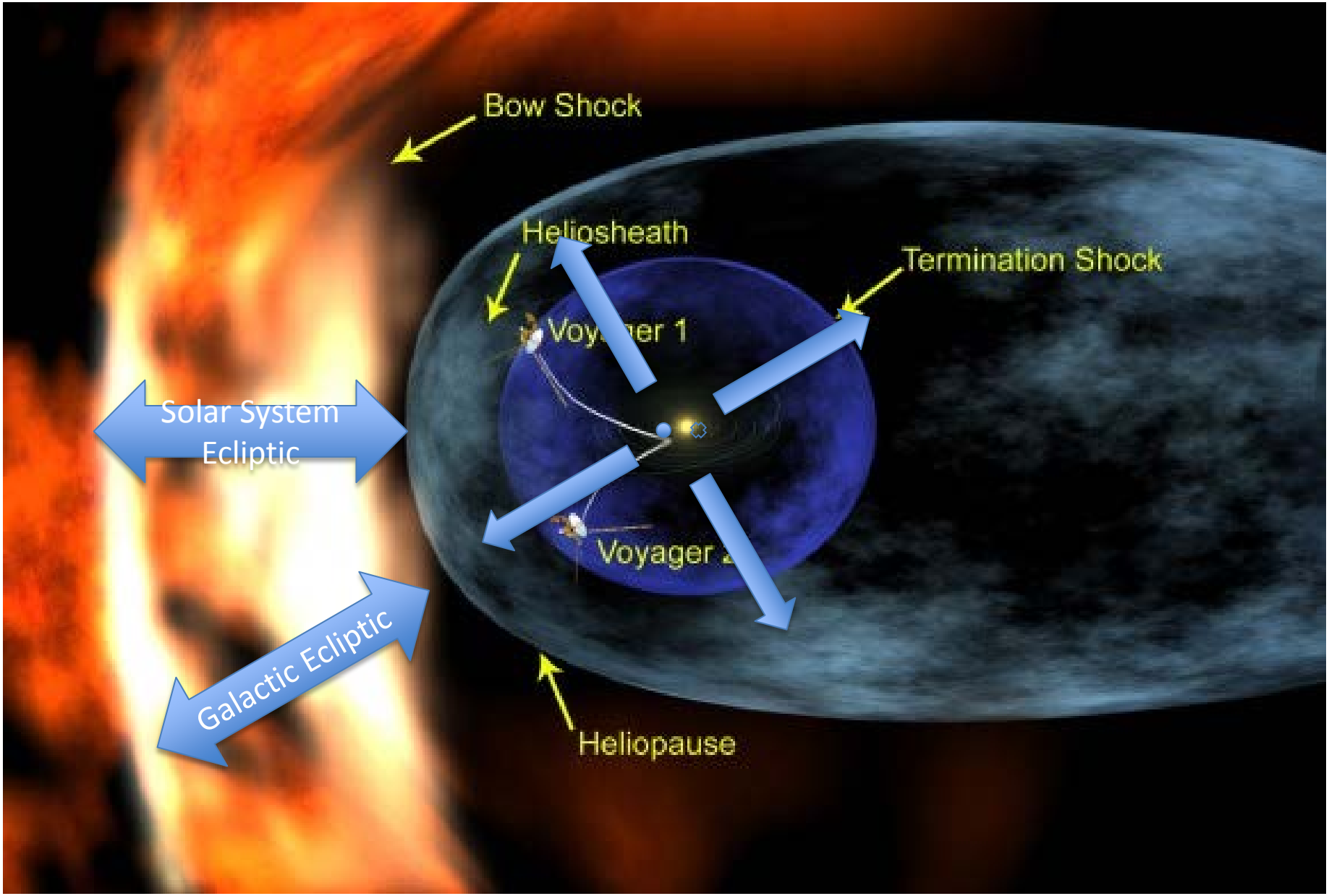
Solar System vs Galactic Ecliptic



Along Solar System Ecliptic



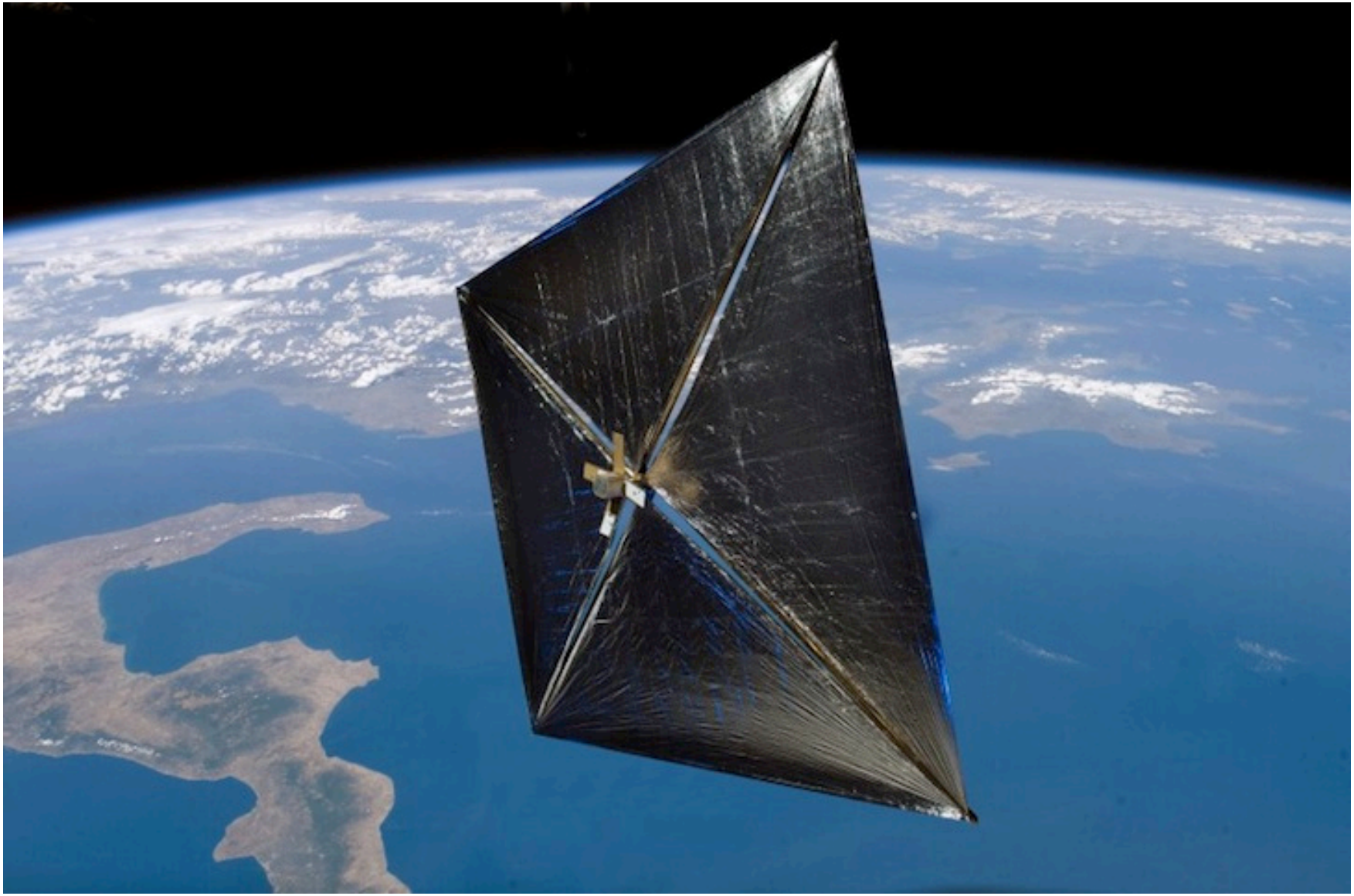
Along Galactic Ecliptic



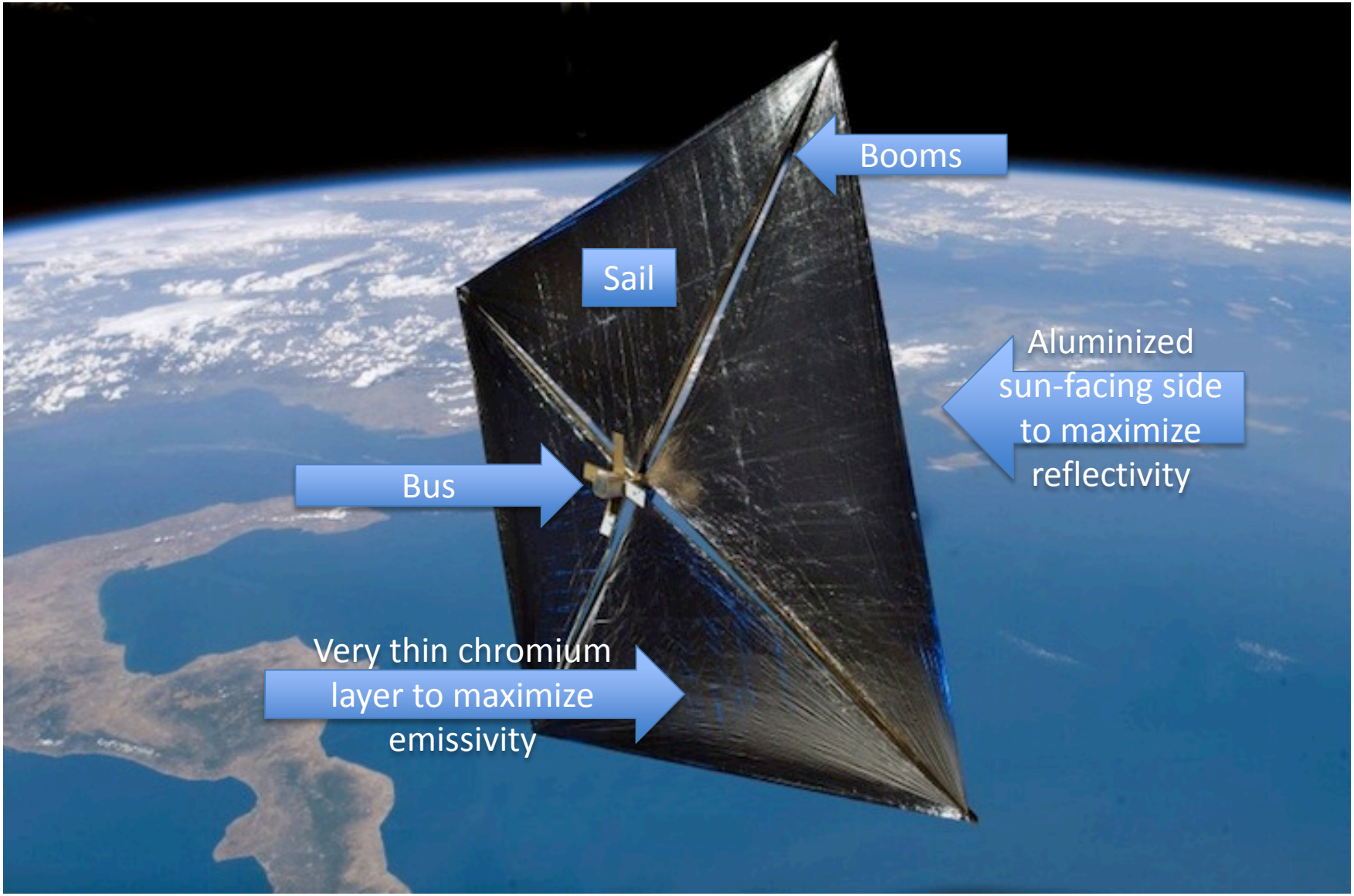
Voyager

- 35 years and counting
- Ballistic Trajectory
- ~34 years to Heliopause
- Multiple Gravity Assists
- Unlikely that near future will see a mission with a with >20 year cruise time. Can we do it in <15?
- Solar Sails

Solar Sail



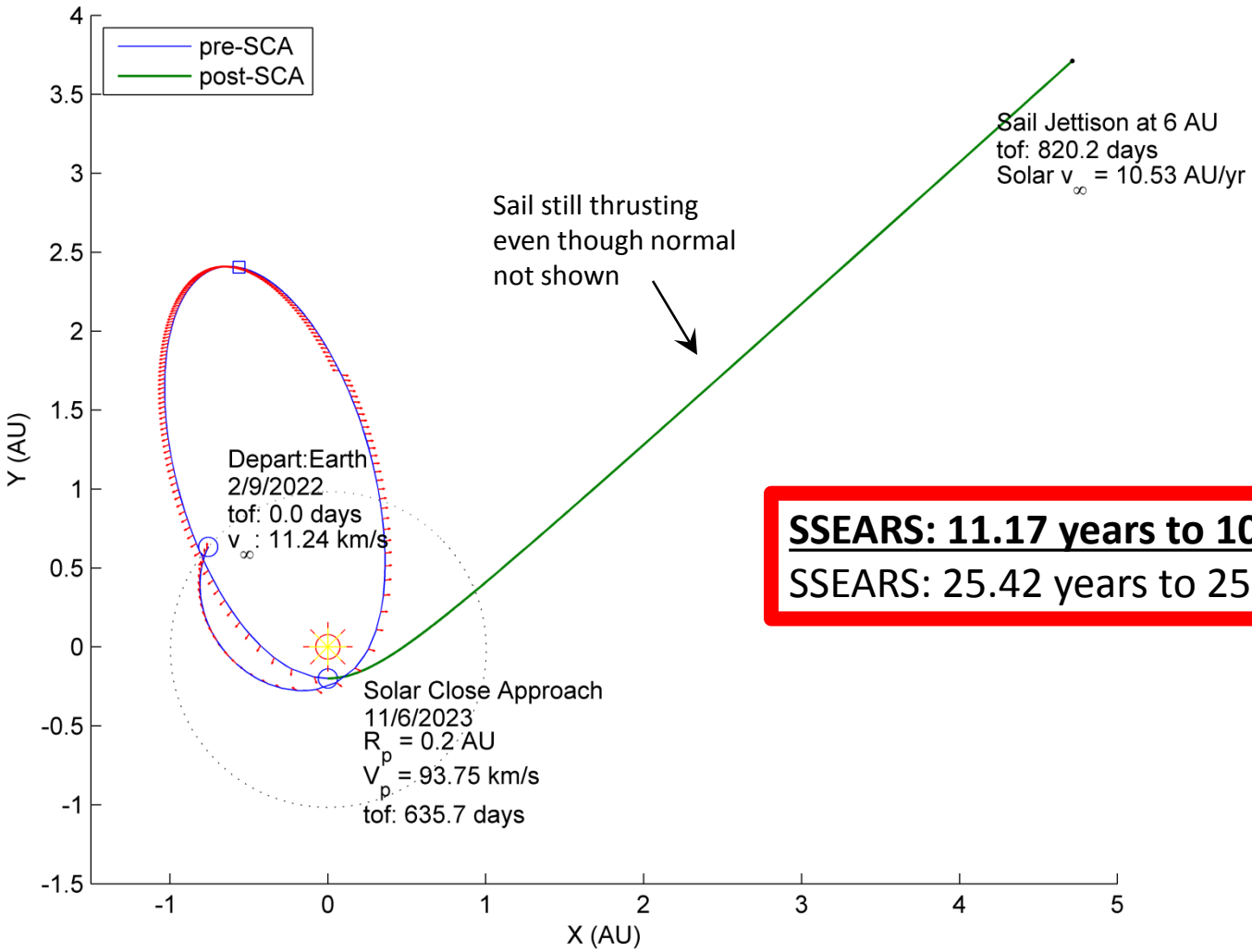
Solar Sail


Booms
Sail
Aluminized sun-facing side to maximize reflectivity
Bus
Very thin chromium layer to maximize emissivity

Tips for "Quickly" Leaving Solar System… How?

- **GOAL**: *maximize hyperbolic escape velocity*
- Spacecraft (*minimize M/A*)
  - As large sail area as possible (A)
  - Spacecraft as light as possible (M)
- Trajectory (*maximize V/R*)
  - Get as close to Sun as feasible (R)
  - Solar close approach speed as fast as possible (V)

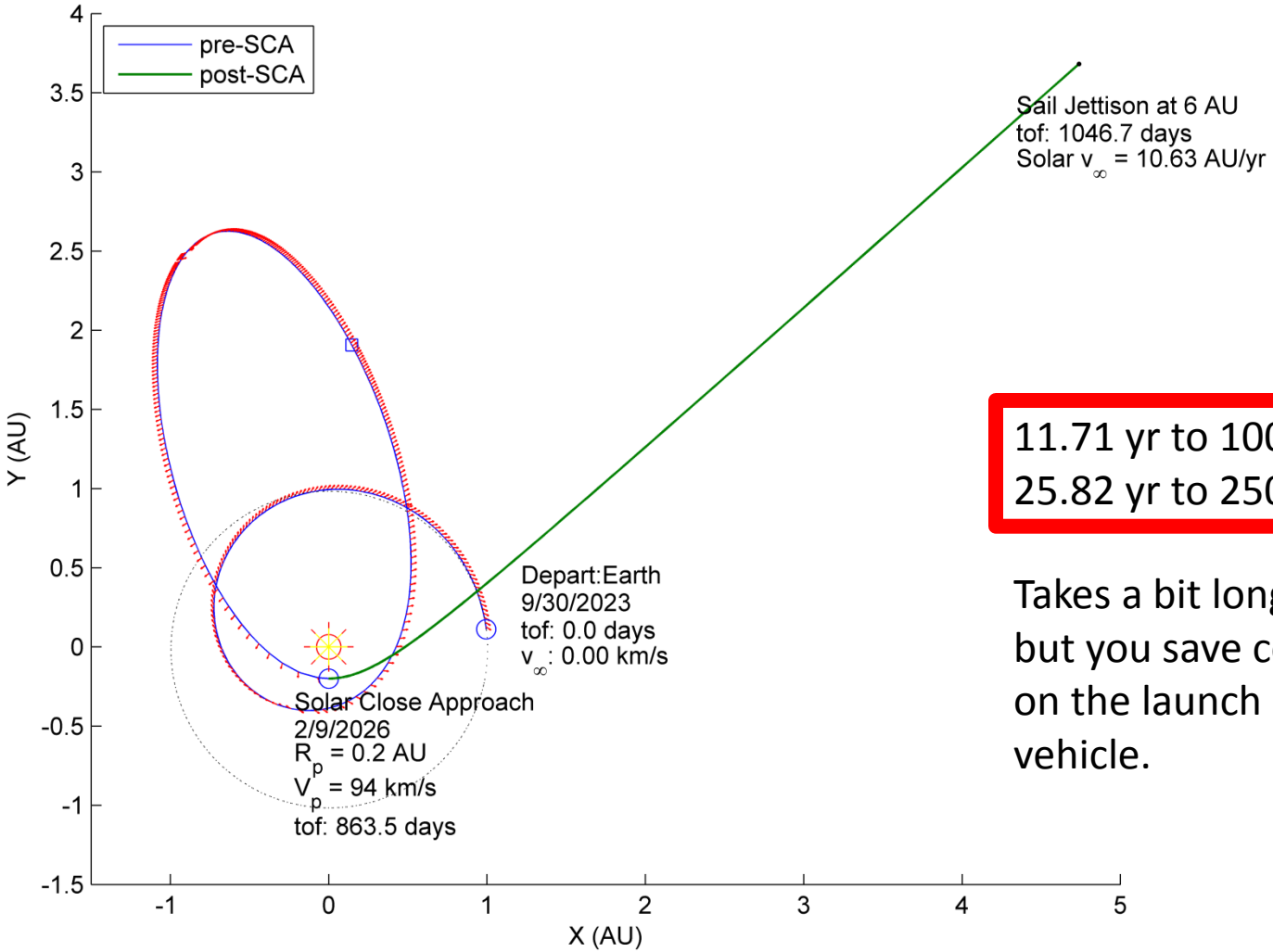
Using Upper stage to exit earth Orbit



SSEARS: 11.17 years to 100 AU

SSEARS: 25.42 years to 250 AU

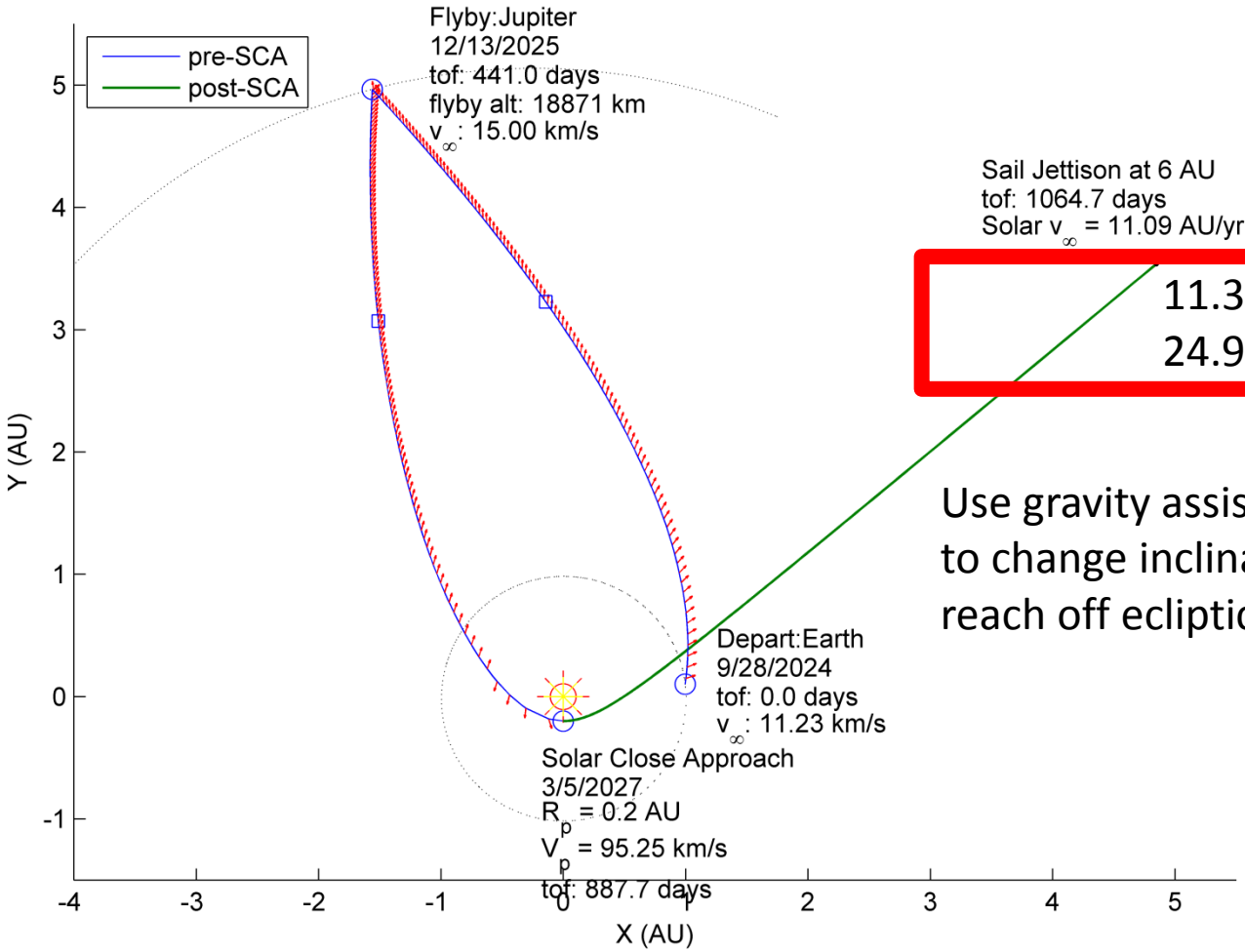
Using sail to exit earth Orbit



11.71 yr to 100 AU
25.82 yr to 250 AU

Takes a bit longer, but you save cost on the launch vehicle.

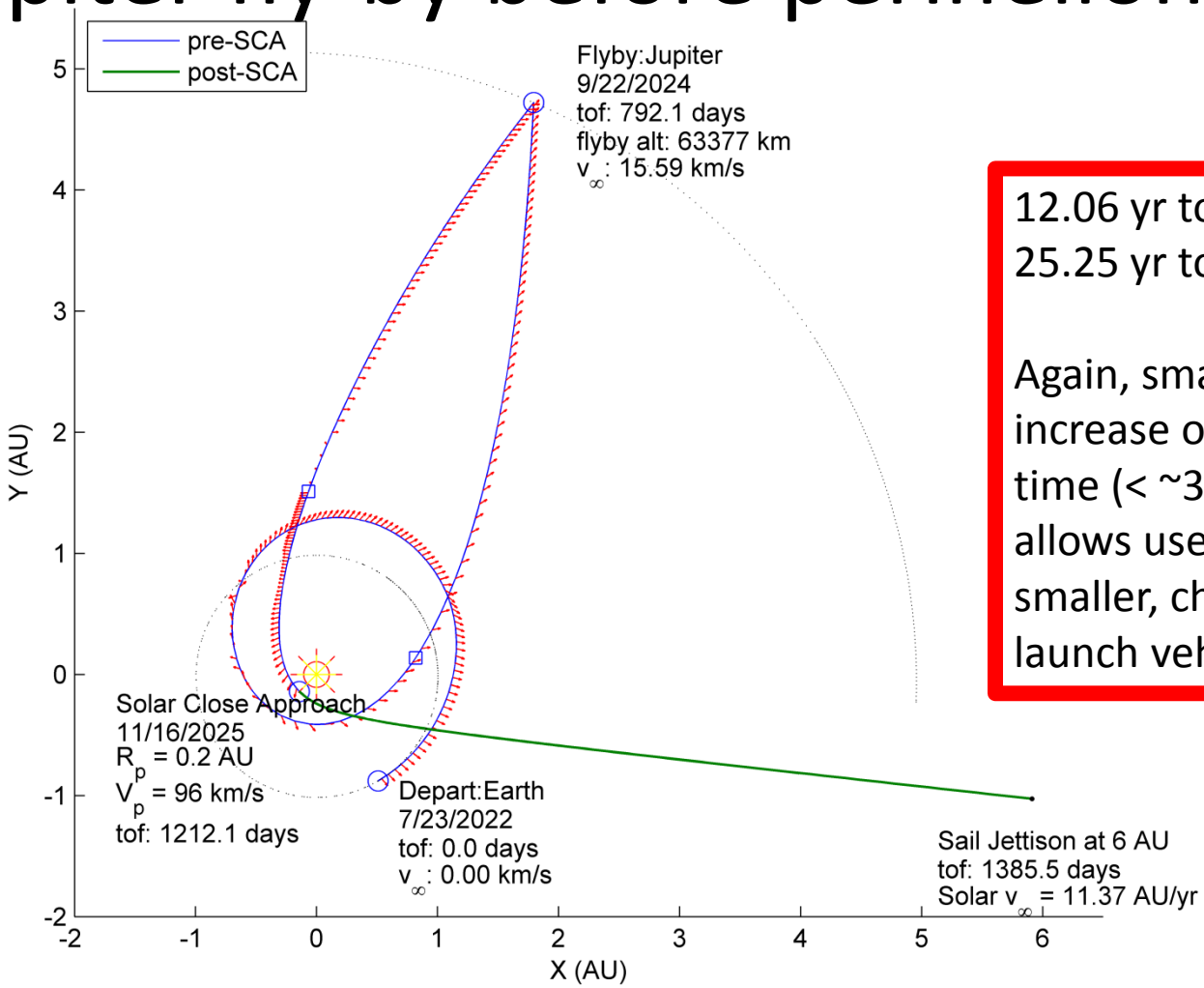
Using Upper stage to exit earth Orbit, then Jupiter fly-by before perihelion



11.39 yr to 100 AU
24.92 yr to 250 AU

Use gravity assist with Jupiter to change inclination and reach off ecliptic targets.

Using sail to exit earth orbit, then Jupiter fly-by before perihelion



12.06 yr to 100 AU
25.25 yr to 250 AU

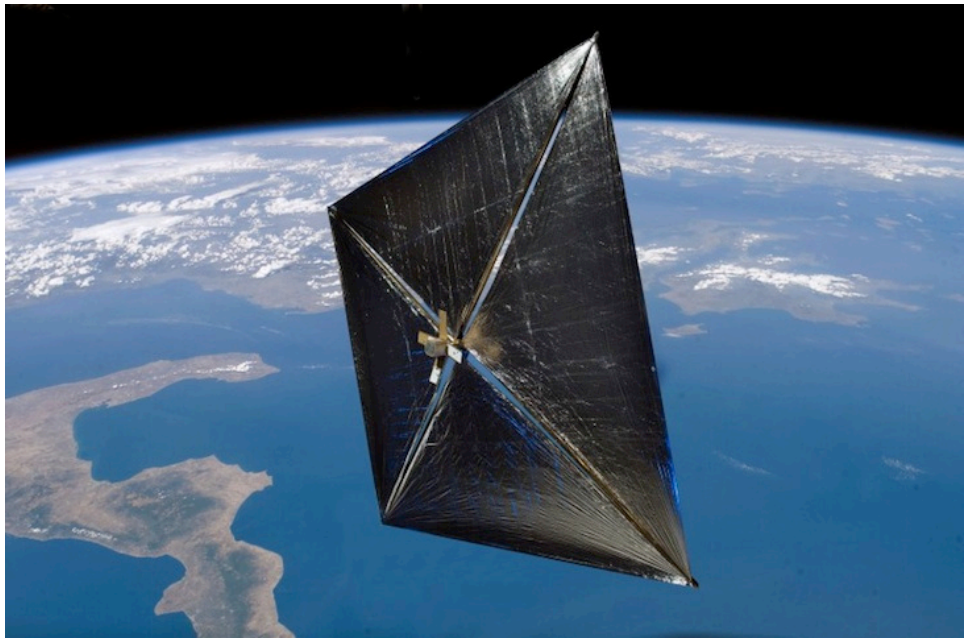
Again, small increase of transit time (< ~300 days) allows use of smaller, cheaper launch vehicle.

Architecture -> Spacecraft

- What spacecraft exist today that we can study?

Sunjammer

- Manufactured by L'Garde, Inc.
- Sunjammer s/c has particles/fields detectors
- 34x34m sail, 5 micron Kapton film
- Vanes for attitude control



- Can we scale it?

Instruments

- Plasma monitors
- Ion spectrometer
- Plasma wave monitor
- High energy particle detectors
- Cosmic Ray Detector
- Energetic Neutral Particle Spectrometer
- Magnetometer
- Meteoroid impact detector

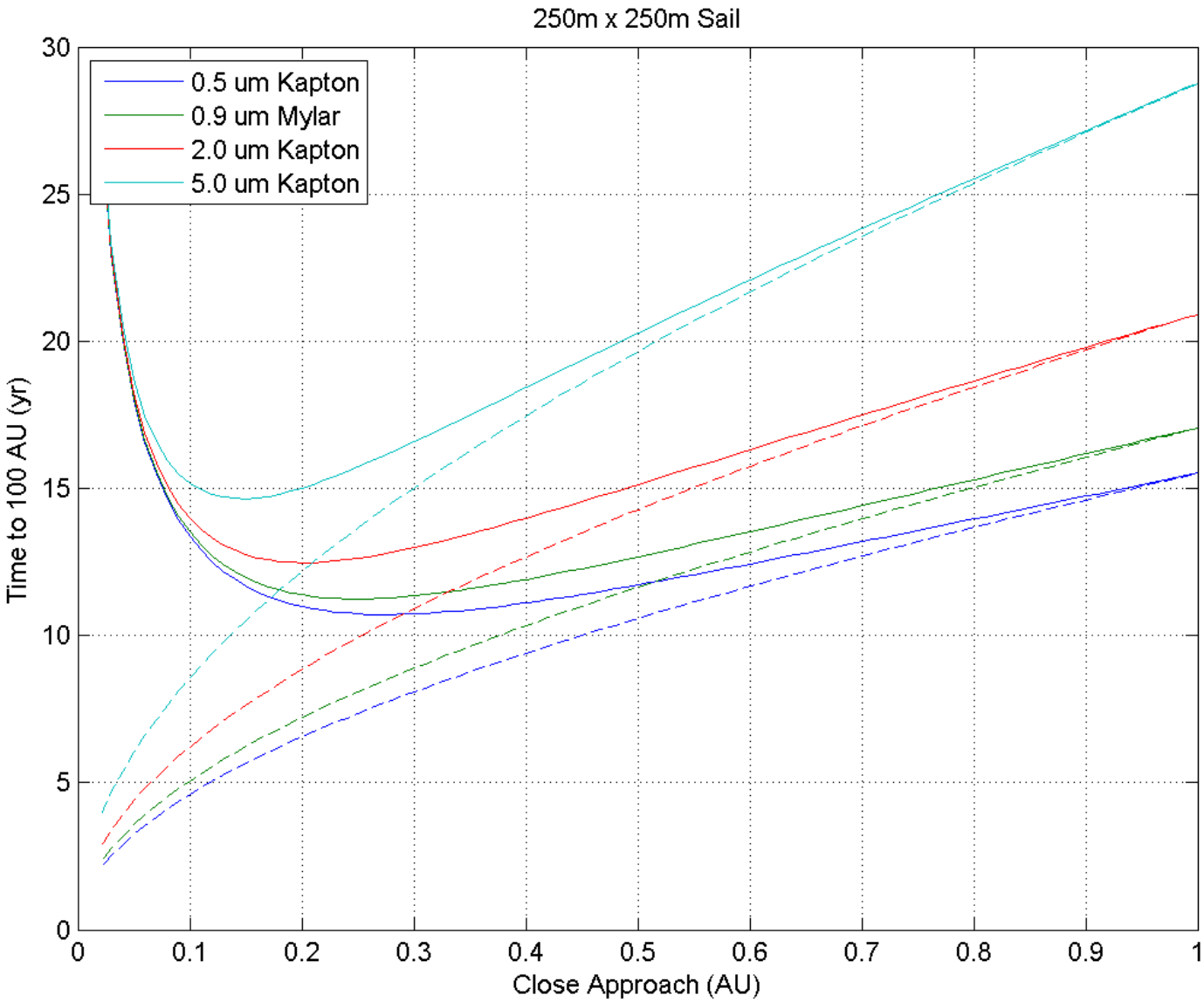
Instrument Masses

Table 1 - Small Interstellar Probe Science Payload

Instrument	1994 Mass (kg)	1994 Power (W)	1994 Data rate@ 200AU (bps)	1990 Study Mass (kg)	1990 Study Power (W)	1990 Study Data rate@ 200AU (bps)
Magnetometer	1	0.5	1	4	4	1
Plasma waves, radio	3	3	5	11	6	30
Neutral H, He, O Energetic neutral atoms	3	3	4	4	5	10
Interstellar plasma ions (+ & -) Interstellar & solar wind electrons Solar wind ions	4	4	10	20	14	20
Interstellar plasma mass & charge comp. Suprathermal & pickup ions	6	6	5	25	20	75
Anomalous/galactic cosmic ray isotopes	3	2	3	22	17	40
Cosmic ray H, He, & electrons	2.5	2	5	10	10	30
Gamma ray bursts	0.5	1	3			
UV photometer	0.5	0.5	1	1	1	10
Dust	1.5	1.5	0.1	8	9	10
IR Spectrometer	not included			20	10	10
Subtotal	25	23.5	37	125	96	236
DPU	2	1.5	0			
Total	27	25	37			
Goal	20	20	50			

Mewaldt et al, 1995

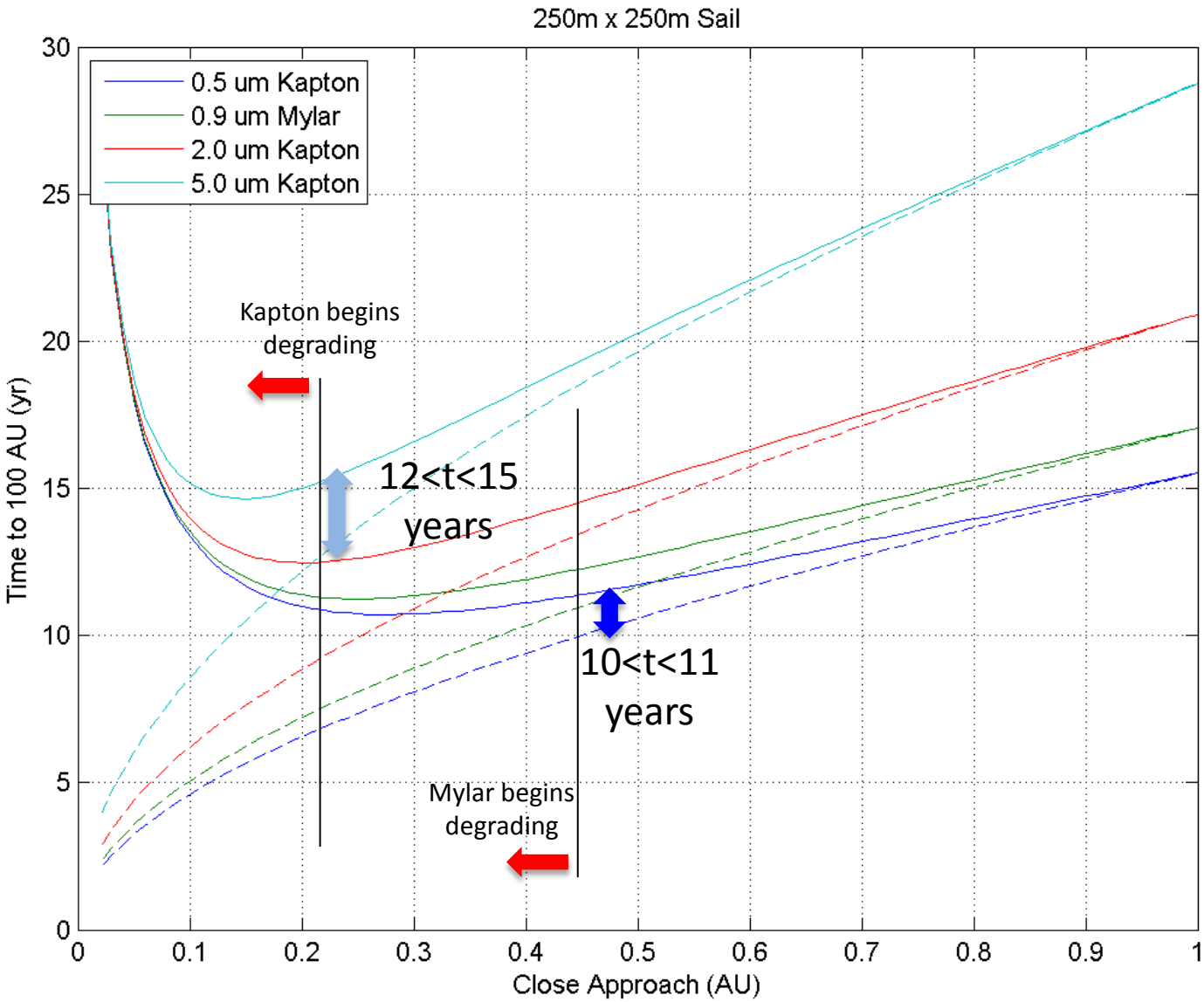
Time to 100 AU With 250x250m sail and 110kg bus



Conservative Boom Mass Scaling

Aggressive Boom Mass Scaling

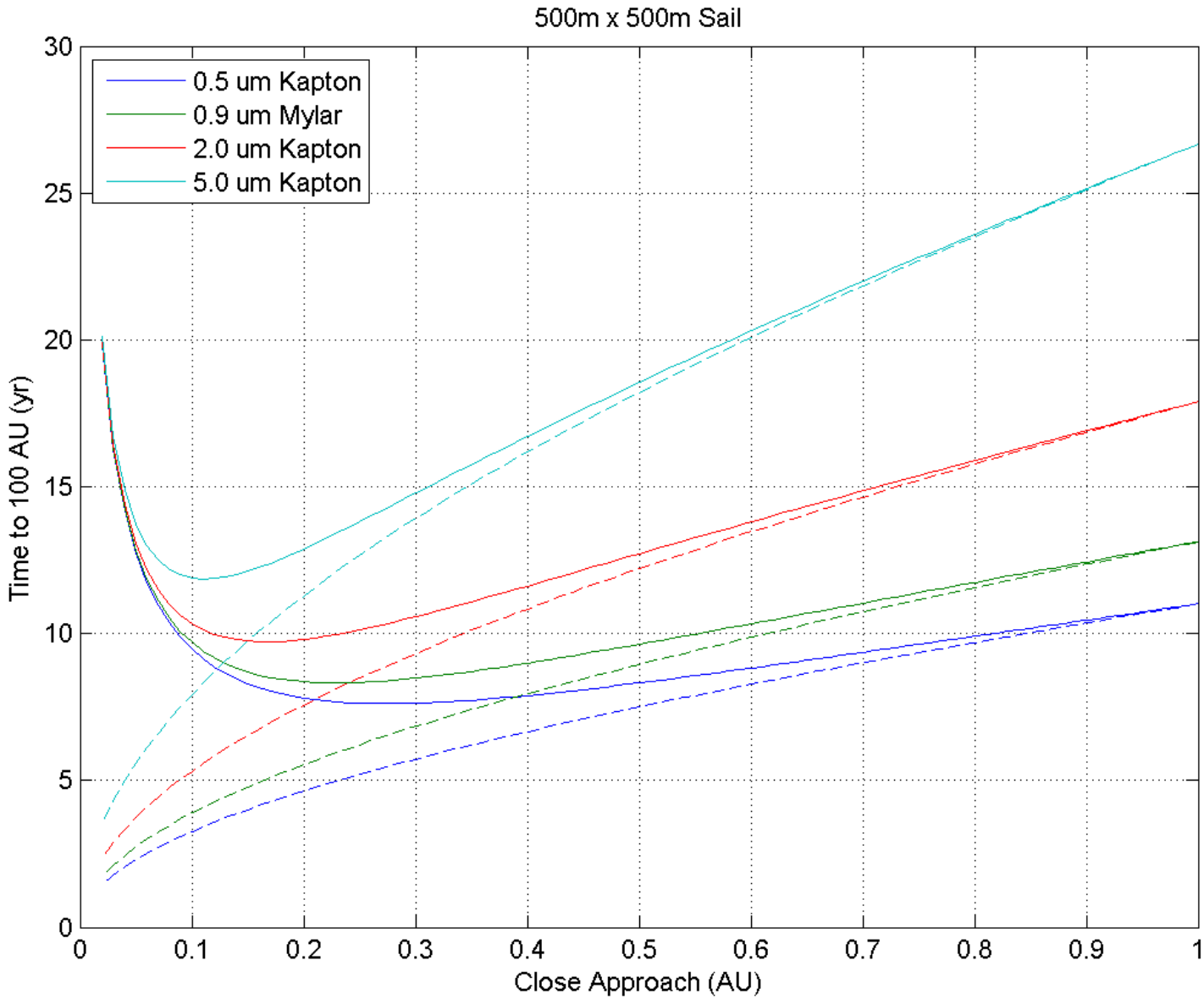
Time to 100 AU With 250x250m sail and 110kg bus



Conservative Boom Mass Scaling

Aggressive Boom Mass Scaling

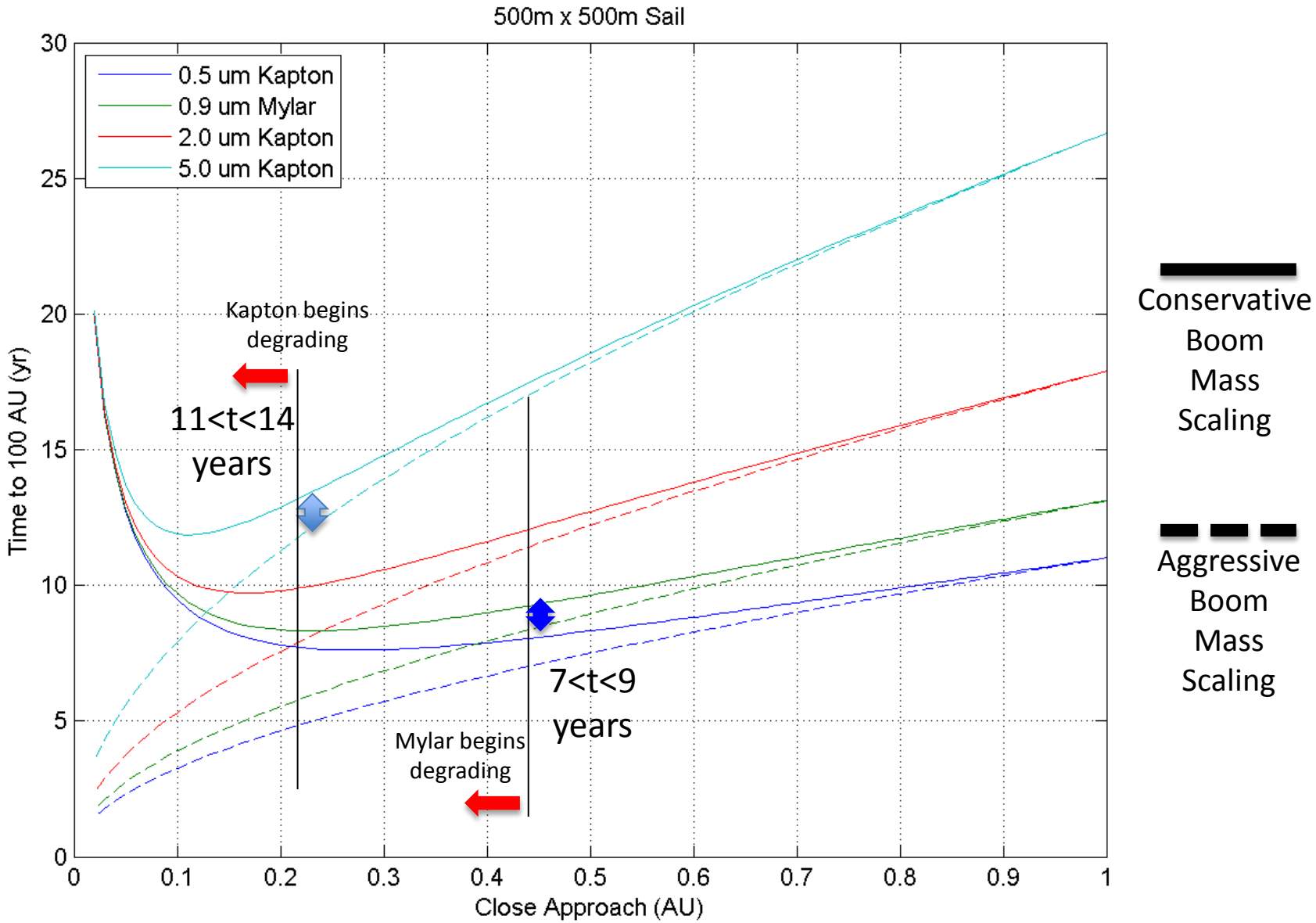
Time to 100 AU With 500x500m sail and 110kg bus



Conservative Boom Mass Scaling

Aggressive Boom Mass Scaling

Time to 100 AU With 500x500m sail and 110kg bus



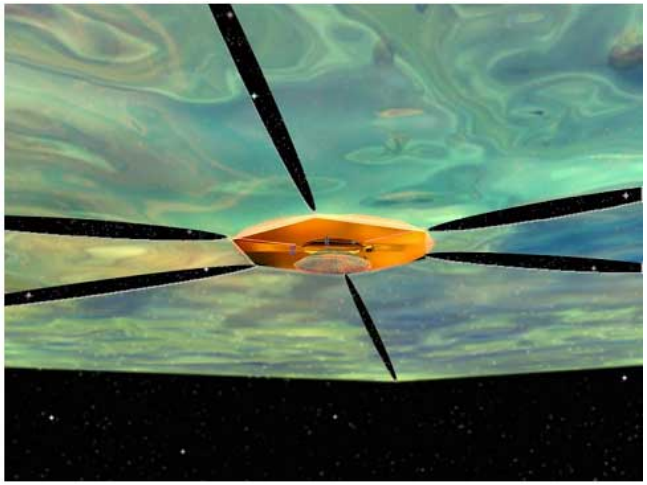
Cost Scaling

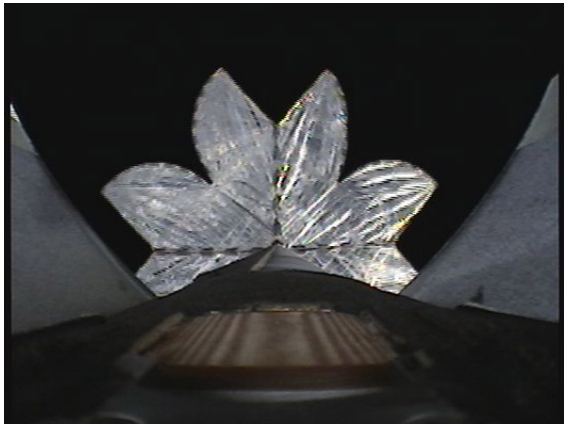
- Sunjammer spacecraft costs ~12M
- Sunjammer is secondary payload

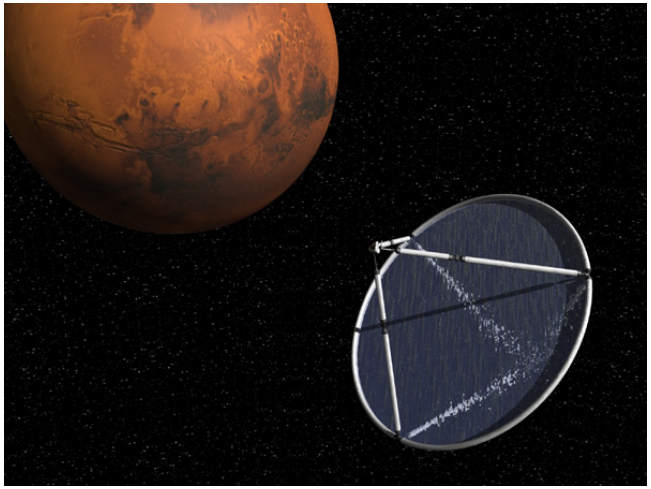
- No cost models yet for 250x250m sail, but even if we assume it's 10x more – can still build a dozen spacecraft for ~1.5-2B.

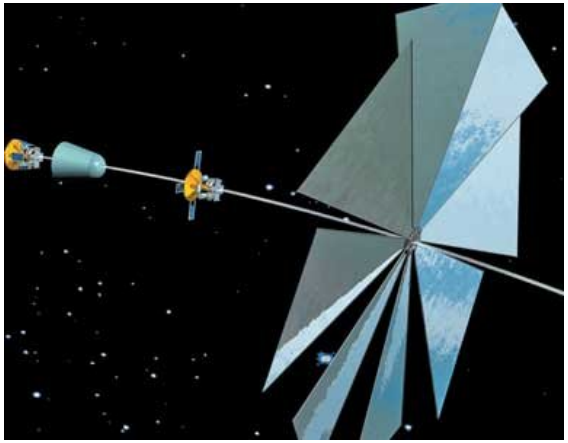
- Economics of Scale
- May be able to launch multiple spacecraft with same LV

Other Sail Designs to Study









Summary Slide

- Spacecraft velocities of 10-12 AU/year, which is the 3-4x Voyager solar system escape velocities are feasible with solar sails and modern materials (with future materials in the works)
- Desirable instrument suite for heliopause study can be accommodated on such a spacecraft
- Identified variables in real life terms that will affect architecture (perihelion distance, sail thickness, boom architecture, etc)

Phase 2 Plans

- Update instrument masses
- Determine communication needs/options
- Investigate Thermoforming fabrication method
- Determine safe perijove distance
- Material performance testing for Kapton:
  - Elogation vs temperature
  - Degradation vs time and temperature
  - Degradation vs time and radiation
- Identify actual launch dates/trajectories to maximize science return
- Investigate ablative material on nano-structure for sail
- Investigate Joe Ritter's NIAC work for attitude control
- Attend "Gossamer Systems: Analysis and Design Course in Sep. 2013"
- Sail performance vs rate of degradation
- …

Thank you NIAC!

- Jackie Green
- Andrew Shapiro
- Henry Garrett
- Andrew Shapiro
- Brian Trease

- John West
- Morgan Cable
- Joshua Schoolcraft
- Morgan Hendry
- Josh Ravich

- Boeing

- L'Garde Inc.

Leaders

- C. McInnes
- G. Vulpetti
- C. Sauer
- C. Yen
- M. Gruntmann
- A. Clarke
- B. Forward
- B. Frisbee
- R. McNutt

Backup Slides

Scaling Sunjammer 250x250m sail Kapton

Sail Thickness (micron)	Perihelion (au)	Time to 100 AU (yr)	Velocity (au/yr)

***Dupont: 2.5 micron Kapton film is visible over the horizon, pending the business case**

**Effective acceleration decreases as we get closer to the sun because we need more mass in the booms to handle the solar pressure load.

Scaling Sunjammer 500x500m sail Kapton

Sail Thickness (micron)	Perihelion (au)	Time to 100 AU (yr)	Velocity (au/yr)
5 (current SOA)	.2	23.6	~4
2*	.5 **.2** .1**	12.7 **9.81** 10.4**	7.8 **10.2** 9.6**
.5	.5 **.2** .1**	8.31 **7.81** 9.47**	12 **12.8** 10.5**

***Dupont: 2.5 micron Kapton film is visible over the horizon, pending the business case**

**Effective acceleration decreases as we get closer to the sun because we need more mass in the booms to handle the solar pressure load.

Scaling Sunjammer 250x250m sail Mylar

- .9 micron mylar

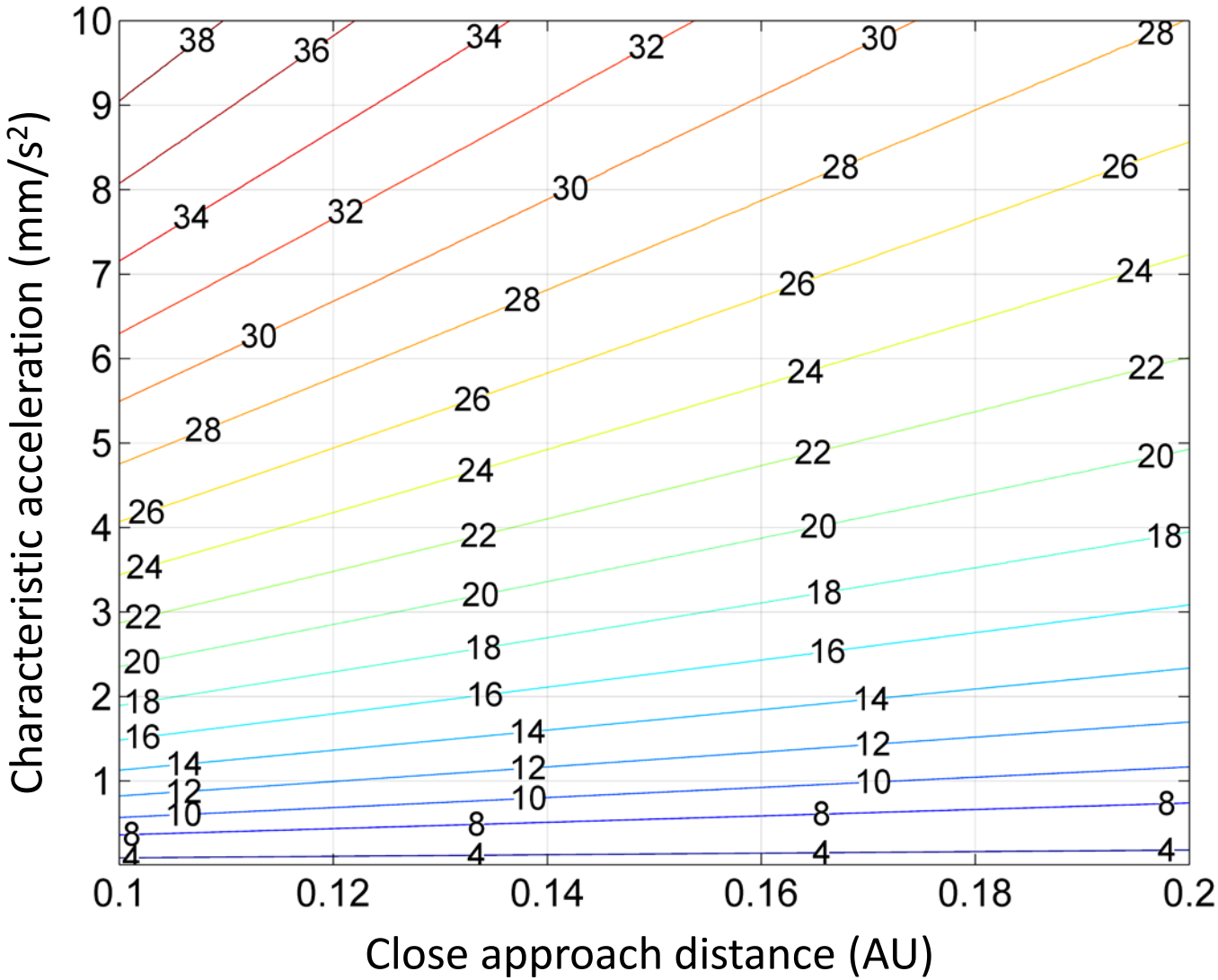
Scaling Sunjammer 500x500m sail Mylar

- .9 mylar

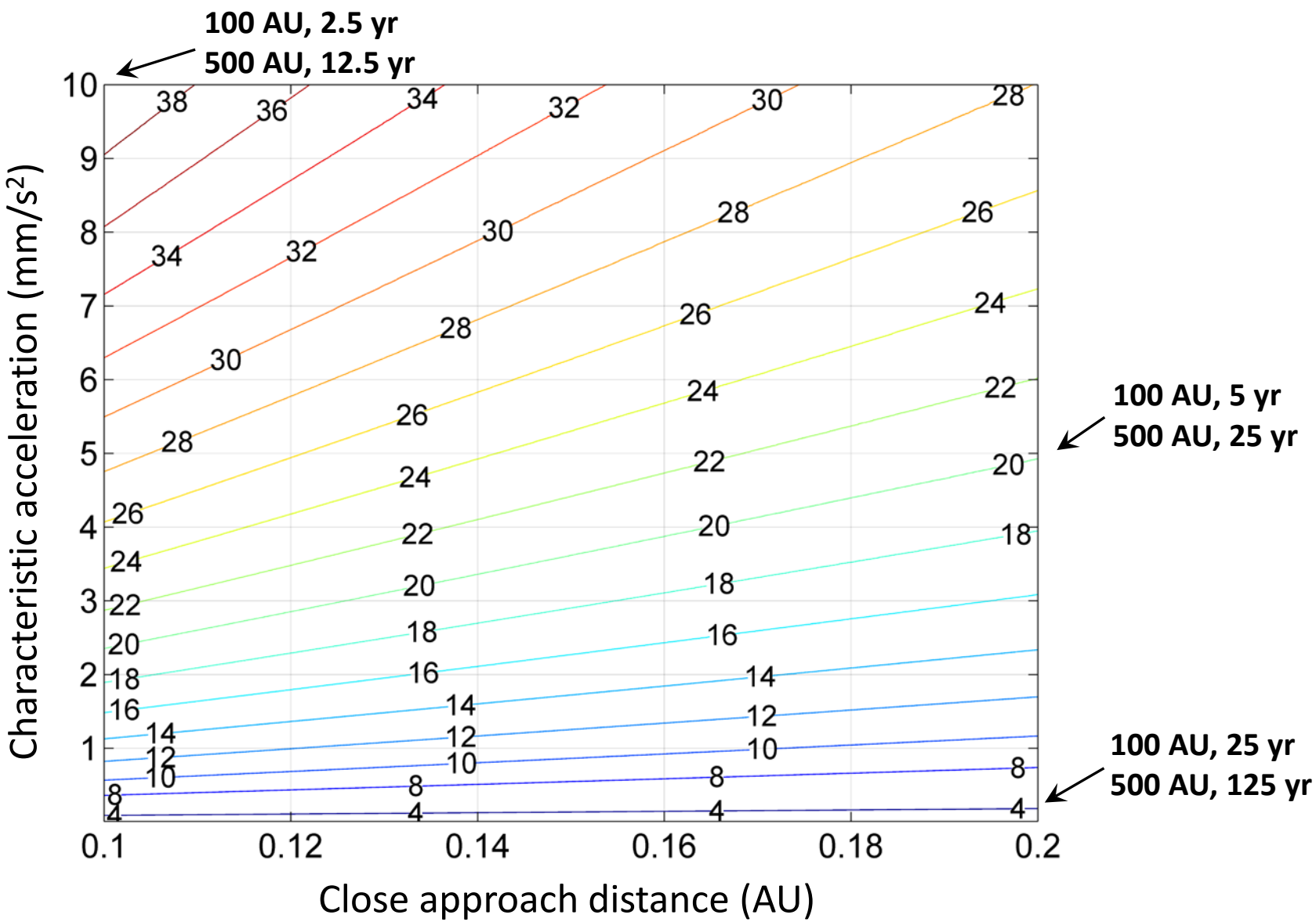
Optimal Solar System Escape Trajectories

Dan Grebow

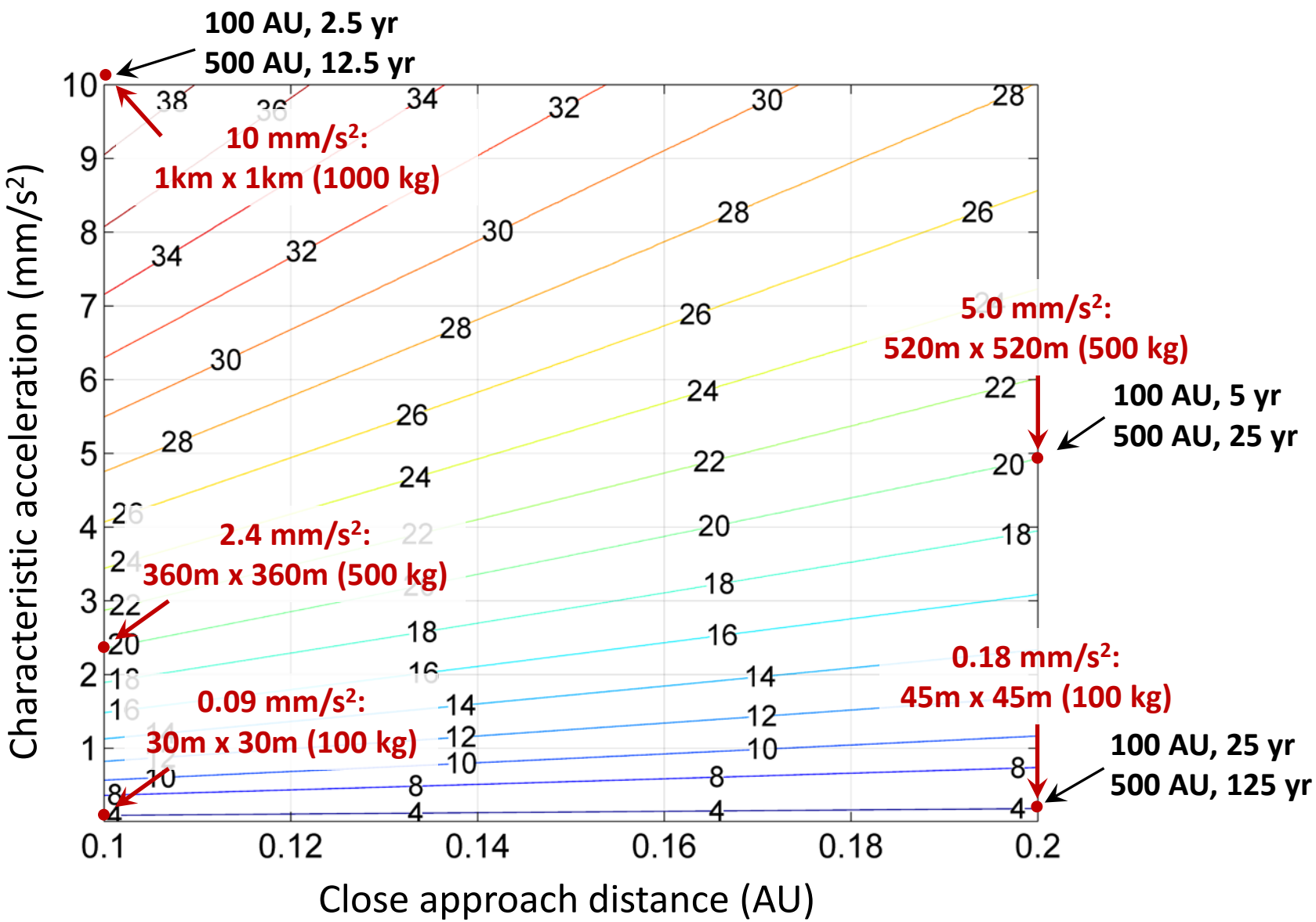
Escape Speed (AU/yr) at 6 AU



Escape Speed (AU/yr) at 6 AU



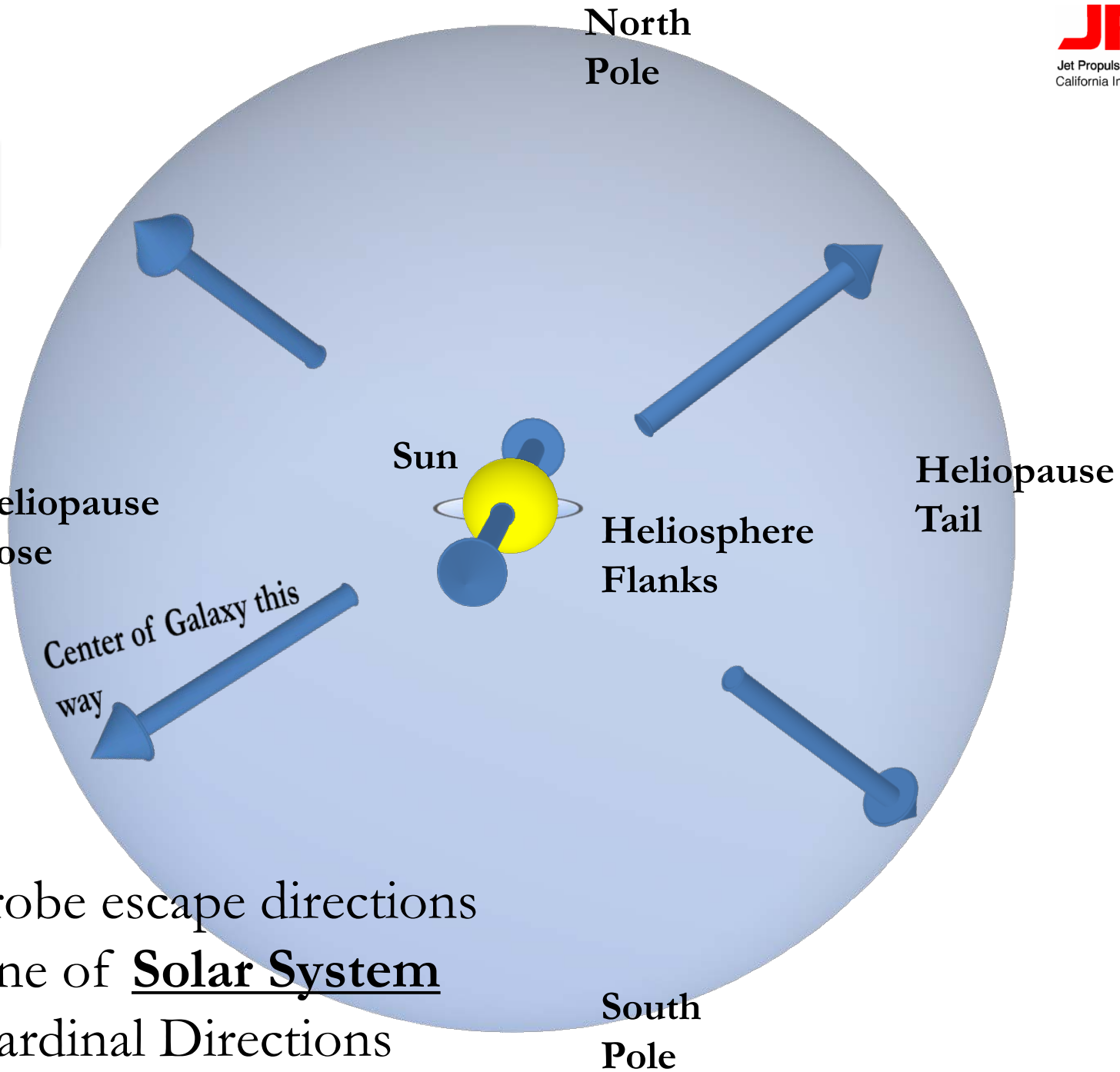
Escape Speed (AU/yr) at 6 AU



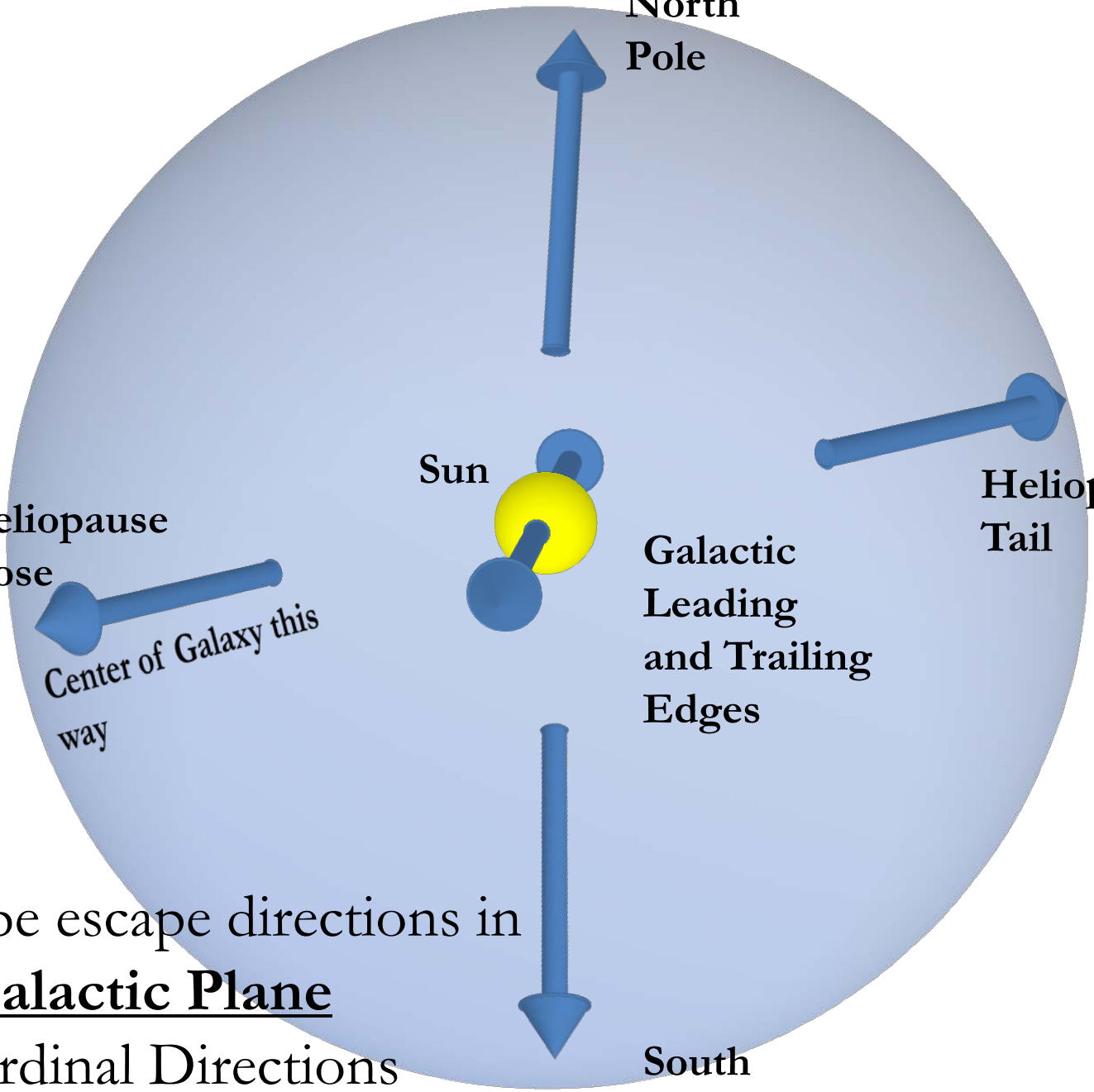
Instruments

- Plasma monitors: ~1 eV- 100 keV electrons
- ~1 eV-100 keV ion spectrometer (Faraday cup, mass spectrometer, or something similar)
- Plasma wave monitor: ~1 kHz-1 Mhz
- High energy particle detectors: ~100 keV-30 MeV electrons
- ~100 keV-100 MeV ion spectrometer
- Cosmic Ray Detector: Heavy ions 1 MeV/nucleon-10 GeV/nucleon
- Energetic Neutral Particle Spectrometer
- Magnetic field: 1 pT vector magnetometer
- Meteoroid impact detetor

Put in "compass"



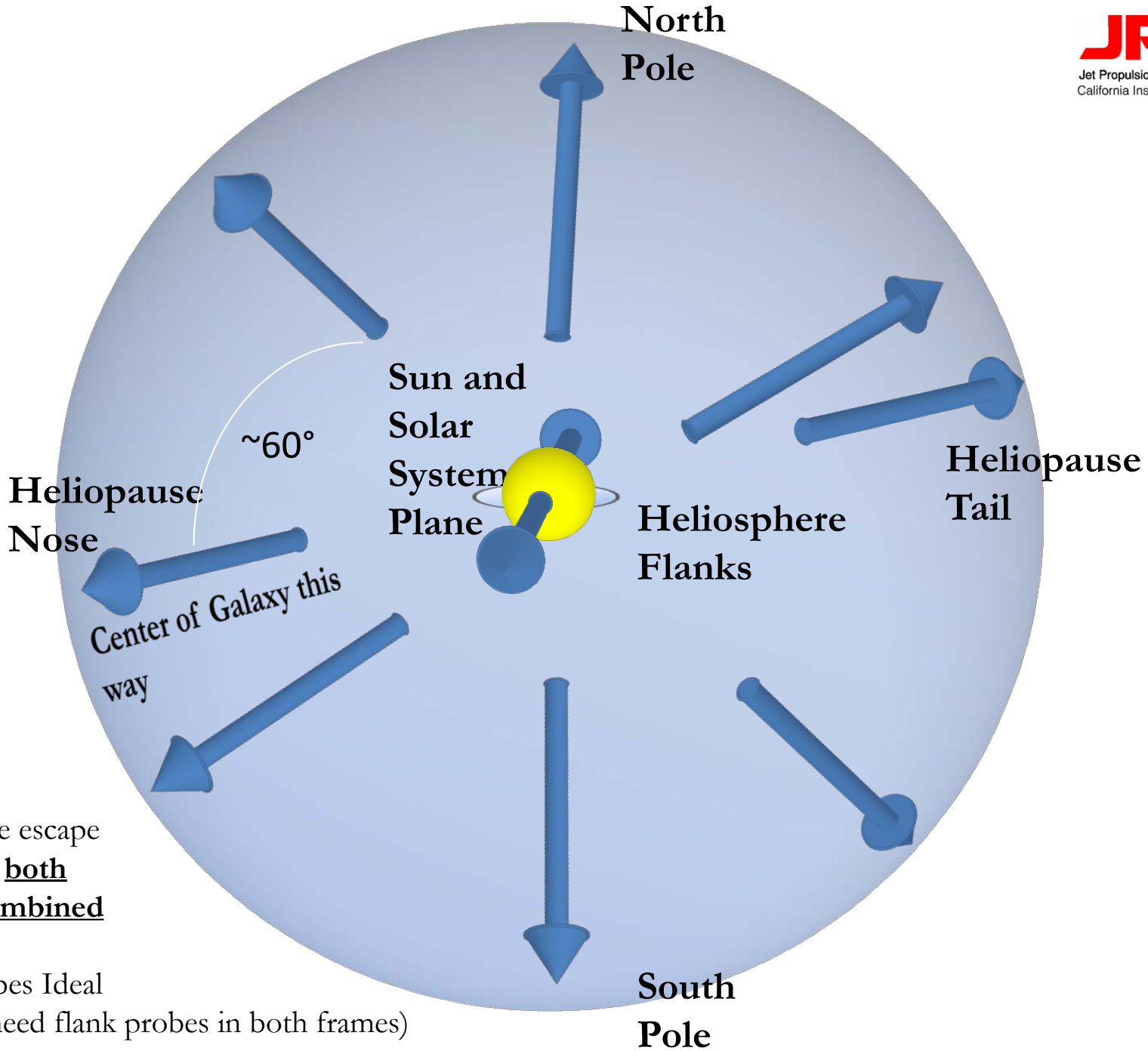
Ideal probe escape directions
in Plane of **Solar System**
6 Cardinal Directions



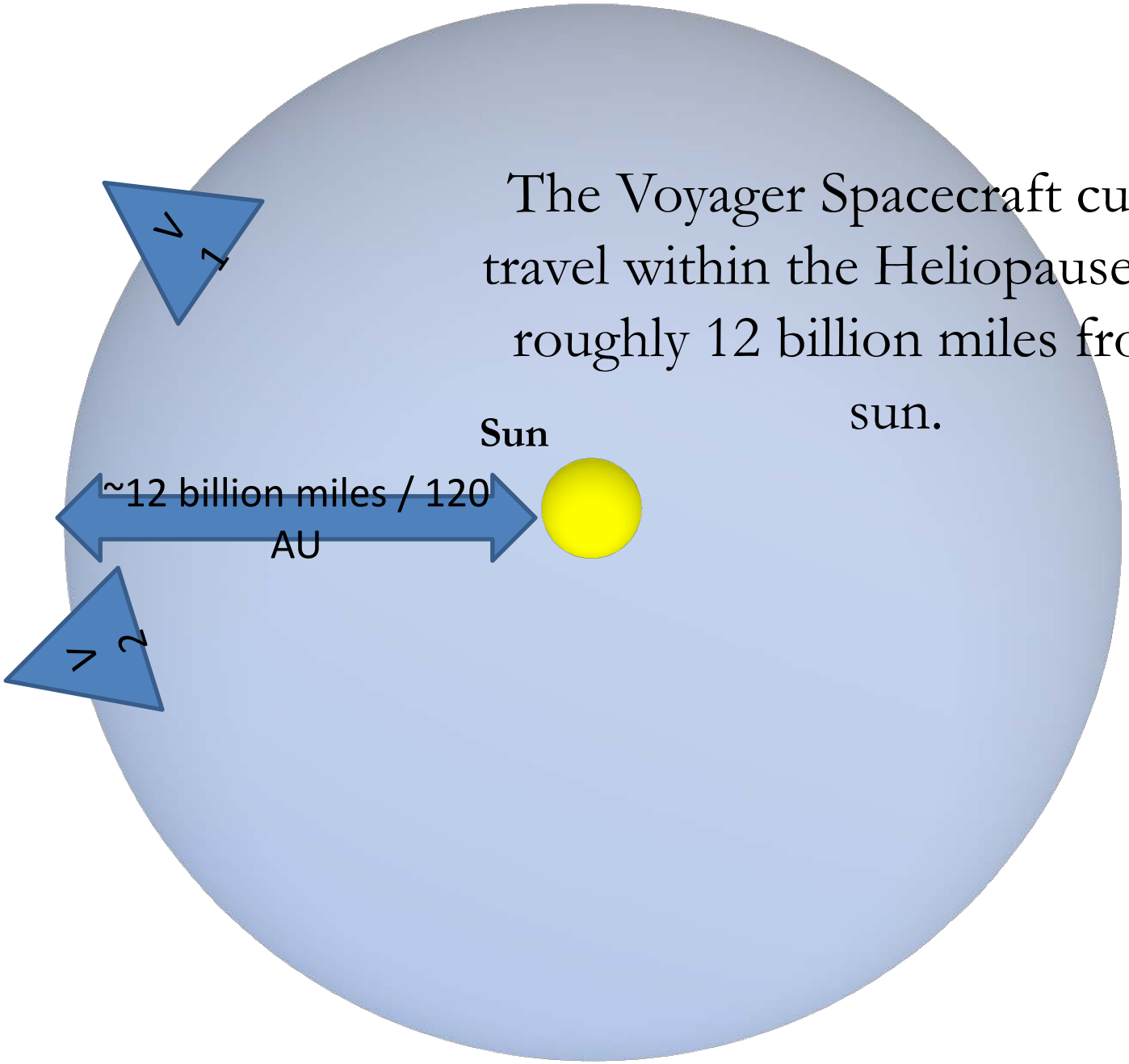
Ideal probe escape directions in

Galactic Plane

6 Cardinal Directions



Ideal probe escape directions, **both frames combined**

10-12 Probes Ideal
(may not need flank probes in both frames)

The Voyager Spacecraft currently travel within the Heliopause region, roughly 12 billion miles from the sun.