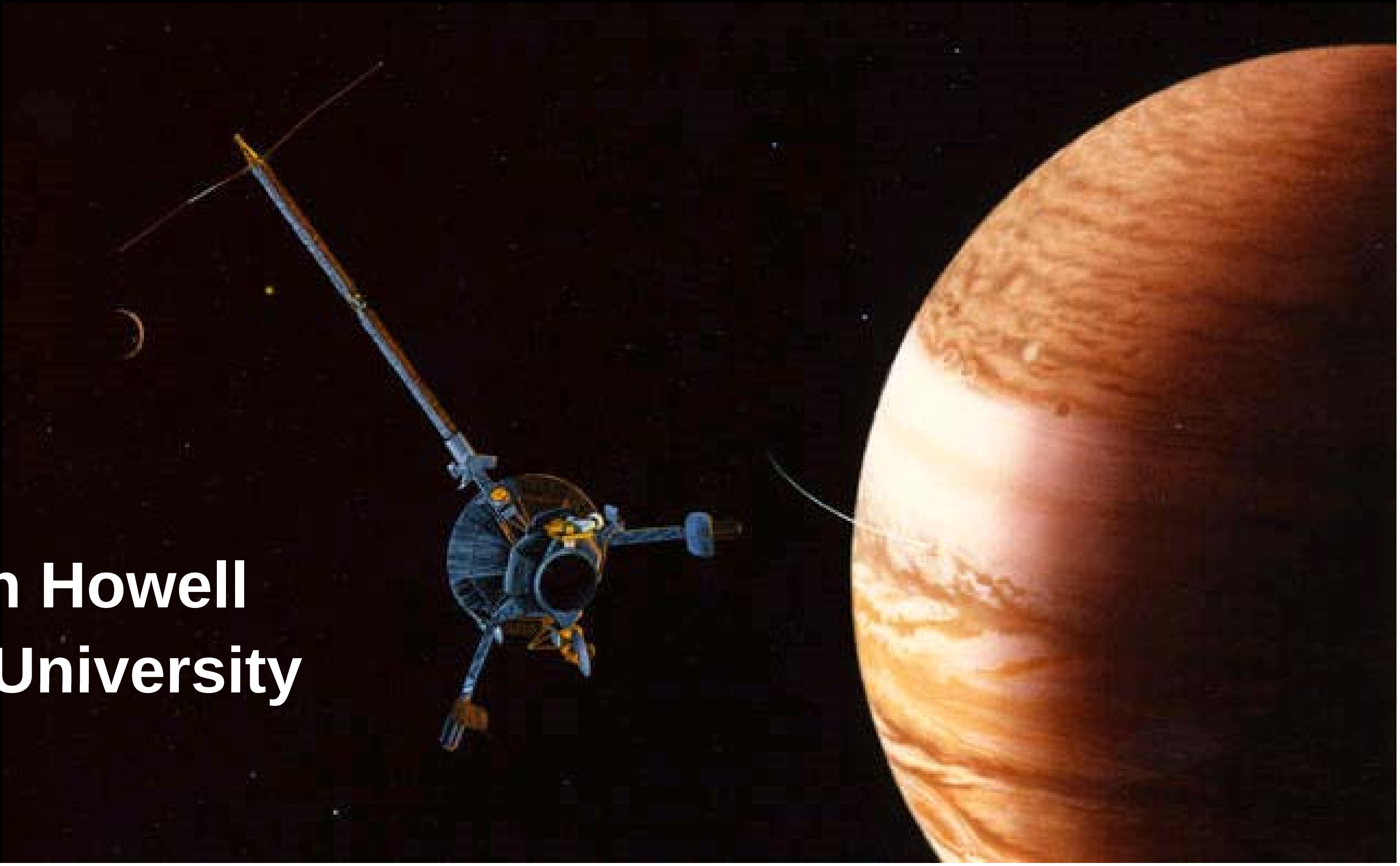
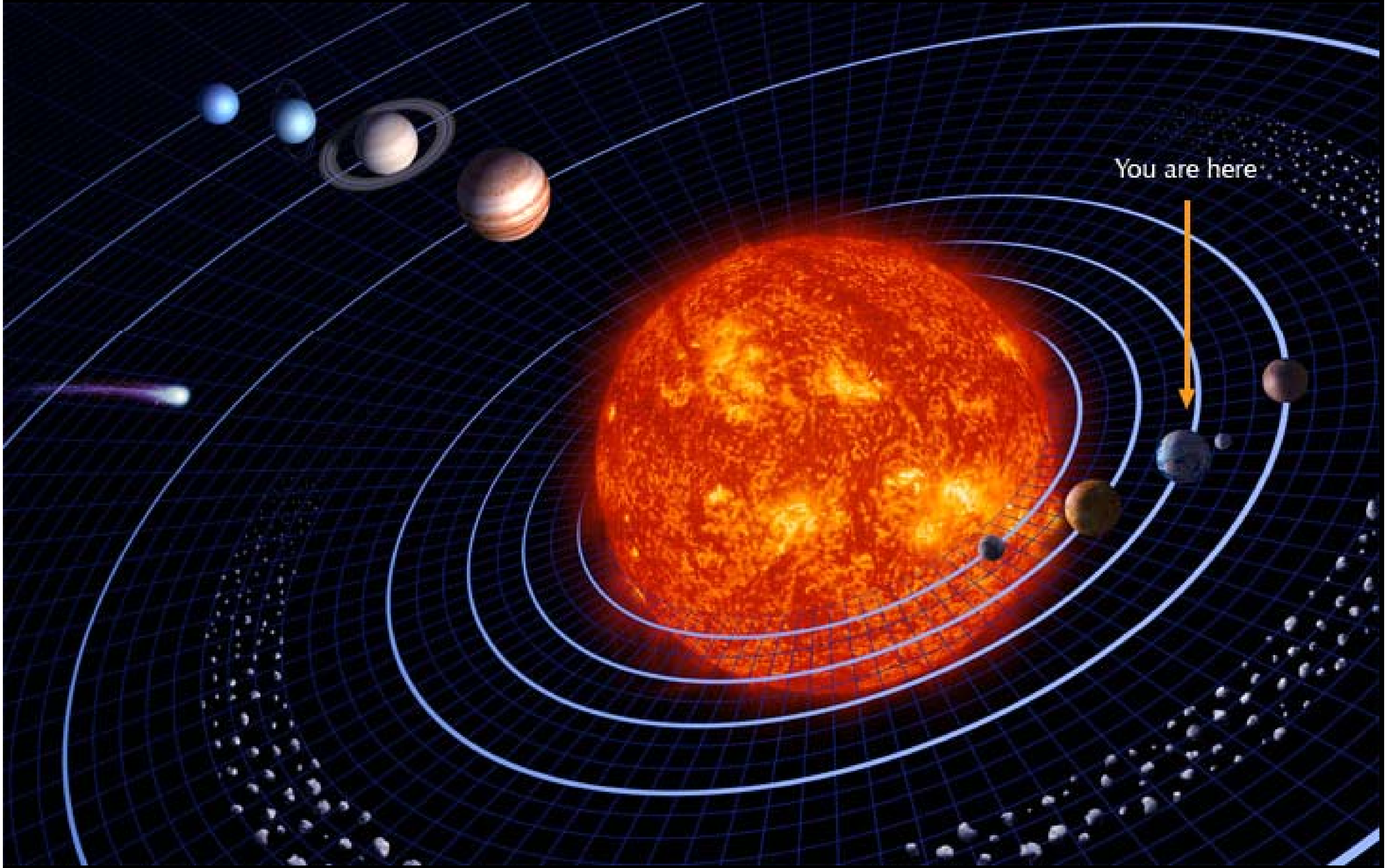
Mission Design:
Exploring the Solar System

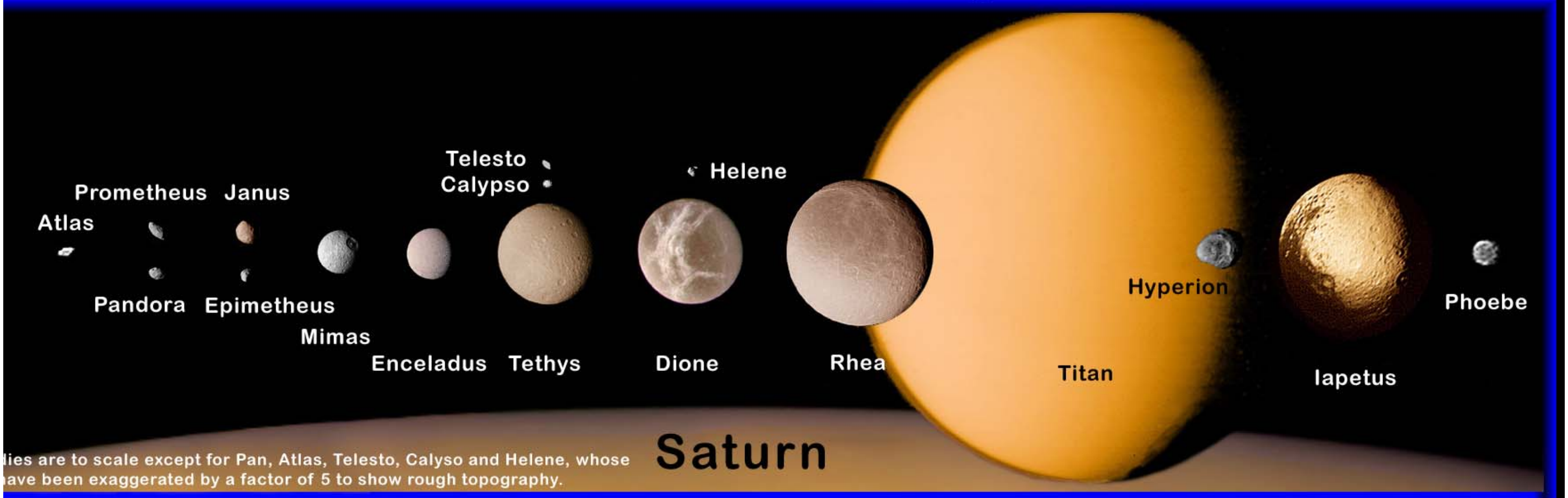


Kathleen Howell
Purdue University

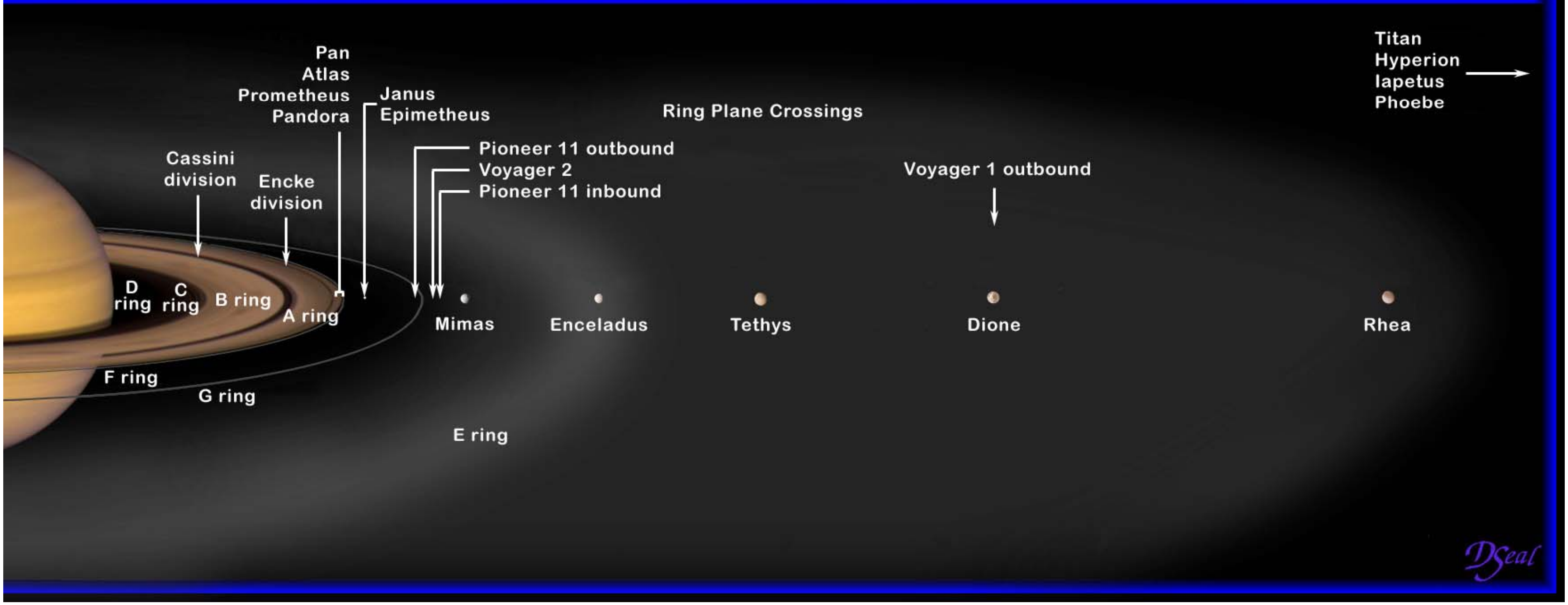
Potential Destinations?



Planets: Saturn?



ies are to scale except for Pan, Atlas, Telesto, Calyso and Helene, whose
ave been exaggerated by a factor of 5 to show rough topography.



Dwarf Planet?

Dwarf Planet:

(a) in orbit around the Sun

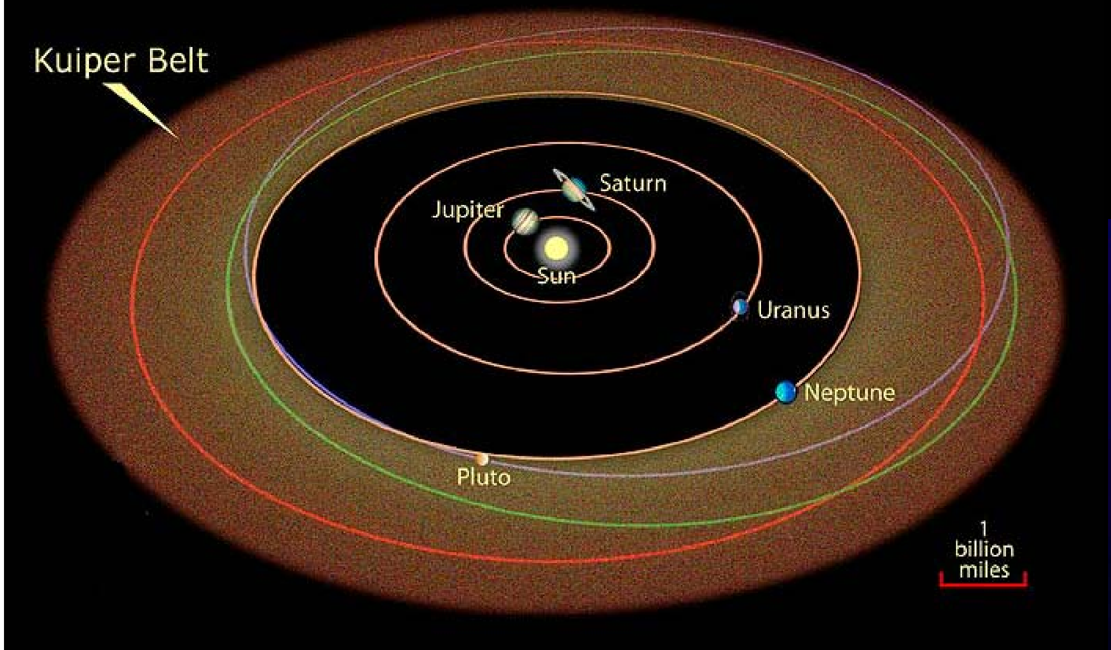
(b) sufficient mass for self-gravity to assume nearly round shape

(c) neighborhood around orbit not cleared

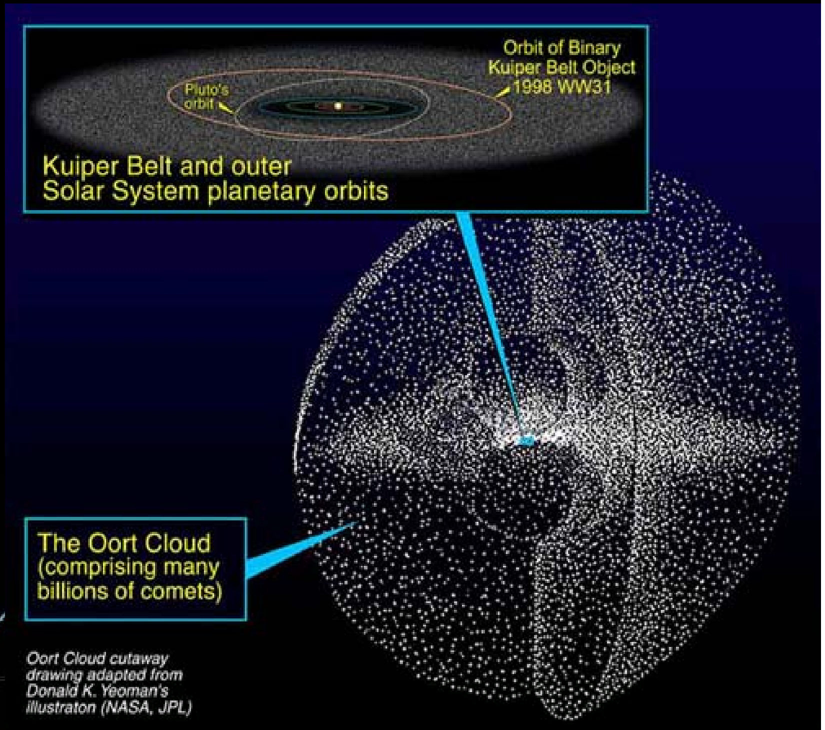
(d) is not a satellite

(d) is not a satellite

Kuiper Belt Object?

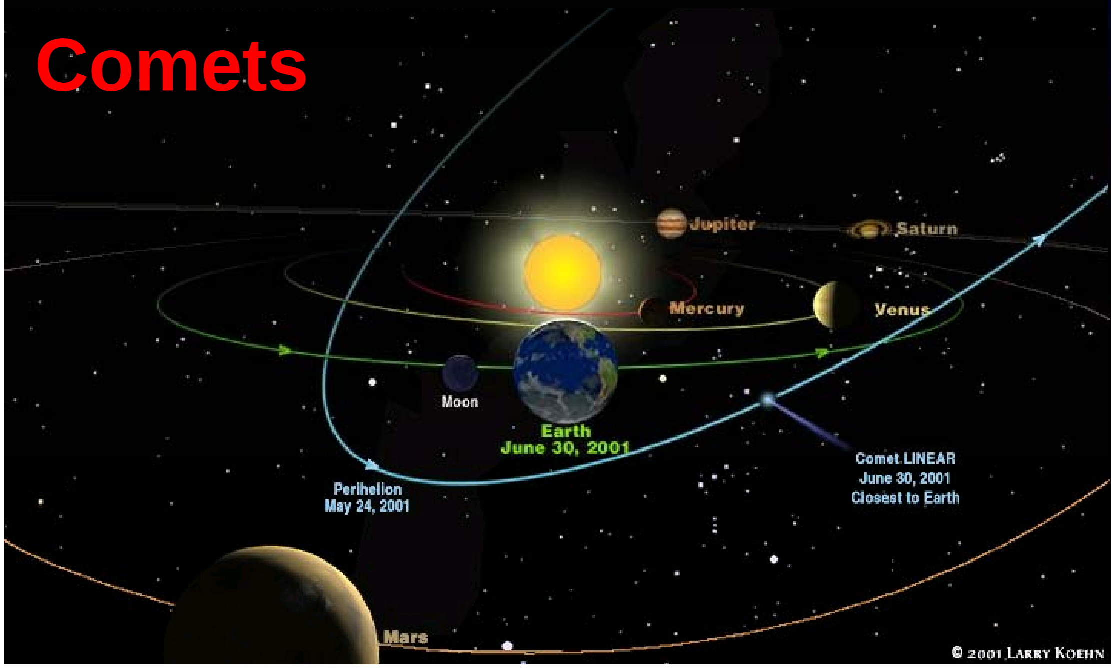


Oort Cloud Object?

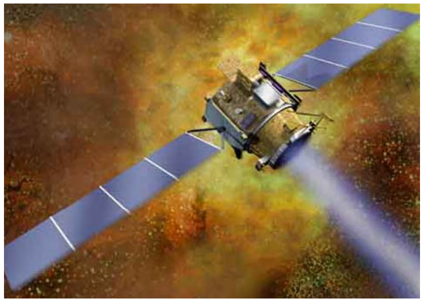


Oort Cloud cutaway drawing adapted from Donald K. Yeoman's illustraton (NASA, JPL)

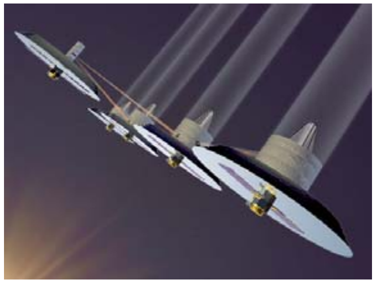
Comets



© 2001 Larry Koehn



Mission Design



Mission Architectures

Mission Requirements

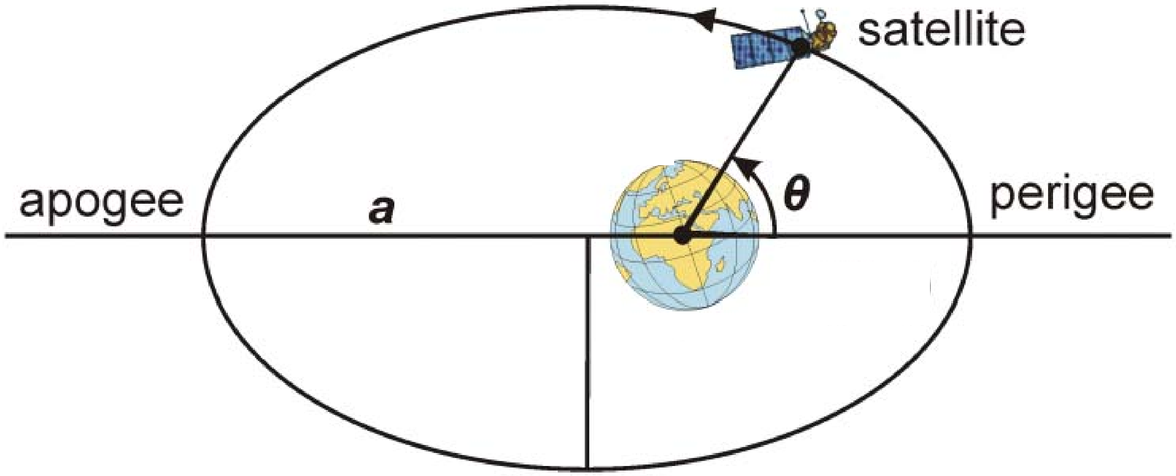
Mission Planning

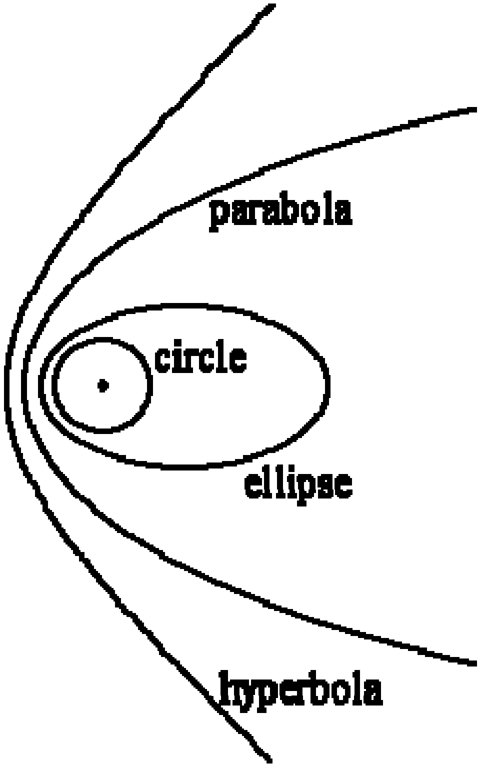
Technology Utilization

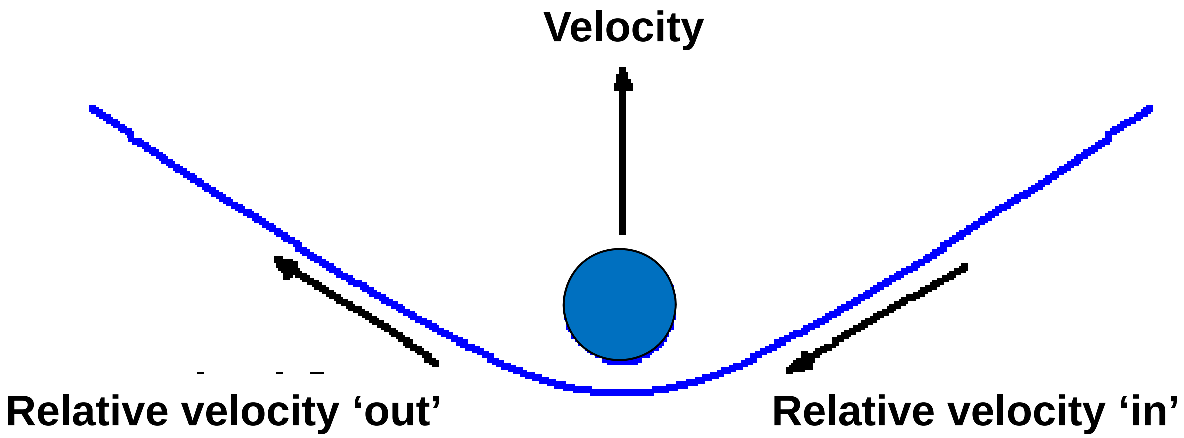
Cost/Performance Analysis

- Science Objectives
- Spacecraft Concept
- Orbit Design
- Tracking Facilities
- Launch Vehicle Performance
- Navigation Design
- Payload Concept
- Operations Concept

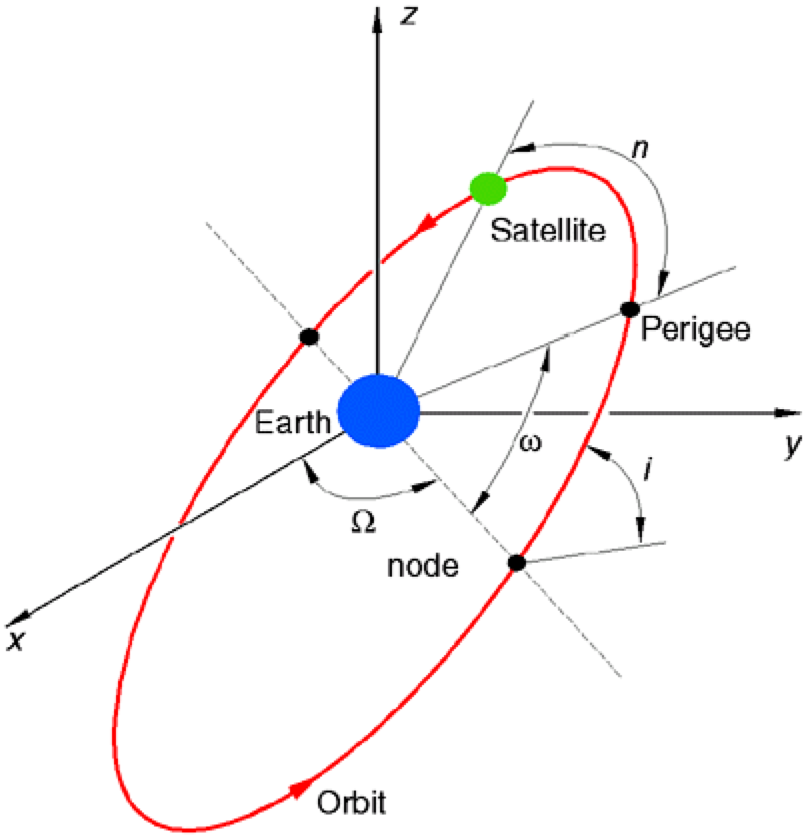
Conics from Kepler and Newton

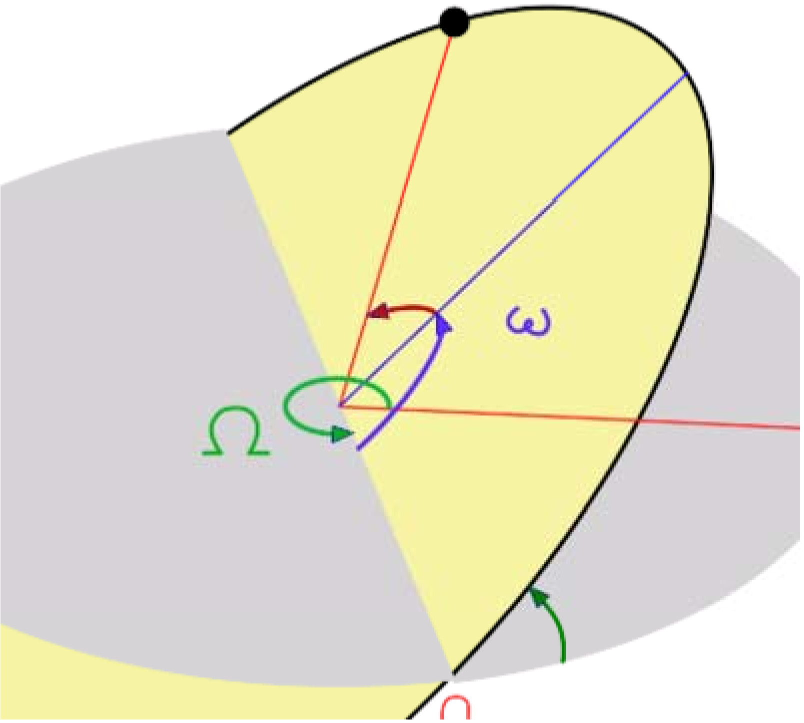




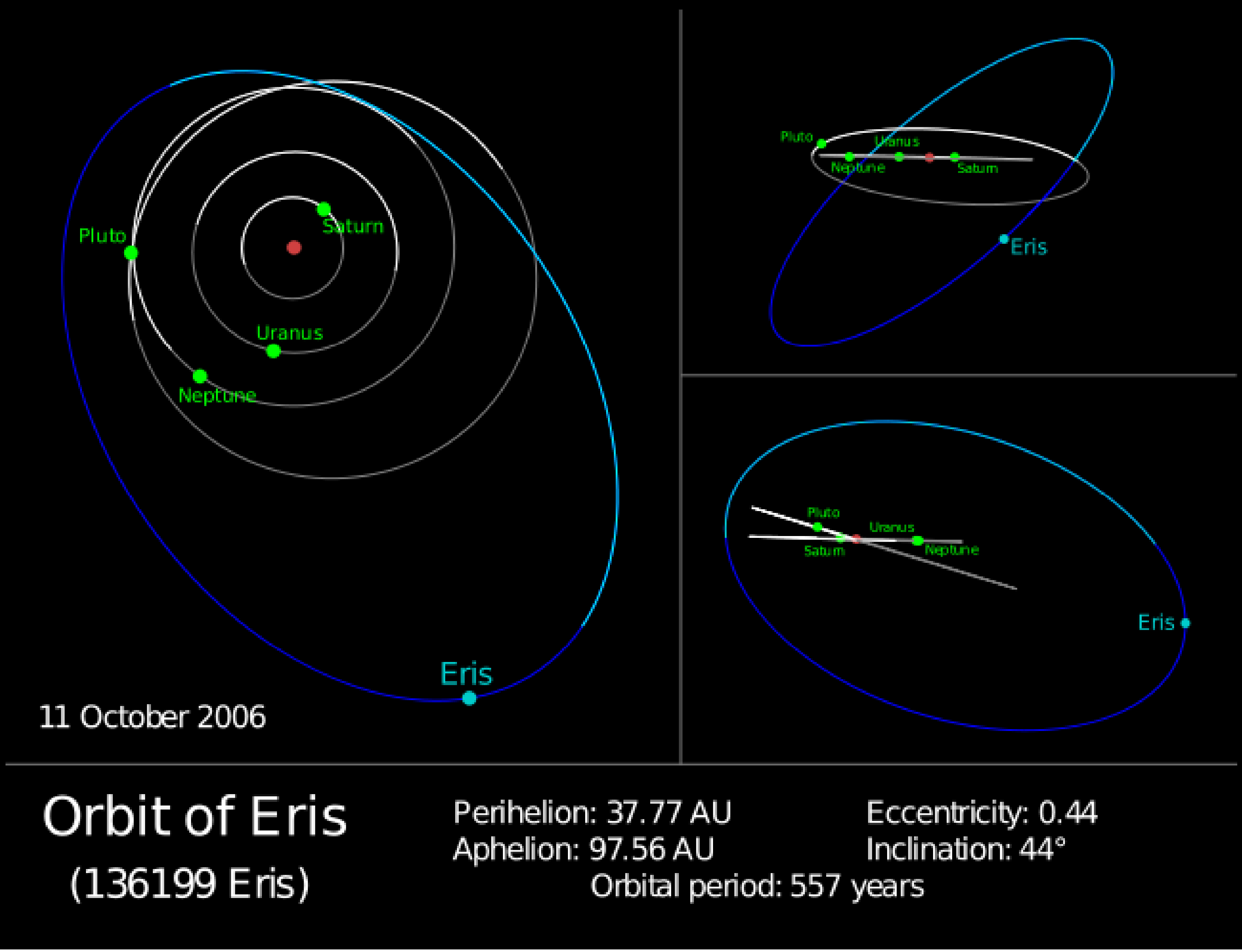


Conic Orbits: Three-dimensional Characteristics





Dwarf Planet Eris



Orbit of Eris
(136199 Eris)

Perihelion: 37.77 AU
Aphelion: 97.56 AU
Eccentricity: 0.44
Inclination: 44°
Orbital period: 557 years

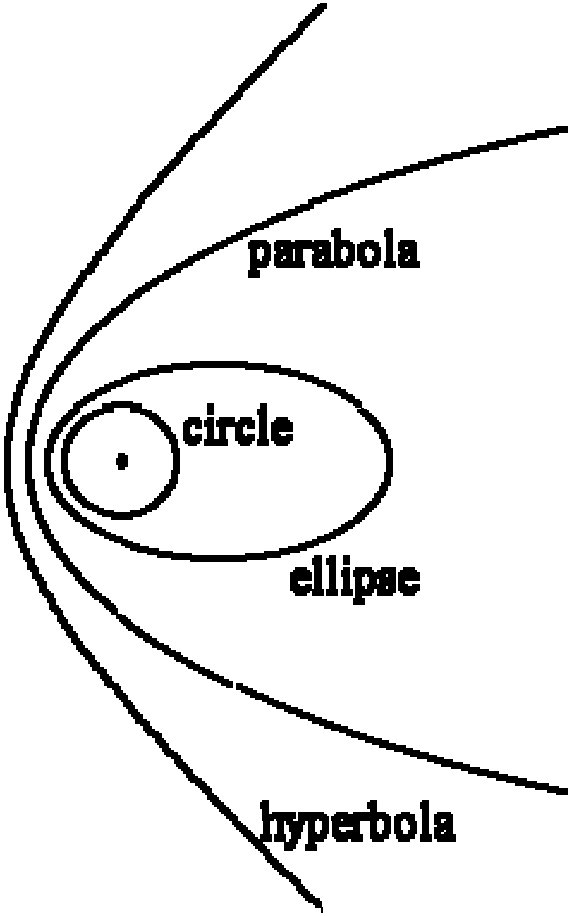
Problem:

Design spacecraft trajectory ⇒ <u>specific</u> requirements

Approach:

Traditional Two-Body

- Analytical Solns { ellipses, parabolas, hyperbolas
- Identify various trajectory arcs; patch together
- Transition to full model
- Optimize in full model

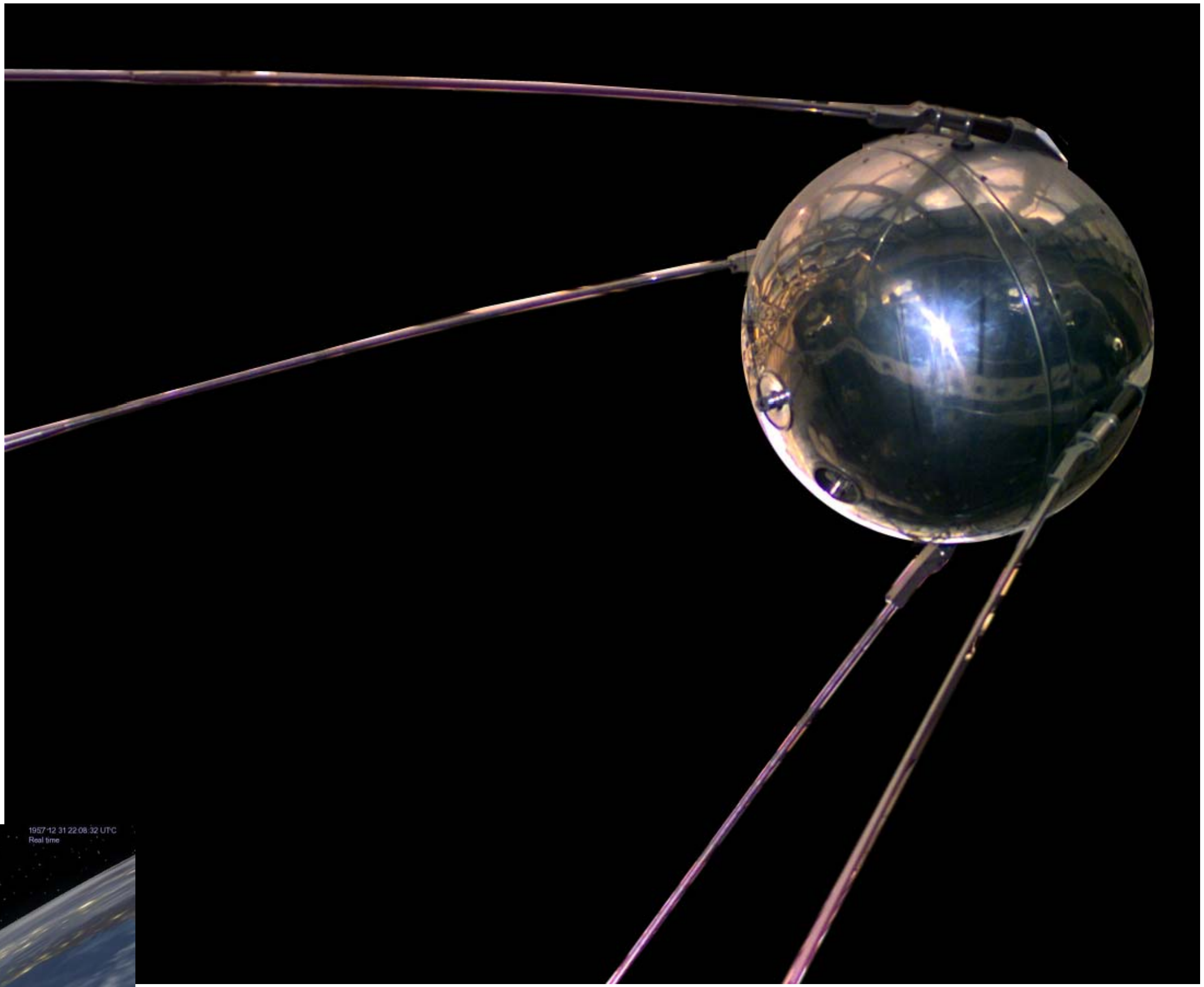


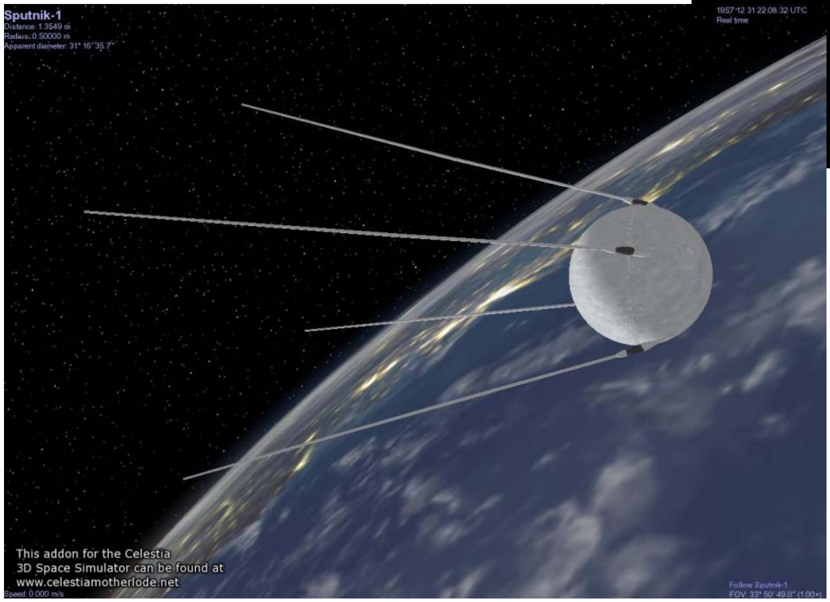
Sputnik

Launch: October 4, 1957
1st in Sputnik Program

Technology First !!

Orbit: 7310 x 6586 km
96.2 minutes/rev



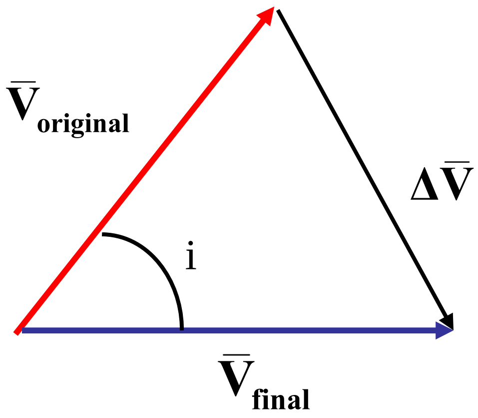


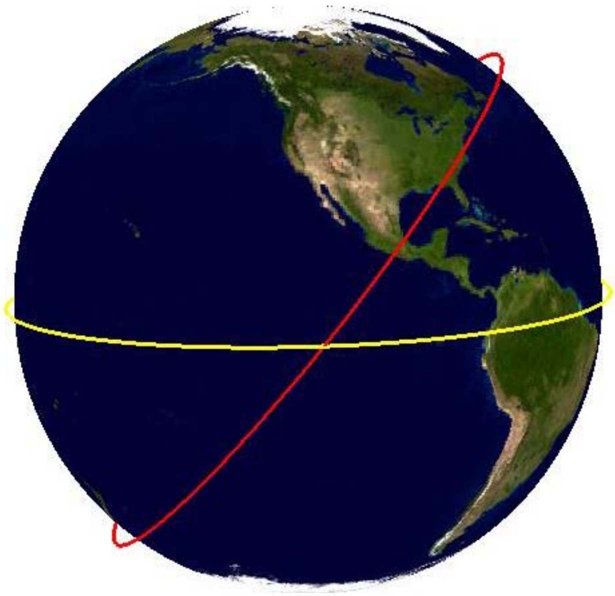
This addon for the Celestia
3D Space Simulator can be found at
www.celestiamotherlode.net

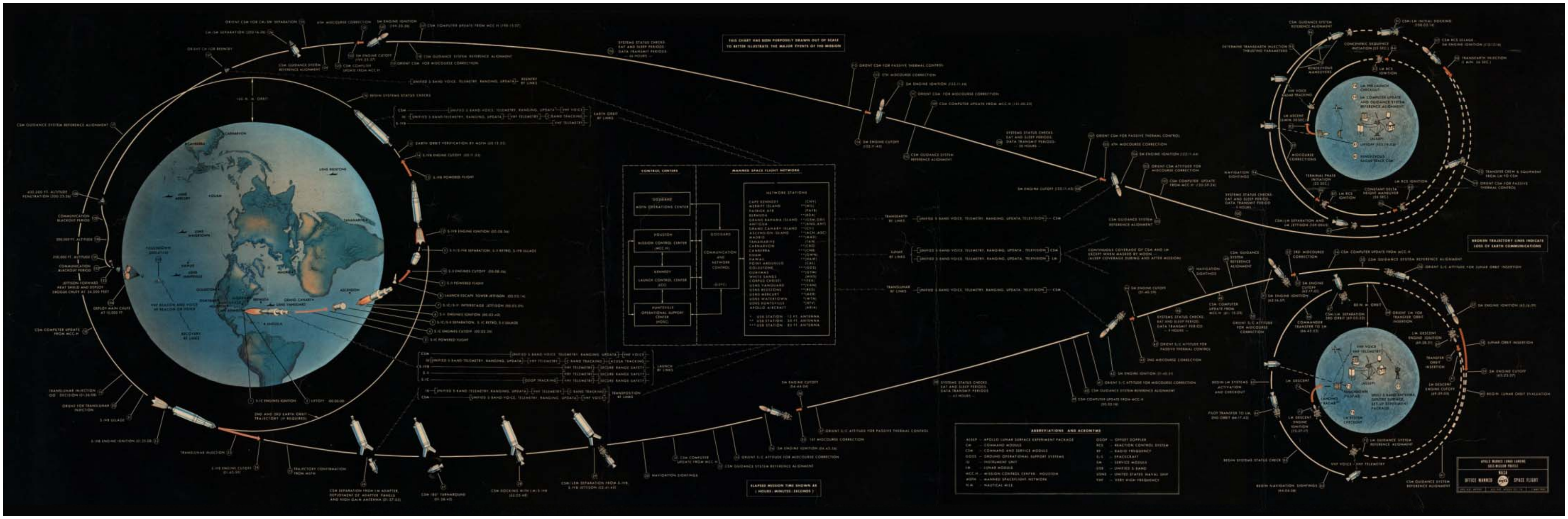
Science measurements:
- **Density of upper layer of atmosphere**
  - **→ changes in orbit**
- **Radio signal distribution data in ionosphere**
- **Meteoroid detection**

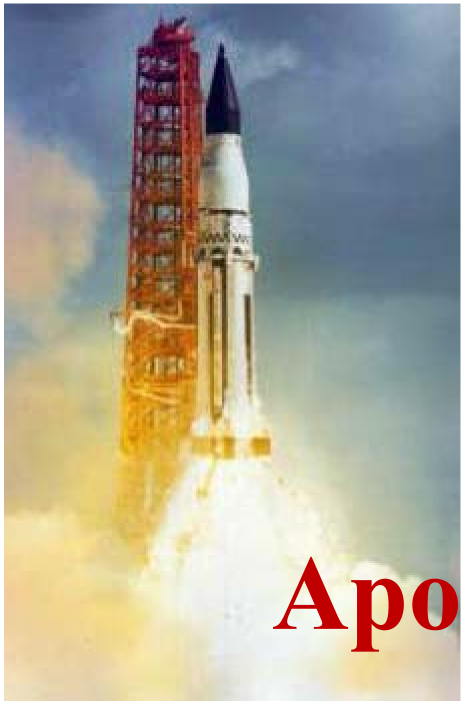
Play #1

ISS Trajectory

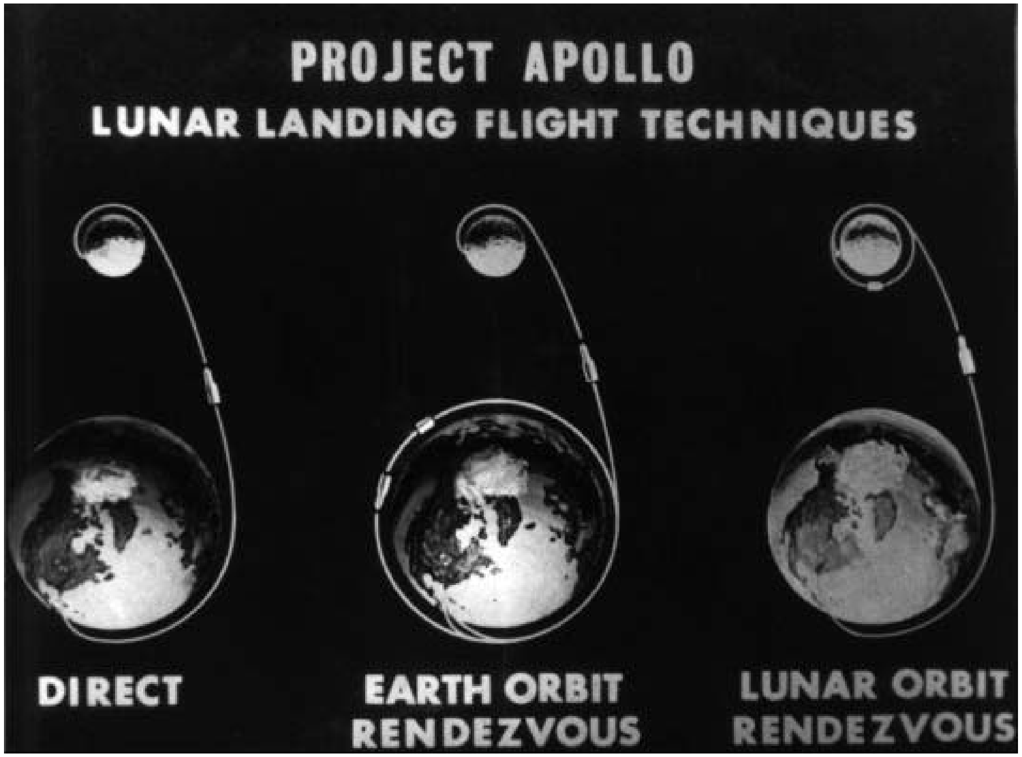




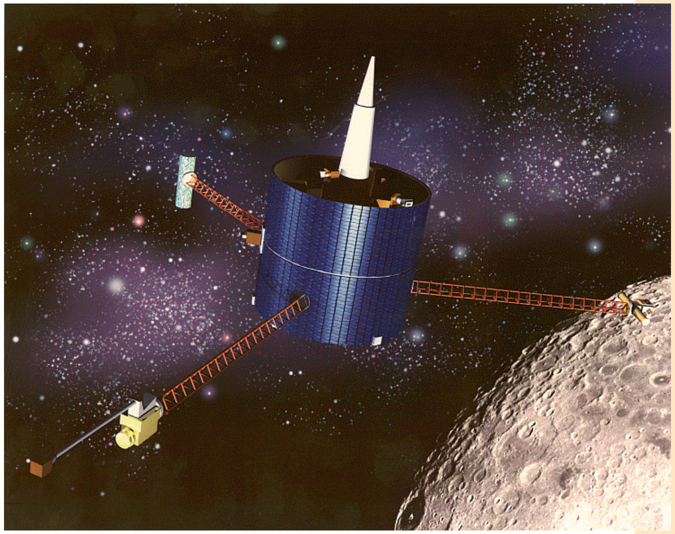


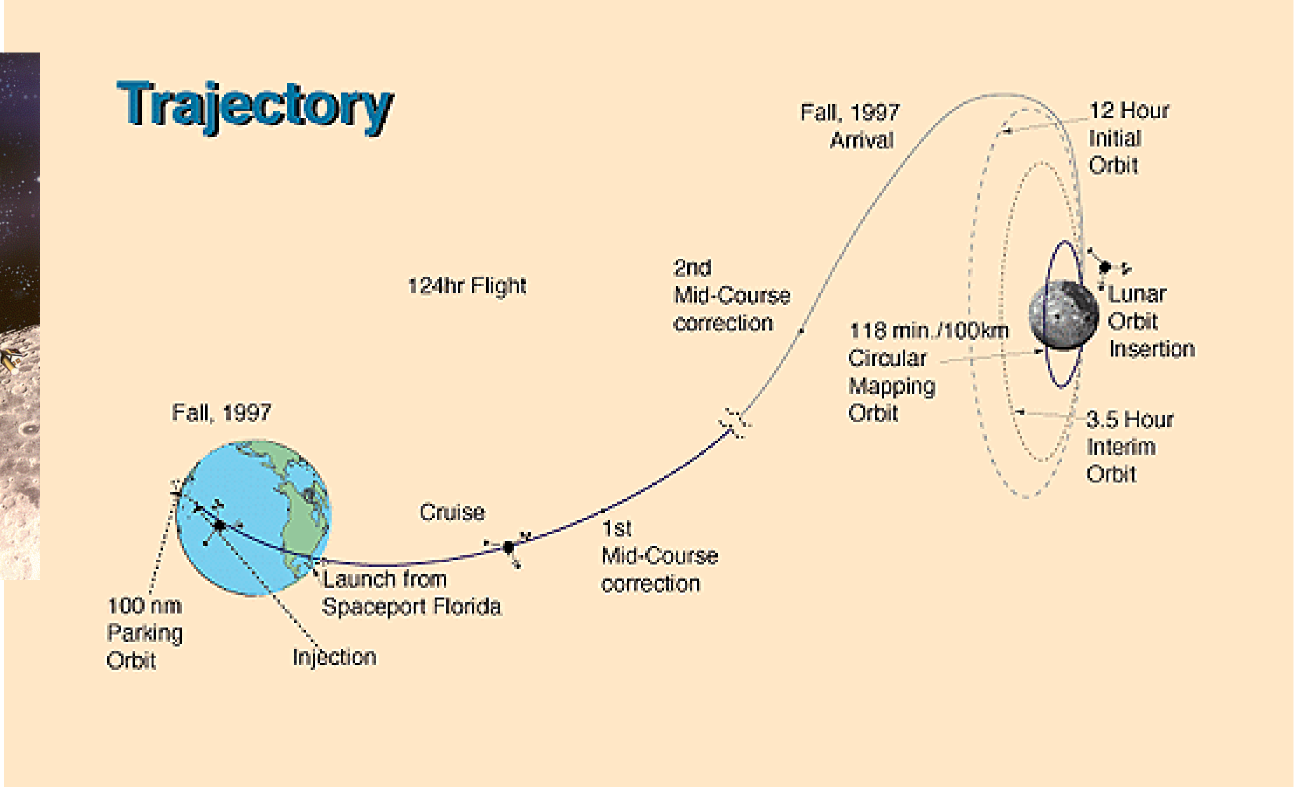


Apollo 11


PROJECT APOLLO
LUNAR LANDING FLIGHT TECHNIQUES
DIRECT
EARTH ORBIT RENDEZVOUS
LUNAR ORBIT RENDEZVOUS

Lunar Prospector





Type: Orbiter

Central Body: Earth

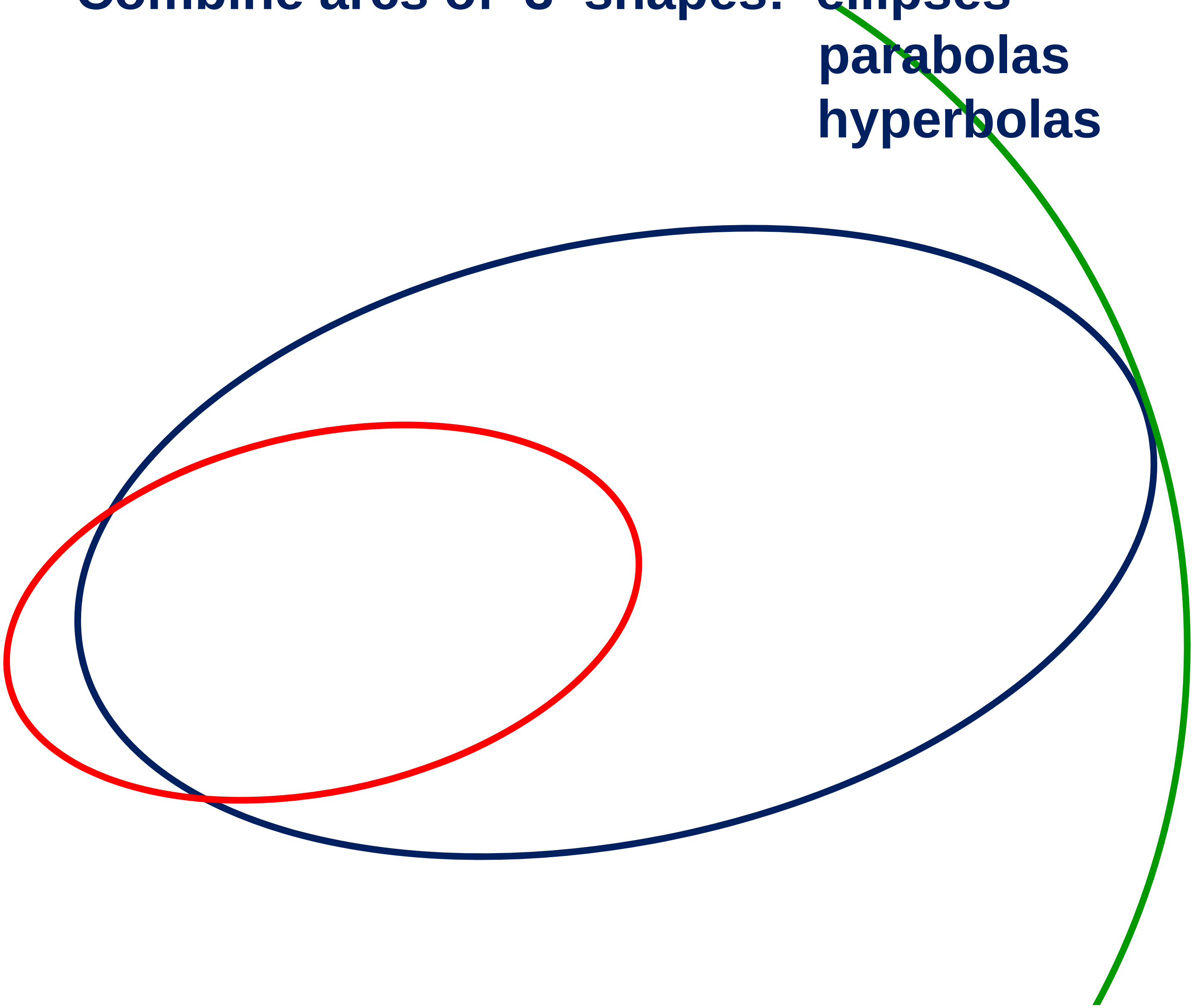
Epoch start: 1998-01-07 03:30:00 UTC

Orbital Parameters

Periapsis	Apoapsis	Period	Inclination	Eccentricity
1.0309300422668457 RE	56.290000915527344 RE	216.10000610351562 hours	29.200000762939453°	0.9640300273895264

Trajectory Design

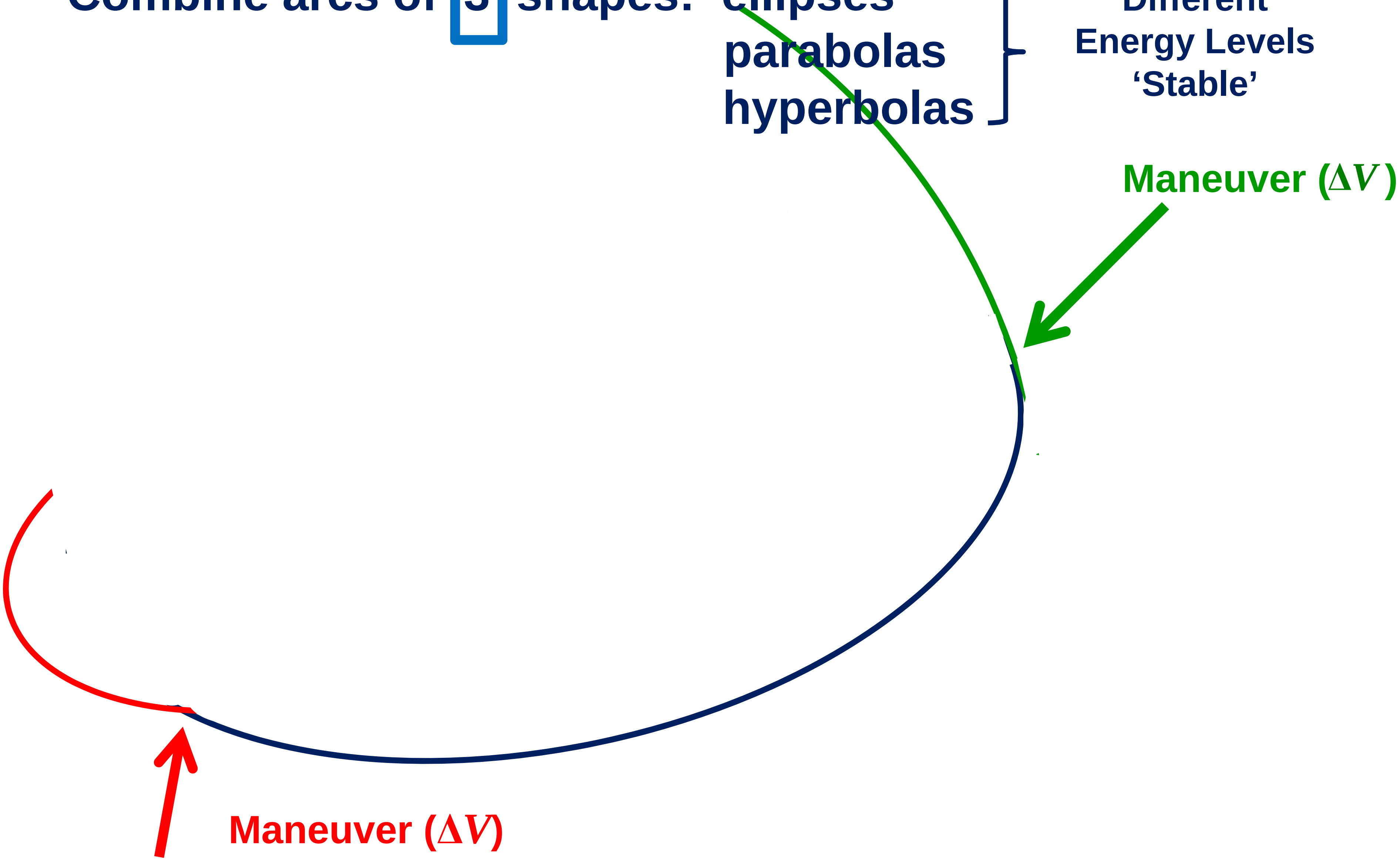
Combine arcs of 3 shapes: ellipses
parabolas
hyperbolas



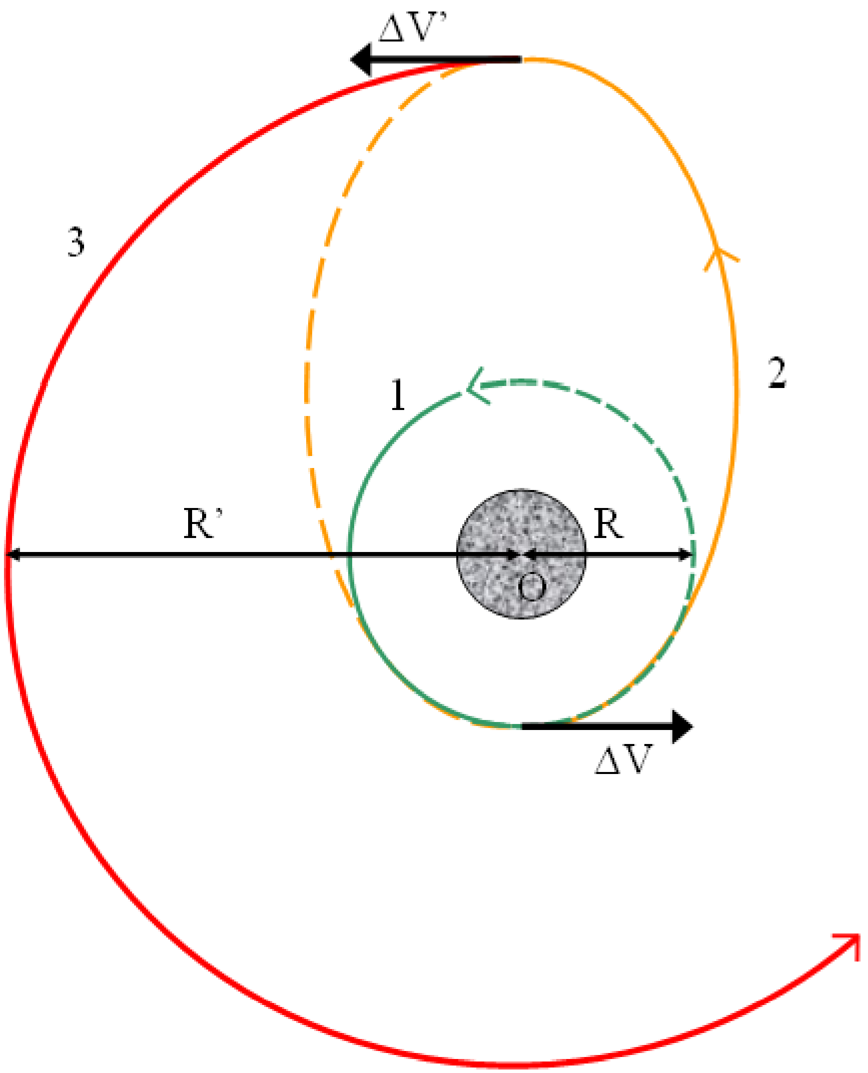
Trajectory Design

Combine arcs of 3 shapes: ellipses
parabolas
hyperbolas

Different
Energy Levels
'Stable'

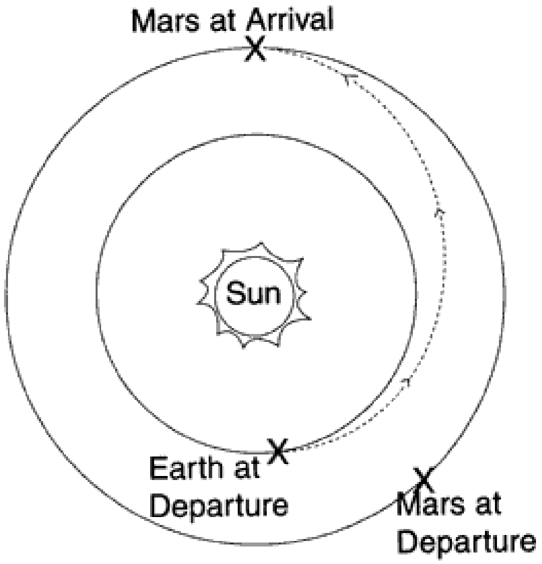


Hohmann Transfer



Construction:

1. Circular #1
2. Maneuver to Ellipse #2
3. Remain in Ellipse #2; return
4. Maneuver to Ellipse #3



Hohmann Transfer to Uranus

TOF = 16 years

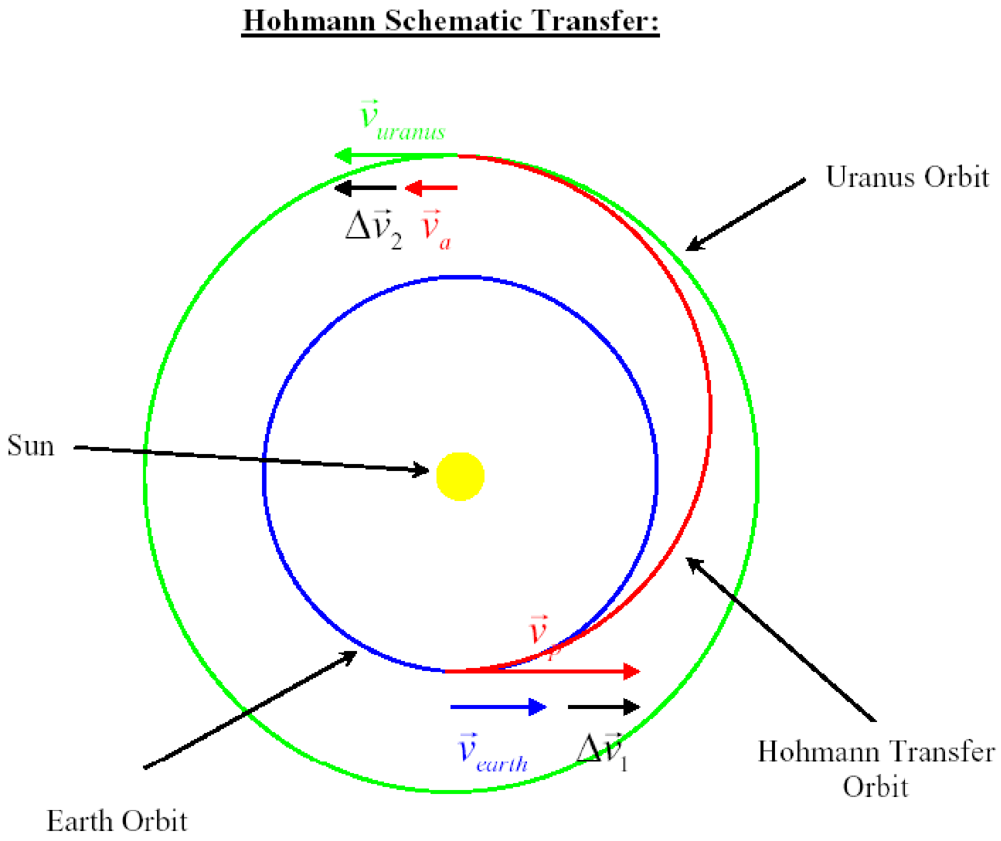
ΔV = 16 km/s

Hohmann

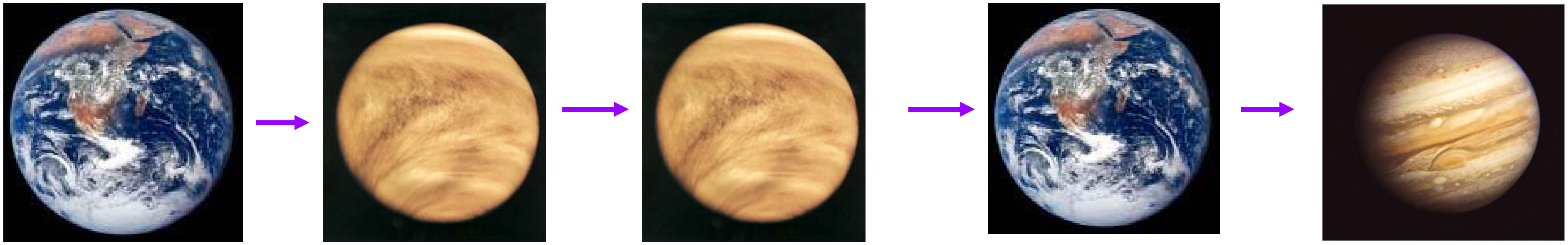
→ not the way to get to Uranus!!!

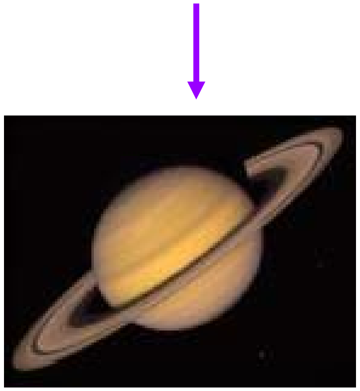
Both Voyager launches on Titan III-Centaurs; only enough energy to reach Jupiter

Both used gravity assists to reach final destinations and even out of the solar system!



Cassini to Saturn





Transfer Trajectory:

Depart Earth 10/97

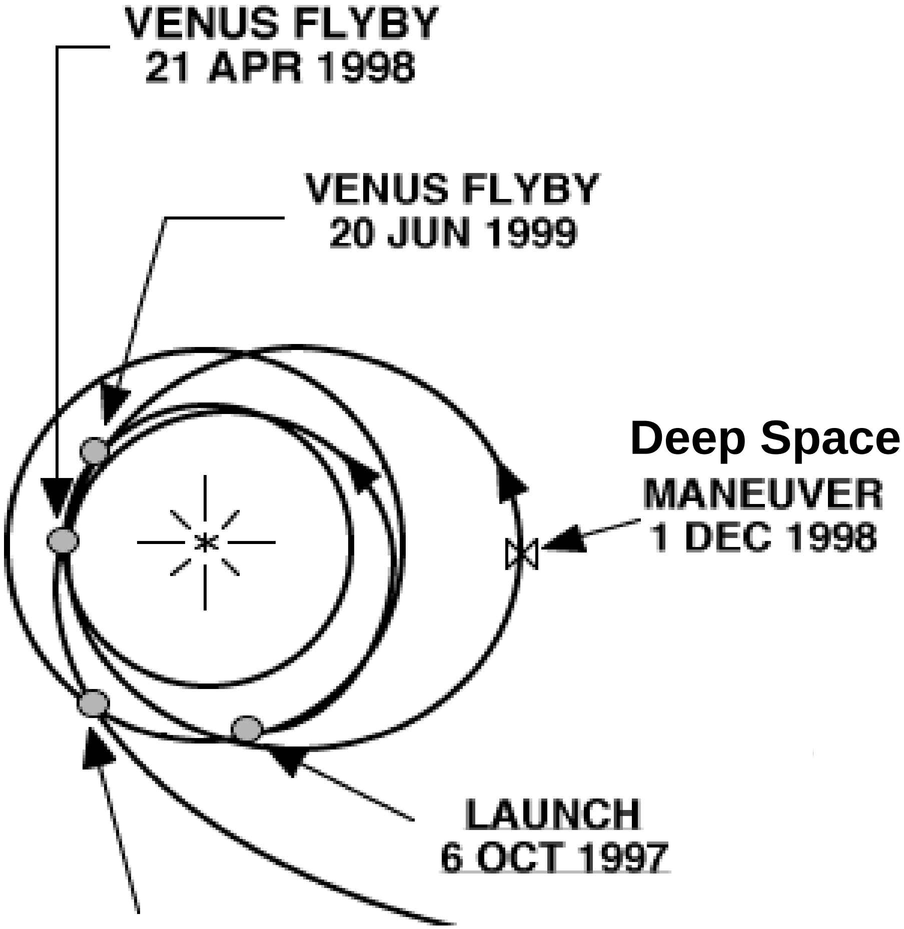
Pass Venus 4/98

Pass Venus 6/99

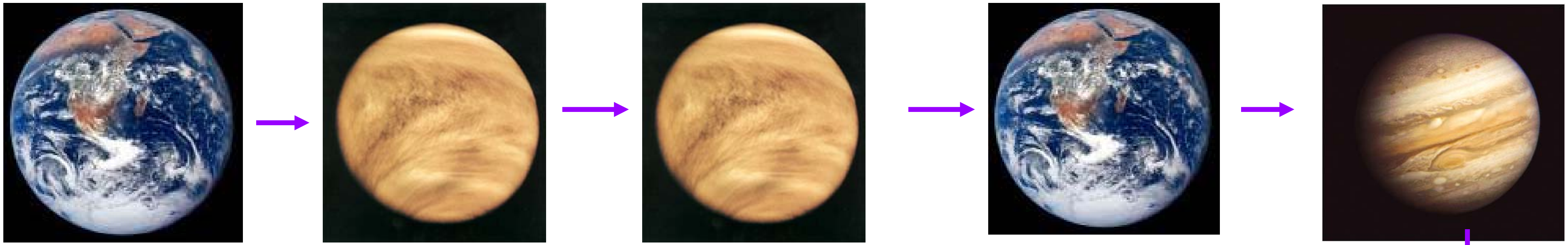
Pass Earth 8/99

Pass Jupiter 12/00

Arrive Saturn 7/04



Cassini to Saturn



Transfer Trajectory:

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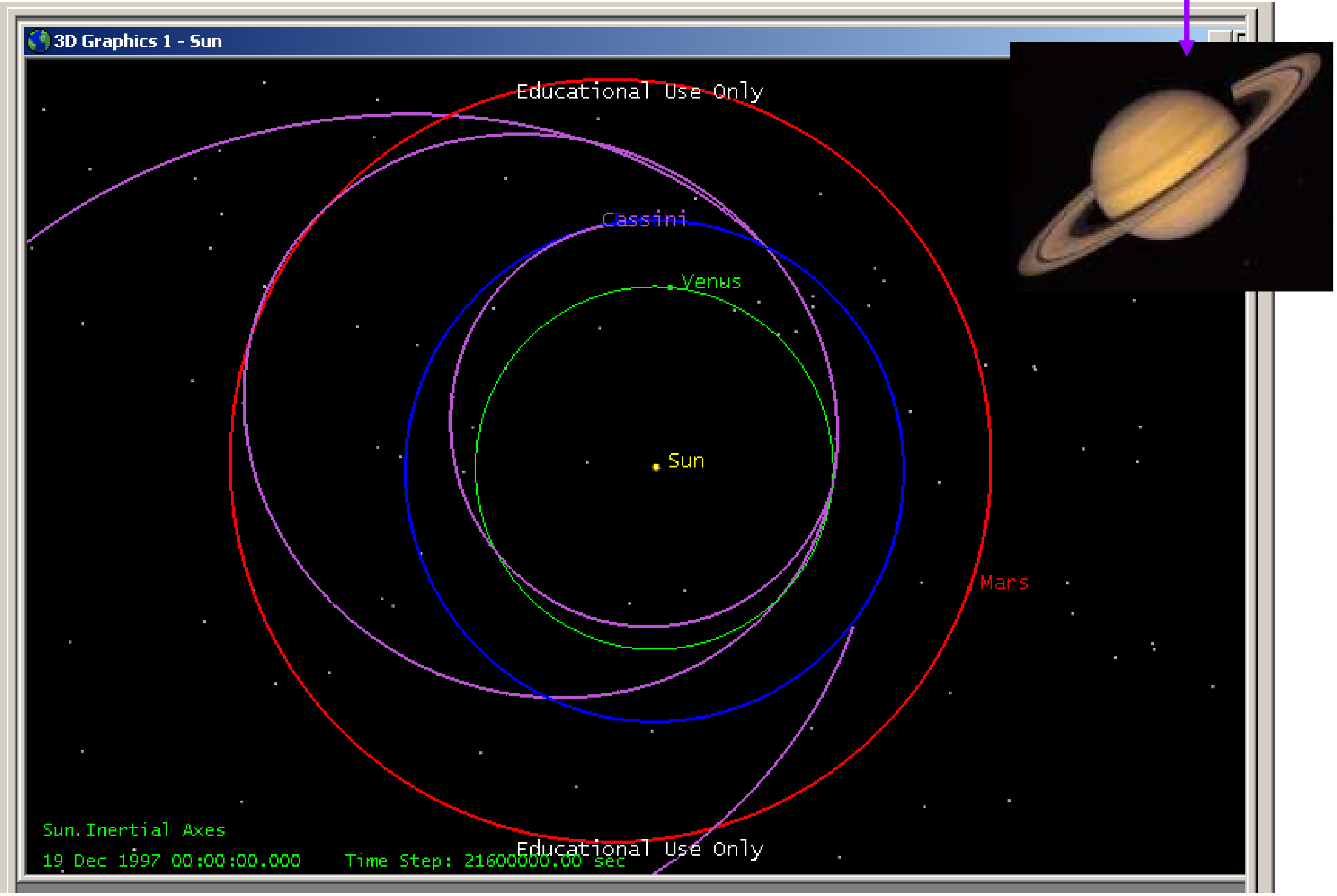
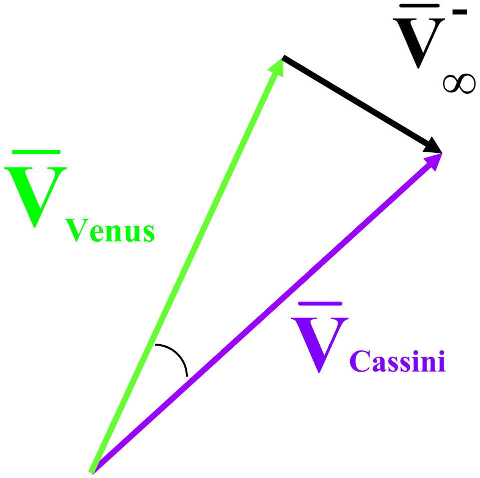
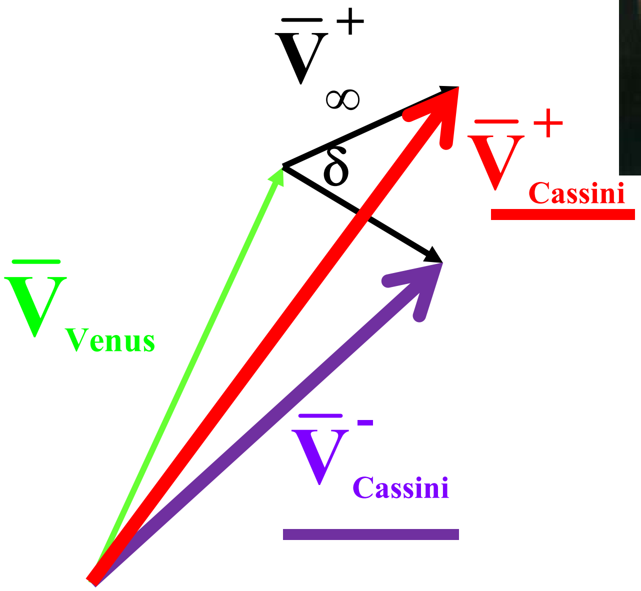


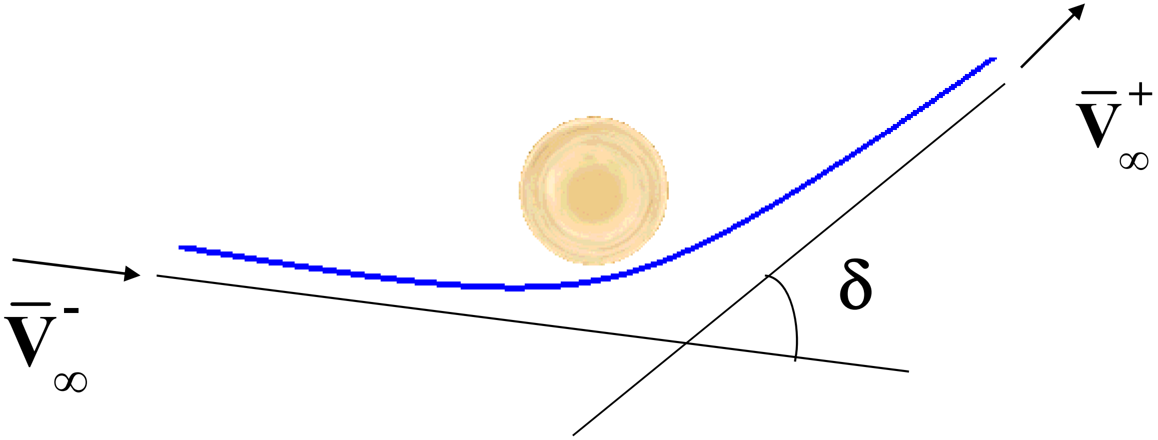
Sun.Inertial Axes

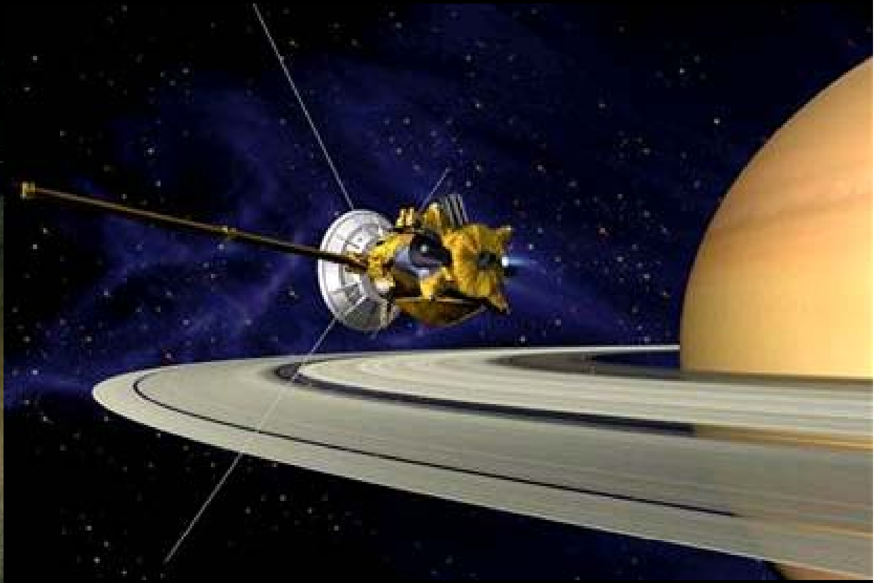
19 Dec 1997 00:00:00.000 Time Step: 21600000.00 sec

Venus Flyby


$\bar{V}_\infty^-$
$\bar{V}_{Venus}$
$\bar{V}_{Cassini}$

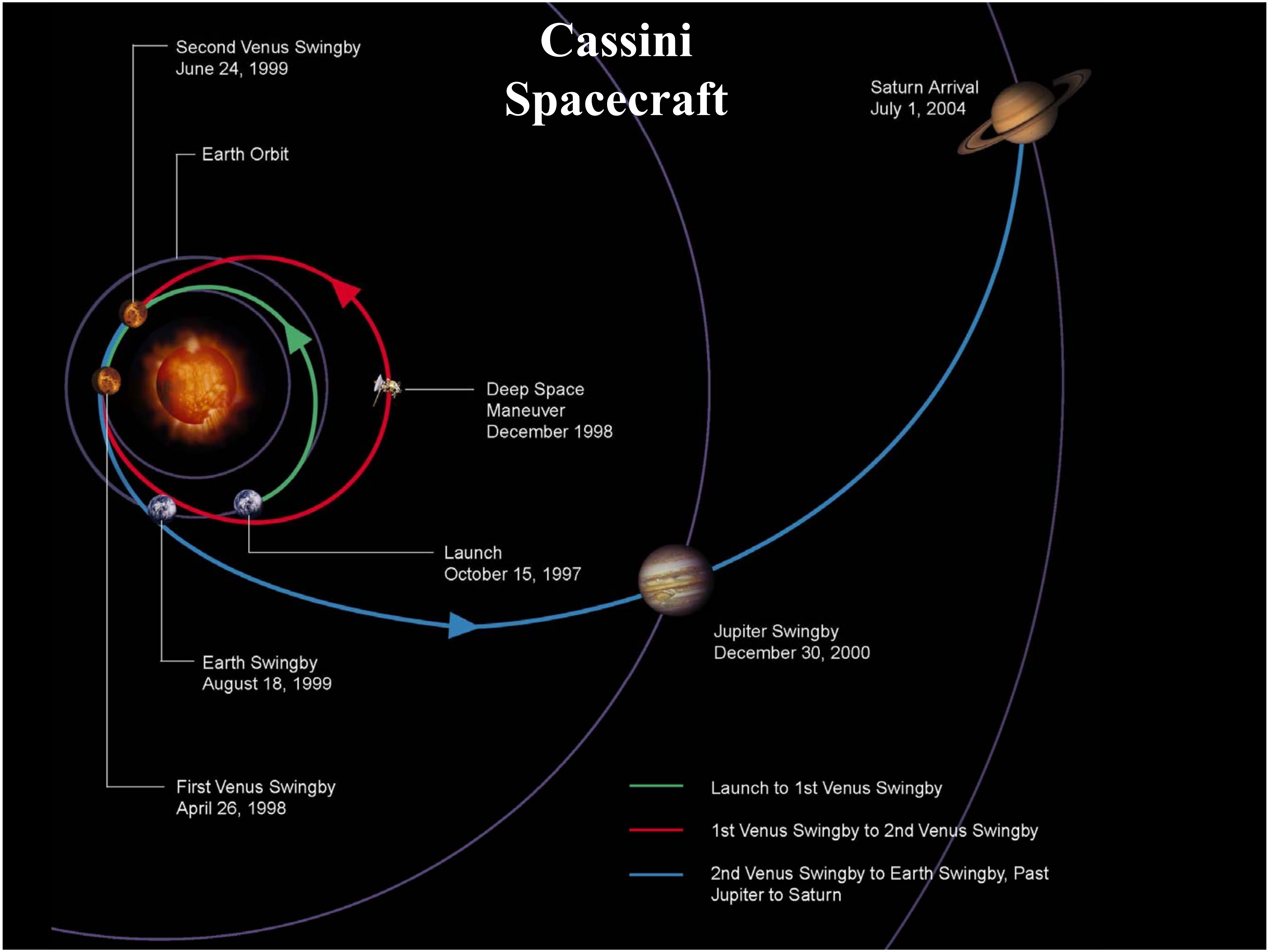

$\bar{V}_\infty^+$
δ
$\bar{V}_{Cassini}^+$
$\bar{V}_{Venus}$
$\bar{V}_{Cassini}^-$


$\bar{V}_\infty^+$
δ
$\bar{V}_\infty^-$



Cassini Launch
October 1997

Cassini Spacecraft



Second Venus Swingby
June 24, 1999

Earth Orbit

Saturn Arrival
July 1, 2004

Deep Space
Maneuver
December 1998

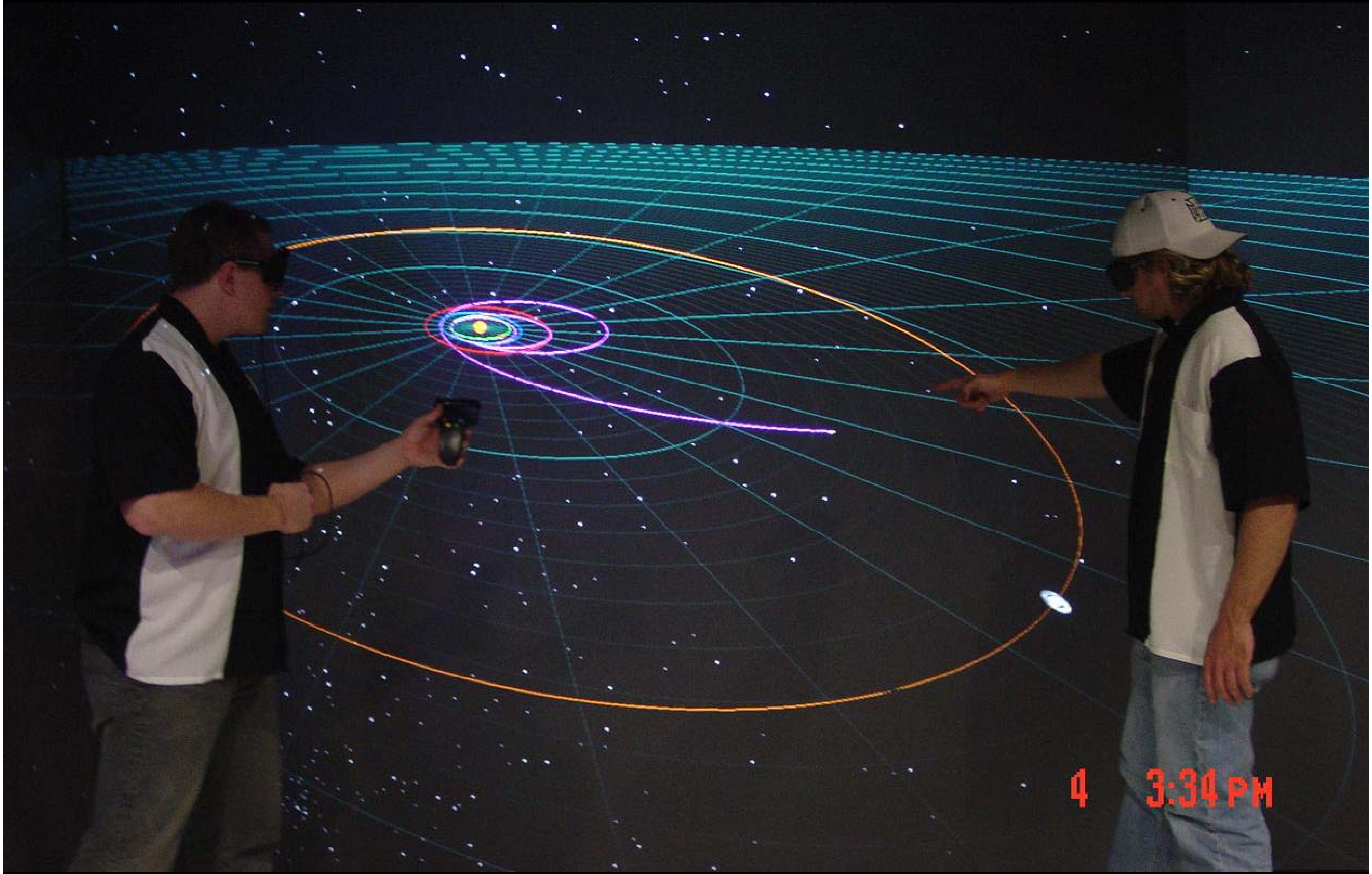
Launch
October 15, 1997

Jupiter Swingby
December 30, 2000

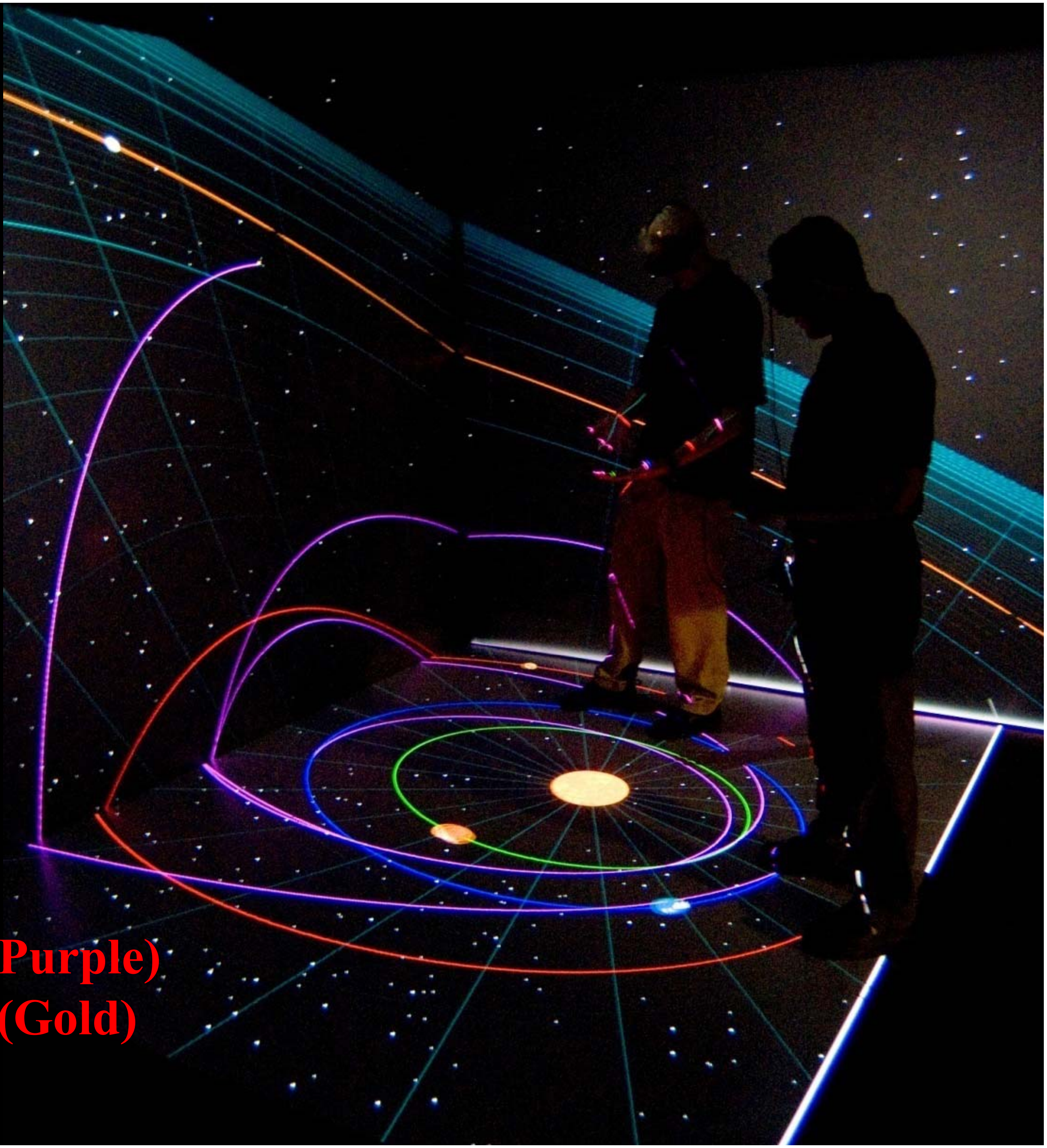
Earth Swingby
August 18, 1999

First Venus Swingby
April 26, 1998

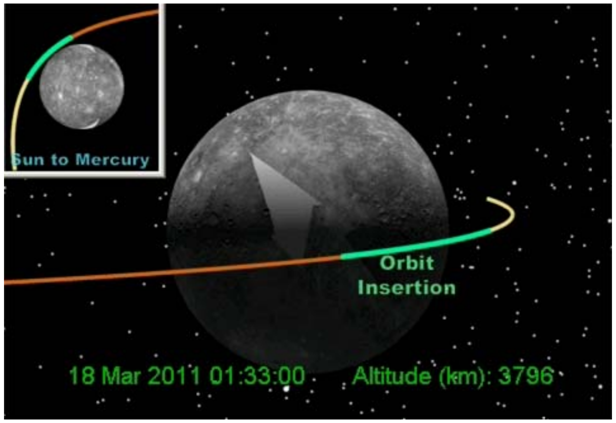
- 🟩 Launch to 1st Venus Swingby
- 🟥 1st Venus Swingby to 2nd Venus Swingby
- 🟦 2nd Venus Swingby to Earth Swingby, Past Jupiter to Saturn



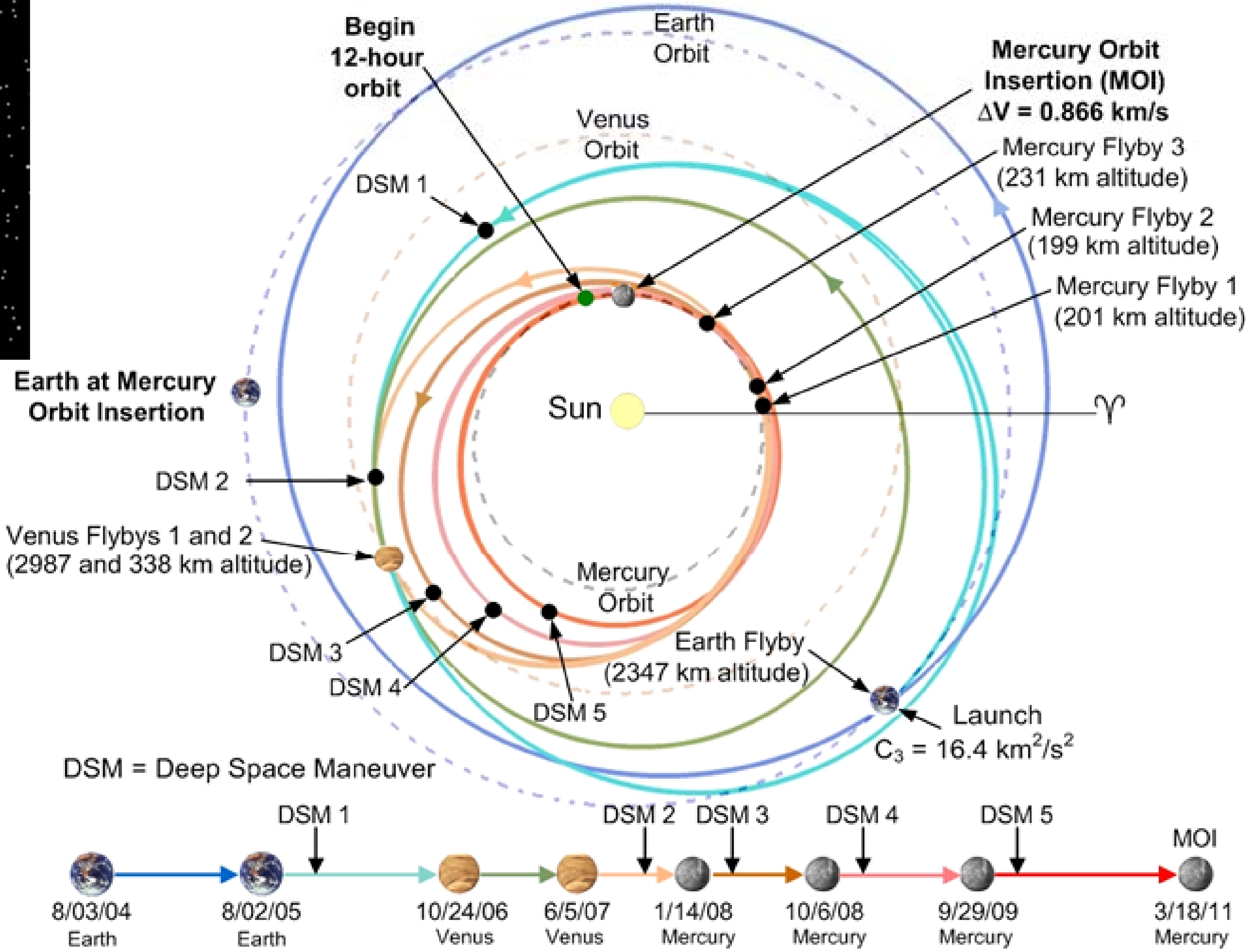
Cassini Spacecraft (Purple) Enroute to Saturn (Gold Orbit)

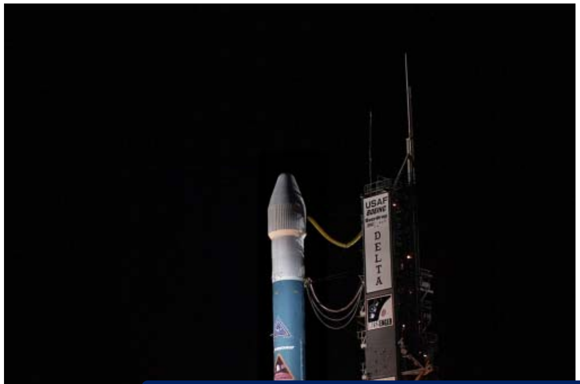


Cassini Spacecraft (Purple)
Enroute to Saturn (Gold)



Mercury Messenger



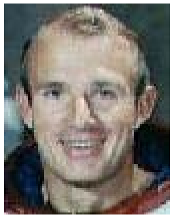


Science and exploration goals cannot always be met using conics, even with gravity assists!!

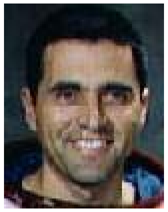
Innovation in Trajectory Design 1970's

Apollo 18

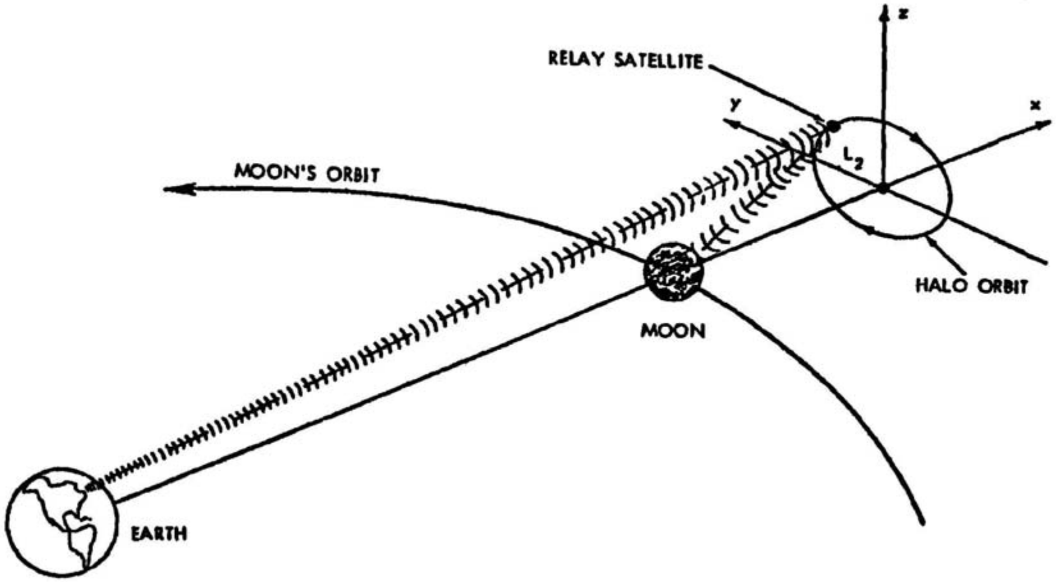
Gordon

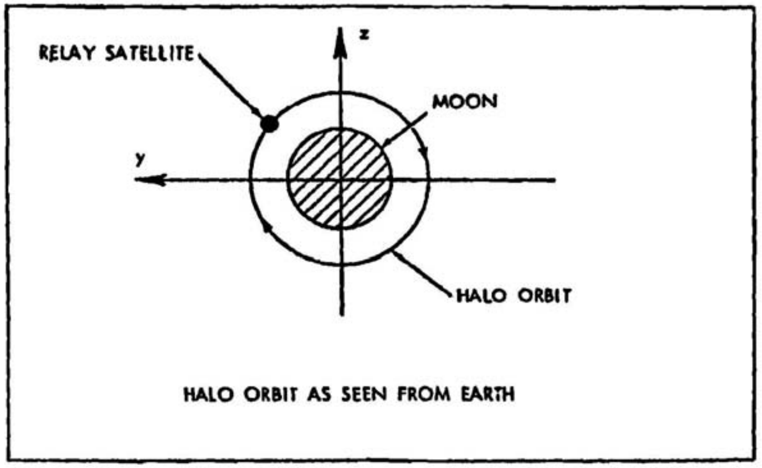


Brand



Schmitt

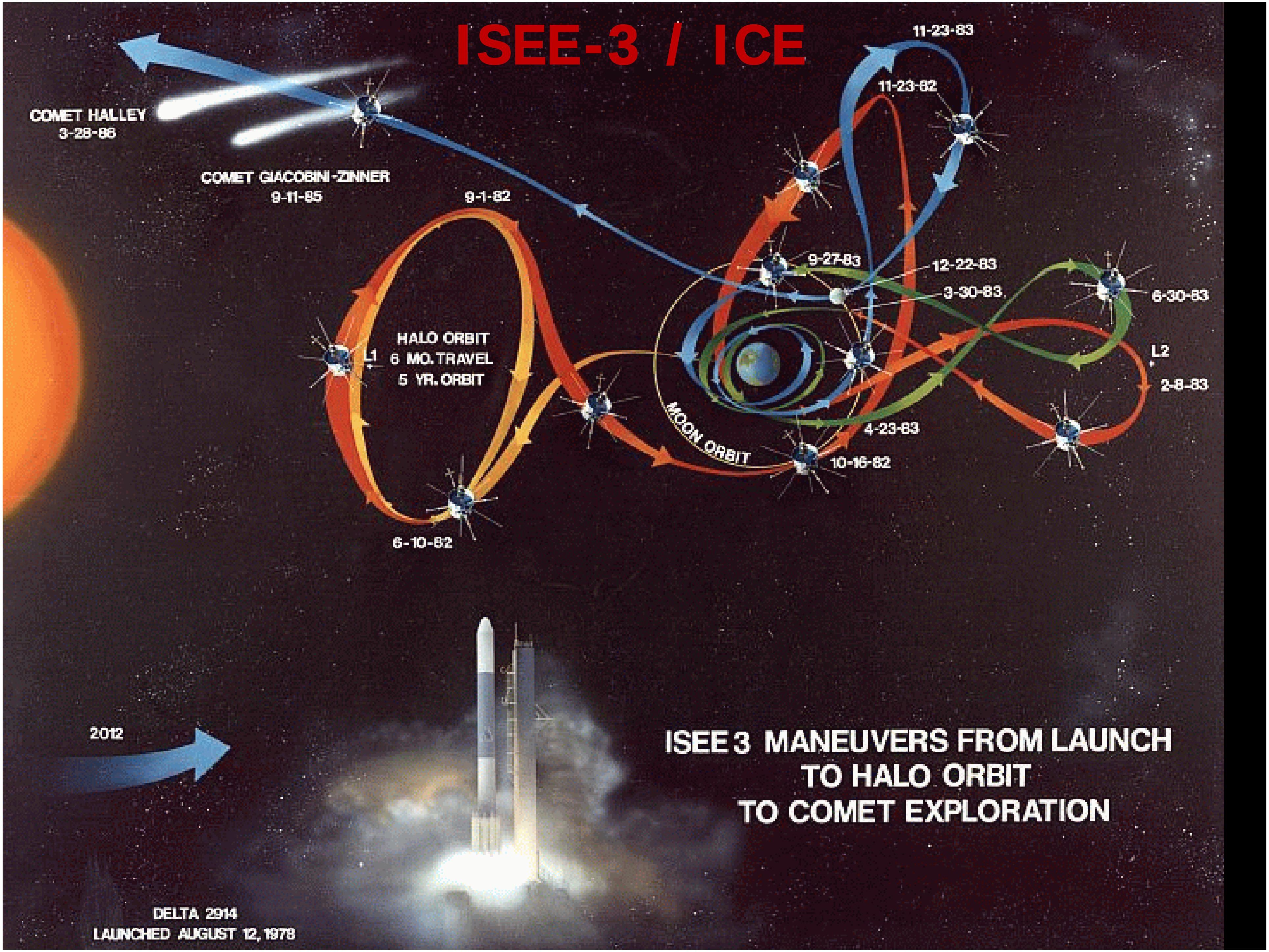




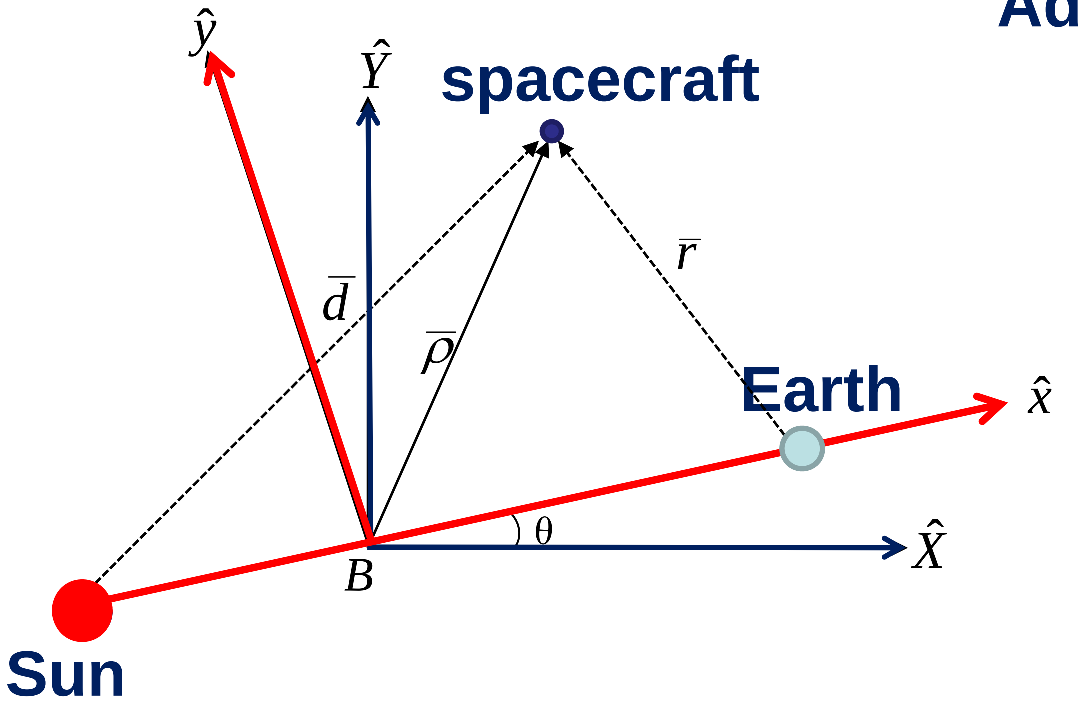
HALO ORBIT AS SEEN FROM EARTH

Courtesy: NASA

ISEE-3 / ICE


COMET HALLEY
3-28-86
COMET GIACOBINI-ZINNER
9-11-85
9-1-82
11-23-83
11-23-82
9-27-83
12-22-83
3-30-83
6-30-83
L2
2-8-83
4-23-83
10-16-82
MOON ORBIT
HALO ORBIT
6 MO. TRAVEL
5 YR. ORBIT
L1
6-10-82
2012
ISEE 3 MANEUVERS FROM LAUNCH
TO HALO ORBIT
TO COMET EXPLORATION
DELTA 2914
LAUNCHED AUGUST 12, 1978

Poincaré → Three-Body Problem



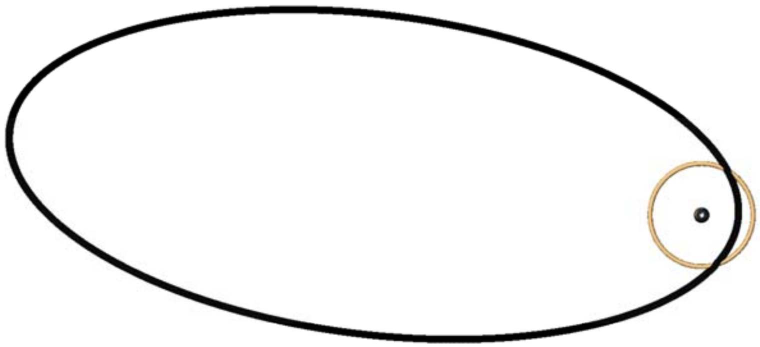
Modern Computers +
Advances in Mathematics

⇓

Two assumptions expand options:

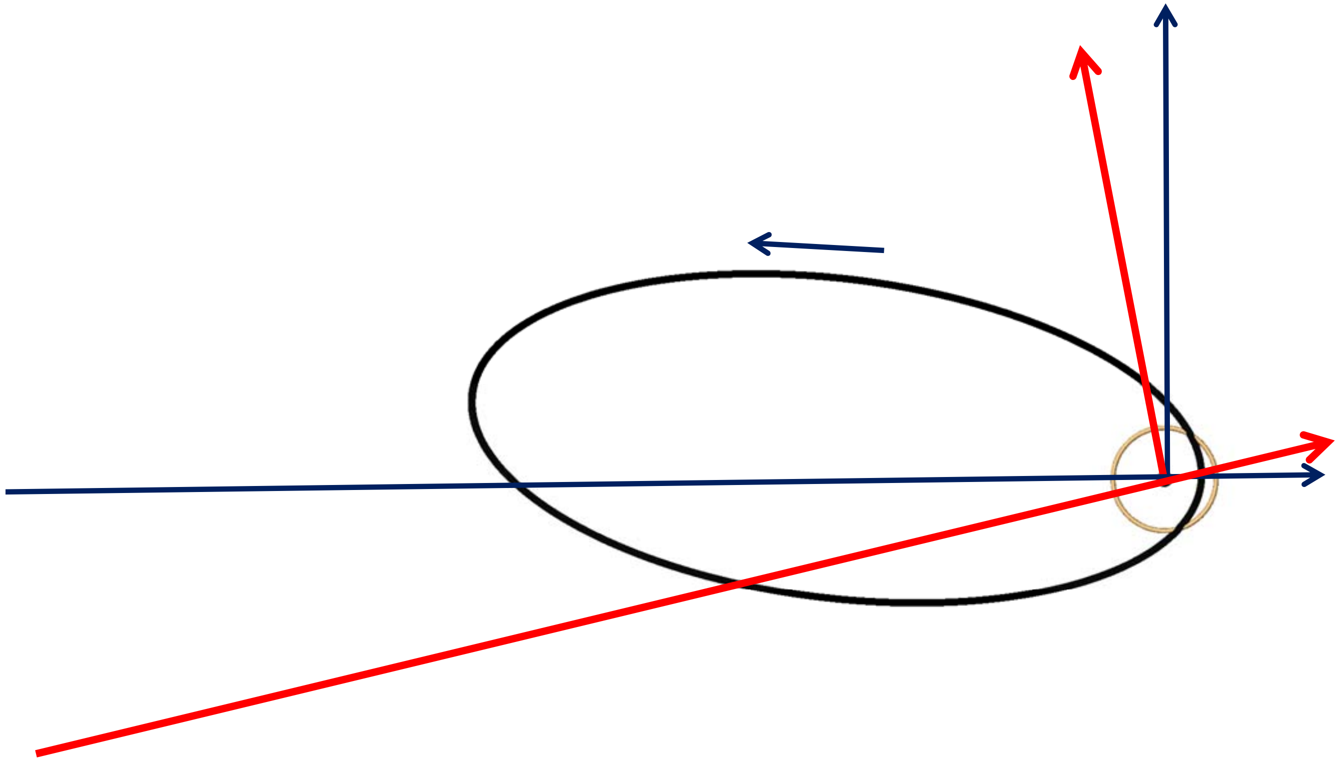
1. **New perspective: View from Earth?**
2. **Multiple Gravity Fields**

Orbit propagated for 4 conic periods:
4*19 days = 75.7 days



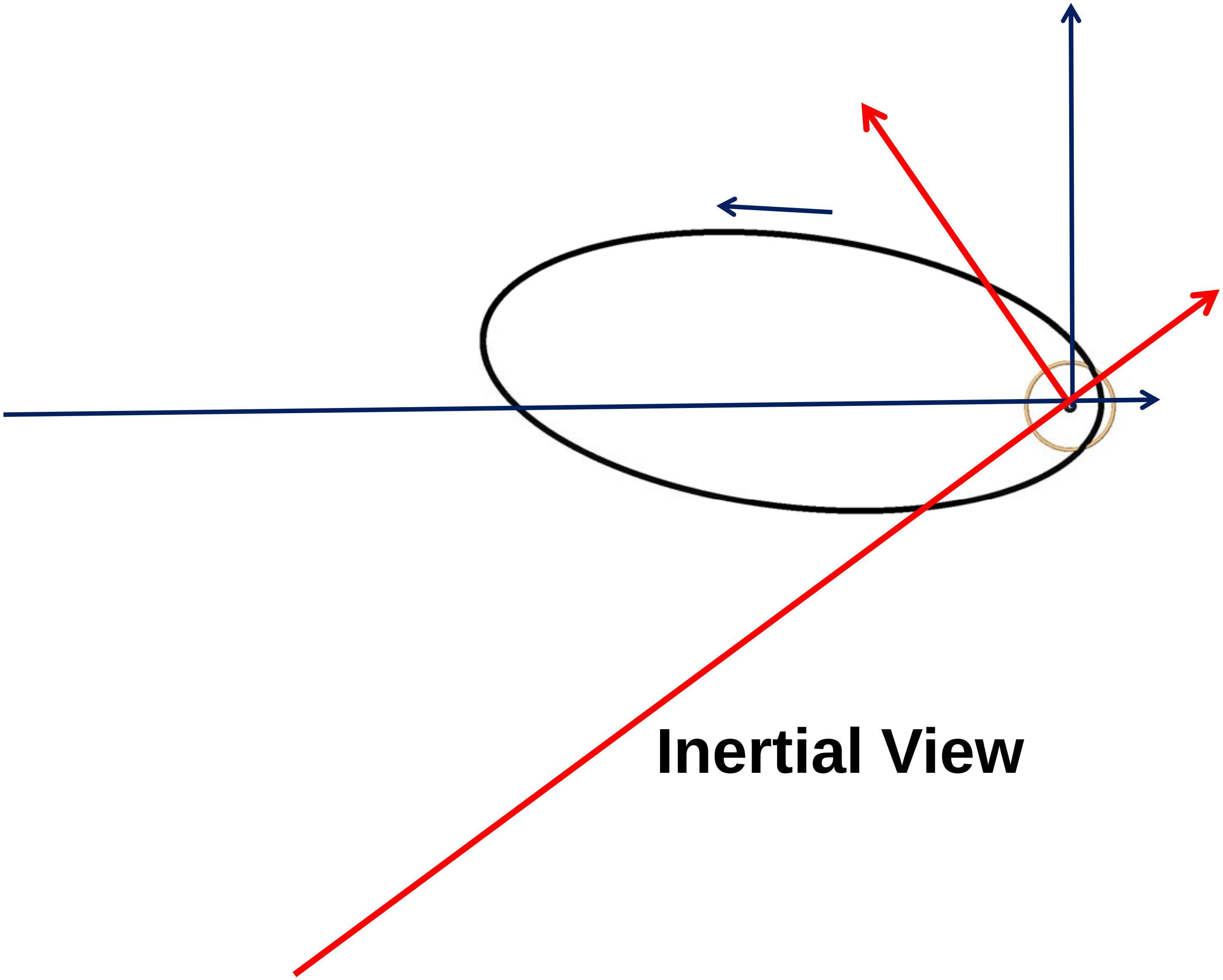
Inertial View

Orbits propagated for 4 conic periods:
4*19 days = 75.7 days

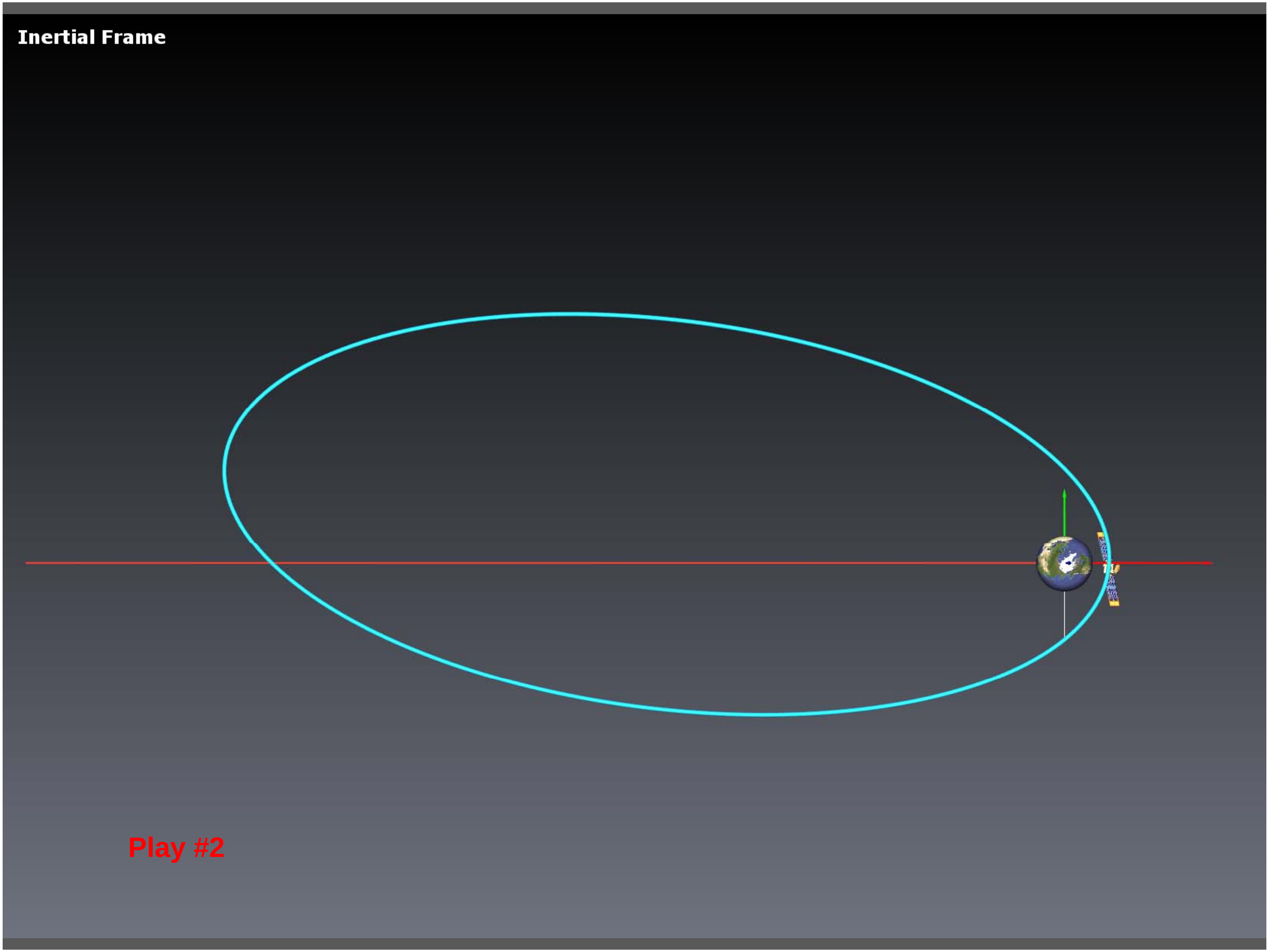


Inertial View

Orbit propagated for 4 conic periods:
4*19 days = 75.7 days

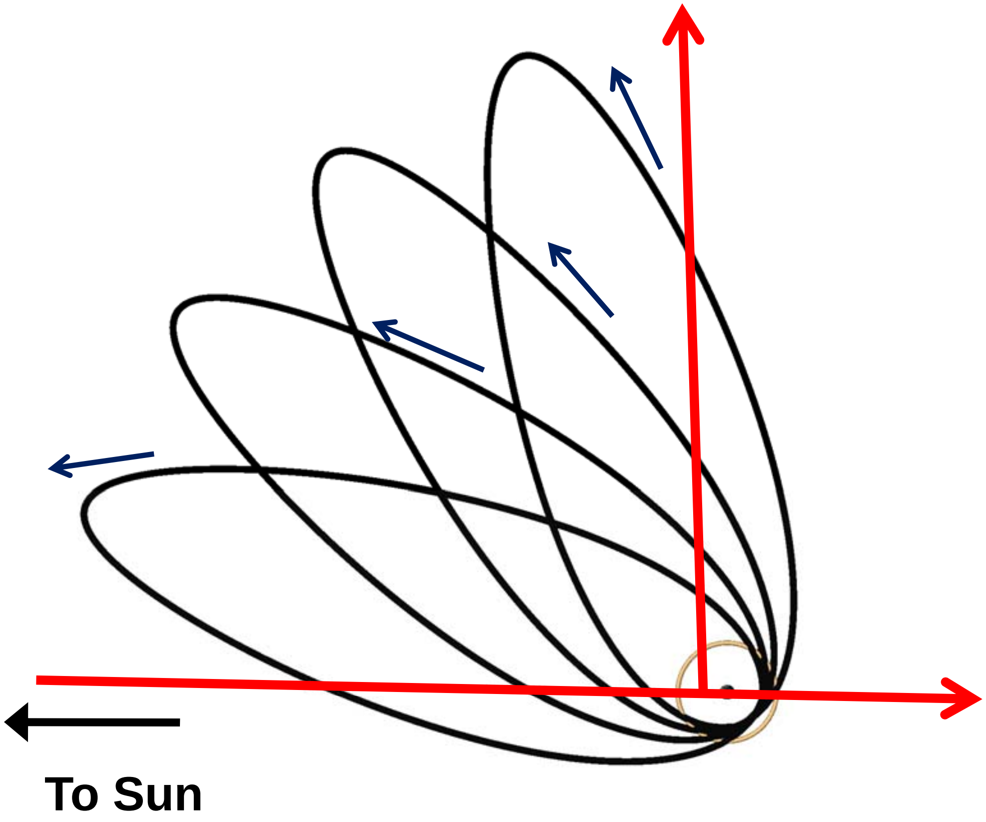


Inertial View



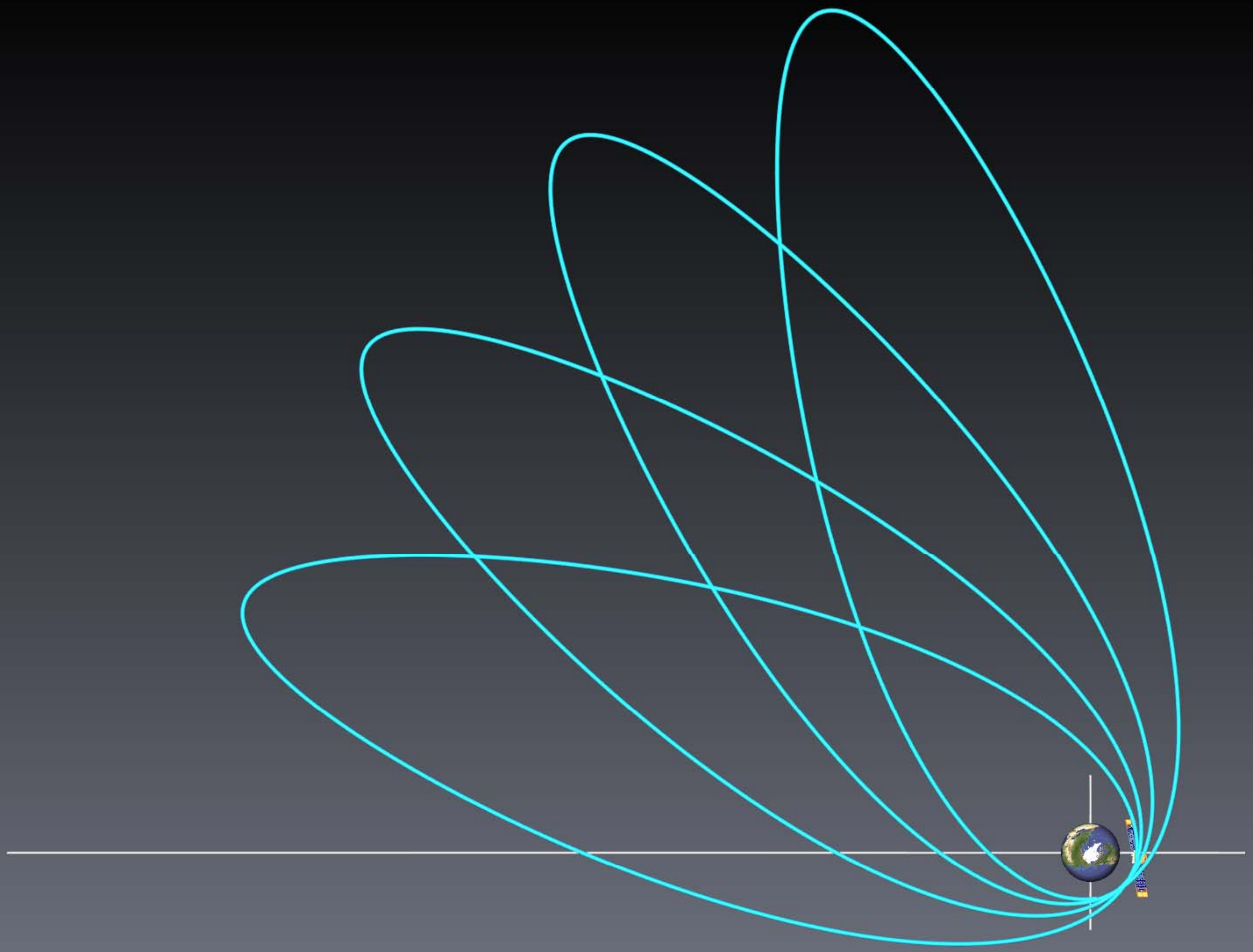
Play #2

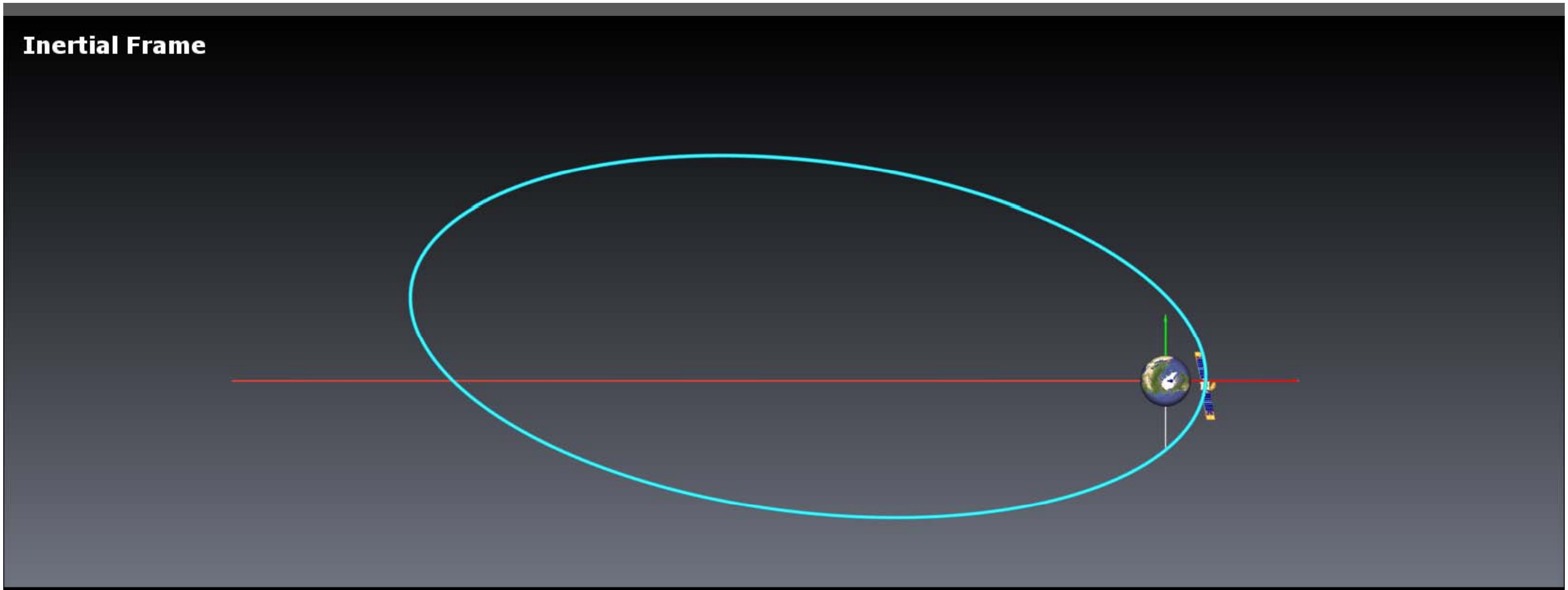
Orbit propagated for 4 conic periods:
4*19 days = 75.7 days

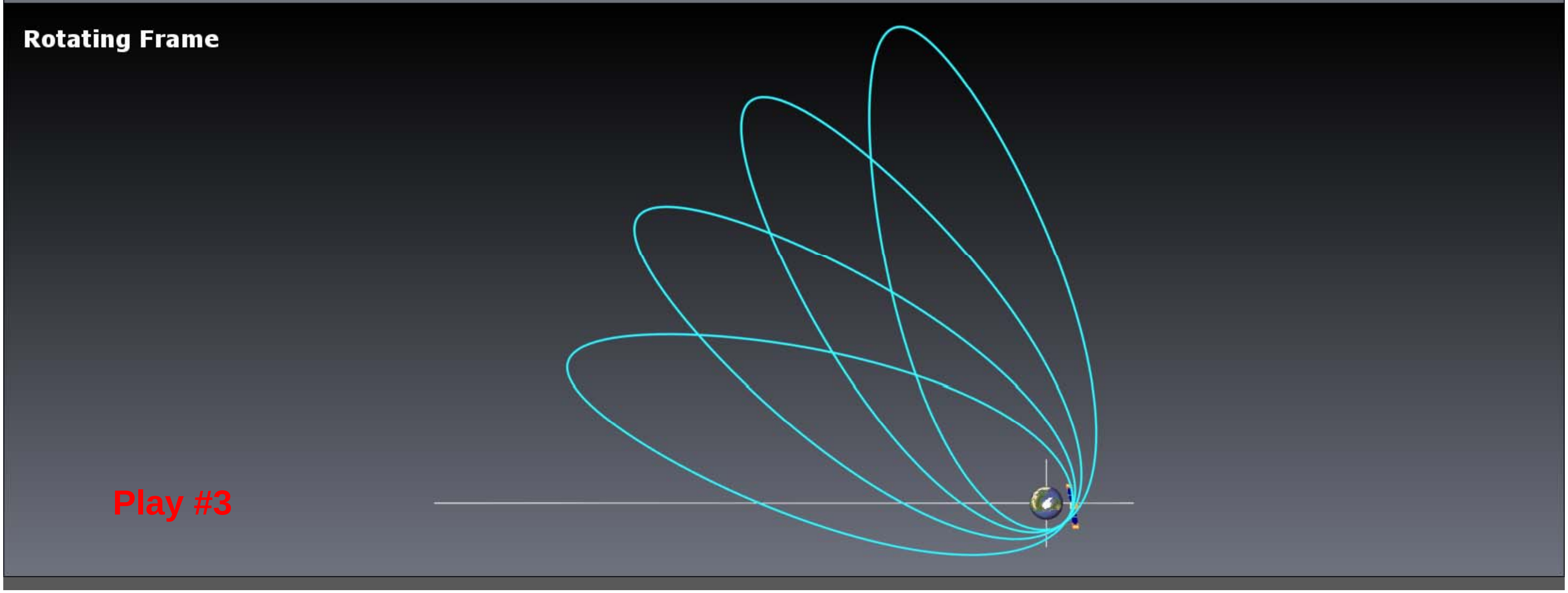


Rotating View

Rotating Frame

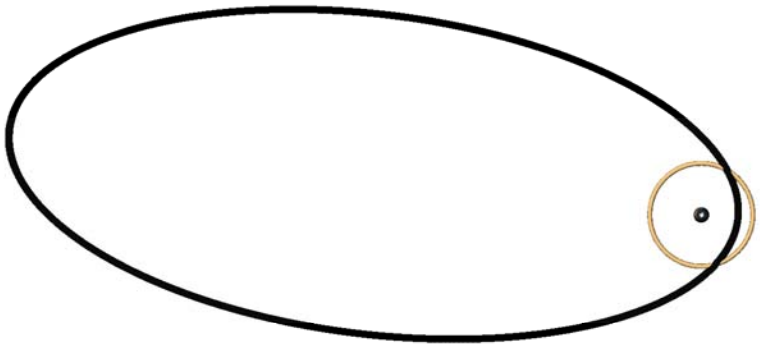






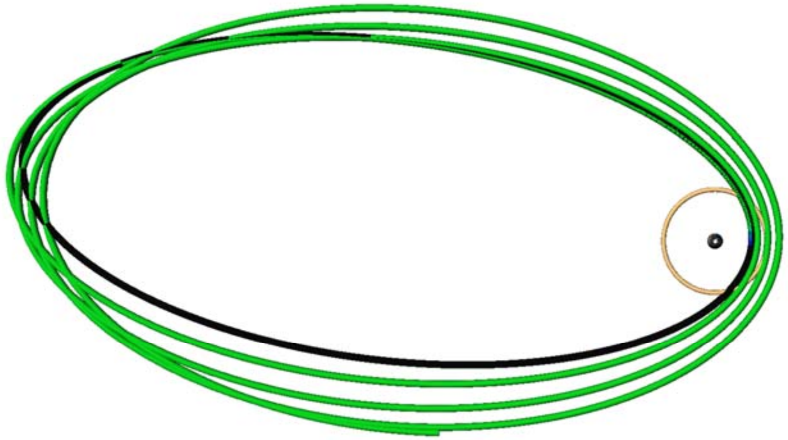
Play #3

Orbit propagated for 4 conic periods:
4*19 days = 75.7 days



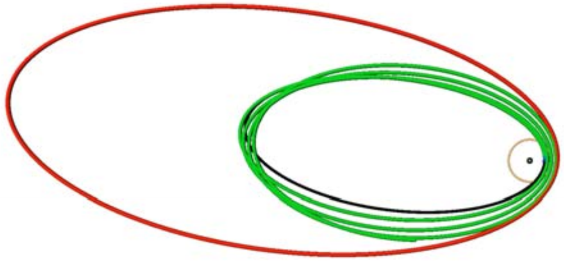
Inertial View

Orbits propagated for 4 conic periods:
4*19 days = 75.7 days



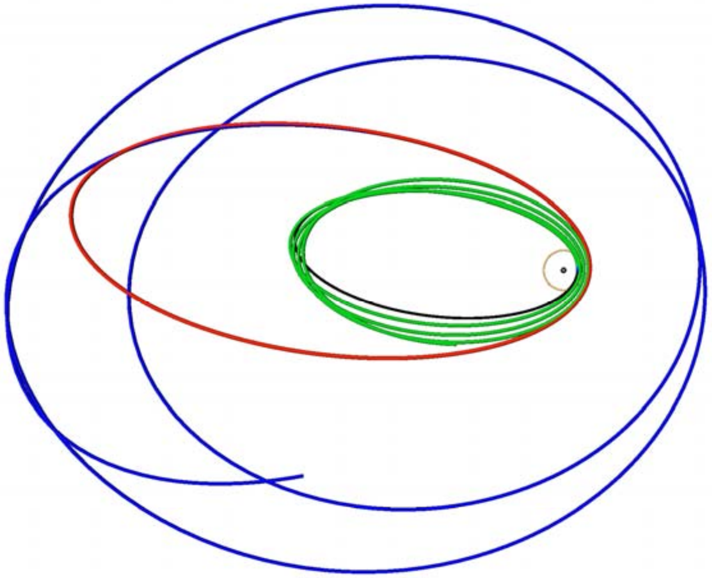
Inertial View

Orbits propagated for 4 conic periods:
4*47 days = 188 days



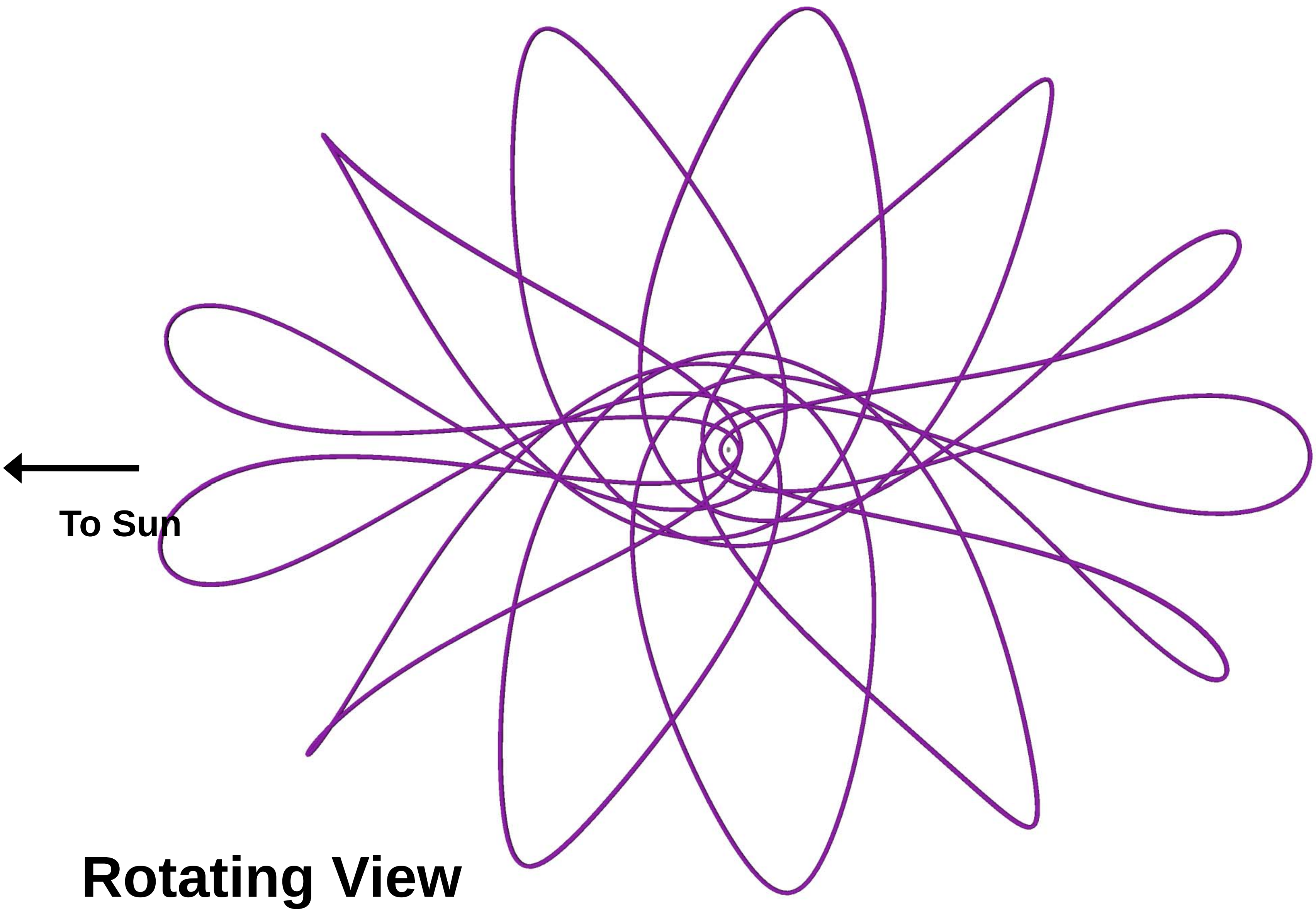
Inertial View

Orbits propagated for 4 conic periods:
4*47 days = 188 days



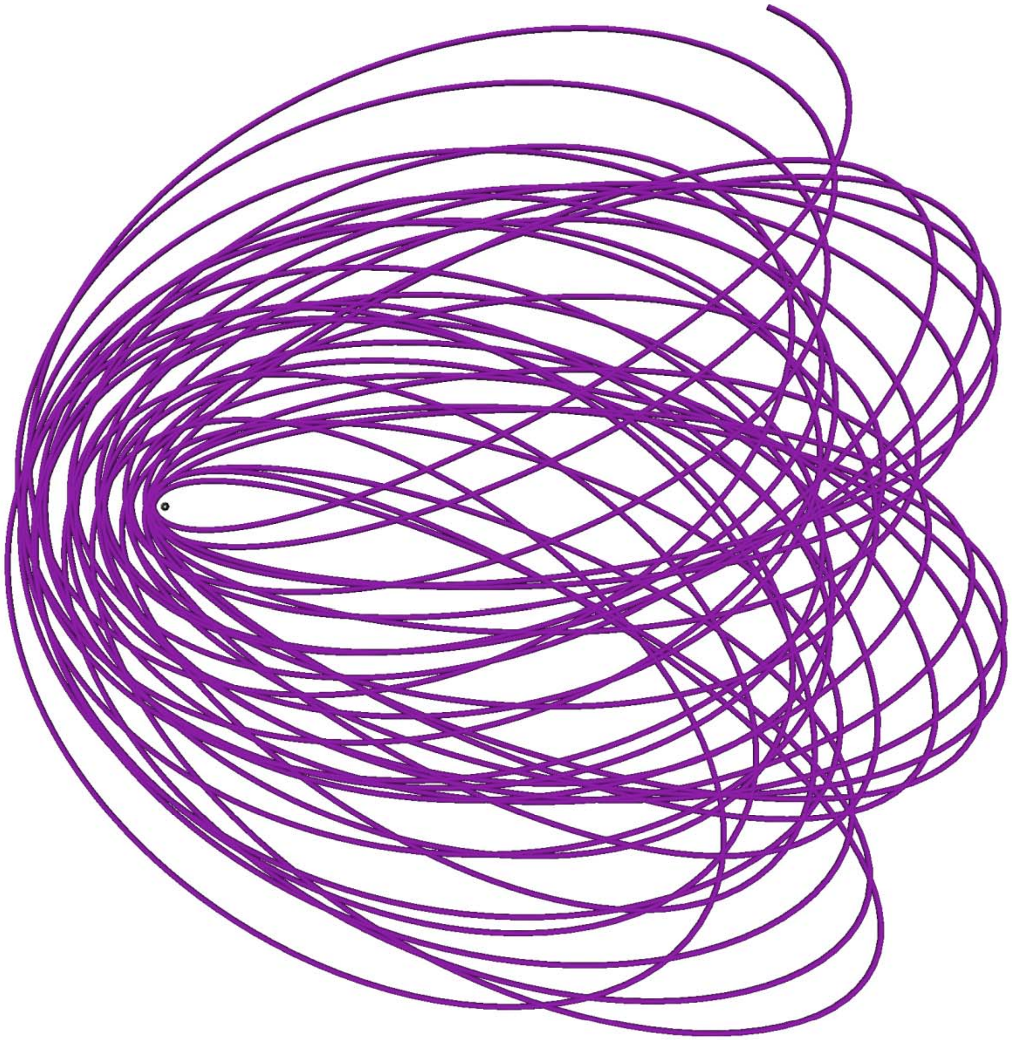
Inertial View

Resonant orbit propagated for 5.2 year

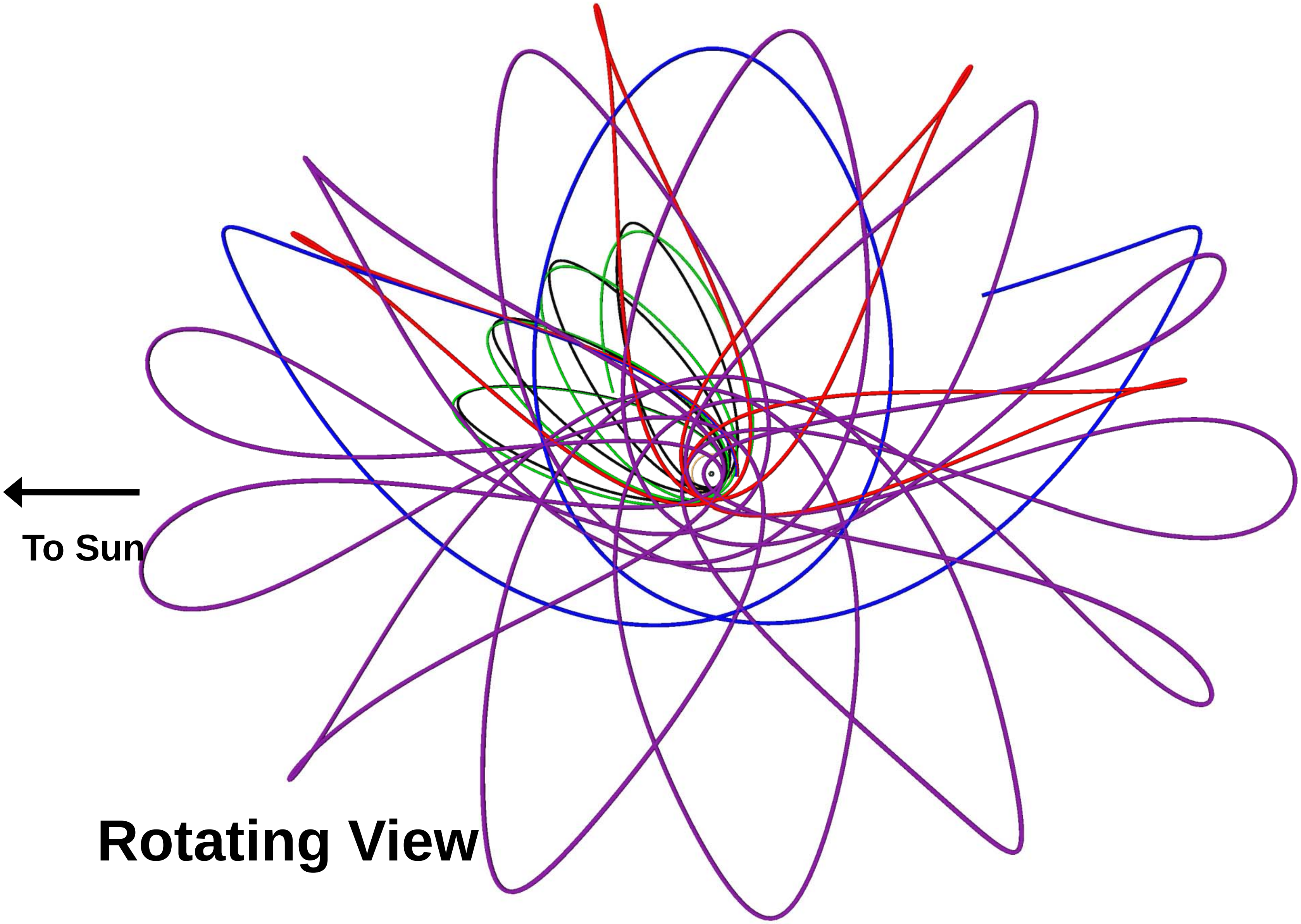


Rotating View

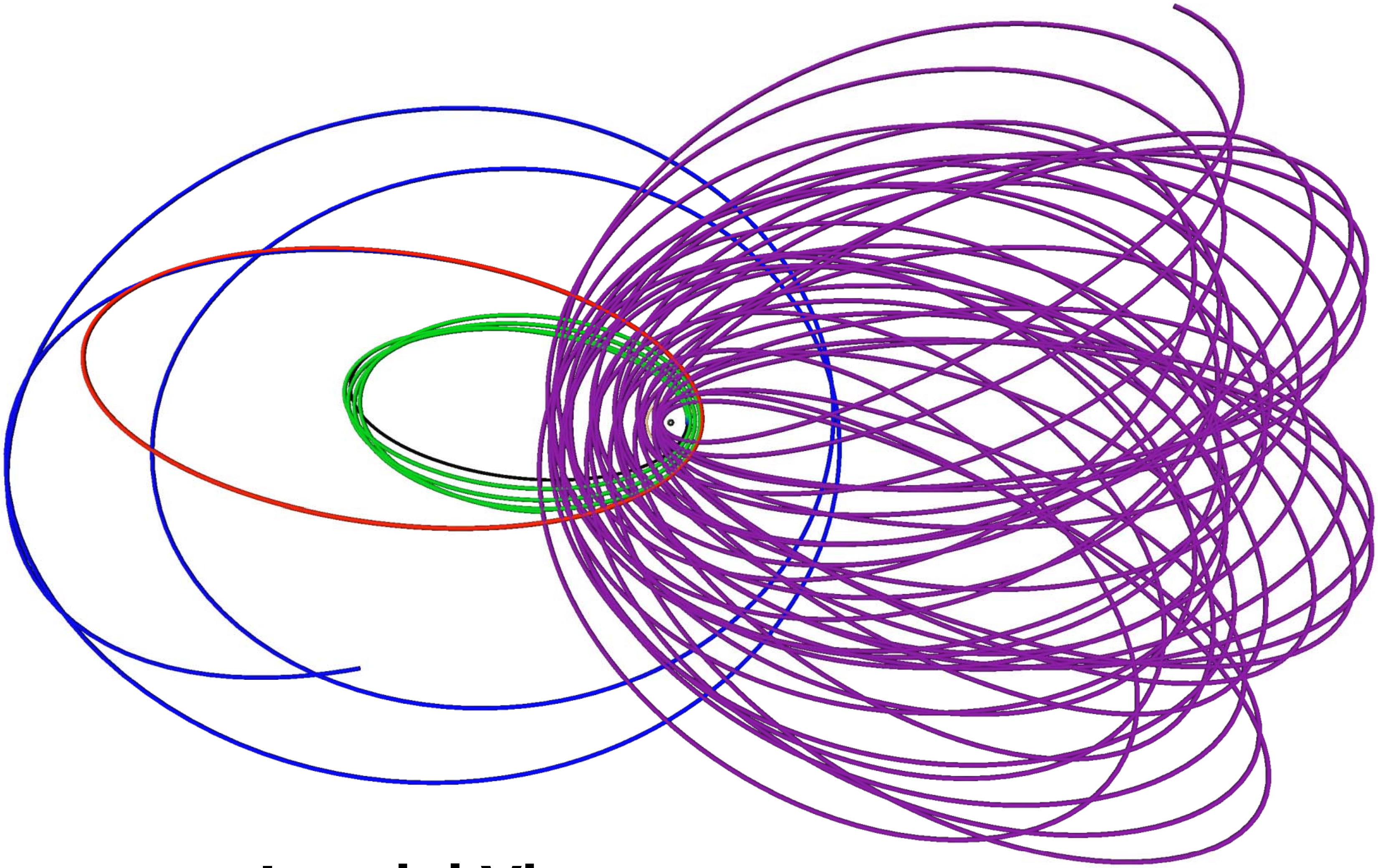
Resonant orbit propagated for 5.2 years



Inertial View



Rotating View



Inertial View

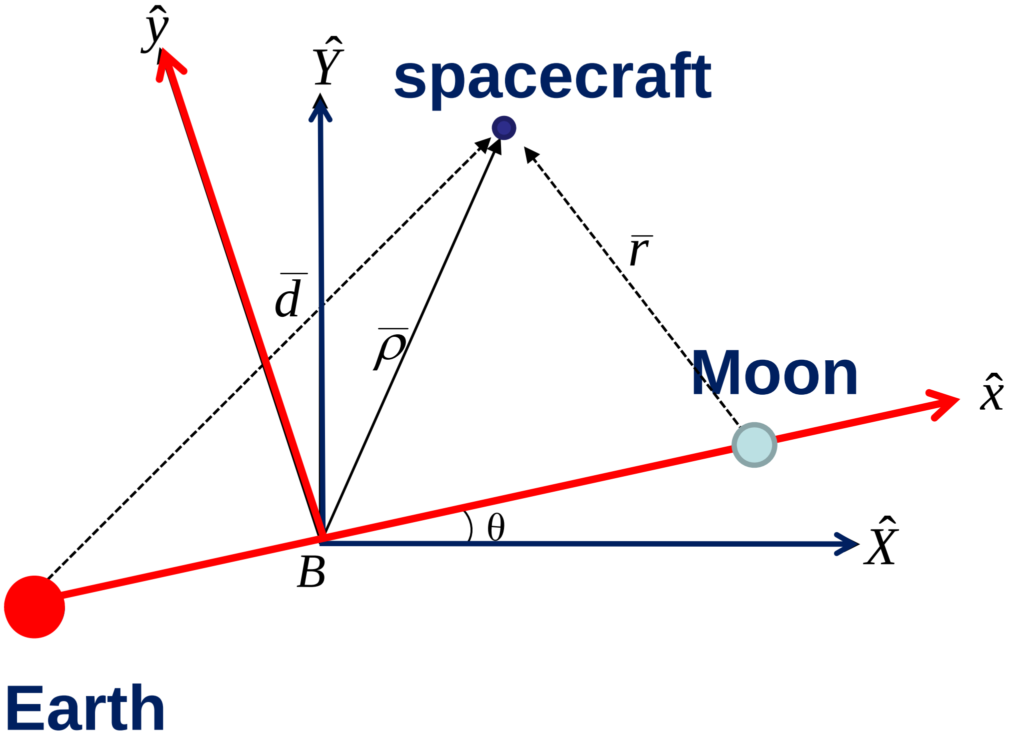
Problem:

Design spacecraft trajectory ⇒ specific requirements

Approaches:

Traditional Two-Body	N-Body Regimes (even N = 3)
• Analytical Solns $\left\{ \begin{array}{l} \text{ellipses} \\ \text{parabolas} \\ \text{hyperbolas} \end{array} \right.$	• No analytical solutions • Limited knowledge of solution arcs
• Identify various trajectory arcs; patch together	• Little understanding of arc “overlap”
• Transition to full model	• Transition → propagate single state
• Optimize in full model	• Optimizing relies on GOOD guess;

Poincaré → Three-Body Problem



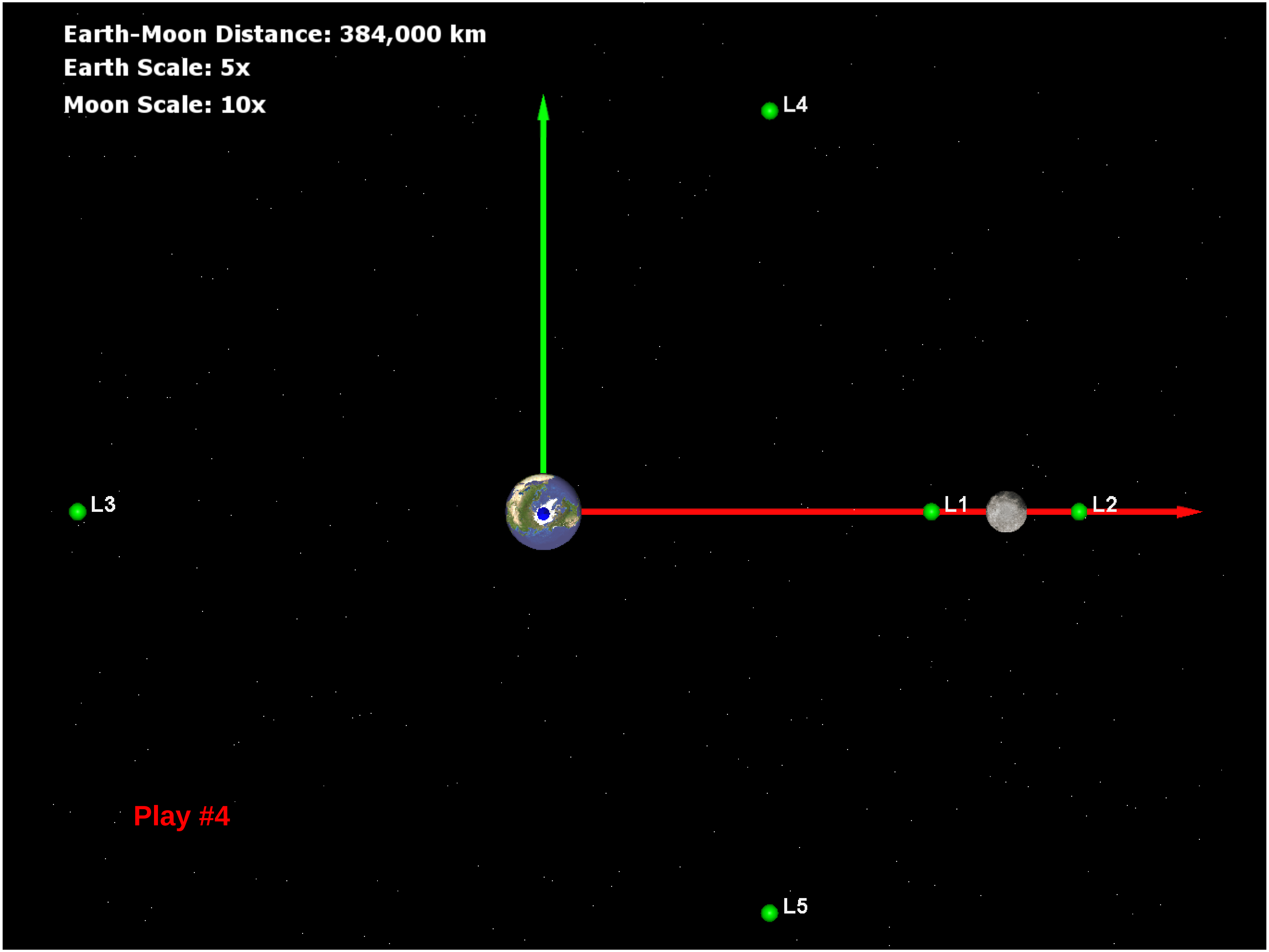
New View + Additional
Grav Fields

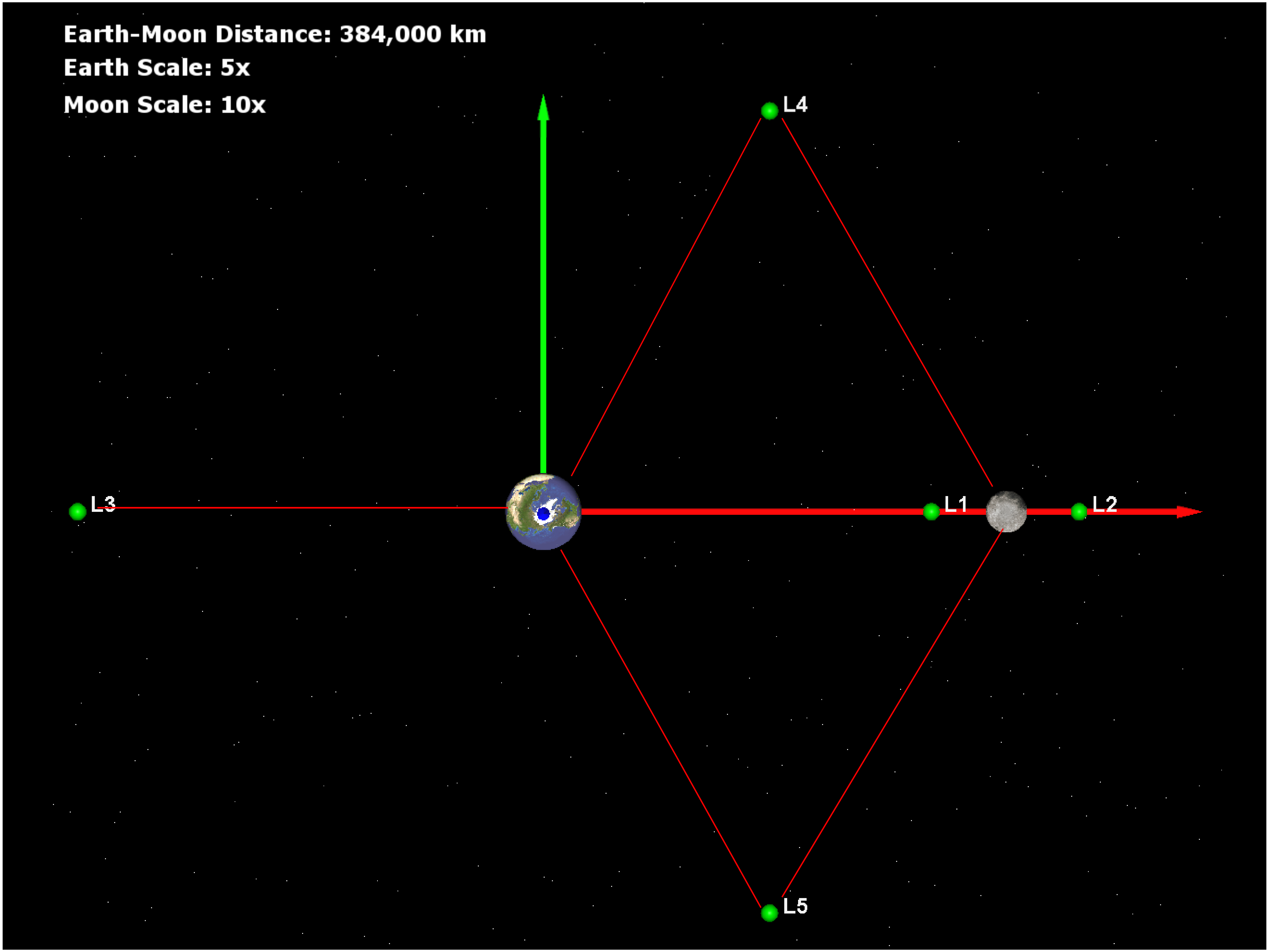
⬇

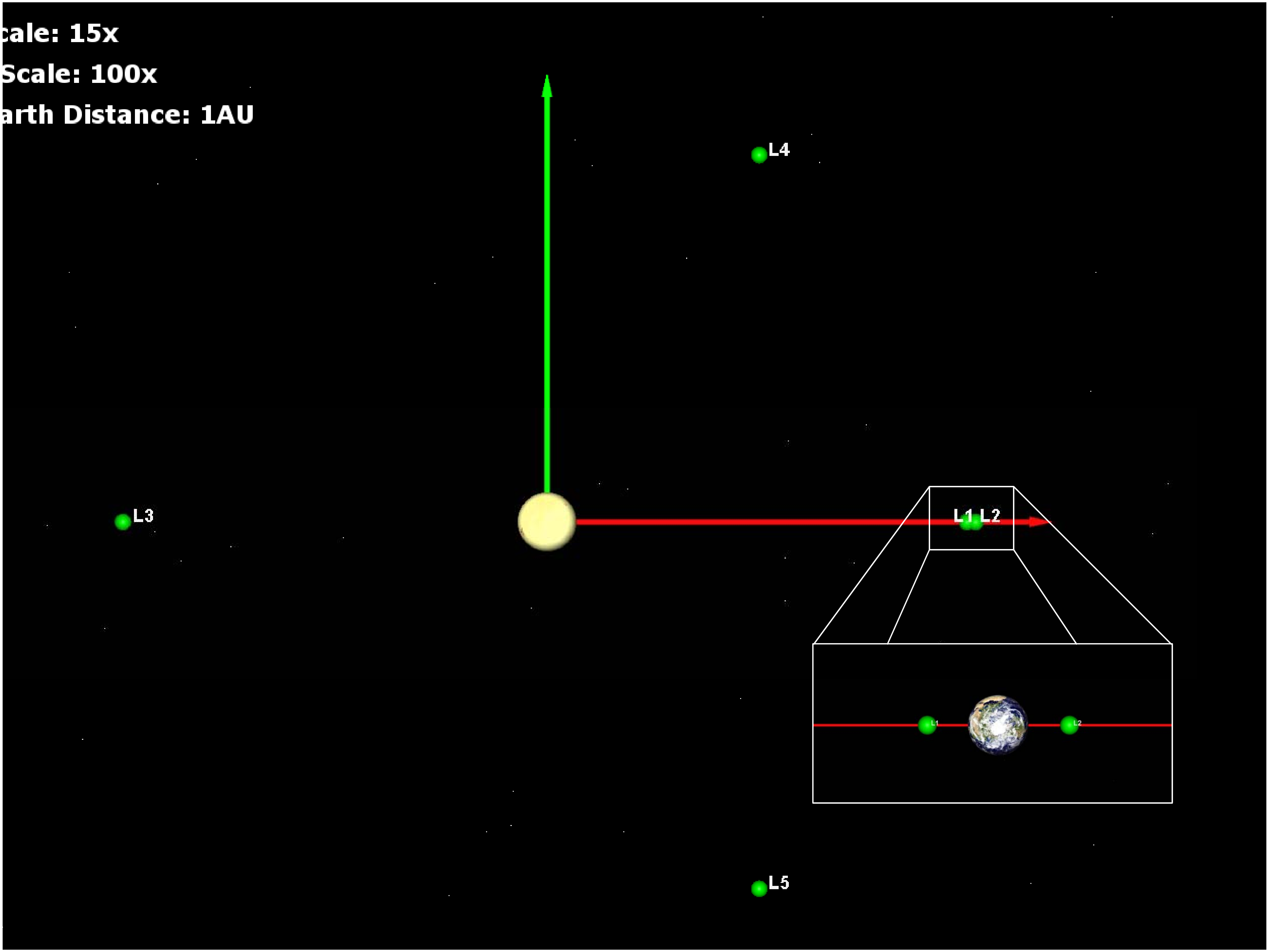
What new options exist?

1. How do we find new solutions?
2. What do they look like?
3. How do we start?

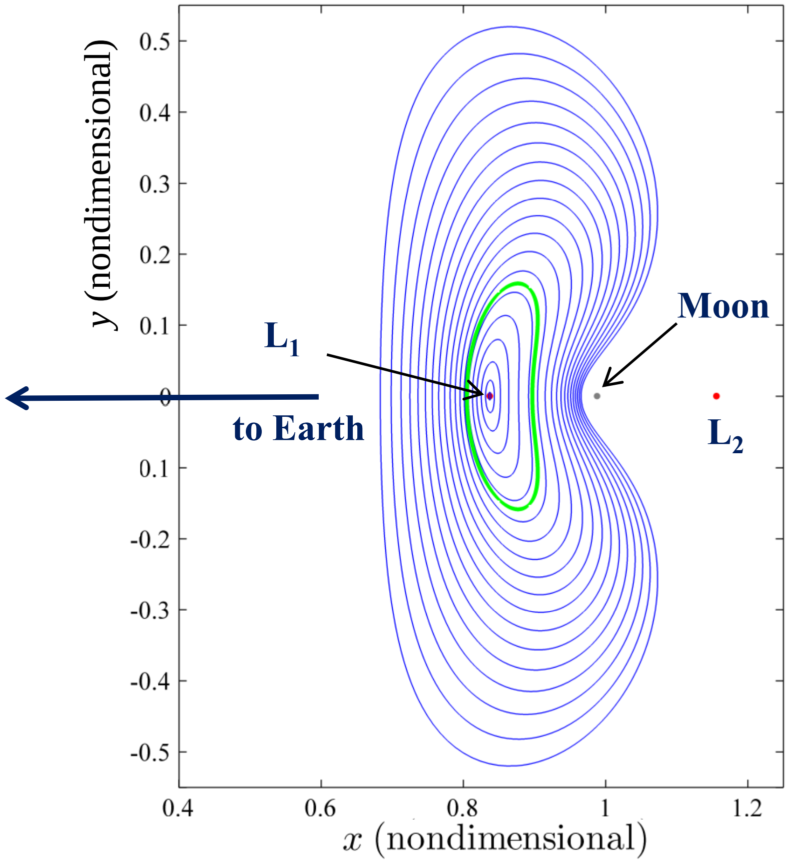
Equilibrium Solutions

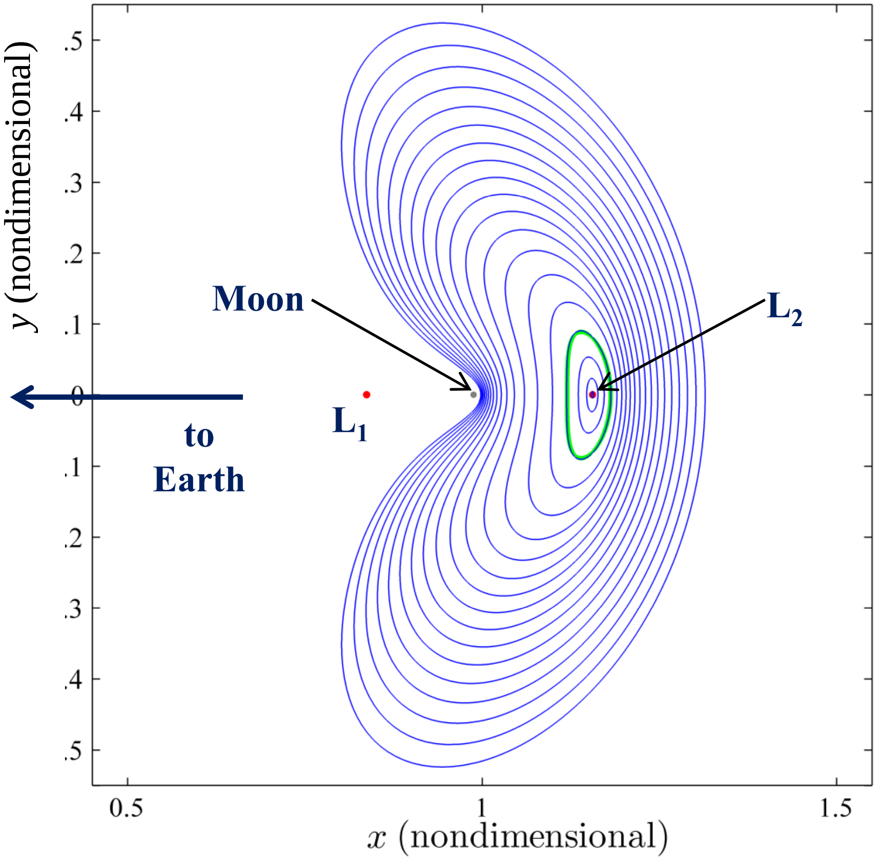

Earth-Moon Distance: 384,000 km
Earth Scale: 5x
Moon Scale: 10x
L4
L3
L1
L2
L5
Play #4

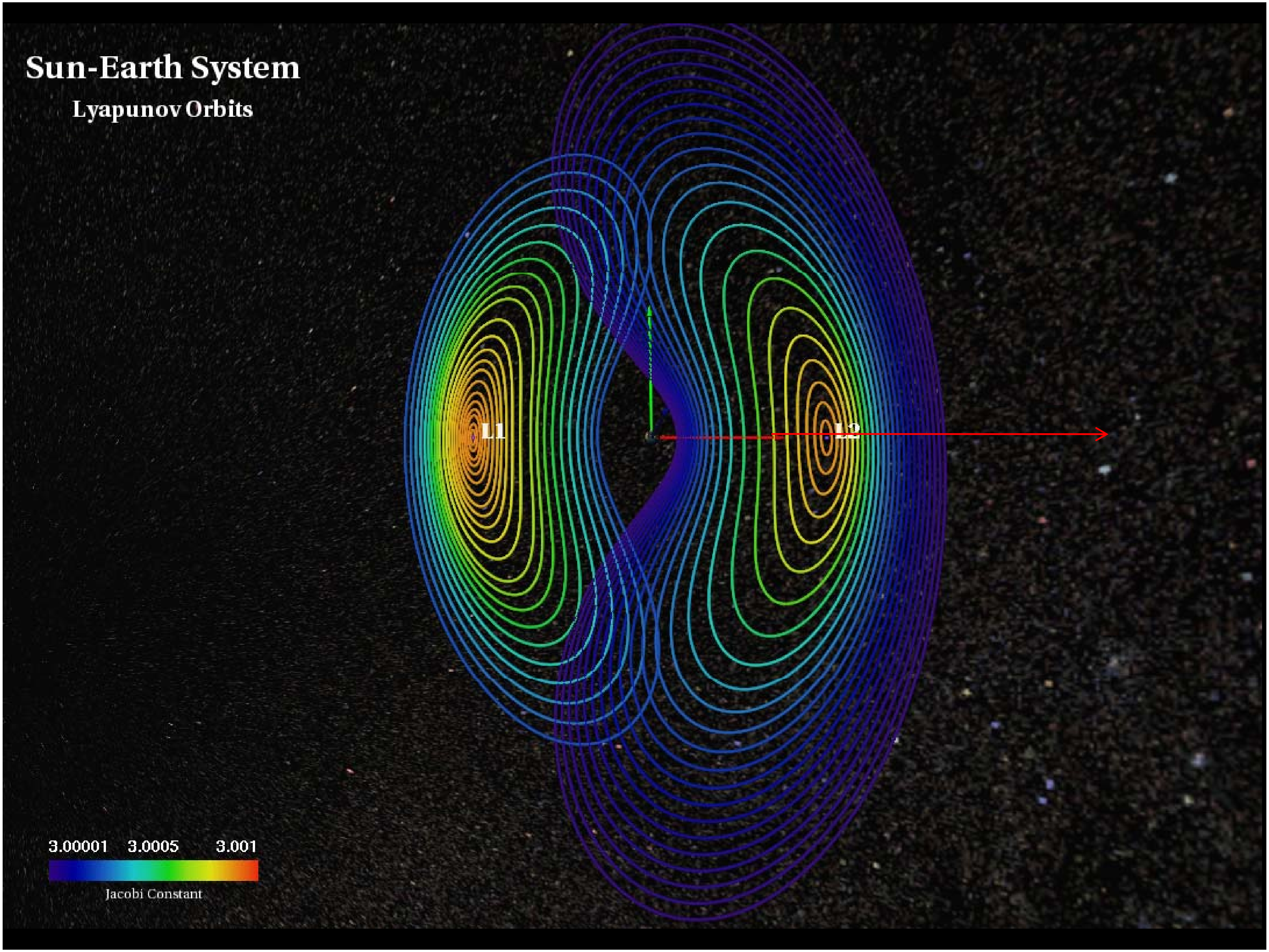

Earth-Moon Distance: 384,000 km
Earth Scale: 5x
Moon Scale: 10x
L4
L3
L1
L2
L5


cale: 15x
Scale: 100x
arth Distance: 1AU
L4
L3
L1
L2
L5
L1
L2

L_1 and L_2 Lyapunov Families



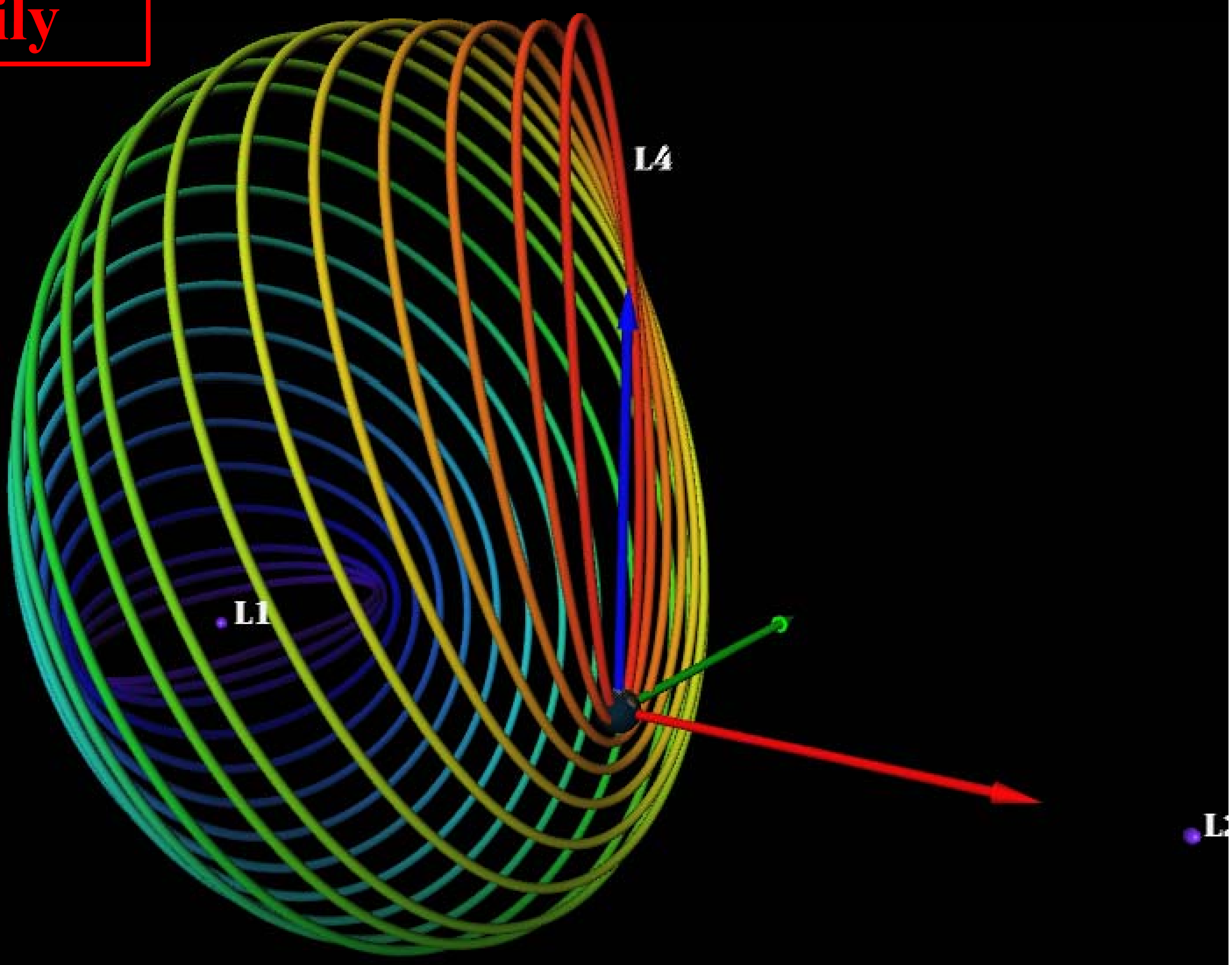




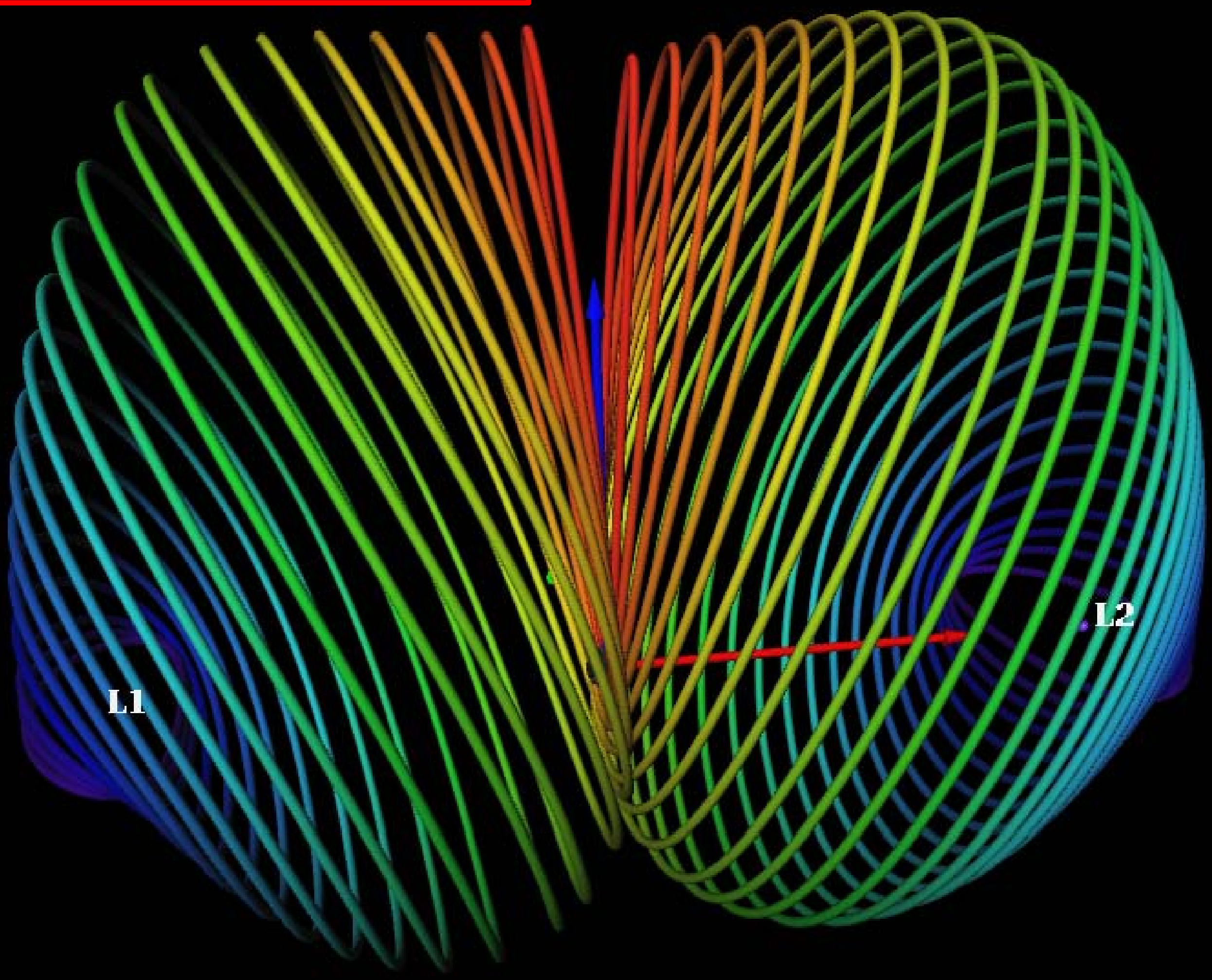
Sun-Earth System

Lyapunov Orbits

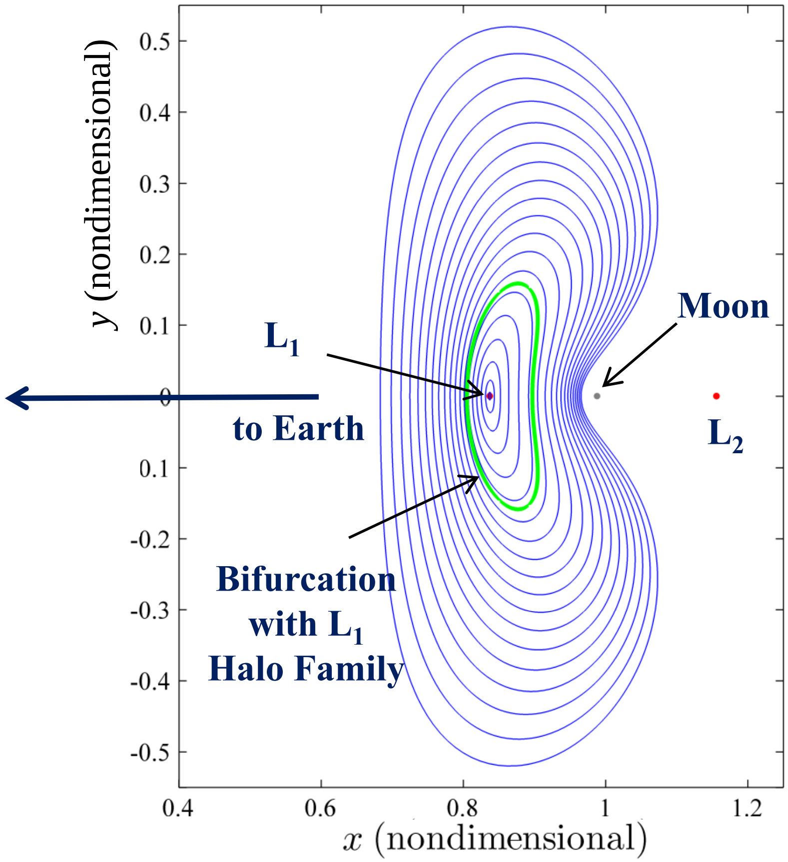
L_1 Halo Family

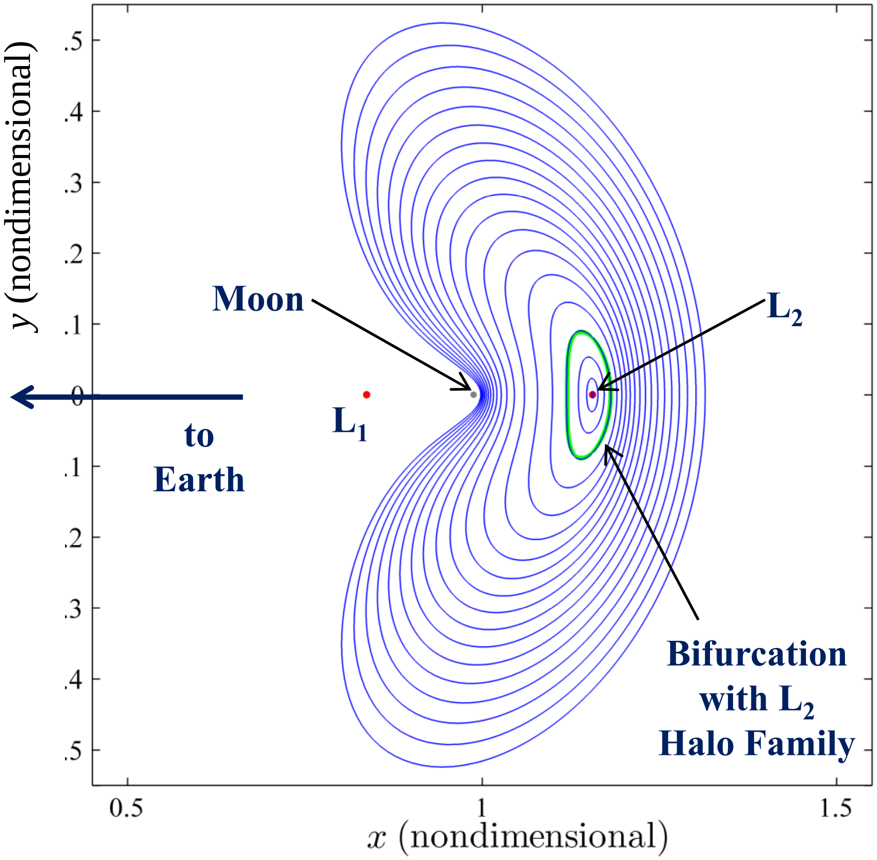


L_1 and L_2 Halo Families

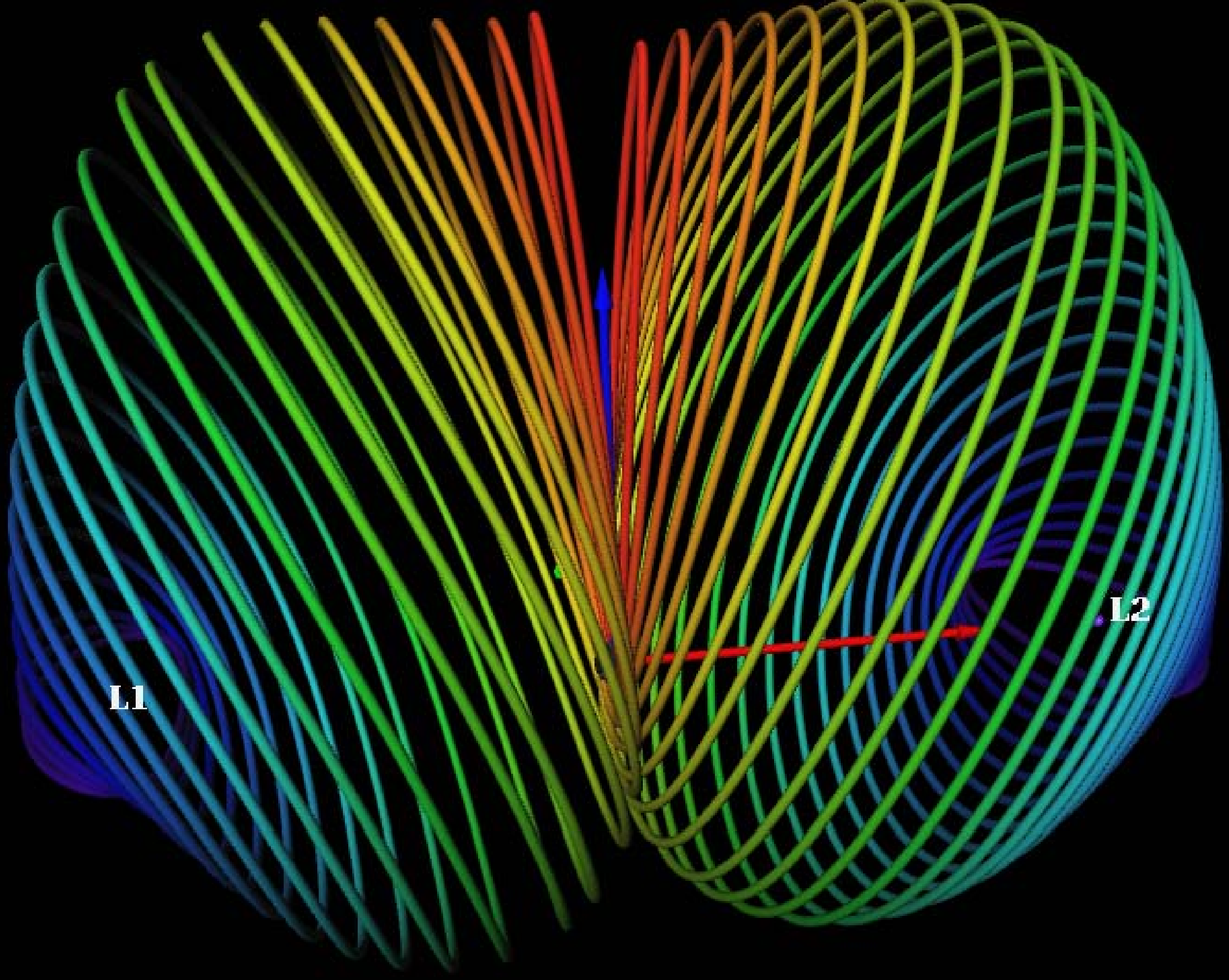


L_1 and L_2 Lyapunov Families



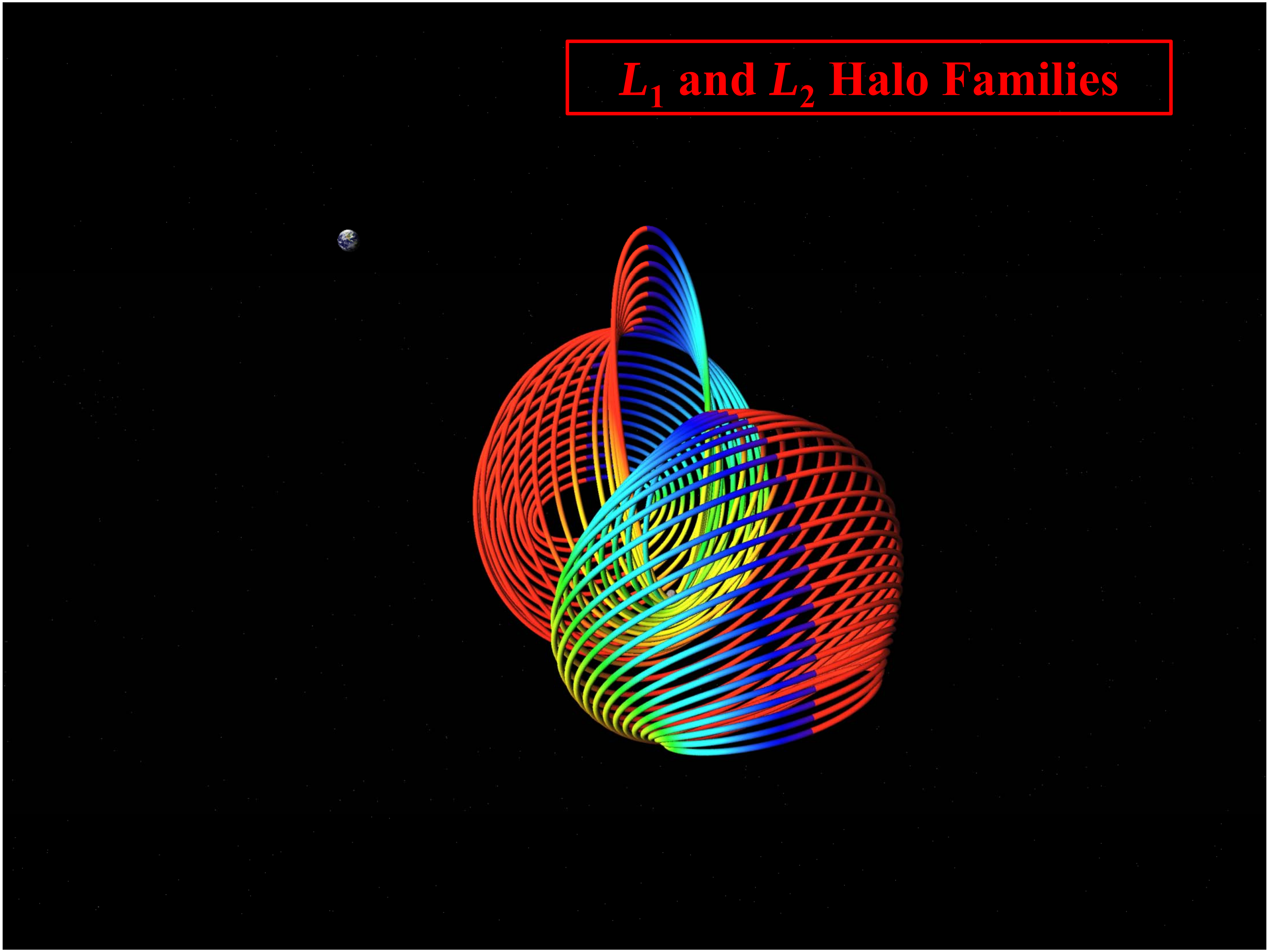


L_1 and L_2 Halo Families

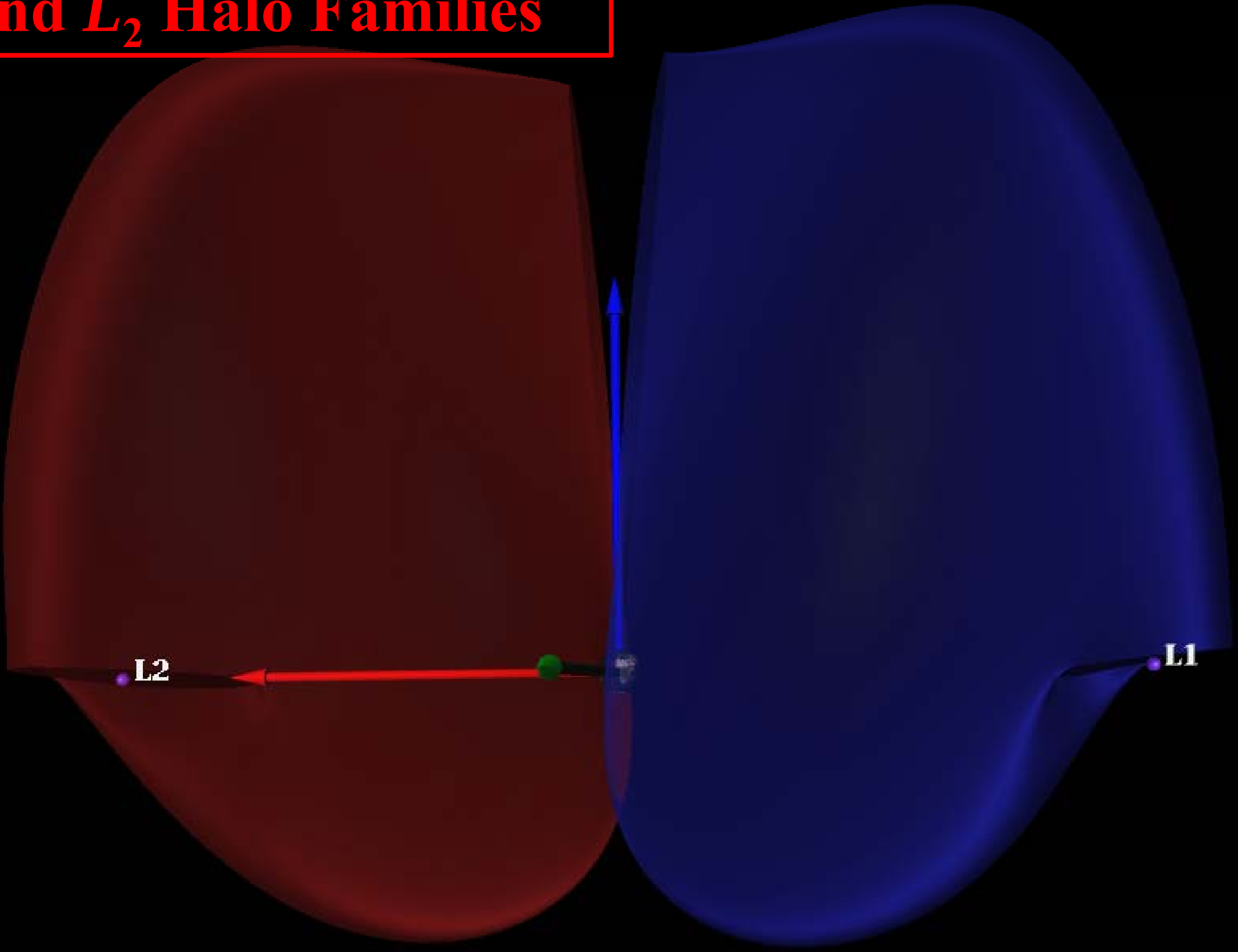


Play #5 Play #6

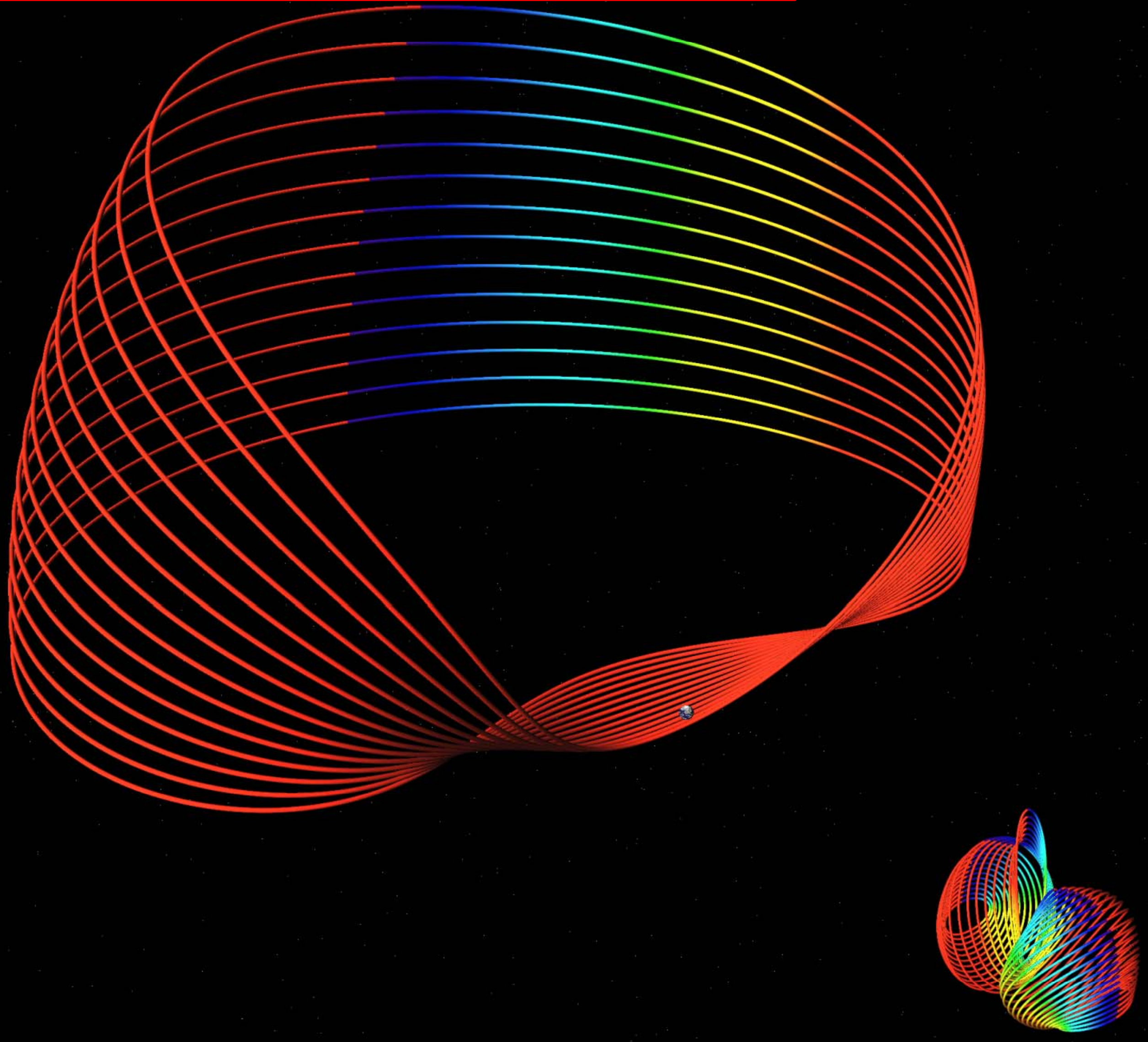
L_1 and L_2 Halo Families



L_1 and L_2 Halo Families



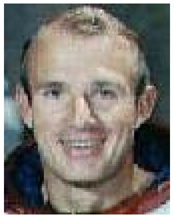
L_1, L_2, L_3 Halo Families



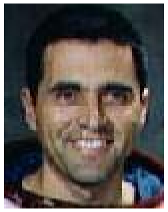
Innovation in Trajectory Design 1970's

Apollo 18

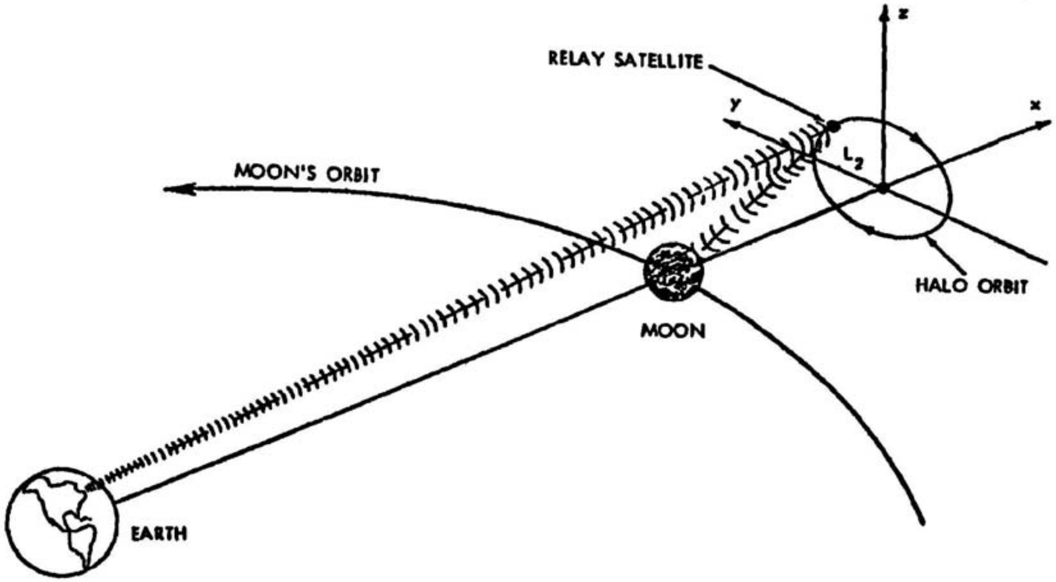
Gordon

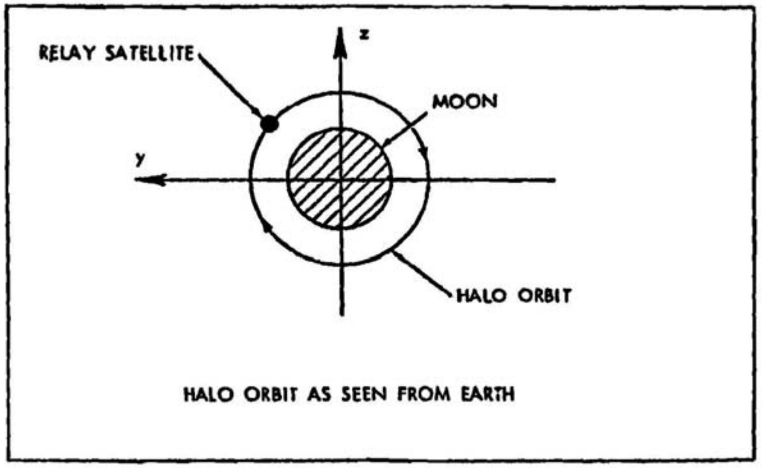


Brand



Schmitt

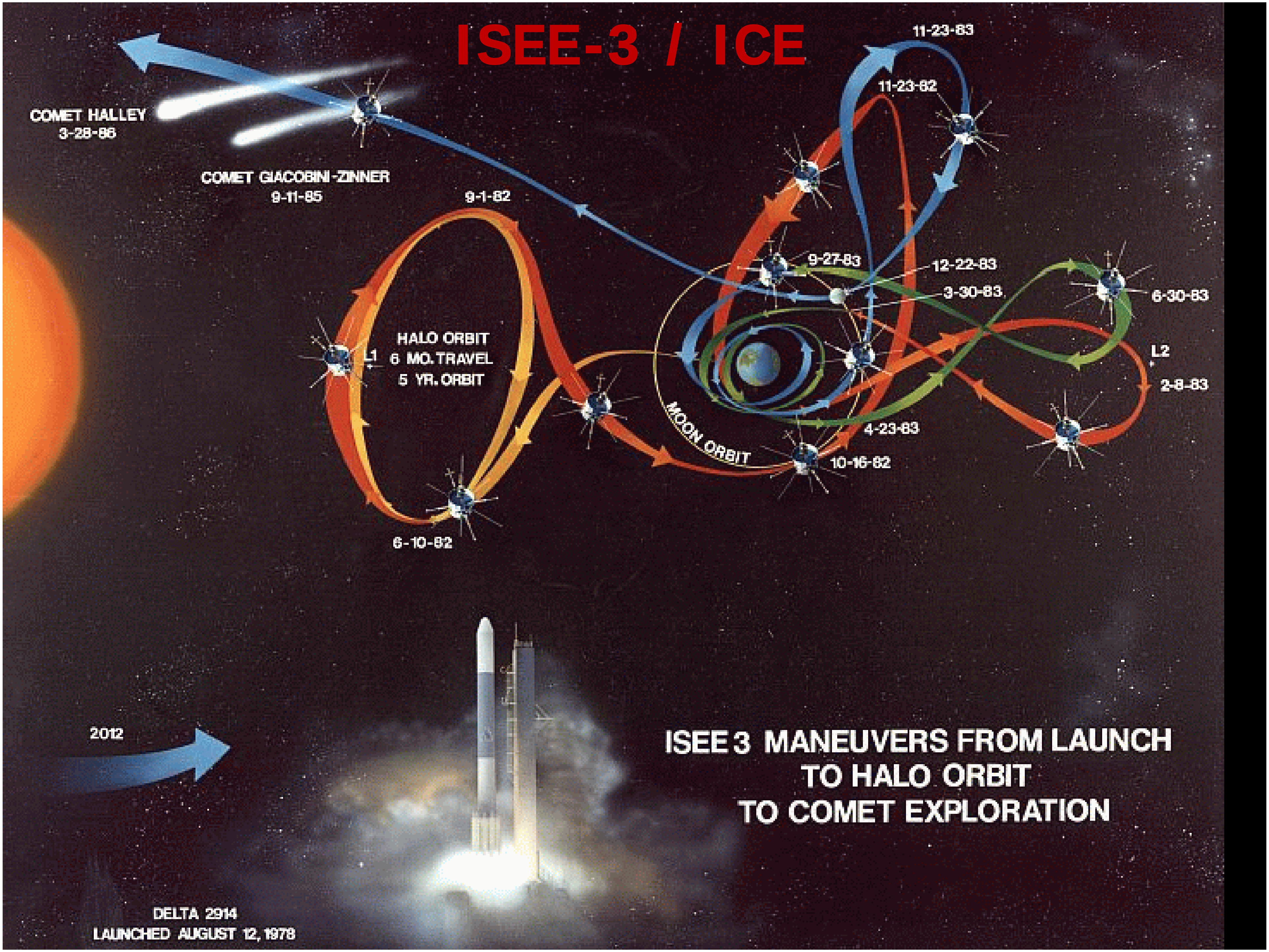


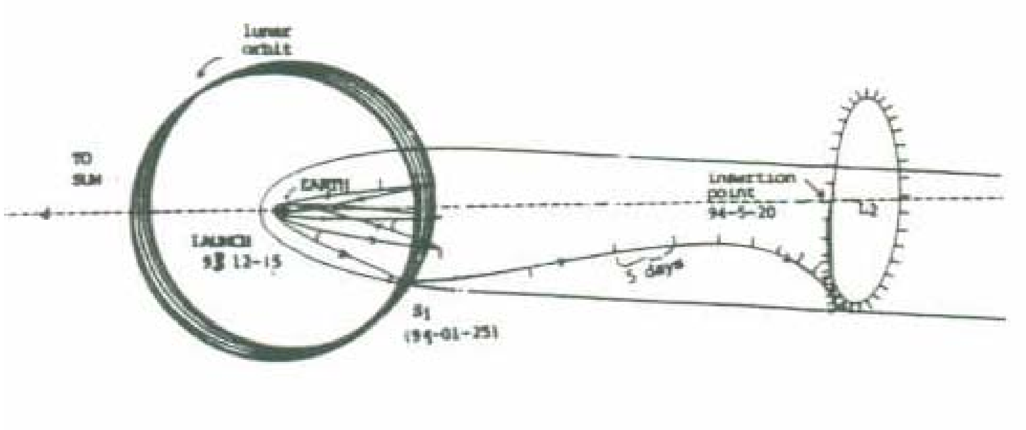


HALO ORBIT AS SEEN FROM EARTH

Courtesy: NASA

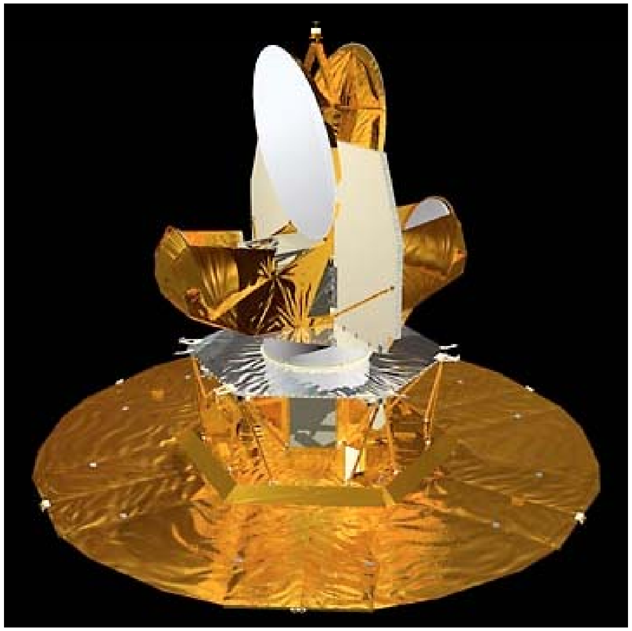
ISEE-3 / ICE

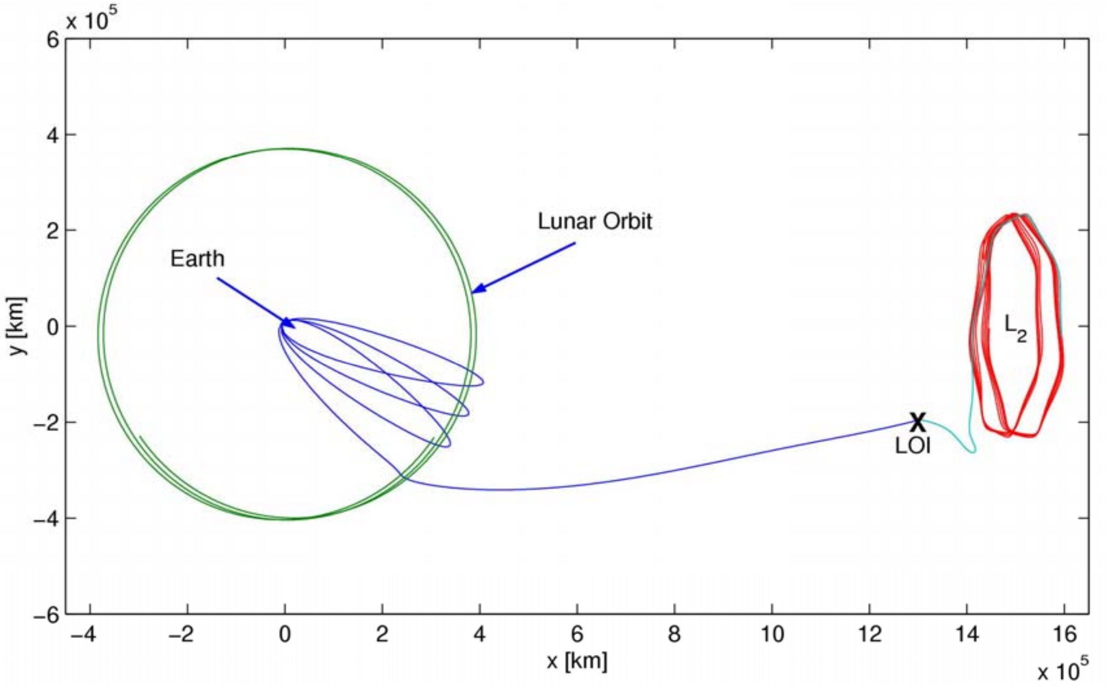

COMET HALLEY
3-28-86
COMET GIACOBINI-ZINNER
9-11-85
11-23-83
11-23-82
9-1-82
9-27-83
12-22-83
3-30-83
6-30-83
HALO ORBIT
6 MO. TRAVEL
5 YR. ORBIT
L1
L2
2-8-83
MOON ORBIT
4-23-83
10-16-82
6-10-82
2012
ISEE 3 MANEUVERS FROM LAUNCH
TO HALO ORBIT
TO COMET EXPLORATION
DELTA 2914
LAUNCHED AUGUST 12, 1978


lunar orbit
TO SUN
EARTH
LAUNCH 93 12-15
insertion point 94-5-20
L2
5 days
S_1 (94-01-25)

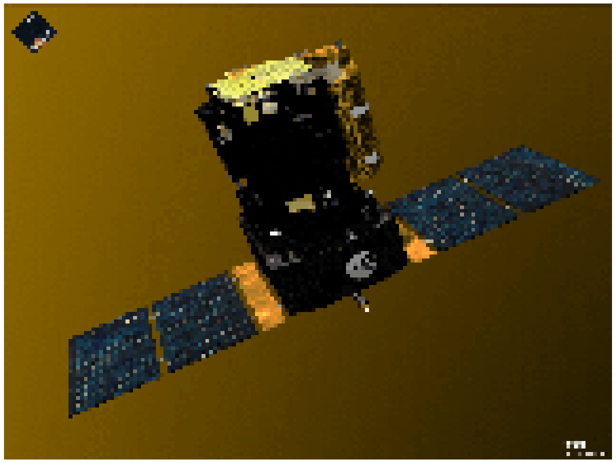
Relict-2

MAP



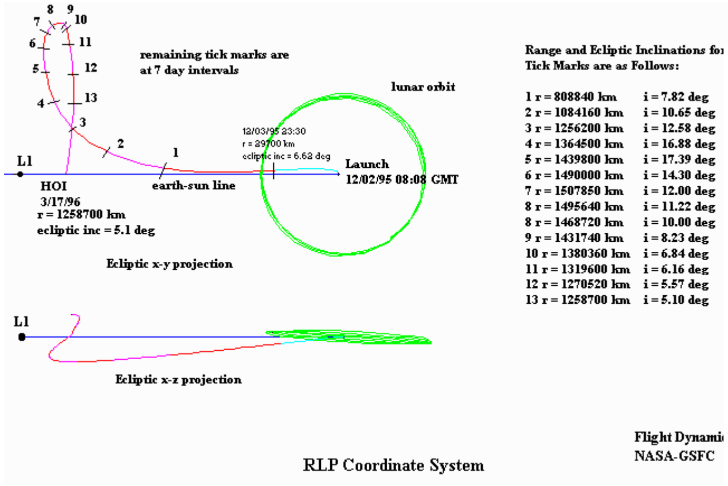

x 10^5
6
4
2
0
−2
−4
−6
y [km]
Lunar Orbit
Earth
L_2
X
LOI
−4
−2
0
2
4
6
8
10
12
14
16
x [km]
x 10^5

SOHO



Mission: ⊕ to L_1

- L_1 Halo Orbit: Az= 120,000 km, Ay=666,672 km

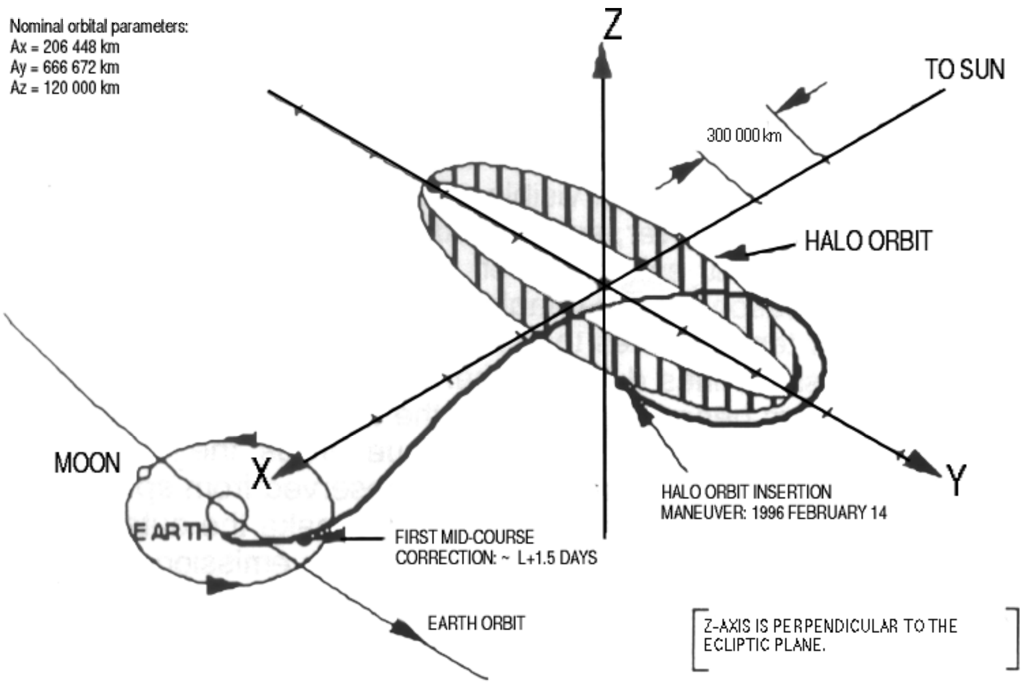


Range and Ecliptic Inclinations fo
Tick Marks are as Follows:

1 r = 808840 km i = 7.82 deg
2 r = 1084160 km i = 10.65 deg
3 r = 1256200 km i = 12.58 deg
4 r = 1364500 km i = 16.88 deg
5 r = 1439800 km i = 17.39 deg
6 r = 1490000 km i = 14.30 deg
7 r = 1507850 km i = 12.00 deg
8 r = 1495640 km i = 11.22 deg
8 r = 1468720 km i = 10.00 deg
9 r = 1431740 km i = 8.23 deg
10 r = 1380360 km i = 6.84 deg
11 r = 1319600 km i = 6.16 deg
12 r = 1270520 km i = 5.57 deg
13 r = 1258700 km i = 5.10 deg

Flight Dynami
NASA-GSFC

RLP Coordinate System

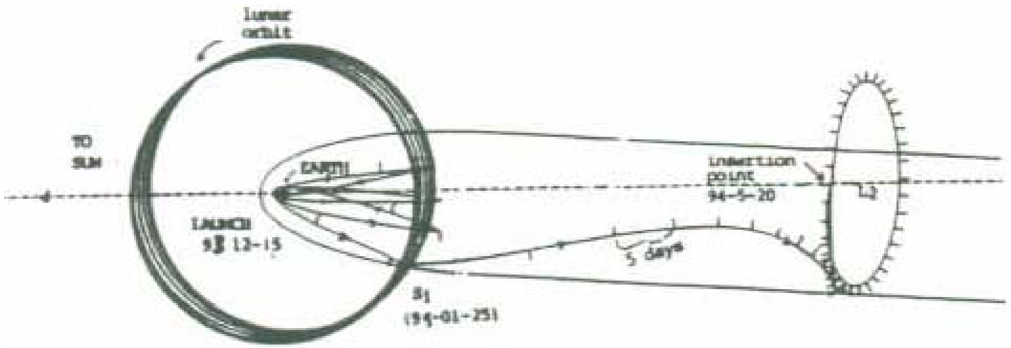


Nominal orbital parameters:
Ax = 206 448 km
Ay = 666 672 km
Az = 120 000 km

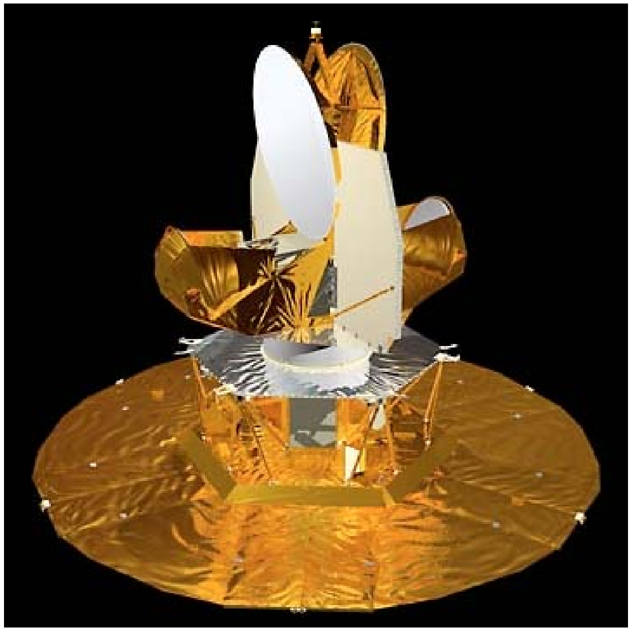
Z-AXIS IS PERPENDICULAR TO THE ECLIPTIC PLANE.

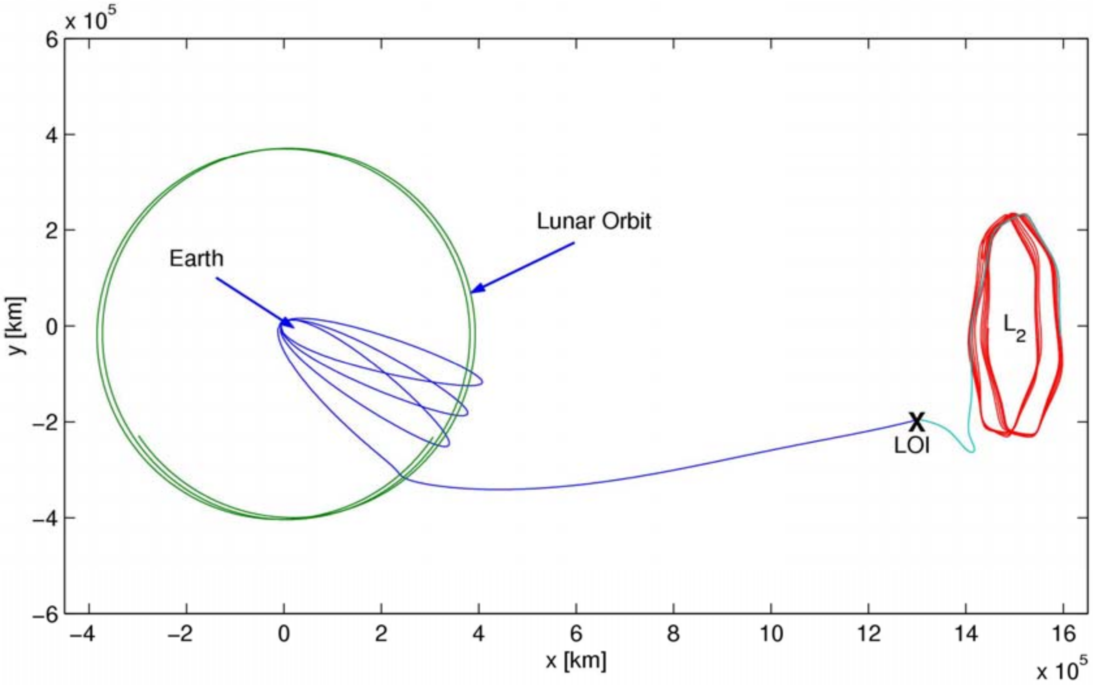
SOHO orbit schematic

Relict-2


lunar orbit
TO SUN
EARTH
LAUNCH
93 12-15
insertion point
94-5-20
L2
5 days
S_1
(94-01-25)

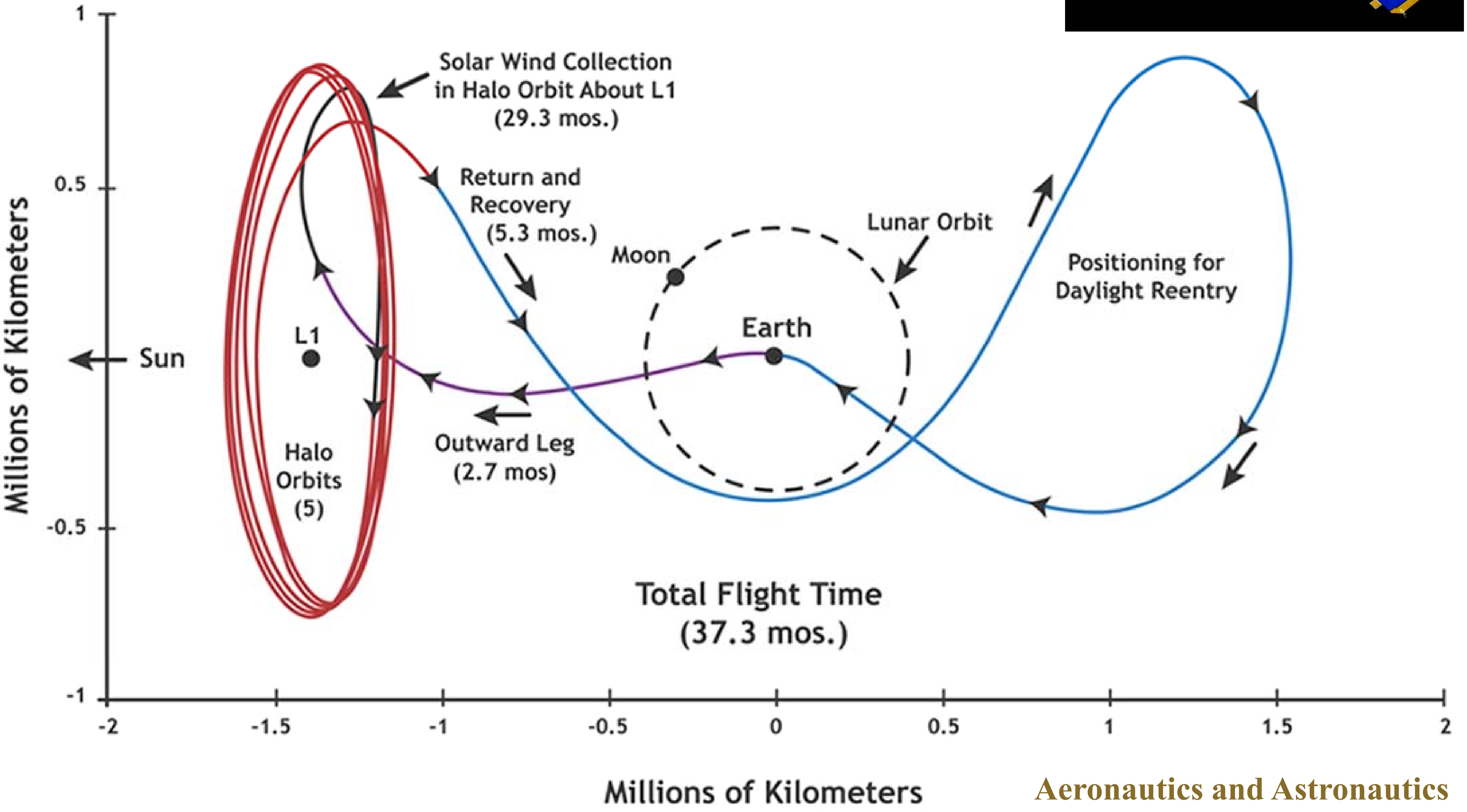
MAP

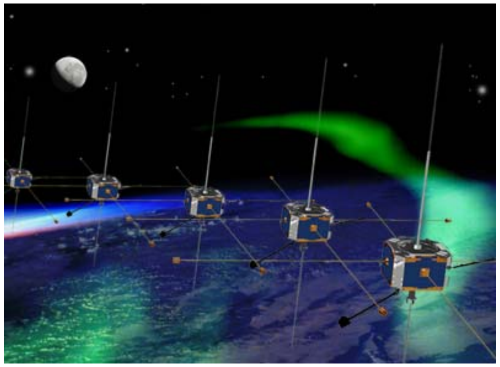



x 10^5
6
4
2
0
−2
−4
−6
y [km]
−4
−2
0
2
4
6
8
10
12
14
16
x [km]
x 10^5
Lunar Orbit
Earth
LOI
L_2

PURDUE
UNIVERSITY

Genesis Trajectory





THEMIS Background: Substorms

PRIME MISSION (FY08-09) SCIENCE GOALS:

Primary:

“How do substorms operate?”

– One of oldest, most important questions in Geophysics

– A turning point in understanding
of the dynamic magnetosphere

First bonus science:

“What accelerates storm-time ‘killer’ electrons?”

– A significant contribution to space weather science

Second bonus science:

“What controls efficiency of solar wind – magnetosphere coupling?”

– Provides global context of solar wind & magnetosphere interaction

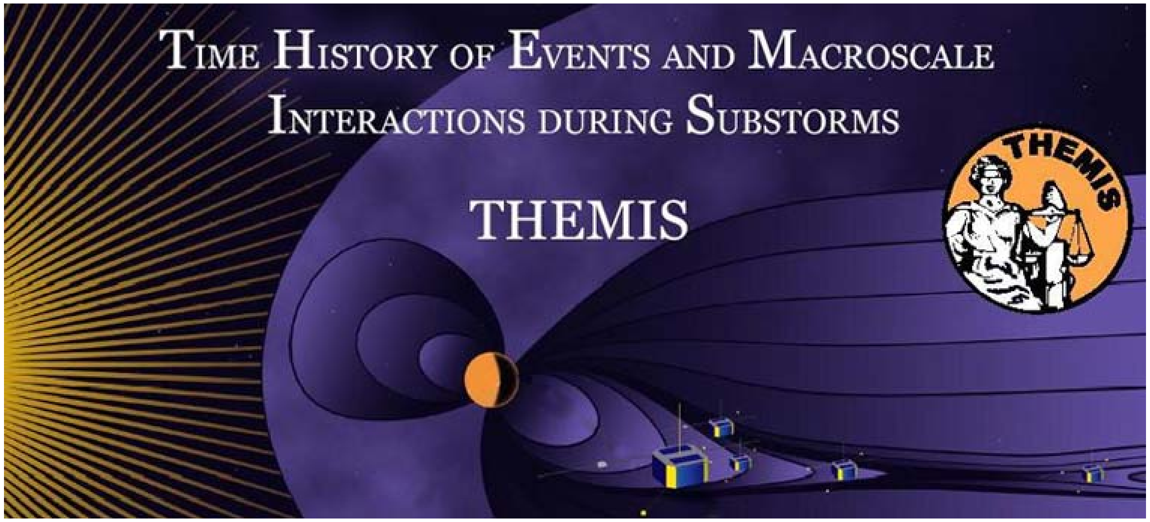
RESOLVING THE PHYSICS OF ONSET AND EVOLUTION OF SUBSTORMS

Principal Investigator
Vassilis Angelopoulos, UCLA

Mission Operations Manager
Manfred Bester, UCB

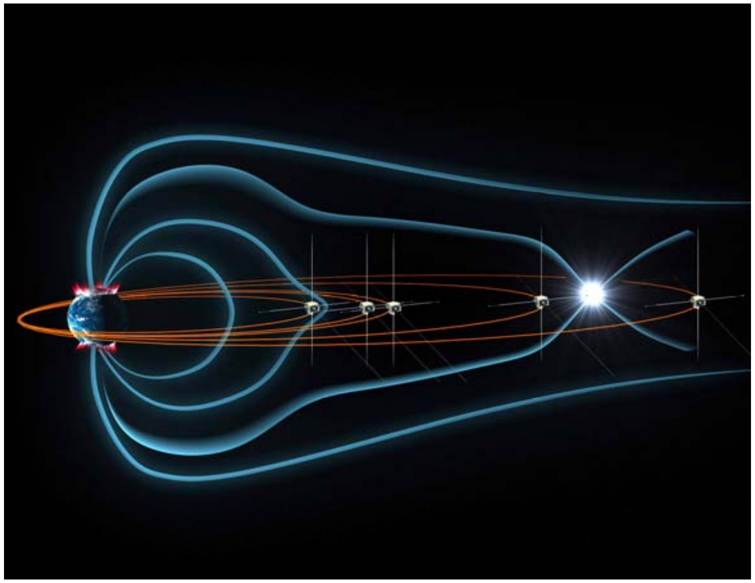
EPO Lead
Laura Peticolas, UCB

THEMIS



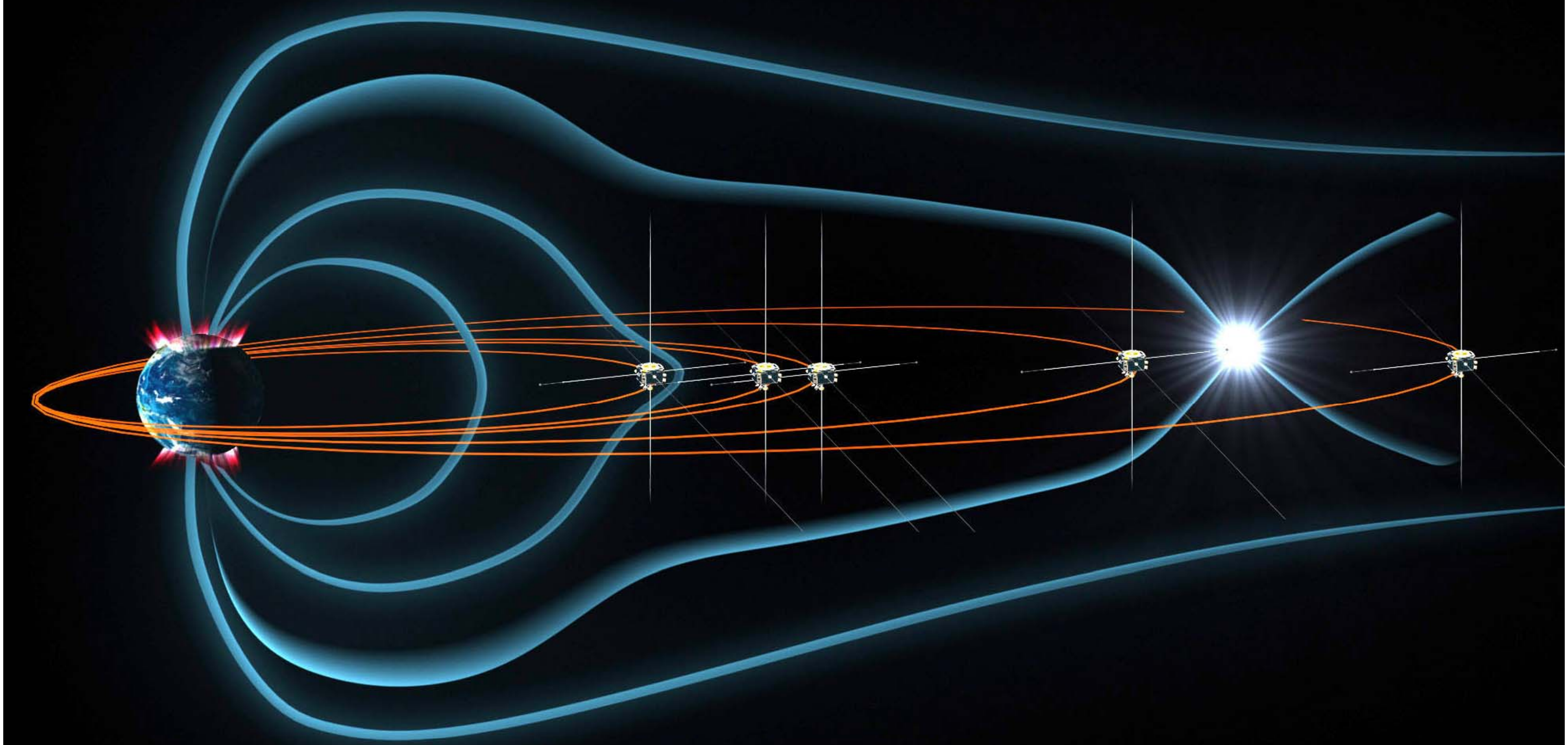
Primary Objective:
identify physical mechanism that leads to explosive release of energy in substorms

- 2-year mission (launch 2/07); 5 identical probes
- First NASA launch of five satellites to study substorms
- THEMIS probes align over North Am @ 4 day intervals
- Alignments - in situ measurements of particles/fields → identify region where substorm energy release; insight into process
- Successful result -- Explosion of magnetic energy at 1/3 distance to moon powers substorms due to magnetic reconnection (stressed magnetic field lines suddenly "snap" to a new shape)

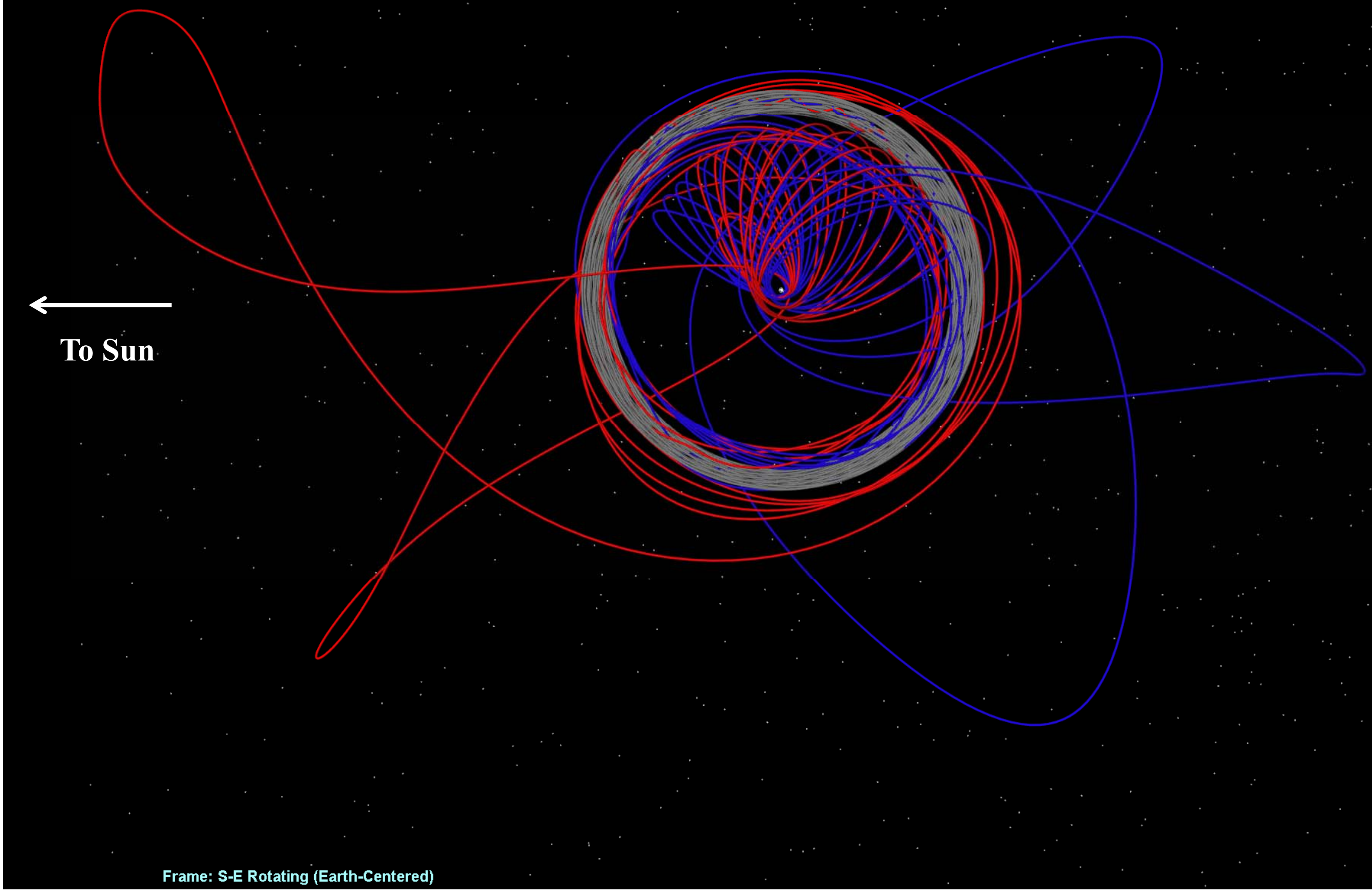


Blue - Earth's magnetic field over the night side
White flash - energy released during substorms

→ night side magnetic field acts as slingshot;
propels electrons toward Earth.



Artemis P1 /P2 Baseline Trajectory



Trajectory Baseline

Lunar Gravity + Solar Perturbation + Libration Point Orbits + Lunar Orbits

Elliptical Earth Orbits

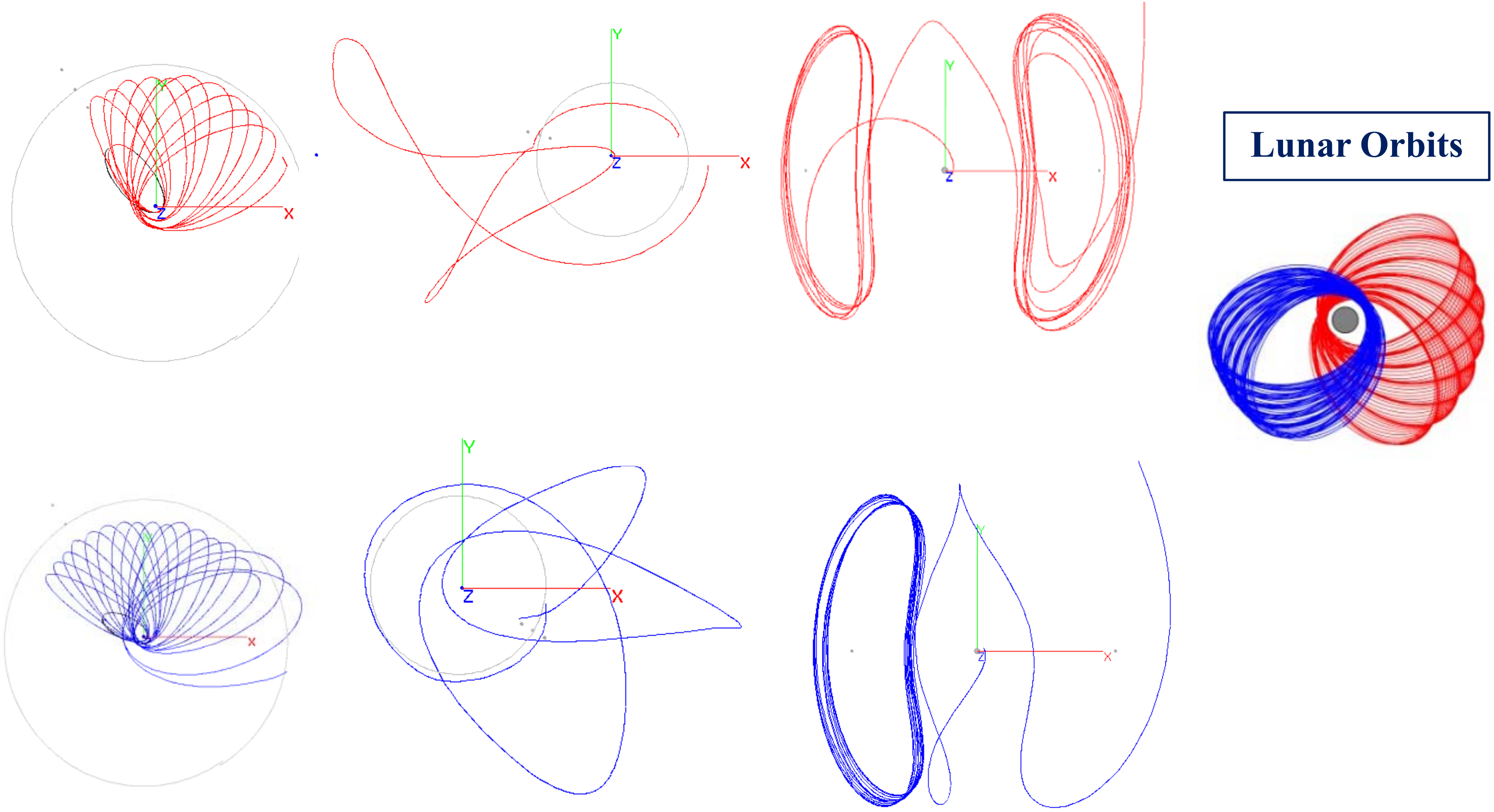
Translunar Trajectory

Lissajous Orbits

Lunar Orbits

P1

P2



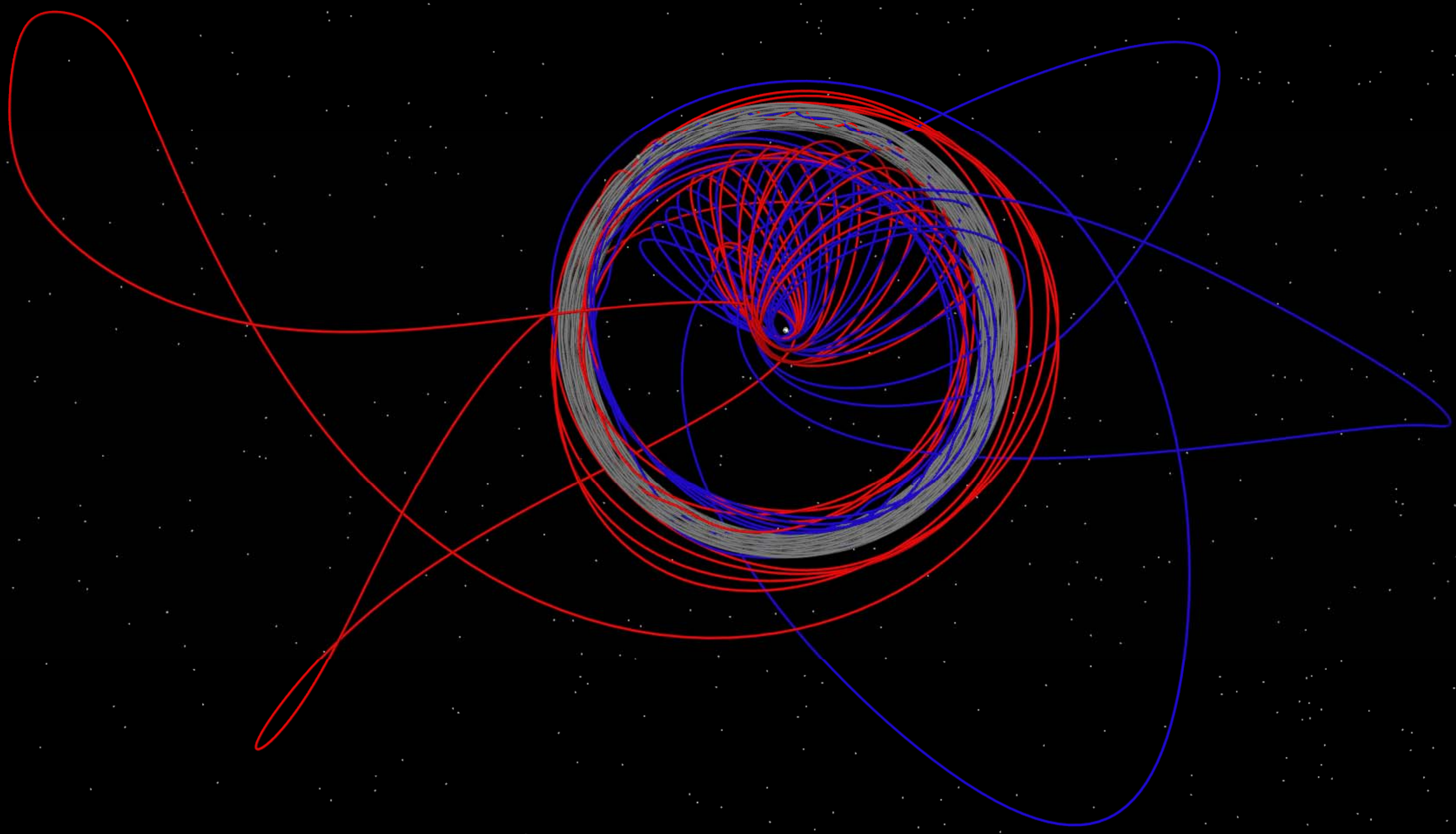
Phase 1

Phase 2

Phase 3

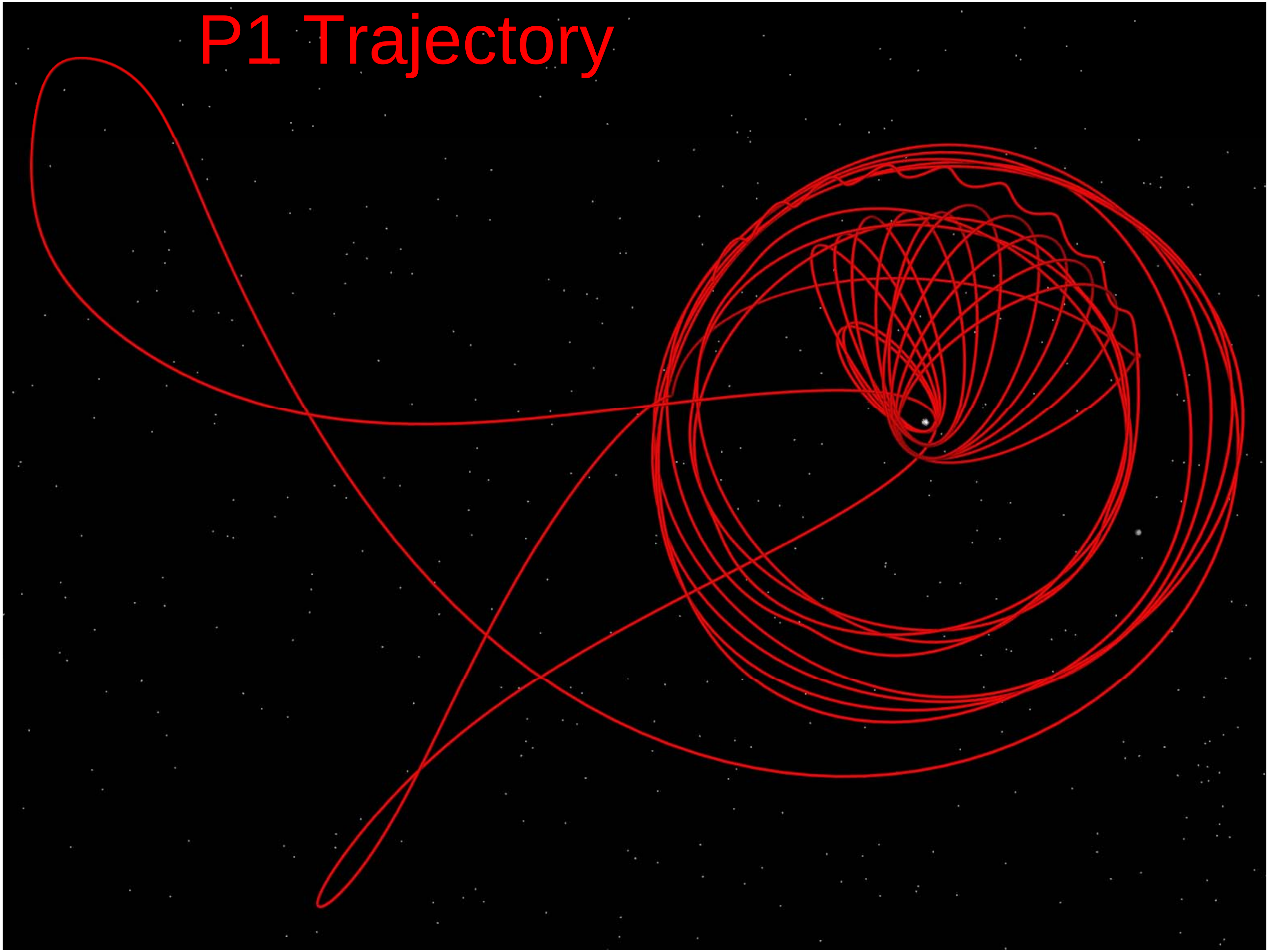
Phase 4

Artemis P1 /P2 Baseline Trajectory

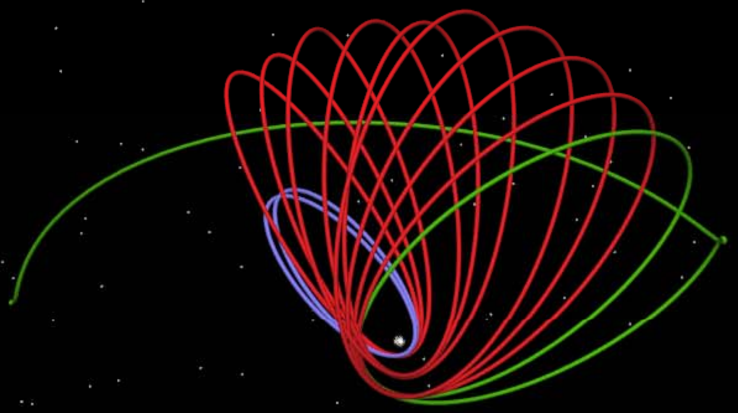


Frame: S-E Rotating (Earth-Centered)

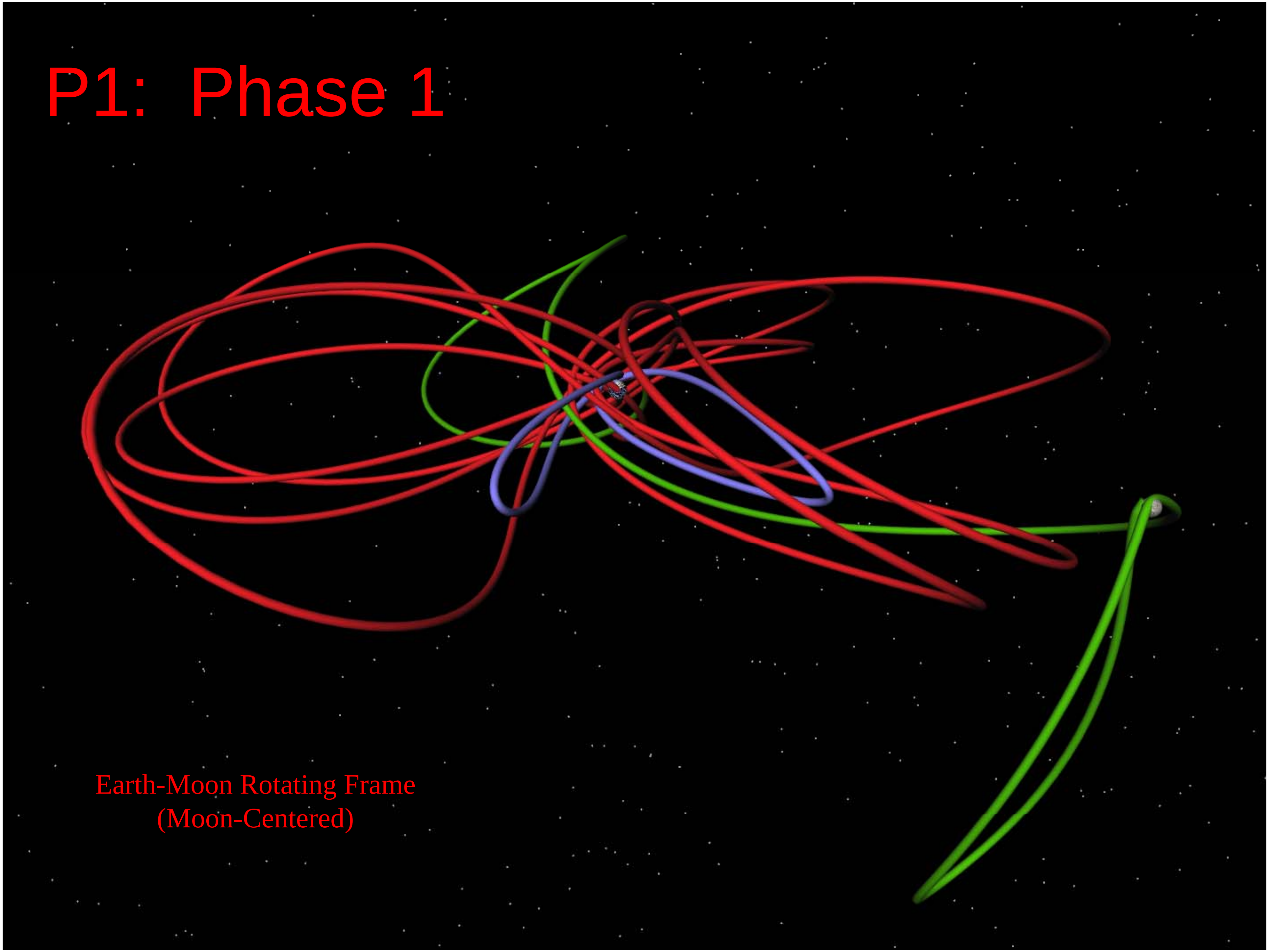
P1 Trajectory



P1: Phase 1

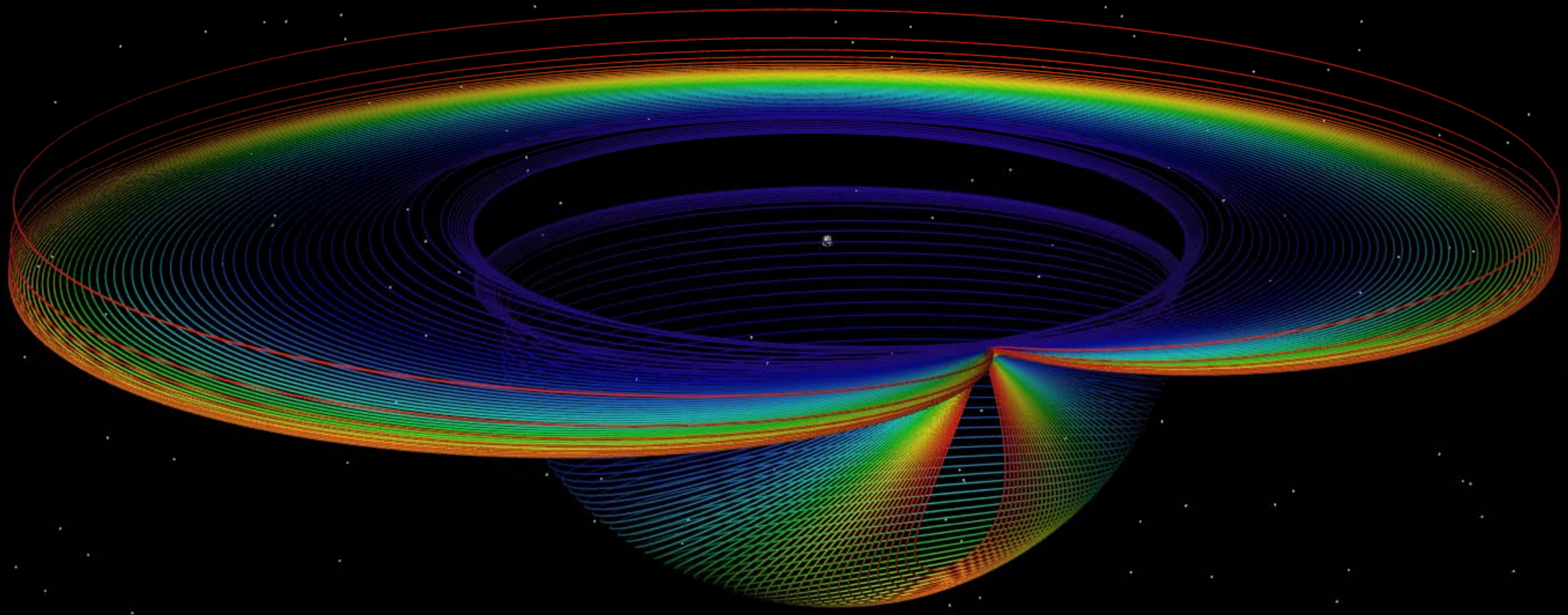


P1: Phase 1



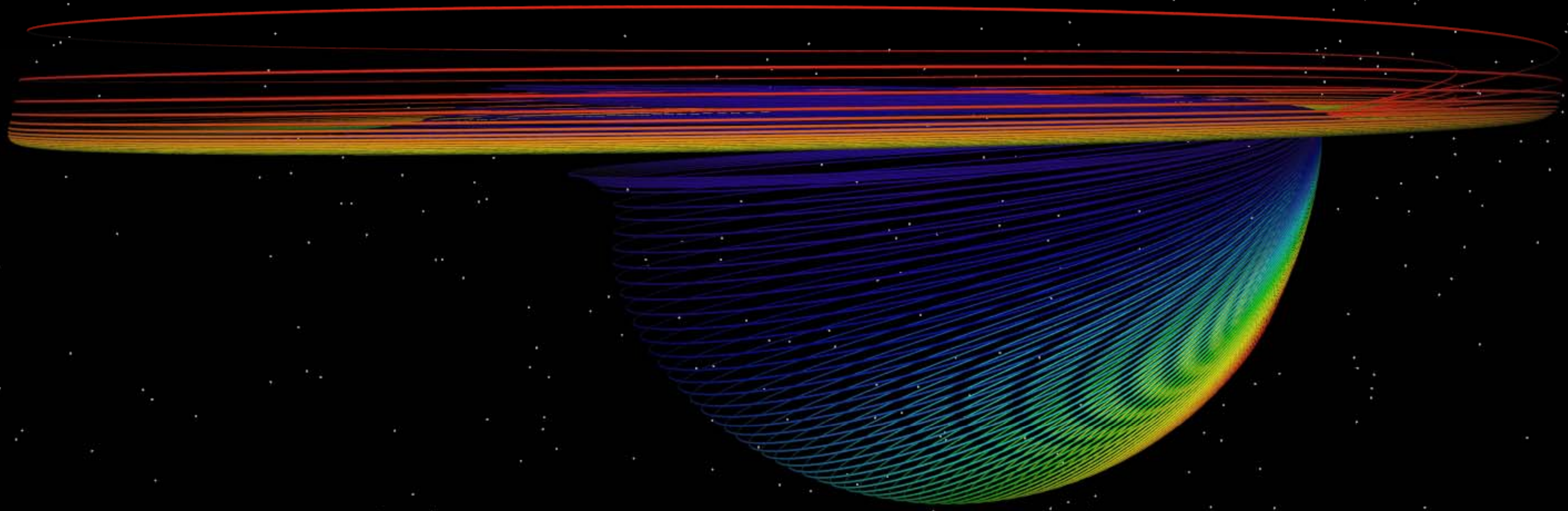
Earth-Moon Rotating Frame
(Moon-Centered)

P1 Backflip Family



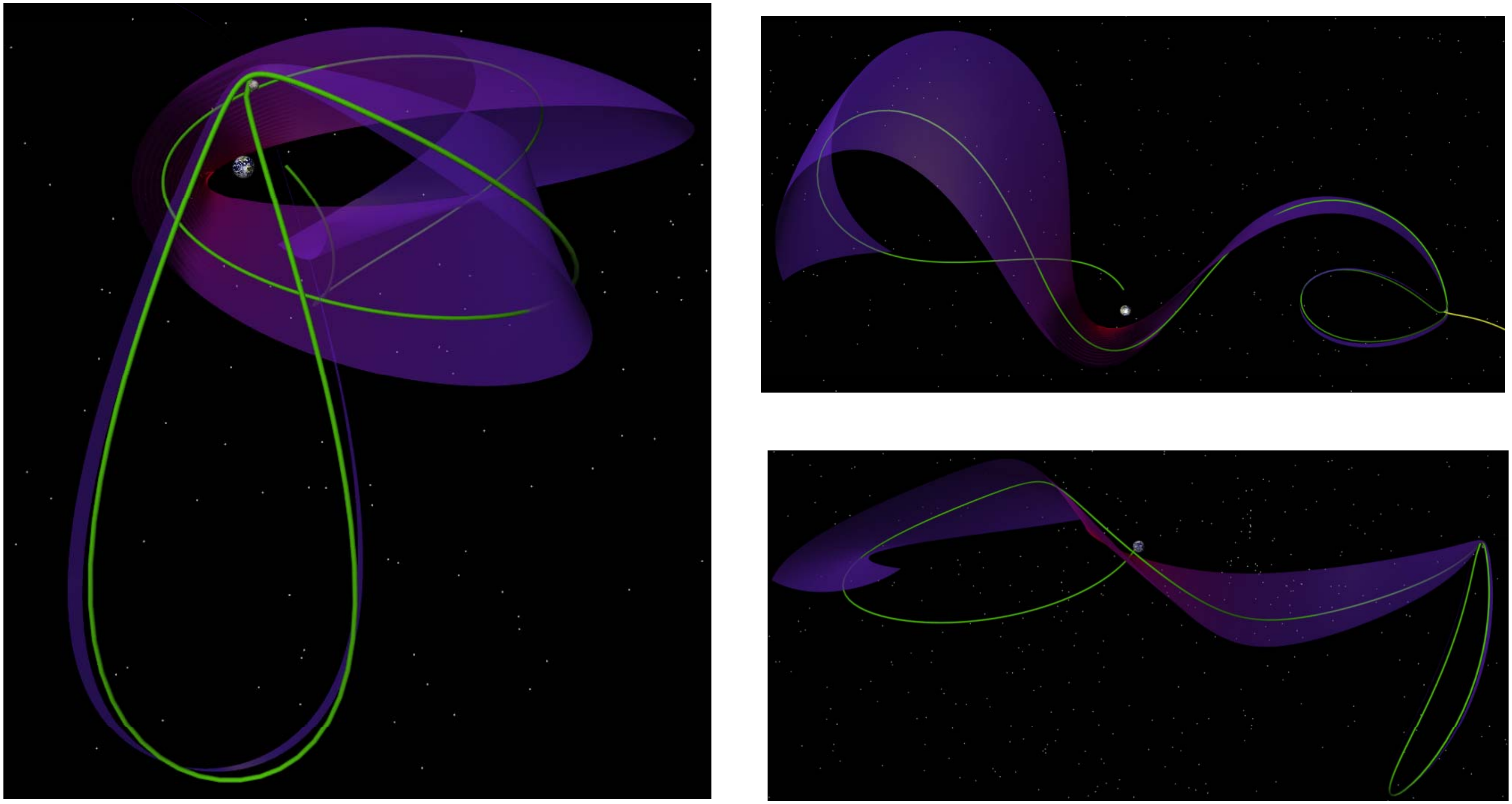
Earth-Moon Rotating Frame
(Moon-Centered)

P1 Backflip Family

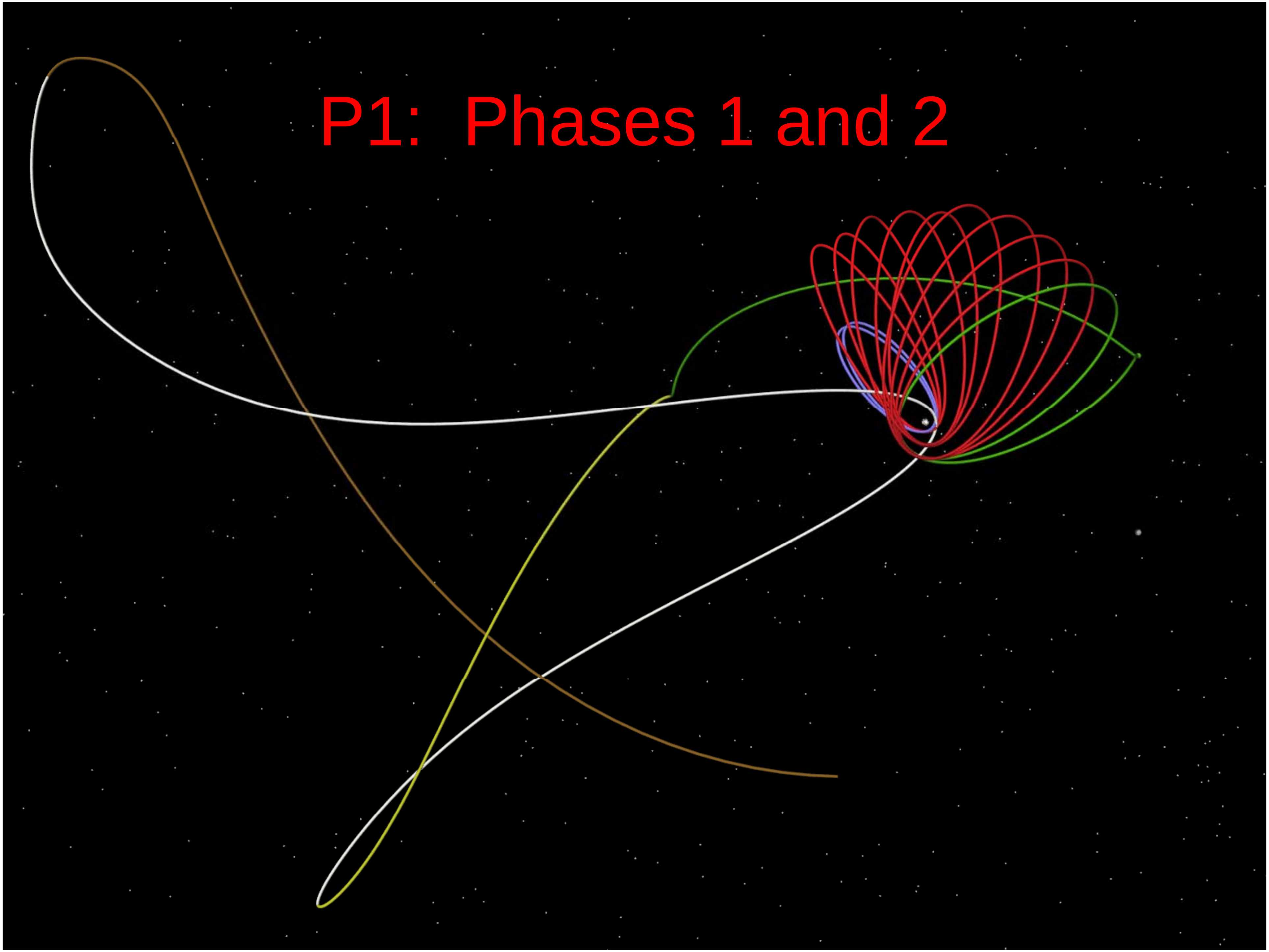


Earth-Moon Rotating Frame
(Moon-Centered)

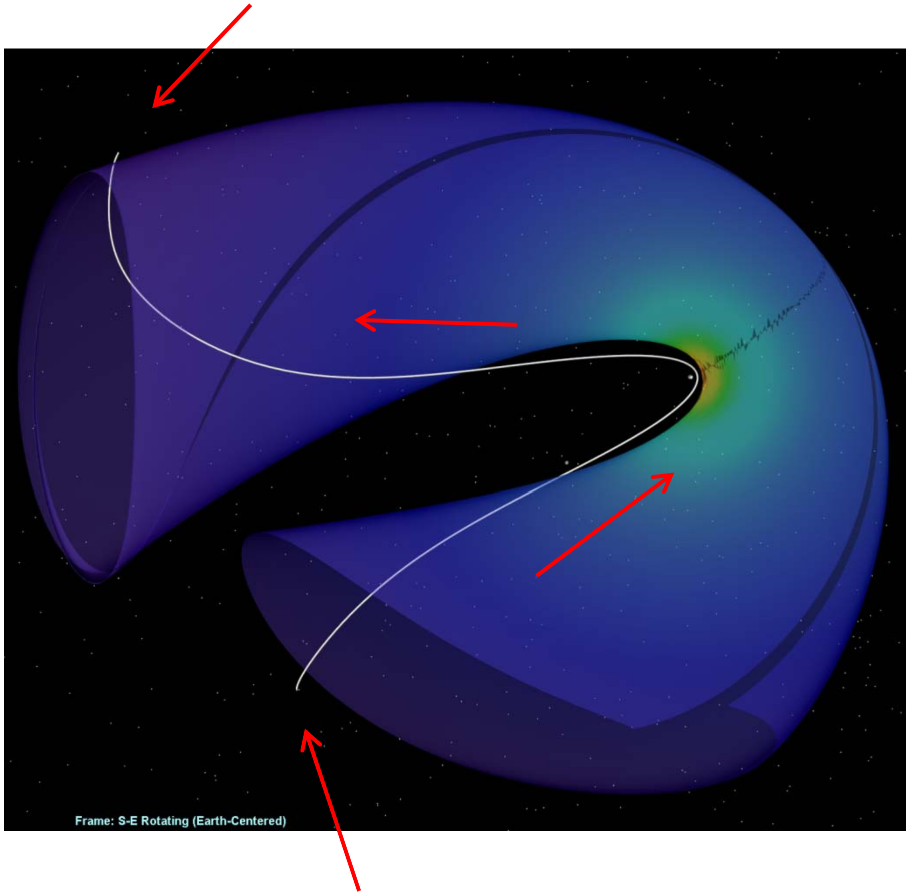
Backflip Stable Manifold
Earth-Moon Rotating Frame



P1: Phases 1 and 2



P1 Phase 2



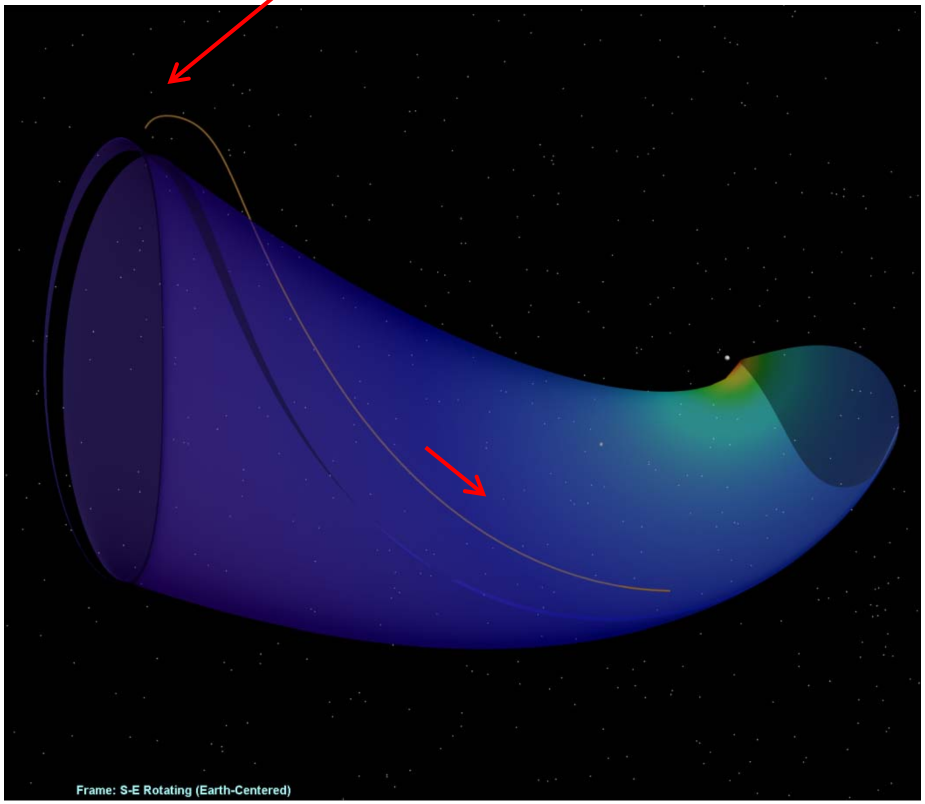
Max Range

Deep-Space Maneuver (DSM)

- **DSM on 2010 March 15**
- **Sun-Earth L_1 Lissajous Stable Manifold**

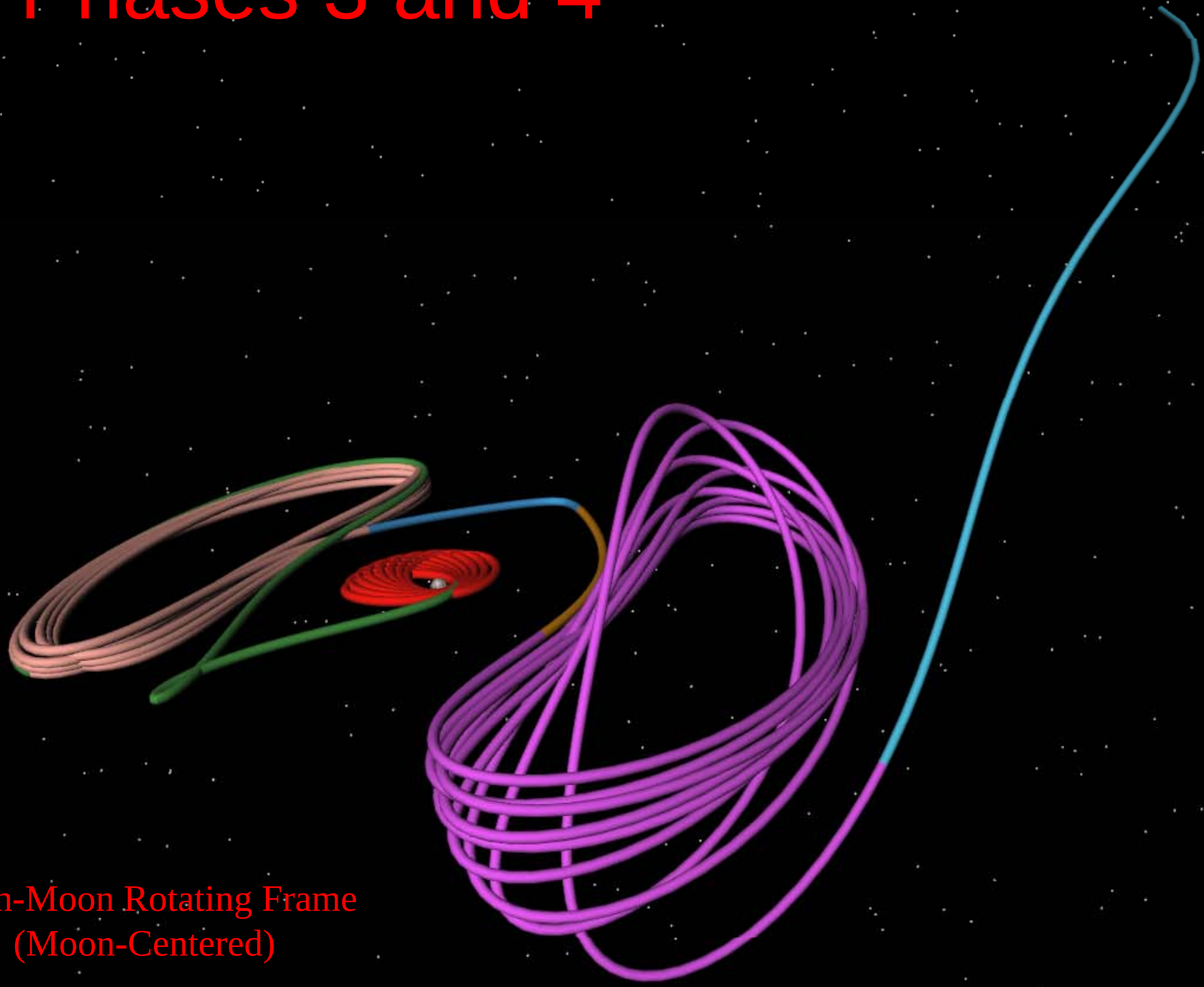
P1: Phase 2

- Max Range (6-Jun-2010)
- Trajectory and Sun-Earth L_1 Lissajous Unstable Manifold



Max Range

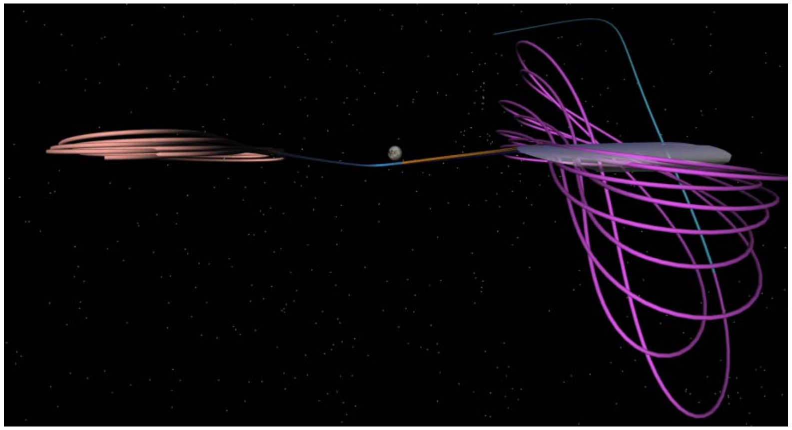
P1: Phases 3 and 4

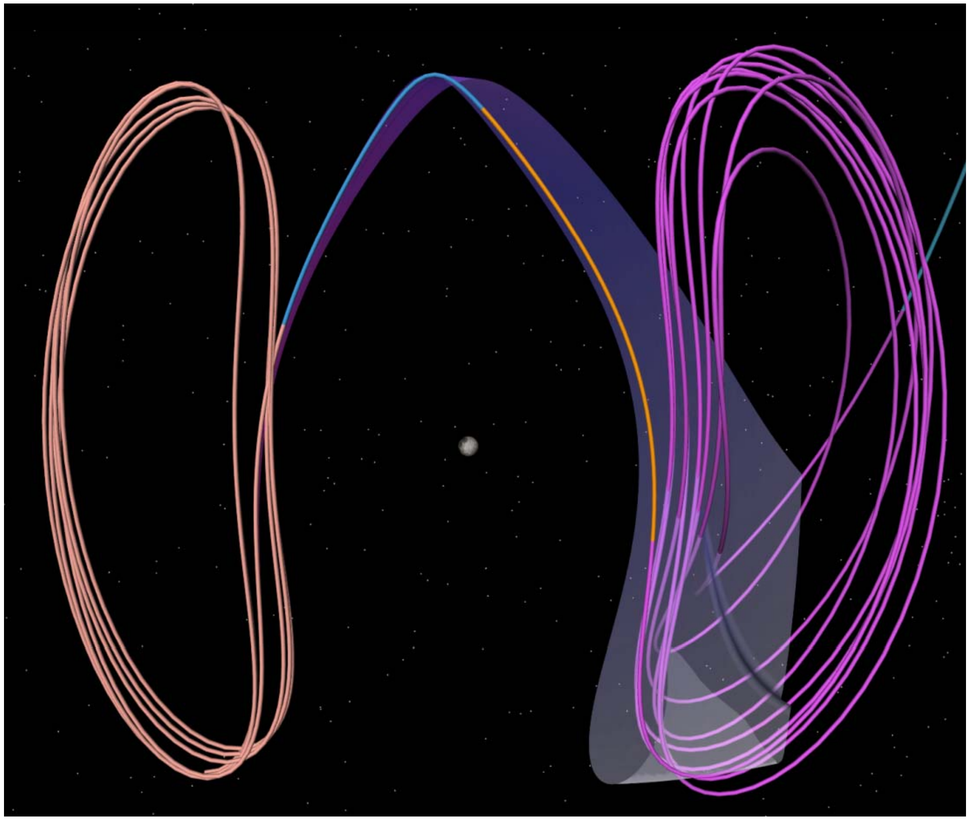


Earth-Moon Rotating Frame
(Moon-Centered)

P1 Phase 3
Two viewpoints on the L_1 to L_2 transfer

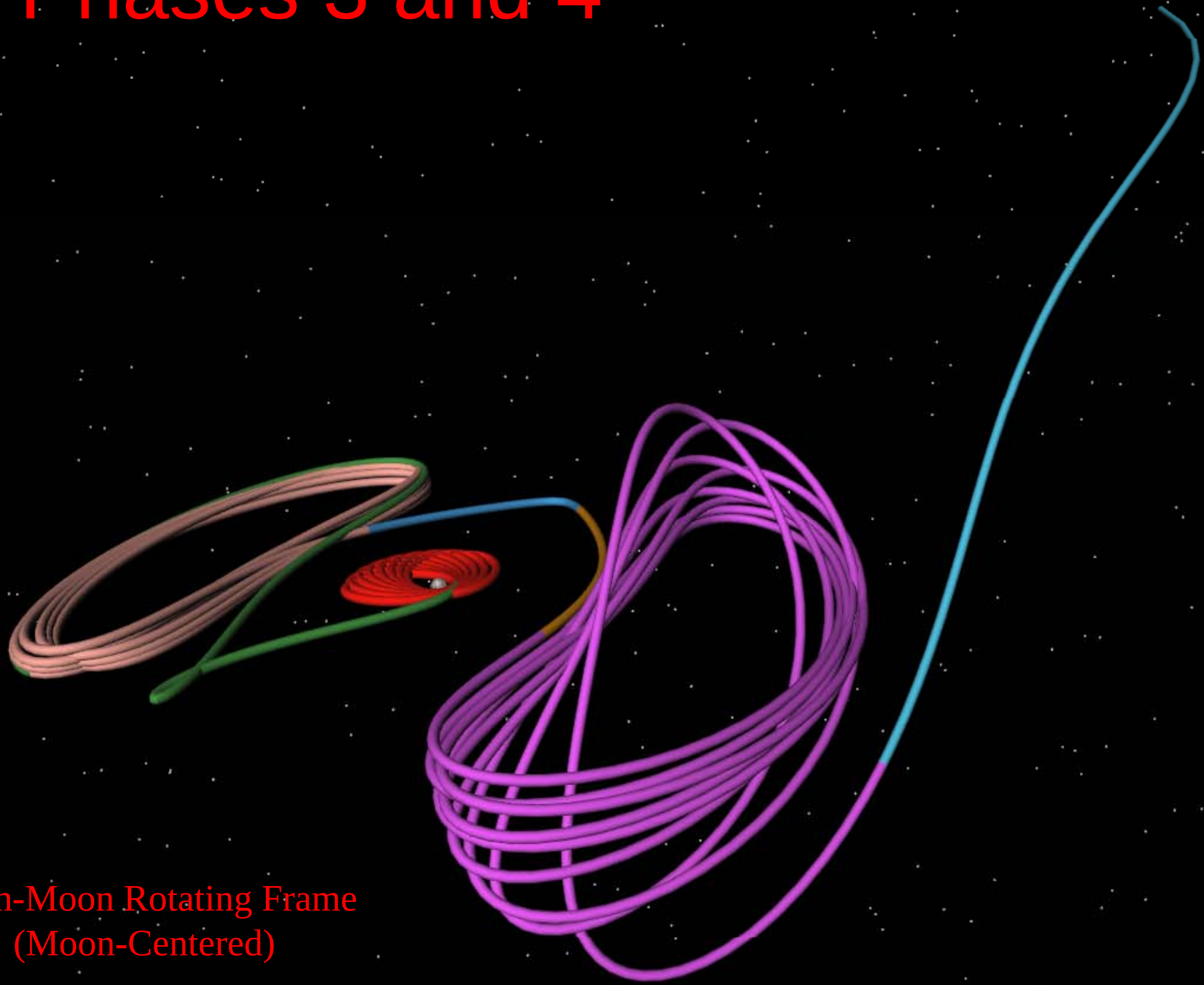
- **Simultaneously matches the stable manifold surface associated with the**





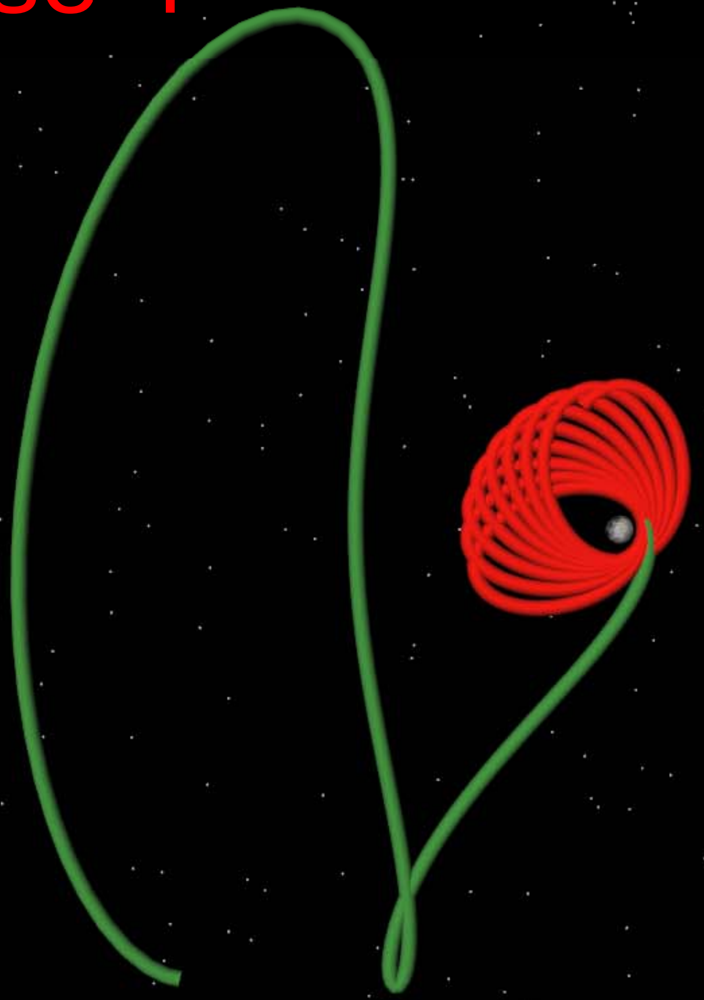
P1Phase3

P1: Phases 3 and 4



Earth-Moon Rotating Frame
(Moon-Centered)

P1: Phase 4



Earth-Moon Rotating Frame
(Moon-Centered)

Artemis P1 /P2 Baseline Trajectory Design