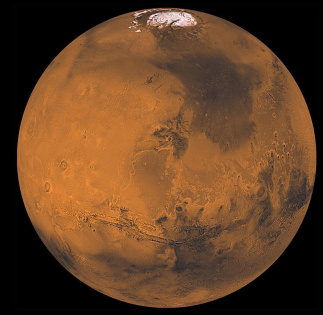
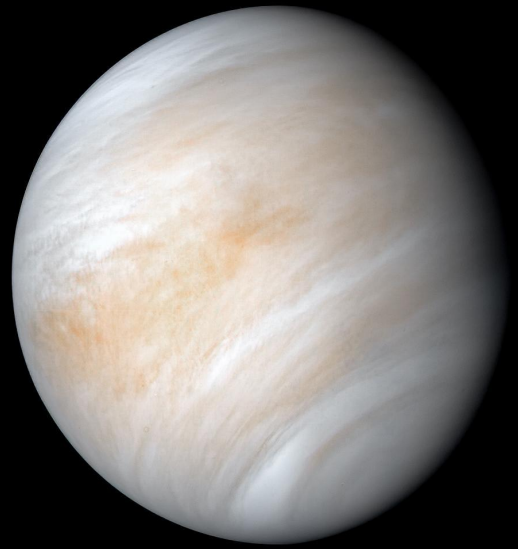


Venus Science Enabled by Human Proximity Workshop

Keck Institute for Space Studies

Human Mars Mission
Interplanetary Trajectories Perspective



Patrick R. Chai
Exploration System Development Mission Directorate
Mars Architecture Team

Background

- Mars “Opposition Class” missions have been of interest recently to enable shorter roundtrip missions to Mars; these mission can utilize Venus flybys to help reduce the total energy required

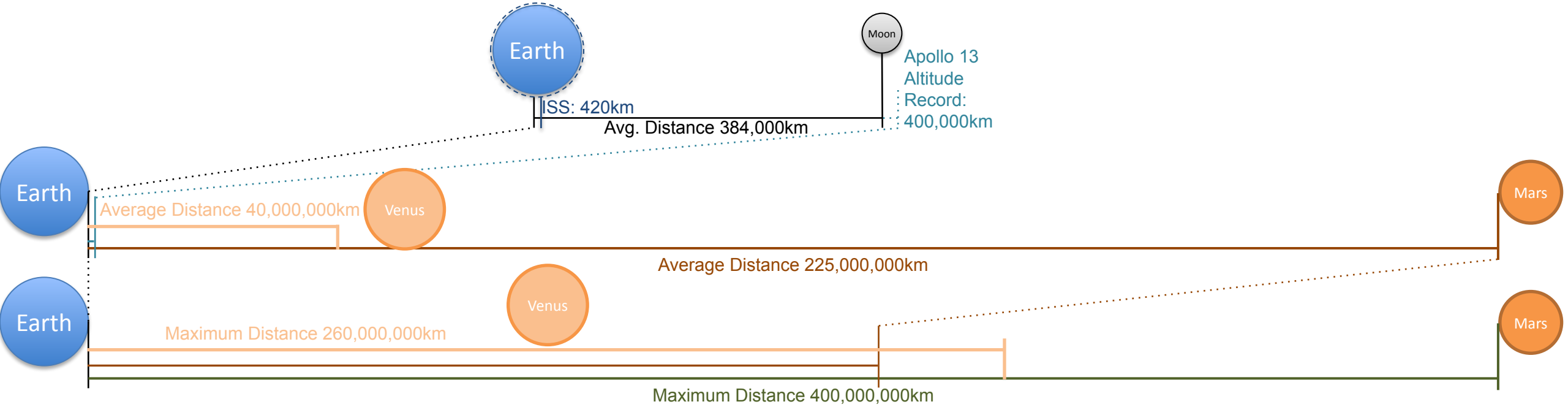
- Compared to longer minimum energy “Conjunction Class” missions which utilize the planet’s natural motion around the Sun to minimize the roundtrip energy

- ESDMD Mars Architecture Team (MAT) has been performing analysis to define the trade space and integrate with internal and external stakeholders to help identify potential options

Deep Space Mission "Change of Reference"

Earth is no longer the center of the reference frame

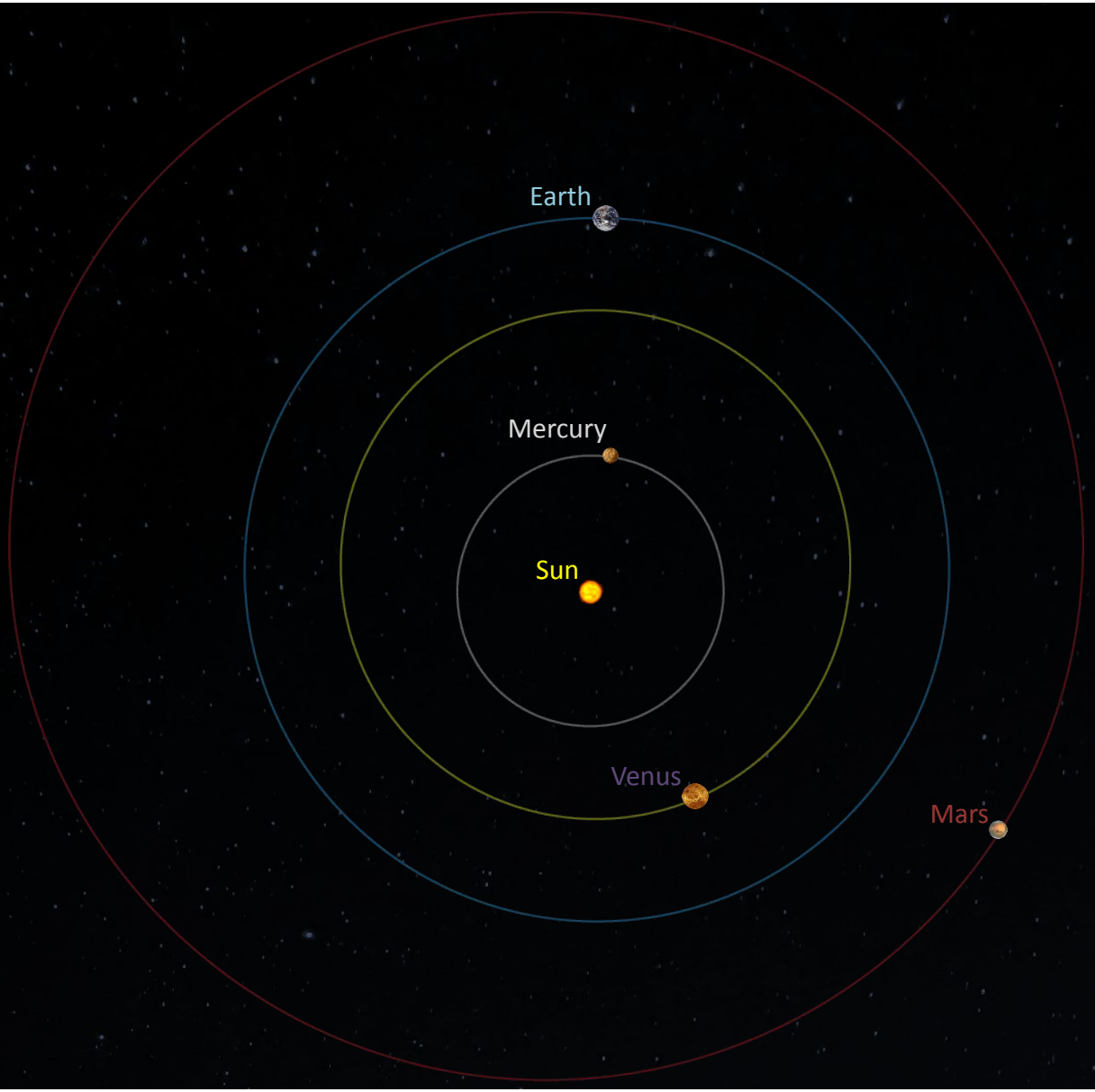
All scales and reference of existing human spaceflight are no longer representative



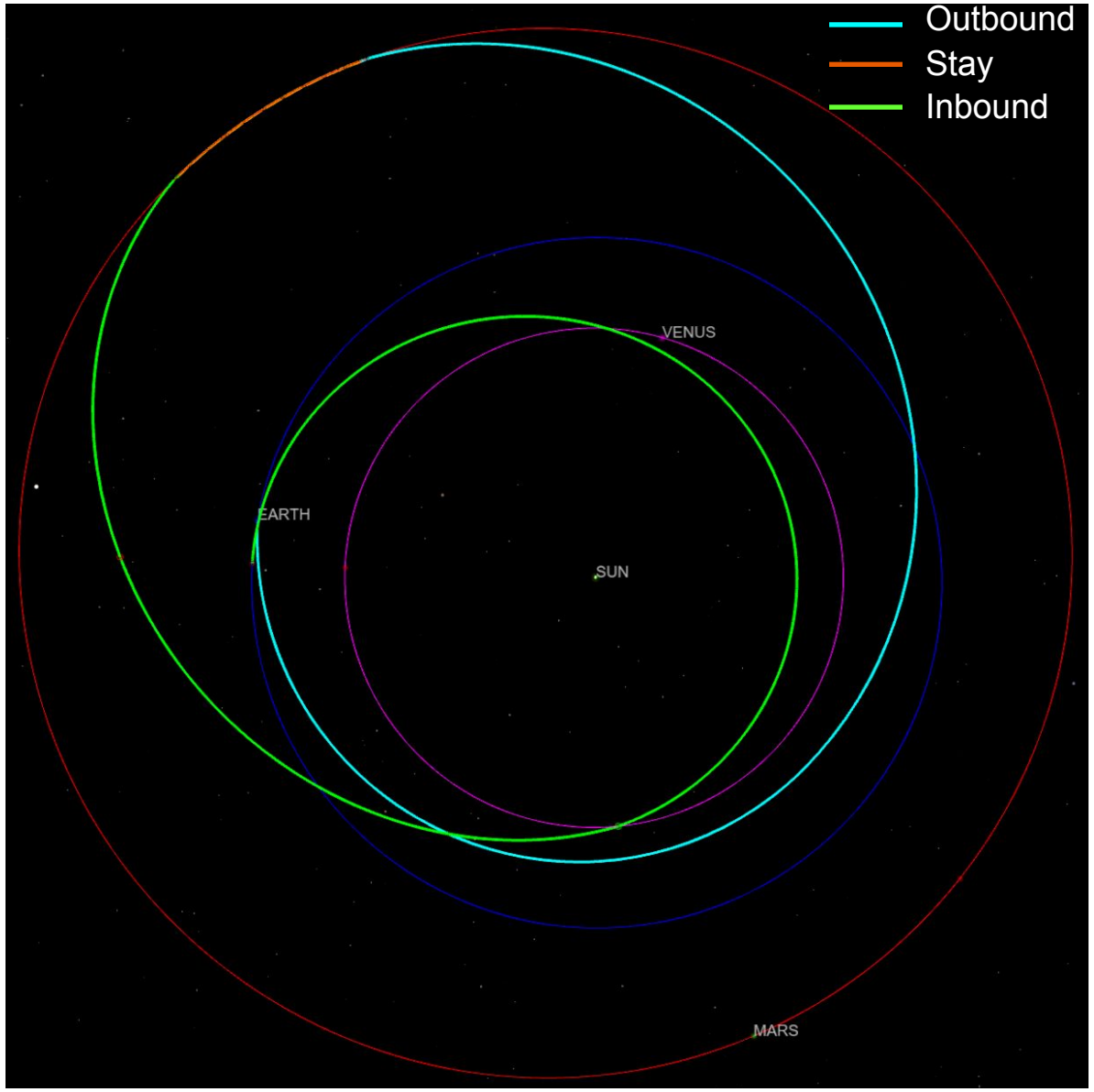
Roundtrip Distance Traveled will be Significantly More!

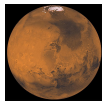
Getting to Mars or Venus

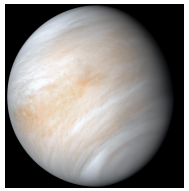
- Interplanetary Transits are governed by heliocentric orbital dynamics
- Relative Velocity between Planets & Spacecraft will dictate the energy required
- Phasing is most important, must depart and arrive at the right time to minimize energy



Example Mars + Venus Flyby Mission

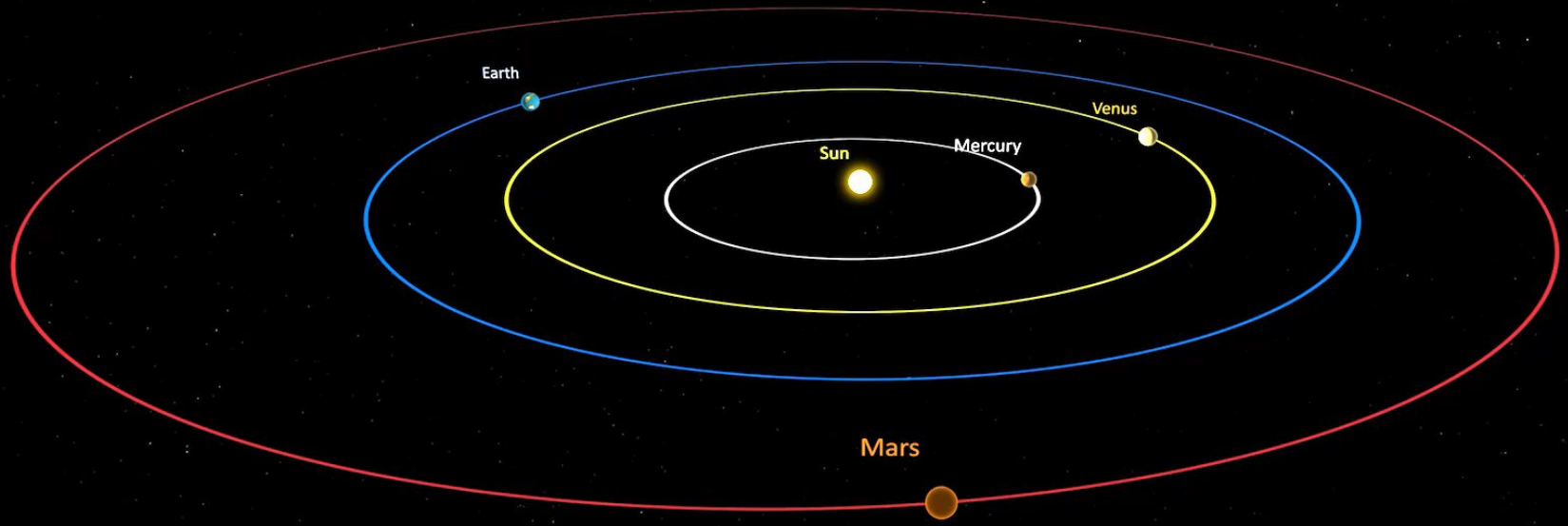






2039 High Energy Roundtrip Mission to Mars with a Venus Flyby		
From 400x400,000 km High Earth Orbit To: 1-Day Period Elliptical Mars Orbit		
Earth Departure	03/11/2039	
Mars Arrival	01/29/2040	
Mars Departure	03/20/2040	
Venus Flyby	10/05/2040	
Earth Arrival	03/18/2041	
Outbound	324	
Stay	51	
Inbound	363	
Total	738	Days
Total ΔV	8,867	m/s

Visualization of Example Mars Mission with Venus Flyby



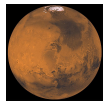
DAY 0

DAY 574 2040/10/05 16:08:06

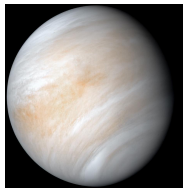
Venus Close Approach:
~3,000 km Above Surface

Total Close Approach Time:
~20 minutes

Example Direct Roundtrip Mission Comparisons

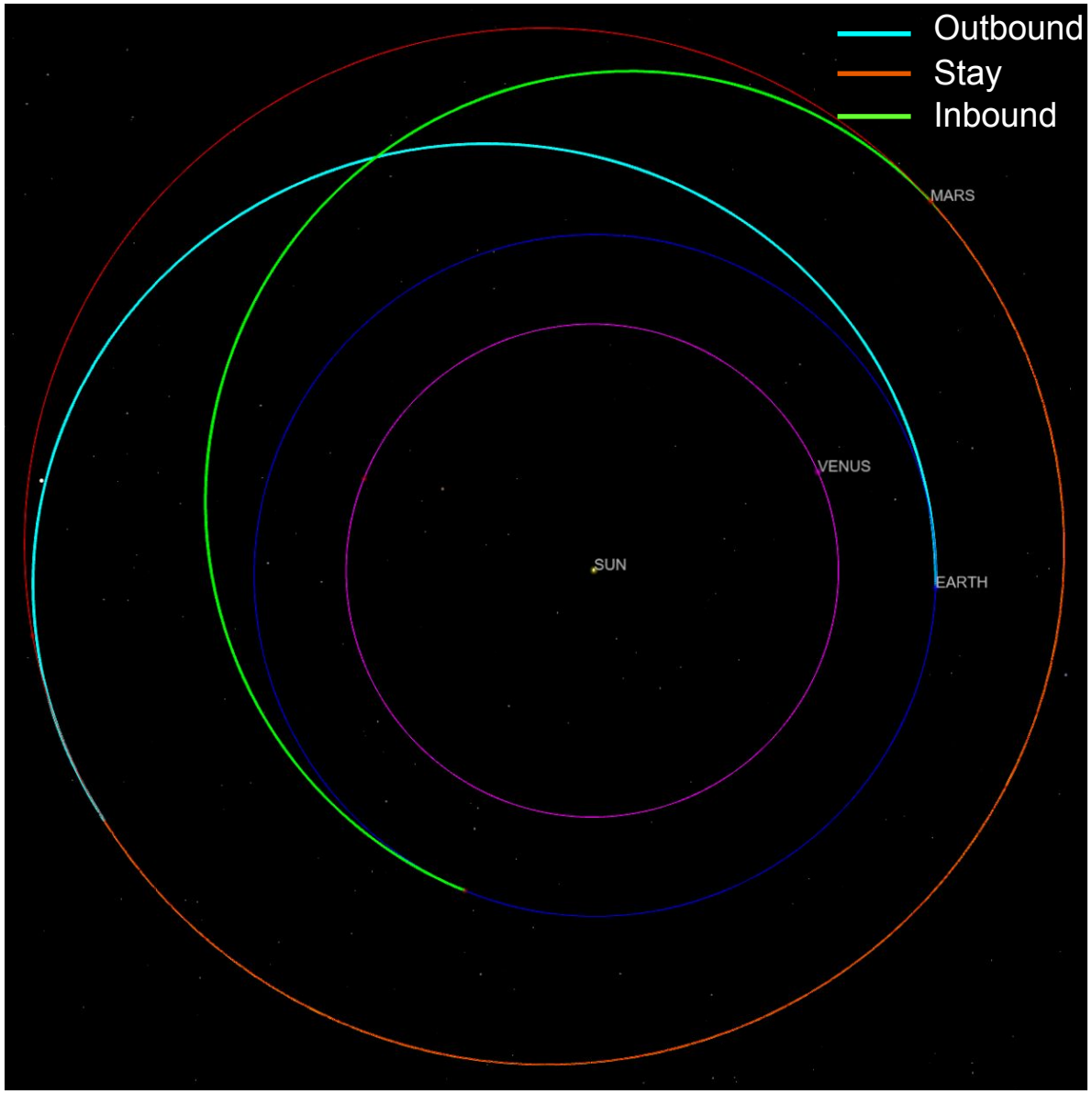


2039 Minmum Energy Roundtrip Mission to Mars		
From 400x400,000 km High Earth Orbit To: 1-Day Period Elliptical Mars Orbit		
Earth Departure	09/20/2039	
Mars Arrival	08/25/2040	
Mars Departure	08/07/2041	
Earth Arrival	05/29/2042	
Outbound	340	
Stay	347	
Inbound	296	
Total	982	Days
Total ΔV	2,952	m/s

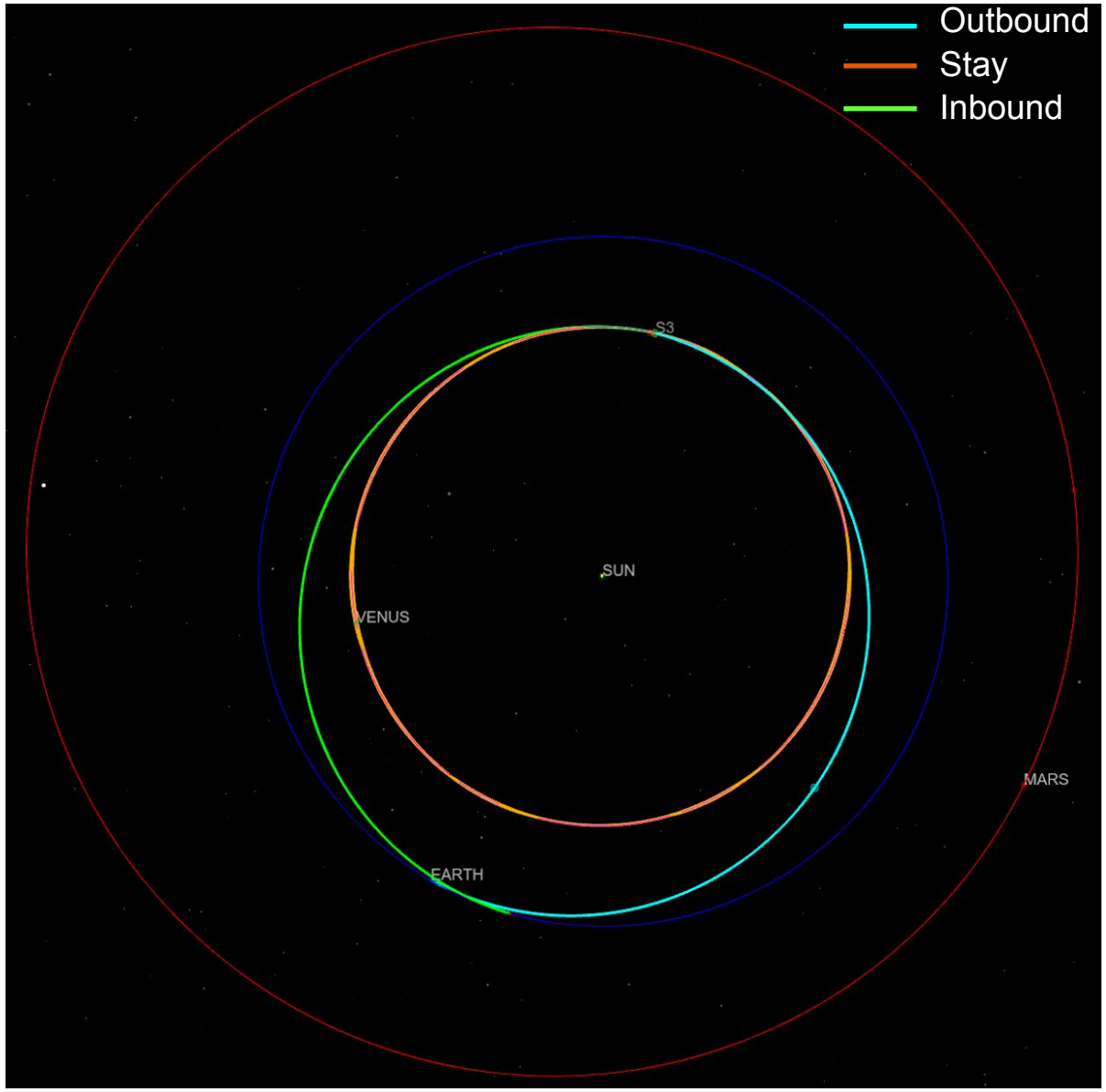


2039 Minimum Energy Roundtrip Mission to Venus		
From 400x400,000 km High Earth Orbit To: 1-Day Period Elliptical Venus Orbit		
Earth Departure	07/20/2039	
Venus Arrival	12/22/2039	
Venus Departure	03/17/2041	
Earth Arrival	08/04/2041	
Outbound	155	
Stay	450	
Inbound	140	
Total	745	Days
Total ΔV	2,218	m/s

Example Roundtrip Mission Comparisons



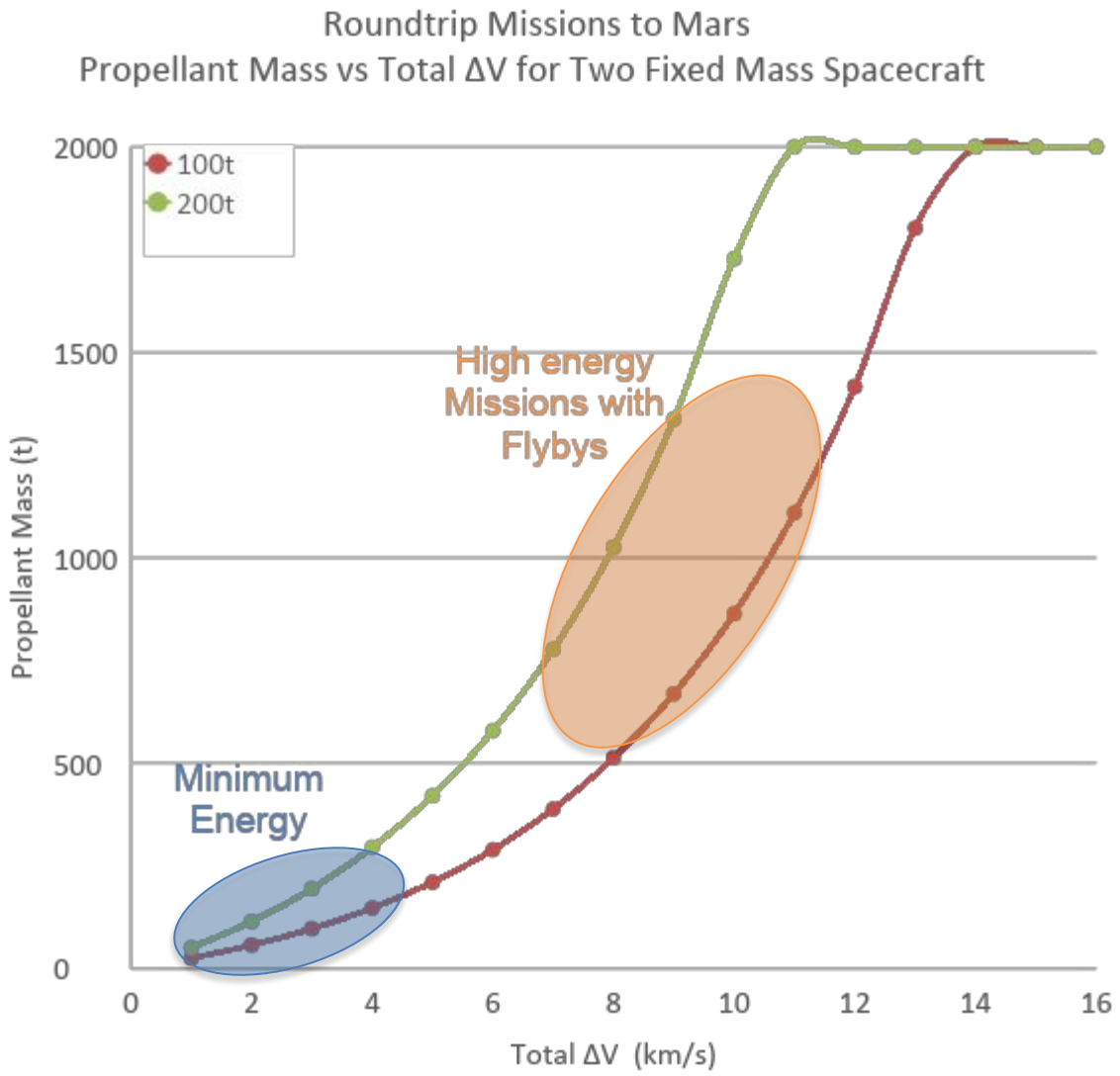
2039 Minimum Energy Roundtrip to Mars – 982 Day Roundtrip



2039 Minimum Energy Roundtrip to Venus – 745 Days Roundtrip

The Energy cost

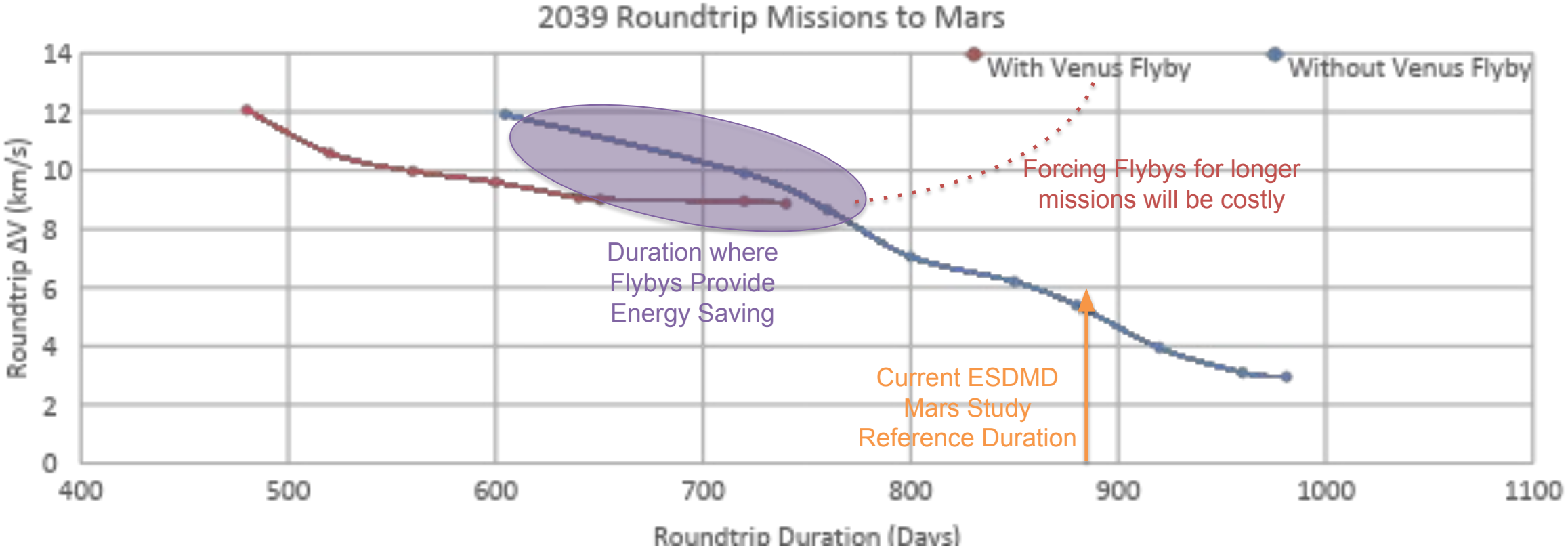
- ΔV requirement translates to an exponential growth in mass
- Figure shows the propellant mass required for a 100t and 200t spacecraft (including habitation) with chemical propulsion system
- Minimum Energy Roundtrip mission ΔVs are in the 2-4 km/s range
- Mars + Venus Flyby missions ΔVs are in the 7-10 km/s range



When does it make sense?

- **Venus flyby in the context of a Mars mission would help reduce the energy required, but only for very short duration missions to Mars**

- **These missions are very high energy and require significant amount of mass to be launched and assembled in orbit**



Summary

- Conjunction (minimum energy) vs Opposition (high energy) has been a big part of the talking point, with opposition enabled by Venus flybys
- Mars and Venus missions trade space is not bimodal, but rather a continuous space with regards to mission duration
- Direct missions to Venus are somewhat comparable to Mars, but more analysis will be needed to understand the trade space
- Venus flybys as part of a Mars mission are only worthwhile if total mission duration is suppressed, and will require significant technology investment and/or large number of launches to assemble the spacecraft