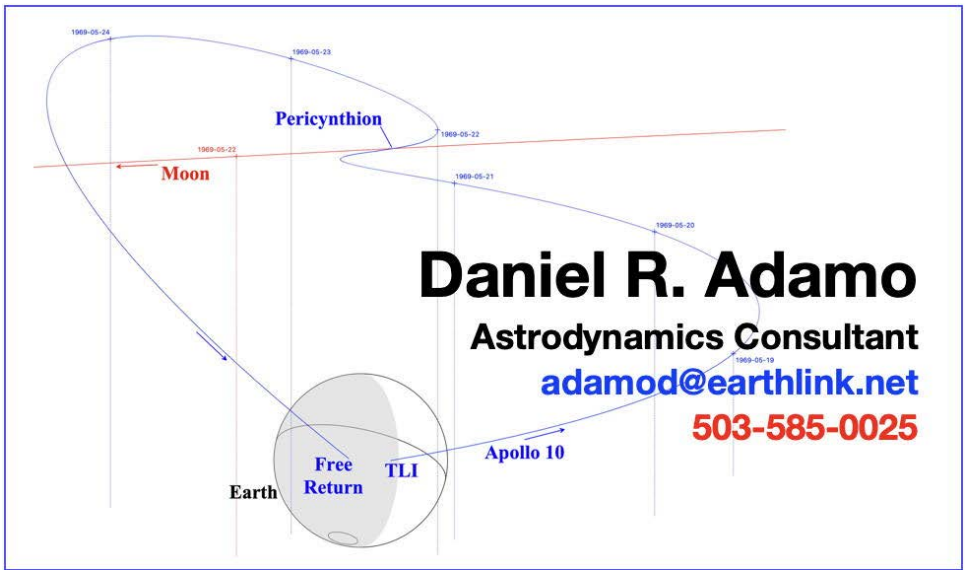
Spanning The Earth/Mars Chasm
With Interplanetary Synodic-Resonant Waypoints

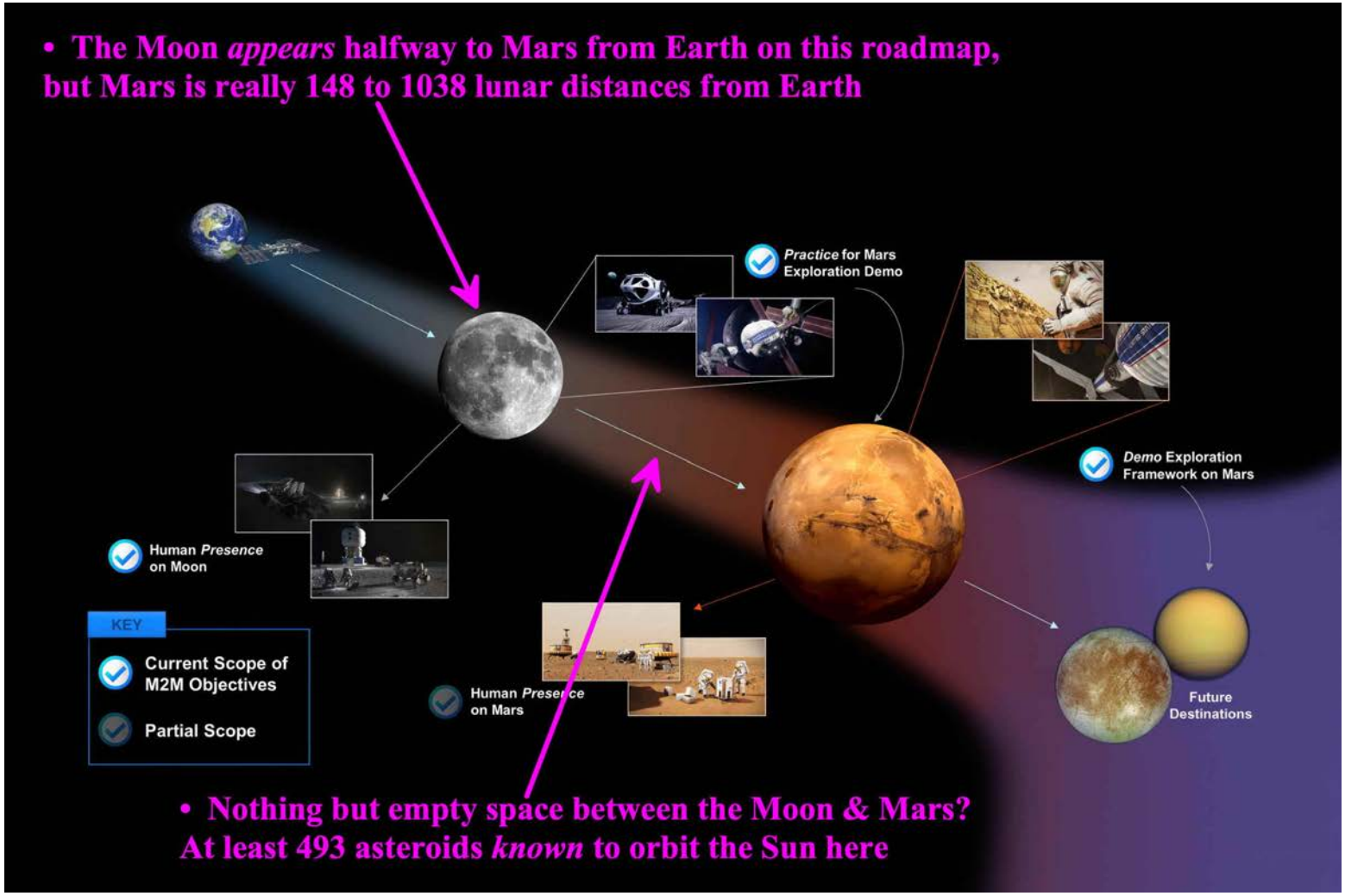


AIAA Houston Section Lunch 'n Learn (LnL)

18 March 2025

Interplanetary Synodic-Resonant Waypoints (WPs)

The Chasm: What's Wrong With NASA's Moon to Mars (M2M) Roadmap?[1]



[1] Reference https://www.nasa.gov/wp-content/uploads/2023/04/m2m_strategy_and_objectives_development.pdf?emrc=c21aff?emrc=c21aff, p. 6 (accessed 12 Mar 2025).

Interplanetary Synodic-Resonant Waypoints (WPs)

No Wonder We've Remained About 20 Years From Landing Humans On Mars Since Dr. Wernher von Braun First Addressed The Problem in 1948[2]

- Mars is orders of magnitude more remote than the Moon: add a "not to scale" disclaimer to the M2M roadmap and reduce mistaken "Mars is easy" expectations among stakeholders
- Add interplanetary "waypoints" (WPs) to the M2M roadmap and reduce travel far from aid/haven

Transport Technology Solves Difficult Problems By Decomposing Them Into More Tractable "Stages"

- Before railroads, *stage*coaches swapped spent horses for fresh ones at strategic depots
- Missouri-to-California mail delivery via Pony Express relay in about 10 days circa 1860
- Single stage to Earth orbit capability remains elusive: only multi-stage rockets in use today
- If it's so difficult/dangerous, why do we insist on flying humans from Earth to Mars nonstop?
  - Place WPs in orbit about the Sun between Earth and Mars at which to routinely loiter en route, topping off consumables and optionally delivering or supplementing payload mass
  - Select WP orbits providing maximum availability naturally, with minimal propulsion

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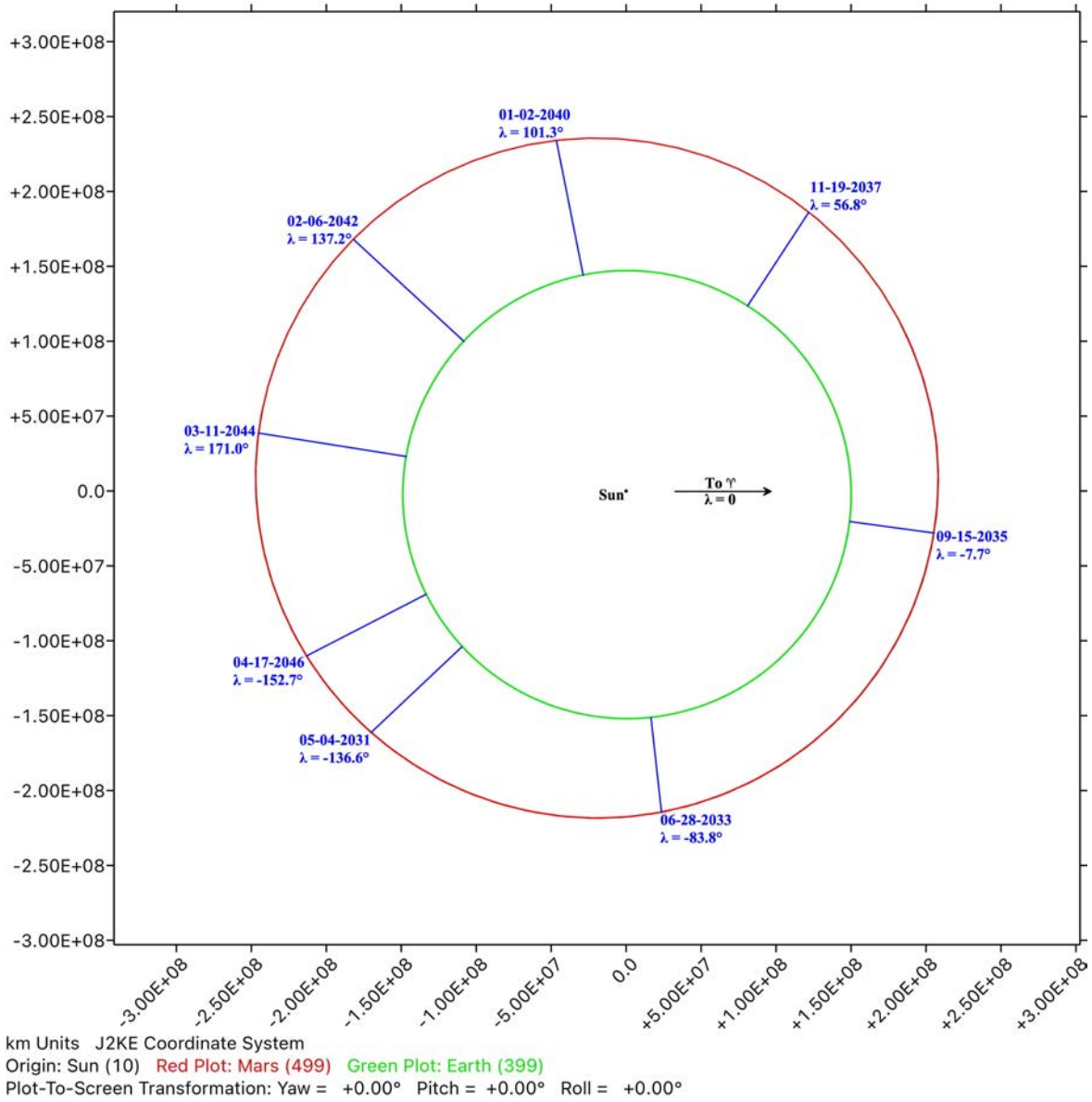
[2] Reference https://en.wikipedia.org/wiki/The_Mars_Project (accessed 12 Mar 2025).

Interplanetary Synodic-Resonant Waypoints (WPs)

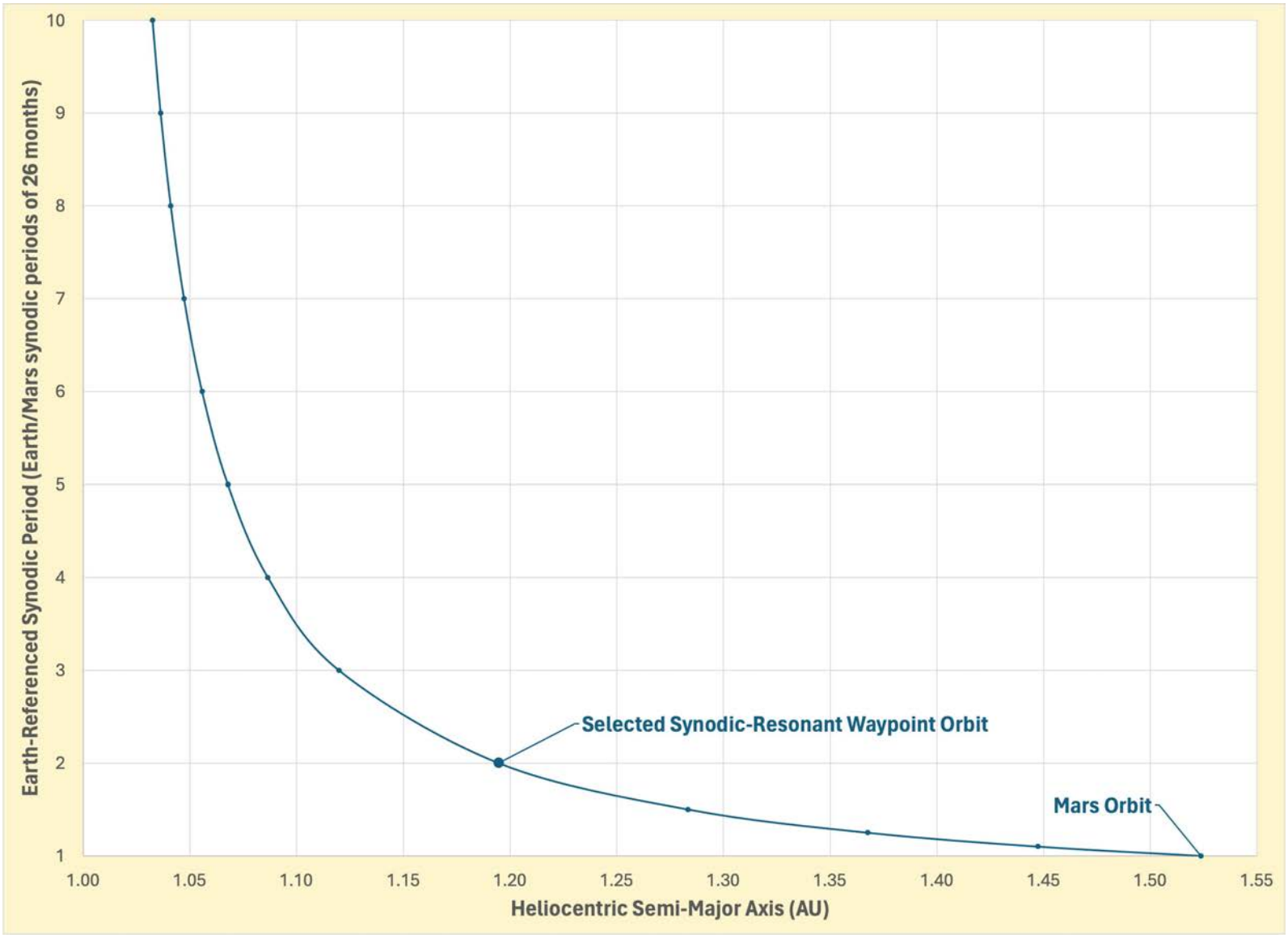
Earth/Mars Transit Opportunities Arise When Mars Is Near Opposition



- Average time between oppositions is 26 months, the synodic period τ of Mars referenced to Earth
- Because τ is 2 months more than 2 years, successive oppositions advance in ecliptic longitude λ by about 360*2/12 = 60°
- Due to Mars orbit eccentricity, intervals between opposition dates vary as they cycle through λ over 15 years, a *synodic sequence* T_S

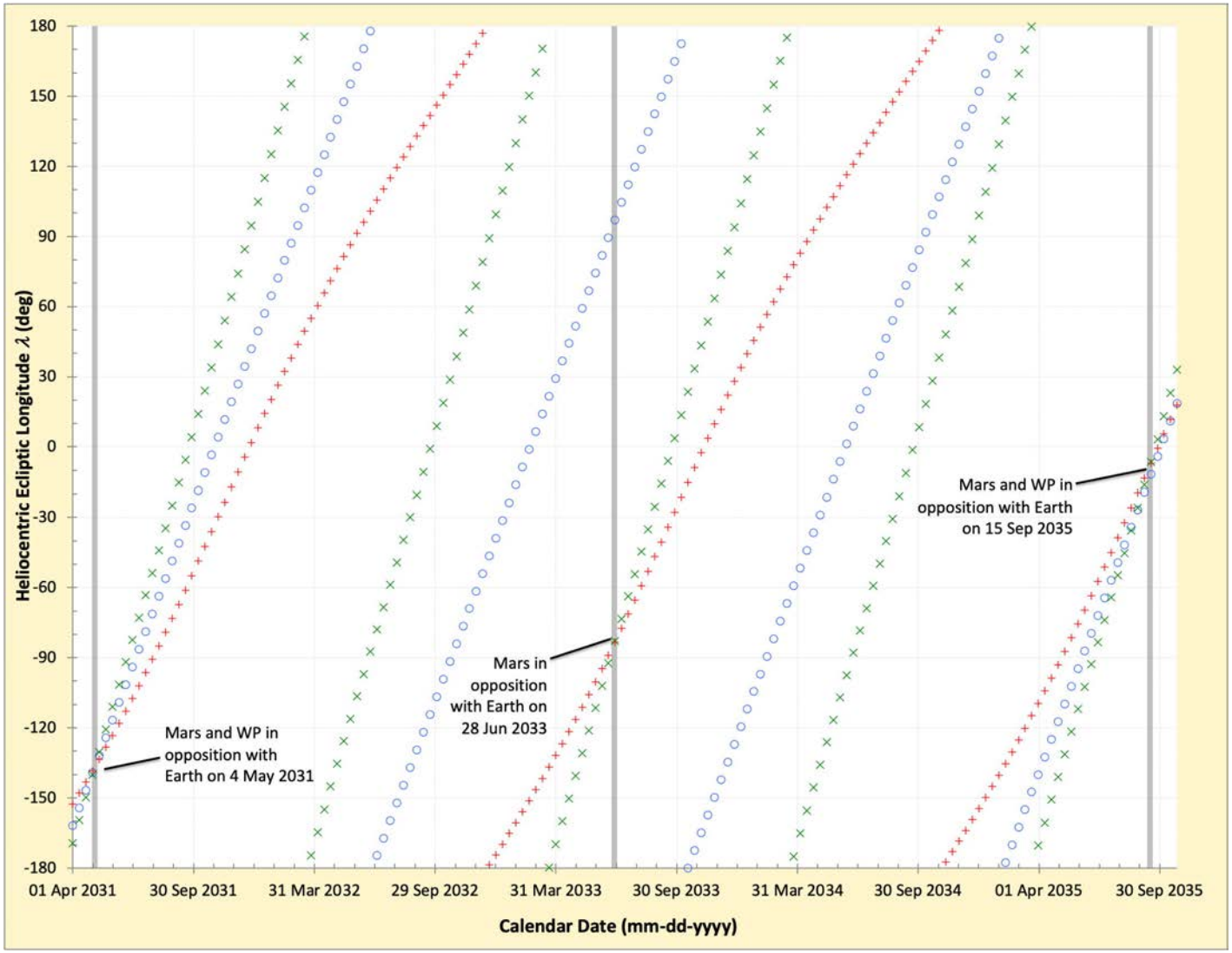
Interplanetary Synodic-Resonant Waypoints (WPs)

The Selected WP Orbit Is Available During 50% Of Earth/Mars Oppositions



Interplanetary Synodic-Resonant Waypoints (WPs)

A WP Availability Cycle Plays Out Over $2\tau = 52$ Months = 4.27 Years



- X = Earth
- \+ = Mars
- ◯ = WP

with λ at 05-04-2031 opposition

$\lambda_{31} = -136.6°$

Interplanetary Synodic-Resonant Waypoints (WPs)

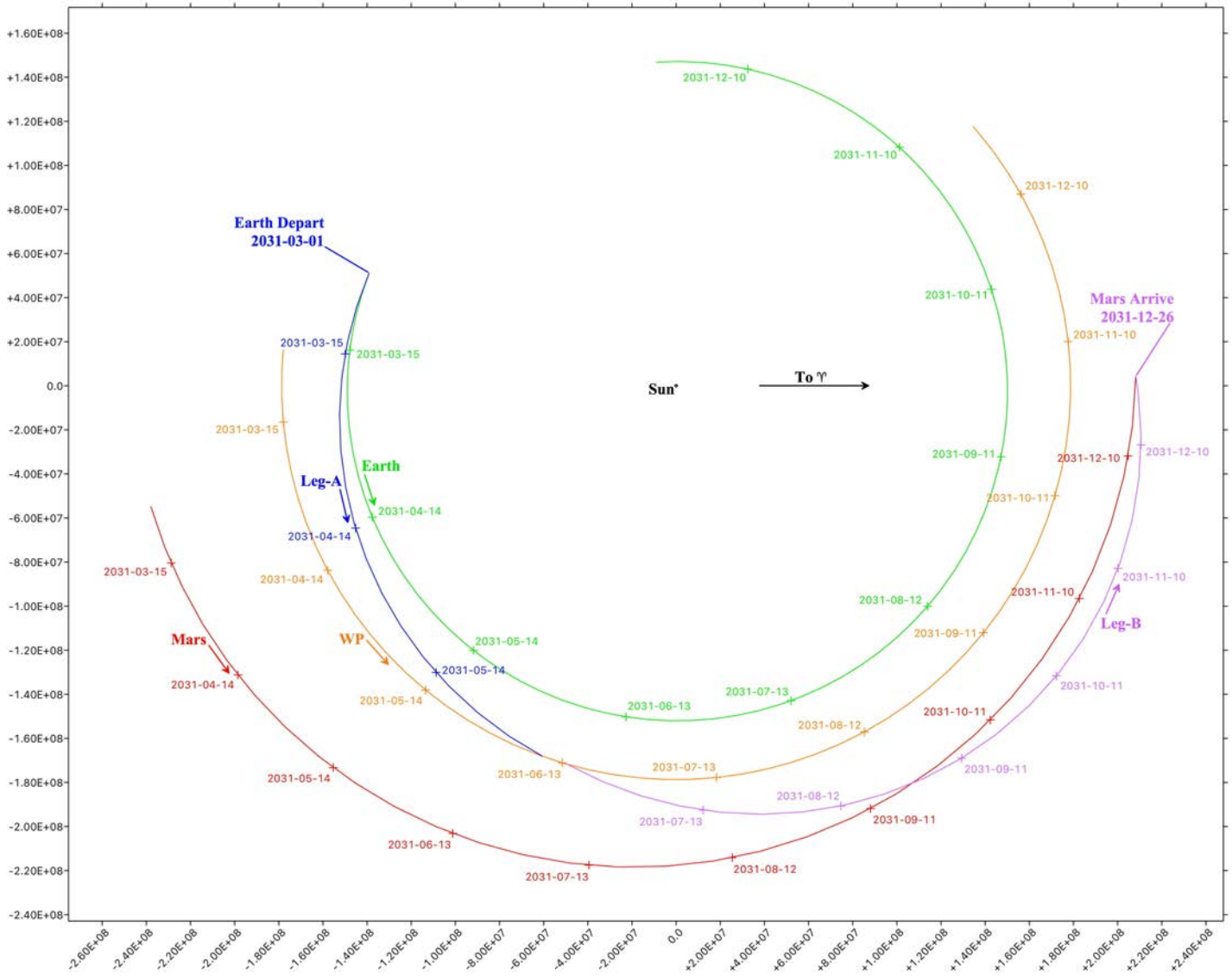
In General, A λ_{31} = -136.6° WP Is Suboptimal With Respect To Earth/Mars Transits

- Define an optimality metric $\sum v_\infty$ as the sum of four hyperbolic asymptote speeds
  - Earth-to-Mars transits are composed of Leg-A, a WP loiter, and Leg-B stages, while Mars-to-Earth transits are composed of Leg-C, a WP loiter, and Leg-D stages
  - Earth-to-Mars (Leg-AB) transit $\sum v_\infty = v_{\infty Adep} + v_{\infty Aarr} + v_{\infty Bdep} + v_{\infty Barr}$
  - Mars-to-Earth (Leg-CD) transit $\sum v_\infty = v_{\infty Cdep} + v_{\infty Carr} + v_{\infty Ddep} + v_{\infty Darr}$
- Use the method of embedded trajectory grids to evaluate $\sum v_\infty$ for thousands of Leg-AB or Leg-CD transits using 2-Leg Lambert (2LL) scans at 5-day granularity
  - Comparable to NHATS methodology[3], but a roundtrip itinerary starting at Earth is not imposed
  - Compliancy limits include maximum time-of-flight, minimum WP loiter, and maximum $\sum v_\infty$
  - Step through an opposition season, computing Leg-A/C transits for various WP arrival dates
  - For each compliant Leg-A/C transit, compute compliant Leg-B/D trajectories for various WP loiter times and arrival dates
  - Identify the compliant Leg-AB/CD transit with minimum $\sum v_\infty$ during the 2LL scan

[3] Reference https://cneos.jpl.nasa.gov/nhats/intro.html (accessed 12 Mar 2025).

Interplanetary Synodic-Resonant Waypoints (WPs)

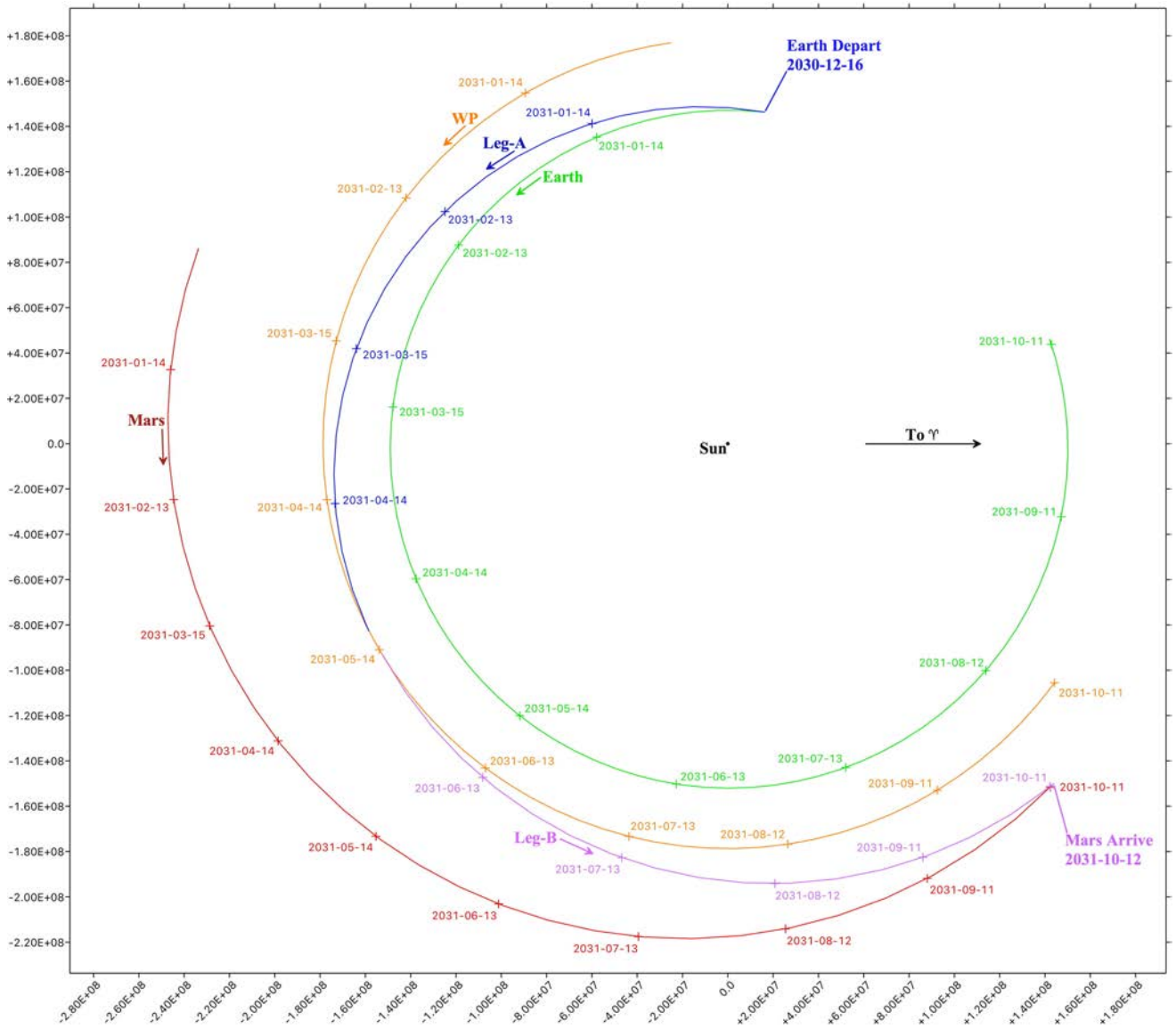
The λ_{31} = -136.6° WP Is Over-Phased For Earth-To-Mars Transits



- Plot is of minimum $\sum v_\infty$ Leg-AB transit circa 2031 for this WP
- Leg-B must cruise outside the orbit of Mars for more than 90 days because Leg-A had to leave Earth too late

Interplanetary Synodic-Resonant Waypoints (WPs)

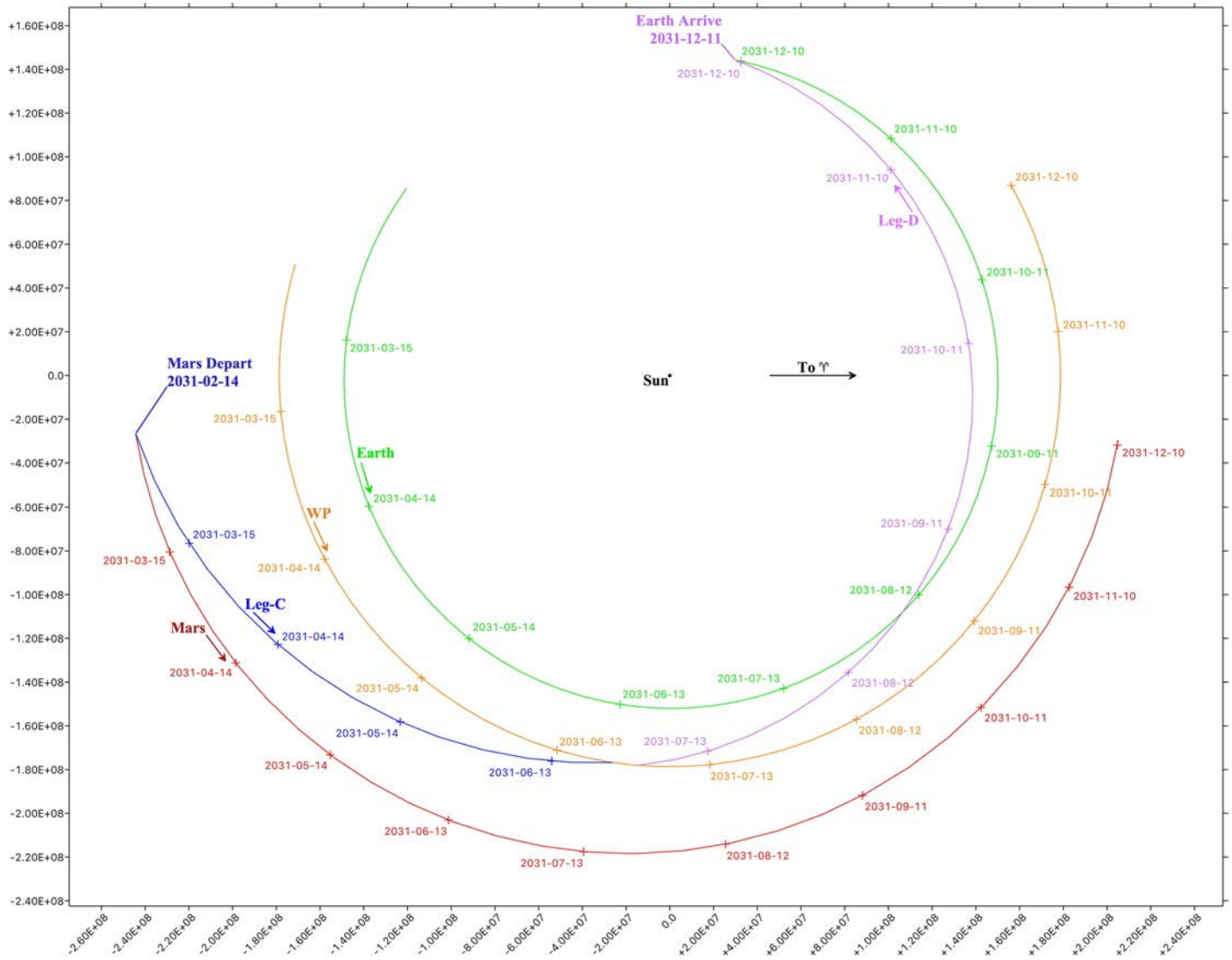
The λ_{31} = -156.6° WP Produces Most Efficient Earth-To-Mars Transits



- Plot is of minimum $\sum v_\infty$ Leg-AB transit circa 2031 for this WP
- Note this transit always remains between the orbits of Earth and Mars

Interplanetary Synodic-Resonant Waypoints (WPs)

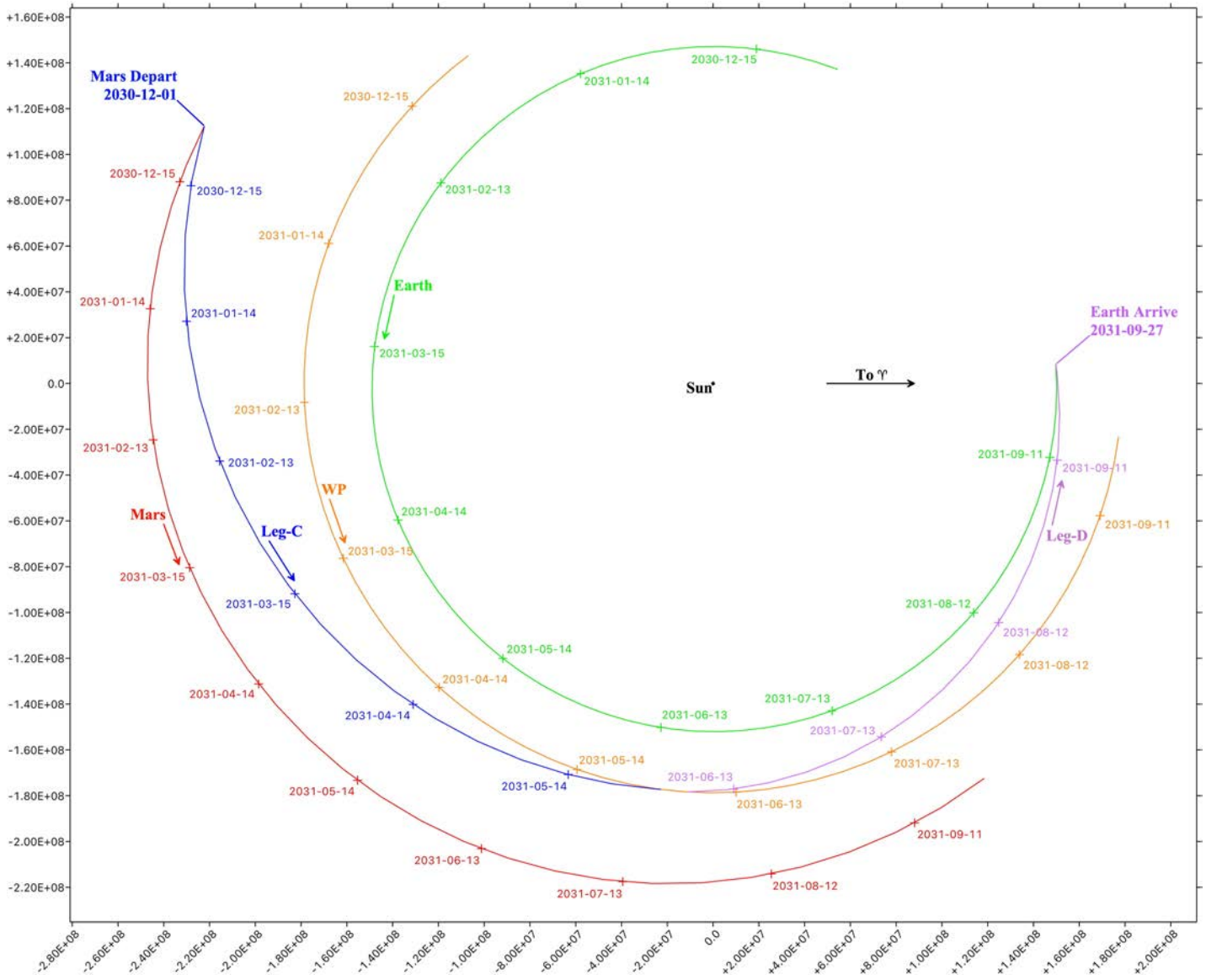
The λ_{31} = -136.6° WP Is Under-Phased For Mars-To-Earth Transits



- Plot is of minimum $\sum v_\infty$ Leg-CD transit circa 2031 for this WP
- Leg-D must cruise inside the orbit of Earth for more than 90 days because Leg-C had to leave Mars too late

Interplanetary Synodic-Resonant Waypoints (WPs)

The λ_{31} = -116.6° WP Produces Most Efficient Mars-To-Earth Transits



- Plot is of minimum $\sum v_\infty$ Leg-CD transit circa 2031 for this WP
- Note this transit always remains between the orbits of Earth and Mars

Interplanetary Synodic-Resonant Waypoints (WPs)

Two Optimally Phased λ_{33} WPs Support Interleaved Transits Starting Circa 2033

- Therefore, a constellation of 4 WPs supports all Leg-AB and Leg-CD transits

WP Phasing	Supported Transits	Supported Opposition Seasons
λ_{31} = -156.6°	Leg-AB	2031, 2035, 2040, 2044, …
λ_{31} = -116.6°	Leg-CD	2031, 2035, 2040, 2044, …
λ_{33} = -93.8°	Leg-AB	2033, 2037, 2042, 2046, …
λ_{33} = -63.8°	Leg-CD	2033, 2037, 2042, 2046, …

- Note variations in $\sum v_\infty$ due to Mars heliocentric distance at transit arrive (Leg-B)/depart (Leg-C)[4]

Opposition Season	Leg-AB WP			Leg-CD WP		
	Phasing	Minimum $\sum v_\infty$ (km/s)		Phasing	Minimum $\sum v_\infty$ (km/s)	
2031	λ_{31} = -156.6°	9.480	*6.747*	λ_{31} = -116.6°	12.279	*7.226*
2033	λ_{33} = -93.8°	7.729	*6.336*	λ_{33} = -63.8°	11.310	*6.033*
2035	λ_{31} = -156.6°	13.797	*5.855*	λ_{31} = -116.6°	8.774	*5.980*
2037	λ_{33} = -93.8°	11.318	*7.013*	λ_{33} = -63.8°	8.945	*6.930*
2040	λ_{31} = -156.6°	15.044	*7.206*	λ_{31} = -116.6°	12.224	*5.950*
2042	λ_{33} = -93.8°	13.985	*5.772*	λ_{33} = -63.8°	13.264	*5.654*
2044	λ_{31} = -156.6°	12.545	*5.811*	λ_{31} = -116.6°	12.857	*7.122*
2046	λ_{33} = -93.8°	12.545	*6.416*	λ_{33} = -63.8°	12.441	*7.507*

[4] Italicized $\sum v_\infty$ values pertain to contemporaneous single-leg (nonstop) transits to which WP phasing λ_{31} and λ_{33} values do not apply.

Interplanetary Synodic-Resonant Waypoints (WPs)

Variations In Maximum Deliverable Payload Mass Are Complex Between Nonstop And Contemporaneous 2-Leg Itineraries Over T_S

- Assume propellant mass m_P can be replenished and payload mass m_Y can be exchanged/augmented during a 5-day WP loiter
- Assume transits flown by vehicle with inert mass m_i = 100,000 kg, maximum total mass m_X = 1,300,000 kg, and specific impulse I_{SP} = 380 s (producing propulsive exhaust speed v_{EX} = 3.726546 km/s)[5]
- Assume propellant mass m_P and m_Y can be freely exchanged such that $m_i + m_P + m_Y = m_X$ at a departure and $m_P = 0$ at an arrival
- Assume Earth departures/arrivals from a circular parking orbit at height of +185 km and Mars departures/arrivals from a circular parking orbit at height +382 km
- Document mission parameters for the nonstop and 2-leg minimum $\sum v_\infty$ transits originating at Earth and Mars during each opposition season from 2031 through 2046
  - Transit phase elapsed time (PET) since original departure at the end of each leg in the transit
  - Maximum deliverable m_Y at the end of each leg in the transit

[5] Reference https://en.wikipedia.org/wiki/SpaceX_Starship (accessed 9 Nov 2024).

Interplanetary Synodic-Resonant Waypoints (WPs)

Variations In Maximum Deliverable Payload Mass Are Complex Between Nonstop And Contemporaneous 2-Leg Itineraries Over T_S (continued)

- Earth-to-Mars minimum $\sum v_\infty$ transits

Opposition Year	Itinerary	Waypoint Arrival		Mars Arrival	
		PET (d)	m_Y (kg)	PET (d)	m_Y (kg)
2031	Nonstop			285	142,566
	Leg-AB	145	218,034	300	**295,439**
2033	Nonstop			200	154,848
	Leg-AB	145	198,011	300	**351,466**
2035	Nonstop			200	176,938
	Leg-AB	120	195,250	300	**63,817**
2037	Nonstop			220	149,804
	Leg-AB	125	194,784	300	**155,138**
2040	Nonstop			300	143,770
	Leg-AB	120	179,231	300	**69,288**
2042	Nonstop			300	179,238
	Leg-AB	115	101,454	300	**84,509**
2044	Nonstop			300	174,951
	Leg-AB	125	176,186	300	**153,424**
2046	Nonstop			290	154,442
	Leg-AB	130	118,788	300	**109,614**

Interplanetary Synodic-Resonant Waypoints (WPs)

Variations In Maximum Deliverable Payload Mass Are Complex Between Nonstop And Contemporaneous 2-Leg Itineraries Over T_S (continued)

- Mars-to-Earth minimum $\sum v_\infty$ transits

Opposition Year	Itinerary	Waypoint Arrival		Earth Arrival	
		PET (d)	m_Y (kg)	PET (d)	m_Y (kg)
2031	Nonstop			235	143,558
	Leg-CD	180	134,638	300	**181,906**
2033	Nonstop			215	174,623
	Leg- CD	160	157,282	300	**211,818**
2035	Nonstop			195	168,506
	Leg- CD	145	281,879	300	**217,104**
2037	Nonstop			270	138,276
	Leg- CD	145	286,771	300	**174,225**
2040	Nonstop			285	166,496
	Leg- CD	170	146,322	300	**113,668**
2042	Nonstop			300	178,882
	Leg- CD	180	96,468	300	**112,222**
2044	Nonstop			300	142,240
	Leg- CD	185	108,465	300	**140,910**
2046	Nonstop			245	136,992
	Leg- CD	180	119,756	300	**175,799**

Interplanetary Synodic-Resonant Waypoints (WPs)

Variations In Maximum Deliverable Payload Mass Are Complex Between Nonstop And Contemporaneous 2-Leg Itineraries Over T_S (concluded)

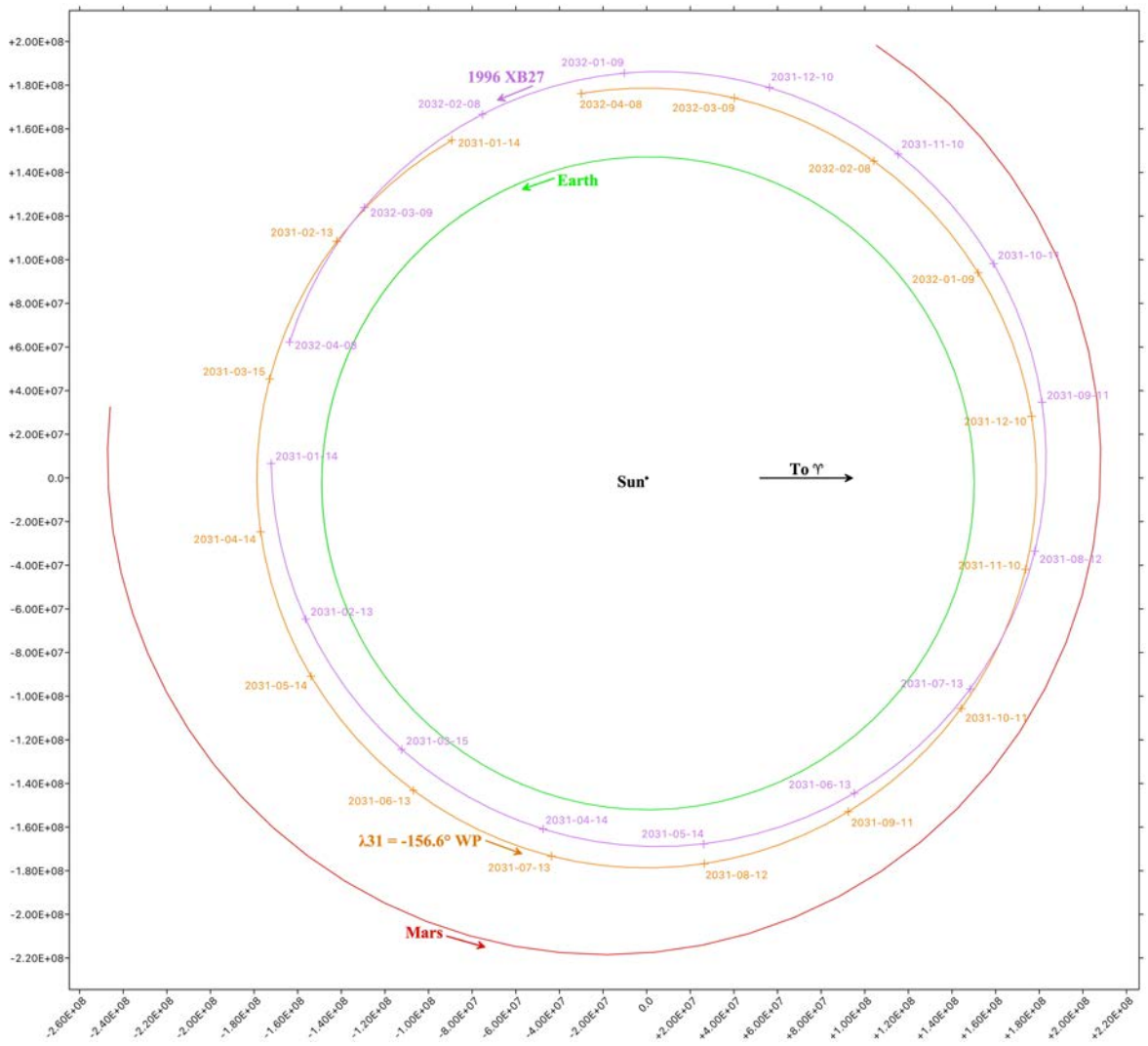
Itinerary	Total m_Y Deliverable Over T_S (15 years) To WP (kg)	To Mars (kg)
Nonstop		1,276,558
Leg-AB	1,381,738	**1,282,696**

Itinerary	Total m_Y Deliverable Over T_S (15 years) To WP (kg)	To Earth (kg)
Nonstop		1,249,572
Leg-CD	1,331,582	**1,327,652**

- Are similar economics in play with U.S. commercial air travel? Only about 4% of bookable East/West Coast passenger itineraries are nonstop among the 4 most-patronized airlines.

Interplanetary Synodic-Resonant Waypoints (WPs)

Known Asteroids To Build & Supply WPs Are Abundant & Accessible[6]

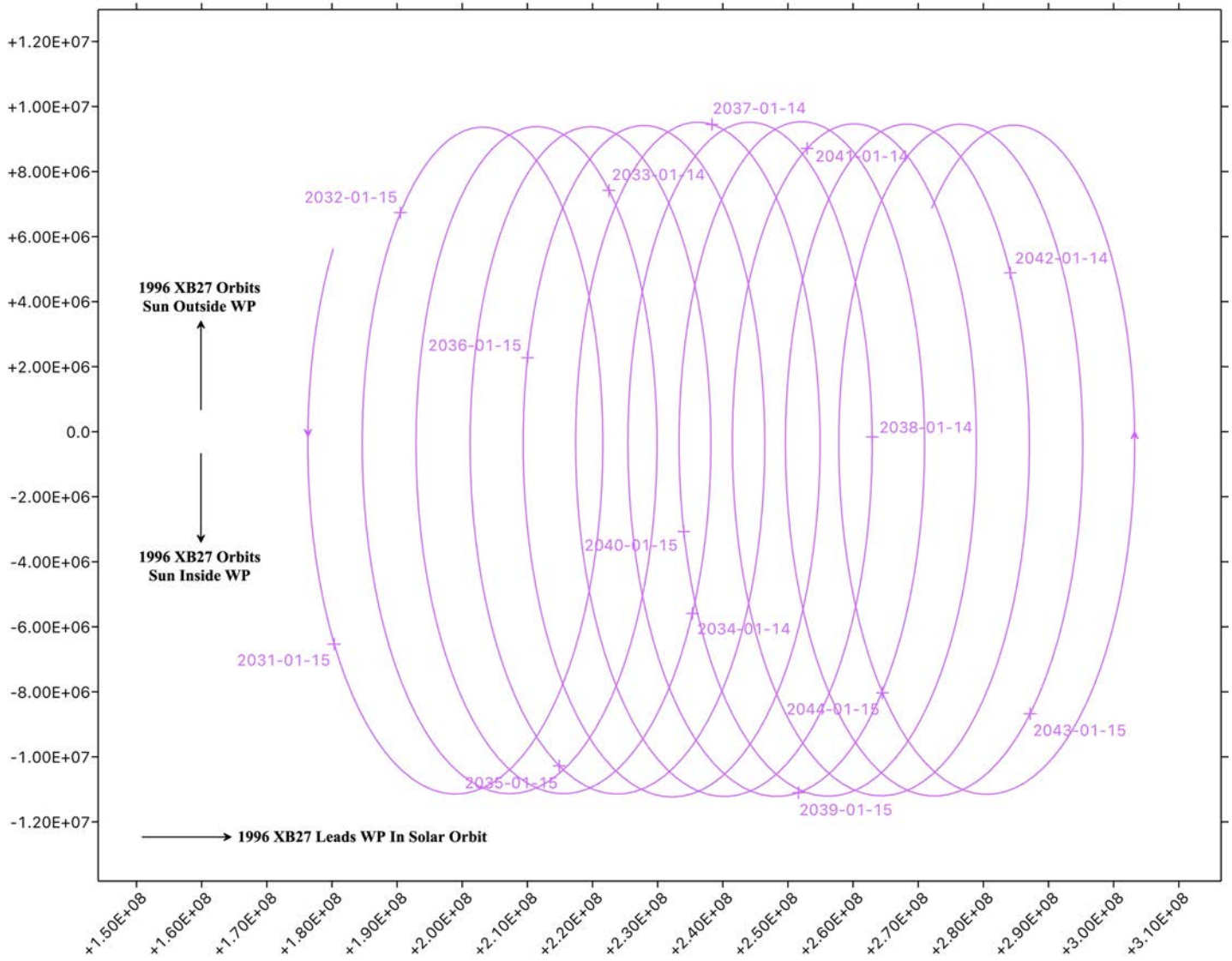


- The rate of asteroid discoveries will only increase as new survey telescopes become operational
- In this example, the λ_{31} = -156.6° WP (**orange**) is to be supplied from asteroid 1996 XB_{27} (**violet**)
- The estimated diameter of 1996 XB_{27} is 100 to 245 meters

[6] As of 12 March 2025, catalogued NEAs orbiting the Sun between Earth and Mars numbered 493.

Interplanetary Synodic-Resonant Waypoints (WPs)

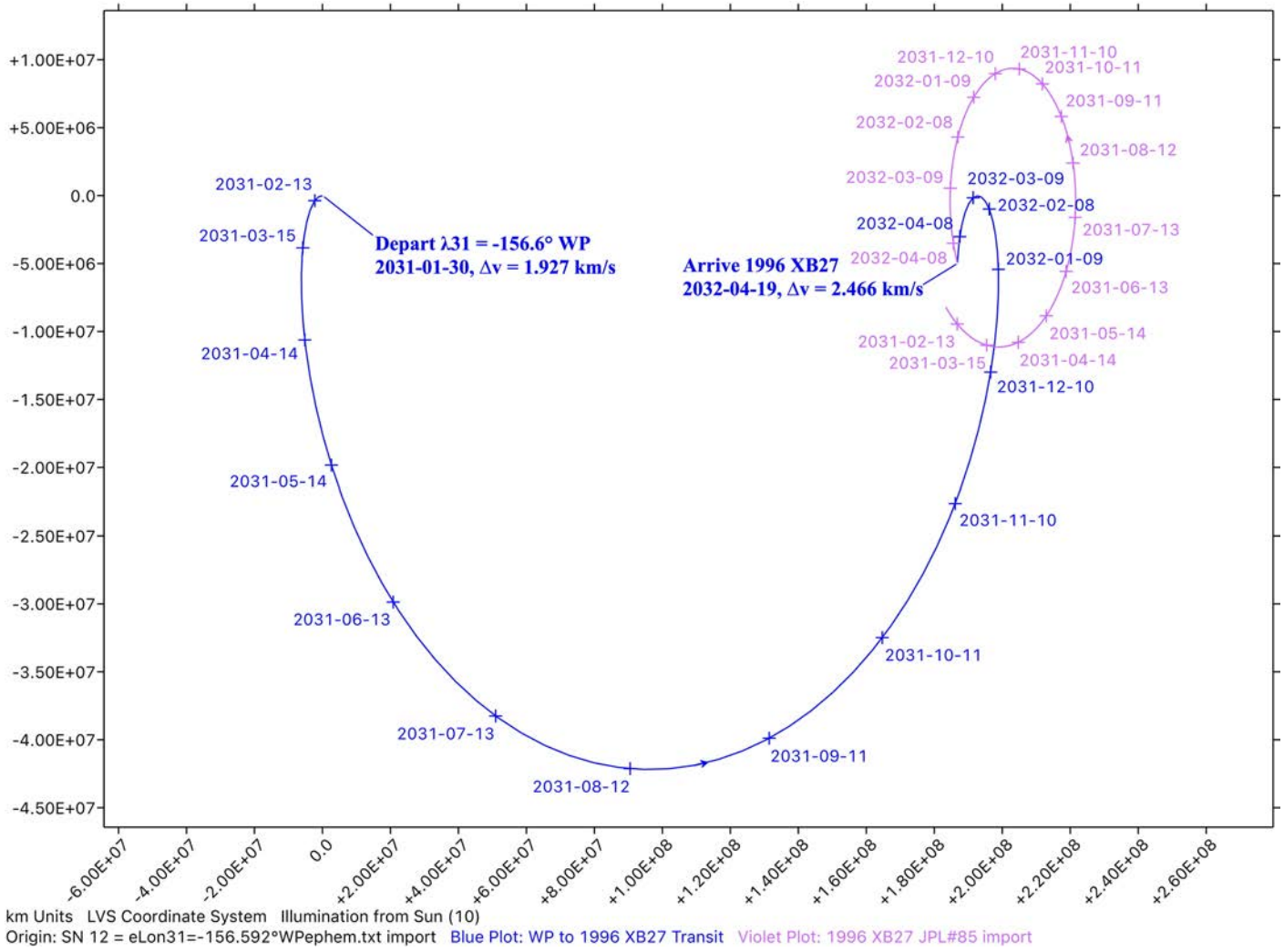
Known Asteroids To Build & Supply WPs Are Abundant & Accessible (continued)



- In 2031, 1996 XB_{27} leads the WP in orbit about the Sun by more than 170 million km
- The lead increases by < 7 million km per Earth year

Interplanetary Synodic-Resonant Waypoints (WPs)

Known Asteroids To Build & Supply WPs Are Abundant & Accessible (continued)

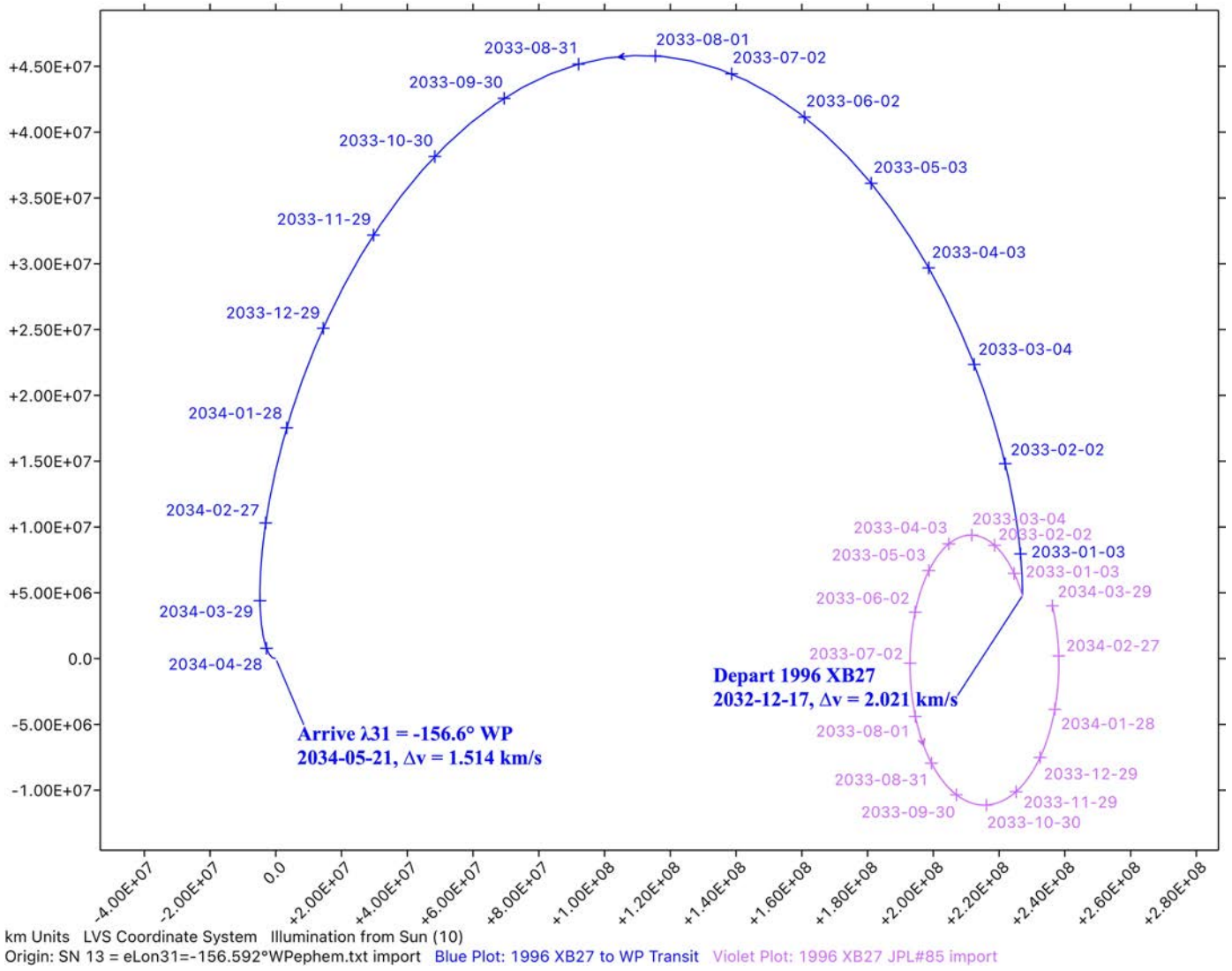


- Outbound transit to 1996 XB_{27} requires 445 days
- One-way m_Y = 299,926 kg[7]
- Leads to 242-day loiter at 1996 XB_{27}

[7] For reference, International Space Station mass is near 400,000 kg

Interplanetary Synodic-Resonant Waypoints (WPs)

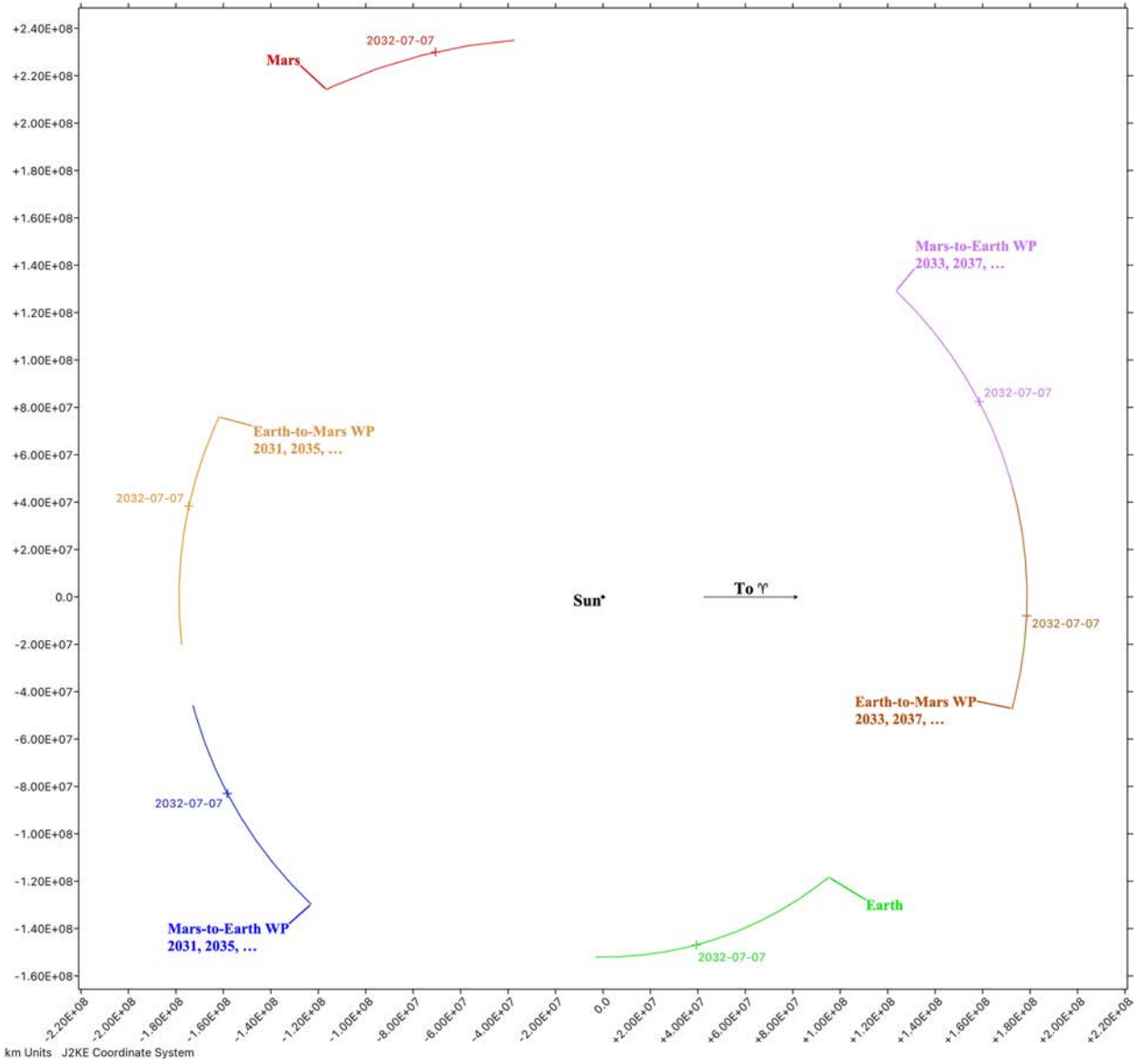
Known Asteroids To Build & Supply WPs Are Abundant & Accessible (concluded)



- Return transit to WP requires 520 days
- One-way m_Y = 403,468 kg
- Roundtrip duration = 1207 days = 3.3 years

Interplanetary Synodic-Resonant Waypoints (WPs)

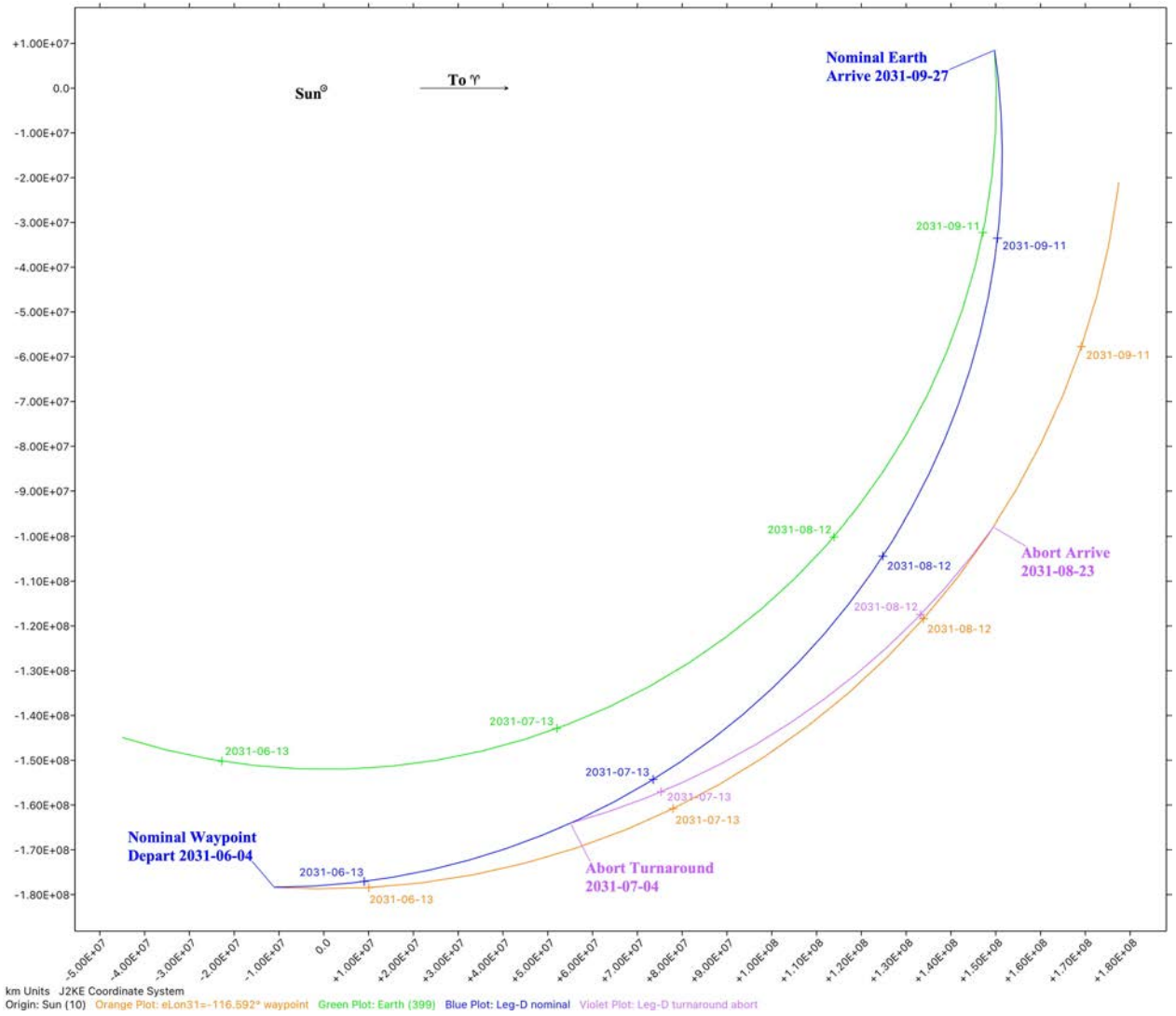
WPs Serve As Communications Relays During Earth/Mars Solar Conjunctions



- Line-of-sight between Earth and Mars is too close to the Sun for communications from 39 to 51 days during every τ
- At these times, any of the four WPs can serve as a "bent pipe" communication relay

Interplanetary Synodic-Resonant Waypoints (WPs)

WPs Offer Proximal Haven Following Interplanetary Transit Abort



- This scenario commences with 2031's minimum $\sum v_\infty$ Leg-D nominal trajectory
- Thirty days after departing the λ_{31} = -116.6° WP for Earth, a return abort is initiated with jettison to $m_Y = 0$
- WP return abort is achieved 80 days after nominal WP departure with +27,323 kg propellant margin

Interplanetary Synodic-Resonant Waypoints (WPs)

WPs Support Interplanetary Exploration And Commerce In Many Ways

- A WP loiter breaks any nonstop transport consumption requirement into two smaller staged segments
- Four WPs serve every Earth/Mars transit opportunity. Each WP is utilized every 4.27 years (on average) without modifications to the WP orbit.
- More cargo mass can be transported to Earth, Mars, and WPs over time than with nonstop Earth/Mars transits using the same spacecraft
- Mass for WP construction and resupply can be obtained from adjacent near-Earth asteroids
- Any WP can serve as an Earth/Mars communications relay to eliminate outages that would otherwise arise when the two planets are on opposite sides of the Sun
- A nominally utilized WP also provides additional forward and turnaround abort destination options

Original Waypoints Research Published In AIAA's *Journal of Spacecraft and Rockets* (ref. "Synodic-Resonant Earth/Mars Waypoints" At https://doi.org/10.2514/1.A36186)