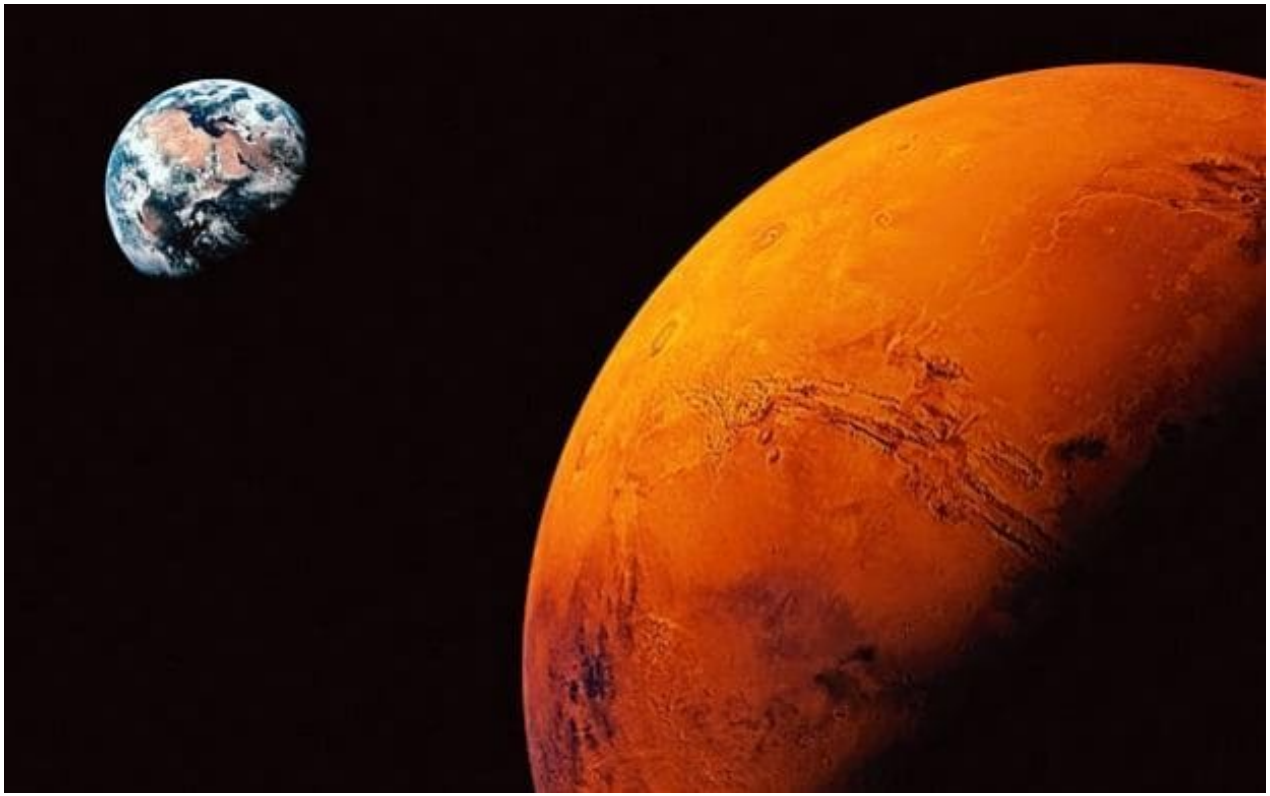

Low excess speed triple cyclers of Venus, Earth, and Mars

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2017 AAS/AIAA Astrodynamics Specialists Conference

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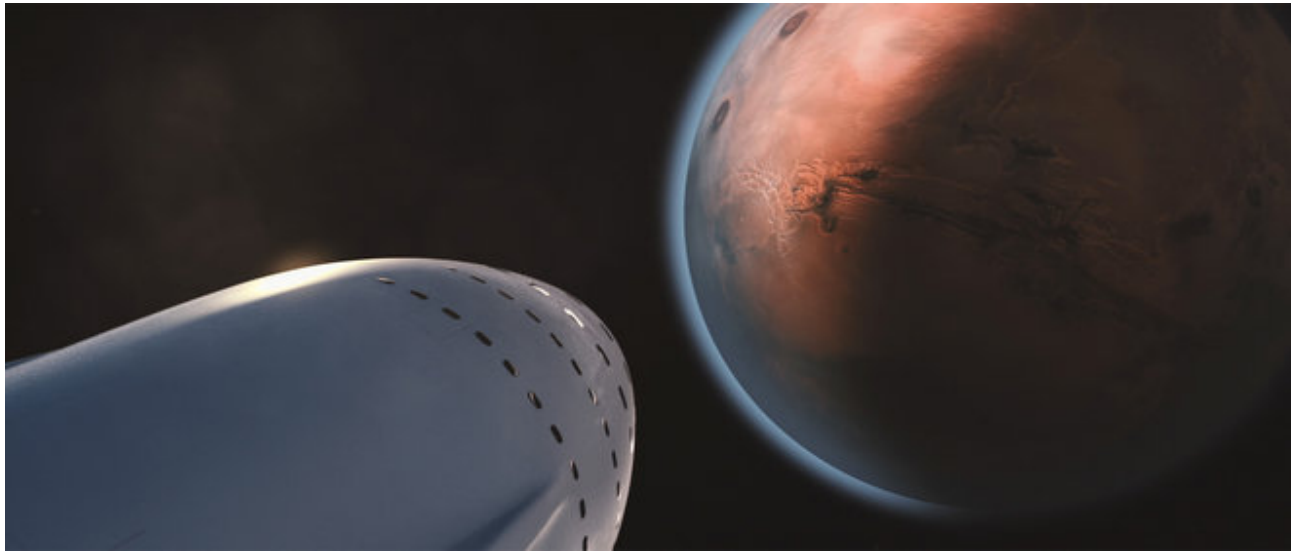
Motivation

- Future large-scale transport between Earth and Mars likely requires an efficient architecture
  - Many trajectory options may be involved
  - This work adds the triple cycler to the available options

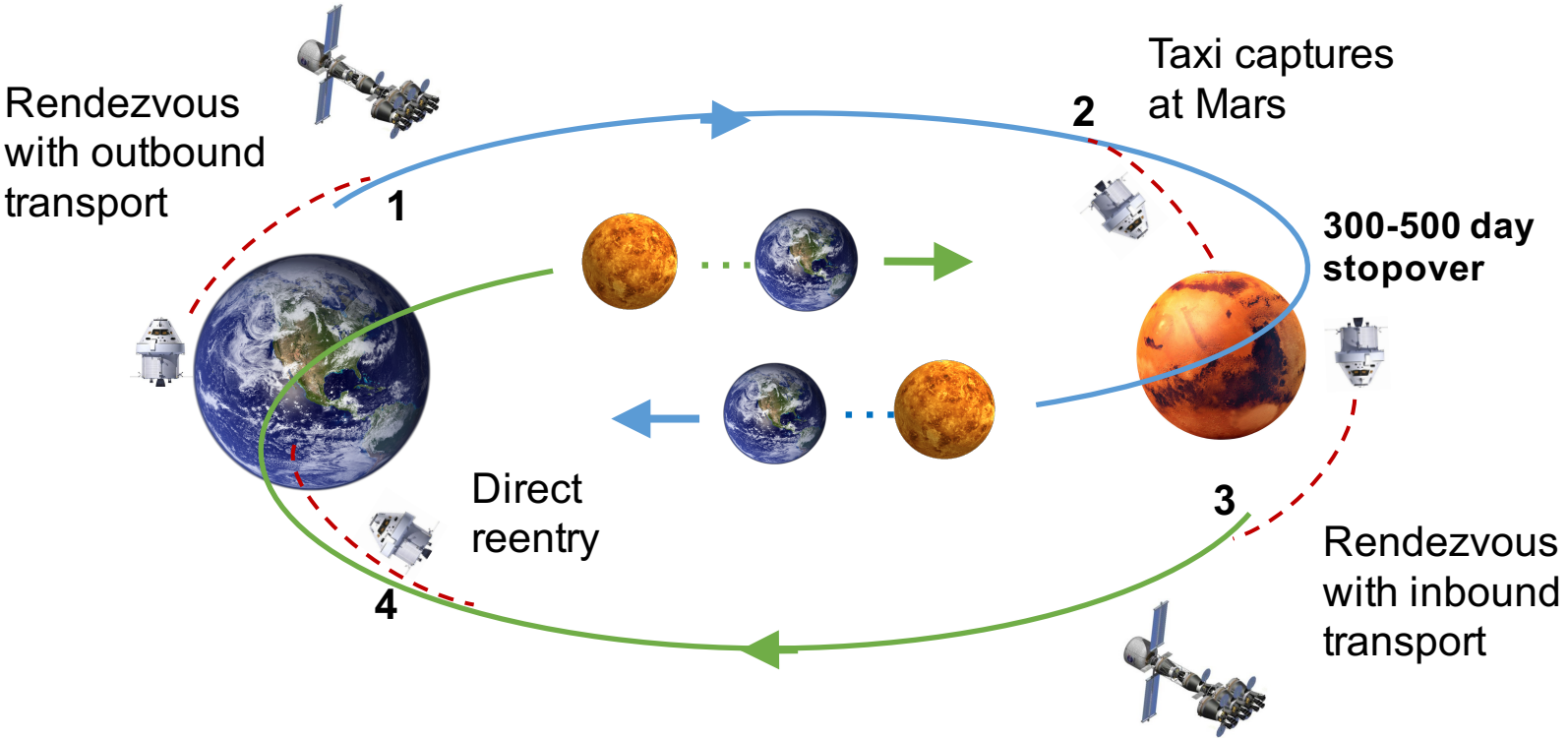


Motivation

- Well-known Earth-Mars cyclers (S1L1, Aldrin) suffer from large maintenance ΔV and/or large excess speed (v_∞) for some opportunities

- Previously shown that Venus encounters can setup low-energy Earth-Mars transfers
  - Can Venus be used similarly to enable cyclers with low-energy characteristics on Earth-Mars (or Mars-Earth) transit legs?

Triple Cycler Architecture



- **Cycle:** Portion of trajectory with flight time equal to an integer number of T_{syn}, and that starts and ends at the same body (Earth or Mars in this work).
- **Repeat period:** The flight time of a single cycle.

The Ballistic Triple Cycler

- VEM synodic period is around 6.4 years (~3 EM synodic periods)
  - Inertially repeat every 32 years

- The cyclers in this work:
  - **Ballistic**: No impulsive maneuvers (only gravity assist)
  - **Low-energy**: Ensure Earth-Mars (or Mars-Earth) legs have low excess speeds by enforcing near-Hohmann arcs
  - **Additional flybys**: used to setup near-Hohmann legs on subsequent cycles
  - **Repeat periods**: 1 and 2 synodic periods (6.4 and 12.8 years)

The Ballistic Triple Cycler

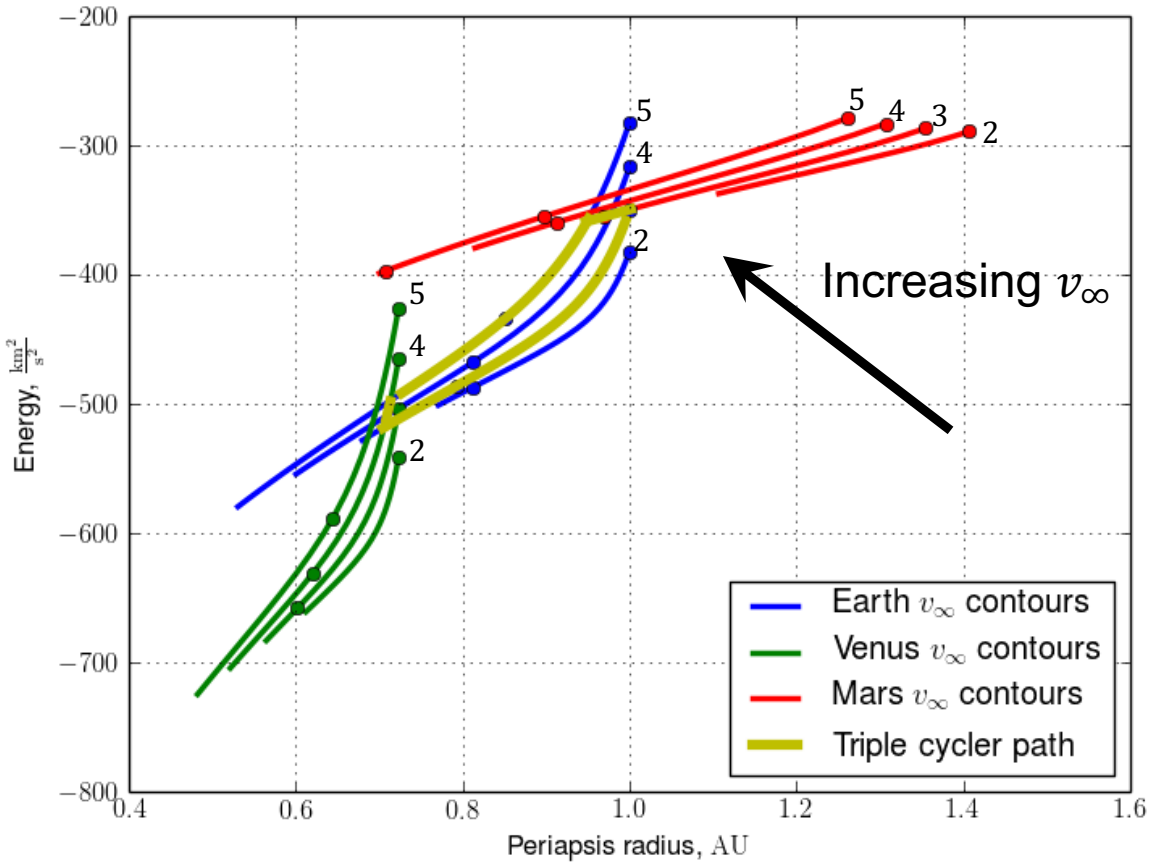
- Families defined by:
  - Itinerary
  - Number of synodic periods in cycle (1 or 2)

Outbound	Inbound
EMEVE	MEVEM
EMEEVE	MEEVEM
EMEVVE	MEVVEM
EMEVEE	MEVEEM
EMMEVE	MEVEMM

- Itineraries limited by energy
  - Earth-Mars near-Hohmann cannot encounter Venus without first encountering Earth
  - Similarly, cannot go directly from Venus to Mars

The Ballistic Triple Cycler

- Tisserand plot illustrates the triple cycler concept

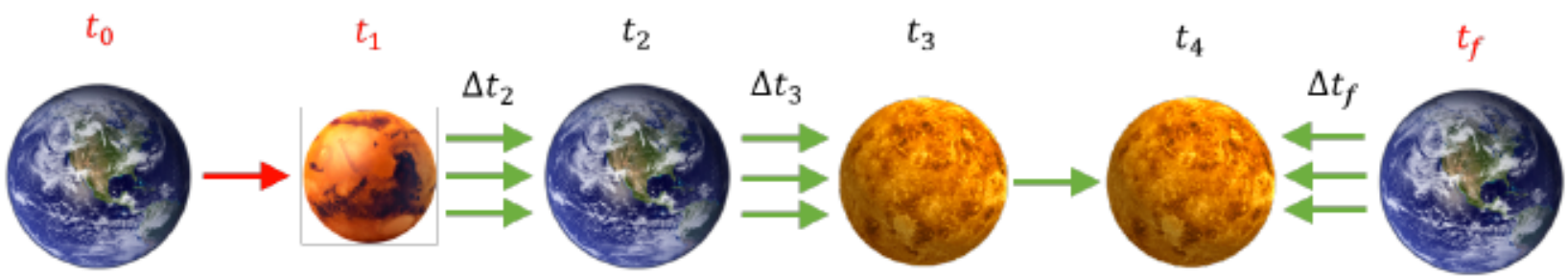


Methodology

- Broad multi-leg Lambert search with constraints
  - Zero-sphere-of-influence patched conics with DE430 ephemeris
  - Searches initialized from set of initial leg seeds (near-Hohmann) for given Earth-Mars opportunity
  - Locate encounter dates over a grid which satisfy altitude and C3 match constraints at the flybys

$$\|v_\infty(t_i^+) - v_\infty(t_i^-)\| < \Delta v_\infty^{\max} \qquad 100\text{ km} < r_p(t_i) - R_{\text{planet}} < 100{,}000\text{ km}$$

Single seed EMEEVE search



Seed indicated in red

Lambert arcs searches shown in green

Methodology

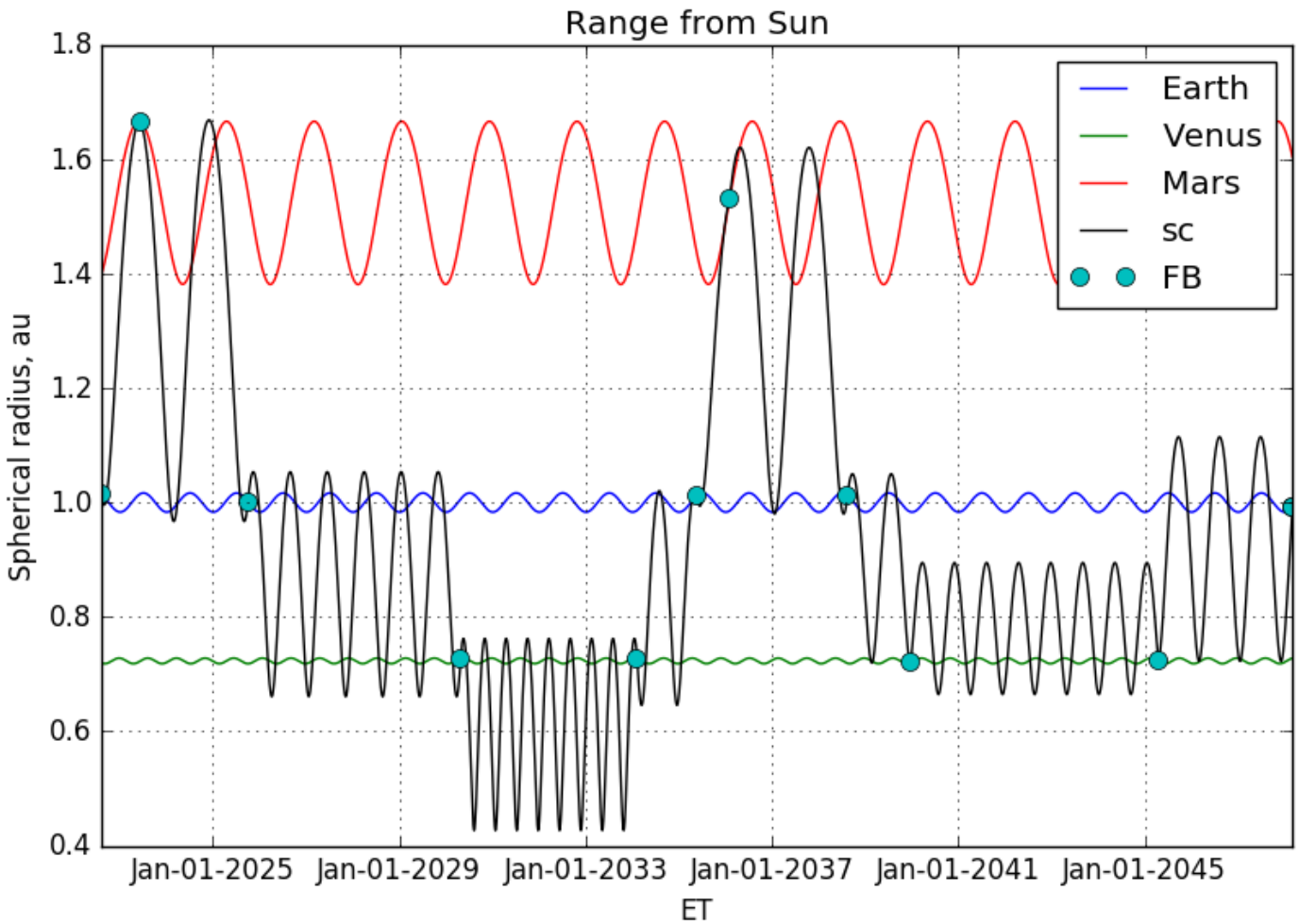
- Because planets do not exactly repeat, solutions will not continue into the 2nd cycle without large maneuver
  - Need method to build multi-cycle trajectories from single-cycle solutions

- Consecutive sets of feasible broad search trajectories are matched-up to yield two cycle trajectories
  - The matching is a manageable combinatorial problem
  - Could continue this procedure into 3rd, 4th cycles

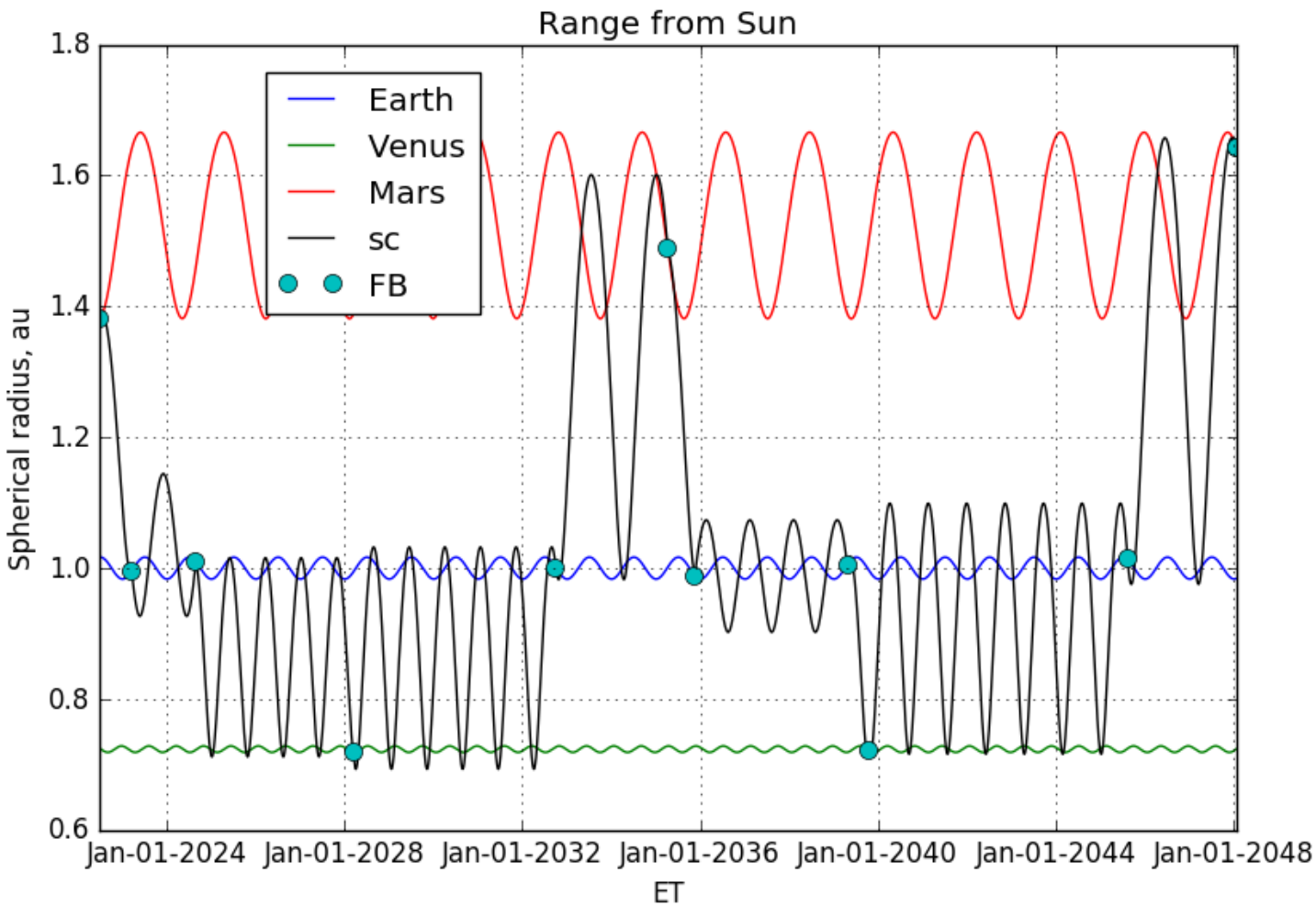
Results

- No feasible solutions with repeat period of one synodic period (6.4 years)
  - But many if we allow a single slightly subsurface flyby
- Thousands of previously undocumented two synodic period solutions were found
  - Transit leg excess speeds maintained below 5 km/sec over 12 consecutive opportunities
  - By comparison, the best S1L1 has excess speeds over 7 km/sec on some opportunities
- A couple select two-cycle solutions were optimized with N-body gravity
  - Converged to be ballistic
  - Control-point break-point optimization scheme discussed in paper

Outbound Example (2022)

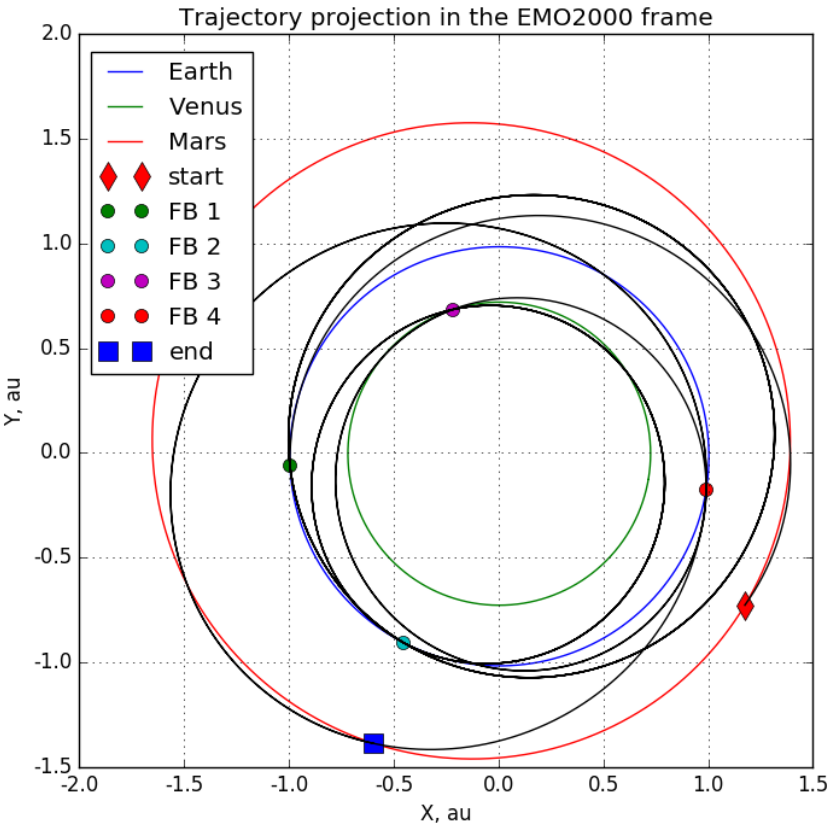


Inbound Example (2022)

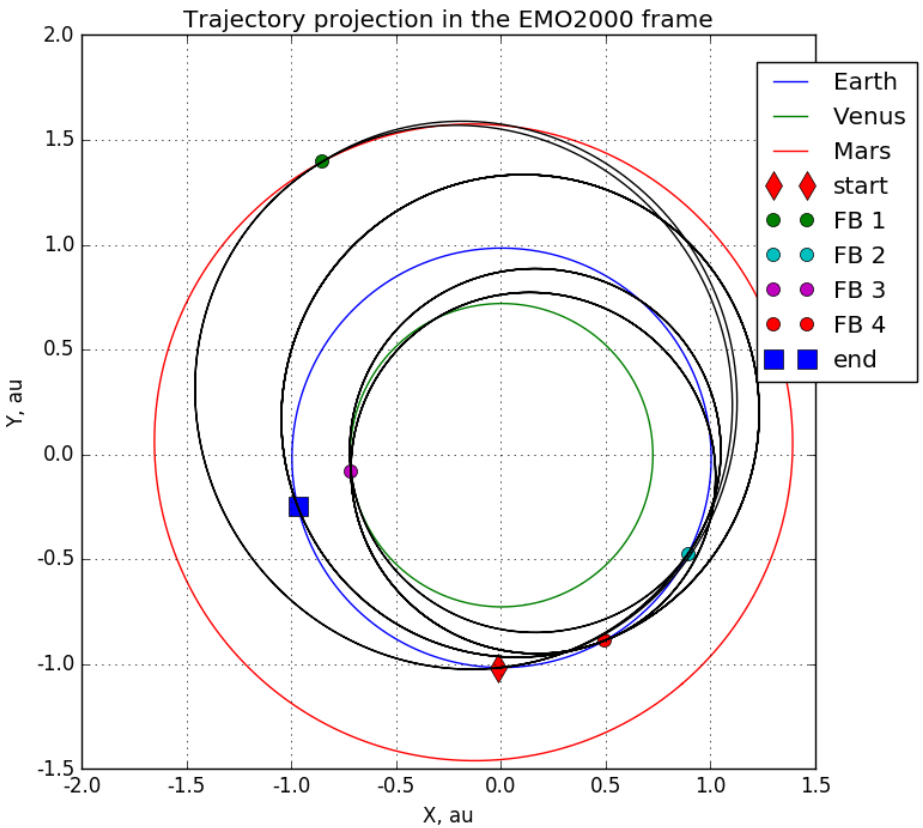


Single cycle trajectory examples

Inbound MEEVEM



Outbound EMEVEE



Optimized triple cycler architecture

- **Seven round-trip missions may be extracted:**

Outbound					Inbound				
Body	Date	v_∞, km/sec	Transit, days	Taxi Δv, km/sec	Body	Date	v_∞, km/sec	Transit, days	Taxi Δv, km/sec
Earth	30-Jun-2020	4.76		4.22	Mars	24-Jun-2022	3.85		2.77
Mars	05-May-2021	2.90	309	2.24	Earth	19-Mar-2023	3.48	268	3.78
Earth	26-Sep-2022	4.88		4.28	Mars	25-Jul-2024	2.94		2.26
Mars	08-May-2023	2.59	224	2.09	Earth	15-May-2025	2.95	294	3.64
Earth	28-Sep-2024	3.59		3.82	Mars	26-Aug-2026	3.16		2.37
Mars	03-Aug-2025	2.55	309	2.07	Earth	11-Jun-2027	3.47	289	3.78
Earth	05-Oct-2026	3.70		3.85	Mars	05-Oct-2028	2.79		2.18
Mars	05-Aug-2027	2.99	304	2.29	Earth	10-Aug-2029	4.71	309	4.21
Earth	02-Jan-2029	4.20		4.02	Mars	03-Dec-2030	2.73		2.15
Mars	03-Sep-2029	3.76	244	2.72	Earth	25-Jul-2031	4.61	234	4.17
Earth	21-Dec-2030	3.58		3.81	Mars	14-Feb-2033	2.48		2.04
Mars	11-Sep-2031	3.66	264	2.66	Earth	21-Sep-2033	3.41	219	3.76
Earth	14-Apr-2033	4.26		4.04	Mars	08-Apr-2035	3.12		2.35
Mars	04-Dec-2033	3.93	234	2.82	Earth	17-Nov-2035	2.97	223	3.64

Conclusions

- Various families of triple planet ballistic cycler discovered for the first time
  - Earth-Mars cyclers with Venus flybys enable repeatable transport legs with excess speed consistently below 5 km/s
  - The S1L1 Earth-Mars cycler (best in literature in terms of energy characteristics) has speeds over 7 km/s
  - Taxi vehicle ΔV reduced by 1-10 km/s per round-trip mission
- But, more transport vehicles required to cover every Earth-Mars and Mars-Earth opportunity (12 compared to 4 for the S1L1)
- Low energy entails relatively long transit leg flight times

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