Mission Design for Deep Space Nano/Micro Spacecraft Utilizing Lunar Orbital Platform-Gateway Opportunities

Naoya Ozaki
Institute of Space and Astronautical Science,
Japan Aerospace Exploration Agency

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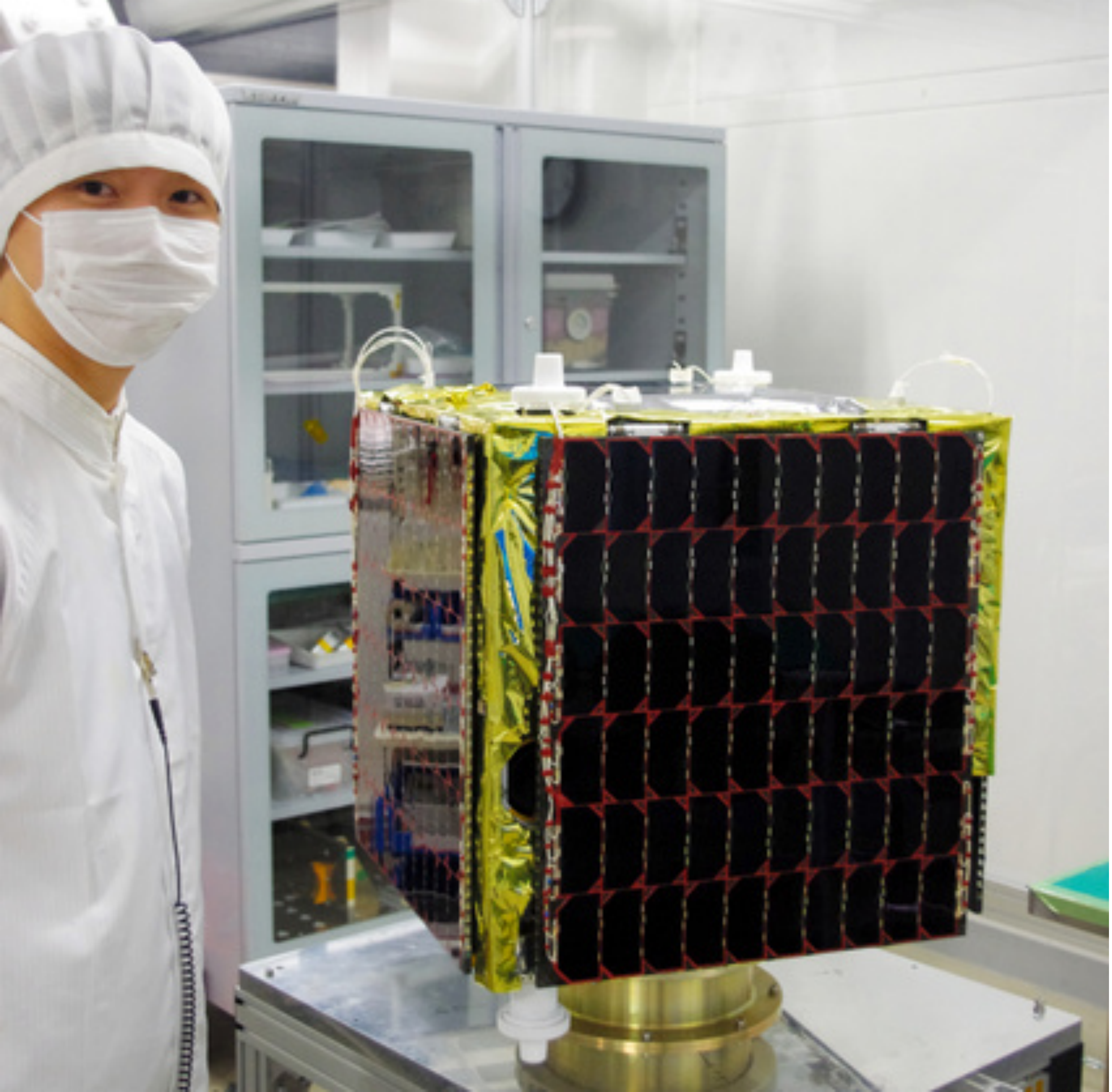
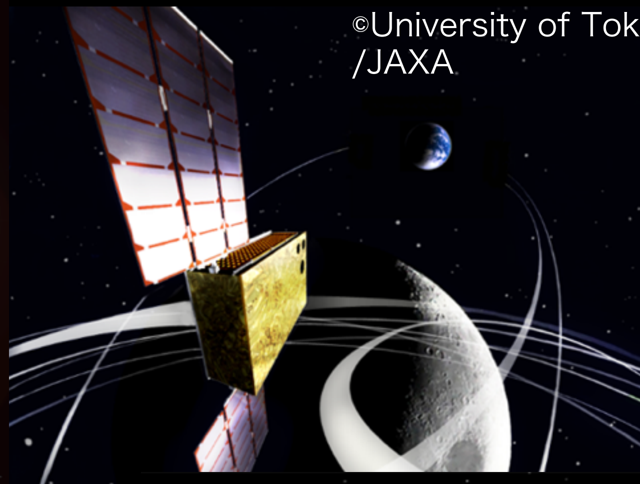
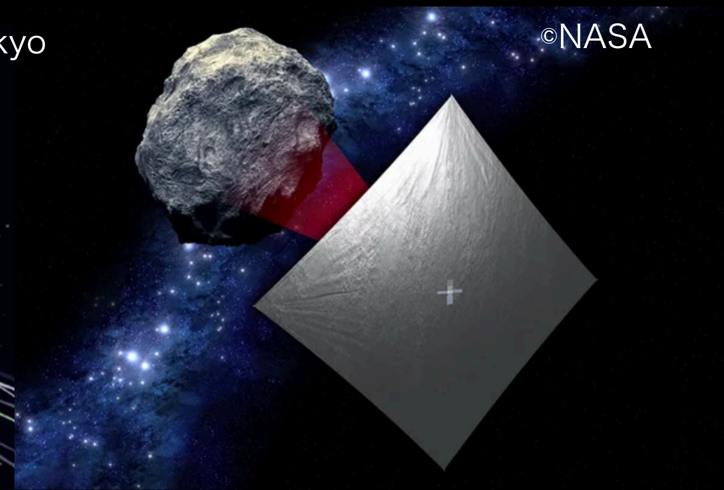
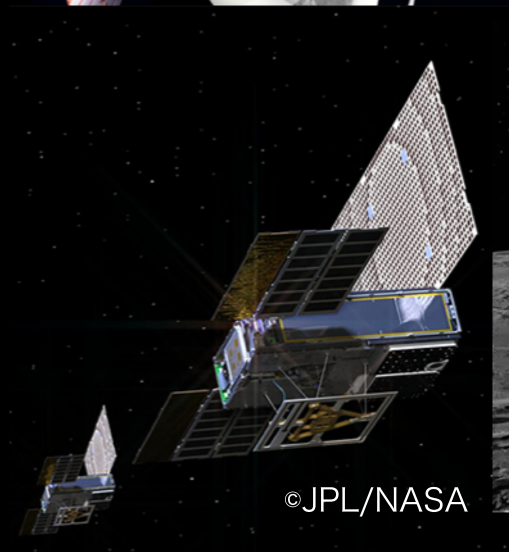


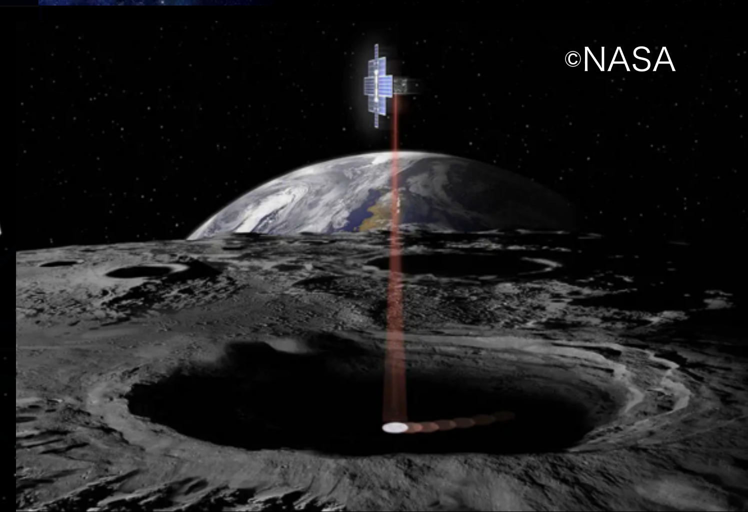
P R O C Y O N

Deep Space CubeSats







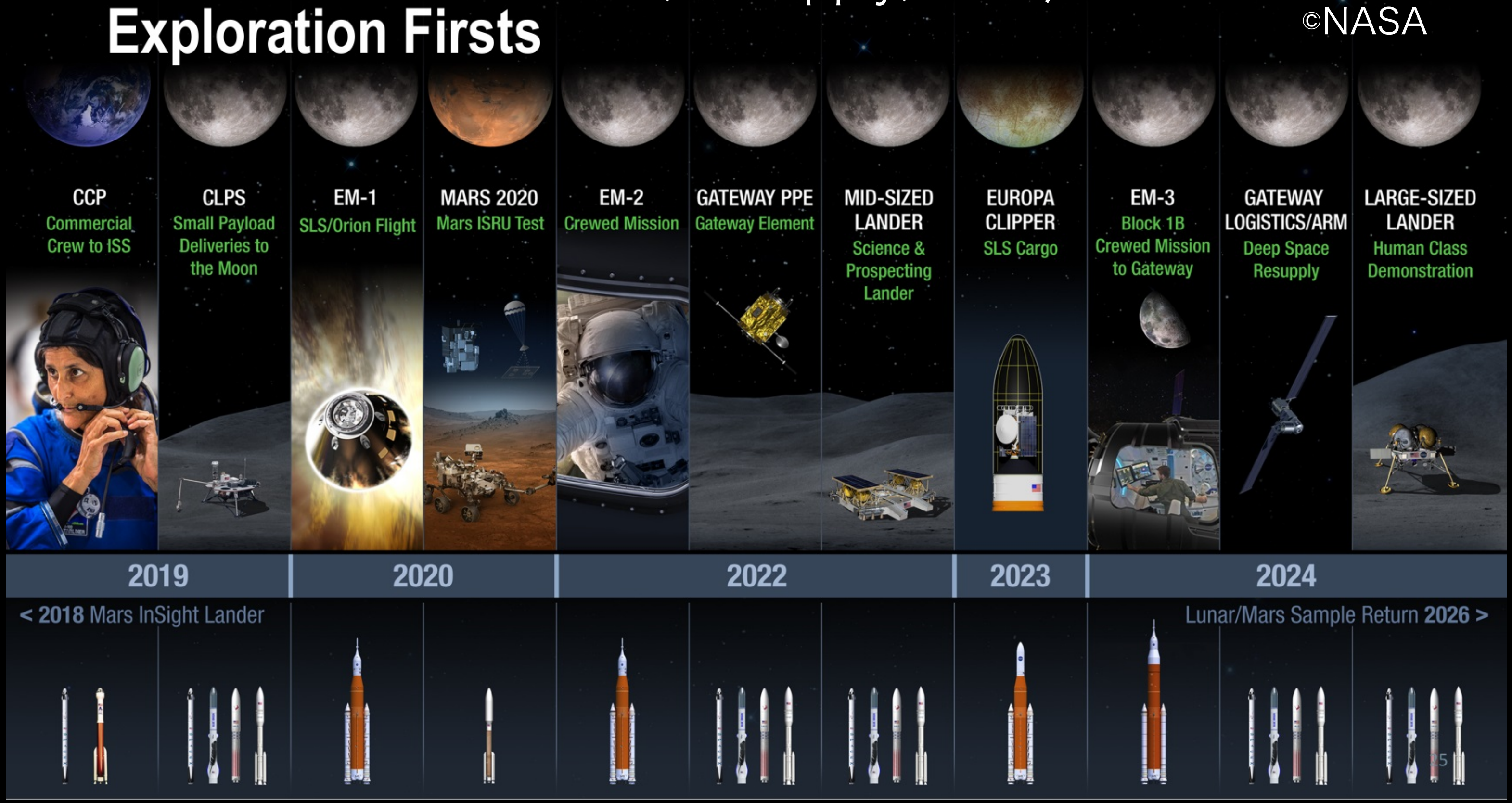


Lunar Orbital Platform-Gateway (In 2020s)

LOP-G Related Launch Opportunities

Starting from NASA's Artemis-1,
we can expect **more than 10 CubeSats are launched to deep space every year**.
(Launch for LOP-G Construction, Resupply, etc…)

©NASA

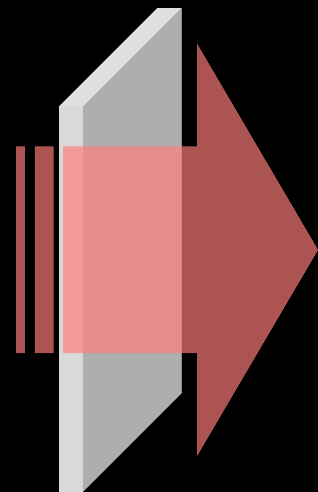


NASA Updates Lunar Gateway Plans, NASA Spaceflight.com (Accessed on March 16, 2019)
https://www.nasaspaceflight.com/2018/09/nasa-lunar-gateway-plans/

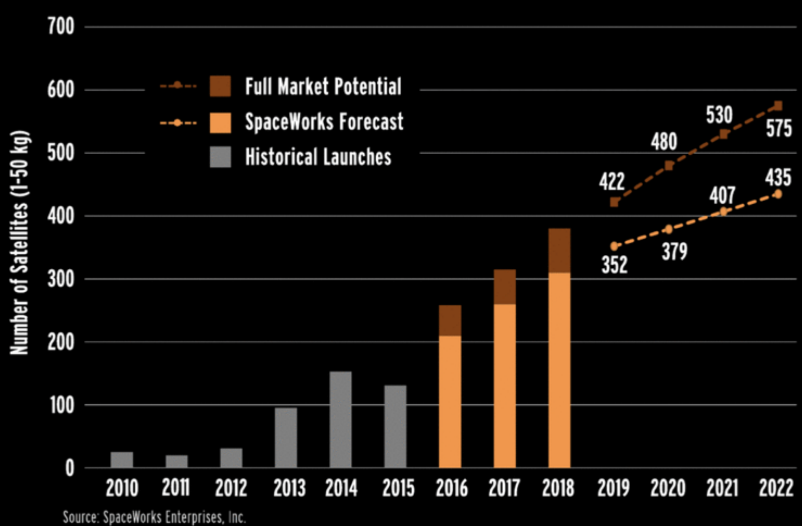
A New World Opened by LOP-G and Nano/Micro Spacecraft

Innovation in Earth satellite (Low cost, short lead time)

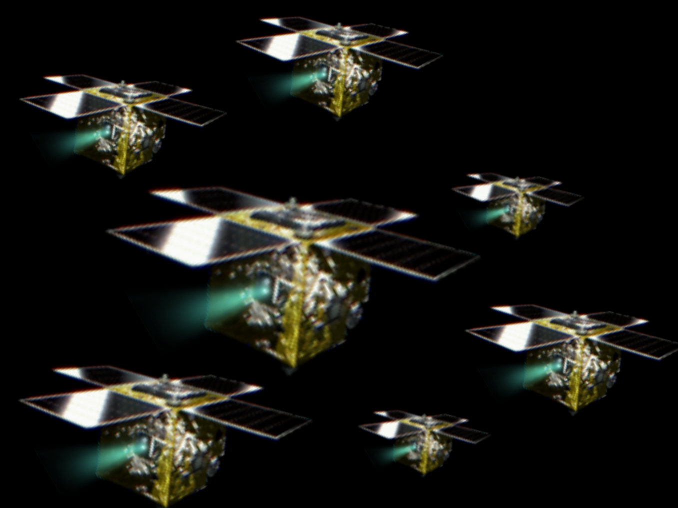
- Explosion in numbers
- Frequent missions
- Expansion of stakeholders (Startups, universities, etc)



<u>Similar innovation will happen in deep space missions!!</u>



Number of Satellite Launched For A Year

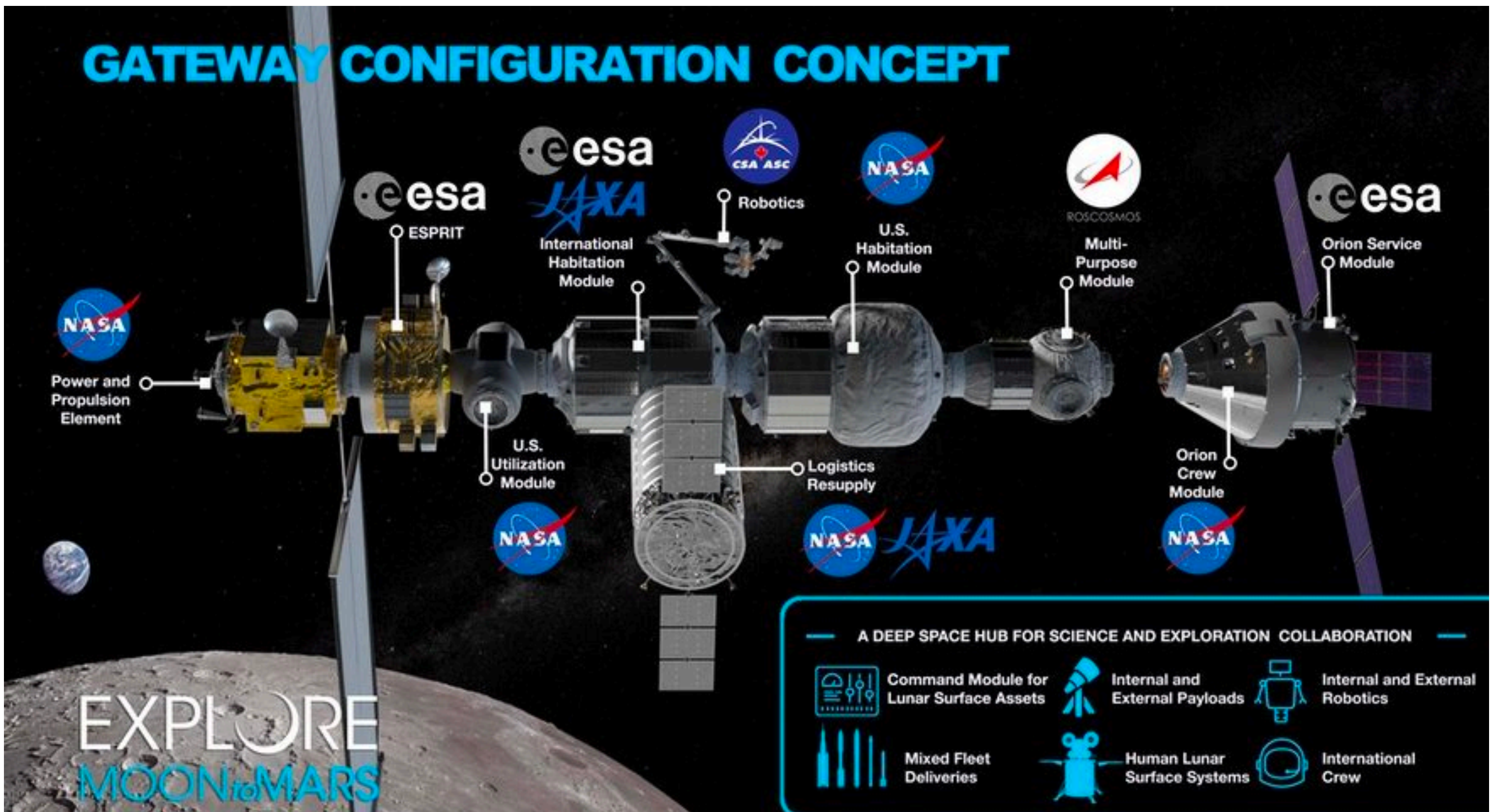


Satellites Born From UNISEC Activities

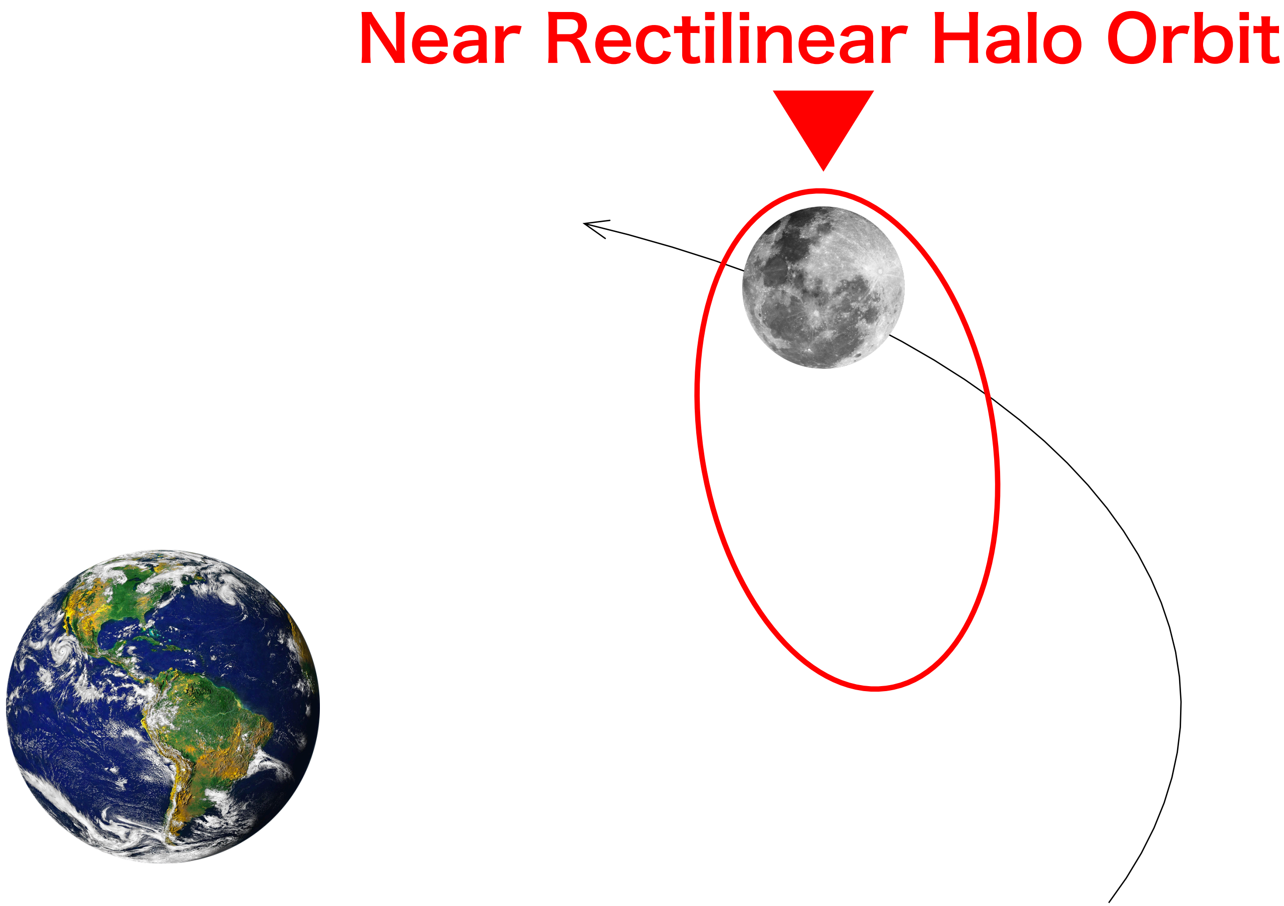
http://unisec.jp/unisec/satellites.html (Info. in 2019, accessed on July 11, 2020)

What is Lunar Orbital Platform-Gateway (LOP-G)??

Lunar Orbital Platform-Gateway (LOP-G) is a planned **space station in lunar orbit**. **NASA's Artemis program** plays a major role to develop the Gateway in collaboration with commercial and international partners: ESA, JAXA, CSA, Roscosmos, etc.

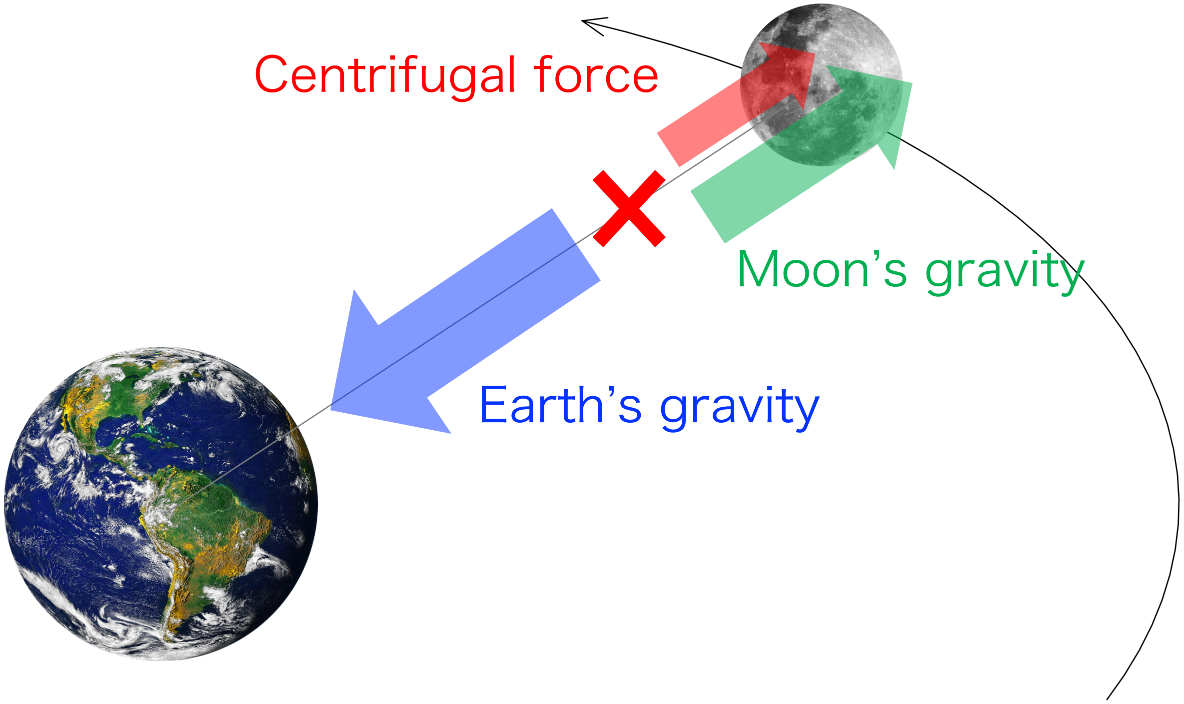


Where is the Gateway??



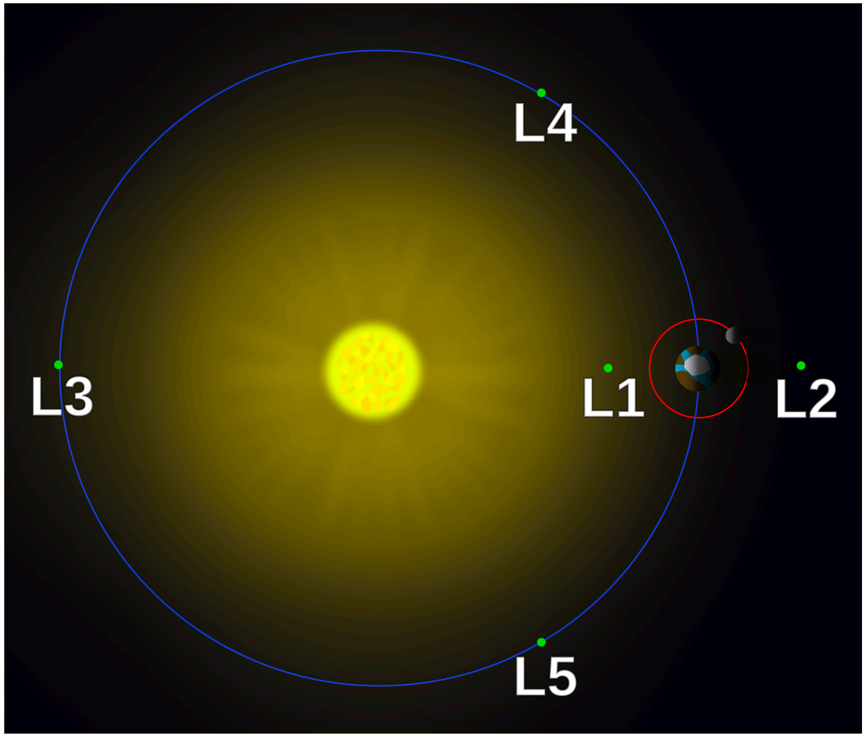
A type of Halo orbits under the Earth and Moon gravity.

Where is the Gateway??



The equilibrium point where the earth's gravity, the moon's gravity, and the centrifugal force balance each other is called **the Lagrange point**.

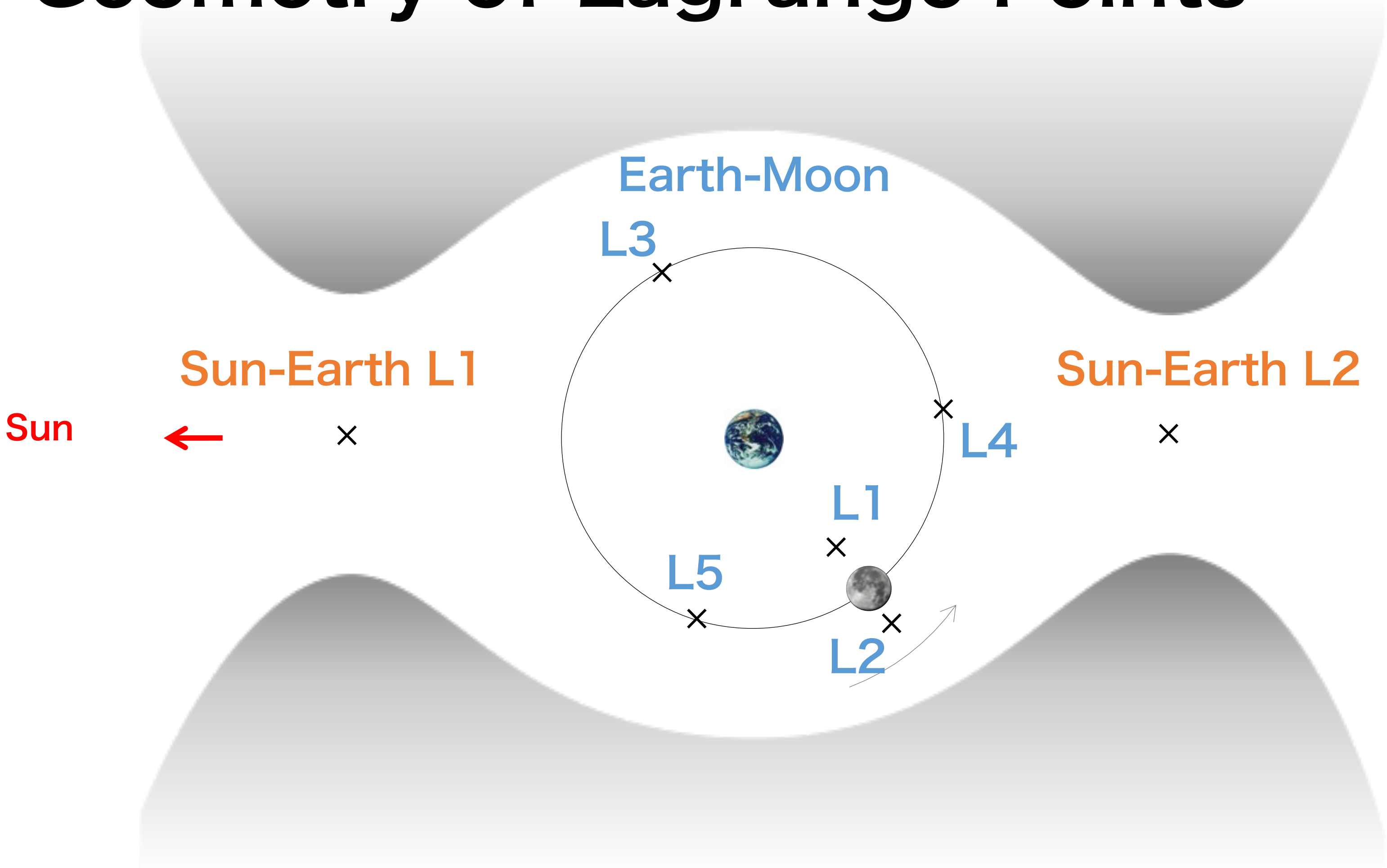
Lagrange Points



Five types of Lagrange points exist in each three-body dynamical system.

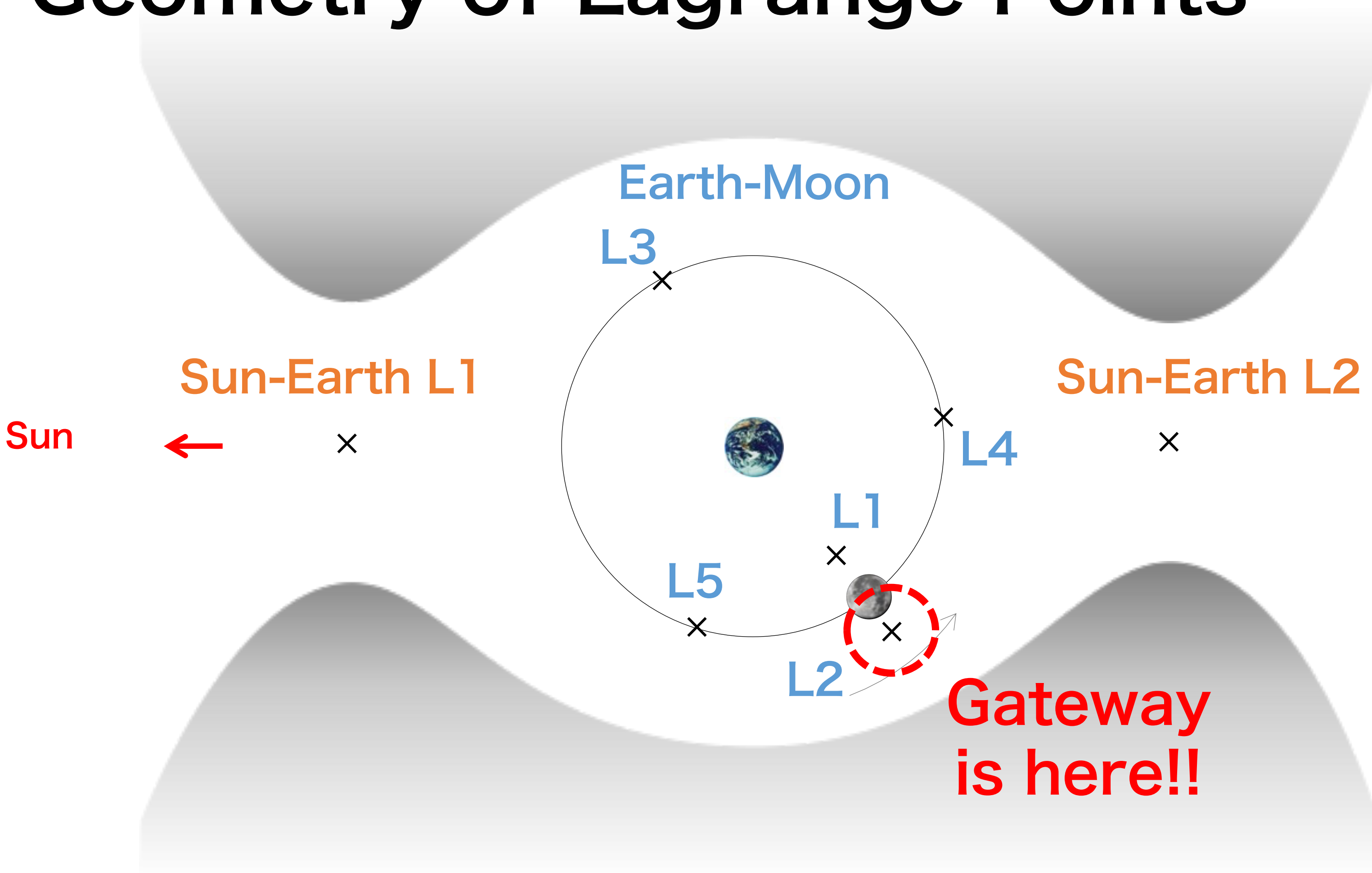
Ex) Earth-Moon L2 Lagrange point
Sun-Earth L1 Lagrange point

Geometry of Lagrange Points



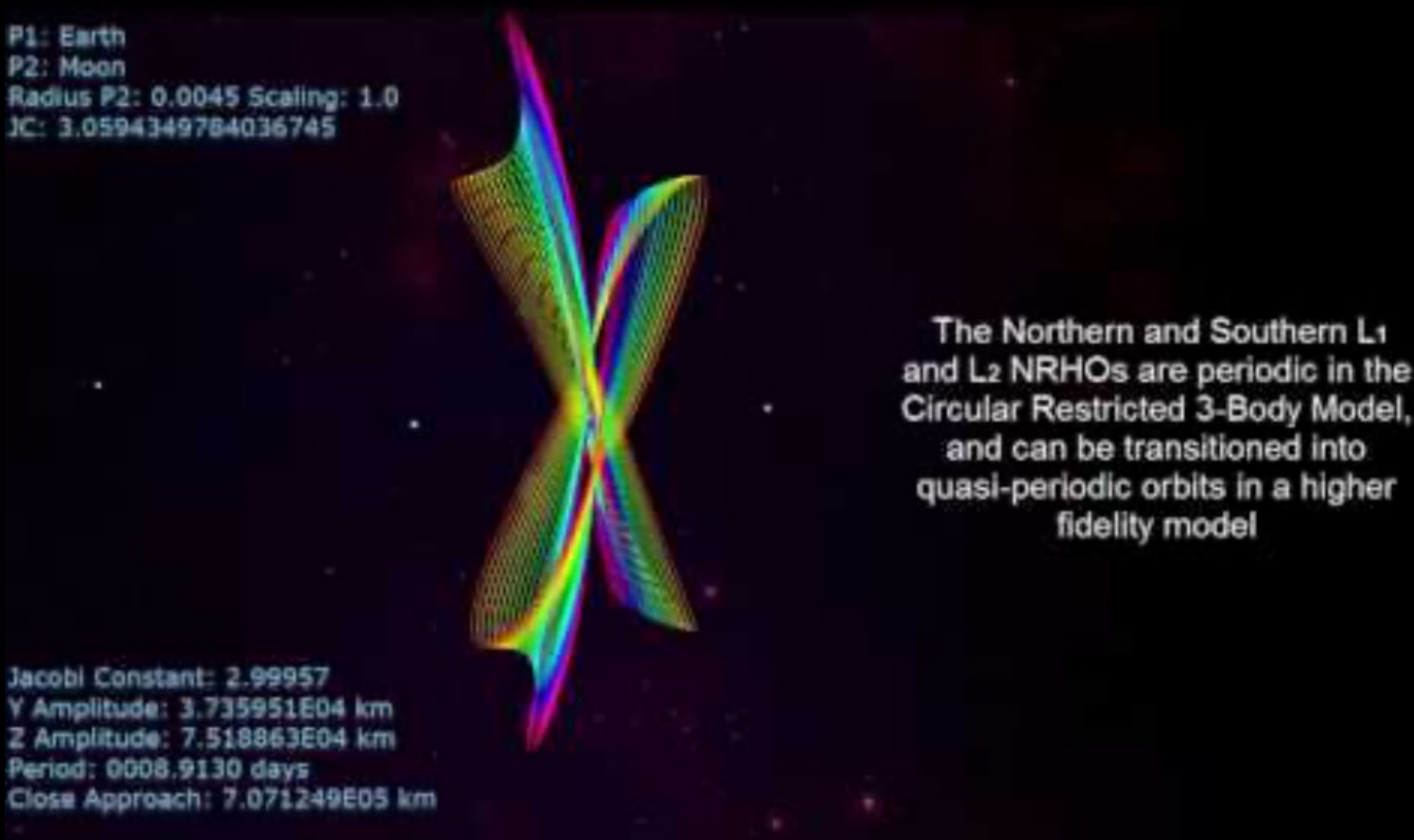
Sun-Earth line fixed rotational frame.

Geometry of Lagrange Points



Sun-Earth line fixed rotational frame.

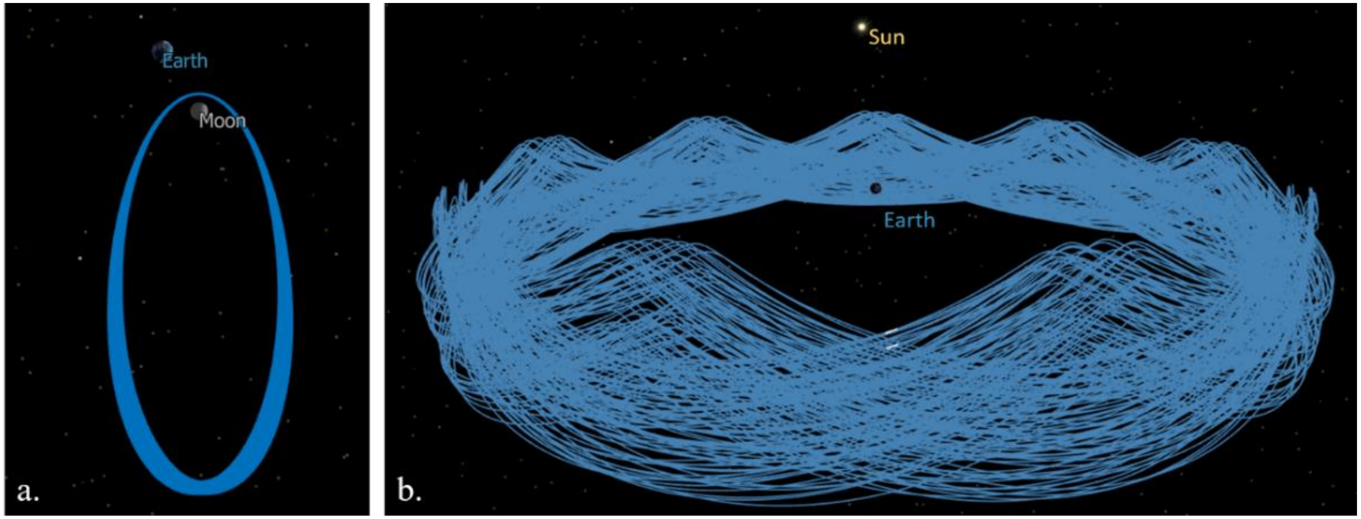
Near Rectilinear Halo Orbit



Near Rectilinear Halo Orbit (NRHO)

Characteristics of NRHO

- **Geometric relationship to the Earth is always the same**
- Halo orbits are unstable (**easility reachable/escapable**) and spacecraft cannot stay in the orbits without station keeping maneuvers, but NRHO is less stable than general Halo orbits.
- Gateway will be constructed in 9:2 synodic resonant NRHO (SRHO), where **the station never experiences eclipse**.
- For 9:2 SRHO, the perilune altitude is 1458-1820km, and the apolune altitude is 68267-70112km.

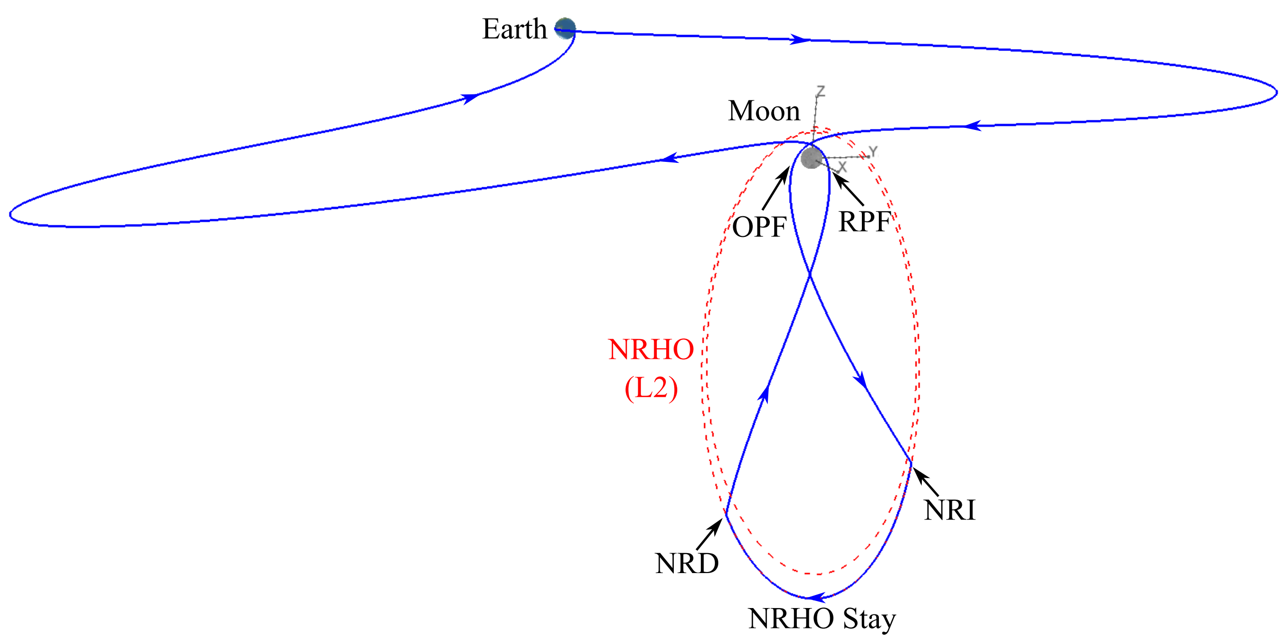


(D.C. Davis, F.S.Khoury, et al. , *AAS*, 2020)

Launch Condition for Gateway Construction Opportunity

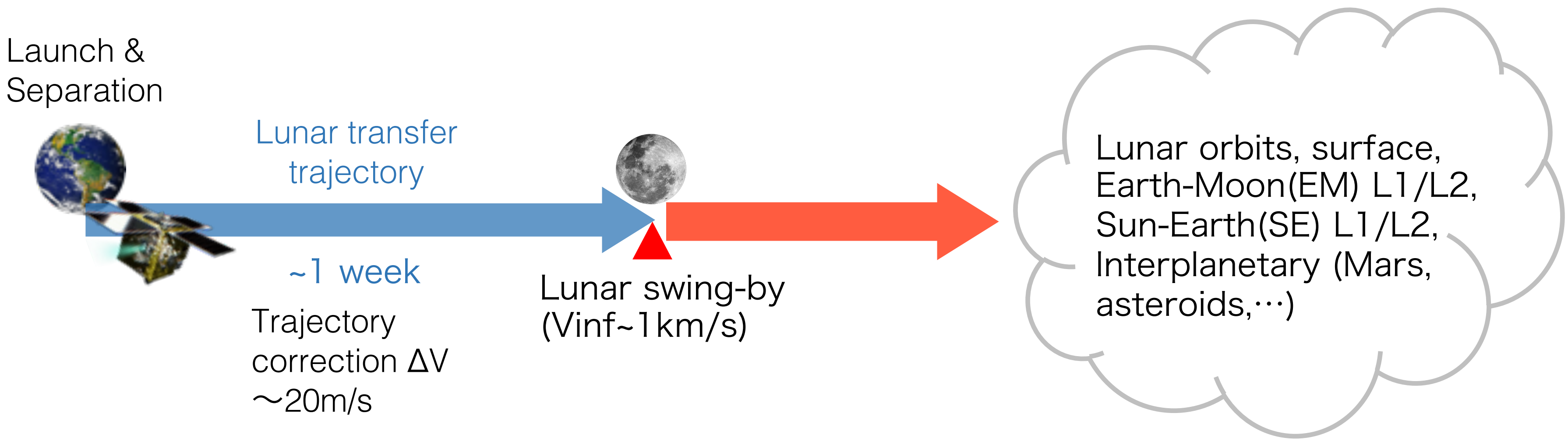
For gateway construction opportunities, the spacecraft is expected to be launched into **lunar transfer trajectory** (as was the case with Artemis 1).

Using lunar swing-by on this orbit, the spacecraft can fly to **interplanetary space (to asteroid, Mars, …), periodic orbits in Lagrange points, and so on**.



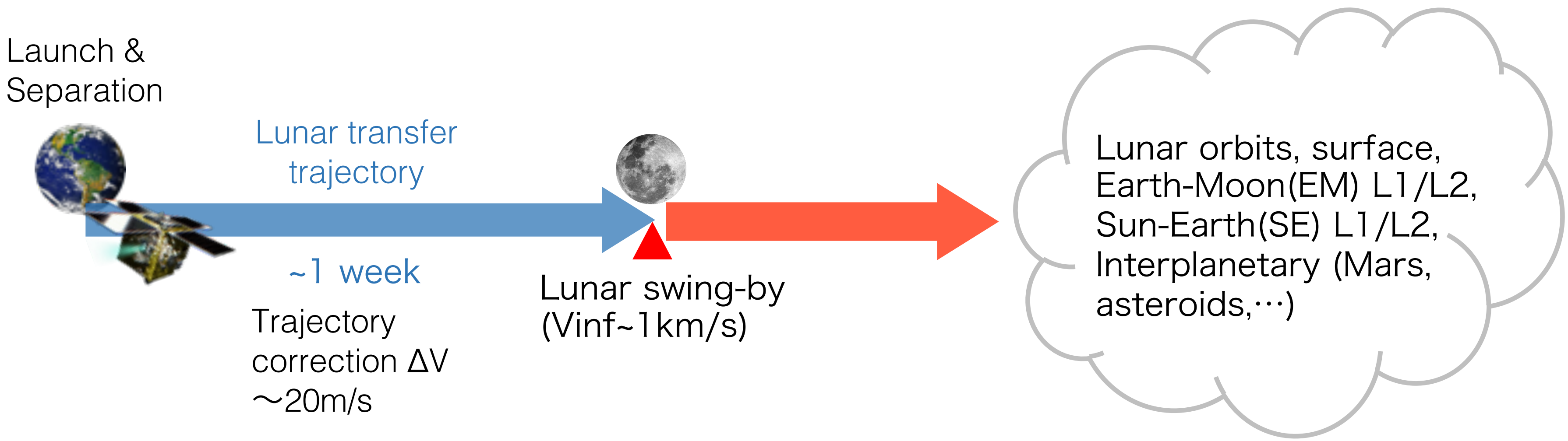
(J. Williams, D.E. Lee, et al. , *AAS*, 2017)

Mission Utilizing Gateway Construction Opportunity



Possible mission scenario for early Artemis opportunity (such as Artemis 2)

Mission Utilizing Gateway Construction Opportunity



1) To Sun-Earth L1/L2: Ballistic transfer without ΔV

2) To Lunar Surface:

3) To Lunar orbits, Earth-Moon L1/L2:

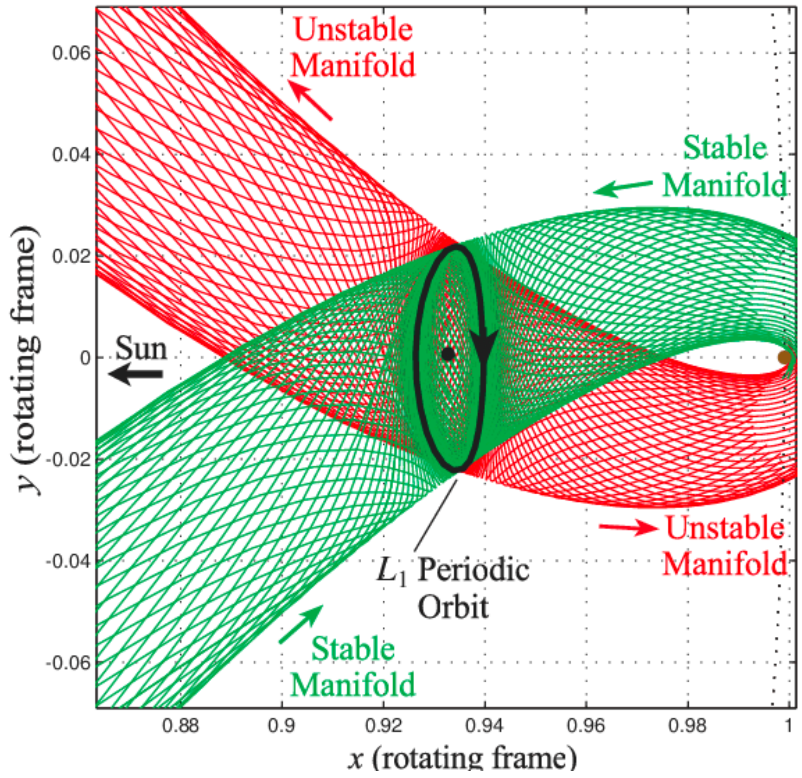
4) To Interplanetary (Mars, asteroids):

1) Transfer to Sun-Earth L1/L2 Points

There is a manifold structure in periodic orbits around Lagrange points.

When a small ΔV disturb at each difference phase on the periodic orbit, the spacecraft leaves the periodic orbits on a group of orbits called **the unstable manifold.**

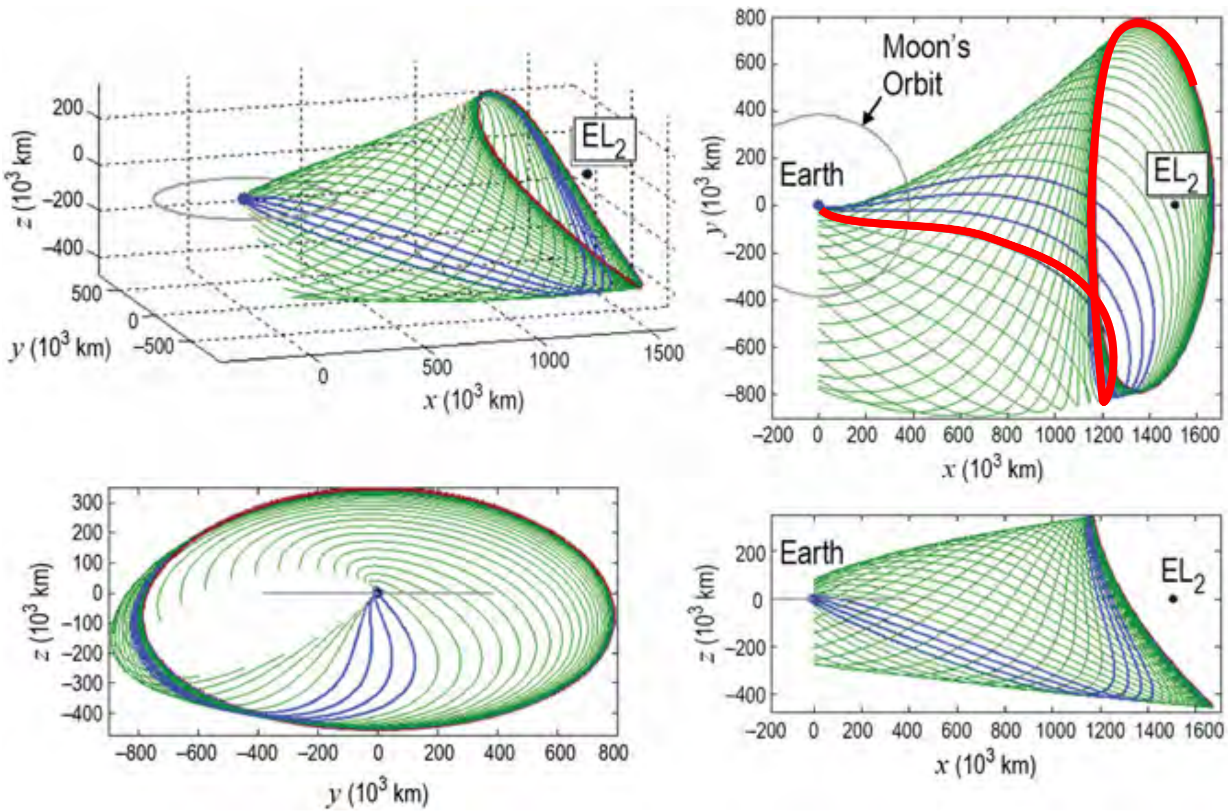
Because of the symmetry, the spacecraft can asymptoticaly approach a period orbit by riding on a group of orbits called **the stable manifold.**



(W.S., Koon, M.W., Lo, et al. , *AAS*, 2000)

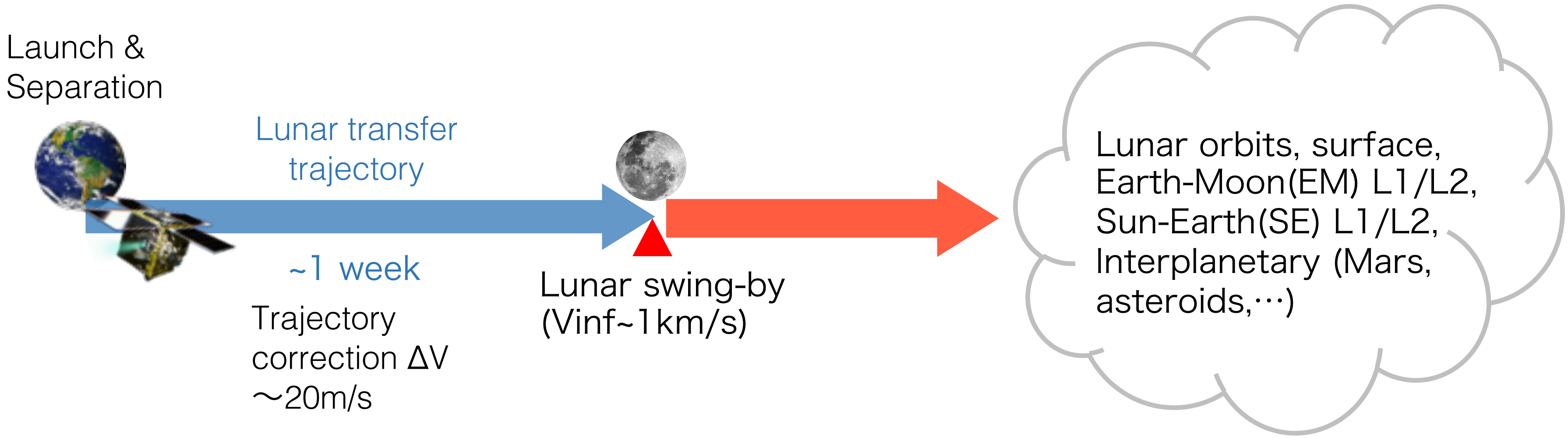
1) Transfer to Sun-Earth L1/L2 Points

By selecting a single trajectory on a stable manifold, the spacecraft can ballistically tranfer to the periodic orbit around the Lagrange point.



(J.S.Parker and R.L.Anderson, *JPL*, p.97, 2013)

Mission Utilizing Gateway Construction Opportunity



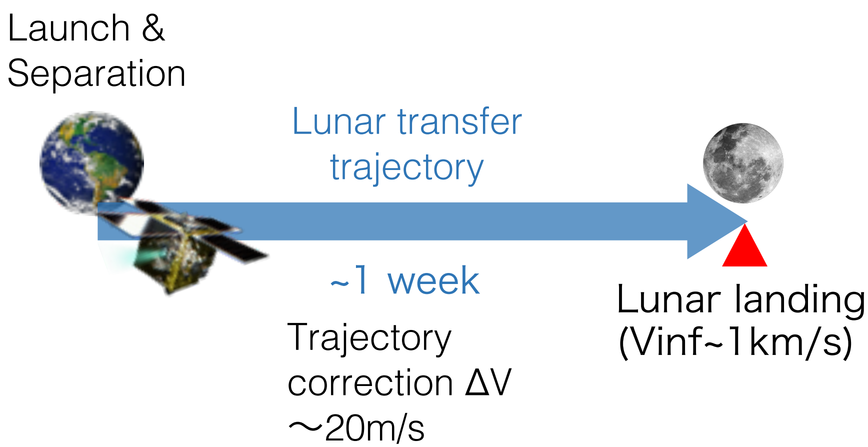
1) To Sun-Earth L1/L2: Ballistic transfer without ΔV

2) To Lunar Surface: Landing with 2.5km/s ΔV

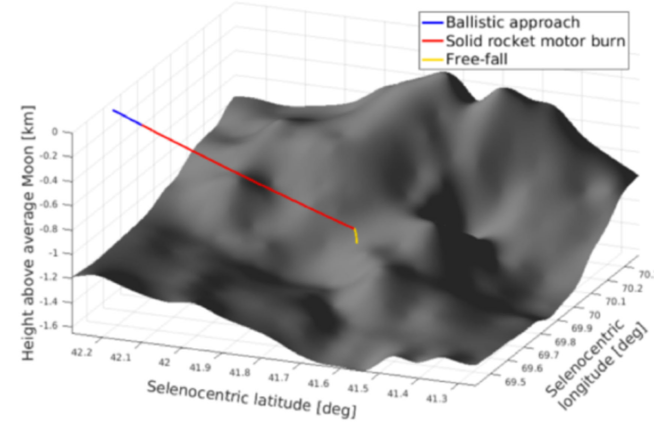
3) To Lunar orbits, Earth-Moon L1/L2:

4) To Interplanetary (Mars, asteroids):

2) Landing on Lunar Surface



OMOTENASHI Trajectory



(S. Campagnola, et al., IEEE, 2019)

It is possible to estimate the landing ΔV by assuming a two-body problem (patched conics)

In the vicinity of the moon, vis-viva equation (orbital-energy-invariance law) gives

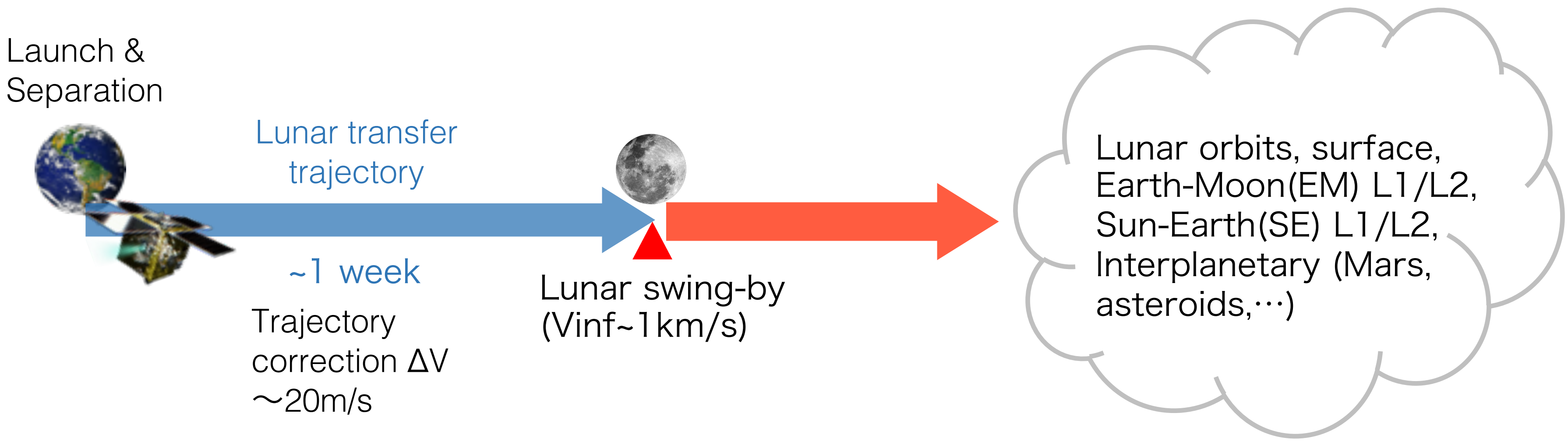
$$\frac{1}{2}v^2 - \frac{GM_M}{r} = \frac{1}{2}v_\infty^2$$

Suppose that $v_\infty = 0.82\mathrm{km/s}$ (example of Artemis 1) and $r = r_M$ (lunar radius), te velocity is

$$v = 2.514\ \mathrm{km/s}$$

In order to land on the moon, we need to cancel this velocity, i.e., **ΔV~2.5km/s.**

Mission Utilizing Gateway Construction Opportunity



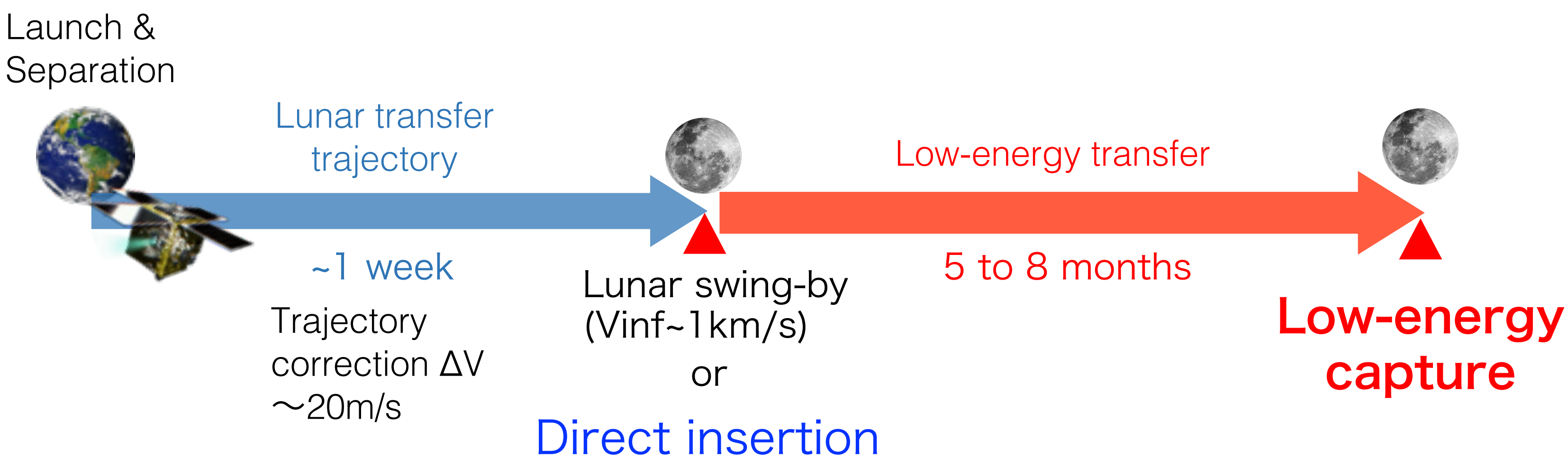
1) To Sun-Earth L1/L2: Ballistic transfer without ΔV

2) To Lunar Surface: Landing with 2.5km/s ΔV

3) To Lunar orbits, Earth-Moon L1/L2: Direct insertion or Low-energy transfer/capture by reducing Vinf.

4) To Interplanetary (Mars, asteroids):

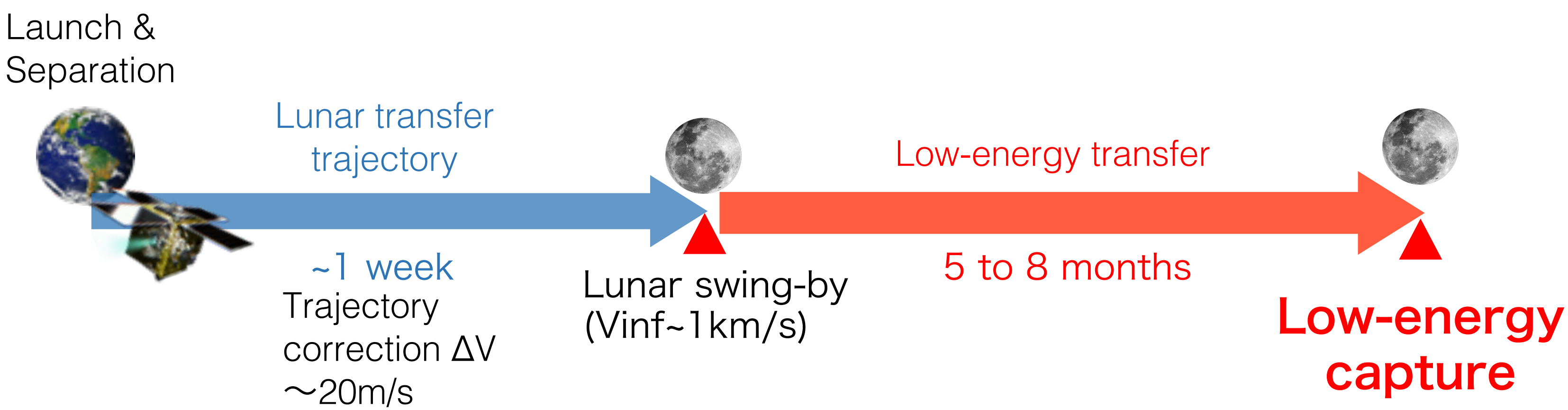
3) Transfer to Lunar Orbits or Earth-Moon L1/L2 points



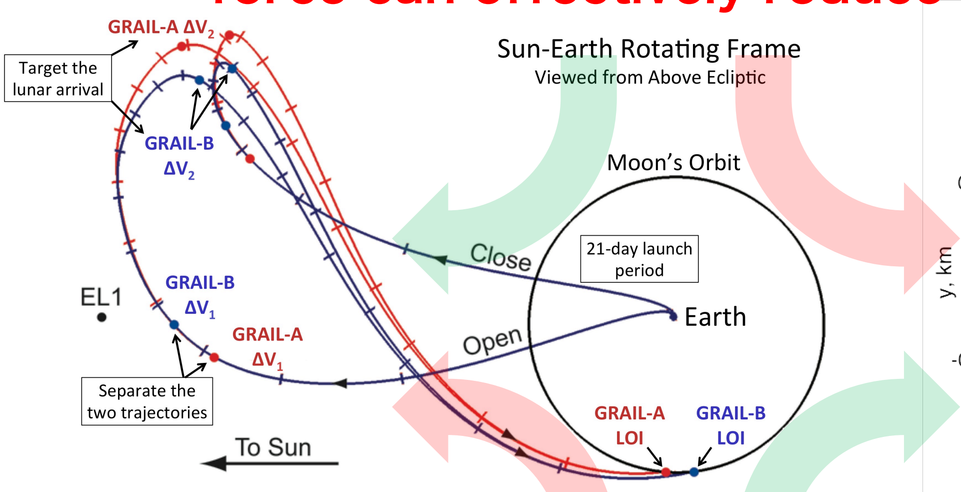
For direct insertion, it is possible to estimate the insertion ΔV by assuming a two-body problem (patched conics). The ΔV is about 0.5-1km/s.

For low-energy transfer/capture, the solar tidal force can effectively reduce Vinf. For NRHO or other Halo orbits, only about 10m/s ΔV is required for the insertion.

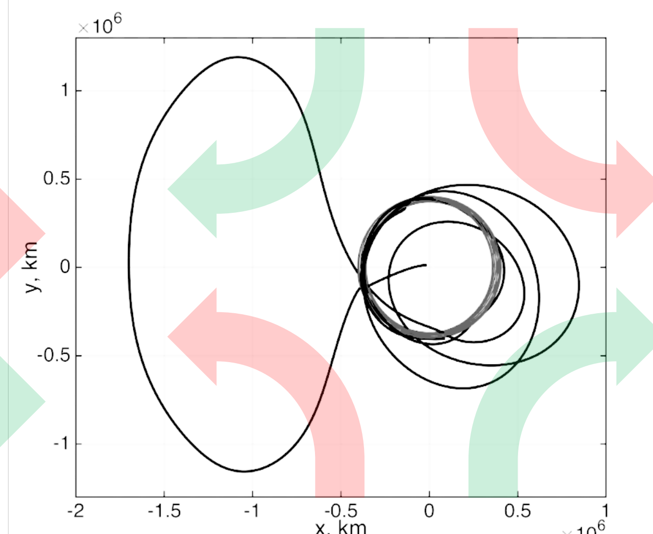
3) Transfer to Lunar Orbits or Earth-Moon L1/L2 points



For low-energy transfer/capture, the solar tidal force can effectively reduce Vinf without ΔV.

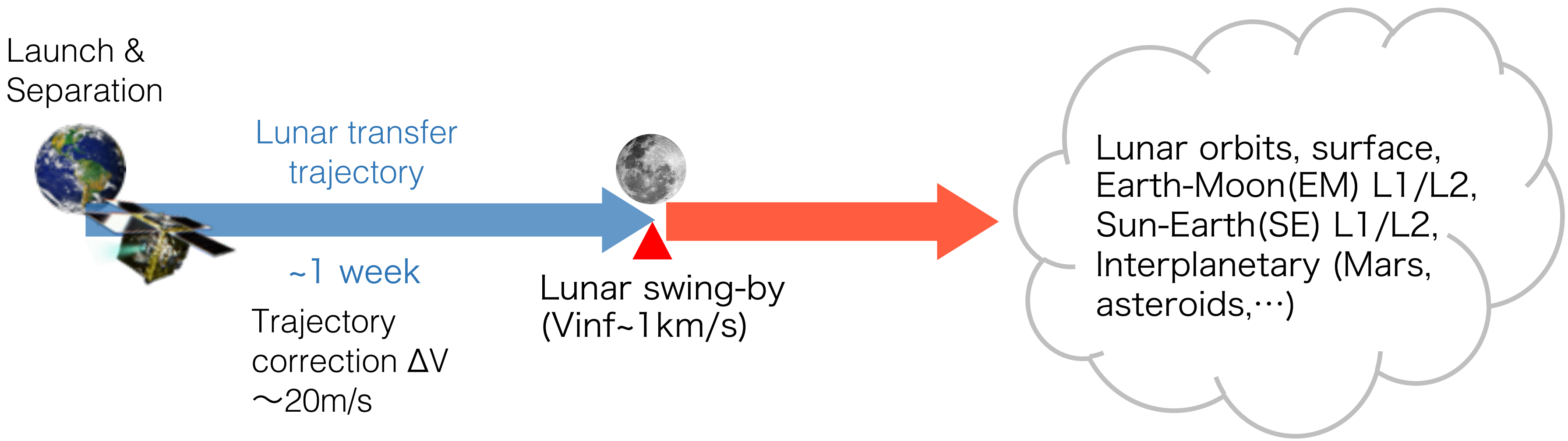


GRAIL(NASA) trajectory (J.S. Parker, R.L. Anderson, *AAS*, 2011)



EQUULEUS trajectory (example)

Mission Utilizing Gateway Construction Opportunity



1) To Sun-Earth L1/L2: Ballistic transfer without ΔV

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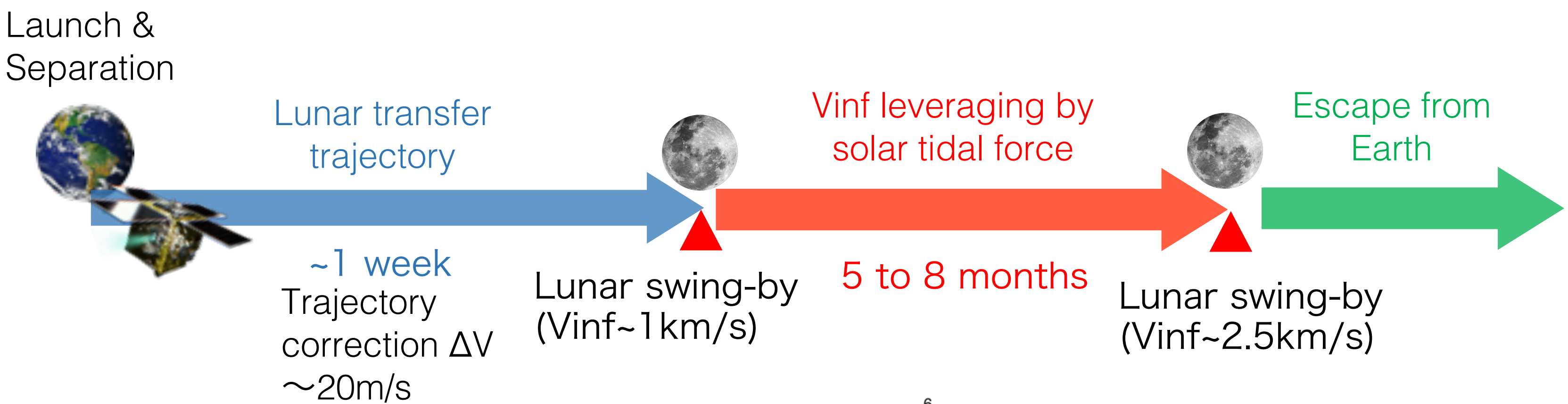
3) To Lunar orbits, Earth-Moon L1/L2: Direct insertion or Low-energy transfer/capture by reducing Vinf.

4) To Interplanetary (Mars, asteroids): Escaping by leveraging Vinf.

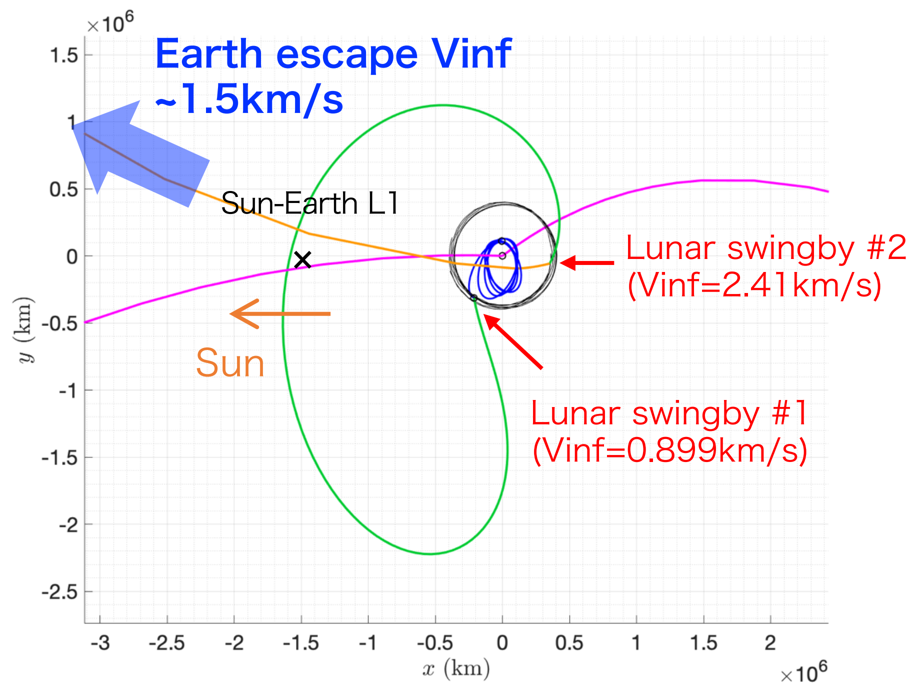
4) To Interplanetary Space (Mars, etc)



Exploiting solar gravity (tidal forces) can **increase the Vinf with respect to the moon!!**

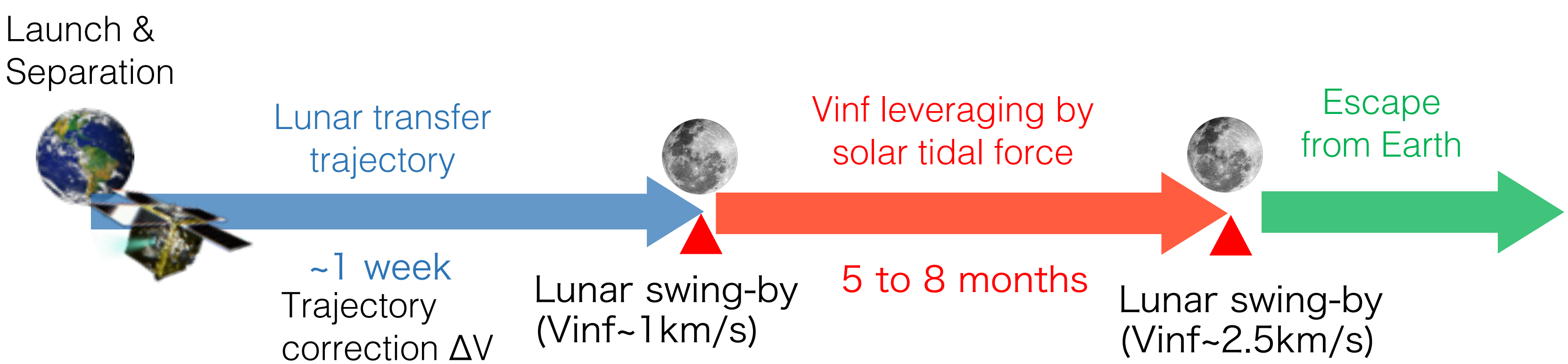
In this case, the maximum Vinf w.r.t. the Earth is about 1.5km/s.

The interplanetary trajectory can be design under two-body problem (patched conics) with Vinf<1.5km/s.



DESTINY+ Trajectory
(Ozaki, et al., 2019)

4) To Interplanetary Space (Mars, etc)



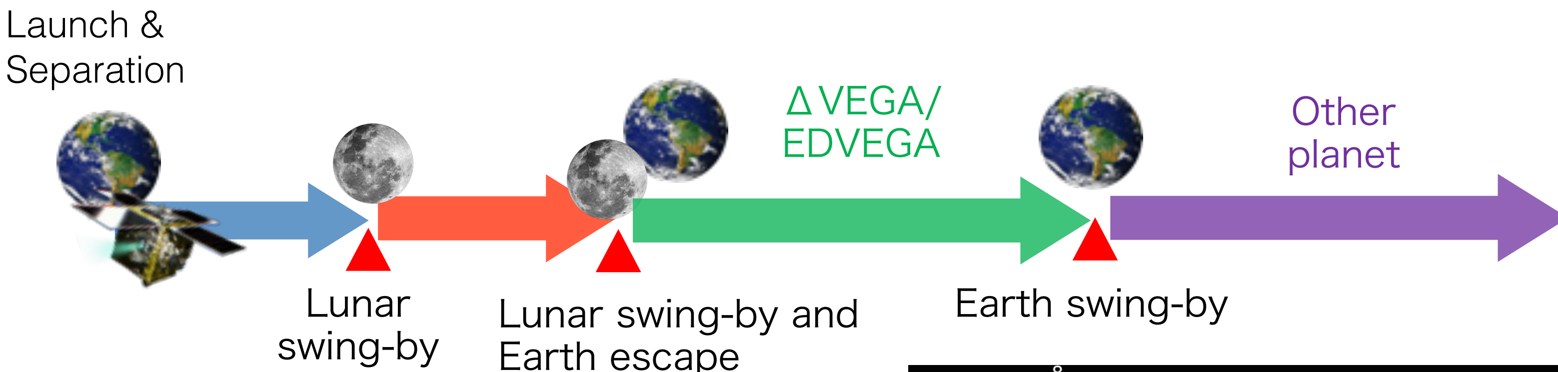
Reachable Planet for each Earth departure Vinf

(under Hohmann transfer assumption)

Planet	Earth departure Vinf, km/s
Mercury	7.53
Venus	2.50
Asteroid	Depending on the body
Mars	2.94
Jupiter	8.49
Saturn	10.29

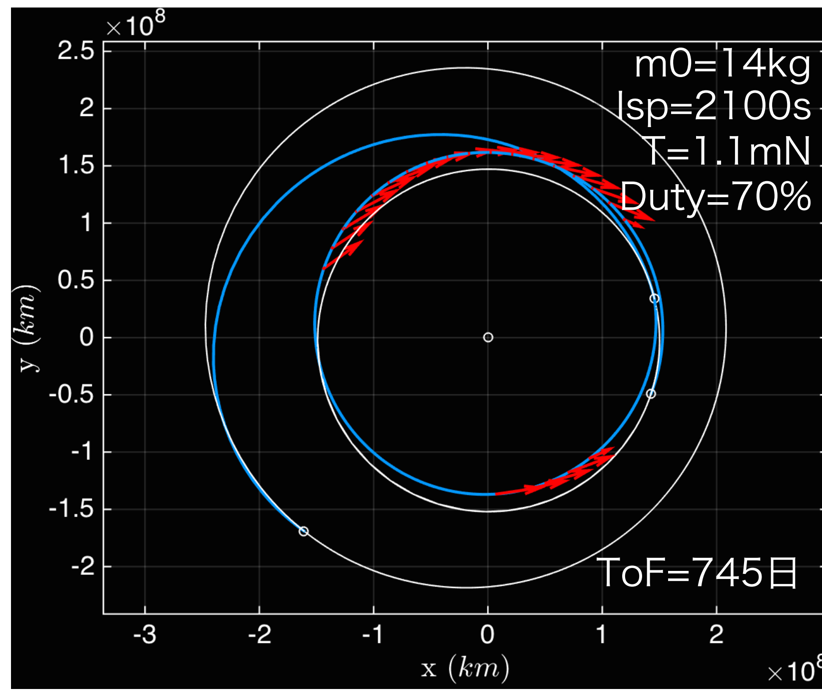
We cannot reach most of them with Vinf=1.5km/s

4) To Interplanetary Space (Mars, etc)



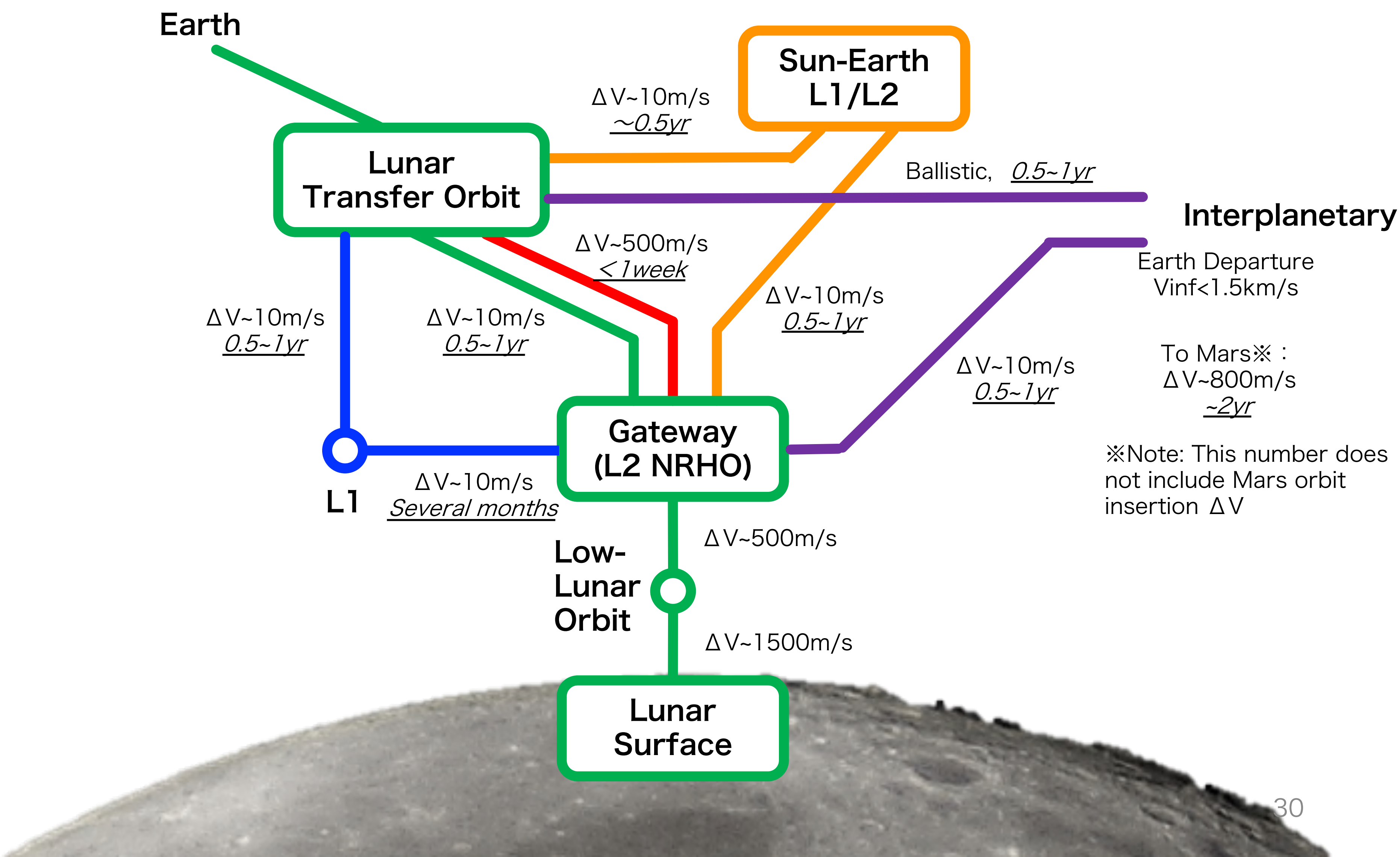
V-infinity leveraging transfer (or ΔVEGA/EDVEGA) can effectively increase the Earth departure Vinf.

If we want to increase Vinf from 1.5km/s to 3.0km/s (reachable to Mars), **we need 0.83km/s ΔV (about half of Vinf increment)**



V-Infinity Leveraging Transfer to Mars

Gateway Metro Map



Possible Small Sat Mission Utilizing LOP-G

When we assume that we can deliver 6U CubeSat to LOP-G (or SLS/Artemis-1 like trajectory), the following missions are possible.

Target	Possible Using Current Technology	Challenging, Could Be Possible in the Future
Moon	**Moon orbiter**	**(Soft?) Landing**
Asteroid	**Flyby to NEAs**	**Rendezvous to NEAs**, Exploration to main belt asteroids
Lagrange Points	**Earth-Moon halo, Sun-Earth halo**	—
Mars, Venus	—	**Flyby exploration**, Orbiter? Lander?
Outer Planet	—	Dependent exploration (Stand alone mission could be possible if innovative technologies are developed)

Bold: Possible missions by SLS, Artemis-2

Summary

- What is the Lunar Gateway?
- Which orbit can the spacecraft transfer from lunar transfer orbit (Gateway construction opportunities)
- Which type of mission can the small spacecraft do by utilizing the Gateway opportunity.