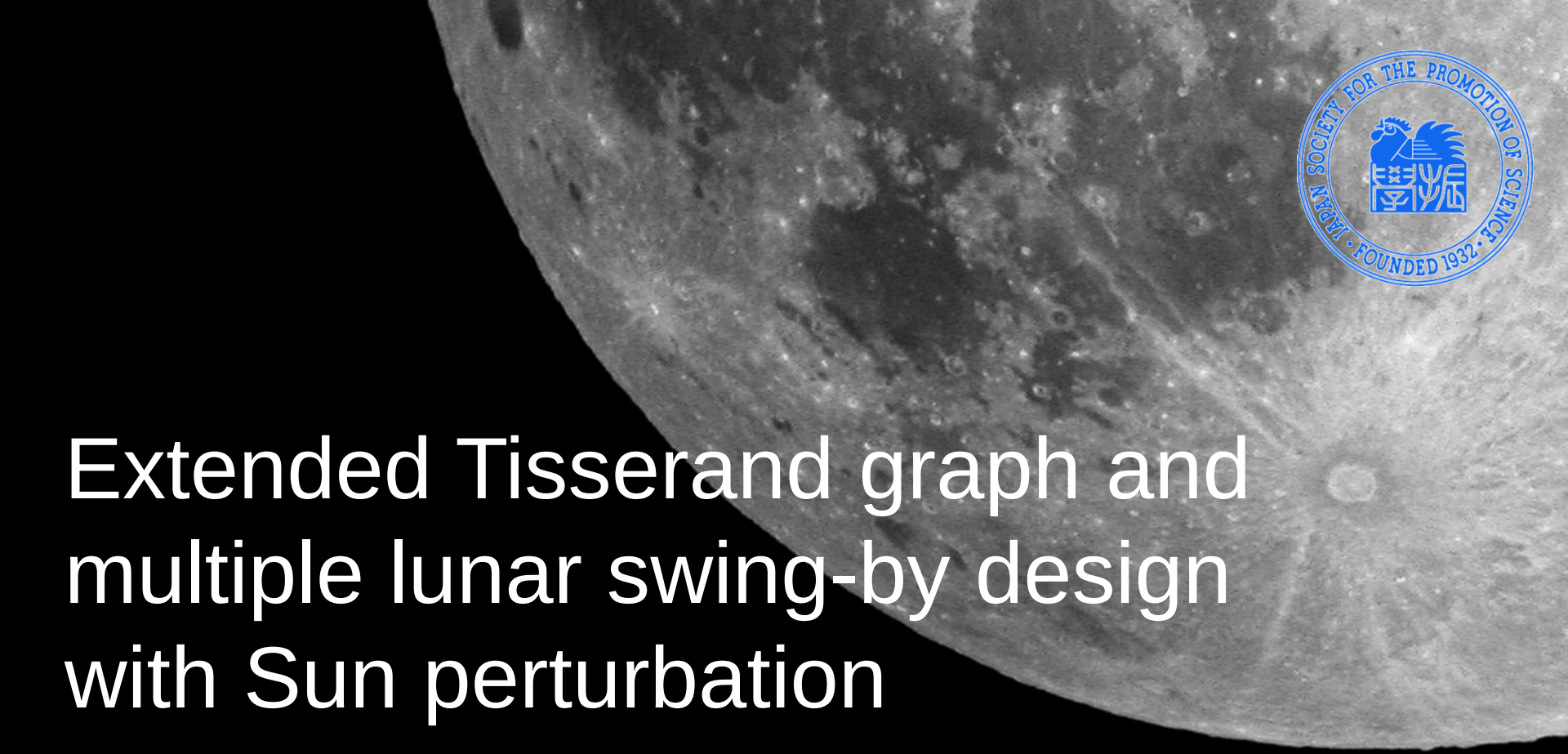

Extended Tisserand graph and multiple lunar swing-by design with Sun perturbation

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6th ICATT. Darmstadt, Germany

Outline

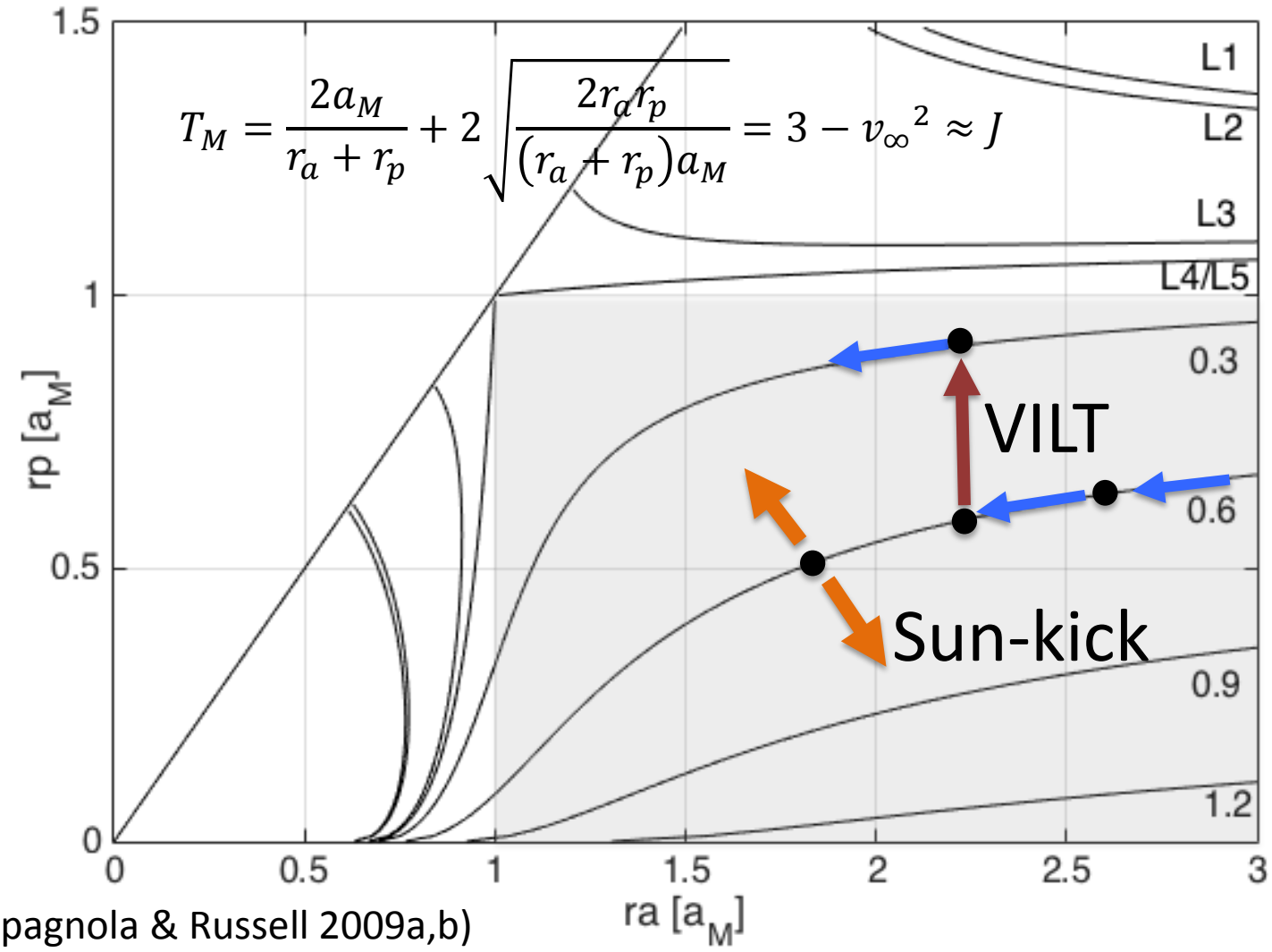
- Intro
- Tisserand-Poincaré graph and extension
- Lunar transfer database
- Application examples
  - EQUULEUS
  - DESTINY
- Conclusions

http://destiny.isas.jaxa.jp/

Background and rationale

- New trends in small missions:
  - Small sats / CubeSats beyond LEO, beyond cislunar space?
- Launch / escape strategies
  - Piggy-back / secondary payloads
  - Spiralling from LEO
  - Limited choice of date and target orbits conditions
- **Moon: single, massive, close to ecliptic, high potential**
  - Pump up/down
  - Phasing
  - Transfers

Tisserand-Poincare graph



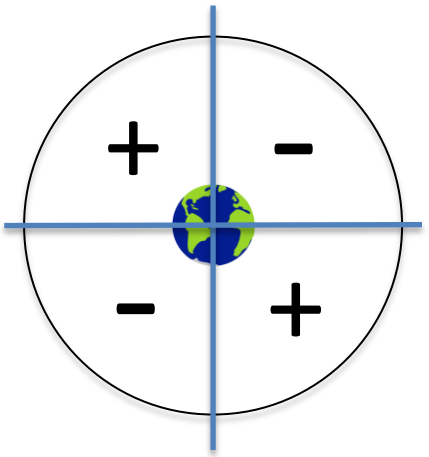
(Campagnola & Russell 2009a,b)

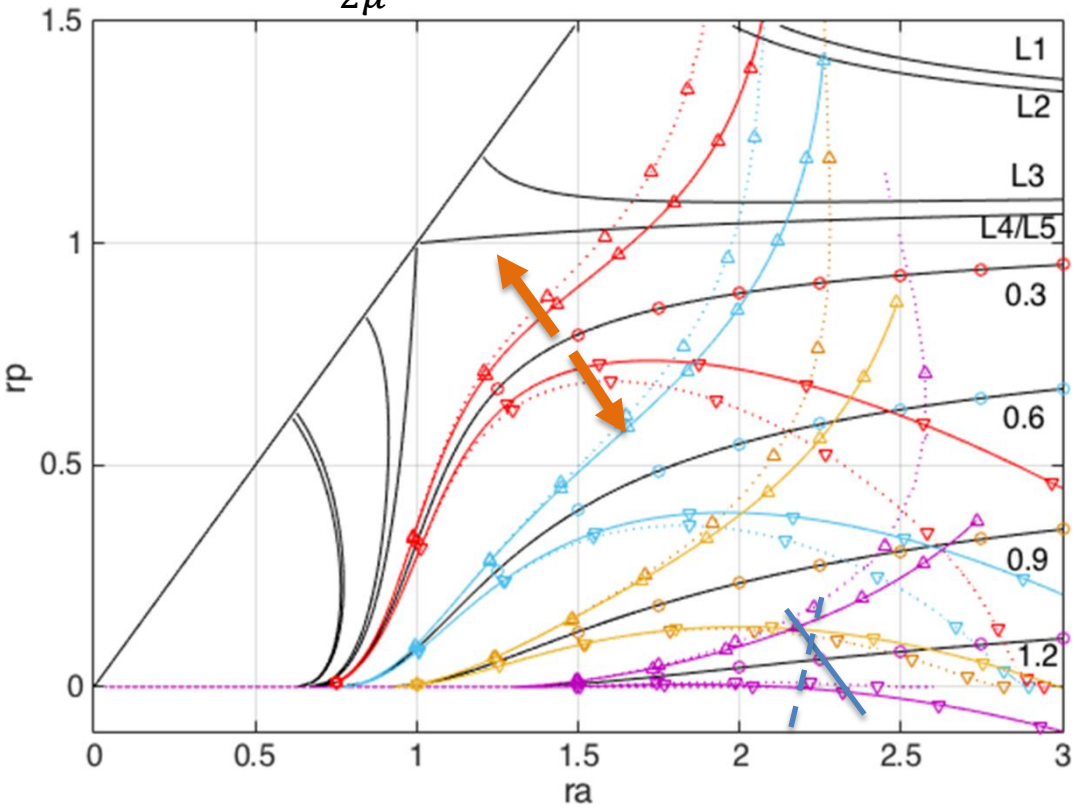
Extension with Sun perturbation

- Analytical approximation (continuous)

$\Delta a \approx 0$ →Lines of slope -1

$\Delta e = 15\frac{\pi}{2\mu}a^3 e\sqrt{1-e^2}\sin 2(\omega_p - \theta)$→ quadrants





- Numerical propagation (dashed)
  - Similar slope for low vel or low apocentres
  - Greater deviations achievable
- Issues: geometry dependant, multiple revs, deviations at ↑r_a,v

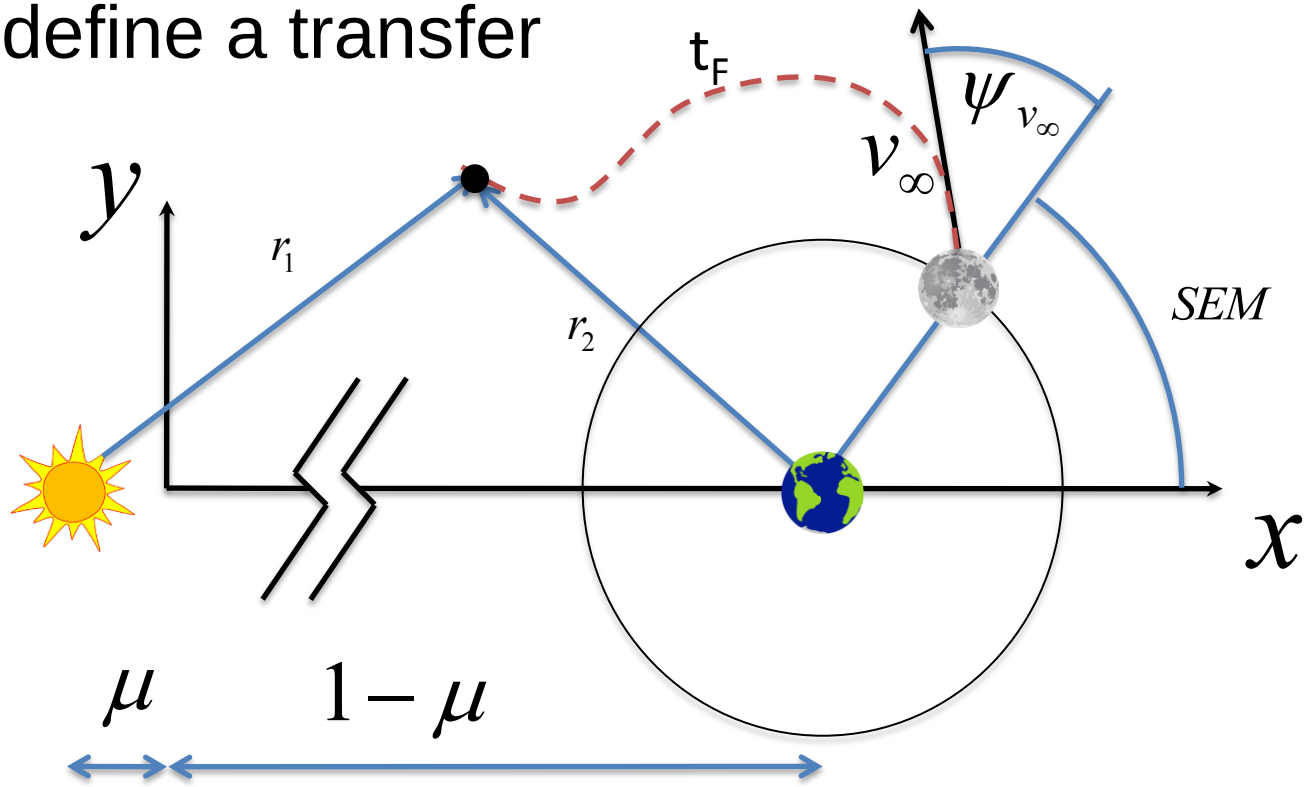
Introducing: The "Mooning" Database

- Planar CR3BP
  - Neglect e_E, e_M, i_M → planar, pseudo epoch-free transfers
  - Transfers repeat every Moon period
- Families generated with continuation method
- Database stored for quick and easy access
- Generation of first guesses for full-model optimisation
  - "Substitute" Lambert arc calculations
  - Usual methods used in multiple gravity assists can be build on top (branch and pruning, genetic algorithms…)
- Extend to multiple revolutions + additional families

(Lantoine & McElrath 2014)

Synodic frame and transfer parameters

- 4 variables define a transfer



Database of transfers stored:

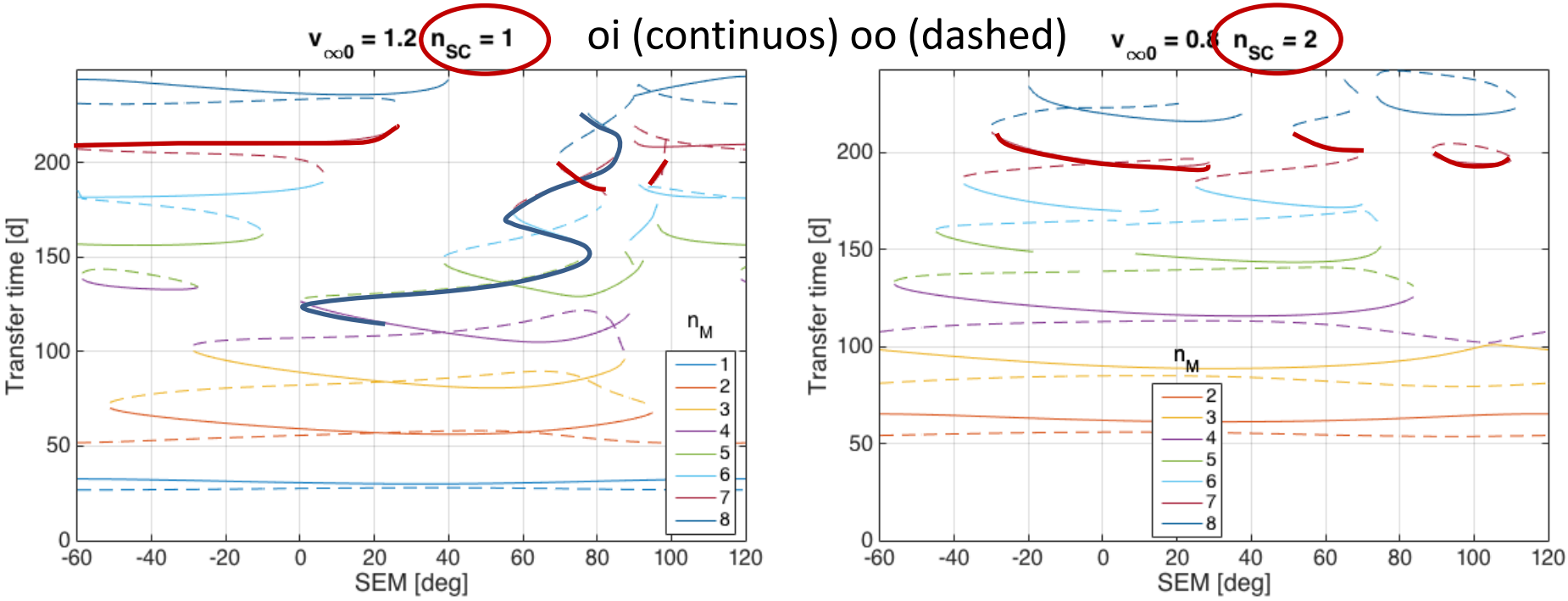
$$\underbrace{SEM, v_\infty, \Psi_{v_\infty}}_{\text{initial}}, t_F, \underbrace{SEM, v_\infty, \Psi_{v_\infty}}_{\text{final}}, r_{2min}$$

“Mooning” Database Structure

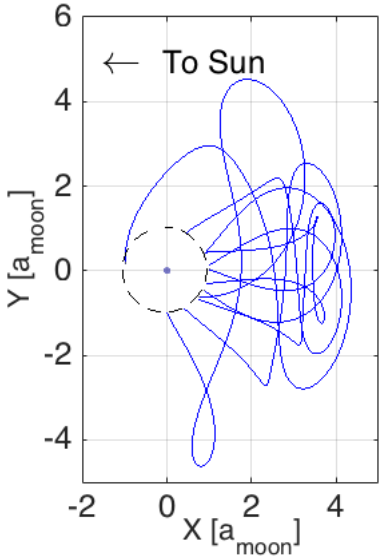
- Four types: *oo, oi, ii, io*

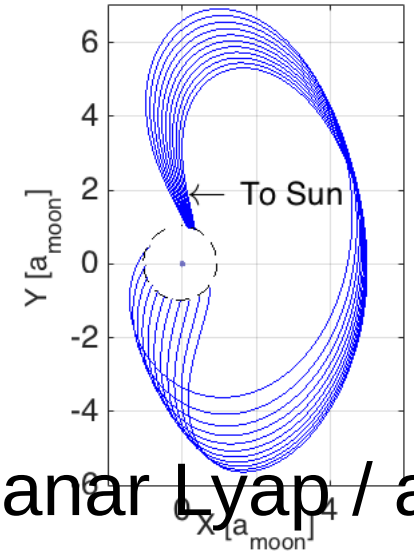
Outgoing: $\cos(\Psi_{v_\infty}) > 0$
Incoming: $\cos(\Psi_{v_\infty}) < 0$

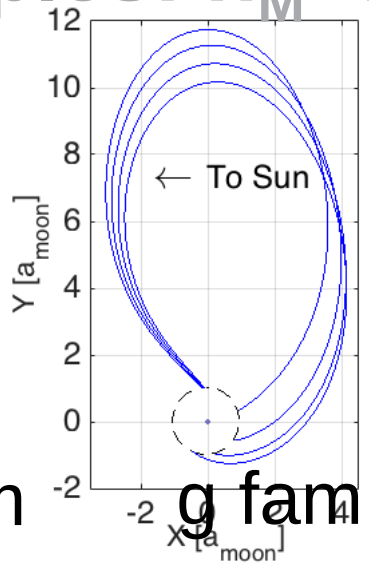
- Families branch off and reconnect (loops, helix)
- Example connections *oi-oo*: tangent to Moon orbit



Database sub-families examples: n_M=7



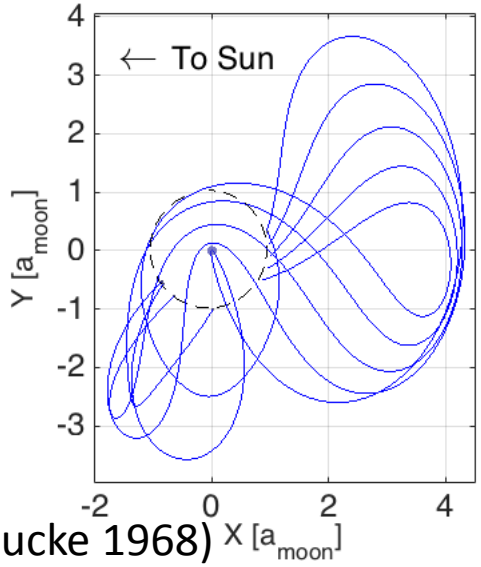


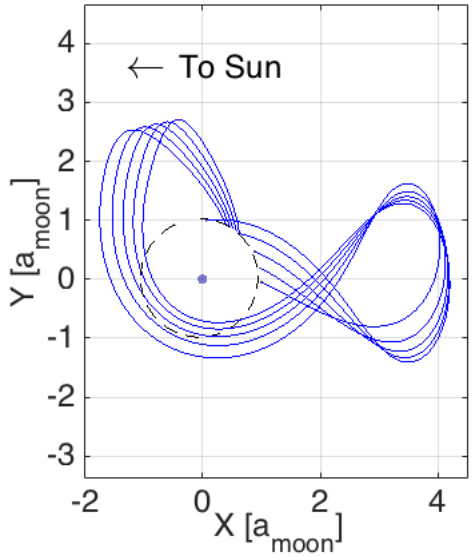


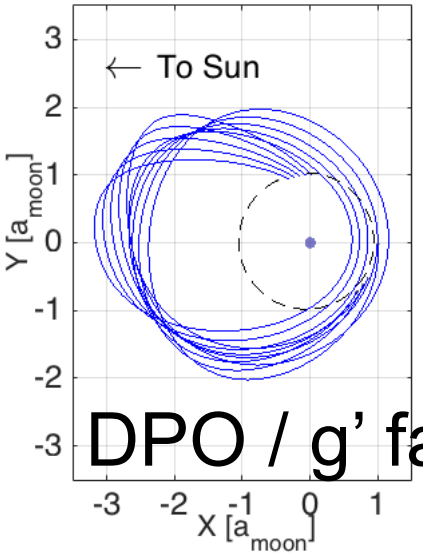
n_{SC}=1

Planar Lyap / a fam

g fam







n_{SC}=2

DPO / g' fam

(Broucke 1968)

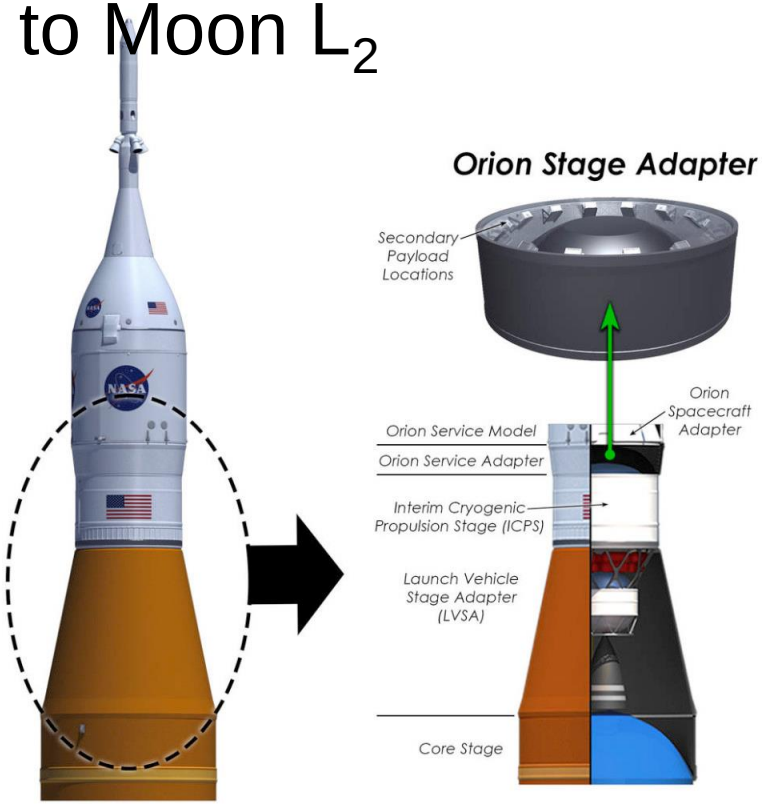
Applications

Two opposite problems:

- EQUULEUS: decrease velocity (+phasing)
- DESTINY: increase velocity (+phasing)

Application 1: EQUULEUS

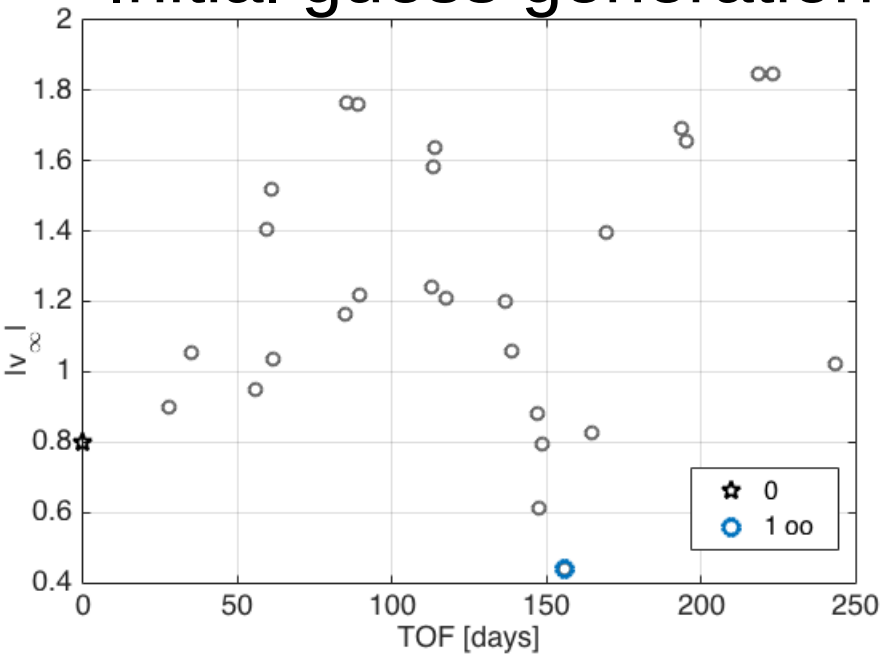
- NASA offering 11-13 Secondary Payload opportunities on SLS EM-1 test launch
- JAXA proposed EQUULEUS to Moon L_2
- 6U CubeSat: study plasmasphere, navigation and control WSB
- Launch “moon-bound”: v_∞=0.8 km/s
- Reduction of velocity to libration orbit

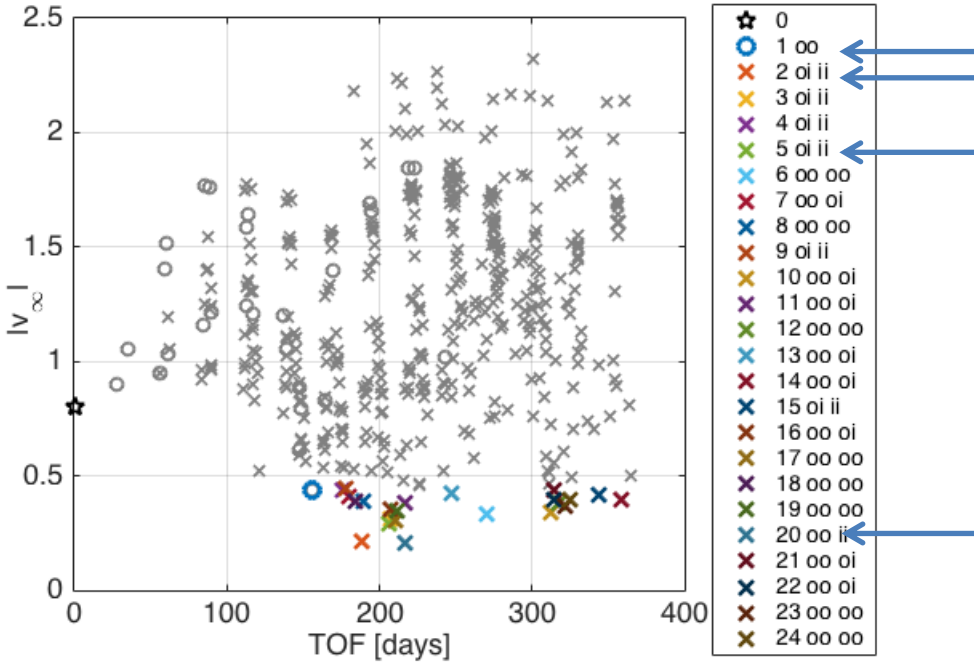


http://www.nasa.gov/content/exploration-mission-1-secondary-payloads

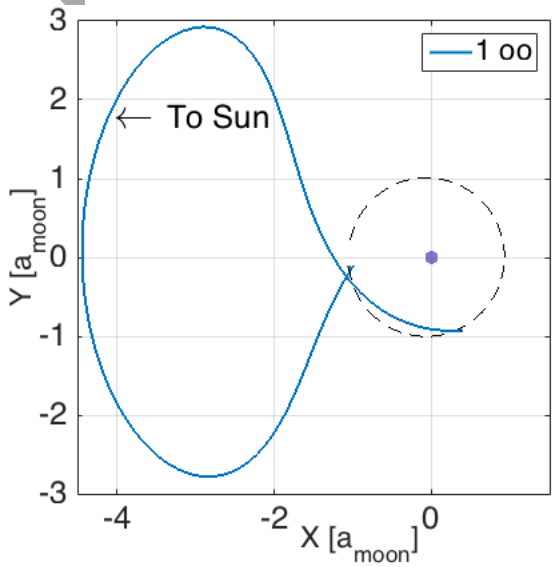
Application 1: EQUULEUS results

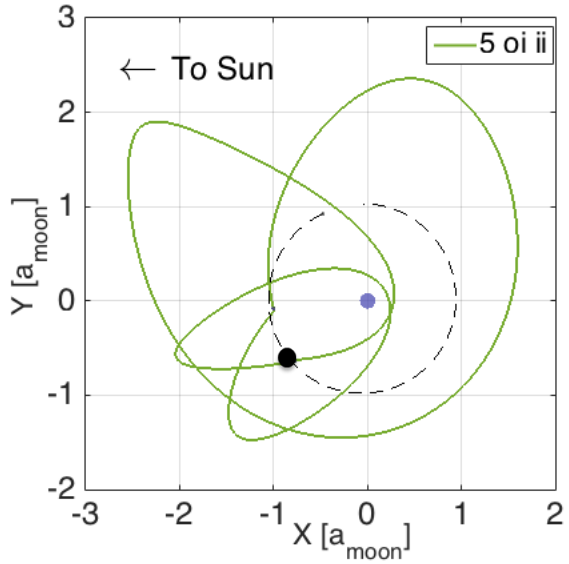
- One leg transfers: 25, one with $v_\infty < 0.45$
- Two leg transfers: 468, 24 with $v_\infty < 0.45$
- Branch and pruning can be recursively applied
- Initial guess generation

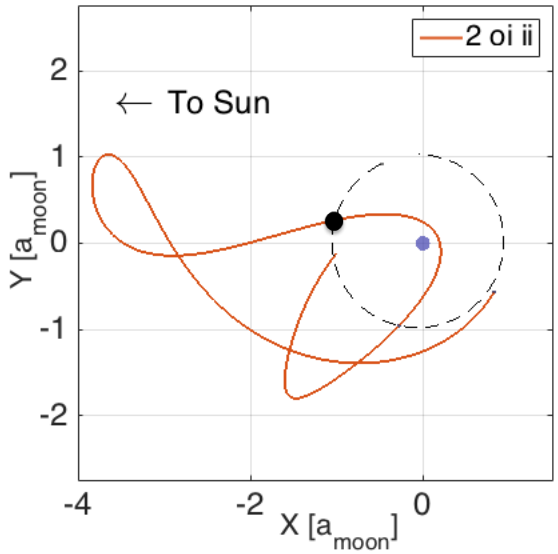


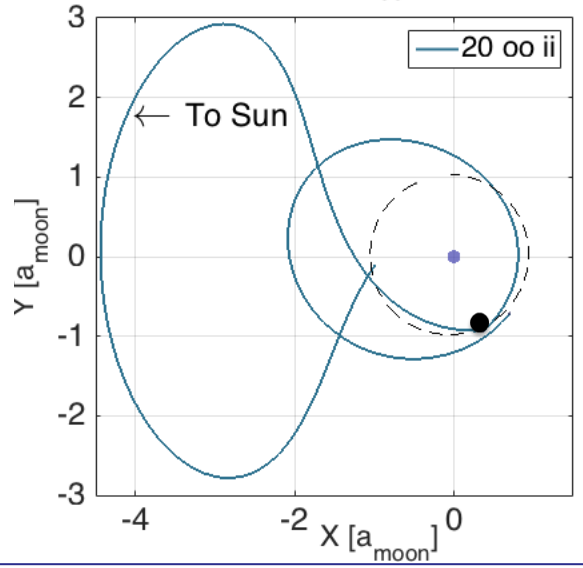


EQUULEUS selected transfers





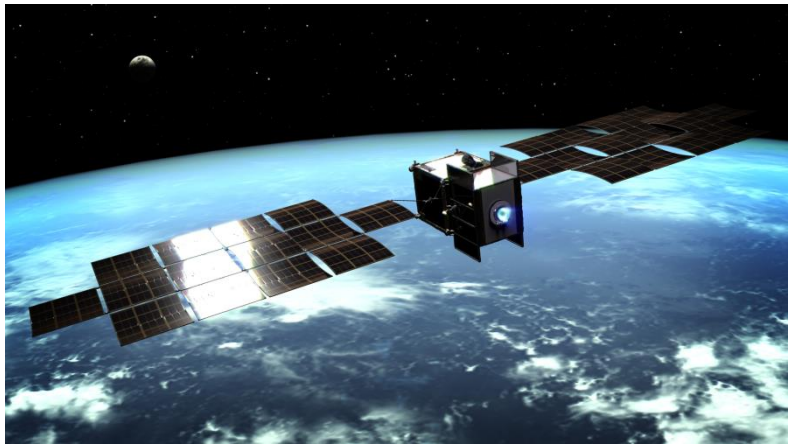


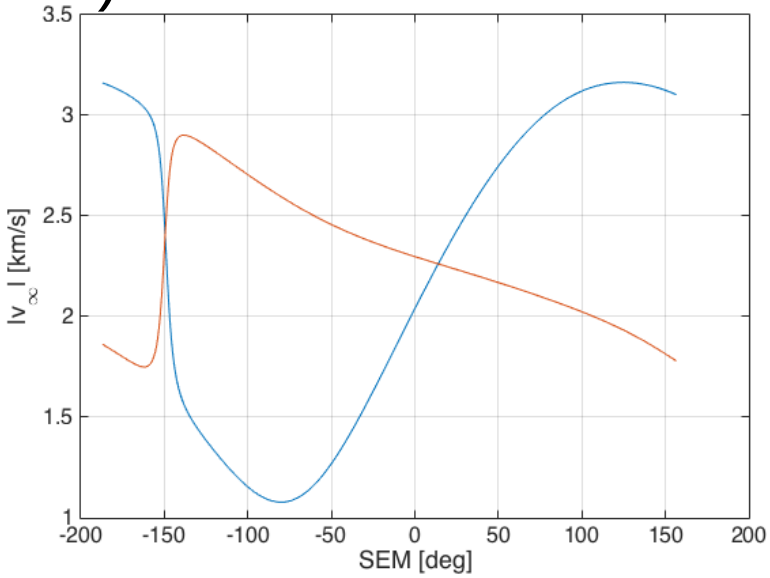


- 1 leg *oo*
- 2 legs $v_\infty < 0.3$
  - *oi ii* (n_{SC}=1)
  - *oi ii* (n_{SC}=1)
  - *oo ii* (low fb height: unfeasible?)
- Tangent transfers: lower velocity

Application 2: DESTINY

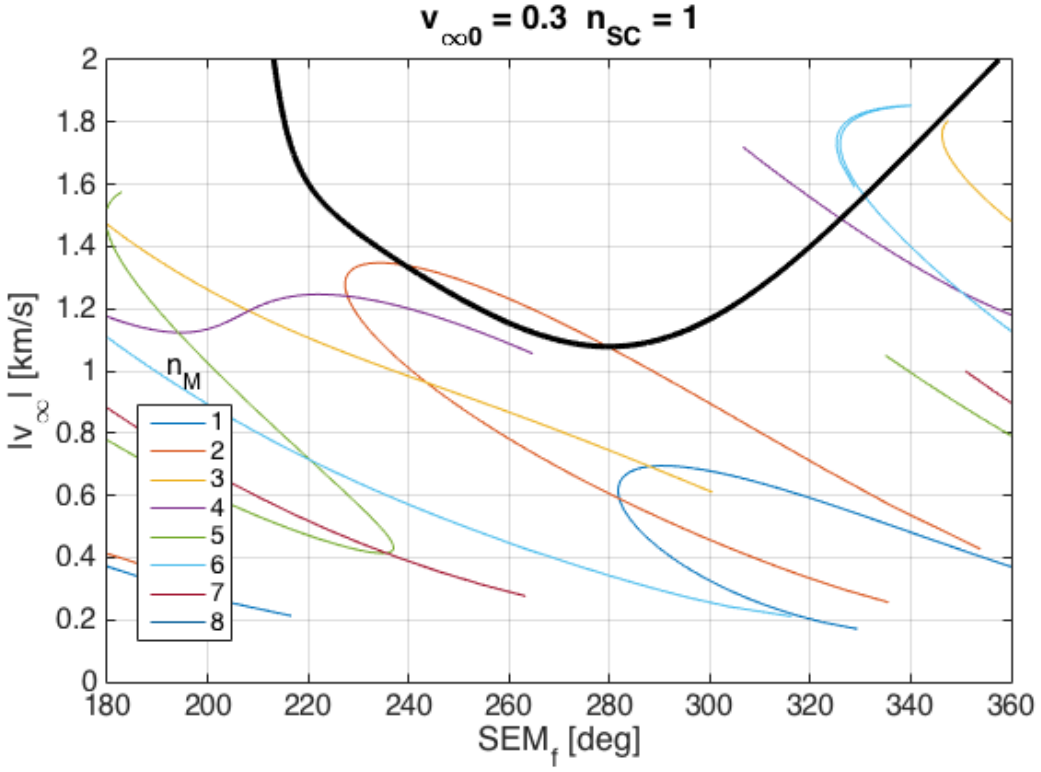
- Interplanetary low-thrust traj. to asteroid Phaethon
- Escape from Earth-Moon system at least 1.5 km/s
  - Connect with spiral up with multiple flybys
  - Last swing-by velocity wrt Moon 2.08 km/s
  - SEM-vinf feasible pairs (1-3 km/s)
- Database search



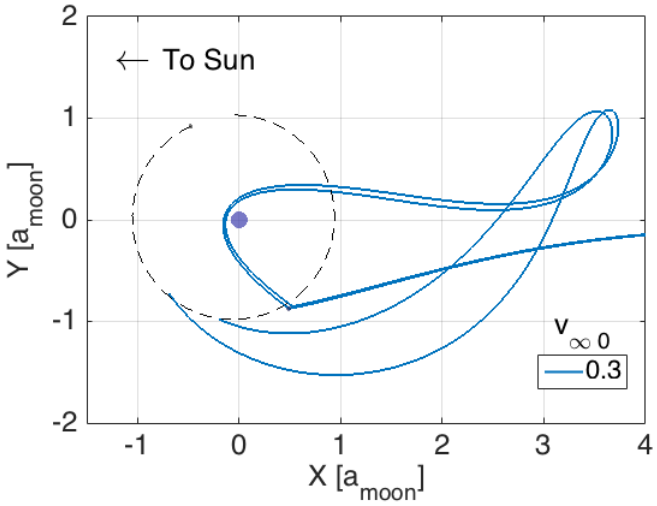


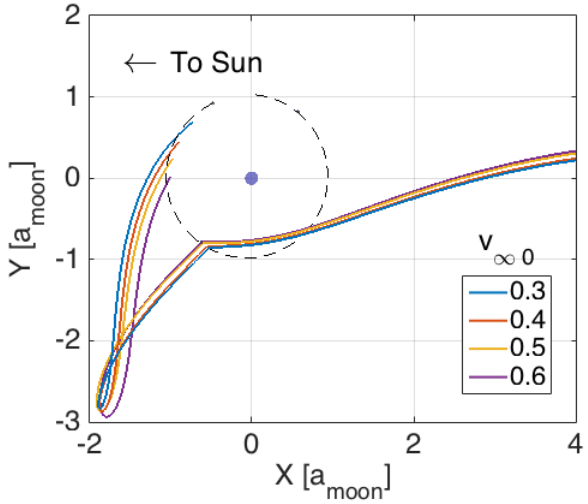
DESTINY: Final leg search

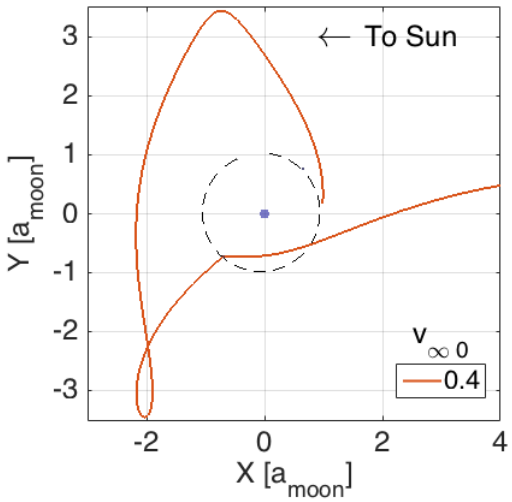
- Assume last swing-by velocity < 2 km/s
- SEM-vinf pairs intersection with families 0.3-0.6 km/s
- Check rotation vinf latitude feasible
- Multiple solutions

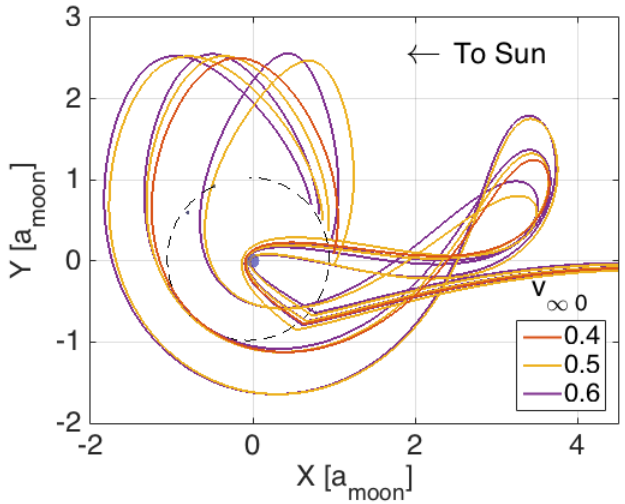


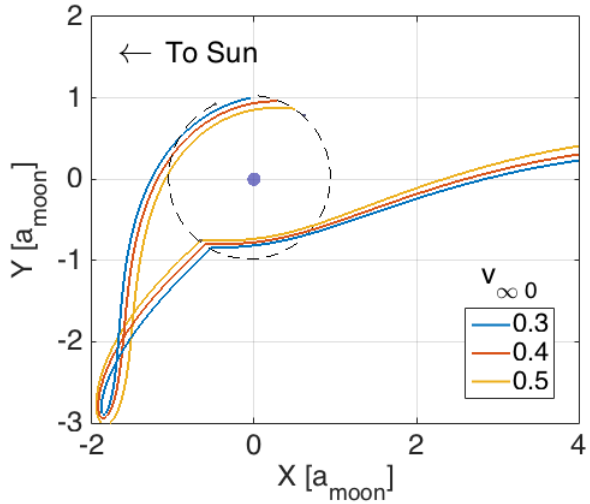
DESTINY: transfer options







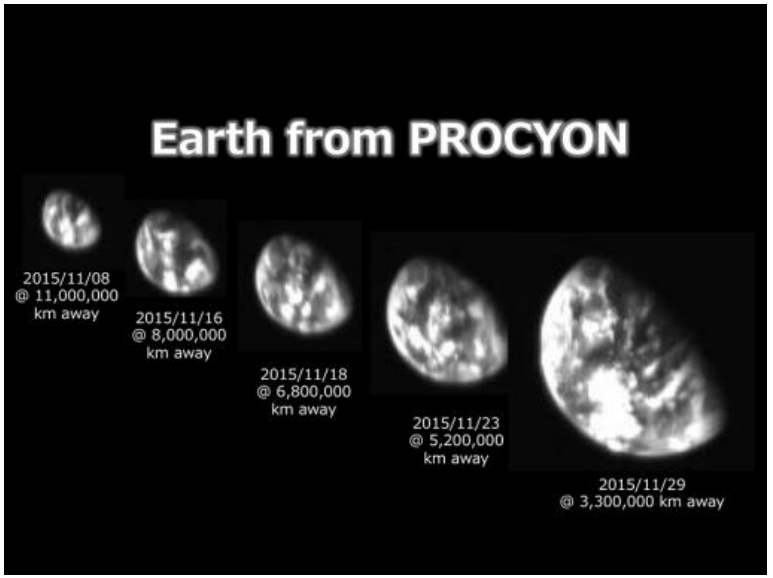




- Vel: 0.3-0.6 km/s
- Diverse shapes
- Multiple options
- Recursively backwards…

Conclusions and future work

- Small missions will benefit of trajectory design with one/multiple lunar swing-bys
- T-P graph allows estimation of reachable regions
- Database of trajectories built → easy generation of initial guesses
- Application examples
- Ongoing / future work:
  - Extension of database
  - Regularized eq. of motion
  - Pseudo-arclength continuation
  - Include π transfers (3D)



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