CALTECH
Control & Dynamical Systems

Design of a Multi-Moon Orbiter

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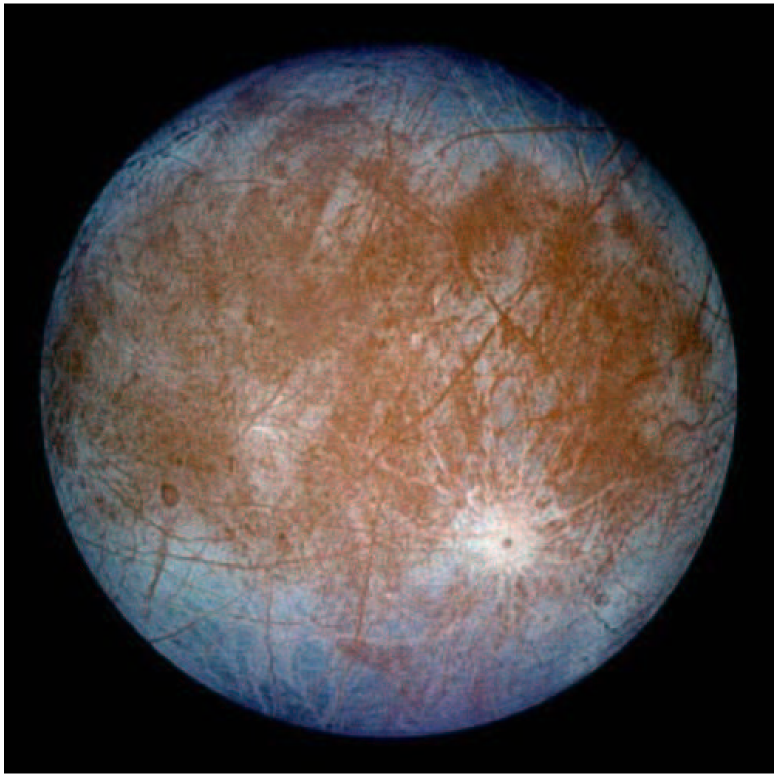
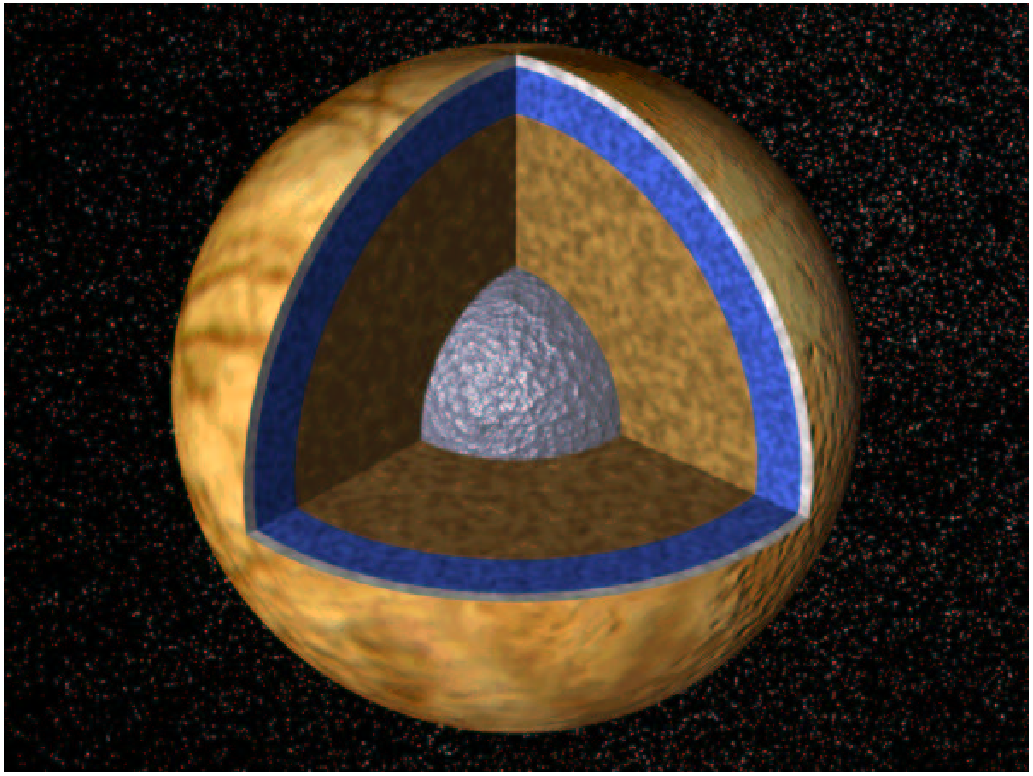
Interplanetary Mission Design

- ***Use natural dynamics for fuel efficiency***
  - **Dynamical channels** connect planets and moons.
  - Trajectory generation using invariant manifolds in the 3-body problem suggests new numerical algorithms for interplanetary missions
- ***Current research importance***
  - Design **fuel efficient** interplanetary trajectories
  - (1) *Multi-Moon Orbiter* to multiple Jovian moons
  - (2) Earth orbit to lunar orbit

Mission to Europa

- ***Motivation: Oceans and life on Europa?***
  - There is international interest in sending a scientific spacecraft to orbit and study **Europa**.





Multi-Moon Orbiter

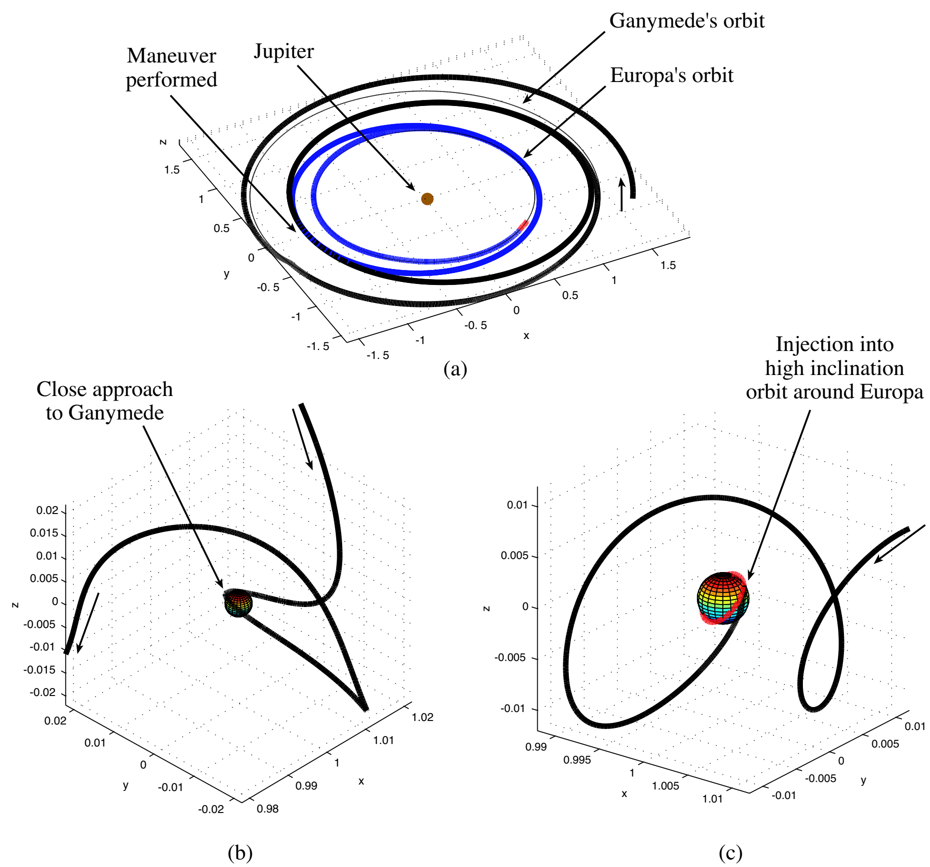
- ***Orbit each moon in a single mission***
  - Other Jovian moons are also worthy of study
    - All may have oceans, evidence from *Galileo* suggests

Multi-Moon Orbiter

- We propose a trajectory design procedure which uses little fuel and allows a **single spacecraft to orbit multiple moons**
- Orbit each moon for much longer than the quick flybys of previous missions
- Using a standard "patched-conics" approach, the ΔV necessary would be prohibitively high
- By decomposing the N-body problem into 3-body problems and using the natural dynamics of the 3-body problem, the ΔV can be lowered significantly

Multi-Moon Orbiter

- ***First attempt:***
  - A Ganymede-Europa Orbiter was constructed
    - ΔV of 1400 m/s was half the Hohmann transfer
    - Gómez, Koon, Lo, Marsden, Masdemont, and Ross [2001]



Multi-Moon Orbiter—Refinement

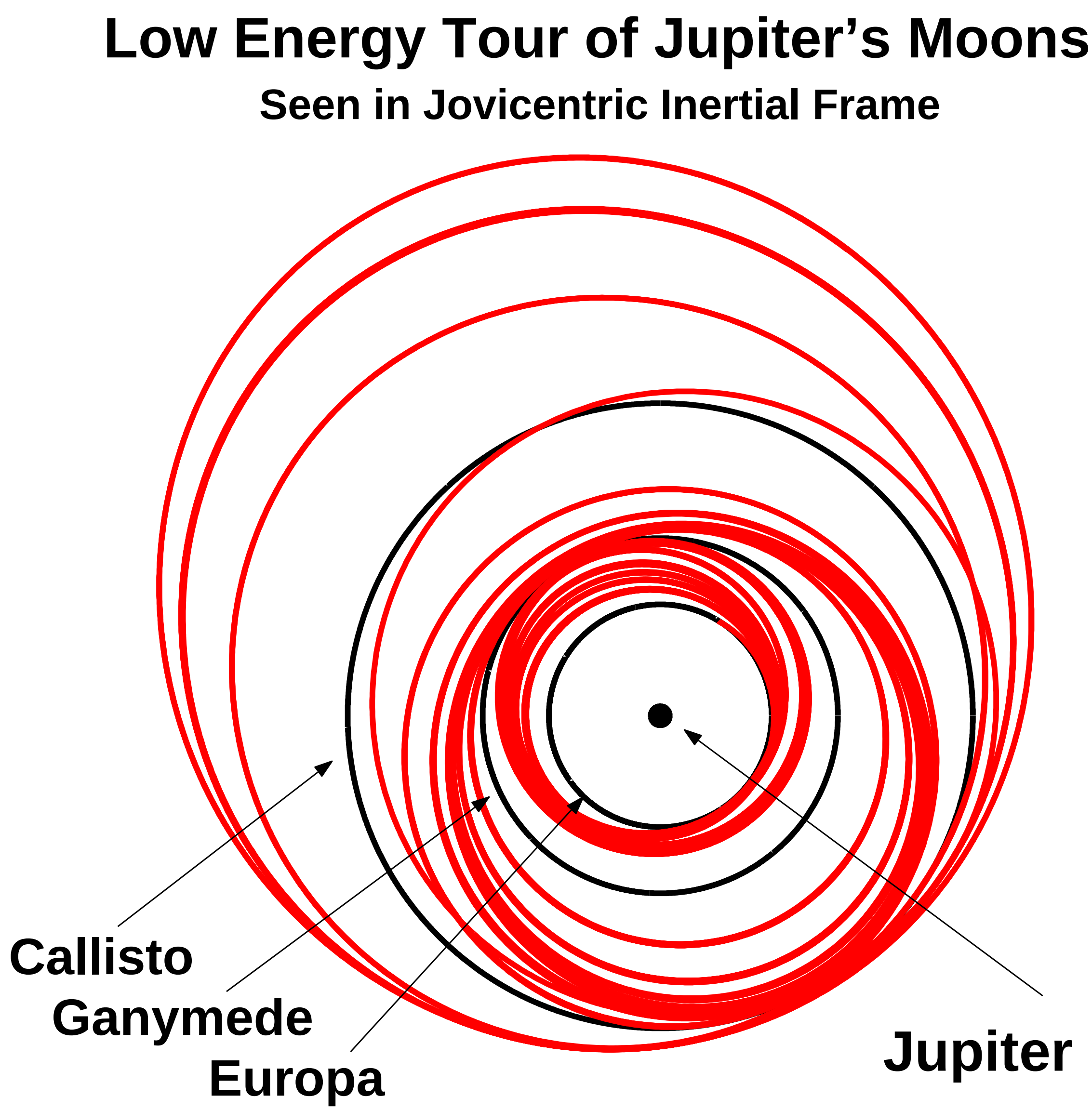
- Preceding ΔV of 1400 m/s for the Ganymede-Europa orbiter was half the Hohmann transfer (that is, using patched conics, as in manned moon missions)
- Desirable to decrease ΔV further—one now does not *directly* "tube-hop", but rather makes more refined use of the phase space structure
- New things: *resonant gravity assists* with the moons
- Interesting: still fits well with the tube-hopping method

Multi-Moon Orbiter

- ***Second attempt:***
  - Desirable to decrease ΔV further
  - One can consider using **resonant gravity assists** with the moons, leading to ballistic captures
  - Consider the following tour of Jupiter's moons
    - Begin in an eccentric orbit with perijove at Callisto's orbit, achievable using a patched-conics trajectory from the Earth to Jupiter
    - Orbit Callisto, Ganymede, and Europa

Multi-Moon Orbiter

- $\Delta V = 22$ m/s, but flight time is a few years



Multi-Moon Orbiter

Results are promising

- This result is preliminary
  - Model is a restricted bicircular 5-body problem
  - A user-assisted algorithm was necessary to produce it
  - An automated algorithm is a future goal
- Future challenges
  - The flight time is too long; should be reduced below 18 months
  - Evidence to be presented later in this talk suggests that a significant decrease in flight time can be gained for a modest increase in ΔV
  - Radiation dose is not accounted for; will be included in future models

Construction Procedure

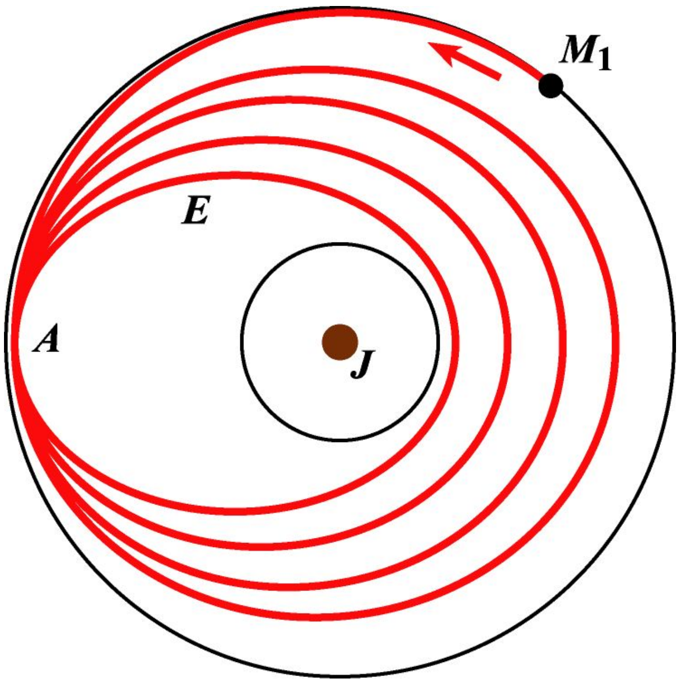
- ***Building blocks***
  - **Patched three-body model:** linking two adjacent three-body systems
  - **Inter-moon transfer:** decreasing Jovian energy via resonant gravity assists
  - **Orbiting each moon:** ballistic capture and escape
  - **Small impulsive manuevers:** to steer spacecraft in sensitive phase space
- ***We will give some background on these issues***

Inter-Moon Transfer

- Spacecraft gets a gravity assist from outer moon M_1 when it passes through apoapse if **near a resonance**
- When periapse close to inner moon M_2's orbit is reached, it takes "control"; this occurs for ellipse E

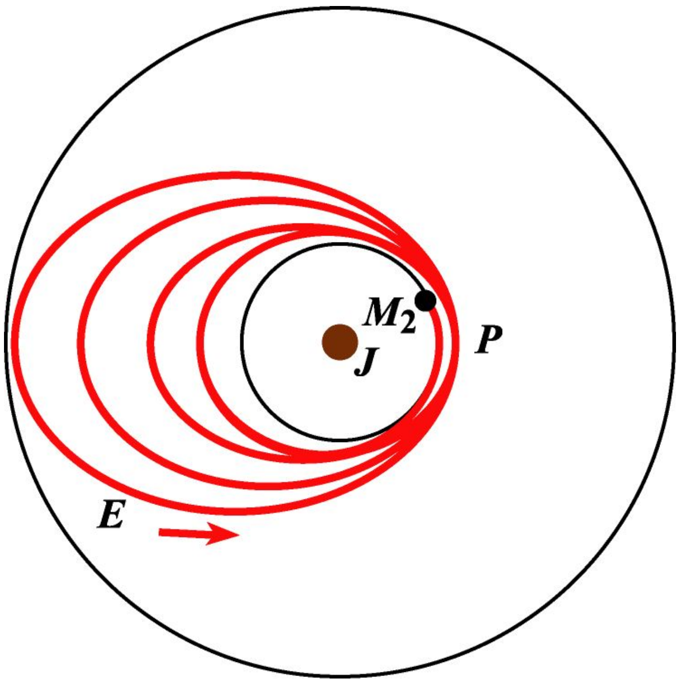
Leaving moon M_1

Apoapse A fixed



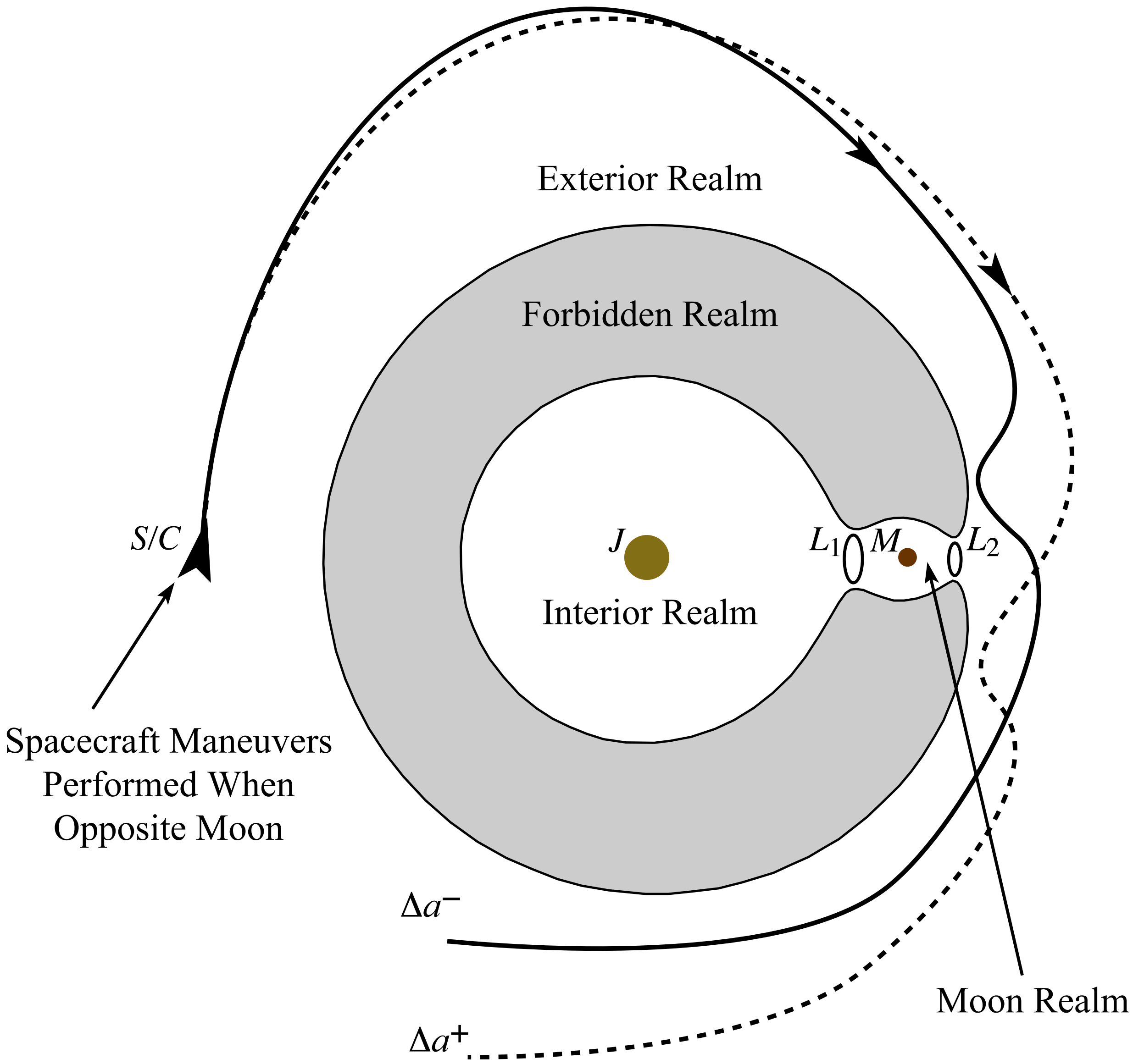
Approaching moon M_2

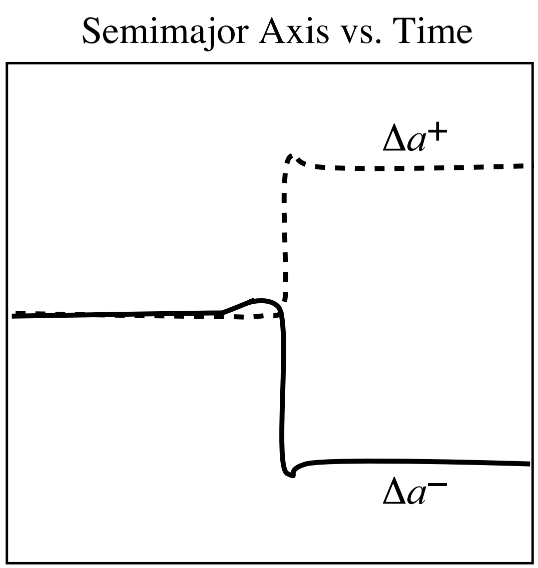
Periapse P fixed



Inter-Moon Transfer

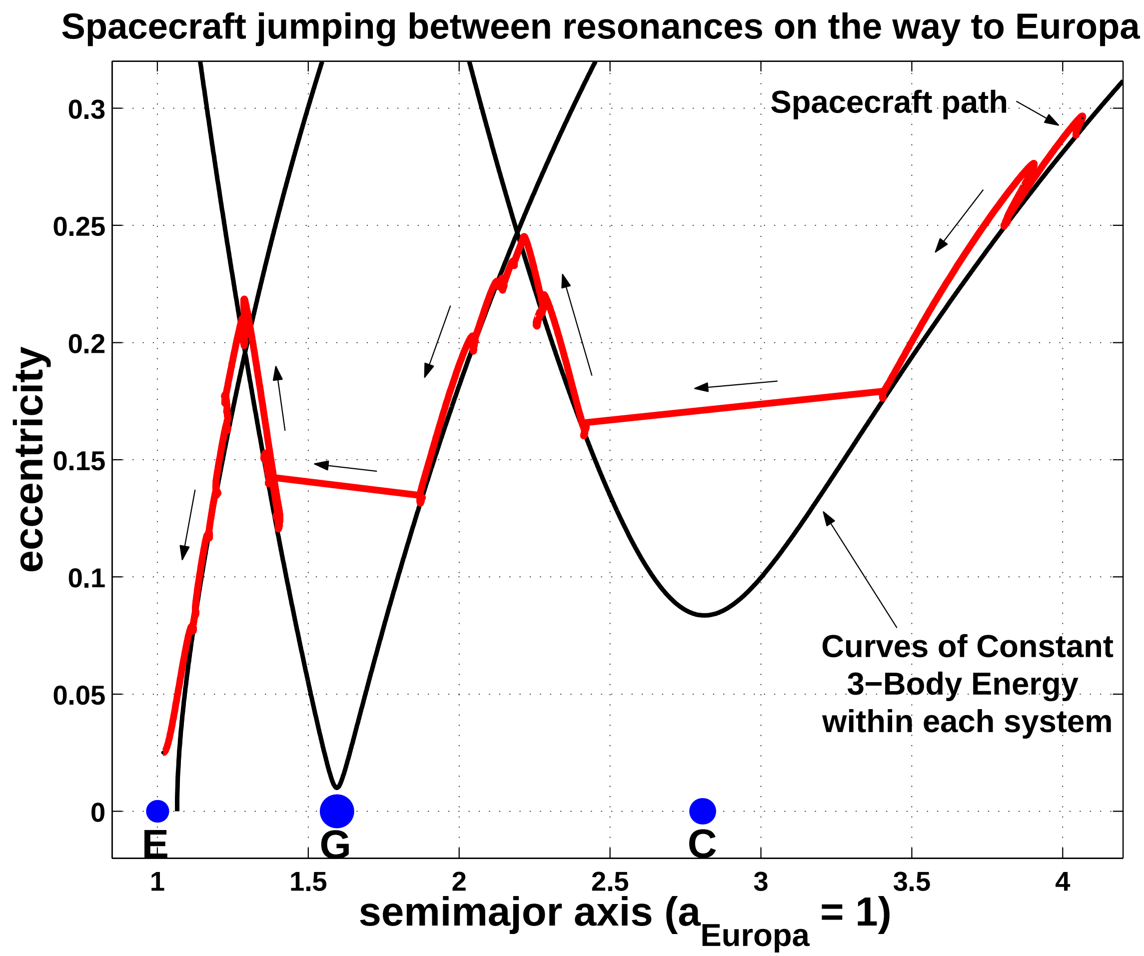
- Small impulsive maneuvers are performed at opposition





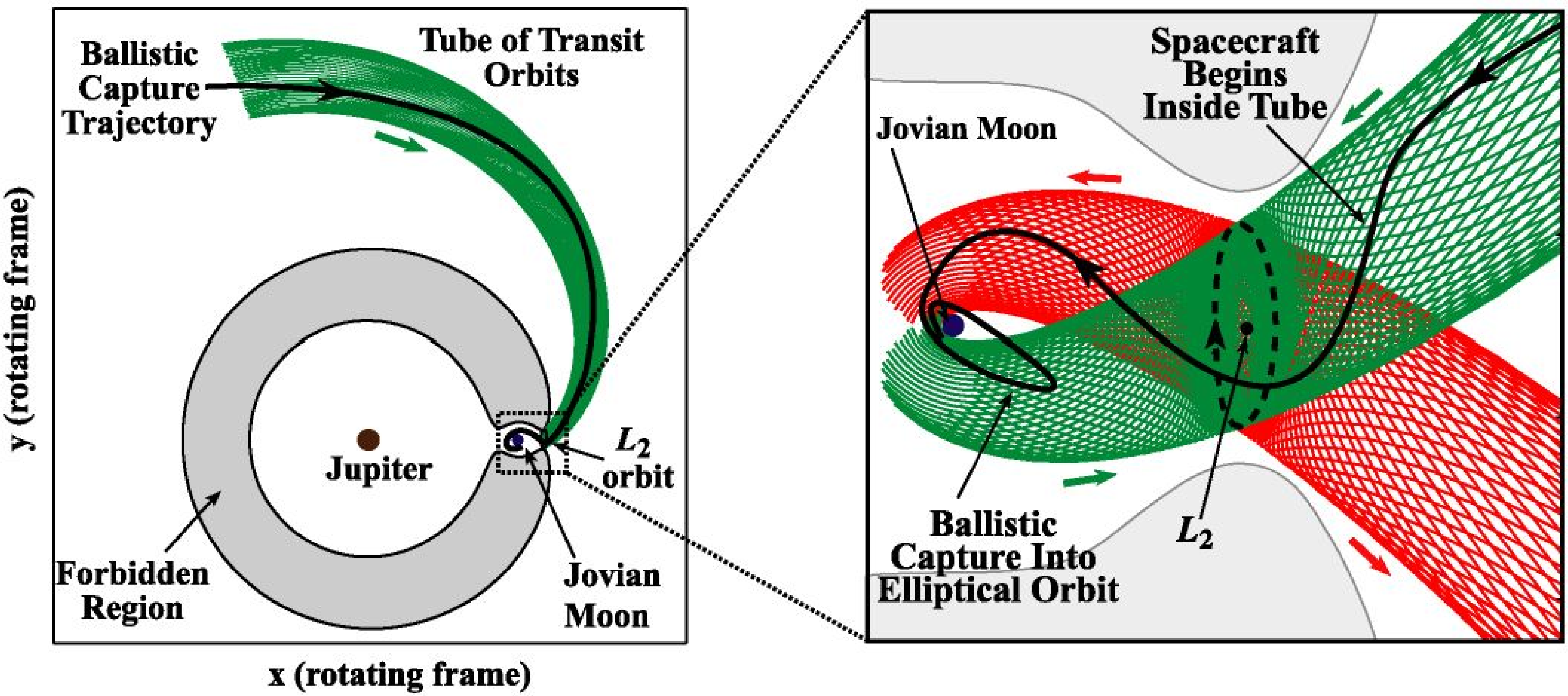
Inter-Moon Transfer

- The transfer between three-body systems occurs when energy surfaces intersect; can be seen on semimajor axis vs. eccentricity diagram (similar to Tisserand curves of Longuski et al.)



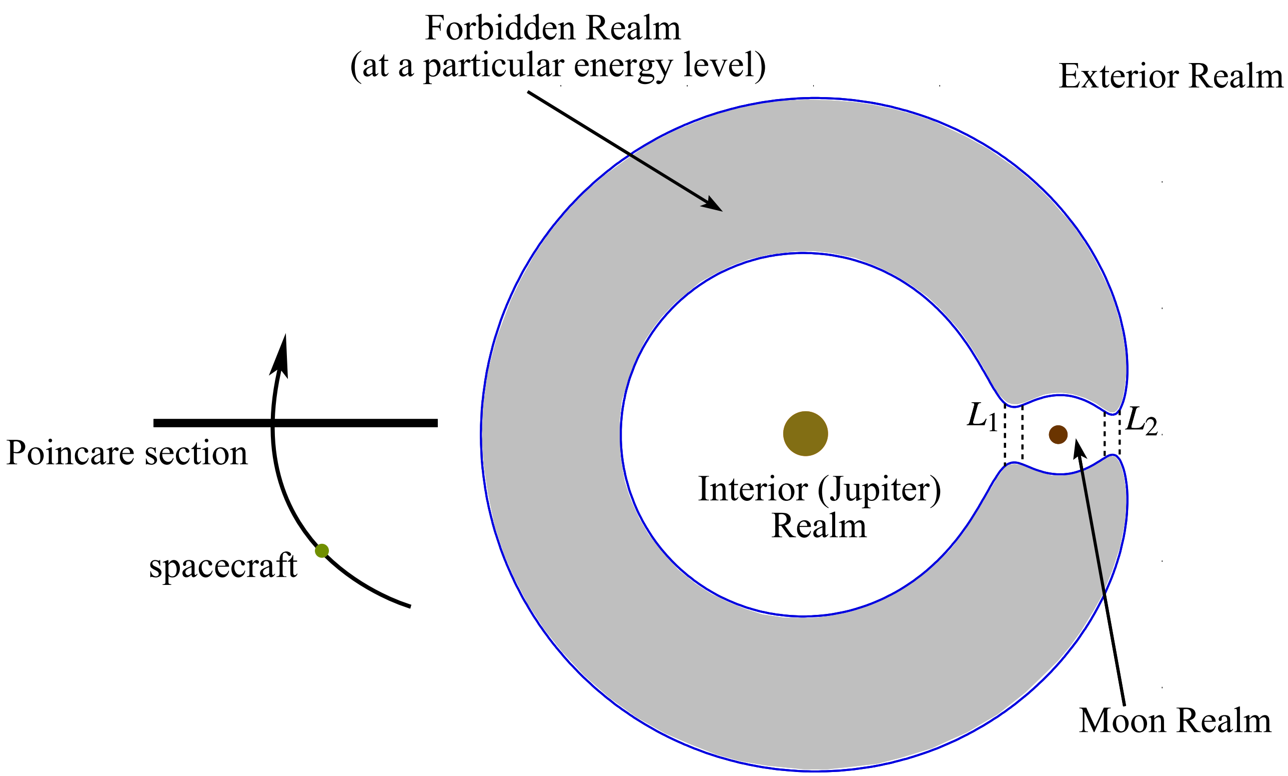
Ballistic Capture

- An L_2 orbit manifold tube leading to ballistic capture around a moon is shown schematically
- Escape is the time reverse of ballistic capture



Why Does It Work?

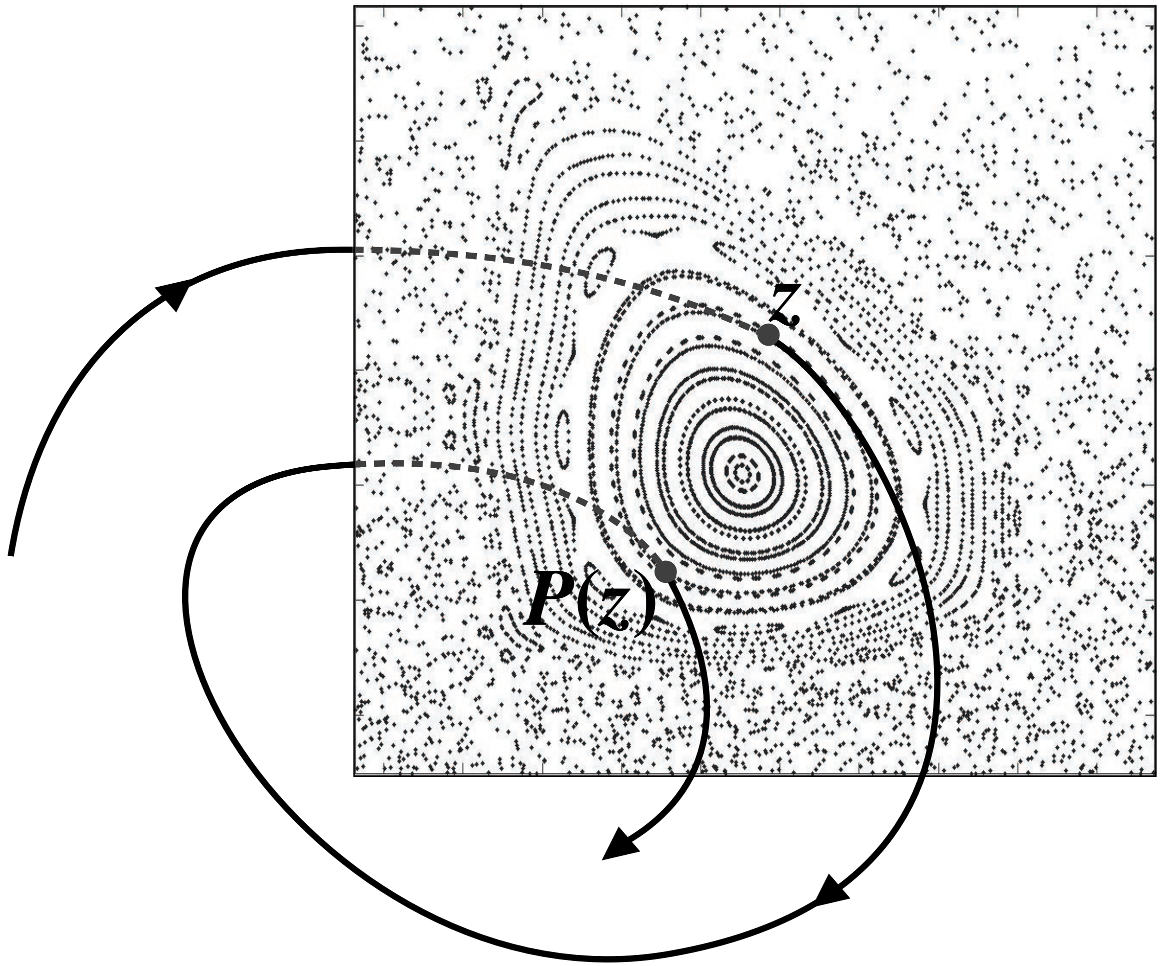
- Recall the **planar circular restricted three-body problem**: motion of a spacecraft in the gravitational field of two larger bodies in circular motion.
  - View in rotating frame $\Longrightarrow$ constant energy E



Rotating frame: different realms of motion at energy E.

Poincaré Surface of Section

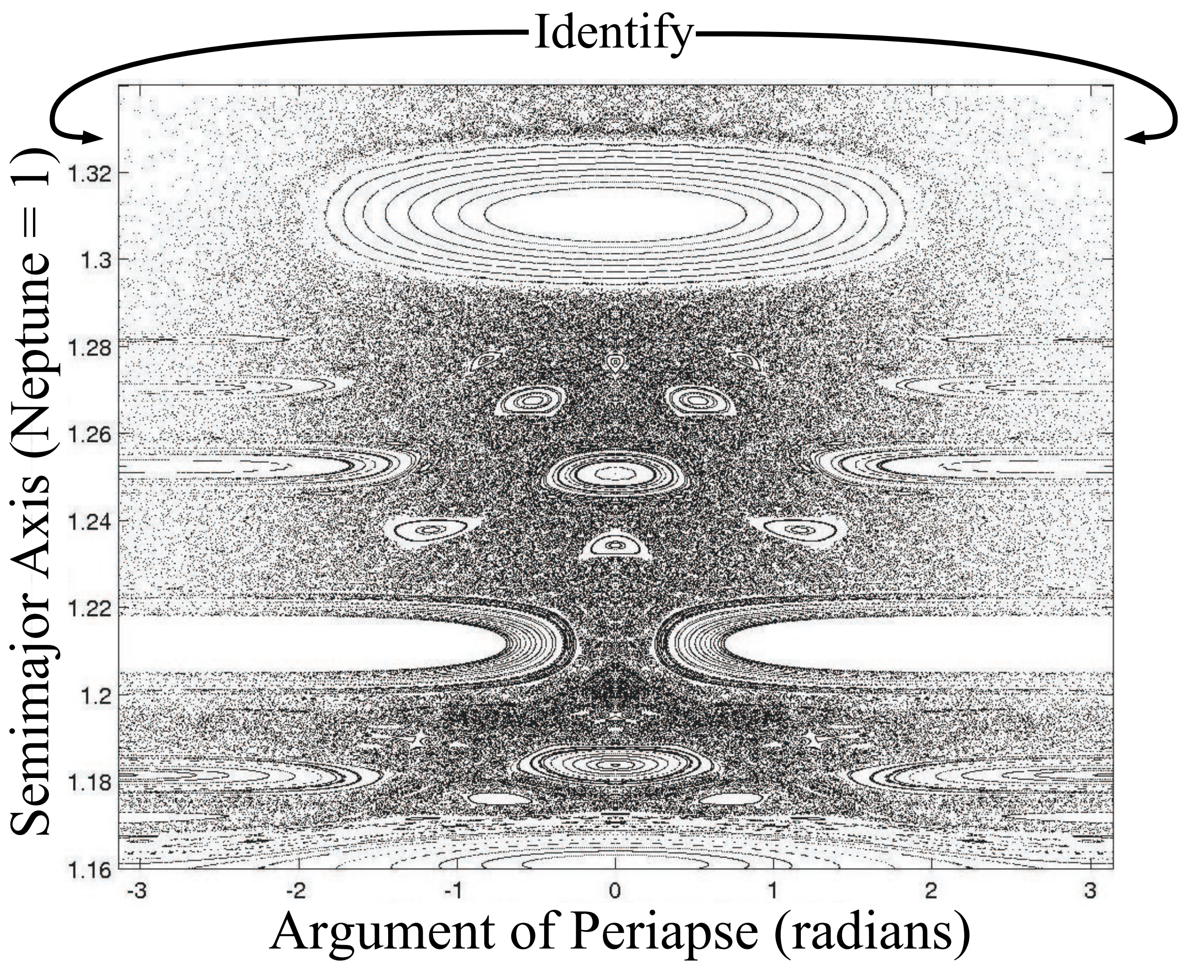
Study Poincaré surface of section at fixed energy E, reducing system to a 2-dimensional area preserving map.



Poincaré surface of section

Poincaré Surface of Section

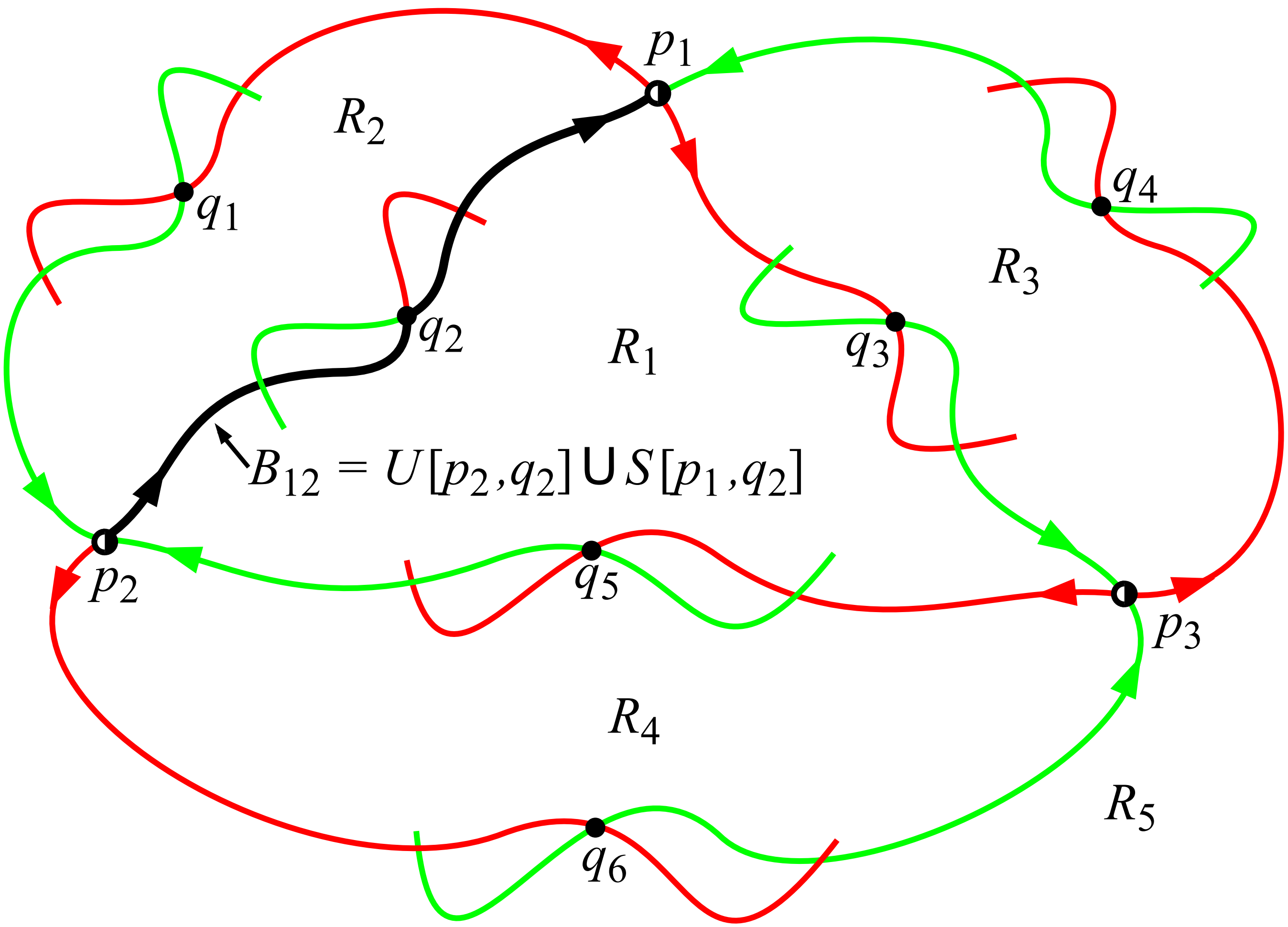
Poincaré section reveals mixed phase space structure: KAM tori and a "chaotic sea" are visible.



Poincaré surface of section

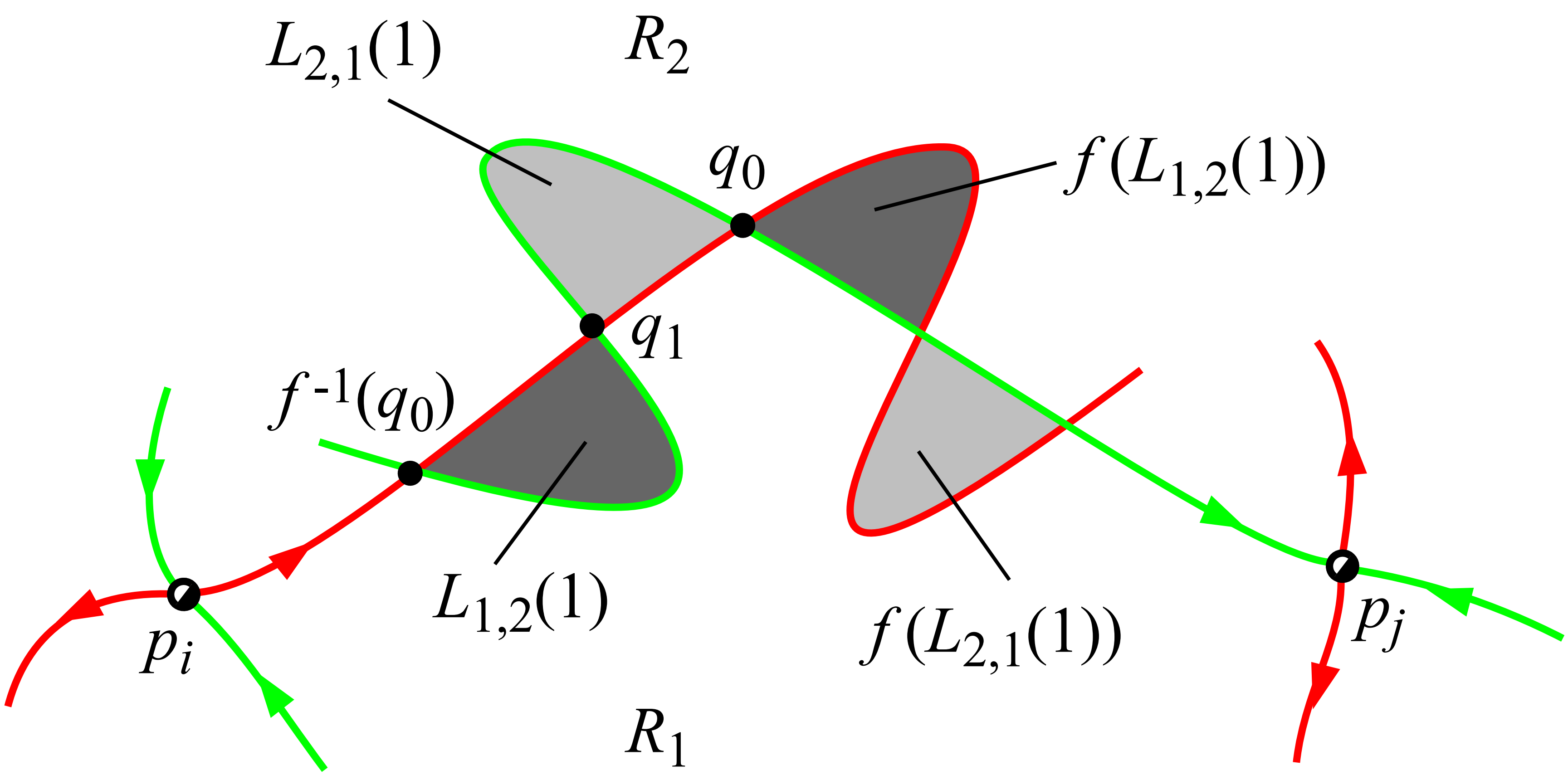
Transport in Poincaré Section

Phase space divided into regions $R_i, i = 1, \ldots, N_R$ bounded by segments of stable and unstable manifolds of unstable fixed points.



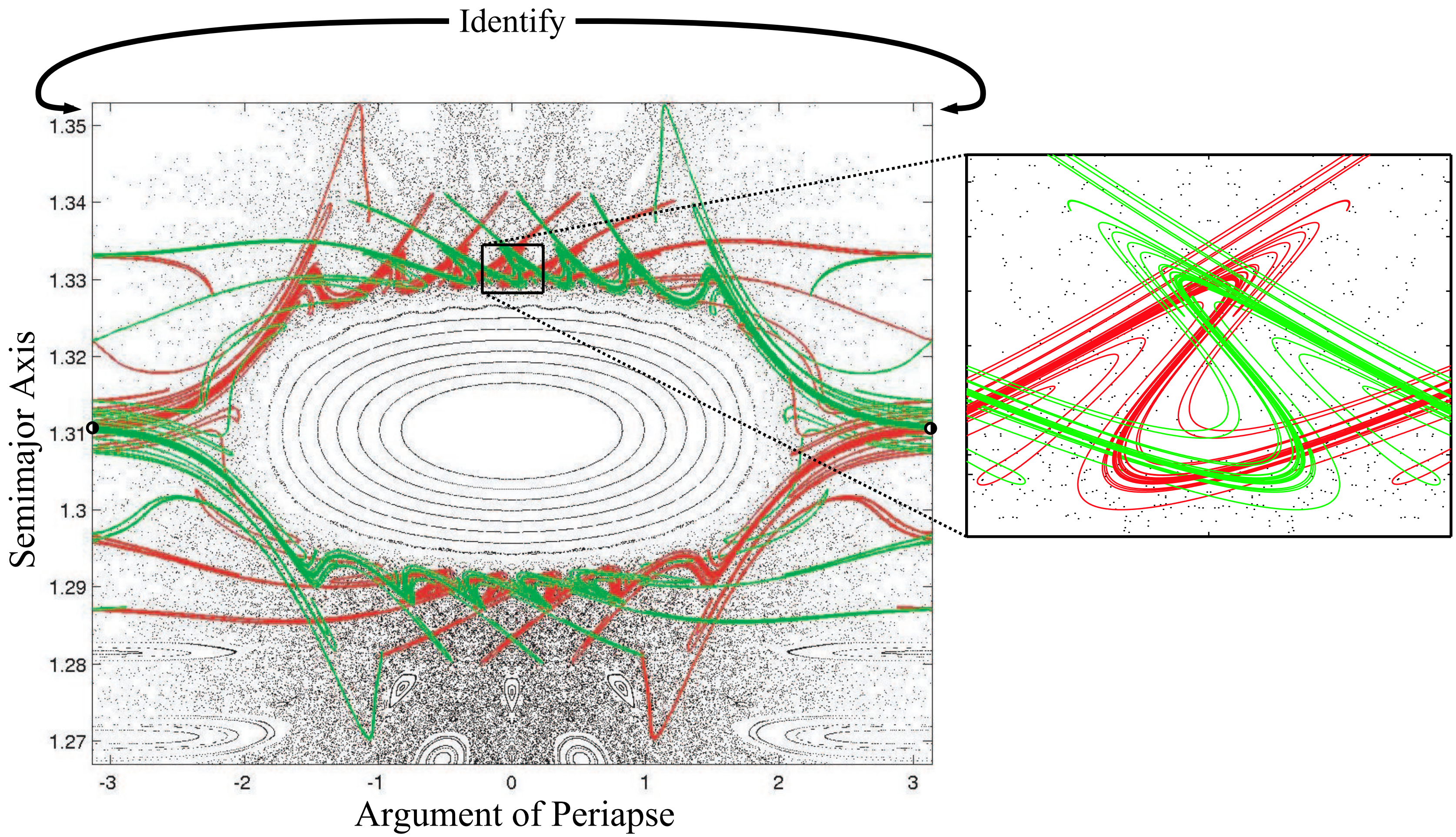
Lobe Dynamics

Transport btwn regions computed via **lobe dynamics.**



Movement btwn Resonances

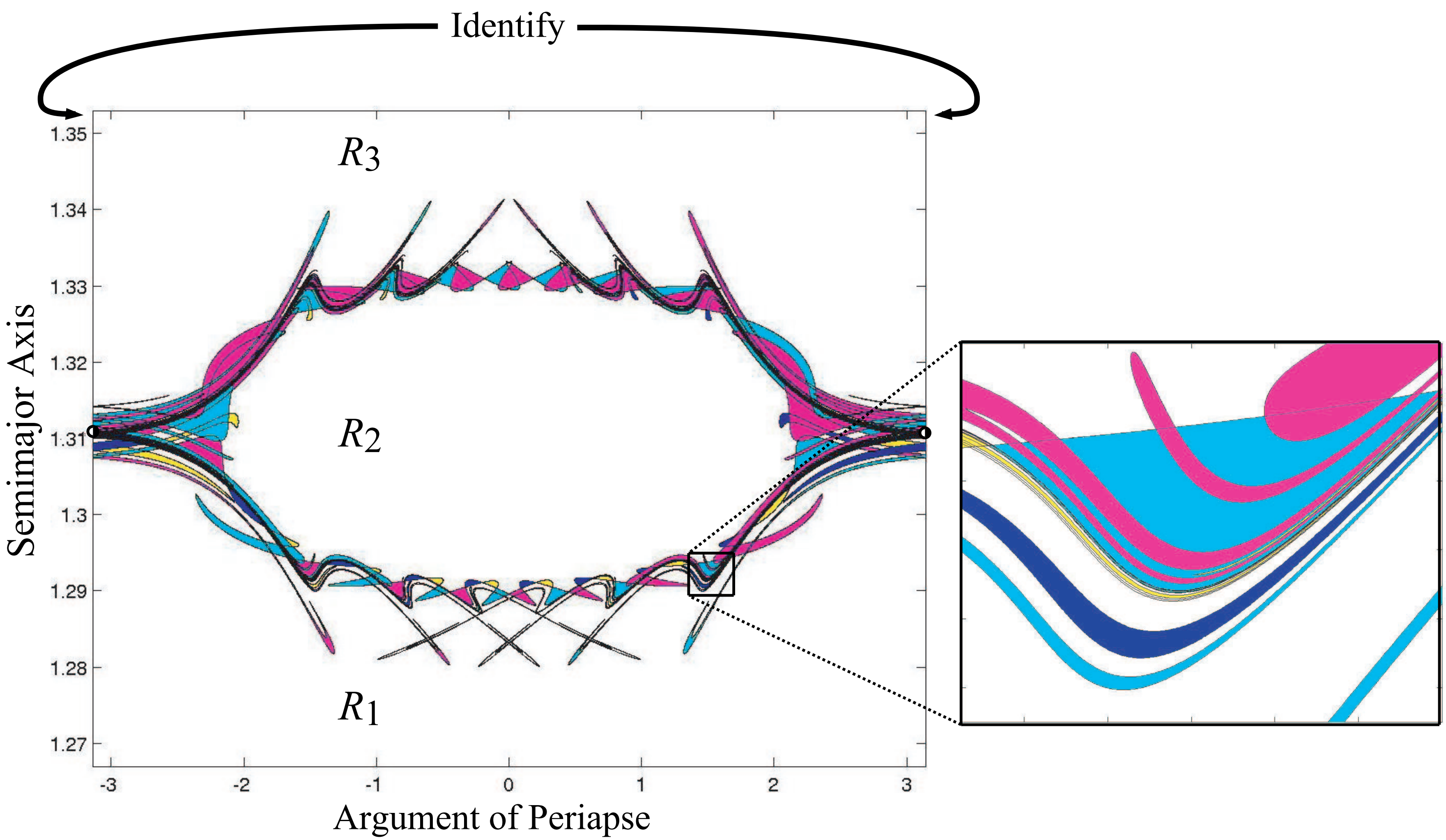
We can compute manifolds which naturally divide the phase space into **resonance regions.**



Unstable and stable manifolds in **red** and **green**, resp.

Movement btwn Resonances

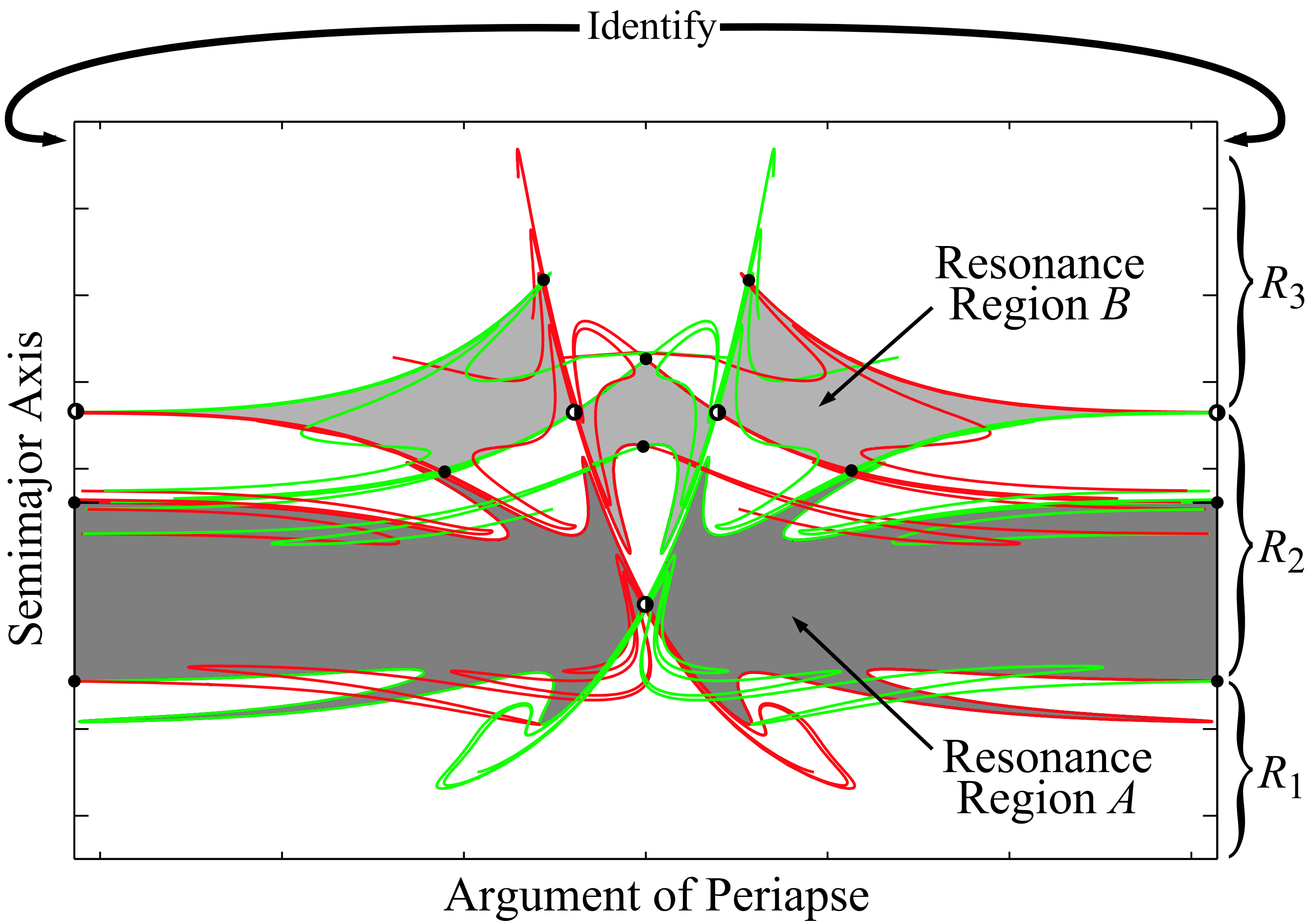
Transport and mixing between regions can be computed.



Four sequences of color coded lobes are shown.

Movement btwn Resonances

Navigation from one resonance to another, essential for the Multi-Moon Orbiter, can be performed.



Resonances and Tubes

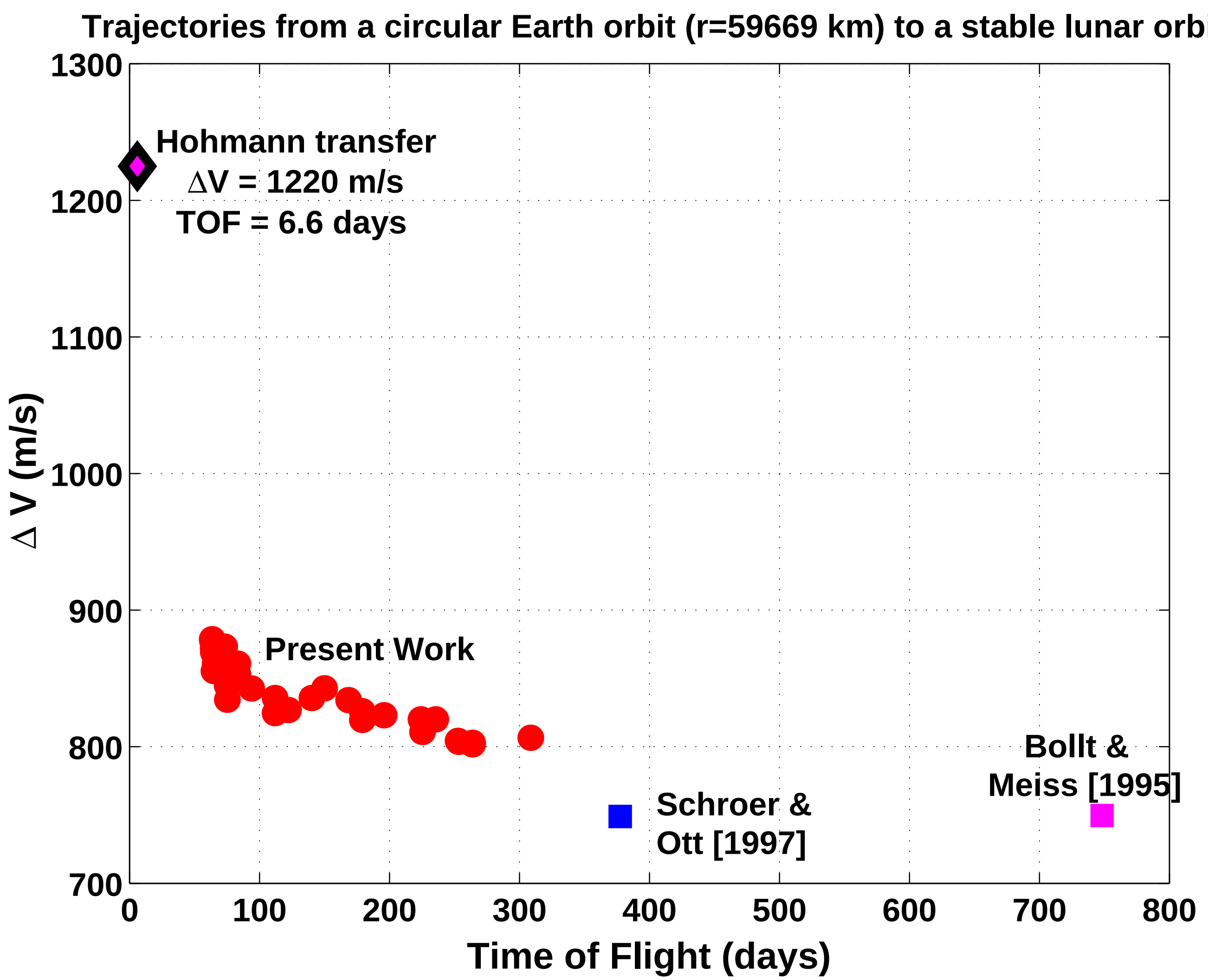
- ***Resonances and tubes are linked***
  - It has been observed that the tubes of capture (resp., escape) orbits are coming from (resp., going to) certain resonances.
  - Resonances are a function of energy E and the mass parameter μ
  - Koon, Lo, Marsden, Ross [2001]

Earth to Moon Trajectories

- *Similar methods can be applied to near-Earth space to study the* ΔV *verses time trade-off*

Earth to Moon Trajectories

- **Results**: much shorter transfer times than previous authors for only slightly more ΔV

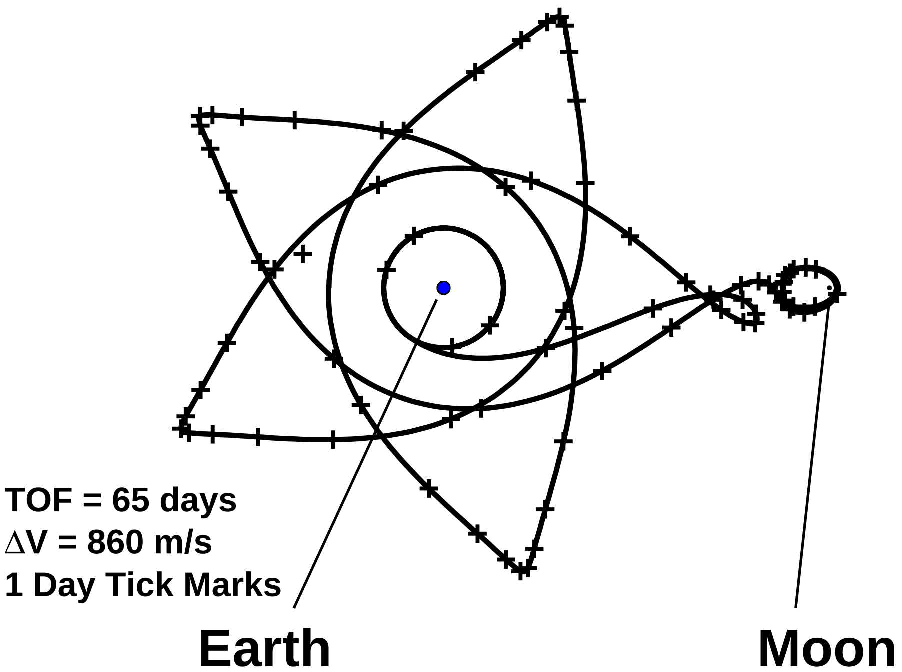


Earth to Moon Trajectories

- Compare with Bollt and Meiss [1995]
  - A tenth of the time for only 100 m/s more

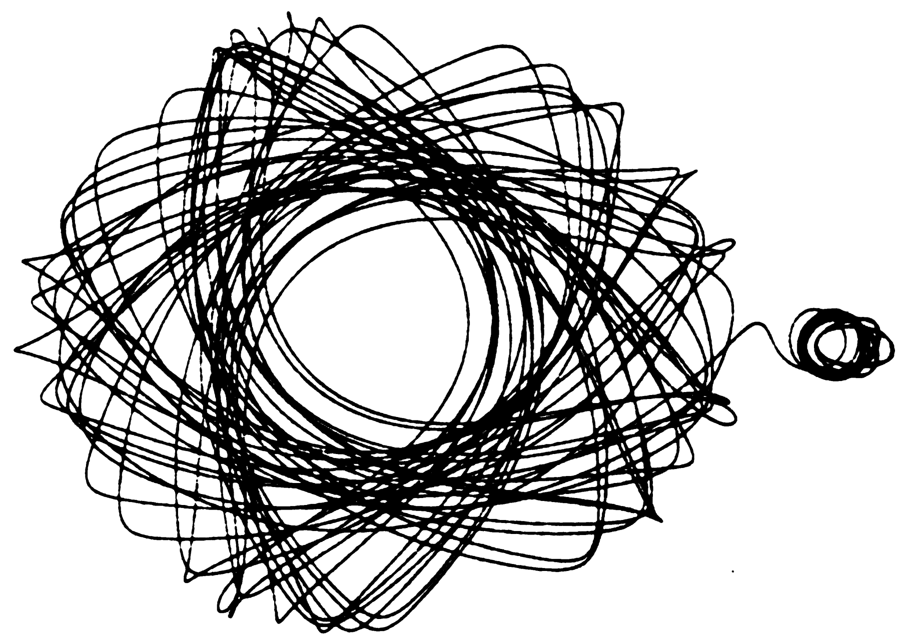
Current Result

65 days, $\Delta V = 860$ m/s

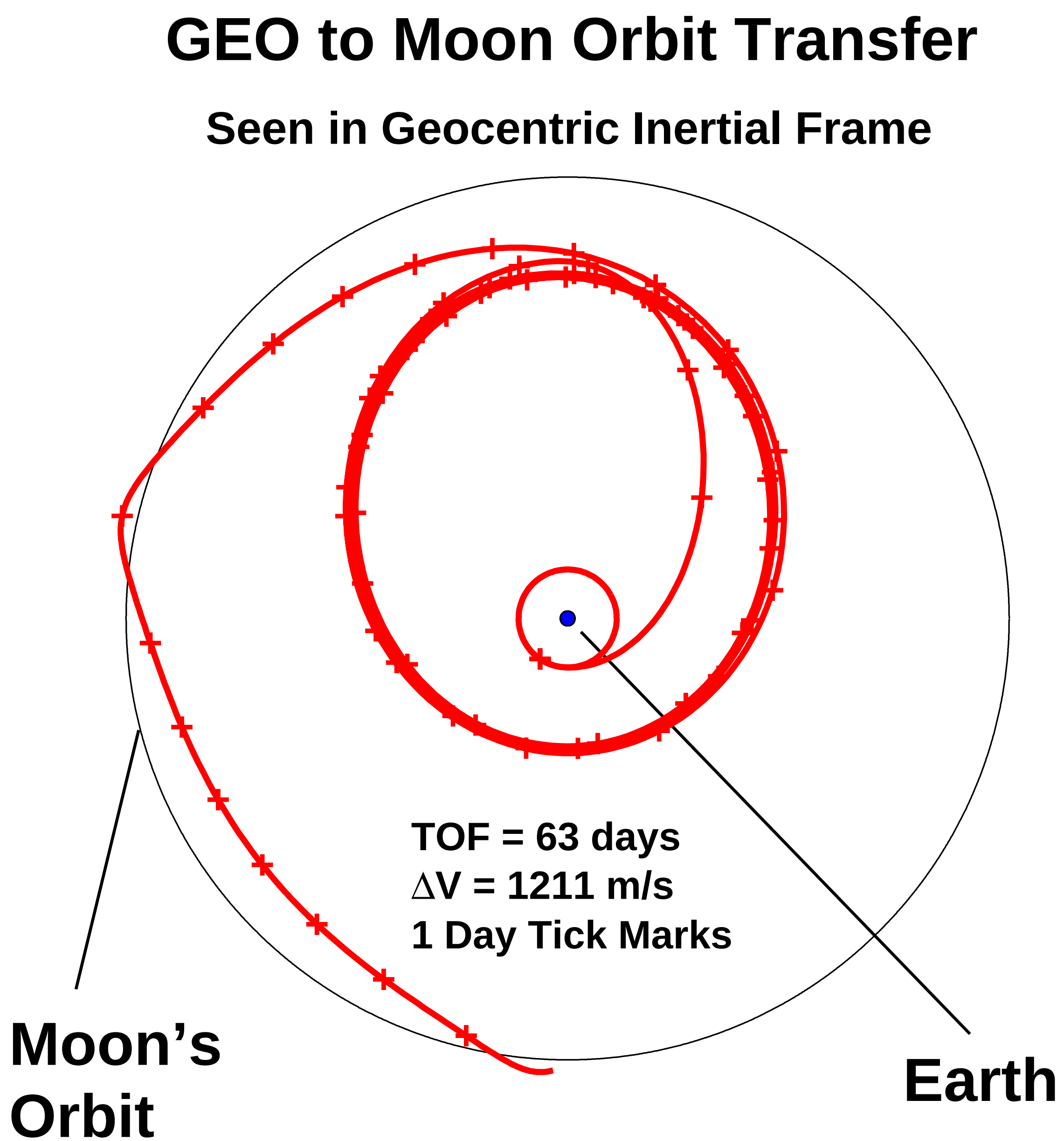


Bollt and Meiss [1995]

748 days, $\Delta V = 750$ m/s



e.g., GEO to Lunar Orbit



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For papers, movies, etc., visit the websites:

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