Approaching Moons in Highly Nonlinear, Chaotic Environments With Applications to Europa Lander

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Pre-Decisional Information – For Planning and Discussion Purposes Only.

Overview

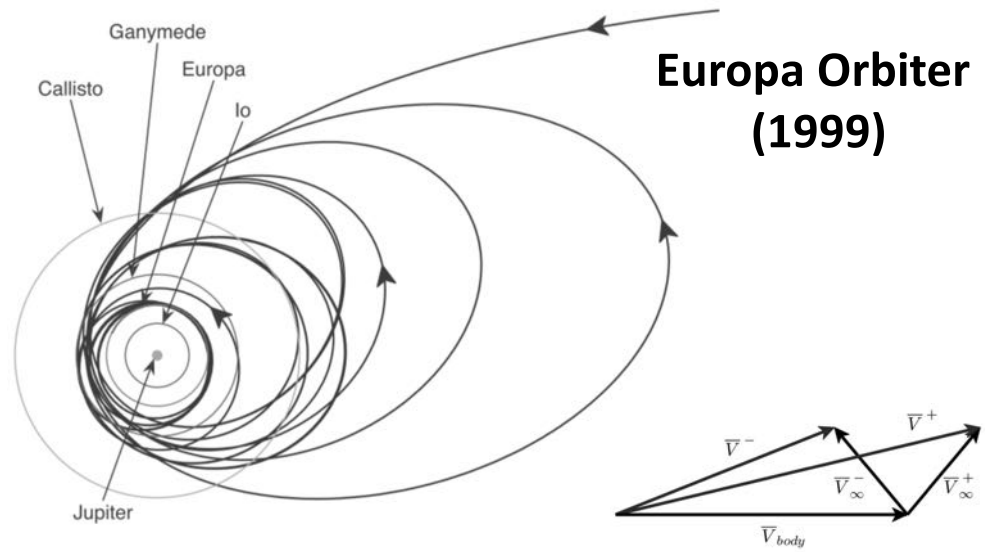
- General Tour Prior to Endgame
  - Resonant Orbit Families
  - Invariant Manifolds and Heteroclinic Connections
- Endgame: Final Resonances & Approach
  - *Planar* Approach via Invariant Manifolds
  - Rigorous *Spatial* Approach & Transit
- Europa Lander Mission Concept Applications
  - Approach Analysis
  - Including Maneuvers and Constraints

Pre-Decisional Information – For Planning and Discussion Purposes Only.

Early Tour & Resonant Work

Two-Body Analysis Methods (Patched-Conic)

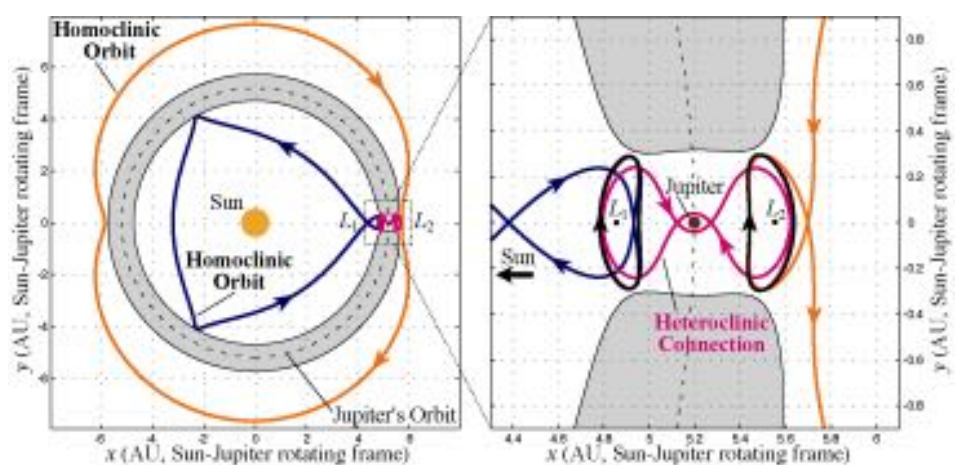
- Tour Design: Use two-body elliptical orbits with flybys to modify energy [Uphoff, 1976]
- Endgame: Large numerical integrations and intuition [Europa Orbiter, 1999]



Europa Orbiter (1999)

Chaos & Low-Energy Transport Using Resonance

- Use resonant orbits to speed general transit in Hamiltonian systems [Bollt & Meiss, 1995; Schroer & Ott, 1997]
- Jupiter comet 3:2 to 2:3 resonance transition [Koon, Lo, Marsden, Ross (2000), Howell, Marchand, Lo (2000), Belbruno, Marsden (1997)]

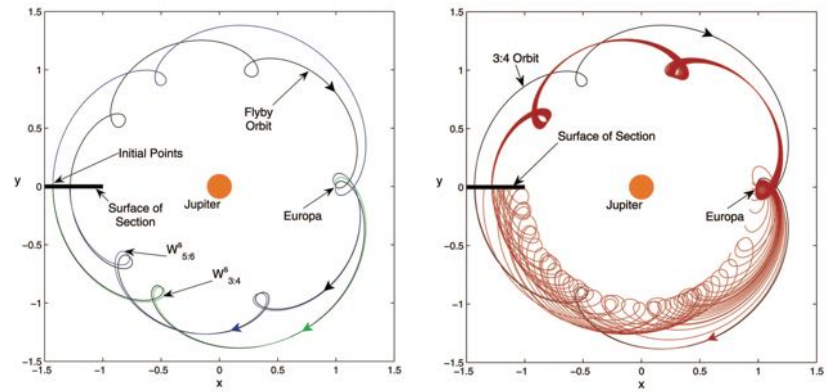


Koon, Lo, Marsden, Ross (2000)

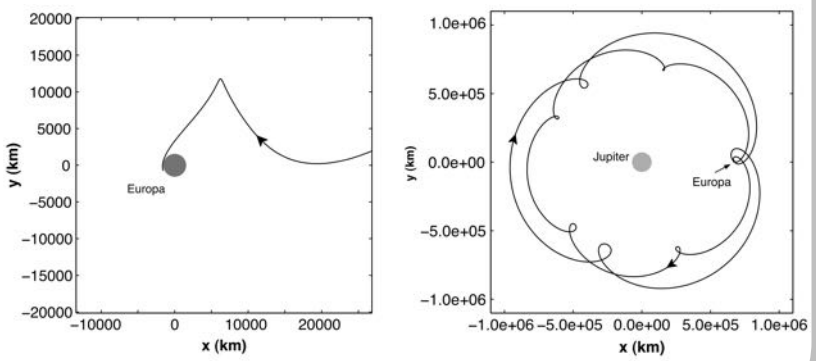
Resonant Orbits Key for Multi-Body Trajectory Design

Ballistic, impulsive, and low-thrust trajectories obtained with optimizers and heuristic methods follow invariant manifolds of resonant orbits [Anderson & Lo 2004-2009]

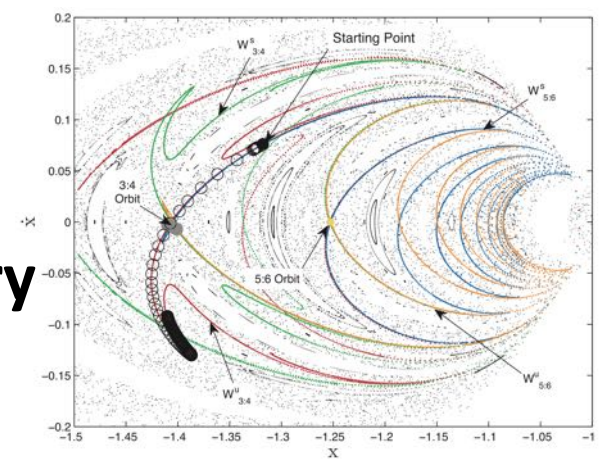
Ballistic Flyby Trajectory



Impulsive Europa Orbiter Trajectory

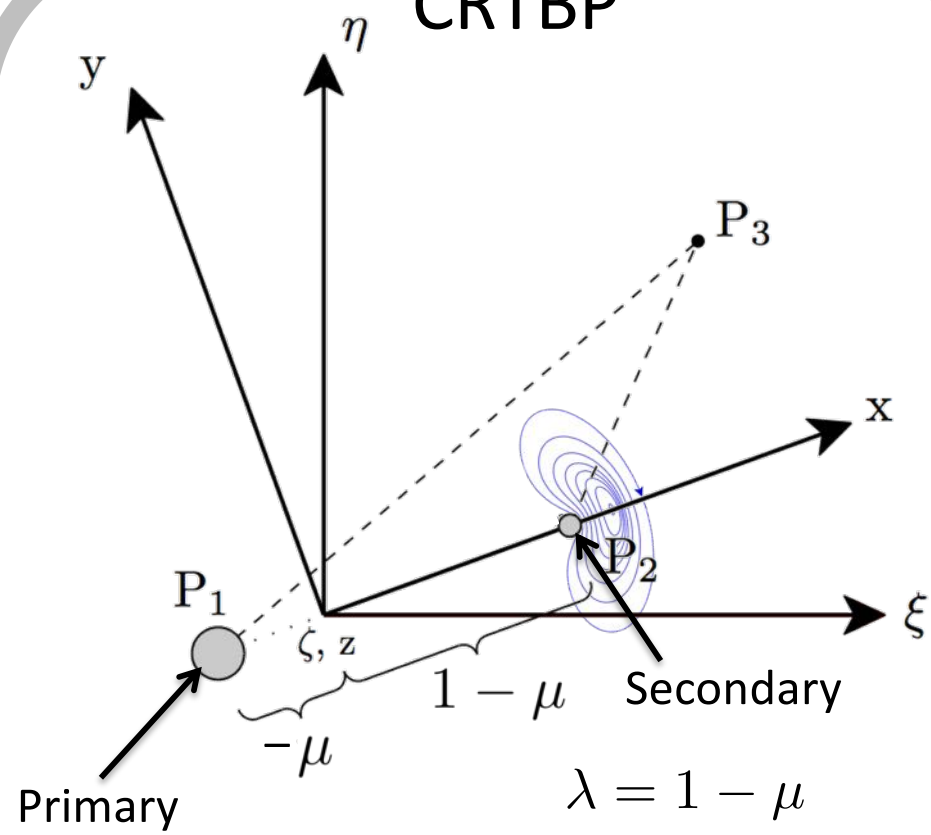


Low Thrust Trajectory



Circular Restricted Three-Body Problem

CRTBP



$$\lambda = 1 - \mu$$

Distance to primary: $\rho_1(x, y, z)$

Distance to secondary: $\rho_2(x, y, z)$

Equations of Motion

$$\ddot{x} = \partial_x \Phi(x, y, z) - 2\dot{y}$$
$$\ddot{y} = \partial_y \Phi(x, y, z) + 2\dot{x}$$
$$\ddot{z} = \partial_z \Phi(x, y, z)$$

where:

$$\Phi(x, y, z) = \frac{1}{2}(x^2 + y^2) + U(x, y, z)$$

$$U(x, y, z) = \lambda/\rho_1(x, y, z) + \mu/\rho_2(x, y, z)$$

Alternative Notation: $q = (x, y, z)'$

$$\ddot{q} = \nabla\Phi(q) + 2A\dot{q}$$

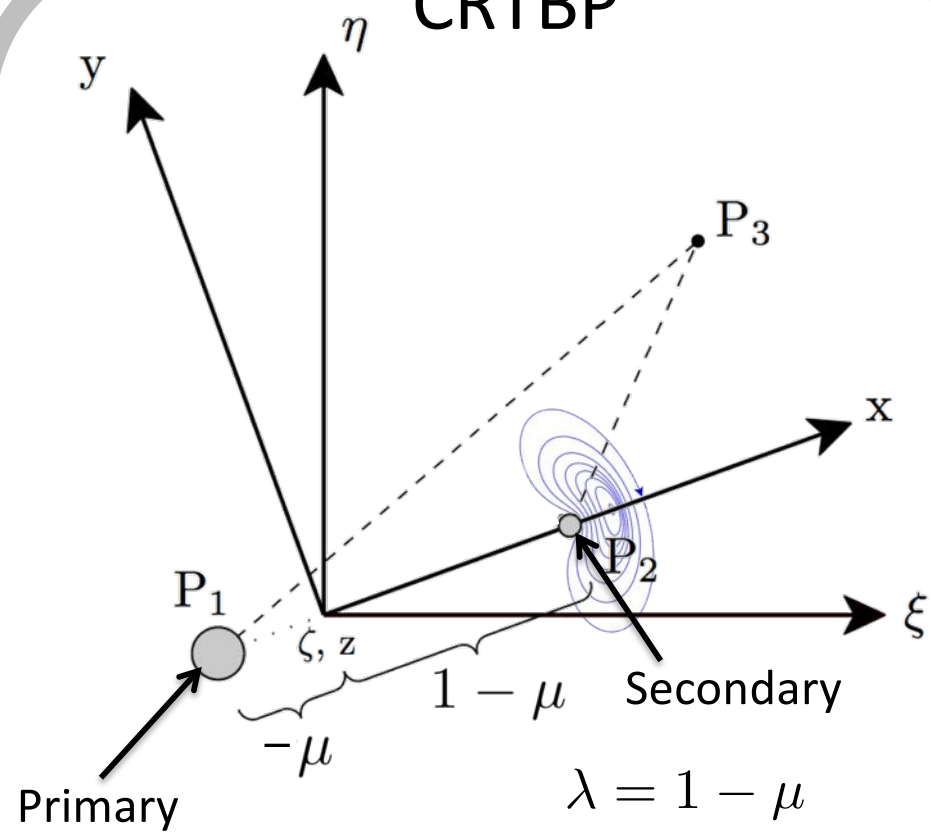
$$\nabla\Phi(q) = Fq + \lambda(E - q)\rho_1{}^{-3} + \mu(M - q)\rho_2{}^{-3}$$

$$A = \begin{pmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \text{and} \quad F = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$E = (-\mu, 0, 0) \quad M = (\lambda, 0, 0)$$

Circular Restricted Three-Body Problem: Libration Points

CRTBP

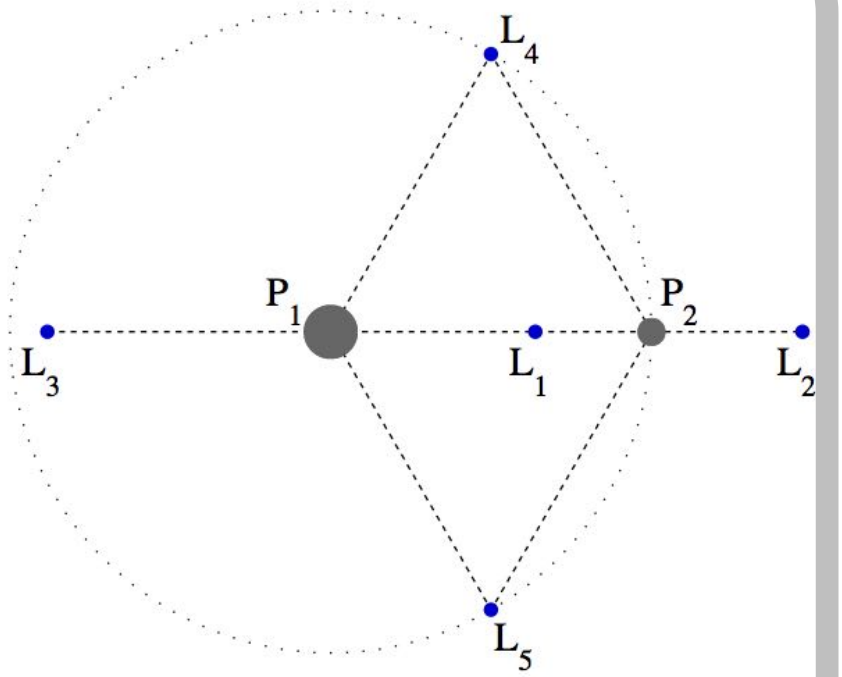


$$\lambda = 1 - \mu$$

Distance to primary: $\rho_1(x, y, z)$

Distance to secondary: $\rho_2(x, y, z)$

L_1, L_2, L_3, L_4, L_5: Libration Points

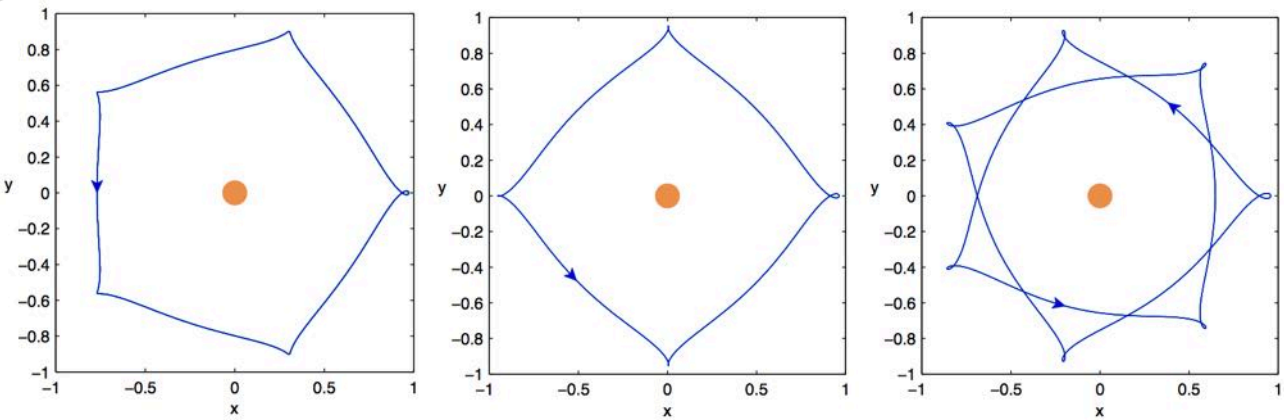


Jacobi Constant:

$$C = x^2 + y^2 + \frac{2(1-\mu)}{r_1} + \frac{2\mu}{r_2} - \dot{x}^2 - \dot{y}^2 - \dot{z}^2$$

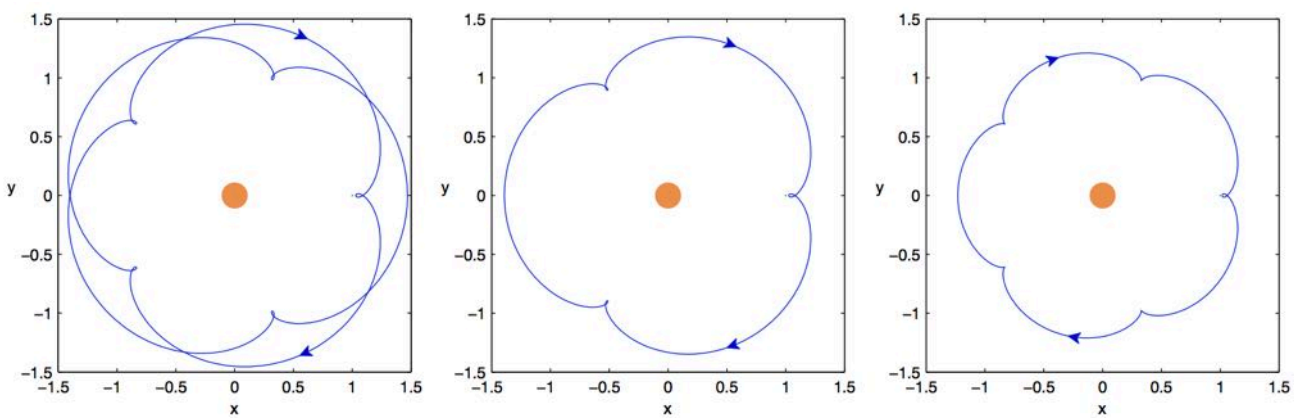
General Tour Design Using Resonant Orbits

Resonant Orbits of Interest



5:4 Orbit 4:3 Orbit 7:5 Orbit

Jupiter-Ganymede Interior Resonances
C = 3.0068

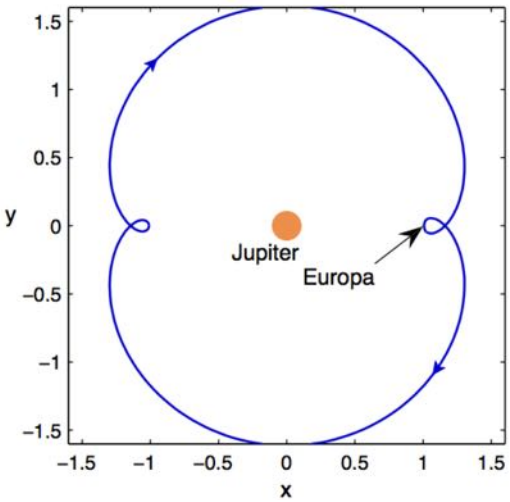


5:7 Orbit 3:4 Orbit 5:6 Orbit

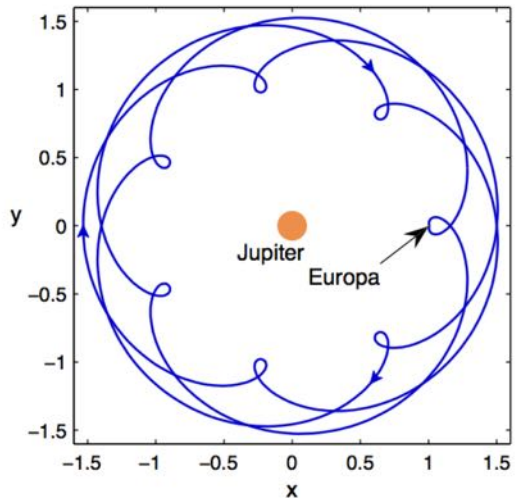
Jupiter-Europa Exterior Resonance
C ≈ 3.0024

Resonant Orbit Overview

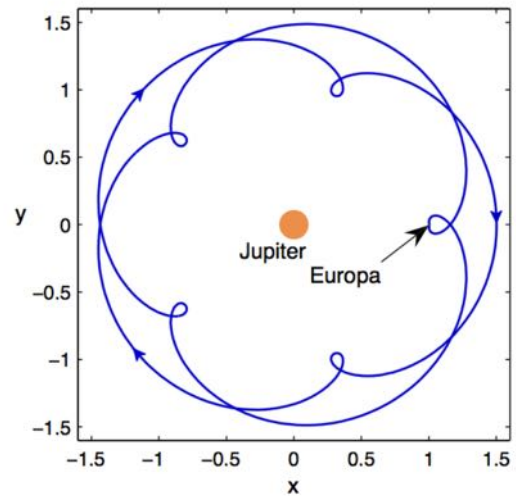
(Modified Single-Shooting Method)



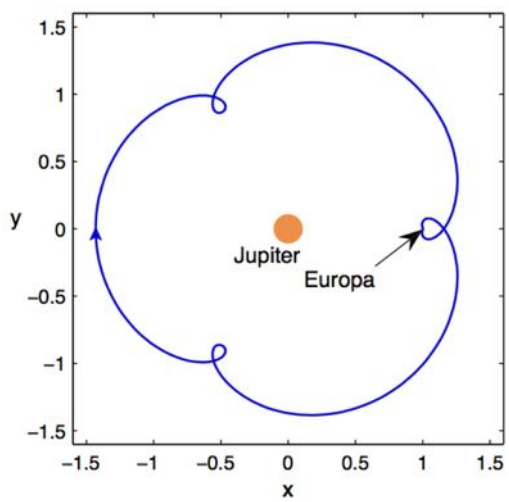
2:3



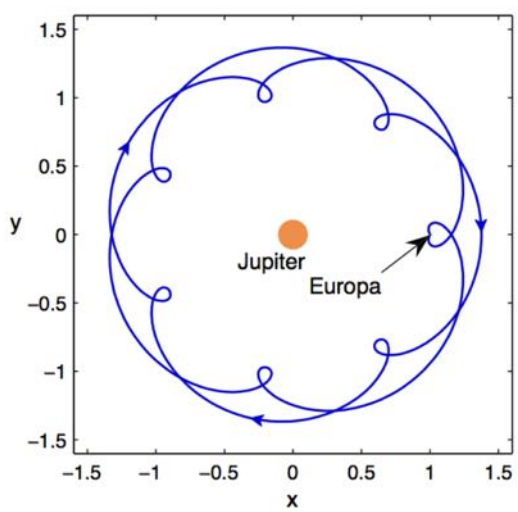
7:10



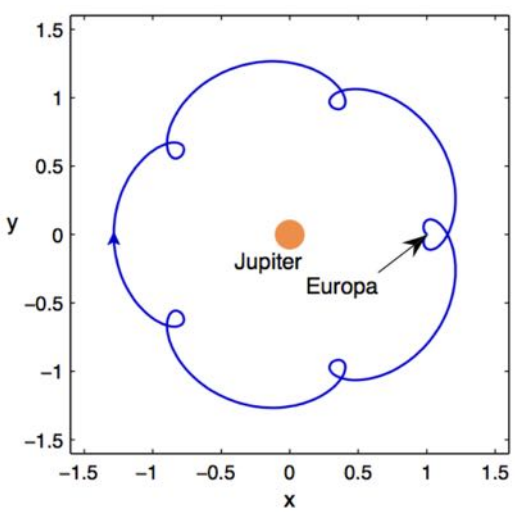
5:7



3:4



7:9

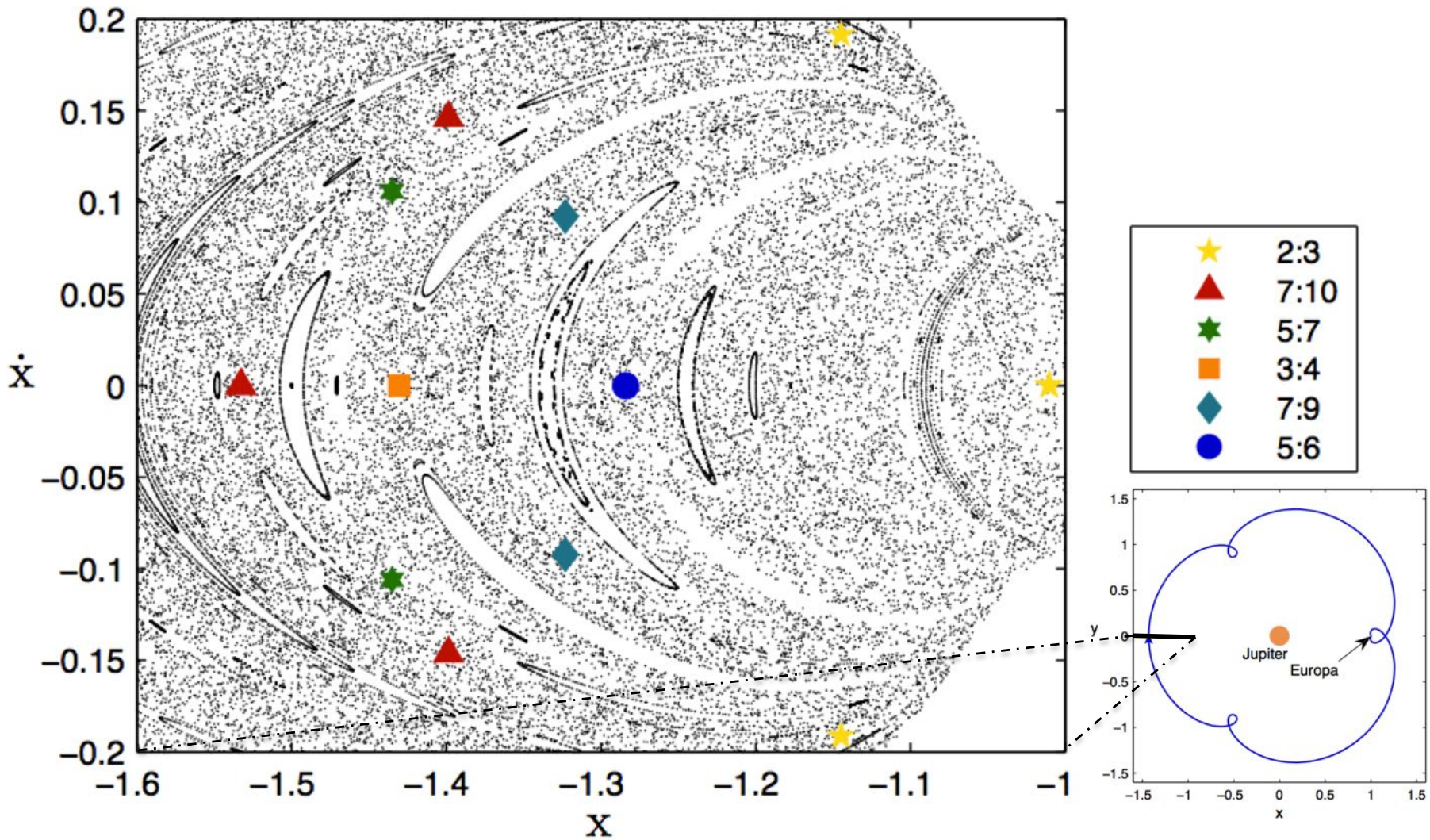


5:6

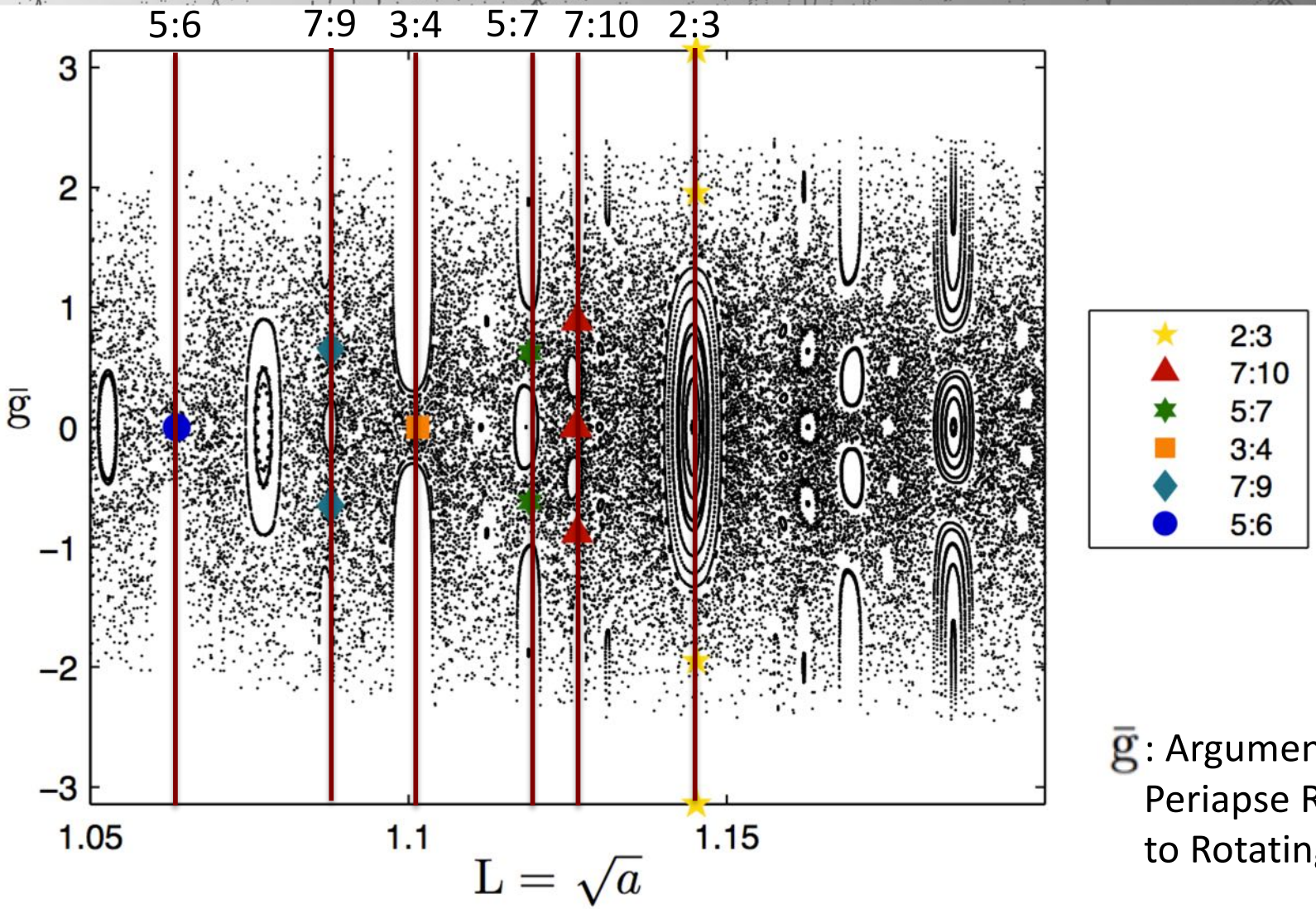
2:3
7:10
5:7
3:4
7:9
5:6

More Unstable

Surface of Section Intersections



Resonances



$\bar{g}$: Argument of Periapse Relative to Rotating Frame

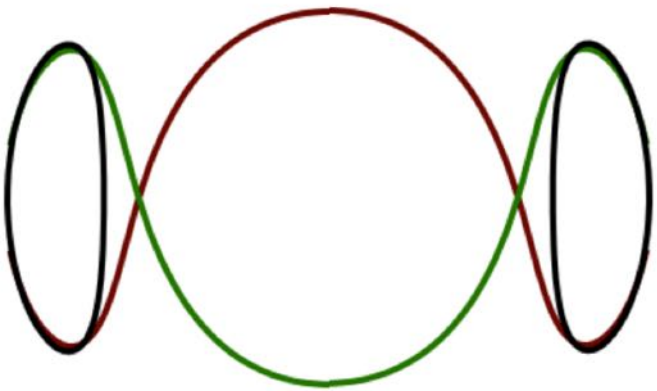
Heteroclinic Connections

- Trajectories connecting different orbits via invariant manifolds (W^s, W^u):

$$W^s_{a:b} \cap W^u_{c:d}$$

$a{:}b$ – Target Resonance, $c{:}d$ – Initial Resonance

- Compute by searching for W^s and W^u intersections from different orbits in surface of section



Trajectories on invariant manifolds approach orbit asymptotically, but come close quickly.

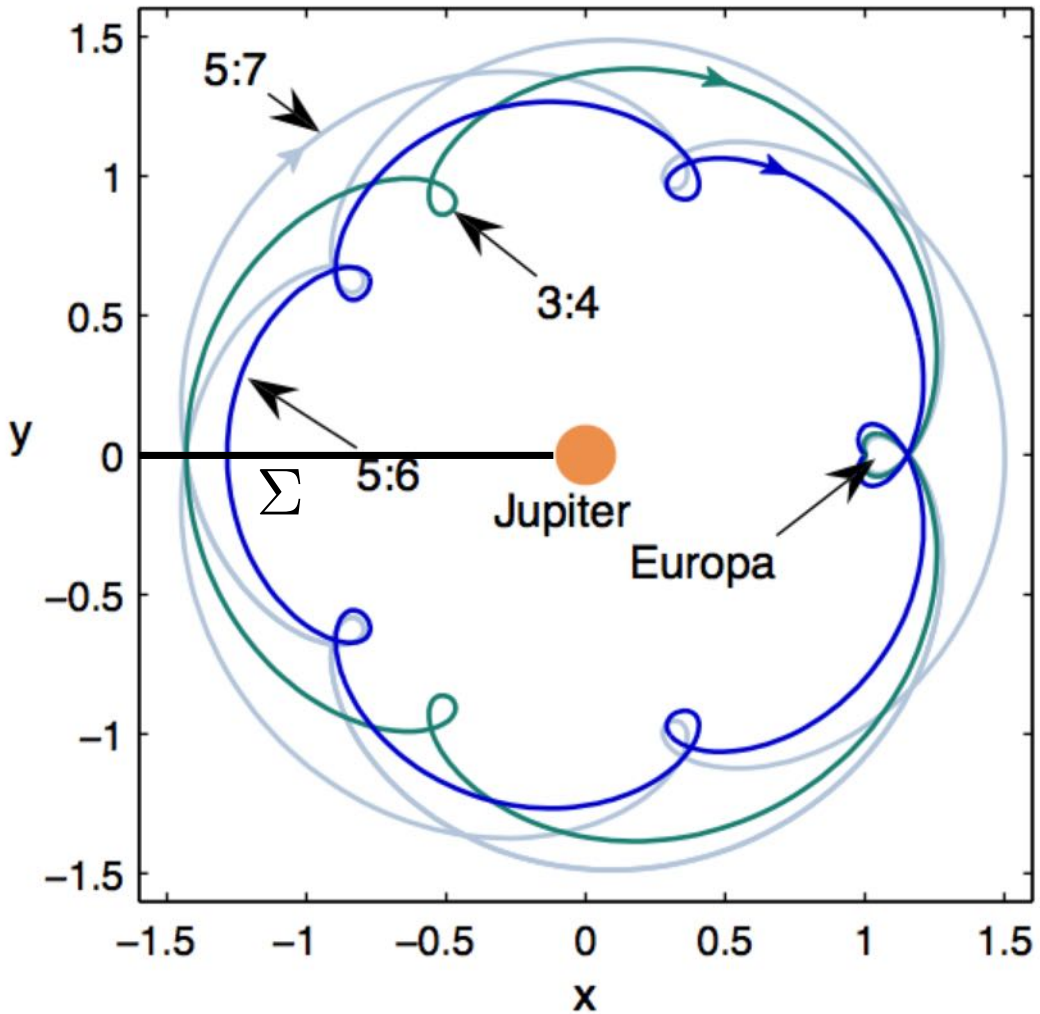
Heteroclinic Chain Cases

Components

- Compute desired resonant orbits
- Continue orbits to desired C
- Compute invariant manifolds of resonant orbits
- Compute intersections with Σ
- Select heteroclinic connections from crossing
- Chain resonances together
- Differentially correct to obtain continuous trajectory

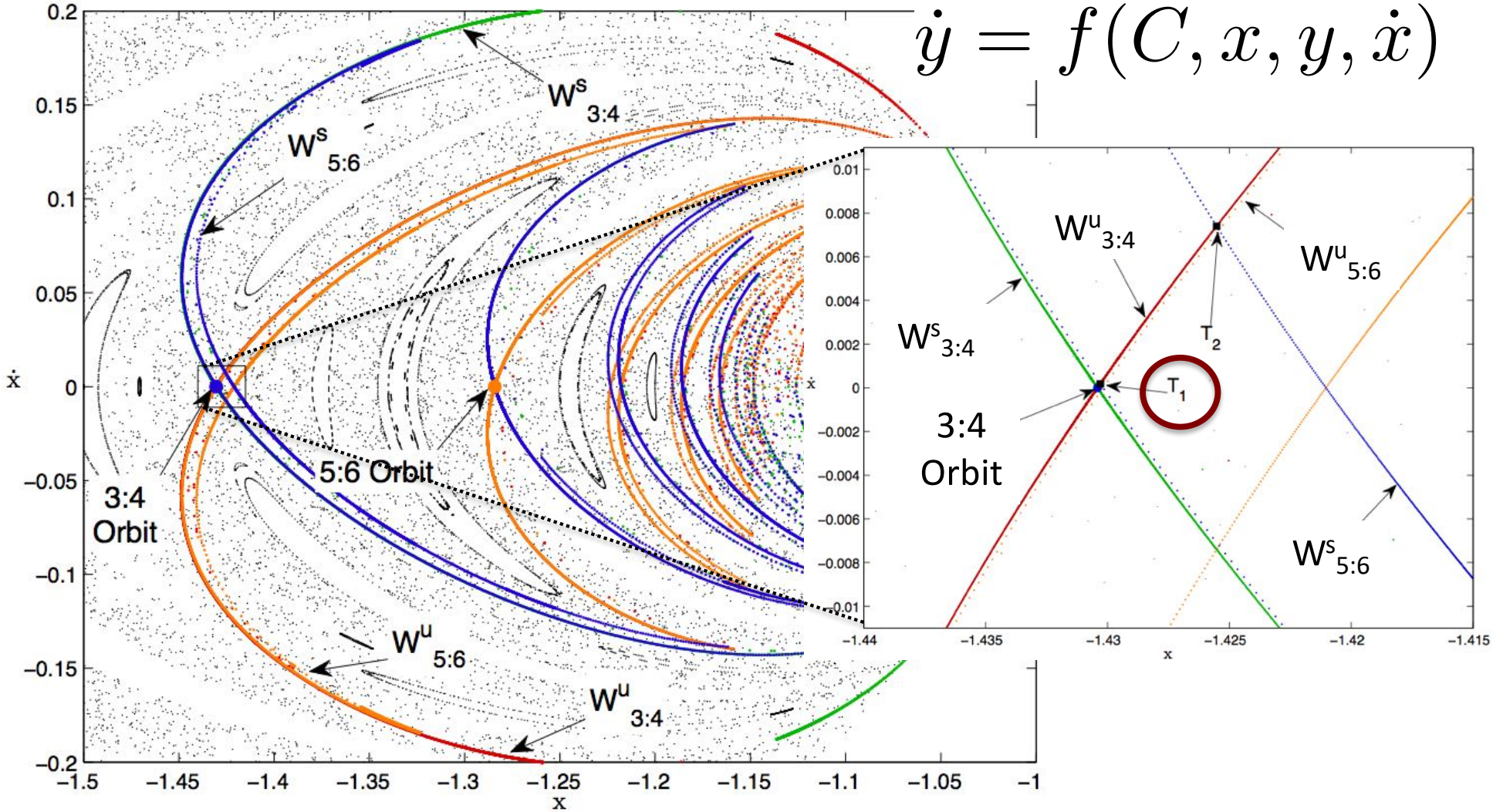
- At C_{flyby} = 2.9916
  - 3:4 → 5:6
  - 5:7 → 3:4 → 5:6
  - 7:10 → 3:4 → 5:6
  - 5:7 → 3:4 → 7:9 → 5:6
- At C_m = 2.9974
  - 3:4 → 5:6

5:7 – 3:4 – 5:6 Case: Connect Multiple Orbits

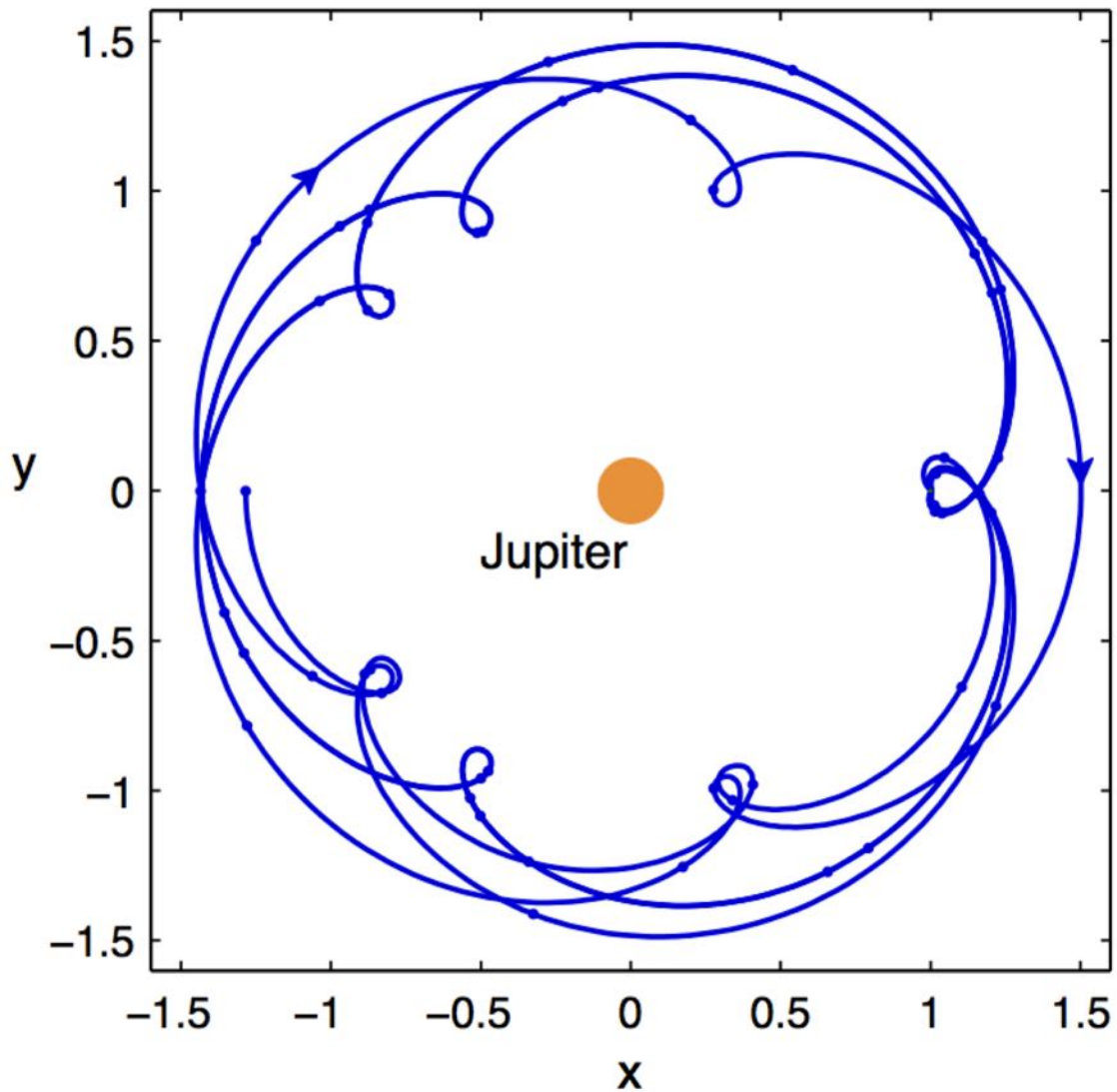


3:4-5:6 Heteroclinic Connection from Poincaré Section

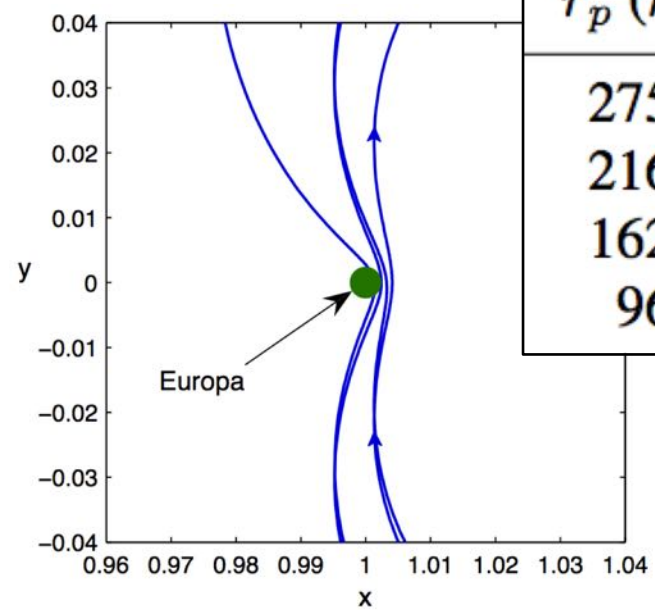
$$\dot{y} = f(C, x, y, \dot{x})$$



Differentially Corrected Trajectory (5:7 - 3:4 - 5:6)



- Total position difference: 1.719156 (m)
- Total velocity difference: 0.000041 (m/s)

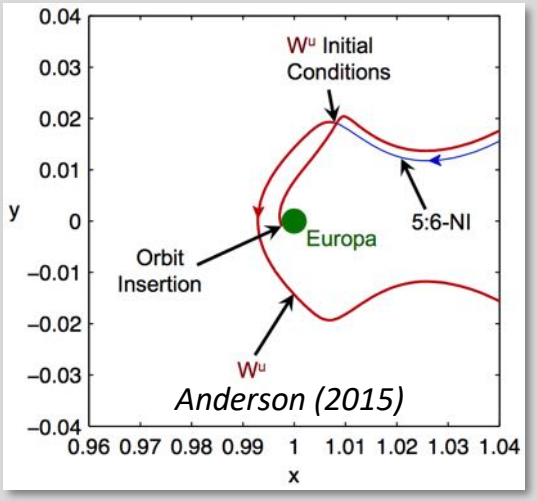


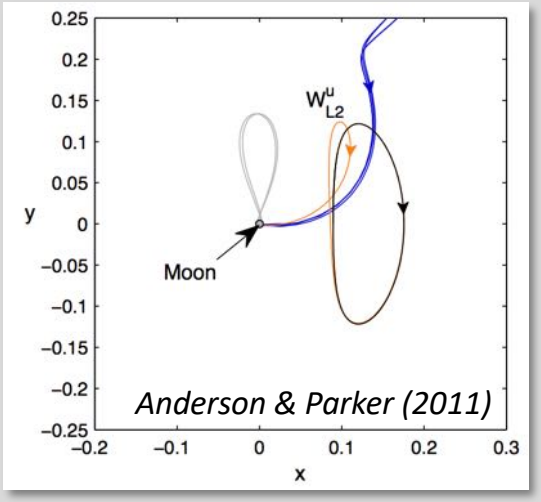
r_p (km)
2754.7
2162.4
1628.0
960.7

Approach Using Invariant Manifolds

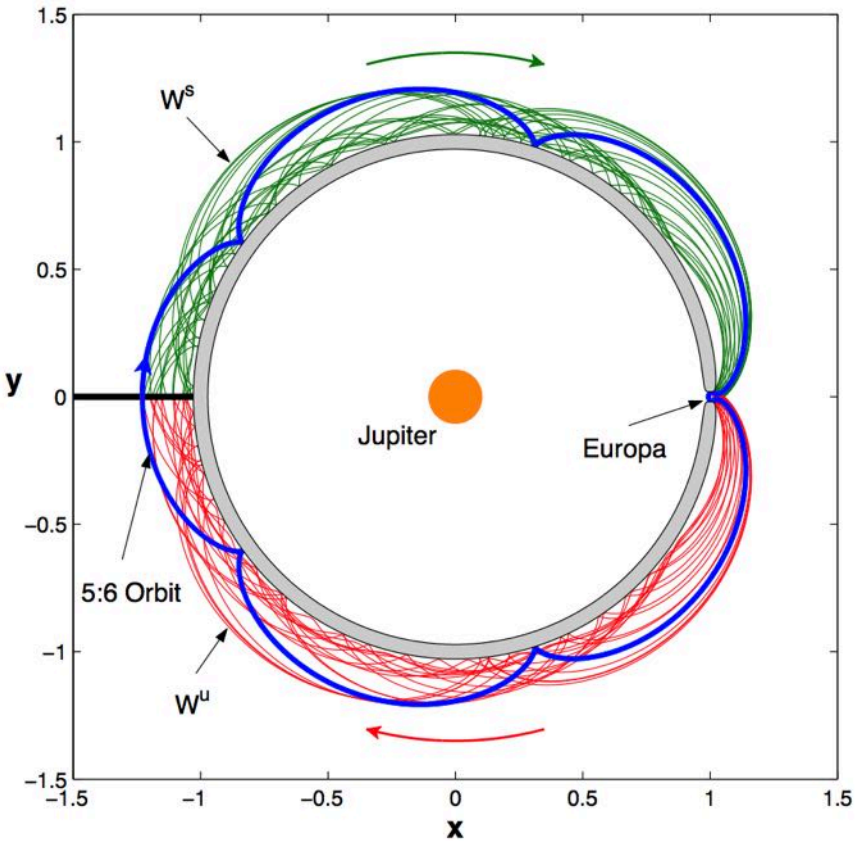
Approach Design Techniques

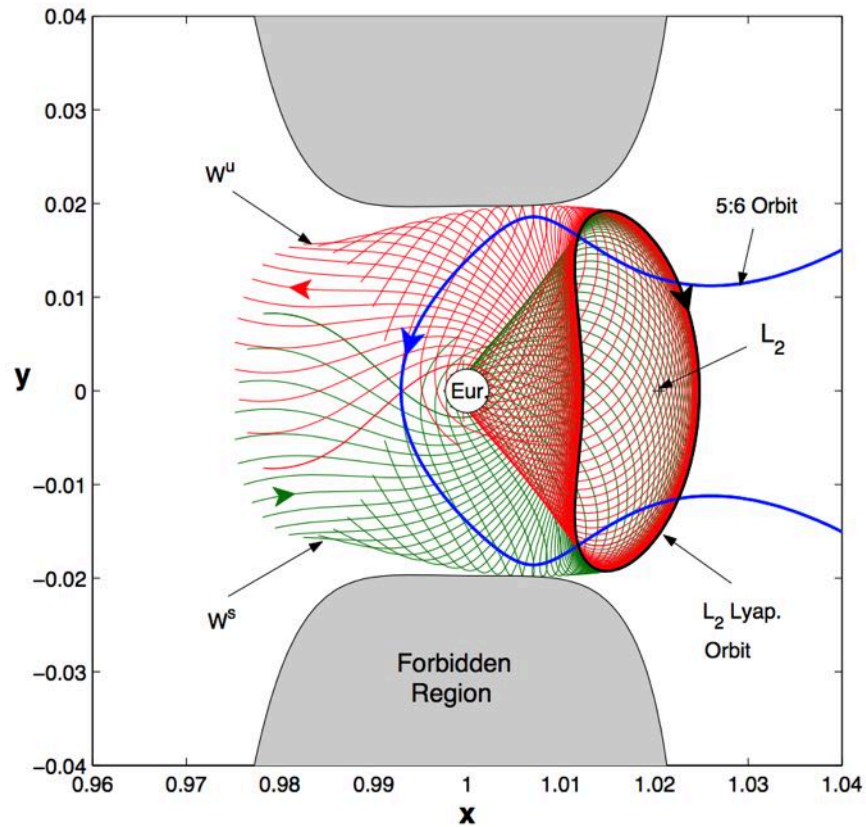
- Backward Integration & Trajectory Catalog
  - Europa Orbiter [Sweetser et al., Johannesen et al., 1999]
  - PTool for approach [Finlayson, 1999]
  - Maximize apoapse in PTool [Grebow et al. (2011)]
- Transfer between libration orbits of Moons [Koon, Lo, Marsden, & Ross (2002)]
- Low-thrust trajectories [Whiffen, 2001] heuristically follow libration orbit invariant manifolds [Lo (2001)]
- Planar Europa Orbiter follows invariant manifolds of libration orbit for approach [Anderson & Lo (2004)]
- Lunar approaches from Earth follow invariant manifolds [Anderson & Parker (2011)]





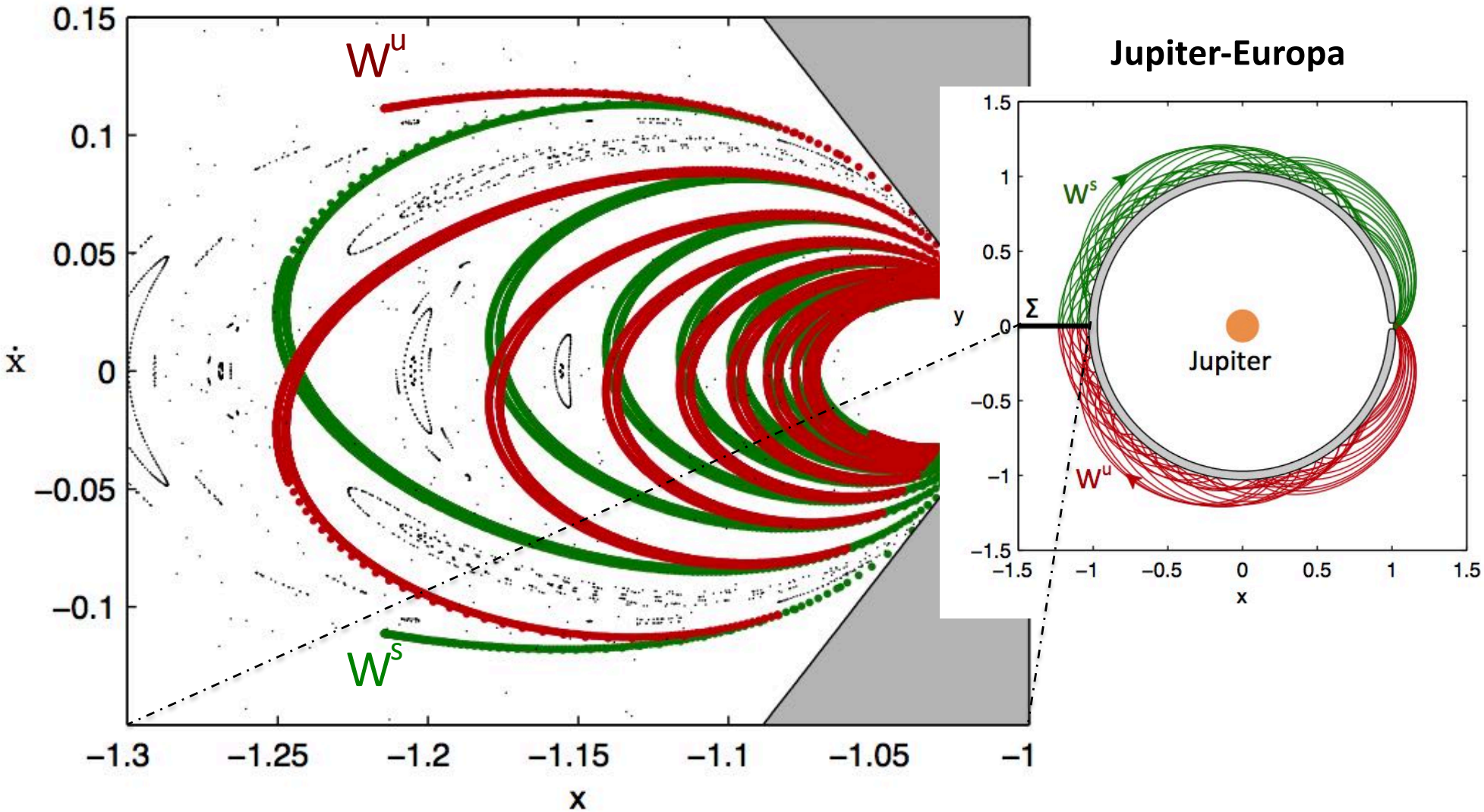
Approach Via Invariant Manifolds (Jupiter-Europa)



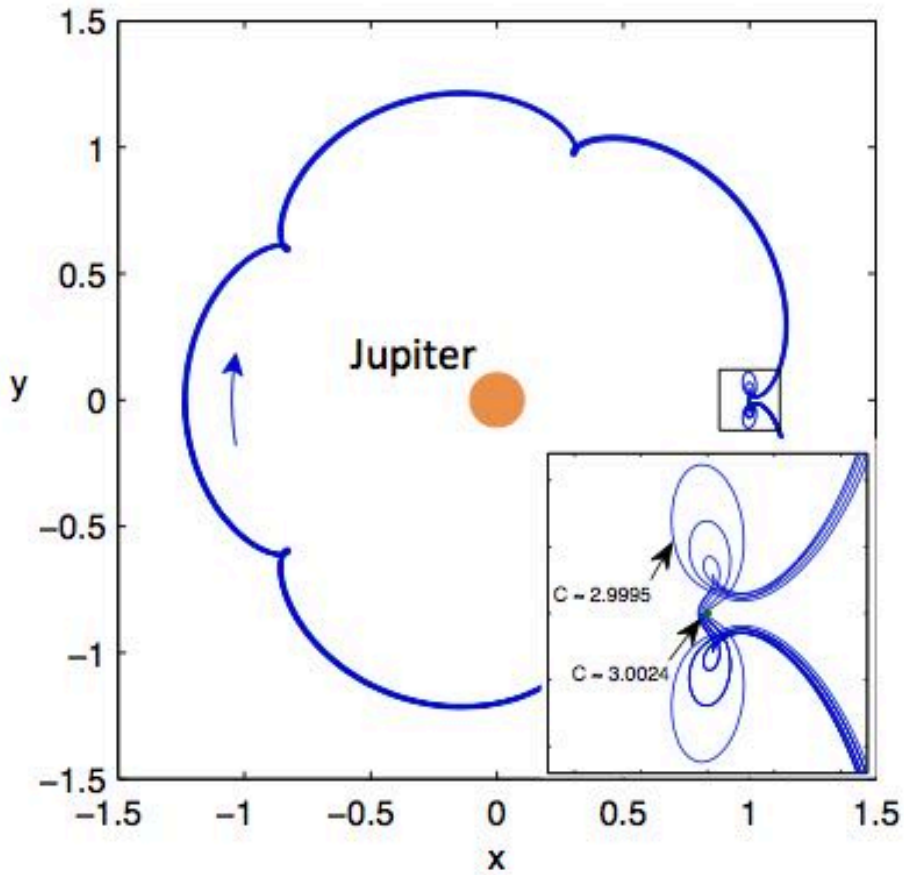


Approach Via Invariant Manifolds

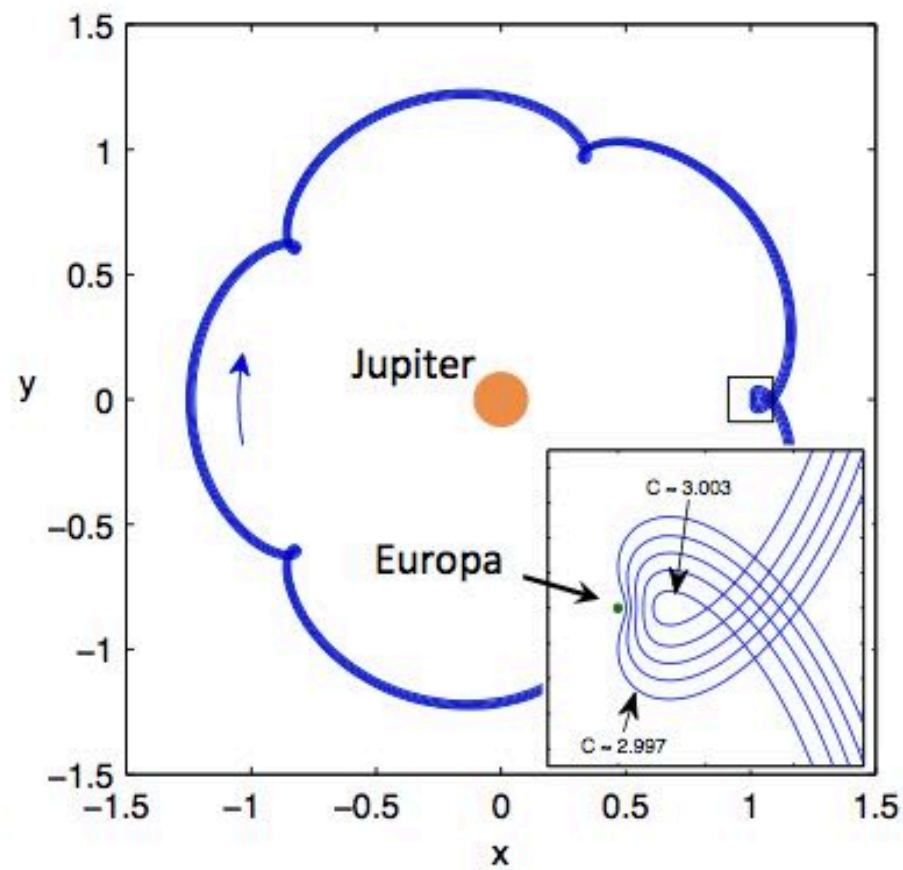
[Anderson – 2015]



5:6 Resonant Orbits for Jupiter-Europa

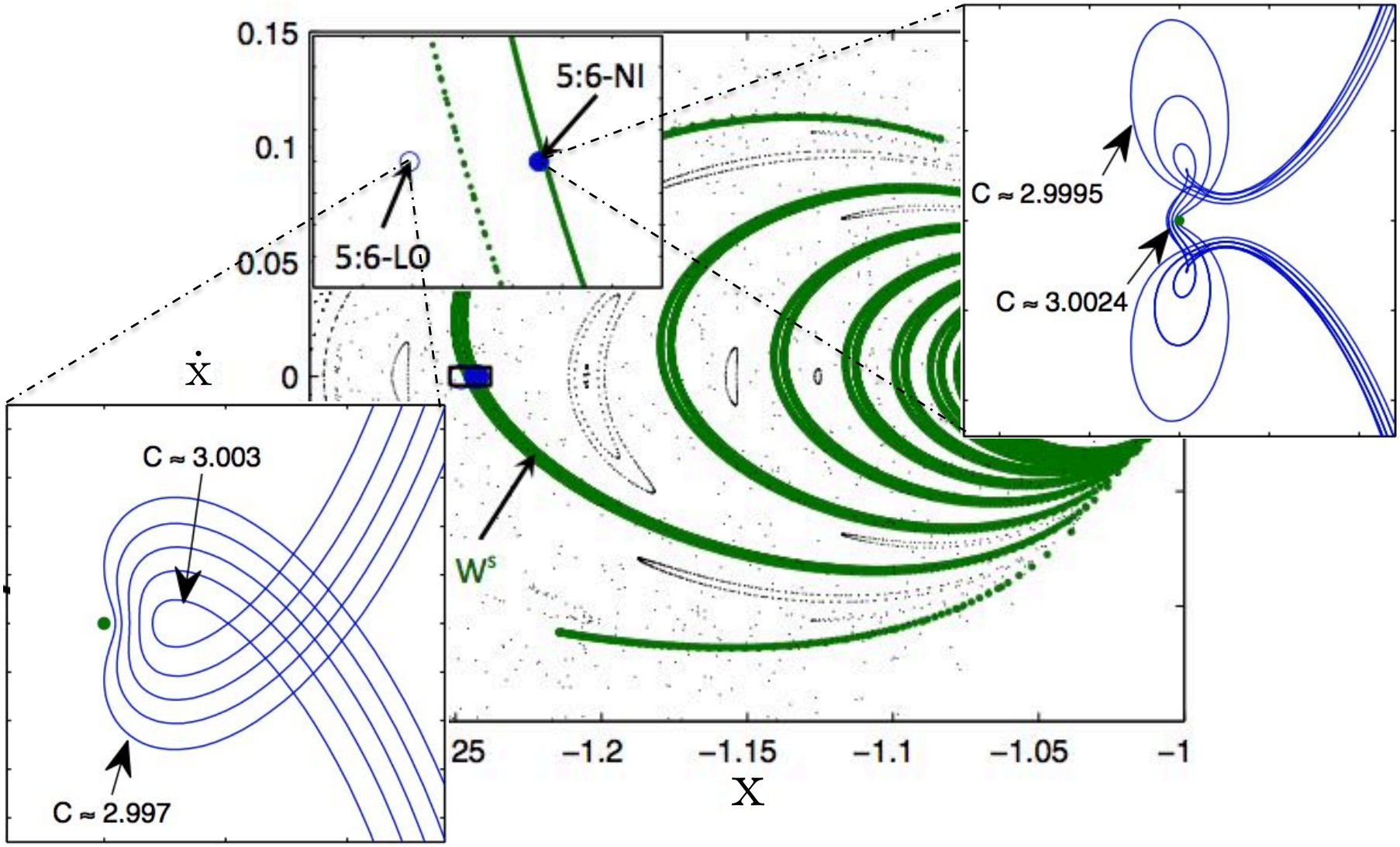


5:6-NI

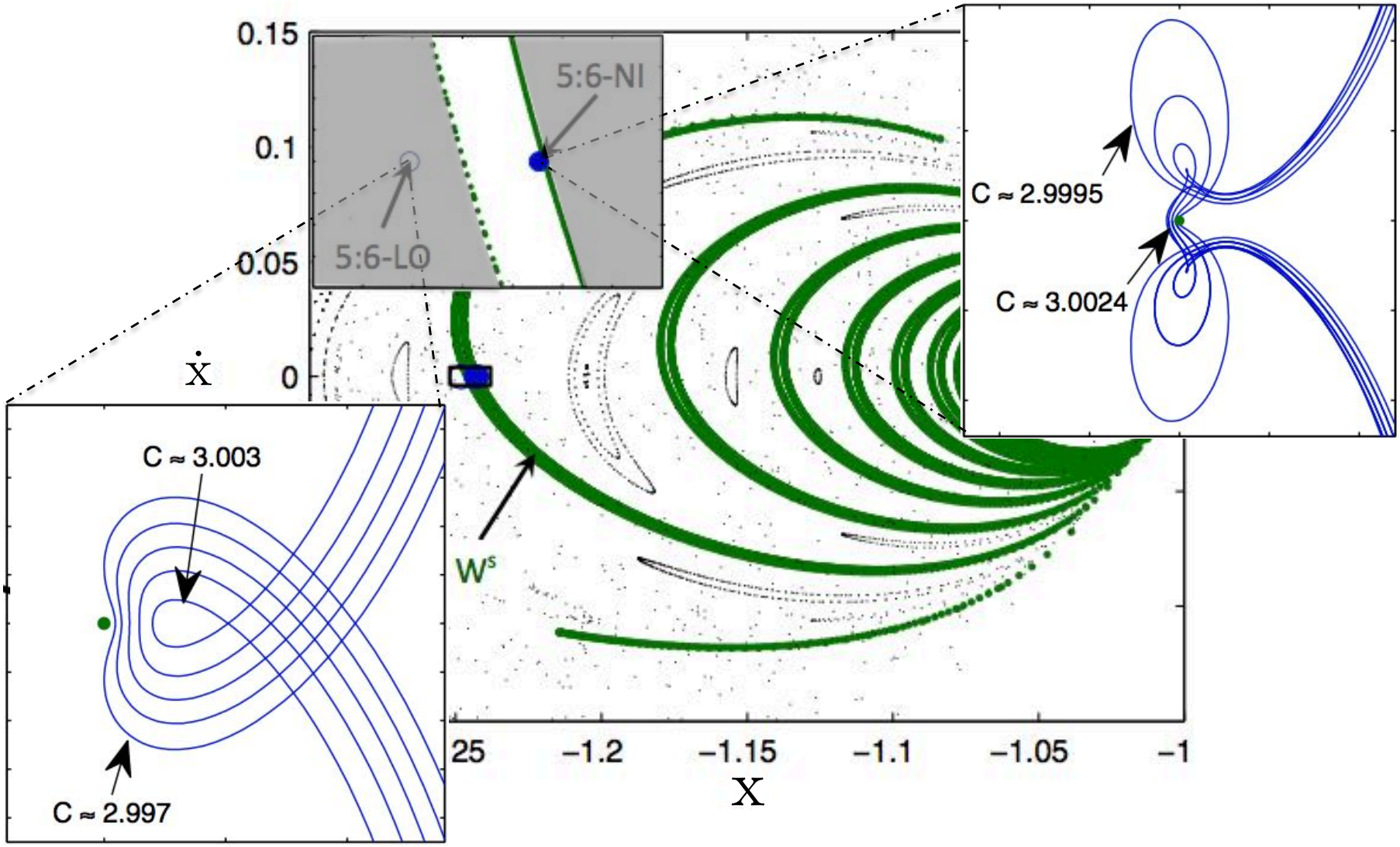


5:6-LO

5:6-NI within $W^s_{\text{Lyap.}}$

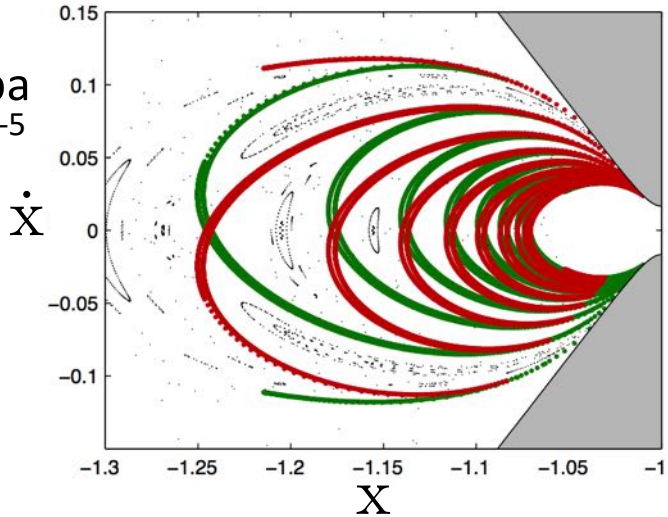


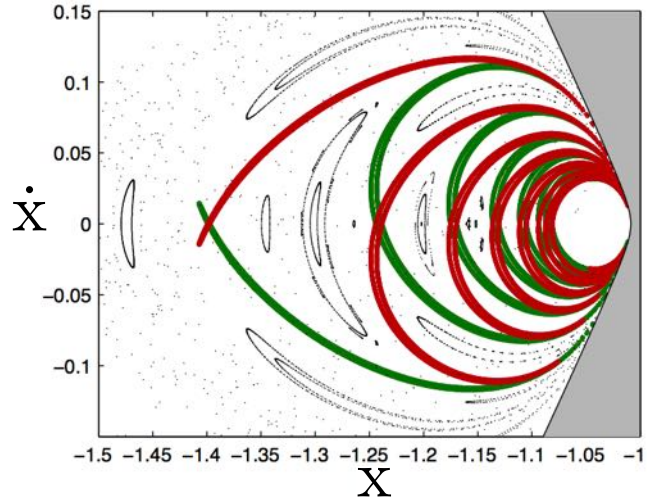
5:6-NI within $W^s_{\text{Lyap.}}$



Lyapunov Orbit Changes with System

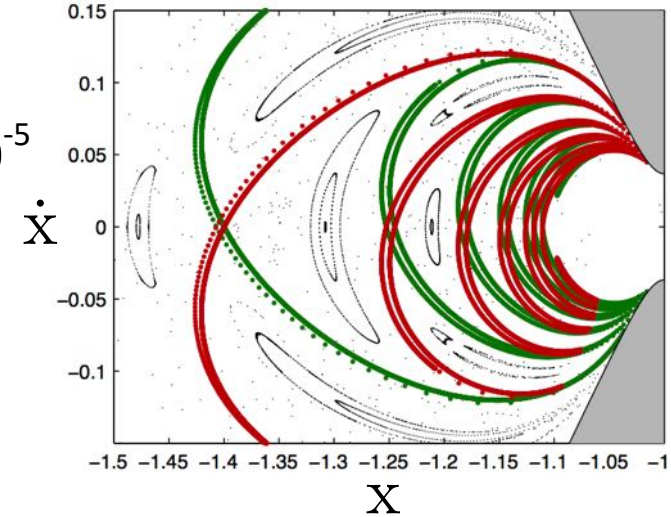
Jupiter-Europa
$\mu \approx 2.53 \times 10^{-5}$

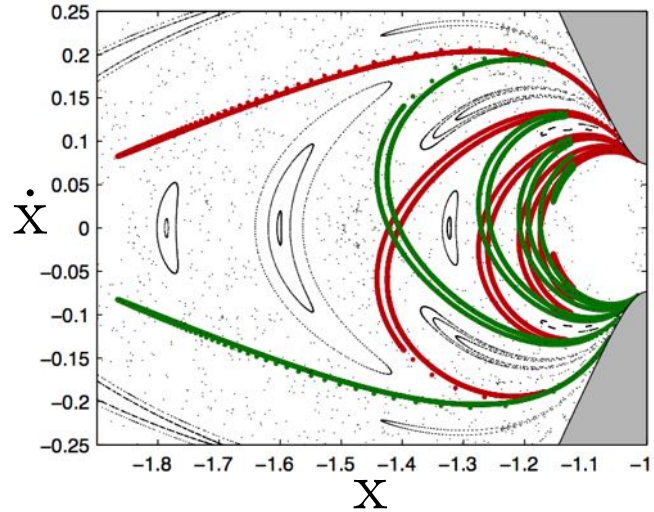




Jupiter-Io
$\mu \approx 4.71 \times 10^{-5}$

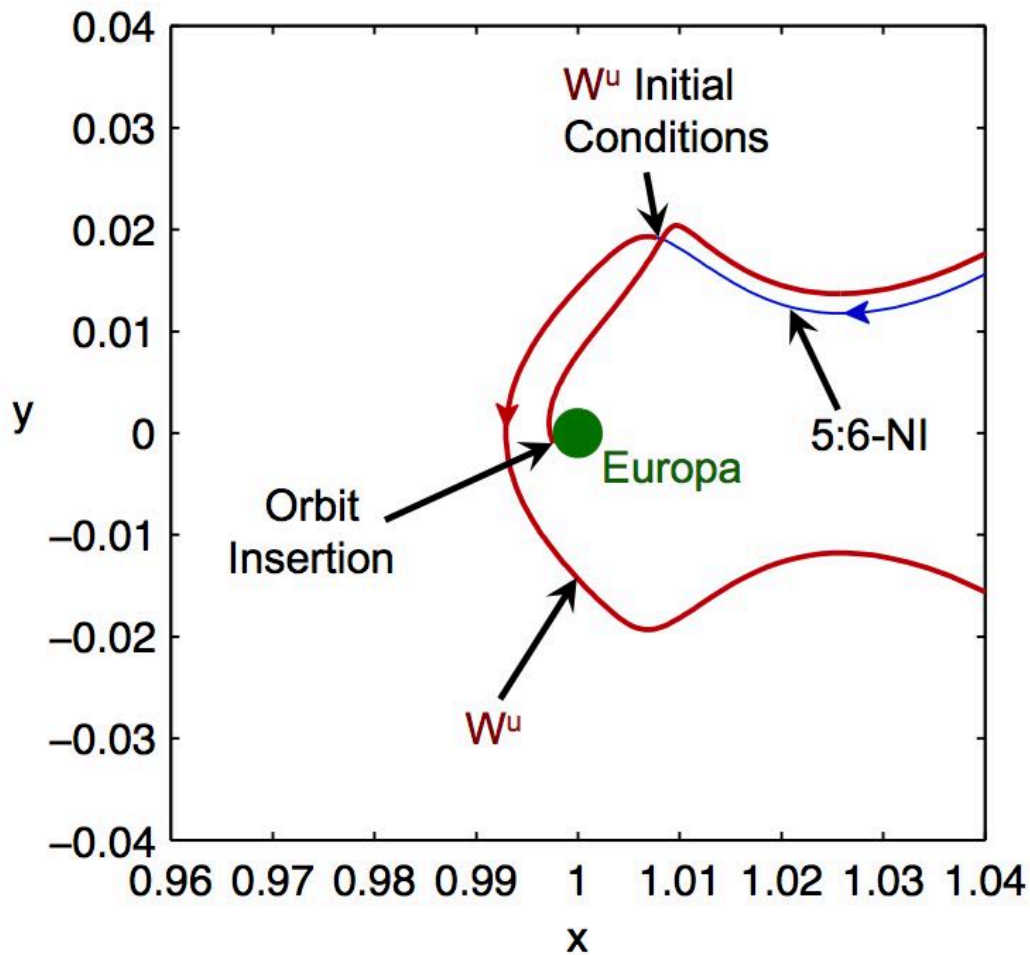
Jupiter-Ganymede
$\mu \approx 7.80 \times 10^{-5}$





Saturn-Titan
$\mu \approx 2.37 \times 10^{-4}$

Orbit Insertion via 5:6 Resonant Orbit Unstable Manifold



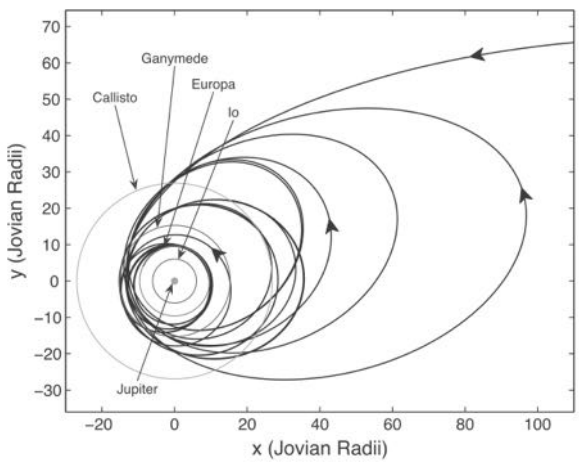
C = 3.0024
Altitude = 200 km
ΔV = 467.4 m/s

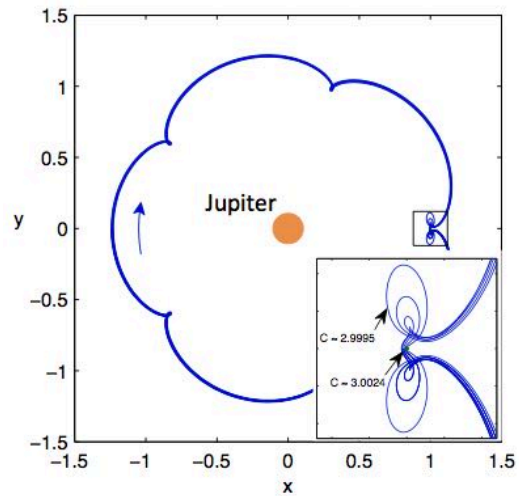
TOF = 23.5 days

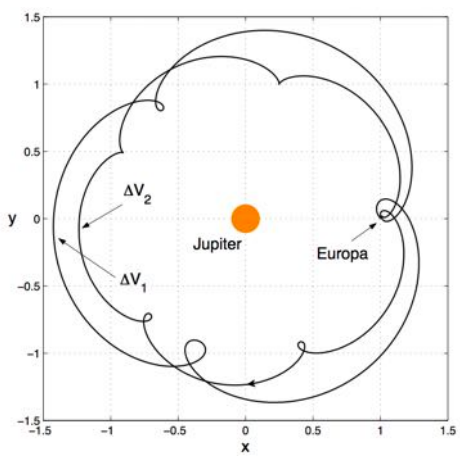
From Σ:
TOF = 11.5 days
(~ 4.5 days less Lyapunov Orbit)

The Approach Problem

Tour → Final Resonance → Approach

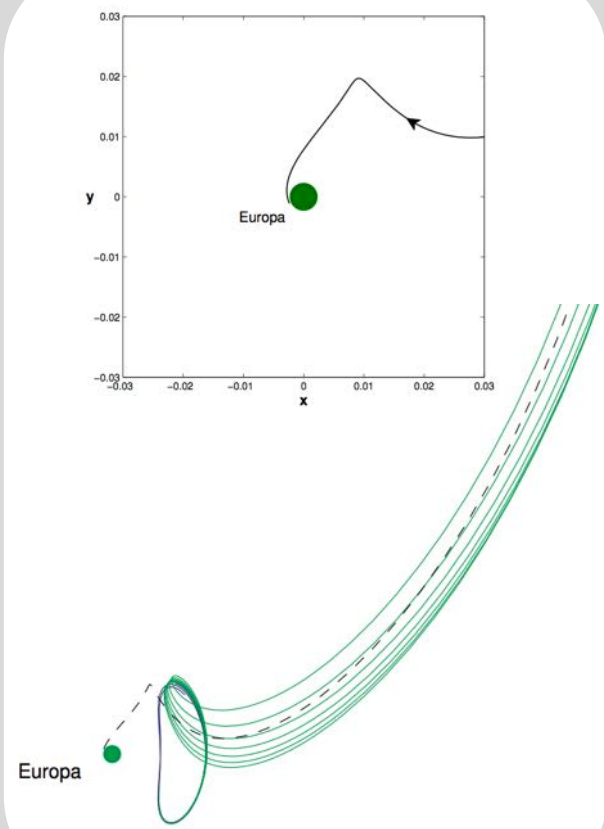






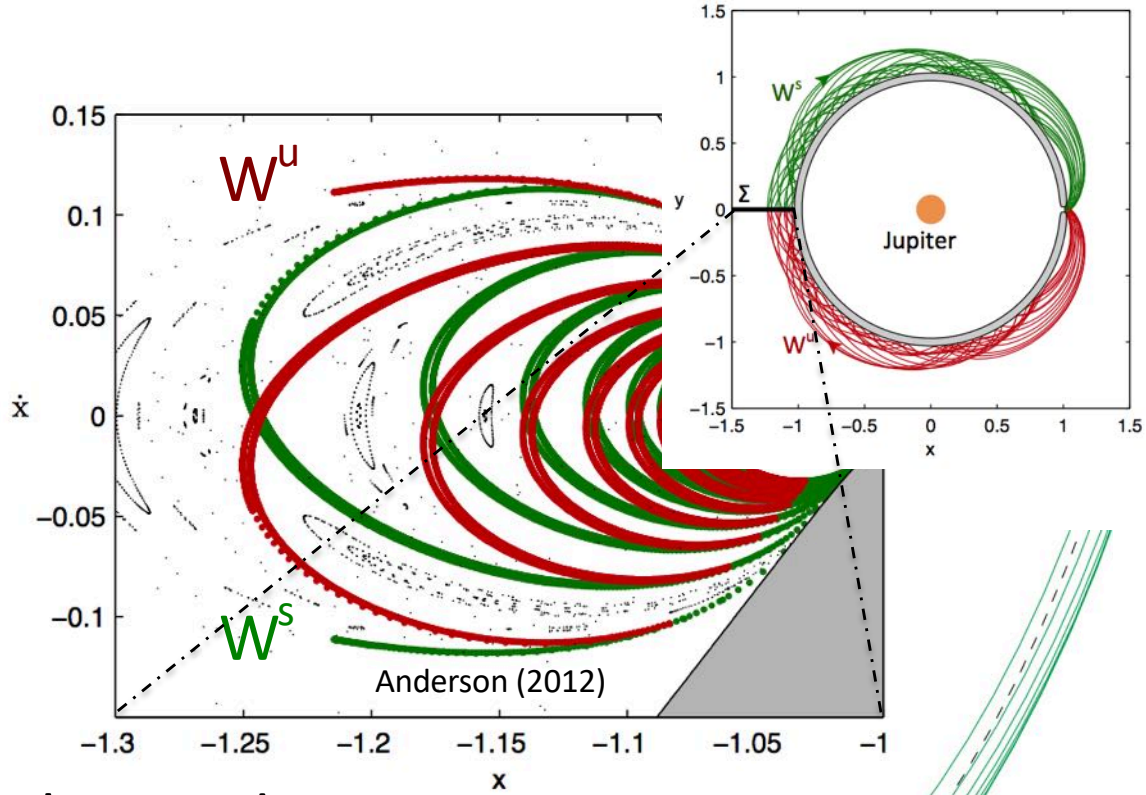
Approach Characteristics

- Multi-Body
- Often 3D (Inclined Orbit)
- Difficult Design
- Potential to Save ΔV

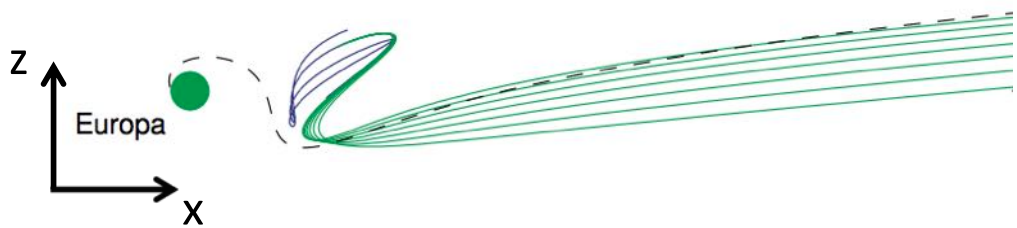


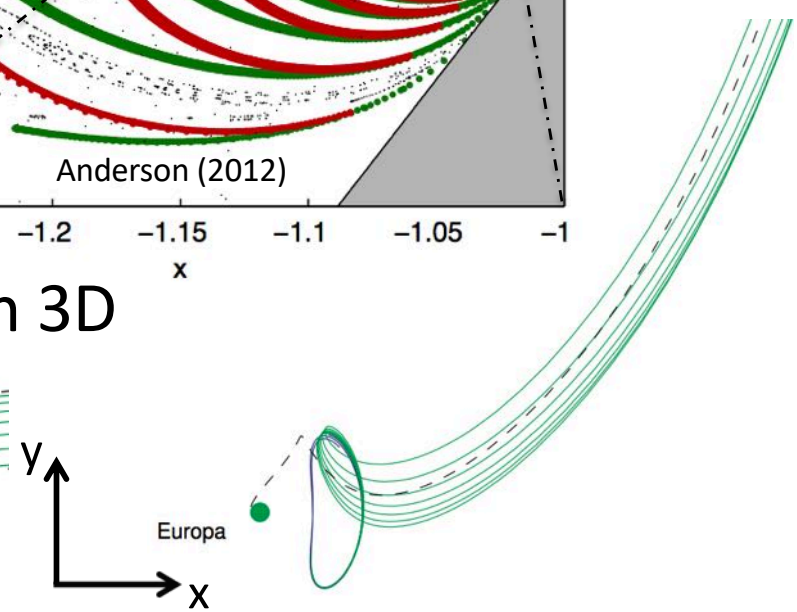
Invariant Manifolds Closely Tied to Approach

- Planar Problem
  - I.M. used to find resonance for final approach
  - Tied to specific resonant orbits
  - Approach found via Resonant orbit W^u or following libration orbit W^u, W^s

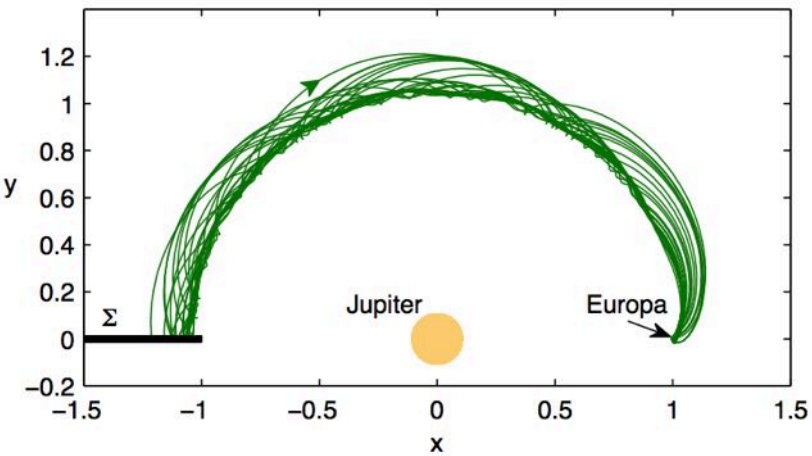


- Heuristic Relationship Observed in 3D

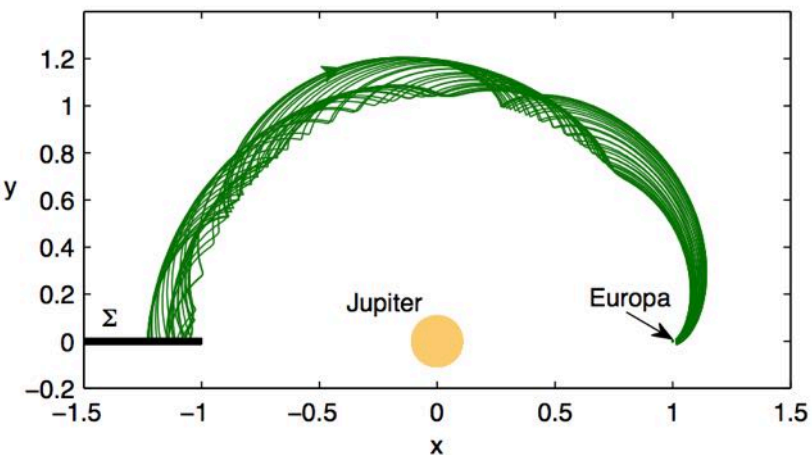




Use Periods for Initial Insight into Spatial Problem

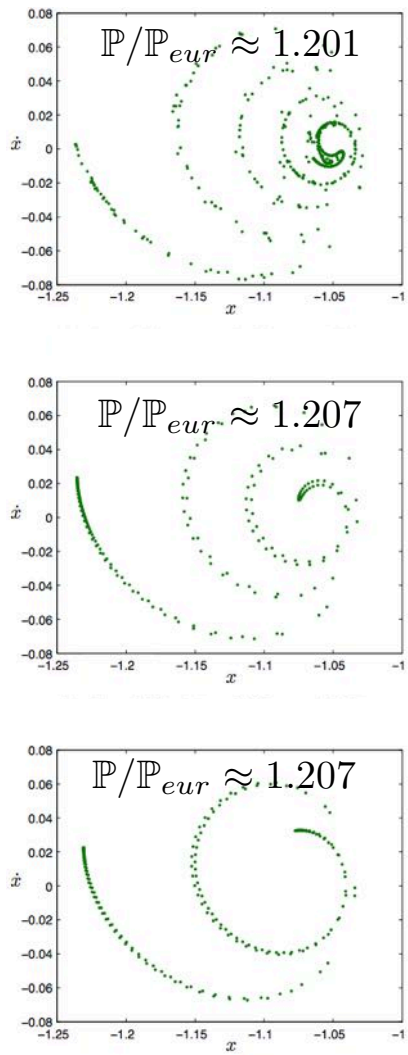


C = 3.001

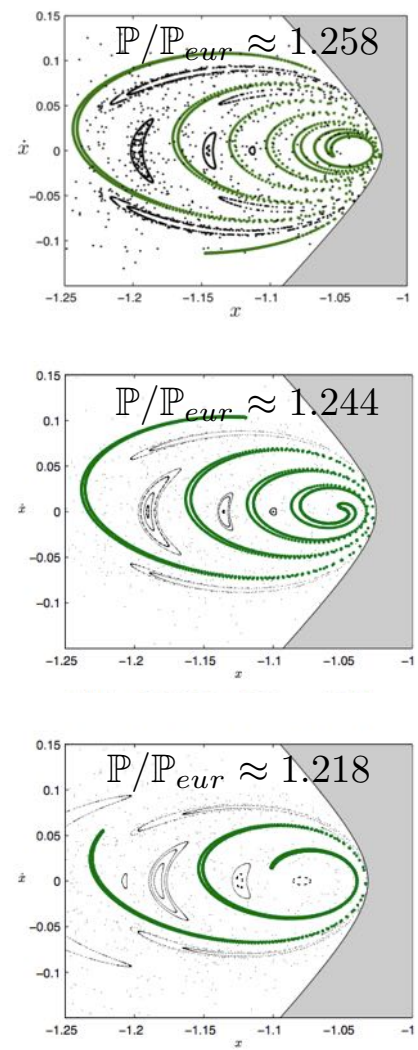


C = 3.003

Spatial



Planar



C = 3.001

2D: Greater Variation

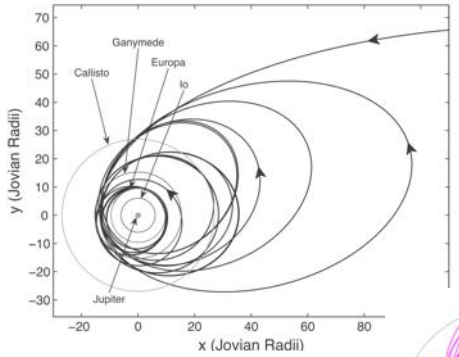
C = 3.002

C = 3.003

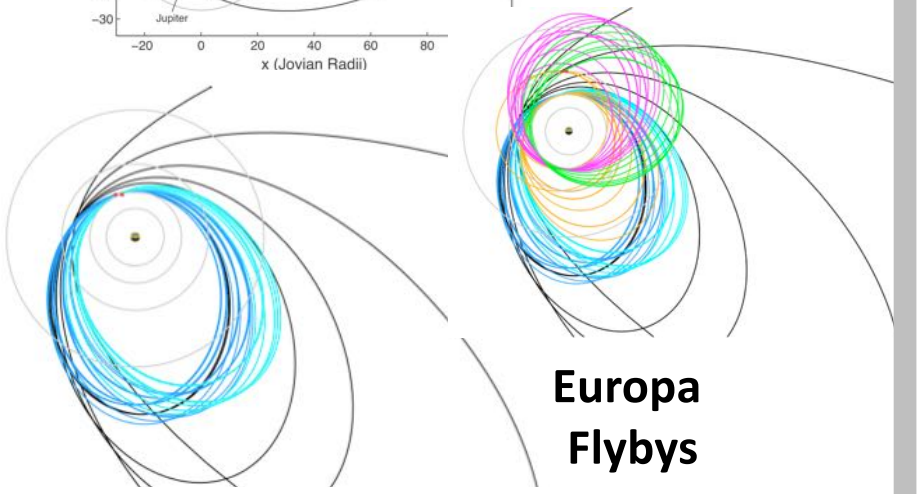
Europa Lander Applications

Europa Orbiter & Europa Clipper

Europa Missions



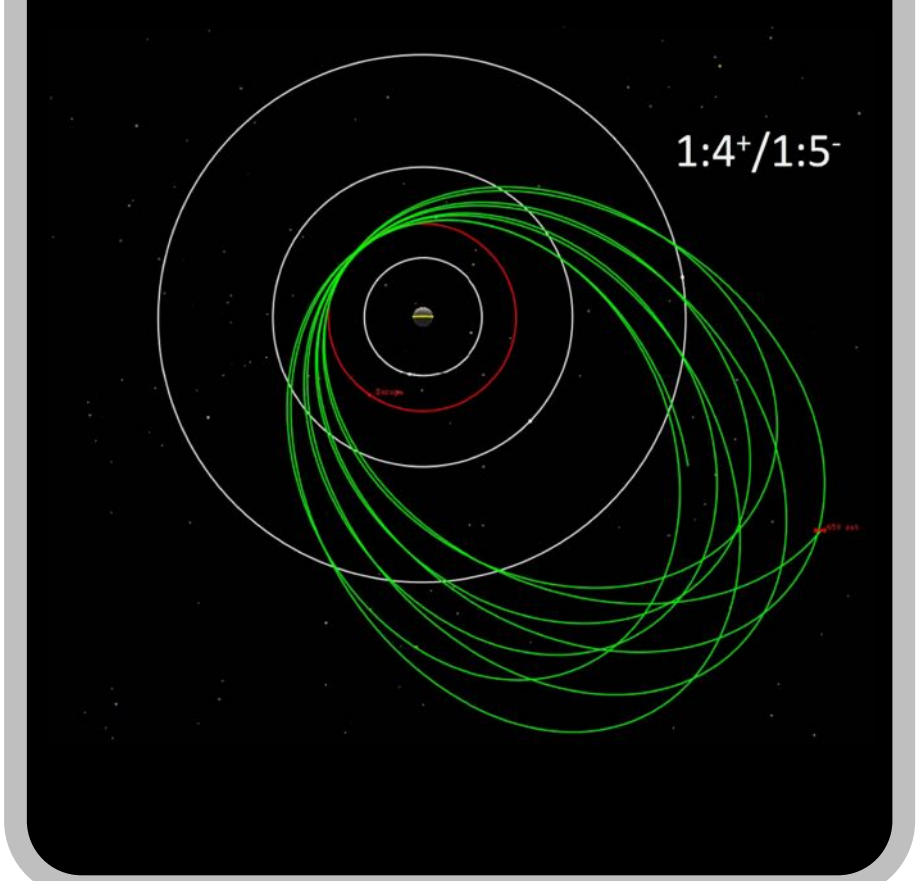
Europa Orbiter (1999)



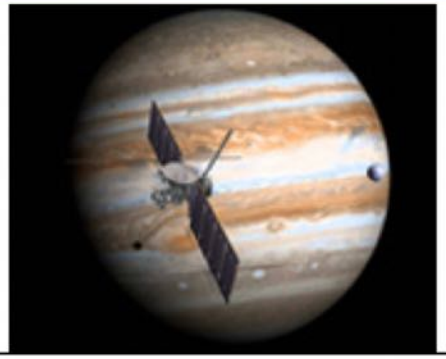
Europa Flybys

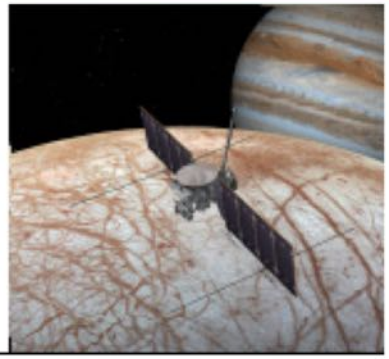
Buffington, Campagnola, Petropoulos (2012)

Europa Clipper Petal Rotation



Europa Clipper Mission Overview





Launch

Period: 7/9/23 – 7/29/23 (SLS)

Period: 5/24/23 – 6/13/23 (ELV)

Cruise:

2.5 - 2.7 Years (SLS)

6.4 Years (ELV)

Jupiter Orbit Insertion

1/15/26 or 4/25/26 (SLS)

1/15/30 (ELV)
6.5 to 7.5 hour burn

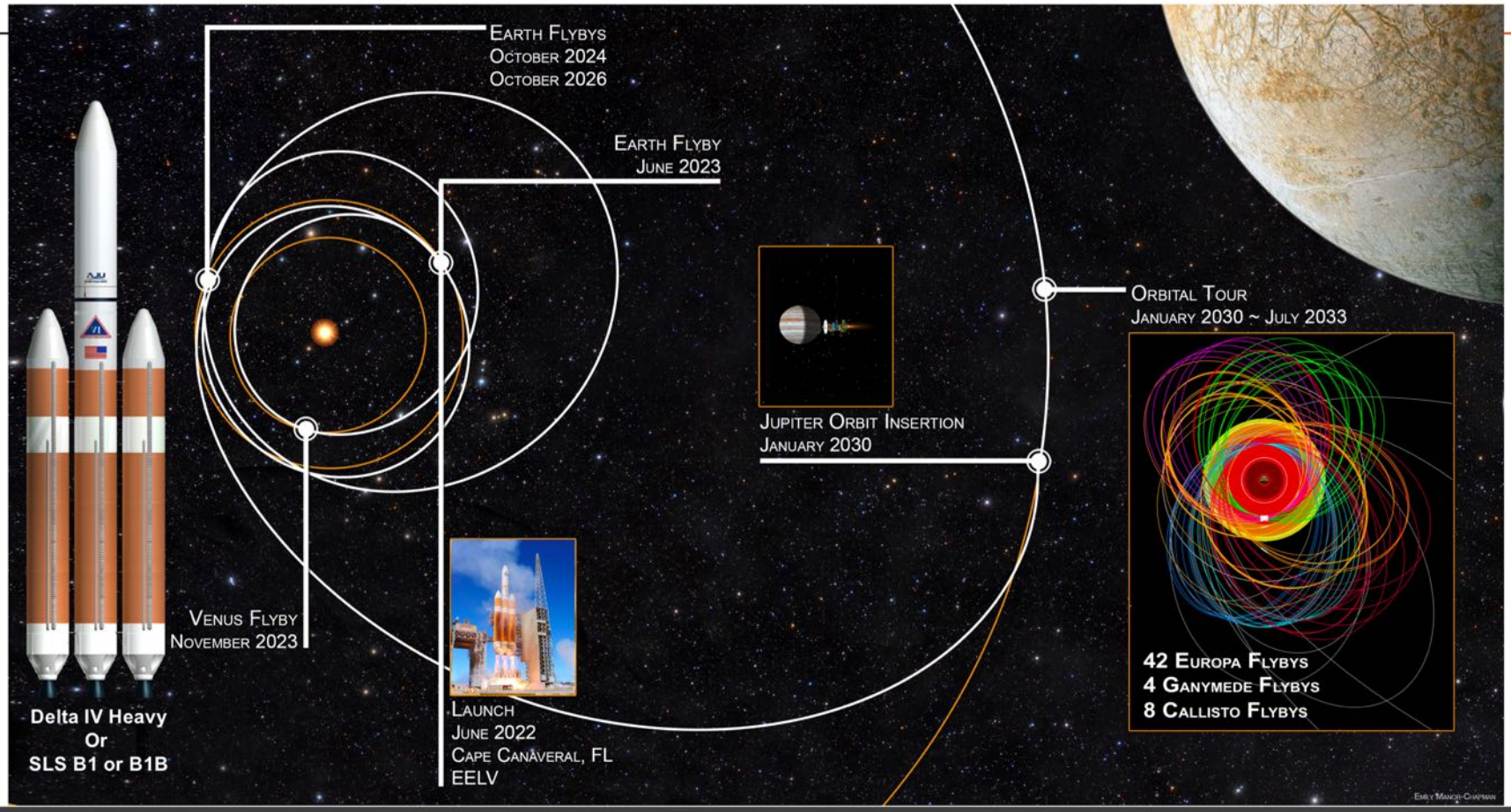
Jovian System Operations

Transition to Europa Science: 12 months
Prime Europa Flyby Campaign: 36 months
Multiple (40+) Flyby Encounters of Europa

EUROPA 2/28/2017 © 2017 California Institute of Technology. Government Sponsorship Acknowledged.

[Credit: Brent Buffington]

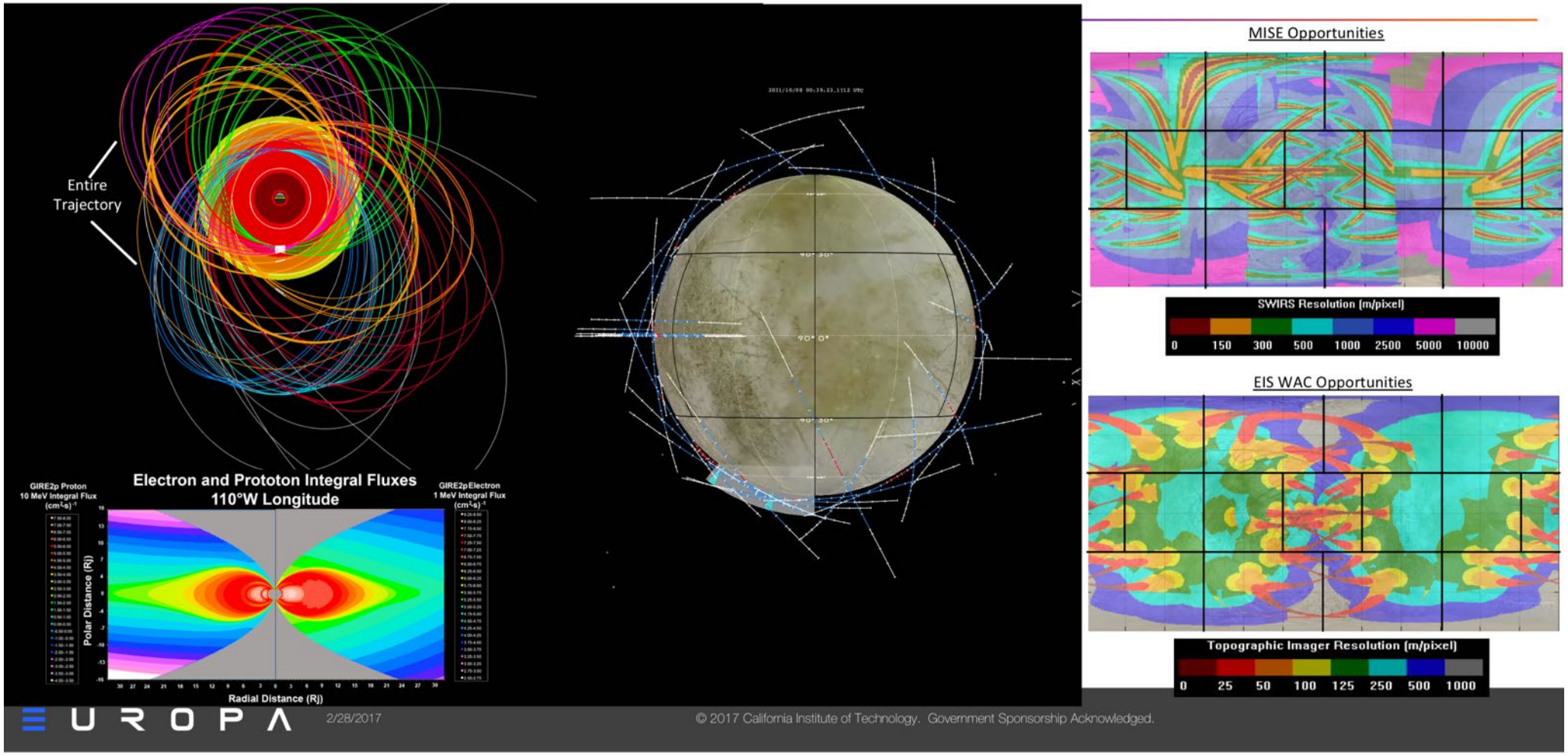
EVEEGA Interplanetary Trajectory



EUROPA 2/28/2017 © 2017 California Institute of Technology. Government Sponsorship Acknowledged.

[Credit: Brent Buffington]

Jupiter Tour Design Strategy



[Credit: Brent Buffington]

Europa Lander Goals

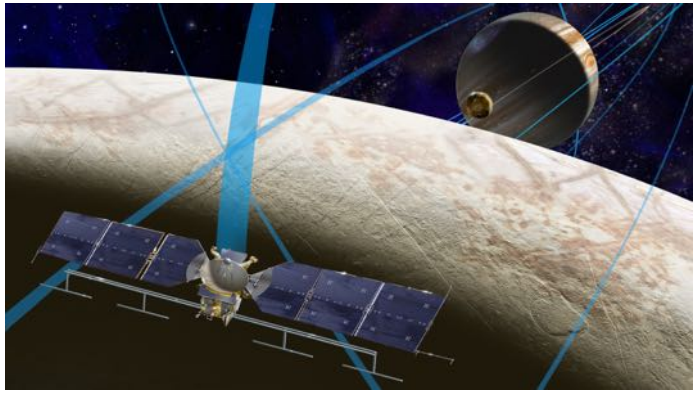
Europa Lander Study:

2016 Report

- Search for biosignatures on Europa
- Assess the habitability of Europa via *in situ* techniques
- Characterize surface and subsurface properties to support future exploration

Pre-Decisional Information – For Planning and Discussion Purposes Only.

Trajectory Design Overview



- Europa Clipper will observe from orbit, but taking *in situ* measurements from the surface is key in the search for biosignatures.
- Low-energy trajectories provide a fuel efficient mechanisms for Europa approach.
- A **petit grand tour** gradually reduces the spacecraft's two-body energy of via three-body gravity flybys of the moons in a resonant hopping sequence.
- Once close enough to Europa, the **L_2 gateway** is the natural target for the final approach.

[Hernandez, Restrepo & Anderson]

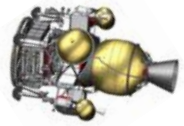
Pre-Decisional Information – For Planning and Discussion Purposes Only.

Europa Lander Mission Concept

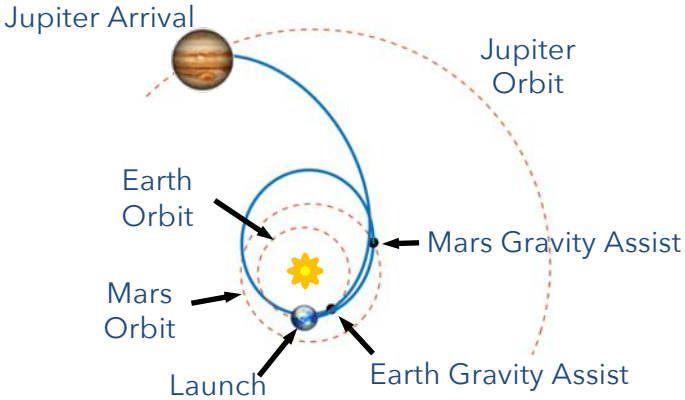
Launch
- SLS Block 1B

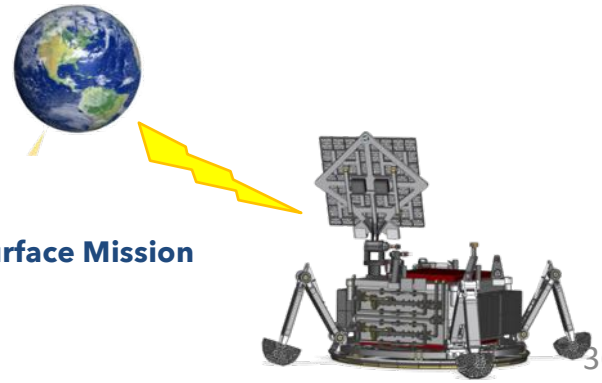
Cruise/Jovian Tour

Carrier Stage



Deorbit, Descent, Landing





Surface Mission

Credit: Tim McElrath, Roger Gibbs

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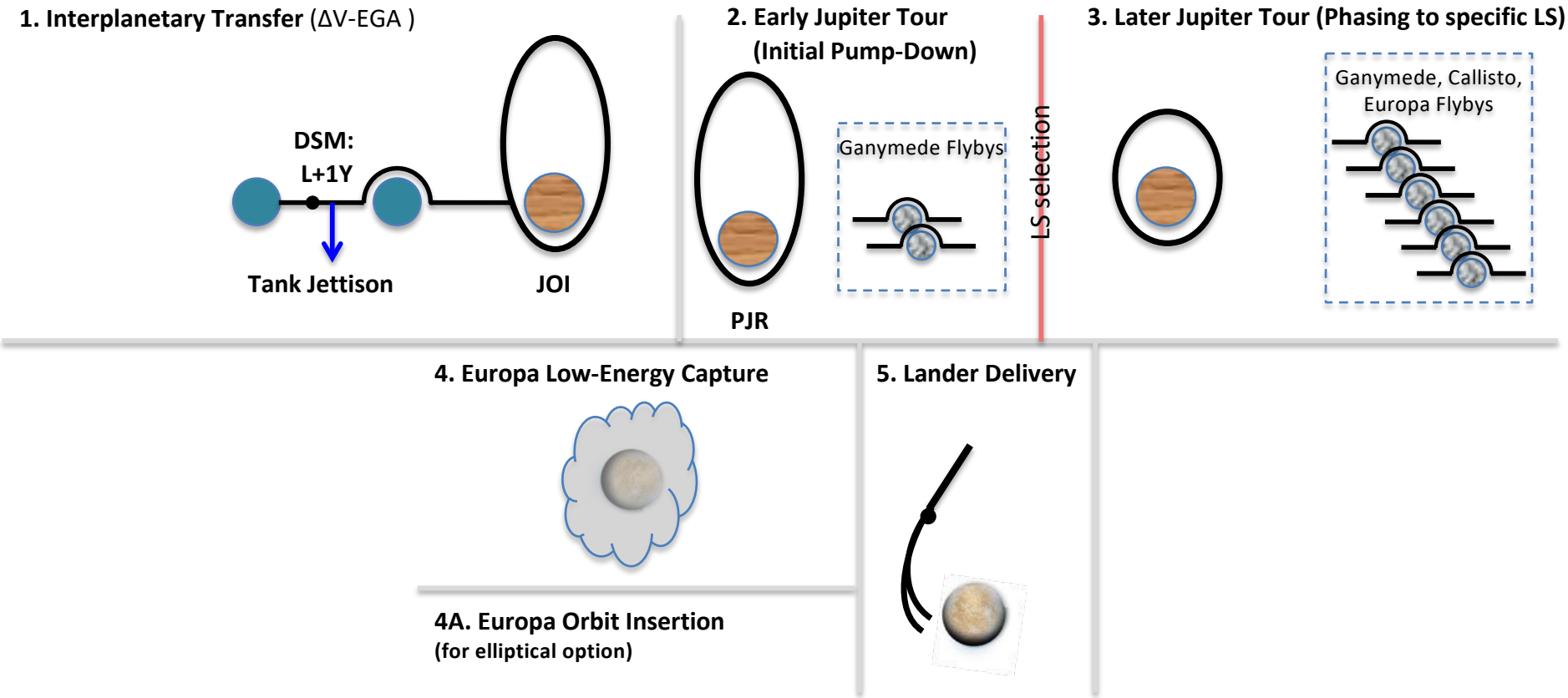
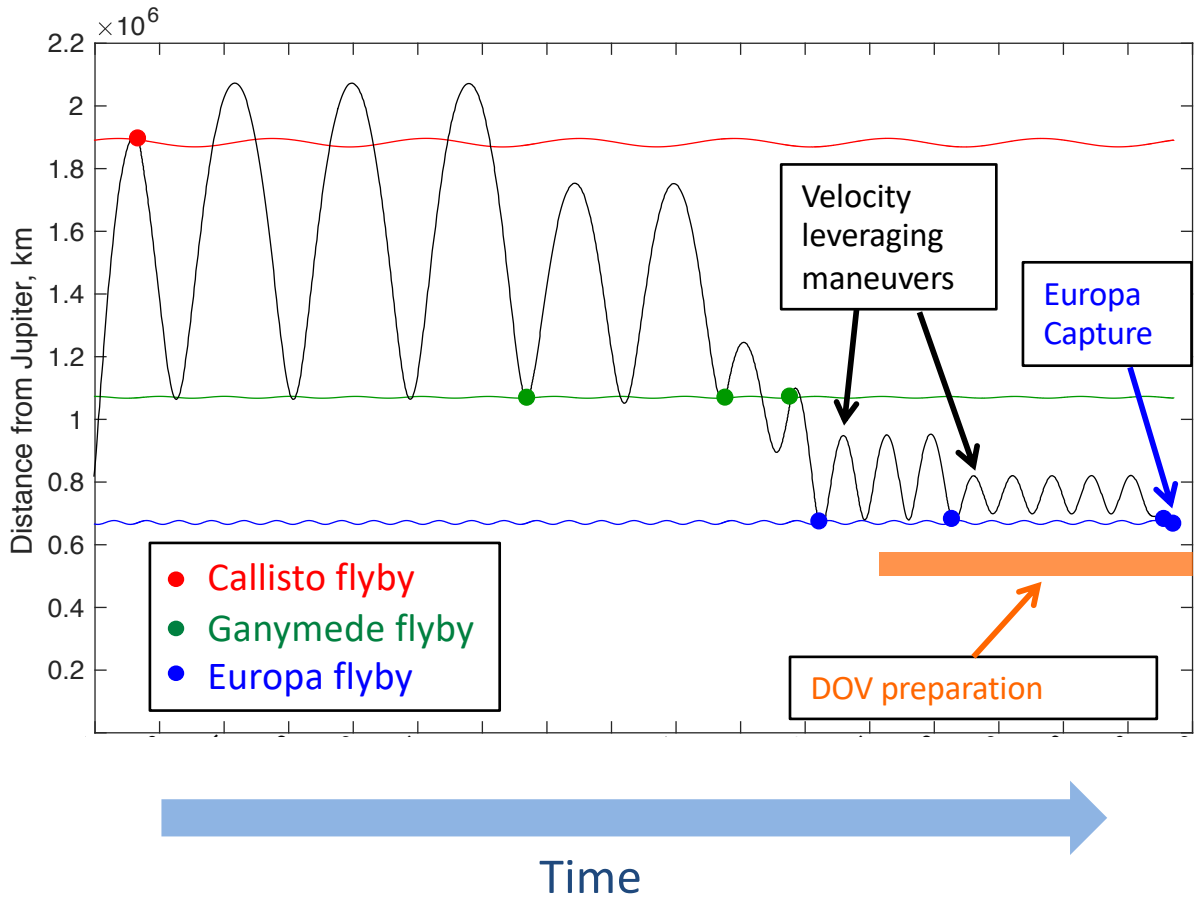
Mission Trajectory Elements



Credit: Tim McElrath, Roger Gibbs

Pre-Decisional Information – For Planning and Discussion Purposes Only.

Tour Endgame, Leading to Low Energy Europa Capture

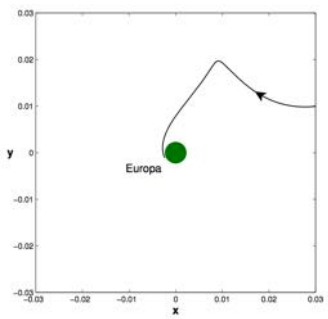


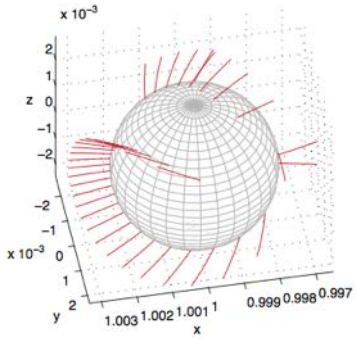
Credit: Tim McElrath, Roger Gibbs

Pre-Decisional Information – For Planning and Discussion Purposes Only.

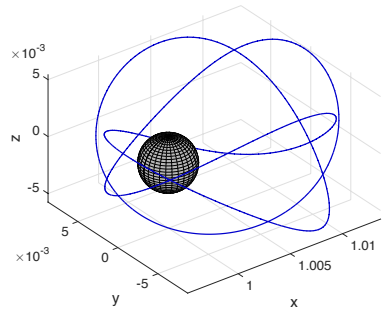
Mission Scenarios for Europa Approach

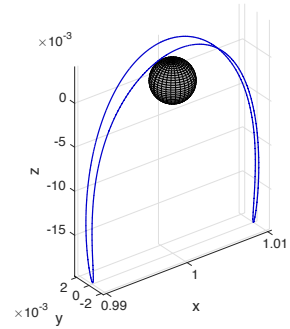
Direct Landing



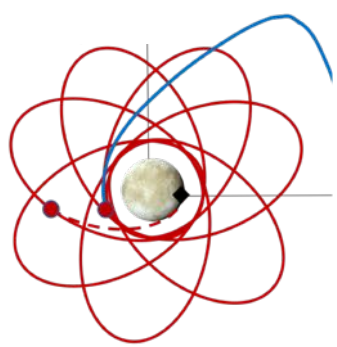


Relay Orbiter

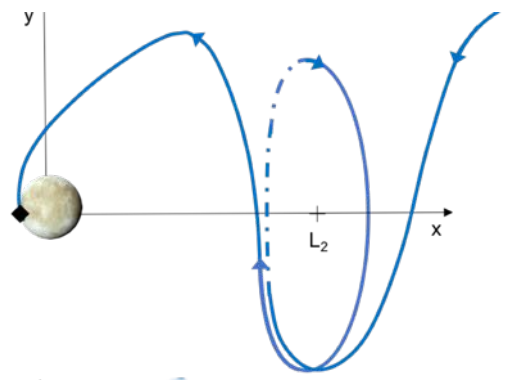




Europa Phasing Orbit

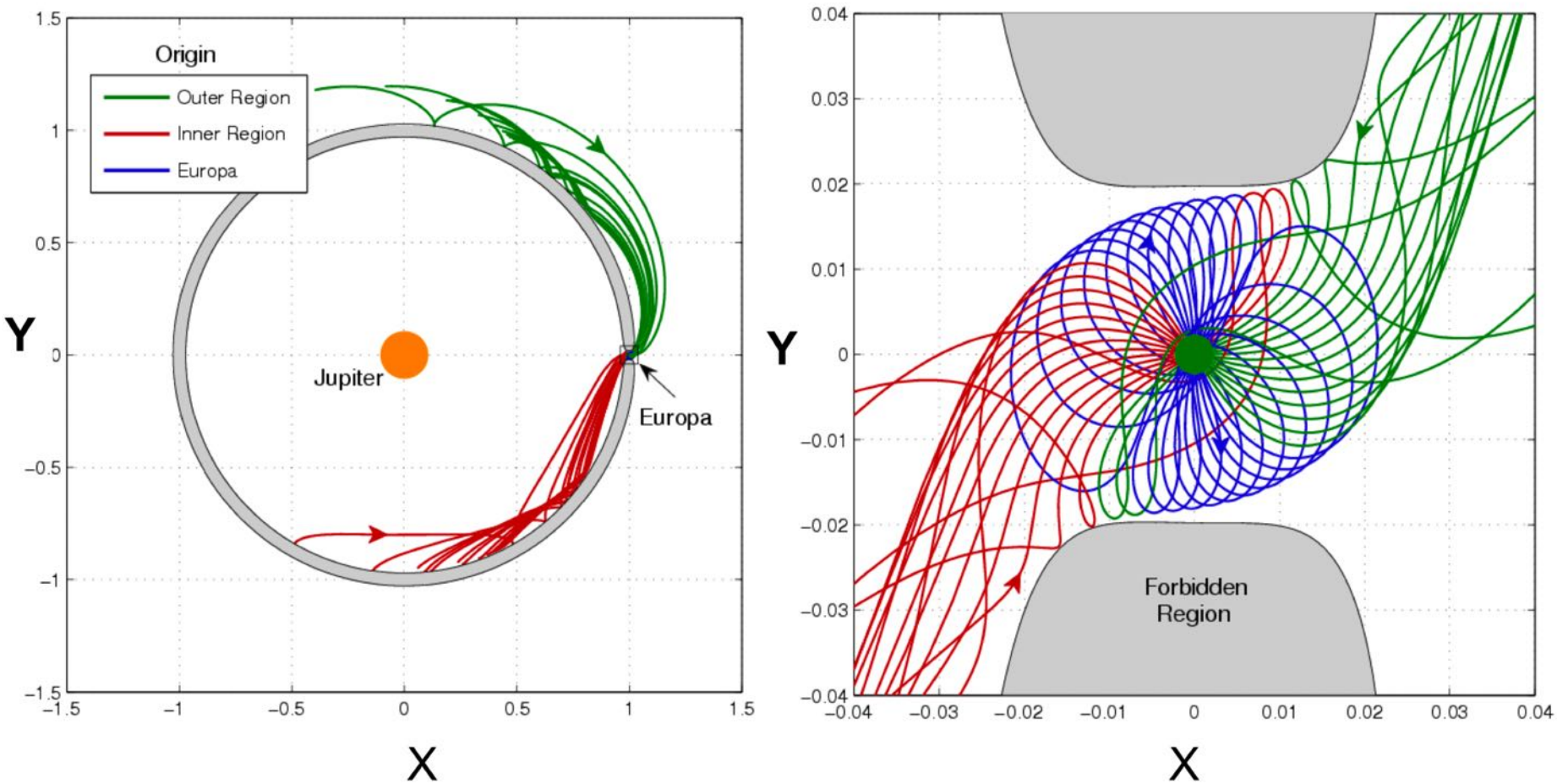


Libration Point Phasing Orbit

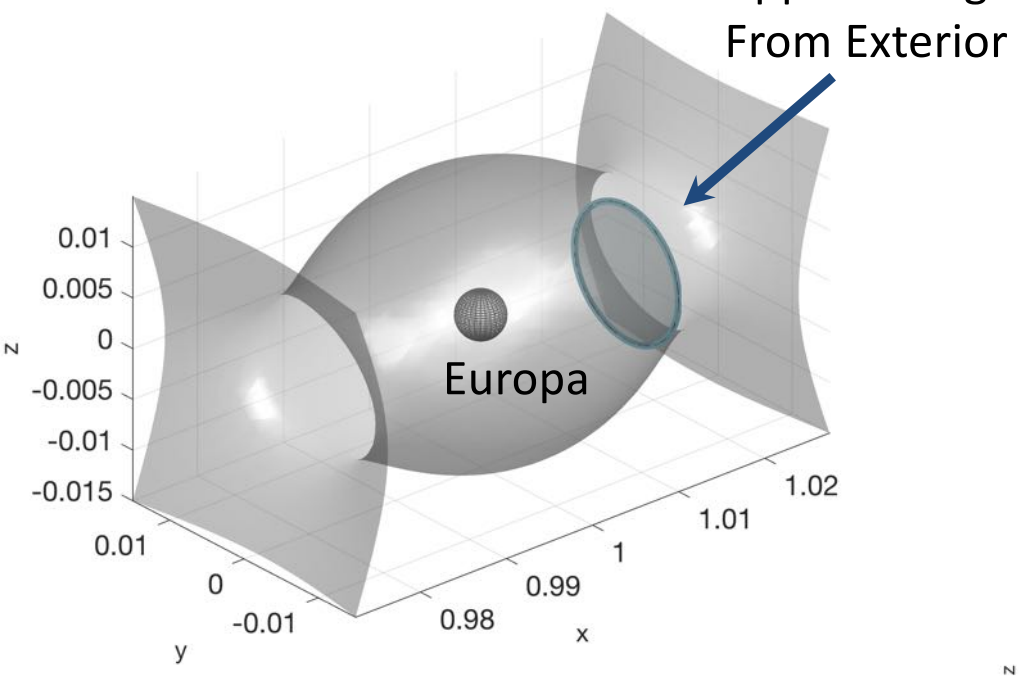


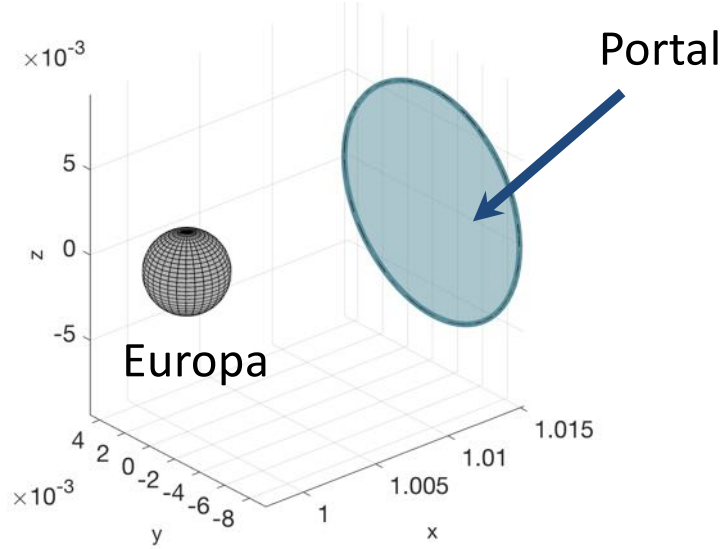
Impact Orbits Approaching Europa

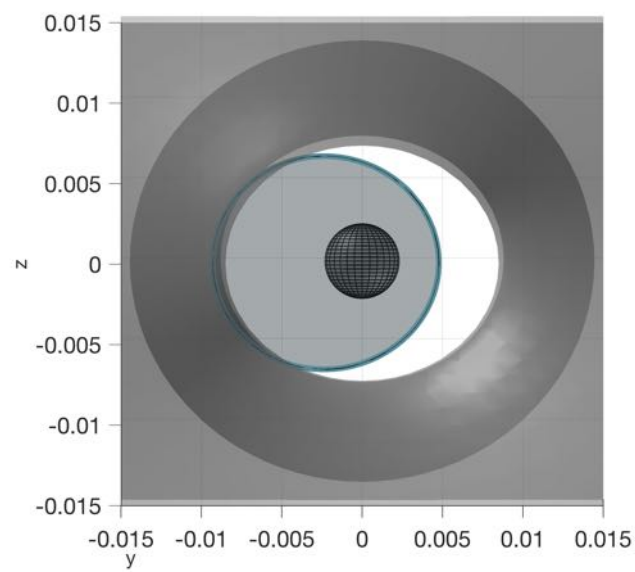
(C ≈ 3.0025)



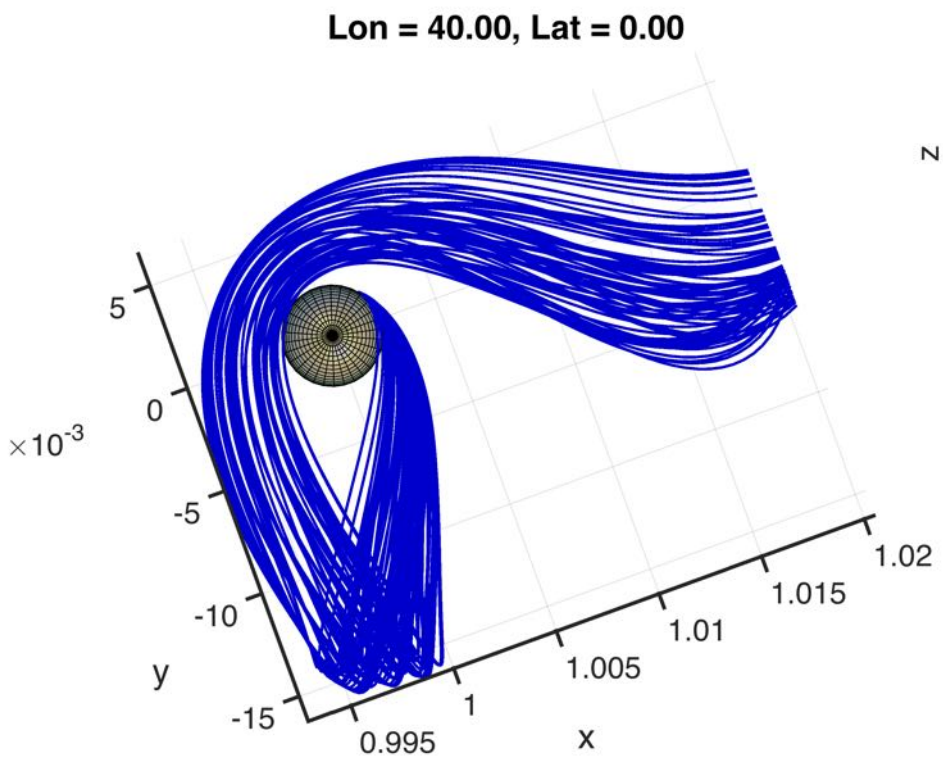
Europa Approach through L_2 Gateway

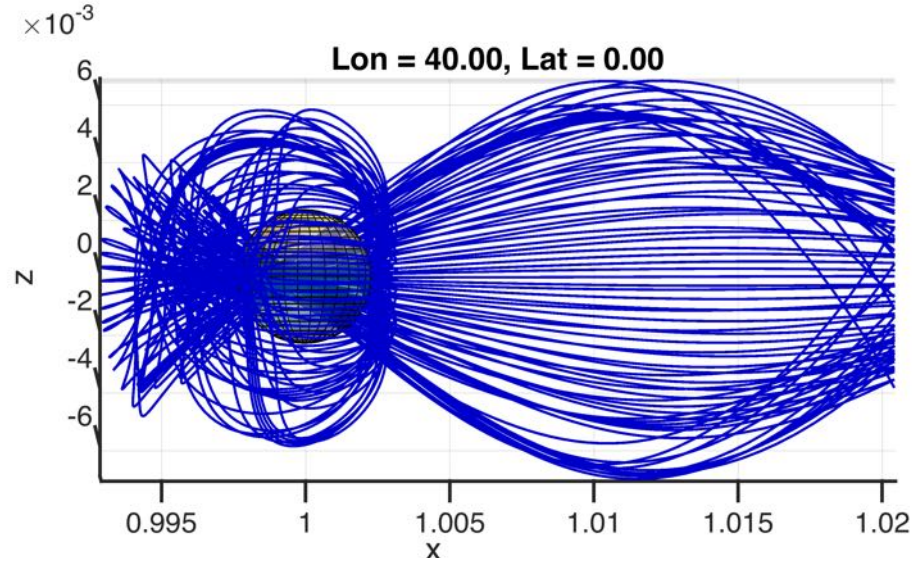


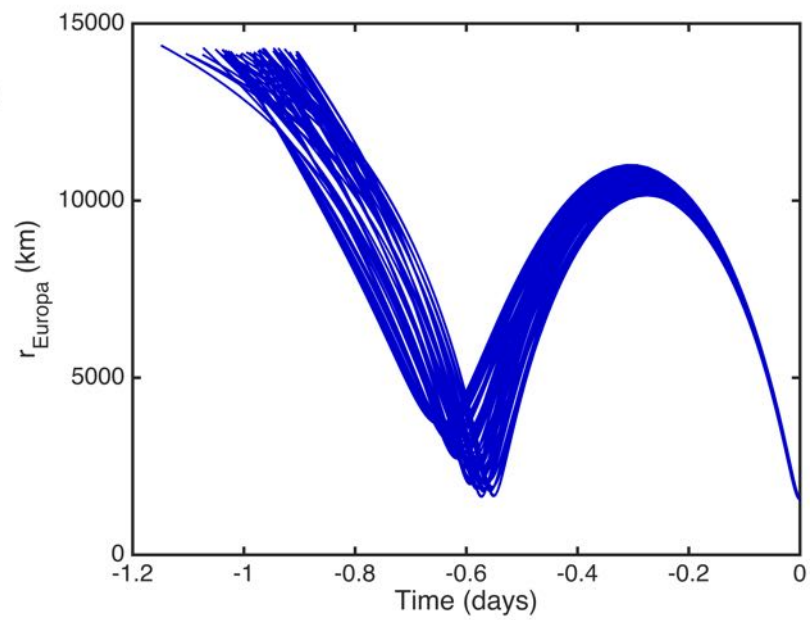




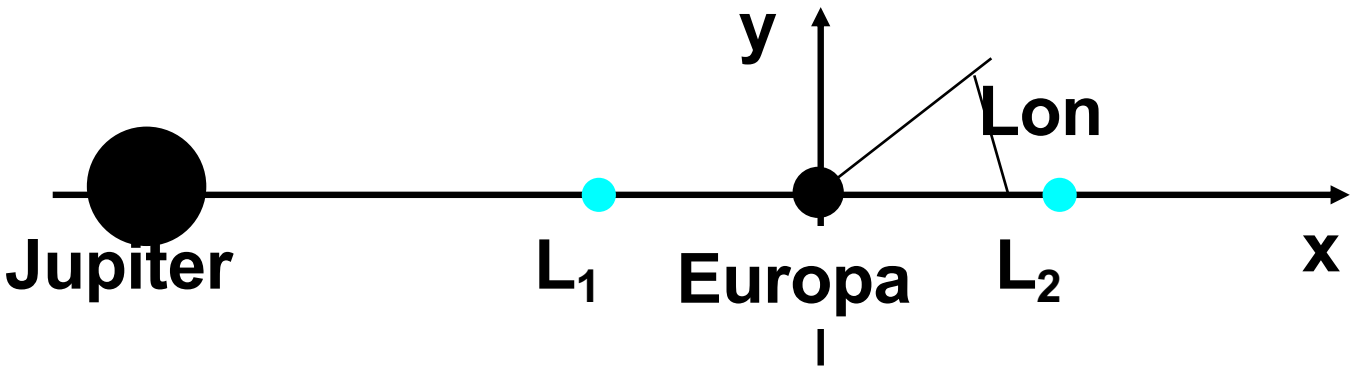
Trajectories Approaching Europa's Surface







Coordinate System on Sphere

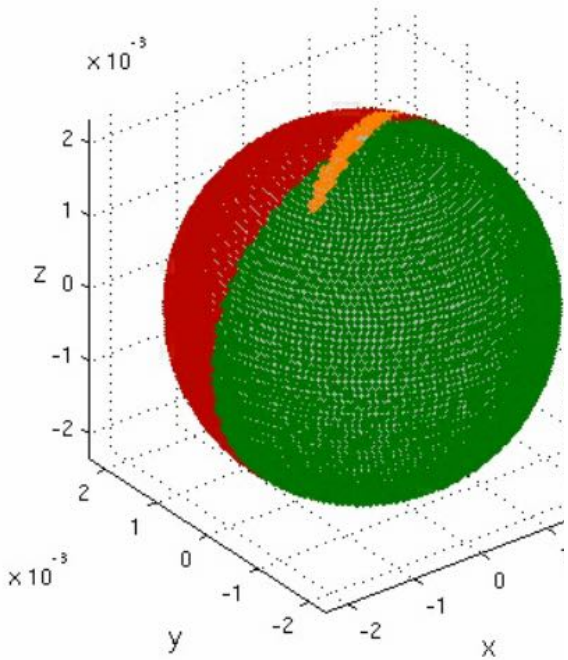


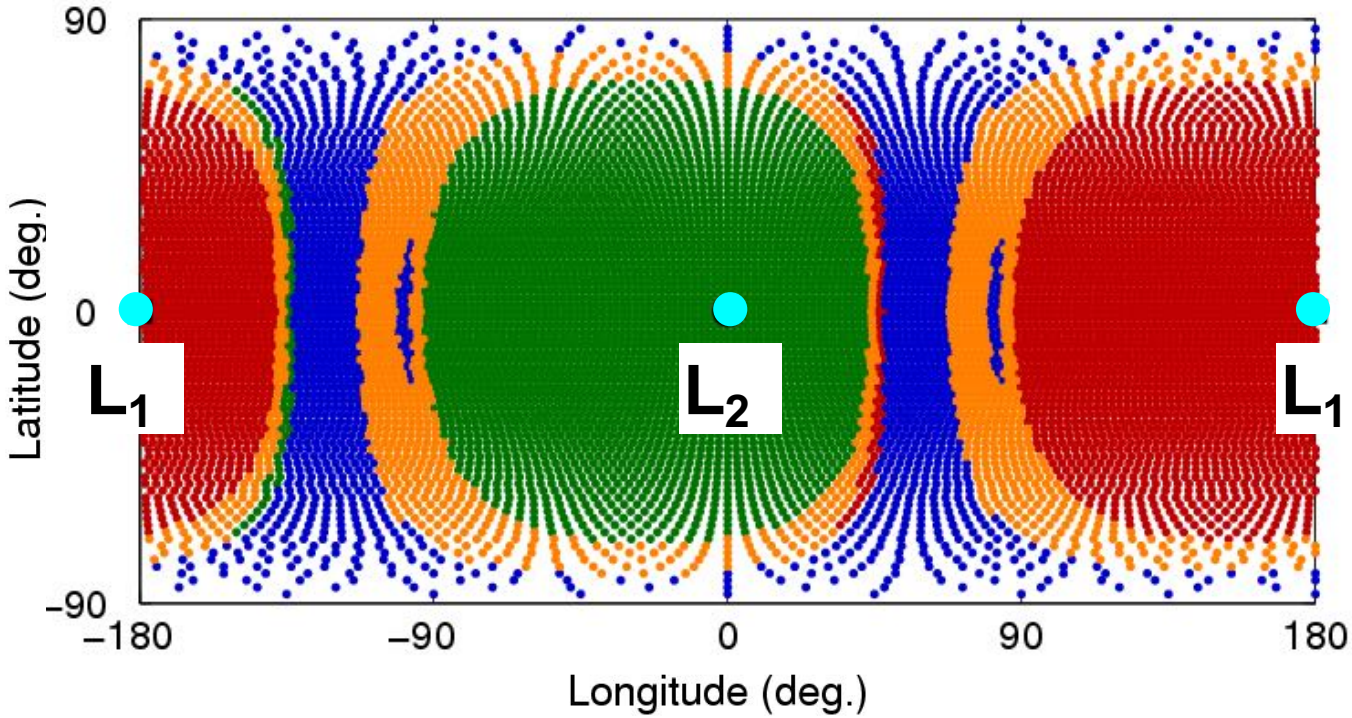
Exterior Region

Interior Region

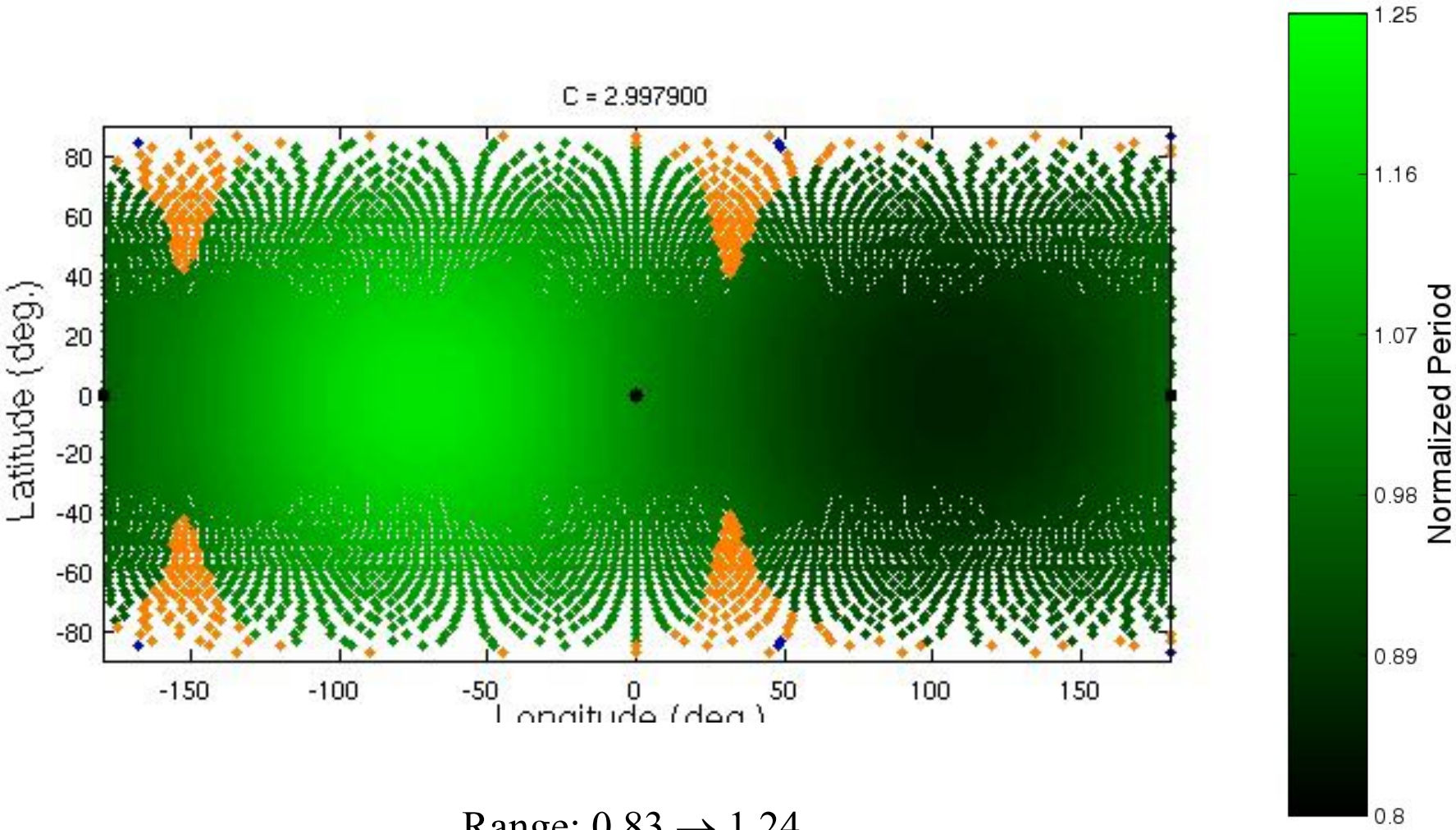
Europa Ballistic

Near Europa



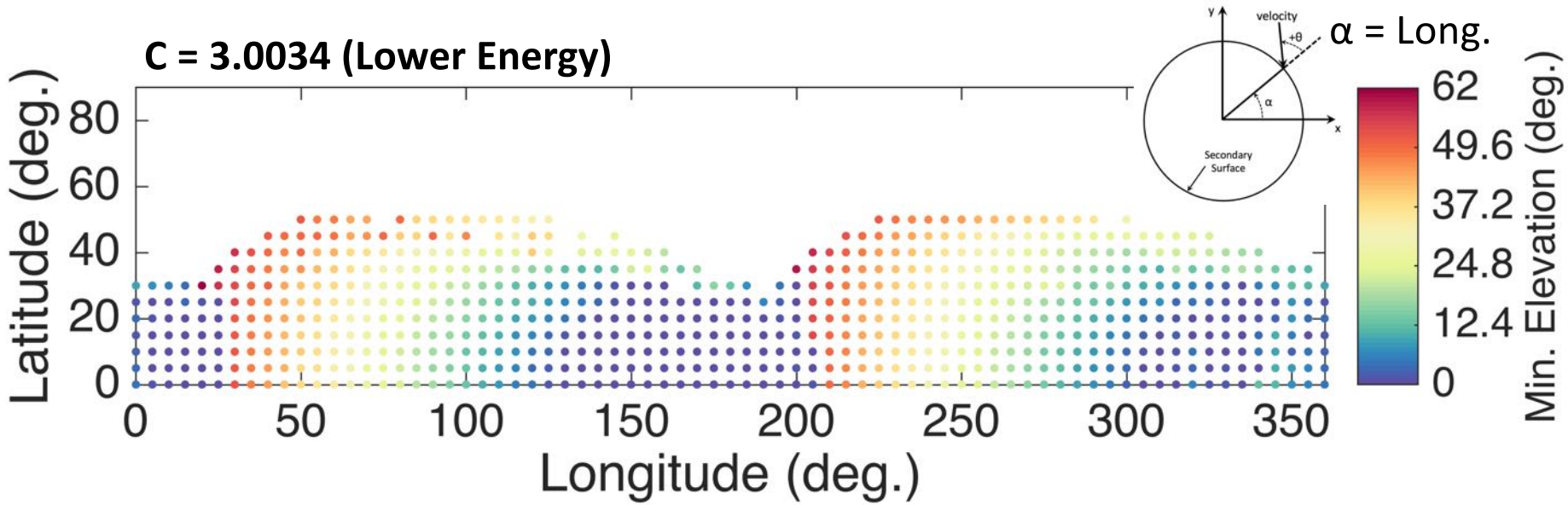


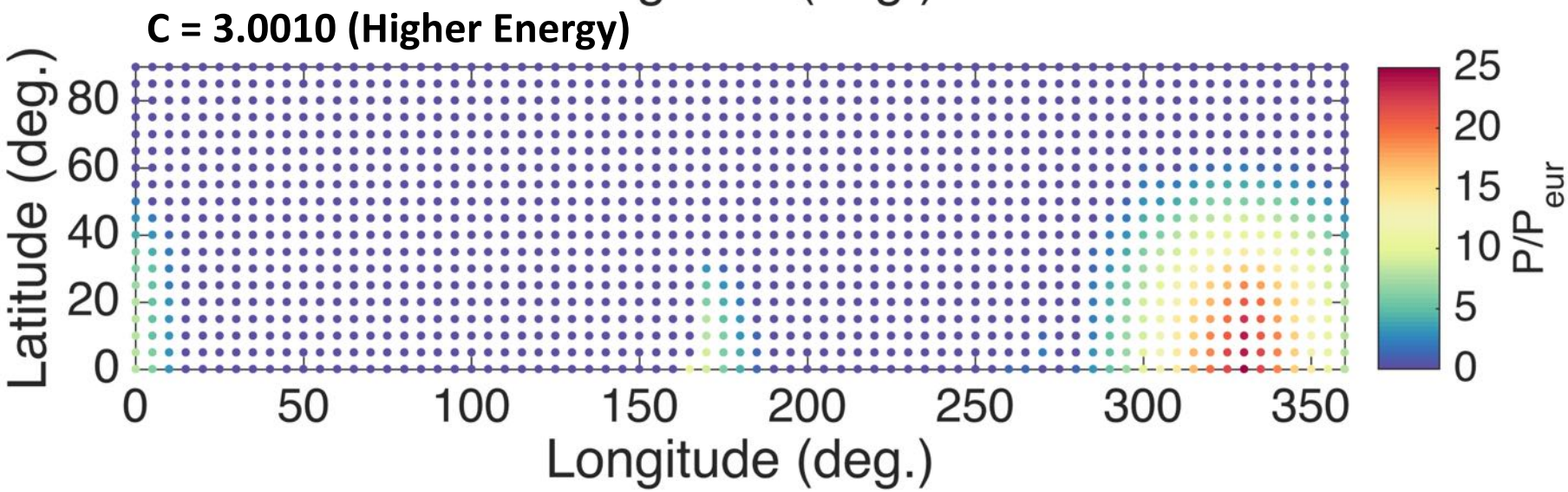
Resonance (Period) Variations



Range: 0.83 → 1.24

Landing Site Options: Min Elevation

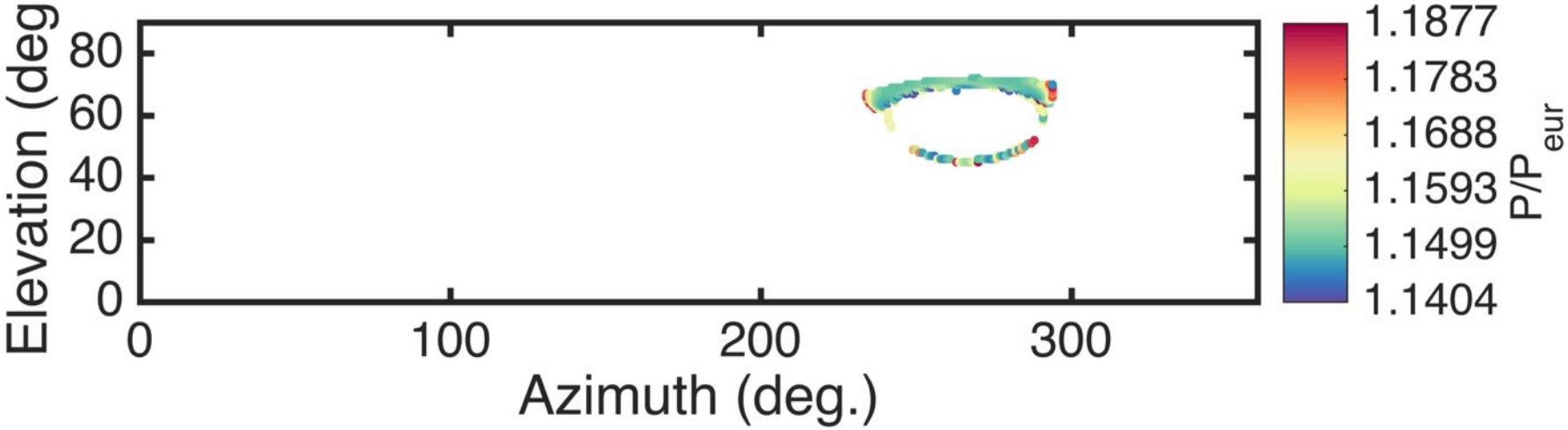




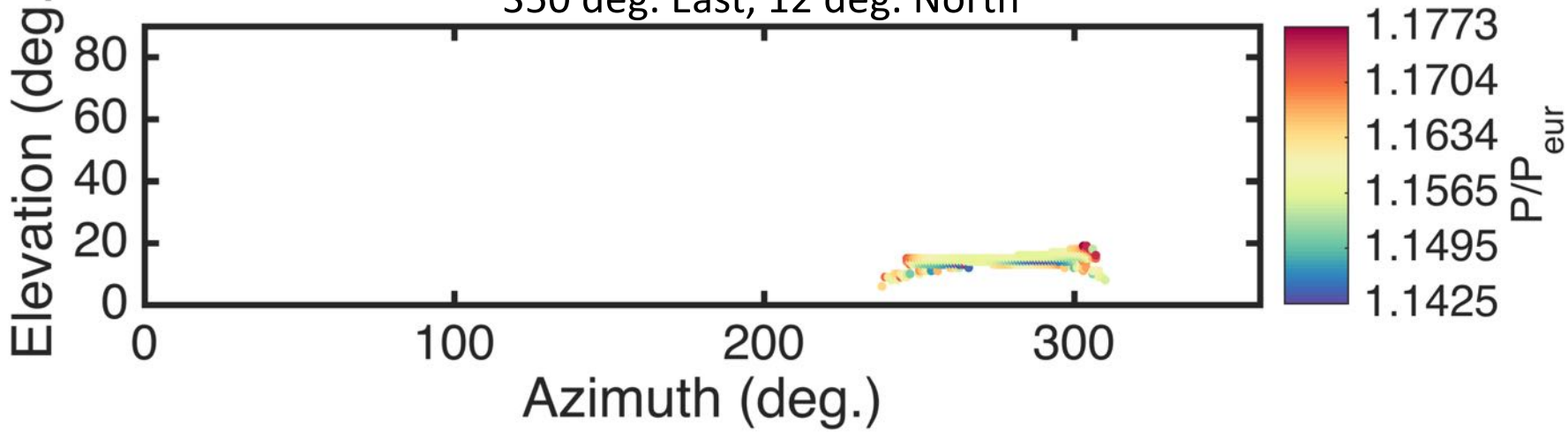
Pre-Decisional Information — For Planning and Discussion Purposes Only

Landing Site Options: Min Elevation

37 deg. East, 6 deg. North



350 deg. East, 12 deg. North



Pre-Decisional Information — For Planning and Discussion Purposes Only

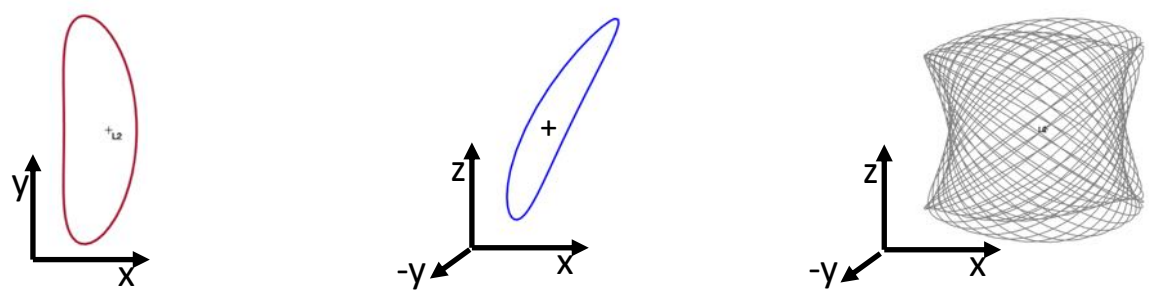
Approach Using Lissajous Orbits

[Hernandez, Restrepo & Anderson]

- Mission constraints: lighting conditions at the time of landing, staging locations to decouple the approach, global surface coverage,…
- Strategy: Divide the trajectory design after Jupiter insertion into three separate steps
  1. the moon tour
  2. **a low-energy capture in the vicinity of Europa and a phasing stage**
  3. the landing

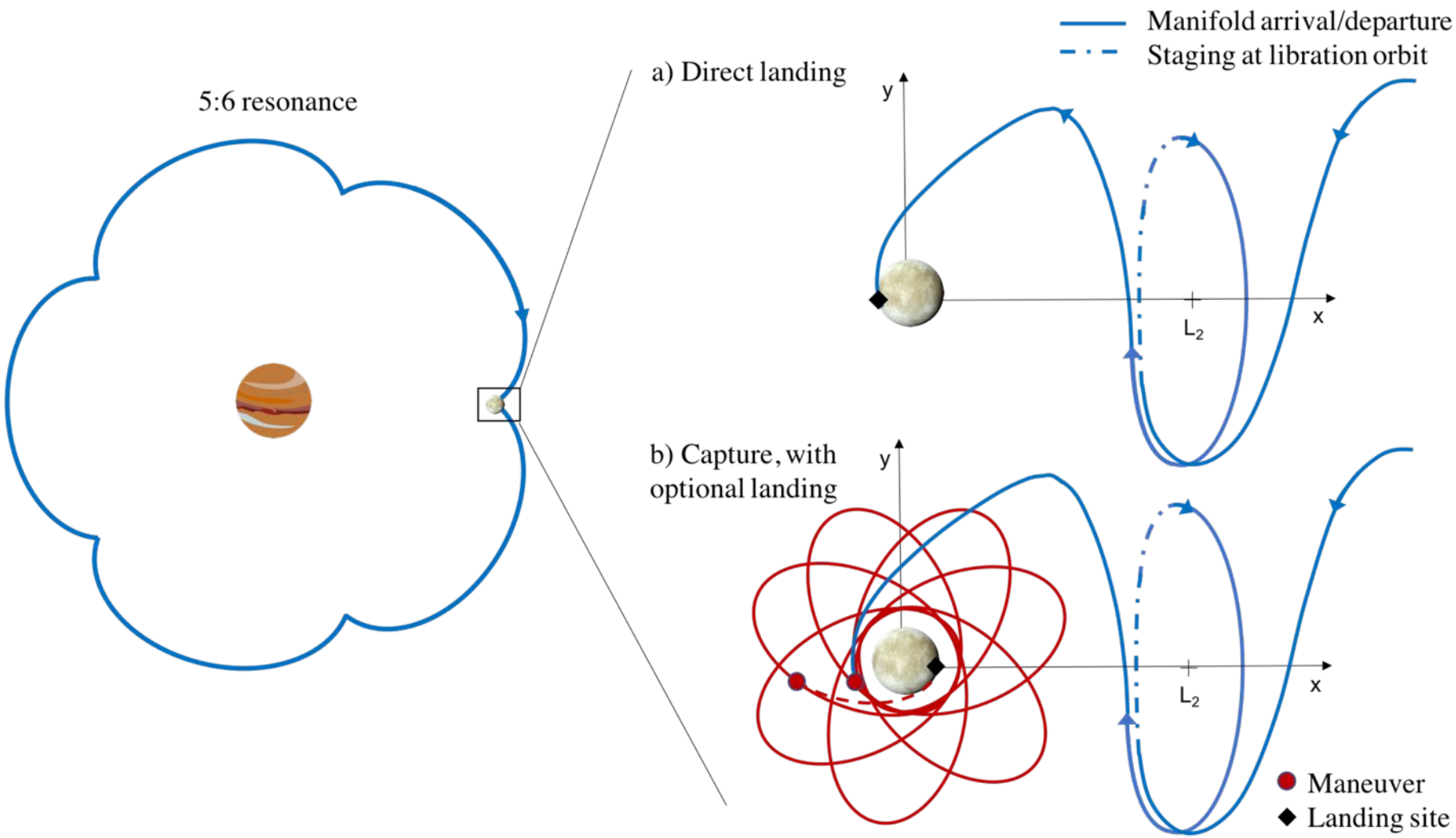
- Systematic approach to solve 2): stable and unstable manifolds of libration point orbits are computed to connect the libration staging orbit with:
  - **low-energy resonant capture** (propagated backward in time)
  - landing/stable capture (propagated forward in time)

- Libration point orbits:
  1. Lyapunov
  2. Halos
  3. **Lissajous**



Determine which resonances and range of energies freely connect with libration point orbits by propagating their invariant manifolds backward in time.

Approach Using Lissajous Orbits

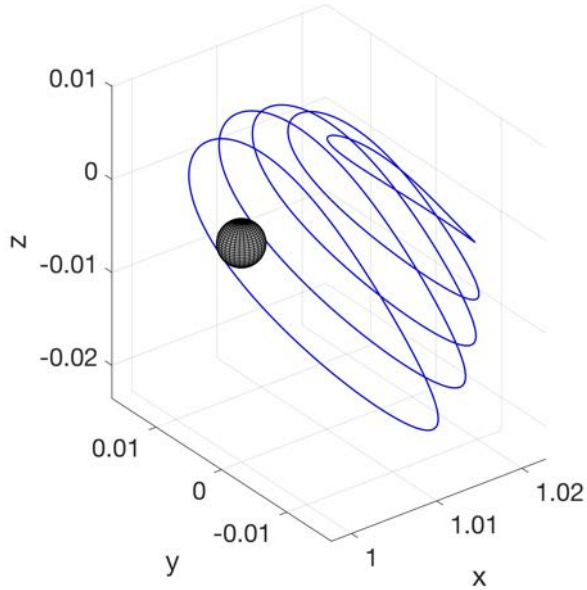


[Hernandez, Restrepo & Anderson]

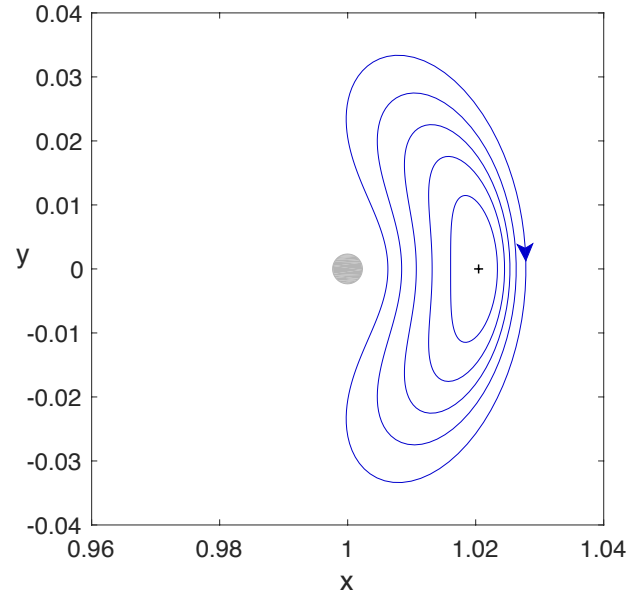
Reachable Resonances from Lyapunov and Halo Orbits

- Lyapunov and halo orbits are computed
- Range of Jacobi constants from 3.00318 (low energy) to 3.001 (high energy)

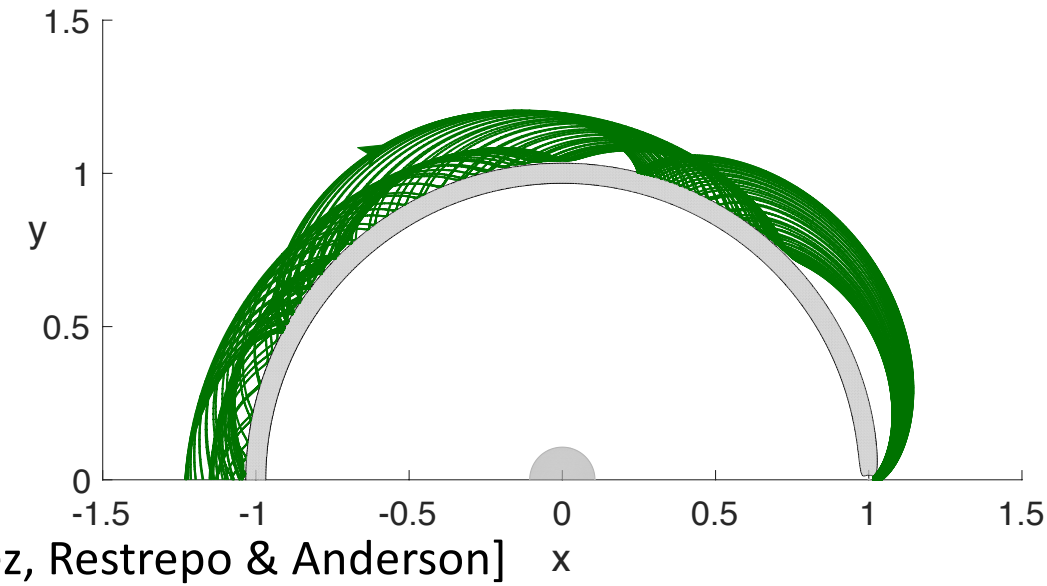
Halos



Lyapunov



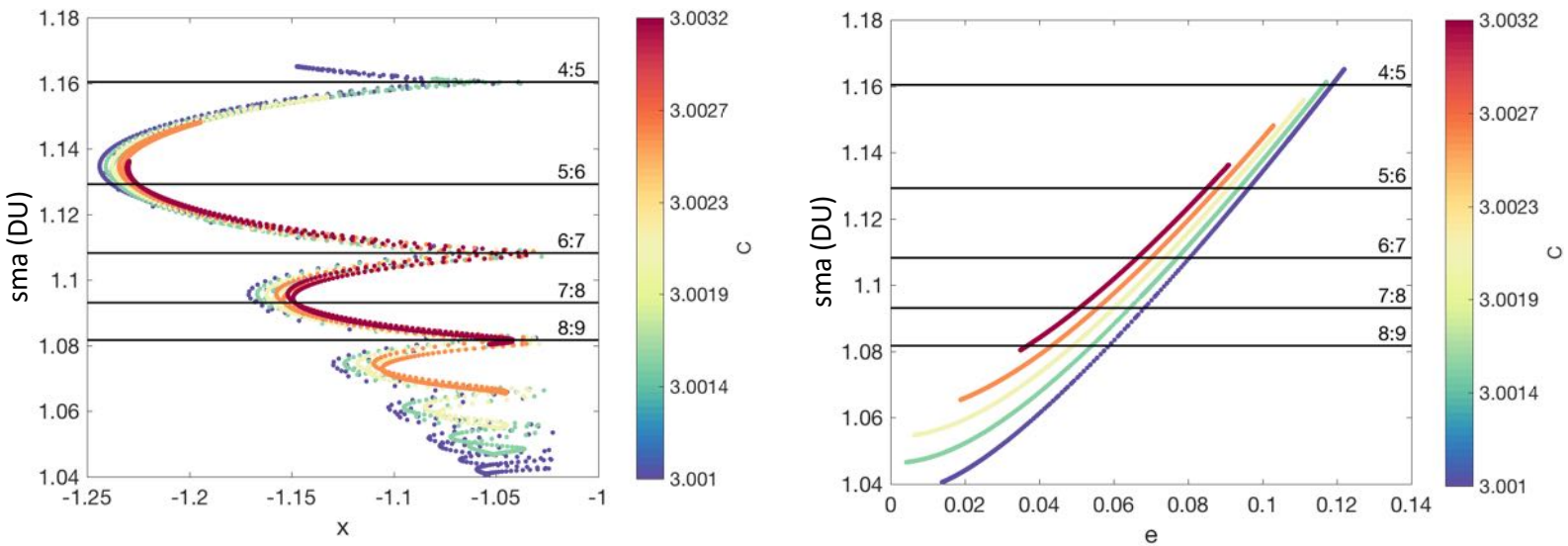
- Stable manifolds propagated backward in time.
- Connect with the last resonance of the moon tour.
- Manifold is propagated backwards in time until it crosses the negative x-axis, which is used as a Poincare section.



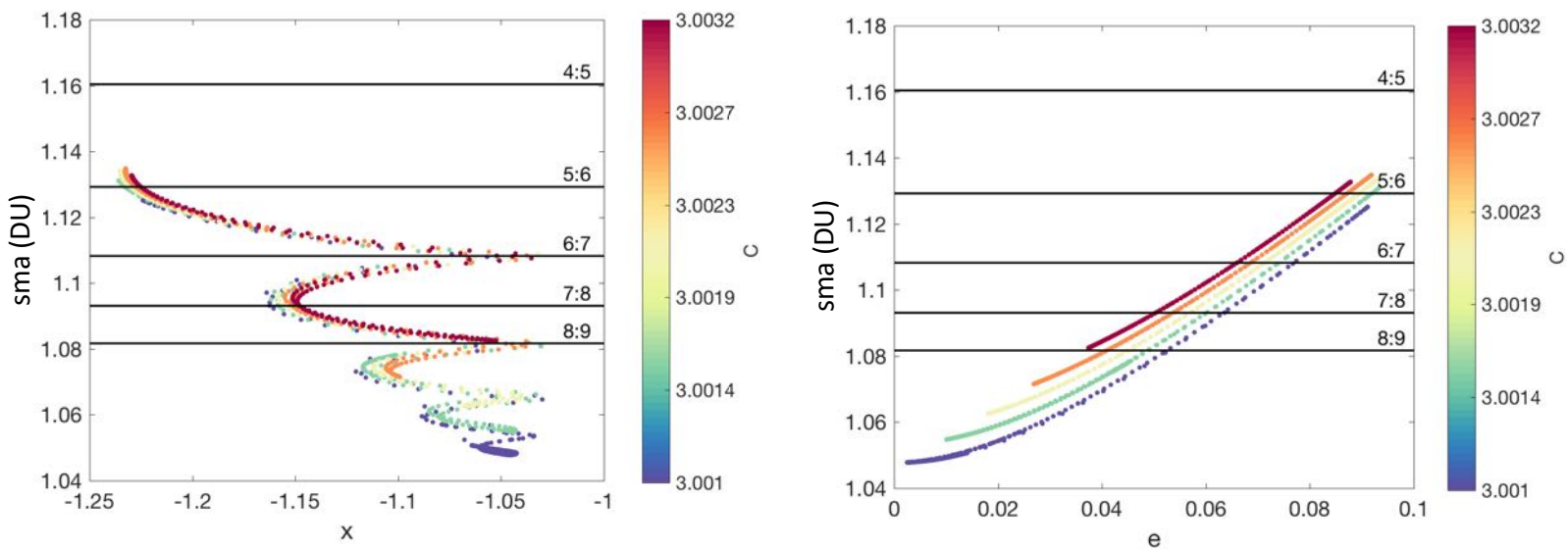
[Hernandez, Restrepo & Anderson]

Reachable Resonances from Lyapunov and Halo Orbits

Lyapunov



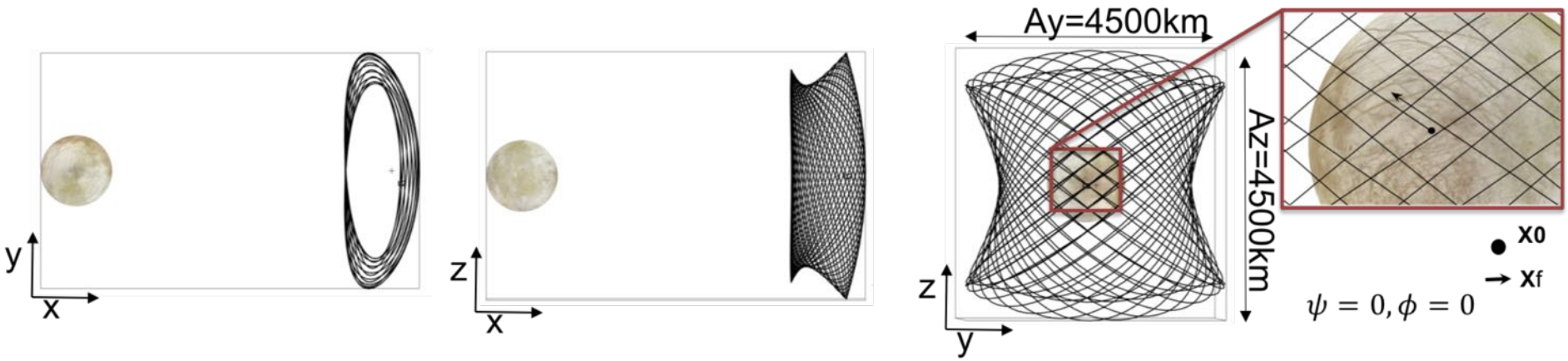
Halo



[Hernandez, Restrepo & Anderson]

Generating a Database of Lissajous Orbits

- Lissajous orbits are quasi-periodic structures that live in a 2-d torus
  - Symmetric wrt x-y and x-z plane
  - Characterized by Ay and Az amplitude, initial in-plane and out-of-plane angles
  - Non-periodicity is seen in y-z plane, where the in-plane phase completes 360 but not exactly.

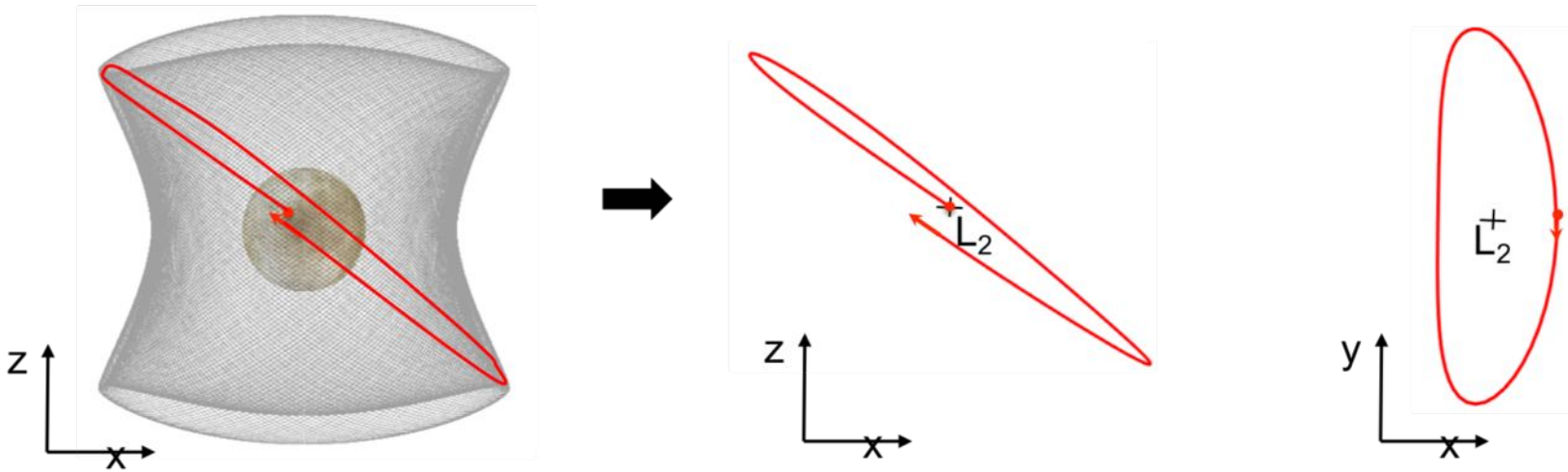


- Computing manifolds of torus can be complicated and computationally expensive
- To simplify, individual revs of Lissajous are considered and approximate invariant manifolds are computed.
- Database is generated via multi-shooting technique

[Hernandez, Restrepo & Anderson]

Generating a Database of Lissajous Orbits

- Lissajous torus approximated by generating individual Lissajous revs all around its surface.
- The initial conditions of the Lissajous rev start at the x-y plane ($\psi = 0$) with $\phi = 0$, and it is propagated until it completes a full out-of-plane cycle, returning to the x-y plane.
- Individual revs are generated with a small in-plane phase difference ($\Delta\phi$) in their initial conditions.

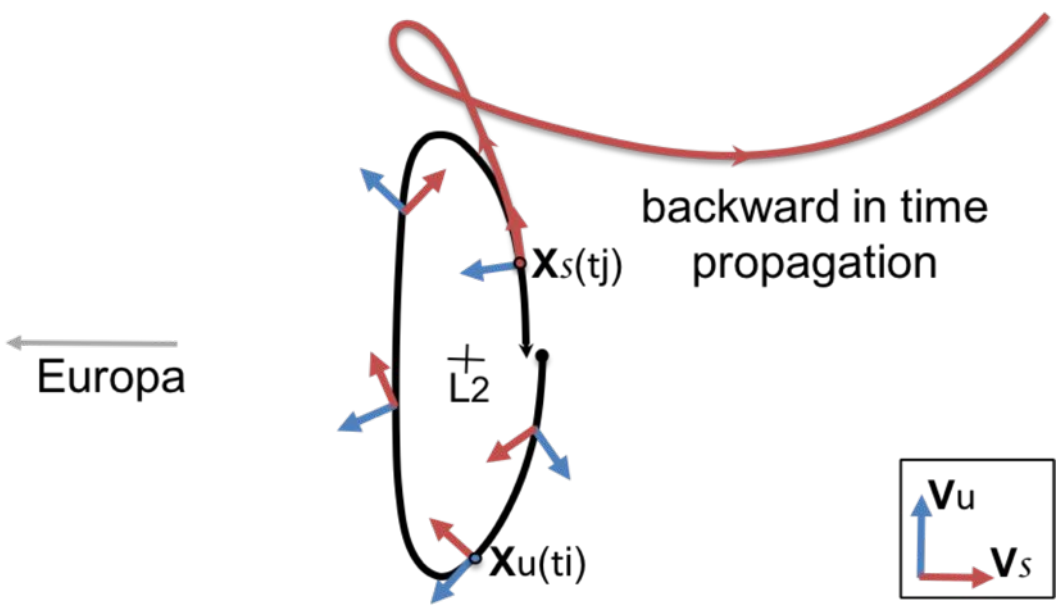


- The database:
  - A_y from 1000 km ≤ A_y ≤ 12000 km in 500 km intervals
  - A_z from 2000 km ≤ A_z ≤ 12000 km by 100 km intervals
  - Total of of 1100 Lissajous, 200 revs/Lissajous, total of 220,000 Lissajous revs

[Hernandez, Restrepo & Anderson]

Approximate Invariant Manifolds

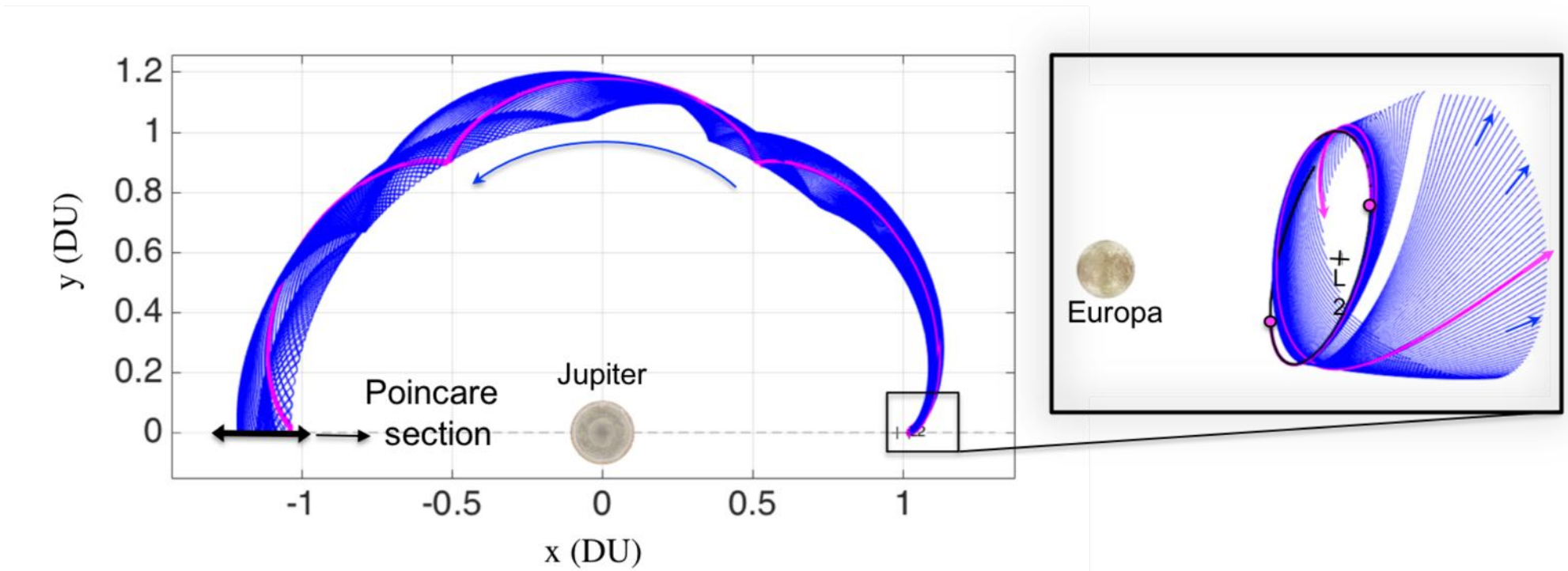
- Each Lissajous rev acts as a good approximation of a periodic orbit.
- The invariant manifold of the Lissajous torus can be approximated by combining the approximate invariant manifolds of each of the individual revs.
- The STM is propagated for each rev from t_0 to T_{rev} to obtain an *approximate* monodromy matrix $\Phi(T_{rev},t_0)$.
- Invariant manifolds are computed with same procedure as for periodic orbits.
- Stable manifold trajectory propagated backwards in time at τ_j for one Lissajous rev. Each Lissajous rev is discretized in 100 points from t_0 to T_{rev}.



[Hernandez, Restrepo & Anderson]

Computing Resonance Value

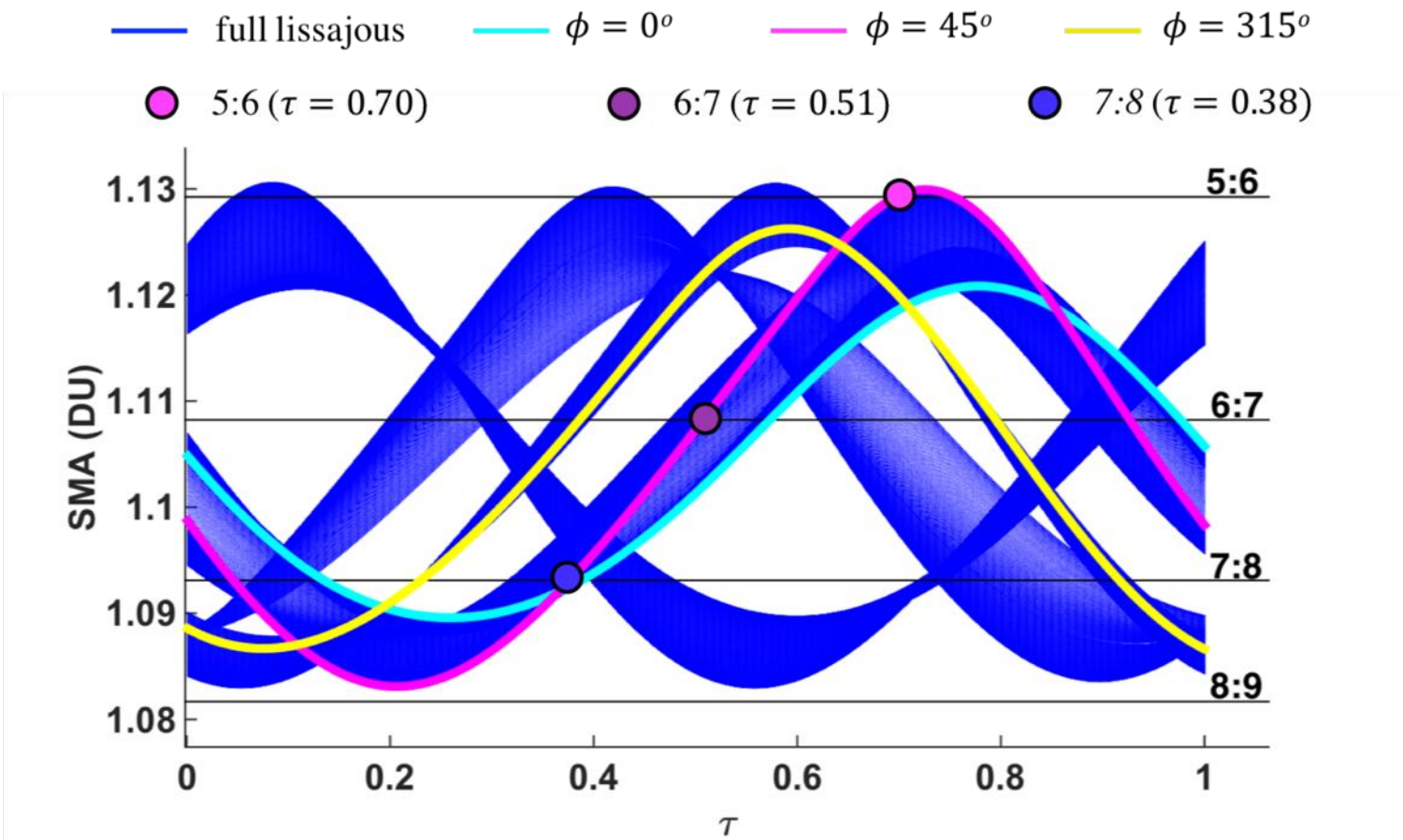
- Stable manifold of one Lissajous rev propagated backward in time.
- These trajectories are the ones that connect with the last resonance of the moon tour.
- In order to determine the value of the resonance associated to each trajectory, the manifold is propagated backwards in time until it crosses the negative x-axis, which is used as a Poincare section.
- Using the state at this intersection, the osculating semi-major axis with respect to Jupiter is used to determine the resonance at which each trajectory arrives.



[Hernandez, Restrepo & Anderson]

Reachable Resonances from Lissajous Orbits

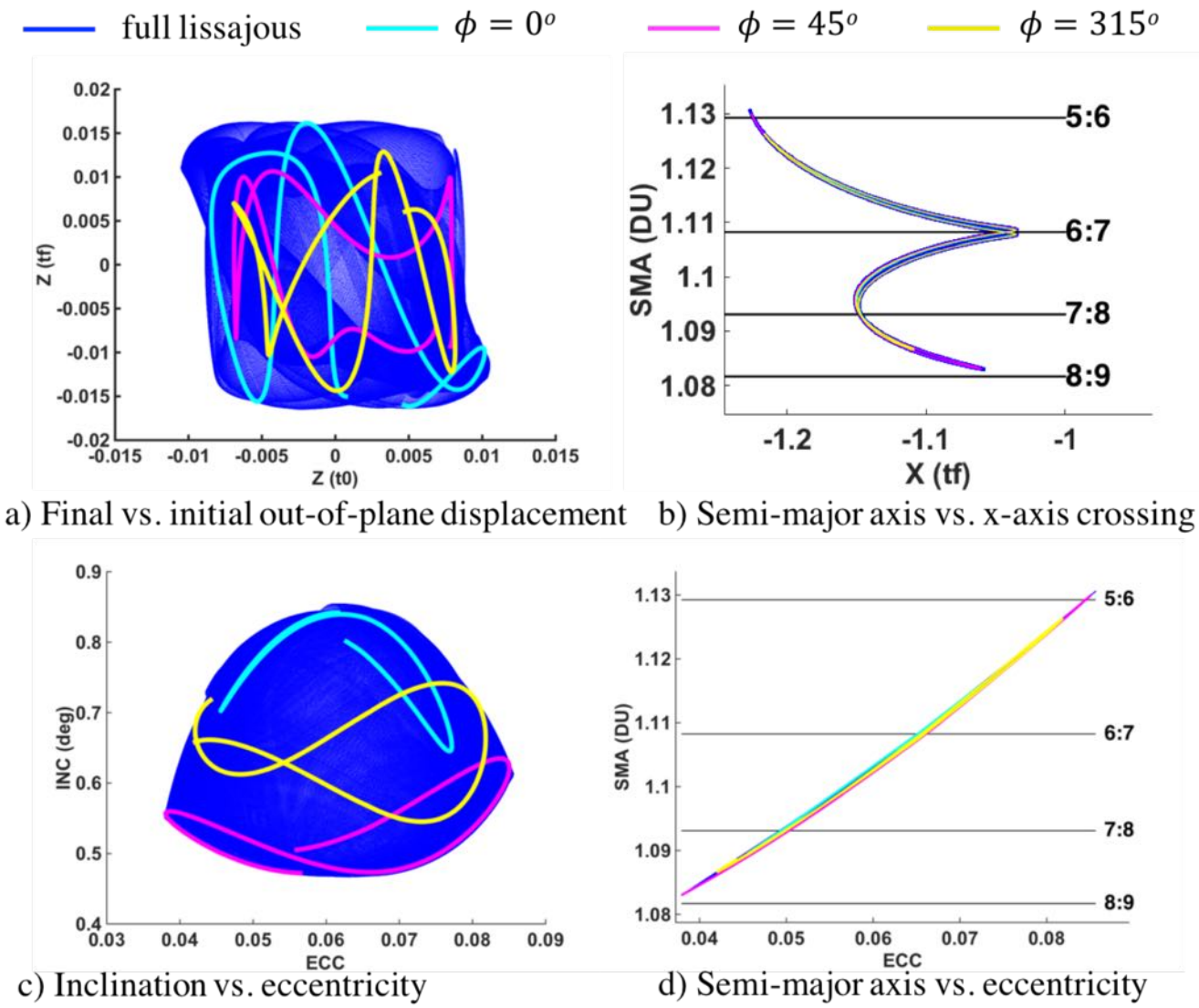
- **Example:** Lissajous Ay = 5500 km and Az = 5500 km, JC = 3.0031, ε = 10−6.
- The departure location from the Lissajous rev, represented as 0 ≤ τ ≤ 1, determines the resonance value reached by the manifold trajectory.
- Four families emerge for the entire Lissajous orbit, each family corresponding to a quarter revolution of Lissajous revs.



[Hernandez, Restrepo & Anderson]

Reachable Resonances from Lissajous Orbits

- **Example:** Lissajous Ay = 5500 km and Az = 5500 km, JC = 3.0031, ε = 10−6.



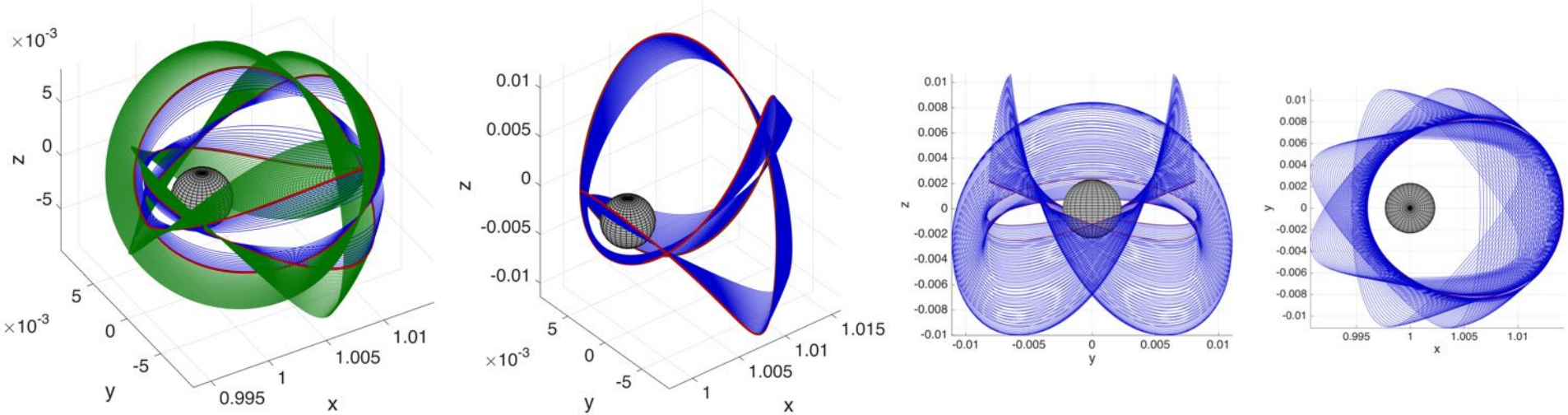
a) Final vs. initial out-of-plane displacement b) Semi-major axis vs. x-axis crossing

c) Inclination vs. eccentricity d) Semi-major axis vs. eccentricity

[Hernandez, Restrepo & Anderson]

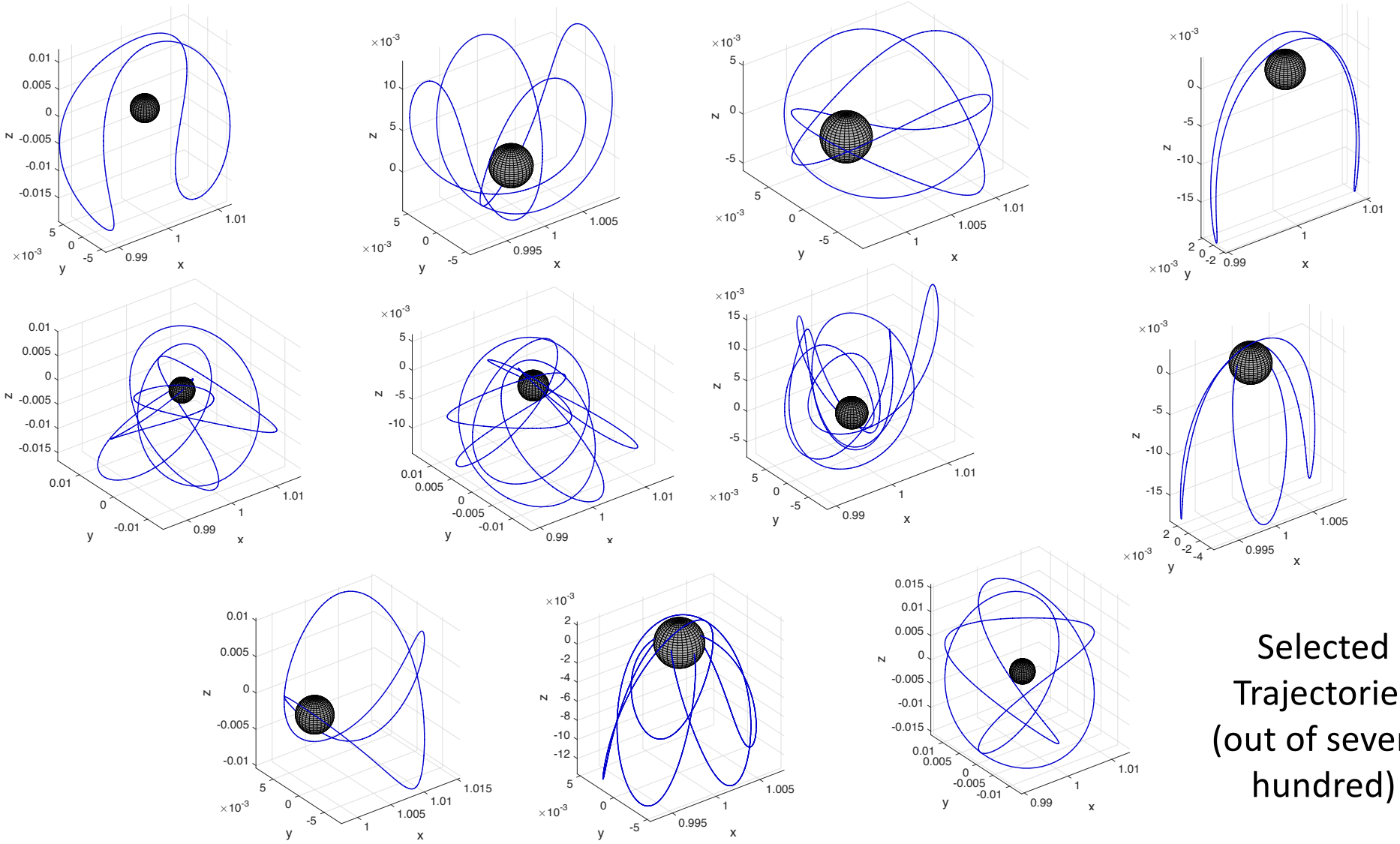
Orbits for Relay Option

- Early concepts include a relay spacecraft
  - Requires good visibility over selected landing site
  - Optimal orbit varies with the landing site
  - High latitudes typically more challenging



Cell-Mapping Europa Orbits

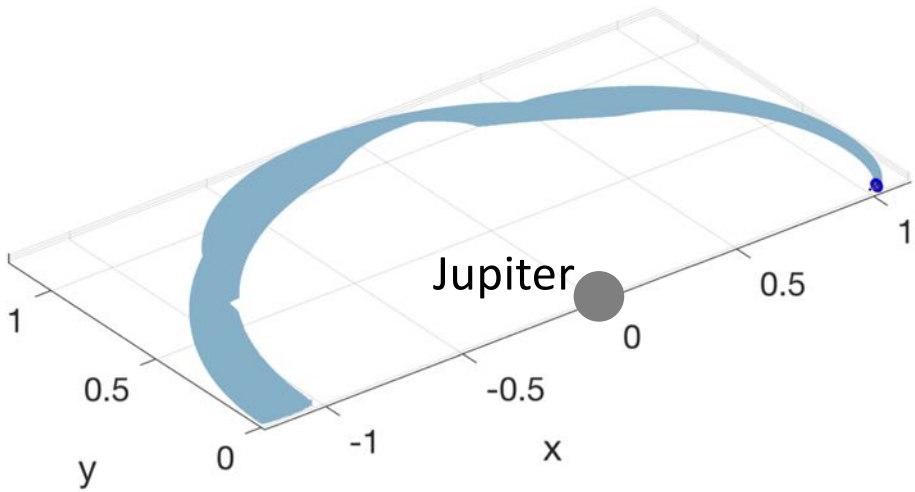
(Period = 1.8 – 5.5 days)

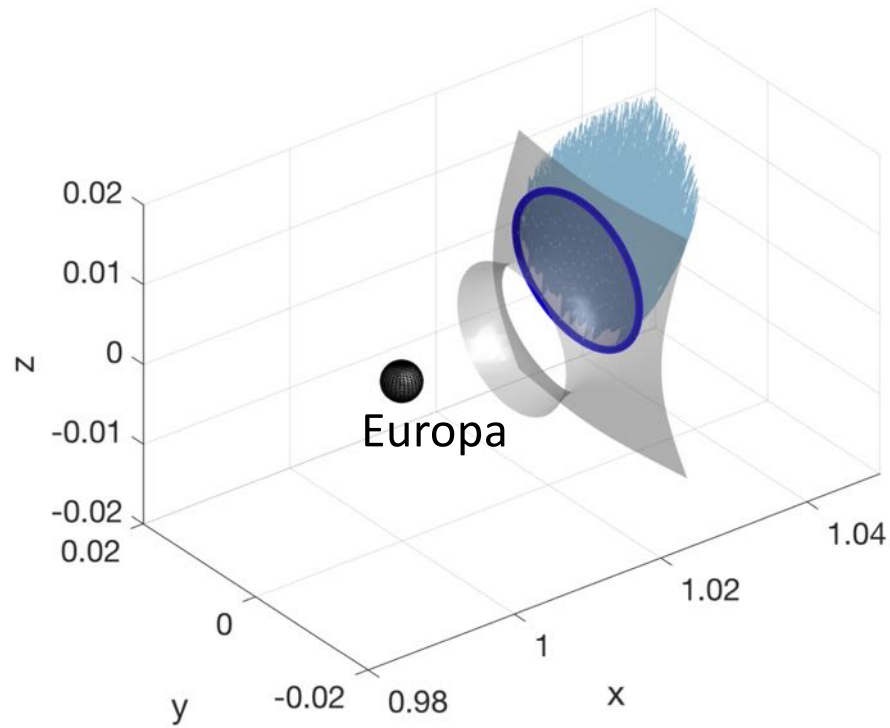


Selected Trajectories (out of several hundred)

Europa Endgame & Approach With Maneuvers

- Set of approach trajectories from last resonance
- Tie into rest of tour with maneuvers and intermediate flybys



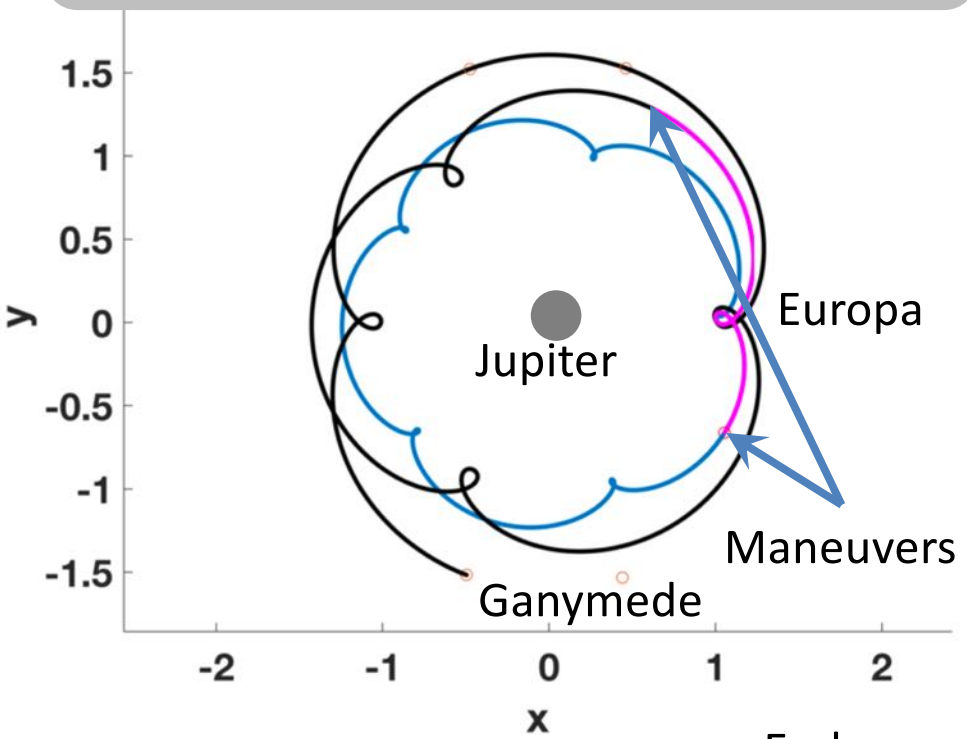


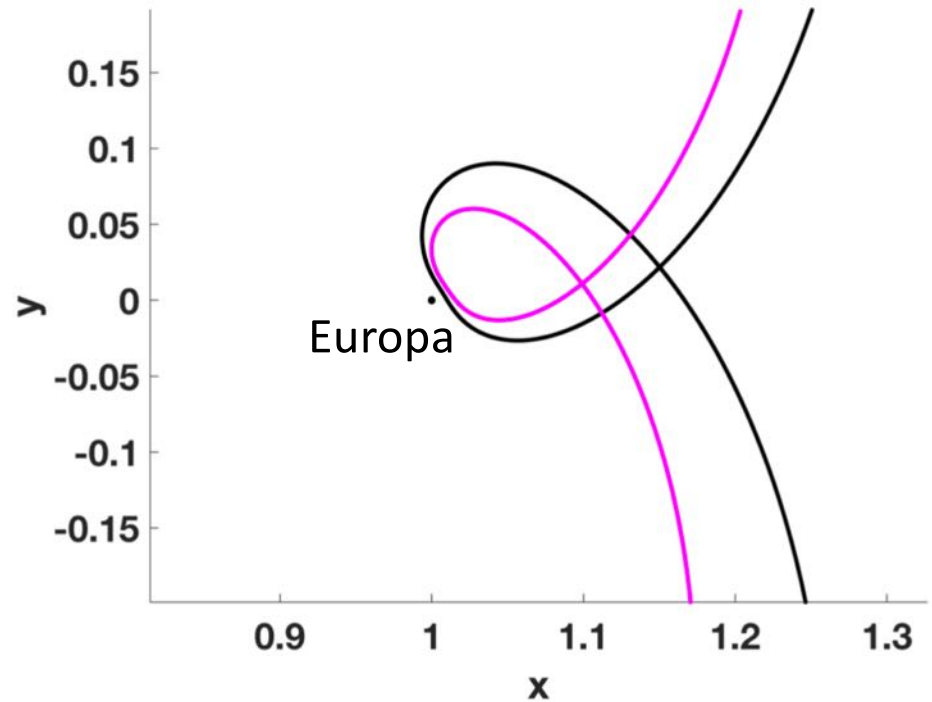
[Anderson, Campagnola, Koh, McElrath, Woollands]

Europa Approach With Maneuvers

- Maneuvers used to modify semimajor axis and energy of S/C for endgame
- Transition through 3:4 and 5:6 resonances

- Ties endgame to last Ganymede flyby
- Ensure proper phasing for our





Endgame total ΔV = 105 m/s

[Anderson, Campagnola, Koh, McElrath, Woollands]

Concluding Remarks

- Resonant orbit W^u & W^s provide
  - Very low ΔV heteroclinic connection in one CRTBP
  - Different connections/trajectory options
- Invariant manifolds bound exterior and interior resonances on final approach
- Feasible approach scenarios for Europa Lander:
  - Lissajous orbit invariant manifolds
  - Resonant orbit invariant manifolds
  - Transit through portals using isolating blocks
- Intermediate ΔVs make transfer from Ganymede for endgame possible

Pre-Decisional Information – For Planning and Discussion Purposes Only.

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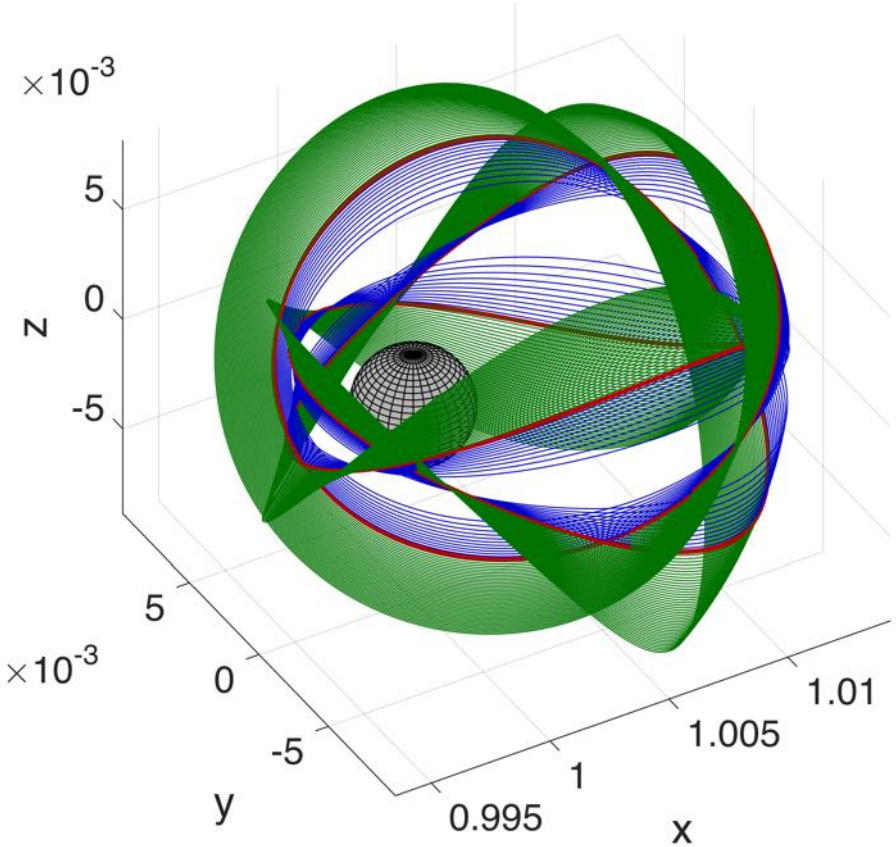
Backup

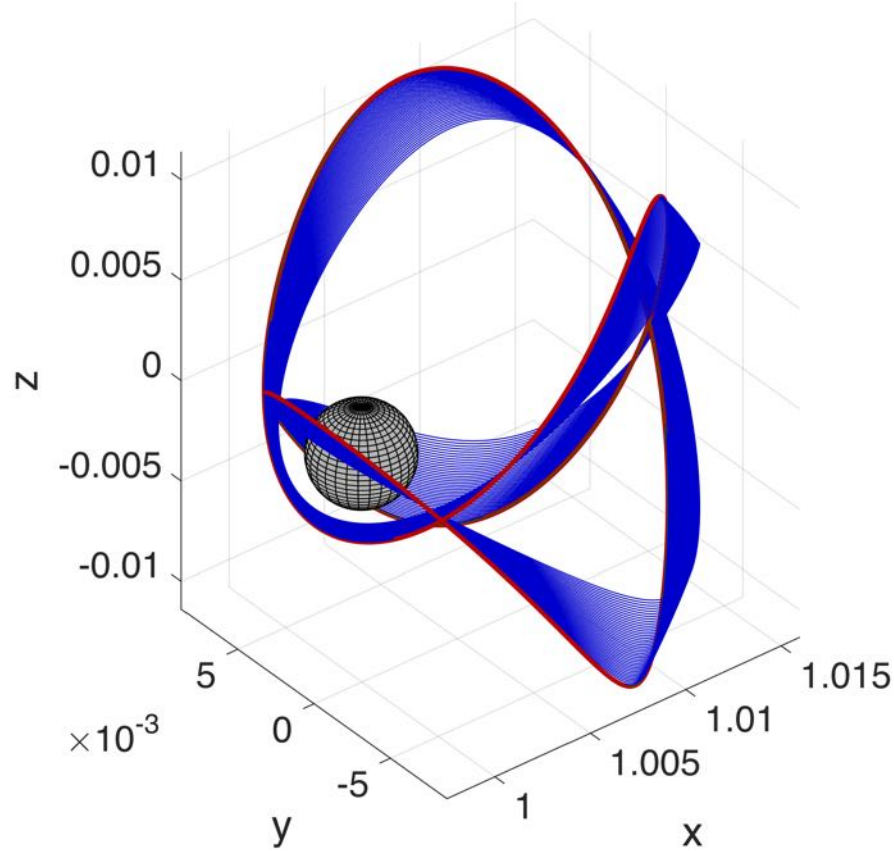
Realistic Constraints for Landing Trajectory

- Sun Elevation Angle
- Local Solar Time
- Periapsis Drop Maneuver Size
- Periapsis Velocity
- Eclipse Time
- Distance to Earth

Periodic Orbit Continuation

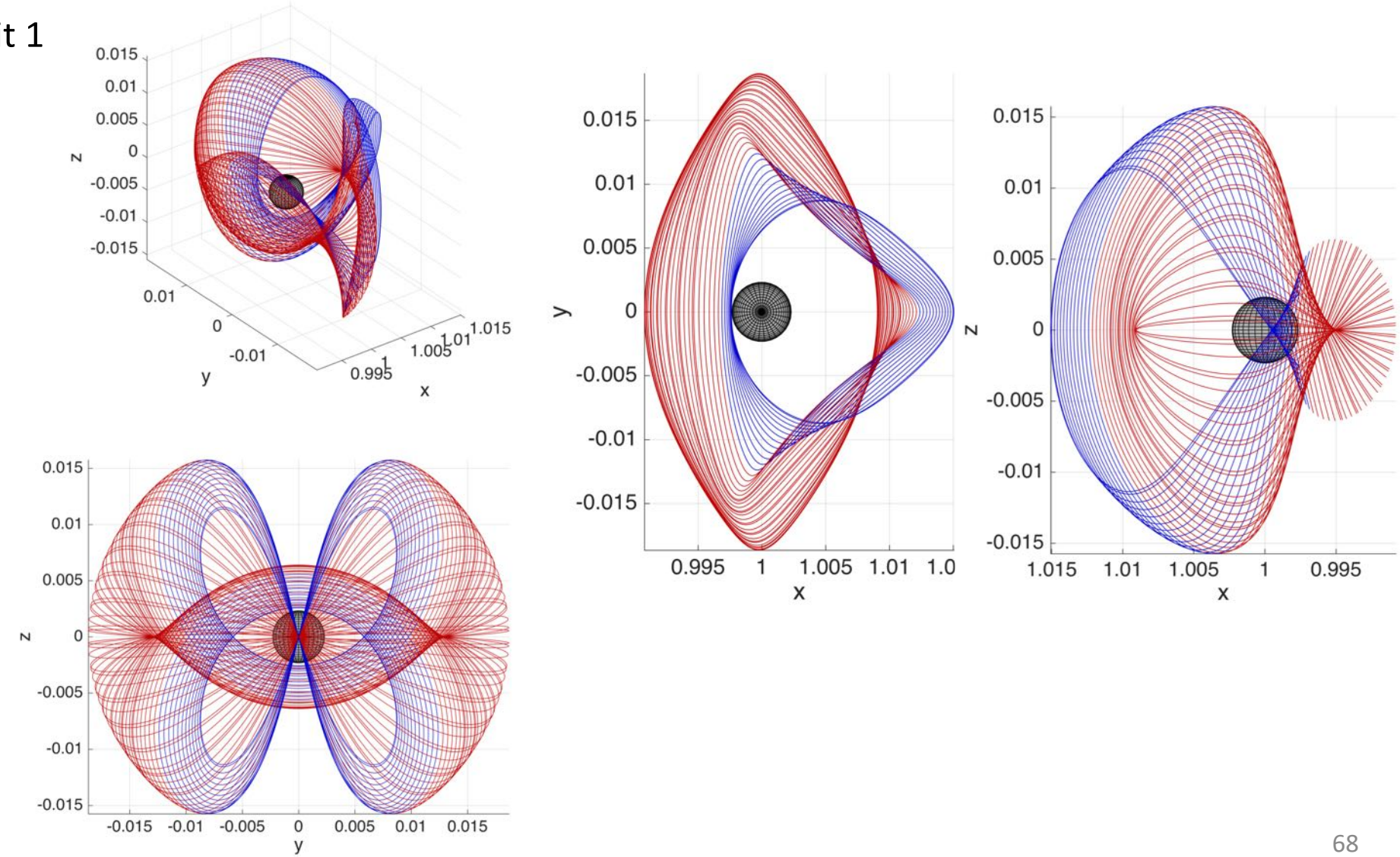
Initial Continuation of Orbits Near the Original Orbit





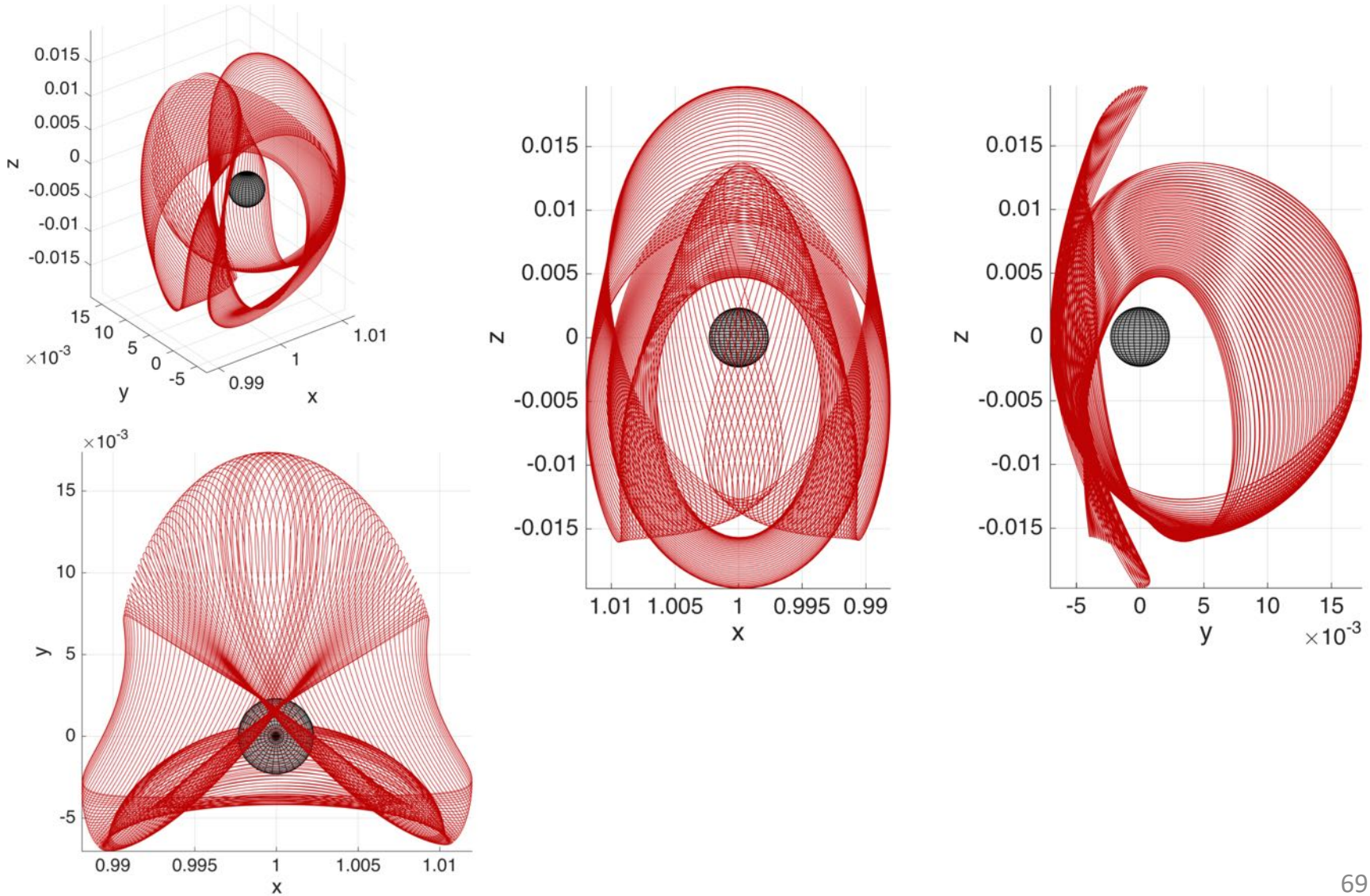
Periodic Orbit Continuation Extended

Orbit 1



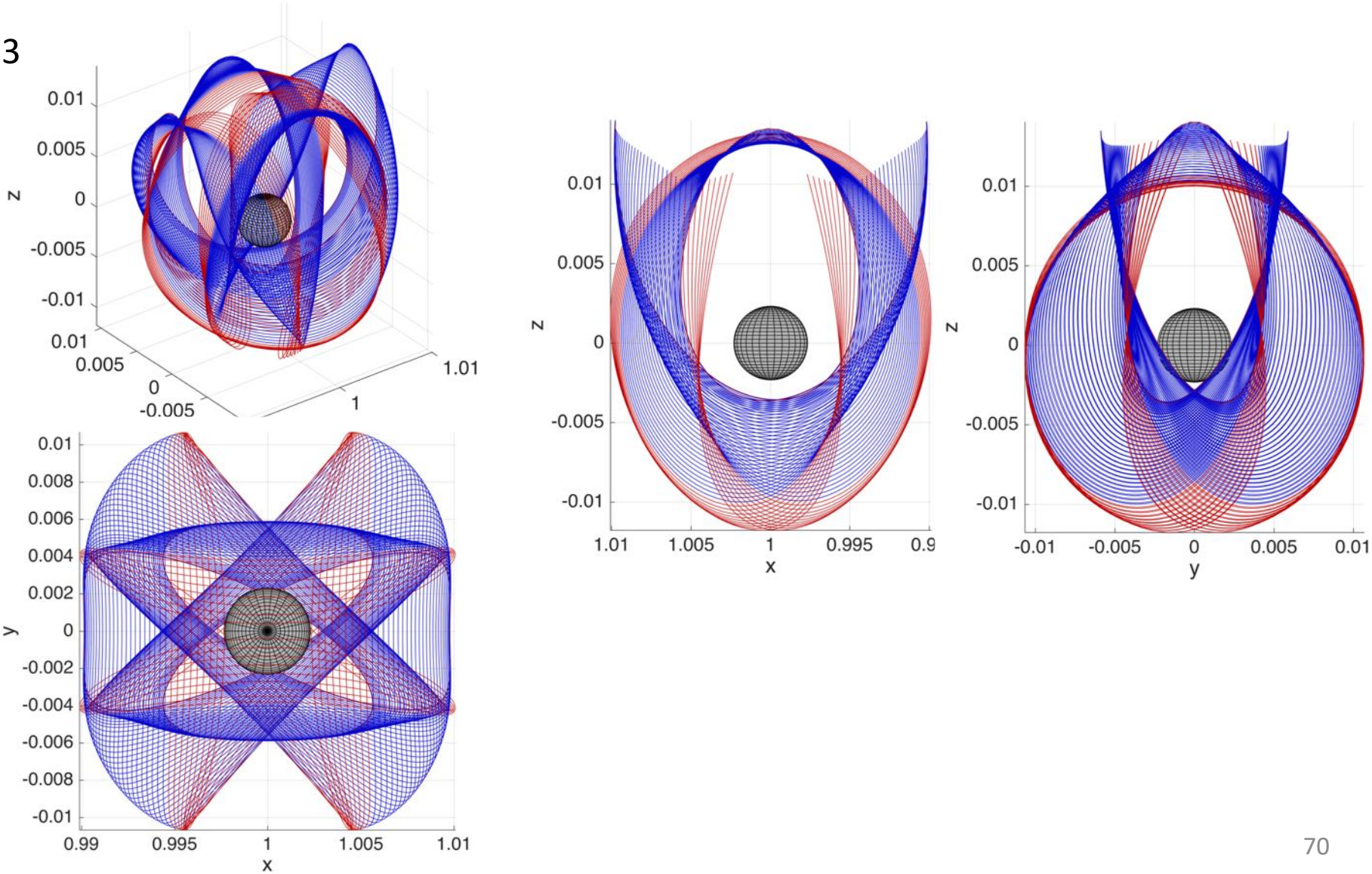
Periodic Orbit Continuation Extended

Orbit 2



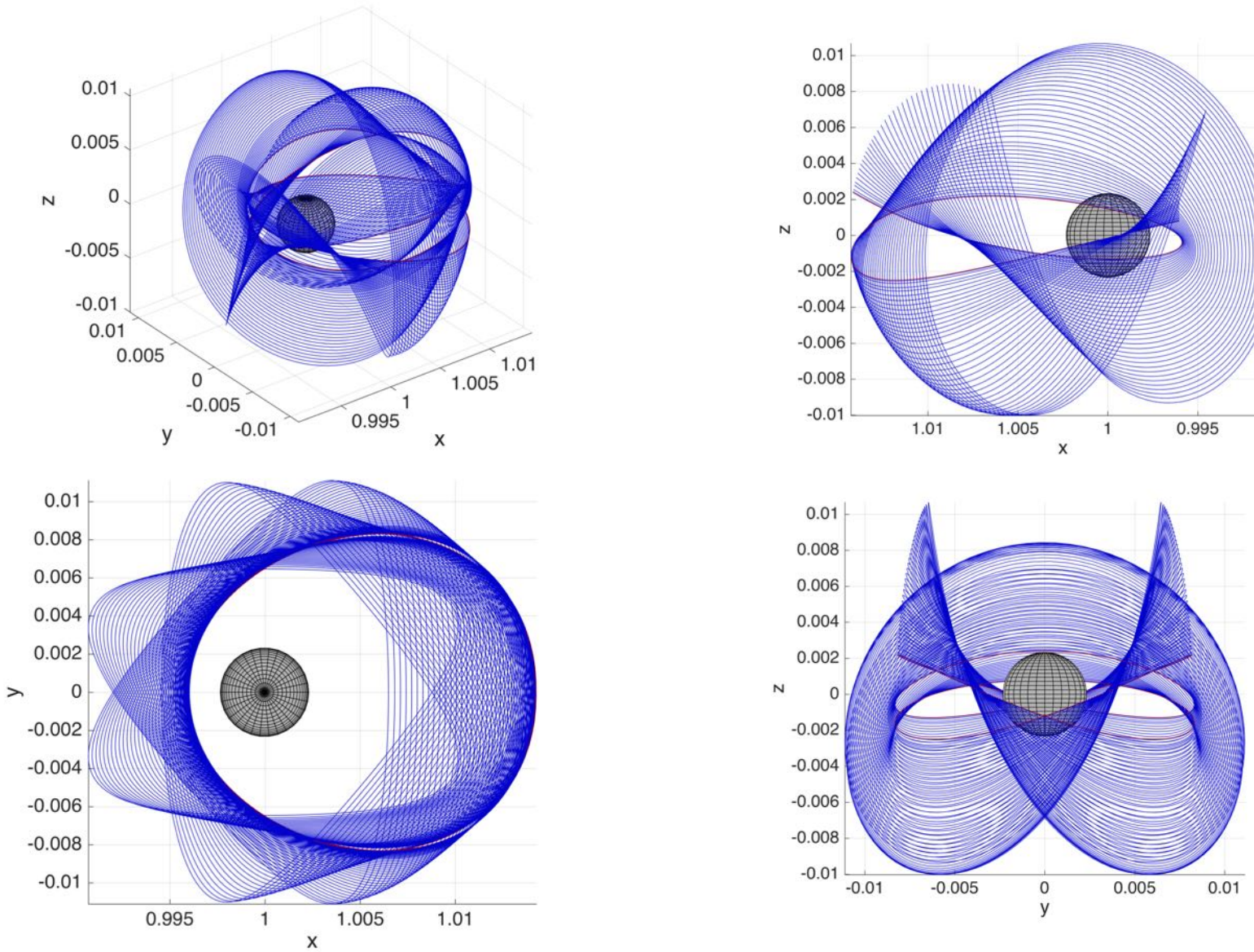
Periodic Orbit Continuation Extended

Orbit 3



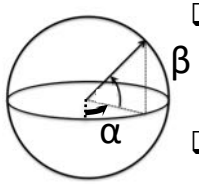
Periodic Orbit Continuation Extended

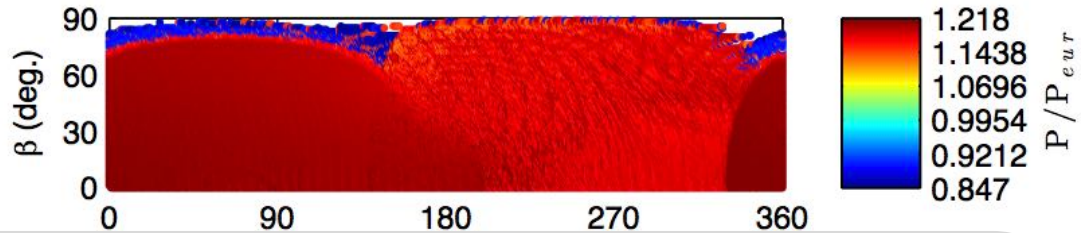
Orbit 4

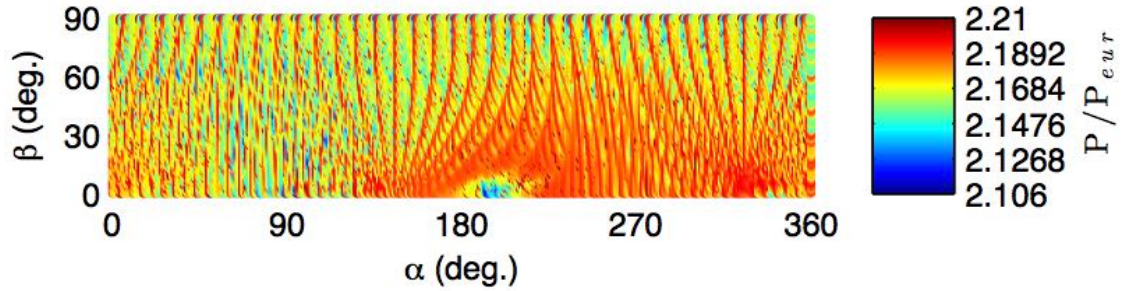


Maximum Resonances for Collision Orbit Approaches to Surface

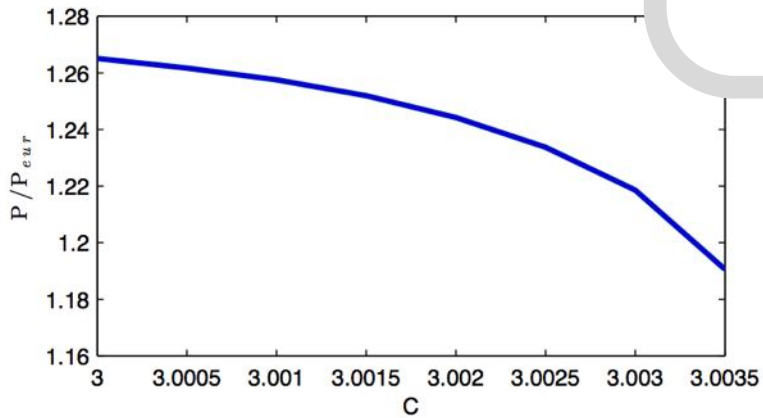
- Backward Integration
  - Cover surface with grid
    - 1° in α (lon.), β (lat.)
  - Collision orbits (normal) &
    varying azimuth, elevat
- Find maximum resonanc
  each grid point as f(C)
- Lyapunov orbits' W^{s}
  resonances bound max.

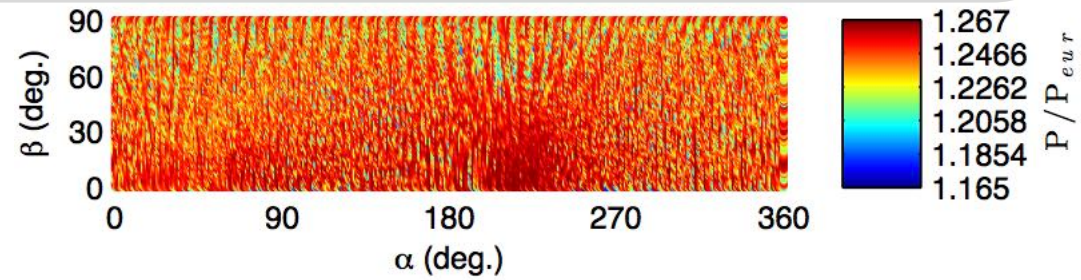






Sun-Jupiter, C = 3.03



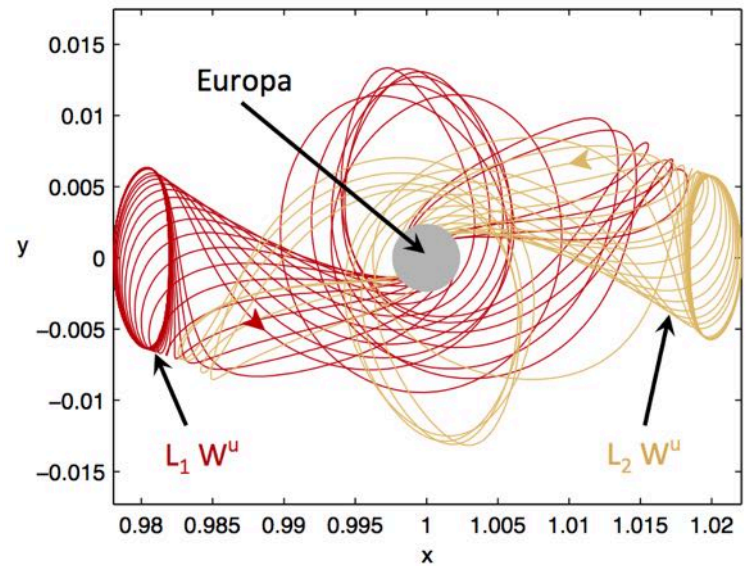


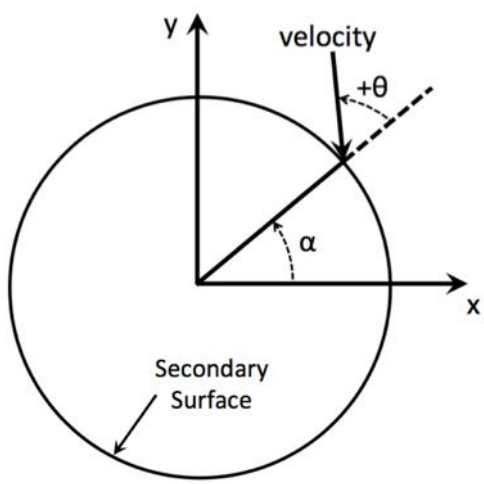
C = 2.9997485, Max. $P/P_{eur} \approx 1.267$

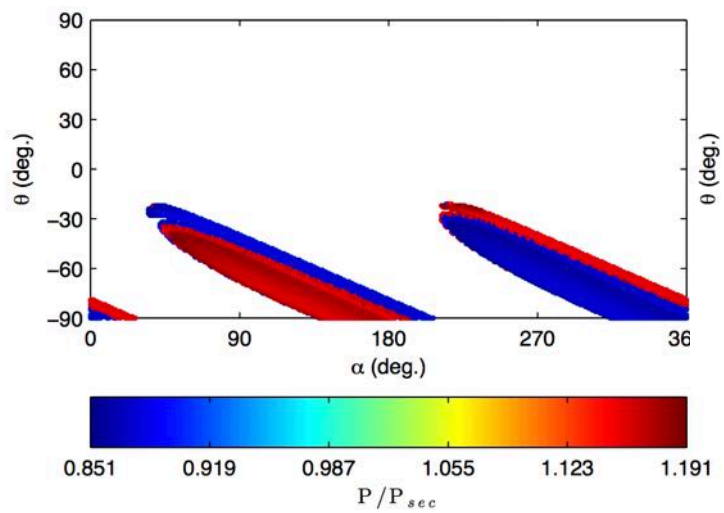
Manifolds Relative to Approach Orbits: Planar Case

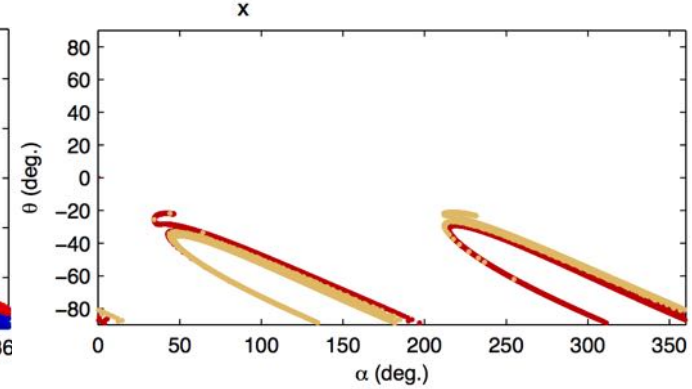
- Compute W^u intersections with secondary
- Compare to approach (collision) trajectories
- Anderson & Lo (2005), Kirchbach et al. (2005), Anderson & Parker (2011)

$C = 3.0035 < C_{L2}$

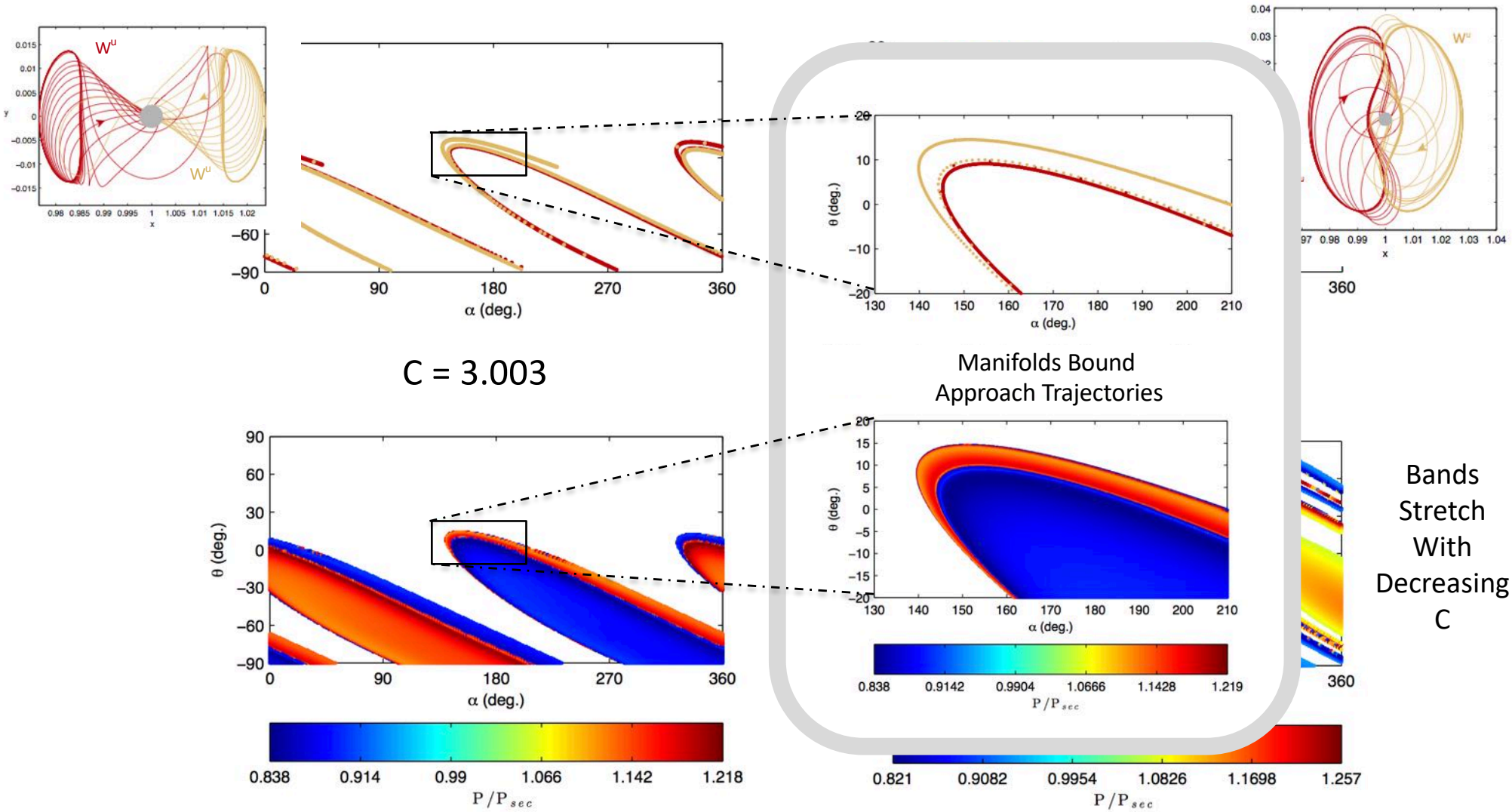








Manifolds Relative to Approach Orbits: Variation with C



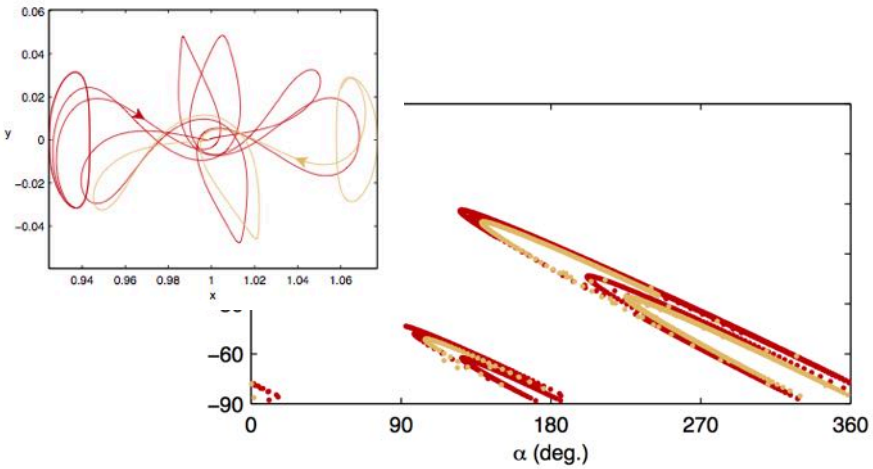
C = 3.003

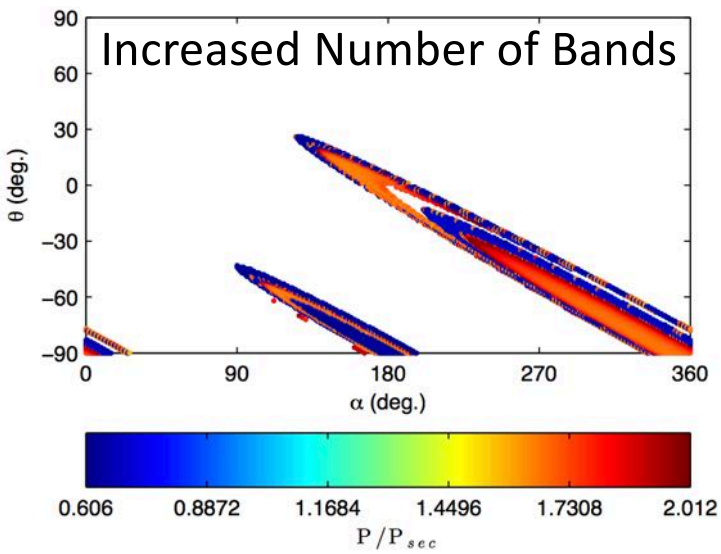
Manifolds Bound Approach Trajectories

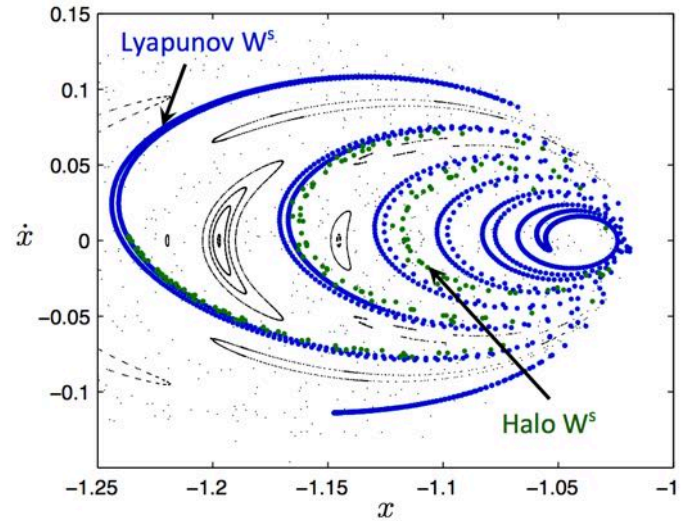
Bands Stretch With Decreasing C

Effects of Changing System & Ephemeris

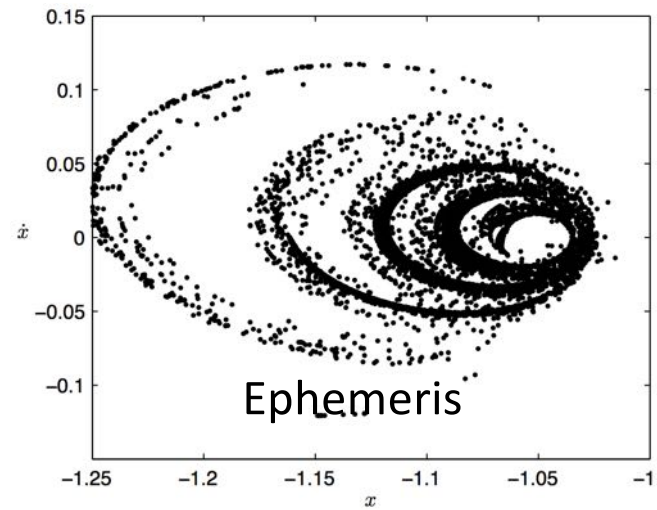
Sun-Jupiter, C = 3.035







Libration Orbit Invariant Manifold Intersections

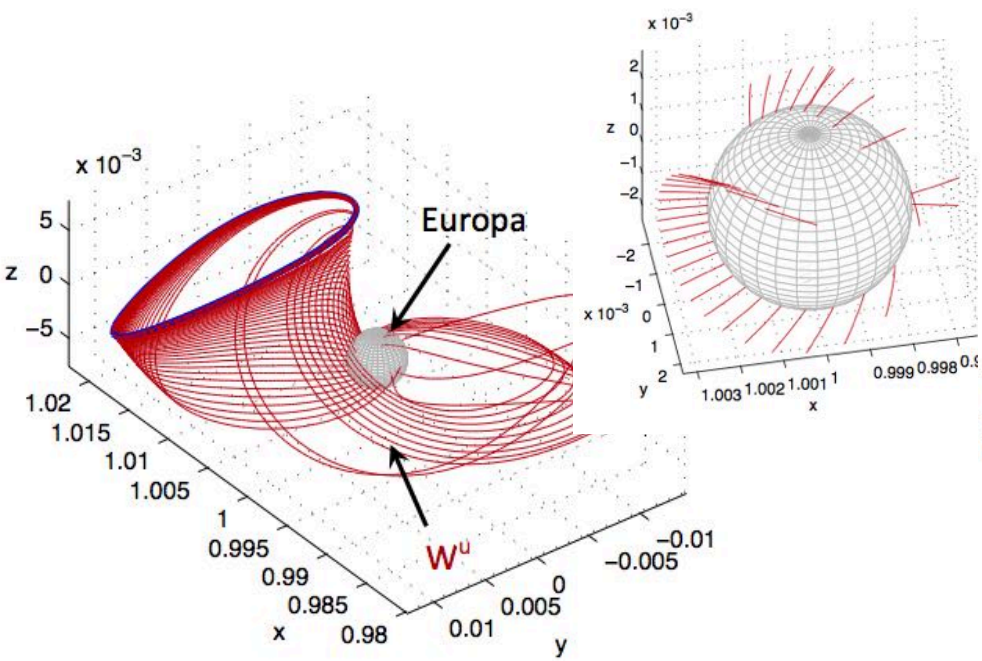
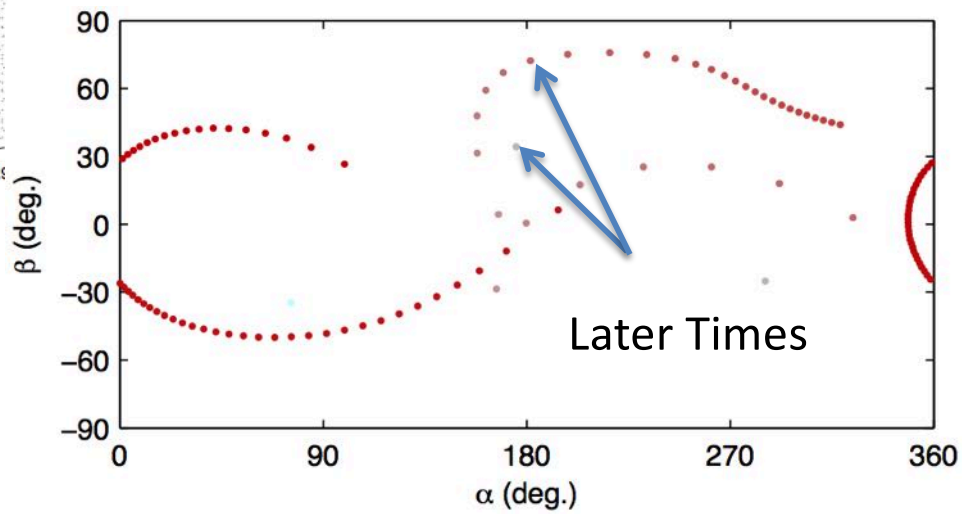


Integration From α,β = 0

Spatial Invariant Manifold Approach Near Europa (Final Leg)

- Compute W^u Intersections in Configuration space

L_2 Halo, C = 3.003



- Examine direct approaches (TOF < 4π)
- Impacts as a function of time (lighter = later)