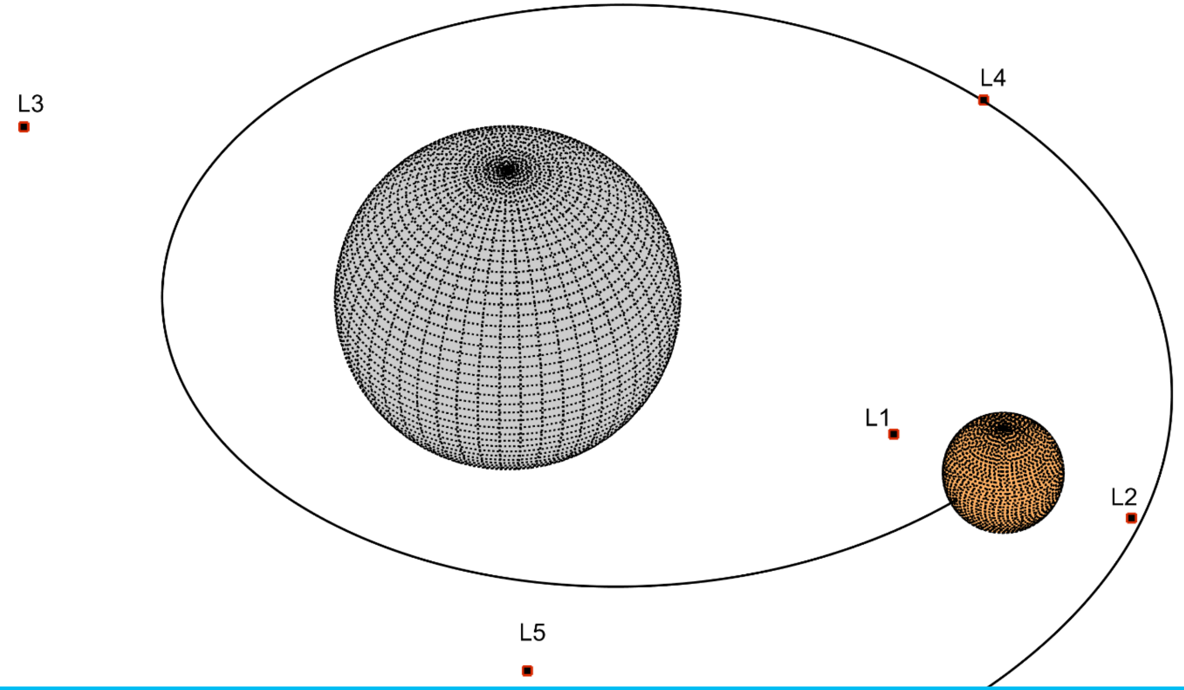
# CubeSat Landing Opportunities for Binary Asteroid Exploration





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- Dynamical Model: Circular Restricted Three Body Problem (CR3BP)
- Mission Architecture
- Target Binary Asteroids
- Transfer Trajectory Generation
- Results
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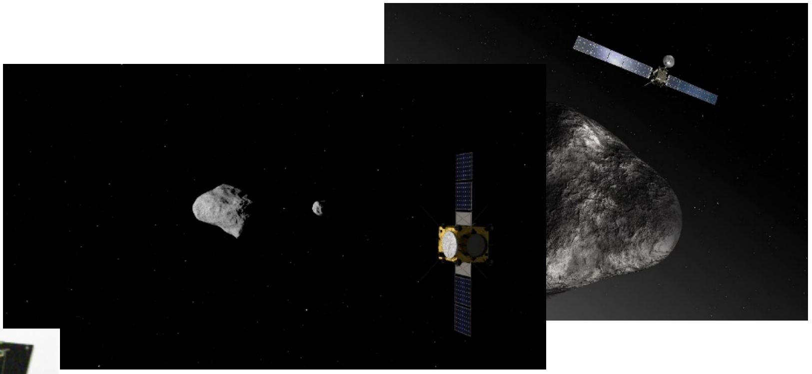
# Motivation

Small body exploration

- Scientific & Technological Challenge
- Resource Utilisation
- Planetary Defence

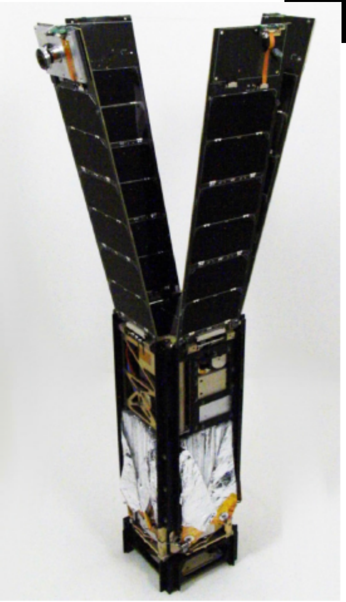


Rosetta (right), Asteroid Impact Mission (AIM) (left).

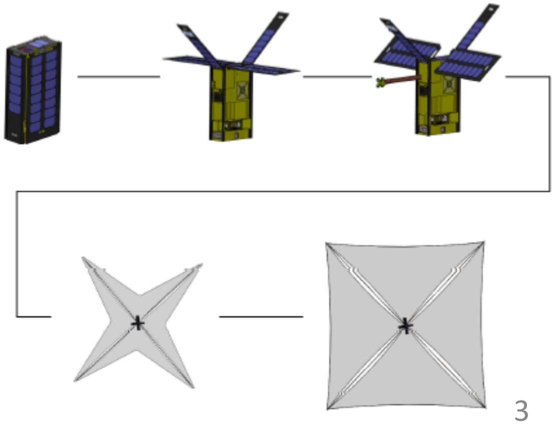
Credits: ESA (2014, 2015),

CubeSat

- Simple
- Low mass, low cost
- Increasing Reliability

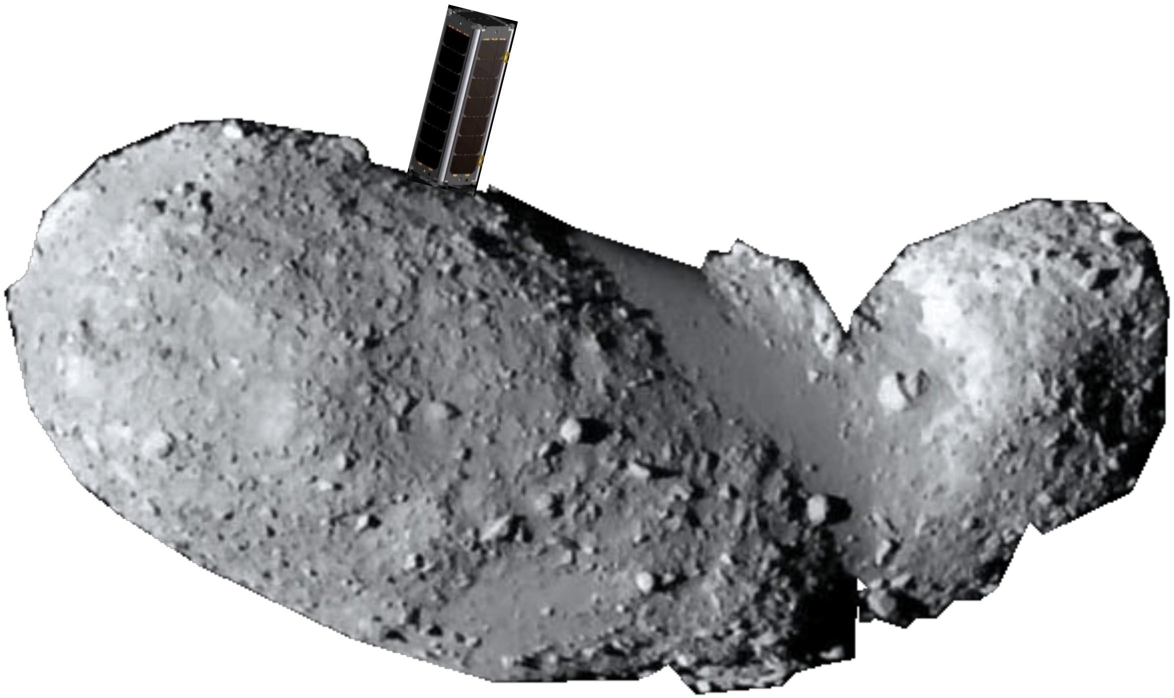


Various CubeSats
Credits: Staehle et al., 2011



# Motivation

Exploiting astrodynamics: A different approach to landing problem



# Dynamical Model: Circular Restricted Three Body Problem (CR3BP)

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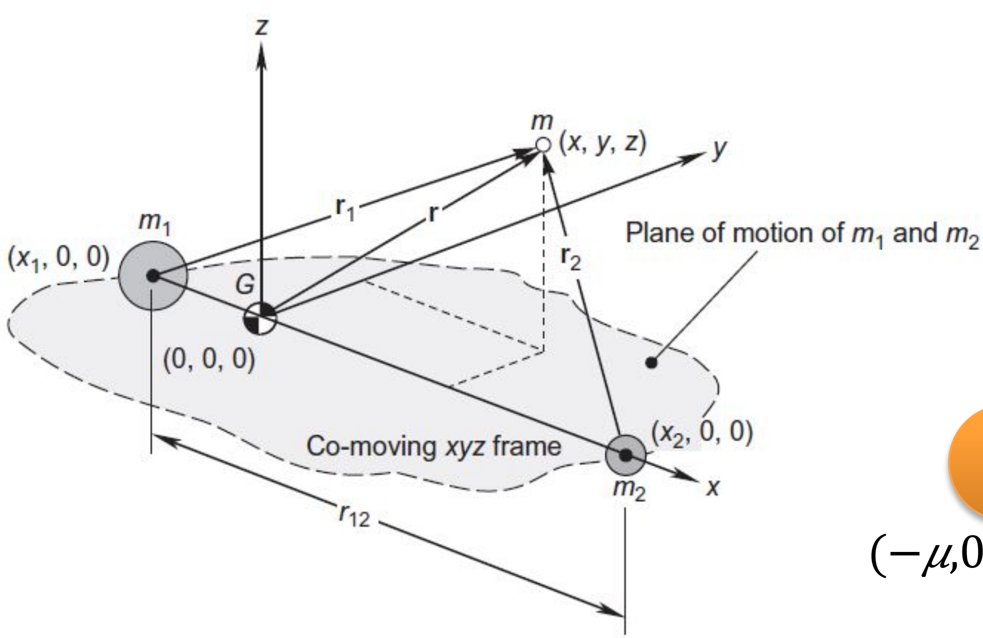
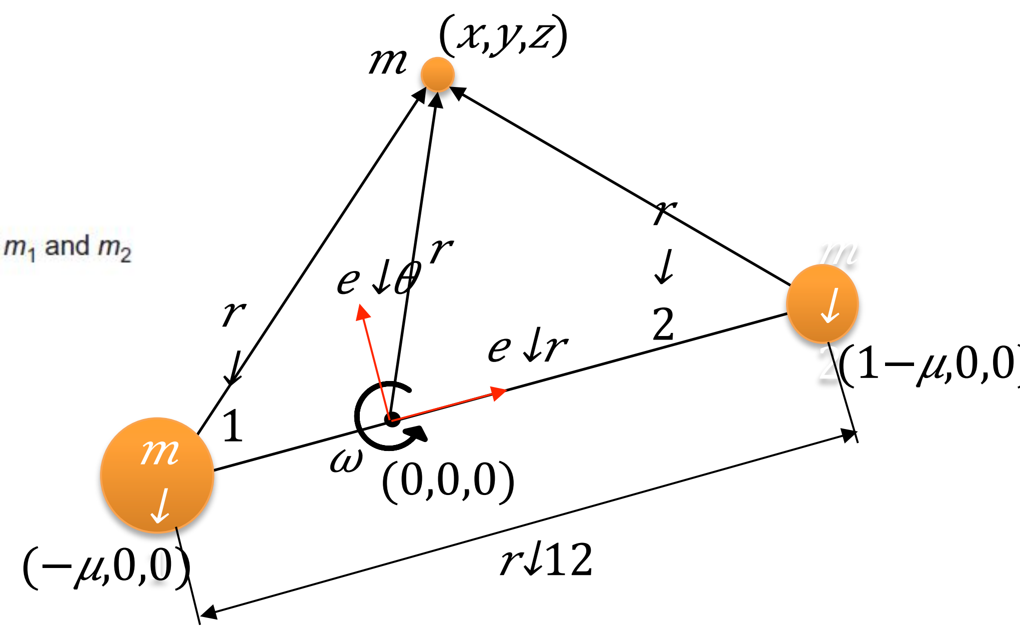


# CR3BP: Equations of Motion

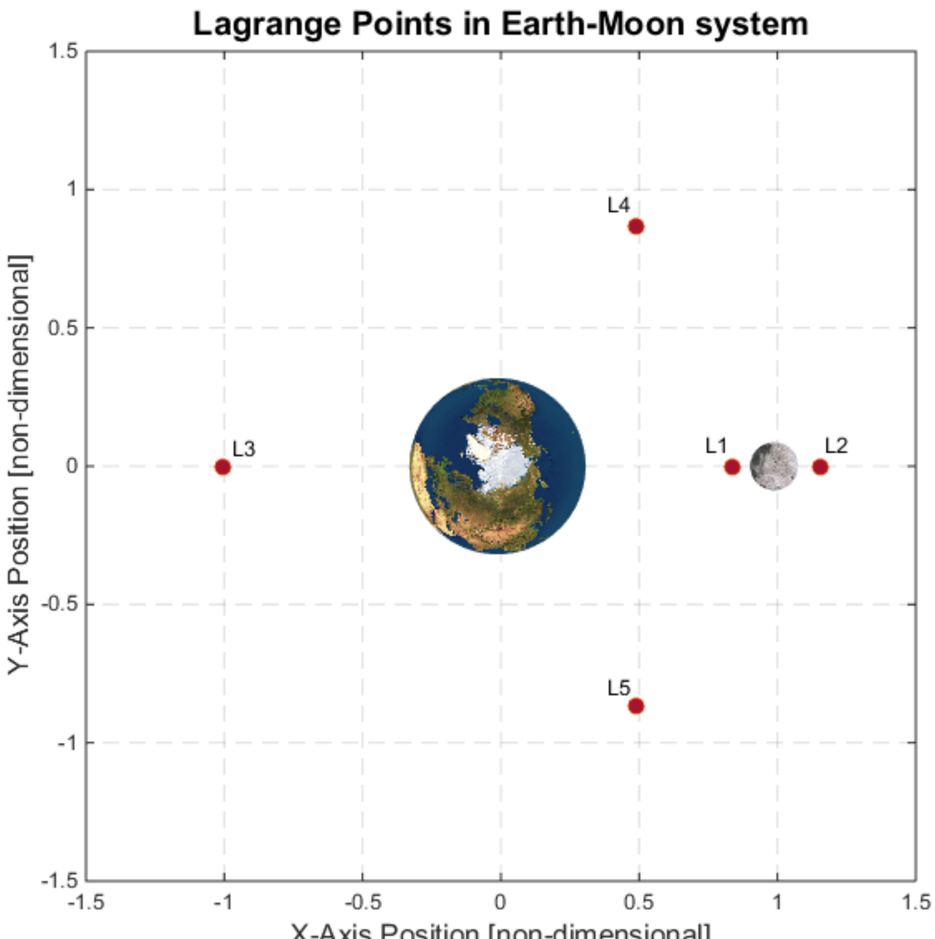
$$x - 2y = U_x = x - (1-\mu)(x+\mu)/r_1^3 - \mu(x-1+\mu)/r_2^3$$

$$y + 2x = U_y = y - (1-\mu)y/r_1^3 - \mu y/r_2^3$$

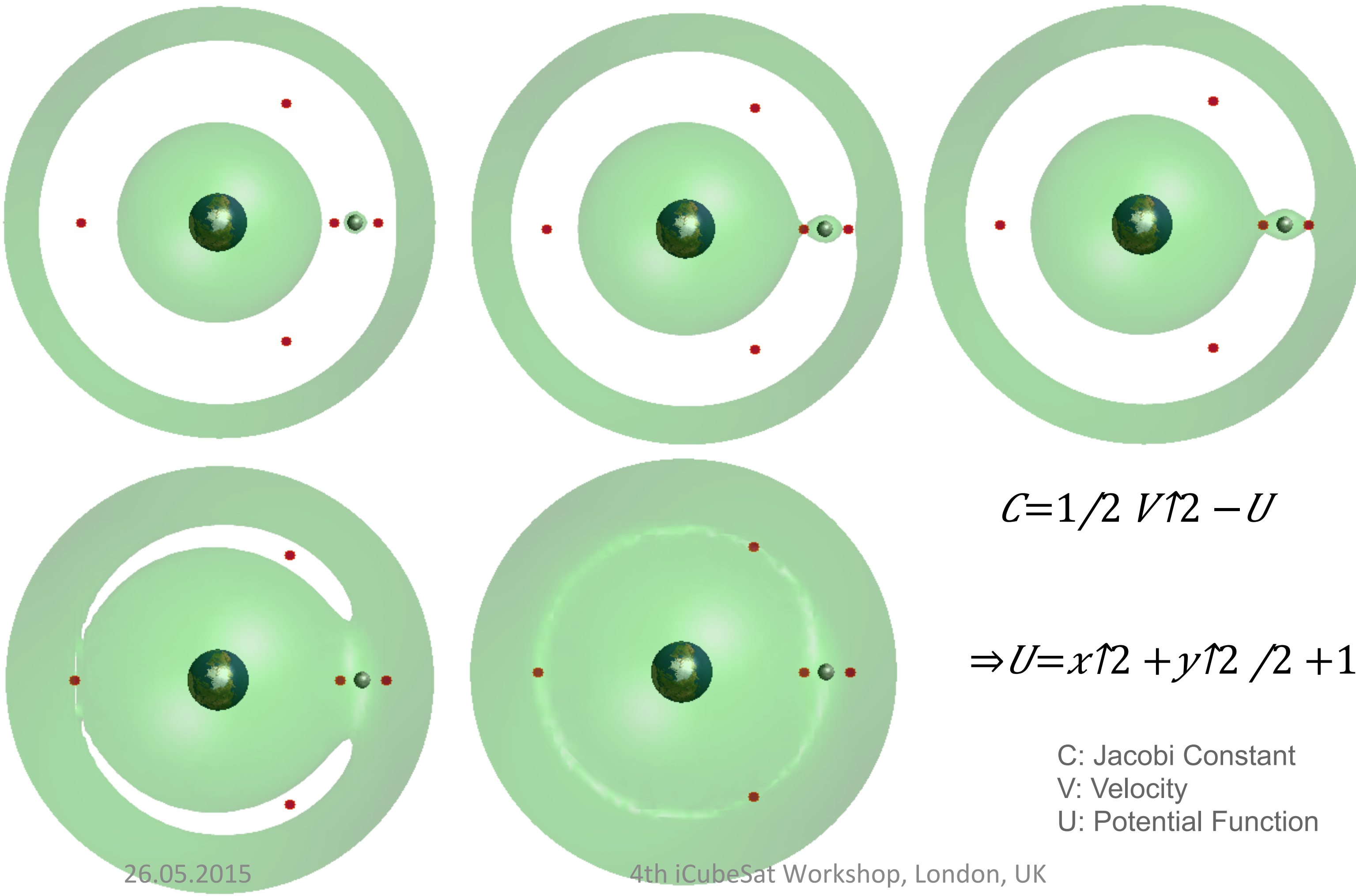
$$z \qquad = U_z = -(1-\mu)z/r_1^3 - \mu z/r_2^3$$

$$\mu = m_2 / m_1 + m_2$$

# CR3BP: Lagrange Points



# CR3BP: Zero Velocity Surfaces

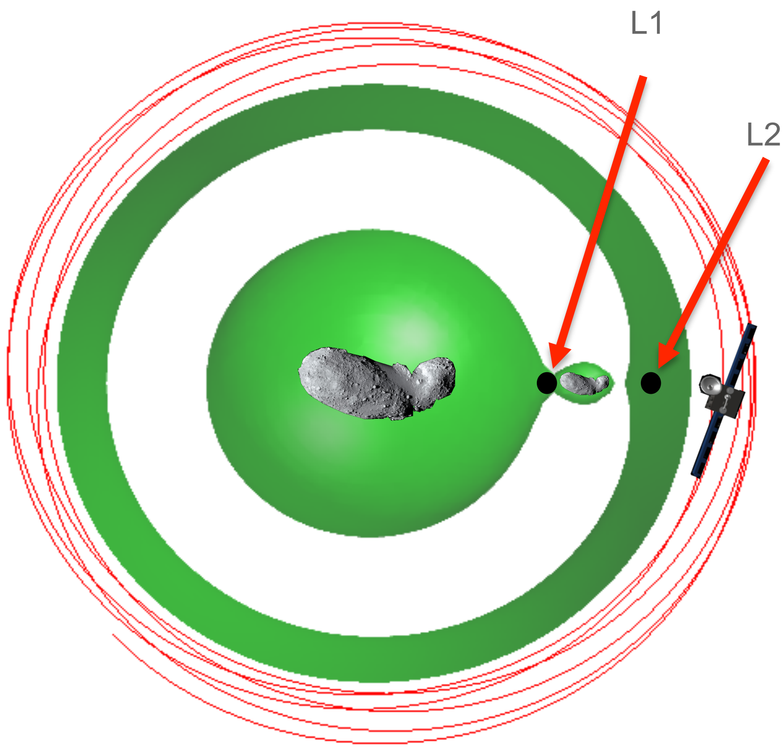


$$C = \frac{1}{2} V^2 - U$$

$$\Rightarrow U = \frac{x^2 + y^2}{2} + \frac{1-\mu}{r_1} + \frac{\mu}{r_2}$$

C: Jacobi Constant
V: Velocity
U: Potential Function

# Mission Architecture




- Mothership + CubeSat
  - Max deployment velocity 2 m/s
- Target: A binary asteroid system
  - ~15% of NEA population (Margot et al., 2002)
- Operational orbit in exterior region
  - Collision risk ruled out
- L2 is closed
  - No possible motion to interior region
- Landing on smaller companion (secondary) in local vertical direction
  - Maximum energy damping

# Target Binary Asteroid Systems

### Hypothetical Binary Asteroid

| | Primary | Secondary |
|---|---|---|
| Radius [m] | 1000 | 0.35 x $R_{primary}$ |
| Density [g/cm$^3$] | 2.6 (Yárnoz et al., 2014) | |
| Mass [kg] | 1.1 x $10^{13}$ | 4.7 x $10^{11}$ |
| Mass Parameter (μ) | 0.0411 | |
| Orbit semi-major axis [m] | 3.25 x $R_{primary}$ | |
| Orbital period [h] | 11.74648 | |
| Sphere of Influence [m] | 18952.93 | |

### 1996GT (65803) Didymos

| | Primary | Secondary |
|---|---|---|
| Radius [m] | 375 ± 50 | 85 ± 15 |
| Density [g/cm$^3$] | 1.7 ± 0.4 | |
| Mass [kg] | 3.75 x $10^{11}$ | 4.37 x $10^{9}$ |
| Mass Parameter (μ) | 0.0115 | |
| Orbit semi-major axis [m] | 1056.2 | |
| Orbital period [h] | 11.8992 | |
| Sphere of Influence [m] | 4868.81 | |

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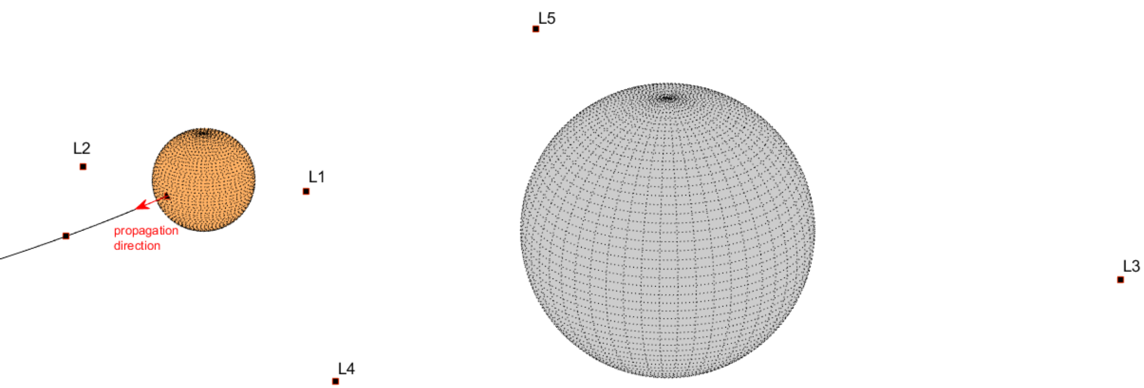
# Transfer Trajectory Generation

Initial State =

$$[x, y, z, x, y, z]$$




- Backwards integration from the surface
- Local vertical landing
- BiSection transfer trajectory search (Ren & Shan, 2014)
  - Upper and lower boundary velocities

# Transfer Trajectory Generation

Determination of initial interval

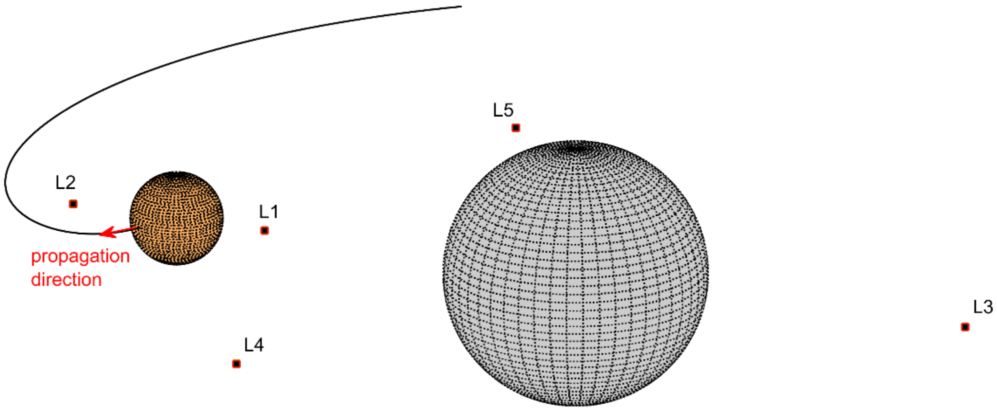
- Velocities at L2 gate energy

Bisection method of transfer trajectory generation

- Backwards integration in CR3BP

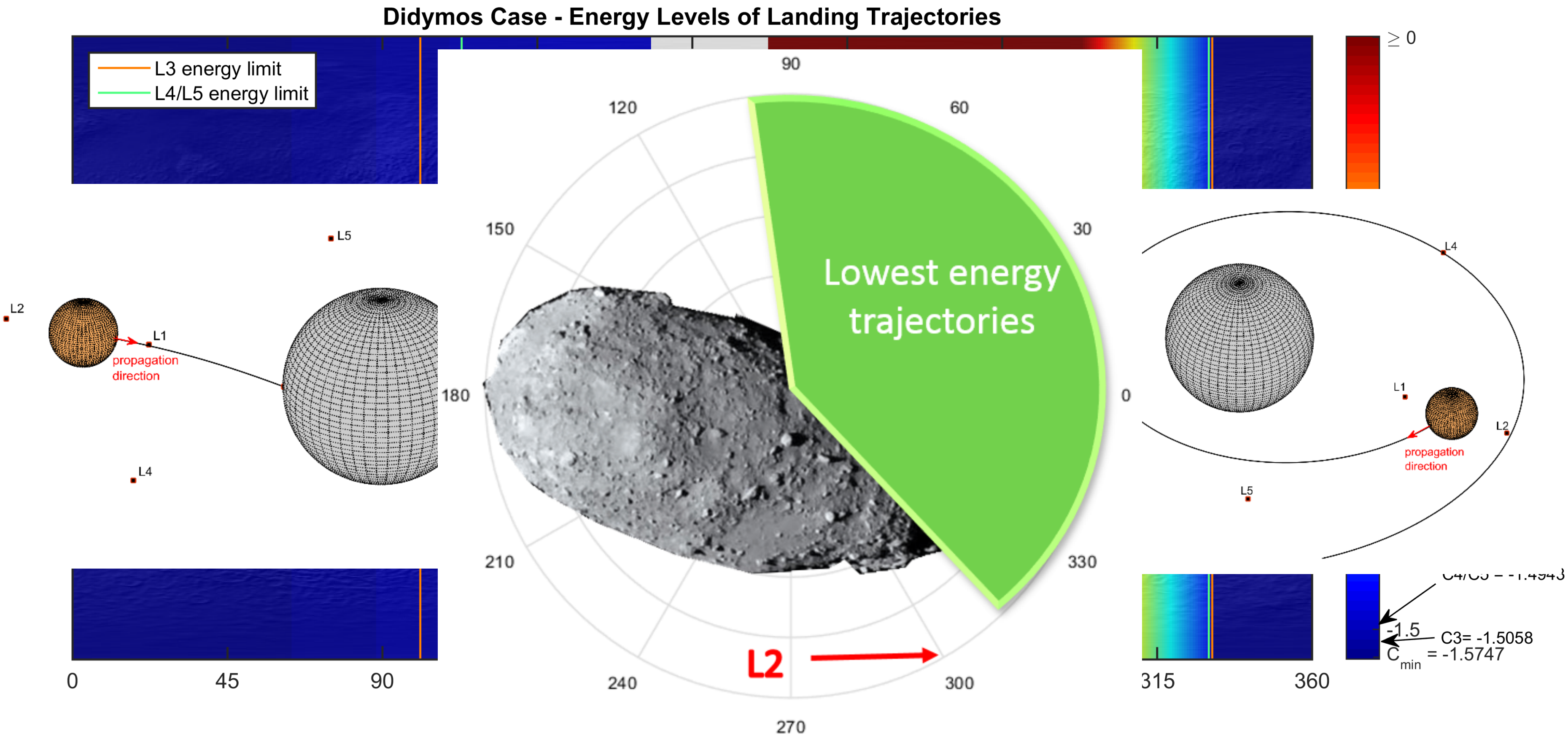
Transfer trajectories

- Energies, Landing velocities, Deployment positions and velocities



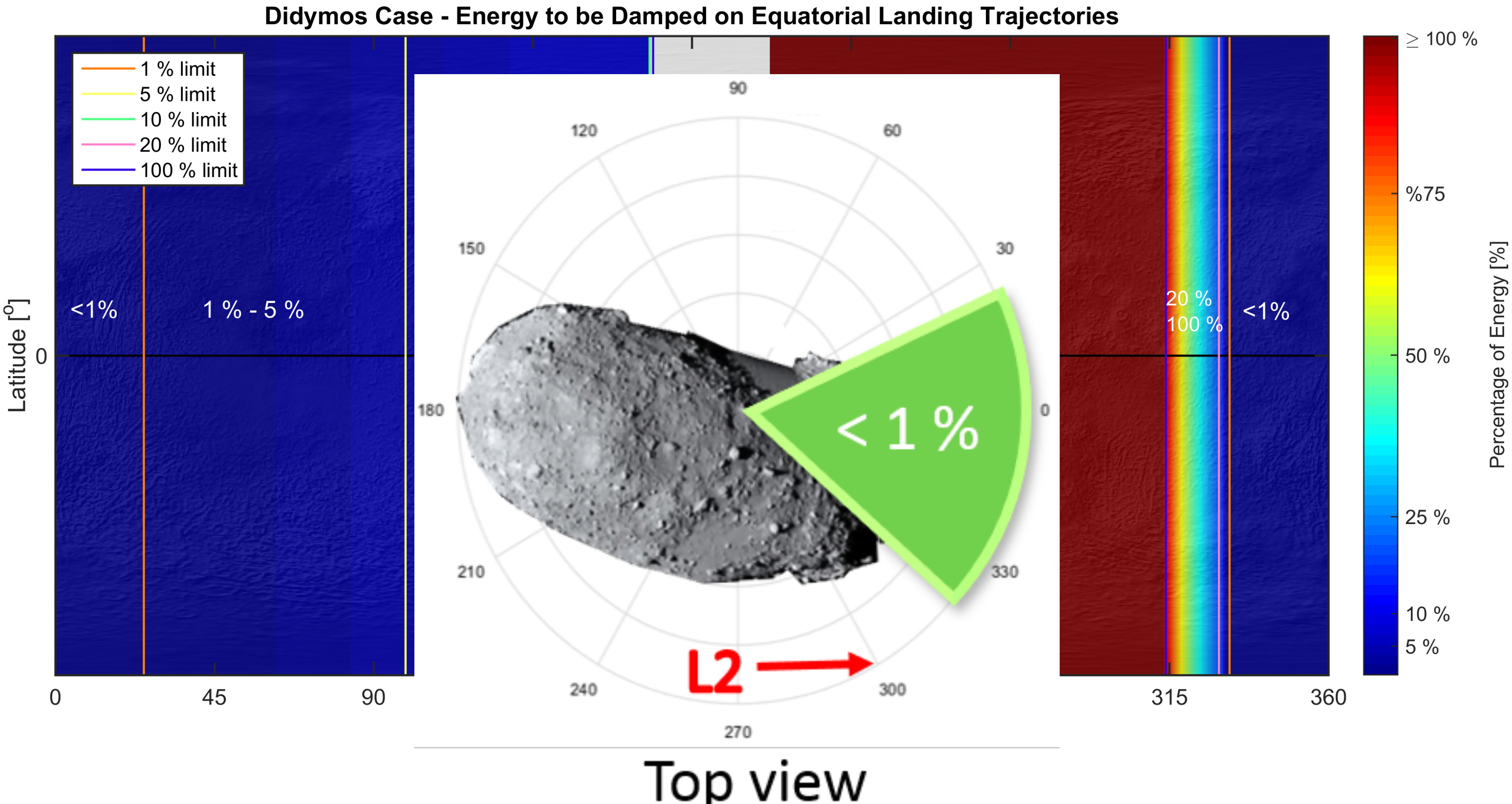

Based on the work Ren & Shan (2014)

# Results: Equatorial Landing Trajectories




Top view

# Results: Equatorial Landing Trajectories



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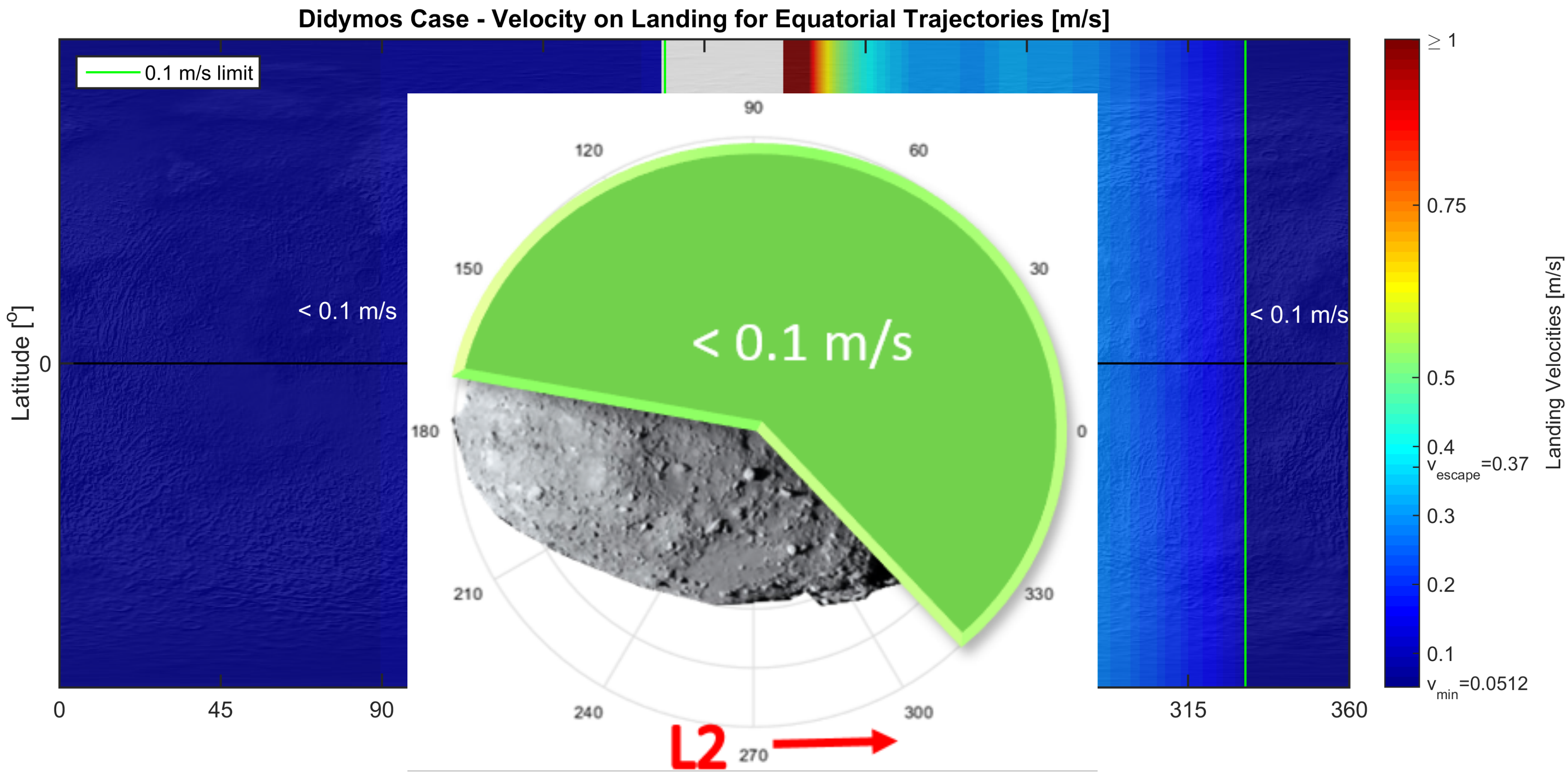
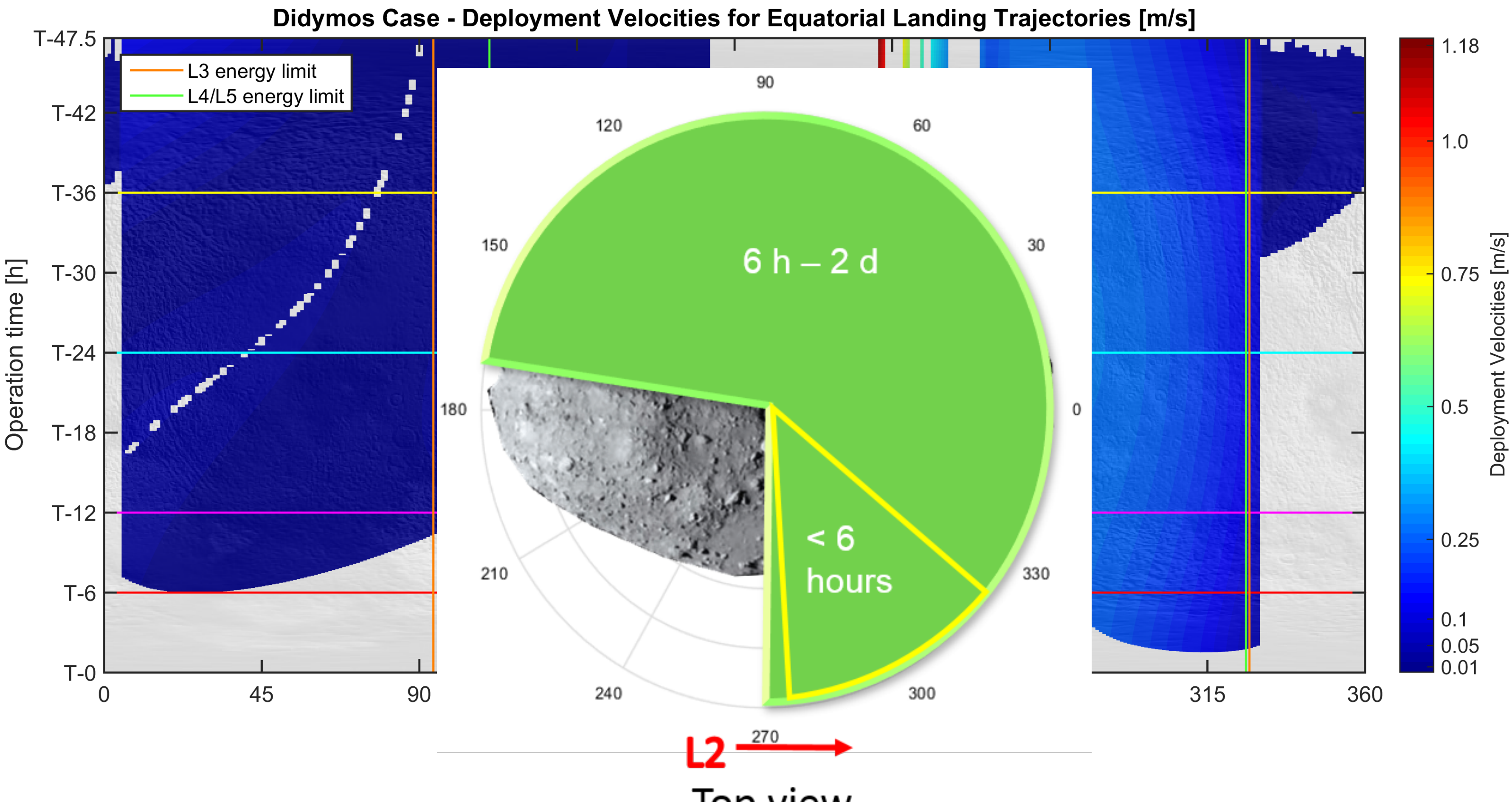
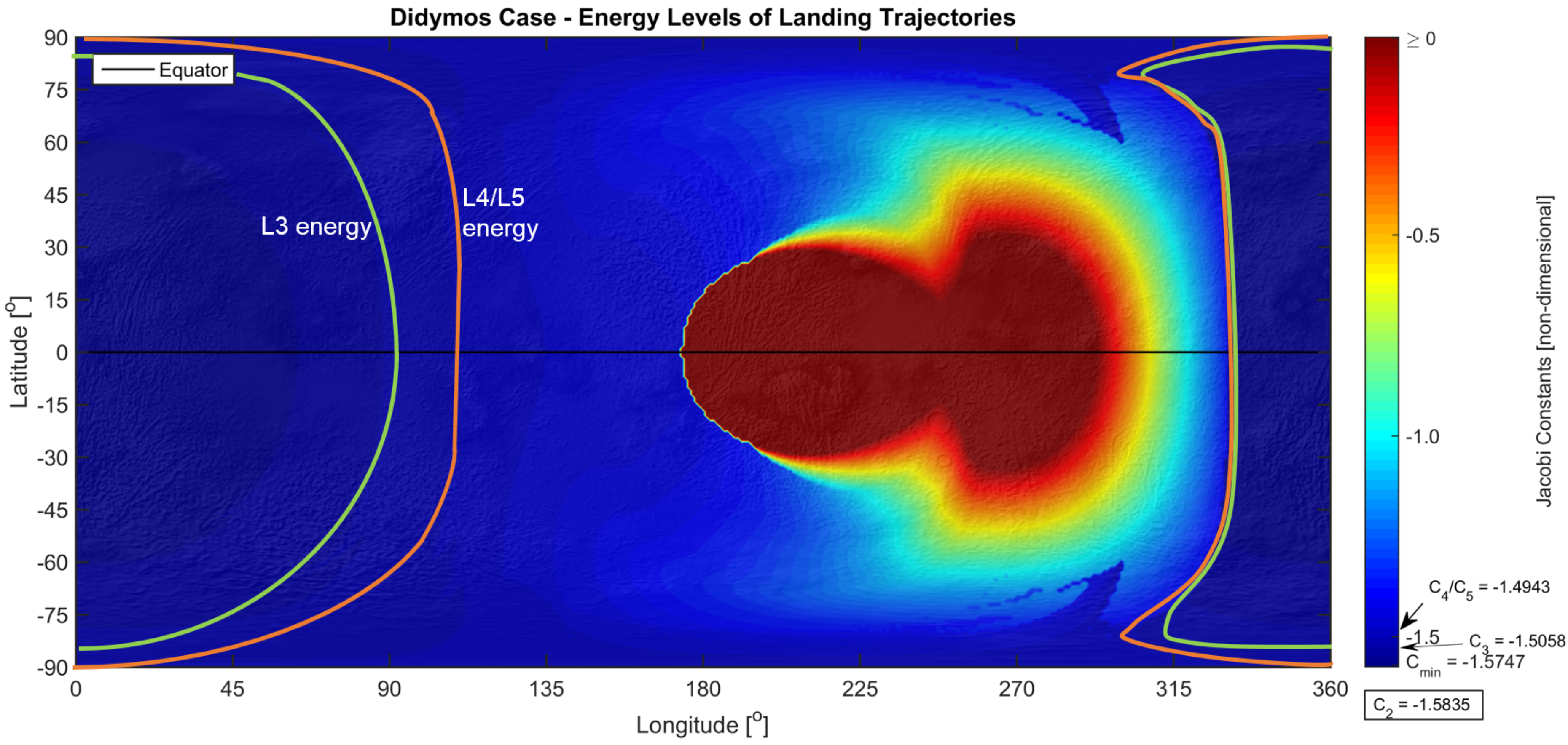



Top view

# Results: Equatorial Landing Trajectories



# Results: Landing Trajectories in 3D



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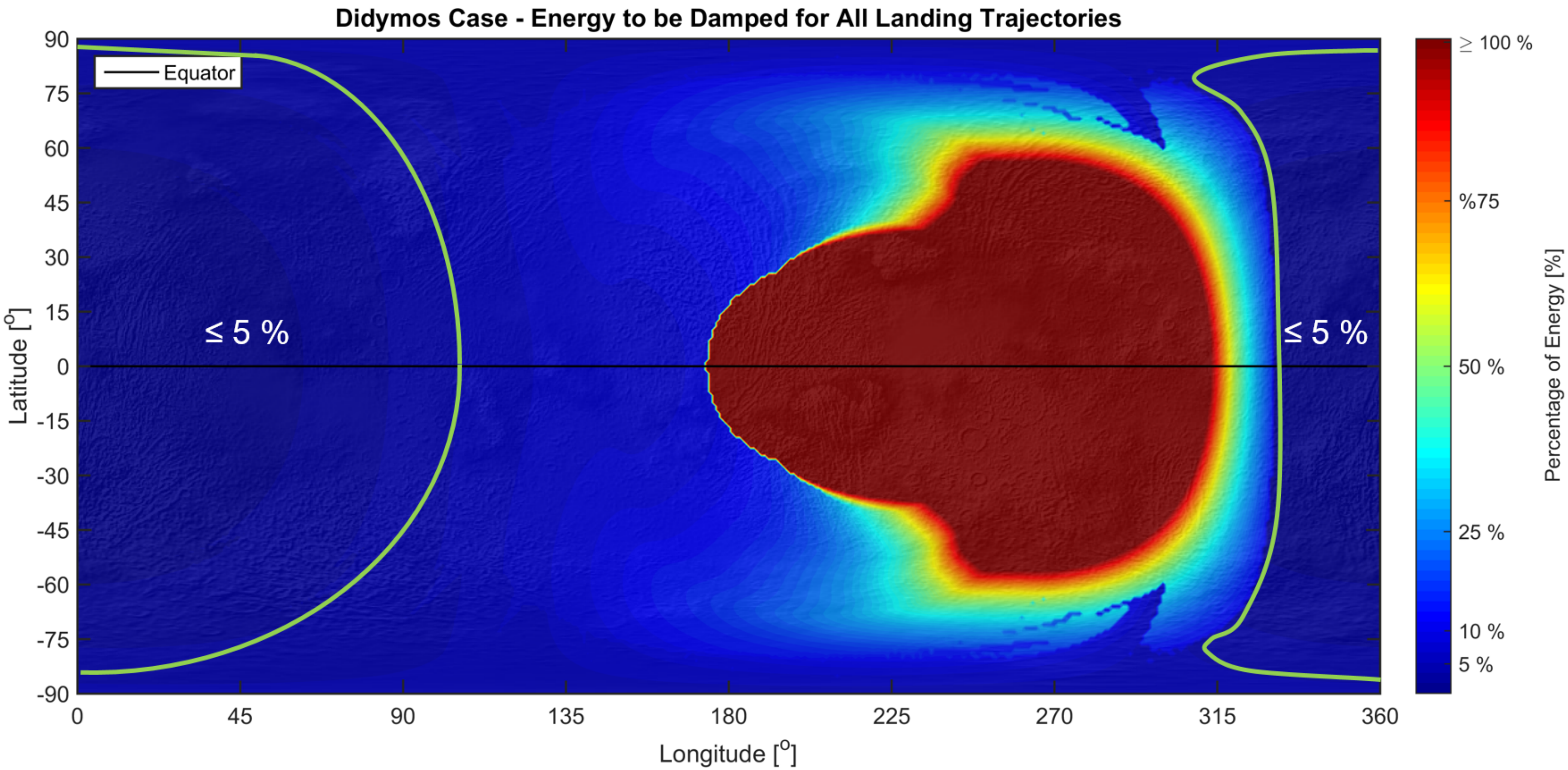

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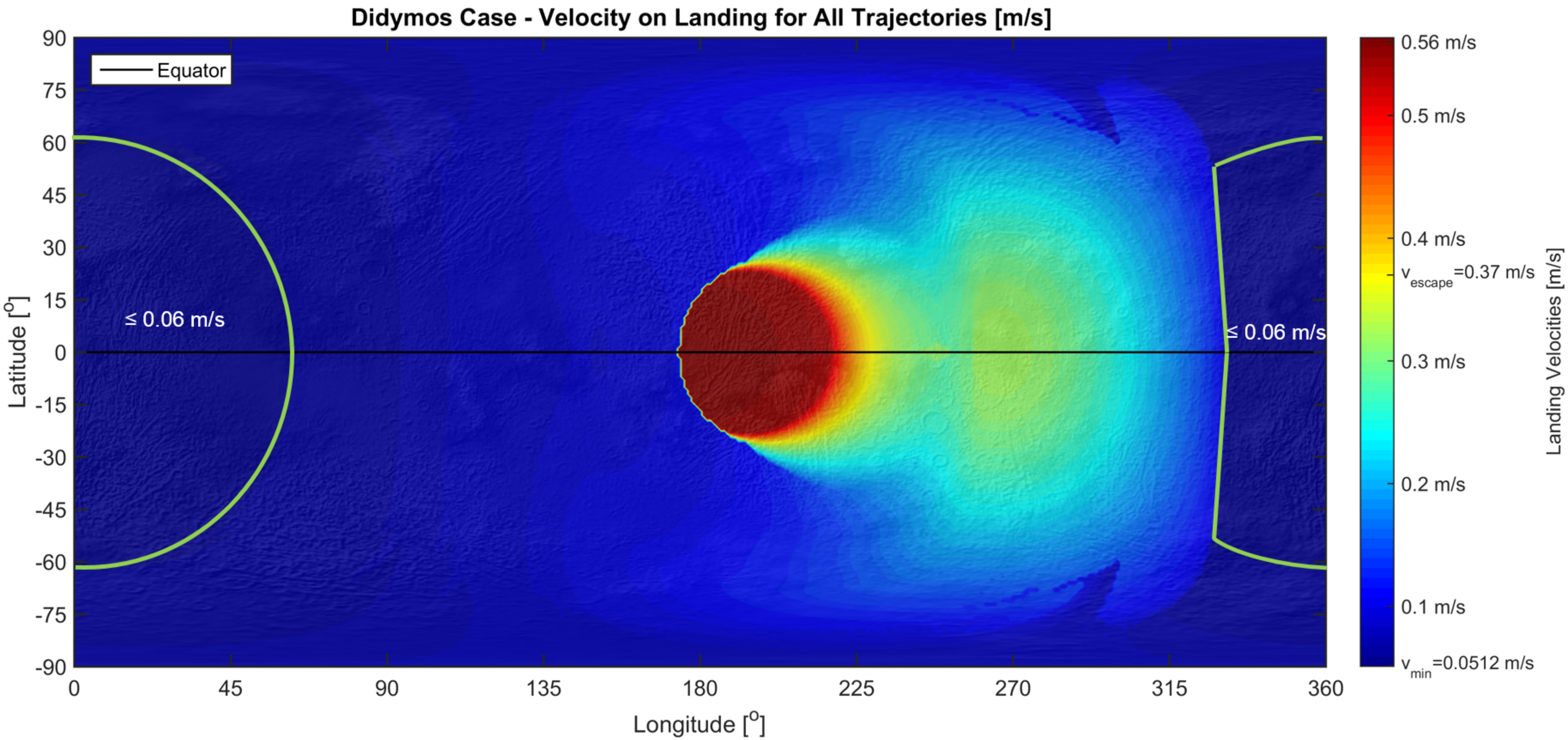

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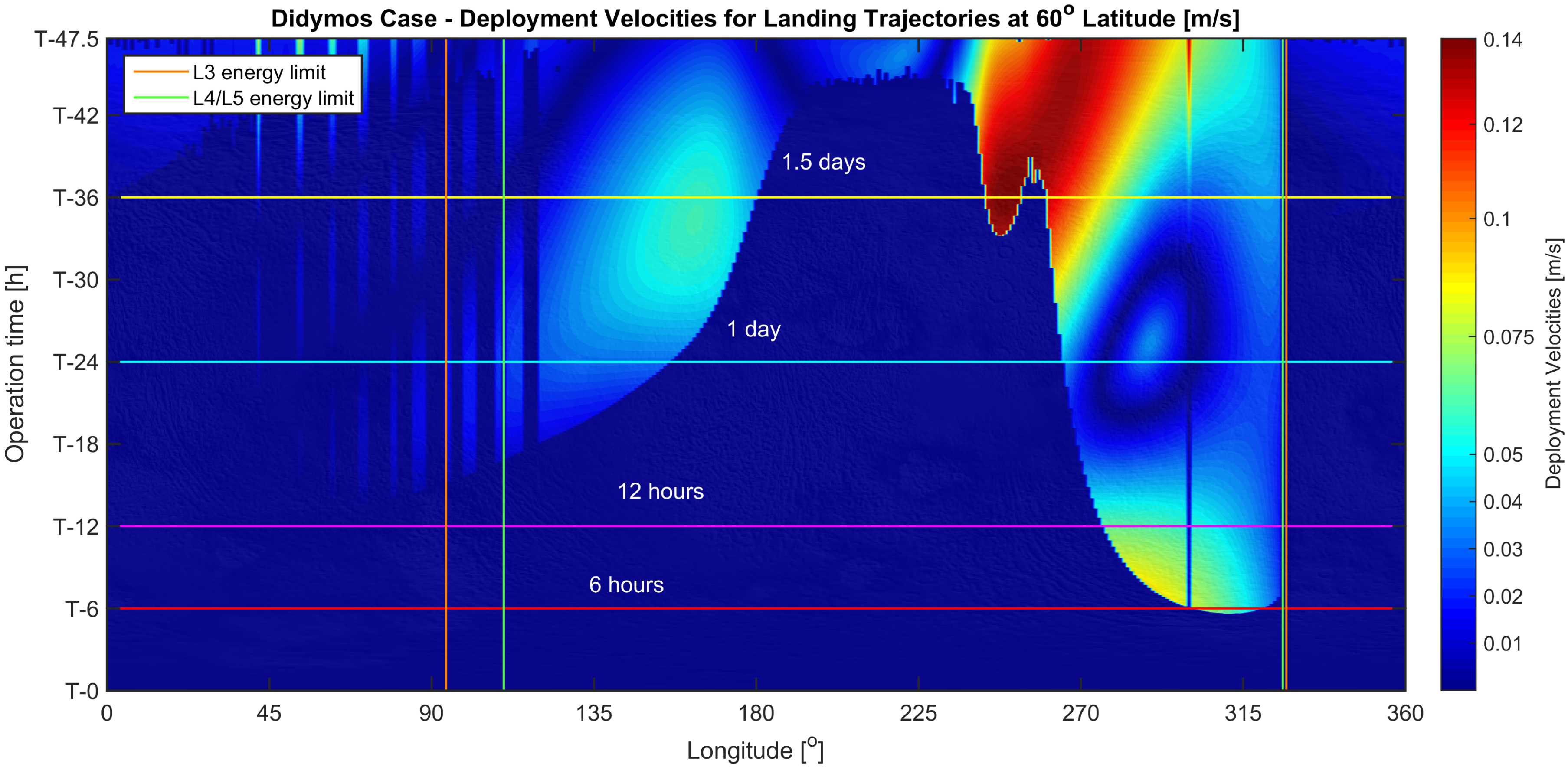

# Results: Conclusion

- Equatorial regions offer more opportunities for landing than higher latitudes
- The regions closer to L2 point requires less energy to land
  - Thus, lower landing velocities
- The regions closer to L2 point offers more latitudes to be landed by less than L3 energy (up to polar latitudes)
- Deployment options for landings that are less than 6 hours are limited, at least 6-12 hours should be considered
- Deployment velocities are within the limits
- The higher density and increasing size result in more energetic landings
- Adding different perturbations would provide different insights to results

# What's next?

- Trajectories under the effect of solar radiation pressure
- Uncertainty analysis
- Trajectories in Full R3BP with different perturbing sources
- Trajectories in Bi-CR3BP with the Sun – Binary system (or with Jupiter for main belt binaries)
- Accurate shape, surface, density, gravity models
- Mission opportunities – Payload/Subsystem studies for novel Cubesat missions for asteroid exploration

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Thank you !

Questions?

# Results: Landing on hypothetical binary asteroid in comparison to Didymos

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| | | Hypothetical Binary Asteroid | |
|---|---|---|---|
| Size | Density | Larger | Higher |
| Energies of trajectories | | Higher | |
| Percentage excess energy with respect to L2 energy | | Higher | |
| Landing velocities | | Higher | |
| Deployment velocities | Deployment positions | Higher | Various |
| Landing duration | | Various | |

# Mission opportunities – Preliminary thoughts

- Multiple asteroid visits
  - Mothership concept
  - Optimised Low-thrust trajectories

- Asteroid subsurface mapping
  - Imaging spectrometers
  - Radars
  - Seismometers
- Surface imaging
  - Panoramic cameras
- Gravitational measurements
  - Accelerometers

} Multipoint measurements