Photon-sail trajectories towards exoplanet Proxima b using heteroclinic connections

T. J. Rotmans

M. J. Heiligers

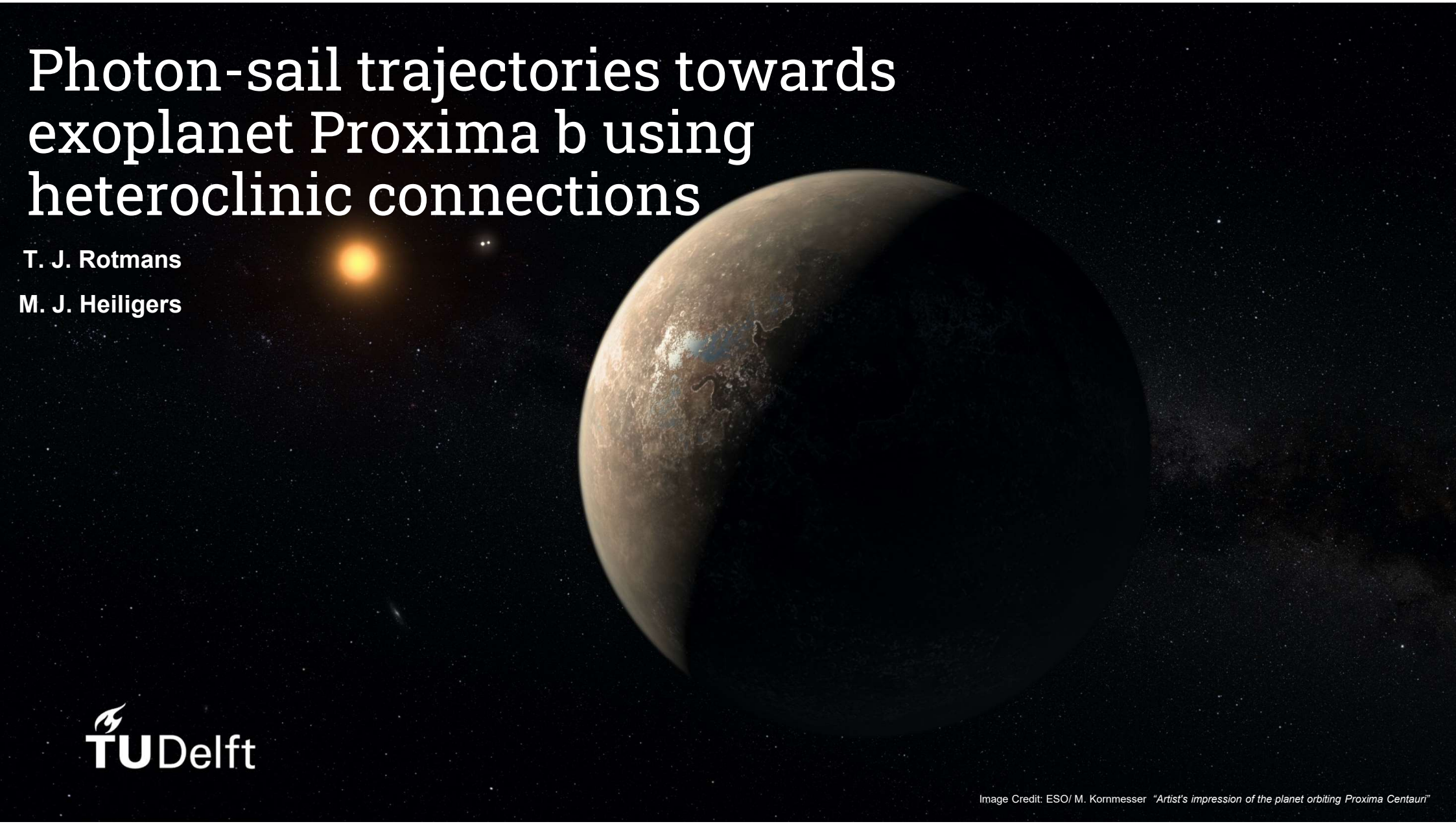

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Image Credit: ESO/ M. Kornmesser *"Artist's impression of the planet orbiting Proxima Centauri"*

Inspiration

Breakthough Starshot

- Mission to Alpha Centauri
- Swarm of sails to Proxima b
- Appr. 20 yrs travel time

Heller & Hippke (2017)

“Deceleration of high-velocity photon sails into bound orbits at Alpha Centauri”

Schoutetens, Dachwald & Heiligers (2021)

“Optimization of photon-sail trajectories in the Alpha Centauri system using evolutionary neural networks”

Capture in bound orbit in 70-80 years

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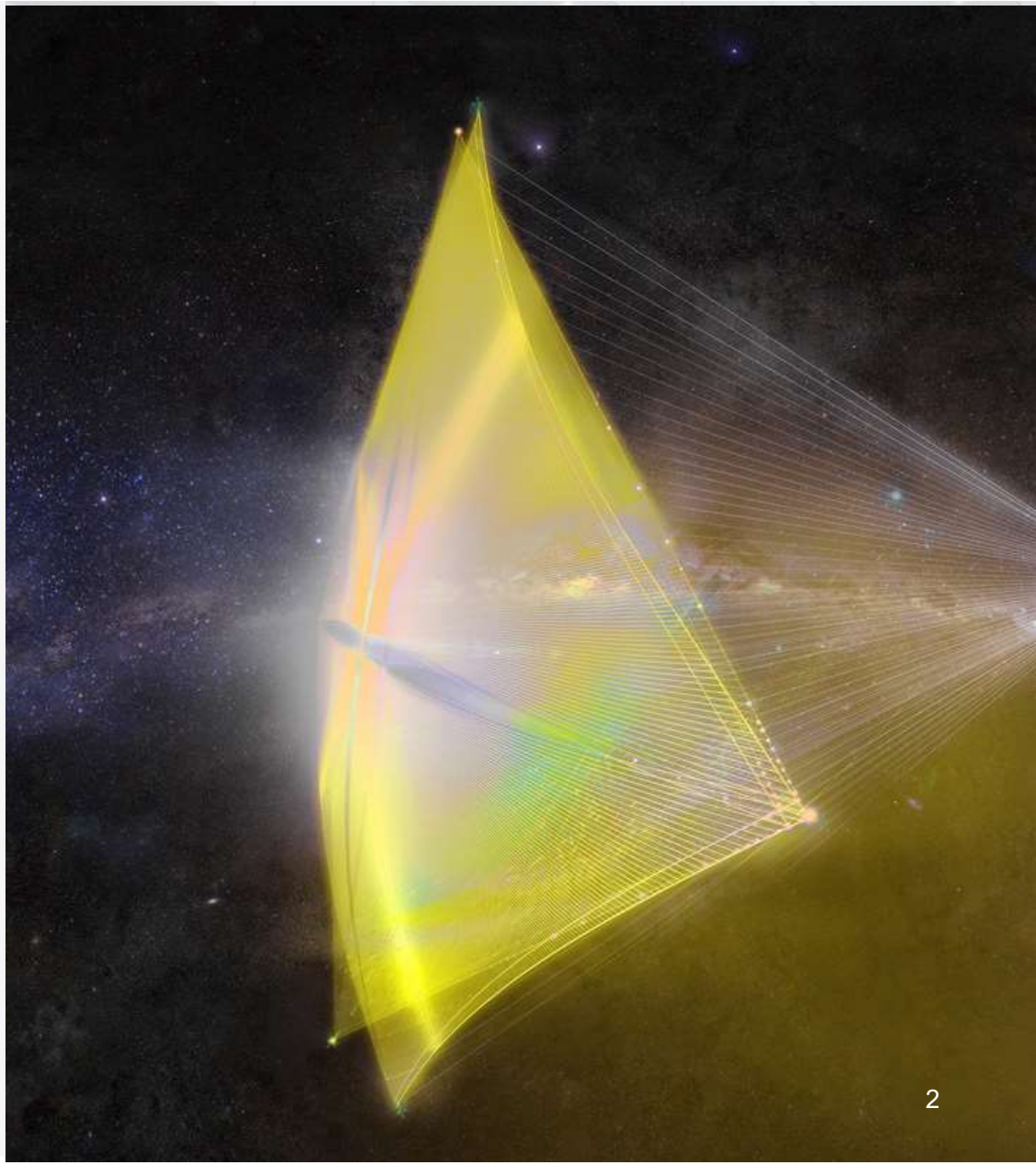
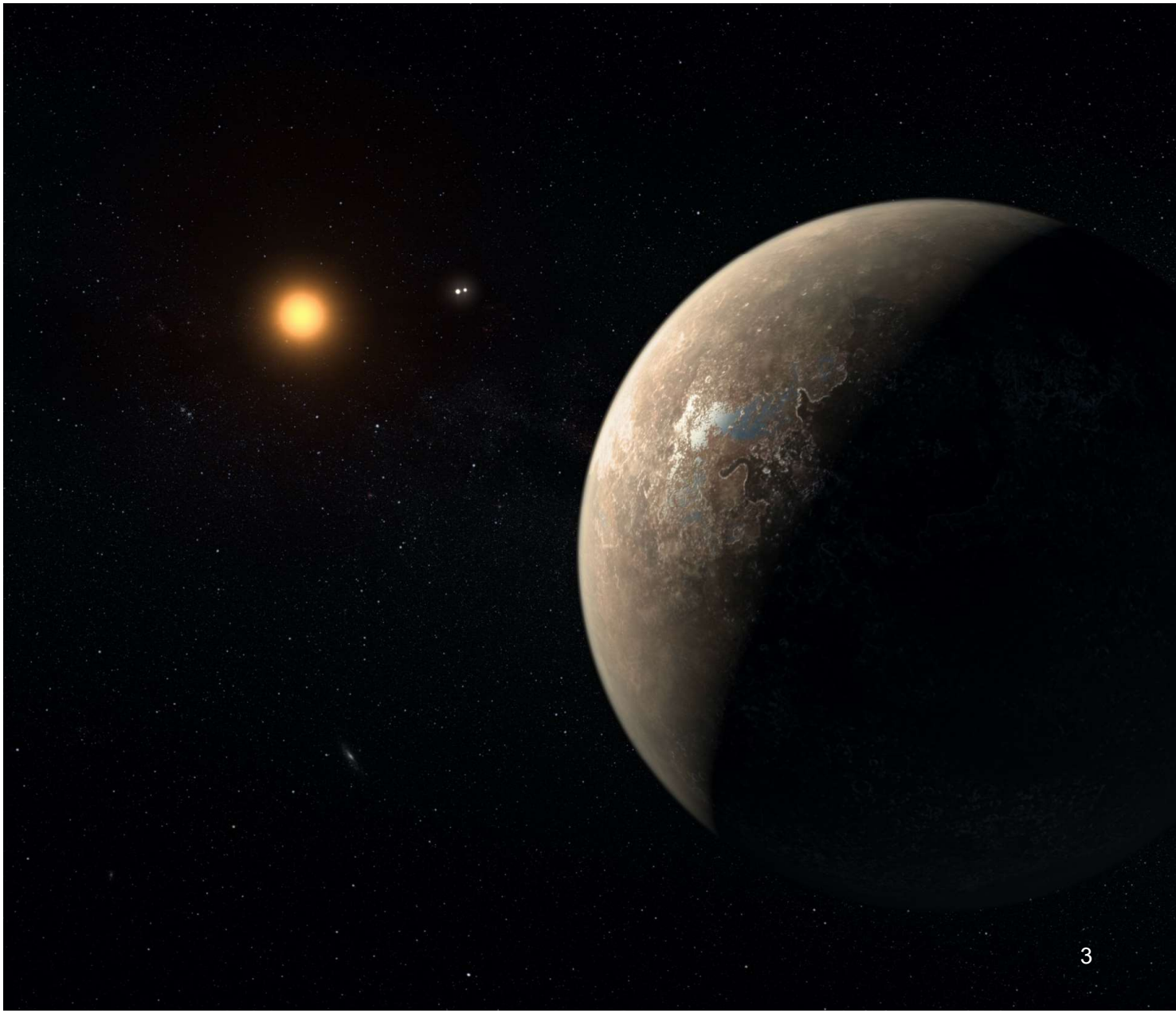


Outline

- **Introduction**
  - Alpha Centauri
  - Heteroclinic connections
- Methodology
- Results
- Conclusions



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Alpha Centauri

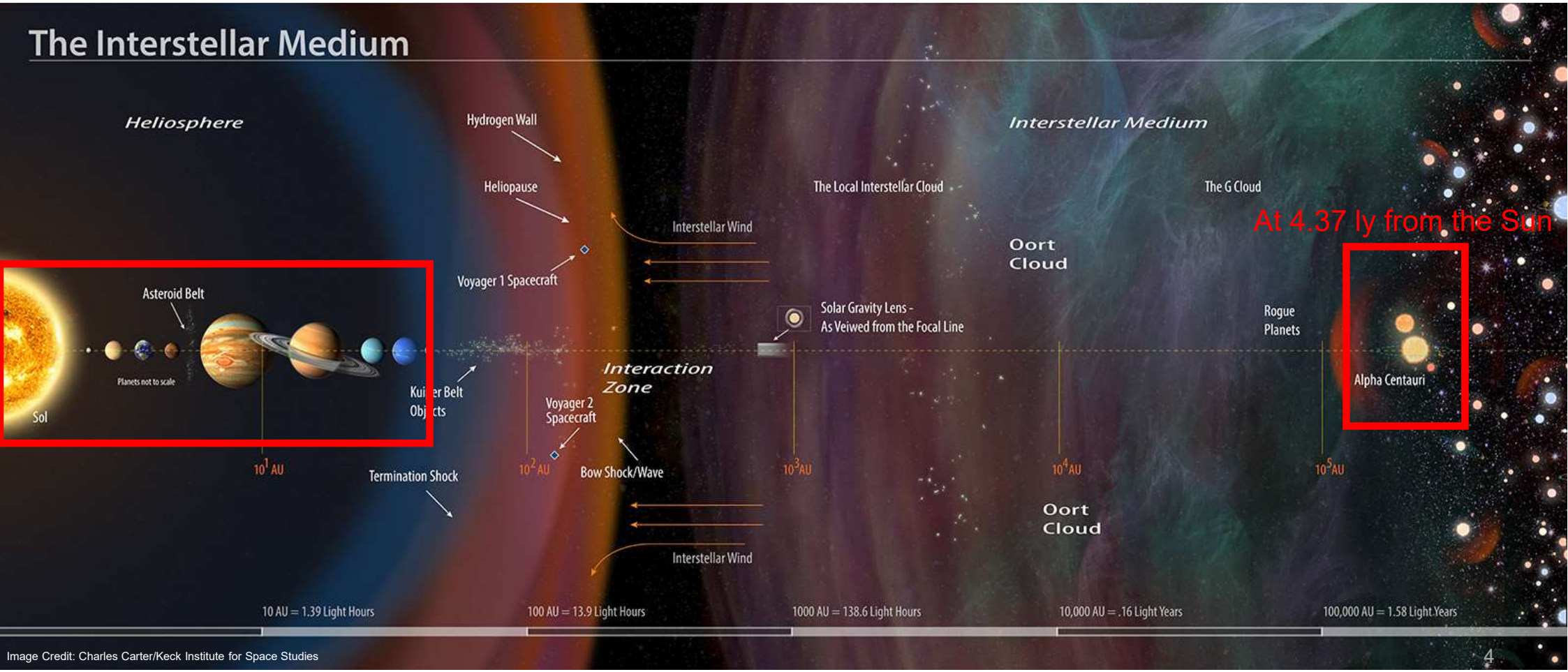
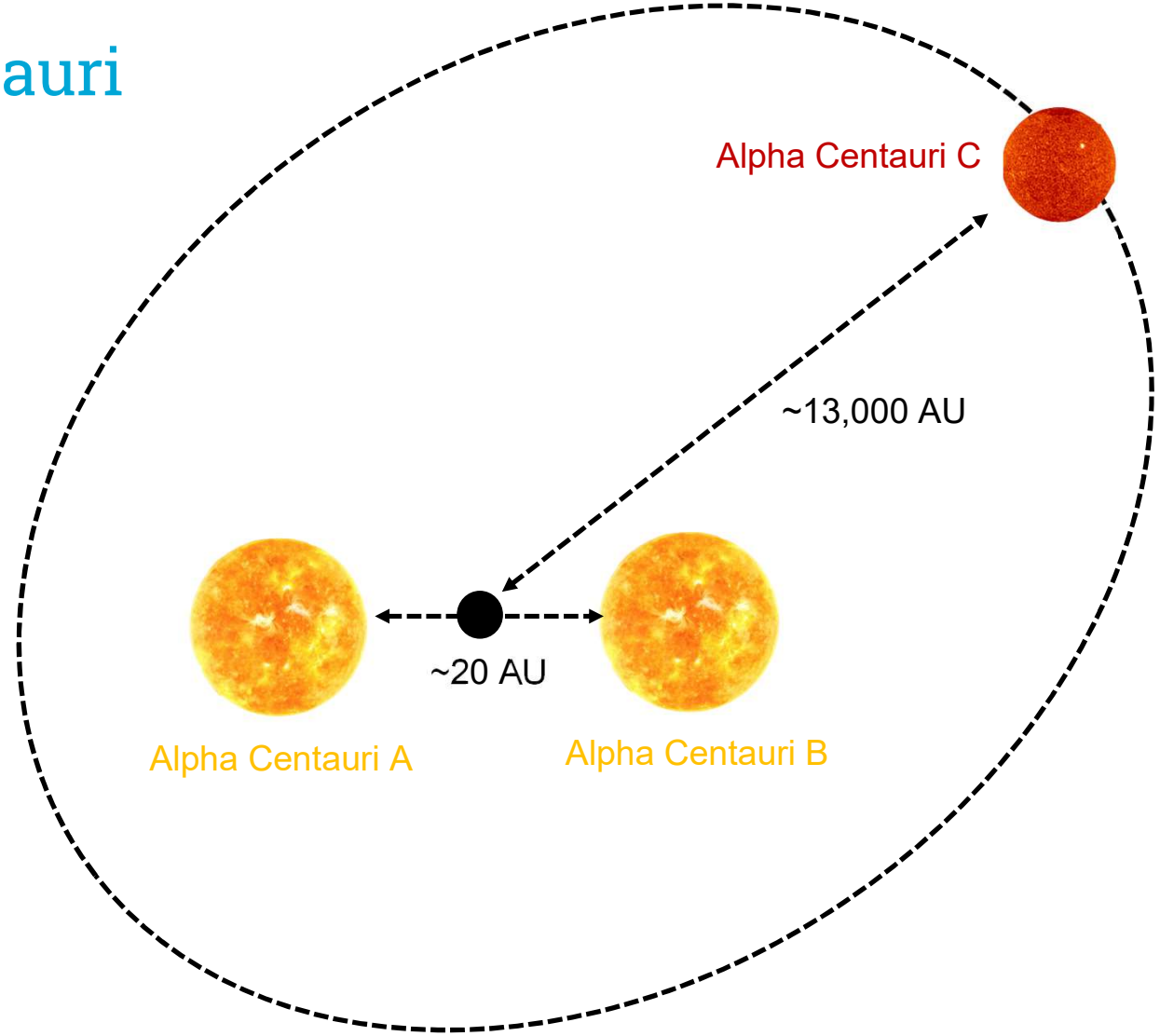


Image Credit: Charles Carter/Keck Institute for Space Studies

Alpha Centauri



AC-C

red-dwarf star

luminosity = 0.0015 * Sun's luminosity

mass = 0.12 * Sun's mass

period = 511,000 years

sma = 8,200 AU

AC-A / AC-B

binary star system

both similar to Sun

eccentricity = 0.52

period = 80 years

sma = 23.5AU

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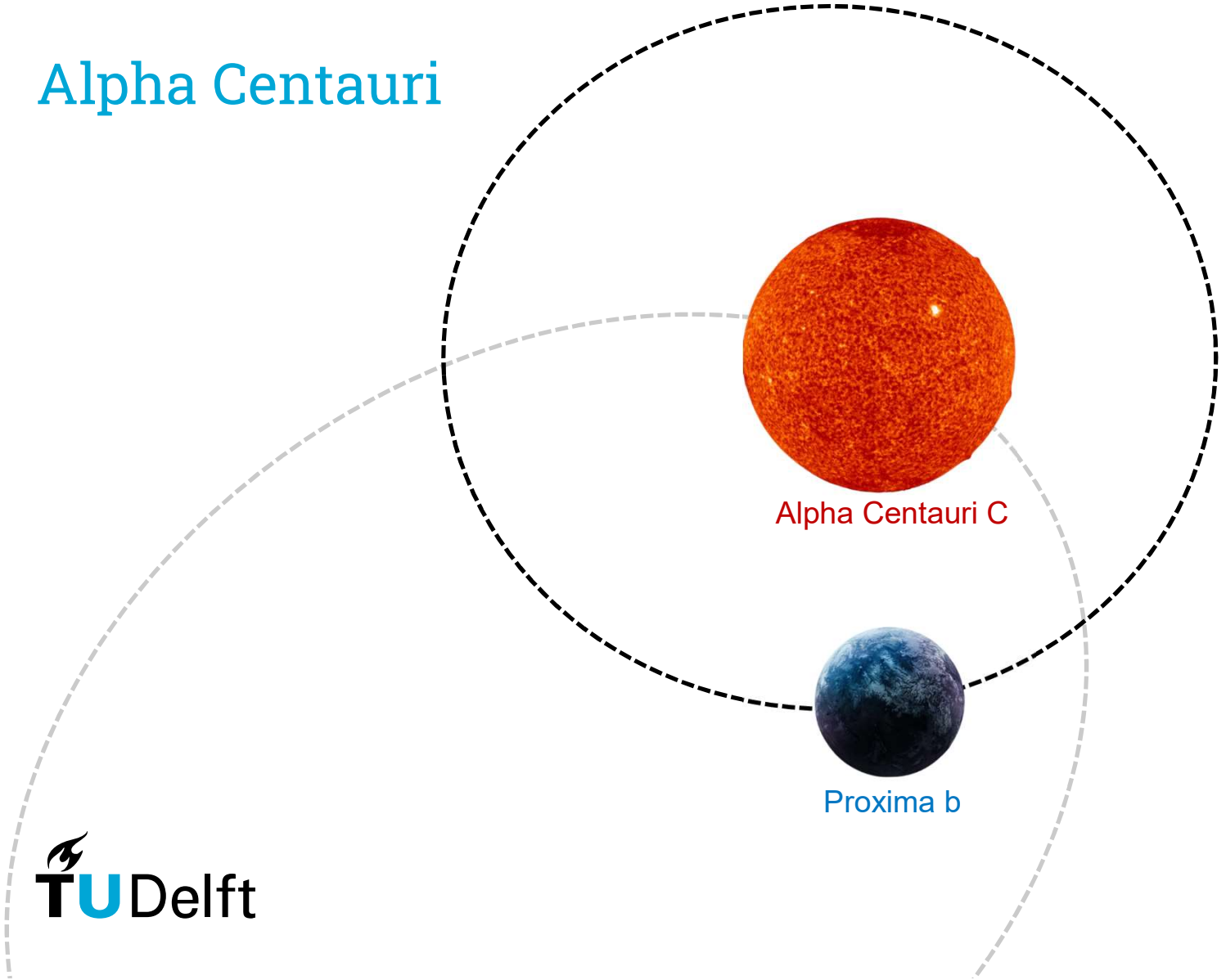
Alpha Centauri



Breakthrough Initiatives

Proposed mission to Proxima b in 2036

Breakthrough Starshot

Swarm of photon sails

Proxima b

rocky exoplanet

habitable zone

mass = 1.3 * Earth's mass

eccentricity = 0.1

period = 11.186 days

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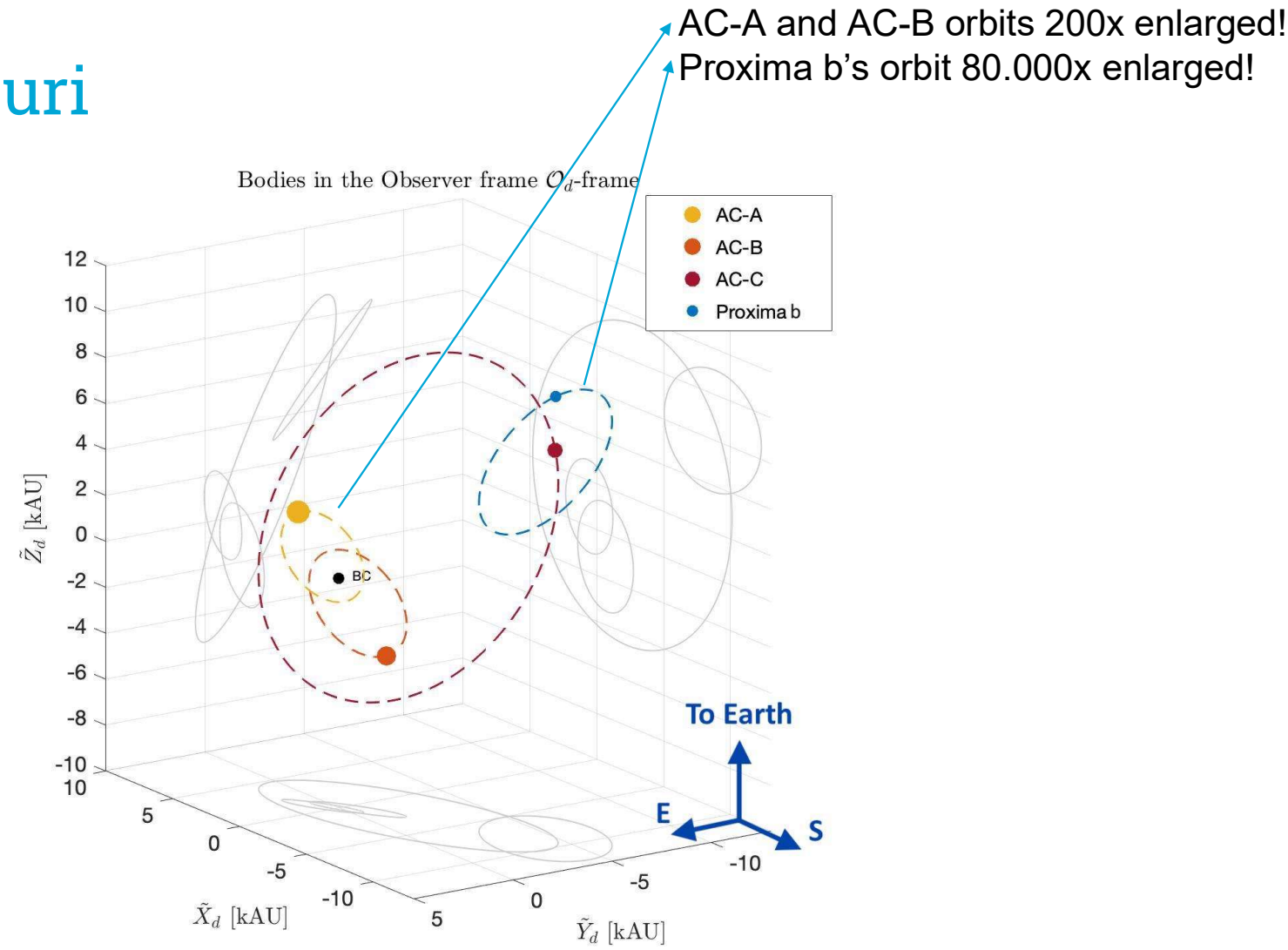
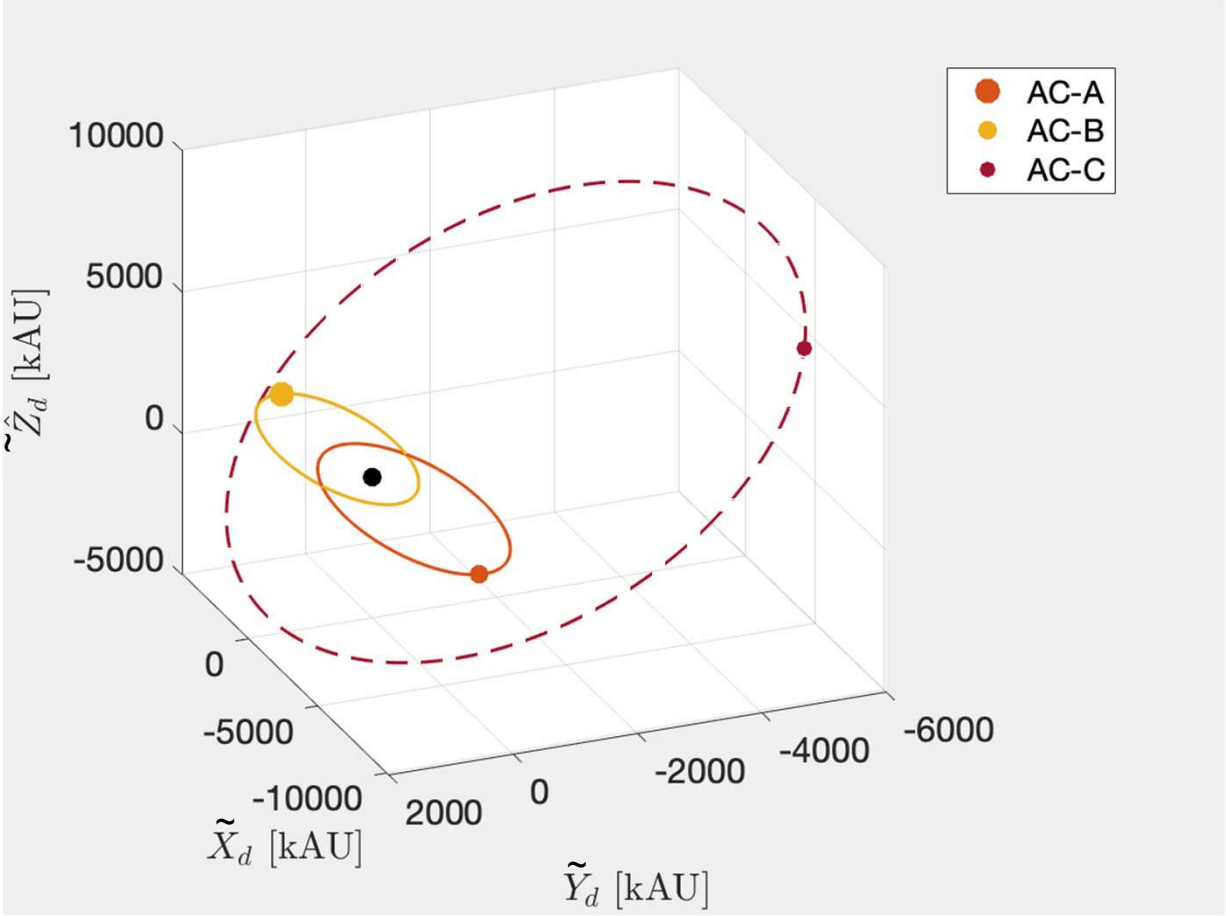
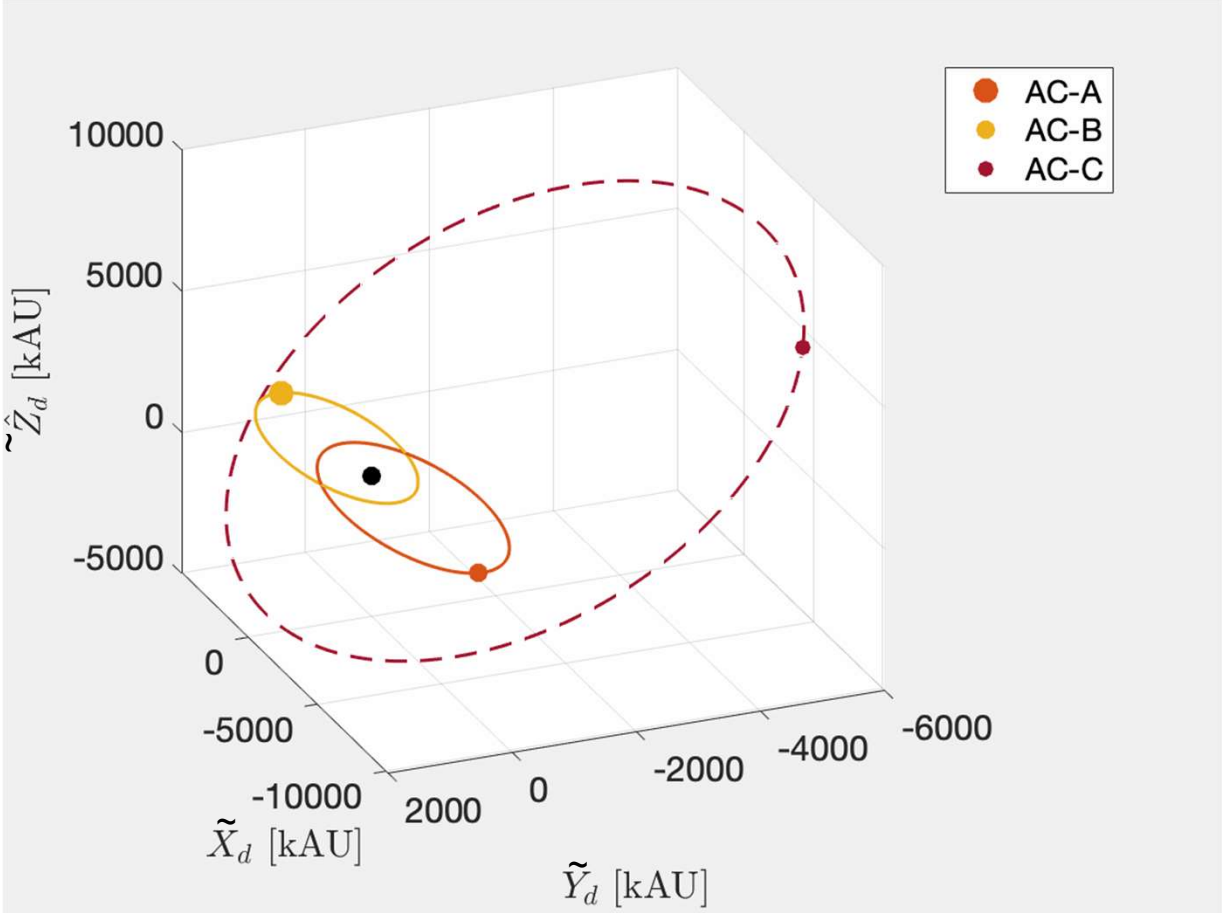
Alpha Centauri



Alpha Centauri – moving stars



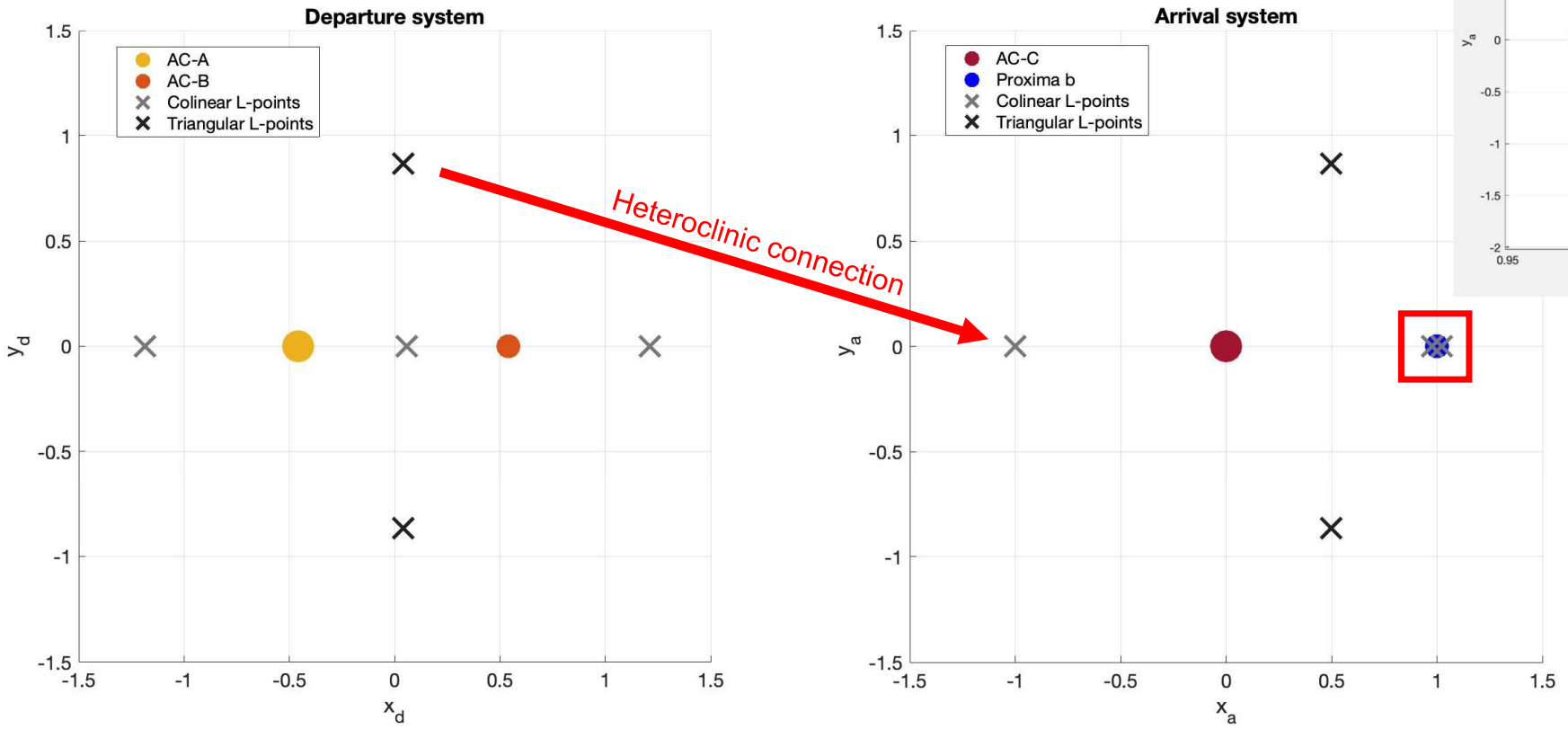
Alpha Centauri – moving stars

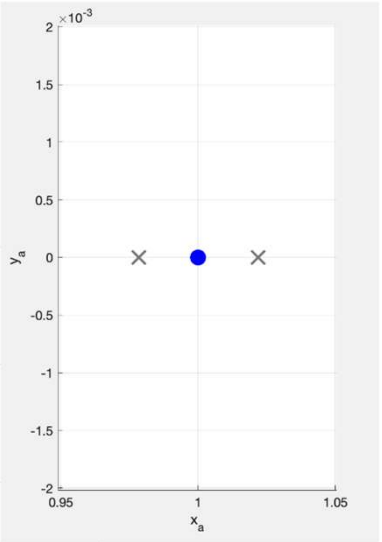


Heteroclinic connections

- Connections between Lagrange points
  - 5 points in a 2-body system
  - Centrifugal and gravitational forces balance each other
  - Rotate along with these masses
  - Few orbit corrections required
  - James Webb Space Telescope

Lagrange points in Alpha Centauri





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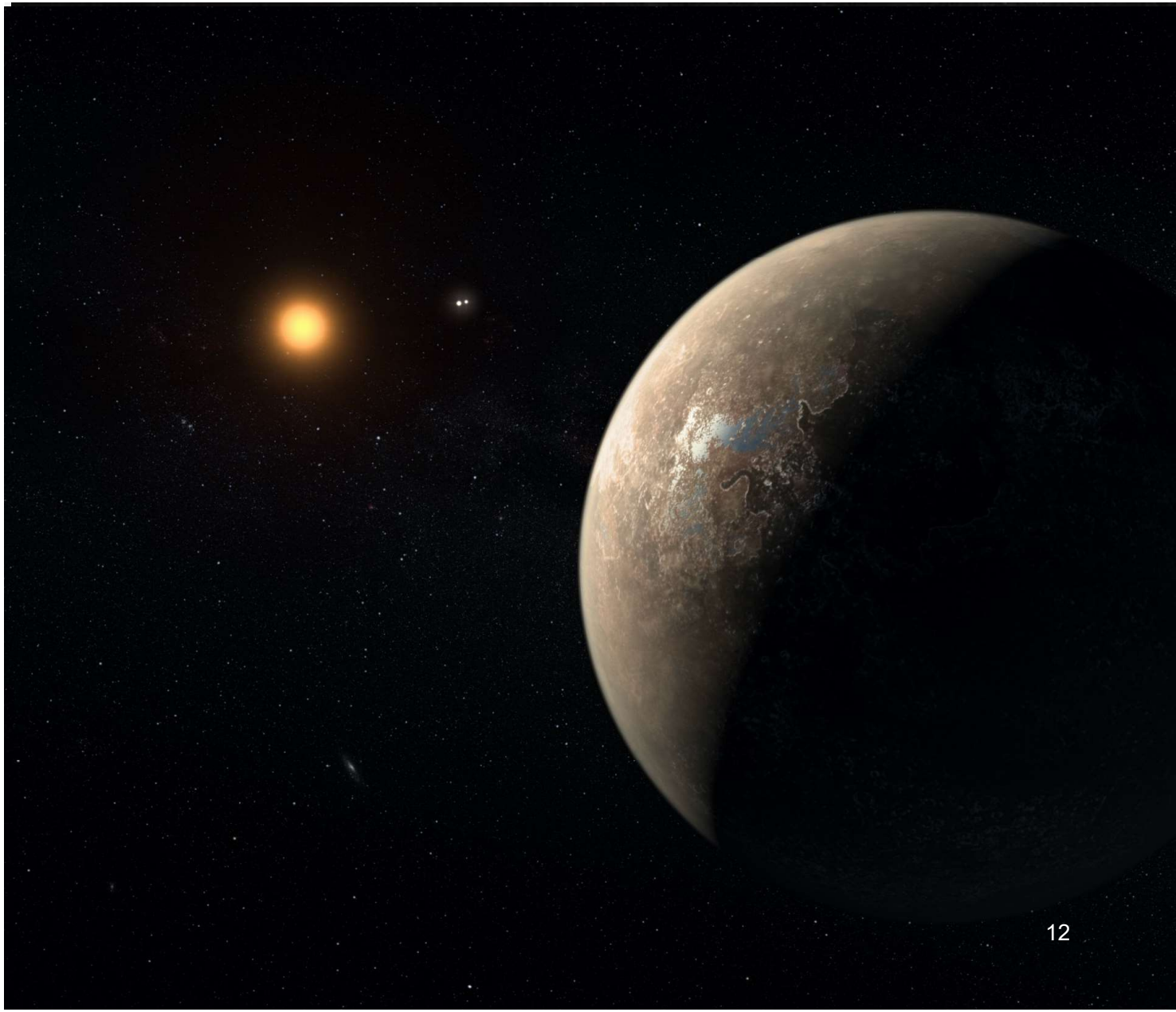

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Methodology

Two phase approach:

Define departure system

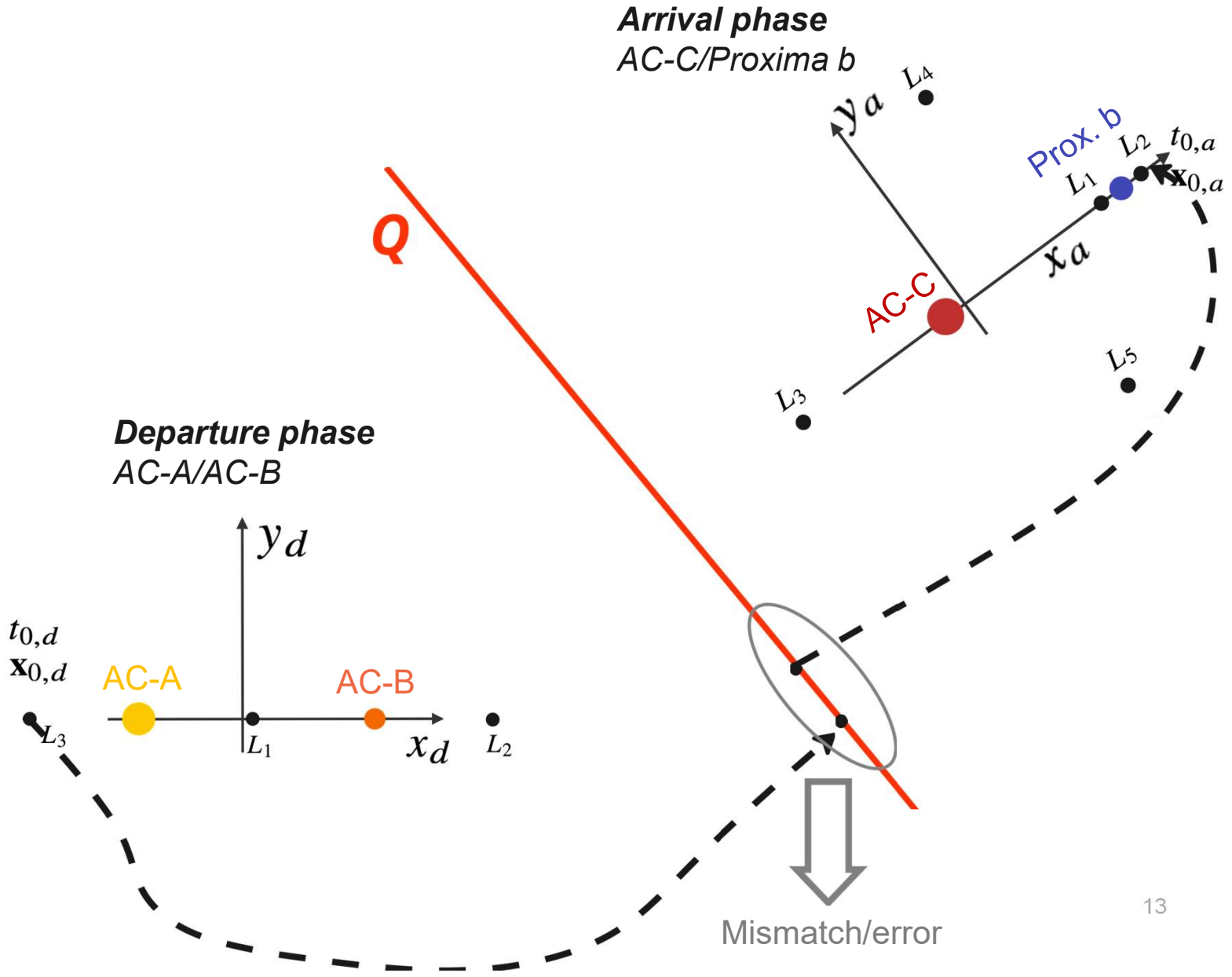
Define arrival system

Place section Q

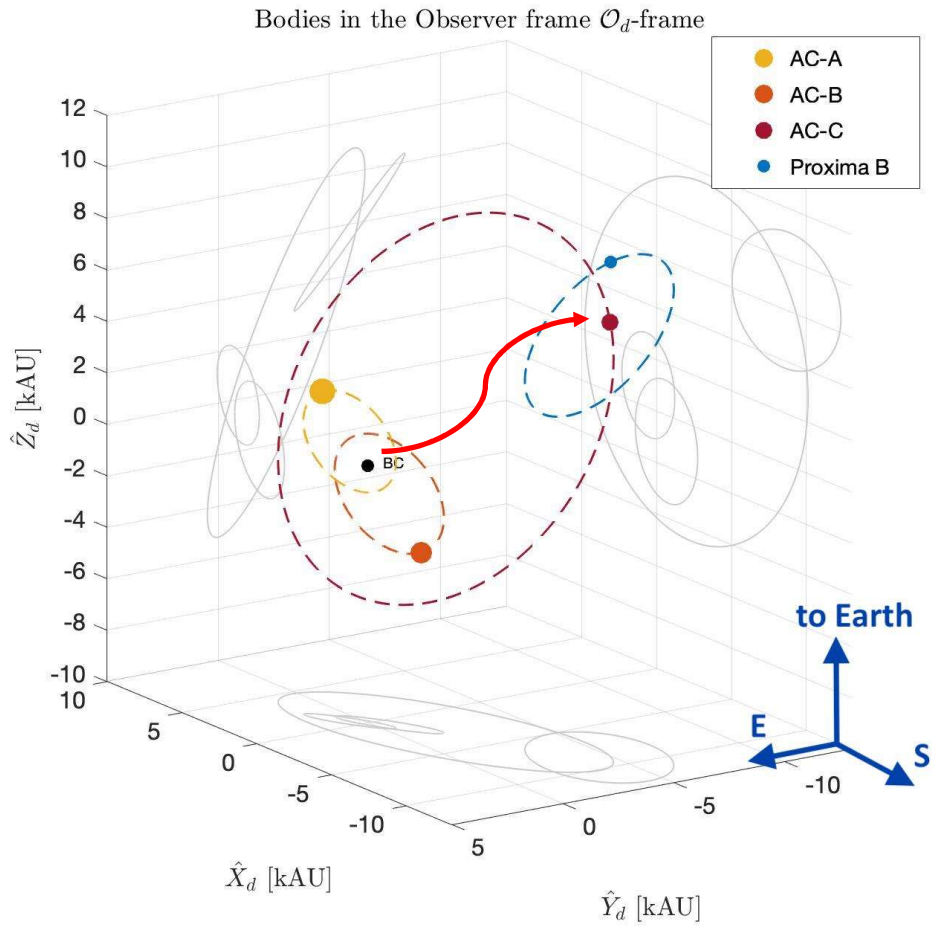
Compute departure trajectory

Compute arrival trajectory

Evaluate the mismatch/error



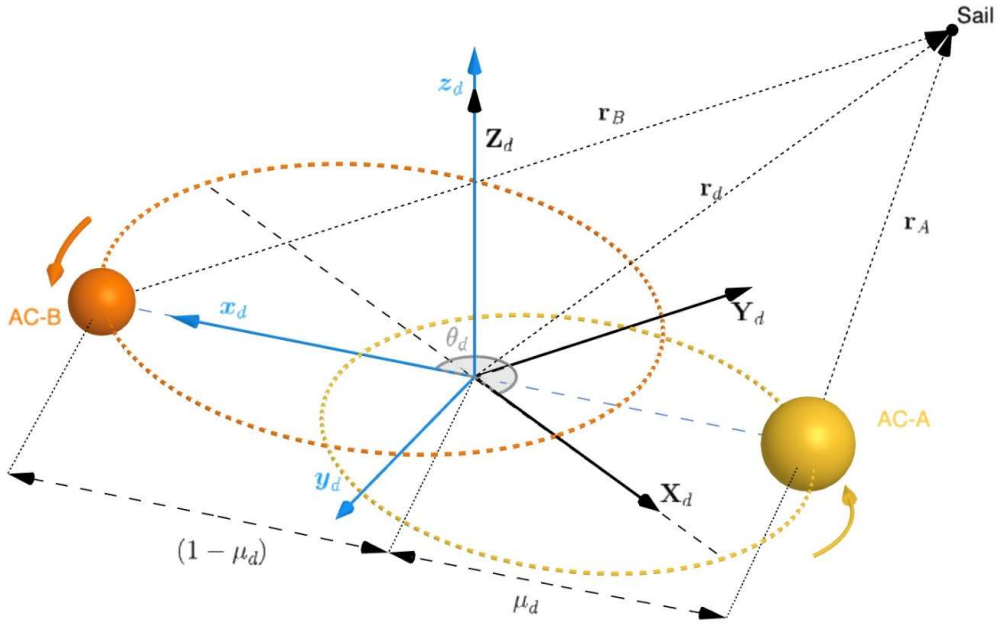
Methodology



Dynamical model

Elliptic restricted three-body problem (ERTBP)

- Describes the motion of a massless particle relative to 2 large masses
- 2 large masses move in elliptic orbits about the barycenter
- Motion described using a rotating, dimensionless frame
- Can be augmented by a photon sail



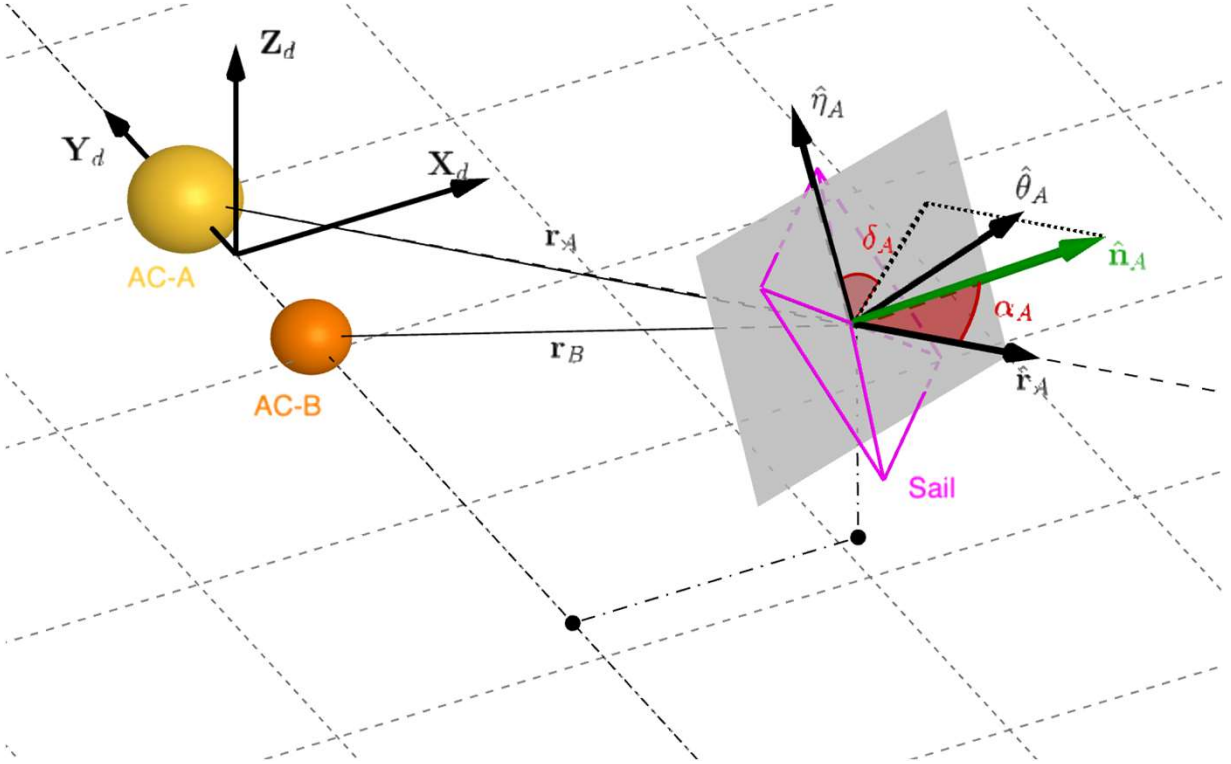
Photon-sail model

Ideal sail model

- Perfectly reflecting sail
- No absorption, re-rediation, or wrinkles

Sail attitude and efficiency

- Cone angle α
- Clock angle δ
- Lightness number β



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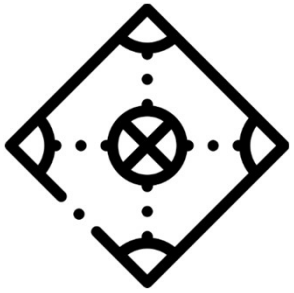
Sail configurations

Sail 1



One-sided

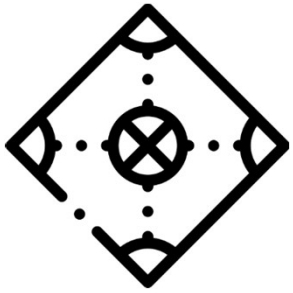
β = 100

25x25 m

Graphene sail

10 gram payload

Sail 2



Double-sided

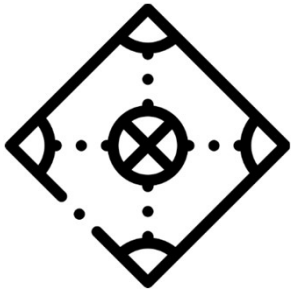
β = 100

25x25 m

Graphene sail

10 gram payload

Sail 3



One-sided

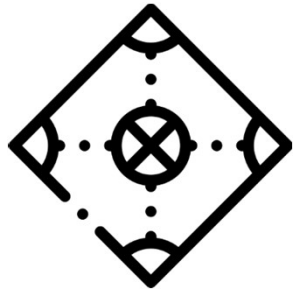
β = 1779

315x315 m

Graphene sail

10 gram payload

Sail 4



Double-sided

β = 1779

315x315 m

Graphene sail

10 gram payload

Current technology allows for β = 0.01-0.05 !!

7.6e-4 g/m2

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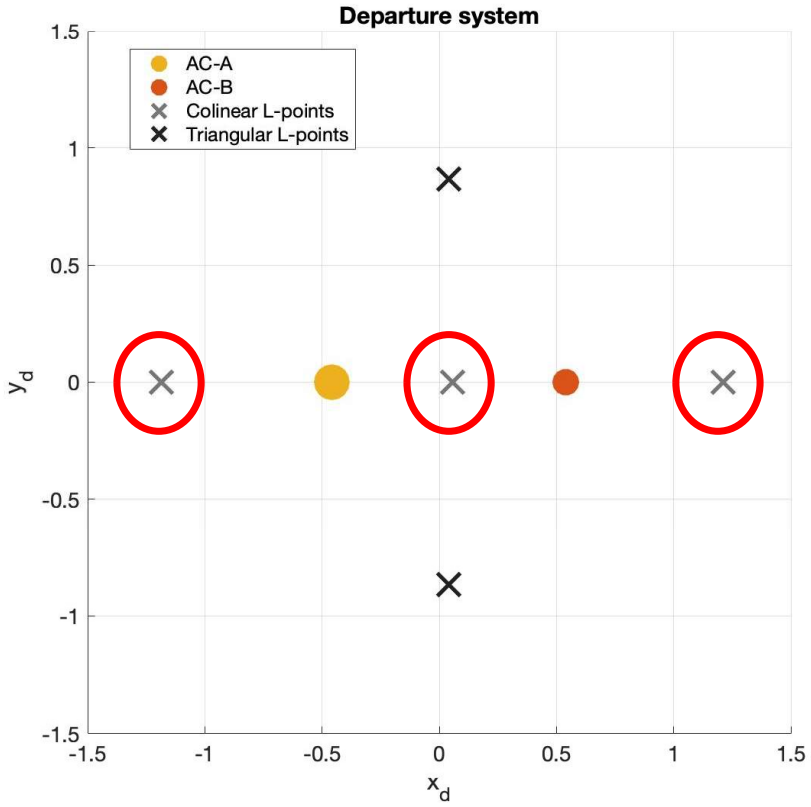
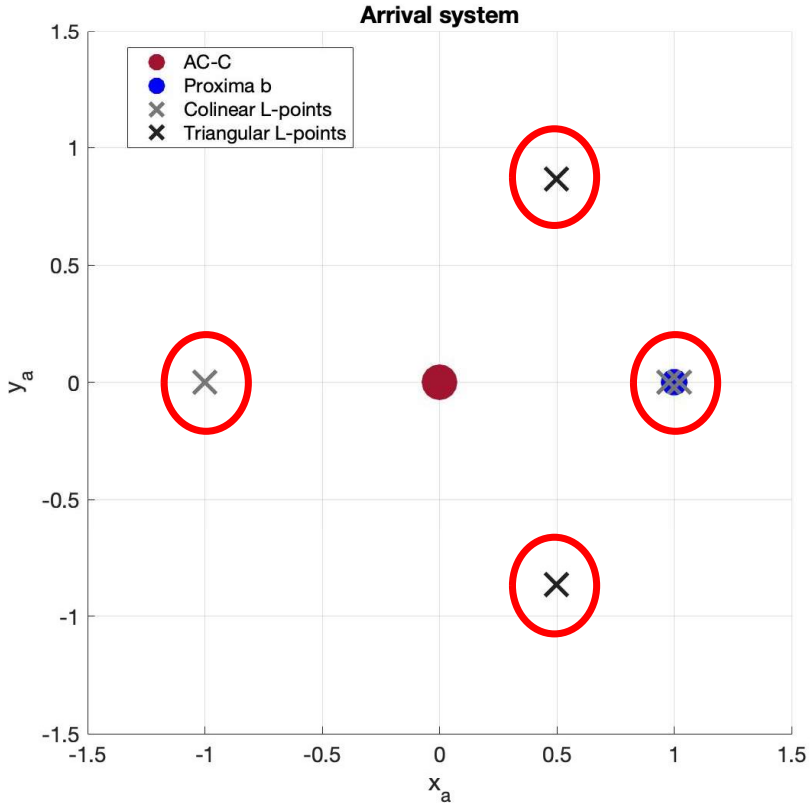
Departure/arrival locations



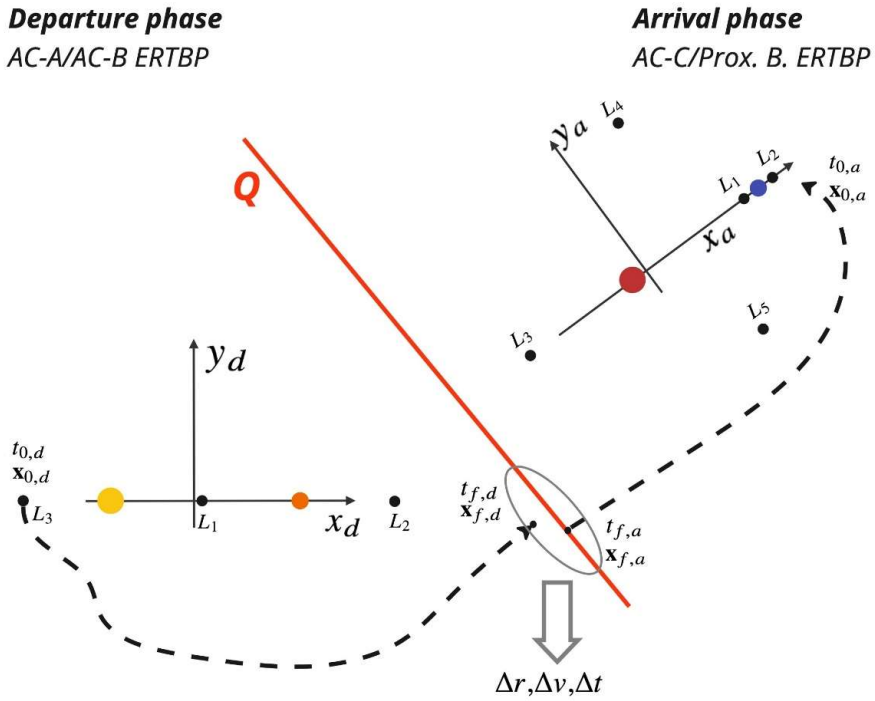


Optimization problem

- Connecting the *departure* phase with the *arrival* phase
- Constant sail attitude
- Evaluation at surface Q:
  - Position mismatch Δr
  - Velocity mismatch Δv
  - Time mismatch Δt

Two optimization techniques

- Grid search
- Genetic algorithm



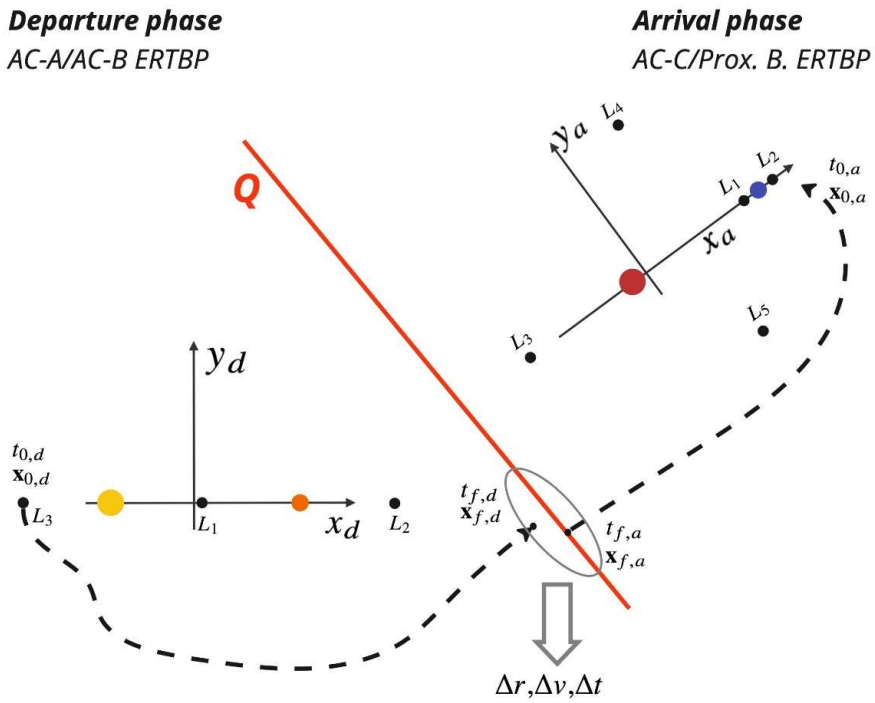
Optimization problem

6 decision variables: $\left[\ \alpha_A \quad \alpha_C \quad \delta_A \quad \delta_C \quad t_d \quad t_a\ \right]$

Cone angle during departure/arrival

Clock angle during departure/arrival

Departure/arrival times



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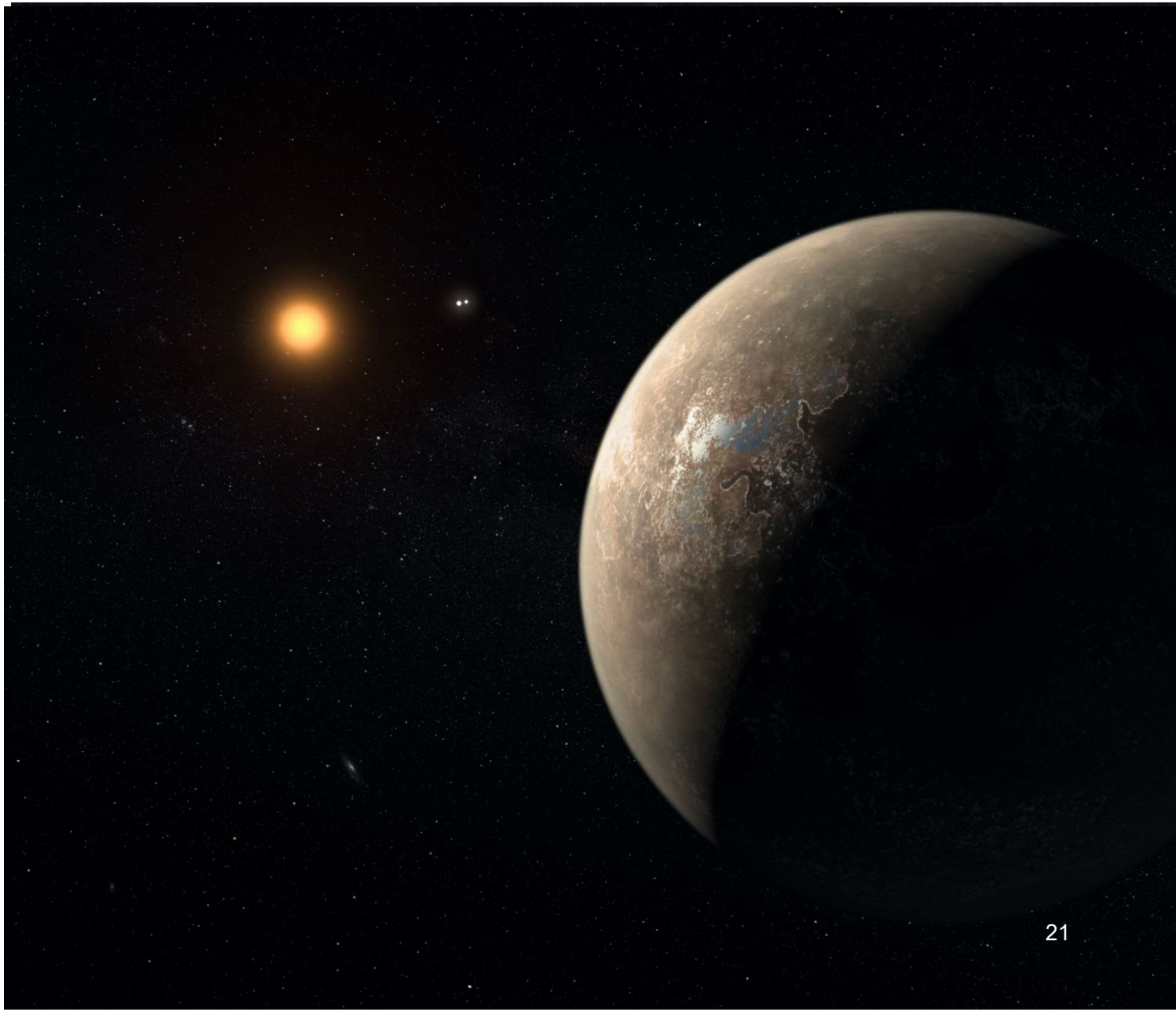

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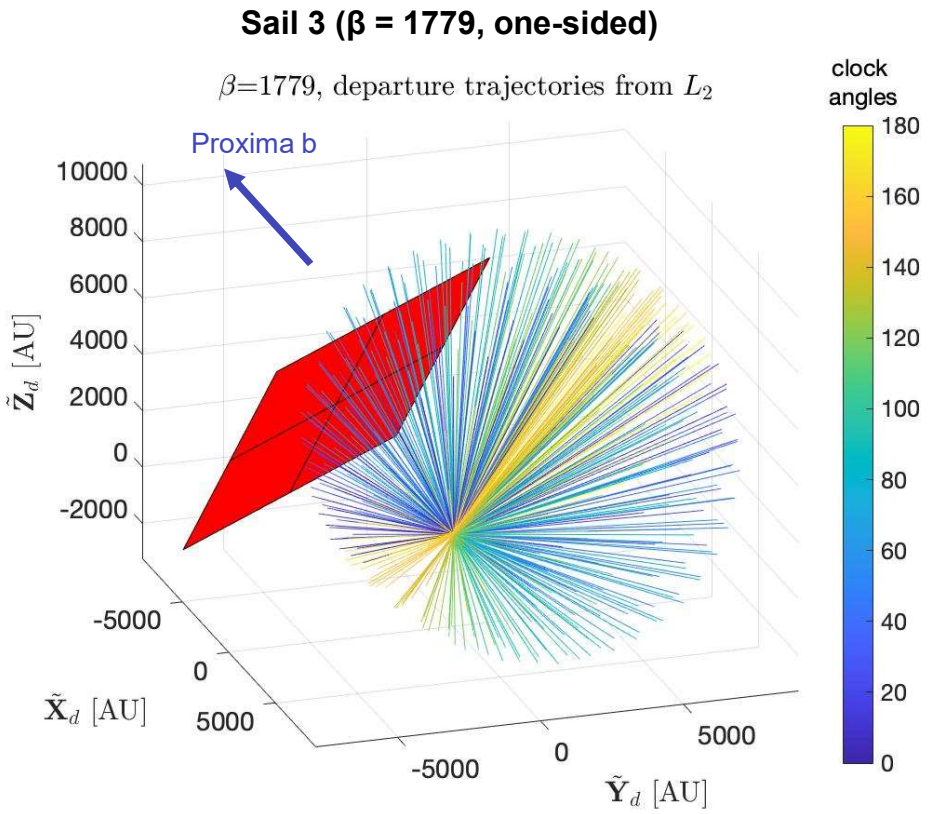
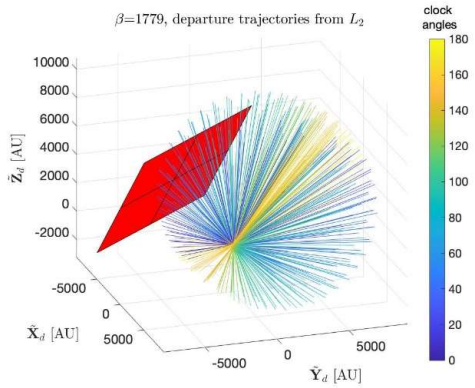
Results grid search (departure system)

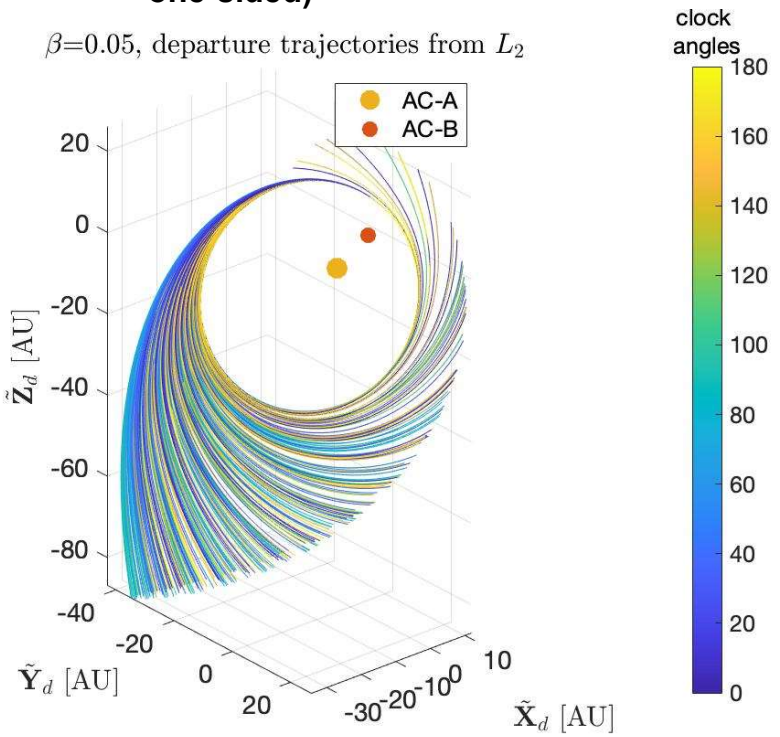


Results grid search (departure system)

Sail 3 (β = 1779, one-sided)



Currently feasible sail (β = 0.05, one-sided)



Results grid search – preliminary conclusions

Velocity mismatch difficult to overcome

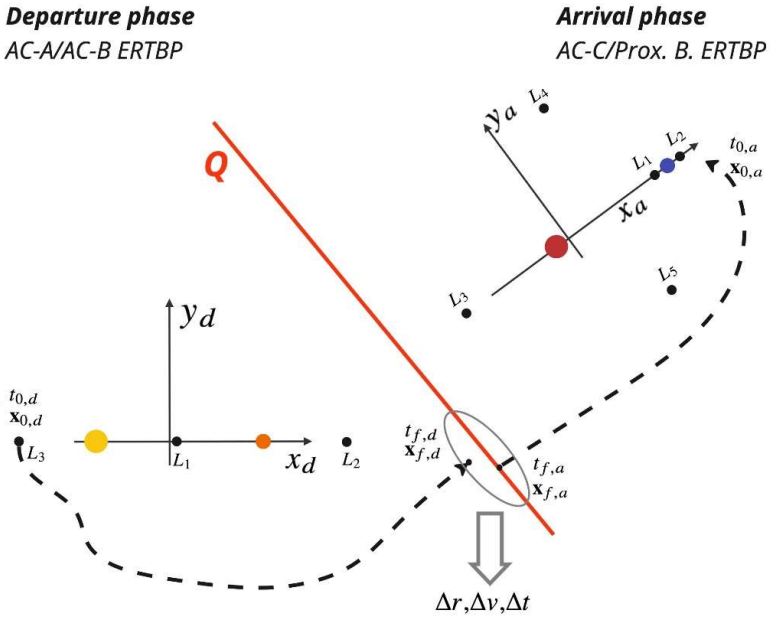
- Acceleration of the sail in the departure system much larger than the deceleration in the arrival system
- Due to the different compositions of the systems

Departure location is of large influence on the results

The addition of a double-sided reflective sail does not add value over a one-sided sail

Most promising connection for sail 1: L_2-point in AC-A/B to the L_1-point in AC-C/Prox b

Most promising connection for sail 3: L_2-point in AC-A/B to the L_3-point in AC-C/Prox b

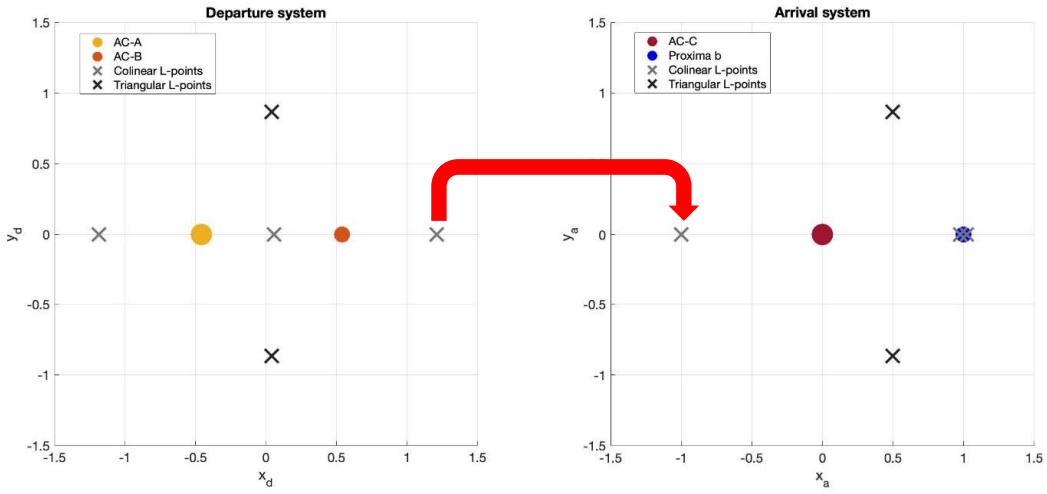


Results genetic algorithm

Best trajectory for sail configuration 3 (fastest transfer trajectory)

- One-sided
- β = 1779
- 315x315 m
- Graphene sail
- 10 gram payload

From the L_2-point in AC-A/B to the L_3-point in AC-C/Proxima b



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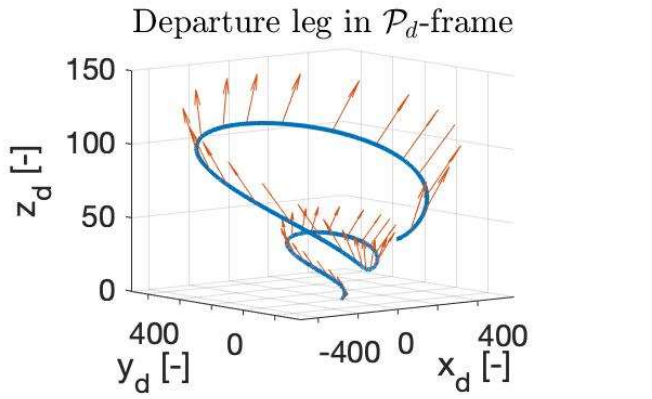
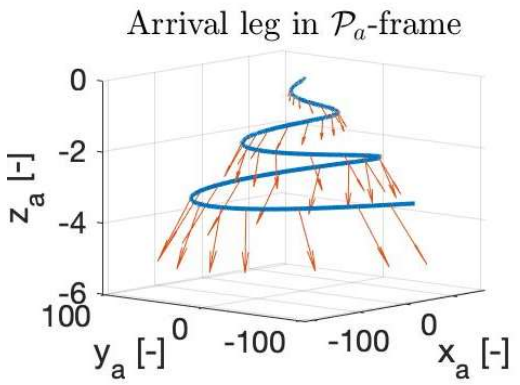
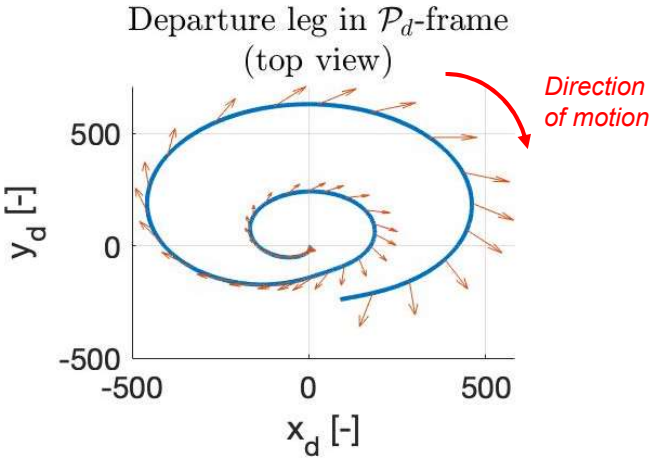
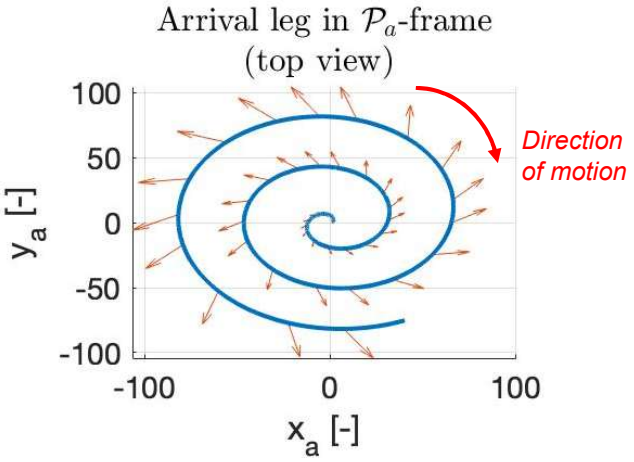
Results GA – sail configuration 3

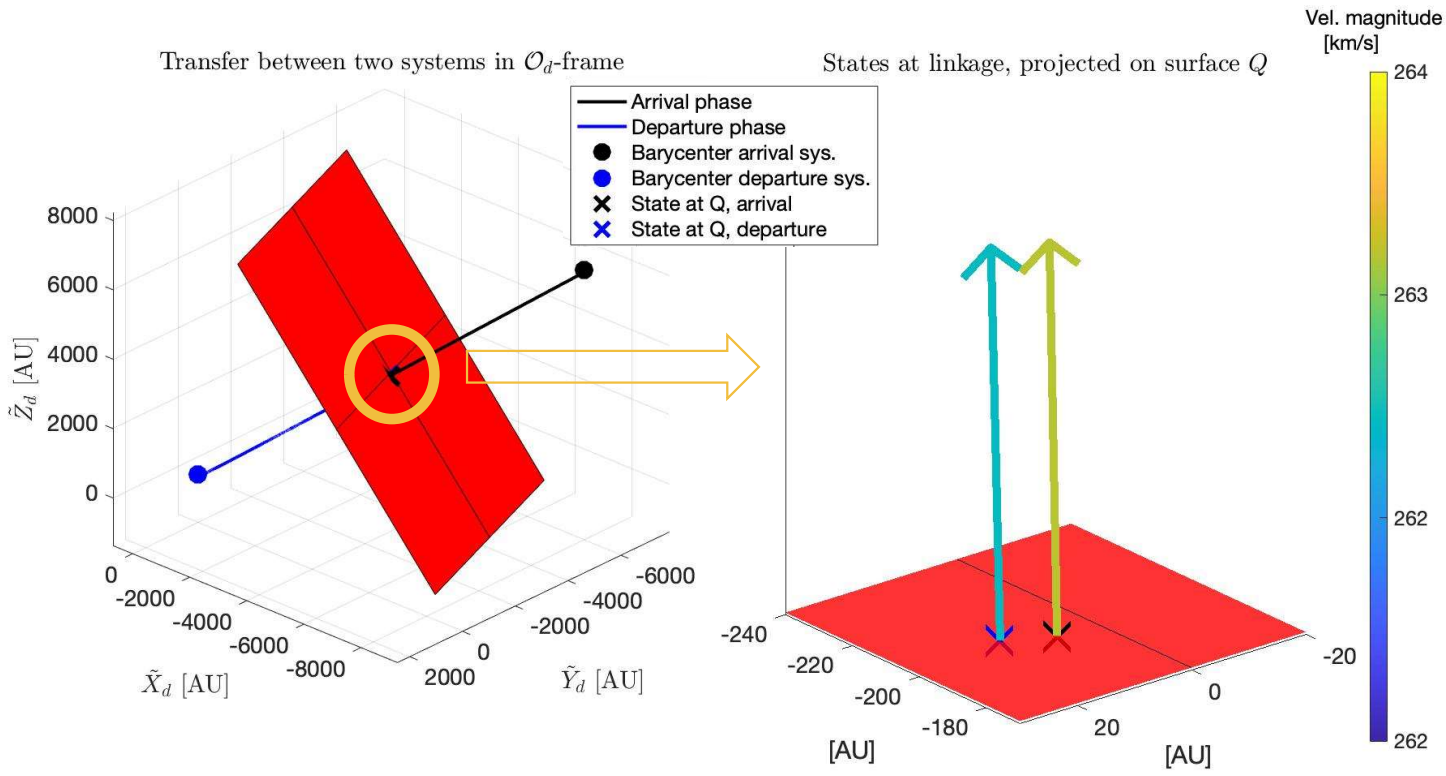








Results GA – sail configuration 3



Best transfer

Sail configuration 3

- Departure from AC-A/AC-B in *2144*
  Arrival at AC-C/Proxima b in *2379*
- Total transfer time 235 years
- Remaining link errors:
  - Position Δr = *9 AU*
  - Velocity Δv = *761 m/s*
  - Time Δt = *161 days*

Sail configuration 1

- Departure from AC-A/AC-B in *2143*
  Arrival at AC-C/Proxima b in *3168*
- Total transfer time 1025 years
- Remaining link errors:
  - Position Δr = *70 AU*
  - Velocity Δv = *236 m/s*
  - Time Δt = *281 days*

Considered small compared to:

- Total distance travelled (~13,000 AU)
- Velocity on Q (57,000 – 263,000 m/s)
- Total travel time (235 – 1025 yrs)

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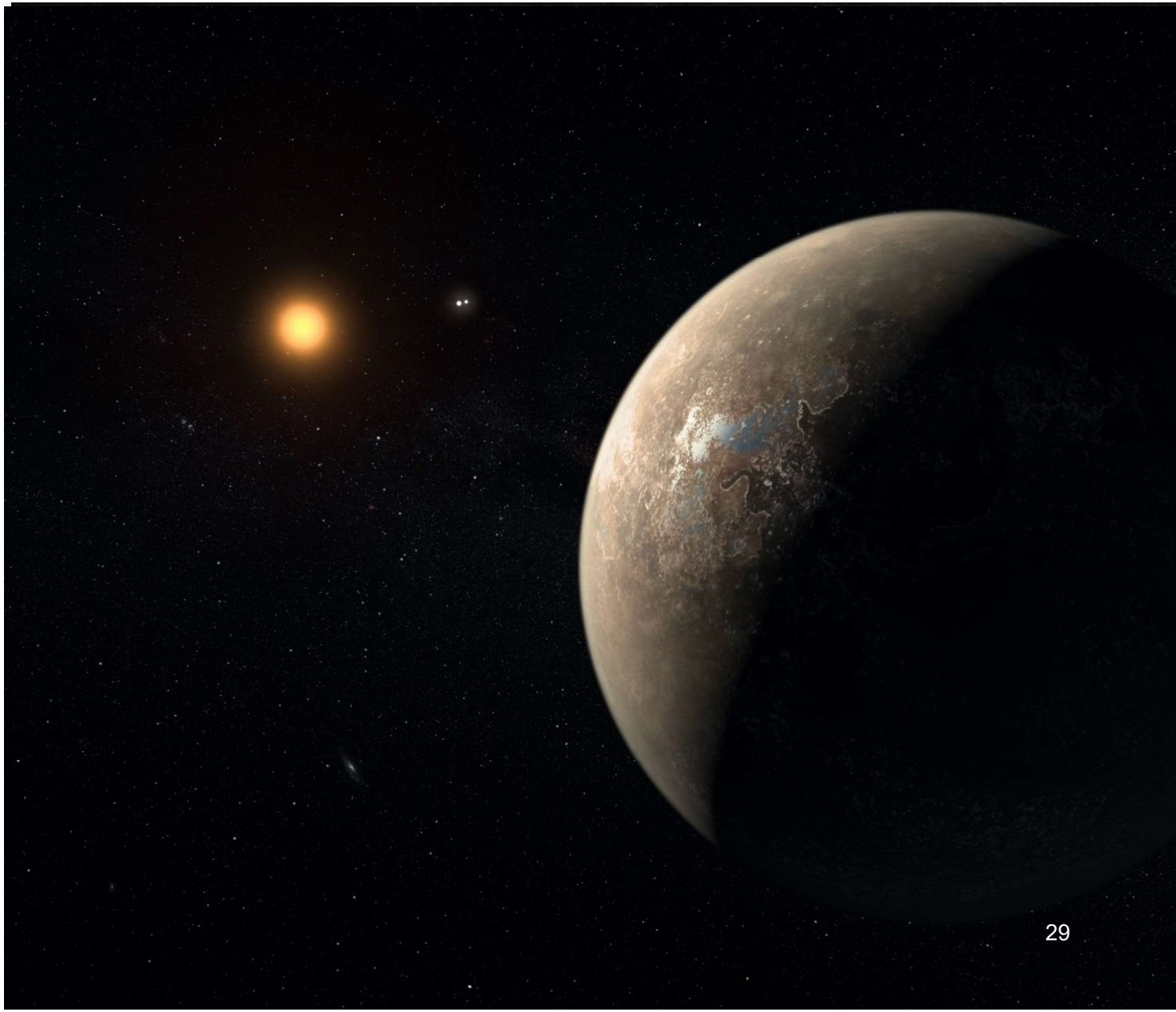

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Conclusions

- This research proved that it is possible to find transfers to Proxima b using photon-sail augmented heteroclinic connections
- The best solutions found contained small remaining errors relative to the total distance travelled, the velocity on surface Q and the total travel time
- A very futuristic sail configuration is needed to keep the transfer times reasonable
- The combination of applying a grid search and a genetic algorithm proved to be an efficient method that gave both a good insight in the problem and was capable of finding (sub-)optimal solutions
- The different nature of the two systems (considering luminosity's, one or two stars, mass of the stars) make that especially finding a proper velocity link is challenging
- The best suitable Lagrange point in the departure system is the L2 point, limiting the velocity build-up during departure phase
- The introduction of a double-sided reflective sail did not prove to have any benefit over a one-sided sail in the current methodology


Questions?

Limitations

- Missing/uncertain data about Alpha Centauri
- Sail degradation over time
- Sail technology
- Suitable optimization tool