POLITECNICO MILANO 1863 | DEPARTMENT OF AEROSPACE SCIENCE AND TECHNOLOGY

COMPASS

Modeling of Debris Mitigation Strategies to Support Evidence-Based Decision-Making

03 June 2026 | **Alex Shi, Martina Rusconi,** Ian Christensen, Peter Martinez, Camilla Colombo

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Green Species

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Overview

- Motivation and Research Objectives
- Methodology
- Simulation Setup
    - Scenarios and Parameters
    - Objective Functions
- Results and Discussion – Findings & Limitations
- Conclusions and Future Work

Motivation and research objectives

Motivation

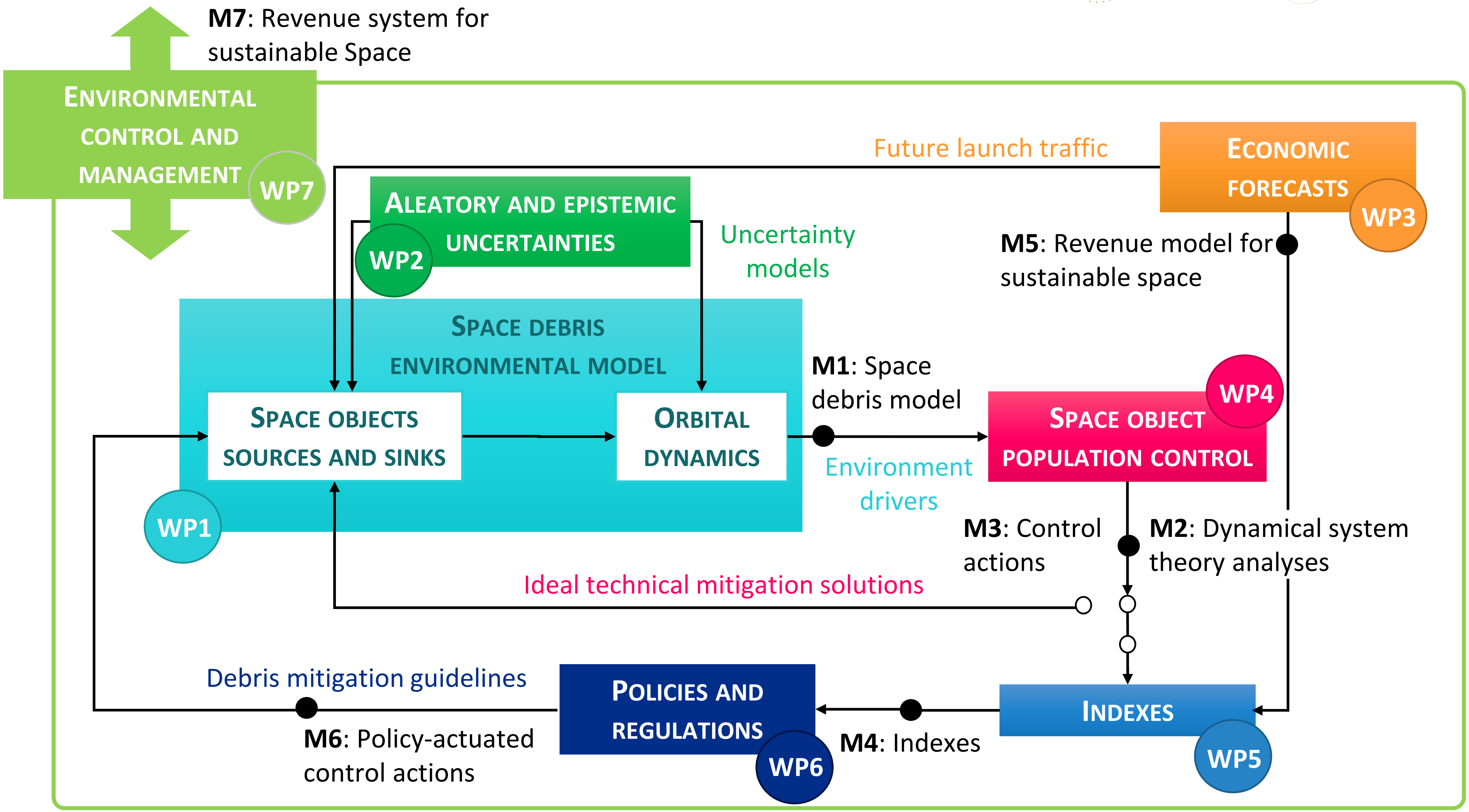
- Space activity has been growing rapidly, contributing to **orbital congestion** risks
- **Policy** and **operational debris mitigation strategies have not kept pace** with this growth
- Debris evolution models exist, but **link to policy and operator decision-making** can be strengthened

Research objectives:

Model and test debris mitigation strategies (e.g., post mission disposal/PMD) guided by a control model under **different operating scenarios**

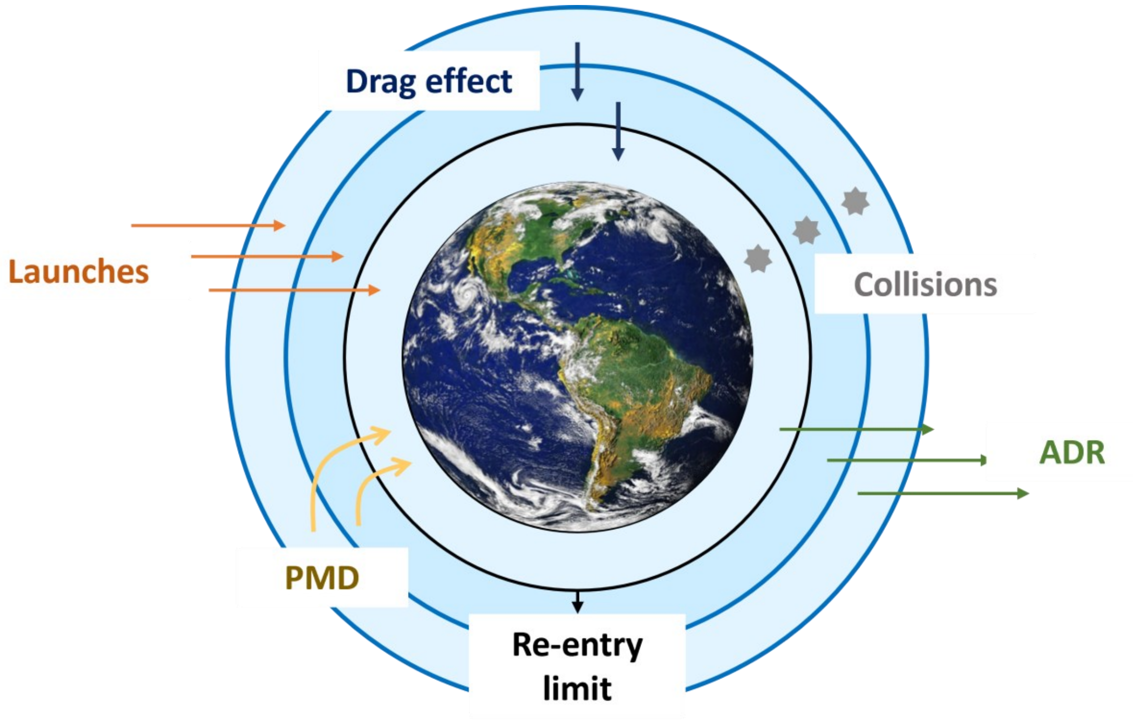
Measure and **quantify mitigation outcomes**

Enable **evidence-based decision-making**, including calibration of debris mitigation policies and operations


M7: Revenue system for sustainable Space
ENVIRONMENTAL CONTROL AND MANAGEMENT
WP7
Future launch traffic
ECONOMIC FORECASTS
WP3
ALEATORY AND EPISTEMIC UNCERTAINTIES
WP2
Uncertainty models
M5: Revenue model for sustainable space
SPACE DEBRIS ENVIRONMENTAL MODEL
SPACE OBJECTS SOURCES AND SINKS
ORBITAL DYNAMICS
WP1
M1: Space debris model
WP4
SPACE OBJECT POPULATION CONTROL
Environment drivers
M3: Control actions
M2: Dynamical system theory analyses
Ideal technical mitigation solutions
Debris mitigation guidelines
POLICIES AND REGULATIONS
WP6
INDEXES
WP5
M6: Policy-actuated control actions
M4: Indexes

Methodology

Space debris population control



Density-based 1-D approach

- Balance of the spatial density in time
- One-dimensional model in orbital radius

Density variation in a shell = Atmospheric drag dynamics + Sources − Sinks

Number of objects categories per shell

3
- Active objects
- Inactive objects
- Fragments

Methodology

Space debris population control

i^{th} shell

Active objects (ao)

$$\frac{dn_{ao_i}}{dt} = - \boxed{\text{Colliding object}} + \boxed{\text{Launches}} - \boxed{\text{Objects at EOL}}$$

Inactive objects (io)

$$\frac{dn_{io_i}}{dt} = \boxed{\text{Atmospheric drag dynamics}} - \boxed{\text{Colliding object}} + (1-\lambda)\boxed{\text{Objects at EOL PMD}} - \alpha\boxed{\text{ADR rate}}$$

Fragments (f)

$$\frac{dn_{f_i}}{dt} = \boxed{\text{Atmospheric drag dynamics}} + \boxed{\text{Fragments from collision}} - \boxed{\text{Colliding fragments}}$$

PMD λ
Two contributions

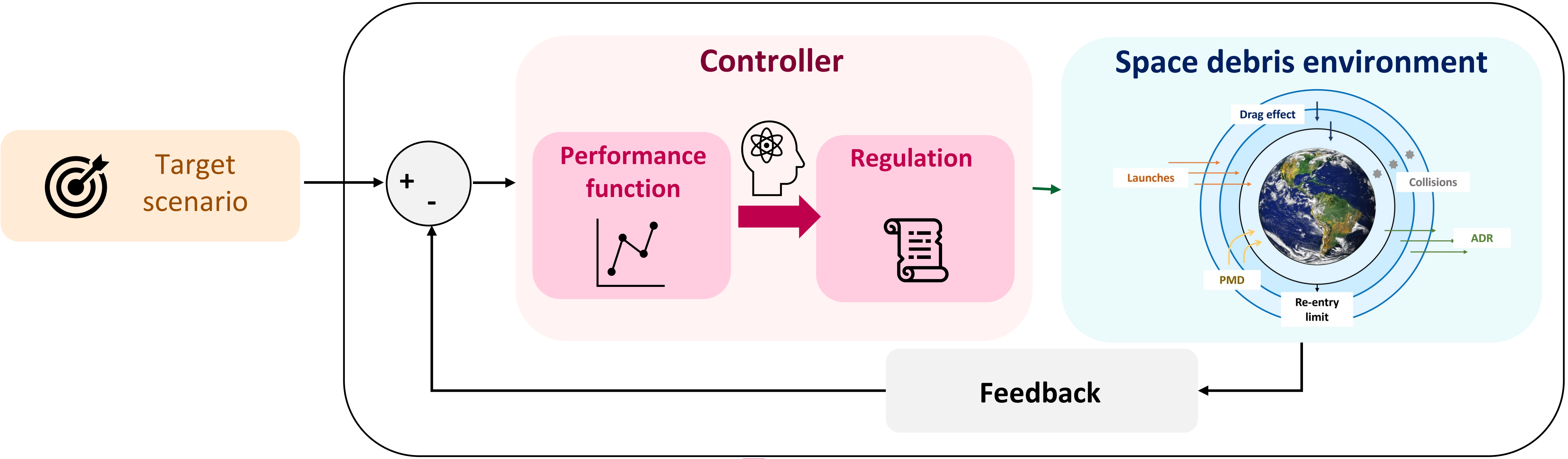
λ_{RE}
Direct re-entry
Objects at EOL are removed from the environment

λ_{RO}
PMD de-orbit
Objects at EOL are relocated to lower altitude for re-entry within a prescribed time

Mitigation inputs

Methodology

Space debris population control



Ideal long-term mitigation strategy to reach the target scenario

PMD re-orbit and direct re-entry application in space and time

Balance mitigation cost and distance from target

Scenarios and Parameters

Launch traffic for fringe/non-constellation payloads (L)

L1: Stabilized launch activity (e.g., benchmarked to recent launch rates)
Assumes space demand has plateaued
L2: Growing launch activity (e.g., exponential growth model)
Assumes space demand will continue to grow

PMD re-entry time limit (P)

P1: De-orbit limit = 25 years

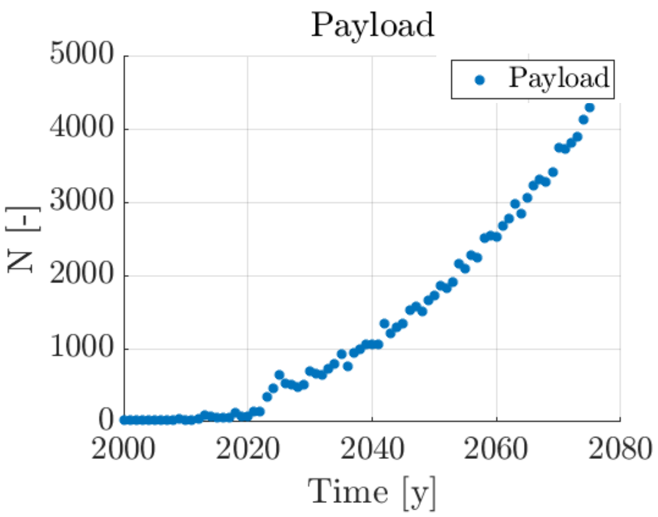
P2: De-orbit limit = 5 years

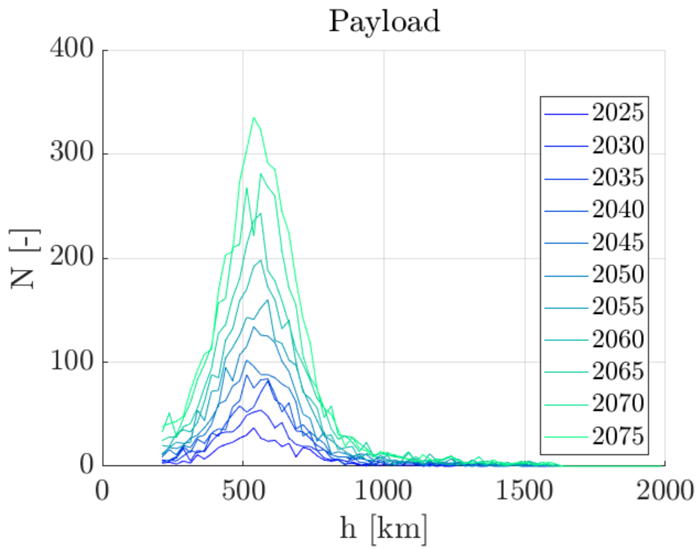
4 scenario types: L1 x P1, L1 x P2, L2 x P1, L2 x P2

Parameter	Value
Orbital region	LEO
Number of objects categories	3 (Active intact objects, Inactive intact objects, Small fragments)
Initial population	01-2025 objects population from DISCOS and debris data from MASTER
Operational lifetime *Lifetime and launch profile set individually for each category*	• Rocket bodies: 1 y • Constellation payloads: 5 y • Non-constellation payloads: 8 y
Collision avoidance maneuver (CAM) efficiency	• 95%
Altitude band width	• 25 km
Simulation time	• 50 years
Control input	**PMD de-orbit and direct re-entry success of active intact objects**

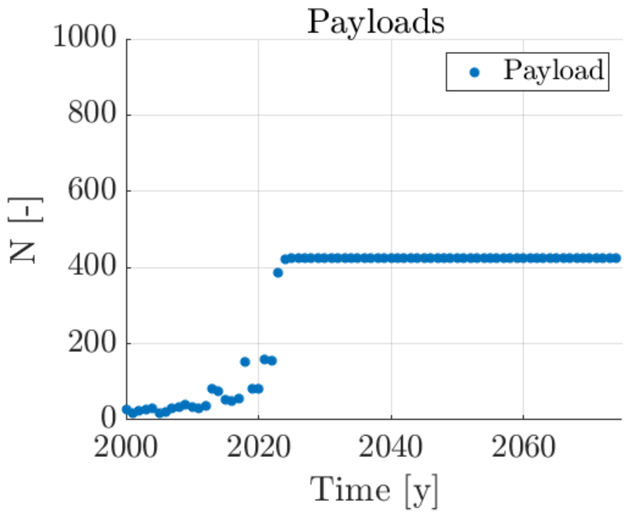
Launch traffic for non-constellation payloads

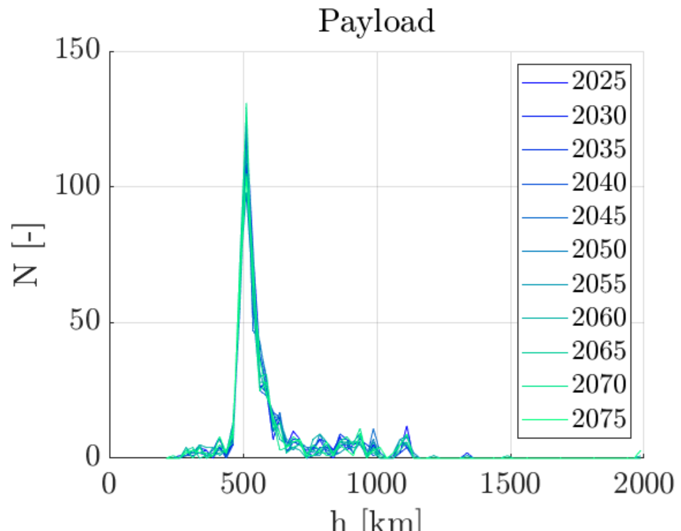
Growing launch activity (L2)





Stabilized launch activity (L1)





Assumptions for L1 & L2:

- Constellation launch rates assumed to be the same (complete and replenish 2025 catalog)
- Growth of rocket bodies assumed negligible (development of reusable vehicles etc.)

Objective functions

Cumulative collision probability for a nominal satellite mission

At each simulation time step

- **Representative satellite** launched into each 25-km altitude bin (Payload not belonging to constellation).
- **Cumulative collision probability** over the **satellite mission lifetime (P_c)** is computed, using the **current orbital population**

$$P_c = \underbrace{\int_{Op} P_{c_i}}_{P_c \text{ during operational phase}} + \alpha \underbrace{\int_{PMD} P_{c_i}}_{P_c \text{ following successful PMD}} + \underbrace{(1-\alpha)\int_{Fail} P_{c_i}}_{P_c \text{ following failed PMD}}$$

Residual Annual Collision Rate (ACR)

At each simulation time step

- **Representative manoeuvrable satellite** launched into each 25-km altitude bin, with user-defined CAM efficacy
- Residual ACR with CAM (*RRes*) is computed, using the **current orbital population**

$$RRes = (1 - \beta_{CAM})ACR$$

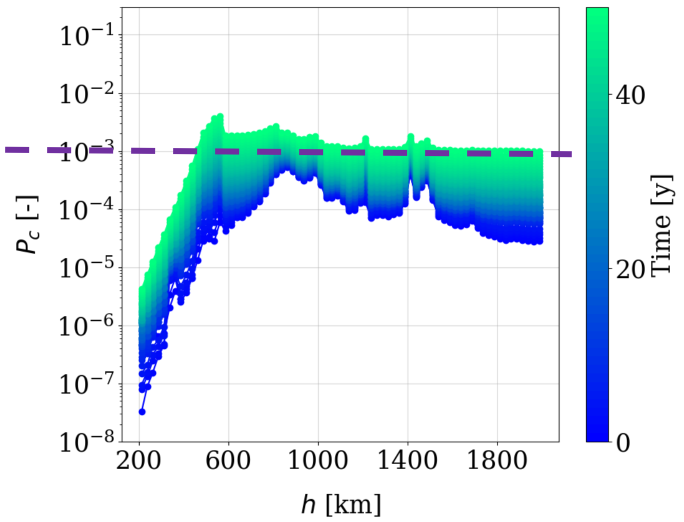
Objective function targets with controller input

Cumulative PC over satellite mission lifetime

- To keep below **regulatory threshold of P_c=1E-3** at all times
- Satellite mission lifetime = Operational + Inactive
    - Inactive: Considers both successful and failed PMD

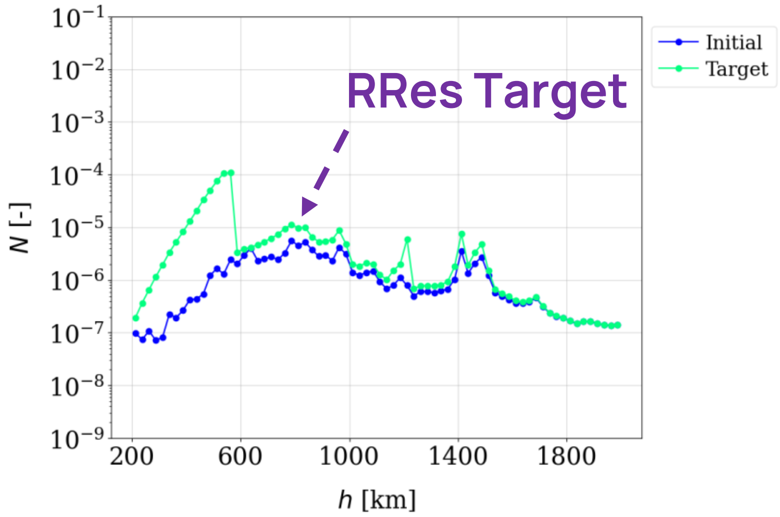
Example: L2 x P2

P_c=1E-3



Residual ACR

- To keep below **target *RRes* profile** at all times
- Defined as end-of-sim *RRes* profile with **99% CAM efficiency**
- Equivalent to asking: *What PMD strategy would it take to achieve a risk reduction equivalent (or close) to ra**ising CAM efficiency from 95% to 99%**?*
- Each scenario has a different target profile!



Other tracked metrics

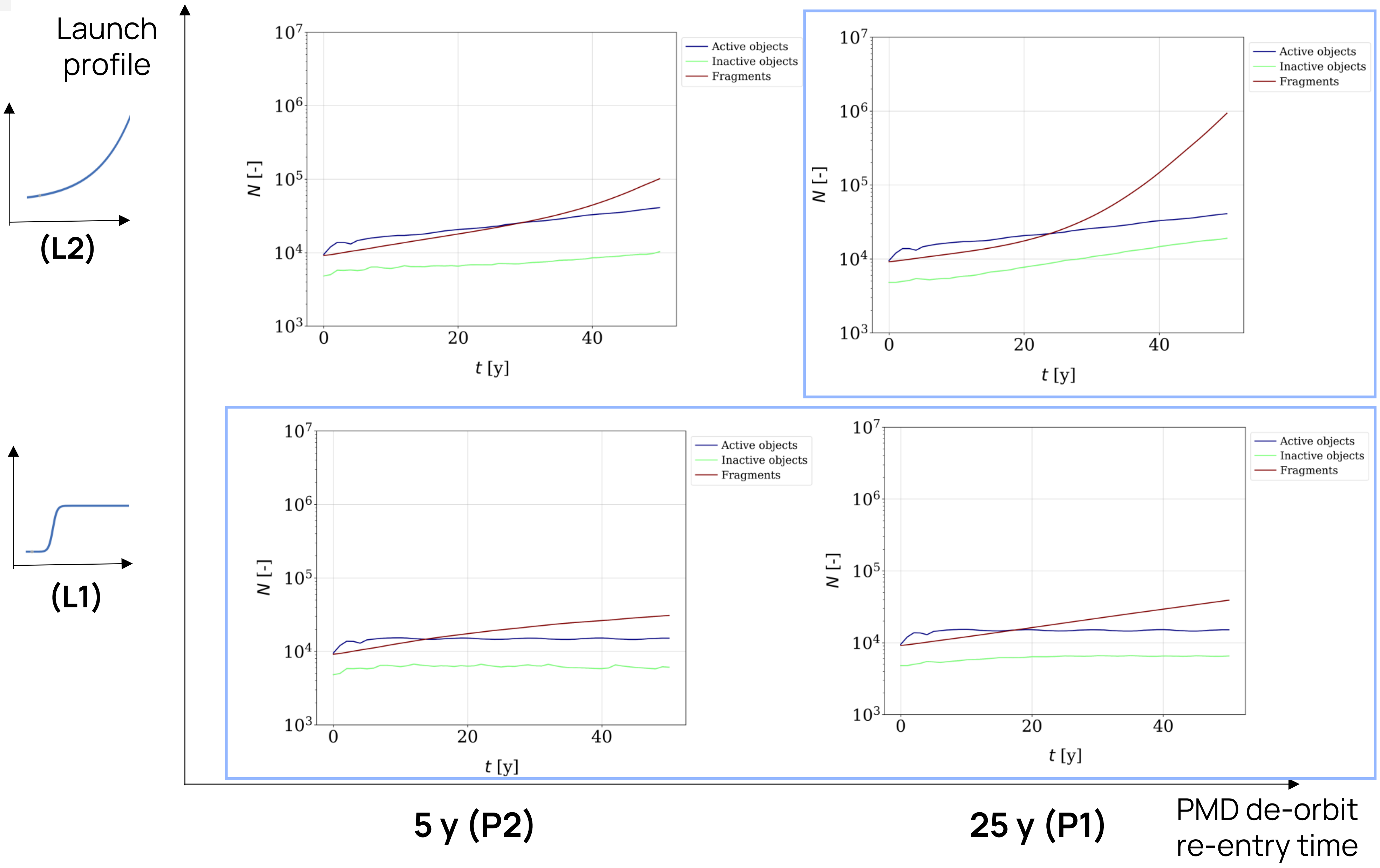
- **Number of objects**: Evolution of the total no. of active objects, inactive objects, and fragments
  - Gives a sense of **total orbital congestion**
- **Cost function values:** Evolution over time
  - Gives a sense of **how far the initial scenario is from the control target**: Effort required to meet (or approach) control target + final error
- **Annual number of objects de-orbited** (PMD and direct re-entry): Distribution by altitude band
  - Measures amount of "**control action**" at different altitudes
- **Annual CAM rate**: Distribution by altitude band
  - Gives a sense of **operational cost** at different altitudes

Simulation Results

Controlling for Cumulative PC

Number of objects

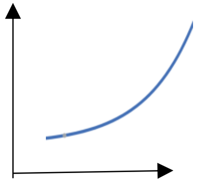
- In all scenarios, **fragments dominate** final orbital population
- Even if launch rates plateau (L1), fragments can increase due to collisions with existing objects
- Signs of **runaway population growth** in L2 x P1 scenario



Cost function value

- **Total cost = Controller effort + Residual PC**
- Higher cost: Larger gap between initial scenario and control target
    - 25-yr PMD (P1): Residual PC dominates
    - 5-yr PMD (P2): Control effort dominates
- Overall, L2 x P1 scenario considerably "worse" than others

Launch profile



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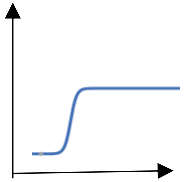

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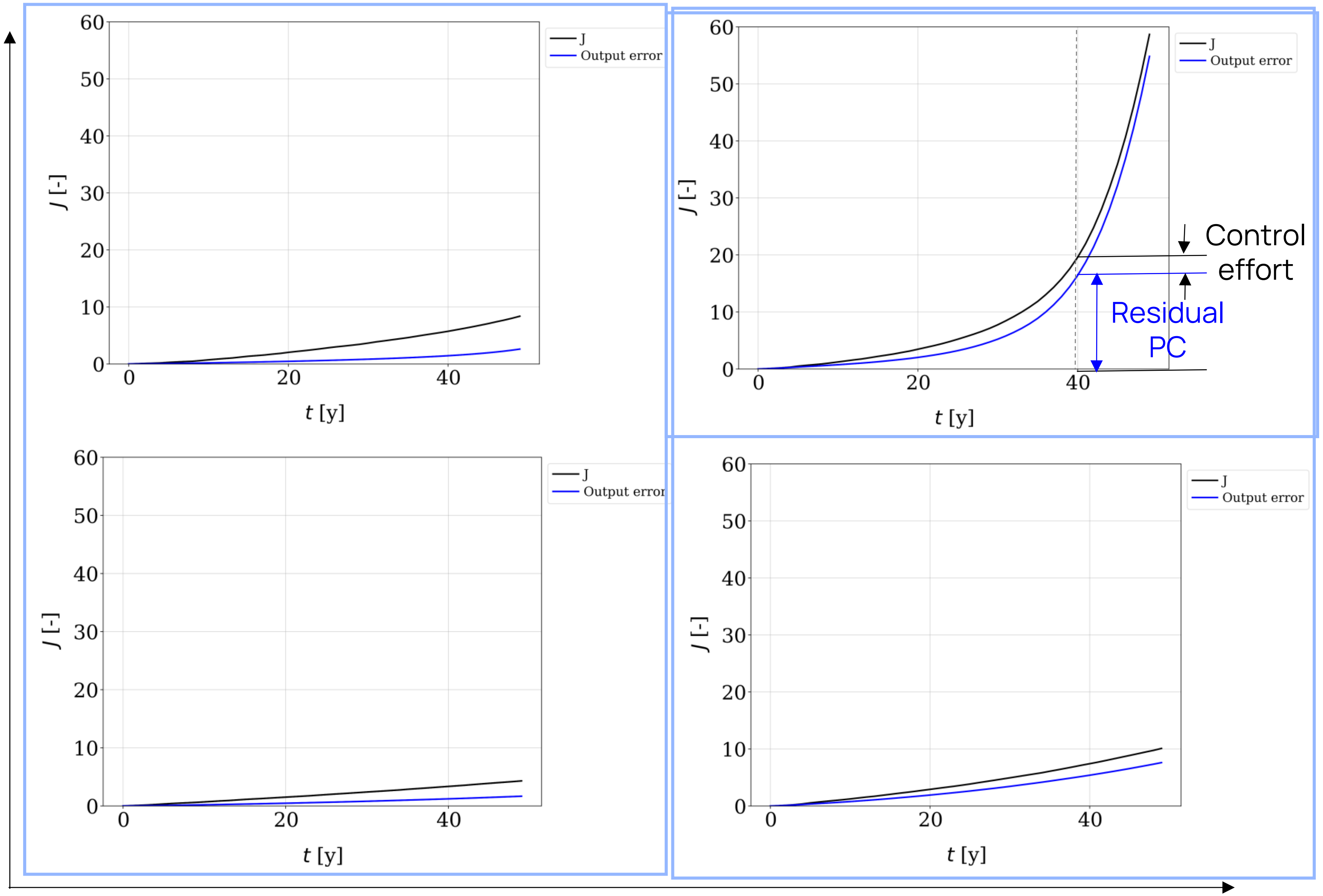


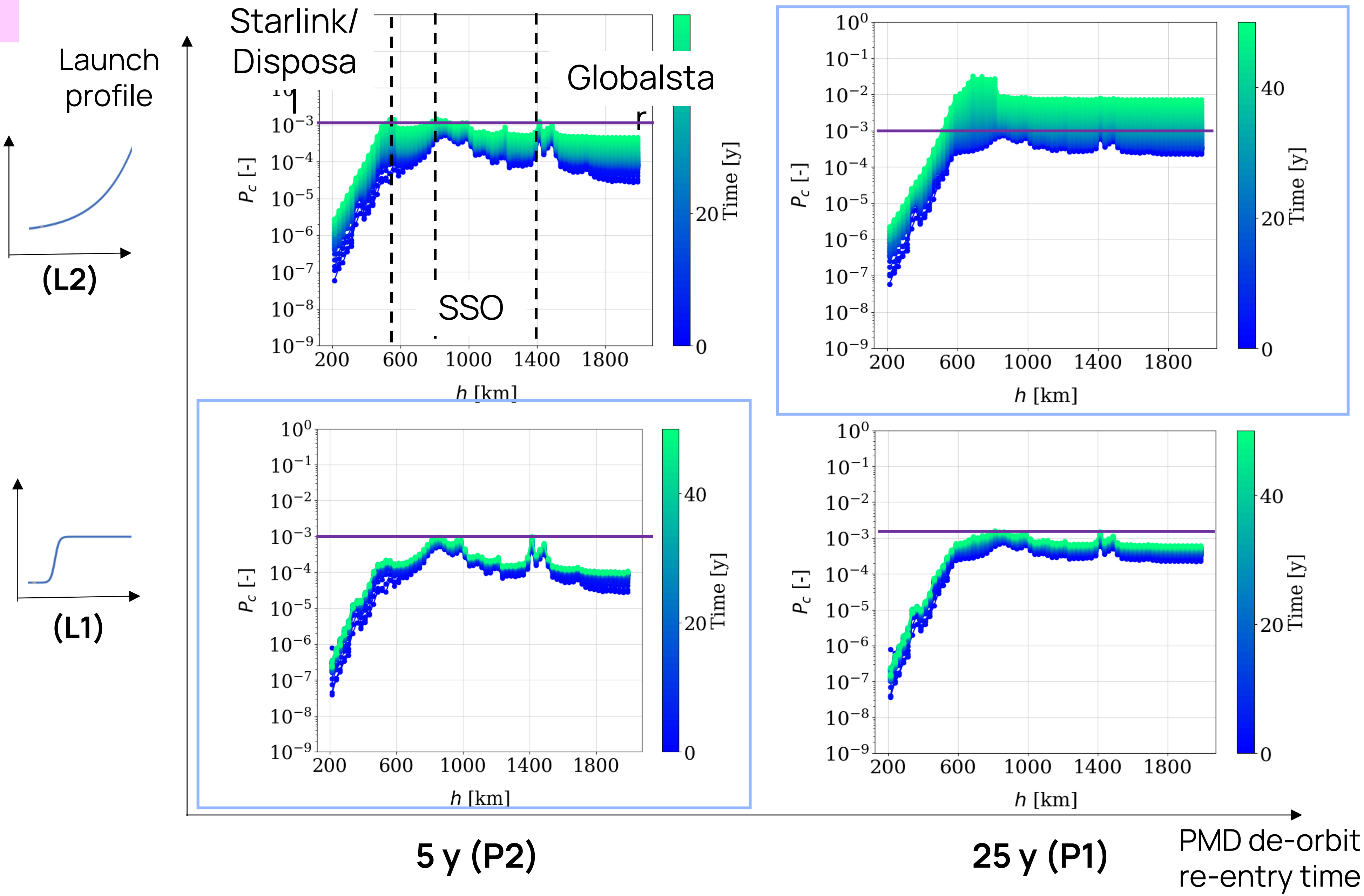
5 y (P2)

25 y (P1)

PMD de-orbit re-entry time

Cumulative PC

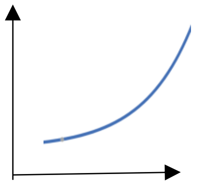
- 1E-3 PC target only **achievable in most optimistic scenario** (L1 x P2)
- Least optimistic scenario (L2 x P1): 1E-3 PC target **exceeded by Yr16**
- PC peaks correspond to
  - **550/675 km:** Starlink, Disposal altitudes
  - **800km:** SSO, debris
  - **1400km:** Globalstar



Distribution of Annual PMDs

- No PMD below disposal altitude
- PMD distribution tracks launch traffic distribution
- **Higher launch rate (L2): More objects to de-orbit**
- **Longer PMD limit (P1):** Controller limits PMD to **mitigate disposal orbit congestion**

Launch profile



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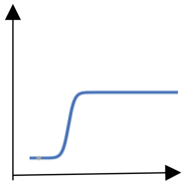

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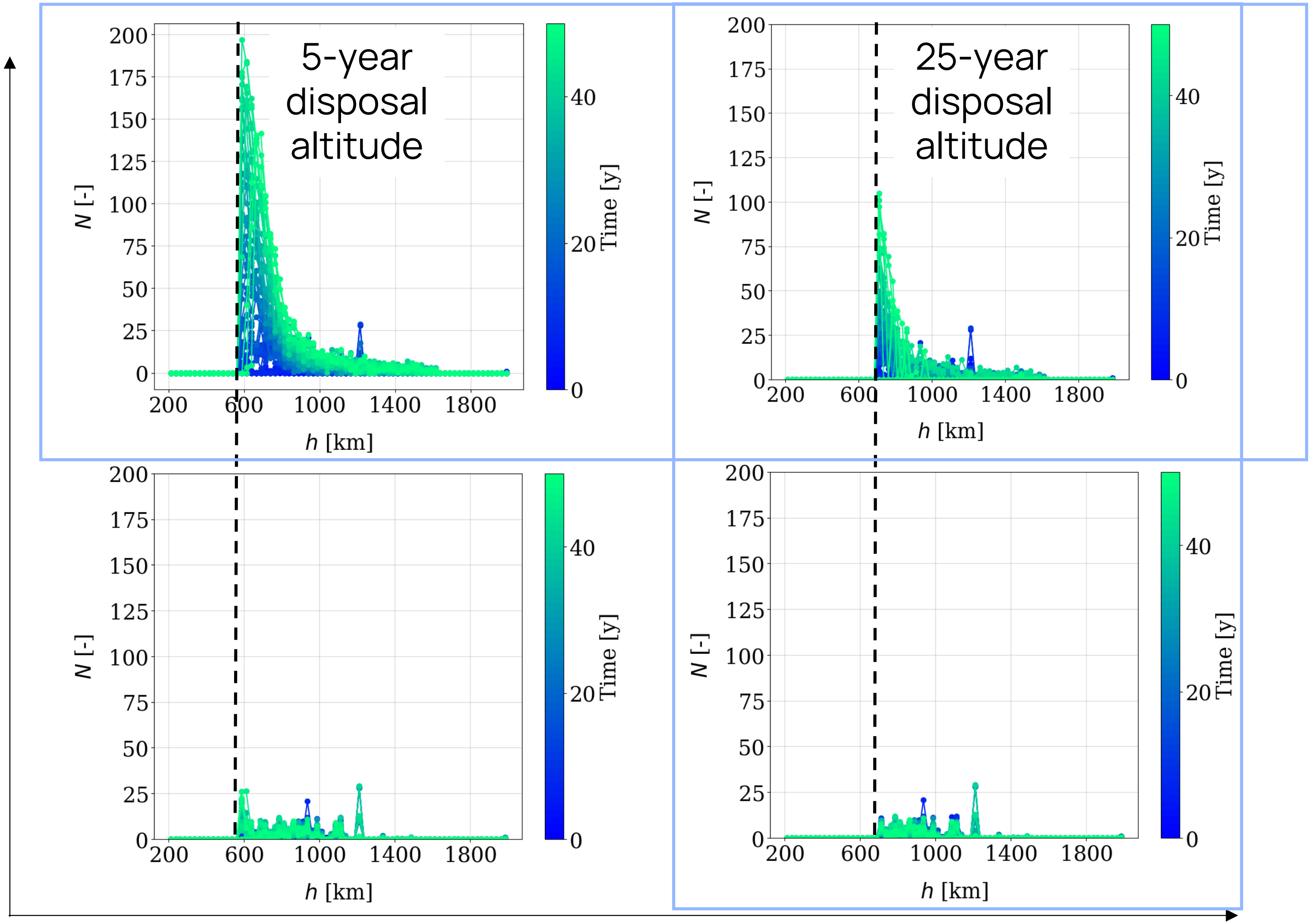


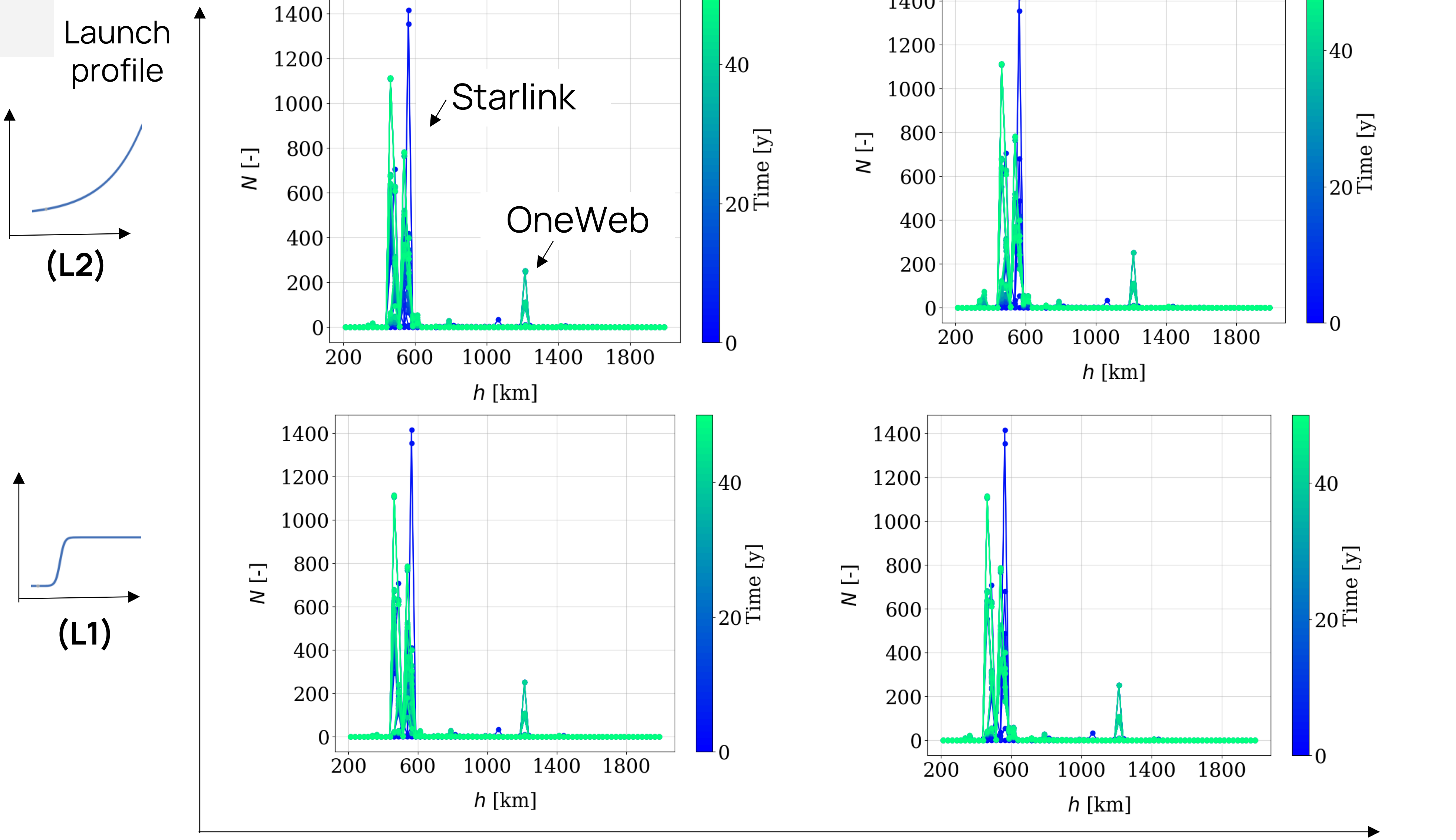
5 y (P2)

25 y (P1)

PMD de-orbit re-entry time

Distribution of annual direct re-entries

- Unlike PMD, direct re-entries can occur at all altitudes
- Concentrated at **large constellation** altitudes (e.g., Starlink, OneWeb)
- Only replacement launches considered for constellations
- Under these assumptions, **direct re-entry strategies for constellations relatively insensitive** to fringe satellite launch rates and PMD limits



5 y (P2)

25 y (P1)

PMD de-orbit re-entry time

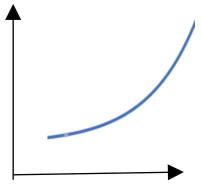
Simulation Results

Controlling for Residual ACR

Number of objects

- Similar trends as controlling for cumulative PC
  - **Fragments dominate** final population
  - **Runaway population growth** in L2 x P1 scenario
- L2 scenarios: **higher numbers overall** as target profile allows room for growth (see next slide)

Launch profile



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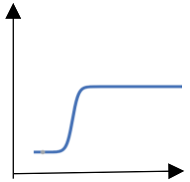

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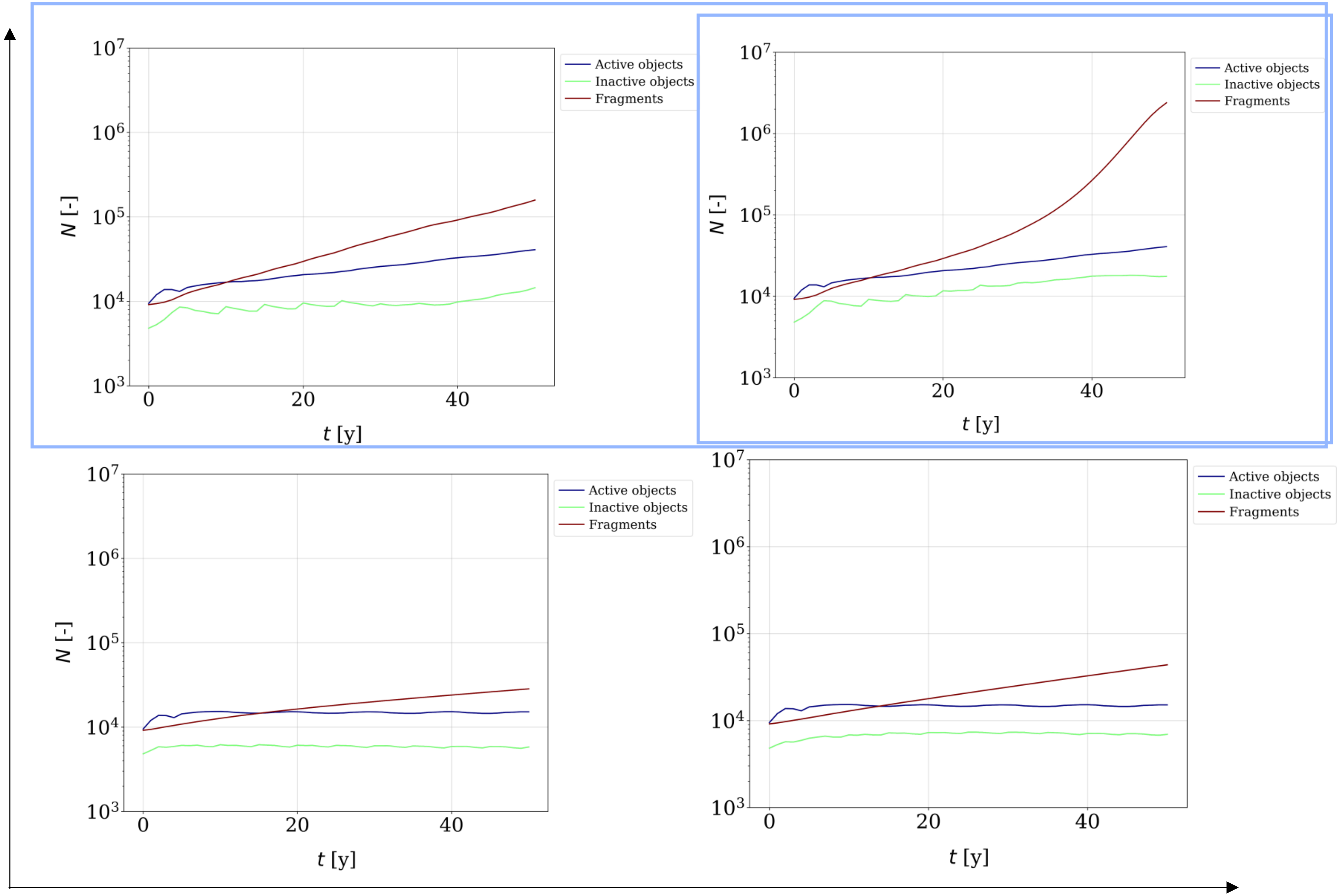


5 y (P2)

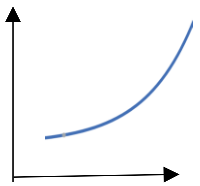
25 y (P1)

PMD de-orbit re-entry time

Residual ACR vs target

- PMD and direct re-entry remove inactive objects, and **does not directly reduce ACR between active objects**
- At **altitudes with many active objects** (e.g., Starlink, OneWeb), inefficient to make up for CAM by increasing disposal
- At **low altitudes**, PMD lever not applicable (direct re-entry only), so **harder to meet target**

Launch profile



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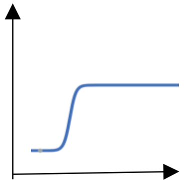

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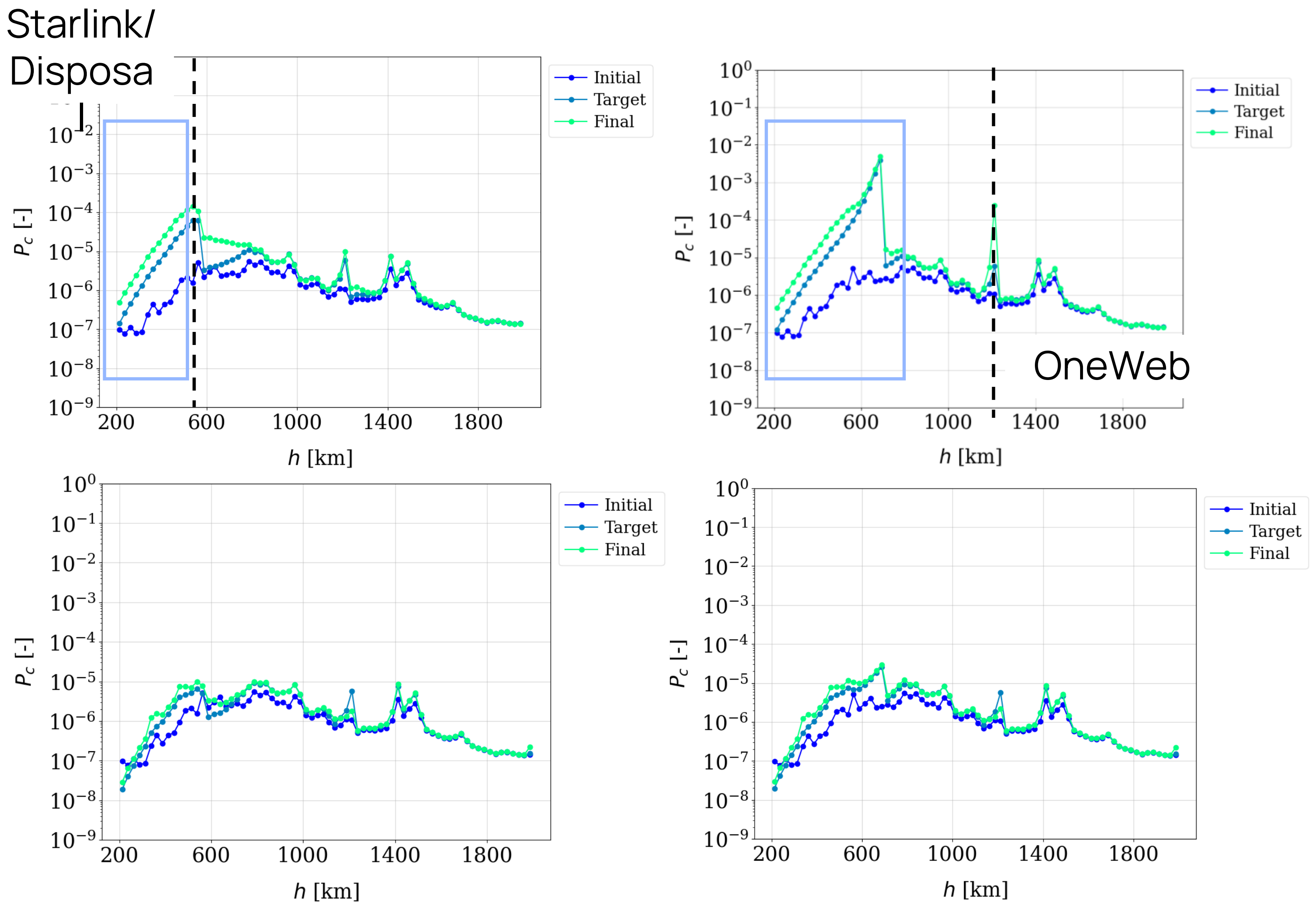


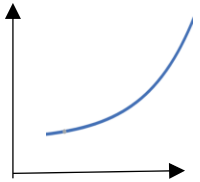
5 y (P2) **25 y (P1)**

PMD de-orbit re-entry time

Annual CAM rate

- CAM rates increase with:
  - **Higher launch rate**: more **active objects at all altitudes**
  - **Longer PMD time**: more **inactive objects at low altitudes**
- **CAM rates peak** at:
  - Altitudes with **many active objects** (e.g., Starlink, OneWeb, Globalstar)
  - **Disposal altitudes**

Launch profile



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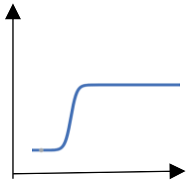

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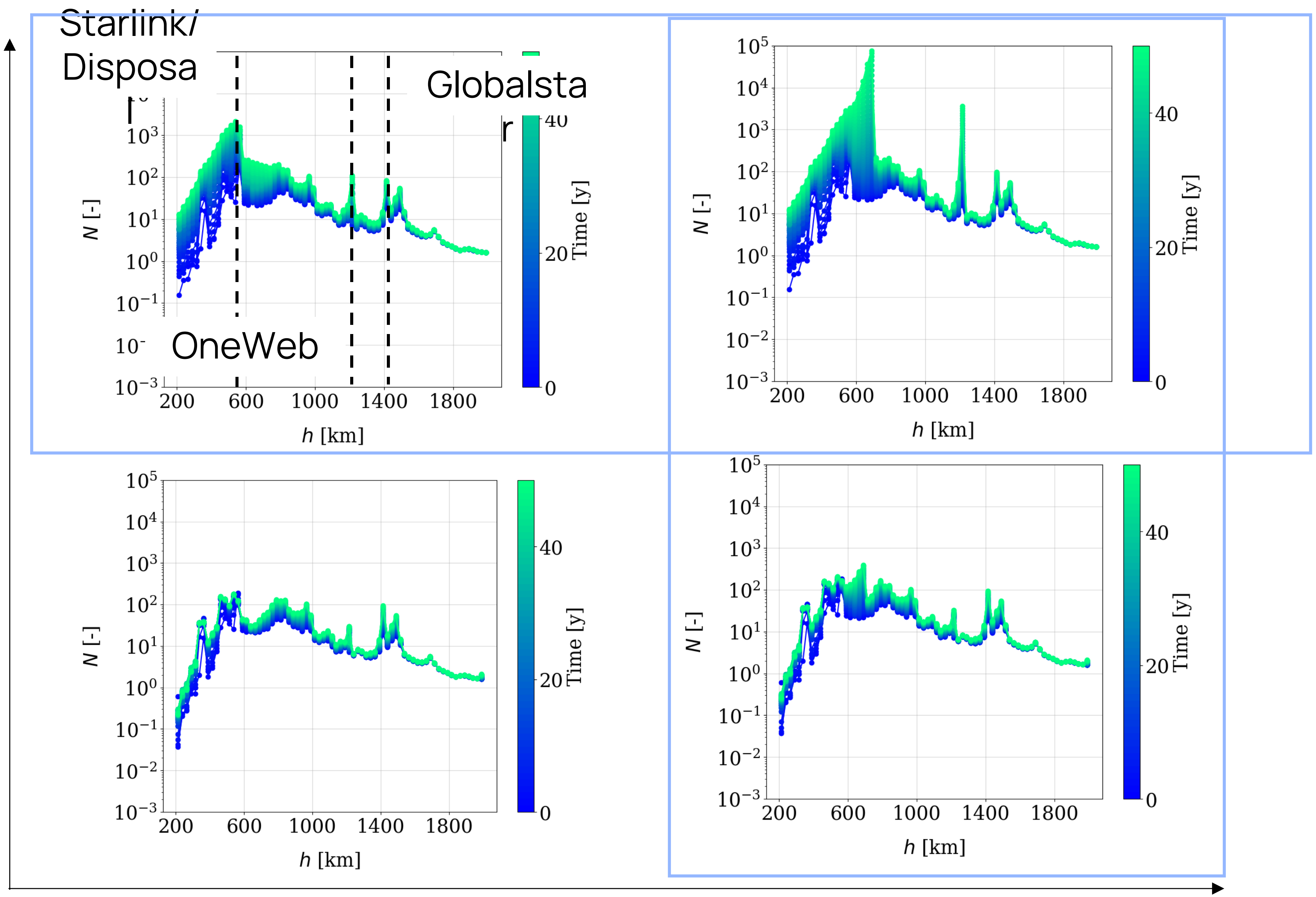


5 y (P2)

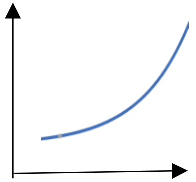
25 y (P1)

PMD de-orbit re-entry time

Distribution of Annual PMDs

- Similar trends as controlling for PC
  - More PMD at higher launch rate (L2)
  - Fewer PMD at longer PMD limits (P1)
- Some small differences in height of peaks due to **differences in target profile**

Launch profile



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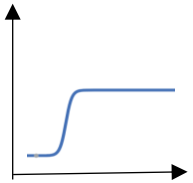

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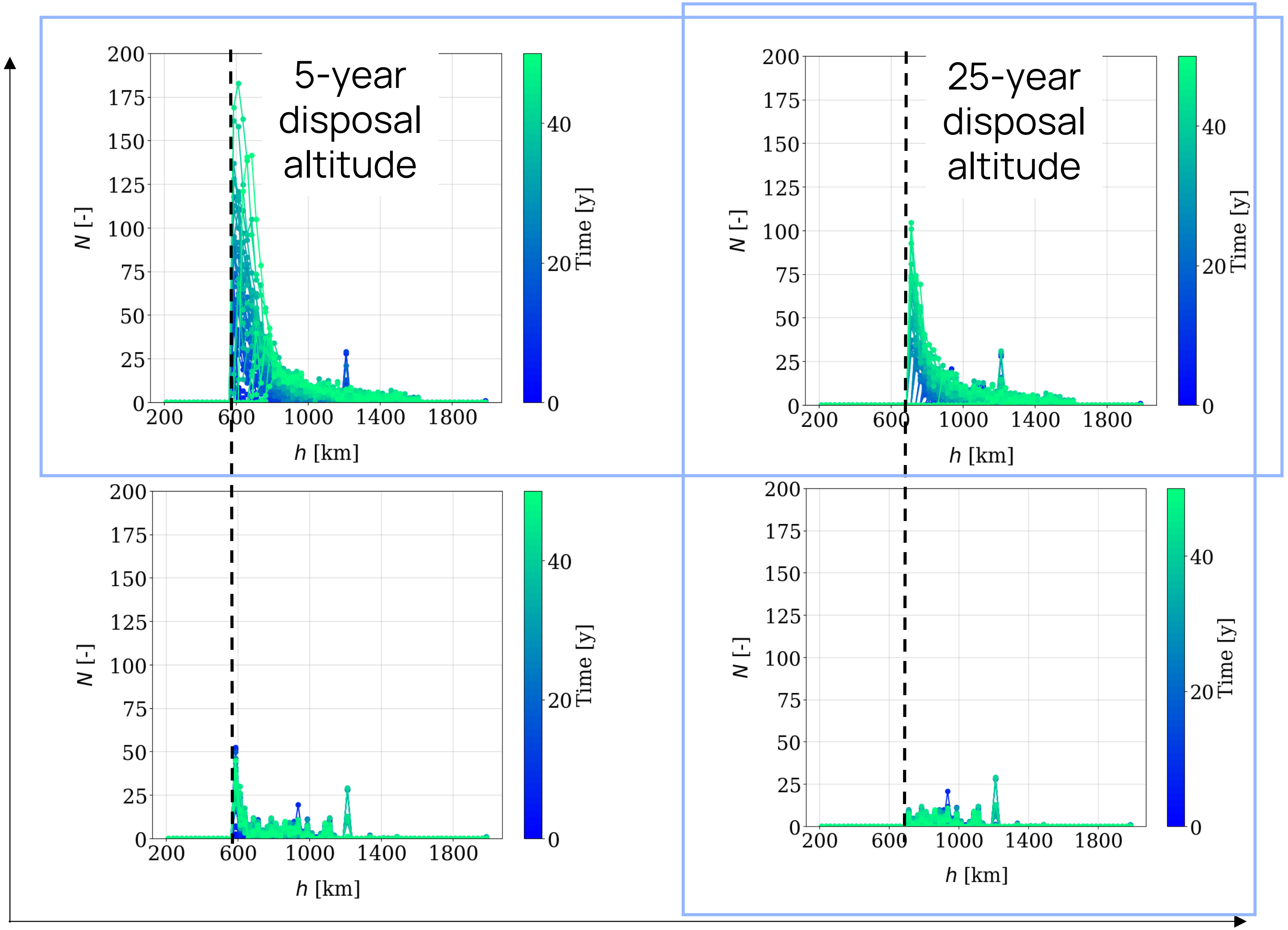


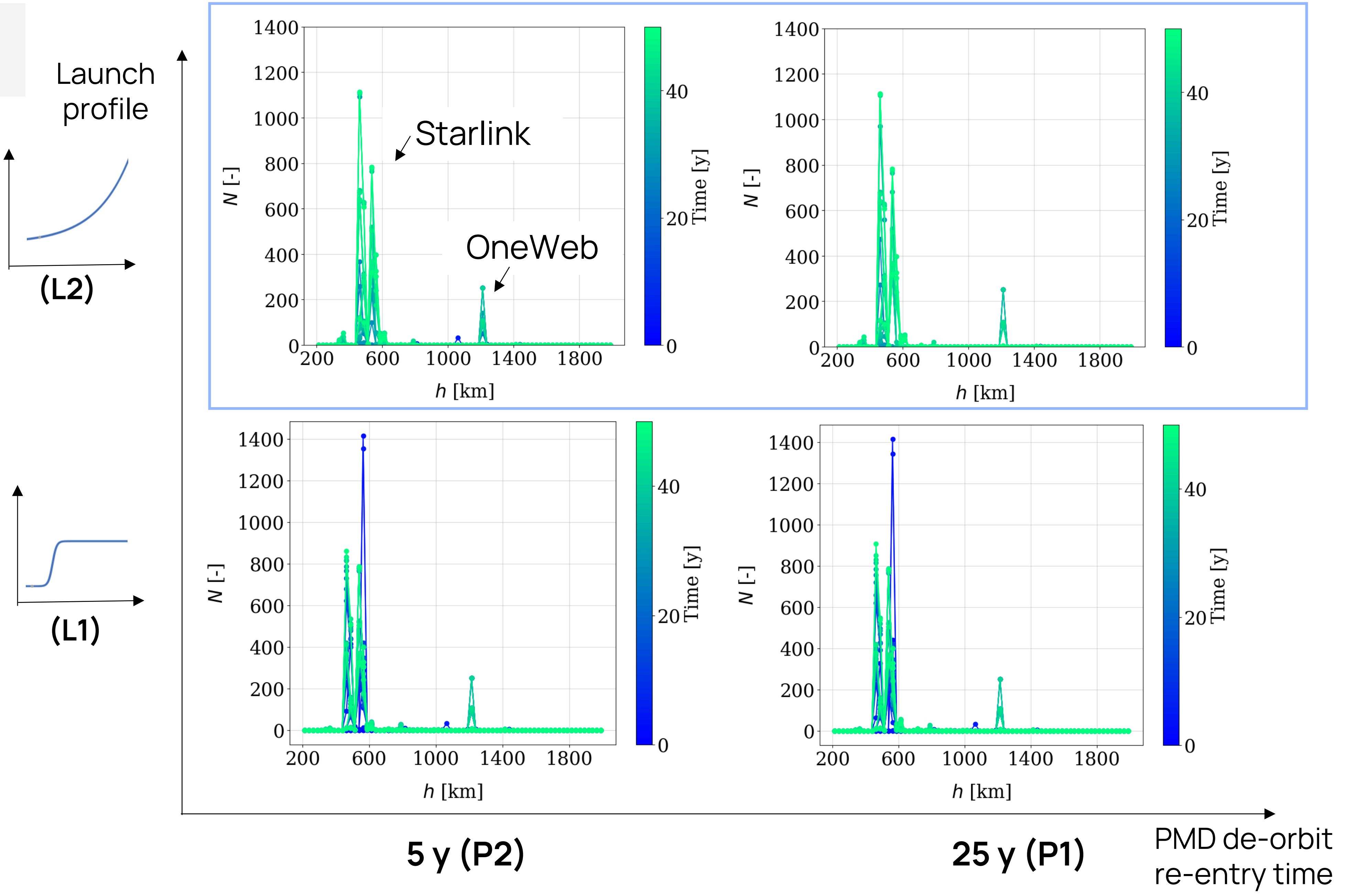
5 y (P2)

25 y (P1)

PMD de-orbit re-entry time

Distribution of annual direct re-entries

- Similar trends as controlling for PC
- L2 scenarios see fewer re-entries as **target profiles allow room for growth**



Summary of findings and implications

- Across all scenarios, **fragments dominate** at the end of simulation time (50 years): Growing launch rates + 25-year PMD limit scenario shows **signs of runaway debris growth**
- At **25-year PMD limit** or higher **(more realistic) launch rates**, **no amount of PMD alone can keep cumulative PC < 1E-3** over simulation time
    - Shorter PMD limits (e.g., 5-year or direct re-entry) can help meet PC target if launch rates are modest
    - At altitudes with many **active objects, increasing disposal** (PMD or direct re-entry) **may not make up for CAM efficiency**
    - Other interventions (e.g., active debris removal, frozen orbit configurations) may be required
- Need to be mindful of **risk spikes (PC, RRes, CAM rates) at disposal orbits**
    - Optimal PMD strategy may result in fewer disposals for longer PMD limits
    - **Harsher effects for longer PMD limits** due to accumulation of objects; **Direct re-entry** may ease this

Risk estimates are likely conservative

- **Constellation growth not yet considered** → likely to drive bulk of actual growth
  - Does not include several major planned constellations (e.g., Guowang, TeraWave, orbital data centers)
  - Does not include planned expansion of existing constellations (e.g., Starlink)
- Assumes **high CAM efficiency** of ~95%
- Assumes 90% of constellation satellites can perform direct re-entry at end of life
- Assumes **PMD success can go up to 99%**
- Assumes negligible growth in rocket body population
- Only considers **trackable objects** (fragmentation due to impact with lethal non-trackable debris not included)

Conclusions and future work

- Use of controlled simulation model to generate insights for policy- and operational decision-making
  - Policy impact comparison of 5- and 25-year PMD limits:
    - 5-year PMD reduces risks significantly,
    - Yet even 5-year PMD **may not meet current regulatory thresholds (e.g., PC < 1E-3) under more realistic launch projections**
  - Provides a sense of **operational costs and risks at different altitudes** (to support orbit selection etc.)

- **PMD addresses collision risks involving inactive objects and cannot reduce active-active conjunctions**
  - Lowering residual risk floor will require other measures (e.g., increase CAM efficiency, frozen orbit configurations)

- Future work will expand scope to include more policy and technology levers and improve model realism

Possible directions for future work: Mentimeter discussion

Foundations to Sustainability: What Should We Control in Space?

- Launch traffic scenarios with a few major planned constellations
- Delay in control action/input to account for lead times required to update policy and regulatory frameworks
- Account for jurisdictional differences in regulatory regimes (e.g., different PMD timelines)
- Optimize disposal orbit selection based on risk
- Allow different CAM efficiencies for different satellite species/objects
- Other policy/technology levers, e.g., active debris removal
- Consider non-debris externalities (e.g. light pollution or human casualty risk)

(with thanks to input from Amazon Leo, Telesat, Planet, Safe Heavens)

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