Cost and Benefit Analysis of Mitigating, Tracking, and Remediating Orbital Debris

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Summary Up Front

- This study estimated the costs and benefits associated with debris mitigation, tracking, and remediation
  - Improves upon the phase 1 risk model from 2023
  - Demonstrates that measuring risks from debris in dollars enables comparisons of the effectiveness of mitigation, tracking, and remediation
  - Finds that debris remediation can be as cost-effective as tracking and mitigation
  - Finds that removing defunct spacecraft from orbit faster than 25 years is a cost-effective way to reduce risk

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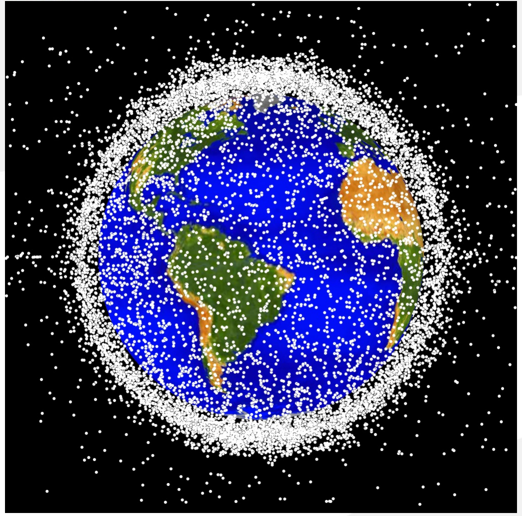
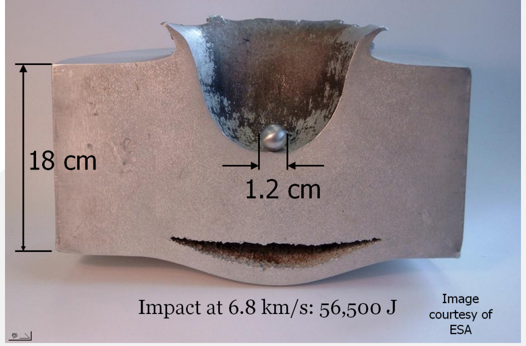
Risks From Orbital Debris are Growing

- Orbital debris: any human-made object orbiting Earth that no longer serves any useful purpose
- Risk—probability times consequence—grows with the number of debris and spacecraft
- Consequences are costs to spacecraft operators, including:
  - Assess predicted close approaches
  - Maneuver to avoid tracked debris
  - Effects of collisions with untracked debris
- Current metrics and modeling are not sufficient to support holistic frameworks



Space debris hazards



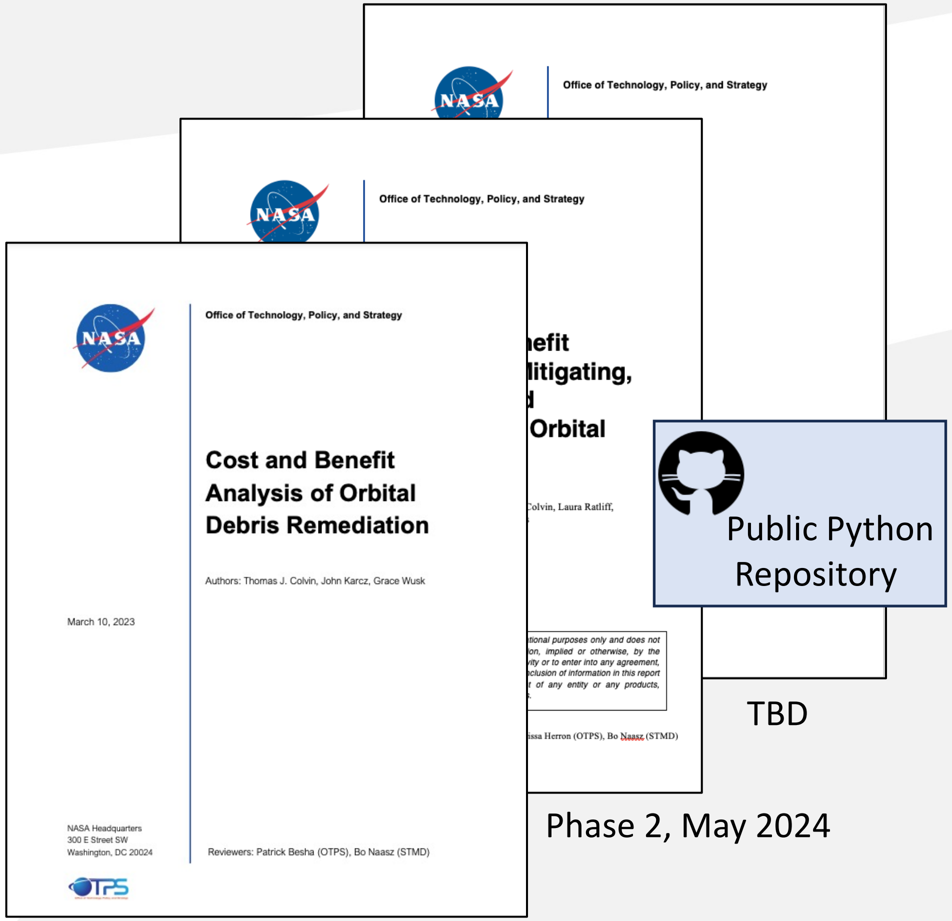
Impact at 6.8 km/s: 56,500 J

Image courtesy of ESA

Problem: It is unclear what the most cost-effective means are to reduce the risks of debris

Study Objectives

- OTPS is building a capability to:
  - Calculate net present value for risk-reducing actions
  - Identify optimal portfolios of actions to reduce risk
  - Quantitatively analyze space sustainability policies
- This study addresses major limitations of the 2023 effort:
  - Improves risk calculations by modeling new sources of debris, including mm-size debris, and orbital decay
  - Broadening scope beyond remediation to include mitigation and tracking of debris
- The report and this presentation provides:
  - Update on OTPS' development of this capability
  - Demonstration of ability to compare seemingly incommensurate actions
  - Discussion of two selected findings in the study



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Cost and Benefit Analysis of Orbital Debris Remediation

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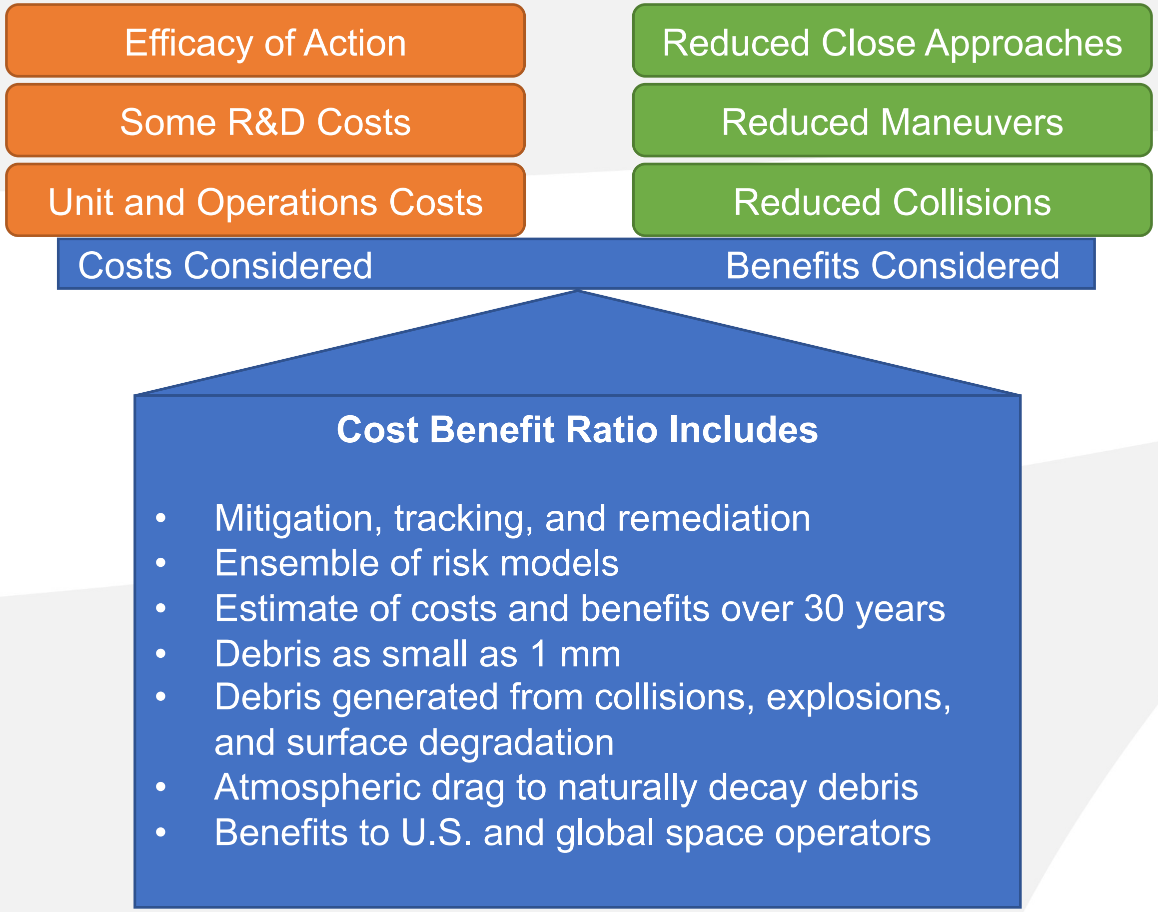
Phase 1, March 2023

Phase 2, May 2024

TBD

Study Scope



Efficacy of Action

Some R&D Costs

Unit and Operations Costs

Costs Considered

Reduced Close Approaches

Reduced Maneuvers

Reduced Collisions

Benefits Considered

Cost Benefit Ratio Includes

- Mitigation, tracking, and remediation
- Ensemble of risk models
- Estimate of costs and benefits over 30 years
- Debris as small as 1 mm
- Debris generated from collisions, explosions, and surface degradation
- Atmospheric drag to naturally decay debris
- Benefits to U.S. and global space operators

This analysis is for information purposes and does not indicate a commitment or intention by NASA to adopt any policy or analytic approach.

Details Not Yet Included

Policy Issues	Polices can be created or modified if an action is highly advantageous
Spacecraft in GEO	Dynamics of risks in GEO are substantially different than LEO
Independent Cost Estimates	Attractive actions can be prioritized for higher fidelity cost estimation
Discount Rates	Introduces complexity and is unlikely to change our results
Time to Deploy	We are looking for the most *efficient* actions, not the fastest to deploy
Tailored Actions	Actions apply to all spacecraft operators, all the time
Interdependencies	This study only considers each risk-reducing action independently

Post-Mission Disposal (PMD)

- Spacecraft use their own propulsion system to maneuver to a disposal orbit from which they will naturally deorbit in N-years
- 25-Year Rule: all spacecraft must deorbit within 25 years of ending their mission
  - Chosen because shorter times have little effect on the number of high-altitude debris
- Our risk approach shows:
  - Net benefits increase as deorbit timeline goes to zero years
  - Derelict spacecraft can shed debris that places all spacecraft in lower orbits at risk
  - Placing derelicts in congested orbits, can *add* more risk than it takes away

Credit: ©ESA

Caveats:

- Assumes 90% compliance across the global spacecraft population;
- Disposes spacecraft that already possess maneuver capability;
- Does not include disposal of rocket bodies; and

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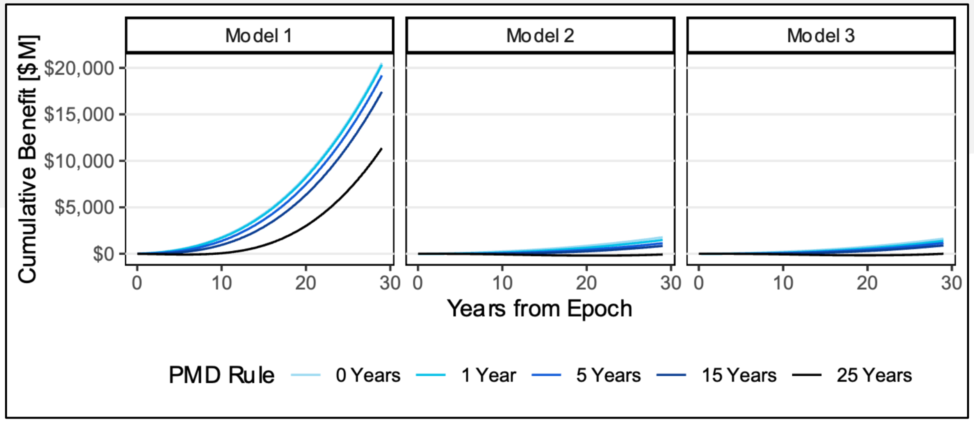
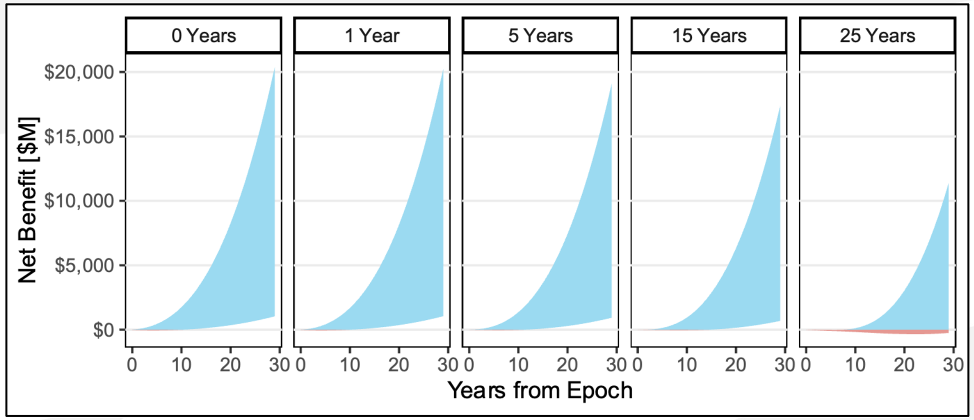
Elements of the PMD Analysis

Benefits: High and Low from Ensemble of Models

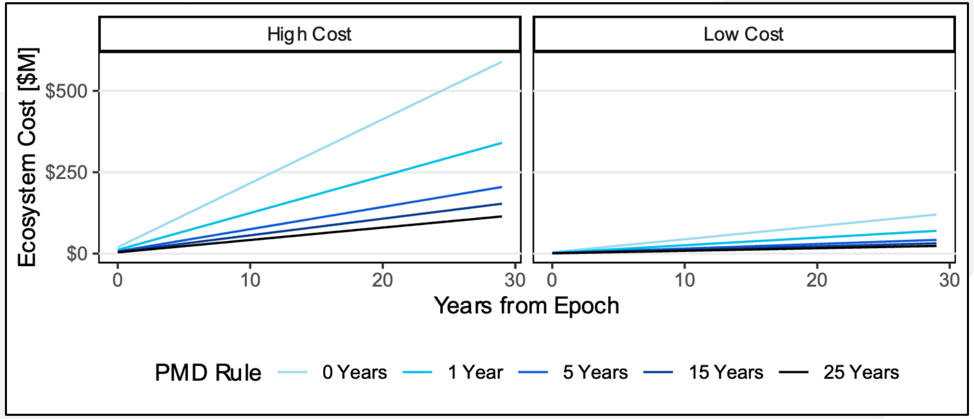


Net Benefit (*Benefit - Cost*)

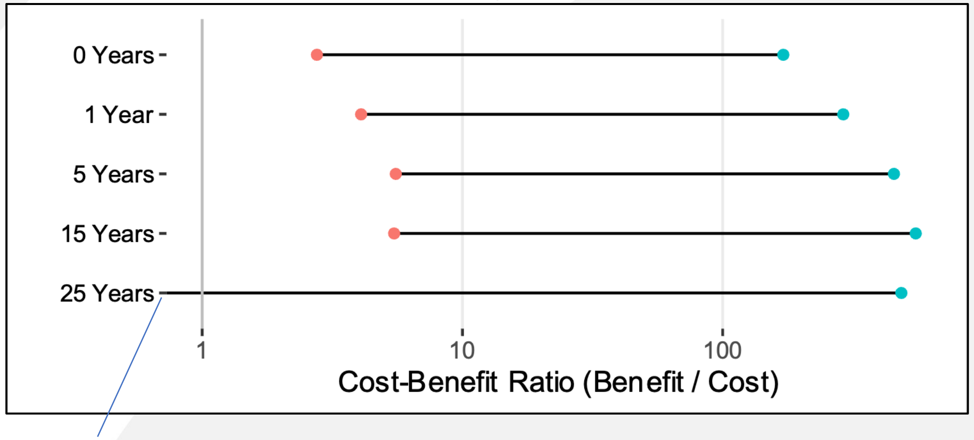


Possible Range

Cost: High and Low Options



Cost-Benefit Ratio (*Benefit / Cost*) at 30 Years



Negative pessimistic bound

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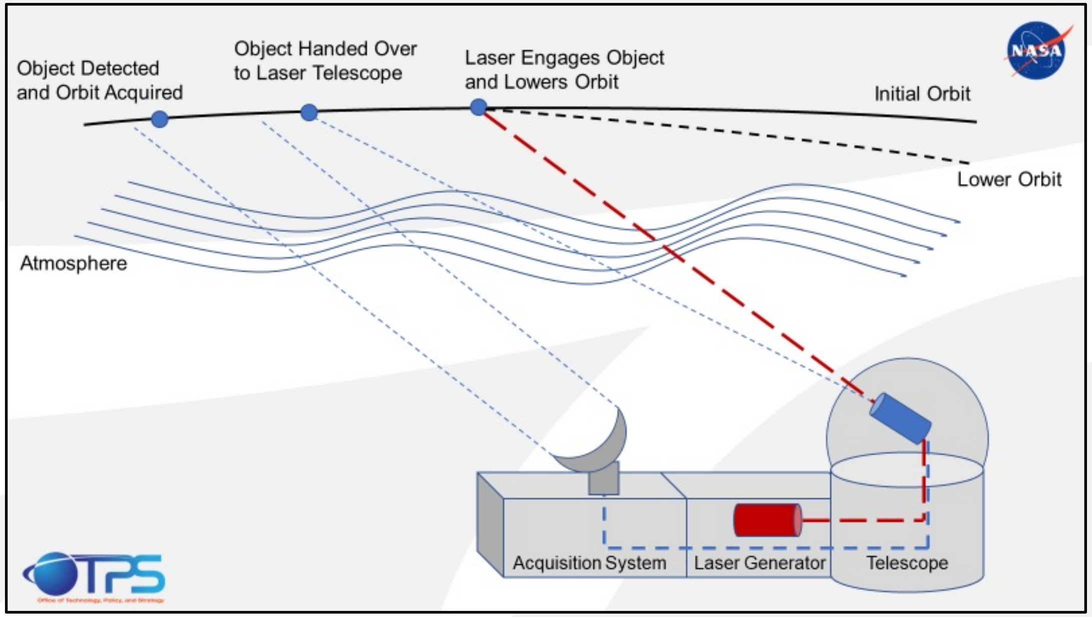
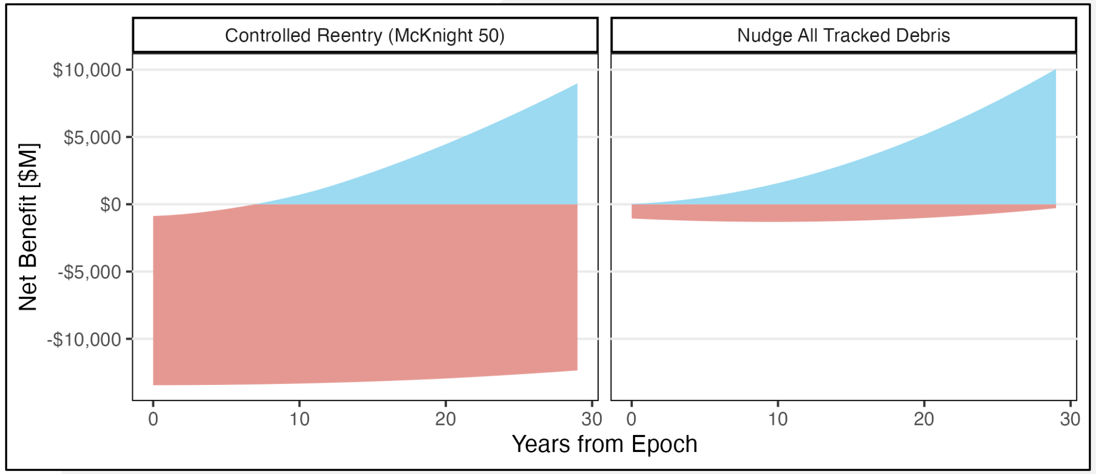
Just-in-Time Collision Avoidance (JCA)

- Waits for a potential collision between debris, then nudges one piece of debris to avoid the collision
- Analysis considers ground- and space-based laser systems to perform the nudging
- Effectively gives all tracked debris in LEO the ability to do collision avoidance maneuvers
- Our financial risk approach shows:
  - Only eliminates collision risk with debris
  - Higher potential net benefits than removing fifty large debris
  - JCA is potentially low cost and highly scalable





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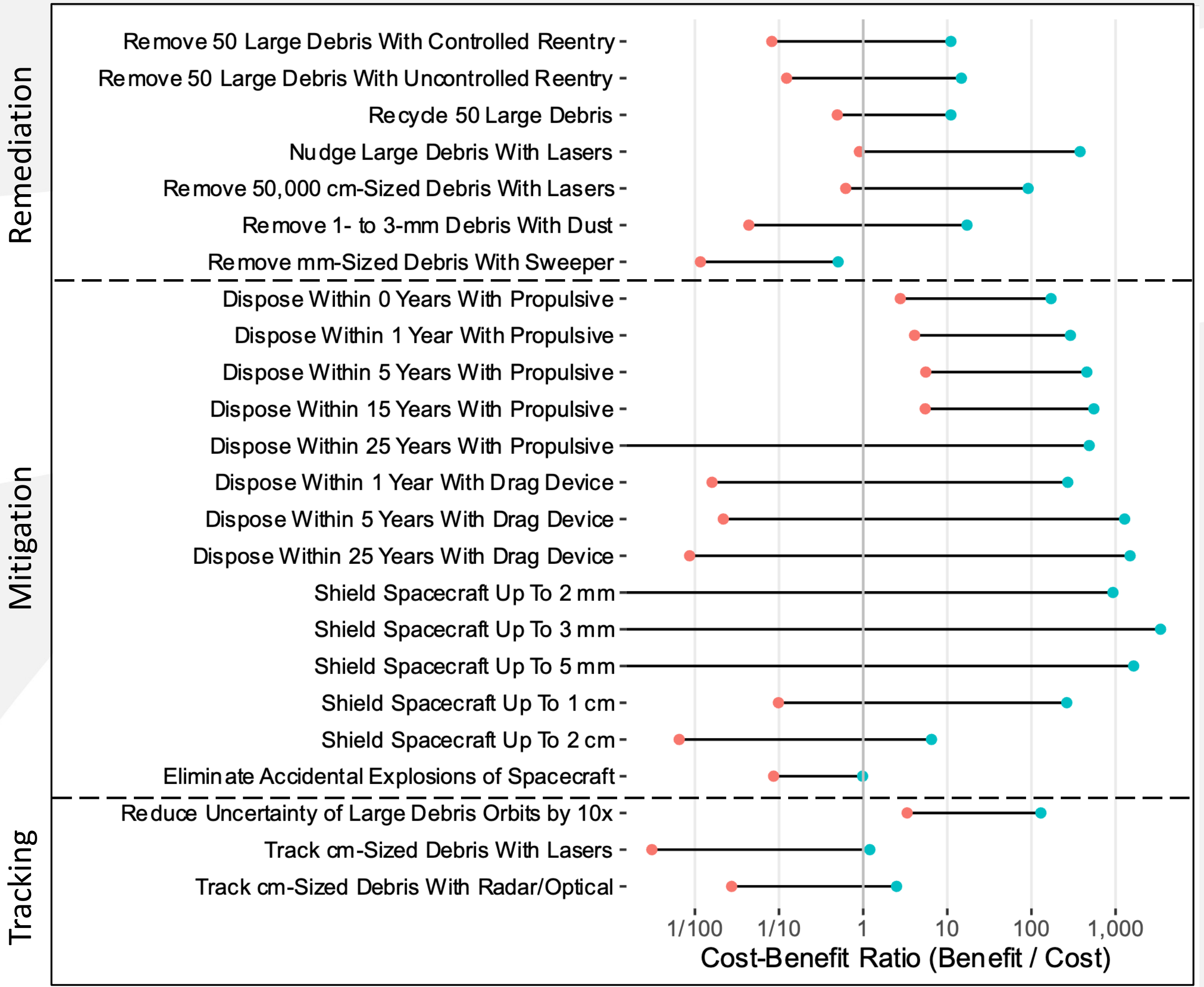
Summary of Cost-Benefit Ratios

Most Cost-Effective Actions

- **Remediation**
  - Just-in-time collision avoidance is the most cost-effective
  - Ranking of cost-effectiveness is the same compared to previous study
- **Mitigation**
  - Shielding up to 3mm debris with substantial caveats, then
  - Reducing post-mission disposal timelines to a 0-year rule
- **Tracking**
  - On-demand tracking of high-risk conjunctions with >10 cm debris



Conclusions

- Demonstrates the ability to compare the costs and benefits across the landscape of methods including remediation, mitigation, and tracking
- Uncovers potential insights to effectively achieving space sustainability
  - Debris remediation can be just as cost-effective as mitigation and tracking
  - Removing defunct spacecraft from orbit faster than 25 years is likely a cost-effective way to reduce risk
  - On-demand tracking of debris has effective returns even under pessimistic assumptions
- Advances the space community’s ability to holistically account for orbital debris
  - An additional lens to identify space sustainability problems and solutions
  - Highlights sensitivities to assumptions about small debris, such as surface degradation and lethality

Potential Next Steps

- Open source our model
- Gather feedback on Phase II report and input into future work
- Continue to advance our ability to inform cost-effective actions
  - Improve estimates of technology development costs and deployment timelines
  - Calculate net present value by discounting cash flows
  - Identify optimal portfolios of risk-reducing actions

Backups

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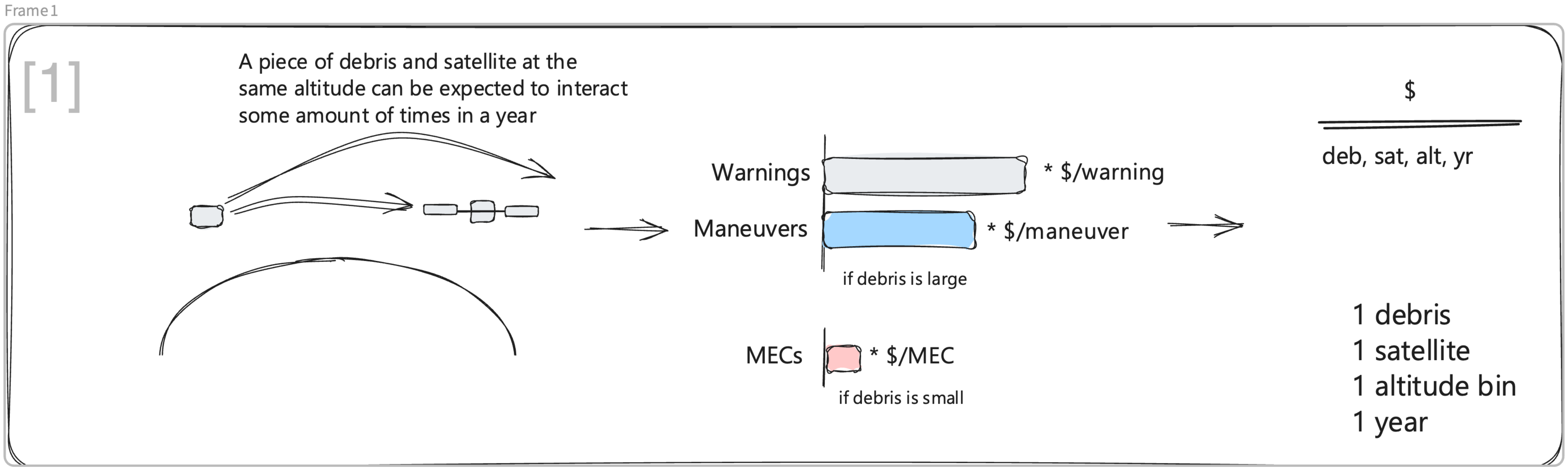
Methodology (1/5)

Large debris can be expected to cause a certain number of warnings and collision avoidance maneuvers, while untracked debris cause a certain number of mission ending collisions; the risk is the sum of the expected events multiplied by the consequences for the spacecraft operator.



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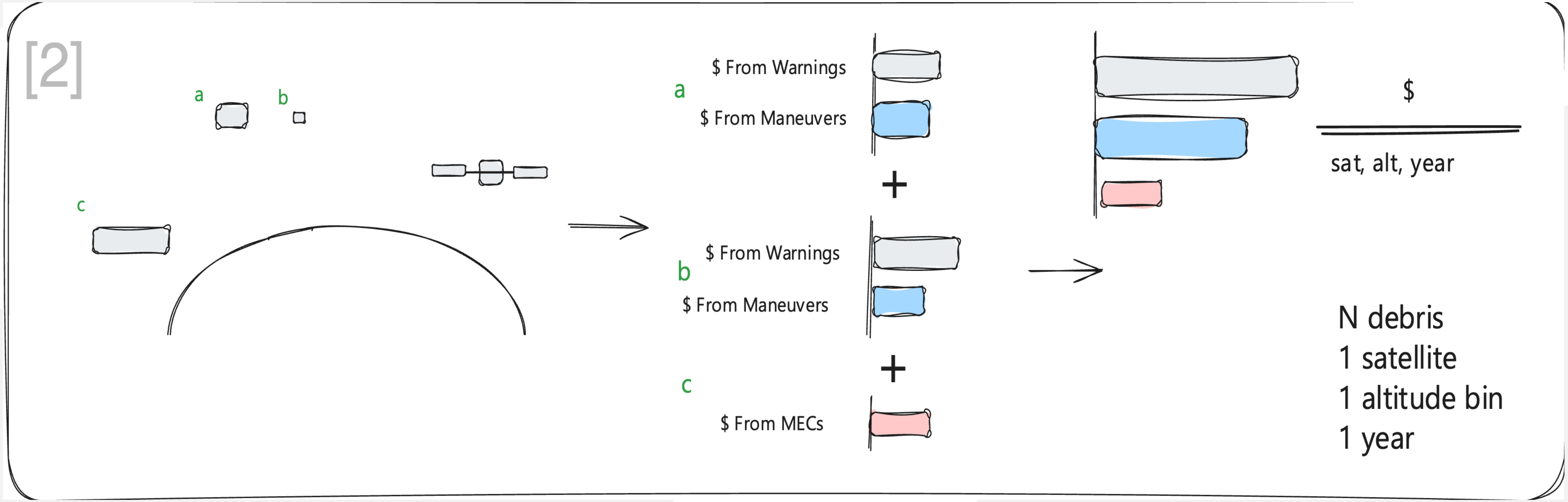
Methodology (2/5)

Each piece of debris creates risks to a spacecraft, and the total risk to the spacecraft is the sum of the risks contributed by all debris.



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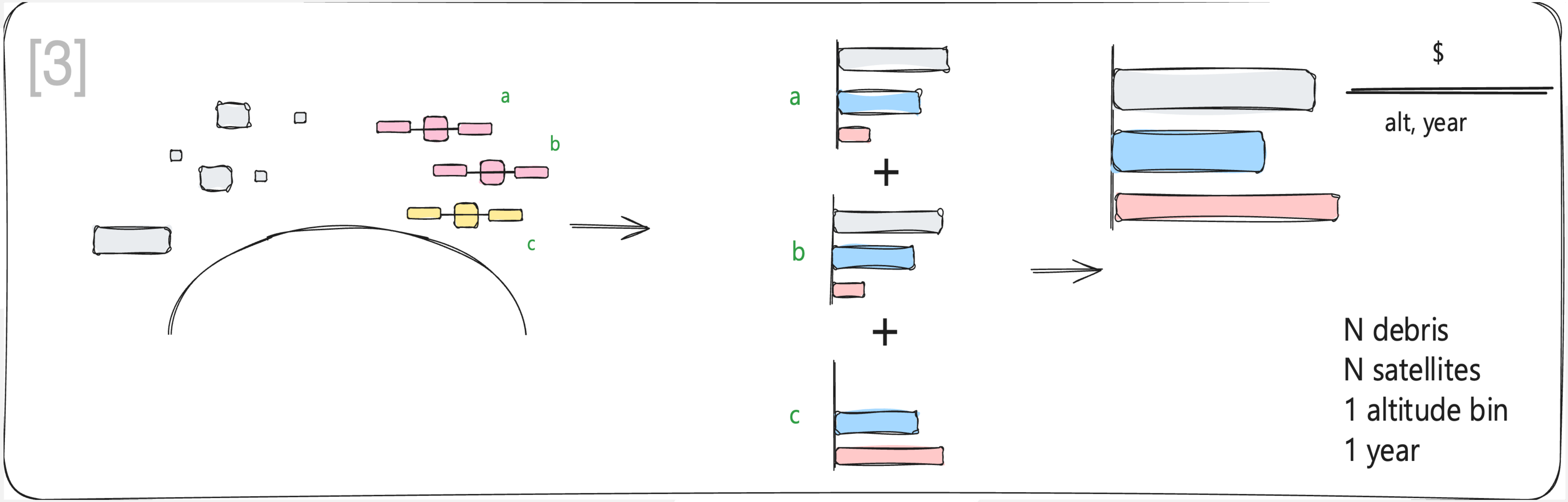
Methodology (3/5)

Debris pose risks to each nearby spacecraft, so the total risk in a location (i.e., altitude band) is the sum of the effects of all debris on each spacecraft .



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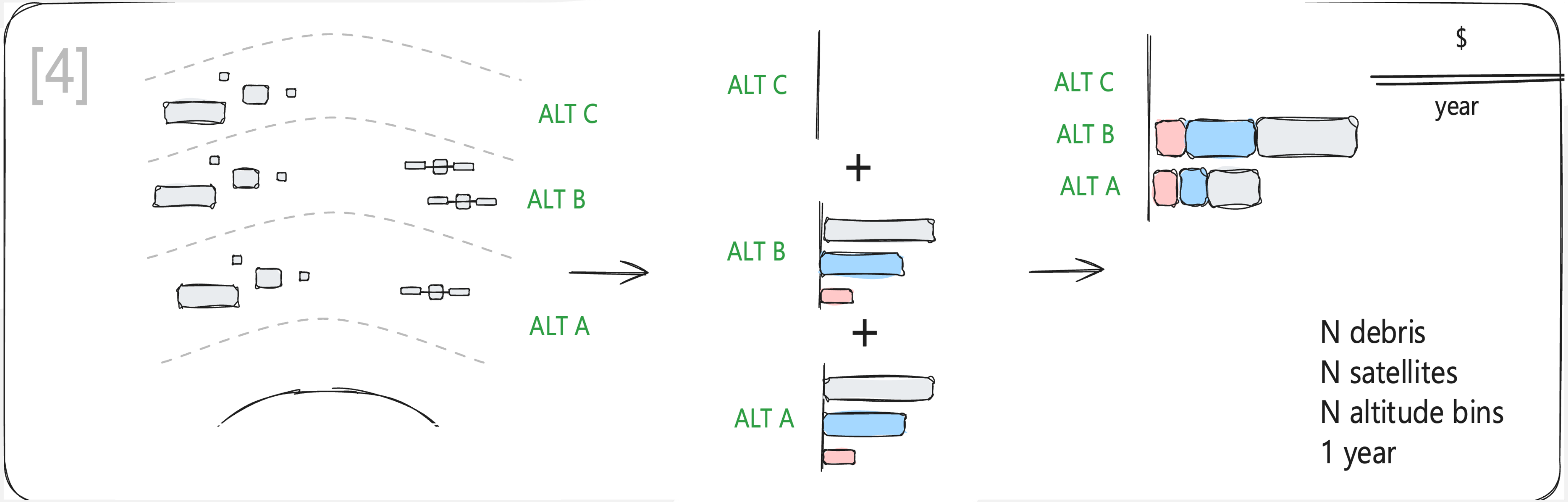
Methodology (4/5)

Multiple altitudes can be treated separately—as “particles in a box”—and the total risk is the sum of the risk in each altitude bin.



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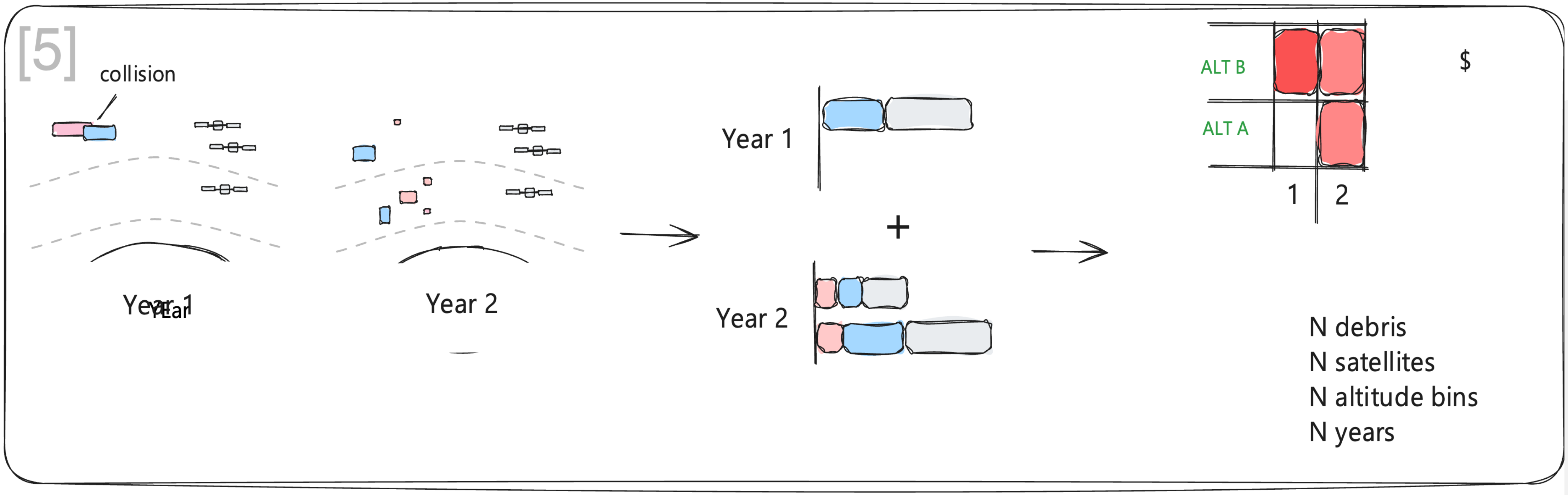
Methodology (5/5)

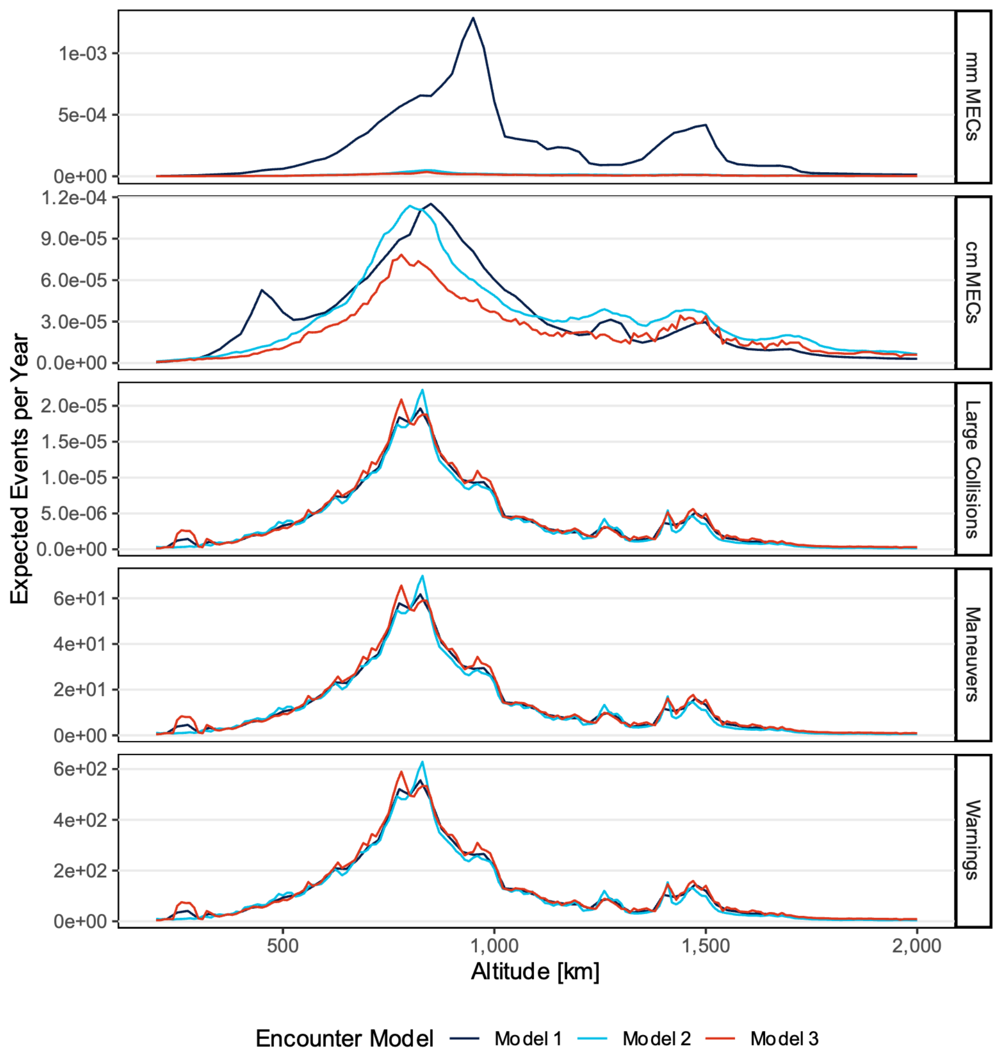
The environment changes with time—for example, a collision might introduce new debris in year two—and we sum the increased risk posed by the new debris over a 30 year time horizon to estimate the cumulative risk overall. Therefore, we can estimate the risk in any LEO environment over time



Encounter Models

We use three different models to form an ensemble

Encounter Model	Description	Model Source
Model 1	The reference model, extrapolating the number of encounters from the flux provided by ORDEM.	ORDEM
Model 2	The COMSPOC Volumetric Encounter Model (VEM), from which their Number of Encounters Assessment Tool (NEAT) is derived.	MASTER
Model 3	LeoLabs risk model and data based on the kinetic gas theory.	MASTER



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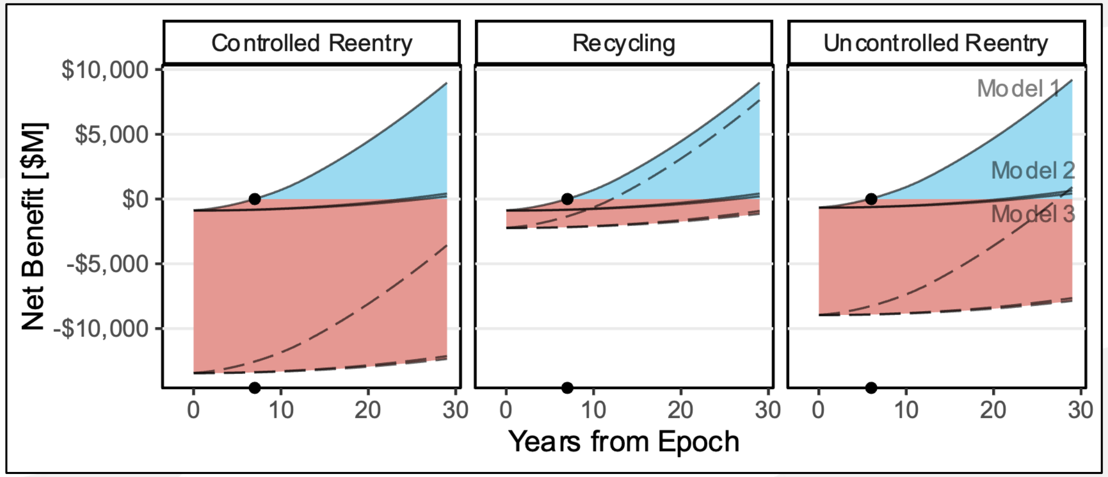
Actions Investigated

- **Mitigate**: Limiting the generation of debris caused by normal operations
  - Reduce intentional debris, reduce accidental explosions, reduce collisions through mission design, and disposal of spacecraft
- **Characterize**: Understand (small) debris to support mitigation efforts
  - Statistics regarding size, shape, composition, and orbital parameters
- **Track**: Maintain custody of debris to support collision avoidance
  - Radar, telescopes, laser ranging, observing ionospheric disturbances
- **Remediation**: Reduce the risks associated with existing orbital debris
  - Move it, remove it, or reuse it.

Net Benefits: Remediating Large Debris

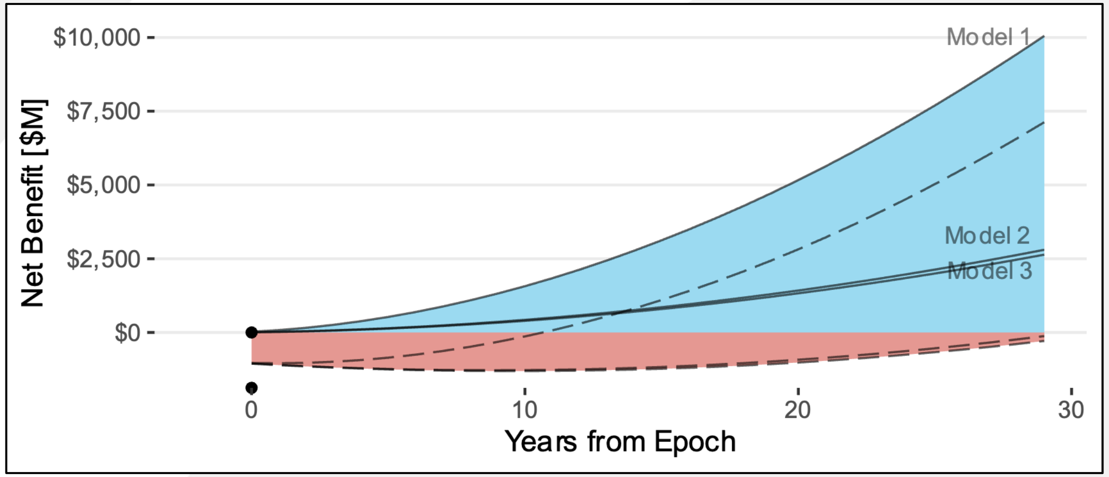
Remove or Recycle Top 50 Derelicts

- 800–9,000 kg objects from 625–1,175 km
- Can have significant net benefits if removal costs less than $3,000/kg and high surface degradation



Nudge All Derelicts

- Sounding Rockets, Ground- and Space-Based Lasers
- All tracked debris in LEO



Net Benefits: Remediating Small Debris

Remove 1-10 Centimeter Debris

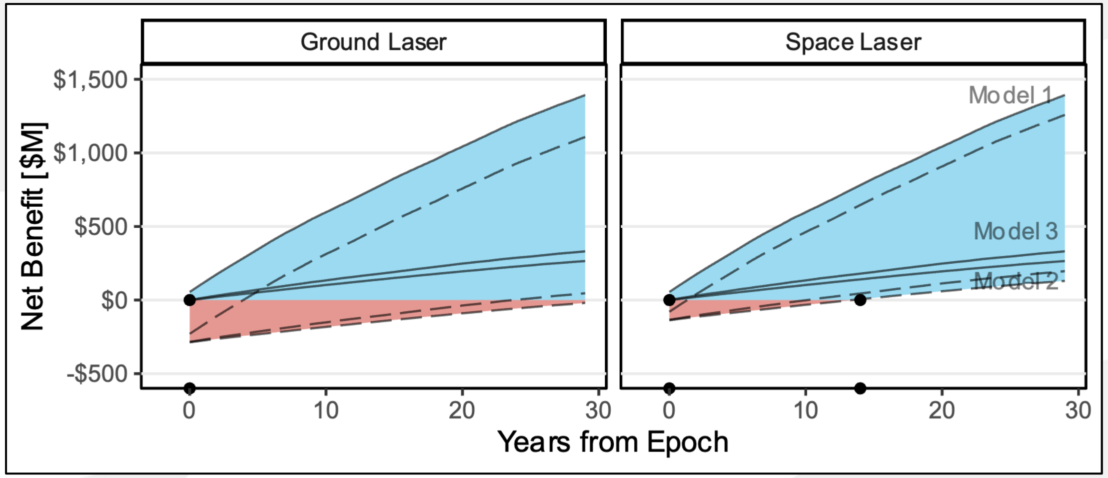
- Ground- or space-based laser
- 50,000 debris from 450 – 850 km

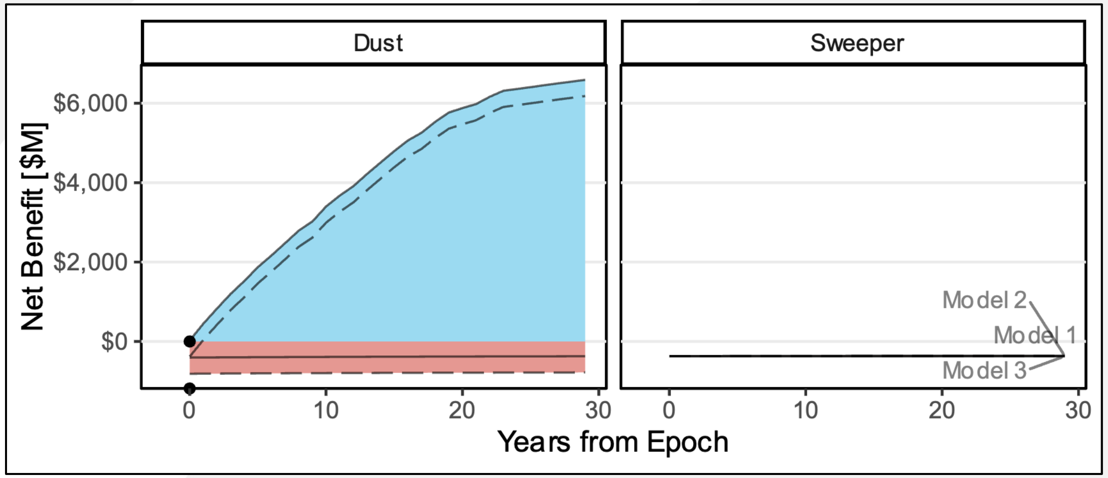
Remove 1-10 Millimeter Debris

- Wide-Area Sweeper
- Up to 1.2 million debris from 800 – 850 km

Remove 1-3 Millimeter Debris

- Injection of Tungsten Dust at 1,100 km
- Up to 1.8 billion debris





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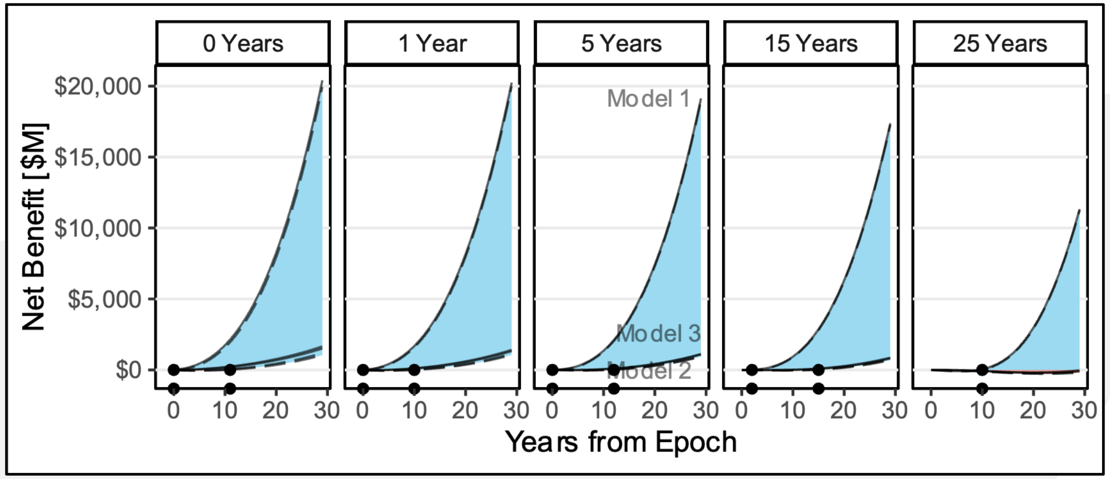
Net Benefits: Mitigation

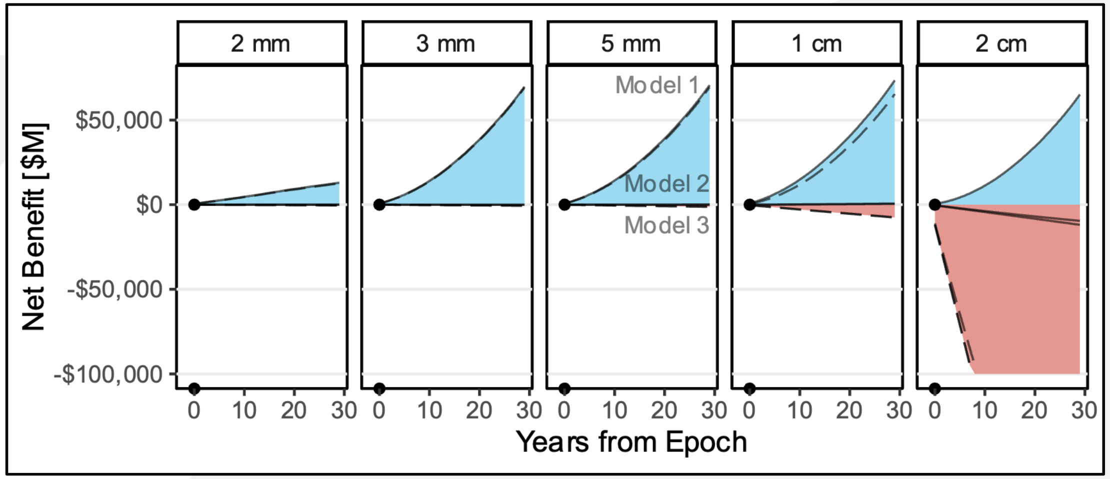
Post-Mission Disposal

- Deorbit spacecraft at end of mission within N years using propulsion
- Deorbiting spacecraft immediately has highest net benefit



Shielding

- Spacecraft typically shielded to 1 mm to prevent mission-ending collisions
- High net benefits for shielding up to 3 mm with steep diminishing returns



Results not shown:

- PMD with drag devices
- Spacecraft passivation

Net Benefits: Tracking

Track All >10cm Debris Better

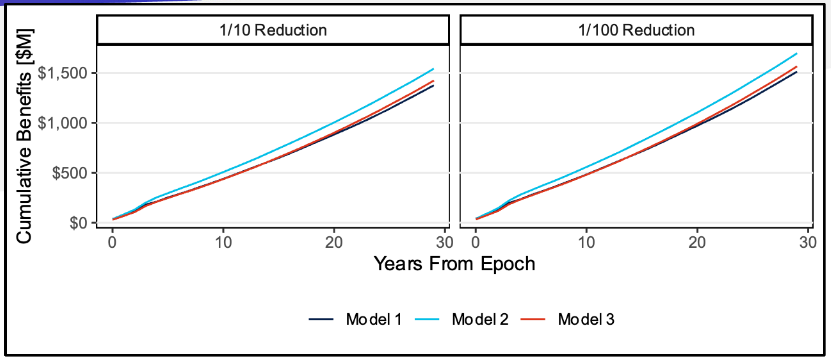
- Reduced uncertainty of orbits for *all* debris leads to fewer warnings and maneuvers
- Only estimated benefits of 10x and 100x reduced uncertainty, did not estimate costs

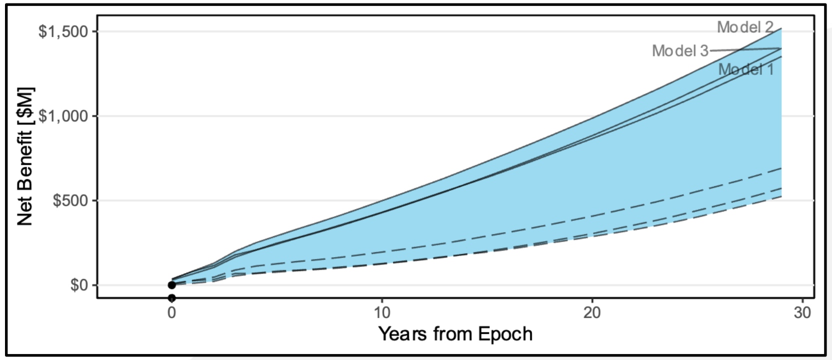
On-Demand Tracking of >10cm Debris

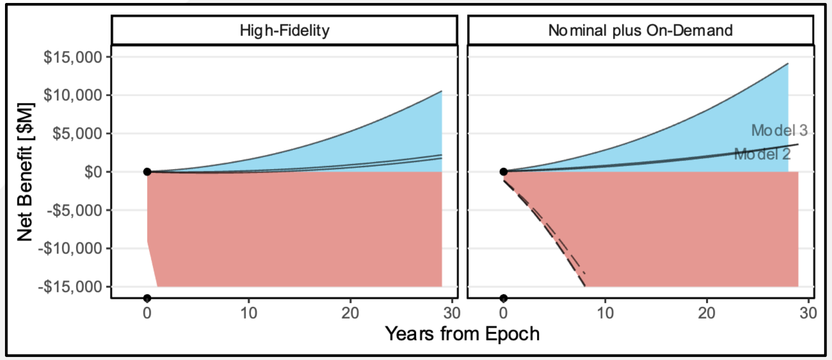
- Reduced uncertainty of predicted high-risk conjunctions
- Cheap service leads to robust net benefits

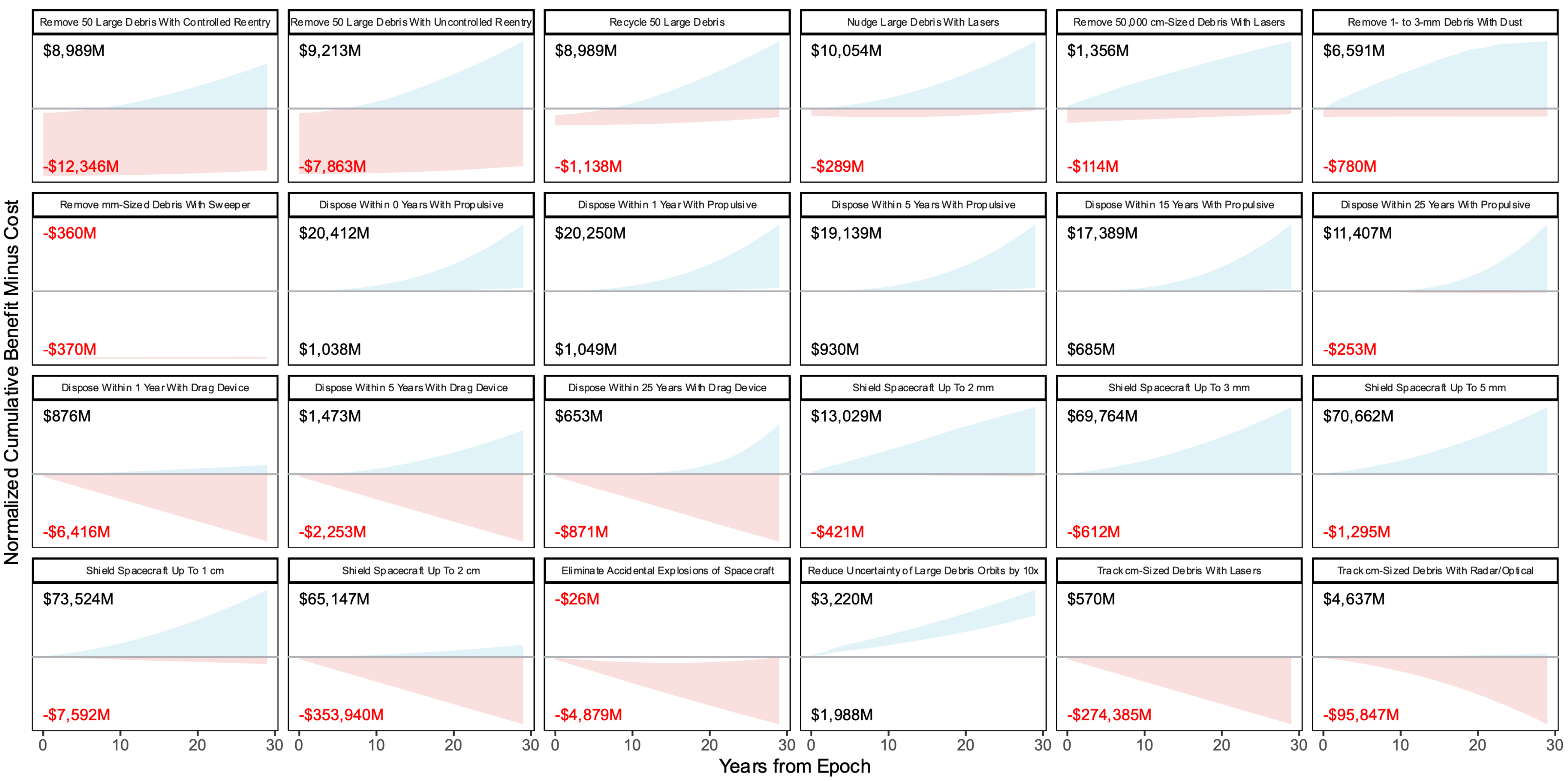
Track 1-10cm Debris

- Ground-based radar, laser, passive optical
- Requires 10-100x reduced uncertainty compared to >10 cm tracking to reach net benefit









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Interrelated Actions

Taking one risk-reducing action changes the effectiveness of other actions

- Lower year PMD rules reduce the need for passivation measures
- JCA nudging would decrease the difference between PMD rules
- Increasing shielding reduces the value of remediation and mitigation
- Characterization could change our understanding of the most effective risk-reducing portfolio