National Aeronautics and Space Administration

Orbital Debris and Future Environment Remediation

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OCT Technical Seminar

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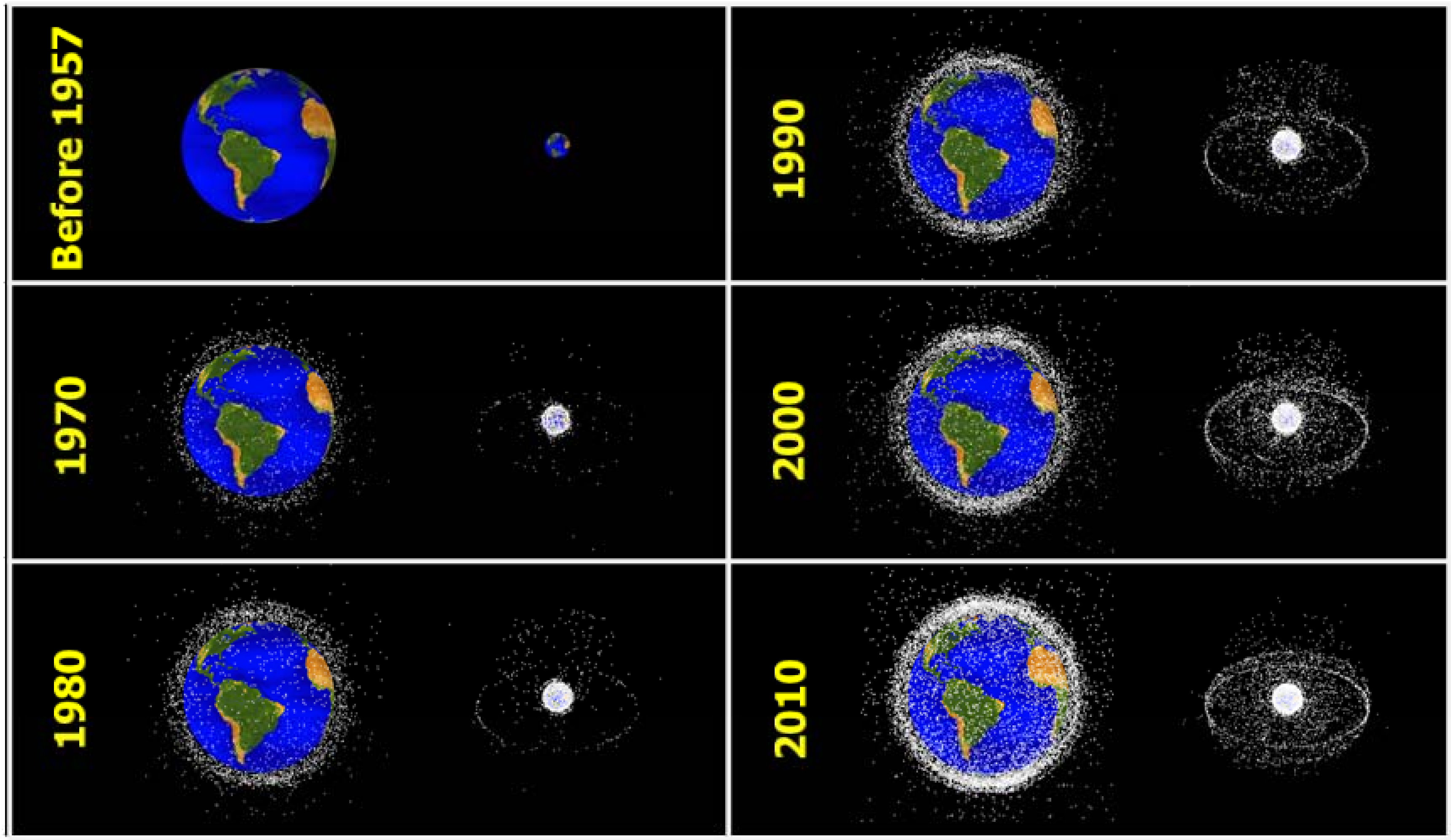
Outline

- **An overview of the historical and current orbital debris environment**
- **Projected growth of the future debris population**
- **The need for active debris removal (ADR)**
- **A grand challenge for the 21st century**
- **The forward path**

An Overview of the Orbital Debris Environment

The Near-Earth Environment (1957-2010)



- **Only objects in the US Space Surveillance Network (SSN) catalog are shown**
- **Sizes of the dots are not to scale**

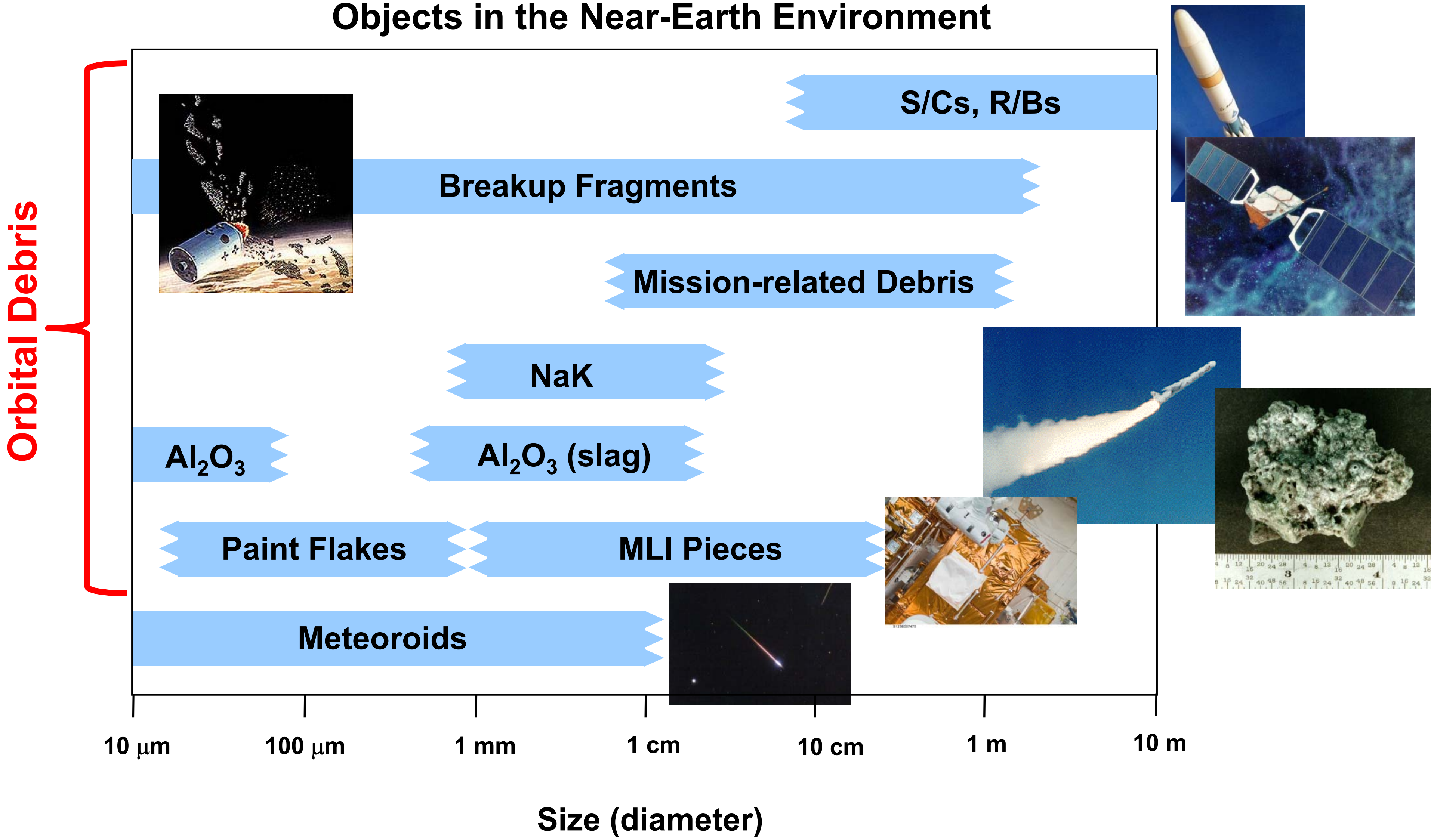
What Is Orbital Debris?

- **Orbital debris is any man-made object in orbit about the Earth that no longer serves a useful purpose**

- **Examples**
  - Spent upper stages (*i.e*., rocket bodies), retired spacecraft (*i.e*., payloads)
  - Mission-related debris: objects released during normal mission operations (engine covers, yo-yo despin weights, *etc.*)
  - Breakup fragments (via explosions or collisions)
  - Solid rocket motor effluents (Al_2O_3 slag and dust particles)
  - NaK droplets (coolant leaked from Russian nuclear reactors)
  - Surface degradation debris (paint flakes, *etc.*)

The Orbital Debris Family

Objects in the Near-Earth Environment



How Much Junk Is Currently Up There?

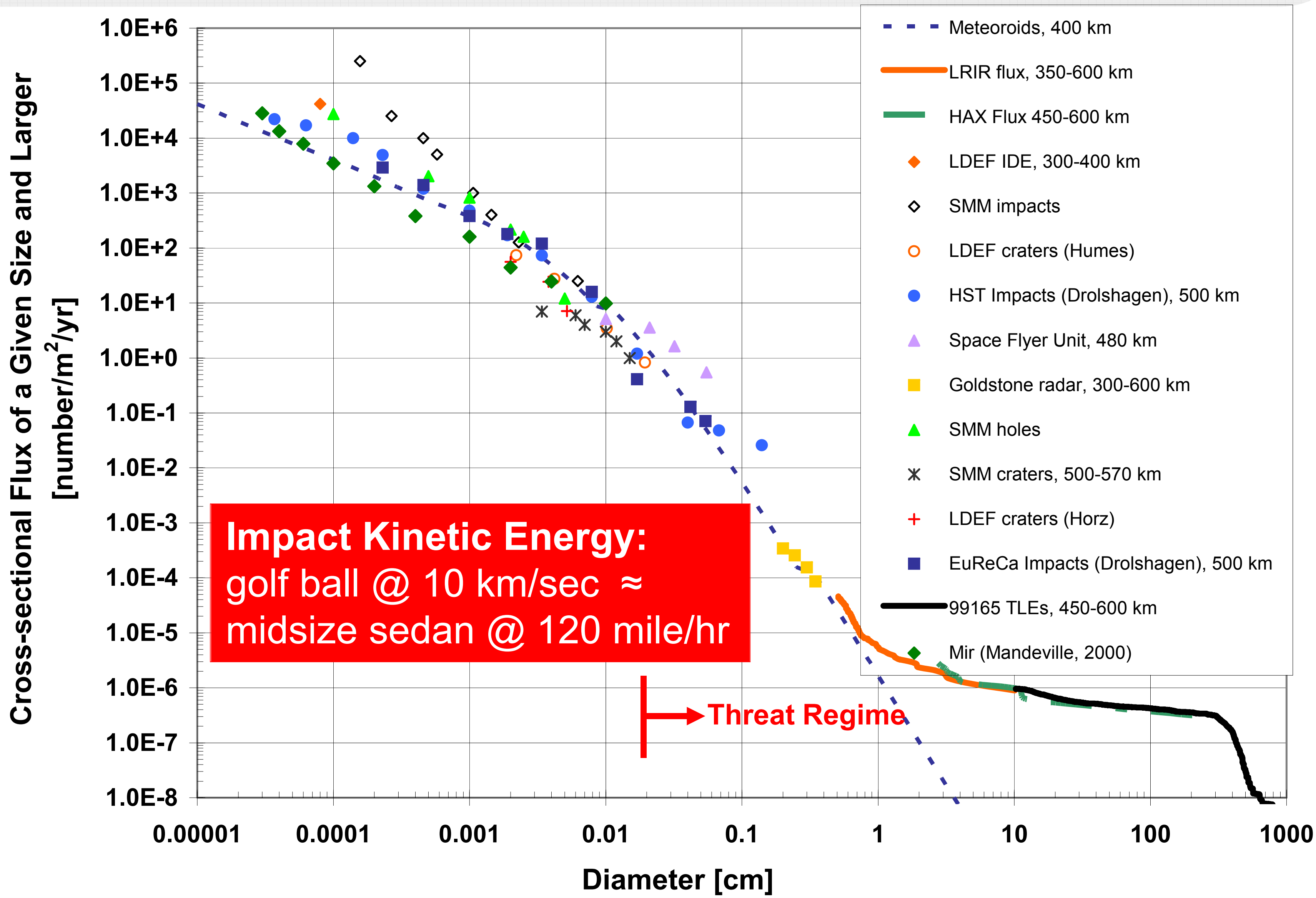
Softball size or larger (≥10 cm): ~22,000 (tracked by the Space Surveillance Network)

Marble size or larger (≥1 cm): ~500,000

Dot or larger (≥1 mm): ~100,000,000 (a grain of salt)

- **Total mass: ~6300 tons LEO-to-GEO (~2500 tons in LEO)**
- **Debris as small as 0.2 mm pose a realistic threat to Human Space Flight (EVA suit penetration, Shuttle window replacement, *etc.*) and critical national space assets**

The Environment



Shuttle Vulnerabilities

Potential Shuttle Damage

Window Replacement

EVA Suit Penetration

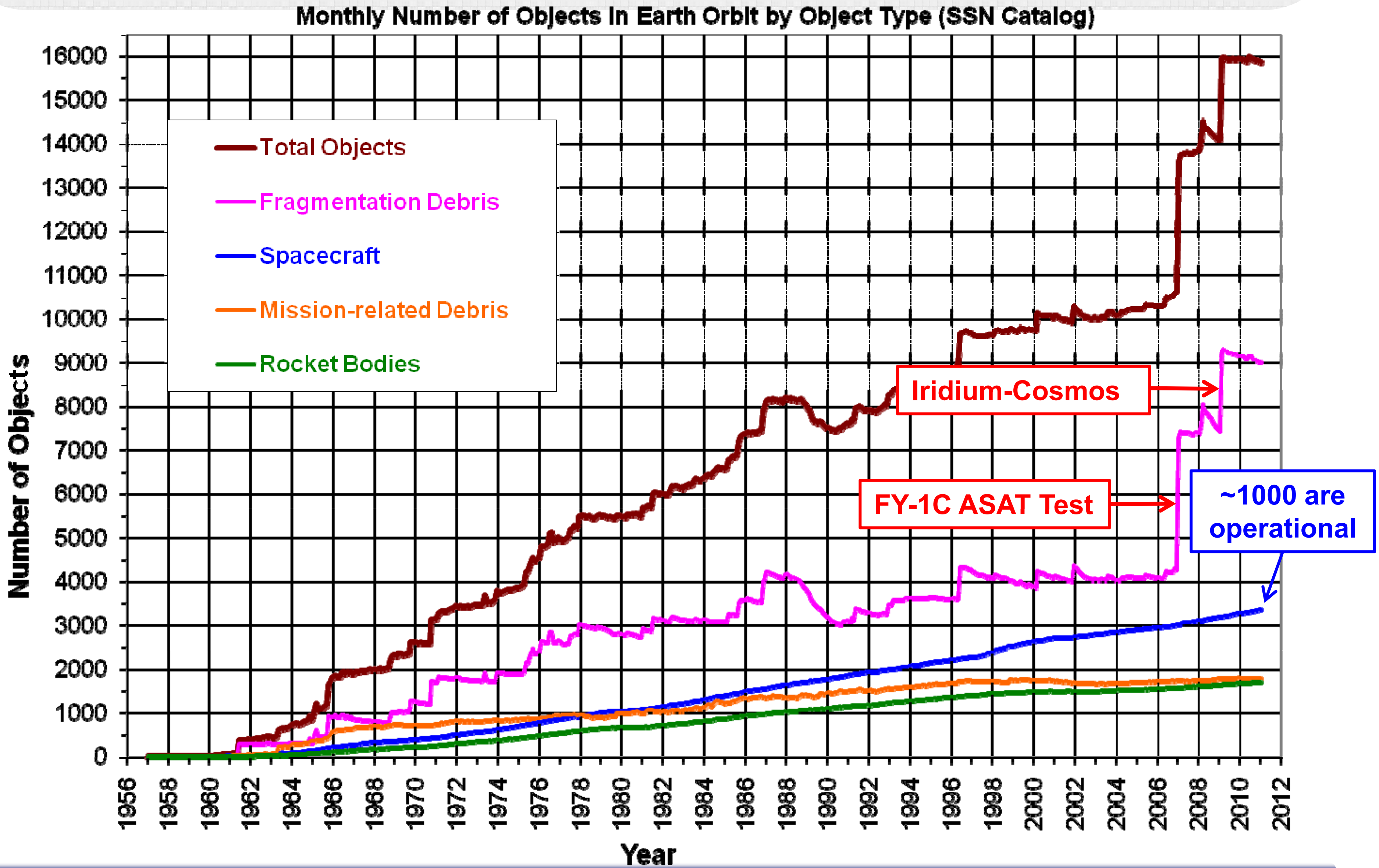
Radiator Penetration

- **Shuttle Loss of Crew and Vehicle (LOCV) risks from MMOD impact damage are in the range of 1 in 250 to 1 in 300 per mission**
  - The risks vary with altitude, mission duration, and attitude
  - OD to MM is about 2:1 at ISS altitude

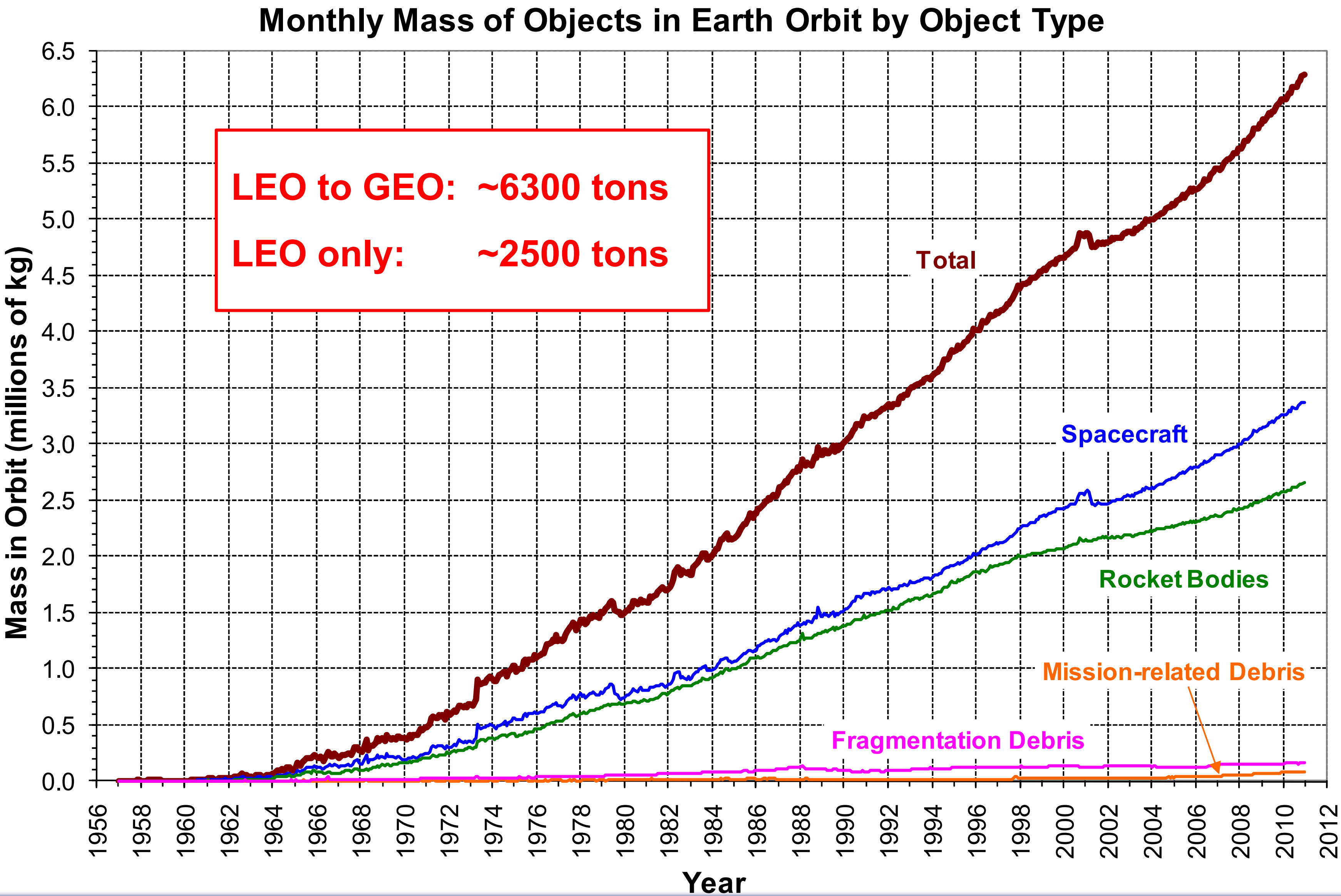
0.001 0.01 0.1 1 10 100 1000

Debris Diameter in Centimeters

Growth of the Historical Catalog Populations

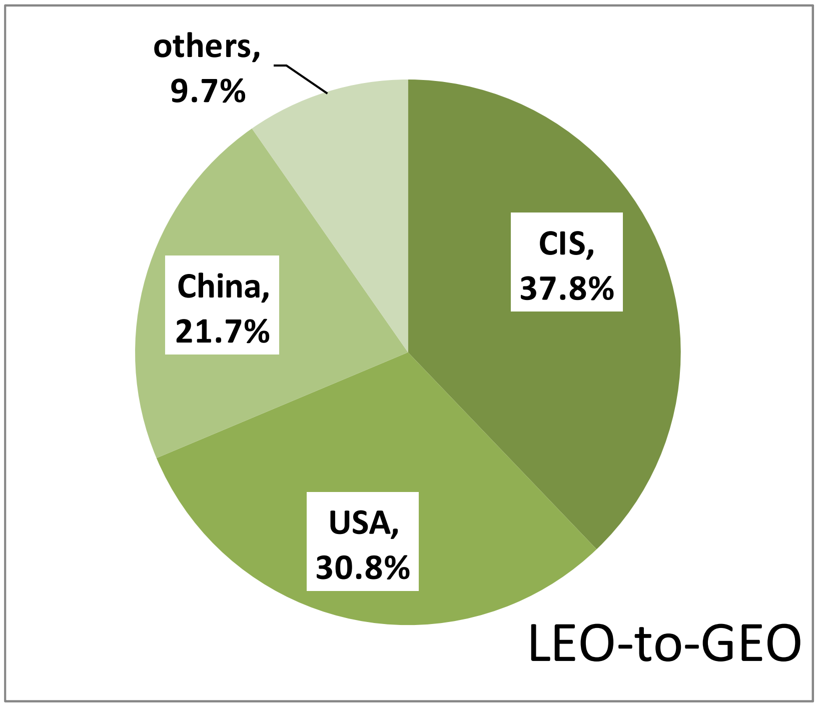


Mass in Orbit

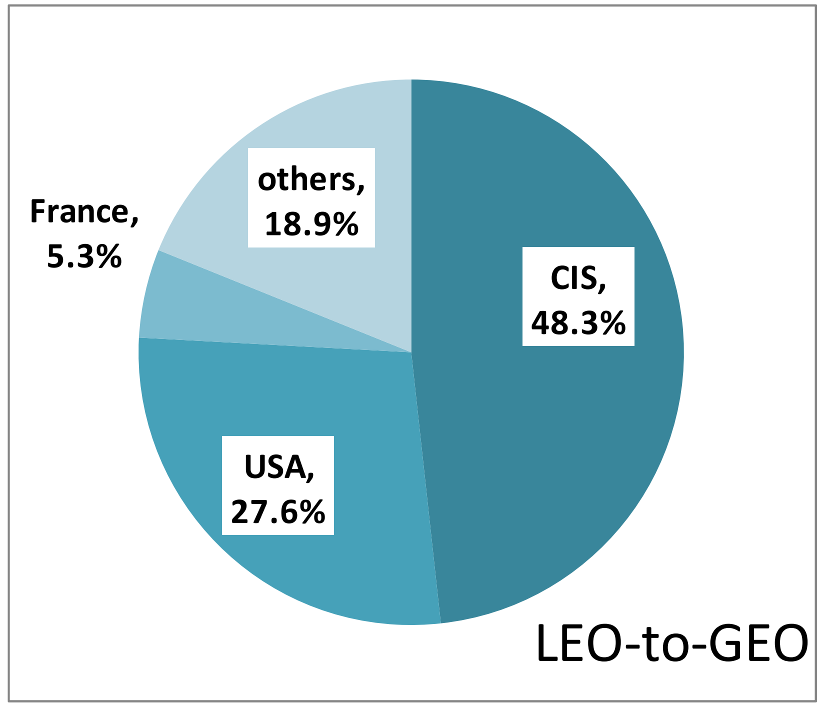


Sources of the Catalog Population – All

Number Breakdown



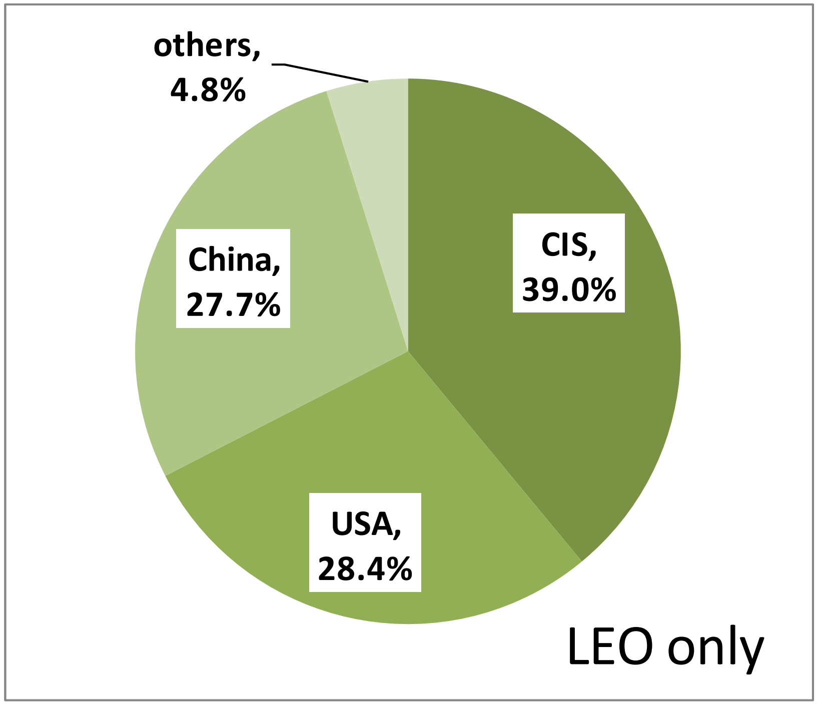
Mass Breakdown



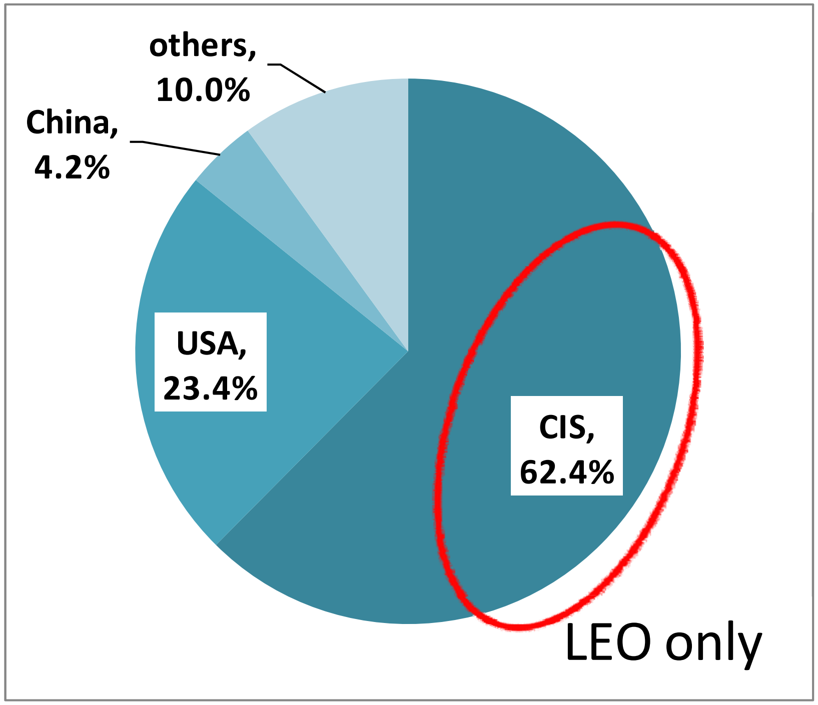
CIS = Russian Federation

Sources of the Catalog Population – LEO Only

Number Breakdown

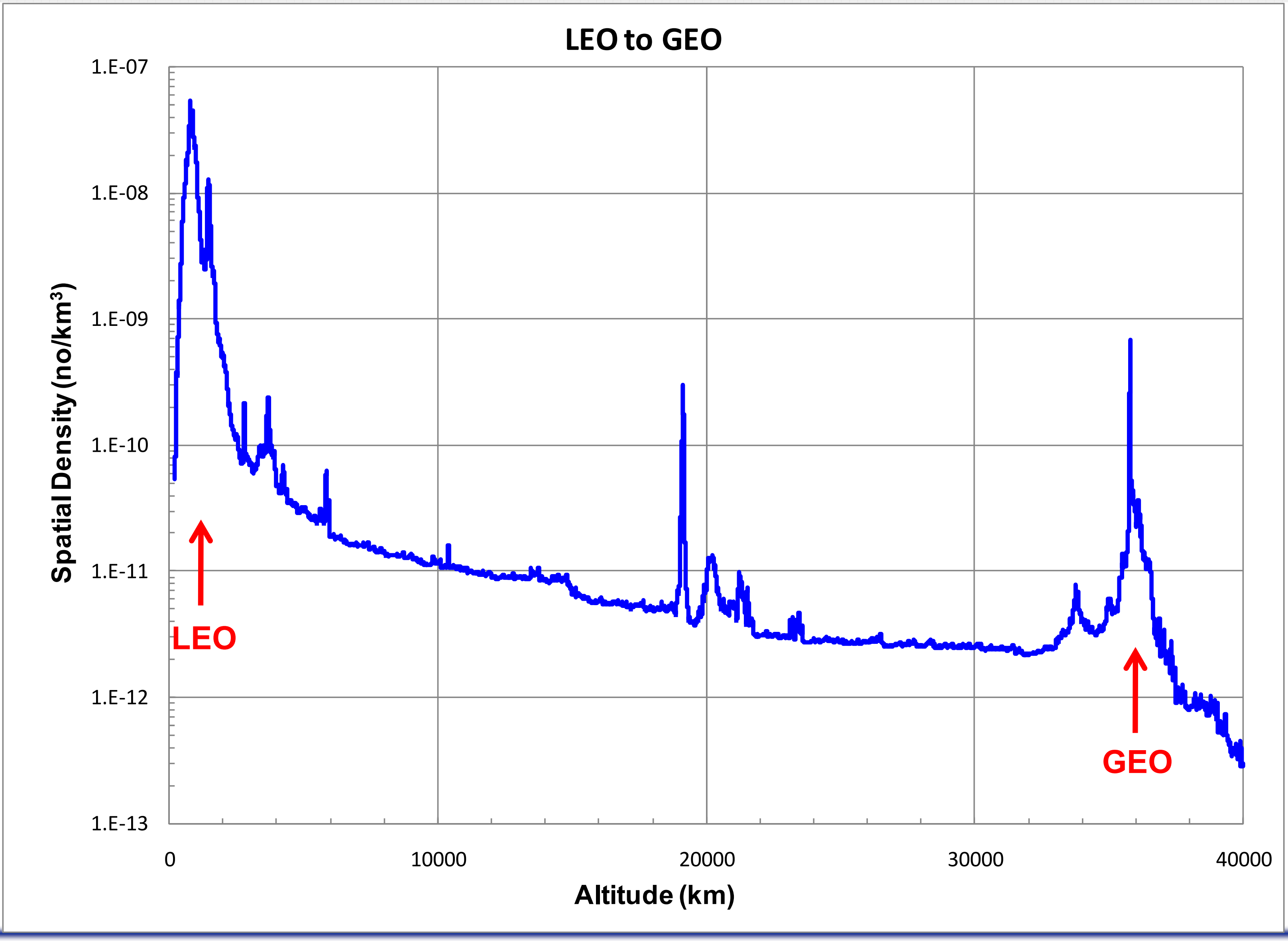


Mass Breakdown

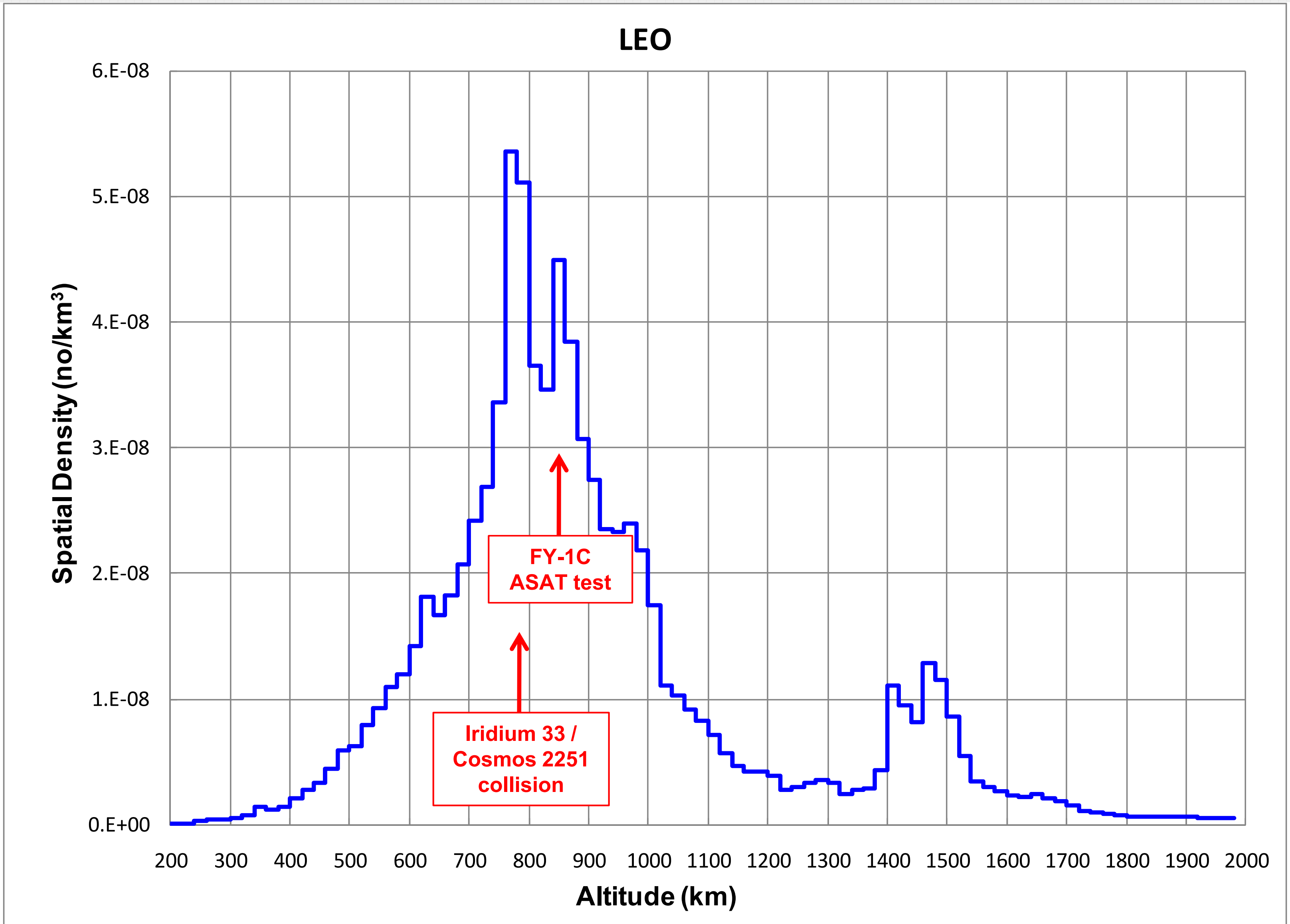


CIS = Russian Federation

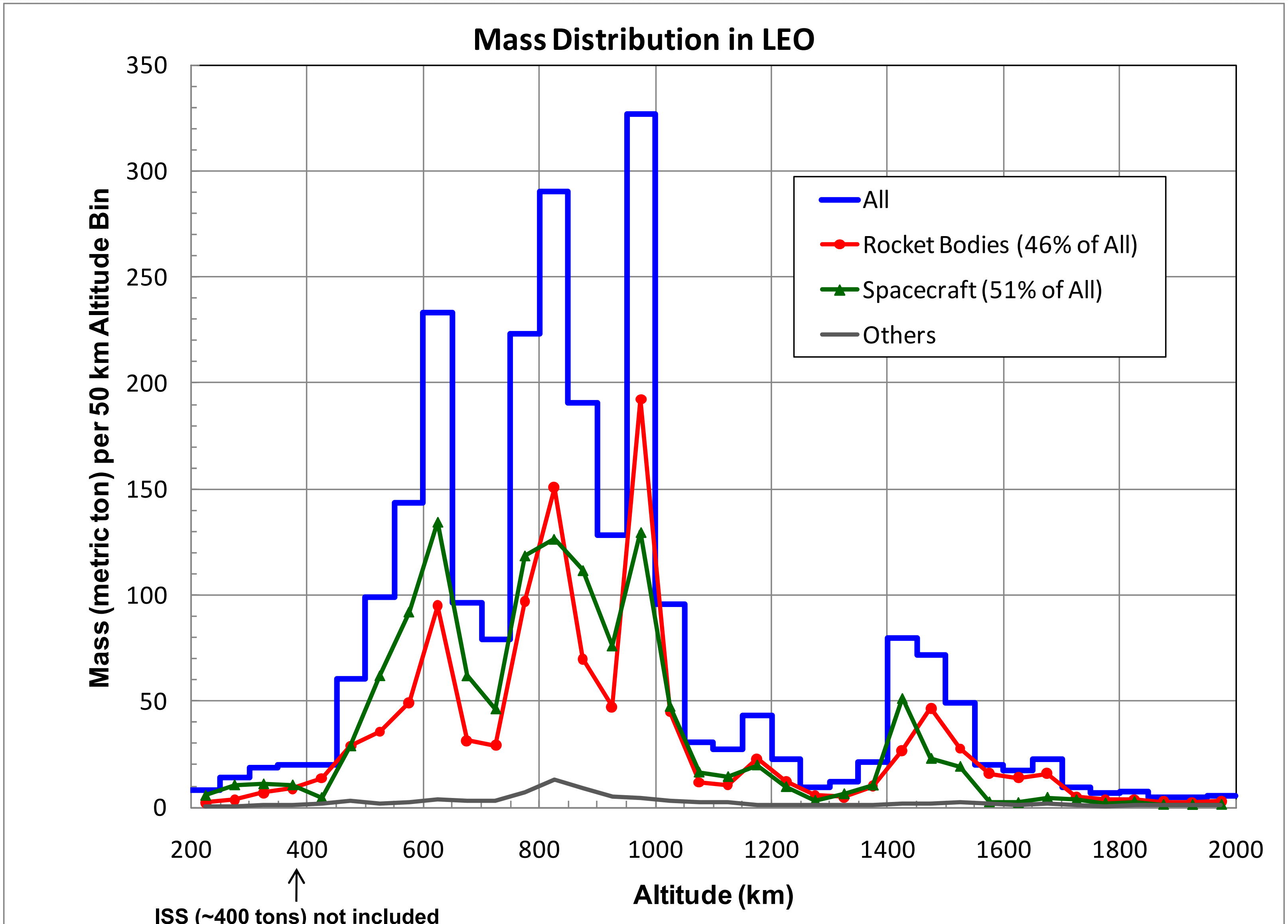
Spatial Density of the Catalog Population (1/2)



Spatial Density of the Catalog Population (2/2)



Mass Distribution in LEO



Projected Growth of the Future Debris Environment

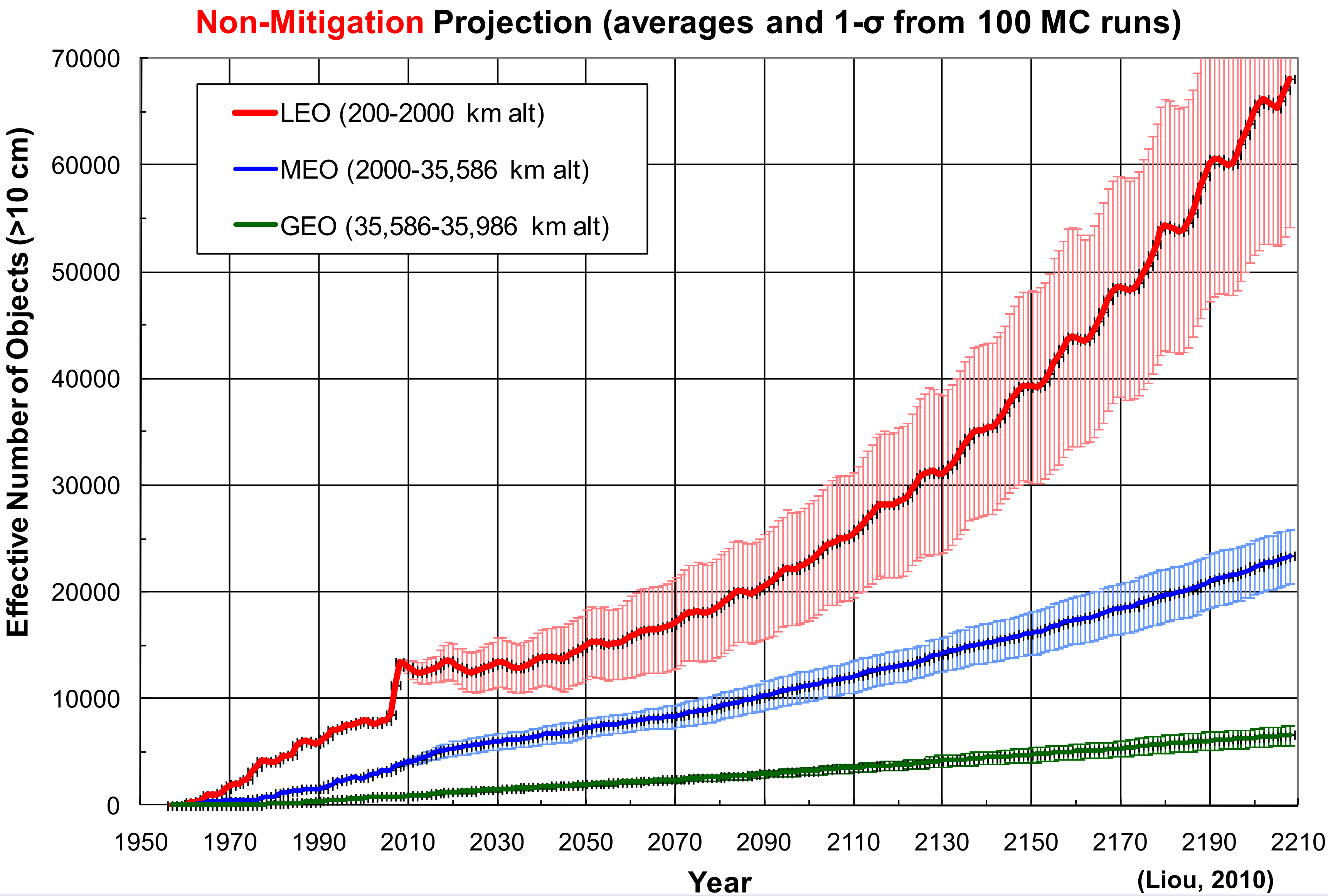
Debris Environment Modeling

- **All environment simulations are based on LEGEND (an LEO-to-GEO Environment Debris model)**
  - LEGEND is the high fidelity orbital debris evolutionary model developed by the NASA Orbital Debris Program Office
  - LEGEND simulates objects individually, incorporates major perturbations in orbit propagation, and includes major source and sink mechanisms (launches, breakups, decays)
  - Ten peer-reviewed journal papers have been published on LEGEND and its applications since 2004
  - This seminar will focus on ≥10 cm objects and limit the future projection to 200 years

Peer-Reviewed Journal Publications
(LEGEND and LEGEND Applications)

1. Liou, J.-C. *et al*., LEGEND – A three-dimensional LEO-to-GEO debris evolutionary model. *Adv. Space Res*. 34, 5, 981-986, 2004.
2. Liou, J.-C. and Johnson, N.L., A LEO satellite postmission disposal study using LEGEND, *Acta Astronautica* 57, 324-329, 2005.
3. Liou, J.-C., Collision activities in the future orbital debris environment, *Adv. Space Res*. 38, 9, 2102-2106, 2006.
4. Liou, J.-C. and Johnson, N.L., Risks in space from orbiting debris, *Science* 311, 340-341, 2006.
5. Liou, J.-C., A statistic analysis of the future debris environment, *Acta Astronautica* 62, 264-271, 2008.
6. Liou, J.-C. and Johnson, N.L., Instability of the present LEO satellite population, *Adv. Space Res*. 41, 1046-1053, 2008.
7. Liou, J.-C. and Johnson, N.L., Characterization of the cataloged Fengyun-1C fragments and their long-term effect on the LEO environment, *Adv. Space Res*. 43, 1407-1415, 2009.
8. Liou, J.-C. and Johnson, N.L., A sensitivity study of the effectiveness of active debris removal in LEO, *Acta Astronautica* 64, 236-243, 2009.
9. Liou, J.-C. *et al*., Controlling the growth of future LEO debris populations with active debris removal, *Acta Astronautica* 66, 648-653, 2010.
10. Liou, J.-C., An active debris removal parametric study for LEO environment remediation, *Adv. Space Res*. 47, 1865-1876, 2011.

Future Projection – The Worst Case Scenario
(Regular Satellite Launches, but No Mitigation Measures)



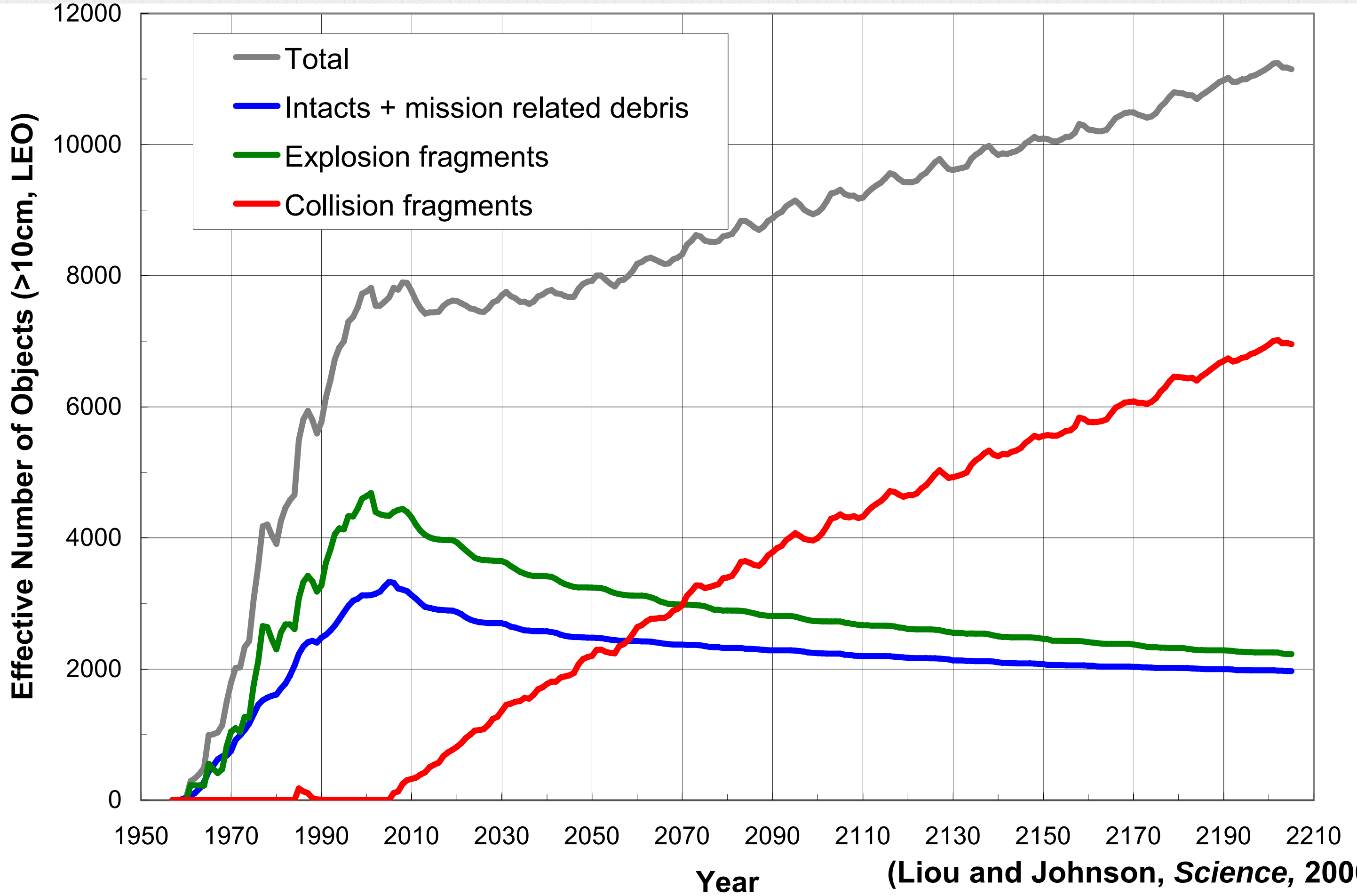
(Liou, 2010)

Assessments of the Non-Mitigation Projection

- **LEO: the non-mitigation scenario predicts the debris population (≥10 cm objects) will have a rapid non-linear increase in the next 200 years**
  - This is a well-known trend (the "Kessler Syndrome") that was the motivation for developing the currently-adopted mitigation measures in the last 15 years
- **MEO and GEO: the non-mitigation scenario predicts a moderate population growth**
  - Only a few accidental collisions between ≥10 cm objects are predicted in the next 200 years
  - The currently-adopted mitigation measures (including EOL maneuvers in GEO) will <u>further</u> limit the population growth
  - Environment remediation is not urgent

Will the Commonly-Adopted Mitigation Measures Stabilize the Future LEO Environment?

Future Projection – The Best Case Scenario
(No New Launches Beyond 1/1/2006)



(Liou and Johnson, *Science*, 2006)

- **Collision fragments replace other decaying debris through the next 50 years, keeping the total population approximately constant**
- **Beyond 2055, the rate of decaying debris decreases, leading to a net increase in the overall satellite population due to collisions**

Assessments of the No-New-Launches Scenario

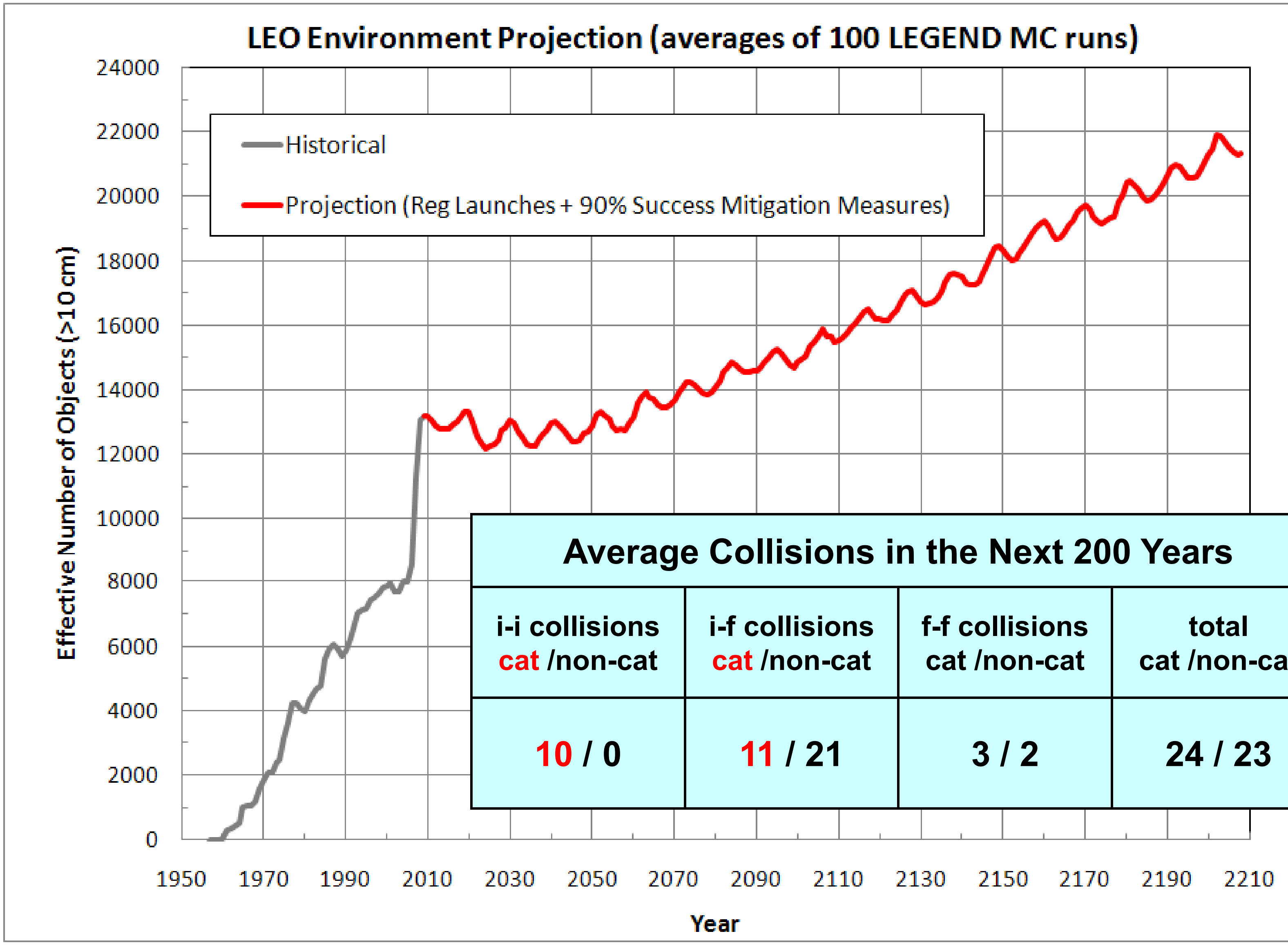
- **In reality, the situation will be worse than the "no new launches" scenario as**
  - Satellites launches will continue
  - Major breakups may continue to occur (*e.g.*, Fengyun-1C)
- **Postmission disposal (such as a 25-year decay rule) will help, but will be insufficient to prevent the self-generating phenomenon from happening**
- **To preserve the near-Earth space for future generations, ADR must be considered**

Conclusions of the 2006 Paper

- **"The current debris population in the LEO region has reached the point where the environment is unstable and collisions will become the most dominant debris-generating mechanism in the future."**
- **"Only remediation of the near-Earth environment – the removal of existing large objects from orbit – can prevent future problems for research in and commercialization of space."**

- Liou and Johnson, ***Science***, 20 January 2006

Environment Projection With Mitigation Measures



Average Collisions in the Next 200 Years			
i-i collisions cat /non-cat	i-f collisions cat /non-cat	f-f collisions cat /non-cat	total cat /non-cat
10 / 0	11 / 21	3 / 2	24 / 23

International Consensus

- **The LEO environment instability issue is under investigation by the Inter-Agency Space Debris Coordination Committee (IADC) members**

- **An official "Stability of the Future LEO Environment" comparison study, was initiated in 2009**
  – Six participating members: NASA (lead), ASI, ESA, ISRO, JAXA, and UKSA
  – Results from the six different models are consistent with one another, *i.e.*, even with a good implementation of the commonly-adopted mitigation measures, the LEO debris population is expected to increase in the next 200 years
  – Study summary was presented at the April 2011 IADC meeting

Inter–Agency Space Debris Coordination Committee

Preserving the Environment with Active Debris Removal (ADR*)

***ADR = Removing debris beyond guidelines of current mitigation measures**

Key Questions for ADR

- **Where is the most critical region for ADR?**
- **What are the mission objectives?**
- **What objects should be removed first?**
  - The debris environment is very dynamic. Breakups of large intacts generate small debris, small debris decay over time,…
- **What are the benefits to the environment?**
- **How to do it?**

→ **The answers will drive the top-level requirements, the necessary technology development, and the implementation of ADR operations**

How to Define Mission Success?

- **Mission objectives guide the removal target selection criteria and the execution of ADR**
- **Common objectives**
  - Follow practical/mission constraints (in altitude, inclination, class, size, *etc*.)
  - Maximize benefit-to-cost ratio
- **Specific objectives**
  - Control population growth (≥10 cm or others)
  - Limit collision activities

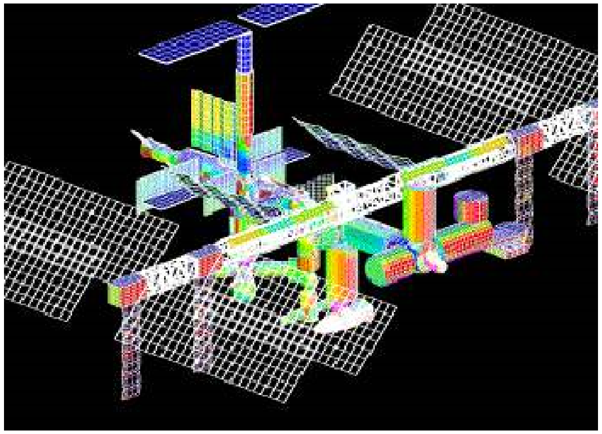
    } Target large & massive intacts
  - Mitigate mission-ending risks (not necessarily catastrophic destruction) to operational payloads
  - Mitigate risks to human space activities

    } Target small debris
  - And so on

Target Small Debris

One Example: Risks From Small Debris

- **The U.S. segments of the ISS are protected against orbital debris about 1.4 cm and smaller**
  - "Currently," the number of objects between 1.5 cm and 10 cm, with orbits crossing that of the ISS, is approximately 1200
    - **~800 of them are between 1.5 cm and 3 cm**
  - To reduce 50% of the ISS-crossing orbital debris in this size range (1.5 cm to 3 cm) will require, for example, a debris collector/remover with an area-time product of ~1000 km^2 year



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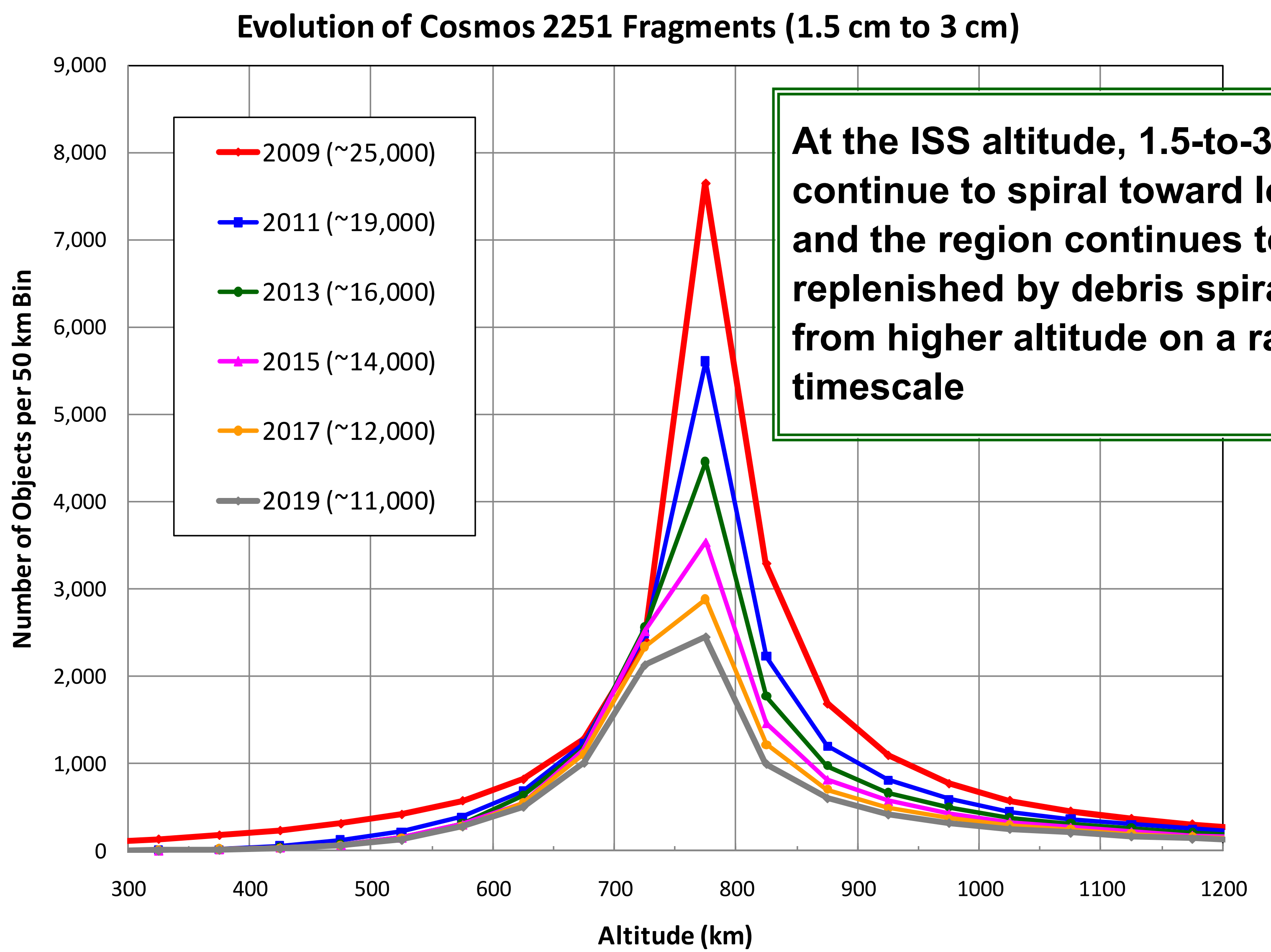
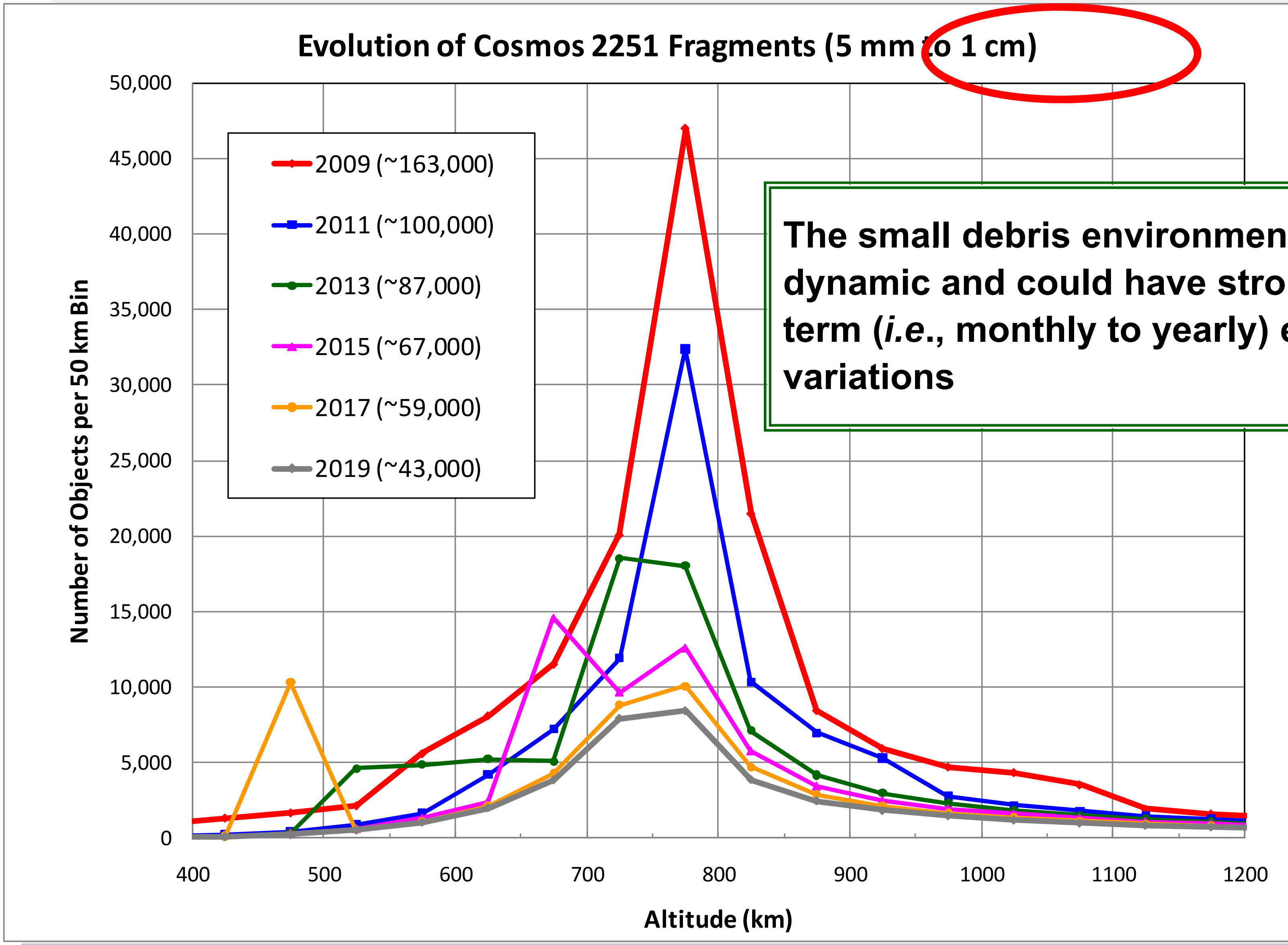
Small Debris Environment Is Highly Dynamic (1/2)



At the ISS altitude, 1.5-to-3 cm debris continue to spiral toward lower altitude, and the region continues to be replenished by debris spiraling down from higher altitude on a rapid (yearly) timescale

Small Debris Environment Is Highly Dynamic (2/2)



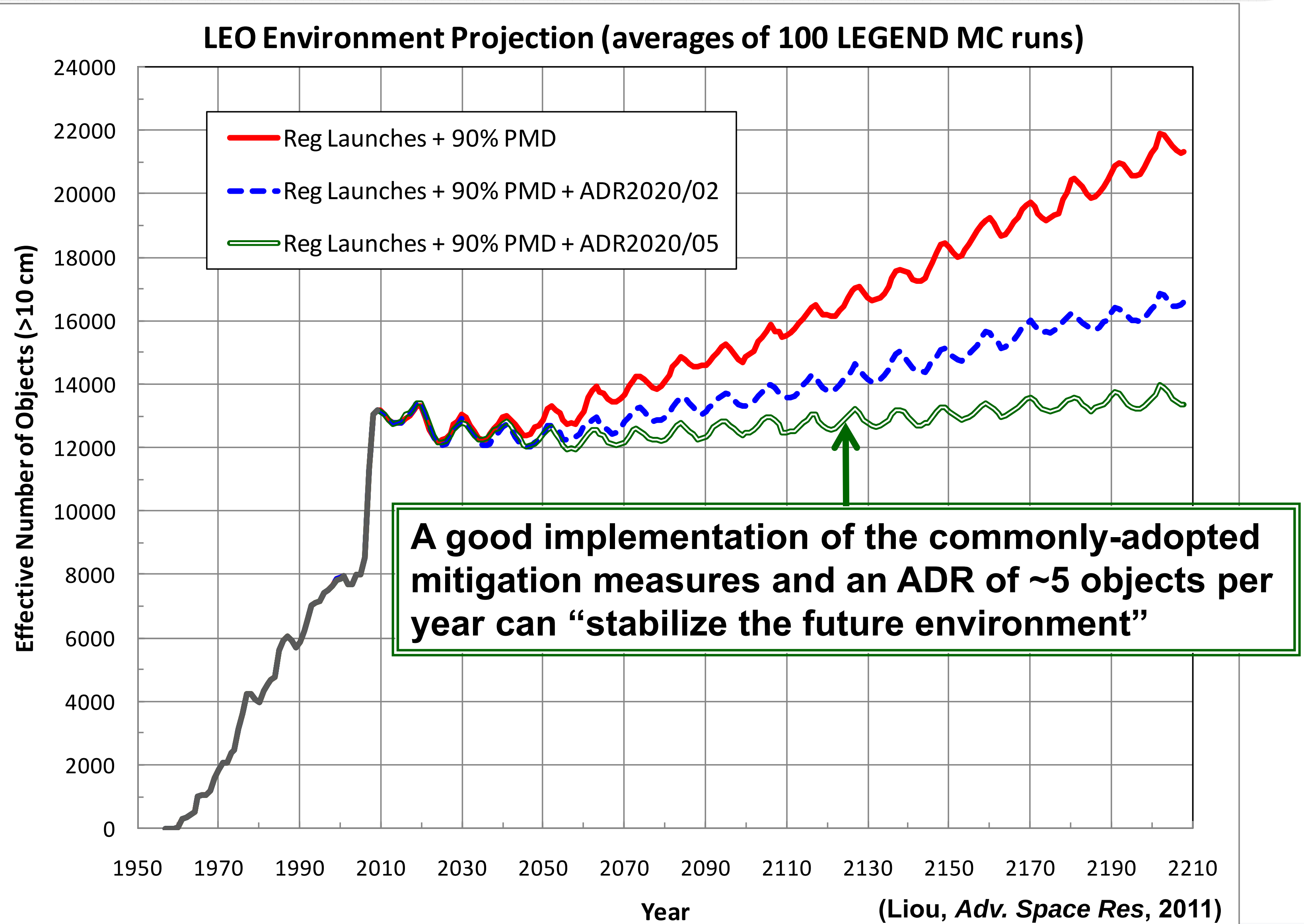
The small debris environment is highly dynamic and could have strong short-term (*i.e.*, monthly to yearly) episodic variations

Target Large Debris

Targeting the Root Cause of the Problem

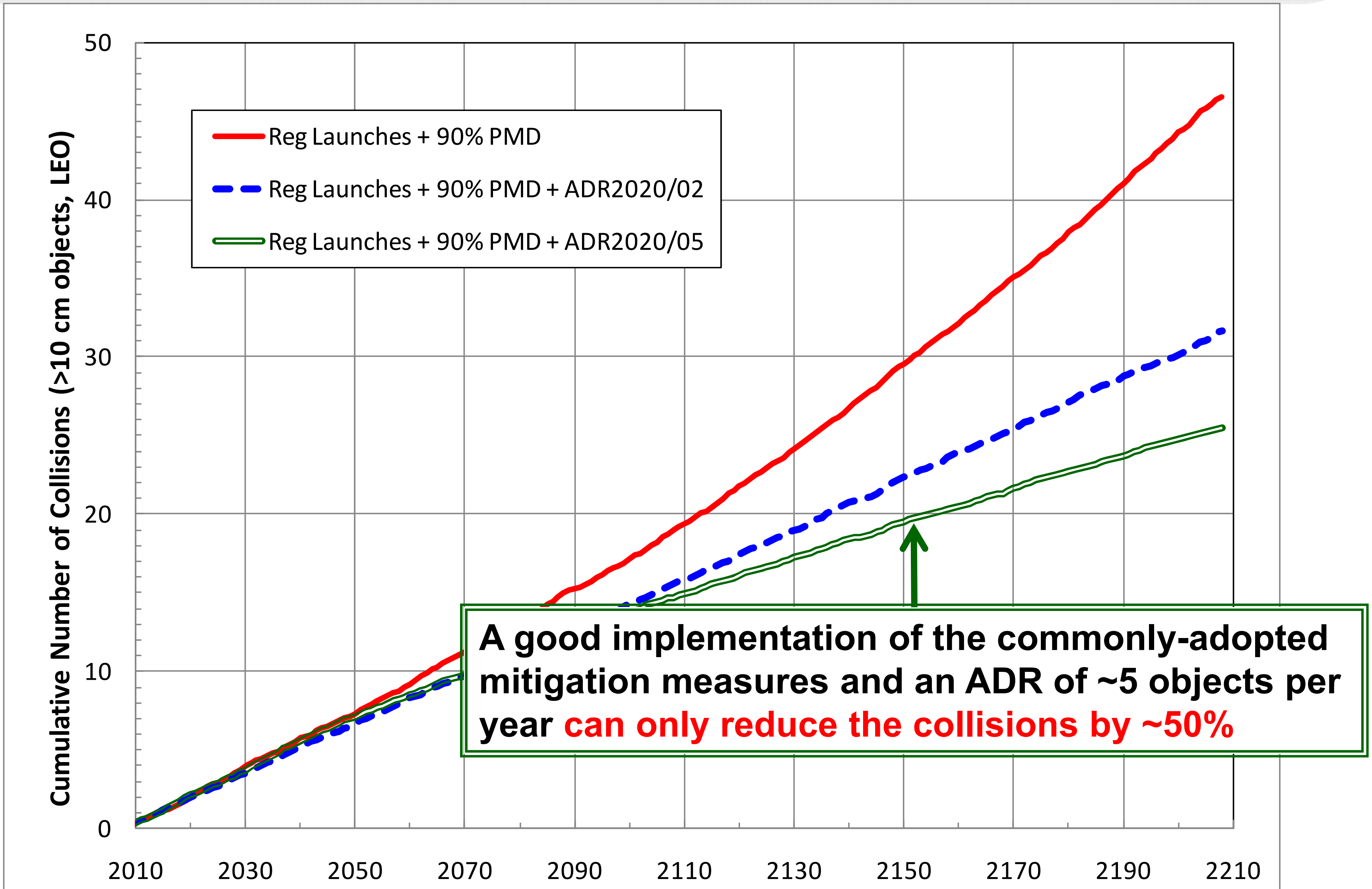
- **A 2008-2009 NASA study shows that the two key elements to stabilize the future LEO environment (in the next 200 years) are**
  - A good implementation of the commonly-adopted mitigation measures (passivation, 25-year rule, avoid intentional destruction, *etc.)*
  - An active debris removal of about five objects per year
    - **These are objects with the highest [M × P_{coll}]**
    - **Many (but not all) of the potential targets in the current environment are spent Russian SL upper stages**
      - **Masses: 1.4 to 8.9 tons**
      - **Dimensions: 2 to 4 m in diameter, 6 to 12 m in length**
      - **Altitudes: ~600 to ~1000 km regions**
      - **Inclinations: ~7 well-defined bands**

Controlling Debris Growth with ADR



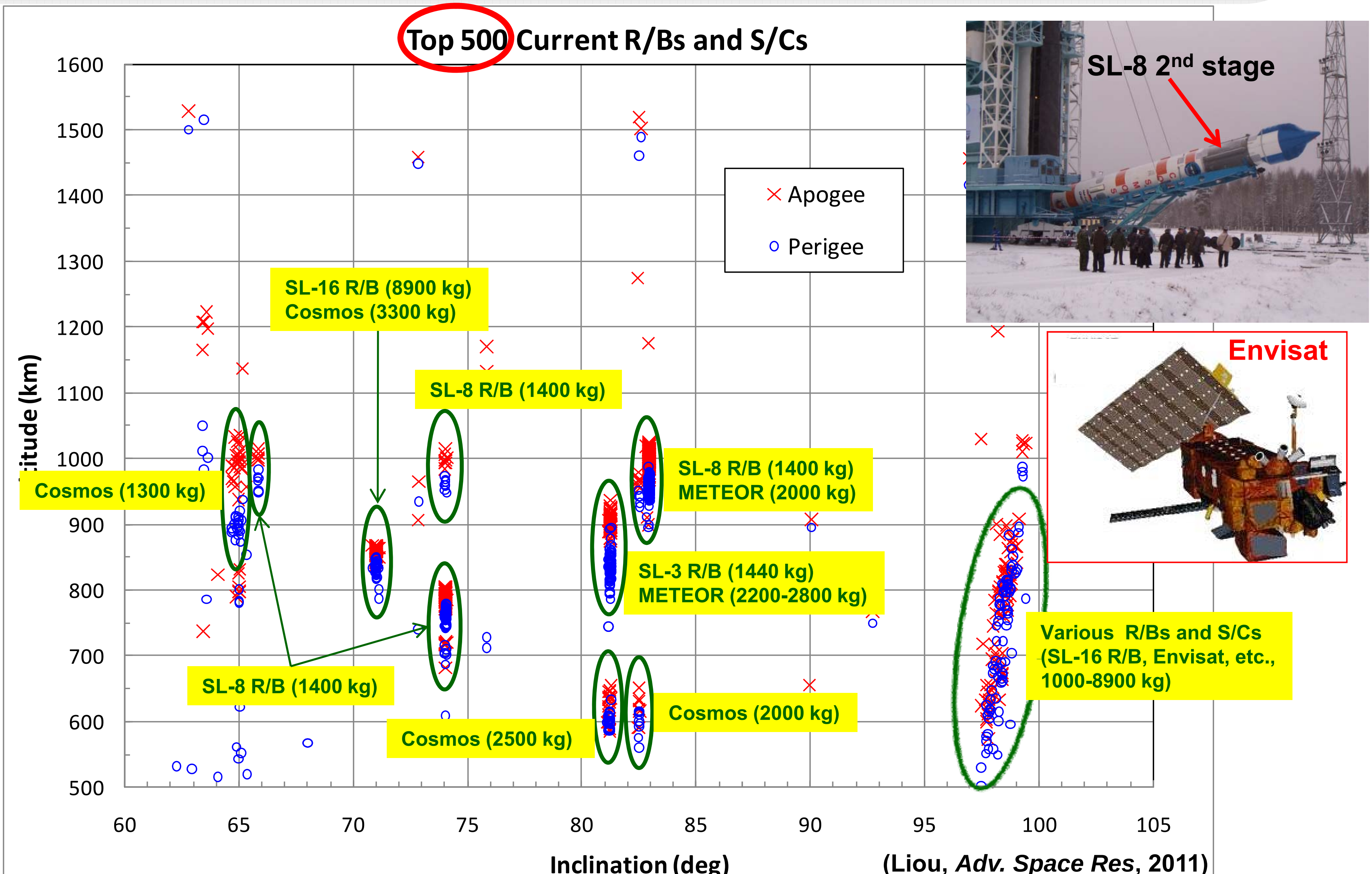
(Liou, *Adv. Space Res*, 2011)

Projected Collision Activities in LEO



(Liou, *Adv. Space Res*, 2011)

Potential Active Debris Removal Targets



(Liou, *Adv. Space Res*, 2011)

National Space Policy of the United States of America (28 June 2010)

- **Orbital debris is mentioned on 4 different pages for a total of 10 times in this 14-page policy document**
- **On page 7:**

> ***Preserving the Space Environment and the Responsible Use of Space***
>
> **Preserve the Space Environment.** For the purposes of minimizing debris and preserving the space environment for the responsible, peaceful, and safe use of all users, the United States shall:
>
> - …
> - Pursue research and development of technologies and techniques, through the Administrator of the National Aeronautics and Space Administration (NASA) and the Secretary of Defense, to mitigate and remove on-orbit debris, reduce hazards, and increase understanding of the current and future debris environment; and
> - …

Challenges for ADR Operations

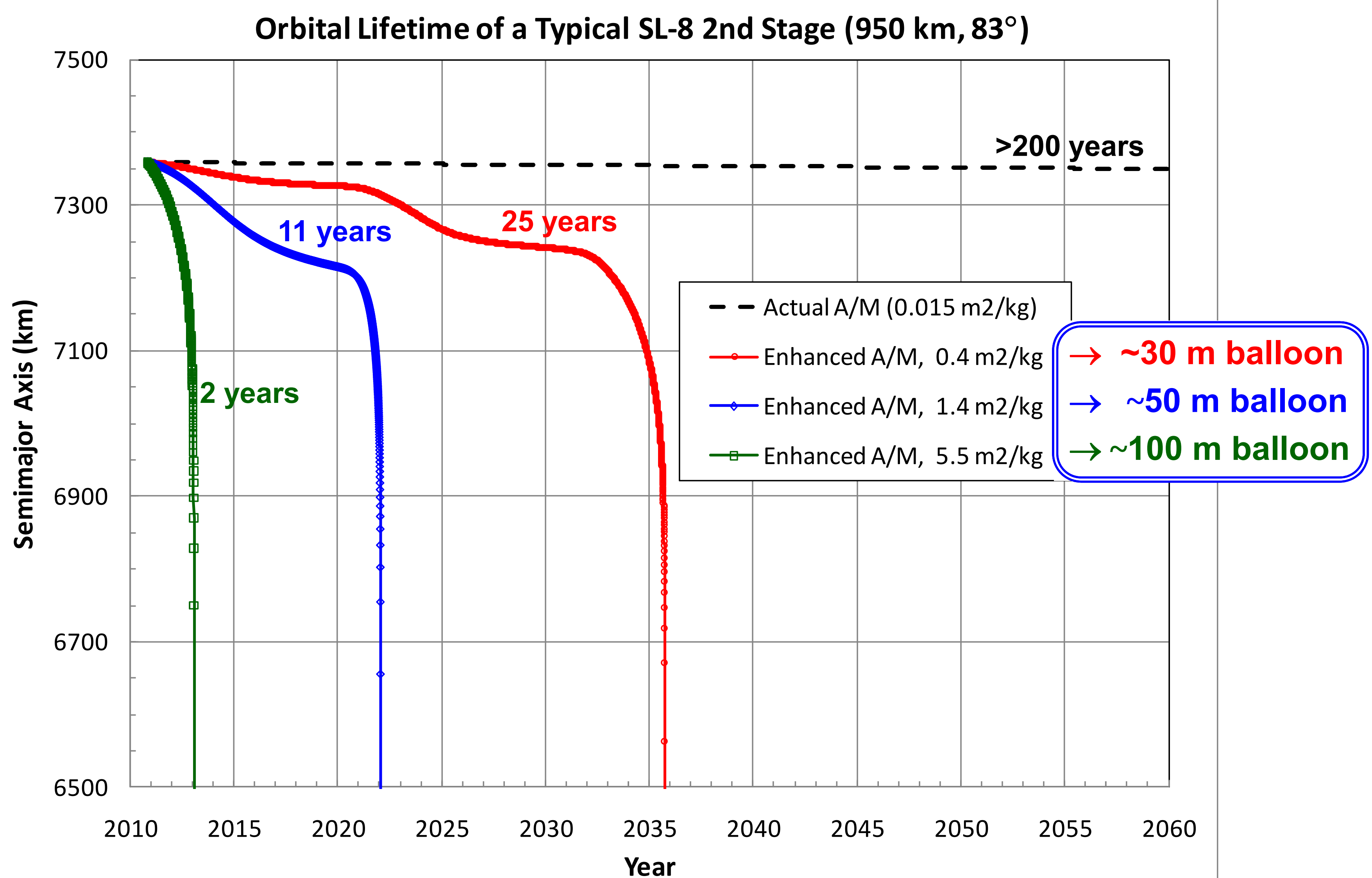
Operations	Technology Challenges
Launch	Single-object removal per launch is not feasible from cost perspective
Propulsion	Solid, liquid, tether, plasma, laser, drag-enhancement devices, others?
Precision Tracking	Ground or space-based
GN&C and Rendezvous	Autonomous, non-cooperative targets
Stabilization (of the tumbling targets)	Physical or non-physical, how
Capture or Attachment	Physical (where, how) or non-physical (how), do no harm
Deorbit or Graveyard Orbit	When, where, reentry ground risks

- **Other requirements:**
  - Affordable cost
  - Repeatability of the removal system (in space)

The First Step

- **Identify top-level requirements for an <u>end-to-end</u> ADR operation**
  - Launch, propulsion, precision tracking, GN&C, rendezvous, stabilization, capture/attachment, and deorbit/graveyard maneuvers
  - Define stakeholders and their expectations to drive the development of a concept of operations
- **Conduct mission design analyses and establish a feasible forward plan**
  - Identify TRLs of existing technologies
  - Evaluate pros and cons of different technologies (*e.g*., space tug vs. drag-enhancement devices)
  - Identify technology gaps (*e.g*., ways to stabilize a massive, non-cooperative, fast spinning/tumbling target)
  - Perform trade studies (*e.g*., physical vs. non-physical capture; deorbit vs. graveyard orbit)

An Example – Deorbit With Drag-Enhancement Devices



Recent ADR Activities at the National and International Levels

NASA-DARPA International Conference on Orbital Debris Removal (Dec. 2009)

- **The 2.5-day conference included 10 sessions**
  - Understanding the Problem; Solution Framework; Legal & Economic; Operational Concepts; Using Environmental Forces; Capturing Objects; Orbital Transfer; Technical Requirements; In Situ vs. Remote Solutions; Laser Systems
  - Had 275 participants from 10 countries; 52 presentations plus 4 keynote speeches
- **The conference reflected a growing concern for the future debris environment**
- **It represented the first joint effort for different communities to explore the issues and challenges of active debris removal**

Other Major ADR Events (1/2)

- **International Science and Technology Center (ISTC) Space Debris Mitigation Workshop**
  - A two-day workshop in Moscow in April 2010
  - An international group of experts (IGOE) panel was formed to develop plans for ISTC's participation in future ADR activities
  - ISTC provides a good potential mechanism for Russian contributions
- **1St European Workshop on Active Debris Removal**
  - A one-day event hosted by CNES in Paris in June 2010
  - Included more than 100 participants
  - Solidified CNES' plan to move forward with an ADR demonstration mission
- **ADR sessions at AIAA, COSPAR, EUCASS, IAC, *etc.***

Other Major ADR Events (2/2)

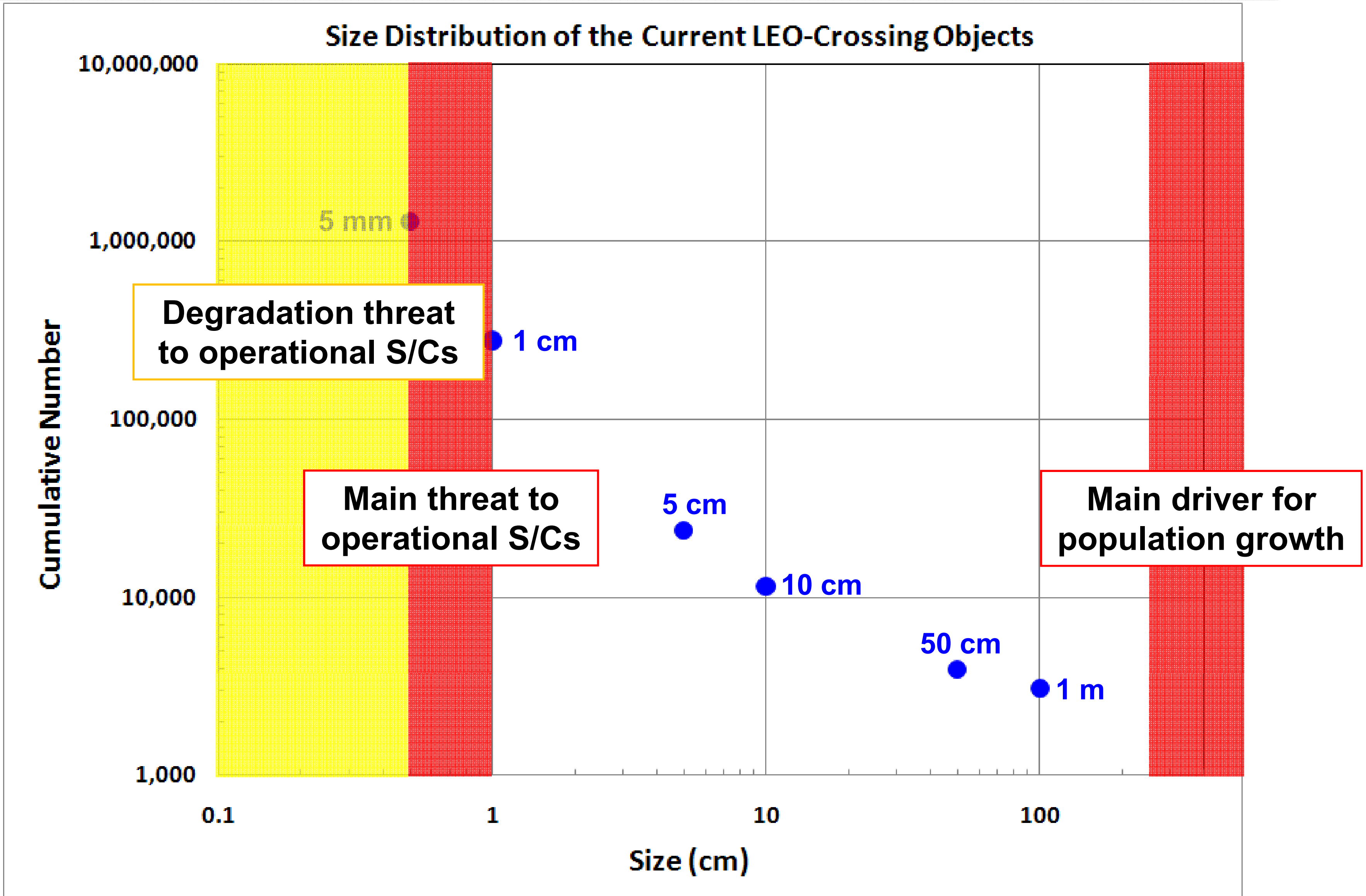
- **International Academy of Astronautics**
  - Is conducting a study to survey existing ADR technologies (led by ESA and NASA)
- **Inter-Agency Space Debris Coordination Committee**
  - Has just completed a LEO environment instability study (led by NASA)
  - Is drafting a white paper on the future LEO debris environment and the need for ADR

Summary

Concluding Remarks (1/4)

- **The LEO debris population will continue to increase even with a good implementation of the commonly-adopted mitigation measures**
  - The increase is driven by catastrophic collisions involving large and massive intacts
  - The major mission-ending risks for most operational satellites, however, comes from impacts with debris just above the threshold of the protection shields (~5 mm to 1 cm)

Concluding Remarks (2/4)



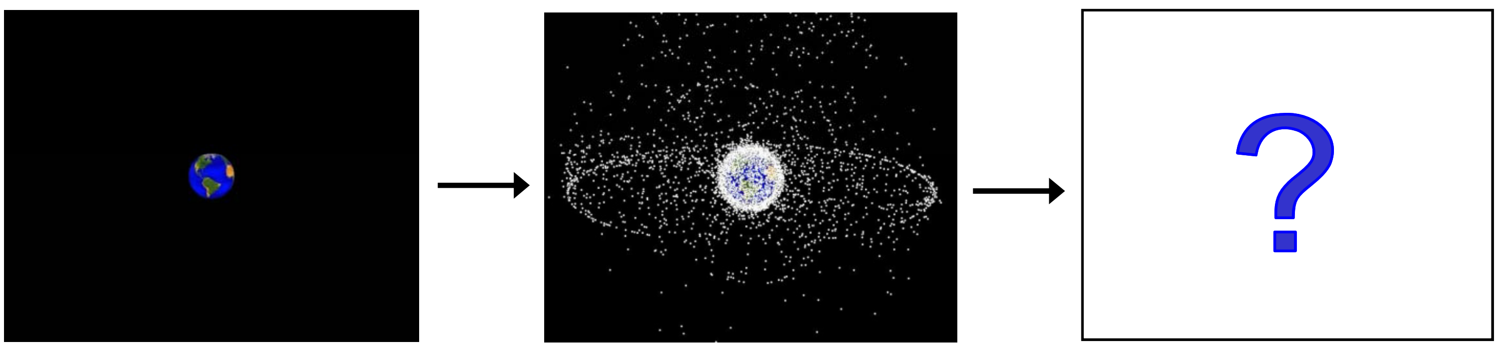
Concluding Remarks (3/4)

- **To address the root cause of the population growth → Target objects with the highest [M × P_{coll}]**
  - To maintain the future LEO debris population at a level similar to the current environment requires an ADR of ~5 massive intacts per year
- **To address the main threat to operational satellites → Target objects in the 5-mm-to-1-cm regime**
  - The small debris environment is highly dynamic and will require a long-term operation to achieve the objective
- **Targeting anything in between will NOT be the most effective means to remediate the environment nor mitigate risks to operational satellites**

Concluding Remarks (4/4)

- **There is a need for a top-level, long-term strategic plan for environment remediation**
  - Define "what is acceptable"
  - Define the mission objectives
  - Establish a roadmap/timeframe to move forward
- **The community must commit the necessary resources to support the development of low-cost and viable removal technologies**
  - Encourage dual-use technologies
- **Address non-technical issues, such as policy, coordination, ownership, legal, and liability at the national and international levels**

Preserving the Environment for Future Generations



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Backup Charts

Why Should Satellite Owners/Operations Care?

- **JSpOC is providing conjunction assessments for all operational satellites, but**
- **The major risk for operational satellites actually comes from impacts with small debris**
- **As the debris population increases**
  - More frequent conjunction assessments will be needed
  - More collision avoidance maneuvers (*i.e.*, ΔV) will be needed
    - **"Now, once every couple of weeks we do a maneuver" – S. Smith, Iridium EVP, December 2010**
    - **A total of 126 COLA maneuvers were conducted by satellite owners in 2010**
  - More debris impact shields (*i.e.*, mass) will be needed to meet the same requirement for probability of no penetration (PNP)
  - The risks for potential critical failure will increase
    - **Number of impacts by 0.5 cm debris (with an average impact speed of 10 km/sec) to all operational satellites in LEO is about 1 to 2 per year in the current environment**

Four Essential "Cs" for ADR

- Consensus
- Cooperation
- Collaboration
- Contributions