National Aeronautics and Space Administration

Orbital Debris Modeling and the Future Orbital Debris Environment

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Outline

- **LEGEND – NASA's Orbital debris (OD) evolutionary model**
- **Projected growth of the future OD populations**
- **OD mitigation**
  - Limiting the generation of new and long-lived debris ("prevention")
- **OD environment remediation**
  - Removing debris beyond the guidelines of the current mitigation measures ("treatment")

Engineering vs Evolutionary Models

- **Orbital debris (OD) engineering model**
  - Is a mathematical tool capable of predicting current and near-term OD impact risks for critical space assets (ISS, *etc*.)
  - Examples: ORDEM (NASA), MASTER (ESA)
- **Orbital debris evolutionary model**
  - Is a physical model capable of predicting future debris environment based on user-specified scenarios
  - Examples: LEGEND (NASA), DAMAGE (UKSA), DELTA (ESA), LEODEEM (JAXA), SDM (ASI)

The Current OD Environment

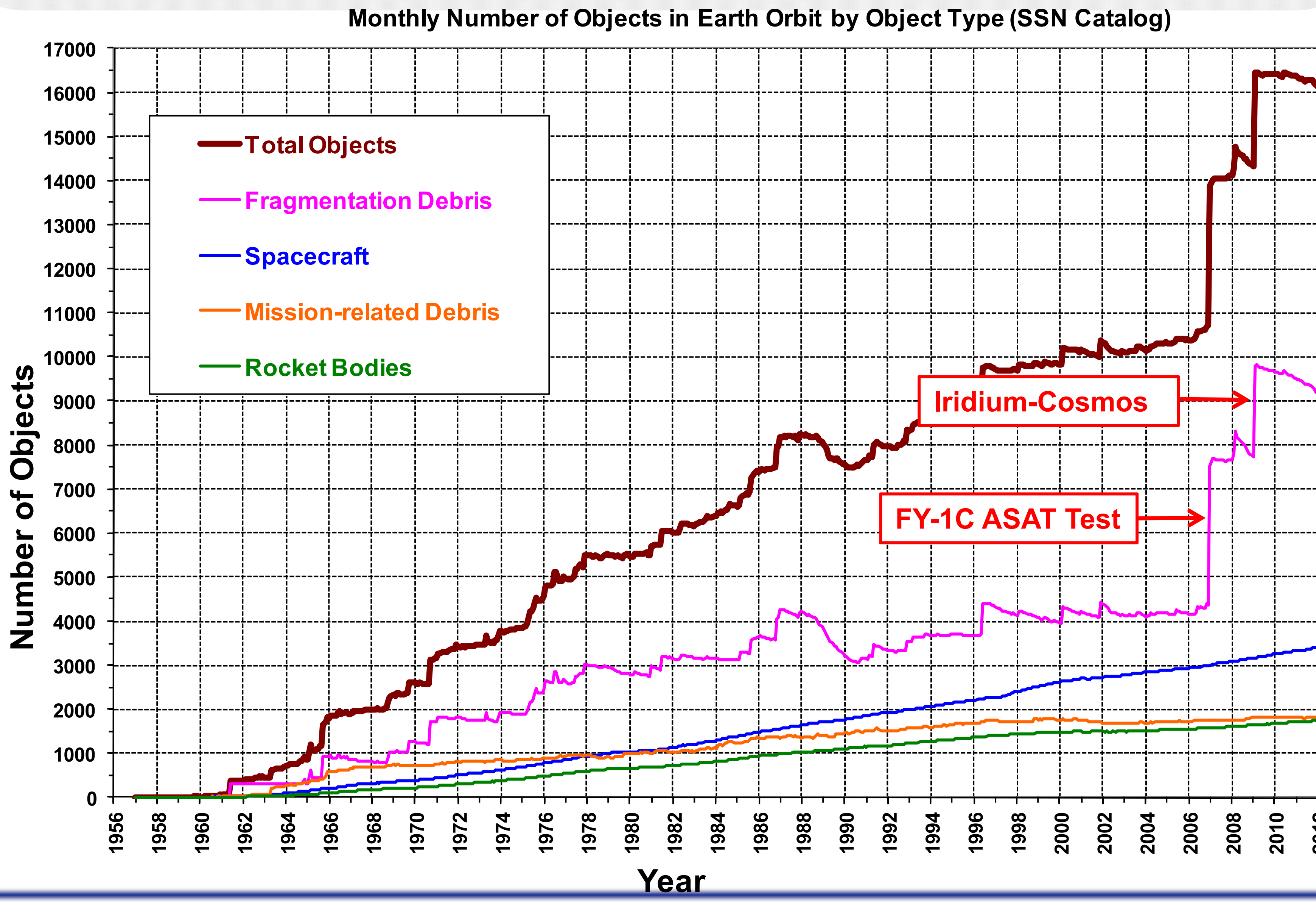
Softball size or larger (≥10 cm): ~22,000
(tracked by the Space Surveillance Network, SSN)

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

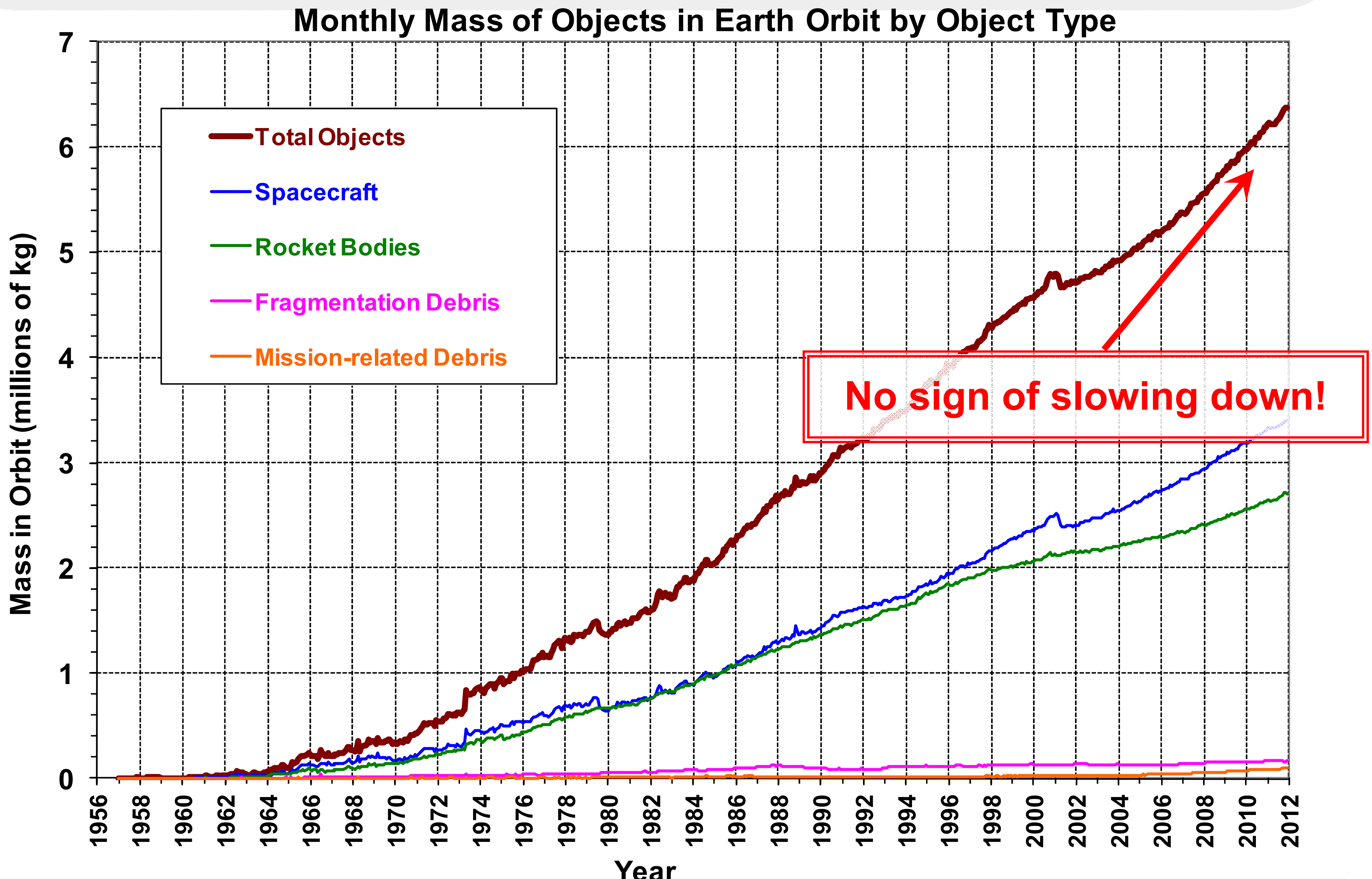
Dot or larger (≥1 mm): >100,000,000
(a grain of salt)

- **Total mass: ~6300 tons LEO-to-GEO (~2700 tons in LEO)**
- **Due to high impact speed in space (~10 km/s in LEO), even sub-mm debris pose a realistic threat to human spaceflight and robotic missions**

Growth of the Cataloged Populations



Mass in Orbit



LEGEND – The NASA Orbital Debris Evolutionary Model

LEGEND Overview (1/2)

- **LEGEND, A <u>LE</u>O-to-<u>G</u>EO <u>en</u>vironment <u>d</u>ebris model**
  - Is a high fidelity, three-dimensional numerical simulation model for long-term orbital debris evolutionary studies
  - Replaces the previous one-dimensional, LEO only model, EVOLVE
  - Includes intacts (rocket bodies and spacecraft), mission-related debris (rings, caps, *etc.*), and explosion/collision fragments
  - Handles objects individually
  - Is capable of simulating objects down to 1 mm in size, but the focus has been on ≥10 cm objects
  - Covers altitudes up to 40,000 km
  - Can project the environment several hundred years into the future

LEGEND Overview (2/2)

- **LEGEND, an orbital debris evolutionary model**
  - Uses a deterministic approach to mimic the historical debris environment based on recorded launches and breakups
  - Uses a Monte Carlo approach and an innovative, pair-wise collision probability evaluation algorithm to simulate future collision activities
  - Analyzes future debris environment based on user-specified launch traffics, postmission disposal, and active debris removal options
  - Ten peer-reviewed journal papers have been published about LEGEND and its applications since 2004

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.

Development History

- **History**

  2003: Completed the historical component

  2005: Developed the "Cube" collision probability evaluation algorithm

  2006: Completed the future projection component

  2006: Added the postmission disposal mitigation options

  2007: Added the new capabilities to evaluate and identify individual objects for removal

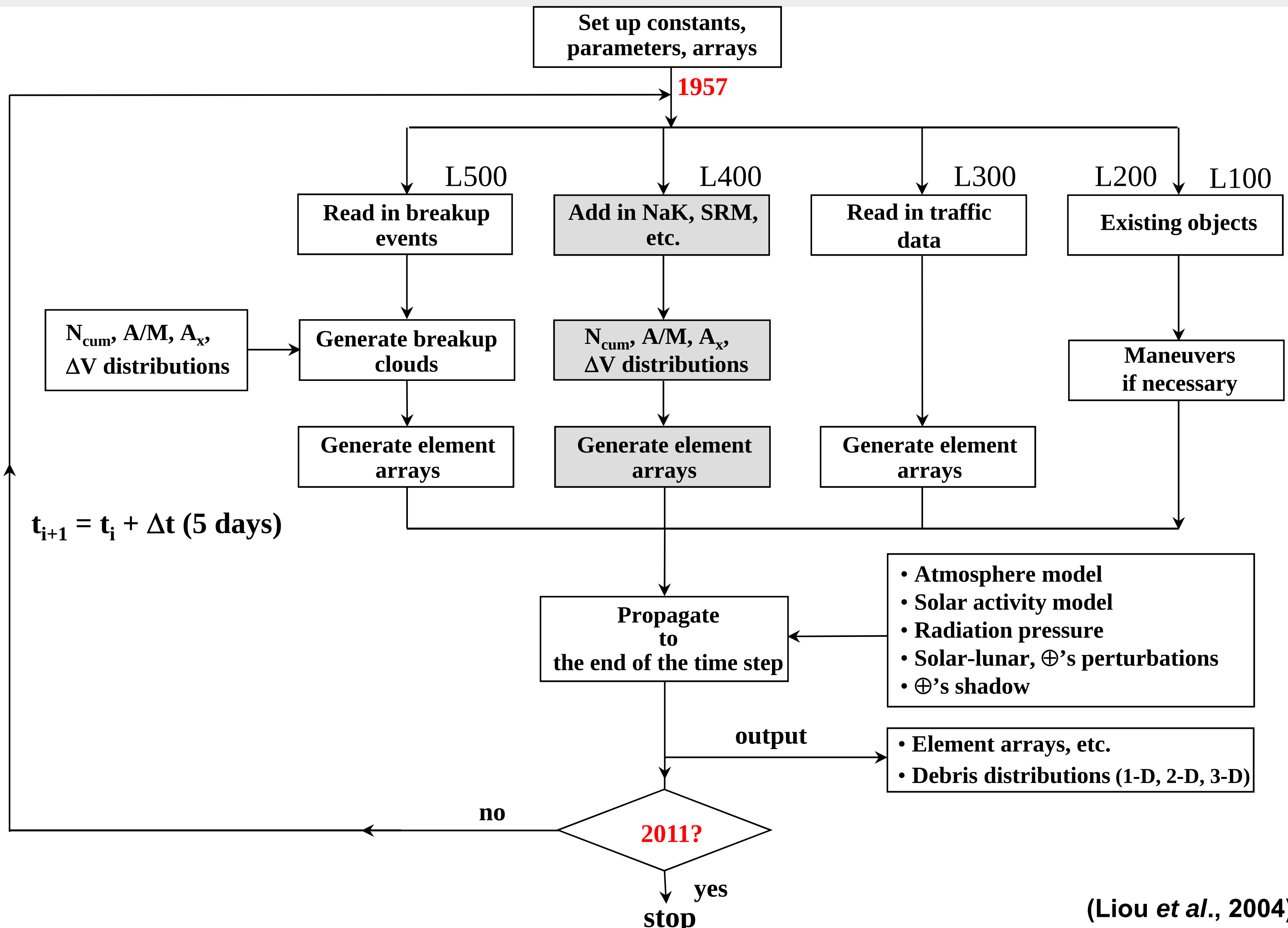
  2008: Added additional options and output information for debris removal

- **Future Improvements**
  - Increase the computational speed of the two orbit propagators
  - Validate model predictions for sub-10 cm populations

The LEGEND Code

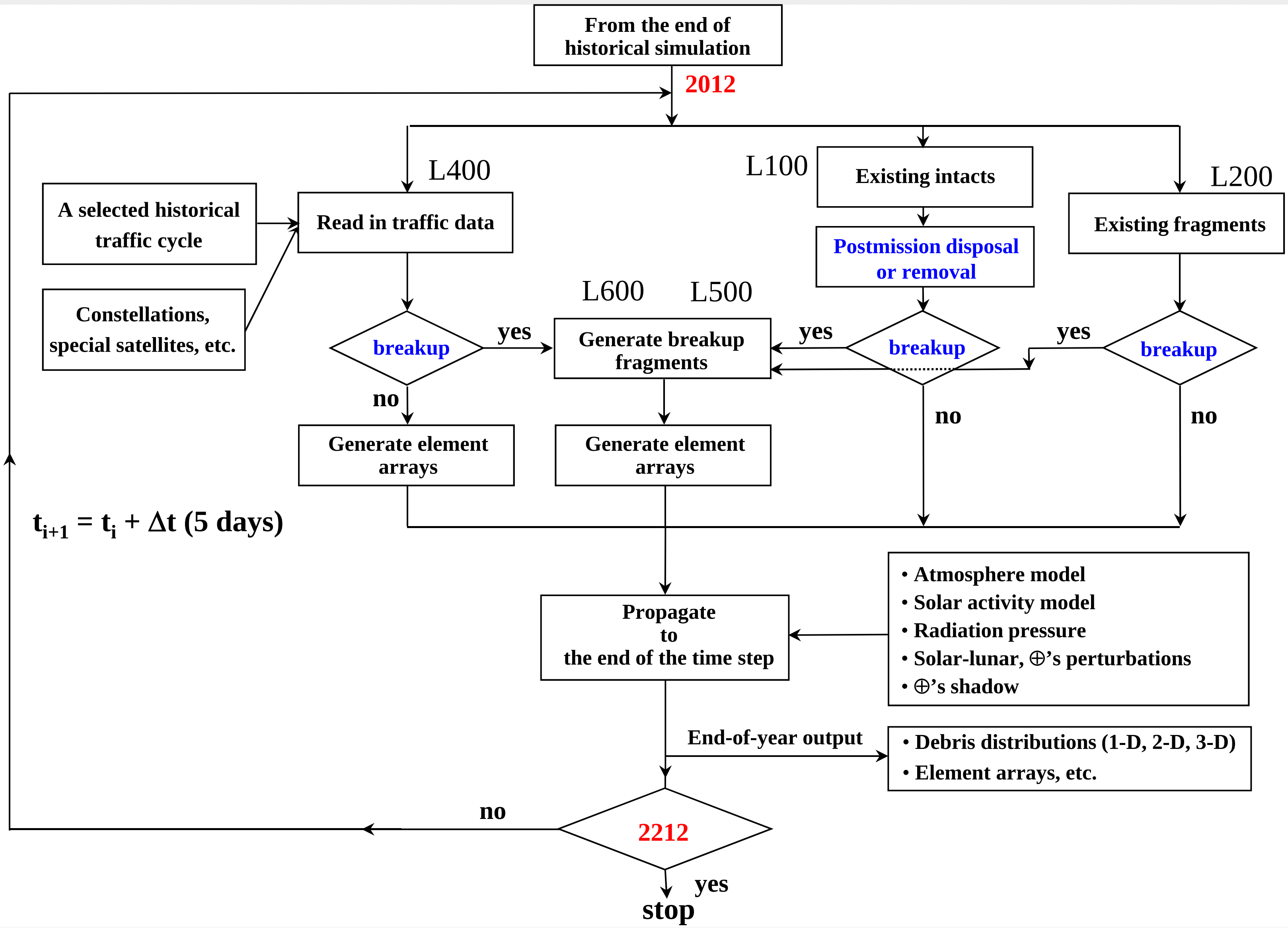
- **LEGEND is written in Fortran**
  - Includes ~18,000 lines of Fortran code
- **LEGEND runs on Unix/Linux-based workstations**
  - Typical runtime: ~days to weeks
- **LEGEND is only available to a few well-trained Orbital Debris Program Office scientists**

LEGEND Architecture (1/2)



(Liou *et al*., 2004)

LEGEND Architecture (2/2)



LEGEND Supporting Models (1/4)

- **DBS database: a comprehensive record of historical launches and breakup events**
  - Time, type, orbit, physical properties (mass, area), *etc*.
  - The database is updated annually
- **Space Surveillance Network (SSN) catalogs**
  - Daily records of the historical growth of the ≥10 cm debris population
  - Basis of empirical area-to-mass ratio (A/M) distributions of large breakup fragments
  - New files are downloaded from “Space Track” website daily
- **Future launch traffic model**
  - Typically a repeat of the last 8-year cycle, as commonly adopted by the international debris modeling community

LEGEND Supporting Models (2/4)

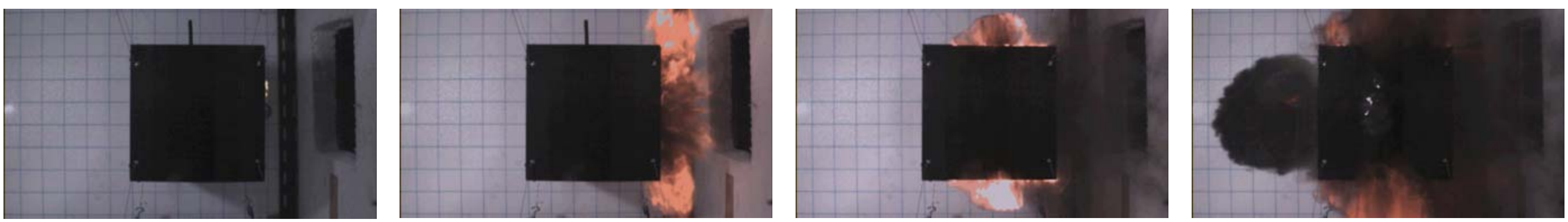
- **Atmospheric drag model**
  - Jacchia atmospheric density model (1977)
  - Drag perturbation equations based on King-Hele (1987)
- **Solar flux (at 10.7 cm wavelength) model consisting of three components**
  - Historical daily records available from the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC)
  - Short-term projection provided by NOAA/SWPC – currently through 2019
  - Long-term projection is a repeat of a 13th-order sine and cosine functional fit to Solar Cycles 18 to 23 (1944 – 2010)
    - **Similar to projections developed for long-term debris evolutionary models by other space agencies (ASI, UKSA, *etc*.)**

LEGEND Supporting Models (3/4)

- **GEOprop orbital propagator**
  - Propagates objects near geosynchronous (GEO) region
  - Perturbations include solar and lunar gravitational forces, solar radiation pressure, and Earth's gravity-field zonal (J_2, J_3, and J_4) and tesserral ($J_{2,2}$, $J_{3,1}$, $J_{3,3}$, $J_{4,2}$, and $J_{4,4}$) harmonics
- **Prop3D orbit propagator**
  - Propagates orbits of objects in LEO and GTO regions
  - Perturbations include atmospheric drag, solar and lunar gravitational forces, solar radiation pressure, and Earth's gravity-field zonal harmonics J_2, J_3, and J_4
- **Both propagators compare reasonably well with the evolutions of the SSN cataloged objects**

LEGEND Supporting Models (4/4)

- **NASA Standard Satellite Breakup Model**
  - Describes the outcome of an explosion or collision
    - **Fragment size, A/M, and ΔV distributions**
  - Based on seven, well-observed on-orbit explosions, several ground-based impact experiments, and one on-orbit collision



LEGEND Applications

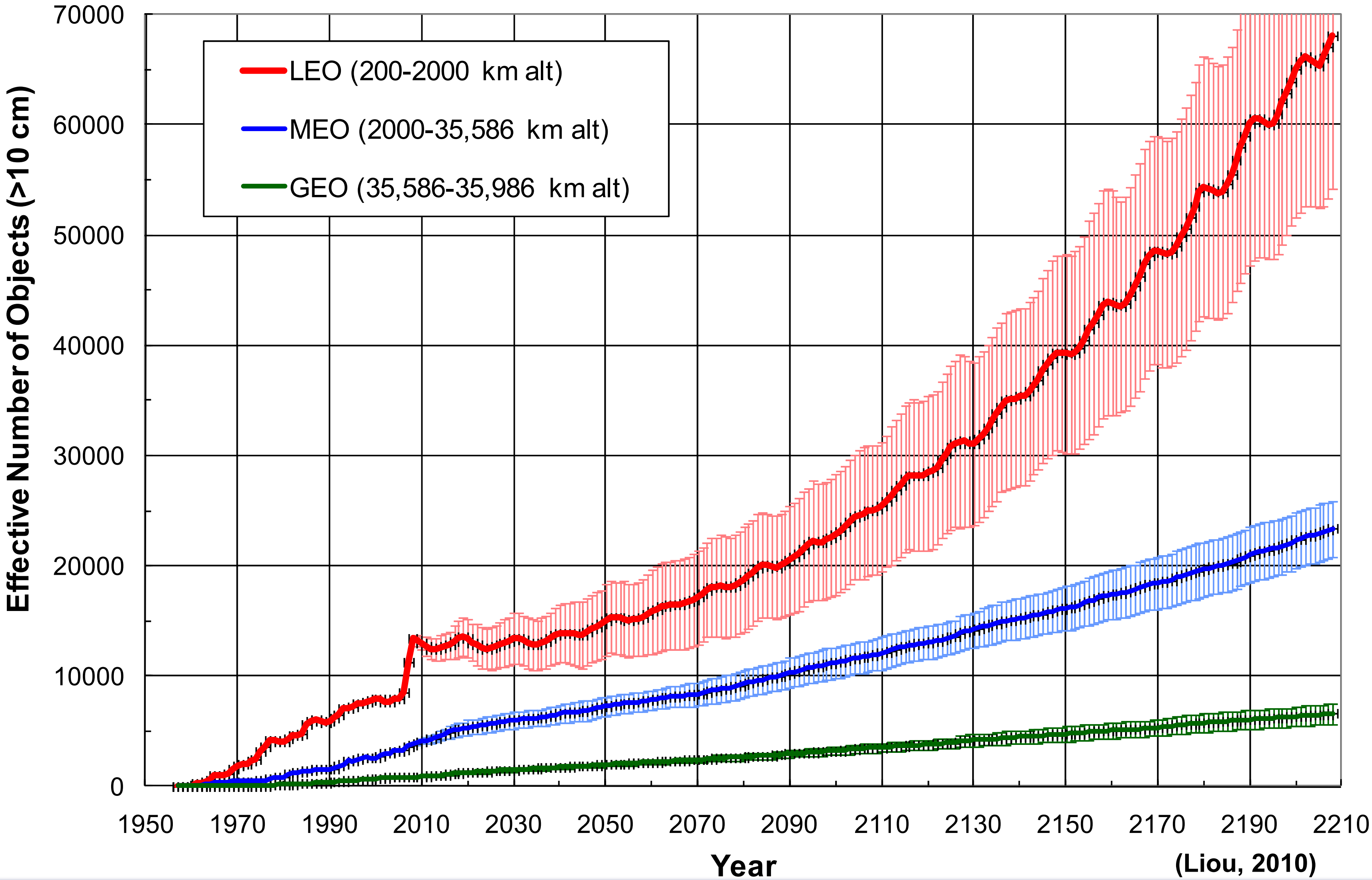
- **LEGEND is the tool the NASA Orbital Debris Program Office uses to**
  - Provide debris environment projection for the next 200 years
    - **Based on user-specified scenarios (launch traffic, postmission disposal, and active debris removal options, *etc.*)**
  - Evaluate the instability of the current debris environment
  - Assess the growth of the future debris populations
  - Characterize the effectiveness of the NASA, U.S., and international debris **mitigation** measures
  - Quantify the benefits of active debris removal (ADR) for environment **remediation**

Projected Growth of the Future Debris Environment

(Worst case, best case, and “realistic” scenarios)

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

Non-Mitigation Projection (averages and 1-σ from 100 MC runs)



(Liou, 2010)

Assessments of the Non-Mitigation Projection

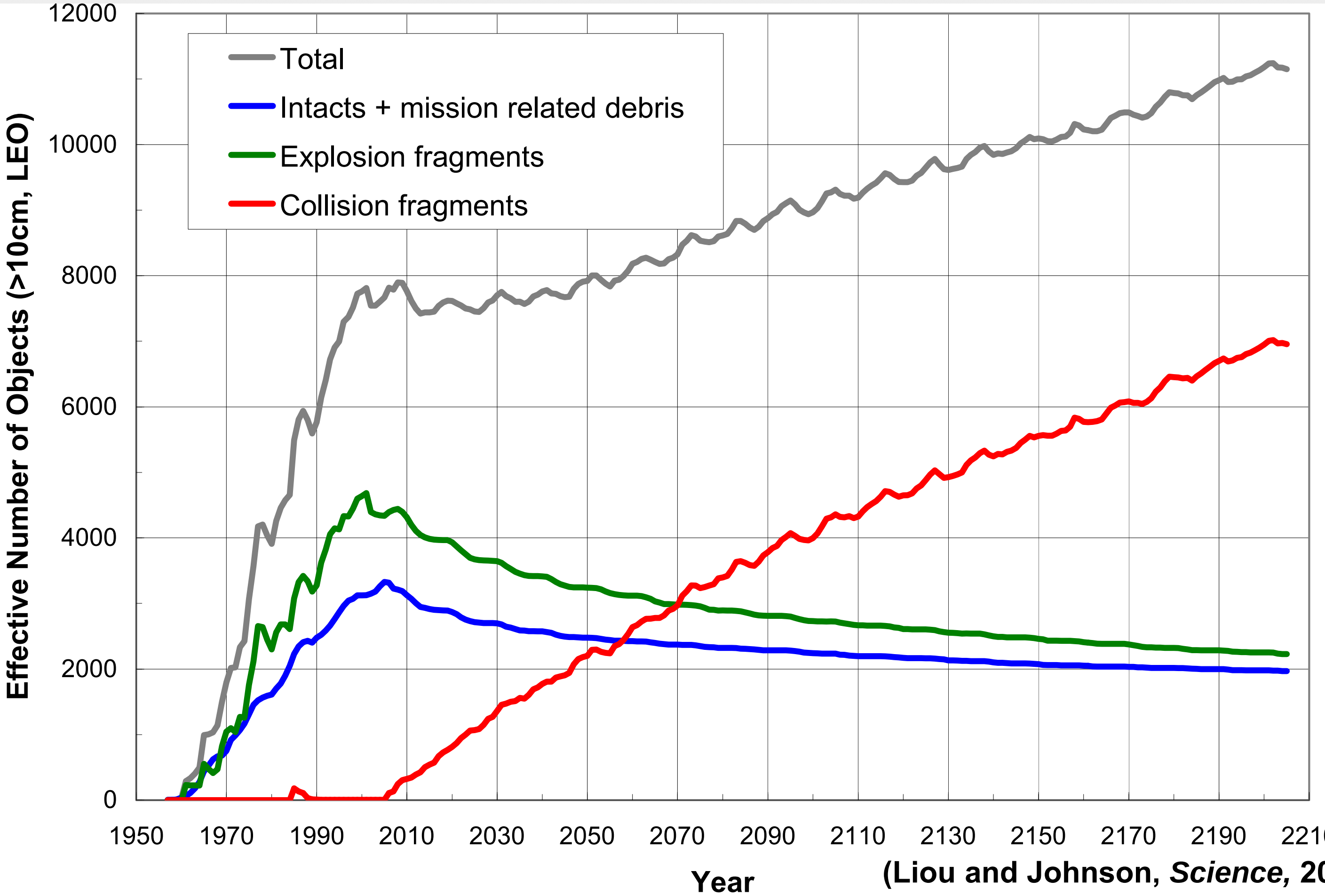
- **LEO: the non-mitigation scenario predicts the debris population (≥10 cm objects) will have a rapid non-linear increase in the next 200 years**
  - This is a well-known trend (the “Kessler Syndrome”) that was the motivation for developing the currently-adopted mitigation measures (*e.g.*, the 25-yr rule) in the last 20 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 further limit the population growth
  - Environment remediation is not urgent in MEO and GEO

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

*Mitigation = Limit the generation of new/long-lived debris (NPR 8715.6A, NASA-STD-8719.14, USG OD Mitigation Standard Practices, UN Debris Mitigation Guidelines, *etc.*)

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**
  - Satellite launches will continue
  - Major unexpected breakups may continue to occur
- **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, more aggressive measures, such as active debris removal (ADR*), must be considered**

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

Previous Studies – It Will Happen

- **Increasing debris population may lead to collision cascade (Kessler and Cour-Palais 1978; Eichler and Rex 1989)**
- **The "critical density" concept was pioneered by Kessler (1991) to describe the threshold of the instability**
- **Various analytical, semi-analytical, and numerical studies, based on different model assumptions and different future traffic rates (constant, increased, with or without postmission disposal, *etc*.) have been performed**
  - Su (1993); Rossi *et al*. (1994); Anselmo *et al*. (1997); Kessler (2000); Kessler and Anz-Meador (2001); Krisko *et al*. (2001)
- **These studies indicate that, as the space activities continue, the LEO debris populations at some altitudes are unstable and population growth may be inevitable**

The 2006 NASA Study – It Already Happened

- **"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***, January 2006

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

US Government Orbital Debris Mitigation Standard Practices (2001)

- **Objectives**
  - Control of debris released during normal operations
  - Minimization of debris generated by accidental explosions
  - Selection of safe flight profile and operational configuration
  - Postmission disposal of space structure
- **The 2006 US. National Space Policy directs departments and agencies to follow the Standard Practices for operations in space**

OBJECTIVE

1. CONTROL OF DEBRIS RELEASED DURING NORMAL OPERATIONS

Programs and projects will assess and limit the amount of debris released in a planned manner during normal operations.

MITIGATION STANDARD PRACTICES

1-1. *In all operational orbit regimes:* Spacecraft and upper stages should be designed to eliminate or minimize debris released during normal operations. Each instance of planned release of debris larger than 5 mm in any dimension that remains on orbit for more than 25 years should be evaluated and justified on the basis of cost effectiveness and mission requirements.

OBJECTIVE

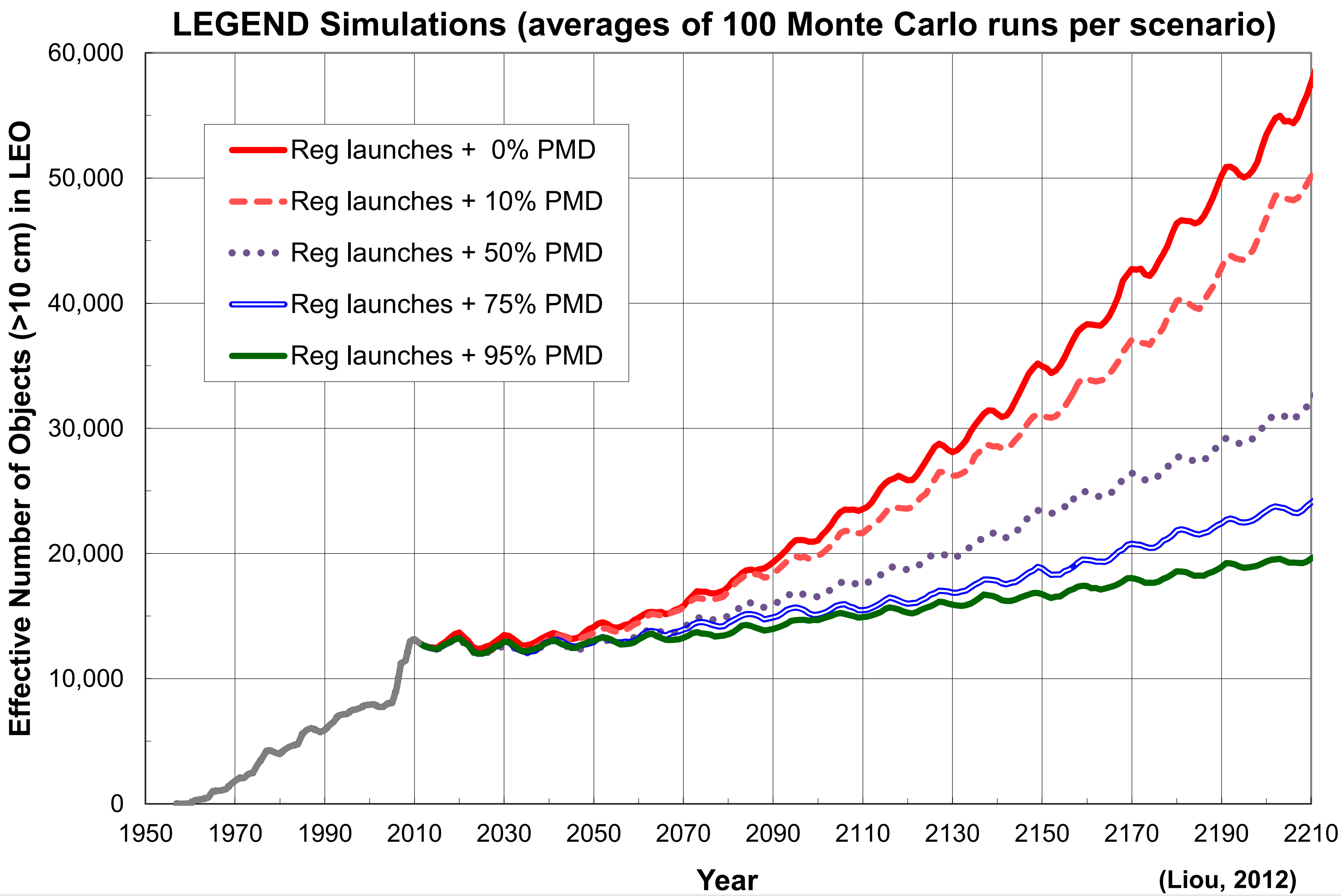
2. MINIMIZING DEBRIS GENERATED BY ACCIDENTAL EXPLOSIONS

Programs and projects will assess and limit the probability of accidental explosion during and after completion of mission operations.

MITIGATION STANDARD PRACTICES

2-1. *Limiting the risk to other space systems from accidental explosions during mission operations:* In developing the design of a spacecraft or upper stage, each program, via failure mode and effects analyses or equivalent analyses, should demonstrate either that there is no credible failure mode for accidental explosion, or, if such credible failure modes exist, design or operational procedures will limit the probability of the occurrence of such failure modes.

OD Mitigation – Effective First Defense



Options for Environment Remediation

Key Questions for Environment Remediation

- **Where is the most critical region?**
- **What are the mission objectives?**
- **What objects should be targeted 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 the 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 (small & large debris)
  - Limit collision activities
  - Mitigate mission-ending risks (not necessarily catastrophic destruction) to operational payloads
  - Mitigate risks to human space activities
  - And so on

} Focus on large & massive intacts (Control population growth; Limit collision activities)

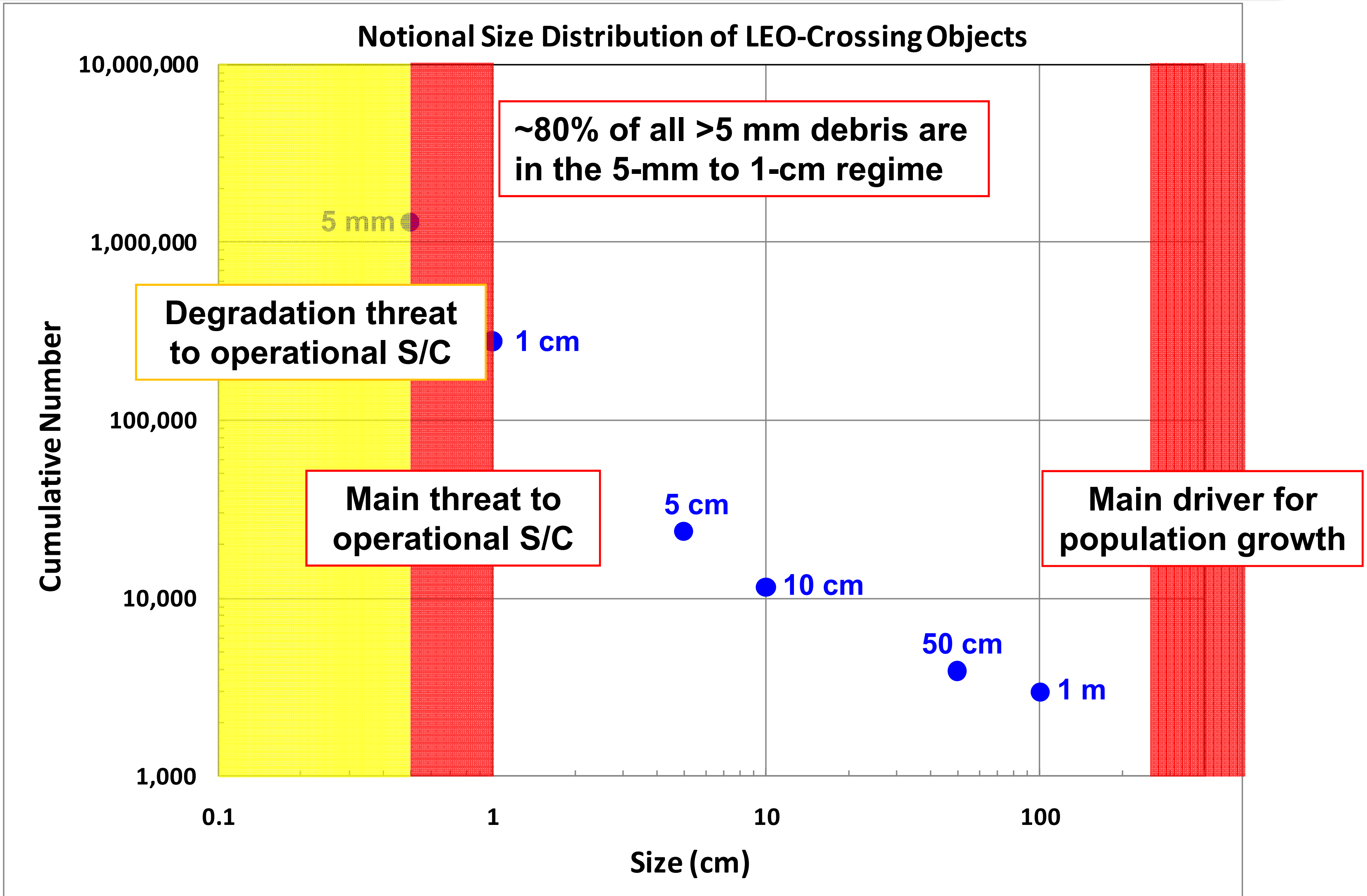
} Focus on small debris (Mitigate mission-ending risks; Mitigate risks to human space activities)

Problems and Solutions

- **The problem: LEO debris population will continue to increase even with a good implementation of the commonly-adopted mitigation measures**
  - The root-cause of the increase is catastrophic collisions involving large/massive intact objects (R/Bs and S/C)
  - The major mission-ending risks for most operational S/C, however, come from impacts with debris just above the threshold of the protection shields (~5-mm to 1-cm)

- **A <u>solution-driven</u> approach is to seek**
  - Concepts for removal of massive intacts with high $P_{collision}$
  - Concepts capable of preventing collisions involving intacts
  - Concepts for removal of 5-mm to 1-cm debris

Targets for Environment Remediation



Options for LEO Environment Remediation

- **Removal of massive intact objects with high collision probabilities to <u>address the root cause</u> of the future debris population growth problem**
- **Removal of 5-mm to 1-cm debris to mitigate the main threat for operational spacecraft**
- **Prevention of major debris-generating collisions involving massive intact objects as a potential <u>short-term</u> solution**

Challenges for Small Debris Removal

- **Targets are small**
  - Approximately 5-mm to 1-cm
- **Targets are numerous (>500,000)**
  - For any meaningful risk reduction, removal of a significant number of targets is needed
- **Targets are not tracked by SSN**
- **Targets are highly dynamic**
  - Long-term operations are needed
- **Concepts proposed by various groups: large-area collectors, laser removal, tungsten dust, *etc.***

Challenges for Collision Prevention

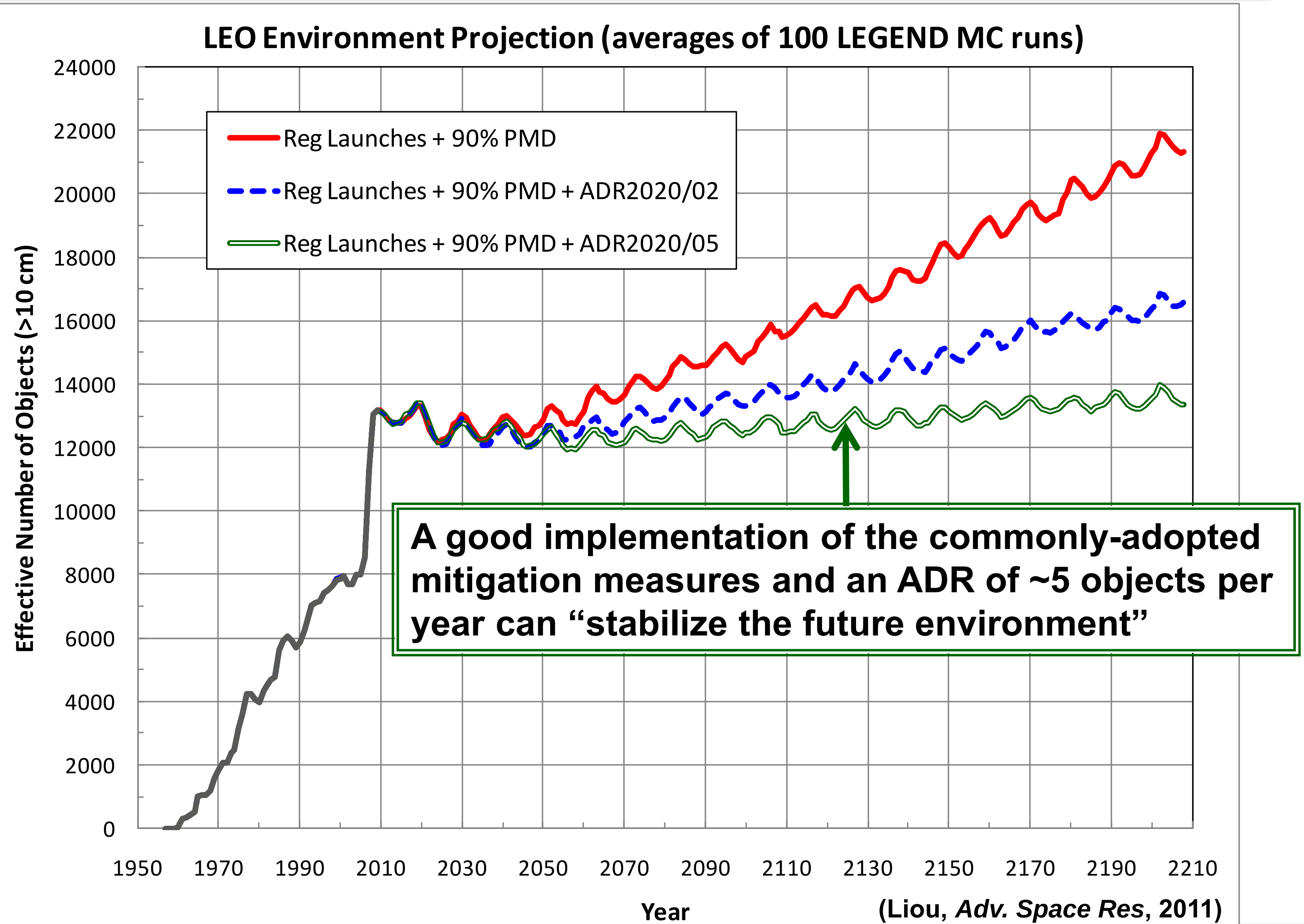
- **To allow for actionable collision prevention operations**
  - Conjunction assessments for R/Bs and retired S/C are needed
  - Dramatic improvements to debris tracking and conjunction assessment accuracy are necessary
- **Collision prevention operations must be applied to most, if not all, conjunction warnings**
- **Targets are limited in number, but ~2/3 are large and massive R/Bs or S/C (up to 9 metric tons dry mass)**
- **Concepts proposed by various groups: ballistic intercept, frozen mist, laser-nudging, *etc.***

Target Large Debris

Targeting the Root Cause of the Problem

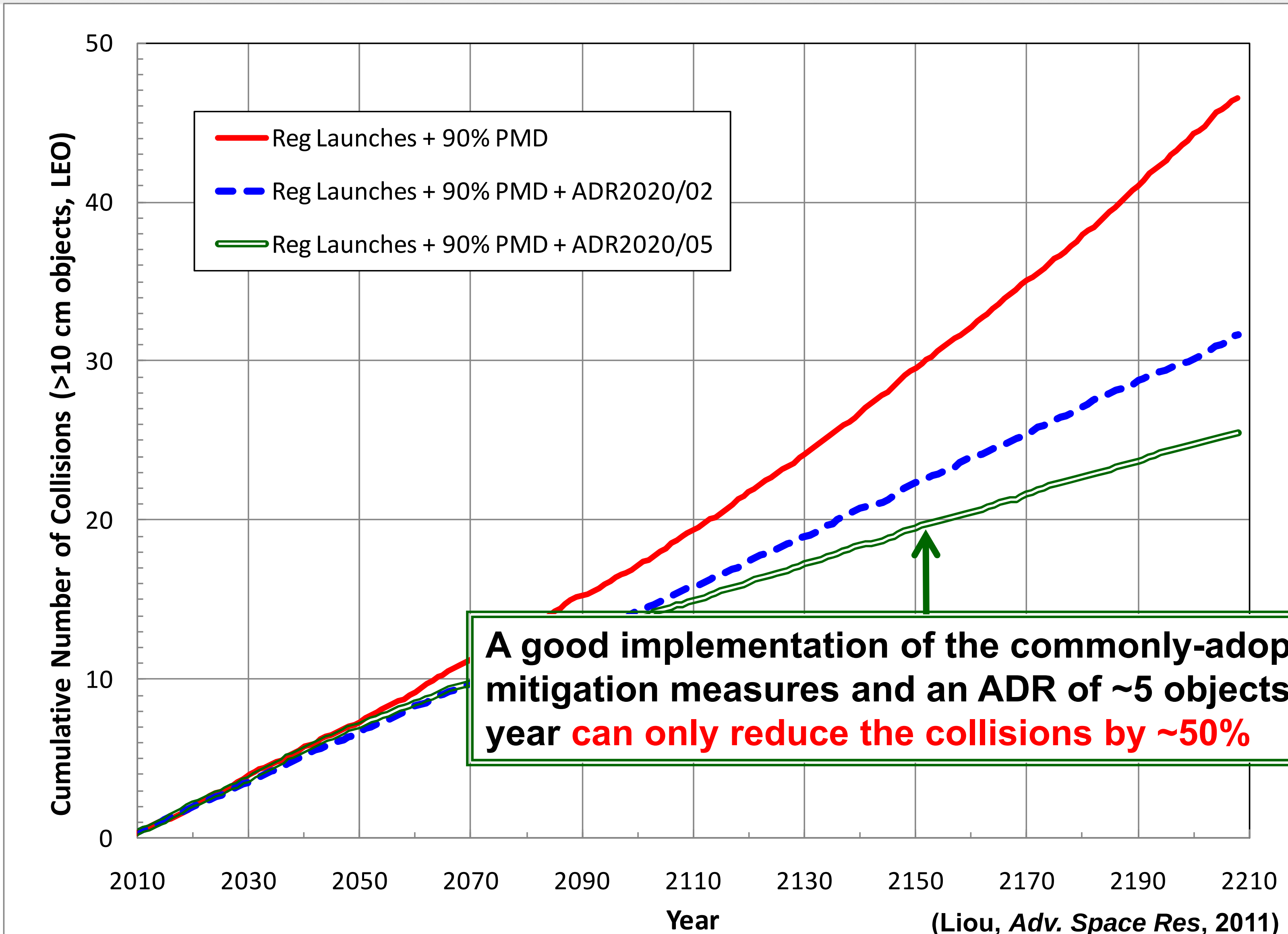
- **A 2008-2009 NASA study shows that the two key elements to stabilize the future LEO environment (in the next 200 years) are**
  - A good implementation of the commonly-adopted mitigation measures (passivation, 25-year rule, avoid intentional destruction, *etc.)*
  - An active debris removal of about 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



A good implementation of the commonly-adopted mitigation measures and an ADR of ~5 objects per year can only reduce the collisions by ~50%

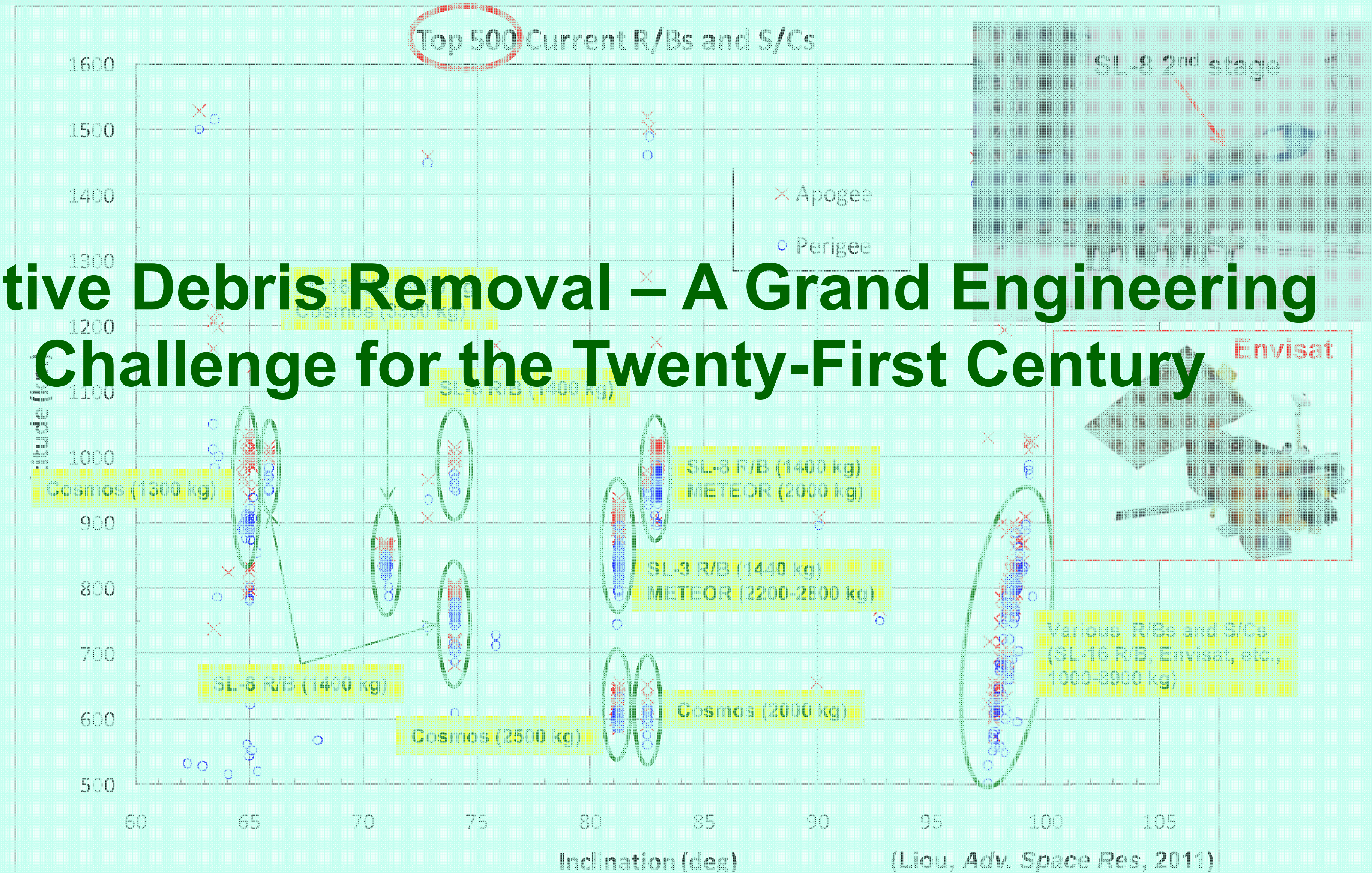
(Liou, *Adv. Space Res*, 2011)

About the "Five Objects Per Year"

- **The "removing five objects per year can stabilize the LEO environment" conclusion is somewhat notional. It is intended to serve as a guidance for ADR planning.**
- **Assumptions in the LEGEND ADR simulations**
  – Nominal launches during the projection period
  – 90% compliance of the commonly-adopted mitigation measures
  – ADR operations starts in 2020
  – Target selection is based on each object's mass and P_{coll}
  – No operational constraints on target selection
  – Immediate removal of objects from the environment
  – Average solar activity cycle

Potential Active Debris Removal Targets

Active Debris Removal – A Grand Engineering Challenge for the Twenty-First Century



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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 may not be 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)	Contact or non-contact (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)
  - Target R/Bs first?

The First Step

- **Identify top-level requirements for an end-to-end ADR operation**
  - Launch, propulsion, precision tracking, GN&C, rendezvous, stabilization, capture/attachment, deorbit, ground support, etc
  - 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 concepts (*e.g*., space tugs vs. drag-enhancement devices)
  - Identify technology gaps (*e.g*., ways to stabilize/capture a massive, non-cooperative, fast tumbling target)
  - Perform trade studies (*e.g*., physical vs. non-physical capture; deorbit vs. graveyard orbit; cost; risks)

Summary

Concluding Remarks (1/3)

- **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 intact objects
  - The major mission-ending risks for most operational S/C, however, come from impacts with debris just above the threshold of the protection shields (~5 mm to 1 cm)

Concluding Remarks (2/3)

- **To address the root cause of the population growth (for large <u>and</u> small debris)**
  → Target objects with the highest [$M \times P_{coll}$]
  - 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 S/C**
  → 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

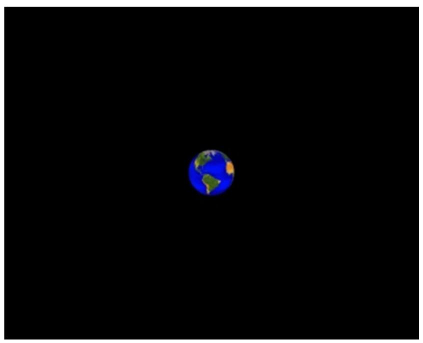
- **Targeting anything else will NOT be the most effective means to remediate the environment nor to mitigate risks to operational S/C**

Concluding Remarks (3/3)

- **There is a need for a top-level, long-term strategic plan for environment remediation**
  - Define “what is the acceptable threat level”
  - 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 multi-purpose 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

- **Four Essential “Cs” are needed at the international level**
  - Consensus
  - Cooperation
  - Collaboration
  - Contributions



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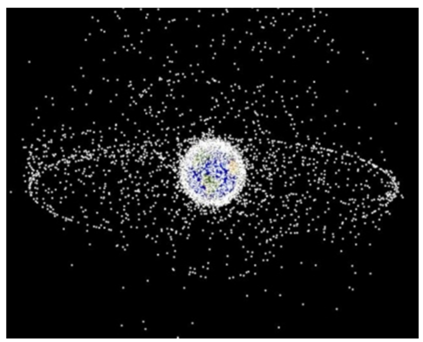

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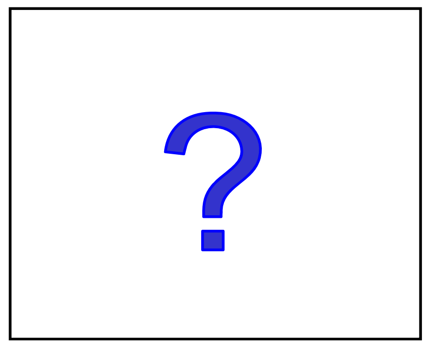

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