National Aeronautics and Space Administration

Orbital Debris and Future Environment Remediation

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Outline

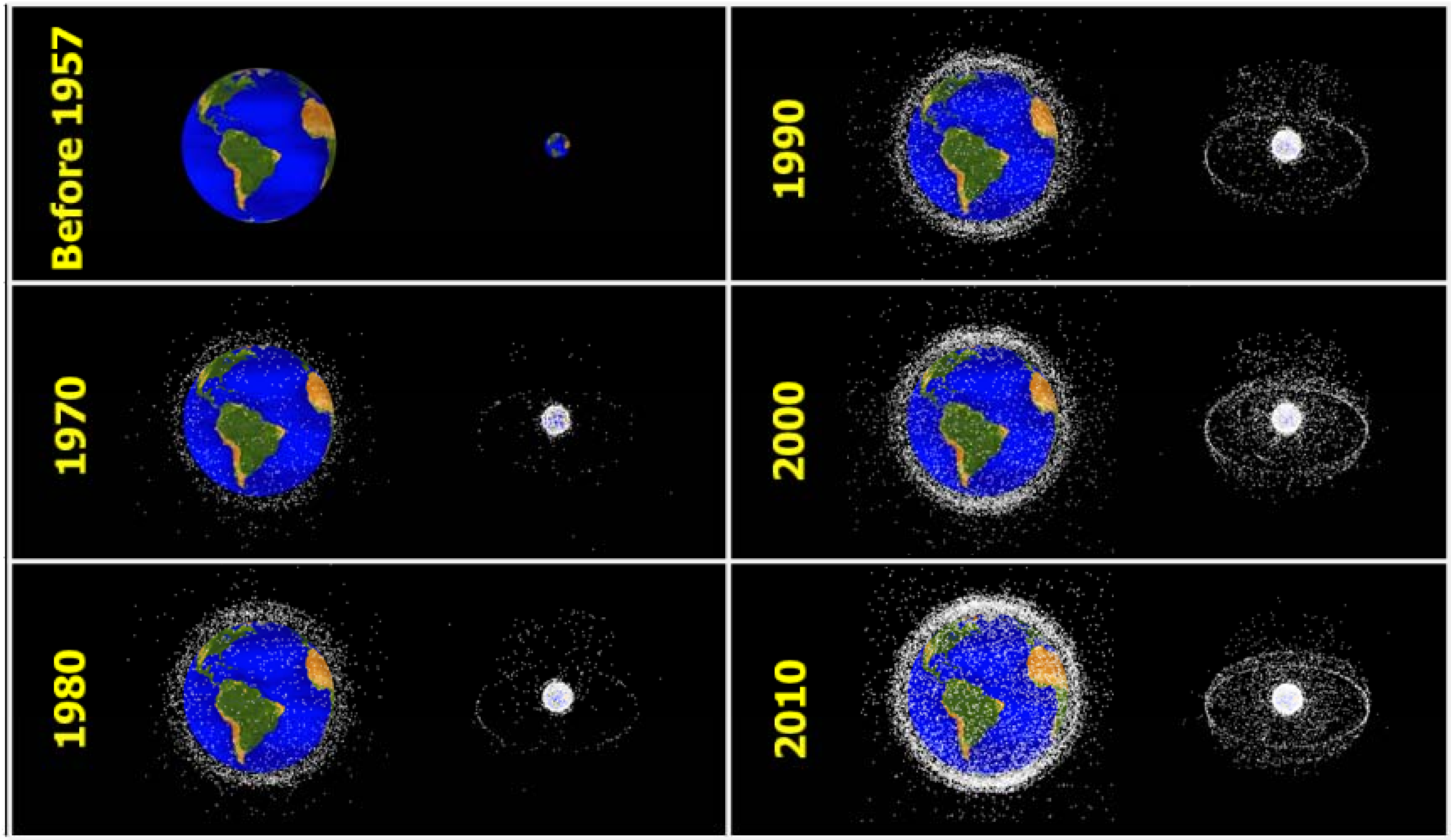
- **Part 1 (Nov 21st): The Near-Earth Orbital Debris Environment**
  – Overview of the orbital debris populations
  – Optical, radar, and in-situ measurements
  – Orbital debris modeling

- **Part 2 (Nov 22nd): Environment Remediation and Active Debris Removal**
  – Projected growth of the future debris population
  – The need for active debris removal (ADR)
  – A grand challenge for the 21st century
  – The forward path

Part 1: The Near-Earth Orbital Debris Environment

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**

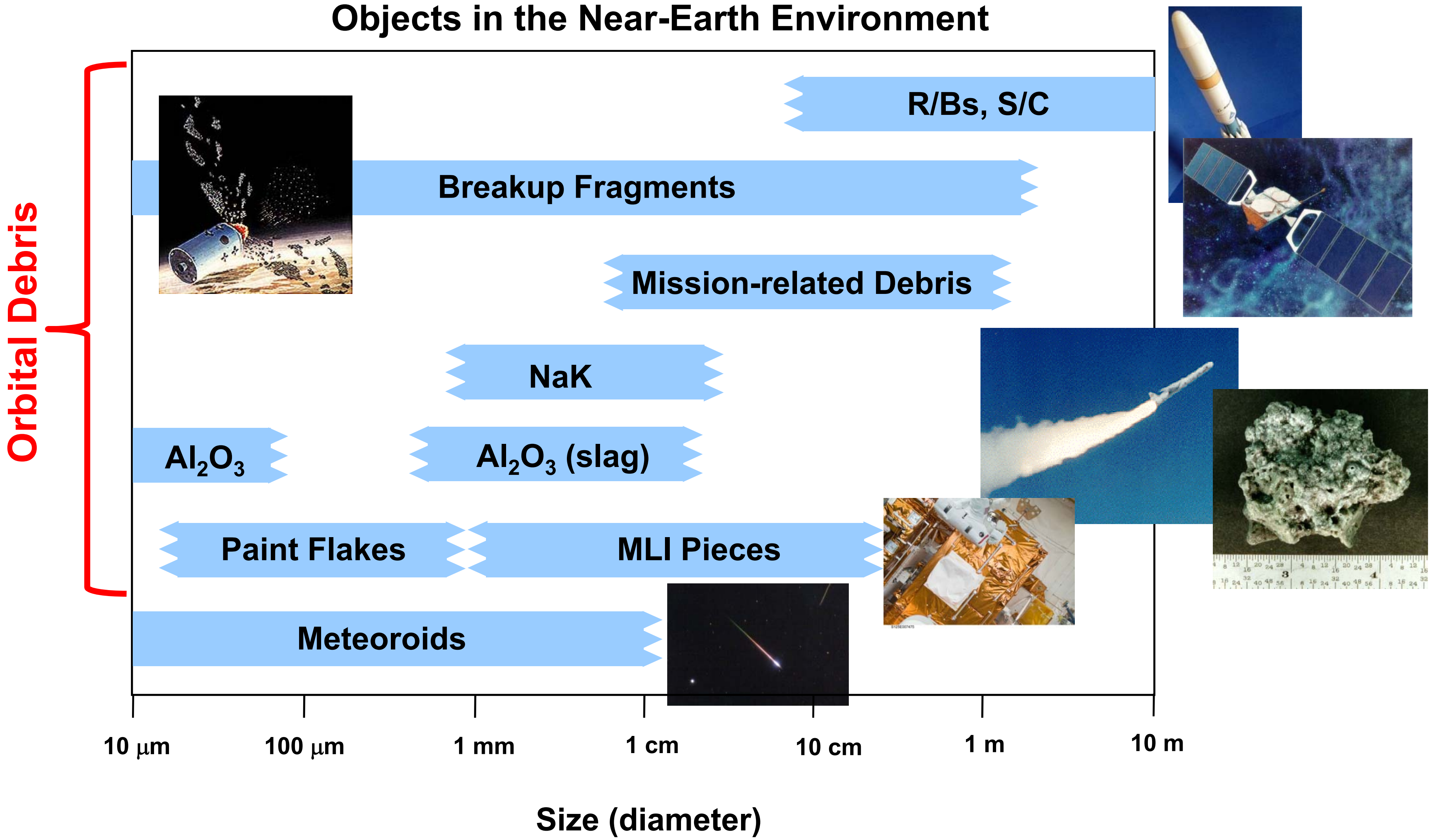
What Is Orbital Debris?

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

- **Examples**
  - Intacts: Spent rocket bodies (R/Bs, *i.e*., upper stages) and retired spacecraft (S/C*, i.e*., payloads)
  - Breakup fragments (via explosions or collisions)
  - Mission-related debris: objects released during normal mission operations (engine covers, yo-yo despin weights, *etc.*)
  - 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?

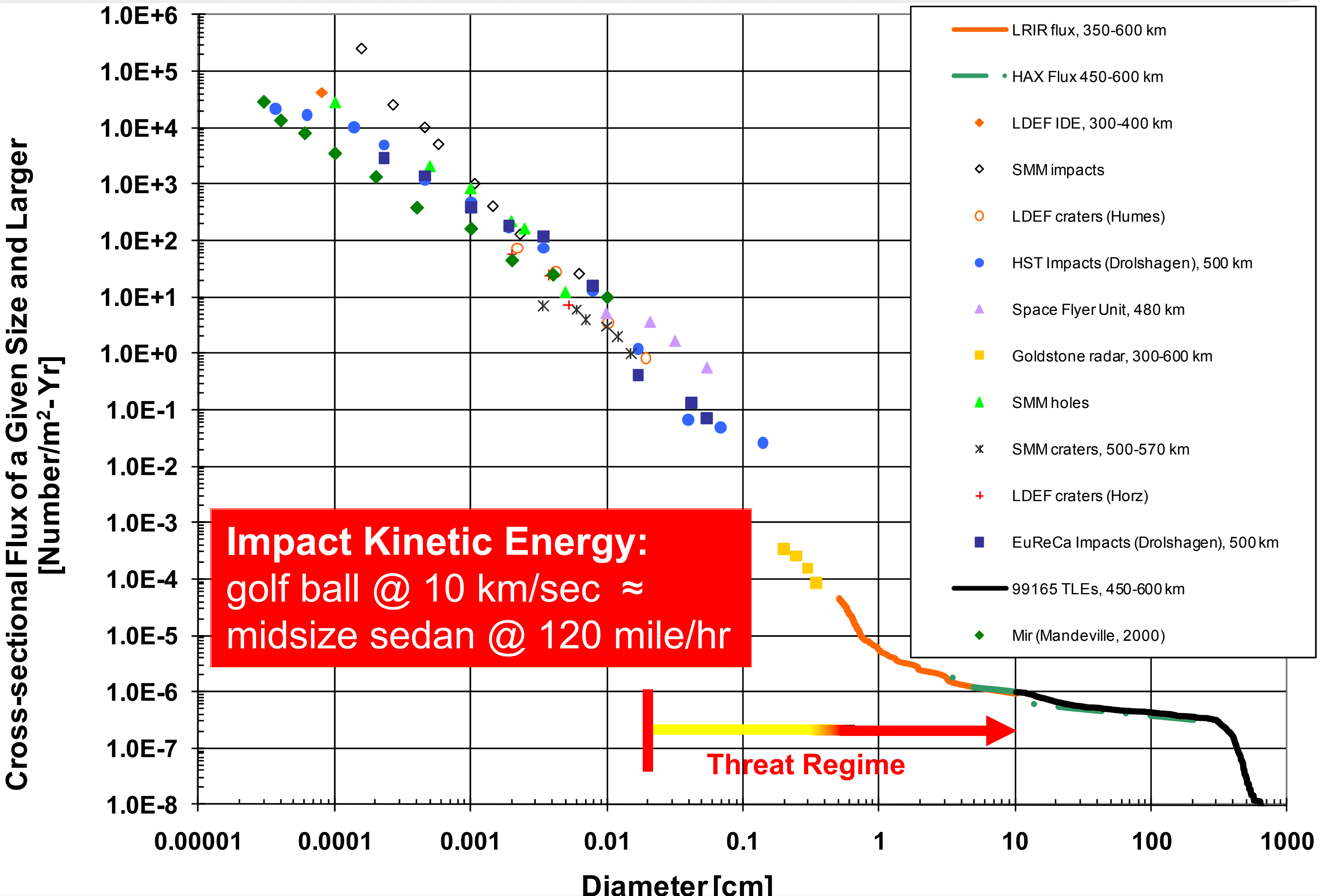
Softball size or larger (≥10 cm): ~22,000 (tracked by the Space Surveillance Network)

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 (~2700 tons in LEO)**
- **Debris as small as 0.2 mm pose a realistic threat to Human Space Flight (EVA suit penetration, Shuttle window replacement)**

The Environment



An Example – Shuttle Vulnerabilities

Potential Shuttle Damage

Window Replacement

EVA Suit Penetration

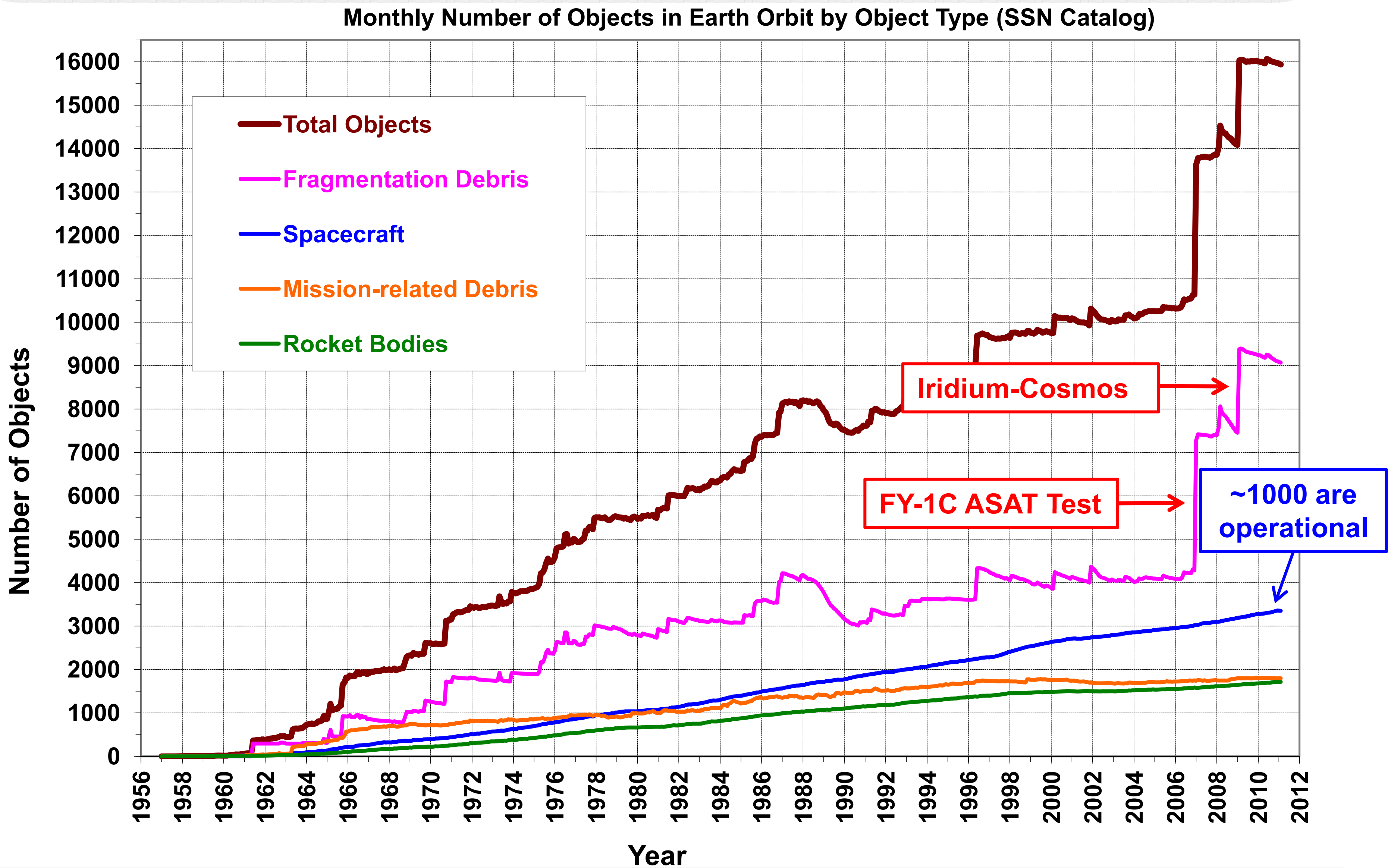
Radiator Penetration

- **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

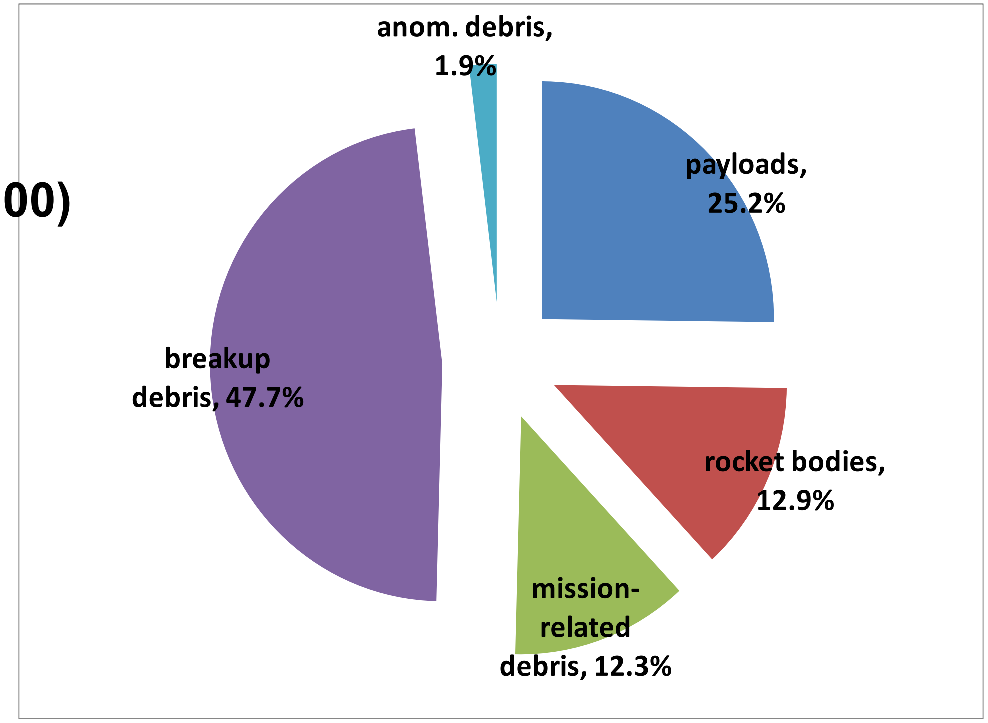


Sources of the Catalog Populations

- **~4700 launches conducted worldwide since 1957**
- **208 known breakups**
  - Major events:
    - **Titan Transtage (473, 1965)**
    - **Agena D stage (373, 1970)**
    - **Ariane 1 stage (489, 1986)**
    - **Pegasus HAPS (709, 1996)**
    - **Long March 4 stage (316, 2000)**
    - **PSLV (326, 2001)**
    - **Fengyun 1C (~3200, 2007)**
    - **Briz-M (>1000[a], 2007)**
    - **Cosmos 2421 (509, 2008)**
    - **Iridium 33 (>700, 2009)**
    - **Cosmos 2251 (>1500, 2009)**

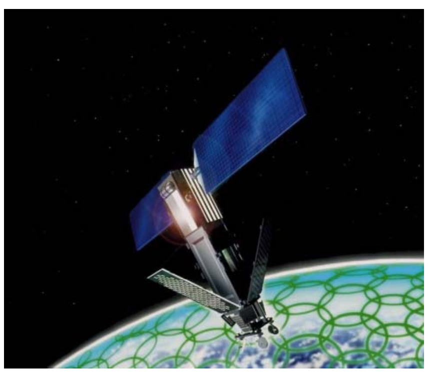
[a]initial report

Source Breakdown



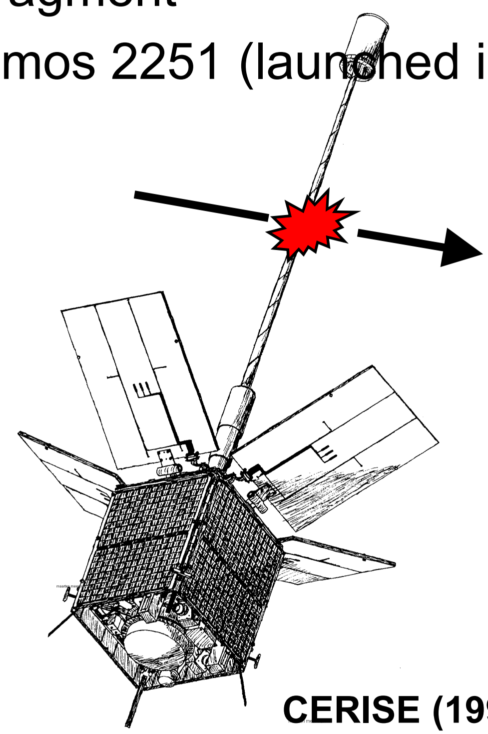
Accidental On-Orbit Collisions

- **Four accidental collisions between cataloged objects have been identified**
  - 1991: Russian Sat (launched in 1988) ↔ Russian fragment
  - 1996: French Sat (launched in 1995) ↔ French fragment
  - 2005: US R/B (launched in 1974) ↔ PRC fragment
  - 2009: Iridium 33 (launched in 1997) ↔ Cosmos 2251 (launched in 1993)



Iridium33 (560 kg)

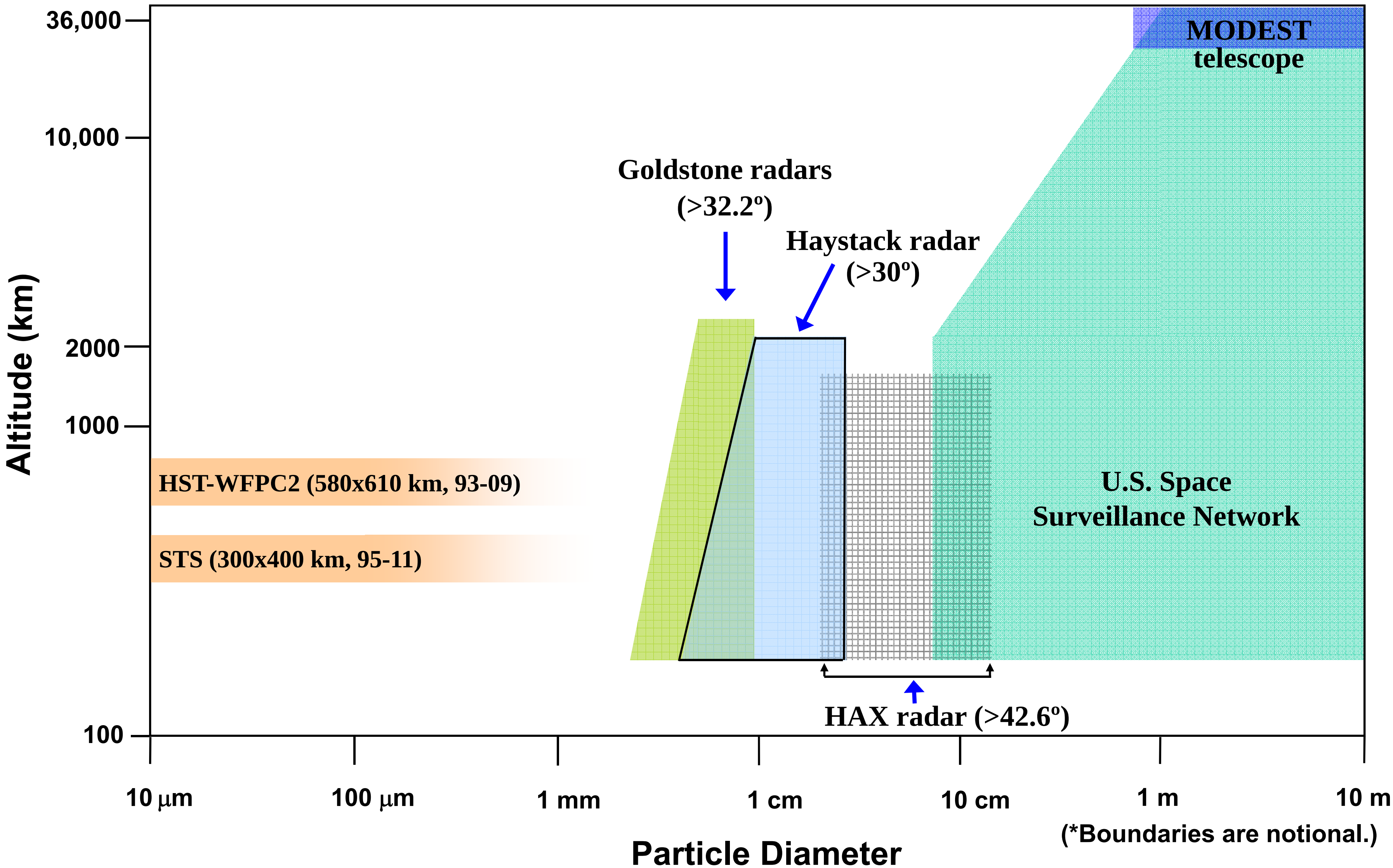
Cosmos 2251 (900 kg)



CERISE (1996)

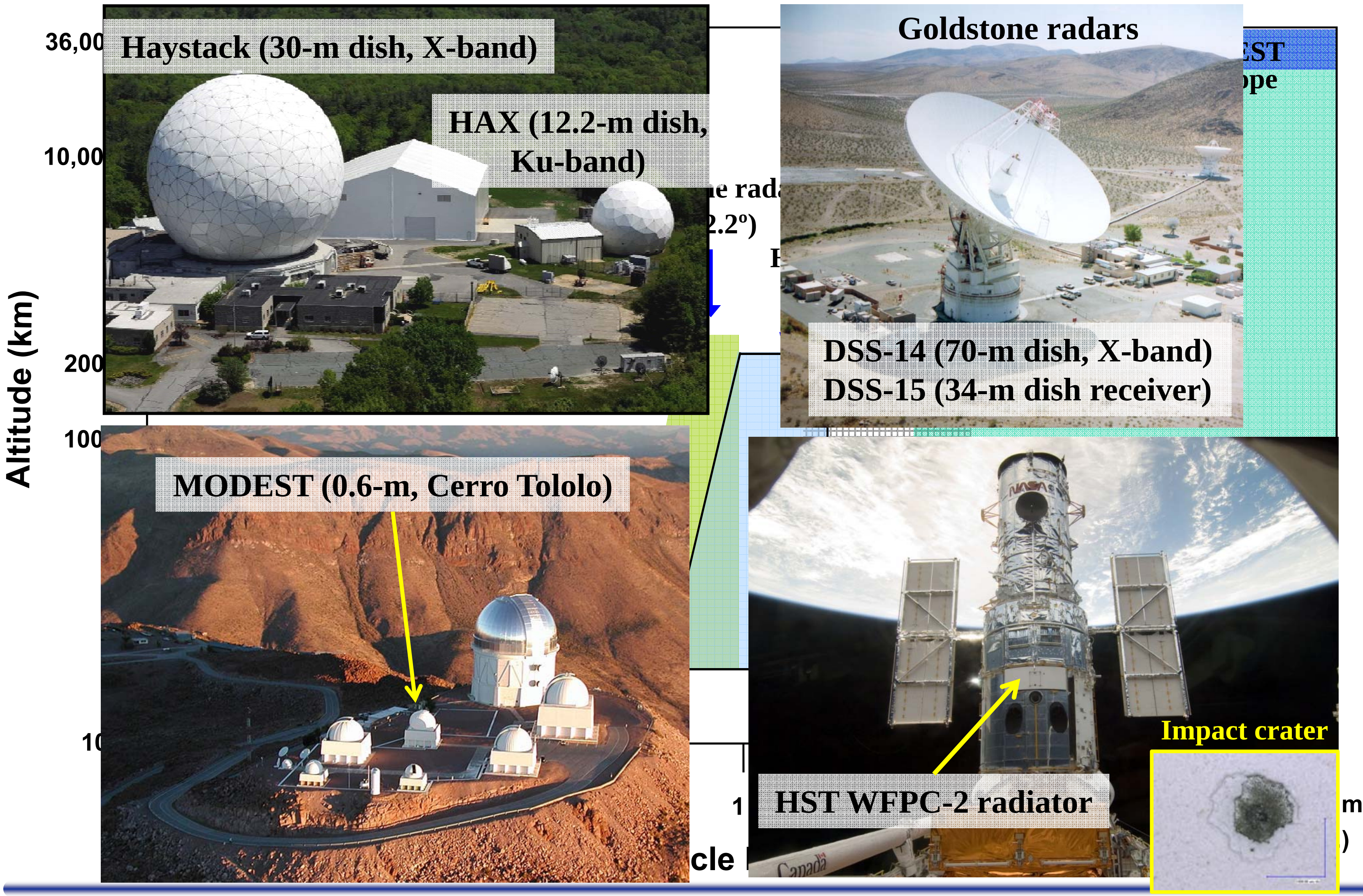
Optical, Radar, and In-Situ Measurements

Current NASA Debris Data (1/2)



(*Boundaries are notional.)

Current NASA Debris Data (2/2)

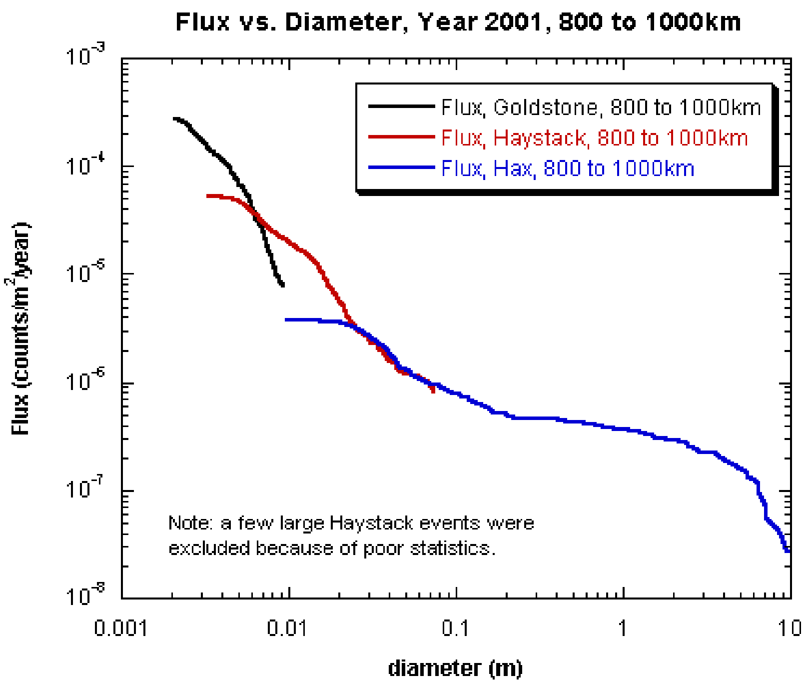


NASA RADAR Observations

- Signal processing
- Object detection/correlation
- Debris size estimation
- Orbit determination
- Environment definition

Goldstone

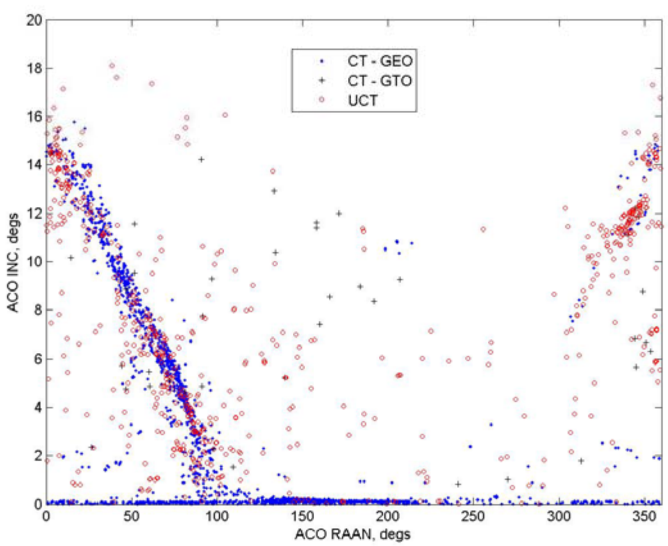
Haystack and HAX



NASA Optical Observations

- Photometric and spectral measurements
- Object detection and correlation
- Optical Measurement Center (OMC)
- Surface material identification
- Orbit determination
- Environment definition

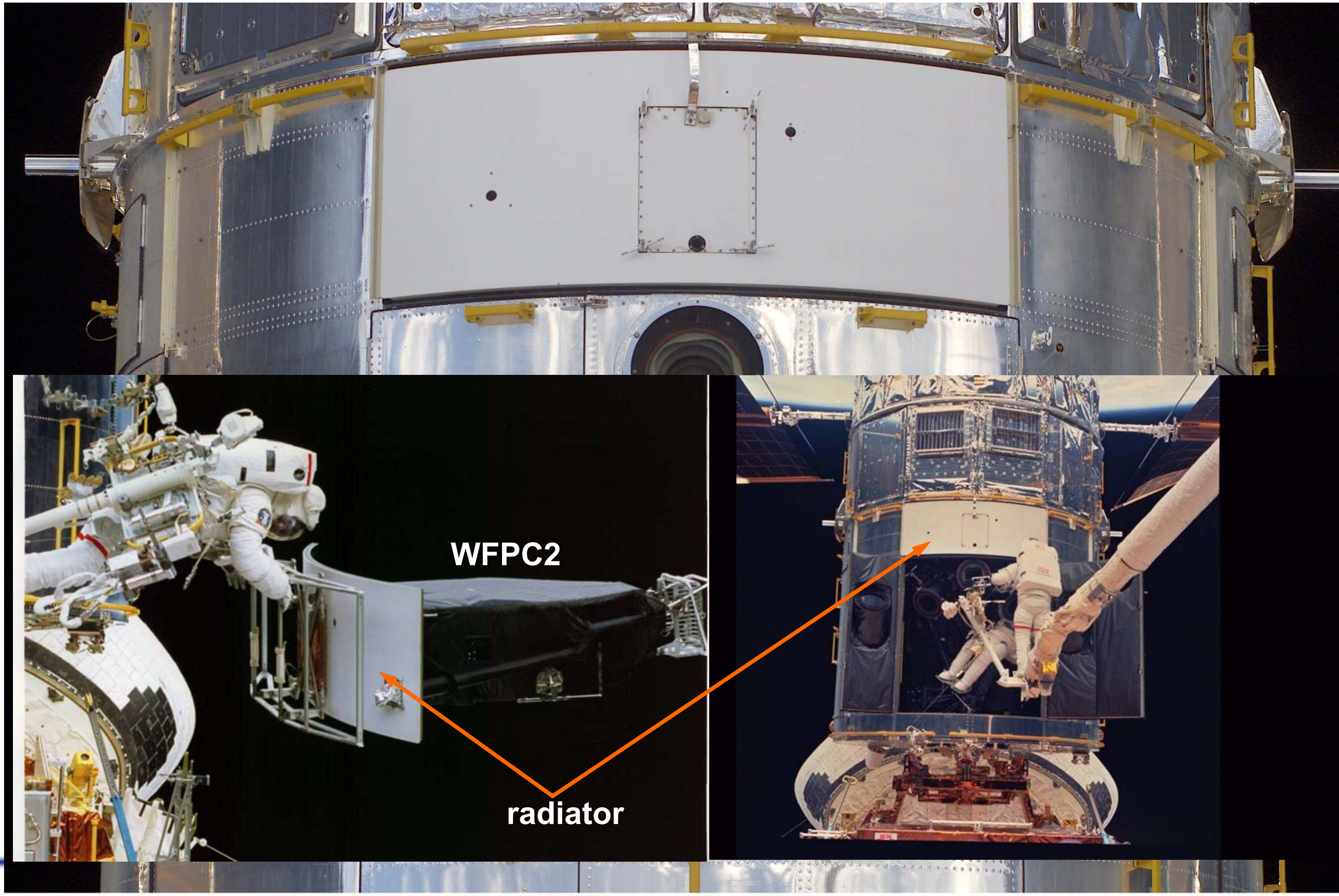
MODEST



OMC

MCAT

In-Situ Data from Returned Surfaces



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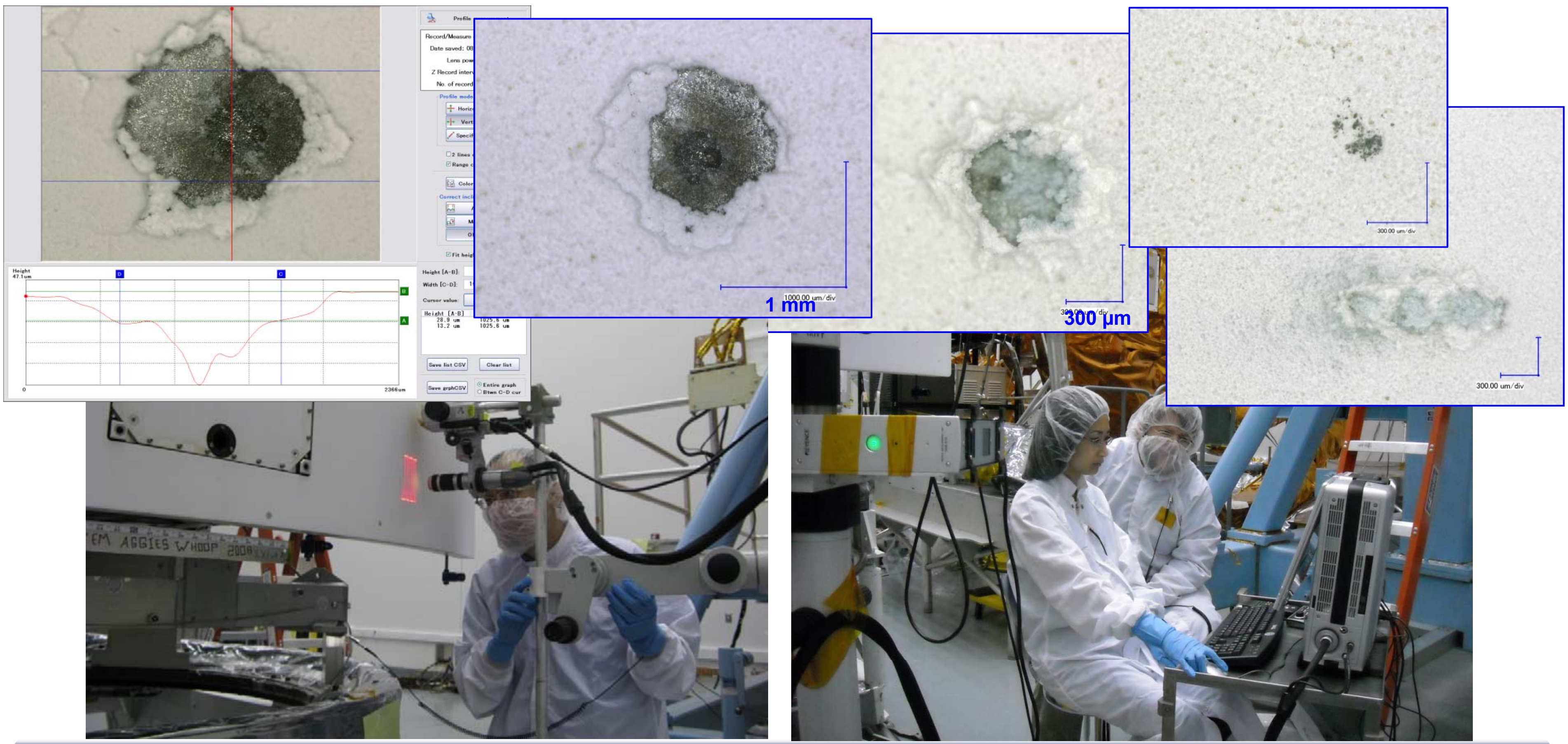
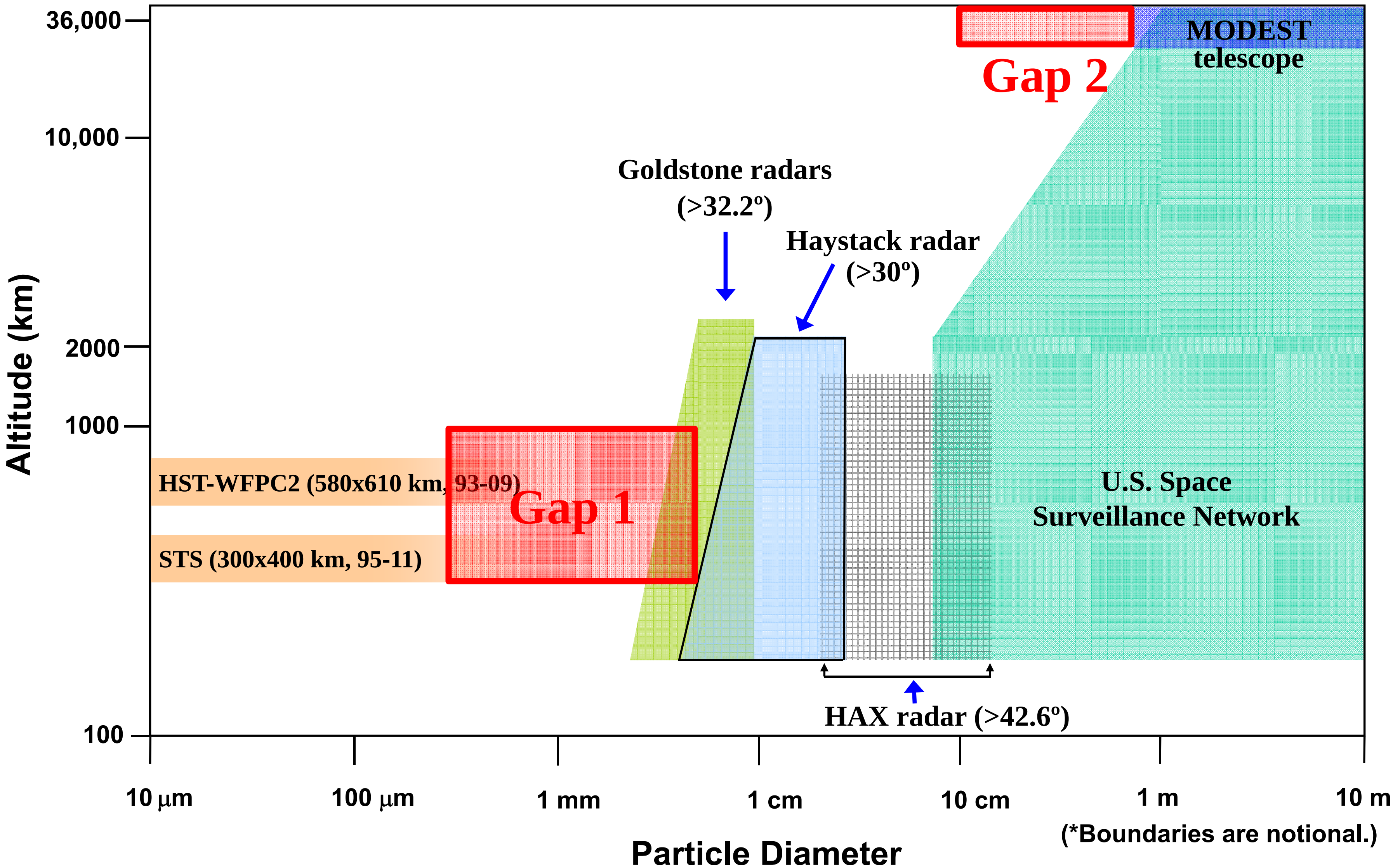
Inspection of the HST WFPC2 Radiator

- **685 impact features (≥300 µm) were identified**
  - Recorded each impact feature's shape, size, depth, and volume



Critical Data Gaps

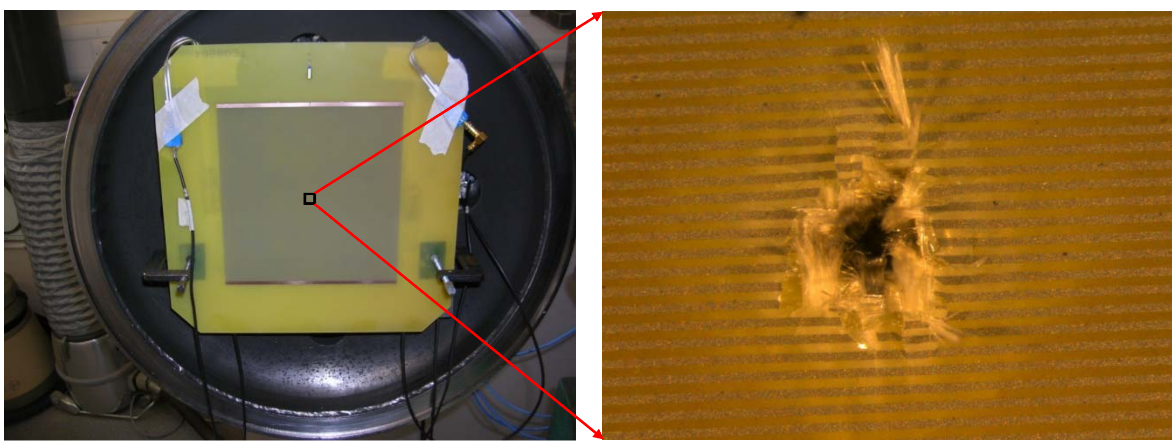


Future NASA Debris Telescope

- **NASA Meter Class Autonomous Telescope (MCAT)**
  - 1.3 m aperture, 0.96° field of view, f/4
  - Located at Kwajalein Atoll (9°N, 168°E)
  - Target detection limits
    - **GEO ~10 cm diameter (20.5 V-mag)**
  - Primary objectives
    - **GEO debris down to ~10 cm**
    - **LEO debris with low inclinations and high eccentricities**
    - **Simultaneous radar-optical observations**
  - Expected operations ~2012

A New Particle Impact Detection Technology

- **Debris Resistive/Acoustic Grid Orbital Navy Sensor (DRAGONS)**
  - Objective: A low-cost/mass/power experiment to detect and characterize 0.1 to 1 mm MMOD particles at 800-1000 km altitude
  - Components: (1) a large surface ($\geq$1 m^2) coated with thin resistive grids, (2) acoustic sensors attached to the backside of the board/film
  - Team: USNA, NASA/ODPO, Kent (UK), NRL, VT
  - Status: Presented to the annual DoD Space Experiment Review Board (SERB) since 2007, no firm flight opportunity identified by STP



Hypervelocity Impact Tests

- Resistive grid width: 75 μm
- Projectile: 0.3 mm stainless steel
- Impact speed: 5.06 km/sec
- Impact angle: normal
- Two PVDF acoustic sensors attached to the board

Modeling

General Orbital Debris Modeling (1/2)

- **Evolutionary model**
  - Is a physical model (such as LEGEND) capable of predicting future debris environment
  - Supports the development of US/NASA debris mitigation guidelines and safety standards
- **Engineering model**
  - Is a mathematical model (such as ORDEM) capable of predicting OD impact risks for the International Space Station and other critical space assets
- **Satellite breakup model**
  - Describes the outcome of a satellite breakup (explosion or collision)

General Orbital Debris Modeling (2/2)

- **Reentry risk assessments**
  - Uses Object Reentry Survival Analysis Tool (ORSAT) to evaluate satellite reentry risks
  - The risk of human casualty from surviving debris shall not exceed 1 in 10,000 (NASA Standard 8719.14)

Delta II propellant tank (Georgetown, TX, 1997)

Titanium casting of STAR-48B SRM (Saudi Arabia, 2001)

Titanium casting of STAR-48B SRM (Argentina, 2004)

LEGEND

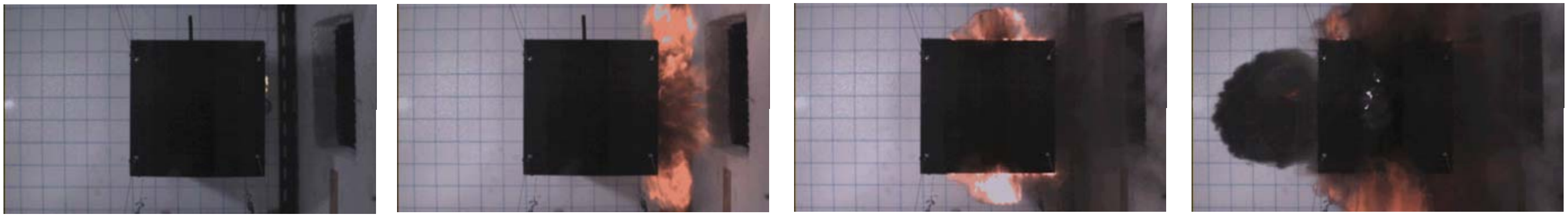
- **LEGEND, A LEO-to-GEO Environment Debris model**
  - Is a high fidelity, three-dimensional numerical simulation model for long-term orbital debris evolutionary studies
  - Includes intacts (rocket bodies and spacecraft), mission-related debris (rings, caps, *etc*), and explosion/collision fragments
  - 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
  - Projects future environment based on user-specified launch traffics, postmission disposal and active debris removal options
  - Nine peer-reviewed journal papers have been published about LEGEND and its applications since 2004

ORDEM

- **ORDEM, An Orbital Debris Engineering Model**
  - Is a mathematical model for orbital debris impact risk assessments for the International Space Station and other critical space assets
  - Describes the orbital debris environment in terms of spatial density, impact velocity distribution, impact flux, etc
  - Is based on recent empirical radar, optical, and in-situ measurement data
  - The current model, ORDEM2000, is available for download at http://www.orbitaldebris.jsc.nasa.gov/model/engrmodel.html
  - An updated version, ORDEM 3.0, will be released in the coming months
    - **Extends the coverage to GEO**
    - **Includes uncertainty estimates**

Satellite Breakup Model

- **The NASA Standard Breakup Model**
  - Describes the outcome of a typical satellite explosion or collision
    - **Size, area-to-mass ratio, and ΔV distributions of the fragments**
  - Is a key element for short- and long-term debris modeling
  - Is based on observations of on-orbit breakup events and laboratory experiments
  - Has been adopted by major international space agencies for their debris evolutionary models
  - A new ground-based satellite impact experiment is underway



DAS

- **DAS, the NASA Debris Assessment Software**
  - Is designed to assist NASA Programs in performing orbital debris assessments for their planned missions
    - **Assessment requirements are described in NASA-STD-8719.14 "Process for Limiting Orbital Debris"**
    - **DAS 2.0 addresses requirements point-by-point**
      - **Limit number and orbital lifetime of debris passing through LEO, limit liftime of objects passing near GEO, limit probability of accidental explosion during mission operations, etc.**
  - Includes orbit propagators (for LEO, GTO, and GEO), debris environment model, and a simplified version of NASA's Object Reentry Survival Analysis Tool (ORSAT) for reentry-survivability assessments
  - Is available for download at http://www.orbitaldebris.jsc.nasa.gov/mitigate/das.html

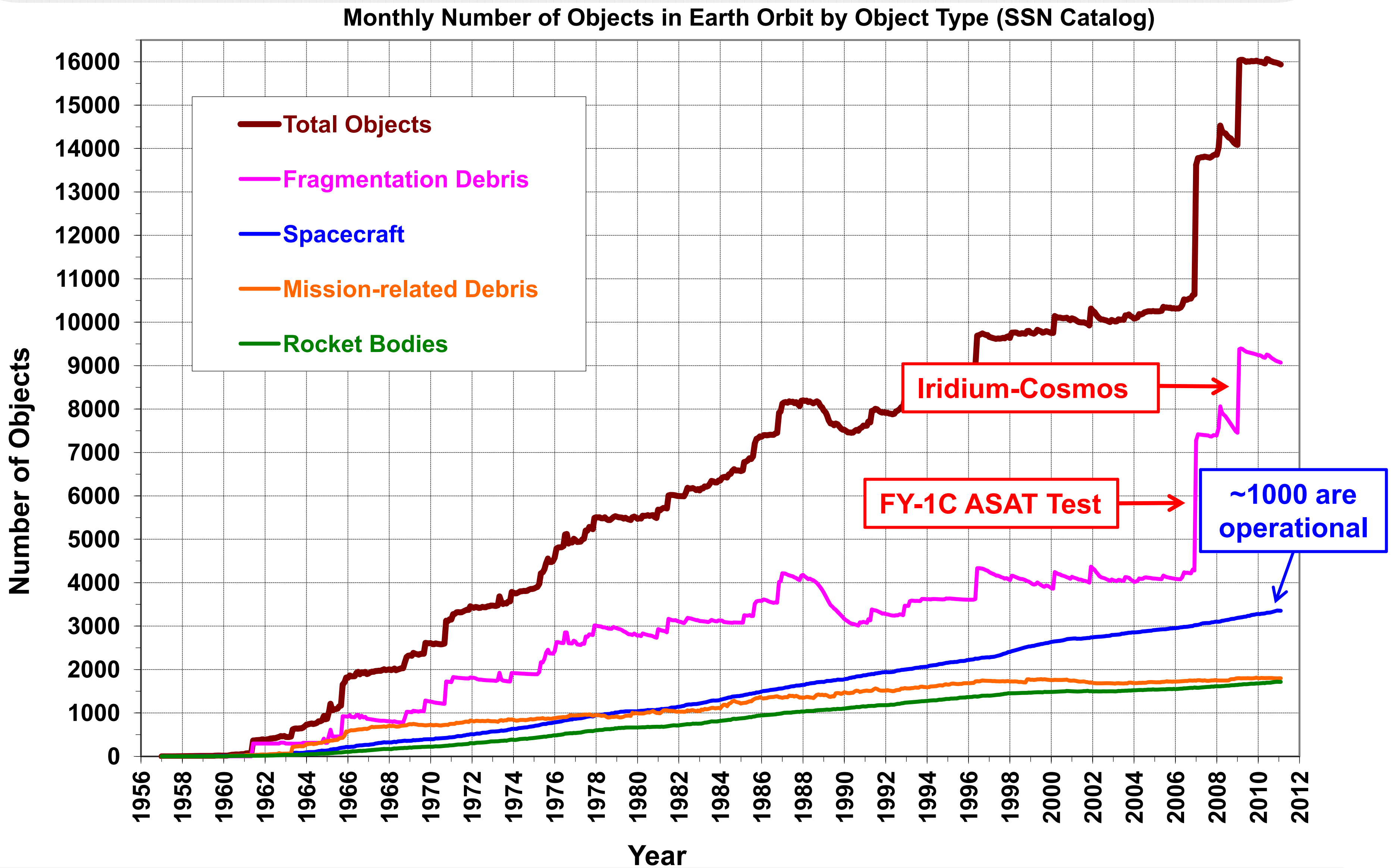
ORSAT

- **ORSAT, NASA's Object Reentry Survival Analysis Tool**
  - Is designed to provide a high fidelity assessment of space vehicle and component reentry survivability
    - **Per U.S. Government Orbital Debris Mitigation Standard Practices, the threshold of human casualty risk from reentering debris shall not exceed 1 in 10,000 per reentry event**
  - Includes trajectory, atmosphere, aerodynamics, aerothermodynamics, thermal / ablation, and debris casualty area analyses
  - Outputs component demise altitude or location, surviving mass, kinetic energy of impact, and human casualty risk

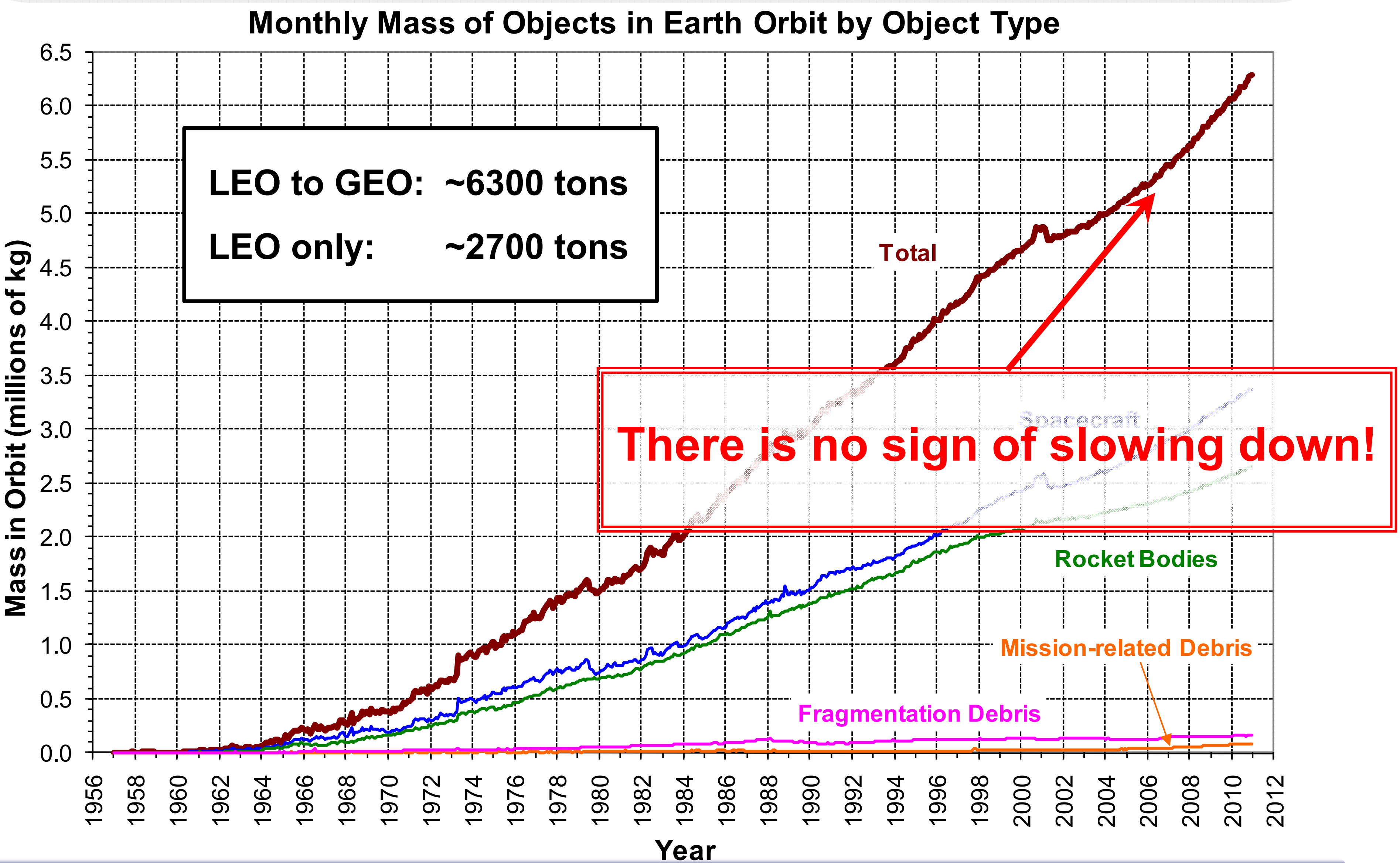
Questions for Part I?

Part 2: Near-Earth Environment Remediation and Active Debris Removal

Growth of the Historical Catalog Populations



Mass in Orbit



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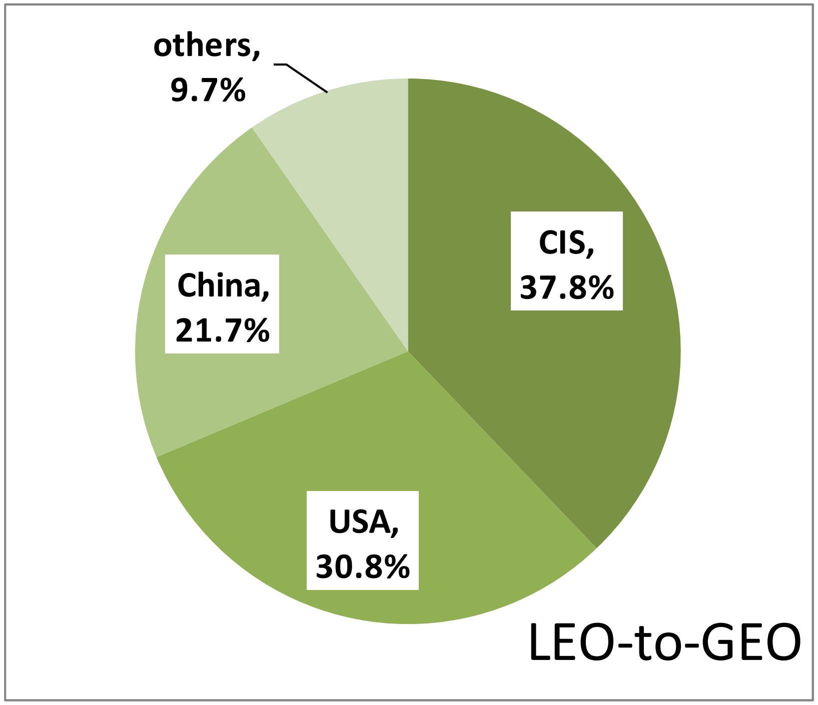
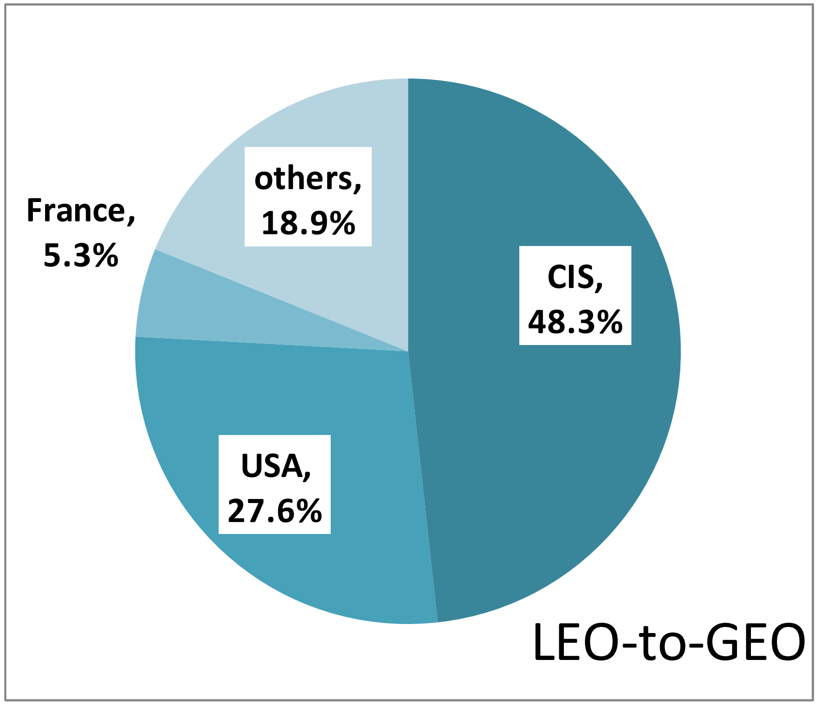
Sources of the Catalog Population – All

Number Breakdown



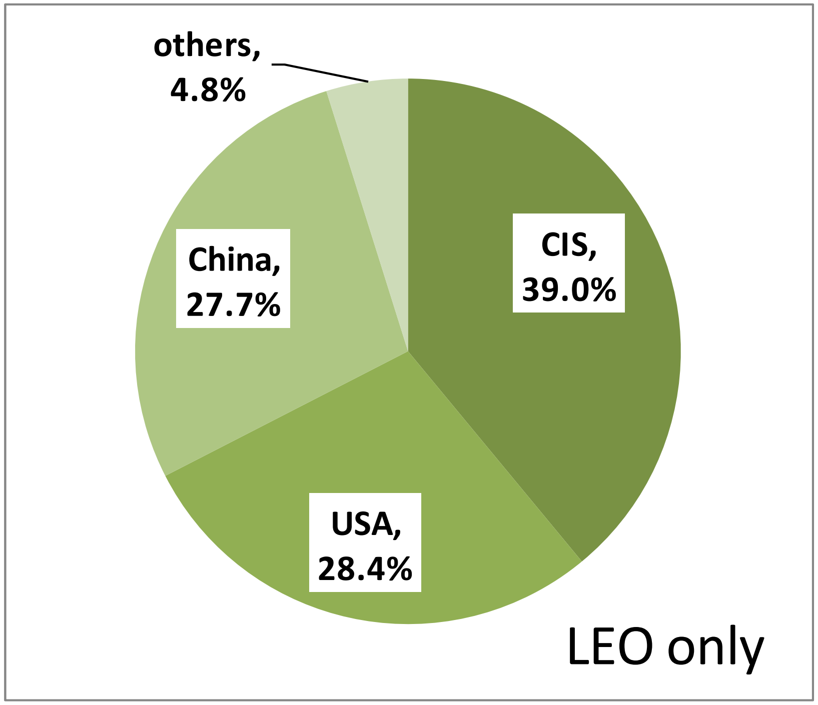
Mass Breakdown



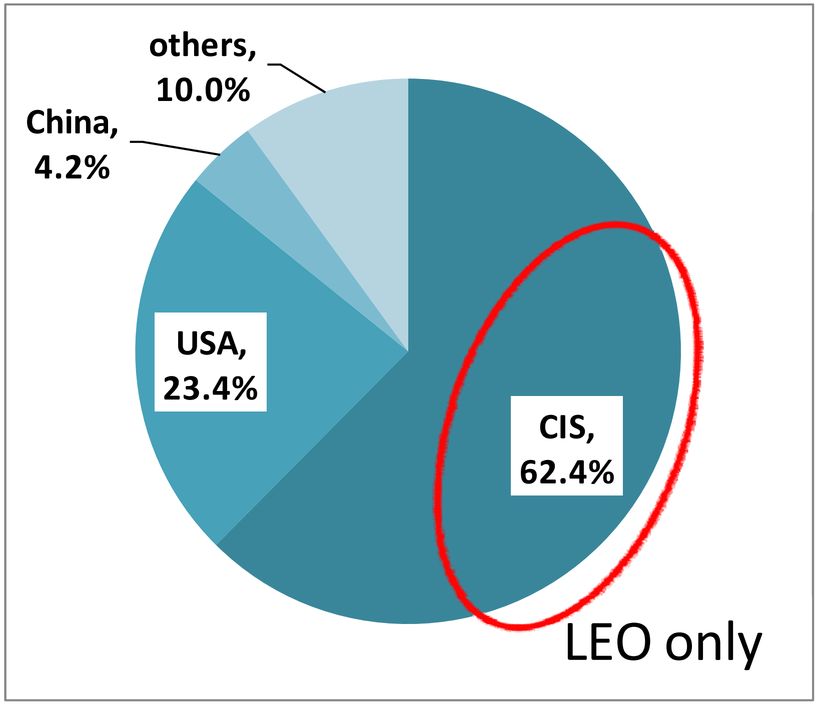
CIS = Former Soviet Republics

Sources of the Catalog Population – LEO Only

Number Breakdown

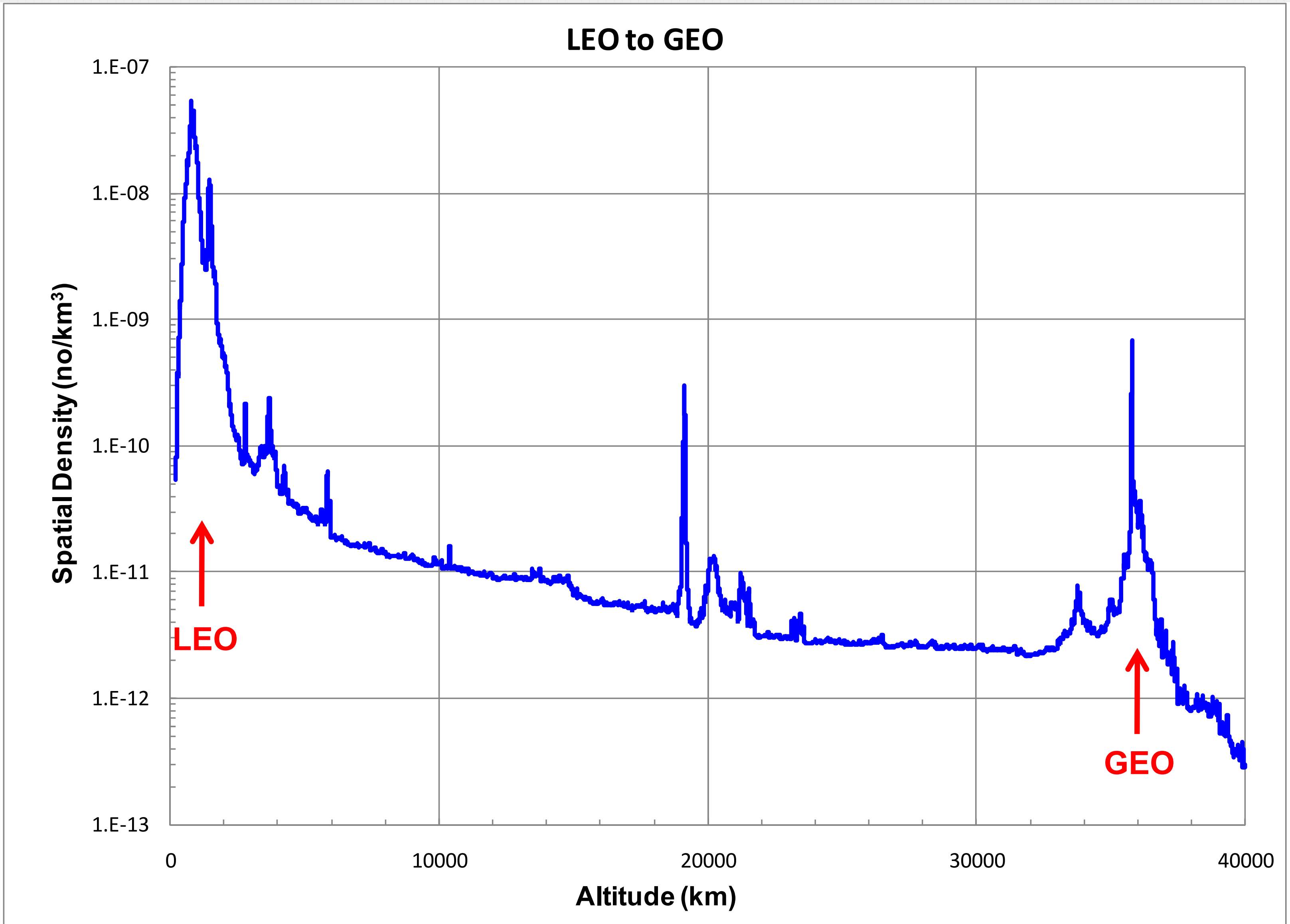


Mass Breakdown

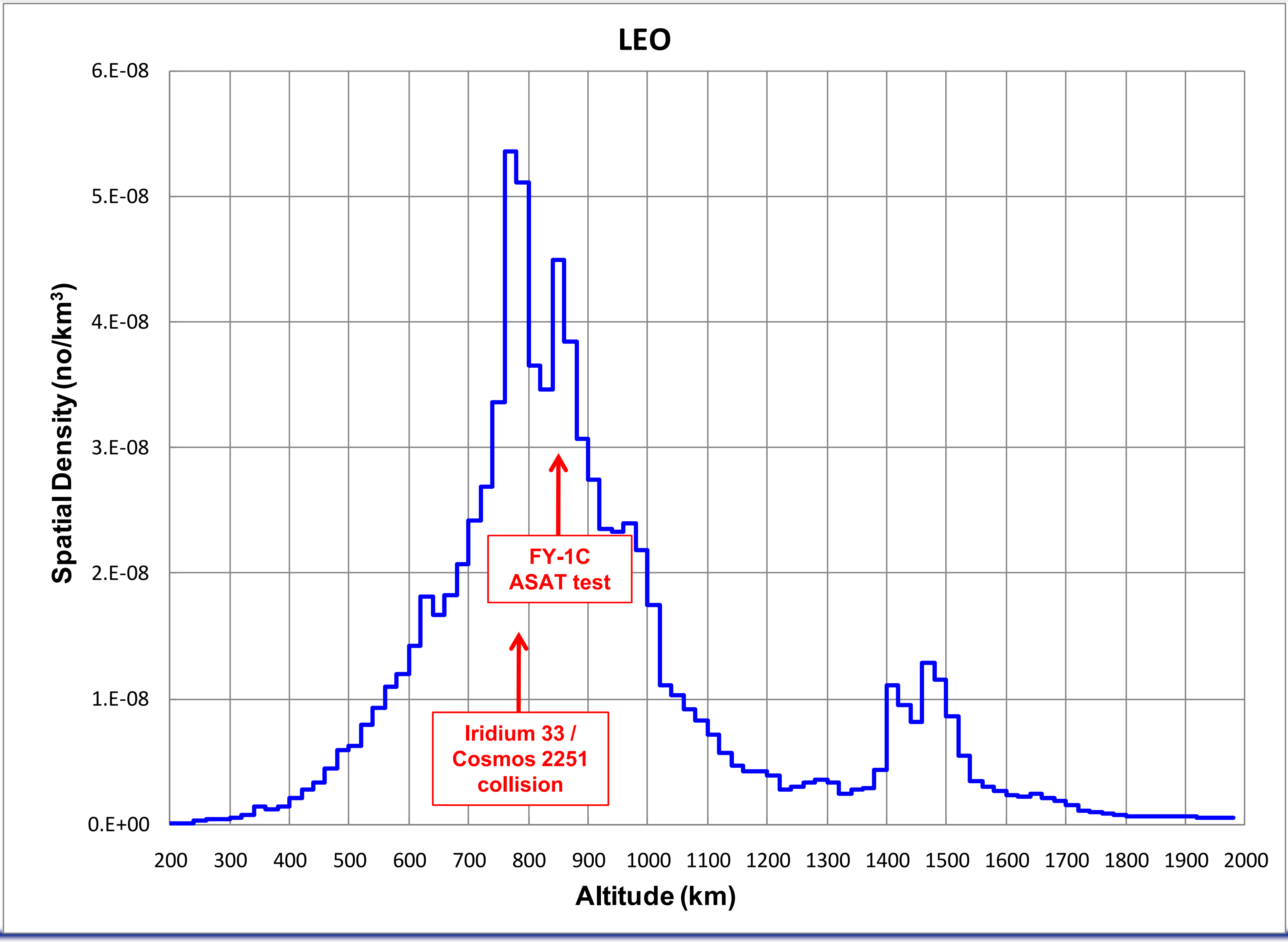


CIS = Former Soviet Republics

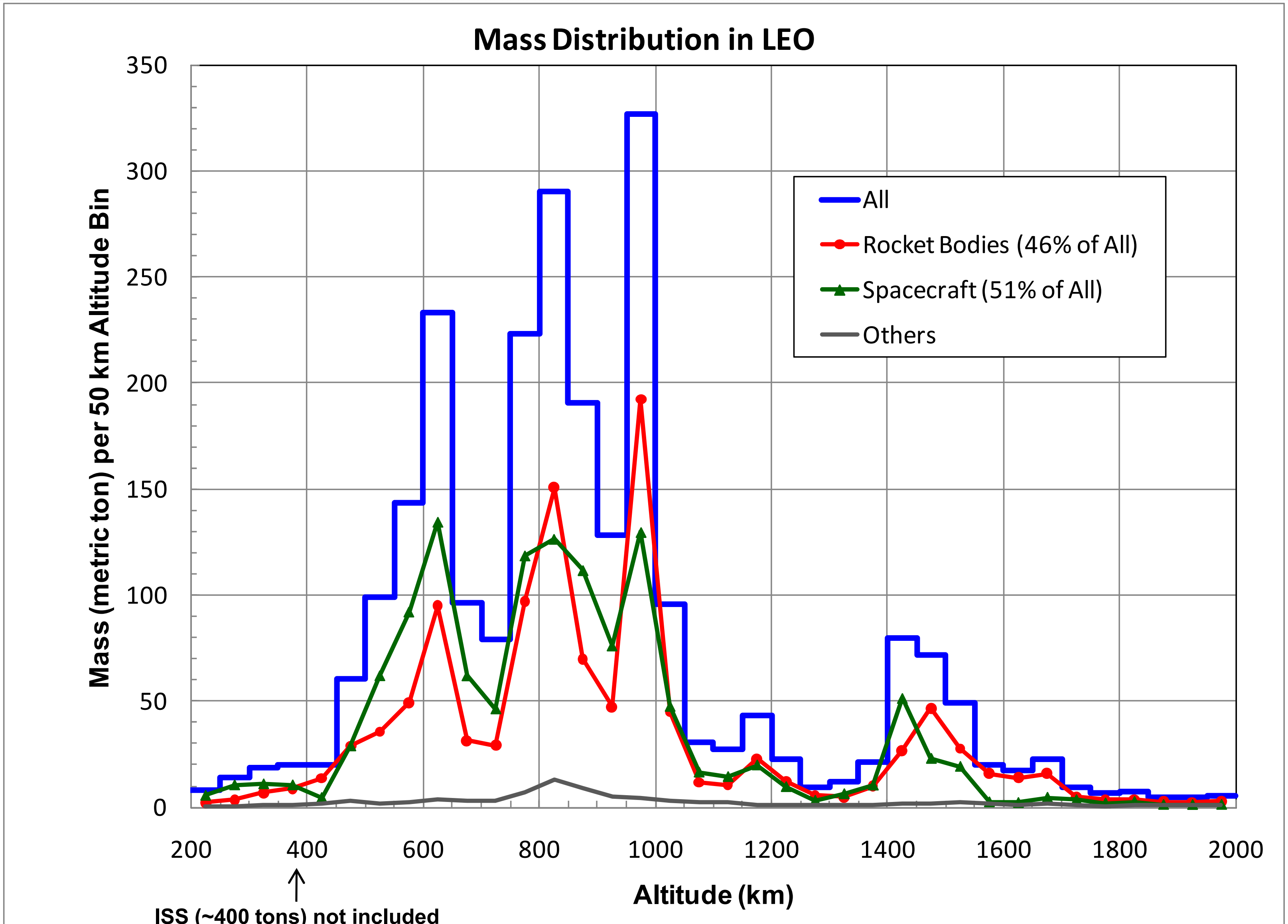
Spatial Density of the Catalog Population (1/2)



Spatial Density of the Catalog Population (2/2)



Mass Distribution in LEO



JCL

Projected Growth of the Future Debris Environment

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

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
  - The following discussions will focus on ≥10 cm objects and limit the future projection to 200 years

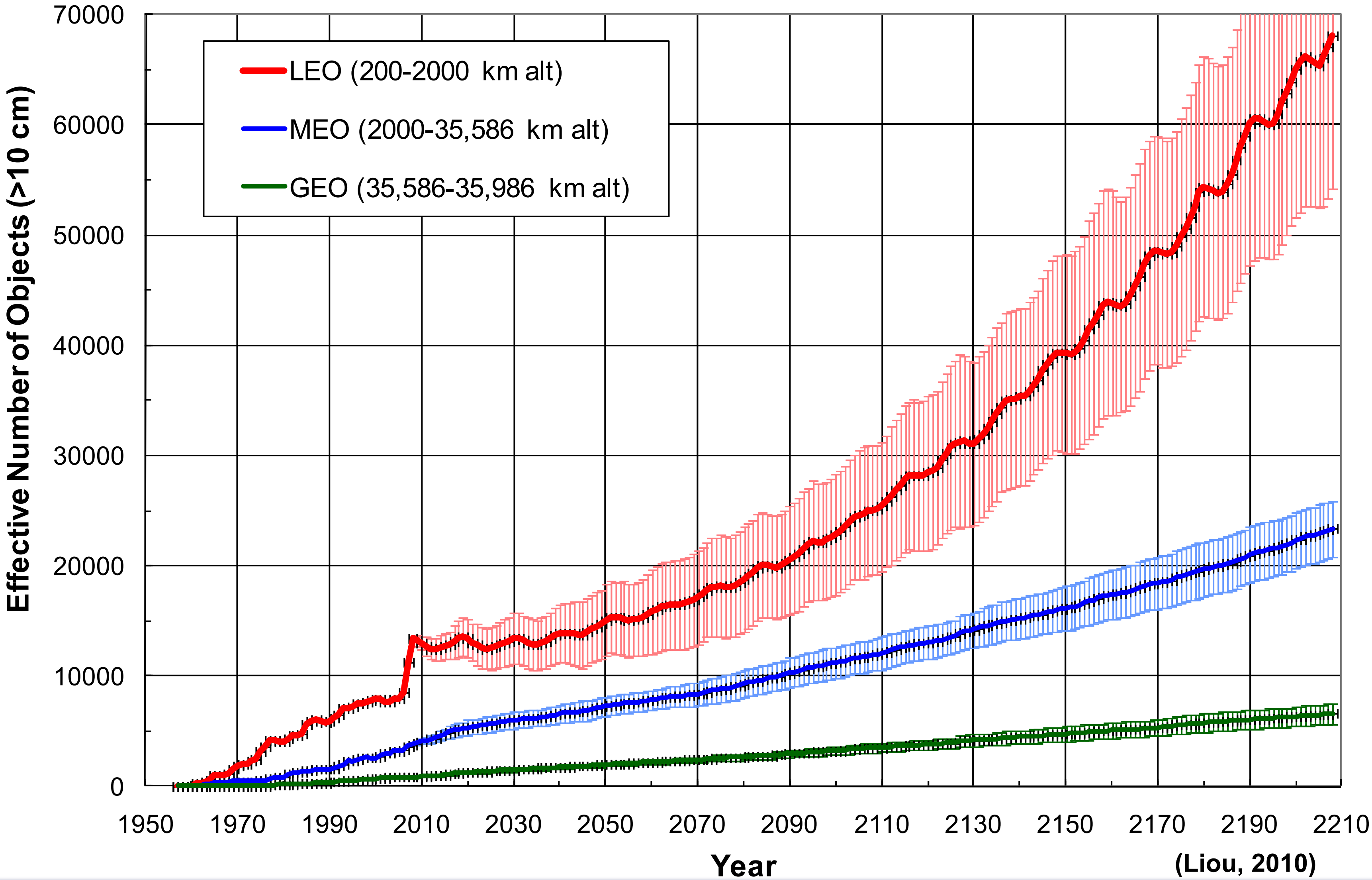
Peer-Reviewed Journal Publications
(LEGEND and LEGEND Applications)

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.

National Aeronautics and Space Administration

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

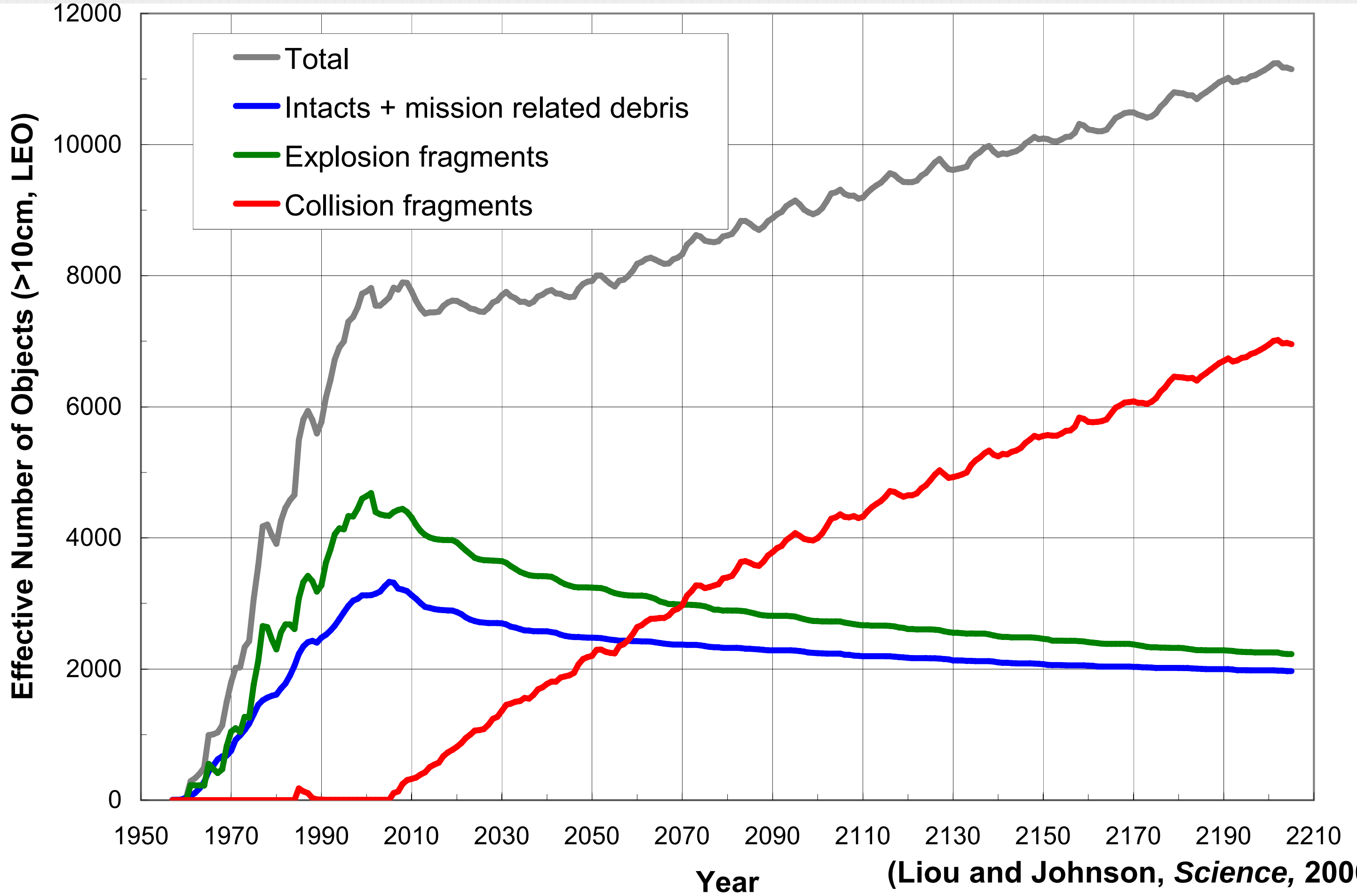
- **LEO: the non-mitigation scenario predicts the debris population (≥10 cm objects) will have a rapid non-linear increase in the next 200 years**
  - This is a well-known trend (the "Kessler Syndrome") that was the motivation for developing the currently-adopted mitigation measures (*e.g*., the 25-yr rule) in the last 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 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**
  - Satellites launches will continue
  - Major unexpected 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**

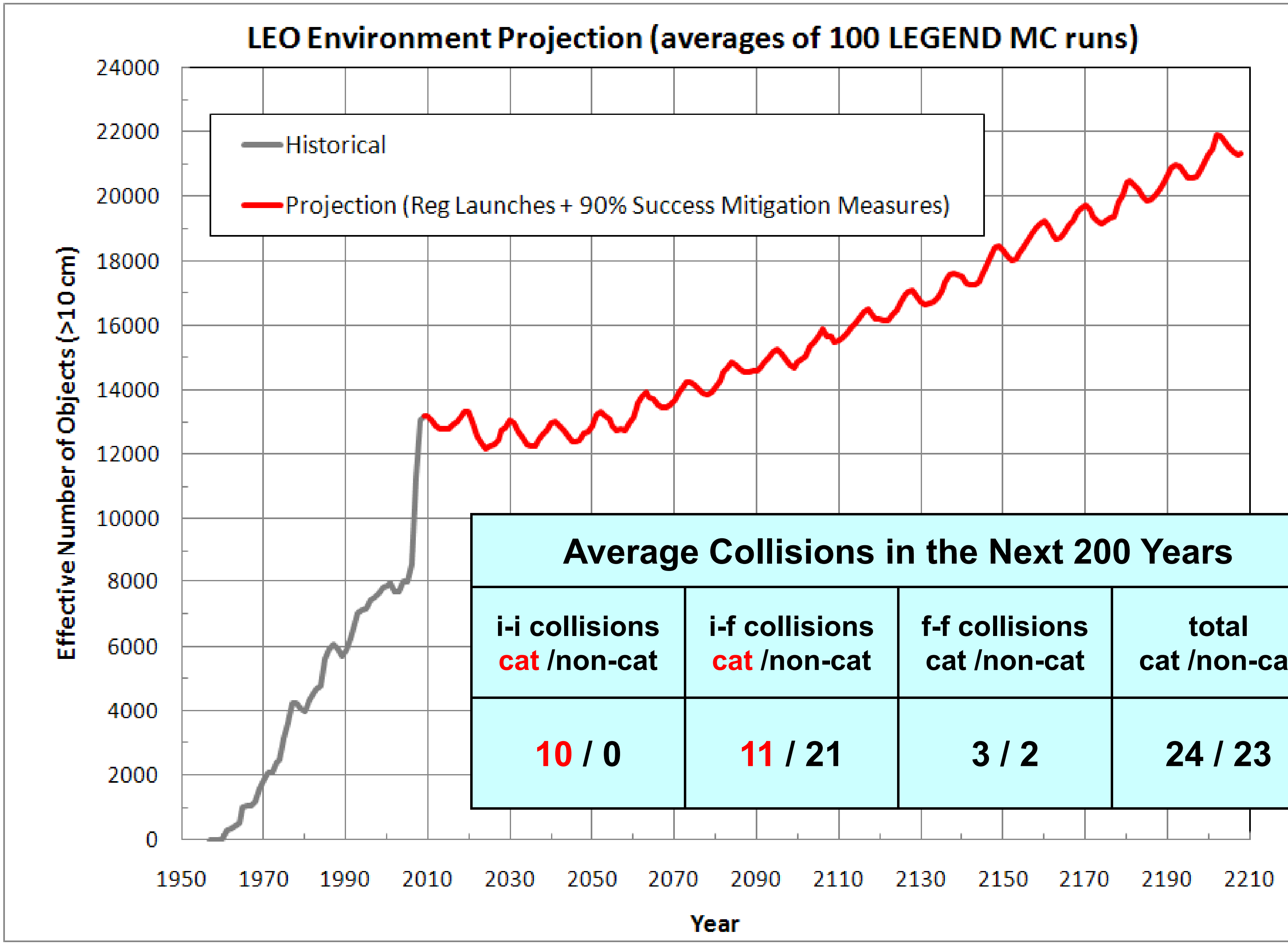
- **To preserve the near-Earth space for future generations, ADR must be considered**

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 (small & large debris)
  - Limit collision activities

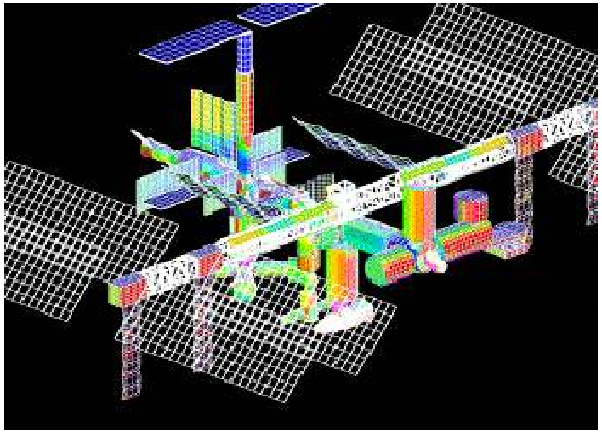
    Target large & massive intacts
  - Mitigate mission-ending risks (not necessarily catastrophic destruction) to operational payloads
  - Mitigate risks to human space activities

    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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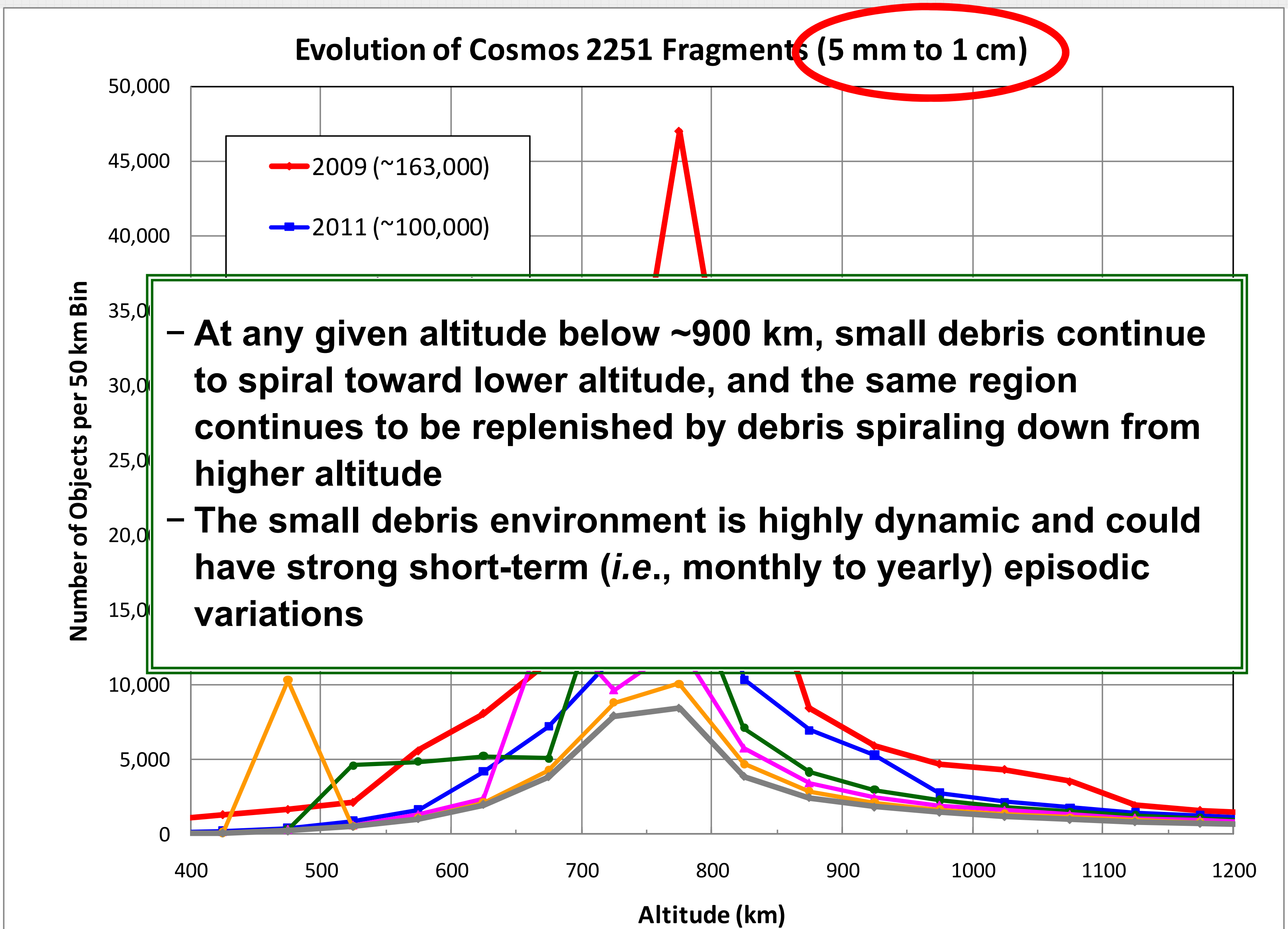
Small Debris Environment Is Highly Dynamic



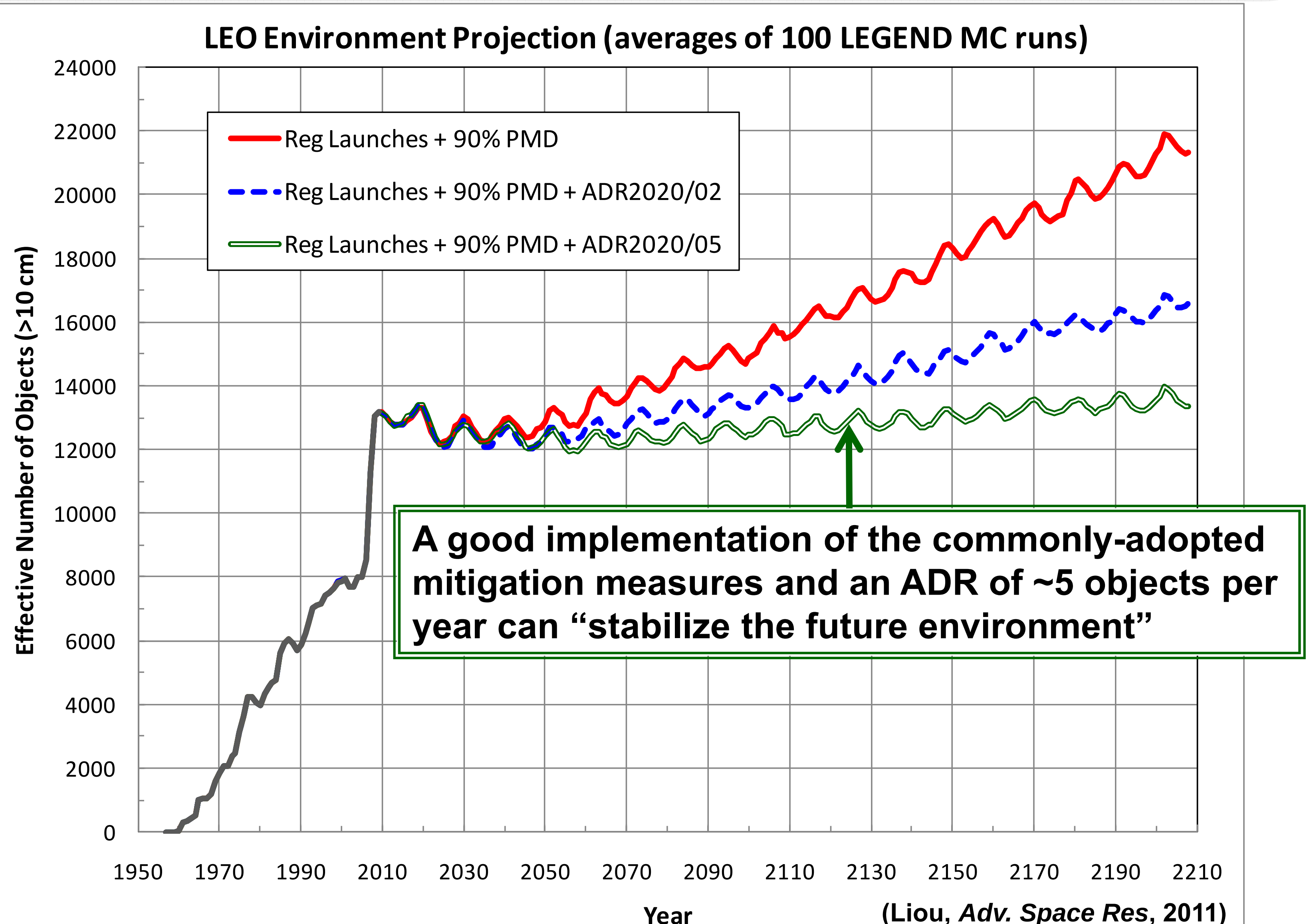
- At any given altitude below ~900 km, small debris continue to spiral toward lower altitude, and the same region continues to be replenished by debris spiraling down from higher altitude
- The small debris environment is highly dynamic and could have strong short-term (*i.e.*, monthly to yearly) episodic variations

Target Large Debris

Targeting the Root Cause of the Problem

- **A 2008-2009 NASA study shows that the two key elements to <u>stabilize the future LEO environment</u> (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 <u>about five objects per year</u>
    - **These are objects with the highest [$M \times P_{coll}$]**
    - **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)

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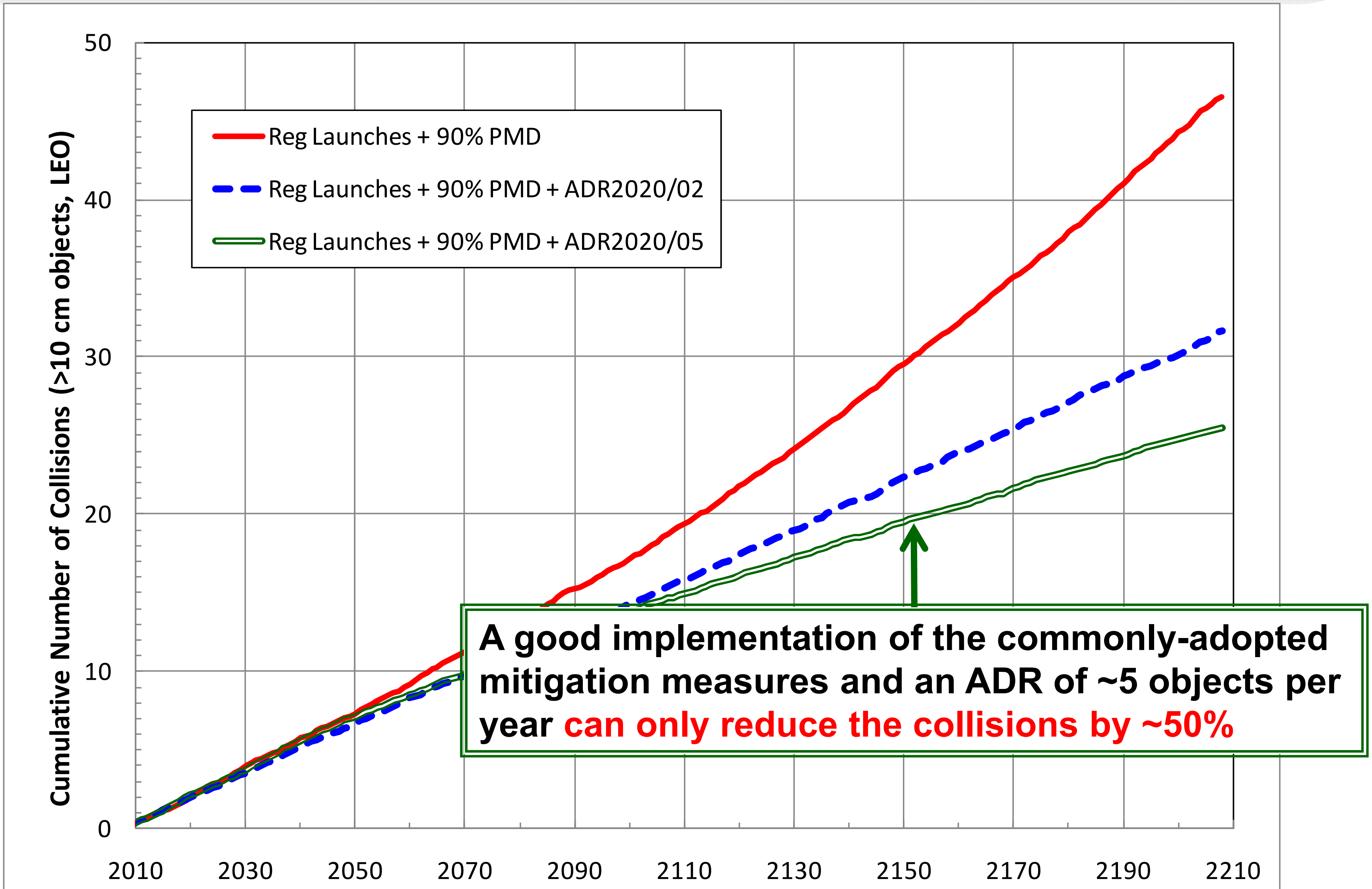
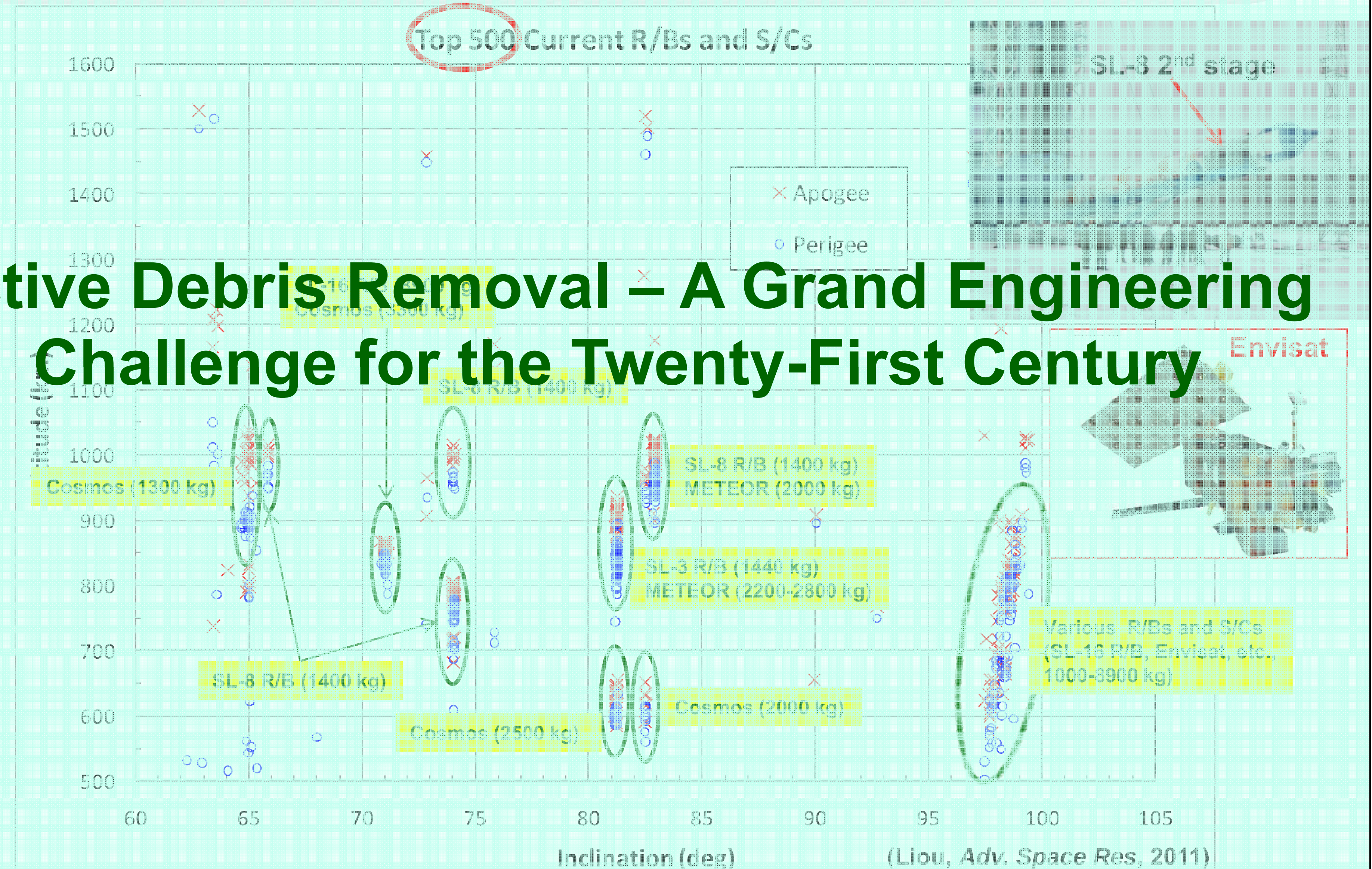
Projected Collision Activities in LEO



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

Potential Active Debris Removal Targets

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



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

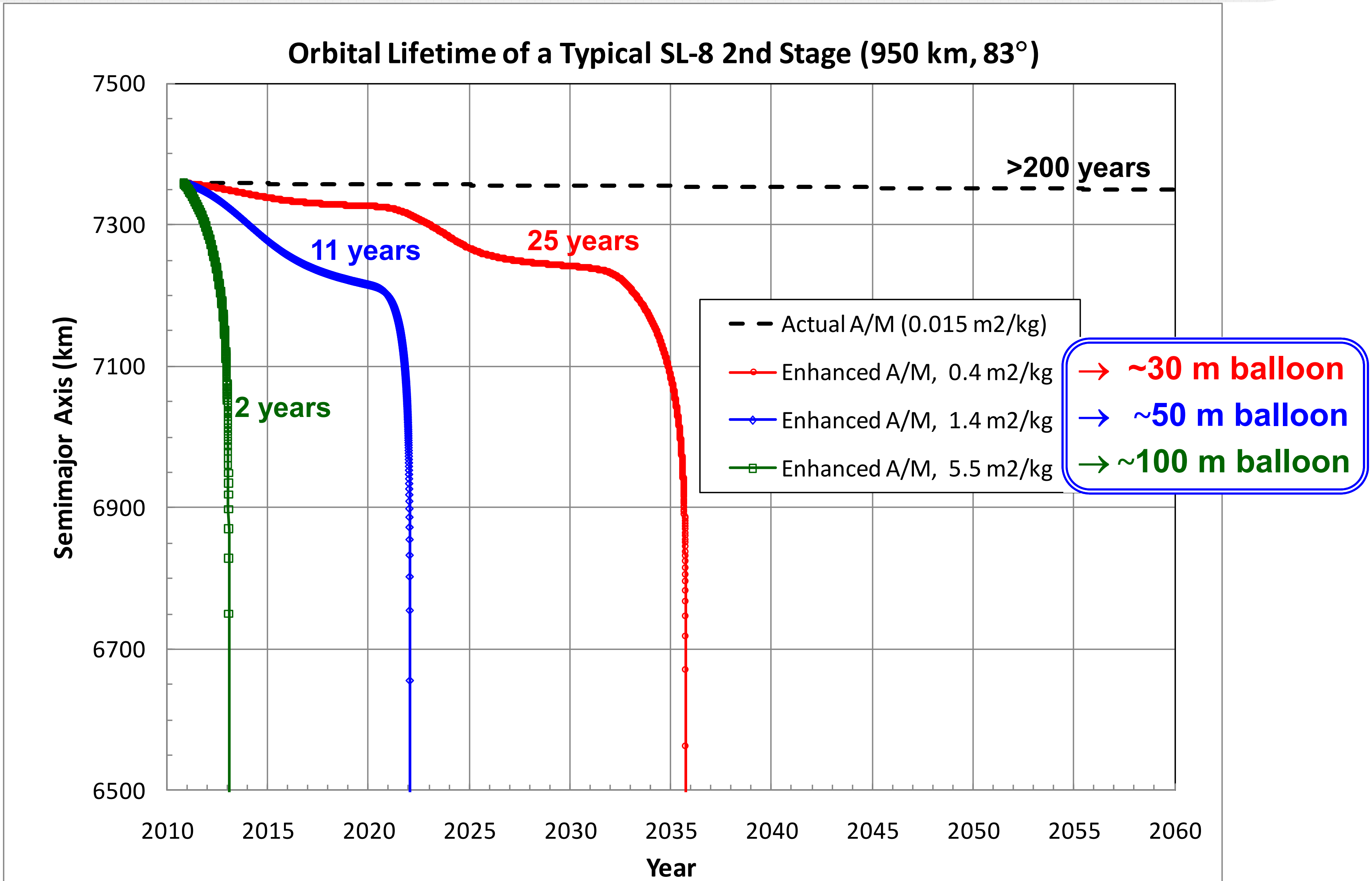
Operations	Technology Challenges
Launch	Single-object removal per launch is not feasible from cost perspective
Propulsion	Solid, liquid, tether, plasma, laser, drag-enhancement devices, others?
Precision Tracking	Ground or space-based
GN&C and Rendezvous	Autonomous, non-cooperative targets
Stabilization (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)
  - Target R/Bs first

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

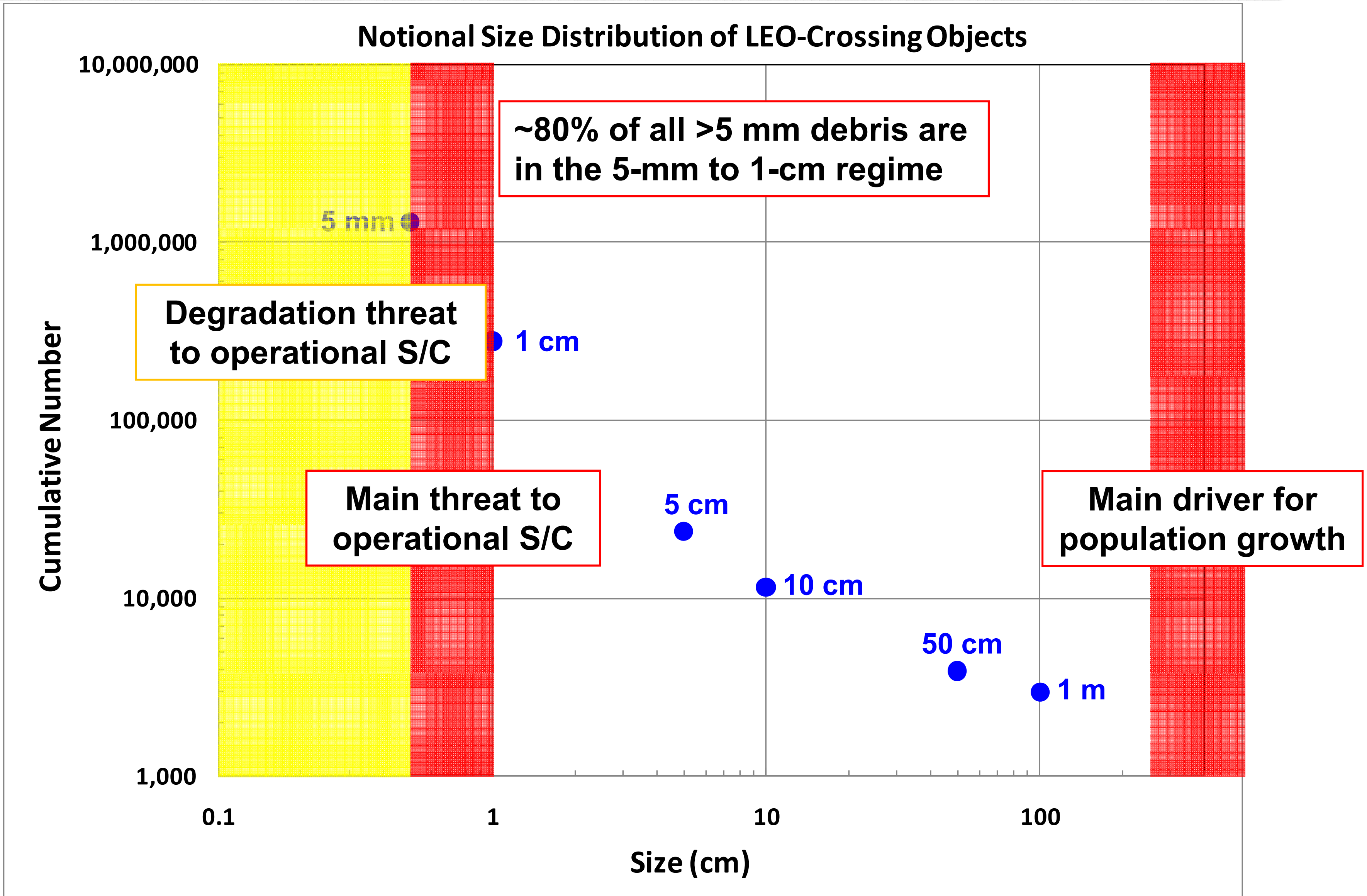


Summary

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 (for large <u>and</u> small debris)**

  → 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

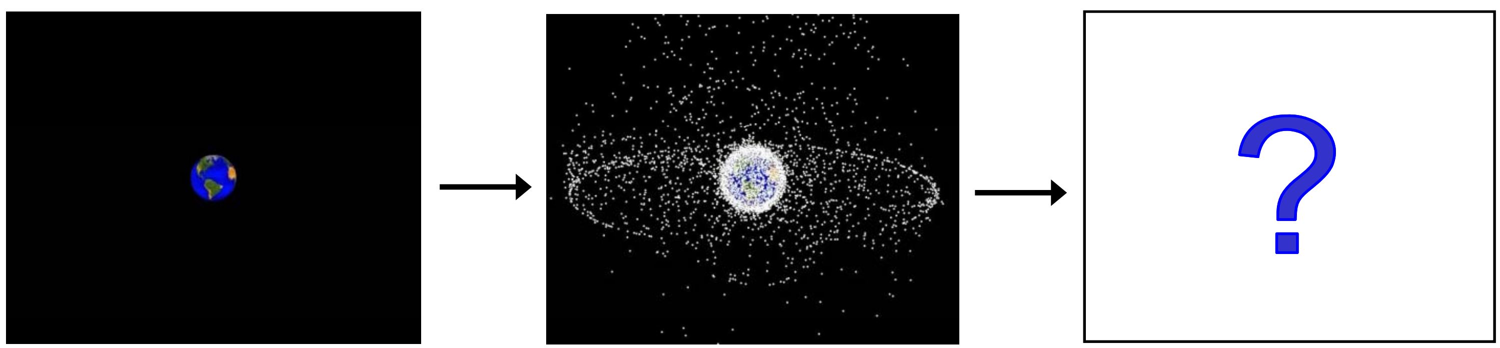
- **Targeting anything else will NOT be the most effective means to remediate the environment nor to mitigate risks to operational satellites**

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 <u>national and international</u> levels**

Preserving the Environment for Future Generations

- **Four Essential "Cs" for ADR**
  - Consensus
  - Cooperation
  - Collaboration
  - Contributions



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