The Space Weather Community's Role in Decision-Making for Orbital Debris

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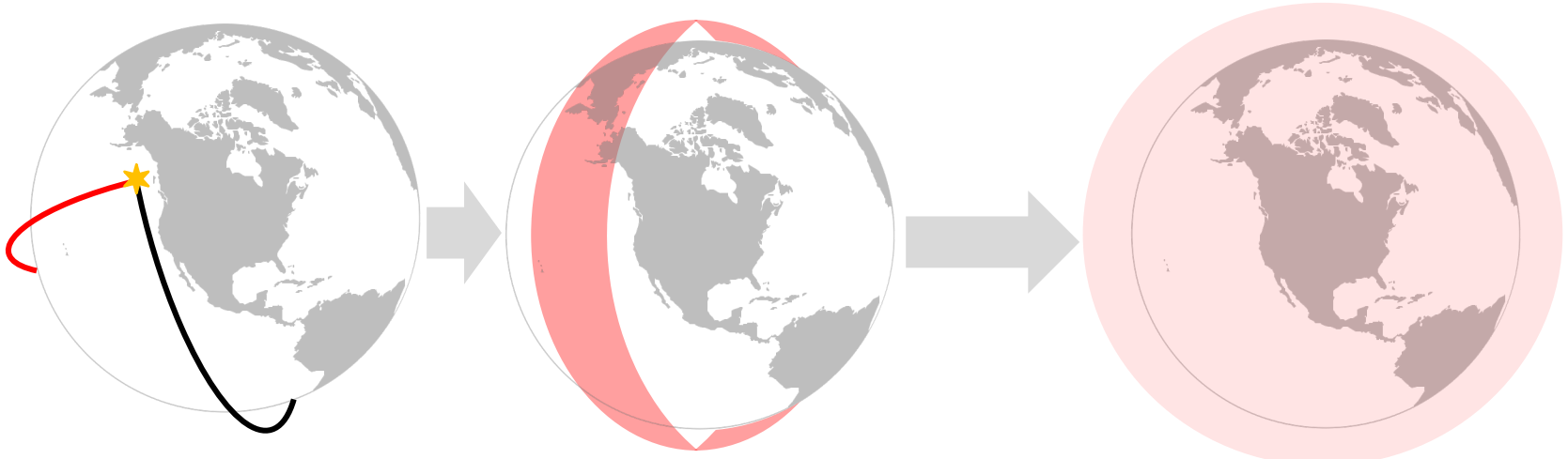
A Cautionary Tale

11 Jan. 2007
Chinese Fengyun-1C ASAT Test
>2,500 debris fragments >10 cm

22 Jan. 2013
Russian BLITS satellite struck and destroyed by small debris
(Unknown origin)

28 Jan 2012
19 April 2020
10 Nov. 2021
24 Aug. 2023
25 Nov. 2024
ISS performs collision avoidance maneuvers due to Fengyun-1C debris
*(**Thousands** of additional maneuvers by other operators)*

Time



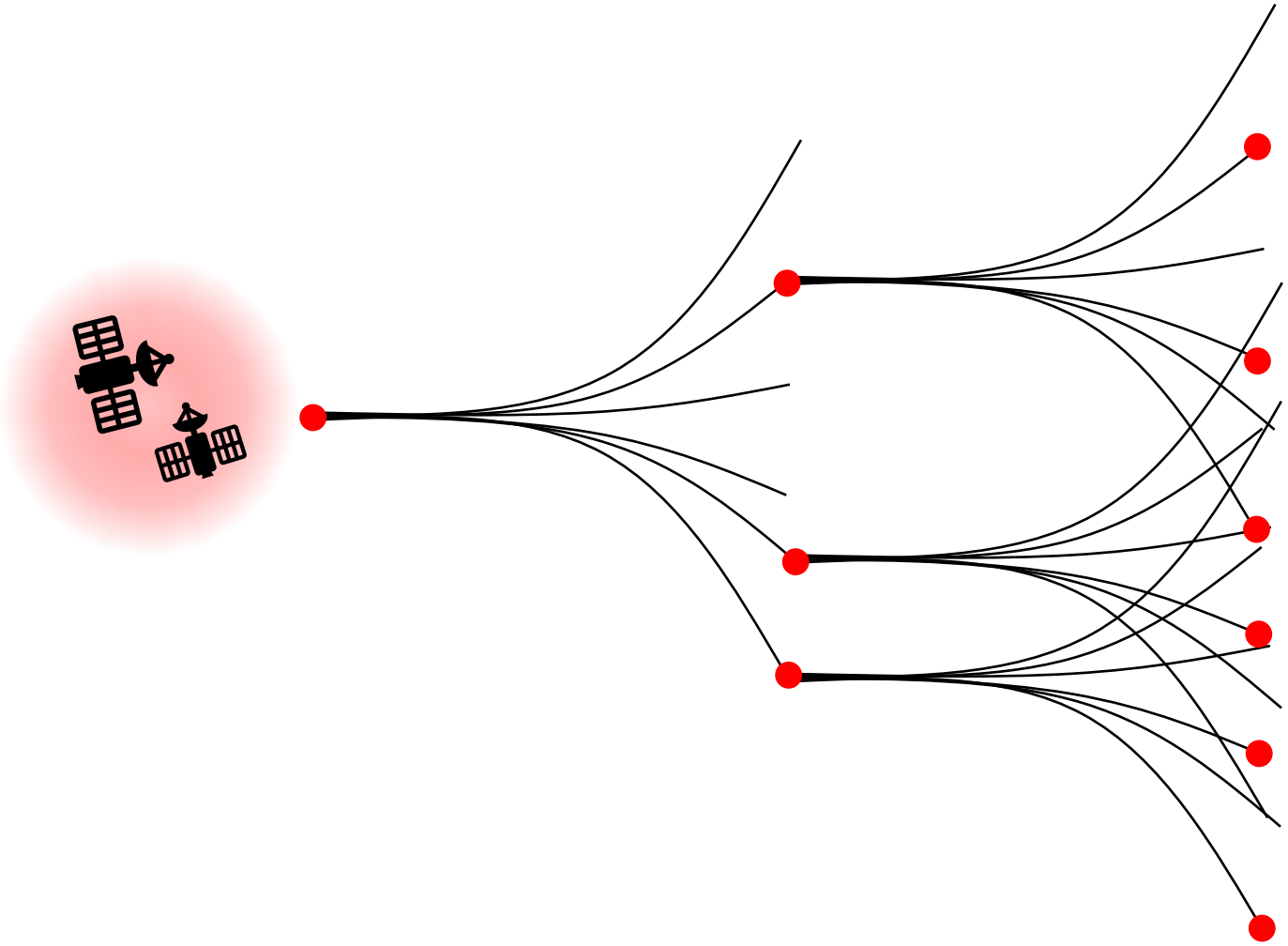
1 month later

Years later

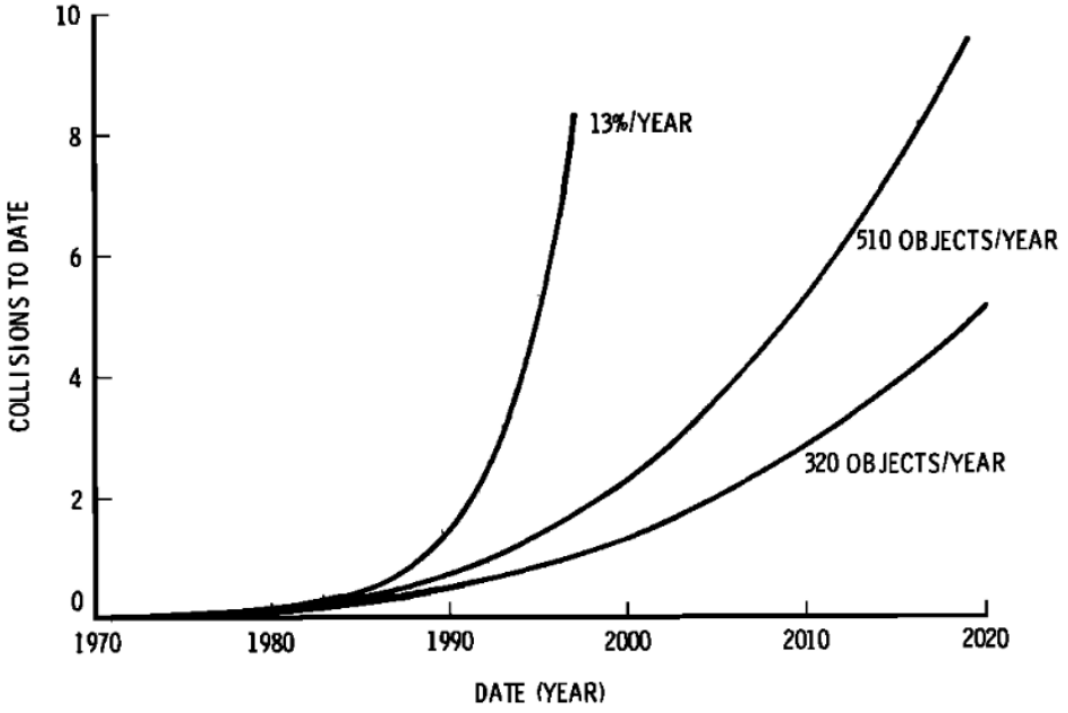
5 Nov. 2025
Debris strike to Shenzhou-20 space capsule jeopardizes Chinese astronaut return
(Unknown origin)

Kessler Syndrome

Self-perpetuating debris growth from cascading collisions

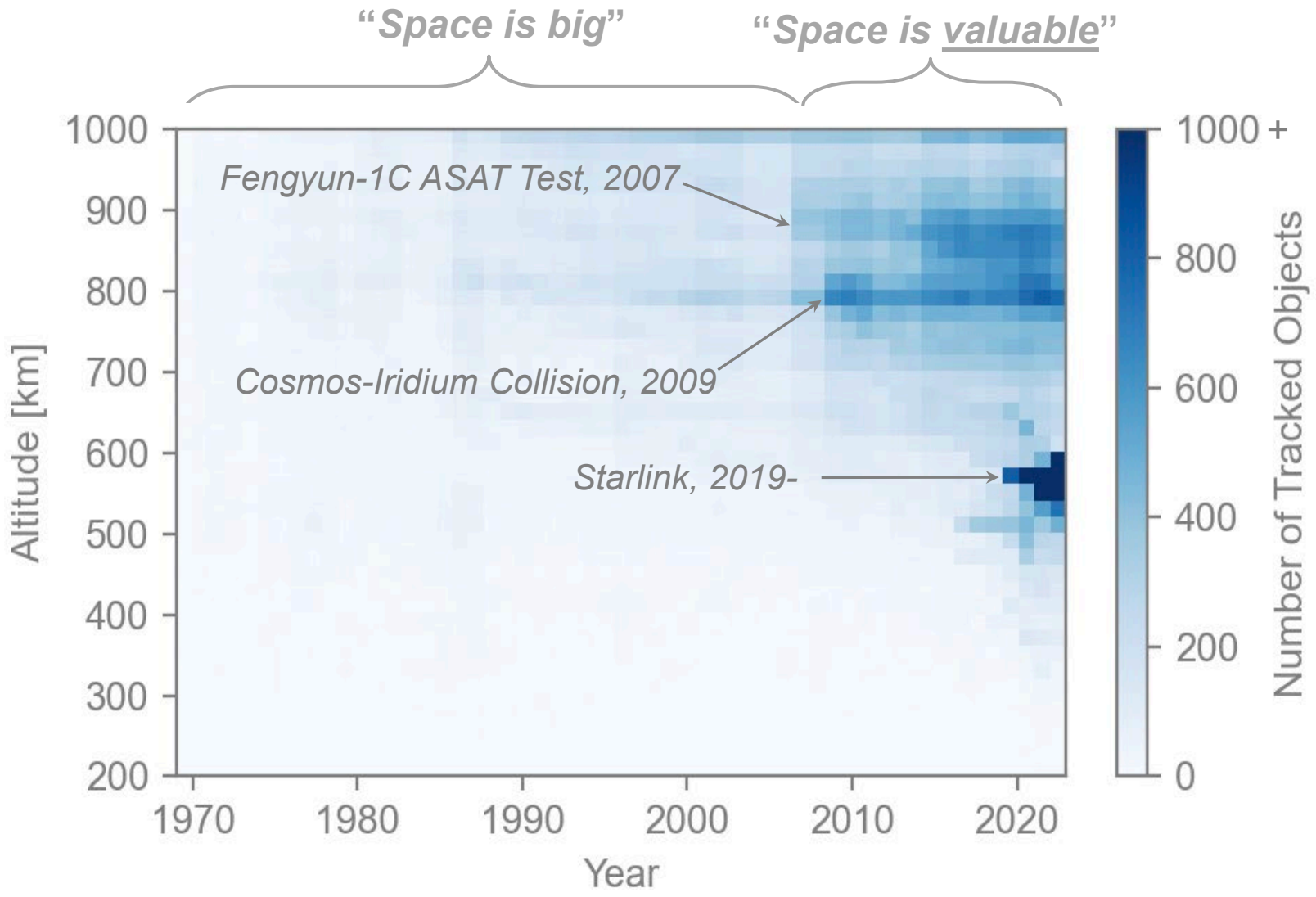


Kessler and Cour-Palais (1978)



Original paper: Kessler, D. J., & Cour-Palais, B. G. (1978). Collision frequency of artificial satellites: The creation of a debris belt. *Journal of Geophysical Research: Space Physics*, *83*(A6), 2637-2646.

A Congested and Contested Low Earth Orbit (LEO)



Avoiding Kessler Syndrome

What can we do to avoid unacceptable debris accumulation?

Short-term

Long-term

Avoiding Kessler Syndrome

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	Short-term	Long-term
Action	**Avoid creating new debris**	**Launch and operate satellites sustainably**

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Tool	• Space traffic coordination • Collision avoidance maneuvers	• Post-mission Disposal • Debris Evolutionary Modeling

Avoiding Kessler Syndrome

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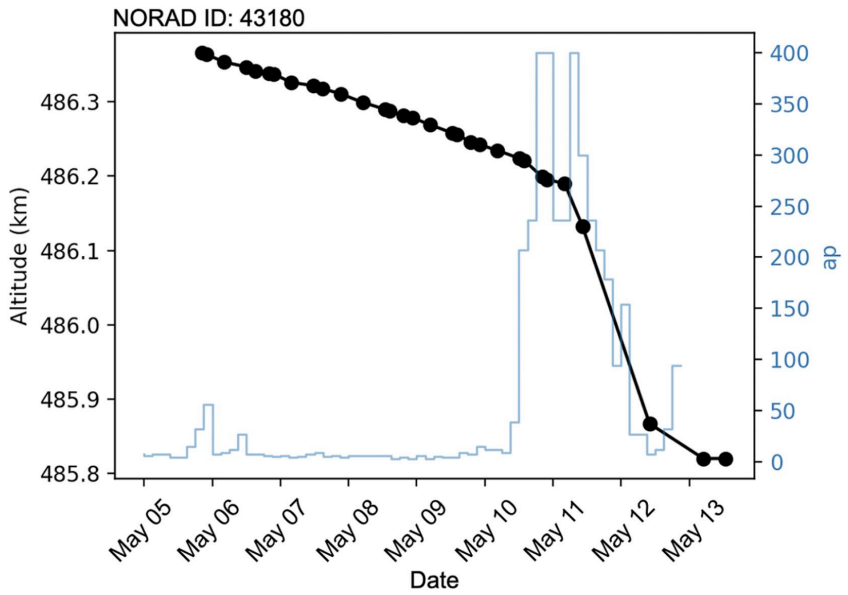
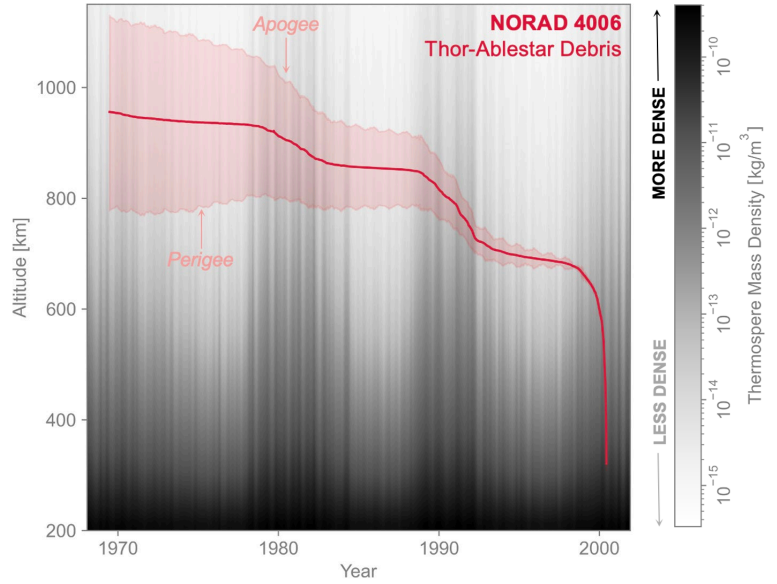
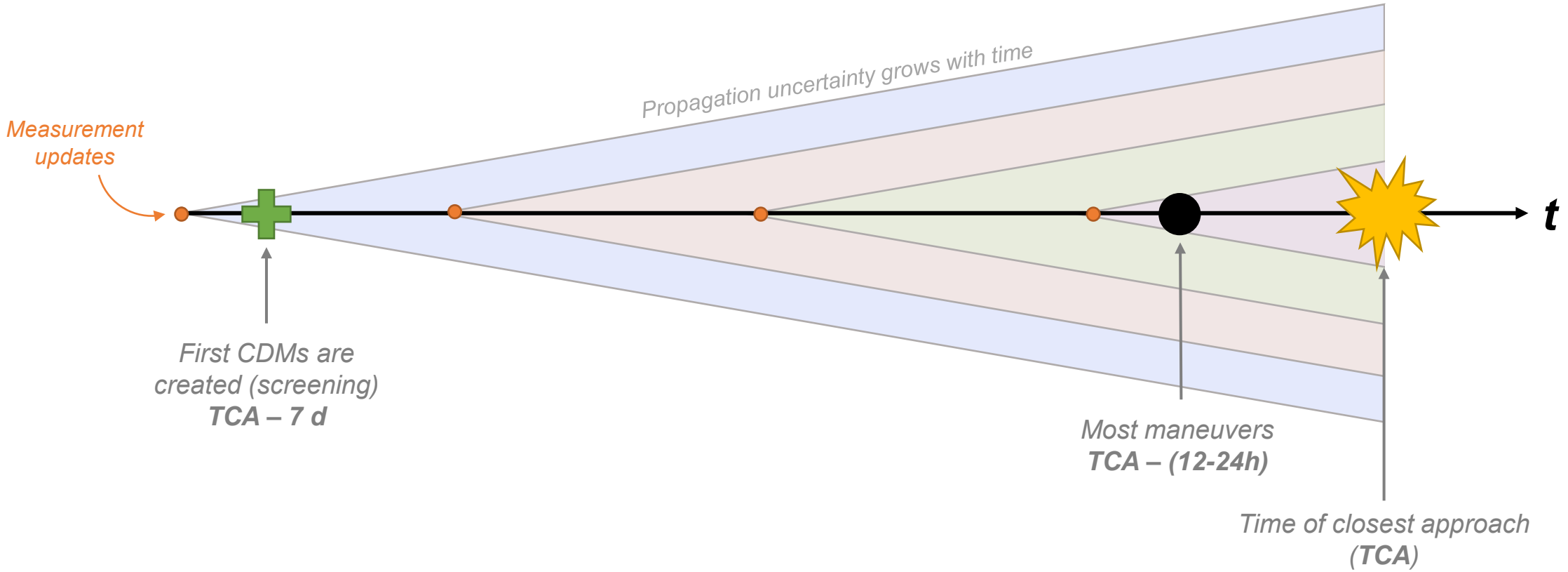
	Short-term	Long-term
Action	**Avoid creating new debris**	**Launch and operate satellites sustainably**
Tool	• **Space traffic coordination** • **Collision avoidance maneuvers**	• **Post-mission Disposal** • **Debris Evolutionary Modeling**
Space Weather?	**Drag is unpredictable** (because of geomagnetic storms)	**Drag is unpredictable** (because of space climate variability)





Short-term: Satellite Collision Avoidance (COLA)



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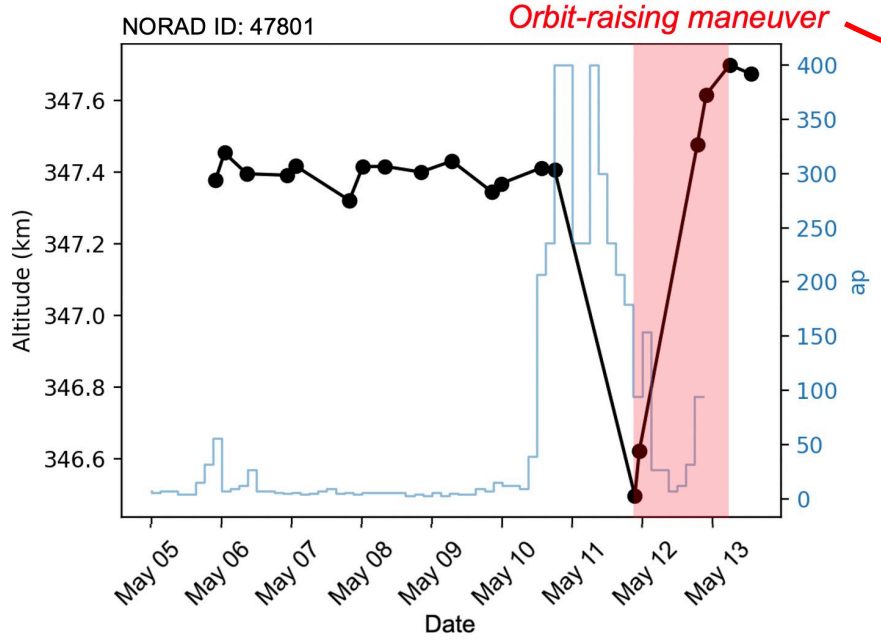
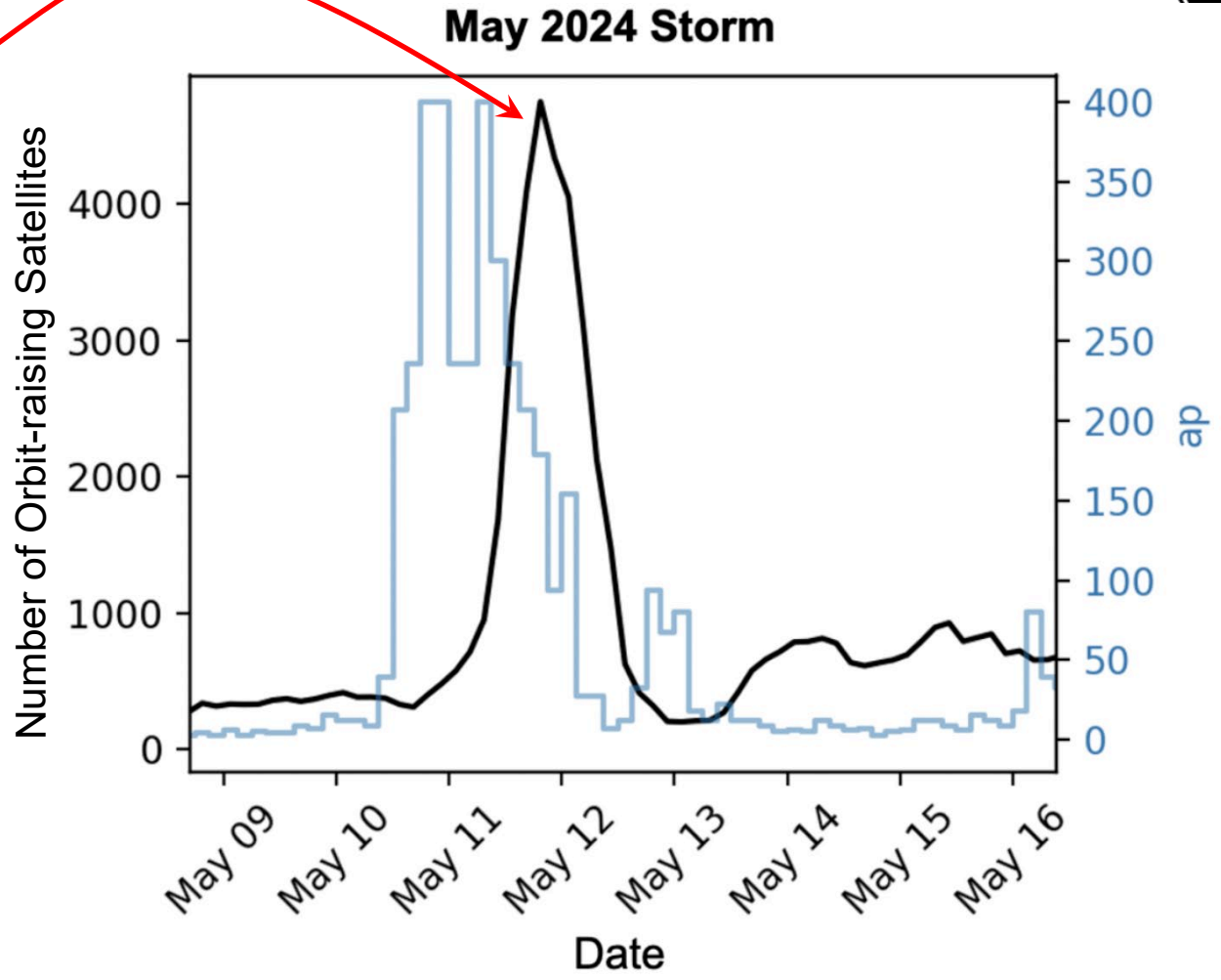




SPACE.com

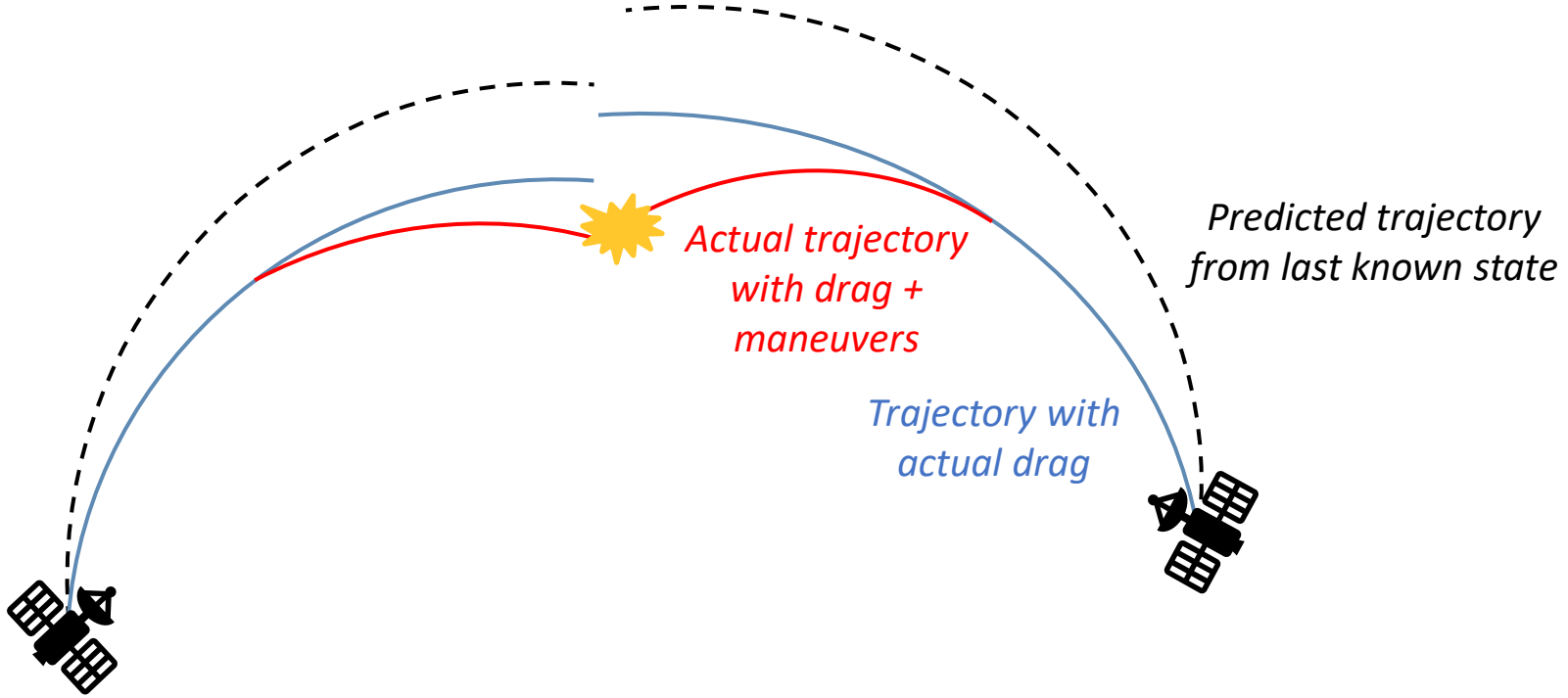
May solar superstorm caused largest 'mass migration' of satellites in history

News By Tereza Pultarova published July 19, 2024

Short-term: Satellite Collision Avoidance (COLA)

Predicted satellite trajectories can be very wrong
(from poor storm forecasts)

Satellites perform unplanned maneuvers *en masse*
(to maintain their orbital slots)



COLA capabilities were developed as strategies for risk mitigation but have instead become the *enabling infrastructure* that makes large LEO constellations possible today. Robustness issues represent a real risk to the LEO environment.

Long-term: Debris Evolutionary Modeling

Trace **sources** and **sinks** of new debris

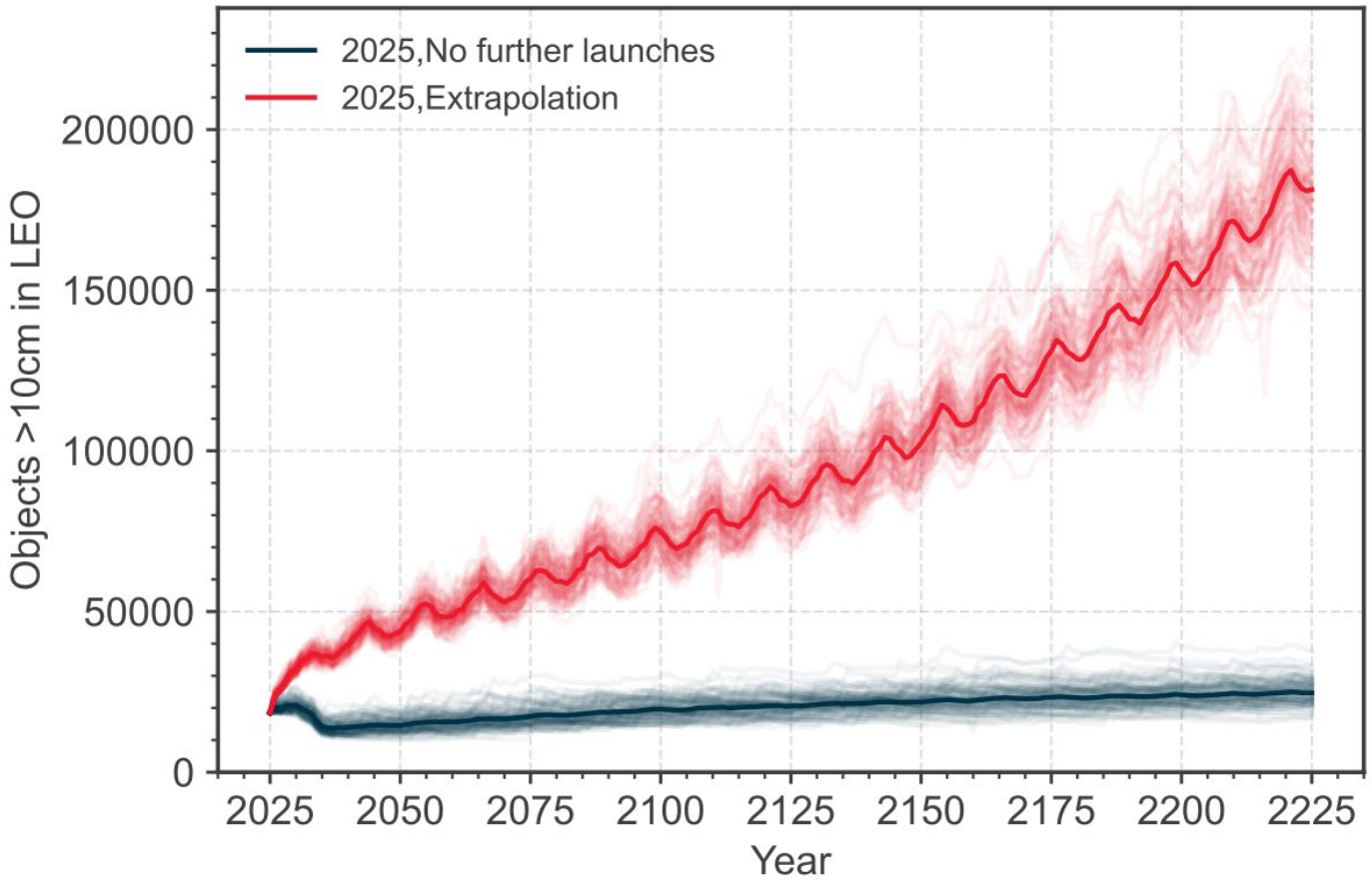
Collisions
Explosions
Anti-sat weapons
Derelict sats/RBs

Passive drag decay
Post-mission disposal

Typical Environment Assumptions

Solar activity remains consistent with recent observations.

Constant atmospheric composition



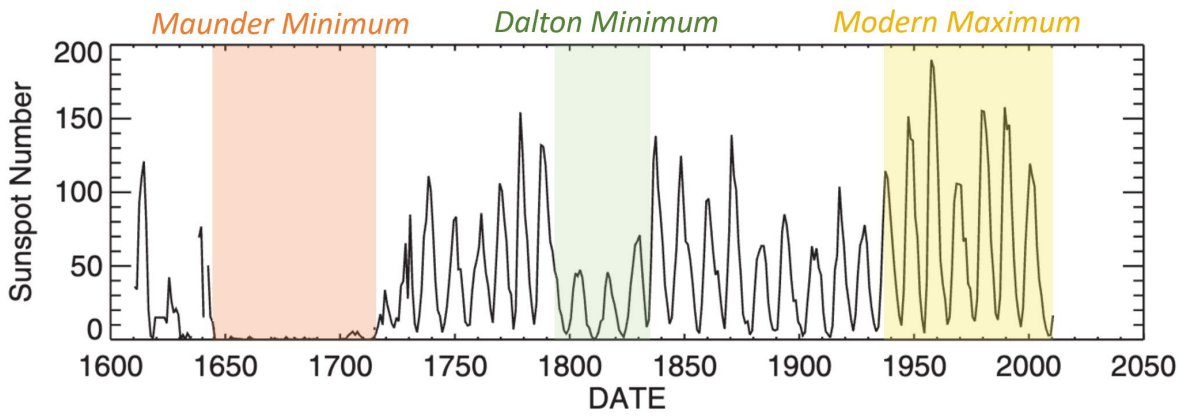
ESA Space Environment Report (2025)

Long-term: Variable Solar Activity

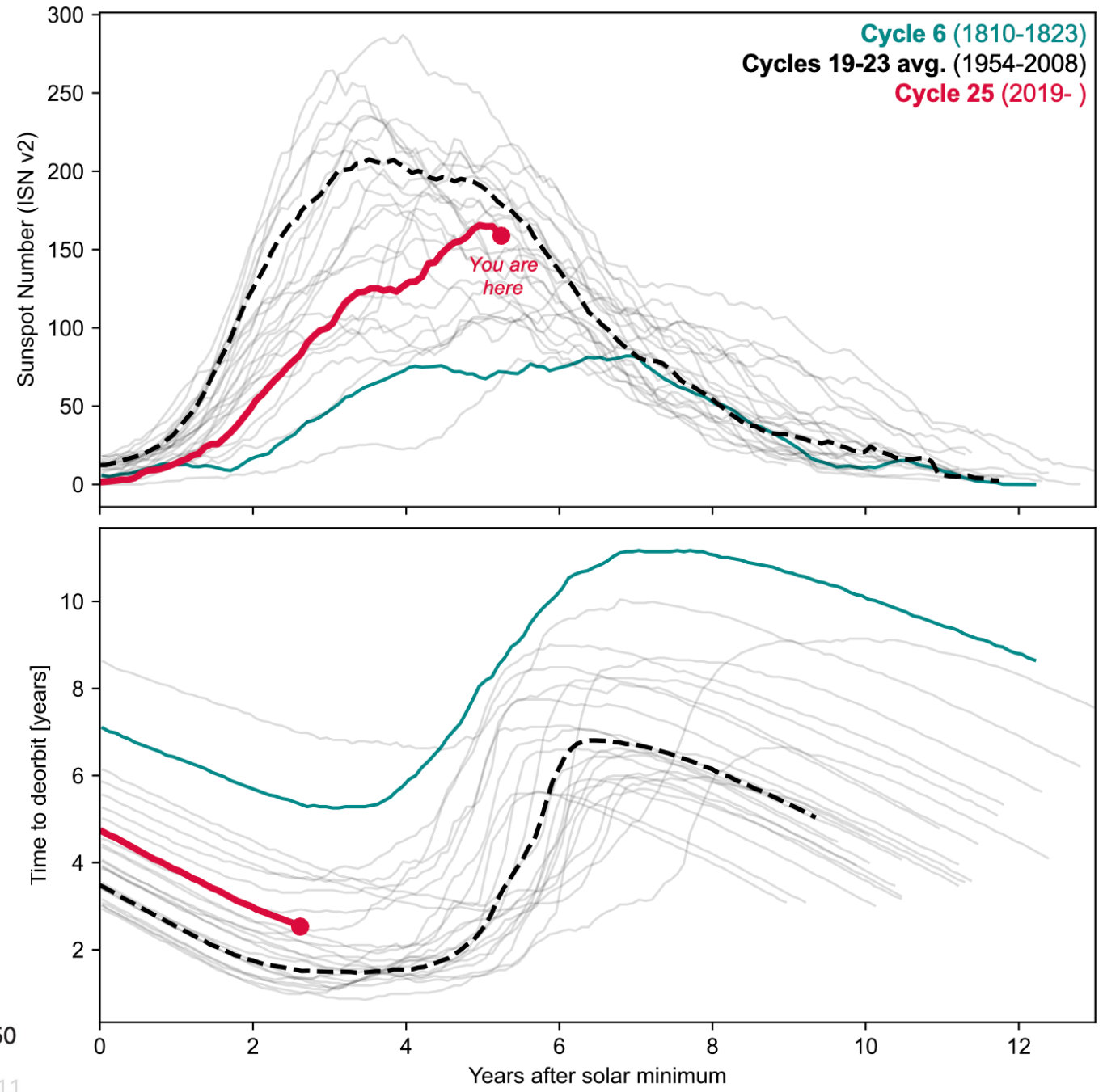
Poor Assumption

Solar activity remains consistent with recent observations.

To predict the evolution of debris populations, we need to better understand the long-term variability of the sun, and what that means for debris residence time in orbit.



Adapted from Priest, 2011



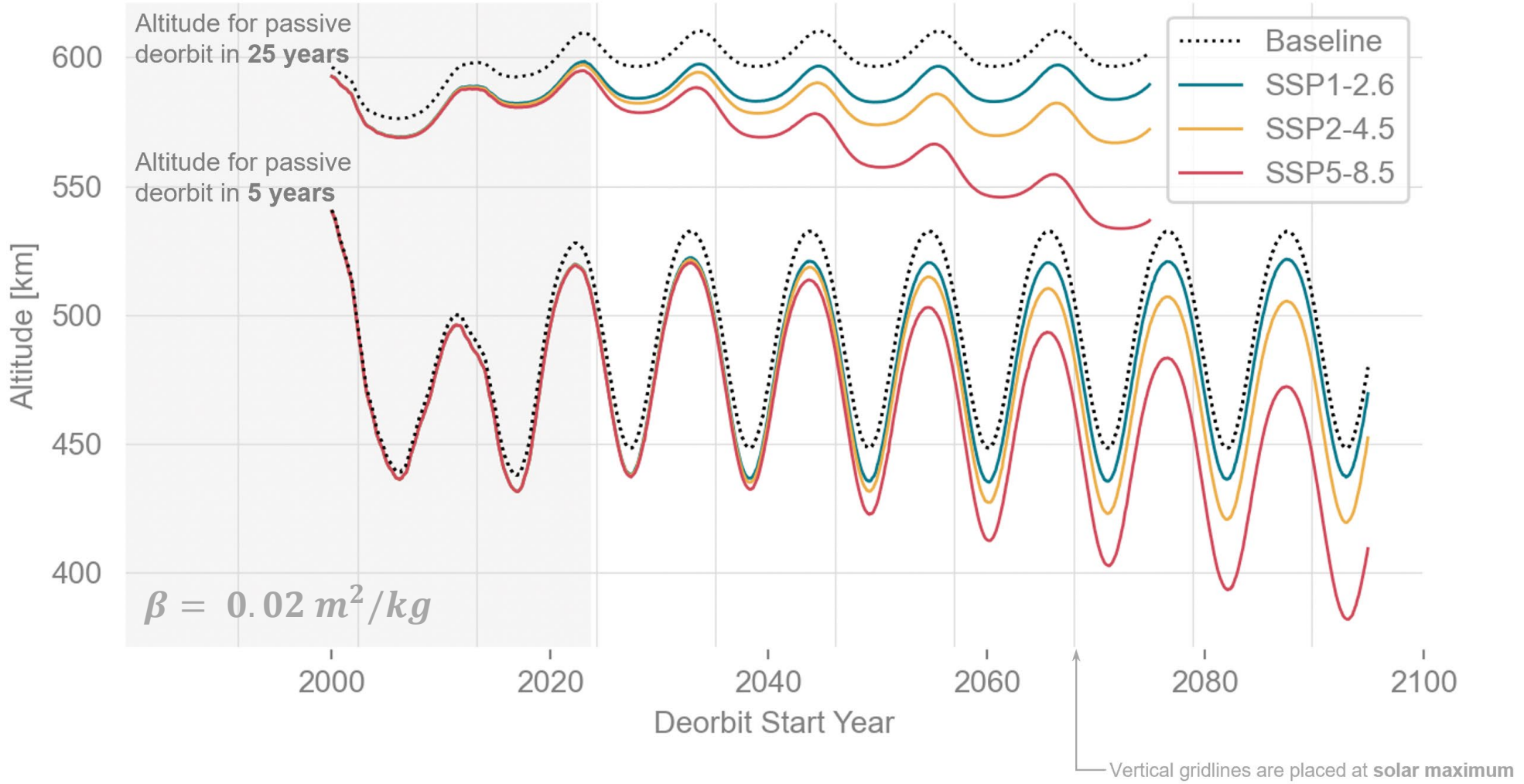
$\beta = 0.02\ m^2/kg, \quad h_0 = 500\ km$

Long-term: Changes in Atmospheric Composition

Shared Socioeconomic Pathways (SSPs) for GHG emissions

Poor Assumption

Constant atmospheric composition



Parker, W.E., Brown, M.K. & Linares, R. Greenhouse gases reduce the satellite carrying capacity of low Earth orbit. *Nat Sustain* **8**, 363–372 (2025). https://doi.org/10.1038/s41893-025-01512-0

How do we help mitigate Kessler syndrome?

We need to balance the **short-term benefits** of our space activities with the **long-term preservation** of a viable environment. Improving our space weather knowledge helps us find that balance.

- **Variables we <u>can</u> control**: Launch traffic, operating behaviors, disposal practices, data sharing, etc.
- **Variables we <u>cannot</u> control:** Environmental changes

- **Tasks for the Space Weather Community:**
  - Improve forecasts of geomagnetic activity drivers (with uncertainty!) → prevents new collisions *today*.
  - Better understand long-term variability of the sun (decades-centuries) → Informs policy decisions for space conservation.
  - Explore the relationship between a changing Earth climate and space weather → prepares us for what's to come.

For more information, see:

Parker, William. *Satellite Drag and Sustainable Space Operations in a Dynamic Thermosphere*. 2025. Massachusetts Institute of Technology, PhD dissertation.

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