A Coupled Space Weather Impact Model for Satellite Fleet Vulnerability and Economic Loss Under a 1-in-100-Year Solar Energetic Particle Event

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ABSTRACT

We estimate that a 1-in-100-year SEP event would cause radiation-induced failures in roughly 322 US satellites, with a combined replacement value of $5.9B. These failures are concentrated in high-altitude LEO and HEO orbits, where trapped radiation doses already approach typical component thresholds. GPS and commercial satellite communications are not significantly affected. Earth observation and military services experience the largest disruption, with estimated daily economic impacts of $130M, $410M, and $1.7B under our likely, moderate, and worst-case scenarios.

BACKGROUND

Modern economies depend critically on satellite infrastructure, yet the aggregate economic consequences of extreme space weather events remain poorly quantified. Available impact estimates are largely scenario-based and lack explicit grounding in the underlying particle environment, the orbital exposure of the satellite fleet, or the dose-to-failure response of spacecraft electronics. C-SWIM addresses this gap by coupling four modules into a single integrated framework that traces hazard, exposure, vulnerability, and economic impact through one physically consistent pipeline. We ask the following three questions:

1. What is the SEP exposure of US operational satellites during a 1-in-100-year geomagnetic storm?
2. What is the fleet-wide failure probability under this event, accounting for trapped radiation dose and orbital regime?
3. What are the resulting economic impacts across the US economic sectors?

DATA & METHODS

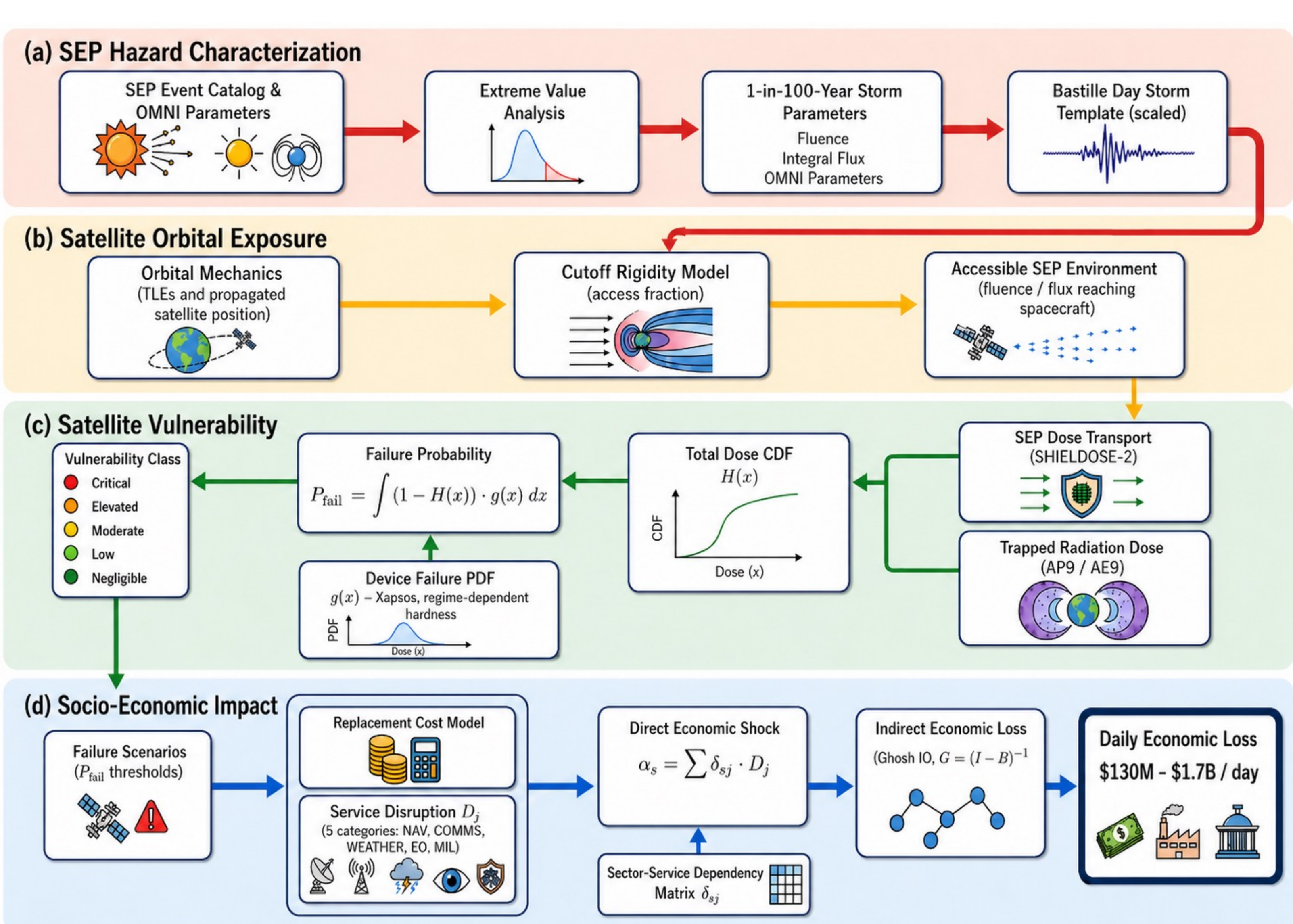

Figure 1. Coupled framework linking SEP hazard, orbital exposure, satellite vulnerability, and economic impact.

DATA & METHODS CONT'D

C-SWIM couples four modules into a single pipeline:

(a) Hazard. Extreme-value analysis of 160 SEP events observed by GOES (1996–2025) and OMNI solar wind data yields the 1-in-100-year fluence and storm-driver parameters. The Bastille Day 2000 event provides the storm-time template.

(b) Exposure. 12,860 US operational satellites are propagated through a storm-time cutoff rigidity model that combines OTSO particle tracing with a machine-learning surrogate ($R^2 = 0.997$).

(c) Vulnerability. Total ionizing dose is computed from SHIELDOSE-2 (SEP) and AP9/AE9 (trapped radiation), then convolved with Xapsos regime-dependent device-hardness distributions to obtain satellite-level failure probability.

(d) Impact. Each failure scenario yields a corresponding replacement-cost loss and service disruption across five service categories. These are propagated using a Ghosh input-output model spanning 13 BEA economic sectors to estimate daily economic losses.

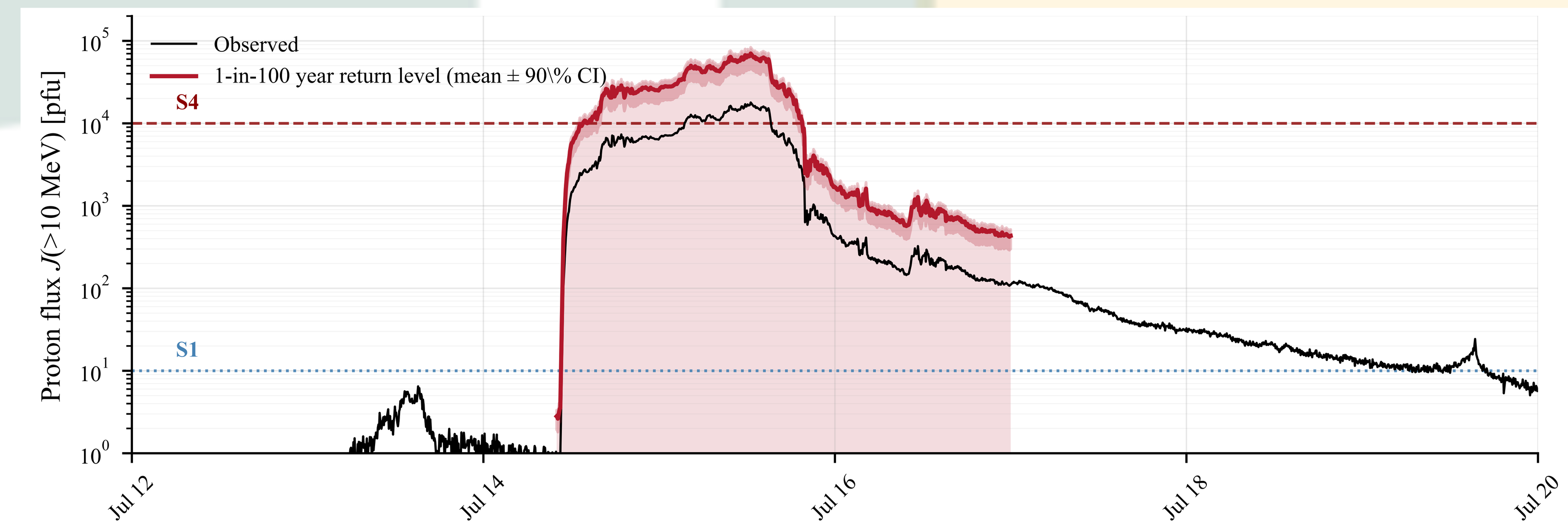

Figure 2. Bastille Day 2000 proton flux (black) and 1-in-100-year scaled return level (red). S1 and S4 are NOAA radiation storm thresholds.

RESULTS

- Storm-time magnetospheric compression **suppresses cutoff rigidity by 1–1.5 GV** at mid-latitudes.
- Mean particle access fraction reaches 0.40 at GEO and 0.36 at MEO, but only 0.07 at LEO.
- **322 satellites** (2.5%) are classified as Critical with failure probability above 10^{-2}, and another 321 fall into the Elevated category.
- Risk is concentrated in high-altitude LEO orbits above 1000 km in polar inclinations, along with HEO orbits.

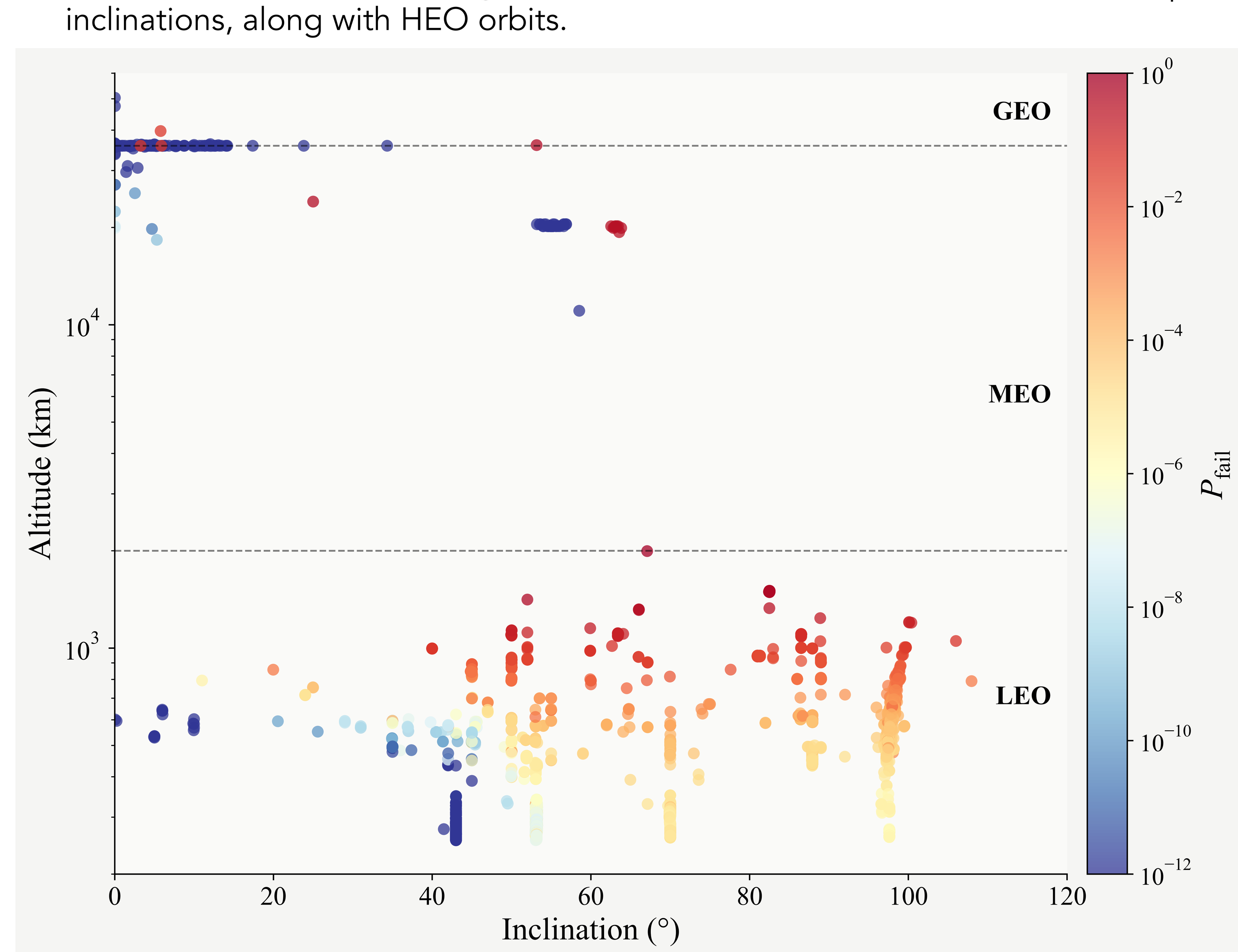

Figure 3. Failure probability across 12,860 US satellites by altitude and inclination. Critical and elevated risk concentrate in high-altitude LEO and HEO orbits.

RESULTS – CONT'D

- MEO and GEO assets show negligible failure probability under typical radiation-hardened design assumptions.
- Expected capital loss of **$5.9B ± $0.9B** against a fleet value of $318.8B
- Daily economic losses: **$130M (Case 1) → $410M (Case 2) → $1.7B (Case 3)**

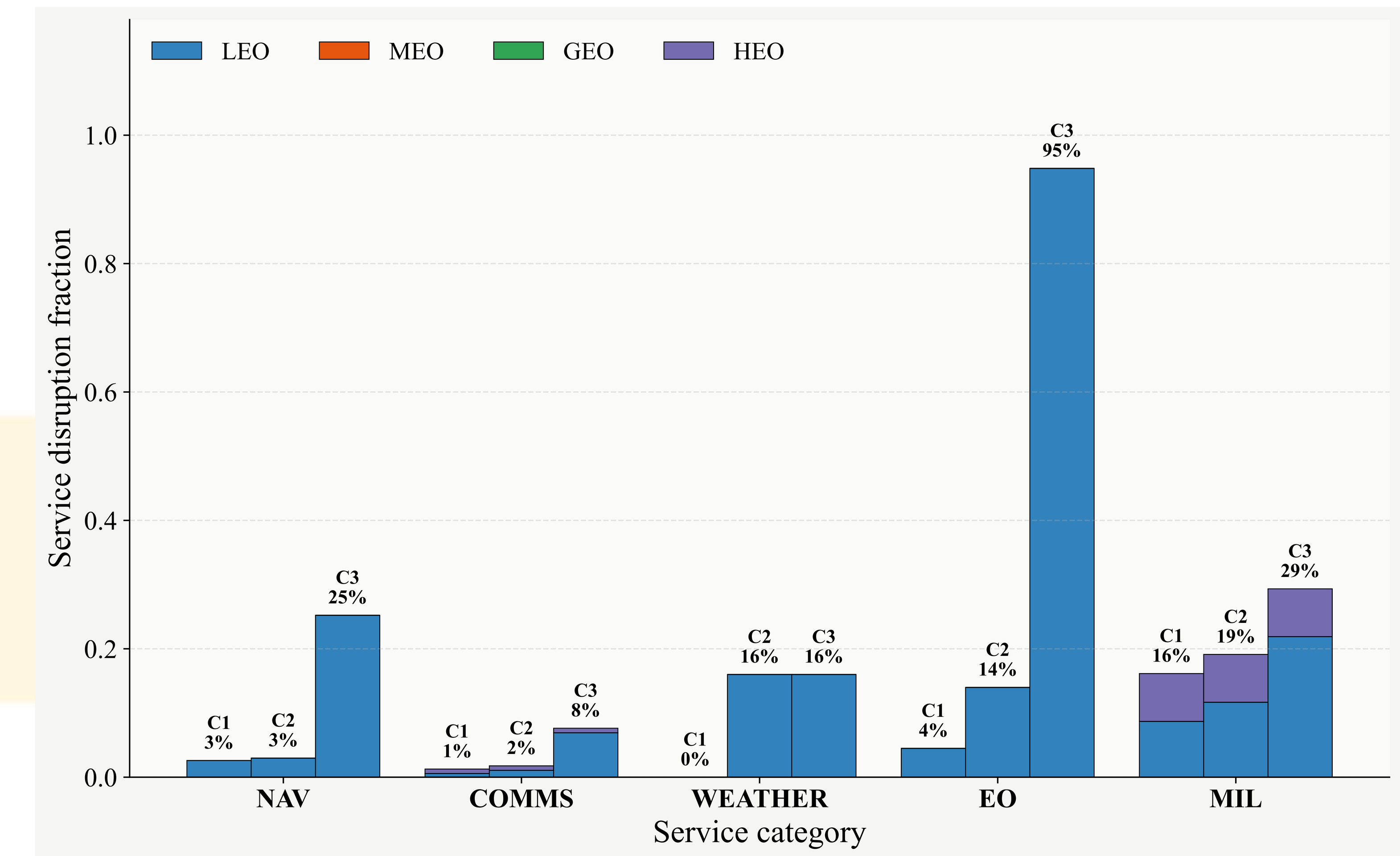

Figure 4. Service disruption by orbital regime across three failure scenarios. Earth observation reaches 95% disruption in the worst case.

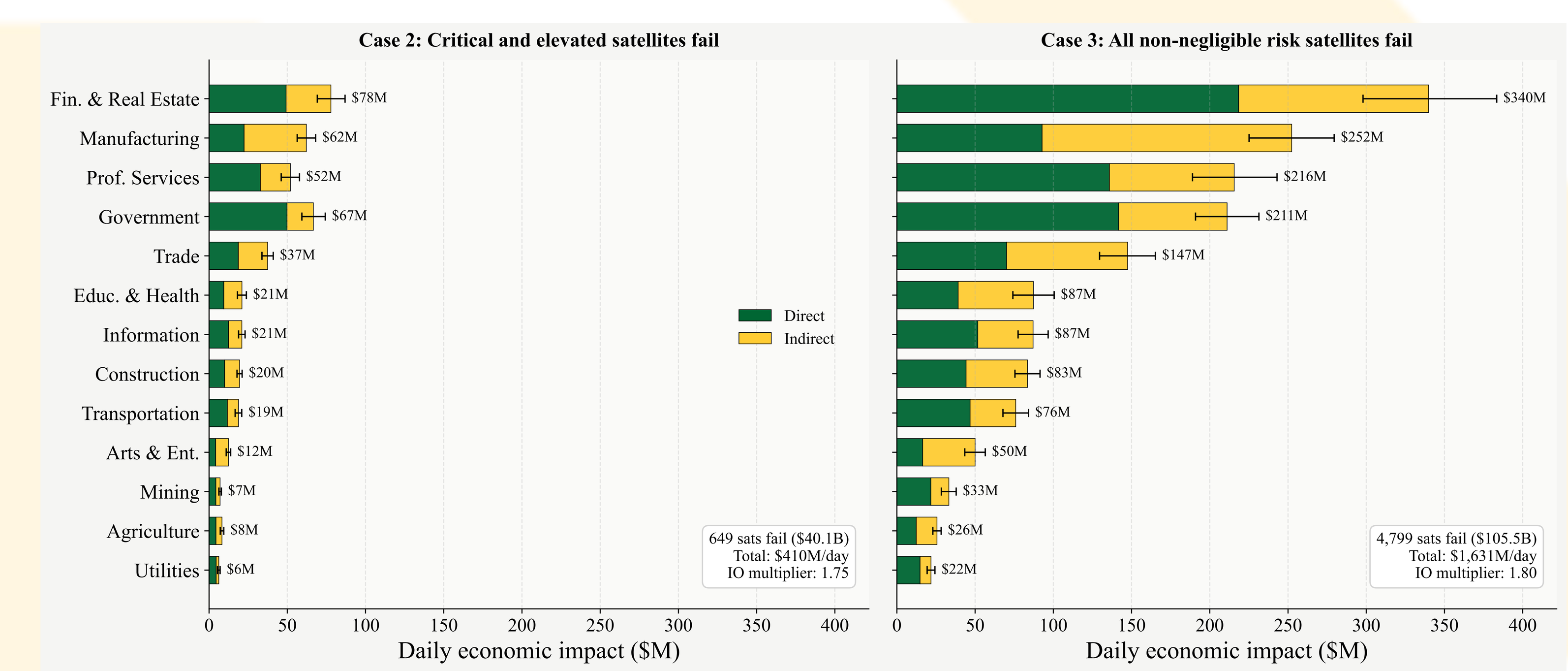

Figure 5. Sectoral daily economic impact under Case 2 and Case 3, decomposed into direct losses (green) and indirect supply-chain losses (gold).

DISCUSSION

GPS and commercial satellite communications are resilient. Radiation-hardened design and constellation redundancy provide effective protection against century-scale events. Approximately 643 satellites, those classified as Critical or Elevated risk, account for essentially all dose-induced failure risk in the US fleet. Targeted hardening of high-altitude LEO and HEO assets would eliminate most of this economic exposure. C-SWIM is the first physics-grounded, fleet-scale framework coupling SEP hazard, satellite vulnerability, and macroeconomic impact. **It directly advances Objectives 1 and 2 of the National Space Weather Strategy.**

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