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Uncertainty-Aware Spacecraft Guidance & Navigation Under Space Weather

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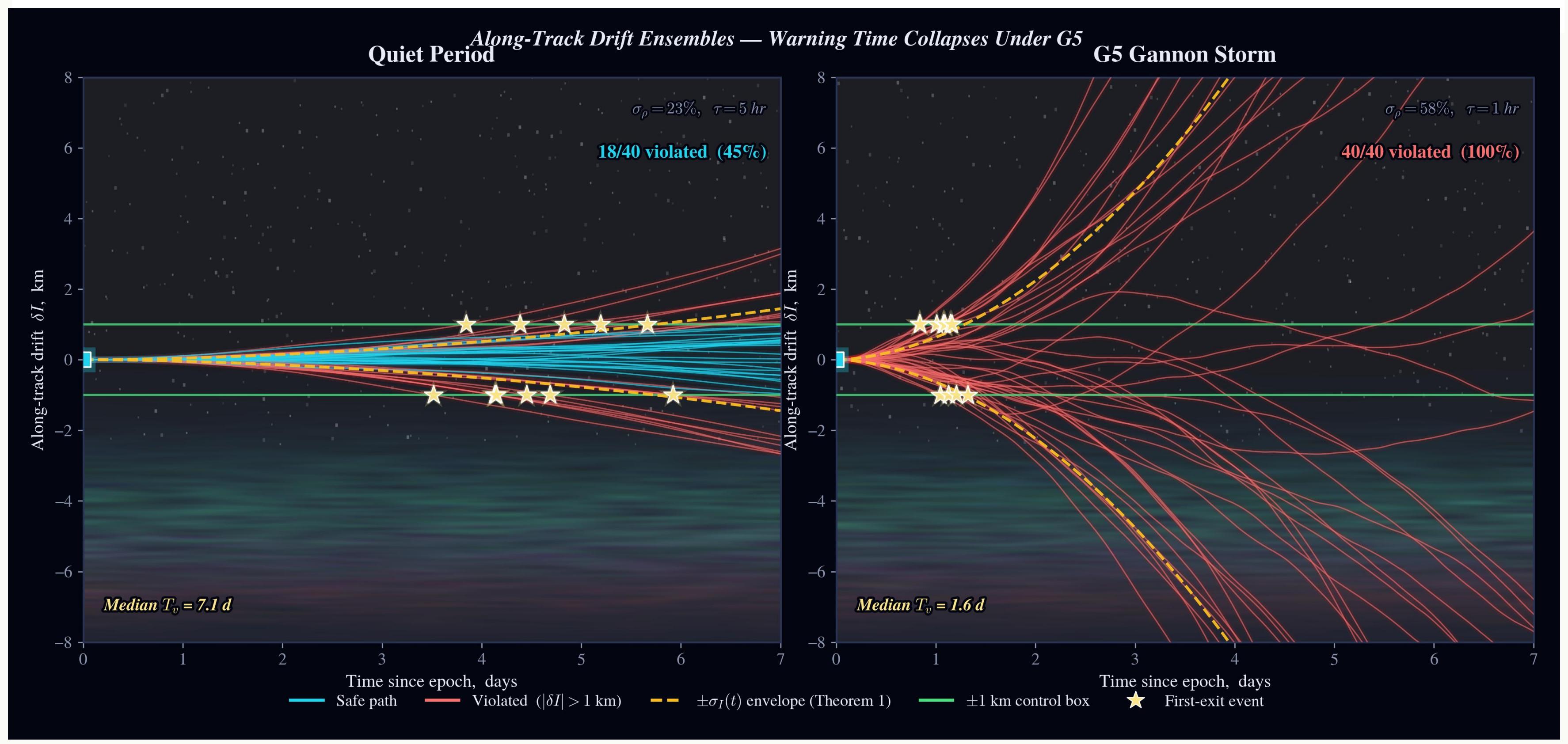
The Problem

Thermospheric density is the dominant error source in LEO orbit prediction. Empirical models disagree by 20–40% during quiet conditions, and densities enhance by factors of 2–5× within hours during geomagnetic storms. Current space-weather products deliver calibrated density uncertainty σρ — but the translation to operational decisions stops there. No closed-form expression exists in the open astrodynamics literature for the probability that a satellite violates its station-keeping tolerance by time t. Operators are left with two options: apply a blanket conservative margin or wait for post-event tracking data.

Warning Time Collapses Under Geomagnetic Storms

Ensemble of along-track drift trajectories δI(t) under quiet vs. G5 Gannon storm conditions, ±1 km station-keeping tolerance.

Each trajectory is a Monte Carlo realization of the along-track drift under calibrated density uncertainty. Green paths remain inside the ±1 km control box; red paths violate. Stars mark first-exit events. Under G5 conditions, 100% of trajectories violate by day 2, versus <5% under quiet conditions at the same epoch.


Along-Track Drift Ensembles — Warning Time Collapses Under G5

From Uncertainty to Decision

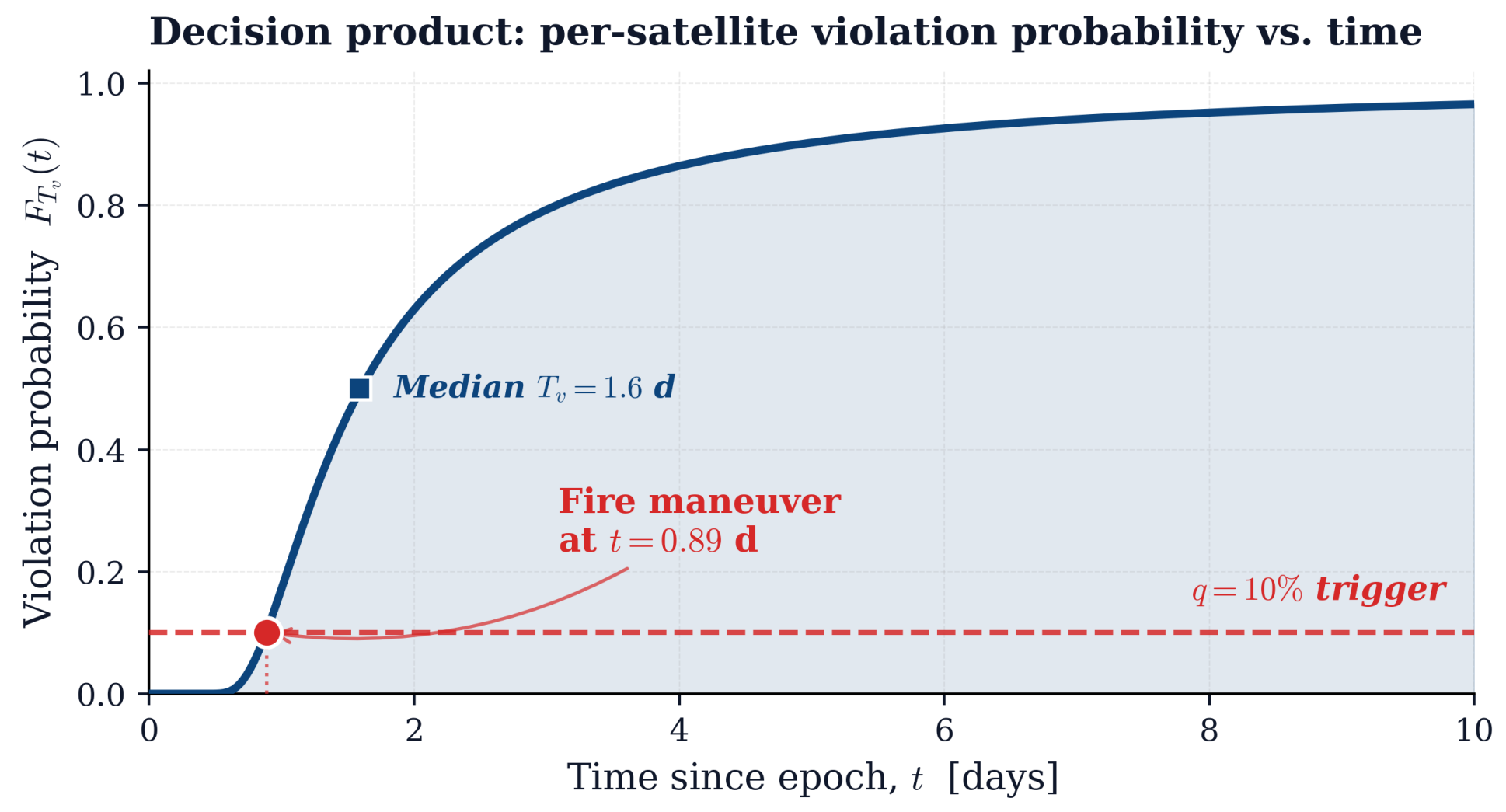
We derive a closed-form first-exit CDF that maps any calibrated density uncertainty forecast directly to a per-satellite maneuver-decision product

Theorem 1 — *First-exit CDF for Gaussian density uncertainty*

$$F_{T_v}(t) = 2\left[1 - \Phi\!\left(\frac{\Delta I_{\max}}{\sigma_I(t)}\right)\right] + \mathcal{R}(t)$$

$\mathcal{R}(t) < 4.7 \times 10^{-3}$ *(operationally negligible)*

Along-track drift $\delta I(t)$ is Gaussian at every epoch;
first-exit probability from the Gaussian tail.


Decision product: per-satellite violation probability vs. time

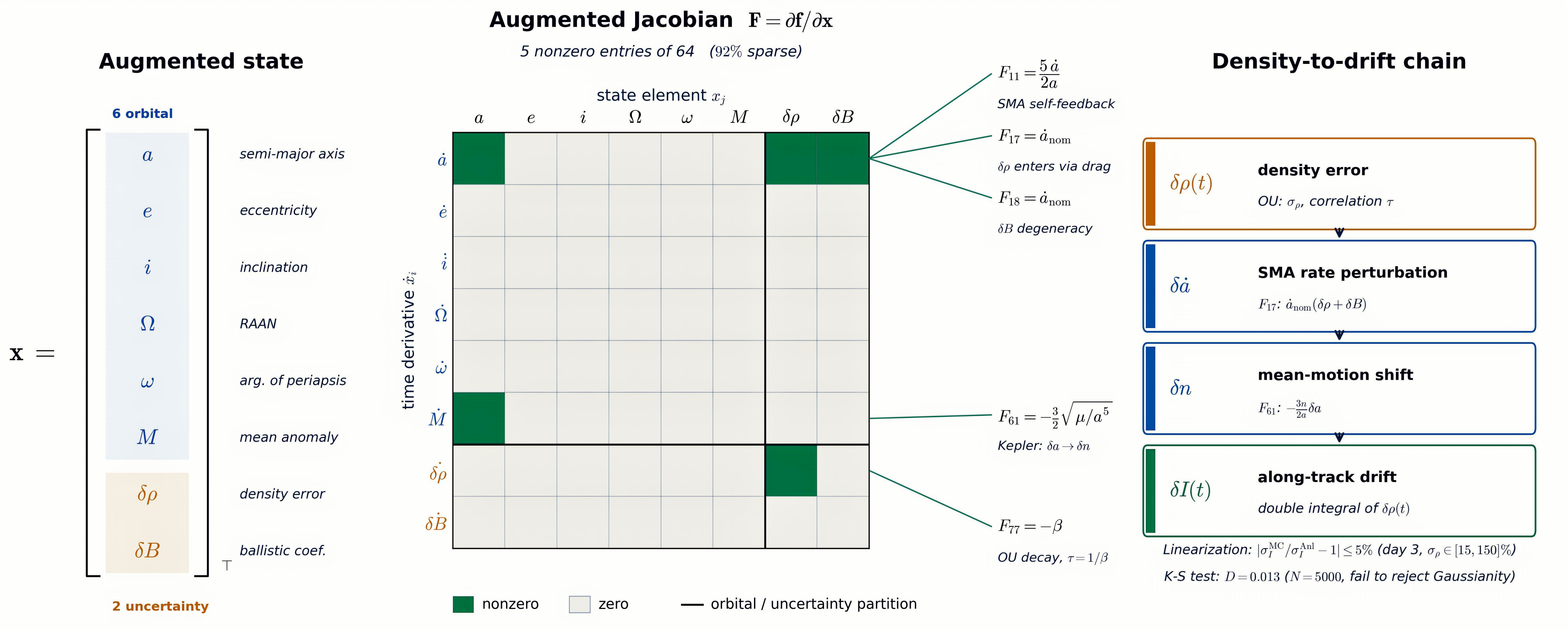
$50\ \mu$s
per satellite
closed-form CDF eval

$\sim 10^4 \times$
faster than Monte Carlo
10,000 sats in < 1 s

4 S/C
validated against
TLE + GPS truth

The Framework

Density and ballistic coefficient uncertainty propagate through drag-specialized Gauss Variational Equations to produce along-track covariance σI(t), which feeds the first-exit CDF.



$\delta\rho(t)$ **density error**
OU: σ_ρ, correlation τ

$\delta\dot{a}$ **SMA rate perturbation**
F_{17}: $\dot{a}_{\rm nom}(\delta\rho + \delta B)$

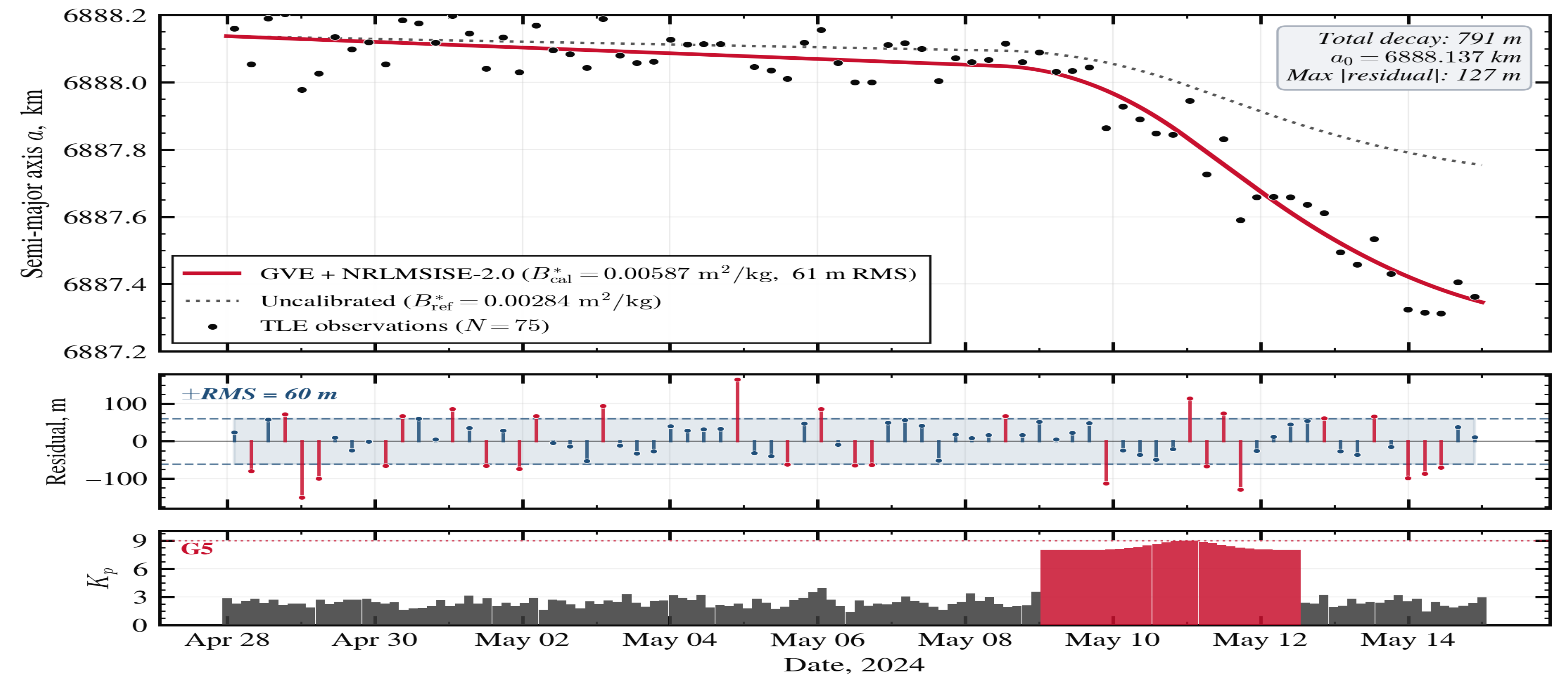
δn **mean-motion shift**
F_{61}: $-\frac{3n}{2a}\delta a$

$\delta I(t)$ **along-track drift**
double integral of $\delta\rho(t)$

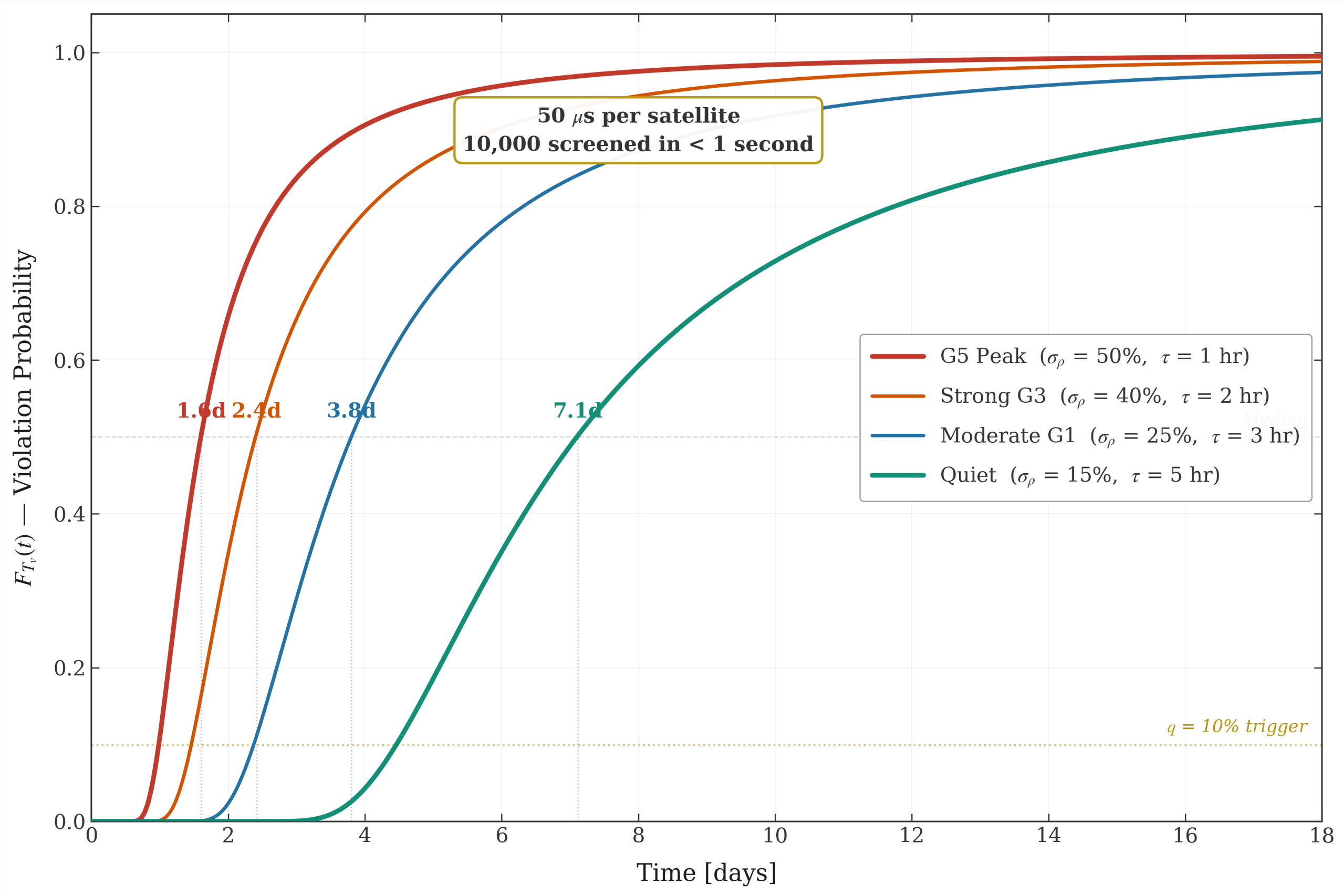
Linearization: $|\sigma_I^{\rm MC}/\sigma_I^{\rm Anl} - 1| \le 5\%$ (day 3, $\sigma_\rho \in [15, 150]\%$)
K-S test: $D = 0.013$ ($N = 5000$, fail to reject Gaussianity)

Real Orbit Fit

GVE propagator validated against KANOPUS-V 3 TLE data during May 2024 Gannon G5. Calibrated B* = 0.00587 m²/kg over 75 observations. 61 m RMS over 791 m of observed decay (7.7%).



First-exit CDF: theorem 1 across storm conditions

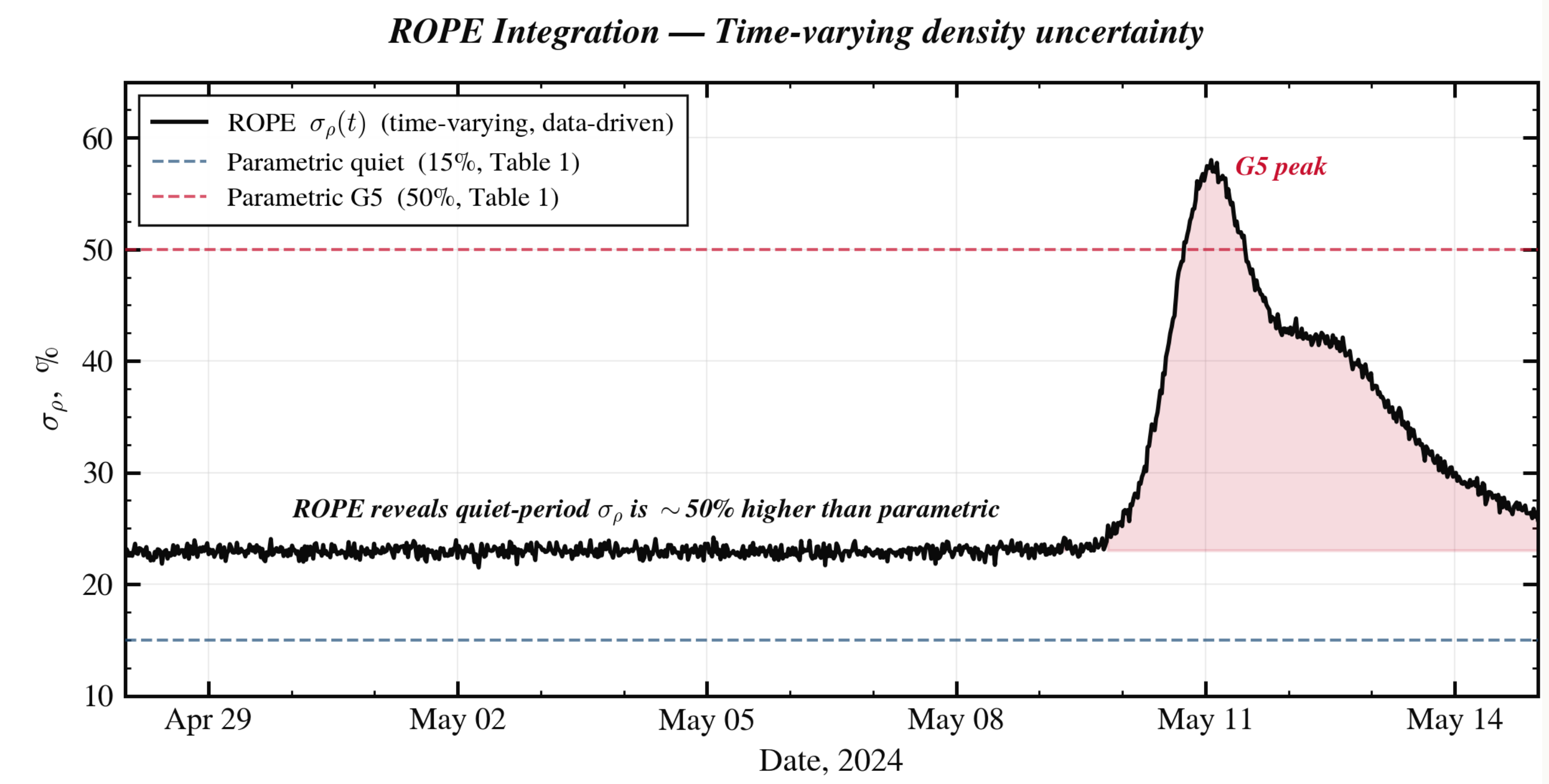


Median lead time degrades from 7.1 days (quiet) → 1.6 days (G5 peak) a 4.3× reduction. Scaling laws $T_v \propto \Delta I^{(1/2)}$ $T_v \propto \tau^{(-1/3)}$ confirmed to ±2%.

Toward ROPE Integration

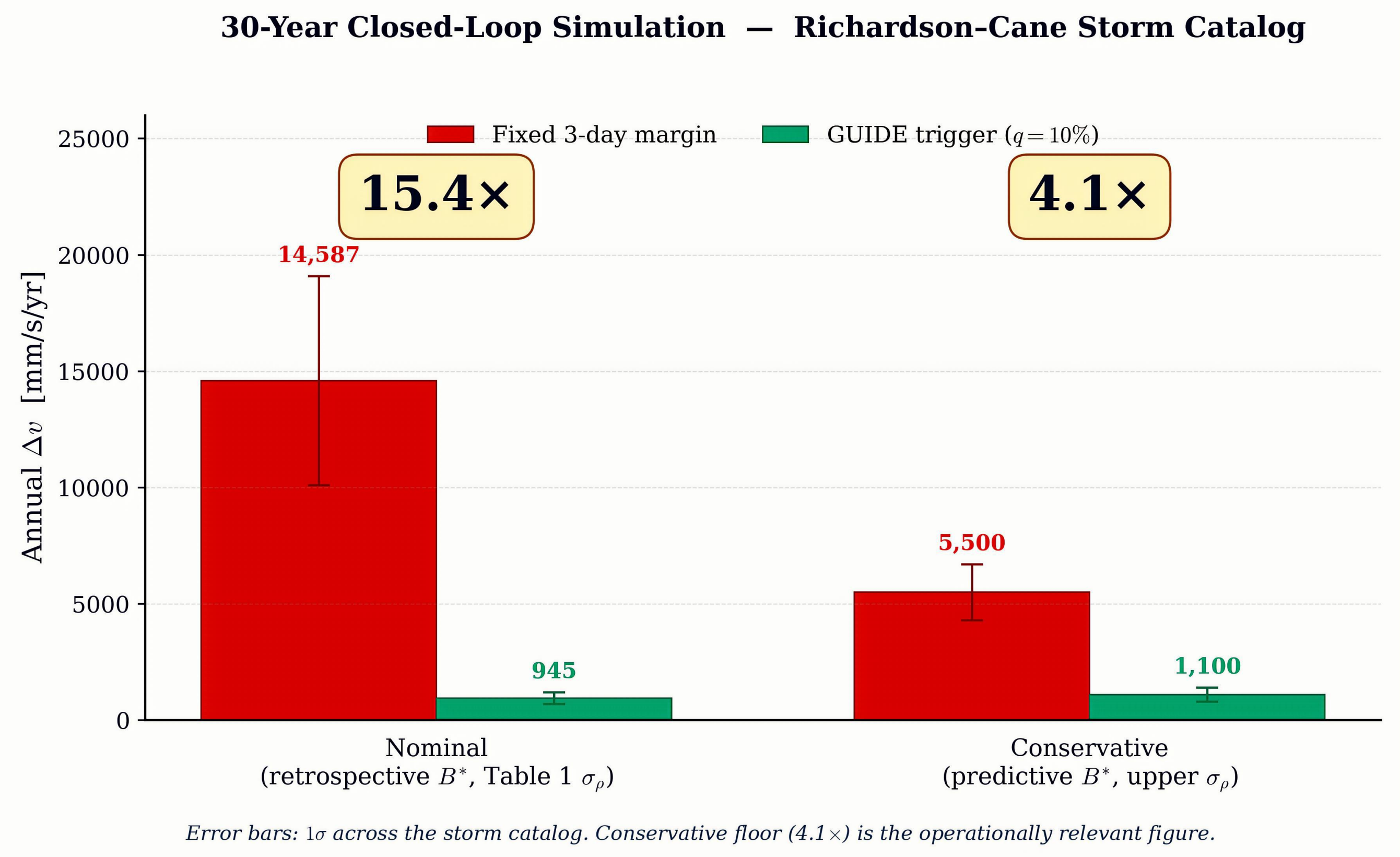
Time-varying σρ(t) from data-driven ensemble replaces static assumptions.

Static parameterizations systematically underestimate quiet-time station-keeping risk.


ROPE Integration — Time-varying density uncertainty

Operational Impact

GUIDE trigger (FTv > 10%) vs. fixed 3-day margin across 30 years of realistic space weather. Triggers deliver at least 4.1× fuel savings under worst-case calibration assumptions, rising to 15.4× under nominal conditions.


30-Year Closed-Loop Simulation — Richardson-Cane Storm Catalog

Error bars: 1σ across the storm catalog. Conservative floor (4.1×) is the operationally relevant figure.

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