EARTHQUAKES · RESEARCH REVIEW

Earthquake Forecasting: Alternative Precursors Explored

A graded survey of alternative earthquake-precursor research — LAIC, heliophysical coupling, deep-earth tectonic waves, and the statistics that separate signal from selection bias.

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> **Operational note — Blot Echo runtime (2026-02).** Carrington's in-app Blot Echo layer draws a single forecast zone from each slab-relative deep-focus earthquake, with each zone's intensity decaying on a 48-hour half-life; a qualifying shallow earthquake inside an active zone is shown as a confirmed-hit marker. It is an experimental research layer. Method details: `research/docs/methods/blot-echo/current-operational-model-2026-02.md`.

Scope & evidence classes. This report grades every claim it surveys: **ESTABLISHED** — replicated, broad peer-reviewed consensus; **CONTESTED** — real evidence, but disputed or mixed; **HYPOTHESIS** — a proposed mechanism with limited or no confirmation. It is a graded review of the published literature, **not a forecast, a prediction, or advice for emergency planning**. For official earthquake information, consult the USGS and your local civil authorities.

1. Introduction: The Epistemological Crisis in Seismology

The quest to predict earthquakes—specifically, the ability to deterministically specify the time, location, and magnitude of impending large shallow events—remains one of the most contentious and elusive challenges in the geosciences. For over a century, seismology has oscillated between fervent optimism, driven by new models or observational technologies, and deep pessimism, precipitated by the failure of those models to prevent catastrophic loss of life. **ESTABLISHED** The current official consensus, maintained by agencies such as the United States Geological Survey (USGS) and the Japan Meteorological Agency, is that reliable short-term *prediction* is not currently possible; under some theoretical frameworks it may be inherently unachievable because of the chaotic nature of rupture nucleation (U.S. Geological Survey, n.d.). Consequently the operational focus has shifted toward

Probabilistic Seismic Hazard Assessment (PSHA), Earthquake Early Warning, and—most relevant here—time-dependent *forecasting*.

This prevailing narrative of "impossibility" is challenged by a parallel stream of research at the intersection of geophysics, atmospheric science, heliophysics, and statistical physics. CONTESTED This body of work argues that the failure to predict may stem not only from inherent randomness in the crust but also from an overly narrow focus on mechanical seismic precursors such as foreshocks and crustal strain. Over the last two decades, and particularly with dedicated satellite missions like DEMETER, Swarm, and CSES, many studies have reported non-seismic anomalies in the lithosphere, atmosphere, and ionosphere before large earthquakes. The evidential status of those anomalies remains uneven: co-seismic coupling is well established, but *pre*-seismic diagnostic skill still depends heavily on retrospective filtering, source discrimination, and—rarely—prospective testing.

This report is a feasibility study of these alternative methodologies. It examines the Lithosphere-Atmosphere-Ionosphere Coupling (LAIC) model, the controversial correlations between space weather and seismicity, the historical "Blot Hypothesis" of deep-focus precursors, ground-based electromagnetic methods, and the statistical machinery used to validate any of them. The throughline is a single discipline: a candidate signal earns operational status only when it adds out-of-sample skill over the seismicity-rate and seasonal baselines that already exist—and, as the closing sections show, none has yet done so prospectively.

To evaluate feasibility rigorously, one must disentangle the terminology that confuses the public and policymakers. ESTABLISHED "Earthquake prediction" is classically defined as a statement specifying the time, location, and magnitude of a future event with narrow uncertainties (e.g., "a magnitude 7.0 will strike Tokyo on Friday"). This strict definition has set a bar that no current technology can clear. "Earthquake forecasting," by contrast, is a probabilistic assessment—akin to modern meteorology—defining an increased likelihood of an event over a specific time window and spatial area (e.g., "a 60% probability of $M > 6.0$ in the Nankai Trough within 30 days").

The feasibility explored here concerns the latter: moving from the multi-decadal probabilities of PSHA maps—useful for building codes but useless for evacuation—to time-dependent forecasts on the scale of days to weeks. That intermediate-term capability, if achieved, would be a genuine advance in disaster risk reduction.

The pessimism of modern mainstream seismology is rooted in the "dilatancy-diffusion" era of the 1970s, when researchers believed volume changes in rock before failure would inevitably produce detectable precursors such as changes in the Vp/Vs ratio and groundwater fluctuations. ESTABLISHED The apparent success of the 1975 Haicheng prediction, based on foreshocks and groundwater anomalies, seemed to validate the approach; the failure to anticipate the devastating 1976 Tangshan earthquake shattered that confidence.

By the 1990s the theoretical landscape shifted toward Self-Organized Criticality (SOC). **CONTESTED** In the SOC view the crust sits perpetually near a critical state where any small perturbation can trigger rupture, and the final size of an earthquake is set by the heterogeneous stress field encountered as the rupture propagates, not by the nucleation. If that model holds strictly, a magnitude 8 begins exactly like a magnitude 1, and magnitude-scaling precursors are physically impossible—the strong-skeptic position later argued in *Science* by Geller et al. (1997).

HYPOTHESIS Yet this view is not universal. The "critical point" hypothesis holds that while the exact moment of failure is stochastic, the approach of a large system toward instability can be marked by accelerated moment release and the synchronization of diverse physical fields. It is within this framework—not against it—that non-seismic precursors find their physical justification. The remainder of this report weighs the evidence for each.

2. The Lithosphere-Atmosphere-Ionosphere Coupling (LAIC) Model

HYPOTHESIS The LAIC model is the most comprehensive physical framework attempting to explain how a subterranean process could generate signals in the upper atmosphere and ionosphere. Unlike purely statistical correlations, LAIC proposes a sequential cause-and-effect chain transporting energy from the ground to geospace, uniting thermal hotspots, electromagnetic emissions, and ionospheric irregularities under one mechanism (Picozza, Conti & Sotgiu 2021). Its physical plausibility is real; its *operational* reliability is what the rest of this section interrogates.

HYPOTHESIS The central engine of LAIC is the ionization of the lower atmosphere over the preparation zone. As stress accumulates, micro-fracturing (dilatancy) increases crustal permeability, opening pathways for gases—CO_2, CH_4, H_2, and critically the radioactive noble gas Radon-222—to escape to the surface. Radon-222 (half-life 3.8 days) is a potent ionizer through alpha decay; a pulse released from a stressed fault can generate large numbers of air ions in the planetary boundary layer.

This initial ionization is proposed to trigger a cascade:

- new air ions attach to water molecules, forming heavy cluster ions.
- condensation onto ions is exothermic, predicted to appear as increased Outgoing Longwave Radiation (OLR) and Surface Latent Heat Flux over the epicentral area—a candidate physical cause for reported "thermal anomalies."
- a dense cloud of heavy cluster ions alters the air column's conductivity.
- the Earth behaves as a spherical capacitor with a near-surface field of ~100–120 V/m; the local conductivity change disrupts this circuit.

through electric-field penetration, the disturbance is proposed to propagate into the E and F layers, altering electron density and Total Electron Content (TEC). Because the ionosphere is a magnetized plasma, such irregularities drift along field lines, so a satellite anomaly may be shifted toward the magnetic equator relative to the epicenter.

CONTESTED The thermal anomaly is one of LAIC's most testable predictions. Historically, thermal-infrared anomalies before earthquakes were dismissed as coincidental weather; LAIC supplies a specific physical cause (latent heat of ion hydration). Retrospective analyses of major events—e.g., the 2008 Wenchuan and 2015 Nepal earthquakes—have reported localized OLR increases of roughly 20–100 W/m^2 appearing 2–14 days before the mainshock, often stationary relative to the fault rather than migrating like weather systems (Picozza, Conti & Sotgiu 2021).

The reliability of thermal precursors is complicated by competing heat sources—anthropogenic emissions, seasonal variation, soil moisture—so background-subtraction algorithms are required to isolate any transient signal. Higher-resolution sensors sharpen case studies without resolving causation: ECOSTRESS thermal-monitoring time series over the restless Campi Flegrei caldera illustrate how better sensors improve anomaly detection without, on their own, establishing a seismic cause (Piscini & Fidani 2025). CONTESTED The strongest recent geochemical case is a helium-isotope anomaly recorded in groundwater before the 2024 Noto Peninsula earthquake by a pre-existing monitoring network—valuable precisely because the instrumentation predated the event, though still a single case rather than a validated rule (Kagoshima et al. 2025).

CONTESTED The upper branch of LAIC—ionospheric perturbation—has been the focus of dedicated space missions, because the ionosphere can amplify weak ground-level electric fields through plasma instabilities. The evidence here is a genuine split between positive case studies and negative large-N tests.

The French DEMETER satellite was the first spacecraft designed for seismo-ionospheric coupling, measuring ULF/ELF/VLF waves and plasma parameters in low Earth orbit. CONTESTED A statistical analysis of the whole dataset found a weak but significant decrease in ULF wave intensity and ion density over earthquake zones roughly four hours before the shock; however, the signal-to-noise ratio was too low to forecast individual events, and the four-hour timing sits awkwardly against LAIC's "days to weeks" prediction.

The China Seismo-Electromagnetic Satellite (CSES / Zhangheng-1), launched in 2018, carries more sensitive instrumentation. CONTESTED Retrospective analyses report electron-density and electron-temperature anomalies exceeding background thresholds 1–5 days before the February 2023 Turkey

M7.8/M7.5 doublet, and synchronous plasma-parameter enhancements before the January 2024 Noto Peninsula M7.6 earthquake. These are retrospective, single-event observations: persuasive individually, but each selected after the earthquake was known.

ESA's three-satellite Swarm mission, primarily geomagnetic, has been used to cross-validate CSES findings. **CONTESTED** Machine-learning analyses of Swarm data have reported magnetic anomalies preceding events such as the 2017 Mexico and 2020 Croatia earthquakes, sometimes months in advance—an intriguing but unconfirmed long-preparation signature. A large 2014–2024 study correlating Swarm magnetic-field and TEC data against M4+ earthquakes extends this record while underscoring that most reported associations remain weak and retrospective (Semlali et al. 2025).

CONTESTED The decisive tests are the large-N ones, and they lean negative. A global analysis spanning 129 stations and 57.8 million TEC measurements found

(Cullen et al. 2024). Apparent single-station anomalies are largely reproduced by randomized surrogate catalogues once solar and geomagnetic effects are removed (Ikuta & Oba 2022), and at least one widely cited TEC enhancement has been shown to be an artifact of the analysis method rather than a seismic signal (Eisenbeis & Occhipinti 2021). Positive case studies persist—e.g., a reported TEC precursor associated with the 2024 Noto earthquake (Nayak et al. 2024)—but the contrast between abundant positive case studies and negative population tests is the defining tension of the ionospheric branch.

ESTABLISHED Even granting the physics, operational LAIC forecasting faces formidable hurdles:

The ionosphere is dominated by solar activity and lower-atmosphere weather. A geomagnetic storm can mask any subtle pre-seismic signal entirely; separating a "seismic" perturbation from a "solar" one demands multi-parameter analysis and real-time space-weather indices (Dst, Kp). During a storm, seismo-ionospheric forecasting reliability falls to near zero.

Field-line geometry can map a ground-level electric field to the ionosphere at a different latitude—or the opposite hemisphere—complicating any attempt to trace an observed anomaly back to a specific epicenter.

Ionospheric anomalies also occur in seismically quiet periods. A high False Alarm Ratio is the central barrier to public use: a system that warns on every anomaly quickly loses trust.

The conservative reading, shared by the field's own critical reviews, is that TEC, TID, radon, thermal, and EM signals belong in research and diagnostic contexts—shown with provenance and contamination flags and benchmarked against seismic baselines—rather than as standalone warnings (Picozza, Conti & Sotgiu 2021).

3. The Heliophysical Connection: Space Weather and Earthquakes

CONTESTED The proposition that solar activity—flares, coronal mass ejections, the solar wind—could trigger earthquakes is among the most controversial hypotheses in geophysics. **ESTABLISHED** The USGS position is blunt: "it has never been demonstrated that there is a causal relationship between space weather and earthquakes" (U.S. Geological Survey, n.d.). The skepticism is grounded in energy scales—solar-terrestrial stresses are orders of magnitude smaller than tectonic stresses. The counter-argument is that, in a crust poised near criticality, even a minute, sharply-timed perturbation might tip a fault already at failure.

HYPOTHESIS The leading proposed mechanism is the reverse piezoelectric effect. Quartz, abundant in continental crust, deforms when an electric field is applied to it. The triggering chain runs: a solar event compresses the magnetosphere → a geomagnetic storm produces rapid magnetic-field fluctuations → Faraday induction drives geomagnetically induced currents and telluric electric fields through the crust → in quartz-rich fault zones those fields impose a small mechanical strain. The strain is minute (estimated 10^{-8}–10^{-7} in fractional terms); advocates argue that for a fault already at the breaking point, a sudden electromagnetic "jerk" could nonetheless overcome static friction.

CONTESTED Large-scale statistical studies have tried to move this beyond speculation, and the picture is genuinely mixed. A 20-year analysis pairing SOHO solar data with the ISC-GEM catalogue reported a significant correlation between solar-proton density and large ($M > 5.6$) earthquakes at a ~24-hour lag, with a chance probability quoted below 10^{-5} (Marchitelli et al. 2020).

That correlation has not gone unchallenged—and the challenges are the stronger work. Re-analysing 333 $M \geq 7$ events (2000–2022), Akhoondzadeh & De Santis (2022) found solar/geomagnetic anomalies in the day before roughly a third of events—but found the *same* rate in 100 synthetic surrogate catalogues, concluding the apparent link is statistically indistinguishable from chance. An interacting-point-process study placed any genuine proton-flux contribution at an upper bound near 28% of seismic intensity—directional but modest (Lyubushin & Rodionov 2025). And the broadest canonical test of solar-terrestrial triggering found the effect to be statistically insignificant across the global catalogue (Love & Thomas 2013). Other surveys keep the door ajar to a weak space-weather influence under quiet conditions (Sorokin & Novikov 2024), but the weight of rigorous evidence is that a strong, exploitable space-weather trigger has not been demonstrated.

ESTABLISHED The primary quantitative critique is decisive on its own terms. Stress changes from geomagnetically induced currents are estimated in Pascals; the stress drop in an earthquake is in MegaPascals—six orders of magnitude larger. The standard reductio is the tides: solid-Earth and ocean tides impose kilopascal-scale stresses twice daily, yet their measurable correlation with seismicity is small. If far larger tidal stresses barely register, far smaller space-weather stresses should register less.

HYPOTHESIS Laboratory work offers a narrow rejoinder: spring-block experiments suggest that the *nature* of a perturbation can matter as much as its magnitude, with sharp electromagnetic pulses able to trigger slip in faults held at 98–99% of failure stress, apparently by momentarily reducing friction rather than by adding static stress. This keeps the hypothesis alive in principle, but the gap between a benchtop fault at the edge of failure and a heterogeneous crustal fault remains the unbridged problem.

4. Deep Earth Processes: The ”Blot” Hypothesis and Tectonic Waves

CONTESTED A distinct strand concerns the predictive relationship between deep-focus earthquakes (depth > 300 km) and subsequent shallow events—the historical "Blot Hypothesis" of energy migrating upward through a subducting slab.

In the 1960s–70s the French geophysicist Claude Blot, working on Pacific subduction zones, observed apparent regularities in seismic sequences and proposed that a deep "energy phenomenon" migrates upward over months to a year before triggering shallow earthquakes and eruptions, with empirical time-delay formulas. HYPOTHESIS Blot's rigid, deterministic formulas were largely rejected as lacking a mechanism. ESTABLISHED Stress transfer itself is mainstream: a large deep-focus event alters the stress field throughout the slab, and viscoelastic relaxation can redistribute stress over weeks to years. CONTESTED Whether that coupling yields a usable deep-to-shallow *precursor* on Blot's timescales is far less settled—the broad association is plausible and loosely consistent with his observed delays, but the deterministic precision Blot claimed is considered overstated and the predictive skill has not been independently established.

HYPOTHESIS A modern, highly theoretical evolution is the "Omega-Theory" of Jure Žalohar, commercialized by Quantectum. Drawing on Cosserat (micropolar) continuum mechanics, it holds that earthquakes are synchronized by global "tectonic waves" that propagate slowly through the crust, with events occurring where these waves constructively interfere into "synchronization clouds."

This sits on the fringe of mainstream science. The "tectonic waves" central to the theory have not been detected by standard geodetic networks (GPS/InSAR) at the amplitudes required to trigger faults directly. As of 2026 there is of the Quantectum/Omega-Theory forecasts, and no Quantectum model is registered with the Collaboratory for the Study of Earthquake Predictability (CSEP), which requires forecasts to be locked in advance of the events they target; the reported skill rests on self-assessment against the company's own held-out data, without a third-party reference null.

ESTABLISHED In the laboratory, rigorous support for time-to-failure prediction has emerged from rock mechanics. Machine-learning models trained on the continuous acoustic-emission "noise" of a sample can predict the timing of stick-slip "lab quakes" with high accuracy, detecting subtle shifts in the variance and amplitude of the signal long before failure. HYPOTHESIS This is a genuine proof-of-concept that a preparation phase is *not* silent and carries information about impending failure. The open challenge—unsolved—is detecting the crustal-scale equivalent of those acoustic emissions (micro-seismicity or electromagnetic noise) in the field, where the signal is far weaker and the noise far larger.

5. Electromagnetic Precursors: The Ground-Based Perspective

CONTESTED Where satellites trade coverage for revisit time, ground-based electromagnetic monitoring offers continuous, high-resolution data—and a correspondingly long, unresolved controversy.

Ultra-low-frequency (0.01–10 Hz) magnetic anomalies are among the most-cited ground precursors. CONTESTED The famous case is the 1989 Loma Prieta (M6.9) earthquake: a Stanford magnetometer at Corralitos reportedly recorded a large rise in ULF activity two weeks before, spiking hours before the mainshock (Fraser-Smith et al. 1990). That observation launched the field of seismo-electromagnetics. It has also not survived scrutiny intact: a later re-analysis attributed the Corralitos signal largely to instrumental and external sources rather than a tectonic precursor (Thomas, Love & Johnston 2009). Broader statistical reviews of observatory ULF data report correlations modestly better than chance for M > 5 events within ~100 km, with anomalies typically 1–2 weeks before—suggestive, but well short of operational reliability, and entangled with the difficulty of removing solar-terrestrial noise.

CONTESTED The most persistent ground-based prediction effort is the VAN method (Varotsos, Alexopoulos, Nomicos) in Greece, which monitors "seismic electric signals"—transient geoelectric-potential changes—via dipole networks, and claims numerous successful predictions over three decades. The debate has run for more than thirty years: critics argue the signals are indistinguishable from industrial electrical noise and that the "successes" exploit broad time-and-space windows; supporters argue the chance probability of the hits is vanishingly small. VAN remains one of the few long-running operational prediction attempts, and one of the least resolved.

6. Operational Forecasting and Statistical Validation

ESTABLISHED The transition from hypothesis to operation requires rigorous validation. It is not enough to show a precursor existed before *one* earthquake; one must show it reliably appears before *most* of them and—crucially—stays quiet when no earthquake follows.

The standard tool for evaluating a prediction algorithm is the , which plots the miss rate (earthquakes that occurred with no warning) against the fraction of time under alarm.

- falls on the diagonal: alarm 50% of the time and you catch ~50% of events by chance.
- must fall well below the diagonal—catching a high fraction of events while keeping alarm time low.

CONTESTED Studies of ULF, ionospheric, and synchronization-based precursors typically land "better than random" (probability gains of ~1.5–2.0), confirming the signals carry *some* physical information. **ESTABLISHED** But performance plateaus: catching 80% of events might require being on alert 30–40% of the time. For a city, four months a year of "high alert" is operational paralysis—the false-alarm problem is what keeps these methods out of public evacuation decisions.

ESTABLISHED Recognizing that single precursors are insufficient, the Global Earthquake Forecasting System project (2015–2018), funded largely by the reinsurance industry, attempted to integrate ground signals (radon, groundwater, ULF) and space signals (ionosphere, thermal) into unified, time-dependent probability maps. Its conclusion was sobering: no single signal was robust enough for reliable operational prediction, and multi-parameter observation must be paired with rigorous statistical testing rather than simple signal stacking.

It is worth being precise about how that effort ended. The GEFS organizers' own synthesis concluded that most non-seismic precursor studies, taken individually, do not provide strong enough evidence, and that a systematic search of the DEMETER archive did not reveal a robust precursory pattern (Sornette, Ouillon, Mignan & Freund 2021). No operational successor to GEFS exists; the most ambitious private effort, QuakeFinder, ended data collection in 2023. **ESTABLISHED** What actually became operational was not precursor-based at all—it was seismicity-rate forecasting. Operational Earthquake Forecasting built on Epidemic-Type Aftershock Sequence (ETAS) models is now the expert first choice in Italy, New Zealand, and the United States (Mizrahi et al. 2024, *Reviews of Geophysics*) and has been validated over a decade of prospective use. This is the bar everything above must clear: a non-seismic precursor is useful only if it adds out-of-sample skill *on top of* a seismicity-rate baseline, prospectively—a test the field has not yet passed.

7. Synthesis and Future Outlook

ESTABLISHED The feasibility of forecasting large shallow earthquakes is not a binary "possible/impossible." It is a spectrum of probability gain, and the honest position is that the gain available from non-seismic precursors today is small, fragile, and unproven prospectively.

HYPOTHESIS The most defensible path forward is an evidence-gated ensemble rather than a deterministic precursor stack. No single layer is clean; each has false positives, false negatives, and contamination pathways. A useful system asks, for every layer, whether it adds skill *after* the strongest baselines are already in hand:

- — ETAS, EEPAS, foreshock clustering, geodetic strain, and catalogue history define the benchmark every alternative must beat. ESTABLISHED
- — TEC/TID, radon, thermal, hydrochemical, Swarm, CSES, and ground EM can supply diagnostic context *if* their contamination controls are explicit. CONTESTED
- — Blot-style deep-earthquake signals can remain visible where they are measured and backtested, but deterministic migration claims should not be promoted without independent validation. HYPOTHESIS

A signal graduates from "research context" to "forecast method" only if it improves prospective or pseudo-prospective scoring against clear baselines, keeps false-alarm cost tolerable, and preserves its skill after correlated inputs are ablated. That is a high bar, and it is the right one.

CONTESTED The future of the field lies in larger datasets, careful baselines, and machine learning. New instrumentation keeps arriving: into a Sun-synchronous orbit phased 180° from CSES-01, roughly halving the constellation's global revisit time to ~2.5 days and adding an ionospheric photometer and a combined vector-plus-scalar magnetometer; its seismic-precursor results are not yet published.

ESTABLISHED That optimism must be tempered by how machine learning has actually performed on real catalogues. In a controlled benchmark, at earthquake forecasting (Stockman, Lawson & Werner 2024, EarthquakeNPP). A cross-disciplinary review found that a large share of AI–earthquake studies report no baseline comparison, with many high-accuracy claims traceable to data leakage, and concluded there is still no indispensable correlation between earthquakes and the ionosphere (Zhang, Wen, Sornette & Zhan 2025). The failure mode is concrete: in 2026 a *Scientific Reports* paper claiming high machine-learning prediction accuracy for Los Angeles was because its data were split without respecting time order, inflating the reported accuracy (retraction note, 2026). The promise of AI is real, but so is the discipline it demands: chronological validation, an honest baseline, and prospective rather than retrospective testing.

CONTESTED The field's current state shows clearly on a single large event. Before the 28 March 2025 Mw 7.7 Myanmar earthquake, one study reported a total-electron-content change beginning about 36 minutes before the mainshock, scaling with magnitude roughly as prior events would predict (Heki &

Zhan 2026, *Geophysical Journal International*). Yet the event occurred during the recovery phase of a geomagnetic storm, and an independent analysis could not rule out that the pre-event ionospheric signal was storm-recovery rather than seismic (Obasanjo et al. 2026). Two lessons follow. First, a 36-minute lead—even if entirely real—is not an evacuation window. Second, the same event produced both a precursor claim and its confounder. That is the field in miniature.

ESTABLISHED The official position on deterministic earthquake prediction has not materially changed: exact short-term prediction remains unsupported. What is evolving is the operational *forecasting* discipline—time-dependent probabilities, prospective testing, and transparent communication of uncertainty. Alternative precursors remain scientifically important because they may describe real lithosphere-atmosphere-ionosphere coupling, but their current role is hypothesis generation and diagnostic context, not warning. A forecast should come from validated probability gain over an honest baseline, never from the presence of an anomaly alone.

Limitations and Open Questions

ESTABLISHED This report is a literature review, and it inherits the literature's limitations:

Positive case studies are far easier to publish than null results, and most reported precursors are identified *after* the earthquake is known. The large-N tests that correct for this lean negative (Cullen et al. 2024; Akhoondzadeh & De Santis 2022).

Several mechanisms (radon ionization, reverse piezoelectricity, stress transfer) are physically plausible but produce signals near or below the noise floor of current instruments and amid strong solar, atmospheric, and anthropogenic confounders.

No proposed space-weather mechanism closes the six-order-of-magnitude gap between induced stresses and seismic stress drops; the strongest defense is qualitative (timing/criticality), not quantitative.

Almost no non-seismic precursor has been evaluated in a locked, pre-registered, prospective framework against a seismicity-rate baseline. Until that is routine, "better than random" in retrospect should not be read as operational skill.

Whether CSES-02's improved revisit and instrumentation yields a *prospectively* testable ionospheric signal; whether geochemical networks (e.g., helium-isotope monitoring) deliver repeatable, pre-instrumented cases; and whether leakage-safe machine learning can extract a signal that genuinely beats ETAS.

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