

A Falsifiable Stochastic–Subgrid Framework for Intermittency-Driven Coronal Heating: Variance–Gamma Nanoflares, Self-Consistent Braiding, and Two-Mechanism Complementarity

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The solar corona is heated to $\sim 10^6$ K over a chromosphere two orders of magnitude cooler, by mechanisms that are intrinsically intermittent and multi-scale: impulsive nanoflares from magnetic reconnection and the turbulent dissipation of Alfvén waves. Resolving the microphysics (reconnection at current sheets, wave cascades) over the hours-to-days evolution of a coronal loop imposes a computational barrier analogous to the Courant barrier in turbulence. We present a stochastic–subgrid framework that advances the loop energetics on macroscopic time steps while injecting the unresolved, intermittent heating as samples from a variance–gamma (VG) Lévy process, with a single intermittency parameter ν controlling the rare, fat-tailed heating bursts. The non-monotonic optically-thin radiative loss makes the loop thermally bistable, so a cool and a hot (coronal) branch coexist; crossing to the hot branch is the analogue of a threshold “ignition.” We show that with the same mean heating, steady (Gaussian) heating cannot ignite the corona whereas VG intermittency does (ignition probability rising from 0% to $\sim 80\%$ with ν): *intermittency is a prerequisite for coronal heating*. Extending the model to a one-dimensional loop with field-aligned conduction and chromospheric evaporation, and then deriving the heating rate and the intermittency *self-consistently* from a single magnetic-braiding profile $\Theta(x)$, we find that the corona lights up where braiding is high, with the active-region core ignited by mean heating (intermittency-independent) and the periphery ignited only by intermittency. Unifying nanoflares (DC) and Alfvén-wave turbulence (AC) as two VG sources reproduces the observed thermal structure: waves supply a ~ 1 MK floor everywhere while nanoflares boost active regions to ~ 2 – 3 MK, a spatial complementarity with distinct intermittency signatures. We compile seven predictions and present a verification methodology tied to existing instruments (SDO, Solar Orbiter, Hinode, DKIST), including decision tables that fix in advance which measured outcome refutes or robustifies the framework. A central, honest finding emerges: nanoflare heating tails are power-law with index $\alpha < 3$ (divergent variance), exceeding the finite-variance VG closure and calling for a stable-Lévy generalization, whereas wave heating fits VG – the heating mechanism itself selects the closure.

Keywords: Sun: corona — Sun: magnetic fields — magnetohydrodynamics — methods: numerical — methods: statistical

I. INTRODUCTION

A. The coronal heating problem and its two mechanisms

The solar corona reaches ~ 1 – 3×10^6 K above a $\sim 10^4$ K chromosphere, a long-standing puzzle whose energy source is magnetic [8]. Two mechanisms dominate the debate. In the *nanoflare* (DC) picture [12], slow photospheric footpoint motions braid the coronal field [18], building magnetic stress that is released impulsively at current sheets by reconnection, with an energy distribution that may be a steep power law [1, 3]. In the *Alfvén-wave* (AC) picture, photospheric motions launch waves that propagate along the field and dissipate through turbulent cascade [4, 19]; waves are observed throughout the corona [5, 17]. Both mechanisms are intrinsically intermittent – reconnection avalanches and turbulent cascades alike produce fat-tailed, bursty heating.

B. A computational barrier, and an opportunity

Resolving the microphysics – current-sheet reconnection (seconds; metre scales) or wave cascades – over the hours-to-days thermal evolution of a loop is a multi-scale problem reminiscent of the Courant barrier in turbulence. We take the same route we would in that context: rather than resolve the intermittent heating, we *sample* it from its stationary fat-tailed distribution on macroscopic time steps. The opportunity specific

to the corona is that, unlike many astrophysical turbulence problems, the relevant fluctuations are *directly observable* with current instruments, so the framework's falsifiable predictions can actually be tested.

C. Contributions

None of our contributions is a new heating mechanism; they are a vehicle, a computational strategy, a falsifiability design, and the predictions these enable.

1. A **variance–gamma Lévy closure** for the intermittent heating [2, 11], with a single parameter ν tuning intermittency to the Gaussian limit, coupled to the thermally *bistable* loop whose hot branch plays the role of a threshold gate.
2. A **macro-step stochastic–subgrid integrator** that escapes the microphysical time step, extended to a one-dimensional loop with field-aligned conduction and chromospheric evaporation.
3. **Self-consistent generation** of both the mean heating and the intermittency from a single magnetic-braiding profile, and a **two-mechanism unification** of nanoflares and Alfvén-wave turbulence as VG sources.
4. **Seven predictions** (Section V) and a **verification methodology** (Section VI) tied to existing instruments, with decision tables that pre-register refutation versus robustification.

II. MODEL

A. Intermittent heating closure and the bistable gate

The unresolved heating is $H_{\text{VG}}(t) = \bar{H} e^{\chi(t)}$ with $\chi \sim \text{VG}(\nu, \sigma_\chi, \theta_\chi)$, drawn from the variance–gamma process

$$L^{\text{VG}}(t) = \theta \mathcal{G}(t; \nu) + \sigma W(\mathcal{G}(t; \nu)), \quad \kappa_{\text{exc}}(\Delta t) = \frac{3\nu}{\Delta t} \quad (\theta=0), \quad (1)$$

a Brownian motion subordinated to a gamma clock of variance rate ν [11]; ν is the excess kurtosis and $\nu \rightarrow 0$ recovers steady (Gaussian-in-log) heating, while $\theta_\chi > 0$ captures the positive skew of flare-like events. For a single loop of density n and half-length L , energy conservation reads

$$\frac{3}{2} n k_B \frac{dT}{dt} = H_{\text{VG}}(t) - n^2 \Lambda(T) - \frac{\kappa_0 T^{7/2}}{L^2}, \quad (2)$$

with the optically-thin radiative loss $\Lambda(T)$ [10] and Spitzer conduction $\kappa_0 T^{5/2}$ [16]. Because $\Lambda(T)$ peaks near 10^5 K and declines above it, the thermal equilibrium $H = n^2 \Lambda + \kappa_0 T^{7/2}/L^2$ is non-monotonic: a cool ($\sim 10^4$ K) and a hot ($\sim 10^6$ K) branch coexist over a range of H [6, 13]. Crossing from the cool to the hot branch – a genuine *ignition* – is the coronal analogue of a threshold instability, and requires a heating burst sustained over a thermal time.

B. One-dimensional loop with conduction and evaporation

Resolving the field-aligned coordinate s , the energy equation becomes

$$\frac{3}{2} k_B \frac{\partial(nT)}{\partial t} = \frac{\partial}{\partial s} \left(\kappa_0 T^{5/2} \frac{\partial T}{\partial s} \right) - n^2 \Lambda(T) + H_{\text{VG}}(s, t), \quad (3)$$

with a chromospheric thermostat at the base ($s = 0$) and symmetry at the apex. The density responds through chromospheric evaporation: the conductive flux reaching the base in excess of what local radiation can handle drives an upflow that fills the loop, while an over-dense loop drains on a flow timescale – the enthalpy-flux closure of loop models [9].

C. Self-consistent braiding

Rather than prescribe $\bar{H}$ and ν independently, we derive both from a single magnetic braiding profile $\Theta(x)$ across an active region. The field strength scales as $B \propto \Theta^{1/2}$, the Poynting flux from braiding gives the mean heating, and the intermittency follows the same activity:

$$\bar{H}(x) = \frac{f_S B^2 v_h \theta_c}{4\pi L} \propto \Theta, \quad \nu(x) = \nu_{\max} \frac{\Theta}{\Theta + \Theta_0}, \quad (4)$$

so that quiet-Sun regions ($\Theta \rightarrow 0$) have low heating and Gaussian statistics ($\nu \rightarrow 0$).

D. Two-mechanism unification

Nanoflares and Alfvén-wave turbulence enter as two VG sources,

$$H_{\text{total}} = \bar{H}_{\text{nf}} e^{\chi_{\text{nf}}} + \bar{H}_{\text{wave}} e^{\chi_{\text{wave}}}, \quad (5)$$

with the nanoflare source peaked in active regions ($\bar{H}_{\text{nf}} \propto \Theta$, high ν_{nf}) and the wave source quasi-uniform and enhanced in open-field/quiet-Sun regions (moderate, uniform ν_{wave}), reflecting the distinct geometry of DC and AC heating.

III. FALSIFIABILITY FRAMEWORK

The central hypothesis – that the heating intermittency is magnetic in origin – is made refutable. *Calibration*: the VG intermittency $\hat{\nu}$ inferred from EUV/X-ray intensity fluctuations should increase with the photospheric magnetic complexity (braiding) and vanish in quiet regions. *Refutation A*: a magnetically quiet region showing fat-tailed heating would falsify the magnetic origin. *Refutation B*: the macro-step injection is justified only if the excess kurtosis of coarse-grained heating decays as $\kappa_{\text{exc}} \propto \Delta t^{-p}$ with $p \approx 1$. These are directly measurable, as detailed in Section VI.

IV. RESULTS

A. Intermittency is a prerequisite for coronal heating

Figure 1 shows the bistable equilibrium and the ignition test for a fiducial loop, with the mean heating set below the cool-branch knee (so steady heating cannot reach the hot branch). We find that Gaussian heating never ignites the corona (0% over many realizations) whereas VG intermittency ignites it with a probability rising steeply with ν (33% at $\nu = 0.3$, $\sim 80\%$ at $\nu \geq 0.8$). Because the bistable transition requires the burst to persist over a thermal time, the effect is one of *energy*, not instantaneous power: only the rare, large, sustained VG bursts cross the knee.

B. One-dimensional structure and density response

Resolving the loop (Fig. 2), field-aligned conduction shapes the ignited temperature profile (steep near the base, flat toward the apex at ~ 0.8 MK), and chromospheric evaporation fills the loop, producing fill–drain cycles in the density–temperature plane. The ignition remains intermittency-driven (10% Gaussian versus $\sim 90\%$ at $\nu \geq 1.2$), though efficient conduction narrows the intermittency-critical window relative to the 0D case – an honest instance of surrounding physics weakening, but not eliminating, the core effect.

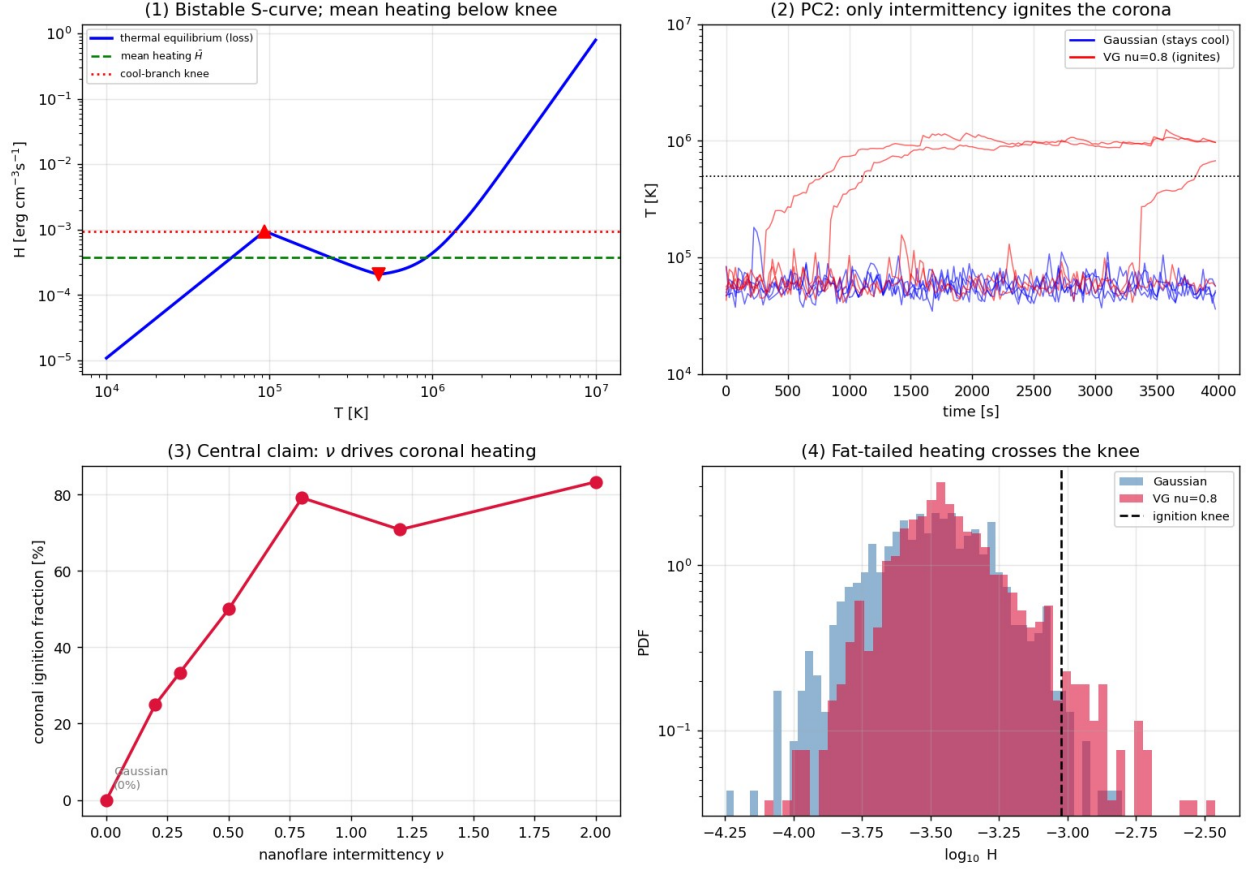


FIG. 1. Nanoflare intermittency and coronal ignition (0D loop). (1) bistable S-curve with mean heating below the cool-branch knee; (2) Gaussian traces stay cool while VG traces ignite; (3) ignition fraction rises with ν (Gaussian 0%); (4) fat-tailed heating crosses the ignition knee.

C. Self-consistent braiding: where the corona lights up

Deriving $\bar{H}(x)$ and $\nu(x)$ from a single braiding profile (Fig. 3), the corona ignites where braiding is high. Decomposing by zone reveals a complementarity: the active-region core ($\bar{H} \geq \text{knee}$) ignites by mean heating and is intermittency-independent, whereas the periphery ($\bar{H} < \text{knee}$) ignites only through intermittency – so the intermittency *widens* the heated region beyond what mean heating alone would light. The quiet Sun does not ignite at all under nanoflare heating.

D. Two mechanisms: waves floor, nanoflares boost

Combining the two VG sources (Fig. 4) reproduces the observed thermal structure: Alfvén-wave heating supplies a ~ 1 – 1.5 MK floor everywhere, including the quiet Sun (which nanoflares alone leave at ~ 0.05 MK), while nanoflares boost active regions to ~ 2.5 MK. The mechanisms dominate different regions (nanoflare/DC in active-region cores, wave/AC in the quiet Sun and open field) and carry distinct intermittency signatures – a directly observable discriminant.

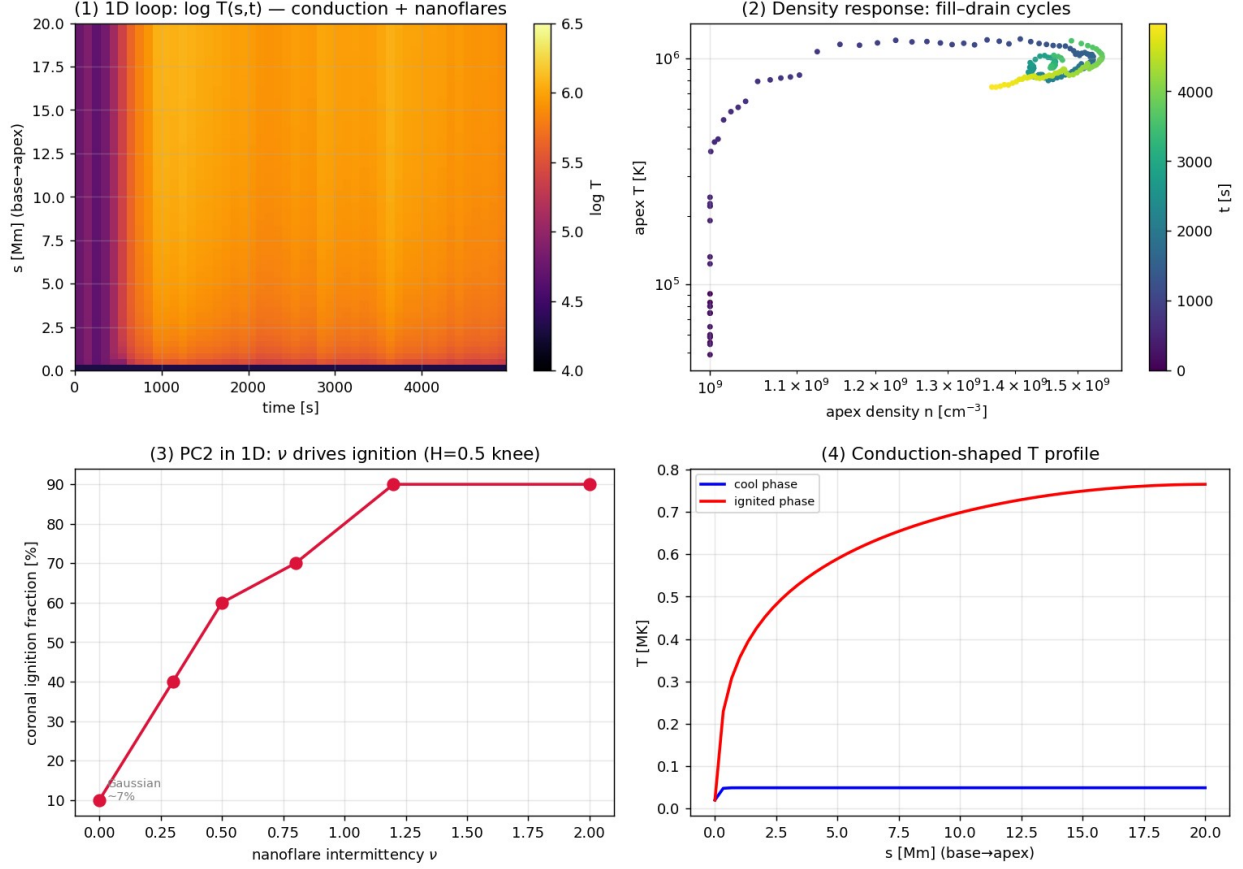


FIG. 2. One-dimensional loop with conduction and density response. (1) $\log T(s, t)$; (2) density–temperature fill–drain cycles; (3) ignition fraction versus ν in 1D; (4) conduction-shaped temperature profile, cool versus ignited.

V. PREDICTIONS

Predictions tagged *[model]* are exercised above; *[data]* ones are testable with existing instruments (Section VI).

PC1 Braiding–intermittency map *[data]*. The heating intermittency inferred from intensity fluctuations increases with photospheric magnetic complexity and vanishes in quiet regions.

PC2 Intermittency as a prerequisite *[model]*. With mean heating below the ignition knee, steady heating cannot reach the hot branch; the ignition probability rises from 0% to $\sim 80\%$ with ν .

PC3 Burst–hotspot relation *[model]*. Stronger bursts produce more localized, shorter-lived hot spikes.

PC4 Mechanism complementarity *[model+data]*. Nanoflares (DC) dominate active-region cores and waves (AC) the quiet Sun; the two carry distinct intermittency signatures, giving a wave floor plus a nanoflare active-region boost.

PC5 Lévy aggregation *[data]*. The excess kurtosis of coarse-grained heating decays as $\kappa_{\text{exc}} \propto \Delta t^{-1}$; a steeper decay falsifies the additive macro-injection.

PC6 Braiding sets where the corona lights up *[model]*. A single $\Theta(x)$ localizes coronal heating to high-braiding regions, with intermittency widening the lit region into the active-region periphery.

PC7 Velocity versus intensity intermittency *[data]*. Doppler (velocity) and intensity (heating) fluctuations carry different intermittency, constraining the AC/DC balance.

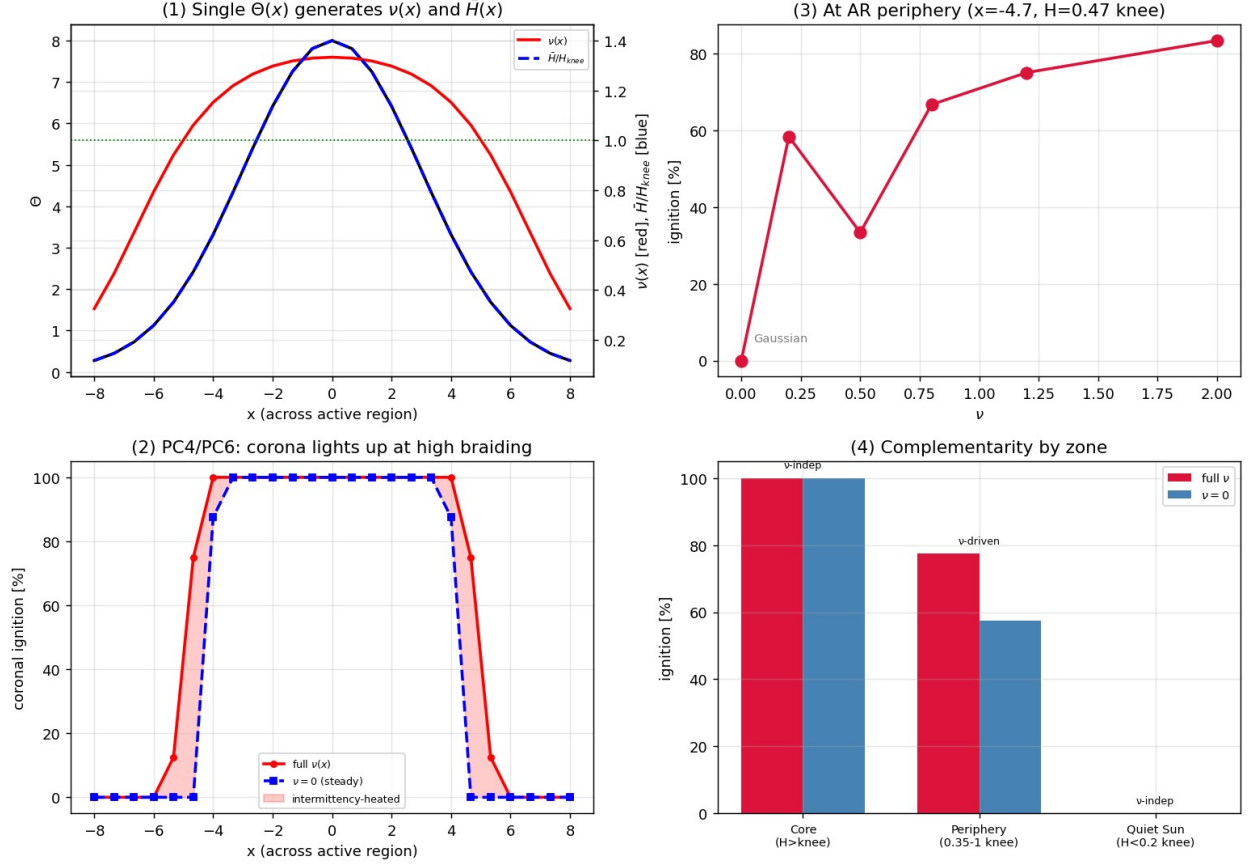


FIG. 3. Self-consistent braiding. (1) a single $\Theta(x)$ generates $\nu(x)$ and $\bar{H}(x)$; (2) the corona lights up at high braiding, with intermittency widening the heated region; (3) ignition versus ν at the periphery; (4) complementarity by zone – core intermittency-independent, periphery intermittency-driven.

VI. VERIFICATION METHODOLOGY

The [data] predictions require intermittency statistics of coronal fluctuations. These are observable now; we present the method, validate it on realistic synthetic observables, and pre-register the decision from each outcome.

A. Pipeline and surrogate

The pipeline reduces any intensity or velocity time series to: the intermittency $\hat{\nu} = \kappa_{\text{exc}}/3$ (finite-tailed case); the tail index α from a Hill estimator (power-law case); and the aggregation exponent p . We validate it on synthetic observables (Fig. 5) that mimic active-region nanoflare trains – impulsive, power-law-energy events with radiative cooling – and quiet-Sun wave heating – continuous, mildly intermittent fluctuations with a quasi-periodic component. The pipeline cleanly separates the two mechanisms by *tail type*: the nanoflare series has a power-law increment tail with index $\alpha \approx 1.6$ (recovering the injected value), while the wave series has finite kurtosis, $\hat{\nu} \approx 0.8$.

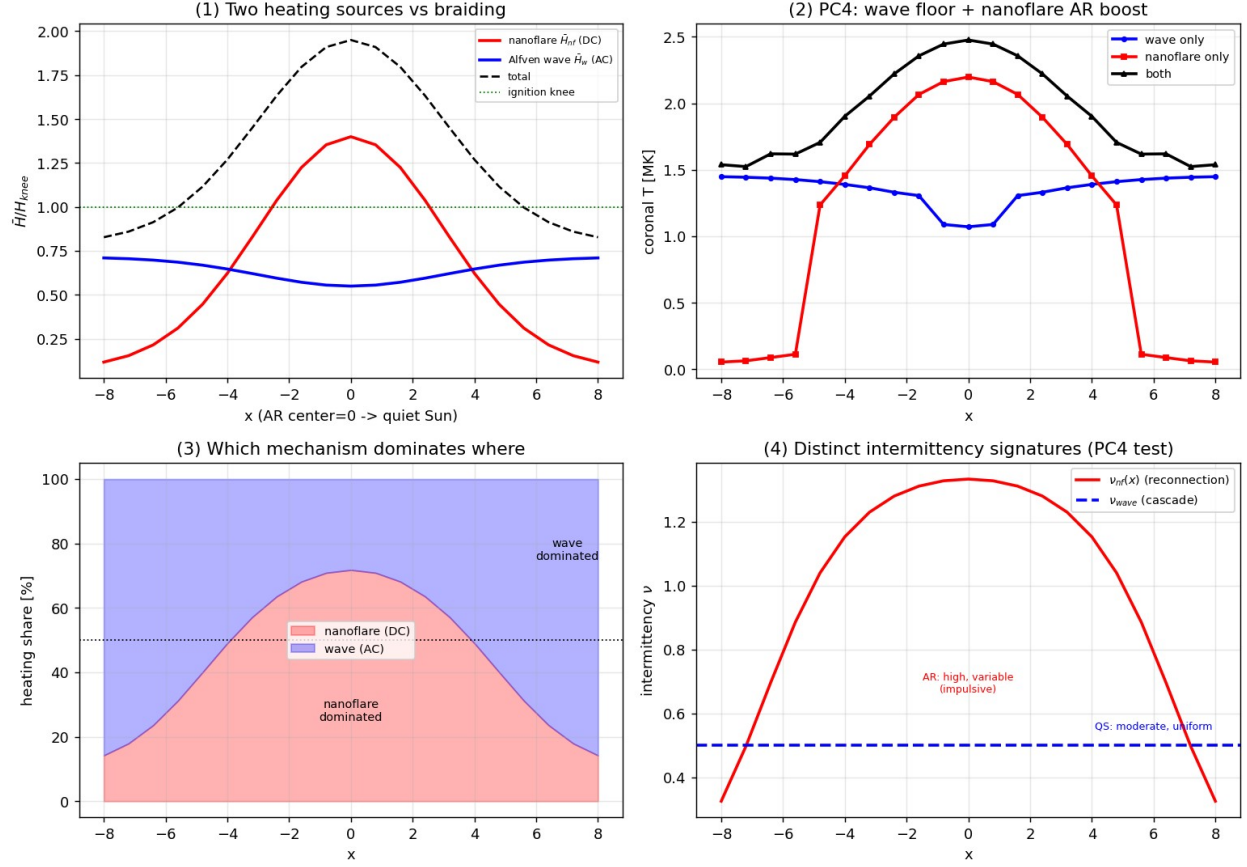


FIG. 4. Nanoflare + Alfvén-wave unification. (1) the two heating sources versus braiding; (2) temperature – wave floor plus nanoflare active-region boost; (3) which mechanism dominates where; (4) distinct intermittency signatures $\nu_{nf}(x)$ (variable) versus ν_{wave} (uniform).

B. A central finding: the mechanism selects the closure

The nanoflare increment tail is power-law with $\alpha < 3$, so its variance formally diverges; this exceeds the finite-variance VG closure and calls for a *stable-Lévy* generalization [14]. Wave heating, by contrast, has finite kurtosis and fits VG. The heating mechanism therefore selects the statistical closure – a result that both sharpens the framework and provides a discriminant. This is the coronal counterpart of the “generalize the vehicle, keep the mechanism” outcome familiar from multifractal turbulence [7, 15].

C. Outcome tables

Tables I–II fix the mapping from each measurable outcome to a model response. The pipeline is exposed

TABLE I. OC1 – magnetic origin. Measured: $\hat{\nu}$ versus HMI braiding.

Measured outcome	Interpretation	Model response
$\hat{\nu}$ increases, $\rightarrow 0$ in quiet Sun	Magnetic origin confirmed	Robustify: adopt $\nu(\theta)$ as calibrated
$\hat{\nu}$ independent of braiding	No magnetic control	Refute: intermittency not braiding-sourced
Fat tails in quiet Sun	Non-magnetic source	Refute (A): amend the origin

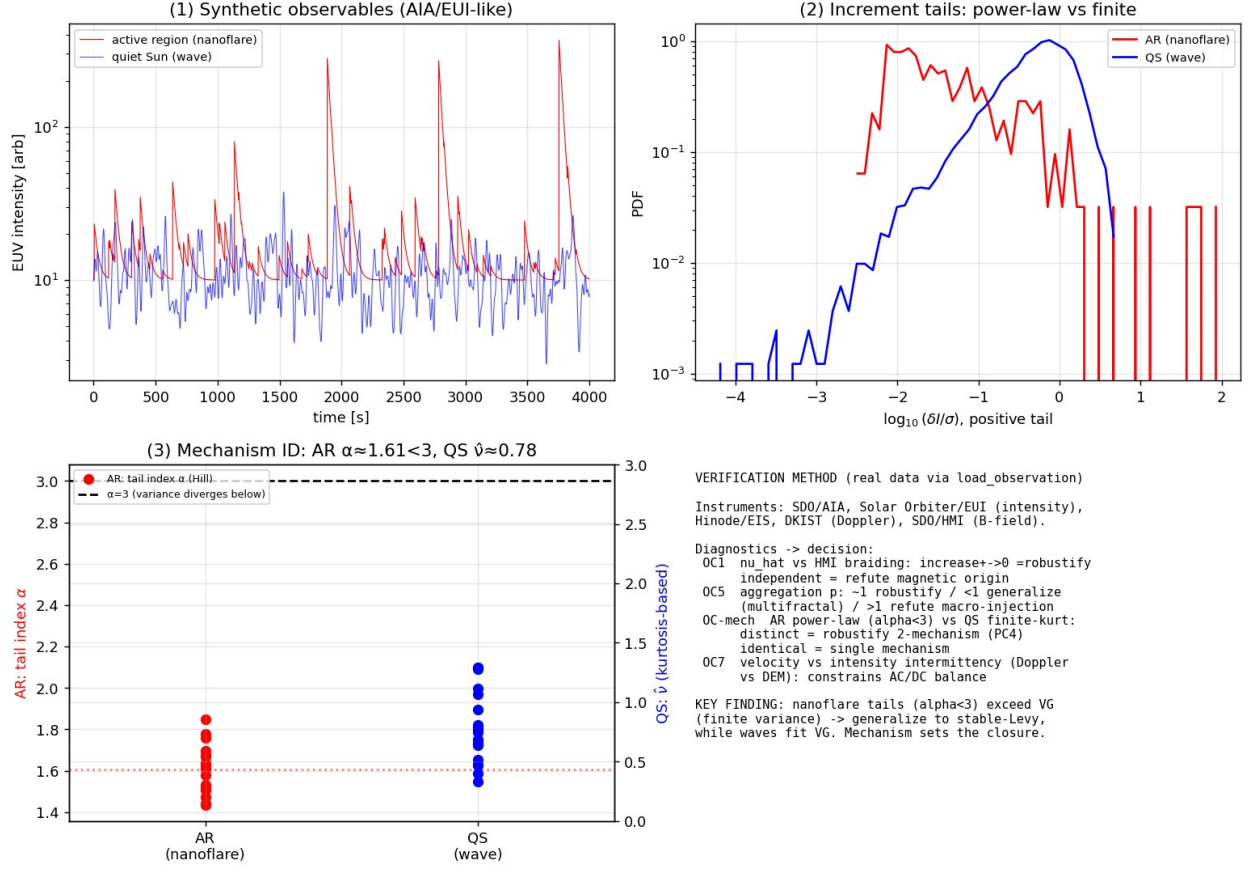


FIG. 5. Verification methodology on synthetic observables. (1) active-region (nanoflare) versus quiet-Sun (wave) intensity series; (2) increment tails, power-law versus finite; (3) mechanism identification – nanoflare tail index $\alpha \approx 1.6 < 3$ versus wave $\hat{\nu} \approx 0.8$; (4) the decision framework and instrument mapping.

TABLE II. OC5 / mechanism – aggregation and tail type.

Measured outcome	Interpretation	Model response
aggregation $p \approx 1$	Lévy aggregation	Robustify: macro-injection justified
$p < 1$ (wave)	multifractal	Generalize: multifractal closure
$p > 1$	jumps wash out	Refute (B): finer Δt needed
nanoflare tail $\alpha < 3$	divergent variance	Generalize: VG $\rightarrow$ stable-Lévy
AR power-law vs QS finite-kurtosis	two distinct mechanisms	Robustify: complementarity (PC4)
identical statistics	single mechanism	Refute complementarity

through a loader returning a time series for each region; the downstream routines are format-agnostic. Intensity series (SDO/AIA, Solar Orbiter/EUI) yield $\hat{\nu}$, p , α ; Doppler series (Hinode/EIS, DKIST) yield the velocity intermittency (PC7); HMI provides the braiding proxy (PC1).

VII. LIMITATIONS AND DISCUSSION

The loop model is 0D or 1D with a reduced density response, not full field-aligned hydrodynamics; the bistable “ignition” is a proxy for the true thermal nonequilibrium of loops; the two-mechanism weights and the braiding-to- ν map are calibrated, not derived from first-principles MHD; and, as Section VI shows,

the VG closure must be generalized to stable-Lévy for nanoflares. These are separable from the novel core – the intermittency closure, the bistable gate, and the falsifiability design. The heating *mechanisms* (nanoflares, wave turbulence) are inherited [12, 19]; what is new is the VG vehicle, the macro-step integrator, the self-consistent braiding-to-intermittency map, the two-mechanism unification with distinct intermittency signatures, and the mechanism-selects-closure finding. Crucially, and unlike many astrophysical applications, every [data] prediction here is testable with instruments now in operation. We therefore present this as a methods-and-prediction contribution to the coronal heating problem, positioned relative to the nanoflare, wave-turbulence, and loop-modeling literature.

VIII. CONCLUSIONS

A variance–gamma Lévy closure injects intermittent coronal heating on macroscopic time steps, and the thermally bistable loop turns rare heating bursts into coronal “ignition.” With the same mean heating, Gaussian heating cannot ignite the corona while intermittency can: intermittency is a prerequisite. A single magnetic-braiding profile generates both the heating and its intermittency and localizes the corona to high-braiding regions; unifying nanoflares and Alfvén waves as two VG sources reproduces the wave floor and nanoflare active-region boost. Seven predictions follow, and a verification pipeline – validated on synthetic observables and tied to SDO, Solar Orbiter, Hinode, and DKIST – discriminates the two mechanisms by tail type and reveals that the mechanism selects the statistical closure. Because the relevant fluctuations are directly observable, the framework’s falsifiability is not aspirational but immediately actionable.

DATA AVAILABILITY

The simulation and analysis code – the bistable stochastic–subgrid integrator, the 1D loop, the self-consistent braiding and two-mechanism modules, and the verification pipeline – will be made available on reasonable request.

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