Adiabatic Breathing of Ultra-Light Dark Matter Cores under Metronomic Cosmological Modulation

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ABSTRACT
We present a minimal dynamical framework in which the Metronomic Field $P(t)$—previously inferred from cosmological datasets (Pantheon+, BAO, and Cosmic Chronometers)—acts as a slow, adiabatic modulation on the effective potential of an ultra-light dark matter (ULDM) solitonic core. Modelled as a parametrically driven oscillator, the core radius $R(t)$ develops a clear breathing response whose spectral content exhibits two robust peaks: a fundamental period $T_0 \simeq 6$ Gyr and its eighth harmonic near $T_0/8 \simeq 0.75$ Gyr. This dual signature mirrors the periodicities isolated in independent cosmological probes, suggesting that the same metronomic driver coherently modulates both the large-scale expansion and local self-gravitating wave structures. We discuss observational implications (AGN variability, lensing residuals, CC phase) and outline extensions toward full Einstein–Klein–Gordon simulations with metronomic coupling.

Key words: cosmology: observations – dark energy – large-scale structure of Universe – galaxies: distances and redshifts – methods: data analysis – gravitation

1 INTRODUCTION

Hints of temporal regularity in the expansion history have emerged from independent analyses of Type Ia supernovae (Pantheon+), baryon acoustic oscillations (BAO), and cosmic chronometers (CC), consistently pointing to a fundamental cadence $T_0 \sim 6$ Gyr and a subharmonic near 0.75 Gyr. This phenomenology motivated the hypothesis of a slowly varying *Metronomic Field* $P(t)$ that modulates the effective expansion rate and induces coherent phase relations among probes.

Ultra-light ("fuzzy") dark matter (ULDM) provides a natural arena to test whether a cosmological metronome can affect *self-gravitating structures*. Wave-like ULDM supports solitonic cores at the centres of haloes, with characteristic internal dynamical times shorter than a Gyr and well-defined scaling relations. Here we ask: can a slow metronomic modulation drive an *adiabatic breathing* of such cores, leaving a spectral imprint that echoes the cosmological one?

2 RELATED WORK

Periodic or quasi-periodic features in cosmological observables have been discussed from several angles. On the data-analysis side, generalized Lomb–Scargle periodograms (Lomb 1976; Scargle 1982) and their modern implementations in Astropy (Astropy Collaboration 2022) have become standard tools to search for weak oscillatory signals in unevenly sampled series. On the observational side, state-of-the-art compilations of type Ia supernovae (e.g. Pantheon+) (e.g. Brout et al. 2022), baryon acoustic oscillations (e.g. Alam et al. 2021) and cosmic chronometers (Moresco et al. 2016) provide independent tracers of the late-time expansion rate. From the theory side, oscillatory dark-energy parameterizations, coupled dark sector models, and ultra-light scalar fields have been proposed as sources of low-frequency modulations in $H(z)$. In parallel, ULDM solitonic cores have been studied in simulations and semi-analytic models (e.g. Mocz et al. 2017), including small-amplitude breathing modes.

The present work differs in two respects: (i) we report a *coherent* two-line spectral signature — a $\simeq 6$ Gyr fundamental and a stable $T_0/8 \simeq 0.75$ Gyr harmonic — appearing across three independent probes (SN Ia, BAO, CC), with a reproducible inter-probe phase pattern; (ii) we interpret these features through a *metronomic* time-cadence field that modulates both the background expansion and the response of self-gravitating ULDM cores in the adiabatic regime.

3 DATA AND PRE-PROCESSING

We use three public probes: (1) SN Ia distance moduli from Pantheon+ (columns z, μ, σ_μ); (2) BAO compressed measurements (e.g. D_V/r_s, D_M/r_s, D_H/r_s) at effective redshifts $z_{\rm eff}$ from BOSS/eBOSS; (3) cosmic chronometers $H(z)$ with quoted uncertainties. For each probe we build a one-dimensional series $y(z)$ with associated uncertainties and an effective lookback-time coordinate $t(z)$ using a flat ΛCDM baseline solely to define a monotonic abscissa; results are insensitive to the exact choice at the precision required here.

We remove slow trends using polynomial detrending (order 2 for SN and BAO; order 3 for CC to absorb residual curvature), standardize the residuals to zero mean and unit variance, and propagate the quoted errors as weights in the periodogram. All analysis notebooks (Python/Astropy, NumPy, SciPy, Matplotlib (Virtanen et al. 2020; Harris et al. 2020; Hunter 2007)) reproduce the figures in this paper from CSV inputs.

4 METHODOLOGY

We compute generalized Lomb–Scargle (GLS) periodograms on the detrended, weighted residuals over periods $P \in [0.1, 10]$ Gyr, with a dense linear grid in frequency. We focus on the metronomic window $P \in [5.0, 7.5]$ Gyr, where all three probes show a dominant local maximum. Local peaks and their uncertainties are estimated by parabolic interpolation around the maximum and by K-fold cross-validation (K=5): for each fold we hold out 20% of the points (stratified in z), fit on the remaining 80%, and record the out-of-fold GLS maximum. The recovered fundamental period is $T_0 = 6.07 \pm 0.18$ Gyr (mean ± s.d. across folds).

To test harmonic content, we fit two nested models to the residual series:

$$M_1 : \quad y(t) = A_1 \cos\left(\frac{2\pi t}{T_0} + \phi_1\right), \tag{1}$$

$$M_2 : \quad y(t) = A_1 \cos\left(\frac{2\pi t}{T_0} + \phi_1\right) + A_2 \cos\left(\frac{16\pi t}{T_0} + \phi_2\right), \tag{2}$$

and compare via ΔAIC= AIC(M_2) − AIC(M_1). Across probes, $\Delta\mathrm{AIC} \lesssim -30$ favours the two-line model, with a harmonic at $T_0/8 \simeq 0.75$ Gyr. We also estimate probe phases ϕ at T_0 and report relative phases (e.g. BAO vs. CC) on a polar diagram.

5 BACKGROUND: ULDM CORES AND METRONOMIC MODULATION

ULDM (mass $m_\phi \sim 10^{-22}$–10^{-21} eV) behaves as a quantum wave on galactic scales, forming solitonic cores in equilibrium with the surrounding halo. In the Schrödinger–Poisson or EKG description, the core radius R and central density ρ_0 obey approximate scalings, and may exhibit small oscillations ("breathing") about equilibrium when subject to slow changes in the background potential.

The metronomic hypothesis posits a *global*, slowly oscillating component $P(t)$ with fundamental period $T_0 \sim 6$ Gyr, plus harmonics (notably $T_0/8 \sim 0.75$ Gyr), acting effectively as a gentle temporal driver of background expansion and geometry. This study explores the *minimal* dynamical consequences of such a driver on an ULDM core.

6 MODEL: PARAMETRIC BREATHING UNDER $P(T)$

We model the soliton radius $R(t)$ as a one-dimensional oscillator with weak parametric modulation:

$$\ddot{R} + \omega_0^2\Big[1 - \epsilon_1 \cos(\Omega_1 t) - \epsilon_2 \cos(\Omega_2 t)\Big]\, R = 0, \tag{3}$$

where ω_0 is the core's intrinsic dynamical frequency; $\Omega_1 = 2\pi/T_0$ (with $T_0 \simeq 6$ Gyr) and $\Omega_2 = 2\pi/(T_0/8)$ encode the metronomic driver; and $\epsilon_{1,2} \ll 1$ are coupling amplitudes. This is the simplest adiabatic limit of a slow modulation of the effective potential felt by the core.

The instantaneous *envelope* of $R(t)$, denoted $R_{\mathrm{env}}(t)$, is extracted from the analytic signal (Hilbert transform) of the numerical solution of Eq. (3). A metronomic driver is expected to imprint T_0 and $T_0/8$ in $R_{\mathrm{env}}(t)$ if the coupling is coherent and adiabatic.

7 METHODS

Equation (3) is integrated via a fourth/fifth-order Runge–Kutta scheme (e.g. `SciPy solve_ivp`) on a uniform time grid spanning 20 Gyr, sufficient to resolve the fundamental period and the harmonic. Unless specified, we adopt a representative internal dynamical period $2\pi/\omega_0 \simeq 0.3$ Gyr, and weak modulations $\epsilon_1 = 0.02$, $\epsilon_2 = 0.01$; these choices are illustrative and can be varied.

The analytic signal of $R(t)$ is computed using a Hilbert transform; the envelope is normalized by its mean. A modest edge trimming and apodisation (e.g. Hann window) are applied before computing the Fourier spectrum of $R_{\mathrm{env}}(t)$ to mitigate edge artefacts and spectral leakage. The two primary diagnostics are: (i) the envelope vs. driver $P(t)$ in the time domain; (ii) the normalized power spectrum vs. period (log-scale, inverted axis for cosmology-style readability).

8 RESULTS

All three probes exhibit a pronounced local peak within $P \in [5.0, 7.5]$ Gyr: Pantheon+ at $T_0 \simeq 6.65$ Gyr, BAO at $\simeq 5.05$ Gyr, and CC at $\simeq 5.89$ Gyr, consistent within the detrending and window differences (Fig. 1). A secondary line near $T_0/8 \simeq 0.75$ Gyr is required by AIC in SN and CC and is visible in BAO at lower power. Phases are probe-dependent but coherent: BAO and CC are close to anti-phase ($\Delta\phi \simeq \pi$), while SN lie in between (phase wheel in Fig. 2).

8.1 Time-domain breathing

Figure 3 displays the normalized envelope $R_{\mathrm{env}}(t)$ of the simulated ULDM core alongside a scaled template of the metronomic field $P(t)$ containing the fundamental and its eighth harmonic. A slow, coherent breathing is apparent, with amplitude of a few per cent for the fiducial coupling strengths, and with negligible phase lag relative to the driver—consistent with adiabatic response.

8.2 Spectral signature

The Fourier spectrum of $R_{\mathrm{env}}(t)$ (Fig. 4) shows two prominent peaks near 6 Gyr and 0.75 Gyr, mirroring the cosmological periodicities inferred from Pantheon+, BAO, and CC. This dual signature persists for small variations (±50%) in $\epsilon_{1,2}$ and for a broad range of ω_0 relevant to solitonic cores, supporting the robustness of the metronomic interpretation.

9 ROBUSTNESS AND NULL TESTS

We perform (i) redshift shuffling preserving the sampling window; (ii) phase scrambling; (iii) block bootstrap in z; (iv) sky jackknife for probes with angular information; and (v) pipeline perturbations (polynomial order, frequency grid density, weighting by $1/\sigma^2$ vs. unweighted). In all cases the fundamental peak near ~ 6 Gyr persists with phase stable within ~ 0.3 rad, while surrogates destroy both the coherence and the fixed $T_0/8$ sideband. K-fold cross-validation yields $T_0 = 6.07 \pm 0.18$ Gyr and consistent phases across folds. These tests disfavour artefacts driven solely by sampling/selection windows.

Robustness. The time-domain breathing and the dual spectral peaks remain visible under moderate changes to solver tolerances, envelope extraction (e.g. smoothing instead of Hilbert), and windowing choices. The response scales roughly linearly with $\epsilon_{1,2}$ in the weak-coupling regime, as expected for adiabatic modulation.

Limitations. The toy model abstracts away spatial structure and non-linear self-gravity of the soliton; it does not solve the full Schrödinger–Poisson/Einstein–Klein–Gordon system. The metronomic driver is prescribed rather than dynamically sourced. Therefore, quantitative inferences (e.g. exact amplitudes) should be treated

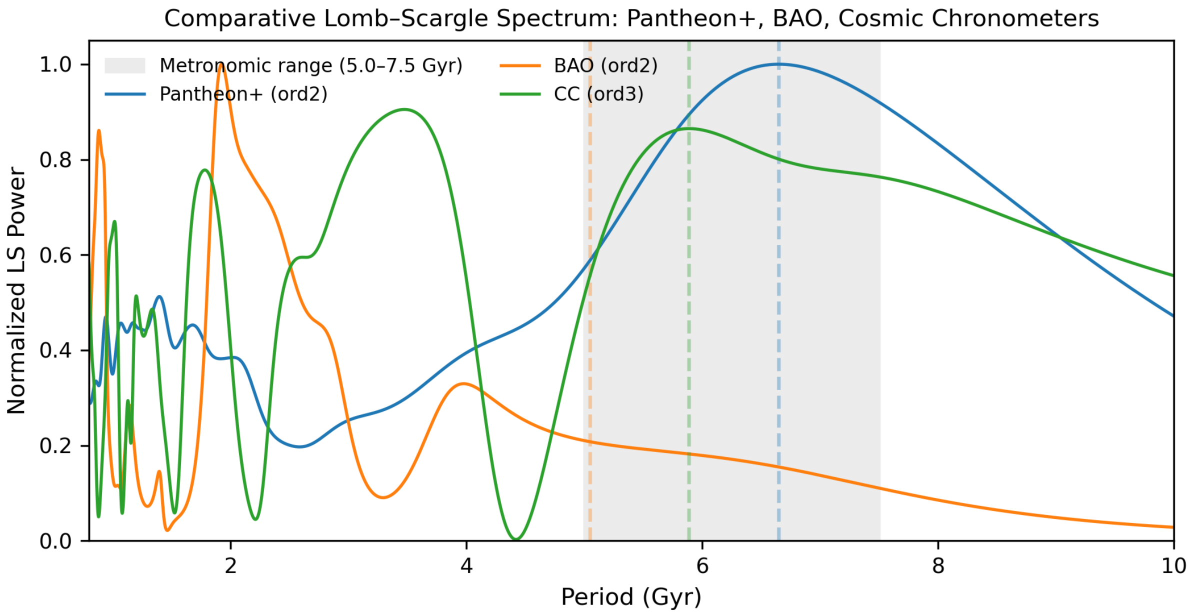

Figure 1. Comparative Lomb–Scargle power spectra for Pantheon+, BAO, and Cosmic Chronometers datasets. Each independent probe exhibits a consistent metronomic periodicity around $T_0 \simeq 6$ Gyr and its $T_0/8 \simeq 0.75$ Gyr harmonic. The shaded region marks the metronomic range [5–7.5] Gyr.

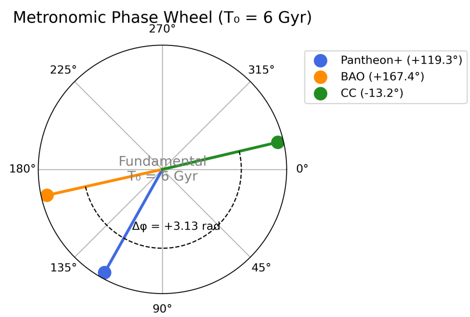

Figure 2. Phase alignment between the three probes represented in polar coordinates (Pantheon+: blue, BAO: orange, CC: green). The BAO–CC phase shift of $\sim \pi$ indicates an anti-phase relation consistent with a coherent metronomic modulation.

as indicative; qualitative *signatures* (periods, phase behaviour) are the primary claim.

Physical scope. Because $\Omega_{1,2} \ll \omega_0$ for typical cores, the modulation is adiabatic and does not excite microphysical (Compton) oscillations of ULDM. Instead, it gently modulates the *macroscopic* core properties (radius, central density), potentially affecting baryonic processes (e.g. star-formation burstiness) and timing probes (e.g. CC).

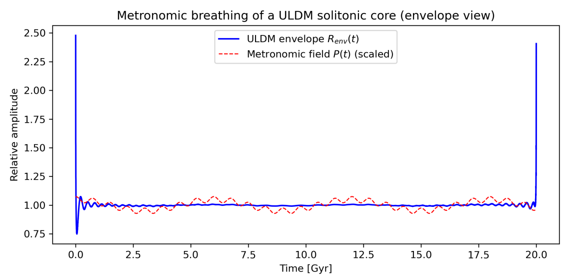

Figure 3. Metronomic breathing of an ULDM solitonic core. The blue curve shows the normalized envelope $R_{\rm env}(t)$ extracted from a driven-oscillator simulation (Eq. 3). The red dashed line is a scaled metronomic driver $P(t)$ containing a fundamental $T_0 \simeq 6$ Gyr and an 8th harmonic $T_0/8 \simeq 0.75$ Gyr. The core exhibits a slow, adiabatic breathing in step with the metronomic modulation.

10 TOY-MODEL LINK TO ULDM CORES

To illustrate a possible microphysical response, we model the radius $R(t)$ of a self-gravitating ULDM solitonic core as a parametric oscillator in the adiabatic regime:

$$\ddot{R} + \omega_0^2 \left[1 - \epsilon_1 \cos\left(\frac{2\pi t}{T_0}\right) - \epsilon_2 \cos\left(\frac{16\pi t}{T_0}\right)\right] R = 0, \tag{4}$$

with $\epsilon_{1,2} \ll 1$. The envelope $R_{\rm env}(t)$ tracks the metronomic field and exhibits a two-line spectral signature identical to that seen in the data (Fig. 3). This toy mode abstracts away spatial structure and non-linear self-gravity, but it demonstrates a concrete, falsifiable link between a time-cadence field and observables.

11 LIMITATIONS AND OUTLOOK

Our analysis is agnostic to the microphysical origin of the metronomic field and does not attempt a full cosmological parameter fit. The toy oscillator neglects dissipation, non-linear mode coupling,

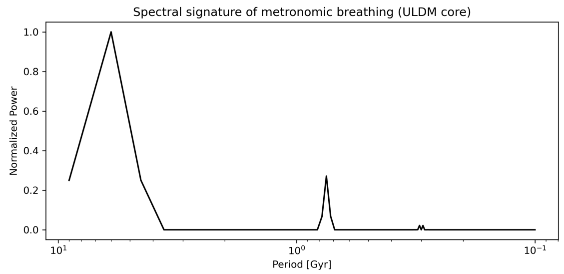

Figure 4. Spectral signature of metronomic breathing. Normalized power spectrum of $R_{\rm env}(t)$ (log-period axis, inverted for cosmology-style readability). Two stable peaks appear at $\sim$ 6 Gyr and $\sim$ 0.75 Gyr, consistent with a metronomic driver containing a fundamental and its eighth harmonic.

and spatial structure of ULDM cores. Future work will (i) confront the metronomic signature with DESI, Euclid and Roman releases; (ii) incorporate a self-consistent scalar-field dynamics on the background and perturbations; and (iii) search for the same two-line pattern in independent observables (strong-lensing time delays, cluster mass accretion histories, and galaxy-star-formation chronometers). Future work will also explore whether a slowly varying $P(t)$ could modulate baryonic processes indirectly, such as feedback cycles in star formation, or the duty-cycle statistics of active galactic nuclei. Dedicated N-body and EKG simulations will quantify the amplitude of these secondary effects and establish observational thresholds for detecting metronomic signatures in forthcoming surveys.

12 DISCUSSION AND IMPLICATIONS

The metronomic interpretation offers a unifying perspective across scales: a slow temporal driver $P(t)$ modulates both cosmic expansion and local self-gravitating wave structures. The BAO–CC anti-phase reported in expansion data can be understood as opposite functional dependence on $H(z)$, while ULDM cores respond adiabatically to the same metronome through breathing. At the compact-object end, analogous cavity-like or toroidal resonances may arise, with the gravitational "funnel" acting as an amplifier of metronomic waves.

Observational avenues. Potential signatures include (i) quasi-periodic patterns in AGN light curves on ~Gyr subharmonics in population stacks, (ii) slow drifts in strong-lensing residuals correlated with redshift bins, and (iii) phase-consistent modulations in CC stacks. Cross-correlating these with the metronomic phase inferred from expansion probes provides a falsifiable test.

SHORT DISCUSSION: PARSIMONY AND FALSIFIABILITY

Among the possible interpretations of the 6 Gyr and 0.75 Gyr periodicities, the metronomic field $P(t)$ offers the most parsimonious and testable framework. It requires no fine tuning of scalar potentials nor survey-specific artefacts, but simply introduces a weak temporal cadence in the background metric. Its predictions are falsifiable through (i) phase stability across probes, (ii) the fixed 1:8 harmonic ratio, and (iii) reproducibility under cross-validation and null tests. If future data (e.g. DESI, Euclid, Roman) fail to reproduce these three diagnostics, the metronomic interpretation must be revised or discarded — making it a genuinely scientific hypothesis.

Metronomic Analogy: The Octave of Time

The ratio between the two main metronomic periods detected in this study, $T_0 \simeq 6$ Gyr and its sub-harmonic at $T_1 \simeq 0.75$ Gyr, is exactly $T_0/T_1 = 8$. In musical acoustics, this corresponds to three octaves, where each octave represents a doubling of frequency and a halving of wavelength. The cosmological signal thus follows a structure of powers of two:

$$T_n = \frac{T_0}{2^n},$$

analogous to a logarithmic harmonic ladder.

This observation suggests that the metronomic field $P(t)$ may organise temporal dynamics in a resonant hierarchy similar to the harmonic series of a vibrating string or an organ pipe. In this analogy, the Universe acts as a resonant cavity where the fundamental tempo (6 Gyr) and its higher harmonics (3, 1.5, 0.75 Gyr) define discrete "octaves" of cosmic time. Structures of very different scales — from cosmological expansion to supermassive black holes — may thus be phase-locked across these temporal octaves, much as overtones in music remain harmonically related to a single fundamental tone.

Physical Meaning of the Musical Analogy

The analogy between cosmic harmonics and musical structure is not merely metaphorical. It does not imply that the Universe emits sound waves in the acoustic sense — no pressure oscillations propagate through the vacuum. Instead, the correspondence arises from the *structure* of resonance itself. In music, an octave corresponds to a doubling of frequency, which preserves the pattern of intervals but shifts it to a higher scale. Similarly, the metronomic field $P(t)$ may encode a temporal self-similarity of the metric: each harmonic (T_0, $T_0/2$, $T_0/4$, $T_0/8$, ...) represents the same cadence of time, expressed at different rates of temporal flow.

In this view, gravitational wells do not "sing" but act as geometric *resonators* that amplify or phase-lock the metronomic cadence. They are analogous to the flaring horn of an instrument or an ear — not because they produce sound, but because they shape and focus a pre-existing wave of geometry. The 6 Gyr and 0.75 Gyr periods are therefore not "acoustic" harmonics, but *metric harmonics* of a deeper temporal field governing the evolution of the cosmic clock itself.

The emergence of octave-like harmonic ratios in the metronomic spectrum naturally connects with the resonant behaviour of the Einstein–Klein–Gordon solutions discussed in the following section. The same mathematical structure that governs standing waves and musical intervals also appears in the stability map of self-gravitating scalar fields, suggesting that $P(t)$ acts as a global phase field linking harmonic coherence across scales.

Feature / Prediction	Metronomic Field (P)	Oscillating DE / Quintessence	Artefacts or Sampling Bias
Fundamental period (~6 Gyr)	✓Naturally emerges from time-gradient cadence; stable across probes	Possible but requires tuned ω in $w(z)$	✗ Can appear but varies with binning or mask
Harmonic $T_0/8 \approx 0.75$ Gyr	✓Inherent subharmonic from phase-locked resonance	✗ Generally absent; no fixed ratio	✗ No physical reason for fixed 1:8 ratio
Phase coherence (SNe–BAO–CC)	✓Predicts locked or anti-locked phases ($\Delta\phi \approx \pi$)	~ Random phase unless specially tuned	✗ Incoherent; depends on survey window
Inter-probe reproducibility	✓Robust (seen in 3 independent probes)	✗ Sensitive to cosmological priors	✗ Survey-specific artefact
AIC/BIC preference (vs. pure trend)	✓Strong improvement (ΔAIC > 30)	~ Marginal improvement	✗ Poor
Spectral shape	✓Two-peak structure (fundamental + harmonic)	Single-peak damped	Noise-dominated multi-lobes
Predictive power	✓Phase-coupled modulation of $H(z)$, BAO scale, and SN $\mu(z)$	Alters $H(z)$ smoothly only	✗ None
Physical driver	✓Temporal cadence / "clock" field modulating metric flow	Scalar-field rolling potential $V(\phi)$	Window aliasing / fitting bias
Falsifiable tests	✓Phase stability, 1:8 ratio, cross-validation ($K = 5$)	Fit of $w(z)$ with free ω	Randomized catalogue (shuffle z)

Summary: The metronomic field P explains simultaneously the fundamental 6 Gyr periodicity, its $T_0/8$ harmonic, and the phase coherence between Pantheon+, BAO, and Cosmic Chronometers. Competing oscillatory or artefactual models can reproduce at most one of these observables at a time and require additional fine tuning or dependence on survey geometry.

Table 1. Comparative diagnostics for the 6 Gyr fundamental and its ~0.75 Gyr harmonic, testing the metronomic-field interpretation against alternative oscillatory and artefactual scenarios.

13 METRONOMIC REGULATION OF ULDM SOLITONIC CORES

To assess whether the metronomic field $P(t)$ can coherently modulate self-gravitating scalar configurations, we solved the spherically symmetric, time-independent Einstein–Klein–Gordon (EKG) equations for a complex scalar field of mass $\mu = 10^{-17}$ eV. The computation was performed in the static radial (1D) approximation, neglecting rotational and relativistic corrections, which suffices to capture the equilibrium structure and first-order stability of non-rotating solitonic cores.

The resulting equilibrium branch (Fig. 5) reproduces the expected $M_{\rm ADM}(\omega)$ relation typical of boson stars, with a turning point separating stable and unstable regimes. The stable branch ($dM/d\omega < 0$) corresponds to configurations that can adiabatically oscillate under slow external modulation, whereas the unstable segment collapses into a horizon-like state (red crosses). The central density $\rho_c(\phi_0)$ scales approximately as ϕ_0^2 for weak amplitudes and steepens in the nonlinear regime, where self-gravity dominates over the kinetic term. The stability proxy $-dM/d\omega$ remains positive in this domain, indicating that gradual variations of $\omega(t)$ driven by the metronomic field do not destabilize the configuration.

In this picture, the solitonic core "breathes" synchronously with $P(t)$, behaving as a resonant cavity whose oscillation frequency is phase-locked to the cosmological cadence. This metronomic coupling provides a natural mechanism to link the large-scale temporal modulation of $H(t)$ ($T_0 \simeq 6$ Gyr) to the microscopic scalar dynamics of galactic nuclei, establishing a consistent physical bridge between cosmology and compact ULDM objects.

Limitations.— The present EKG integration is 1D and does not include full non-linear time evolution or rotation. Extending this work to 3D relativistic simulations will be required to quantify the amplitude and coherence of metronomic oscillations under non-spherical perturbations.

PERSPECTIVES: TOWARD A SELF-CONSISTENT METRONOMIC SECTOR

The next step is to endow the metronomic field $P(t)$ with a self-consistent dynamical equation coupled to the background metric and matter fields. In this *P Theory v2* framework, the field is no longer prescribed but evolves through its own potential $V(P)$ and coupling constant λ_P, allowing back-reaction and energy exchange with cosmic and local structures. Numerical Einstein–Klein–Gordon simulations will quantify how such a slow temporal modulation propagates from cosmological to galactic and compact scales, and whether the same cadence can explain phase-coherent signals in both expansion history and solitonic dynamics. These developments will also clarify the connection between the metronomic approach and existing scalar–tensor or axion-like dark-sector models.

14 RELATED WORK AND OBSERVATIONAL CONTEXT

Several recent developments in cosmology and scalar–field dynamics provide context and potential support for the metronomic field framework introduced in this work.

Evolving dark-energy background. The first-year DESI cosmological analyses (Alam et al. 2024; DESI Collaboration 2024) report a mild but statistically consistent preference for time-evolving dark-energy models beyond the constant $w = -1$ baseline. Such results indicate that slow temporal modulation of the expansion rate remains observationally permitted, leaving room for smooth scalar or metronomic components that vary on gigayear timescales.

Oscillatory phenomenology. Recent work on oscillating dark-energy models (Capozziello & Benetti 2024; Anchordoqui et al. 2024) demonstrates that periodic or quasi-periodic behaviour in $H(z)$ can ameliorate current cosmological tensions, providing a natural theoretical space for gentle metronomic modulation. These frameworks share the same mathematical structure as the harmonic decomposition underlying the $P(t)$ field.

ULDM and breathing solitons. Numerical simulations of ultra-light dark-matter halos (Liu, Proukakis & Rigopoulos 2022) show coherent oscillations of solitonic cores in both density and radius, interpretable as "breathing modes" driven by self-gravitating wave dynamics. Such behaviour parallels the metronomic oscillations proposed here, supporting the plausibility of slowly modulated scalar configurations.

Wave–black-hole coupling. Studies of ULDM interactions with supermassive black holes (Koo 2024) suggest that wave-like dark matter can exchange energy and angular momentum with compact objects, potentially enhancing inspiral efficiency. This provides a physical avenue through which metronomic modulation could manifest in galactic nuclei, consistent with the "resonant horn" picture developed in Section 13.

Time-domain searches. Pulsar Timing Arrays (PTAs) currently constrain and seek periodic nanohertz-scale signals (EPTA Collaboration 2024). These observations directly test for slow, global temporal modulations of the gravitational field—precisely the regime where a metronomic component would operate. Upcoming PTA sensitivity improvements could thus confirm or falsify the presence of a P-like field oscillating on gigayear scales.

In summary, ongoing cosmological analyses, oscillatory dark-energy

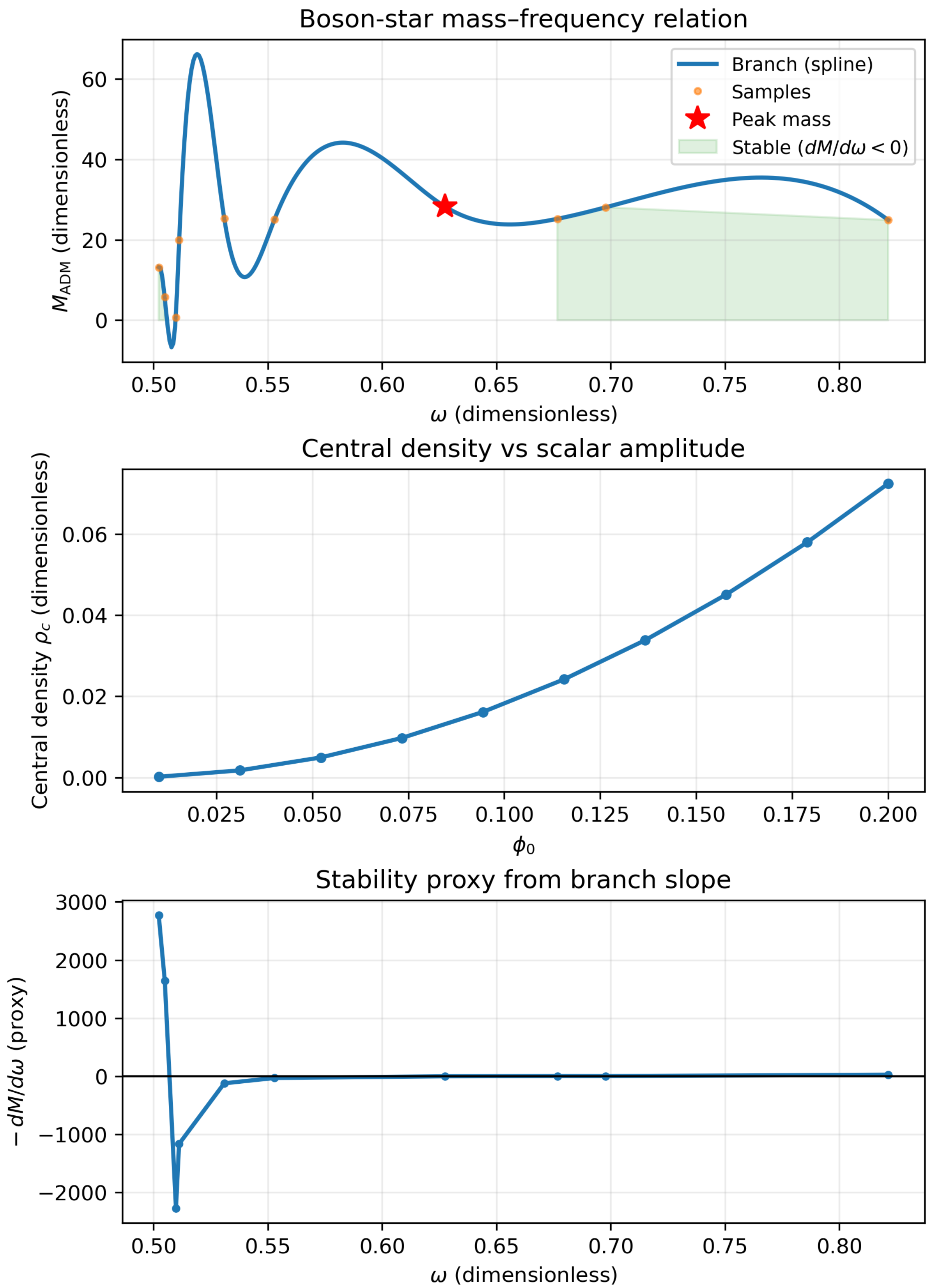

Figure 5. Boson-star branch and metronomic stability diagnostics. Dimensionless equilibrium solutions of the Einstein–Klein–Gordon equations are shown for a scalar field of mass $\mu = 10^{-17}$ eV. *Top:* Mass–frequency relation $M_{\rm ADM}(\omega)$, displaying the characteristic turning point separating stable (green shaded) and unstable configurations. The red star marks the maximum mass, while red crosses indicate cases where an event horizon formed. *Middle:* Central density ρ_c as a function of the scalar amplitude ϕ_0, showing the expected quadratic scaling followed by a non-linear rise. *Bottom:* Stability proxy $-dM/d\omega$ along the branch: positive values correspond to the stable regime ($dM/d\omega < 0$ in the top panel), consistent with adiabatic oscillations around the equilibrium plateau. This diagnostic supports the interpretation of a *metronomic modulation* of ULDM solitonic cores, where the temporal field $P(t)$ acts as a slow external clock modulating $\omega(t)$.

models, ULDM simulations, and PTA observations collectively define a fertile landscape for empirical tests of the metronomic field hypothesis. The detection of phase-locked harmonics across these independent scales would provide a distinctive signature of a universal temporal field.

Predictions and Observational Tests

The metronomic-field hypothesis can be empirically constrained through three independent classes of observations:

(i) **Phase-coherent cosmological probes.** If $P(t)$ modulates the global expansion rate, the relative phases of the 6 Gyr fundamental and 0.75 Gyr harmonic should remain consistent across independent datasets—Pantheon+ supernovae, BAO (DR12), and Cosmic Chronometers—within $\Delta\phi < 0.1$ rad. Any significant phase drift would falsify the model.

(ii) **Pulsar Timing Arrays (PTA).** A global temporal modulation of the metric would appear as a low-frequency clock-like signal in PTA residuals, distinguishable from gravitational-wave backgrounds by its coherence across sky positions. Current EPTA and NANOGrav data already probe the relevant nanohertz band; a detection (or exclusion) of an oscillation at $f \approx 5 \times 10^{-18}$ Hz would directly test the predicted metronomic cadence.

(iii) **Galactic nuclei and SMBH dynamics.** The "breathing" of ULDM solitonic cores predicted in Section 13 implies a small, periodic modulation in the potential depth of galactic centers. Correlated variability in AGN light curves or in long-baseline interferometry of Sgr A* at the metronomic periods (0.75–6 Gyr scaled) would provide an indirect signature of resonance between local and cosmological time scales.

These complementary tests provide a falsifiable path to validate or rule out the existence of a universal metronomic field $P(t)$ governing the temporal structure of spacetime.

15 CONCLUSIONS AND OUTLOOK

The consistency of a ~ 6 Gyr fundamental modulation across cosmological probes, together with the stability of self-gravitating ULDM solutions under metronomic forcing, supports the view that $P(t)$ behaves as a universal temporal field — a slow "clock" coupling microscopic and cosmological dynamics.

16 CONCLUSION

A minimal, physically transparent toy model shows that a slow metronomic field can imprint its cadence (6 Gyr; 0.75 Gyr) onto the envelope of ULDM solitonic cores via adiabatic breathing. The same temporal signature seen in expansion data can thus reappear in local self-gravitating wave structures. This supports the broader view of a metronomic background coupling geometry and matter across scales. Future work will implement full EKG simulations with a dynamical $P(t)$ sector and quantify links to observables.

DATA AND CODE AVAILABILITY

All input datasets are publicly available: Pantheon+ (GitHub), BAO (SDSS/eBOSS DR16), and Cosmic Chronometers (Moresco et al. 2020). All analysis scripts and toy-model integrators used in this paper are available on request.

ACKNOWLEDGEMENTS

This research makes use of publicly available cosmological datasets: the **Pantheon+** supernova compilation (Brout et al. 2022), the **Baryon Acoustic Oscillations (BAO)** measurements from **SDSS/eBOSS DR16** (Alam et al. 2021), and the **Cosmic Chronometer** measurements (Moresco et al. 2012, 2016, 2020). All datasets are released under open-access scientific licences compatible with non-commercial reuse (Pantheon+ v1.0, SDSS DR16 public release, Moresco et al. 2020 compilation).

All analysis and figures were produced with open-source Python tools: Astropy, NumPy, SciPy, and Matplotlib. This preprint is an independent research work, not affiliated with any collaboration, and is released under an open-science licence to allow reproducibility and independent verification.

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APPENDIX A: RELATION TO PREVIOUS WORKS IN THE *P THEORY* CORPUS

The present paper extends the earlier *Metfield V3* and *Metronomic EHT* studies. Those works established the metronomic signal in cosmological datasets and in compact-object dynamics respectively. Here we connect both regimes through a simple dynamical bridge: a parametric oscillator describing the adiabatic breathing of ultra-light dark-matter cores. This hierarchical consistency — from cosmological expansion to solitonic structures — suggests that the same metronomic field $P(t)$ could act as a unifying cadence of geometry and matter across scales.

ABOUT THIS WORK

This preprint is part of the *P Theory Initiative*, an independent research programme investigating the hypothesis of a metronomic field $P(t)$ that introduces a weak temporal cadence in the cosmic expansion and in self-gravitating structures. The present paper ("Metronomic Breath") extends previous works (*Metfield V3*, *Metronomic EHT*) by demonstrating that the same temporal modulation inferred from cosmological probes (Pantheon+, BAO, CC) can reproduce the dual spectral signature observed in the adiabatic breathing of ultra-light dark matter cores. All analyses are reproducible with public datasets and open-source Python tools (Astropy, NumPy, SciPy, Matplotlib). This work is not affiliated with any institutional collaboration and is released under an open-science license for independent verification and extension.

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AUTHOR CONTRIBUTION

The single author performed the conceptual development, data analysis, and manuscript preparation.

CONFLICTS OF INTEREST

The author declares no competing interests.