Anomalous Negative Integrated Sachs-Wolfe Effect from Evolving Metric Signature Boundaries in Cosmic Voids

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Abstract

Hansen et al. (2025) reported a highly significant achromatic CMB temperature anomaly in the local universe ($z < 0.03$): a temperature excess of 2.7σ–3.6σ in cosmic voids and a deficit exceeding 5σ in dense filaments, with an amplitude approximately ten times larger than standard ΛCDM Integrated Sachs-Wolfe (ISW) predictions. We show that this anomaly arises naturally if the metric signature of spacetime varies with local energy density, as proposed in a companion paper [Henderson, 2026a]. In regions where the phase parameter φ governing the metric component $g_{00} = -(1 - 2\varphi)$ evolves in time—specifically, at advancing phase boundaries where the Lorentzian signature weakens as voids expand and cool—the time derivative of the gravitational potential $\dot{\Phi}$ is enhanced relative to the standard ISW prediction. This enhanced $\dot{\Phi}$ produces a localised, anomalous negative ISW effect: CMB photons traversing the evolving boundary are achromatically blueshifted (heated) in voids and redshifted (cooled) in filaments. The predicted signal is inherently achromatic, preserving the blackbody spectrum, consistent with the Hansen et al. observations. The mechanism is supported by recent work of Alexandre, Gielen, and Magueijo (2024), who demonstrated that metric signature change across degenerate boundaries implies a change in the effective cosmological constant, providing the physical driver for the enhanced potential evolution. We identify specific observational tests, including the redshift dependence of the anomaly amplitude and its correlation with void expansion rate, capable of confirming or excluding this mechanism.

1. Introduction

The Integrated Sachs-Wolfe (ISW) effect [1, 2] describes the net energy change of a CMB photon traversing a time-evolving gravitational potential. In a matter-dominated universe, gravitational potentials are constant and the ISW contribution vanishes. In a dark-energy-dominated universe, potentials decay as structures are stretched by accelerated expansion, producing a small net blueshift for photons crossing overdensities and a small net redshift for photons crossing voids. The predicted amplitude in standard ΛCDM is of order $\Delta T \sim 1\text{–}10\ \mu K$, depending on the void or structure depth.

Hansen et al. [3] reported an observed signal that contradicts this prediction in both sign and magnitude. Cross-correlating Planck CMB temperature maps with local galaxy density fields at $z < 0.03$, they found a temperature excess (heating) of 2.7σ–3.6σ in cosmic voids and a temperature deficit (cooling) exceeding 5σ in dense filaments and halos. The mean temperature difference between void and galaxy lines of sight is approximately 41 μK. This is an order of magnitude larger than ΛCDM ISW predictions and, crucially, has the opposite sign for voids: standard ISW predicts void cooling, while Hansen et al. observe void heating.

The signal is achromatic across Planck and WMAP frequency bands (44–217 GHz), preserving the blackbody spectrum [3]. This achromaticity rules out thermal energy injection mechanisms such as the thermal Sunyaev-Zel'dovich (tSZ) effect [4], which produces characteristic y-type spectral distortions. The observed signal is consistent only with a gravitational frequency shift—a mechanism that uniformly scales all photon frequencies.

In a companion paper [5], we showed that a spatially varying metric signature—parameterised by $g_{00} = -(1 - 2\varphi)$ with φ correlated to local energy density—produces differential clock rates between voids and filaments consistent with the Seifert et al. [6, 7] Pantheon+ result ($\ln B > 5$ for differential expansion). That analysis treated φ as static within each region. In this paper, we consider the consequences of a time-evolving φ—specifically, the dynamical evolution of the phase boundary as voids expand and cool.

2. The Enhanced ISW Mechanism

2.1 Standard ISW review

The ISW temperature anisotropy is given by the line-of-sight integral [1]:

$$\Delta T/T = -(2/c^3) \int \dot{\Phi}\, d\lambda \quad (1)$$

where Φ is the Newtonian gravitational potential and the integral is along the photon's null geodesic parameterised by affine parameter λ. In standard ΛCDM, $\dot{\Phi}$ is determined by the competition between gravitational collapse (which deepens potentials) and dark energy (which stretches and shallows them). For voids in the late universe, ΛCDM predicts $\dot{\Phi} > 0$ (potentials decaying), producing a net redshift (cooling) for photons traversing voids.

2.2 Modified potential evolution from signature change

In the framework of [5], the effective gravitational potential in a region with phase parameter φ is modified. If φ is time-dependent—specifically, if the phase boundary is advancing as the void expands and cools—then $\dot{\varphi} \neq 0$, and the time derivative of the effective potential acquires an additional term:

$$\dot{\Phi}_{eff} = \dot{\Phi}_{\Lambda CDM} + \dot{\Phi}_{\varphi} \quad (2)$$

where $\dot{\Phi}_{\Lambda CDM}$ is the standard potential evolution from dark energy and $\dot{\Phi}_{\varphi}$ is the contribution from the evolving metric signature. The sign and magnitude of $\dot{\Phi}_{\varphi}$ depend on how the effective gravitational coupling changes as φ increases.

Alexandre, Gielen, and Magueijo [8] recently demonstrated that metric signature change across a degenerate boundary (g_{00} passing through zero) implies a change in both the sign and magnitude of the effective cosmological constant Λ. Specifically, the transition from Lorentzian to Euclidean signature is accompanied by a shift in the vacuum energy density. In our parameterisation, an increasing φ (advancing phase boundary) corresponds to a locally increasing effective Λ within the transitioning region.

A locally increasing Λ at the void boundary drives accelerated local expansion, which causes gravitational potentials to deepen more rapidly than in standard ΛCDM. This produces $\dot{\Phi}_{\varphi} < 0$—a negative contribution to the potential derivative. When this negative term dominates the standard positive $\dot{\Phi}_{\Lambda CDM}$, the total $\dot{\Phi}_{eff}$ changes sign. Photons traversing the void boundary experience a net blueshift rather than the standard redshift:

$$\Delta T/T = -(2/c^3) \int (\dot{\Phi}_{\Lambda CDM} + \dot{\Phi}_{\varphi})\, d\lambda > 0 \quad \text{when } |\dot{\Phi}_{\varphi}| > |\dot{\Phi}_{\Lambda CDM}| \quad (3)$$

The void appears hot. Conversely, in dense filaments where $\varphi \approx 0$ and $\dot{\varphi} \approx 0$, only the standard $\dot{\Phi}_{\Lambda CDM}$ operates. The filament appears cold by comparison. This is the observed Hansen phenomenology.

2.3 Achromaticity

The enhanced ISW mechanism is inherently achromatic. The gravitational frequency shift $\Delta\nu/\nu = \Delta\Phi/c^2$ applies uniformly to all photon frequencies. A blackbody spectrum passing through a region of evolving potential is uniformly rescaled to a blackbody at a different effective temperature. No spectral distortions of any kind (y-type or μ-type) are produced. This is a known, fundamental property of gravitational frequency shifts [9] and is consistent with the achromatic character of the Hansen anomaly across 44–217 GHz.

2.4 Amplitude

The standard ISW contribution in ΛCDM for local voids produces $\Delta T \sim 1$–10 μK. The observed Hansen anomaly is $\Delta T \sim 41$ μK—approximately ten times larger. For the enhanced mechanism to account for the discrepancy, we require:

$$|\dot{\Phi}\_\varphi| \approx 10 \times |\dot{\Phi}\_\Lambda\text{CDM}| \quad (4)$$

This implies that the rate of potential evolution driven by the advancing phase boundary must exceed the standard dark-energy-driven evolution by approximately one order of magnitude in the void boundary region. Whether this magnitude is achievable depends on the rate $\dot{\varphi}$, which is set by the void's cooling rate and the threshold energy density for the signature transition. A detailed calculation of $\dot{\varphi}$ from void expansion dynamics is beyond the scope of this letter and will be presented in future work.

We note, however, that the required enhancement is not unreasonable. The phase transition represents a qualitative change in the metric structure—a fundamentally different physical process from the gentle stretching of potentials by a cosmological constant. First-order phase transitions in condensed matter routinely produce dynamical effects orders of magnitude larger than the equilibrium background evolution, precisely because they involve the crossing of an energy barrier rather than smooth adiabatic change.

3. Consistency with Observations and Constraints

3.1 Spatial localisation

The enhanced ISW effect operates only at the advancing phase boundary—the transitioning region where $\dot{\varphi} \neq 0$. In the deep void interior (where φ may have already reached its equilibrium value and $\dot{\varphi} \approx 0$) and in dense filaments (where $\varphi \approx 0$ throughout), the standard ISW applies. The anomalous signal is therefore localised to the boundary layer between environments, not distributed throughout the void.

Hansen et al. [3] found that their anomaly is most pronounced for the largest voids ($R > 16.5$ Mpc). This is consistent with the phase boundary mechanism: larger voids have longer boundaries, more total boundary area, and greater integrated $\dot{\Phi}\_\varphi$ along the photon path.

3.2 Complementarity with the clock-rate mechanism

The companion paper [5] demonstrated that a static φ produces differential clock rates (a zeroth-order effect of $g_{00} \neq -1$). The present mechanism involves a time-evolving φ producing enhanced potential derivatives (a first-order effect of $\dot{\varphi} \neq 0$). These are mathematically independent: the clock-rate effect is an integral of proper time at fixed spatial position, while the

ISW effect is an integral of conformal time along a null geodesic. Both can operate simultaneously without contradiction.

Together, the two papers offer a unified account: the static void interior produces the differential expansion observed by Seifert et al. [6, 7] in the Pantheon+ dataset, while the dynamic void boundary produces the enhanced achromatic ISW signal observed by Hansen et al. [3] in the CMB.

3.3 GW170817

As shown in [5], the modified metric $g_{00} = -(1 - 2\varphi)$ produces identical phase velocities for electromagnetic and gravitational radiation. The relative speed constraint from GW170817 [10] ($|\Delta c|/c < 10^{-15}$) is automatically satisfied. The enhanced ISW effect operates through the time evolution of the potential, not through differential wave propagation speeds, and is therefore unconstrained by multi-messenger observations.

3.4 COBE/FIRAS constraints

The COBE/FIRAS instrument constrains the global y-parameter to $|y| < 1.5 \times 10^{-5}$ and the μ-parameter to $|\mu| < 9 \times 10^{-5}$ [11]. The enhanced ISW mechanism predicts $y = 0$ and $\mu = 0$ identically, since gravitational frequency shifts produce no spectral distortions. The prediction is trivially consistent with FIRAS bounds.

4. Distinguishing Tests

4.1 Redshift dependence of the anomaly

The enhanced ISW mechanism predicts that the void heating anomaly should be strongest at late times (low redshift), when voids are deepest and the phase boundary is most actively advancing. At higher redshifts, voids were shallower and the universe was denser; the phase transition would have been less advanced or absent. The anomaly amplitude should therefore decrease with increasing redshift.

Standard ΛCDM ISW also increases at late times (as dark energy dominates), but with a specific redshift profile governed by $\Omega_\Lambda(z)$. The phase boundary mechanism predicts a steeper redshift dependence, because the phase transition is threshold-dependent: below a critical density, $\dot{\varphi}$ activates sharply; above it, $\dot{\varphi} = 0$. This produces a sharper onset in redshift than the smooth $\Omega_\Lambda(z)$ profile.

4.2 Correlation with void expansion rate

The mechanism predicts that the ISW anomaly amplitude should correlate with the local void expansion rate. Voids that are currently expanding fastest have the most rapidly advancing phase boundaries (largest $\dot{\varphi}$), and should show the strongest temperature excess. This can be tested by cross-correlating the Hansen temperature maps with void peculiar velocity profiles from surveys such as CosmicFlows-4 [12].

Standard ISW predicts a correlation with potential depth, not expansion rate. These are related but not identical: a deep, slowly expanding void and a shallow, rapidly expanding void would produce similar standard ISW but different enhanced ISW signals. Separating these contributions requires velocity data independent of the temperature measurement.

4.3 Angular profile of the anomaly

The phase boundary mechanism localises the enhanced $\dot{\Phi}$ to the transition region between the void interior and the surrounding filaments. The temperature anomaly should therefore peak not at the void centre but at the void boundary—the shell where φ is actively evolving. Standard ISW, driven by potential decay throughout the void volume, predicts a more centrally concentrated signal.

This angular profile difference is testable with existing Planck data by stacking void temperature profiles and measuring whether the excess peaks at the centre (standard ISW) or at the effective radius (enhanced boundary ISW).

4.4 Spectral distortion test

As with the companion paper [5], the definitive test is spectral. The enhanced ISW mechanism predicts identically zero y-type and μ-type spectral distortions. Detection of non-zero spectral distortions in the void temperature anomaly by next-generation CMB spectroscopy missions (PIXIE [13], PRISTINE [14]) at amplitudes exceeding $\Delta y > 10^{-8}$ would exclude this mechanism as the primary driver.

5. Discussion

The mechanism presented here transforms the Hansen et al. CMB void anomaly from an unexplained observational puzzle into a specific prediction of evolving metric signature boundaries. The key physical insight is that the anomaly is not produced by literal thermal heating of the photon field, but by the gravitational blueshift arising from an enhanced time-derivative of the gravitational potential at an advancing phase boundary.

The theoretical foundation rests on three established results: (i) the ISW effect itself, a standard prediction of general relativity [1]; (ii) the Barbero formalism [15] and associated junction conditions [16, 17] for signature-changing metrics; and (iii) the Alexandre-Gielen-Magueijo result [8] demonstrating that signature change implies a shift in the effective cosmological constant. The synthesis of these three results—applying the Λ-shift from signature change as the driver of enhanced potential evolution in voids—appears to be novel.

The achromaticity of the predicted signal is a direct consequence of the gravitational nature of the mechanism. In the companion geometric framework [18], dark matter is not a kinetic particle species but a frozen field configuration—a projection of a higher-dimensional Ginzburg–Landau scalar field. Such frozen geometry gravitates but has no particle degrees of freedom capable of scattering photons chromatically. The absence of any non-gravitational coupling between the dark sector and the photon field guarantees that the ISW signal is the only channel through which the phase transition communicates with the CMB.

We acknowledge significant limitations. The rate $\dot{\varphi}$ has not been derived from first principles; the requirement that $|\dot{\Phi}_\varphi| \approx 10|\dot{\Phi}_{\Lambda CDM}|$ is a phenomenological constraint, not a prediction. A complete theory must specify the dynamics governing φ as a function of local energy density and cosmic time. Additionally, the connection between the Barbero-Immirzi parameter and the effective metric component g_{00} requires formal derivation rather than the effective parameterisation employed here.

These limitations notwithstanding, the mechanism provides: (i) the correct sign (void heating, filament cooling); (ii) the correct spectral character (achromatic, blackbody-preserving); (iii) the correct order of magnitude (given a single phenomenological parameter); and (iv) specific, falsifiable predictions distinguishing it from standard ISW and from competing explanations. No other proposed mechanism simultaneously satisfies all four of these constraints.

6. Conclusion

We have shown that an advancing metric signature boundary in cosmic voids—where the phase parameter φ governing g_{00} evolves in time as voids expand and cool—produces an enhanced, anomalous negative Integrated Sachs-Wolfe effect. The predicted signal is achromatic, has the correct sign (void heating, filament cooling), and requires a single phenomenological parameter ($\dot{\varphi}$ at the boundary) to match the observed amplitude of the Hansen et al. (2025) anomaly.

Combined with the companion result [5] that static φ produces differential clock rates consistent with the Seifert et al. Pantheon+ analysis, these two papers provide a unified geometric account of two major observational anomalies in the local universe. The static void interior drives differential expansion; the dynamic void boundary drives the anomalous CMB heating. Both arise from a single hypothesis: the metric signature of spacetime varies with local energy density.

If confirmed by the proposed tests—particularly the angular localisation of the anomaly at void boundaries and its correlation with void expansion rates—this result would provide direct observational evidence for an evolving metric signature in the late universe.

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