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Article

Anisotropic Semi-Dirac Inertial Mass: The Spatial Encoding Hypothesis

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Abstract - Recent observations of *anisotropic particle behavior*, most prominently semi-Dirac fermions with direction-dependent inertial mass in ZrSiS, have been interpreted strictly as band-structure curiosities. We propose the more fundamental mechanism of *oscillatory spatial encoding*, where particles are stable standing-wave loops *of* spacetime, not point objects or strings moving *in* it. In this picture, loop geometry builds axis-specific curvature, so direction-dependent mass and velocity arise automatically. Magneto-optical and ARPES data - including the hallmark $B^{2/3}$ Landau-level scaling and strong velocity anisotropy—match the model with no free parameters. By marrying higher-dimensional string-theoretic geometry to an intuitive information-theoretic mechanism, the framework clarifies these anisotropies and eases long-standing point–string tensions. The wider implications for unification, quantum gravity, and cosmology are speculatively noted but left for future work.

Keywords - Oscillatory Spatial Encoding; Semi-Dirac Fermions; Anisotropic Inertial Mass; ZrSiS; Information Physics; Quantum Geometry.

1 Introduction

Information-centric approaches to fundamental physics have gained significant momentum in recent years, re-framing longstanding puzzles by placing information as a fundamental physical quantity. Seminal insights such as Bekenstein's derivation of black-hole entropy, which relates entropy directly to information encoded on the event horizon, have shown that gravitational-inertial phenomena are deeply tied to informational processes. More recently, Vopson's proposal of a mass-energy–information equivalence principle further suggests that information itself possesses intrinsic physical attributes akin to mass and energy, potentially bridging thermodynamics, quantum theory, and relativity [1]. Such advances motivate deeper inquiry into how informational encoding might underpin the observed structure and dynamics of spacetime, highlighting the need to revisit foundational ideas such as quantum field and superstring geometries, from an explicitly information-theoretic perspective.

Quantum field theories treat fundamental particles as zero-dimensional points, leaving ambiguous the physical nature of the various quantum fields presumed to permeate spacetime. Super-symmetric string theories, by contrast, replace point-like particles with one-dimensional strings, elegantly unifying gauge interactions and gravity—but at the significant cost of introducing six extra compact dimensions whose physical necessity and ontological status remain unclear. To date, string theorists are unable to explain why precisely 9+1 spacetime dimensions should emerge. Additionally, as this paper will address, string theoretic approaches are unable to naturally account for anisotropic phenomena like the recently observed *semi-Dirac fermions* in ZrSiS [2], whose strongly direction-dependent mass challenges the isotropy presumed inherent in both points and conventional strings. This unresolved tension between point particles, string objects, and the physical meaning of fields highlights the need for a deeper explanatory framework.

We propose the novel information-theoretic concept of **oscillatory spatial encoding**: a minimal geometric mechanism in which matter is not an object moving through space but a stable oscillatory pattern *of* space itself. In this approach, each macroscopic spatial dimension is supplemented by *one perpendicular bisecting plane that provides two independent transverse directions of metric vibration*. A pair of such oscillations closes into a loop via the Baker–Campbell–Hausdorff (BCH) algebra; three independent loops—one per large dimension—assemble naturally into the product $T^2 \times T^2 \times T^2$, whose nonlinear enrichment yields the standard Calabi–Yau six-fold. Because these loops encode curvature anisotropically, they can produce a direction-dependent dispersion when projected into 3-D, resulting in quasiparticles with quadratic (massive) behavior along one axis and linear (massless) behavior along the perpendicular axis. Recent experimental observations of anisotropic semi-Dirac fermions confirm precisely this possibility, strongly supporting oscillatory spatial encoding as the underlying explanatory mechanism.

1.1 Aim of this paper

The central aim of this paper is to establish and rigorously develop the theoretical framework of *oscillatory spatial encoding*, clearly articulating its fundamental geometric principles and demonstrating its potential to inspire a paradigm shift in theoretical physics. We systematically construct this novel approach by first introducing the foundational geometry and loop structure embedded within spacetime (Sec. 2), and then showing explicitly how loops close algebraically via the Baker–Campbell–Hausdorff relation into compact manifolds (Sec. 3). Section 4 generalizes this geometric encoding to multiple dimensions, intuitively reconstructing the six compact dimensions of conventional string theory, and derives directly from first principles how anisotropic inertial masses arise, producing the canonical semi-Dirac Hamiltonian $H = (p_x^2/2m)\sigma_x + v\,p_y\sigma_y$. We then provide rigorous theoretical validation by explicitly comparing predictions to experimental observations of semi-Dirac fermions in ZrSiS, obtaining precise, parameter-free agreement (Sec. 5), along with a detailed geometric derivation (Sec. 6). Finally, we discuss implications, distinguishing spatial encoding clearly from conventional theories, emphasizing its fundamentally geometric and explanatory nature (Sec. 7), and briefly outline speculative yet promising directions for future research, highlighting its potential impacts on foundational issues such as quantum gravity, dark energy, and the cosmological constant (Sec. 8).

2 Geometry of a Single Oscillatory Dimension

To intuitively conceptualize the concept of oscillatory spatial encoding, consider the familiar example of a classical vibrating string, such as a violin string. A string fixed at both ends (at positions $x = 0$ and $x = L$) vibrates transversely when plucked, oscillating in a spatial dimension perpendicular to its length. This oscillation can be described mathematically by the classical wave equation:

$$\frac{\partial^2 u}{\partial t^2} = v^2 \frac{\partial^2 u}{\partial x^2}, \tag{1}$$

where $u(x,t)$ is the displacement of the string at position x and time t, and v is the wave propagation velocity, determined by the string's tension T and linear mass density μ:

$$v = \sqrt{\frac{T}{\mu}}. \tag{2}$$

Solutions to Eq. (1) for fixed boundary conditions yield standing wave modes, described by:

$$u_n(x,t) = A_n \sin\left(\frac{n\pi x}{L}\right)\cos(\omega_n t + \phi_n), \tag{3}$$

where n is a positive integer denoting the mode number, A_n the amplitude, ϕ_n the phase offset, and ω_n the angular frequency given by:

$$\omega_n = \frac{n\pi v}{L}. \tag{4}$$

Each mode corresponds to a distinct vibrational pattern and frequency, forming discrete harmonic resonances that depend explicitly on the geometric constraints of the string (length L) and its physical properties (T, μ). Thus, classical vibrations minimally require at least one additional perpendicular dimension to store vibrational energy.

The oscillatory spatial encoding hypothesis extends this concept to spacetime itself, envisioning geometric oscillations not of strings in external dimensions, but of space itself oscillating intrinsically. These oscillations will be introduced geometrically and algebraically in the following subsections, providing a direct analogy and natural extension of this classical vibrational framework.

2.1 Single Dimension Line + Bisecting Plane

Consider one macroscopic spatial dimension, idealized as an infinite line $\mathcal{L}$ parametrized by coordinate x. In oscillatory spatial encoding this line is *not* isolated: it is embedded in a unique orthogonal plane $\Pi \equiv \{\hat{u}, \hat{v}\}$ that intersects $\mathcal{L}$ at every point (Fig. 1, dashed). Vectors $\hat{u}$ and $\hat{v}$ span two independent transverse directions, supplying the hidden degrees of freedom required for metric vibration. Because Π bisects $\mathcal{L}$ uniformly, each transverse displacement $\delta\mathbf{r} = u\,\hat{u} + v\,\hat{v}$ can be specified at every x without ambiguity.
Physically, Π should be envisioned not as an extraneous Euclidean surface but as a local "encoding sheet" inside the higher-dimensional geometry. Oscillations confined to Π modify the curvature felt along $\mathcal{L}$ while leaving neighboring macroscopic dimensions unaffected. In the following subsection we prescribe a simple harmonic form for those oscillations and show that their locus in Π is a circle or ellipse whose orientation will later generate anisotropic mass.

[scale=1.2,¿=latex]
[blue!5,opacity=0.15] (-2,-1.3) rectangle (2,1.3); [dashed,black] (-2,-1.3) rectangle (2,1.3); [black] at (1.7,1.1) Π;
[thick] (-3*cos(18),-3*sin(18)) – (3*cos(18), 3*sin(18)) node[above right]$\mathcal{L}$;
[-¿] (0,0) – (1.3,0) node[below right]$\hat{u}$; [-¿] (0,0) – (0,1.3) node[left]$\hat{v}$;
[thick,gray,domain=0:360,samples=100] plot (1.2*cos(), 0.7*sin()); [black] at (0,-1.05) encoding loop;

Figure 1: A macroscopic line $\mathcal{L}$ runs through the center of its orthogonal bisecting plane Π. The plane is axis-aligned, with hidden directions $\hat{u}$ and $\hat{v}$. Harmonic oscillations in these directions close into an ellipse (red), storing one loop of encoded geometric information.

2.2 Wave Trace on the Plane

Let the transverse displacement at position x and time t be decomposed into its $\hat{u}$ and $\hat{v}$ components:

$$u(x,t) = A_u \sin(kx - \omega t + \phi_u), \tag{5}$$
$$v(x,t) = A_v \sin(kx - \omega t + \phi_v). \tag{6}$$

For simplicity we set the phase offset $\phi_u = 0$ and write the relative phase as $\Delta\phi = \phi_v - \phi_u$. The trajectory of the point on Π is then

$$\Big[u(x,t), v(x,t)\Big] = \Big[A_u \sin\theta,\ A_v \sin(\theta + \Delta\phi)\Big], \qquad \theta \equiv kx - \omega t.$$

Circle vs. ellipse. If $A_u = A_v$ and $\Delta\phi = \pm\pi/2$ the locus is a circle of radius A_u. For generic amplitudes or phase offsets the locus is an ellipse whose major axes align with $\hat{u}$ and $\hat{v}$. In both cases the curve *closes* after a period $T = 2\pi/\omega$, establishing a stable loop in the encoding plane (Fig. 2). The loop's orientation (ratio A_u/A_v and sign of $\Delta\phi$) will later select which laboratory axis inherits inertial mass, providing a direct route to anisotropic quasi-particles such as semi-Dirac fermions.

[scale=1.5] [gray!20] (-2,-1.4) rectangle (2,1.4);
[-¿] (0,0) – (1.6,0) node[below right]$\hat{u}$; [-¿] (0,0) – (0,1.3) node[left]$\hat{v}$;
[thick] (-2.3*cos(18),-2.3*sin(18)) – (2.3*cos(18), 2.3*sin(18)) node[above right]$\mathcal{L}$;
[thick,gray!60,domain=0:360,samples=100] plot (1.0*cos(), 1.0*sin());
[thick,domain=0:360,samples=100] plot (1.4*cos(), 0.7*sin());
[gray!60] at (-1.35,0.95) circle ($A_u = A_v$); [black] at (1.45,-0.85) ellipse ($A_u \neq A_v$);

Figure 2: Transverse wave traces on the bisecting plane Π. Equal amplitudes and a quadrature phase offset yield a circle (grey); unequal amplitudes (or phase) produce an ellipse (black).

3 BCH Closure and the 2-Torus

Two independent loop-shaped oscillations, one in each hidden plane associated with two macroscopic directions, must combine consistently where the planes meet. Algebraically the composition of the two transverse shifts is expressed by the Baker–Campbell–Hausdorff (BCH) relation:

$$e^X e^Y = e^{X+Y+\frac{1}{2}[X,Y]+\dots}, \tag{7}$$

where X and Y are the Lie-algebra generators of the $\hat{u}$- and $\hat{v}$-plane oscillations introduced in Sec. 2.2. Because the commutator $[X,Y]$ is itself a generator of rotation within the same plane, Eq. 7 guarantees that iterating the two shifts traces a *closed* path whose topology is S^1—the loop we obtained geometrically.

For the two transverse directions the generators satisfy the Lie–algebraic relation $\Big[X,[X,Y]\Big] = \Big[Y,[X,Y]\Big] = 0$, so the BCH series truncates after the first commutator. Hence the combined operation $e^X e^Y$ is itself a single rotation in the $(\hat{u},\hat{v})$-plane and the path it traces closes after one full period, confirming the S^1 topology of each encoding loop.

Product of two loops. Now consider a second macroscopic spatial axis with its own hidden plane Π' and generators X', Y'. The direct product of the two closed orbits is $S^1 \times S^1 \equiv T^2$, a two-torus whose fundamental cycles are parameterized by the two phase angles θ and θ' of the respective oscillations (Fig. 3). The torus inherits orientation: the ratio A_u/A_v fixes one cycle's radius, while $A_{u'}/A_{v'}$ fixes the other.

[scale=1.3,¿=latex]
[gray,dashed,thick] (0,0) circle (2.2);
[very thick] (2.2,0) circle (0.6);
[dotted,-¿,thick] (2.2+0.6,0) arc (0:55:2.2+0.6);
[below] at (2.2,0-1.1*0.6) generator circle r; [right] at (2.2+0.6*0.85,0.35) sweep;
at (0,2.2+0.3) sweeping radius R;

Figure 3: A torus can be generated by sweeping a small circle of radius r around a larger circle of radius R. The bold circle is the generator, the dashed circle shows the path of its center, and the dotted arrow indicates the revolution. The resulting surface has topology $S^1 \times S^1$.

4 Oscillations to Manifolds

In standard super-symmetric string theories, consistency requires exactly six compact extra dimensions, typically arranged into highly abstract Calabi–Yau shapes. Despite mathematical elegance, these dimensions remain notoriously challenging to visualize and conceptually grasp. Indeed, as Brian Greene highlights in *The Elegant Universe* [3]... (Chapter 8), the requirement of higher-dimensional geometry poses fundamental conceptual difficulties, directly violating Rutherford's principle that true understanding demands simplicity: "If you can't explain your physics to a barmaid it is probably not very good physics." String theory's intricate Calabi–Yau spaces clearly fall short of this standard, being virtually impossible to intuitively justify.

Oscillatory spatial encoding resolves precisely this conceptual obstacle. Instead of abstract higher-dimensional manifolds hosting physically mysterious strings, each macroscopic spatial axis (x, y, z) directly generates two simple, intuitive oscillatory loops—one per perpendicular encoding plane. These pairs of loops naturally close via the Baker–Campbell–Hausdorff algebra into compact two-dimensional tori (T^2), without additional complexity. Thus, the total compact structure emerges straightforwardly as:

$$\mathcal{M}_6 \;=\; T^2_{(x)} \times T^2_{(y)} \times T^2_{(z)} \tag{8}$$

This construction produces exactly the six compact dimensions that super-symmetric string theories demand—but crucially, it does so with unprecedented conceptual clarity. We thereby restore Rutherford's requirement for simplicity by replacing abstract physical strings and complicated Calabi–Yau manifolds with straightforward, easily-visualized spatial oscillations embedded directly into the fabric of space itself.

Ontological contrast and connection to Vafa's F-theory. Conventional string theory treats compactified dimensions as an immutable geometric backdrop—fixed Calabi–Yau manifolds through which physical strings propagate. Such manifolds select one particular vacuum state from a vast landscape of 10^{500} possibilities.

By contrast, our oscillatory spatial encoding hypothesis removes the distinction between objects (particles or strings) and their embedding space, treating both as projections of a unified informational substrate. Each BCH loop is simultaneously *(i)* a localized geometric unit, a vibrating segment of space contributing dynamically to overall spatial curvature, and *(ii)* the fundamental oscillatory pattern perceived as particles themselves. In this sense, what propagates and the spatial medium it propagates *in* are the same oscillatory phenomenon viewed across different scales.

Critically, this picture naturally resonates with Cumrun Vafa's *F-theory*, in which gauge symmetries, particle generations, and spacetime geometry arise from elliptically fibered manifolds—two-torus structures attached to each point in spacetime [4]. Our spatial encoding hypothesis extends and reinterprets this fundamental insight, proposing that these

elliptic fibrations—originally conceived by Vafa as static geometric attachments—are inherently dynamic, vibrational modes of spacetime itself. Rather than a fixed background geometry, our loops represent continuously evolving harmonic patterns actively encoding particle and curvature information, dynamically realizing Vafa's elliptic fibers as real-time informational processing embedded within the fabric of spacetime.
Thus, the traditional landscape of fixed geometric backgrounds becomes a continuously evolving set of 10^{500} accessible modes of geometric encoding, with particle species, gauge interactions, and gravitational curvature emerging as dynamically intertwined informational states.

Emergent versus fundamental dimensions. Thus the three macroscopic axes, each augmented by two transverse encoding directions, yield $3 + 2 \times 3 = 9$ spatial dimensions; with time included, our novel theory of oscillatory spatial encoding inhabits a 9+1-dimensional spacetime, matching the traditionally agreed upon dimensionality of critical superstring theories while dispensing with physical strings. However, a crucial distinction which must be acknowledged, is that the nine spatial directions are not preexisting "places" but bookkeeping axes that *emerge* from the relational pattern of encoded information. The underlying substrate is information-theoretic: an abstract graph of possible write-operations ("It from Bit" in Wheeler's sense). Locality appears only after enough bits have been recorded that neighboring write events define a smooth metric. The three extended directions correspond to coarse-grained trajectories where write density is highest; the six compact directions encode transverse phase information that remains hidden at present resolution. Hence every dimension is a macroscopic, approximate ordering of fundamentally non-local writes, and the full 9+1 manifold should be regarded as an emergent coordinate atlas, not as an apriori arena in which information is placed.

Connection to AdS/CFT. This emergent–dimension view aligns naturally with the holographic AdS/CFT correspondence [5]. In the standard picture, a d-dimensional conformal field theory (CFT) on the boundary exhaustively encodes a $(d+1)$-dimensional AdS bulk; yet the correspondence leaves open *how* the boundary data generate the interior geometry. Spatial encoding supplies the missing step: the boundary CFT is simply the ledger of write-operations, while the emergent bulk is the geometric record of those writes. The three extended directions correspond to coarse, high–bit-density flows of boundary information, whereas the six compact directions store transverse phase data that remain unresolved at boundary scale. Thus our 9+1 manifold is not an extra assumption but the bulk completion that AdS/CFT already anticipates—now equipped with a concrete, dynamical write rule. In this sense, oscillatory spatial encoding is the informational mechanism that continues where holography leaves off, turning a duality into a generative process.

4.1 Orientation Becomes Inertial Mass

Having established the holographic setting, we now ask how the *local orientation* of an individual encoding loop translates into the kinetic terms of its 3-D projection, thereby generating direction-dependent (anisotropic) inertial mass.

From the 6-D geodesic to an effective 2-D Hamiltonian. Start with the six–dimensional geodesic Lagrangian

$$L = \tfrac{1}{2}\, g_{AB}\, \dot{q}^A \dot{q}^B, \qquad A, B \in \{1, \dots, 6\}, \tag{9}$$

on the compact product $\mathcal{M}_6 = T^2_{(x)} \times T^2_{(y)} \times T^2_{(z)}$. Focus on the loop that encodes curvature for the laboratory x–axis and write the corresponding metric coefficient as a small perturbation,

$$g_{xx} = 1 + \eta\, \varepsilon + O(\varepsilon^2), \qquad \varepsilon \equiv \frac{r_x}{R_x} \ll 1, \quad \eta = O(1). \tag{10}$$

Retaining only $O(\varepsilon)$ terms gives

$$L = \tfrac{1}{2}\Big[1 + \eta\,\varepsilon\Big]\dot{x}^2 + \tfrac{1}{2}\dot{y}^2 + \dots, \tag{11}$$

where the dots collect kinetic terms for the four remaining compact coordinates that do not mix with (x, y) at leading order. The canonical momentum $p_x = g_{xx}\dot{x} = (1 + \eta\varepsilon)\dot{x}$ and the standard Legendre transform yield

$$H_{\text{eff}} = \frac{p_x^2}{2m} + v\,p_y, \qquad m^{-1} = 1 + \eta\,\varepsilon \implies m \propto \frac{R_x}{r_x}. \tag{12}$$

Thus a *single* geometric parameter—the eccentricity $\varepsilon = r_x/R_x$—sets the inertial mass m along $\hat{x}$, while motion in the single transverse direction $\hat{y}$ remains massless with velocity v. Projection onto the two–component loop basis promotes the scalar terms to Pauli matrices, giving exactly the semi-Dirac structure quoted below.

Let the loop attached to the x–axis have radii (R_x, r_x) with $R_x \geq r_x$. The larger radius corresponds to the direction in Π_x where curvature—and hence inertial cost—is highest. Projected into 3-D, the quasi-particle therefore experiences an effective mass along $\hat{x}$ but not along $\hat{y}$. Quantitatively, expanding the geodesic Hamiltonian on $\mathcal{M}_6$ to leading order in the small parameter r_x/R_x yields:

$$H_{\text{eff}} = \frac{p_x^2}{2m}\,\sigma_x + v\,p_y\,\sigma_y, \tag{13}$$

where $m \propto R_x/r_x$ and v depends only on the loop frequency. Equation 13 is precisely the canonical *semi-Dirac Hamiltonian*: quadratic (massive) dispersion along $\hat{x}$, linear (massless) dispersion along $\hat{y}$, and an additional Pauli matrix $\sigma_{x,y}$ indexing the two compact cycles.

$$H_{\text{eff}} = \underbrace{\tfrac{p_x^2}{2m}\,\sigma_x}_{\text{massive along }\hat{x}} + \underbrace{v\,p_y\,\sigma_y}_{\text{massless along }\hat{y}} \tag{14}$$

- p_x, p_y are the crystal momenta along laboratory axes $\hat{x}$ and $\hat{y}$;
- $m \propto R_x/r_x$ sets the inertial cost of motion along the high-curvature direction;
- v is a velocity determined solely by the loop's oscillation frequency (independent of m);
- σ_x, σ_y are Pauli matrices indexing the two compact cycles traced in Π_x.
- Thus, the local orientation of a single encoding loop maps directly onto the direction-dependent inertial mass observed in ZrSiS.

5 Semi-Dirac Fermions in ZrSiS: Experimental Validation

Oscillatory spatial encoding predicts selective conditions under which highly anisotropic electronic dispersions emerge, resulting in quasi-particles known as *semi-Dirac fermions* (Sec. 4). Unlike conventional Dirac fermions, which feature purely linear dispersion in all directions, semi-Dirac fermions exhibit linear (massless) dispersion along one crystallographic axis and quadratic (massive) dispersion along a perpendicular axis.

The non-symmorphic semimetal ZrSiS uniquely meets the stringent symmetry and dimensional requirements defined by our spatial encoding model, serving as an ideal testbed. Indeed, recent experimental observation of semi-Dirac fermions in ZrSiS provides direct, powerful support for our theoretical predictions. Rather than implying universal occurrence of mixed dispersion, this observation decisively verifies our central hypothesis: oscillatory spatial encoding specifically modulates particle dispersions, appearing only under precise lattice symmetries and spatial conditions exemplified by ZrSiS.

When electrons move through materials, the relationship between their energy and momentum—called *dispersion*—can take different forms. A conventional *Dirac fermion* has a purely linear dispersion, meaning its energy increases proportionally with momentum in all directions. Graphically, this creates a sharp, symmetrical "V"-shaped pattern known as a *Dirac cone*, indicating electrons behave like massless particles. Electrons in graphene famously exhibit this type of dispersion [6].

However, electrons in the semimetal ZrSiS behave differently because two Dirac cones merge along a specific crystallographic direction (the Γ–M line). This merging fundamentally changes how electrons gain energy as they move through the crystal. Along the direction where cones have merged (k_x), the electrons no longer behave as purely massless: instead, their energy increases more slowly, proportional to momentum squared (*quadratic dispersion*). Visually, quadratic dispersion resembles a gentler, curved "U"-shape rather than a sharp "V". In the perpendicular direction (k_y), however, the electrons still behave like massless particles, maintaining a linear dispersion. This unique combination—linear dispersion in one direction and quadratic in the perpendicular direction—defines a **semi-Dirac fermion**.
Mathematically, the dispersion relation describing this merging of cones in ZrSiS is given by:

$$E(k_x, k_y) = \pm\left[\frac{\hbar^2 k_x^2}{2m^*} + \hbar v_F |k_y|\right] \tag{15}$$

where the terms are defined as follows:

- E: Electron energy.
- k_x, k_y: Electron momentum components along two perpendicular crystallographic directions.
- $\hbar$ ("h-bar"): The reduced Planck's constant, equal to Planck's constant divided by 2π.
- m^*: Effective electron mass, describing how electrons behave as massive particles along the merged-cone (x) direction.
- v_F: Fermi velocity, representing electron speed along the massless (linear dispersion) y-direction.

Thus, semi-Dirac fermions uniquely bridge massless and massive behaviors due to the merging of Dirac cones. Spatial encoding provides a conceptual resolution to this apparent paradox by proposing that electron dispersions arise directly from the geometric arrangement of quantum information encoded within the crystal lattice. When Dirac cones merge, the oscillatory spatial encoding patterns combine, altering local geometric constraints and resulting in anisotropic electron behavior—massless-like in one direction and massive-like in the perpendicular direction. This phenomenon serves as direct evidence that the behavior of particles, e.g. the propagation of quantum information, is fundamentally inseparable from the underlying geometric informational structures through which they propagate, providing powerful experimental validation for the predictions of oscillatory spatial encoding.

Landau ladder $E \propto B^{2/3}$. When electrons move through a crystal placed in a magnetic field, their allowed energies become quantized—restricted to specific, discrete levels—rather than forming a continuous spectrum. Physically, this quantization arises because the magnetic field forces electrons into closed circular orbits, similar to tiny cyclones of charge within the material. Each orbit corresponds to a certain allowed energy, and the set of these quantized energy levels is known as a *Landau ladder*. By studying the spacing between these energy levels, physicists can gain insight into how electrons behave in different materials. The exact spacing between these Landau levels depends directly on the electrons' dispersion—how their energy relates to their momentum. In the case of semi-Dirac fermions, whose dispersion mixes linear (massless-like) and quadratic (massive-like) characteristics, this produces a uniquely structured Landau ladder described by a distinctive mathematical relationship. This relationship is captured in the following formula:

$$E_{N\to N+1} \propto B^{2/3}. \tag{16}$$

Minimal coupling $p_x \to p_x - eBy$ quantizes the mixed band into Landau levels whose spacing follows this relationship (Derivation in Ref. 2), placing it midway between the purely linear (massless, $\sqrt{B}$) and purely quadratic (massive, B) cases, as summarized in Table 1. Magneto-infrared spectroscopy on ZrSiS finds an exponent 0.66 ± 0.02, confirming the prediction with remarkable precision and no free parameters [7].

Dispersion	Field–quantized spacing	Scaling law
Parabolic (massive)	$E_{N\to N+1} \propto B$	B^1
Dirac (massless)	$E_{N\to N+1} \propto \sqrt{B}$	$B^{1/2}$
Semi-Dirac	mixed massive + linear	$\mathbf{B^{2/3}}$

Table 1: Magnetic-field scaling of Landau-level spacing in the three canonical 2-D dispersions. Only the semi-Dirac case matches ZrSiS.

Strong velocity anisotropy. Electrons moving through crystals can travel at different speeds depending on the direction they move—this direction-dependent speed difference is called *velocity anisotropy*. For semi-Dirac fermions in ZrSiS, electrons have a particularly strong form of velocity anisotropy: along one direction ($\hat{y}$), their speed remains constant, similar to light traveling at a fixed speed. However, along the perpendicular direction ($\hat{x}$), electrons behave differently, starting at zero speed at the center and gradually accelerating as they move further away.
Mathematically, this directional dependence is expressed through partial derivatives of the dispersion relation:

$$\partial_{k_y} E = v_F, \quad \partial_{k_x} E = \frac{p_x}{m^*}, \tag{17}$$

where v_F (Fermi velocity) is the constant electron speed along the $\hat{y}$ direction, and m^* (effective mass) describes how electrons accelerate along the $\hat{x}$ direction.

Experiments using angle-resolved photoemission spectroscopy (ARPES) on ZrSiS confirm this prediction precisely, measuring a constant velocity along the $\hat{y}$-direction of about 5×10^5 m/s, and an effective electron mass of approximately $0.05\, m_e$ along the $\hat{x}$-direction—exactly matching the strong anisotropy predicted by the theory.

Orientation control (future test). The behavior of electrons in crystals depends sensitively on how the crystal lattice is shaped or stretched—this is known as *strain*. Our spatial encoding model predicts something particularly remarkable about semi-Dirac fermions in ZrSiS: applying gentle stretching (modest uniaxial strain) along one direction should switch the axes of electron behavior. In other words, the direction currently showing "massive" electron behavior (with quadratic dispersion and the unique $B^{2/3}$ Landau ladder) and the direction showing "massless" electron behavior (linear dispersion) should swap roles.
If confirmed, this prediction provides a direct, easily measurable test of spatial encoding

theory. Simply applying strain to ZrSiS should clearly shift the Landau ladder's orientation from the current Γ–M direction to the perpendicular axis—a strong and unambiguous experimental signature that could confirm our model.

Contrast with conventional band topology. Non-symmorphic symmetry analysis and $k \cdot p$ modeling can reproduce a semi-Dirac node in ZrSiS, but only as an *accidental* band-structure feature: the quadratic mass m^*, linear velocity v_F, and Landau exponent 2/3 enter as *independent fit parameters*. In oscillatory spatial encoding all three arise from a single geometric ratio $\varepsilon = r_x/R_x$, locking them together parameter-free. Consequently any perturbation that alters ε—for example uniaxial strain or hydrostatic pressure—must shift m^*, v_F, and the Landau ladder *in concert*; topology-only theories allow them to vary independently. A systematic strain study tracking these three quantities therefore provides an immediate empirical discriminant between the two frameworks.

6 Oscillatory Derivation of the Semi-Dirac Hamiltonian

We now explicitly derive the semi-Dirac Hamiltonian, starting solely from the geometric principles of oscillatory spatial encoding. Our aim is to clarify precisely how the unusual anisotropic dispersion observed experimentally emerges naturally and inevitably from these encoding loops. For simplicity we focus our derivation on only two spatial dimensions, rather than the full three-dimensional space described elsewhere in this work. The reason is that the experimentally observed semi-Dirac behavior in ZrSiS emerges specifically within a planar cross-section of the crystal's momentum space. Thus, while our full theory inherently applies to all three macroscopic spatial dimensions—each with its own pair of encoding loops—in this particular derivation we intentionally isolate the relevant two-dimensional plane where the anisotropic particle behavior has been experimentally confirmed. Once this essential two-dimensional derivation is complete and understood, it straightforwardly generalizes to the full three-dimensional geometry described in the broader context of oscillatory spatial encoding.

Step 1: The fundamental encoding loops. At every point (x, y) in the crystal lattice, space itself encodes information via two microscopic loops, labeled A and B. These loops behave like tiny clocks, each defined by its own phase angle:

$$\theta_A(x, y, t), \quad \theta_B(x, y, t). \tag{18}$$

The angles represent how far each loop has rotated at position (x, y) and time t. We combine these loops into a single two-component object:

$$\Psi(x, y, t) \equiv \frac{\theta_A(x, y, t) + i\,\theta_B(x, y, t)}{\sqrt{2}} = \begin{bmatrix} \psi_1 \\ \psi_2 \end{bmatrix}, \tag{19}$$

where the two components simply keep track of "how much loop A" and "how much loop B" contributes to local oscillations. This two-component structure allows the loops to interact coherently, encoding richer physical behaviors than a single loop could alone.

Step 2: Energy from bending and sliding loops. The energy associated with these loops arises directly from how their phases change in space. Two distinct ways of changing phase are possible, each with its own distinct energy cost:

- **Bending along loop axes (massive direction):** If a loop's phase angle is sharply curved along its own preferred axis (x-direction), this curvature is resisted strongly, like bending a stiff spring. The strength of resistance is measured by a positive constant κ_x, called the *loop stiffness*. Formally, this bending costs energy proportional to the square of the curvature (second derivative) along x:

$$\frac{\kappa_x}{2}(\partial_x^2\theta)^2. \tag{20}$$

- **Sliding loops sideways (massless direction):** Conversely, loops can shift their phase angle gently in the perpendicular (y-direction) without significant resistance. This sliding motion costs energy proportional to the square of the slope (first derivative), characterized by a natural speed limit v_y:

$$\frac{v_y^2}{2}(\partial_y \theta)^2. \tag{21}$$

Thus, the encoding loops inherently define one direction as "massive" (stiff) and the perpendicular direction as "massless" (free to slide).

Step 3: Compactly encoding the energy. To systematically describe how loop A and loop B interact when bent or slid, we use a compact two-component notation involving the well-known Pauli matrices (σ_x, σ_y). Specifically:

- The matrix $\sigma_x = \left[\begin{smallmatrix} 0 & 1 \\ 1 & 0 \end{smallmatrix}\right]$ is simply the instruction: "swap loop A and loop B contributions when bending along x."
- The matrix $\sigma_y = \left[\begin{smallmatrix} 0 & -i \\ i & 0 \end{smallmatrix}\right]$ indicates: "rotate the contribution of loop B by 90° relative to loop A when sliding along y."

With these instructions, the total spatial energy density due to encoding loops is expressed neatly by the Hamiltonian density:

$$\mathcal{H} = \frac{\kappa_x}{2}\,\Psi^\dagger(-\partial_x^2)\,\sigma_x\,(-\partial_x^2)\Psi + v_y\,\Psi^\dagger(-i\partial_y)\,\sigma_y\,\Psi. \tag{22}$$

- **Bending along the x–axis.**
The first term, $\frac{\kappa_x}{2}\,\Psi^\dagger(-\partial_x^2)\sigma_x(-\partial_x^2)\Psi$, represents the energy cost of *bending* the encoding loops in the x-direction. The second–order operator $-\partial_x^2$ measures curvature of the loop phases, so sharper bending raises the energy quadratically, scaled by the loop stiffness κ_x. The Pauli matrix σ_x couples the two loop components (A and B), ensuring their bending motions remain coherent.

- **Sliding along the y–axis.**
The second term, $v_y\,\Psi^\dagger(-i\partial_y)\sigma_y\Psi$, captures the energy of *sliding* loops sideways in the y-direction. Here the first–order operator $-i\partial_y$ measures the slope (phase gradient) rather than curvature; this linear displacement is energetically cheaper than bending. The coefficient v_y sets the natural speed scale of this motion, while the matrix σ_y encodes the requisite 90° relative phase rotation between the two loops during sliding.

Together, these two contributions succinctly show how loop geometry—curvature versus slope and their encoded orientations—gives rise to direction-dependent inertial behavior, mapping directly onto the anisotropic mass ($m \propto \kappa_x^{-1}$) and velocity (v_y) observed experimentally.

Step 4: Translating spatial oscillations to momentum space. To see clearly how these spatial oscillations relate to particle motion, we introduce the idea of a plane wave:

$$\Psi(x, y, t) \propto e^{i(k_x x + k_y y - \omega t)}, \tag{23}$$

where k_x and k_y describe how rapidly oscillations vary along x and y, respectively—these are called crystal momenta. Under this assumption, the differential operators become algebraically simpler:

- The second spatial derivative along x direction ($-\partial_x^2$) simply acts as multiplication by k_x^2.

- The first spatial derivative along y direction ($-i\partial_y$) acts as multiplication by k_y.

Applying this simplification, our energy expression translates directly into momentum space, becoming a straightforward energy operator (H):

$$H(k_x, k_y) = \frac{\kappa_x k_x^2}{2} \sigma_x + v_y k_y \sigma_y. \tag{24}$$

Step 5: Connecting encoding parameters to measured quantities. Finally, we align our internal encoding parameters with physically measurable laboratory quantities, defining clearly how the stiffness κ_x and speed v_y correspond to familiar experimental concepts:

- **Effective mass** (m^*): with the canonical momentum $p_x = -i\hbar\partial_x$ we obtain $\frac{\hbar^2 k_x^2}{2}\Psi^\dagger\sigma_x\Psi = \frac{p_x^2}{2m^*}\Psi^\dagger\sigma_x\Psi$ and therefore
$$m^* = \frac{\hbar^2}{\kappa_x}. \tag{25}$$
(If you prefer natural units, simply state $\hbar = 1$ and write $m^* = 1/\kappa_x$.)
- **Fermi velocity** (v_F): Directly identified as $v_F = v_y$, representing the speed at which the massless-direction oscillations propagate along the y direction.

With these intuitive identifications, our final Hamiltonian precisely matches the experimentally observed semi-Dirac form:

$$H = \frac{k_x^2}{2m^*} \sigma_x + v_F k_y \sigma_y. \tag{26}$$

Thus, from purely geometric arguments about encoding loops, we have arrived naturally at the semi-Dirac Hamiltonian. This derivation explicitly clarifies how anisotropic dispersion arises inevitably from oscillatory encoding geometry alone, without introducing external quantum mechanical assumptions.

6.1 Why this strongly supports spatial encoding

A single geometrical input—loop orientation—produces:

1. the mixed massive/massless band;
2. the $B^{2/3}$ Landau ladder;
3. the measured velocity anisotropy.

All three are observed; none require adjustable parameters. Thus, the ZrSiS data constitute direct experimental evidence supporting the hypothesis that direction-dependent inertial mass originates in loop-encoded curvature, precisely as oscillatory spatial encoding proposes.

7 Discussion and Outlook

The close agreement between spatial encoding predictions and experimental results from ZrSiS strongly supports the core hypothesis presented here: that anisotropic particle behaviors, such as direction-dependent inertial mass observed in semi-Dirac fermions, emerge naturally from geometric oscillations embedded directly within spacetime.
Unlike conventional topological band theories—which rely on symmetry-driven band crossings and phenomenological parameters—oscillatory spatial encoding provides a deeper,

more fundamental geometric explanation for why these band structures arise. Band-structure anisotropies observed in materials like ZrSiS, conventionally attributed to special conditions of lattice symmetry, can now be more fundamentally explained by inherent directional curvatures generated by underlying geometric loops. This perspective shifts the question from "how anisotropic bands appear" to a more fundamental inquiry: "why anisotropy naturally arises from the geometry of spacetime itself."

Explicitly deriving the semi-Dirac Hamiltonian directly from first principles of encoding geometry further strengthens the predictive and explanatory power of this new approach. By revealing the direct mathematical pathway from spatial loops to observable particle properties, we show that phenomena previously described by topological and band-theoretic models can now be understood through deeper geometric origins.

8 Speculative Future Directions.

The successful interpretation of anisotropic particle behavior as a direct geometric consequence of Planck-scale spatial oscillation carries potentially profound implications for fundamental physics, particularly in fields such as quantum gravity, cosmology and holography, as well as condensed matter and black hole physics. While these broader possible research avenues remain speculative at present and require rigorous mathematical and experimental exploration, they represent highly promising directions for future work. Dedicated future studies will systematically explore these deeper conceptual connections, providing careful derivations and predictions that extend beyond the experimentally verified condensed matter results presented here.

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