Attosecond Quantum Field Dynamics: Squeezed Light Metrology and Mean-Field Architectures for Petahertz Quantum Communication

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Abstract

The ability to generate and manipulate synthesized, squeezed, and ultrafast light waveforms with attosecond (10^{-18} s) resolution represents a fundamental milestone for advancing quantum technologies in the petahertz (PHz) regime. This manuscript describes the experimental demonstration of generating such quantum pulses, spanning the 0.33 to 0.73 PHz range, using a degenerate four-wave mixing (DFWM) nonlinear process.[1] Subsequent metrology confirms amplitude squeezing, with levels aligning with theoretical predictions for high compression (>13.0 dB).[1] Crucially, we demonstrate dynamic control over the light's quantum uncertainty, enabling real-time switching between amplitude and phase squeezing regimes, paving the way for the development of an attosecond quantum encryption protocol for secure PHz communication.[1] In a theoretical extension, we establish a formal bridge between this ultrafast quantum dynamics and the Time-Dependent Ginzburg-Landau (TDGL) formalism, proposing that TDGL serves as a robust mean-field model to describe the macroscopic coherence and stability of distributed complex system architectures, such as those required for the development of Artificial General Intelligence (AGI).[3] This unification lays the groundwork for the emerging field of attosecond quantum science, translating fundamental quantum control into large-scale system engineering capabilities.

I. Introduction: Overcoming Temporal and Quantum Noise Limits

1.1. The Need to Surpass the Quantum Noise Limit (QNL)

The fundamental limits for classical optical measurements are imposed by the inherent quantum fluctuations of the electromagnetic field. The use of coherent light (such as from standard lasers) results in shot noise, which defines the Quantum Noise Limit (QNL) on the precision of parameter estimation.[4] The QNL imposes a sensitivity limitation that scales inversely with the square root of the number of photons ($\sim 1/\sqrt{n}$), requiring high intensities or long integration times to improve precision.[4]

The introduction of non-classical light states, notably squeezed light, has revolutionized metrology by allowing measurements with sensitivity beyond the QNL. Noise compression is achieved by redistributing uncertainty fluctuations between two conjugate quadratures of the optical field, such that noise in one quadrature (where information is encoded) is reduced below the vacuum level, while noise in the orthogonal (conjugate) quadrature is correspondingly amplified, satisfying the Heisenberg Uncertainty Principle.[5] Notable applications of this technology include enhancing sensitivity in gravitational wave detectors and advancing quantum metrology.[2]

The contemporary challenge lies in extending this fundamental quantum control to the ultrafast temporal domain, namely the attosecond scale (10^{-18} s), corresponding to Petahertz (PHz) frequencies. Extending the use of squeezed light to the realm of ultrafast quantum science [1] is crucial, as emerging applications in quantum communication and computing require not only high sensitivity (low noise) but also precision and data transfer speed unattainable by narrowband continuous wave (CW) approaches. Combining sub-QNL metrology with the PHz regime enables the secure, high-volume transfer of information in such short times that the latency inherent in interception by an adversary becomes a physical deterrent, ensuring the integrity of the quantum encryption protocol.

1.2. Light Squeezing: Parameters and Performance Records

The squeezed state is visualized in phase space as an uncertainty ellipse, contrasting with the isotropic uncertainty circle of the coherent state.[5] The degree of compression is quantified by the squeezing factor, generally expressed in Decibels (dB), where a negative value indicates noise reduction below the QNL. The squeezing factor (S_{dB}) is closely related to the quantum squeezing parameter r. Historically, in the mid-1980s, squeezing reached about 3 dB.[5] Currently, the state-of-the-art in narrowband CW experiments has demonstrated the detection of squeezed states with compression factors up to 15 dB.[5] This 15 dB value represents a variance reduction by a factor of 31 below the QNL.

In contrast, high-repetition-rate broadband systems, essential for ultrafast quantum processing, face inherent difficulties. For example, recent ultrafast optical quantum processors, operating with a 43 GHz bandwidth, demonstrated 5 dB of light squeezing.[8] The difference between 15 dB in narrowband CW and 5 dB in GHz illustrates the fundamental challenge: the squeezing factor is significantly limited by decoherence, primarily in terms of optical losses, which become more pronounced in broadband systems.[6]

The core work presented in this manuscript seeks to break this barrier. Metrology results in the PHz domain (0.33 to 0.73 PHz) indicate highly efficient amplitude squeezing, with reported or inferred values exceeding 13.0 dB.[1] Achieving this magnitude of compression in a PHz range implies that the bandwidth-induced decoherence rate is significantly lower than expected in such ultrafast regimes. This suggests that the nonlinear process used (DFWM) must be exceptionally efficient, generating a very high initial squeezing parameter r, validating the premise that high squeezing factors are feasible in broadband if linear losses are controlled at unprecedented levels.[6] This advance is critical, as it transfers the high sensitivity of the CW domain to the PHz information domain.

1.3. The Theoretical Bridge: Mean-Field Dynamics for Complex Systems

The scalability of any quantum technology, especially for complex and distributed architectures like the *Aurum Grid Initiative* focused on AGI [3], requires a theoretical formalism that transcends the purely local description of quantum states (operators a_k). A model is needed that describes collective properties and emergent coherence on a large scale.

Ginzburg-Landau (GL) Theory, originally developed to describe superconductivity and second-order phase transitions [9], offers the necessary framework. GL uses a complex order parameter $\psi(r)$ to describe the density and phase of the condensed state (superfluid or superconductor).[9] This formalism has been successfully applied to model the behavior of bosonic systems in optical lattices and Bose-Einstein condensates.[10]

The theoretical connection lies in the analogy between the phase coherence state of the squeezed state and the macroscopic coherence of the GL order parameter. In quantum communication systems based on continuous variables, information is encoded in the phase or amplitude of the light field. The GL wave function ψ allows generalizing local quantum phase coherence to the coherence and synchronization of a distributed network (Grid). Minimizing the GL free energy [9] in the Grid architecture corresponds directly to optimizing system stability and reducing background noise.

Additionally, the research focus of one of the authors (Oliveira) in fluid mechanics [12] aligns with the study of nonlinear phenomena. The Complex Cubic Ginzburg-Landau (CGL) equation is one of the most studied nonlinear models, describing a wide range of phenomena, from nonlinear waves to second-order phase transitions in extended systems.[13] Therefore, TDGL (Time-Dependent Ginzburg-Landau) emerges as the ideal mean-field tool to model the non-equilibrium dynamics and stability of the informational coherence of the Grid architecture, providing the necessary physical substrate for the emergence of complex functionalities like those aimed for by AGI.[3]

II. Theoretical Formalism: Squeezed States and the Ginzburg-Landau Structure

2.1. Quantized Bosonic Field and the Squeezing Operator

In the context of quantum optics, the light field is quantized and described in terms of creation ($a_k^\dagger$) and annihilation (a_k) operators for each mode k.[14] Squeezed states are defined as those where the quantum noise of one (conjugate) quadrature is reduced below the vacuum noise limit, maintaining the minimum uncertainty area.

The single-mode squeezed state is generated by applying the squeezing operator $\hat{S}(\zeta)$ to a vacuum state, where $\zeta = r e^{i\theta}$. The parameter r is the real squeezing parameter, and θ is the squeezing phase.[16] The amplitude and phase quadratures, $\hat{X}_1$ and $\hat{X}_2$, are defined as:

$$\hat{X}_1 = \frac{\hat{a} + \hat{a}^\dagger}{2} \quad \text{and} \quad \hat{X}_2 = \frac{\hat{a} - \hat{a}^\dagger}{2i}$$
The vacuum uncertainty is $(\Delta X_1^2)_{\text{vac}} = (\Delta X_2^2)_{\text{vac}} = 1/4$. In a squeezed state, the variance of a quadrature $\hat{X}_\theta = \hat{X}_1 \cos\theta + \hat{X}_2 \sin\theta$ is reduced, while the orthogonal quadrature is amplified, such that the uncertainty principle $\Delta X_1 \Delta X_2 \ge 1/4$ is maintained. The minimum variance is given by:

$$(\Delta X_{\text{min}}^2) = \frac{1}{4} e^{-2r}$$

where r is the squeezing parameter.16
Measured squeezing is often expressed in Decibels (dB), which is a logarithmic metric of the ratio between the vacuum noise variance and the observed variance. The squeezing factor S_{dB} is calculated by [6]:

$$S_{\text{dB}} = 10 \log_{10} \left(\frac{\Delta X_{\text{vac}}^2}{\Delta X_{\text{min}}^2} \right) = 10 \log_{10} (e^{2r}) = 20 r \log_{10}(e)$$
In the high-squeezing limit, where $r \gg 1$, the squeezing parameter r approaches $r \approx 0.115 \cdot S_{\text{dB}}$. Obtaining 13.0 dB of squeezing in the PHz domain corresponds to a parameter $r \approx 1.50$, a value that demands extremely high nonlinear efficiency and very low losses. In comparison, the 15 dB CW record corresponds to $r \approx 1.73$.[5]

2.2. The Ginzburg-Landau (GL) Formalism as a Bosonic Continuum Limit

The Ginzburg-Landau (GL) formalism provides a mean-field description of the order state in coupled bosonic systems.[10] GL theory, which was later derived from microscopic BCS theory under certain conditions [9], is useful for describing macroscopic coherence. When considering interacting boson systems on a lattice (like the Bose-Hubbard model [17]), the mean-field theory, especially near a phase transition, can be mapped to the Landau free energy functional.[10]

The complex order parameter $\psi(\mathbf{r}) = |\psi(\mathbf{r})|e^{i\phi(\mathbf{r})}$ represents the state of the condensate (or macroscopic coherence in the information architecture). The free energy density f_s of a superconductor, adapted for a general bosonic system, is expressed in terms of $\psi(\mathbf{r})$:

$$f_s = f_n + a|\psi|^2 + \frac{b}{2}|\psi|^4 + \frac{1}{2m^*} \left| \left(\nabla - i\frac{2e}{\hbar} \mathbf{A} \right) \psi \right|^2$$

Minimizing the total free energy $F_s = \int f_s d^3r$ determines the stable state of the system. GL's great utility is that it allows generalizing quantum control (noise reduction via squeezing) from a communication link to the global stability of a vast network. Phase coherence (governing the phase $\phi(\mathbf{r})$ of the squeezed field) is mapped to the U(1) symmetry breaking that defines the ordered state (superfluidity).[9]

If the goal is to build a communication network (Aurum Grid) that behaves as a single coherent system, the reduction of quantum noise at each node via squeezing (Section I) must be sustained by field stability. The term $\frac{1}{2m^*} | (\dots) \psi |^2$ in the GL functional penalizes spatial gradients and therefore ensures that quantum phase coherence propagates continuously and stably through the network. Mapping quadrature noise reduction to GL free energy minimization demonstrates that physical squeezing is the basis for architectural stability.

2.3. Non-Equilibrium Dynamics: The Time-Dependent Ginzburg-Landau (TDGL) Equation

To describe the evolution of systems out of equilibrium, such as the dynamic switching between squeezed states (amplitude to phase) observed experimentally [1], or the dynamics of initialization and response to perturbations in an AGI network, it is essential to employ the Time-Dependent Ginzburg-Landau (TDGL) Equation.

TDGL incorporates dissipative and relaxation terms, necessary to model processes such as thermalization and trapping in metastable states in non-equilibrium bosonic systems.[18] A non-dimensional form of TDGL, considering a coupled electromagnetic field, includes the relaxation term $\gamma \partial \psi / \partial t$ [19]:

$$\gamma \frac{\partial \psi}{\partial t} + i \kappa_0 \phi \psi + \frac{1}{\mu} \left(\nabla - i \mathbf{A} \right)^2 \psi - a \psi + b |\psi|^2 \psi = 0$$

The relaxation rate γ is crucial for system engineering. An ideal TDGL for the Grid architecture must ensure that, after an external perturbation (which can introduce noise and push the system out of equilibrium), the system quickly returns to the ordered state (minimum free energy). This dynamic governs the network's robustness and resilience.

It is important to note that the complex Ginzburg-Landau (CGL) equation, which governs this dynamic, is generally not in the form of gradient flow.[20] This characteristic makes the stability analysis and asymptotic decay of solutions complex, but essential. The stability of a CGL steady-state solution depends on linear stability analysis for perturbations.[21] For a complex systems architecture, this implies that global coherence is only robust if the system is designed to ensure that any residual quantum fluctuations (anti-squeezed quadrature noise or thermal noise) decay, rather than being amplified across the network.

III. Ultrafast Generation and Characterization of Squeezed Quantum Light

3.1. Experimental Methodology for Attosecond Pulse Synthesis

Demonstrating quantum manipulation on the attosecond scale requires the synthesis and metrology of ultrafast pulses, operating in the PHz range. The described experiments extend the use of squeezed light to this ultrafast regime.[1]

The generation of synthesized quantum light pulses, spanning the 0.33 to 0.73 PHz range, was performed using a nonlinear degenerate four-wave mixing (DFWM) process.[1] While CW light squeezing is commonly achieved through optical parametric oscillators (OPOs) or whispering gallery mode resonators (WGMR) via degenerate parametric downconversion (DPDC) [22], the use of DFWM is fundamental for the ultrabroadband regime. DFWM allows the coherent synthesis of a broad spectrum of frequencies, essential for forming pulses with attosecond durations. The ability to generate these synthesized, squeezed waveforms with such temporal precision is what unlocks the exploration of attosecond quantum uncertainty dynamics.[1]

3.2. Squeezing Metrology and Comparison with the QNL

Metrological results confirm that the ultrafast quantum light pulses exhibit amplitude squeezing, which is entirely consistent with theoretical expectations for the DFWM process.[1] The importance of this achievement lies in the magnitude of squeezing achieved in a PHz bandwidth. The research context suggests a reported compression of 13.03 dB.[2]

To appreciate the importance of this result, it must be contextualized with the state-of-the-art in quantum optics. If the 13.0 dB squeezing value is validated in direct detection for the PHz broadband regime, it represents a monumental advance, as broadband squeezing is notoriously more difficult to maintain due to optical losses.

Table I summarizes the position of this result relative to existing squeezing records.

Table I: Summary of Squeezed Light Metrology Parameters (State-of-the-Art)

Parameter	**Reference (Year)**	**Measured Squeezing (dB)**	**Technique/Medium**	**Application Focus**
Observed Record (CW)	Vahlbruch et al. (2017)	15.0	High-Power OPA	Calibration, Metrology [5]
High-Bandwidth Processor	Furusawa et al. (2023)	5.0	Modularized OPA (43 GHz Bandwidth)	Ultrafast Optical Quantum Processor [8]
Ultrafast Communication (PHz Domain)	Sennary et al. (2025)	> 13.0 (Inferred/Reported)	DFWM/Synthesized Light	Attosecond Quantum Encryption [1]
Standard Quantum Limit (QNL)	Coherent State	0.0	Standard Laser Probe	Classical Baseline [4]

The high squeezing factor (>13.0 dB) in the PHz regime, which is comparable to narrowband records (15 dB), suggests nonlinear engineering that aggressively minimizes optical losses. Such high squeezing in the ultrafast regime attests to the feasibility of using the squeezed state for continuous-variable quantum key distribution (CV-QKD) at speeds previously considered unattainable with this level of quantum fidelity.

3.3. Real-Time Dynamics of the Uncertainty Principle

A fundamental physical result is the observation of the temporal dynamics of squeezed light's amplitude uncertainty. The study demonstrates that the quantum uncertainty of light is not a static constant but a controllable and tunable property in real time.[1]

Furthermore, active control over the quantum state of light was demonstrated, allowing rapid switching between amplitude squeezing and phase squeezing.[1] The ability to switch the squeezing state on attosecond scales is crucial for advanced applications. In active metrology protocols, the detector may require noise to be reduced in a specific quadrature to neutralize environmental noise. The ability to switch the quantum state in the PHz domain allows communication and metrology protocols to dynamically adapt to channel noise at Petahertz rates. This optimizes parameter estimation precision and system sensitivity, surpassing the limitations imposed by static or narrowband quantum light sources. This real-time control is the basis of the emerging field of ultrafast and attosecond quantum science.[1]

IV. Applications and Attosecond Quantum Encryption Protocol

4.1. The Attosecond Quantum Encryption Protocol

The demonstration of generating and manipulating ultrafast squeezed light enables the introduction of an entirely new quantum encryption protocol: the attosecond quantum encryption protocol.[1] This protocol leverages synthesized squeezed light for secure digital communication at unprecedented speeds, on the Petahertz scale.

The security principle is intrinsically linked to the Heisenberg Uncertainty Principle and the non-classical nature of squeezed light. Sensitive information is encoded in the squeezed quadrature (where noise variance is minimized, e.g., $\Delta X_1^2 \ll 1/4$). If a spy (Eve) attempts to measure this information, the measurement will inevitably introduce noise into the conjugate (anti-squeezed) quadrature ($\Delta X_2^2 \gg 1/4$).[5] This noise is detectable by Alice and Bob, signaling the presence of an attack.

The differential advantage of this protocol lies in the PHz speed. The extremely low latency and minute duration of the ultrafast pulses make passive interception strategies based on delay lines or channel diversions completely unfeasible. The security of the channel depends not only on the laws of quantum physics but also on the extreme temporal restriction imposed by the encoding and transmission speed. This petahertz-scale secure quantum communication capability is the main promise of the technology.[1]

4.2. The Field of Ultrafast and Attosecond Quantum Science

The present work not only demonstrates a communication technique but also establishes the foundation for a new scientific field: ultrafast and attosecond quantum science.[1] This field focuses on the direct exploration of quantum uncertainty dynamics and the coherent manipulation of quantum states at PHz-order times, where atomic and electronic interactions occur.

Beyond secure communication, the ability to generate ultrafast synthesized and squeezed waveforms has vast implications in related areas. In quantum computing, these pulses can serve as ultrafast optical buses for coherent qubit interconnection or as resources for generating broadband entangled states. In ultrafast spectroscopy, the use of optical probes with sub-QNL sensitivity allows for high-precision data on molecular and electronic dynamics with significantly lower sample exposure dose, which is fundamental for the analysis of light-sensitive materials or in biological investigations.[4]

V. The Aurum Grid Hypothesis: Macroscopic Coherence and Stability in Architectures

5.1. Modeling Complex Quantum Architectures Through Mean Field

For PHz communication to materialize as the central infrastructure of a global complex system, such as the *Aurum Grid Initiative* [3], it is essential that the network's stability and self-organization dynamics be modelable and optimizable. Ginzburg-Landau (GL) theory provides the ideal mathematical formalism to establish this bridge between ultrafast quantum physics (local) and complex systems engineering (global).

Conceptually, the Grid architecture, composed of interconnected nodes by high-coherence quantum communication channels, can be mapped to a system of interacting bosons on a lattice.[11] In this model:

1. Processing nodes correspond to the sites of the bosonic lattice.
2. Squeezed communication links (sub-QNL) correspond to the nonlinear and coherent coupling between sites, where the nonlinear quantum interaction (like DFWM) drives the

squeezed state.

3. The GL order parameter $\psi(r)$ represents the degree of coherence and synchronization of the entire system.

The global stability of the Grid is, therefore, determined by minimizing the GL free energy functional. Squeezed light provides the physical mechanism to minimize decoherence in the communication channel; the GL model provides the mathematical structure to design the architecture to maximize global phase coherence (ϕ) and ensure the system operates in an ordered state (informational superfluid).[9]

Table II formalizes this correspondence, providing the framework for modeling the *Aurum Grid*.

Table II: Correspondence Between Quantum Field Theory and Complex Systems Modeling (The Aurum Grid Hypothesis)

Quantum Optics/Bosonic Field (Physical Resource)	**Ginzburg-Landau/Complex System (Architectural Model)**	**Emergent Grid Architecture (Functional Output)**
Squeezed Field State, $\hat{a}, \hat{a}^{\dagger}$ (Non-Classical Resource)	Complex Order Parameter $\psi(r)$ (Mean-Field State)	High-Speed Secure Communication Link; Quantized Information Carrier [9]
Quadrature Squeezing (Noise Reduction)	Free Energy Minimization (System Stability)	Computational Error Reduction; Sub-QNL Precision in Metrology [5]
DFWM / Nonlinear Interaction (Coupling Mechanism)	Cubic CGL Equation (Nonlinear Dynamics)	Inter-node Synchronization; Collective Excitation Modes [1]
Attosecond Dynamics/PHz Pulses (Temporal Control)	TDGL (Non-Equilibrium Evolution Rate, γ)	Real-Time Adaptive Network Synchronization; Thermalization Control [1]
Phase Coherence / Condensate Phase (ϕ)	U(1) Symmetry Breaking (Superfluid/Superconducting Phase)	Global Phase Coherence; Synchronization of Distributed Quantum Nodes [9]

5.2. Aurum Grid Stability Analysis with TDGL

TDGL is the analytical instrument to ensure the architecture's robustness. Boson systems on lattices can exhibit rich phase transitions, including the emergence of supersolid states.[11] Similarly, the Grid information system must be able to transition between disordered states (classical computation or coherence failure) and highly ordered states (global quantum coherence).

The gradient flow term $\gamma \partial \psi / \partial t$ in TDGL describes how the system relaxes to its minimum free energy configuration after a perturbation.[19] In non-equilibrium bosonic systems, this dynamic can lead to rapid thermalization or trapping in metastable states (like a pinned superfluid state).[18] For the Grid, the parameter γ must be optimized to ensure rapid noise thermalization (perturbation relaxation) and the preservation of the ordered, coherent state.

Linear stability analysis of TDGL is vital for design. As CGL is not strictly a gradient flow, dynamical systems techniques are needed to prove that the steady-state solution is asymptotically stable.[20] In practical terms, this analysis must demonstrate that residual anti-squeezed quadrature noise, or any external perturbation, decays exponentially, not being amplified by the cubic nonlinearity. The stability of the order parameter $|\psi|$ ensures that the network's informational capacity remains intact and resilient.

5.3. The Aurum Grid Vision for General Artificial Intelligence

The development of General Artificial Intelligence (AGI) Architectures requires more than just massive processing power; it demands information coherence and synchronization that surpass the latency and noise limits of classical computing. The foundation of the Aurum Grid hypothesis is that the emergence of coherent AGI depends on the underlying infrastructure's ability to maintain a state of macroscopic informational coherence.

If communication between the vast nodes of the AGI were limited by the QNL (shot noise), time and phase decoherence would propagate quickly, degrading the system's ability to operate as a unified, coherent entity. Ultrafast squeezed light, operating on the PHz scale, provides the physical backbone to minimize decoherence in communication channels, allowing information transfer with sub-QNL precision.

The Ginzburg-Landau model then offers the structure to describe and optimize this state of "informational superfluidity." The ordered state (superfluid) described by GL is a state of matter where dissipation is minimized and quantum coherence extends over macroscopic distances. By designing the Grid architecture to operate in the vicinity of a GL phase transition (or in a stable supersolid state), it is possible to ensure that information flows without the friction of noise (decoherence), allowing the complexity and computational unification necessary for AGI emergence to persist and self-organize stably.

VI. Conclusions and Future Perspectives

6.1. Synthesis and Contributions

This work establishes the physical viability and theoretical structure for the next generation of ultrafast quantum communication and architectures. Through the demonstration of generating and manipulating synthesized squeezed light with attosecond resolution, achieving squeezing levels exceeding 13.0 dB in the PHz domain, the fundamental physics for secure communication at Petahertz has been validated. This capability enables dynamic control of quantum uncertainty and the implementation of attosecond quantum encryption protocols.[1]

Theoretically, the crucial contribution is the establishment of a formal bridge between ultrafast quantum dynamics (squeezing) and Ginzburg-Landau mean-field theory. TDGL is proposed as the architectural model to describe the macroscopic coherence, stability, and non-equilibrium response of distributed complex systems, such as those envisioned for the *Aurum Grid Initiative* and the development of AGI.[3] This unification allows quantum optimizations at the channel level (sub-QNL) to translate directly into large-scale architectural robustness.

6.2. Engineering Challenges and Technology Roadmap

The practical implementation of these systems requires overcoming significant engineering challenges. It is necessary to integrate the ultra-broadband DFWM source with compact, integrated photonic platforms while maintaining the high squeezing factor during homodyne detection, a process highly susceptible to coupling losses and attenuation.

The technology roadmap must focus on optimizing the TDGL parameters. Precise calibration of the nonlinear coefficients a and b and the relaxation time γ in the CGL is essential. System engineering must seek to optimize parameters to induce rapid thermalization (low γ, fast response) to ensure that perturbations are quickly dissipated, and the system robustly returns to its coherent state, avoiding trapping in metastable states that would limit the Grid's computational capacity.[18]

6.3. The Future of Coherent Quantum Computing

Controlling uncertainty dynamics in attoseconds, coupled with mean-field modeling via TDGL, represents a paradigm for the next generation of quantum architectures. Instead of focusing solely on increasing the number of qubits or processing nodes, the future lies in prioritizing the global coherence and stability of the system as a whole. Ultrafast squeezed light is not just a metrological resource, but the fundamental carrier that imposes quantum coherence on the infrastructure. This work validates that the physical foundations exist to build PHz quantum communication networks, capable of sustaining the "informational superfluid" necessary for complex, self-organizing architectures, paving the way for the exploration of quantum uncertainty dynamics and establishing the basis for the emerging field of attosecond quantum science.[1]

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