

Axion signal searching using hybrid nuclear-electronic spin systems

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Conventional nuclear magnetic resonance searches for the galactic axion wind face technical challenges at lower frequencies, where the sensitivity of inductive readout scales less efficiently. In the pulsed architecture, a nuclear control sequence filters the axion field, a final $\pi/2$ pulse maps phase onto population, and the electron spin reads the resulting hyperfine-conditioned shift. We demonstrate analytically that this dispersive upconversion preserves the specific sidereal and annual modulation signatures required to distinguish dark matter signals from instrumental backgrounds. When instantiated in a silicon ^{209}Bi donor platform, the hybrid sensor is projected to outperform direct nuclear detection by more than an order of magnitude over the mass range 10^{-16} – 10^{-10} eV. With additional collective and resonant enhancements, the design can reach discovery-level sensitivity to Dine-Fischler-Srednicki-Zhitnitsky-scale axion-nucleon couplings after integration over the measurement time, establishing hyperfine-mediated sensing as a compact solid-state path for dark-matter searches.

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Introduction. Searches for ultralight dark matter, including axions and axionlike particles (ALPs), have attracted broad interest in quantum sensing and particle physics [1–20]. For axions/ALPs with derivative couplings to nucleon spins, the field acts as an effective axion wind that drives nuclear spins at the Compton frequency $\omega_a \simeq m_a c^2/\hbar$ and produces sidereal and annual modulations in the laboratory frame [21,22]. These directional modulations provide an astrophysical test ground against terrestrial backgrounds.

Nuclear magnetic resonance (NMR) searches, exemplified by CASPER-Wind, exploit large nuclear polarization and long coherence to set leading bounds on axion–nucleon wind couplings [23–27]. Axion-driven sample magnetization can be read out inductively, where the pickup voltage scales as $V \propto d\Phi/dt \propto \omega_a$, or via precision magnetometry (e.g., SQUIDS or atomic magnetometers) that measures flux or field more directly. In the coherent averaging regime, the optimal coherent integration time is limited by the axion coherence time $\tau_a \propto 1/\omega_a$, so the explicit ω_a in inductive voltage pickup partly cancels and, for an otherwise white noise floor, $\text{SNR} \propto \omega_a \sqrt{\tau_a} \sim \sqrt{\omega_a}$.

Compared with nuclei, electron spins have a much larger gyromagnetic ratio and benefit from mature,

high-sensitivity readout, including spin-to-charge conversion via Pauli spin blockade and gate or microwave-based dispersive reflectometry [28–31]. In donor and quantum dot platforms the strong hyperfine interaction $\mathbf{AI} \cdot \mathbf{S}$ tightly couples nuclear and electronic degrees of freedom, enabling nuclear dynamics to be mapped onto charge or electron-spin observables with high fidelity [32–35]. Recent spin-echo experiments in Ge hole-spin qubits have resolved hyperfine mediated nuclear-bath dynamics through the qubit response, directly demonstrating nuclear to spin-qubit transduction in a semiconductor platform [36]. This motivates hybrid sensors in which a nuclear ensemble acts as the axion-sensitive element while a coupled electron provides fast readout. The central challenge is to bridge the disparate nuclear and electronic timescales and energy scales, and to transduce the nuclear response into the electronic domain without degrading the spatiotemporal coherence or sidereal and annual signatures.

Here we develop a hyperfine-mediated upconversion readout for axion-wind searches. As a benchmark, we quote sensitivity relative to the Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) class of QCD axion models, which arise in two-Higgs-doublet extensions of the Standard Model and predict axion couplings to Standard-Model fermions set by the Peccei-Quinn scale. In this work we target the axion-nucleon wind coupling that drives nuclear spins; the electron spin is used as a transduction/readout channel via hyperfine-mediated upconversion rather than as the primary axion-coupled sensor.

Building on Refs. [37–39], we extend the approach to a nuclear-electronic hybrid architecture with collective

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enhancement. First, we construct a filter function formalism for nuclear-electronic transduction, defining a hybrid gain G_{hyb} and nuclear filter function $Y_N(\omega)$ that give platform-independent expressions for sensitivity. Second, we show that hyperfine upconversion preserves the axion-wind kinematics: after demodulation, the electronic record contains a sidereal component at $\Omega_\star$, a pure annual component at $\Omega_\oplus$, and mixed sidebands at $\Omega_\star \pm \Omega_\oplus$, providing a geometric veto against terrestrial systematics. When the axion coherence time is shorter than the observation baseline, these harmonics describe deterministic modulation of segment amplitudes or covariance rather than a single phase-coherent waveform over the complete run. Finally, we validate the approach in a silicon ^{209}Bi donor system, incorporating realistic coherence times, control pulse constraints, and readout noise to benchmark the performance against state-of-the-art NMR strategies. We highlight Si: ^{209}Bi donors because their large isotropic hyperfine coupling enables strong transduction together with established control and long coherence in enriched silicon. This combination makes Si:Bi particularly advantageous for hyperfine-mediated upconversion.

We find that the hybrid readout can improve the readout-limited sensitivity relative to direct nuclear detection across the accessible mass range. With collective nuclear-spin enhancement and a high- Q resonator, the idealized benchmark overlaps part of the DFSZ reference region for a one-year dwell at each scanned mass point. At low masses the overall reach of wind searches is often limited by the readout chain rather than by nuclear coherence alone, particularly for pickup-coil voltage detection with its explicit ω_a transduction factor. Hyperfine-mediated nuclear-to-electron transduction removes this explicit inductive penalty by mapping the axion-driven nuclear response onto a high-bandwidth electronic readout channel, leaving the remaining frequency dependence set by τ_a and by the control-sequence filter functions.

Model and theory. Unless otherwise stated, we set $\hbar = c = 1$ and express Hamiltonians in angular-frequency units. We consider a semiconductor donor system with a spin-1/2 electron $\mathbf{S}$ and a nuclear spin $\mathbf{I}$ (for ^{209}Bi , $I = 9/2$) in a static magnetic field $\mathbf{B} = B_z \hat{z}$ [40,41]. The laboratory-frame Hamiltonian is

$$H_{\text{total}} = \omega_e S_z + \omega_N I_z + \mathbf{A} \mathbf{S} \cdot \mathbf{I} + H_{aN}(t). \quad (1)$$

The electron and nuclear Larmor frequencies are $\omega_e = |\gamma_e| B_z$ and $\omega_N = \gamma_N B_z$, where γ_e is the electron gyromagnetic ratio. The isotropic hyperfine interaction constant A is taken from experiment. For a donor-bound nucleus the secular hyperfine term shifts the nuclear precession frequency to $\omega_N^{\text{eff}} = \gamma_N B_z \pm A/2$, depending on the electron spin state; for Si: ^{209}Bi this places the nuclear drive near 737 MHz rather than at the bare nuclear Zeeman frequency.

All sequences below are defined in the corresponding nuclear rotating frame. Because an electron spin flip shifts ω_N^{eff} by $\sim A$ and thereby destroys the accumulated nuclear phase, the protocol additionally requires $T_1^{(e)} \gg \tau_N$ throughout the nuclear interrogation window.

The axion-nucleon interaction is written as an effective field $H_{aN}(t) = -\gamma_N \mathbf{I} \cdot \mathbf{B}_a(t)$, with $\mathbf{B}_a(t) = \mathbf{B}_{a,0} \cos(\omega_a t + \phi)$. We use the dimensionful derivative coupling $g_{aNN} = C_N/f_a$ and the dimensionless coupling plotted in Fig. 4, $g_{an} \equiv m_N g_{aNN}$. In angular-frequency units, $\mathbf{B}_a = g_{aNN} \nabla a / (\hbar \gamma_N) = g_{an} \nabla a / (m_N \hbar \gamma_N)$. The fixed Galactic-frame direction of $\mathbf{B}_a$ leads to sidereal and annual modulations in the lab frame, and the drive remains coherent for a time τ_a set by the velocity dispersion. The coherence time of this drive is characterized by $\tau_a \simeq 2\pi/(m_a v_0^2)$ under the standard halo model (SHM).

We focus on the longitudinal component of the axion-induced field, $B_{a,z}(t)$, which modulates the nuclear Larmor frequency. To cover a broad frequency range, we use standard Ramsey/echo and multipulse sequences (e.g., Ramsey, Hahn echo, XY8, and Carr–Purcell–Meiboom–Gill (CPMG)) to shape the nuclear spectral response [42–44]. The spectral sensitivity of a sequence is characterized by its filter function $Y_N(\omega)$, the Fourier transform of the time-domain sensitivity function $y_N(t) \in \{0, \pm 1\}$ over the sensing duration. The values ± 1 correspond to free-precession segments whose sign is toggled by pulses, while 0 accounts for intervals with negligible phase accumulation. For a narrowband axion field $B_{a,z}(t) = B_a \cos(\omega_a t + \phi)$, the accumulated phase φ_N at the end of the sequence is given by

$$\varphi_N \approx \gamma_N B_a |Y_N(\omega_a)| \cos(\omega_a t_0 + \Phi_{\text{off}}), \quad (2)$$

where t_0 marks the start of the sequence and Φ_{off} includes the phase of the filter function and the axion field.

The choice of sequence determines the detection window. The Ramsey sequence ($y_N = 1$) exhibits a low-pass filter response $|Y_N(\omega)| \approx \tau \sin c(\omega\tau/2)$, maximizing sensitivity to ultralight axion fields. Conversely, Hahn echo and CPMG sequences act as bandpass filters, suppressing low-frequency noise while extending sensitivity to higher-frequency (oscillating) axion fields determined by the pulse spacing [45–47].

Experimentally, the nuclear spin is initialized in a superposition state (e.g., along $\hat{x}$). After accumulating the axion-induced phase φ_N over time τ , a final $\pi/2$ pulse maps this transverse phase onto the longitudinal polarization $\langle I_z \rangle$. In the small-signal limit ($|\varphi_N| \ll 1$), the observable signal is proportional to the phase, $\delta \langle I_z \rangle \approx I \varphi_N$, allowing direct readout of the axion interaction. In the dispersive regime the hyperfine interaction produces a longitudinal shift of the electron splitting proportional to I_z , enabling nuclear-to-electron transduction.

The effective Hamiltonian $H_{\text{eff}} = (\omega_e + A I_z) S_z + \omega_N I_z$ indicates that the nuclear polarization acts as a local field

modulating the electron Larmor frequency. Consequently, the axion-driven nuclear dynamics are dispersively upconverted into an electron frequency modulation (FM): $\delta\omega_e(t) = A_{\text{eff}} I |\gamma_N Y_N(\omega_a) B_{a,z}| \cos(\omega_a t + \phi)$. Here, the signal amplitude is proportional to the nuclear filter gain $|Y_N|$, and we introduce $A_{\text{eff}} = AG_{\text{drv}}$ to generalize the static hyperfine coupling to driven schemes like Hartmann-Hahn resonance or Floquet dressing, where the effective interaction strength is dynamically enhanced.

We express the transduced signal as an effective electron field $B_{\text{eff}}^{(e)} \equiv \delta\omega_{e,0}/\gamma_e$ and define the intrinsic single-unit hybrid gain:

$$G_{\text{hyb}}(\omega_a; \rho_D) = \frac{AI\gamma_N}{\gamma_e} |Y_N(\omega_a)| G_{\text{drv}} \left[1 + \mathcal{O}\left(\frac{A}{2\Delta}\right) \right], \quad (3)$$

where $G_{\text{drv}} = 1$ without dressing or driving. At donor density ρ_D , density enters only through $\tau_N(\rho_D)$ in Y_N ; collective and resonator gains are excluded from Eq. (3). In an electron Ramsey or echo probe with sensitivity function $y_e(t)$ and sinusoidal frequency modulation $\delta\omega_e(t) = \delta\omega_{e,0} \cos(\omega_a t)$, continuous readout yields Bessel sidebands at $\omega_e \pm n\omega_a$ with modulation index $\beta = \delta\omega_{e,0}/\omega_a$. The axion wind direction $\hat{u}_a$ is fixed in the Galactic frame while the laboratory quantization axis rotates with Earth, so the projection $R(t)\hat{u}_a \cdot \hat{z}$ generates a sidereal component at $\Omega_\star$ and annual sidebands at $\Omega_\star \pm \Omega_\oplus$ [39,48]. After upconversion, the modulation spectrum retains the characteristic sidereal triplet and annual sidebands, providing an instrument-independent astrophysical signature.

Having established how the axion signal maps onto an effective electron field and its modulation pattern, we now quantify the resulting signal-to-noise performance in the electron and nuclear channels. We distinguish the coherent duration of an individual sensing block, bounded by $T_2^{(e,N)}$ and τ_a , from the accumulated effective integration time $T_{\text{int}}^{(e,N),\text{eff}}$, which also includes the duty cycle and the adopted rule for combining repeated coherent segments.

In the Ramsey limit $\omega_a \tau_N \ll 1$, the nuclear response is approximately flat over the interrogation time, while echo/CPMG sequences produce narrowband peaks. Long nuclear coherence, strong hyperfine coupling, and low electron readout noise allow the upconversion scheme to surpass direct nuclear readout whenever $T_{\text{eff}}^{(e)}$ and τ_a are large enough to support coherent integration. Including both readout noise floors, the intrinsic readout-channel ratio at fixed donor density is

$$\left. \frac{\text{SNR}_e}{\text{SNR}_N} \right|_{\rho_D} = G_{\text{hyb}}(\omega_a; \rho_D) \frac{\eta_B^{(N)}}{\eta_B^{(e)}} \sqrt{\frac{T_{\text{int}}^{(e),\text{eff}}}{T_{\text{int}}^{(N),\text{eff}}}}, \quad (4)$$

Here $\eta_B^{(N,e)}$ are readout-channel magnetic sensitivities; all factors are evaluated at the same ρ_D , before optional collective and resonator resources [48]. Hybrid readout wins when the right-hand side exceeds unity.

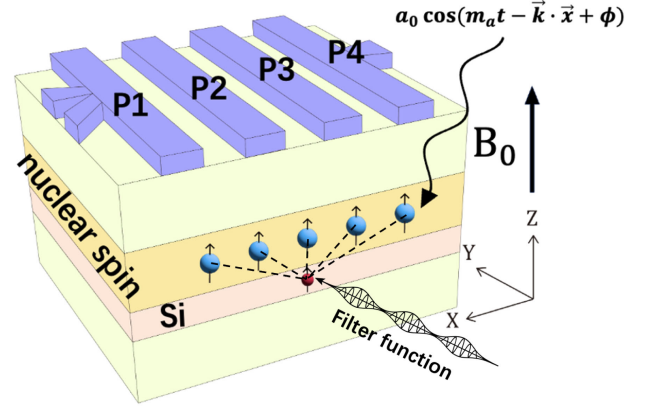


FIG. 1. Single-unit-cell schematic; the sensor uses an array of N coupled units. Local contact hyperfine coupling enables fast, high-bandwidth readout of the axion-sensitive donor nuclear spin (blue) by the gate-defined electron spin (red). The static field $B_0 = B_z \hat{z}$ sets the quantization axis, and gates P1-P4 schematically define confinement. Compatible silicon-donor, electron- and hole-spin, and CMOS implementations are described in Refs. [49–63].

Experimental proposal. The device shown in Fig. 1 is a chip-integrated hybrid nuclear-electronic spin sensor designed for axion and ALP wind searches. All functional elements, including the donor ensemble, electrostatic control gates, microwave drive lines, and dispersive readout circuitry, are integrated on a single cryogenic platform. The chip operates inside radio-frequency and magnetic shielding to suppress ambient electromagnetic interference and low-frequency magnetic-field noise. Such noise sources are particularly critical because the axion signal is expected to exhibit sidereal modulation at frequency $\Omega_\star$ and annual sidebands at $\Omega_\star \pm \Omega_\oplus$.

Suppressing environmental magnetic fluctuations at these frequencies is therefore essential to avoid systematic backgrounds that could mimic the expected modulation pattern. The device is thermally anchored to a dilution refrigerator stage at $T \lesssim 100$ mK, which ensures long electron and nuclear coherence times, reduces thermal spin polarization noise, and stabilizes dispersive electron readout [64,65]. Superconducting NbTi wiring together with filtered twisted-pair lines is used inside the shielded enclosure to suppress Johnson noise, attenuate high-frequency leakage, and minimize microwave phase noise in the control and readout chain. Under these conditions the dominant sensitivity limitation is set by quantum projection noise and amplifier noise rather than technical electromagnetic backgrounds.

Si: ^{209}Bi gives the largest ideal hyperfine-mediated gain because $A/2\pi = 1.475$ GHz, whereas a proof-of-principle experiment could instead use $^{28}\text{Si}:$ ^{31}P . The smaller hyperfine interaction of $^{28}\text{Si}:$ ^{31}P ($A/2\pi = 117$ MHz) reduces the hybrid gain in Eq. (3), but the platform offers mature single-donor control, high-fidelity spin-to-charge readout,

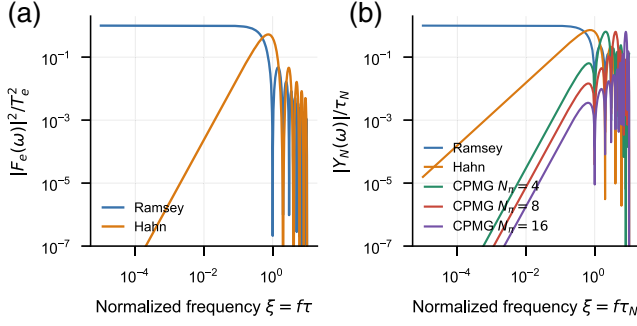


FIG. 2. (a) Normalized Ramsey and Hahn electron filters, shown for reference; the pulsed readout uses $F_e(0)$. (b) Nuclear toggling-filter amplitude for $N_\pi = 4, 8, 16$, with CPMG passbands near $\xi = f\tau_N \simeq N_\pi/2$.

and well-established coherence benchmarks. A proof-of-principle validation of the hyperfine-mediated transduction and modulation fingerprint therefore does not require the maximal coupling strength of Bi and could be realized in existing ^{28}Si : ^{31}P platforms before scaling to high-gain Bi ensembles. A comparison of these materials is given in the Supplemental Material [48].

Results. Figure 4 presents a forward-looking sensitivity projection that includes optional collective enhancement and resonator-assisted gain. The projection uses $G_{\text{tot}}^{(e)} \equiv \mathcal{G}_{\text{geom}} F_{\text{enh}}[N_{\text{eff}}(\rho_D)] G_{\text{res}}(Q) G_{\text{hyb}}(\omega_a; \rho_D)$, so density

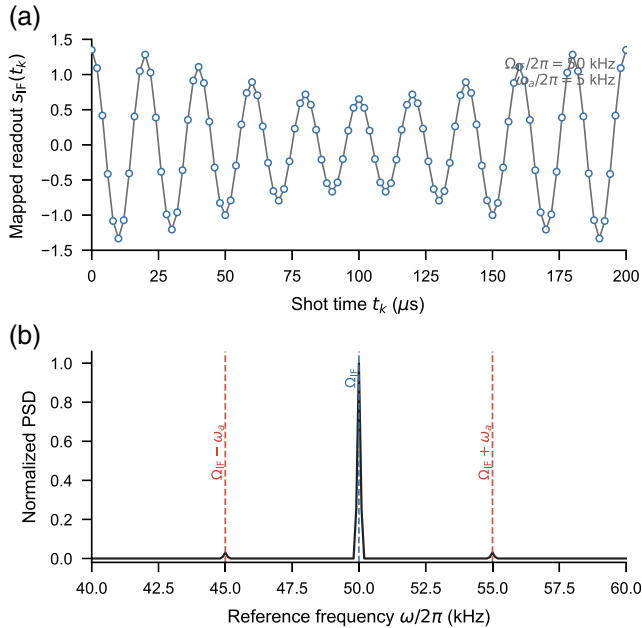


FIG. 3. (a) Shot-resolved electron samples after repeated nuclear sensing and phase mapping, displayed about $\Omega_{\text{IF}}/2\pi = 50$ kHz with modulation $\omega_a/2\pi = 5$ kHz. (b) Spectrum of the same record. This pulsed heterodyne visualization assumes neither spin locking nor a second electron filter at ω_a .

enters separately through N_{eff} and Y_N . Resource and geometry assumptions are listed in the Supplemental Material [48]. Importantly, experimental validation of the hyperfine-mediated upconversion and modulation fingerprint does not require these enhancements and can be performed at the single-donor or small-array level.

To estimate the axion-search sensitivity of the proposed sensors, we normalize the hybrid gain of each isotope to the sensitivity baseline introduced in Ref. [37]. Building on Eq. (3), we evaluate the nuclear filter $Y_N(\omega)$ together with the quasistatic electron mapping response $F_e(0)$ for a Ramsey/Hahn/CPMG sequence bank and determine the corresponding scan bands from the nuclear passbands. At fixed density and with optional resources held fixed, Eq. (4) therefore isolates the intrinsic hyperfine advantage of ^{209}Bi .

$$H_p(\omega; \tau_N, N_\pi) = R_e Y_N(\omega; \tau_N, N_\pi), \quad R_e \equiv F_e(0)/T_e. \quad (5)$$

This is the pulsed spectral response, rather than $F_e(\omega)Y_N(\omega)$. The electron filter in Fig. 2(a) is therefore shown only for reference. For the standard CPMG convention, the nuclear passband is centered near $f_c \simeq N_\pi/(2\tau_N)$ with a width of order $1/\tau_N$. The nuclear filter Y_N defines the tunable detection band, while $F_e(0)$ sets the electron-readout contrast. The corresponding shot-resolved pulsed-heterodyne readout and its spectrum are shown in Fig. 3.

Within this bounded window, the projected pulsed matched-filter signal-to-noise ratio is

$$\text{SNR}_e^{\text{tot}}(\omega_a, \rho_D) = \frac{G_{\text{tot}}^{(e)} |B_{a,z}|}{\eta_B^{(e)}} \sqrt{T_{\text{int}}^{(e), \text{eff}}}. \quad (6)$$

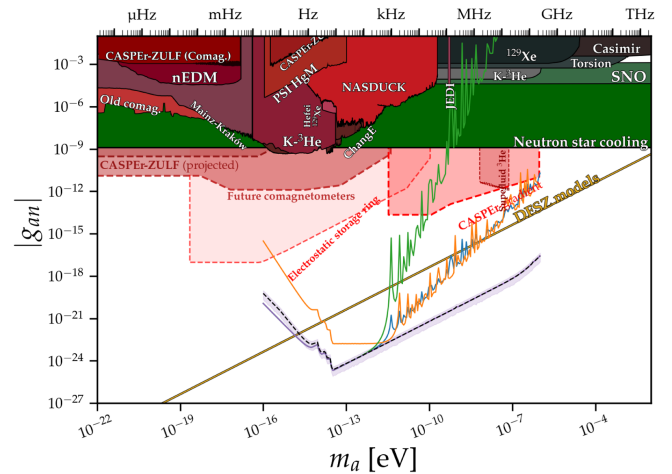


FIG. 4. Projected local 5σ sensitivity to $g_{an} \equiv m_N g_{aNN}$ for ^{209}Bi under Ramsey, Hahn echo, XY8, and a separate continuous-drive benchmark. This is an idealized per-mass-point benchmark, not an exclusion. Purple shading shows simulated noise spread. The Supplemental Material lists device/noise assumptions; DFSZ and existing limits, partly from Ref. [66], are shown for reference.

The intrinsic frequency dependence is carried by $G_{\text{hyb}} \propto |Y_N[\omega_a; \tau_N(\rho_D)]|$; the electron factor is the quasi-static mapping response $R_e = F_e(0)/T_e$, not a second filter at ω_a . The scan constraints and pulse-selection rules are given in the Supplemental Material [48].

Supplemental Material Fig. 1 shows the corresponding A - and τ_N -dependence of the intrinsic transduction.

Conclusion. In summary, we propose a hybrid nuclear-electronic upconversion scheme for axion-wind sensing while retaining sidereal and annual directional signatures.

Using a long-lived, axion-coupled nuclear ensemble and hyperfine transfer to a fast electronic readout, the method is compatible with silicon-donor spin platforms and standard control and readout methods. Monte Carlo simulations indicate the largest gain for Si:²⁰⁹Bi donors. With collective enhancement and resonator coupling, the idealized benchmark overlaps part of the DFSZ reference region over $m_a = 10^{-16}$ – 10^{-10} eV.

Data availability. The data are not publicly available. The data are available from the authors upon reasonable request.

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