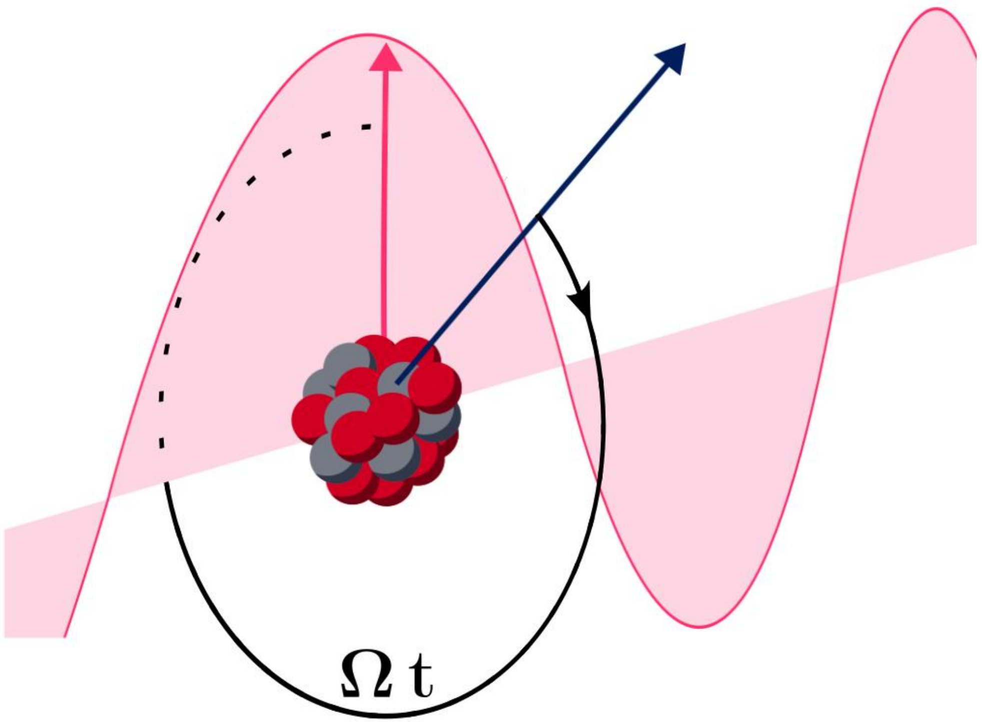
TeV PARTICLE ASTROPHYSICS 2026 · TENDO, JAPAN

Broadband Axion Dark Matter Search via Heterodyne Atom Interferometry

A quantum lock-in amplifier for ultralight-field searches



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Problem

PROBLEM

For an axion signal at the μHz → Technical 1/f noise buries it.

THE TALK IN ONE LINE

Problem → trick

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TRICK

Heterodyning: Modulate the sensor's coupling, not the field. The signal moves, the magnetic noise does not.

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REACH

Shot-noise-limited $g_a NN \lesssim 10^{-10}\ \mathrm{GeV}^{-1}$, flat across five decades of axion mass.

The method is not specific to axions

THE PROBLEM

The ultralight axion

$$\mathcal{H}_a = -g_{aNN}\nabla a \cdot \mathbf{s}$$

$$\omega_a = \frac{m_a c^2}{\hbar}$$

- Axion's gradient exerts an oscillating torque on the nuclear spin
- $\rho_{DM} \simeq 0.3$ GeV cm^{-3}, $v_r \simeq 10^{-3}c$ set the field amplitude
- $\tau_{coh} \approx 5 \times 10^3$ year at $\omega_a = 1$ μHz $\simeq 10^{-20}$ eV a one-year integration is coherent,

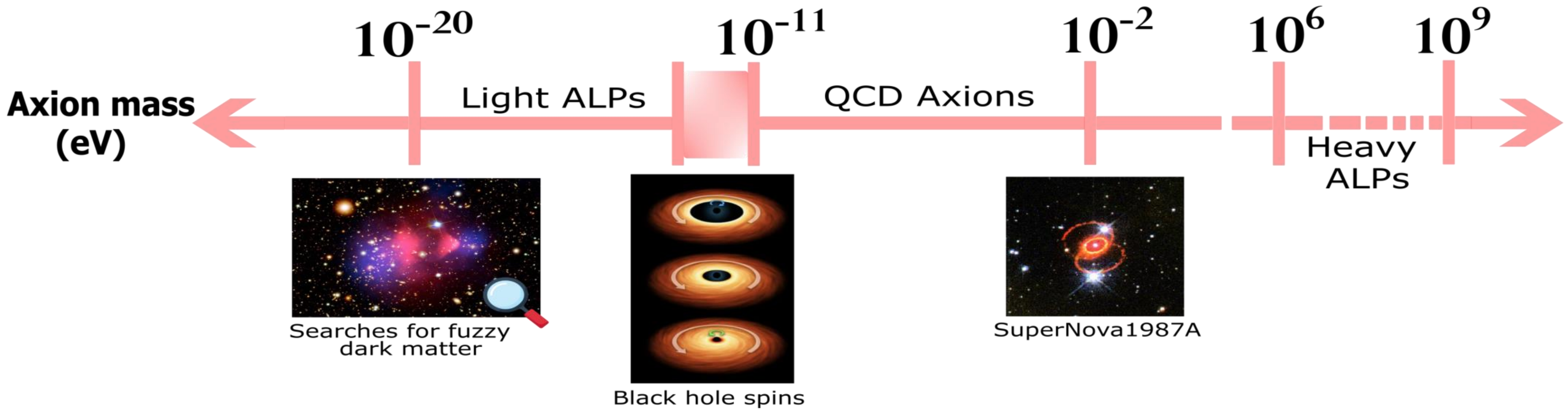

FIGURE 1. Axion particle mass (in eV) for various dark-matter candidates.

THE PROBLEM

Below ~10 mHz every search hits the same wall

Magnetic drift, electronic flicker and seismic motion all rise as $S_n(\omega) \propto 1/f^n$.

This is a detection-frequency problem, not an integration-time problem.

- Longer τ does not move you below the floor
- A Ramsey clock detects at DC : the worst possible place
- Lowest-mass window is still open

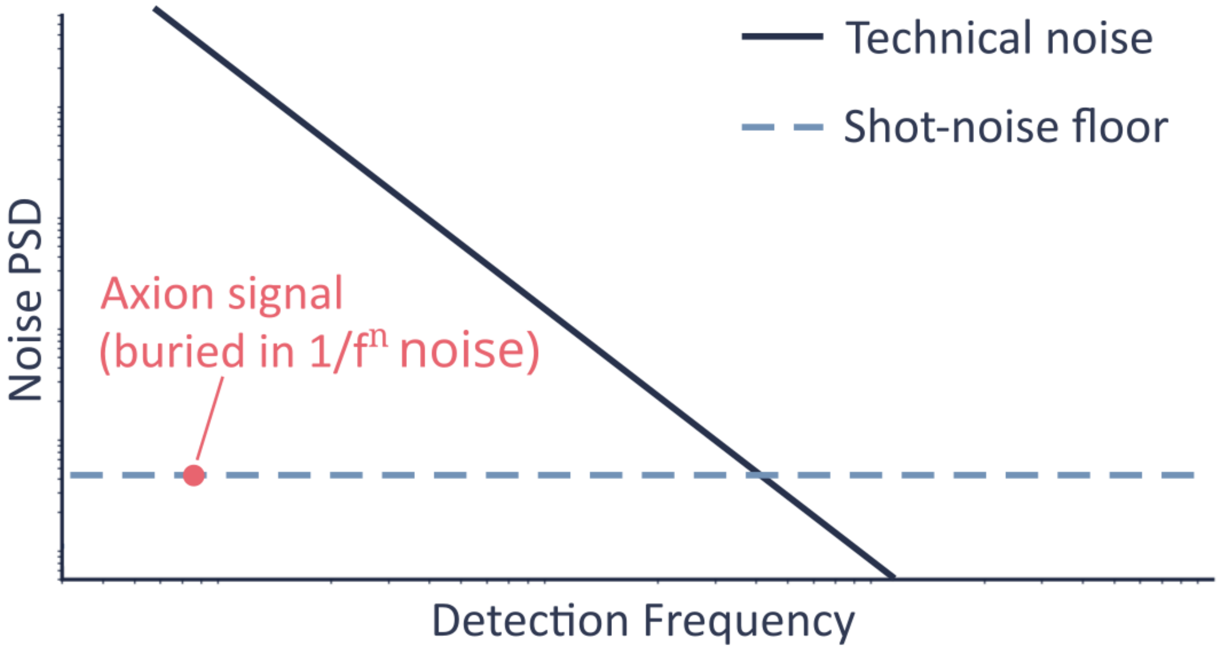

FIGURE 2. Signal buried under the rising $1/f^n$ noise floor at low detection frequency.

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THE TRICK

Don't move the source : move the coupling

$$\Delta\phi = \frac{1}{\hbar}\int_0^T g(t)\,\Delta E(t)\,dt$$

$$H(\omega) = \int_0^T g(t)e^{i\omega t}dt$$

g(t) = +1 detect at DC	**g(t) = cos(Ωt)** **detect at ±Ω**

The transfer function only knows g(t): the sensor cannot tell the difference. Quantum analog of lock-in amplifier.

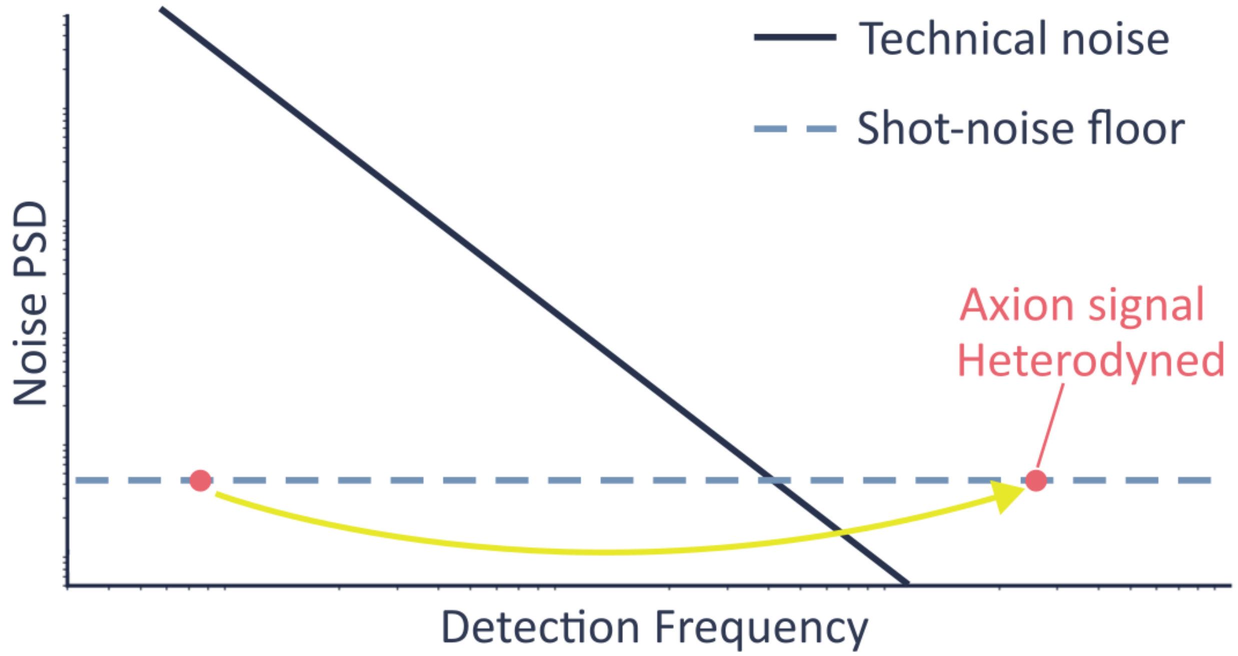
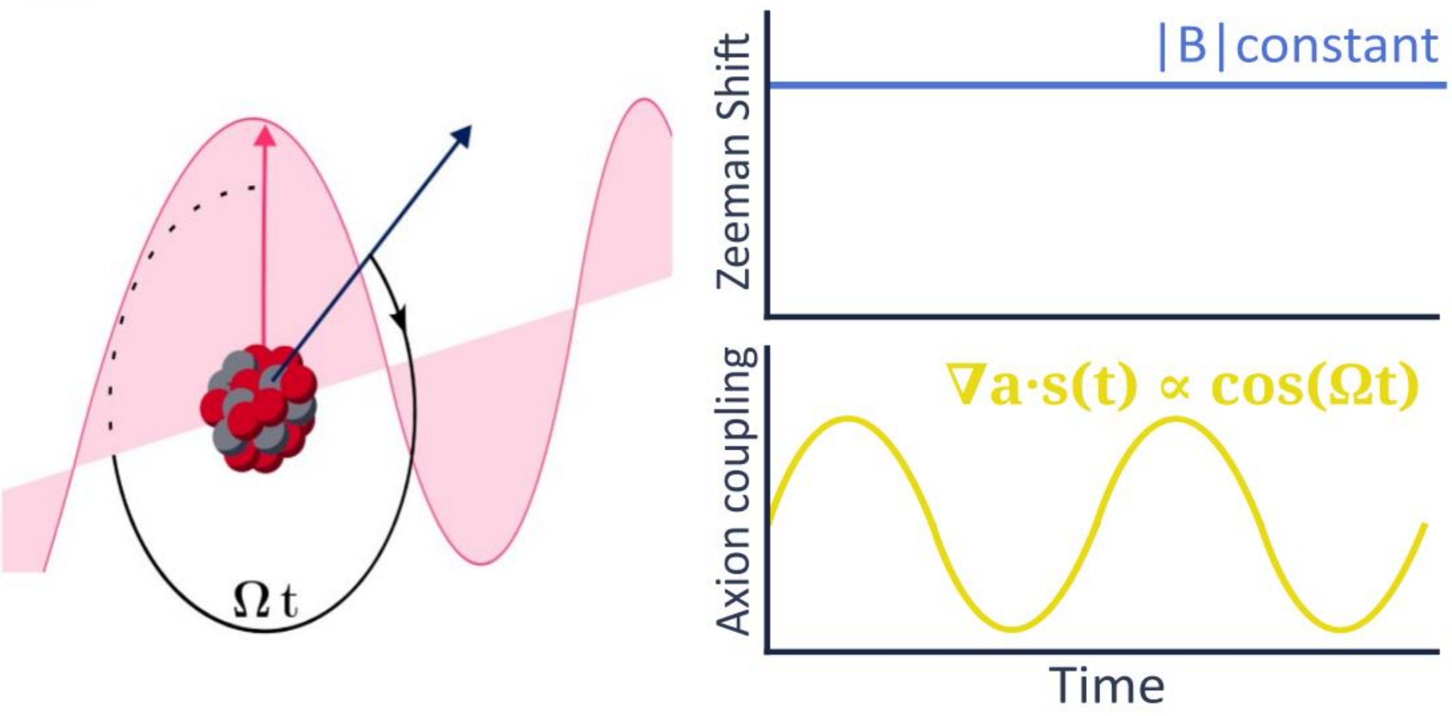


FIGURE 3. Signal buried under the rising $1/f^n$ noise floor at low detection frequency.

THE TRICK

The coupling knows $\vec{B}$, the Zeeman shift only |B|



- B(t) : the direction rotates, the magnitude is fixed
- Spin follows adiabatically: $\nabla a \cdot s(t) \propto \cos(\Omega t)$

→ signal up-converted around Ω

- Zeeman phase depends on |B| only

→ unchanged, stays at low frequency

FIGURE 4. **Left**: B rotating in the x–y plane at fixed amplitude, the spin follows adiabatically. **Right**: |B(t)| flat in time while $\nabla a \cdot s(t)$ is oscillating at Ω.

Over one shot the axion is frozen. The microhertz oscillation shows up shot-to-shot over the year.

THE TRICK

Differential and co-located optical-lattice clock

- Two arms of opposite nuclear-spin
- Laser phase noise is common-mode
- J = 0 in both clock states

→ Stark shifts and first-order Zeeman cancel

- No spatial separation of the wavepackets

→ no gravity-gradient noise

- Table-top apparatus, competitive with

hundred-meter scale devices

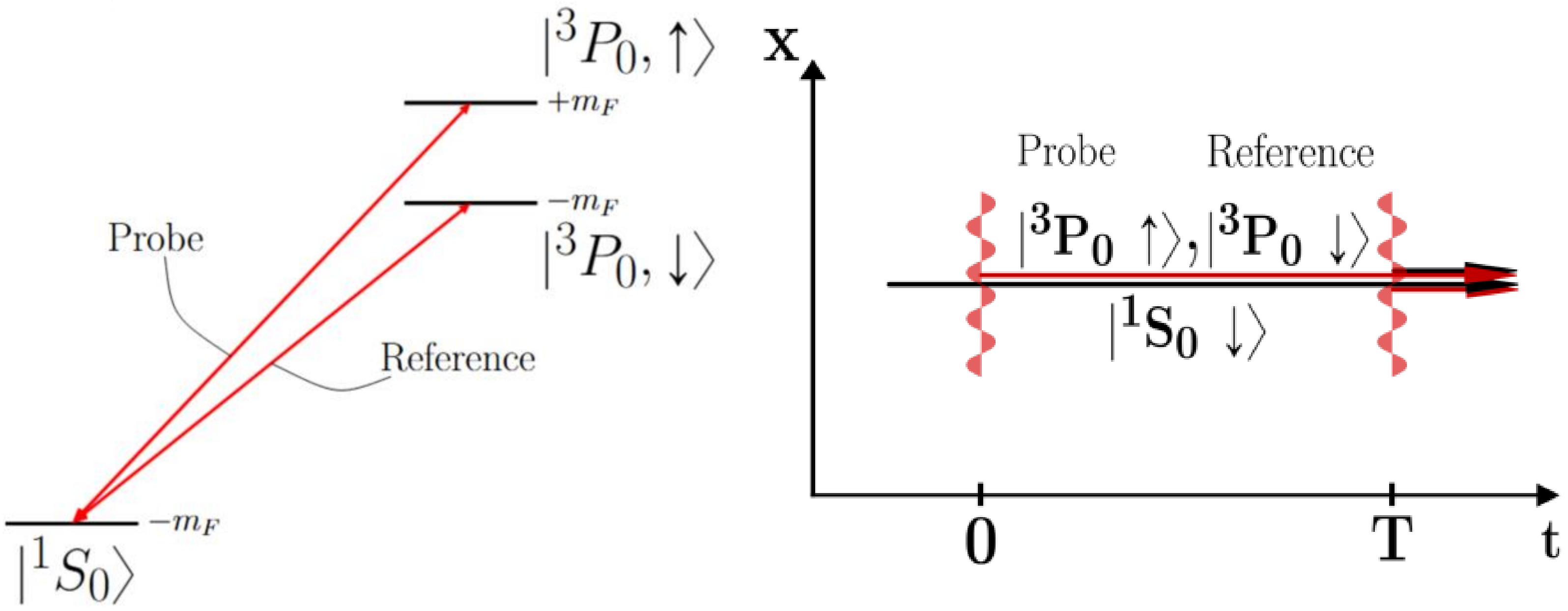


FIGURE 5. **Left:** Relevant strontium level structure. **Right**: Ramsey sequence: π/2 → free evolution T → π/2 → population difference.

Two orthogonal coil pairs, driven in quadrature

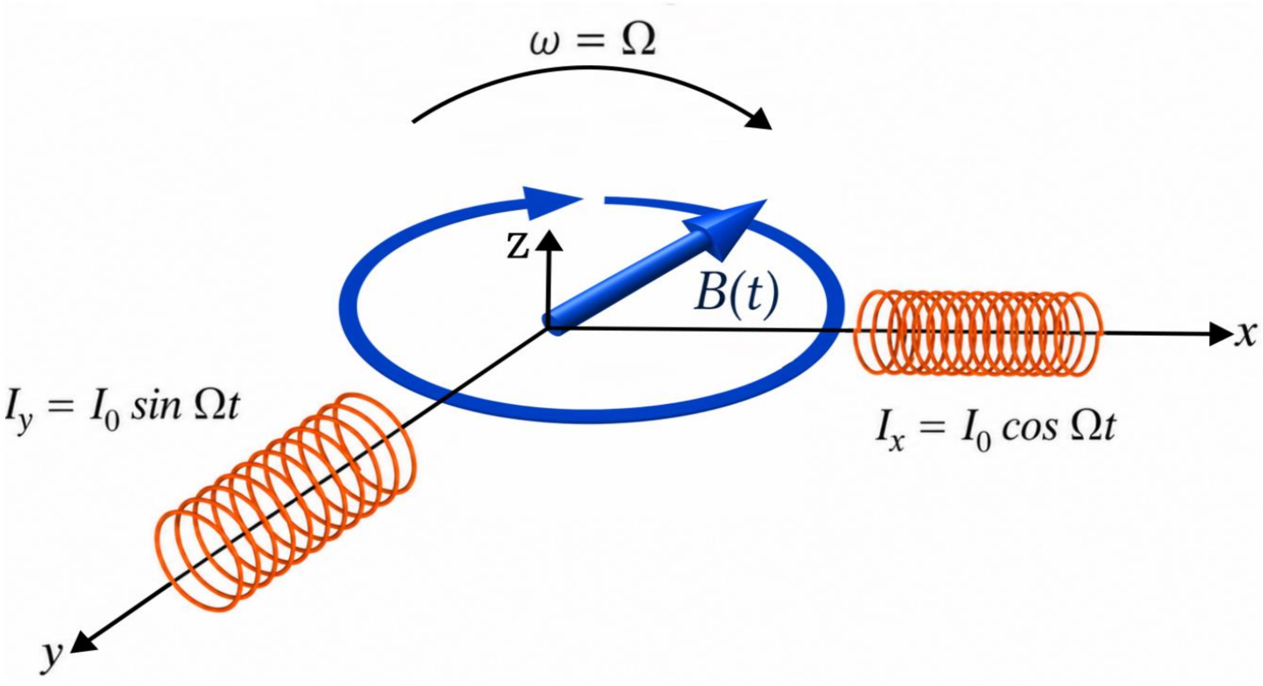


FIGURE 6. Rotating field B(t) generated by two orthogonal coil pairs driven in quadrature at Ω.

- Adiabatic condition: $\Omega \ll g_F \mu_B B_0/\hbar$
- ^{87}Sr at B_0 = 1 mT → $\Omega \ll$ 10 kHz

We only need **100 mHz**

- Spin follows the B field with no Zeeman transitions

Optical alternative

Δm_I reversed by laser pulses → **Square-wave modulation**. Lower B_0, fewer systematics, arbitrary waveforms, no constraint on cloud position. But the *Zeeman shift* is up-converted too.

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Heterodyne, Direct or Resonant

Heterodyne

CONDITION

$\omega_a \ll \Omega = 1/T$

MODULATION

$g(t) = \cos(\Omega t)$

Escapes the $1/f^n$ band entirely

Direct

CONDITION

$\omega_a \lesssim 1/T$

MODULATION

$g(t) = +1$

Plain Ramsey

Resonant

CONDITION

$\Omega = \omega_a \gg 1/T$

MODULATION $g(t)$

$g(t) = \cos(\omega_a t)$

Tuning Ω to $\omega_a \rightarrow$ DC signal

At high Ω the rotating field induces eddy currents far larger than in the heterodyne protocol

A flat exclusion curve across five decades of axion mass

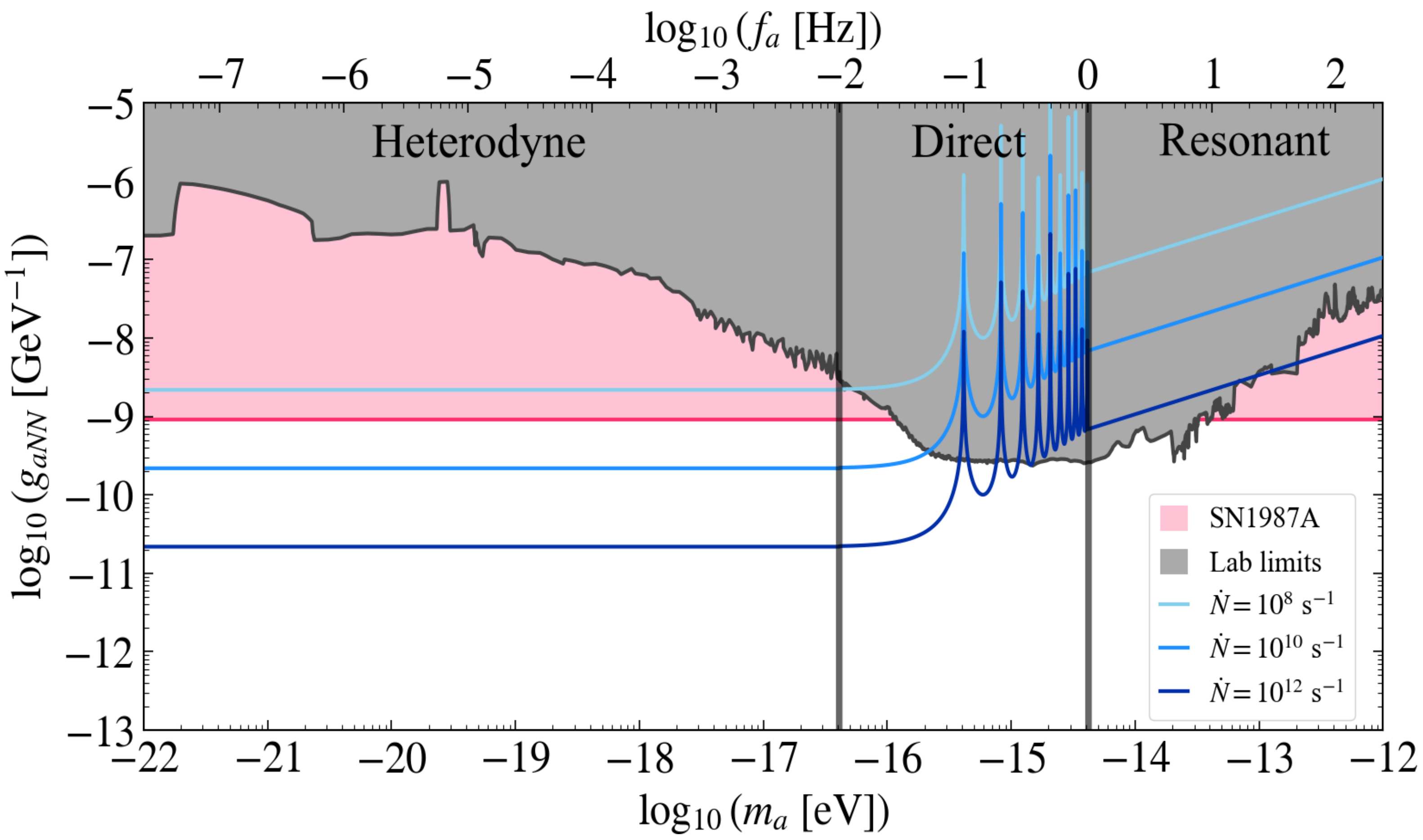


FIGURE 7. Projected exclusion sensitivity for g_{aNN} vs axion mass for the three regimes: Heterodyne, Direct and Resonant.

$$g_{aNN}^{\min} = \frac{2\hbar C}{E_0 T}\sqrt{\frac{1}{\dot{N}\tau_{int}}}$$

C depend on the regime: C = 2 for Heterodyne

T = 10s, τ_{int} = 1 year.

Once the signal is out of the $1/f^n$ band, g_{aNN} no longer depends on the axion frequency ω_a → flatness.

2×10^{-10} GeV^{-1}

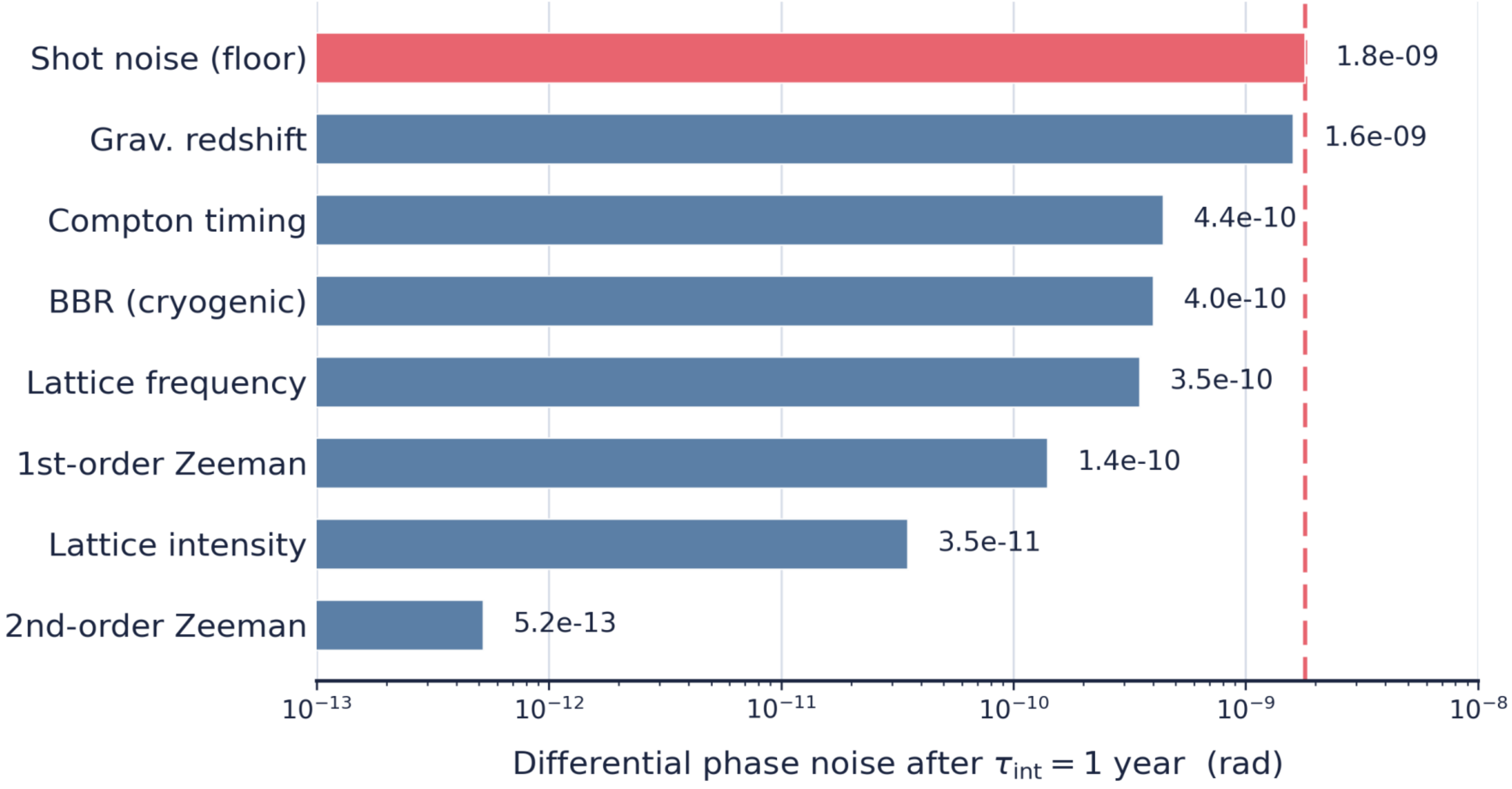
near term, $\dot{N} = 10^{10}$ s^{-1}

The projection falls below super-nova cooling bound across the whole heterodyne window.

THE REACH

Every systematic sits below the shot-noise floor

^{87}Sr, $T = 10$ s, $B_0 = 1$ mT, $\dot{N} = 10^{10}$ s^{-1}, $\tau_{int} = 1$ year



- Most systematics killed by co-location
- BBR → Cryogenic shielding
- Compton timing→ Sub-ns synchronisation
- Redshift → Micron-level co-location

Heterodyning turns a non-averaging systematic into an averaging one.

LOOKING AHEAD

Beyond axions: a general principle for quantum sensing

Any quantum sensor whose coupling to a target field can be periodically modulated can be moved out of its technical-noise band: coherently inside the atomic wavefunction.

Dark photons

Kinetic-mixing searches with the same differential-clock architecture

Gradient-coupled scalars

Screened fifth-force and scalar dark-matter candidates

Oscillating constants

Time variation of α, m_e/m_p and other couplings

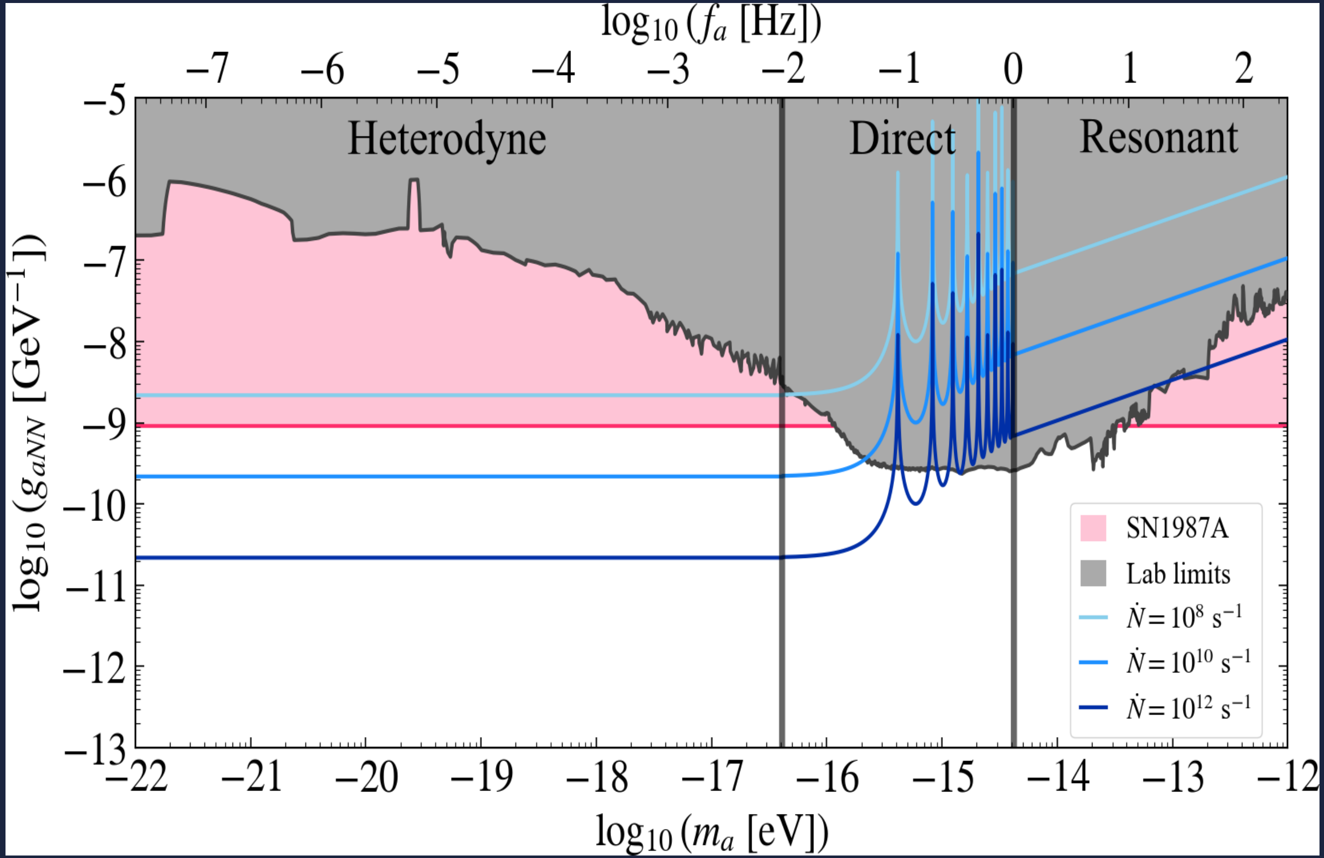
The requirement is only that the coupling can be modulated, not the field .

CONCLUSION

Modulate the coupling, not the field → a quantum lock-in

Geometric modulation moves the signal, not the magnetic noise

$g_a NN \lesssim 10^{-10}$ GeV^{-1}, flat over $m_a \sim 10^{-22} - 10^{-17}$ eV



Thank you

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BACKUP SLIDES

Full differential phase noise budget (Table II)

Source	δϕ per cycle	δϕ after 1 year	Condition
1st-order Zeeman	2.5×10^{-7}	1.4×10^{-10}	white δB at Ω
2nd-order Zeeman	9.3×10^{-10}	5.2×10^{-13}	white δB at Ω
BBR (cryogenic)	7.1×10^{-7}	4.0×10^{-10}	white δT
Gravitational redshift	3.0×10^{-6}	1.6×10^{-9}	co-located clouds, δz = 1 μm
Compton timing	7.9×10^{-7}	4.4×10^{-10}	white jitter, δt = 10 ps
Lattice frequency	6.3×10^{-7}	3.5×10^{-10}	δv_m^rms = 10 Hz
Lattice intensity	6.3×10^{-8}	3.5×10^{-11}	(δI/I)^rms = 10^{-4}
Shot noise	**3.2×10^{-6}**	**1.8×10^{-9}**	

^{87}Sr, T = 10 s, B_0 = 1 mT, Δm_F = 9, $\dot{N} = 10^{10}\ s^{-1}$, temperature ≤ 10 μK.

Adiabaticity, eddy currents and the choice of B_0

- Adiabatic following requires $\Omega \ll g_F \mu_B B_0 / \hbar$ — large B_0 buys margin
- ^{87}Sr, B_0 = 1 mT: Larmor ≈ 10 kHz, five orders above the 100 mHz we use
- Second-order Zeeman shift $\Delta\nu = -0.233\, B_0^2$ Hz (B_0 in gauss) = −23.3 Hz at 1 mT
- Scalar and m_F-independent for $J = 0$ → common-mode, cancels differentially
- Residual comes only from shot-to-shot fluctuation δB_0 → 2.9×10^{-9} rad, three orders below shot noise
- Eddy currents scale with Ω — the reason regime 3 is technically limited at high modulation frequency

Which modulation waveform, and why

Rotating B (used here)	Selective. Acts on the orientation of B at fixed $\lvert B \rvert$, so the Zeeman phase stays static. No harmonics. Works for any nuclear spin, including $\Delta m_F = 9$. Cost: large B_0 for adiabaticity.
Bipolar square, $g = \mathrm{sgn}[\cos \Omega t]$	No DC component, maximises the Fourier component at Ω. Harmonics at $n\Omega$.
Unipolar, $g = \frac{1}{2}(1 + \mathrm{sgn}[\cos \Omega t])$	Deleterious: the surviving DC component re-introduces exactly the $1/f^n$ noise the protocol exists to avoid.
Optical ($\sigma\pm$ π-pulse pair)	Much smaller B_0, fewer eddy currents, arbitrary waveforms, no constraint on cloud position. But not selective: the first-order Zeeman shift $\propto \Delta m_I$ is up-converted with the signal.

Sidereal signature: what no systematic can fake

- Earth's rotation varies the projection of the galactic axion gradient onto the lab spin axis
- The signal amplitude is modulated at $\omega_{sid} \approx 2\pi \times 11.6\ \mu\text{Hz}$
- Two interferometers with orthogonal spin axes give 90°-offset sidereal modulations
- The same two interferometers remove the $\sin\theta_1$ blind angle — all gradient directions covered
- No laboratory systematic reproduces this pattern

☐ FIGURE 6 — DRAW (optional)

Cartoon: Earth rotating, galactic axion gradient fixed in the sky, projection onto the lab spin axis sweeping over a sidereal day. Small inset: the resulting amplitude modulation, plus the 90°-offset second interferometer.

Coherence time and the $\sqrt{\tau}$ scaling

- The axion field is not monochromatic: $Q \approx 10^6$ gives $\tau_{coh} \simeq Q/\omega_a$
- At $\omega_a = 1$ μHz, $\tau_{coh} \approx 5 \times 10^3$ yr — a one-year integration is deep in the coherent regime
- For $\tau_{int} \ll \tau_{coh}$ the delta-function PSD is replaced by $\tau_{int}/2\pi$ and sensitivity improves as $\sqrt{\tau_{int}}$
- For $\tau_{int} \gtrsim \tau_{coh}$ the signal spreads over independent bins and must be summed incoherently ($\tau^{1/4}$)
- This matters only at the high-mass end of the window

State preparation and detection

- Optical pumping into $|{}^1S_0, \downarrow\rangle$; bi-chromatic $\pi/2$ from a single AOM driven at two frequencies
- Superposition of $|{}^1S_0,\downarrow\rangle$, $|{}^3P_0,\downarrow\rangle$ (reference, $\Delta m_I = 0$) and $|{}^3P_0,\uparrow\rangle$ (probe, $\Delta m_I = 1$)
- Closing $\pi/2$ maps ϕ_a onto the two m_F populations; extracted by ellipse fitting
- Sequential detection after transfer to ${}^1S_0$, or shelving-based readout
- At 1 mT the two π transitions $|{}^3P_0, m_F = \pm 9/2\rangle \to |{}^3S_1, m_F = \pm 9/2\rangle$ are split by 45 MHz in ${}^{87}Sr$
- Spin squeezing can push below shot noise, generally at the cost of bandwidth

Choice of atom, and the electron-spin extension

- Fermionic AEL with I = 1/2 (^{111}Cd, ^{171}Yb): simple single-photon $\Delta m\_F = 1$
- ^{87}Sr has $\Delta m\_F = 9$ between extrema — larger signal, but a larger first-order Zeeman lever arm
- $g\_F \approx -1 \times 10^{-4}$ for both clock states: only the nuclear spin couples
- Bosonic AEL on $^1S_0 \to {}^3P_2$ extends the method to the electron spin–axion coupling
- $\dot{N} = 10^{12}\ s^{-1}$ needs a large-area lattice or a continuous atomic beam