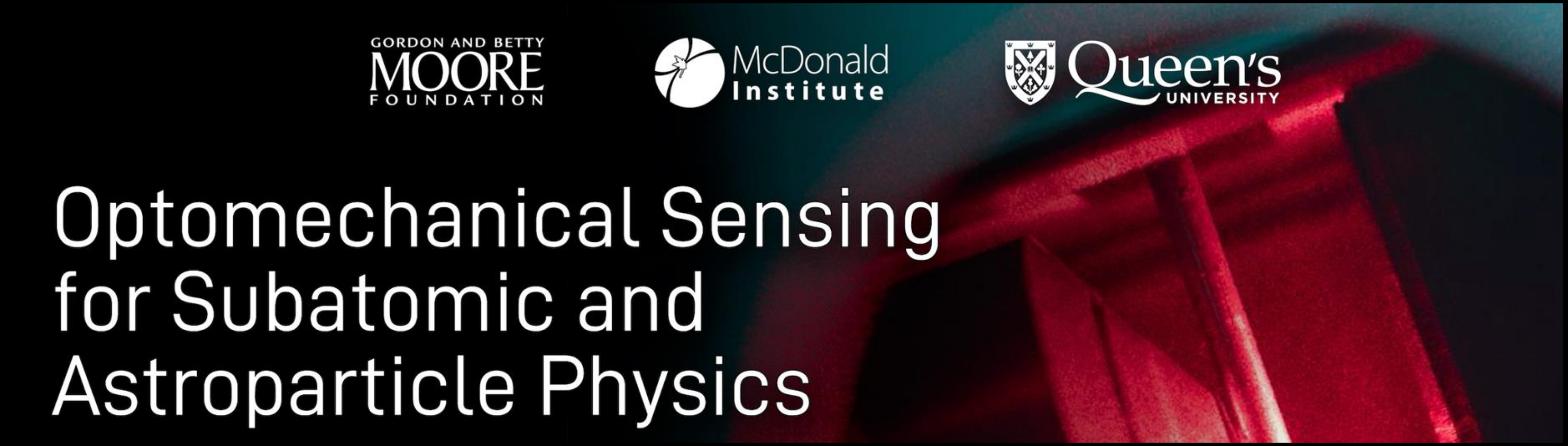


High Energy Theory and Scope Overview for Optomechanical Sensing

Zhen Liu
University of Minnesota

U.S. DEPARTMENT of ENERGY
ALFRED P. SLOAN FOUNDATION
SQMS

Outline

What dark matter/sector could be

Fields, particles and macroscopic objects

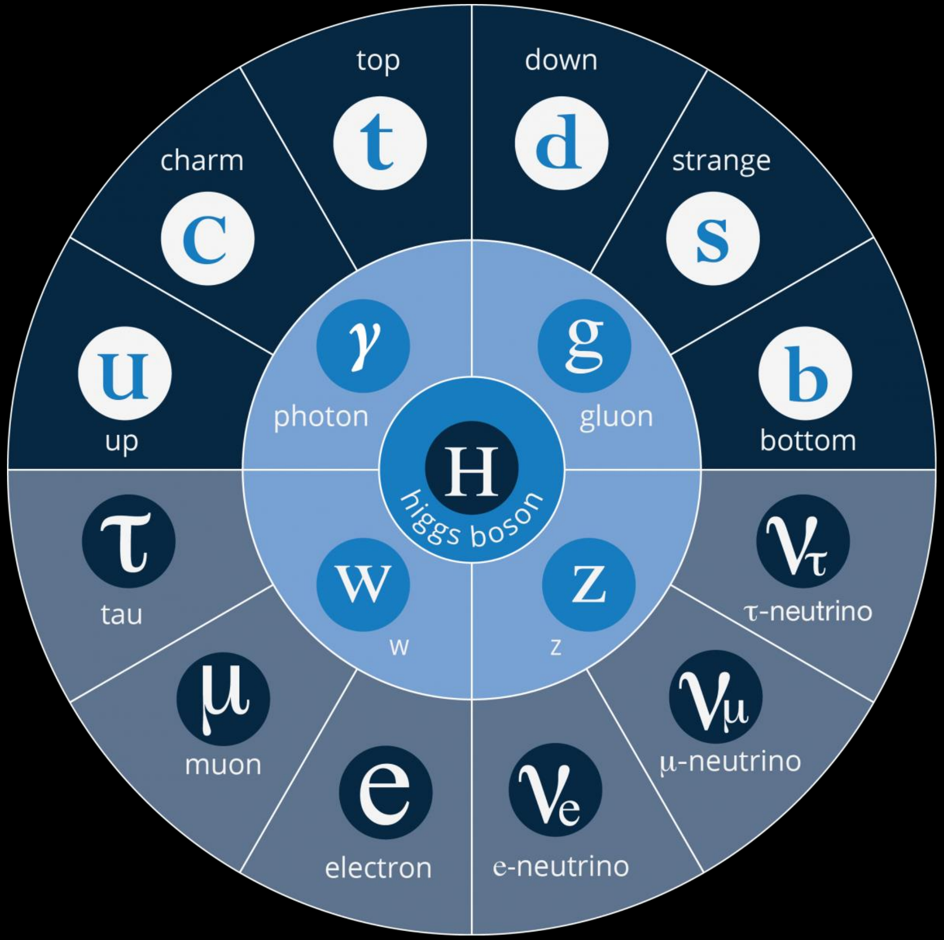
How it could interact with matter

A broad theory landscape, organized by couplings

Aspects of sensing

Mechanical signals, quantum resources and non-DM searches

The particles and interactions we know

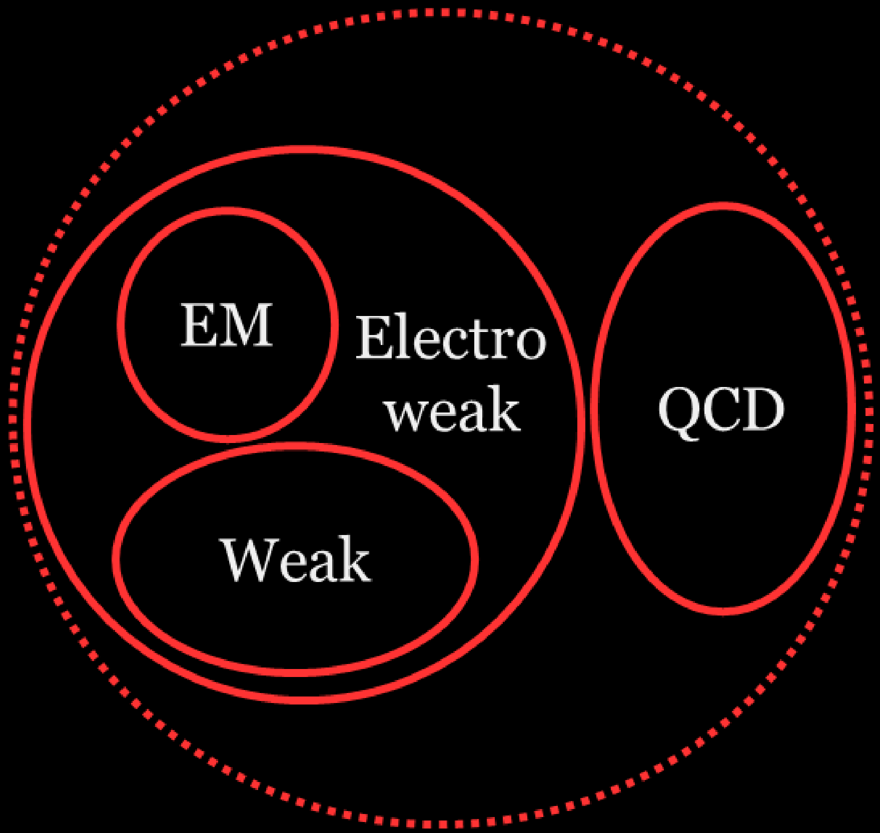


Matter has several kinds of charge.

Different interactions probe different properties of the same object.

The Standard Model is successful. But it has many profound and open questions.

Dark sector may have its own interactions

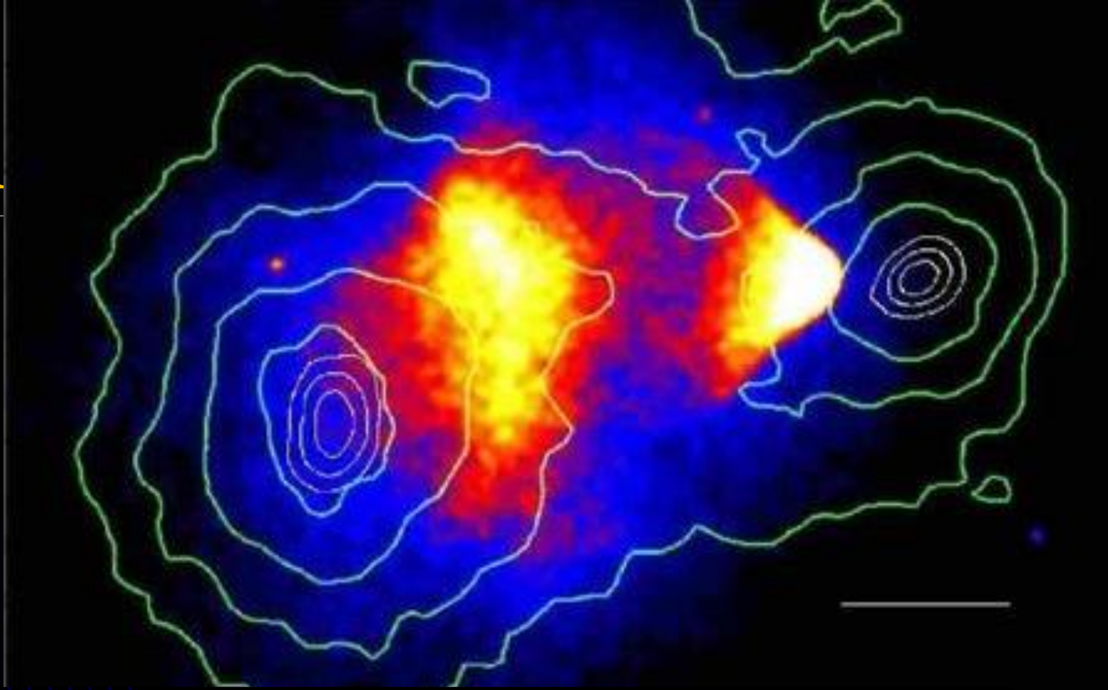


A hidden sector may contain

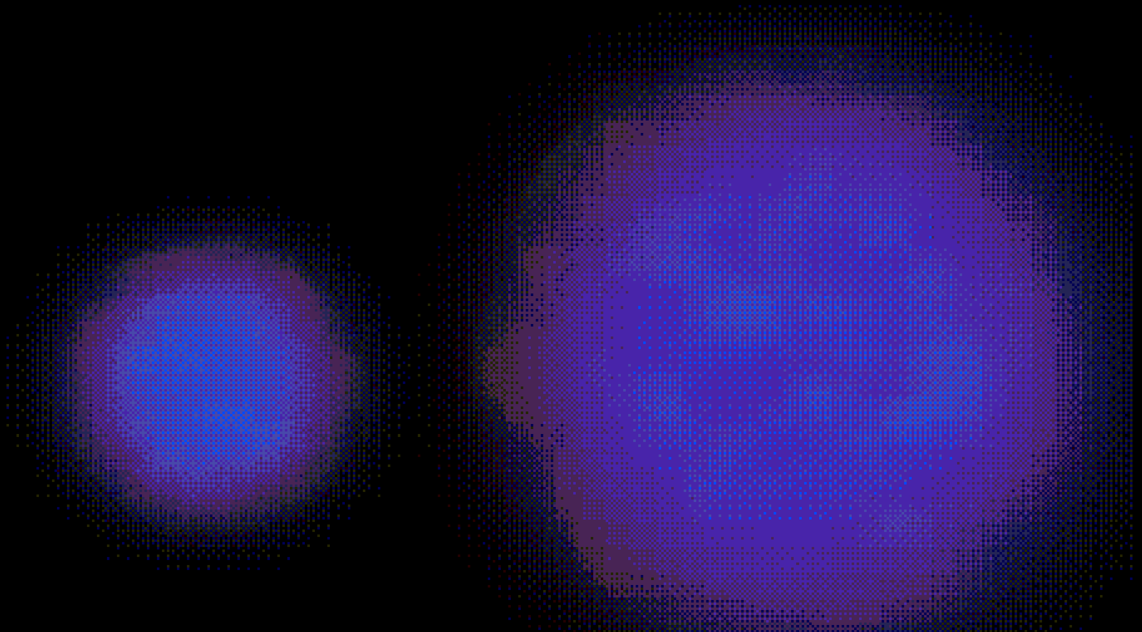
new particles and forces,
its own symmetry breaking,
and composite objects.

A weak connection to ordinary matter
can become a precision-sensing signal.

Gravity reveals an unseen com



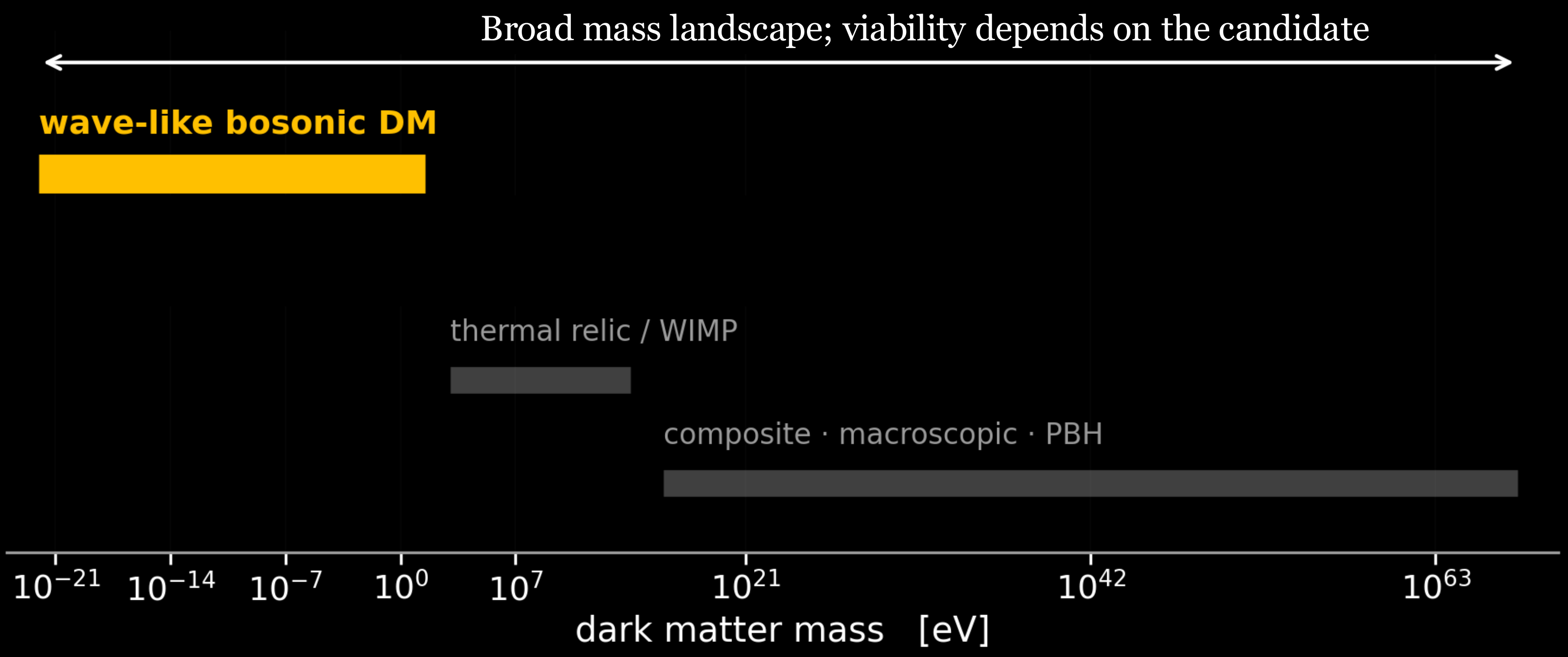
- ~85% of matter is DM
- Build the structure of the universe
- (Very) weakly coupled (to us)
- What is Dark Matter?



Dark matter is real; its mass is not known

Gravity tells us about abundance and distribution; microscopic identity remains unknown.

The mass landscape spans wave-like, particle-like and macroscopic possibilities.



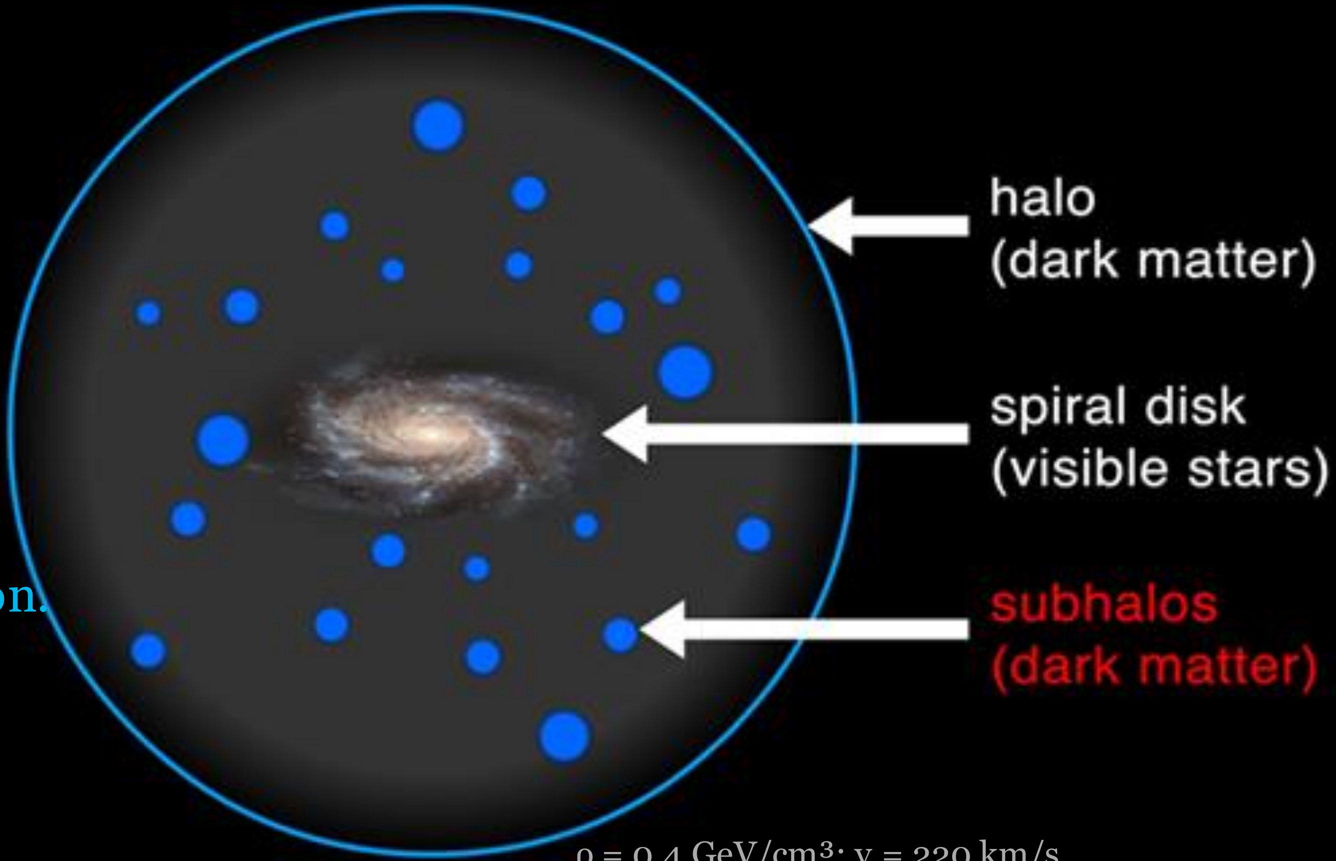
DM is close to particle physicists' hearts: see the response to the recent LZ candidate excess (2609.02823).

The wave / particle divide

Quanta per de Broglie volume

$$\mathcal{N} = \frac{\rho}{m}\left(\frac{2\pi}{mv}\right)^3$$

Large occupation permits a wave description.
It does not fix the quantum state.



ρ = 0.4 GeV/cm³; v = 220 km/s

Pauli phase-space bounds exclude ultralight fermions as the dominant conventional collisionless halo DM.

THE WAVE

Analytic illustration for this talk; Cheong, Rodd & Wang, 2408.04696

Write it as a classical field

So the right starting point is the field itself:

$$\phi(t, \mathbf{x}) = \phi_0 \cos(\omega t - \mathbf{k} \cdot \mathbf{x} + \delta)$$

$$\omega \simeq m \qquad |\mathbf{k}| \simeq mv \qquad v \sim 10^{-3}$$

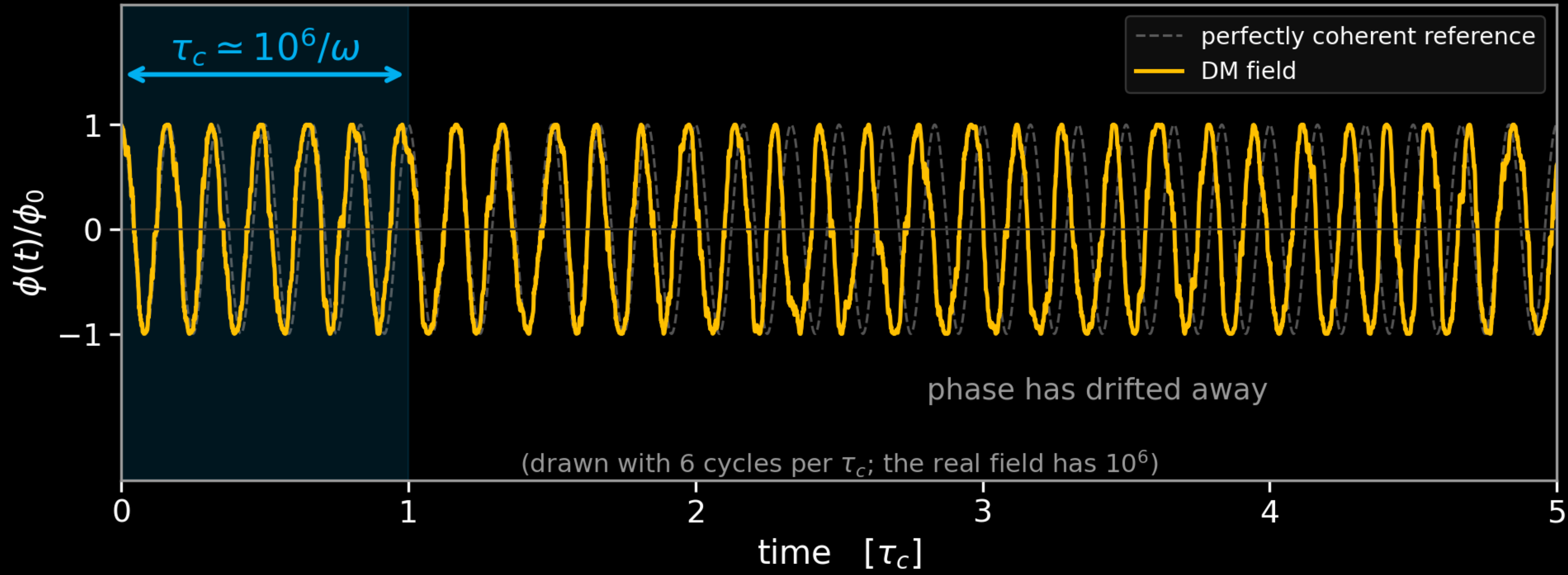
(field–theory expressions on the following slides use $\hbar = c = 1$)

A coherence patch can fill your entire laboratory.

The DM is approximately a Q ≈ 10^6 oscillator

Halo velocity dispersion $v \sim 10^{-3}$ smears the frequency by $\Delta\omega/\omega \approx v^2/2$.

Phase memory survives $\sim 10^6$ cycles; the coherence length scales as $1/(mv)$.



THE WAVE

Derevianko, 1605.09717; Foster–Rodd–Safdi, 1711.10489; Carney, Hook, ZL, Taylor & Zhao — 1908.04797 Cheong–Rodd–Wang, 2408.04696; Kalia, 2504.16990

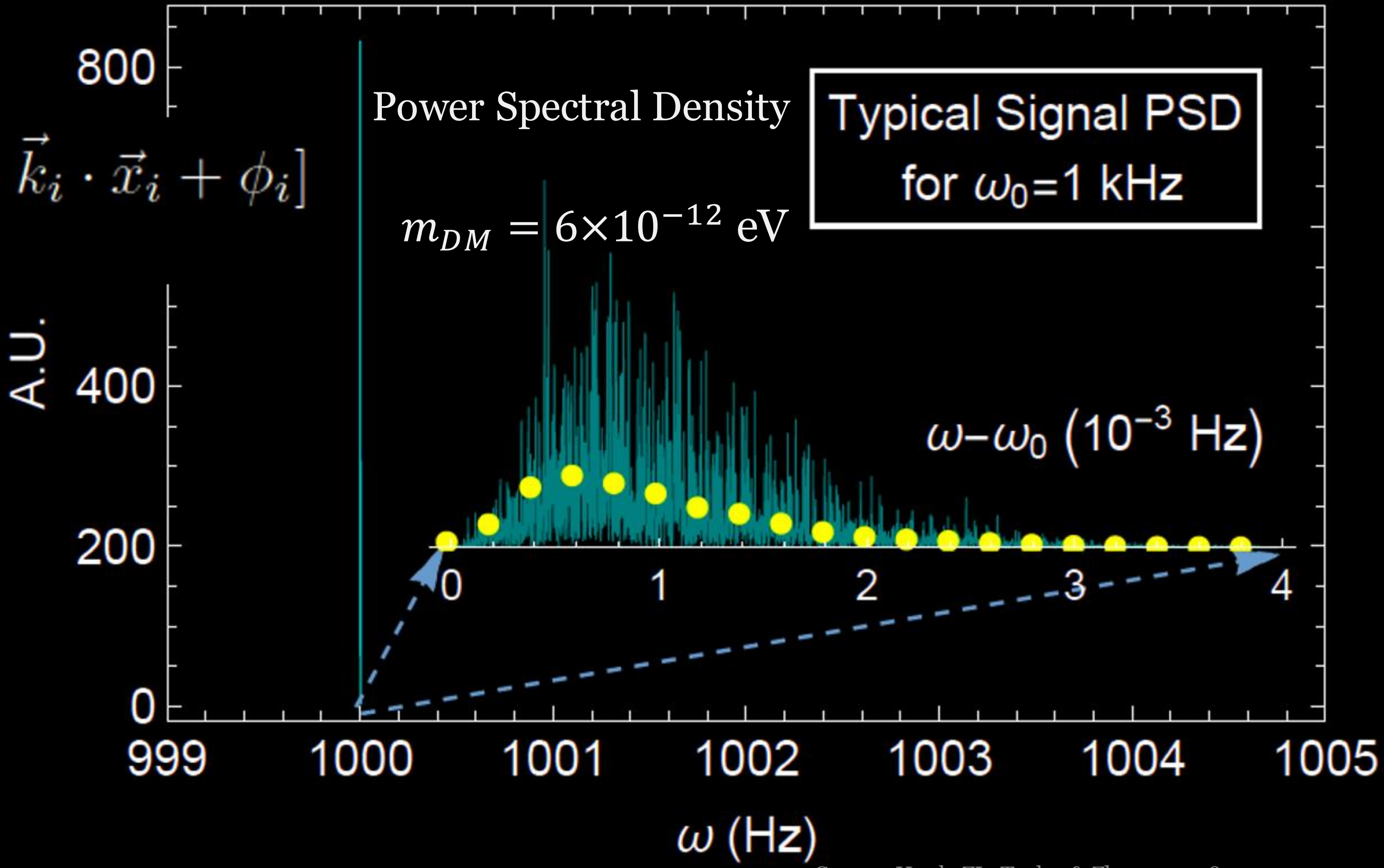
Ultralight DM profile: power spectra

$$\vec{A}(t,\vec{x}) = \sum_i \vec{A}_i \sin[\omega_i t - \vec{k}_i \cdot \vec{x}_i + \phi_i]$$

Almost monochromatic

- very long coherence time
- very long coherent distance

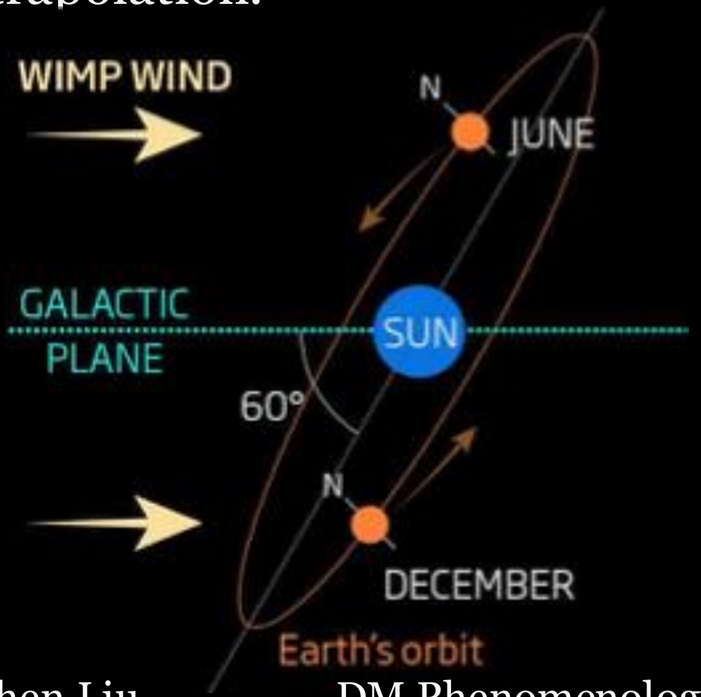
Coherence time set by the velocity dispersion (10^-3) feeding into frequency dispersion (10^-6)



Carney, Hook, ZL, Taylor & Zhao — 1908.04797

Ultralight DM profile: modulation

Further dispersion caused by earth's motion:
Daily modulation and annual modulation possible to further check consistency and DM property extrapolation.

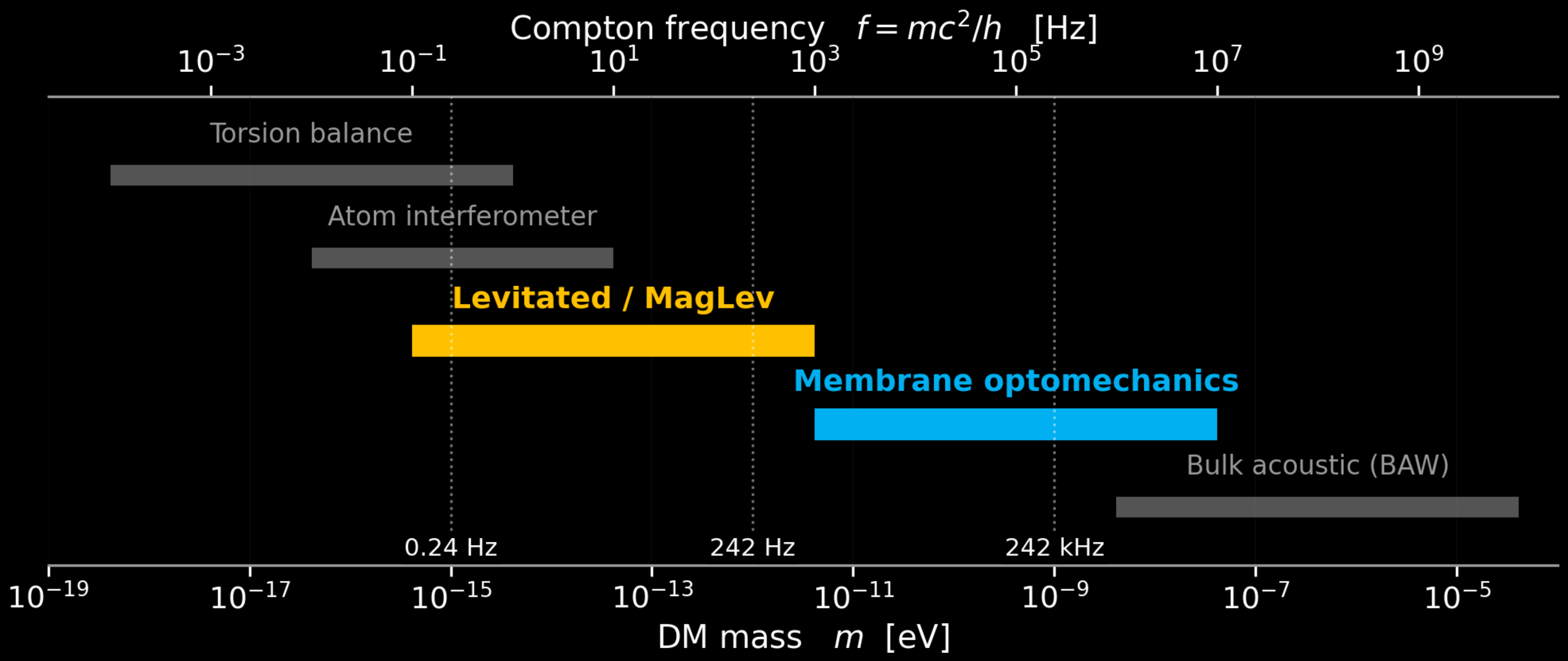


$$
\begin{aligned}
f_{G,x,i} &= N_{B-L} g_{B-L} \omega_i A_n \sin(\theta_{A,i}) \cos(\phi_{A,i} - \omega_E t) \\
&\quad \times \sin(\omega_i t - \vec{k}_i \cdot \vec{x}_s + \phi_i) \\
&\simeq N_{B-L} g_{B-L} \omega_i A_n \sin(\theta_{A,i}) \cos(\phi_{A,i} - \omega_E t) \\
&\quad \times \sin(\omega_i t + \phi_i) \\
f_{G,y,i} &\simeq N_{B-L} g_{B-L} \omega_i A_n \sin(\theta_{A,i}) \sin(\phi_{A,i} - \omega_E t) \\
&\quad \times \sin(\omega_i t + \phi_i) \\
f_{G,z,i} &\simeq N_{B-L} g_{B-L} \omega_i A_n \cos(\theta_{A,i}) \sin(\omega_i t + \phi_i)
\end{aligned}
$$

Compton frequency sets your band

$$f = \frac{mc^2}{h} = 2.4\times10^{14}\ \mathrm{Hz}\left(\frac{mc^2}{\mathrm{eV}}\right)$$

For a linearly driven resonance, frequency selects a preferred mass.



Schematic, overlapping instrument bands. A torsion balance can use optomechanical readout.

Snowmass ULDM review., 2203.14915

THE WAVE

Outline

What dark matter could be

Fields, particles and macroscopic objects

How it could interact with matter

A broad theory landscape, organized by couplings

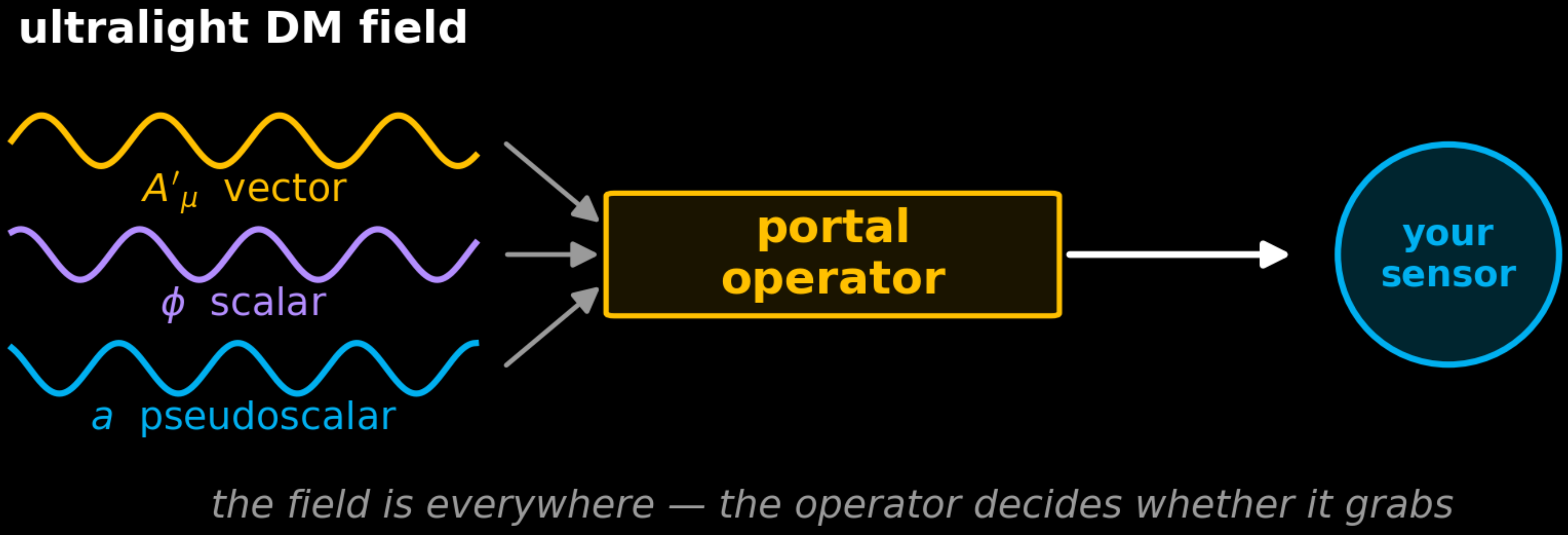
What quantum sensors can measure

Mechanical signals, quantum resources and non-DM searches

How does a field talk to matter?

The field passes through your apparatus whether or not you can see it.

It takes an interaction operator to turn that into something you can measure.



Gravity remains without a nongravitational portal.

Representative families: spin 0, spin 1, ... Massive spin 2 is another possibility.

EFT is one useful language

Symmetries organize possible interactions; models explain their origin.

Spin 1

$$\frac{\varepsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

$$g A'_{\mu} J^{\mu}$$

$$B - L,\ B,\ L,\ L_i - L_j$$

$$B - 3L_i, \ldots$$

i, j = e, μ, τ; i ≠ j

Spin 0, CP even

$$\phi F^2,\ \phi G^2,\ m_i \phi \bar{\psi}_i \psi_i$$

$$\phi |H|^2, \quad \phi^2 |H|^2, \ldots$$

Linear and quadratic portals

Spin 0, CP odd

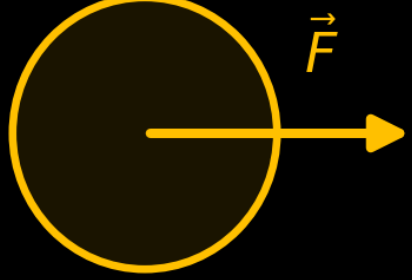
$$\frac{a}{f_a} \frac{\alpha_s}{8\pi} G \tilde{G}$$

$$\frac{g_{a\gamma}}{4} a F \tilde{F}$$

$$\frac{\partial_\mu a}{2 f_a} \sum_i c_i \bar{\psi}_i \gamma^\mu \gamma^5 \psi_i$$

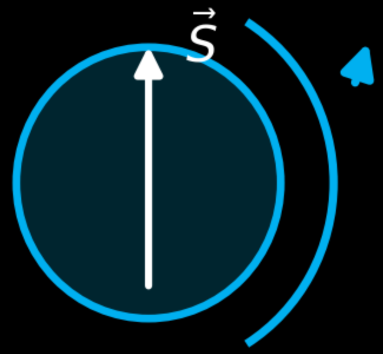
All SM fermions; effective p, n below QCD

What a mechanical sensor measures



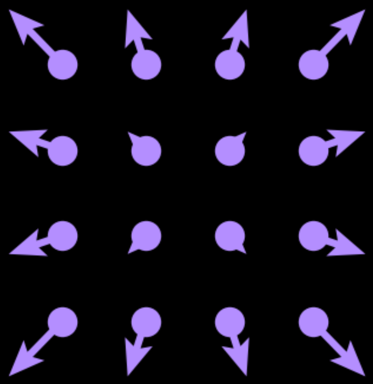
FORCE

on the centre of mass



TORQUE

on a polarised spin



STRAIN

inside the body

Force, torque and strain are common mechanical observables.

The selection rule

coupling

↓

force / torque / strain

↓

experiment

The rest of this talk fills in this map.

Vector dark matter

A massive spin-1 field

Mass from Stückelberg, or from a dark Higgs.

Produced by misalignment, inflationary fluctuations, or cosmic strings.

Kinetic mixing is dimension four; the vector mass has a separate origin.

VECTOR

Nelson & Scholtz — arXiv:1105.2812; Graham, Mardon & Rajendran — arXiv:1504.02102

Kinetic mixing

One operator, one parameter:

$$\mathcal{L} \supset \frac{\varepsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

A rotation of the gauge fields removes the mixing and gives every charged Standard-Model particle a coupling $\varepsilon e Q$ under A'.

VECTOR

Holdom (1986); review: Fabbrichesi, Gabrielli & Lanfranchi — arXiv:2005.01515

What kinetic mixing does to Maxwell

Dark matter enters Maxwell's equations as a source:

$$\nabla\times\mathbf{B} - \partial_t\mathbf{E} = \mathbf{J}_{\text{eff}}$$

$$\mathbf{J}_{\text{eff}} = -\varepsilon m^2\mathbf{A}'$$

An effective current filling space, oscillating at the dark-photon frequency.

No cavity is required; boundaries determine the fields your sensor sees.

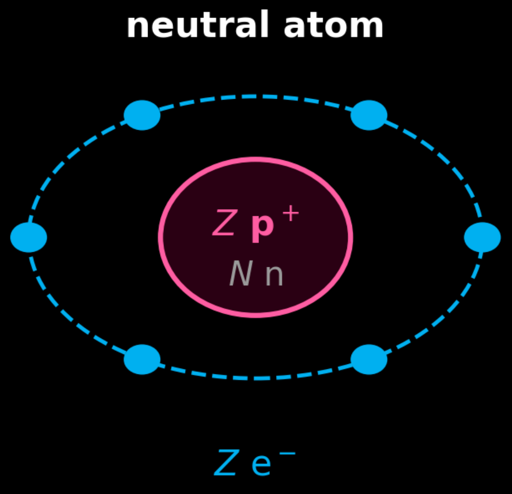
VECTOR · **FORCE**

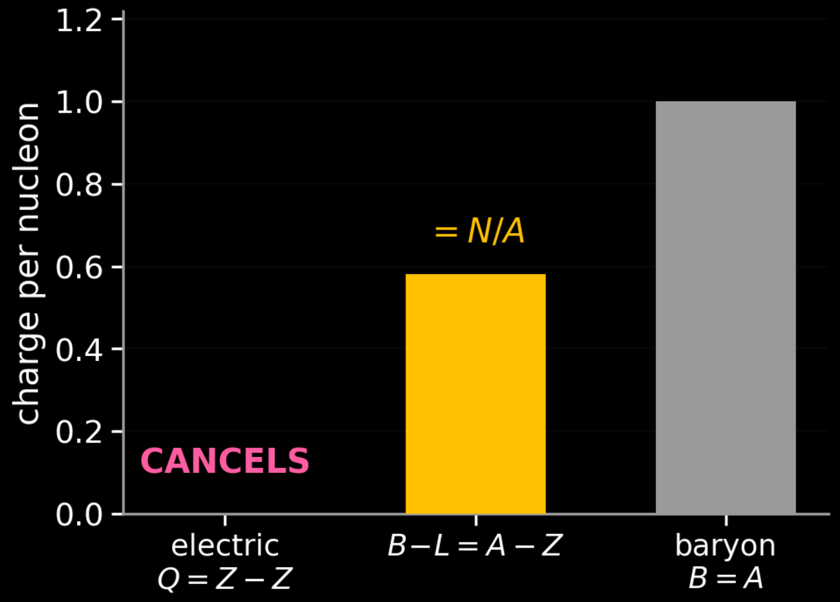
Chaudhuri et al., DM Radio — arXiv:1411.7382

Kinetic mixing and neutral sensors

A uniform electric field gives no net center-of-mass force on a neutral body.

Dipoles, gradients and electromagnetic transduction can still produce a response.





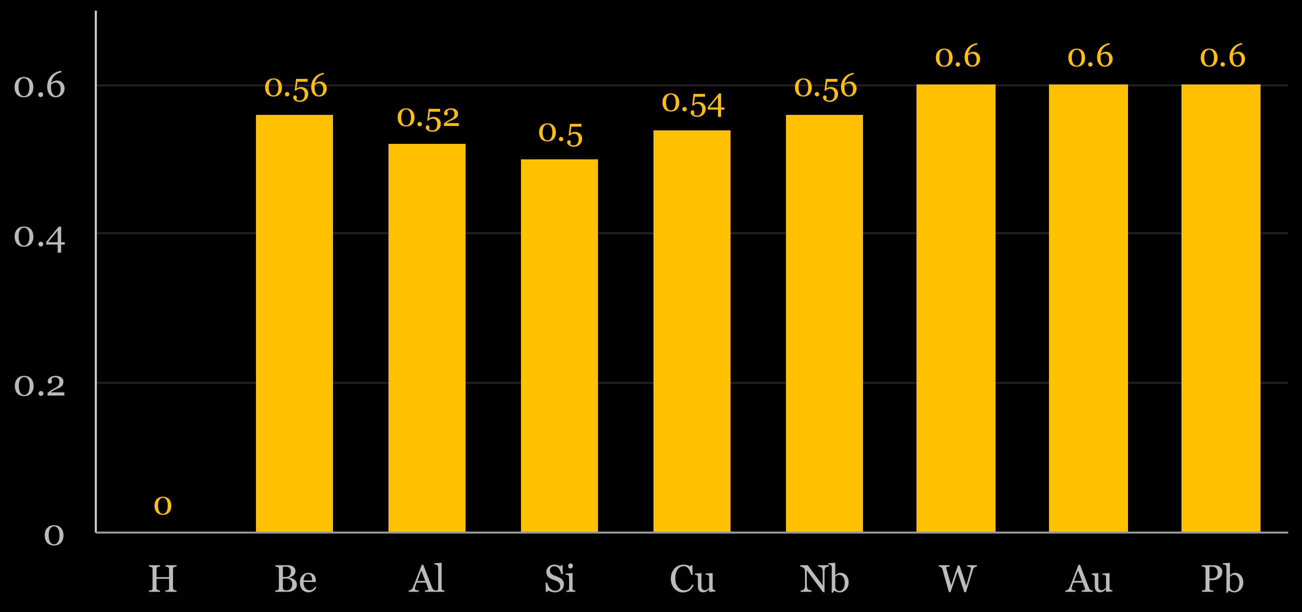
A challenge for mechanics: the residual signal depends on the apparatus.

VECTOR · **FORCE**

Graham et al., 1512.06165; Higgins, Kalia & ZL , 2310.18398

Other vector charges drive neutral matter

For B – L, the charge of a neutral atom is its neutron number.



Composition matters

$$\Delta a = gE'\Delta\left(\frac{Q}{M}\right)$$

The reference body moves too.

Illustrative neutron fractions. Neutral-atom electric charge is zero for every material.

Graham et al., 1512.06165; Carney, Hook, ZL, Taylor & Zhao, 1908.04797

The broader vector-charge menu

Vector coupling	Neutral-atom charge	Mechanical implication
Kinetic mixing	0	Dipole / gradient / EM conversion
$B - L$	N	Composition contrast
B	A	Nearly common-mode acceleration
L	Z	Electron-to-mass contrast

A different charge assignment changes both the target and the reference response.

B, L are anomalous, but not B-L;---anomalous means other heavy particles are needed in the theory.

Graham et al., 1512.06165; Fabbrichesi et al., 2005.01515

Lepton flavor changes the charge

Ordinary matter contains electrons, but no muons or taus.

Representative current	Charge of a neutral atom
$L_e - L_\mu, \quad L_e - L_\tau$	Z
$L_\mu - L_\tau$	$0 \quad$ (tree level)
$B - 3L_e$	$A - 3Z$
$B - 3L_\mu, \quad B - 3L_\tau$	A

The same apparatus can respond differently to different flavor choices.

All the above choices are anomaly-free.

VECTOR · FORCE

Ma, hep-ph/9709474; Fabbrichesi et al., 2005.01515

Vector survival is a dynamical question

Resonant conversion can transfer energy between a dark photon and a plasma.

Nonlinear plasma response can saturate that conversion.

Viability depends on the model, production history and medium.

Hook, Huang & Shalaby, 2510.13956; McCarthy et al., 2406.02546

Pseudoscalar dark matter

Axions and ALPs

An approximate shift symmetry can protect a small mass.
The QCD axion addresses strong CP; broader theories motivate many ALPs.

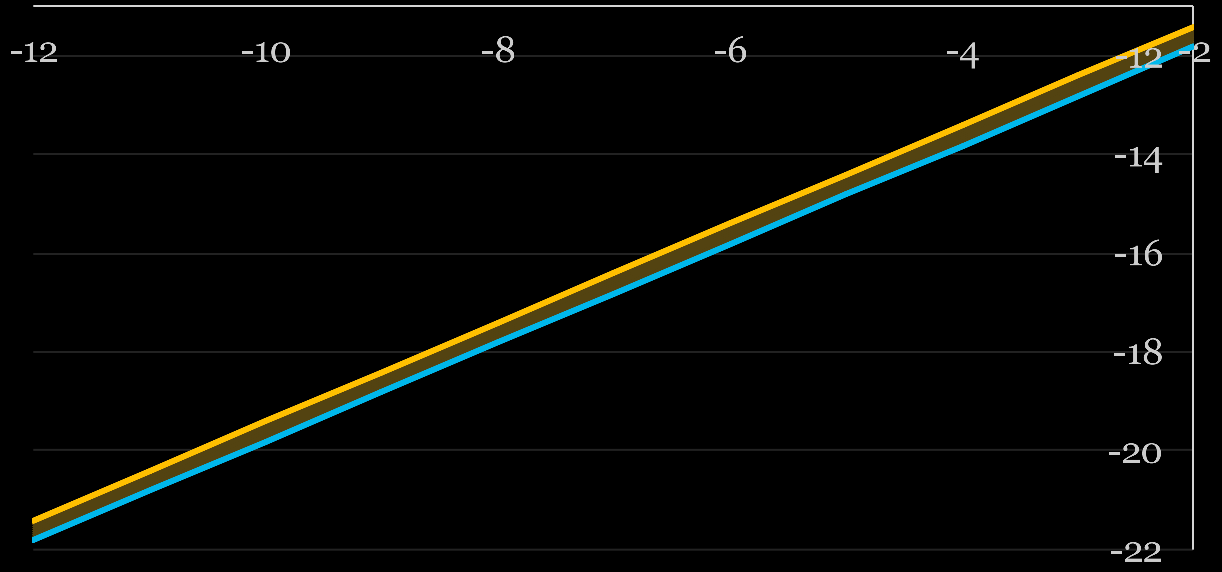
Photon, gluon and fermion operators give different experimental handles.

Peccei & Quinn (1977); Svrcek & Witten — hep-th/0605206; Arvanitaki et al. — arXiv:0905.4720

The QCD axion gives us a target

The strong-CP puzzle: why is the neutron EDM so small?

Axion dynamics relax the effective QCD CP angle.



KSVZ (E/N = 0)

DFSZ (E/N = 8/3)

QCD fixes mass versus $1/f_a$.

$$m_a \simeq 5.7\,\mu\text{eV}\left(\frac{10^{12}\ \text{GeV}}{f_a}\right)$$

Photon coupling adds
a model-dependent coefficient.

$$g_{a\gamma} = \frac{\alpha C_\gamma}{2\pi f_a}$$

Representative KSVZ / DFSZ benchmarks; this interval does not contain every QCD-axion model.

PSEUDOSCALAR

The ALP coupling menu

Gluons

$$\frac{a}{f_a}\frac{\alpha_s}{8\pi}G\tilde{G}$$

Oscillating nuclear CP-odd moments

Photons

$$\frac{a}{f_a}\frac{\alpha}{8\pi}aF\tilde{F}$$

Conversion in electromagnetic fields

Fermions

$$\frac{\partial_\mu a}{2f_a}\sum_i c_i\,\bar{\psi}_i\gamma^\mu\gamma^5\psi_i$$

Species-dependent spin couplings

Quarks and leptons at high energy; effective proton and neutron couplings at low energy.

PSEUDOSCALAR

Budker et al., 1306.6089; Walter et al., 2504.16044; Winter et al., 2609.07908

Operator I: the gluon coupling

$$\mathcal{L} \supset \frac{a}{f_a}\frac{\alpha_s}{8\pi} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

The dark matter field becomes an oscillating QCD θ–angle.

$$d_n \approx 2.4{\times}10^{-16}\,\bar{\theta}(t)\,e\cdot\text{cm}$$

The result is an oscillating nucleon EDM, with CP-odd nuclear moments alongside it.

In a polarised piezoelectric crystal that stress is mechanical: the piezoaxionic effect.

PSEUDOSCALAR · **TORQUE**

Pospelov & Ritz — hep-ph/9904483; piezoaxionic — arXiv:2112.11466

Operator II: the photon coupling

$$\mathcal{L} \supset \frac{g_{a\gamma}}{4} \, aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

Maxwell picks up a new source, proportional to the field you already have:

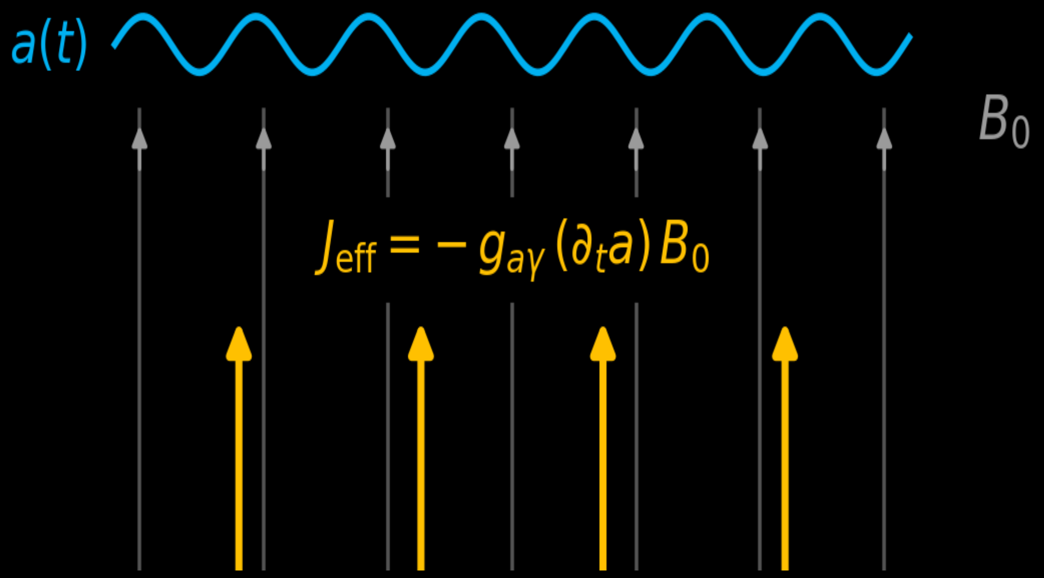
$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = -g_{a\gamma}(\partial_t a)\mathbf{B}_0$$

PSEUDOSCALAR · **FORCE**

Sikivie (1983); Irastorza & Redondo — arXiv:1801.08127

Axion conversion in a magnetic trap

a(t) is a time trace of the local field.



Local current illustration; the actual trap field is nonuniform.

The applied field selects the current direction.

The trap geometry and boundaries determine the induced field and force.

The DM velocity direction enters differently in the spin–gradient coupling.

PSEUDOSCALAR · FORCE

Effective-current schematic from the reference deck; physics: Higgins, Kalia & ZL, 2310.18398

Operator III: spin–gradient coupling

$$\mathcal{L}_{a\psi} = \frac{\partial_\mu a}{2f_a}\sum_i c_i\,\bar{\psi}_i\gamma^\mu\gamma^5\psi_i$$

The axion gradient acts as a species-dependent pseudo-magnetic field.

$$\mathbf{B}_{\mathrm{eff}} \propto \nabla a \sim m_a \mathbf{v} a_0$$

Electrons, protons and neutrons have distinct couplings and spin responses.

Conventionally called “axion wind”; CASPEr also uses the name “Gradient”.

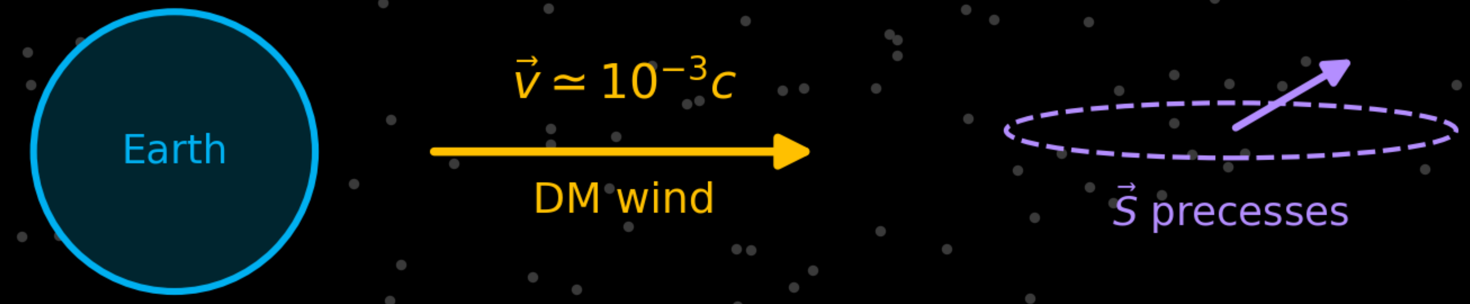
PSEUDOSCALAR · **TORQUE**

Graham & Rajendran, 1306.6088; Berlin et al., 2312.11601; Walter et al., 2504.16044

...and what it does to spins

A polarised ensemble feels a torque; halo statistics set its directional response.

As the Earth turns, the signal can show a characteristic sidereal modulation.



$$\vec{B}_{\rm eff} \propto \vec{\nabla} a \propto m_a v\, a_0$$

direction fixed by the halo ⇒ daily modulation as Earth rotates

PSEUDOSCALAR · **TORQUE**

Budker et al., 1306.6089; CASPEr-Gradient: Walter et al., 2504.16044; Electric: Winter et al., 2609.07908

Scalar dark matter

Moduli, dilatons and Higgs portals

Scalar couplings can change masses and material dimensions.

Composition-dependent forces connect scalars and B – L vectors to EP tests.

An ultralight scalar still needs a radiative-stability explanation.

SCALAR

Damour & Polyakov — hep-th/9401069; Damour & Donoghue — arXiv:1007.2790

The scalar coupling menu

At linear order, one operator per Standard-Model parameter:

$$\mathcal{L} \supset \frac{\phi}{\mathrm{M}}\left[d_e \frac{F^2}{4e^2} - d_g \frac{\beta_3}{2g_3} G^2 - \sum_i \left(d_{m_i} + \gamma_{m_i} d_g\right) m_i \bar{\psi}_i \psi_i\right]$$

Each coefficient d_i says how strongly one constant of nature responds.

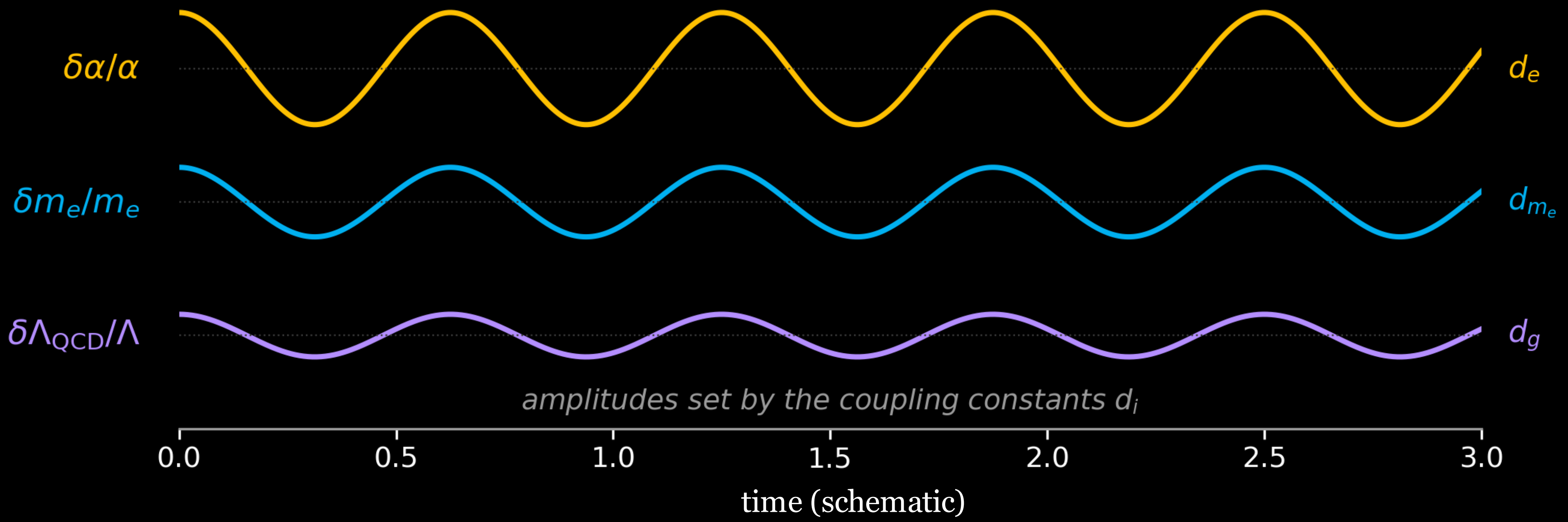
Linear and quadratic portals are both possible.

$$\phi|H|^2, \quad \phi^2|H|^2, \quad \phi^2\mathcal{O}_{\mathrm{SM}}, \ldots$$

Damour & Donoghue — arXiv:1007.2792

The constants oscillate

α, m_e and $\Lambda_{\rm QCD}$ all oscillate at $\omega = m_\phi$, each with its own amplitude.



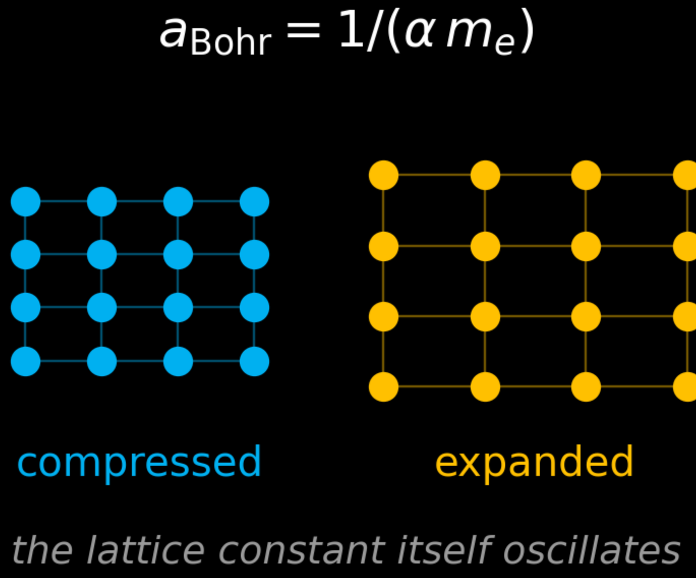
SCALAR

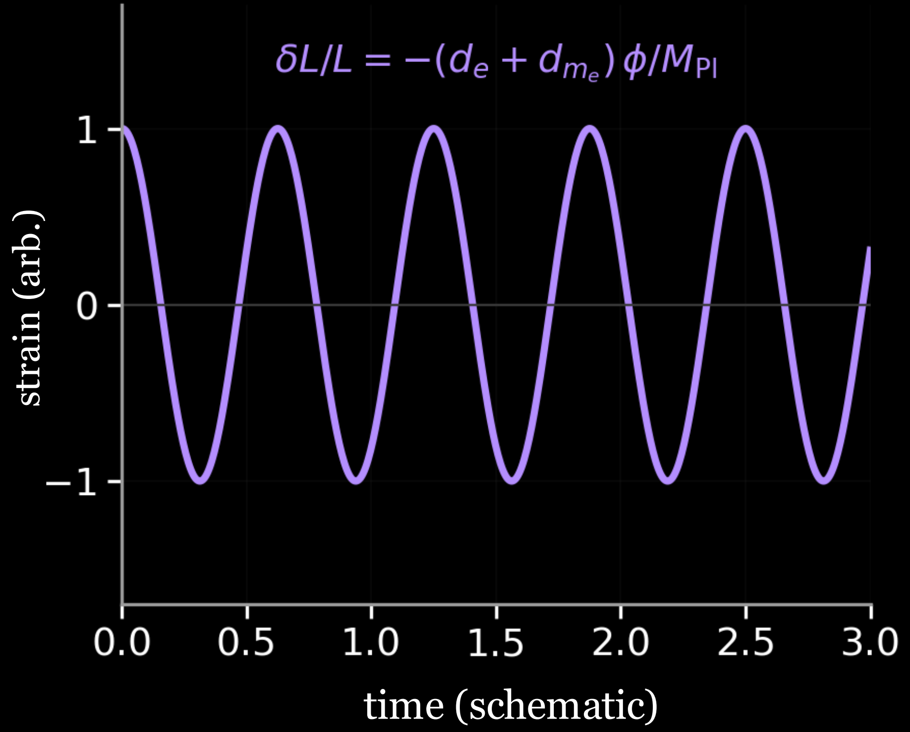
Arvanitaki, Huang & Van Tilburg — arXiv:1405.2925; Stadnik & Flambaum — arXiv:1503.08540

Consequence I: solids breathe

The Bohr radius is $1/(\alpha m_e)$. If α and m_e wobble, every lattice spacing wobbles too.

That is a direct strain signal, and it needs no equivalence-principle test.





SCALAR · **STRAIN**

Arvanitaki, Dimopoulos & Van Tilburg — arXiv:1508.01798; Manley et al. — arXiv:1910.07574

Consequence II: weight oscillates

Most of a nucleon's mass is QCD binding energy:

$$m_N \propto \Lambda_{\text{QCD}}(t)$$

So the mass of every test body oscillates at the Compton frequency,

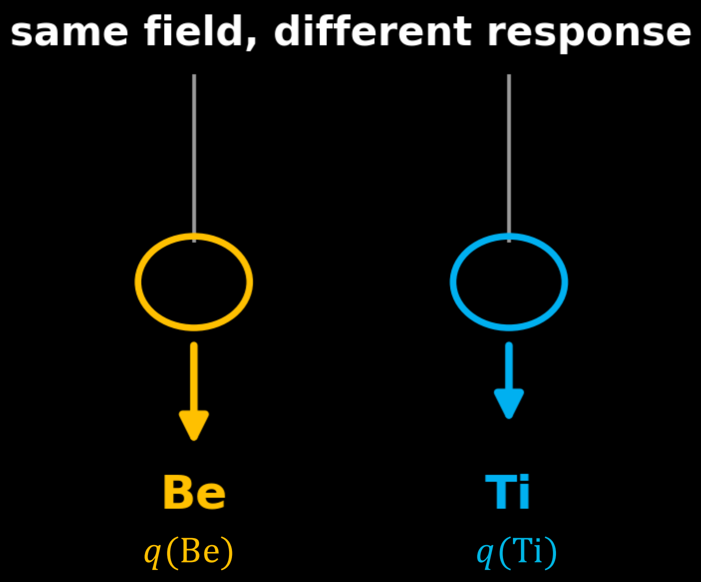
and so does its apparent weight in the Earth's field.

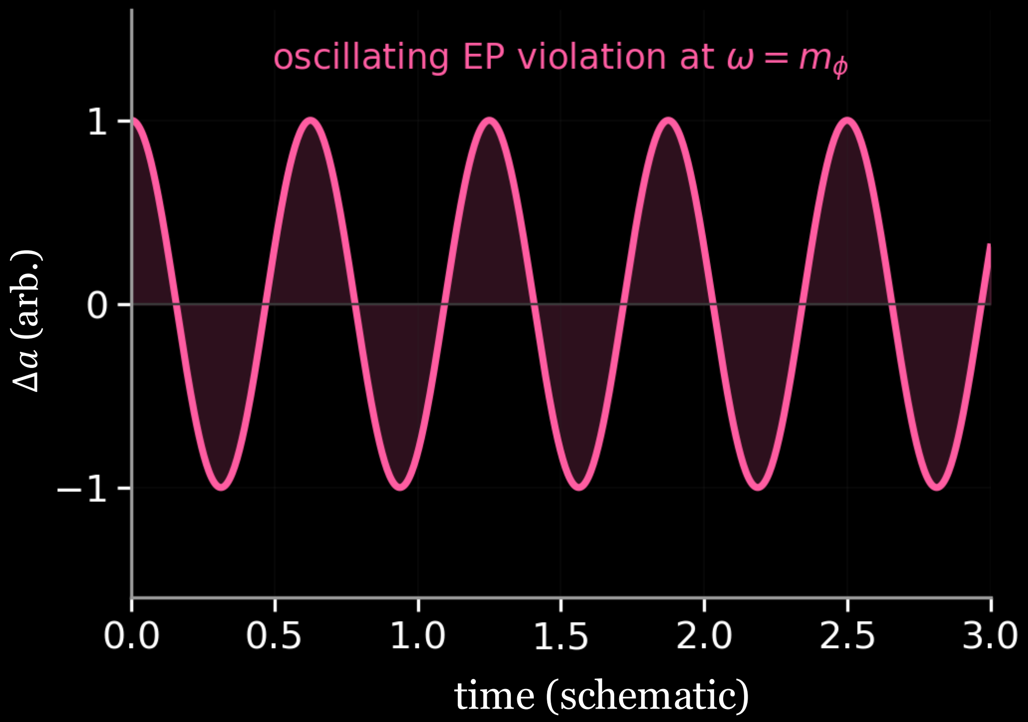
The measured force depends on the support and on the responding reference.

Consequence III: EP violation

The dominant QCD mass shift is common to protons and neutrons.

Differential motion probes the smaller composition-dependent terms.





Damour & Donoghue, 1007.2792; Wagner et al., 1207.2442; MICROSCOPE, 2209.15487

More mechanical channels

Piezoaxionic.

$aG\tilde{G}$ → an oscillating Schiff moment → stress in a polarised piezoelectric crystal → an acoustic mode.

Axioelectric translation.

$F_a \simeq -g_{af}\ddot{a}\,\hat{s}$ pushes polarised fermions along the spin direction.

Berlin et al. put the mechanical reach below astrophysical bounds; their route is electromagnetic.

Axial vector.

Couples to spin directly, giving torques enhanced over the axion wind.

BACKUP — THEORY DETAIL

arXiv:2112.11466; arXiv:2312.11601; arXiv:2609.10671

The diversity of ULDM signals

Forces and accelerations

Matter charges, gradients and induced fields

Spin precession and torque

Derivative fermion couplings and CP-odd moments

Strain and resonance shifts

Changing masses, couplings and material scales

SYNTHESIS

Carney, Hook, ZL, Taylor & Zhao, 1908.04797; Higgins, Kalia, ZL, 2310.18398

Outline

What dark matter could be

Fields, particles and macroscopic objects

How it could interact with matter

A broad theory landscape, organized by couplings

Aspects of sensing

Mechanical signals, quantum resources and non-DM searches

Coherence of the local dark-matter field

A shared phase over finite time and distance

$$\tau_c \sim \frac{1}{mv^2}, \qquad \ell_c \sim \frac{1}{mv}$$

Time coherence sets how measurements accumulate.

Spatial coherence sets which sensors share a signal.

Foster, Rodd & Safdi, 1711.10489; Cheong, Rodd & Wang, 2408.04696; Kalia, 2504.16990

Quantum dark matter and quantum sensors

The state of the dark matter

Production can leave nontrivial correlations.
Certifying nonclassicality in the laboratory is extraordinarily difficult.

Quantum resources in the detector

Squeezing and entanglement can improve sensitivity
to an effectively classical dark-matter signal.

QUANTUM SENSING

Cheong–Rodd–Wang, 2408.04696; Bao et al., 2510.05198; 2607.27313; Kalia, 2504.16990

From force noise to coupling reach

The halo fixes the field amplitude, so it is not a free parameter:

$$A'_0 = \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m} \Rightarrow |\mathbf{E}'| = mA'_0 = \sqrt{2\rho_{\mathrm{DM}}}$$

but what you measure is a difference between two bodies:

$$\Delta a = g\Delta(Q/M)p_{\mathrm{eff}}\sqrt{2\rho}$$

$$g_{\min} \simeq \frac{a_{\min}}{|\Delta(Q/M)|p_{\mathrm{eff}}\sqrt{2\rho}}$$

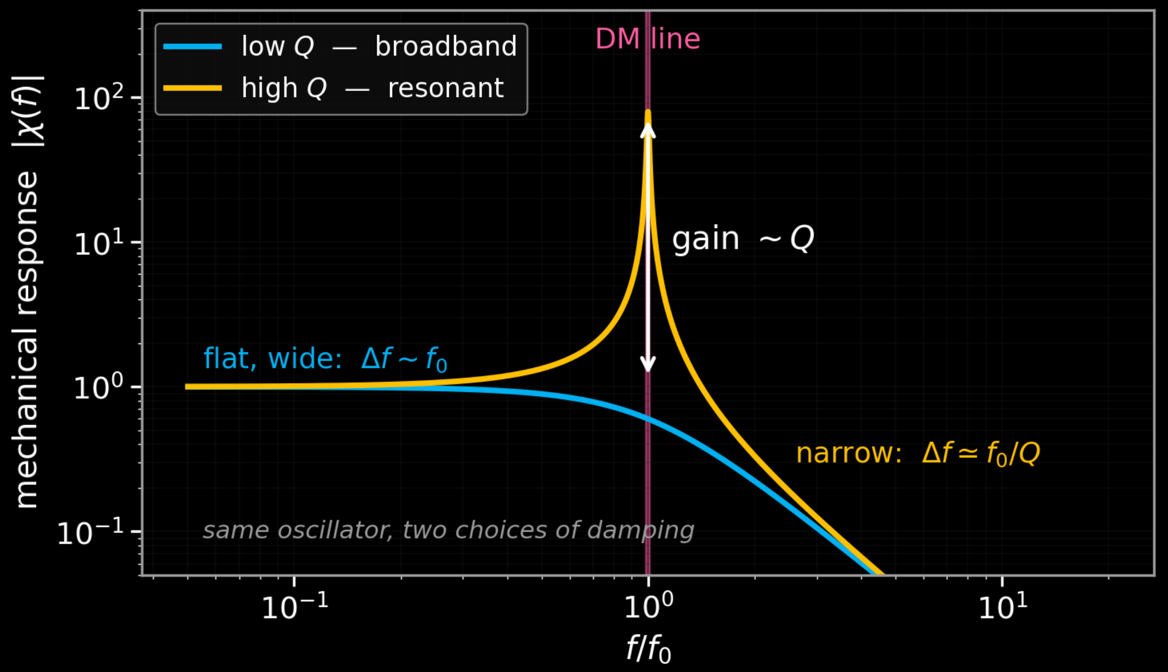
The experiment sets the noise floor, composition contrast and projection.

$\rho = f\rho_{\mathrm{local}}(\text{reach} \propto f^{-1/2})$

SYNTHESIS

Graham et al. — arXiv:1512.06165; Carney, Hook, ZL, Taylor & Zhao — arXiv:1908.04797

Broadband versus resonant: scan rate matters



Resonant buys a factor $\sim Q$ in response, over a bandwidth only f_0/Q wide.

Broadband gives up the gain and keeps the whole band.

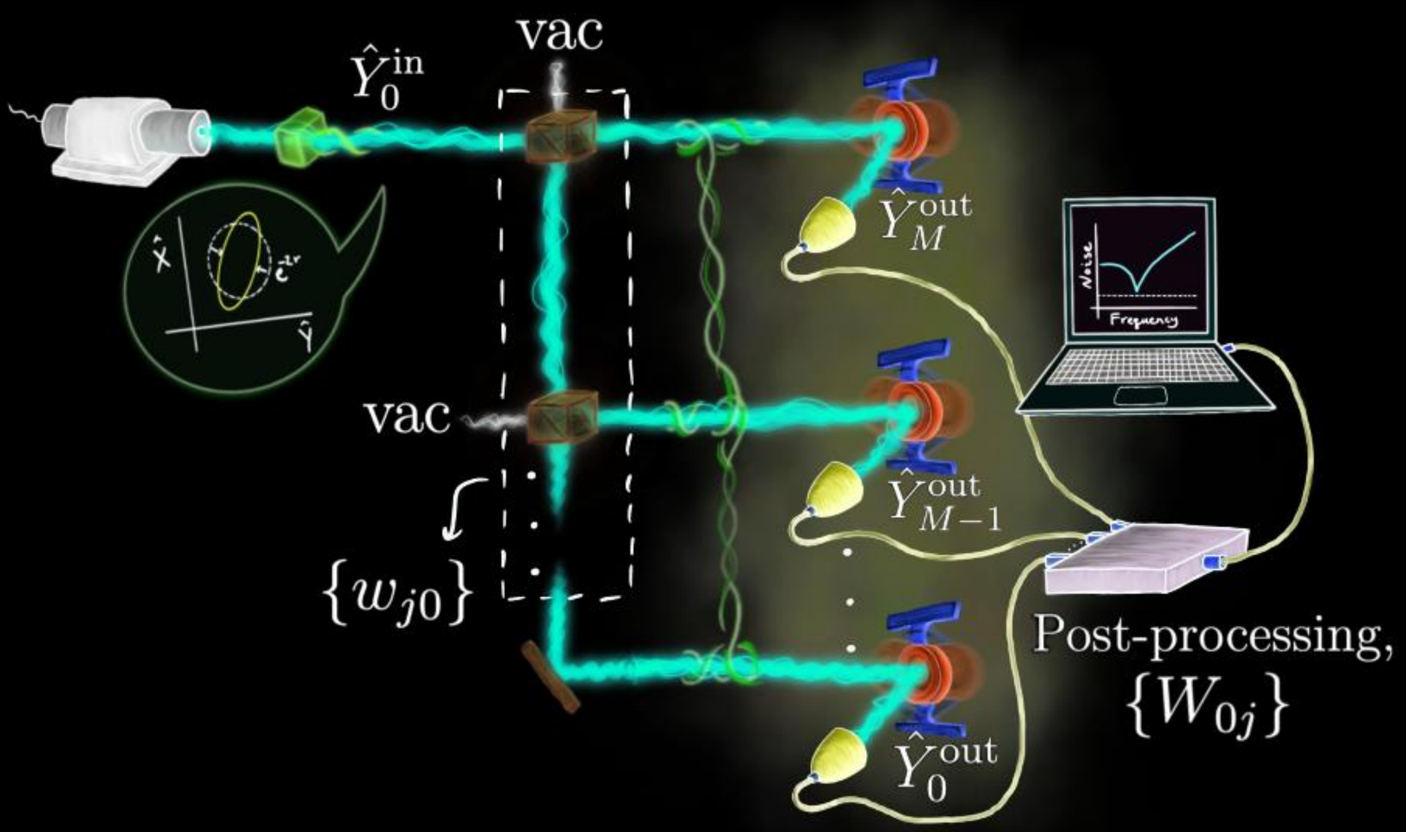
Neither wins in the abstract.

What matters is integrated reach over the mass range you actually care about.

SYNTHESIS

Chaudhuri, Irwin, Graham & Mardon — arXiv:1803.01627

A coherent signal across a sensor network



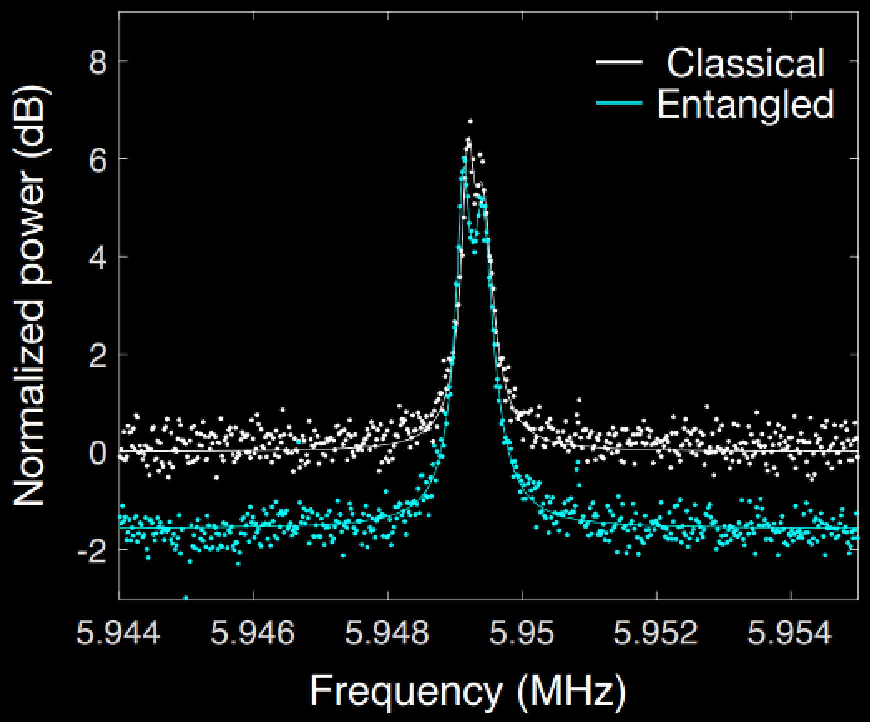
First: combine a spatially coherent signal.

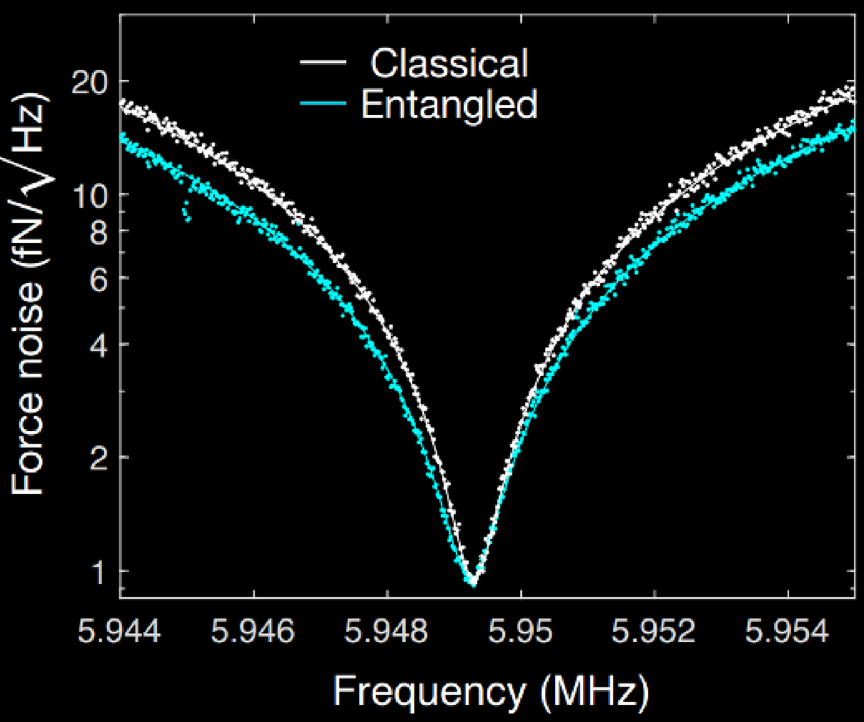
Entangled probes can reduce readout noise further.

Cavity and optomechanical proposals

Brady, Gao, Harnik,ZL, Zhang & Zhuang: 2203.05375; 2210.07291

Squeezing redistributes readout noise





Less noise in the useful quadrature

Loss, back-action and noise limit the usable gain.

QUANTUM RESOURCES

Brady et al., 2203.05375; Xia et al., 2210.16180

Electromagnetic boundaries reshape the signal

$$\mathbf{J}_{\text{eff}} = -\varepsilon m^2 \mathbf{A}'$$

The source fills the apparatus. Boundaries determine the ordinary fields.

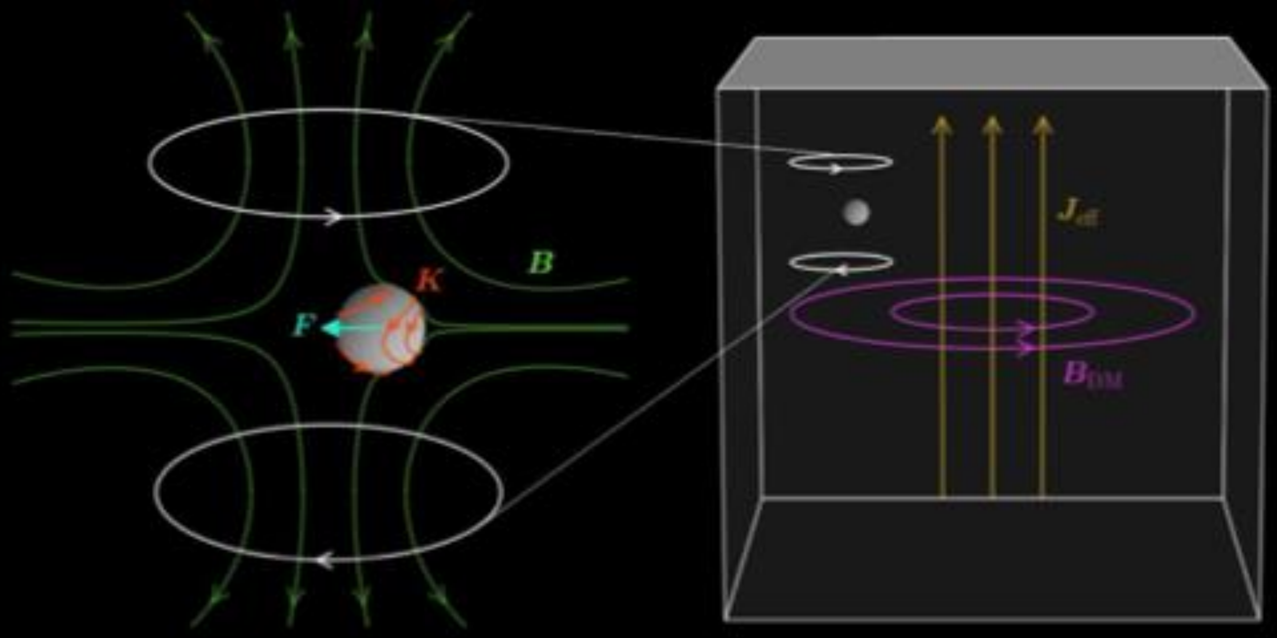
$$B_{\text{sig}} \sim \varepsilon\,(mR)\sqrt{2\rho} \qquad (mR \ll 1)$$

Illustrative quasistatic scaling; geometry and resonances matter.

SYNTHESIS

Chaudhuri et al., 1411.7382; Higgins, Kalia, ZL, 2310.18398

Worked example: levitated superconductor



A superconducting sphere in a quadrupole trap.

The Meissner effect expels B, so the sphere sits where the gradient force balances gravity:

$$\mathbf{F} = -\frac{3V}{2\mu_0}(\mathbf{B}\cdot\nabla)\mathbf{B}$$

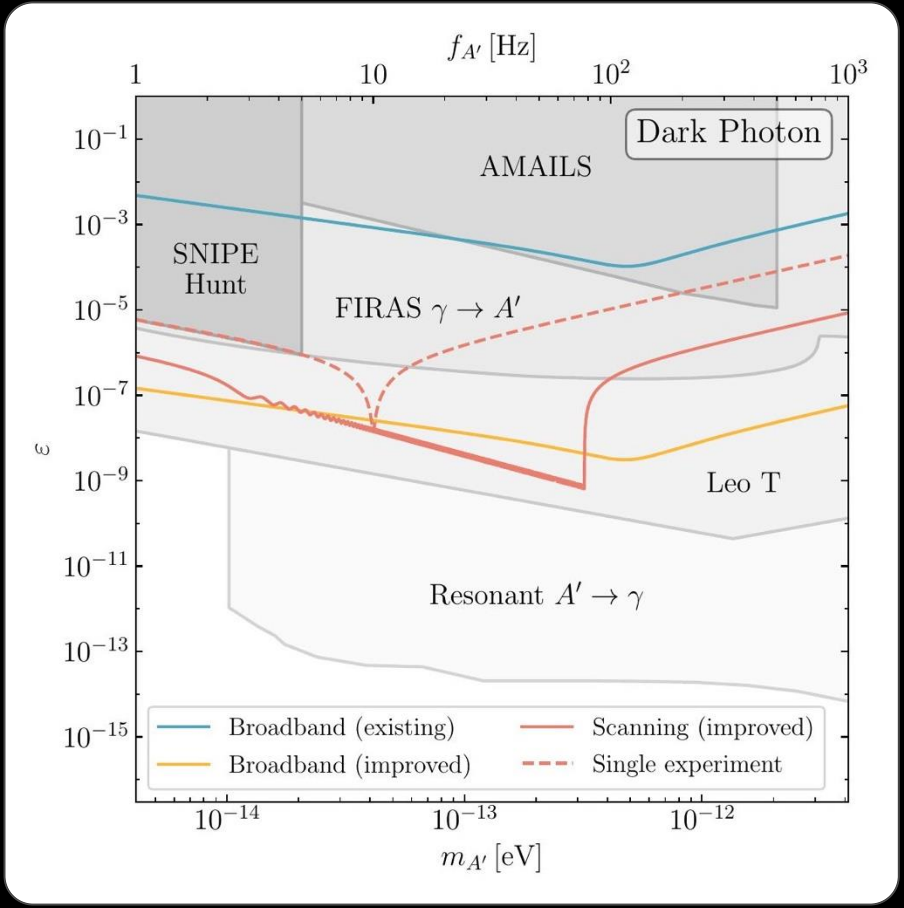
Read out by a SQUID pickup loop.

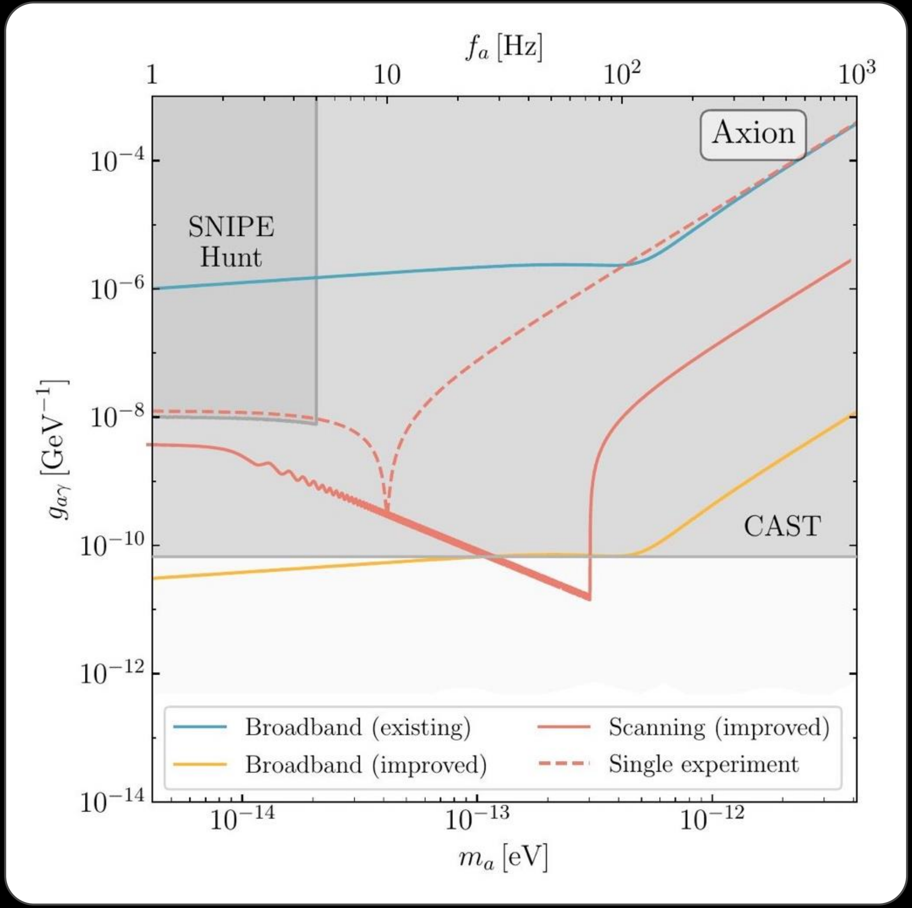
Soft trap, low loss, millikelvin.

WORKED EXAMPLE

G. Higgins, S. Kalia, ZL— arXiv:2310.18398

Projected reach





dark photon ε vs $m_{A'}$

axion–photon $g_{a\gamma}$ vs m_a

Higgins, Kalia & ZL, 2310.18398; levitated-magnet ULDM search: Amaral et al., 2409.03814

WORKED EXAMPLE

Quick comment: laboratory versus astrophysical bounds

Stellar cooling and SN1987A often give a stronger number. Laboratory searches still matter:

They are direct.

Astrophysical bounds constrain production in a hot plasma, not the dark matter that is here now.

They are model-robust.

A screened scalar is heavy in a star and light in a vacuum chamber: different environments.

Their systematics are independent.

A stellar bound rests on a cooling model; a laboratory bound rests on a measured null.

Hardy & Lasenby — arXiv:1611.05852

Outline

What dark matter could be

Fields, particles and macroscopic objects

How it could interact with matter

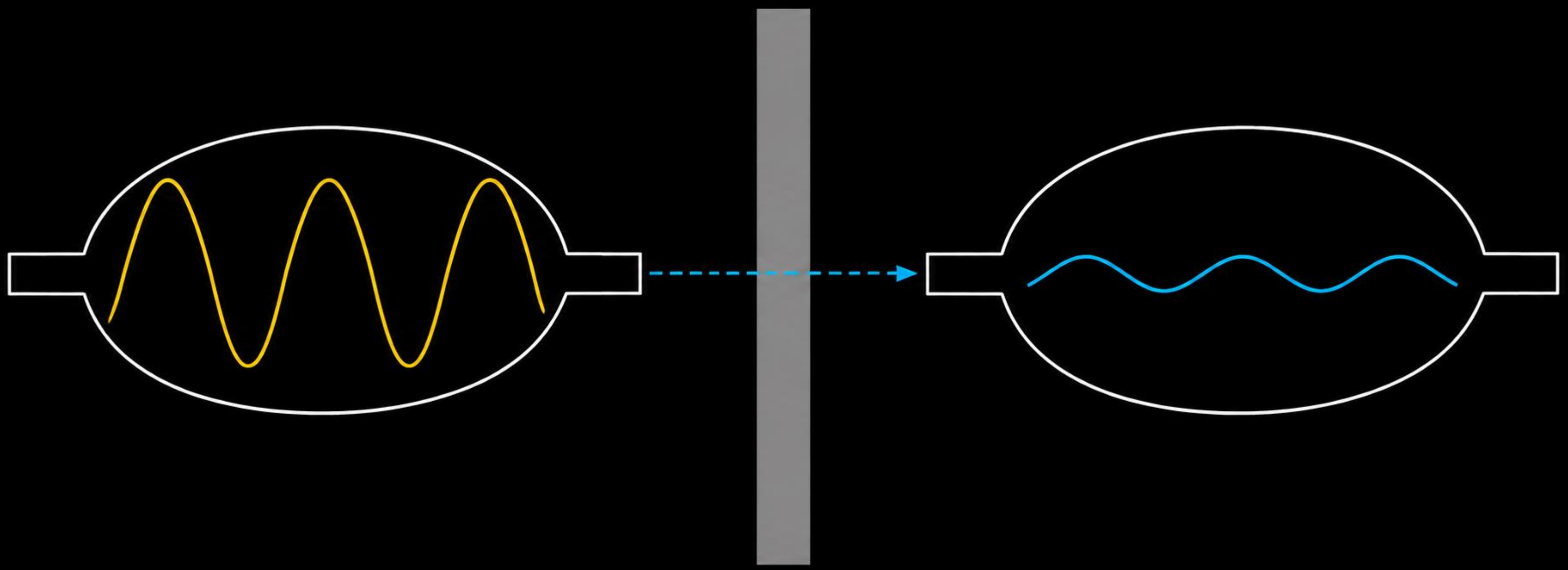
A broad theory landscape, organized by couplings

Aspects of sensing

New forces doesn’t need to be from dark matter

Dark SRF: light shining through a wall

A driven emitter can send a dark-photon field through an electromagnetic barrier.
The laboratory supplies the source; no dark-matter abundance is assumed.



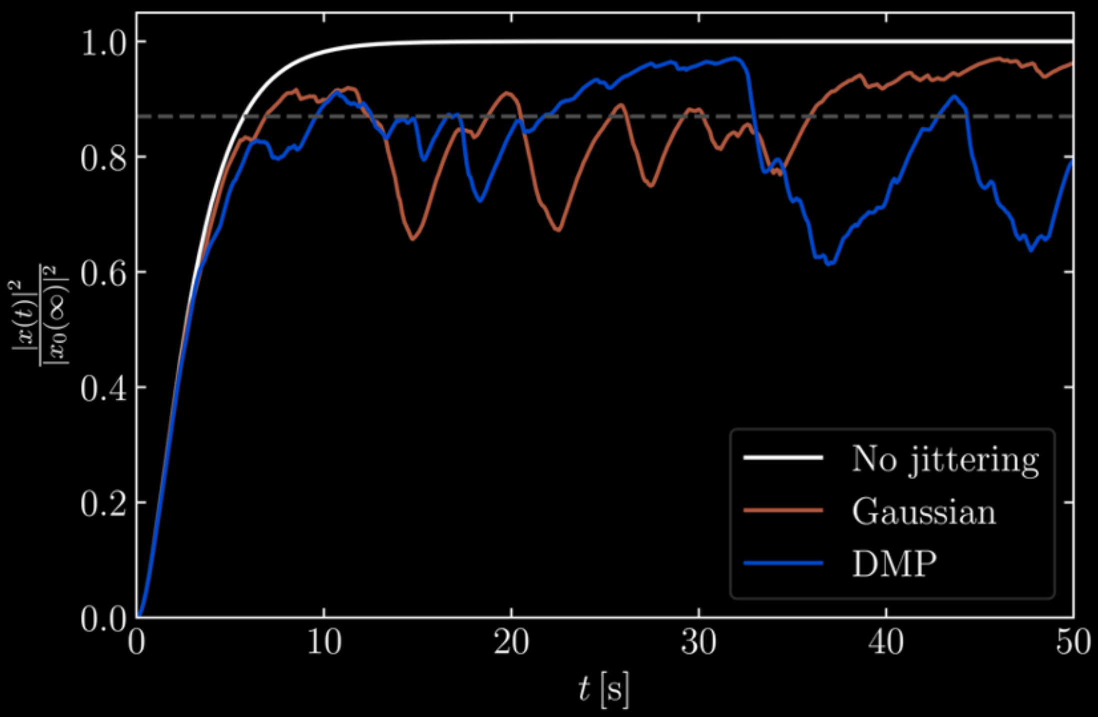
Driven emitter

Shielded receiver

WORKED EXAMPLE

Romanenko et al., 2301.11512; Kalia, ZL et al., 2510.02427;

Frequency jitter and resonant buildup



Phase accumulation matters.

$$\Phi(t, t') = \int_{t'}^{t} \delta\,\omega(s)\, ds$$

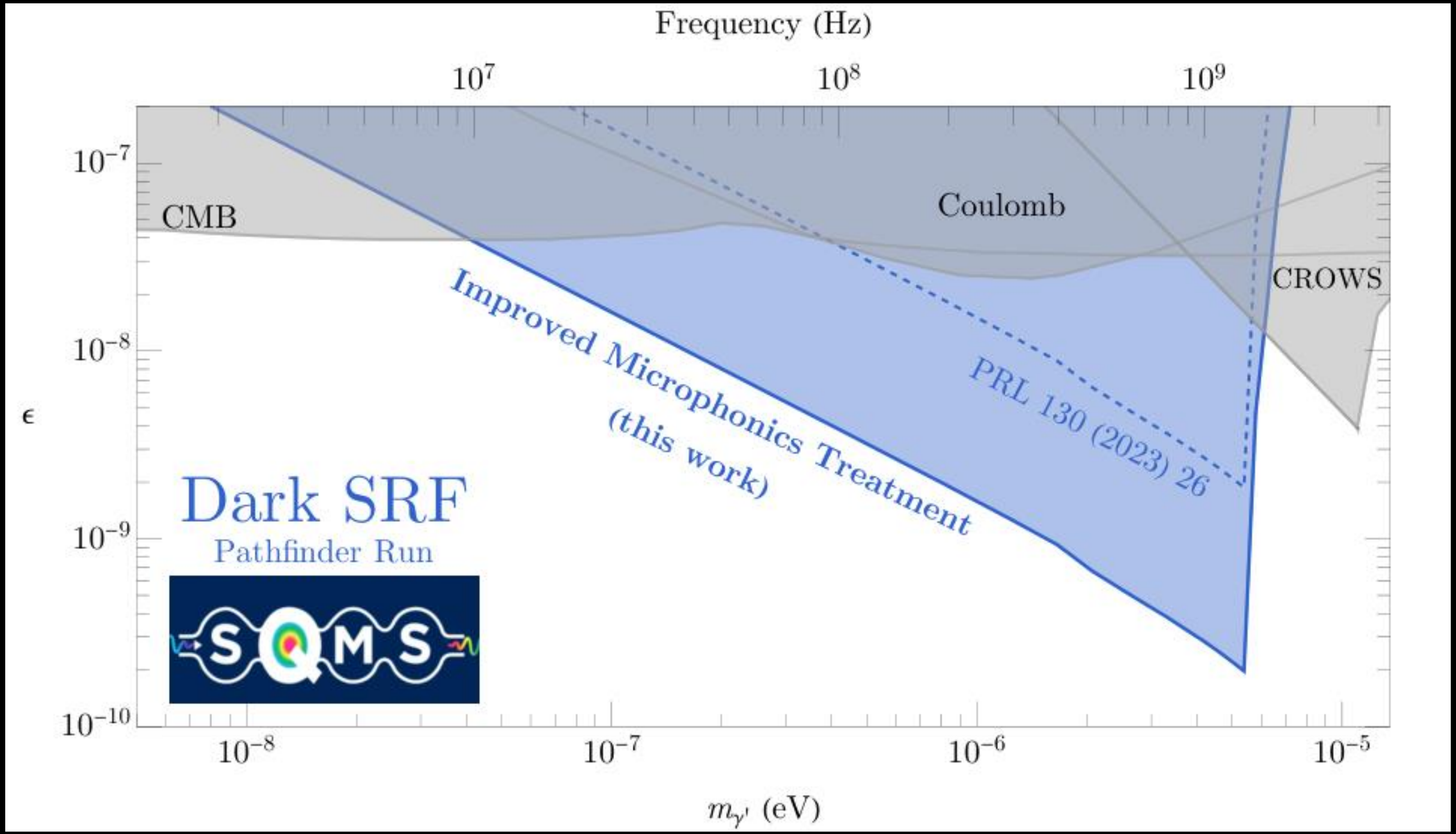
Fast sign changes can limit the loss.

Dark SRF benchmark:
87% of ideal signal power

DARK SRF

Cui, Kalia & ZL, 2504.15307, Fig. 2; Kalia, ZL et al. , 2510.02427

A stronger Dark SRF limit from existing data



About 10× stronger in kinetic mixing

A reanalysis of pathfinder data

No halo-abundance assumption

DARK SRF

Romanenko et al., 2301.11512; Kalia, ZL et al., 2510.02427;

Outline

What dark matter could be

Fields, particles and macroscopic objects

How it could interact with matter

A broad theory landscape, organized by couplings

Aspects of sensing

Dark Matter can also be ultraheavy and gravitational

Particle-like DM transfers momentum

$$\text{DM} + \text{target} \;\rightarrow\; \text{recoil},\; \Delta p,\; \text{excitation}$$

The target measures an individual event.

The mediator and interaction range determine the event rate and spectrum.

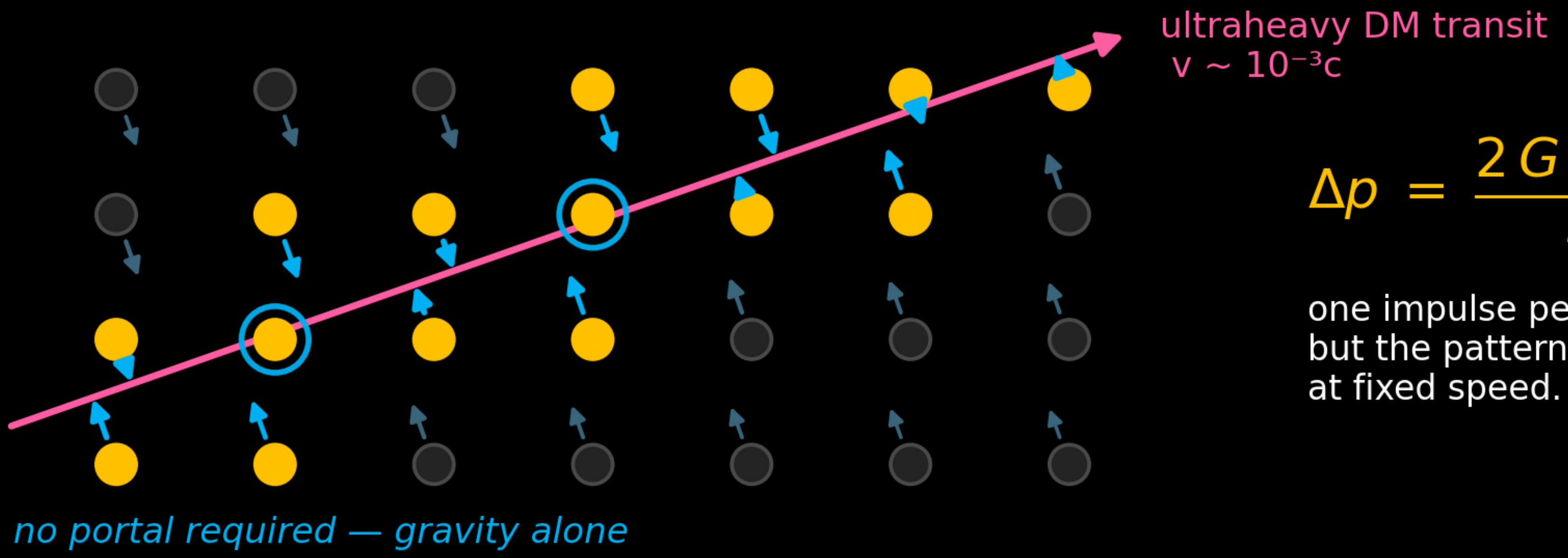
At fixed local density, increasing mass reduces the incident flux.

A crossing becomes a detected event only if the interaction is measurable.

Backup: gravity as the universal coupling

Every candidate couples to gravity; detecting its impulse still demands very low noise.

$m_{\mathrm{DM}} = M_{\mathrm{Pl}}$, **a 1 g sensor at** $b = 1\,\mathrm{cm}$**:** $\Delta p \approx 10^{-24}\,\mathrm{kg}\cdot\mathrm{m/s} \approx 2\,\mathrm{keV}/c$



$$\Delta p = \frac{2\,G\,m_{\mathrm{DM}}M}{b\,v}$$

one impulse per sensor —
but the pattern is a straight line
at fixed speed. That is the signal.

Carney, Ghosh, Krnjaic & Taylor — arXiv:1903.00492

Summary

Ultralight dark matter can behave as a coherent field,

a $Q \approx 10^6$ oscillator whose frequency is its mass.

Representative families contain a broad menu of interactions.

The operator, not the family, decides whether you see

a force, a torque, or a strain.

The scope is broader than uldm, heavy DM, new forces, etc.
Optomechanical sensing full of fudamental physics opportunities

CLOSE

Backup: two axion spin-precession channels

CASPEr-Gradient / Wind

$$H_{\text{spin}} = -\frac{c_N}{f_a}\nabla a \cdot \mathbf{S}$$

Derivative fermion coupling

CASPEr-Electric

$$H_{\text{EDM}} = -\mathbf{d}_N(t) \cdot \mathbf{E}_{\text{eff}}$$

Oscillating CP-odd nuclear moment

Similar spin readout, different interactions.

BACKUP · PSEUDOSCALAR

Budker et al., 1306.6089; Walter et al., 2504.16044; Winter et al., 2609.07908

Backup: examples of scalar screening

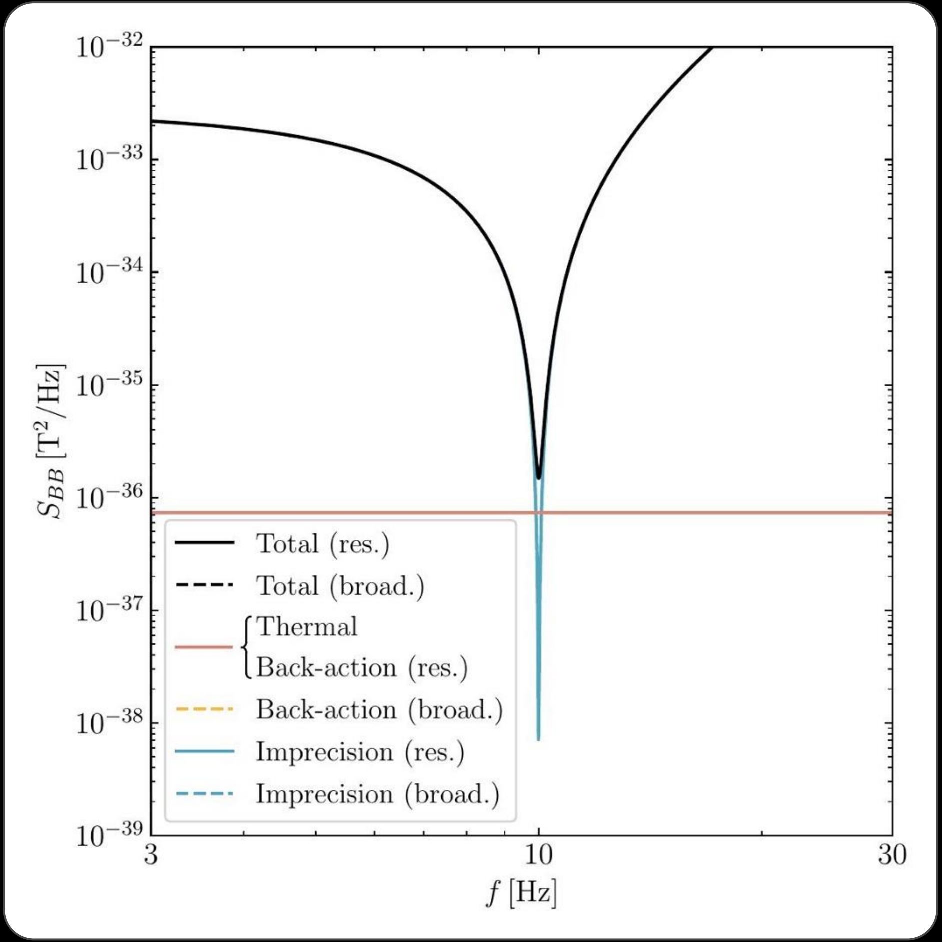
$$V_{\text{eff}}(\phi) = V(\phi) + \rho_{\text{matter}} A(\phi)$$

Chameleon	Dense matter increases the effective mass.
Symmetron	Dense matter restores symmetry and suppresses the coupling.

These fifth-force examples are not automatically ULDM models.

Khoury & Weltman, astro-ph/0309300; Hinterbichler & Khoury, 1001.4525; Hees et al., 1807.04512

Backup: noise budget and the SQL



Three noise sources set the floor:

Thermal: $S \propto 4k_{\mathrm{B}}Tm\Gamma$

→ cryogenics and low gas damping

Imprecision: SQUID flux noise

→ better SQUID, tighter coupling

Back-action: SQUID current noise

→ random force on the sphere

$$S_{\mathrm{imp}}\, S_{\mathrm{ba}} \geq \hbar^2$$

BACKUP

G. Higgins, S. Kalia, ZL— arXiv:2310.18398

Backup: the stochastic amplitude

In the Gaussian random-wave model, the field amplitude follows a Rayleigh distribution, as expected for a sum of many independent, randomly phased modes.

$$P(\phi_0) \propto \frac{\phi_0}{\sigma^2} \exp\left(-\frac{\phi_0^2}{2\sigma^2}\right)$$

A short measurement can land in a low-amplitude realisation.

The likelihood should include that stochastic amplitude.

The correction depends on the field model, observation time and confidence level.

BACKUP

Foster, Rodd & Safdi — arXiv:1711.10489; Centers et al. — arXiv:1905.13650

Backup: how is it produced?

Three ways to make a cold, coherent relic:

Misalignment: the field starts displaced from its minimum and oscillates once $H \approx m$.

Inflationary fluctuations: for a vector, the longitudinal mode is amplified during inflation.

Topological defects: cosmic-string or domain-wall networks radiate the field as they decay.

These mechanisms can give a cold, non-thermal population with a large occupation number.

Preskill–Wise–Wilczek, Abbott–Sikivie, Dine–Fischler (1983); Graham, Mardon & Rajendran — arXiv:1504.02102

Backup: from force to readout

A force is not yet a readout. The mode is what responds:

$$x_n(\omega) = \chi_n(\omega) F_n(\omega), \qquad \chi_n = \frac{1}{M_n(\omega_n^2 - \omega^2 - i\Gamma_n \omega)}$$

F_n is the projection of the force onto that mode, not the total force on the object.

The same caveat bites hardest for strain.

$$u_n(\omega) \simeq \frac{\ell_n \omega^2 \varepsilon_{\rm eq}(\omega)}{\omega_n^2 - \omega^2 - i\Gamma_n \omega}$$

ℓ_n is a signed geometric overlap length: a uniform breathing strain does not drive every mode.

Symmetry, boundaries and readout decide which modes ever see the signal.

BACKUP — THEORY DETAIL

Carney, Hook, **Liu**, Taylor & Zhao — arXiv:1908.04797; Manley et al. — arXiv:1910.07574

Backup: linear and quadratic modulation

$$\frac{\delta X}{X} = d_1 \frac{\phi}{\Lambda} + \frac{d_2}{2} \frac{\phi^2}{\Lambda^2}$$

$$\phi(t) = \frac{\sqrt{2\rho_\phi}}{m_\phi} \cos(m_\phi t)$$

Linear: angular frequency m

$$A_1 = \frac{d_1 \sqrt{2\rho_\phi}}{m_\phi \Lambda}$$

Quadratic: DC + angular frequency 2m

$$A_2 = \frac{d_2 \rho_\phi}{2 m_\phi^2 \Lambda^2}$$

Fixed coefficients and a free harmonic local field. Detector response adds further scaling.

BACKUP · THEORY DETAIL

Hees et al., 1807.04512; Masia-Roig et al., 2202.02645; Banerjee et al., 2211.05174

Backup: quadratic signals also have slow beats

A halo contains many nearby frequencies.

$$\cos(\omega_i t)\cos(\omega_j t) = \frac{1}{2}\cos[(\omega_i - \omega_j)t] + \frac{1}{2}\cos[(\omega_i + \omega_j)t]$$

$$\Delta\omega \sim m_\phi v^2$$

Low-bandwidth sensors can probe intensity fluctuations.

The local field may be screened or amplified; a constant shift needs a measurable reference.

BACKUP · THEORY DETAIL

Hees et al., 1807.04512; Masia-Roig et al., 2202.02645; Banerjee et al., 2211.05174

Backup: occupation does not determine the state

Many quanta per mode do not specify their correlations.

$$\hat{\rho} = \int d^2\alpha \, P(\alpha) \, |\alpha\rangle\langle\alpha|$$

A nonnegative P describes a classical mixture of coherent states.

Production and later evolution determine which state reaches us.

Cheong, Rodd & Wang, 2408.04696; Bao et al., 2510.05198; Kalia, 2504.16990

Backup: certifying quantum DM is difficult

Weak conversion and averaging over many modes suppress distinctive signatures.

$$\hat{c}_{\text{out}} = \sqrt{1-\eta}\,\hat{c}_{\text{in}} + \sqrt{\eta}\,\hat{a}_{\text{eff}}$$

$$\eta \ll 1, \qquad \langle n_c \rangle = \eta \langle n_{\text{eff}} \rangle$$

Quantum sensors can help even when the measured DM signal is effectively classical.

BACKUP · QUANTUM DM

Bao et al., 2510.05198; Bao et al., 2607.27313

Spin-1 DM

$$\frac{1}{2}m_A^2 A_{\mu,0}A_0^\mu \simeq 0.4\ \mathrm{GeV/cm^3}$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$\partial^\mu A_\mu = 0$$

$$E_i \sim m_A A_i \quad >> \quad B^i \sim m_A v_j A_k \epsilon^{ijk}$$