Searching for Scalar Dark Matter with Compact Mechanical Resonators

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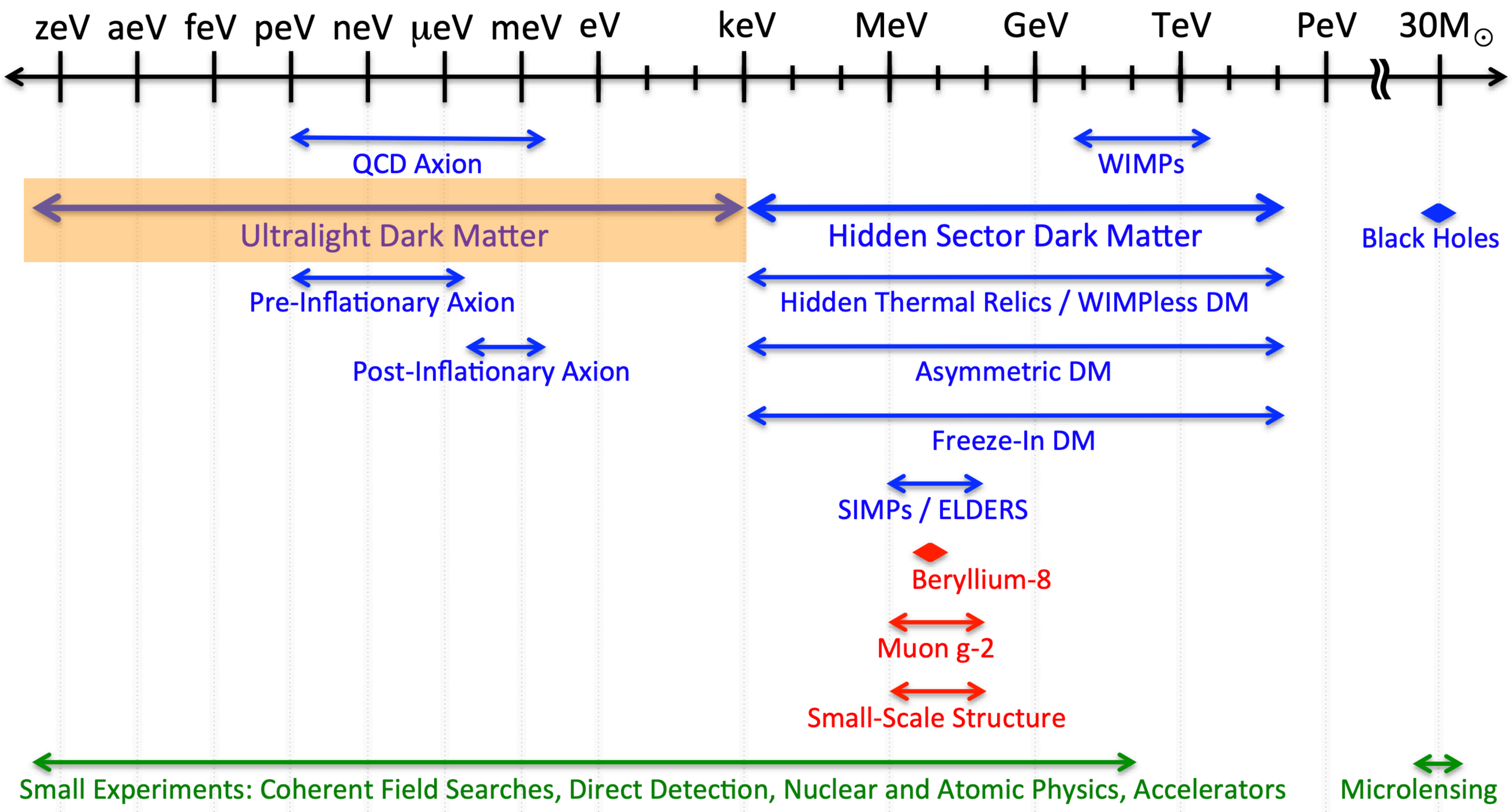
Qualifying Exam
May 7, 2020

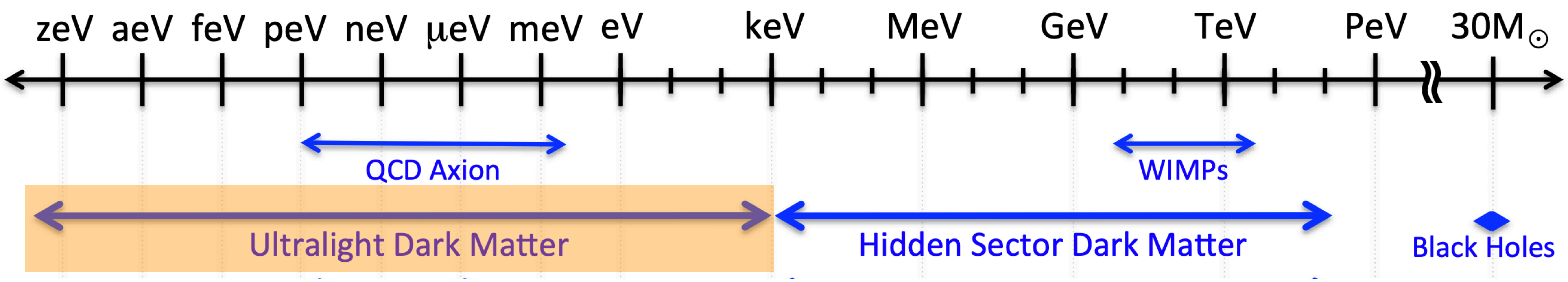
Outline

- Dilaton Dark Matter
- Mechanical Resonators
- Optomechanical Setup

Motivation: Dark Matter



Motivation: Dark Matter



- We essentially only know:
  - Locally $\rho_{\mathrm{DM}} \sim 0.4\,\mathrm{GeV/cm^3}$ and $v_{\mathrm{DM}} \sim 10^{-3}c$
  - Interacts weakly with Standard Model
  - Mostly cold, and stable enough to still exist today

Motivation: Effective Field Theory

- Parametrize action at high scales as $S_\Lambda = \int d^4x \sum_i \Lambda^{4-d_i} g_i(\Lambda) \mathcal{O}_i$
- General expectation as Λ decreases:
    - Initial couplings for $d_i > 4$ shrink, $d_i < 4$ grow
    - Couplings generate each other unless forbidden by symmetries
- At low scales: lowest dimensional operators dominate, mostly independent of UV, and easiest to search for

Leading Couplings for Ultralight Bosons

UV motivation?

Scalar ϕ $\qquad$ $\mathscr{L} \supset \phi F^{\mu\nu} F_{\mu\nu} + \phi G^{\mu\nu} G_{\mu\nu} + \phi \bar{\psi} \psi$

Pseudoscalar a $\qquad$ $\mathscr{L} \supset a F^{\mu\nu} \tilde{F}_{\mu\nu} + a G^{\mu\nu} \tilde{G}_{\mu\nu} + a \bar{\psi} \gamma^5 \psi$

Vector A'_μ $\qquad$ $\mathscr{L} \supset A'_\mu \bar{\psi} \gamma^\mu \psi + F'_{\mu\nu} F^{\mu\nu}$

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Leading Couplings for Ultralight Bosons

		UV motivation
Scalar ϕ	$\mathscr{L} \supset \phi F^{\mu\nu} F_{\mu\nu} + \phi G^{\mu\nu} G_{\mu\nu} + \phi \bar{\psi} \psi$	Higgs portal/relaxion $\phi h^\dagger h$
Pseudoscalar a	$\mathscr{L} \supset a F^{\mu\nu} \tilde{F}_{\mu\nu} + a G^{\mu\nu} \tilde{G}_{\mu\nu} + a \bar{\psi} \gamma^5 \psi$	QCD axion $m_a \sim \Lambda_{\mathrm{QCD}}^2 / f_a$
Vector A'_μ	$\mathscr{L} \supset A'_\mu \bar{\psi} \gamma^\mu \psi + F'_{\mu\nu} F^{\mu\nu}$	Dark $U(1)$ or $U(1)_{B-L}$

Leading Couplings for Ultralight Bosons

		Mass protection
Scalar ϕ	$\mathscr{L} \supset \phi F^{\mu\nu}F_{\mu\nu} + \phi G^{\mu\nu}G_{\mu\nu} + \phi\bar{\psi}\psi$	Can't by symmetry
Pseudoscalar a	$\mathscr{L} \supset aF^{\mu\nu}\tilde{F}_{\mu\nu} + aG^{\mu\nu}\tilde{G}_{\mu\nu} + a\bar{\psi}\gamma^5\psi$	Shift symmetry
Vector A'_μ	$\mathscr{L} \supset A'_\mu\bar{\psi}\gamma^\mu\psi + F'_{\mu\nu}F^{\mu\nu}$	Gauge symmetry

Couplings for Light Dilaton

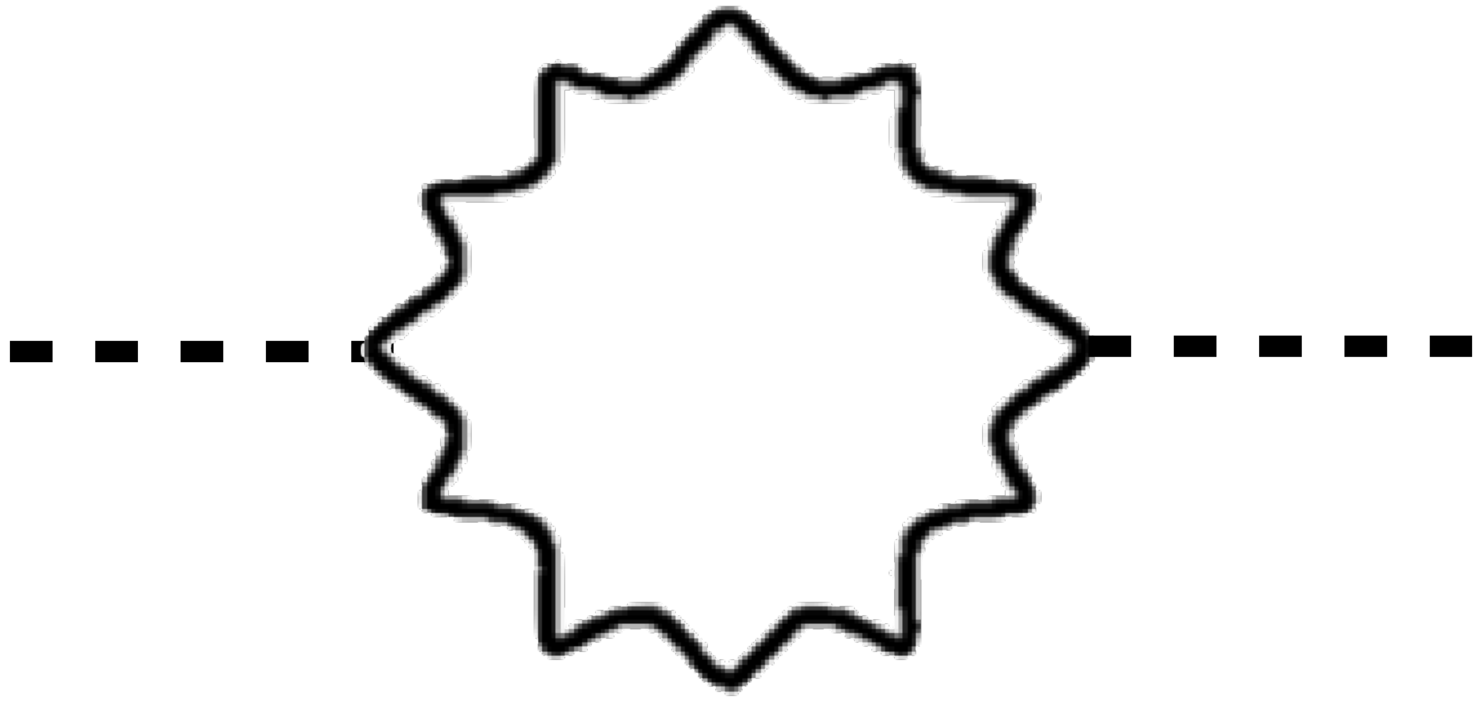
$$\mathscr{L} \supset \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}m^2\phi^2 + \frac{\phi}{M_{\rm pl}}\left(\frac{d_e}{4}F_{\mu\nu}F^{\mu\nu} - d_{m_e} m_e \bar{e} e\right)$$

d_i give coupling strength relative to gravity

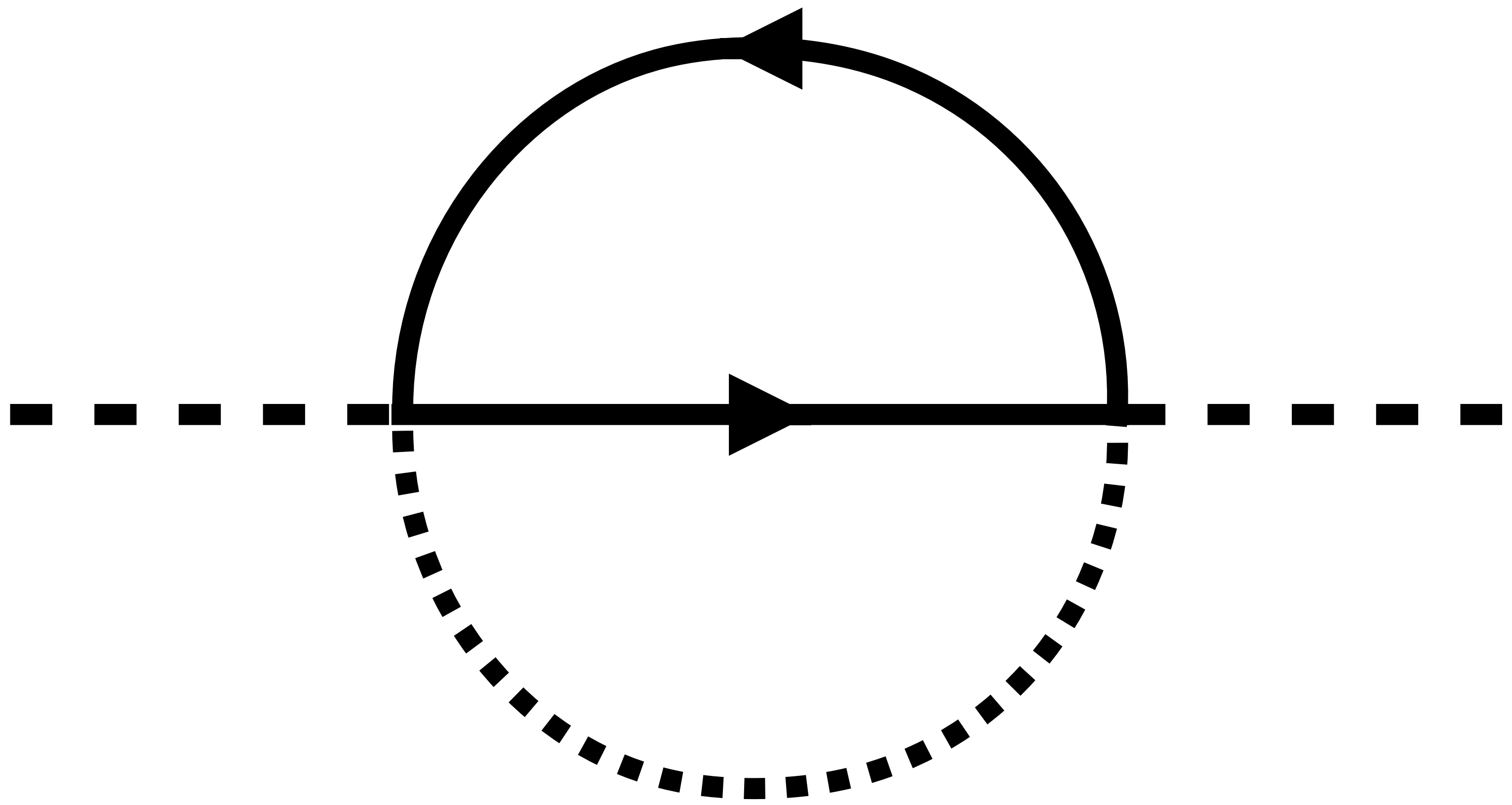
Focus on linear couplings

Mass Corrections

$$\mathscr{L} \supset \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m^2 \phi^2 + \frac{\phi}{M_{\rm pl}} \left(\frac{d_e}{4} B_{\mu\nu} B^{\mu\nu} - d_{m_e} y_e \bar{L} h E \right)$$



$$\delta m^2 = \frac{d_e^2}{2} \frac{1}{(4\pi)^2} \frac{\Lambda^4}{M_{\rm pl}^2}$$



$$\delta m^2 = \frac{d_{m_e}^2 y_e^2}{2} \frac{1}{(4\pi)^4} \frac{\Lambda^4}{M_{\rm pl}^2}$$

For $m \sim 10^{-10}\,\mathrm{eV}$ and $\Lambda = 10\,\mathrm{TeV}$, okay if $d_{m_e} \lesssim 1$

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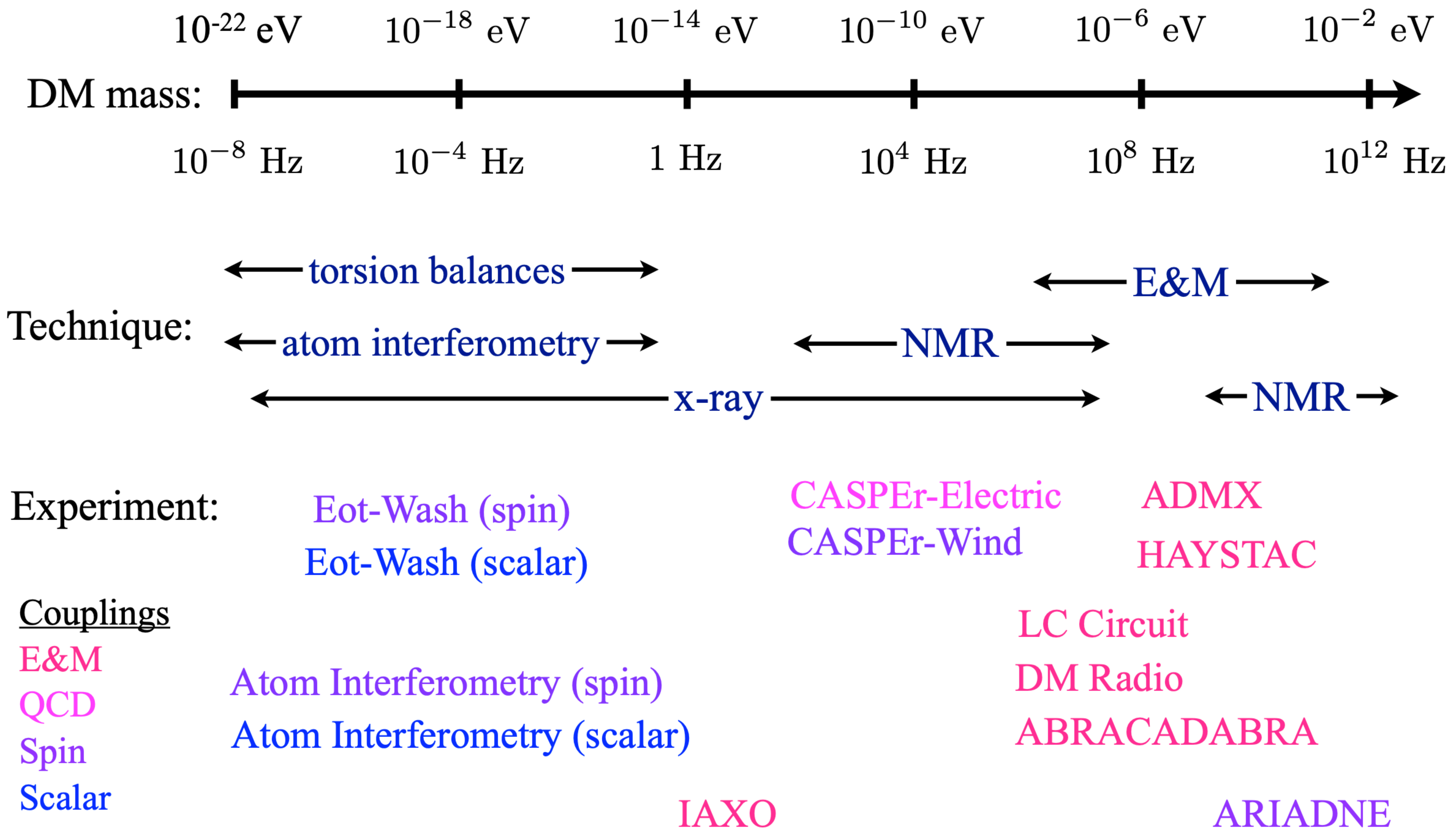
A Crowded Field



A Crowded Field

DM mass: 10^{-22} eV, 10^{-18} eV, 10^{-14} eV, 10^{-10} eV, 10^{-6} eV, 10^{-2} eV

10^{-8} Hz, 10^{-4} Hz, 1 Hz, 10^{4} Hz, 10^{8} Hz, 10^{12} Hz

Technique:
torsion balances
atom interferometry
x-ray
NMR
E&M
NMR

Experiment:
Eot-Wash (spin)
Eot-Wash (scalar)
CASPEr-Electric
CASPEr-Wind
ADMX
HAYSTAC
LC Circuit
DM Radio
ABRACADABRA
Atom Interferometry (spin)
Atom Interferometry (scalar)
IAXO Mechanical Resonators ARIADNE

<u>Couplings</u>
E&M
QCD
Spin
Scalar

Dilaton Effects

$$\mathscr{L} \supset \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m^2 \phi^2 + \frac{\phi}{M_{\mathrm{pl}}} \left(\frac{d_e}{4} F_{\mu\nu} F^{\mu\nu} - d_{m_e} m_e \bar{e} e \right)$$

$$\frac{\delta \alpha}{\alpha} = \frac{d_e \phi}{M_{\mathrm{pl}}} \qquad \frac{\delta m_e}{m_e} = \frac{d_{m_e} \phi}{M_{\mathrm{pl}}} \qquad a_0 \propto \frac{1}{\alpha m_e}$$

Dilaton Effects

$$\mathscr{L} \supset \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}m^2\phi^2 + \frac{\phi}{M_{\mathrm{pl}}}\left(\frac{d_e}{4}F_{\mu\nu}F^{\mu\nu} - d_{m_e} m_e \bar{e} e\right)$$

$$\frac{\delta\alpha}{\alpha} = \frac{d_e \phi}{M_{\mathrm{pl}}} \qquad \frac{\delta m_e}{m_e} = \frac{d_{m_e}\phi}{M_{\mathrm{pl}}} \qquad a_0 \propto \frac{1}{\alpha m_e}$$

For dark matter, $\phi(t) \sim \dfrac{\sqrt{2\rho_{\mathrm{DM}}}}{m}\cos(mt)$

Produces strain $h_{\mathrm{DM}} = (d_{m_e} + d_e)\dfrac{\sqrt{2\rho_{\mathrm{DM}}}}{M_{\mathrm{pl}} m}\cos(mt) \lesssim 10^{-21}$

Mechanical Effects

Scalar ϕ

Vector A'_μ

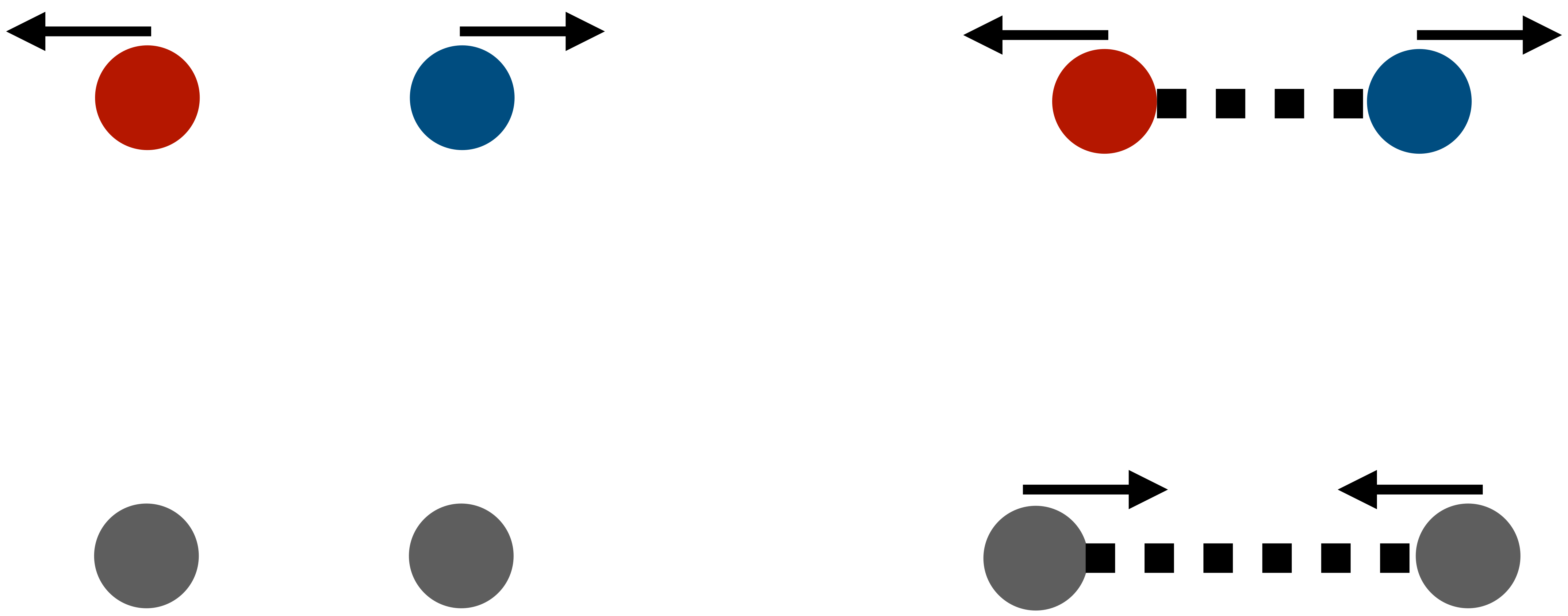
Differential force

Tensor $h_{\mu\nu}$

Mechanical Effects

Scalar ϕ

Vector A'_μ



Differential force

Tensor $h_{\mu\nu}$

No force, separation changes by $h\ell$, quadrupole pattern

Mechanical Effects

Scalar ϕ

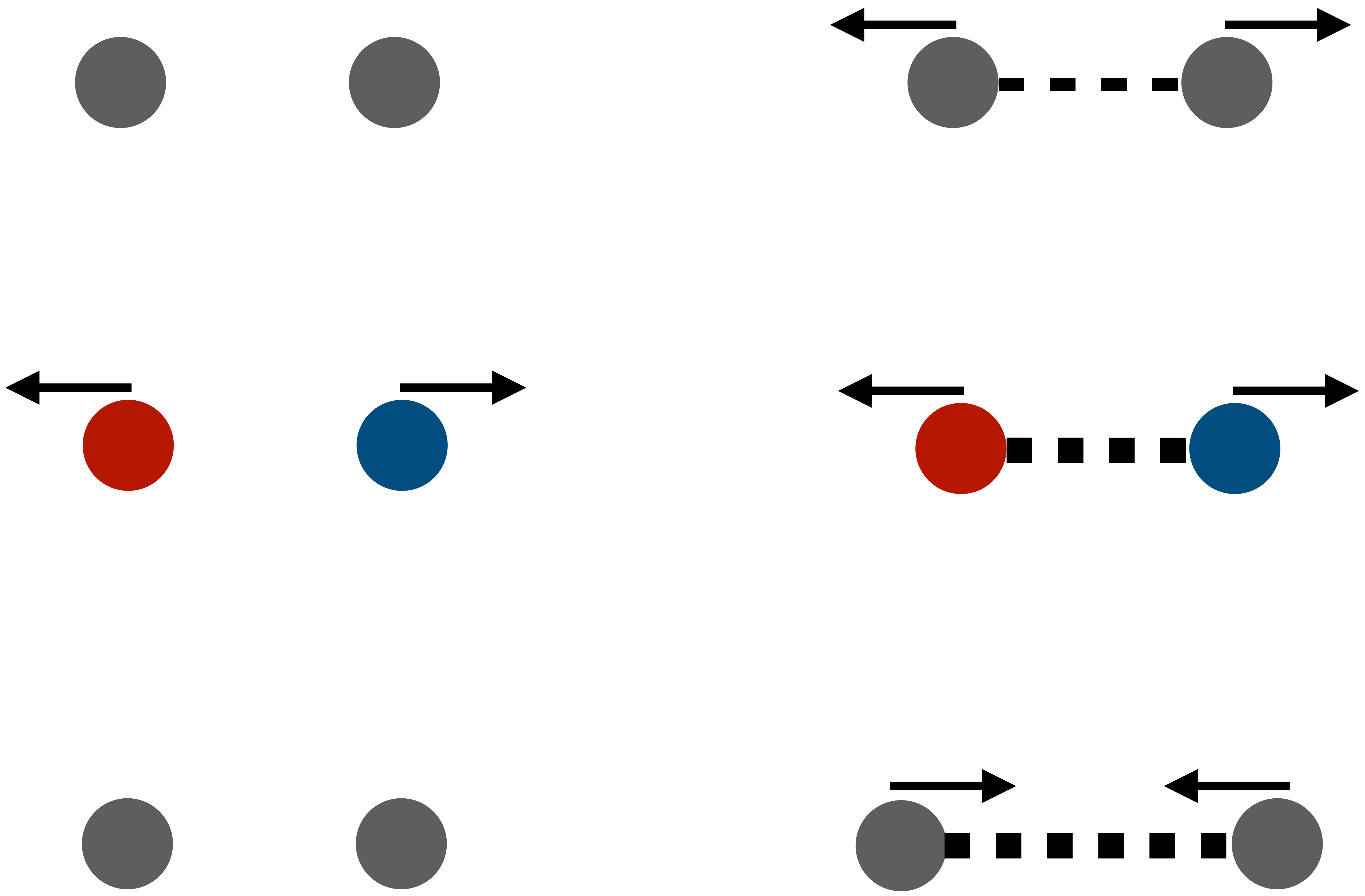
No force, rest length changes by $h\ell$, isotropic

Vector A'_μ

Differential force

Tensor $h_{\mu\nu}$

No force, separation changes by $h\ell$, quadrupole pattern



Mechanical Effects

Scalar ϕ

No force, rest length changes by $h\ell$, isotropic

Can amplify oscillating field resonantly

Tensor $h_{\mu\nu}$

No force, separation changes by $h\ell$, quadrupole pattern

Detecting Strains

Breathing mode displacement q relative to equilibrium:

$$\ddot{q} + \frac{\omega}{Q}\dot{q} + \omega^2 q = \ddot{h}_{\mathrm{DM}}\ell + \frac{f_{\mathrm{th}}}{M}$$

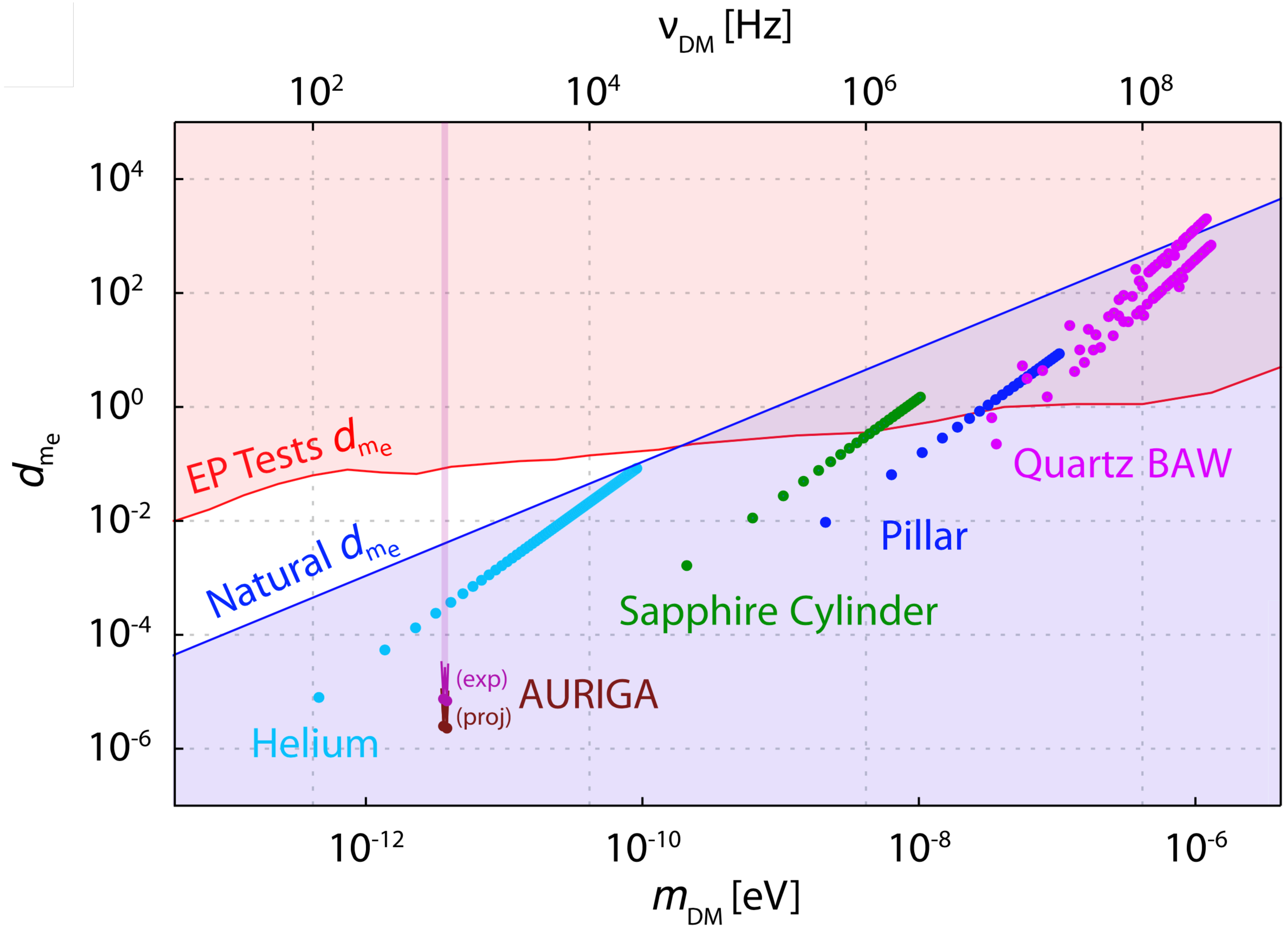
Physical assumptions:

$m \ll \mathrm{eV}$: atoms respond adiabatically

$m \approx \omega$: material responds resonantly

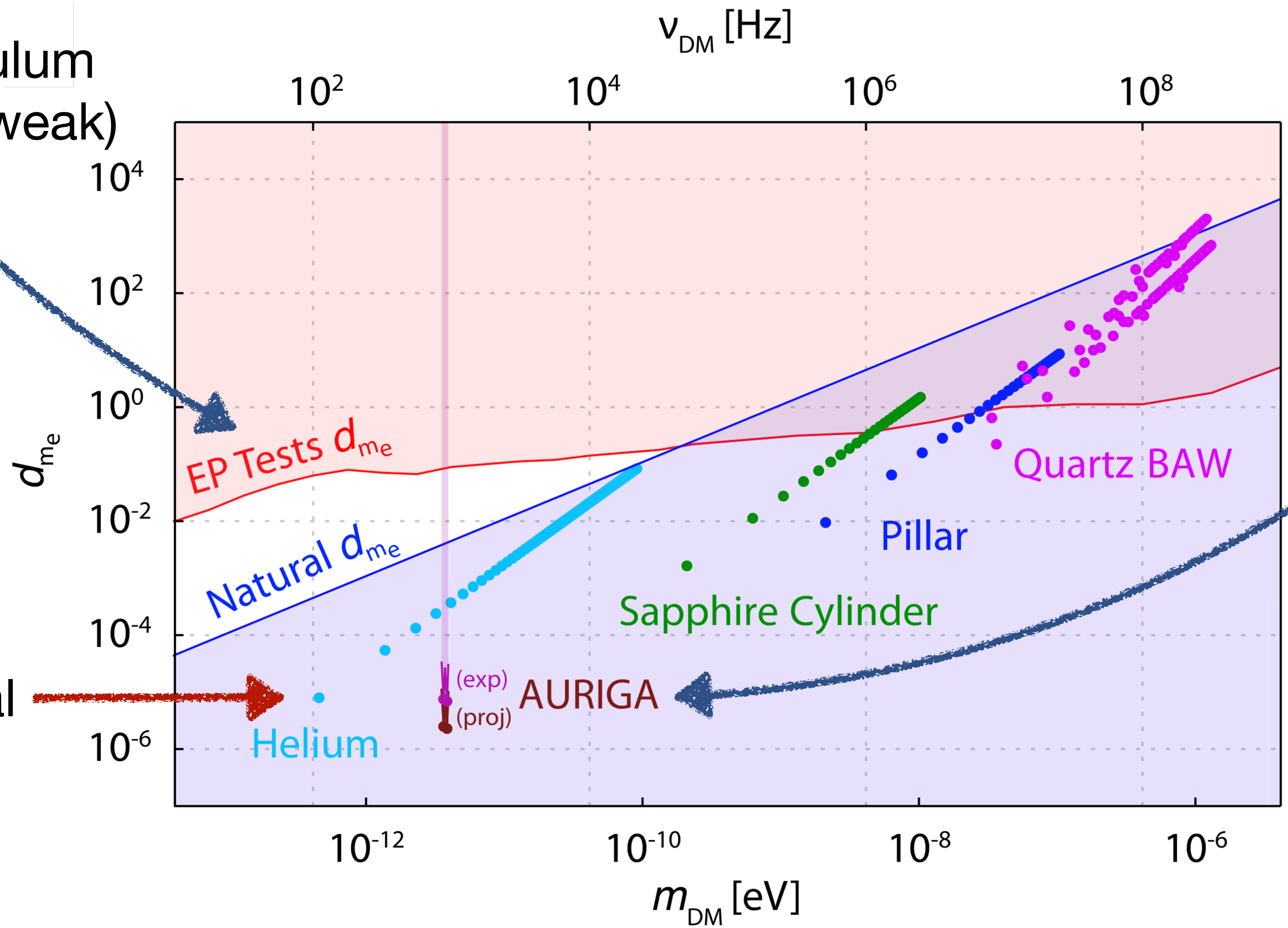
$k = mv \sim \omega/c_s$: constructive effect

Dark Matter Sensitivity



Dark Matter Sensitivity

Torsion pendulum
(EP violation weak)



Gravitational wave detector

New proposal

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Calculating Reach

$$\ddot{q} + \frac{\omega}{Q}\dot{q} + \omega^2 q = \ddot{h}_{\mathrm{DM}}\ell + \frac{f_{\mathrm{th}}}{M}$$

Noise power spectral density:

$$S_{n,hh} \sim \frac{k_B T}{M\ell^2 Q\omega^3} + \text{nonthermal}$$

Signal power spectral density:

$$S_{s,hh} \sim \frac{h_{\mathrm{DM}}^2}{\Delta\omega_{\mathrm{DM}}} \qquad \Delta\omega_{\mathrm{DM}} \sim m v_{\mathrm{DM}}^2$$

Signal to noise ratio:

$$\mathrm{SNR}^2 \sim t_{\mathrm{int}} \int d\omega \left(\frac{S_s(\omega)}{S_n(\omega)} \right)^2$$

Calculating Reach

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Signal power spectral density:

$$S_{s,hh} \sim \frac{h_{\mathrm{DM}}^2}{\Delta\omega_{\mathrm{DM}}} \qquad \Delta\omega_{\mathrm{DM}} \sim m v_{\mathrm{DM}}^2$$

Signal to noise ratio, thermal noise limited:

$$\mathrm{SNR}^2 \sim t_{\mathrm{int}} \int d\omega \left(\frac{S_s(\omega)}{S_n(\omega)} \right)^2 \sim t_{\mathrm{int}} \Delta\omega_{\mathrm{DM}} \left(\frac{S_s}{S_n} \right)^2$$

Calculating Reach

Setting $\mathrm{SNR} \sim 1$ gives:

Cool cryogenically

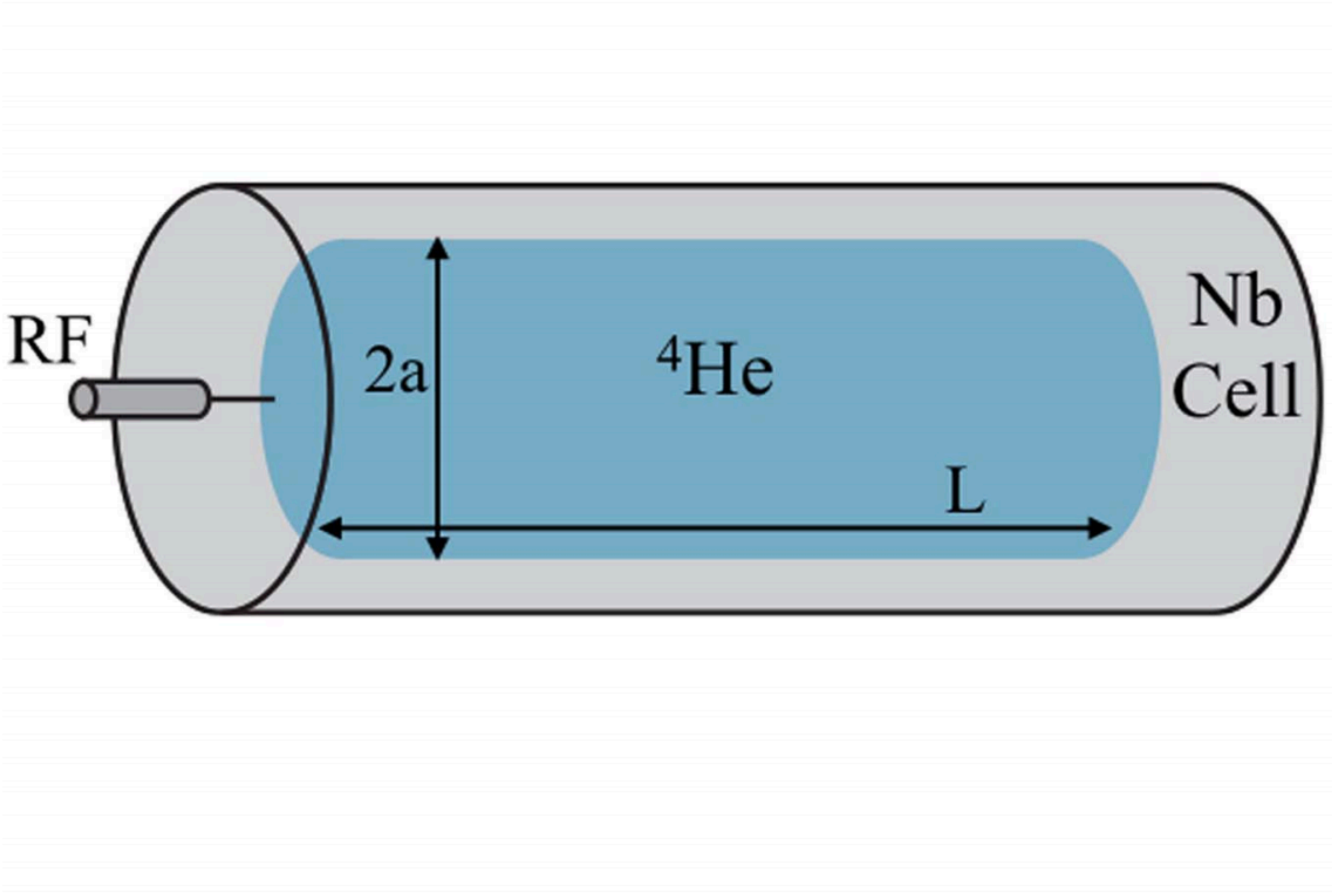
$$h_{\mathrm{min}}^2 \sim \frac{1}{\sqrt{t_{\mathrm{int}}}} \frac{v_{\mathrm{DM}}}{m^{5/2}} \frac{k_B T}{M \ell^2 Q}$$

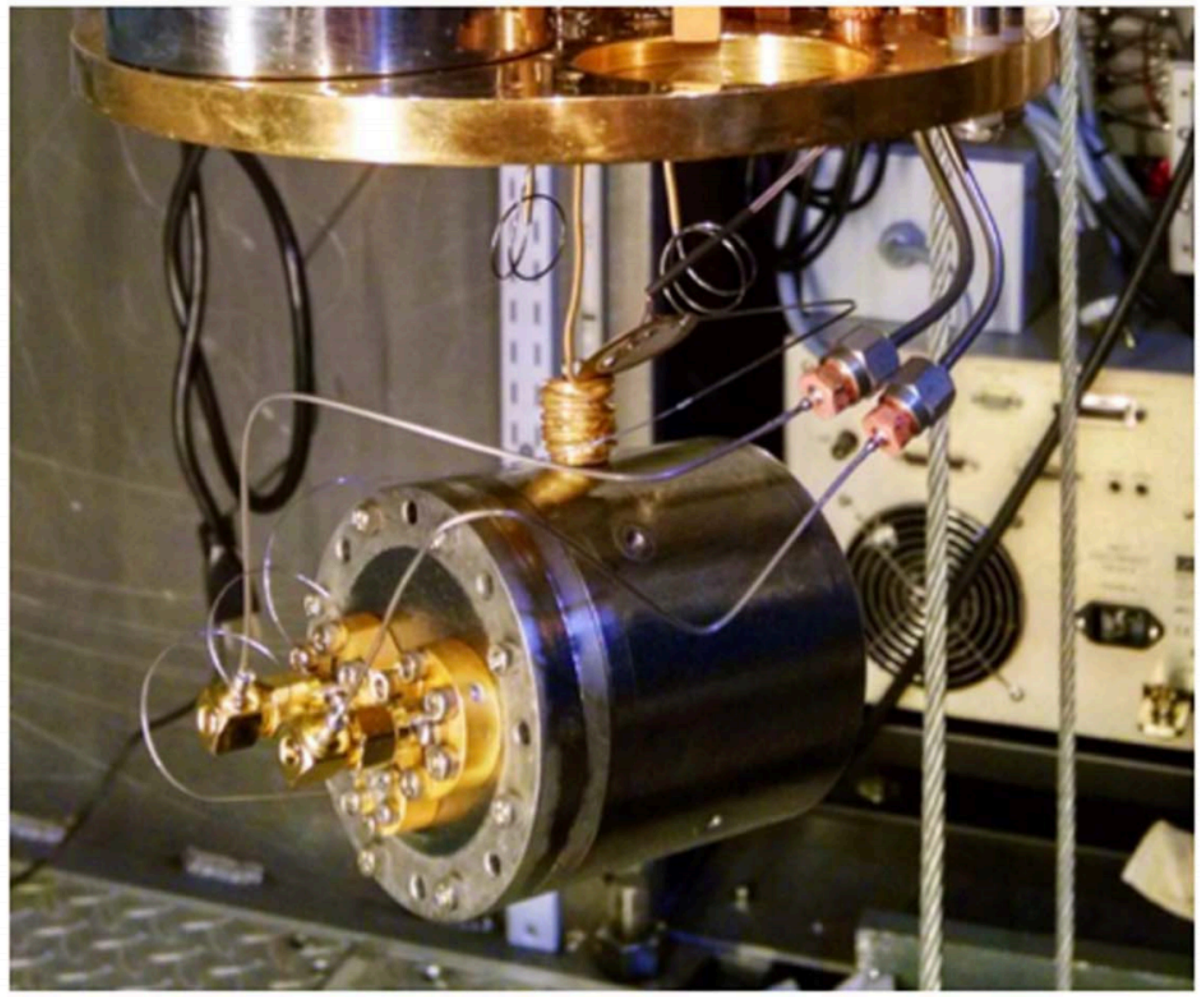
Sets experiment length

Large, heavy, low loss

Higher sound speed helps

Superfluid Helium Resonator

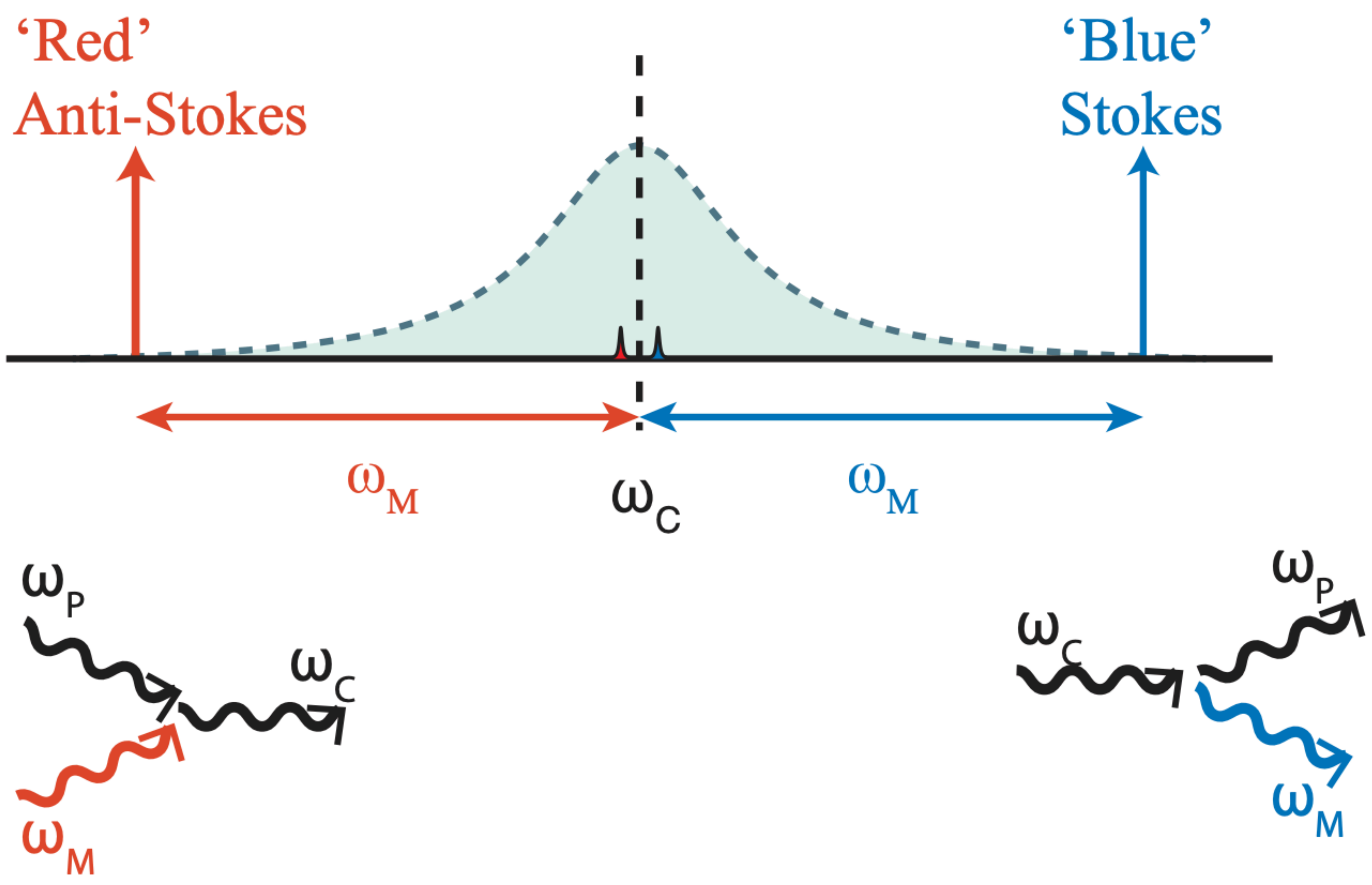




Goals: $T = 10\,\mathrm{mK}$, $Q = 10^9$, $R = 10\,\mathrm{cm}$, $L = 50\,\mathrm{cm}$

Challenges: isotopic purification, cooling, seismic isolation, clamping loss

Optomechanical Readout



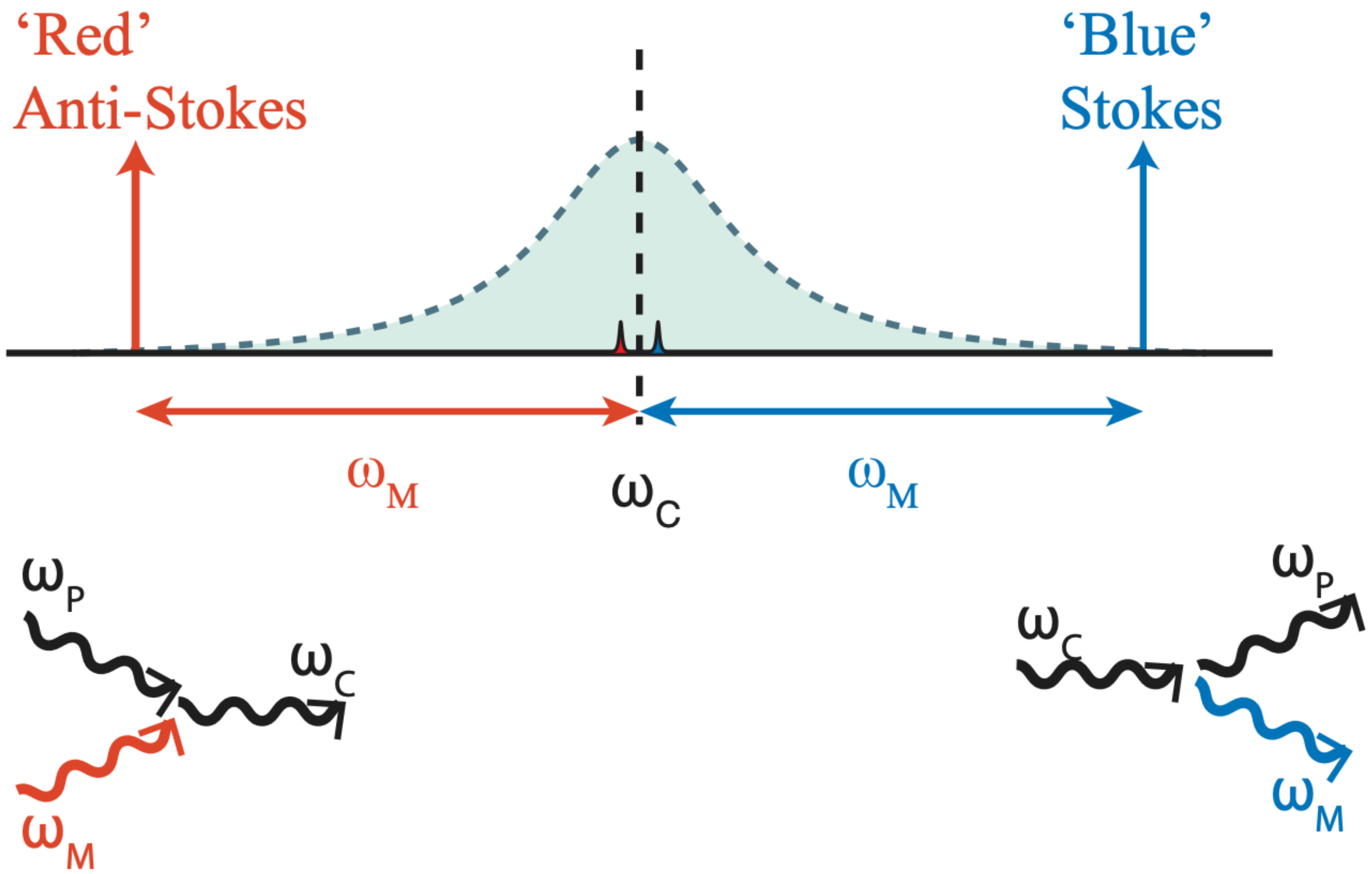
Drive superconducting cavity at red sideband; phonons upconvert photons to resonance

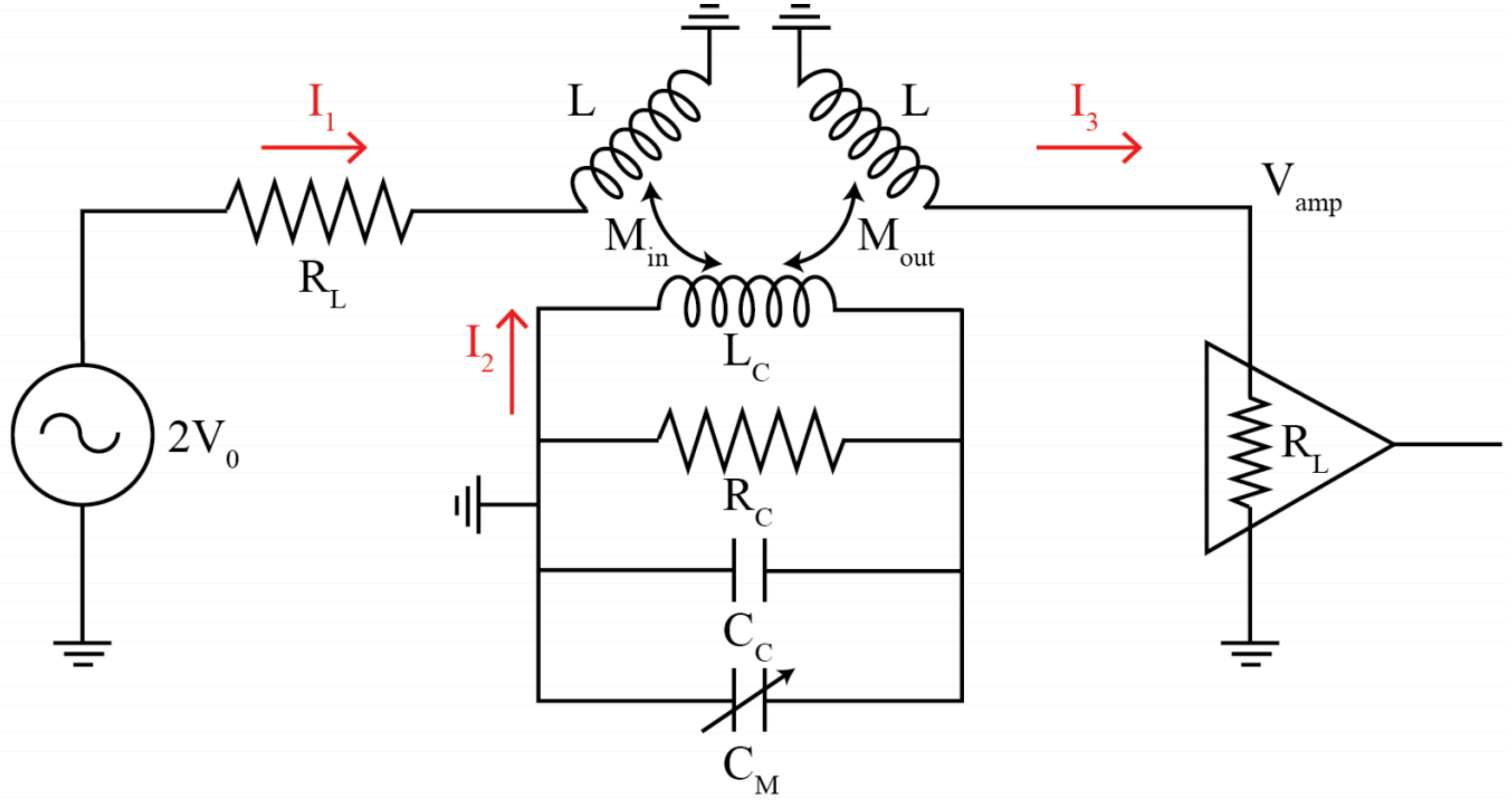
Possible because of optomechanical coupling:

$$g = \frac{\partial \omega_c}{\partial q} \Delta q_{\mathrm{zp}}$$

Could also broaden or cool acoustic mode by backaction

Optomechanical Readout

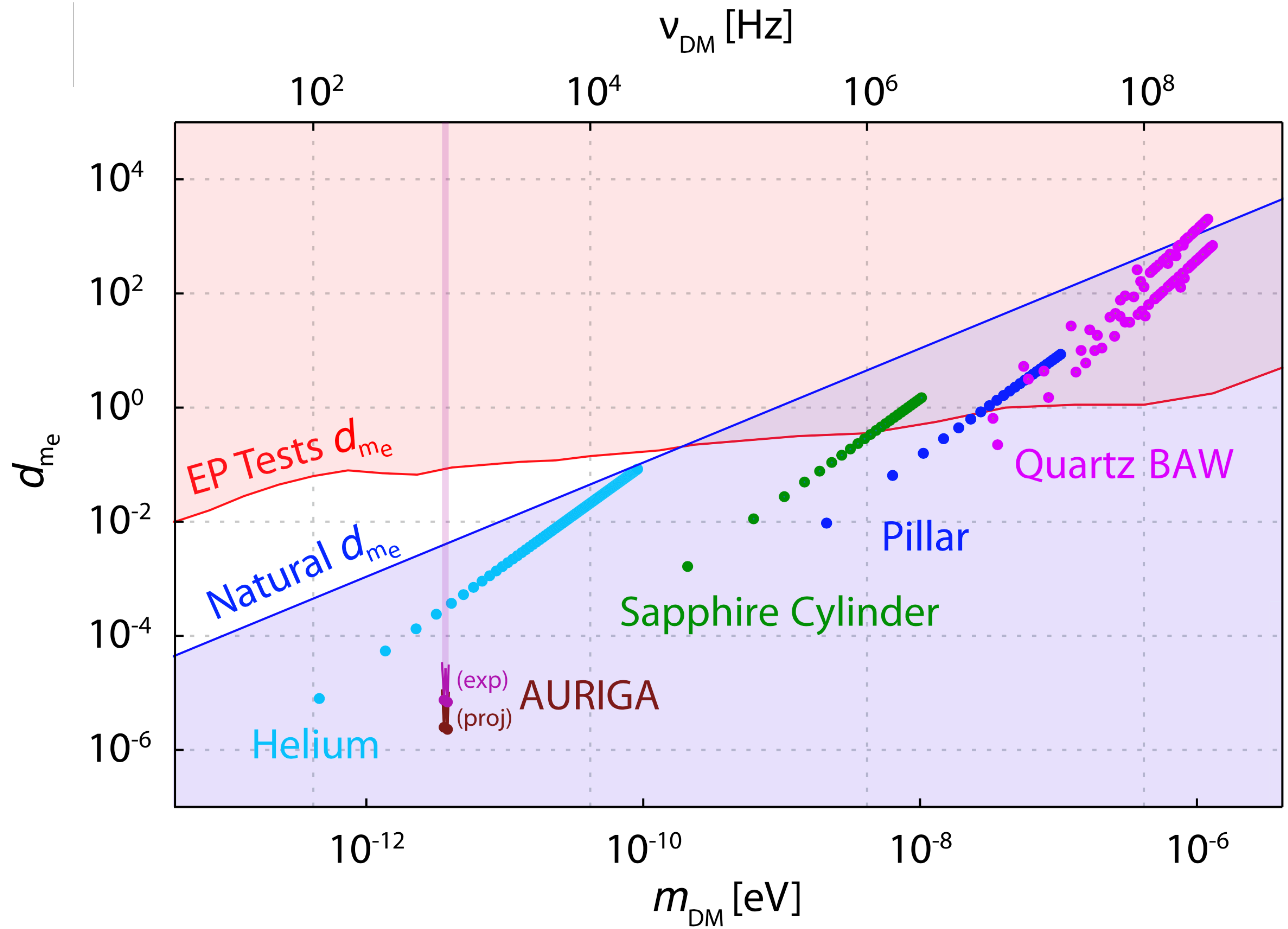




Challenges: cavity losses, oscillator phase noise, amplifier noise, scanning

Thermal noise limited readout not yet demonstrated!

Questions?


ν_{DM} [Hz]
10^2
10^4
10^6
10^8
d_{m_e}
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
EP Tests d_{m_e}
Natural d_{m_e}
Quartz BAW
Pillar
Sapphire Cylinder
(exp)
(proj)
AURIGA
Helium
10^{-12}
10^{-10}
10^{-8}
10^{-6}
m_{DM} [eV]