Searching for new physics—
leaving no stone unturned

Quantum sensing for ultralight dark matter

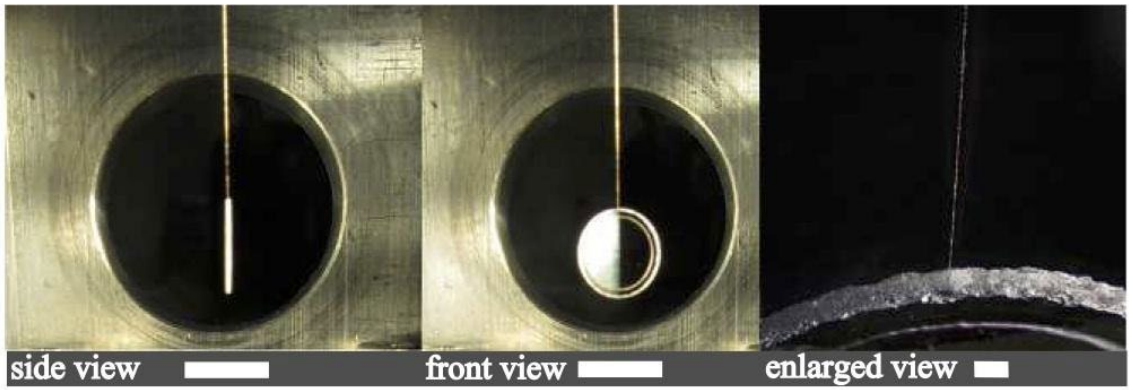
Zhen Liu
Maryland Center for Fundamental Physics (MCFP)
University of Maryland

Based upon work to appear 1908.xxxxx
w D. Carney, A. Hook, J. Taylor, Y. Zhao

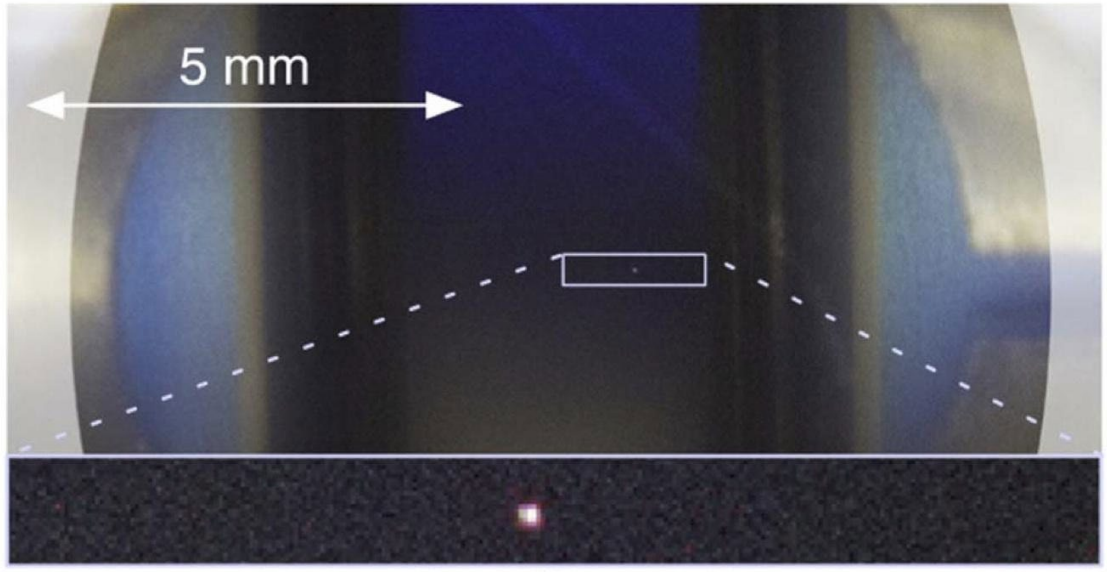
Quantum force sensing

Wide variety of mechanical systems coupled to light used to do quantum-limited force sensing.

Routinely achieve force sensitivities at or below the $10^{-18\text{-}21}$ N/√Hz level.



Matsumoto et al, PRA 2015



Aspelmeyer ICTP slides 2013

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Featured in Physics

Demonstration of Displacement Sensing of a mg-Scale Pendulum for mm- and mg-Scale Gravity Measurements

Nobuyuki Matsumoto, Seth B. Cataño-Lopez, Masakazu Sugawara, Seiya Suzuki, Naofumi Abe, Kentaro Komori, Yuta Michimura, Yoichi Aso, and Keiichi Edamatsu

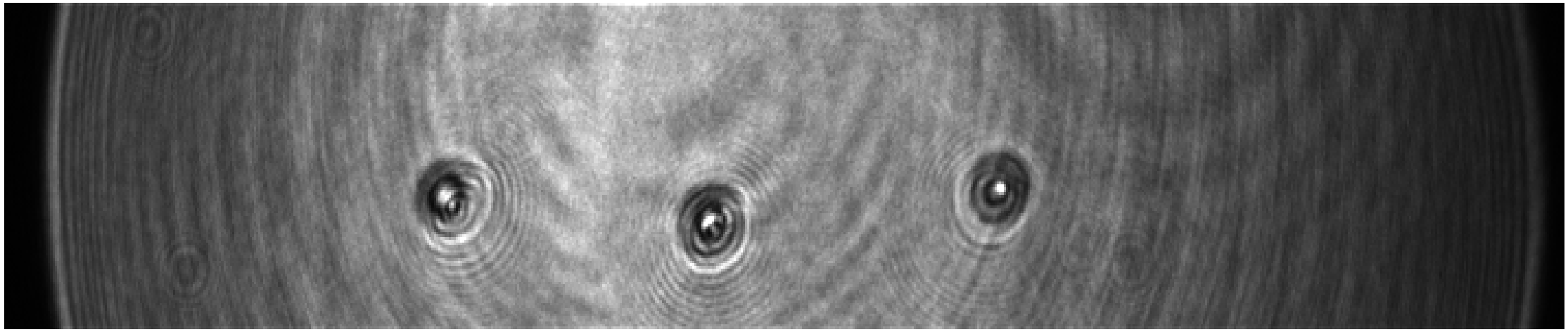
Phys. Rev. Lett. **122**, 071101 – Published 19 February 2019

Physics See Synopsis: Gravity of the Ultralight

$F_N \sim 10^{-17}$ N for two masses m = mg separated by d = mm

Throughout this talk I will use these scales for fiducial detector:
m = 1 mg, frequency = 1 Hz, temperature = 10 mK, size = 1 cm

Photo from Dave Moore (Yale)



$F_N \sim 10^{-17}$ N for two masses m = mg separated by d = mm

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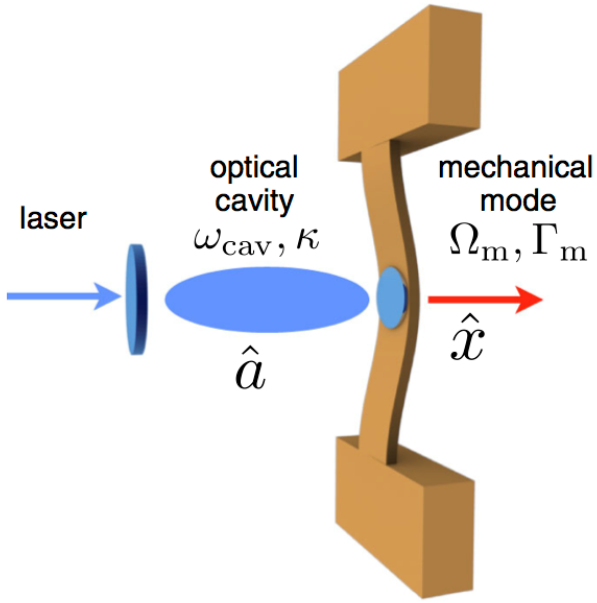
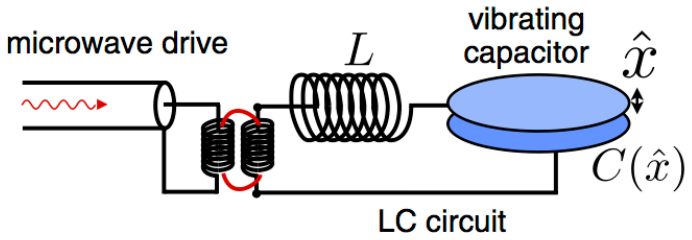
Quantum opto/electromechanical sensing





mechanics

light

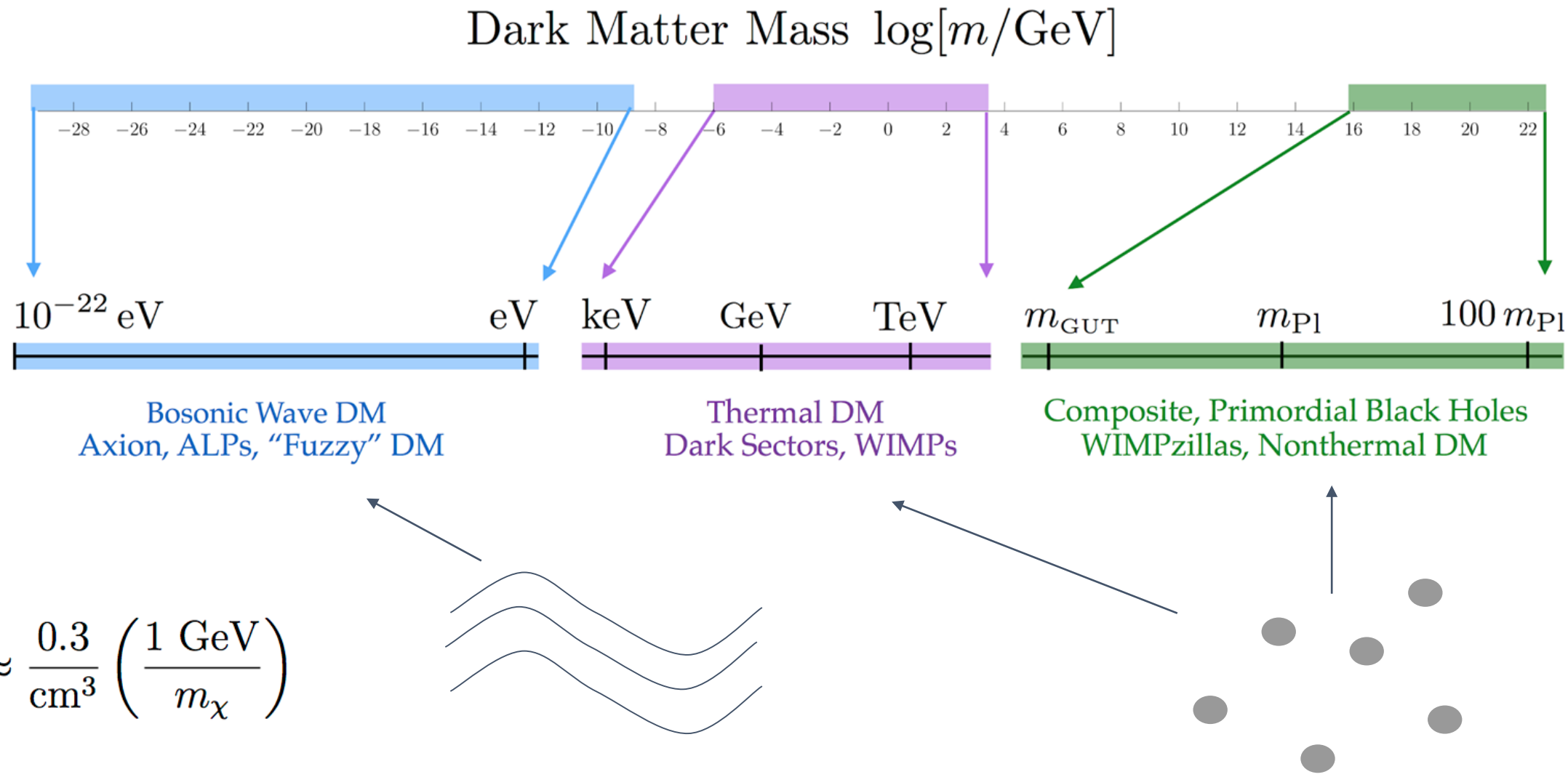
$$H_{OM} = gxX$$

drive-enhanced coupling $g \propto g_0\sqrt{P}$

Strategy: imprint mechanical displacement onto light, measure light, infer force

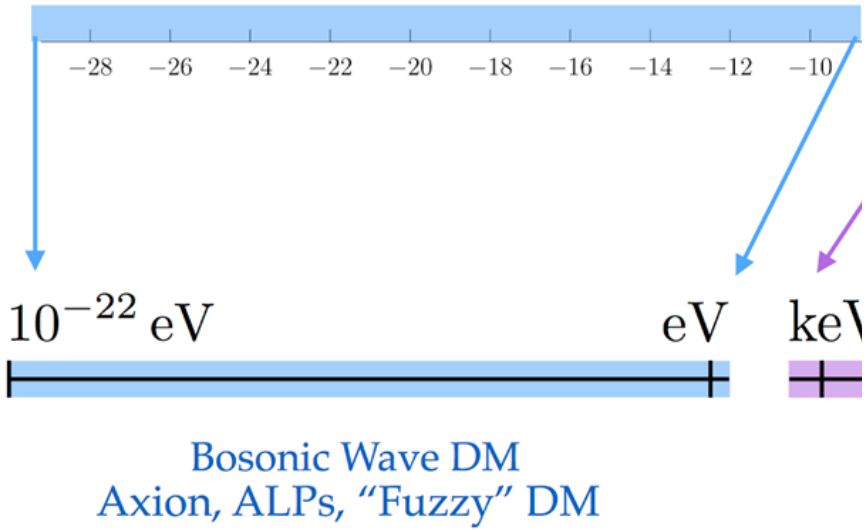
Aspelmeyer, Marquant, Kippenberg (Rev. Mod. Phys 2014)

Dark matter regimes



$$n_{DM} \approx \frac{0.3}{\mathrm{cm}^3}\left(\frac{1\ \mathrm{GeV}}{m_\chi}\right)$$

Dark matter regimes



$$n_{DM} \approx \frac{0.3}{\text{cm}^3}\left(\frac{1\ \text{GeV}}{m_\chi}\right)$$

Ultralight bosonic dark matter:

A dark vector can get a mass by a dark Higgs or through the Stueckelberg mechanism.

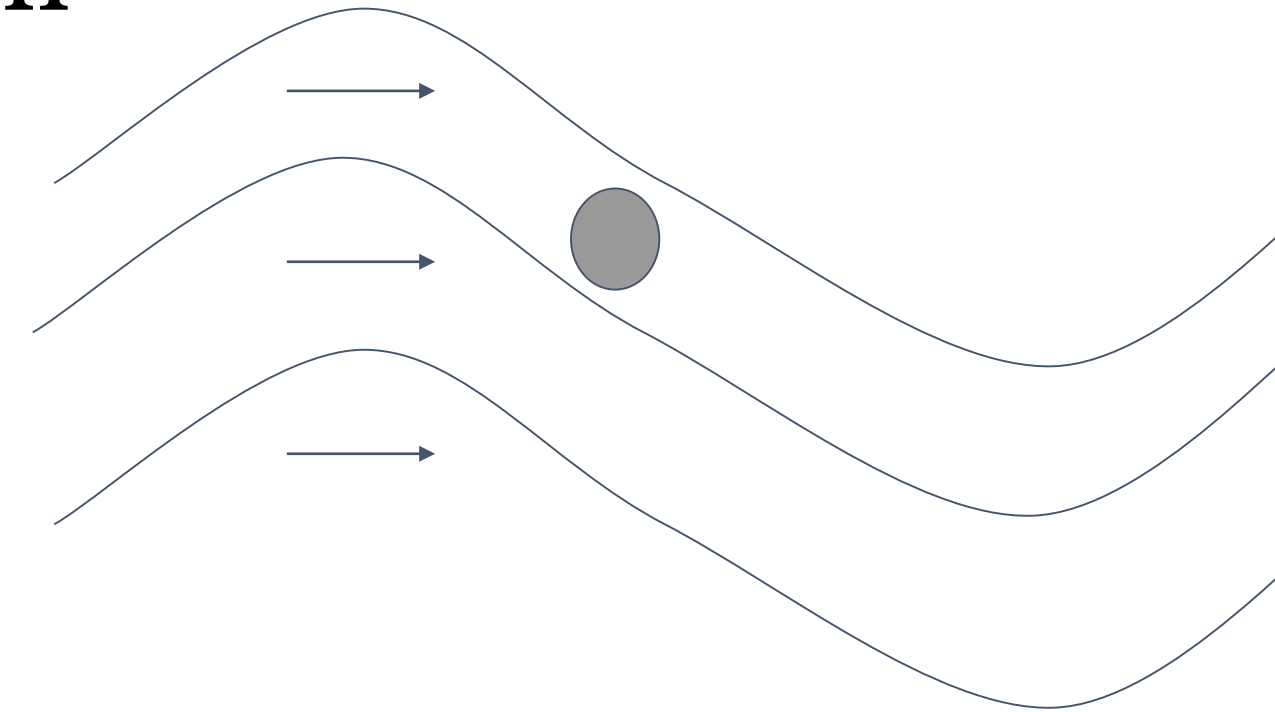
Anomaly free gauge couplings includes B-L, B-L+Y, Li-Lj, etc. Or having new physics at scale 4pi m/g

A dark (pseudo)scalar mass generic and couples to SM through Yukawa, coupling to (spin) mass.

Could be good cold DM candidate, relic set by: Misalignment mechanism, late scalar decay, or cosmic strings, etc.

Ultralight DM detection

Suppose DM consists entirely of a single, very light field: $m\phi \lesssim 1$ meV ($\lambda \gtrsim 10^{-3}$ m).



Locally, this will look like a wave with wavelength > detector size.

If the field couples to an extensive quantity, produces sinusoidal force:

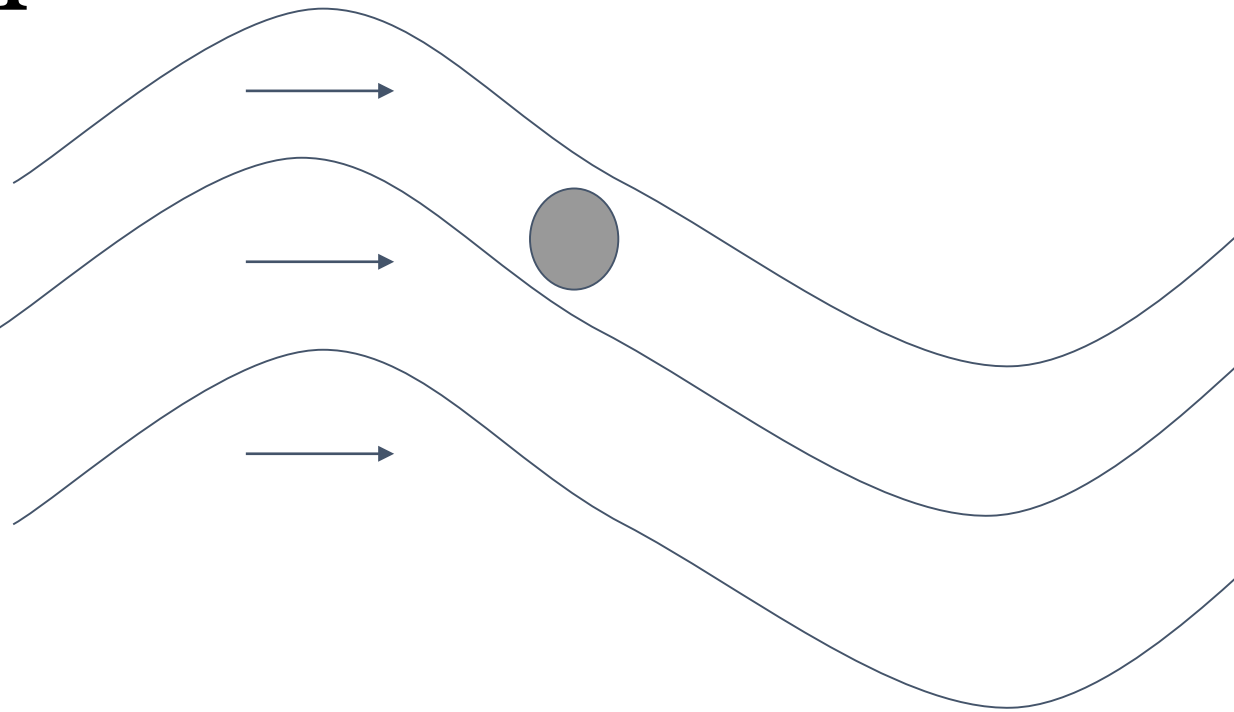
$$\mathcal{L}_{int} = g_{B-L} \not{A} \overline{n} n \longrightarrow F = g_{B-L} N_n F_0 \sin(\omega_s t)$$

Ultralight DM detection

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

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

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



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

$$\mathcal{L}_{int} = g_{B-L} \not{A} \overline{n} n \longrightarrow F = g_{B-L} N_n F_0 \sin(\omega_s t)$$

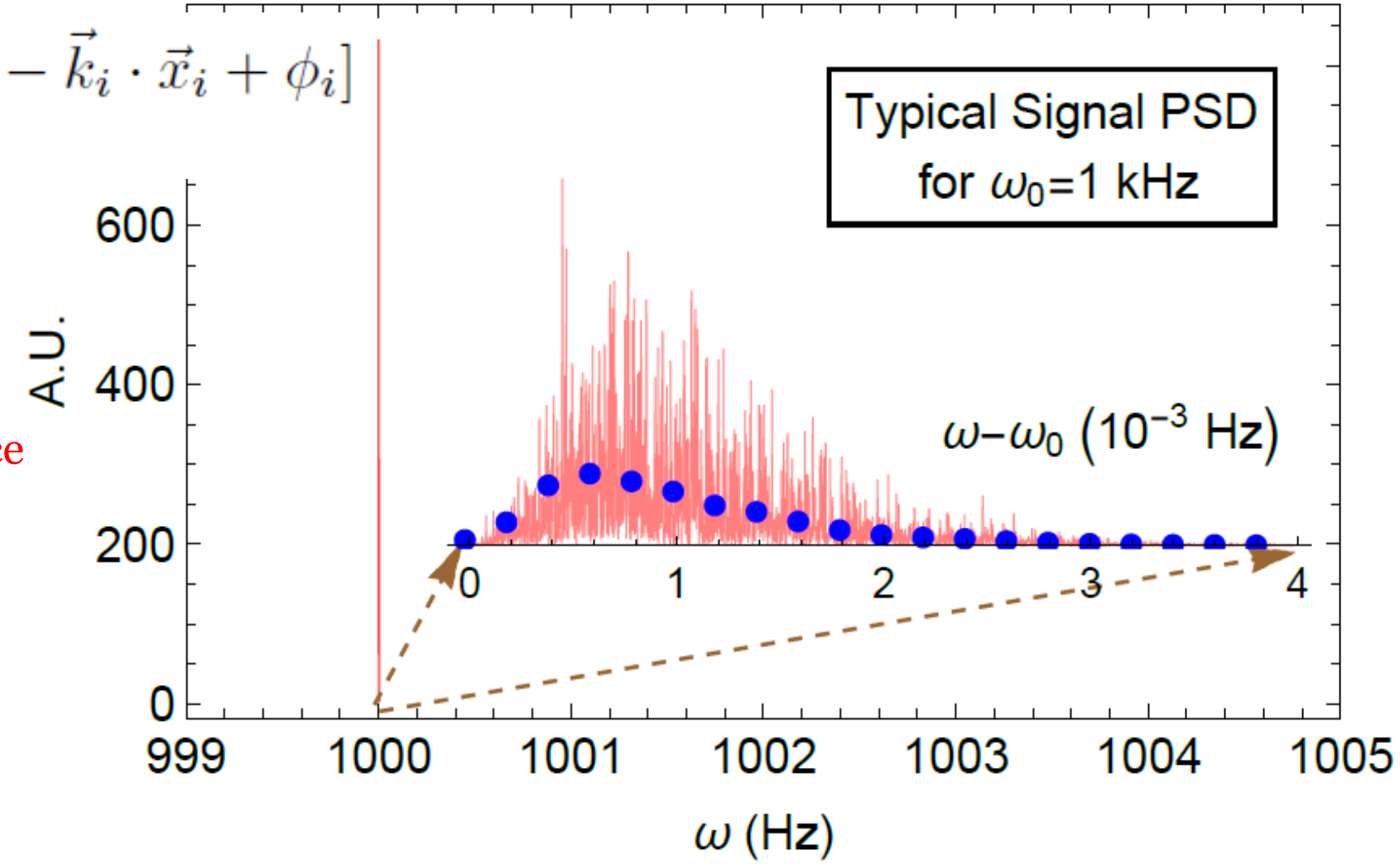
Ultralight DM profile: power spectra

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

Almost monochromatic

- very long coherence time
- very long coherent distance

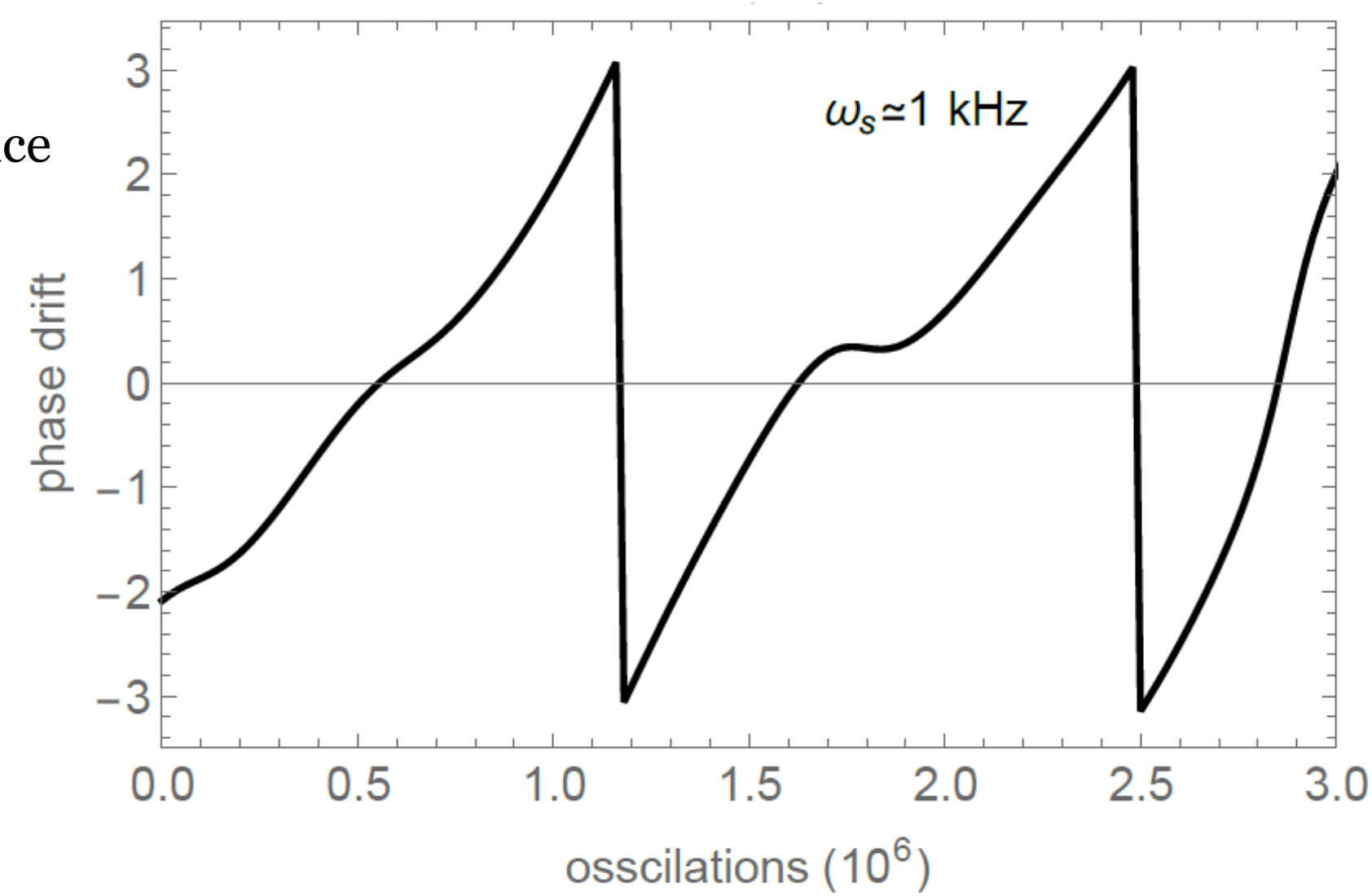
Coherence time set by the velocity dispersion (10^-3) feeding into frequency dispersion (10^-6)



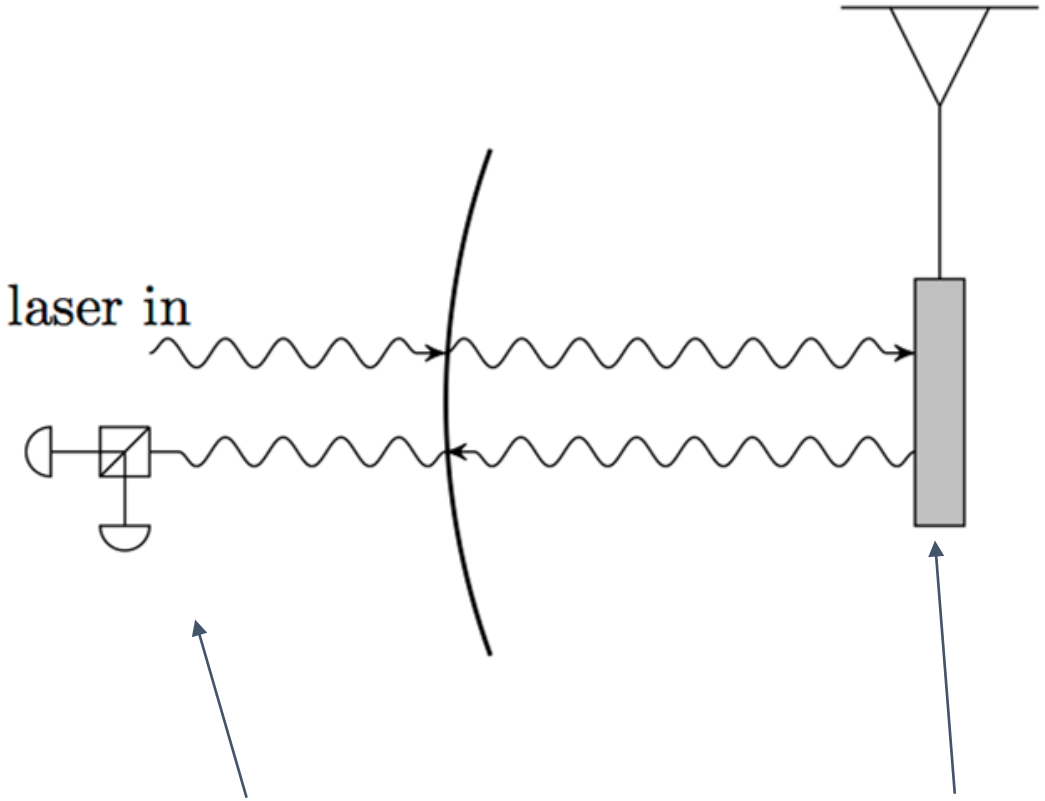
Ultralight DM profile: phase drift

- very long coherence time
- very long coherent distance

Propagation and polarization directions remain constant approximately.
Further dispersion caused by earth's motion:
Daily modulation and annual modulation possible to further check consistency and DM property extrapolation.



Quantum measurement noise



readout light phase via interferometer

light phase shift ~ $x(t_1)$

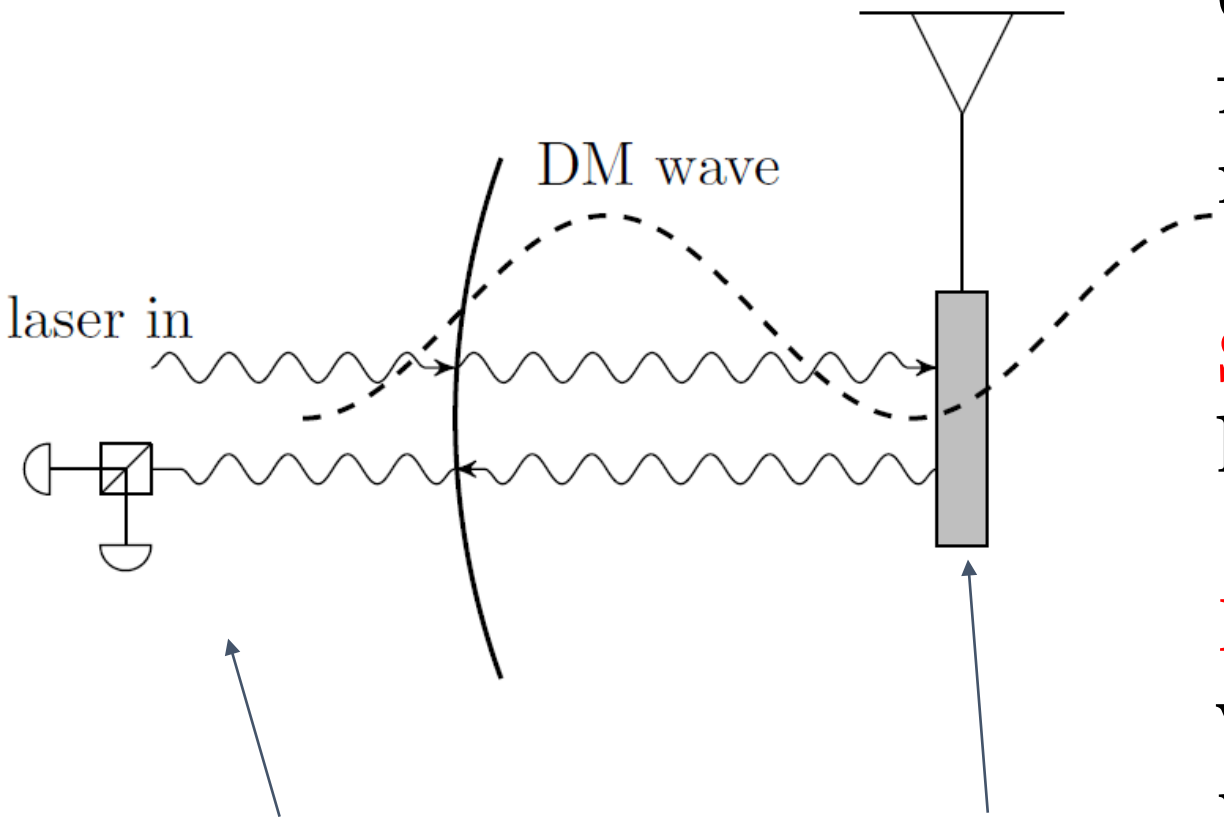
Quantum mechanics imposes fundamental source of noise: the act of measurement itself.

Shot noise (SN): random variations in laser phase read out in detector

Backaction noise (BA): random variations in laser amplitude → random radiation pressure on mechanics

(Standard Quantum Limit) SQL: optimization between SN and BA

Quantum measurement noise



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(Standard Quantum Limit) SQL: optimization between SN and BA

Noise and sensitivity

Total force acting on the sensor:

$$F_{\mathrm{in}}(t) = F_{\mathrm{sig}}(t) + F_{\mathrm{th}}(t) + F_{\mathrm{meas}}(t)$$

thermal noise forces
(environmental)

measurement added-noise force
(fundamental quantum issue)

Key in what follows:

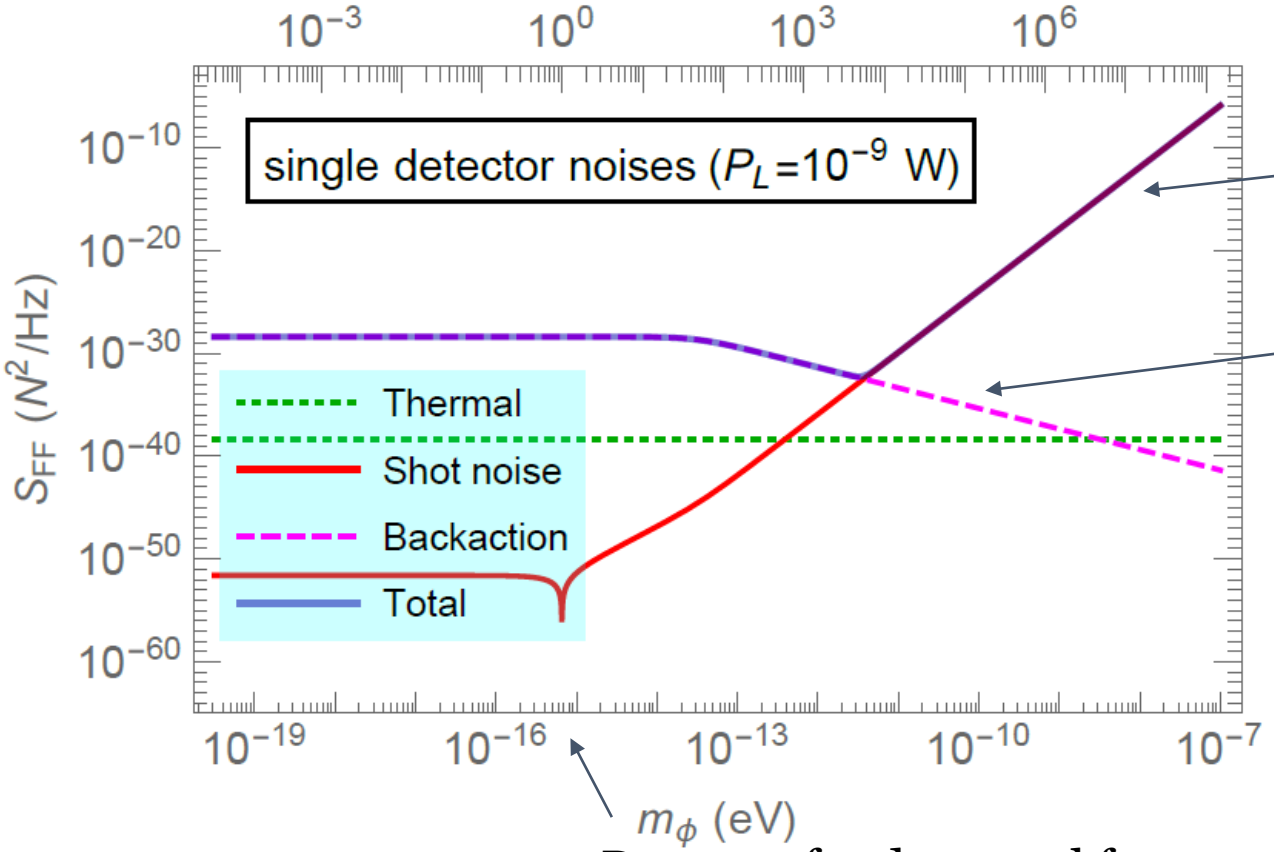
Signal = classical, deterministic

Noise = stochastic, Brownian

Detecting monochromatic forces

Minimum force amplitude detectable:

$$F_* = \sqrt{S_{FF}(\omega_s)/T_{int}}$$



Fluctuations in laser phase (~1/P_L)

Fluctuations in laser amplitude (~P_L)

$$S_{FF}^{T} = \gamma m_s kT + PA_s\sqrt{m_a kT}.$$

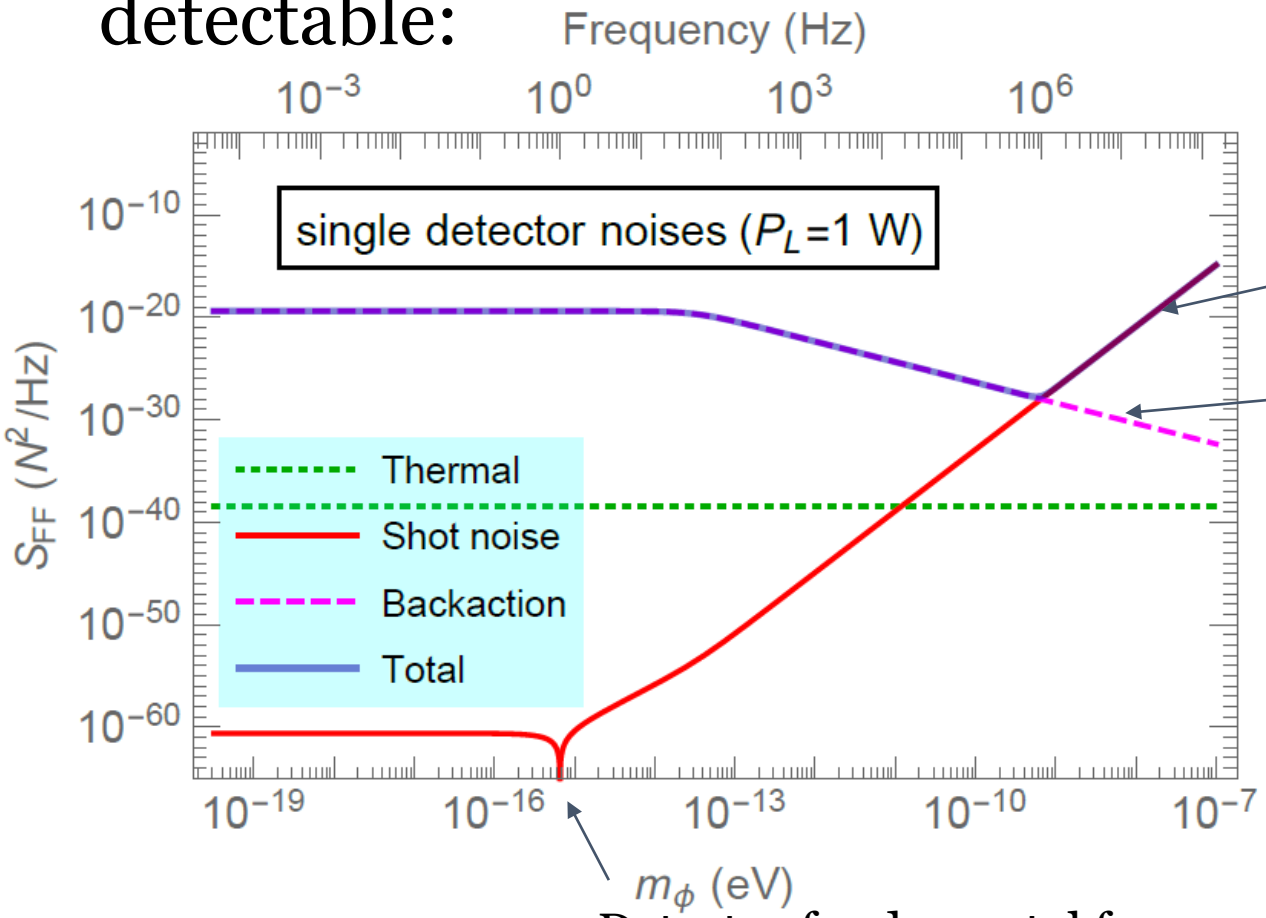
$$S_{FF}^{M,SQL}(\omega_s) = 2m_s\sqrt{(\omega_s^2-\omega_m^2)^2+\gamma^2\omega_m^2}.$$

$$S_{FF}^{M} = S_{FF}^{BA} + S_{FF}^{SN}$$

Detecting monochromatic forces

Minimum force amplitude detectable:

$$F_* = \sqrt{S_{FF}(\omega_s)/T_{int}}$$



Detector fundamental frequency

Fluctuations in laser phase (~$1/P_L$)

Fluctuations in laser amplitude (~P_L)

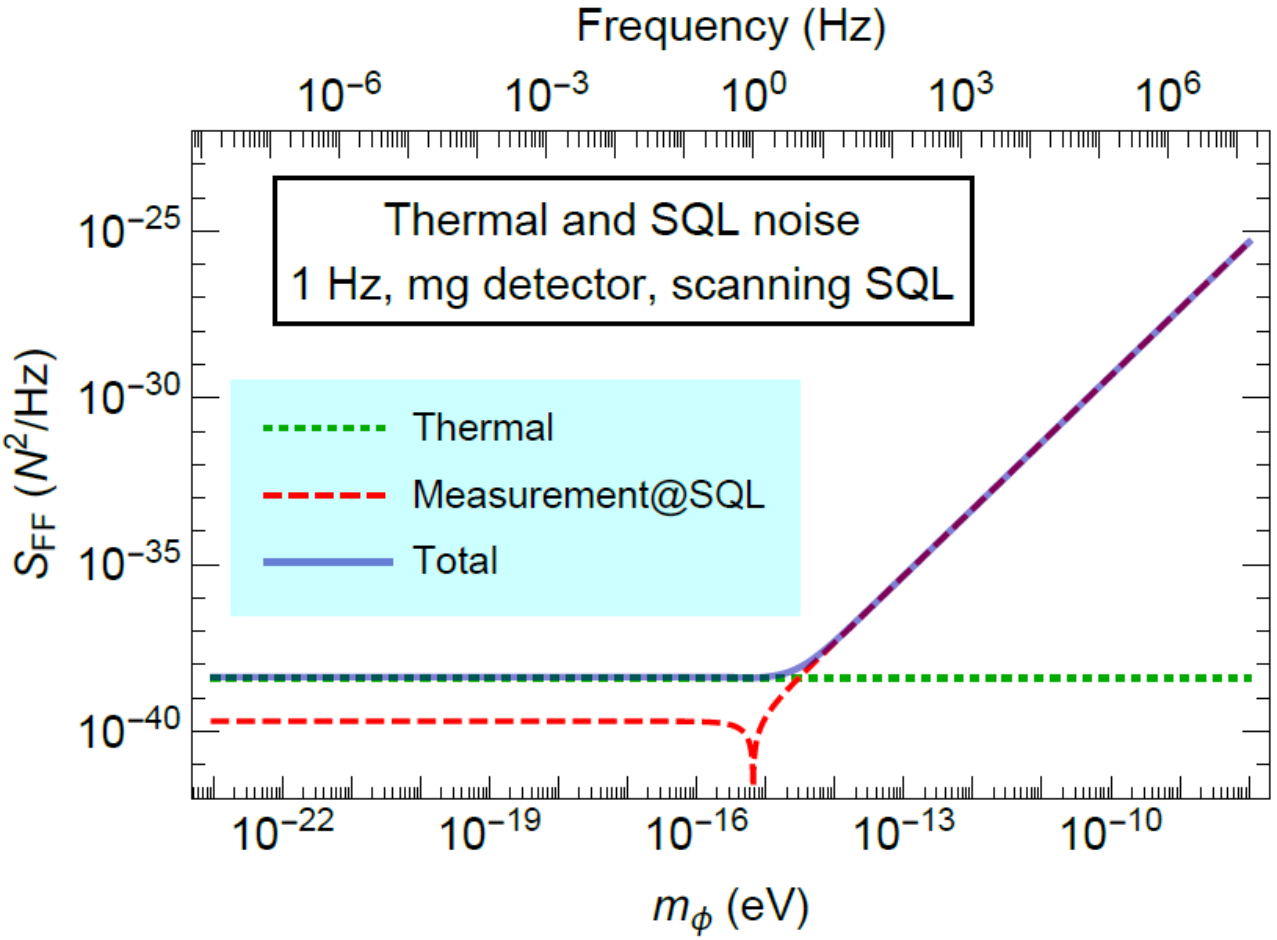
$$S_{FF}^{T} = \gamma m_s kT + PA_s\sqrt{m_a kT}.$$

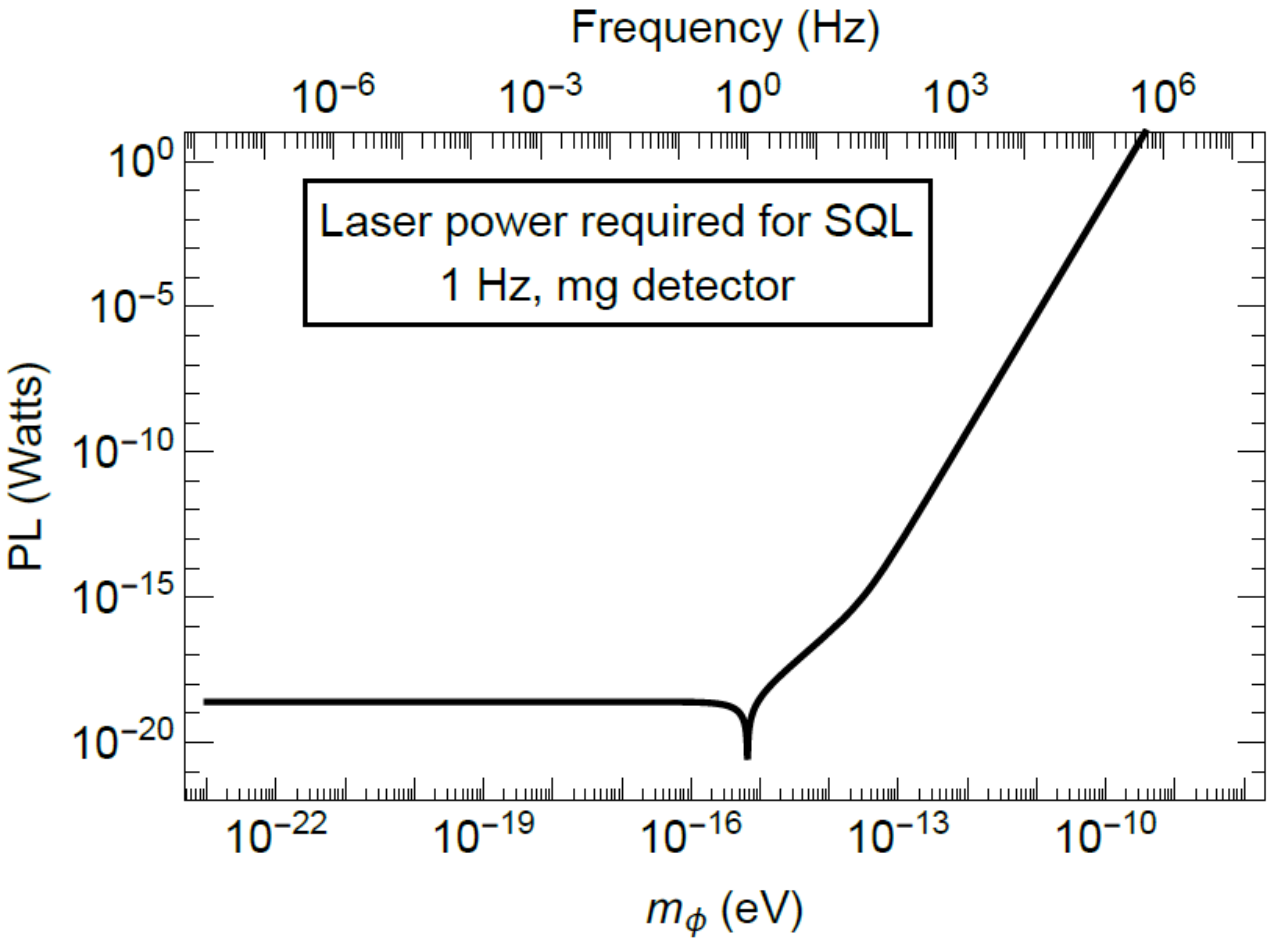
$$S_{FF}^{M,SQL}(\omega_s) = 2m_s\sqrt{(\omega_s^2-\omega_m^2)^2+\gamma^2\omega_m^2}.$$

$$S_{FF}^{M} = S_{FF}^{BA} + S_{FF}^{SN}$$

Detecting monochromatic forces at the SQL

The “SQL” is a frequency-dependent concept:
Tune laser power to a certain value → achieve SQL at a certain frequency



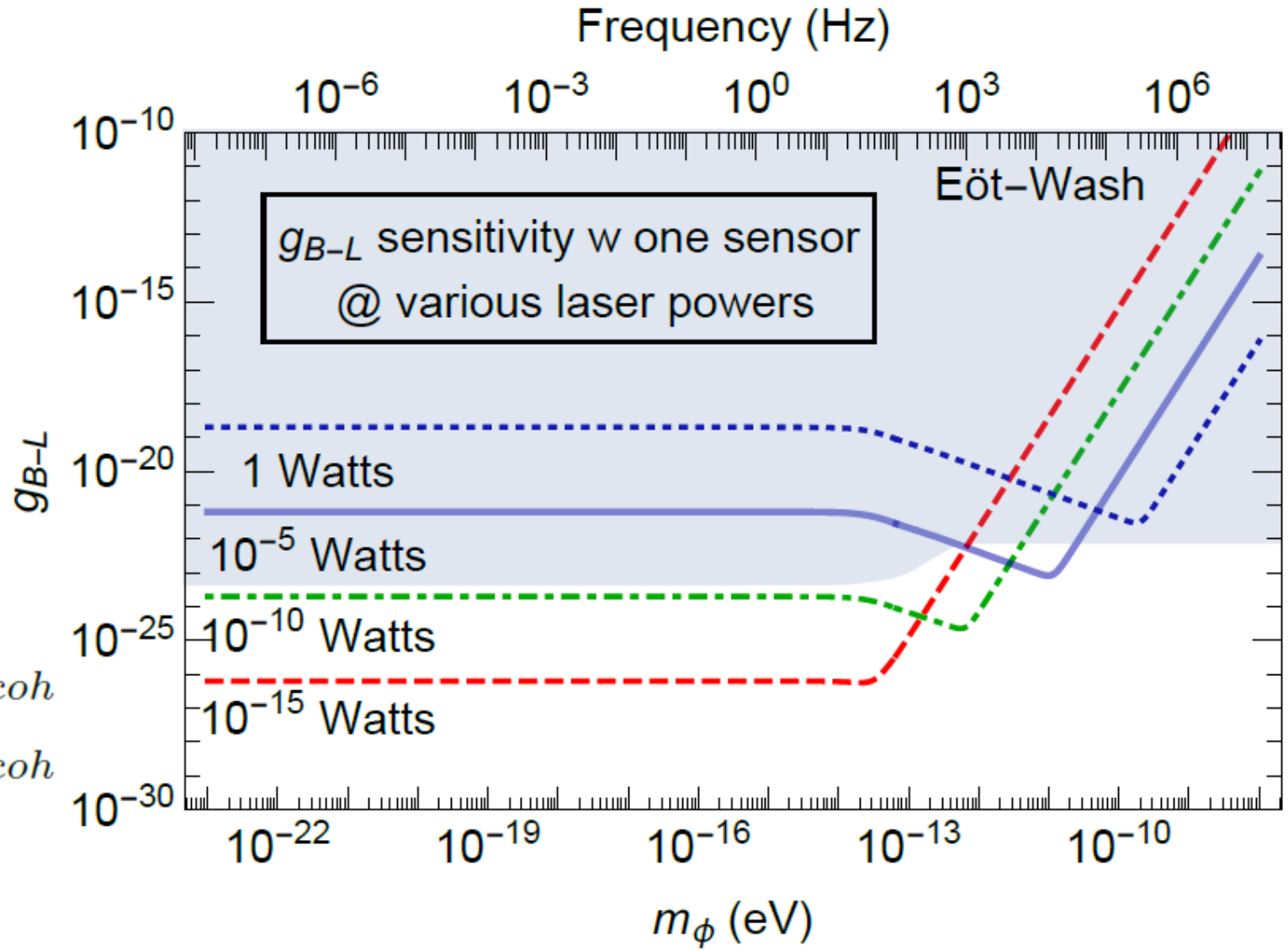


Detection strategy and reach

Tune laser to achieve SQL in “bins”.

Integrate as long as possible for each bin (coherence time or, e.g., laser stability limit)

$$T_{tot} = \begin{cases} T_{int} & T_{int} < T_{coh} \\ \sqrt{T_{int} T_{coh}} & T_{int} > T_{coh} \end{cases}$$

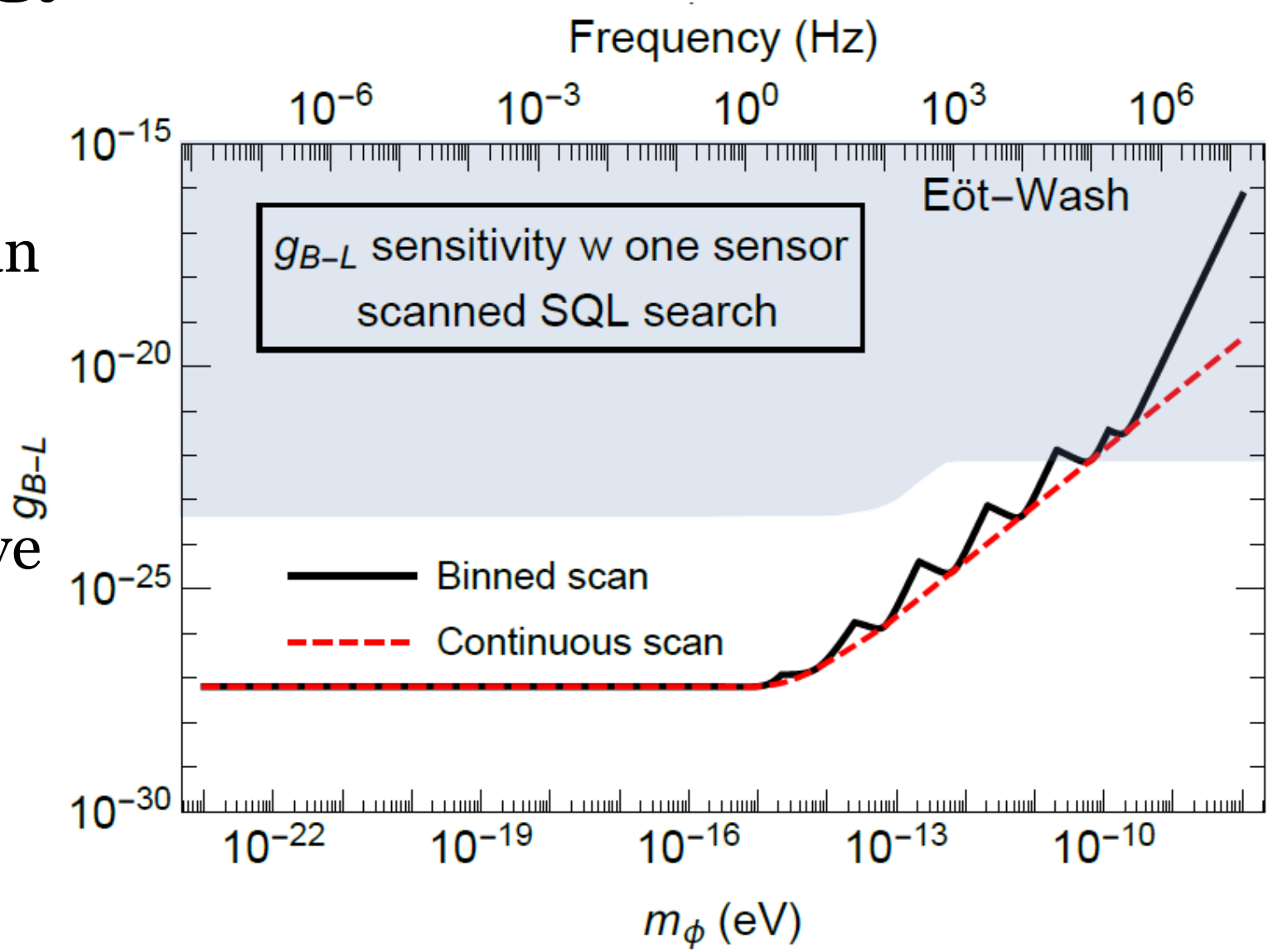


$$g_*^2 = \frac{\gamma m_s kT + 2m_s\sqrt{(\omega_m^2 - \omega_s^2)^2 + \gamma^2\omega_m^2}}{N_{det}N_V^2F_0^2T_{tot}}$$

Detection strategy and reach

7 step scan, each for an hour;
Laser power no larger than 1 Watt (not SQL at high frequencies);

Achieving very competitive sensitivities with demonstrated quantum force sensor sensitivity already

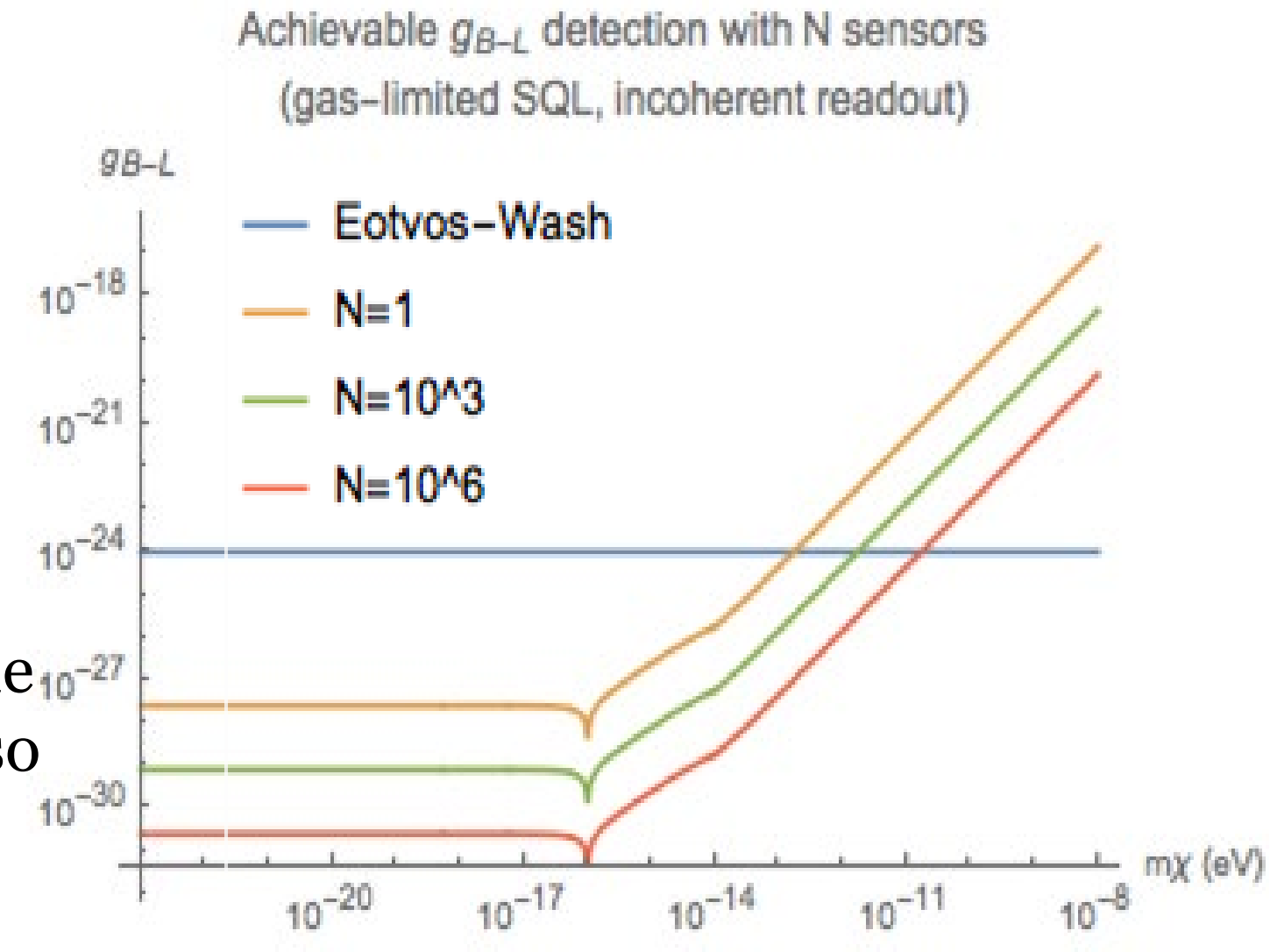


Correlated signals vs. uncorrelated noise

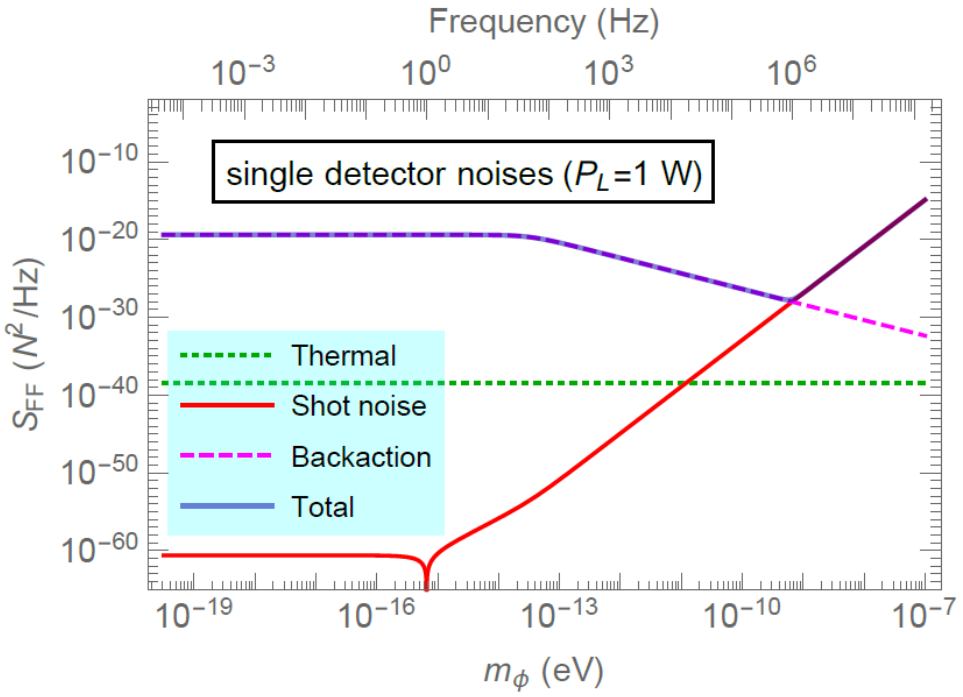
Sensitivity ~1/√N

N = total # sensors

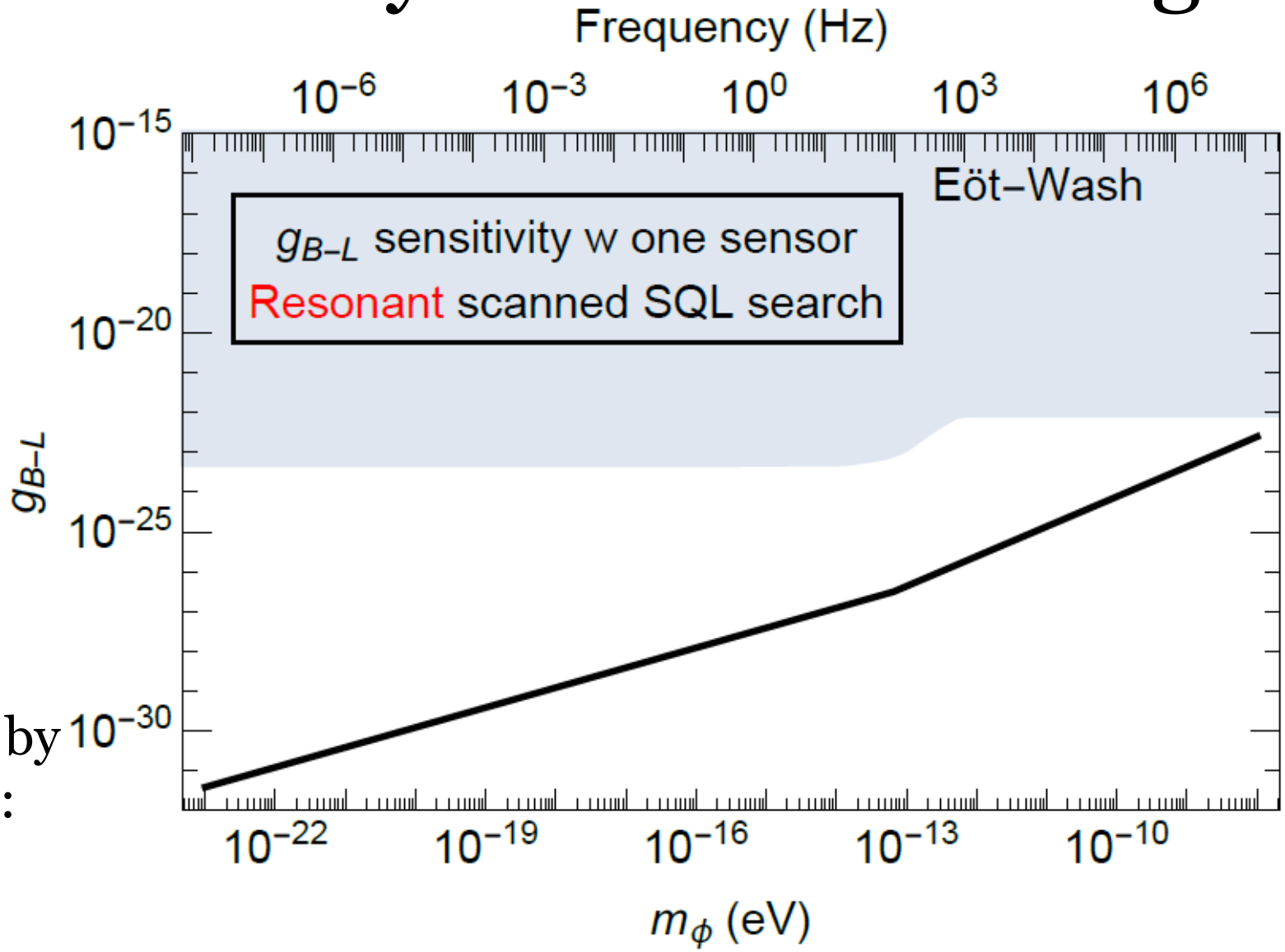
Also, crucial advantage: **exquisite** background rejection, e.g., removal of seismic noises through Equivalence Principle (EP) violating force tests. (also see accelerometer & torsion balance studies)



Further improvement: dynamical stiffening



Possible to change the mechanical sensor frequency by applying a driving laser pulse: future reduces the noise level



Summary and outlook

Turning stones together with the ongoing quantum sensor studies

For small scale mechanical sensors:

- a rapidly scaling sensitivity (root N scaling and N scaling)
- EP test for (systematics and seismic) noise removal
- Many realizations: adding charges to the sensors for different bosonic ultralight DM, e.g., magnetic sensors could be used to search for dipole-coupled forces.
- post-SQL strategy will be most beneficial at frequencies > 1 GHz (for dilution refrigeration temperatures T=10 mK)
- Also applicable to scalar DM (with velocity suppressions in the resulting force)

Backup

nature > light: science & applications > articles > article

Light | Science & Applications

Article | OPEN | Published: 30 May 2018

A new quantum speed-meter interferometer: measuring speed to search for intermediate

Stefan L. Danilishin, Eugene Knyazev, Nikita V. Voronch
Sebastian Steinlechner, Jan-Simon Hennig & Stefan Hild

Light: Science & Applications **7**, Article number: 11 (2018)

nature photonics

Letter | Published: 21 July 2013

Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light

J. Aasi, J. Abadie [...] J. Zweizig

Nature Photonics **7**, 613–619 (2013) | Download Citation

IOPscience

New Journal of Physics

The open access journal at the forefront of physics

Back-action evasion and squeezing of a mechanical resona using a cavity detector

A A Clerk[1,4], F Marquardt[2] and K Jacobs[3]

Published 30 September 2008 • IOP Publishing and Deutsche Physikalische Gesellschaft
New Journal of Physics, Volume 10, September 2008
Focus on Mechanical Systems at the Quantum Limit

Review: Advanced quantum techniques for future gravitational-wave detectors

Danilishin, Khalili, Miao 1903.05223

$$S_{FF}(\omega) = S_{FF}^{SN}(\omega) + S_{FF}^{BA}(\omega) + S_{FF}^{T}(\omega)$$

powers. Here we have plotted sensitivities for a mechanically-coupled sensor of mass $m_s = 1$ mg, mechanical frequency $\omega_m = 1$ Hz, and mechanical damping coefficient $\gamma = 10^{-6}$ Hz in a 1 cm optical cavity. We assume operation at dilution refrigeration temperatures $T = 10$ mK. The incident laser

$$S_{FF}^{SN} = \frac{x_0^2}{G^2\kappa}\frac{1}{|\chi_c\chi_m|^2}$$

$$S_{FF}^{BA} = \frac{G^2\kappa}{x_0^2}|\chi_c|^2$$

$$S_{FF}^{T} = 4\gamma m_s kT.$$

$$S_{FF}^{M} = S_{FF}^{BA} + S_{FF}^{SN}$$

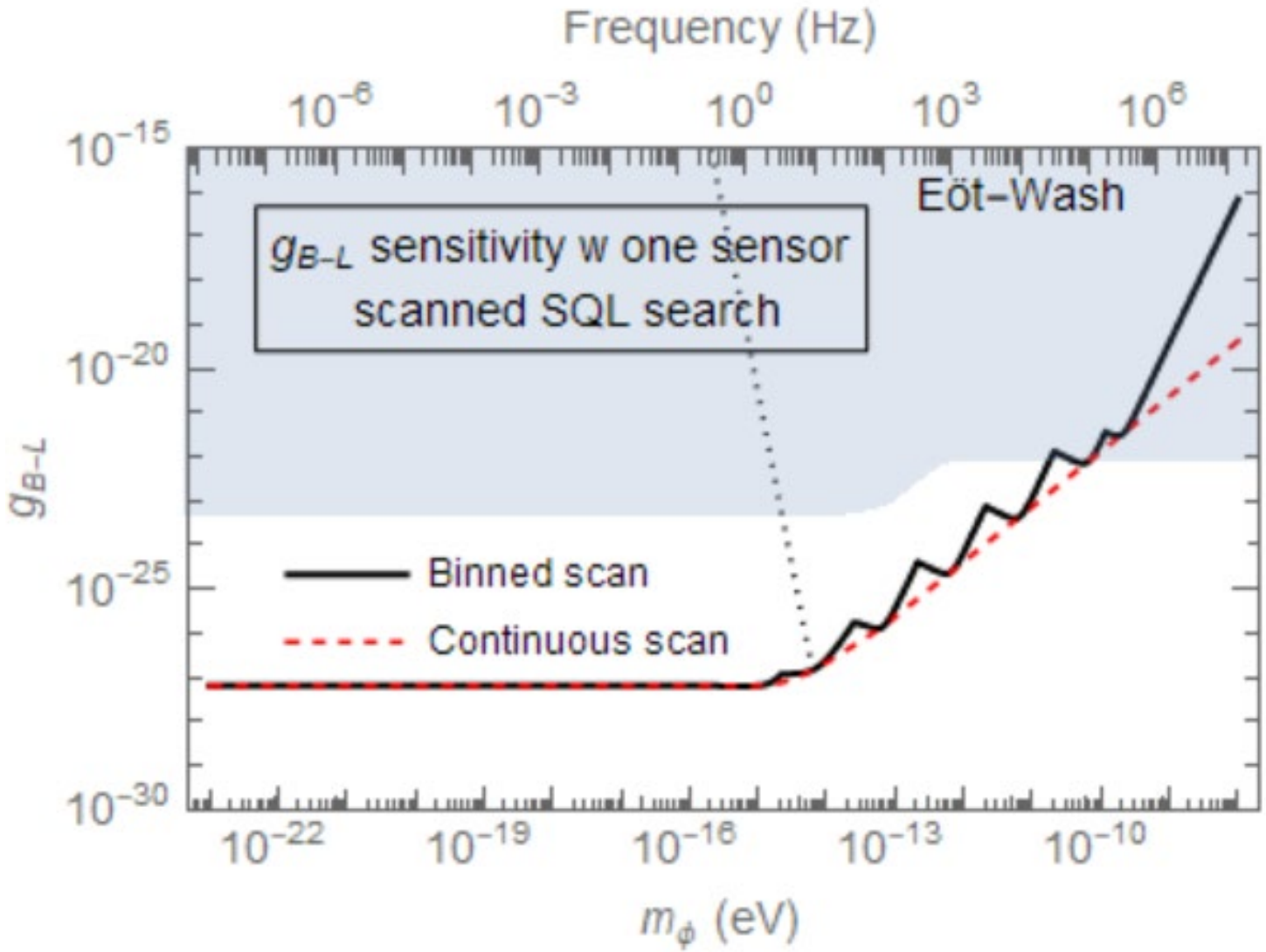
$$S_{FF} = S_{FF}^{T} + S_{FF}^{M} \qquad S_{FF}^{M,SQL,res}(\omega_s) = 2m_s\gamma\omega_s$$

$$S_{FF}^{T} = \gamma m_s kT + PA_s\sqrt{m_a kT}.$$

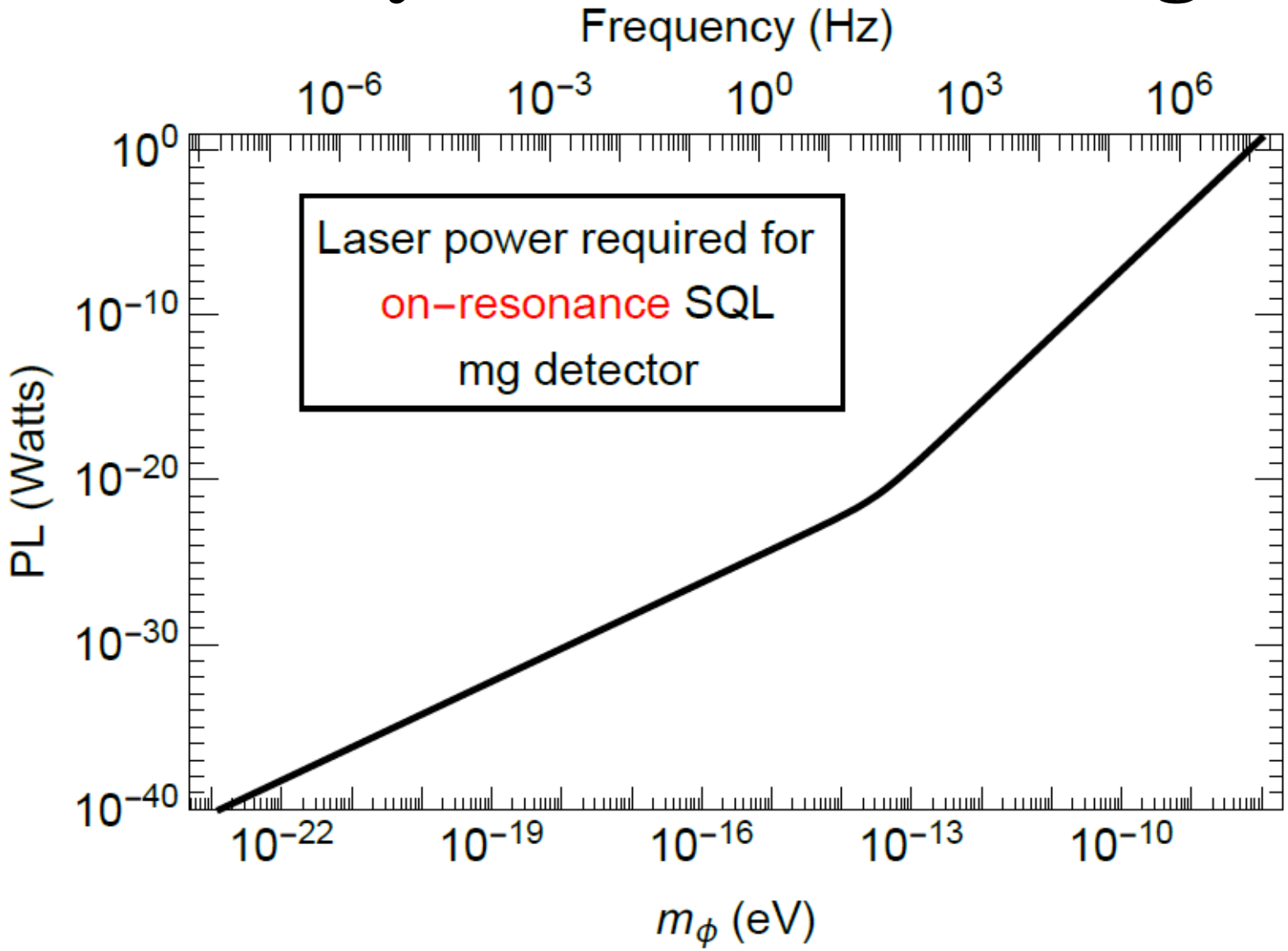
$$S_{FF}^{M,SQL}(\omega_s) = 2m_s\sqrt{(\omega_s^2 - \omega_m^2)^2 + \gamma^2\omega_m^2}.$$

$$g_*^2 = \frac{\gamma m_s(kT + 2\omega_s)}{N_{det}N_V^2F_0^2T_{tot}}$$

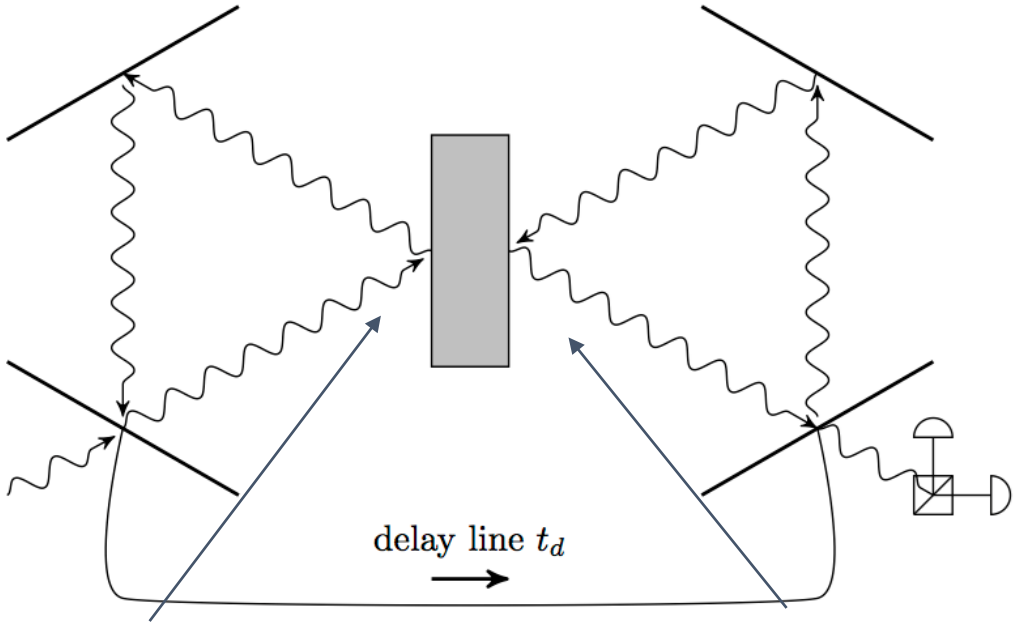
$$g_*^2 = \frac{\gamma m_s kT + 2m_s\sqrt{(\omega_m^2 - \omega_s^2)^2 + \gamma^2\omega_s^2}}{N_{det}N_V^2F_0^2T_{tot}}$$


Frequency (Hz)
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
g_{B-L}
Eöt–Wash
g_{B-L} sensitivity w one sensor
scanned SQL search
Binned scan
Continuous scan
10^{-22}
10^{-19}
10^{-16}
10^{-13}
10^{-10}
m_ϕ (eV)

Further improvement: dynamical stiffening



Impulse measurement is naturally QND

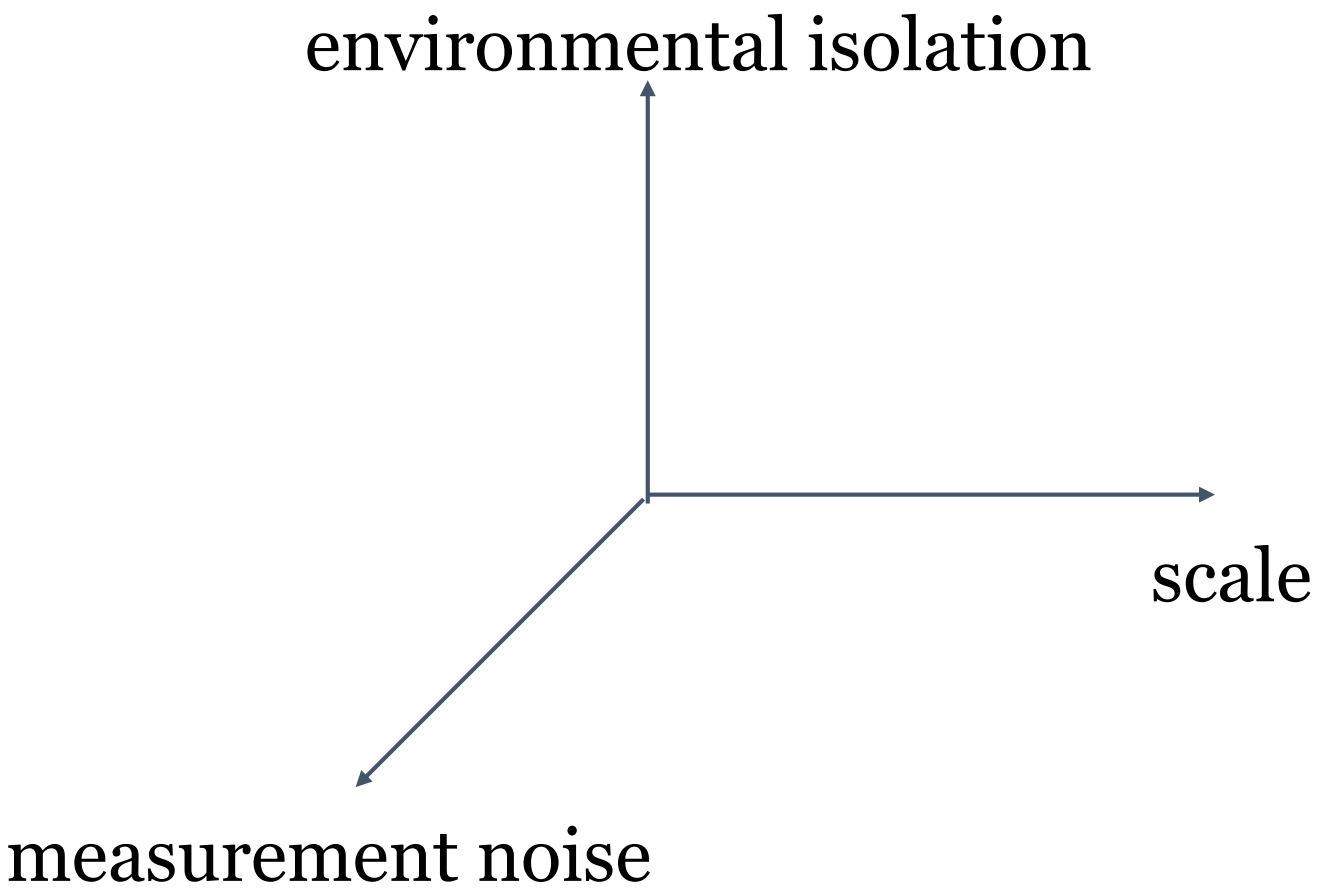


light phase ~ $x(t_1)$
impart +p to mirror

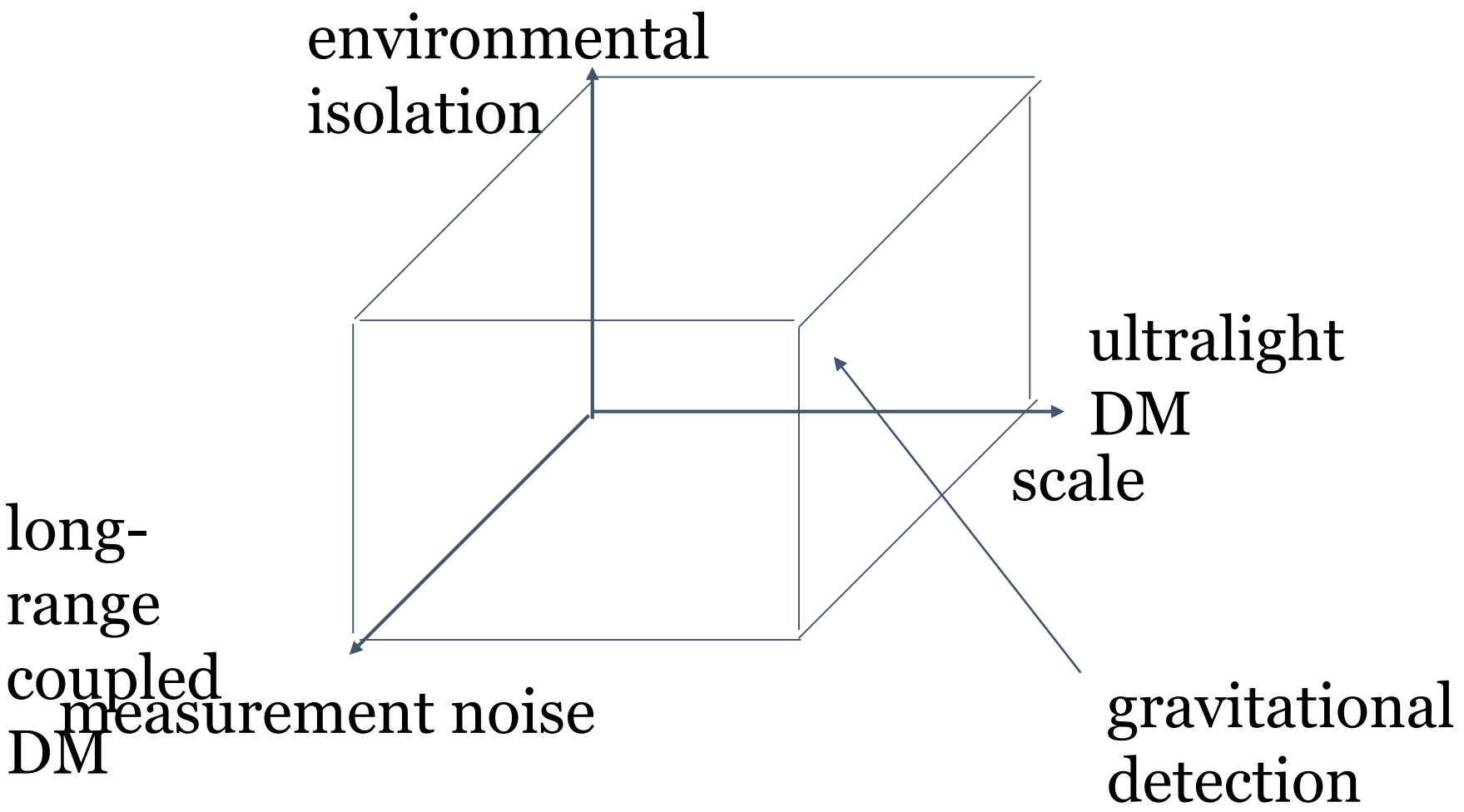
light phase ~ $-x(t_2)$
impart -p to mirror

→ Light phase ~ $x(t_1)$-$x(t_2)$ ~ v, momentum transfer ~ 0.

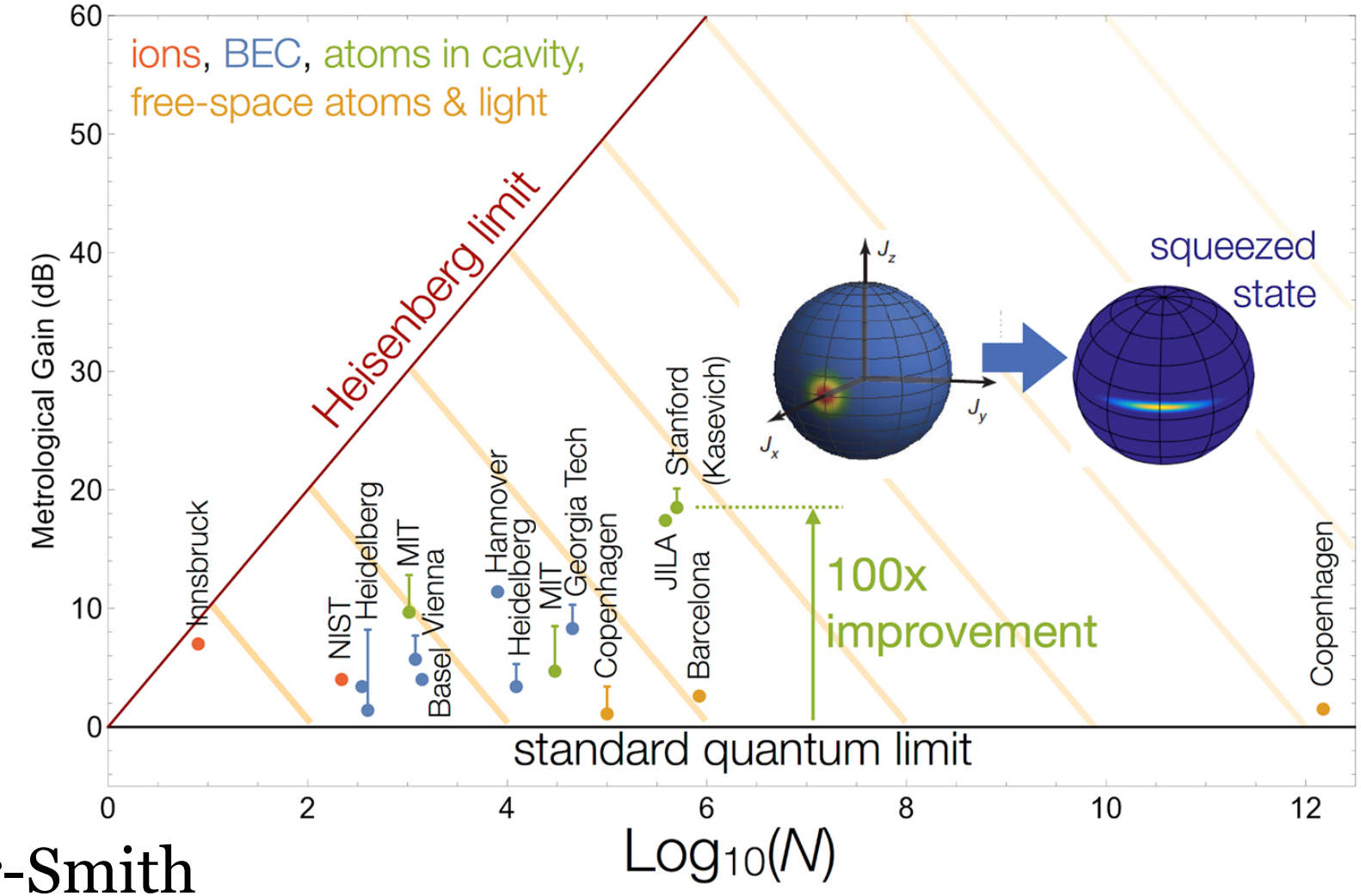
Three big experimental asks



Three big experimental asks

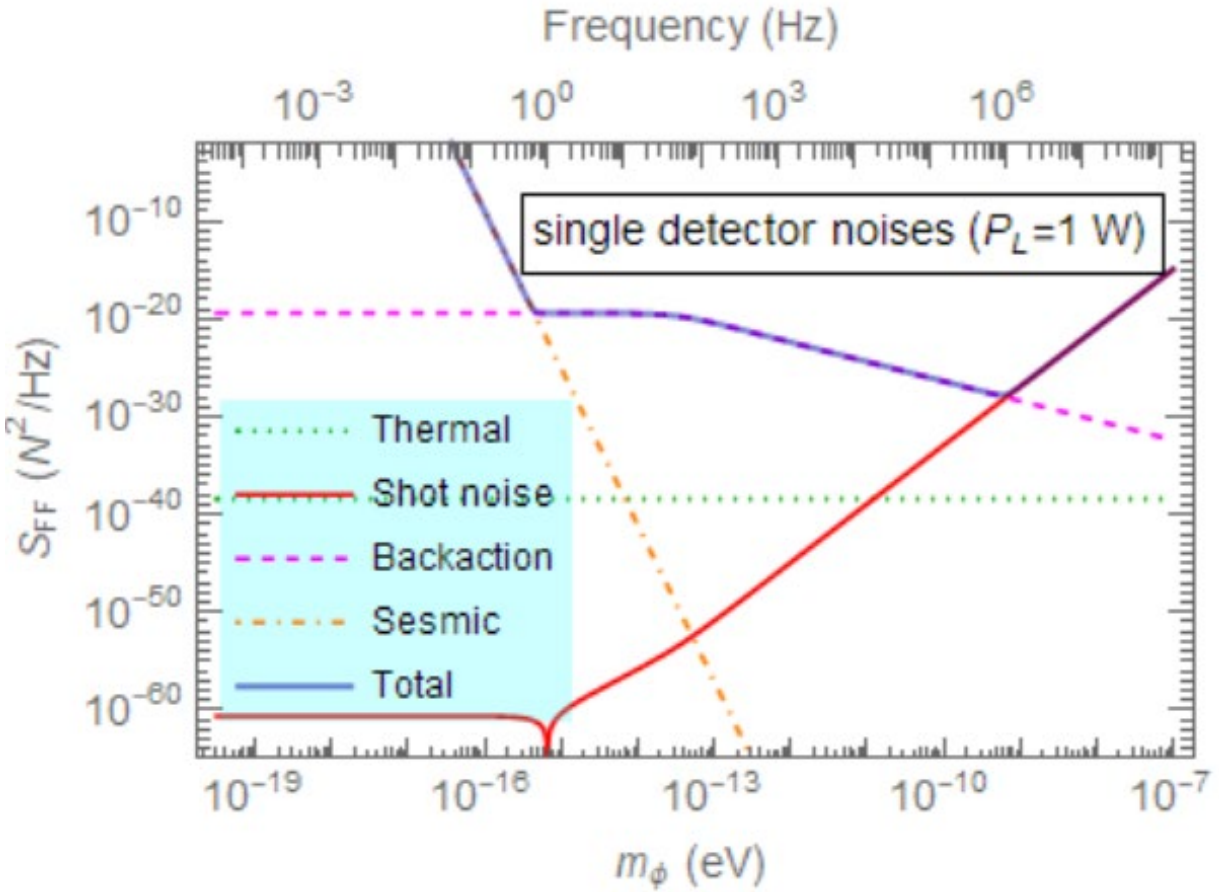


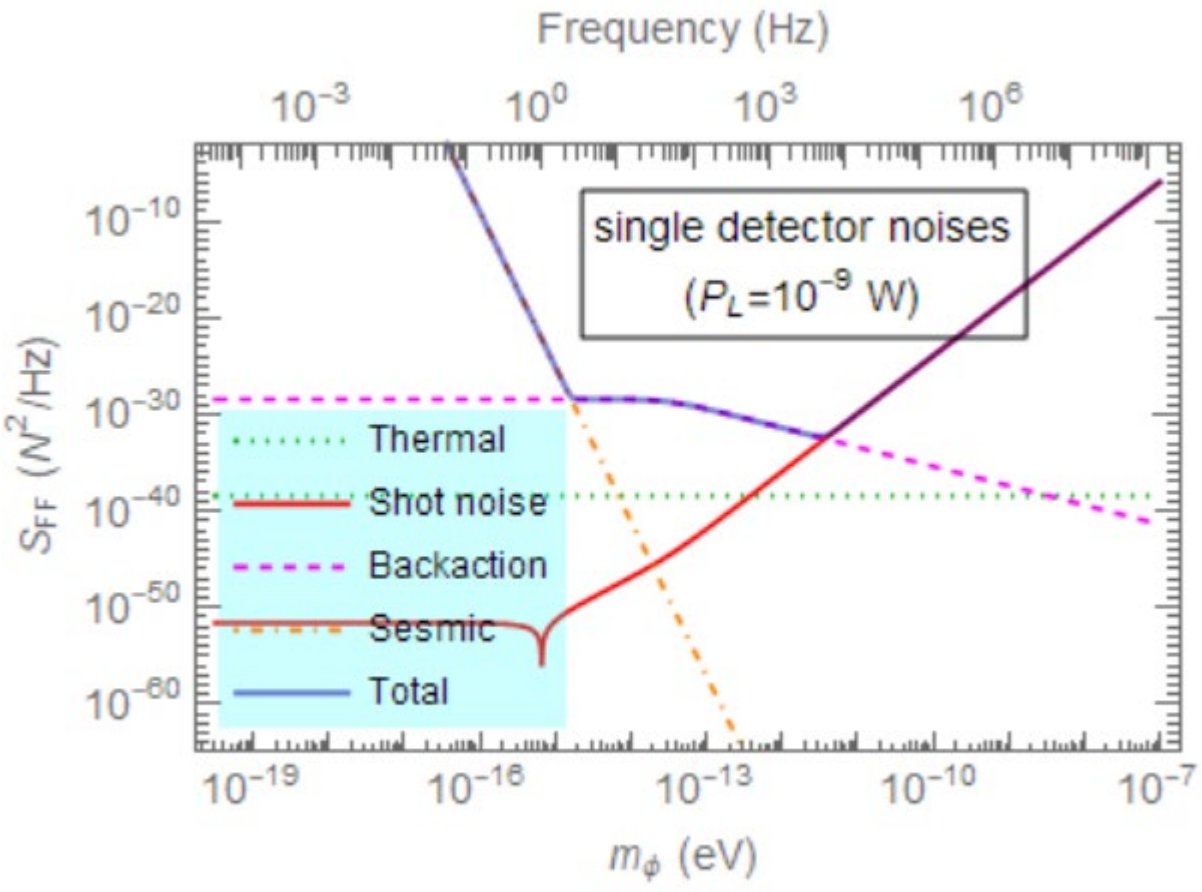
Entanglement-Enhanced Measurements

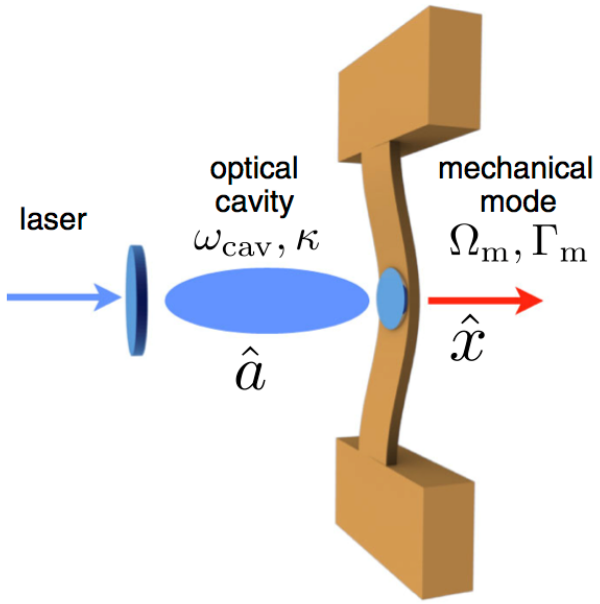


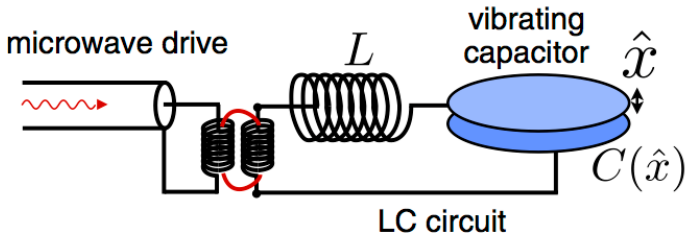
Slide from Monika Schleier-Smith

Noise composition with Seismics









$$\dot{X} = -\Delta Y - \frac{\kappa}{2} X + X_{in}$$

$$\dot{Y} = \Delta Y - \frac{\kappa}{2} Y + Y_{in} + \frac{gx}{x_0}$$

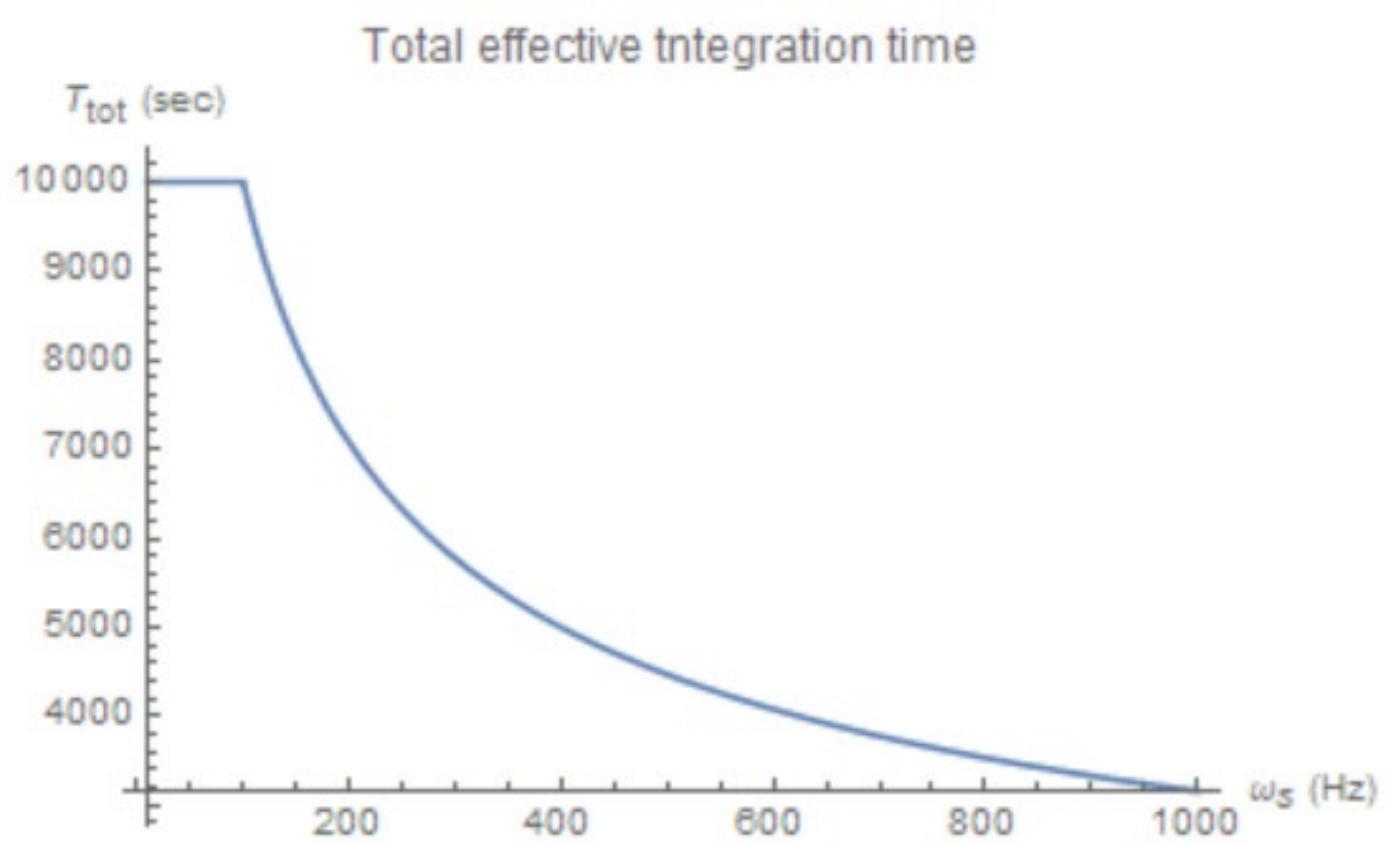
$$\dot{x} = \frac{p}{m}$$

$$\dot{p} = -m\omega_m^2 x - \gamma p + F_{in} + \frac{\hbar g X}{x_0}$$

Damping/loss

"Input noise"
(note signal is part of F_{in})

$$T_{tot} = \begin{cases} T_{int} & T_{int} < T_{coh} \\ \sqrt{T_{int} T_{coh}} & T_{int} > T_{coh} \end{cases}$$



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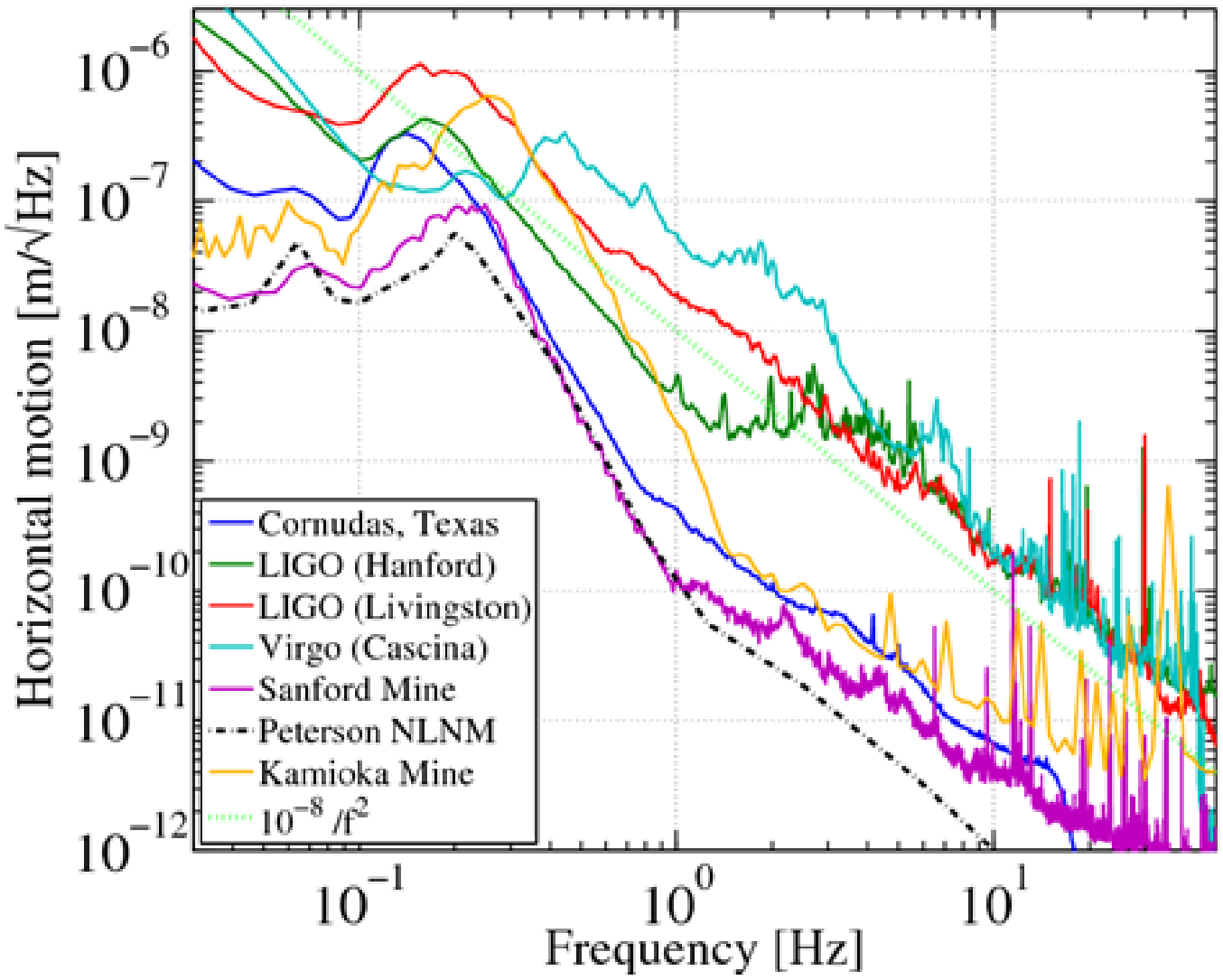
Fermilab


Horizontal motion [m/√Hz]
Frequency [Hz]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-1}
10^{0}
10^{1}
Cornudas, Texas
LIGO (Hanford)
LIGO (Livingston)
Virgo (Cascina)
Sanford Mine
Peterson NLNM
Kamioka Mine
10^{-8} /f^2

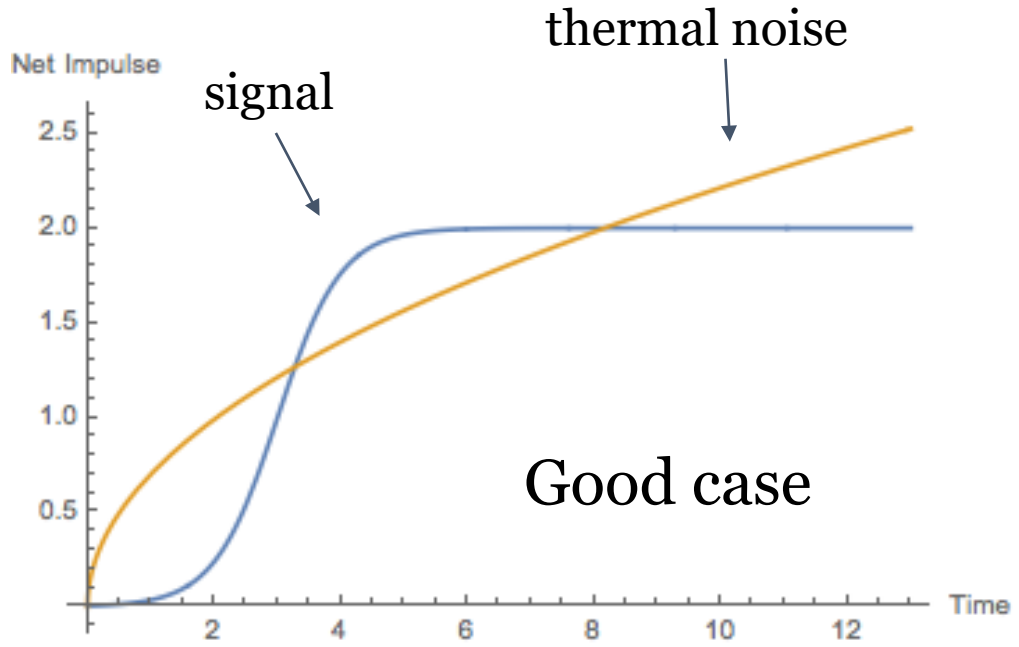
Signal to noise

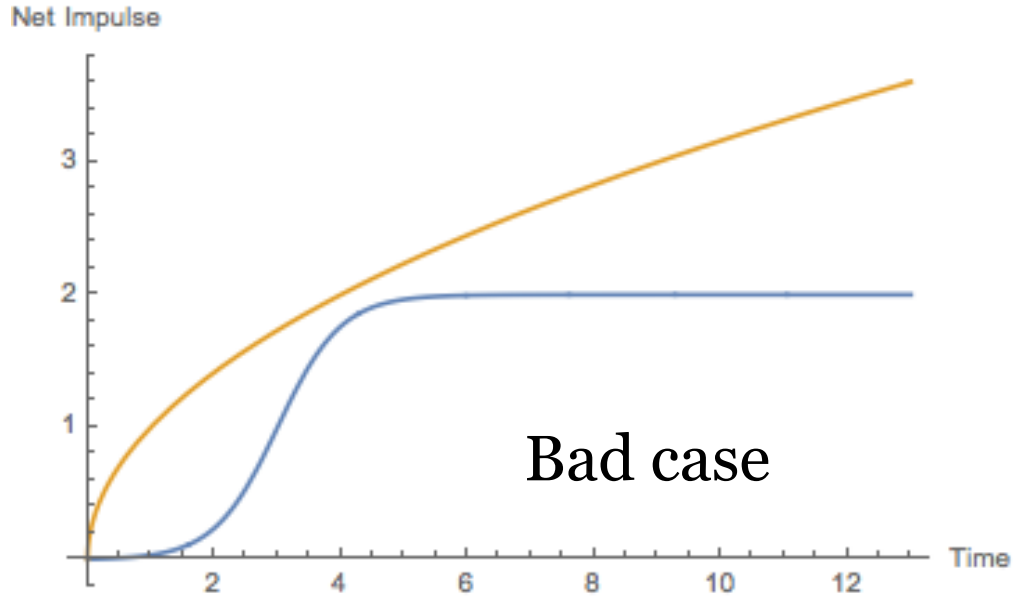
As an observable we will use the total impulse delivered to the sensor:

$$I = \int_{-t_{int}/2}^{t_{int}/2} dt \; F_{\text{sig}}(t)$$

The game is then to see this impulse above the noise:

$$\begin{aligned} \langle \Delta I^2 \rangle &= \int \int dt dt' \; \langle F_{\text{noise}}(t) F_{\text{noise}}(t') \rangle \\ &= \Delta I_T^2 + \Delta I_{\text{meas}}^2 \end{aligned}$$





Torsion balance types:

P. Graham, D. Kaplan, J. Mardon,
S. Rajendran, W. Terrano, 15’