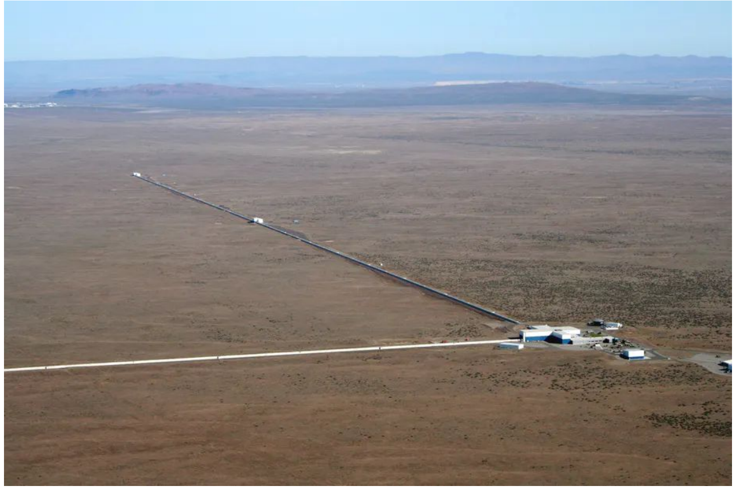
Mechanical quantum sensing for dark matter: heavy, light, ultra-light

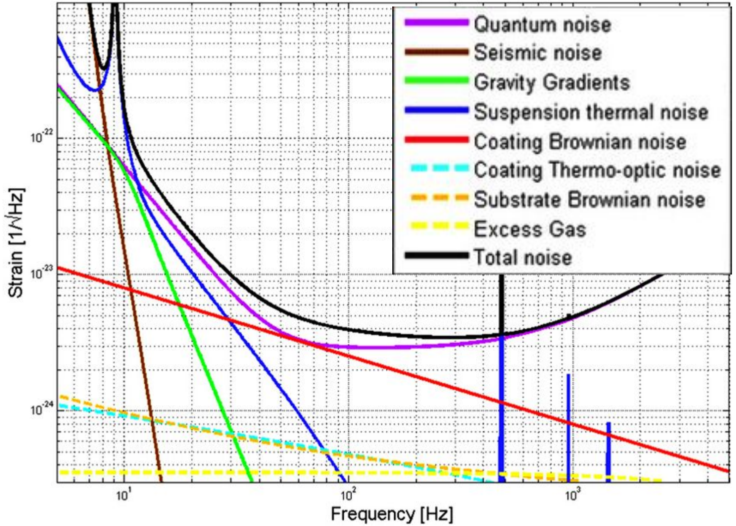
Daniel Carney

BERKELEY LAB

@four_form

Quantum-limited detection



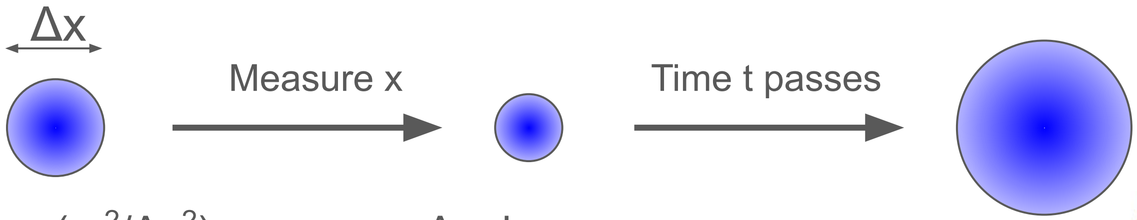


The Sensitivity of the Advanced LIGO Detectors at the Beginning of Gravitational Wave Astronomy
LIGO Collaboration 1604.00439

PHYSICAL REVIEW D VOLUME 23, NUMBER 8 15 APRIL 1981

Quantum-mechanical noise in an interferometer

Carlton M. Caves
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125
(Received 15 August 1980)



$\psi = \exp(-x^2/\Delta x^2)$

$\Delta x \Delta p = \hbar/2$
minimal uncertainty

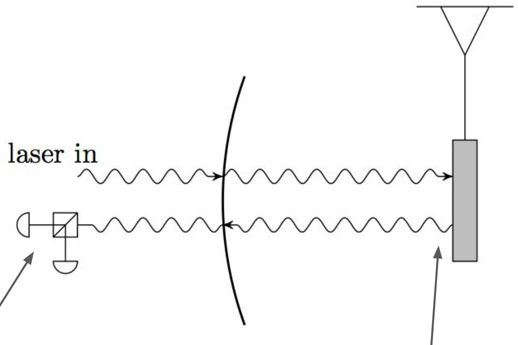
Δx decreases
↓
Δp increases

$$\Delta x \to \Delta x + \frac{\Delta p}{2m} t$$

optimize → "standard quantum limit"

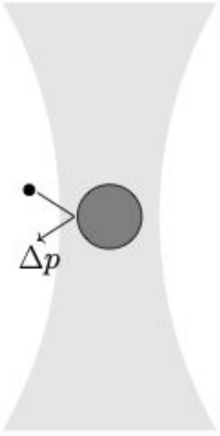
$$\Delta x_{SQL} = \sqrt{\frac{\hbar t}{m}}$$

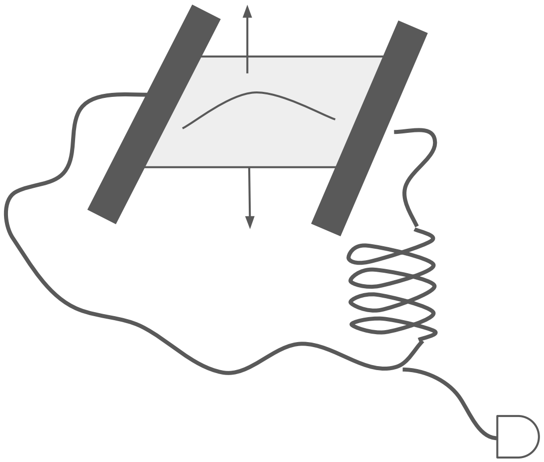
Mechanical quantum sensing

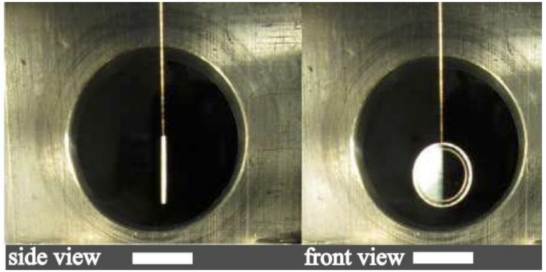


read out light phase via interferometer
→ measure x(t)
→ infer F(t)

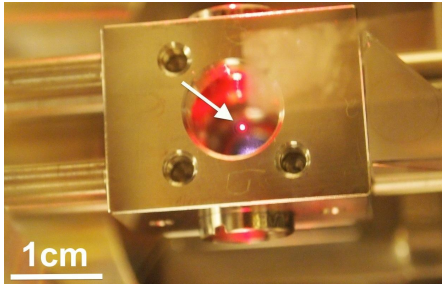
light phase shift ~ x(t)



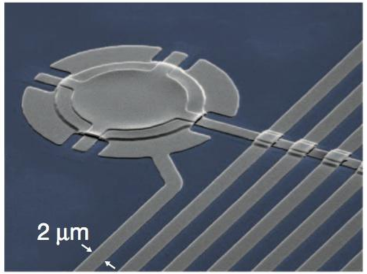




Matsumoto et al, PRA 2015

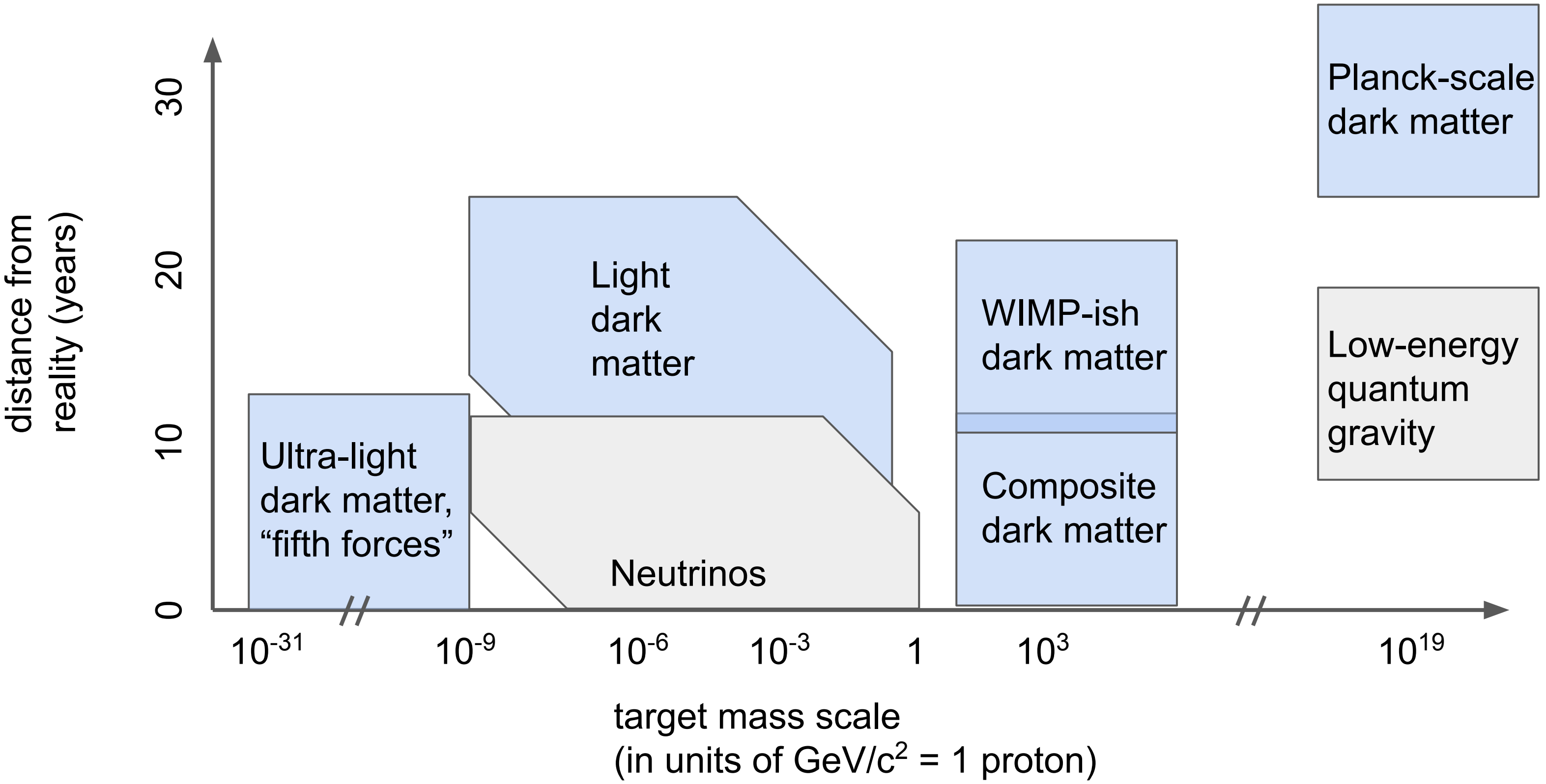


Moore group @ Yale



Teufel et al, Nature 2011

Mechanical sensing targets



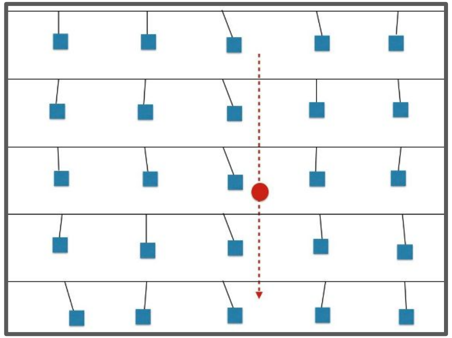
Windchime array concept

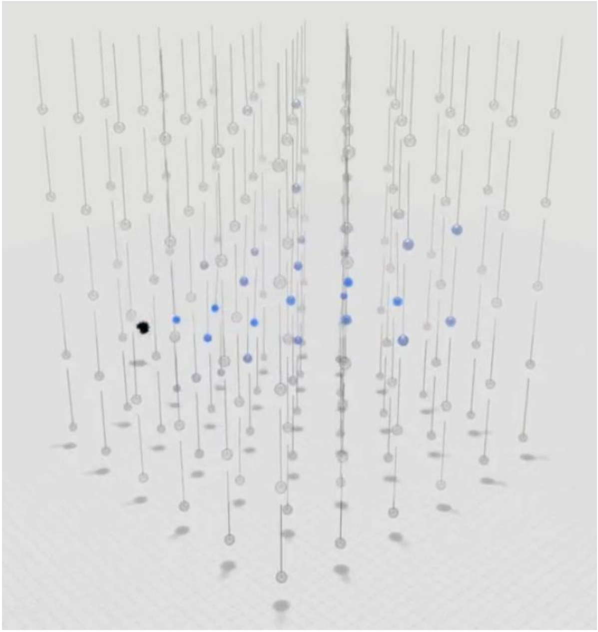
Signal = correlated groups of sensors moving

- Directional info
- Exquisite background rejection
- sqrt(N) noise reduction (N = sensors in group)

Scales to keep in mind: ~ mm-cm spacing, mg-g mass devices, the more detectors the better.

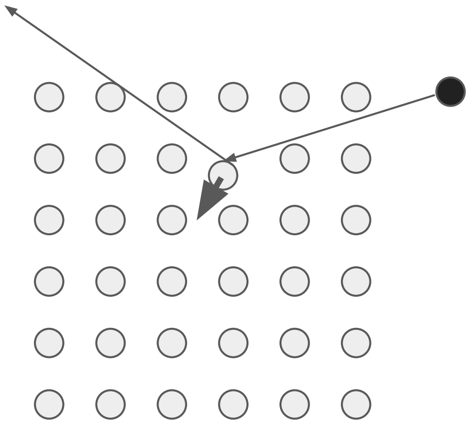
Can look for many signal types with this array.



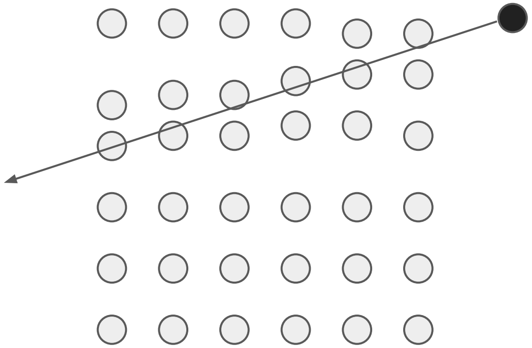


Signal types

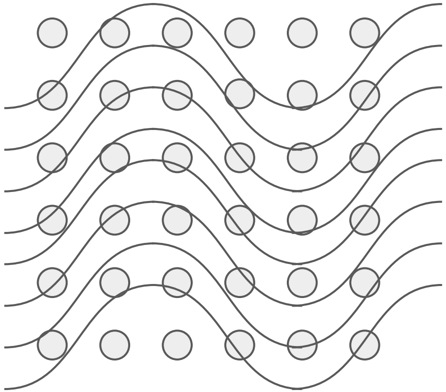
Rest of this talk: using arrays of mechanical sensors to look for various types of potential DM. Generally three types of clear signals:



Single-sensor scattering (traditional “WIMP” type DM)



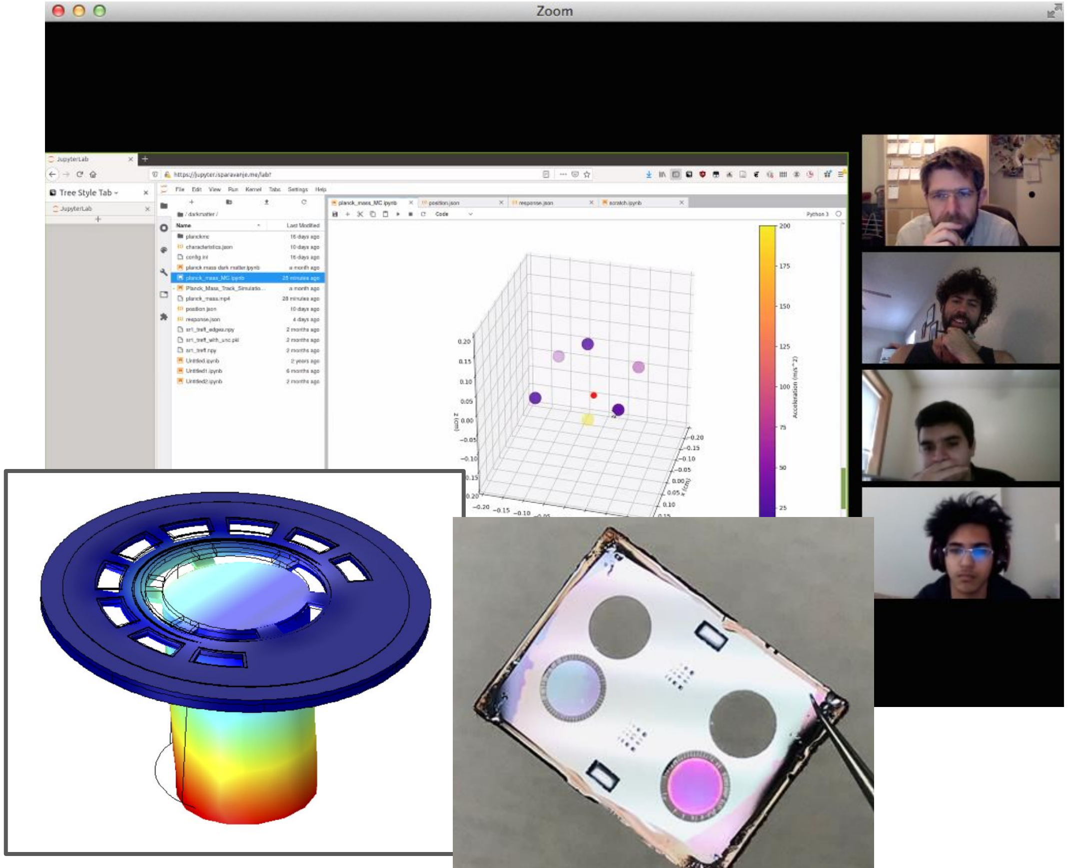
Track-like signals (DM coupled through long range force, e.g. gravity)



Coherent wave-like signals (very light DM with mass < eV, gravitational waves, …)

Windchime in practice

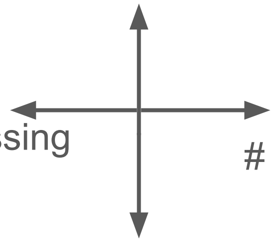
Rafael Lang @ Purdue



Collaboration currently involving Purdue, ORNL, Rice, FNAL, Maryland, Minnesota, NIST, LBL, …

Ultimate goal: gravitational detection w/ 10^6-10^9 sensors (!), << SQL

environmental isolation

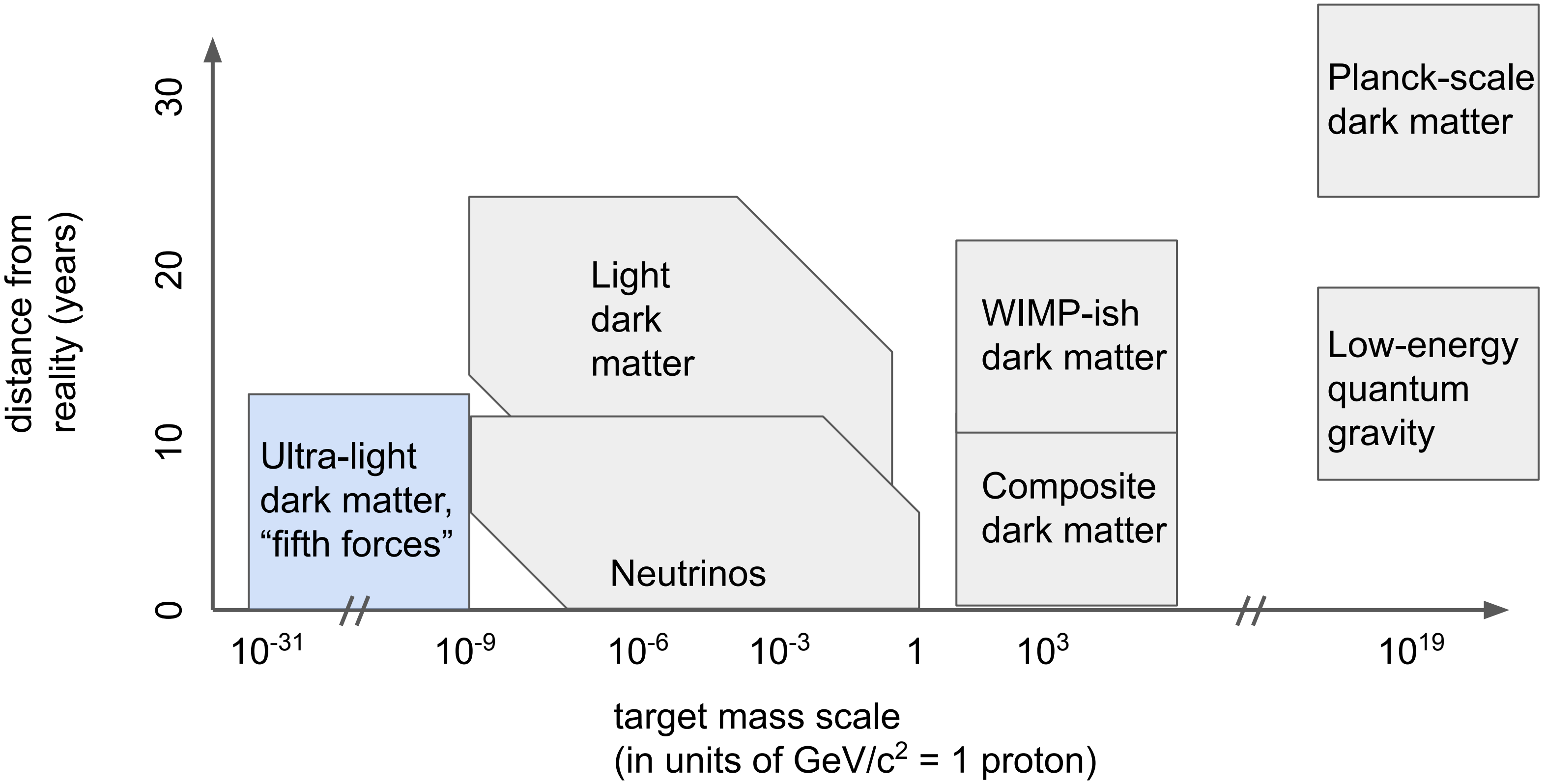


signal processing & computing

sensors

measurement noise

Snowmass: 2203.07242



distance from reality (years)
0
10
20
30
Planck-scale dark matter
Light dark matter
WIMP-ish dark matter
Low-energy quantum gravity
Ultra-light dark matter, “fifth forces”
Composite dark matter
Neutrinos
10^{-31}
10^{-9}
10^{-6}
10^{-3}
1
10^{3}
10^{19}
target mass scale
(in units of GeV/c^2 = 1 proton)

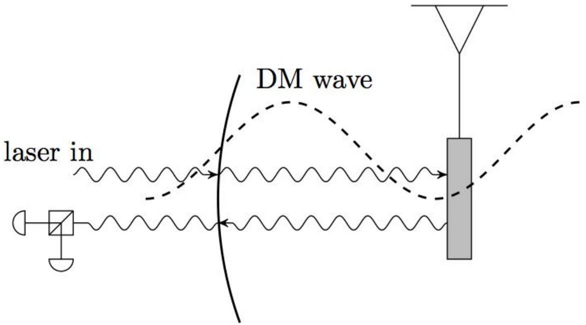
Ultralight DM detection

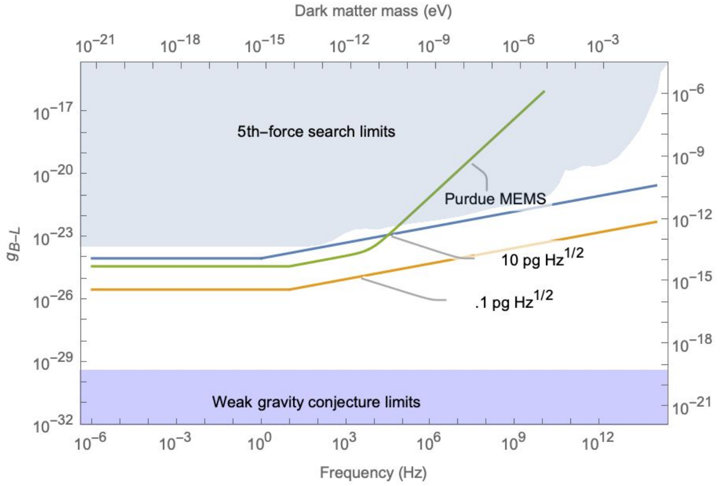
Example: DM m < 0.1 eV, coupled to B-L charge

Coherent, persistent, oscillating force on mechanical sensor → acceleration signal.

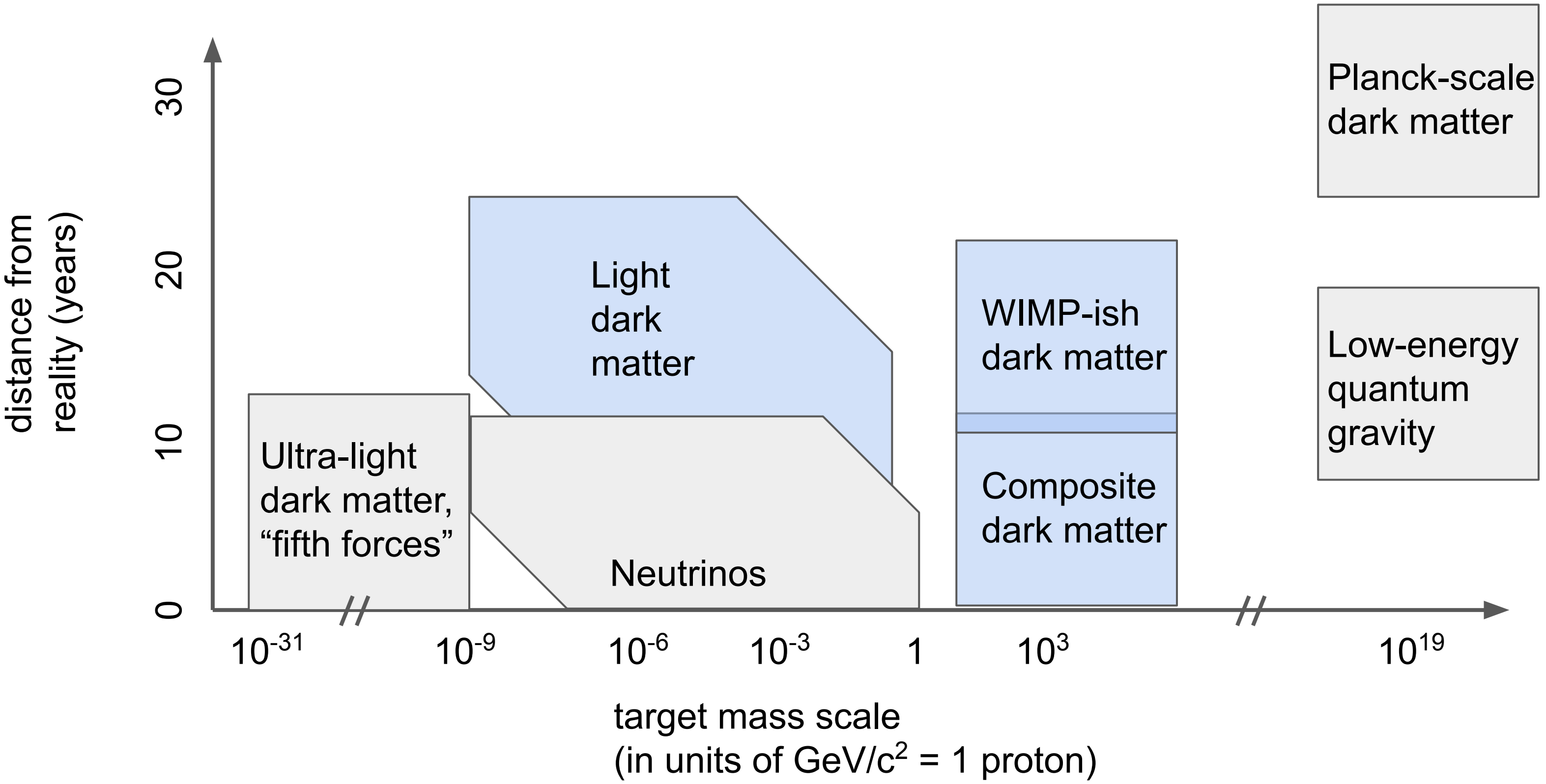
$$\mathcal{L}_{int} = g_{B-L} \not{A} \bar{n} n \longrightarrow F = g_{B-L} N_n F_0 \sin(\omega_s t)$$

For comparison, LISA pathfinder had ~10^{-3} pg/rtHz. With N sensors, get full sqrt(N) noise reduction here.





1512.06165 Graham, Kaplan, Mardon, Rajendran, Terrano
1908.04797 Carney, Hook, Liu, Taylor, Zhao
2203.14915 Safronova, Singh + many (review)



Planck-scale dark matter
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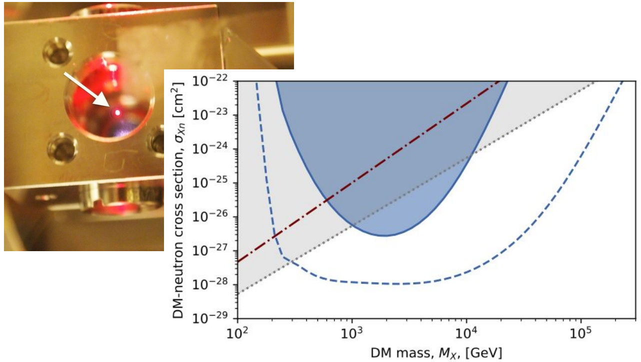
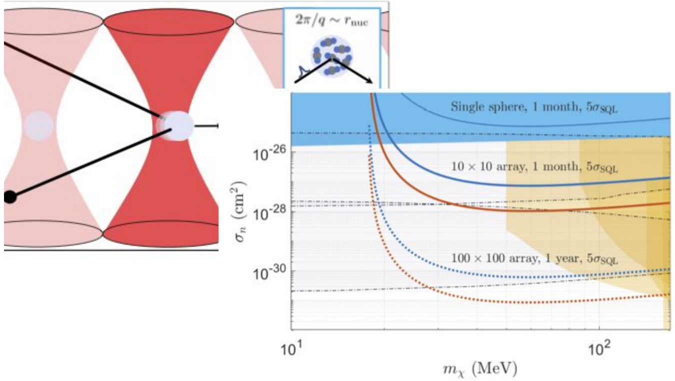
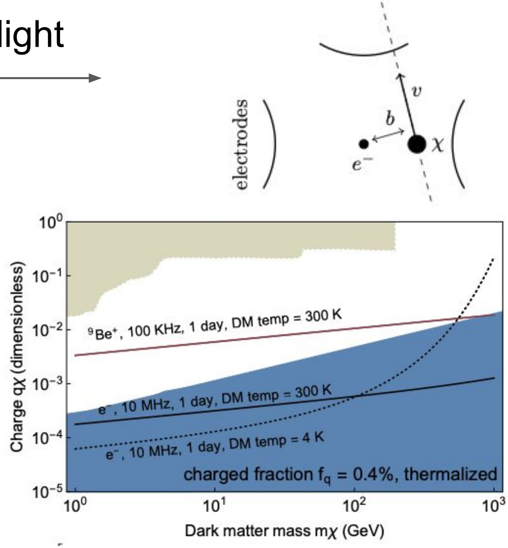
target mass scale
(in units of GeV/c^2 = 1 proton)

Impulses at various mass scales

detector mass — heavy → light







Composite DM coupled through long-range force [experiment]

~ug-scale levitated sphere

Monteiro, Afek, Carney, Krnjaic, Wang, Moore PRL 2020

Coherent elastic DM scattering at ~100 MeV mass [proposal]

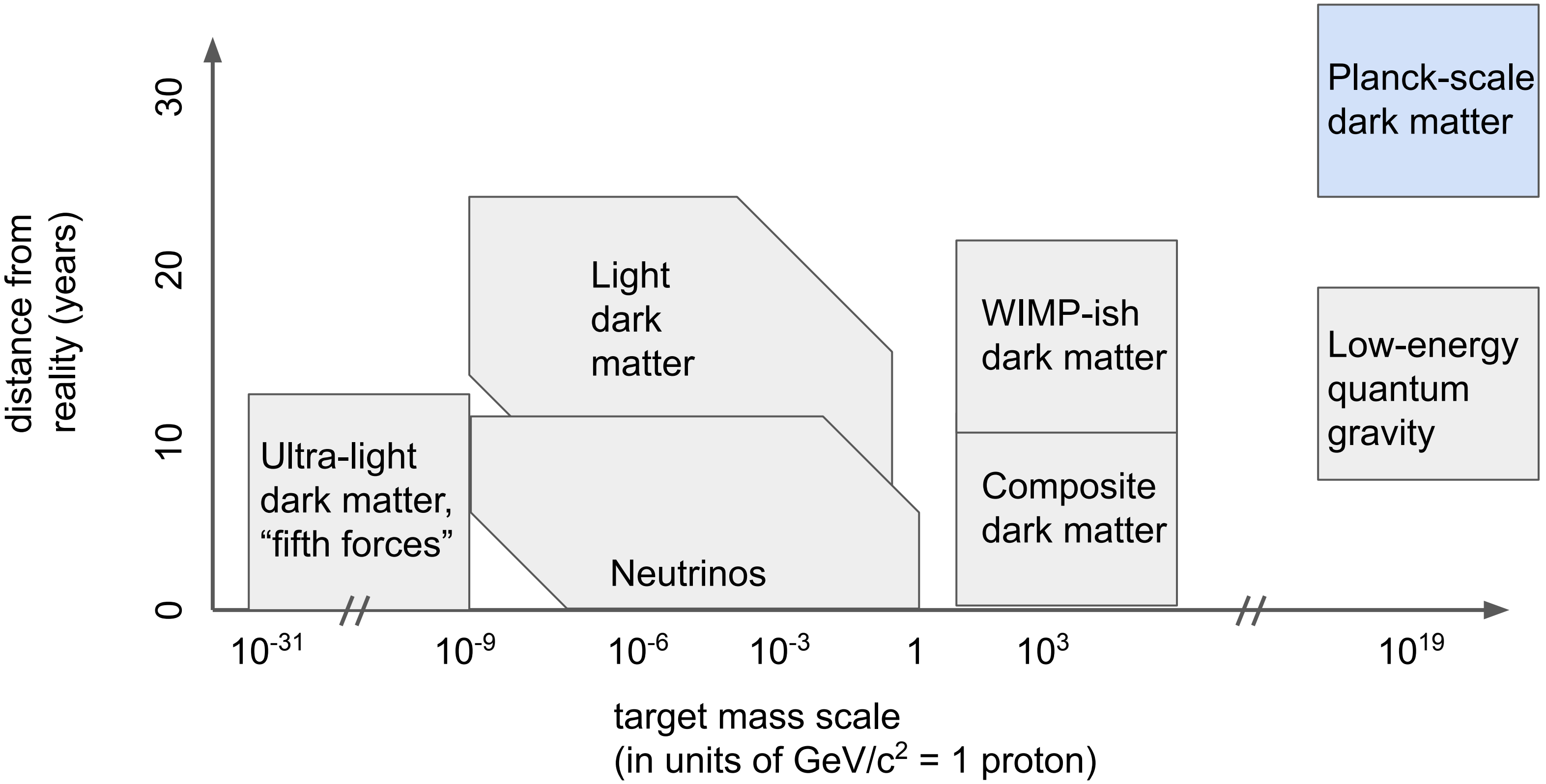
~ng-scale levitated sphere

Afek, Carney, Moore PRL 2022

Rutherford scattering with milli-charged DM [proposal]

single trapped ion/electron

Carney, Haffner, Moore, Taylor PRL 2021



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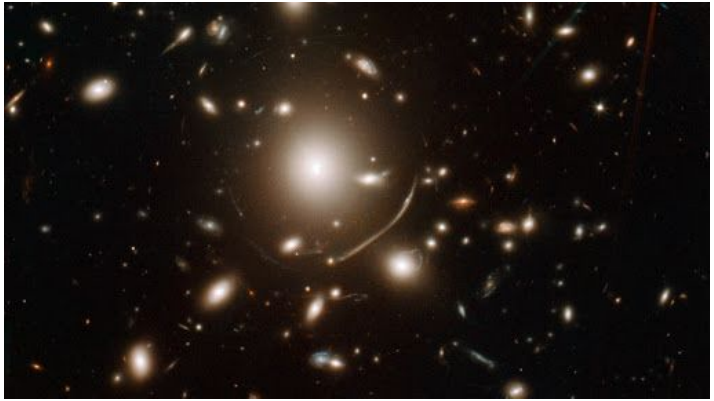
10^{-31}
10^{-9}
10^{-6}
10^{-3}
1
10^{3}
10^{19}
target mass scale
(in units of GeV/c^2 = 1 proton)

Assuming dark matter exists in the first place (!), the *only coupling it is guaranteed to have to visible matter* is through gravity.

Local dark matter density ~ one proton mass per cm^3. Hopeless to try to detect it through this gravitational force in a local lab. Right?

Extremely hard, but maybe possible...

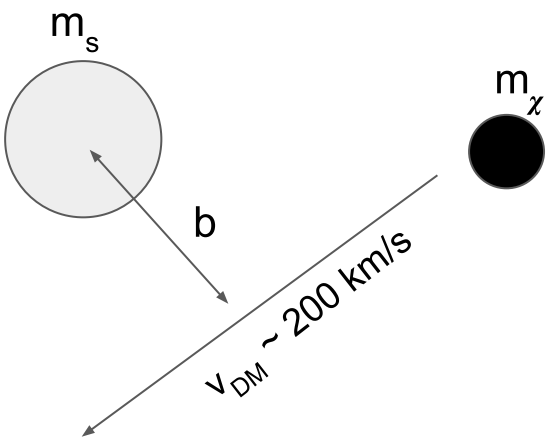


1605.01103 Hall, Callister, Frolov, Muller, Pospelov, Adhikari
1809.00968 Kawasaki
1903.00492 Carney, Ghosh, Krnjaic, Taylor

The basic idea

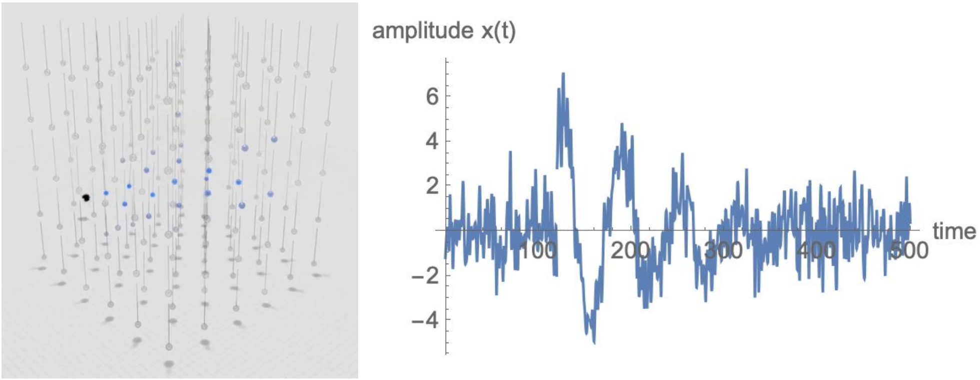
$$F = \frac{G_N m_s m_\chi}{r^2}$$

→ want heavy DM, small impact parameter, very good force sensor



$$R = \frac{\rho_\chi v A_d}{m_\chi} \sim \frac{1}{\text{year}} \left(\frac{m_{\rm Pl}}{m_\chi}\right) \left(\frac{A_d}{1\,\text{m}^2}\right)$$

→ want large area



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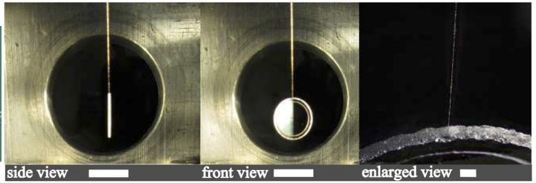

Featured in Physics

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

nature

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Article | Published: 10 March 2021

Measurement of gravitational coupling between millimetre-sized masses

Tobias Westphal, Hans Hepach, Jeremias Pfaff & Markus Aspelmeyer

Nature **591**, 225–228 (2021) | Cite this article

19k Accesses | **18** Citations | **673** Altmetric | Metrics

$F_{grav} = G_N \, m^2/d^2 \sim 10^{-17}$ N

Note the conversion factor $m_{planck} = 0.02$ mg

Our problem is harder: 200 km/s DM velocity → only have ~ns-us time to integrate the signal

SNR at thermal noise level

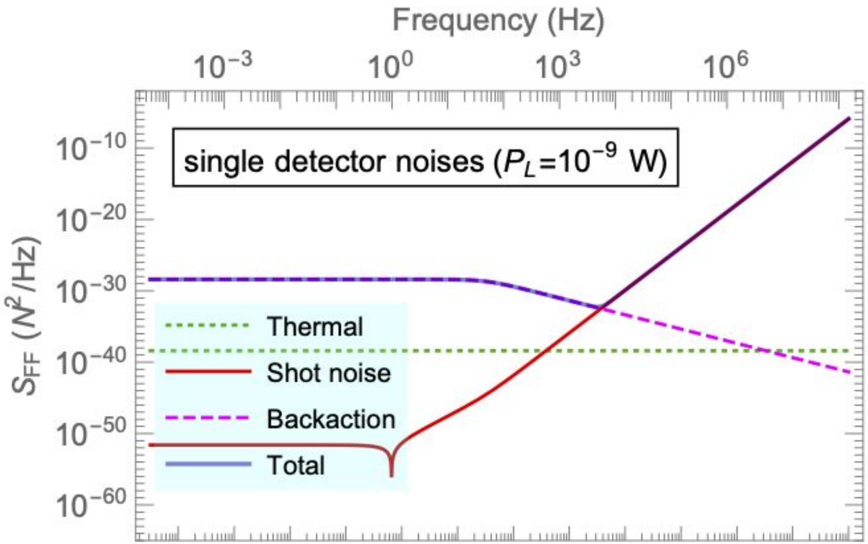
If thermal noise dominates:

$$\mathrm{SNR}_{\mathrm{thermal}} = \frac{G_N m_\chi m_s / bv}{\sqrt{(4 m_s k_B T \omega / Q)(b/v)}}$$
$$\approx 0.5 \times \left(\frac{m_\chi}{1\ \mathrm{mg}}\right) \left(\frac{m_s}{1\ \mathrm{mg}}\right)^{1/2} \left(\frac{1\ \mathrm{mm}}{b}\right)^{3/2}$$

→ **Gravitational detection is possible if we can get to thermal noise floor**

But currently: quantum measurement noise >> thermal.

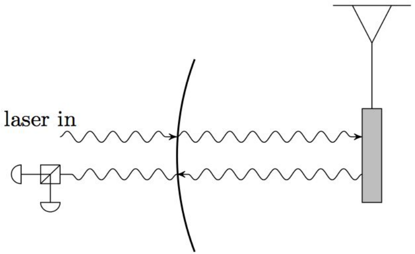
→ **Need to reduce the quantum noise**



Sensor m = 1 mg, frequency = 1 Hz, in dil fridge

1903.00492 Carney, Ghosh, Krnjaic, Taylor

Quantum mechanics and measurement



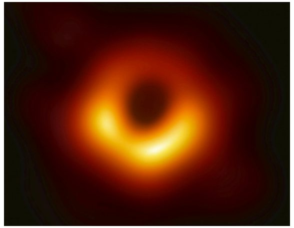
Gravitational DM detection appears to require measurements well beyond the “standard quantum limit”. Is this really possible?

It is not possible with any sensor we have now, and sufficiently scaling/tweaking any current sensor does not look plausible.

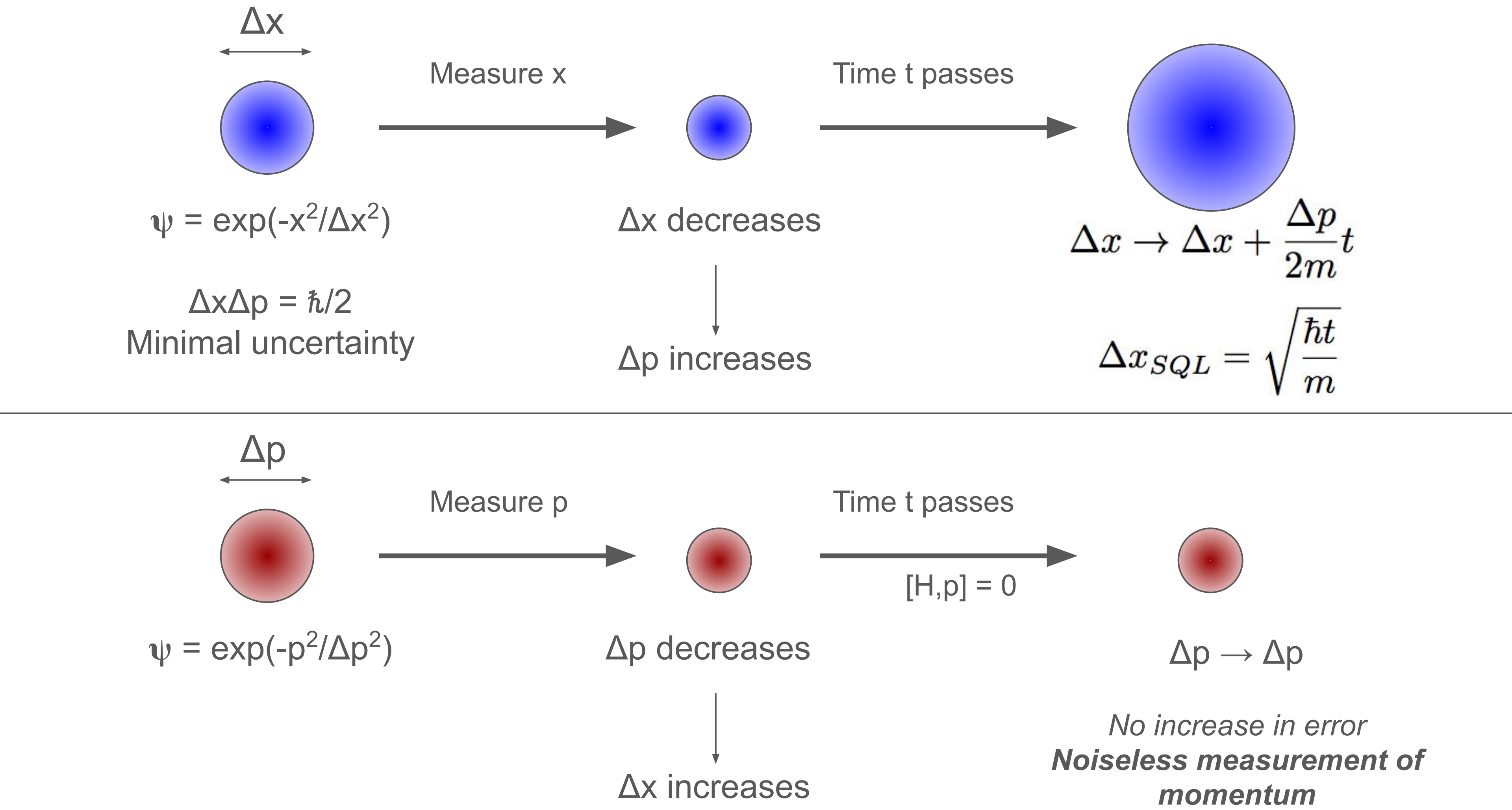
$\Delta x = 0 \rightarrow \Delta p = \infty$

But I think one should proceed without fear.

Quantum mechanics itself does not impose any limit to how precisely one can measure a system. The Caves argument given earlier can be evaded.



Ultimately, the only *fundamental* limit to what is possible in measurement will come from quantum gravity…



Δx
Measure x
Time t passes
$\psi = \exp(-x^2/\Delta x^2)$
Δx decreases
$\Delta x \to \Delta x + \frac{\Delta p}{2m} t$
$\Delta x \Delta p = \hbar/2$
Minimal uncertainty
Δp increases
$\Delta x_{SQL} = \sqrt{\frac{\hbar t}{m}}$
Δp
Measure p
Time t passes
$[H,p] = 0$
$\psi = \exp(-p^2/\Delta p^2)$
Δp decreases
$\Delta p \to \Delta p$
Δx increases
No increase in error
Noiseless measurement of momentum

Outlook

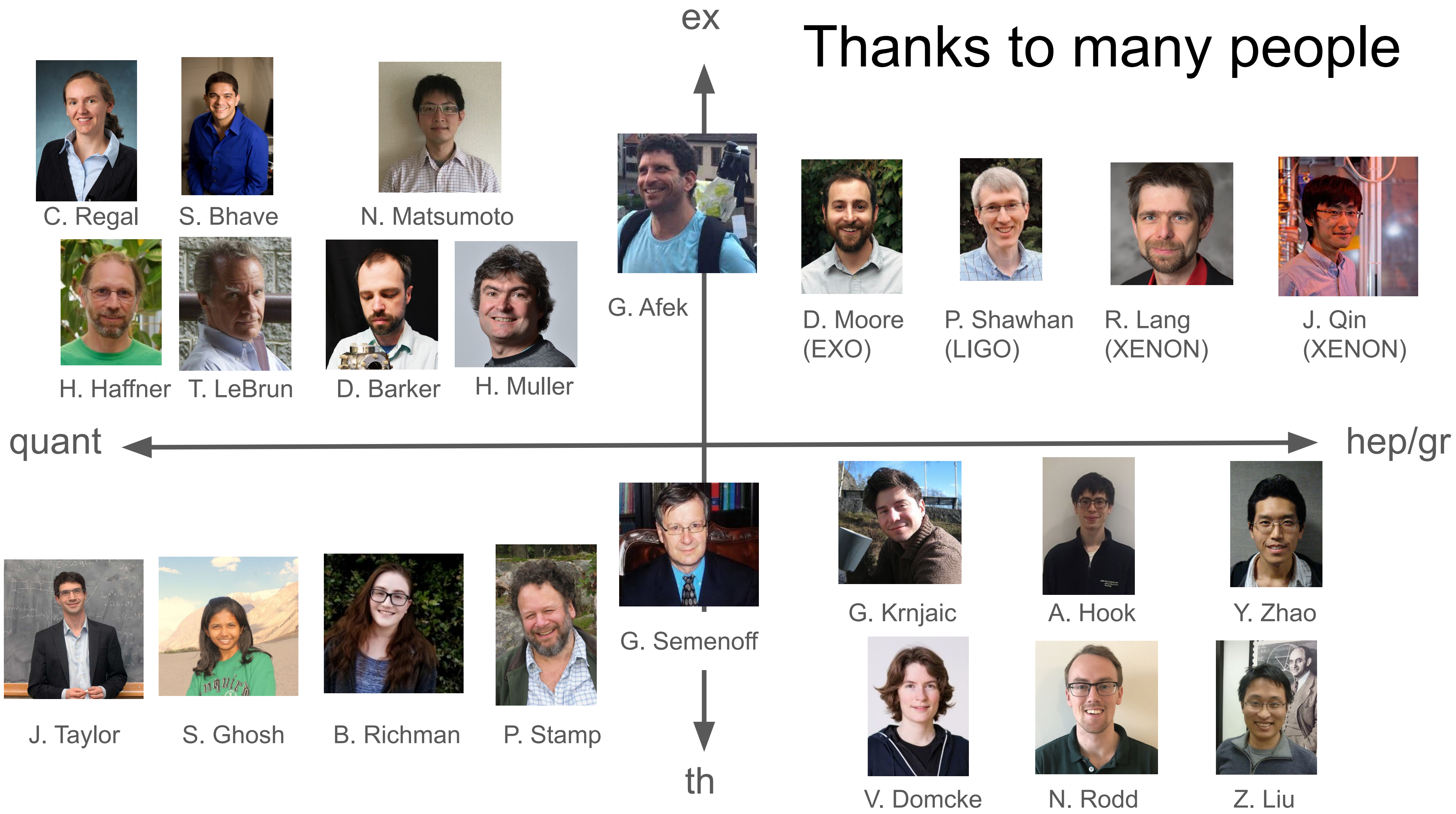
- Gravitational direct detection of Planck-scale DM appears to be possible, but extremely technically challenging

- **Key current research: impulse sensing protocols -- theory and experiment.**

- Between current experiments (~SQL level noise) and what we need (orders of magnitude below SQL), some clear physics targets have emerged: long-range coupled DM, light DM, neutrinos (2207.05883), ultralight DM, …

- At a high level, mechanical sensors are good whenever you want to look for a signal coherent across the size of the sensor. Any good ideas??

Thanks to many people



Backup slides

Quantum limits in impulse sensing

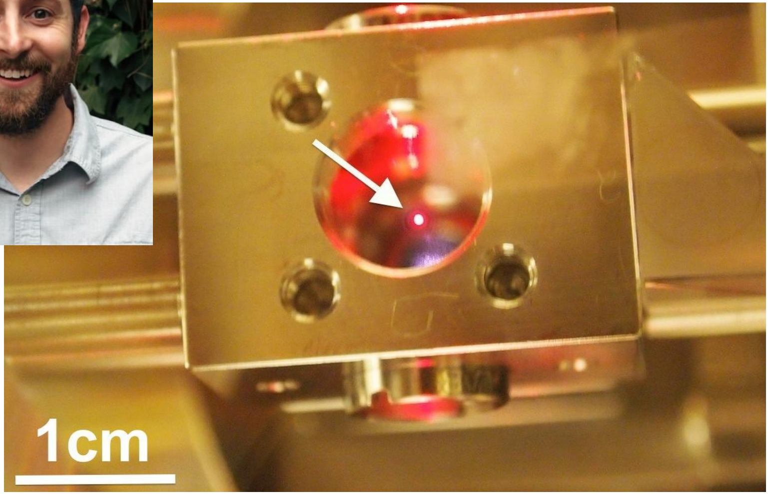
Similarly there's an SQL for impulses:

$$\Delta p_{SQL} = \sqrt{\hbar m_s \omega}$$ → ~ 600 keV (m = 1 ng, ω = 1 kHz)

Measurement at SQL means that you can resolve the motion of the sensor with error = sensor ground state wavefunction uncertainty.

Incredibly, we need to do at least 5 orders of magnitude better than this. Luckily, methods exist. Currently many sensors operate at SQL, a few operate ~10dB below. More on this in a few slides.

Yale experiments



Search for new Interactions in a Microsphere Precision Levitation Experiment (SIMPLE) @ D. Moore group

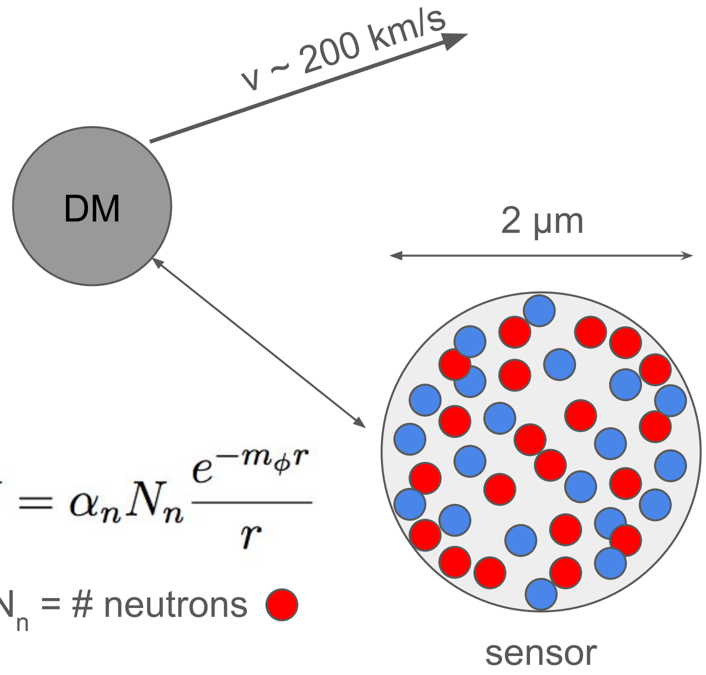
0.1-10 ng dielectric spheres

Optically levitated, stability ~ days

Continuous (biaxial) position monitoring at ~10x SQL level

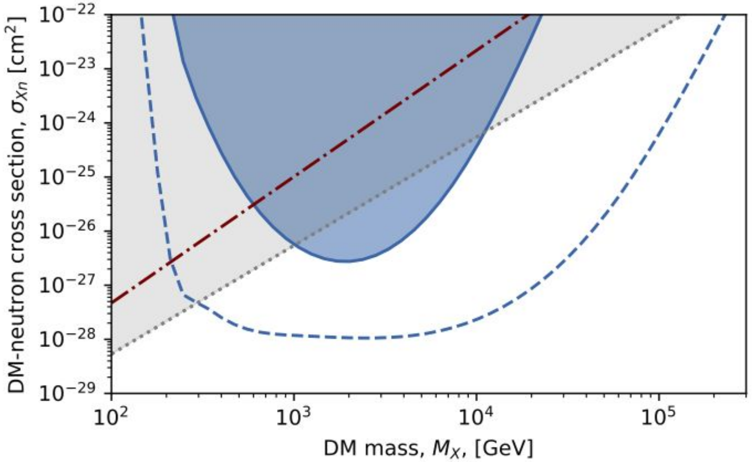
Monitor this sphere for jumps in its motion. If it doesn't jump more than a few times then we can rule out DM models that would have caused jumps.

Composite DM with light mediator



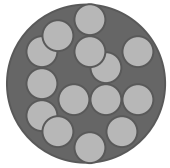
$$V = \alpha_n N_n \frac{e^{-m_\phi r}}{r}$$

N_n = # neutrons



One possible microscopic realization, “dark quark nuggets” coupled through B-L

Lin, Yu, Zurek 1111.0293
Krnjaic, Sigurdson 1406.1171



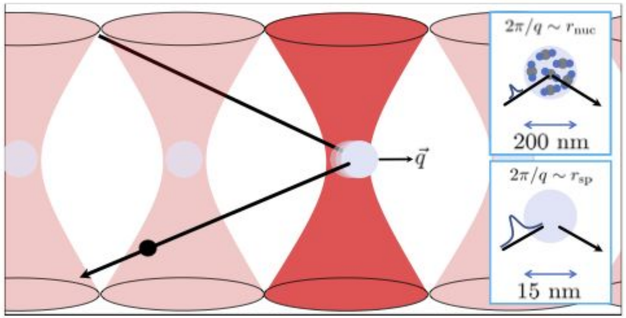
$$\alpha_n \to g_n g_d N_d$$

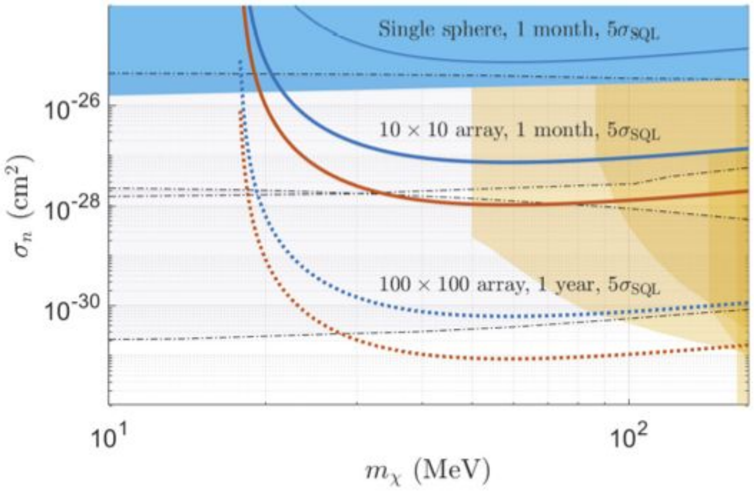
Nanospheres

What can you do with spheres ~ 1000 times smaller? (~10 nm)

Look for lighter dark matter!

In fact you can look for fundamental (non-composite) DM at this scale. It can scatter quantum-coherently off the sphere.





Proposal: Afek, Carney, Moore PRL 2022

Single ions… or electrons?

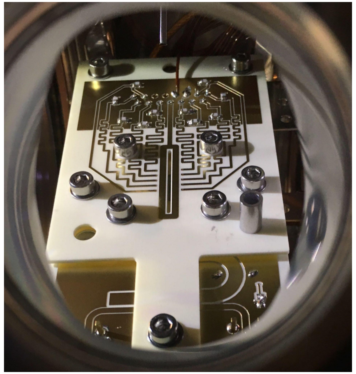
What's the ultimate limit of this idea, in terms of shrinking the sensor?

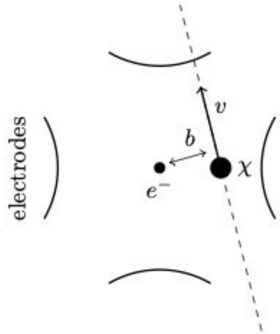
Using a single atom or electron!

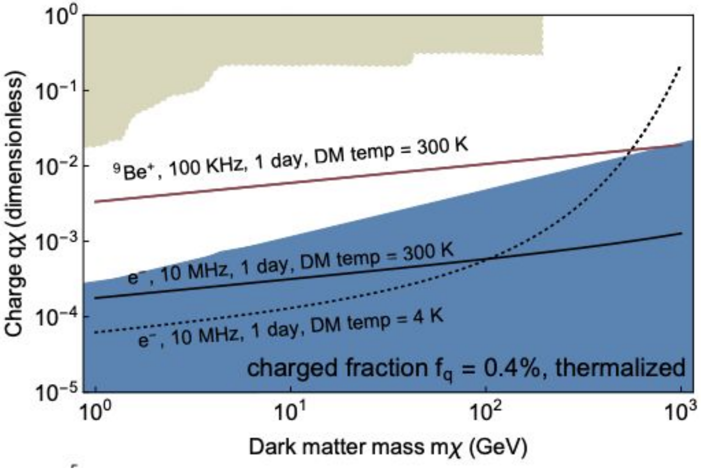
Can search for DM if it has tiny electric charge (~1/1000th the charge of electron).

Current detectors are totally insensitive to this regime

Carney, Haffner, Moore, Taylor PRL 2021







Matched filtering and SNR

Process the raw data via filter (cf. LIGO matching to waveform). For observable, use total impulse, filtered appropriately:

$$O(t_e) = \int f(t_e - t')F(t')dt'$$

Known signal shape (e.g. $F=1/r^2$) and known noise power spectral density N, maximize SNR

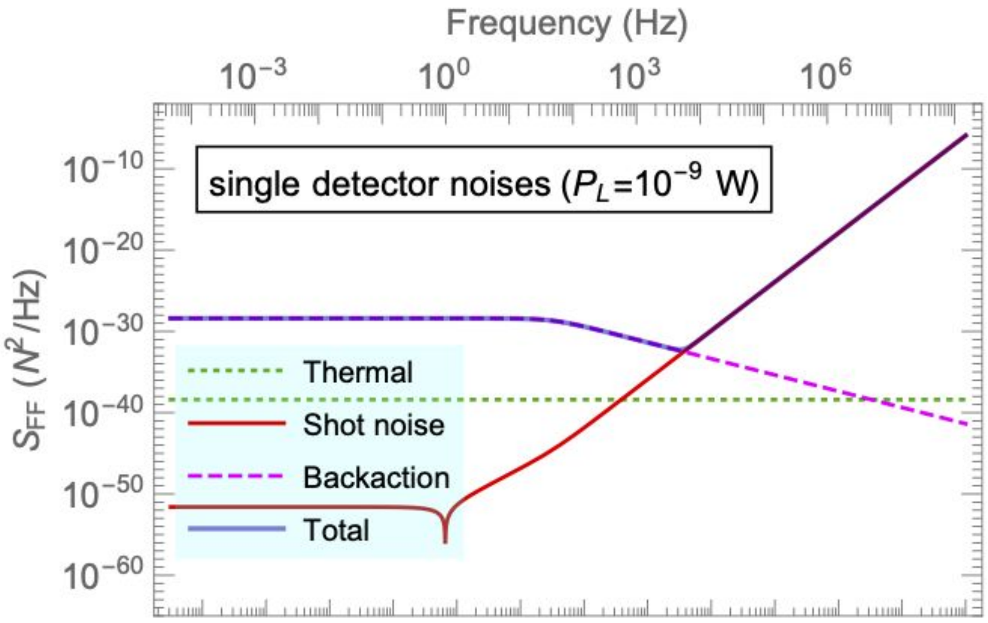
$$f_{\text{opt}}(\nu) = \frac{F_{\text{sig}}(\nu)}{N(\nu)}$$

$$\text{SNR}^2_{\text{opt}} = \int_0^\infty \frac{|F_{\text{sig}}(\nu)|^2}{N(\nu)} d\nu$$

Limits on the noise

If we're looking for a signal with known shape (e.g. $F = Gm^2/r^2$), the best SNR possible is given by

$$\mathrm{SNR} = \sqrt{\int d\nu \frac{|F_s(\nu)|^2}{S_{FF}(\nu)}}$$



For impulses here:

$F_s(\nu)$~ flat up to $1/t_{flyby}$ = v/b ~ 1 MHz - 1 GHz