Windchime

Gravitational Detection of Dark Matter with Mechanical Sensors

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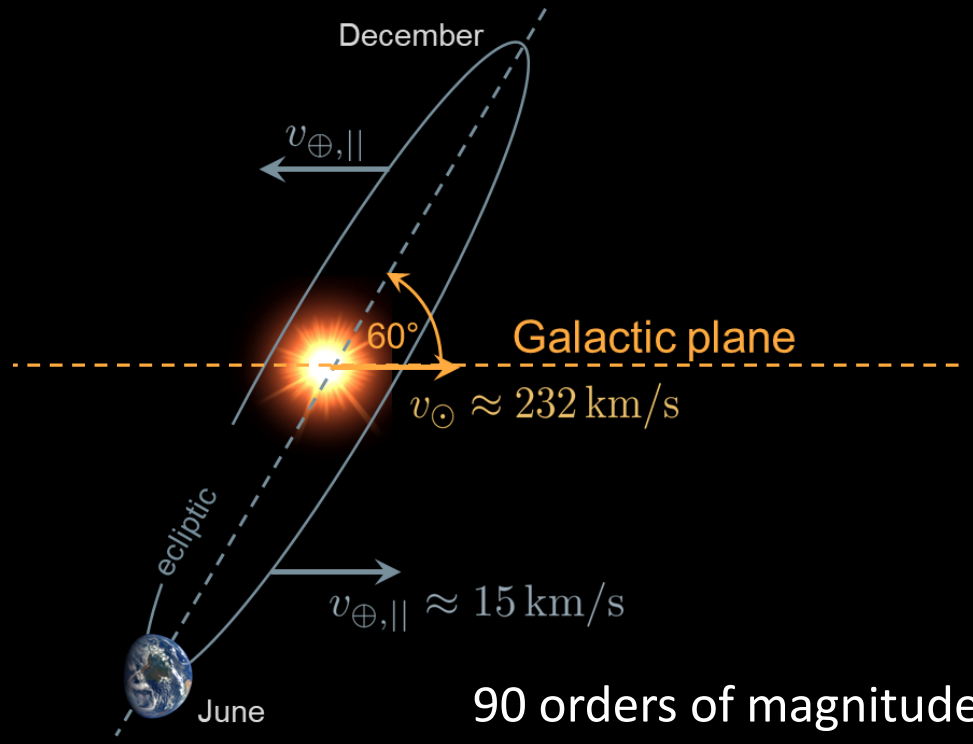
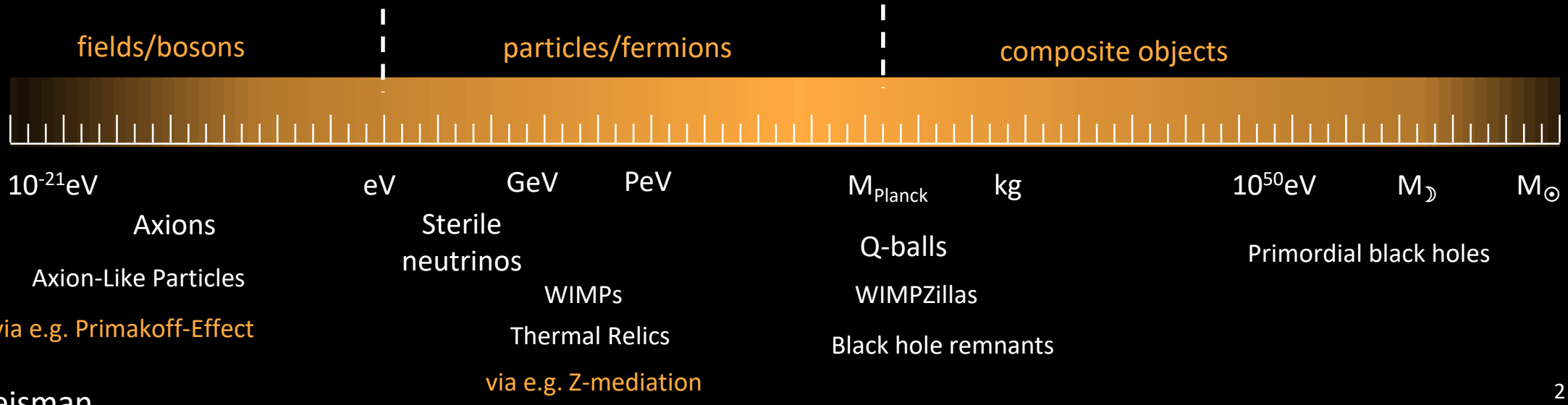
Dark Matter Wind



$0.3\ \frac{\mathrm{GeV}}{\mathrm{cm}^3}$

local dark matter density (SHM)

90 orders of magnitude of dark matter mass to search



Gravitational direct detection at M_{Planck}

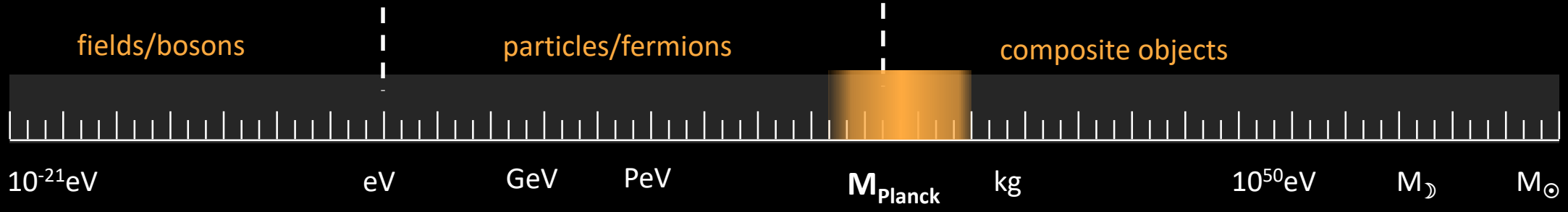
- Gravitational coupling is the **only** guaranteed interaction channel for DM!
- 3D array of optomechanical accelerometers - tracks

Gravitational force of DM:

$\sim m_\chi m_{sensor}$

Accessible DM flux limited by ρ_{DM}:

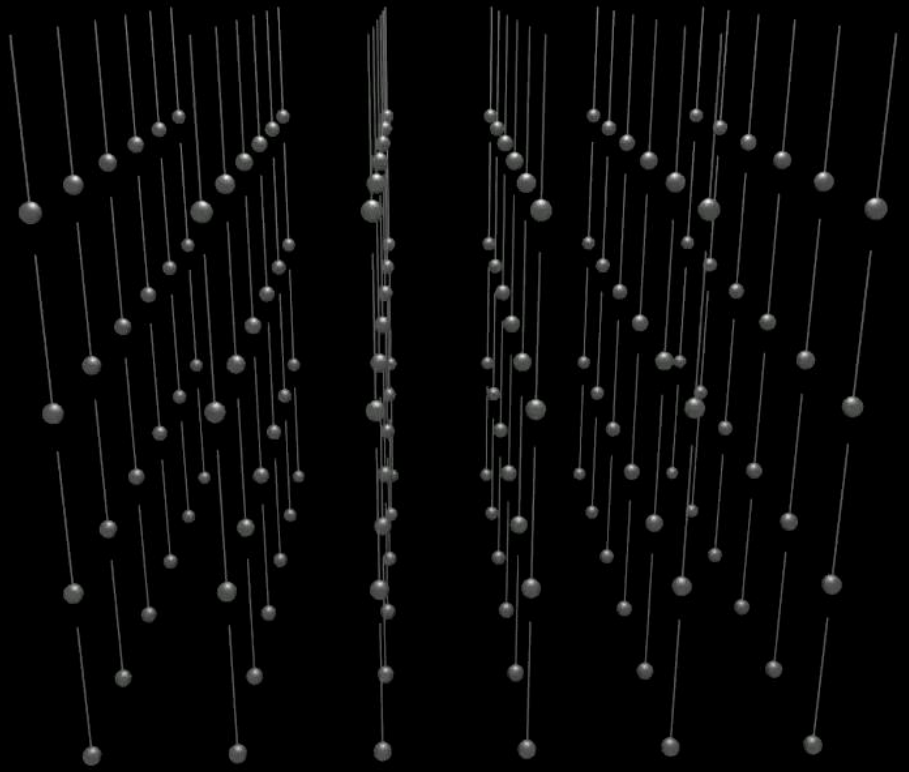
$\sim \text{area}/m_\chi$

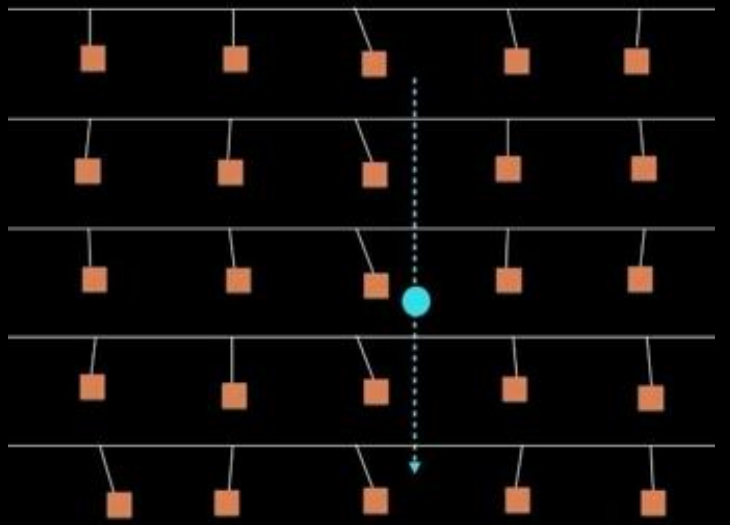


Carney et al. 1903.00492
Ghosh et al. 1910.11892

Well-motivated mass range:
PBH relics, WIMPZillas, Q-balls.

Windchime: Accelerometer Array for DM





Large sensor array

- enhanced SNR
- background rejection
- directional

Quantum enhancement

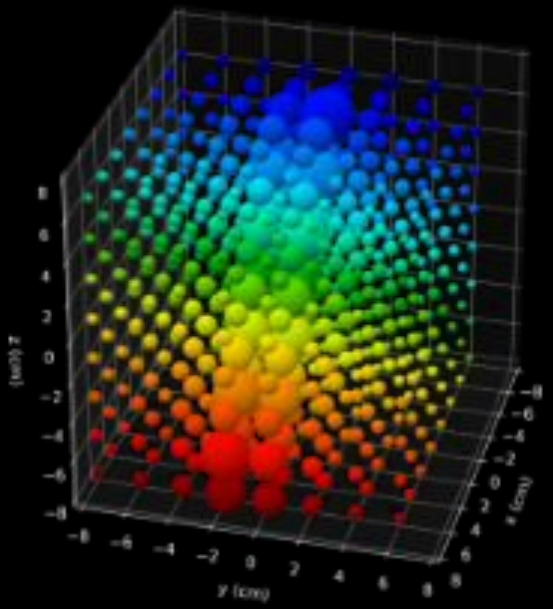
- read out below SQL
- Thermal noise limited sensitivity

Paths to DM detection

Windchime

Computing/Simulation

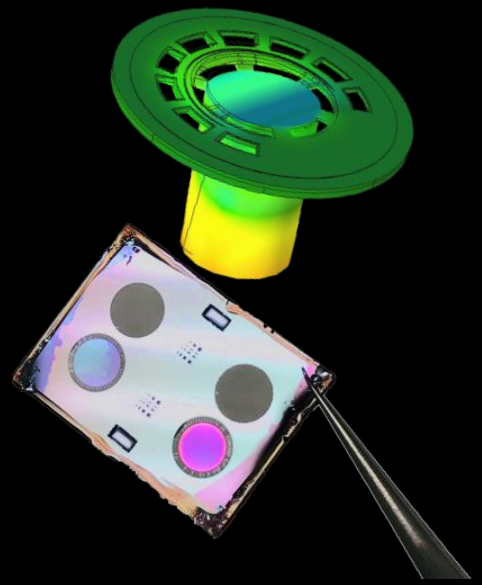
Track finding w/ large datasets



Scale up sensor array

10^9 sensors

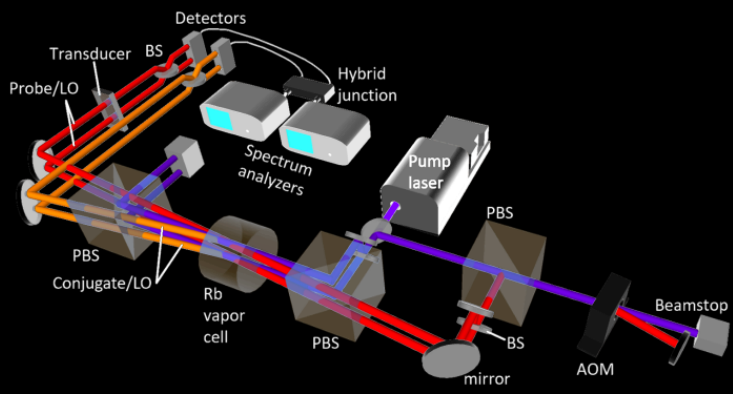
SNR ~ $\sqrt{N}$



Quantum noise suppression

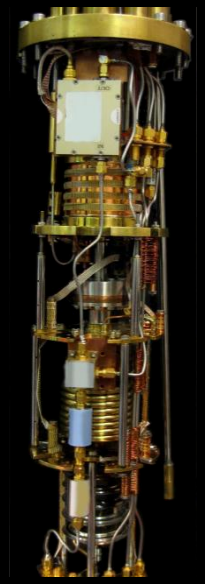
30 dB below SQL

Squeezing + back-action evasion

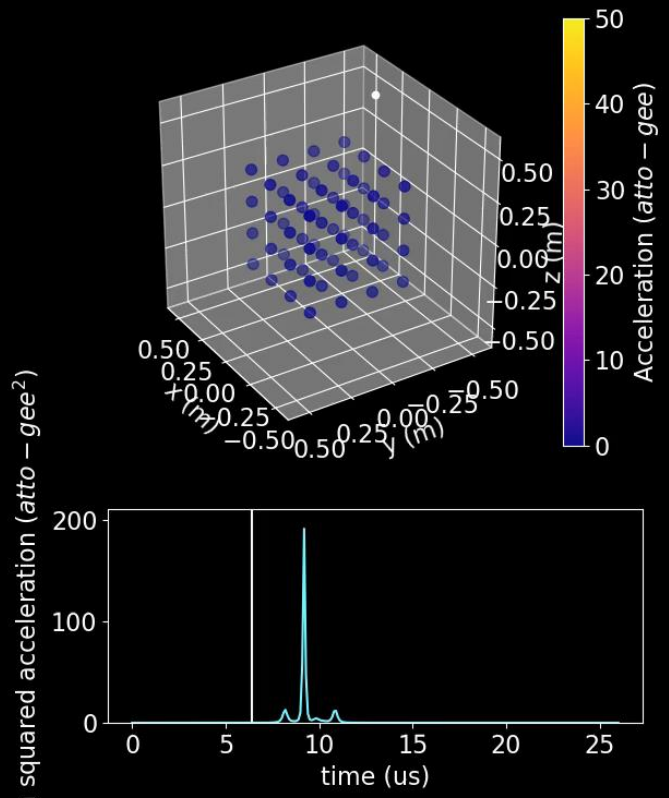


Environmental isolation

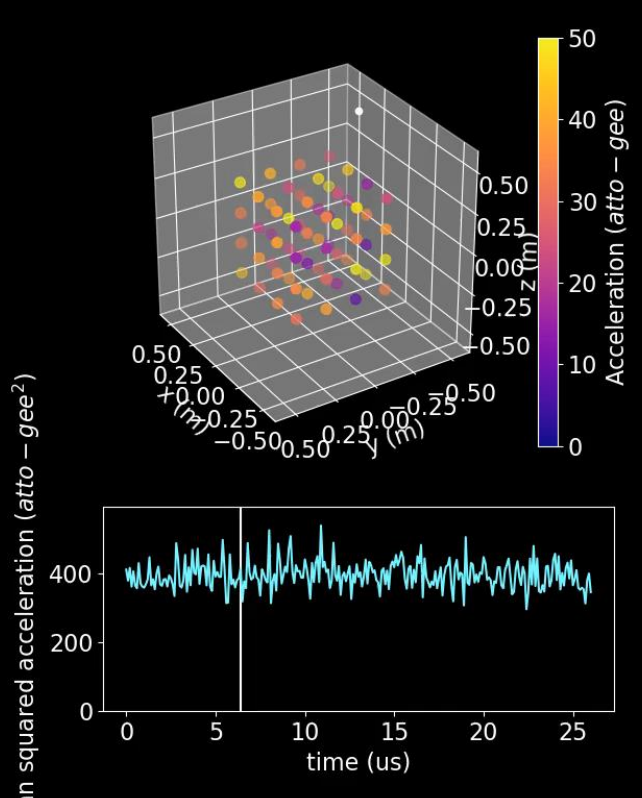
Vacuum and low temperatures



Simulation: tracks in sensor array



Without noise



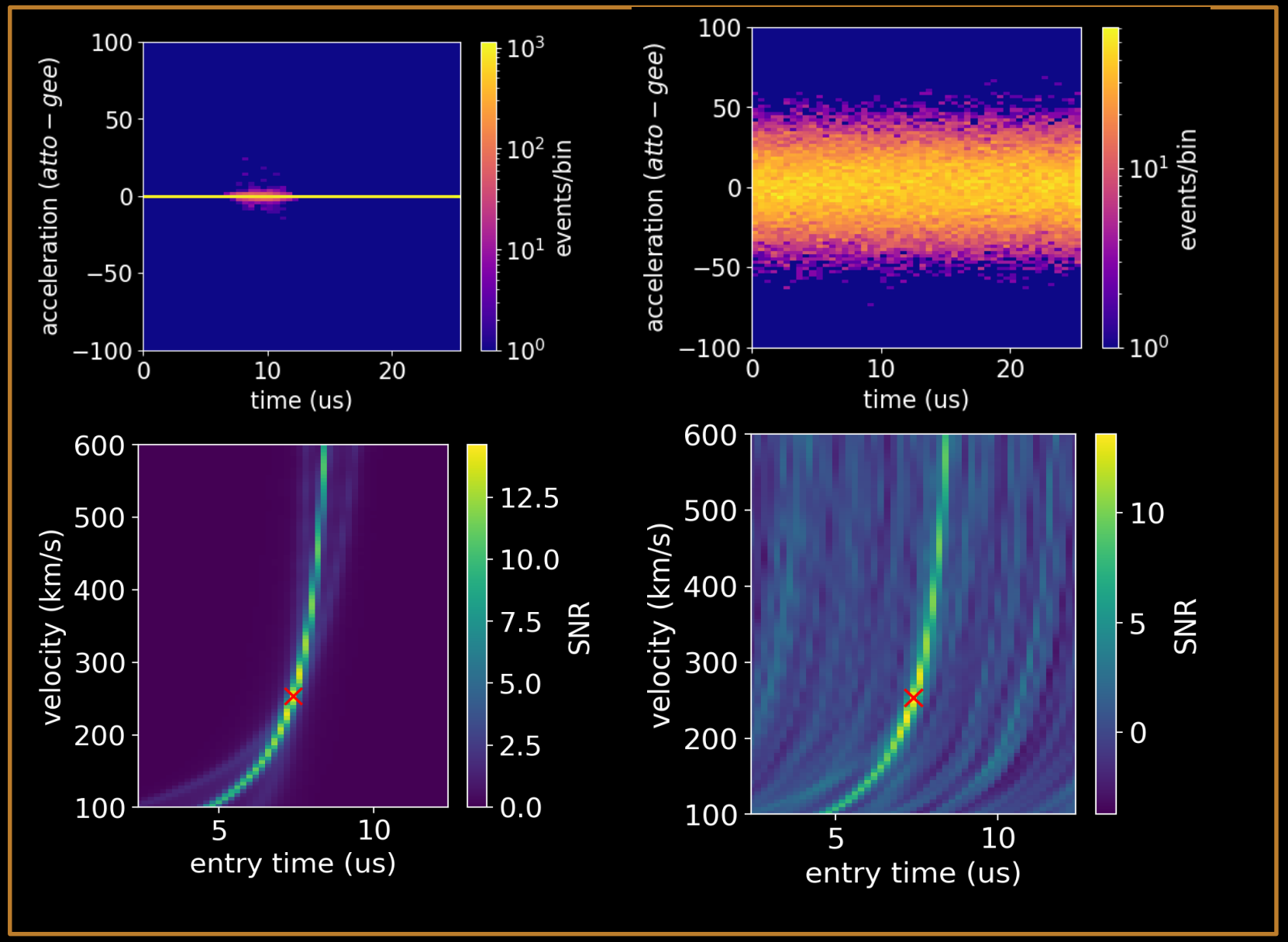
With noise

- 4x4x4 array of accelerometers sampled at 10MHz
- Signal: Planck mass DM particle across the detector
- Noise: ~10^{-22} G/root-Hz

Analysis: recovering signal

Raw Data

Template matching



Without Noise

With Noise

- 6-parameter track
  - Template matching
  - SNR / likelihood
  - Correlation
- Trial factor analysis
- Sensitivity projection

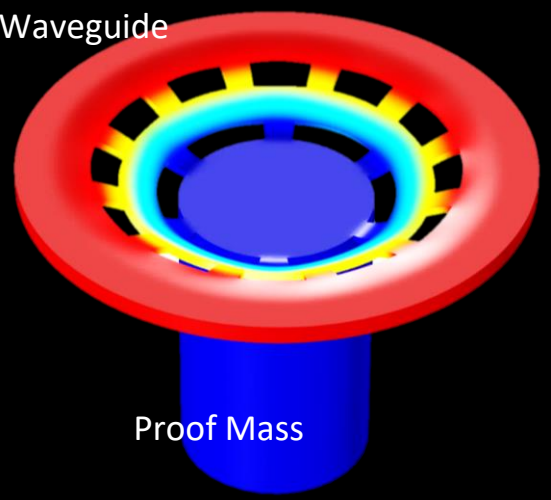
Sensor Development

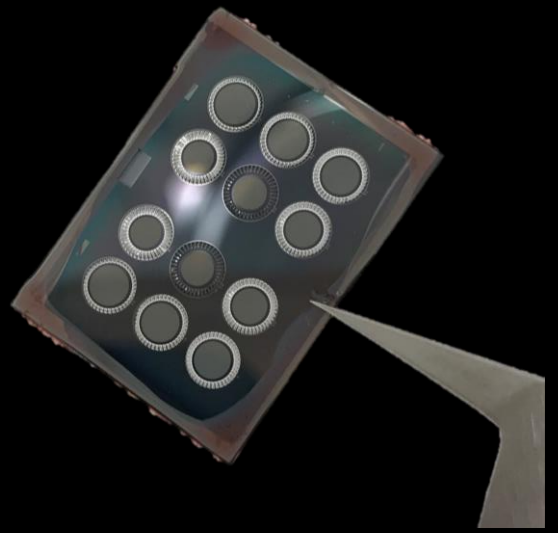
MEMS accelerometer

- ~ 10mg bulk silicon with soft tethers
- Low noise $< 1\ \mu g/\sqrt{Hz}$

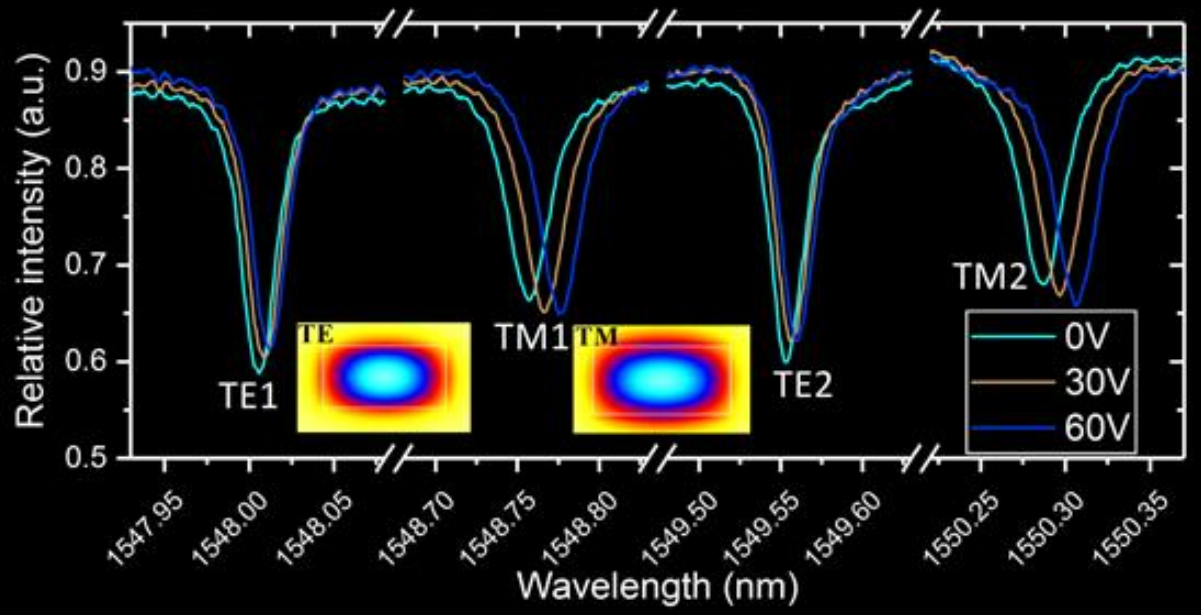
Redundant read-out:

- piezo-electrics
- free-space interferometry
- on-chip photonics





Tunable optical resonance



Dong et al. 1903.08479

Quantum Noise suppression

Thermal noise limit SNR:

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

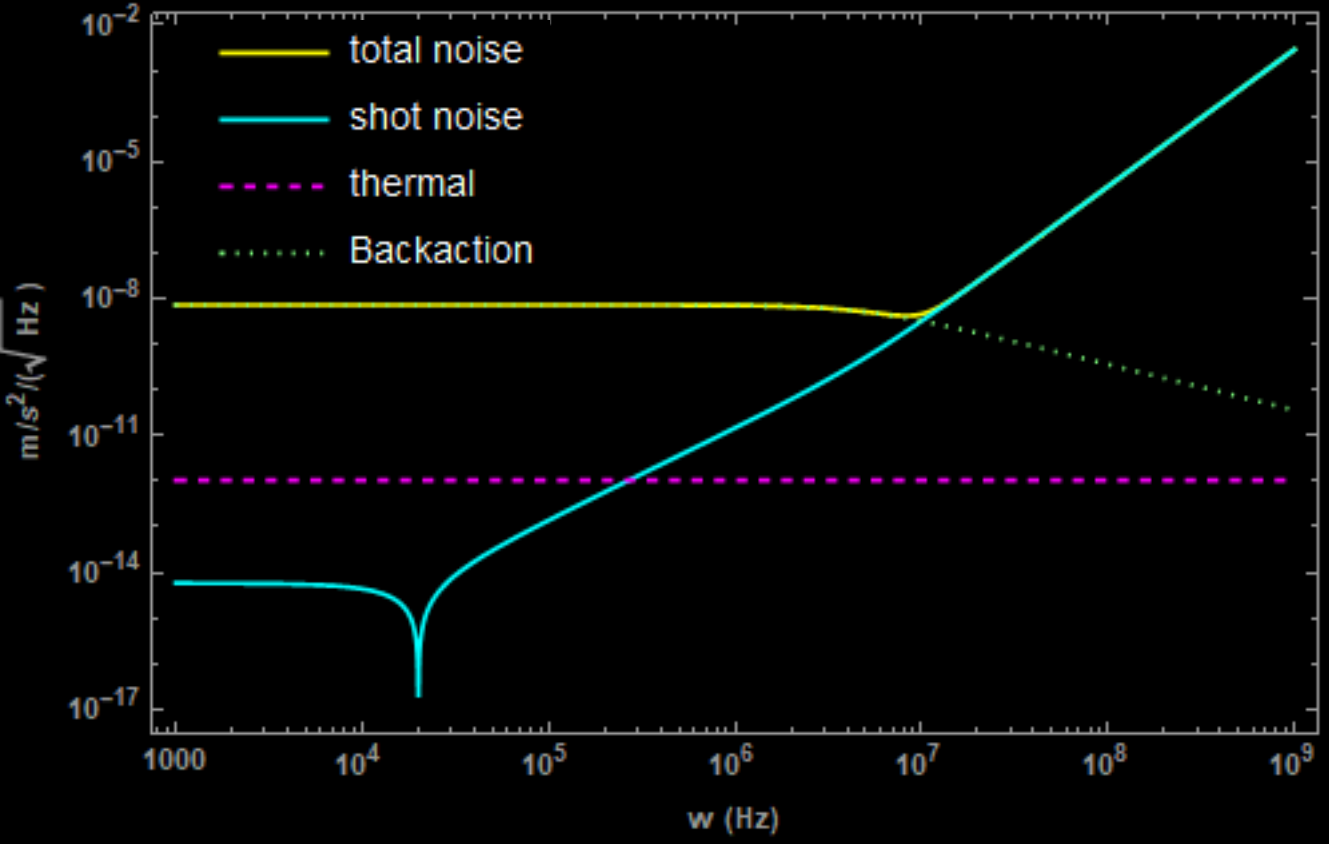
Carney et al. 1903.00492

Measurement noise about 30dB above thermal noise

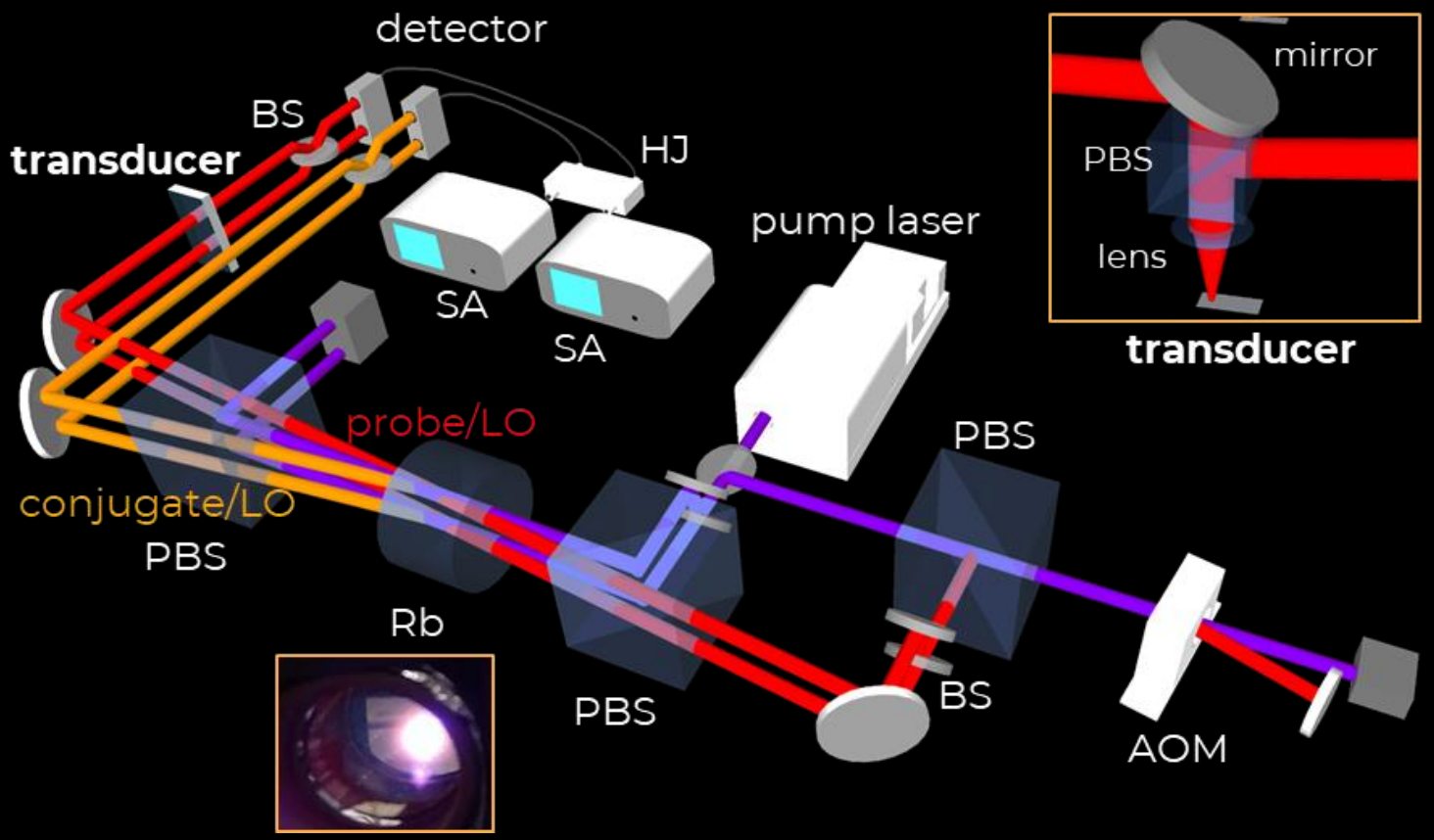
Reduce measurement noise below SQL

- Squeezed light
- Back-action evasion

Noise at standard quantum limit:

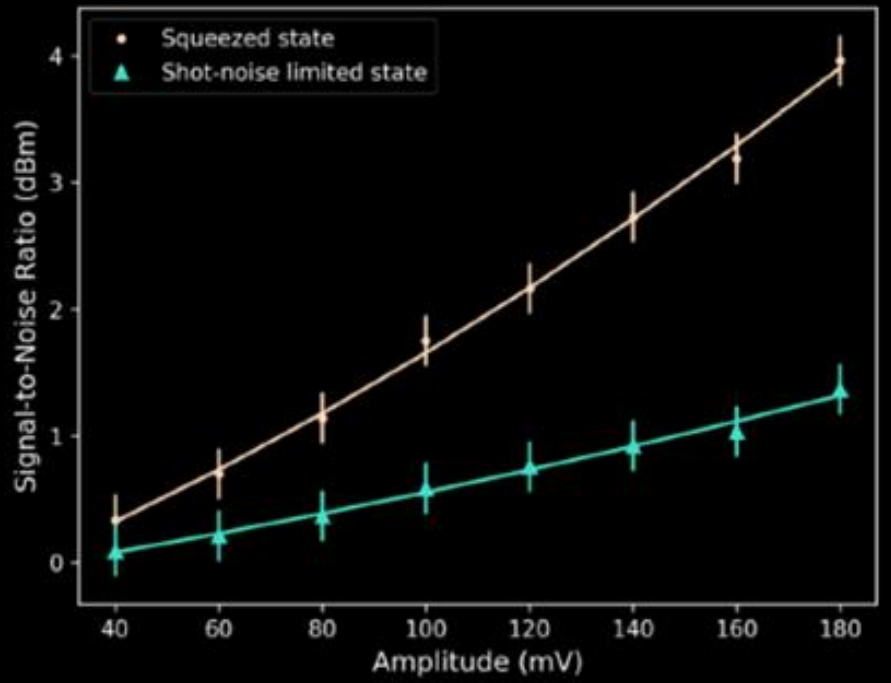


Quantum Noise suppression: Squeezed light



Non-Linear Interferometer uses four wave mixing in Rb cell

beams entangled in amplitude and phase exhibit squeezing

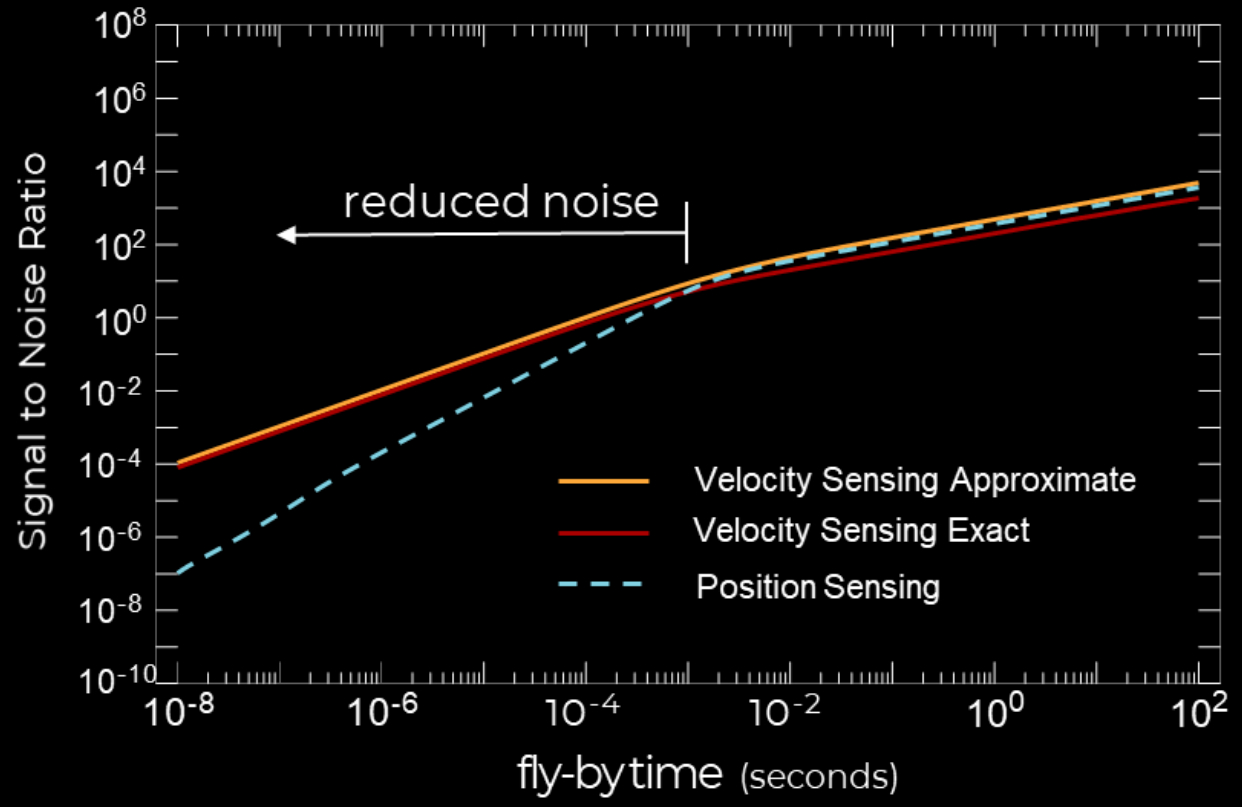


Pooser et al. 1912.10550

Transduce displacement in AFM cantilever/MEMS to phase of opt wave functions

3dB of noise reduction demonstrated

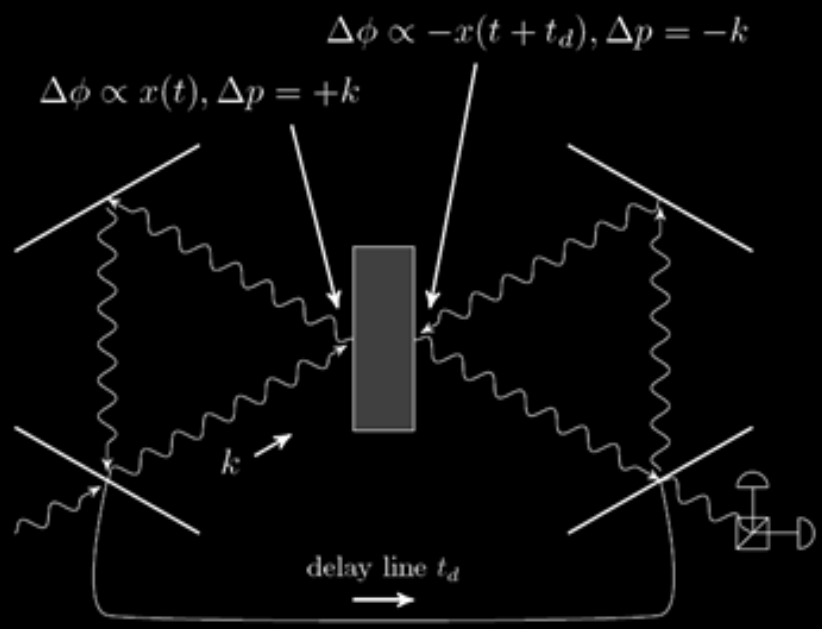
Quantum Noise suppression: back action evasion



Ghosh et al. 1910.11892

Double-ring cavity

$\Delta p_{mirror} \approx 0$

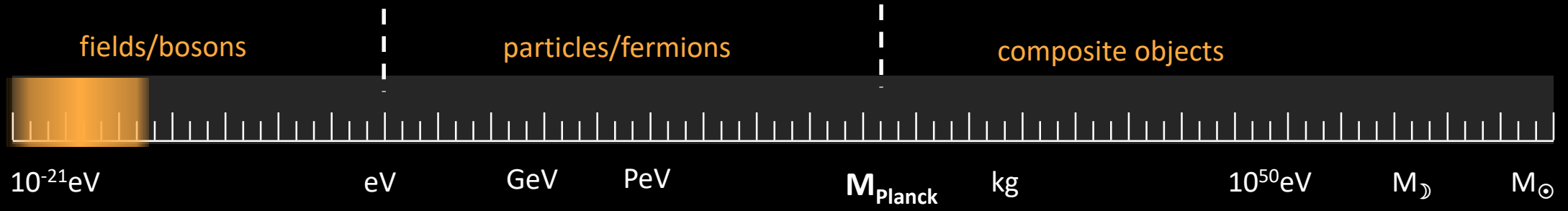


Momentum sensing protocol

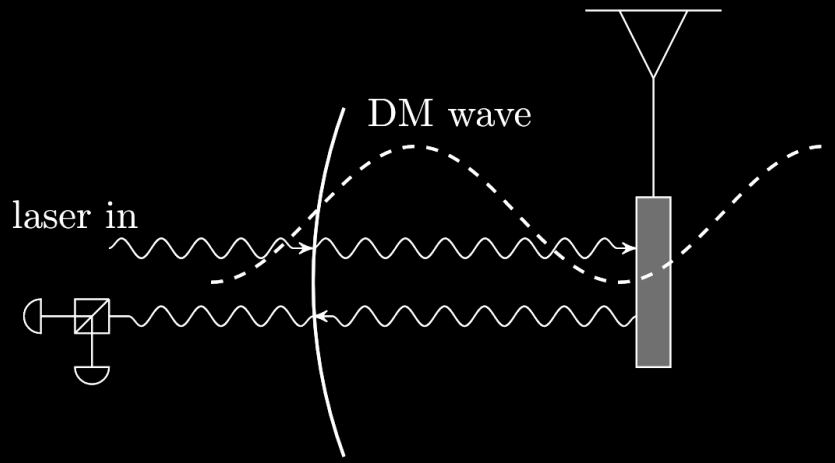
- Resonator velocity coupled to phase of light

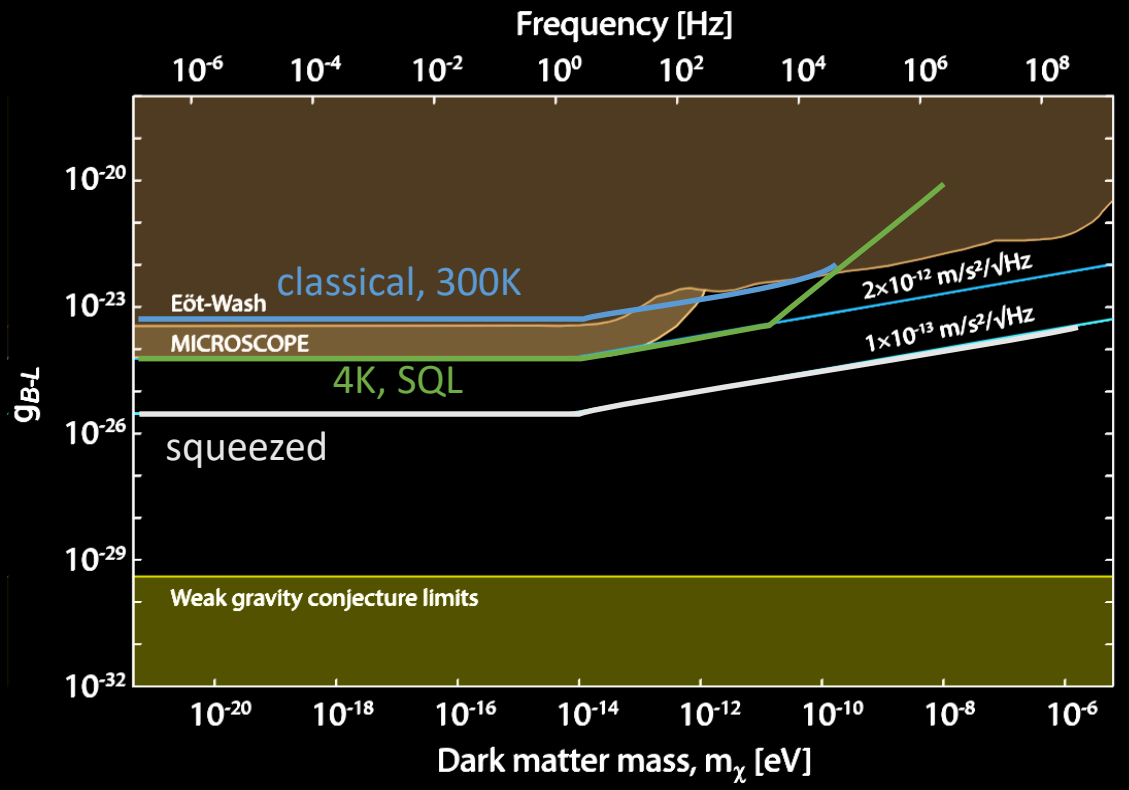
Evan Weisman

Near term: Ultralight DM detection



- Dark matter coupled to neutron (B-L charge)
- Consistent oscillating force on sensor array



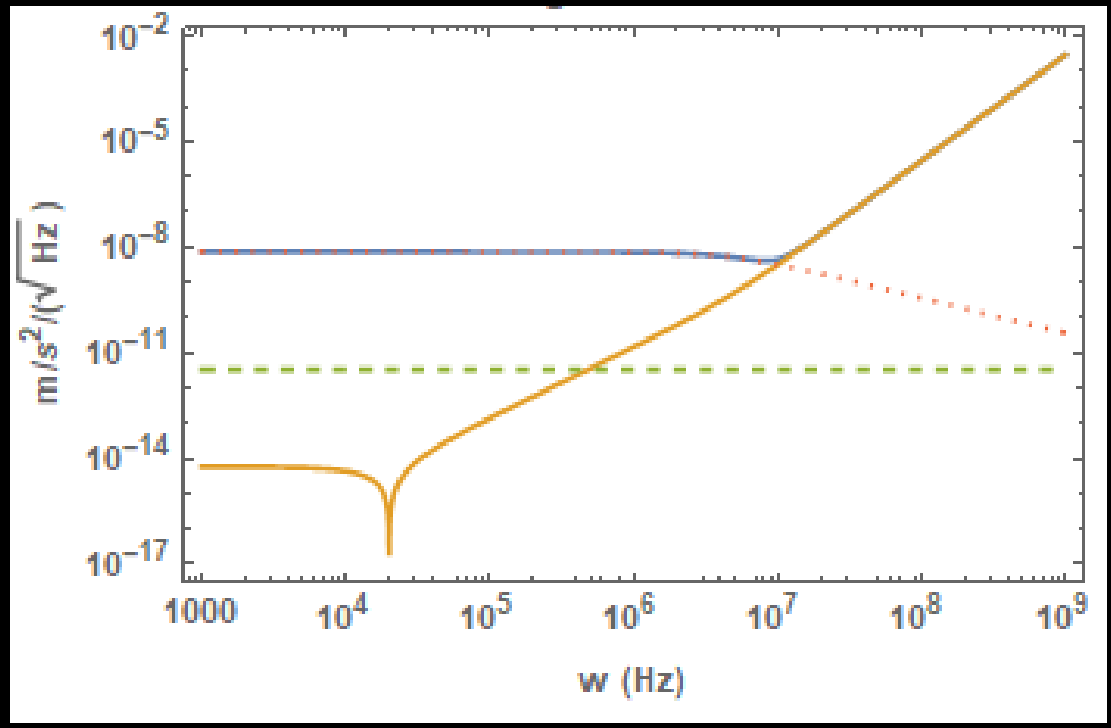


Carney et al. 1908.04797

Conclusion

Windchime aims to gravitationally detect Planck mass dark matter

- Massive optomechanical sensor array, also sensitive to ultra-light DM
- Simulation and analysis framework to find tracks in noise
- Squeezing and back-action evasion to get below SQL


10^{-2}
10^{-5}
10^{-8}
10^{-11}
10^{-14}
10^{-17}
$m/s^2/(\sqrt{Hz})$
1000
10^4
10^5
10^6
10^7
10^8
10^9
w (Hz)