

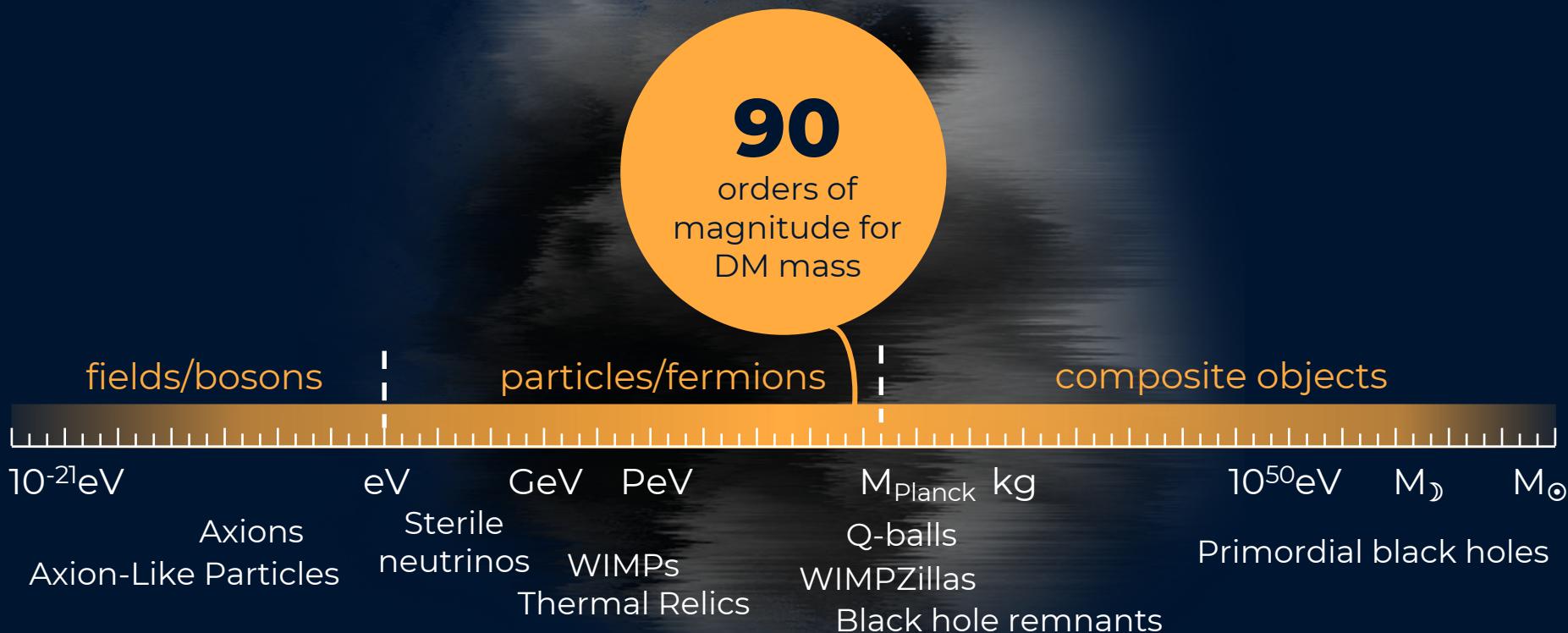
WINDCHIME

Towards the Gravitational
Detection of Dark Matter

Shengchao Li
lishengchao@westlake.edu.cn



Where is Dark Matter?



Assumptions:

via e.g. Primakoff-Effect

via e.g. Z-mediation

Want: gravitational only

Dark Matter around the Planck Mass



Theoretically well-motivated

- Primordial black hole relics [MacGibbon 1987](#), [Aharonov+ 1987](#)
- WIMPZillas! [Kolb+ hep-ph/9810361](#), [1708.04293](#), [Harigaya+ 1606.00923](#)
- Dark quark nuggets [Detmold+ 1406.2276](#), [Gresham+ 1707.02316](#)
- Composite dark matter [Krnjaic+ 1406.1171](#), [Hardy+ 1504.05419](#)
- Planckian interaction [Garny+ 1511.03278](#)
- GUT-scale coannihilation [Berlin 1704.08256](#)
- ... [Azatov+ 2101.05721](#), [Bai+ 1906.04858](#), [Blanco+ 2112.14784](#), [Ema+ 1903.10973](#)

Directly Probing Planck-Mass Dark Matter

10^{-21}eV

eV

GeV

PeV

M_{Planck} kg

10^{50}eV

M_{\odot}

M_{\odot}

Theoretically well-motivated

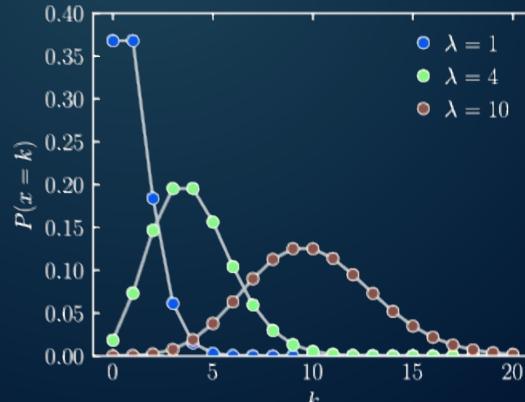
Experimentally accessible in lab

With a fixed mass density, number density $\sim 1/m_{\chi}$
at $m_{\chi} \sim m_{\text{Planck}}$, DM flux $\sim 1/\text{m}^2/\text{year}$

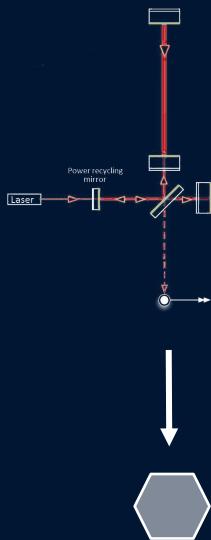
$\sim 0.3 \frac{\text{GeV}}{\text{cm}^3}$

local dark
matter halo
density

Lewin+ 1996



Quantum Sensing for Dark Matter Detection



Theoretically well-motivated
Experimentally accessible in lab

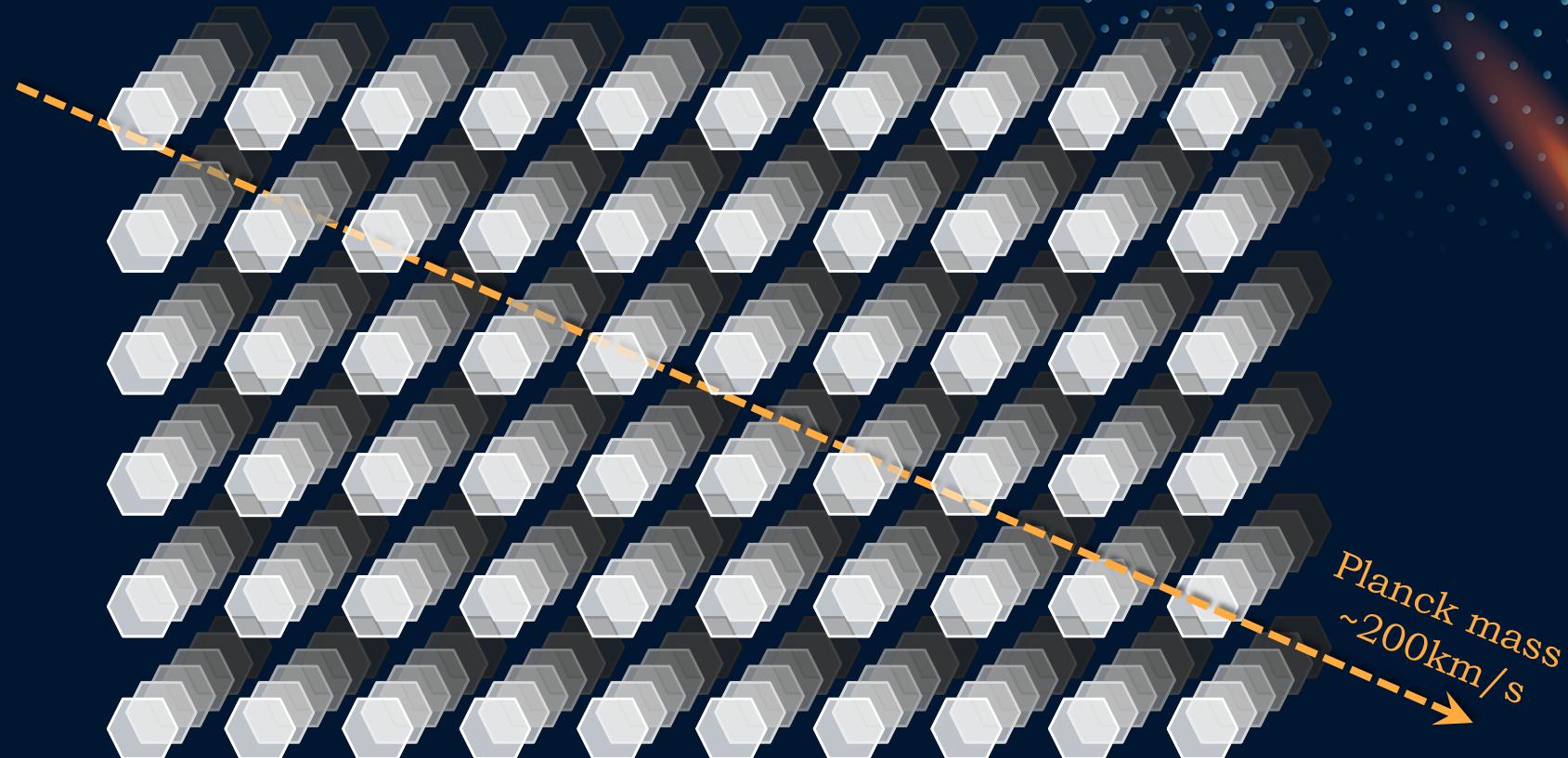
Gravitational detection possible

with help from recent advances in
quantum sensing

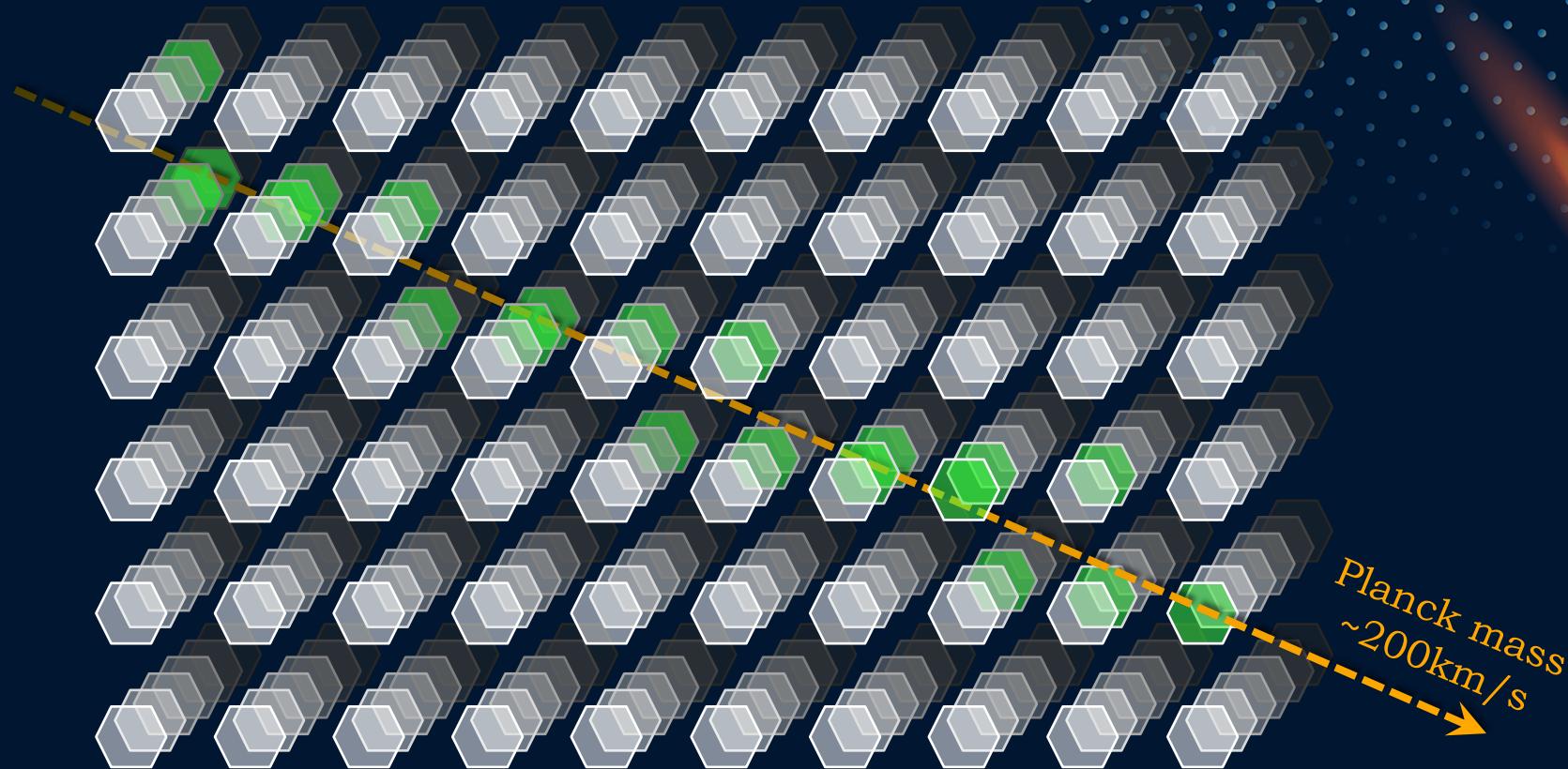
- quantum-enhanced readout
- sensitive accelerometers
- large array

Carney+ 1903.00492, Ghosh+ 1910.11892

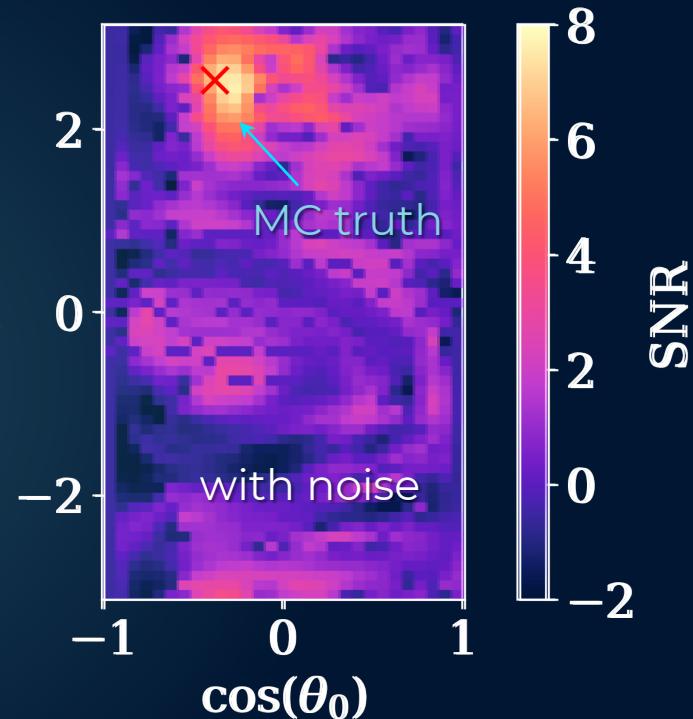
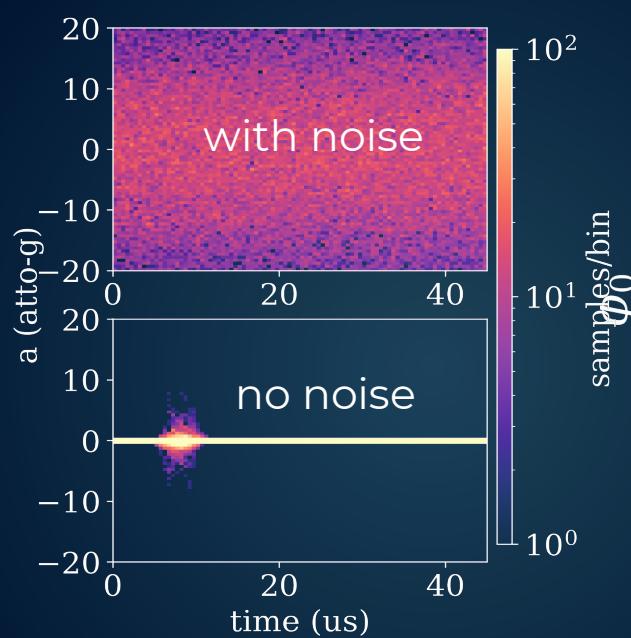
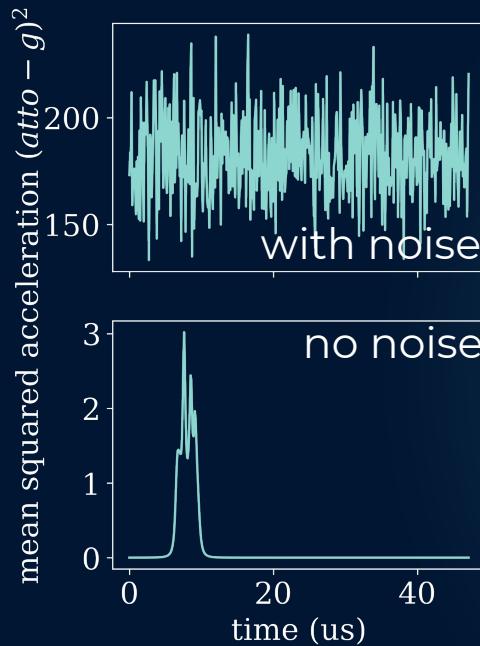
WINDCHIME: A Mechanical Accelerometers Array for DM



WINDCHIME: A Mechanical Accelerometers Array for DM



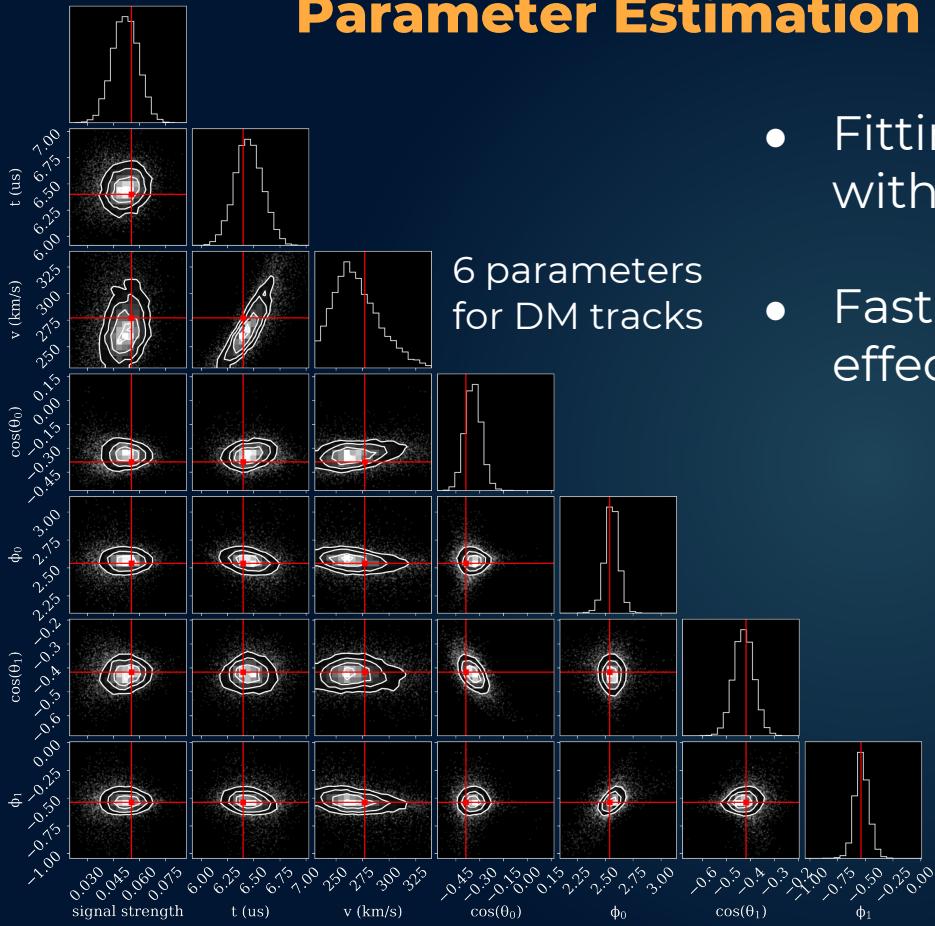
Recovering Track from Noisy Data



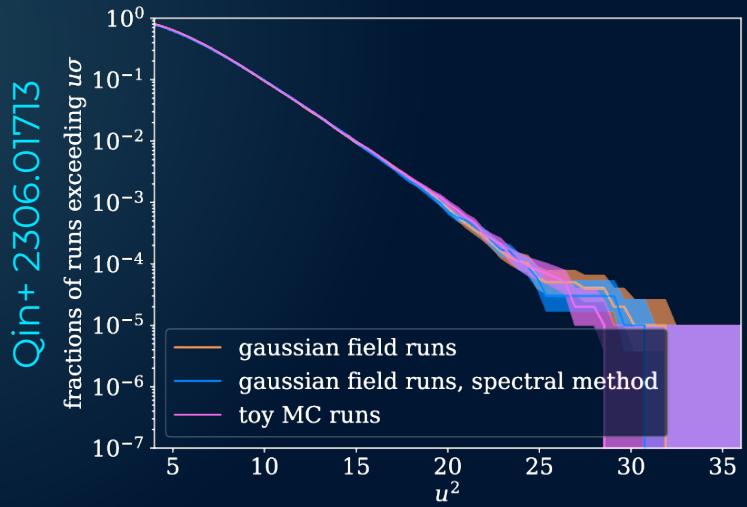
Signal below the single-sensor noise
recovered using Template Matching

Huge trial factor, SNR of
~10 is needed for discovery

Parameter Estimation for DM Track



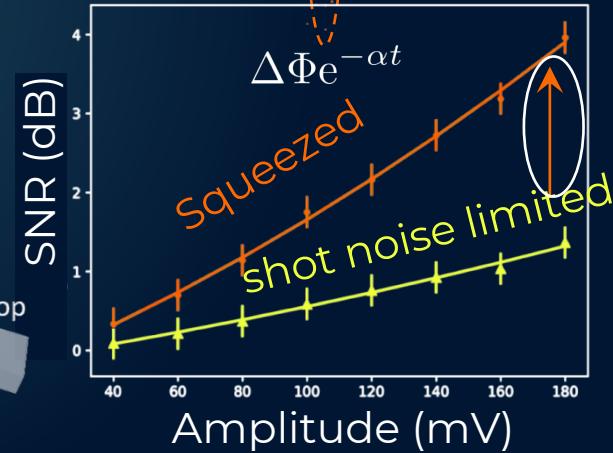
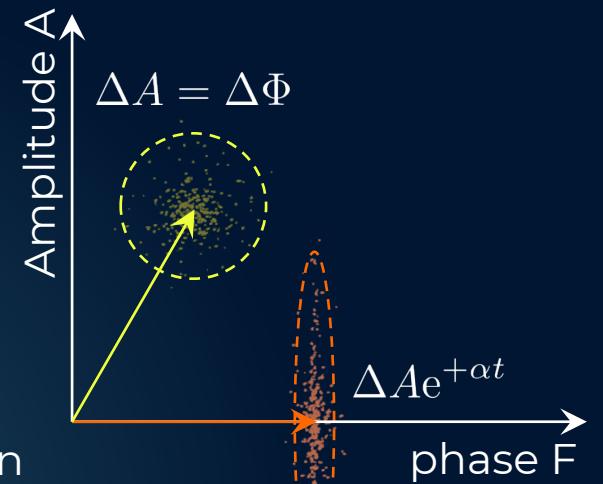
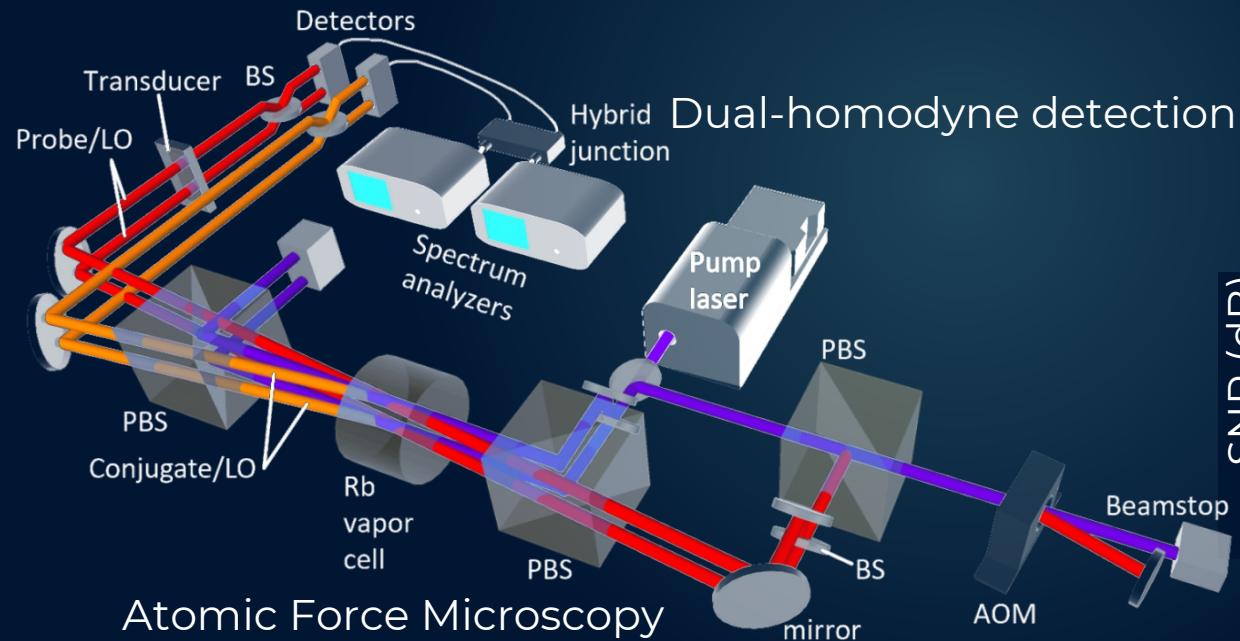
- Fitting track signals buried in noise with Nested sampling / MCMC
- Fast estimation of look-elsewhere effect using Gaussian random fields



Quantum Noise Reduction: Squeezing

Shot noise reduction

-- decrease the counting error of laser photons

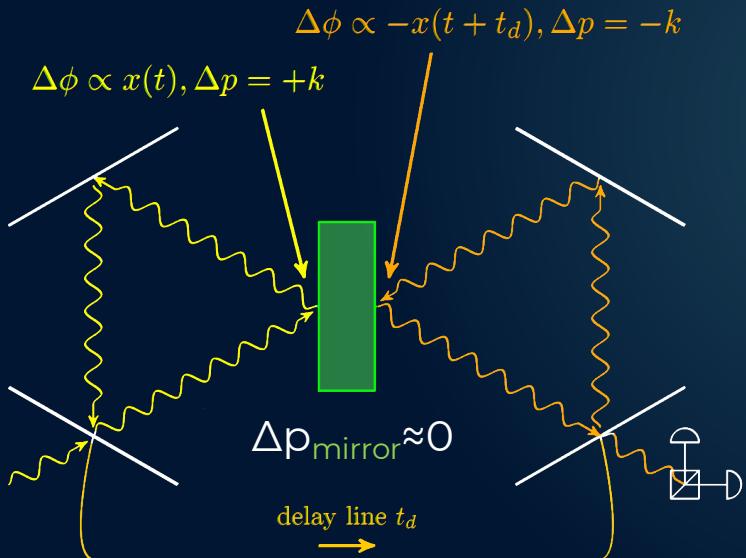


Quantum Noise Reduction: Velocity Sensing

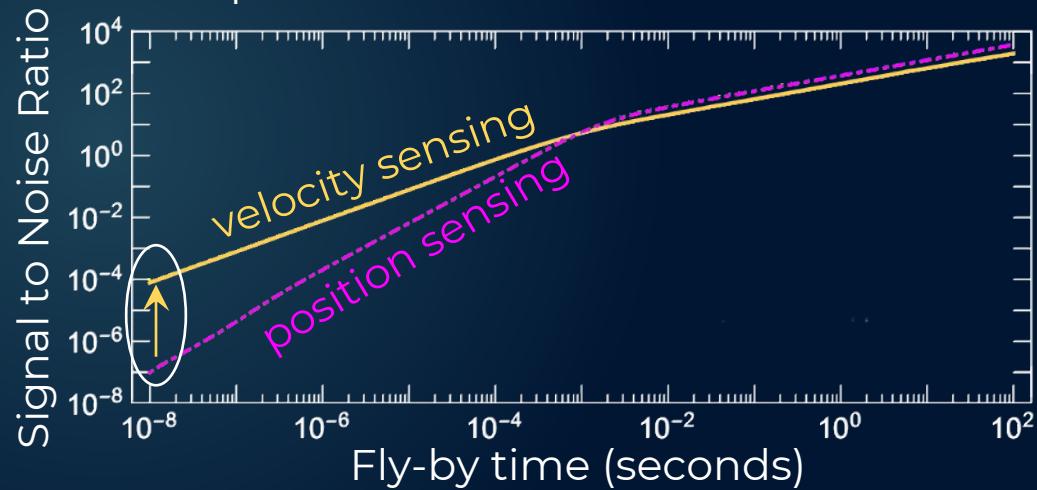
Backaction noise reduction

-- decrease fluctuations from radiation pressure

double-ring optomechanical cavity



DM speed ~ 200 km/s
Impulse on each sensor: $\sim 10^{-8}$ s



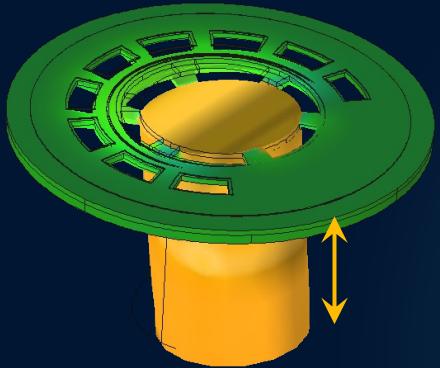
also Quantum Non-demolition measurement

Silicon MEMS Accelerometers

Dong+ 1903.08479

Pooser+ 1912.10550

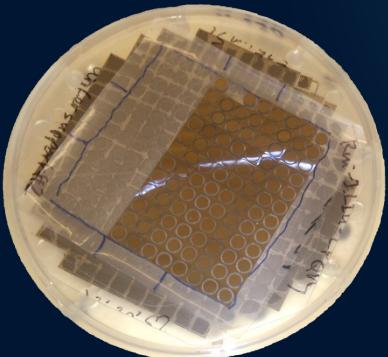
Vaidya+ 1904.07833



Bao+ 2018

- Noise floor $(\omega_0/mQ)^{\frac{1}{2}}$
Cervantes+ 1303.1188
 - Large mass (10 mg)
 - High Q-factor ($> 10^4$)
- Low noise ($< 1\mu g_n/\sqrt{Hz}$)
achieved with a 5 kHz bandwidth

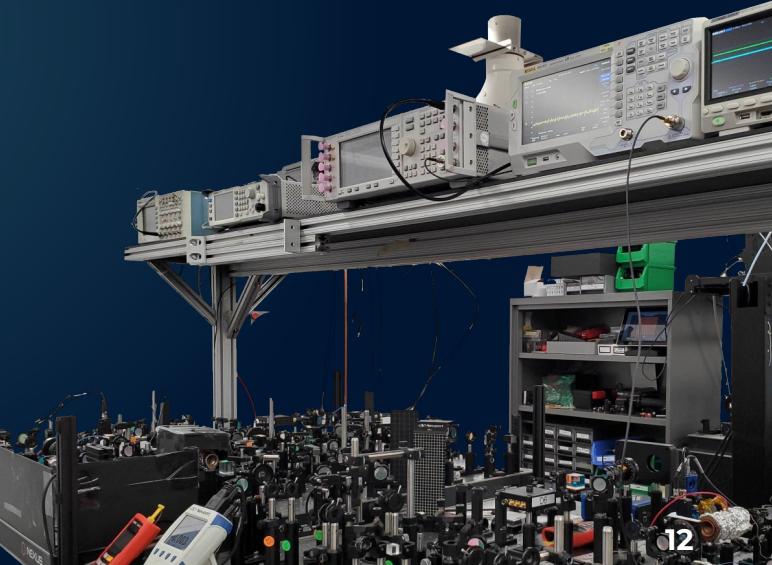
<- On-chip integration
desired for scaling up,
currently 96/wafer
achieved



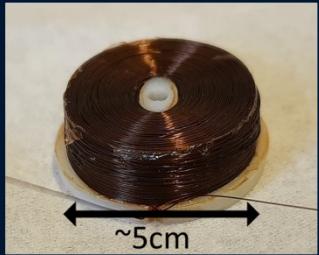
Shengchao Li (Westlake)

Flexible readouts:

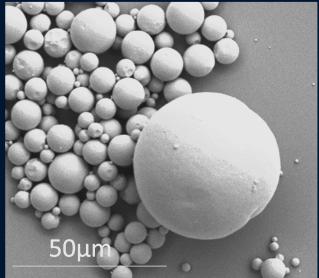
- piezo-electrics
- free-space interferometry
- on-chip photonics



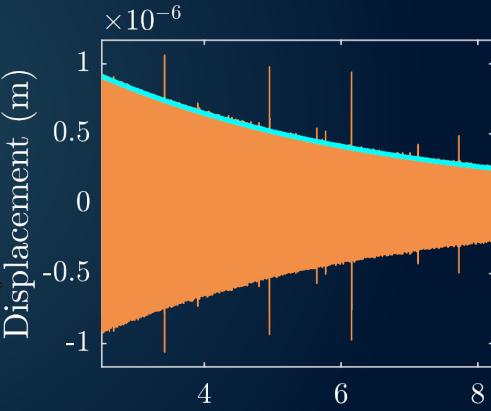
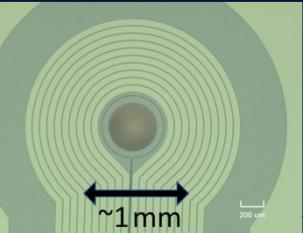
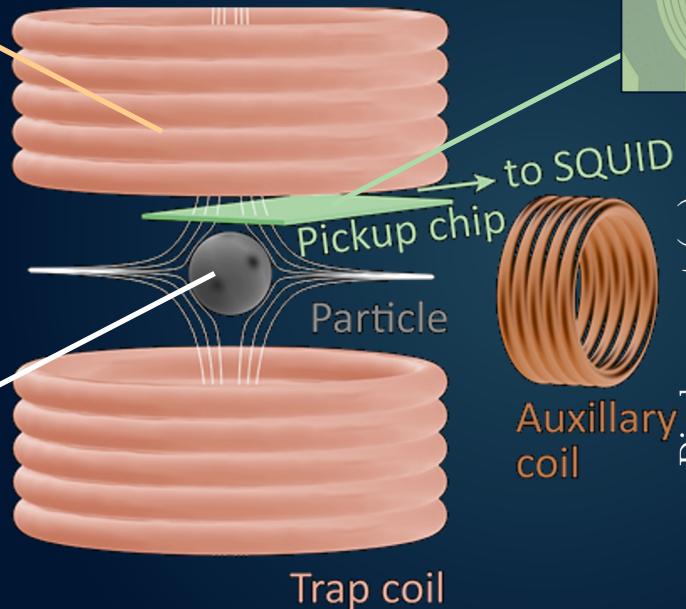
Magnetically Levitated Microspheres



$$\mathcal{E} = -\frac{d\Phi_B}{dt}$$

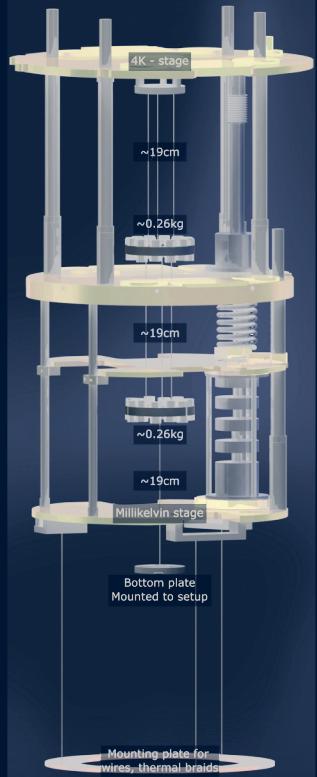


e.g. lead-tin, in μg



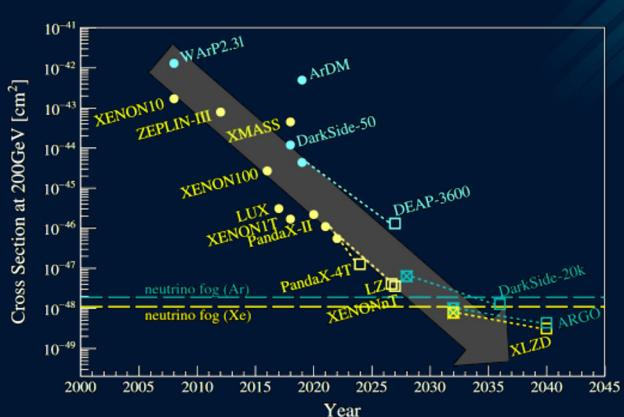
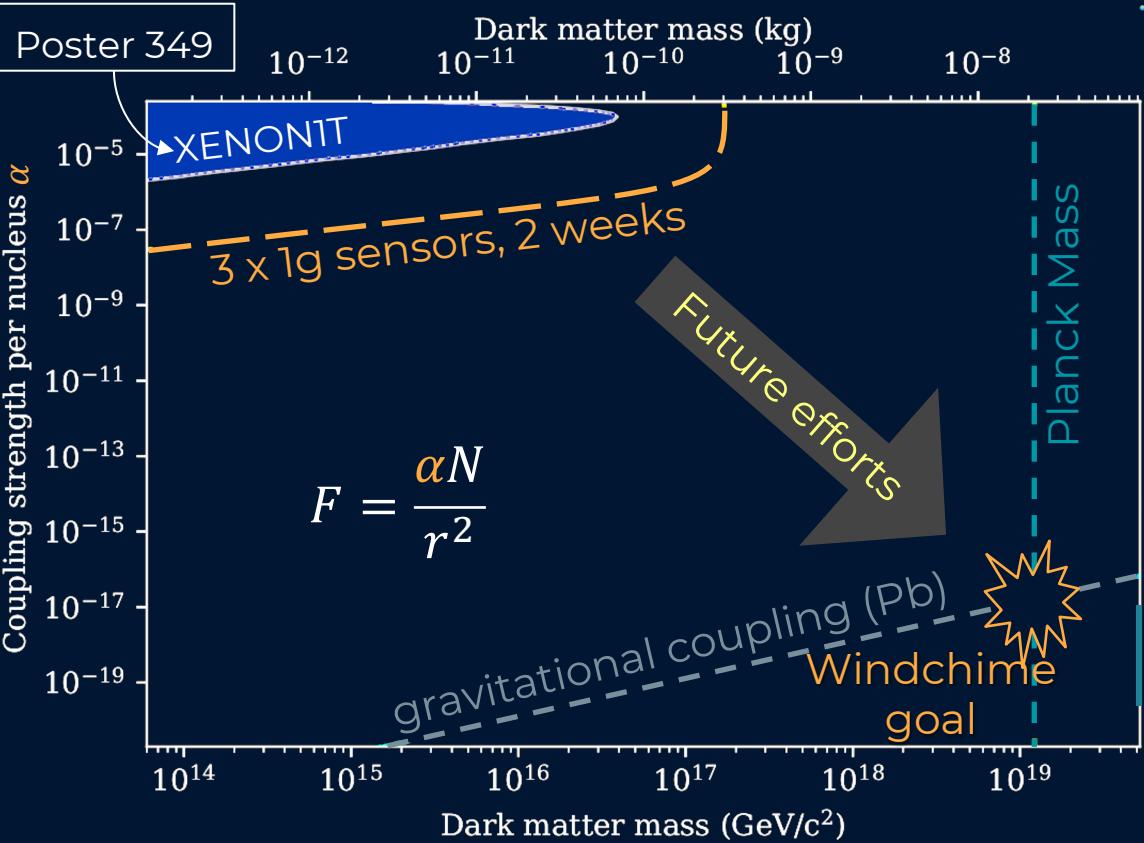
Ringdown:
Q-factor > 10^7

Poster 194 by Gerard Higgins
Hofer, Higgins+ 2211.06289



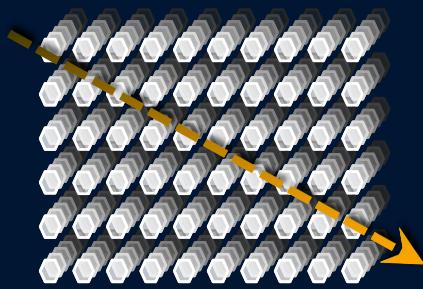
15 mK with
vibration
isolation

Towards Gravitational Detection of Dark Matter



CONCLUSION

Vision: detect dark matter in the lab via *gravity* alone



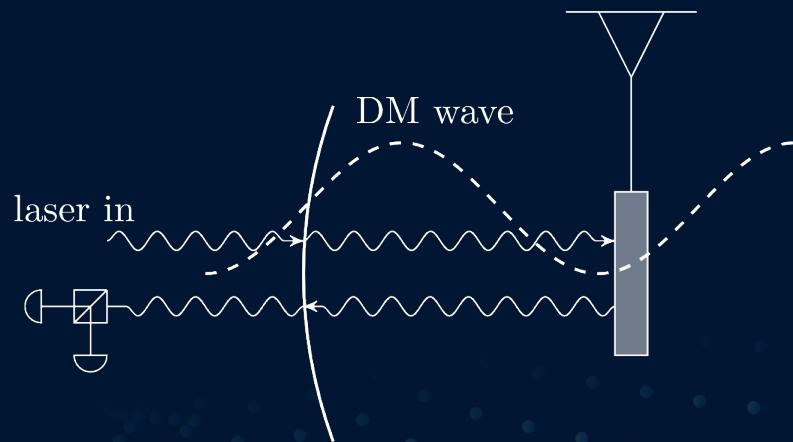
- Use array of sensitive accelerometers with quantum-enhanced readout
- Simulation and analysis to find DM track with noise, with large trail factors taken into account
- Levitated superconductors and MEMS sensors built and tested for pathfinding
- Active developments in quantum sensing techniques to get below SQL

arXiv: 2203.07242

One more thing...

..with the same array..

Ultralight DM Detection



Near-Term Target
Next talk by Dorian Amaral

Carney+ 1908.04797
Manley+ 2007.04899
Carney+ 2008.06074

The Windchime Collaboration



PURDUE
UNIVERSITY



RICE UNIVERSITY



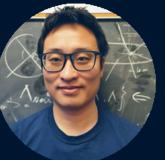
UNIVERSITY OF
MARYLAND



UNIVERSITY OF MINNESOTA

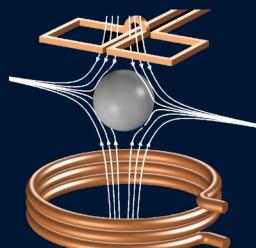
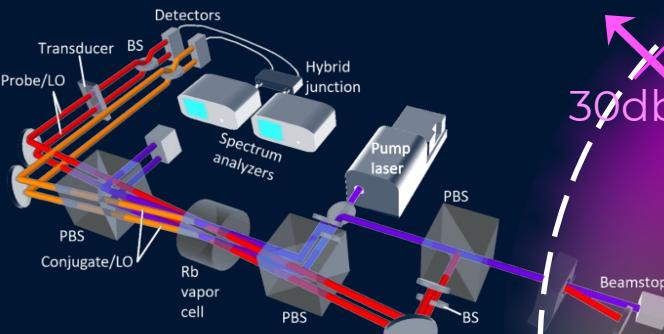


CHALMERS
UNIVERSITY OF TECHNOLOGY

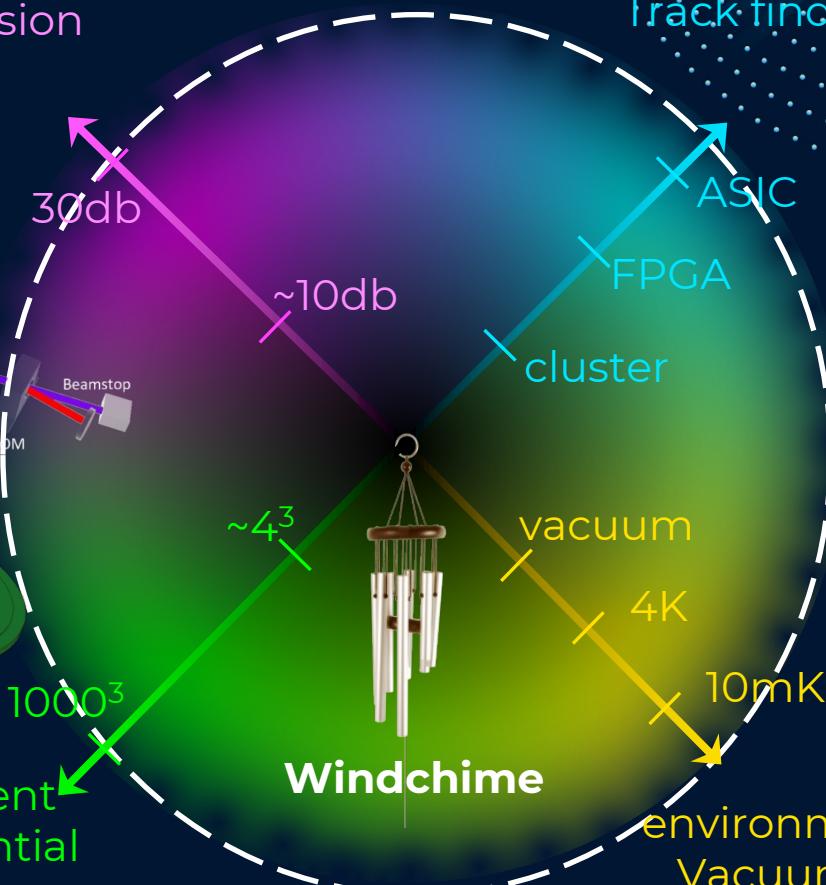


Windchime Roadmap/Challenge

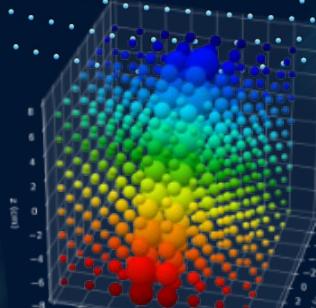
quantum noise suppression
to below the **SQL**



sensor development
with scaling potential



computing:
Track finding, streaming analysis

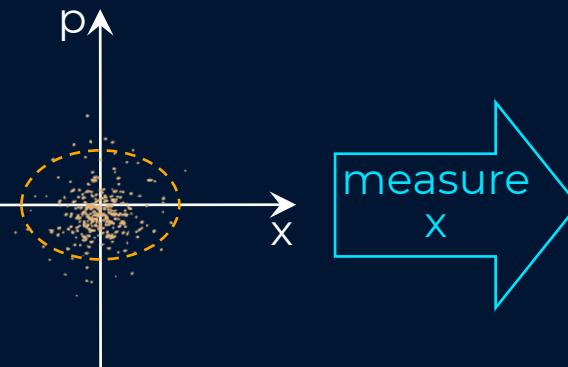


environmental isolation:
Vacuum, refrigerator

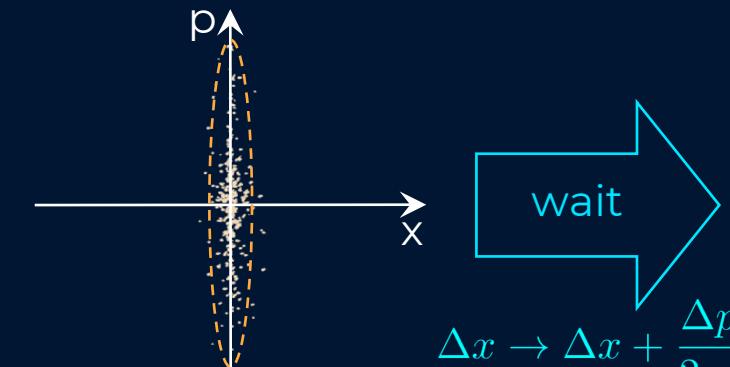


Quantum Back-Action Evasion through Velocity Sensing

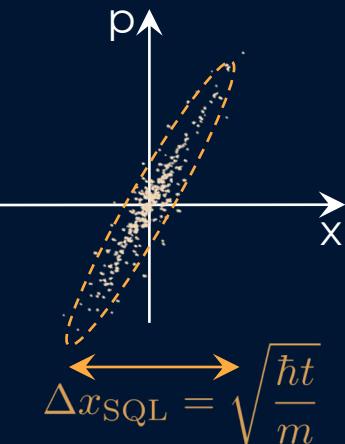
Caves+ Rev. Mod. Phys. 1980



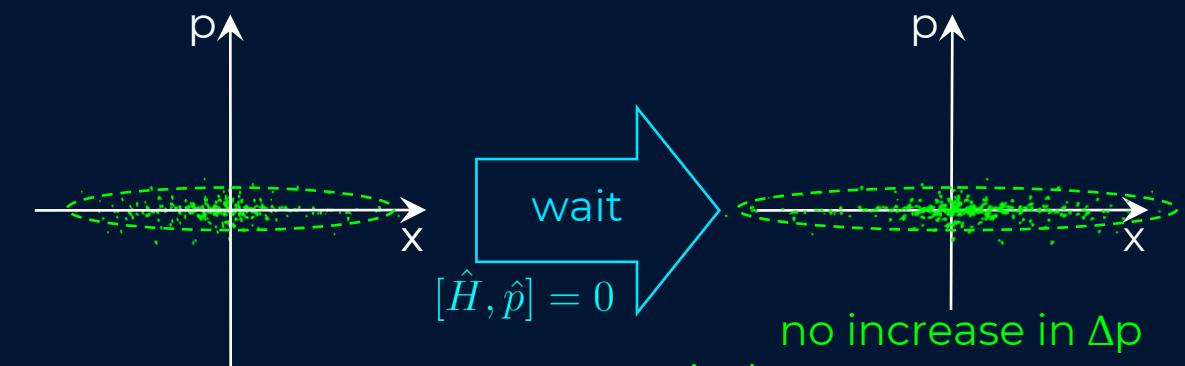
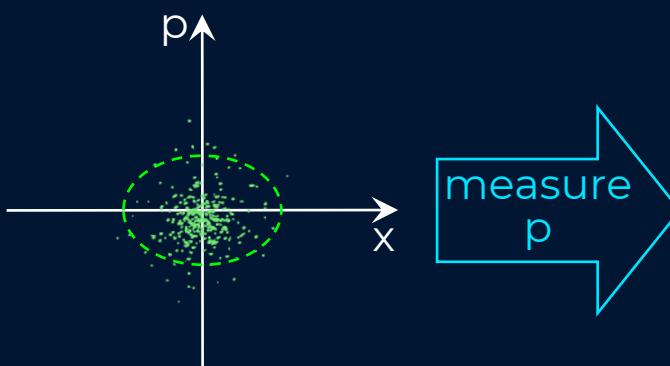
$$\Delta x \Delta p = \hbar/2 \\ \text{minimal uncertainty}$$



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

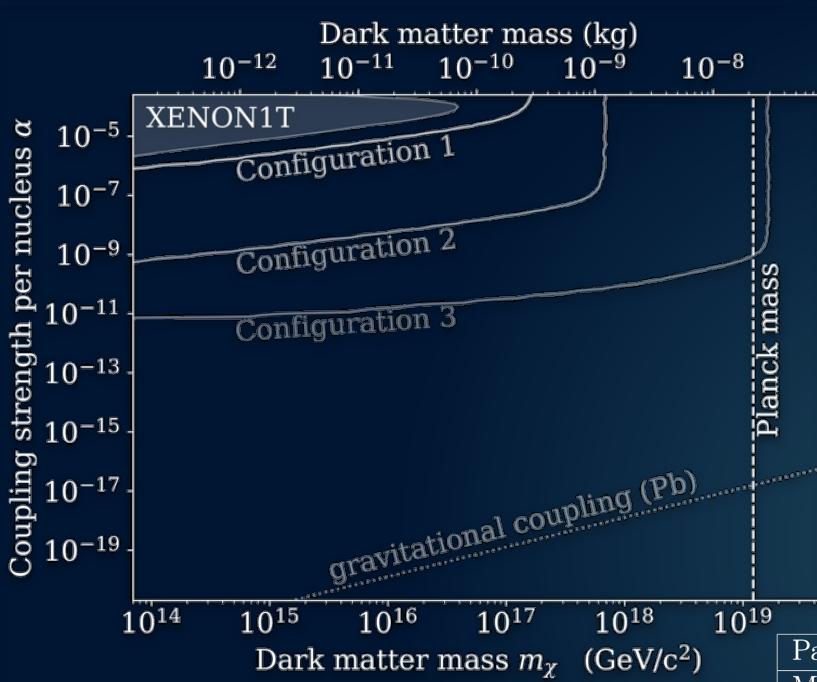


$$\Delta x_{\text{SQL}} = \sqrt{\frac{\hbar t}{m}}$$



$$[\hat{H}, \hat{p}] = 0$$

no increase in Δp
noiseless measurement



Windchime Sensitivity Projections

Parameter	Configuration 1	Configuration 2	Configuration 3
Mechanical quality factor Q_m	10^9	3×10^9	3×10^9
Resonance frequency ω_m	100 Hz	100 Hz	10 Hz
Sensor mass m_s	1 g	1 g	1 g
Sensor density	1.13×10^4 kg/m ³	1.13×10^4 kg/m ³	1.13×10^4 kg/m ³
Pressure P	10^{-14} Pa	10^{-14} Pa	10^{-14} Pa
Temperature T	15 mK	15 mK	15 mK
Noise model	Classical	Quantum	Quantum
Quantum noise reduction ξ	-	15 dB	30 dB
Classical noise PSD S_{xx}	10^{-15} m/ $\sqrt{\text{Hz}}$	-	-
Sensor count	$3 \times 1 \times 1$	$3 \times 1 \times 1$	$10 \times 10 \times 10$
Sensor array size	0.6 m	0.6 m	1.2 m

Protochime: testbed for DAQ and backgrounds



- ADXL1005 MEMS accelerometer array on a platform
 - 42 kHz resonance
 - NI-ADCs MS/s readout
- Test potential issues
 - Data rate/pipeline
 - Noise
 - Ultralight DM background