WP4 Overview
Scaling up Quantum

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DRD5 Collaborator Meeting 30-31st of October 2025

Stockholm University

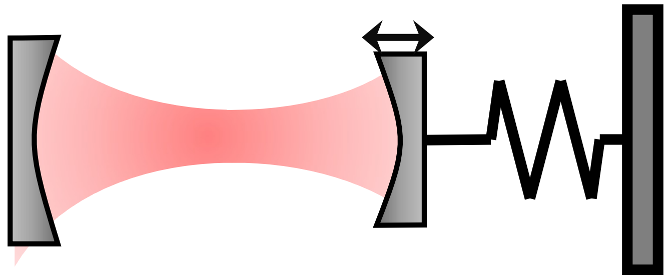
NORDITA
The Nordic Institute for Theoretical Physics

WINQ
Wallenberg Initiative on Networks and Quantum information

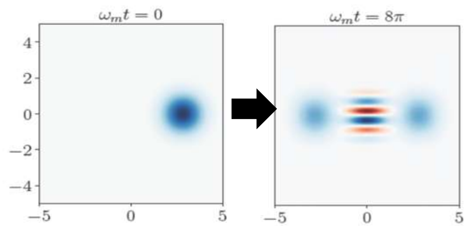
Campus Albano, Stockholm

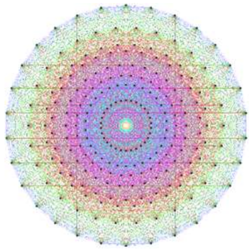
Nordita: Nordic Institute for Theoretical Physics

My research



State Preparation



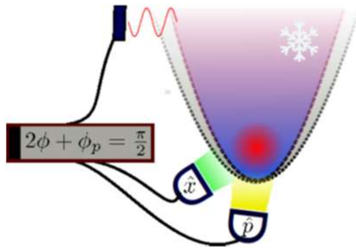


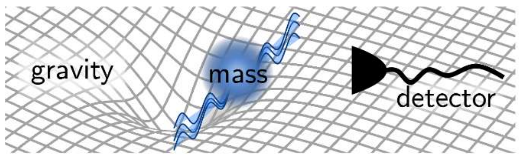
Mathematical Methods

Quantum Nonlinearities

Quantum Control

Quantum Sensing





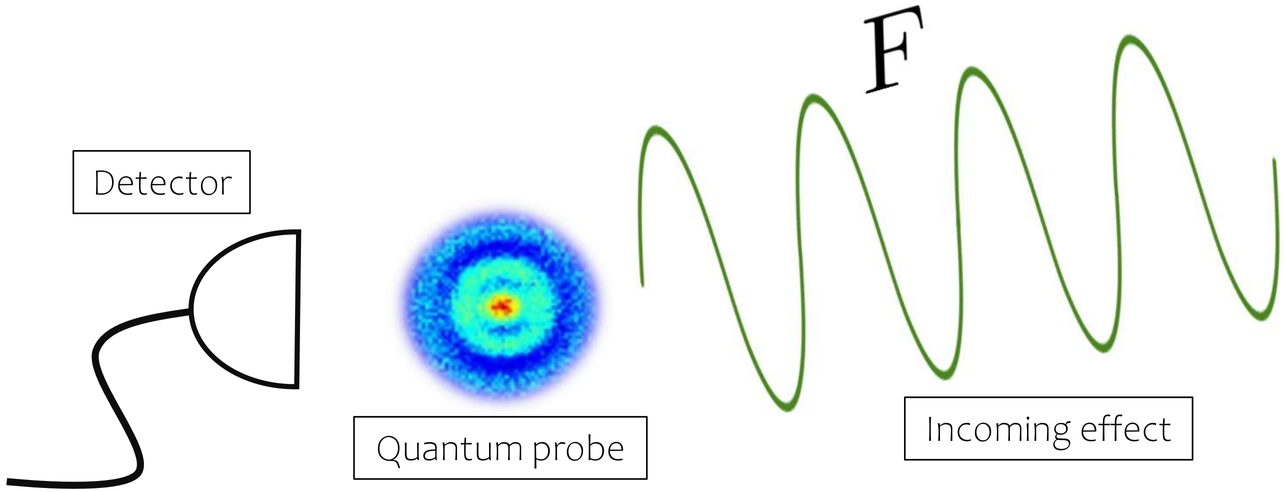
Motivation: Searching for new physics

Leverage quantum sensing advantage in searches for new physics

- Table-top gravitational-wave detectors
- Dark-matter detectors
- Searches for quantum effects of gravity

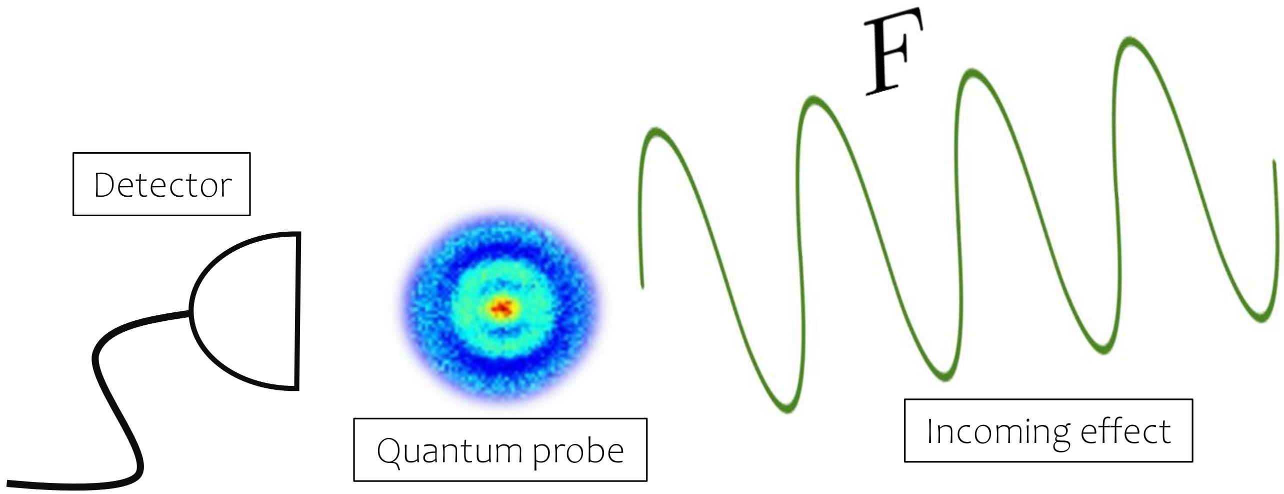
Applications of quantum metrology to HEP are largely outstanding.

Key idea: quantum sensing



The optimal senstivity can be quantified through theoretical tools (quantum Fisher information) or realistic modelling (signal-to-noise-ratio)

Key idea: quantum sensing



Classical sensing limit	$\sigma_F \propto \frac{1}{\sqrt{N}}$
Squeezed states	$\sigma_F < \frac{1}{\sqrt{N}}$
Entanglement/nonlinearity	$\sigma_F \propto \frac{1}{N}$

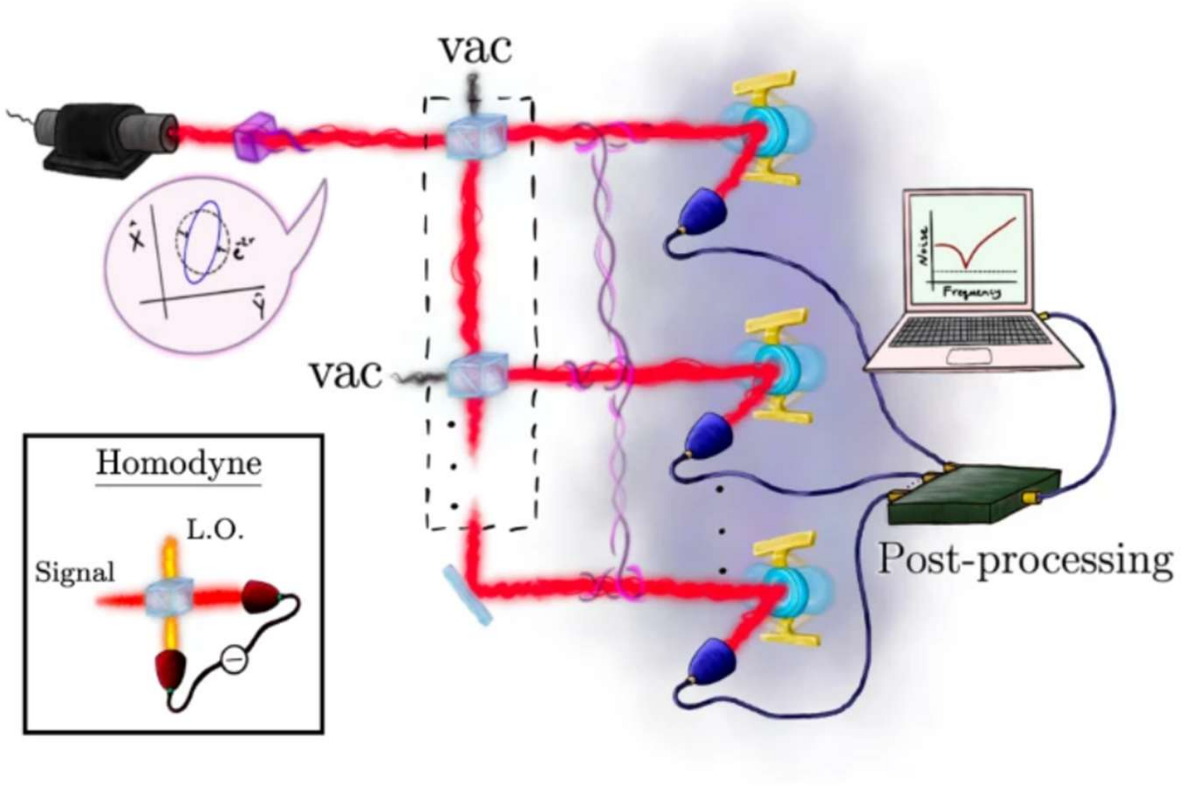
Key idea: Scaling up quantum

Challenges for quantum metrology in HEP:

- Managing decoherence
- Localised systems – small effects
- GWs and DMPs are single events – no sustained continuous signal

One solution: More quantum sensors!

Key idea: Networked quantum systems



Brady, A.J., Chen, X., Xia, Y., Manley, J., Dey Chowdhury, M., Xiao, K., Liu, Z., Harnik, R., Wilson, D.J., Zhang, Z. and Zhuang, Q., 2023. Entanglement-enhanced optomechanical sensor array with application to dark matter searches. *Communications Physics*, *6*(1), p.237.

Key idea: Networked quantum systems

Different scaling strategies

- Many identical sensors operated in parallel
- Large-volume quantum coherent media
- Hybrid or heterogeneous arrays

Challenges for netwroked quantum systems

- Maintaining coherence
- Achieving uniformity
- Coordinating read-out and post-processing
- Maintaining quantum advantage throughout scaling

Subpackages of WP4

WP4a	**Massive spin-polarized ensembles** Arne Wickenbrock (Johannes Gutenberg University Mainz)
WP4b	**Hybrid large-ensemble devices** Nicolas Fourches (CEA/IRFU)
WP4c	**Opto-mechanical large-scale sensors** Andrew Geraci (Northwestern)

WP4a: Massive spin-polarized ensembles

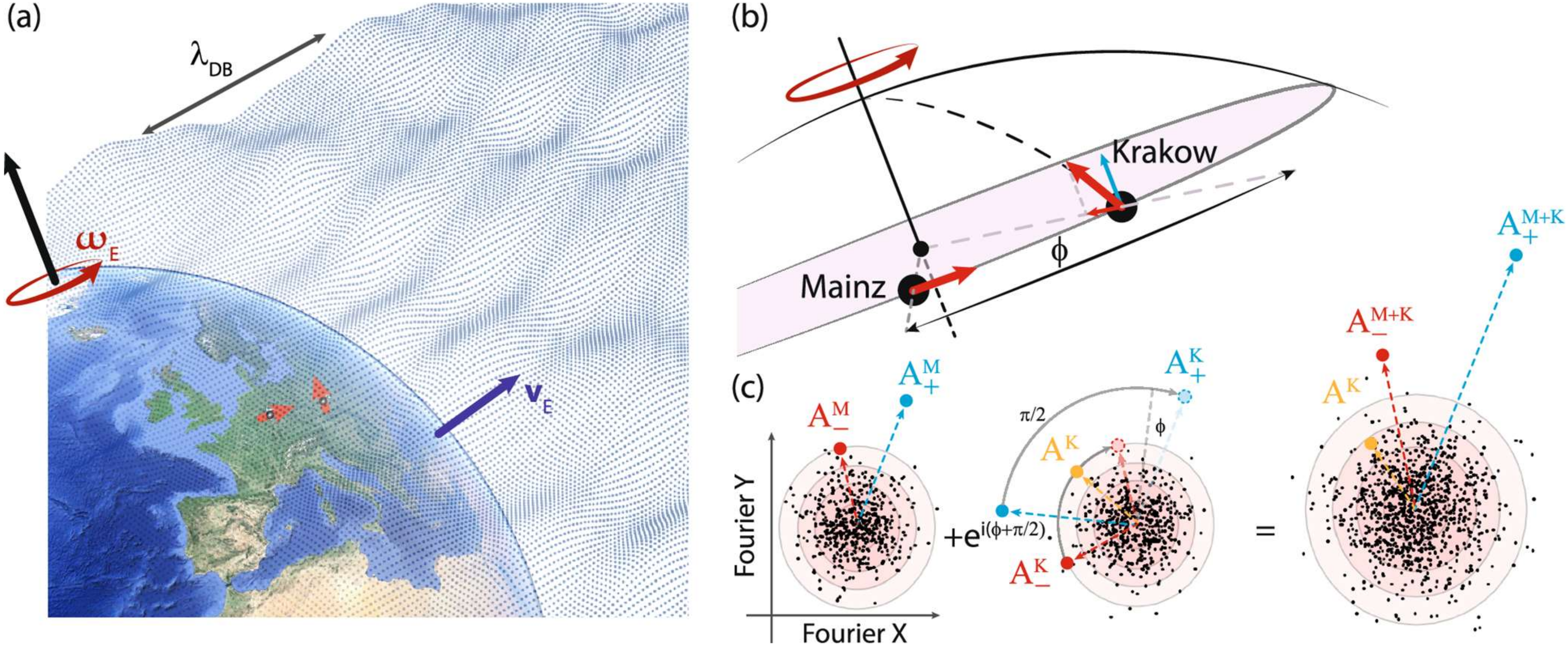
Bulk matter with large numbers of aligned spins

- Spin-polarized solids, gases or liquids
- Levitated ferromagnetic particles or dense nuclear ensembles

Key advantages

- Long coherence times
- High spin-density, can couple to new exotic fields or BSM interactions
- Uniformity of systems
- Applicable to dark-matter/Axion-like particle searches

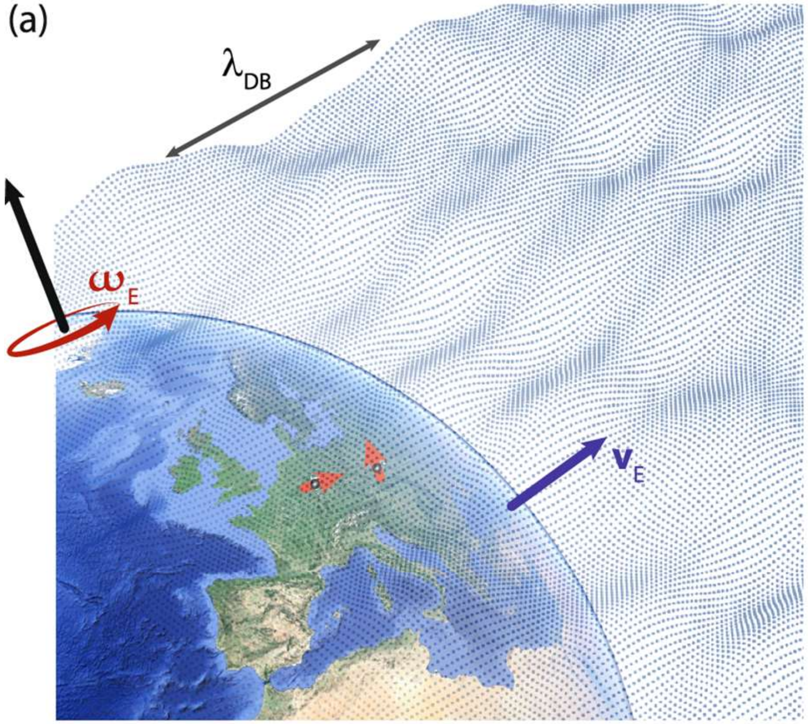
WP4a: Massive spin-polarized ensembles

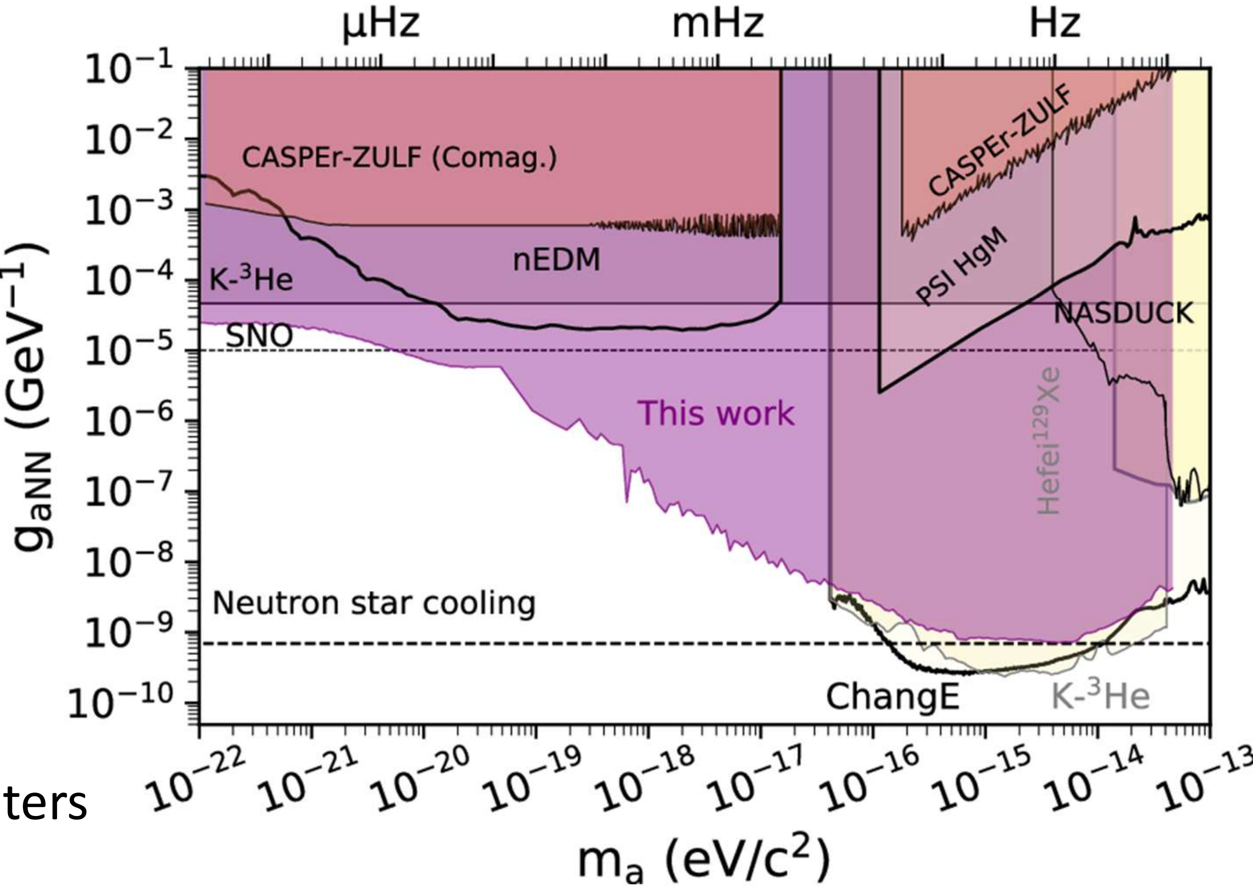


Two atomic K-Rb-^{3}He comagnetometers

Gavilan-Martin D, Łukasiewicz G, Padniuk M, Klinger E, Smolis M, Figueroa NL, Jackson Kimball DF, Sushkov AO, Pustelny S, Budker D, Wickenbrock A. Searching for dark matter with a spin-based interferometer. Nature Communications. 2025 May 28;16(1):4953.

WP4a: Massive spin-polarized ensembles





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WP4b: Hybrid large-ensemble devices

Hybrid devices containing different physical modalities

- Spins + photonics
- Mechanical/optical + soild states
- Semiconductor-based sensors (DoTPiX)

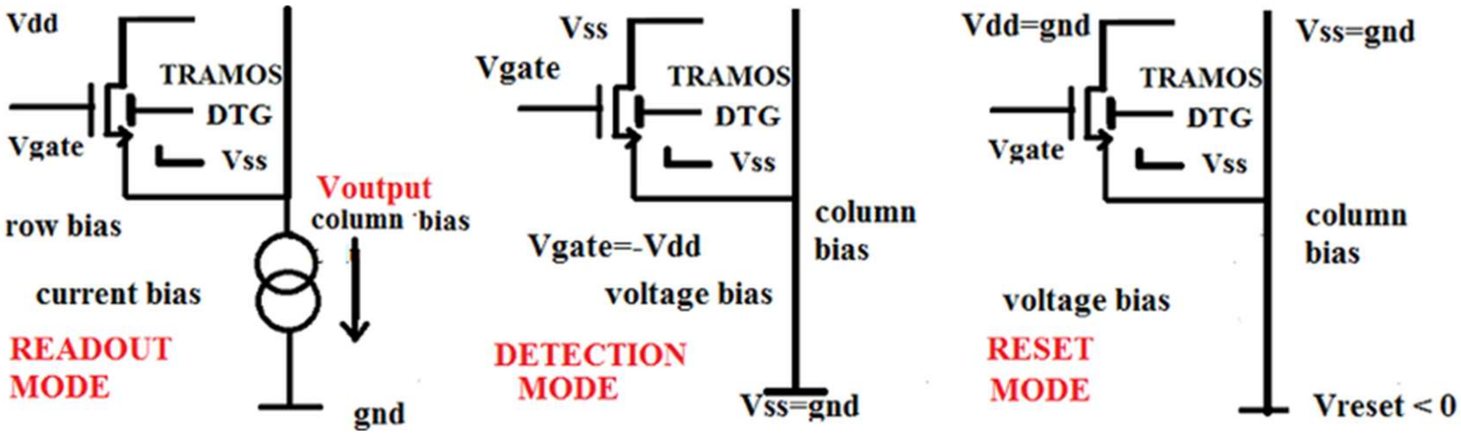
Key advantages

- Transduction of effects between systems (e.g. from spin to optical)
- Integration with HEP infrastructure – detector material considerations

WP4b: Hybrid large-ensemble devices

DoTPiX

- Future colliders require µm resolution and good radiation tolerance
- Use a quantum well structure buried in the transistor to modulate the read-out current



Hoeferkamp MR, Seidel S, Kim S, Metcalfe J, Sumant A, Kagan H, Trischuk W, Boscardin M, Betta GF, Sultan DM, Fourches NT. Novel sensors for particle tracking: a contribution to the Snowmass community planning exercise of 2021. arXiv preprint arXiv:2202.11828. 2022 Feb 23.

WP4c: Optomechanical large-scale sensors

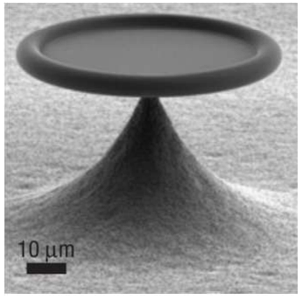
Large-mass mechanical resonators in the quantum regime

- Optomechanical, electromechanical, magnetomechanical
- Hybrid systems coupled with spins
- Motion is controlled and read-out near the quantum limit

Key advantages

- High acceleration sensitivity
- Macroscopic quantum states
- Couple ”strongly” to gravity

WP4c: Optomechanical large-scale sensors



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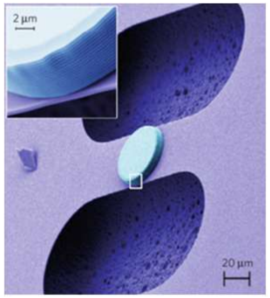

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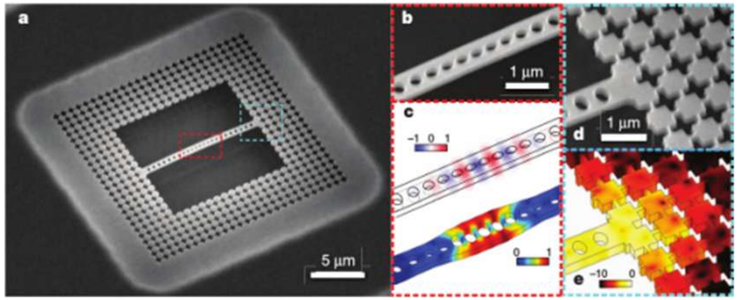

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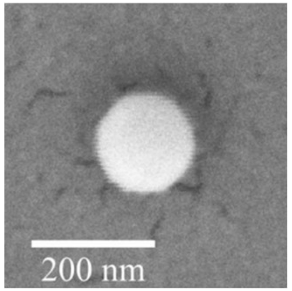

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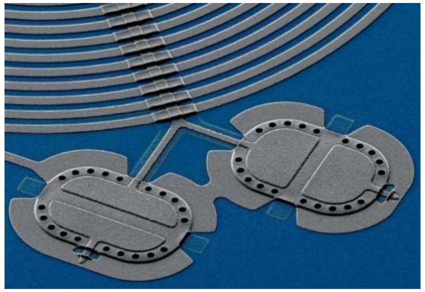

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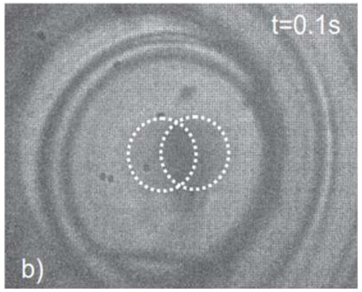

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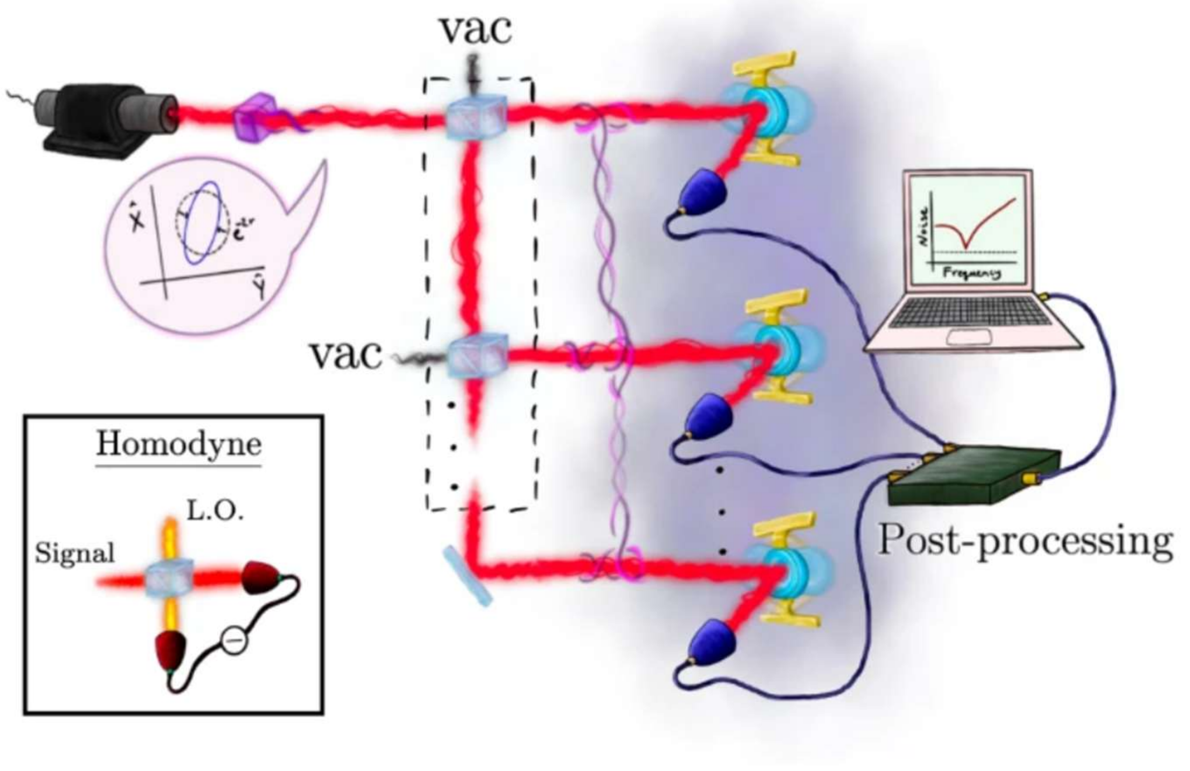
WP4c: Optomechanical large-scale sensors



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Plans for WP4

Immediate goals

- Secure COST action funding for a workshop on “Optomechanics for Particle Physics” (likely in 2027)
- Apply for a Scientific Programme at Nordita, Stockholm, on ”Networked Quantum Sensors” (also likely in 2027)

Happy to discuss!

Thank you for listening!

Contact information

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WP4b: Nicolas Fourches (nicolas.fourches@cea.fr)

WP4c: Andrew Geraci (andrew.geraci@northwestern.edu)