UNIVERSITY OF
OXFORD

Quantum sensing with quantum motional states of trapped ions

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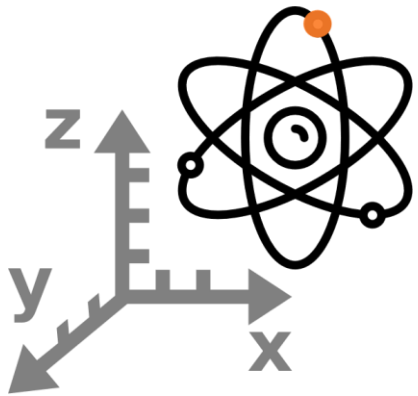
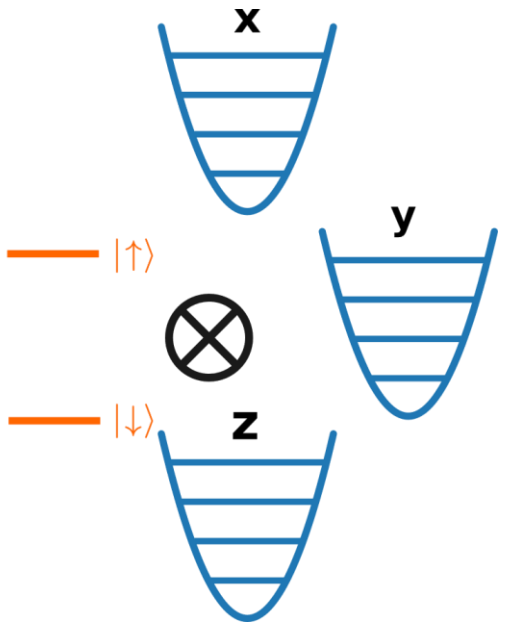
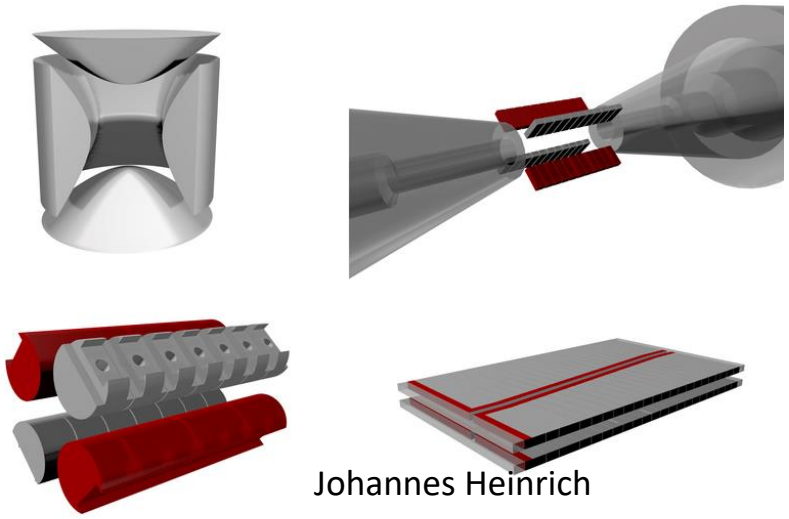




Trapped atomic ions have both internal and external degrees of freedom

Both of them are quantized

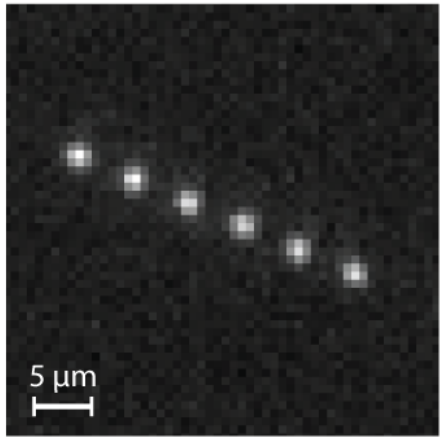
Ions trapped in Paul traps



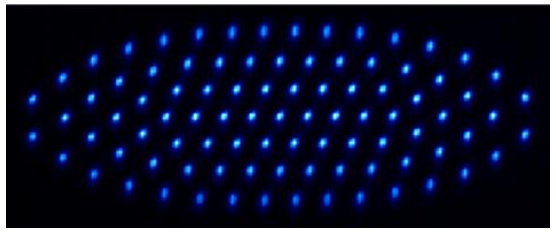
Johannes Heinrich

- **Quantum control via lasers and/or microwave pulses**
- **Single and two qubit** gates fidelities > 99.99 %
- Coherences times > 10 s
- Make good Quantum Computers
- **Make excellent Atomic Clocks / sensors**

Impressive advances on quantum control also in Penning traps



Chain of six Barium ions



2D crystal 91 Calcium ions (Innsbruck)

Trapped-ion quantum computing: Progress and challenges
Applied Physics Reviews 6, 021314 (2019);
Colin D. Bruzewicza et al.

- The internal electronic states of trapped ions serve as exceptionally stable and well-isolated quantum references.

- Fractional frequency uncertainties below 10^{-18}, setting the benchmark for time and frequency standards.

- Entanglement between clocks likely to be the next major improvement

- Make some of the best sensors ever built

- **Motion of ions is in general detrimental for the operation of the atomic clocks**

High-Stability Single-Ion Clock with 5.5×10^{-19} Systematic Uncertainty

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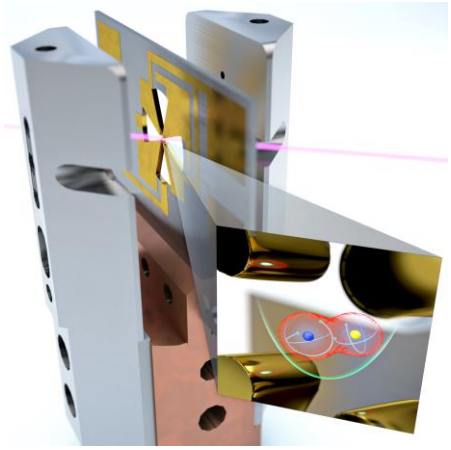
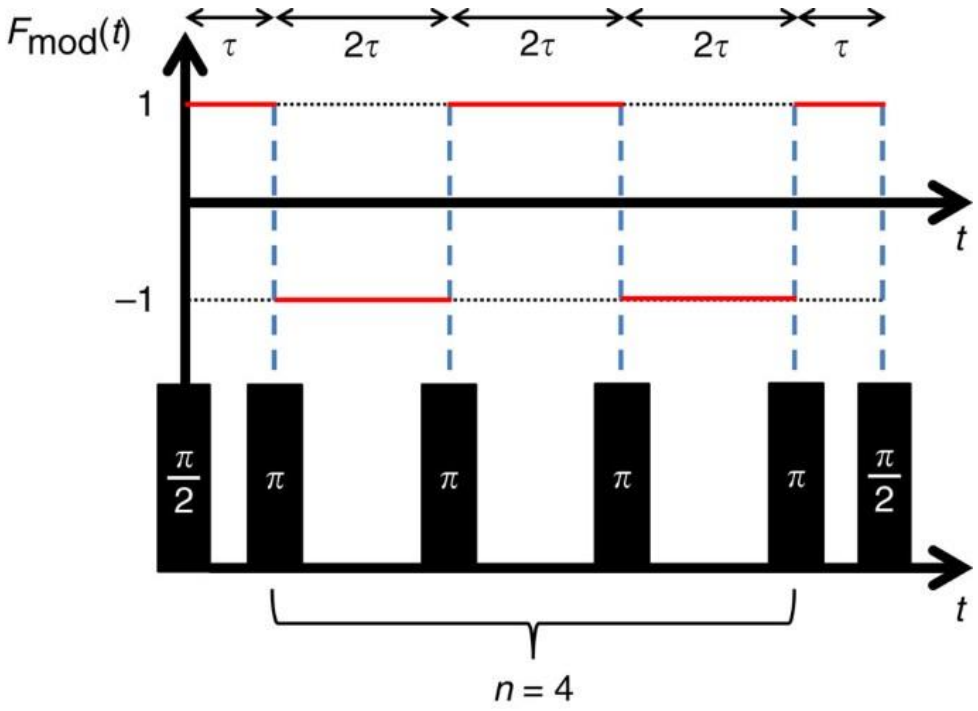
(Received 25 April 2025; accepted 17 June 2025; published 14 July 2025)

We report a single-ion optical atomic clock with a fractional frequency uncertainty of 5.5×10^{-19} and fractional frequency stability of $3.5 \times 10^{-16}/\sqrt{\tau/\mathrm{s}}$, based on quantum logic spectroscopy of a single $^{27}Al^+$ ion. A cotrapped $^{25}Mg^+$ ion provides sympathetic cooling and quantum logic readout of the $^{27}Al^+$ $^1S_0 \leftrightarrow {}^3P_0$ clock transition. A Rabi probe duration of 1 s, enabled by laser stability transfer from a remote cryogenic silicon cavity across a 3.6 km fiber link, results in a threefold reduction in instability compared to previous $^{27}Al^+$ clocks. Systematic uncertainties are lower due to an improved ion trap electrical design, which reduces excess micromotion, and a new vacuum system, which reduces collisional shifts. We also perform a direction-sensitive measurement of the ac magnetic field due to the rf ion trap, eliminating systematic uncertainty due to field orientation.



Sensing using an optical clock transition



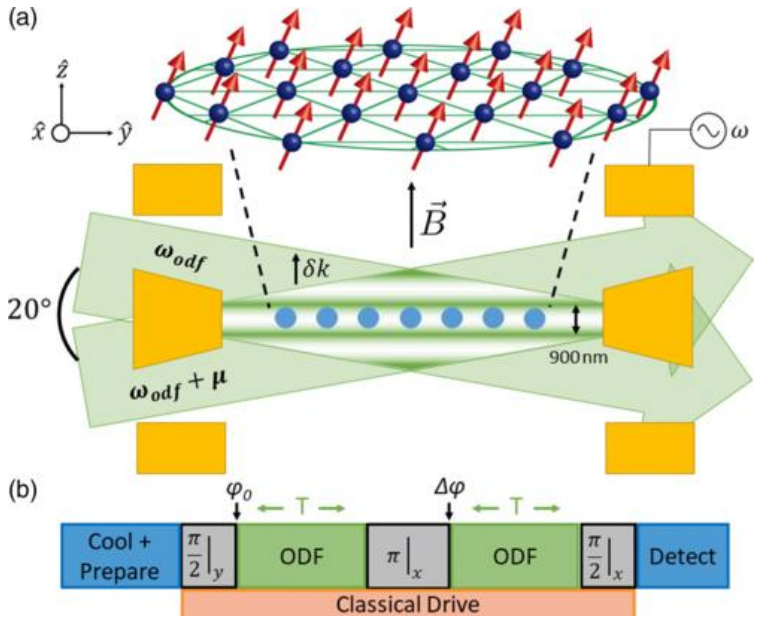
Force amplitude sensitive
2.8×10^{-20} $NHz^{-1/2}$

Quantum lock-in force sensing using optical clock Doppler velocimetry

•Ravid Shaniv & Roee Ozeri

Nature Communications (2017)

Using the motion for force sensing



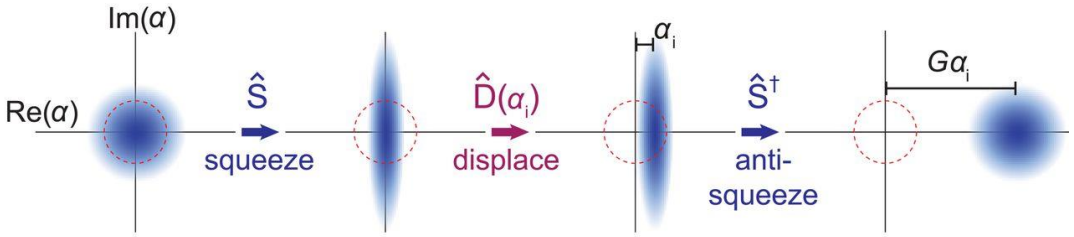
sensitivity of 12 x 10^{-24} N $Hz^{-1/2}$ per ion with a crystal of ~ 88 ions

Phase-coherent sensing of the center-of-mass motion of trapped-ion crystals

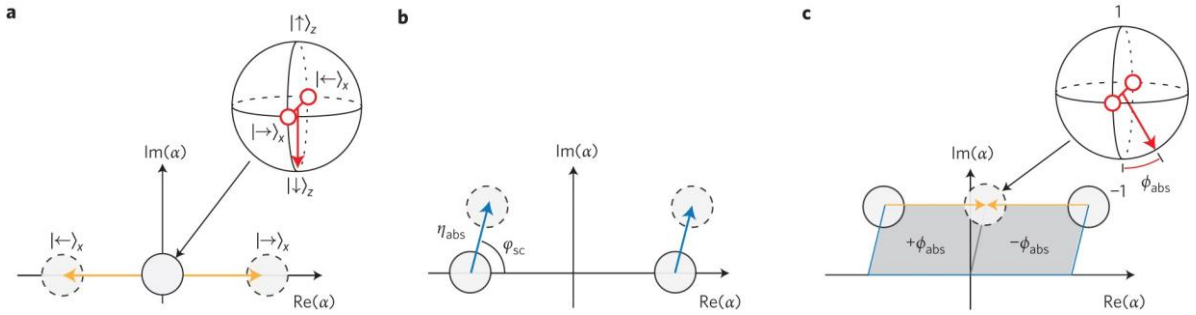
M. Affolter, K. A. Gilmore, J. E. Jordan, and J. J. Bollinger

Phys. Rev. A 102, 052609 (2020)

Using quantum Gaussian states of motion for force measurement

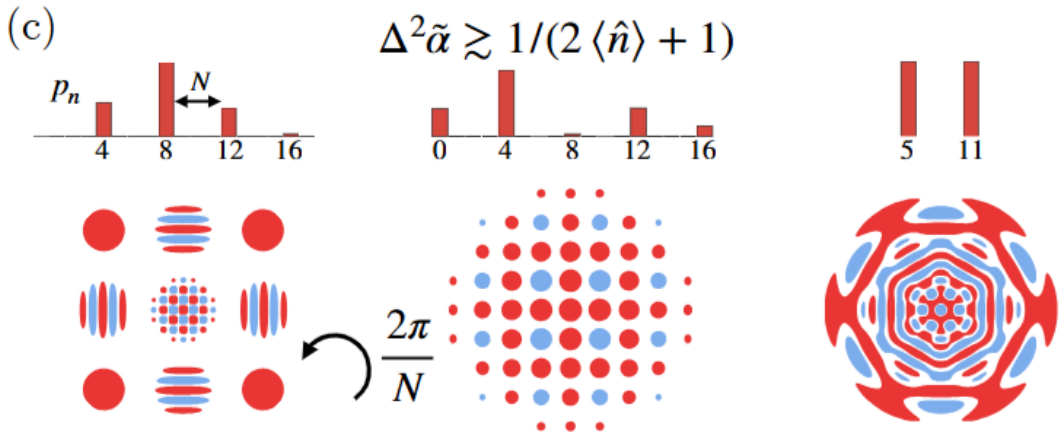


Burd, S. C., et al. "Quantum amplification of mechanical oscillator motion." *Science* 364.6446 (2019): 1163-1165.



Hempel, C., et al. "Entanglement-enhanced detection of single-photon scattering events." *Nature Photonics* 7.8 (2013): 630-633.

Sensing with Non-Gaussian states

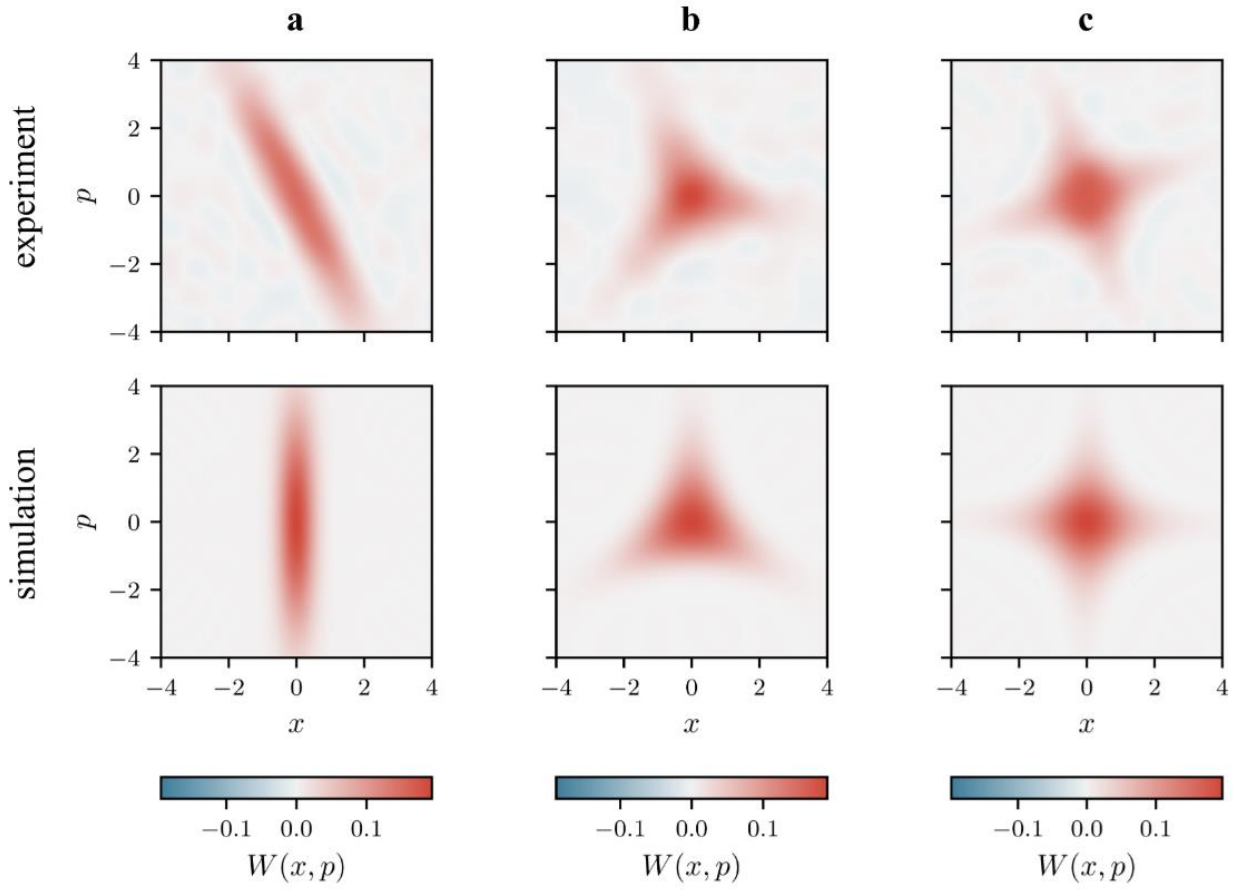


Optimal phase-insensitive force sensing with non-Gaussian states

Piotr T. Grochowski * and Radim Filip †
Department of Optics, Palacký University, 17. listopadu 1192/12, 771 46 Olomouc, Czech Republic

- **Go beyond Gaussian limits:** Enable sensitivities surpassing standard quantum and Heisenberg limits.
- **Sharper phase estimation:** Interference fringes enhance phase resolution.
- **Stronger quantum correlations:** Access forms of entanglement unavailable to Gaussian states.
- **Essential resource:** Required for true quantum advantage in metrology and information processing.
- **Noise resilience:** Certain non-Gaussian states (e.g. GKP) offer robustness against decoherence and loss.

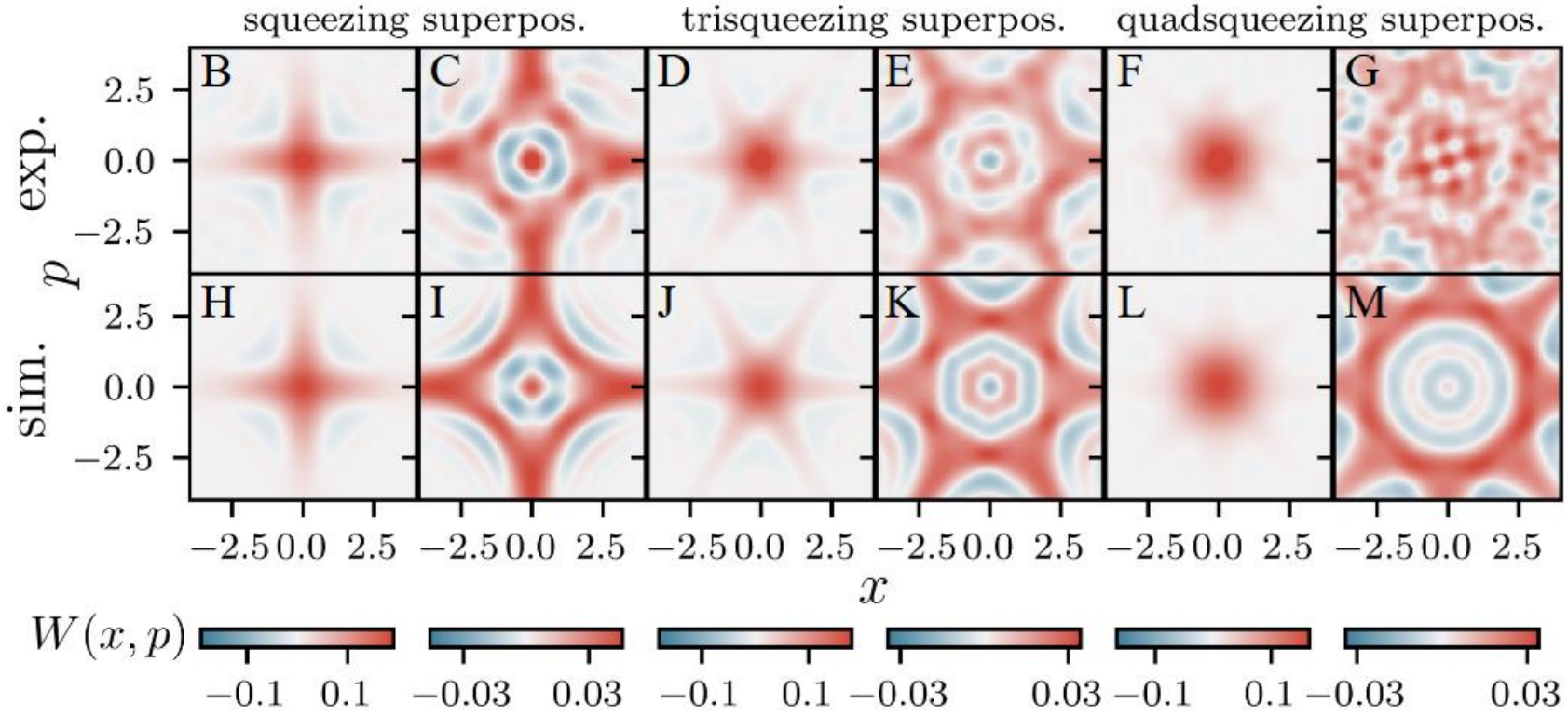
Our work in Oxford: efficient creation of non-Gaussian states of motion



$$\hat{H} = \frac{\hbar\Omega_\alpha}{2}\hat{\sigma}_\alpha(\hat{a}e^{-i\Delta t} + \hat{a}^\dagger e^{i\Delta t}) + \frac{\hbar\Omega_{\alpha'}}{2}\hat{\sigma}_{\alpha'}(\hat{a}e^{-i(m\Delta t+\phi_{\alpha'})} + \hat{a}^\dagger e^{i(m\Delta t+\phi_{\alpha'})}),$$

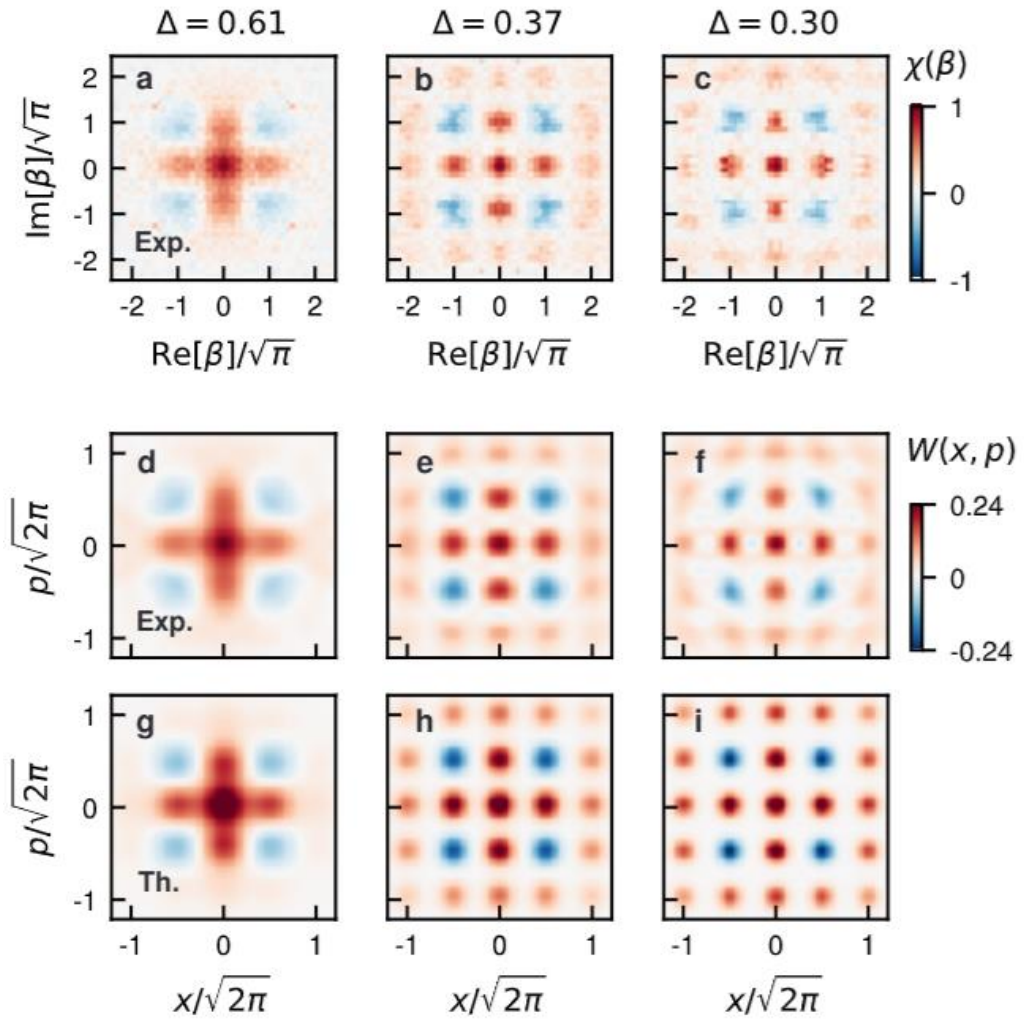
Băzăvan, O., et al. "Squeezing, trisqueezing, and quadsqueezing in a spin-oscillator system." *arXiv preprint arXiv:2403.05471* (2024).

Arbitrary superpositions of non-Gaussian states



Saner, S., et al. "Generating arbitrary superpositions of nonclassical quantum harmonic oscillator states." *arXiv preprint arXiv:2409.03482* (2024).

Grid (GKP) states for multi-parameter sensing



As Δ is increased (and $\langle \hat{n} \rangle$)

We get:

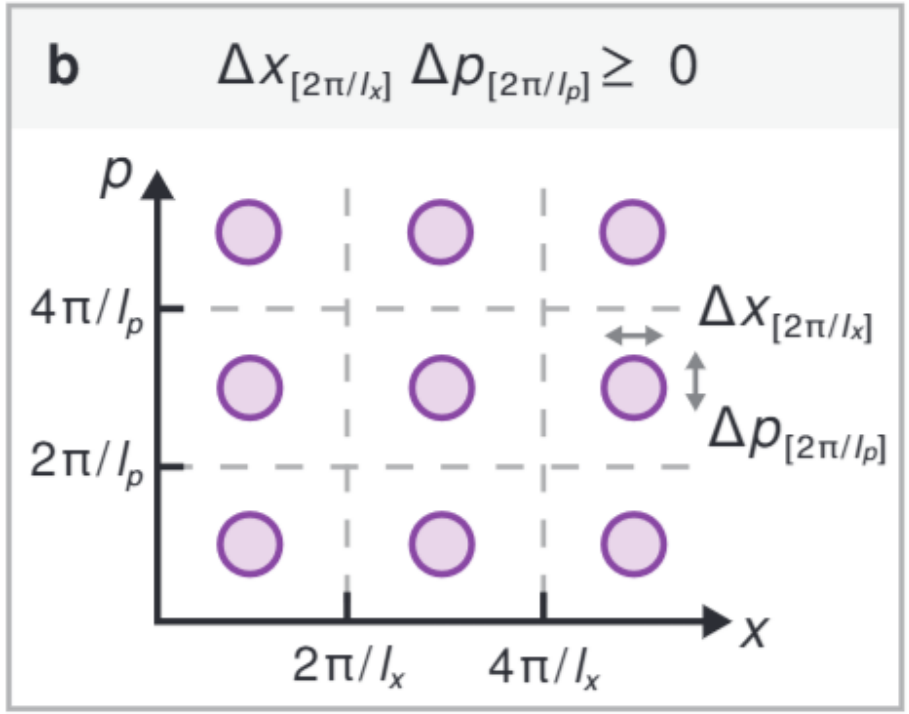
- Better defined blobs
- More squeezing
- More symmetry between x and p
- More sensitivity

Valahu, Christophe H., et al. "Quantum-enhanced multiparameter sensing in a single mode." *Science Advances* 11.39 (2025): eadw9757.

Modular operators

$$\hat{x}_{[m]} = \hat{x} \bmod m = \sum_{k\in\mathcal{Z}} \int dx \; x|x + km\rangle\langle x + km|$$

$$\hat{p}_{[m]} = \hat{p} \bmod m = \sum_{k\in\mathcal{Z}} \int dp \; p|p + km\rangle\langle p + km|$$



Another way to represent modular translations is using “Shift” operators

$$\hat{S}_x = e^{-il_x\hat{x}} = \hat{D}(-il_x/\sqrt{2}),$$
$$\hat{S}_p = e^{-il_p\hat{p}} = \hat{D}(l_p/\sqrt{2}),$$

$$[D(\alpha), D(\beta)] = (e^{\theta} - e^{-\theta})D(\beta)D(\alpha).$$
$$e^{\theta} - e^{-\theta} = 2\sinh(\theta)$$
$$\theta = \frac{1}{2}(\alpha\beta^* - \alpha^*\beta),$$

If, for example:

$$l_x = l_p = \sqrt{2\pi d}$$

$$l_x l_p = 2\pi d \text{ for positive integer } d$$

$$[\hat{S}_x, \hat{S}_p] = 0$$

And both can be measured simultaneously

REVIEWS OF MODERN PHYSICS VOLUME 40, NUMBER 2 APRIL 1968

Phase and Angle Variables in Quantum Mechanics*

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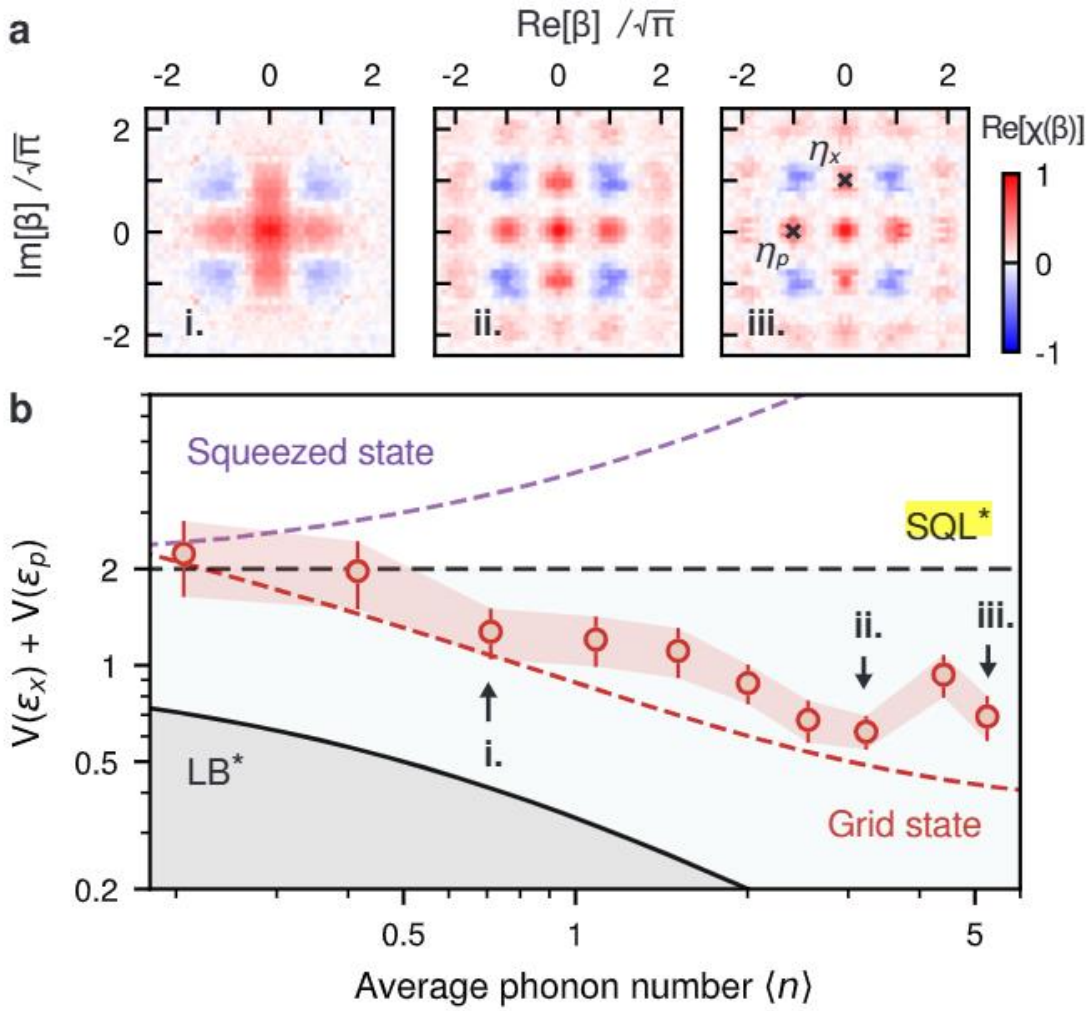
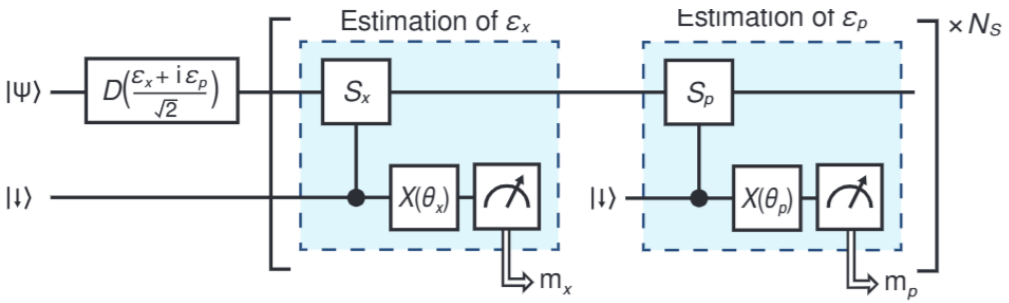
MICHAEL MARTIN NIETO
Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, New York

The quantum-mechanical description of phase and angle variables is reviewed, with emphasis on the proper mathematical description of these coordinates. The relations among the operators and state vectors under consideration are clarified in the context of the Heisenberg uncertainty relations. The familiar case of the azimuthal angle variable φ and its "conjugate" angular momentum L_z is discussed. Various pitfalls associated with the periodicity problem are avoided by employing periodic variables ($\sin\varphi$ and $\cos\varphi$) to describe the phase variable. Well-defined uncertainty relations are derived and discussed. A detailed analysis of the three-dimensional harmonic oscillator excited in coherent states is given. A detailed analysis of the simple harmonic oscillator is given. The usual assumption that a (Hermitian) phase operator ϕ (conjugate to the number operator N) exists is shown to be erroneous. However, cosine and sine operators C and S exist and are the appropriate phase variables. A Poisson bracket argument using action-angle (rather J, $\cos\phi$, $\sin\phi$) variables is used to deduce C and S. The spectra and eigenfunctions of these operators are investigated, along with the important "phase-difference" periodic variables. The properties of the oscillator variables in the various types of states are analyzed with special attention to the uncertainty relations and the transition to the classical limit. The utility of coherent states as a basis for the description of the evolution of the density matrix is emphasized. In this basis it is easy to identify the classical Liouville equation in action-angle variables along with quantum-mechanical "corrections." Mention is made of possible physical applications to superfluid systems.

Sydney experiment:





SQL * = simultaneous standard quantum limit

LB* = simultaneous lower bound of the Fisher information

The lowest variance is obtained at ⟨n⟩ = 3.2(Δ = 0.37), giving a gain of **5.1(5) dB** over the simultaneous SQL

(here and throughout, the terminology SQL*is used to refer to the simultaneous standard quantum limit for two non-commuting quadrature measurements).

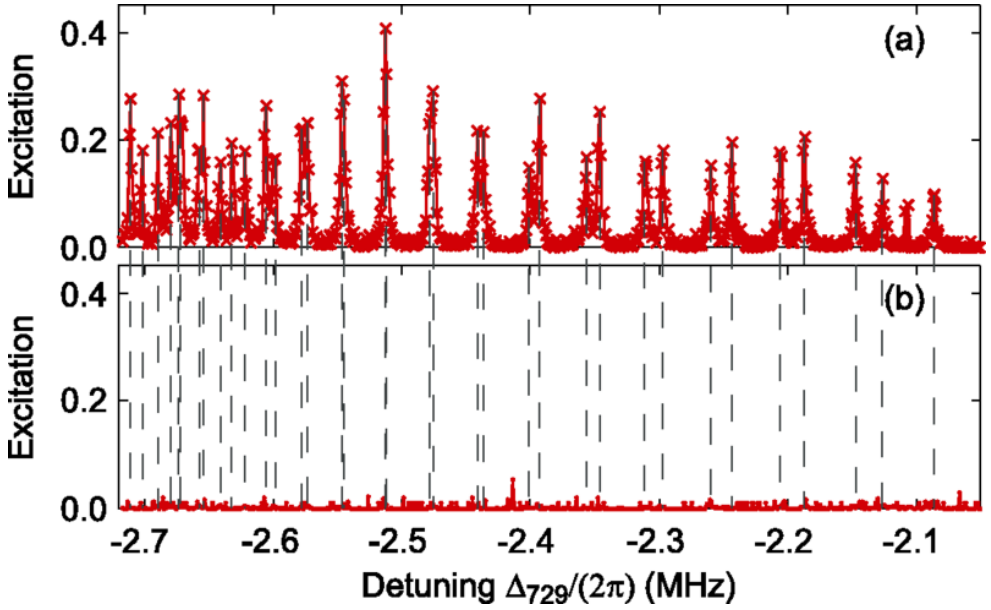
We observe that the variance does not further decrease for ⟨n⟩ > 3.2, and attribute this to bosonic dephasing

Valahu, Christophe H., et al. "Quantum-enhanced multiparameter sensing in a single mode." *Science Advances* 11.39 (2025): eadw9757.

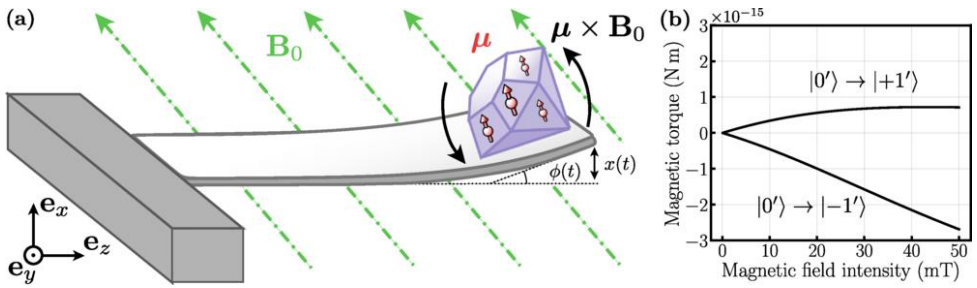
Many opportunities and challenges

- Ions are small but massive particles (10^{-25} kg)
- Narrow band sensors
- Each ion in a Coulomb crystal introduces 3 motional modes.
- In principle, each of the motional modes can be controlled independently
- The physics of creating highly quantum states is the same in any system where you can use Spin-depend forces

$$\hat{U}(t) = |\uparrow\rangle\langle\uparrow| \hat{D}(\alpha(t)) \; + \; |\downarrow\rangle\langle\downarrow| \hat{D}(-\alpha(t)),$$



Some interesting recent results



m_{eff}= 10^{-10} kg

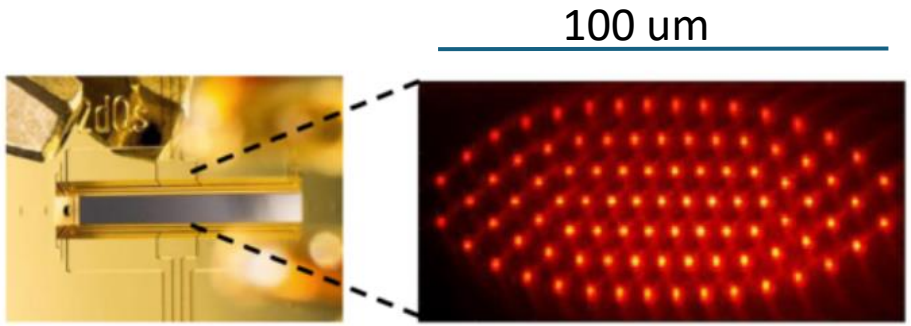
Perdriat, Maxime, et al.
"**Spin-dependent force from an NV center ensemble on a microlever.**"
Physical Review B 112.9 (2025): 094419.

Promising for the creation of quantum states of motion!

Probing high-frequency gravitational waves with entangled vibrational qubits in linear Paul traps

Ryoto Takai

KEK Theory Center, Tsukuba 305-0801, Japan
The Graduate University for Advanced Studies, SOKENDAI, Tsukuba 305-0801, Japan
Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan



Ground state cooling of radial modes of a 2D crystal. Quantum control of the global oscillation modes of the crystal

Hainzer, H., et al. "Correlation spectroscopy with multiqubit-enhanced phase estimation." *Physical Review X* 14.1 (2024): 011033.

Ultralight dark matter detection with trapped-ion interferometry

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[4] *Theoretical Particle Physics and Cosmology (TPPC) Group, Department of Physics, King's College London, Strand, London, WC2R 2LS, UK*
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(Dated: July 25, 2025)