Distributed quantum sensing with networks of entangled atomic ensembles

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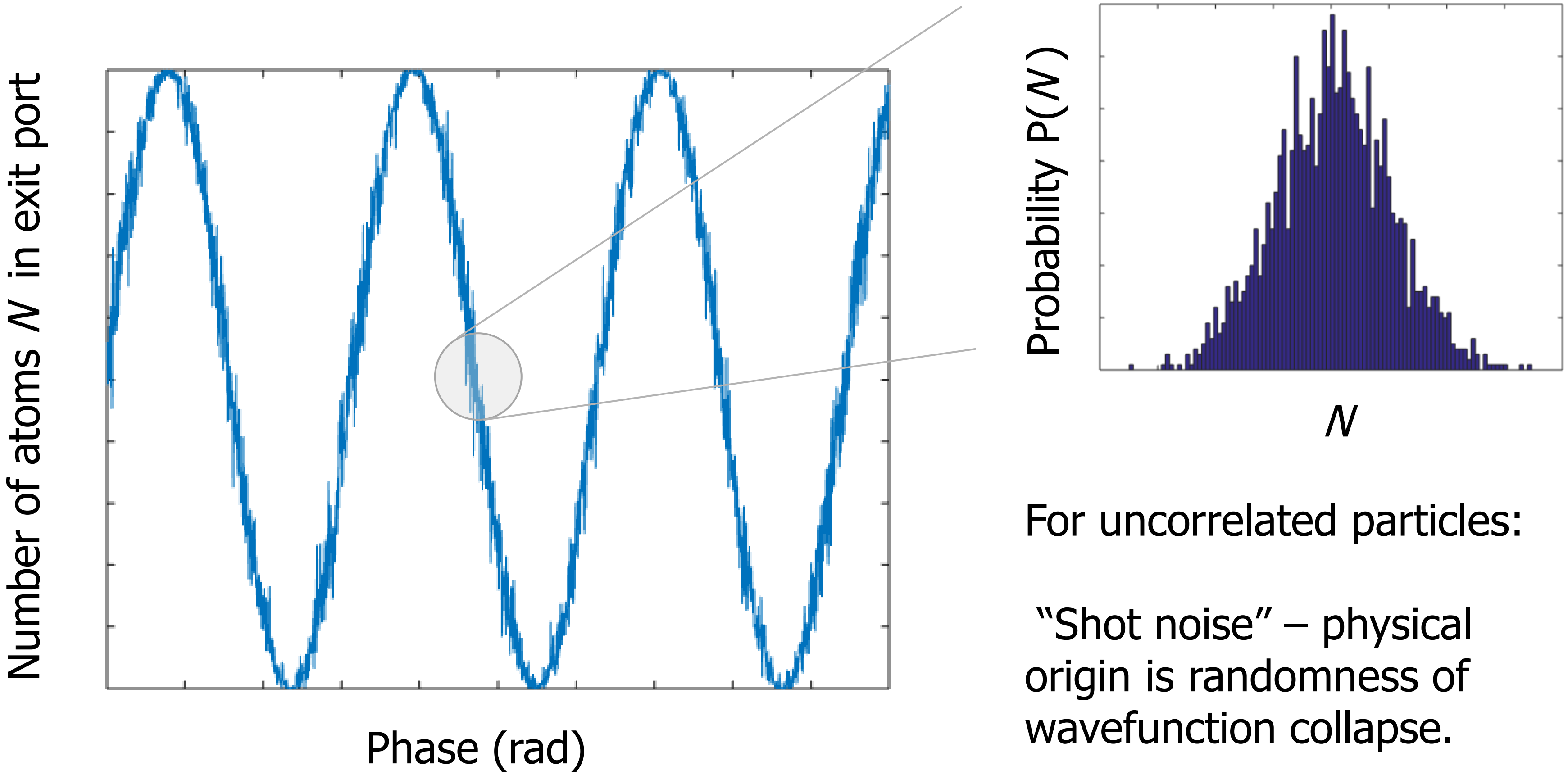
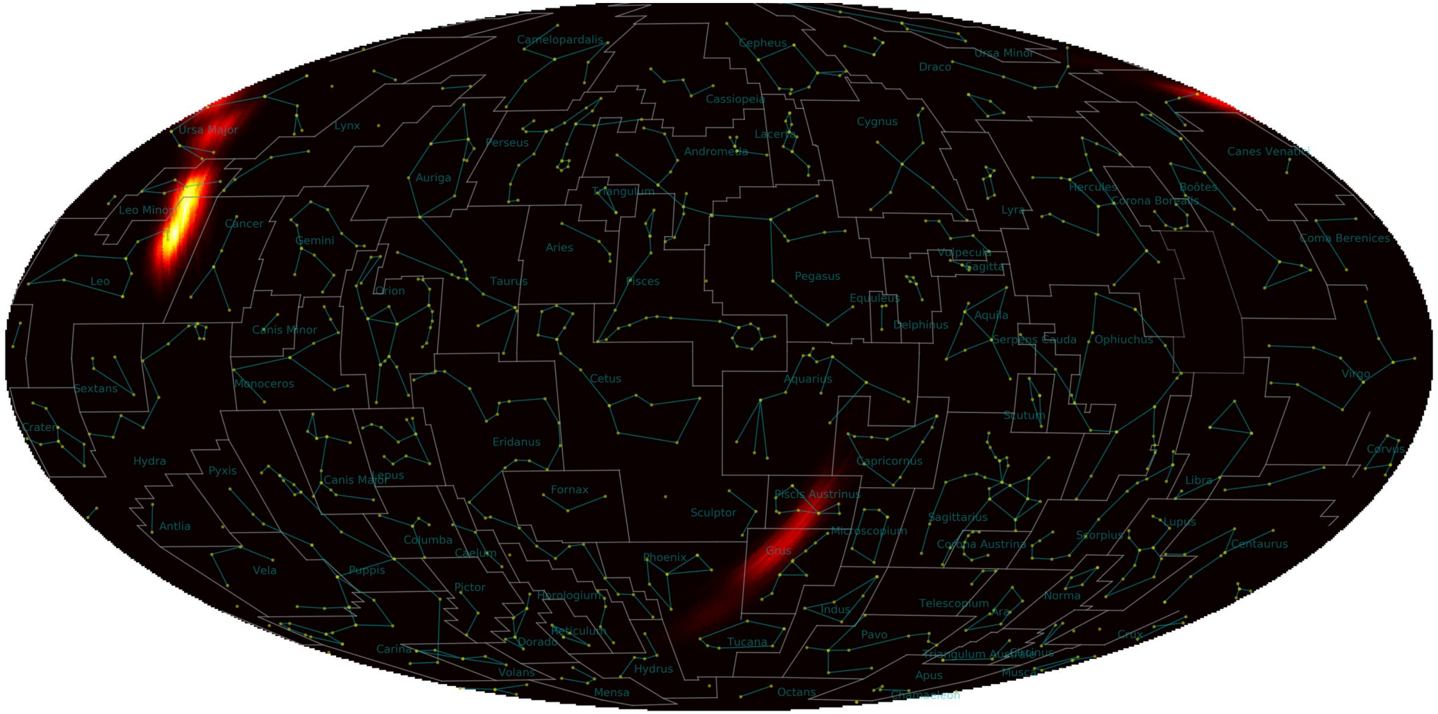
Noise in interferometric sensors



For uncorrelated particles:

“Shot noise” – physical origin is randomness of wavefunction collapse.

LIGO runs with squeezed light

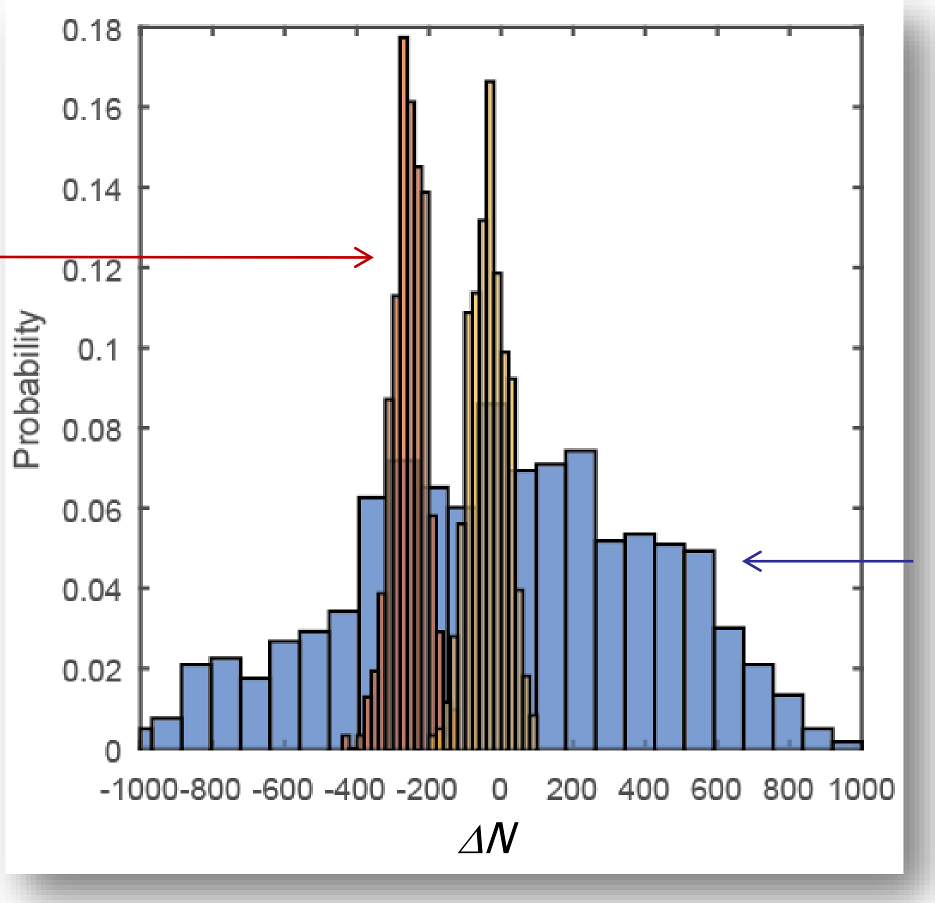


https://www.ligo.caltech.edu/news/ligo20190812

Spin-sqeezed (entangled) single node metrology

Consider N ~ 1e6 atoms, each in a quantum superposition of two ground state energy levels.

Measure probability of finding atoms in one of these states



Entangled atoms

Reduced read-out noise

This data: 20 dB variance reduction

Uncorrelated atoms

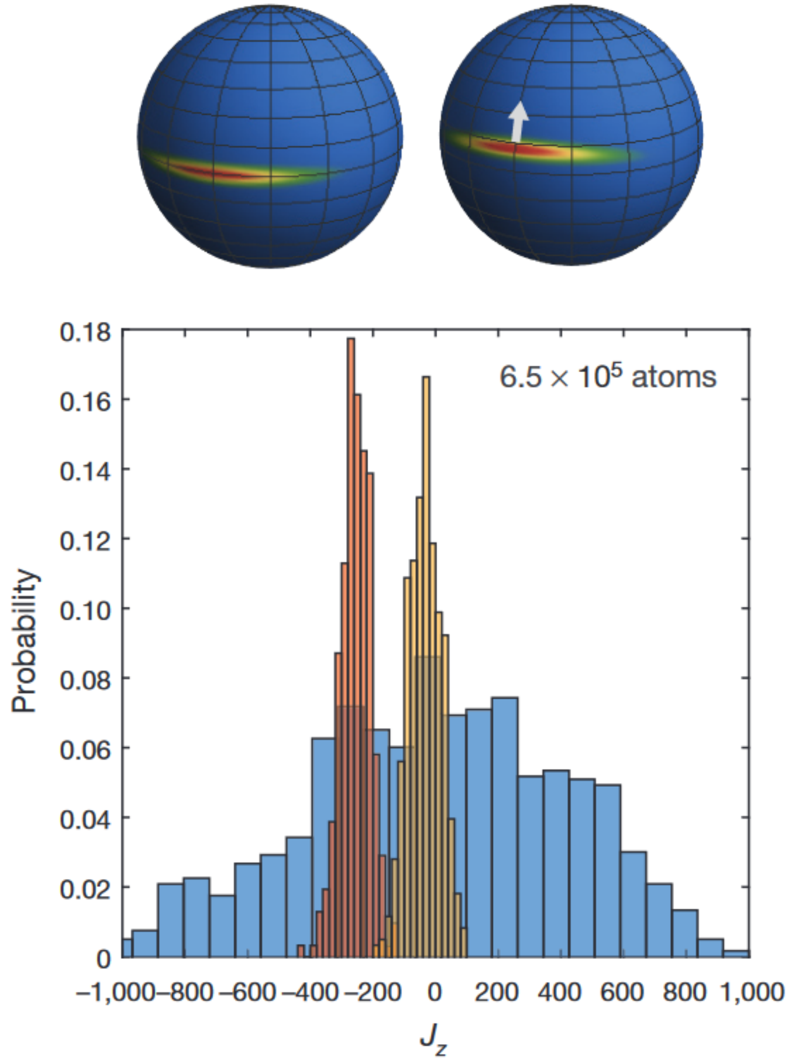
"Shot-noise" Coin-toss statistics

O. Hosten, et al., Nature (2016).

Metrology requires coherence

Noise is reduced via squeezing.

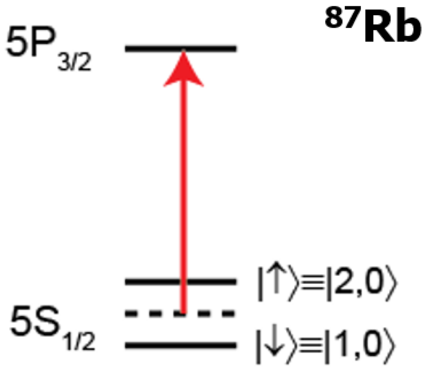
Coherent response is preserved.

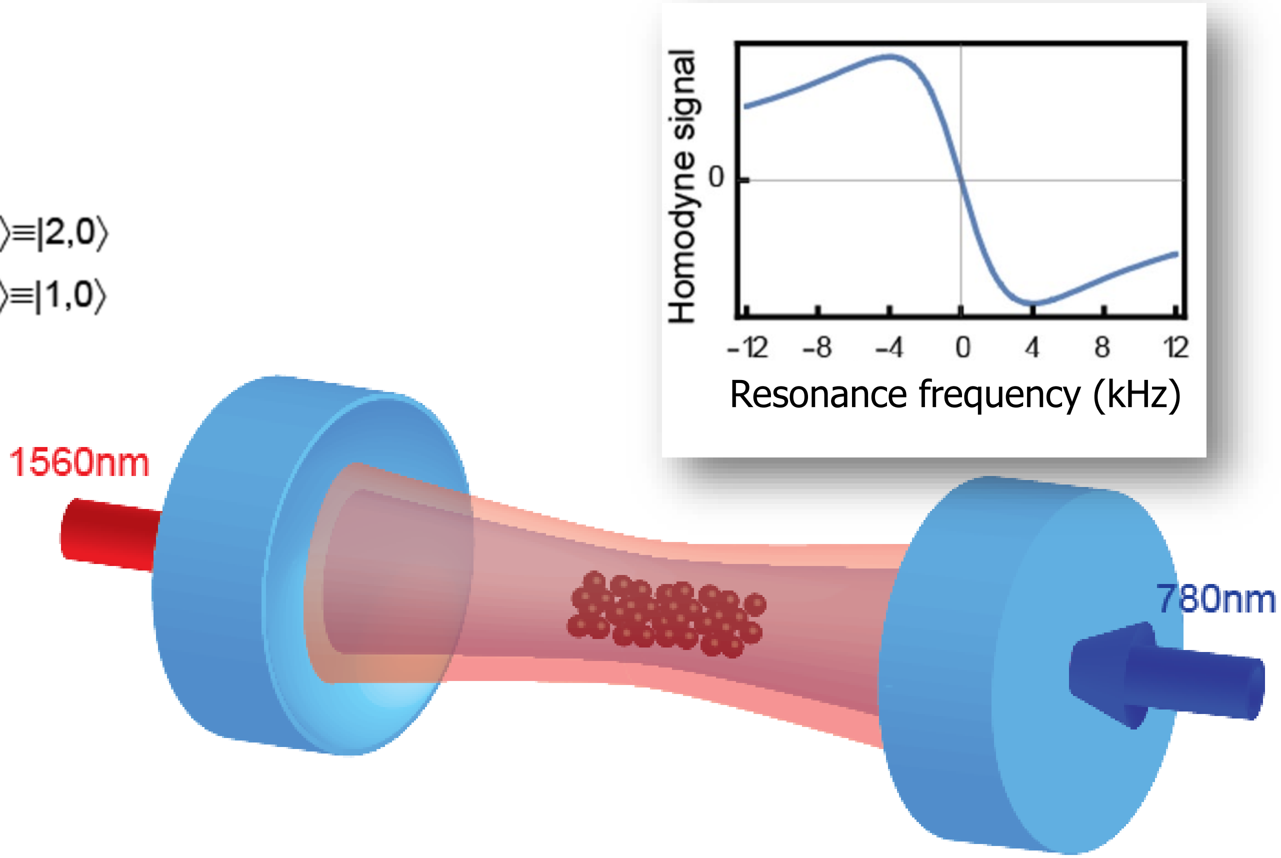


Our method: cavity assisted entanglement

Dispersive atom-cavity interactions are used to realize a quantum non-demolition measurement of atom number.

Measurement results in a metrologically useful many-atom entangled state.



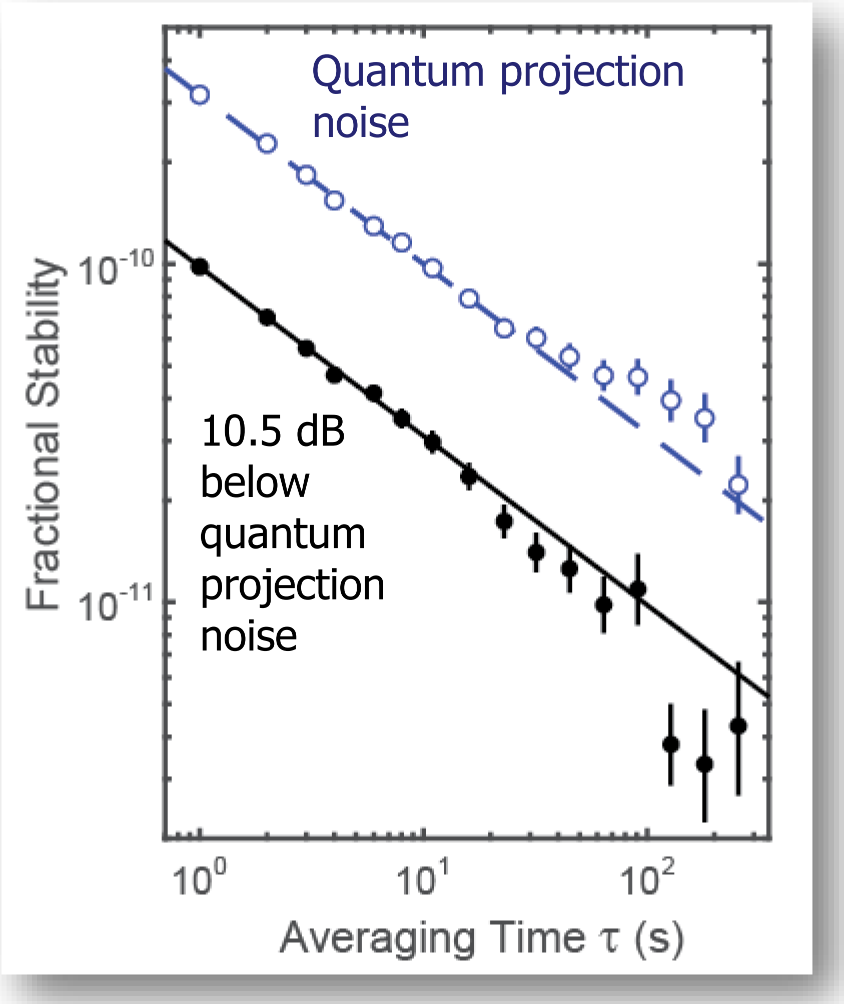


Atomic clock implementation

1×10^5 atoms

220μs interrogation time

1 s update rate



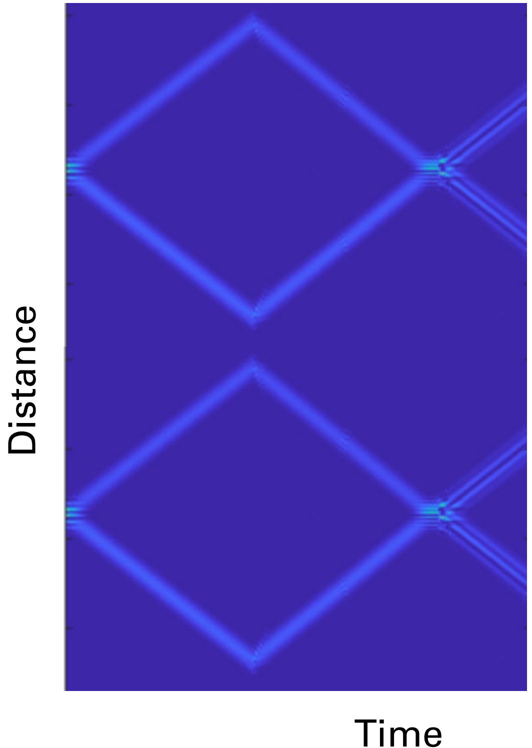
Limited by μ-wave LO phase noise. Hosten, et al., Nature (2016)

Two node quantum sensing

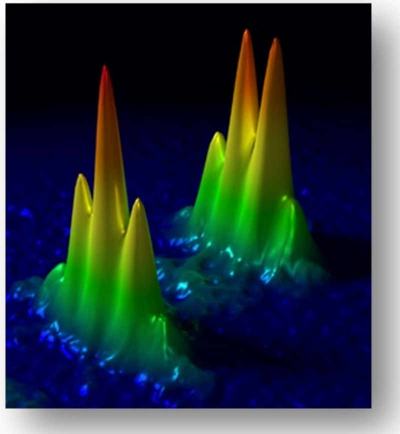
Many precision metrology protocols require comparison between two sensor outputs.

- differential clock measurements
- differential atom interferometry

How can entanglement be exploited to improve the noise performance of the sensor network?



Atom interferometer trajectories

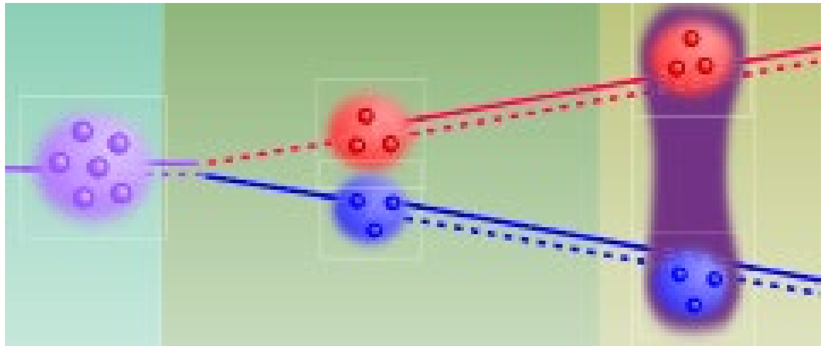


Atom interferometer outputs

Asenbaum, et al. , PRL 2017

Two node entanglement

Experimental protocol:

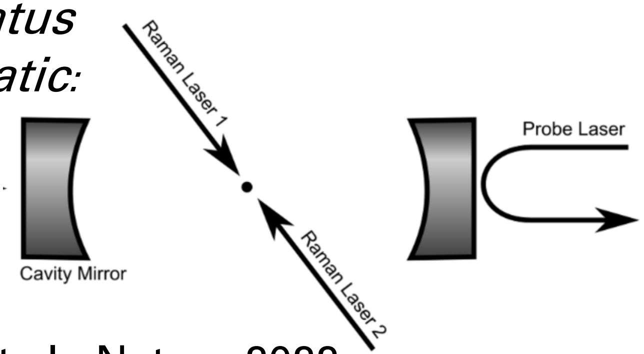


Initial ensemble, coherent spin state

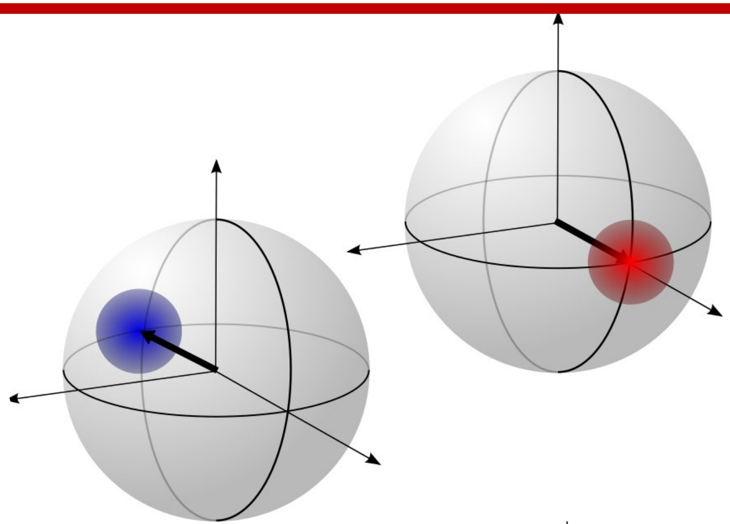
Two nodes (via Doppler sensitive Raman transitions)

Cavity-assisted entanglement

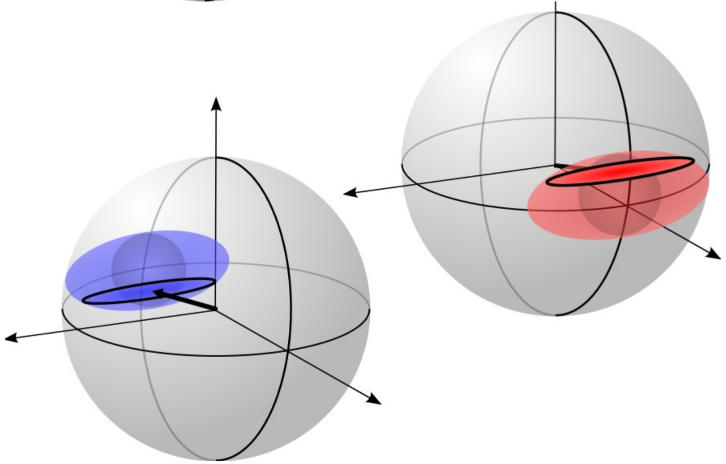
Apparatus schematic:



Malia, et al., Nature 2022



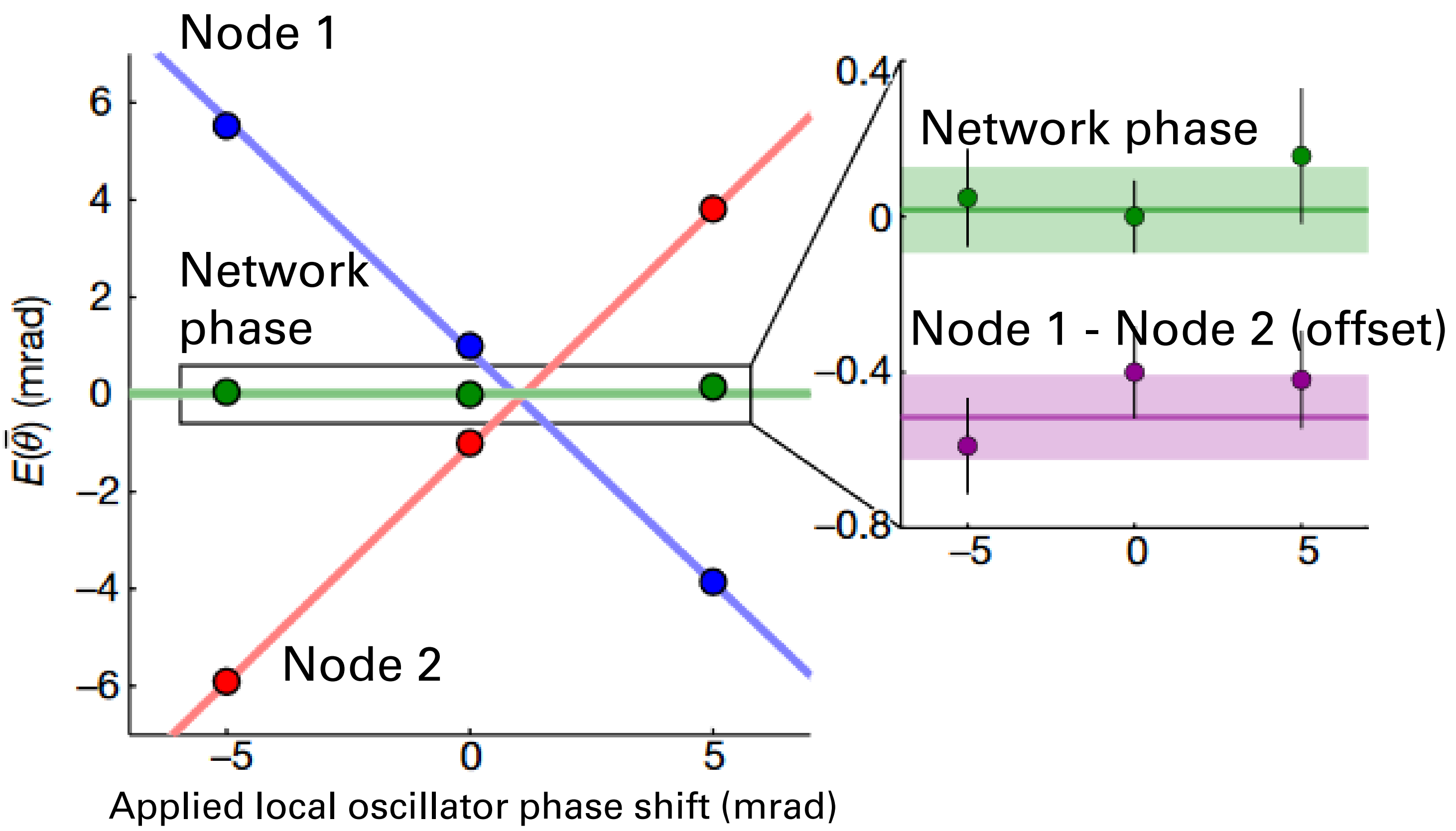
Two spatially separated nodes



Node entanglement via projective cavity measurement

Entanglement interaction leads to broadening of the marginal distribution and number correlation of the conditional distribution.

Two node network phase observable

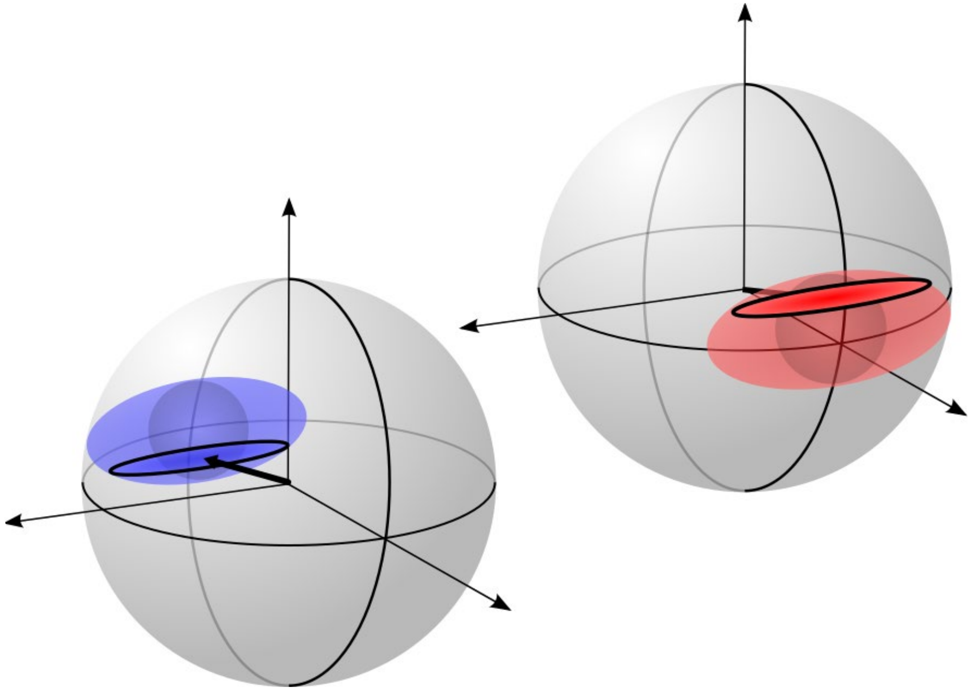


Network (collective) phase observable for M network nodes:

$$\bar{\theta} = \frac{1}{M}\sum_{m=1}^{M} \delta\theta^{(m)}$$

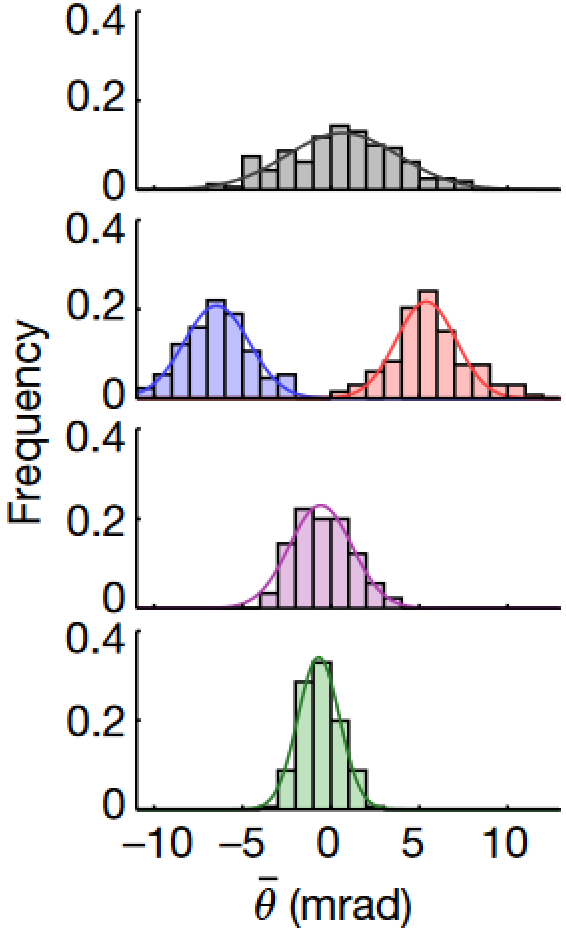
Observable suppresses local oscillator phase noise.

Two node noise



Noise inferred from a second cavity interrogation.

Both nodes share the common cavity mode.



Coherent spin state, 2 node response

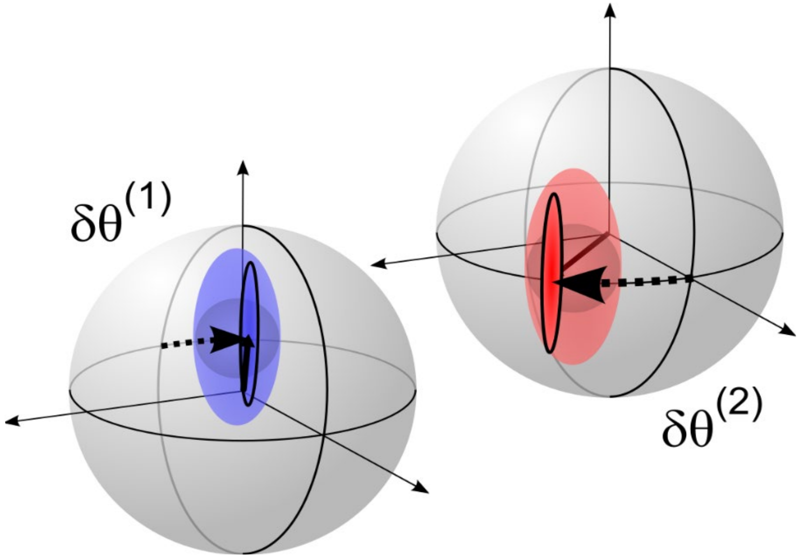
Single node coherent spin state response

Node separable (each node independently squeezed)

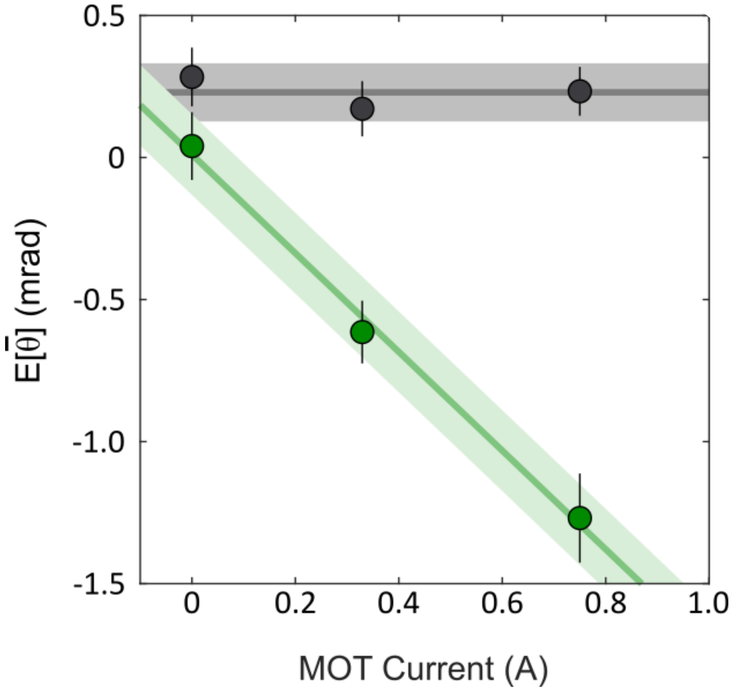
Node entangled

Malia, et al., Nature 2022

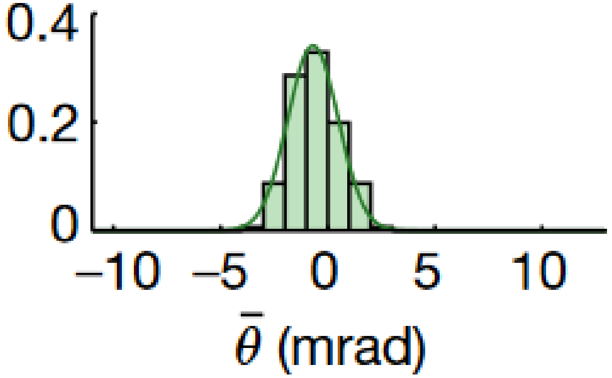
Two node metrology



- Prepare 2 node entangled state (non-destructive measurement of J_z)
- Microwave Ramsey sequence
- Detection (second measurement of J_z)

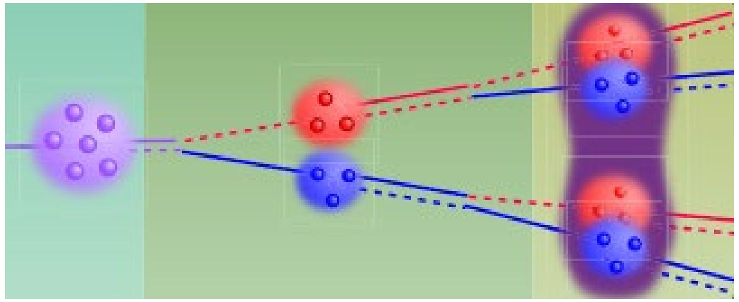


Measured differential phase shift due to magnetic field gradient (green).



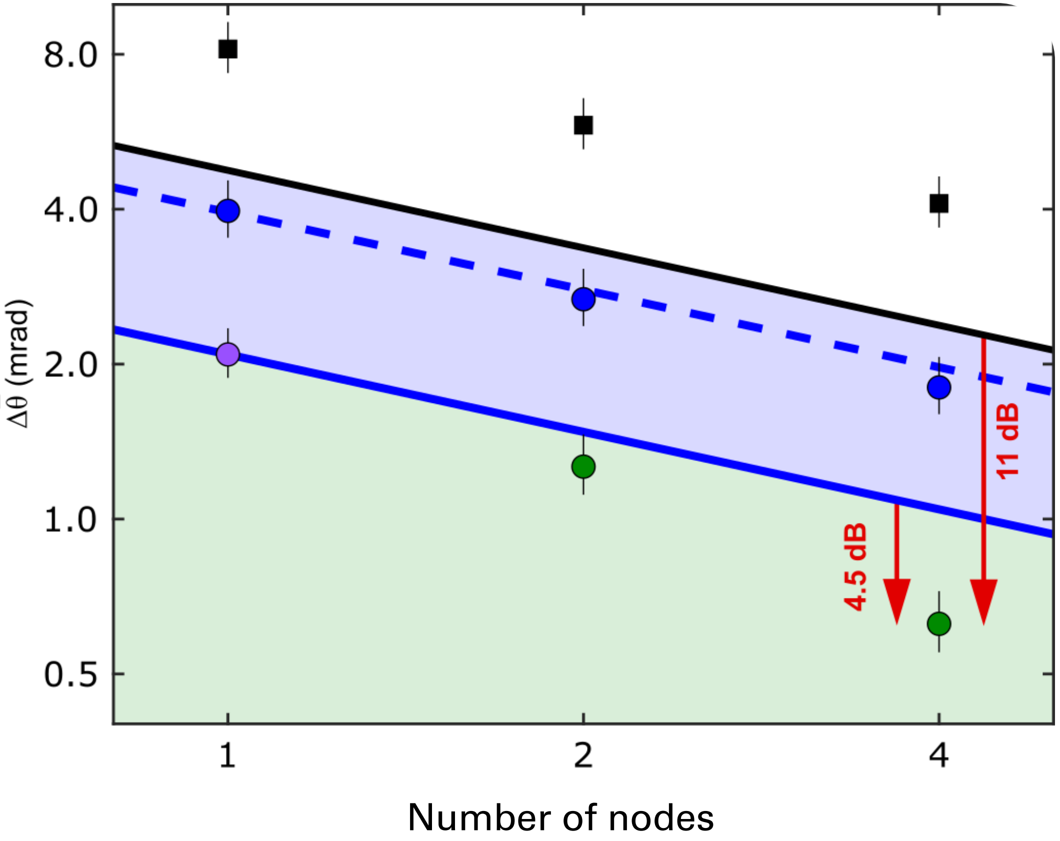
No change in width of detection noise histogram vs. applied phase shift.

Two and four node metrological noise improvement



4 node entangled state preparation

Network phase noise vs. number of nodes



Coherent state + local oscillator noise (black squares)

Projection noise (black line)

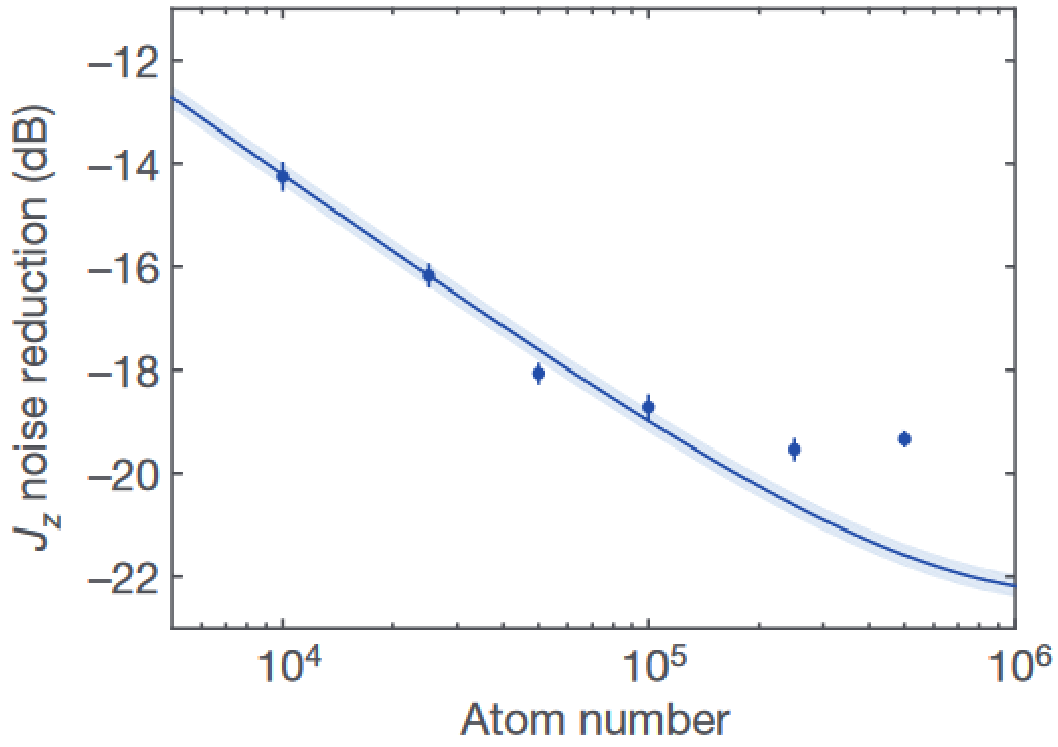
Node separable + local oscillator noise (blue circles)

Node entangled noise (green)

Why?

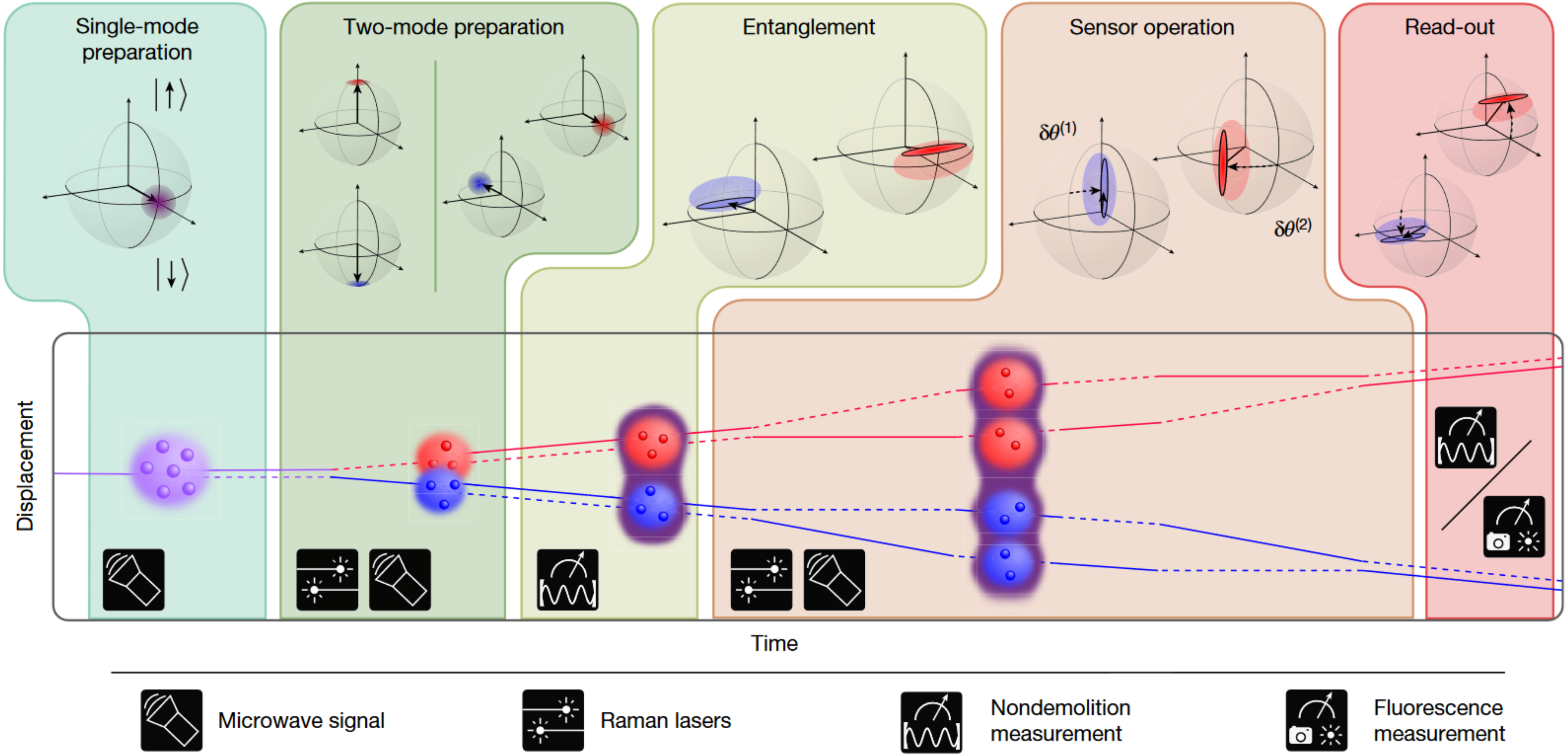
Squeezing efficacy for projective, cavity-assisted, squeezing improves with atom number.

More nodes = more atoms.

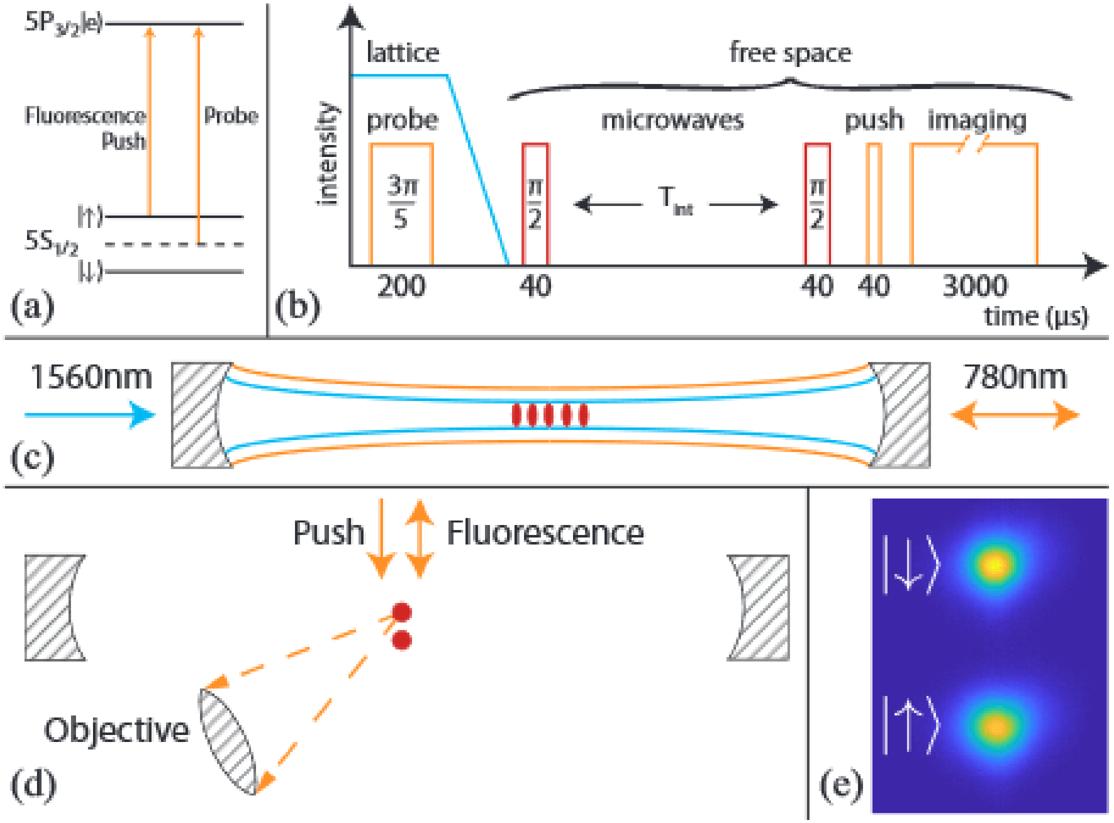


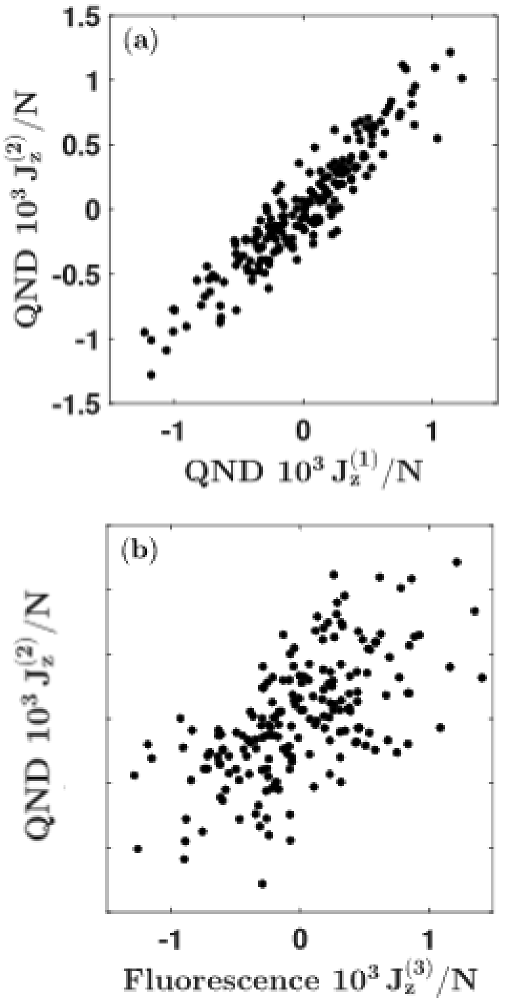
Hosten, et al., Natue 2016

Application to 2 node atom interferometry



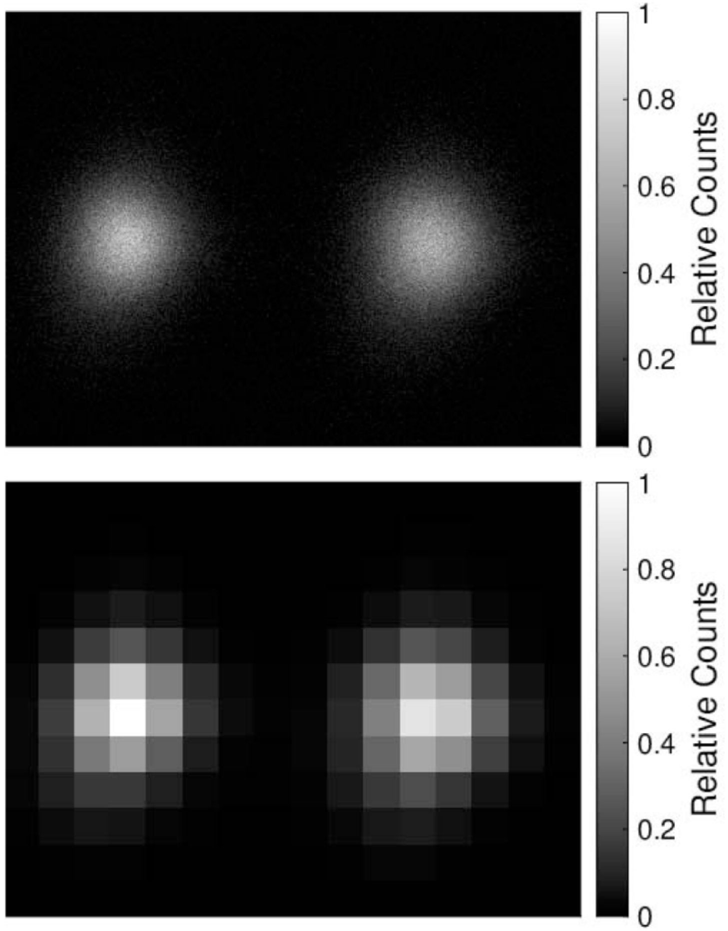
Fluorescence detection



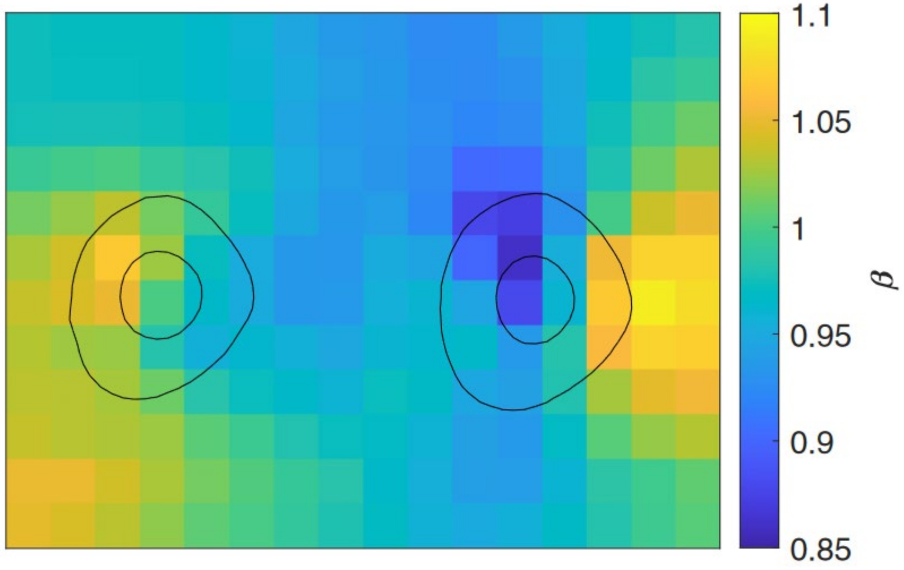


Malia, et al., PRL 2020

Machine learning to train detection system



Raw and pixelated images used for training.



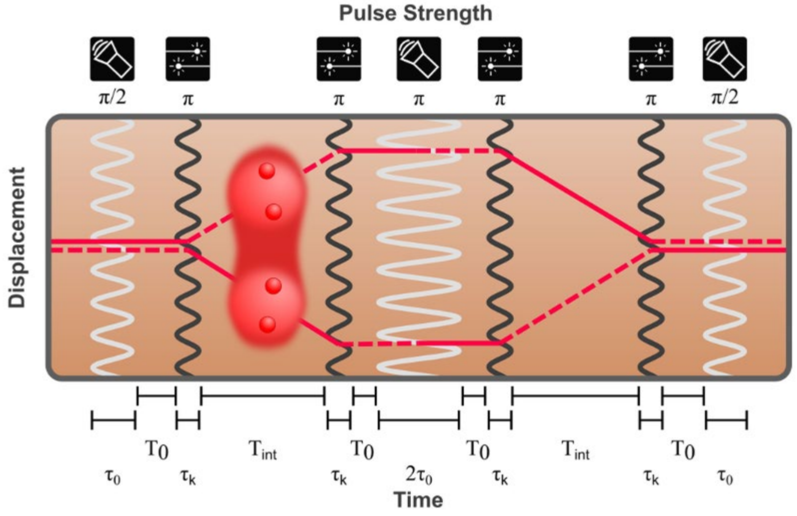
Use machine learning to correct detection inhomogeneities associated with fluorescence imaging.

Train fluorescent images with truth from cavity output.

27% reduction in measurement noise (7.2 dB squeezing).

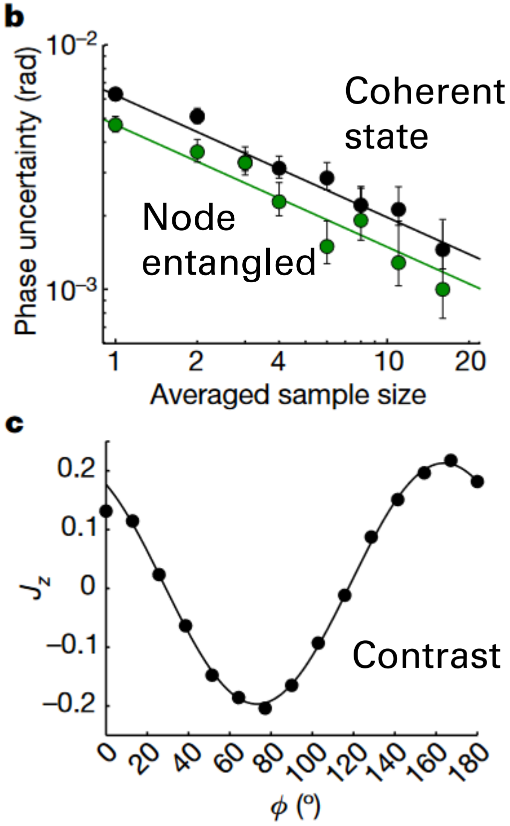
Malia, et al., PRA 2022

Two node atom interferometry demonstration



Single node interferometer sequence.
Microwave interaction (white);
Raman interaction (black).

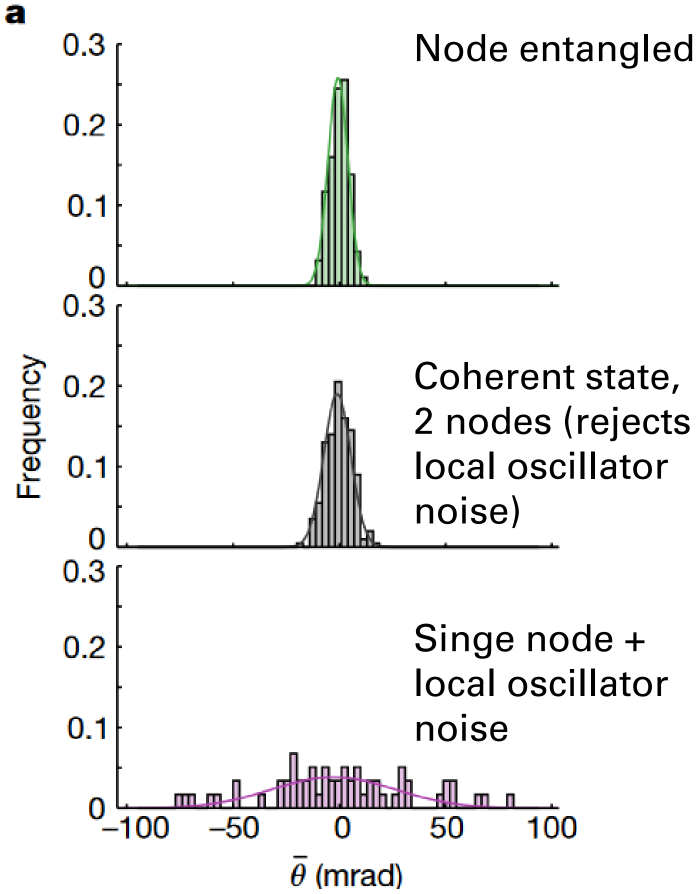
Nodes are separated by 0.16 mm.



Coherent state

Node entangled

Contrast



Node entangled

Coherent state, 2 nodes (rejects local oscillator noise)

Singe node + local oscillator noise

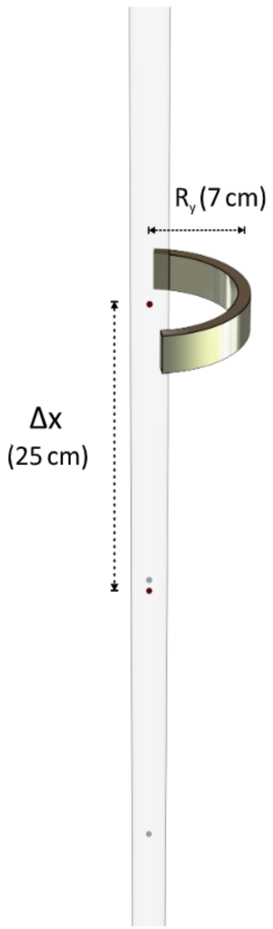
Future application to long baseline atom interferometers

1e-12 g accelerometer resolution using atom interferometry.

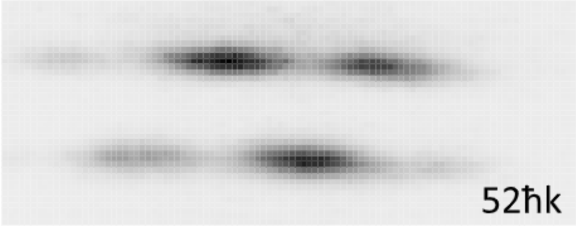
Applications in foundation of QM, DM searches, gravitational wave detection, tests of the equivalence principle and geodesy.

Apparatus

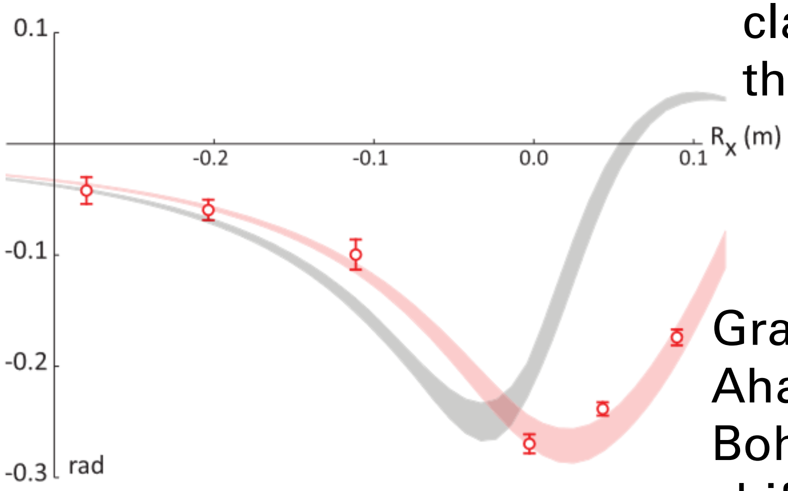
Experiment



Raw data



Results



Semi-classical theory

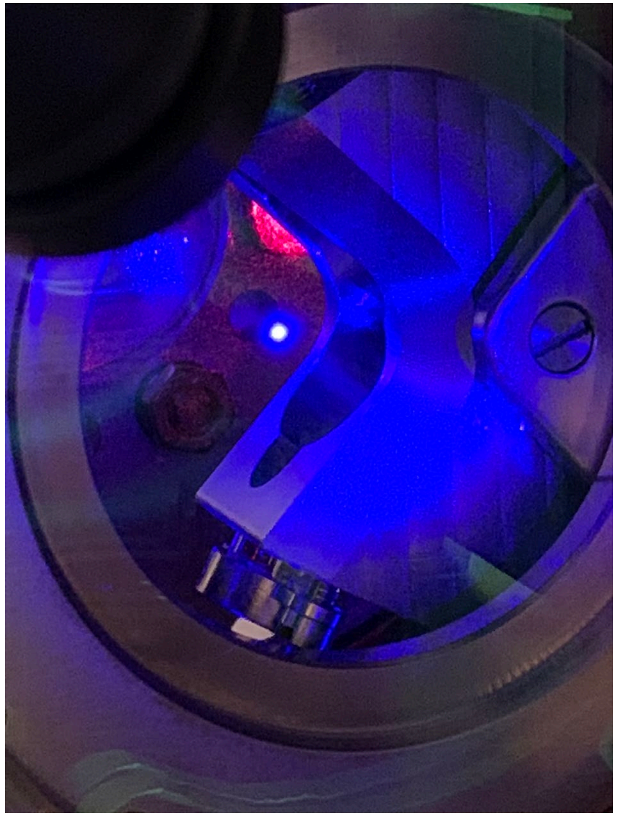
Gravitational Aharonov-Bohm phase shift

Overstreet, et al., Science 2022

Future

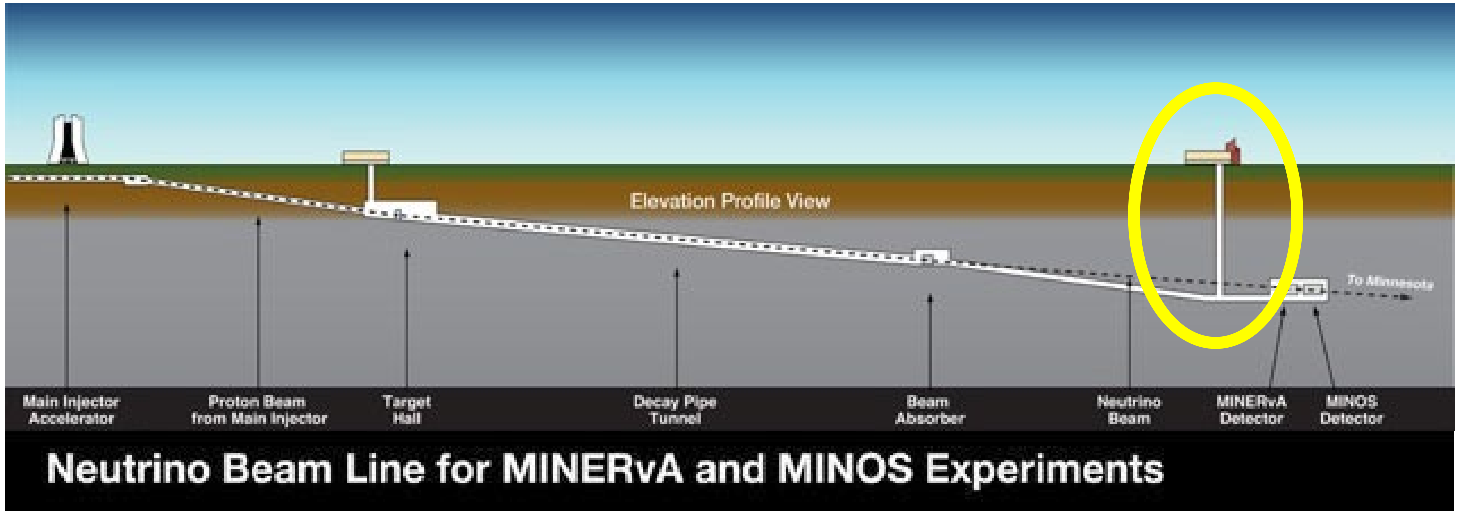
Currently working to implement this protocol with Sr optical clocks:

- gravitational redshift between entangled clock ensembles
- gravitational Aharonov-Bohm effect with entangled ensembles
- large distance scale for network using multiple cavities and low-loss photonic link.



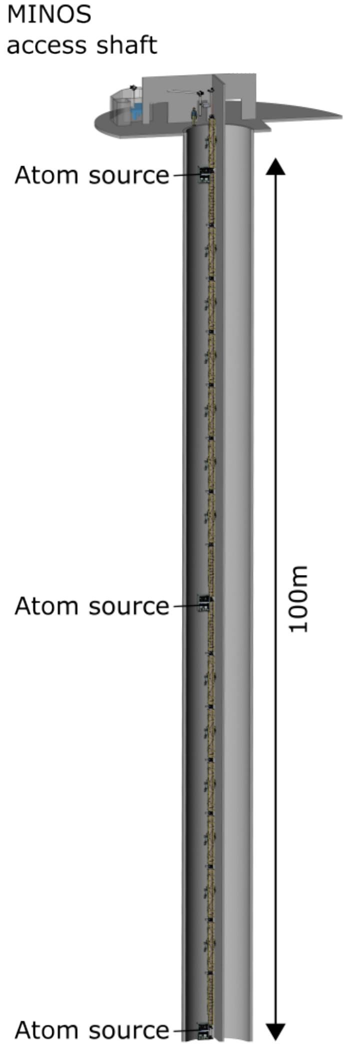
Incorporate into the MAGIS-100 detector

MAGIS-100



100 m separation between atom interferometers

Prototype 0.3 – 3 Hz gravitational wave detector



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Thanks

Onur Hosten (IST Austria)
Nils Engelsen (Chalmers)
Rajiv Krishnakumar (start-up)
Julian Martinez (Brookhaven)
Ben Malia (Cornell)
Yunfan Wu (start-up)
Guglielmo Panelli (PhD student)
Erik Porter (PhD student)
Shuan Burd (post-doc)