INERTIAL SENSING WITH QUANTUM GASES

Inertial Measurement Units (IMU)

Accelerometer:

Sense acceleration

Gyroscope:

Sense rotation

Magnetometer:

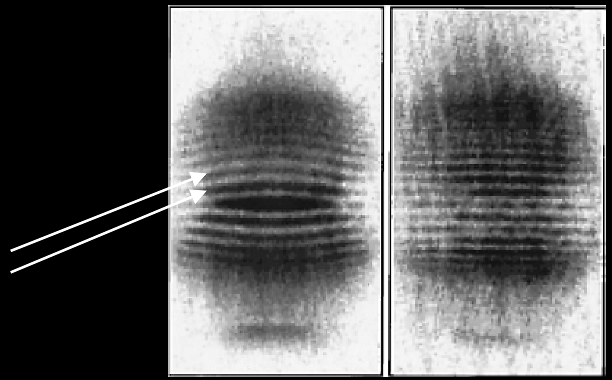
Measure magnetic fields

Atom-based IMUs

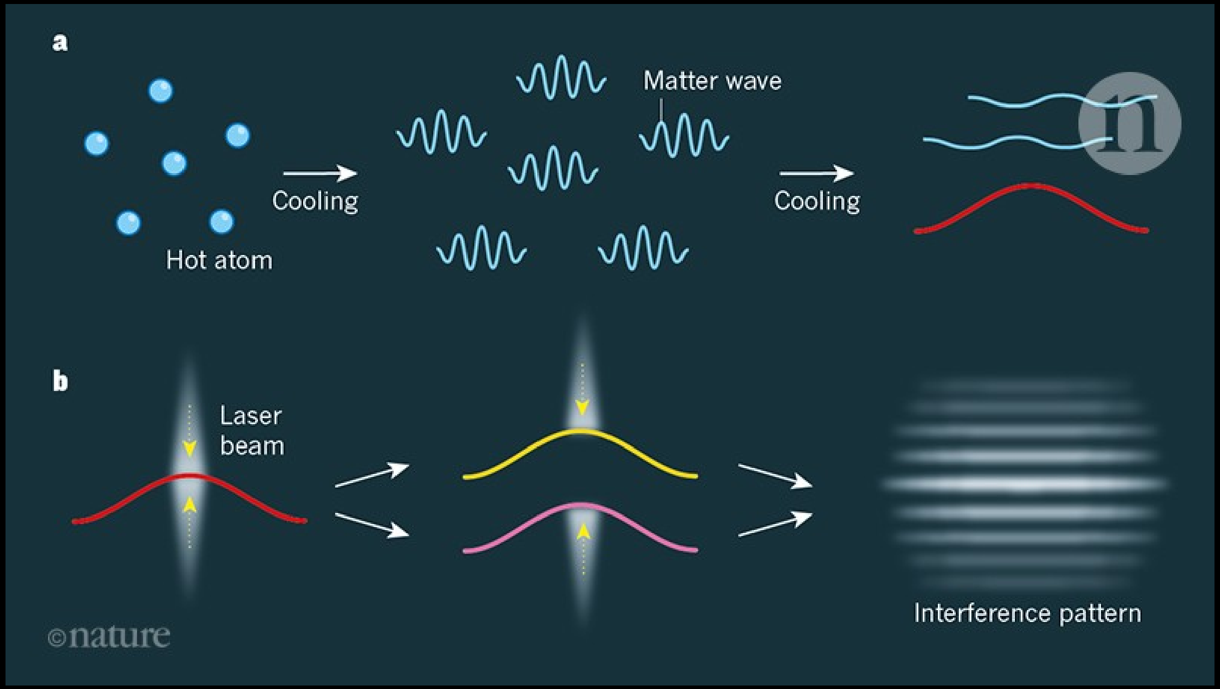
- Key principle: Employ ultra-cold atoms as “sensors”
- Use interference effects to measure *acceleration, magnetic fields and absolute gravity gradients*
- Cool and manipulate atoms in sequences designated for high-precision sensing.

Atom Interferometry

Creating overlapping waves of matter



Fringes

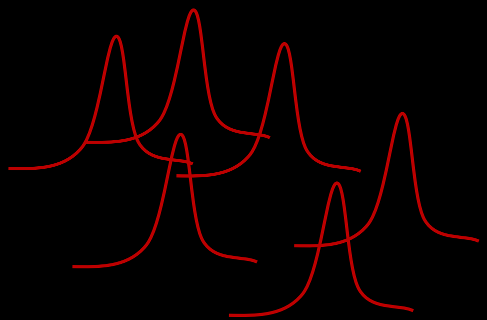


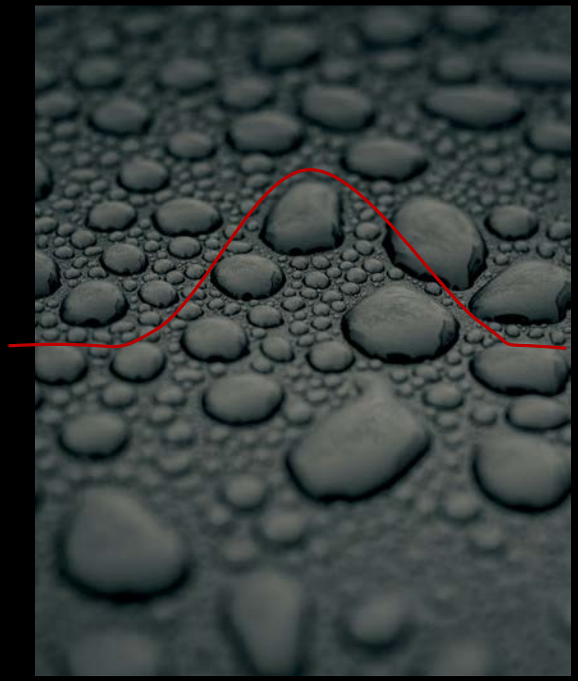
References: *Nature* **562**, 351-352 (2018)

COLD, COLDER, BEC…

Choice of source for atom-based IMUs: thermal or condensed ensembles.

which is better suited?





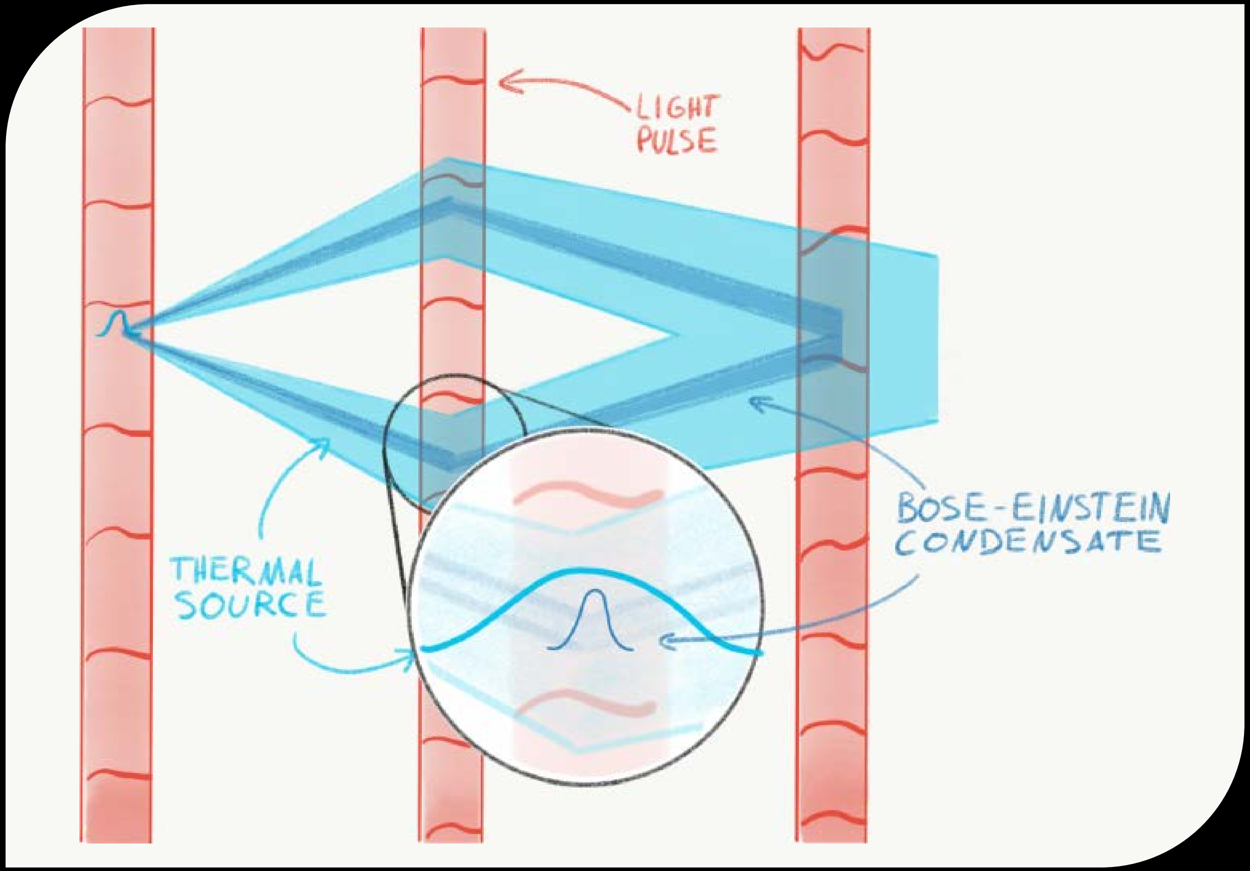
Thermal ensemble (non-condensed):

Atoms *retain individual* wavefunction

Bose-Einstein Condensed ensemble (BEC):

Atoms *form collective* wavefunction

To condense or not condense…



Differences:

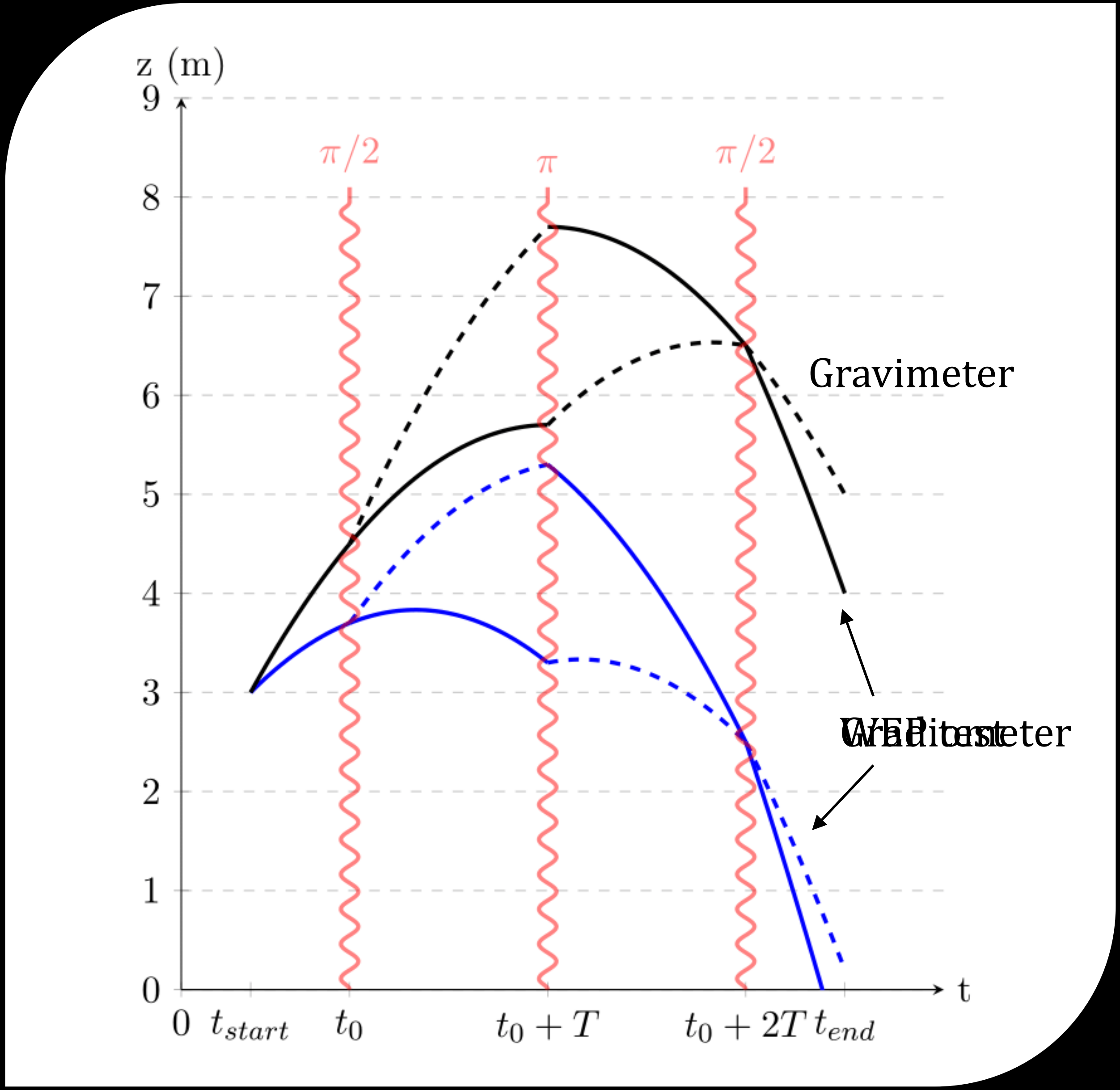
- Number of atoms
- Size of wave package
- Production rate
- Susceptibility to statistical and systematic effects

Read the paper

References: *Eur. Phys. J. D* **75**, 108 (2021)

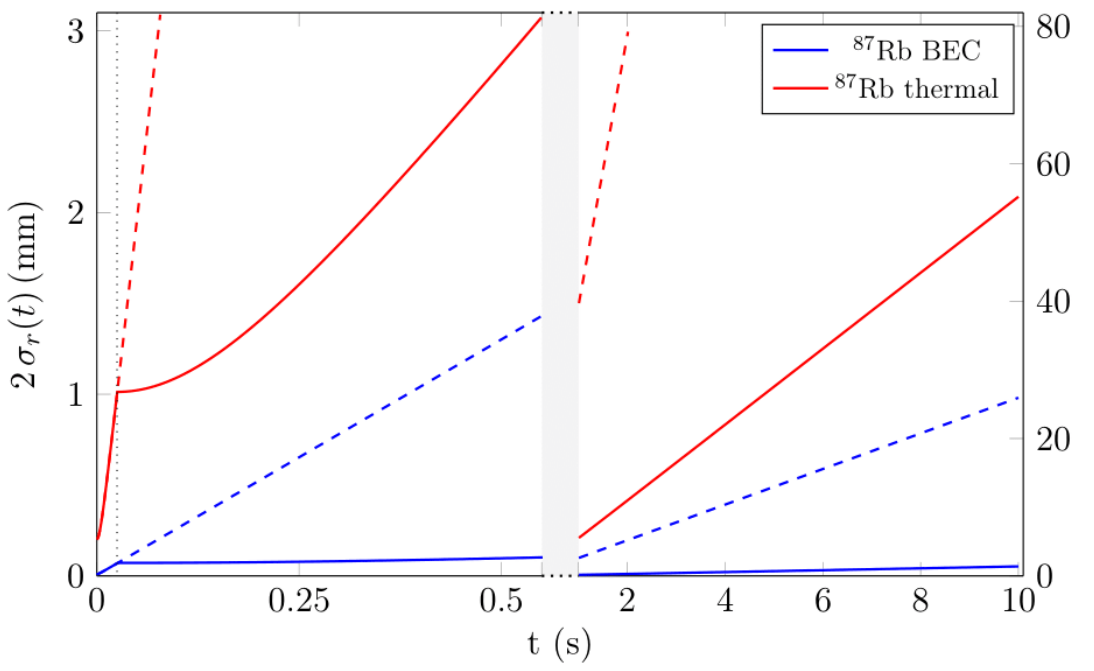
USE CASES

Gravimeter, Gradiometer, WEP test

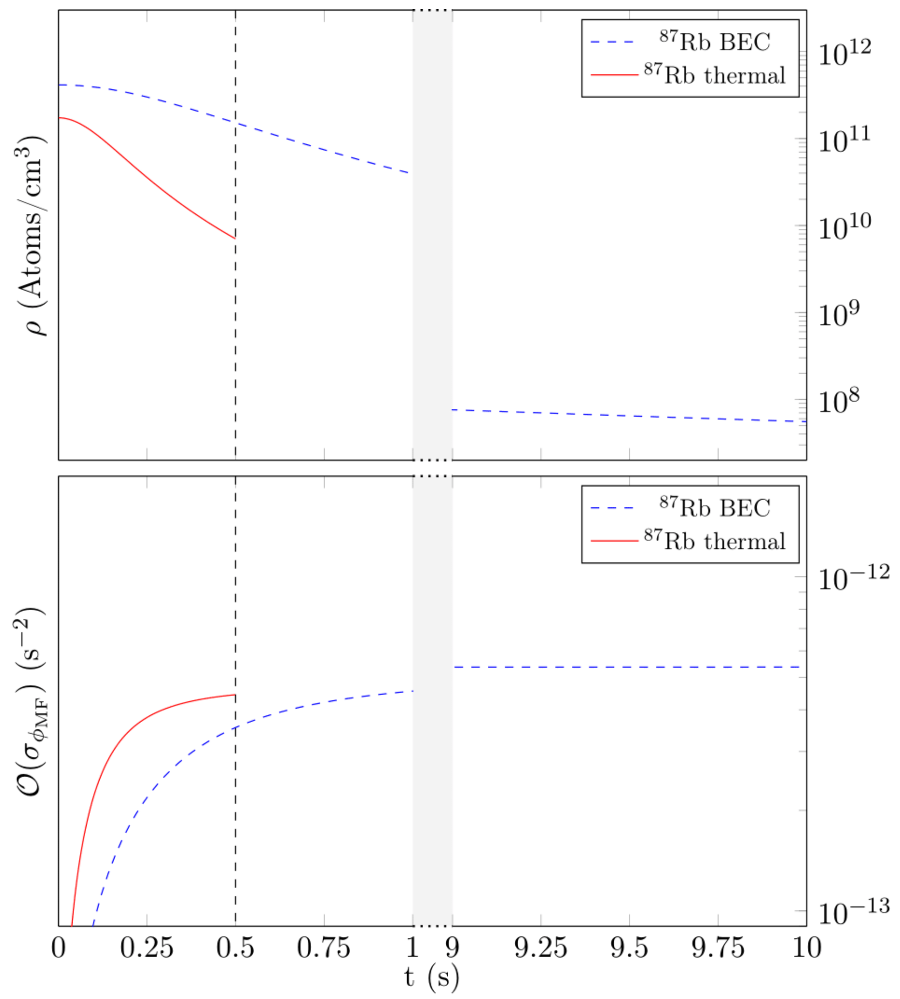


References: *Eur. Phys. J. D* **75**, 108 (2021)

EXPANSION AND COLLIMATION



- Delta Kick Collimation (DKC) to reduce momentum width
- Preservation of phase space density: increased ensemble size
- Necessitates trade-off: expansion rate vs ensemble size.



MEAN FIELD EFFECTS

- Short time-scales: BEC suffers from much stronger mean field effects
- Long time-scales: BECs outperform thermal ensembles
- Reason: different density and expansion behavior

SIZE MATTERS…

Parameter\Case	Gravimeter		Gradiometer		WEP-test	
	thermal	BEC	thermal	BEC	thermal	BEC
N_{at} (initial)	1×10^9	1×10^6	1×10^9	1×10^6	1×10^9	1×10^6
T_{at} (K)	80×10^{-9}	50×10^{-12}	80×10^{-9}	50×10^{-12}	80×10^{-9}	50×10^{-12}
P_{exc}	0.57	0.99	0.33	0.97	0.43	0.99
t_{int} (s); n_{cycle}	3.36; 7	3.45; 3	86400; 72000	86400; 4320	2×10^7; 2.4×10^7	2×10^7; 10^6
ν_0	1		50		10^6	
2T (s)	150×10^{-3}		0.5	10	0.5	10
$\mathcal{O}(\delta_{\phi_{target}})$	$\Delta g/g = 10^{-9}$		$\Gamma = 2.5$ mE$= 2.5 \times 10^{-12}$ s^{-2}		$\eta = 2 \times 10^{-15}$	
$\mathcal{O}(\sigma_{\phi_{SN}})$	1.2×10^{-11}	3.3×10^{-10}	5.0×10^{-13} s^{-2}	5.5×10^{-14} s^{-2}	1.2×10^{-15}	2.1×10^{-16}
$\mathcal{O}(\delta_{\phi_{GG}})$	4.9×10^{-15}	1.1×10^{-14}	2.4×10^{-14} s^{-2}	9.9×10^{-13} s^{-2}	1.1×10^{-17}	4.8×10^{-16}
$\mathcal{O}(\delta_{\phi_{C}})$	1.8×10^{-14}	3.7×10^{-14}	7.0×10^{-14} s^{-2}	1.5×10^{-13} s^{-2}	3.7×10^{-17}	7.6×10^{-17}
$\mathcal{O}(\delta_{\phi_{WFA}})$	3.4×10^{-10}	2.1×10^{-13}	1.0×10^{-12} s^{-2}	4.4×10^{-15} s^{-2}	1.3×10^{-12}	8.0×10^{-16}
$\mathcal{O}(\sigma_{\phi_{MF}})$	1.3×10^{-11}	9.2×10^{-10}	4.7×10^{-13} s^{-2}	5.4×10^{-13} s^{-2}	1.1×10^{-15}	1.8×10^{-15}

BECs:

- smaller size-related effects (GG, CC, WFA)
- comparable mean-field effects at long interrogation times
- preservation of high contrast even at long interferometry times

Thermal:

- low shot noise at short interferometry times (high atom number)
- short cycle rates due to fast production of thermal ensembles
- large sizes at long interrogation times due to high expansion rate

CONCLUSION

EMPLOYING QUANTUM IMUs

Short Interrogation times,
e.g. earth-based or mobile sensors:

Thermal clouds for rapid readouts, noise resilience

Intermediate Interrogation times,
e.g. ASATs, ICBMs:

Trade-off required, potential benefit from BECs.

Long interrogation times,
e.g. space-based missions:

BECs benefit from long integration times.

References: *Eur. Phys. J. D* **75**, 108 (2021)

THANK YOU!

Read the paper

Scan and Connect!