

ATOMIC SOURCES FOR INTERFEROMETRY

REQUIREMENTS, STATUS, PERSPECTIVES

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Phase noise / atom atomic flux considered for gravitational wave detectors based on atom interferometry



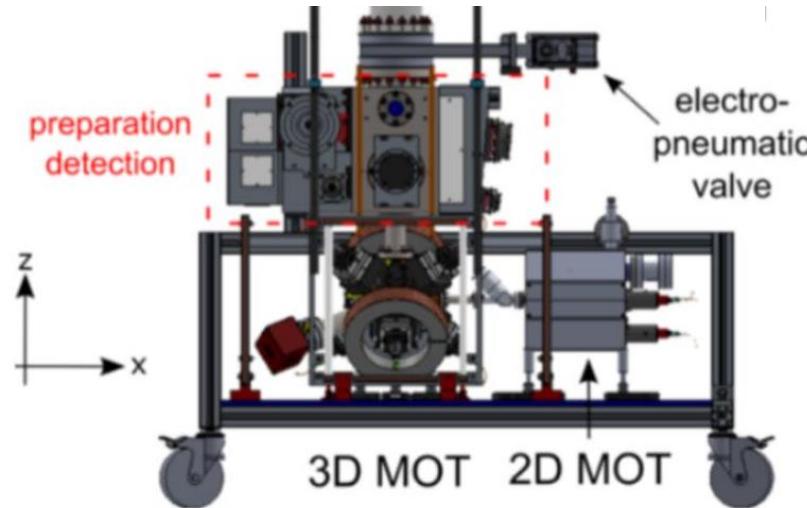
	Phase noise	Atomic flux (without squeezing)
MIGA ¹⁾ (Rb):	$1 \text{ mrad}/\sqrt{\text{Hz}}$	10^6 atoms/s
ELGAR ²⁾ (Rb):	$1 \mu\text{rad}/\sqrt{\text{Hz}}$	10^{12} atoms/s
MAGIS ³⁾ (Sr):	$10^{-3} \text{ rad}/\sqrt{\text{Hz}} - 10^{-5} \text{ rad}/\sqrt{\text{Hz}}$	$10^6 \text{ atoms/s} - 10^{10} \text{ atoms/s}$

Other relevant aspects for the source^{2,3,4)}:

- Expansion rate (beam splitting efficiency, systematic errors / noise)
- Ensemble size (systematic errors / noise, density)
- Ctrl. of position / velocity (systematic errors / noise)
- Cycle time (detector bandwidth)

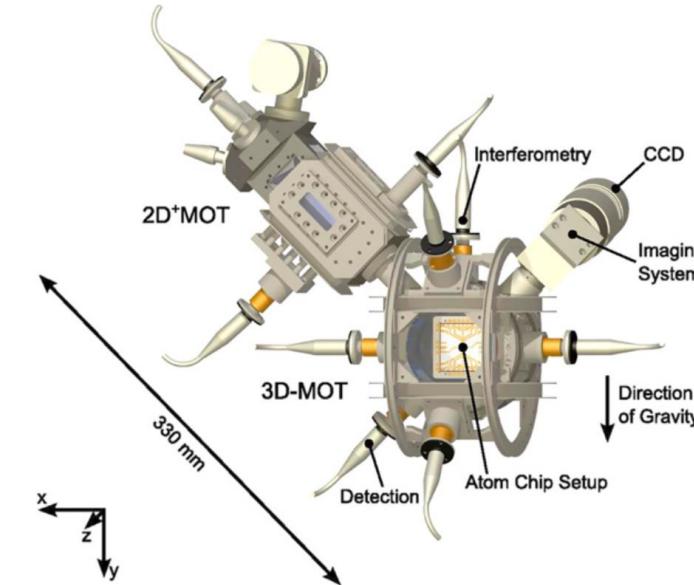
[1) Canuel et al., Scientific Reports 8, 14064 (2018); 2) Canuel et al., Class. Quantum Grav. 37, 225017 (2020); 3) Abe et al., Quantum Sci. Technol. 6, 044003 (2021); 4) Gebbe et al., Nat. Comm. 12, 2544 (2021); Szigeti et al., NJP 14, 023009 (2012); Louchet-Chauvet et al., NJP 13, 065025 (2011); Debs et al., Phys. Rev. A 84, 033610 (2011); S Loriani et al 2019 New J. Phys. 21 063030; Loriani et al., PRD 102, 124043 (2020); Dimopoulos et al., Phys. Rev. D 78, 122002 (2008)]

Providing molasses cooled Rb atoms – examples for 2D- / 3D-MOT systems



MIGA setup¹⁾

- 3D-MOT with 6 independent beams
- 3D-MOT loading rate: $6 \cdot 10^8$ atoms/s
- Molasses temperature: 2 μK

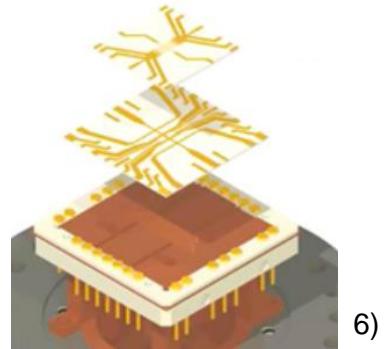
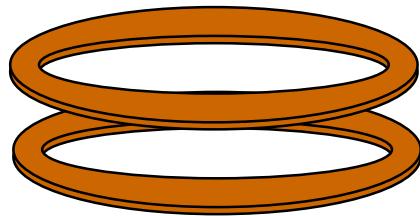


QUANTUS-2 setup²⁾

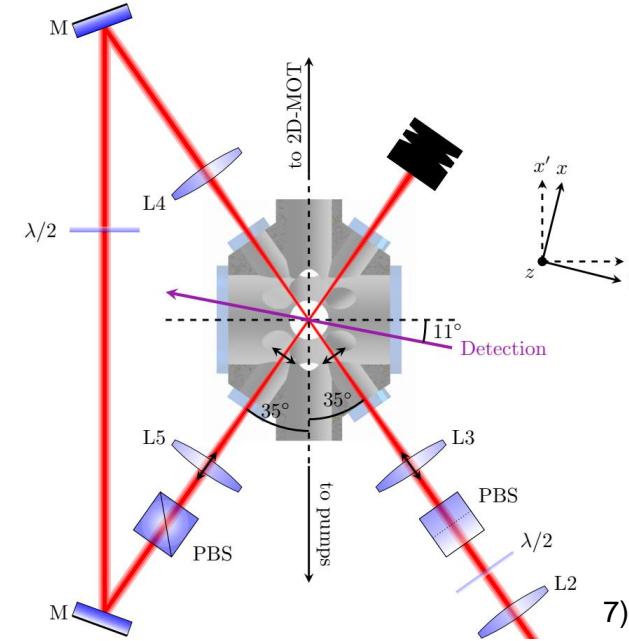
- Chip (mirror) MOT
- 3D-MOT loading rate: $1 \cdot 10^9$ atoms/s
- Saturation: $2.5 \cdot 10^9$ atoms at 4s
- Molasses temperature: 20 μK

[Figures and results from: 1) Beaufils et al., Scientific Reports 12, 19000 (2022), doi:10.1038/s41598-022-23468-3, CC BY 4.0; 2) Rudolph et al., A high-flux BEC source for mobile atom interferometers, New J. Phys. 17 (2015) 065001, doi:10.1088/1367-2630/17/6/065001, CC BY 3.0;
<https://creativecommons.org/licenses/by/3.0/>]

BEC generation



6)



7)

Magnetic traps

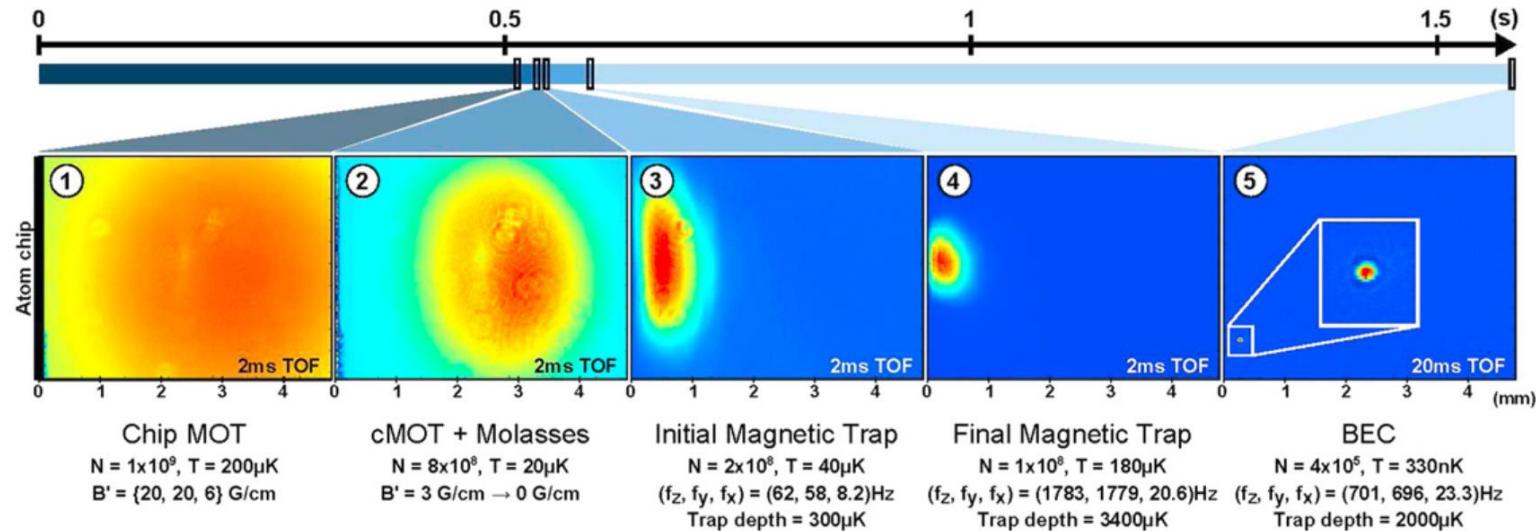
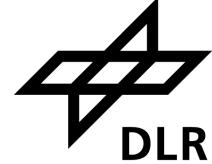
- Cloverleaf style Ioffe Pritchard trap¹⁾:
 - 10^7 ^{87}Rb atoms in ≈ 1 min
- Time-orbiting potential trap + magnetic lens²⁾:
 - $4 \cdot 10^6$ ^{87}Rb atoms at **50 nK** effective temperature
 - 10^5 ^{87}Rb atoms at **3 nK** effective temperature
- Atom chips⁶⁾:
 - 10^5 ^{87}Rb atoms in **1 s**

Optical dipole traps (incl. hybrid loading with magnetic trap)

- Hybrid + ODT³⁾:
 - $2 \cdot 10^6$ ^{87}Rb atoms at **50 nK** in ≈ 10 s
- Painted potentials⁴⁾:
 - $10^5 \{5 \cdot 10^4, 1.2 \cdot 10^6\}$ ^{174}Yb atoms in 1.8 s {1.6 s, 15 s}
- Evaporation in microgravity⁵⁾:
 - $4 \cdot 10^4$ ^{87}Rb atoms at **35 nK** in 13.5 s

[Figures and results from: 1) Streed et al., Rev. Sci. Instrum. 77, 023106 (2006); 2) Dickerson et al., Phys. Rev. Lett 114, 143004 (2015), 50 pK effective temperature in 2D via optical lens reported in Kovachy et al., Phys. Rev. Lett. 114, 143004 (2015); 3) Hardman et al., Phys. Rev. Lett. 117, 138501 (2016); 4) Roy et al., arxiv:1601.05103; 5) Condon et al., Phys. Rev. Lett. 123, 240402 (2019), see also Vogt et al., arXiv:1909.03800; 6) Rudolph et al., New J. Phys. 17 (2015) 065001, CC BY 3.0; 7) Albers et al., Comm. Phys. 5, 60 (2022), CC BY 4.0]

Rapid BEC generation on an atom chip



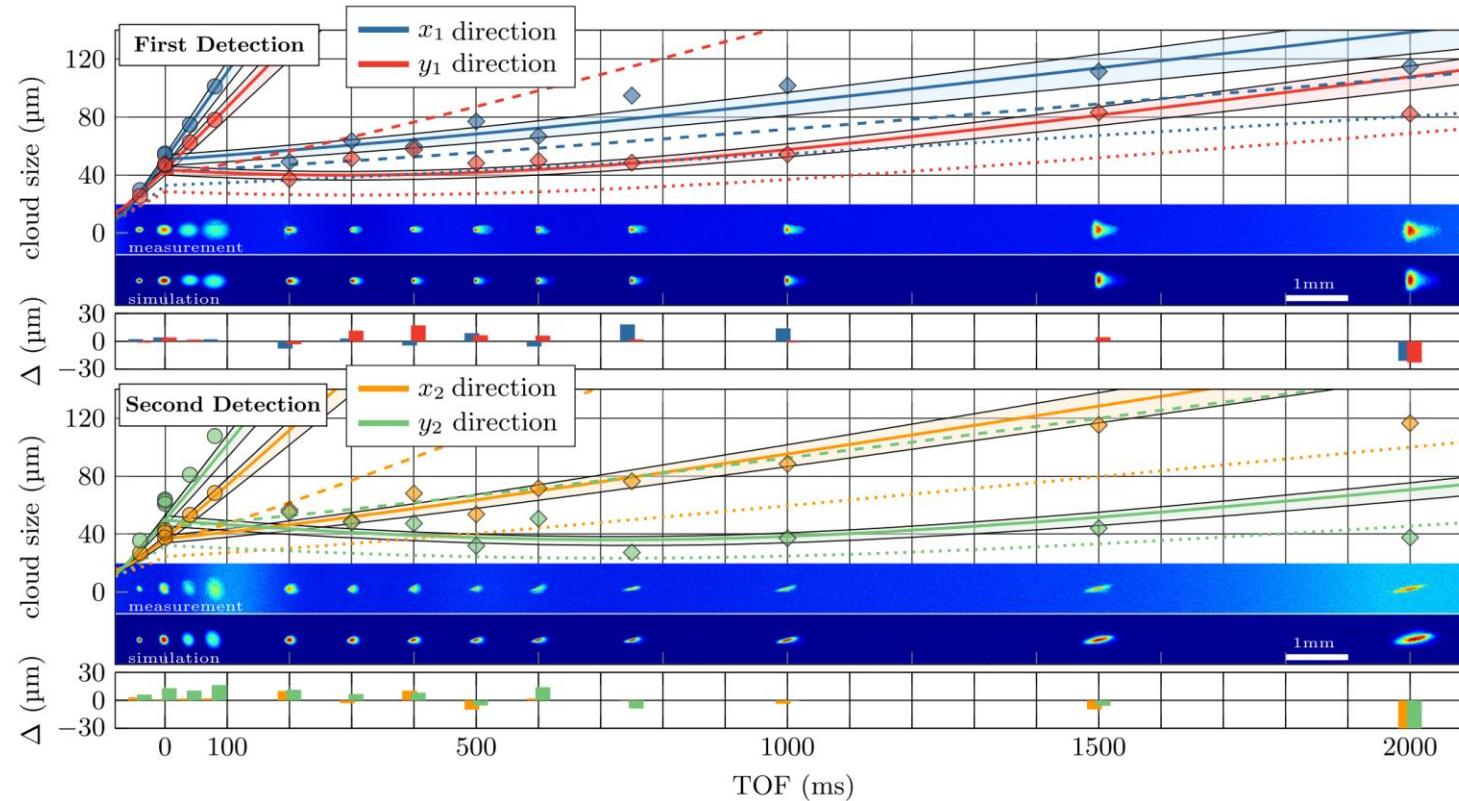
BEC generation performance:

- $4 \cdot 10^4$ atoms in the BEC in **850 ms**
- 10^5 atoms in the BEC in **1 s**
- $4 \cdot 10^5$ atoms in the BEC in **1.6 s**

Towards higher flux: improve vacuum quality, laser power, mode matching to initial magnetic trap

[Figures and results from: Rudolph et al., A high-flux BEC source for mobile atom interferometers, New J. Phys. 17 (2015) 065001, doi:10.1088/1367-2630/17/6/065001, CC BY 3.0; <https://creativecommons.org/licenses/by/3.0/>; BEC: Bose-Einstein condensate]

Delta-kick collimation using the atom chip setup

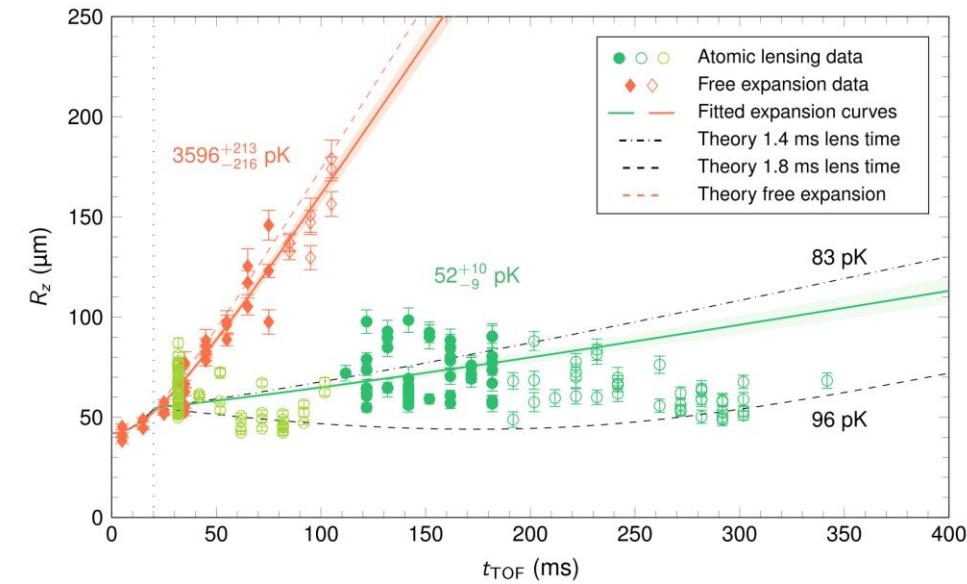
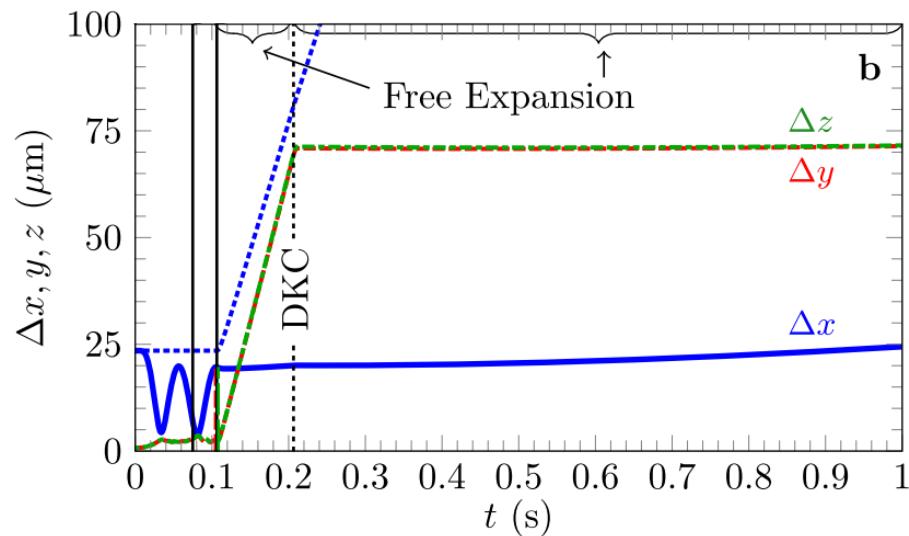


10⁵ atoms in the BEC

Residual kinetic energy (3D): $3/2 \cdot k_B 38^{+6}_{-7} \text{ pK}$

[Figures and results from: Deppner et al., Collective-Mode Enhanced Matter-Wave Optics, Phys. Rev. Lett. 127, 100401 (2021), 10.1103/PhysRevLett.127.100401]

Matter-wave lensing to pK equivalent energies, control of position & velocity



Model / theory for transport / lensing protocol¹⁾

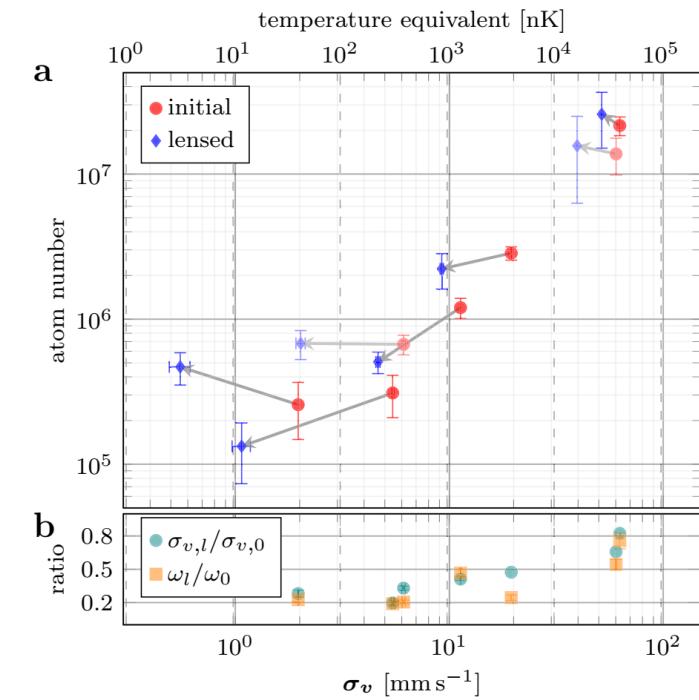
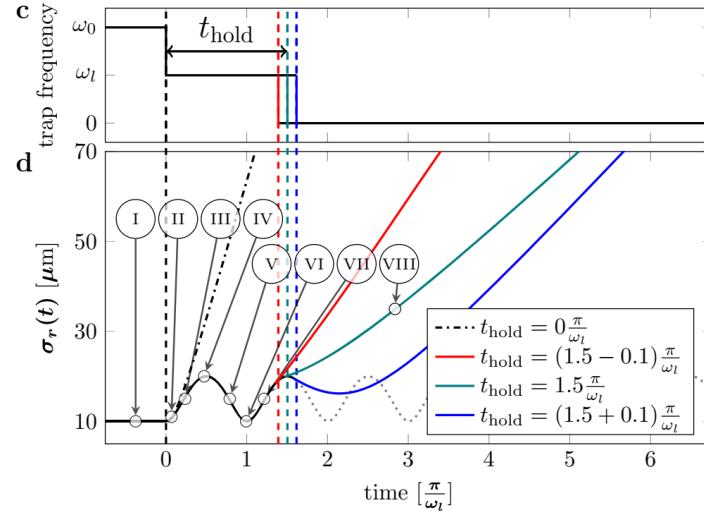
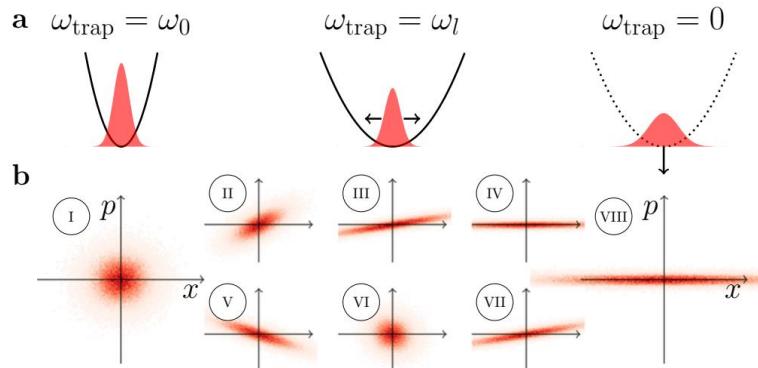
- Transport over **0.9 mm** in **< 100 ms** (μm level control)
- Timed switch-off after CM excitation + pulsed potential for DKC → expansion rates reduced in 3D
- Delta-kick collimation to **2.2 pK** effective temperature (3D)
- DKC to **20 pK** for 0.5 ms timing error

Experimental results from CAL²⁾

- Transport with **< 100 nm** position error
- Tunable release velocities known to **100 $\mu\text{m/s}$**
- Delta-kick collimation to **100 pK** effective temperature (3D)
- DKC to **52(± 10) pK** in z-axis

[Figures and results from: 1) R Corgier et al., Fast manipulation of Bose–Einstein condensates with an atom chip, New J. Phys. 20, 055002 (2018), CC BY 3.0; 2) Gaaloul et al., A space-based quantum gas laboratory at picokelvin energy scales, Nat. Comm. 13,7889 (2022), <https://doi.org/10.1038/s41467-022-35274-6>, CC BY 4.0; <http://creativecommons.org/licenses/by/4.0/>; CM: collective mode; CAL: Cold Atom Lab]

All-optical matter-wave lens using time-averaged potentials



Procedure / results – shortcircuiting the evaporation using ^{87}Rb :

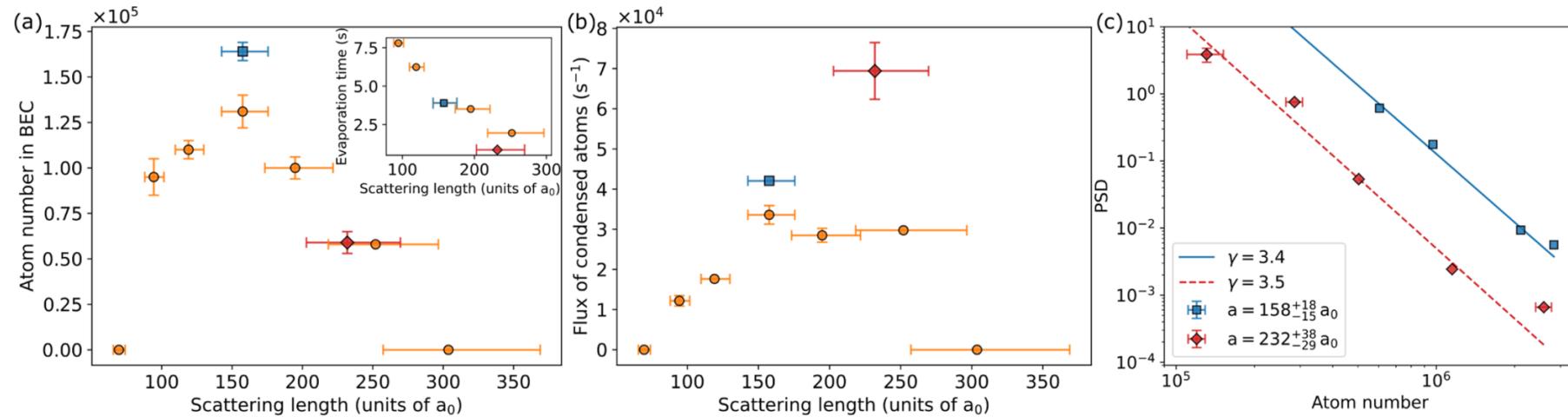
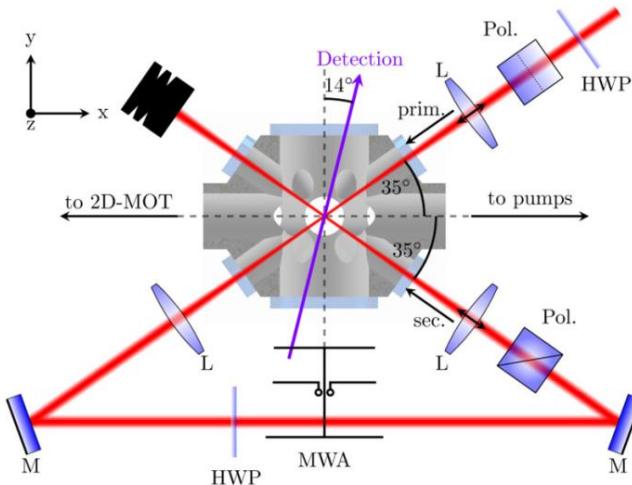
- Evaporation stopped prematurely, followed by rapid decompression (= 2D lens)
- Normal evaporation: BECs with $4 \cdot 10^5 \{5 \cdot 10^4, 2 \cdot 10^5\}$ atoms in 5 s {2 s, 3 s}, effective temperature of 40 nK
- Procedure applied: $4 \cdot 10^5$ atoms, effective temperature of **3.2(0.6) nK**

[Figures and results from: Albers et al., Comm. Phys. 5, 60 (2022), CC BY 4.0]

Rapid BEC generation exploiting Feshbach resonances



(c)

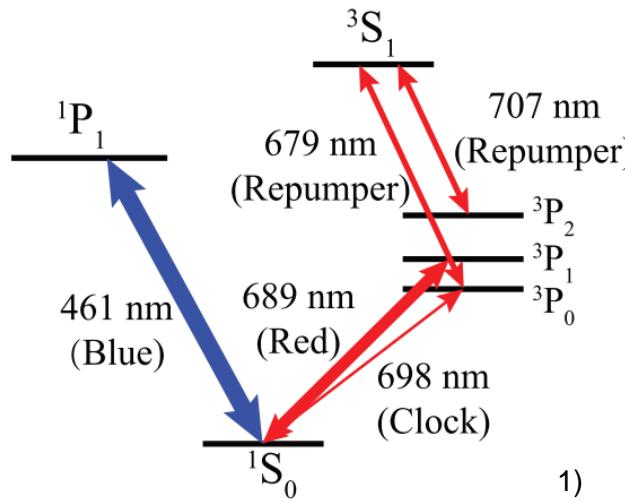


Procedure / results – tuning of rethermalisation rate using ^{39}K :

- D1 gray molasses scheme for loading ODT
- Low-field Feshbach resonances enable tuning of rethermalisation rate
- Fastest BEC: $232 a_0$, **850 ms** evaporation time, $5.8 \cdot 10^4$ atoms
- Largest BEC: $158 a_0$, **3.9 s** evaporation time, $1.6 \cdot 10^5$ atoms

[Figures and results from: Herbst et al., Rapid generation of all-optical ^{39}K Bose-Einstein condensates using a low-field Feshbach resonance, Phys. Rev A 106, 043320 (2022), doi:10.1103/PhysRevA.106.043320, CC BY 4.0]

Laser cooling of Sr – blue & red MOT & BEC generation



Laser cooling:

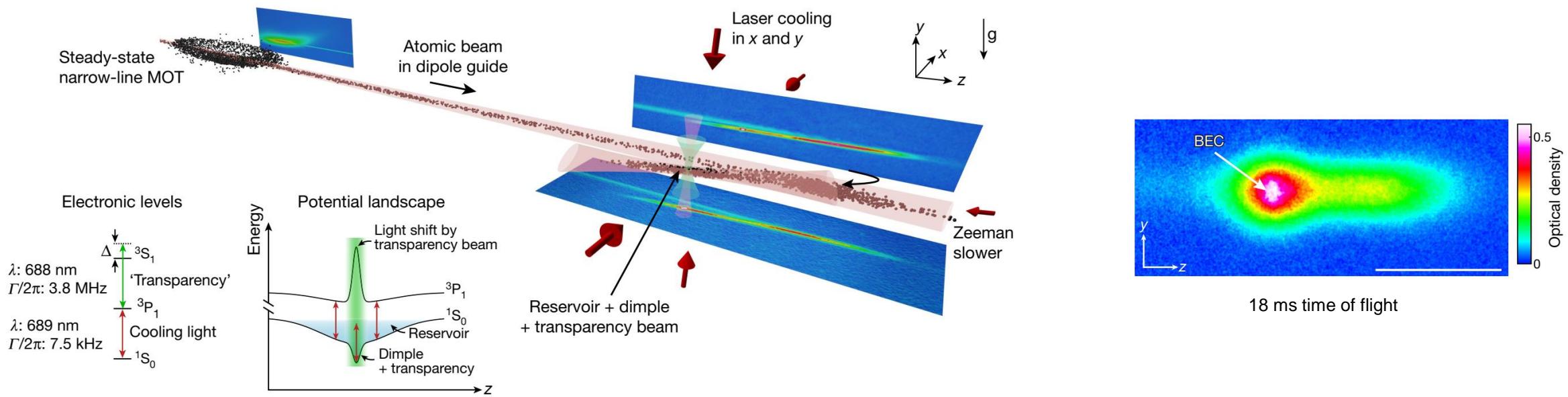
- ^{88}Sr , Zeeman slower + 2-color MOT, red broadband → red single frequency²⁾:
 - $1.5 \cdot 10^7$ atoms at $2.5 \mu\text{K}$ in red single frequency MOT
- ^{88}Sr , Zeeman slower + 2-color MOT¹⁾:
 - $\approx 5 \cdot 10^6$ atoms at $\approx 1 \mu\text{K}$
- ^{88}Sr , dual-stage MOT³⁾:
 - 10^7 atoms at $\approx 3 \mu\text{K}$
- Various isotopes → red single frequency MOT⁴⁾:
 - ^{88}Sr at **400 nK**, ^{84}Sr at **800 nK** (10^7 atoms)
 - ^{87}Sr at **800 nK** (10^7 atoms)

BEC generation (using optical dipole traps):

- ^{84}Sr , crossed optical dipole trap⁴⁾:
 - $3 \cdot 10^5$ atoms, 4.5 s of evaporation; 10^5 atoms with cycle time of 2 s
 - $1.1(1) \cdot 10^7$ atoms, 10 s of evaporation + 40 s accumulation of atoms in reservoir
- ^{86}Sr , ^{88}Sr (via ^{87}Sr)²⁾:
 - BECs with $\approx 10^4$ atoms
- ^{84}Sr , continuous cooling of reservoir + dimple + transparency beam²⁾:
 - BEC with $1.1 \cdot 10^5$ atoms (10^7 atoms in reservoir dipole trap)

[Figures and results from: 1) Liang Hu et al 2020 Class. Quantum Grav. 37 014001, Sr atom interferometry with the optical clock transition as a gravimeter and a gravity gradiometer, doi:10.1088/1361-6382/ab4d18, CC BY 3.0; 2) Poli et al., Appl. Phys. B 117, 1107–1116 (2014); 3) Rudolph et al., Phys. Rev. Lett. 124, 083604 (2020); 3) Stellmer et al., Phys. Rev. Lett. 110, 263003 (2013); 4) Stellmer et al., arXiv:1307.0601]

Continuous Bose-Einstein condensation of ^{84}Sr atoms

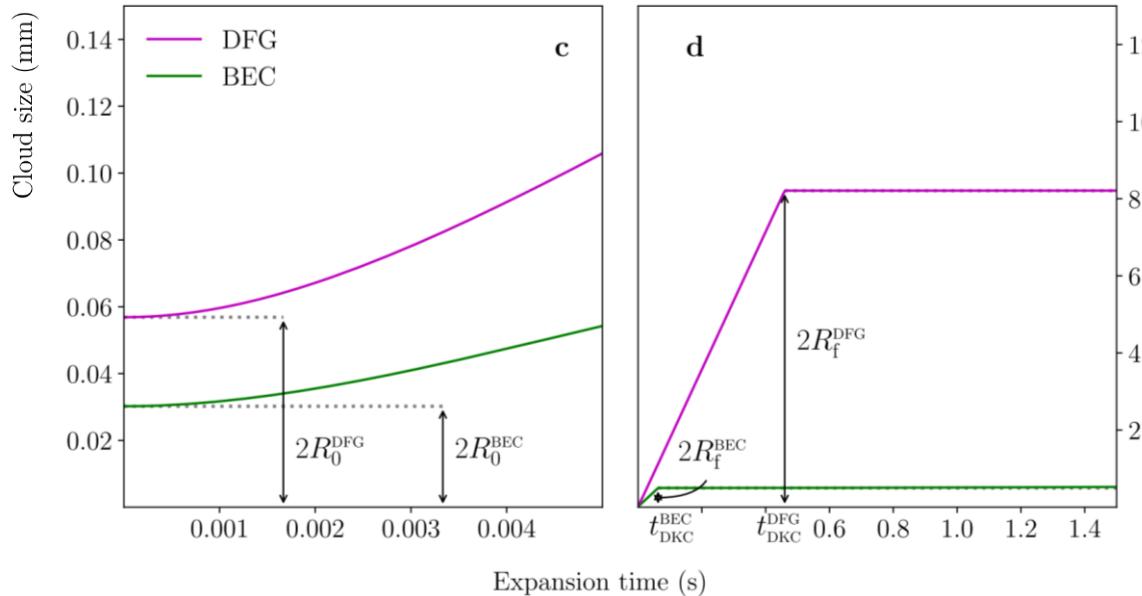


Procedure and experimental results:

- Atoms filling reservoir at μK temperature, slowed by Zeeman slower, loading flux $1.4(2) \cdot 10^6 \text{ atoms/s} \rightarrow$ BEC forms in dimple
- Steady state: $6.9 \cdot 10^5$ atoms at $T_D = 1.03(8) \mu\text{K}$ in dimple, $7.3(1.8) \cdot 10^5$ laser-cooled atoms in reservoir
- Transparency beam enables life times $> 1.5 \text{ s}$ (pure BEC)
- Average BEC atom number $7.400(2.300)$
- Estimated steady-state gain of $2.4(5) \cdot 10^5 \text{ atoms/s}$ into BEC

[Figures and results from: Chen et al., Continuous Bose–Einstein condensation, Nature 606, 683 (2022), doi:10.1038/s41586-022-04731-z, CC BY 4.0]

Collimating fermionic atoms



3D expansion rate $T_{\text{eff}} = 10 \text{ pK}$	BEC		DFG	
	^{174}Yb	^{84}Sr	^{171}Yb	^{87}Sr
Number of atoms			7×10^6	7×10^6
Trapping frequency ($2\pi \text{ Hz}$)		50	50	
Critical temperature (μK)		0.431	0.834	
Initial size $2R_0 (\mu\text{m})$	30.2	41.8	56.86	81.86
Pre-DKC expansion time (t_{DKC}) (ms)	63	61	460	460
Size at lens $2R(t_{\text{DKC}})$ (mm)	0.50	0.67	8.21	11.82
Final size $2R(t_{\text{DKC}} + 2T)$ (mm)				
$T = 40 \text{ s}$	9.27	13.34	12.86	18.51
$T = 100 \text{ s}$	23.15	33.32	26.07	37.53
$T = 160 \text{ s}$	37.03	53.31	40.43	58.20

Theory / model:

- Performance constrained by pre-DKC expansion time (here: **0.5 s**) / size at lens (here: **1.2 cm**)
- Optical delta-kick collimation to **10 pK** effective temperature in principle possible

[Figures and results from: S Loriani et al 2019 New J. Phys. 21 063030, Atomic source selection in space-borne gravitational wave detection, doi:10.1088/1367-2630/ab22d0, CC BY 3.0]

Raman sideband & direct laser cooling



Raman sideband cooling in an optical lattice – results from Cs fountain^{1,2)}:

- $\approx 10^6$ atoms at $0.4 \mu\text{K}$

BEC generation by Raman cooling of ^{87}Rb atoms in an optical dipole trap³⁾:

- Multiple cooling stages: single beam ODT (10^5 atoms) \rightarrow crossed ODT \rightarrow reducing confinement
- $2.5 \cdot 10^4$ atoms with 7% condensate fraction

[1) Chiow et al., Phys. Rev. Lett. 103, 050402 (2009); 2) Estey et al., Phys. Rev. Lett. 115, 083002 (2015); 3) Urvoy et al., Phys. Rev. Lett. 122, 203202 (2019)]

Squeezing



Squeezing on momentum states for Sr atom interferometry – theory / proposal¹⁾:

- Up to **20 dB** beyond SQL predicted, scaling $\Delta\phi \sim N^{-3/4}$ for larger atom numbers

Delta-kick squeezing – theory / proposal²⁾:

- Up to **30 dB** beyond SQL predicted for **10^6** atoms (BEC)

Ramsey spectroscopy with ^{87}Rb atoms – experimental results³⁾:

- **3.7(0.2) dB** below QPN, **$2.4 \cdot 10^5$** atoms, **3.6 ms** Ramsey time

Momentum entanglement with ^{87}Rb atoms – experimental results⁴⁾:

- Squeezing parameter of **-1.9(7) dB**, conditional **-3.1(8) dB**, between two momentum modes, **9300** atoms

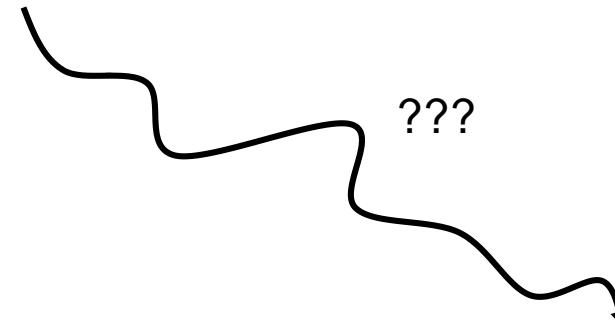
Entanglement-enhanced Mach-Zehnder-like ^{87}Rb atom interferometer – experimental results⁵⁾:

- **1.7(0.5) dB** below SQL, **660(17)** atoms, **0.7 ms** pulse separation time, Raman beam splitters

[1) Salvi et al., Phys. Rev. Lett. 20, 033601 (2018); 2) Corgier et al., Phys. Rev. Lett. 127, 183401 (2021); 3) Malia et al., Phys. Rev. Lett. 125, 043202 (2020); 4) Anders et al., Phys. Rev. Lett. 127, 140402 (2021); 5) Greve et al., Nature 610, 472 (2022)]

Way forward?

Few 10^5 atoms, well collimated, in ≈ 1 s
BECs with 10^7 atoms in ≈ 1 min



$10 \mu\text{rad}/\sqrt{\text{Hz}} - 10^{10} \text{ atoms/s}$
 $1 \mu\text{rad}/\sqrt{\text{Hz}} - 10^{12} \text{ atoms/s}$

Summary & conclusion



Phase noise requirements imply atomic flux up to 10^{12} atoms/s – well controlled / collimated atoms

Atom chips, painted potentials → BECs with few 10^5 atoms in 1 – 2 s demonstrated

Magnetic / optical dipole trap lenses → collimation down to 50 pK effective temperatures demonstrated

Developments ongoing – *further developments needed!*

Summary & conclusion



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Thank you for your attention!