

# Future perspectives for horizontal GWD detection: Large momentum transfer and multi-loop geometries

Sven Abend<sup>1</sup>, Christian Schubert<sup>2</sup>, Dennis Schlippert<sup>1</sup>, and Ernst M. Rasel<sup>1</sup>

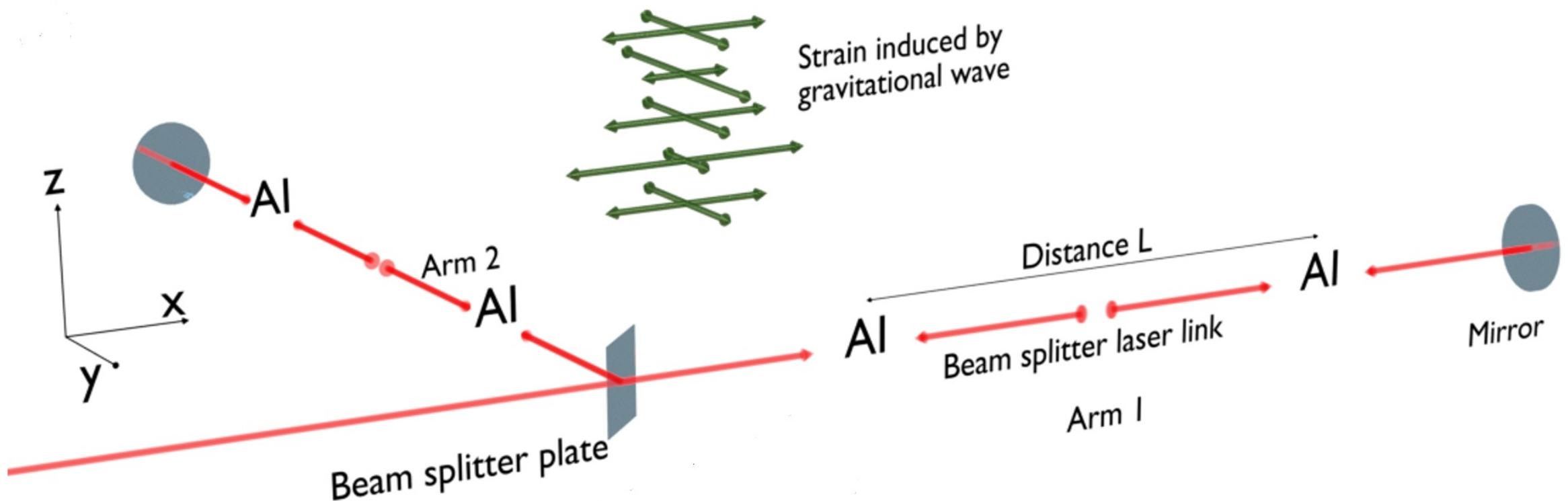
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# Two arm horizontal GWD detector with 4 Al

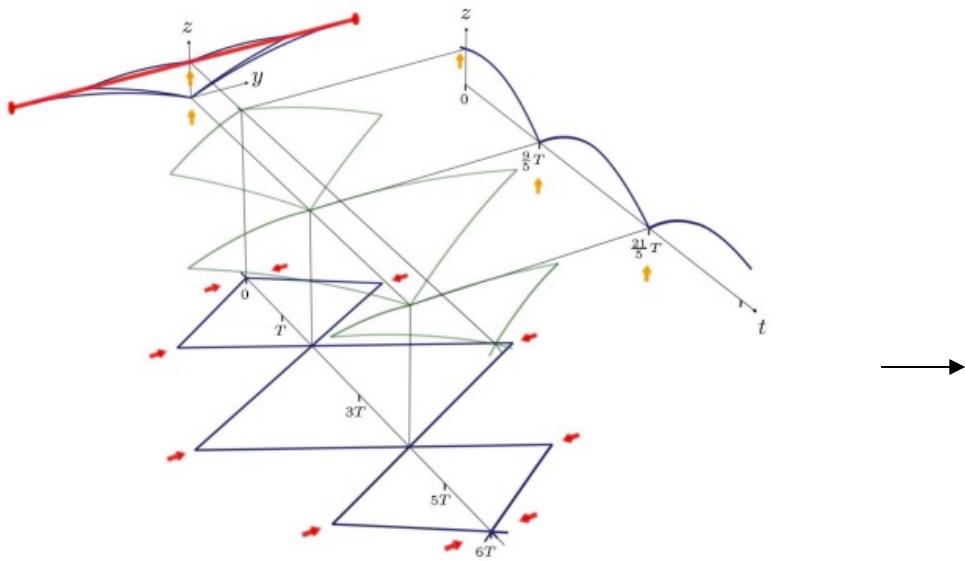


**Phase shift:**

$$\Delta\phi_{\text{GW}} = KhL \sin^4\left(\frac{\omega T}{2}\right) \left(\frac{7 + 8\cos\omega T}{2}\right)$$

$$\Delta L/L < 10^{-19} \text{ @ } 0.3\text{-}5 \text{ Hz} \quad \text{or} \quad \Delta L/L < 10^{-21} \text{ @ } 1 \text{ Hz}$$

# Multi-loop geometry used for GWD

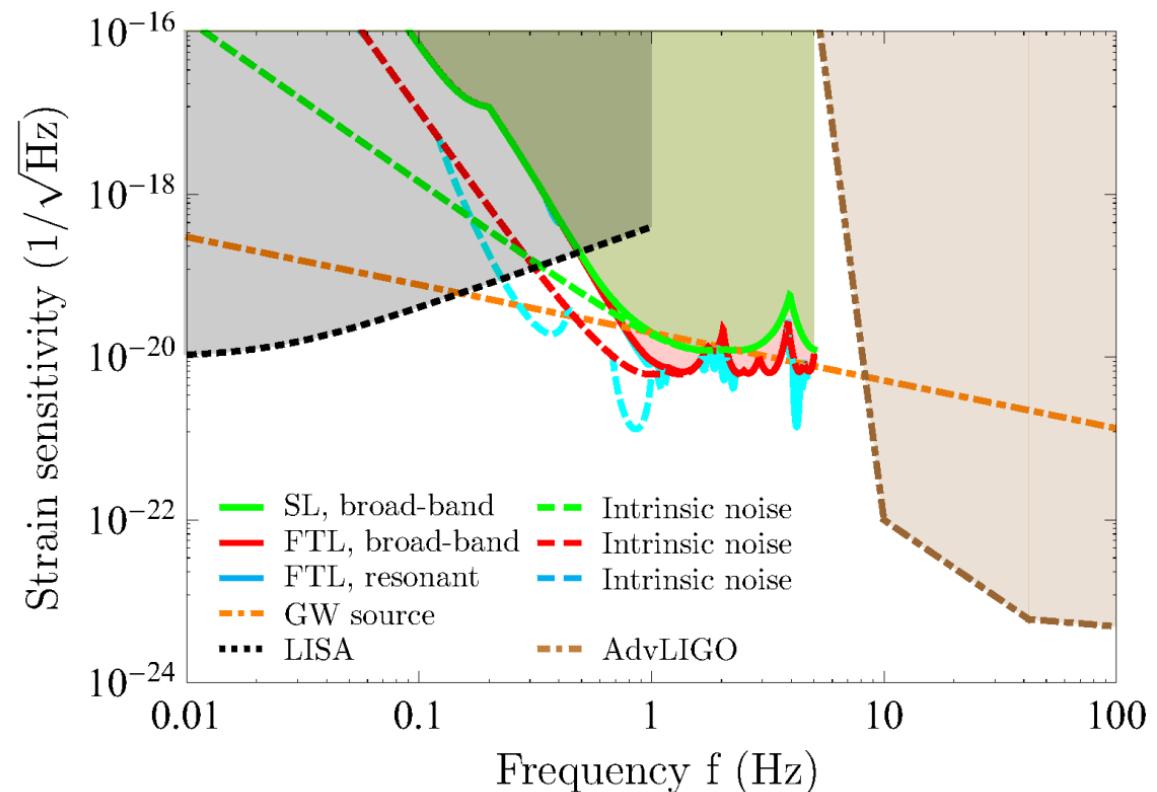


## Anticipated parameters:

- Effective wave vector:  $K \sim 2000 \cdot 2\pi/(780 \text{ nm})$  for Rb87
- Free evolution time:  $T = [0.21 \text{ s}, 0.27 \text{ s}, 0.3 \text{ s}]$
- Cycle rate: 10 Hz
- Phase noise:  $\sigma_\phi = 1 \mu\text{rad Hz}^{-1/2}$
- Baseline:  $L = 10 \text{ km}$

[C. Schubert, D. Schlippert, S. Abend, E. Giese, A. Roura, W. P. Schleich, W. Ertmer, and E. M. Rasel,  
Scalable, symmetric atom interferometer for infrasound gravitational wave detection, arXiv:1909.01951]

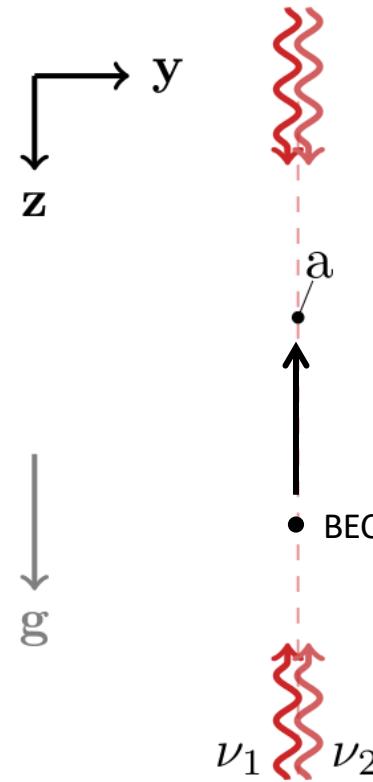
[Jason M. Hogan, David M. S. Johnson, Susannah Dickerson, Tim Kovachy, Alex Sugarbaker, Sheng-wey Chiow, Peter W. Graham, and Mark A. Kasevich, Babak Saif, Surjeet Rajendran, Philippe Bouyer, Bernard D. Seery, Lee Feinberg, and Ritva Keski-Kuha, An Atomic Gravitational Wave Interferometric Sensor in Low Earth Orbit (AGIS-LEO), arXiv:1009.2702]



← Ground based

← Space based

# Multi-loop atom interferometry



## How to form multiple loops?

- launch BEC (small initial momentum & low expansion rate)

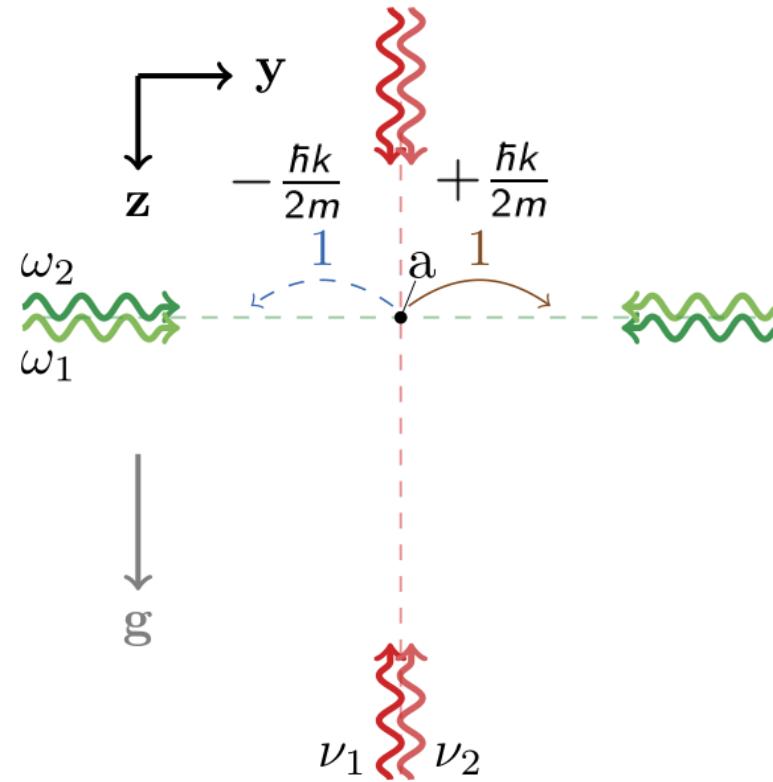
[Atom-chip Fountain Gravimeter, Abend *et al.* 2016 *Phys. Rev. Lett.* **117** 203003]

## Why a multi-loop geometry?

- Large space time area on comparably short baseline
- Exploitation of twin-lattice AI and LMT
- Only a single interferometry beam

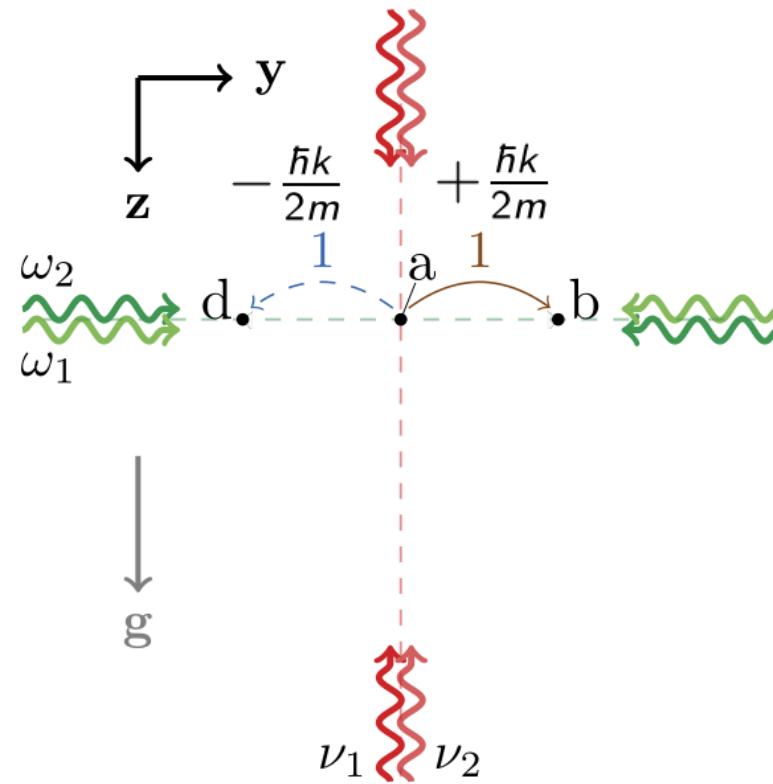
[Gebbe, M. *et al.*, Twin-lattice Atom Interferometry, *Nature communications* **12**(1) 1-7 (2021)]

# Trajectories of multi-loop geometry



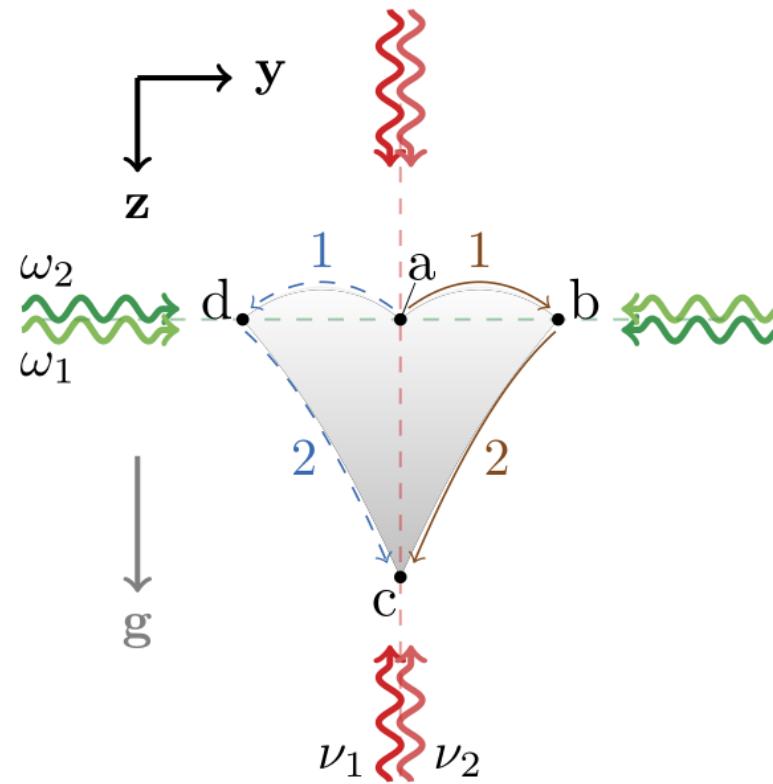
- launch BEC (small initial momentum & low expansion rate)
- horizontal beam splitter: two wave packets drifting apart ( $a$ )

# Trajectories of multi-loop geometry



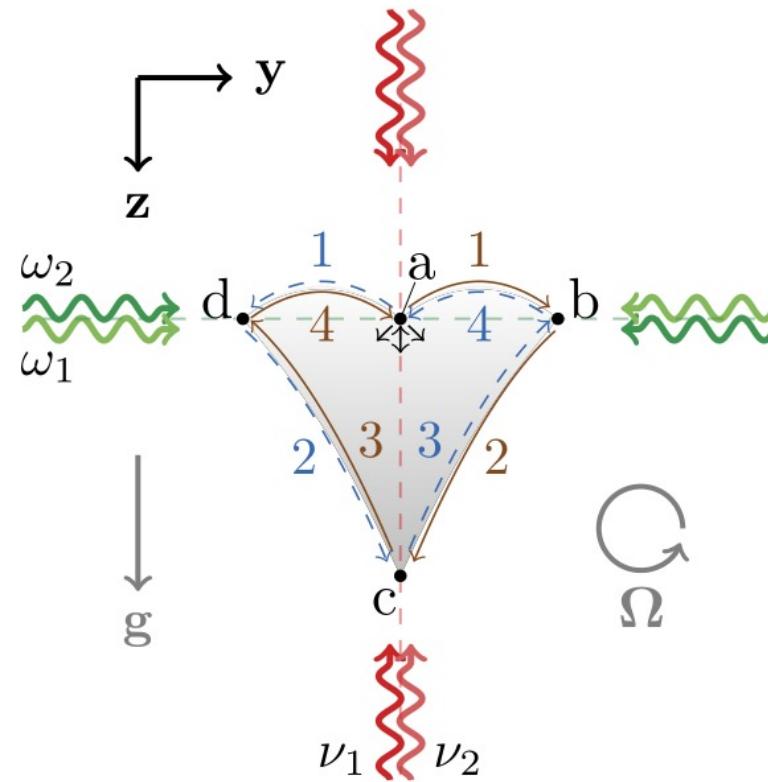
- launch BEC (small initial momentum & low expansion rate)
- horizontal beam splitter: two wave packets drifting apart (a)
- after time  $T$ , invert the movement of the atoms (b,d)

# Trajectories of multi-loop geometry



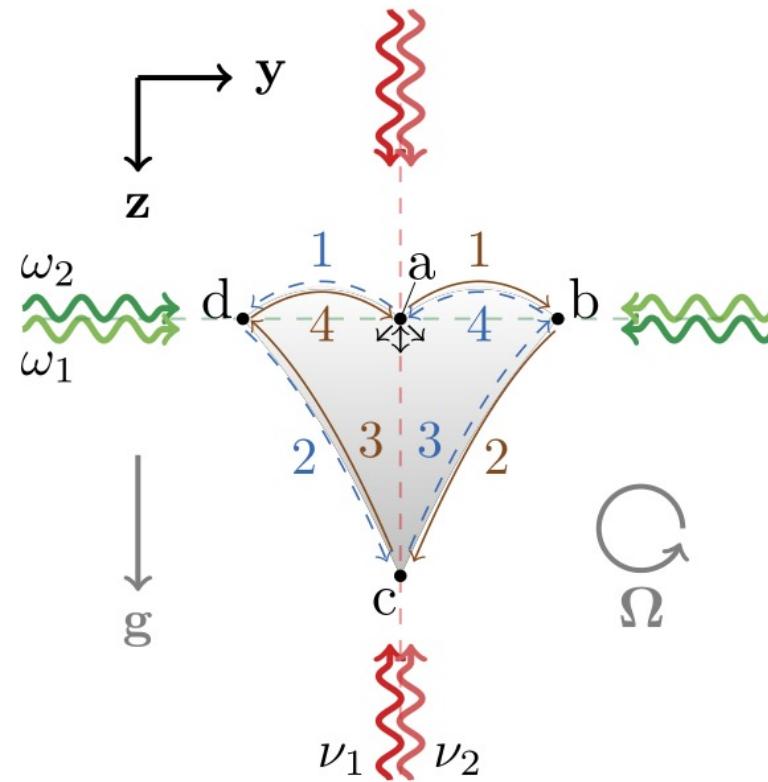
- launch BEC (small initial momentum & low expansion rate)
- horizontal beam splitter: two wave packets drifting apart (a)
- after time  $T$ , invert the movement of the atoms (b,d)
- after time  $2T$ , relaunch atoms and revert momentum (c)

# Trajectories of multi-loop geometry



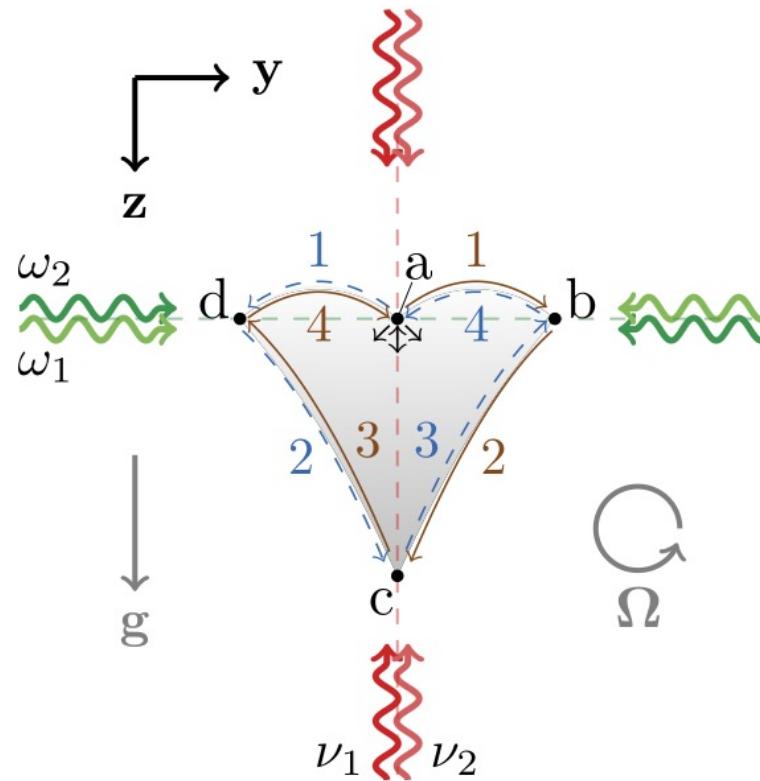
- launch BEC (small initial momentum & low expansion rate)
- horizontal beam splitter: two wave packets drifting apart (a)
- after time  $T$ , invert the movement of the atoms (b,d)
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- after time  $3T$ , deflect atoms towards each other (b,d)

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- launch BEC (small initial momentum & low expansion rate)
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- after time  $3T$ , deflect atoms towards each other (b,d)
- after time  $4T$ , atoms cross falling downwards (a)

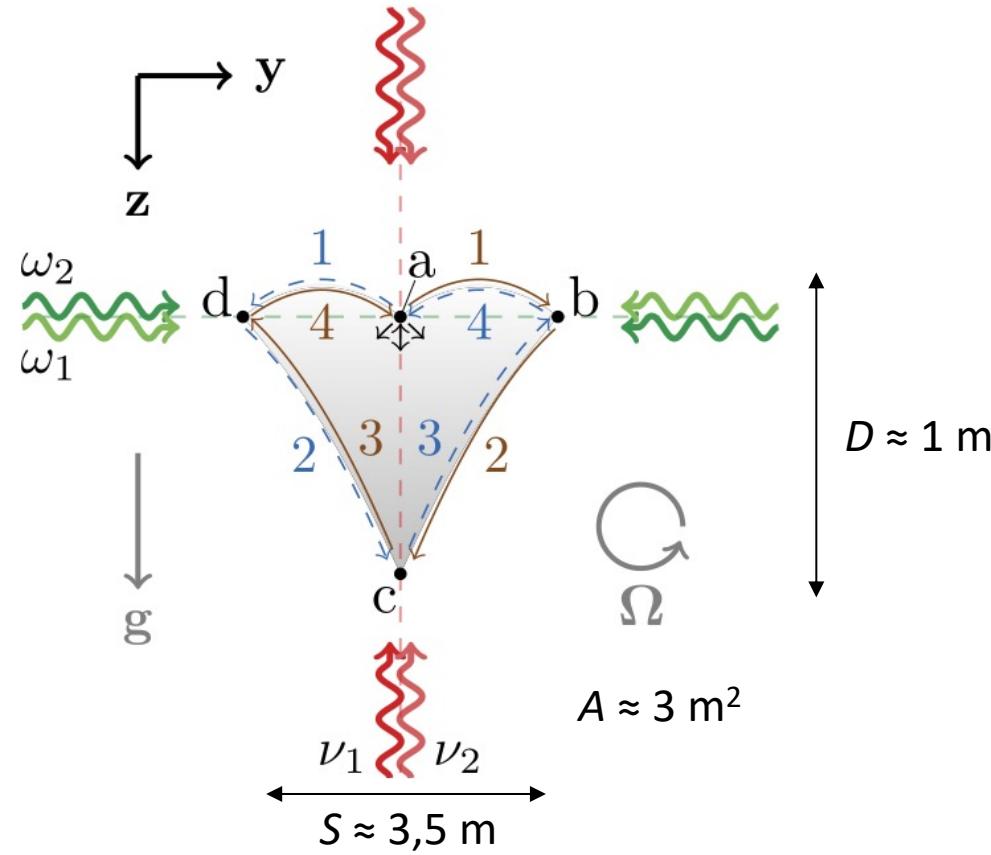
# Trajectories of multi-loop geometry



- launch BEC (small initial momentum & low expansion rate)
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- after time  $3T$ , deflect atoms towards each other (b,d)
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two options:
  1. repeat sequence → form another  $2n$  loop
  2. close interferometer and readout phase  $\phi$

[Schubert, C. et al., Multi-loop atomic Sagnac interferometry, Scientific Reports 11, 16121 (2021)]

# Trajectories of multi-loop geometry



## Anticipated parameters:

- Effective wave vector:  $K \sim 2000 \cdot 2\pi/(780 \text{ nm})$
- Free evolution time:  $T = 0.21 \text{ s}, 0.27 \text{ s}, 0.3 \text{ s}$
- Cycle rate: 10 Hz
- Phase noise:  $\sigma_\phi = 1 \mu\text{rad Hz}^{-1/2}$
- Baseline:  $L = 10 \text{ km}$

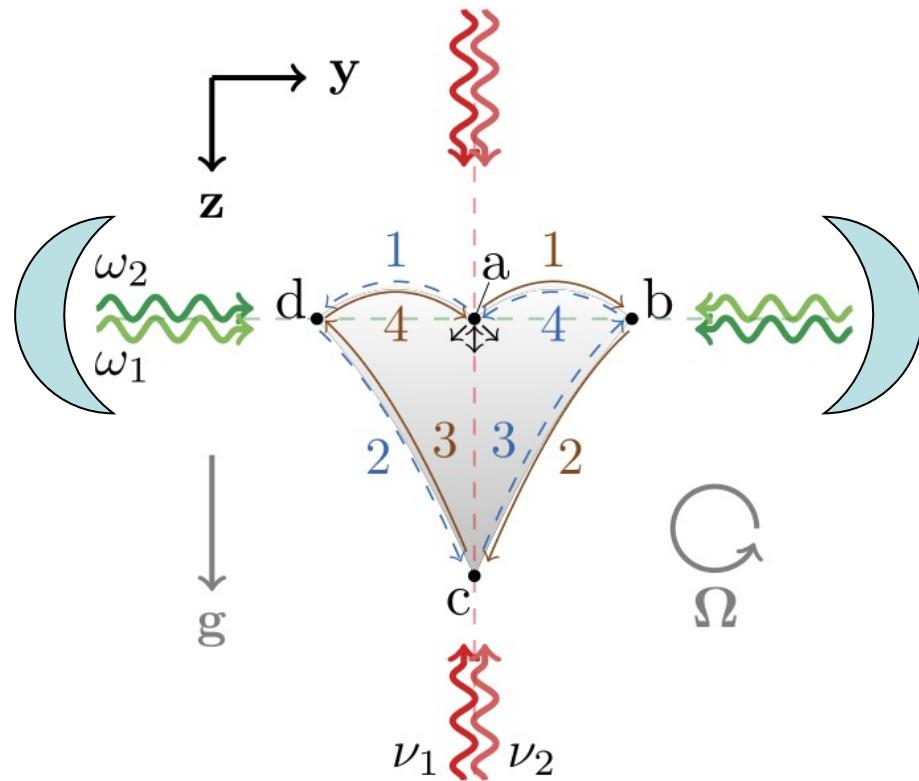
## Geometric errors:

	triple-loop	single-loop
$\delta x$ from $\Gamma \cdot \delta x \cdot kT^2$	n/a	0.4 nm
-pointing launch	n/a	1.4 nrad
$\delta v_x$ from $\Gamma \cdot \delta v_x \cdot kT^3$	n/a	1.7 nm/s
-pointing launch	n/a	0.7 nrad
$\delta v_y$ from Sagnac term	n/a	5.6 pm/s (few fK)
-pointing launch	n/a	2.2 prad
pointing $k$ ( $g$ matched to $10^{-7}$ )	48 prad	100 prad
relative relaunch pointing	1 prad	n/a
absolute relaunch pointing	1 nrad	n/a

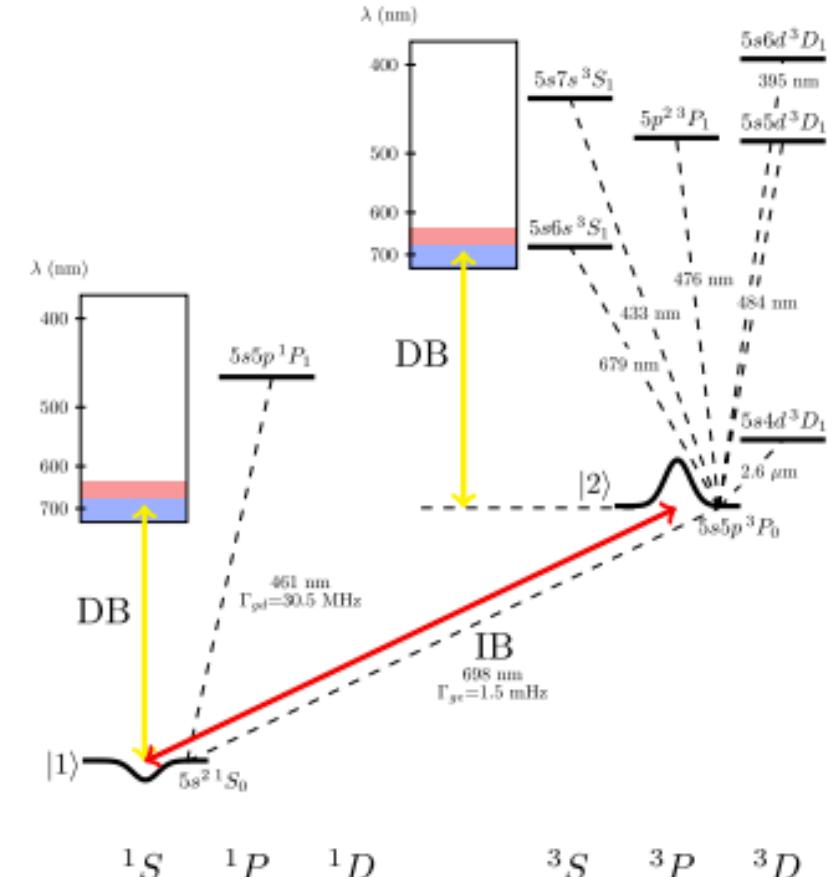
[Schubert, C. et al., Multi-loop atomic Sagnac interferometry, Scientific Reports 11, 16121 (2021)]

# Proposal to realize scheme in a cavity

[A. Bertoldi, C.-H. Feng, D. S. Naik, B. Canuel, P. Bouyer , and M. Prevedelli, Fast Control of Atom-Light Interaction in a Narrow Linewidth Cavity, Phys. Rev. Lett. 127, 013202 (2021)]



$^{87}\text{Sr}$

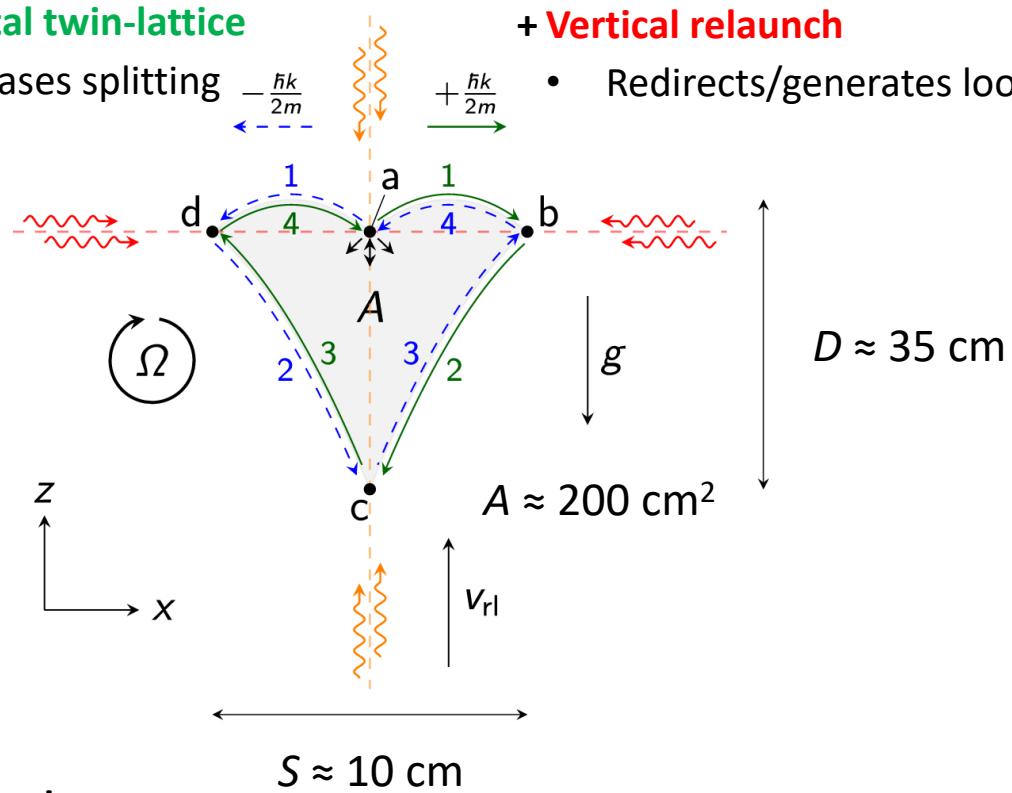


CC BY 4.0

# Multi-loop prototype device

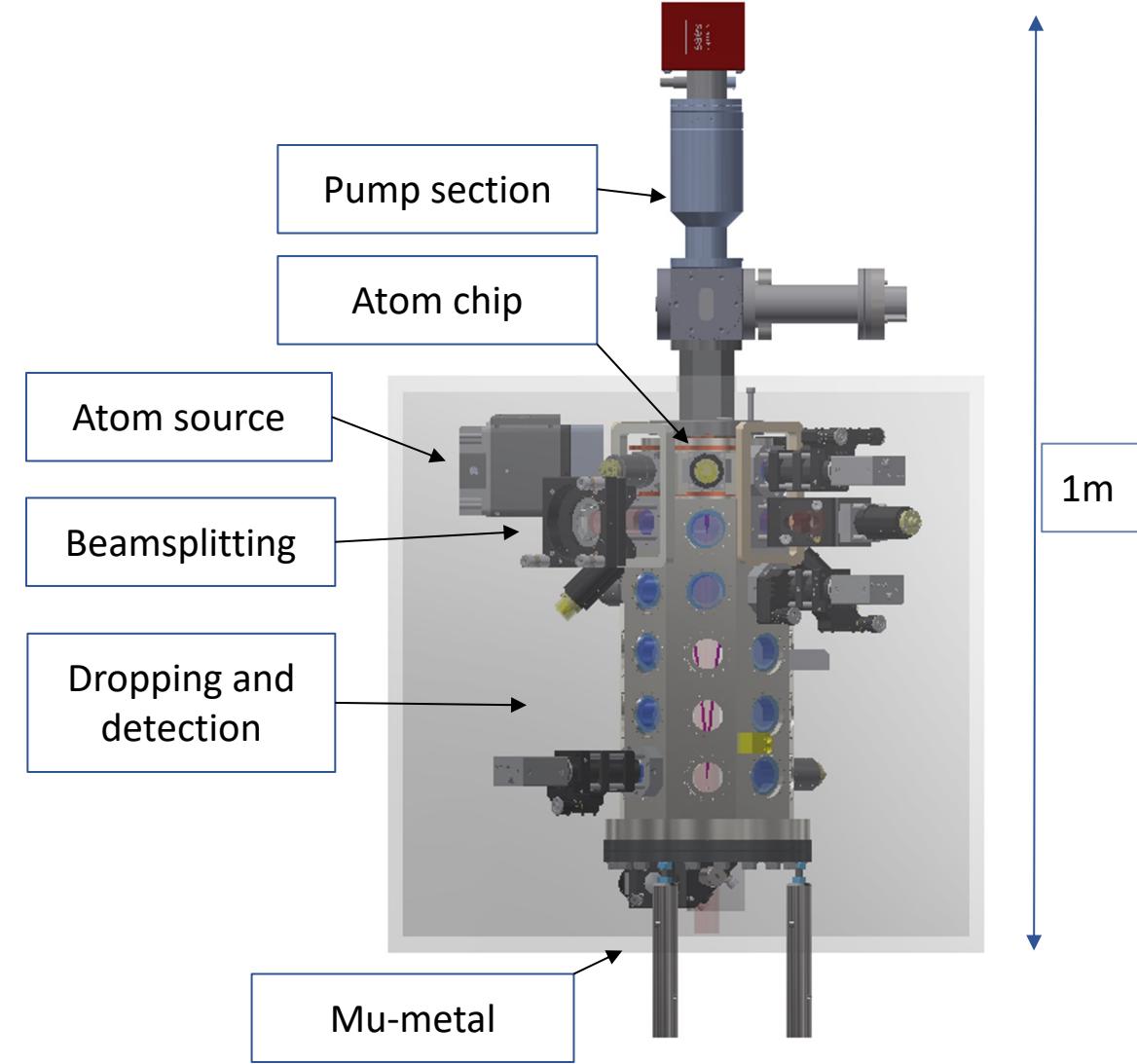
## Horizontal twin-lattice

- Increases splitting  $-\frac{\hbar k}{2m}$   $+\frac{\hbar k}{2m}$



## + Vertical relaunch

- Redirects/generates loops



## Anticipated parameters

- Effective wave vector:  $K \sim 100 \cdot 2\pi/(780 \text{ nm})$
- Free evolution time:  $T = 150 \text{ ms}$
- Cycle rate:  $0.5 \text{ Hz}$
- Atom number:  $10^5 \text{ Rb87 atoms}$

[Schubert, C. et al., Multi-loop atomic Sagnac interferometry, Scientific Reports 11, 16121 (2021)]

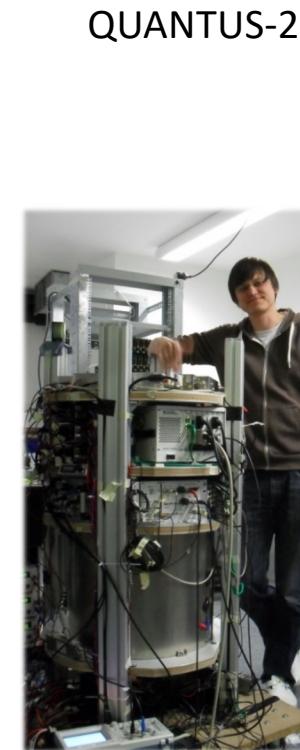
# Heritage from microgravity platforms



Drop tower @ Zarm, Bremen



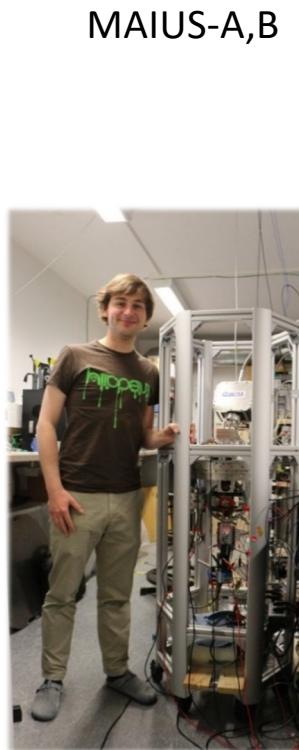
QUANTUS-1



QUANTUS-2



Sounding rocket



MAIUS-A,B



International space station

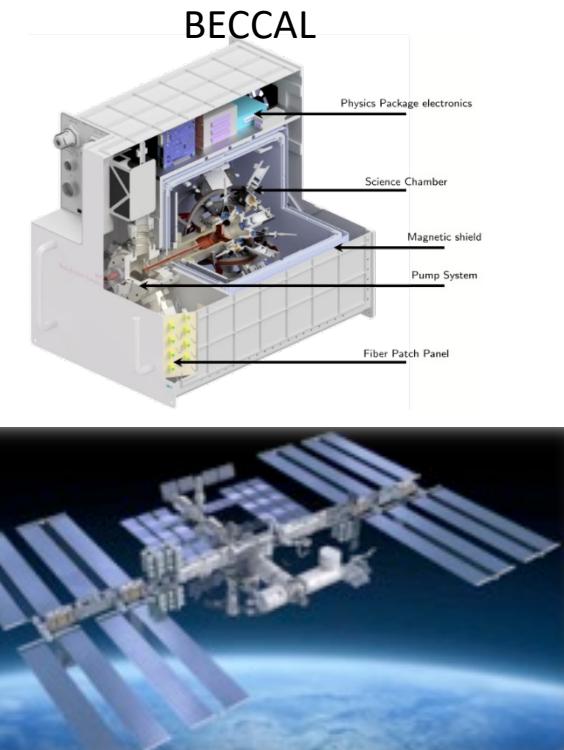
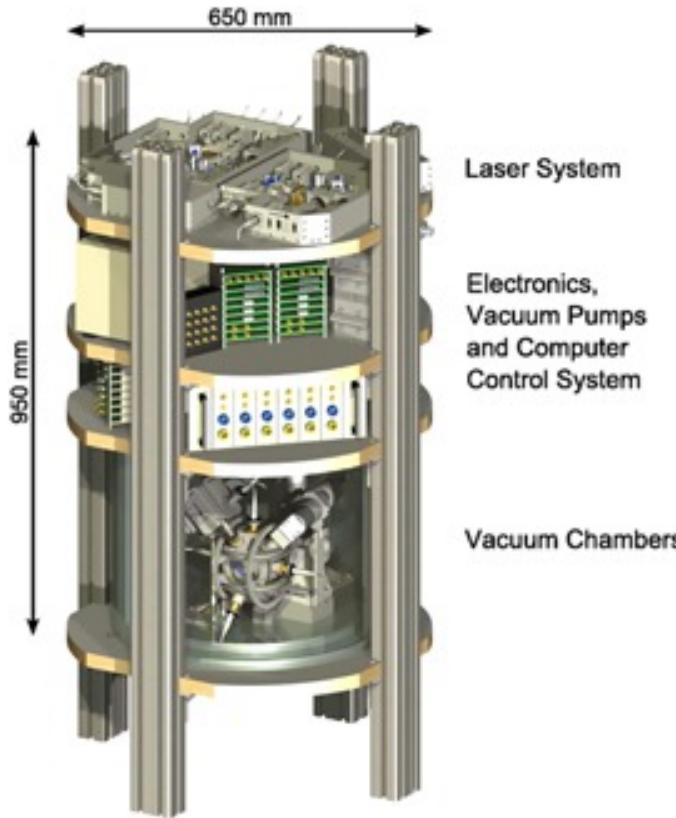


Foto: scibak/ Getty Images

[QUANTUS / MAIUS team; Müntinga et al., PRL 110, 093602 (2013); Rudolph et al., NJP 17, 065001 (2015); Becker et al., Nature 562, 391 (2018), Frye et al. EPJ QT 8, 1 (2021)]

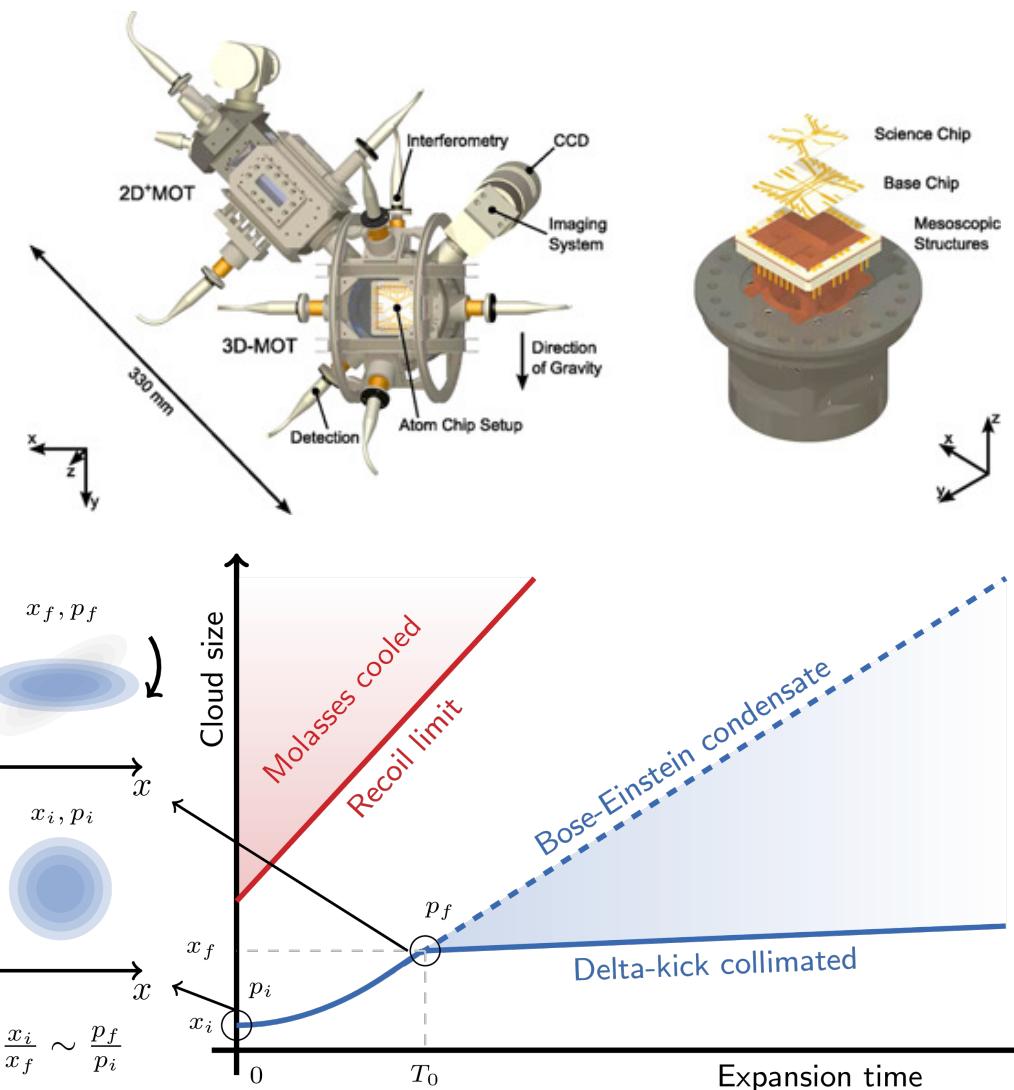
# Atom-chip BEC and delta-kick collimation



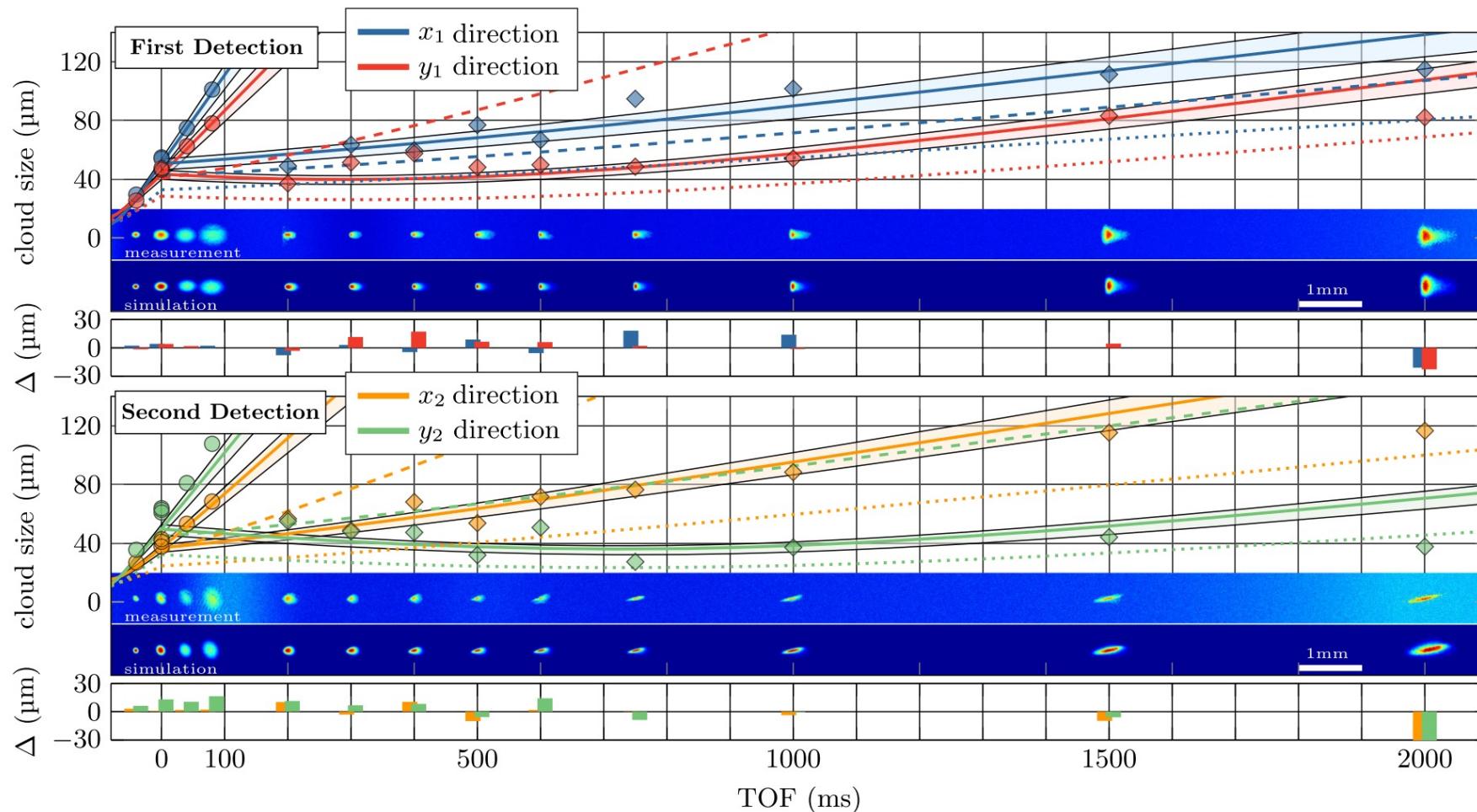
Small size and expansion

- Reduced systematic uncertainties for inertial measurements
- Efficient manipulation/long observation

[Rudolph et al., NJP 17, 065001 (2015)]



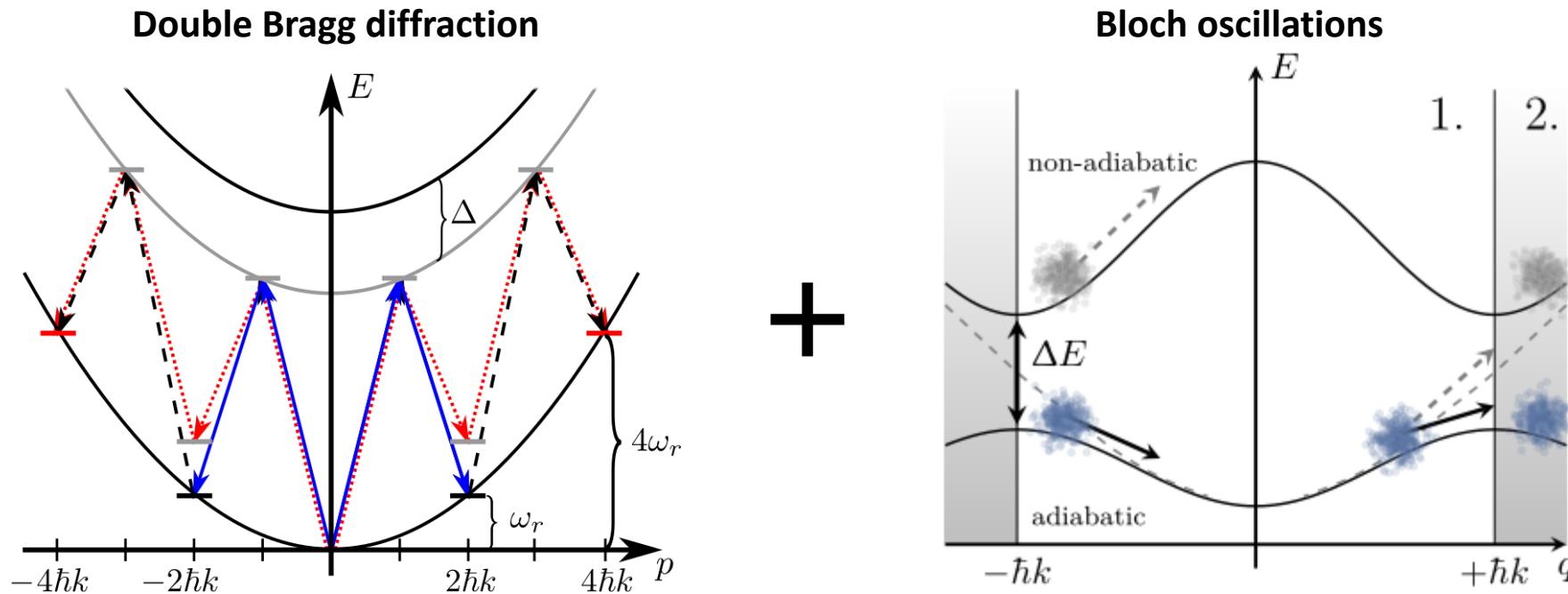
# Atom-chip BEC and delta-kick collimation



- Extended expansion times thanks to the drop tower up to 2 seconds
- Performance:  $10^5$  atoms in BEC generated in roughly 1s collimated to 38 pK

[Deppner, C. et al., Collective-Mode Enhanced Matter-Wave Optics, Phys. Rev. Lett. 127, 100401 (2021)]

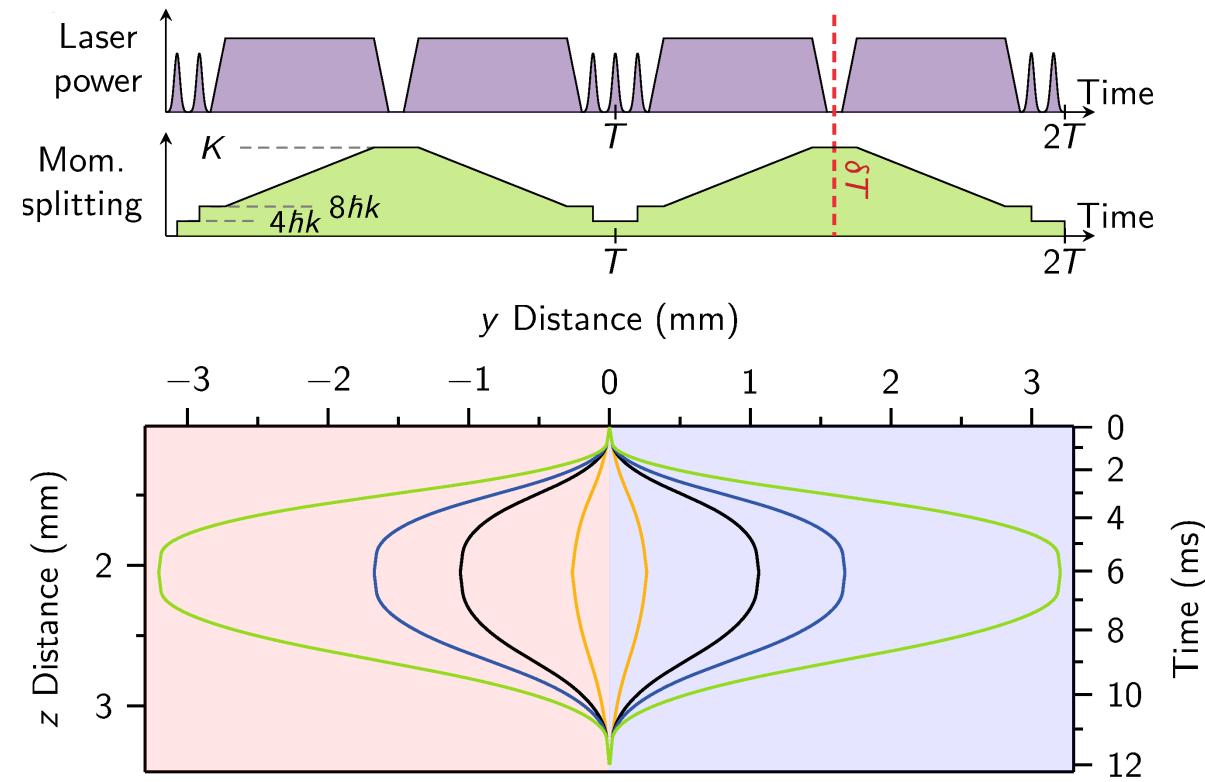
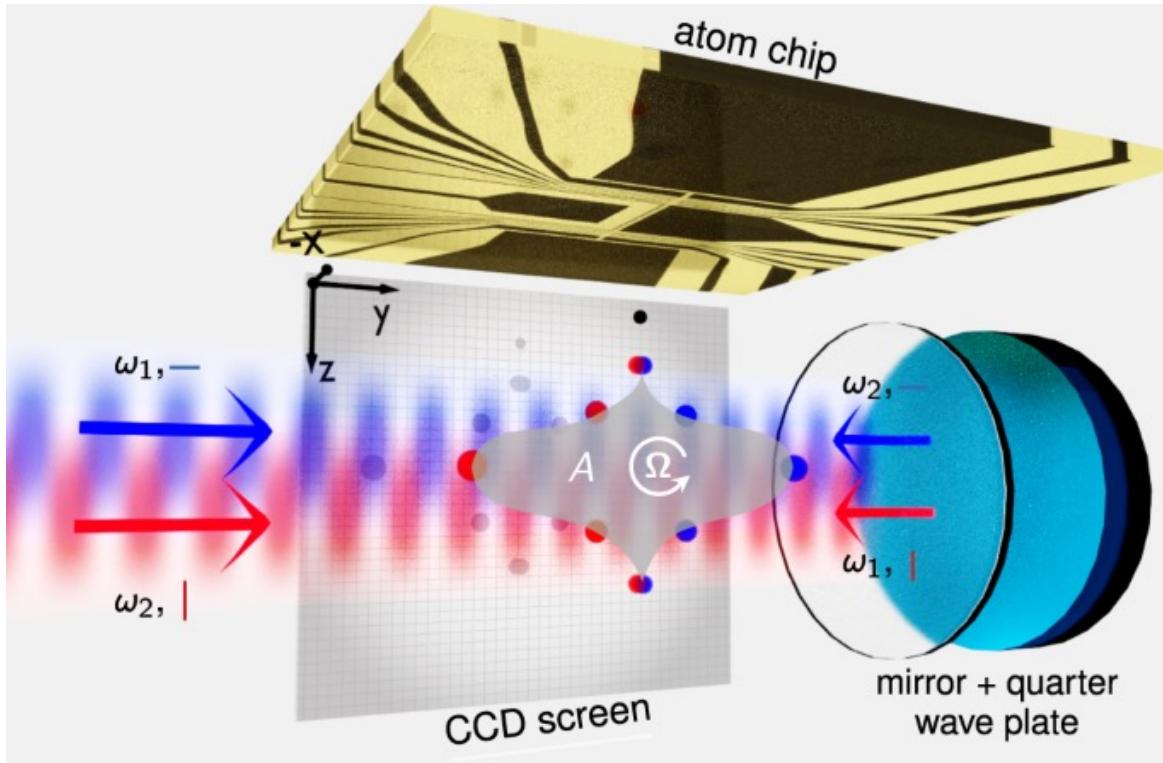
# Horizontal two-photon beam splitting



- Symmetric three momentum state coupling
- Prepare the initial superposition with double Bragg diffraction
- Coherent acceleration with Bloch oscillations

[Ahlers *et al.* Double Bragg Interferometer *Phys. Rev. Lett.* **116** 173601 (2016)]

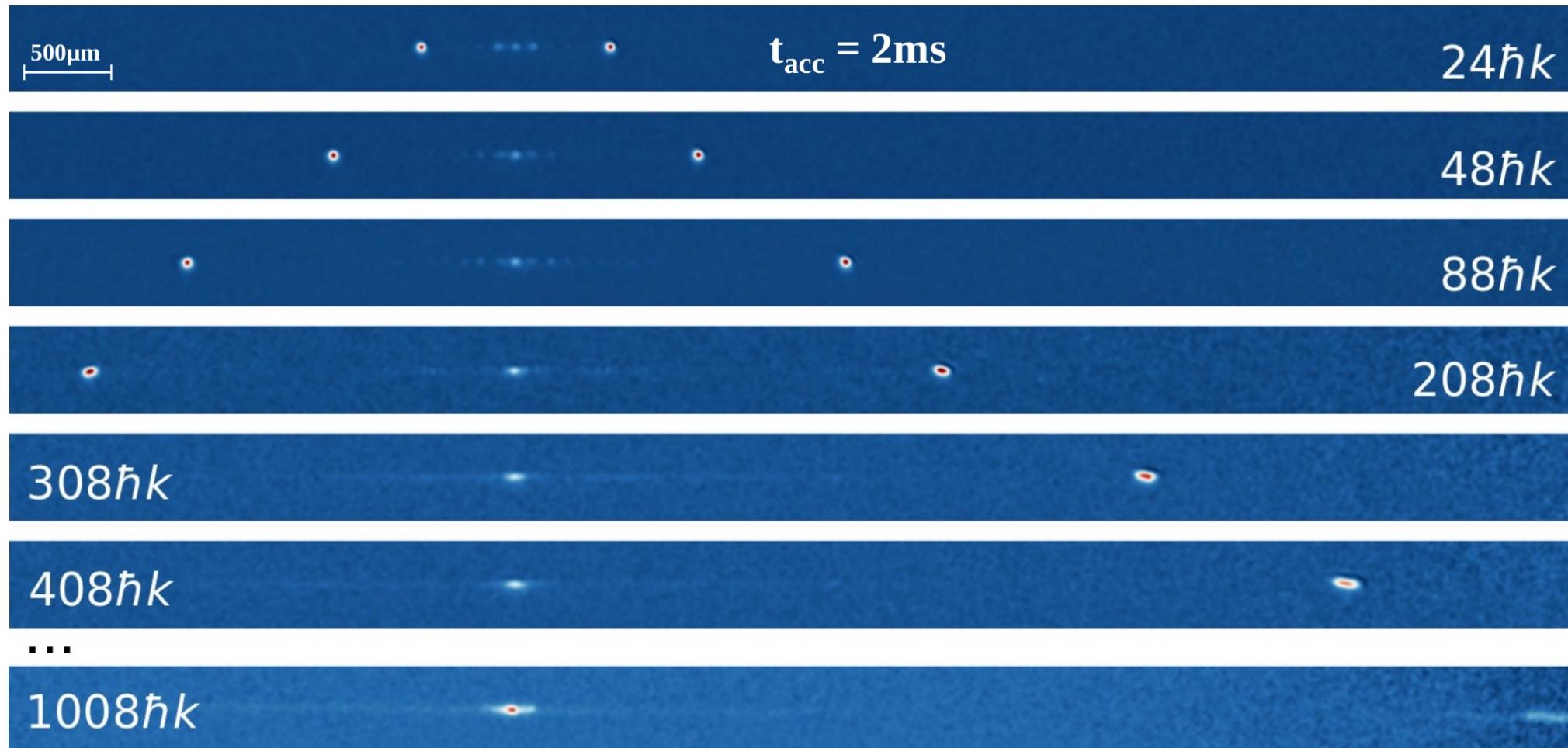
# Twin-lattice atom interferometry



- Retro-reflective configuration sensitive to inertial effects
- Combination of double Bragg diffraction and Bloch Oscillations to achieve large areas
- Interferometry with up to 1632 photon recoils @  $K = 408 \hbar k$

[Gebbe, M. et al., Twin-lattice Atom Interferometry, Nature communications 12(1) 1-7 (2021)]

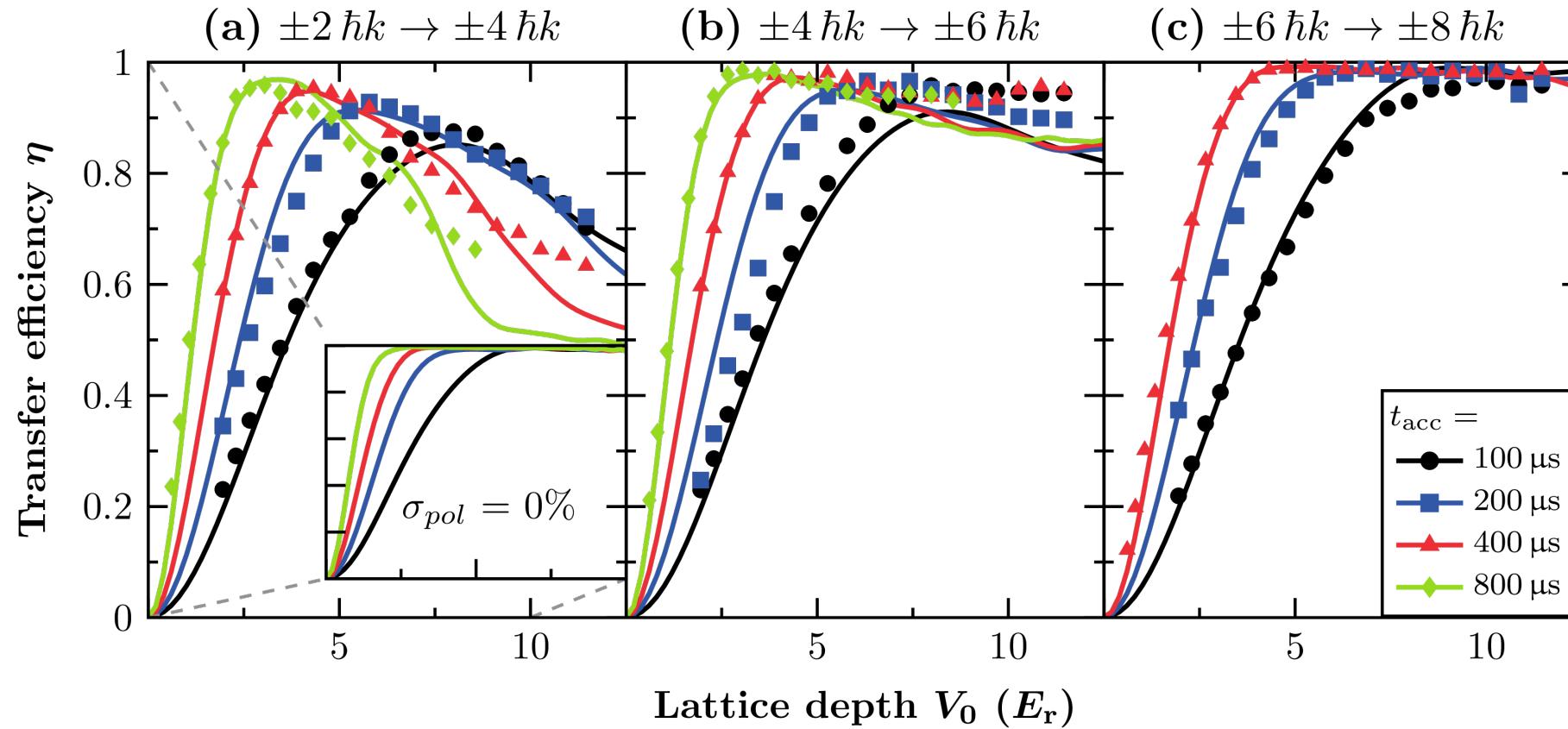
# Scalability of momentum transfer



- Up to 408  $\hbar k$  with moderate losses (within 2 ms)
- Scaled up to 1008  $\hbar k$  (within 4 ms)

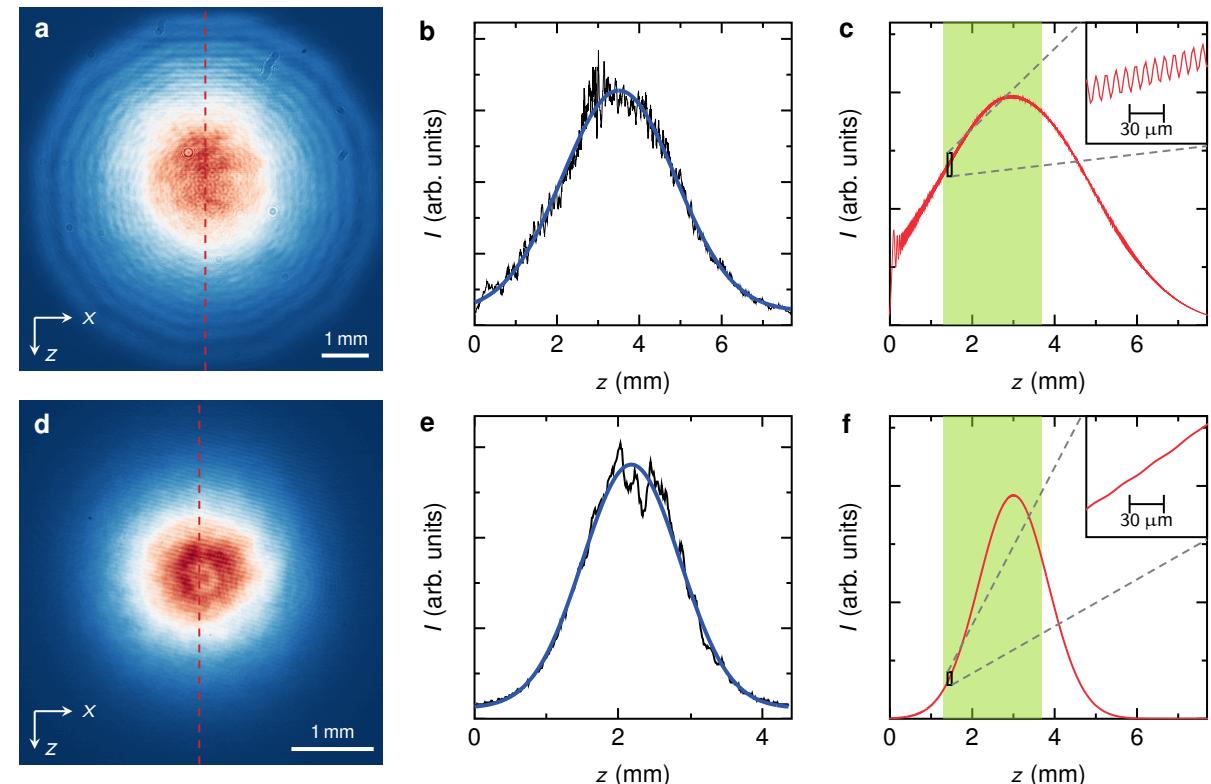
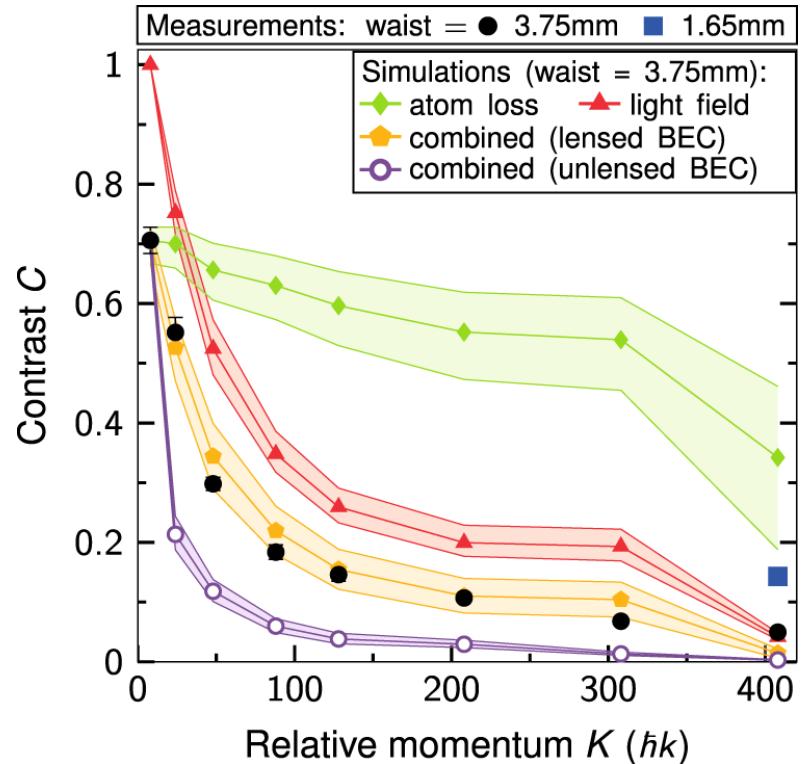
[Gebbe, M. et al., Twin-lattice Atom Interferometry, Nature communications 12(1) 1-7 (2021)]

# Landau-Zener losses in the twin-lattice



- Very little influence of non-resonant lattice expected in an ideal twin lattice
- *But:* additional losses from parasitic lattices from imperfect twin-lattice polarization
- Good quantitative understanding of these losses

# Contrast analysis due to spatial defects



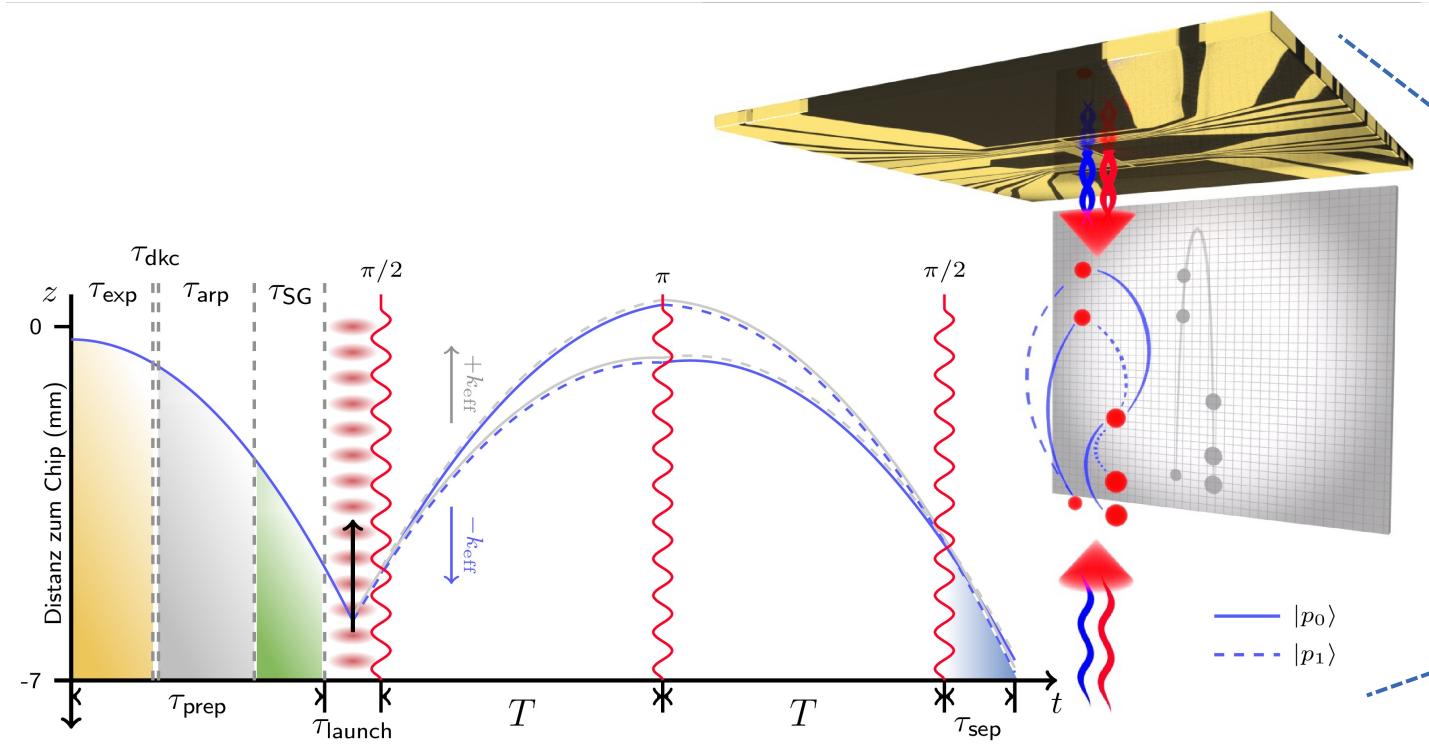
- Contrast/performance well understood → problem with beam because of the compact setup/no cavity
- Atom loss kicks in only if acceleration get too fast → spontaneous emission not an issue

[Gebbe, M. et al., Twin-lattice Atom Interferometry, Nature communications 12(1) 1-7 (2021)]

# Atom-chip fountain gravimeter: re-launch

11  
102  
1004

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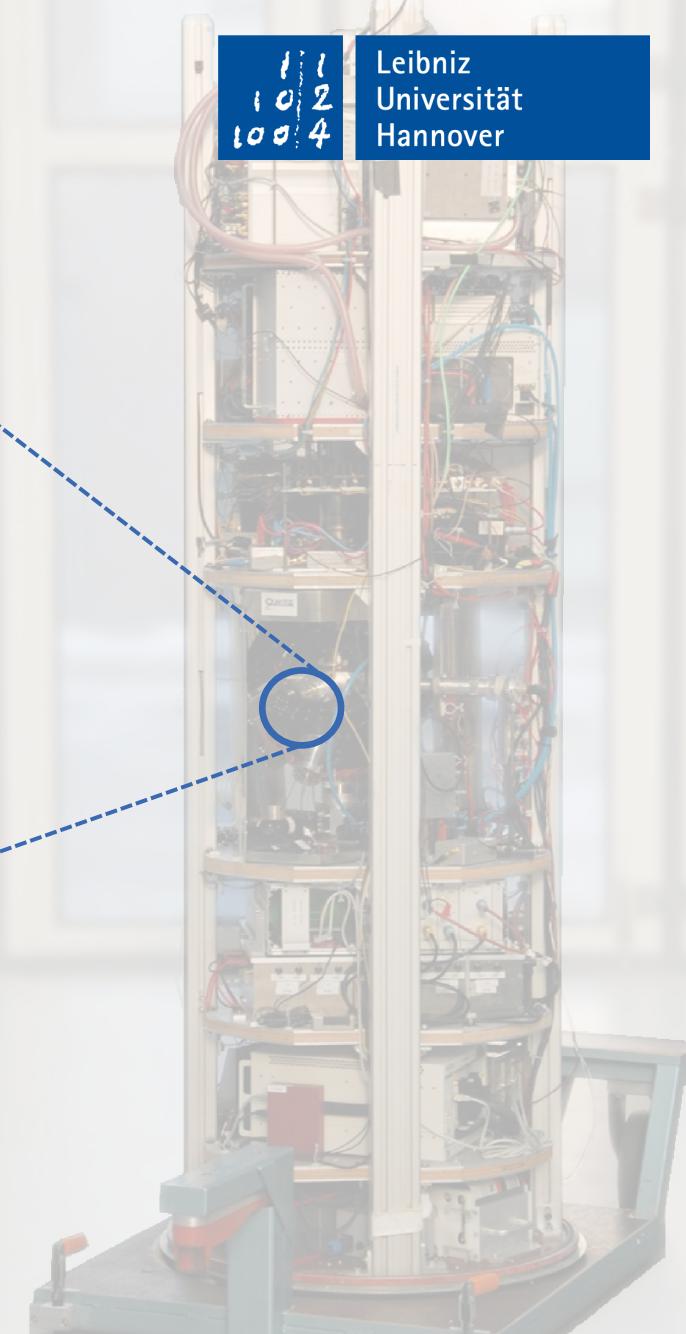


Relaunch implemented a gravimeter

- Single beam configuration drives Bloch Oscillations
- Used to elongate free fall, but not yet inside the AI
- Here: atom chip used as retroreflector

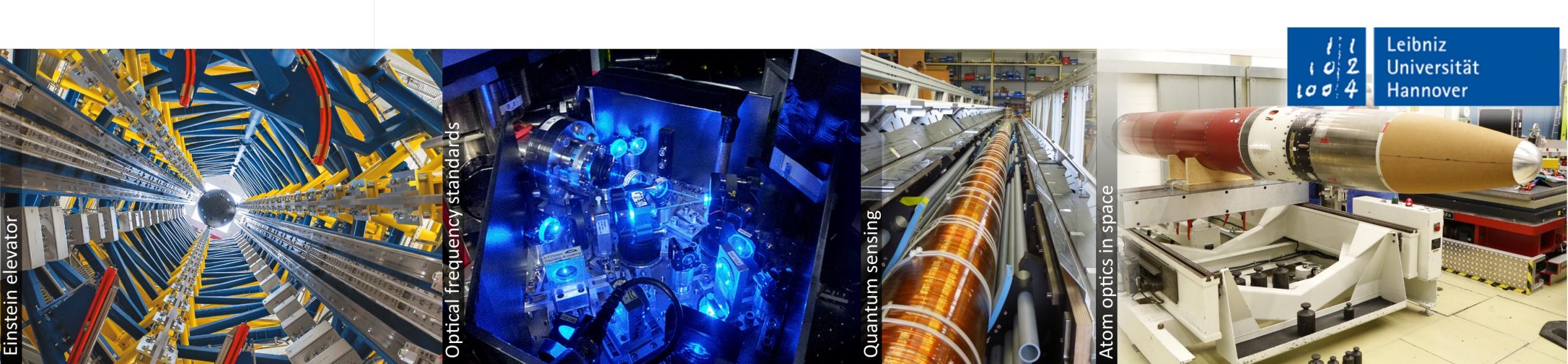
But: Much more experience in the Stanford tower with launch/relaunch

[Abend, S. et al., Atom-chip Fountain Gravimeter, Phys. Rev. Lett. 117, 203003 (2016)]



# Perspectives and questions to be discussed

- How can we transfer the horizontal technology to Earth Alkaline atoms?
  - Possible study/prototype experiments?
- Enhance on beam splitting methods
  - Possible application of cavities (see Dylan's talk)
- Horizontal geometries will enclose a large area
  - Exploration of rotation noise at different sites: maybe Wettzell (ringlaser G)
- What about a 3D sensors? Are there advantages over laser GWD?
  - Combine two horizontal axis and one vertical axis
  - What can we learn from ET? Which sites are they considering:  
ongoing investigations in Euregio Maas-Rhein or Oberlausitz



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# Thank you for your attention!



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