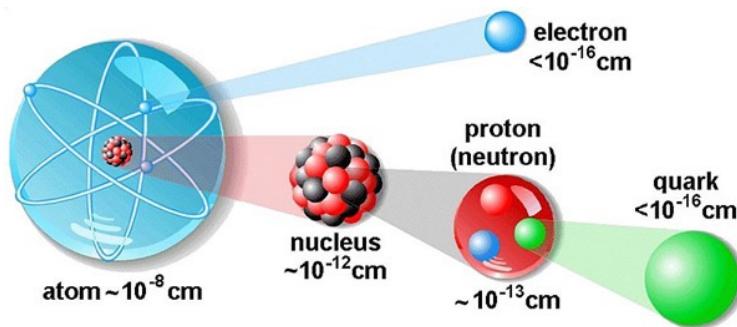


Testing atom neutrality with atom interferometer

Alexandre Gauguet - CERN 13/04/2023

Terrestrial Very-Long-Baseline Atom Interferometry Workshop

Electrical neutrality



Atom neutrality

$$\begin{aligned} q_e + q_p &= 0 \\ q_n &= 0 \end{aligned}$$

Atom neutrality is not a request of the Standard Model of particles.

Electrical neutrality of atoms rests on experimental bases.

C S Unnikrishnan and G T Gillies Metrologia 41 (2004) S125–S135

Laboratory methods

Method	q/q_e	$(q_p+q_e)/q_e$	q_n/q_e
Gas efflux (Piccard and Kessler, 1925)	5×10^{-21}	x	x
Gas efflux (Hillas and Cranshaw, 1959)	1×10^{-21}	3×10^{-20}	3×10^{-20}
Acoustic resonator (Dylla and King, 1973)	1.3×10^{-21}	x	x
Acoustic resonator (Bressi 2011)	1.1×10^{-21}	x	x
Levitator (Marinelli and Morpurgo, 1984)	0.8×10^{-21}	x	x
Atomic beam (Hughes et al., 1988)	3×10^{-21}	1.2×10^{-19}	9×10^{-20}
Neutron beam (Baumann et al., 1988)	x	x	1.1×10^{-21}

From Bressi et al. PRA 83, 052101 (2011)

e-p asymmetry and neutron charge $< 10^{-21} e$

These experiments “were done decades ago, and at the time were rather one-man shows. This is a pity in view of the effort invested in other searches beyond the standard model”

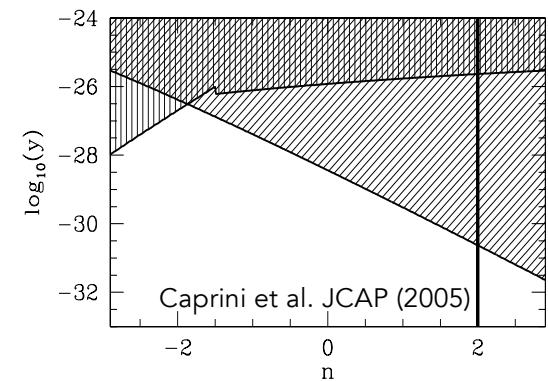
Rev. Mod. Phys. 83, 1111 page 1131

Testing electrical neutrality

Astro & Cosmology:

- Model dependent limits vary between 10^{-20} and $10^{-38} q_e$
Caprini et al. JCAP (2005)
Sengupta Phys. Let. B (2000)

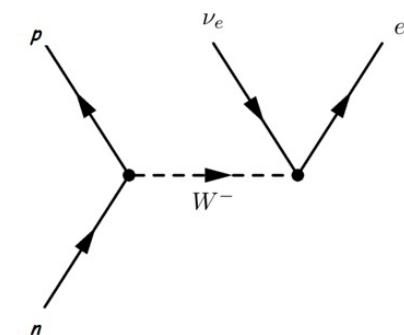
Lab V.S. cosmological constraint on an electrically charged universe



Particles physics point of view:

- Atom neutrality is related to the electric charge quantization. Uniqueness of the charge for leptons and baryons implies, novel connection, «Beyond standard model » between the families of particles.
- Charge neutrino from charge conservation in β -decay : $n \rightarrow p + e^- + \nu_e$

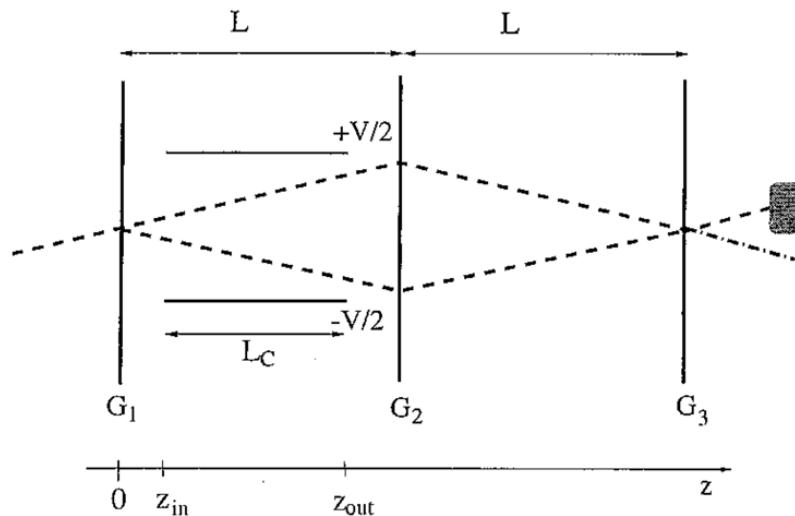
Using limits on charge neutrality into constraints on the theory: Needs for phenomenological models.



Atomic measurements

Measuring Lorentz force:

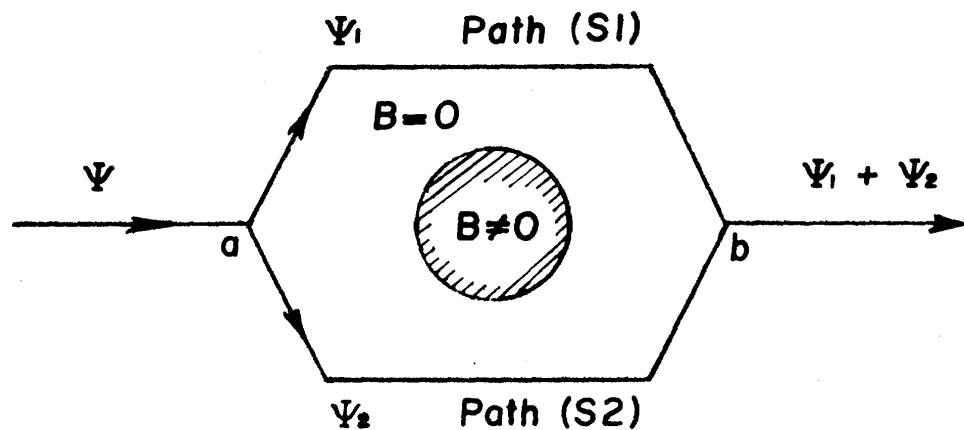
- Atomic & molecular beam deflection method
- Atom interferometry: force measurements



$$\Delta\phi = q_{at} \frac{Ed}{\hbar} \frac{L_C}{c}$$

Accuracy: residual polarisabilities effects, electric fields modeling

Test of neutrality using Aharonov-Bohm effect



$$\Delta\phi = \frac{q}{\hbar} \oint A(r) dr = \frac{q}{\hbar} \Phi_B$$

Testing matter neutrality & minimal coupling

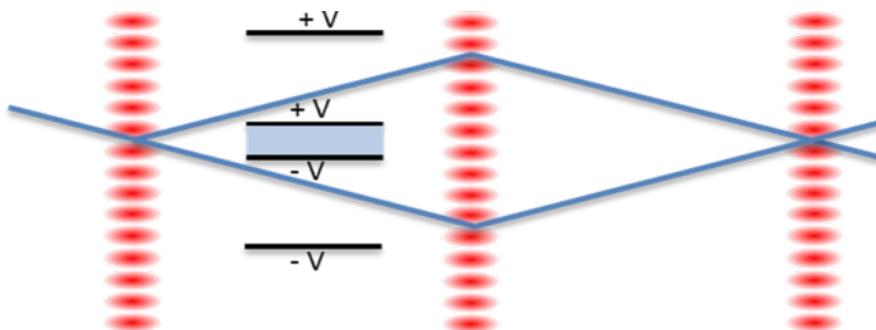
D. Greenberger et al. PRL 47 751 (1981)

Quantum tests of electrical neutrality

Scalar Aharonov-Bohm effect

C. Champenois et al. Lecture Notes in Phys 570, (2001)

A. Arvanitaki et al. PRL 100, 120407 (2008)



Pulsed electrostatic potentials

$$\Delta\phi = q_{\text{Rb}} \frac{2V\tau}{\hbar}$$

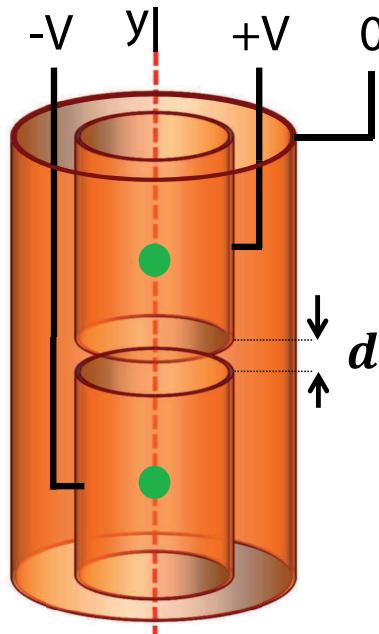
Measurement with two atomic species can disentangle the neutron charge and the electron-proton charge asymmetry.

$$q_{A,Z} = Z(q_e + q_p) + (A - Z)q_n$$

Atoms are neutral

$\Delta\phi = 0,0000(\text{X}) ??$

Sensitivity ?



$$\sigma_\eta = \sigma_\phi \frac{\hbar}{2V\tau} \frac{1}{Aq_e}$$

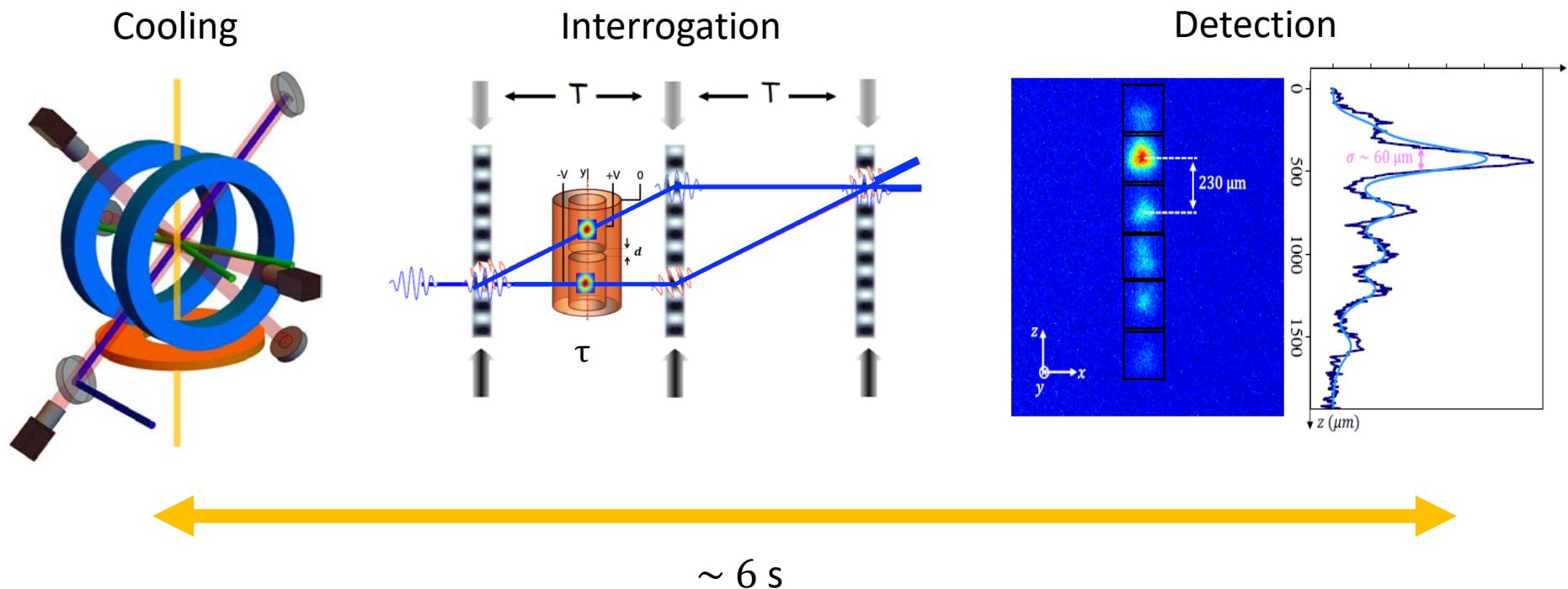
A = 87 nucleons
 $\tau = 500$ ms
 V = 100 kV

$\sigma_\eta = 10^{-28}$ ($10^{-30} q_e$)

Experiment	(Proposed) Site	Baseline L (m)	LMT Optics n	Atom Sources	Phase Noise $\delta\phi$ (rad/ $\sqrt{\text{Hz}}$)
Sr prototype tower	Stanford	10	10^2	2	10^{-3}
MAGIS-100 (initial)	Fermilab (MINOS shaft)	100	10^2	3	10^{-3}
MAGIS-100 (final)	Fermilab (MINOS shaft)	100	4×10^4	3	10^{-5}
MAGIS-km	Homestake mine (SURF)	2000	4×10^4	40	10^{-5}
MAGIS-Space	Medium Earth orbit (MEO)	4×10^7	10^3	2	10^{-4}

Mahiro Abe et al 2021 Quantum Sci. Technol. 6 044003

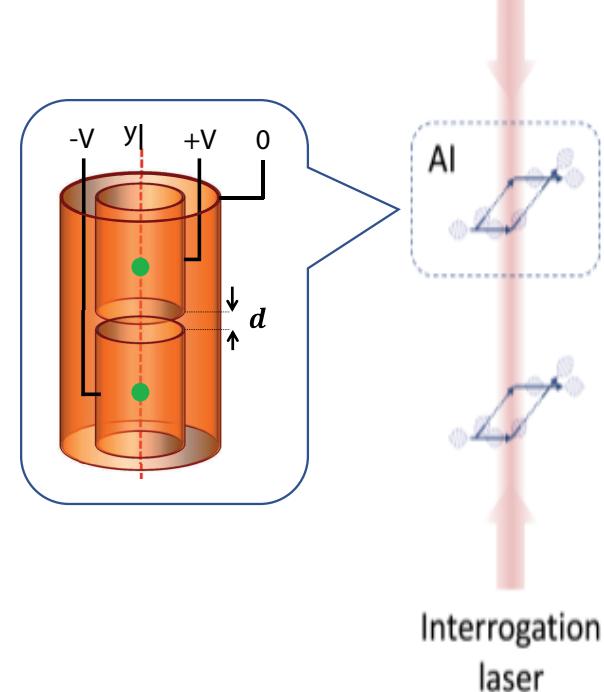
Proof-of-Concept on a table top AI



Target sensitivity

LMT-MZ-Interferometer

- 2 - 10 cm
- LMT = 50 - 200 $\hbar k$
- $2T = 50 - 200$ ms
- $> 5 \cdot 10^4$ detected atoms
- $T < 1$ nK



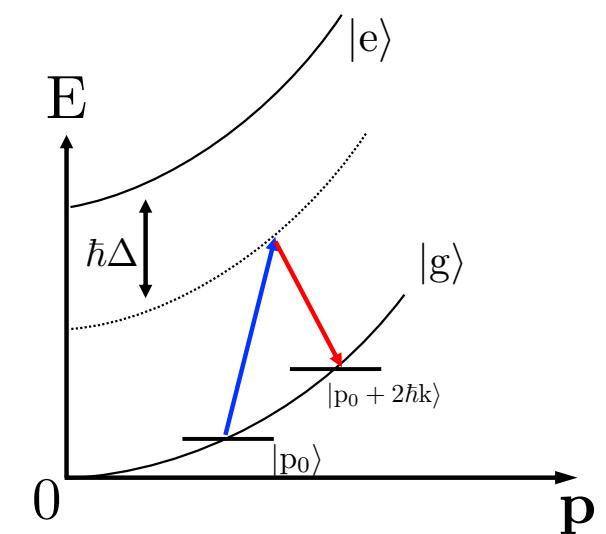
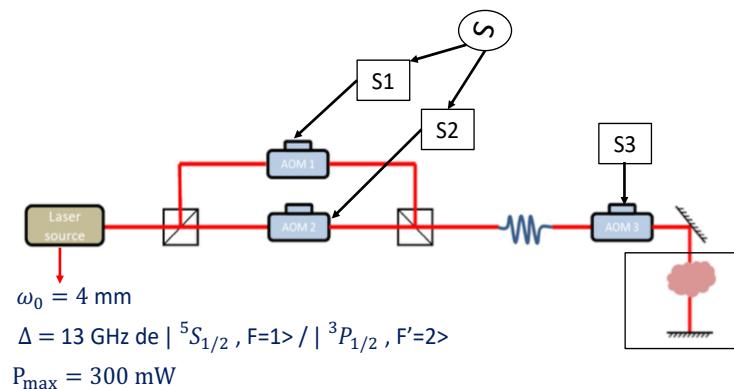
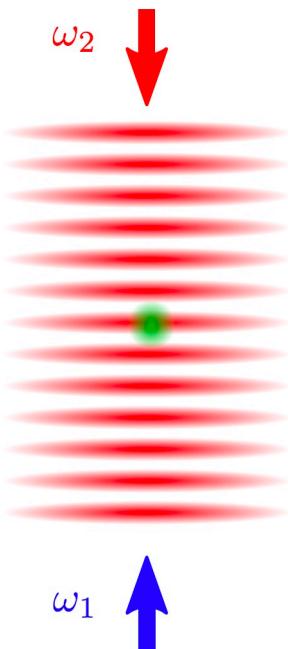
Sensitivity for 2500 measurements:

Single shot limit	Vibration	QPN
σ_{shot}	200 mrad	5 mrad
σ_ϕ	4 mrad	100 μ rad
σ_η	10^{-23}	10^{-24}

$$\sigma_\eta = \sigma_\phi \frac{\hbar}{2V\tau} \frac{1}{Aq_e}$$

$A = 87$ nucleons
 $\tau = 20$ ms
 $V = 20$ kV

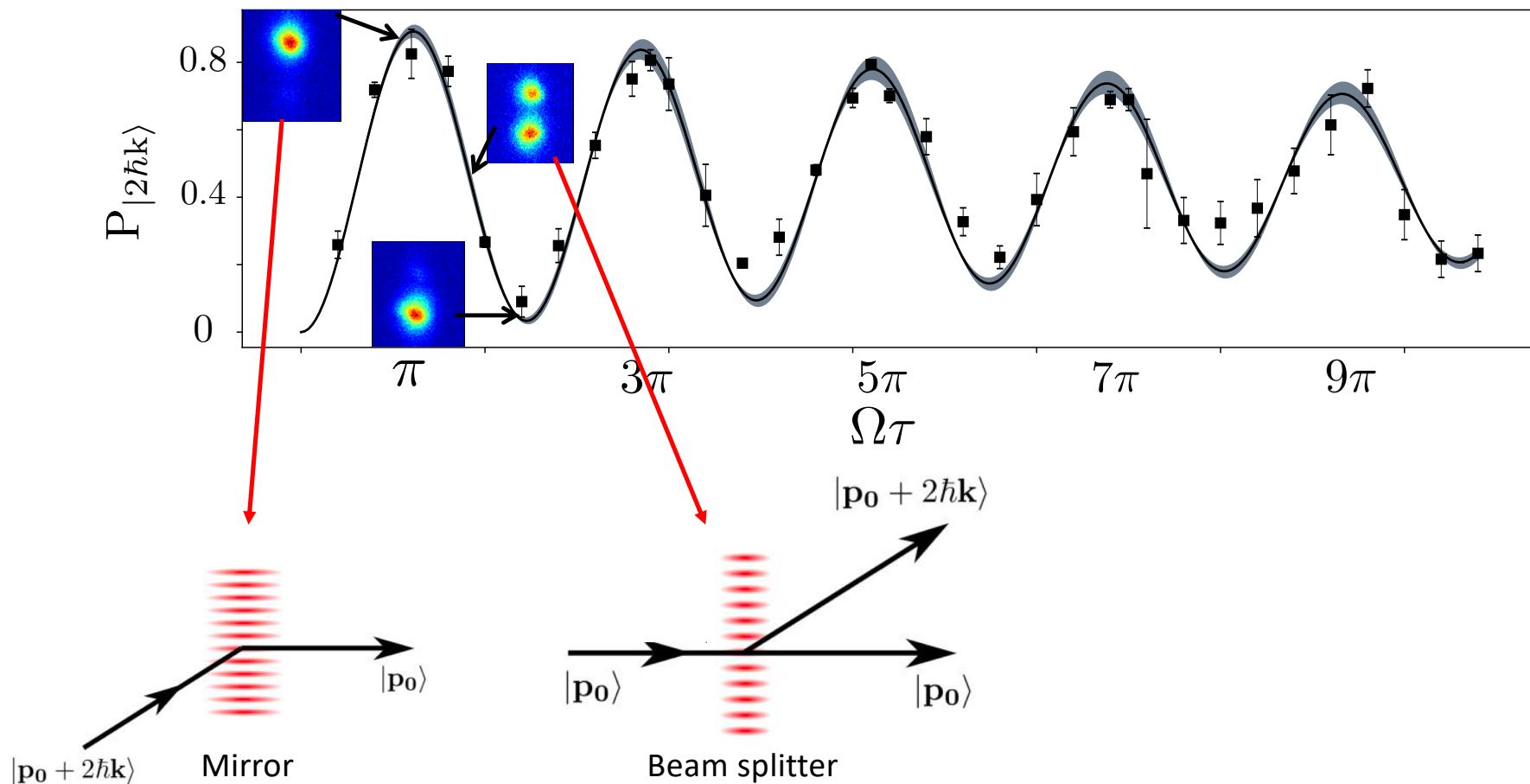
Atom diffraction in a standing wave



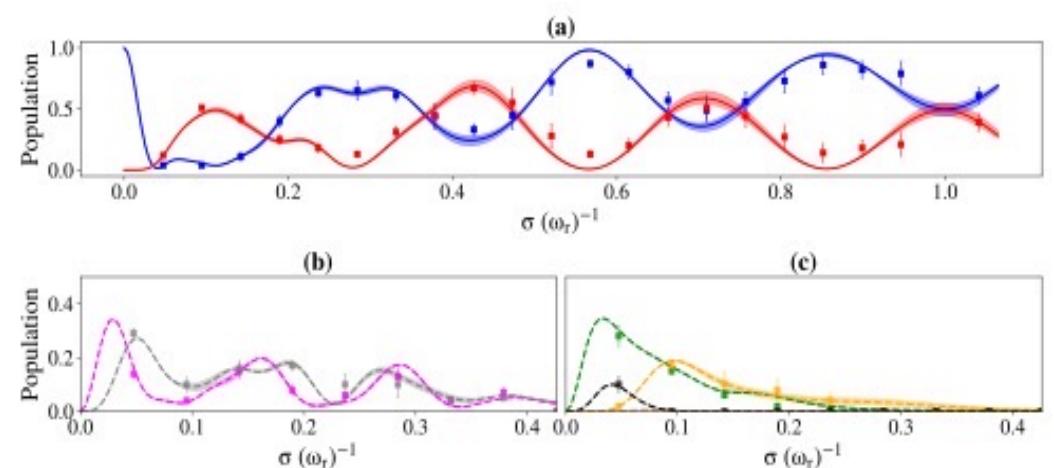
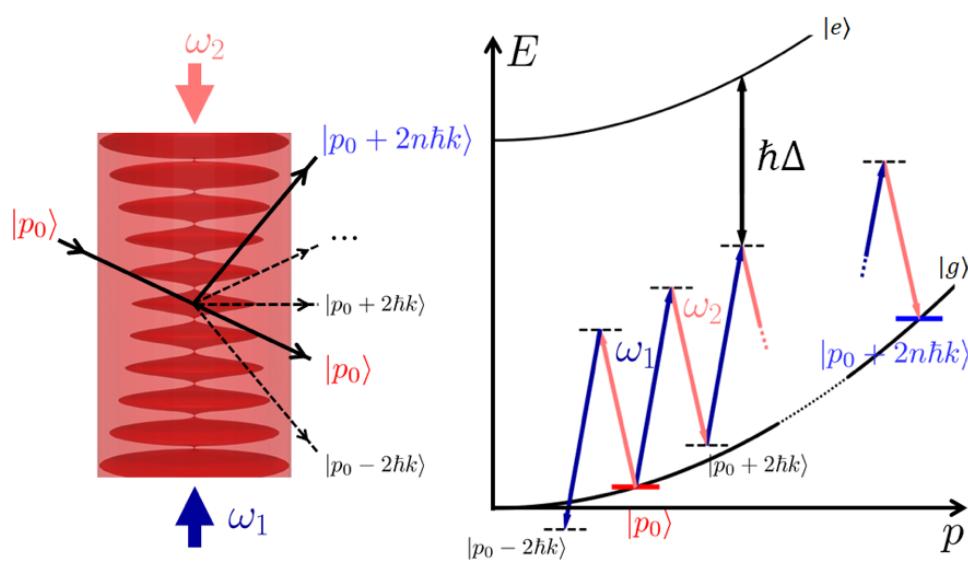
Two-photon transition: $2\hbar k$ momentum transfer

$$| \Psi \rangle = a_0 | p_0 \rangle + a_+ | p_0 + 2\hbar k \rangle$$

Atom mirrors and beam splitters



High order quasi-Bragg



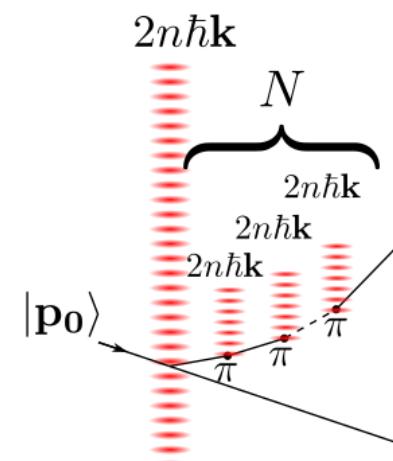
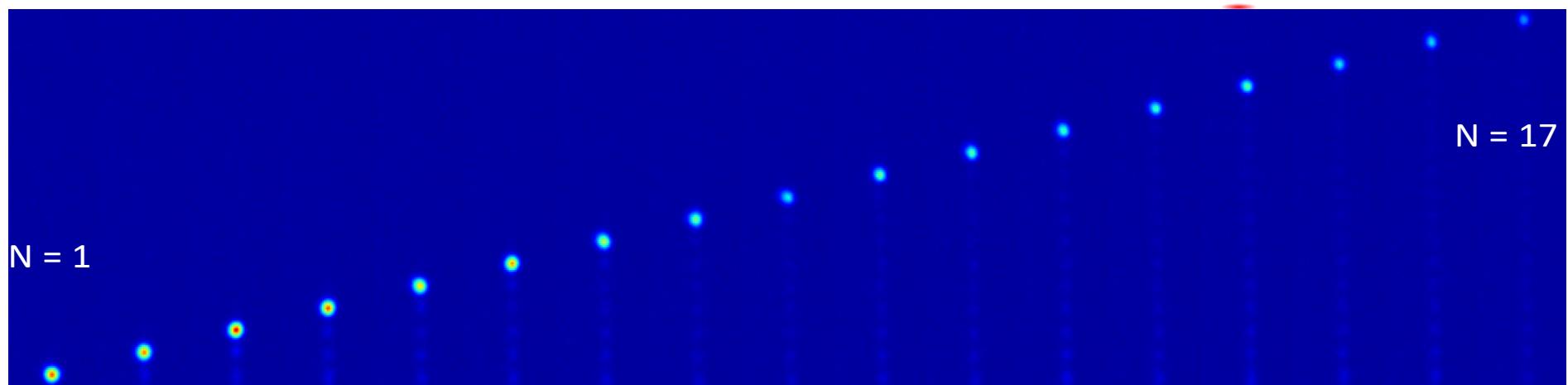
A.Béguin et al. Phys. Rev. A 105, 033302 (2022)

2n-photon transition: $2n\hbar k$ momentum transfer

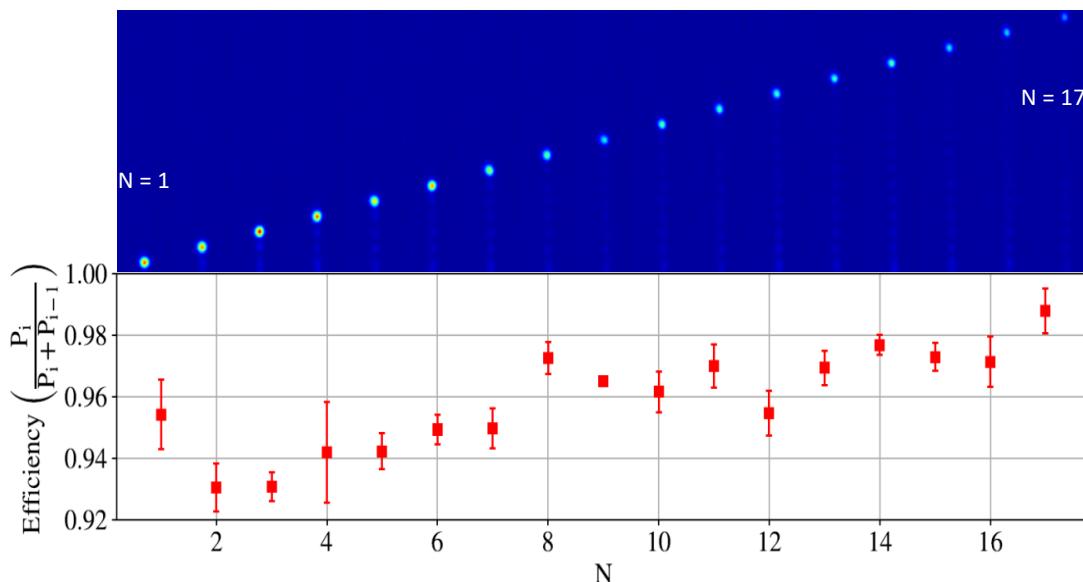
Sequential Bragg Beam Splitter

Beam splitter made with multiple $n = 1$ accelerating (mirror) pulses.

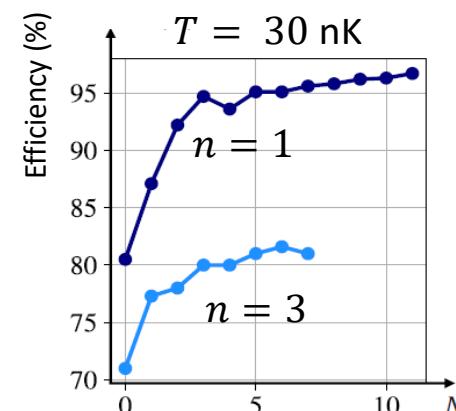
Chiow et al. Phys. Rev. Lett. 107, 130403 (2011)



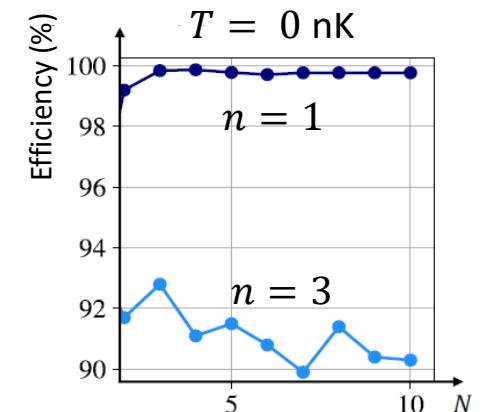
Efficiency



Efficiency improves during the pulse sequence :

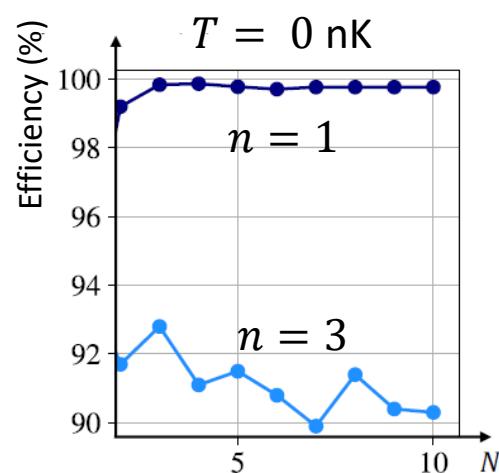
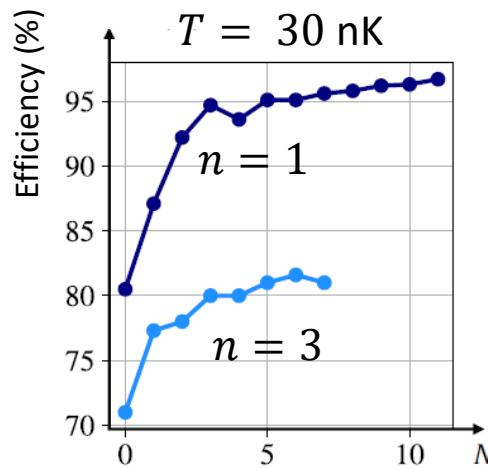


Velocity selection during
the 1st pulses



The transfer at the Nth
pulse can be better than
for a single pulse at zero
temperature ??

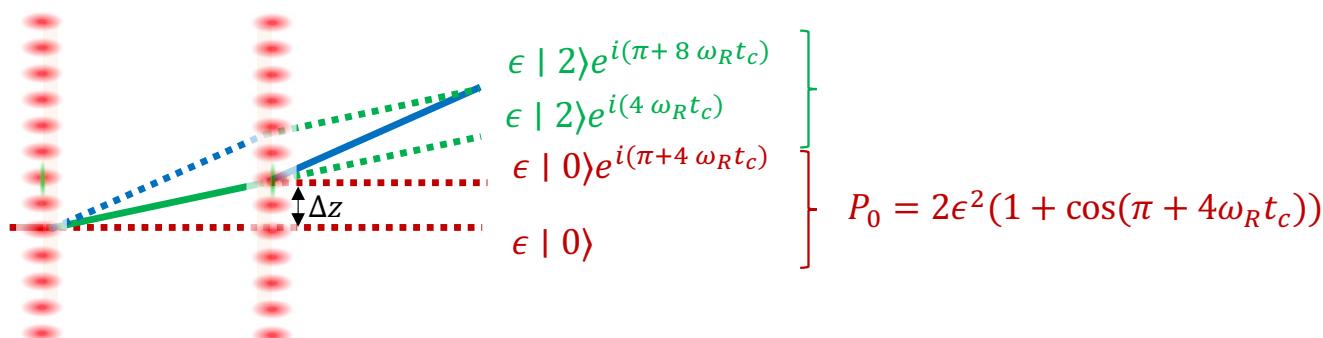
Efficiency



The transfer at the N th pulse can be better than for a single pulse at $T=0$??

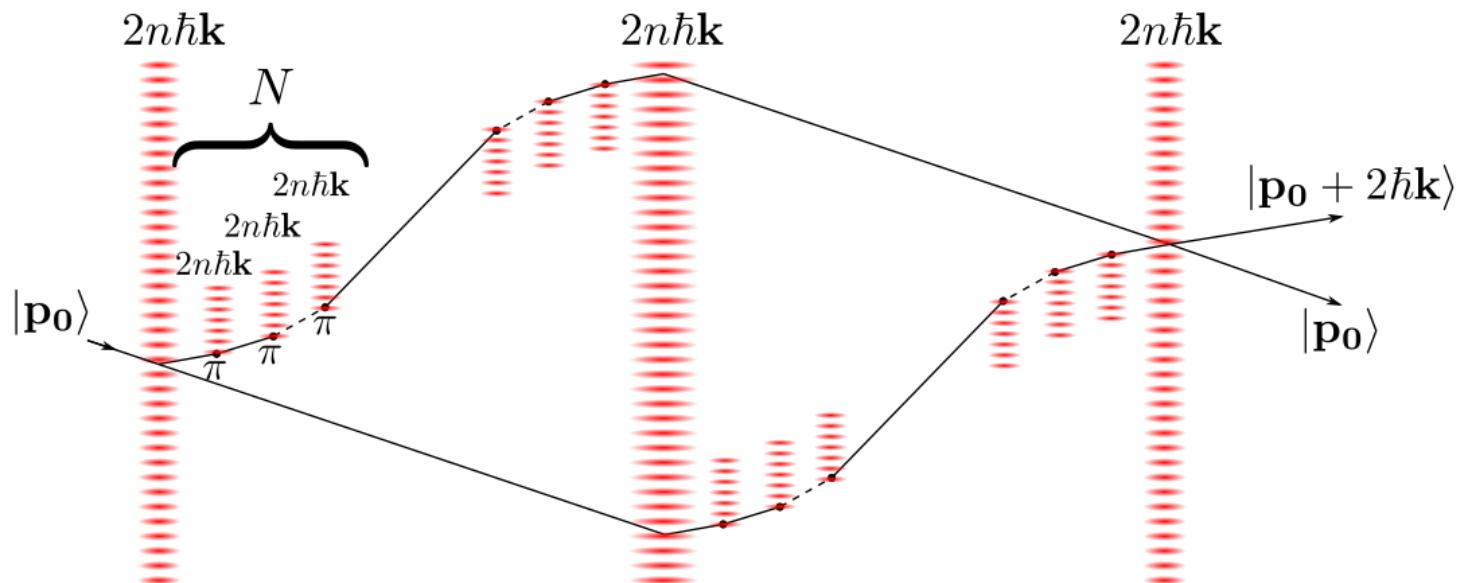


Interferences blocking the loss channels.

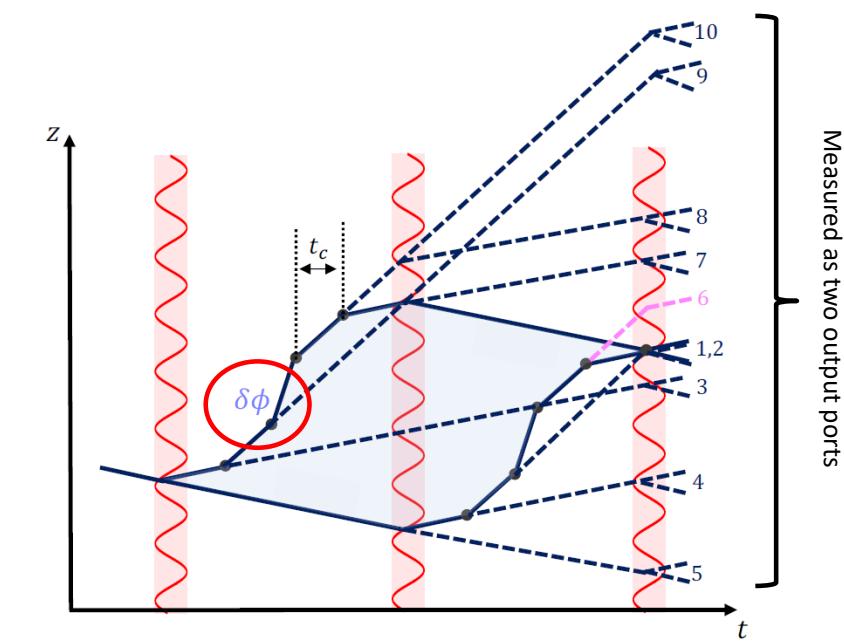
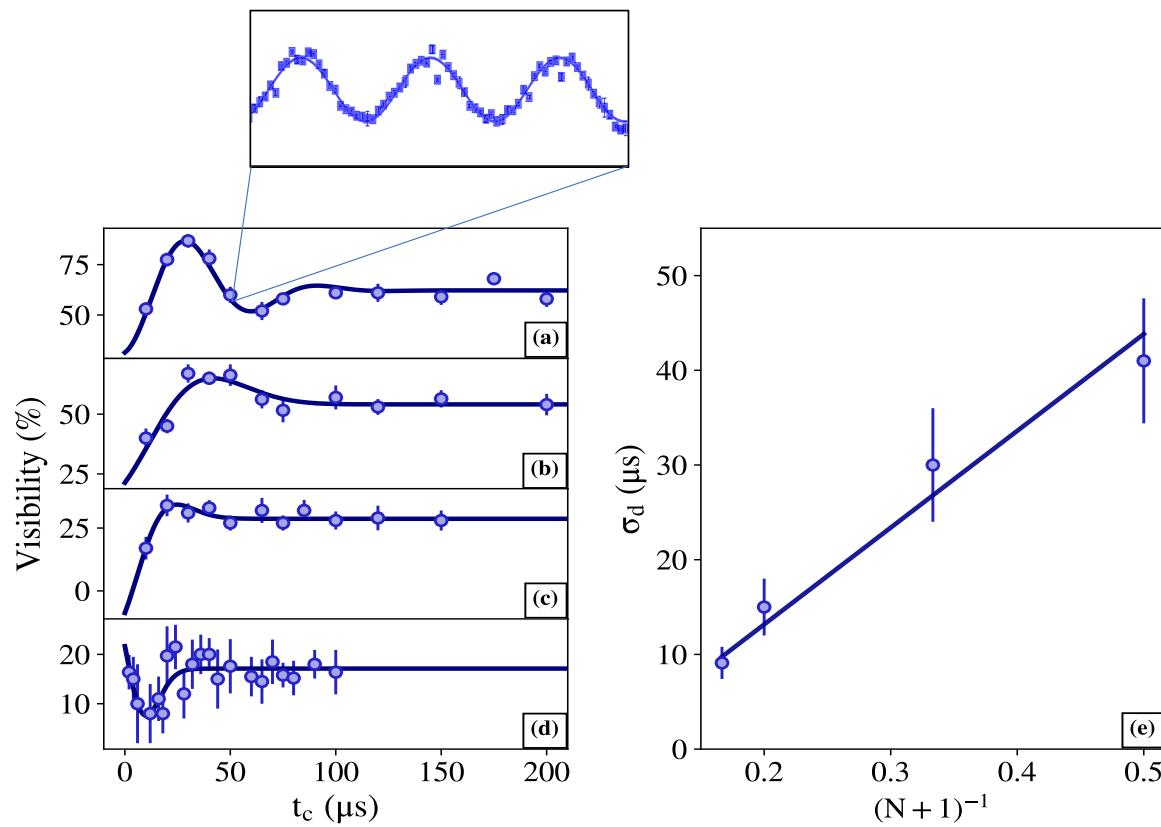


- $\Delta z = \frac{2\hbar k}{m} t_c \ll \xi = \frac{\hbar}{m \sigma_v}$
- $t_c \ll \omega_R^{-1}$

Sequential Bragg Interferometer

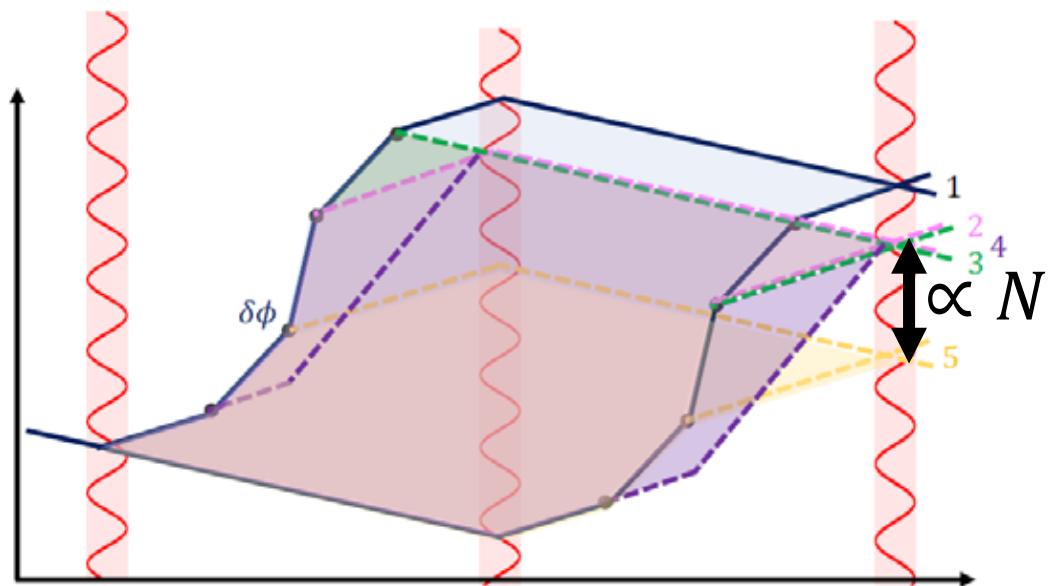


Spurious interferometers



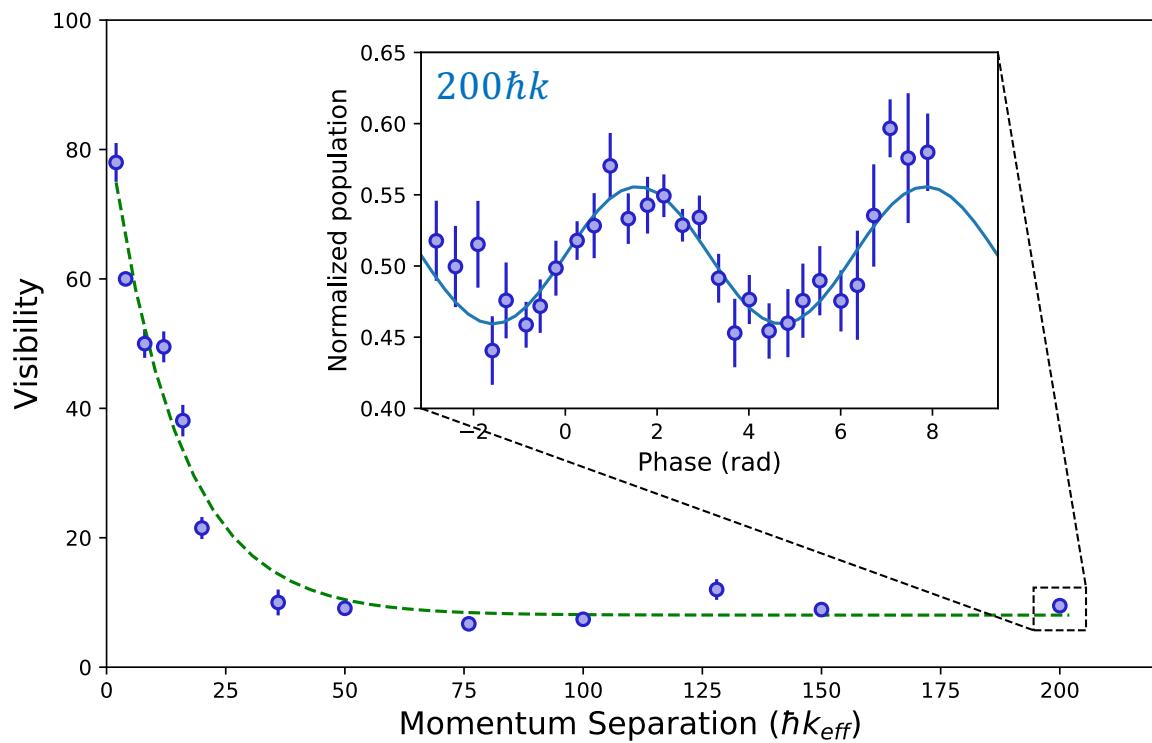
- For long enough t_c « open interferometers » vanish
- Favorable scaling with N

Spurious interferometers



- Closed interferometers need non-resonant transitions with low probability.
- Separation of the interferometers at the output.
→ Favorable scaling with N

LMT interferometer visibility



- 200 $\hbar k$ interferometer with a sequence of 1st order quasi-Bragg pulses (400 pulses).
- Interferometer phase shift $\propto 2N\phi_{\text{laser}}$

Summary

A new approach to test atom neutrality:

- Based on Scalar Aharonov Bohm effect
- Need for a large scale interferometers
- The sensitivity can be a few $10^{-26} q_e$, improving by 5 orders of magnitudes the best current accuracy .
- Possibility to improve by few order of magnitude with very large atom interferometers and advanced atom optics.

LMT-interferometer 200 $\hbar k$:

- Report the impact of parasitic interferometers on the visibility.
- Efficiency enhancement in a sequence of Bragg pulses.
- Demonstration of a 200 $\hbar k$ LMT interferometer.

Atom interferometry team

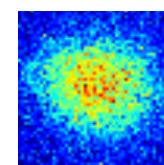
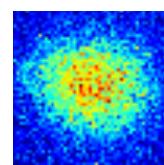


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Φ

