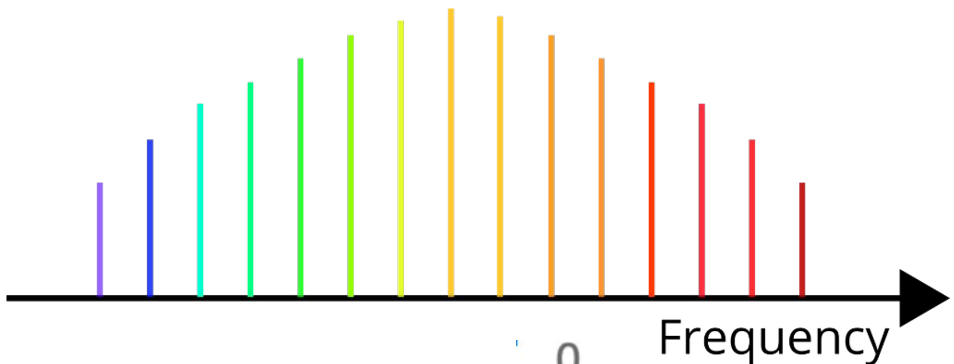
Qombs

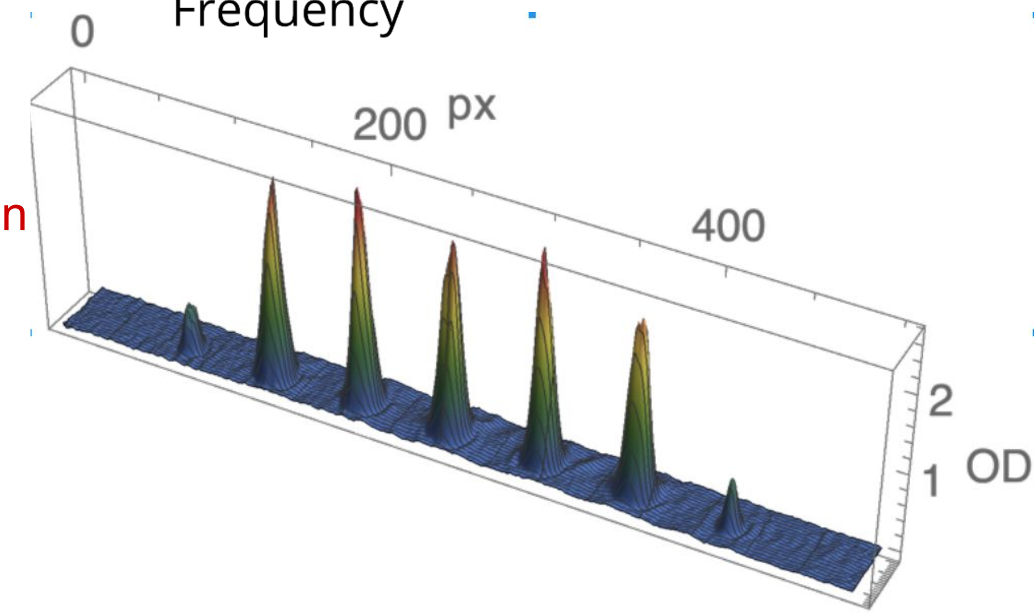
QUANTUM FLAGSHIP

Bosonic “leg”: simulation of frequency comb with atomic comb of momentum components



Goal:

find/study non-classical correlations of atom numbers in momentum “teeth”



Contact interactions analogous to Kerr non-linearity (4-wave mixing)

WP2: quantum coherence with BECs

To investigate the existence of quantum correlations in the emission of QCL-comb, we aim to engineer an atomic analog based on momentum states

T2.4: Arbitrarily filtered, multimode, Kapitza-Dirac interferometer (CNR; M1-M18)

T2.5: Generation and detection of quantum correlations (CNR; M1-M24)

T2.6: Controlling interactions to control quantum correlations (CNR; M18-M36)

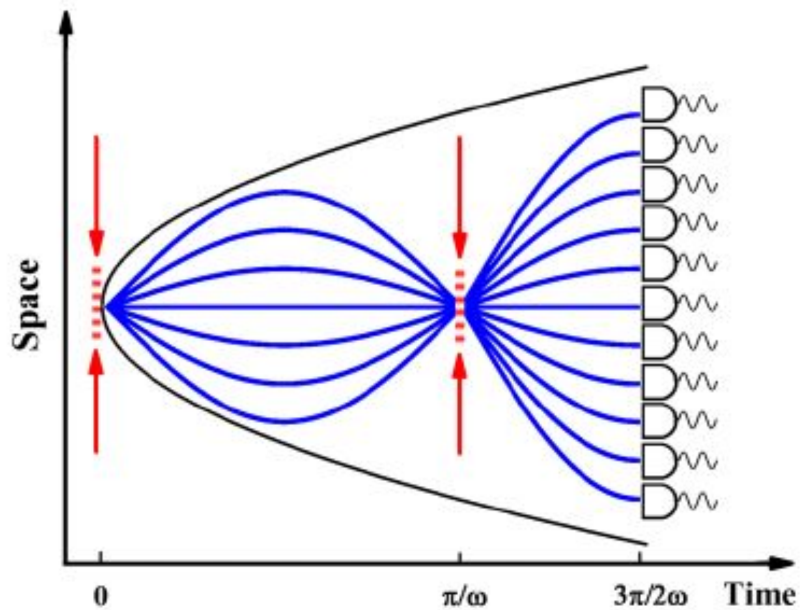
T2.4: Arbitrarily filtered, multimode, Kapitza-Dirac interferometer (M1-M18)

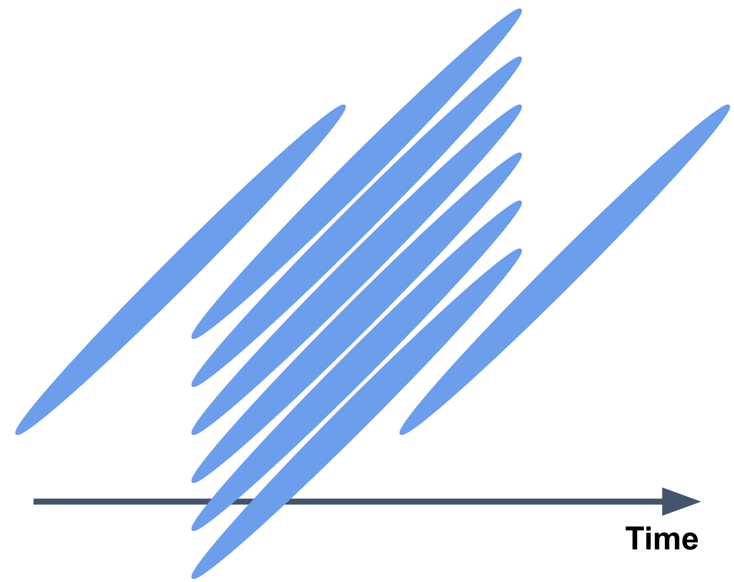
The multiple momentum components corresponding to the comb photonic modes will be obtained from a single trapped Bose-Einstein condensate (BEC), by means of a Kapitza-Dirac pulse.
We will implement the established protocol of trapped Kapitza-Dirac interferometry using a BEC of 87Rb atoms. As a new resource, we will develop an arbitrary “momentum filter” to remove components at will. The use of light masks generated by DMD will grant arbitrary selections.

D2.3: Implementation of Kapitza-Dirac multimode beam-splitter and interferometer (M18)

Kapitza-Dirac interferometer

Proposed by Li et al. [PRL 113, 023003 (2014)],
partially realized in experiment by R.E. Sapiro et al. [PRA 79, 043630 (2009)]

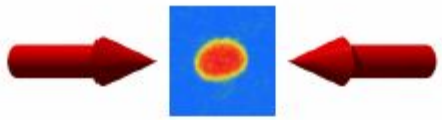




Our sample is elongated 3D condensate
Choice: split along short axis (stronger confinement) to minimize overlap time.

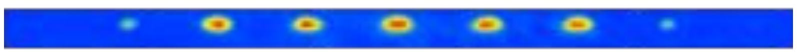
Atomic comb

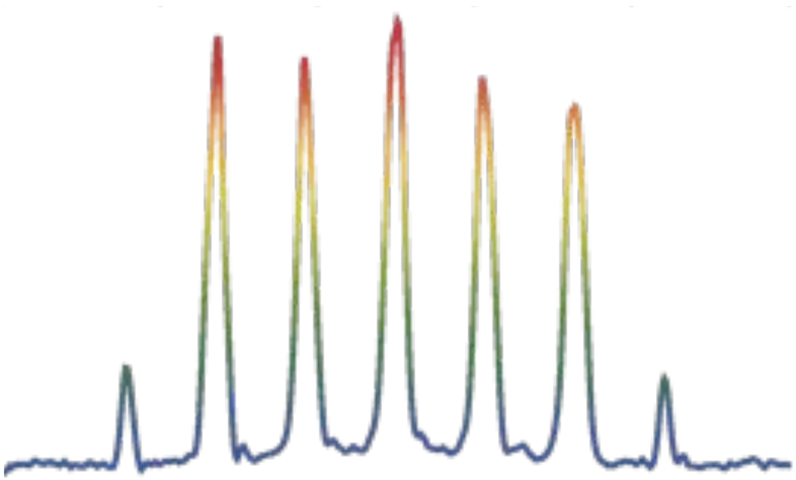
Kapitza-Dirac pulse

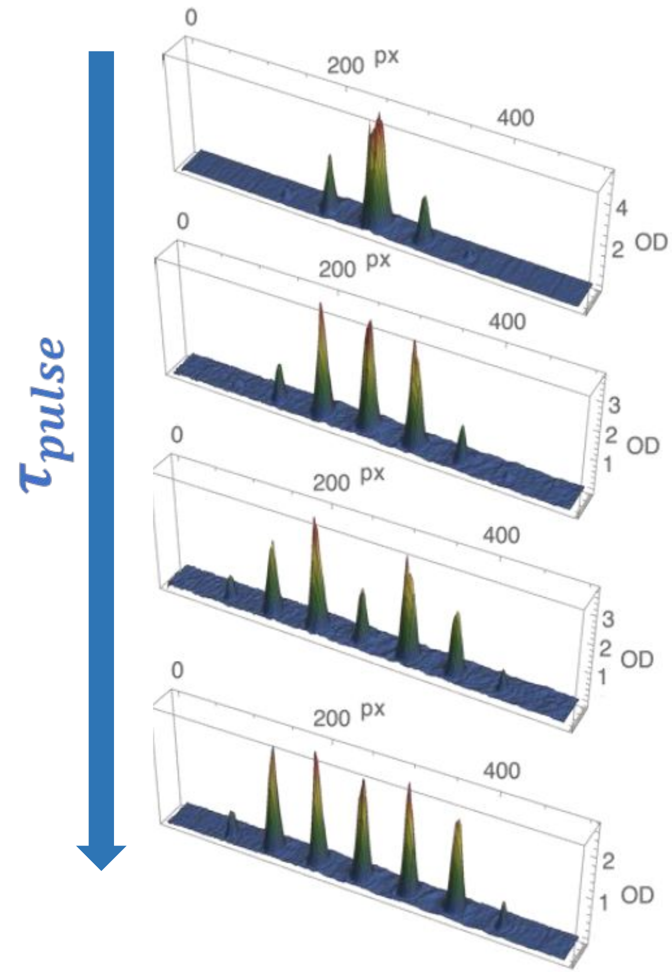


$\tau_{pulse} = 7\ \mu s$

Comb of momentum states



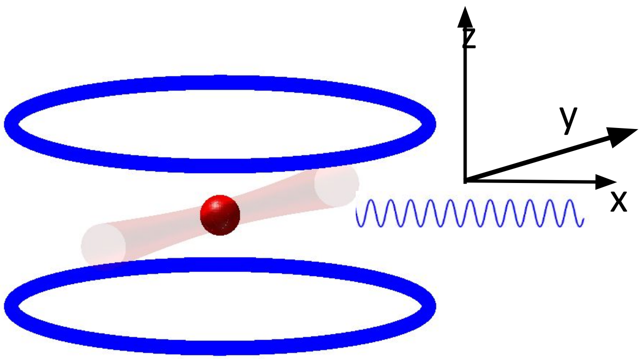




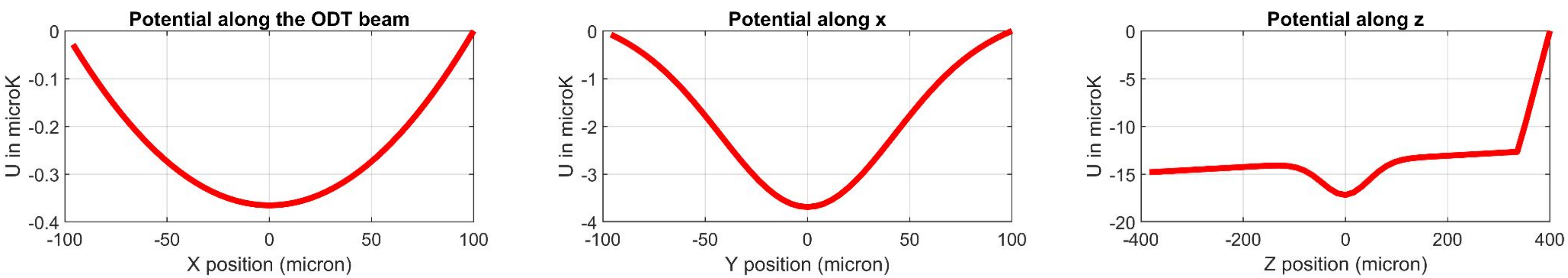
The comb of momentum states MUST be aligned along a normal axis of the harmonic oscillator trap

Hybrid trap

Magnetic quadrupole potential + single beam optical potential
Lattice direction (x) orthogonal to quadrupole axis (z) and optical trap wavevector (y)

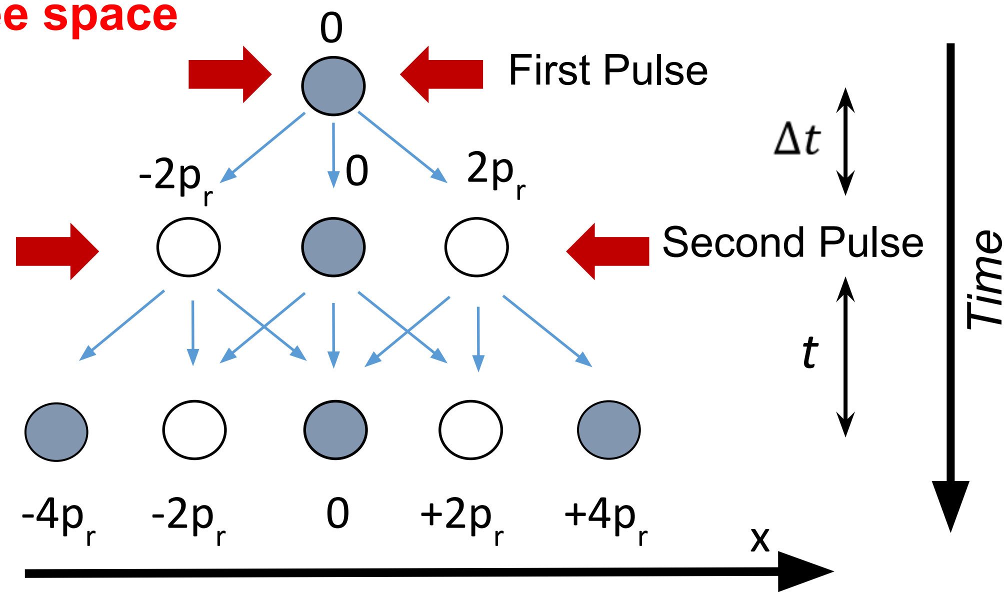


Trap frequencies: $(\omega_x,\omega_y,\omega_z) = 2\pi\,(70, 13, 65)$ Hz
$N = 3\times10^5$ atoms, Thomas-Fermi radii $(R_x,R_y,R_z) = (6,34,7)$ μm



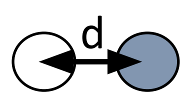
Multimode Kapitza-Dirac interferometer

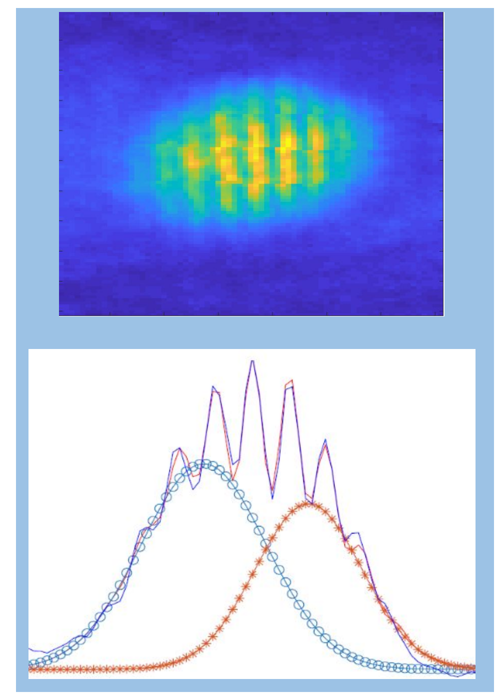
Free space



$$\boldsymbol{p}_r = \hbar \boldsymbol{k}$$
$$\boldsymbol{v}_r = 3.8\, mm/s$$

Interference between two modes





$$\varphi(r) = \varphi_l(r) + \varphi_r(r)e^{\Phi}$$

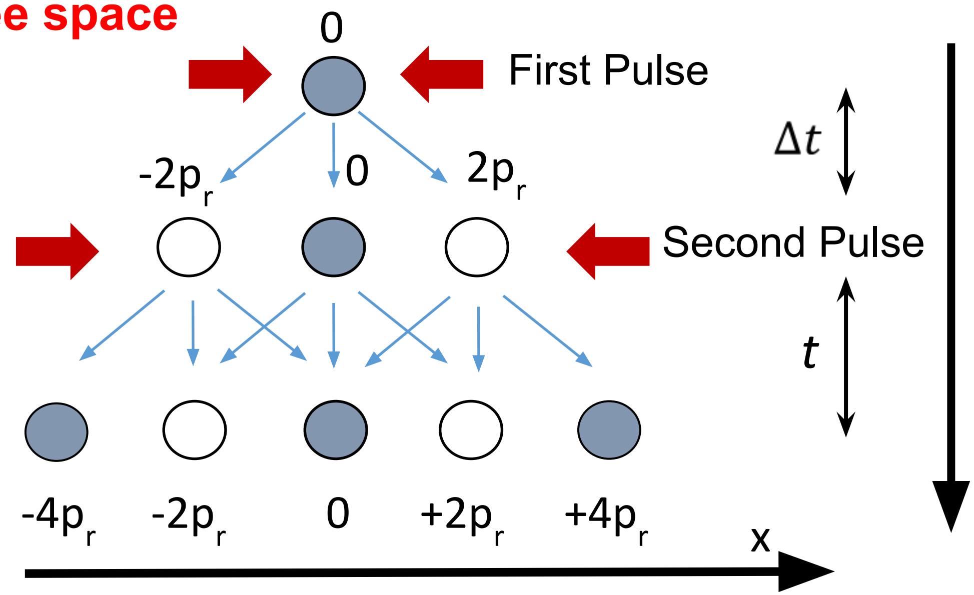
$$n(r,t) = n_l(r,t) + n_r(r,t) + 2\sqrt{n_l(r,t)n_r(r,t)}\, cos\left(\frac{md}{\hbar t}x + \Phi\right)$$

$$\lambda = \frac{ht}{md}$$

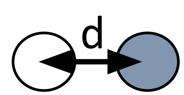
$$d = 2v_r \Delta t$$

“Trampoline” Kapitza-Dirac interferometer

Free space



Interference between two modes



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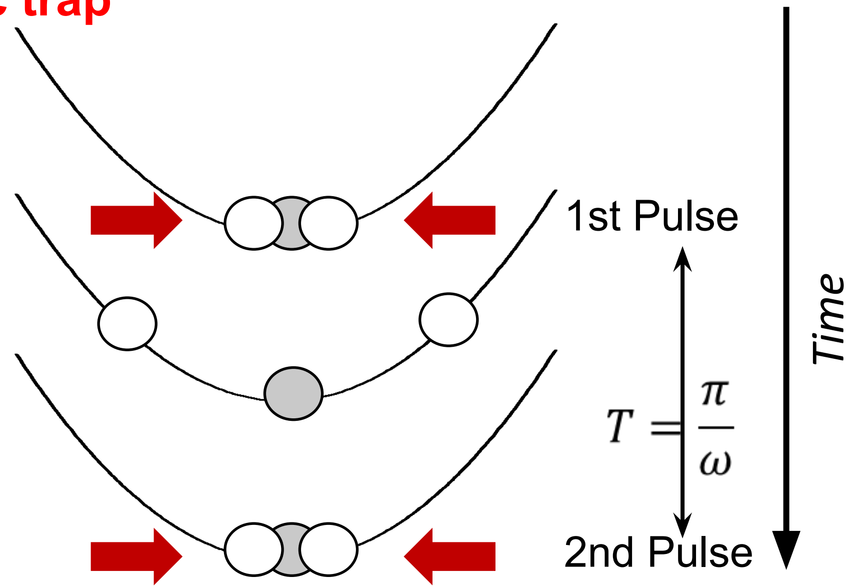
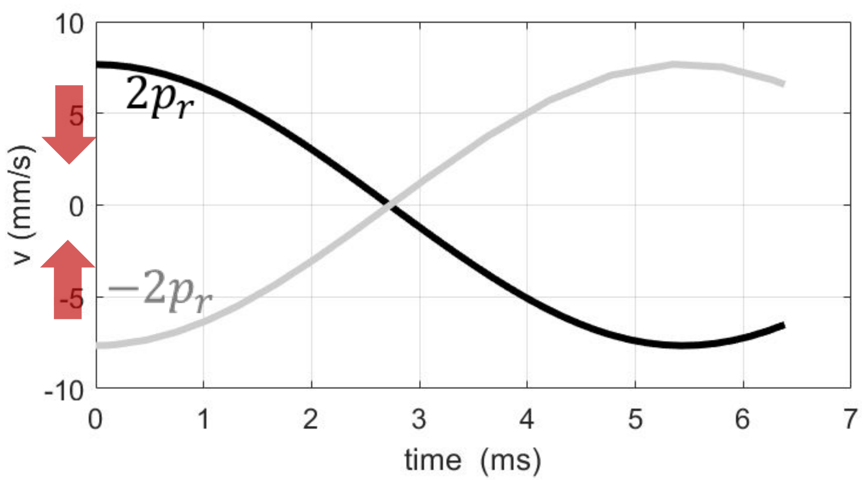
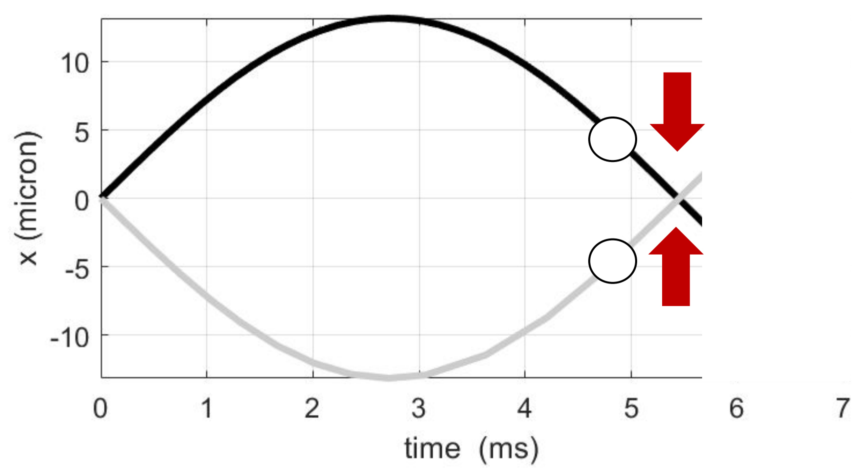
Multimode Kapitza-Dirac interferometer

Harmonic trap







Trapped Kapitza-Dirac interferometer

Kapitza-Dirac pulse and subsequent evolution in trap

trap time [ms]

1

2

3

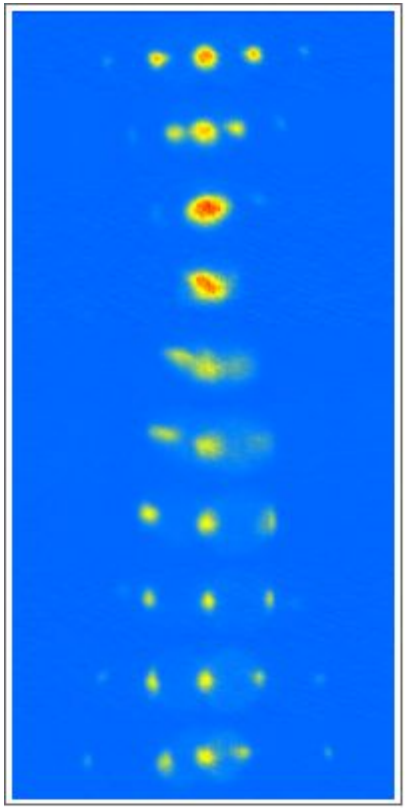
..

..

..

..

8



1st pulse, 10μs

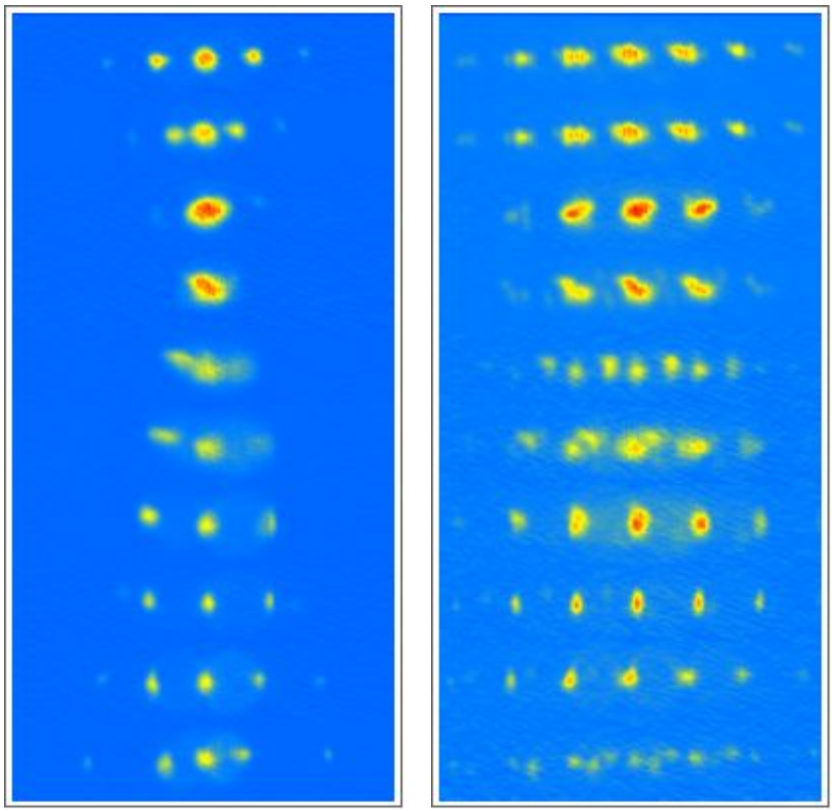
Images after long TOF (32ms)
⟶ momentum distribution

Trapped Kapitza-Dirac interferometer

Kapitza-Dirac pulse and subsequent evolution in trap

trap time [ms]

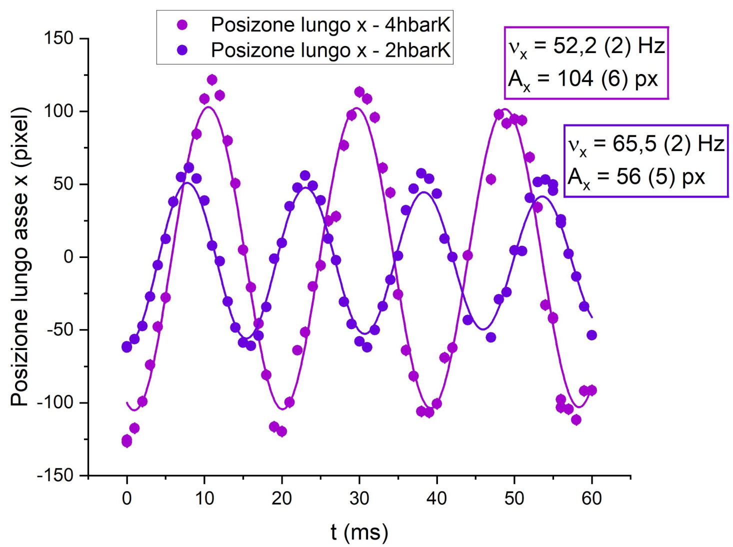
1
2
3
..
..
..
..
8

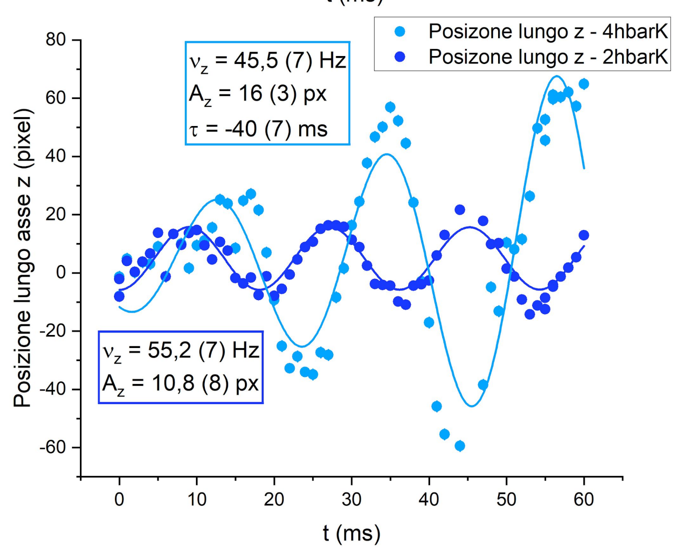


1st pulse, 10μs　　2nd pulse , 10μs

Images after long TOF (32ms)
⟶ momentum distribution

Issues with trapped KD interferometer





- Anharmonicity:
  since oscillation amplitude $2v_R/\omega \sim$ laser beam size,
  BEC at $2v_R$, frequency 52Hz
  BEC at $4v_R$, frequency 66Hz

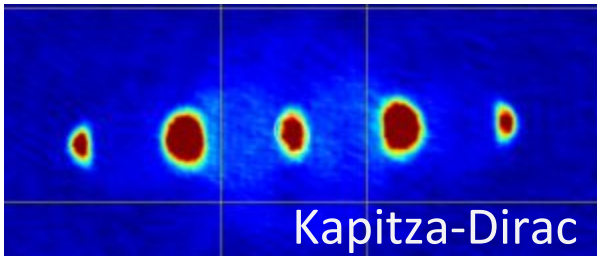
- Motion excited along transverse direction

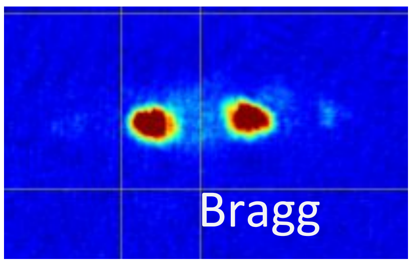
$\longrightarrow$ momentum components do not overlap after trap half-period

Solutions:

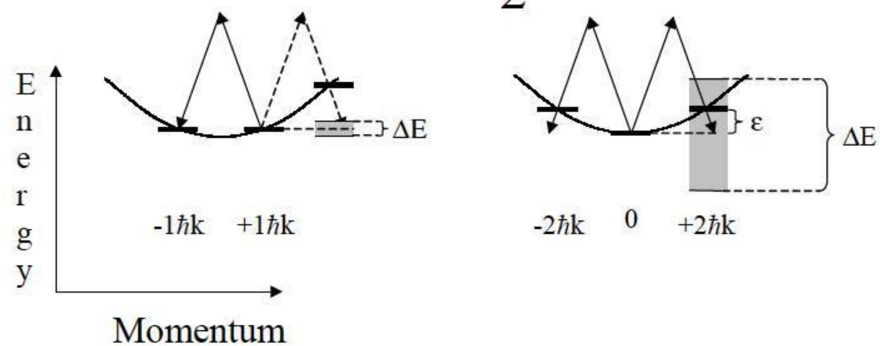
- reduce oscillation amplitude (easy)
- reduce lattice wavevector (more difficult)

From KD to Bragg scattering





$$\Delta E \Delta t \geq \frac{\hbar}{2}$$



Bragg vs. Kapitza-Dirac

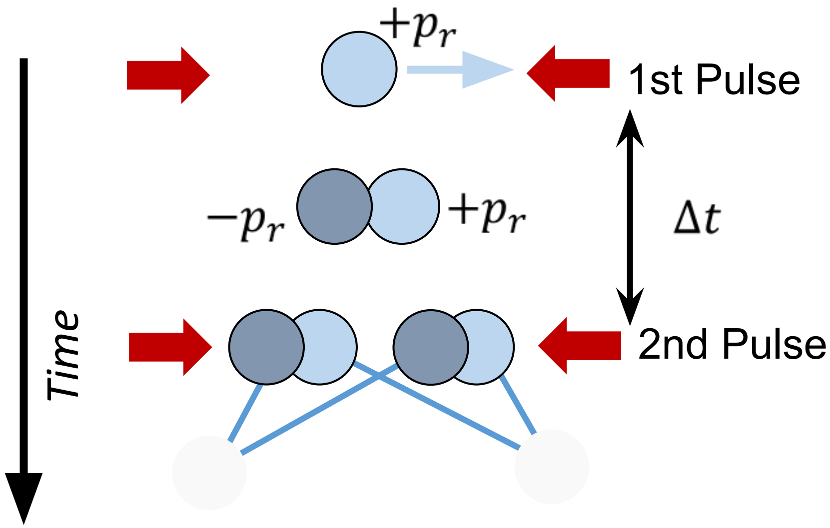
Bragg, long pulse ⟶ energy conservation, only $-v_R$ and $+v_R$ same kin. En.

Advantages: (i) only 2 BECs;

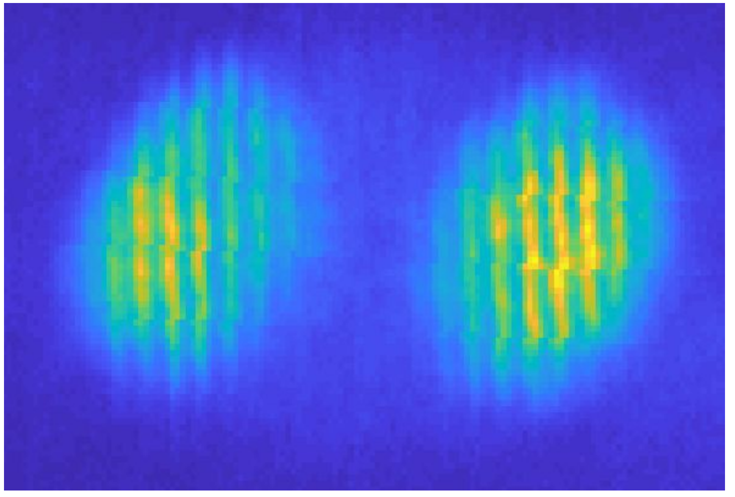
(ii) amplitude of trap oscillations is half

Bragg interferometer, free space

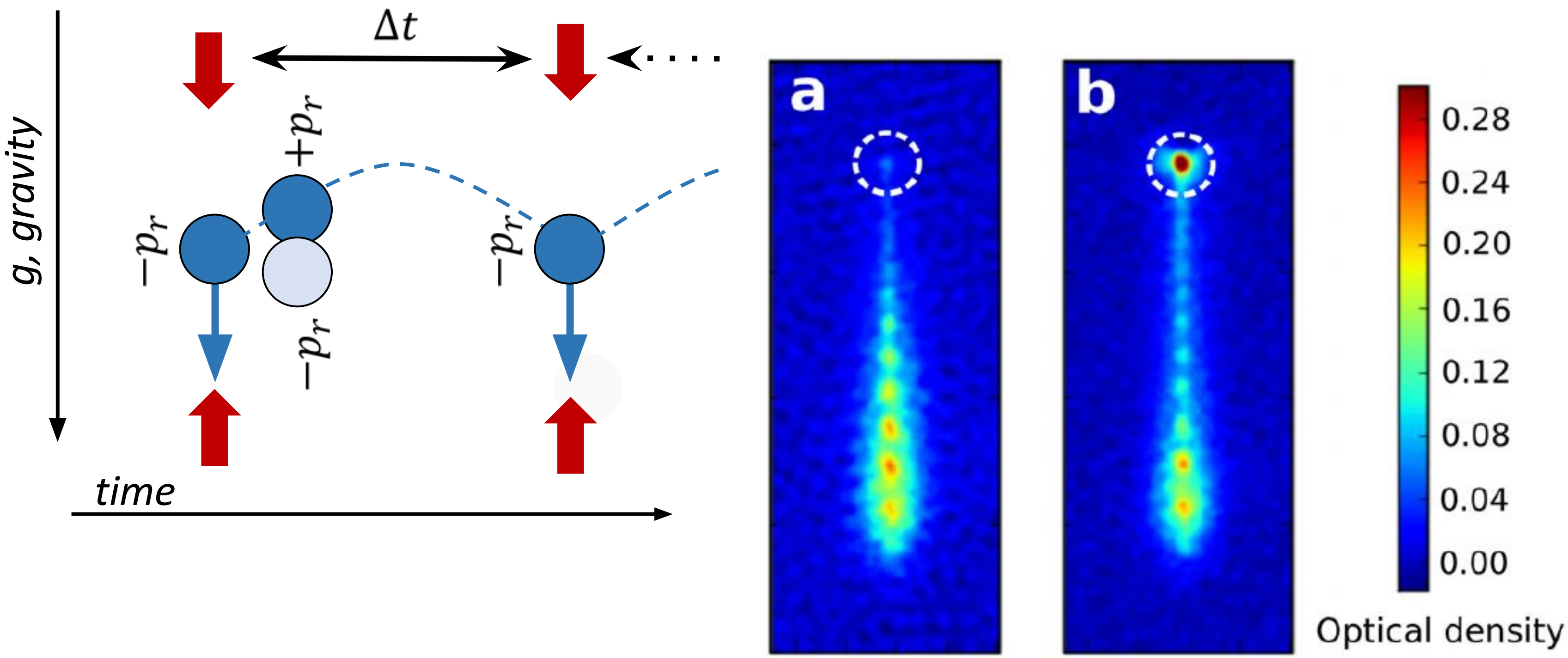
Lattice pulses along horizontal direction



Absorption imaging, after TOF



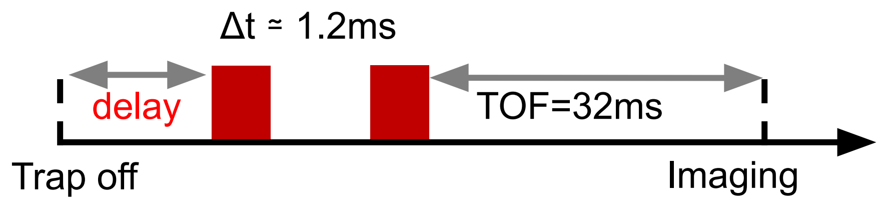
Bragg free-fall ``trampoline'' interferometer

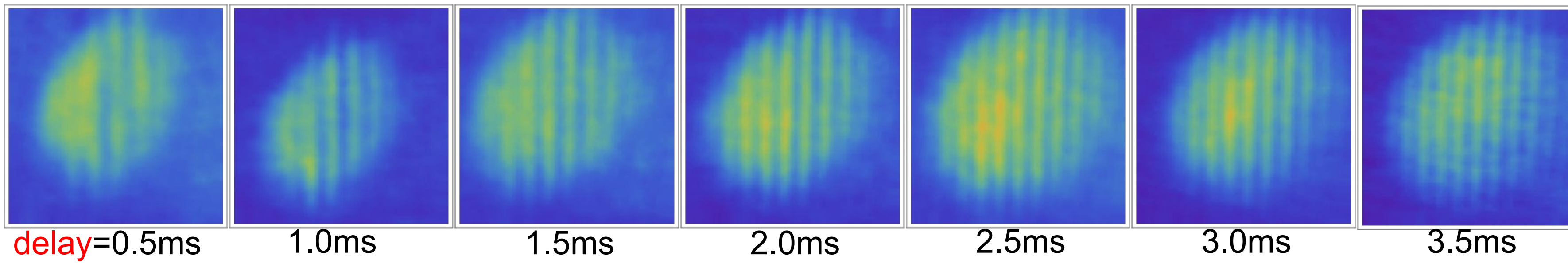


M. Robert-de-Saint-Vincent et al. EPL, 89 (2010) 10002

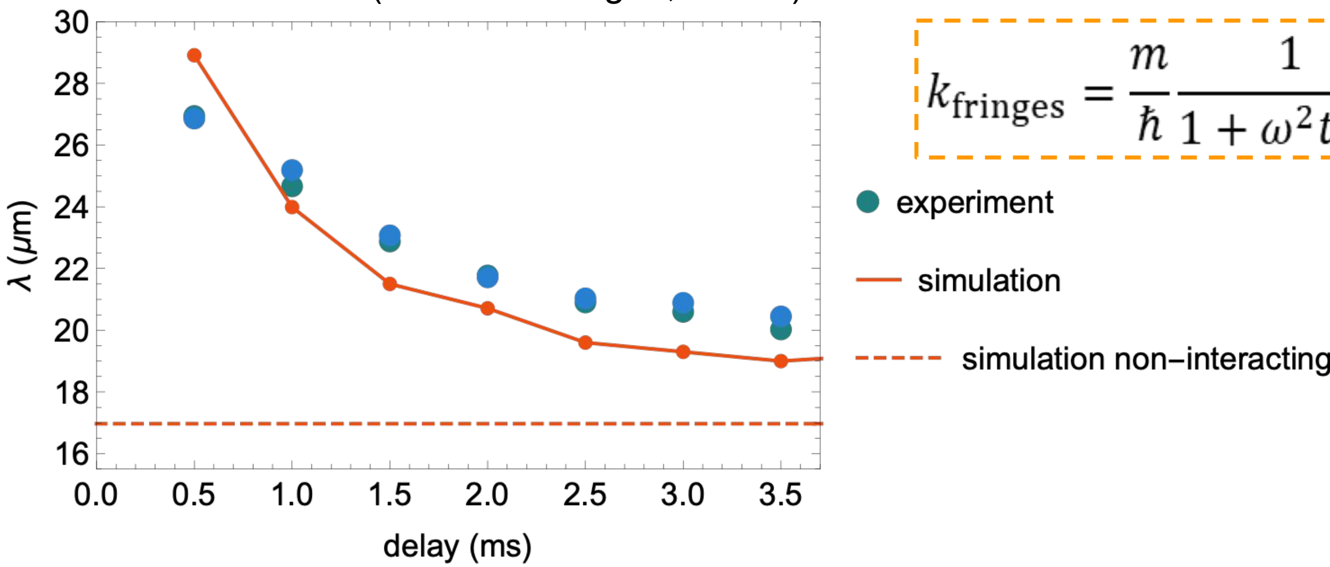
Multiple Bragg pulses: max efficiency at Δt = fall time ⟶ measure gravity (rel. unc. 4 10^{-4})

Bragg interferometer, free space



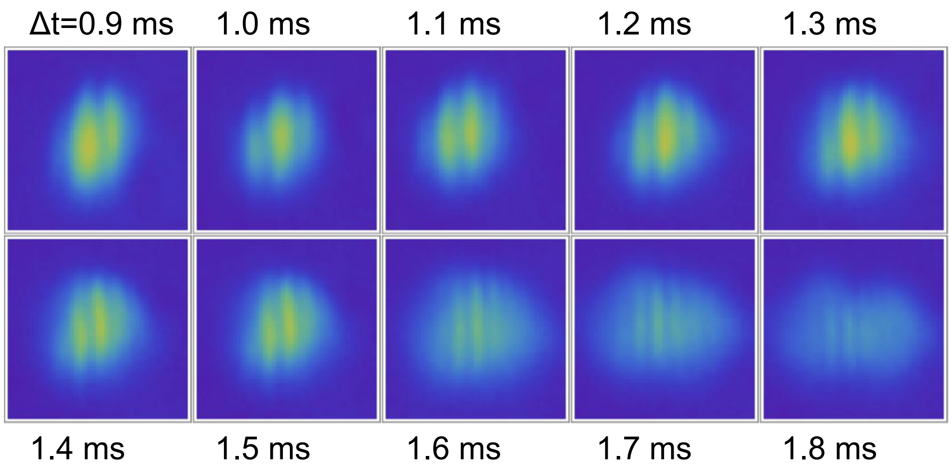


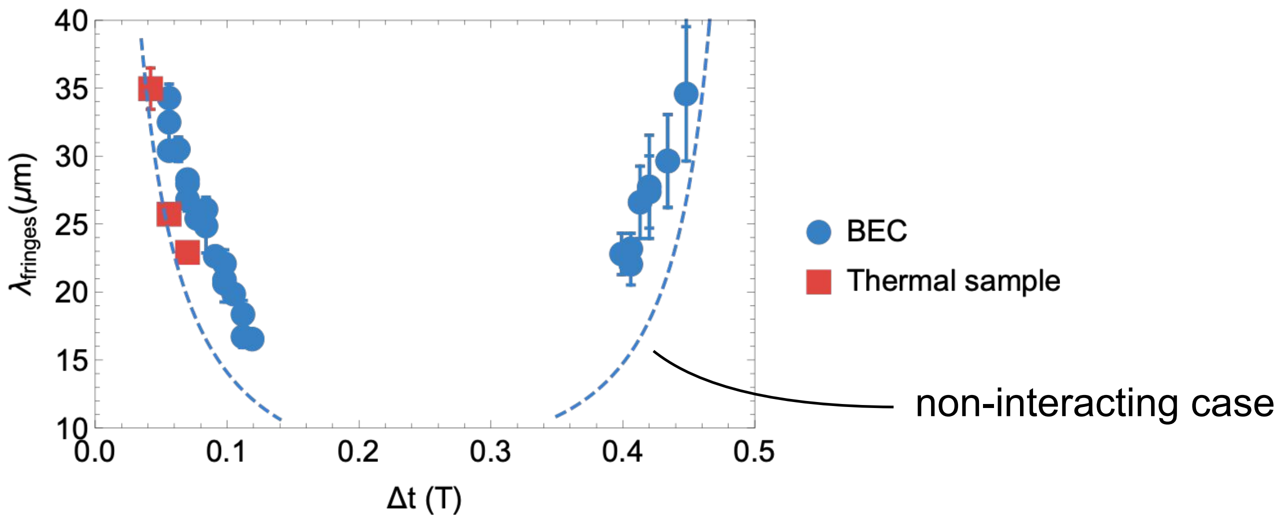
GPE simulation (with M. Modugno, Bilbao)



$$k_{\text{fringes}} = \frac{m}{\hbar} \frac{1}{1+\omega^2 t_{\text{TOF}}^2} \left(\delta v + \frac{\delta x}{t_{\text{TOF}}} \omega t_{\text{TOF}} \right)$$

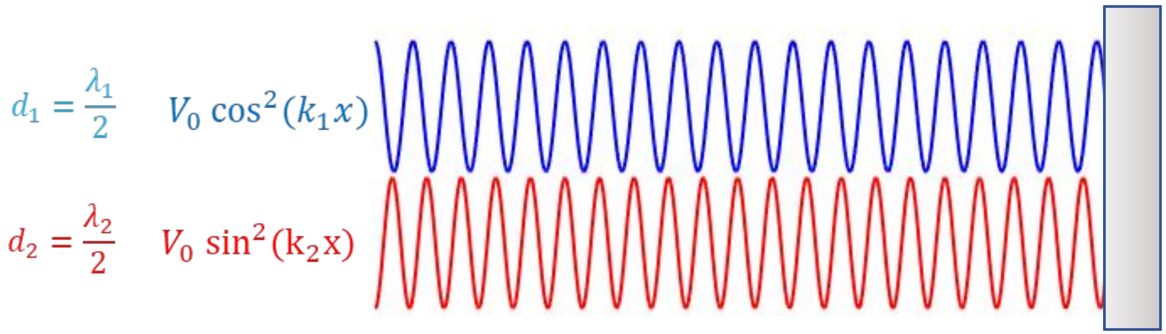
Bragg interferometer in trap, fringe spacing





Novel large spacing lattice

Small wavevector lattice developed by L. Masi, T. Petrucciani and M. Fattori, benefit: reduce v_R hence oscillation amplitude, hence anharmonicity



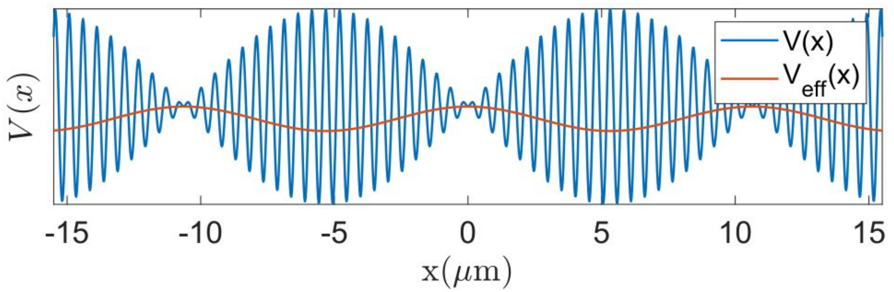
Beat-note between two commensurate wavelengths, n

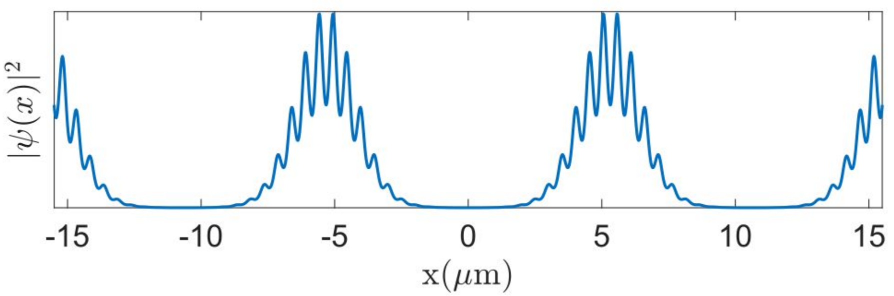
$$\mathbf{n}\,\boldsymbol{\lambda}_1 = (\mathbf{n}+\mathbf{1})\boldsymbol{\lambda}_2$$

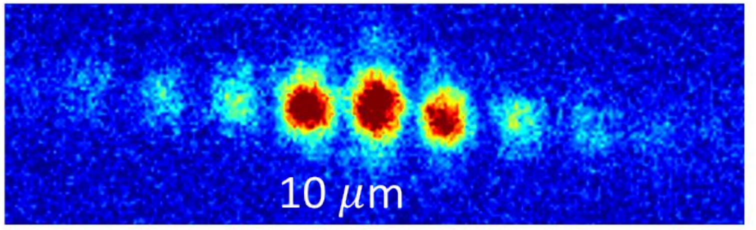
$$\boldsymbol{d} = \frac{\boldsymbol{n}\boldsymbol{\lambda}_1}{\mathbf{2}}$$

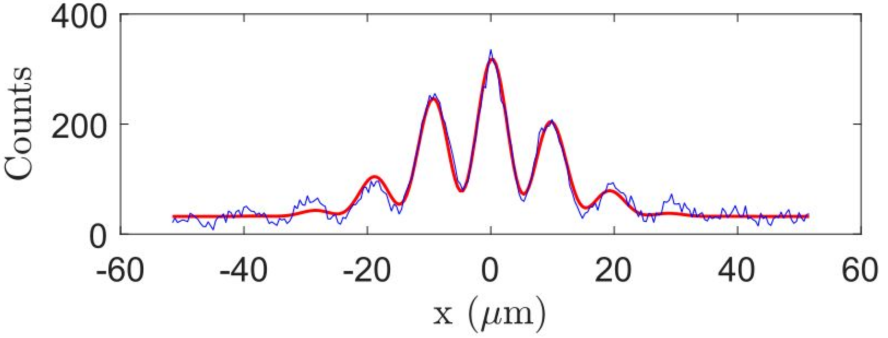
Novel large spacing lattice

Potential equivalent to a large spacing optical lattice

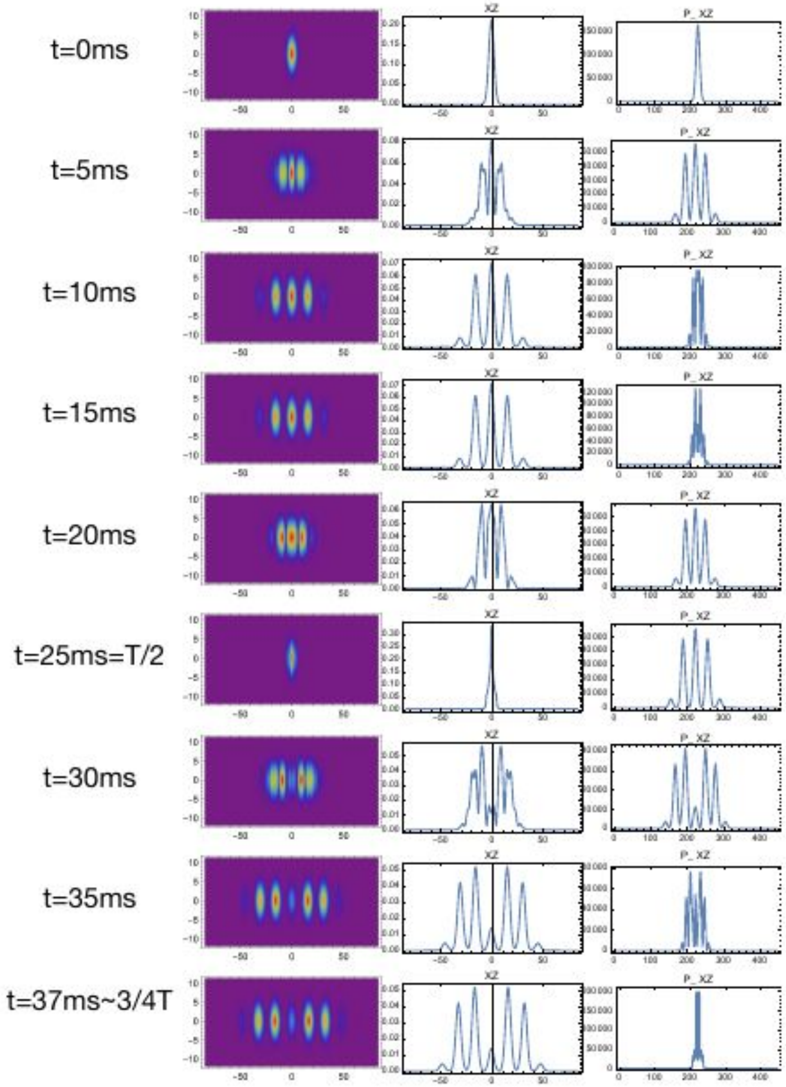








Novel large spacing lattice with ^{39}K



^{39}K benefit:

control of interactions

Currently performing numerical simulations of Kapitza-Dirac trapped interferometer

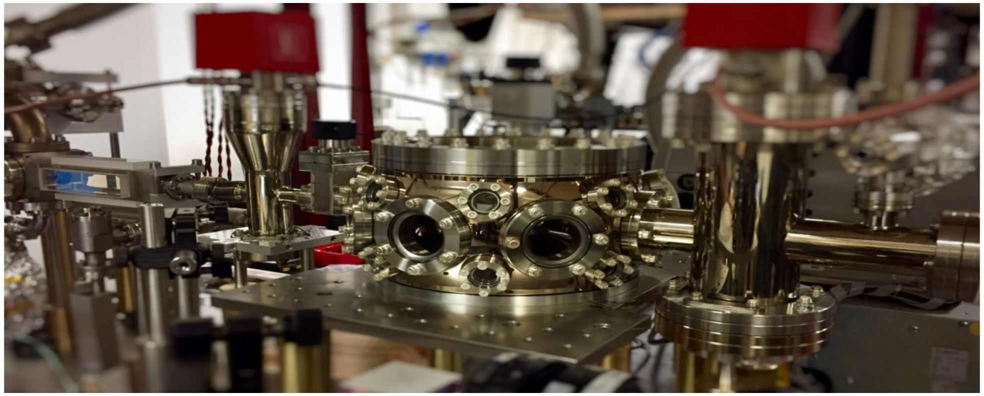
WP2: light masks with DMD

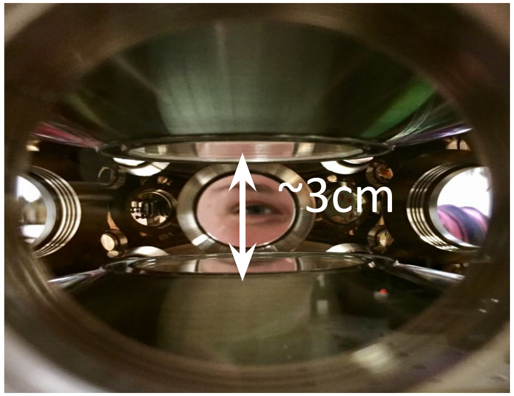
T2.4: Arbitrarily filtered, multimode, Kapitza-Dirac interferometer (CNR; M1-M18)

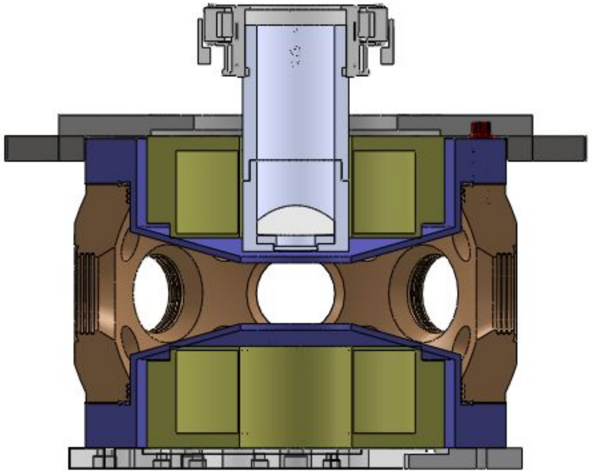
The multiple momentum components corresponding to the comb photonic modes will be obtained from a single trapped Bose-Einstein condensate (BEC), by means of a Kapitza-Dirac pulse.

We will implement the established protocol of trapped Kapitza-Dirac interferometry using a BEC of 87Rb atoms. As a new resource, we will develop an arbitrary “momentum filter” to remove components at will. The use of light masks generated by DMD will grant arbitrary selections.

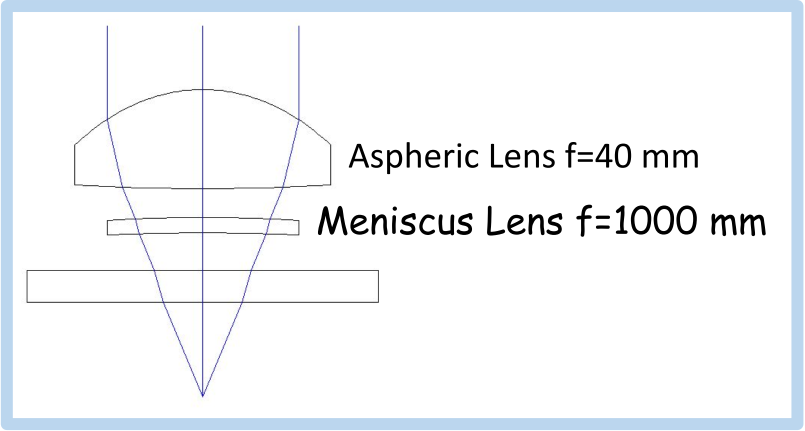
High-resolution imaging system





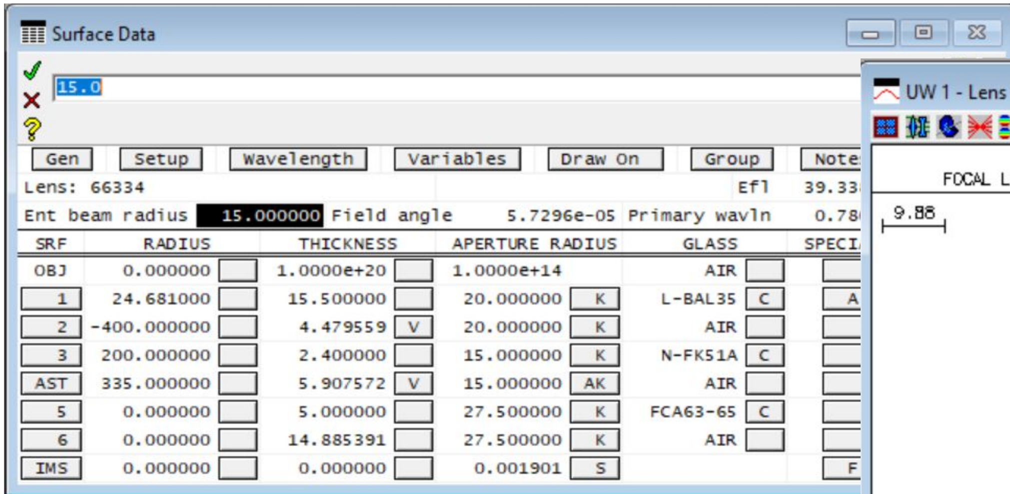


Long working distance microscope

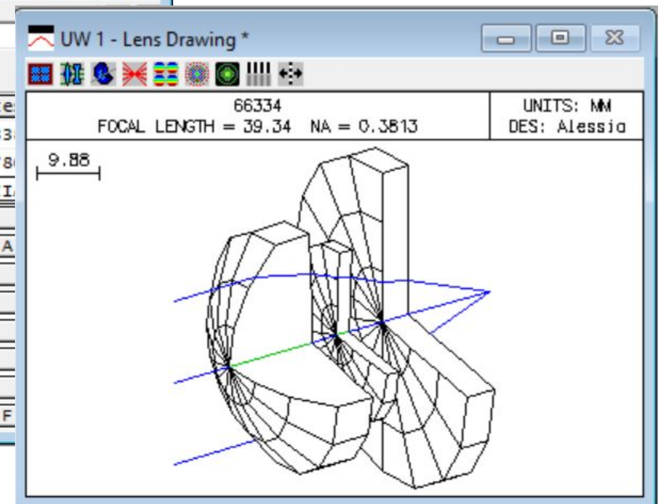


Diffraction-limited resolution: $$r = \frac{1.22\lambda}{2n\sin\theta} = \frac{0.61\lambda}{NA} = 1.2\mu m$$

Design of objective

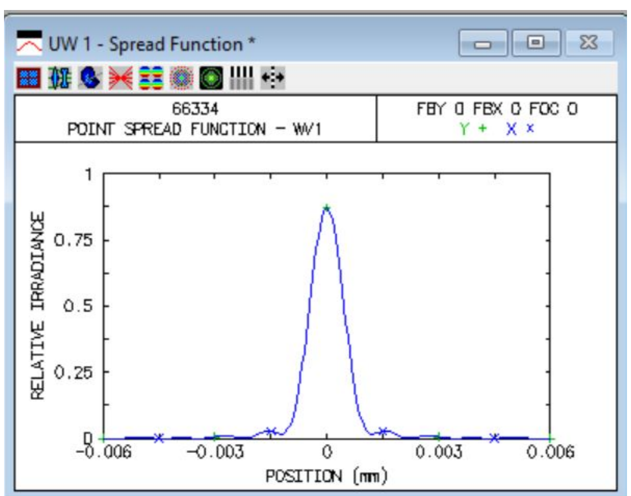


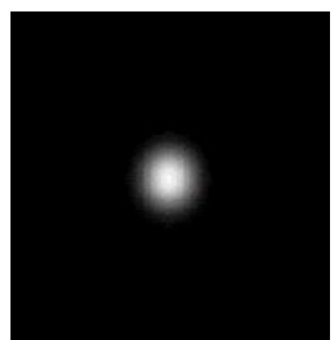
SRF	RADIUS		THICKNESS		APERTURE RADIUS		GLASS		SPECI
OBJ	0.000000		1.0000e+20		1.0000e+14		AIR		
1	24.681000		15.500000		20.000000	K	L-BAL35	C	A
2	-400.000000		4.479559	V	20.000000	K	AIR		
3	200.000000		2.400000		15.000000	K	N-FK51A	C	
AST	335.000000		5.907572	V	15.000000	AK	AIR		
5	0.000000		5.000000		27.500000	K	FCA63-65	C	
6	0.000000		14.885391		27.500000	K	AIR		
IMS	0.000000		0.000000		0.001901	S			F



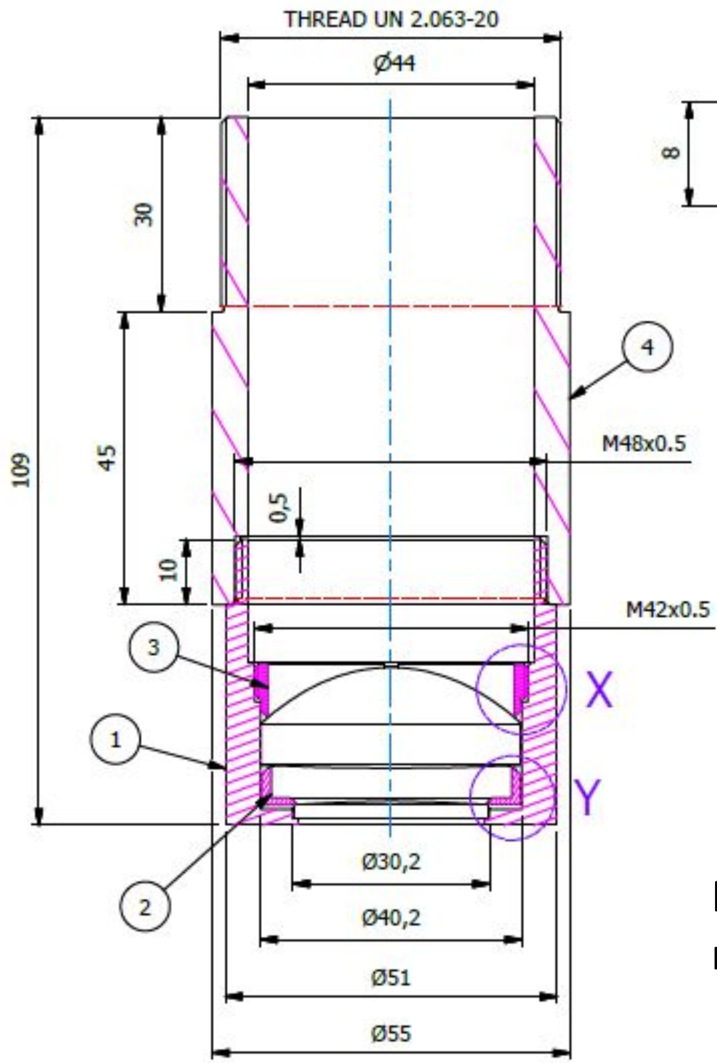
OSLO, https://www.lambdares.com/edu/

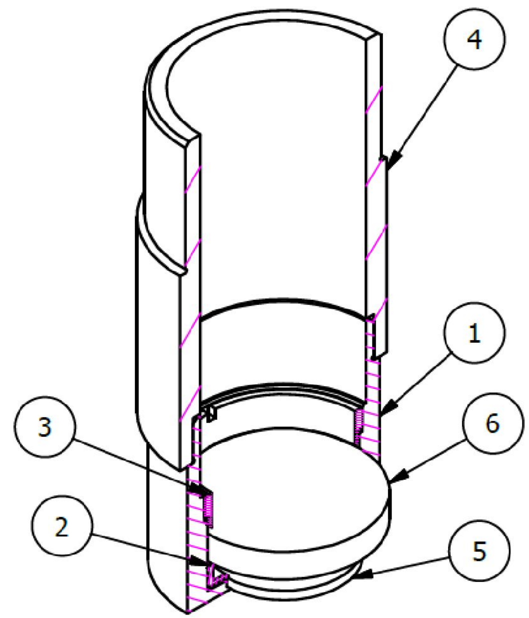
Point Spread Function





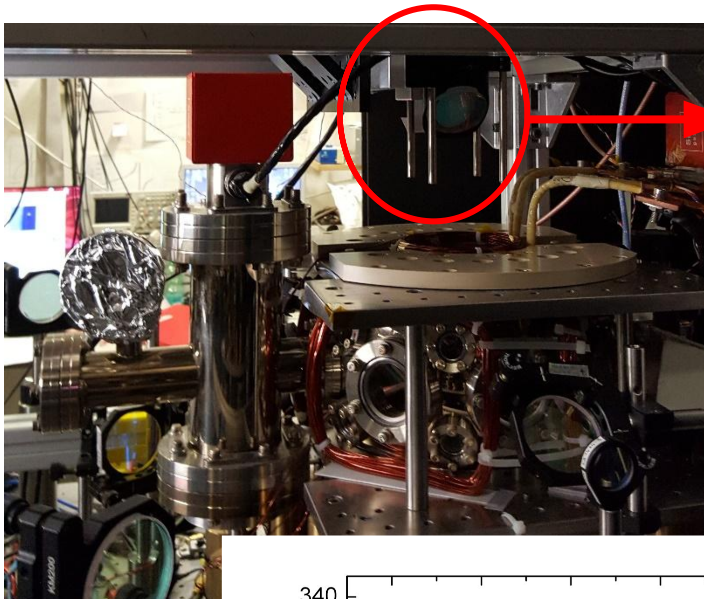
Design of objective case

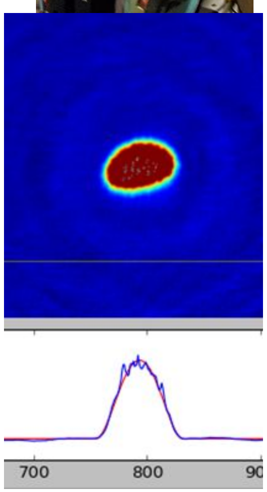


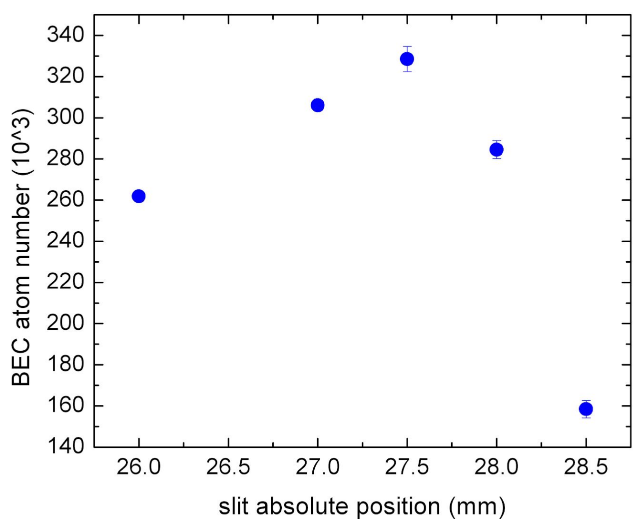


Presence of time-varying magnetic fields:
rigid plastic material, PEEK

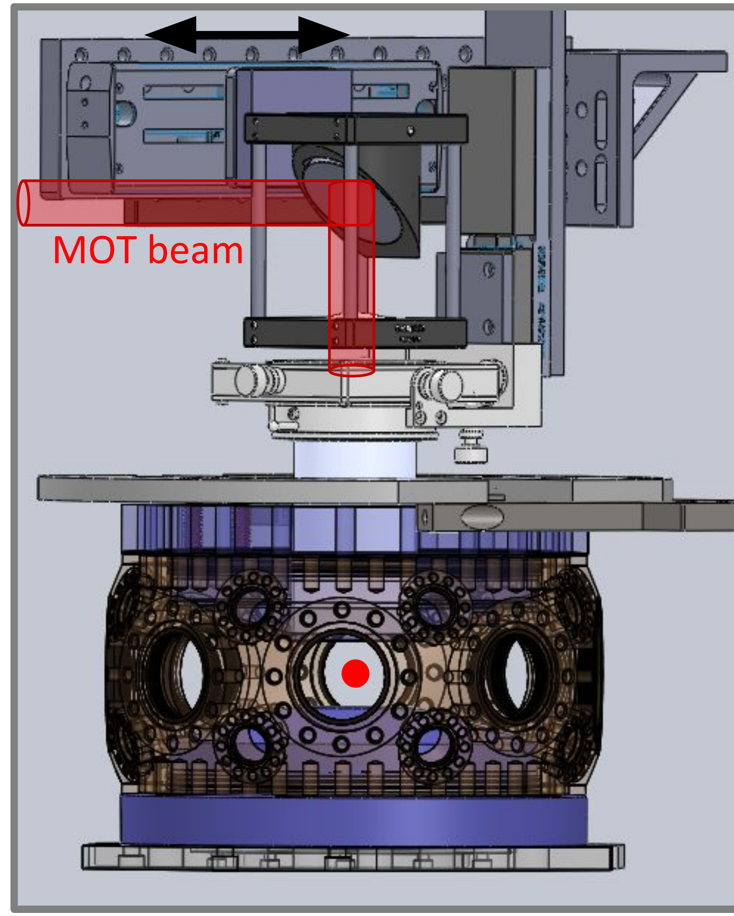
Integration with existing setup







Objective+Flip-Mirror



Conclusions

- **D2.3: Implementation of Kapitza-Dirac multi-mode beam-splitter and interferometer (CNR, M18)**

Kapitza-Dirac multimode: anharmonicity detected and explained
Bragg two modes in trap demonstrated
Fringe spacing explained with numerical simulations, phase stability under investigation
Novel large spacing lattice and ^{39}K to control interactions

- DMD momentum filter

Design and assembly of objective, under test now
Modified setup to integrate objective

Following are back-up slides

Evolution in Trap for short times

$$At\ t = 0\ first\ pulse$$

$$at\ \Delta t < \frac{1}{\omega}\ second\ pulse\ (\Delta t \approx 1ms, \omega = 2\pi \cdot 70\ Hz)$$

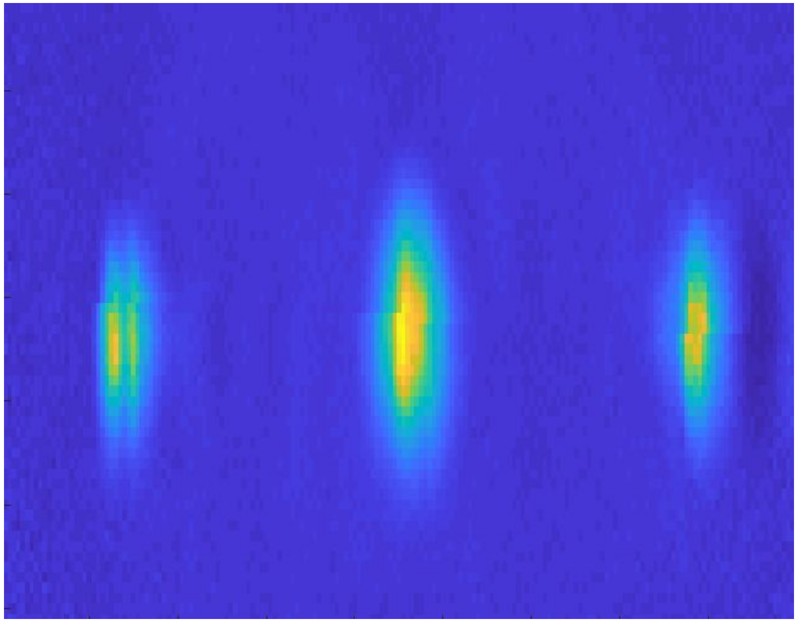
$$x(t) = \frac{2v_r}{\omega}\sin(\omega t) \approx 2v_r t,$$

$$v(t) = 2v_r\cos(\omega t) \approx 2v_r$$

$$k = \frac{m}{\hbar}\frac{1}{1+\omega^2 t_{\mathrm{TOF}}^2}\left(\delta v + \frac{\delta x}{t_{\mathrm{TOF}}}\omega t_{\mathrm{TOF}}\right)$$

$$\delta v = 0\ e\ t_{TOF} > \omega^{-1} \rightarrow k = \frac{md}{\hbar t_{TOF}}$$

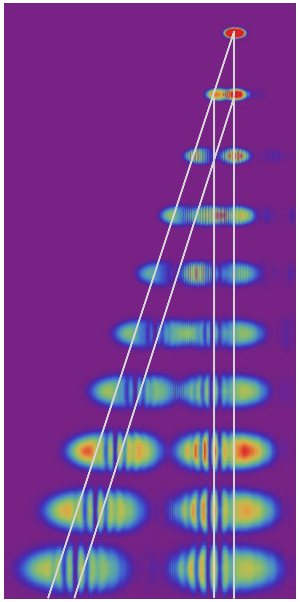
Interference fringes after 32 ms TOF



$$d = 2v_r\Delta t = 7.6\ \mu m$$

$$\lambda = \frac{ht}{md} = 19.2\ \mu m$$

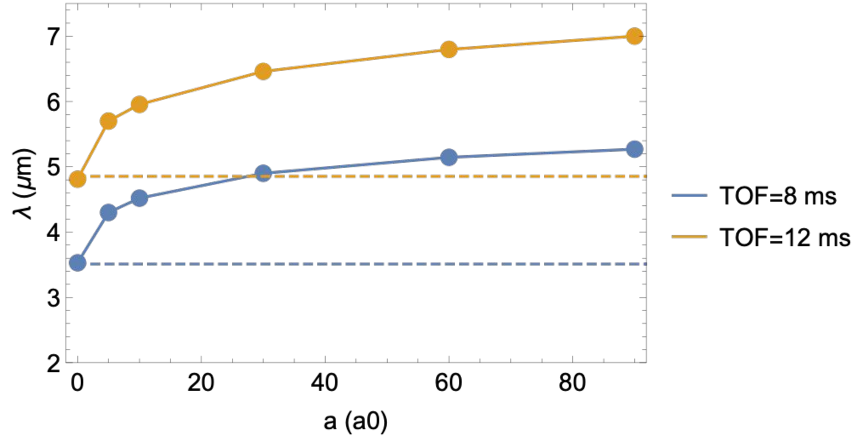
Numerical simulations for different interactions

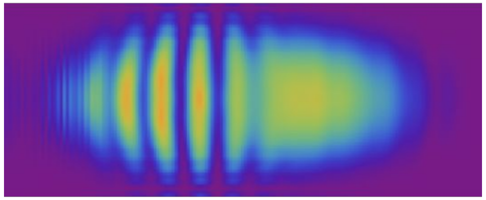


change scattering length a, fix delay and Δt

effects of interactions:

- fringes spacing
- fringes shape
- condensates positions





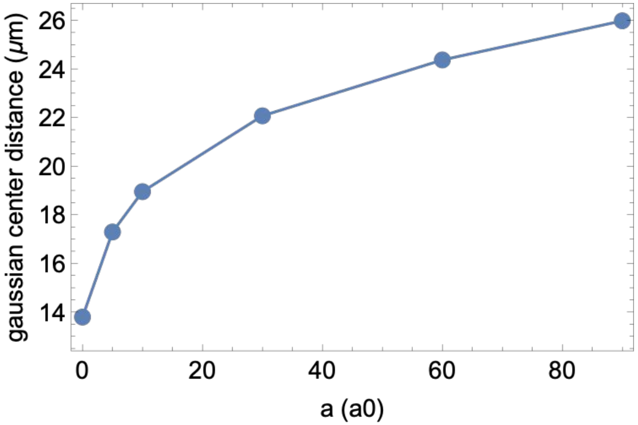
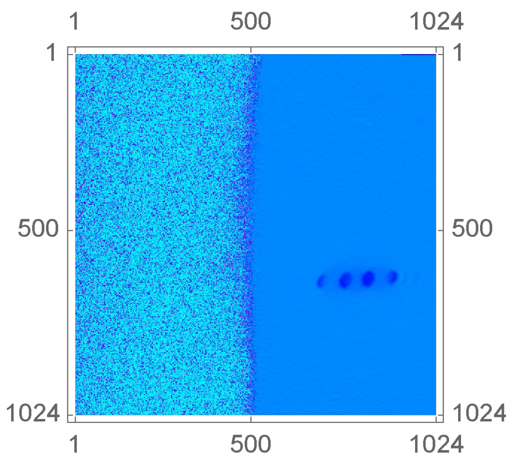
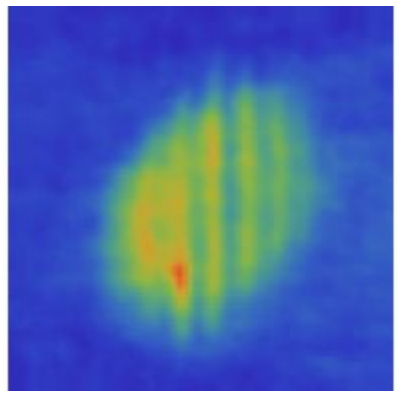
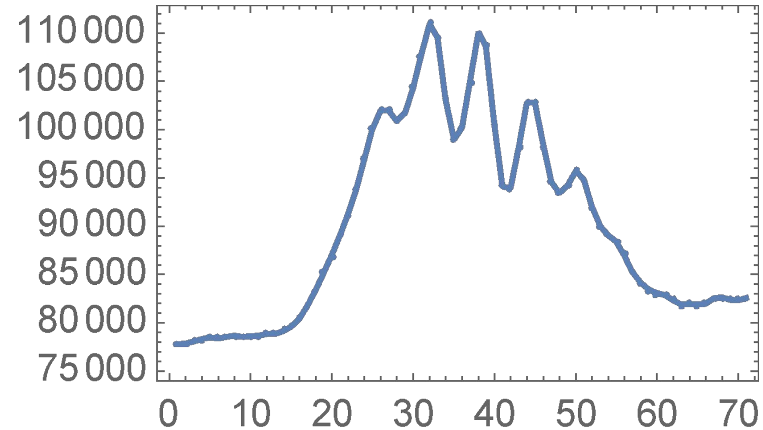


Image fit, interferometer phase



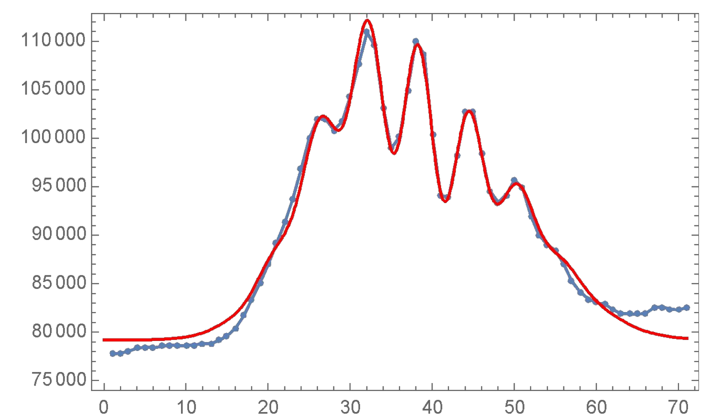




$$n_1 = \frac{A_1^2}{\sqrt{2}\sigma_1} e^{-\frac{(x-x_0)^2}{2\sigma_1^2}}$$

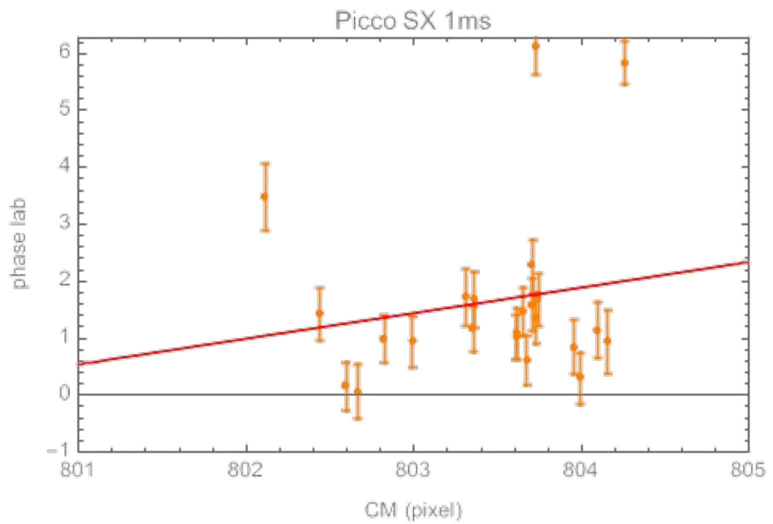
$$n_2 = \frac{A_2^2}{\sqrt{2}\sigma_2} e^{-\frac{(x-(x_0+d))^2}{2\sigma_2^2}}$$

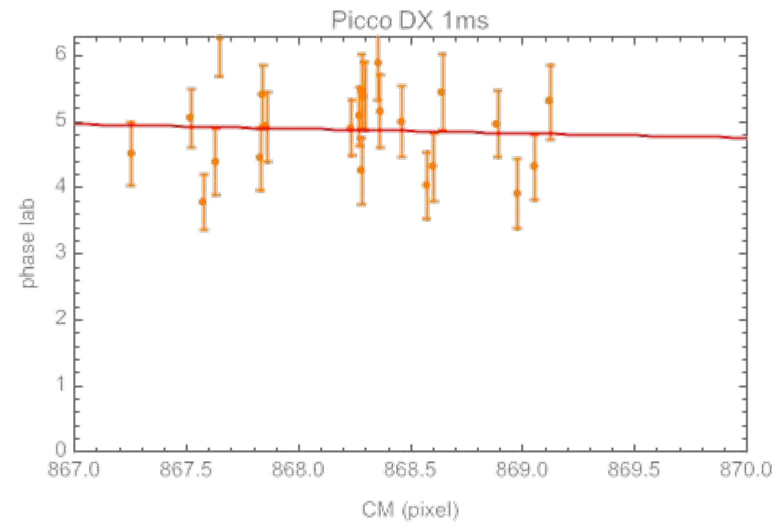
$$f_{FIT} = n_1 + n_2 + 2|C|\sqrt{n_1 n_2}\cos\left(\frac{2\pi}{\lambda}x + \phi\right)$$

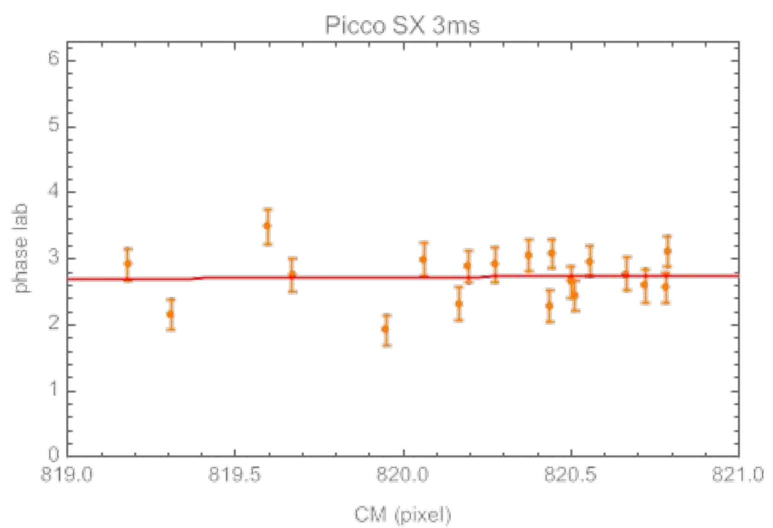


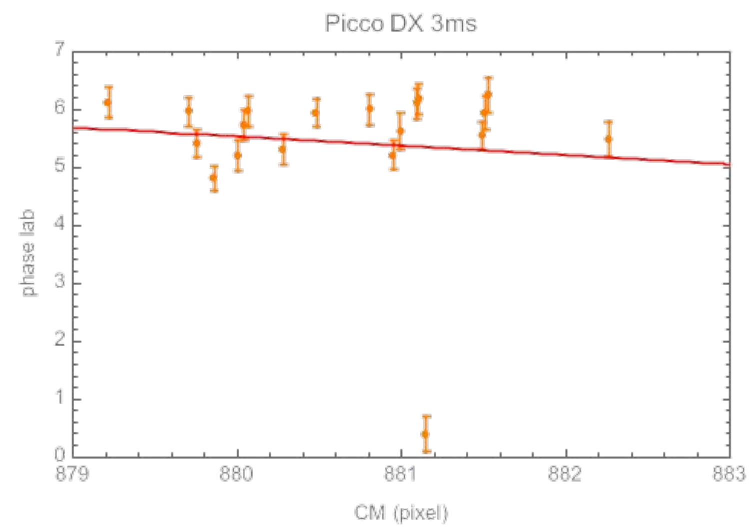
$$A_1, \sigma_1, A_2, \sigma_2, x_0, d, C, \lambda, \phi$$

Interferometer phase, Bragg ToF

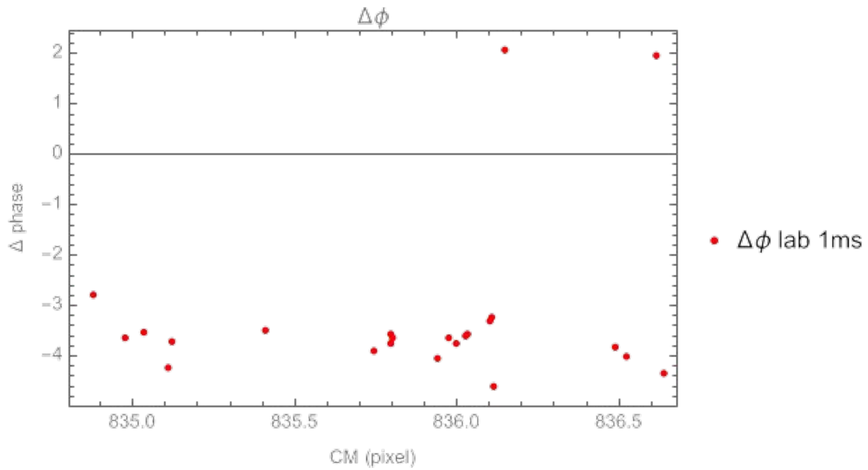


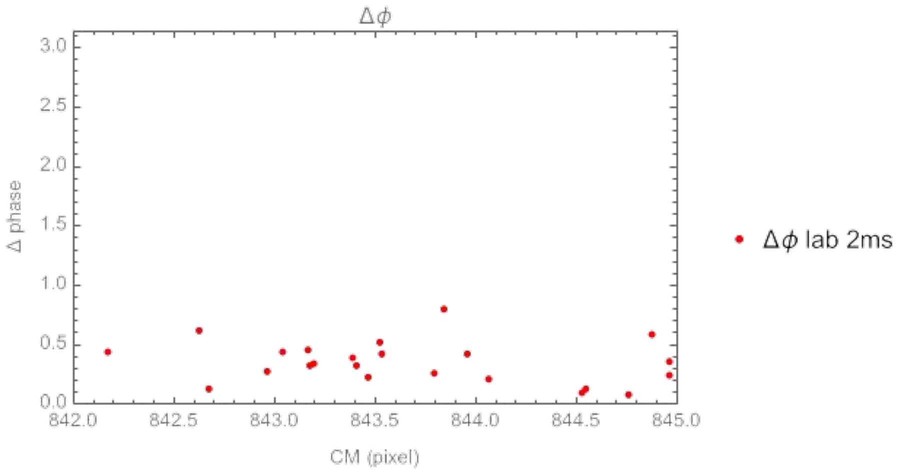


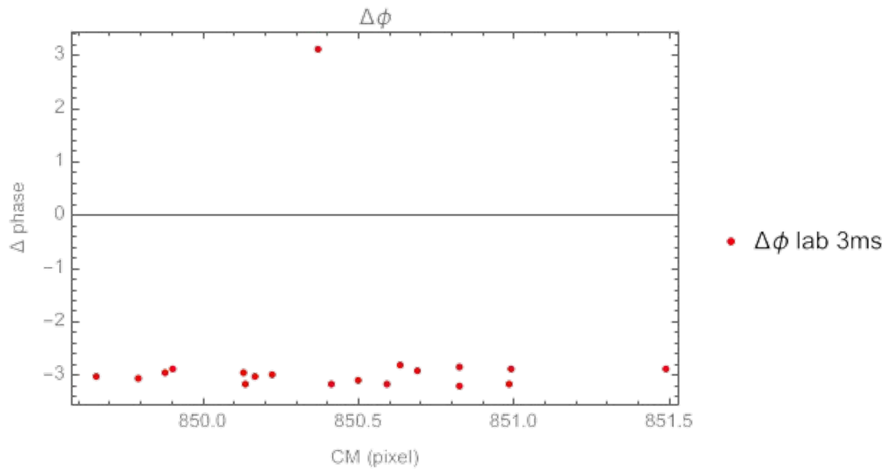




Port comparison, Bragg ToF







Phase – Bragg in trap