Differential Mach-Zehender Interferometry with trapped Bose Einstein condensates

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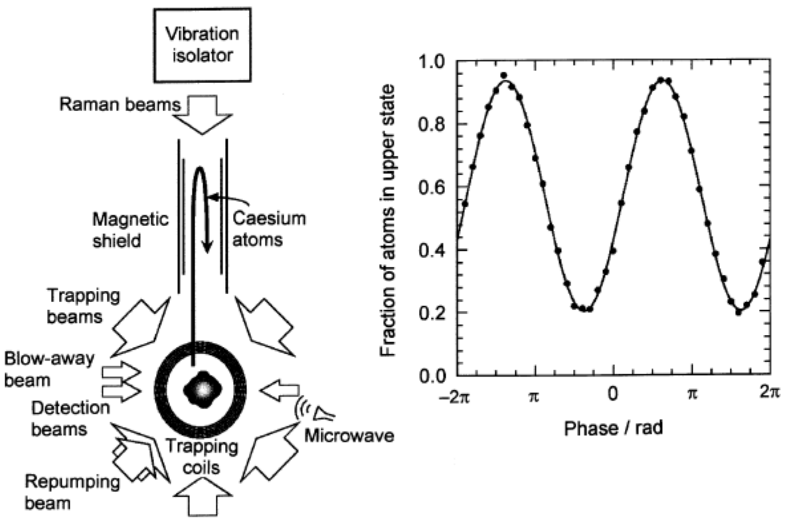
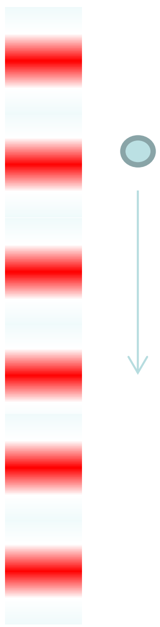
Crete, Greece

Atom interferometry with free falling atoms



A. Peters, K. Y. Chung, S. Chu, *Nature*, **400**, 849-852 (1999)



Classical phase !

$\phi \sim \ell/\lambda, = \frac{1}{2} g T^2/\lambda$

High precision measurements

- Gravity, inertial forces, fundamental constants

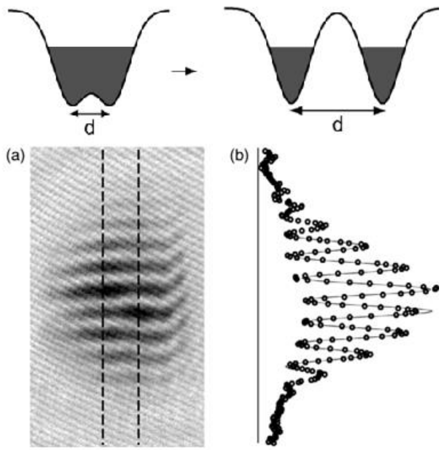
Fundamental physics tests

- Equivalence principle
- GW detection
- Dark matter detection

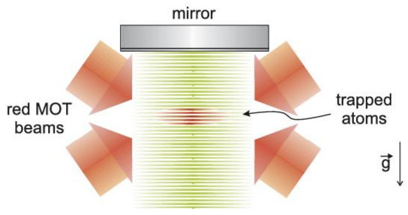
Main limitation

- Low spatial resolution
- Limited interrogation time

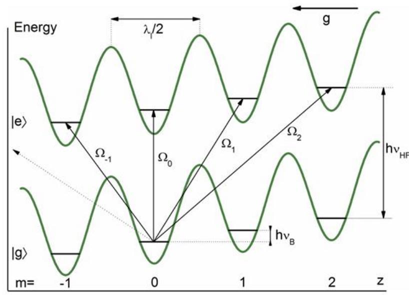
Trapped / Guided Atom Interferometers



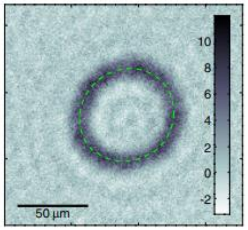
Y. Shin et al. PRL 92 050405 (2004)



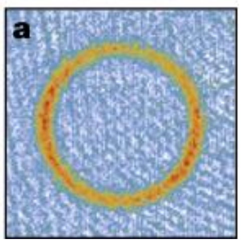
G. Ferrari et al. PRL 97 060402 (2006)



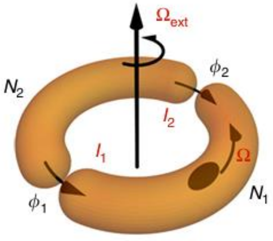
B. Pelle et al. PRA 87 023601 (2013)



Y. Guo, et al. PRL, 124, 025301 (2020)



Saurabh Pandey, et al. Nature, 570, 205 (2019)



C. Ryu et al. Nat. Comm. 11 3338 (2020)

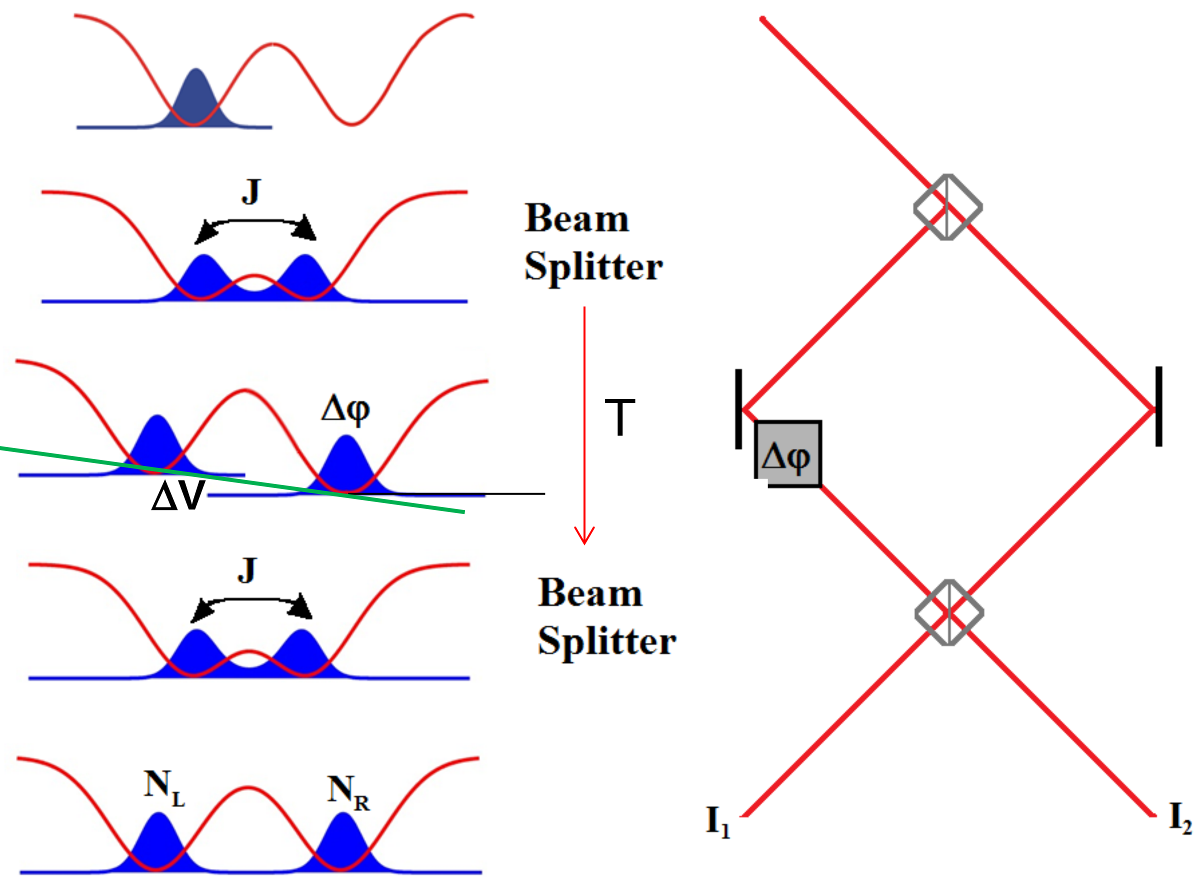
Main advantages

- High spatial resolution ~ μm
- Arbitrarily long interrogation times T

Main problems

- Control the depth and shape of the trapping potential
- Interactions in high density atomic samples

Mach Zender interferometry with BEC in a double-well

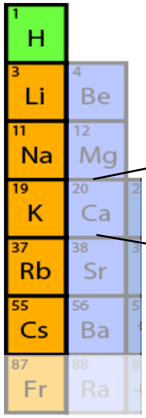


$$\Delta\varphi = \Delta V\, T/h$$

$$\Delta V = F\, d$$

- Ultimate space resolution
- Spatial coherence of a BEC allows large separation d
- Exploitation of quantum entanglement
- Creation of Maximally entangled quantum states like NOON

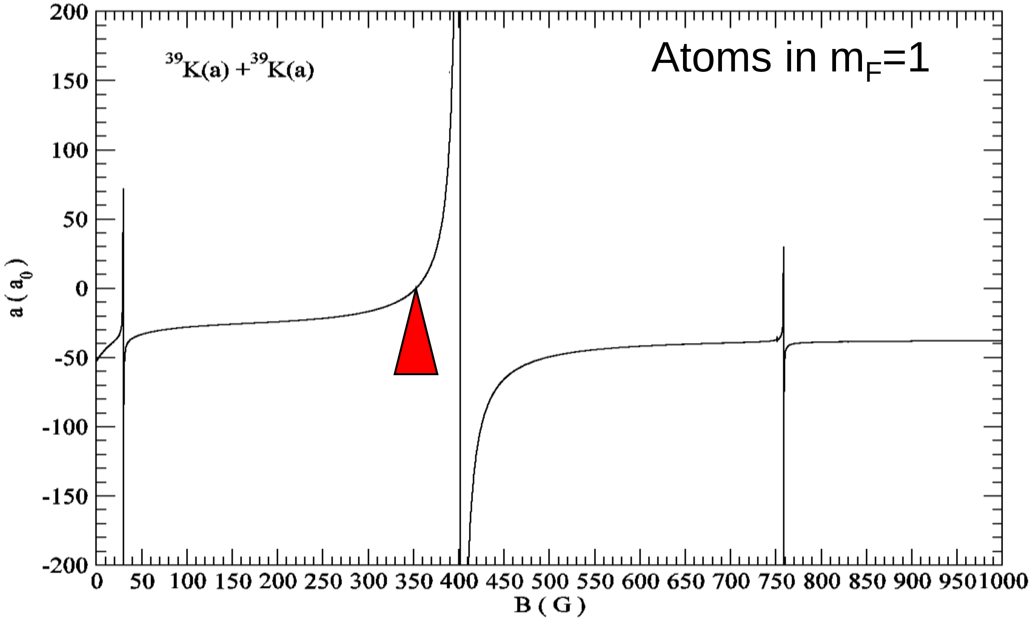
Second problem: interaction induced decoherence



^{41}K boson, condensed — G. Modugno et al, Science **294**, 1320 (2001)

^{40}K fermion

^{39}K boson, a=-33a_0 — De Sarlo et al, PRA **75**, 022715 (2007); D'Errico et al. New J. Phys. **9**, 223 (2007); Roati et al. PRL **99**, 010403 (2007)



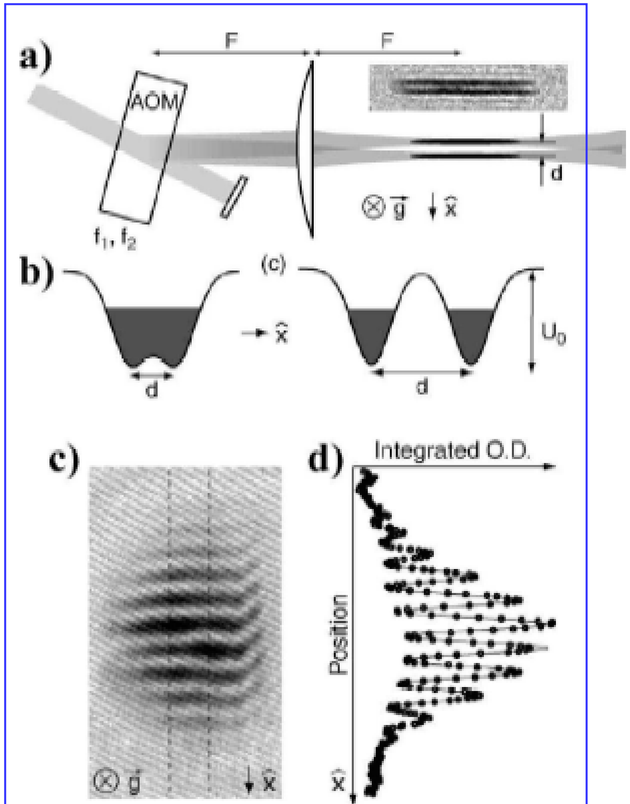
$$a(B) = a_{bg}\left(1 - \frac{\Delta}{B - B_0}\right)$$

$$a(B) \approx \frac{a_{bg}}{\Delta}(B - B_{ZC}) \longrightarrow \boxed{\frac{\Delta a}{\Delta B} = 0.6\ a_0\,/\,\mathrm{G}}$$

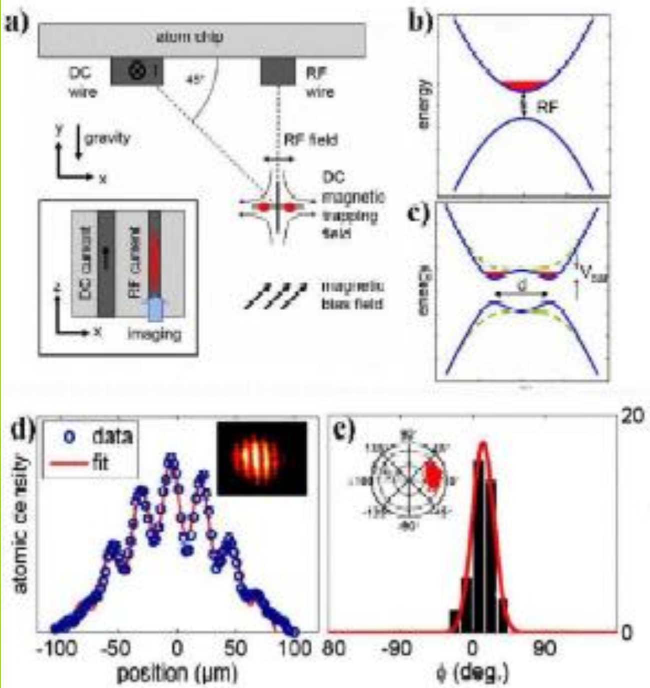
Very high degree of tunability !!

Atom interferometry on the zero crossing of the broad Feshbach resonance

First problem: how to control depth and shape of the trap?



MIT



Ulm, Vienna

Y. Shin, et al., *Phys. Rev. Lett*. **92**, 050405 (2004)

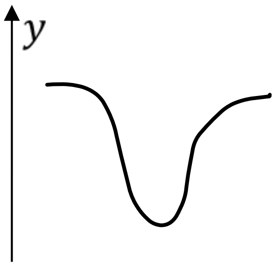
J. Esteve, et al., *Nature* **455**, 1216 (2008).

Florian Baumgärtner, et al. *Phys. Rev. Lett*. **105**, 243003 (2010)

T. Barreda, et al., *Nat. Comm.* **4**, 2077 (2013).

$\Delta y \sim 1\ \mu m$

$\Delta V \sim 1$ kHz



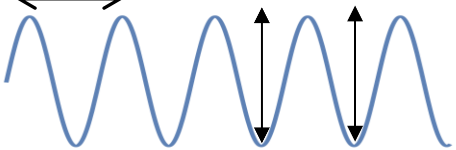
$U \sim 500$ nK

$V \sim h\ 10$ kHz

Optical lattices !!

d

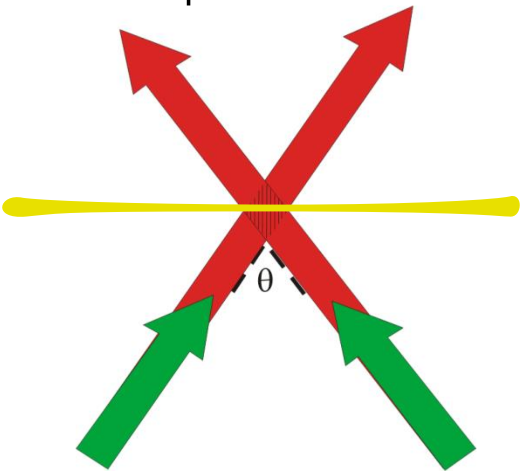
common mode depth fluctuations



$\Delta V = F_{ext}\, d$

Double-well potential: our first idea

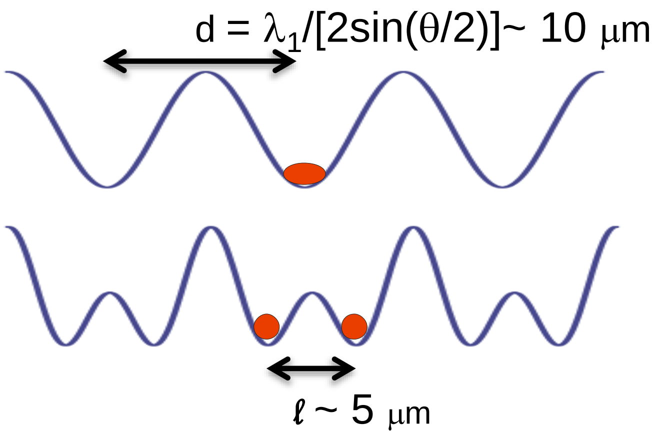
- Super-Lattice



λ_1=1064 nm

Radial confinement

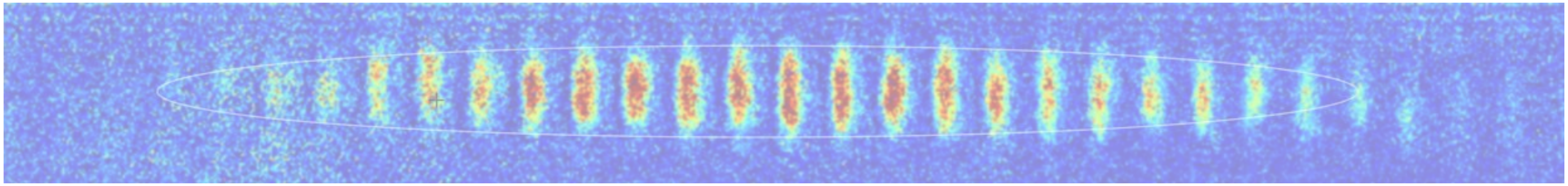
$\lambda_2=\lambda_1/2$=532 nm

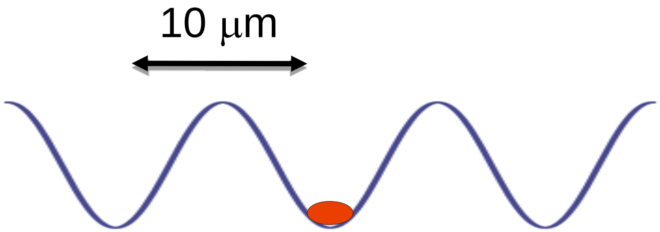


J. Sebby-Strabley, et al., Phys. Rev. A **73**, 033605 2006.

Primary lattice

- atoms loaded into IR lattice with N ~ 1000-4000 per site

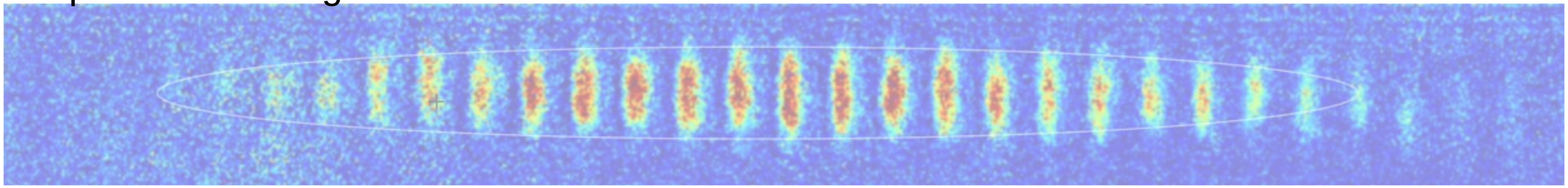


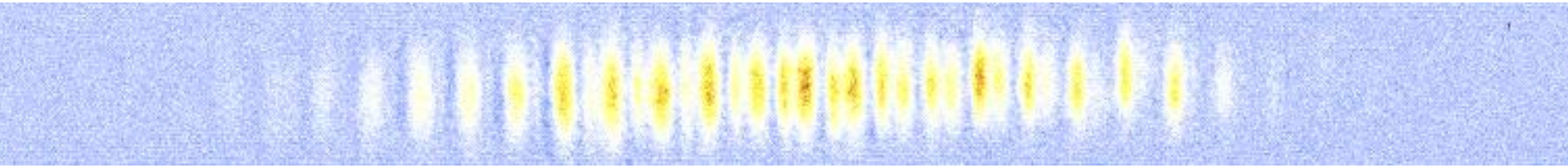


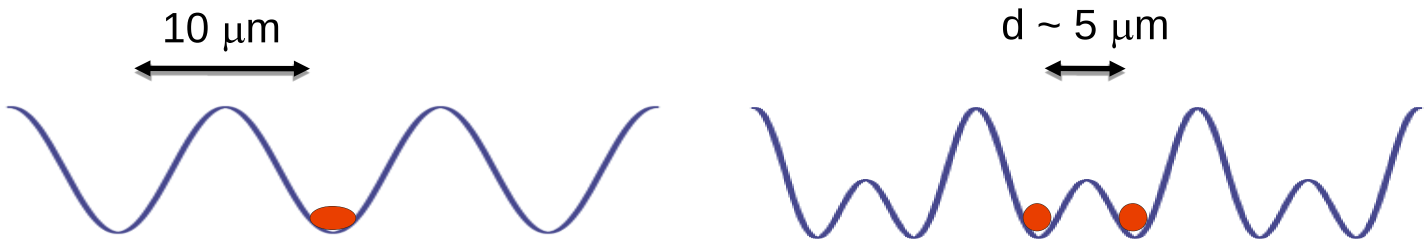
In situ detection: microscope objective with 1.5μm resolution

Primary lattice + Secondary lattice

- atoms loaded into IR lattice with N ~ 1000-2000 per site
- split atoms with green barrier







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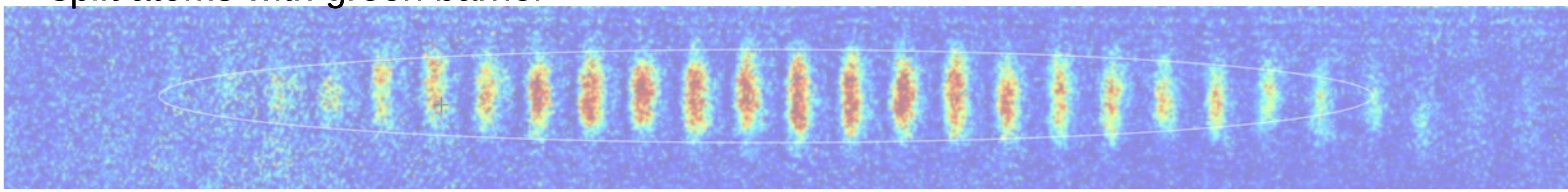
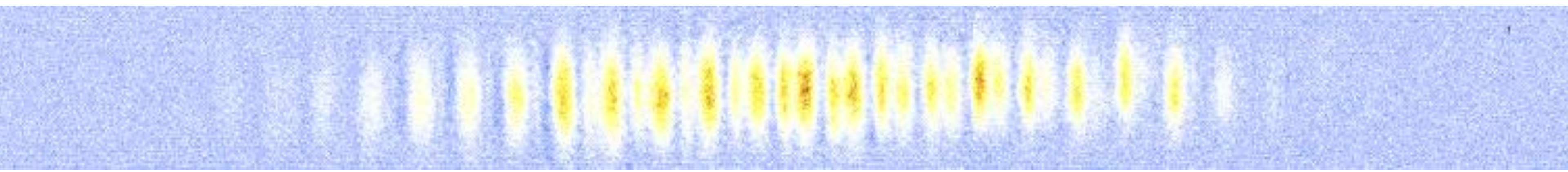
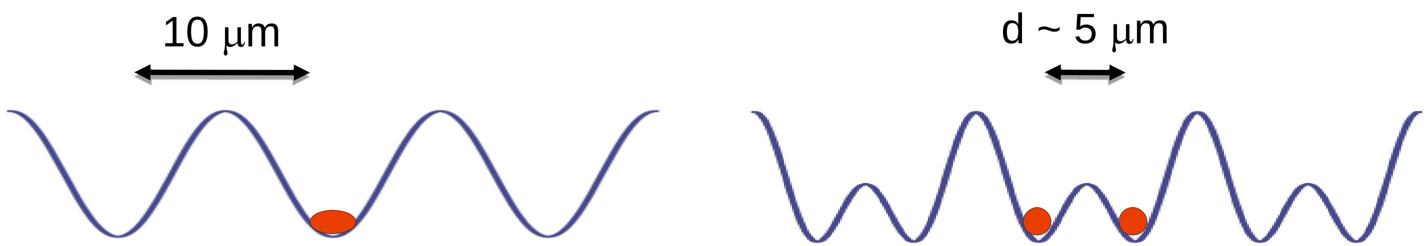






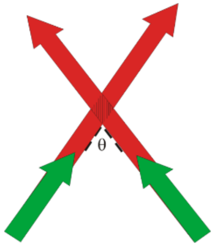
Our control of the barrier is below 1 nm, but we can center it only in one interferometer.

How to improve double well interferometry

- A large spacing superlattice is needed
- Lattices must be created retro-reflecting the laser light on a mirror to minimize sensitivity to misalignments

$$d = \frac{\lambda}{2\sin(\theta/2)}$$

$$\Delta d = \lambda \frac{\cos(\theta/2)}{4\sin(\theta/2)^2} \Delta\theta$$

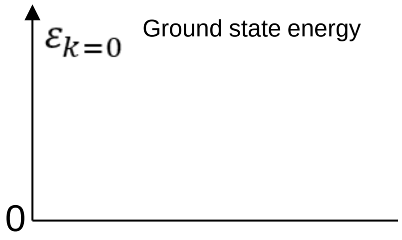


Beat-Note Lattice : the idea

Free particle

$$\psi_k(x) = \sqrt{\frac{1}{L}}\, e^{ikx}$$

$$\varepsilon_k = \frac{\hbar^2 k^2}{2m}$$



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Free particle

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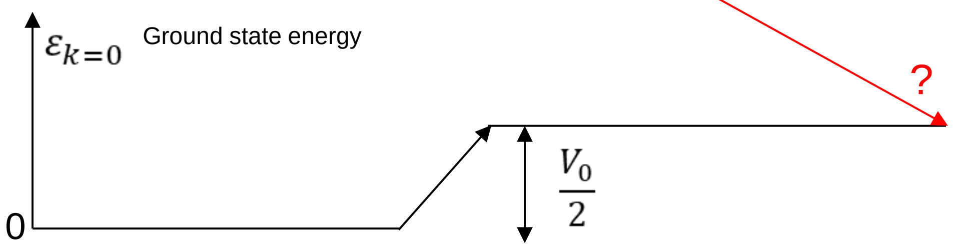
If an optical lattice is switched on

$$V(x) = V_0 cos^2(k_L x) = \frac{V_0}{4}\left(e^{i2k_L x} + e^{-i2k_L x} + 2\right)$$



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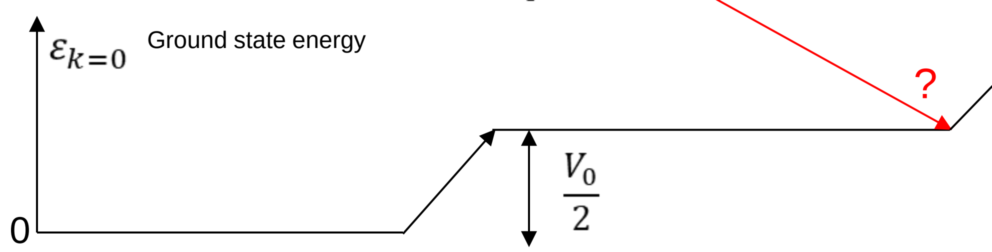

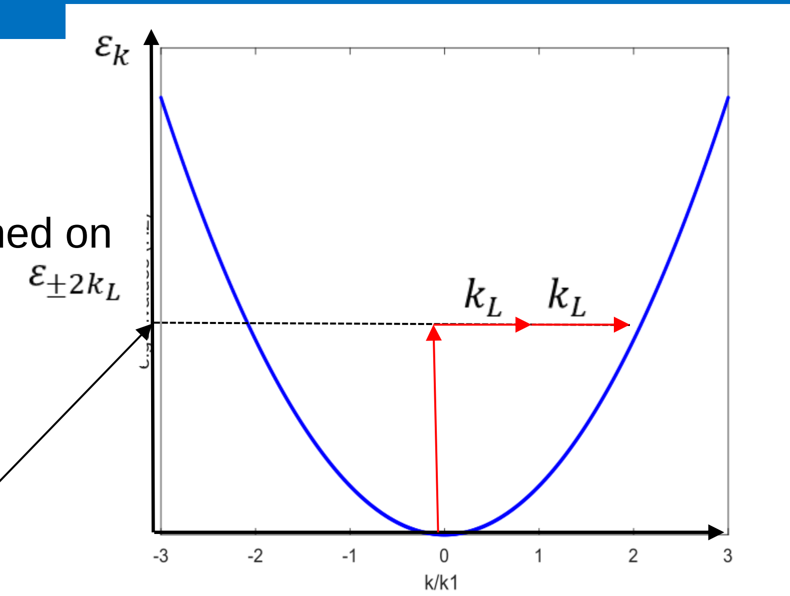

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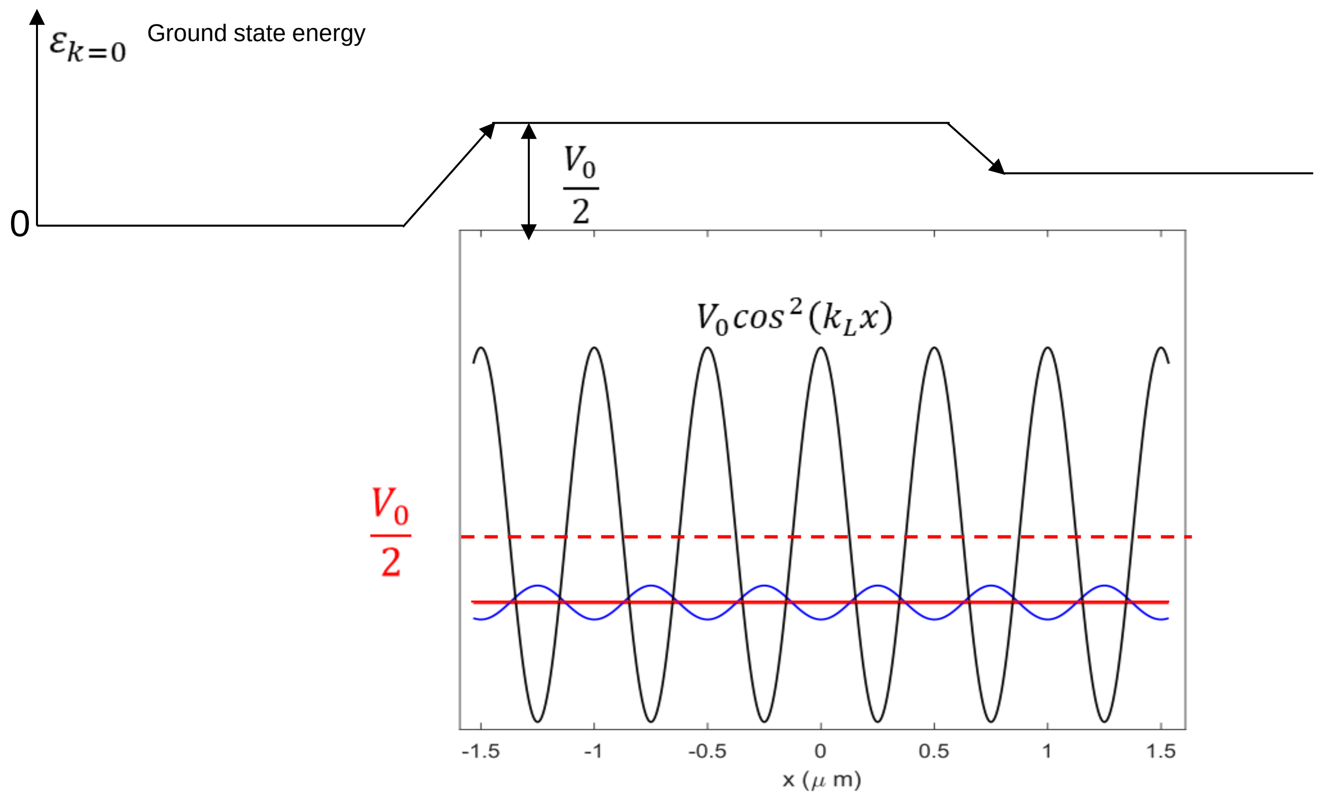
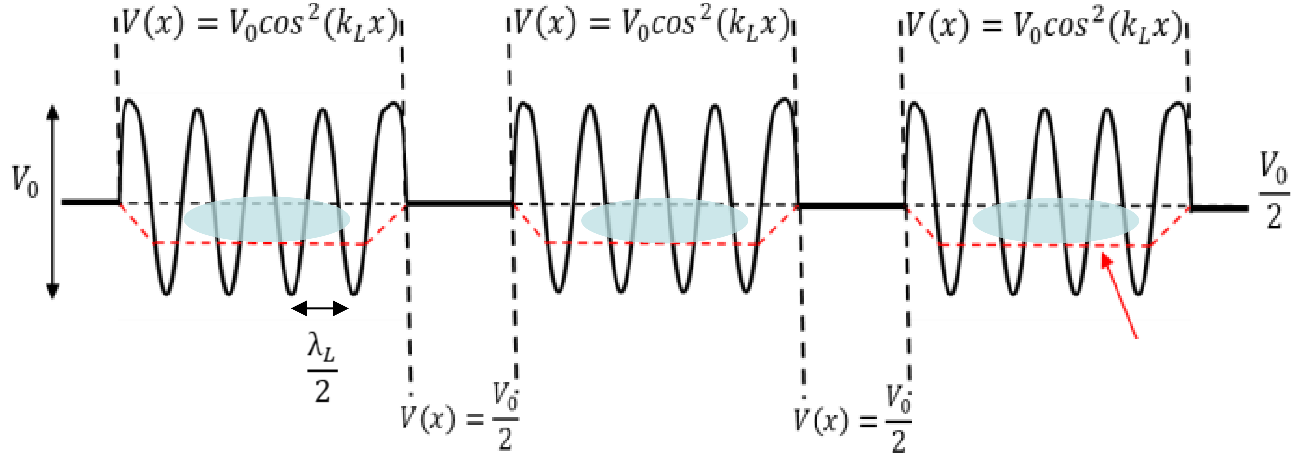
$$\varepsilon_{k=0} = \frac{\boldsymbol{V_0}}{\boldsymbol{2}} - \frac{V_0^2}{32E_R} < \frac{\boldsymbol{V_0}}{\boldsymbol{2}}$$

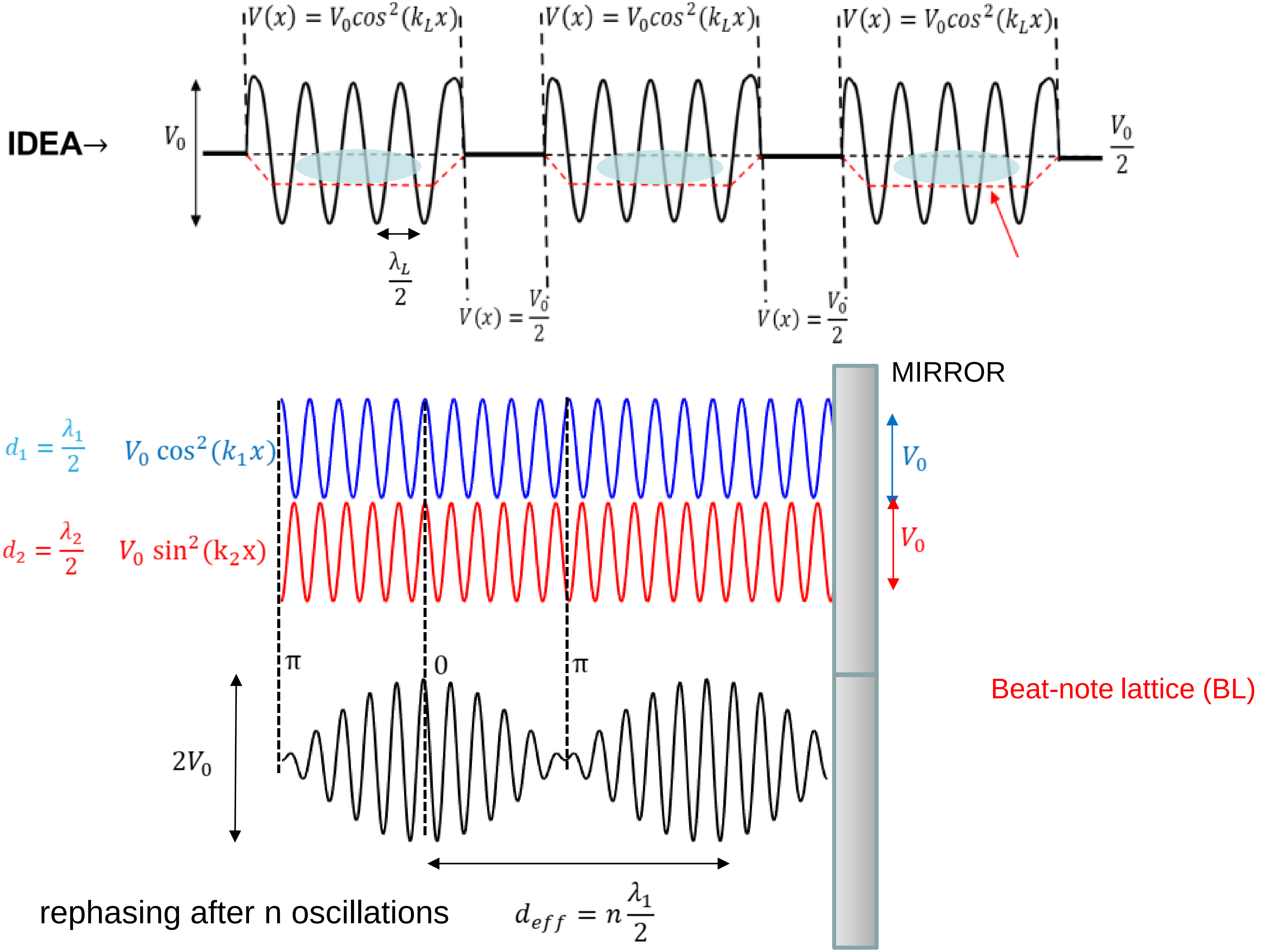


BL : the idea

IDEA→



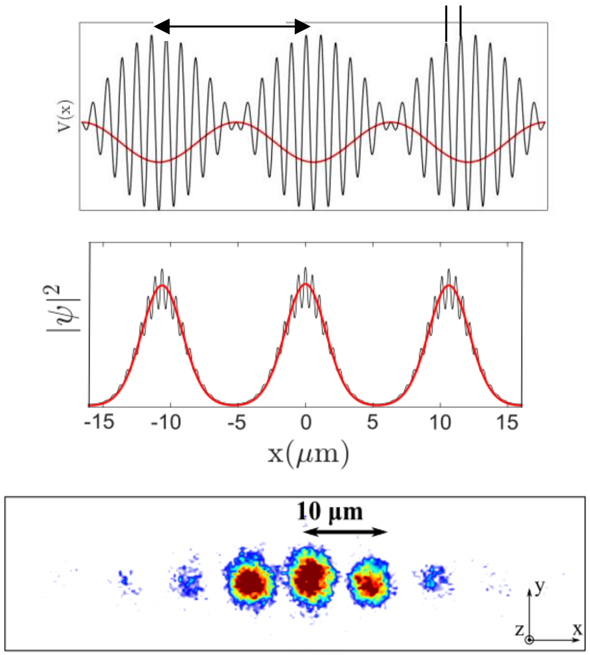
BL : the idea



IDEA→
$V(x) = V_0 cos^2(k_L x)$
V_0
$\frac{V_0}{2}$
$\frac{\lambda_L}{2}$
$V(x) = \frac{V_0}{2}$
MIRROR
$d_1 = \frac{\lambda_1}{2}$
$V_0 \cos^2(k_1 x)$
$d_2 = \frac{\lambda_2}{2}$
$V_0 \sin^2(k_2 x)$
π
0
π
$2V_0$
Beat-note lattice (BL)
rephasing after n oscillations
$d_{eff} = n\frac{\lambda_1}{2}$

Beat-Note Superlattice @ 10 μm

$$d_{eff} = n\frac{\lambda}{2}$$



Effective potential for $V_0 < E_{R+}$

$$V_{eff}(x) = -\frac{V_0^2}{8E_{R+}}\cos^2(k_- x)$$

working conditions

$(n+1)\lambda_1 = n\lambda_2$

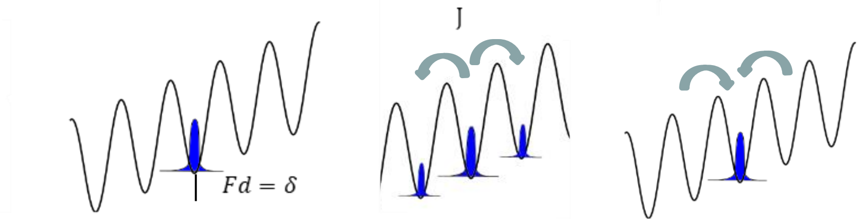
$\lambda_2 = 1013.7$ nm
$\lambda_1 = 1064.5$ nm
n=20

$d_+ \cong 0.5$ μm
$d_- \cong 10.6$ μm

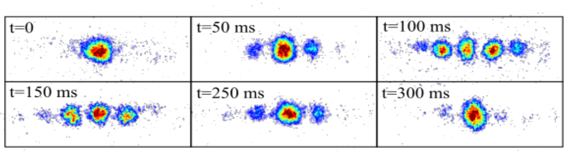
L. Masi, et al. Phys. Rev. Lett. **127**, 020601 –2021

Bloch Oscillations in a BNSL

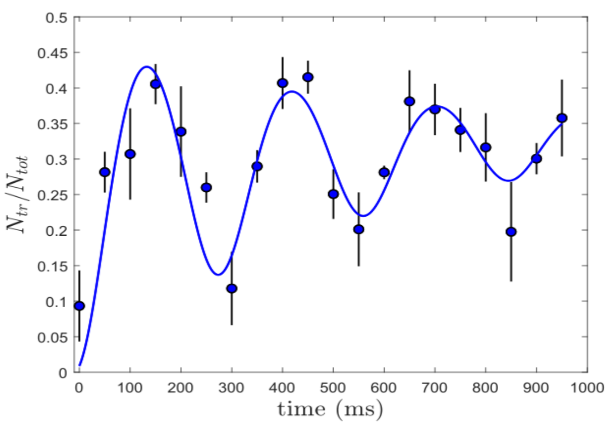
d ≅ 10.6 μm



No interactions



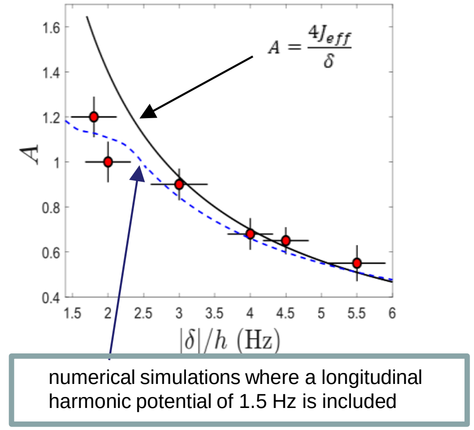
$N \cong 5 * 10^3$ atoms
$V_0 = \sim 0.3E_{R^+}$
Force $\sim 3 * 10^{-4}$g
$\nu = 3$ Hz



Bloch period

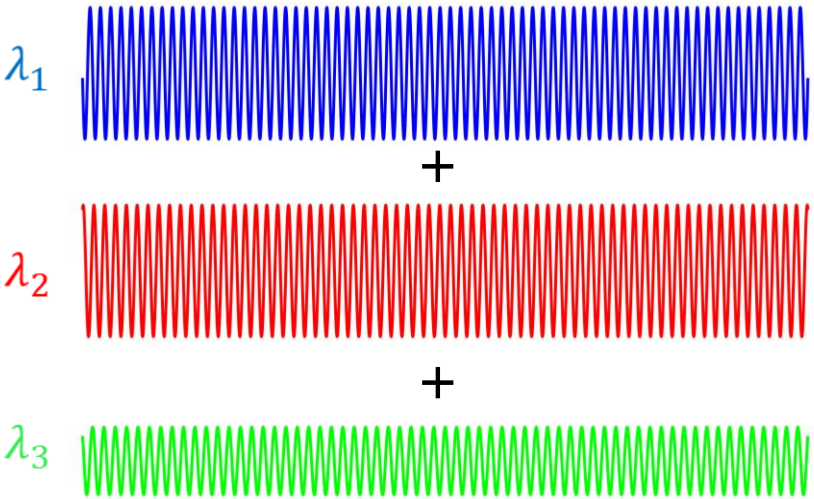
$\tau_B = h/\delta = h/ Fd$

1 second coherence



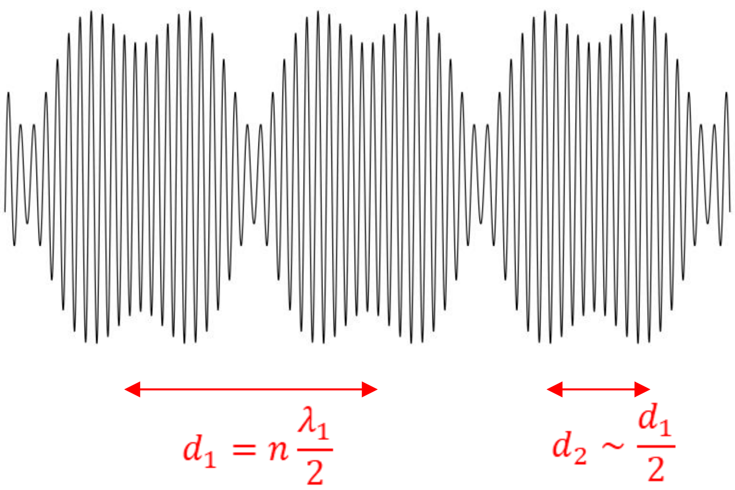
L. Masi, et al. Phys. Rev. Lett. **127**, 020601 –2021

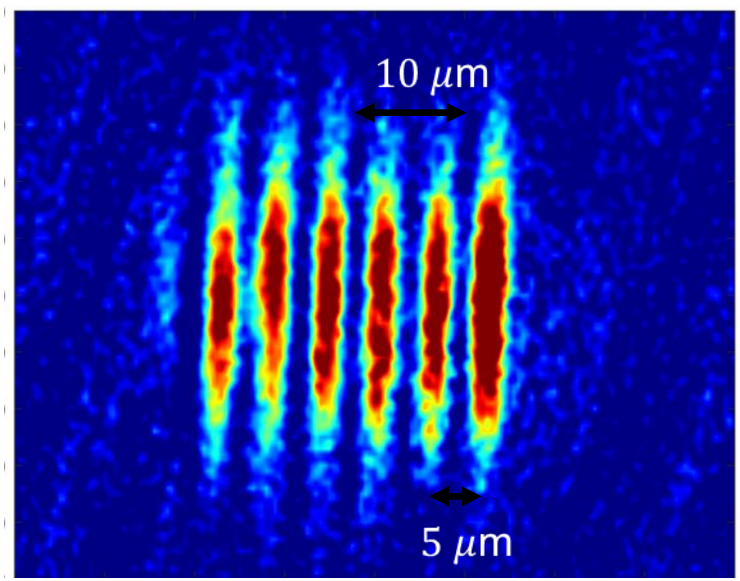
Array of DWs using Beat-note Superlattices



$(n+1)\lambda_1 = n\lambda_2$ $\qquad$ $n\lambda_2 = (n-1)\lambda_3$

$$\begin{cases} \lambda_1 = 1013 \text{ nm} \\ \lambda_2 = 1064 \text{ nm} \\ \lambda_3 = 1120 \text{ nm} \end{cases} \longrightarrow \quad \begin{array}{l} d_1 \sim 10\ \mu\text{m} \\ d_2 \sim 5\ \mu\text{m} \end{array}$$





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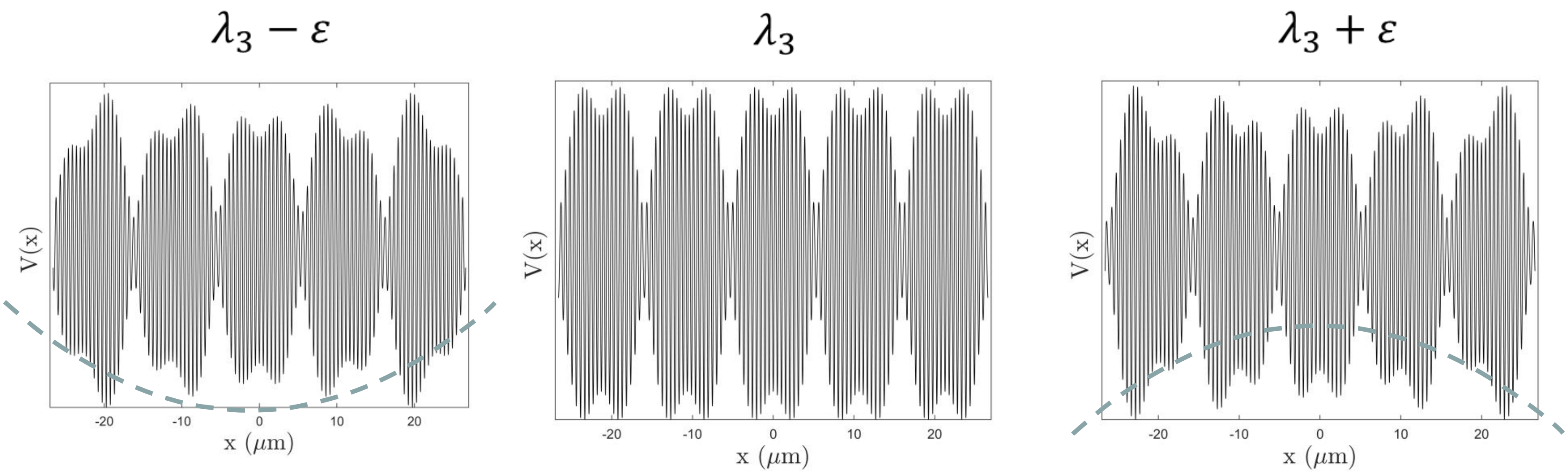
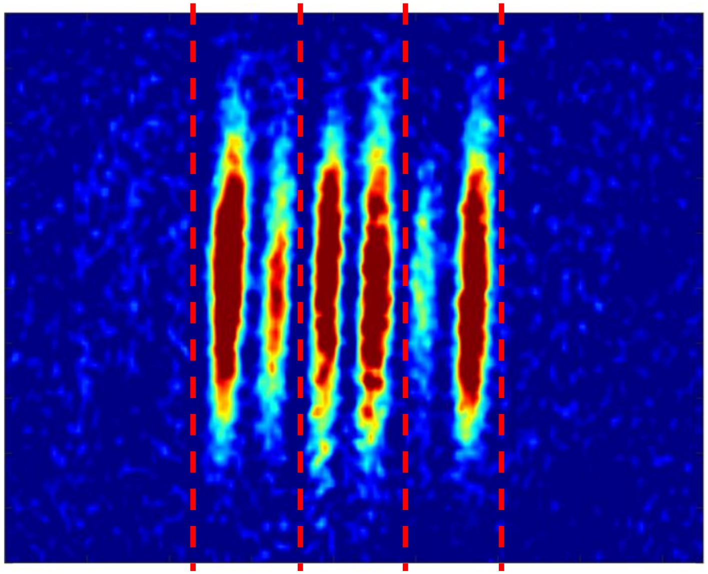


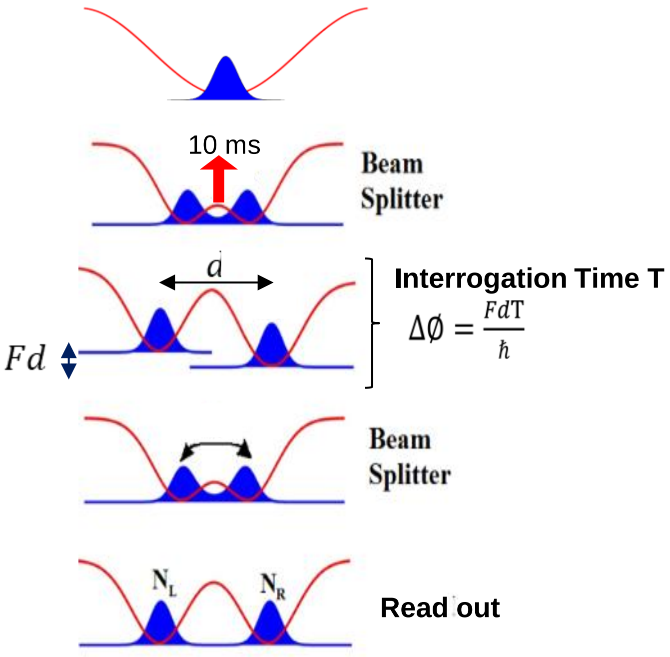
The two BNSL with d=10 μm are not in counterphase anymore and they have different periodicities



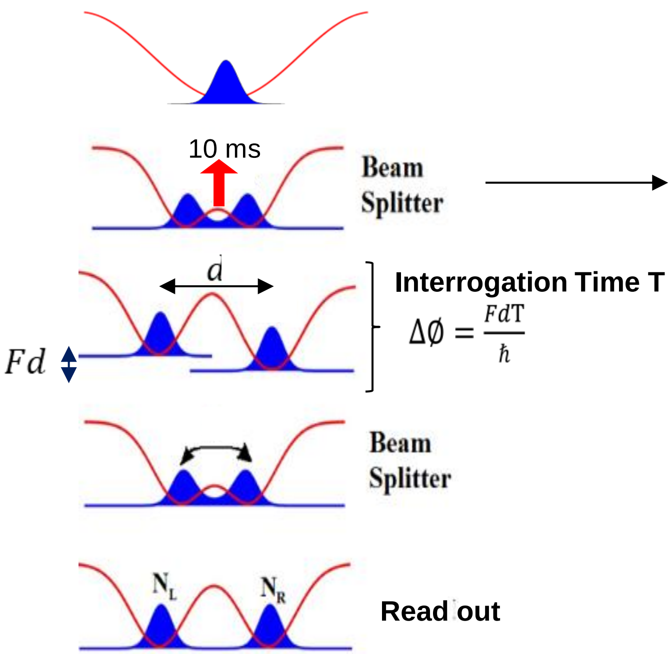
Some numbers:
$\Delta\lambda \sim 0{,}01$ nm

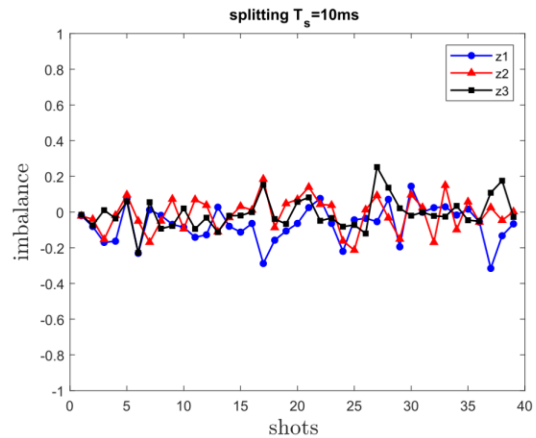
$\Delta E_{i,i+1} \sim 2$ Hz

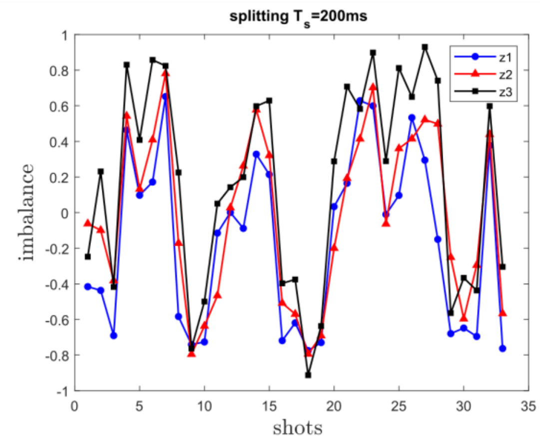
Mach-Zehender



How to measure the interferometric phase ?







$$z = \frac{N_L - N_R}{N_L + N_R}$$

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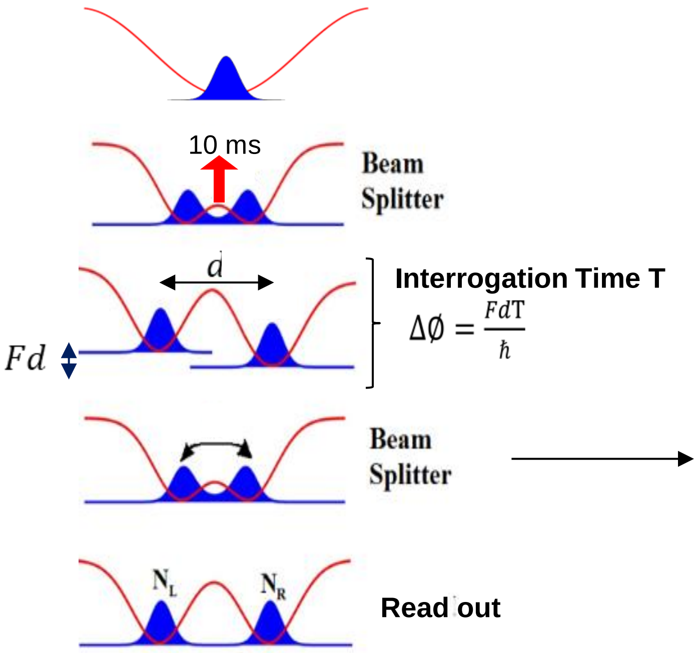
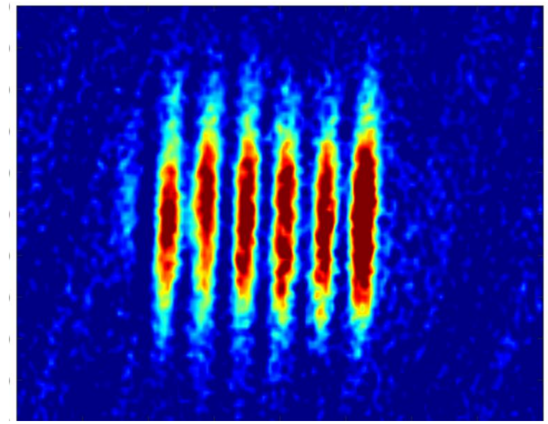


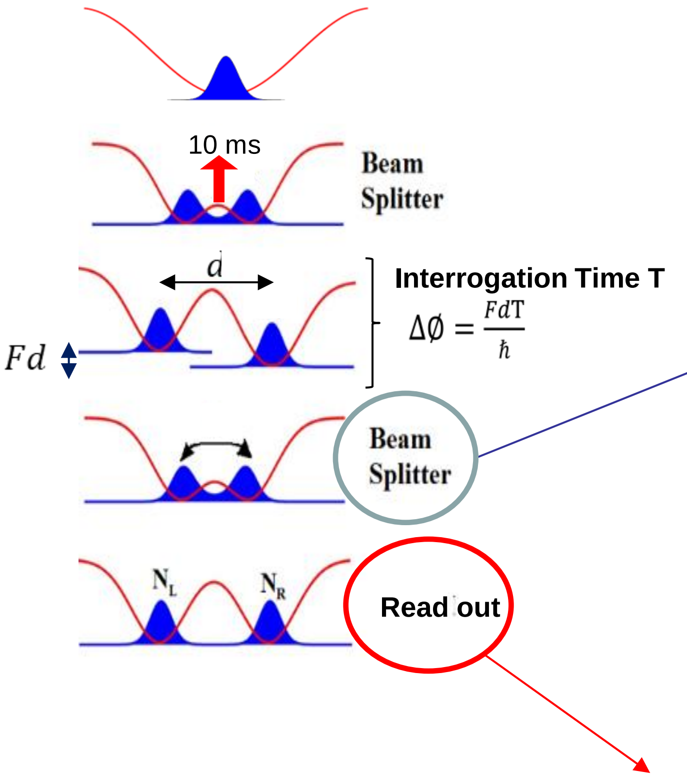
?

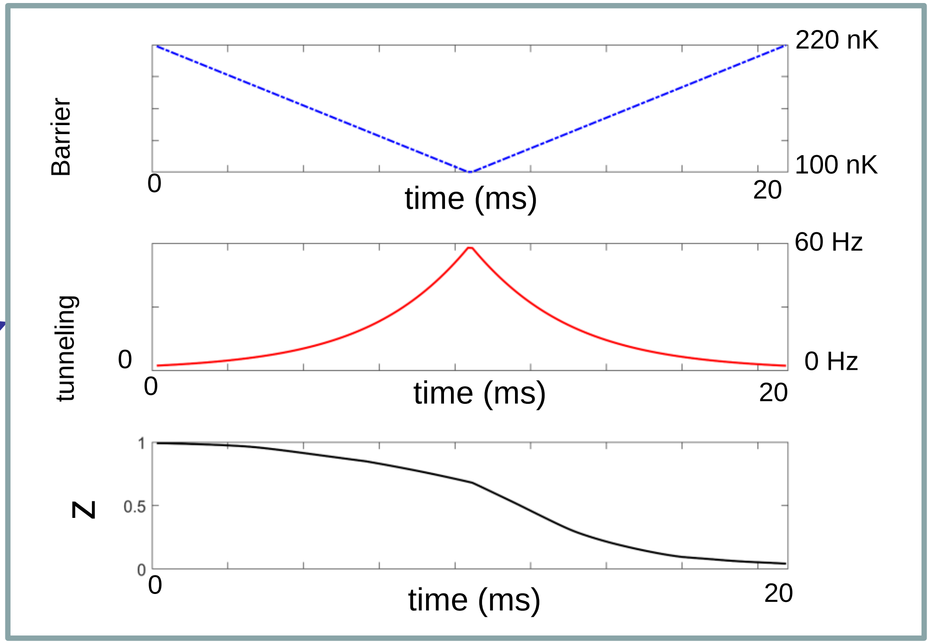


Interference after free expansion not possible !!

T. Berrada et al., Integrated Mach Zehender Interferometer for Bose Einstein Condensates, Nature Comm. 4, 2077, (2013)

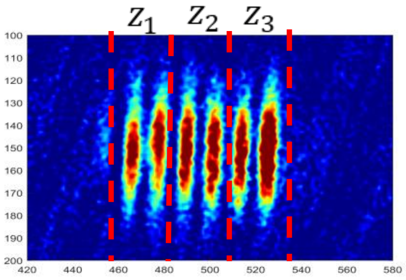
Second Beam Splitter



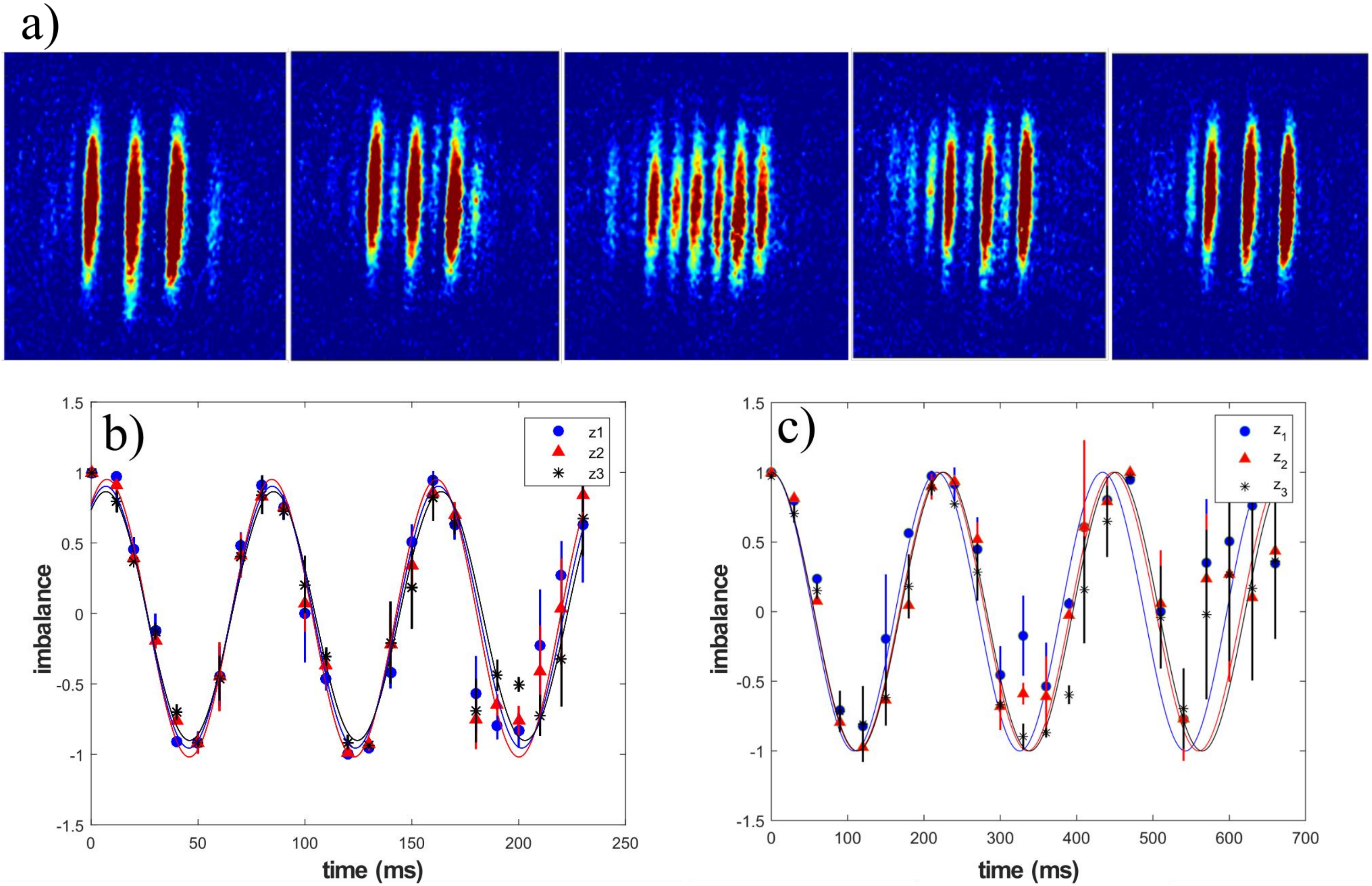


Atomic Imbalance

$$z = \frac{N_L - N_R}{N_L + N_R}$$



Rabi oscillations

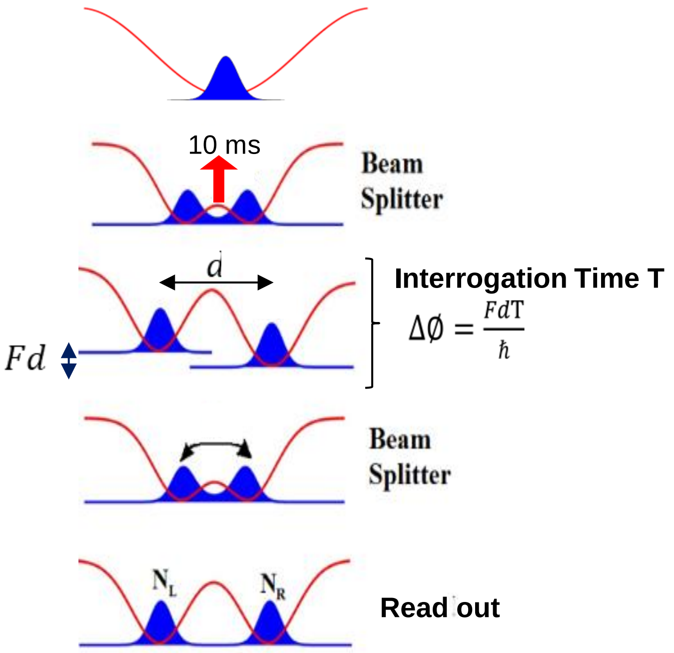


$$z = \frac{N_L - N_R}{N_L + N_R}$$

J/ h ~13 Hz

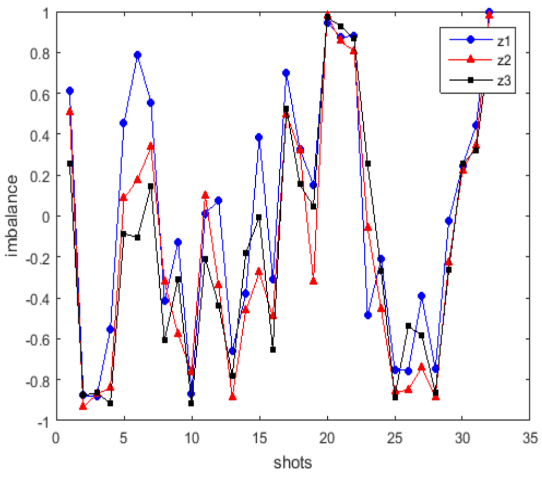
J/ h ~4 Hz

Interferometric sequence with 3 DWs



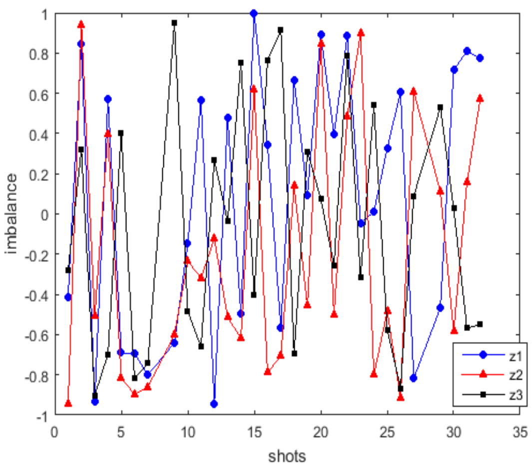
T=20 ms

Correlated output

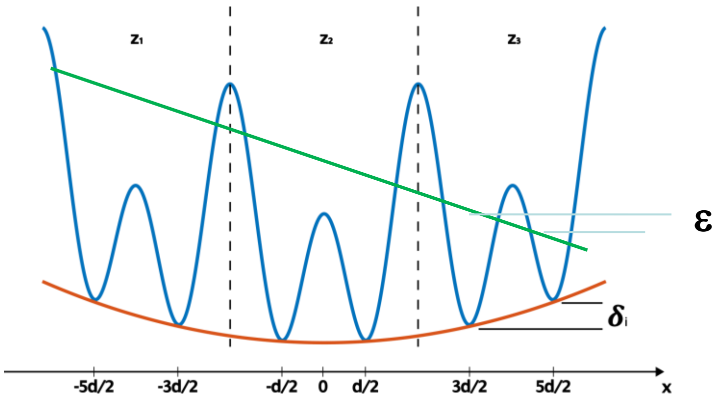


T=100 ms

Lost the correlations ?



Interferometric sequence with 3 DWs



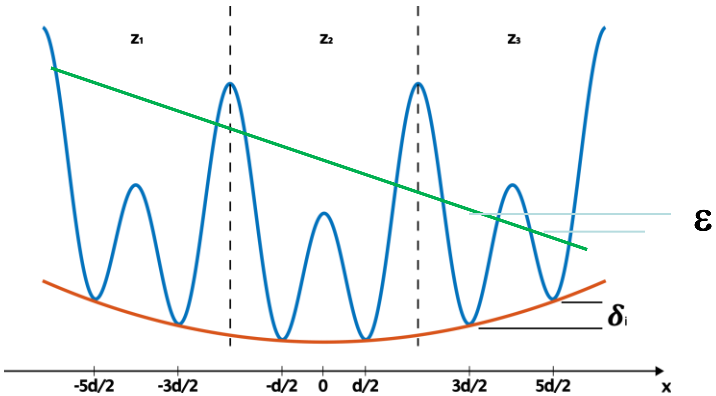
$$z_1 = \sin(\varphi_1) = \sin(-\delta\, T + \varepsilon\, T)$$

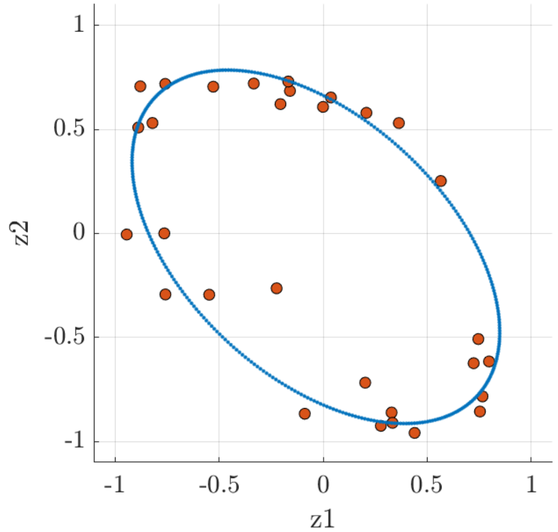
$$z_2 = \sin(\varphi_2) = \sin(\varepsilon\, T)$$

$$z_3 = \sin(\varphi_3) = \sin(\delta\, T + \varepsilon\, T)$$

Analysis on 2 DWs

The noise ε distributes the data on an ellipse with an eccentricity that depends on δ





We can measure $\varphi_2 - \varphi_1 = \delta\, T$

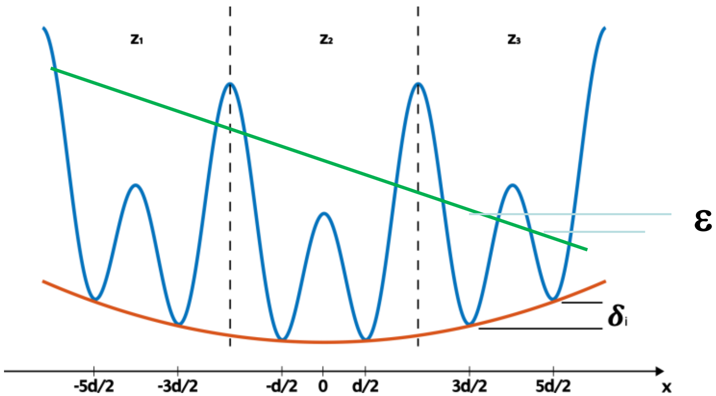
$$z_1 = \sin(\varphi_1) = \sin(-\delta\, T + \varepsilon\, T)$$

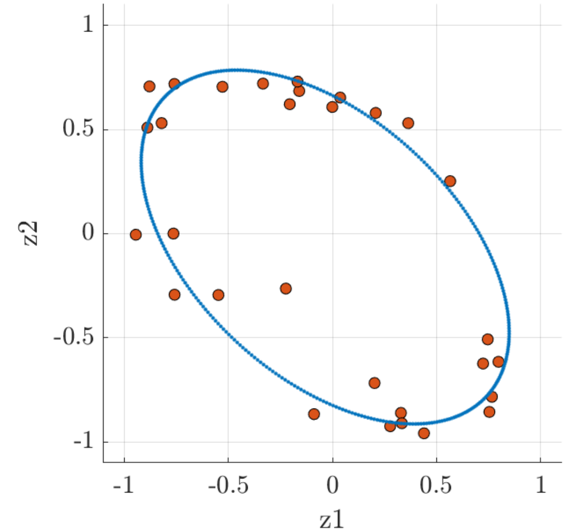
$$z_2 = \sin(\varphi_2) = \sin(\varepsilon\, T)$$

$$z_3 = \sin(\varphi_3) = \sin(\delta\, T + \varepsilon\, T)$$

Gradiometer

The noise ε distributes the data on an ellipse with an eccentricity that depends on δ





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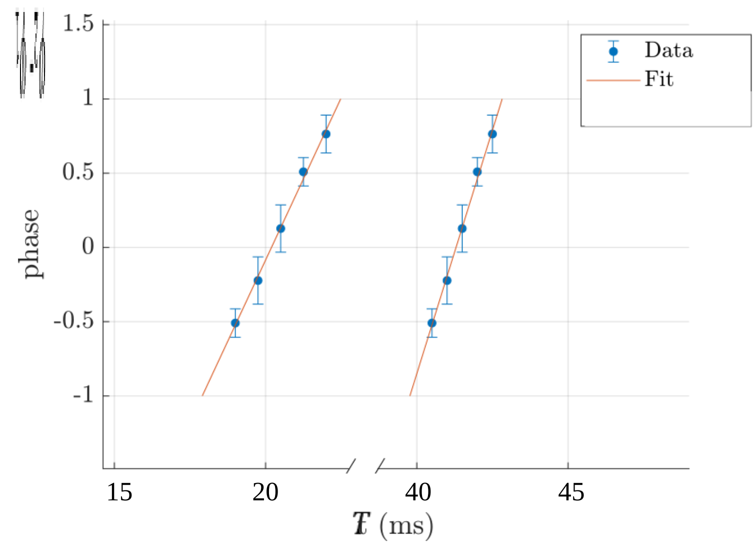
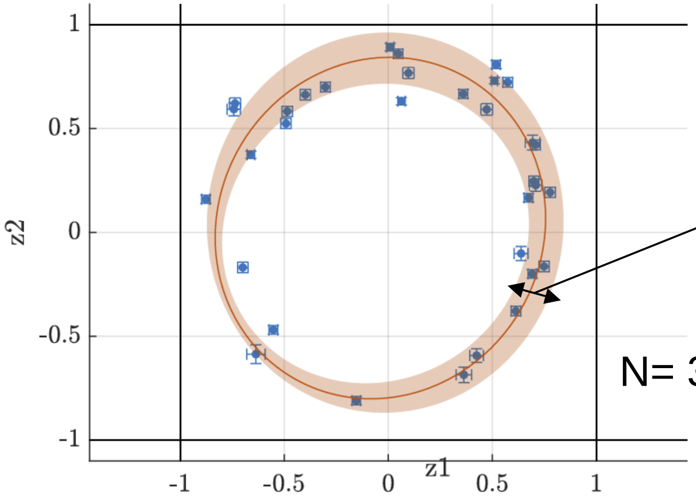


We have realized a trapped atom GRADIOTEMER

Decoherence of the differential phase

$$z_1 = \sin(\varphi_1) = \sin(-\delta\, T + \varepsilon\, T)$$

$$z_2 = \sin(\varphi_2) = \sin(\varepsilon\, T + \Delta\varphi_{uncorr})$$



$\sigma_{\Delta\varphi_{uncorr}}$

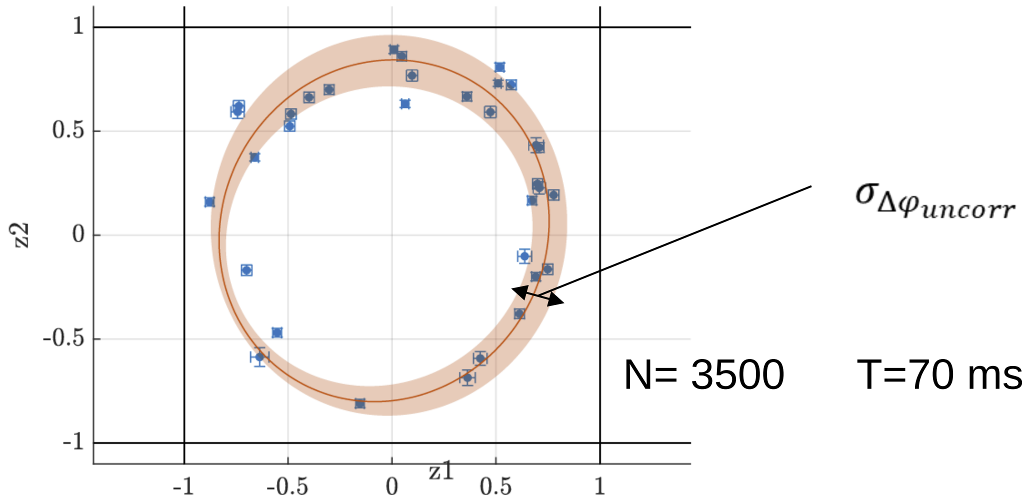
N= 3500 T=70 ms

Decoherence of the differential phase

$$z_1 = \sin(\varphi_1) = \sin(-\delta\, T + \varepsilon\, T)$$

$$z_2 = \sin(\varphi_2) = \sin(\varepsilon\, T + \Delta\varphi_{uncorr})$$

$$\Delta\varphi_{uncorr} \propto \Delta(E_L - E_R)T \propto \Delta z\, a_s T$$



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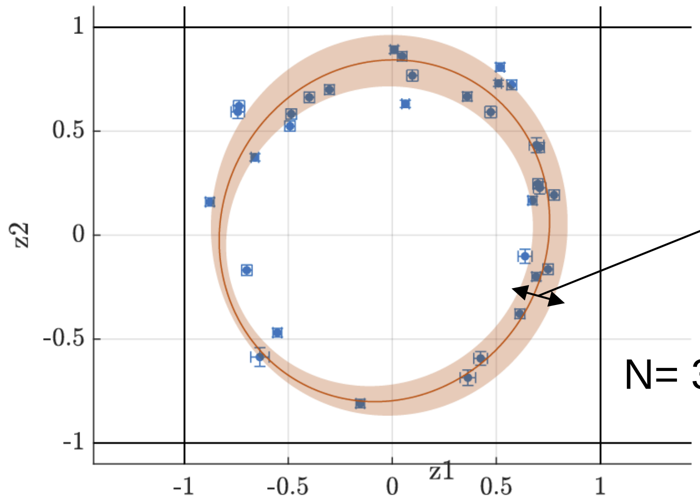
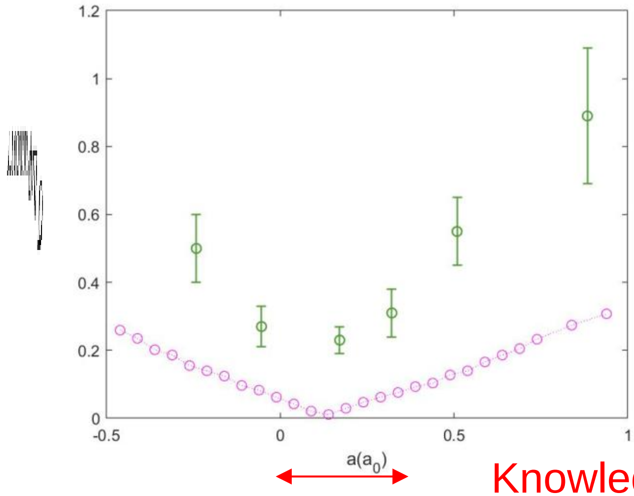


$\sigma_{\Delta\varphi_{uncorr}}$

N= 3500 T=70 ms

$$\sigma_{\Delta\varphi_{uncorr}} \propto \sigma_{\Delta z}\, a_s T \propto \frac{a_s T}{\sqrt{N}}$$



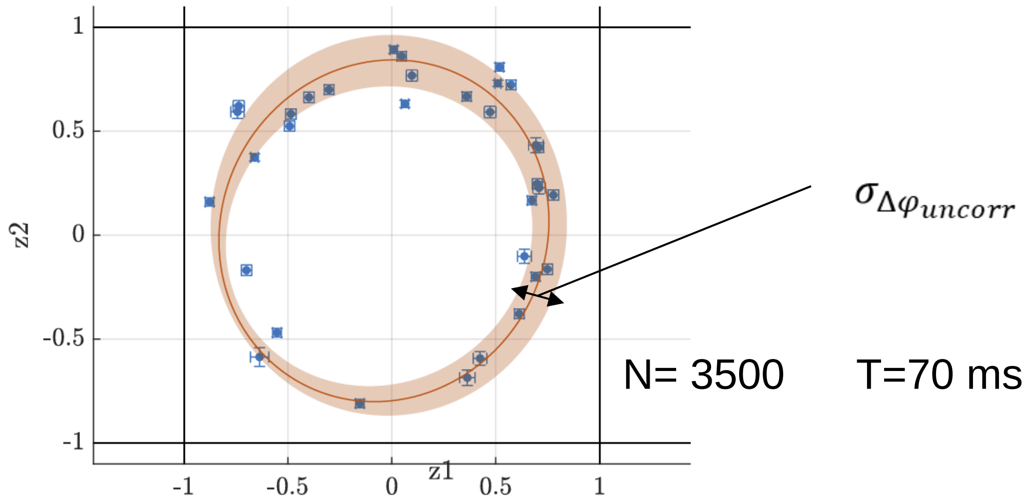
Scattering length control: 0.02 ao

Knowledge of the zero crossing

Decoherence of the differential phase

$$z_1 = \sin(\varphi_1) = \sin(-\delta\, T + \varepsilon\, T)$$

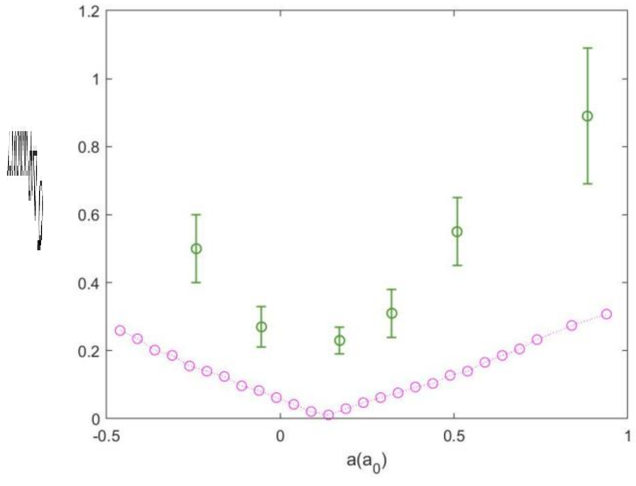
$$z_2 = \sin(\varphi_2) = \sin(\varepsilon\, T + \Delta\varphi_{uncorr})$$

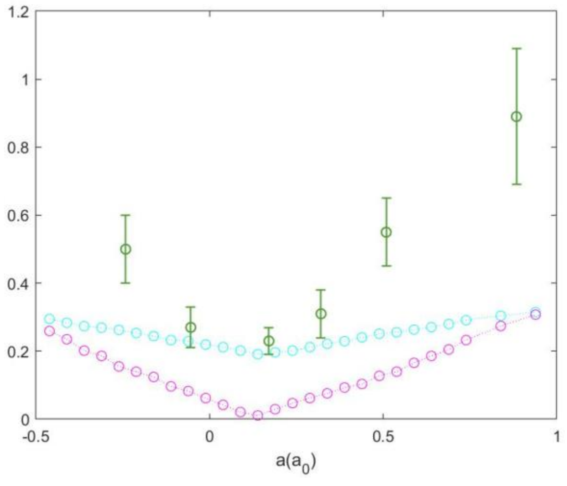


N= 3500 T=70 ms

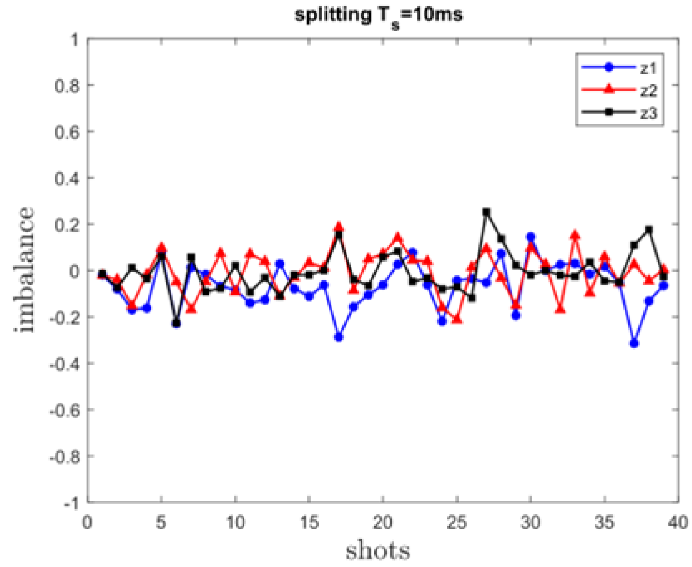
$$\sigma_{\Delta\varphi_{uncorr}} \propto \frac{a_s T}{\sqrt{N}}$$

$$\sigma_{\Delta\varphi_{uncorr}} = \sqrt{\Delta\varphi_{tech}{}^2 + \frac{\alpha a_s{}^2 T^2}{N}}$$





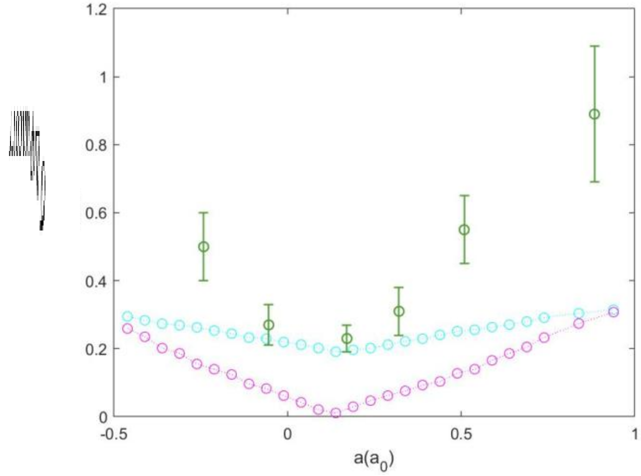
Decoherence of the differential phase

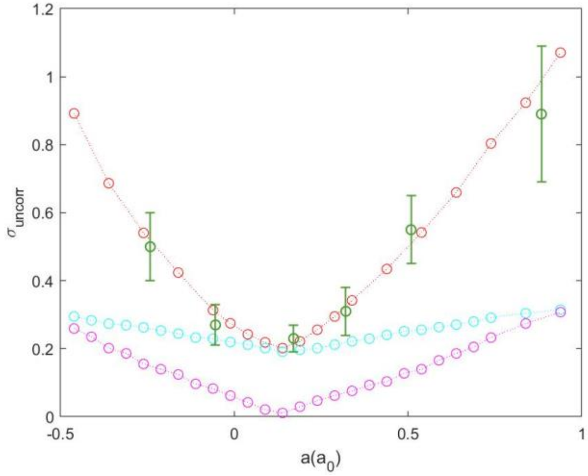


$\gamma > 1$

$$\sigma_{\Delta\varphi_{uncorr}} = \sqrt{\Delta\varphi_{tech}{}^2 + \frac{\alpha a_s{}^2 T^2}{N}}$$

$$\sigma_{\Delta\varphi_{uncorr}} = \sqrt{\Delta\varphi_{tech}{}^2 + \frac{\alpha\gamma a_s{}^2 T^2}{N}}$$

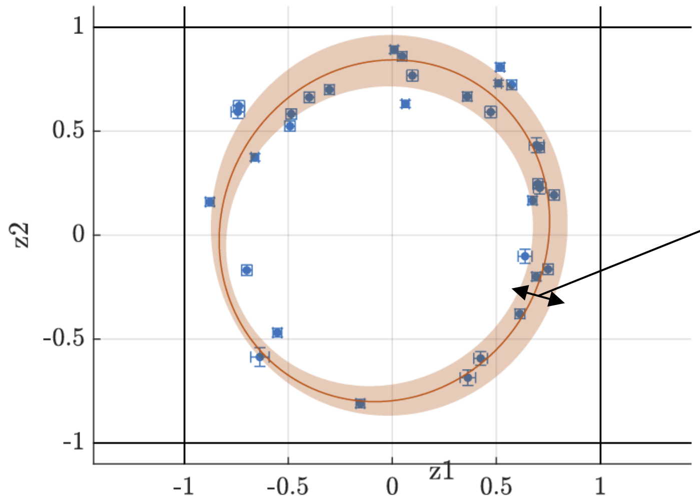




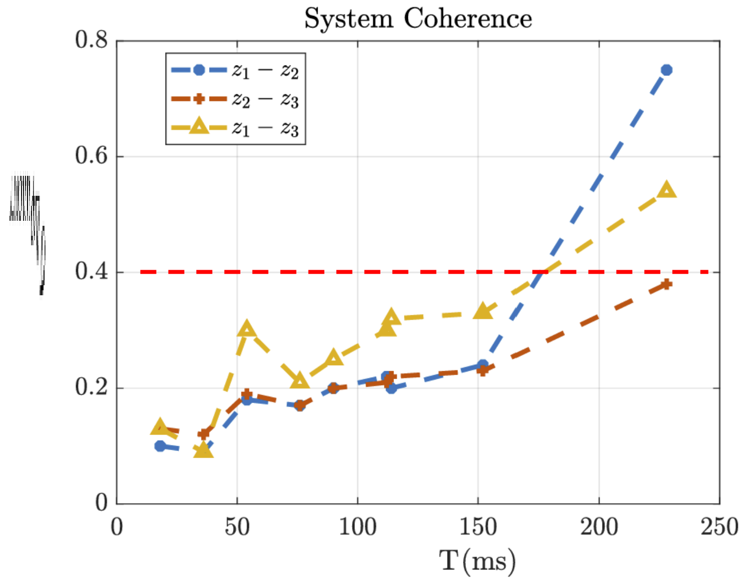
Decoherence of the differential phase

$$z_1 = \sin(\varphi_1) = \sin(-\delta\, T + \varepsilon\, T)$$

$$z_2 = \sin(\varphi_2) = \sin(\varepsilon\, T + \Delta\varphi_{uncorr})$$

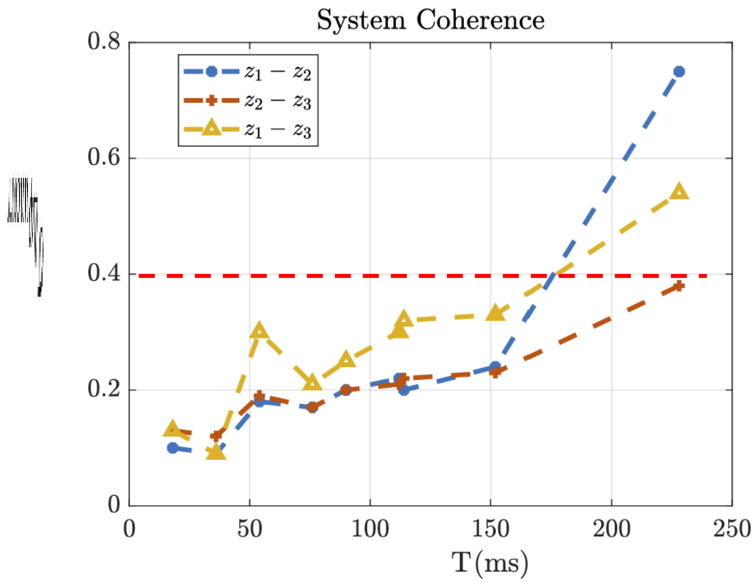


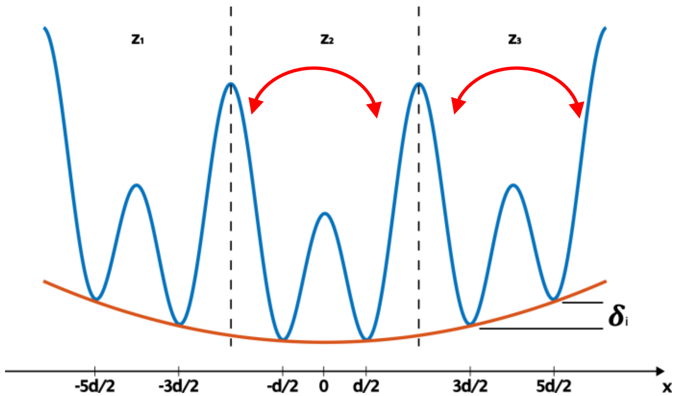
$\sigma_{\Delta\varphi_{uncorr}}$

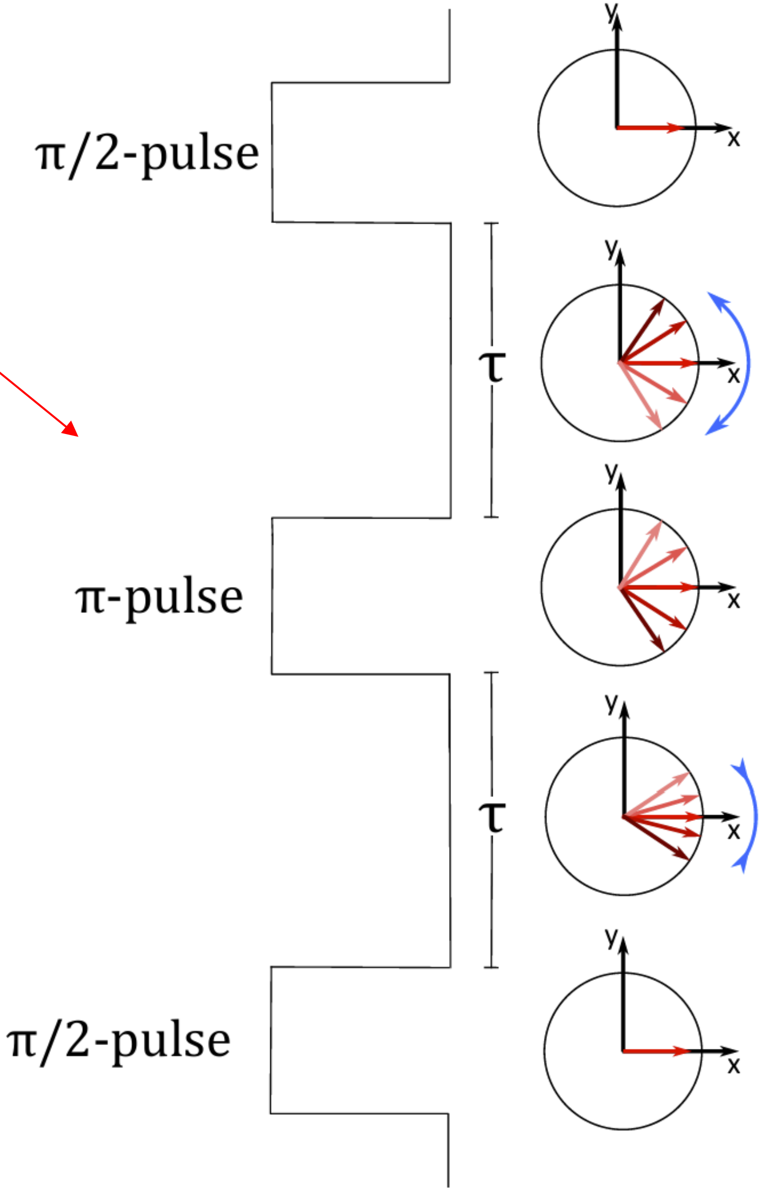


Decoherence
on the minimum
$\sim 3\ rad/s$

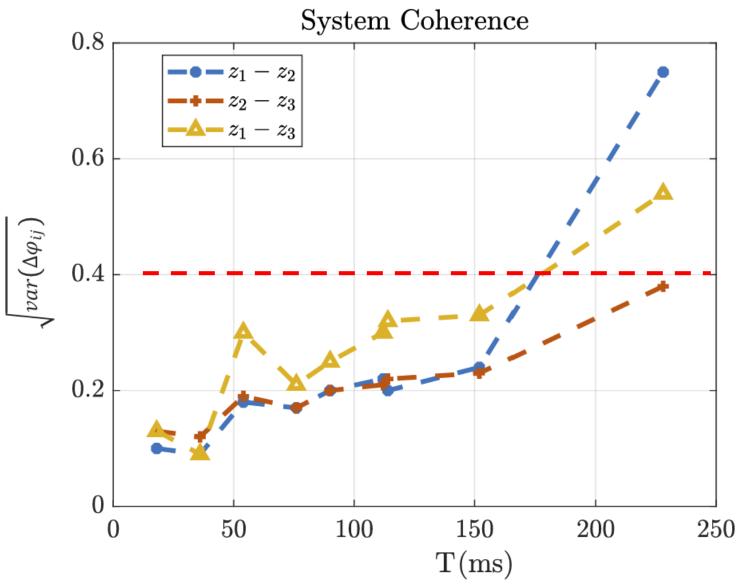
Gradiometer + Spin ECHO

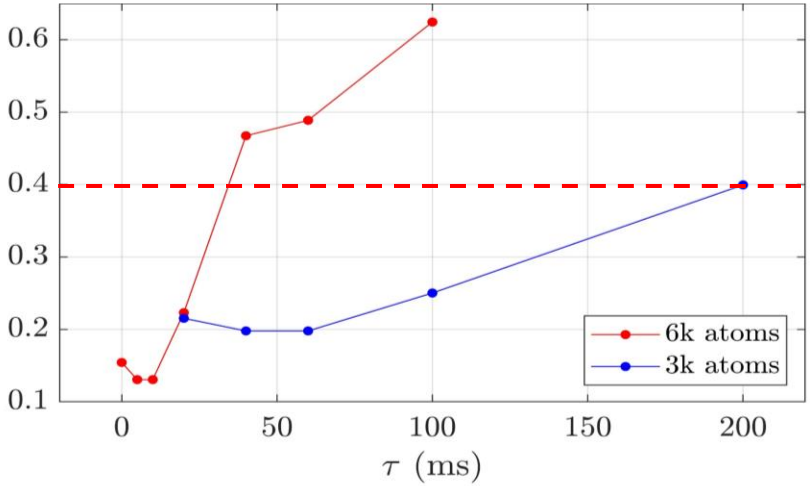


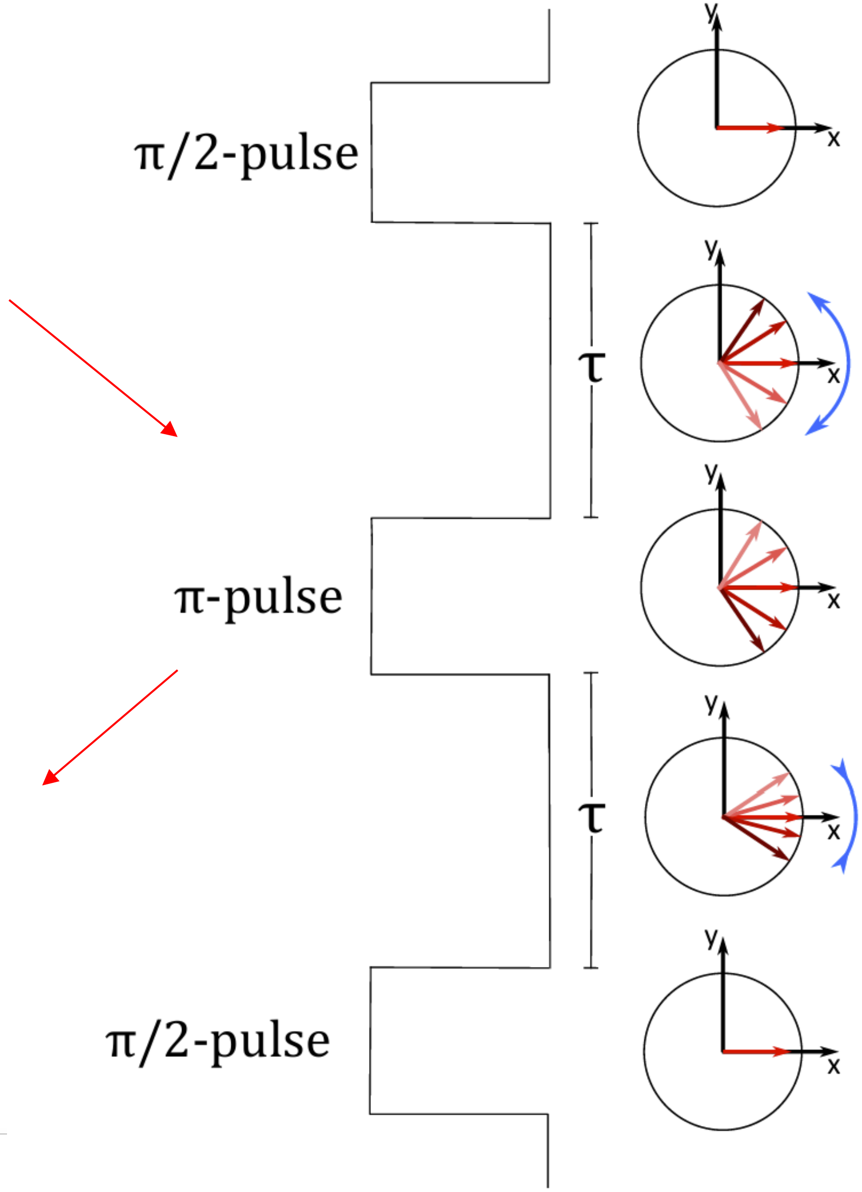




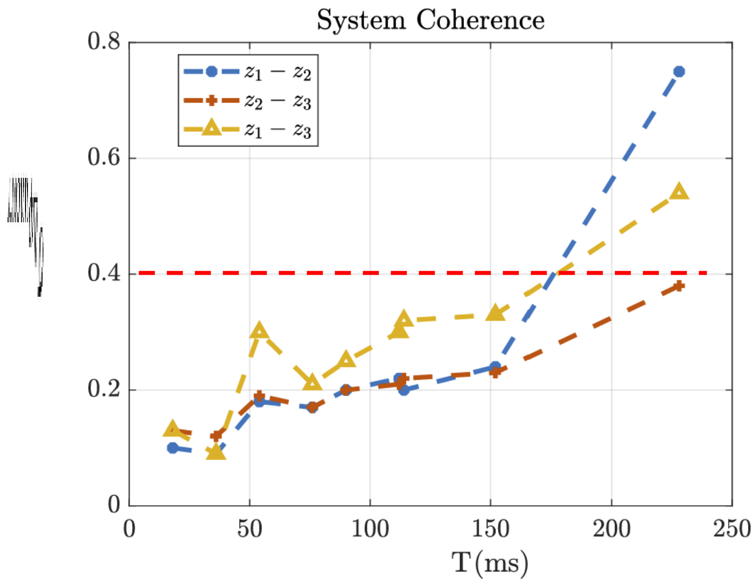
Spin ECHO

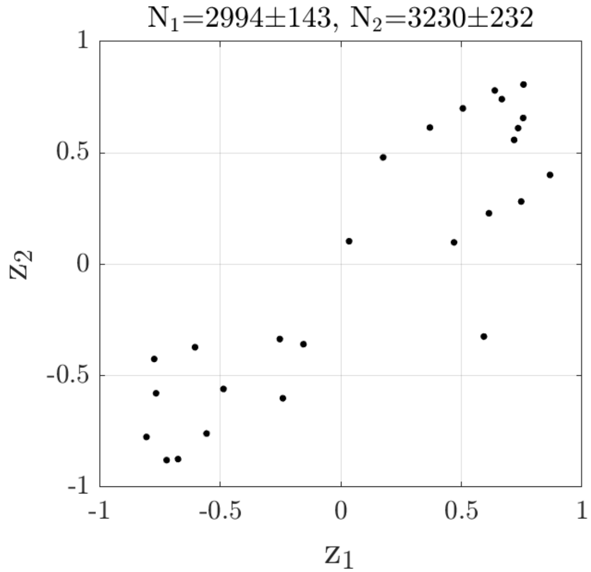

System Coherence
$z_1 - z_2$
$z_2 - z_3$
$z_1 - z_3$
$\sqrt{var(\Delta\varphi_{ij})}$
T(ms)


6k atoms
3k atoms
τ (ms)


π/2-pulse
π-pulse
π/2-pulse
τ
τ
y
x

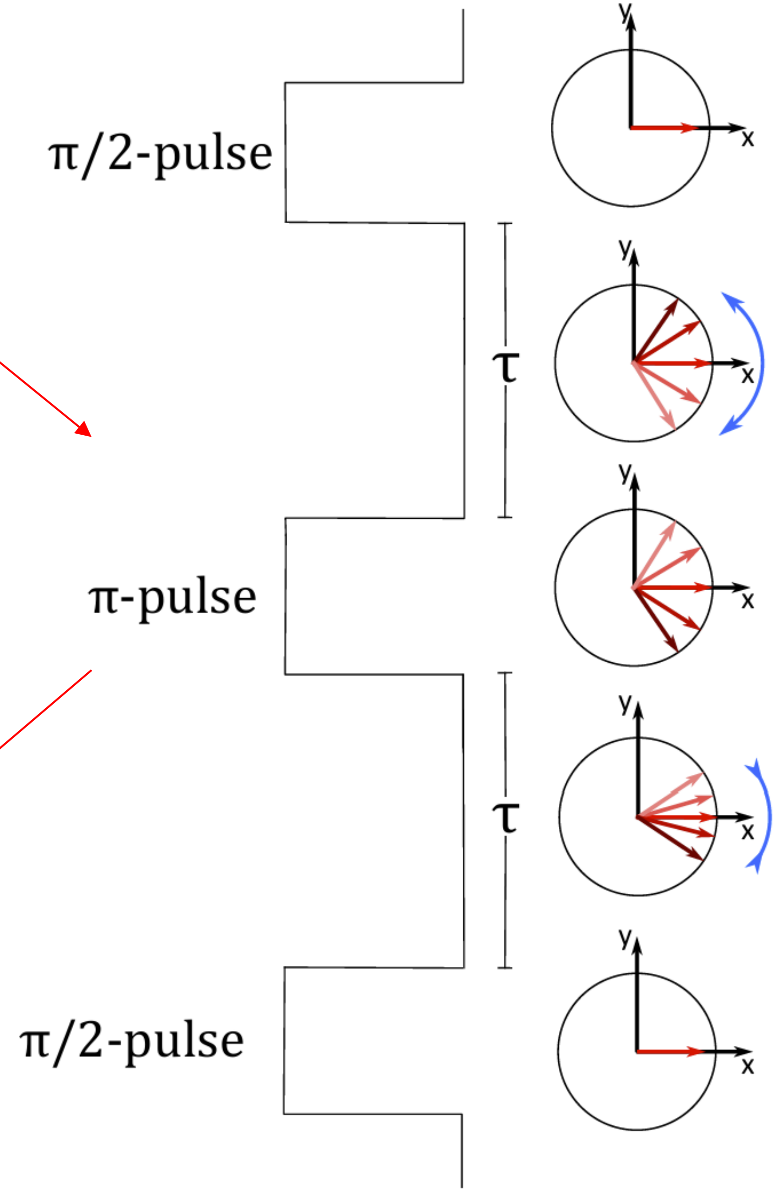
Spin ECHO





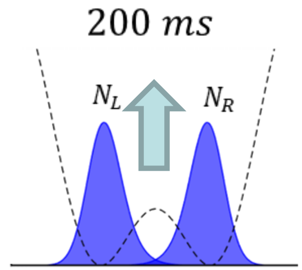
$\tau = 400\ ms$

$\sigma_{uncorr} \sim$ 0.3 rad

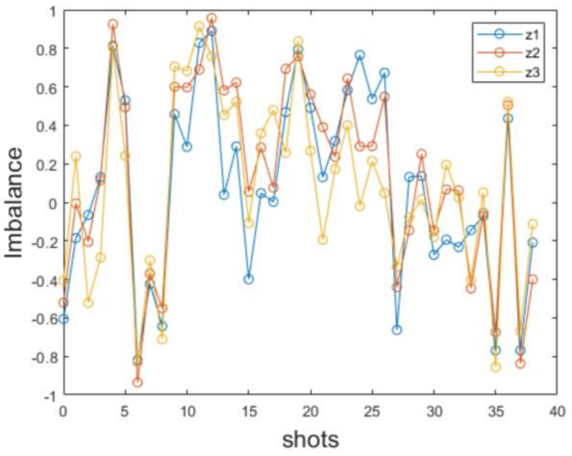


Towards number squeezing with repulsive interactions

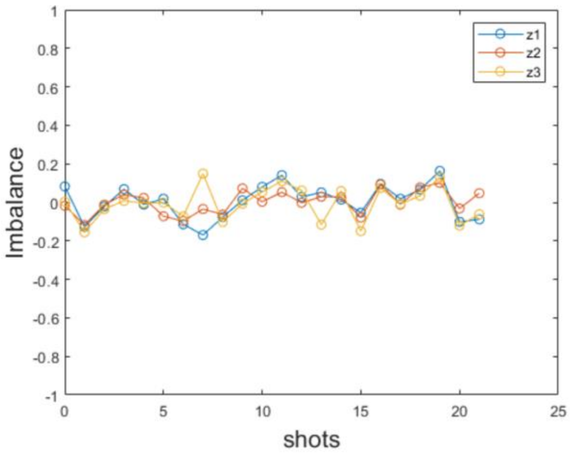
We introduce repulsive interactions during the raising of the barrier



$a = 0a_o$



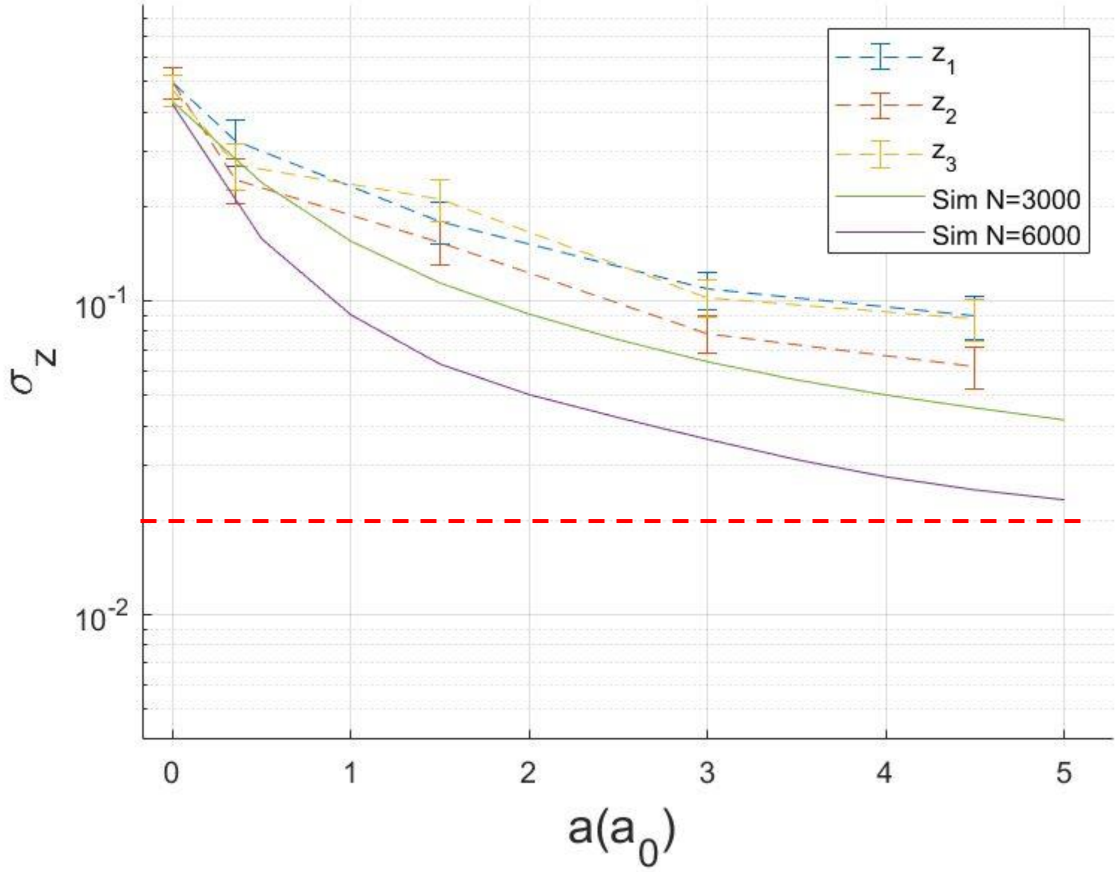
$a = 4{,}5a_o$



J. Esteve, et al. Nature **455** 1216 (2008)

C. Gross, et al. **464** 1165 (2010)
M. F. Riedel, et al. **464** 1170 (2010)

Towards number squeezing with repulsive interactions



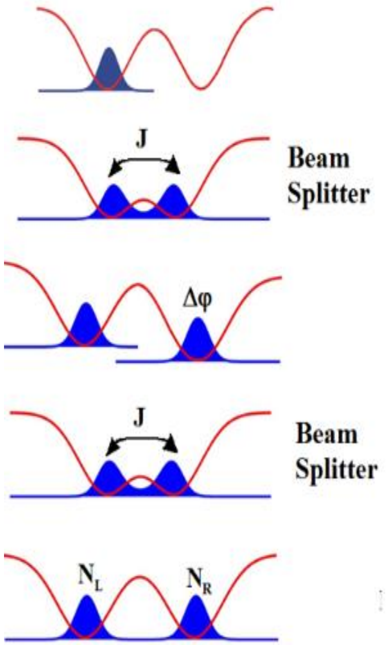
Atomic imbalance
measurments
Vs
Theoretical predictions

Shot noise limit

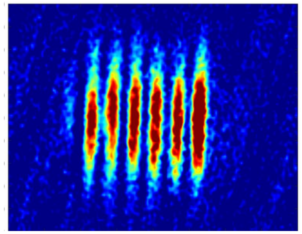
Summary

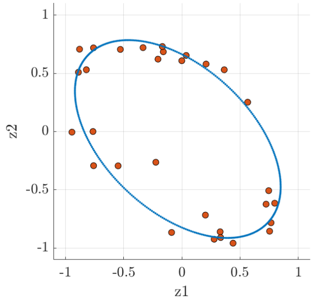
- We have proposed a new kind of lattice potential, i.e. Beat Note Superlattice

- We have demonstrated a trapped atom linear Mach-Zehender with BECs with tunable interactions



- Simultaneous operation of several interferometers
  -> trapped atom gradiometer





- Characterization of interaction induced decoherence

- Mandatory: identify sources of uncorrelated noise.

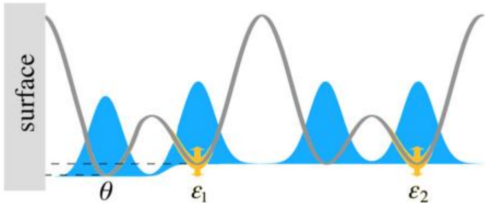
Outlook

- Next order interaction effects using decoherence: three body elastic scattering, light induced dipolar interactions.

- Gradiometry with quantum entengled states

…..in the long term

- Force measurements with high spatial resolution



- Compact, transportable device

The group

A. Santoni C. Mazzinghi

T. Petrucciani <u>M. Fattori</u>

Collaborataions

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M. Inguscio

D.Trypogeorgos

F.S. Cataliotti

Theoretical support

L. Pezzè

A. Smerzi

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