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# Two-Particle Four-Mode Interferometer for Atoms

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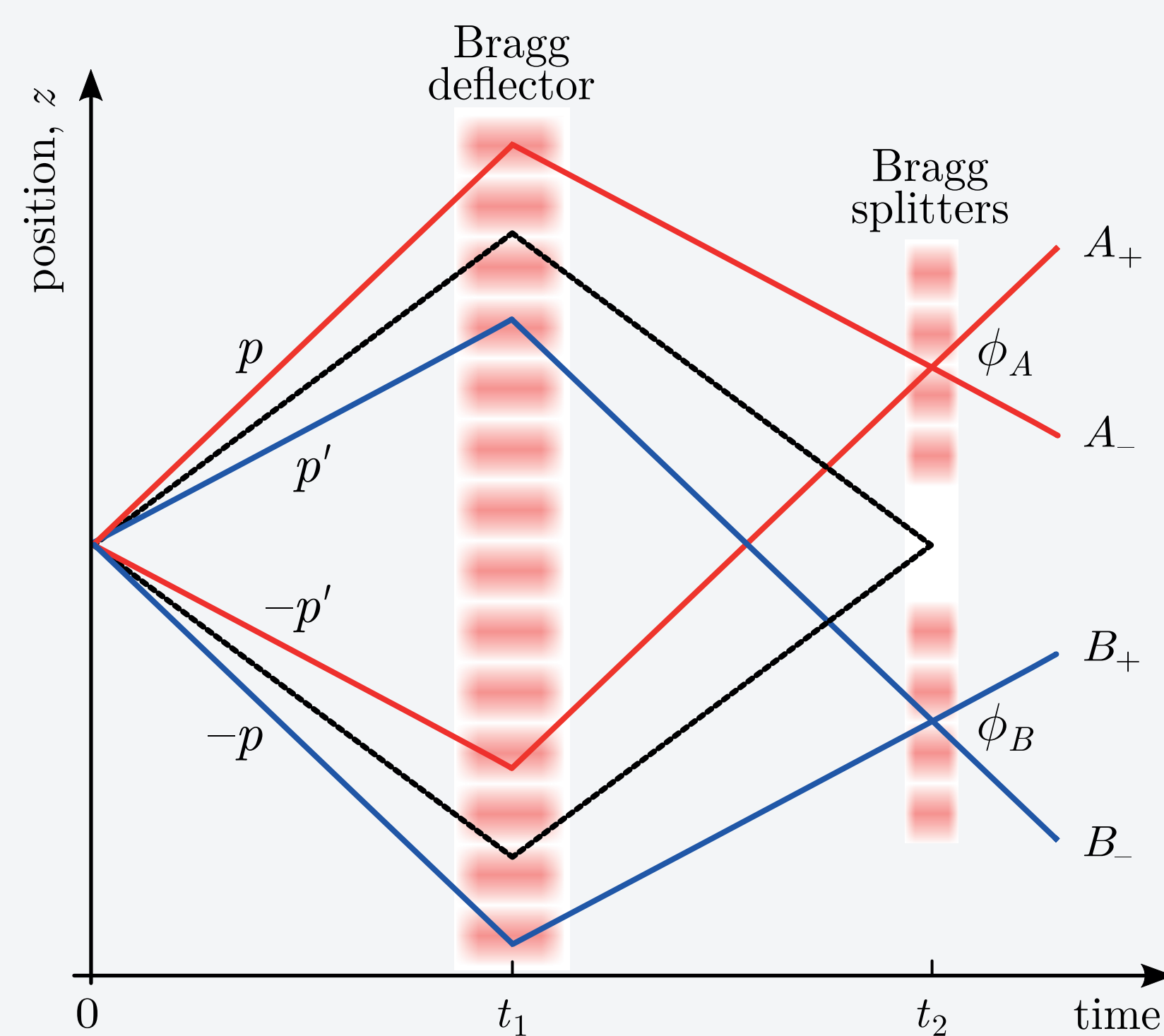
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- We present a **free-space interferometer** to observe **two-particle interference** of a pair of atoms with entangled momenta.
- The source of atom pairs is a Bose-Einstein condensate subject to a dynamical instability, and the interferometer is realized using Bragg diffraction on optical lattices.
- **Our observations rule out the possibility of a purely mixed state at the input of the interferometer.**
- **Our current setup can be extended to enable a test of a Bell inequality on momentum observables.**

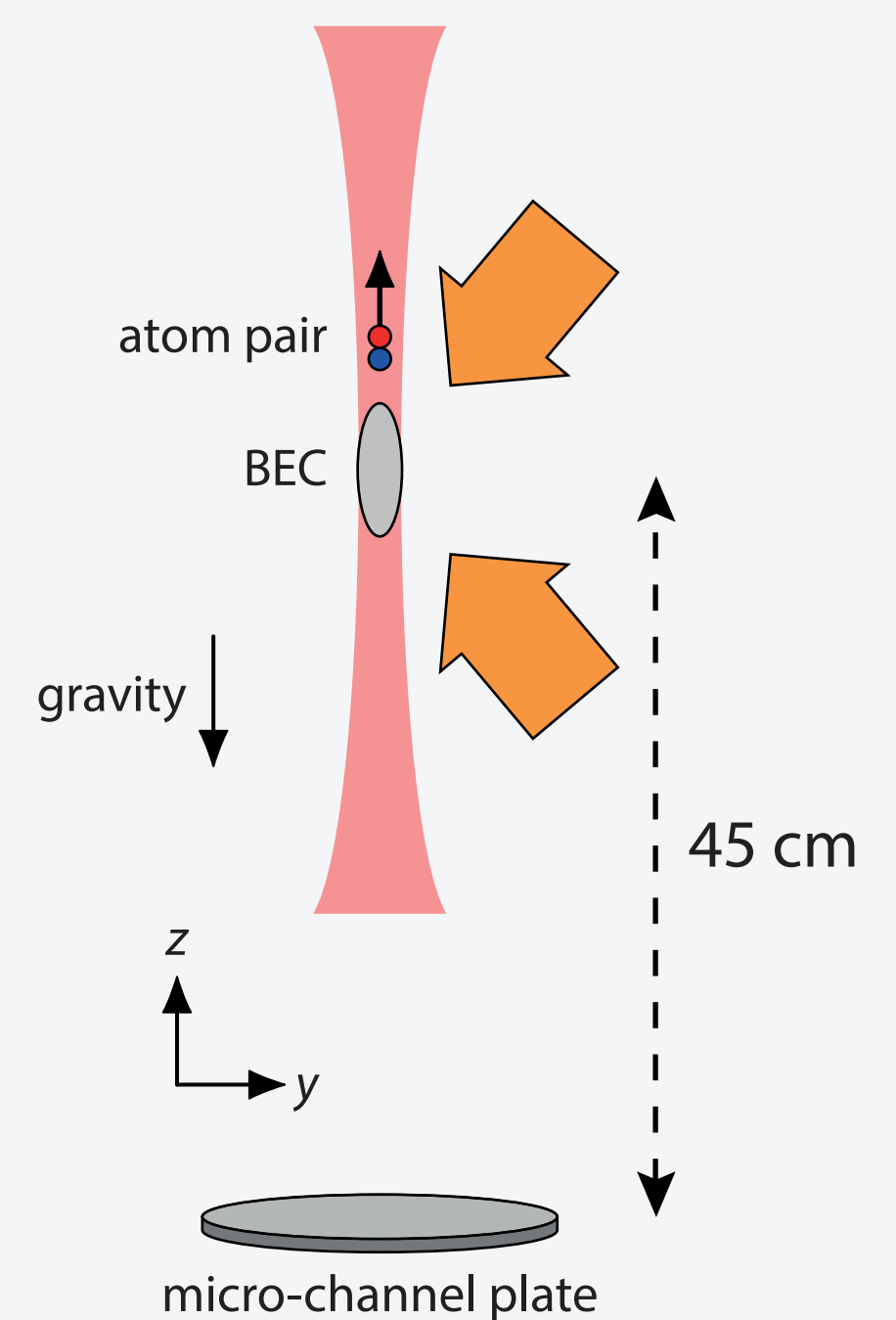
## Interferometer diagram

- Input state:  
 $|\Psi\rangle = \frac{1}{\sqrt{2}}(|p, -p\rangle + |p', -p'\rangle)$
- Joint detection probabilities:  
 $P(A_+, B_+) = P(A_-, B_-) = \frac{1}{2} \cos^2[(\phi_A - \phi_B)/2]$   
 $P(A_+, B_-) = P(A_-, B_+) = \frac{1}{2} \sin^2[(\phi_A - \phi_B)/2]$
- Correlation coefficient:  
 $E = P(A_+, B_+) + P(A_-, B_-)$   
 $\quad - P(A_+, B_-) - P(A_-, B_+)$   
 $\quad = V \cos(\phi_A - \phi_B)$
- **Violation of a Bell inequality if  $V > 1/\sqrt{2}$**



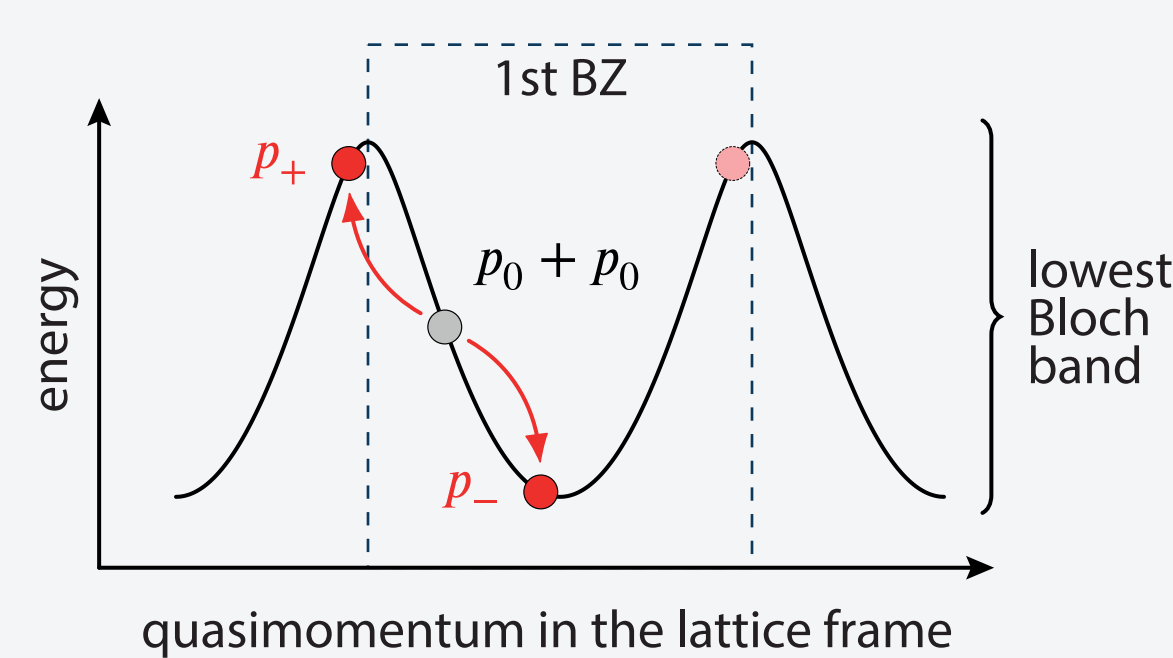
## Setup

- Metastable Helium-4 BEC
- Quasi-1D geometry (vertical)
- Pair emission driven by a moving optical lattice (vertical)
- Interferometer realized in free fall
- Bragg mirrors and splitters
- Detection after 300 ms time of flight  
→ single-atom detection (25% det. eff.)  
→ 3D resolution (x-y position + time)



## Source of atom pairs

- Dynamical instability driven by moving optical lattice  
→ emission of atom pairs with opposite momenta
- Broad resonance  
→ several pairs of modes are coherently populated  
 $|\Psi\rangle \propto \sum (|p_+, p_-\rangle + |p'_+, p'_-\rangle + |p''_+, p''_-\rangle \dots)$

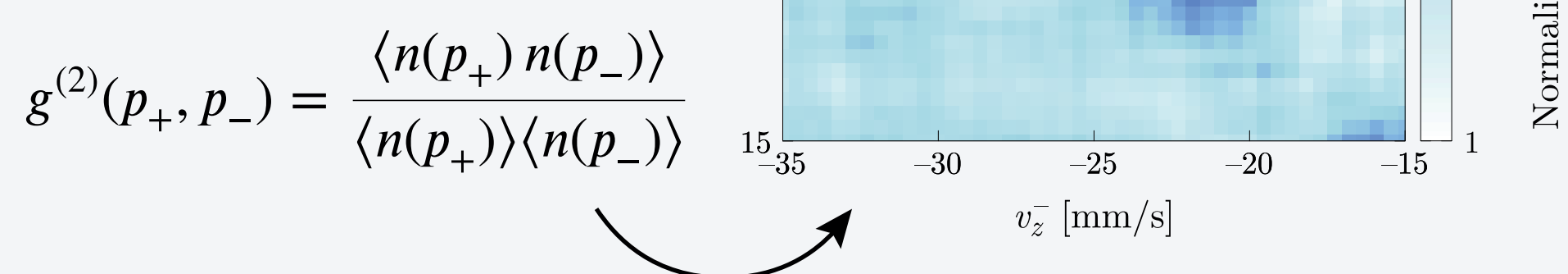


- Filtering the data reduces the state to the desired form:

$$|\Psi\rangle = \frac{1}{\sqrt{2}} (|p_+, p_-\rangle + |p'_+, p'_-\rangle)$$

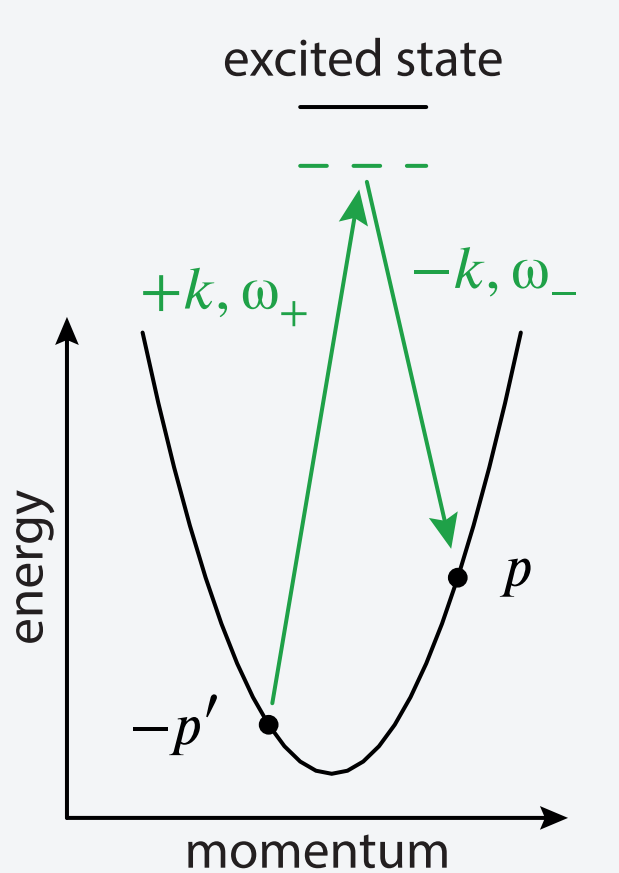
$$|\Psi\rangle = \frac{1}{\sqrt{2}} (|p, -p\rangle + |p', -p'\rangle)$$

center-of-mass frame



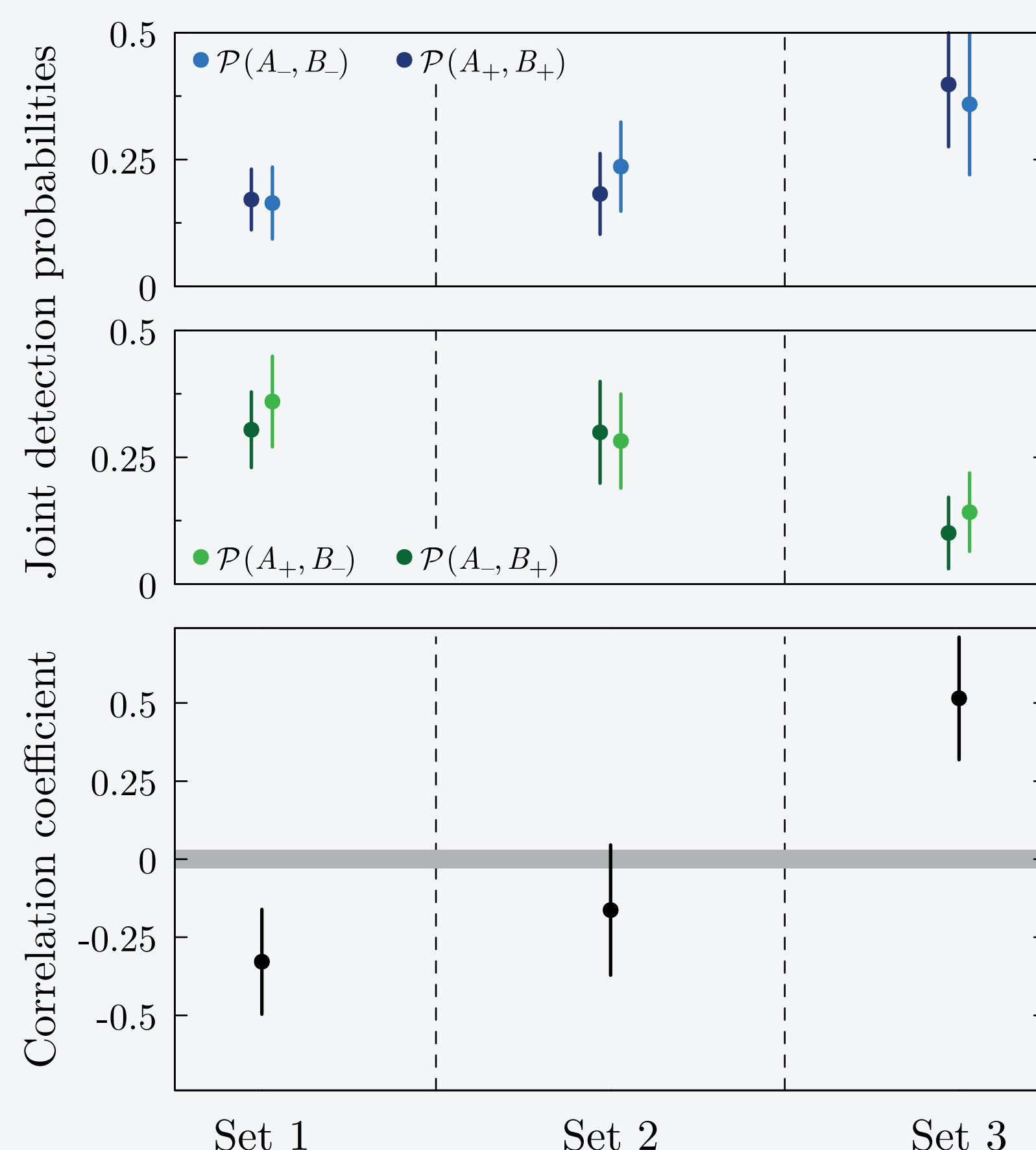
## Bragg mirror and splitters

- Mirror: 100 μs pulse (π-pulse)
- Splitter: 50 μs pulse (π/2-pulse)
- The lasers imprint their phase on the atomic modes ( $\phi_{A,B}$ )
- Spectral broadening induced by the short interaction time:  
→ the same lattice addresses ( $p, -p$ ) and ( $-p, p$ )  
→ addition of a **velocity-dependent phase** away from the energy resonance
- Correlation coefficient:  $E = V \cos(\phi_A - \phi_B - 2\delta\tau)$



## Correlation measurements

- Analysis of 3 different sets of modes  
→ access to 3 different phases ( $\phi_A - \phi_B - 2\delta\tau$ )
- Joint detection probabilities correlated 2-by-2
- **Correlation coefficient different from zero for one data set**  
→  $E = 0.51(20)$  for set 3
- **Rules out the possibility for a totally mixed state**
- **Proof of entanglement?**  
→ need separate Bragg splitters to control the phase  
→ work in progress



## References

Published in Dussarrat et al., PRL 119, 173202 (2017)

- Inspiration for the interferometer:  
→ Horne et al, Phys. Rev. Lett. 62, 2209 (1989)  
→ Rarity and Tapster, Phys. Rev. Lett. 64, 2495 (1990)
- More details on the atom source:  
→ M. Bonneau et al. Phys. Rev. A 87, 061603 (2013)



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