Coherent light scattering from long trapped ion strings

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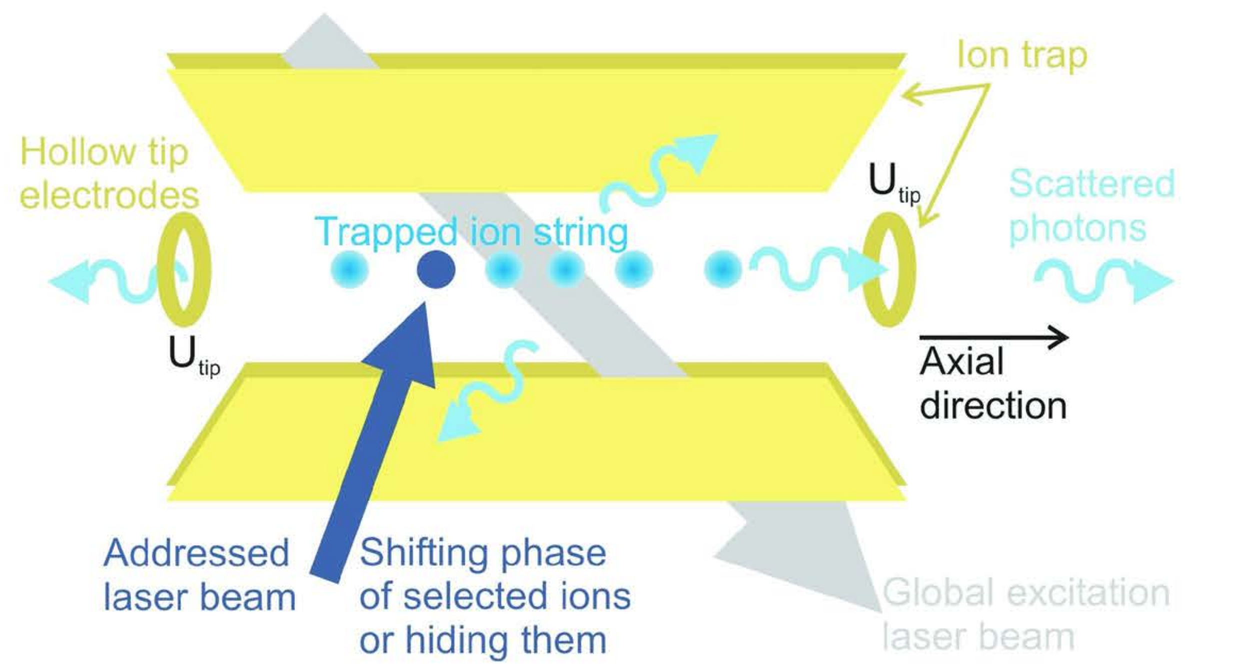
Abstract

We present the observation of controlled interference of light scattered from strings formed by up to 53 $^{40}Ca^{+}$ ions trapped in a single harmonic trap. The scattered light is collected along the crystal symmetry axis, which guarantees spatial indistinguishability of photons scattered by different ions and allows for convenient scaling of the number of contributing particles. The interference phase is tuned by changing the mutual distance between the ions and the observed pattern corresponds qualitatively to a simple theoretical model considering point-like emitters. The observed interference visibility remains in the 0,34 to 0,53 range for all the measured string sizes. The further scalability is limited mostly by the spatially inhomogeneous laser intensity seen by the long ion strings. The presented results open the possibility for experimental investigation of a whole range of fundamental physical phenomena, including engineered directional photon emission, direct detection of quadrature squeezing of atomic resonance fluorescence, and optical generation of genuine multi-partite entanglement between a large number of trapped ions.

Motivation

Programmable source of nonclassical light

- construction of a system of emitters with a long-term sub-wavelength spatial localization, sufficient detection efficiency of scattered light, the essential possibility of individual emitter control, and scalability with respect to the contributing number of emitters



- trapped single ions are currently purest emitters of nonclassical light [1]
- nonclassicality is preserved when scaling their number [2]
- first controllable emission from two-atom system recently demonstrated [3]

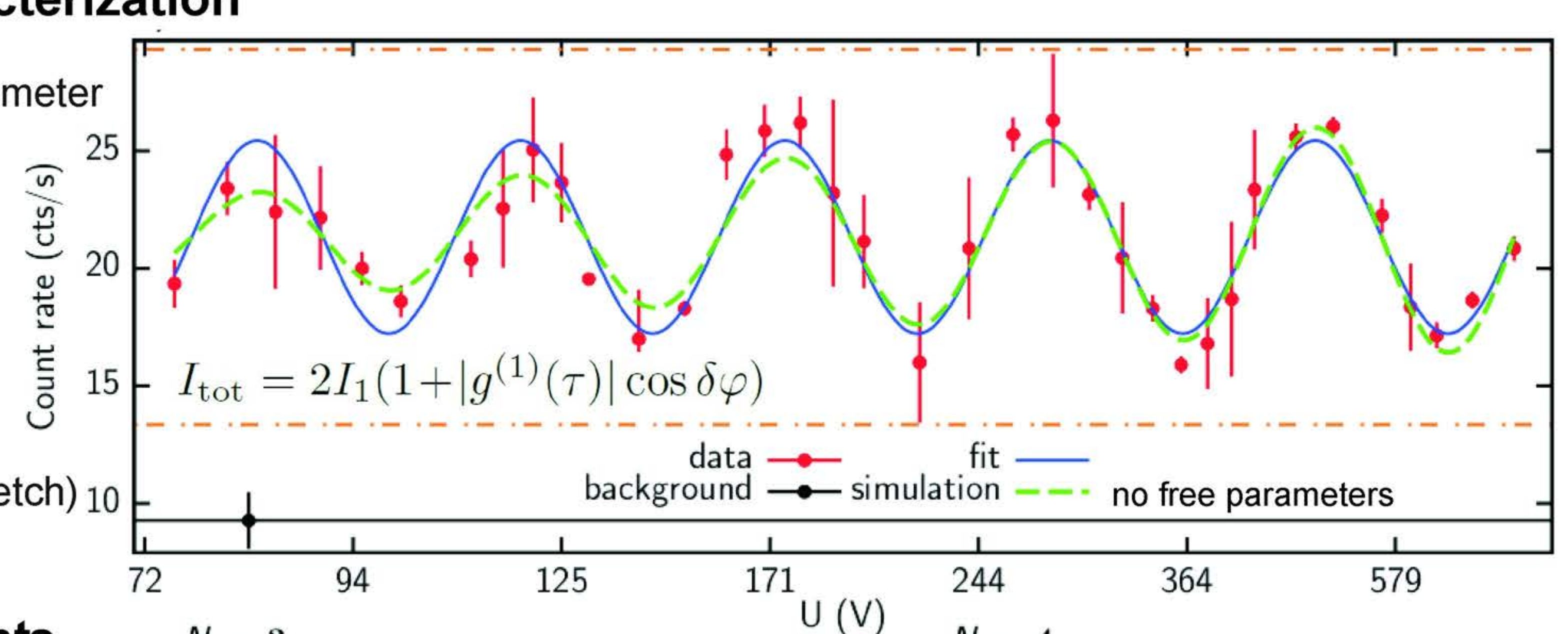
- quadrature squeezing of atomic resonance fluorescence [4]
- allow for optical generation of multi-partite entangled states
- feasible alternative for enhancement of absorption and collection of light

- several experiments concerned with observation of coherent light scattering from trapped ion crystals have been presented [5,6,7], however, missing the scalability to high ion numbers, the previous record is with 4 ions [7]

Measurements

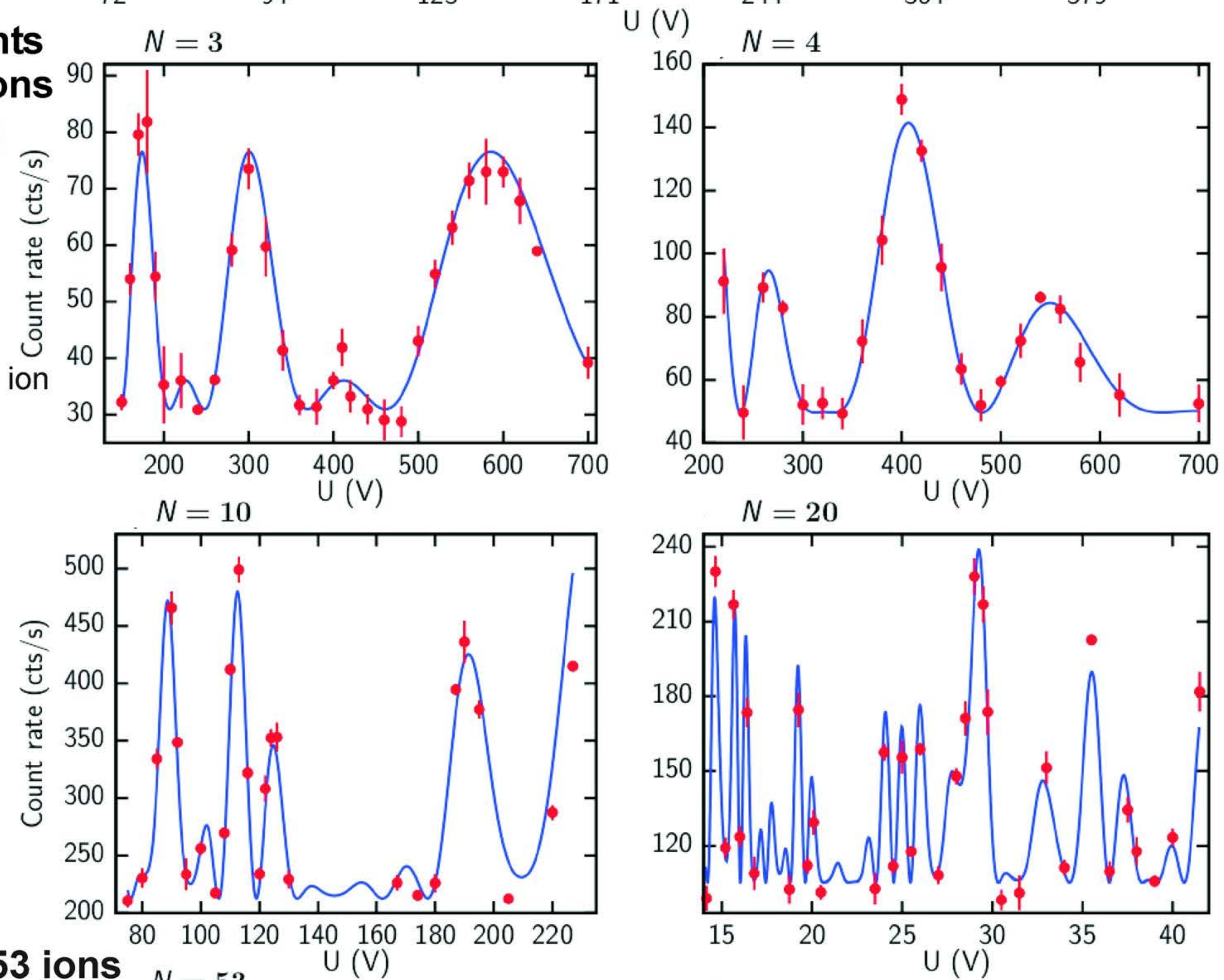
Initial characterization with 2 ions

- *saturation* parameter s_{397} = 0,51 ->Vis. reduction by factor 0,66
- jitter in the relative position of ions due to the *motion* (zig-zag and stretch)



Measurements with many ions

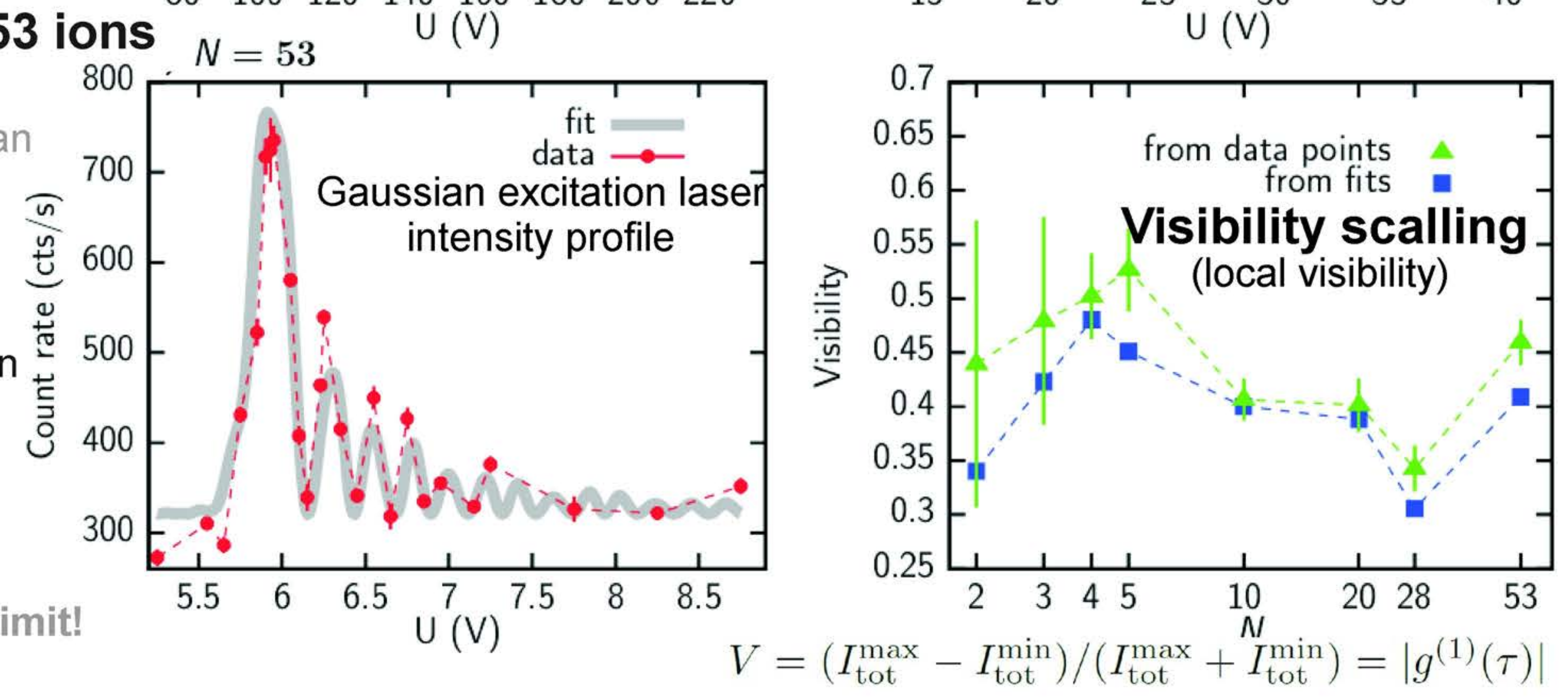
- simulation with equal coherent contributions from all ions
- phase factor calculated from the numerically estimated mean ion positions



String with 53 ions

-include Gaussian intensity profile of the 397 nm beam projected on the axial trapping direction (w_{eff} = 115 μm)

Bare technical limit!



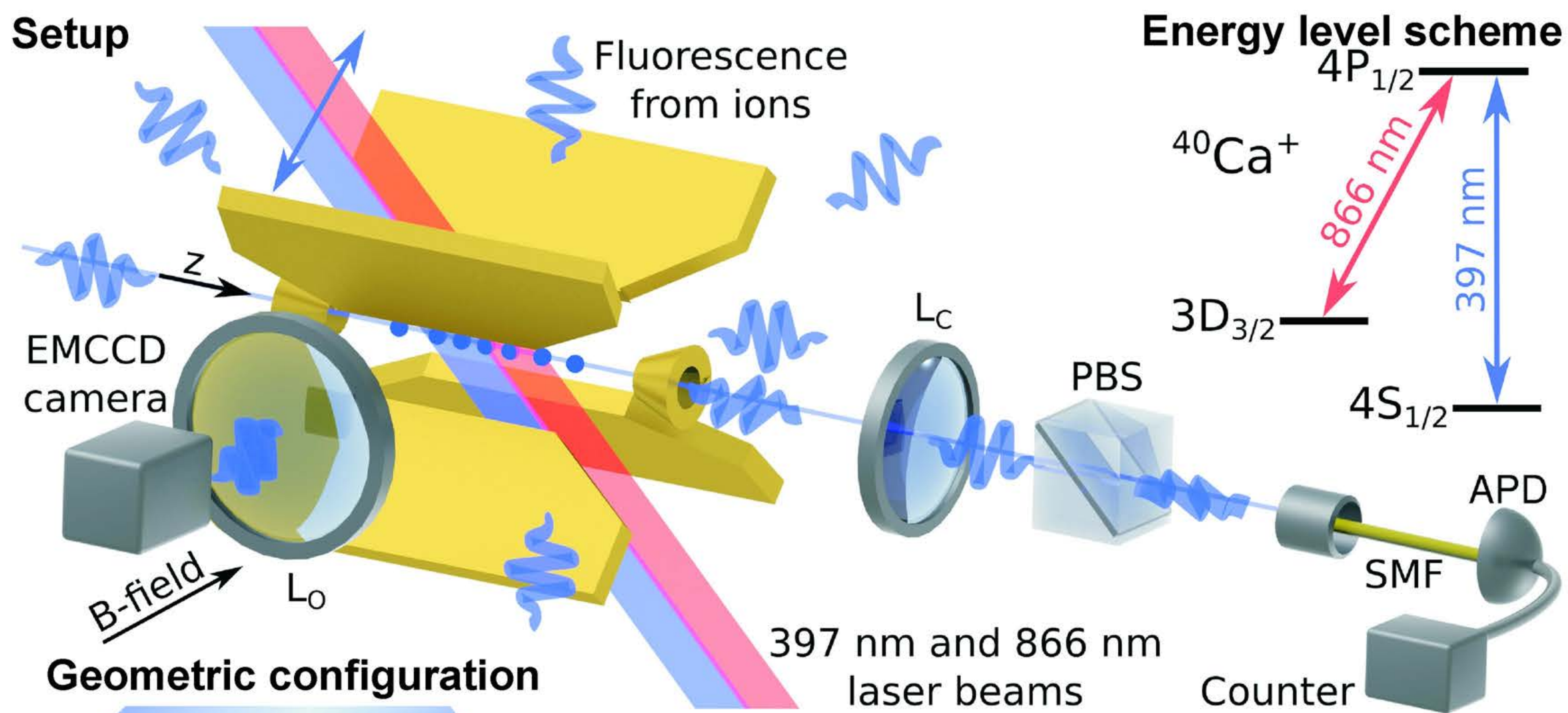
$$V = (I_{tot}^{max} - I_{tot}^{min})/(I_{tot}^{max} + I_{tot}^{min}) = |g^{(1)}(\tau)|$$

Demonstration of collective coherent interaction of light with large ensembles of individual quantum emitters

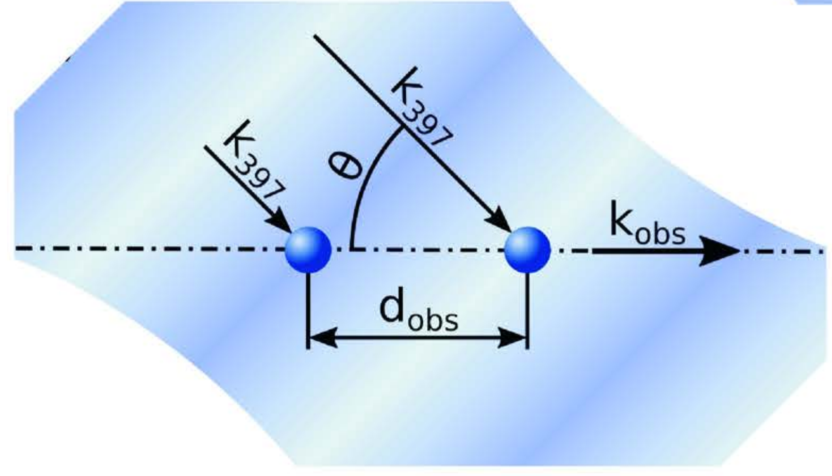
Experiment

Detection along the symmetry axis of the linear trapping potential

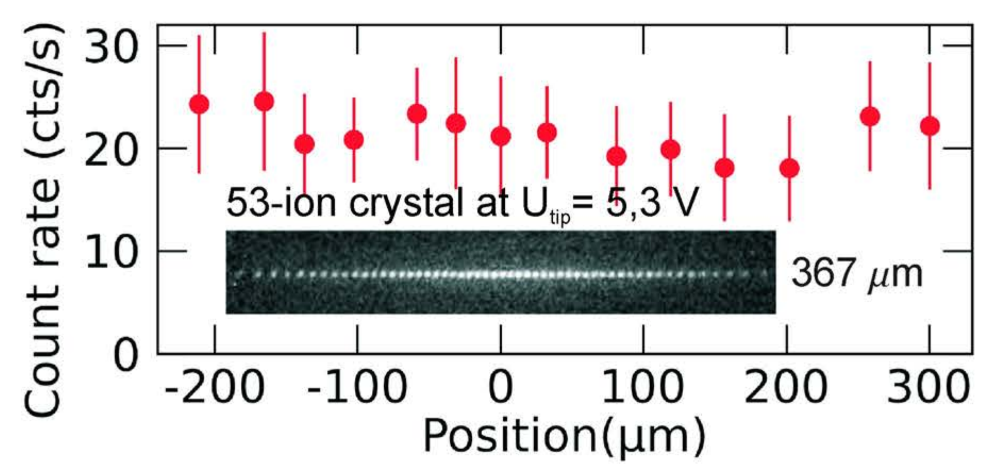
- same detection probability from all ions
- w_0 = 17 μm ~ Rayleigh length of z_R = 2,3 mm
- $f_x \sim f_y \sim$ 1,66 MHz, $f_z \sim$ 60 kHz to 1044 kHz for U_{tip} = 4 V to 900 V



Geometric configuration



Phase delay $\delta\varphi = d_{obs}(1-\cos\theta)\omega/c$



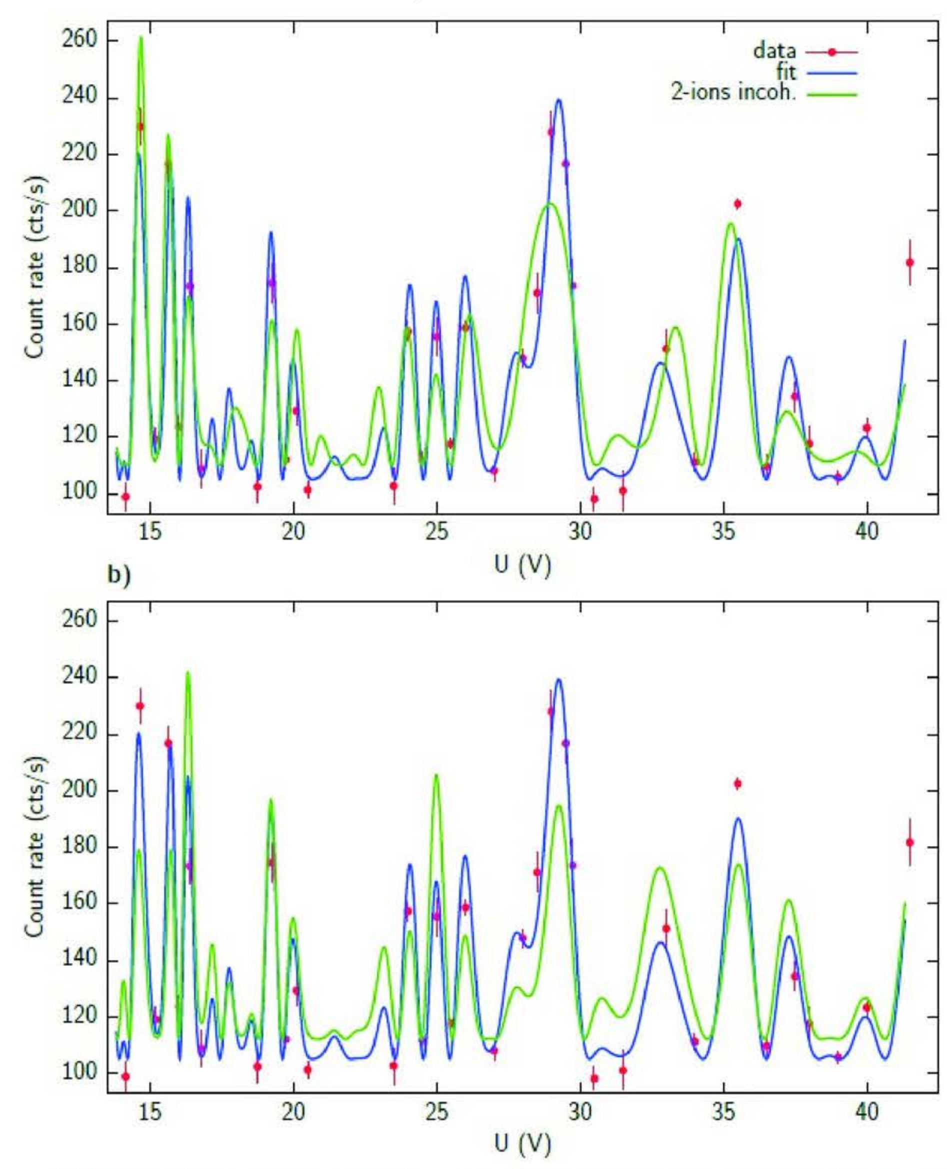
Flat detection efficiency

- detection efficiency $\eta_e = 3.7\times10^{-4}\,\%$ $\quad \eta_m = (3.6\pm0.4)\times10^{-4}\,\%$
- effective solid angle fraction of 1,3x10^{-5}

Analysis

Individual coherent contributions

Example with 20 ions



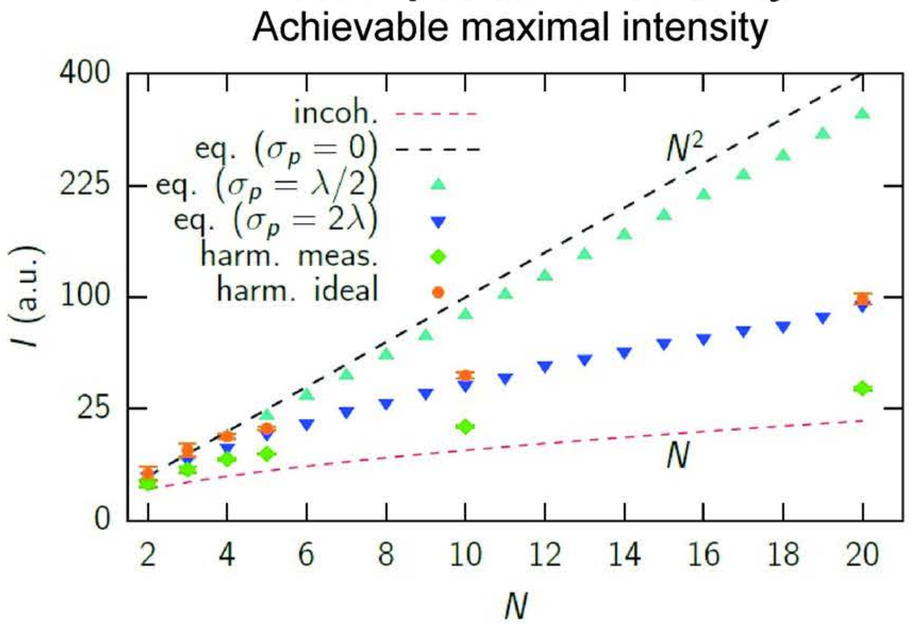
- switching two ions to incoherent changes the interference pattern dramatically
- the same is true for slight gaussian modulation of their coherent contribution

Phase - interference scaling

- **unequal spacing** due to the harmonic trapping potential and Coulomb repulsion
- phenomenologically different behaviour from the equidistant case

Effect of position uncertainty

Achievable maximal intensity



- measured intensity is always substantially higher than in the incoherent case
- idealized equidistant spatial distribution is extremely hard to achieve
- simulation of scattering from particles with random but fixed gaussian uncertainty σ_p

References and acknowledgements

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