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Scalable simultaneous multiqubit readout using an EMCCD camera with 99.99% single-shot fidelity

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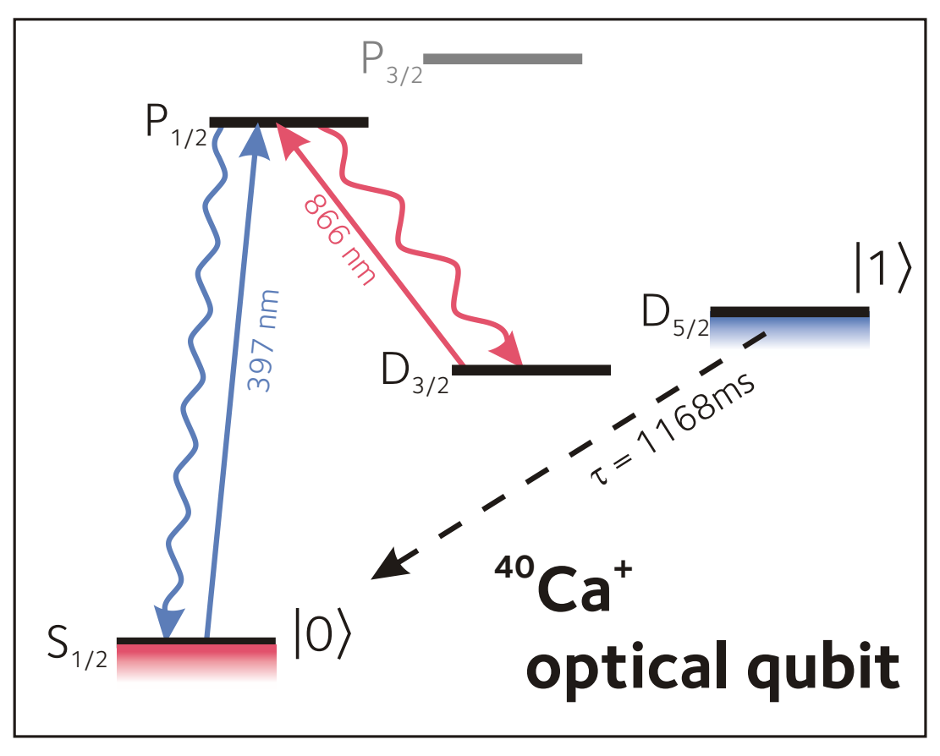
Single and multiple qubit detection

We have recently demonstrated high-fidelity readout of trapped readout of single [1] and multiple [2] optical qubits in trapped $^{40}Ca^+$ ions, reaching a fidelity of 99.99%. Readout is achieved by driving the ($S_{1/2}$ – $P_{1/2}$ – $D_{3/2}$) manifold and detecting the $P_{1/2}$ – $S_{1/2}$ fluorescence. Absence of fluorescence indicates that the qubit was in the metastable $D_{5/2}$ state (lifetime 1168(7) ms).

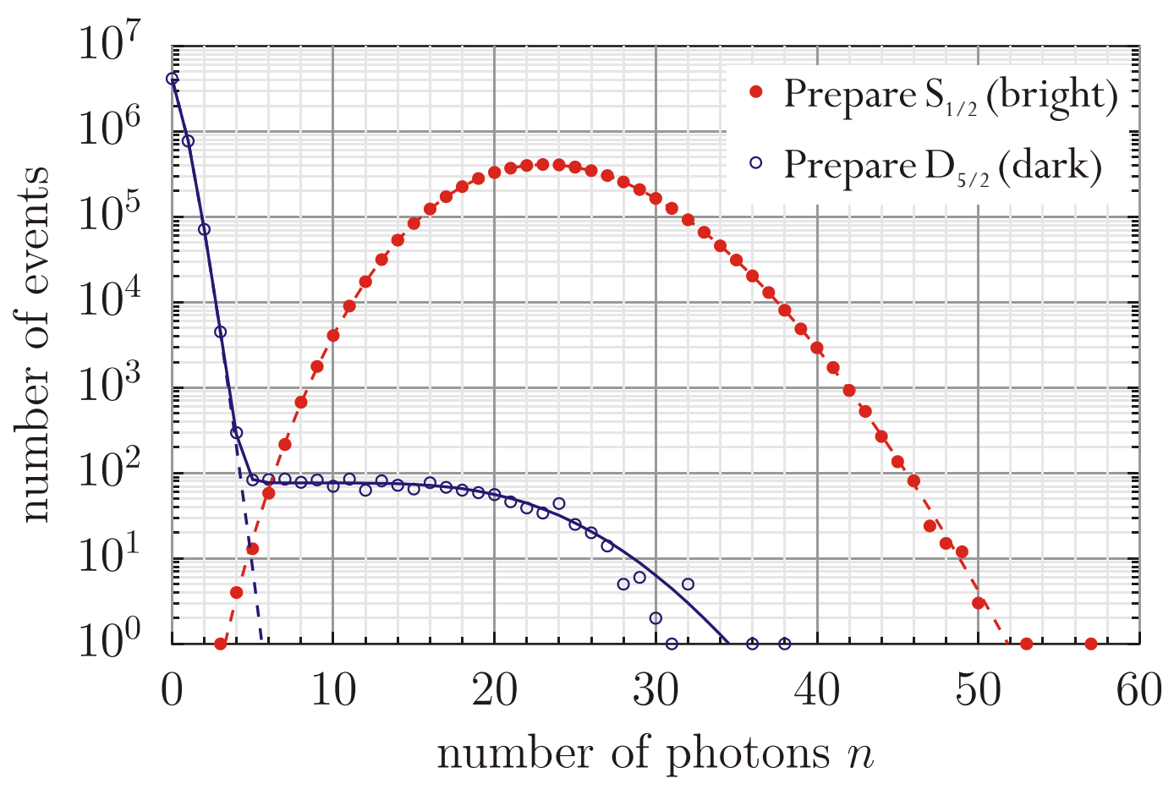
For single qubits, the main source of error in state identification of is due to decay from the $D_{5/2}$ qubit state during the detection period. For multiple qubit readout with a CCD camera there is an additional source of error in the cross-talk between images on the CCD.



$^{40}Ca^+$ optical qubit

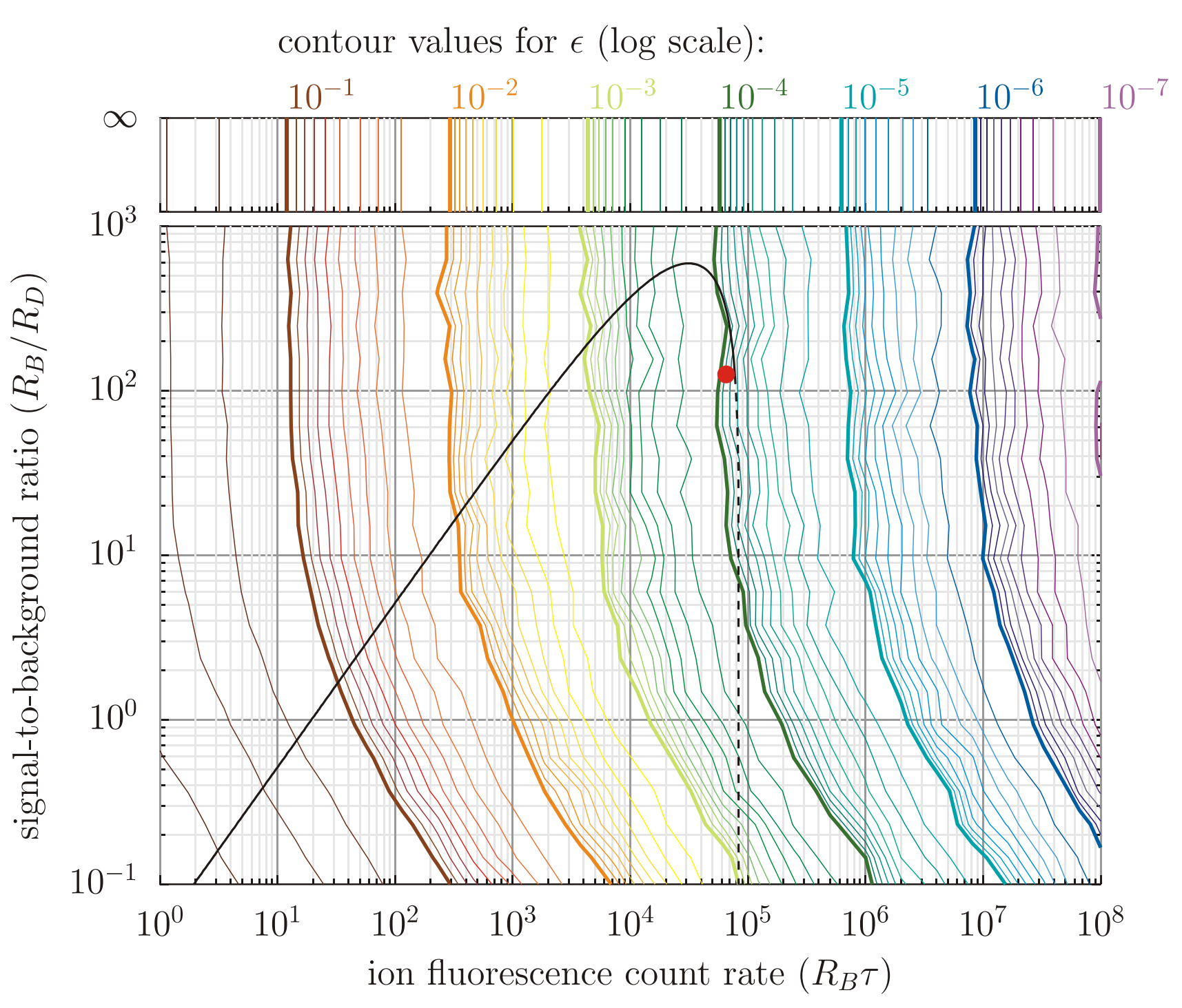
We present experiments and simulations to characterize the cross-talk error (separately from the "decay" contribution) and show that it can be greatly reduced by using a spatial maximum likelihood analysis method which takes into account the known shape of the ion's image and iteratively applies knowledge about its neighbours' states. We review the experiments published in [2] and present further simulations exploring the parameter space associated with the detection.

Single qubit readout: general problem

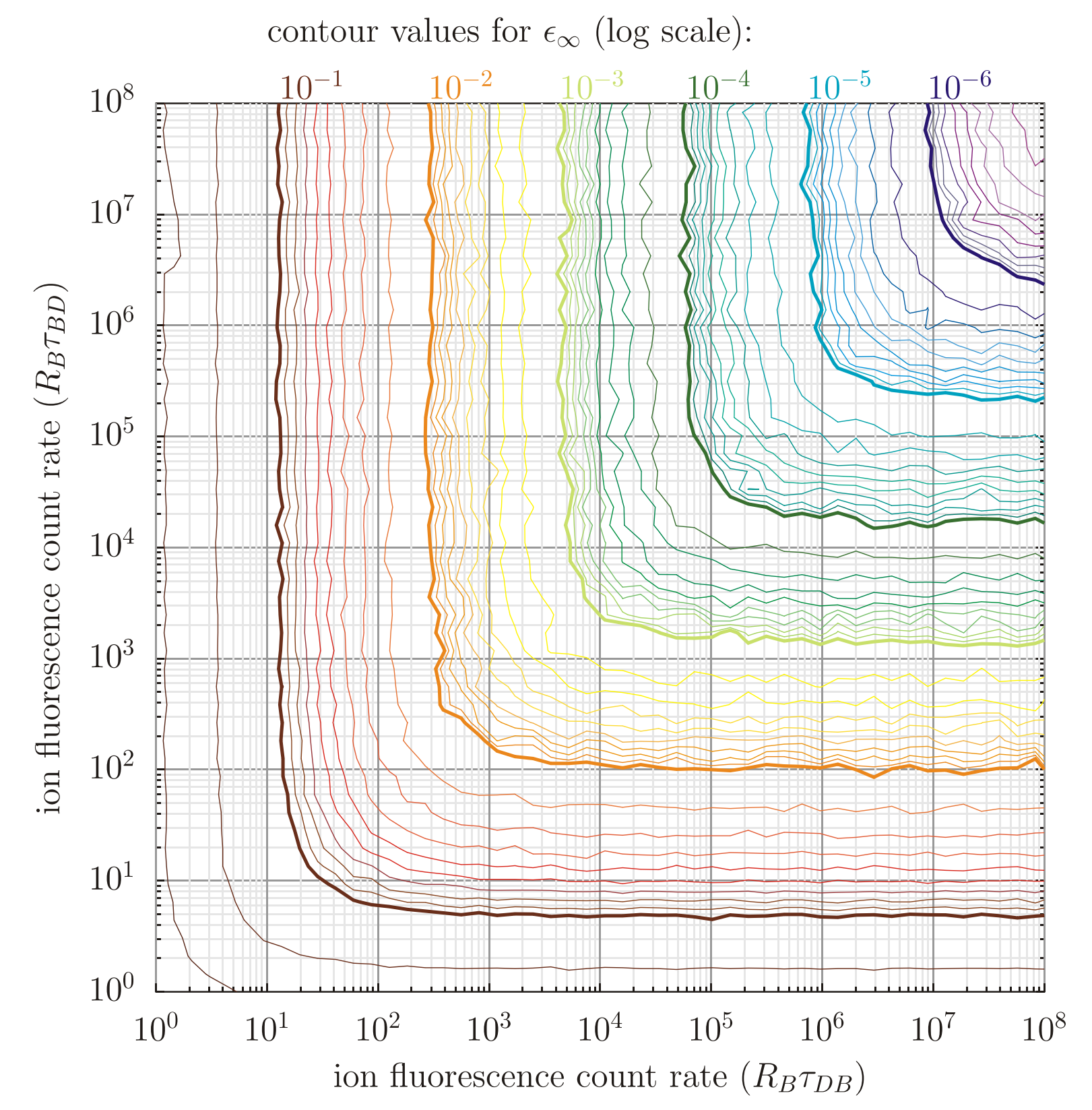


The basic detection problem is characterised by the parameters R_B and R_D, the fluorescence and background photon count rates respectively. During the detection period there may also be transitions between the qubit states: both dark→bright and bright→dark transitions may occur. In the $^{40}Ca^+$ optical qubit the B→D rate is negligible but the lifetime of the "dark" qubit state is $\tau = 1168$ms, and this sets the timescale for the detection problem. Here we show a histogram of photon counts recorded in a 420μs counting period after bright and dark state preparations; for $^{40}Ca^+$ we see typical values of $R_B = 55\,800\ s^{-1}$ and $R_D = 442\ s^{-1}$. Poisson distributions of the same mean are shown (dashed). The 'dark' histogram shows a highly non-Poissonian tail due to the finite probability that the ion will decay from the metastable $D_{5/2}$ state and appear bright.

We define the readout fidelity $F = 1-\varepsilon$, where ε is the probability of making an incorrect state identification. Neglecting spatial information, the parameters R_B, R_D and τ set the limit on the highest F that is possible to achieve with fluorescence-based state detection in the presence of a D→B decay. The two plots below relate to a *time-resolved analysis* [1] of the photon data.



Contours show the minimum error rate ε possible by applying maximum likelihood techniques [1] to the time-resolved photon counting statistics (from Monte-Carlo simulations). The solid curve shows the accessible region for our experiment when varying the intensity of the 397nm laser. We achieve the lowest ε (red dot) by maximuising the fluorescence $R_B\tau$ rather than optimising the signal to background.



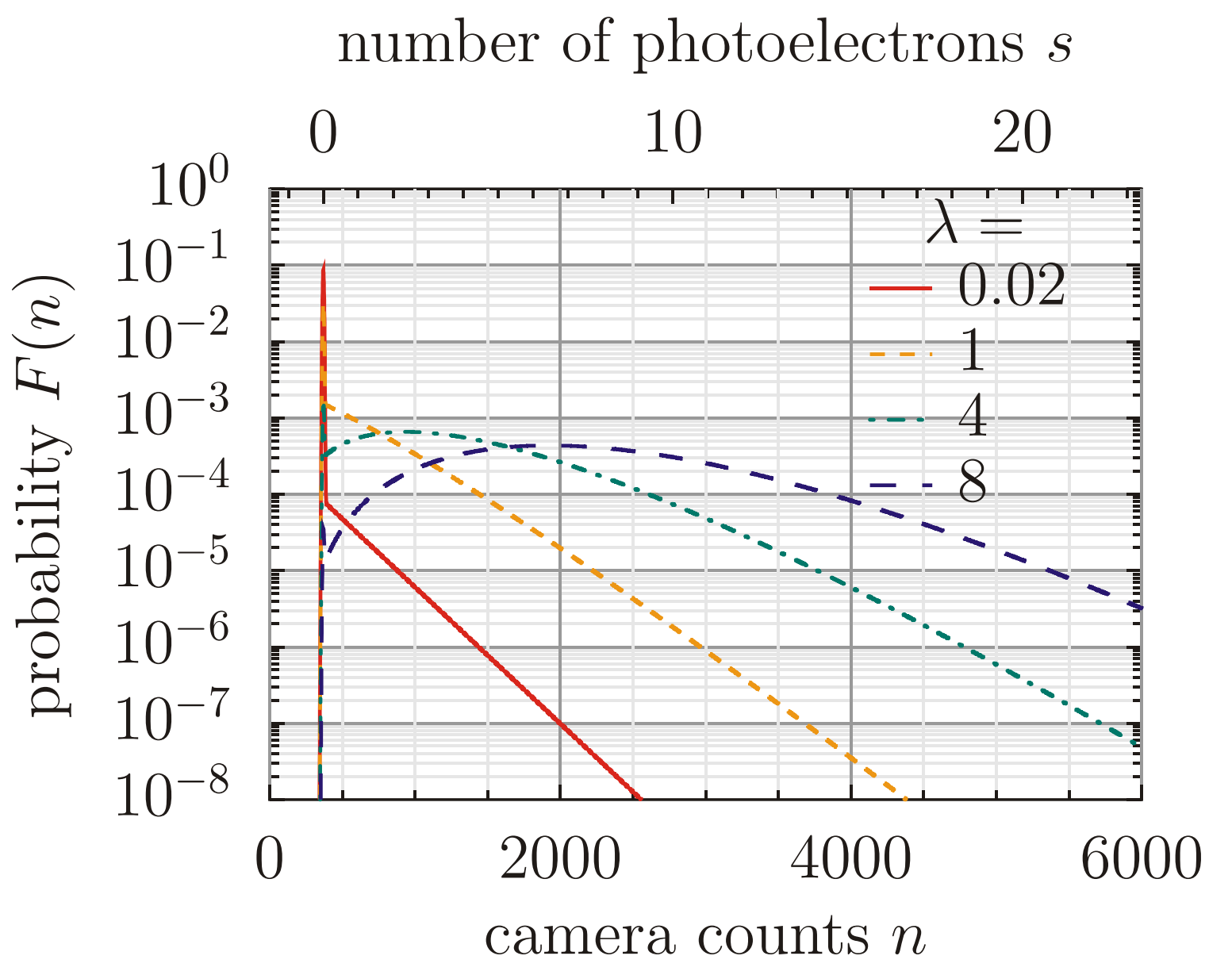
The minimum error rate ε when both D→B and B→D transitions are present, at rates $1/\tau_{DB}$ and $1/\tau_{BD}$ respectively, with $R_B/R_D = 100$. A given B→D rate causes fewer errors than the same D→B rate.

For reasonable signal-to-background ratios (>10), the highest readout fidelity is achieved by maximising the fluorescence, rather than optimising the signal-to-background ratio.

EMCCD camera detection

To distinguish multiple ions we need spatial resolution which can be provided by an EMCCD camera. This consists of a standard frame-transfer CCD architecture, but the information in the pixels is read out after being passed through a gain register which amplifies the signal above the camera readout noise. The action of the register is stochastic and the result is a widened non-Poissonian distribution of counts from the camera. A model of the output has been developed by Basden et al. (see [3]), examples of the output from a single pixel with photons incident from a Poisson distribution of mean λ are shown.

The clock-induced-charge noise present in EMCCD cameras means that it is disadvantageous to collect the data in a time-resolved manner. Therefore we consider only single exposures and infer the ions' states by applying one of the protocols below.

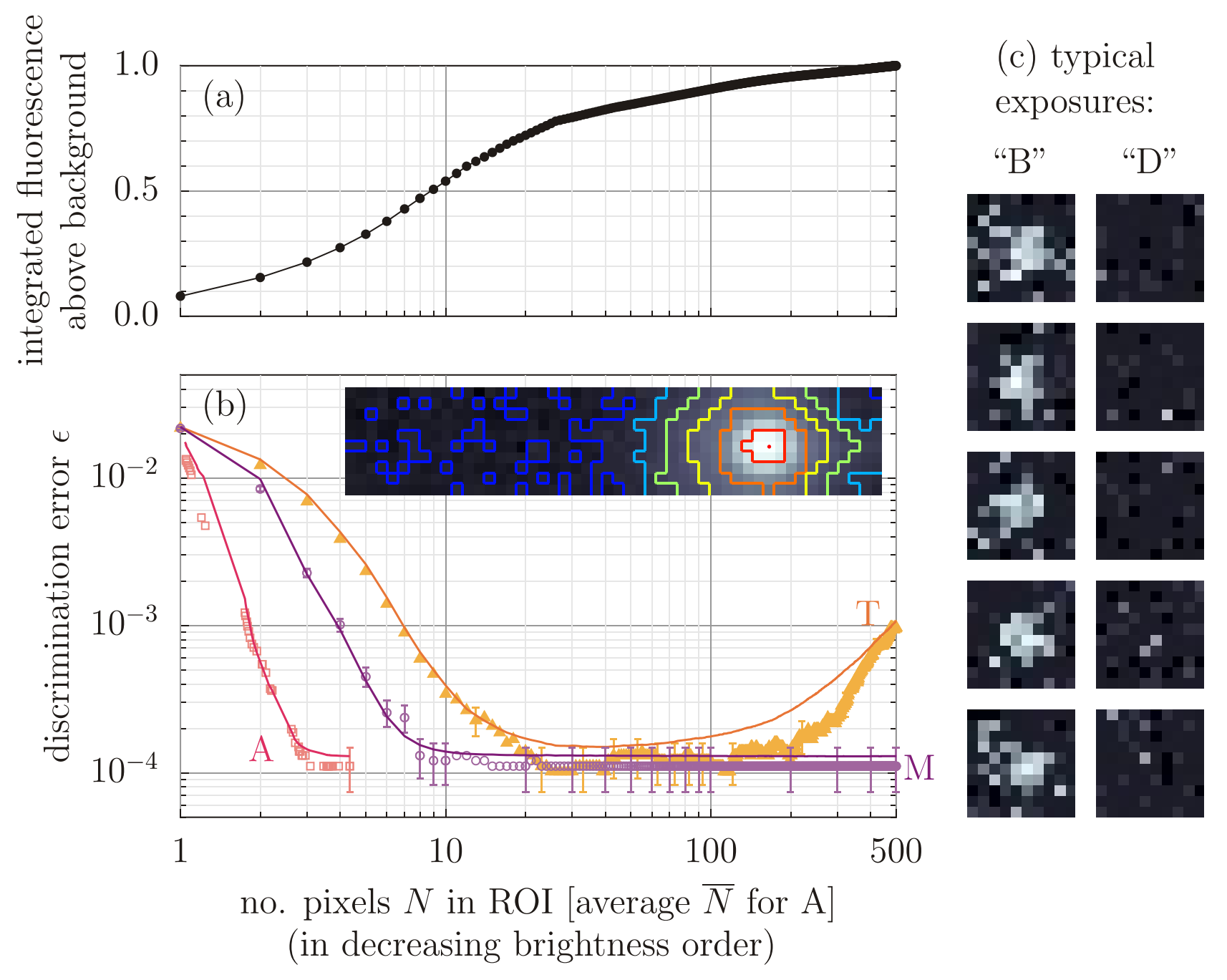


Threshold	**(T)**	Compare *total summed counts* for all pixels in the region of interest (ROI) to the threshold value. Above threshold is 'bright' and below threshold is 'dark.'
Spatial maximum likelihood	**(M)**	Using counts from *individual pixels*, calculate the likelihood p_B that the given set of pixel counts $\{n_i\}$ could have been generated by a 'bright' ion and compare this with the likelihood p_D that the set of pixel counts $\{n_i\}$ arose from an ion which was 'dark'. We infer the ion was in whichever state was more likely.
Adaptive maximum likelihood	**(A)**	Calculate p_B and p_D after each pixel is added to the analysis and calculate the *estimated* error probability using Bayes' theorem. Terminate the protocol when the error falls below some chosen cutoff, or at a certain maximum ROI size, whichever occurs first.
Iterative protocols	**(MN)** **(TN)**	The optimal threshold or probability distributions to use for the above methods depend on the states of the neighbouring ions. Therefore, once an initial guess at the state of the ion string has been made, repeat the analysis for each ion using the optimal thresholds or probability distributions.

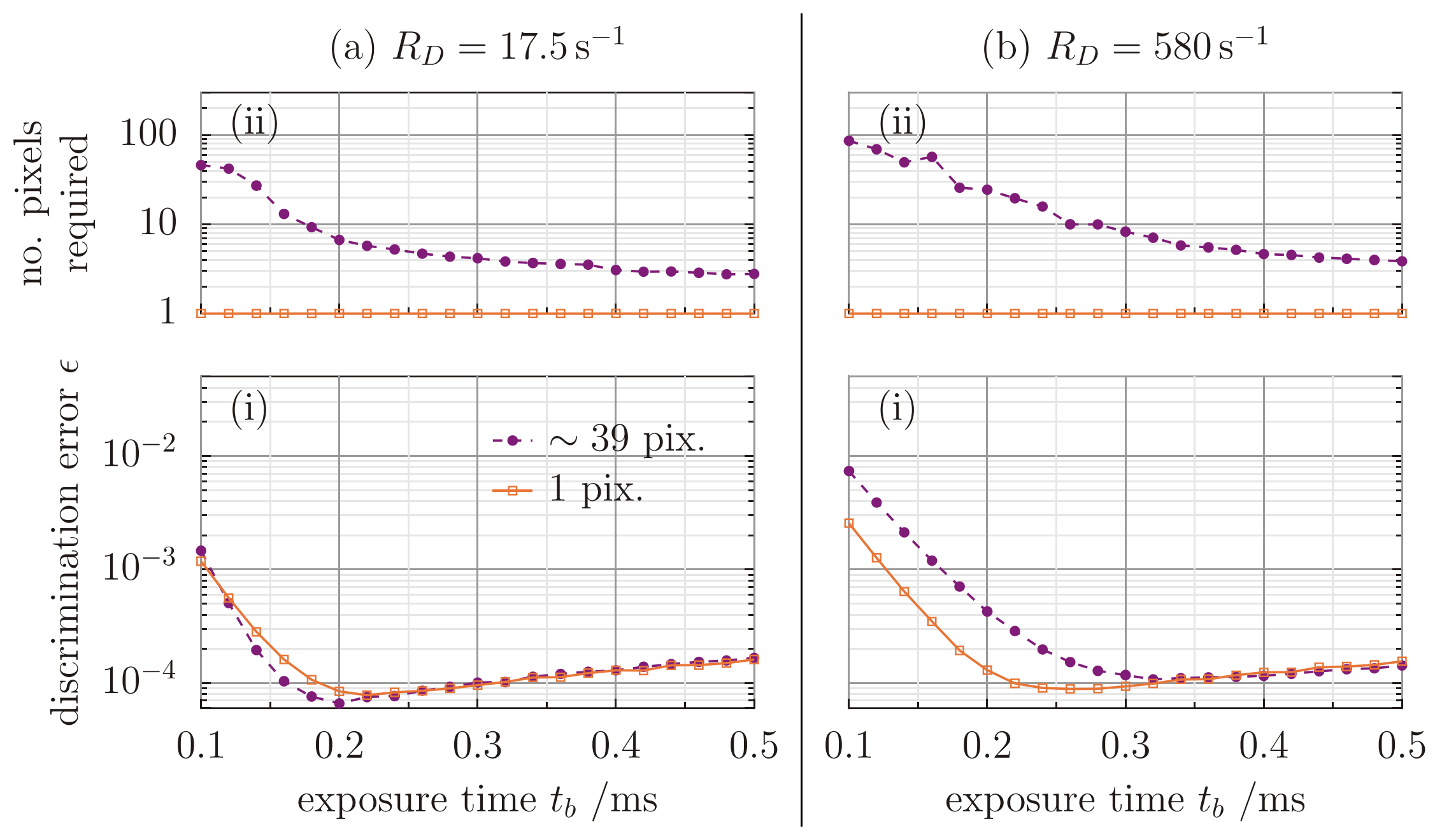
Single qubit EMCCD readout

We apply the spatial threshold and maximum liklihood analysis methods to 400μs exposures of a single ion prepared in a known state. We select an ROI of N pixels for analysis by including pixels in brightness order determined from the long-exposure image (inset). The upper plot shows the distrubition of fluorescence. Method M uses the known spatial distribution of fluorescence from the ion and is therefore more efficient, although it does not lead to lower error as this is still limited by the $D_{5/2}$ decay.

We achieve **99.991(3)%** readout fidelity for a single ion with the EMCCD.



We now consider whether having extra spatial information by spreading the image over several pixels enables us to attain a lower ε, or whether the extra noise present in an EMCCD (and added *per pixel*) outweighs the spatial information. The simulations of single-ion detection presented below compare an Airy function image (with ~39 pixels inside the Airy radius) with the same fluorescence rate on a single pixel. The simulated data (which includes the effects of $D_{5/2}$ decay) is analysed with method A.



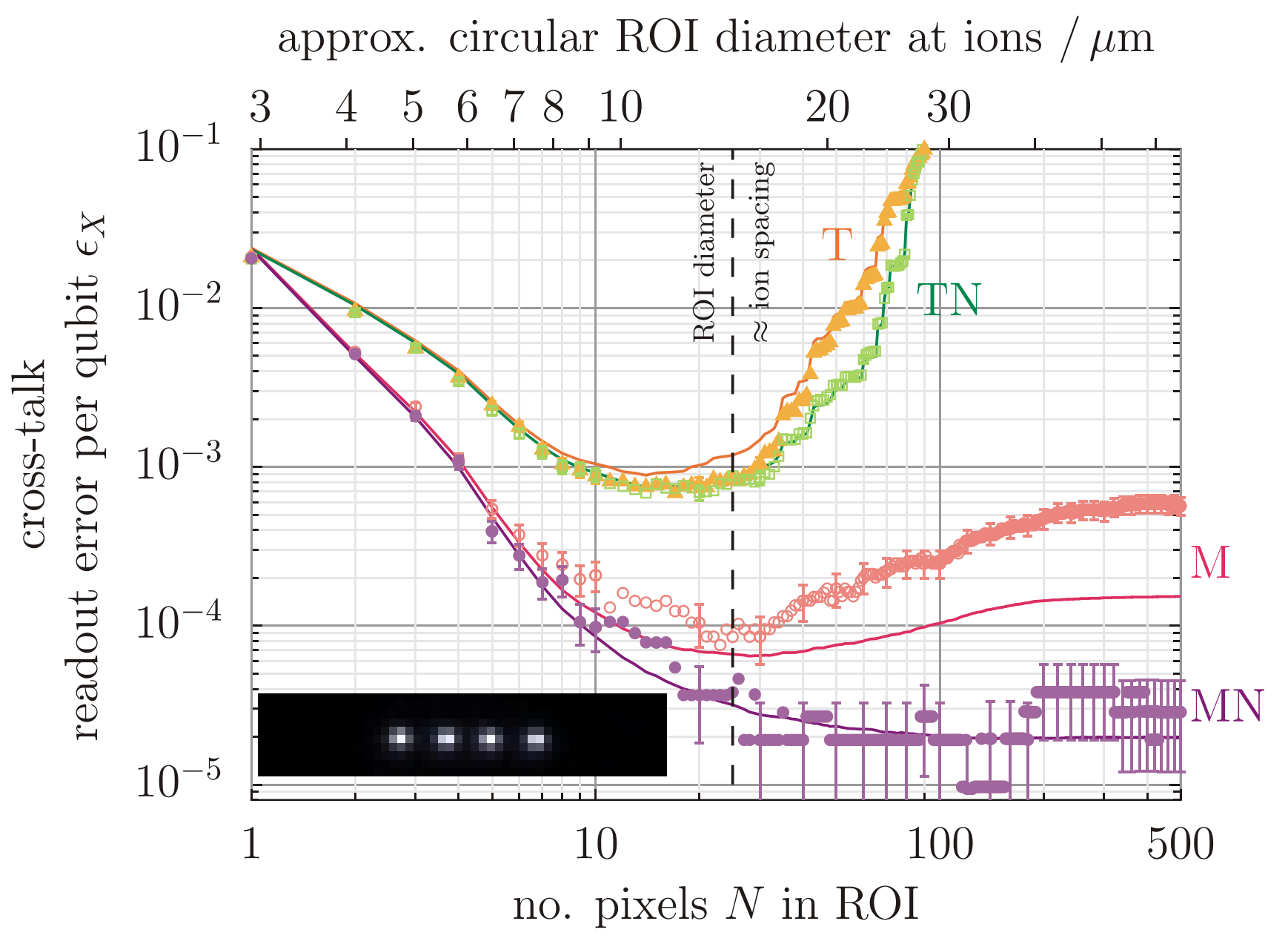
With $R_D = 17.5\ s^{-1}$ an extended image provides an adantage for exposure lengths below $t_b = 250$μs. With $R_D = 580\ s^{-1}$, the extra background light outweighs the spatial information and a single-pixel image leads to the lowest ε.

Note that with a larger background rate R_D we must collect more information to distinguish between "bright" and "dark" states. The minimum possible ε increases and we require a longer t_b to reach it. Additionally, a larger average ROI size is needed (see upper plots).

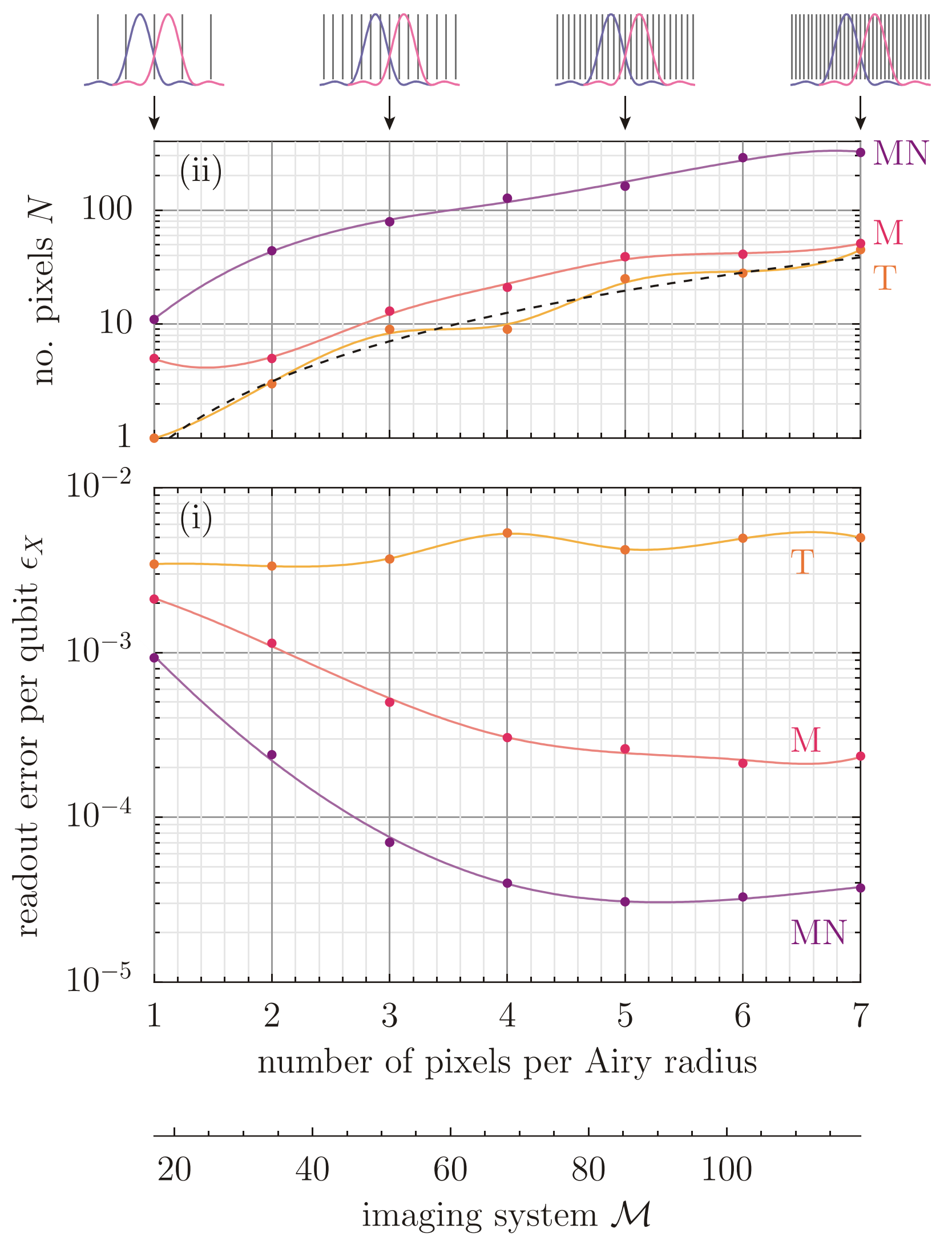
Multiple qubit readout with the EMCCD

We investigate the cross-talk aspect of multiple ion detection by sandwiching the 400μs test exposure between a "pre" and "post" detection. Analysis of the "pre" and "post" frames allows us to determine which state (of the 4-ion string) we have prepared and we can choose to discard all trials where a decay has occured. Analysis of the experimental data with an iterative method (MN) leads to an additional measured "cross-talk error" of only $\varepsilon_x = 0.2(1)\times10^{-4}$ on average, and is even zero for certain N.

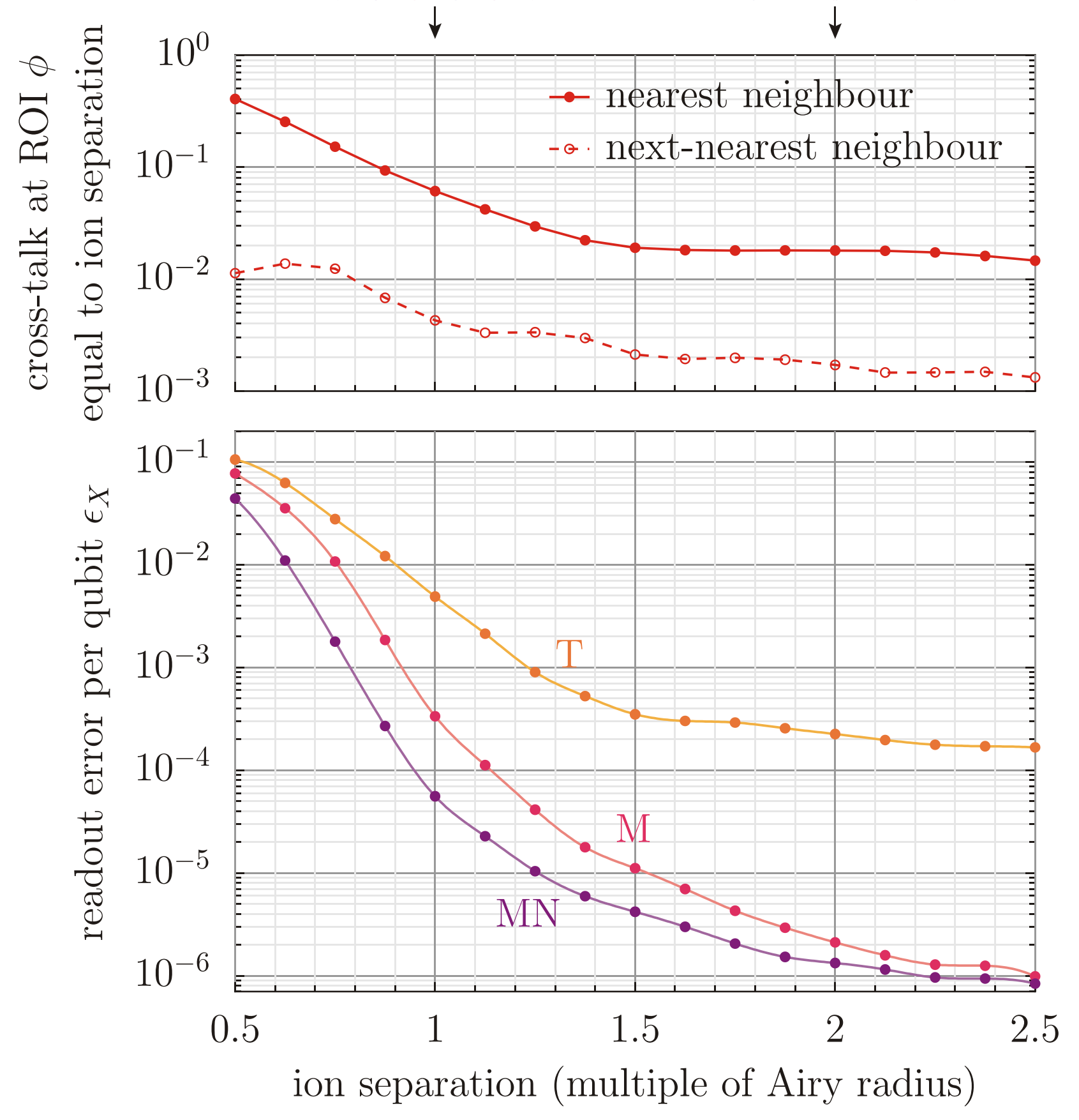
We measure an additional cross-talk error of only **$0.2(1)\times10^{-4}$** for a four-ion string with the EMCCD.



Simulations of the "cross-talk only" experiment with a diffraction-limited imaging system and ions separated by one Airy radius are shown below. We change the system magnification M to alter the spatial resolution of the data. The lowest ε_x occurs when the ions' Airy discs are spread over ~79 pixels (5 pixels per Airy radius).



Simulations to show the performance of analysis methods with changing cross-talk (or changing ion separation). Cross-talk is measured as the amount of neighbour fluorescence as a fraction of that from the ion of interest, falling within an ROI with diameter equal to the ions' separation.



A cross-talk error below **1×10^{-4}** is possible for a diffraction-limited system with the ions separated by just one Airy radius.

[1] High-Fidelity Readout of Trapped-Ion Qubits
A. H. Myerson, D. J. Szwer, S. C. Webster, D. T. C. Allcock, M. J. Curtis, G. Imreh, J. A. Sherman, D. N. Stacey, A. M. Steane, and D. M. Lucas, Phys. Rev. Lett. **100**, 200502 (2008),
DOI:10.1103/PhysRevLett.100.200502

[2] Scalable simultaneous multiqubit readout with 99.99% single-shot fidelity
A. H. Burrell, D. J. Szwer, S. C. Webster and D. M. Lucas, Phys. Rev. A. **81**, 040302 (2010),
DOI:10.1103/PhysRevA.81.040302

We are grateful to Andor Technology for the loan of a demo camera (iXon DU-897).

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