

Supplementary materials for

Yueying WANG, Yiwen HU, Yuehan ZHAO, Cuifang KUANG, Xiang HAO, 2025. Numerical investigation of resolution in single emitter localization-based imaging systems. *Front Inform Technol Electron Eng*, 26(9): 1721-1732. <https://doi.org/10.1631/FITEE.2500015>

Supplementary note 1 Statistical variance of the pixel pitch p with a filling factor α

Considering a flat-top probability density function distributed over $0-p$ in 1D and assuming its distribution as:

$$f(x) = \begin{cases} c & \forall x \in [k_1, k_2], \\ 0 & \forall x \in [0, k_1) \cup (k_2, p]. \end{cases} \quad (\text{S1})$$

$$\alpha = \frac{k_2 - k_1}{p}. \quad (\text{S2})$$

The expectation of this flat-top function on $0-p$ is

$$E(x) = \frac{\int_0^p xf(x)dx}{\int_0^p f(x)dx} = \frac{\frac{cx^2}{2} \Big|_{k_1}^{k_2}}{cx \Big|_{k_1}^{k_2}} = \frac{\frac{c(k_2^2 - k_1^2)}{2}}{c(k_2 - k_1)} = \frac{k_1 + k_2}{2}. \quad (\text{S3})$$

The variance of this flat-top function on $0-p$ is

$$\begin{aligned} \text{Var}[x] &= \frac{\int_0^p (x - E(x))^2 f(x)dx}{\int_0^p f(x)dx} \\ &= \frac{\frac{1}{3} \left(x - \frac{k_1 + k_2}{2}\right)^3 c \Big|_{k_1}^{k_2}}{cx \Big|_{k_1}^{k_2}} \\ &= \frac{c}{3} \frac{\left(\frac{k_2 - k_1}{2}\right)^3 - \left(\frac{k_1 - k_2}{2}\right)^3}{c(k_2 - k_1)} \\ &= \frac{(k_2 - k_1)^2}{12} \\ &= \frac{p^2 \alpha^2}{12}. \end{aligned} \quad (\text{S4})$$

2D case can be calculated the same. Moreover, if the distribution of the valid region within a

pixel pitch is unknown, then another $\frac{p^2(1-\alpha)^2}{12}$ should be added. The filling factor α is usually

so close to 1 that this term can be omitted. Otherwise, when the filling factor α becomes small, we can easily obtain the exact location of the valid region within a pixel pitch.

Supplementary note 2 Localization estimation in the presence of background noise

From the Eq. (6) in the main text, the localization estimate can be written as

$$\langle(\Delta x)^2\rangle = \frac{1}{\sum \frac{N_i}{\sigma_i^2}}. \quad (\text{S5})$$

For computational convenience, this summation can be obtained by replacing it with an integral.

$$\langle(\Delta x)^2\rangle = \frac{1}{\int_{-\infty}^{+\infty} \frac{N_i}{\sigma_i^2} dpi}. \quad (\text{S6})$$

N_i is the distribution of the point spread function on the focal plane. The distribution of N_i varies according to the optical design in different systems. Here we adopt the most classical Gaussian distribution and Eq. (S7) can also be replaced by numerical distributions detected actually. So we have N_i and σ_i given as

$$N_i = \frac{N\alpha\eta}{\sqrt{2\pi}s} e^{-\frac{i^2}{2s^2}}, \quad (\text{S7})$$

$$\sigma_i^2 = N_i + b_1^2 + (b_2 N\alpha\eta)^2. \quad (\text{S8})$$

For Gaussian functions there is

$$N_i' = -\frac{N\alpha\eta}{\sqrt{2\pi}s} \frac{i}{s^2} e^{-\frac{i^2}{2s^2}} = -\frac{i}{s^2} N_i. \quad (\text{S9})$$

Considering the case where the additive noise is much larger than the number of photons that $b_1^2 \gg N_i + (b_2 N\alpha\eta)^2$, we have $\sigma_i^2 \approx b_1^2$.

$$\begin{aligned}
\int_{-\infty}^{+\infty} \frac{N_i^2}{\sigma_i^2} dp_i &\approx \int_{-\infty}^{+\infty} \frac{\left(-\frac{i}{s^2} N_i\right)^2}{b_1^2} dp_i \\
&= \int_{-\infty}^{+\infty} \frac{\left(-\frac{i}{s^2} \frac{N\alpha\eta}{\sqrt{2\pi s}} e^{-\frac{i^2}{2s^2}}\right)^2}{b_1^2} p di \\
&= \frac{pN^2\alpha^2\eta^2}{2\pi s^6 b_1^2} \int_{-\infty}^{+\infty} i^2 e^{-\frac{i^2}{s^2}} di \\
&= \frac{pN^2\alpha^2\eta^2}{2\pi s^6 b_1^2} \int_{-\infty}^{+\infty} s^2 \frac{i^2}{s^2} e^{-\frac{i^2}{s^2}} s d\frac{i}{s} \\
&= \frac{pN^2\alpha^2\eta^2}{2\pi s^3 b_1^2} \int_{-\infty}^{+\infty} \frac{i^2}{s^2} e^{-\frac{i^2}{s^2}} d\frac{i}{s} \\
&= \frac{pN^2\alpha^2\eta^2}{2\pi s^3 b_1^2} \frac{\sqrt{\pi}}{2} \\
&= \frac{pN^2\alpha^2\eta^2}{4\sqrt{\pi} s^3 b_1^2}.
\end{aligned} \tag{S10}$$

Thus, the localization uncertainty is

$$\langle(\Delta x)^2\rangle \approx \frac{4\sqrt{\pi} s^3 b_1^2}{pN^2\alpha^2\eta^2}. \tag{S11}$$

As follows, considering the case where the coefficient of multiplicative noise is much larger than 1, we have $\sigma_i^2 \approx b_2^2$.

$$\begin{aligned}
\int_{-\infty}^{+\infty} \frac{N_i^2}{\sigma_i^2} dpi &= \int_{-\infty}^{+\infty} \frac{\left(-\frac{i}{s^2} N_i\right)^2}{(b_2 N \alpha \eta)^2} dpi \\
&= \int_{-\infty}^{+\infty} \frac{\left(-\frac{i}{s^2} \frac{N \alpha \eta}{\sqrt{2\pi s}} e^{-\frac{i^2}{2s^2}}\right)^2}{(b_2 N \alpha \eta)^2} p di \\
&= \frac{p}{2\pi s^6 b_2^2} \int_{-\infty}^{+\infty} i^2 e^{-\frac{i^2}{s^2}} di \\
&= \frac{p}{2\pi s^6 b_2^2} \int_{-\infty}^{+\infty} s^2 \frac{i^2}{s^2} e^{-\frac{i^2}{s^2}} s d\frac{i}{s} \\
&= \frac{p}{2\pi s^3 b_2^2} \int_{-\infty}^{+\infty} \frac{i^2}{s^2} e^{-\frac{i^2}{s^2}} d\frac{i}{s} \\
&= \frac{p}{2\pi s^3 b_2^2} \frac{\sqrt{\pi}}{2} \\
&= \frac{p}{4\sqrt{\pi} s^3 b_2^2}.
\end{aligned} \tag{S12}$$

So, the localization uncertainty is

$$\langle (\Delta x)^2 \rangle \approx \frac{4\sqrt{\pi} s^3 b_2^2}{p}. \tag{S13}$$

Combining Eqs. (S11) and (S13), we obtain the localization uncertainty due to noise as

$$\langle (\Delta x)^2 \rangle = \frac{4\sqrt{\pi} s^3 b_1^2}{p N^2 \alpha^2 \eta^2} + \frac{4\sqrt{\pi} s^3 b_2^2}{p}, \tag{S14}$$

This equation is obtained by separately computing the cases where additive and multiplicative noise are dominant. Considering the case where the signal dominates and the noise is suppressed, this leads to Eq. (2) in the main text. The complete localization uncertainty is given below. The approximation assumption made earlier may introduce some error. we did numerical calculations to measure this error and the overall deviation did not exceed 15%.

$$\langle (\Delta x_{1D})^2 \rangle = \frac{s^2 + (p\alpha)^2/12}{N\alpha\eta} + \frac{4\sqrt{\pi} s^3 b_1^2}{p N^2 \alpha^2 \eta^2} + \frac{4\sqrt{\pi} s^3 b_2^2}{p}. \tag{S15}$$

In 2D case, the distribution of N_i can be written as

$$N_i = \frac{N\alpha\eta}{2\pi s^2} e^{-\frac{i^2+j^2}{2s^2}}. \quad (\text{S16})$$

And $N_i' = -\frac{i}{s^2} N_i$ hold true.

For additive noise cases we have

$$\begin{aligned} \int_{-\infty}^{+\infty} \frac{N_i'^2}{\sigma_i^2} dpi &= \int_{-\infty}^{+\infty} \frac{\left(-\frac{i}{s^2} N_i\right)^2}{b_1^2} dpidpj \\ &= \int_{-\infty}^{+\infty} \frac{\left(-\frac{i}{s^2} \frac{N\alpha\eta}{2\pi s^2} e^{-\frac{i^2+j^2}{2s^2}}\right)^2}{b_1^2} p^2 didj \\ &= \frac{p^2 N^2 \alpha^2 \eta^2}{4\pi^2 s^8 b_1^2} \int_{-\infty}^{+\infty} i^2 e^{-\frac{i^2}{s^2}} didj \\ &= \frac{p^2 N^2 \alpha^2 \eta^2}{4\pi s^8 b_1^2} \int_{-\infty}^{+\infty} s^2 \frac{i^2}{s^2} e^{-\frac{i^2}{s^2}} s^2 d\frac{i}{s} d\frac{j}{s} \\ &= \frac{p^2 N^2 \alpha^2 \eta^2}{4\pi s^4 b_1^2} \int_{-\infty}^{+\infty} \frac{i^2}{s^2} e^{-\frac{i^2}{s^2}} d\frac{i}{s} d\frac{j}{s} \\ &= \frac{p^2 N^2 \alpha^2 \eta^2}{4\pi^2 s^4 b_1^2} \frac{\pi}{2} \\ &= \frac{p^2 N^2 \alpha^2 \eta^2}{8\pi s^4 b_1^2}. \end{aligned} \quad (\text{S17})$$

So, the localization uncertainty is

$$\langle(\Delta x)^2\rangle \approx \frac{8\pi s^4 b_1^2}{p^2 N^2 \alpha^2 \eta^2}. \quad (\text{S18})$$

And for multiplicative noise cases we have

$$\begin{aligned}
\int_{-\infty}^{+\infty} \frac{N_i}{\sigma_i^2} d^2p_i &= \int_{-\infty}^{+\infty} \frac{(-\frac{i}{s^2} N_i)^2}{(b_2 N \alpha \eta)^2} d^2p_i d^2p_j \\
&= \int_{-\infty}^{+\infty} \frac{(-\frac{i}{s^2} \frac{N \alpha \eta}{2\pi s^2} e^{-\frac{i^2+j^2}{2s^2}})^2}{(b_2 N \alpha \eta)^2} p^2 d^2i d^2j \\
&= \frac{p^2}{4\pi^2 s^8 b_2^2} \int_{-\infty}^{+\infty} i^2 e^{-\frac{i^2}{s^2}} d^2i d^2j \\
&= \frac{p^2}{4\pi s^8 b_2^2} \int_{-\infty}^{+\infty} s^2 \frac{i^2}{s^2} e^{-\frac{i^2}{s^2}} s^2 d\frac{i}{s} d\frac{j}{s} \\
&= \frac{p^2}{4\pi s^4 b_2^2} \int_{-\infty}^{+\infty} \frac{i^2}{s^2} e^{-\frac{i^2}{s^2}} d\frac{i}{s} d\frac{j}{s} \\
&= \frac{p^2}{4\pi s^4 b_2^2} \frac{\pi}{2} \\
&= \frac{p^2}{8\pi s^4 b_2^2}.
\end{aligned} \tag{S19}$$

Thus, the localization uncertainty is

$$\langle (\Delta x)^2 \rangle \approx \frac{8\pi s^4 b_2^2}{p^2}. \tag{S20}$$

And the total localization uncertainty is

$$\langle (\Delta x_{2D})^2 \rangle = \frac{s^2 + (p\alpha)^2/12}{N\alpha\eta} + \frac{8\pi s^4 b_1^2}{p^2 N^2 \alpha^2 \eta^2} + \frac{8\pi s^4 b_2^2}{p^2}. \tag{S21}$$

All the conclusions in one dimension are still true in two dimensions.

Supplementary note 3 Optimal pixel pitch p that minimizes the resolution distance for a fixed PSF width s

From the Eq. (14) in the main text, the resolution considering oversampling can be written as

$$R_{1D} = \begin{cases} \sqrt{2.35^2 \left(\frac{s^2 + (p\alpha)^2/12}{N\alpha\eta} + \frac{4\sqrt{\pi}s^3}{p} \left(\frac{1}{\text{SNR}} - \frac{1}{\sqrt{N\alpha\eta}} \right)^2 \right) + \left(\frac{4p^2}{2.35s} \right)^2} & r > 2p. \\ \sqrt{2.35^2 \left(\frac{s^2 + (p\alpha)^2/12}{N\alpha\eta} + \frac{4\sqrt{\pi}s^3}{p} \left(\frac{1}{\text{SNR}} - \frac{1}{\sqrt{N\alpha\eta}} \right)^2 \right) + (2p)^2} & r \leq 2p. \end{cases} \tag{S22}$$

As can be seen from Fig. 4 in the main text, the extreme value of this piecewise function is in the interval of $r > 2p$. Taking the derivative of a function in this interval with respect to p there is

$$d \sqrt{2.35^2 \left(\frac{s^2 + (p\alpha)^2}{12 N\alpha\eta} + \frac{4\sqrt{\pi}s^3}{p} \left(\frac{1}{\text{SNR}} - \frac{1}{\sqrt{N\alpha\eta}} \right)^2 \right) + \left(\frac{4p^2}{2.35s} \right)^2} / dp = 0, \quad (\text{S23})$$

$$2.35^2 \left(\frac{2p\alpha^2}{12 N\alpha\eta} - \frac{4\sqrt{\pi}s^3}{p^2} \left(\frac{1}{\text{SNR}} - \frac{1}{\sqrt{N\alpha\eta}} \right)^2 \right) + \frac{64p^3}{2.35^2 s^2} = 0.$$

Considering that the number of photons is usually large we ignore the effect of statistical variance of the pixel pitch.

$$2.35^2 \left(\frac{4\sqrt{\pi}s^3}{p^2} \left(\frac{1}{\text{SNR}} - \frac{1}{\sqrt{N\alpha\eta}} \right)^2 \right) = \frac{64p^3}{2.35^2 s^2},$$

$$\left(\frac{1}{\text{SNR}} - \frac{1}{\sqrt{N\alpha\eta}} \right)^2 = \frac{64p^5}{2.35^4 \cdot 4\sqrt{\pi}s^5}, \quad (\text{S24})$$

$$p = 1.276s \left(\frac{1}{\text{SNR}} - \frac{1}{\sqrt{N\alpha\eta}} \right)^{\frac{2}{5}}.$$

The calculation is exactly the same for the 2D case.

Supplementary note 4 Optimal PSF width s that minimizes the resolution distance for a fixed pixel pitch p

For a fixed pixel pitch p , the extreme value of this piecewise function is in the interval of $s \geq 2p$ as well. So, taking the derivative of a function in this interval with respect to s there is

$$d \sqrt{2.35^2 \left(\frac{s^2 + (p\alpha)^2}{12 N\alpha\eta} + \frac{4\sqrt{\pi}s^3}{p} \left(\frac{1}{\text{SNR}} - \frac{1}{\sqrt{N\alpha\eta}} \right)^2 \right) + \left(\frac{4p^2}{2.35s} \right)^2} / ds = 0, \quad (\text{S25})$$

$$2.35^2 \left(\frac{2s}{N\alpha\eta} + \frac{12\sqrt{\pi}s^2}{p} \left(\frac{1}{\text{SNR}} - \frac{1}{\sqrt{N\alpha\eta}} \right)^2 \right) - \frac{32p^4}{2.35^2 s^3} = 0.$$

Considering that the number of photons is usually large we ignore the effect of statistical variance of the pixel pitch.

$$\begin{aligned}
2.35^2 \left(\frac{12\sqrt{\pi}s^2}{p} \left(\frac{1}{\text{SNR}} - \frac{1}{\sqrt{N\alpha\eta}} \right)^2 \right) &= \frac{32p^4}{2.35^2 s^3}, \\
\left(\frac{1}{\text{SNR}} - \frac{1}{\sqrt{N\alpha\eta}} \right)^2 &= \frac{32p^5}{2.35^4 \cdot 12\sqrt{\pi}s^5}, \\
s &= \frac{0.548p}{\left(\frac{1}{\text{SNR}} - \frac{1}{\sqrt{N\alpha\eta}} \right)^{\frac{2}{5}}}.
\end{aligned} \tag{S26}$$

The calculation is exactly the same for the 2D case.

Supplementary note 5 Conditions to achieve resolution beyond the Rayleigh limit

From the Eq. (13) in the main text, the resolution considering oversampling can be written as

$$R_{\text{ID}} = \begin{cases} \sqrt{2.35^2 \left(\frac{s^2 + (p\alpha)^2/12}{N\alpha\eta} + \frac{4\sqrt{\pi}s^3}{p} \left(\frac{1}{\text{SNR}} - \frac{1}{\sqrt{N\alpha\eta}} \right)^2 \right) + \left(\frac{4p^2}{2.35s} \right)^2} & s > 2p. \\ \sqrt{2.35^2 \left(\frac{s^2 + (p\alpha)^2/12}{N\alpha\eta} + \frac{4\sqrt{\pi}s^3}{p} \left(\frac{1}{\text{SNR}} - \frac{1}{\sqrt{N\alpha\eta}} \right)^2 \right) + (2p)^2} & s \leq 2p. \end{cases} \tag{S27}$$

R_{ID} is bound to exceed s when $s \leq 2p$. Achieving resolution x times beyond the Rayleigh limit there is

$$\begin{aligned}
\sqrt{2.35^2 \left(\frac{s^2 + (p\alpha)^2/12}{N\alpha\eta} + \frac{4\sqrt{\pi}s^3}{p} \left(\frac{1}{\text{SNR}} - \frac{1}{\sqrt{N\alpha\eta}} \right)^2 \right) + \left(\frac{4p^2}{2.35s} \right)^2} &< \frac{2.35s}{x}, \\
2.35^2 \left(\frac{s^2 + (p\alpha)^2/12}{N\alpha\eta} + \frac{4\sqrt{\pi}s^3}{p} \left(\frac{1}{\text{SNR}} - \frac{1}{\sqrt{N\alpha\eta}} \right)^2 \right) + \left(\frac{4p^2}{2.35s} \right)^2 &< \frac{2.35^2 s^2}{x^2}, \\
\frac{1}{N\alpha\eta} + \frac{\alpha^2/12}{N\alpha\eta} \frac{p^2}{s^2} + 4\sqrt{\pi} \left(\frac{1}{\text{SNR}} - \frac{1}{\sqrt{N\alpha\eta}} \right)^2 \frac{s}{p} + \frac{16p^4}{2.35^4 s^4} &< \frac{1}{x^2}.
\end{aligned} \tag{S28}$$

To simplify the calculation, let us consider the case where $\alpha=100\%$ and $\eta=100\%$. At the same time, with oversampling factor $f = r/2p$, the inequation to be solved can be written as

$$\frac{1}{N} + \frac{1}{12N} \frac{2.35^2}{4f^2} + 4\sqrt{\pi} \left(\frac{1}{\text{SNR}} - \frac{1}{\sqrt{N}} \right)^2 \frac{2f}{2.35} + \frac{1}{f^4} < \frac{1}{x^2}, \tag{S29}$$

$$\frac{8\sqrt{\pi}}{2.35} \left(\frac{1}{\text{SNR}} - \frac{1}{\sqrt{N}} \right)^2 < \left(\frac{1}{x^2} - \frac{1}{N} \right) \frac{1}{f} - \frac{2.35^2}{48N} \frac{1}{f^3} - \frac{1}{f^5}. \tag{S30}$$

The threshold of SNR, N or f can be calculated by introducing the other two parameters to solve this inequation. It has a basic limitation that the right side of Eq. (S30) cannot be smaller than 0. This leads to a lower bound of f with requirement of x being less than \sqrt{N} included.

$$f > \frac{1}{\sqrt[4]{\frac{1}{x^2} - \frac{1}{N}}} \approx \sqrt{x}. \quad (\text{S31})$$

In addition, we can achieve an optimal f to minimize the threshold of SNR, which is, to make the right side of Eq. (S30) to be maximum. This happens where

$$\begin{aligned} d\left(\left(\frac{1}{x^2} - \frac{1}{N}\right) \frac{1}{f} - \frac{2.35^2}{48N} \frac{1}{f^3} - \frac{1}{f^5}\right) / df &= 0, \\ \frac{5}{f^6} + \frac{2.35^2}{48N} \frac{3}{f^4} - \left(\frac{1}{x^2} - \frac{1}{N}\right) \frac{1}{f^2} &= 0, \\ \frac{1}{f^4} + \frac{2.35^2}{80N} \frac{1}{f^2} - \frac{1}{5} \left(\frac{1}{x^2} - \frac{1}{N}\right) &= 0. \end{aligned} \quad (\text{S32})$$

For well-lit systems, N is usually large. So, ignoring the polynomial in N we get $f \approx \sqrt[4]{5x^2} = 1.50\sqrt{x}$. System performs best under this sampling condition. Both larger or smaller oversampling factor require an increase in the SNR of the system to achieve the same resolution.

For 2D cases, equation same as Eq. (S30) can be written into

$$\frac{32\pi}{2.35^2} \left(\frac{1}{\text{SNR}} - \frac{1}{\sqrt{N}}\right)^2 < \left(\frac{1}{x^2} - \frac{1}{N}\right) \frac{1}{f^2} - \frac{2.35^2}{48N} \frac{1}{f^4} - \frac{1}{f^6}. \quad (\text{S33})$$

The lower bound remains the same as Eq. (S31), and optimal value of f changes into $f \approx \sqrt[4]{3x^2} = 1.32\sqrt{x}$.

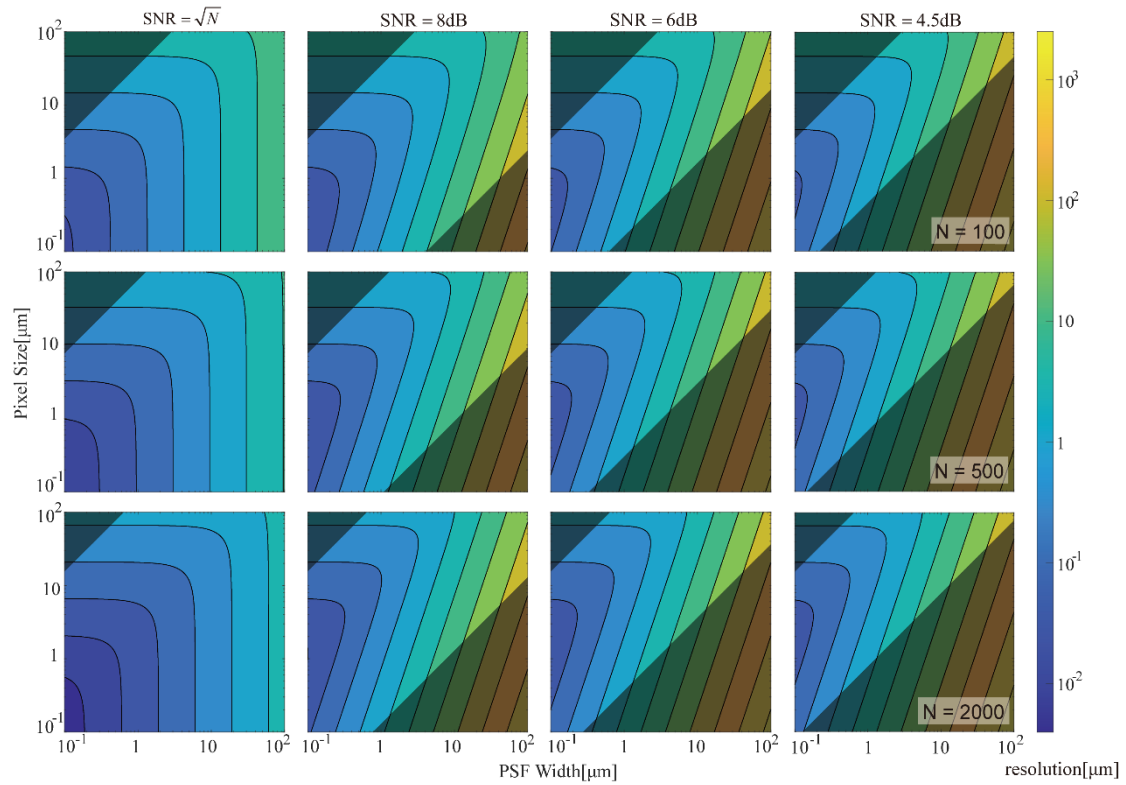


Fig. S1 Resolution as a function of PSF width and pixel size in 1D cases without considering sampling requirement. All is under condition that $\alpha=100\%$ and $\eta=100\%$. Each row has a different number of detected photons and each column is under different SNR. The SNR in the first column is exactly the square root of N , which means there is no background noise exist. The shaded area indicates that the resolution there does not exceed the Rayleigh limit

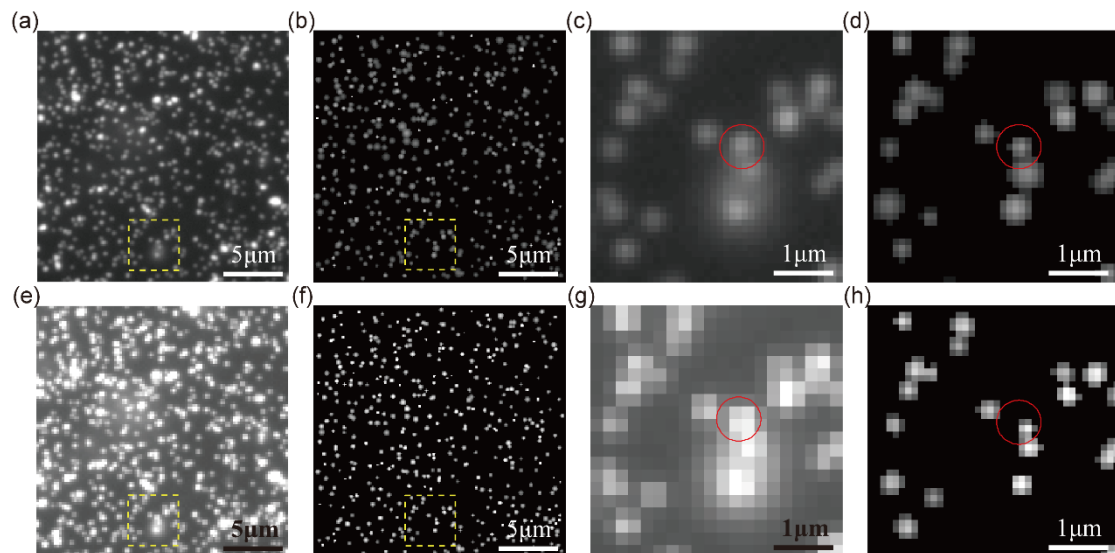


Fig. S2 Inaccuracy of localization illustrated by merging pixels when the sampling rate does not satisfy the Nyquist sampling theorem: (a-d) show the original image and its reconstruction result, and (e-h) are the pixels-merged image and its reconstruction result. The merging method involves combining adjacent 2×2 pixels into a single new pixel, resulting in the intensity of the newly generated image multiple than the original. The

oversampling rate of the original image is approximately 1.33, and is halved after pixel merging. The four pictures on the right display enlarged views of the yellow frame in the four pictures on the left. (b, d, f, h) are single-point positioning images reconstructed without considering correction from sampling rate. To maintain consistency in analysis, interpolation was applied during reconstruction, ensuring that images (f) and (h) retain the same pixel size as before the merging of pixels. The positioning results of the points in the red circle demonstrate that although the image after merging pixel has a smaller theoretical precision value, its positioning results can be deviated from the actual center, leading to greater inaccuracy. In this specific experimental result, the maximum center shift is analyzed to be 1.43 pixels. The experimental data in the figure were obtained from a single-molecule positioning microscope, which uses 647 nm illumination, a numerical aperture (NA) of 1.42, and an equivalent pixel size of 108 nm

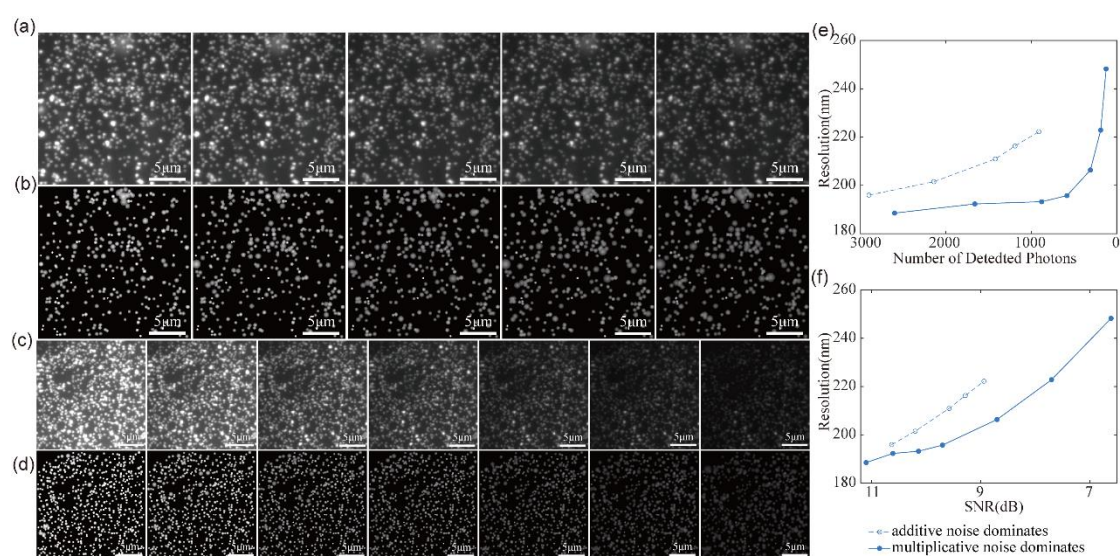


Fig. S3 Resolution changes of the system dominated by additive noise and multiplicative noise: (a) presents a series of images of the same region bleaching by laser illumination under consistent imaging conditions, where the proportion of additive noise steadily increases, (c) illustrates a gradual decrease in laser intensity in the same region, with multiplicative noise progressively taking dominance, their reconstructed images are demonstrated in (b) and (d), and the specific resolution trends are plotted in (e) and (f). In cases dominated by additive noise, the relationship between resolution and photon number is relatively linear. Conversely, in cases dominated by multiplicative noise, as the number of photons increases, improvements in SNR and resolution both decelerate. The experimental conditions of the data in this figure are consistent with those in the previous figure

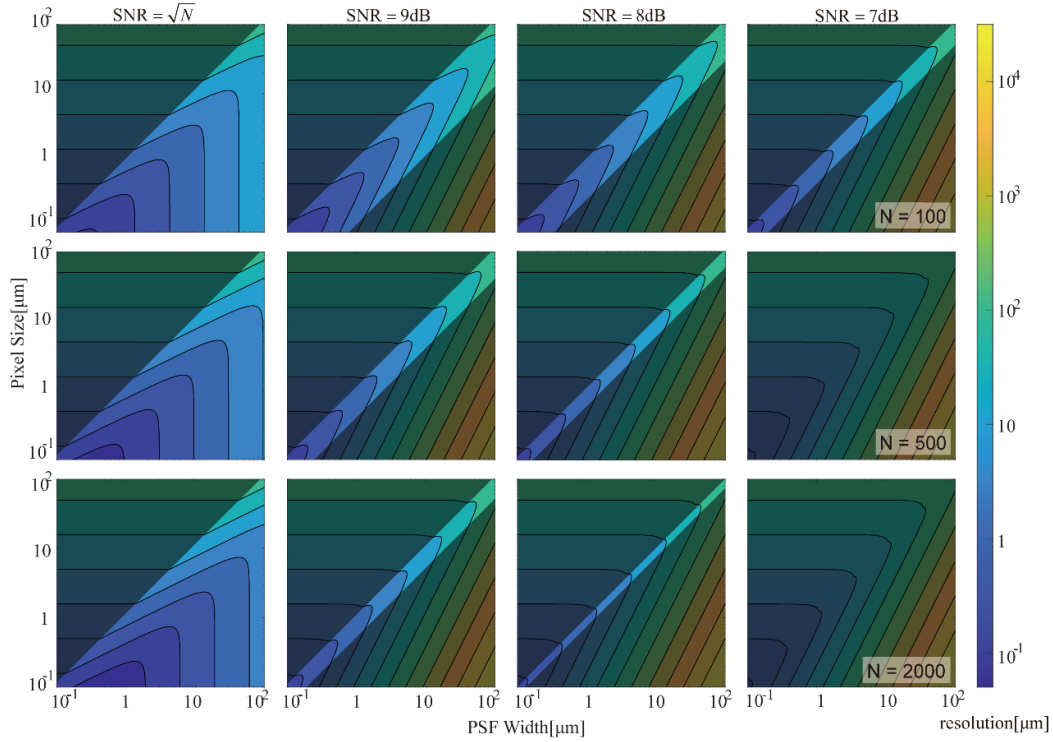


Fig. S4 Resolution as a function of PSF width and pixel size in 2D cases. All is under condition that $\alpha = 100\%$ and $\eta = 100\%$. Each row has a different number of detected photons and each column is under different SNR. The SNR in the first column is exactly the square root of N , which means there is no background noise exist. The shaded area indicates that the resolution there does not exceed the Rayleigh limit

Supplementary Table 1 Lower limit of the oversampling factor under different numbers of detected photons and SNRs to achieve resolution beyond the Rayleigh limit in 1D cases

SNR (dB)	Number of detected photons				
	100	200	500	1000	2000
4.5	1.17	1.28	\	\	\
5	1.10	1.15	1.22	1.28	1.36
6	1.04	1.06	1.09	1.10	1.11
7	1.02	1.03	1.04	1.05	1.06
8	1.01	1.01	1.02	1.03	1.03

Supplementary Table 2 Upper limit of the oversampling factor under different numbers of detected photons and SNRs to achieve resolution beyond the Rayleigh limit in 1D cases

SNR (dB)	Number of detected photons				
	100	200	500	1000	2000
4.5	2.46	1.88	\	\	\
5	3.48	2.68	2.14	1.88	1.67
6	7.18	5.05	3.86	3.41	3.13
7	16.56	9.94	6.90	5.87	5.27
8	47.96	21.40	12.78	10.29	8.94

Supplementary Table 3 Lower limit of the oversampling factor under different numbers of detected photons and SNRs to achieve resolution beyond the Rayleigh limit in 2D cases

SNR (dB)	Number of detected photons				
	100	200	500	1000	2000
7	1.06	1.13	\	\	\
8	1.02	1.04	1.09	1.12	1.17
9	1.01	1.02	1.04	1.05	1.65
10	1.00	1.01	1.02	1.02	1.03
12	\	\	1.00	1.00	1.01

Supplementary Table 4 Upper limit of the oversampling factor under different numbers of detected photons and SNRs to achieve resolution beyond the Rayleigh limit in 2D cases

SNR (dB)	Number of detected photons				
	100	200	500	1000	2000
7	2.30	1.70	\	\	\
8	3.98	2.64	1.99	1.74	1.58
9	9.01	4.23	2.86	2.45	2.22
10	\	7.98	4.23	3.41	3.00
12	\	\	12.74	7.44	5.75