



Nano-emitter Electron Sources for Ultrafast Applications

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Acknowledgements

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How do you increase the brightness of an electron beam without losing charge/current?

$$\text{Beam Brightness} = \frac{\text{Total Charge}}{\text{Phase Space Volume}} = \frac{\text{Total Charge}}{\sigma_x \sigma_y \sigma_t \sigma_{px} \sigma_{py} \sigma_E}$$

For applications like ultrafast electron diffraction,

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10^3 to 10^5 electrons

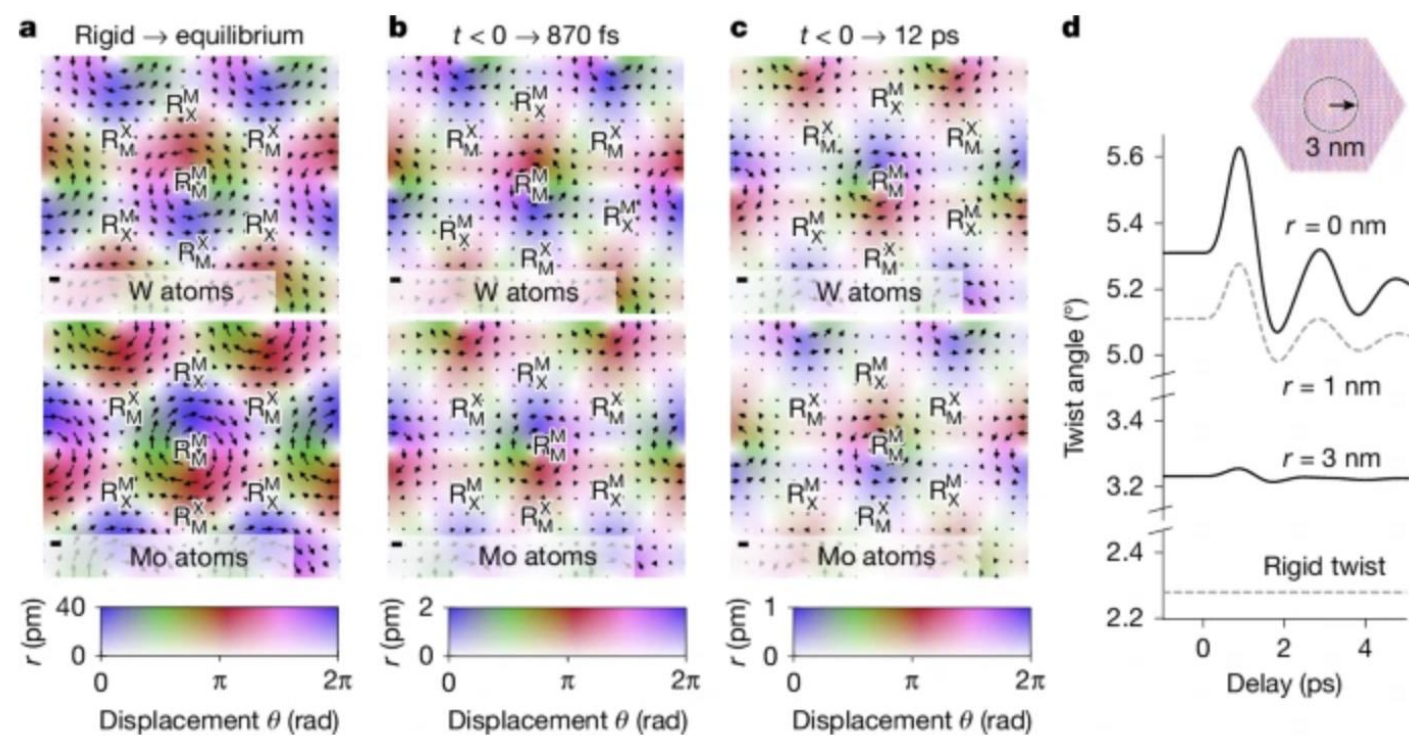


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$10\text{ fs to }1\text{ ps}$



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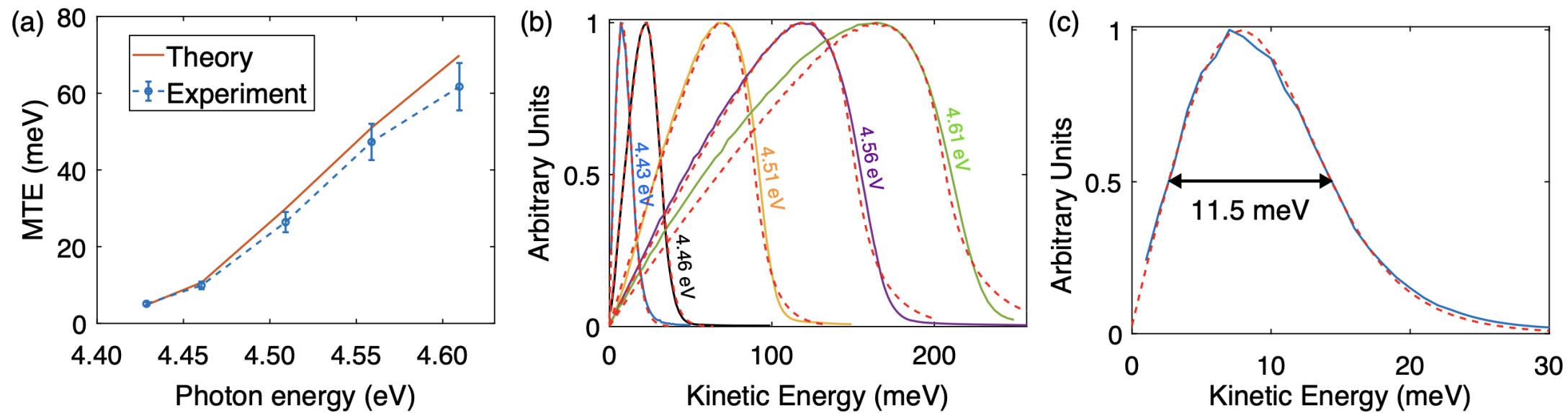
Beam Brightness = $\frac{\text{Total Charge}}{\text{Phase Space Volume}}$ = $\frac{\text{Total Charge}}{\sigma_x \sigma_y \sigma_t \sigma_{px} \sigma_{py} \sigma_E}$

$10^3 \text{ to } 10^5 \text{ electrons}$ (points to Total Charge)

$10 \text{ fs to } 1 \text{ ps}$ (points to σ_t)

$\approx k_B T$ (points to $\sigma_{px} \sigma_{py}$)

Cold copper photoemission

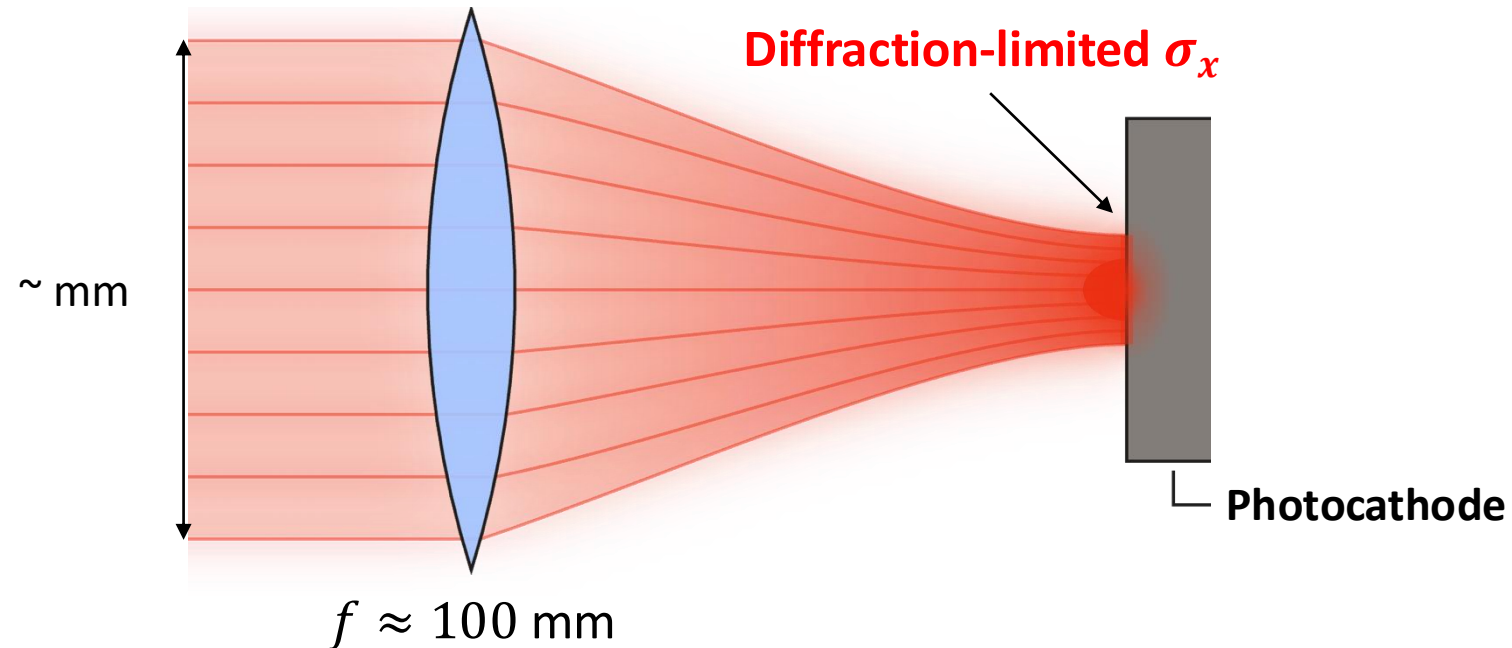


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$\nearrow$ $\nearrow$ $\nwarrow$ $\nwarrow$
 $> 20 \mu\text{m}$ $10 \text{ fs to } 1 \text{ ps}$ $\approx k_B T$



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↙

↗

$\rightarrow 20 \mu\text{m}$ $10 \text{ fs to } 1 \text{ ps}$ $\approx k_B T$

$0.24 \mu\text{m to } 2.4 \mu\text{m}$
with nano-emitters

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 with nano-emitters

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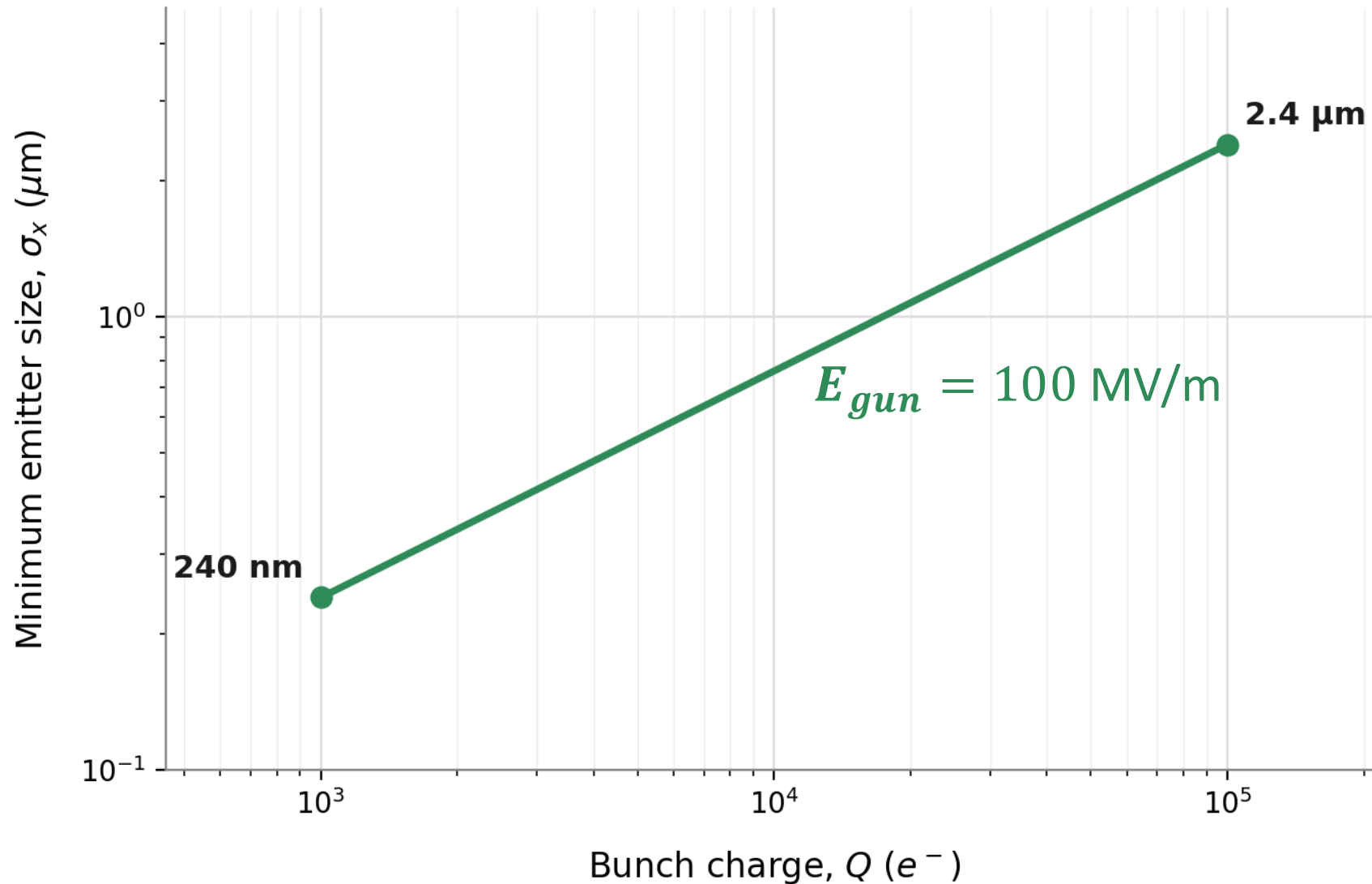
$\approx k_B T$

Besides being small, other benefits of nano-emitters also include:

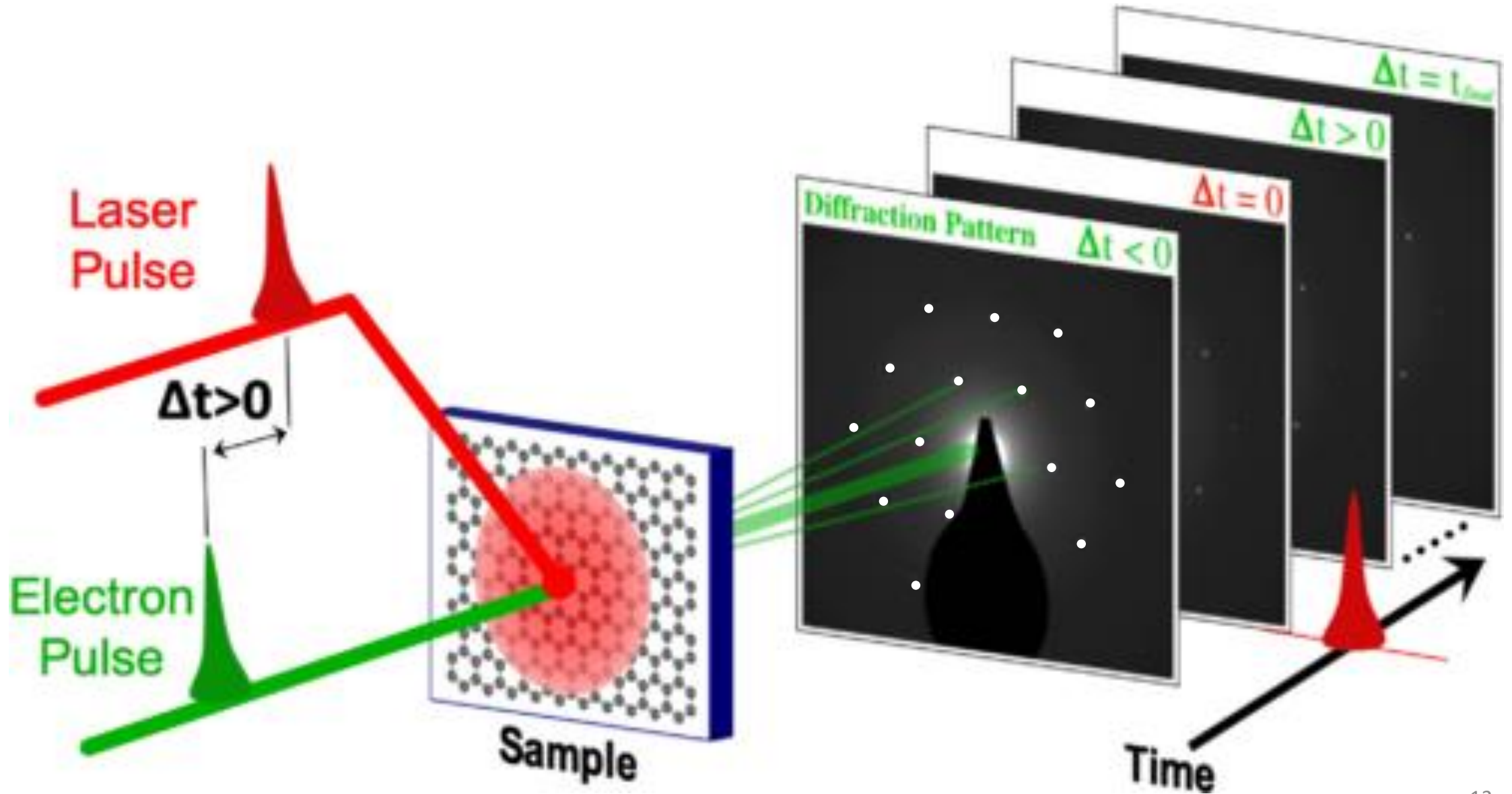
- Easier to make hard edge emission boundaries
- Precise control of position ***and number*** of emitted electrons

Why limit the emission size to 0.24 μm to 2.4 μm ?

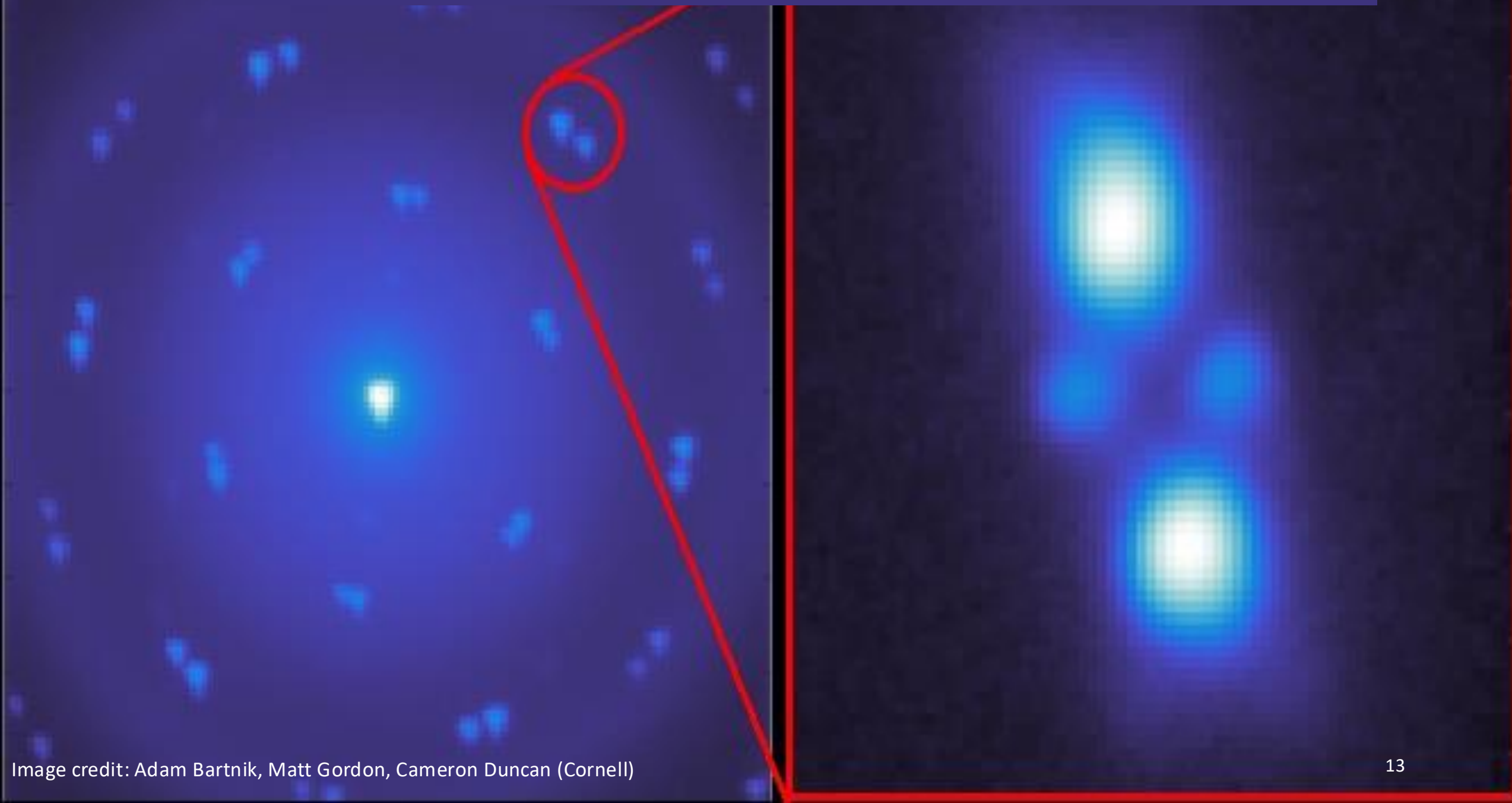
“Space charge limit”: $\sigma_x = \sqrt{\frac{Q}{\epsilon_0 \pi E_{gun}}}$



Implications for ultrafast electron diffraction



Increasing e-beam brightness -> Higher diffraction spot resolution





How do we make nano-emitters?

Photoemission Contrast

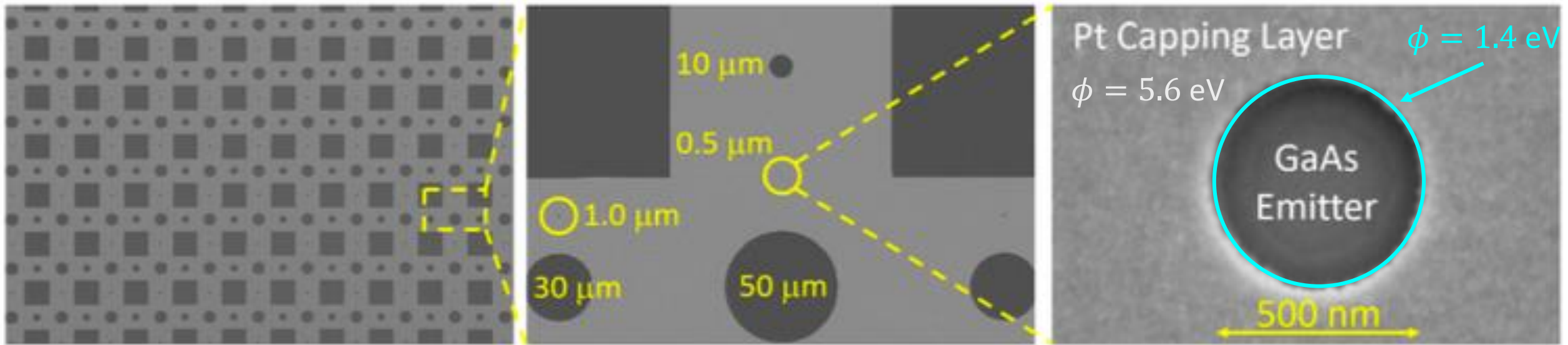


Material "B"
Work function > $h\nu$

Material "A"
Work function < $h\nu$

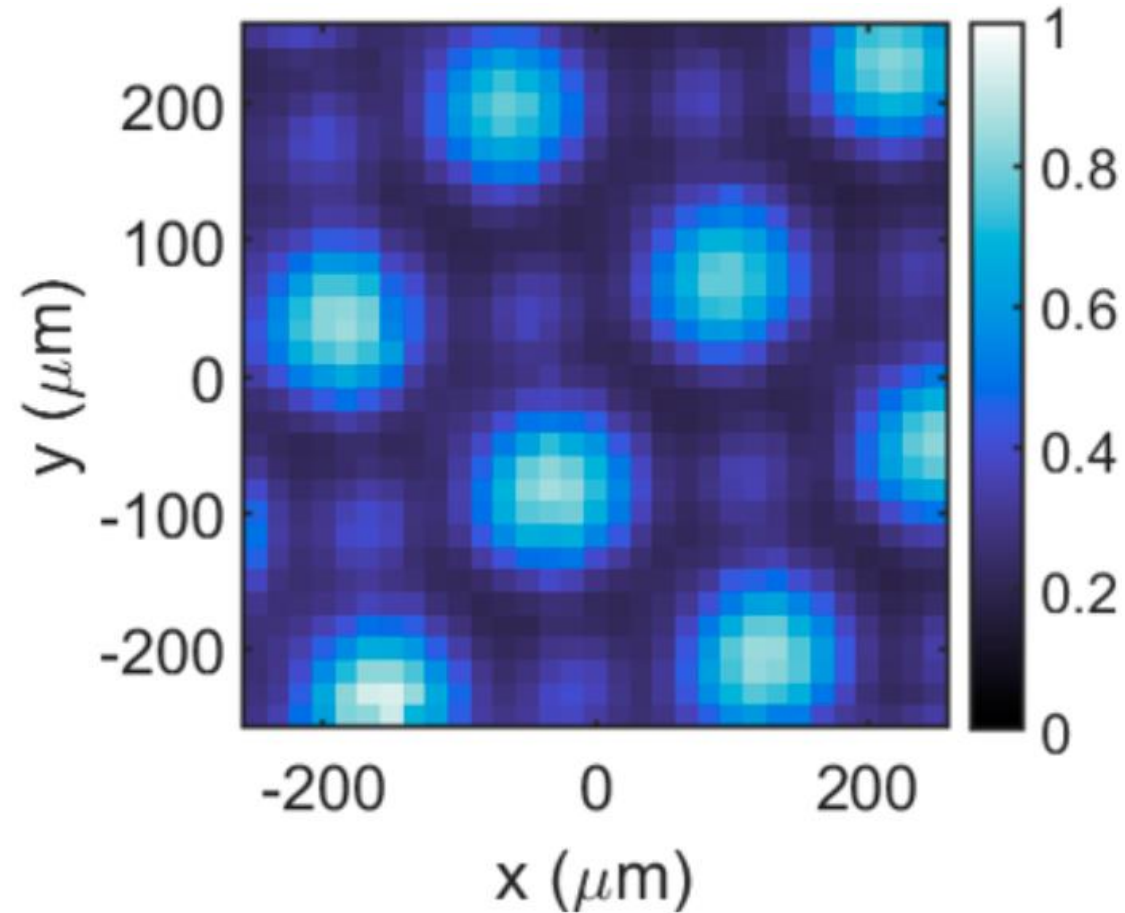
Lithographically-defined emission region

GaAs emitters



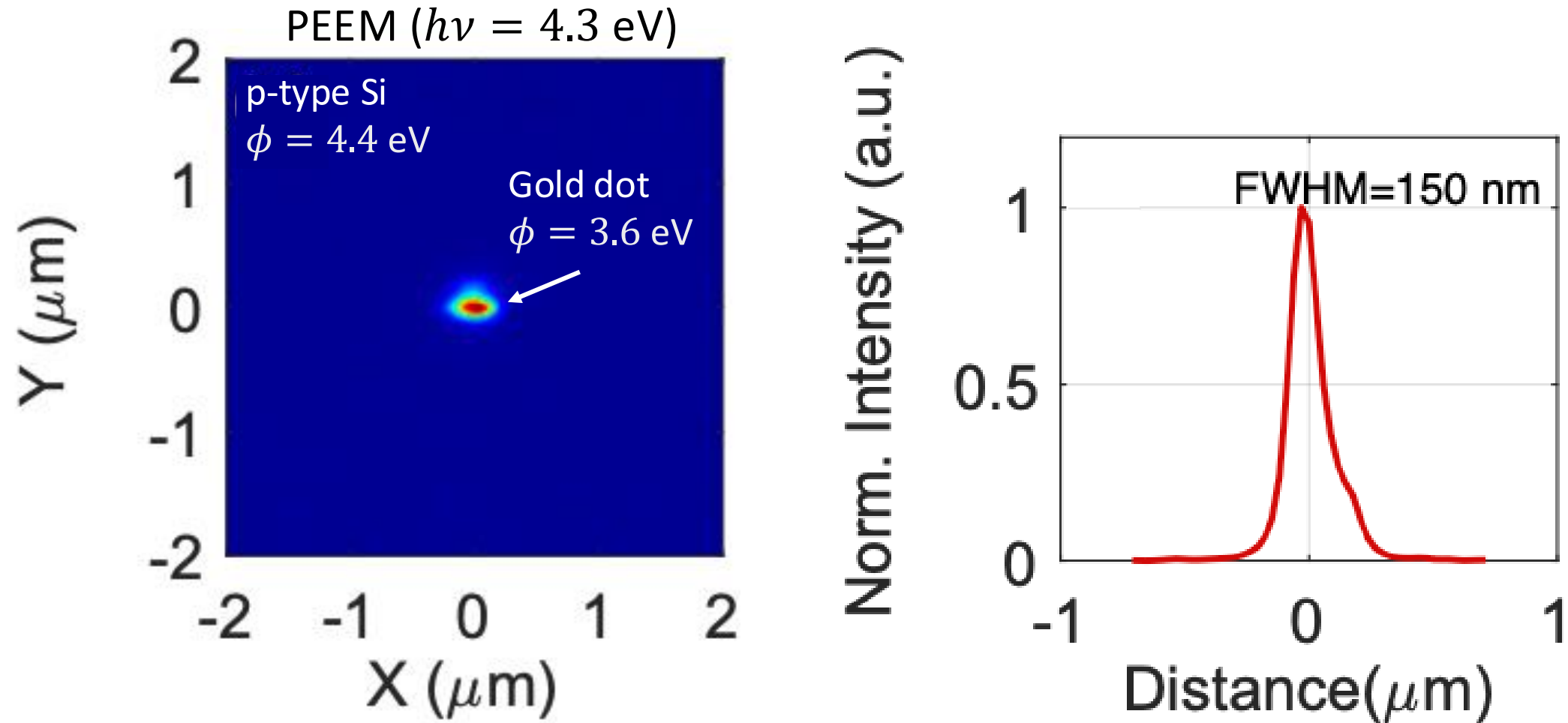
GaAs emitters post-Cs/O activation

Quantum efficiency ($h\nu = 2.3$ eV) spatially mapped here with a laser position scan ($\sigma_x \approx 25$ μm)



QE of GaAs is over 40 times larger than QE of Pt.

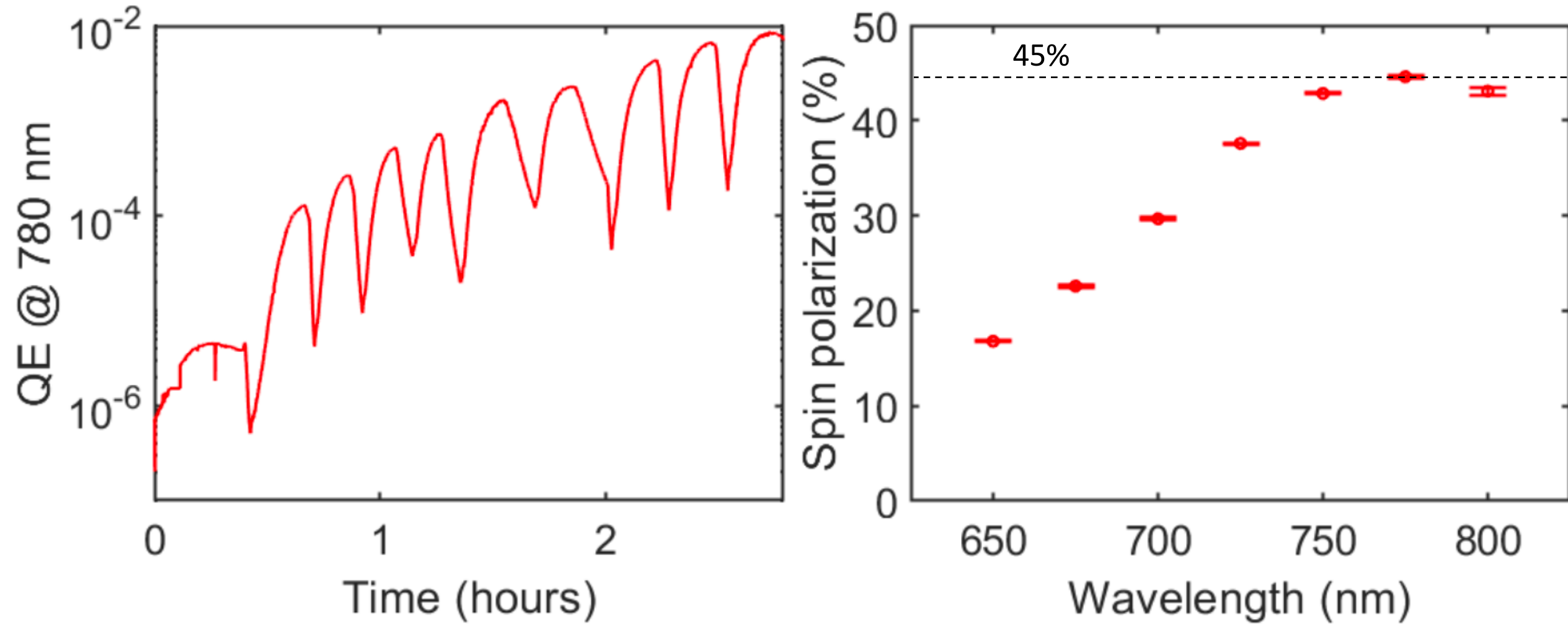
PhotoEmission Electron Microscopy allows for much higher resolution



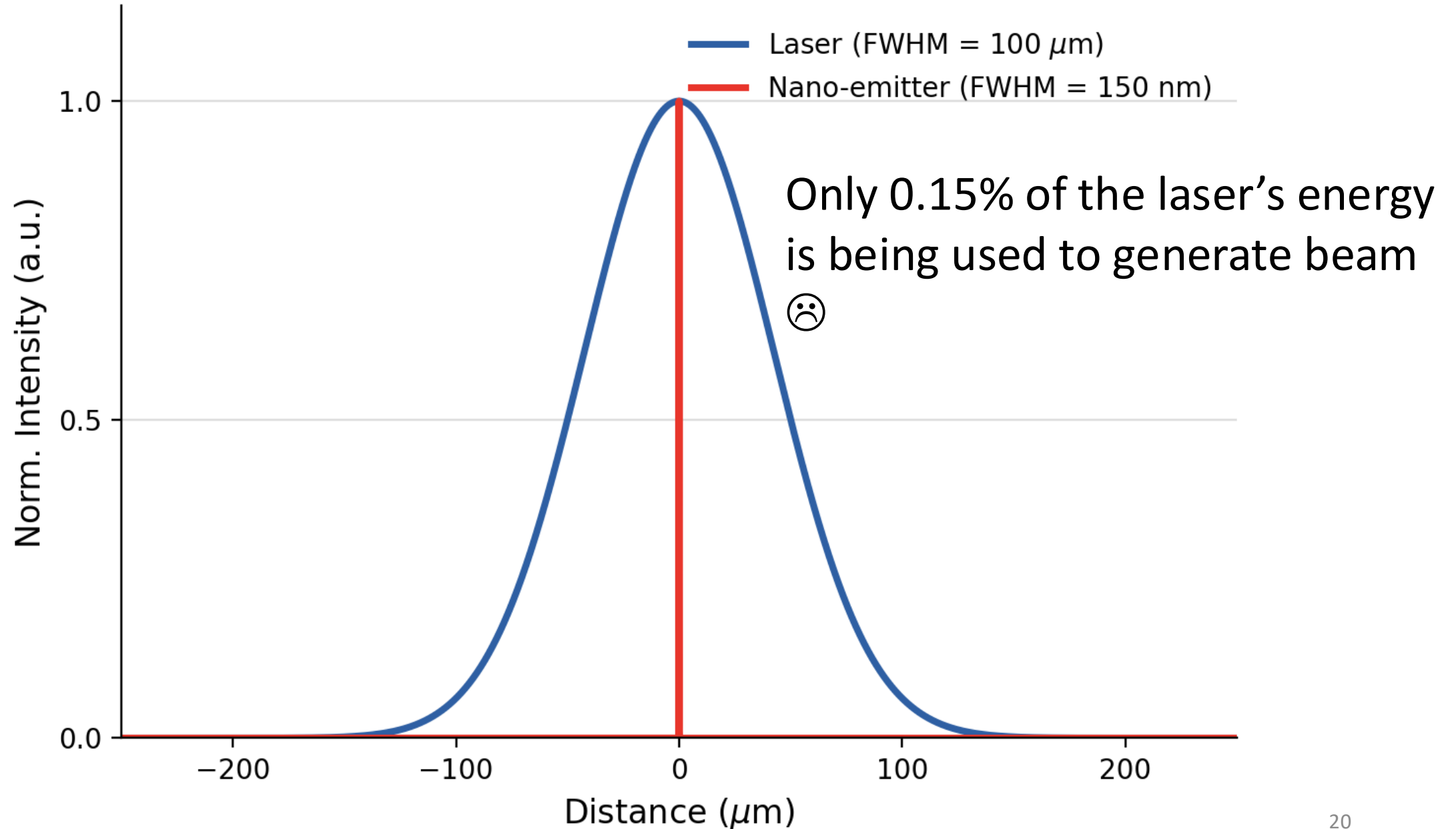
Measured emittance comparable to electron microscope tips!

High charge + Ultrafast Operation?

QE and spin polarization of GaAs emitters remain good after photolithography.



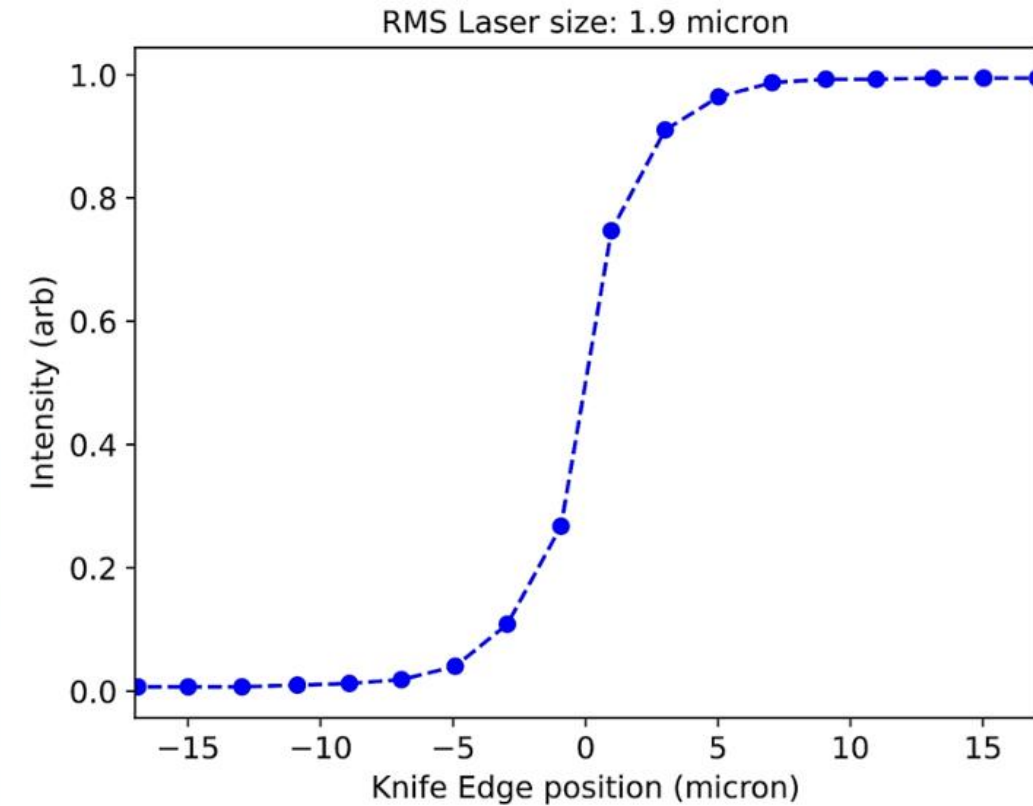
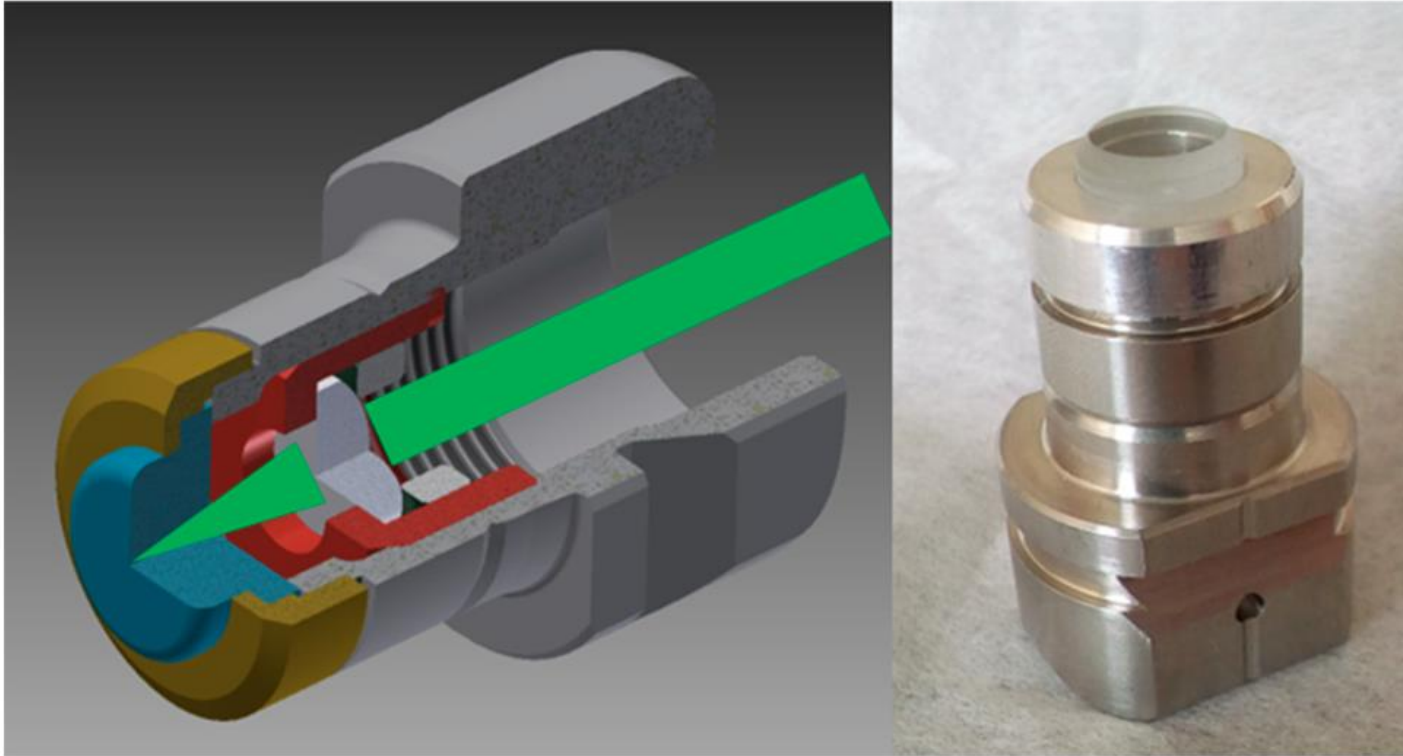
High charge + Ultrafast Operation?



High charge + Ultrafast Operation?

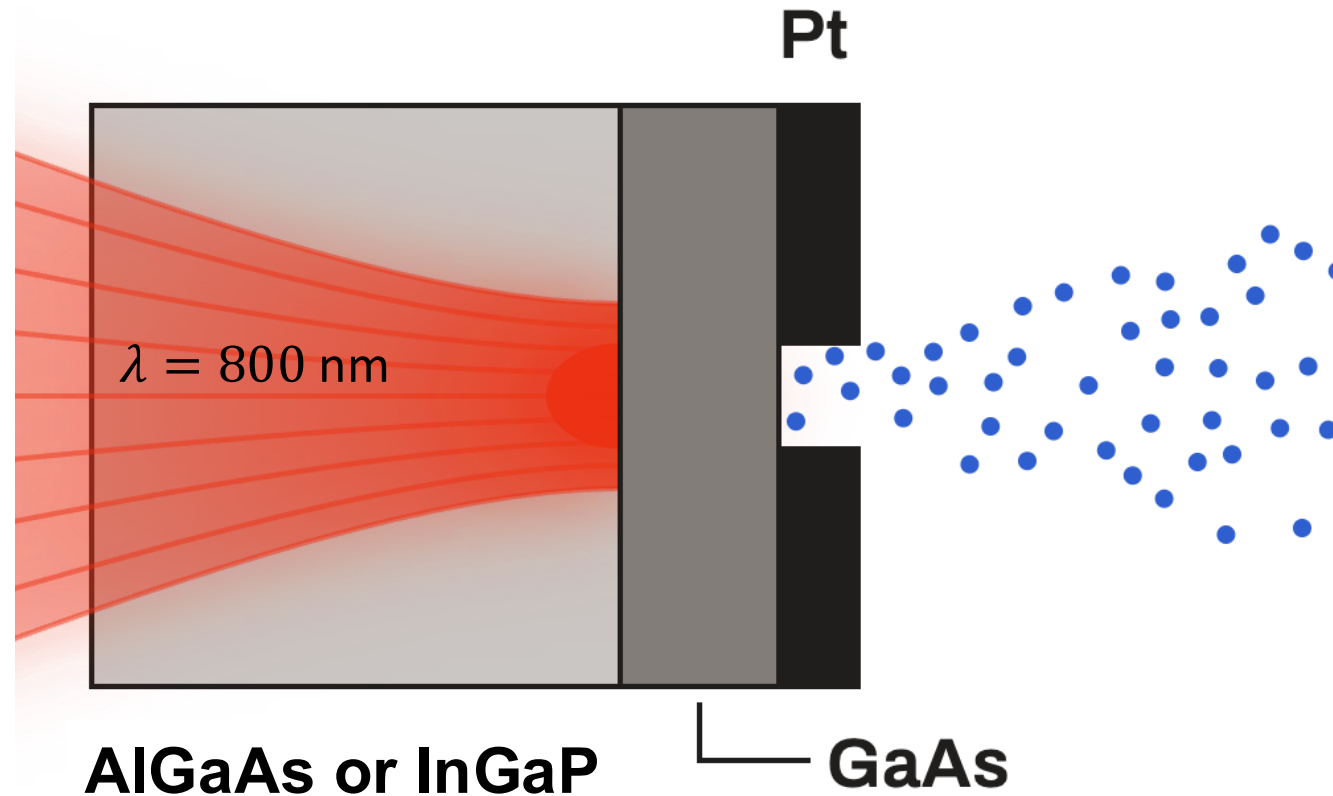
Transmission-mode operation with a lens built into the gun allows for sub-micron laser waists.

Modified INFN/DESY plug



High charge + Ultrafast Operation?

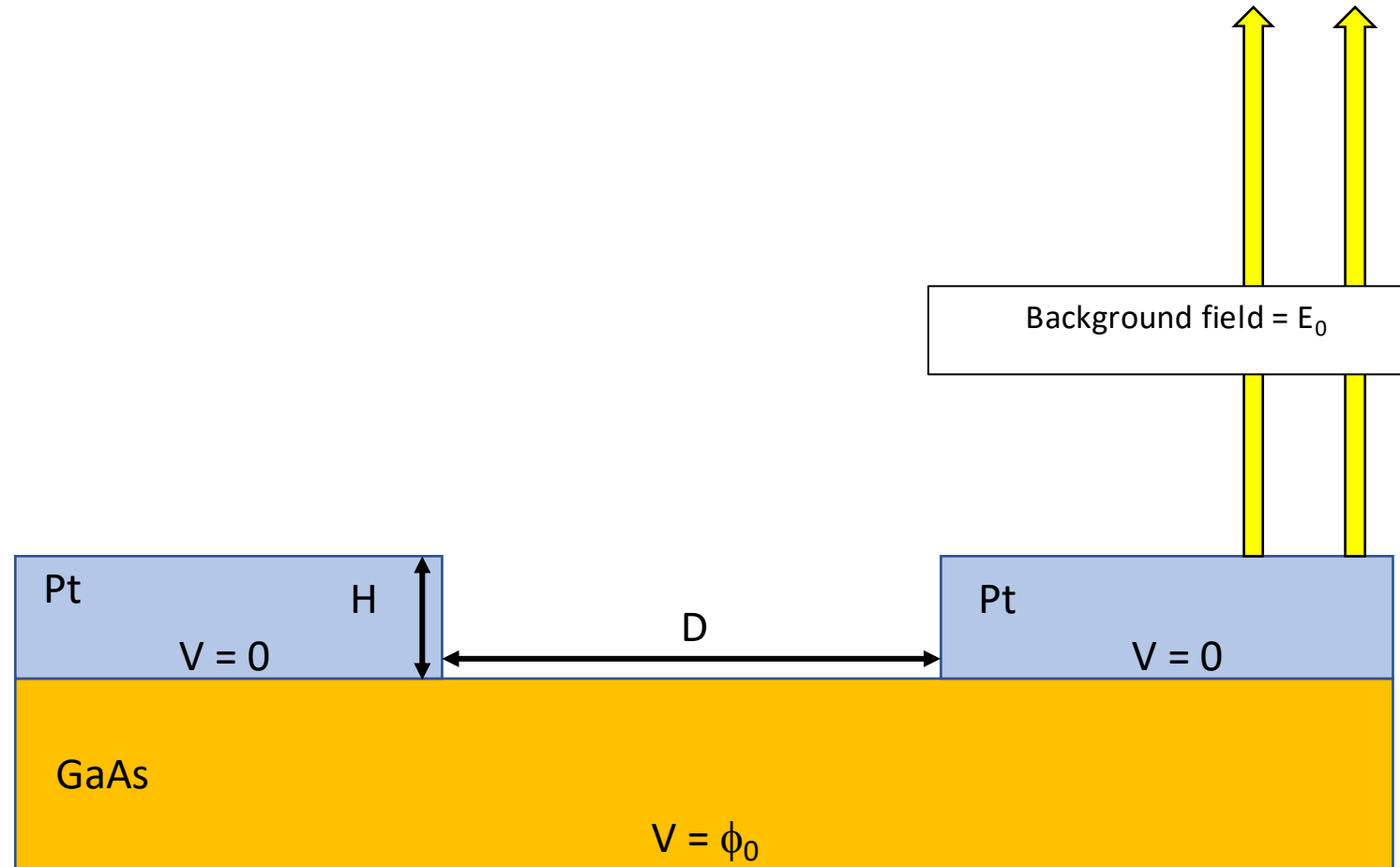
Thin GaAs grown on a transparent substrate like AlGaAs or InGaP would reduce the response time, resulting in shorter bunch lengths for ultrafast operation.



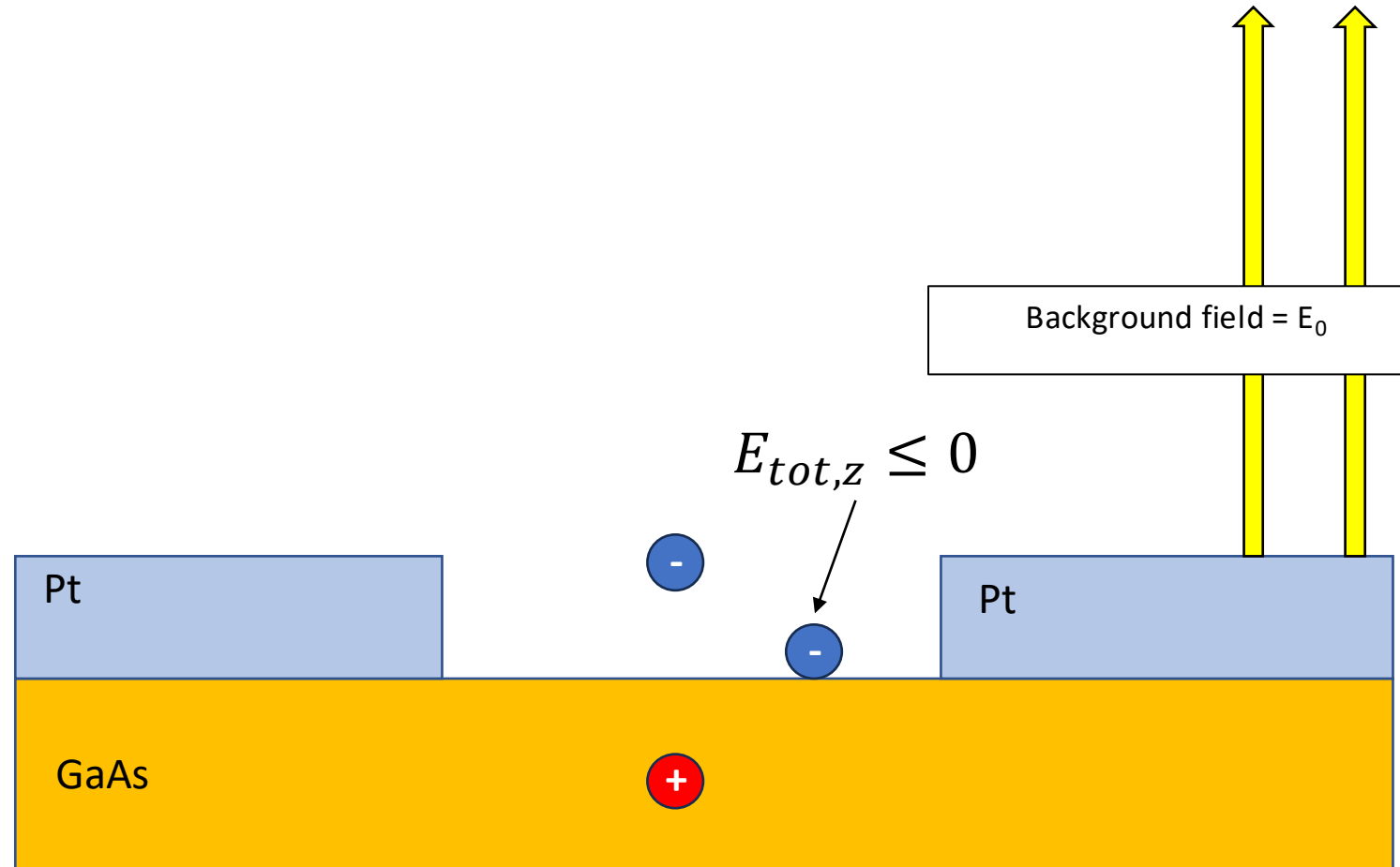


What if we reduced the emitter size below the space charge limit?

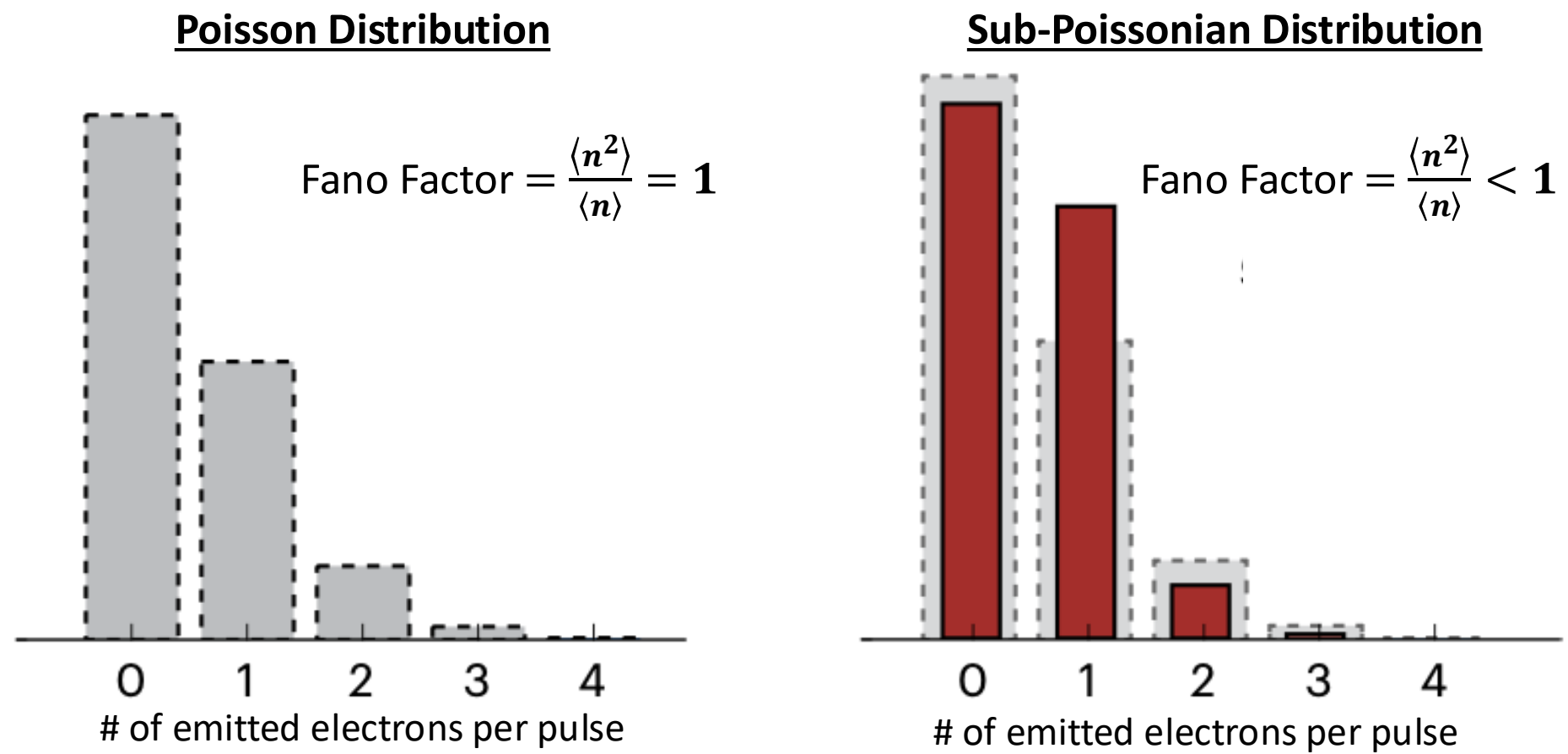
We can imagine tuning the emitter size D to set a maximum bunch charge of single to few electrons at the space charge limit.



We can imagine tuning the emitter size D to set a maximum bunch charge of single to few electrons at the ~~space charge~~ “Coulomb blockade” limit.



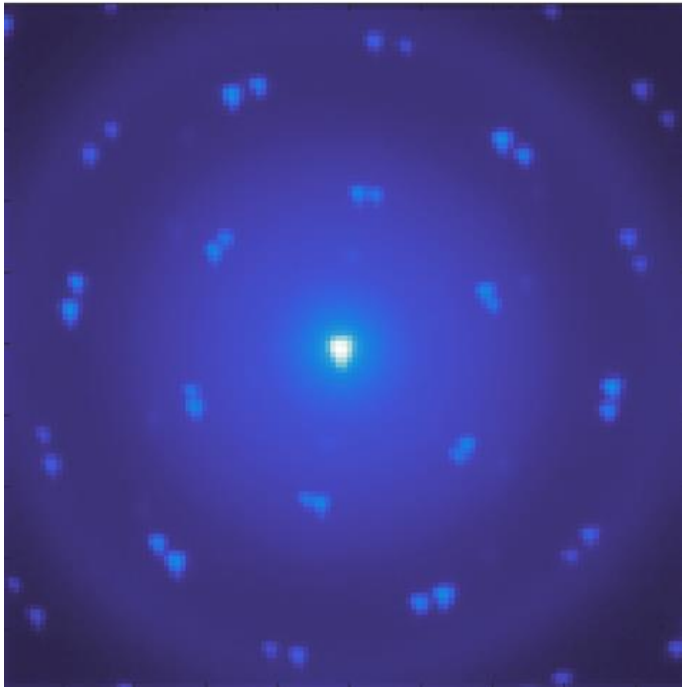
In the Coulomb blockade emission of few electrons, we can achieve sub-Poissonian statistics.



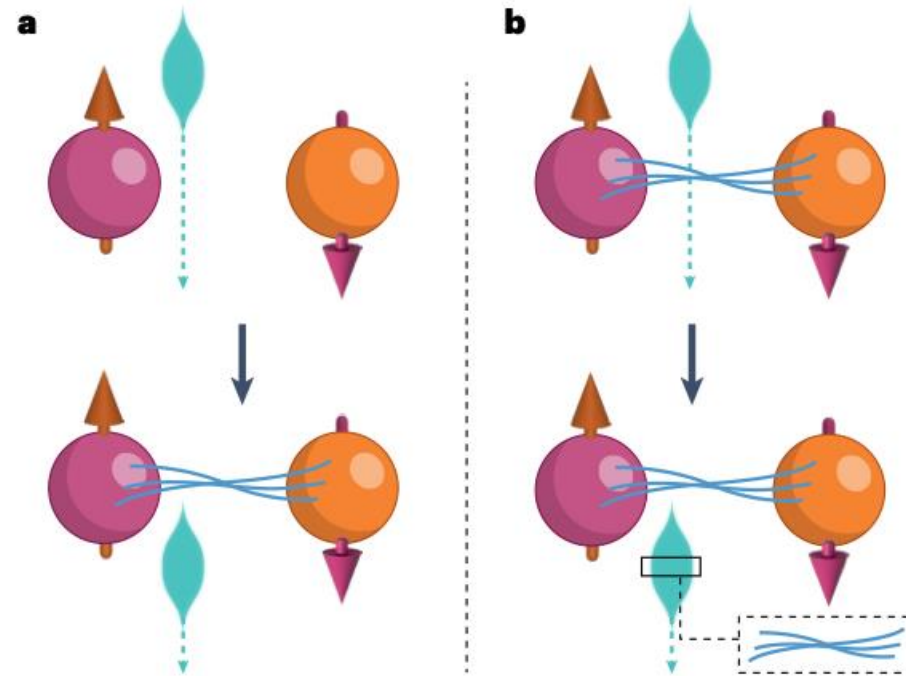
For example, with an average emission of 0.5 electrons, sub-Poissonian emission significantly improves the chances of emitting **only 1 electron per pulse**.

On-demand single electron emission can improve current imaging methods and potentially unlock new ones.

Sub-shot noise UED

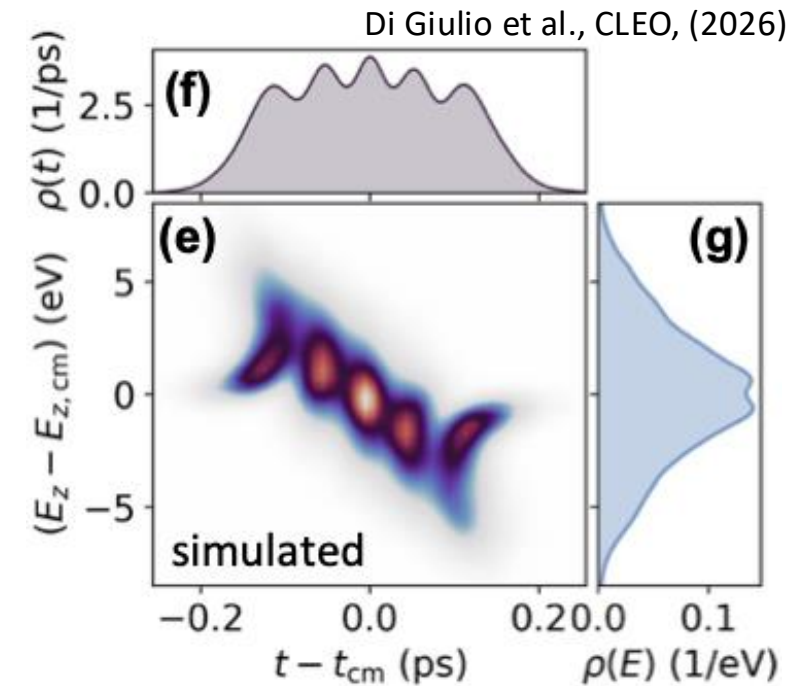


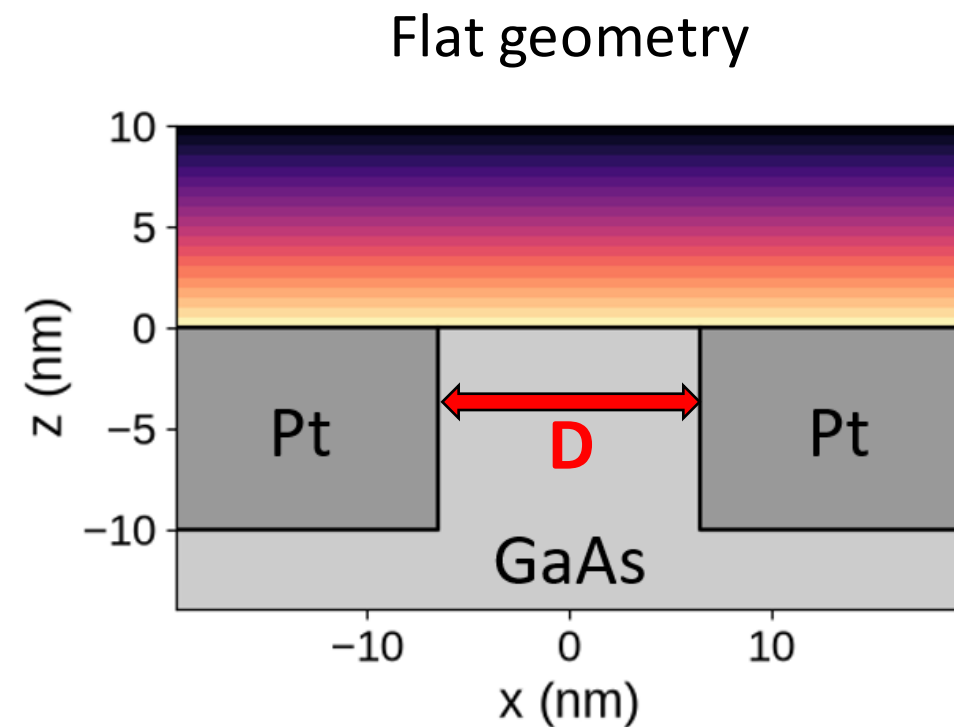
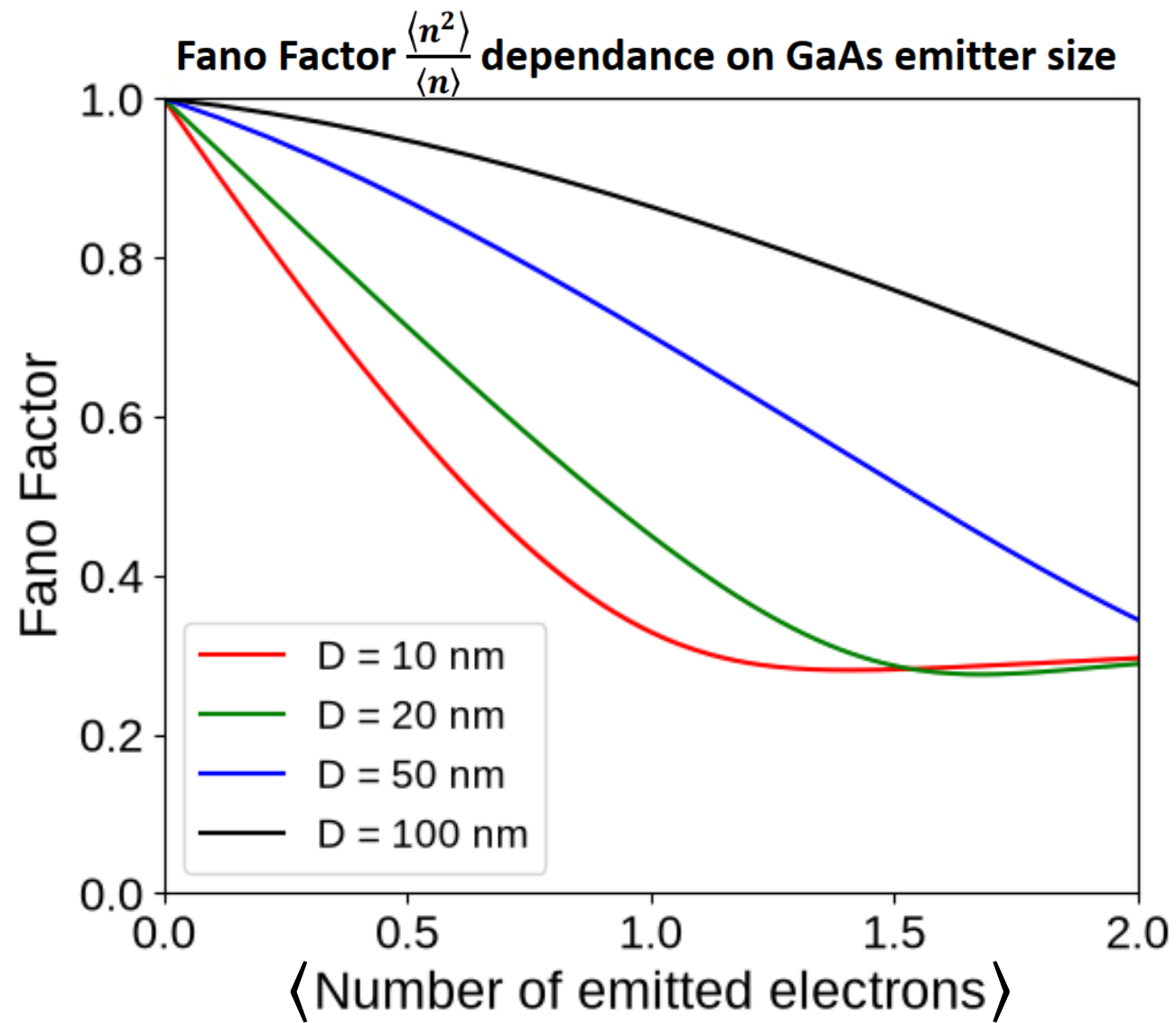
Free electron quantum optics

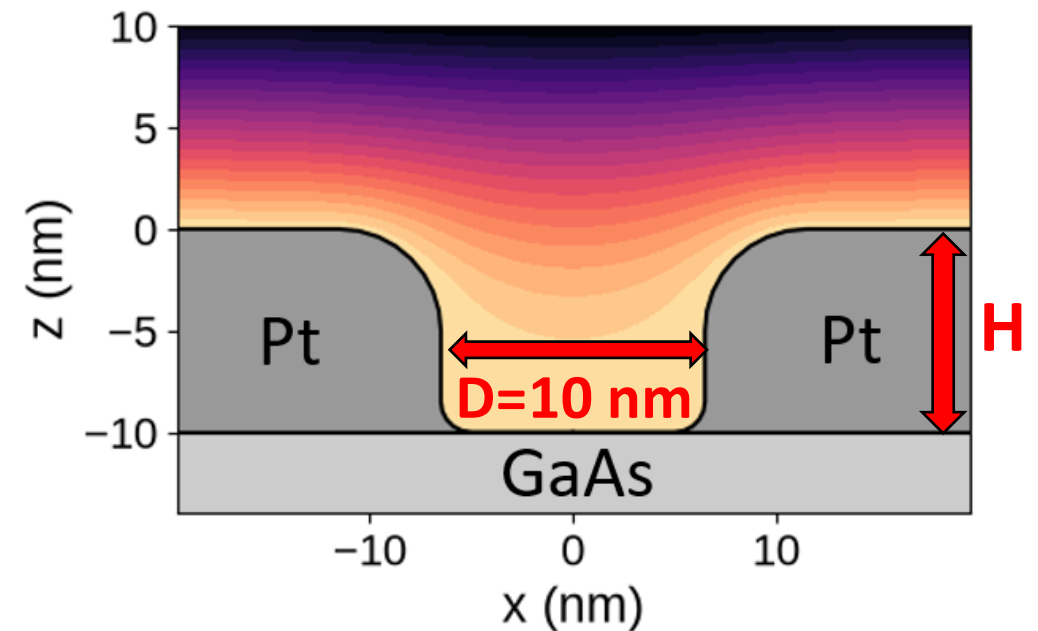
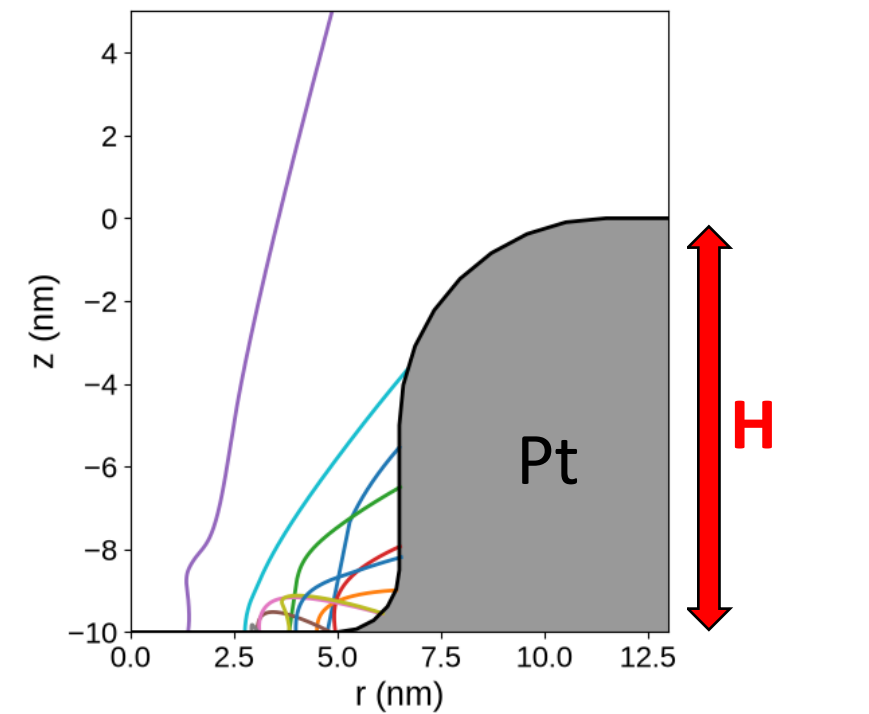
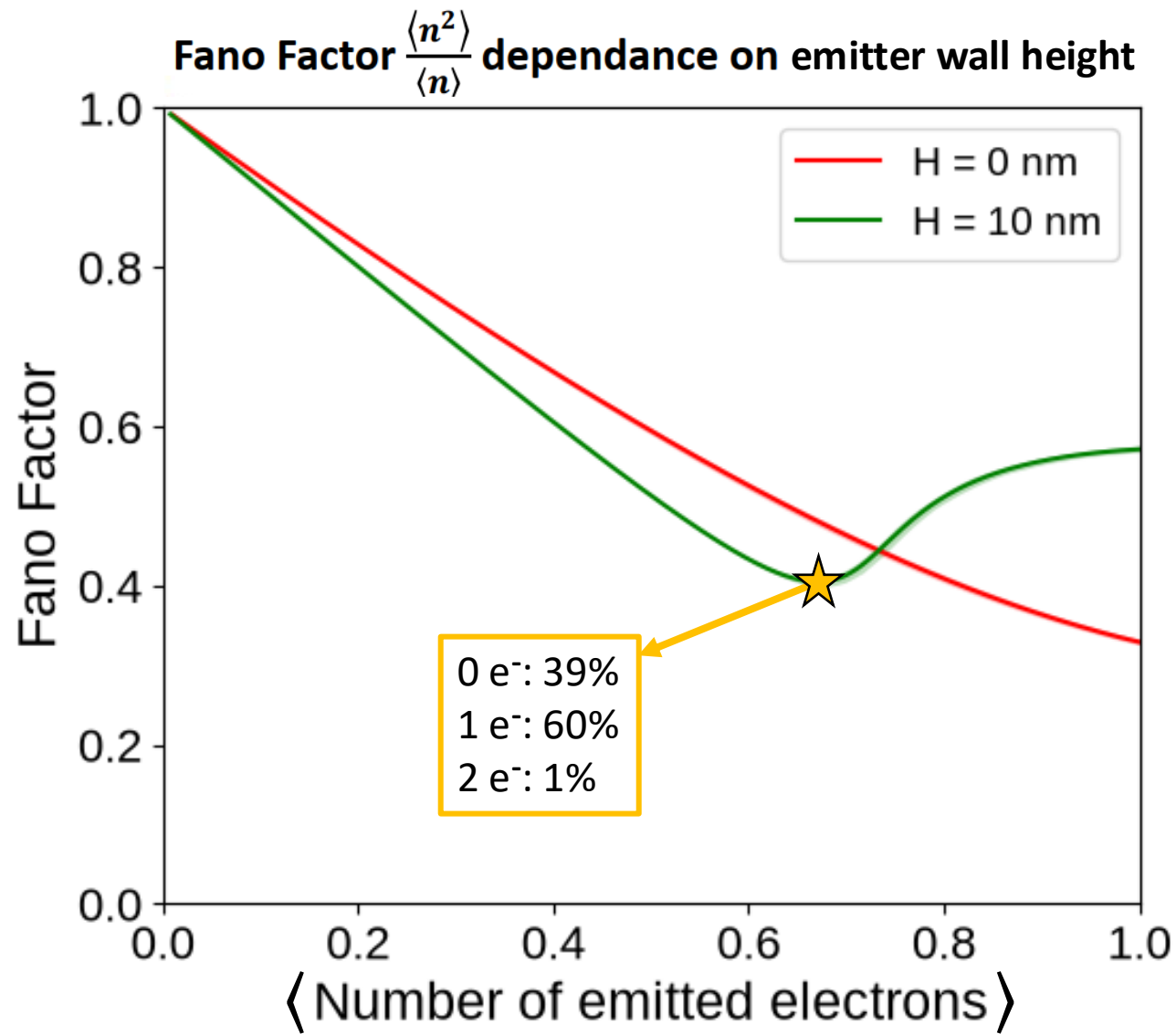


Ruimy et al., Nature Physics **21**, (2025)

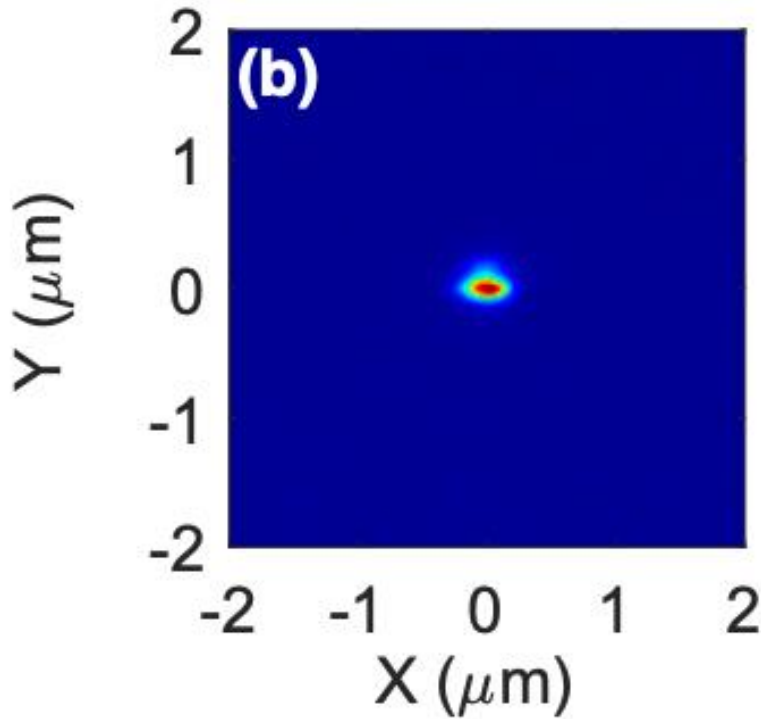
Highly-ordered Electron Beams



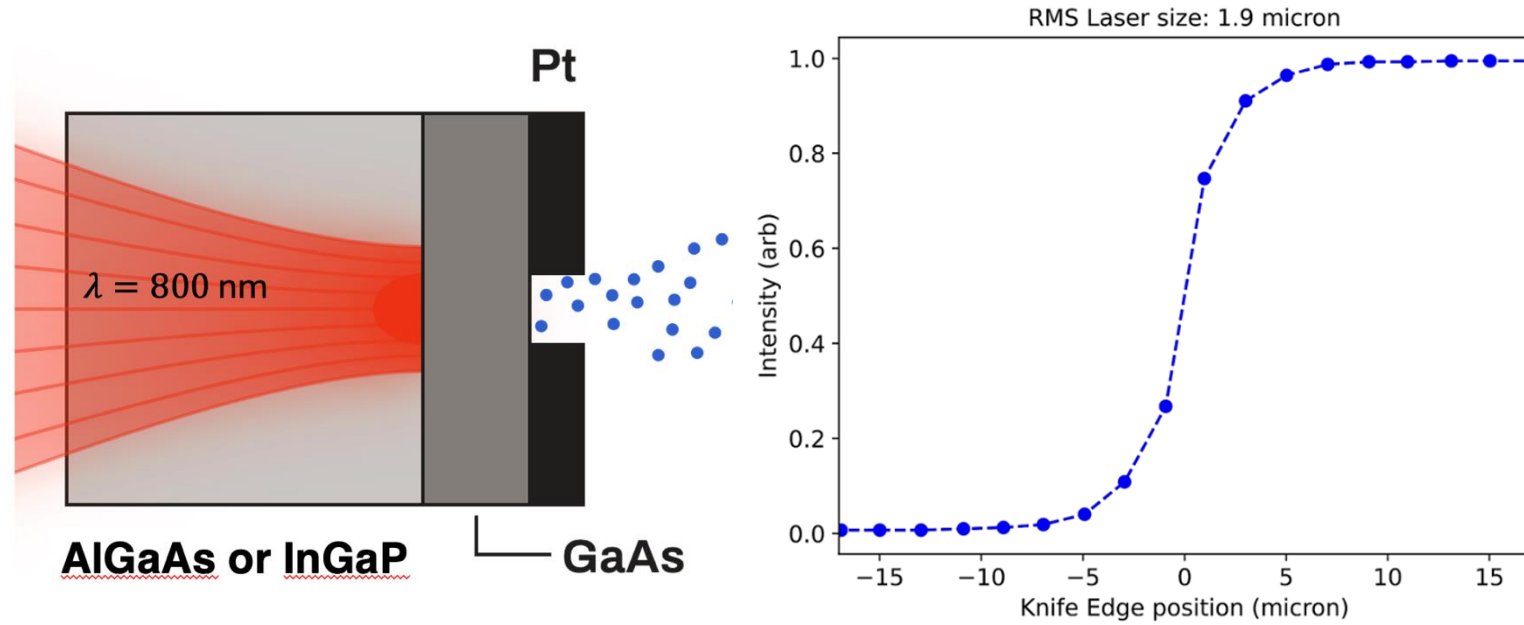




Takeaways

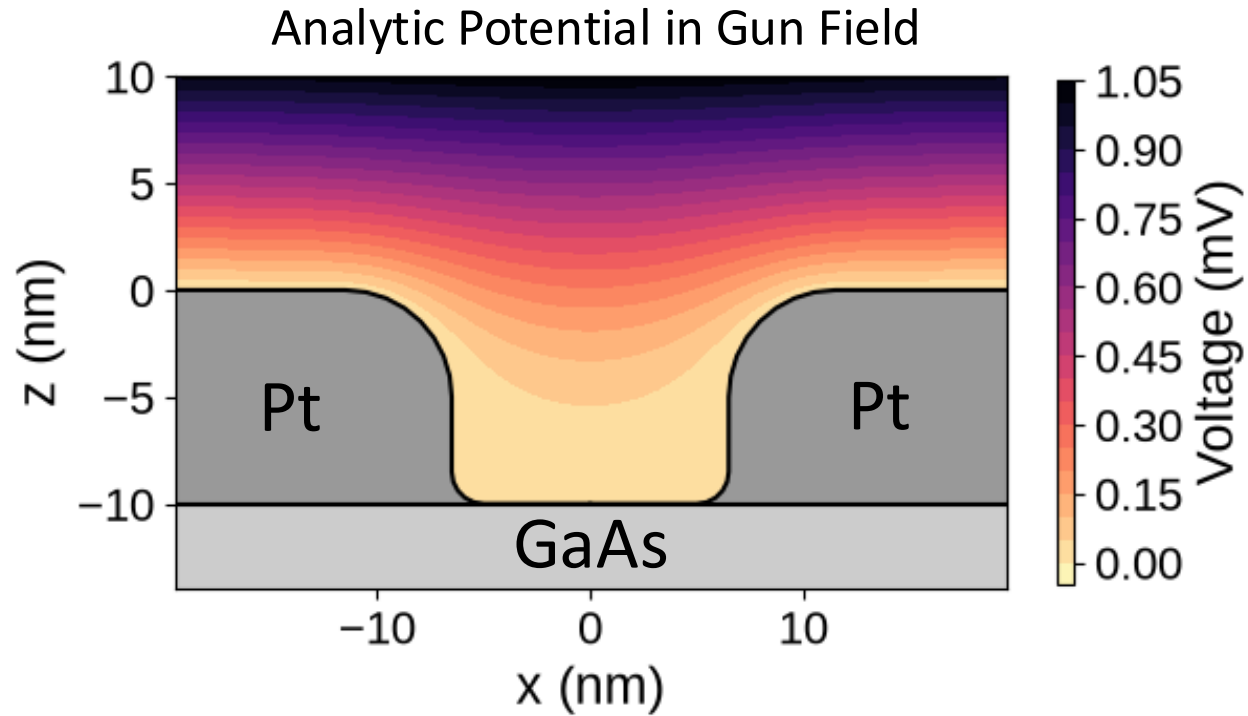


Demonstrated sub-micron electron emission using photoemission contrast.

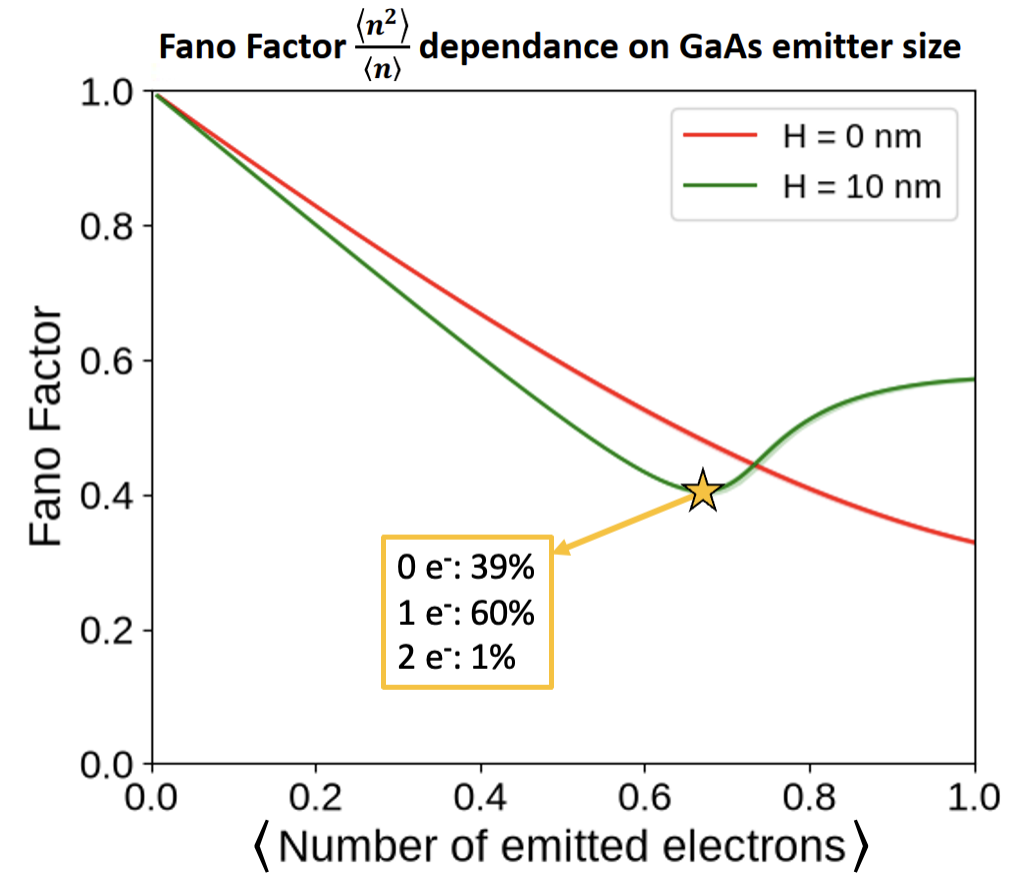


Proposed approach for achieving high charge and small response times with GaAs nanoemitters for ultrafast applications, e.g UED.

Takeaways



Developed model for electron dynamics near nanoemitters.



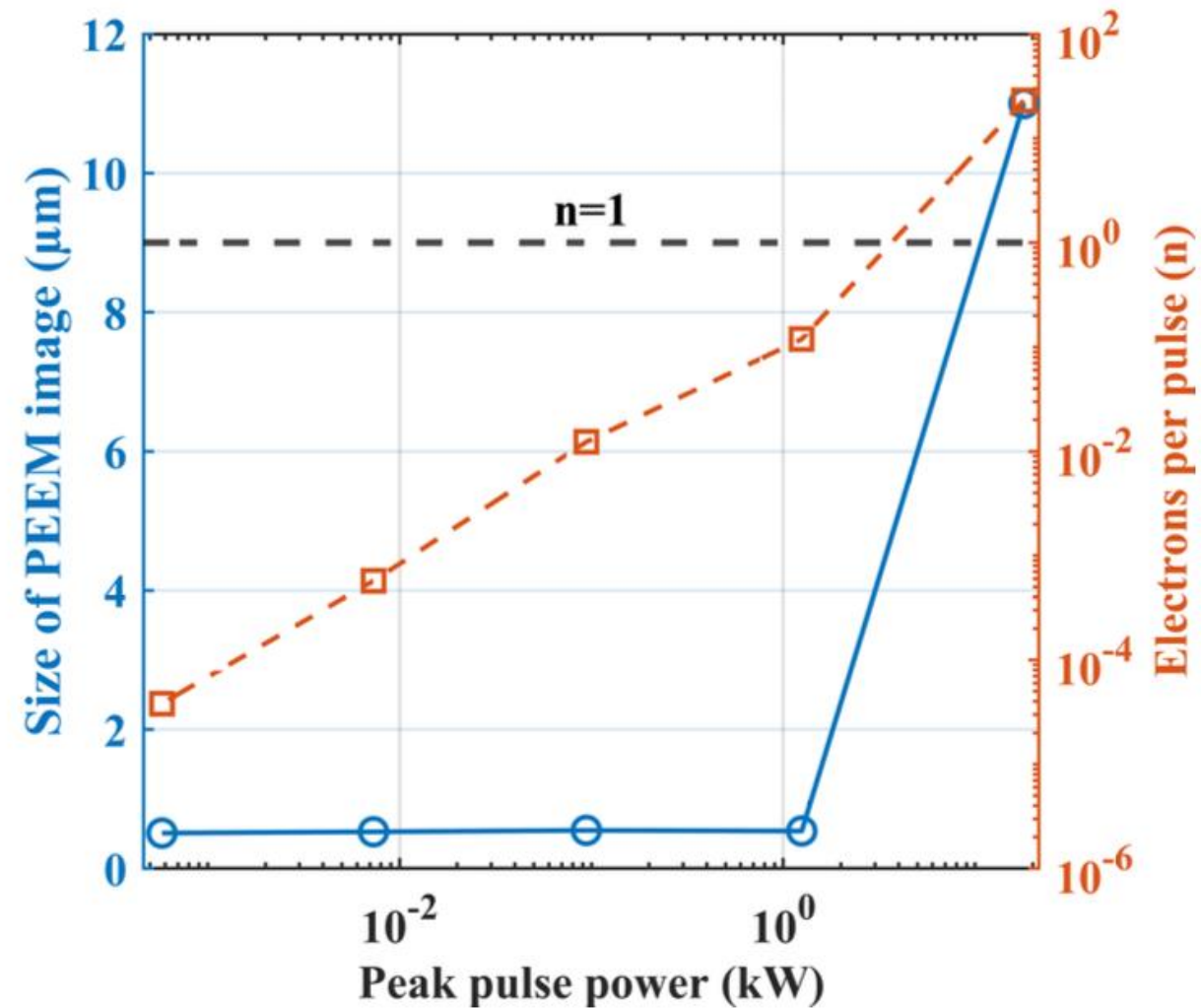
Simulated sub-Poissonian emission for varying emitter geometries, yielding a Fano factor as low as 0.4.



FIN

Backup/abandoned slides

Space charge becomes more effective with increasing the bunch charge and results in broadening of the measured PEEM spot



Photoemission electron microscope measurements of nano-emitters at ASU

