# Optical Voltage Imaging with charge coupled fluorescence of diamond colour centres

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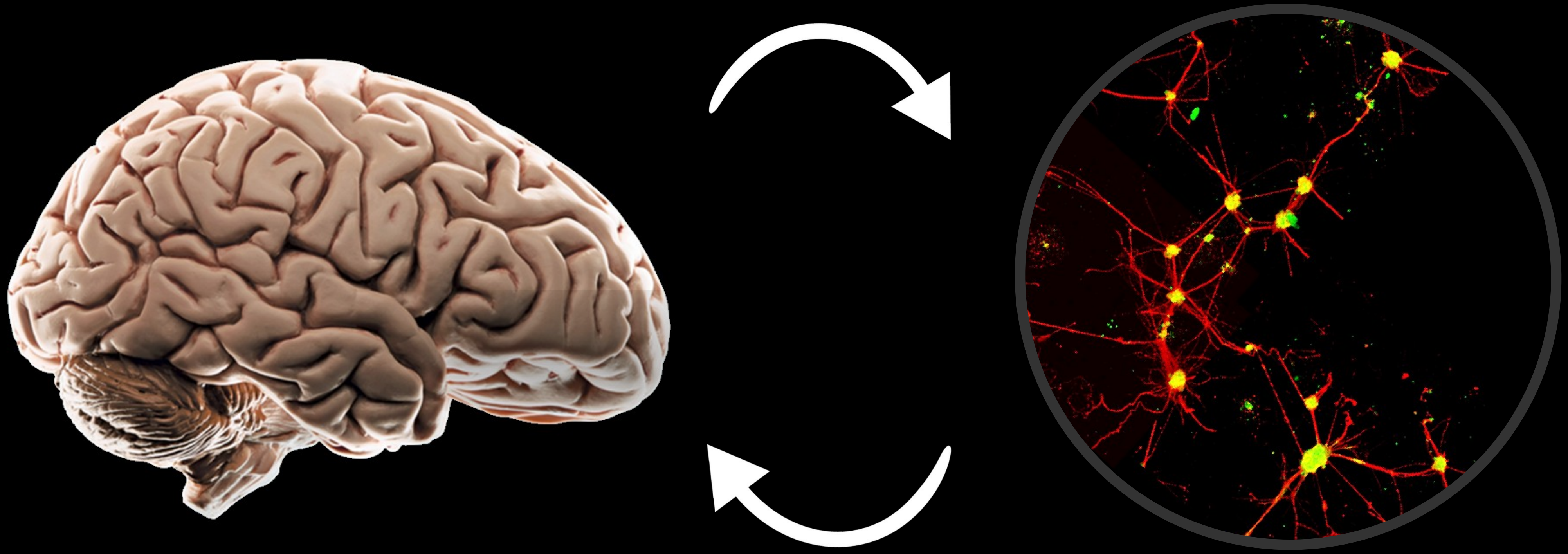
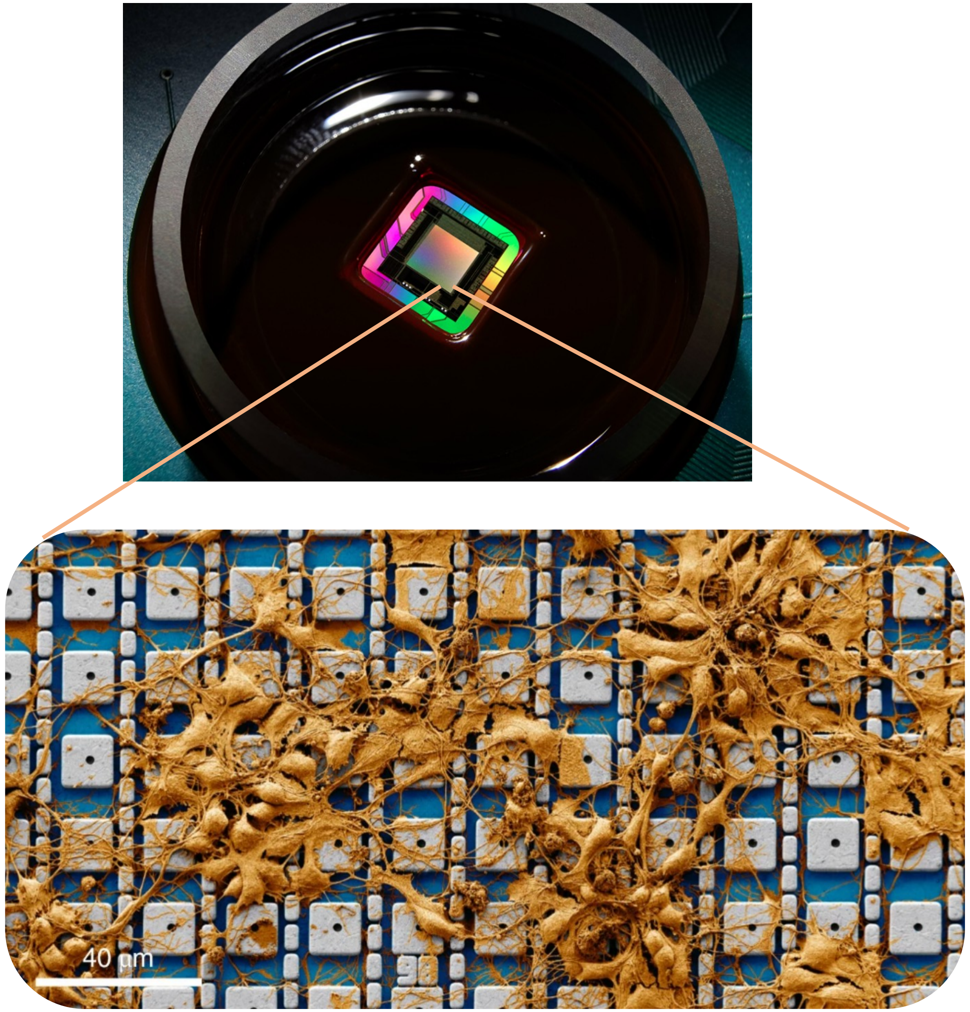
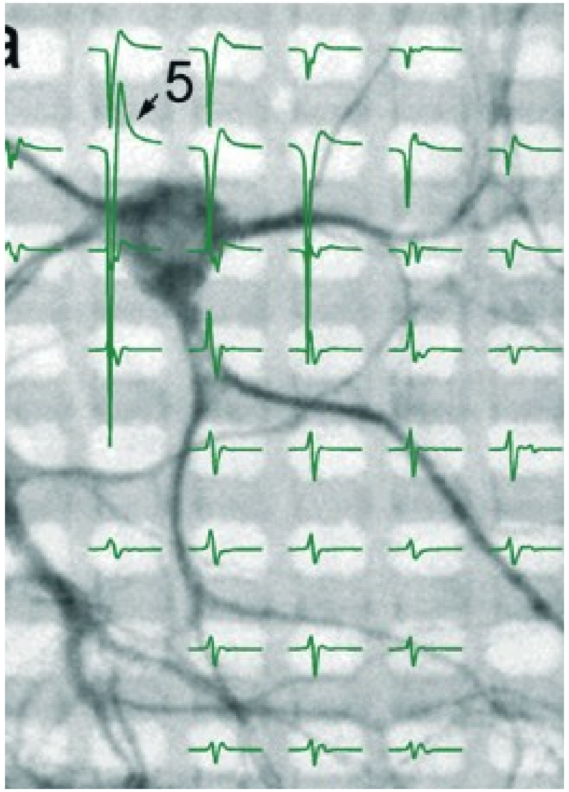
# Cultured neurons to model the brain



# Voltage Imaging

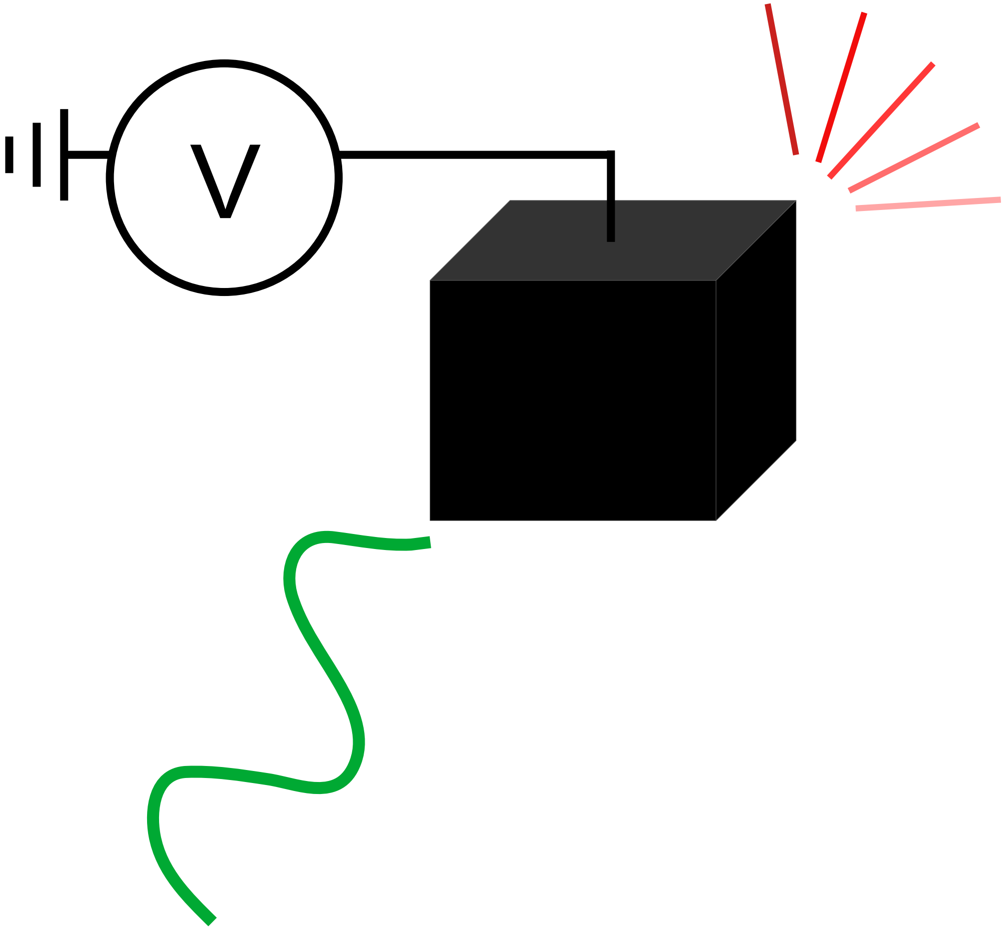



Thermal considerations
Coupling considerations
Limited resolution and scale

Muller, J. et. al. Lab Chip (2015), 15, 2767

# Optical Voltage Imaging



# Optical Voltage Imaging

FRET

Stark
Effect

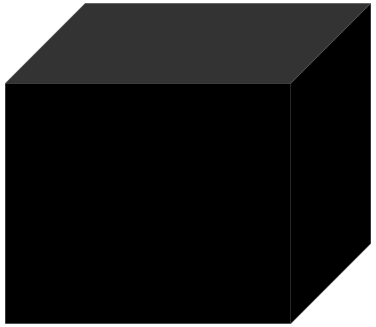
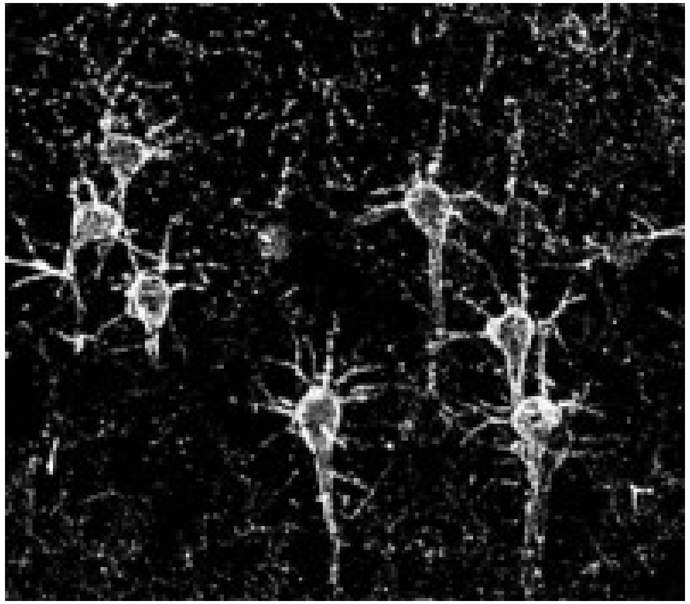
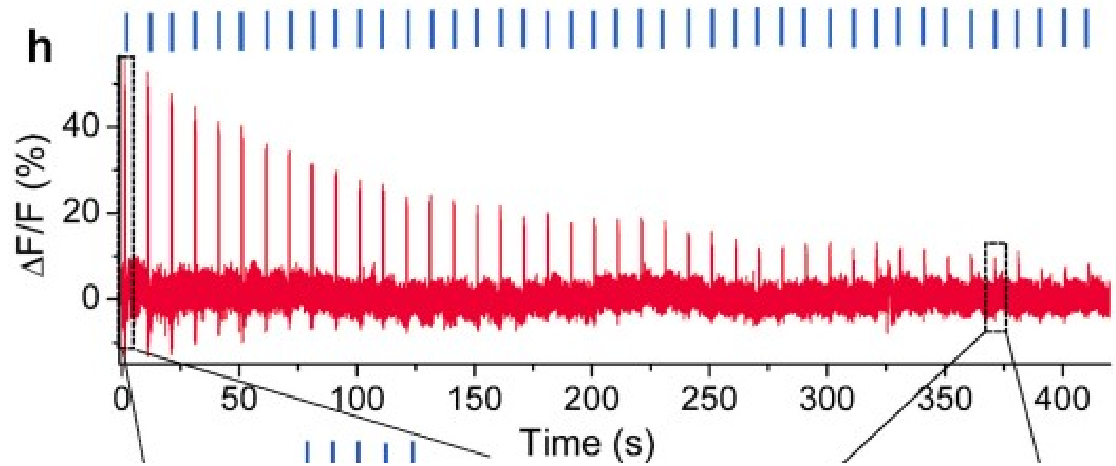


Photo-electron transfer

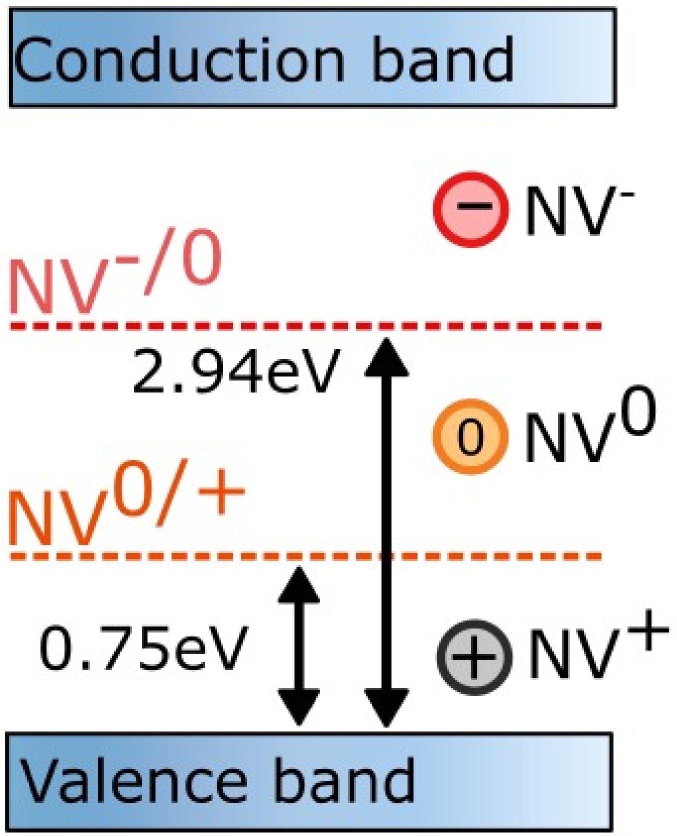
Lifetime
Rate of response
Limited expression / invasive
Not Quantitative

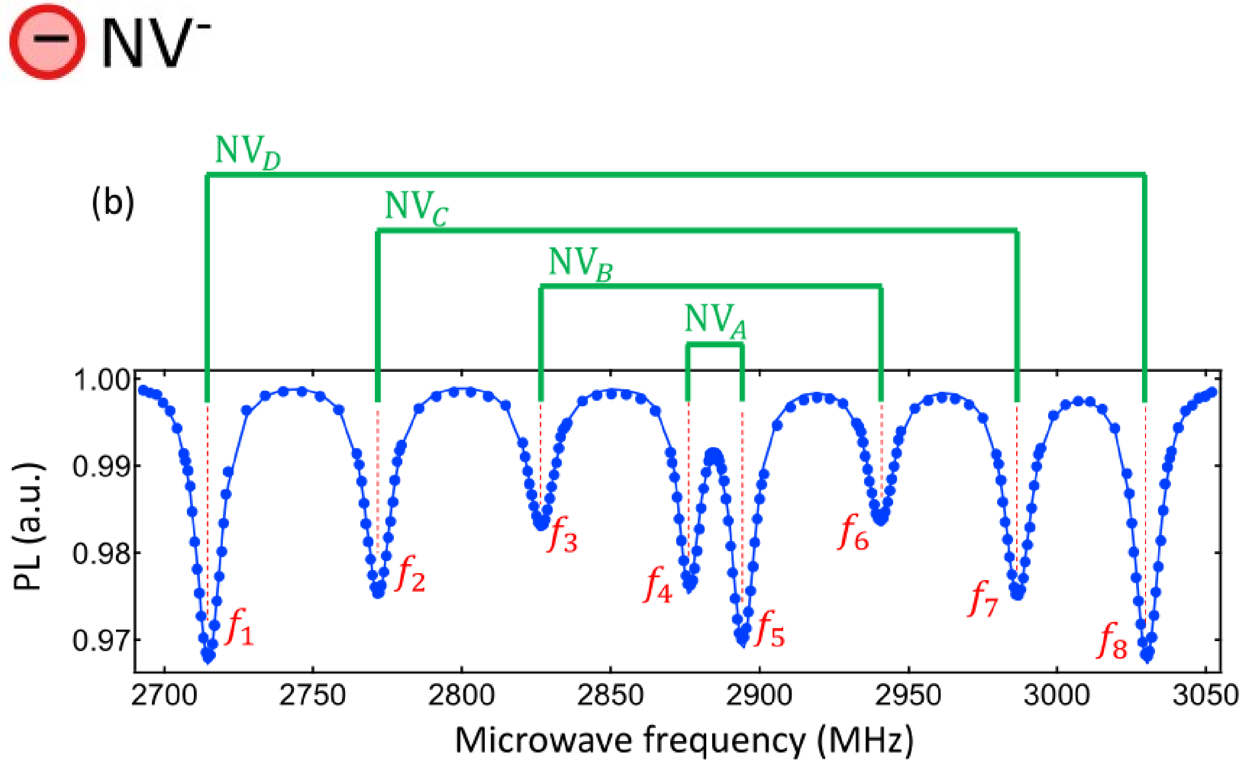





Piatkevich, K.D. et al., *Nature* 2019

# The NV colour center in diamond

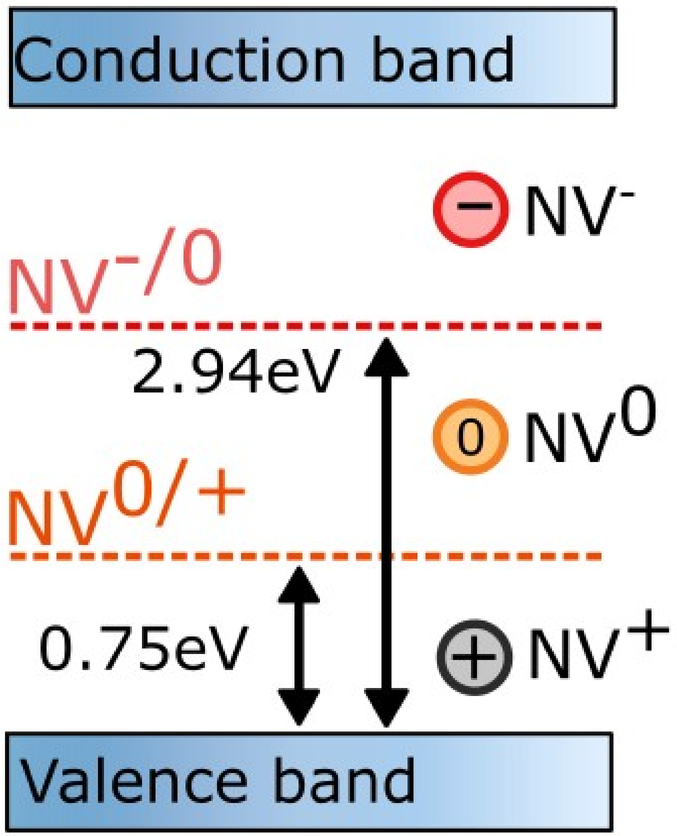


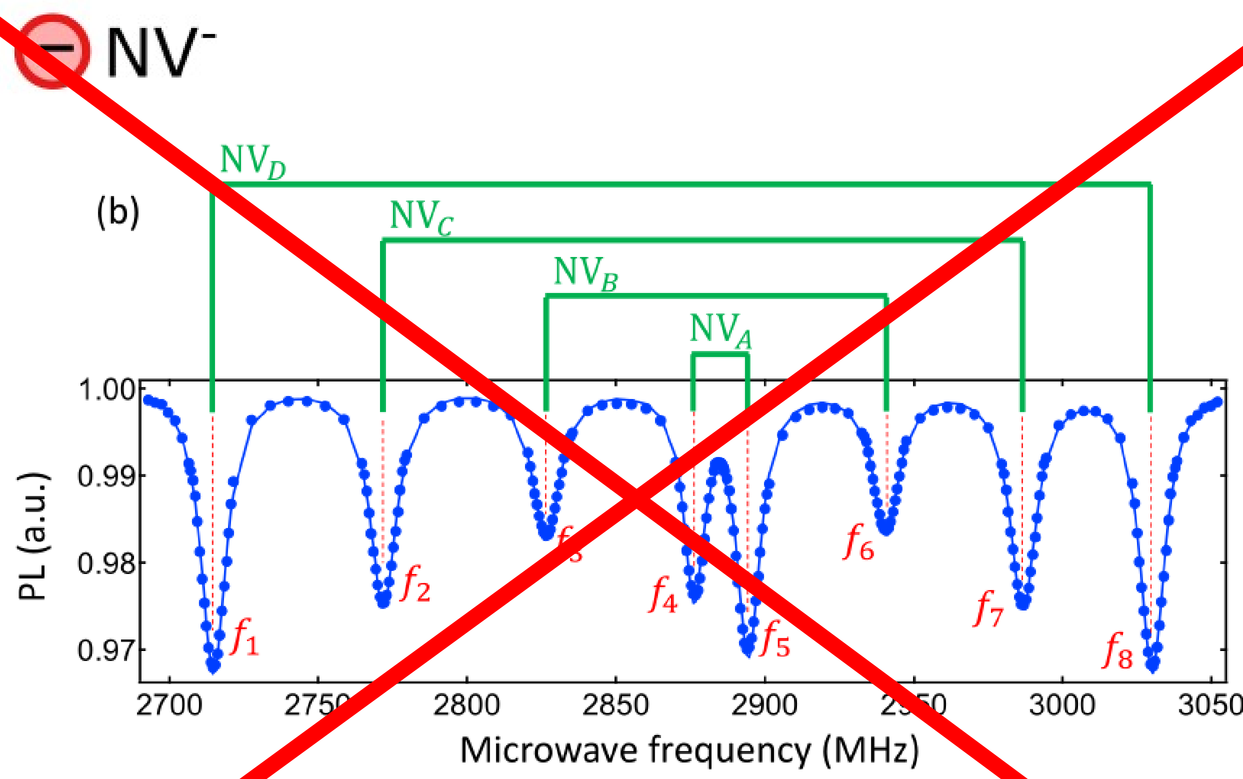




$$\mathcal{H} = (D + k_{\parallel}F_Z)(S_Z^2 - 2/3) + \gamma_{\rm NV}\vec{S}\cdot\vec{B} - k_{\perp}F_X(S_X^2 - S_Y^2) + k_{\perp}F_Y(S_XS_Y + S_YS_X)$$

Broadway, D. A.*, **Dontschuk, N.***, et. al. (2018). Nature Electronics, 1(9), 502–507.

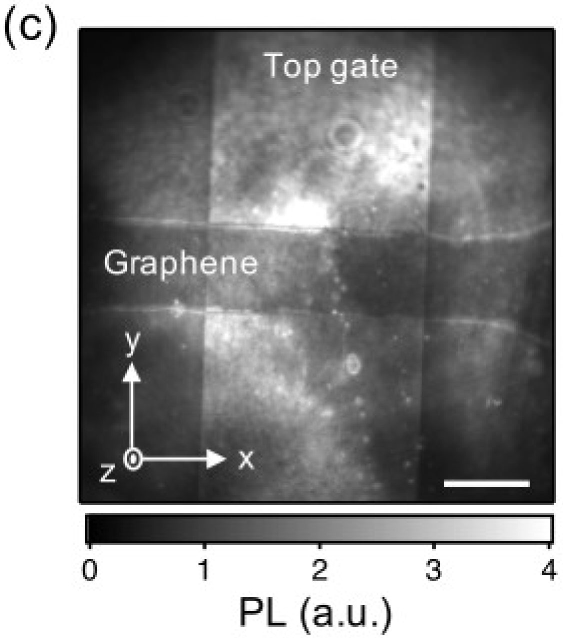
# The NV colour center in diamond

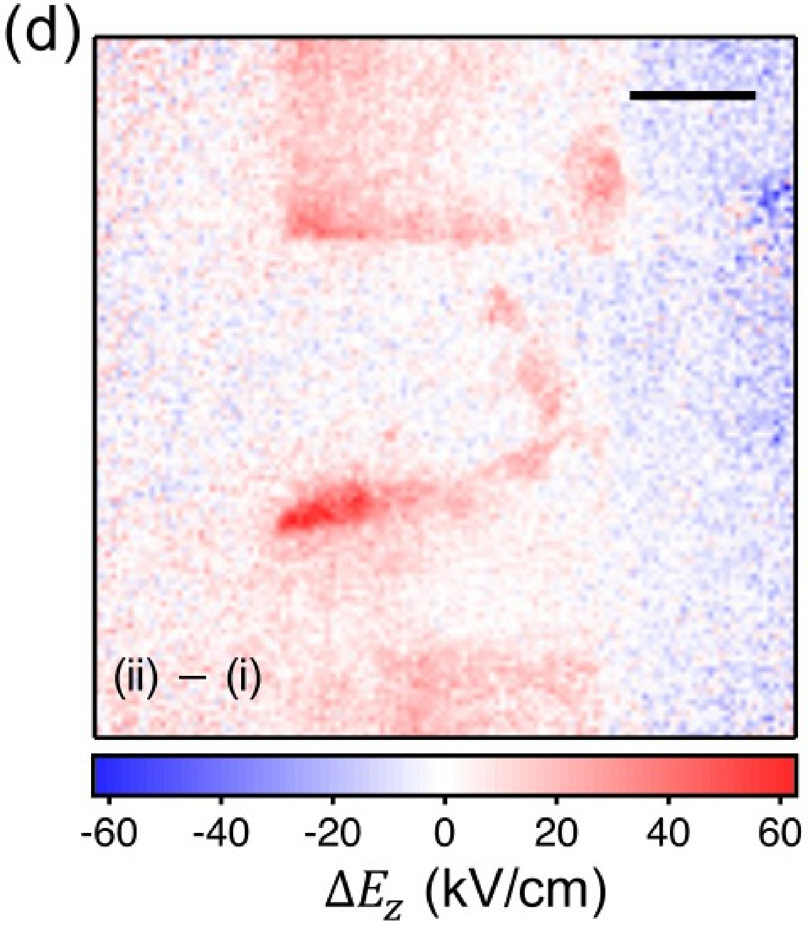


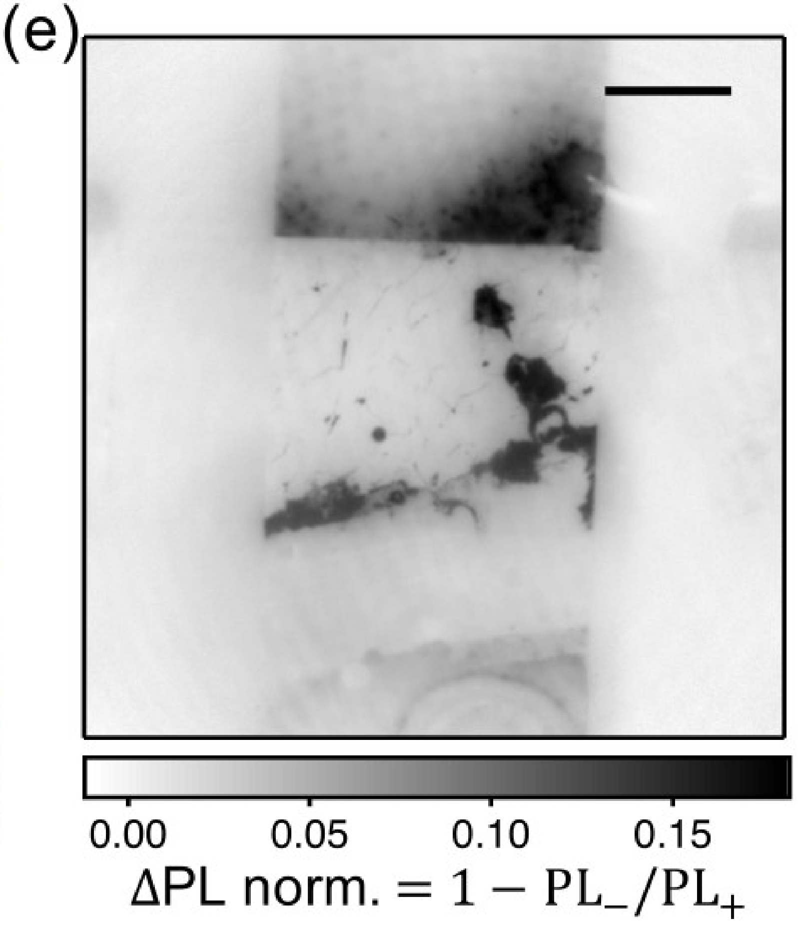

$$\mathcal{H} = (D + k_{\|} F_Z)(S_Z^2 - 2/3) + \gamma_{\mathrm{NV}} \vec{S} \cdot \vec{B}$$
$$- k_{\perp} F_X (S_X^2 - S_Y^2) + k_{\perp} F_Y (S_X S_Y + S_Y S_X)$$

# Charge coupled fluorescence



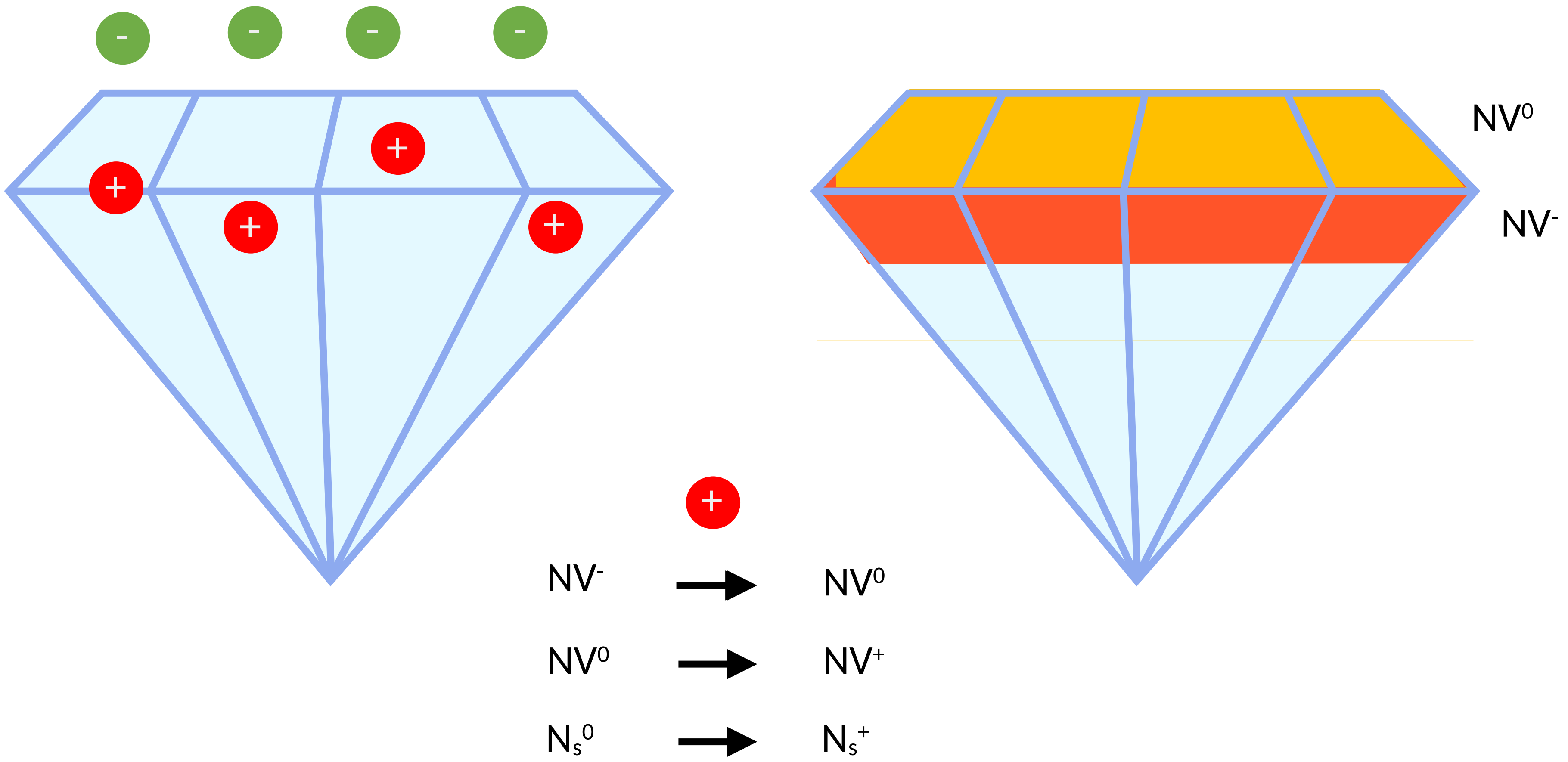

2 days



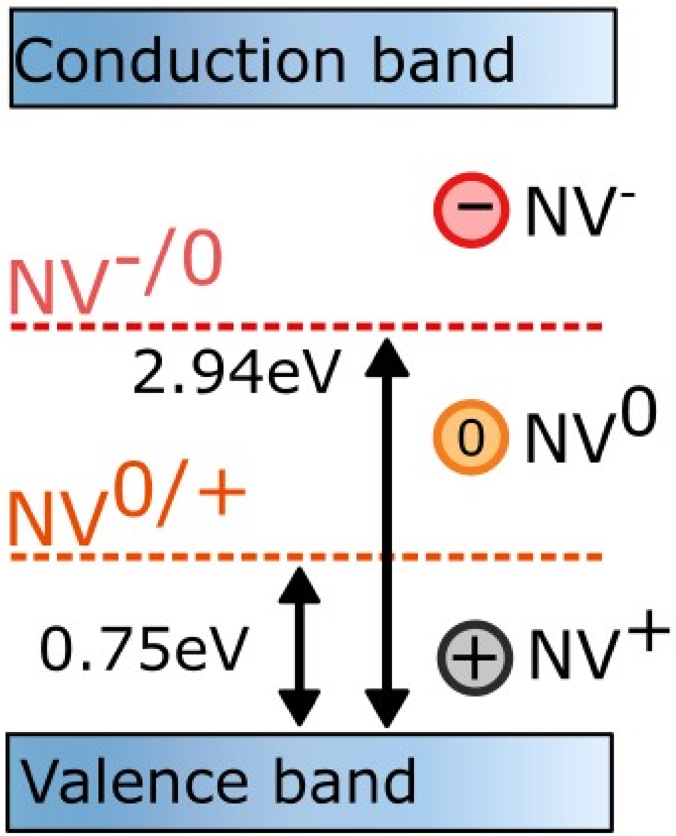

60 ms

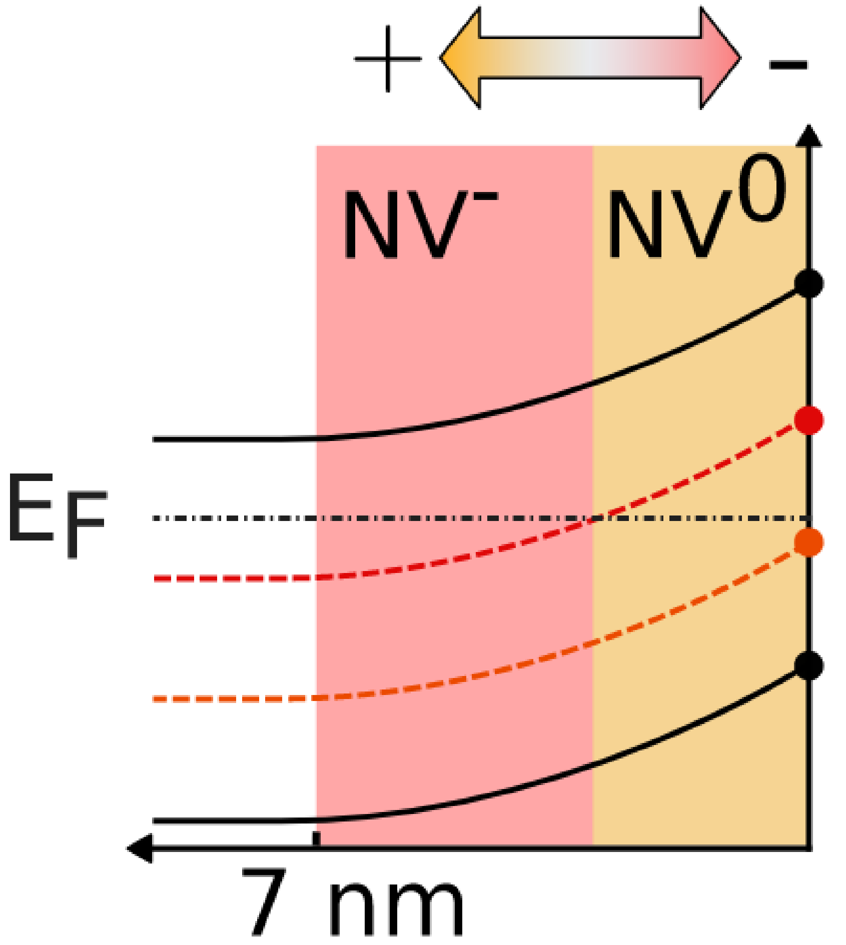
Lillie, S. E., **Dontschuk, N.**,et. al. (2019). Physical Review Applied, 12(2), 24018.

# Coupled how?


-
-
-
-
+
+
+
+
$NV^0$
$NV^-$
+
$NV^- \rightarrow NV^0$
$NV^0 \rightarrow NV^+$
$N_s^0 \rightarrow N_s^+$

# Band description



# Done before.

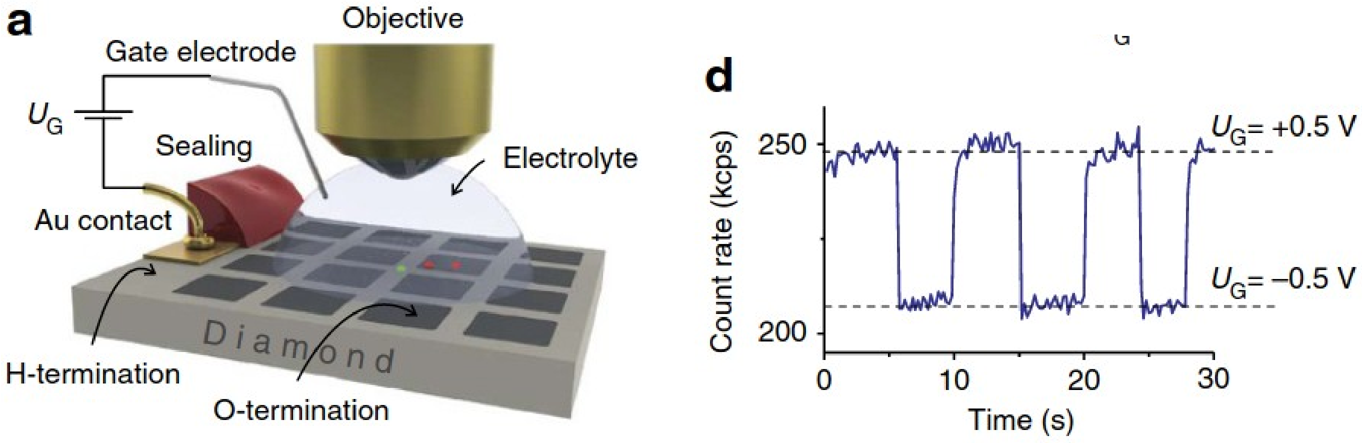
Received 26 Aug 2011 | Accepted 3 Feb 2012 | Published 6 Mar 2012 DOI: 10.1038/ncomms1729

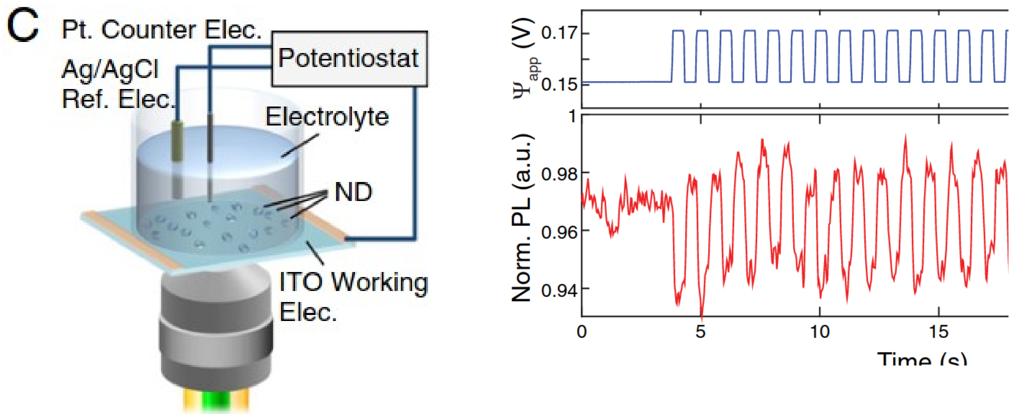
## Charge state manipulation of qubits in diamond

Bernhard Grotz[1], Moritz V. Hauf[2], Markus Dankerl[2], Boris Naydenov[4], Sébastien Pezzagna[3], Jan Meijer[3], Fedor Jelezko[4], Jörg Wrachtrup[1], Martin Stutzmann[2], Friedemann Reinhard[1] & Jose A. Garrido[2]

## Modulation of nitrogen vacancy charge state and fluorescence in nanodiamonds using electrochemical potential

Sinan Karaveli[a,b,1], Ophir Gaathon[a,c,1], Abraham Wolcott[a,c,d,2], Reyu Sakakibara[a], Or A. Shemesh[e,f,h,i], Darcy S. Peterka[g], Edward S. Boyden[e,f,h,i], Jonathan S. Owen[d], Rafael Yuste[g], and Dirk Englund[a,3]



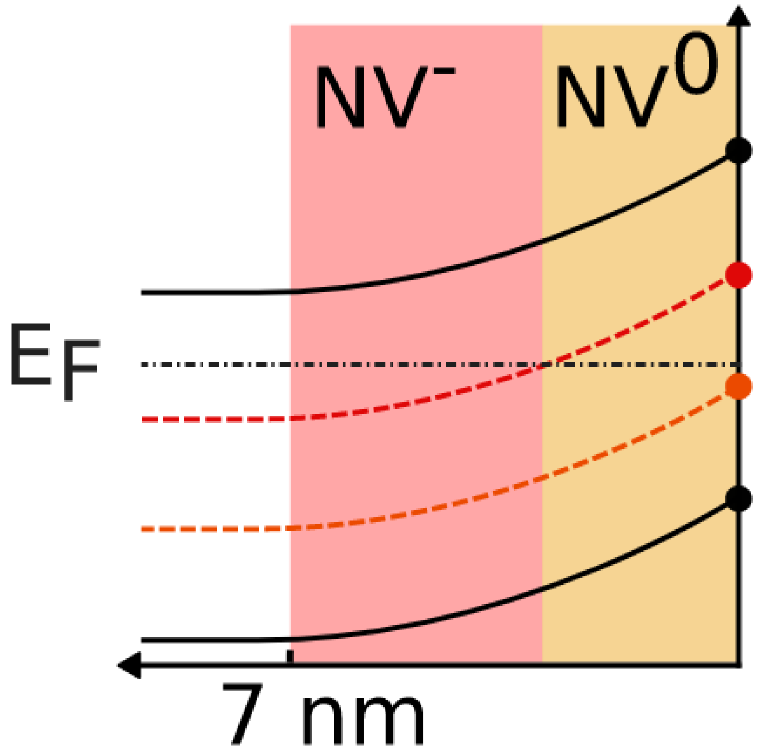

$\beta$ = 0.0002 % $mV^{-1}$

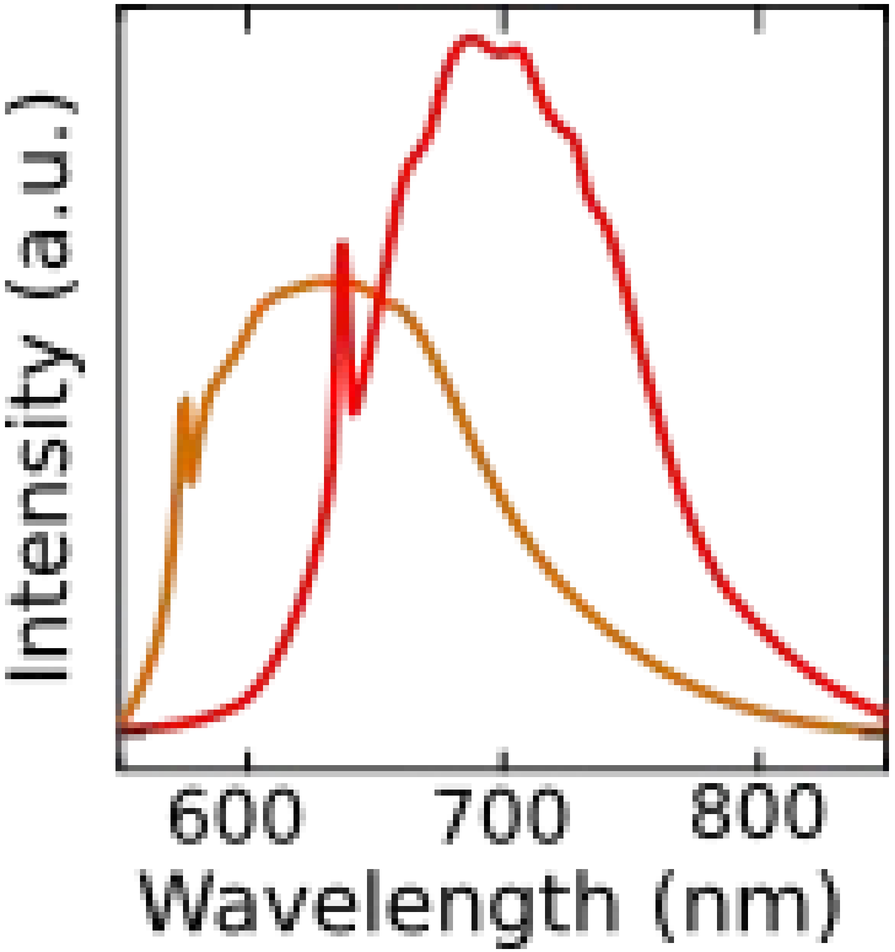
Best nano diamond

$\beta$ = 0.1 % $mV^{-1}$

# Can it be better?

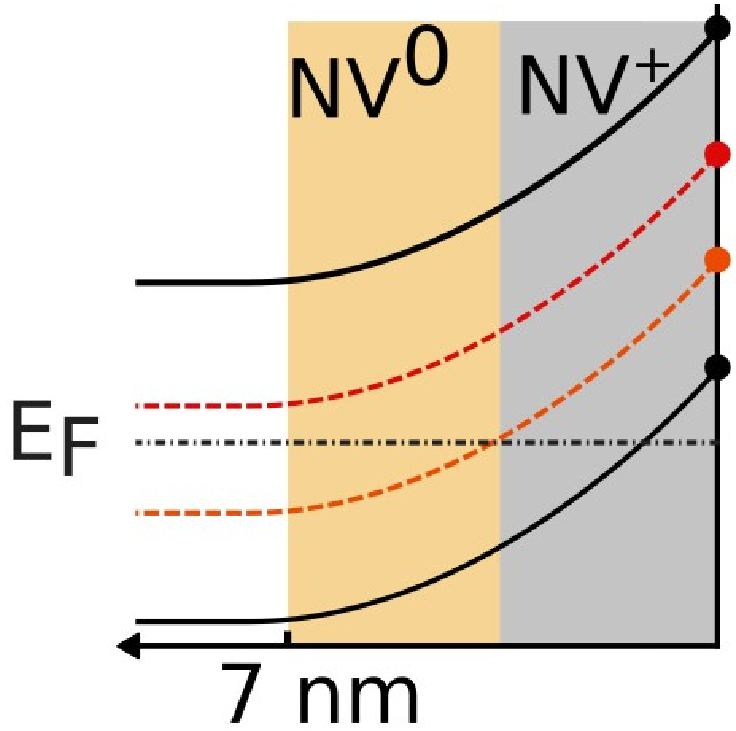
$$\eta = \frac{1}{\beta\sqrt{I_0}}$$

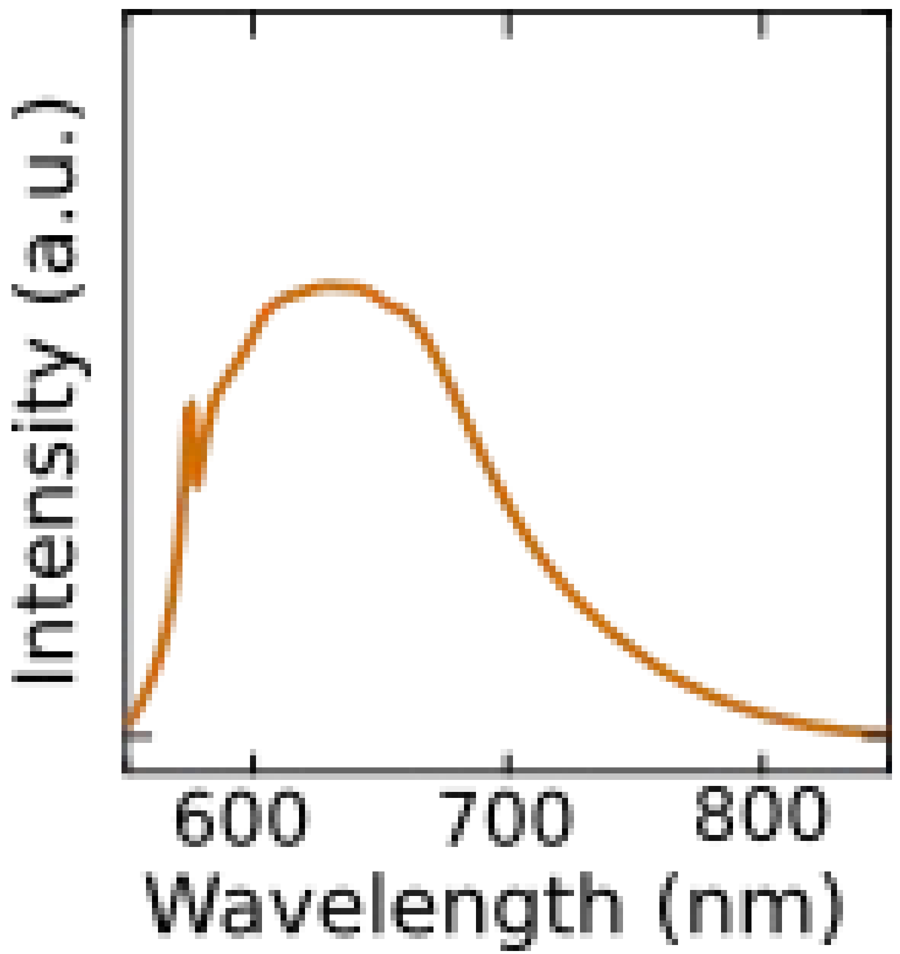


# Easiest improvement

$$\eta = \frac{1}{\beta\sqrt{I_0}}$$



# What next?

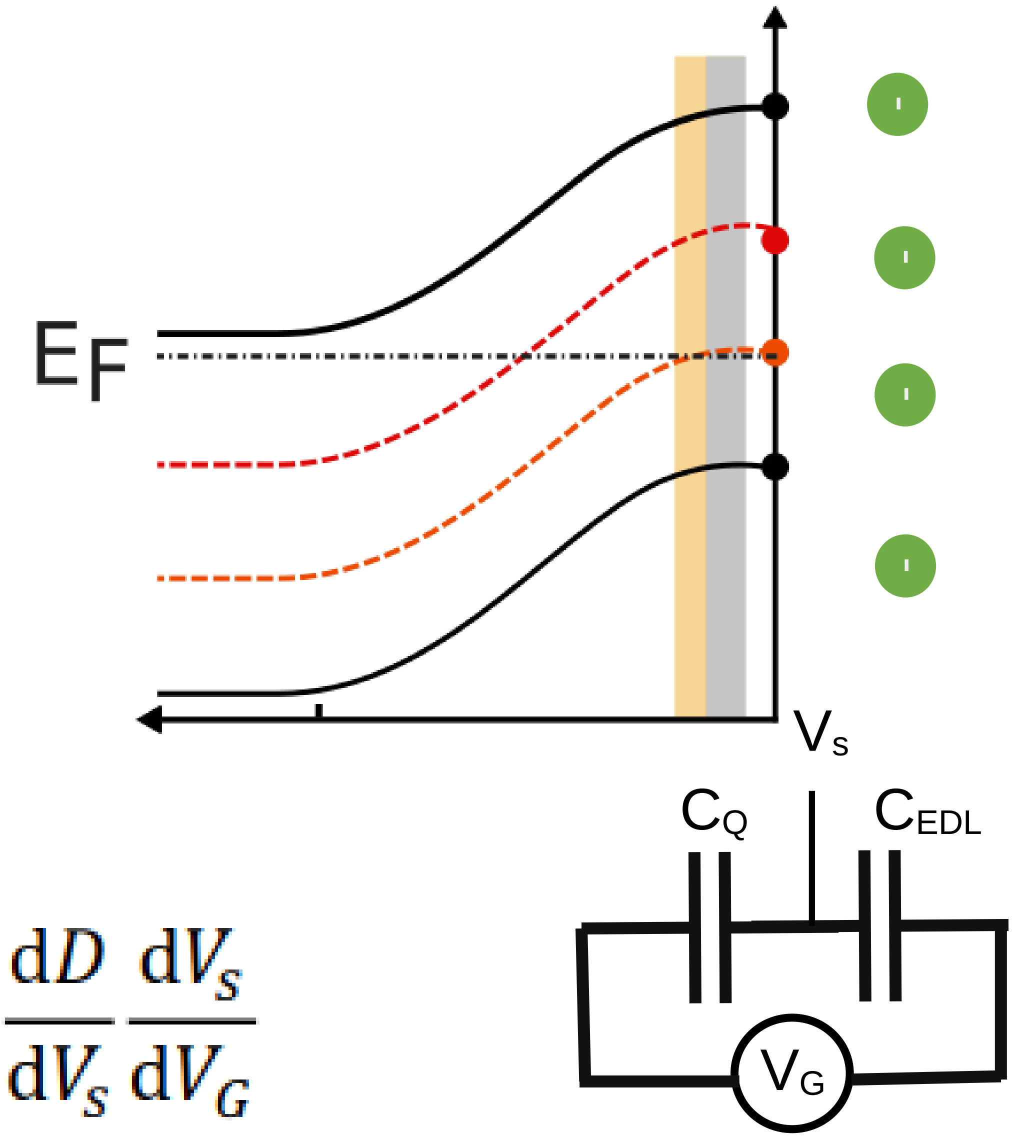
$$D = f_D(V_s) = \frac{1}{1 + exp\left(\frac{E_D + E_F - eV_s}{kT}\right)}$$

$$\frac{\mathrm{d}D}{\mathrm{d}V_S} = \frac{e}{kT} D(1 - D)$$

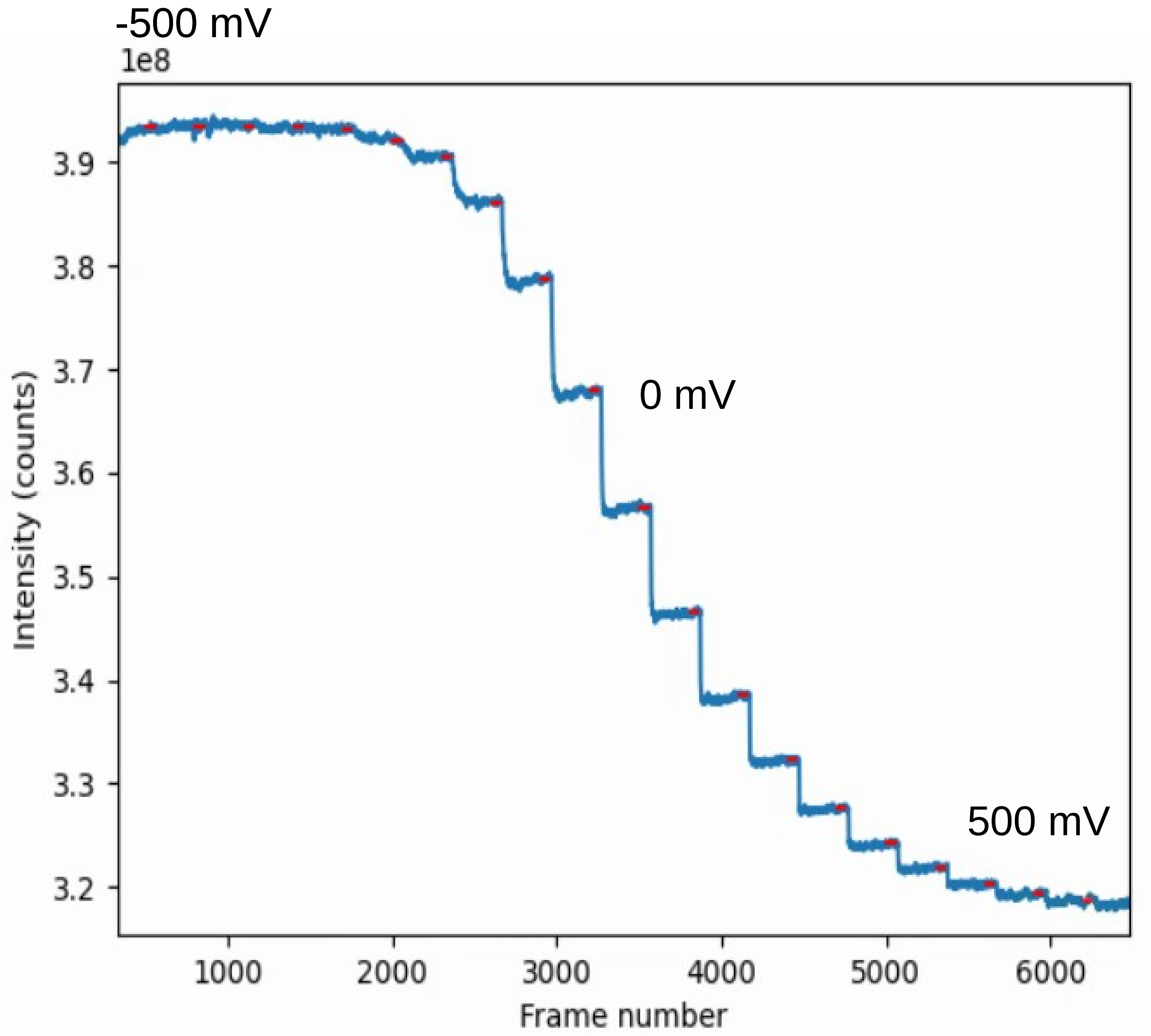
$$\frac{\mathrm{d}V_s}{\mathrm{d}V_G} = \frac{C_{EDL}}{C_{EDL} + C_Q}$$

$$C_Q = \frac{\mathrm{d}D}{\mathrm{d}V_s} \rho \chi e$$

$$\beta = \frac{1}{D}\frac{\mathrm{d}D}{\mathrm{d}V_G} = \frac{1}{D}\frac{\mathrm{d}D}{\mathrm{d}V_s}\frac{\mathrm{d}V_s}{\mathrm{d}V_G}$$

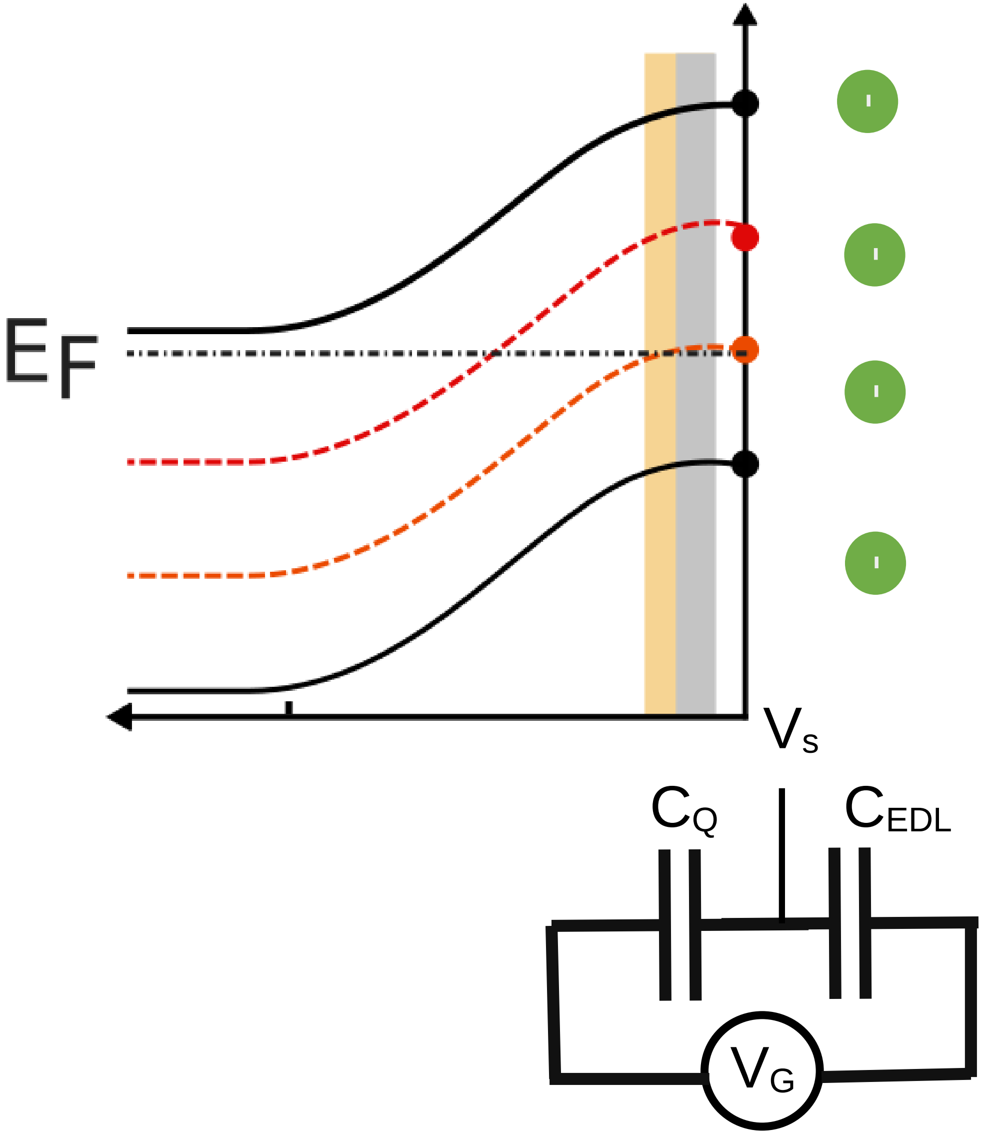


# A quick aside:



# Guidance!

$$\beta = \frac{eC_{EDL}(1-D)}{kTC_{EDL} + \rho\chi e^2 D(1-D)}$$



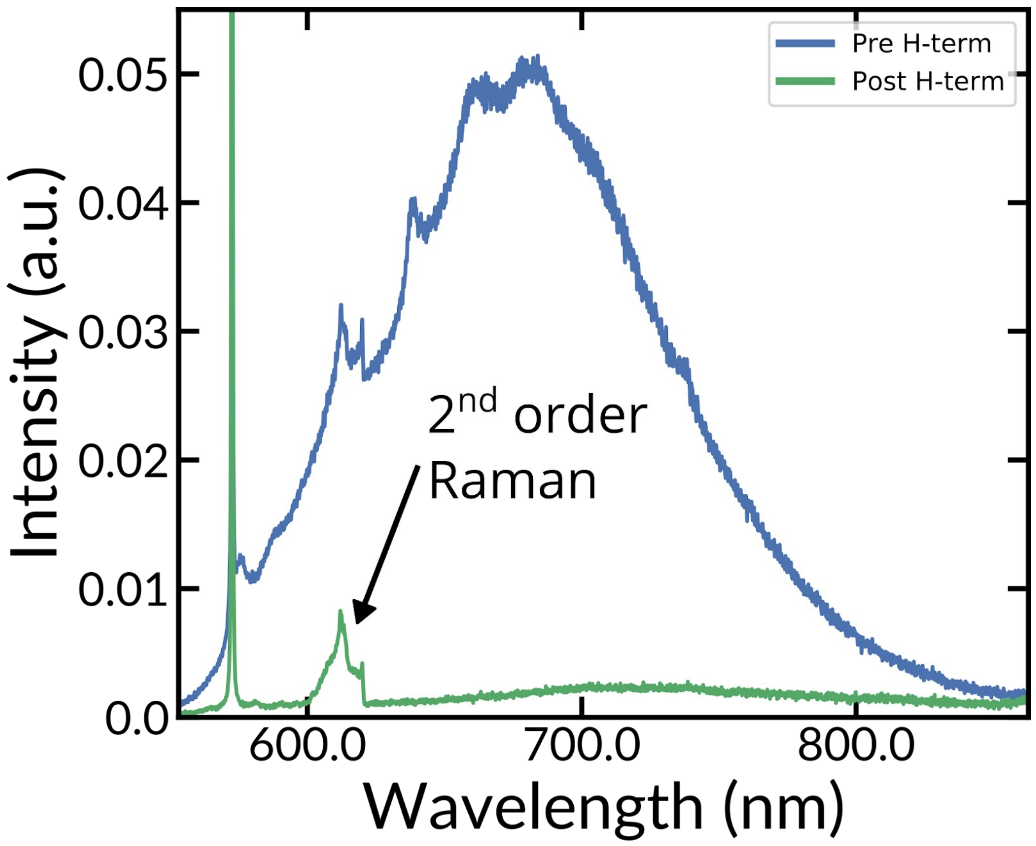

Less $NV^0$ is more.

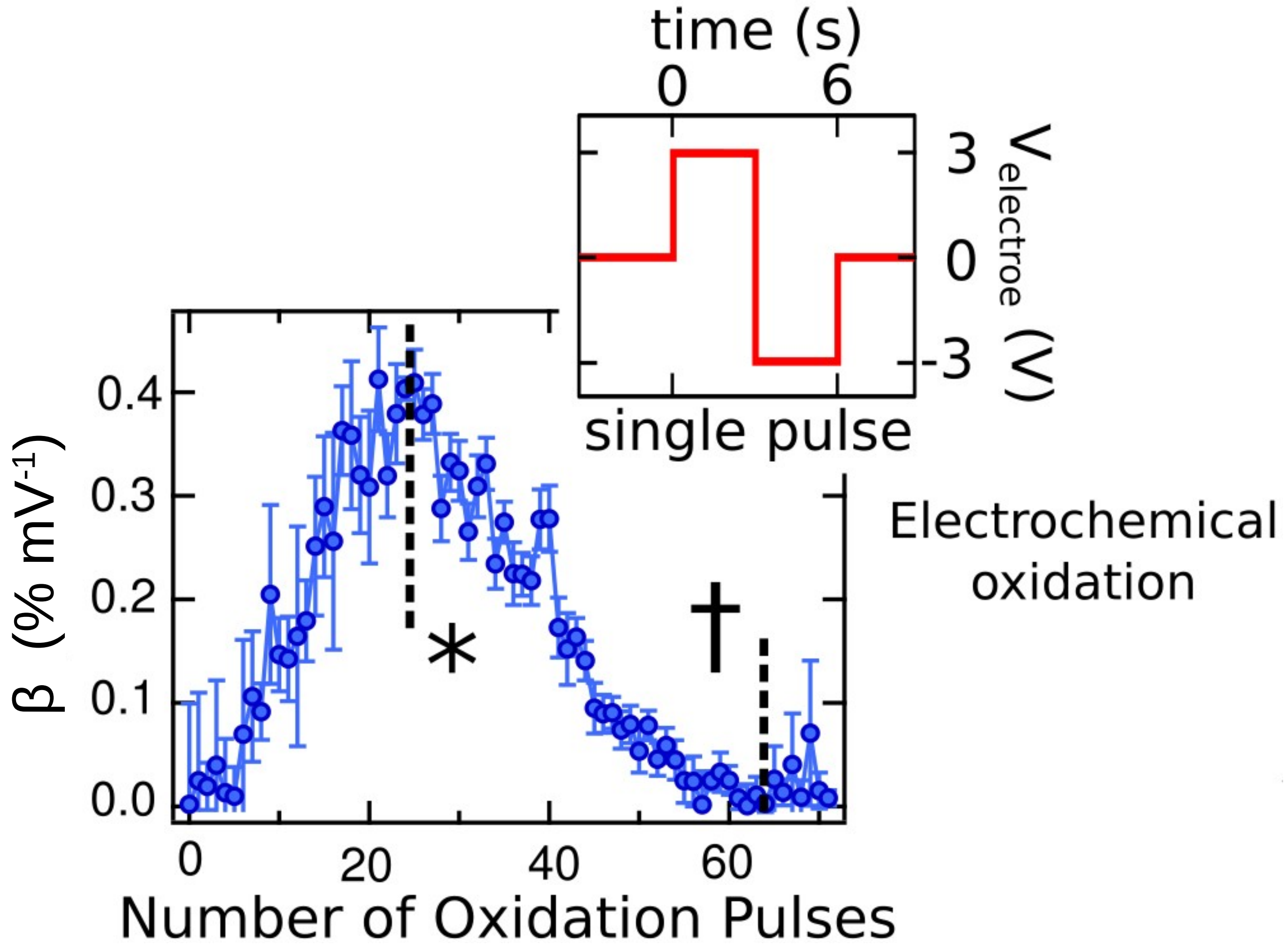
$\beta \approx 4\%\ mV^{-1}$ is an upper limit

Want very thin ensembles

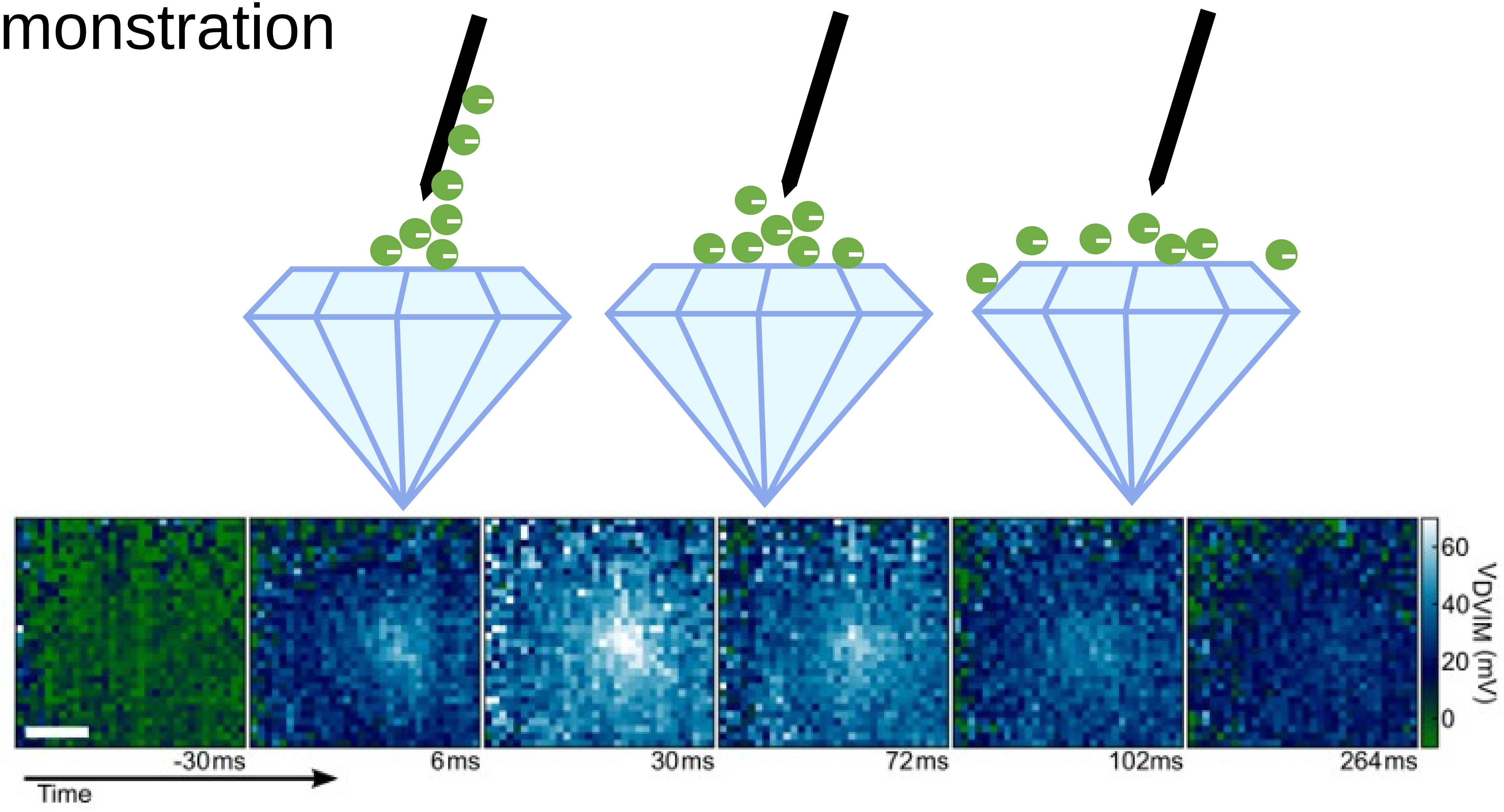
Want ultra-shallow ensembles

# How do we get to the best spot?

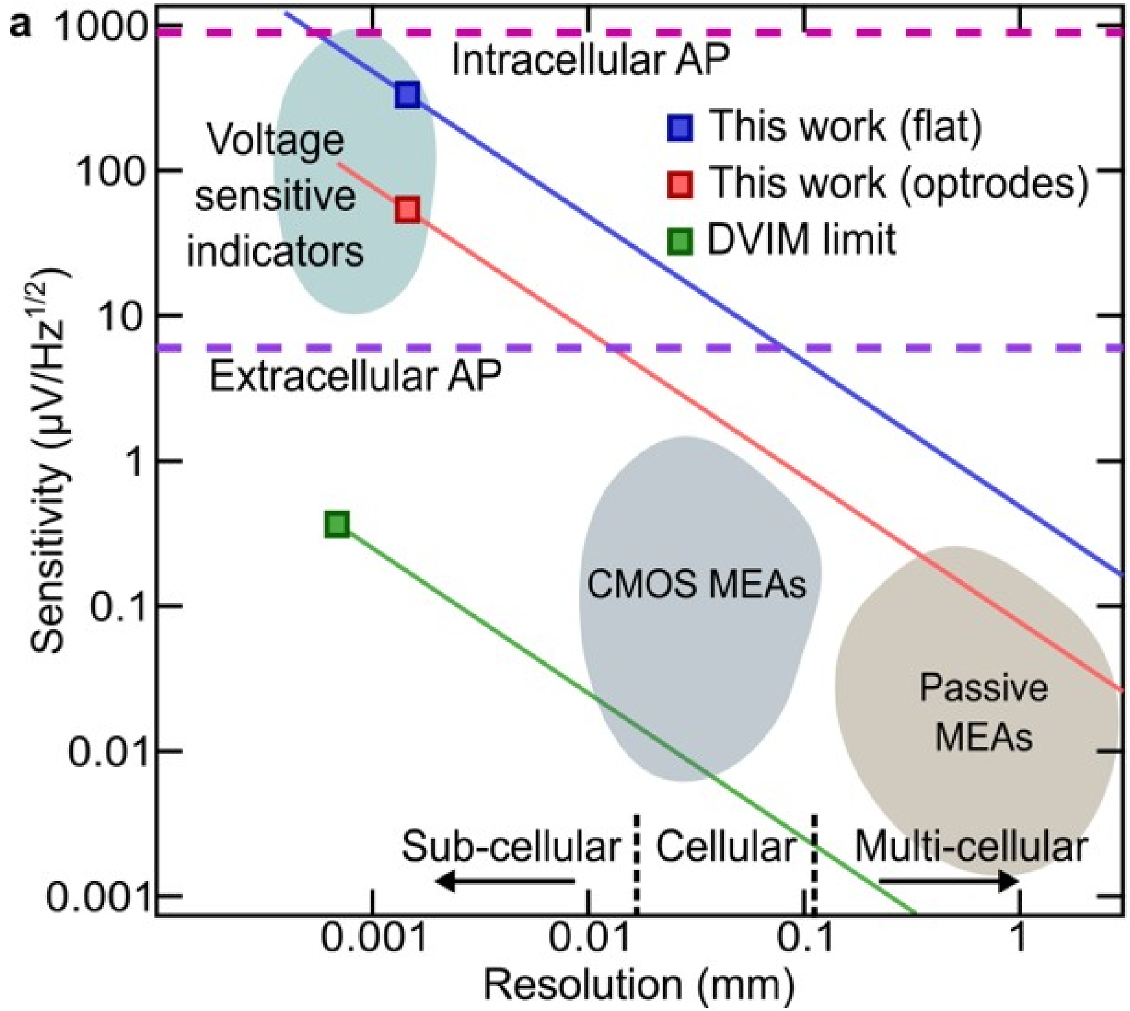


# Demonstration



# Limit?



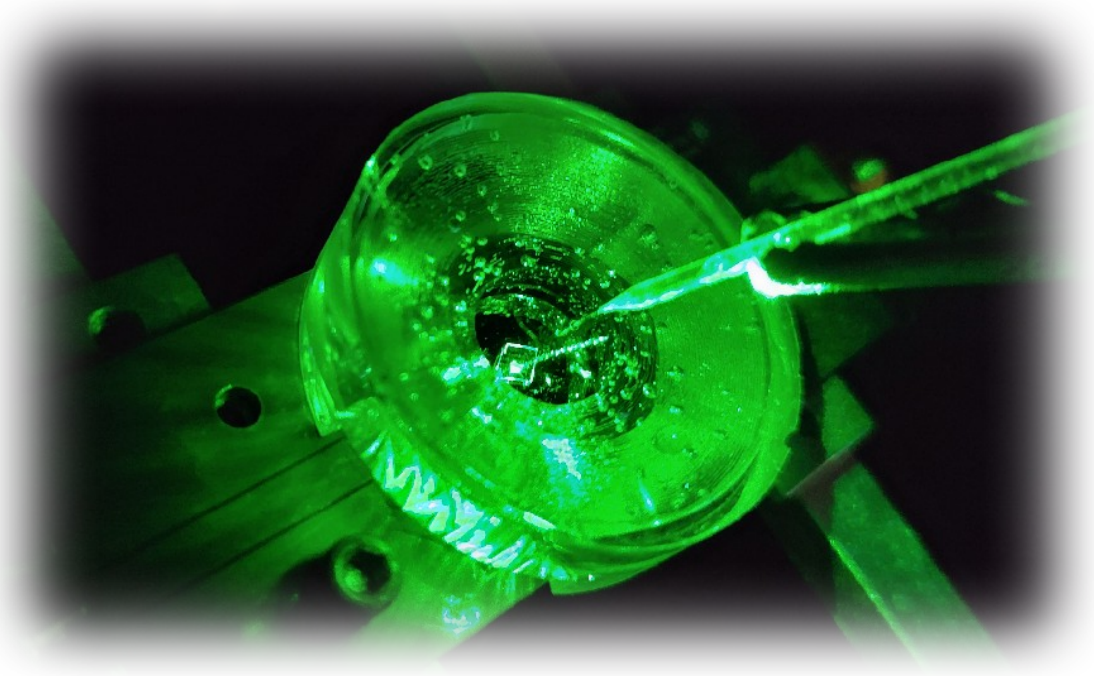

Improve EDL capacitance

Improve cell confirmation

Brighter colour centers

McCloskey, D.*, **Dontschuk, N.***, et. al. Nature Photonics, 16, 730.

# Thank You!



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Liam Hall
**Lloyd Hollenberg**
Jeffery McCallum
Alexander Healey
Erin Grant
Sam Scholten
**Charlie Pattinson**
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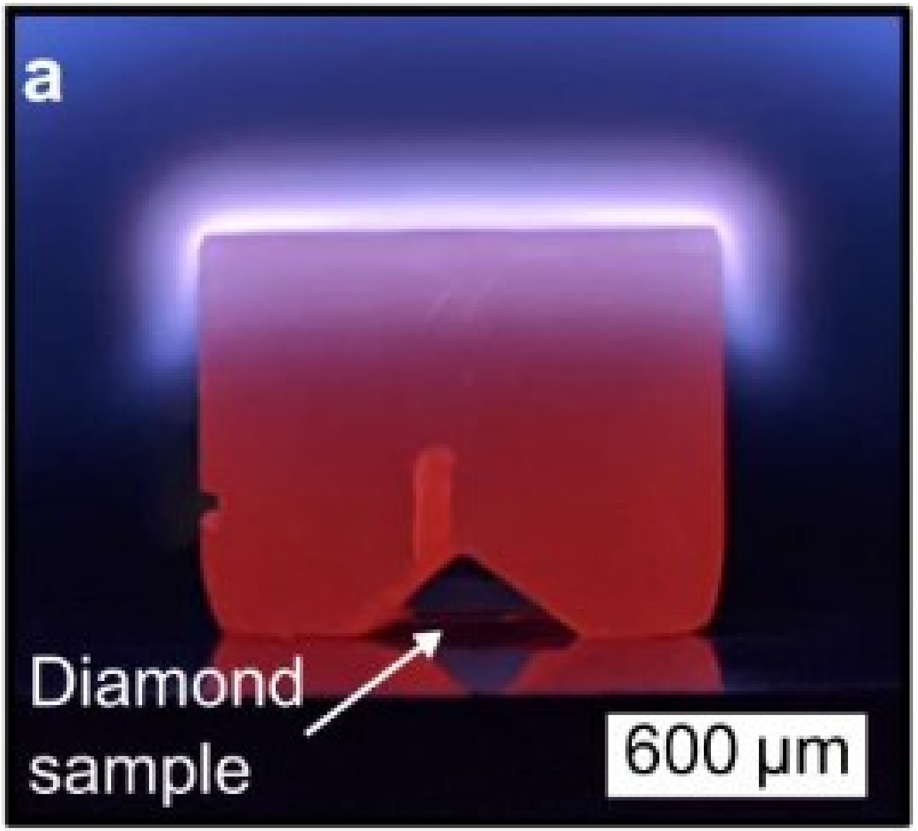
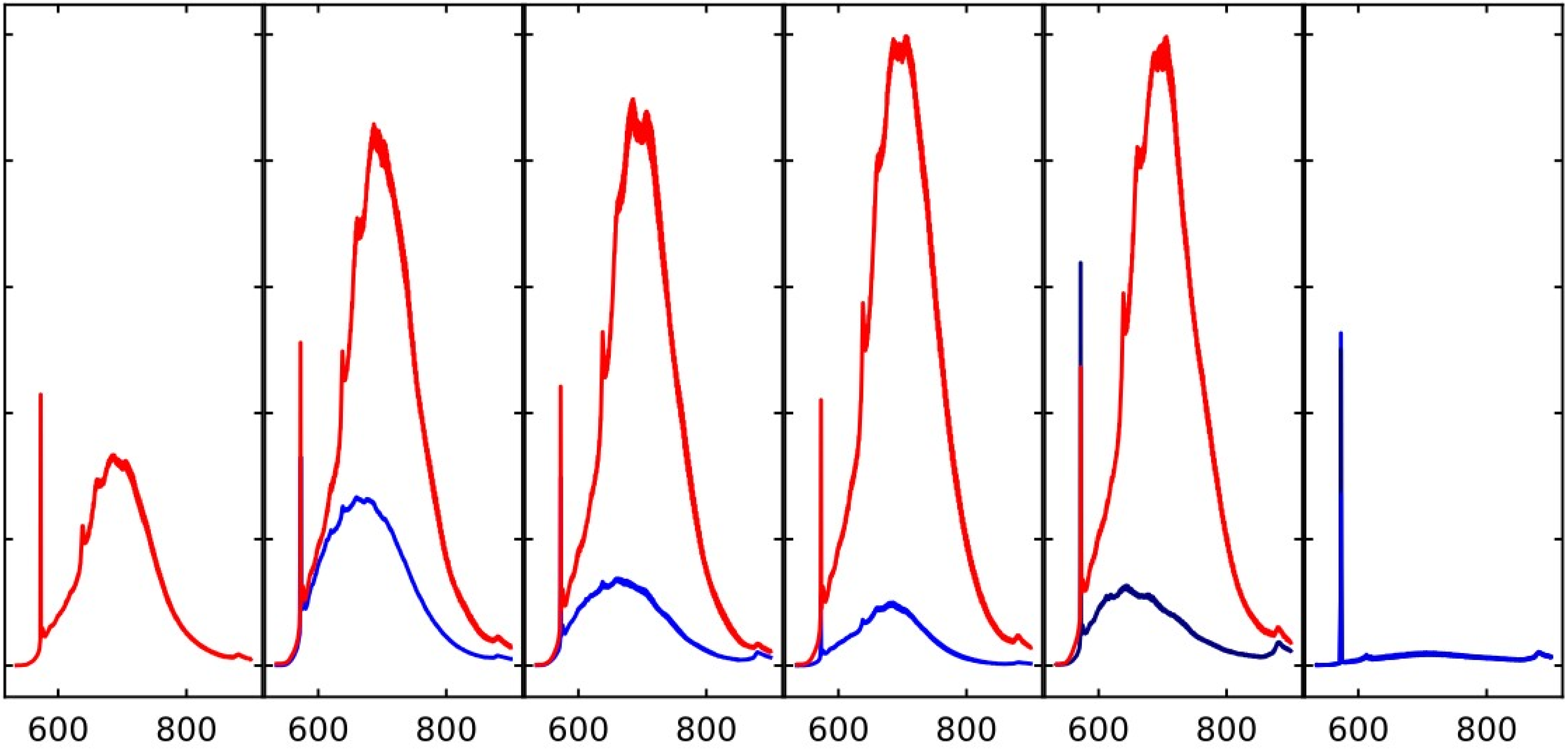
Brett Johnson
Philipp Rheineck
Daniel Roberts
James Belcourt

Nathalie de Leon
Anton Taditch
Alex Schenk
Chris Pakes
**David Broadway**
**Scott Lillie**

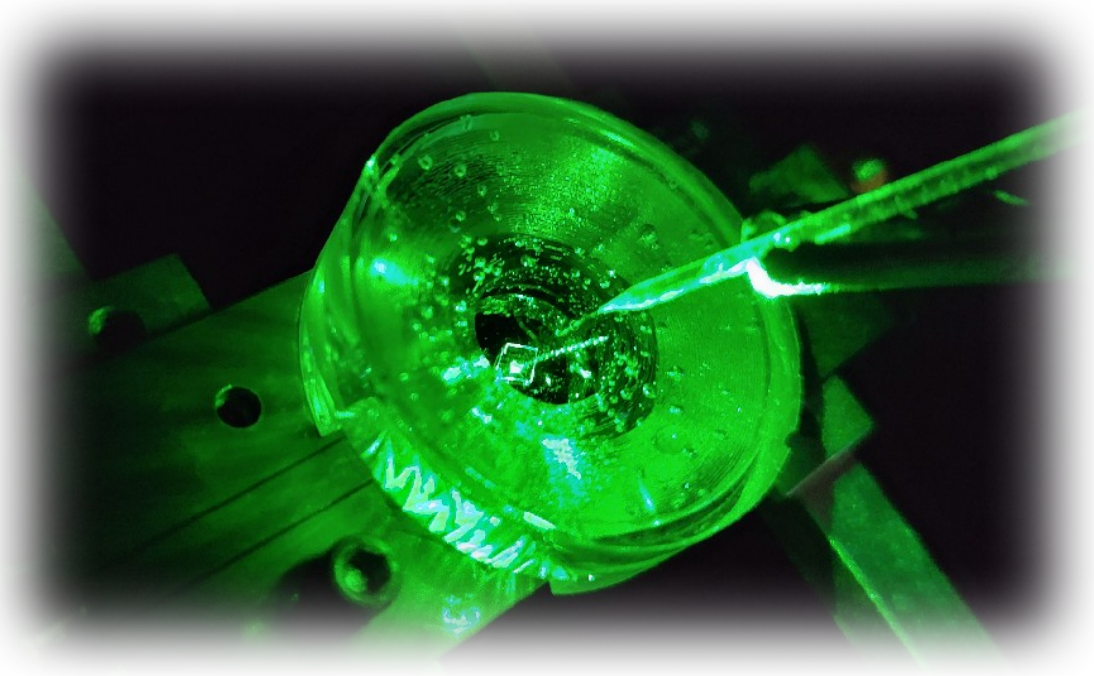
# If we have time...



# A new old way



# Thank You!



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