Camera-based wide field quantum sensing for cell tracking

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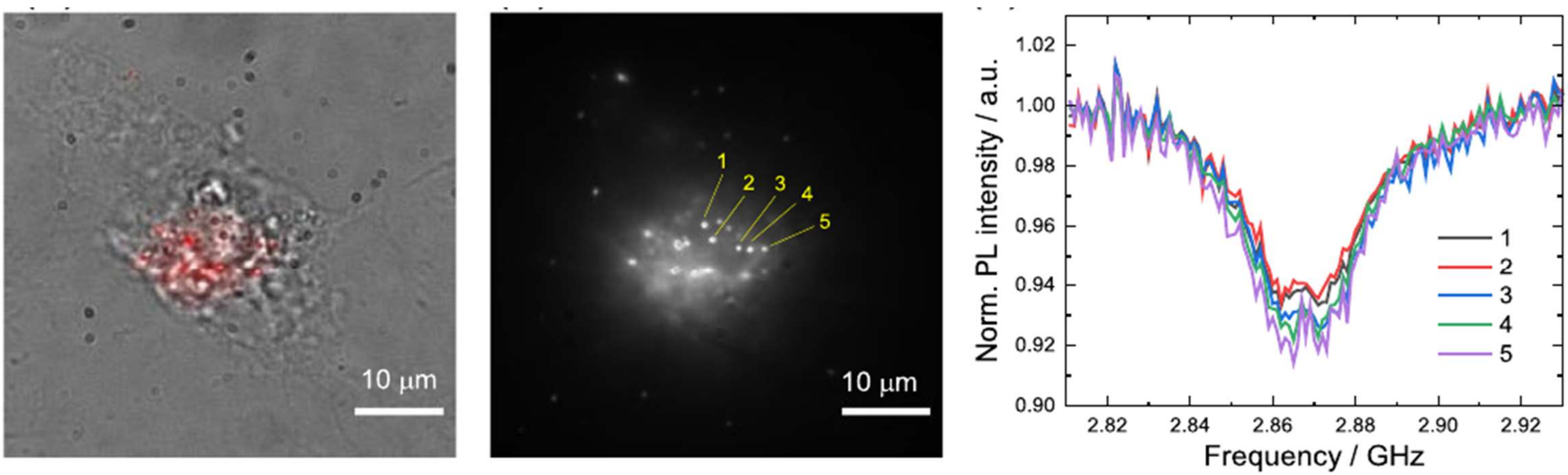
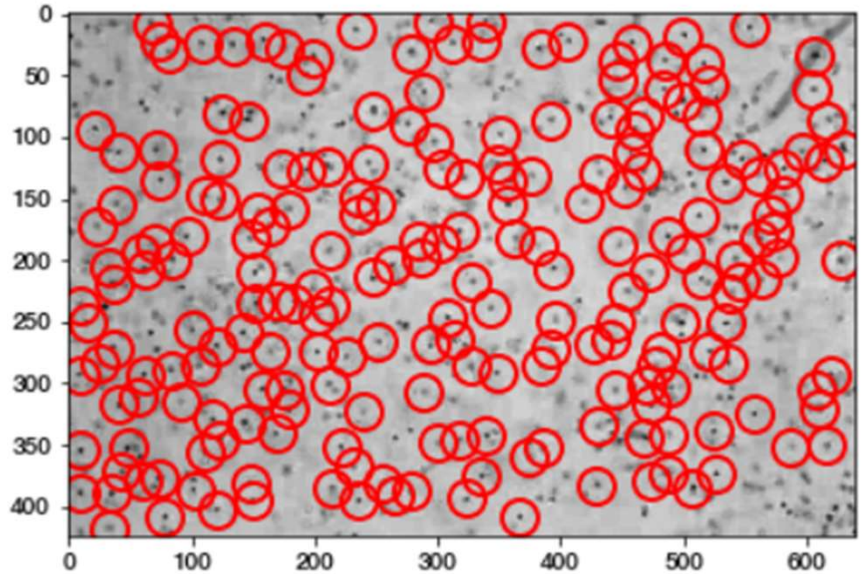
Goal: Wide-field sensing



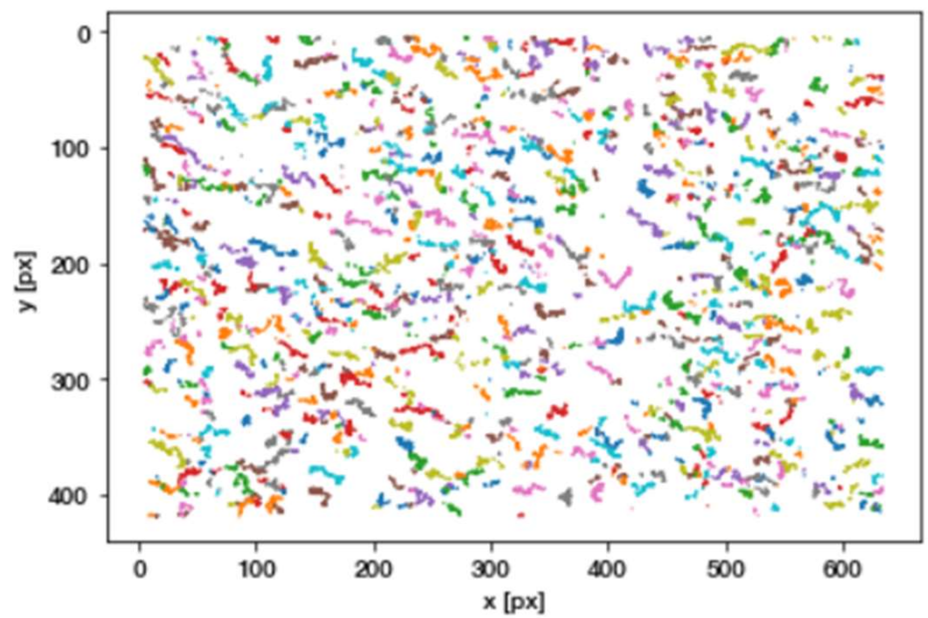
Nishimura et al. 2021: ND-labeled HeLa cells with ODMR spectrum

camera-based simultaneous probing of NVs in large field of view

Method: Particle tracking



Particle identification

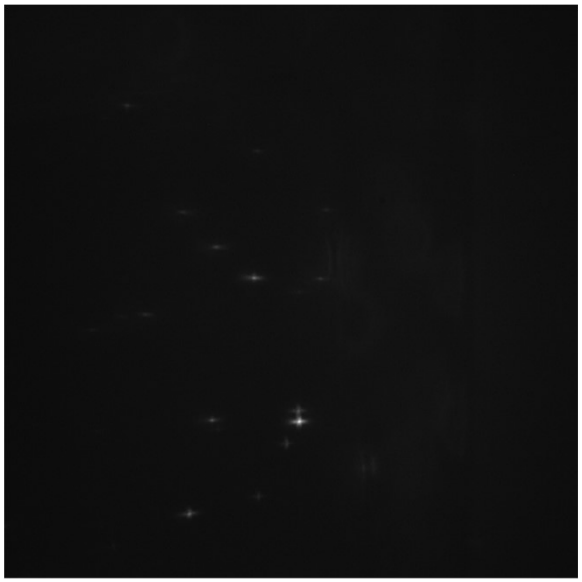


Trajectory linking

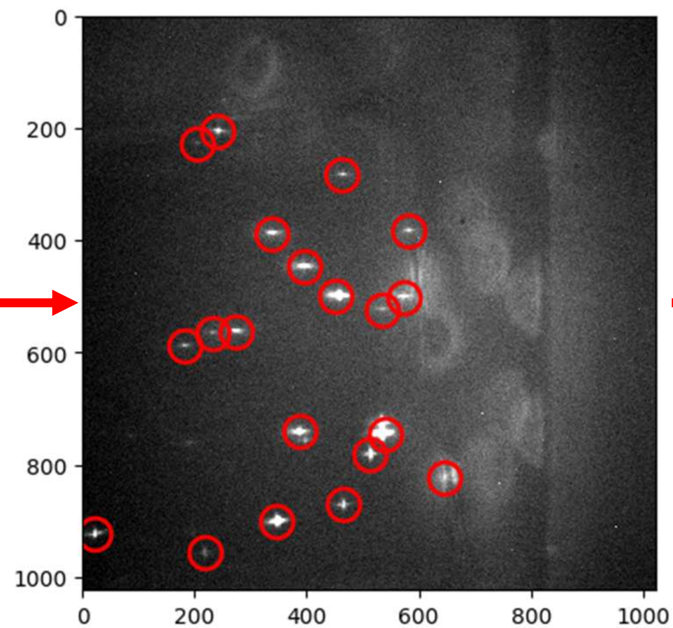
trackpy: Python package for difference of Gaussian (doG) particle tracking

allows us to keep track of fluorescent particles

Examples: Particle tracking

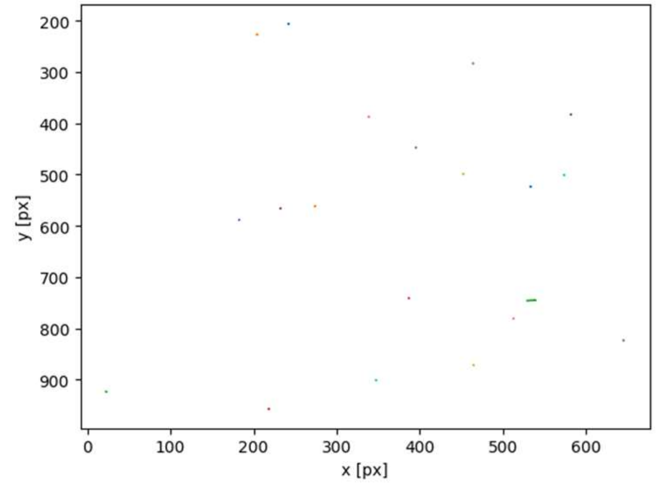


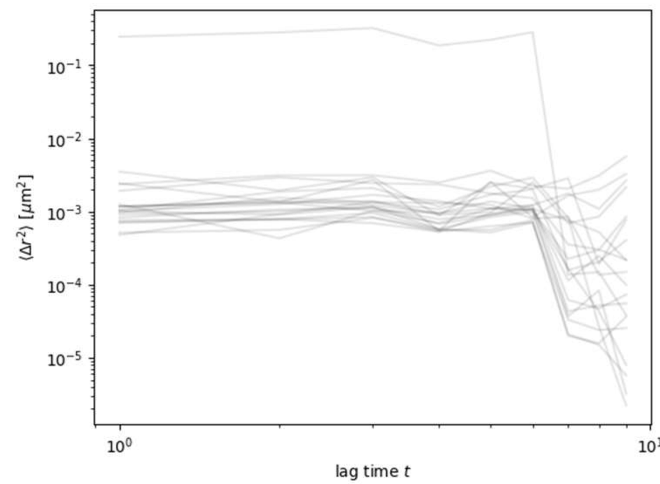
Original video file



ImageJ + trackpy feature finding

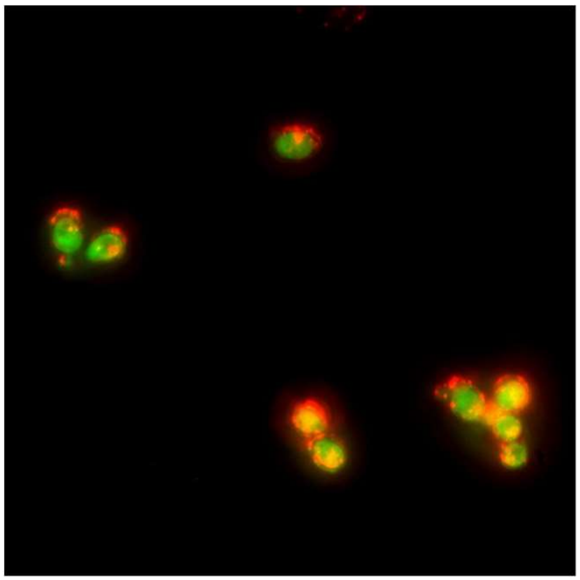
Drift-corrected trajectories



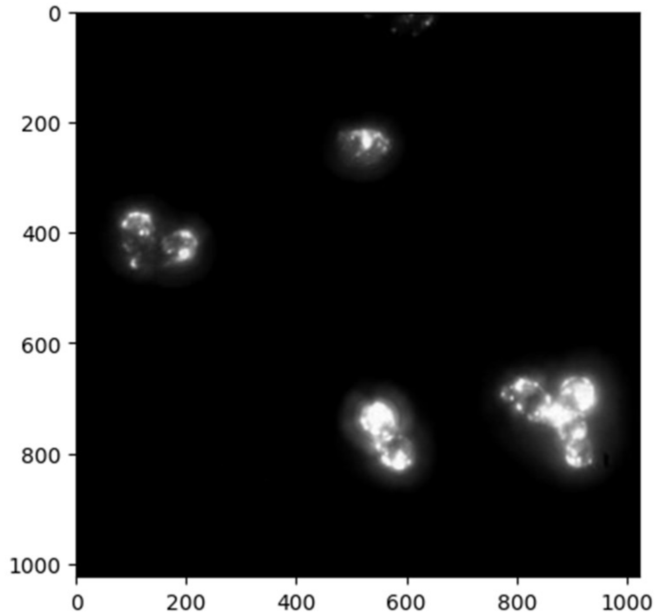


Mean-square displacement (1 fps)

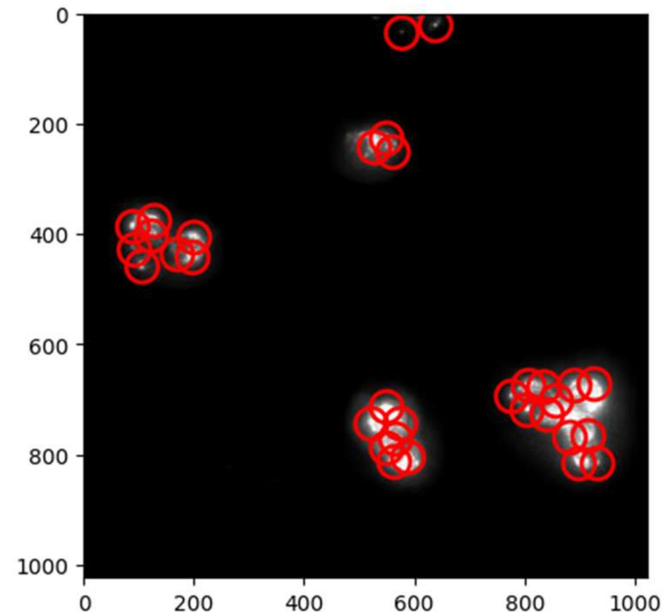
Examples: Particle tracking



Yeast cells + NVs



Red-scale filter



Feature finding

Future goals: particle tracking- improved performance

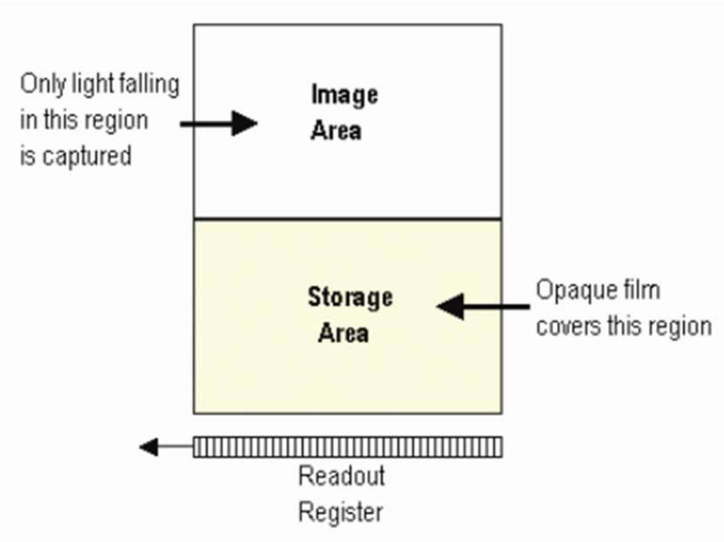
Post-process:

- Automatic parallelized feature-finding

During process:

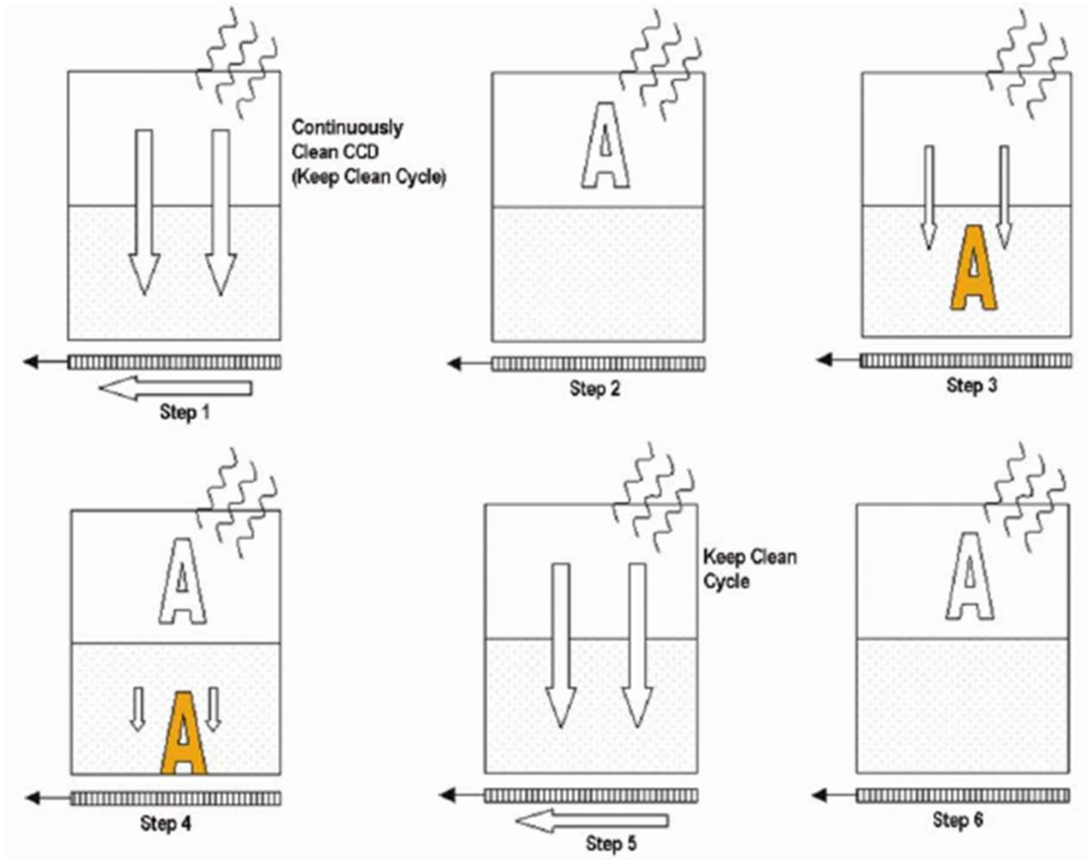
- Streaming possible with HDF5 files and pytables package
- Requires sufficiently long readout time

Method: Pulse sequence



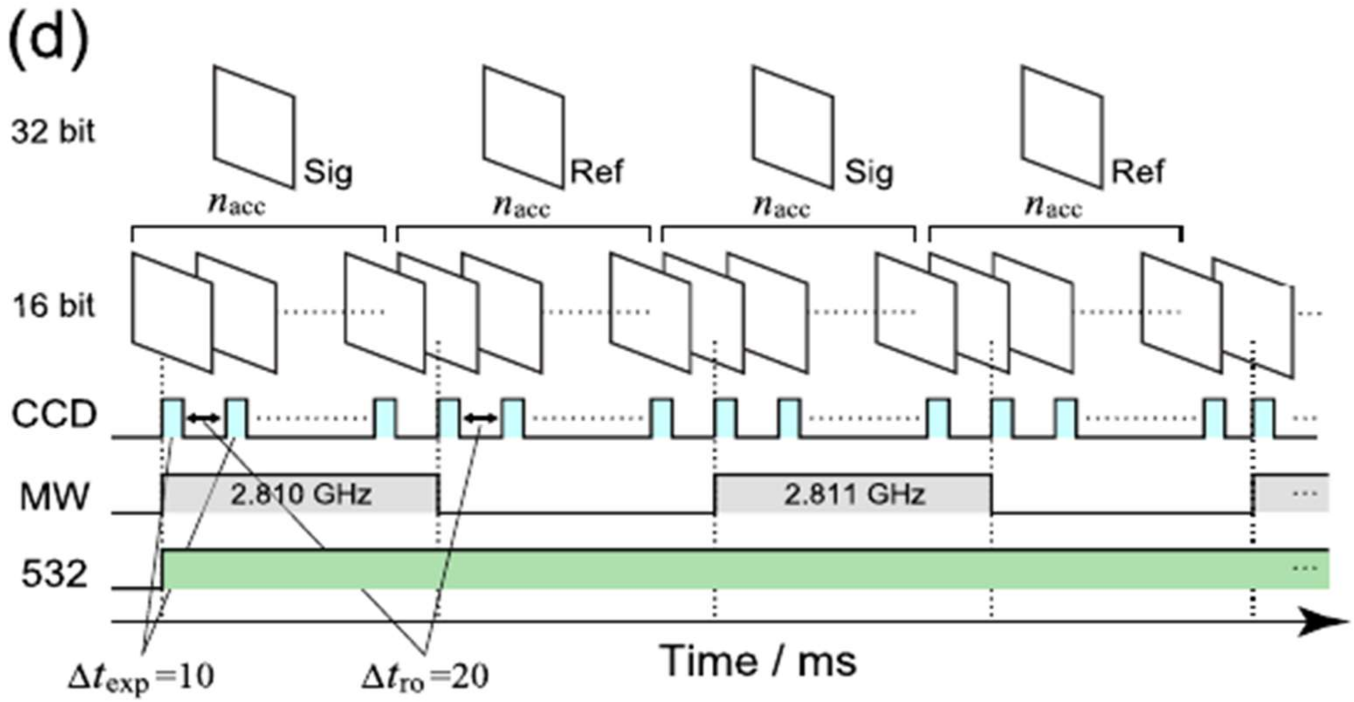
Frame transfer CCD

Exposure time ~39 ms
We can decrease by "**overclocking**" the CCD



Frame rate limited by horizontal readout speed + vertical clock speed

Future goals: Pulse sequence- implementation



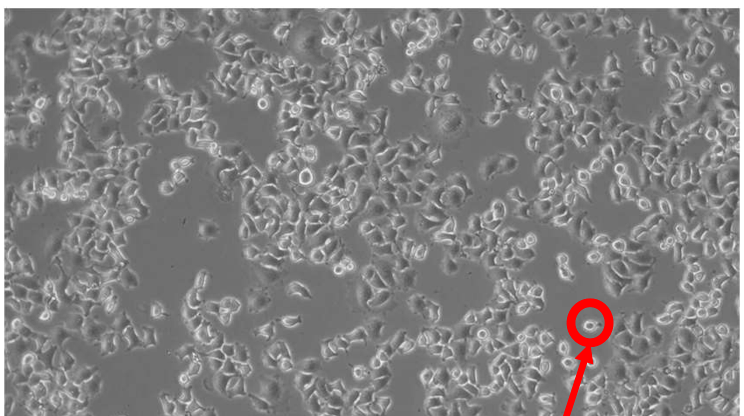
Nishimura et al. 2021

Why have a second exposure time?

Goal: Identify and track cells across time

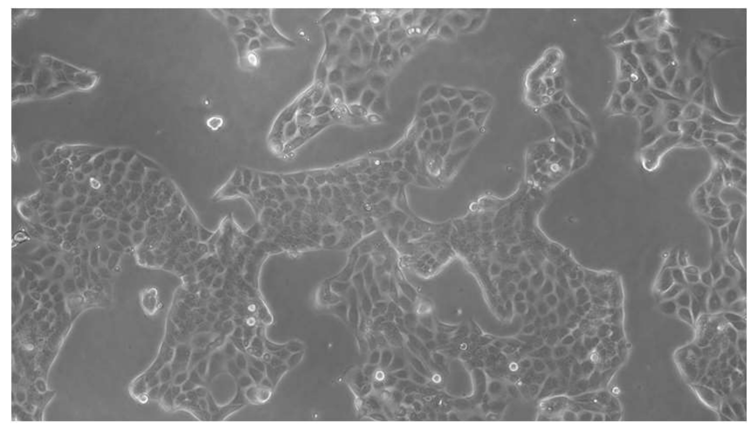
Motivational reasons / questions:

1. Track cytokine level in a cell across time
2. Perturb a cell and observe changes across time



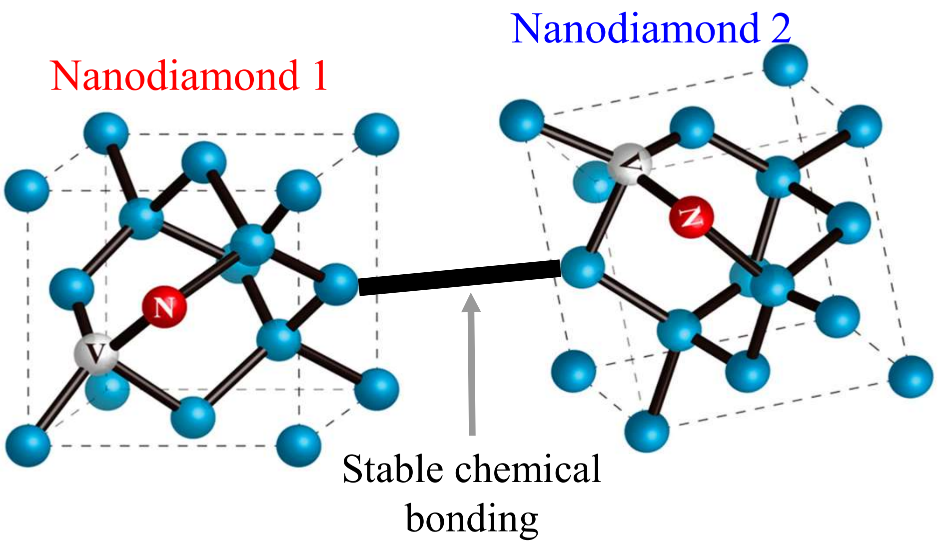
Target cell

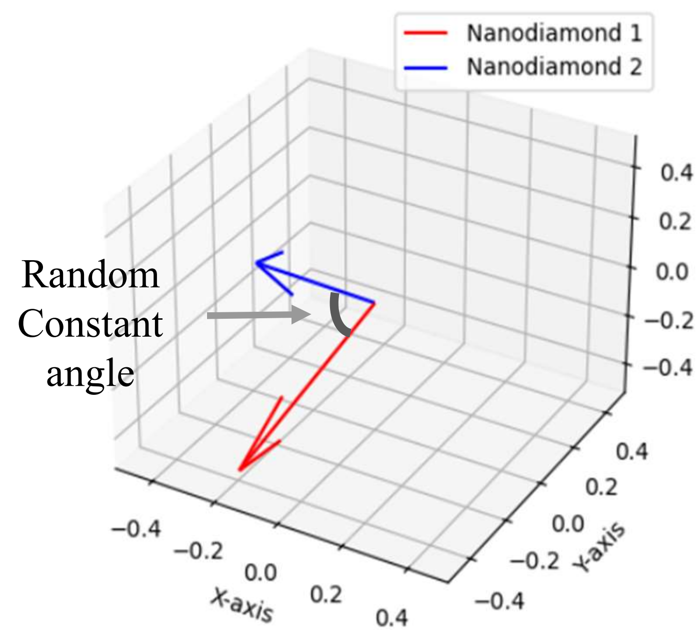
One week after



where's our cell?

Our "barcode": Angle(s) between pair(s) of nanodiamonds

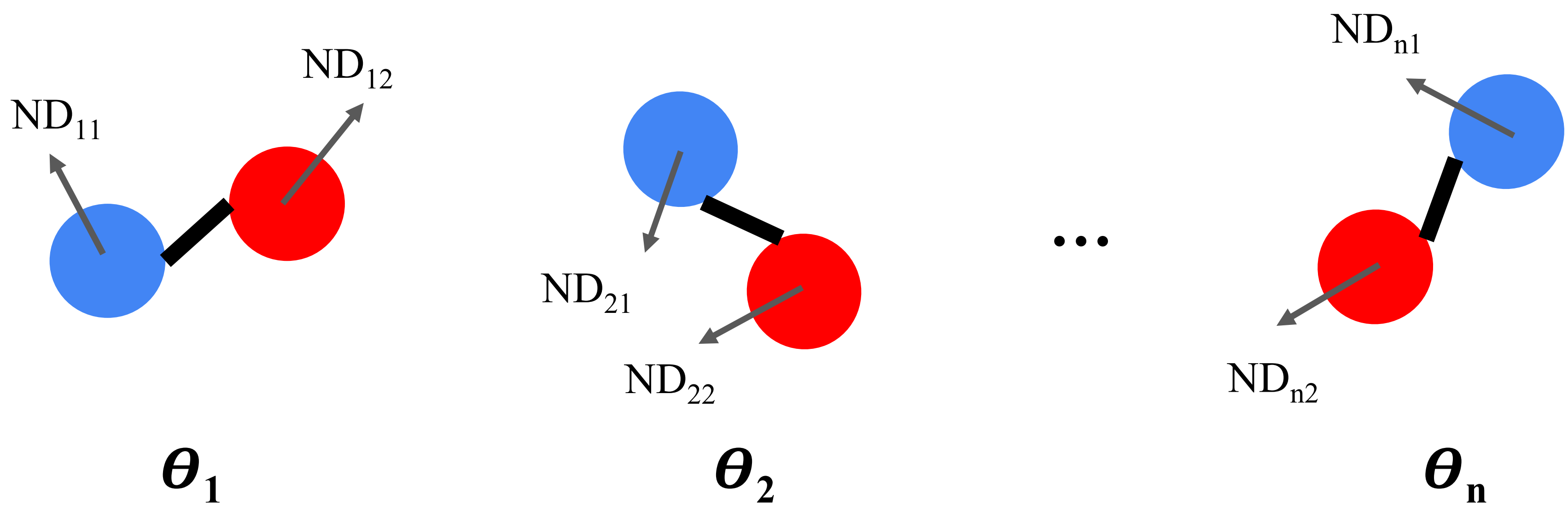




$$\# \text{ of detectable angles} = \frac{180}{\text{resolution}}$$

https://www.mdpi.com/2412-382X/6/1/2

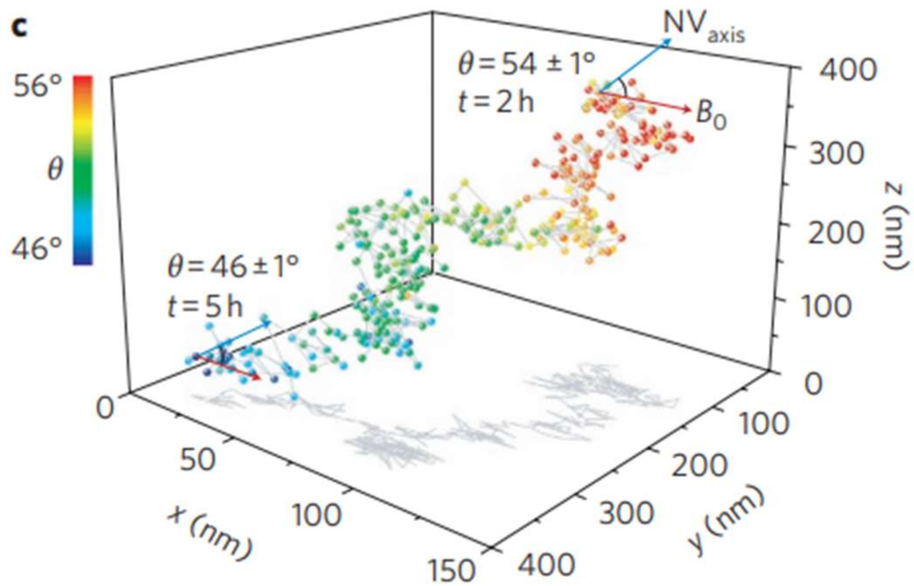
Our "barcode": Angle(s) between pair(s) of nanodiamonds

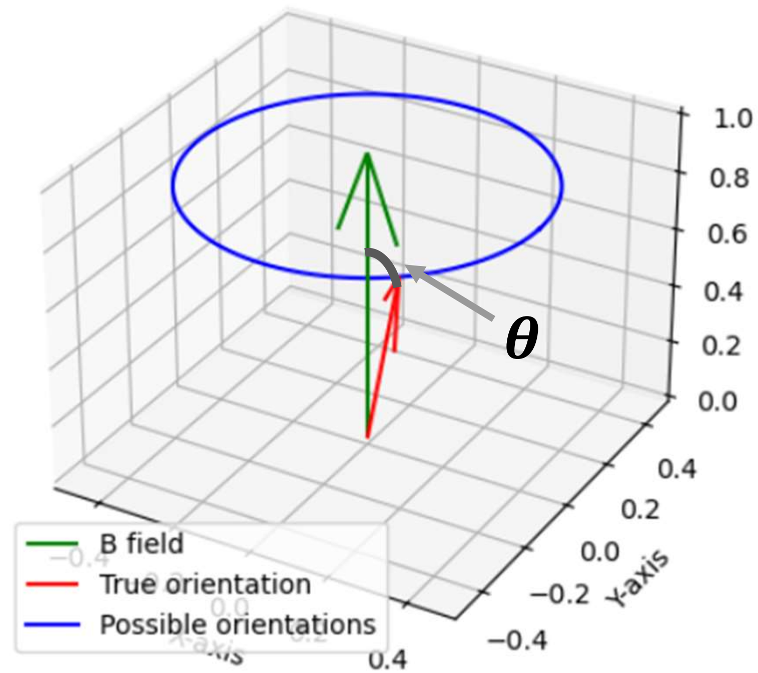


$$\#\text{ of distinct (unordered) barcodes} = \binom{n}{\frac{180}{\text{resolution}}}$$

https://www.mdpi.com/2412-382X/6/1/2

Previous work: McGuinness et.al 2011

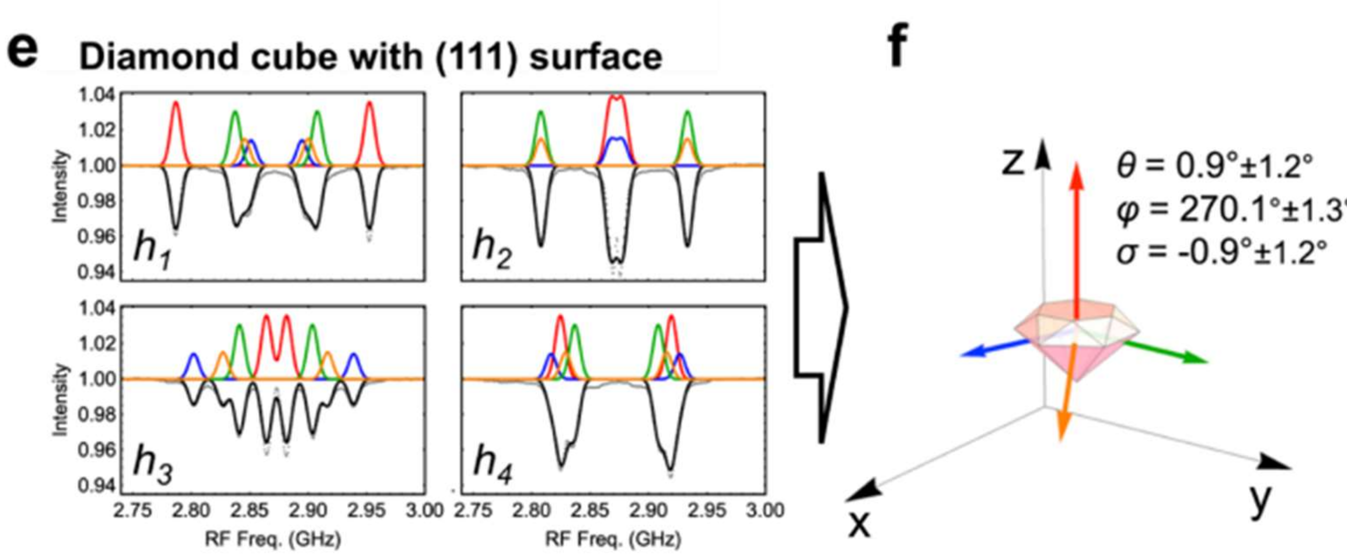




Only projection on B field, no full orientation

https://www.nature.com/articles/nnano.2011.64

Previous work: Igarashi et.al 2020



ODMR gets messy with 8 or 6 peaks

Nanodiamond could rotate between measurements with different B fields

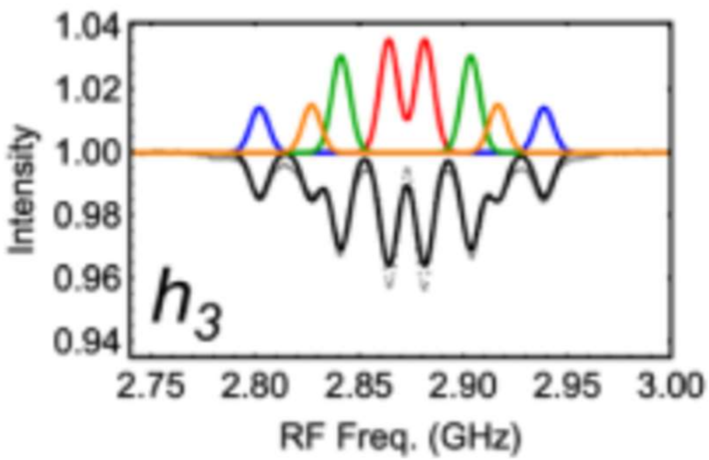
Method: ODMR peak to angle from B field

$$\hat{H} = \overbrace{\hbar D\left[\hat{S}_Z^2 - \frac{2}{3}\right] + \hbar E(\hat{S}_X^2 - \hat{S}_Y^2)}^{\text{zero-field term}} + \overbrace{\hbar\gamma_{nv}\vec{B}\cdot\hat{\vec{S}}}^{\text{magnetic interaction}}$$

$$f = D + \frac{3\gamma e^2|B|^2}{2D}\sin^2(\theta) + \gamma e|B|\cos(\theta)\sqrt{1 + \frac{\gamma e^2|B|^2}{4D^2}\tan^2(\theta)\sin^2(\theta)}$$

Method: ODMR peak to angle from B field

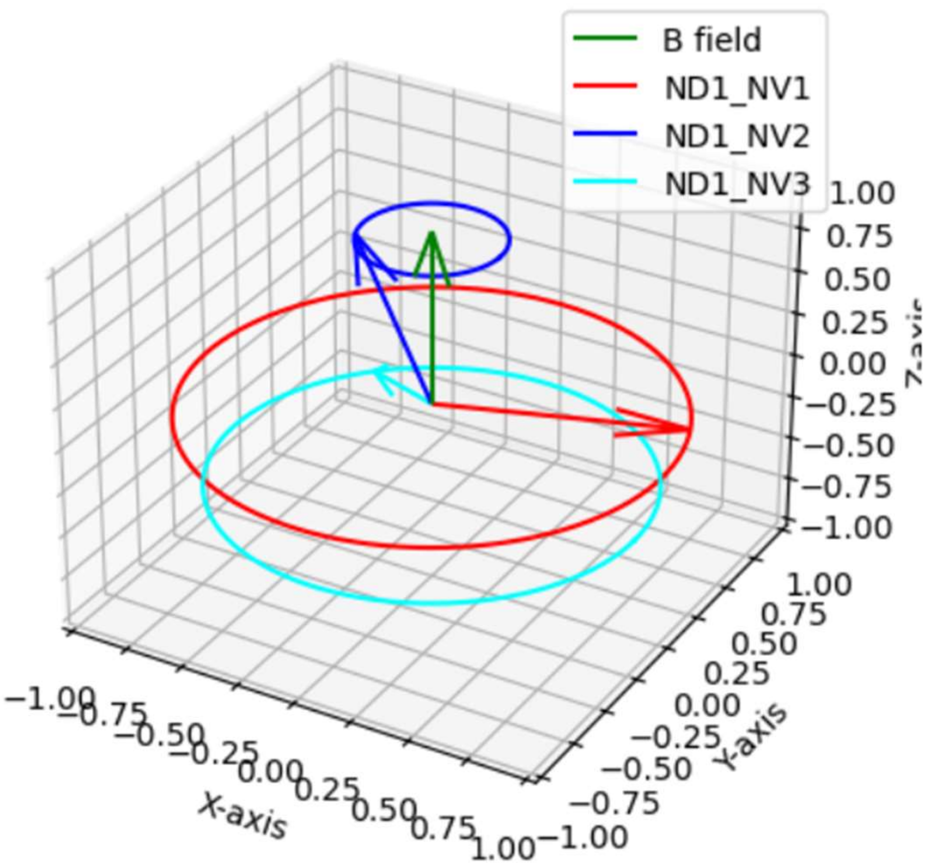
Lorentzian fitting → Peak frequency



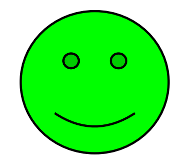
Igarashi et.al 2020

$$\theta(\text{angle from B field}) = f^{-1}(\text{peak frequency})$$

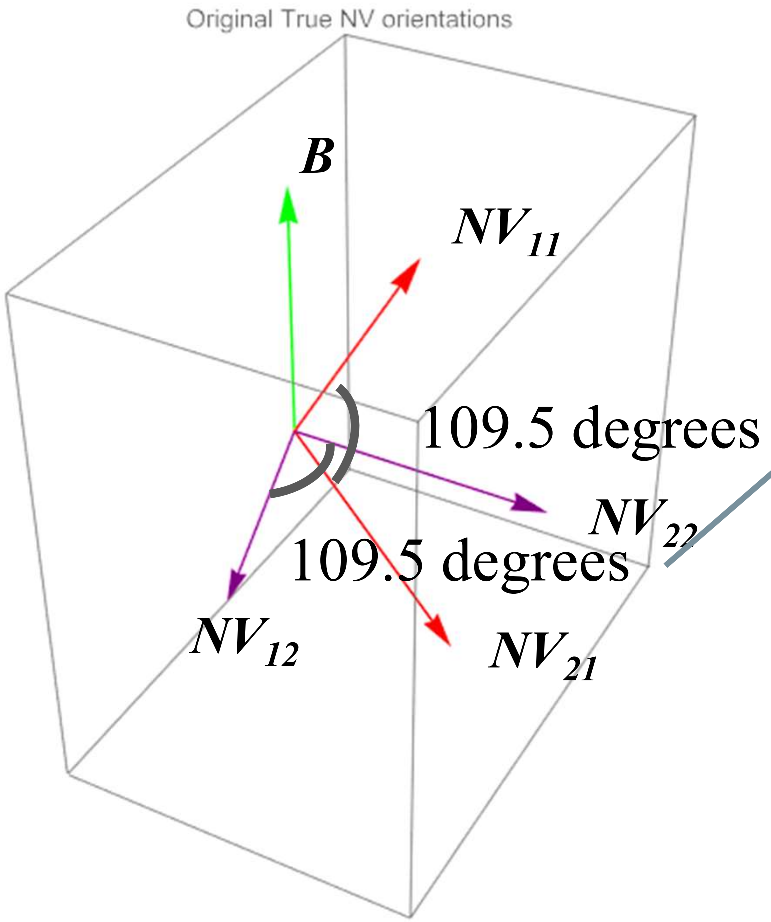
Method: 3 NVs on each diamond (6 NVs total)



$$\begin{cases} NV_1(x_1) = (x_1, f_1(x_1), z_1) \\ NV_2(x_2) = (x_2, f_2(x_2), z_2) \\ NV_2(x_2) = (x_3, f_3(x_3), z_3) \\ \text{angle between}(NV_1(x_1), NV_2(x_2)) = 109.5^\circ \\ \text{angle between}(NV_1(x_1), NV_3(x_3)) = 109.5^\circ \\ \text{angle between}(NV_2(x_2), NV_3(x_3)) = 109.5^\circ \end{cases}$$



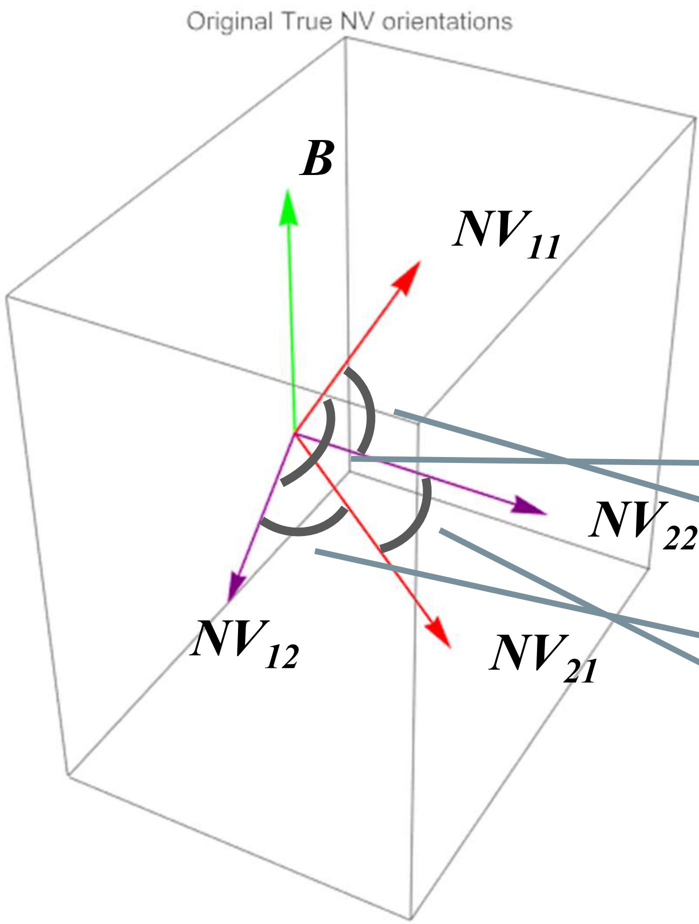
Method: 2 NVs on each diamond (4 NVs total)



$$\begin{cases} \arccos\left(\dfrac{NV_{11}\cdot NV_{21}}{|NV_{11}||NV_{21}|}\right) = 109.5^\circ \\ \arccos\left(\dfrac{NV_{12}\cdot NV_{22}}{|NV_{12}||NV_{22}|}\right) = 109.5^\circ \end{cases}$$

$$\begin{cases} \arccos\left(\dfrac{NV_{11}\cdot NV_{12}}{|NV_{11}||NV_{12}|}\right) = \phi_1 \\ \arccos\left(\dfrac{NV_{11}\cdot NV_{22}}{|NV_{11}||NV_{22}|}\right) = \phi_2 \\ \arccos\left(\dfrac{NV_{21}\cdot NV_{12}}{|NV_{21}||NV_{12}|}\right) = \phi_3 \\ \arccos\left(\dfrac{NV_{21}\cdot NV_{22}}{|NV_{21}||NV_{22}|}\right) = \phi_4 \end{cases}$$

Method: 2 NVs on each diamond (4 NVs total)



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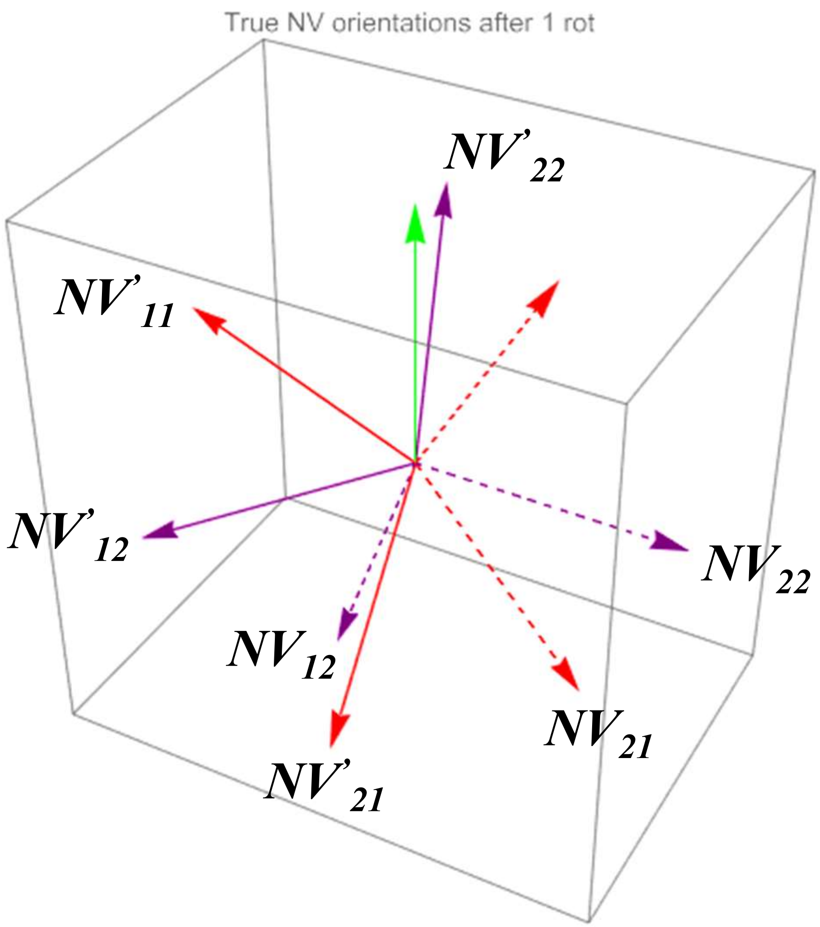
Method: 2 NVs on each diamond (4 NVs total)



$$\begin{cases} \arccos(\frac{NV_{11} \cdot NV_{21}}{|NV_{11}||NV_{21}|}) = 109.5^\circ \\ \arccos(\frac{NV_{12} \cdot NV_{22}}{|NV_{12}||NV_{22}|}) = 109.5^\circ \\ \arccos(\frac{NV'_{11} \cdot NV'_{21}}{|NV'_{11}||NV'_{21}|}) = 109.5^\circ \\ \arccos(\frac{NV'_{12} \cdot NV'_{22}}{|NV'_{12}||NV'_{22}|}) = 109.5^\circ \end{cases}$$

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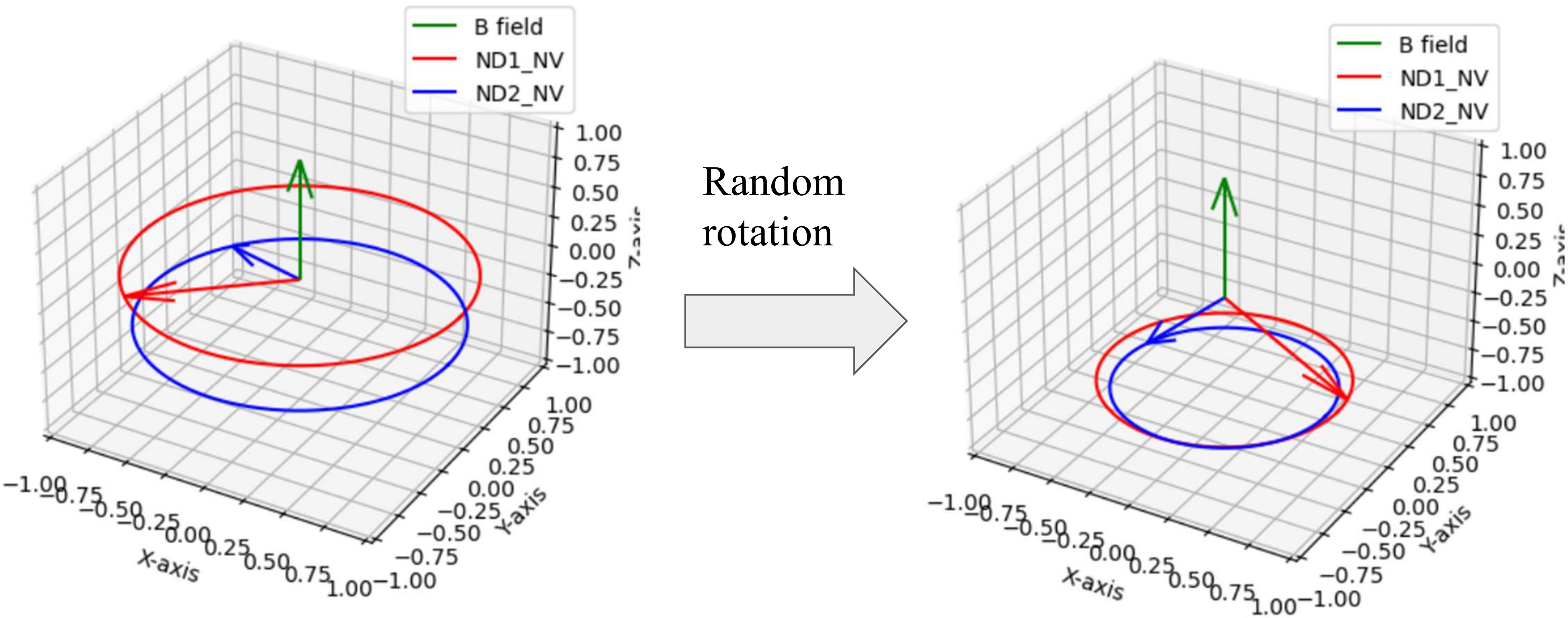
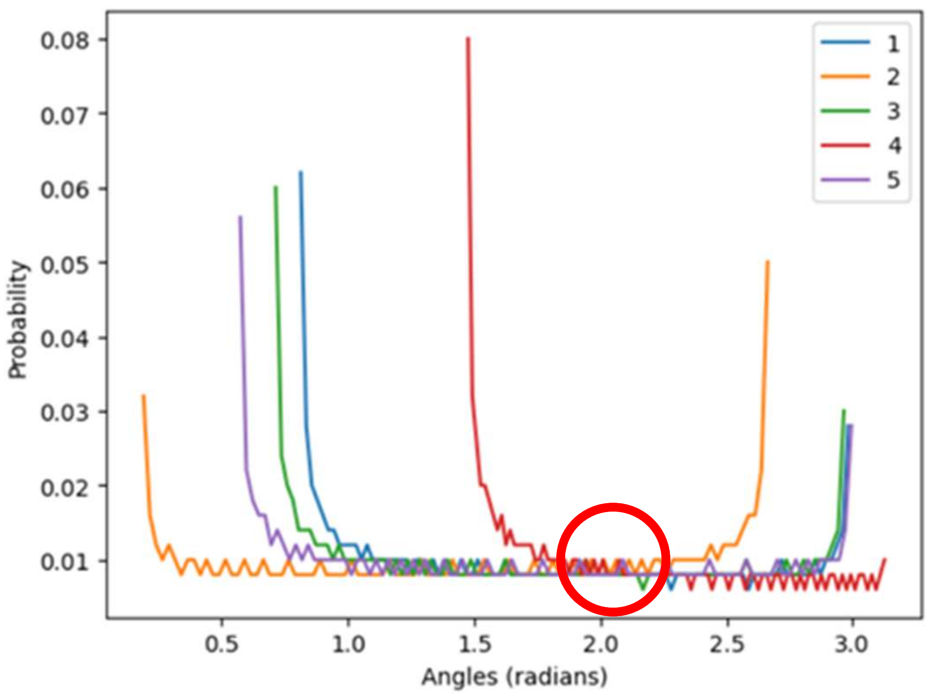
Method: 1 NV on each diamond (2 NVs total)



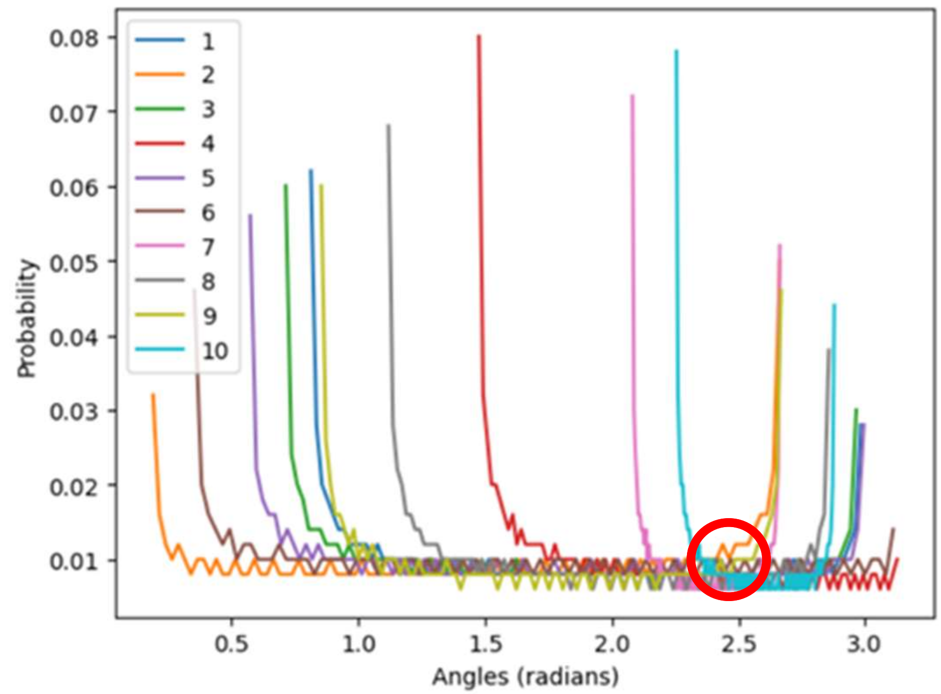
Method: 1 NV on each diamond (2 NVs total)

True inter-angle must be present in every distribution. Find overlaps

(e.g) Possible inter-angles (5 rotations)

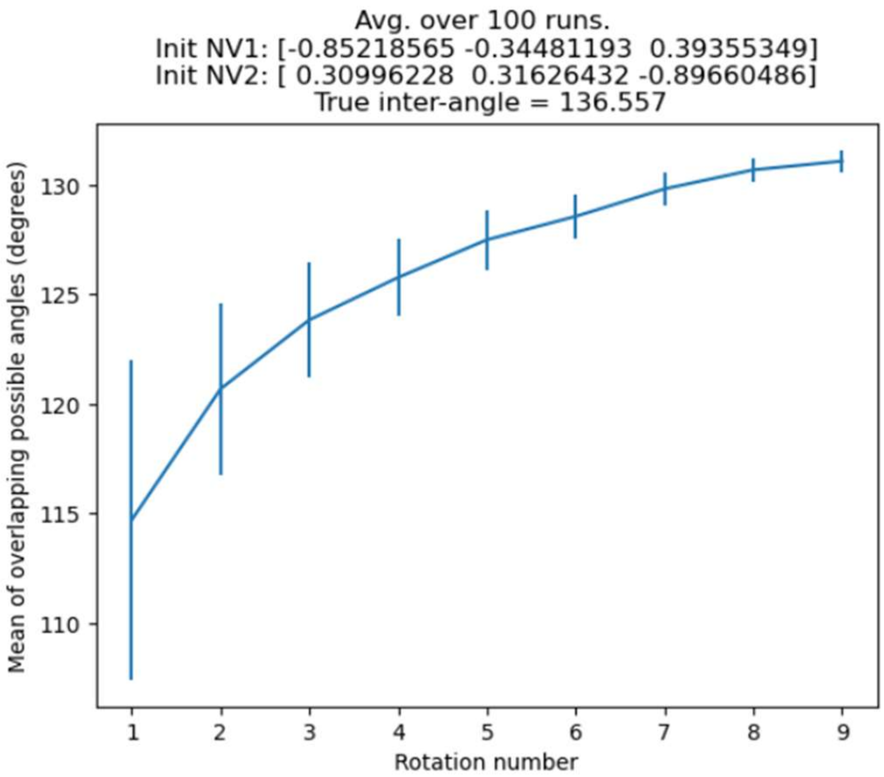


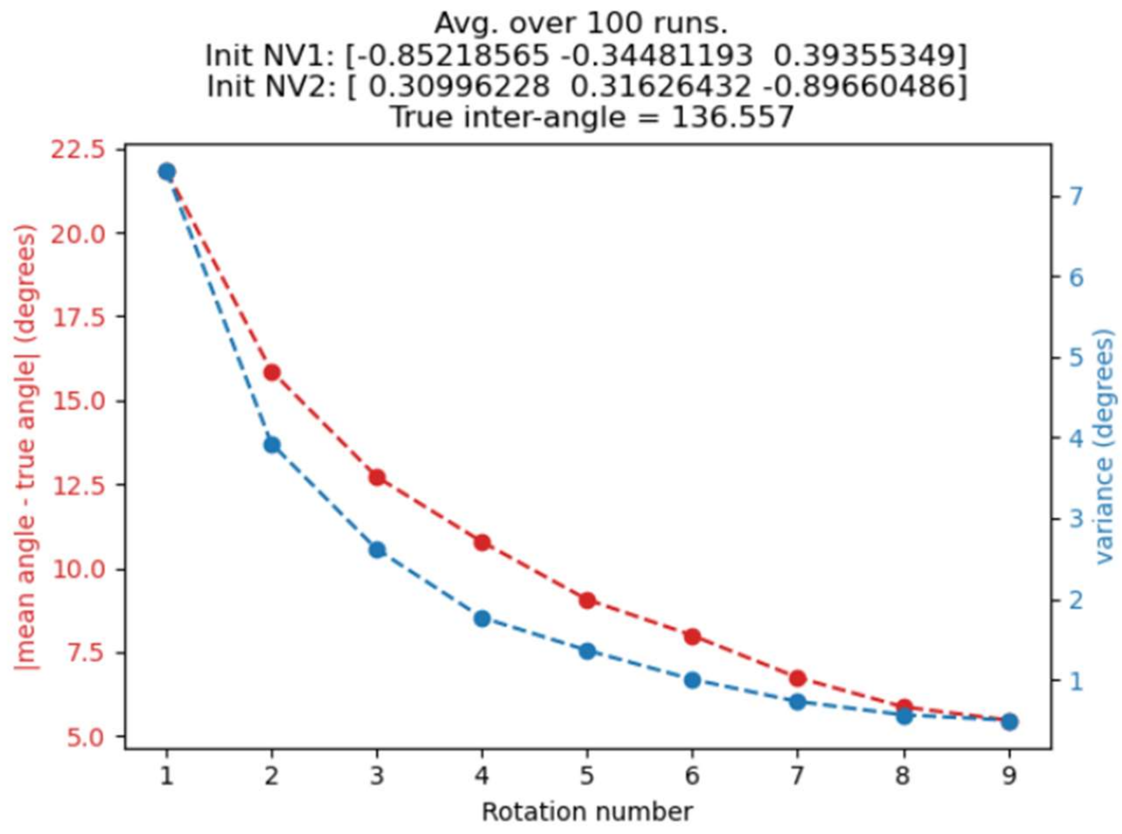
(e.g) Possible inter-angles (10 rotations)



Method: 1 NV on each diamond (2 NVs total)

Example 1





Method: 1 NV on each diamond (2 NVs total)

Example 2