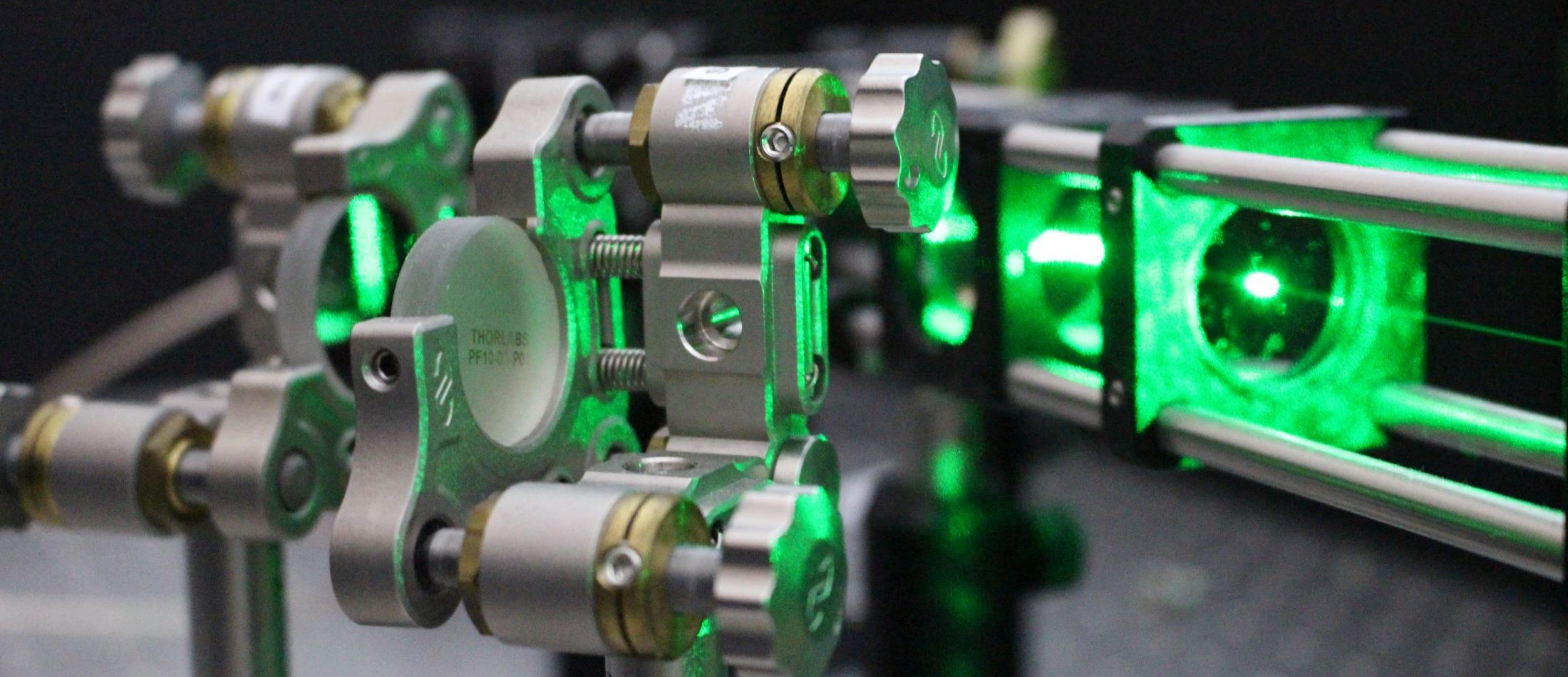
# Levitating microdiamond experiments: towards a test of the quantum nature of gravity

Gavin W Morley, University of Warwick



# Acknowledgments

**Warwick:** Angelo Frangeskou, Colin Stephen, Anis Rahman, Ben Green, Ben Breeze, Alexander Nikitin, Ray Zhou, Guy Stimpson, Yashna Lekhai, Rajesh Patel, Eleanor Nichols, Will Thornley, Ben Wood, James March, Joe Gore, Alex Newman, Stuart Graham

**Groningen:** Anupam Mazumdar

**Southampton:** Hendrik Ulbricht, Marko Toroš

**Queen's University Belfast:** Mauro Paternostro

**Northwestern:** Andrew Geraci

**Queensland:** Gerard Milburn

**Ulm:** Julen Pedernales, Martin Plenio

**Cardiff University:** Laia Gines, Soumen Mandal, Oliver Williams

**Imperial College London:** Chuanqi Wan, Myungshik Kim

**Yale:** David Moore

**Element Six:** Matthew Markham, Andrew Edmonds, Daniel Twitchen

**University College London:** Matteo Scala, Peter Barker, Sougato Bose

elementsix DE BEERS GROUP

[dstl]

NHS

Warwick Quantum

GORDON AND BETTY MOORE FOUNDATION

UKRI Science and Technology Facilities Council

UKRI Innovate UK

UK National Quantum Technology Hub Sensors and Metrology

NATIONAL NUCLEAR LABORATORY

ALFRED P. SLOAN FOUNDATION

UKRI Engineering and Physical Sciences Research Council

DST Diamond Science Technology Centre

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

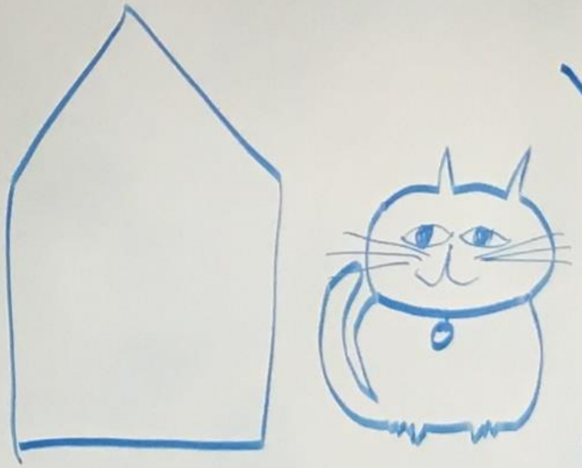
THE ROYAL SOCIETY

Quantum Computing & Simulation Hub

WARWICK THE UNIVERSITY OF WARWICK

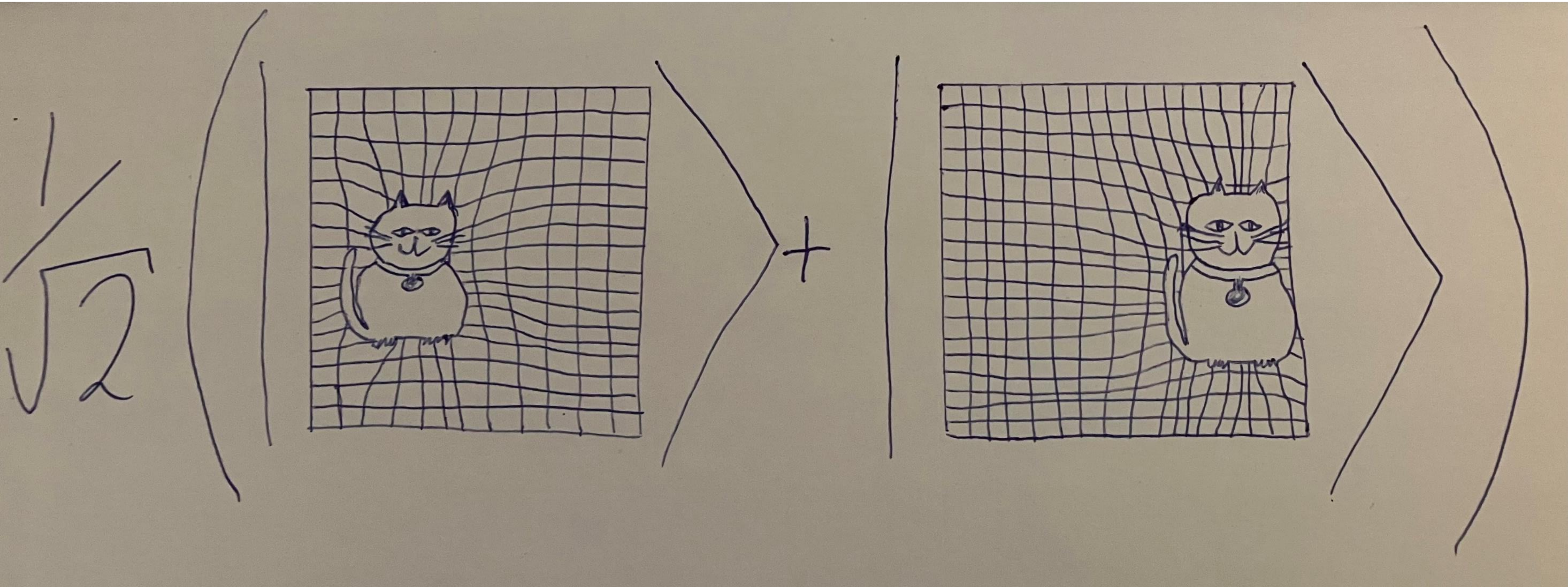
$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|L\rangle + |R\rangle\right)$$

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|L\rangle + |R\rangle\right)$$

$$|\psi\rangle_{cat} = \frac{1}{\sqrt{2}}\Big(\Big|$$  $$\Big\rangle + \Big|$$  $$\Big\rangle\Big)$$

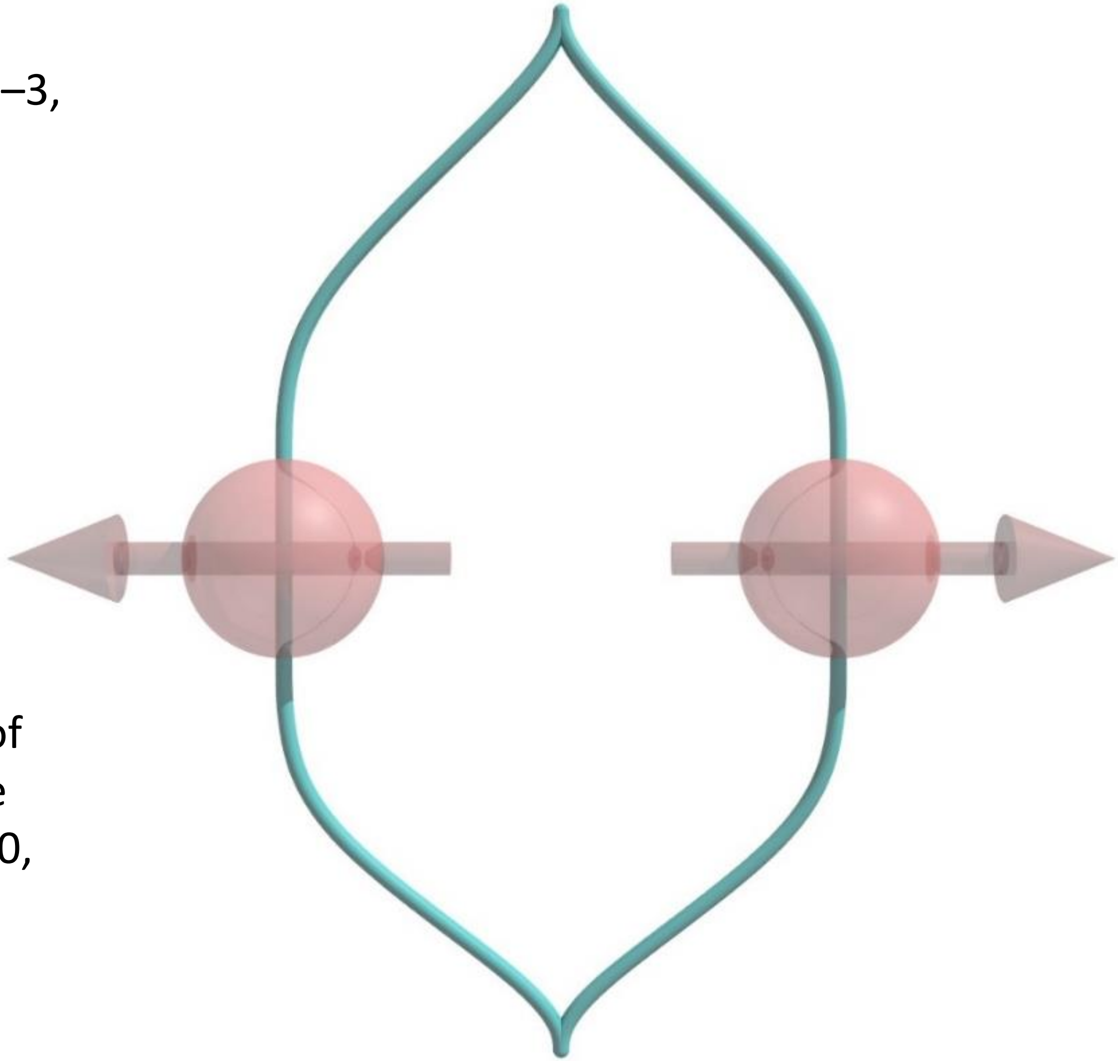
What is the gravitational effect
from a mass in a spatial superposition?

# What is the gravitational effect from a mass in a spatial superposition?

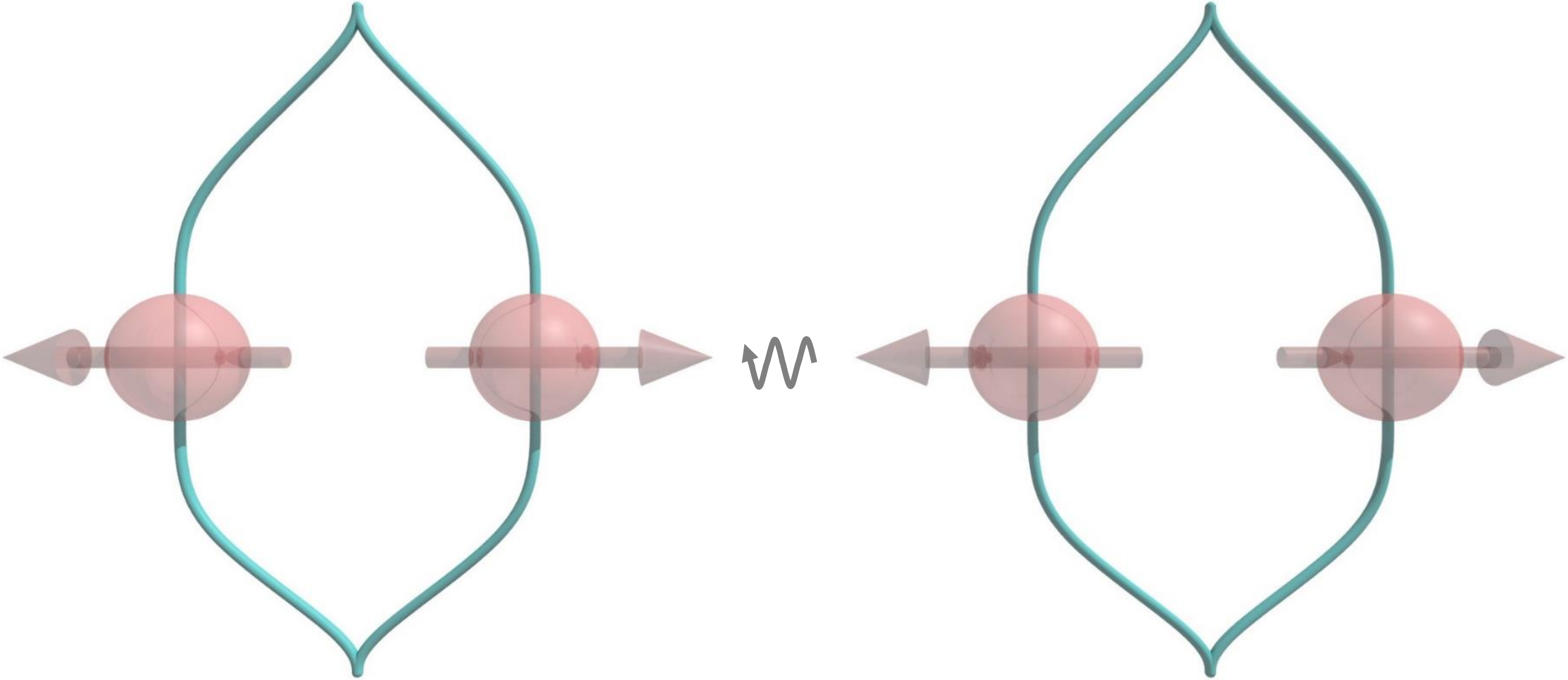


Matvei Bronstein:
G Gorelik, Phys Usp 48, 1039 (2005)
MP Bronstein, Phys Z Sowjetunion 9.2–3, 140 (1936)

Richard Feynman
CM DeWitt, D Rickles (eds), The role of gravitation in physics: report from the 1957 Chapel Hill Conference, page 250, Published 2011



# Can gravity entangle things?



S Bose, A Mazumdar, GWM, H Ulbricht, M Toroš, M Paternostro, AA Geraci, PF Barker, MS Kim & G Milburn, PRL 119, 240401 (2017)

C Marletto & V Vedral, PRL 119, 240402 (2017)

2 µm object, Δx ~ 250 µm

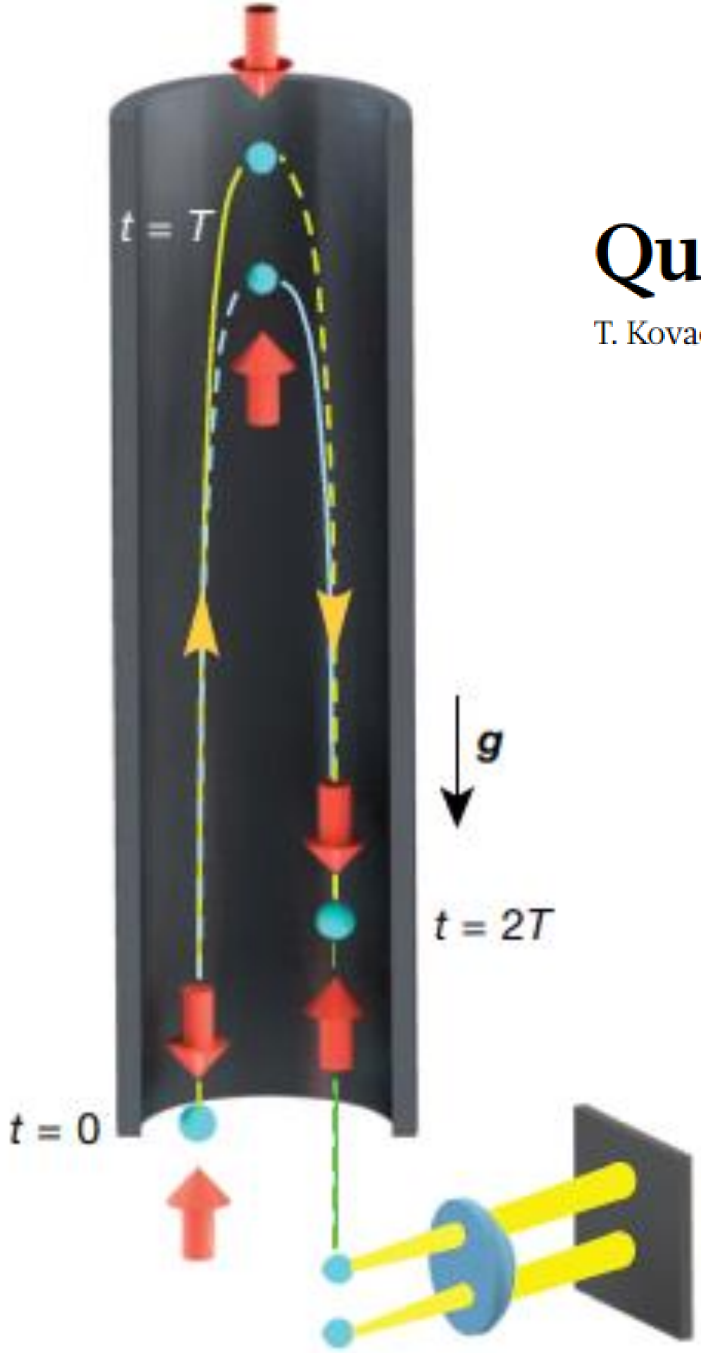
Closest approach ~ 200 µm

Time ~ few seconds

# Maybe gravity is classical?

Diosi, Phys Lett 105A, 199 (1984)
Penrose, Gen Relativ Gravity 28, 581 (1996)
Ghirardi, Rimini and Weber, PRD 34, 470 (1986)
Adler, Nucl Phys B415, 195 (1994)
Bassi, Lochan, Satin, Singh & Ulbricht, RMP 85, 471 (2013)
Kafri, Taylor, Milburn, NJP 16, 065020 (2014)
Oppenheim, Physical Review X 13, 041040 (2023)

# BEC superposition




**Quantum superposition at the half-metre scale**

T. Kovachy[1], P. Asenbaum[1], C. Overstreet[1], C. A. Donnelly[1], S. M. Dickerson[1], A. Sugarbaker[1], J. M. Hogan[1] & M. A. Kasevich[1]

Nature 528, 530 (2015)

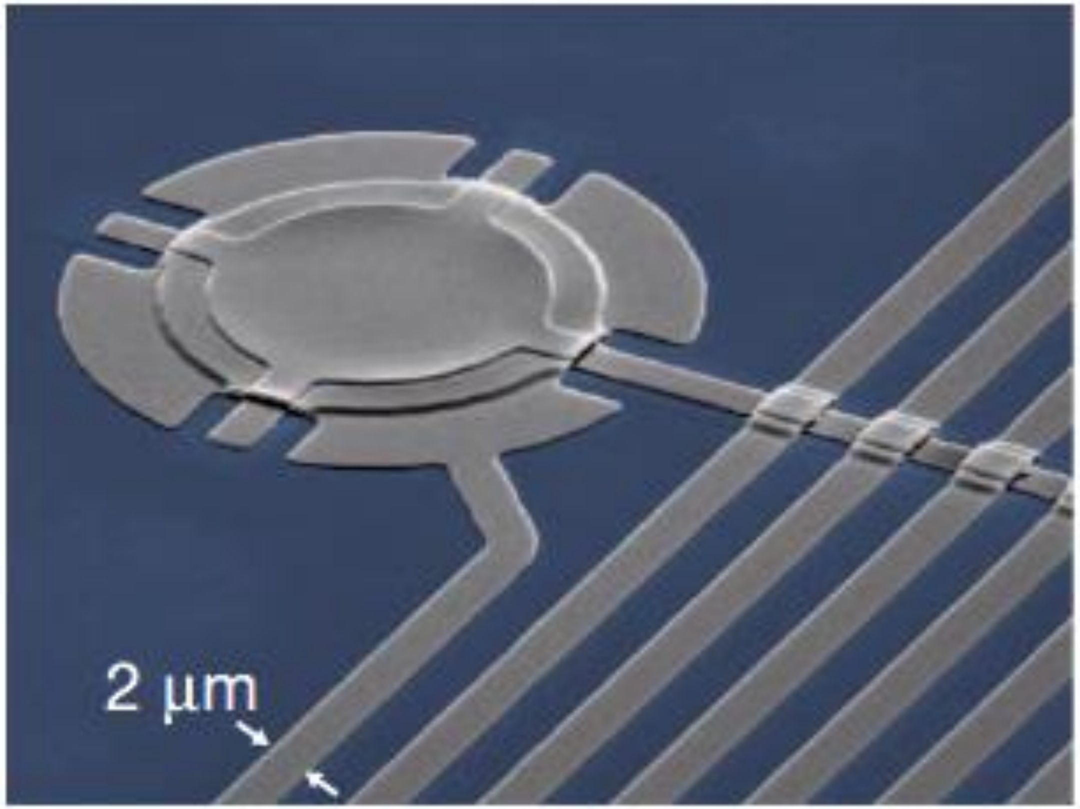
Single atom superposition: not a cat state

The phase was not controlled

Small mass, large superposition distance and time

# Clamped oscillators

- S. Gröblacher, K. Hammerer, M. R. Vanner and M. Aspelmeyer, Nature 460, 724 (2009)
- A. D. O'Connell et al., Nature 464, 697 (2010)
- J. M. Pirkkalainen, S. U. Cho, J. Li, G. S. Paraoanu, P. J. Hakonen & M. A. Sillanpää, Nature 494, 211 (2013)
- A. H. Safavi-Naeini, S. Groblacher, J. T. Hill, J. Chan, M. Aspelmeyer & O. Painter, Nature 500, 185 (2013)
- T. A. Palomaki, J. D. Teufel, R. W. Simmonds and K. W. Lehnert, Science 342, 710 (2013)
- J. B. Clark, F. Lecocq, R. W. Simmonds, J. Aumentado and J. D. Teufel, Nature 541, 191 (2017)
- C. F. Ockeloen-Korppi, E. Damskägg, J. M. Pirkkalainen, M. Asjad, A. A. Clerk, F. Massel, M. J. Woolley & M. A. Sillanpää, Nature 556, 478 (2018)
- R. Riedinger, A. Wallucks, I. Marinković, C. Löschnauer, M. Aspelmeyer, S. Hong and S. Gröblacher, Nature 556, 473 (2018)




Large mass, small superposition distance and time

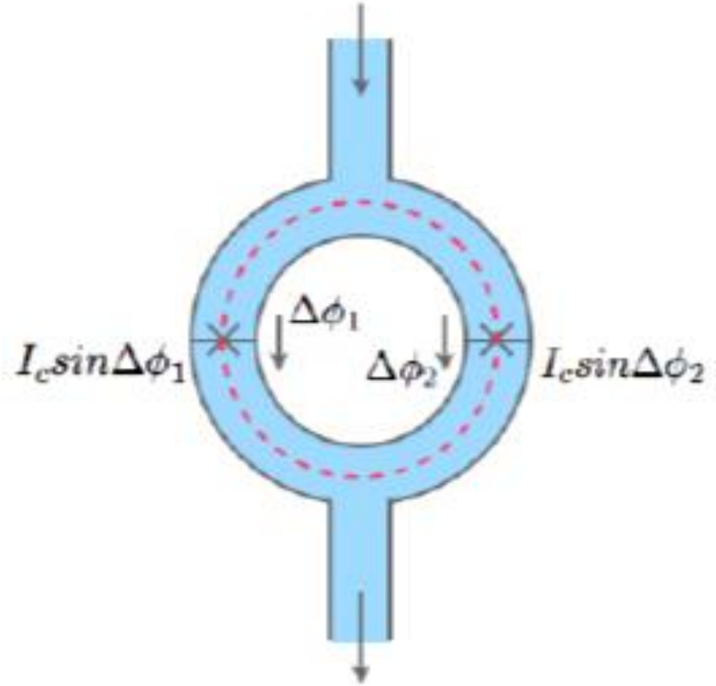
# SQUIDs and SHeQUIDs

SQUIDs:

- J. R. Friedman, V. Patel, W. Chen, S. K. Tolpygo and J. E. Lukens, Nature 406, 43 (2000).
    - Superposition of few μA clockwise and anti-clockwise
- T. Hime, P. A. Reichardt, B. L. T. Plourde, T. L. Robertson, C.-E. Wu, A. V. Ustinov and J. Clarke, Science 314, 1427 (2006).

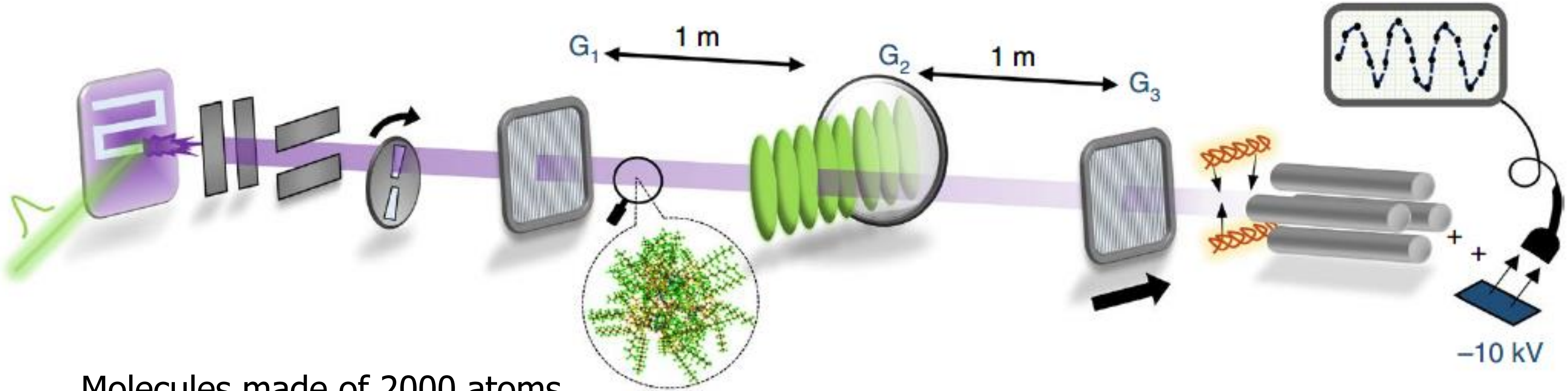
SHeQUIDs:

- S. Backhaus, S. Pereverzev, R. W. Simmonds, A. Loshak, J. C. Davis and R. E. Packard, Nature 392, 687 (1998).
- S. Backhaus, R. W. Simmonds, A. Loshak, J. C. Davis and R. E. Packard, Nature 397, 485 (1999).
- R. W. Simmonds, A. Marchenkov, E. Hoskinson, J. C. Davis and R. E. Packard, Nature 412, 55 (2001).
- R. E. Packard and Y. Sato, Journal of Physics: Conference Series 568, 012015 (2014).




No superposition of mass in two places

# The most macroscopic spatial superposition




Molecules made of 2000 atoms

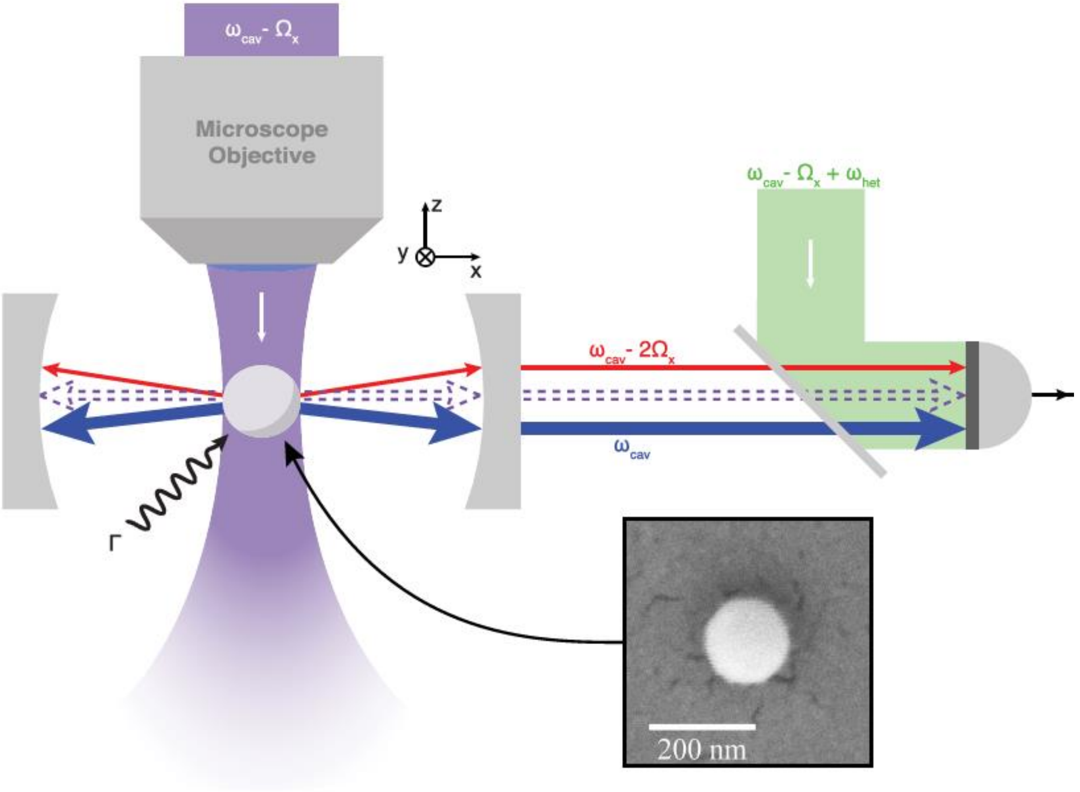
266 nm slit period

Y. Y. Fein, P. Geyer, P. Zwick, F. Kiałka, S. Pedalino, M. Mayor, S. Gerlich & M. Arndt, Nature Physics 15, 1242 (2019)

Average mass, superposition distance and time

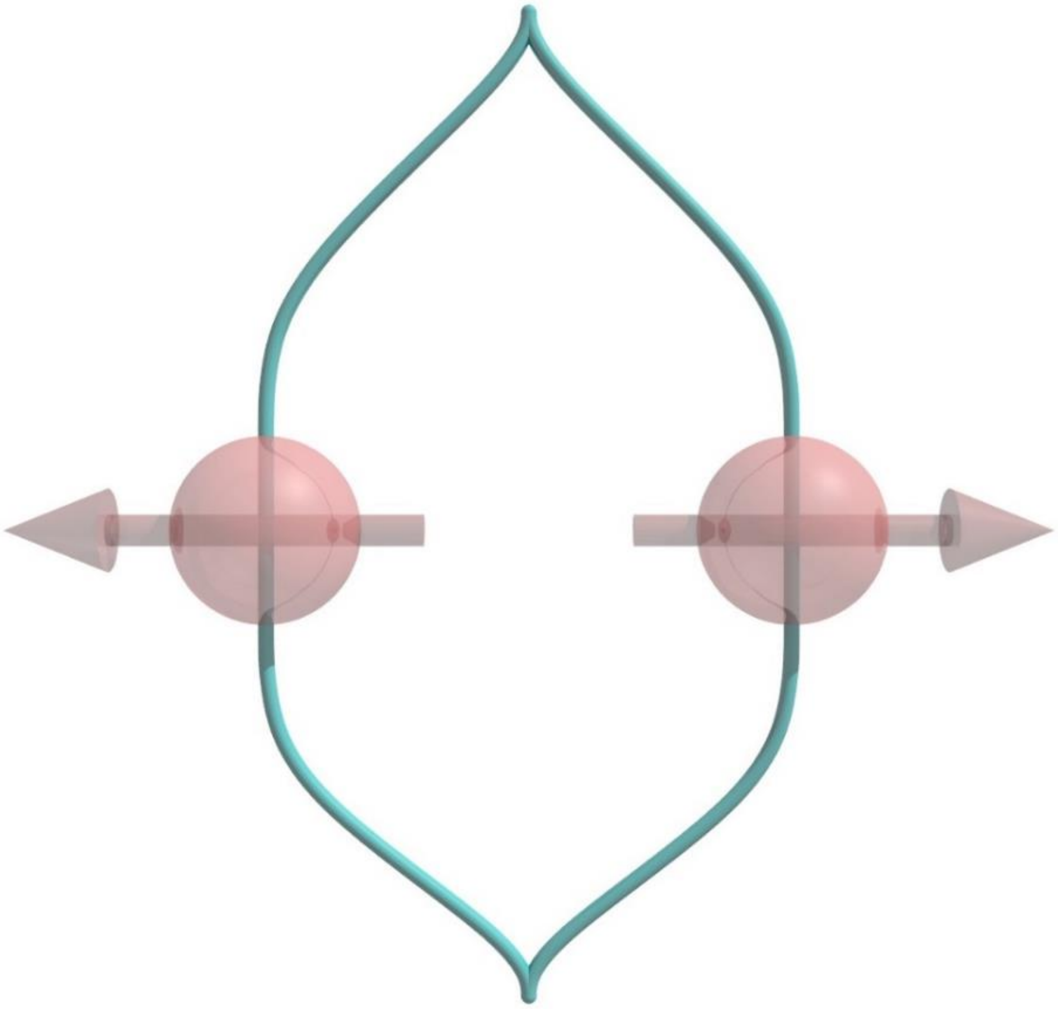
# Levitated nanoparticles in their ground state

- U. Delić, M. Reisenbauer, K. Dare, D. Grass, V. Vuletić, N. Kiesel and M. Aspelmeyer, Science 367, 892 (2020)
- L. Magrini, P. Rosenzweig, C. Bach, A. Deutschmann-Olek, S. G. Hofer, S. Hong, N. Kiesel, A. Kugi and M. Aspelmeyer, Nature 595, 373 (2021)
- F. Tebbenjohanns, M. L. Mattana, M. Rossi, M. Frimmer and L. Novotny, Nature 595, 378 (2021)




No superposition yet

# Our proposal: drop a nanodiamond containing a spin



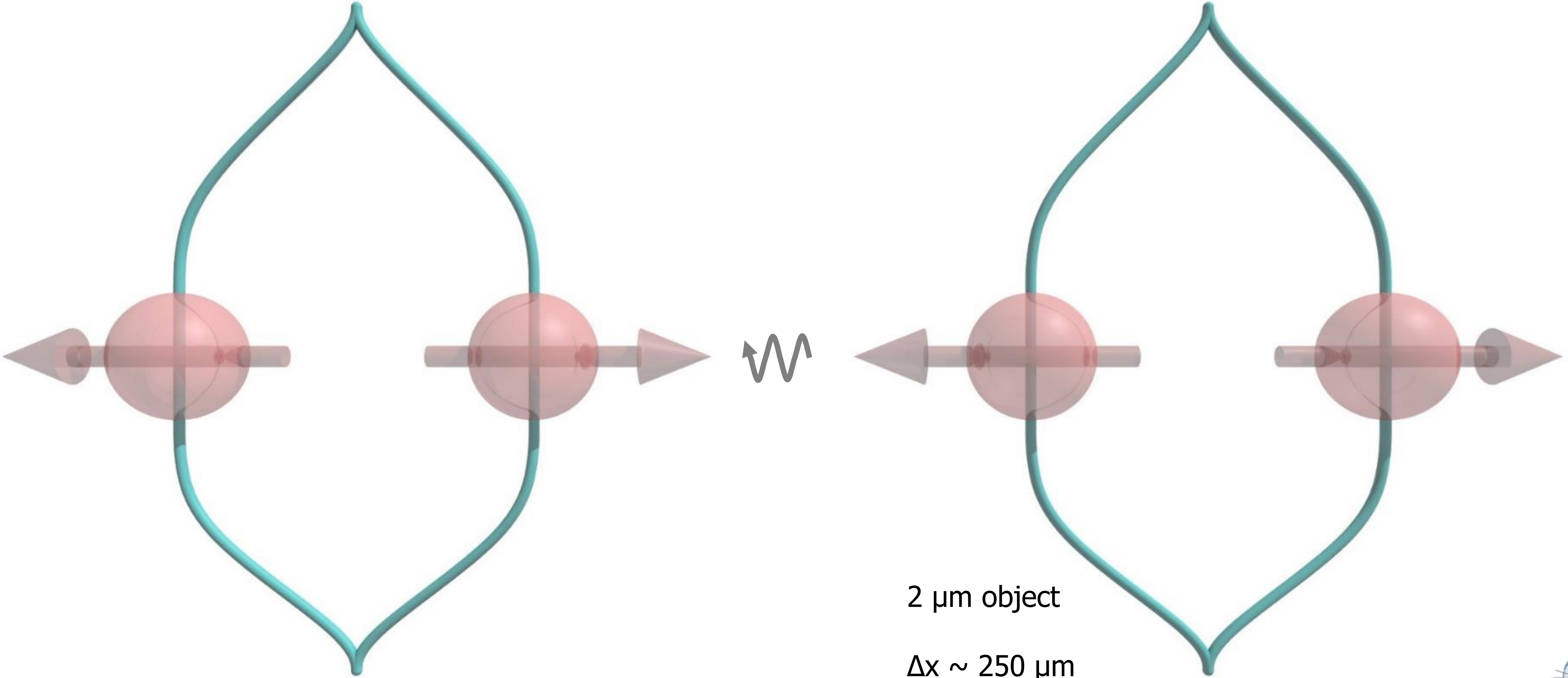
**Proposals from our collaboration:**

- M Scala… & S Bose, PRL **111**, 180403 (2013)
- C Wan…& MS Kim, PRA **93**, 043852 (2016)
- C Wan… & MS Kim, PRL **117**, 143003 (2016)
- S Bose… & G Milburn, PRL **119**, 240401 (2017)
- JS Pedernales, GWM & MB Plenio, PRL **125**, 023602 (2020)
- BD Wood, S Bose & GWM, PRA **105**, 012824 (2022)

**From other groups:**

- Z-q Yin, T Li, X Zhang & LM Duan, PRA **88**, 033614 (2013)

# Can gravity entangle things?



2 μm object

Δx ~ 250 μm

Closest approach ~ 200 μm

S Bose, A Mazumdar, GWM, H Ulbricht, M Toroš, M Paternostro,
AA Geraci, PF Barker, MS Kim & G Milburn, PRL 119, 240401 (2017)

# Nitrogen-vacancy centre (NVC) in diamond

- Magnetometry
- Building a quantum computer
- Levitating nanodiamonds towards a test of the quantum nature of gravity

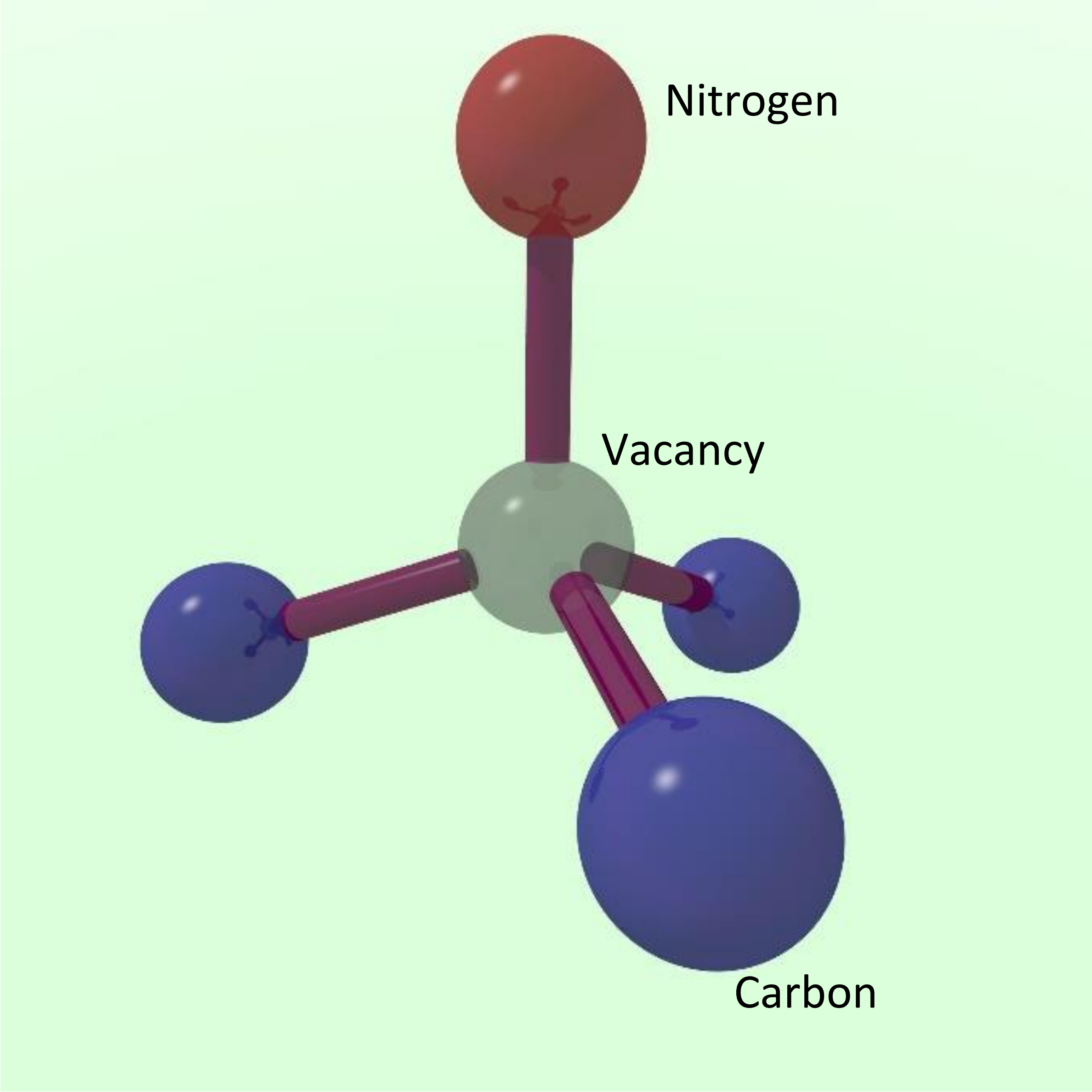
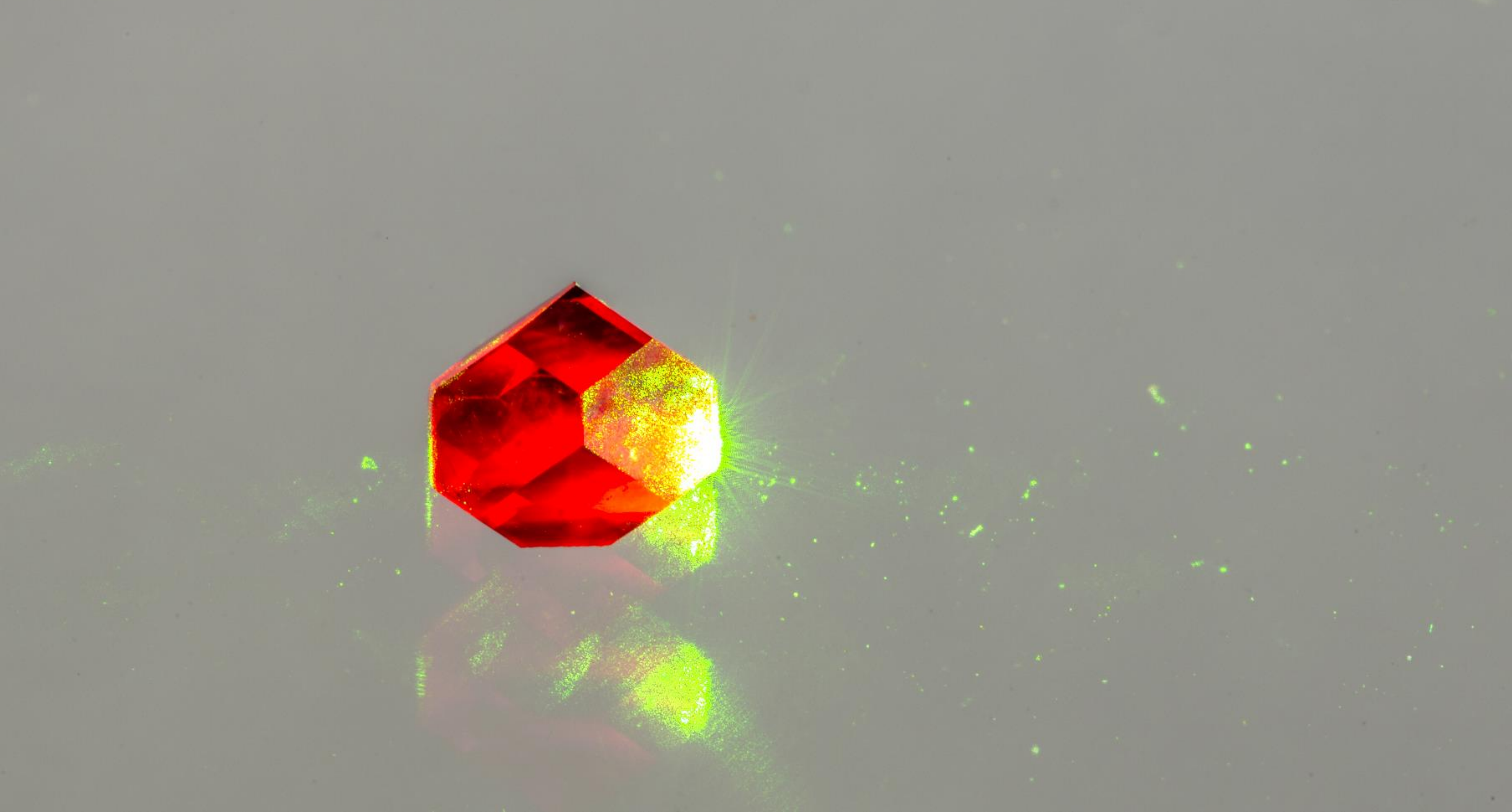
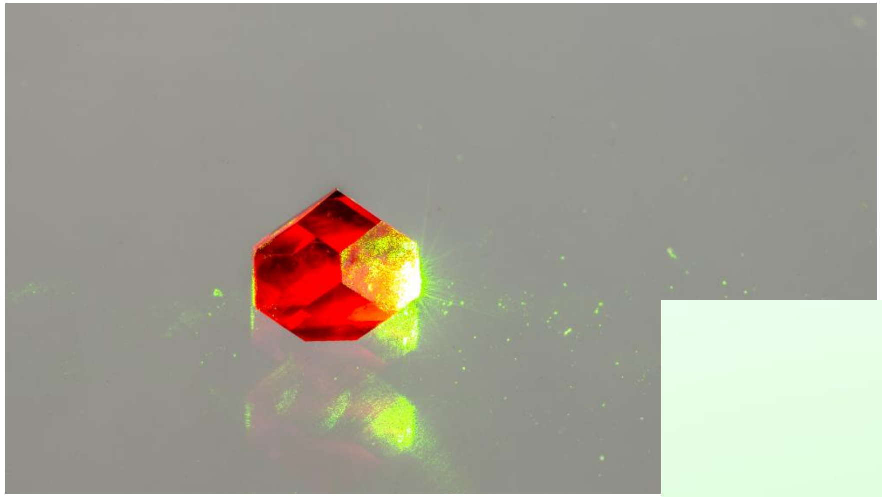
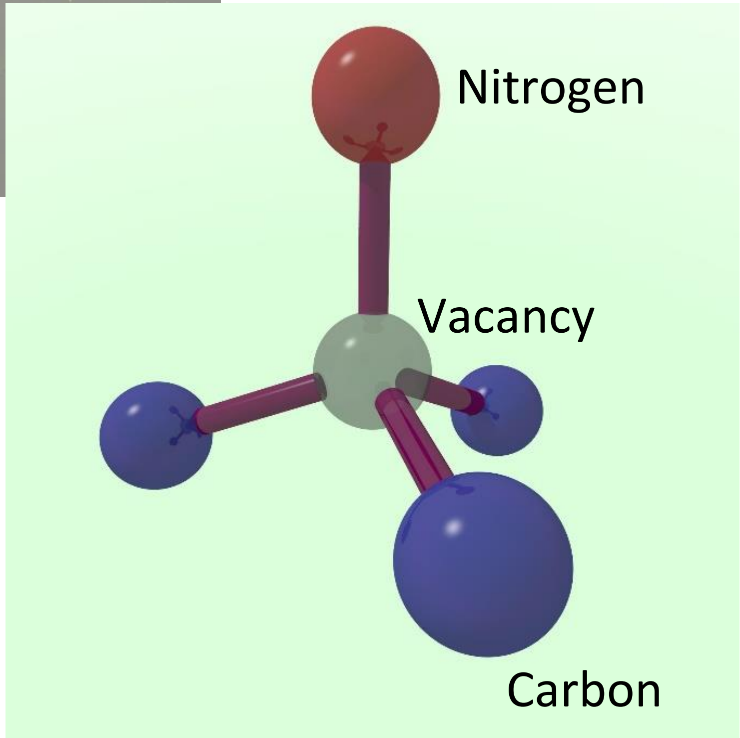


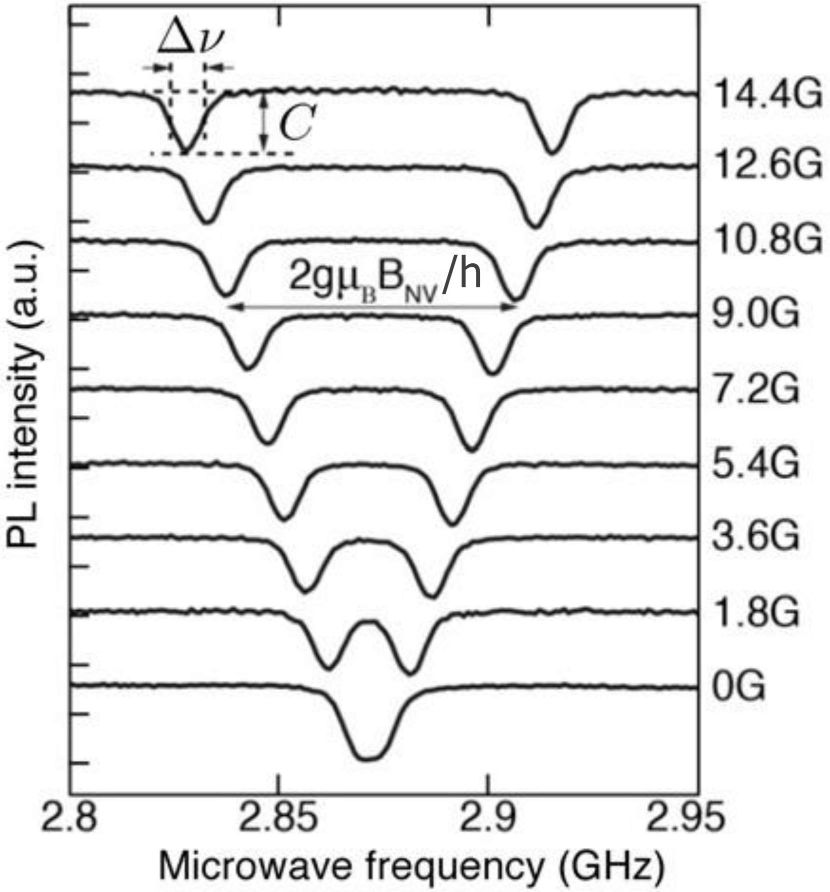
Photo by Jon Newland (Warwick)



# NV centre red fluorescence vs microwave frequency

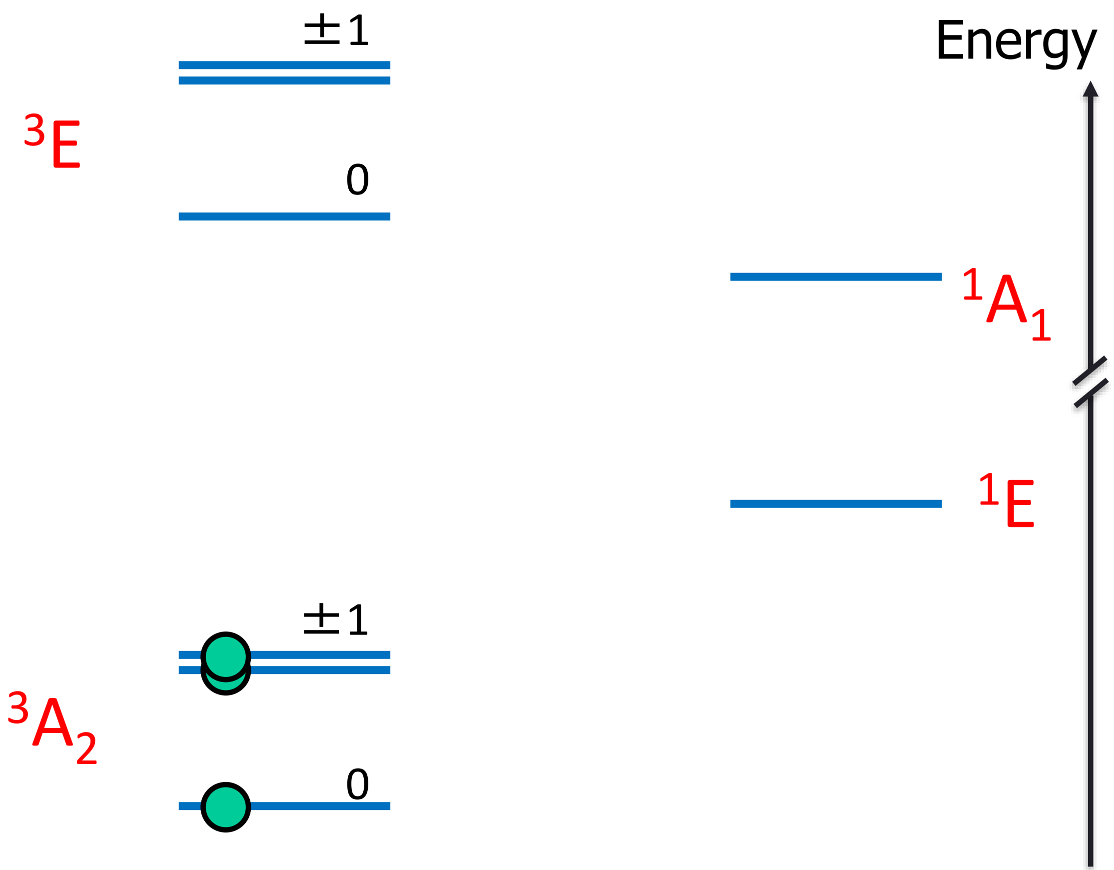


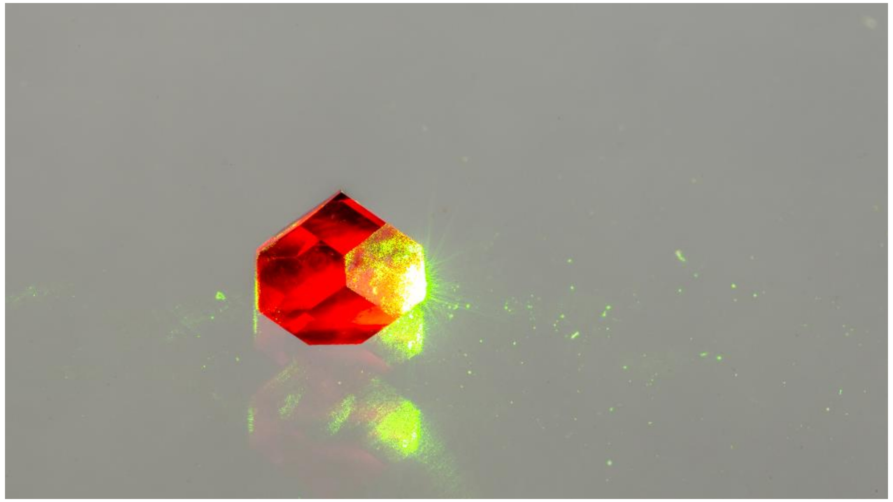


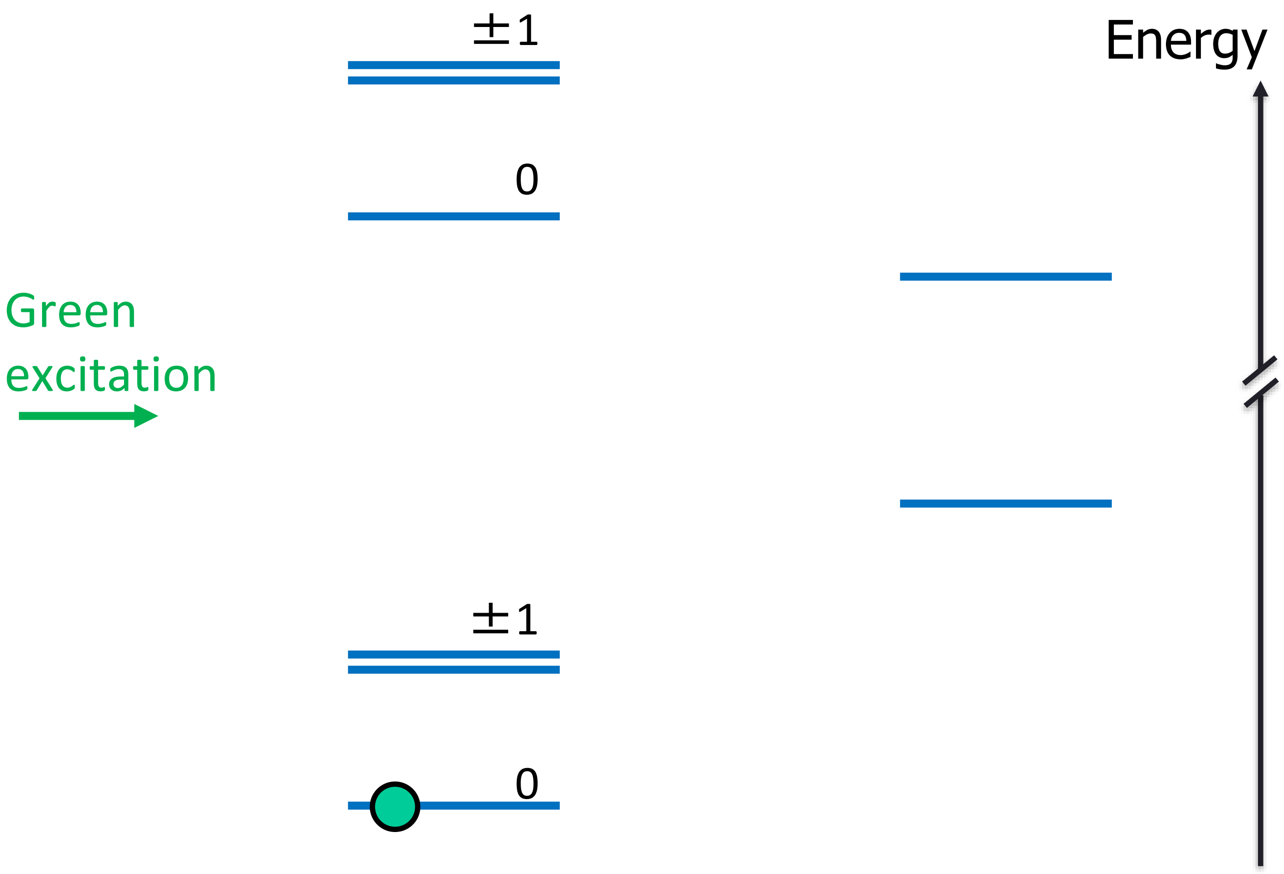

L Rondin *et al*, Rep Prog Phys 77, 056503 (2014)

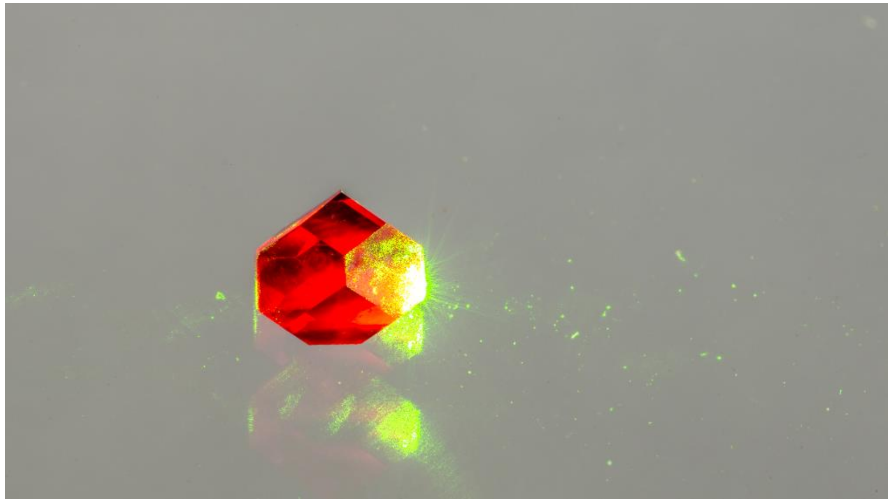
# Nitrogen-vacancy ($NV^-$) energy levels



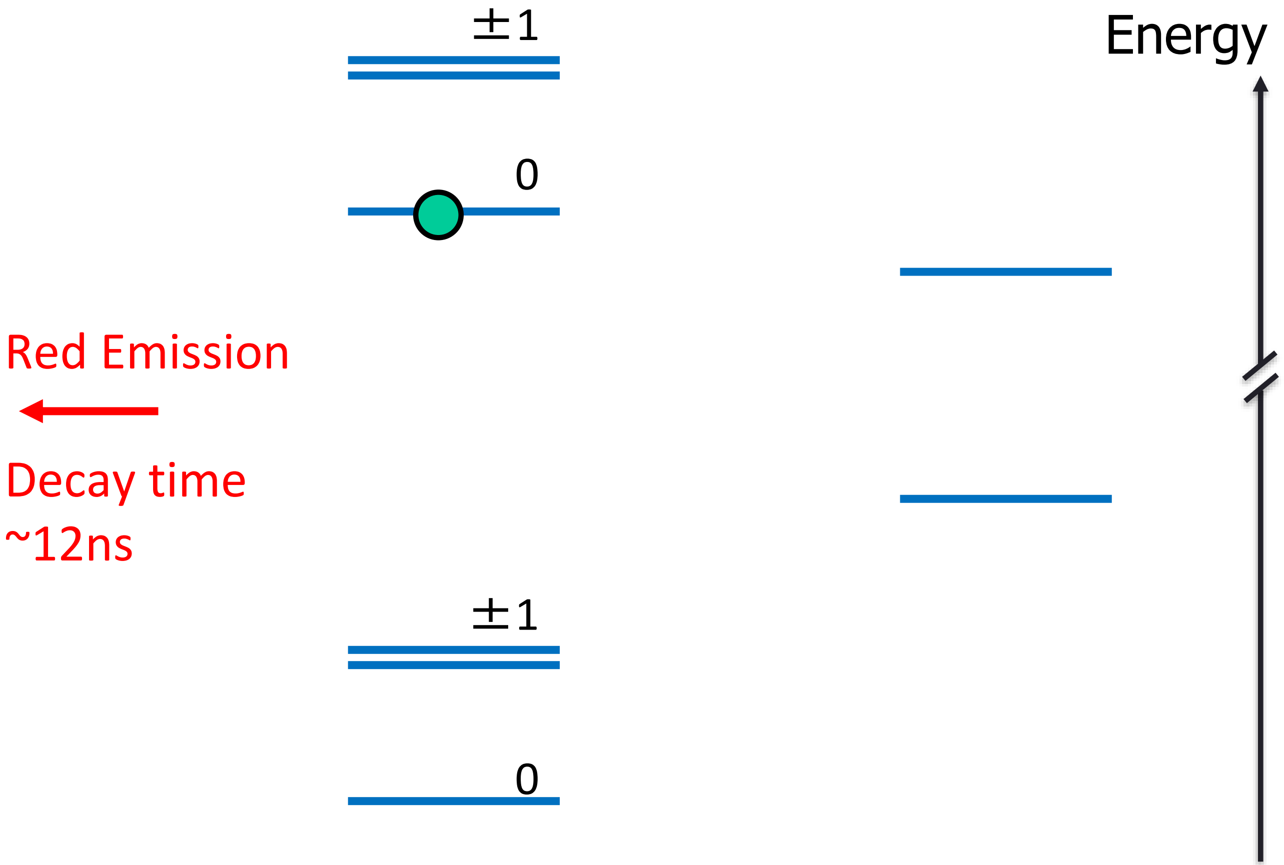



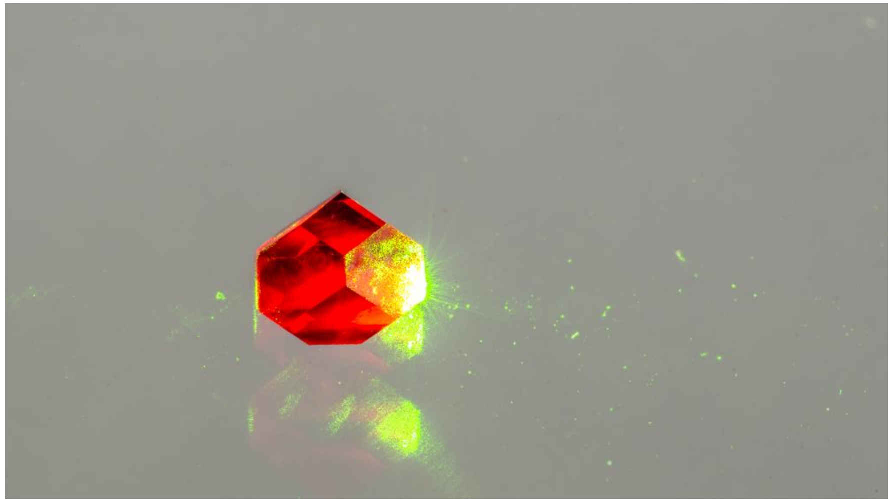
# Nitrogen-vacancy ($NV^-$) energy levels - excite



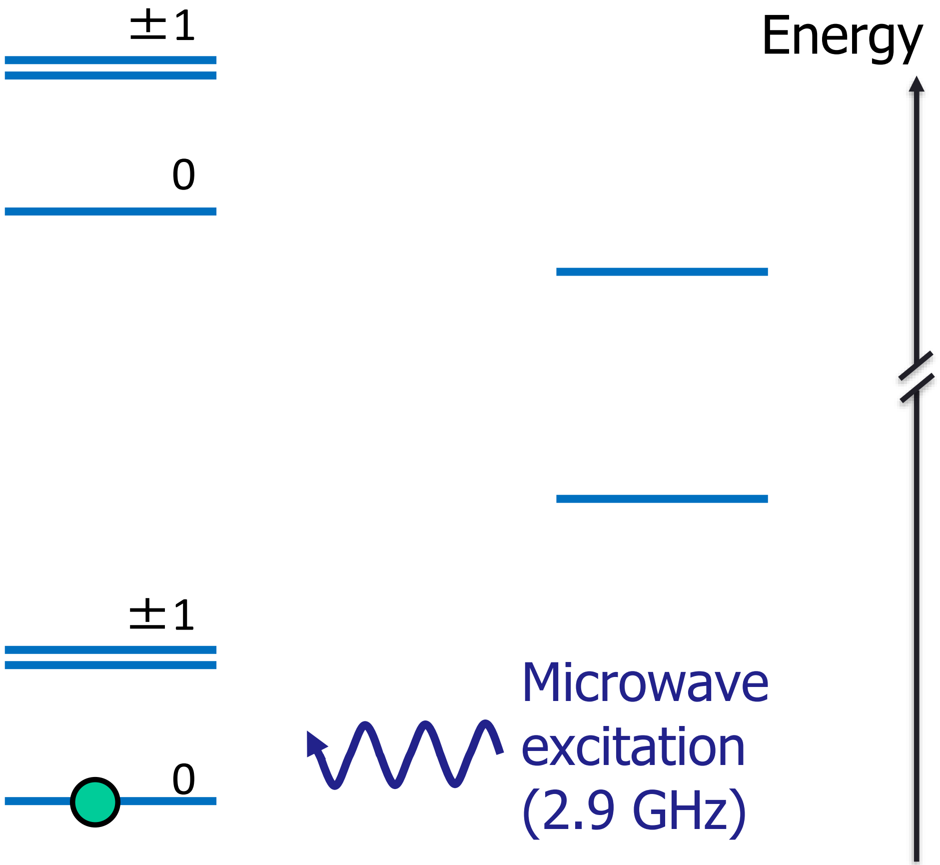



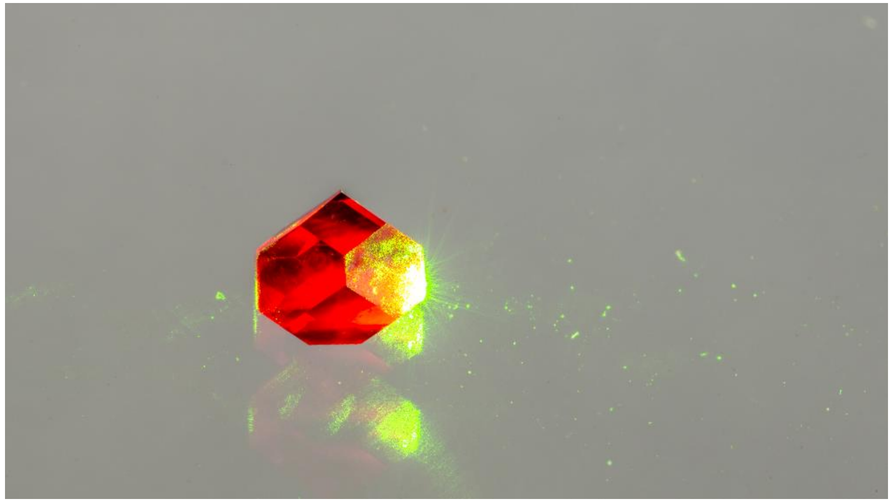
# Nitrogen-vacancy ($NV^-$) energy levels - florescence



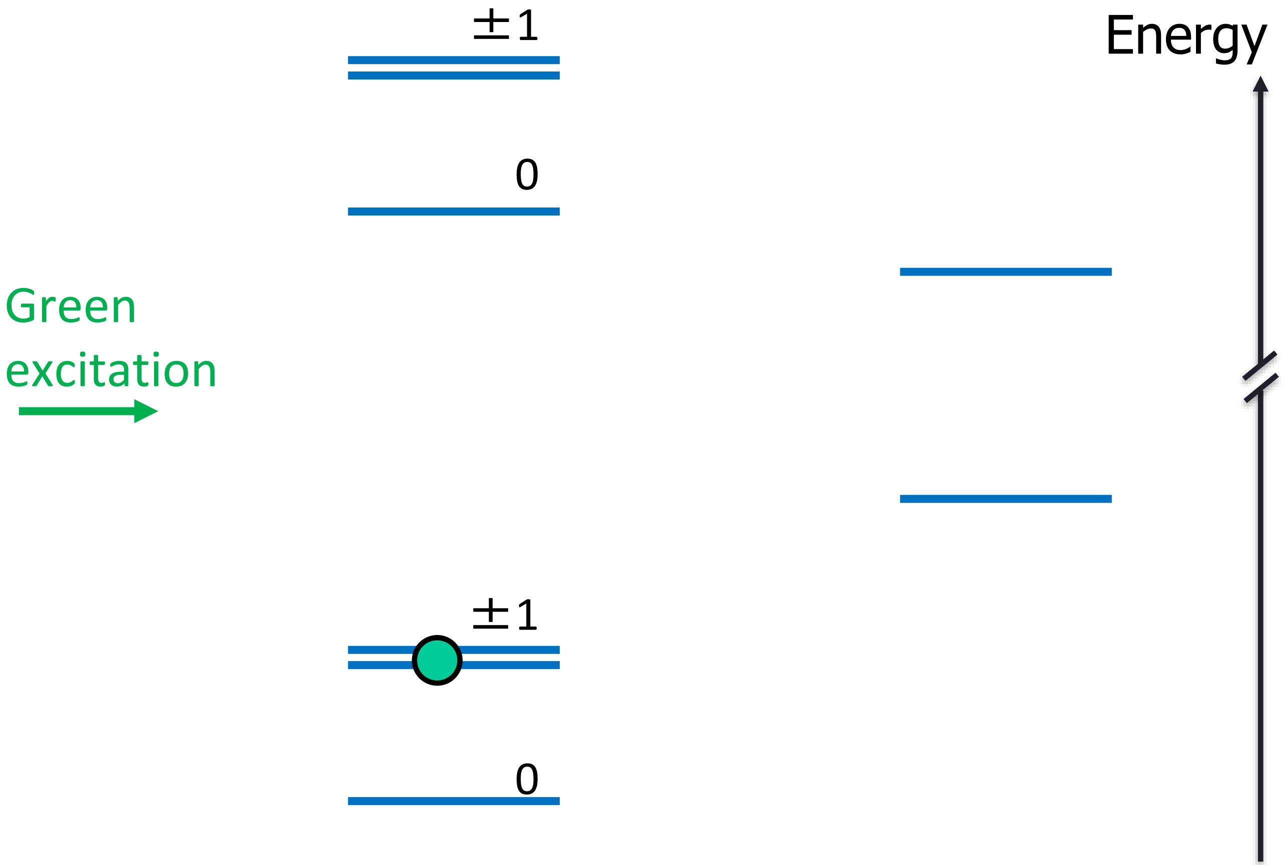



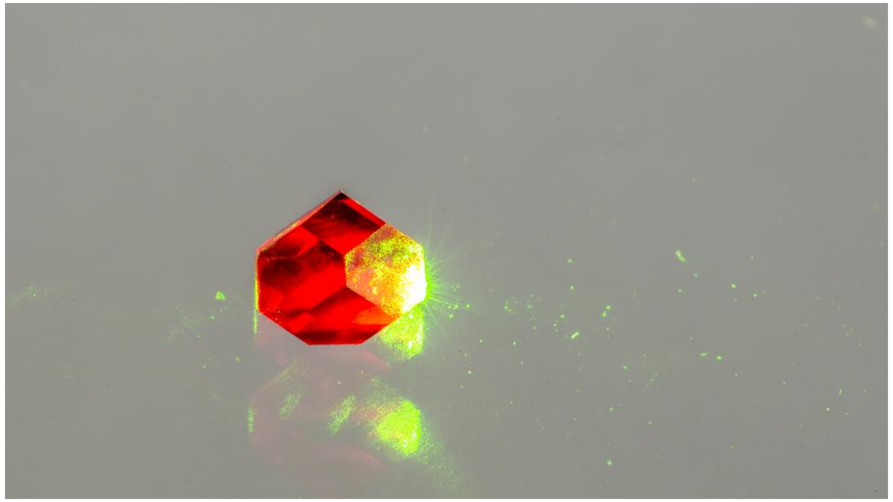
# Nitrogen-vacancy ($NV^-$) energy levels - microwaves



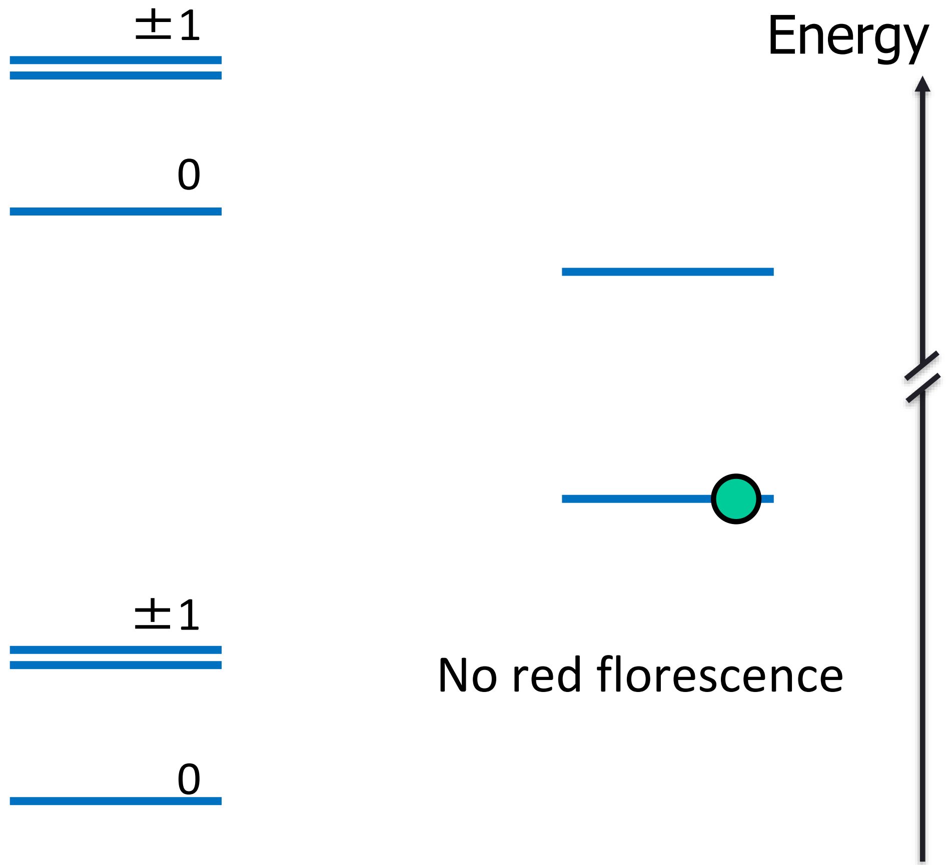



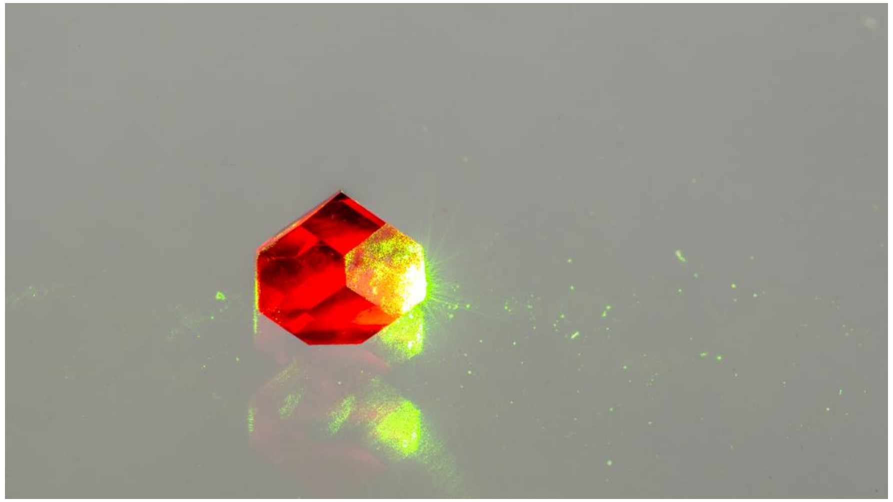
# Nitrogen-vacancy ($NV^-$) energy levels
# - dark state



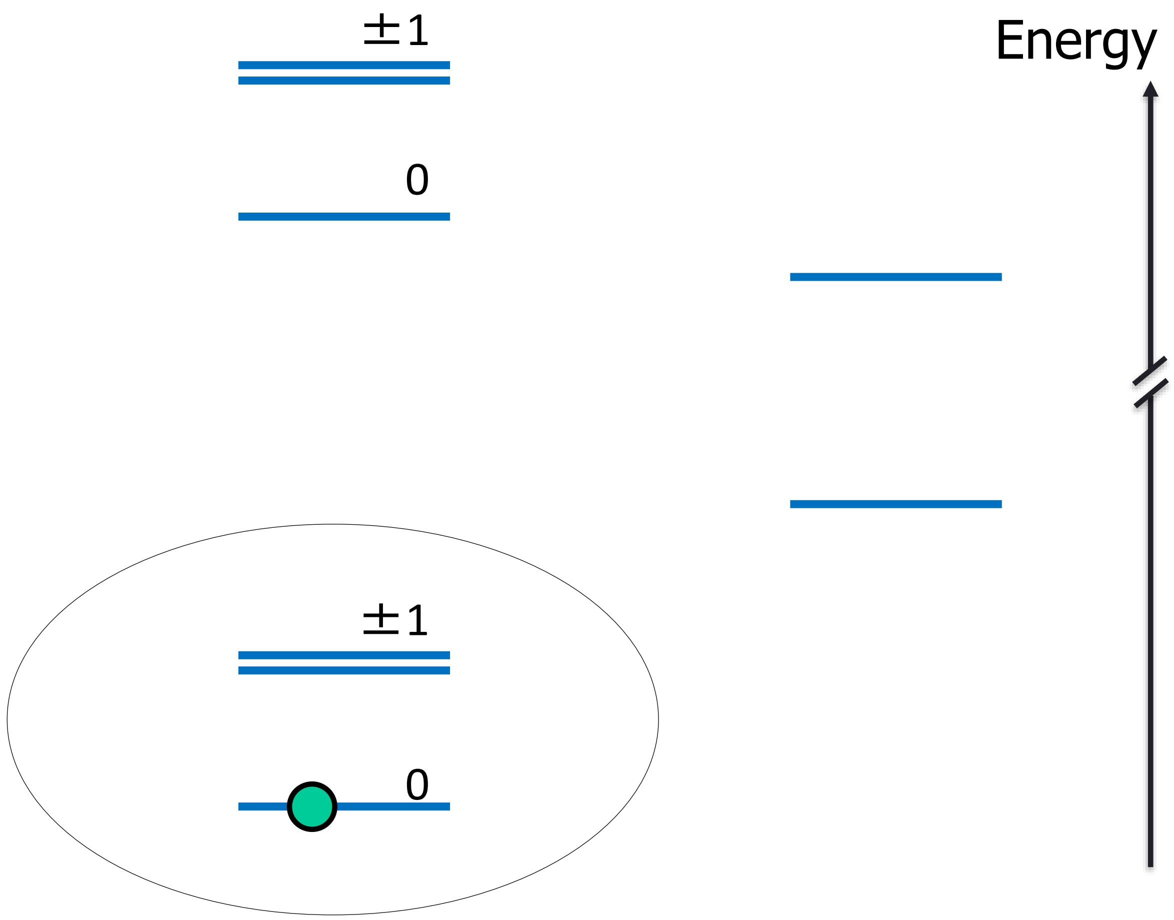



# Nitrogen-vacancy ($NV^-$) energy levels



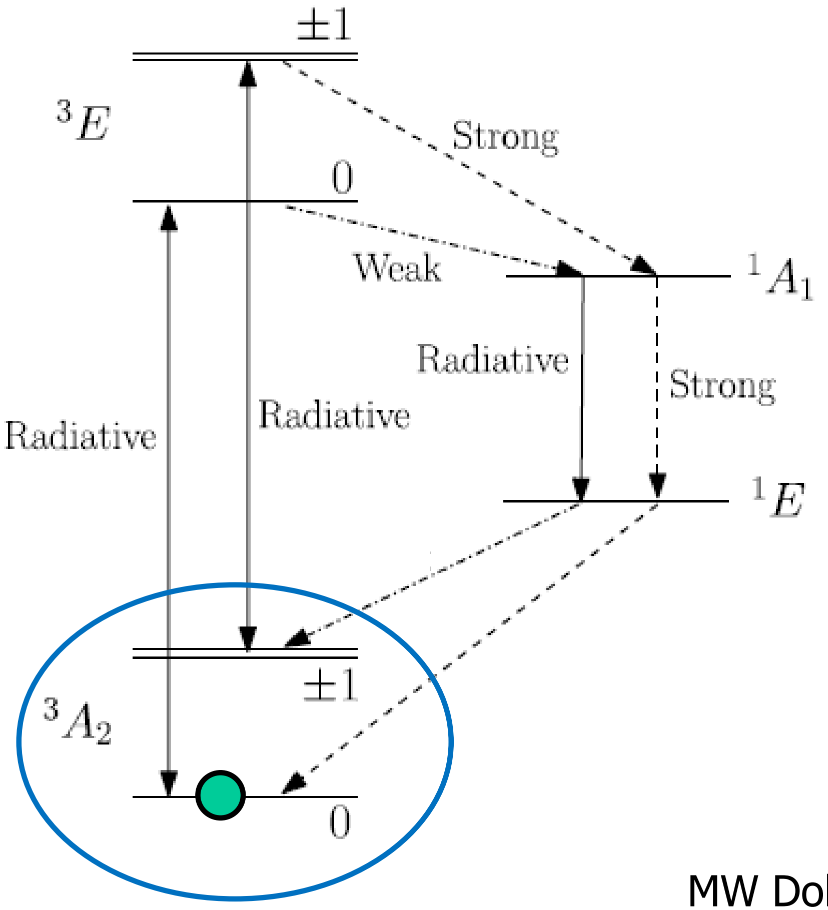
# Nitrogen-vacancy ($NV^-$) energy levels

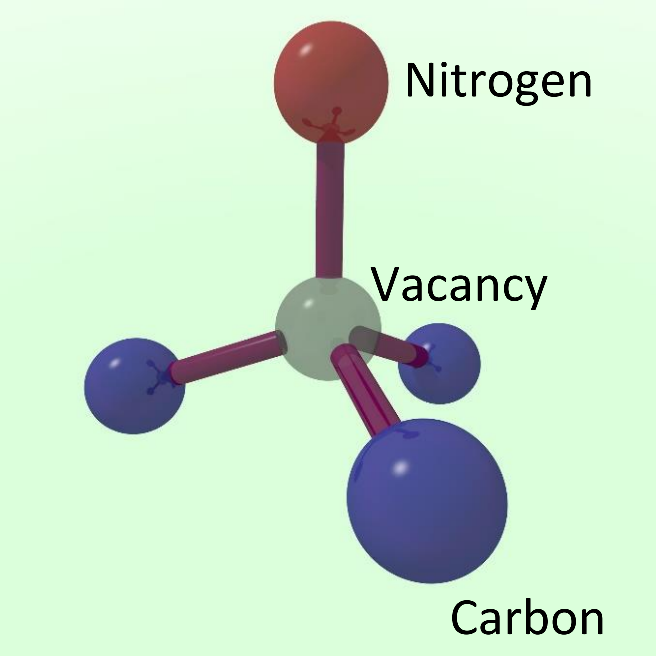



**Green excitation →**

1. Spin polarization
2. Spin-dependent fluorescence

# Nitrogen-vacancy ($NV^-$) energy levels



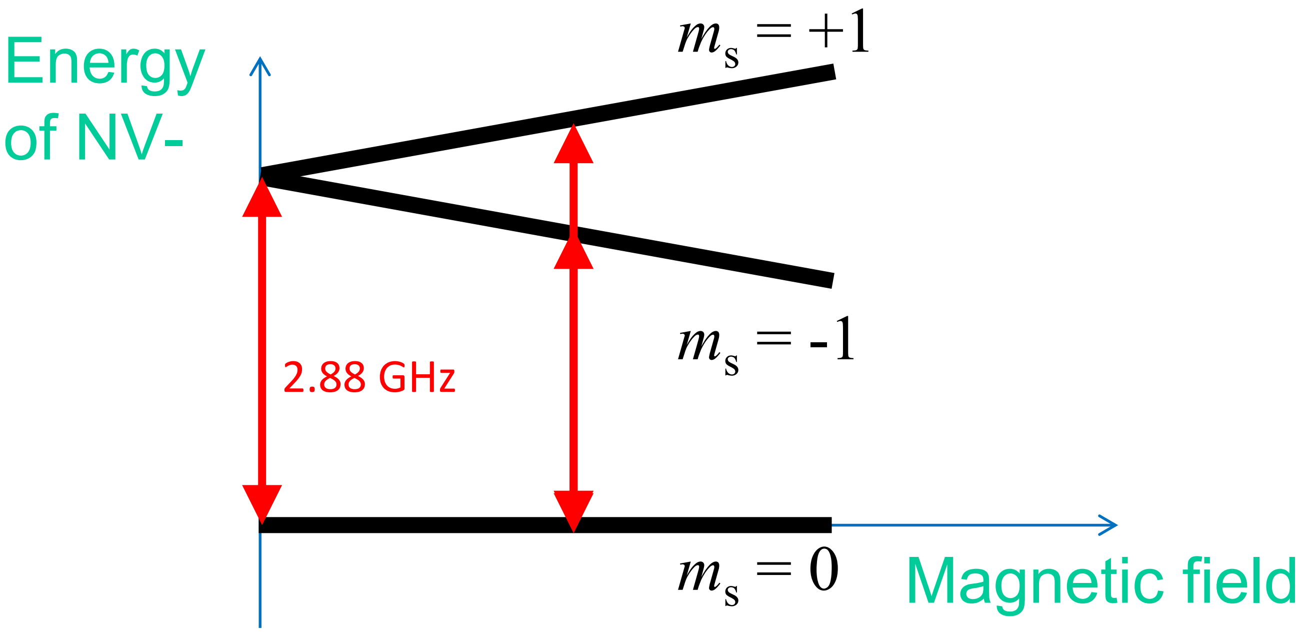



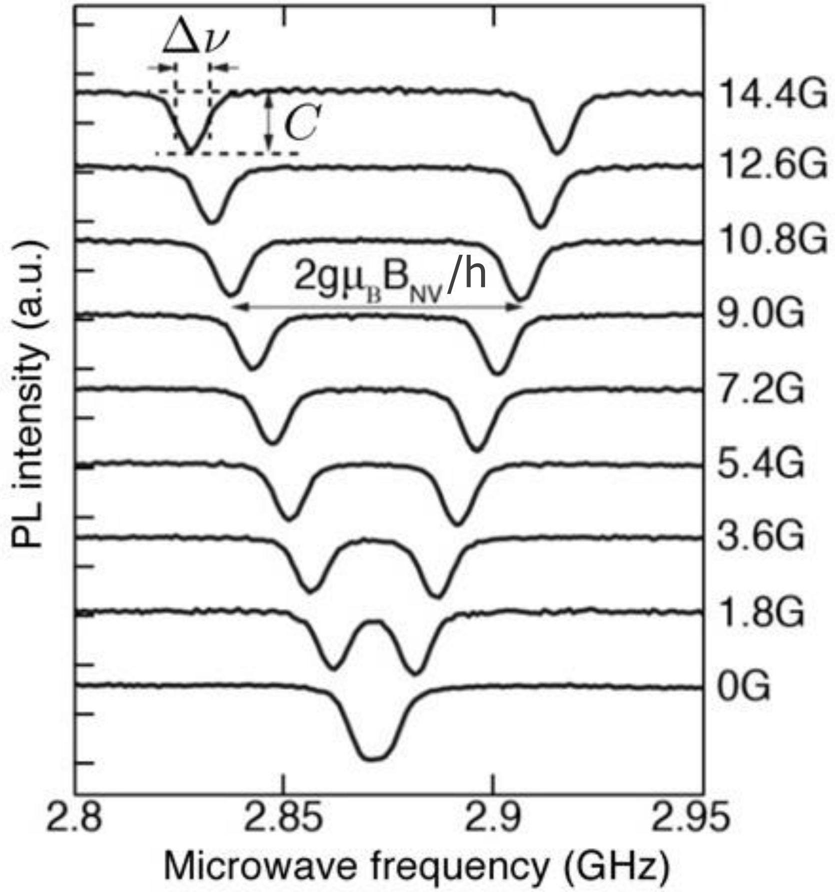

**Green excitation →**

1. Spin polarization
2. Spin-dependent fluorescence

MW Doherty, NB Manson, P Delaney, F Jelezko, J Wrachtrup and LCL Hollenberg, Physics Reports **528**, 1 (2013)

# Nitrogen-vacancy ($NV^-$) magnetometry




Reviews:
JF Barry *et al*, Rev Mod Phys 92, 015004 (2020)
L Rondin *et al*, Rep Prog Phys 77, 056503 (2014)

# Diamond magnetometry

**Fibre-coupled diamond magnetometry:**
RL Patel… & GWM, Phys Rev Applied 14, 044058 (2020)

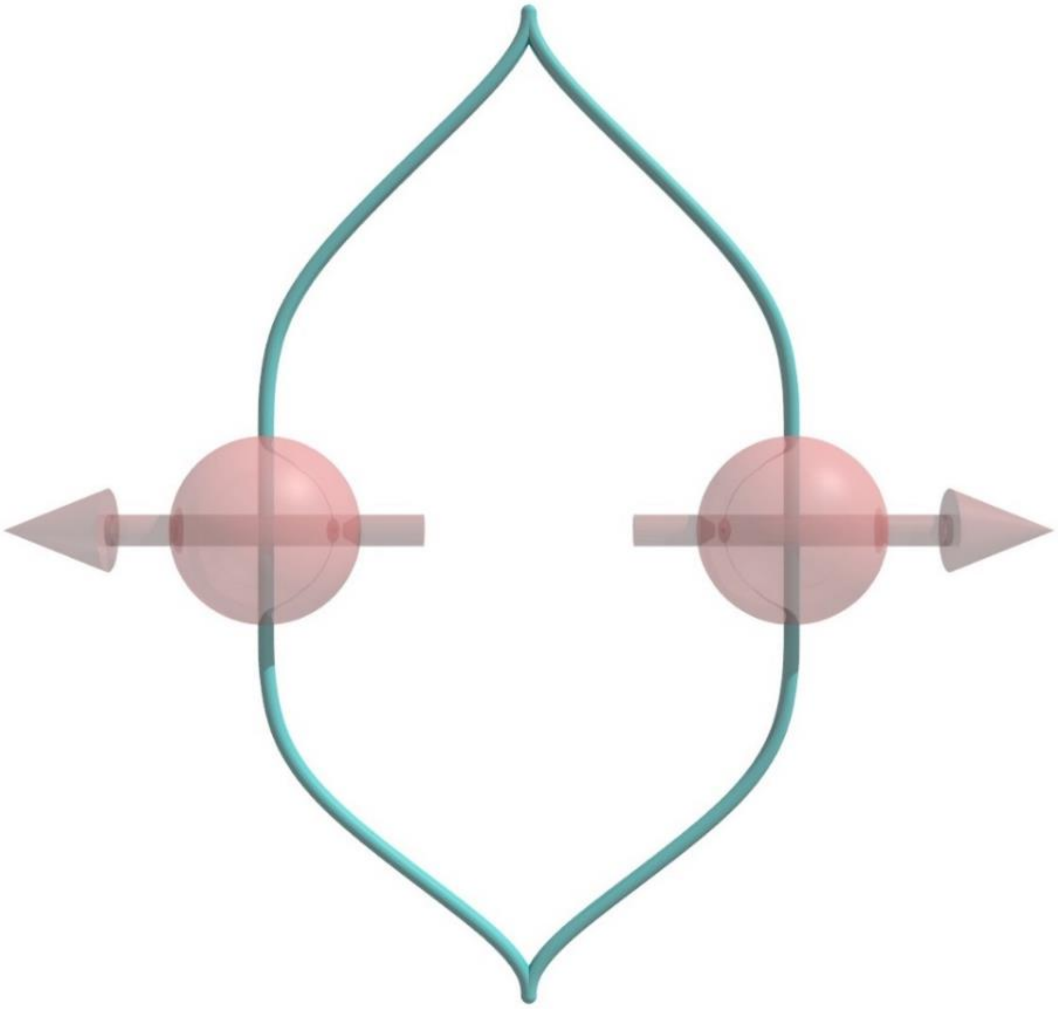
**Imaging steel:**
LQ Zhou… & GWM, Phys Rev Applied 15, 024015 (2021)

**30 pT/√Hz sensitivity:**
SM Graham… & GWM, Phys Rev Applied 19, 044042 (2023)

**Tensor gradiometry:**
AJ Newman… & GWM, Phys Rev Applied 21, 014003 (2024)

**In a van:**
SM Graham… & GWM, arXiv:2401.16090 (2024)

# Our proposal: drop a nanodiamond containing a spin

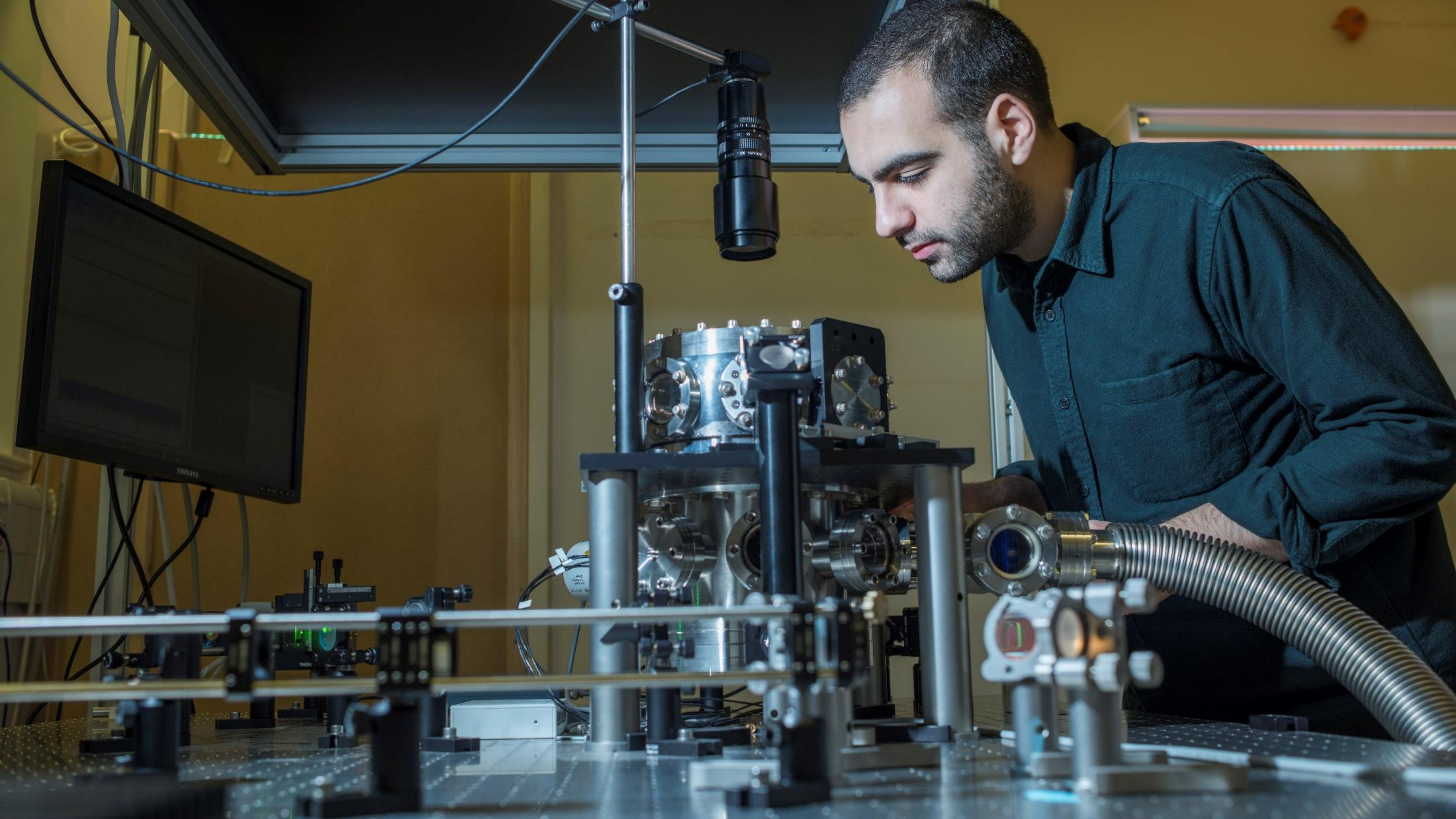


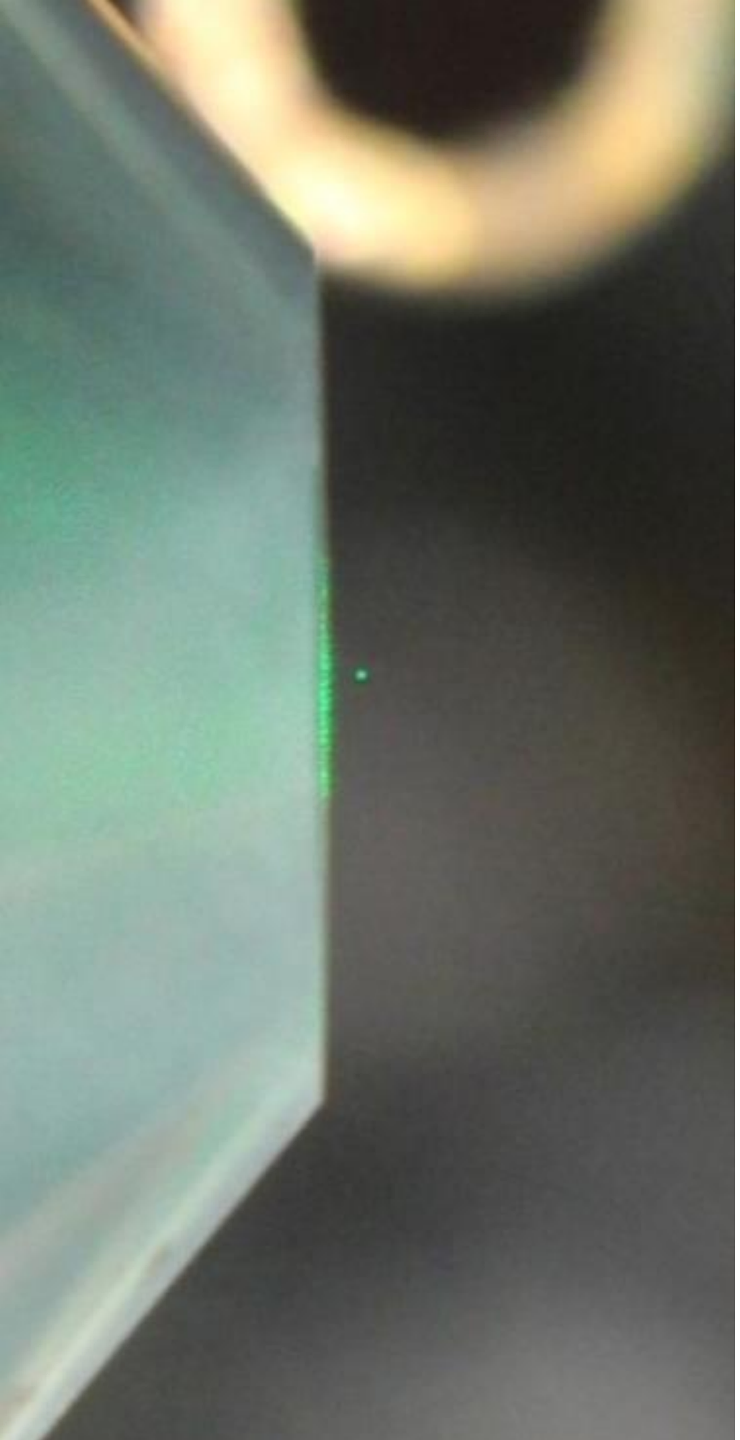
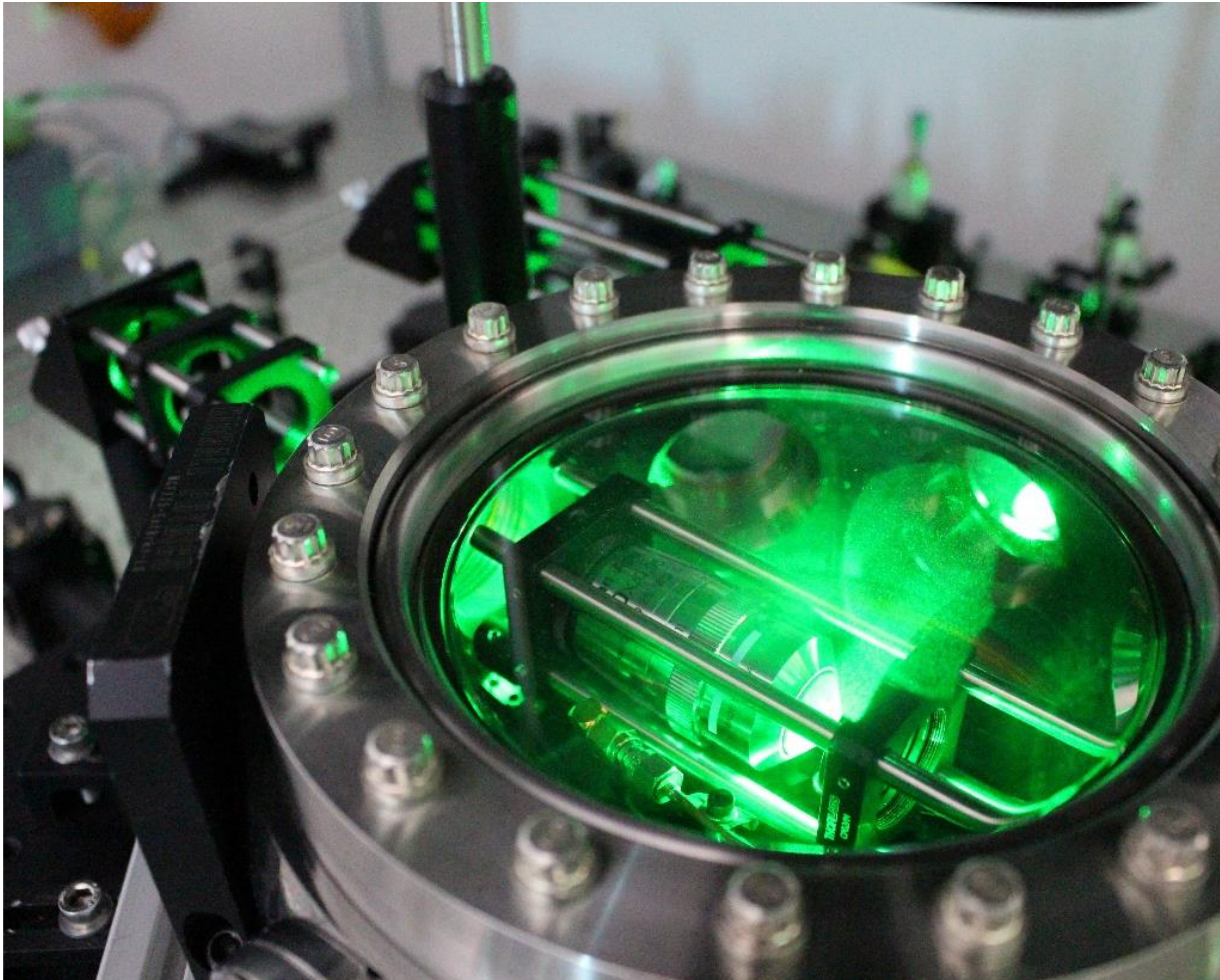
**Proposals from our collaboration:**

- M Scala… & S Bose, PRL **111**, 180403 (2013)
- C Wan…& MS Kim, PRA **93**, 043852 (2016)
- C Wan… & MS Kim, PRL **117**, 143003 (2016)
- S Bose… & G Milburn, PRL **119**, 240401 (2017)
- JS Pedernales, GWM & MB Plenio, PRL **125**, 023602 (2020)
- BD Wood, S Bose & GWM, PRA **105**, 012824 (2022)

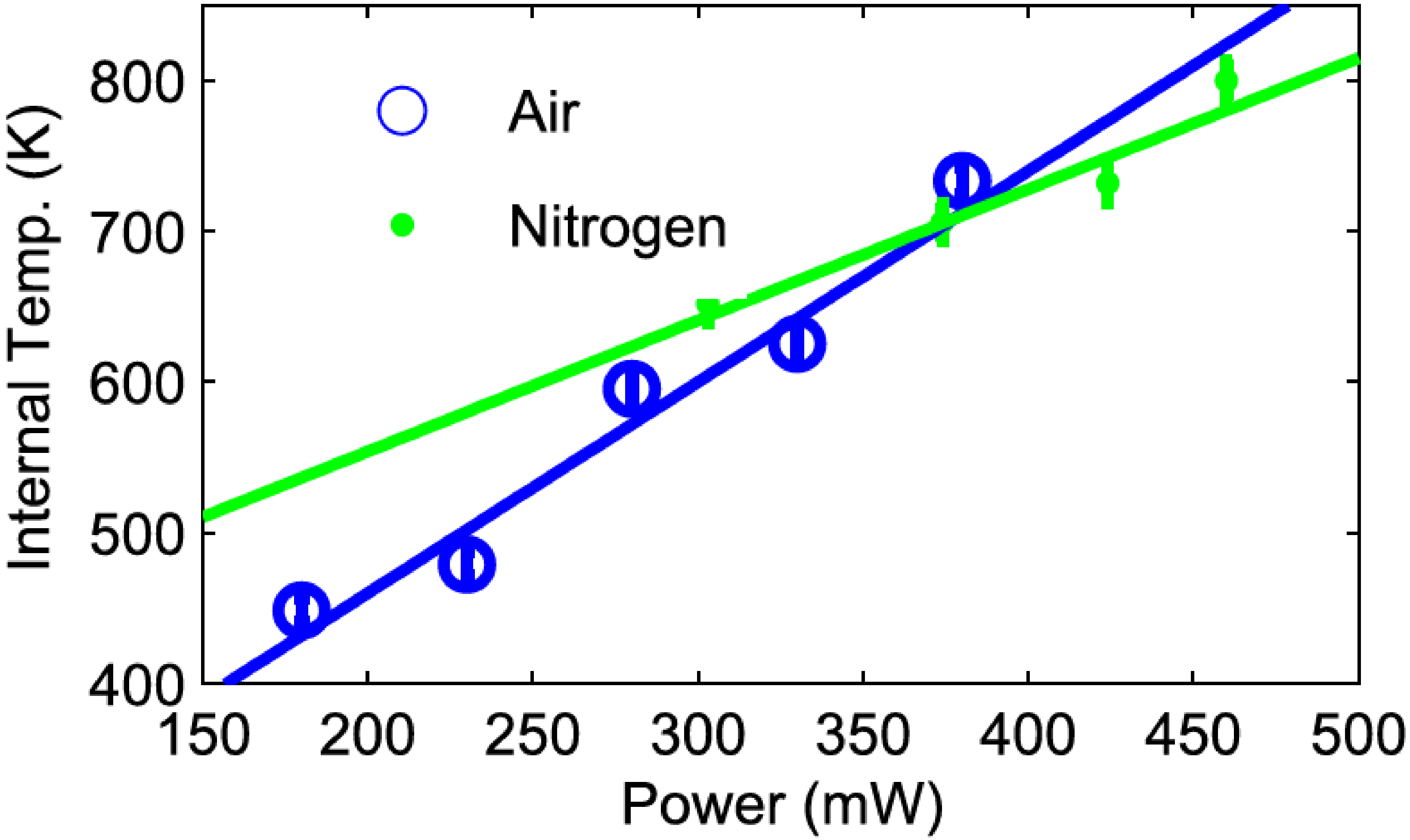
**From other groups:**

- Z-q Yin, T Li, X Zhang & LM Duan, PRA **88**, 033614 (2013)


SAMSUNG

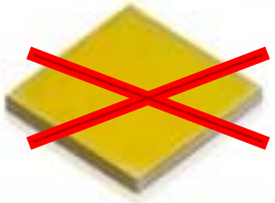
# Optically levitated nanodiamonds overheating




20 mbar

ATMA Rahman *et al.*,
Scientific Reports **6**,
21633 (2016)

# A solution: more pure diamonds

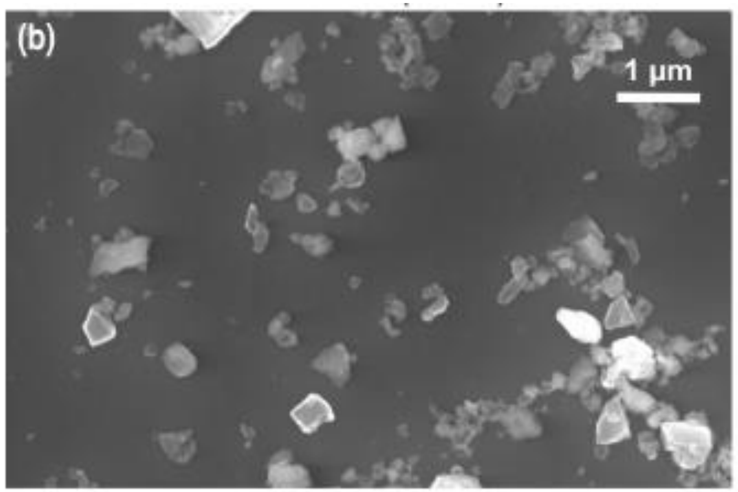


150 ppm nitrogen impurities

120 ppb nitrogen impurities

AC Frangeskou, ATMA Rahman, L Gines, S Mandal, OA Williams, PF Barker & GWM, New Journal of Physics, 20, 043016 (2018)

# A solution: more pure diamonds

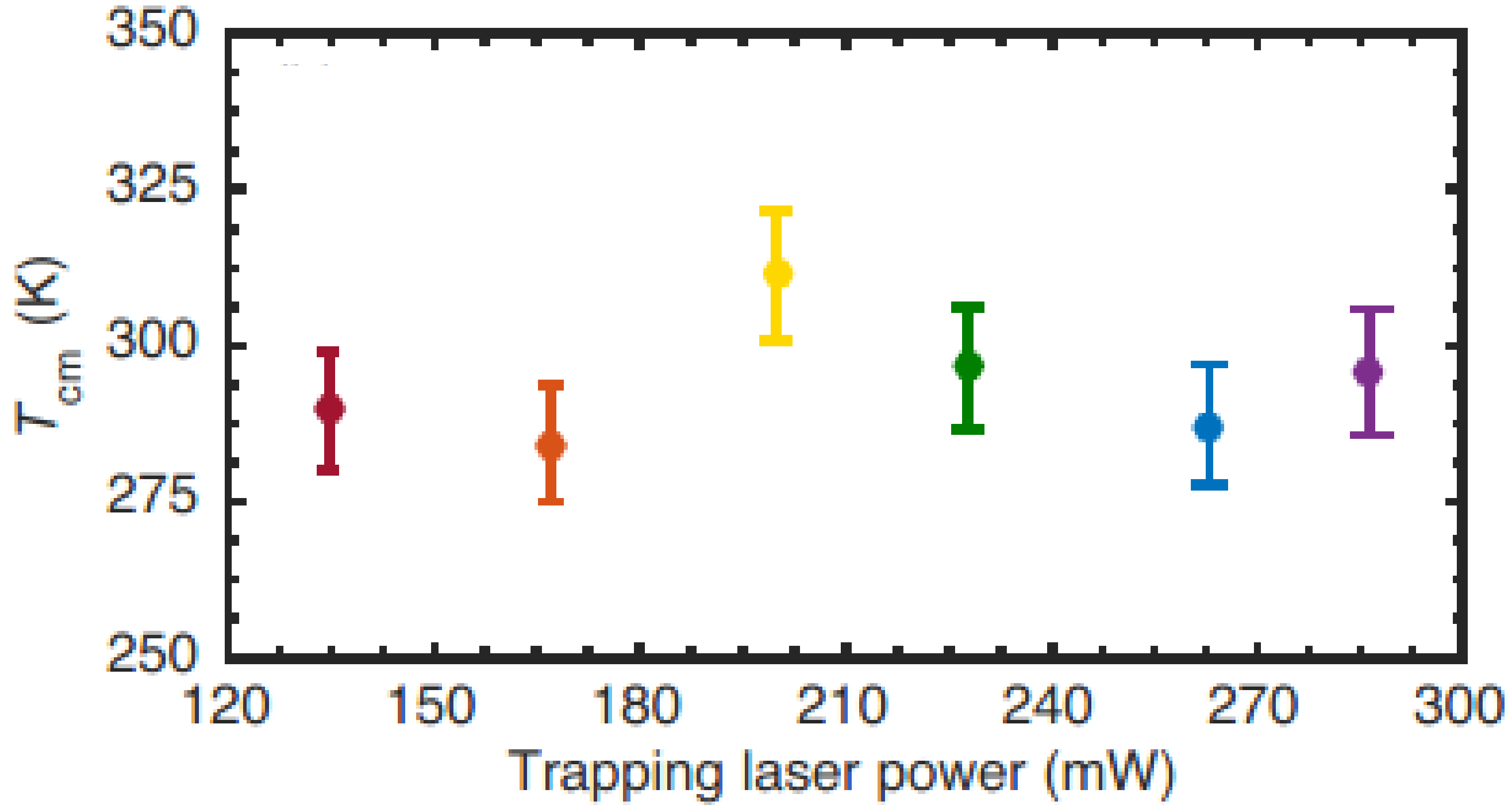



120 ppb nitrogen impurities

Milling by Ollie Williams' group, Cardiff

AC Frangeskou, ATMA Rahman, L Gines, S Mandal, OA Williams, PF Barker & GWM, New Journal of Physics, 20, 043016 (2018)

# Purer nanodiamonds don’t heat up




4 mbar

Still want a magnetic trap to have internal temperature ~5K

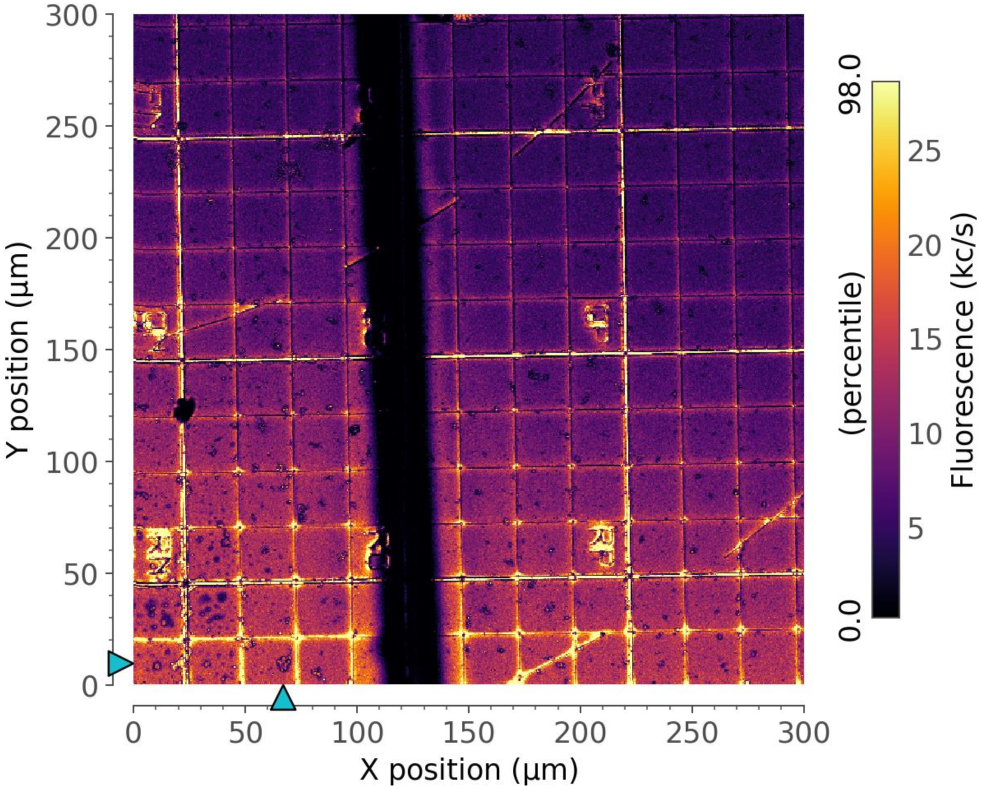
AC Frangeskou, ATMA Rahman, L Gines, S Mandal, OA Williams, PF Barker & GWM, New Journal of Physics, 20, 043016 (2018)

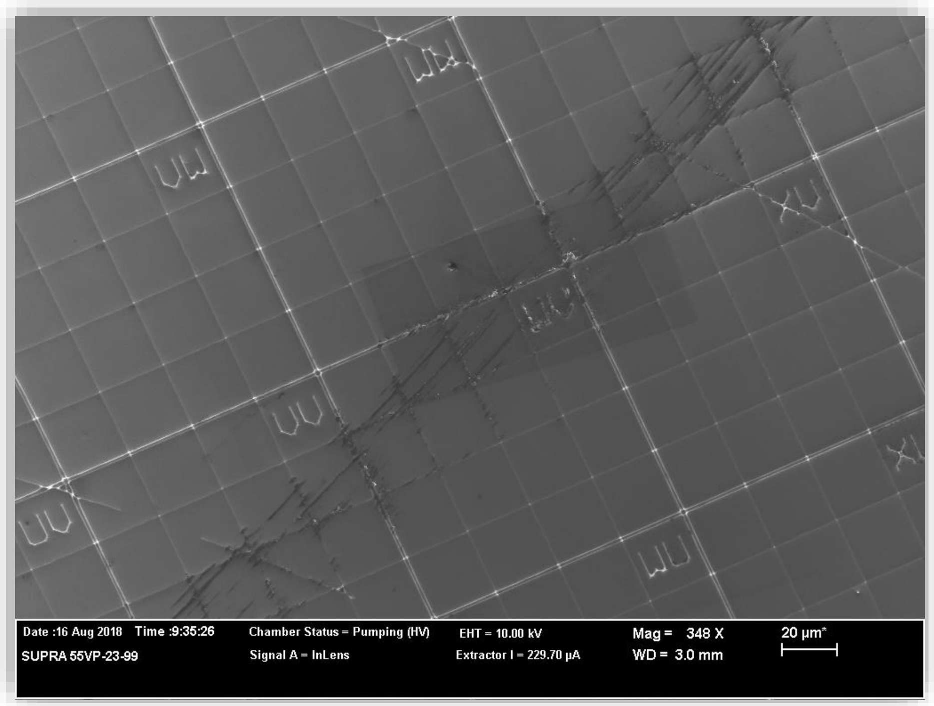
# Imaging our nanodiamonds

Scanning confocal microscopy

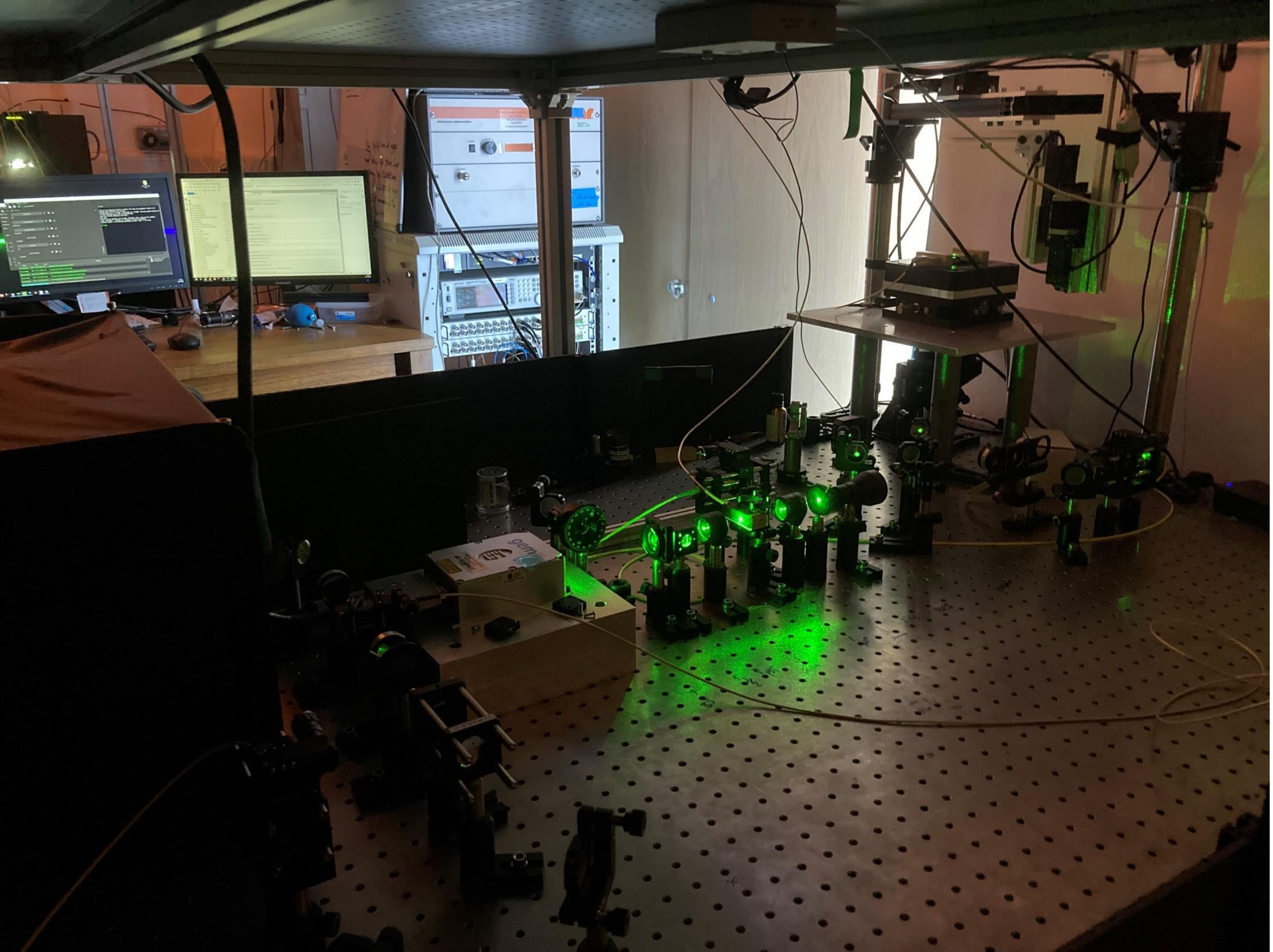
&

Scanning Electron Microscopy (SEM)




Guy Stimpson

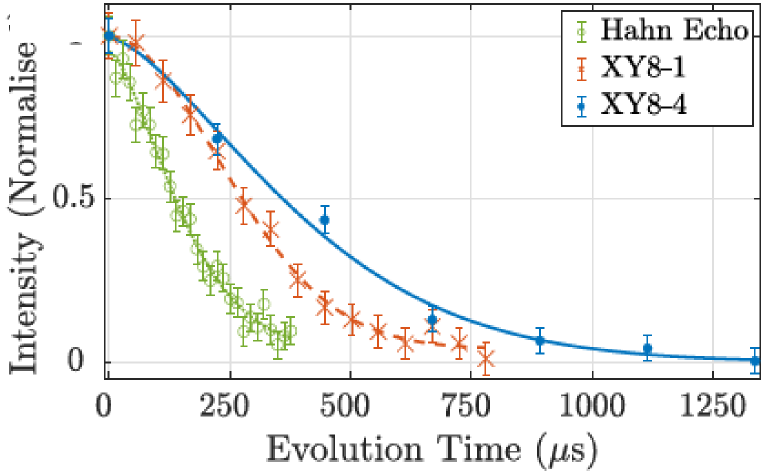


Experiments with single NV in diamond

# Purer nanodiamonds have longer spin coherence

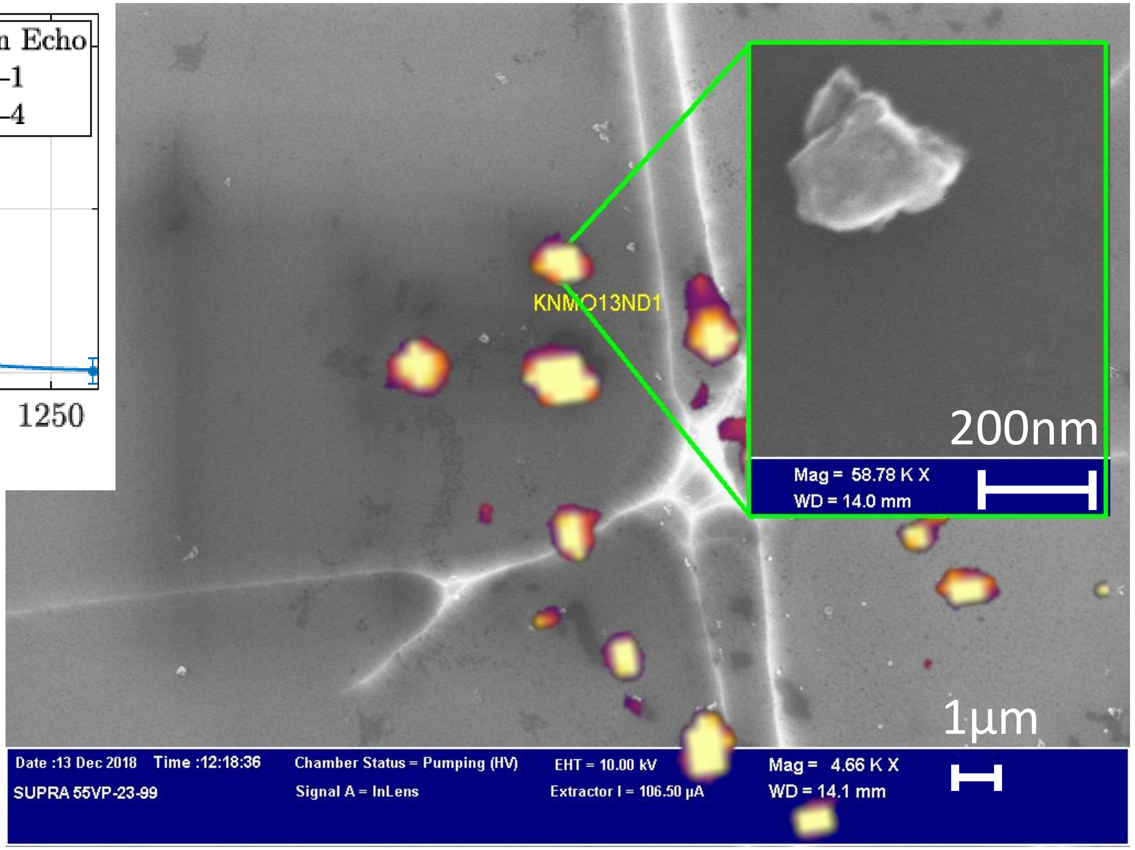
Guy Stimpson

Scanning Electron Microscopy (SEM)



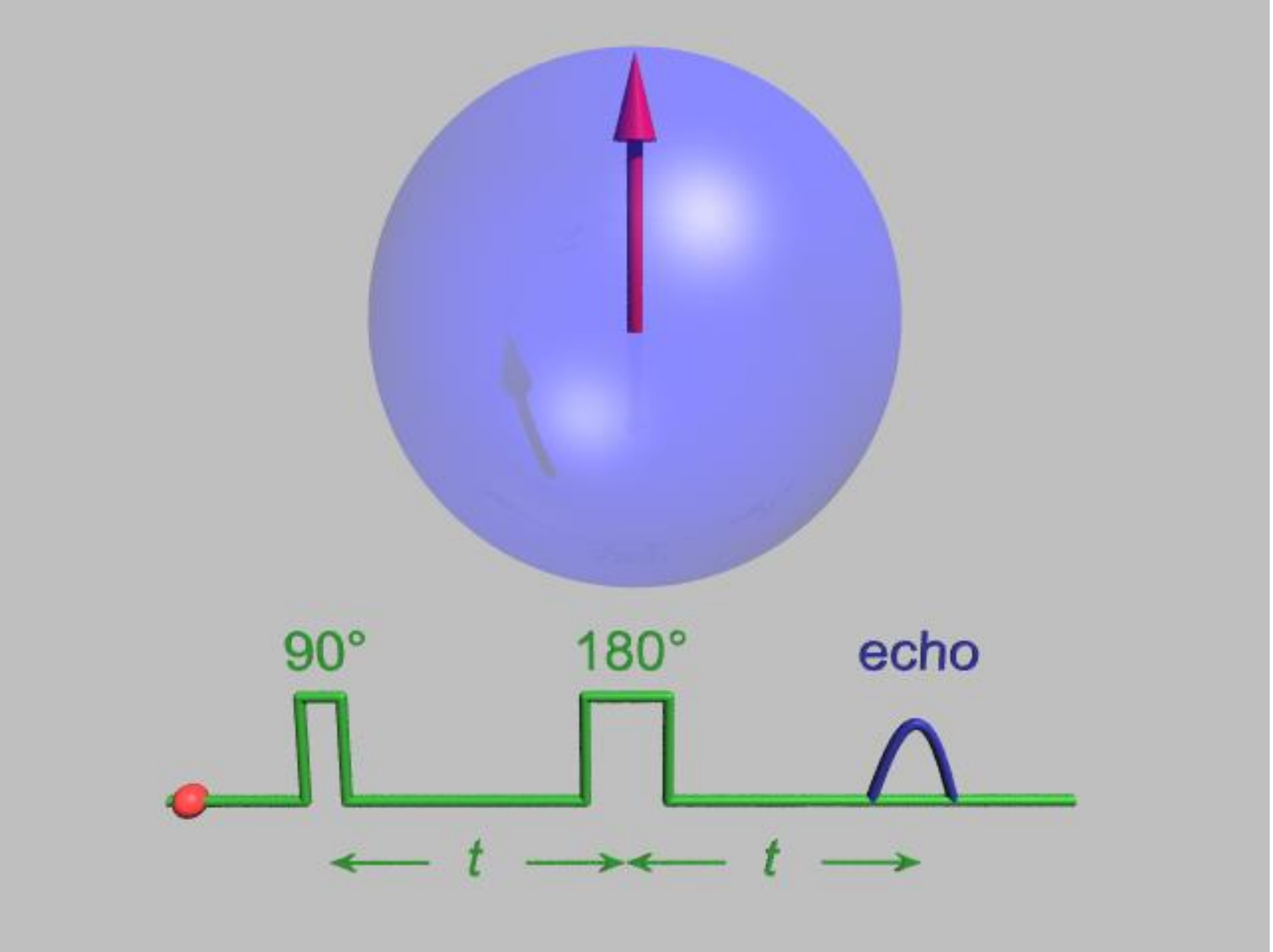

$T_2^{\text{Hahn echo}} = 177\ \mu s$

$T_2^{\text{XY8-4}} = 460\ \mu s$



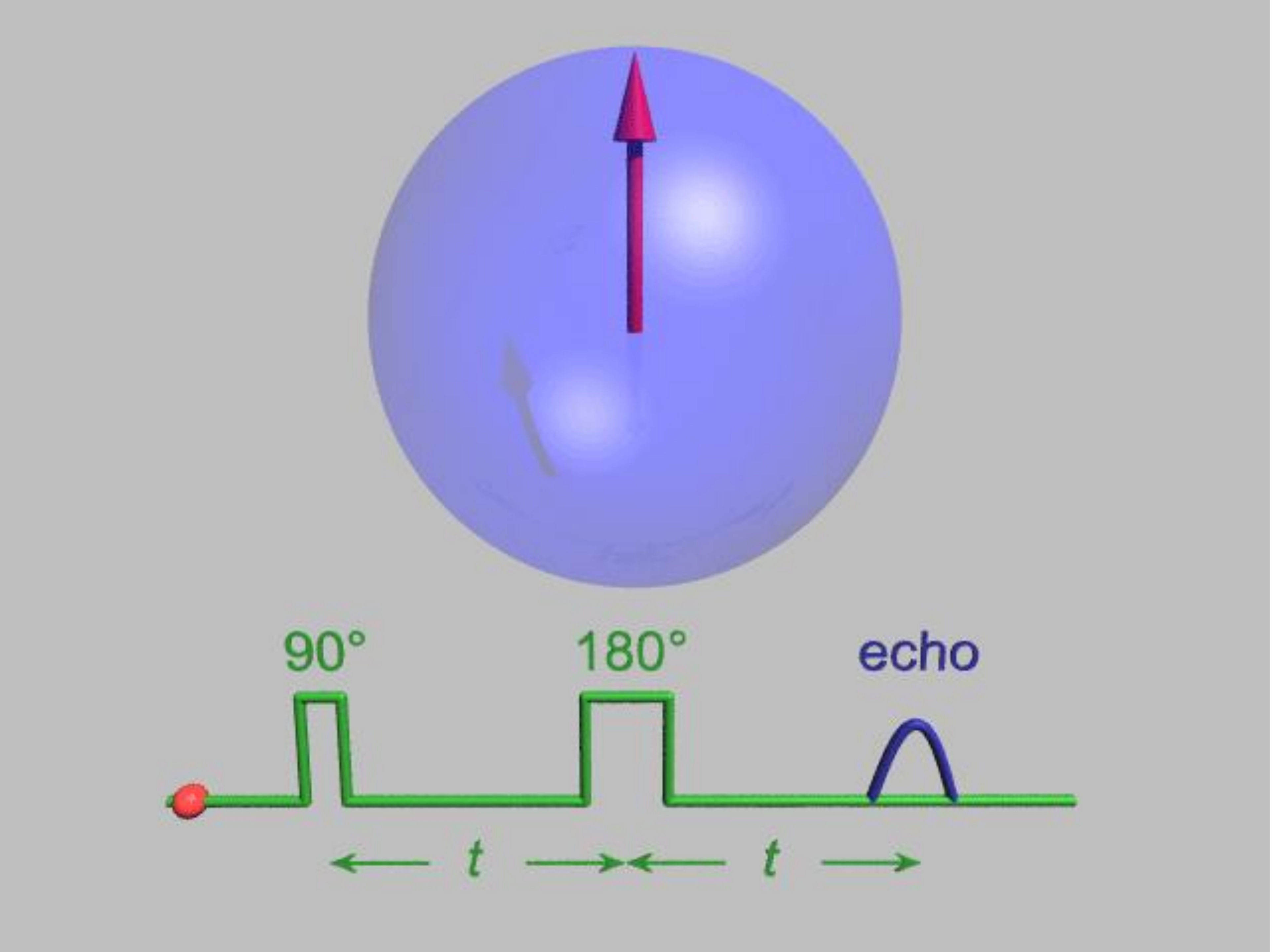

BD Wood, GA Stimpson… & GWM, PRB 105, 205401 (2022)

Ben Wood



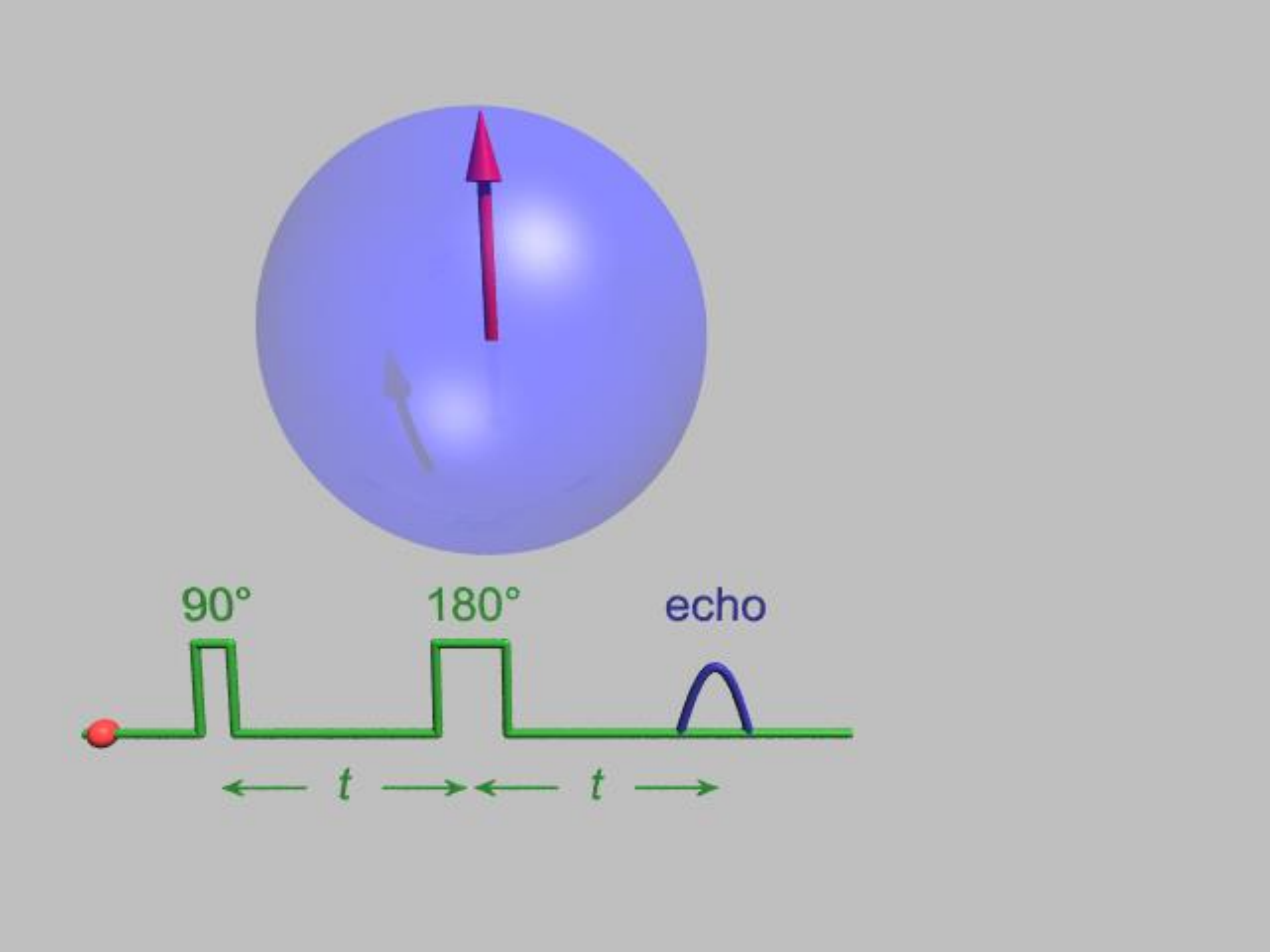

# Spin echo

Erwin L Hahn
(1921-2016)
*Photo: AIP Emilio Segre Visual Archives, Stephen Jacobs Collection*

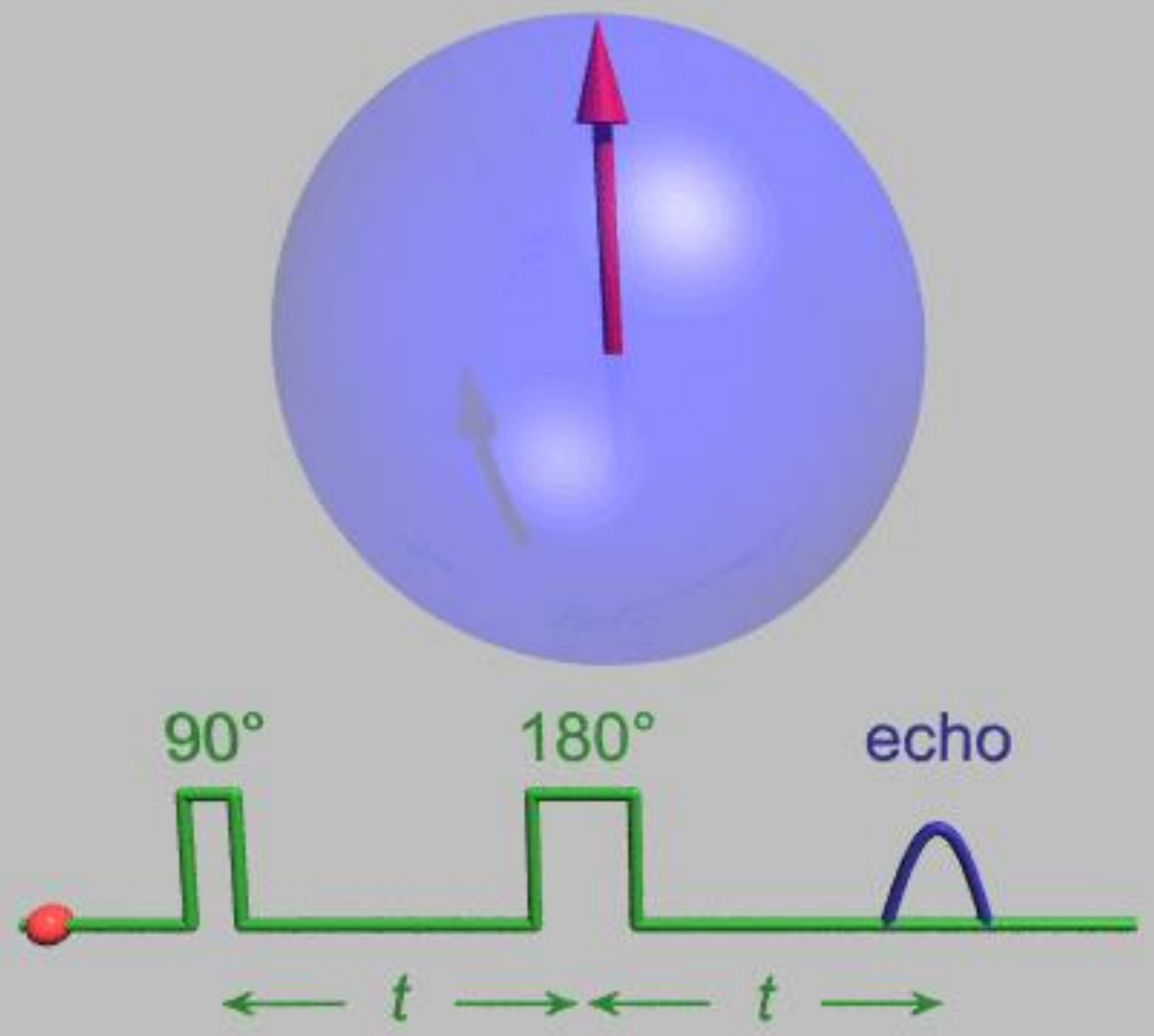



# Spin echo

Erwin L Hahn
(1921-2016)
*Photo: AIP Emilio Segre Visual Archives, Stephen Jacobs Collection*

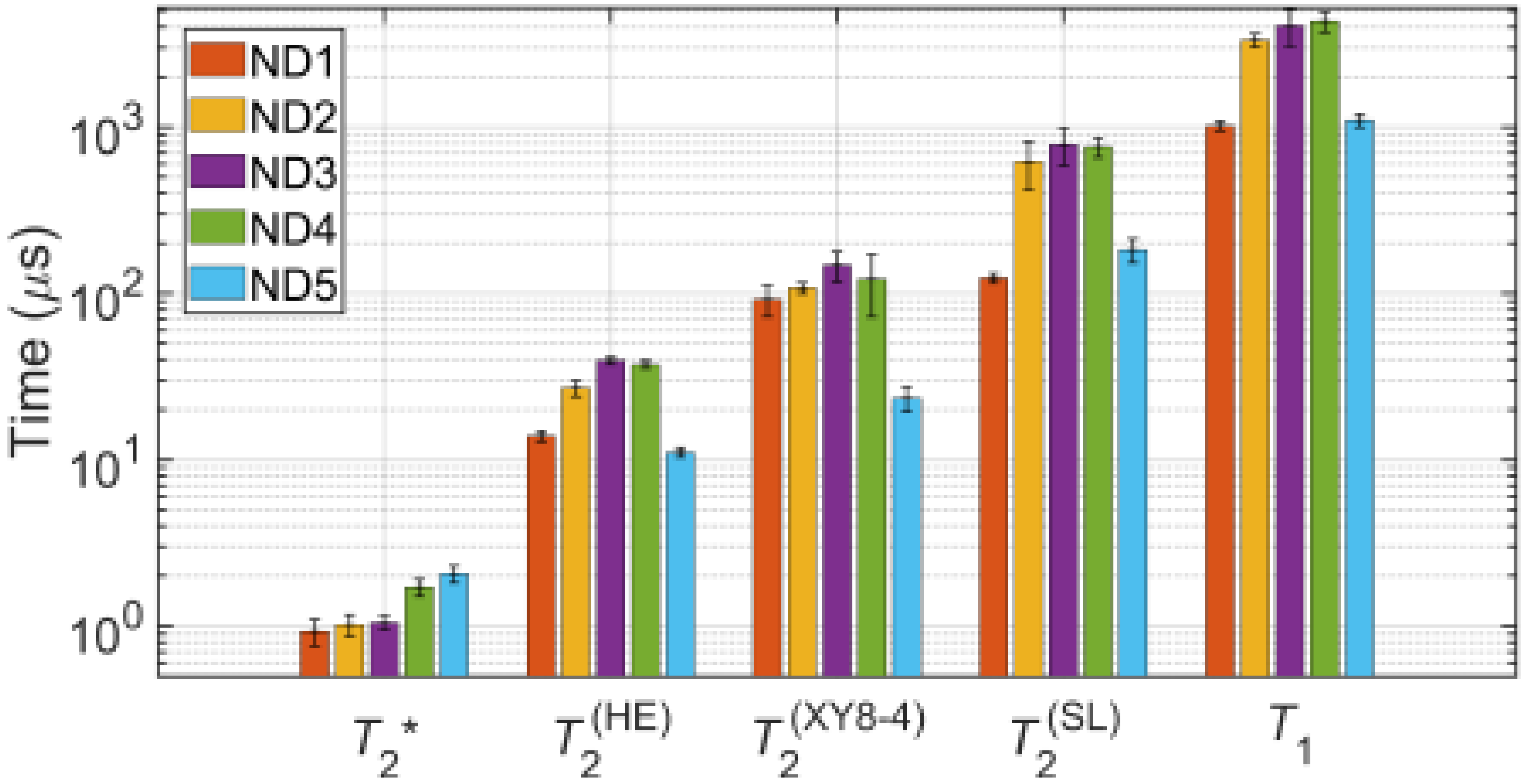



Spin echo decay




Spin echo decay

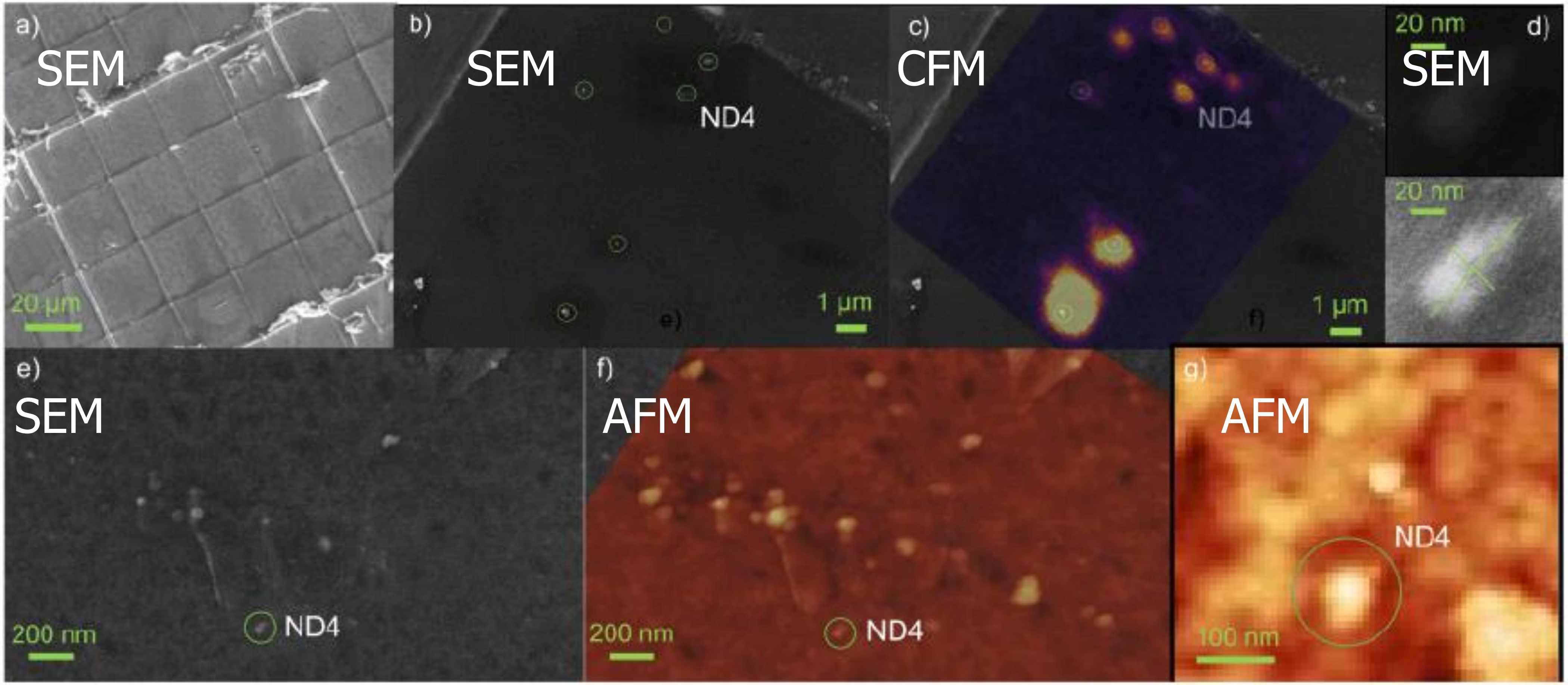
# Longest spin coherence in nanodiamonds




James March

James E March, Benjamin D Wood, Colin J Stephen, Soumen Mandal, Andrew M Edmonds, Daniel J Twitchen, Matthew L Markham, Oliver A Williams & GWM, Physical Review Applied 20, 044045 (2023)

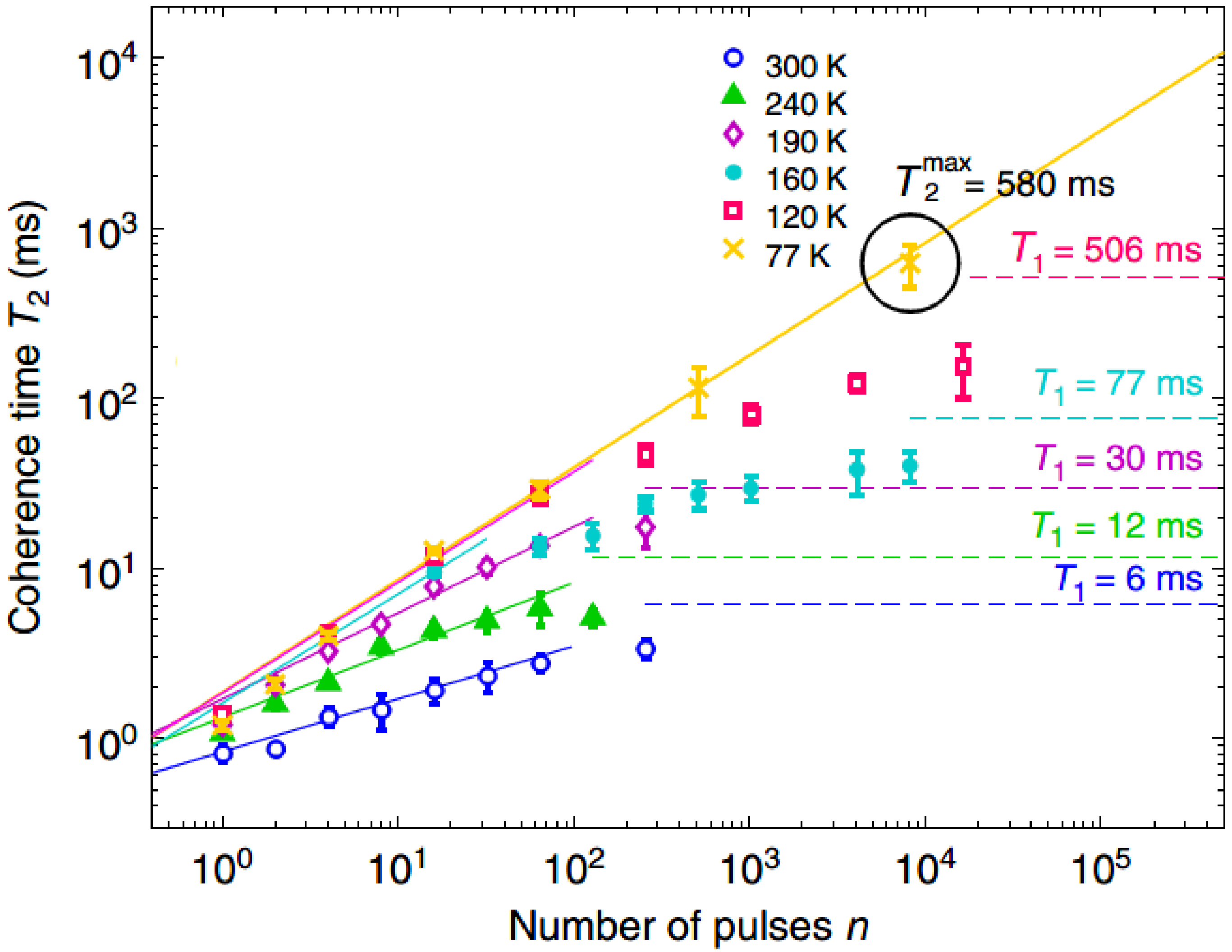
# NV in $^{12}$C nanodiamonds: shape

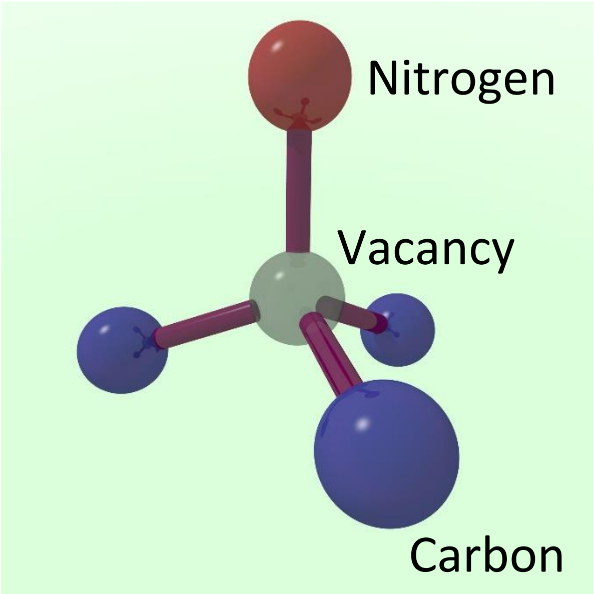



James E March, Benjamin D Wood, Colin J Stephen, Soumen Mandal, Andrew M Edmonds, Daniel J Twitchen, Matthew L Markham, Oliver A Williams & GWM, Physical Review Applied 20, 044045 (2023)

ND4: 50 nm x 80 nm
$T_1$ = 4.3 ms
$T_2^*$ = 1.7 μs
$T_{1\rho}$ = 760 μs

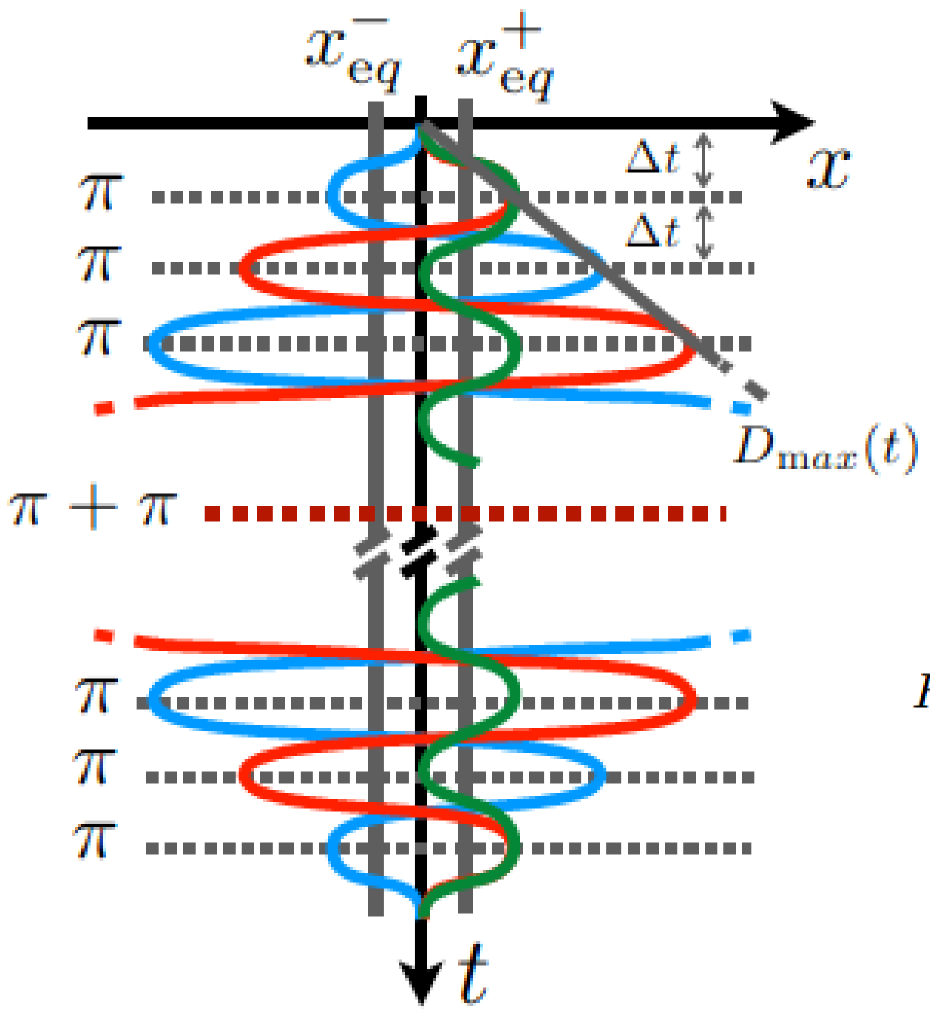
# Nitrogen-vacancy ($NV^-$) centres in bulk diamond




N Bar-Gill, LM Pham, A Jarmola, D Budker & RL Walsworth, Nature Comms 4, 1743 (2013)

# Our proposal: add in motional dynamic decoupling

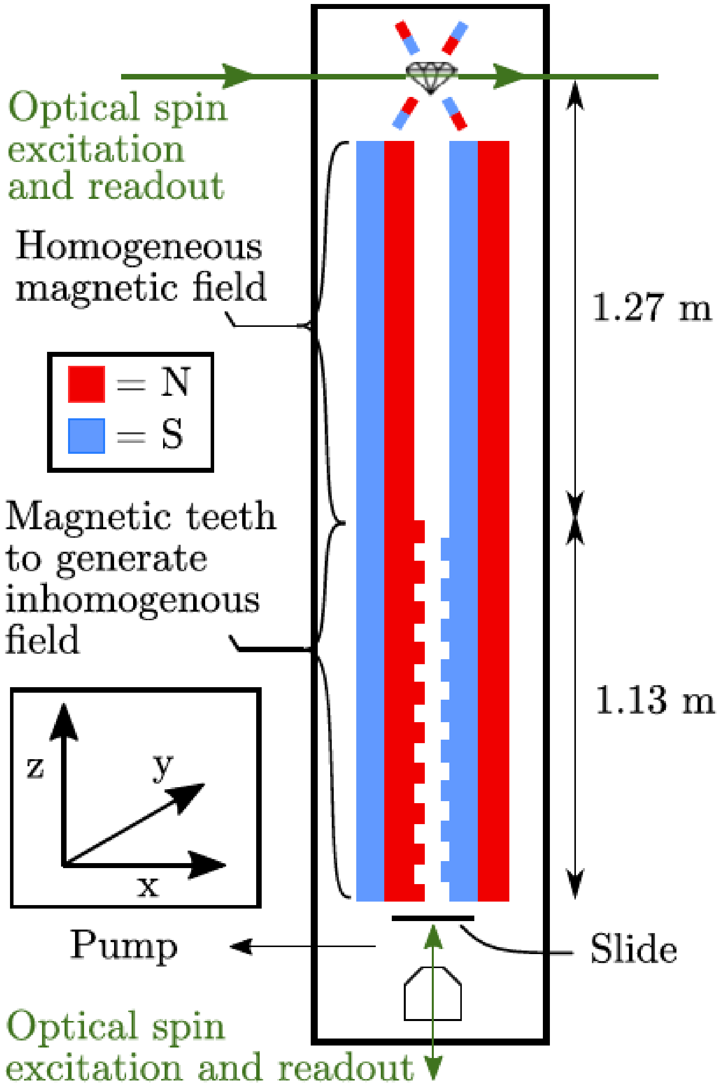



**Proposals from our collaboration:**

- M Scala… & S Bose, PRL **111**, 180403 (2013)
- C Wan…& MS Kim, PRA **93**, 043852 (2016)
- C Wan… & MS Kim, PRL **117**, 143003 (2016)
- S Bose… & G Milburn, PRL **119**, 240401 (2017)
- JS Pedernales, GWM & MB Plenio, PRL **125**, 023602 (2020)
- BD Wood, S Bose & GWM, PRA **105**, 012824 (2022)

$$H = \frac{\hat{p}_x^2}{2m} + g_{\|}\mu_B(\pm B'\hat{x} + B_0)\hat{S}_{z'} + \frac{|\chi|V}{2\mu_0}(\pm B'\hat{x} + B_0)^2 + mg\sin(\phi)\hat{x} + \hbar D\hat{S}_{z'}^2,$$

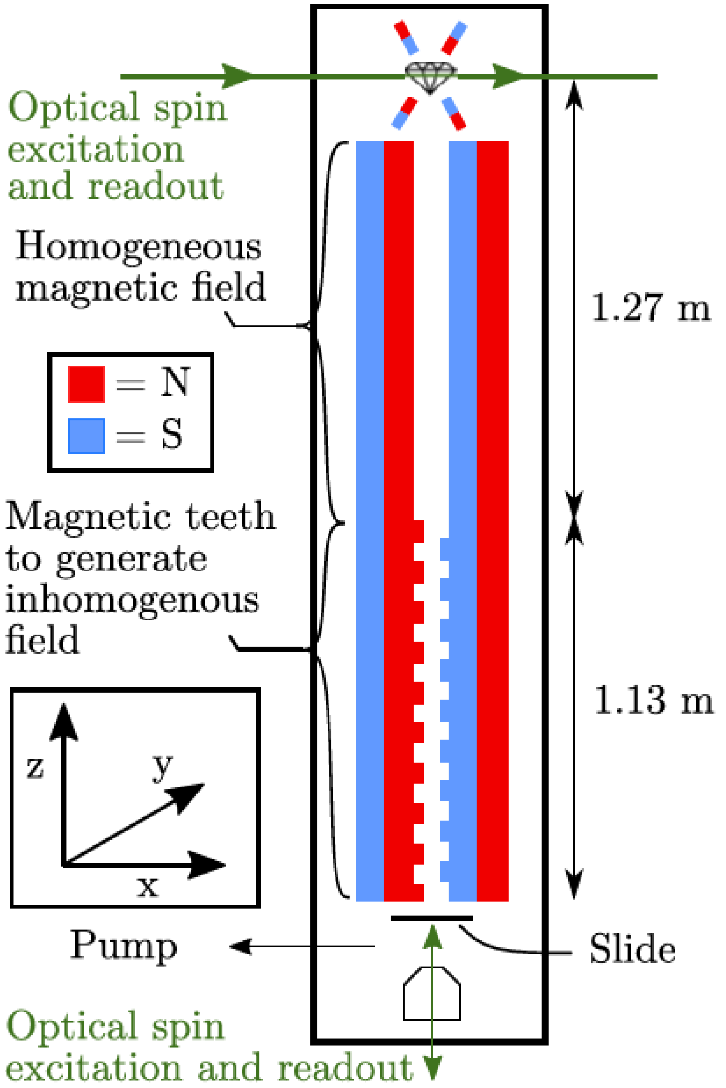
# Our proposal: add in magnetic teeth

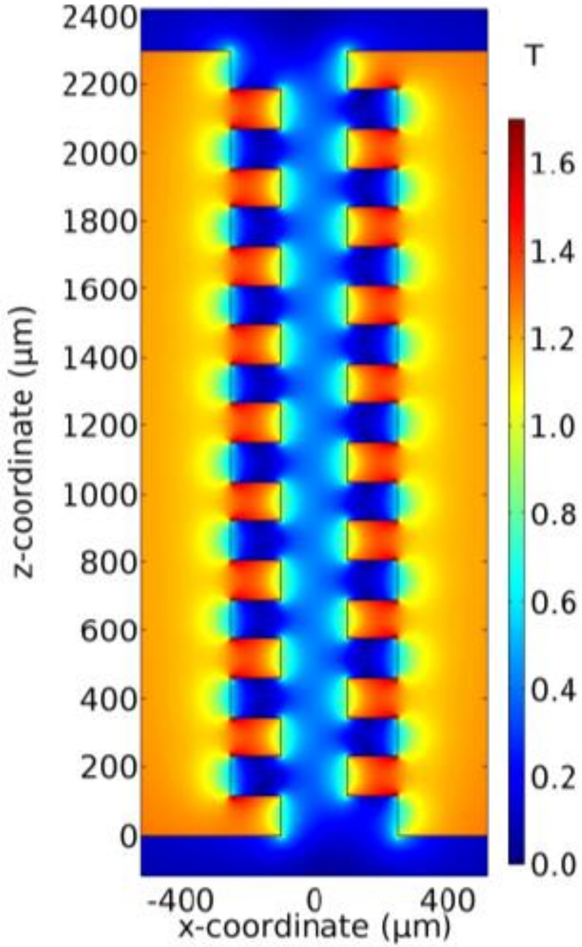


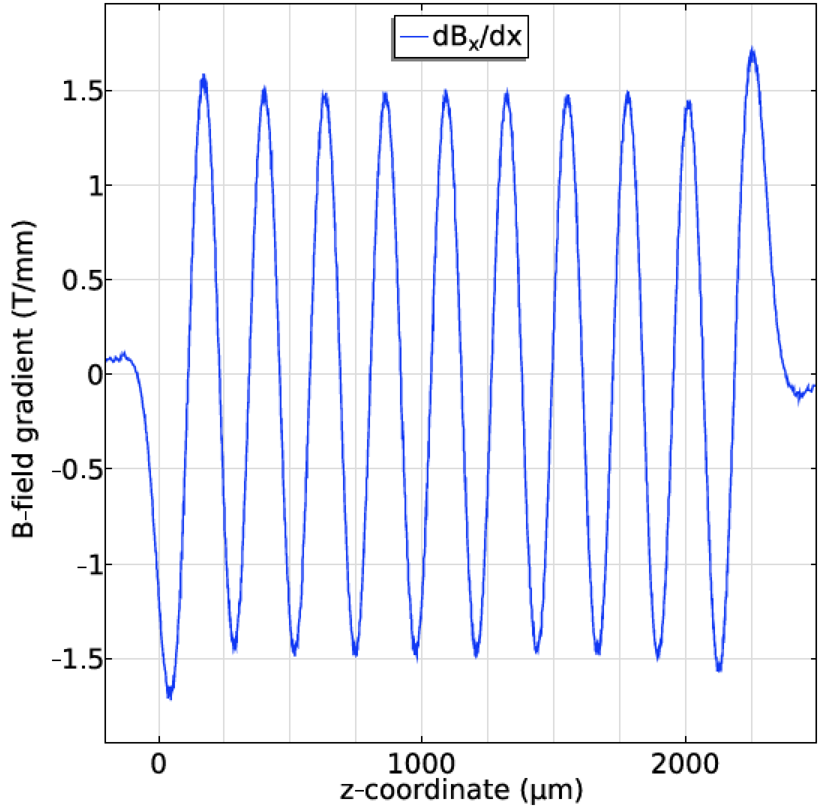

**Proposals from our collaboration:**
- M Scala… & S Bose, PRL **111**, 180403 (2013)
- C Wan…& MS Kim, PRA **93**, 043852 (2016)
- C Wan… & MS Kim, PRL **117**, 143003 (2016)
- S Bose… & G Milburn, PRL **119**, 240401 (2017)
- JS Pedernales, GWM & MB Plenio, PRL **125**, 023602 (2020)
- BD Wood, S Bose & GWM, PRA 105, 012824 (2022)

# Our proposal: add in magnetic teeth

BD Wood, S Bose & GWM, PRA 105, 012824 (2022)

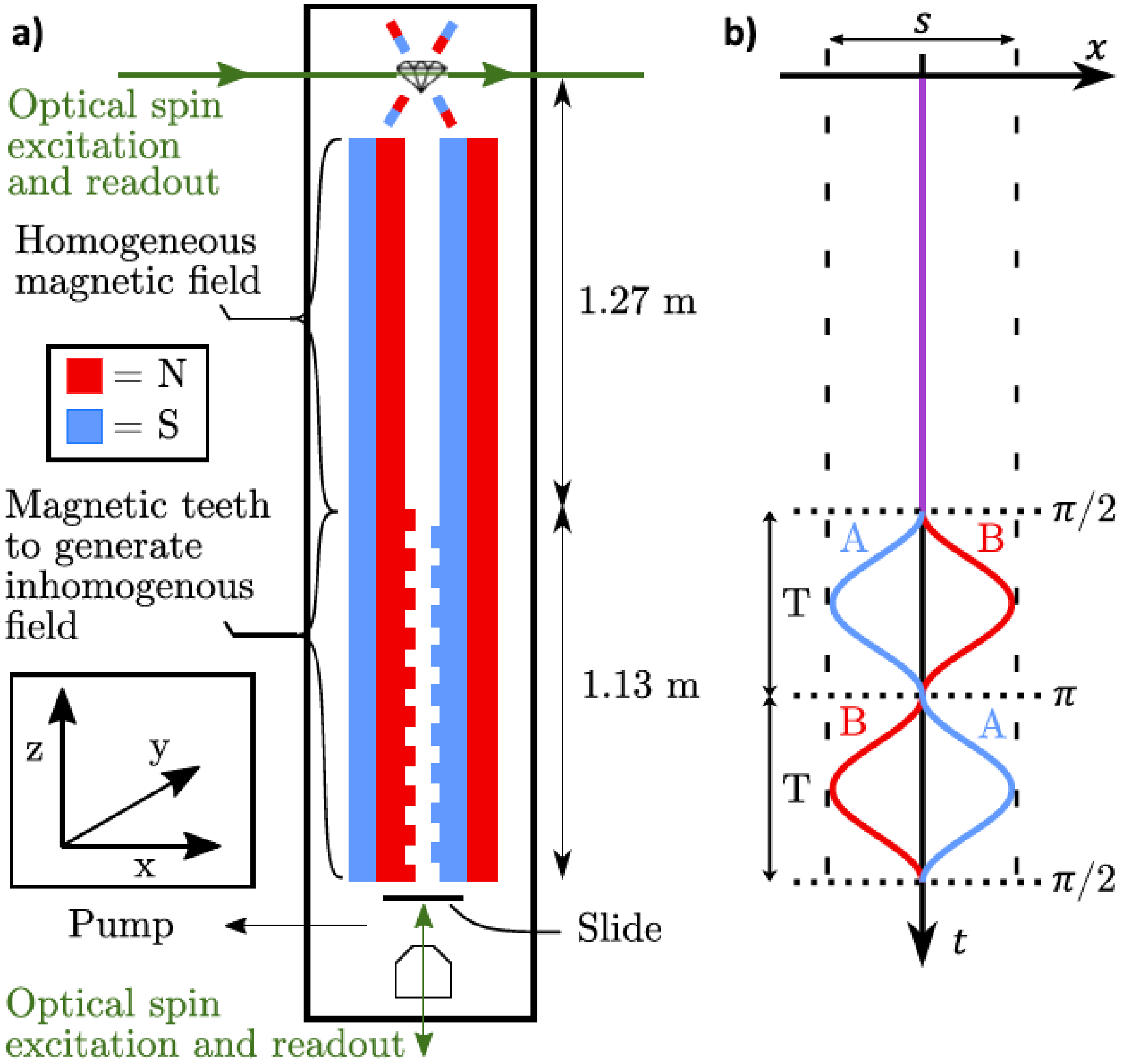


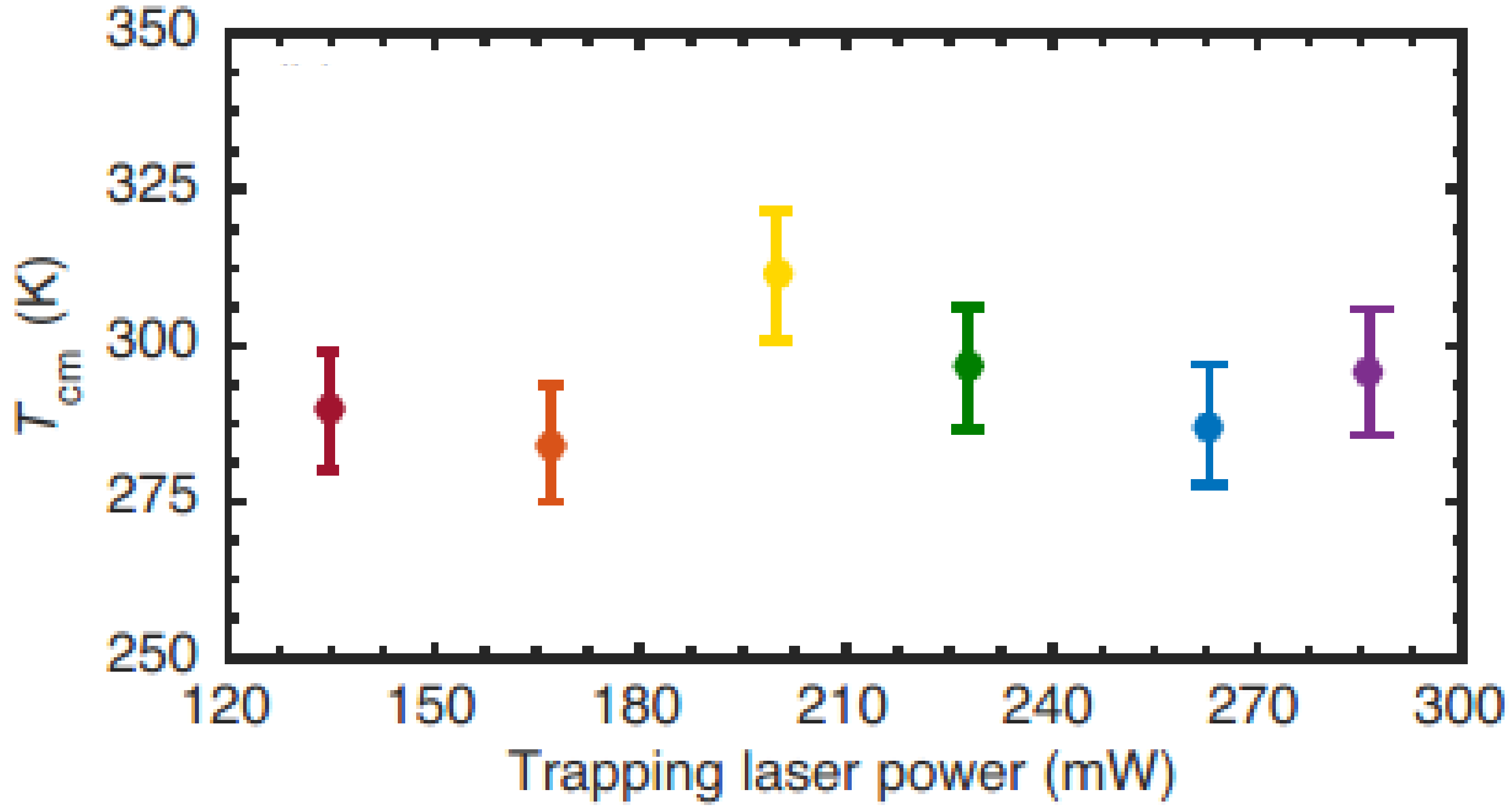




# Our proposal: add in magnetic teeth

BD Wood, S Bose & GWM, PRA 105, 012824 (2022)




# Purer nanodiamonds don't heat up



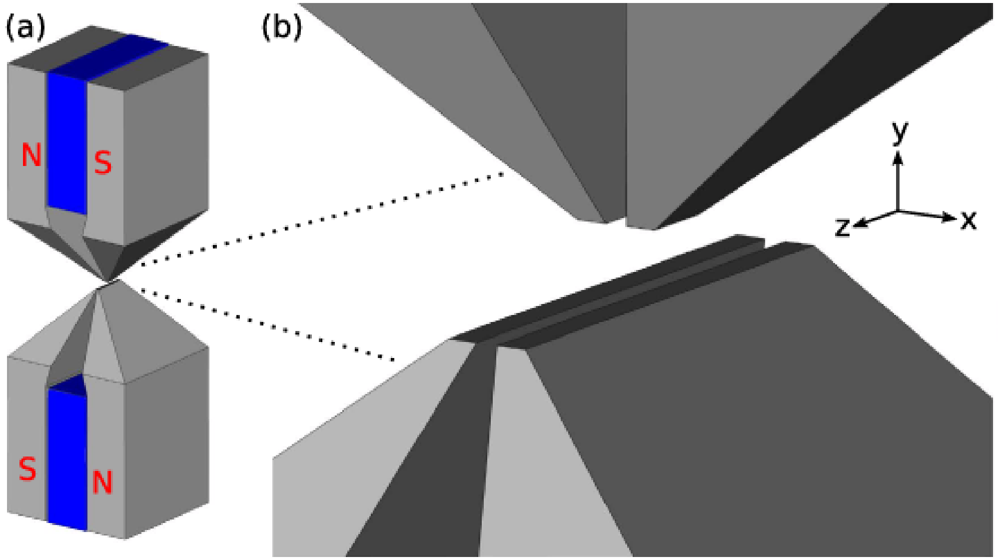

4 mbar

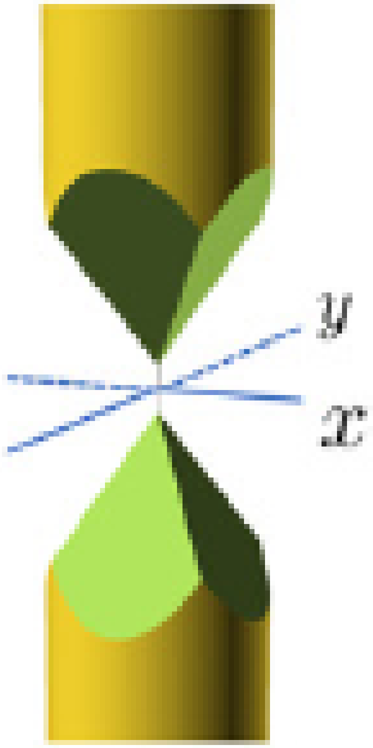
Still want a magnetic trap to have internal temperature ~5K

AC Frangeskou, ATMA Rahman, L Gines, S Mandal, OA Williams, PF Barker & GWM, New Journal of Physics, 20, 043016 (2018)

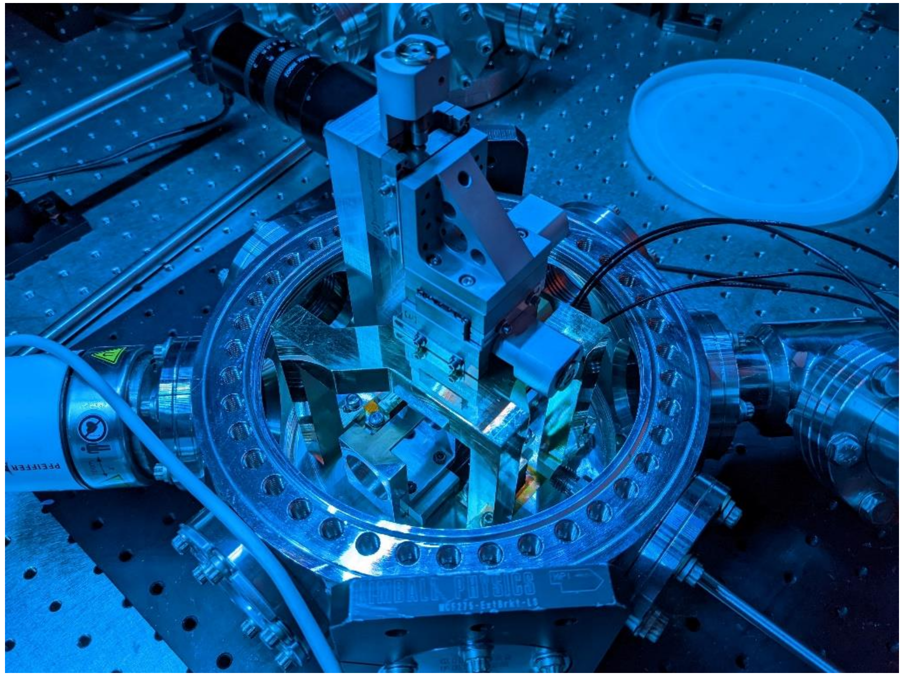
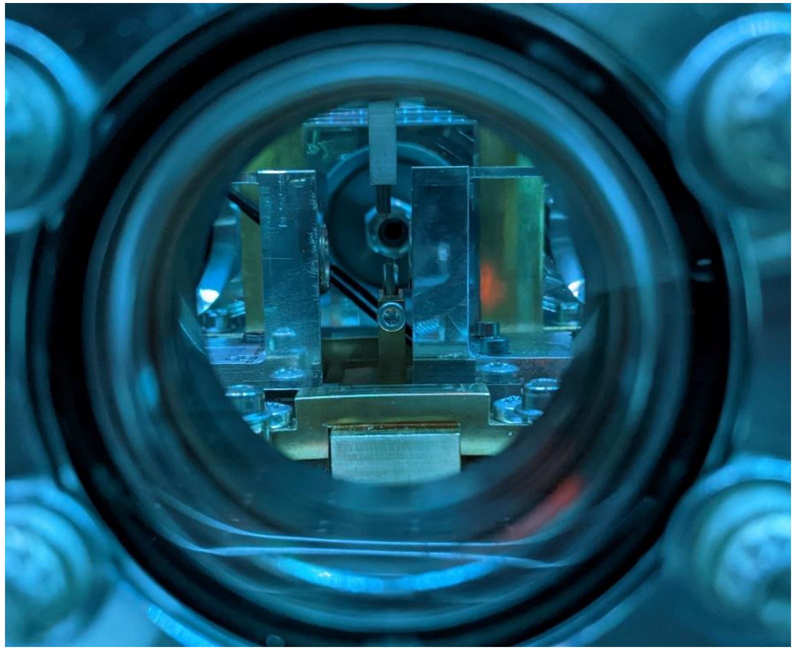
# Magnetic traps for nanodiamonds

J-F Hsu, P Ji, CW Lewandowski & B D'Urso, Sci Rep **6**, 30125 (2016)



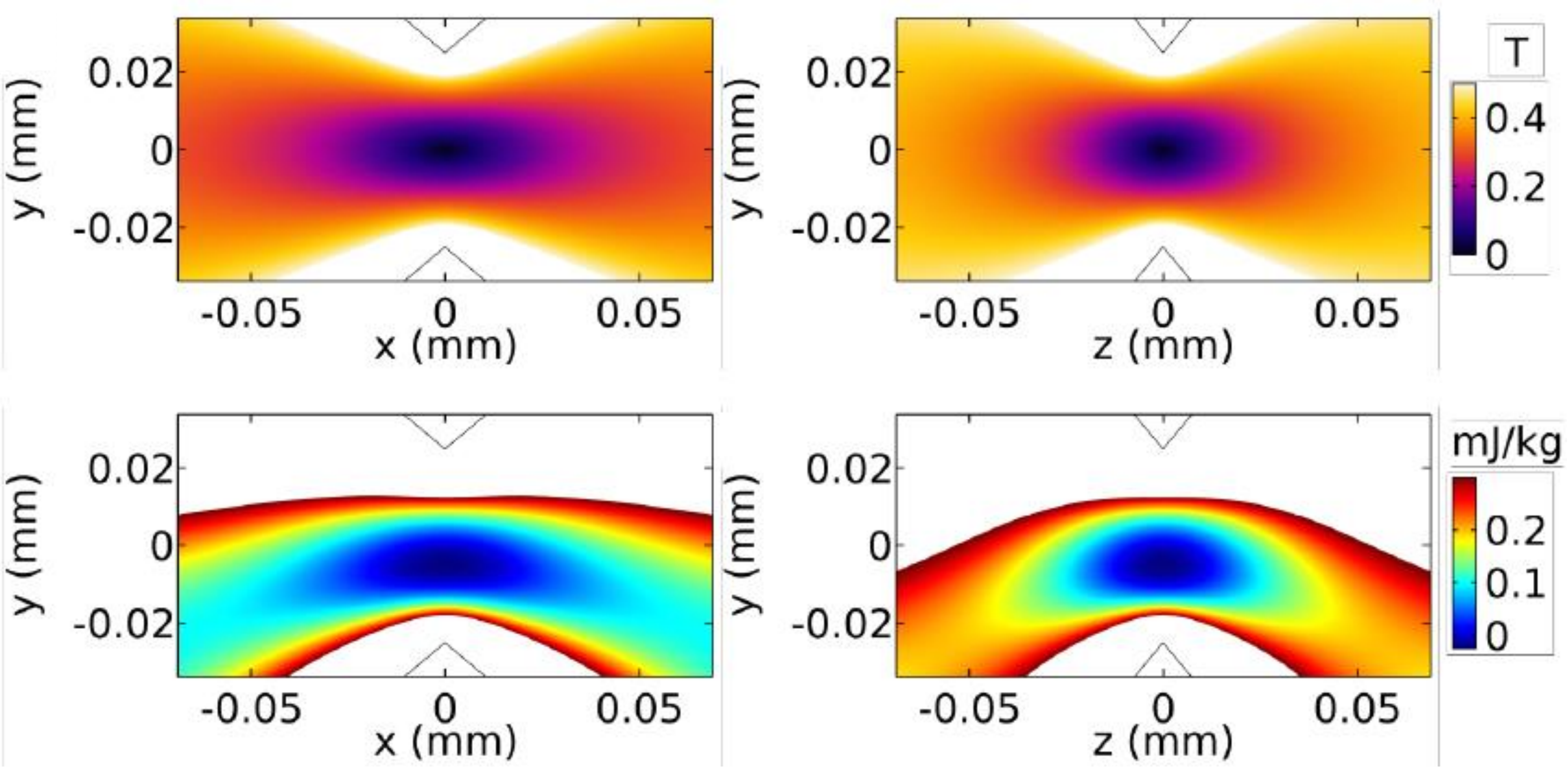

MC O'Brien, S Dunn, JE Downes & J Twamley, APL 114, 053103 (2019)



# Our magnetic trap for nanodiamonds

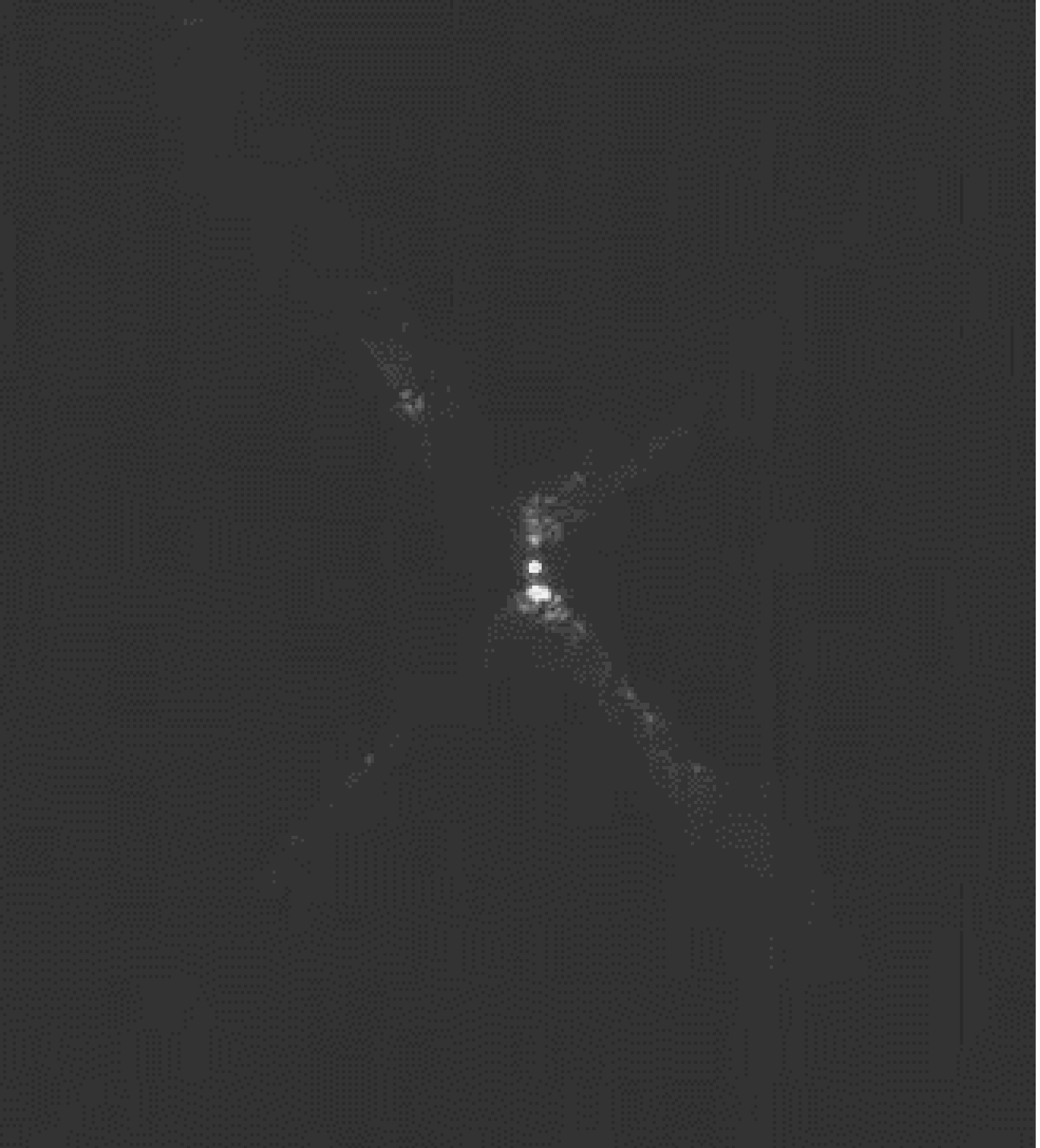
James March and Ben Wood




# Our magnetic trap for nanodiamonds

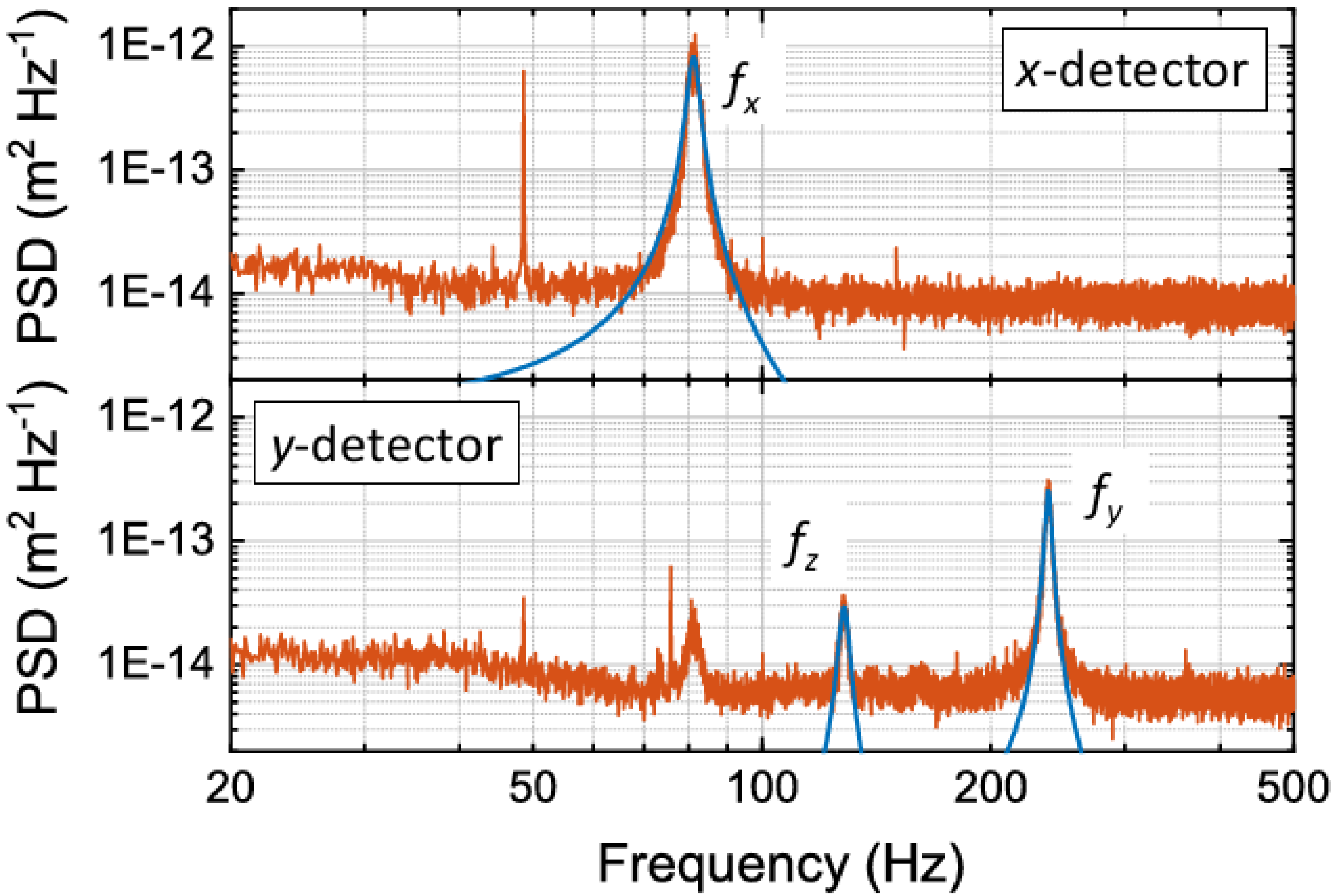
James March and Ben Wood

COMSOL simulations of the magnetic field and trapping potential per unit mass from diamagnetism and gravity

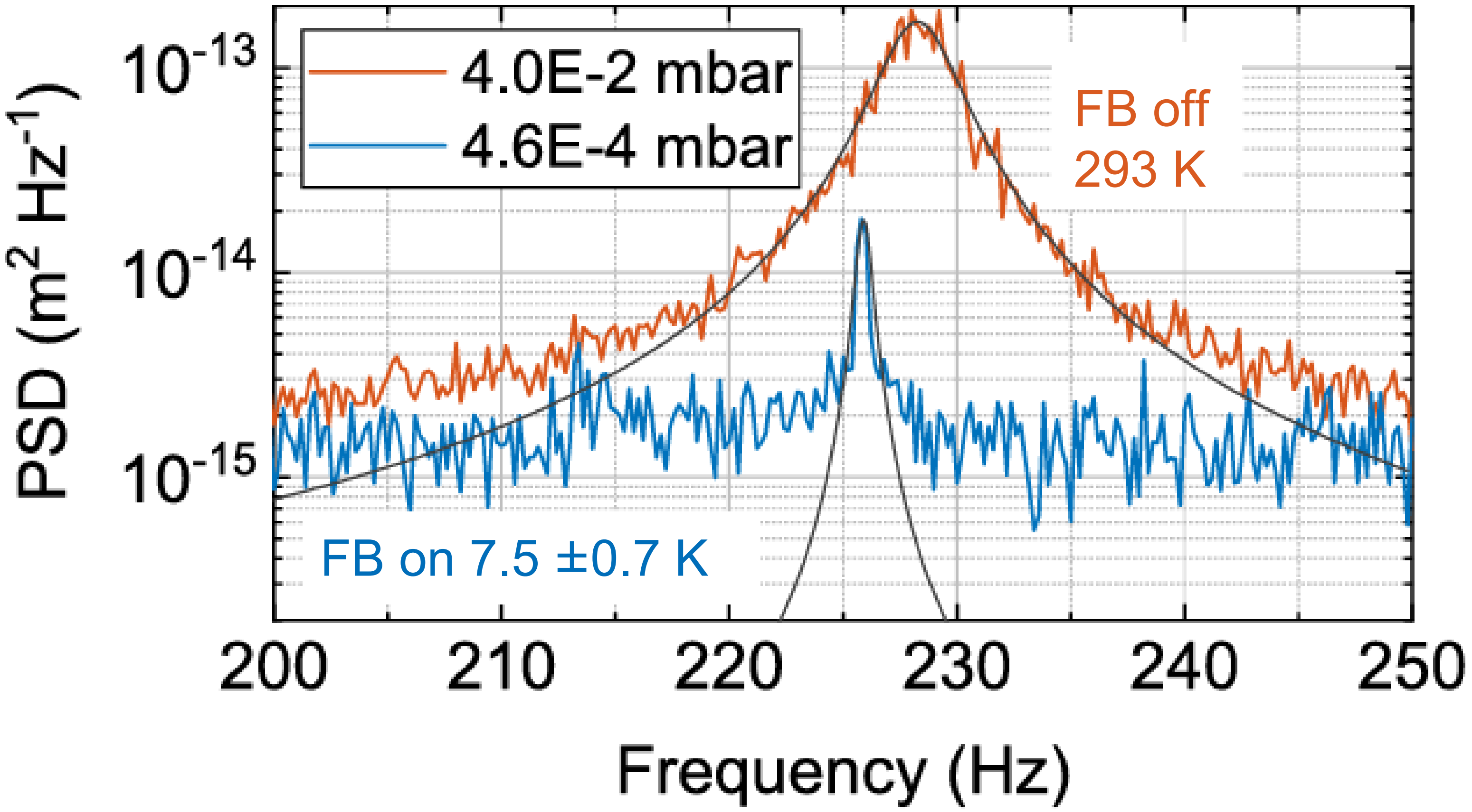


# Our magnetic trap for nanodiamonds

James March and Ben Wood

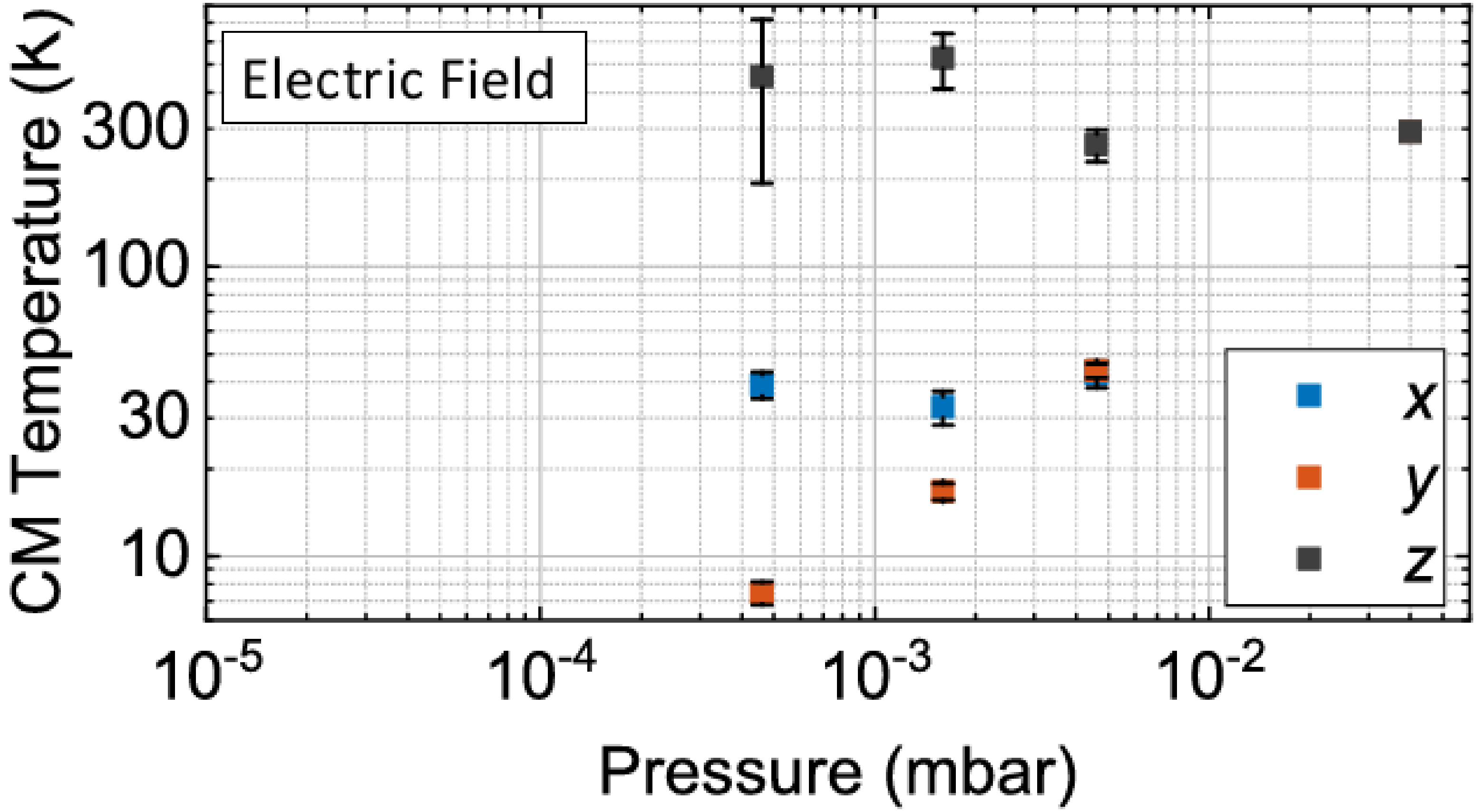



# Our magnetic trap for nanodiamonds



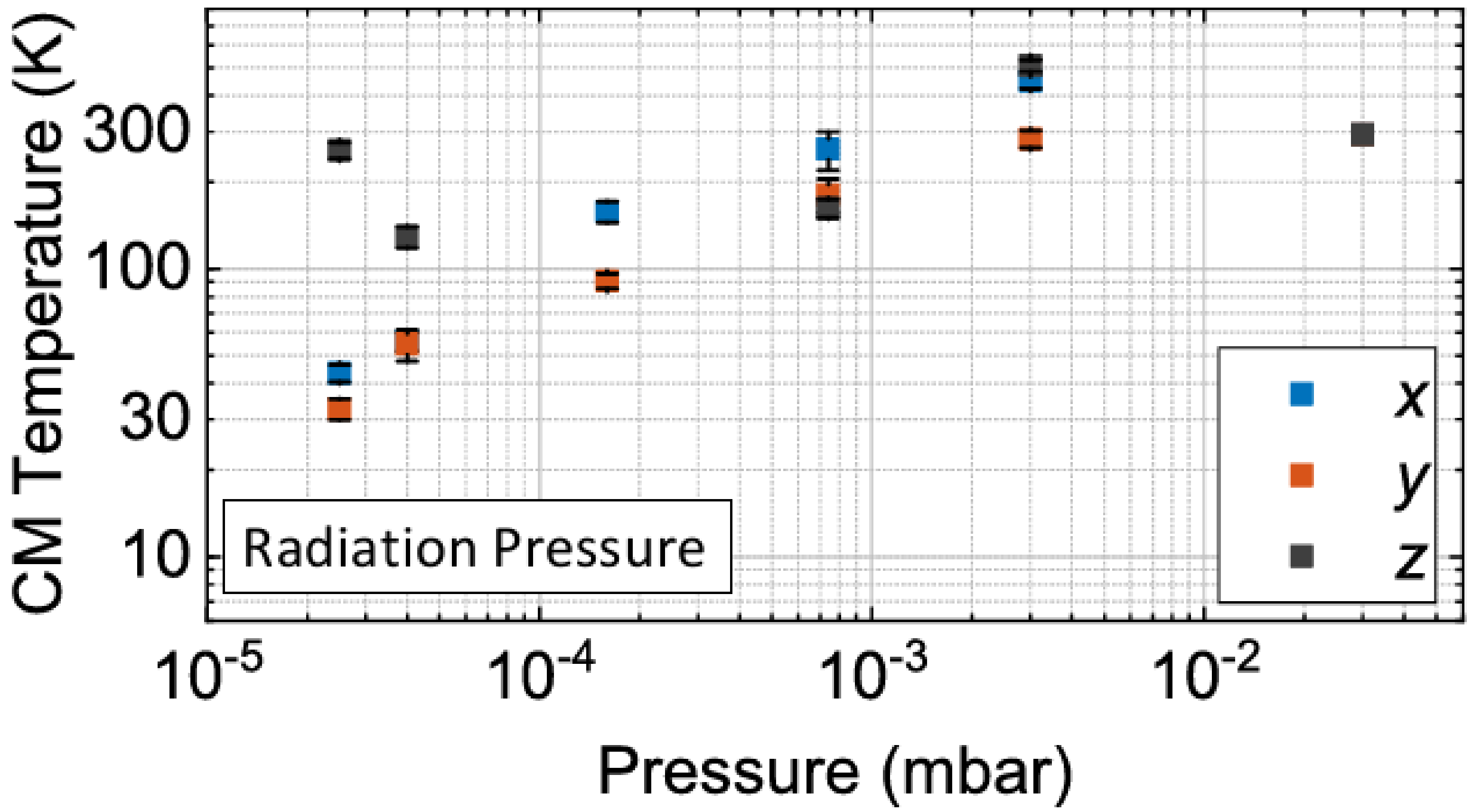

# Our magnetic trap for nanodiamonds

Feedback cooling with electric-field driven velocity damping




# Our magnetic trap for nanodiamonds

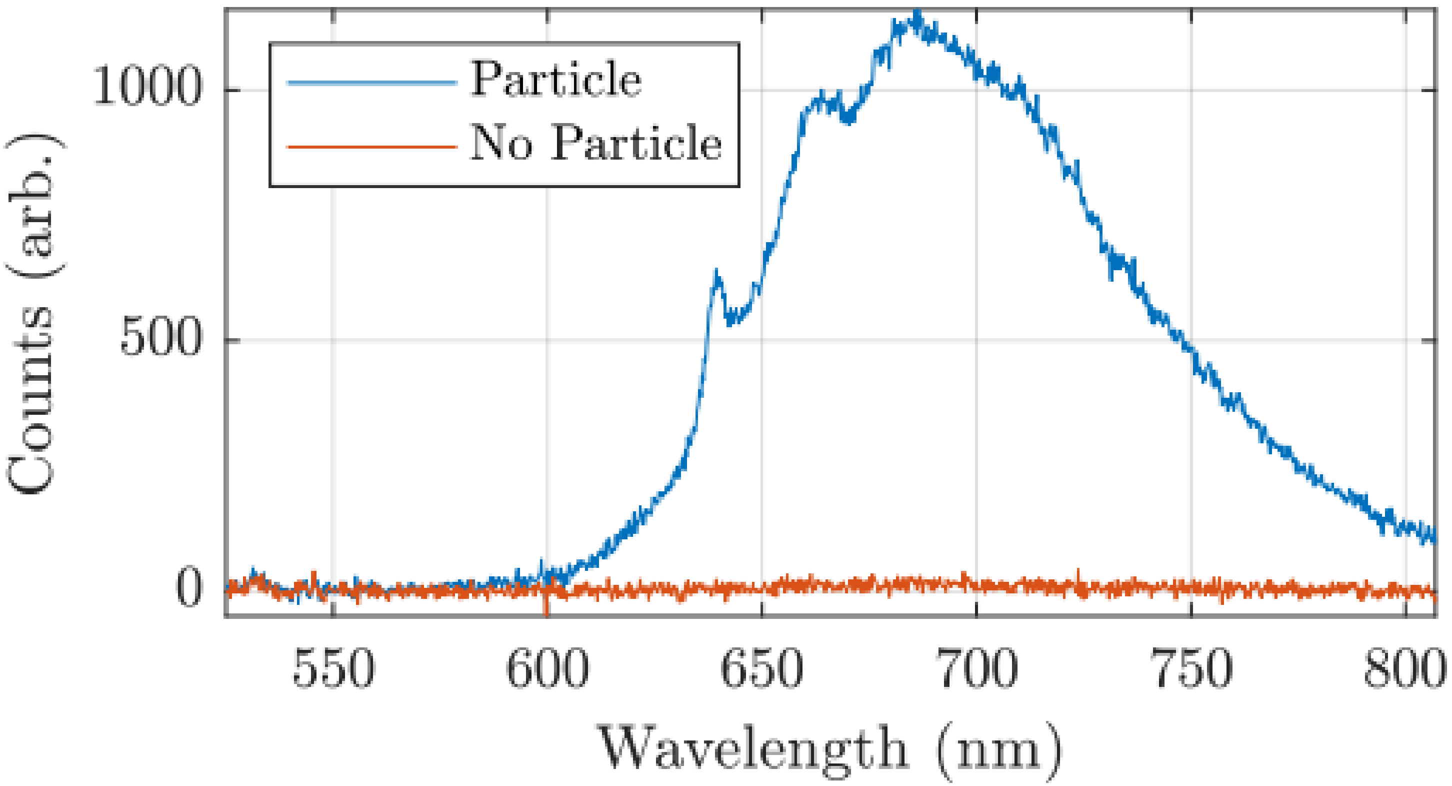
Feedback cooling with electric-field driven velocity damping



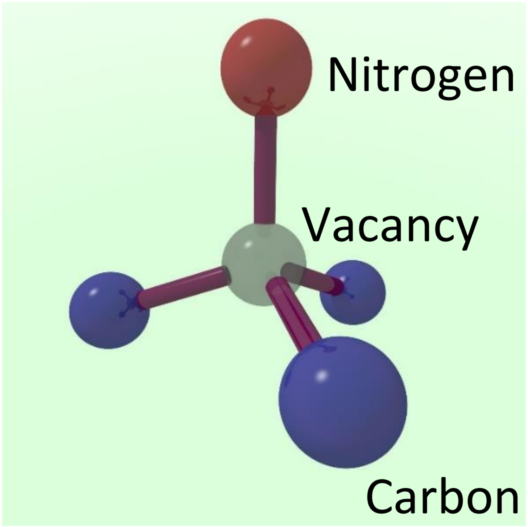

# Our magnetic trap for nanodiamonds

Feedback cooling with electric-field driven velocity damping

Fluorescence from magnetically levitated NV centres

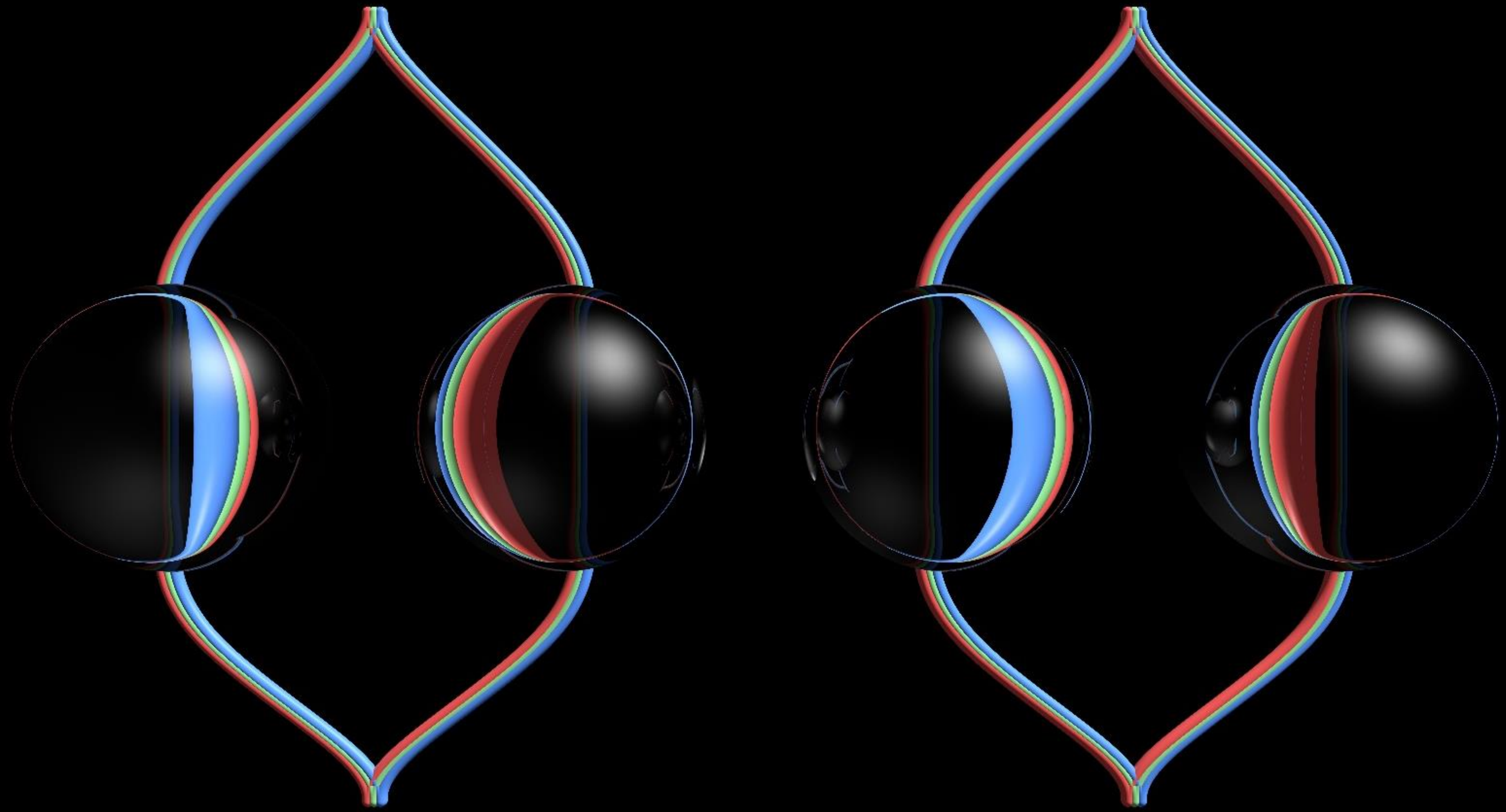



# Our magnetic trap for nanodiamonds




# Conclusions

- Dropping levitated nanodiamonds past magnetic teeth could test the quantum nature of gravity
- Purer nanodiamonds don’t heat up in an optical trap at 4 mbar, and have long-lived spin coherence



**Proposals from our collaboration for testing quantum gravity using a macroscopic superposition:**

- M Scala… & S Bose, PRL 111, 180403 (2013)
- C Wan…& MS Kim, PRA 93, 043852 (2016)
- C Wan… & MS Kim, PRL 117, 143003 (2016)
- S Bose… & G Milburn, PRL 119, 240401 (2017)
- JS Pedernales, GWM & MB Plenio, PRL 125, 023602 (2020)
- BD Wood, S Bose & GWM, PRA 105, 012824 (2022)

**Experiments with nanodiamonds:**

- ATMA Rahman… & PF Barker, Sci Rep 6, 21633 (2016)
- AC Frangeskou… & GWM, NJP 20, 043016 (2018)
- BD Wood… & GWM, PRB 105, 205401 (2022)
- JE March… & GWM, Phys Rev Applied 20, 044045 (2023)

**Fibre-coupled diamond magnetometry:**

- RL Patel… & GWM, Phys Rev Applied 14, 044058 (2020)
- LQ Zhou… & GWM, Phys Rev Applied 15, 024015 (2021)
- SM Graham… & GWM, Phys Rev Applied 19, 044042 (2023)
- AJ Newman… & GWM, Phys Rev Applied 21, 014003 (2024)
- SM Graham… & GWM, arXiv:2401.16090 (2024)

ALFRED P. SLOAN FOUNDATION

GORDON AND BETTY MOORE FOUNDATION

www.MAST-QG.com

Gavin Morley
David Moore
Andrew Geraci
Anupam Mazumdar
Sougato Bose


This way up
Property of:
E. Schrödinger