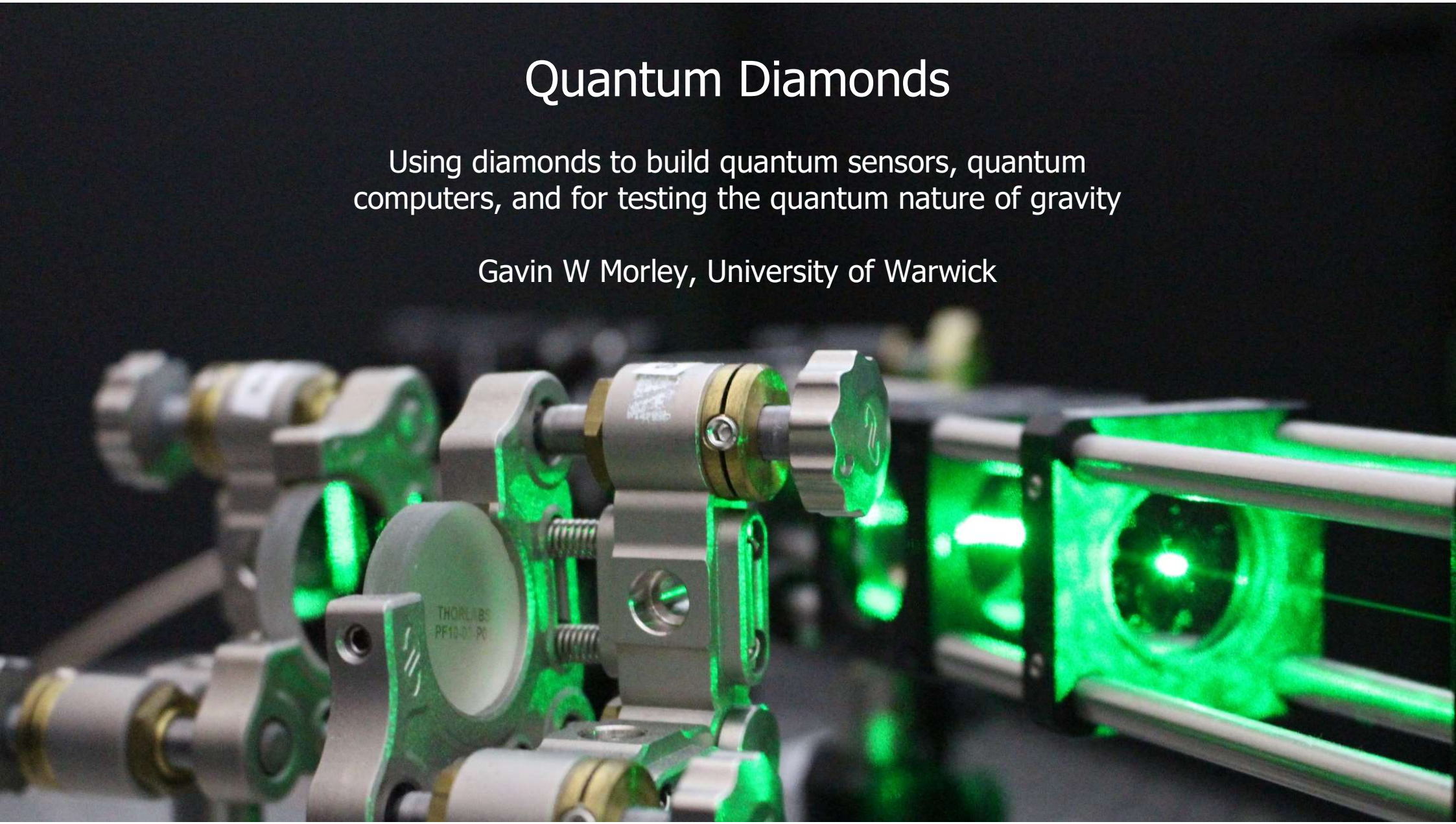
Quantum Diamonds

Using diamonds to build quantum sensors, quantum computers, and for testing 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

Cardiff University: Laia Gines, Soumen Mandal & Oliver Williams

Imperial College London: Chuanqi Wan, Myungshik Kim

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

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

NHS: Faizel Osman

Oxford: Jason Smith's group, Patrick Salter's group

Oxford Instruments Plasma Technology: Colin Welch, Andrew Newton

Element Six: Matthew Markham, Andrew Edmonds, Daniel Twitchen

Tsukuba: Junichi Isoya

NIQRST, Japan: Shinobu Onoda

DSTL: Owen Griffiths

NNL: Doug Offin

[dstl]

elementsix™ DE BEERS GROUP

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UKRI Innovate UK

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NHS

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DST Diamond Science Technology Centre

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

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Quantum Computing & Simulation Hub

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WARWICK THE UNIVERSITY OF WARWICK

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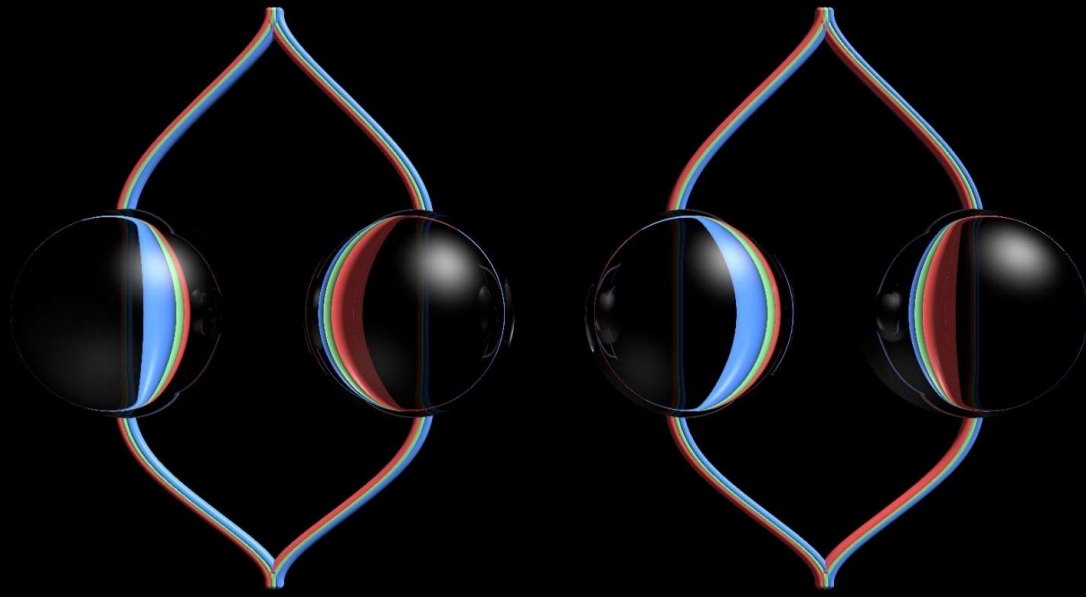
1. Introduction to nitrogen vacancy centres in diamond
2. Magnetometry
3. Nanodiamonds for quantum sensing
4. Towards quantum computing and communication
5. Levitated nanodiamonds towards testing the quantum nature of gravity



Nitrogen-vacancy centres in a diamond

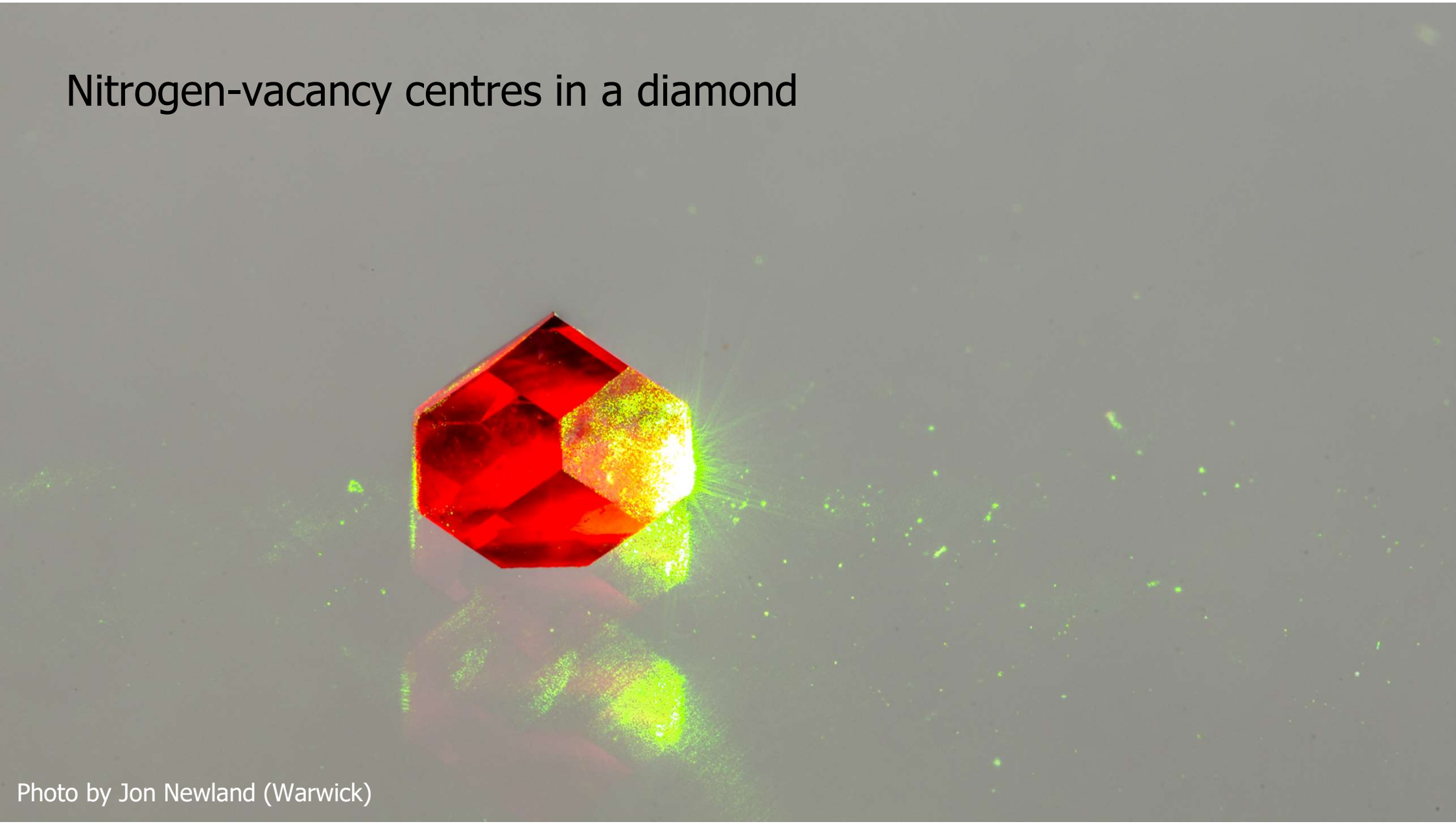
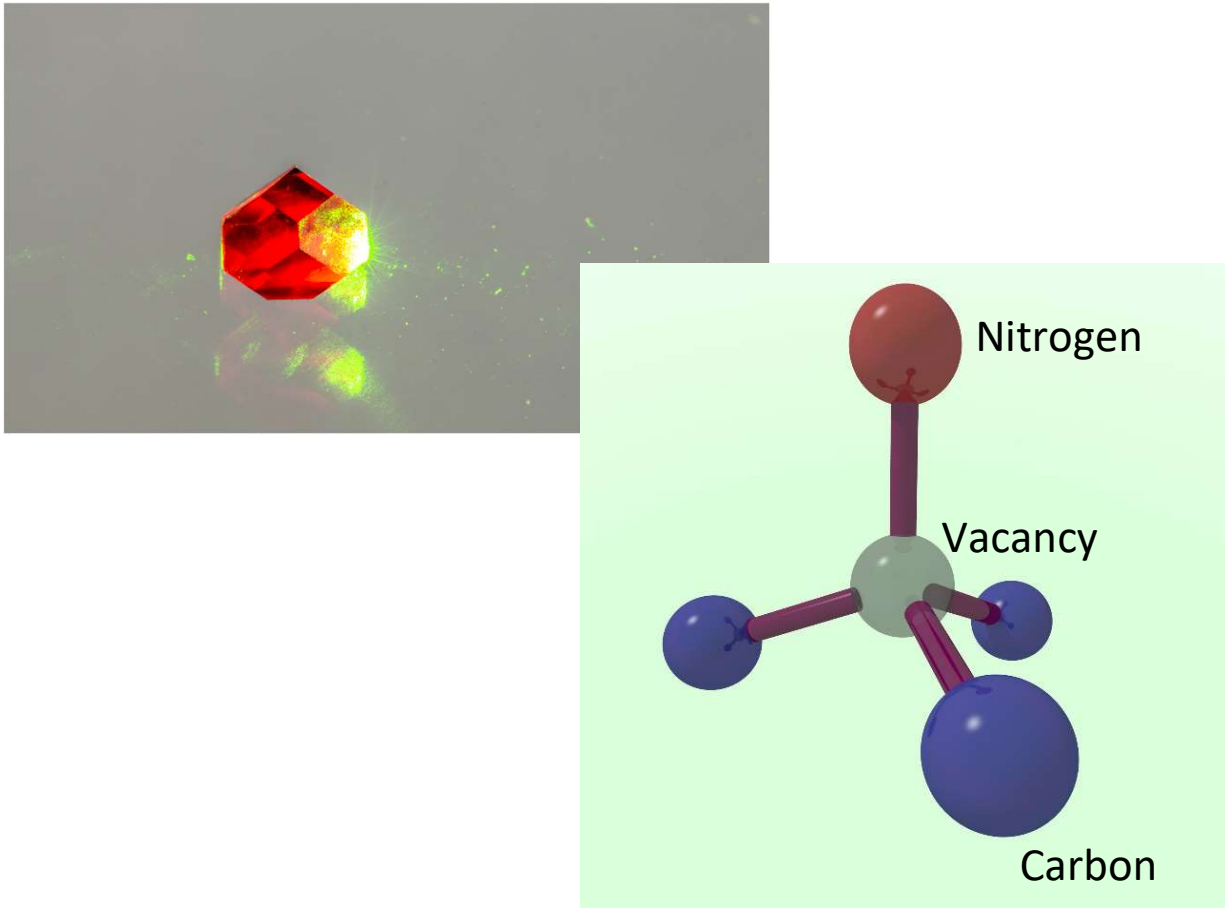
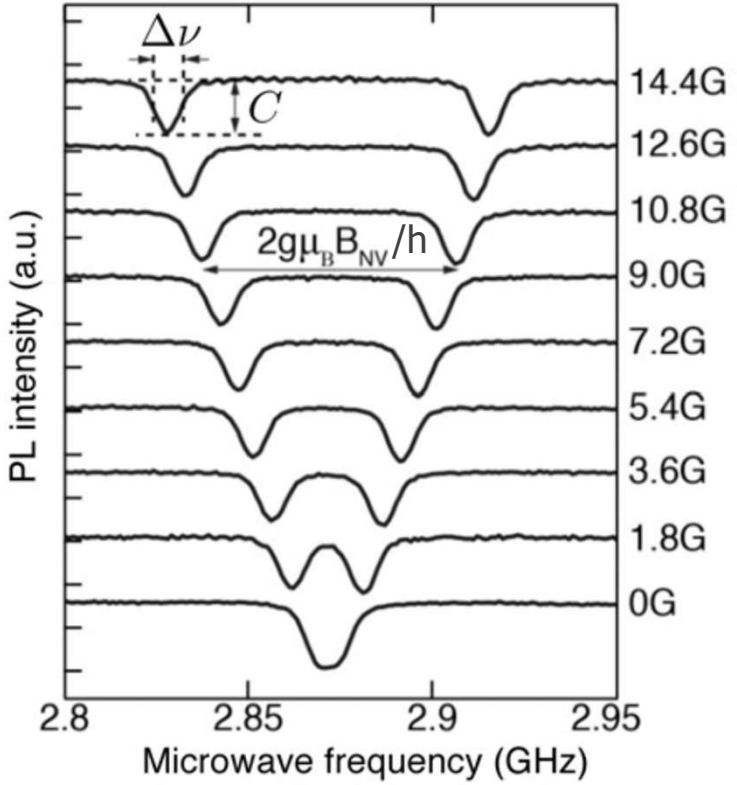


Photo by Jon Newland (Warwick)

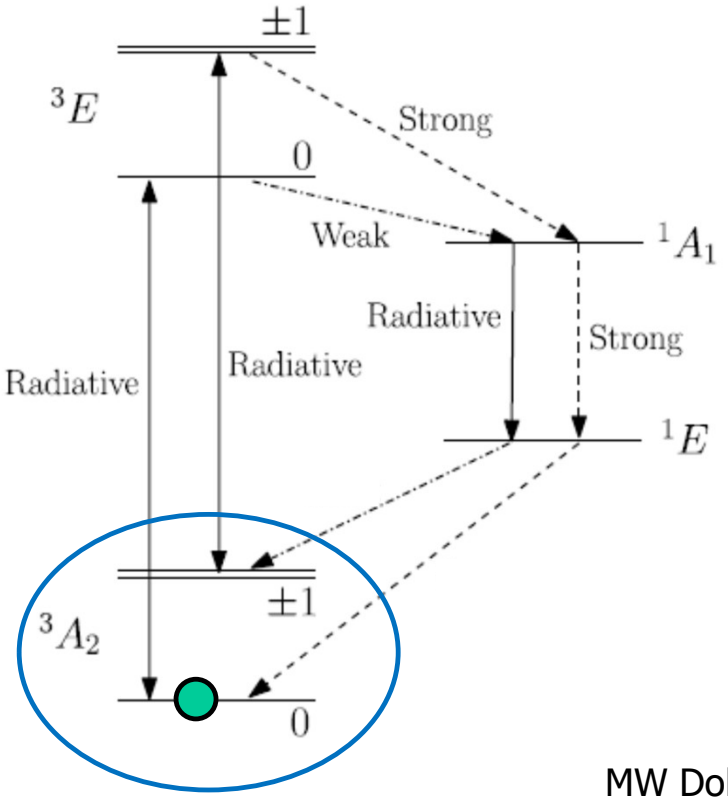
NV centre red fluorescence vs microwave frequency

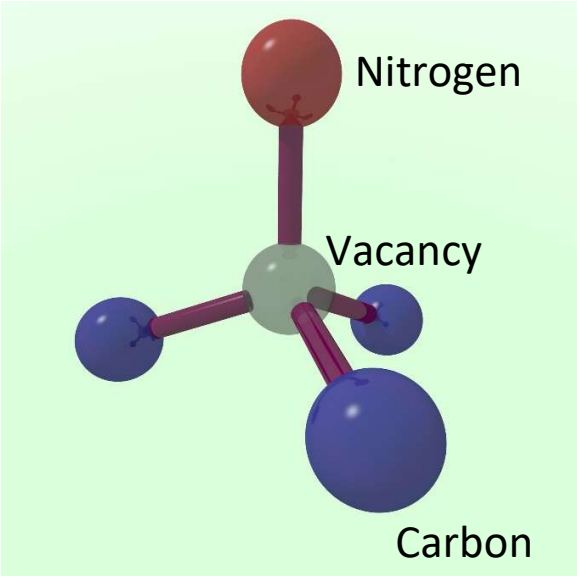




L Rondin *et al*, Rep Prog Phys 77, 056503 (2014)

Nitrogen-vacancy (NV^-) energy levels



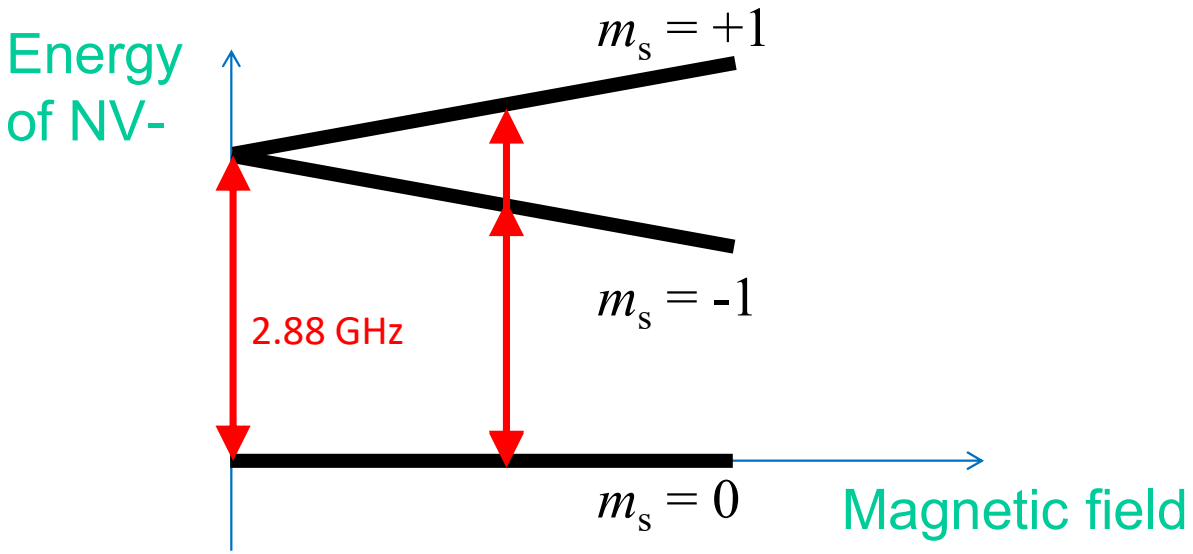


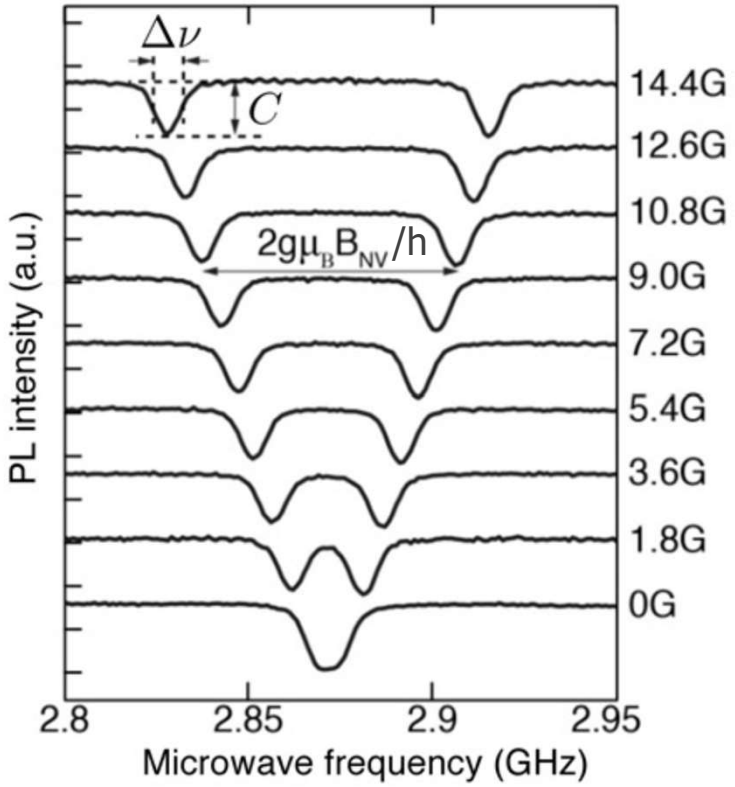
Green excitation →

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

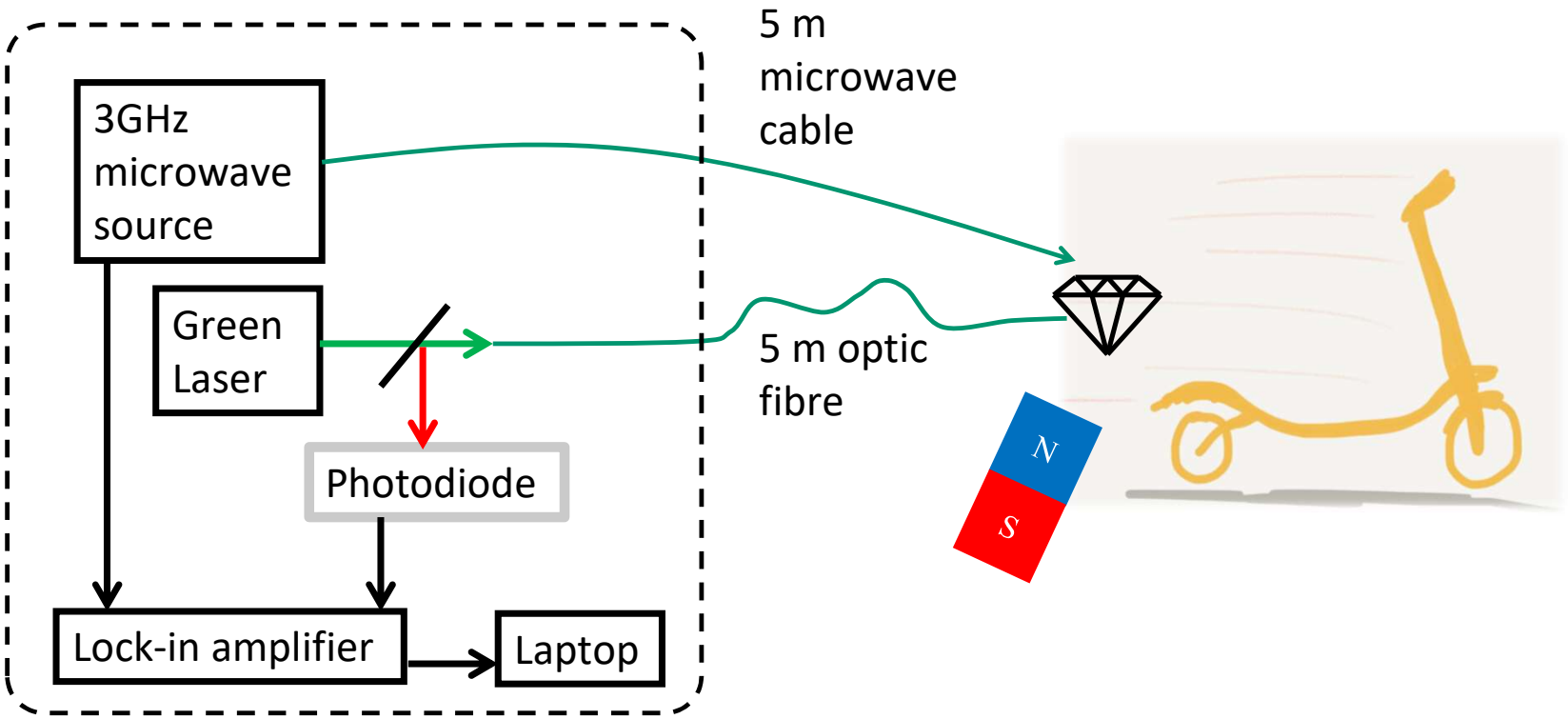




L Rondin *et al*, Rep Prog Phys 77, 056503 (2014)

Nitrogen vacancy centres in diamond for magnetometry

Our fibre-coupled diamond magnetometer: schematic



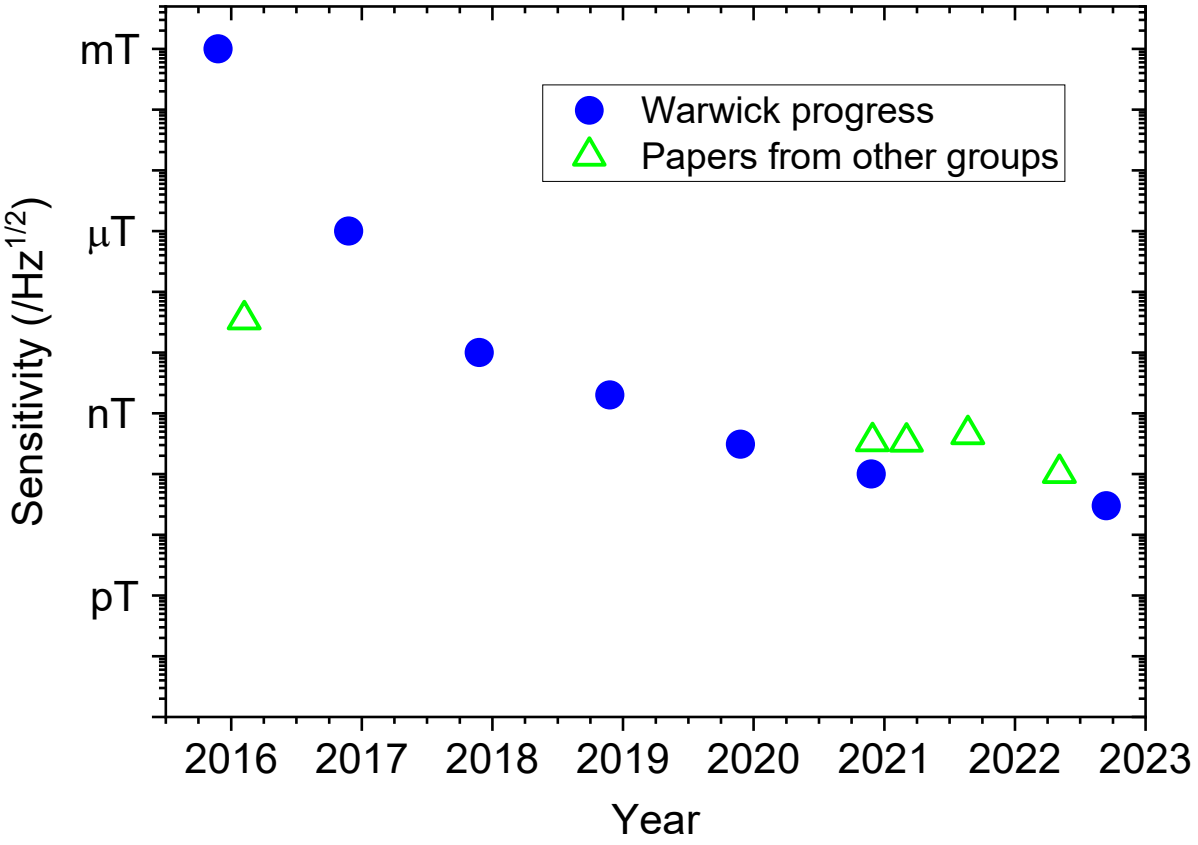
Our fibre-coupled diamond magnetometer

Stuart Graham

Sensitivity between 10-500 Hz is 30 pT/Hz$^{1/2}$.

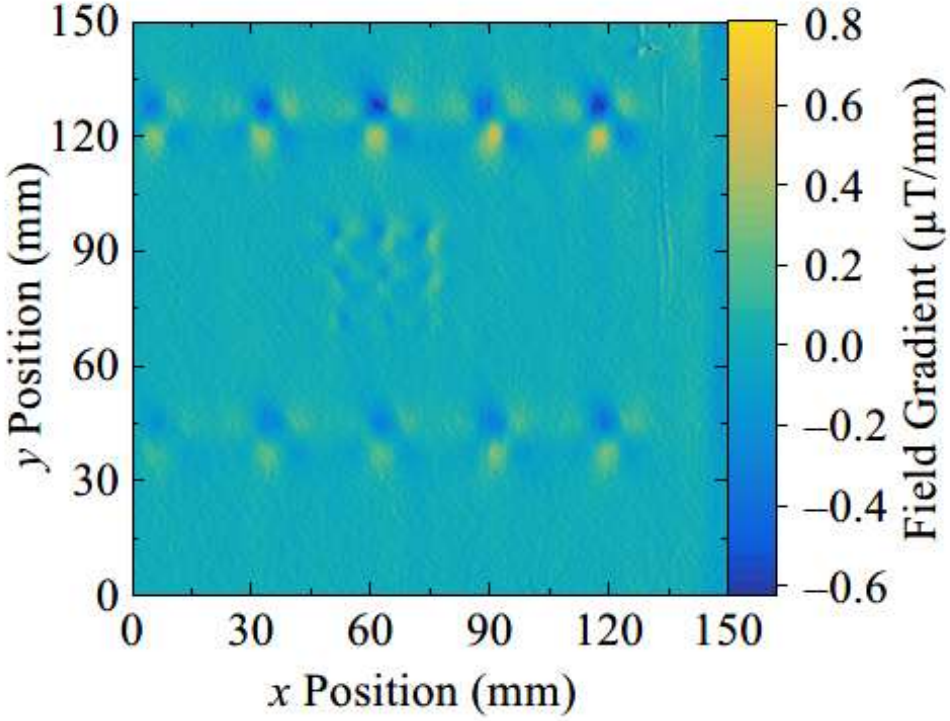
SM Graham, ATMA Rahman, L Munn, RL Patel, AJ Newman, CJ Stephen, G Colston, A Nikitin, AM Edmonds, DJ Twitchen, ML Markham & GWM, Phys Rev Applied 19, 044042 (2023)

Our fibre-coupled diamond magnetometer



- SM Graham… & GWM, Phys Rev Applied 19, 044042 (2023)
- LQ Zhou… & GWM, Phys Rev Applied 15, 024015 (2021)
- RL Patel… & GWM, Phys Rev Applied 14, 044058 (2020)

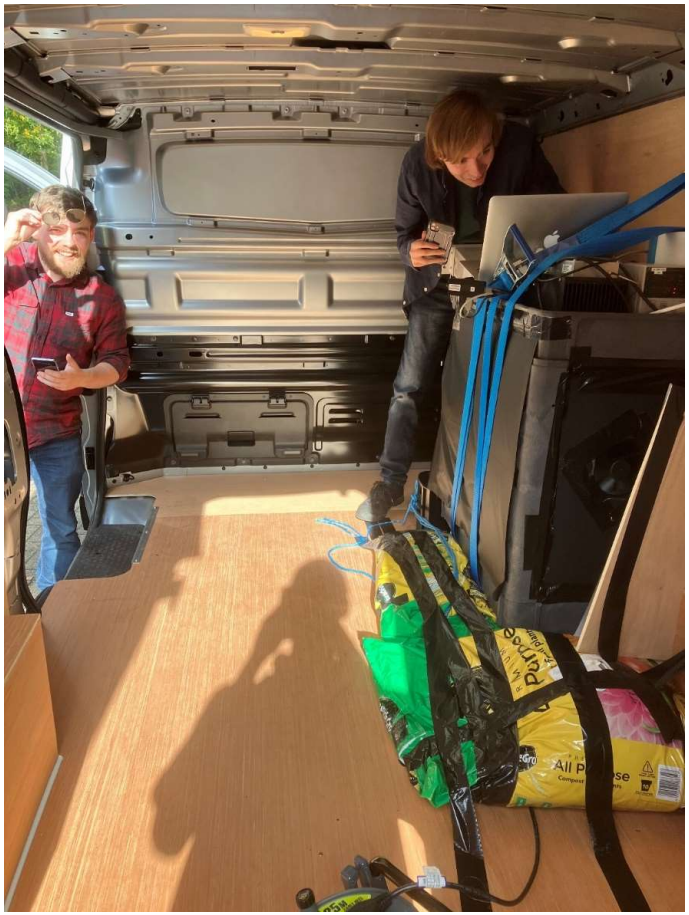
Scanning vector magnetometry

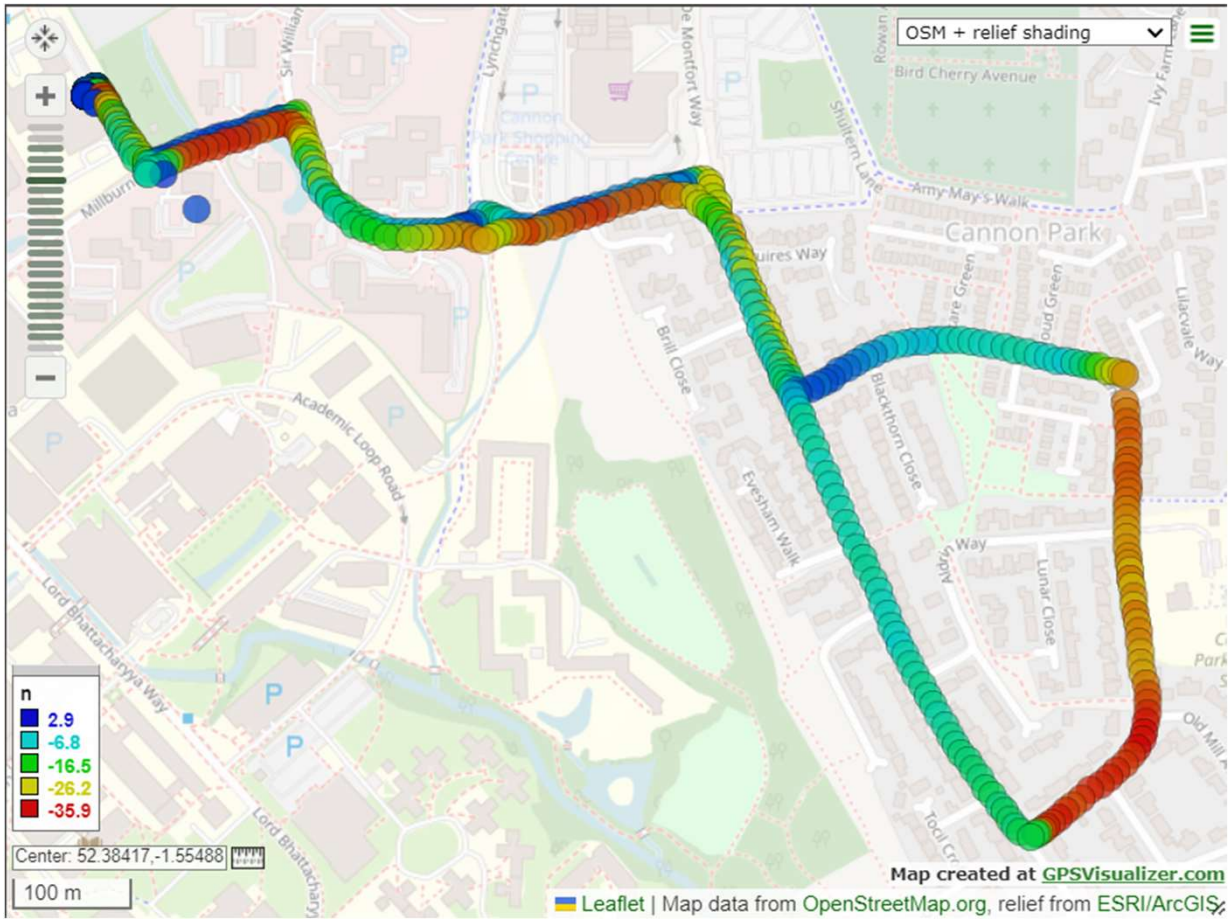


Alex Newman

AJ Newman, SM Graham, AM Edmonds, DJ Twitchen, ML Markham & GWM, Tensor gradiometry with a diamond magnetometer, Physical Review Applied 21, 014003 (2024)

Diamond magnetometry for navigation





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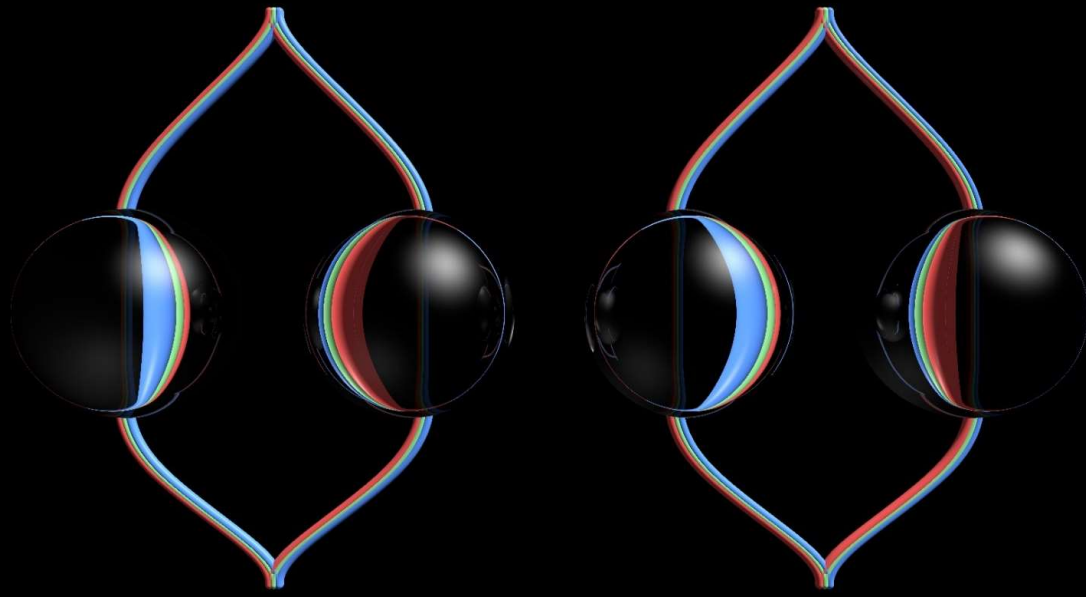
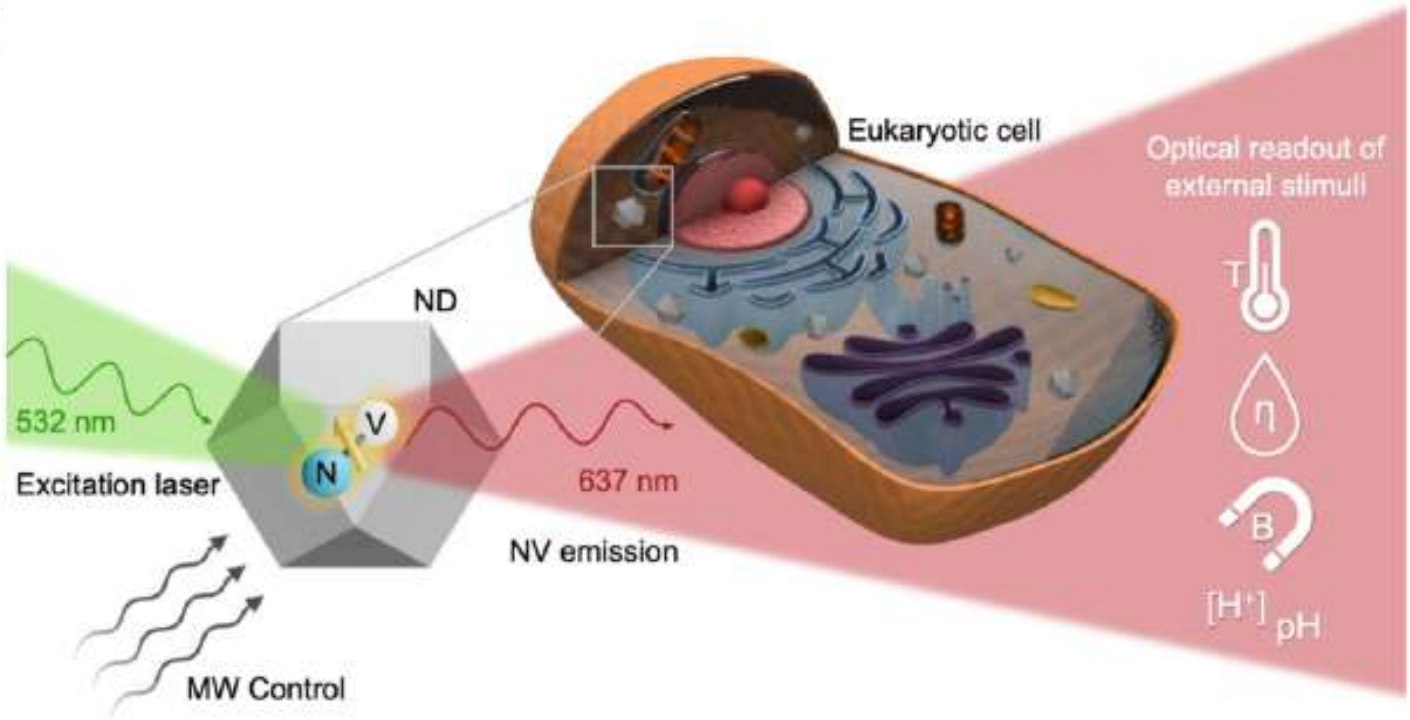
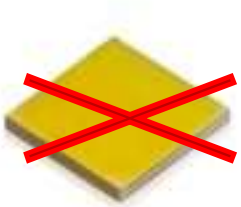


Nanodiamonds for sensing inside cells



Review paper: S Belser, J Hart, Q Gu, L Shanahan & HS Knowles, APL **123**, 020501 (2023)

More pure diamonds

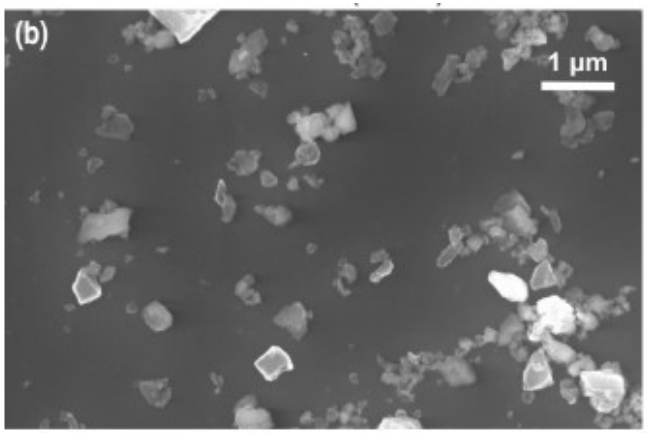


150 ppm nitrogen impurities

120 ppb nitrogen impurities

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

More pure diamonds



120 ppb nitrogen impurities

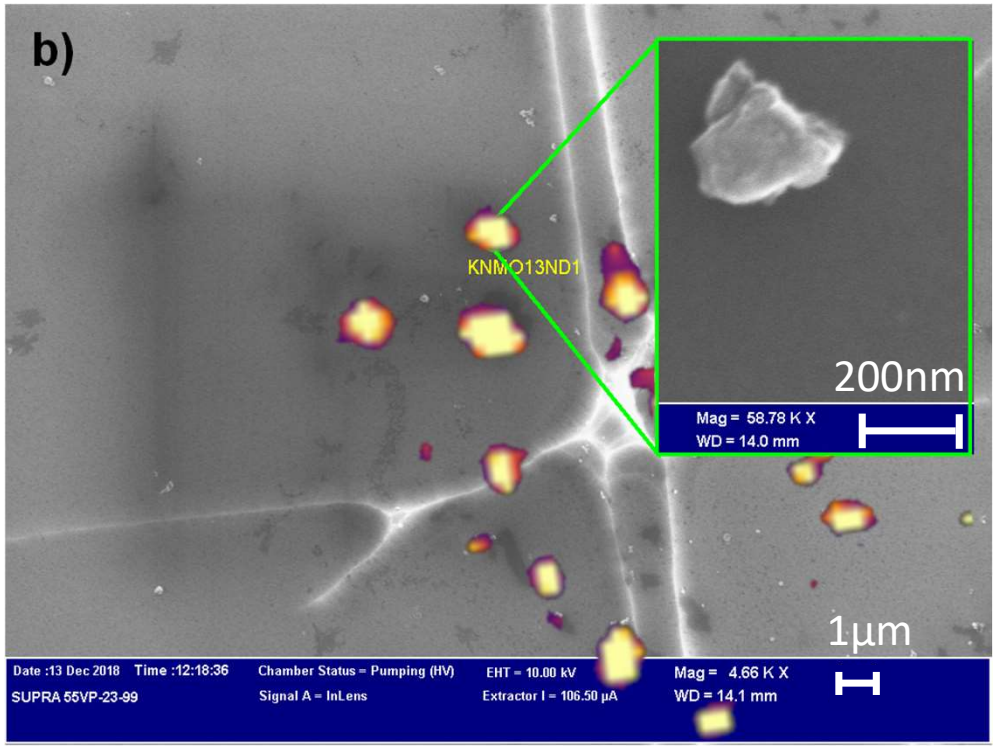
Milling by Ollie Williams' group, Cardiff

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

Purer nanodiamonds have longer spin coherence

Guy Stimpson

Scanning Electron Microscopy (SEM)



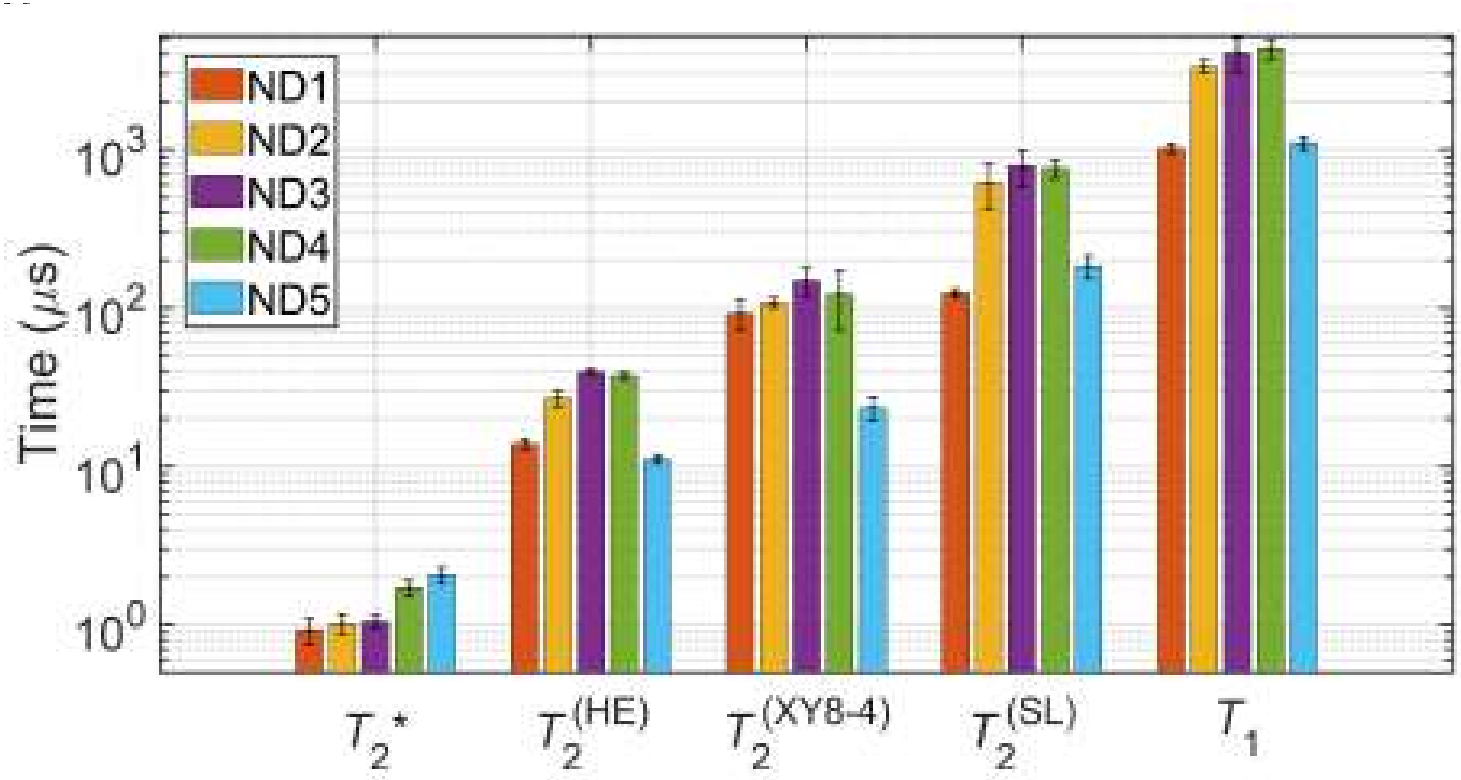
T_2 Hahn echo = 177 µs

T_2 XY8-4 = 460 µs

Ben Wood

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

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)

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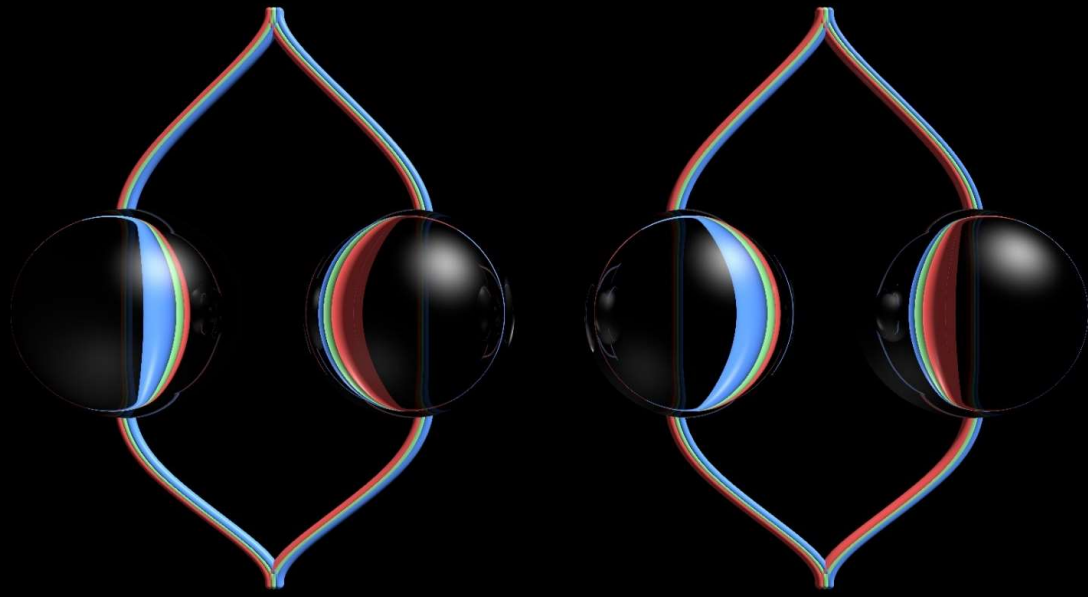
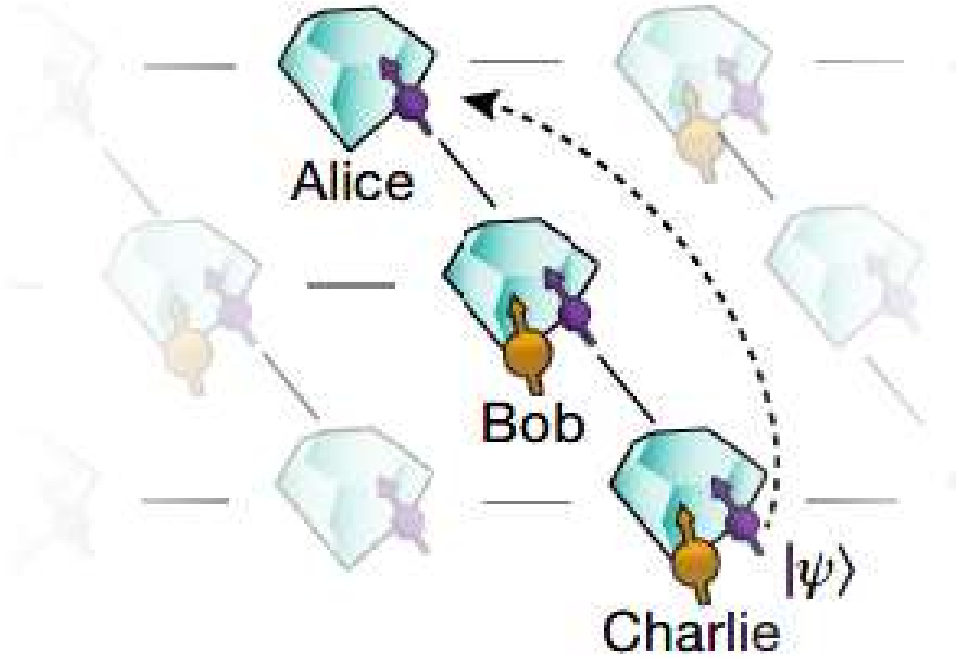
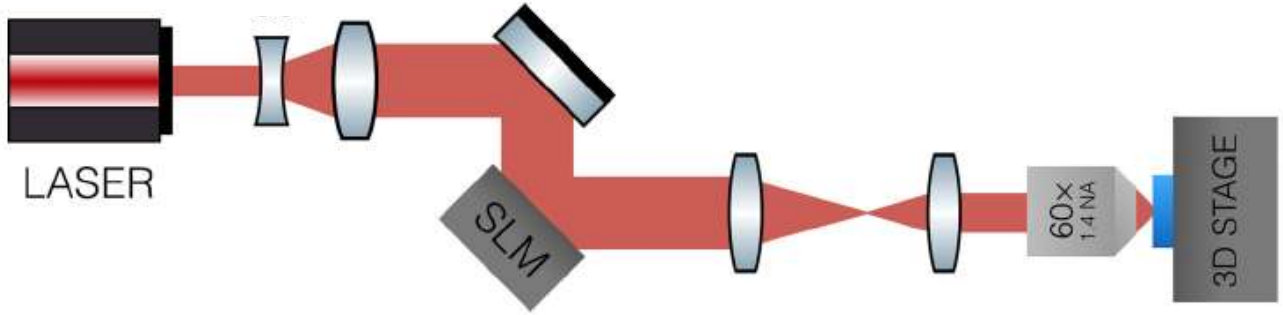


NV centres in diamond for quantum computing and communication



SLN Hermans, M Pompili, HKC Beukers, S Baier, J Borregaard & R Hanson, Nature **605**, 663 (2022)

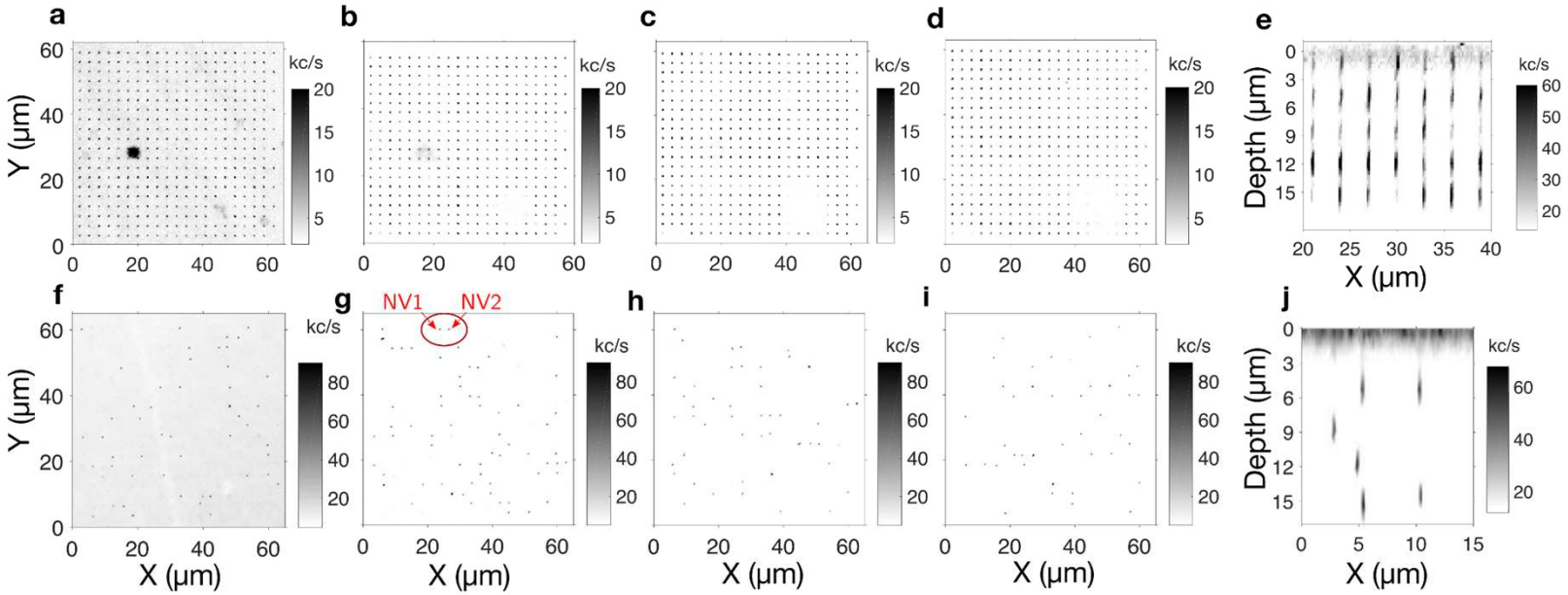
Arrays of good NV^- with laser writing



Jason
Smith

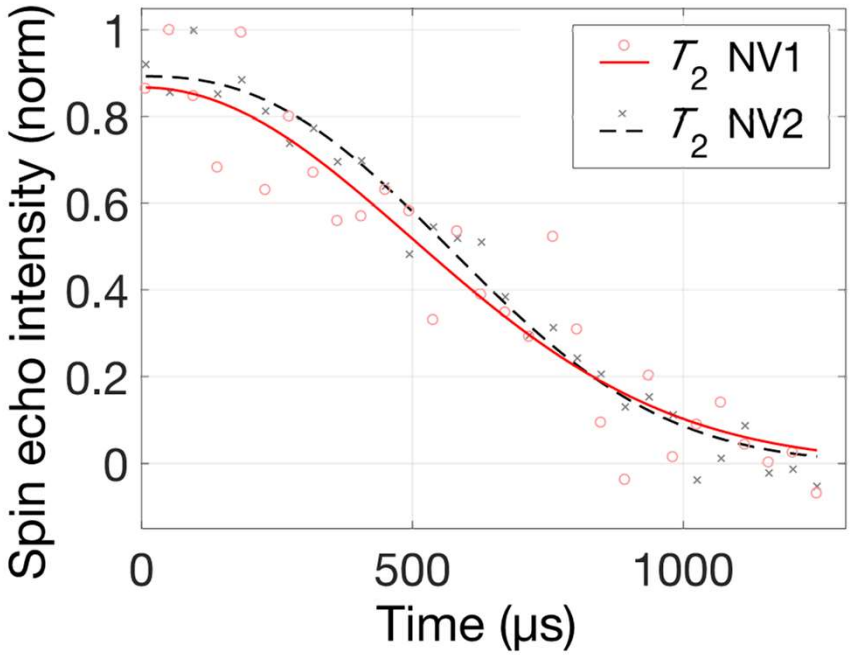
Patrick
Salter

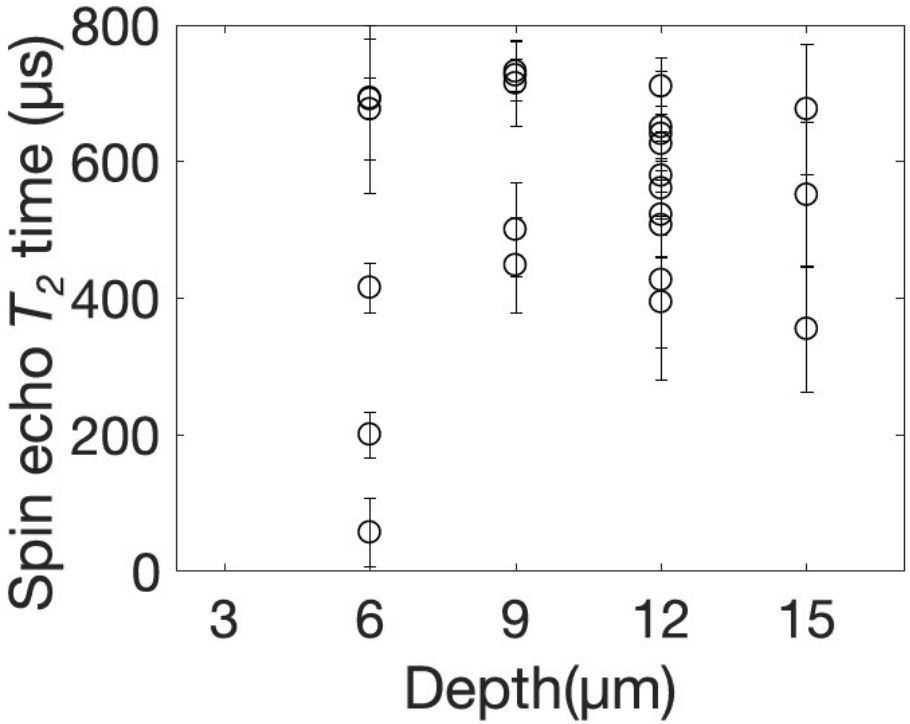
Laser-writing deep nitrogen vacancy centres in diamond



C.J. Stephen, B.L. Green, Y.N.D. Lekhai, L. Weng, P. Hill, S. Johnson, A.C. Frangeskou, P.L. Diggle, M.J. Strain, E. Gu, M.E. Newton, J.M. Smith, P.S. Salter & G.W. Morley, Phys. Rev. Applied 12, 064005 (2019)

Long spin coherence times





C.J. Stephen, B.L. Green, Y.N.D. Lekhai, L. Weng, P. Hill, S. Johnson, A.C. Frangeskou, P.L. Diggle, M.J. Strain, E. Gu, M.E. Newton, J.M. Smith, P.S. Salter & G.W. Morley, Phys. Rev. Applied 12, 064005 (2019)

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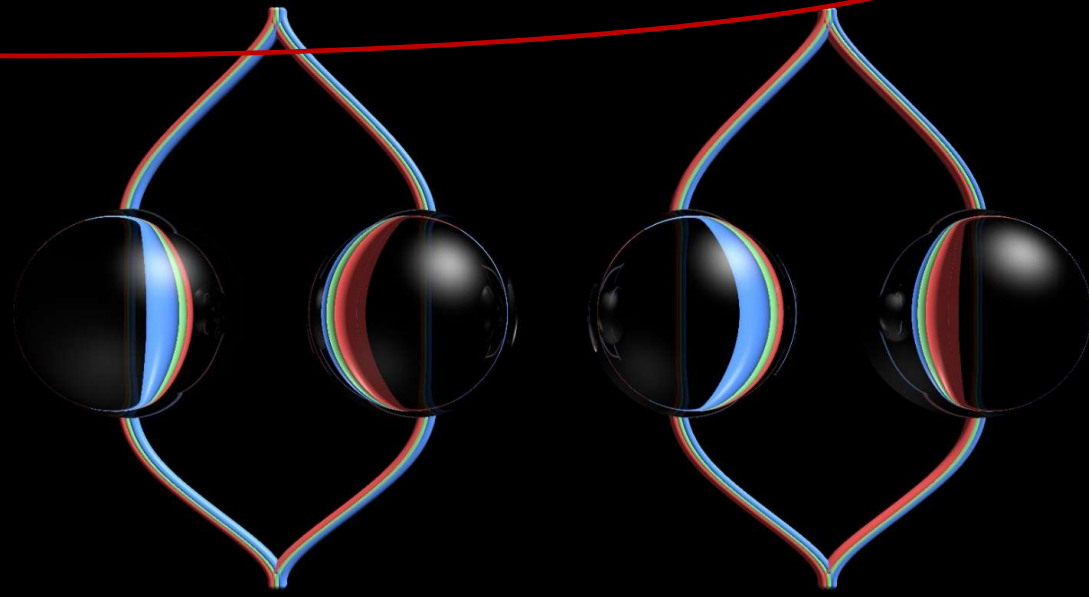
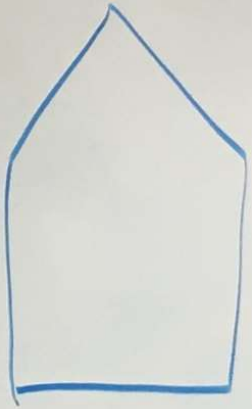


$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|L\rangle + |R\rangle\right)$$

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

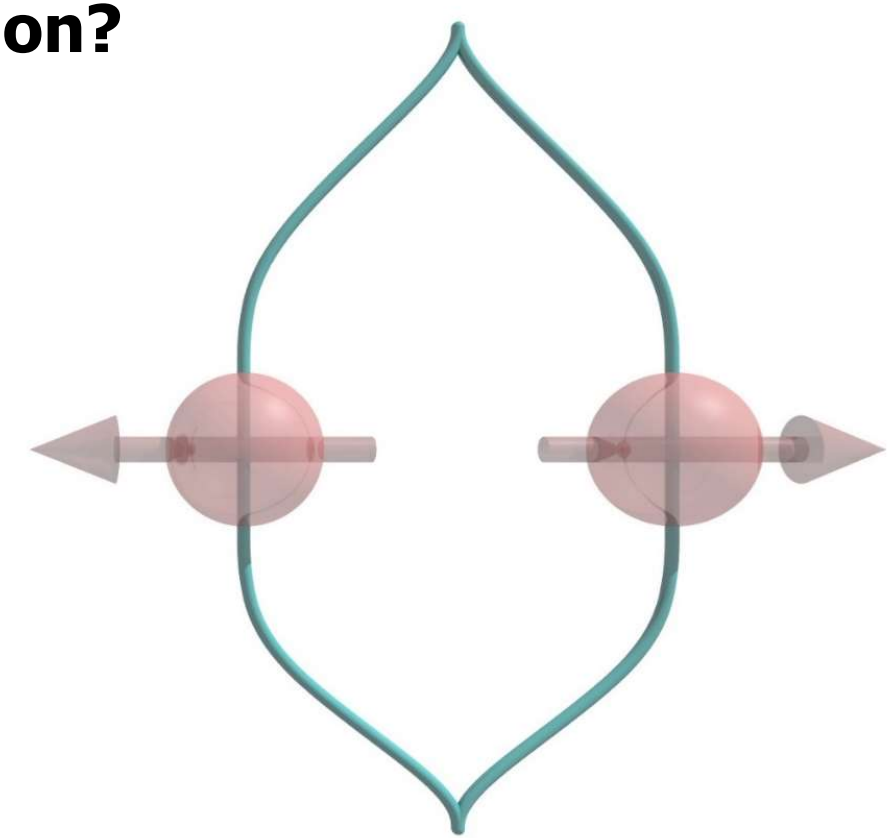
$$|\psi_{cat}\rangle = \frac{1}{\sqrt{2}}\left(\left|\text{  }\right\rangle + \left|\text{  }\right\rangle\right)$$

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

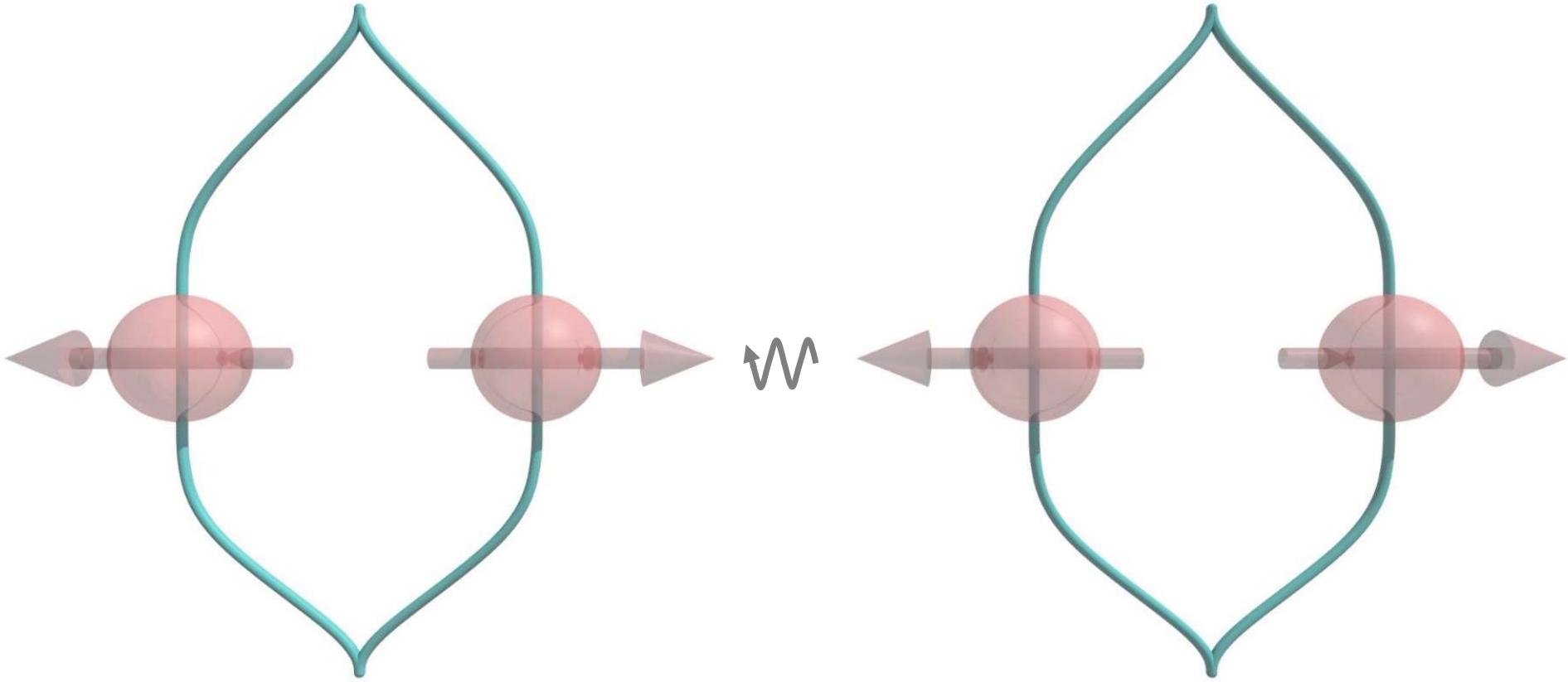
What is the gravitational effect from a mass in a spatial superposition?

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)

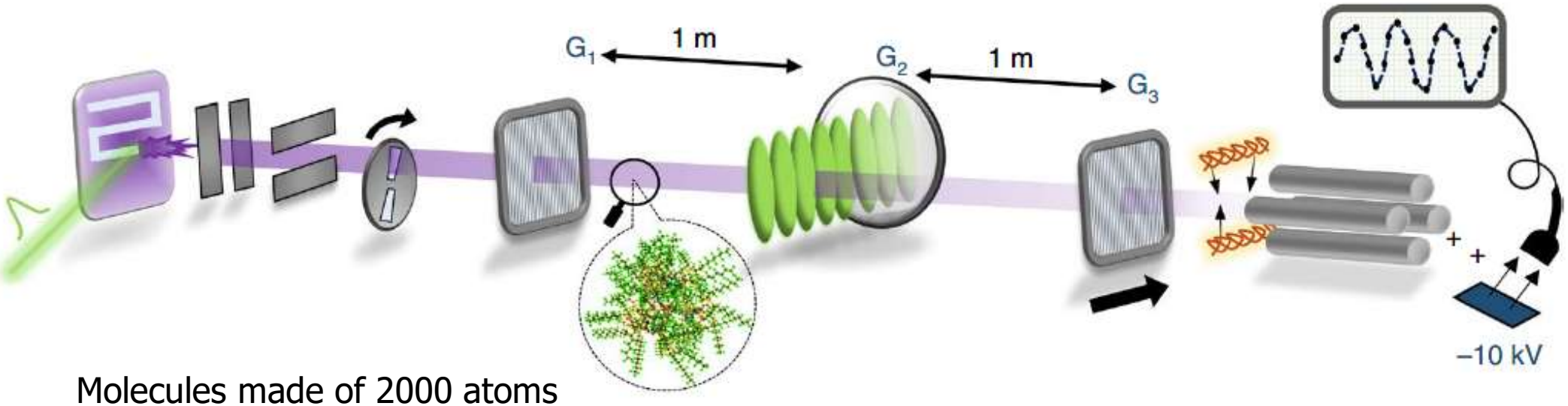
C Marletto & V Vedral, PRL 119, 240402 (2017)

2 μm object, $\Delta x \sim 250$ μm

Closest approach ~ 200 μm

Time ~ 8 s

The most macroscopic spatial superposition

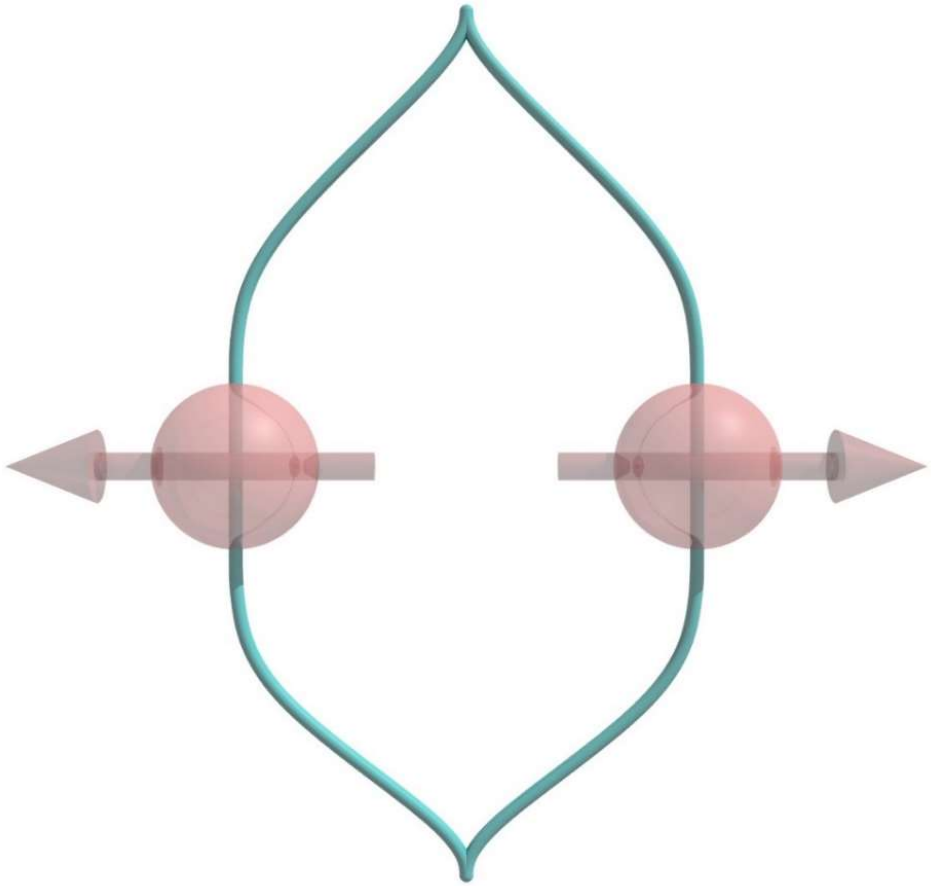


Molecules made of 2000 atoms

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)

Our proposal: drop a nanodiamond containing a spin

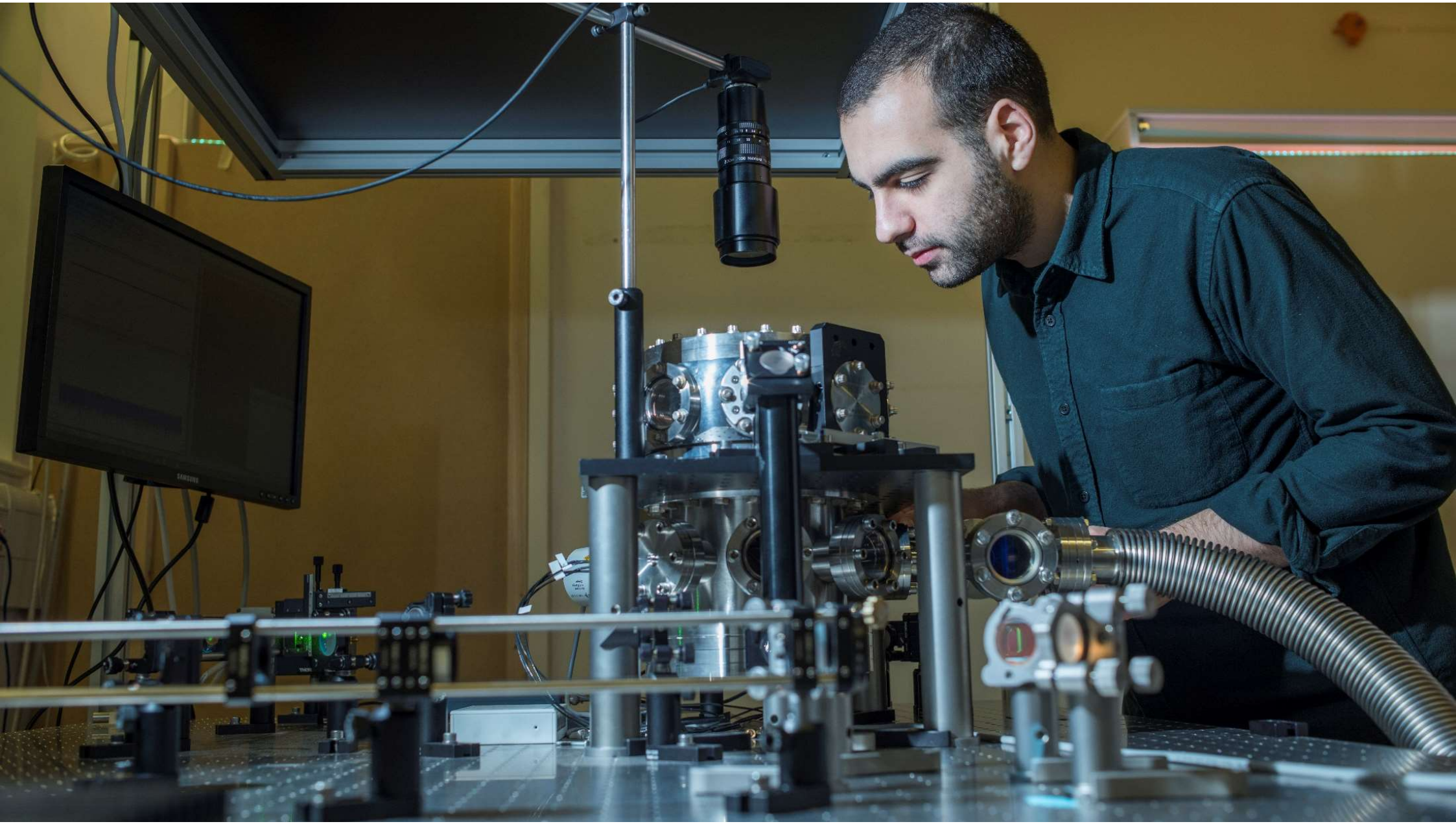


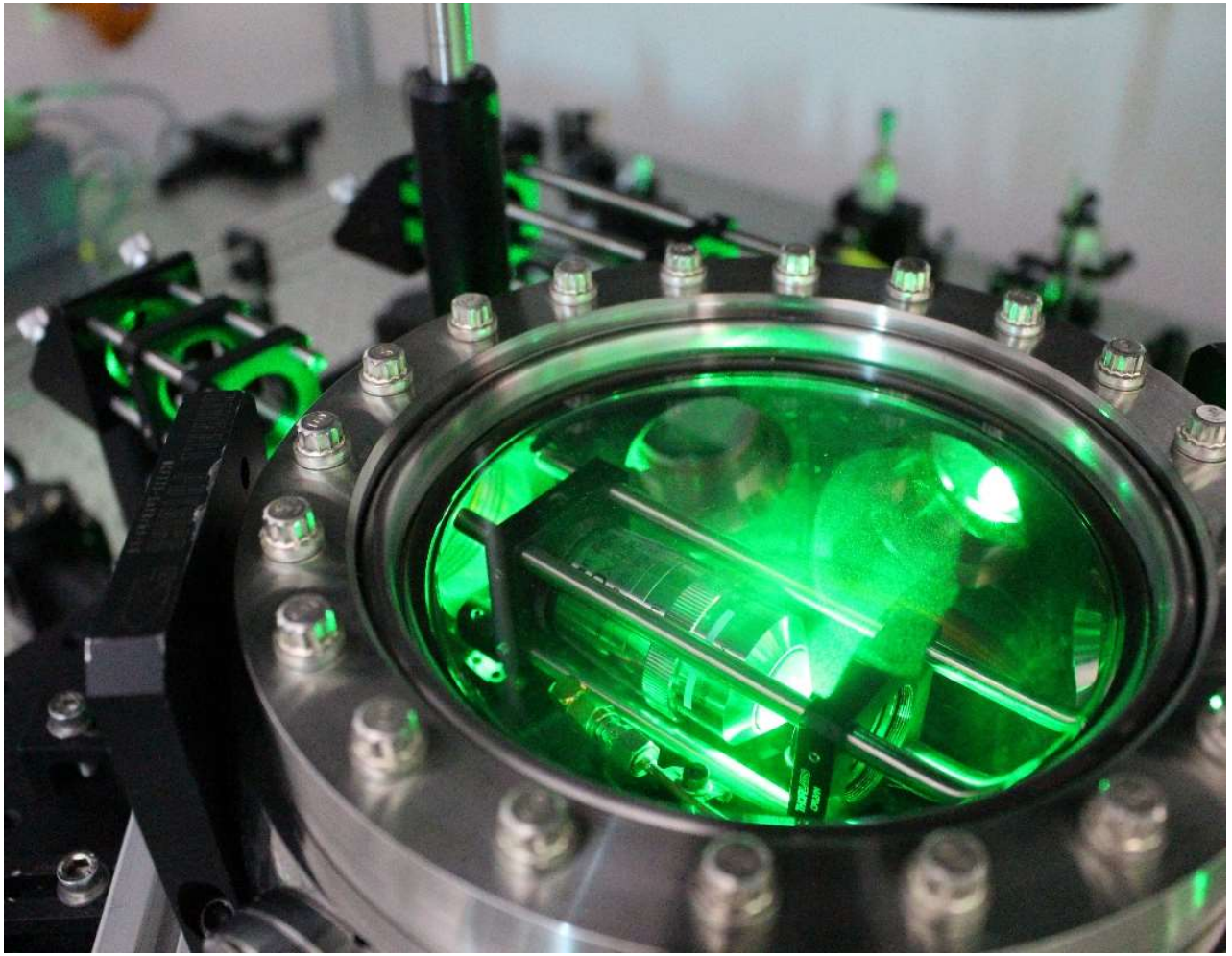
Proposals from our collaboration:

- 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)

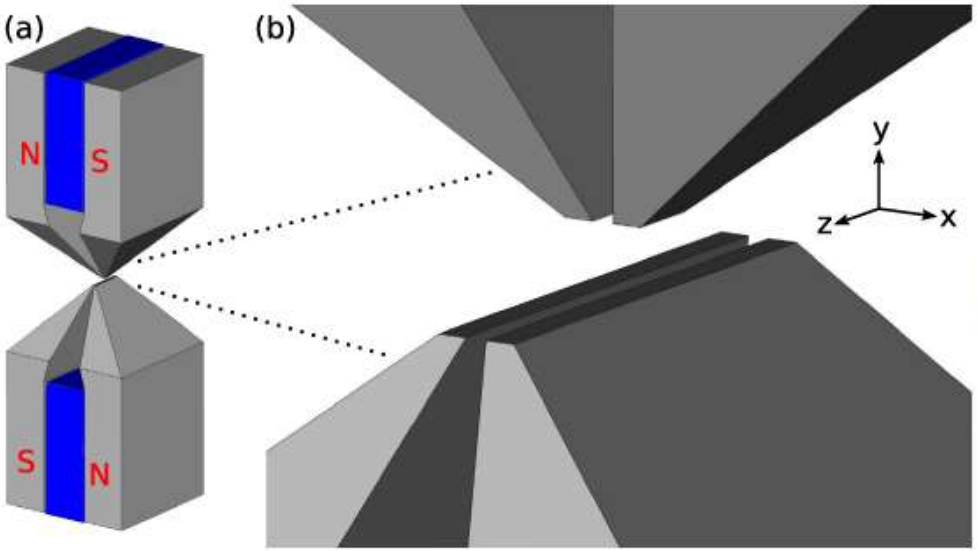


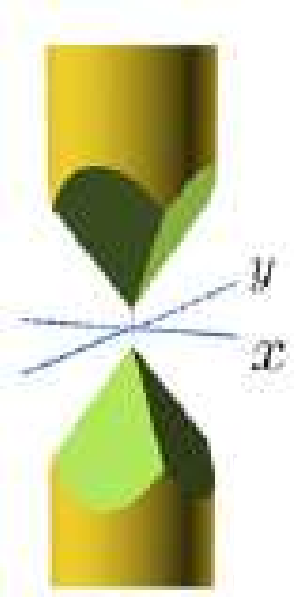


ATMA Rahman… & PF Barker, Scientific Reports **6**, 21633 (2016)
AC Frangeskou… & GWM, NJP, 20, 043016 (2018)
ATMA Rahman… & GW Morley, Rev Scientific Instrum 89, 023109 (2018)

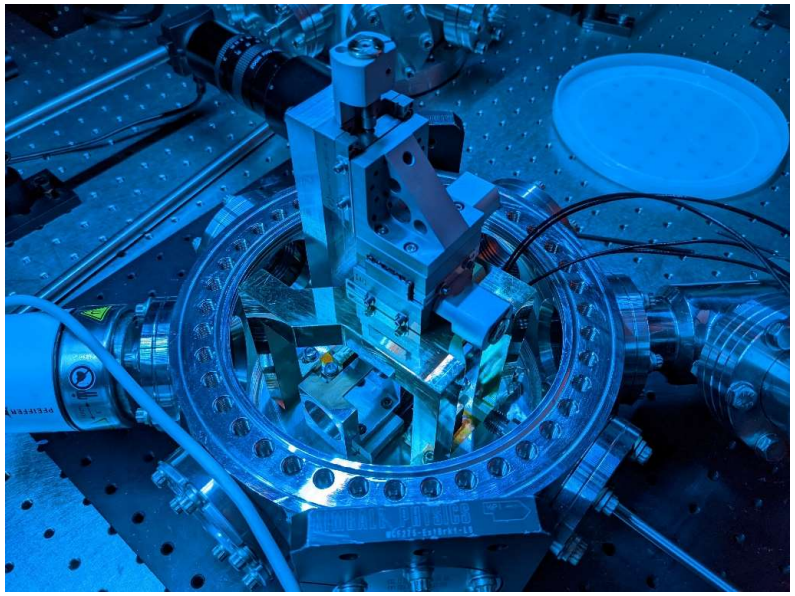
Magnetic traps for microdiamonds

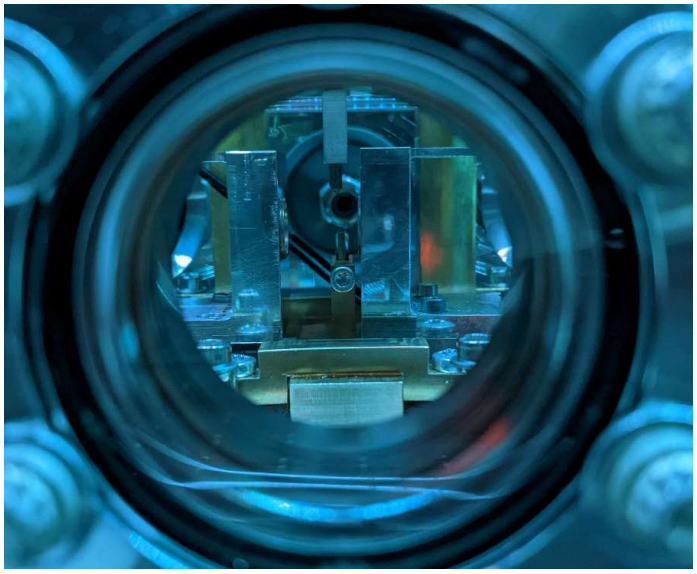
J-F Hsu, P Ji, CW Lewandowski &
B D'Urso, Sci Rep **6**, 30125 (2016)





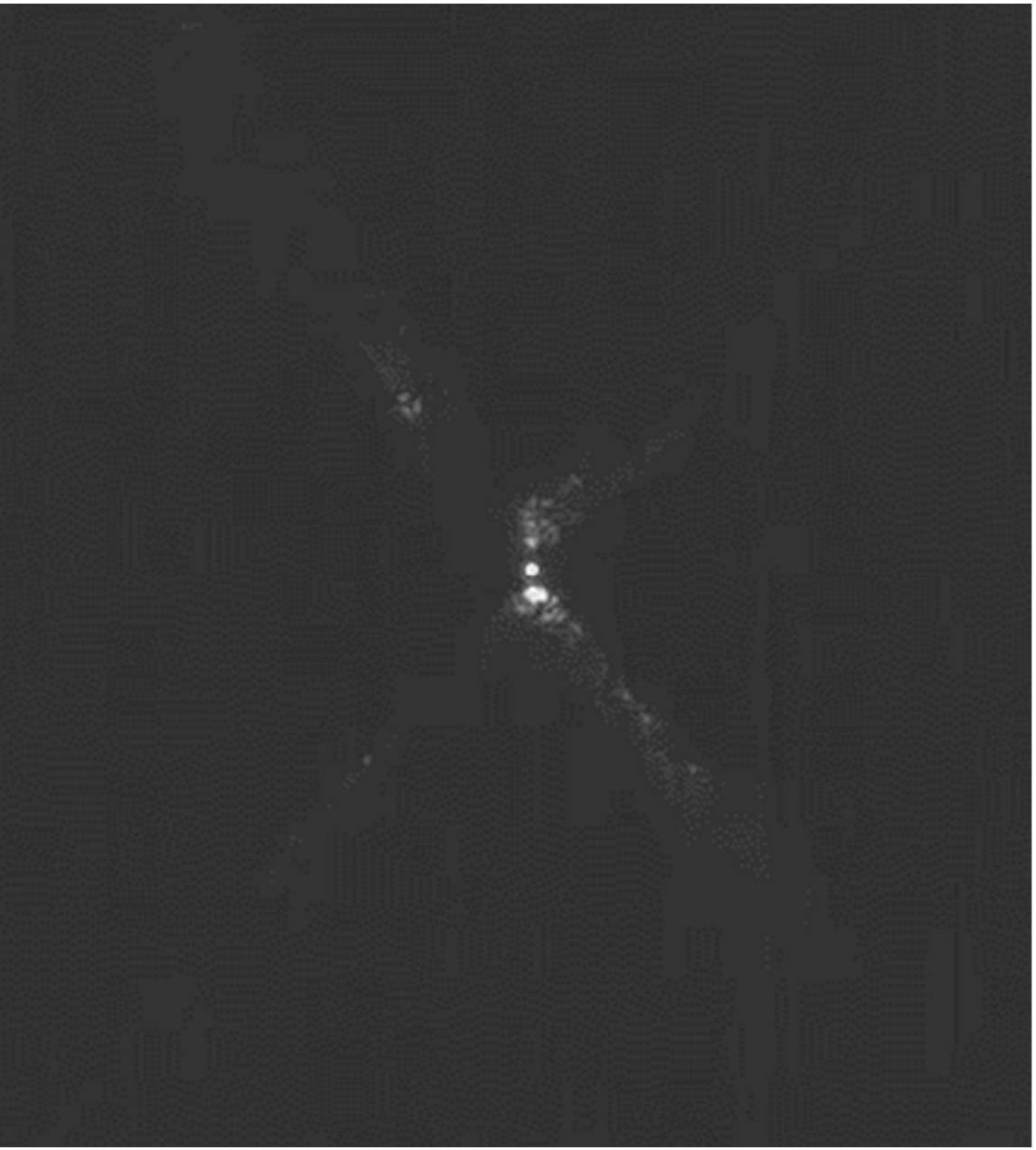
MC O'Brien, S Dunn, JE Downes & J Twamley, APL 114, 053103 (2019)





Our magnetic trap for microdiamonds

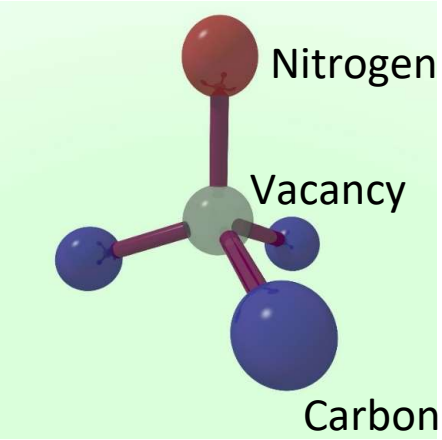
James March and Ben Wood



Our magnetic trap for nanodiamonds

James March and Ben Wood

Conclusions



1. Sensitive fibre-coupled diamond magnetometer

- AJ Newman… & GWM, Phys Rev Applied 21, 014003 (2024)
- SM Graham… & GWM, Phys Rev Applied 19, 044042 (2023)
- LQ Zhou… & GWM, Phys Rev Applied 15, 024015 (2021)

2. Nanodiamonds with the longest spin relaxation and coherence times

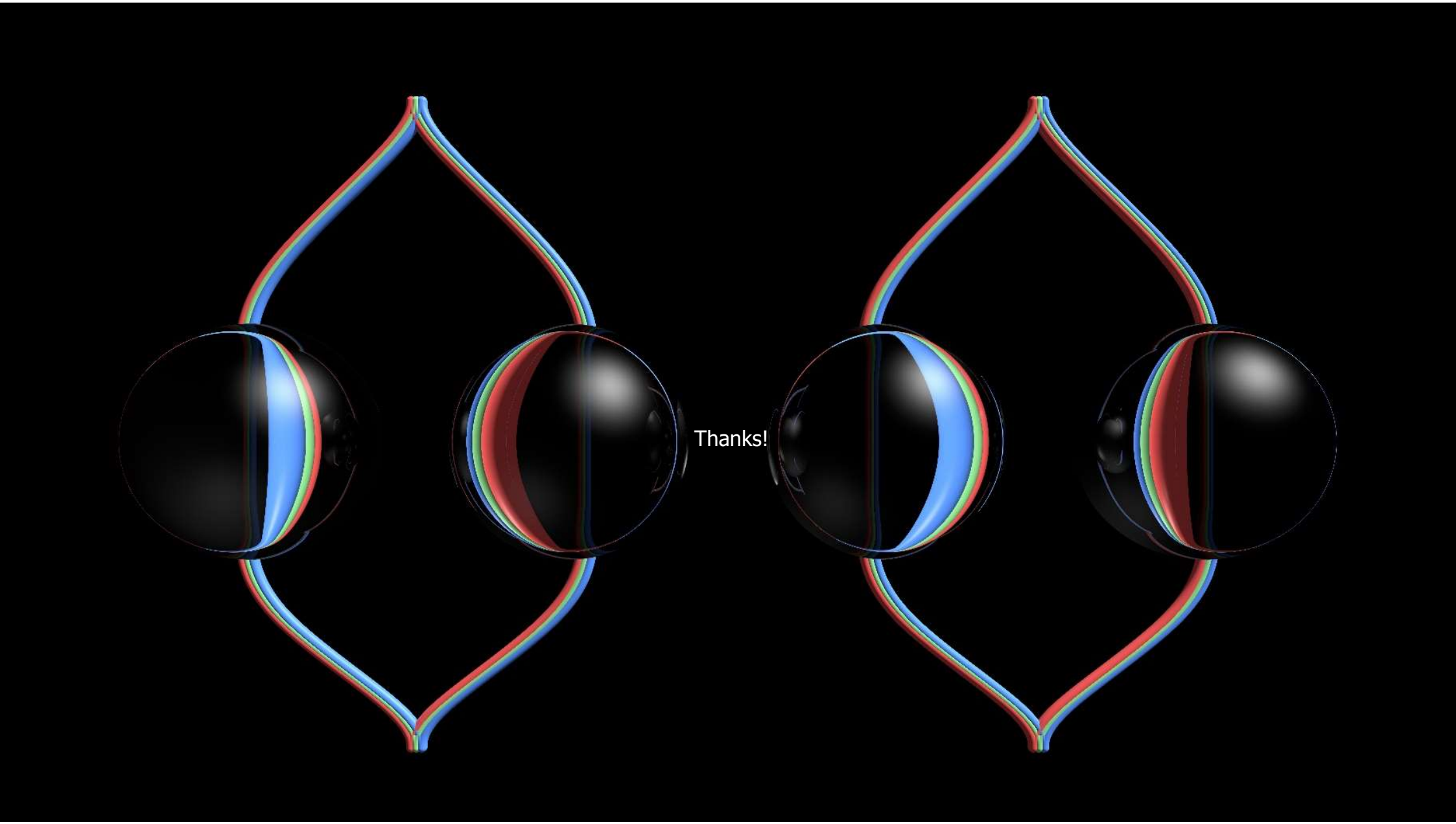
- JE March… & GWM, Phys Rev Applied 20, 044045 (2023)
- BD Wood… & GWM, Phys Rev B 105, 205401 (2022)

3. NV centre arrays for quantum computing & communications

- Y-C Chen... & JM Smith, Nature Photonics 11, 77 (2017)
- CJ Stephen… & GWM, Phys Rev Applied 12, 064005 (2019)

4. Levitated microdiamonds towards testing quantum gravity

- S Bose… & G Milburn, Phys Rev Letters **119**, 240401 (2017)
- BD Wood, S Bose & GWM, Phys Rev A **105**, 012824 (2022)


Thanks!


Property of:
E. Schrödinger
This way up