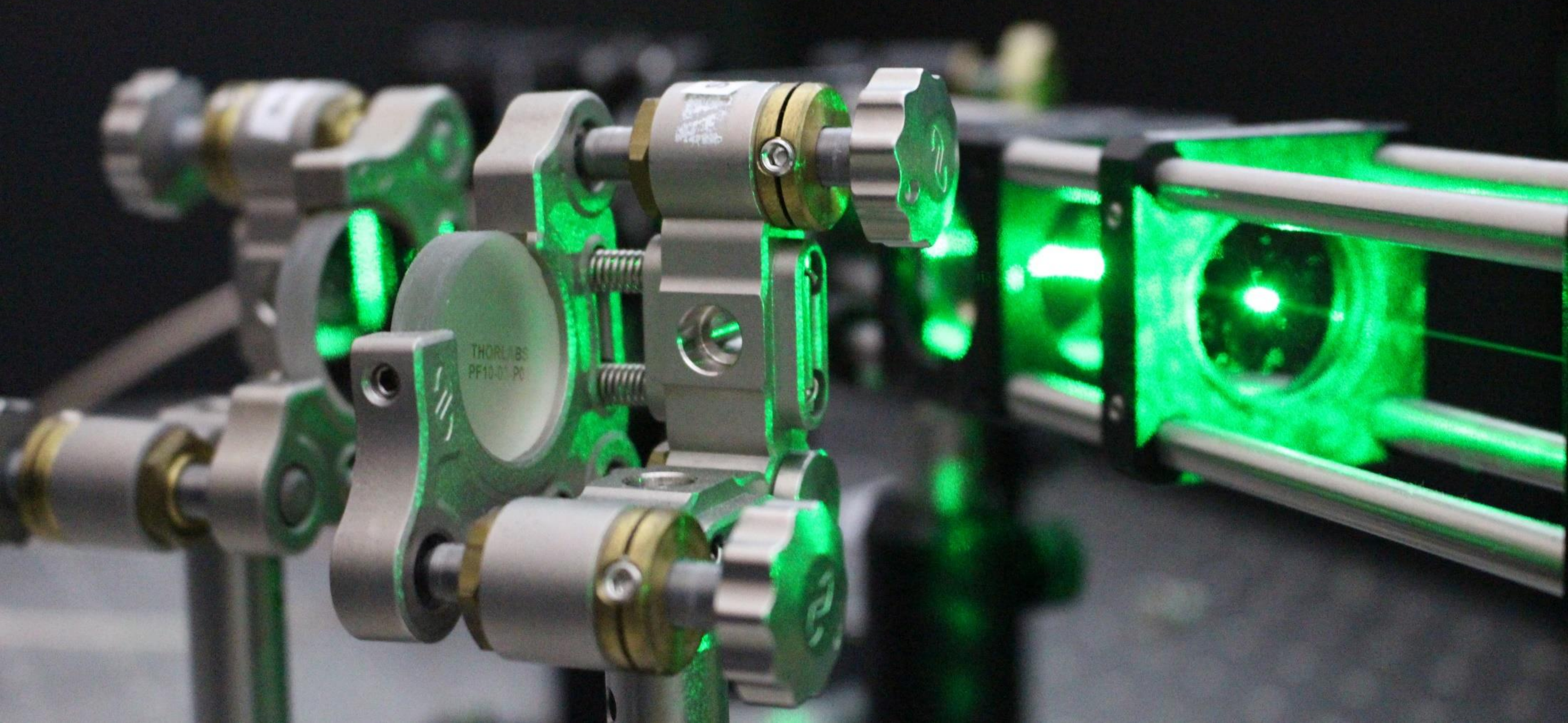
Matter and spin superposition in vacuum experiment (MASSIVE)

Gavin W Morley, University of Warwick



Acknowledgments

Warwick University
Angelo Frangeskou
Colin Stephen
Anis Rahman (now UCL)
Ben Green
Guy Stimpson
Yashna Lekhai

University College London
Peter Barker
Sougato Bose

Imperial College London
Chuanqi Wan
Myungshik Kim

Cardiff University
Laia Gines, Soumen Mandal & Oliver Williams

UK National Quantum Technology Hub Sensors and Metrology

EPSRC Engineering and Physical Sciences Research Council

DST Diamond Science Technology Centre

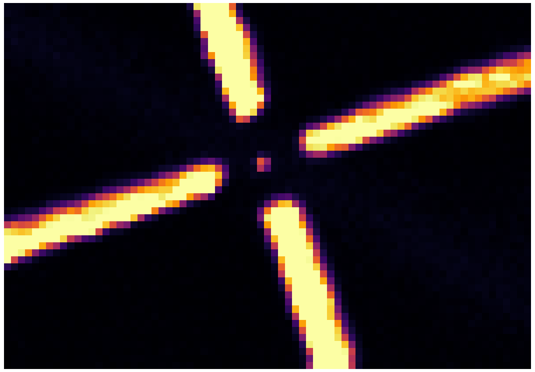
iMR

THE ROYAL SOCIETY

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

NQIT

My background in diamond qubits and sensors



Single spin qubits: CJ Stephen, BL Green, YND Lekhai, L Weng, P Hill, S Johnson, AC Frangeskou, PL Diggle, MJ Strain, E Gu, ME Newton, JM Smith, PS Salter & GW Morley, arXiv 1807.03643 (2018)

Ensemble magnetometer: MW Dale & GW Morley, Medical applications of diamond magnetometry: commercial viability, arXiv:1705.01994 (2017)

OXFORD INSTRUMENTS PLASMA TECHNOLOGY

Bartington Instruments

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UK National Quantum Technology Hub Sensors and Metrology

EPSRC Engineering and Physical Sciences Research Council

DST Diamond Science Technology Centre

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NQIT

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

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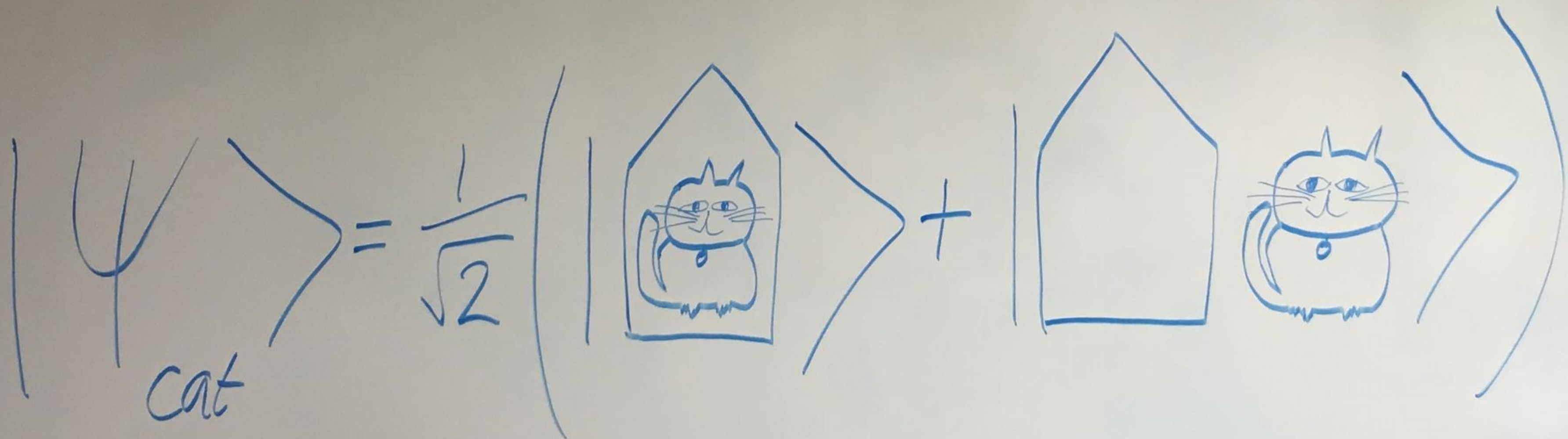
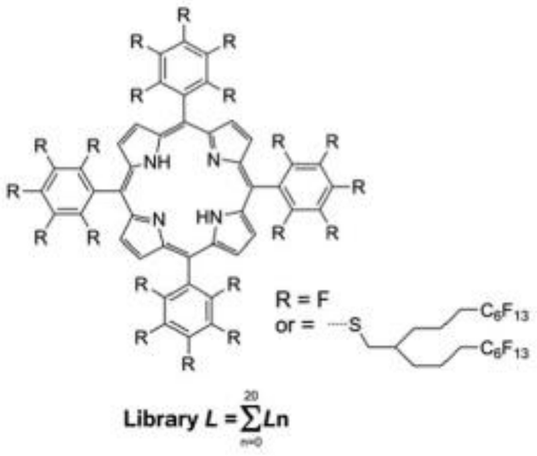
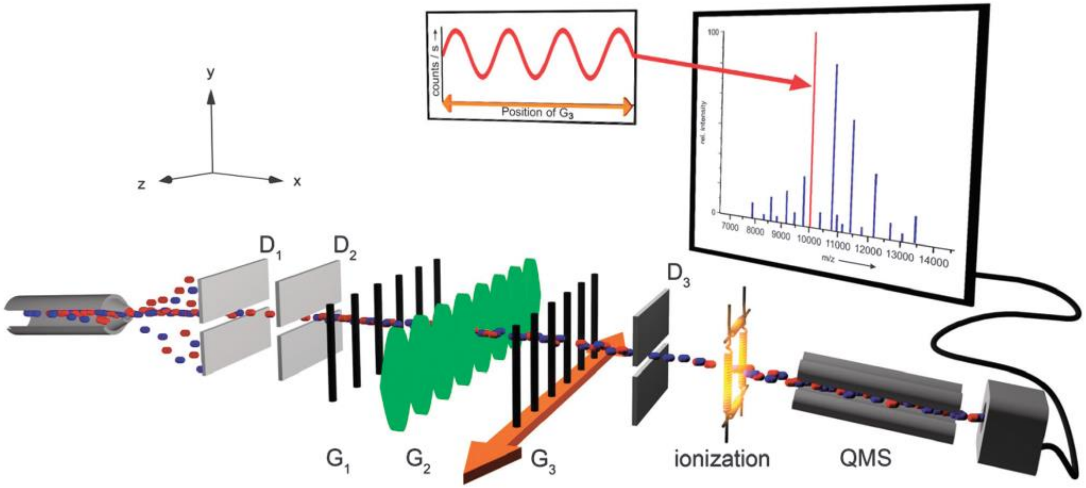


What is the most macroscopic object that can be in a spatial superposition?

Most macroscopic object to date in a spatial superposition





S Gerlich *et al*, Nature Comms **2**, 263 (2011)

T Juffmann *et al*, Nature Nano **7**, 297 (2012)

P Haslinger *et al*, Nature Physics **9**, 144 (2013)

S Eibenberger *et al*, PCCP **15**, 14696 (2013)

Markus Arndt's group

UK groups seeking macroscopic superpositions

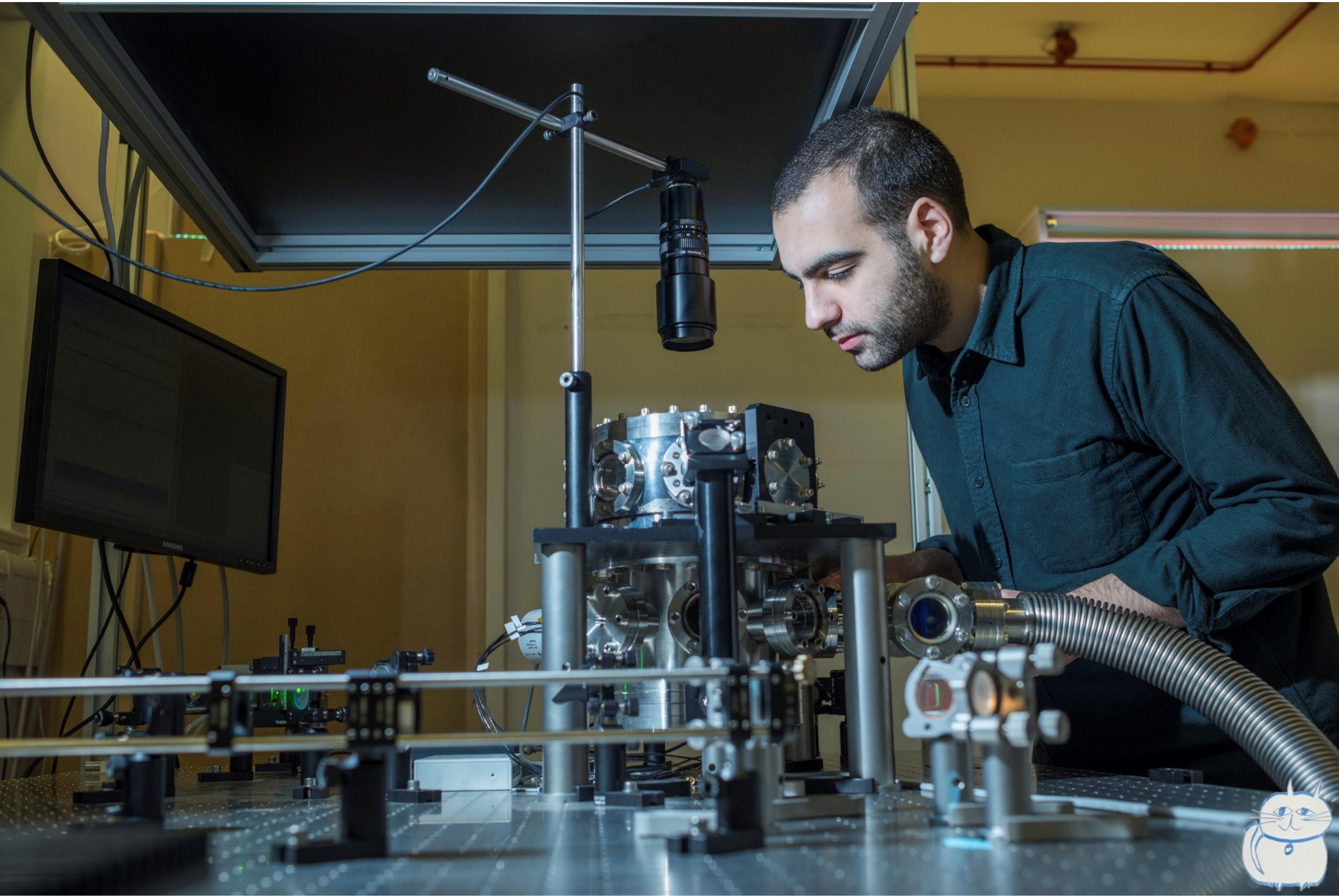
Experimental:

Peter Barker (UCL)
Michael Vanner (Imperial)
Andrew Steane (Oxford)
Gavin Morley (Warwick)
Hendrik Ulbricht (Southampton)
Edward Laird (Lancaster)
James Bateman (Swansea)
James Millen (King's College)

Theory:

Sougato Bose (UCL)
Animesh Datta (Warwick)
Myungshik Kim (Imperial)
Mauro Paternostro (QUB)
Tania Monteiro (UCL)

Our experiment: optically levitated nanodiamond



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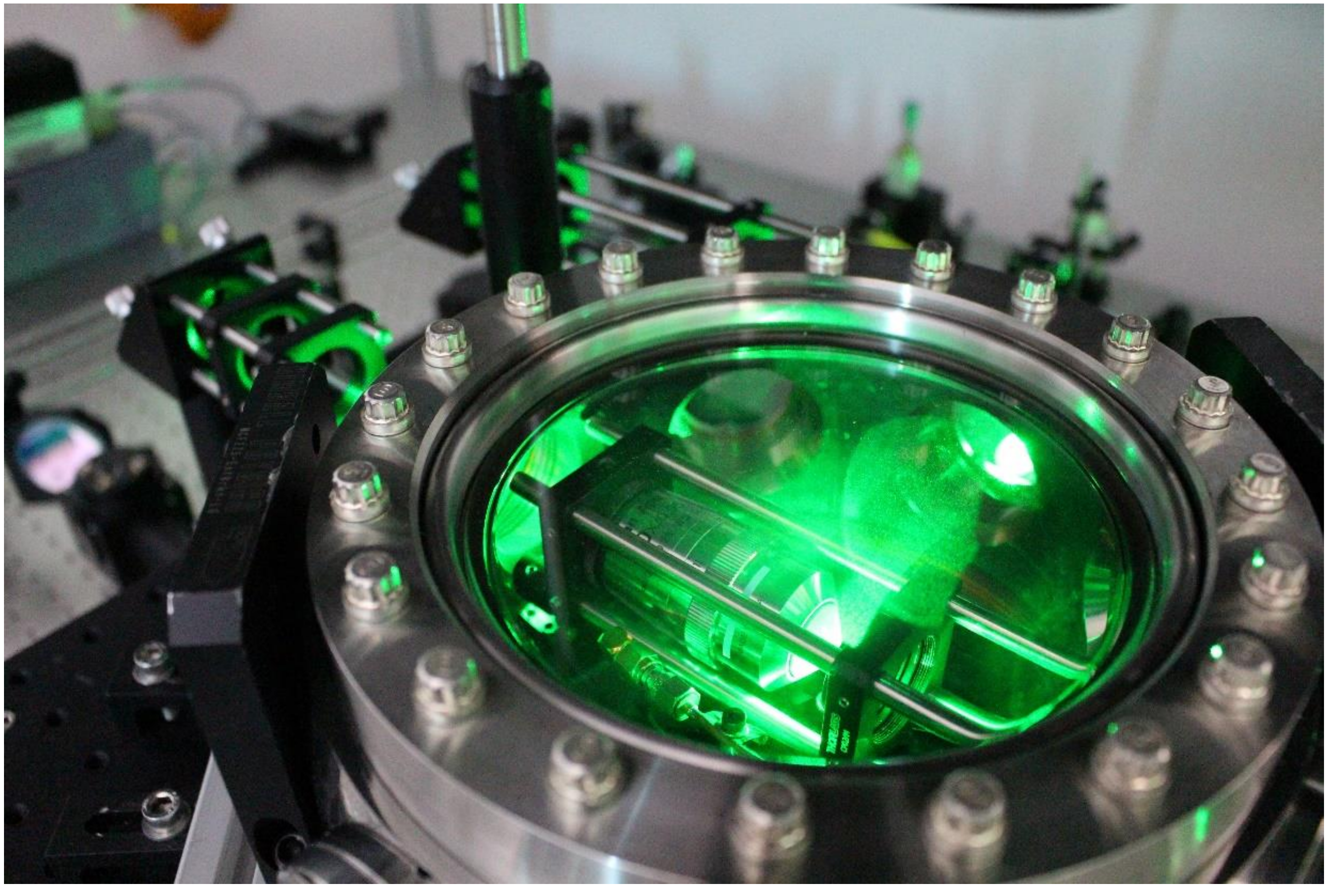
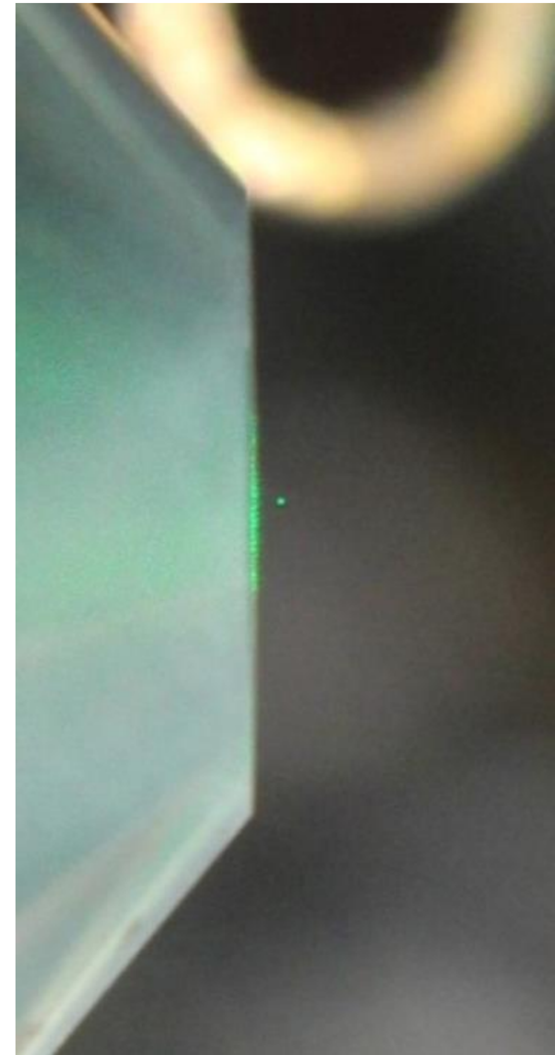
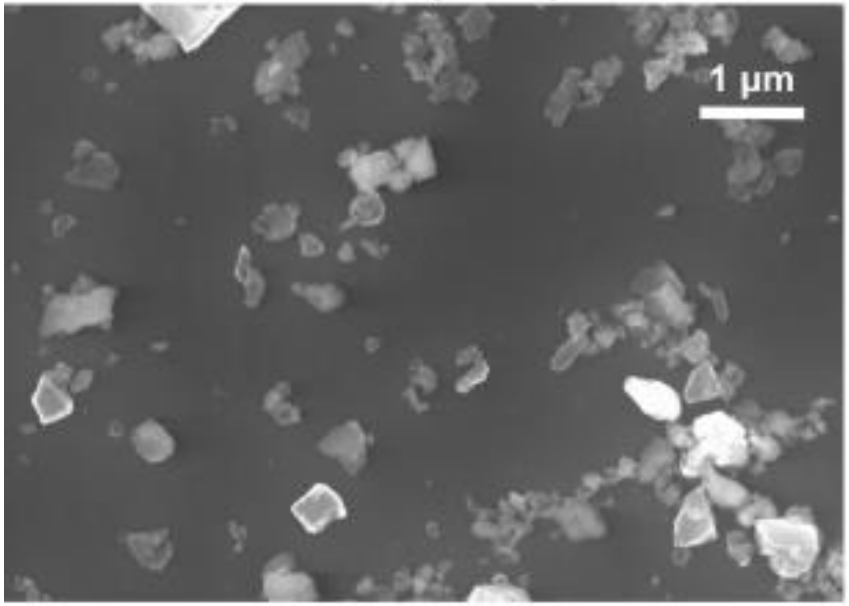
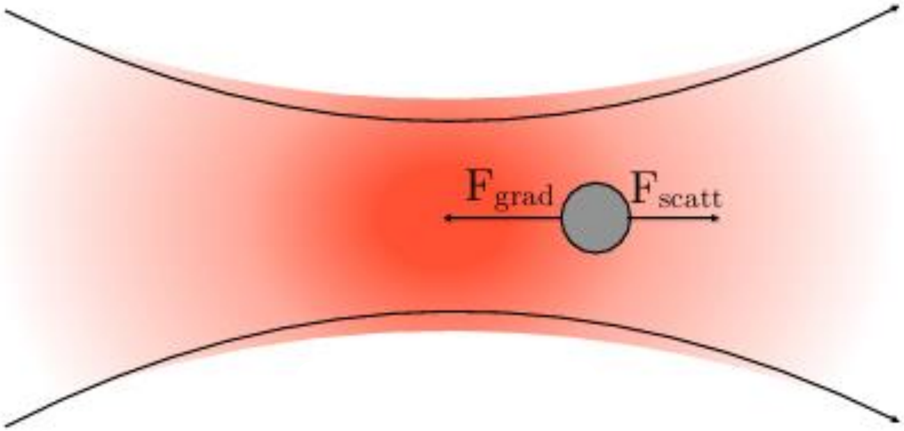




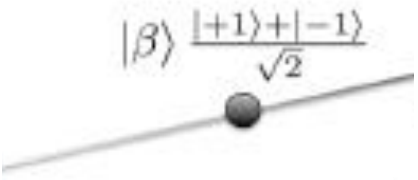
Single beam optical trap



Laser → Objective Lens →



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)
- RJ Marshman… S Bose, arXiv:1807.10830 (2018)
- S Bose & GW Morley, arXiv:1810.07045 (2018)

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

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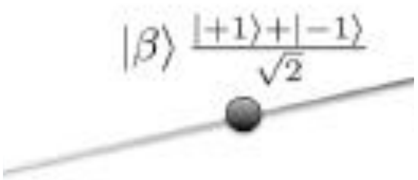

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- RJ Marshman... S Bose, arXiv:1807.10830 (2018)
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$$H = \frac{\hat{p}^2}{2m}$$

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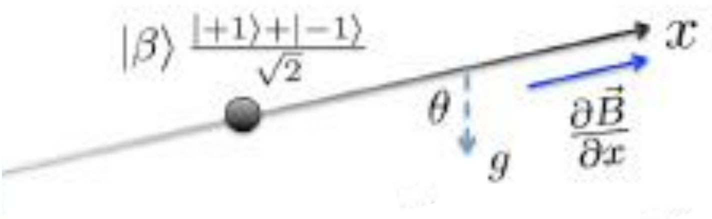

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$$H = \frac{\hat{p}^2}{2m} - g_{\mathrm{NV}}\mu_B \frac{\partial B}{\partial x}\hat{S}_z\,\hat{x} + mg\cos\theta\hat{x}.$$

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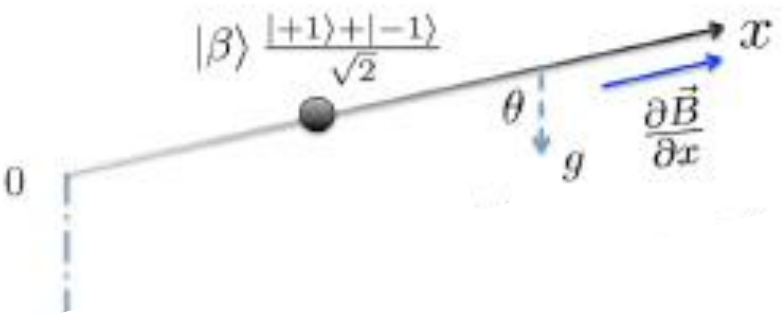

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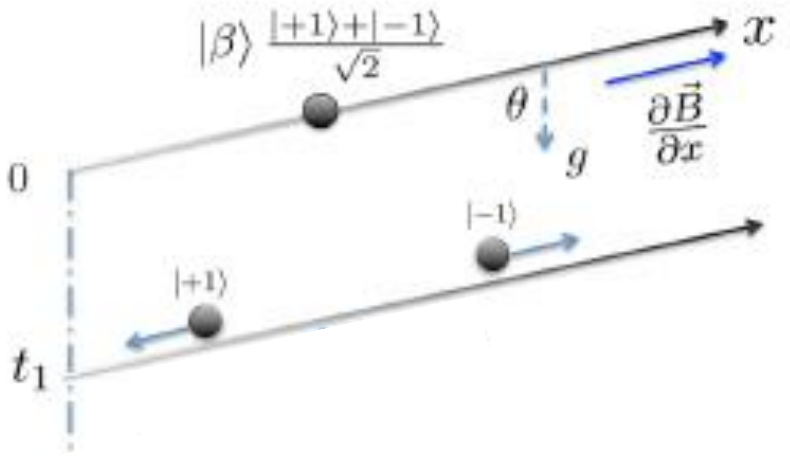

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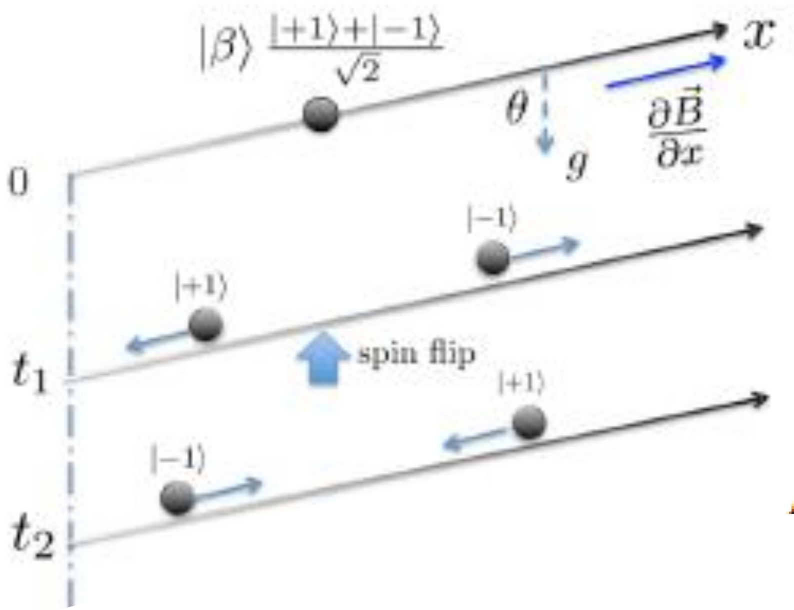

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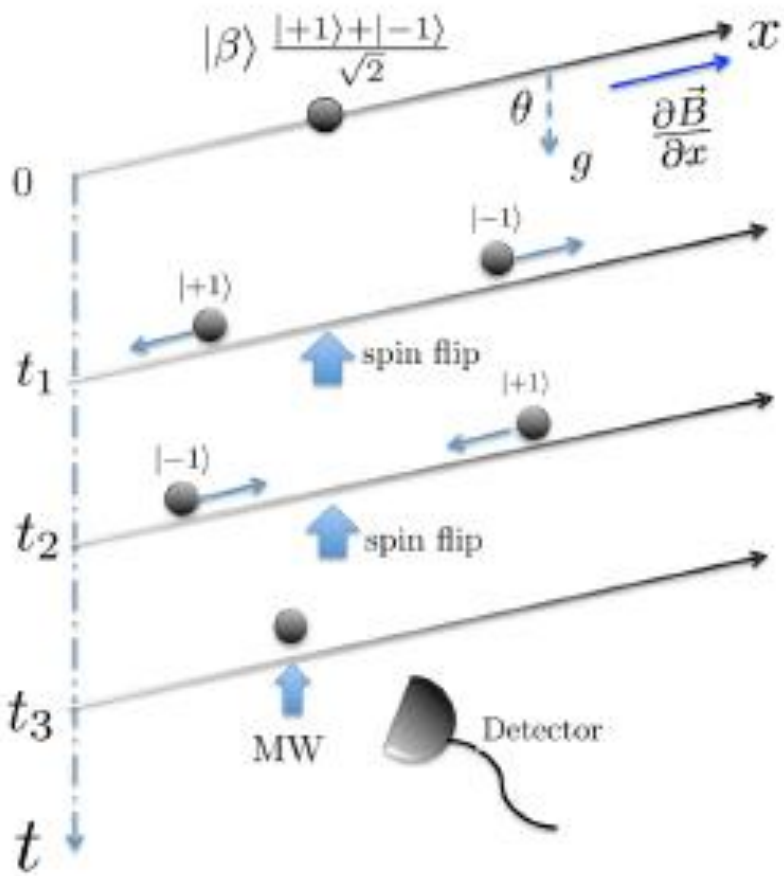

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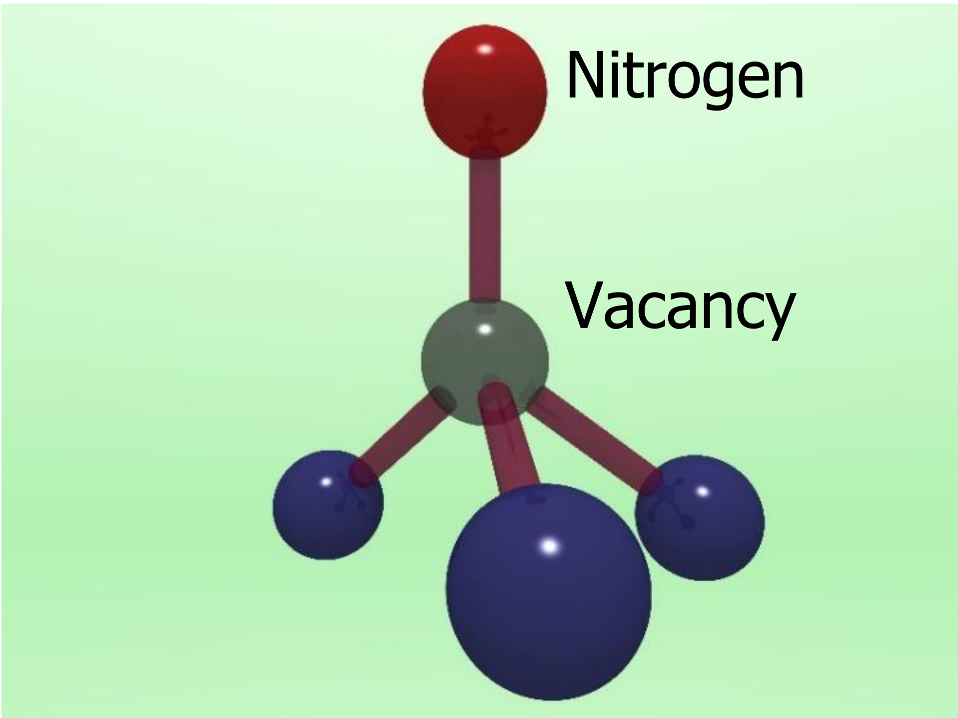
- S Bose... & G Milburn, PRL **119**, 240401 (2017)
- RJ Marshman... S Bose, arXiv:1807.10830 (2018)
- S Bose & GW Morley, arXiv:1810.07045 (2018)

$$H = \frac{\hat{p}^2}{2m} - g_{\rm NV}\mu_B \frac{\partial B}{\partial x}\hat{S}_z\,\hat{x} + mg\cos\theta\hat{x}.$$

$$\frac{1}{\sqrt{2}}(|+1\rangle + e^{-i\phi_g}|-1\rangle)$$

$$\phi_g = (1/16\hbar)gt_3^3 g_{\rm NV}\mu_B(\partial B/\partial x)\cos\theta.$$

Optically-levitated nanodiamond

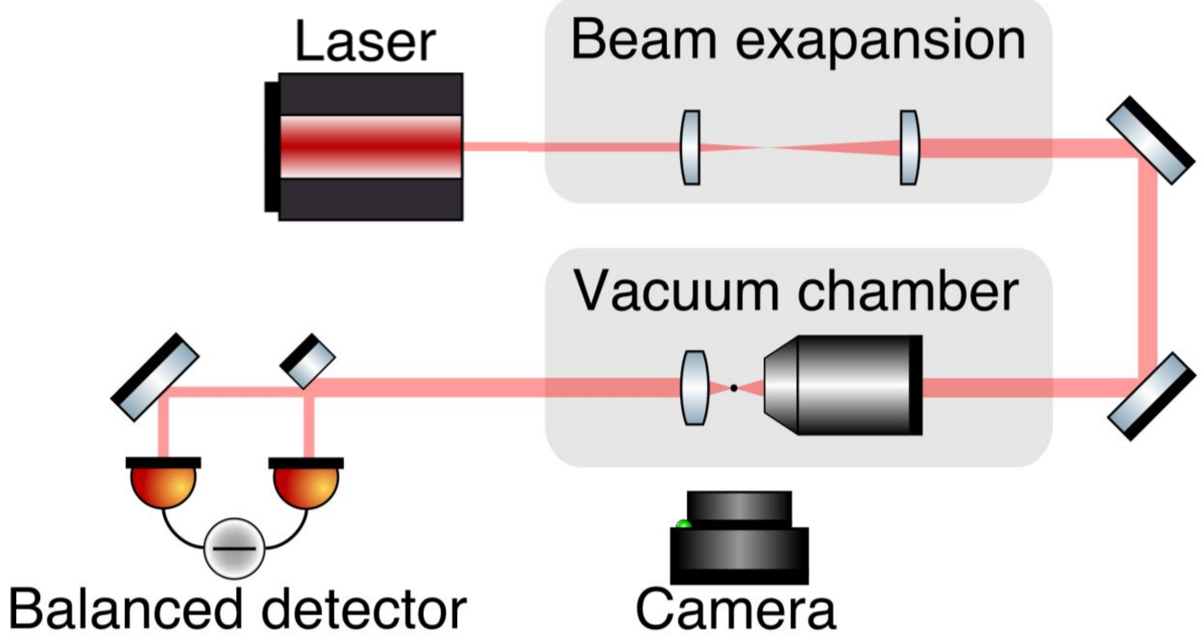


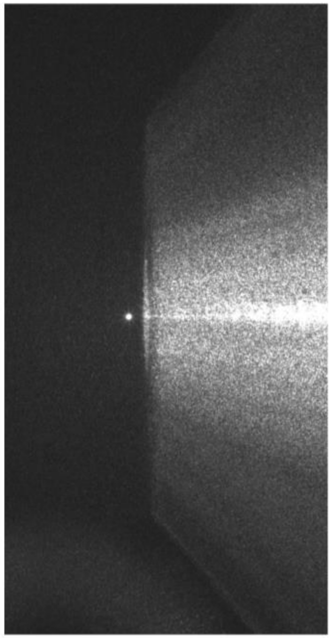
Our results:

- Commercial nanodiamonds overheat

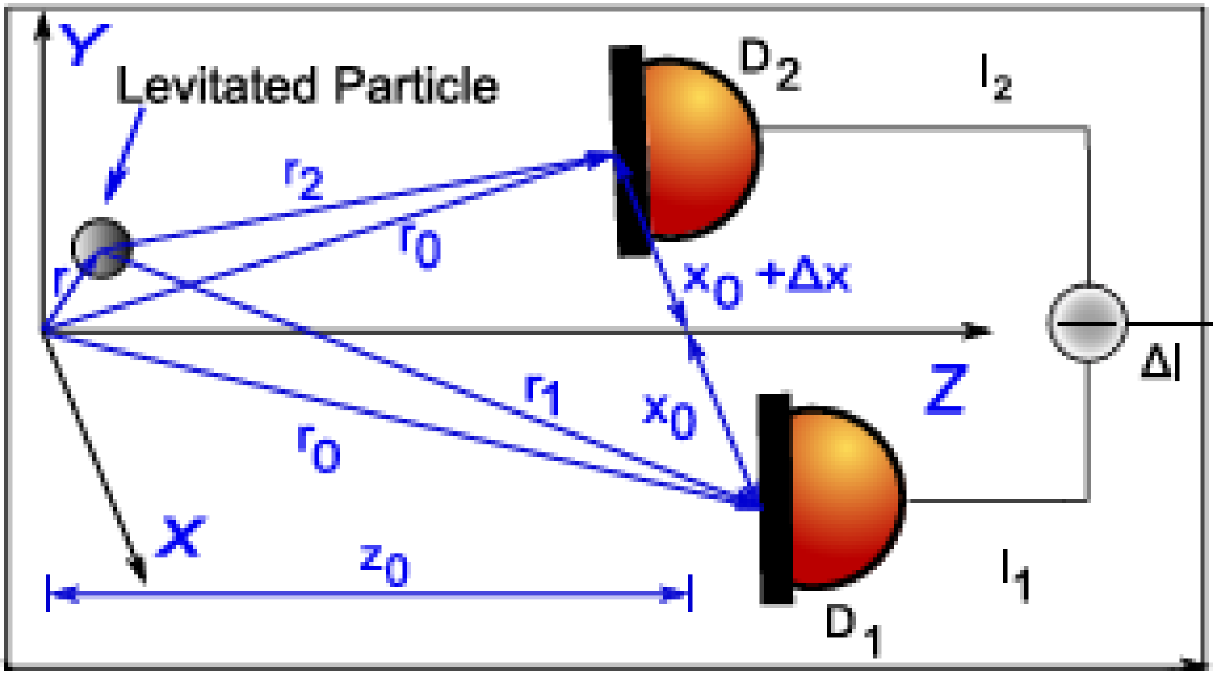
- Our pure nanodiamonds don’t

Our levitating nanodiamonds





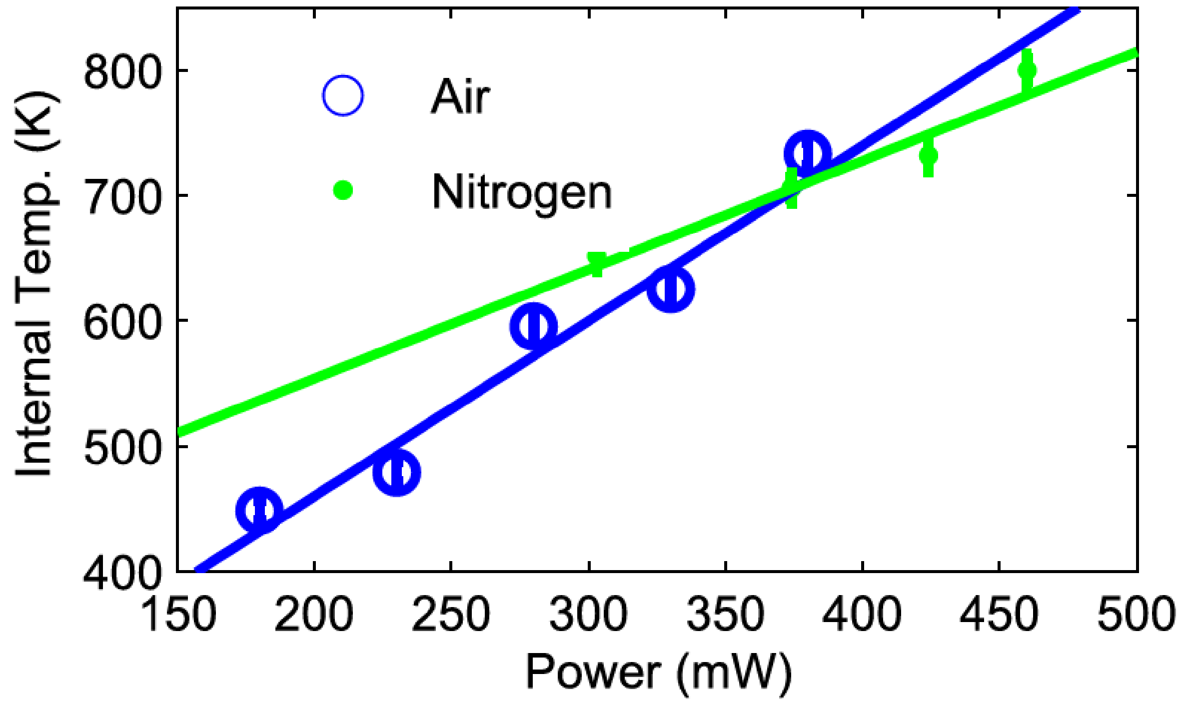
Interferometric balanced detection



ATM Anishur Rahman, AC Frangeskou, PF Barker & GW Morley,
Review of Scientific Instruments **89**, 023109 (2018)

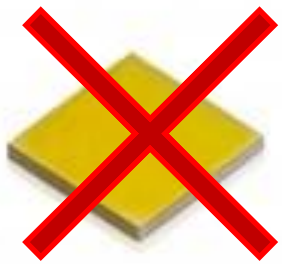
Levitating nanodiamonds overheating

20 mbar



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

A solution: more pure diamonds

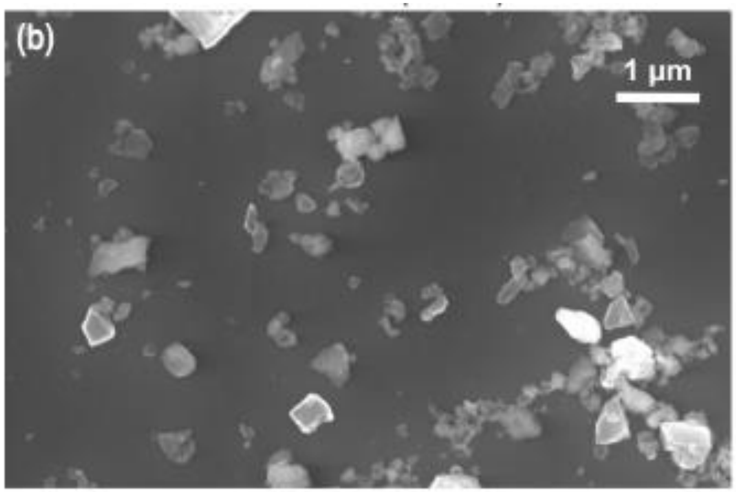


150 ppm nitrogen impurities

120 ppb nitrogen impurities

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

A solution: more pure diamonds



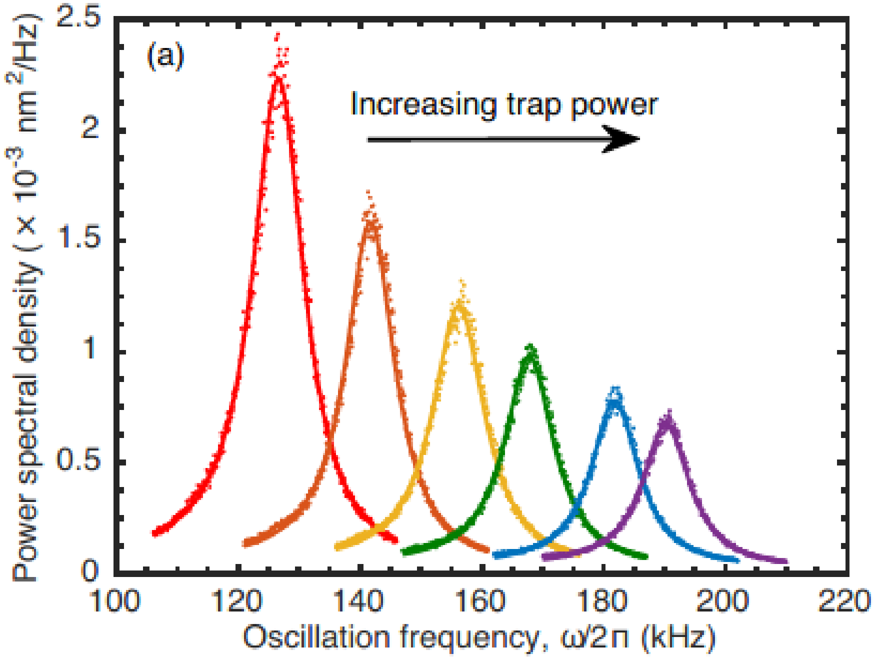
120 ppb nitrogen impurities

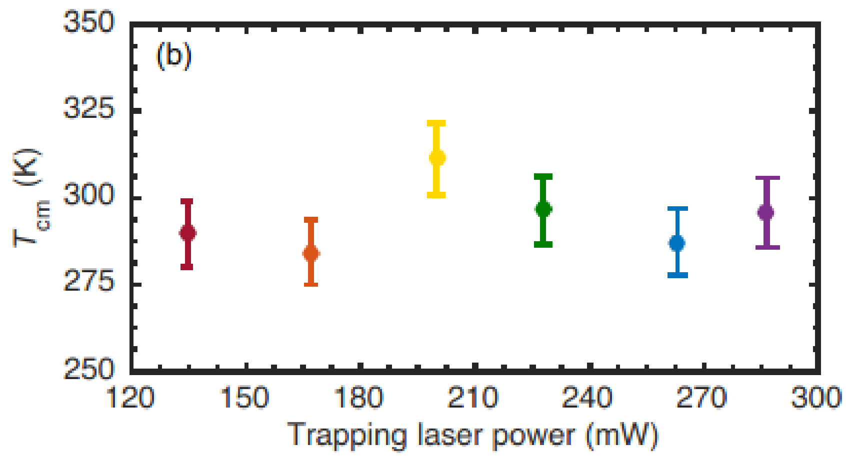
Milling by Ollie Williams' group, Cardiff

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

A solution: more pure nanodiamonds

4 mbar

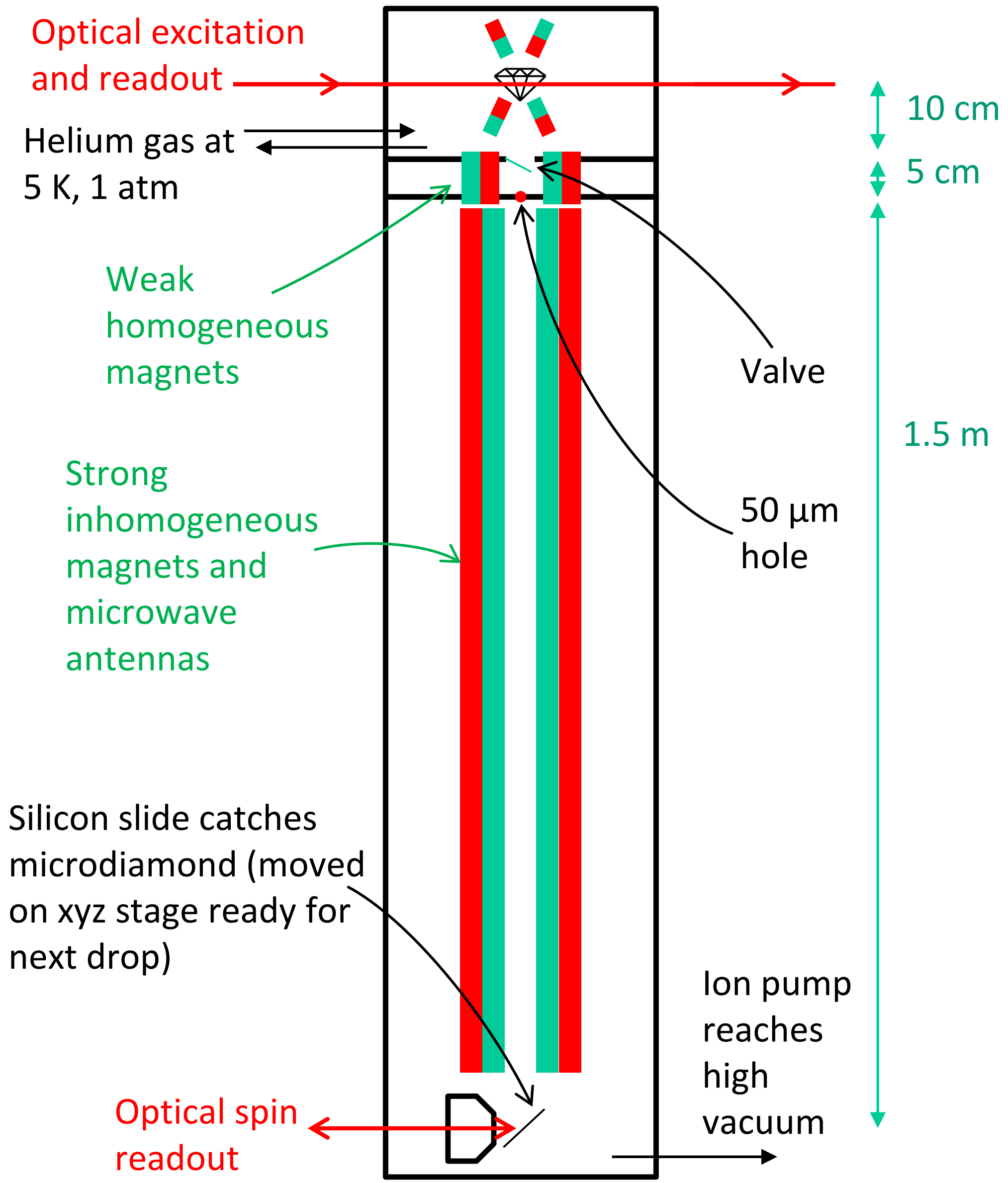




$$S_x(\omega) = \frac{2k_B T_{cm}}{m} \frac{\Gamma_0}{(\omega^2 - \omega_0^2)^2 + \omega^2 \Gamma_0^2}.$$

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

Matter and spin superposition in vacuum experiment (MASSIVE)

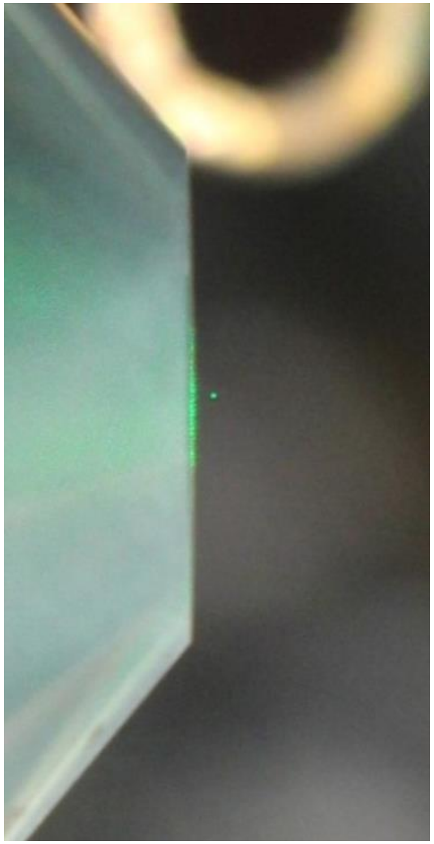


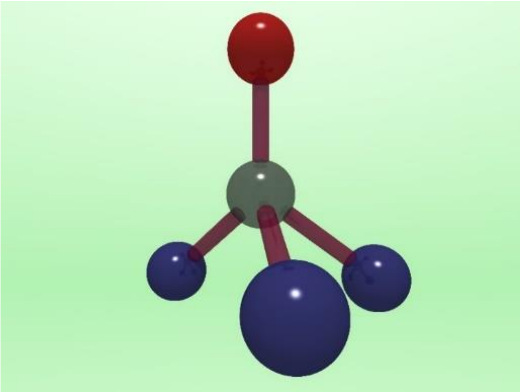
5 K
1 μm diamond (10^{-15} kg, 10^{12} amu)
1 μm superposition
10^4 T/m
0.4 s drop
10^{-15} mbar
Single-shot readout

Sougato Bose and Gavin W Morley, arXiv:1810.07045 October 2018

Conclusion

We propose a new experiment to search for a 1 µm spatial superposition of a 1 µm diamond

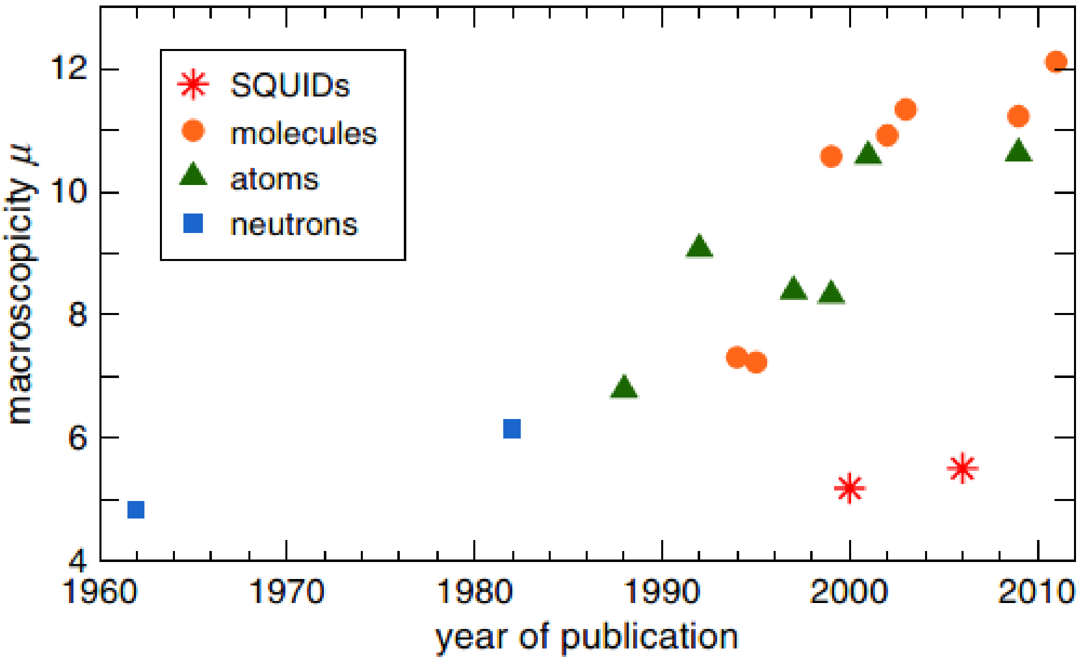




$\mu \sim 28$

Macroscopicity

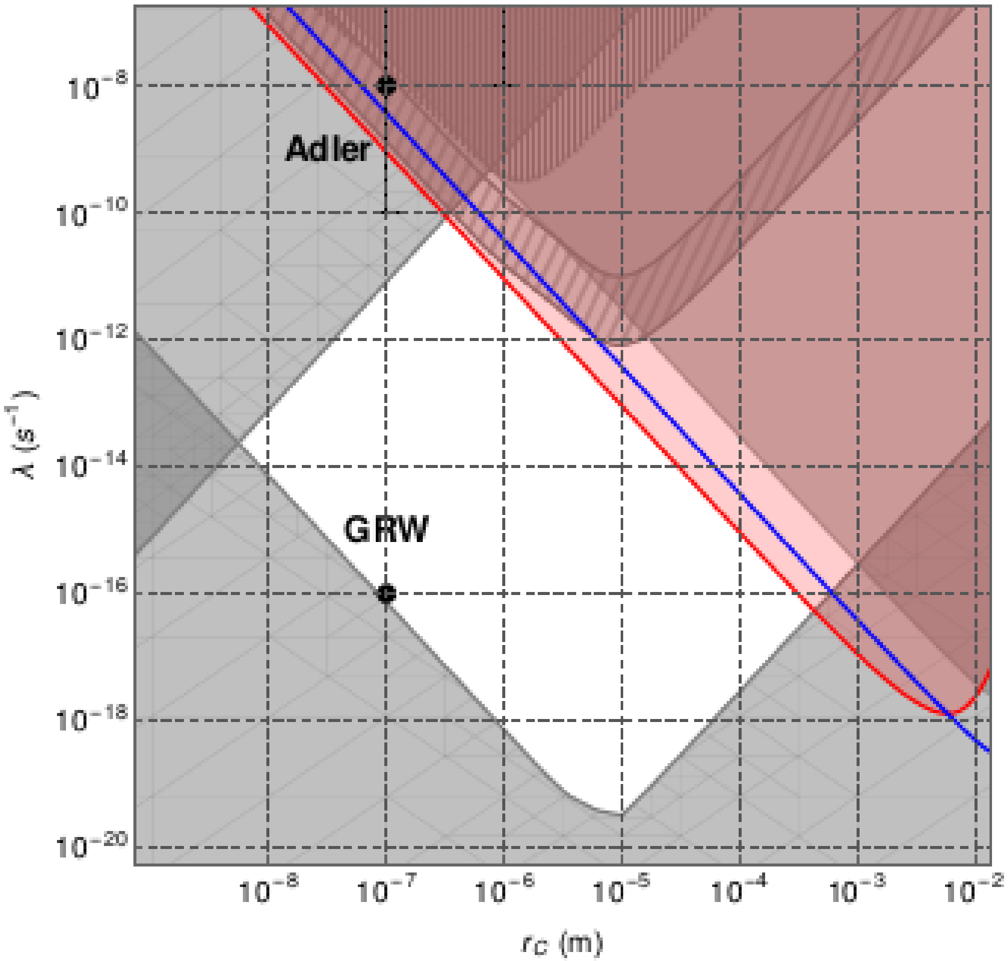
$$\mu \approx \log_{10}\left[\left(\frac{M}{m_e}\right)^2 \frac{t}{1\ \mathrm{s}}\right]$$



Eibenberger et al, PCCP, **15**, 14696 (2013)

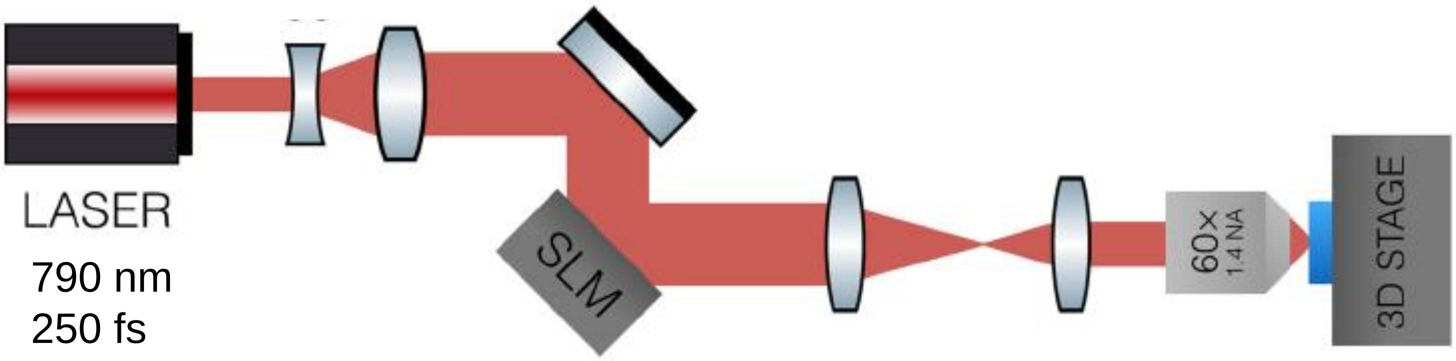
Stefan Nimmrichter and Klaus Hornberger, PRL **110**, 160403 (2013)

Exclusion plot: continuous simultaneous localization

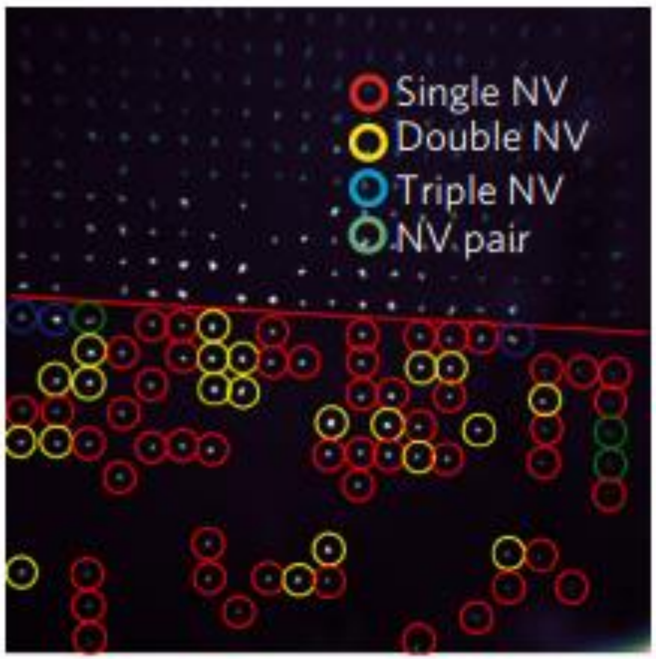


Matteo Carlesso, Mauro Paternostro, Hendrik Ulbricht, Andrea Vinante and Angelo Bassi, arXiv:1708.04812 (2018)

3D Arrays of good NV^- - Laser writing

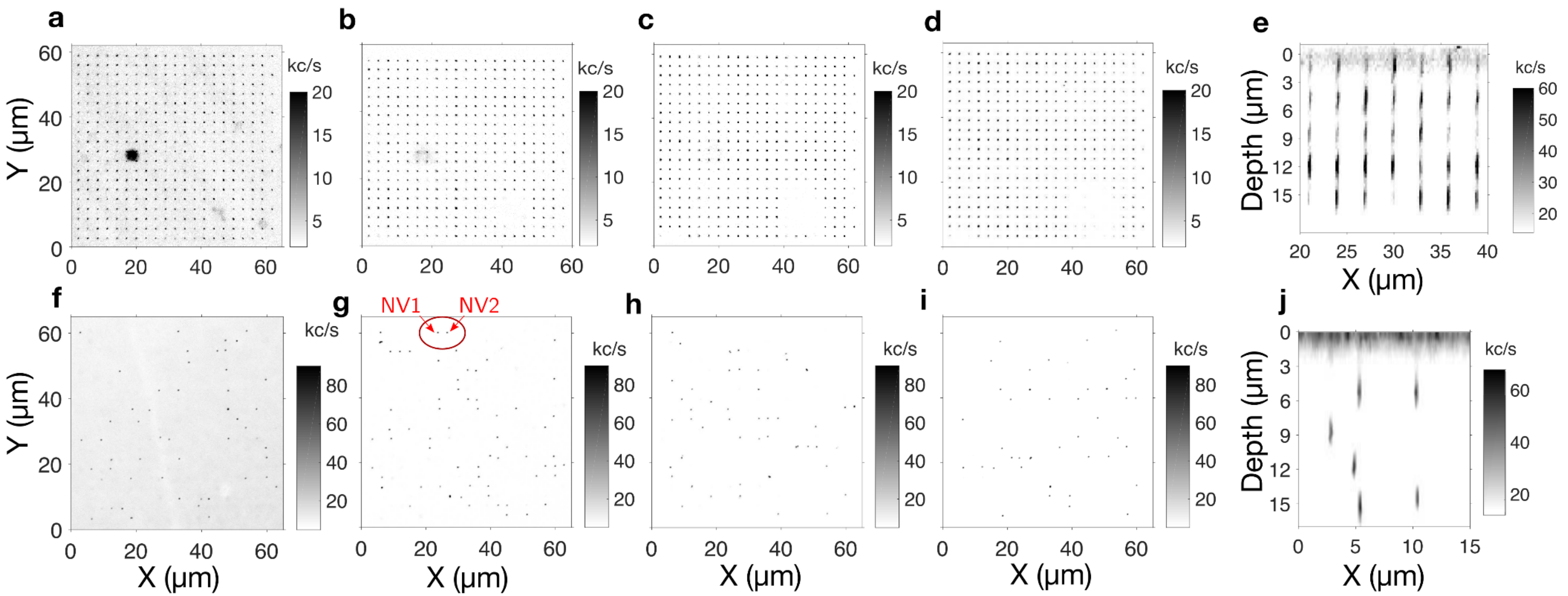


Our previous NV^- laser-writing



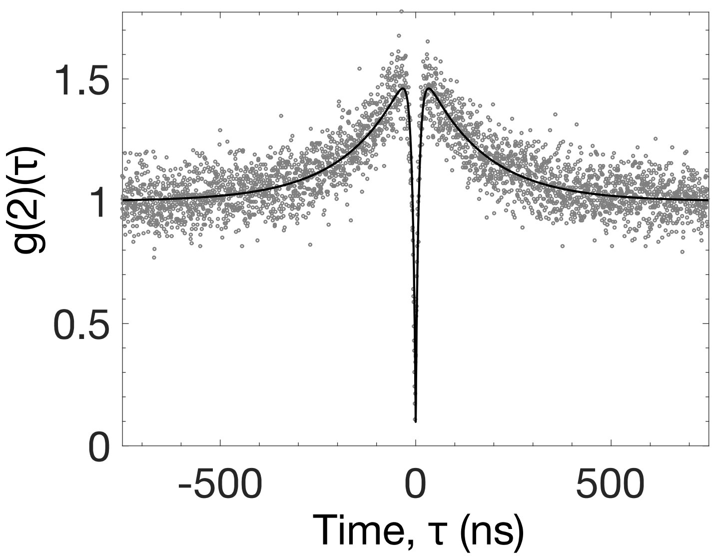
Chen, Salter, Knauer, Weng, Frangeskou, Stephen, Ishmael, Dolan, Johnson, Green, Morley, Newton, Rarity, Booth & Smith, Nat Photon 11, 77 (2017)

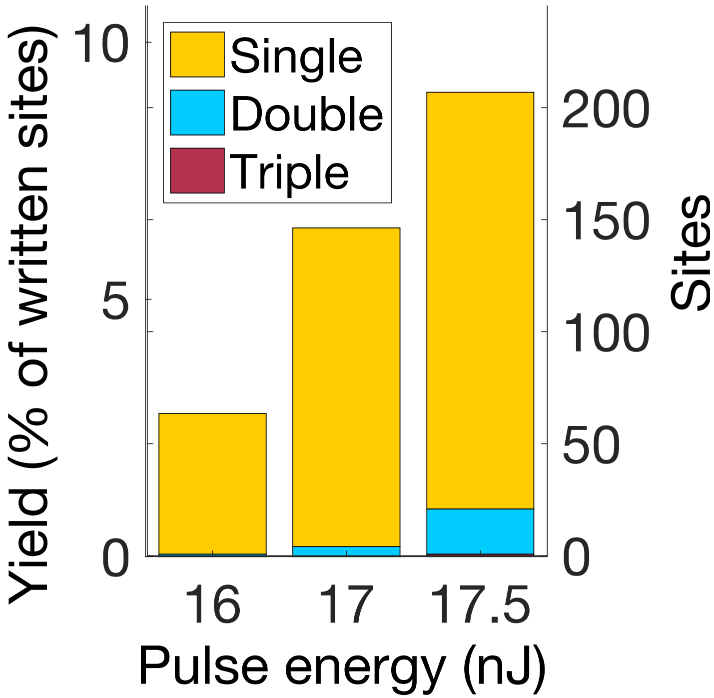
Laser-writing deep nitrogen vacancy centres in diamond



Y-C Chen *et al.*, Nature Photonics 11, 77 (2017)
CJ Stephen *et al.*, arXiv:1807.03643 (2018)
Y-C Chen *et al.*, arXiv:1807.04028 (2018)

Our new 3D NV$^-$ laser-writing: single centres





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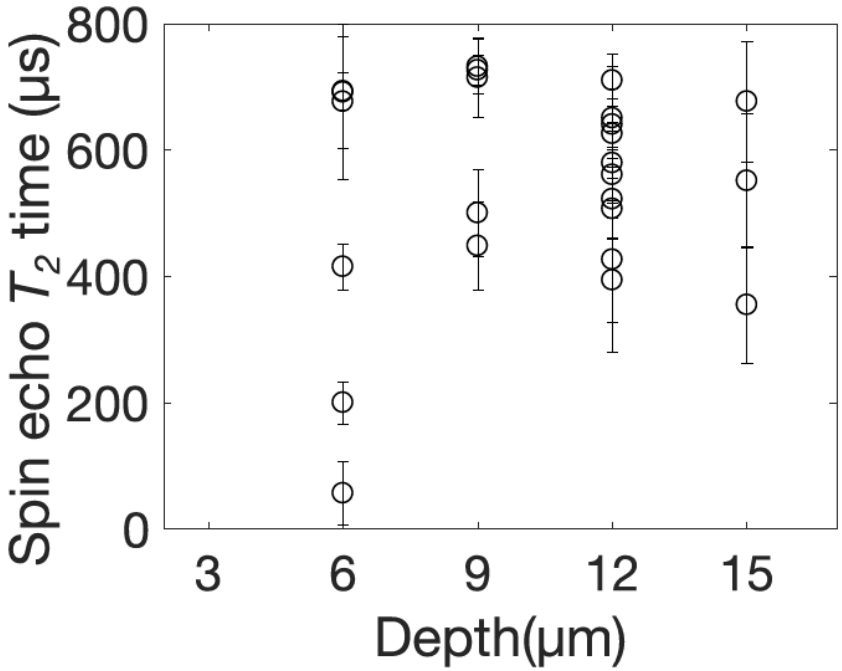

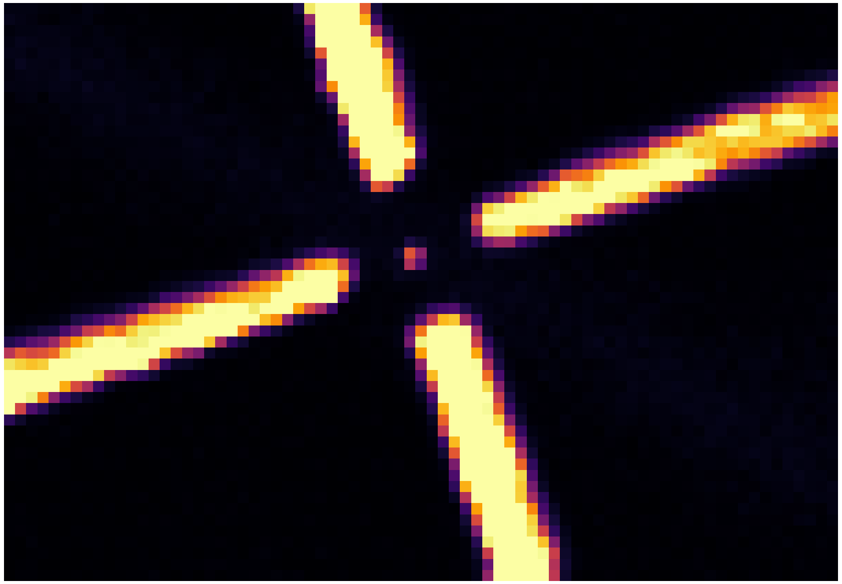

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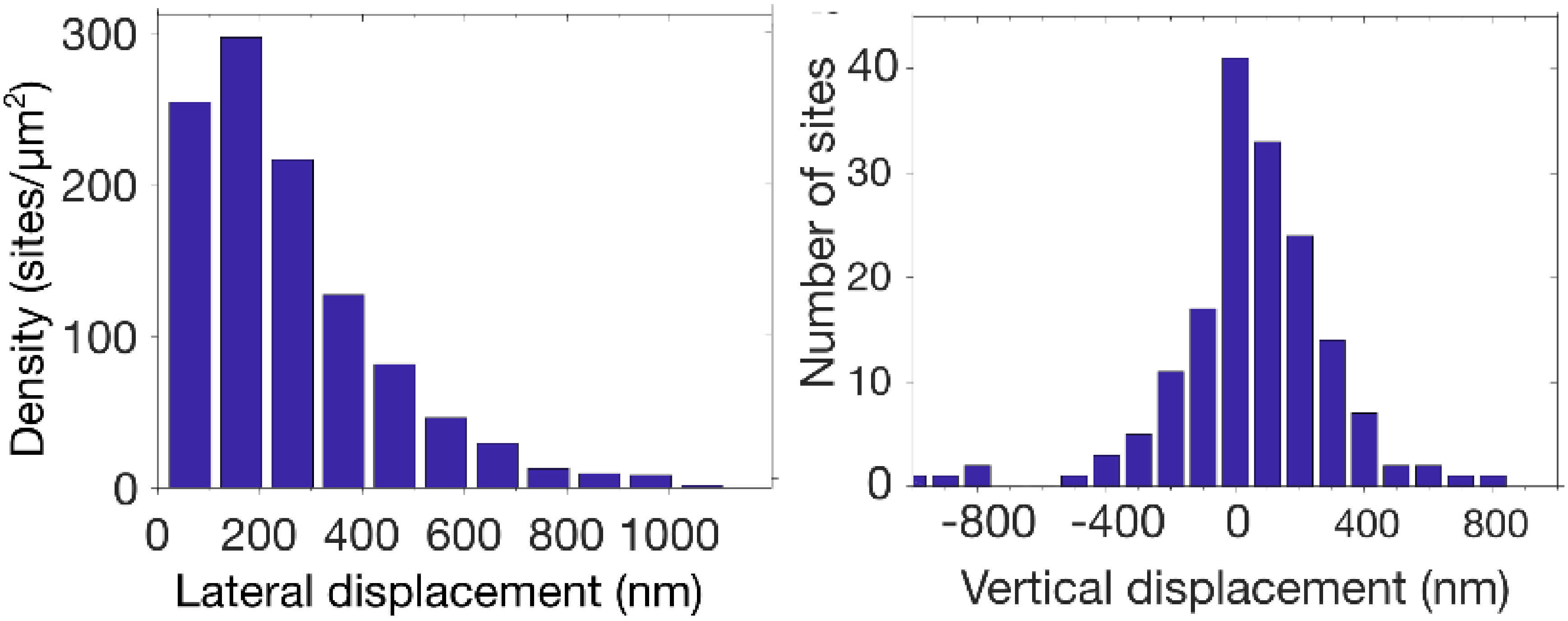
Our new 3D NV$^-$ laser-writing: precision



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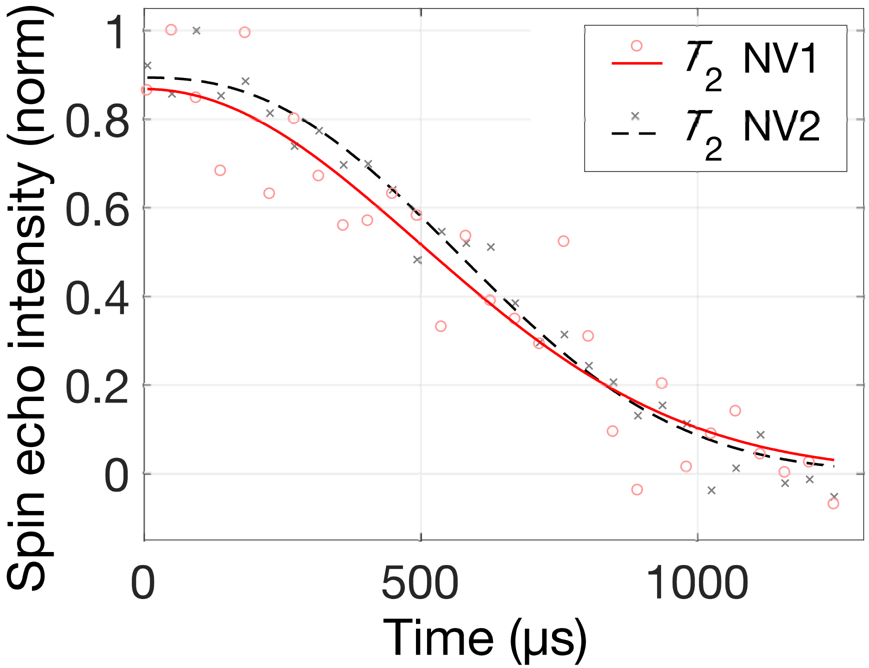
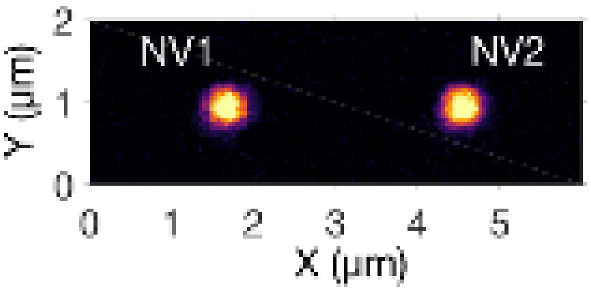
Our new 3D NV$^-$ laser-writing: T_2 times





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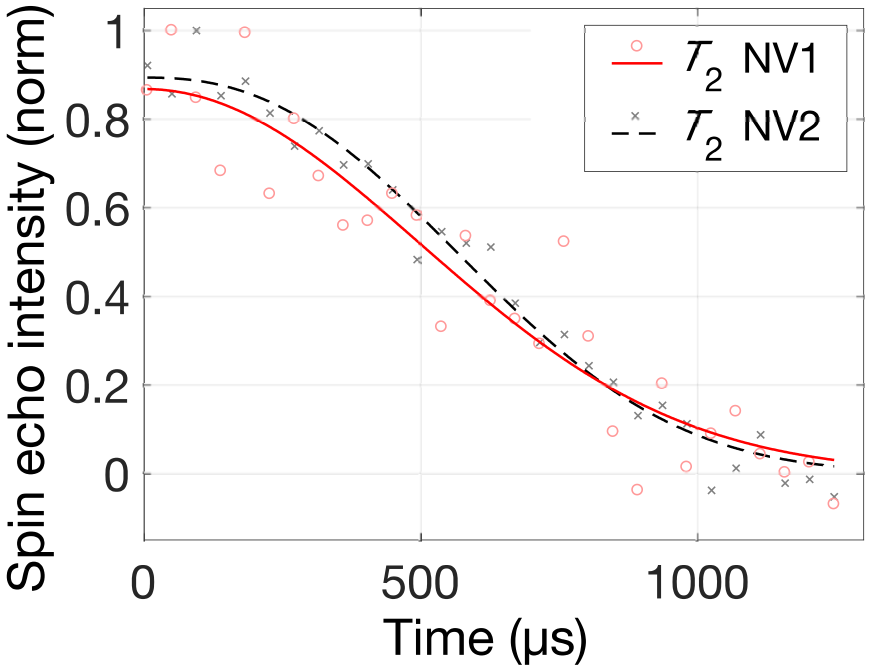

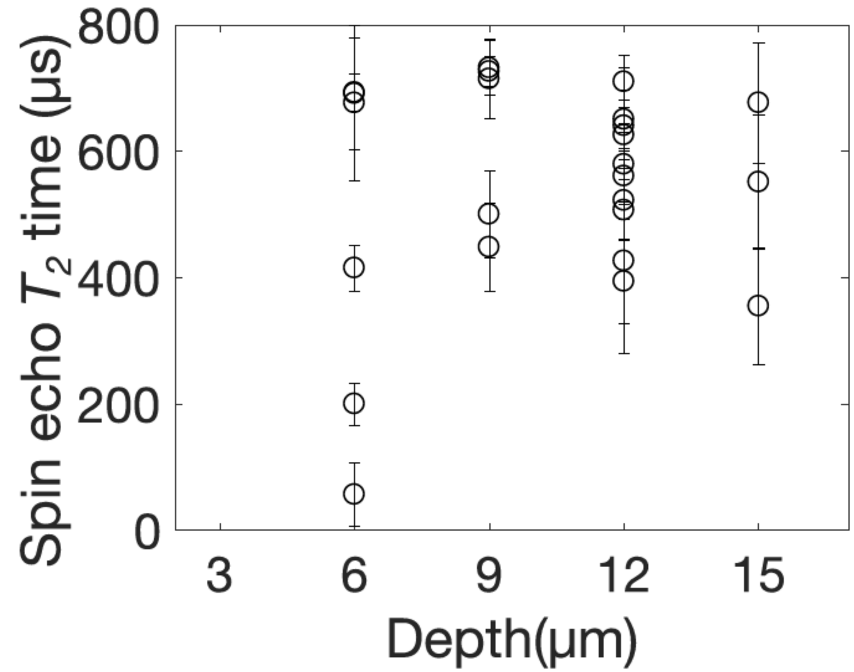

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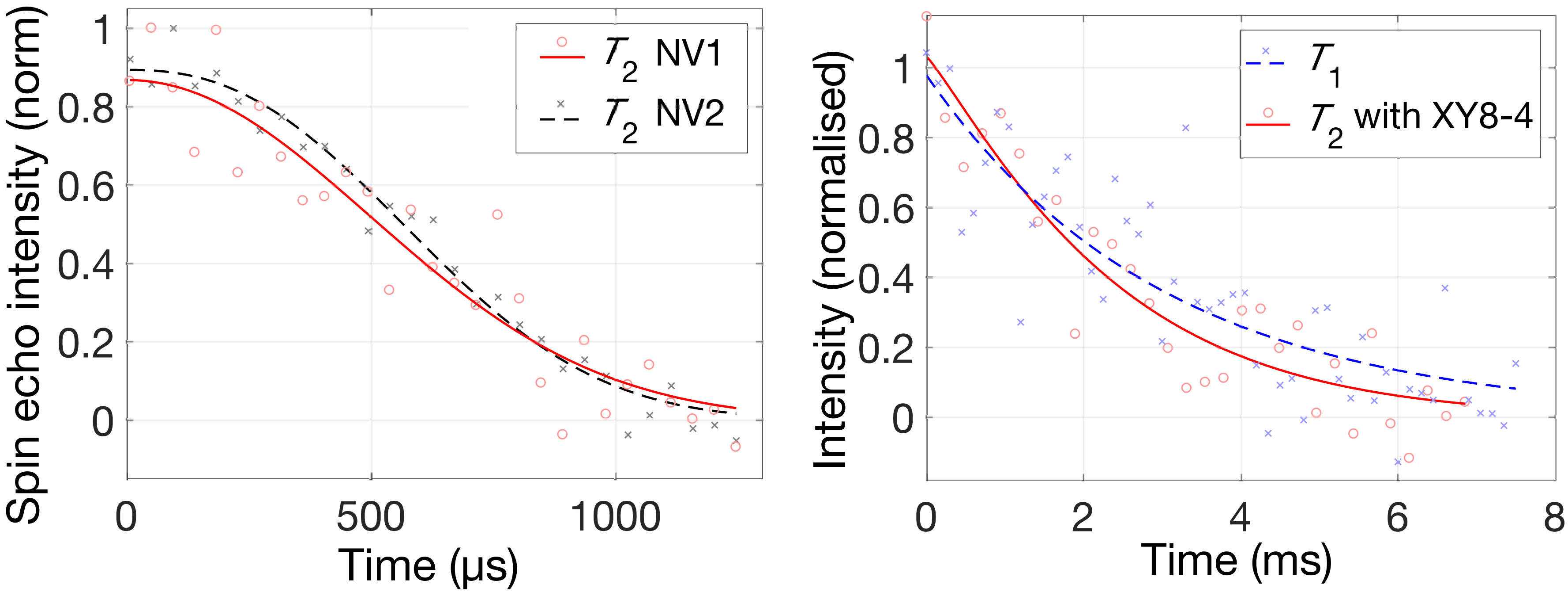
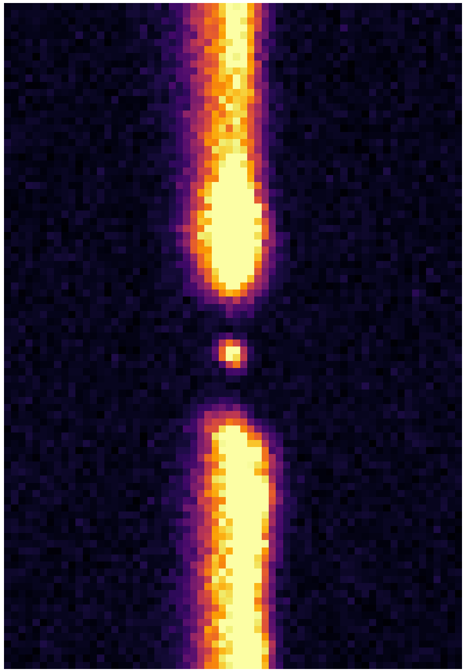
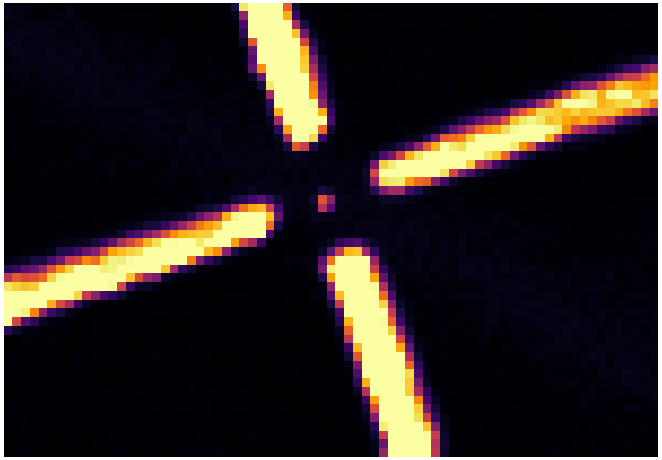
Our new 3D NV$^-$ laser-writing: T_2 times

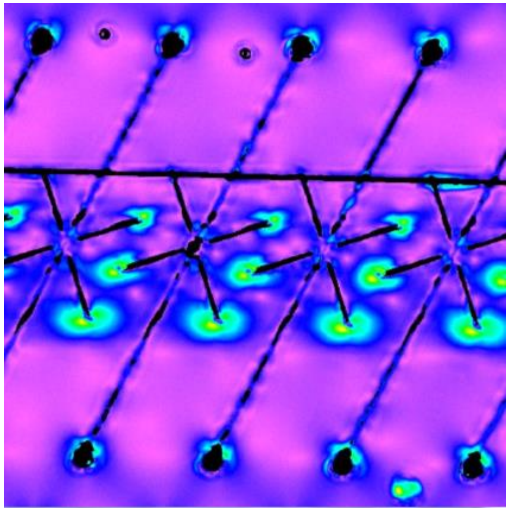


C.J. Stephen, B.L. Green, Y.N.D. Lekhai, L. Weng, P. Hill, S. Johnson, A.C. Frangeskou, P.L. Diggle, M.J. Strain, E. Gu, M.E. Newton, J.M. Smith, P.S. Salter & G.W. Morley, arXiv 1807.03643 (2018)

Our new 3D NV^- laser-writing: with wires







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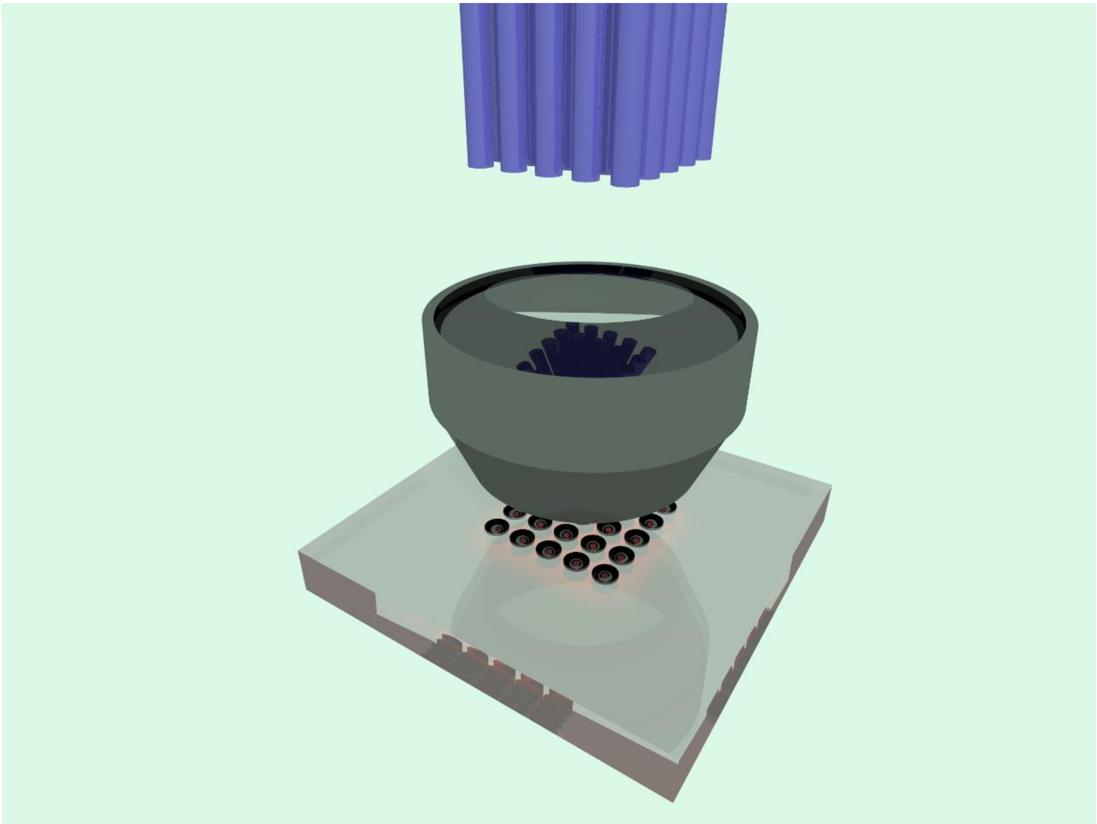
Our new 3D NV^- laser-writing: future plans



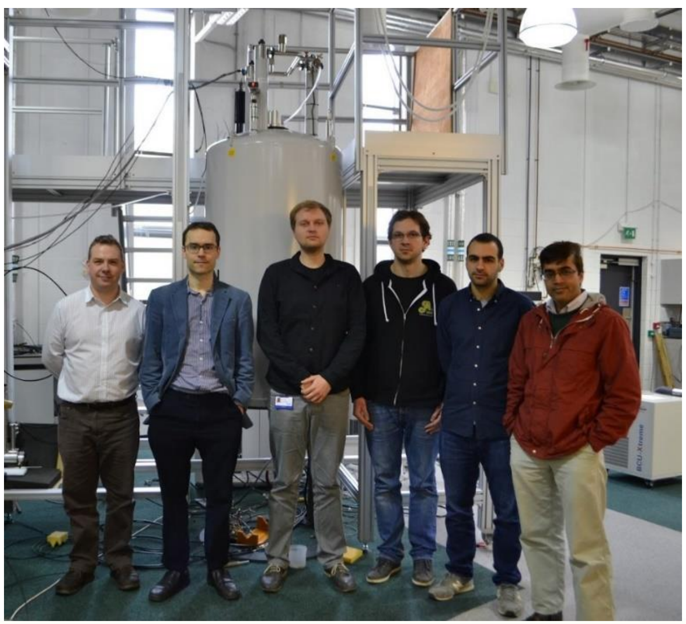
C.J. Stephen, B.L. Green, Y.N.D. Lekhai, L. Weng, P. Hill, S. Johnson, A.C. Frangeskou, P.L. Diggle, M.J. Strain, E. Gu, M.E. Newton, J.M. Smith, P.S. Salter & G.W. Morley, arXiv 1807.03643 (2018)

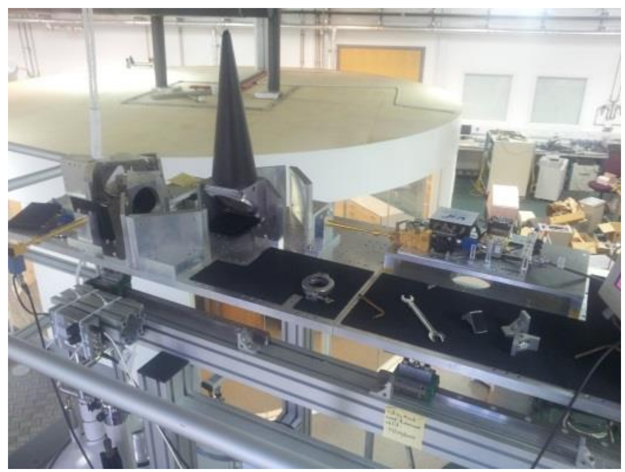
Our nitrogen-vacancy (NV^-) experiments - Ensemble magnetometry

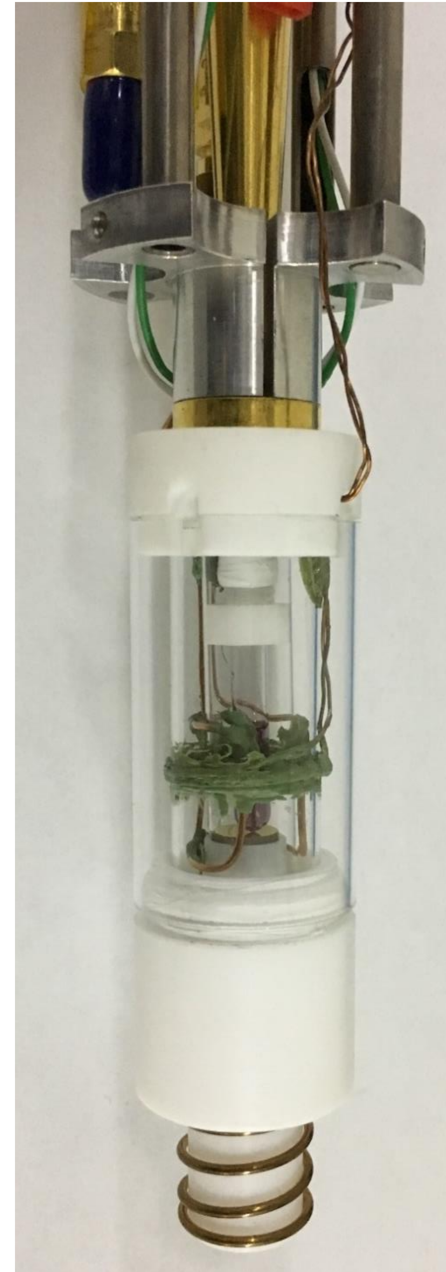
MW Dale & GW Morley, Medical applications of diamond magnetometry: commercial viability, arXiv:1705.01994 (2017)

Collaboration with Mark Newton's group

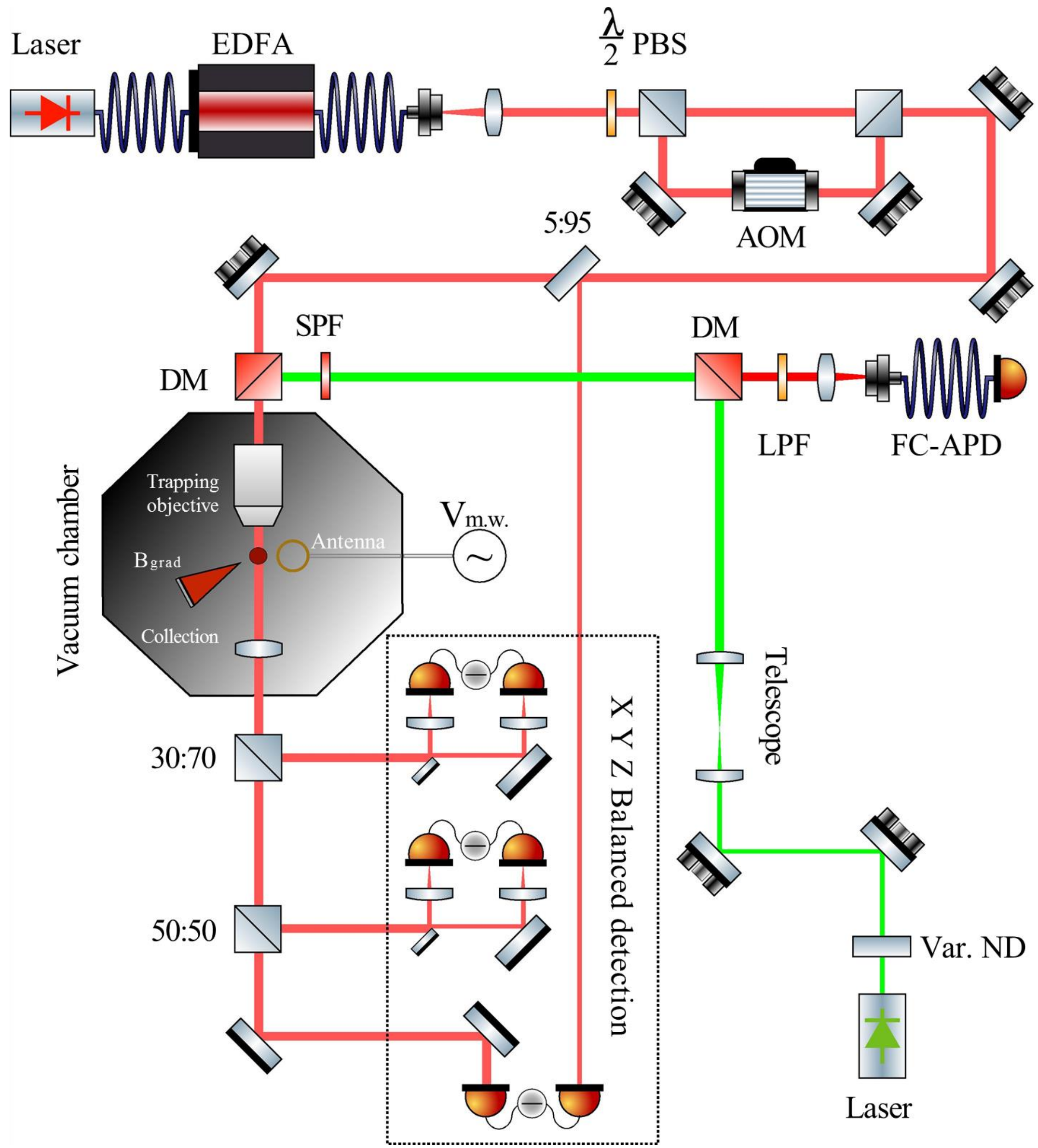
400 GHz EPR and 600 MHz NMR at 14.1 T







Optical setup



Quantum gravity

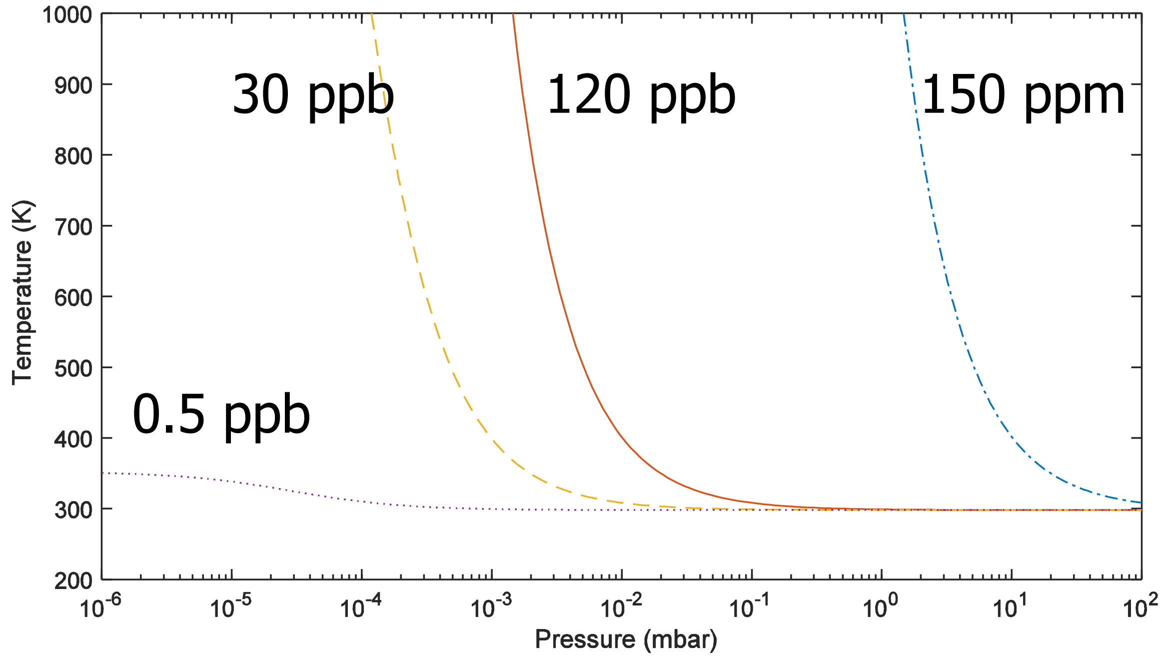
- Albrecht, A., Retzker, A. & Plenio, M. B. Testing quantum gravity by nanodiamond interferometry with nitrogen-vacancy centers. *Physical Review A* **90**, 033834 (2014).

- Mohammad, B., André, G., Sandro, D. & Angelo, B. The Schrödinger–Newton equation and its foundations. *New J. Phys.* **16**, 115007 (2014).

Simulations of more pure nanodiamonds

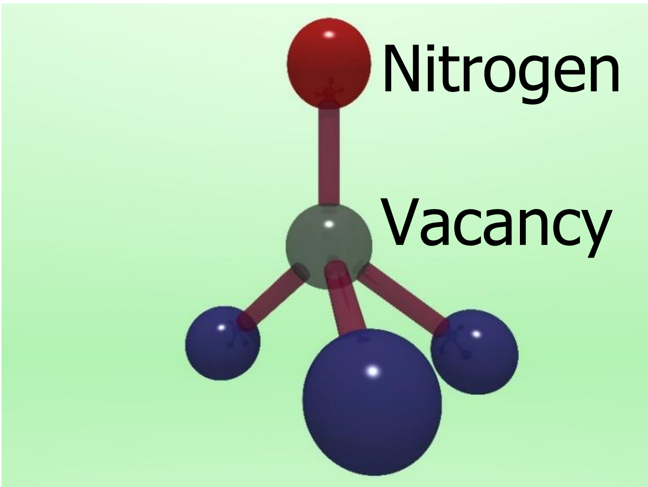
60 GW/m^2,
Radius = 25 nm

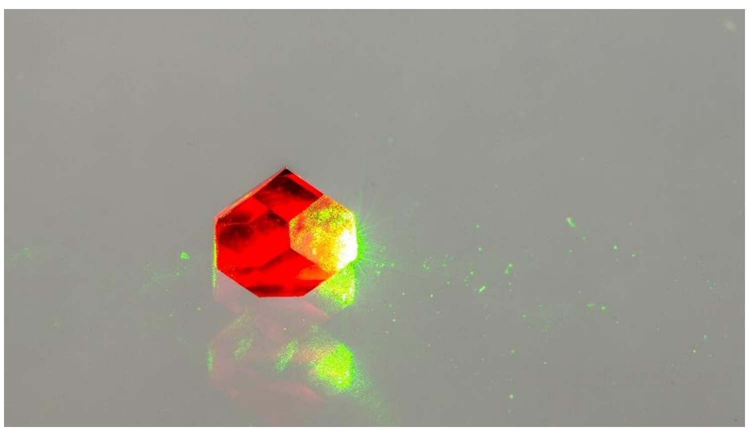
$$C_V V(T-T_0) = \underbrace{3IkV\left(\mathrm{Im}\frac{\epsilon-1}{\epsilon+2}\right)}_{\text{Absorption}} \underbrace{- 6\alpha_g \pi r^2 \bar{v} N_0 \frac{p}{p_0} k_B (T-T_0)}_{\text{Gas}} \underbrace{- \frac{72\zeta(5)V}{\pi^2 c^3 \hbar^4}\left(\mathrm{Im}\frac{\epsilon_{bb}-1}{\epsilon_{bb}+2}\right) k_B^5 T^5}_{\text{Black-body}},$$

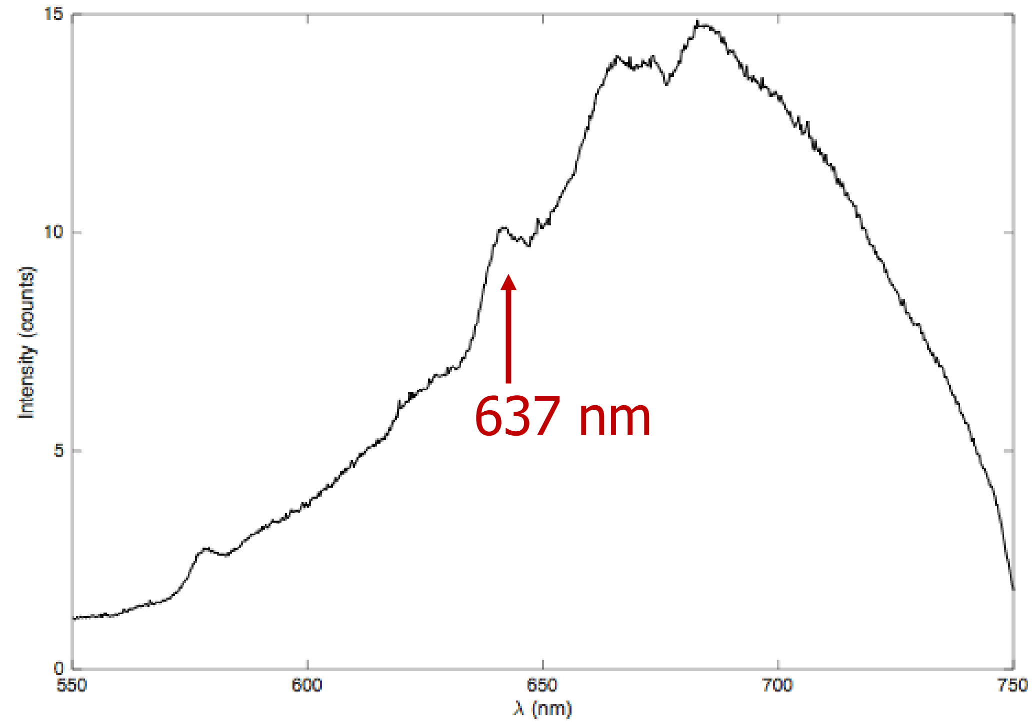


AC Frangeskou *et al.*, arXiv:1608.04724 (2016)

Nitrogen vacancy (NV^-) centres in diamond

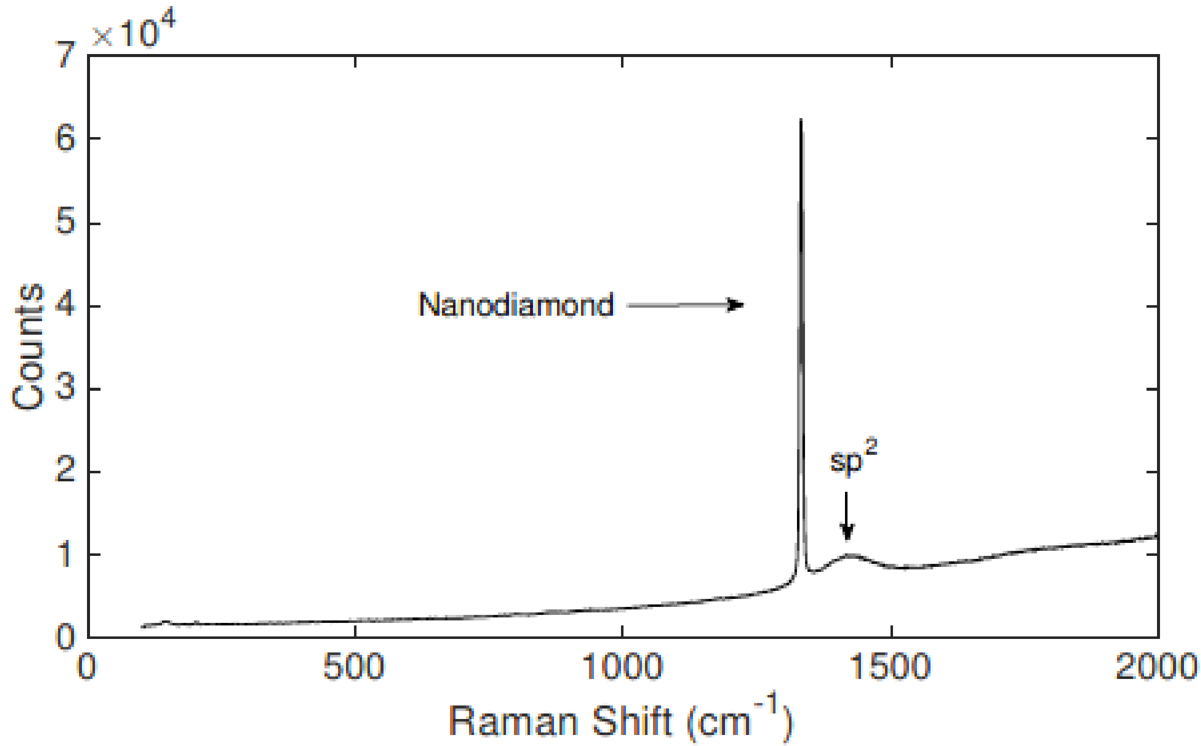






Review: MW Doherty et al, Phys Rep 528, 1 (2013)

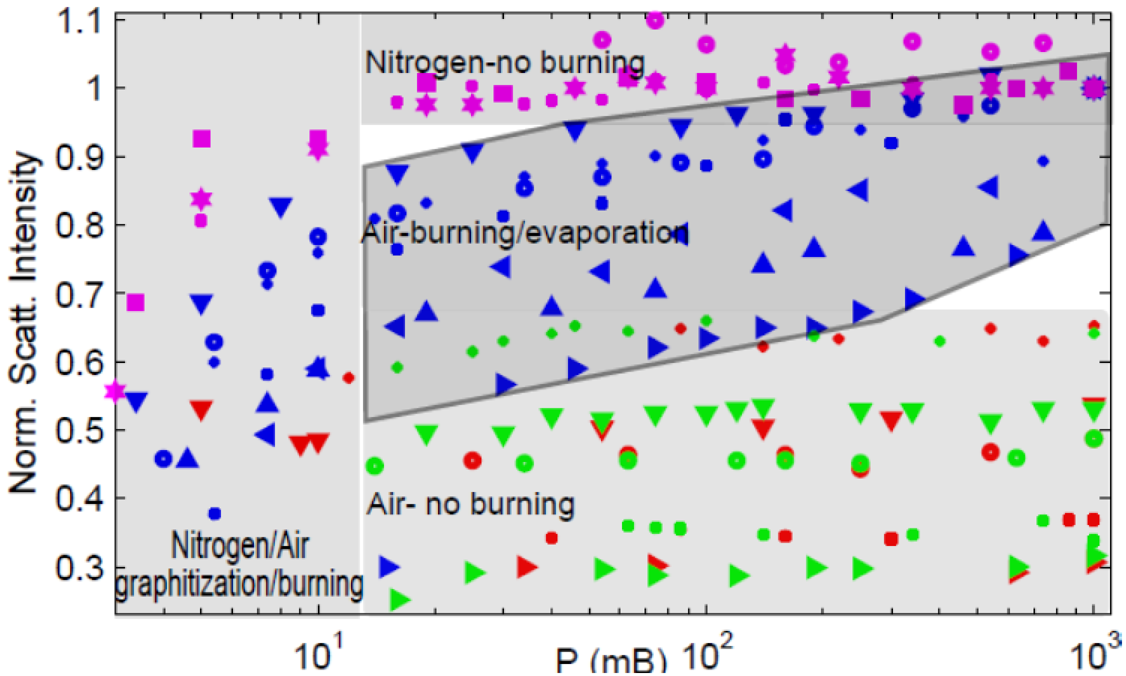
Raman measurements



AC Frangeskou *et al.*, arXiv:1608.04724 (2016)

Levitating nanodiamonds can graphitize

300 mW
trap
power



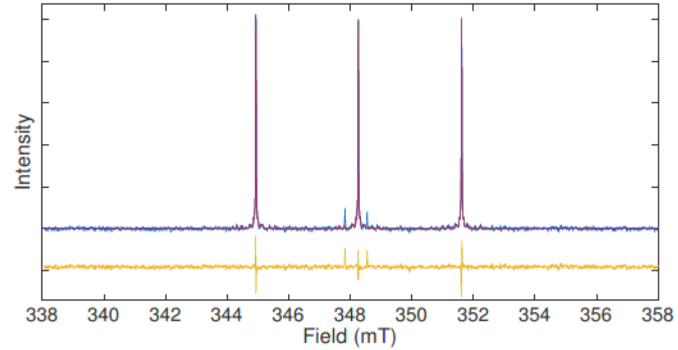
ATMA Rahman *et al.*, Scientific Reports **6**, 21633 (2016)

A solution: more pure diamonds

150 ppm nitrogen impurities

120 ppb nitrogen impurities

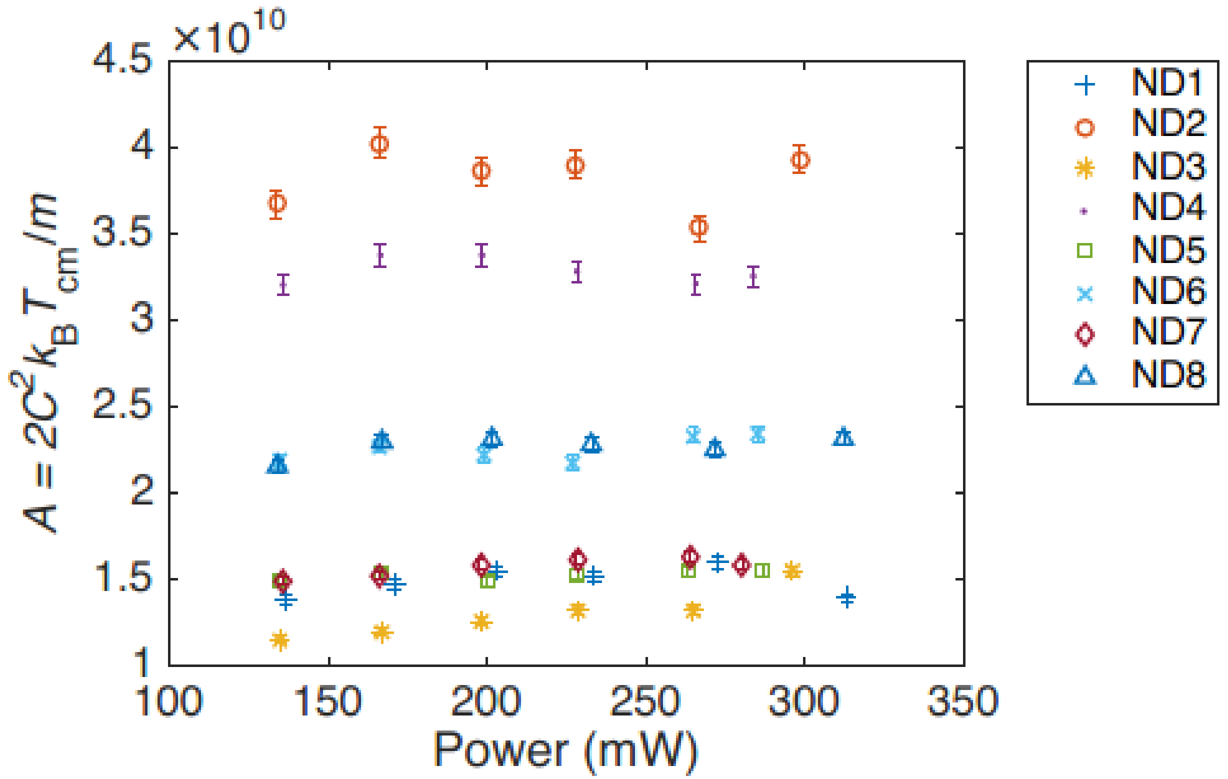
Electron paramagnetic resonance:



AC Frangeskou *et al.*, arXiv:1608.04724 (2016)

A solution: more pure nanodiamonds

4 mbar



AC Frangeskou *et al.*, arXiv:1608.04724 (2016)