Title: Levitating microdiamonds towards testing the macroscopic limits of the quantum superposition principle

Speakers: Gavin Morley

Collection: Indefinite Causal Structure

Date: December 10, 2019 - 9:50 AM

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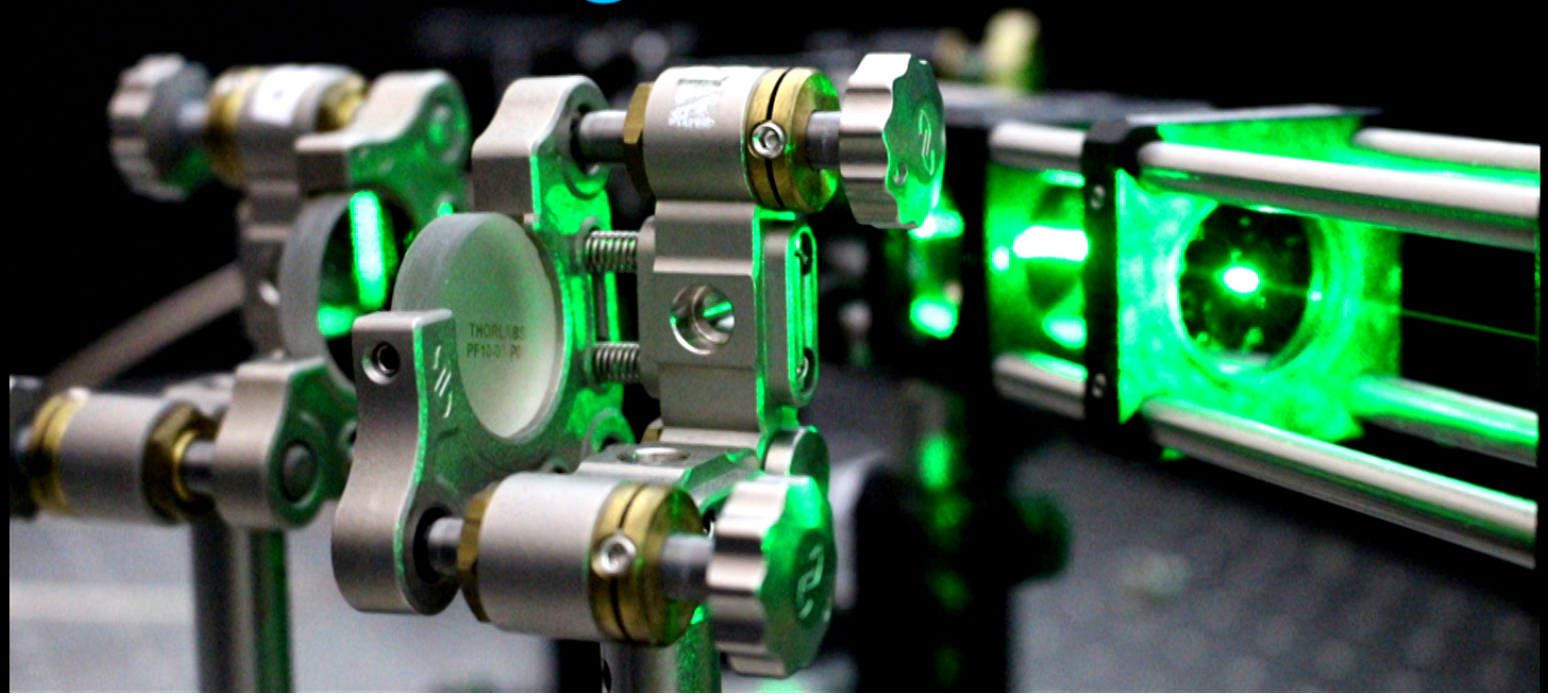
Abstract: We are building an experiment in which a levitated 1 Âµm diamond containing a nitrogen vacancy (NV) centre would be put into a spatial quantum superposition [1-3]. This would be able to test theories of spontaneous wavefunction collapse [4]. We have helped theory collaborators to propose how to do this experiment [5-9], as well as a much more experimentally ambitious extension which would test if gravity permits a quantum superposition [10]. There are related proposals from other groups [11-13].
[1] A. T. M. A. Rahman, A. C. Frangeskou, M. S. Kim, S. Bose, G. W. Morley & P. F. Barker, Sci. Rep. 6, 21633 (2016).
[2] A. T. M. A. Rahman, A. C. Frangeskou, P. F. Barker & G. W. Morley, Rev. Sci. Instrum. 89, 023109 (2018).
[3] A. C. Frangeskou, A. T. M. A. Rahman, L. Gines, S. Mandal, O. A. Williams, P. F. Barker & G. W. Morley, NJP 20, 043016 (2018).
[4] A. Bassi, K. Lochan, S. Satin, T. P. Singh & H. Ulbricht, Rev. Mod. Phys. 85, 471 (2013).
[5] S. Bose & G. W. Morley, arXiv:1810.07045 (2018).
[6] M. Scala, M. S. Kim, G. W. Morley, P. F. Barker & S. Bose, PRL 111, 180403 (2013).
[7] C. Wan, M. Scala, G. W. Morley, A. T. M. A. Rahman, H. Ulbricht, J. Bateman, P. F. Barker, S. Bose & M. S. Kim, PRL 117, 143003 (2016).
[8] R. J. Marshman, A. Mazumdar, G. W. Morley, P. F. Barker, H. Steven & S. Bose, arXiv:1807.10830 (2018).
[9] J. S. Pedernales, G. W. Morley & M. B. Plenio, arXiv:1906.00835 (2019).
[10] S. Bose, A. Mazumdar, G. W. Morley, H. Ulbricht, M. ToroÅ¡, M. Paternostro, A. A. Geraci, P. F. Barker, M. S. Kim & G. Milburn, PRL 119, 240401 (2017).
[11] Z.-q. Yin, T. Li, X. Zhang & L. M. Duan, PRA 88, 033614 (2013).
[12] A. Albrecht, A. Retzker & M. B. Plenio, PRA 90, 033834 (2014).
[13] C. Marletto & V. Vedral, PRL 119, 240402 (2017).

Levitating microdiamonds towards testing the macroscopic limits of the quantum superposition principle

Gavin W Morley, University of Warwick

@gavinmorley



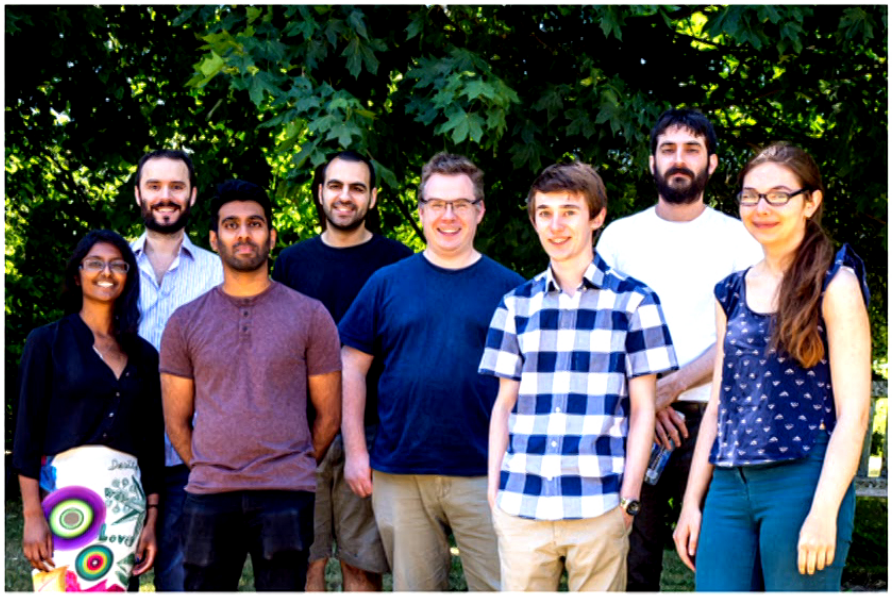
Acknowledgments

Warwick University
Angelo Frangeskou, Colin Stephen, Anis Rahman (now UCL), James March, Ben Green, Ben Breeze, Mark Newton, Guy Stimpson, Yashna Lekhai, Rajesh Patel, Will Thornley, Eleanor Nichols

University College London
Peter Barker & Sougato Bose

Imperial College
Chuanqi Wan & Myungshik Kim

Ulm University
Julen Pedernales & Martin Plenio



Cardiff University
Laia Gines, Soumen Mandal & Oliver Williams

Oxford University
Laiyi Weng, Jason Smith & Patrick Salter

elementsix™

EPSRC Engineering and Physical Sciences Research Council

DST Diamond Science Technology Centre

UK National Quantum Technology Hub Sensors and Metrology

THE ROYAL SOCIETY

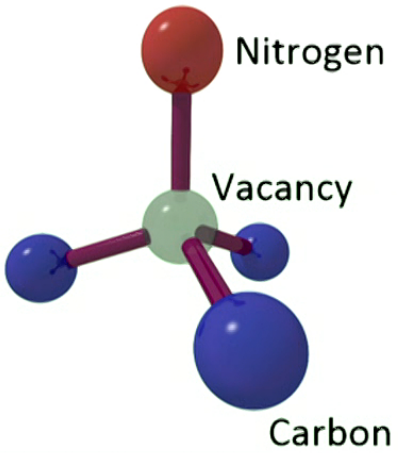
NQIT

Research in my group

a) Levitating microdiamonds towards tests of quantum mechanics

b) Laser writing of nitrogen vacancy (NV) centres in diamond

c) Ensemble magnetometry with NV centres

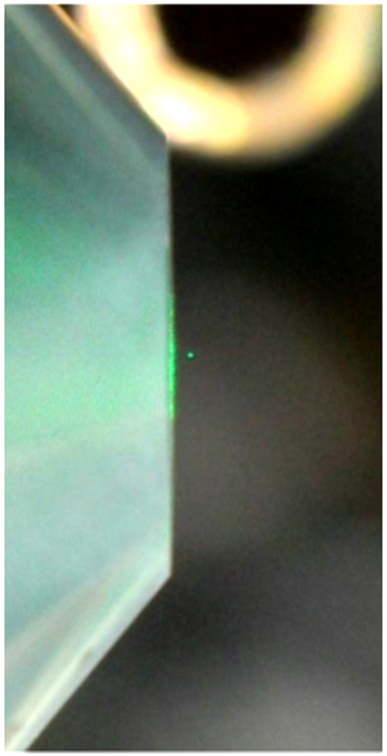


Overview

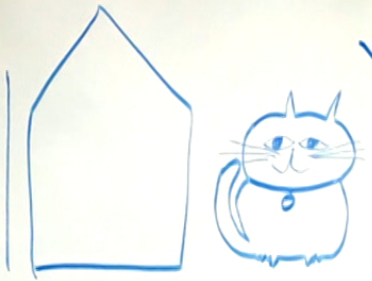
1. Macroscopic quantum superpositions

2. Nitrogen vacancy (NV) centres in diamond and levitated microdiamonds

3. Proposed test of whether gravity permits a quantum superposition

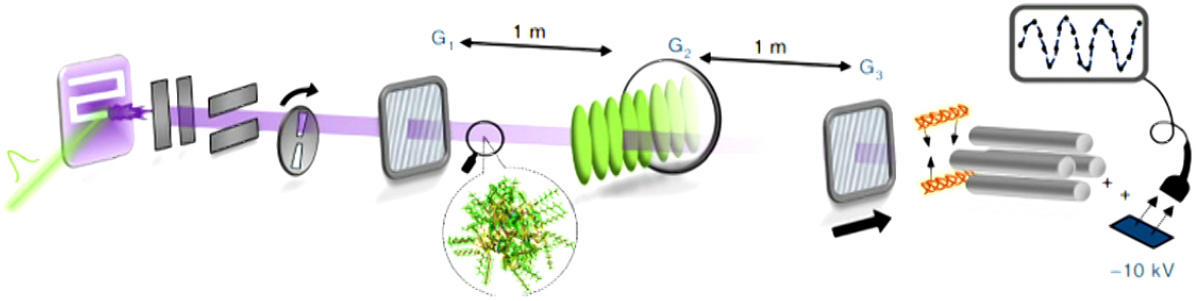


$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|L\rangle + |R\rangle\right)$$

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

Is there a macroscopic limit to quantum superpositions?

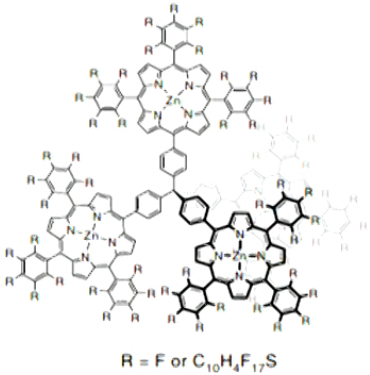
Most macroscopic spatial superposition to date



Markus Arndt's group

266 nm slit width

Y. Y. Fein et al., Nature Phys. 15, 1242 (2019)



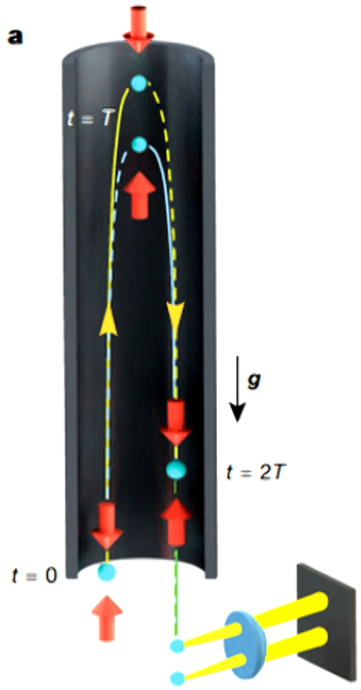
BEC superposition

Quantum superposition at the half-metre scale

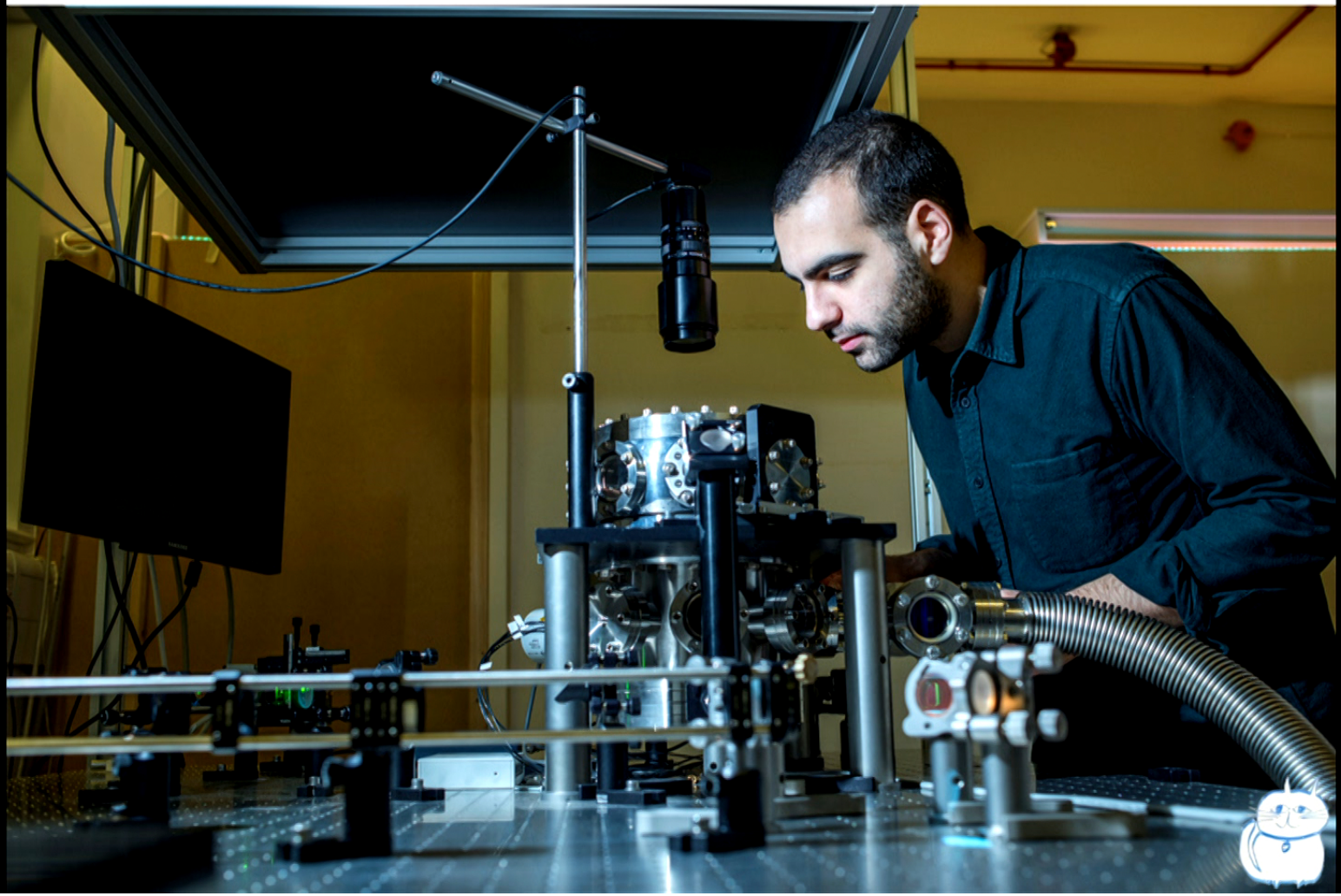
T. Kovachy[1], P. Asenbaum[1], C. Overstreet[1], C. A. Donnelly[1], S. M. Dickerson[1], A. Sugarbaker[1], J. M. Hogan[1] & M. A. Kasevich[1]

Nature 528, 530 (2015)

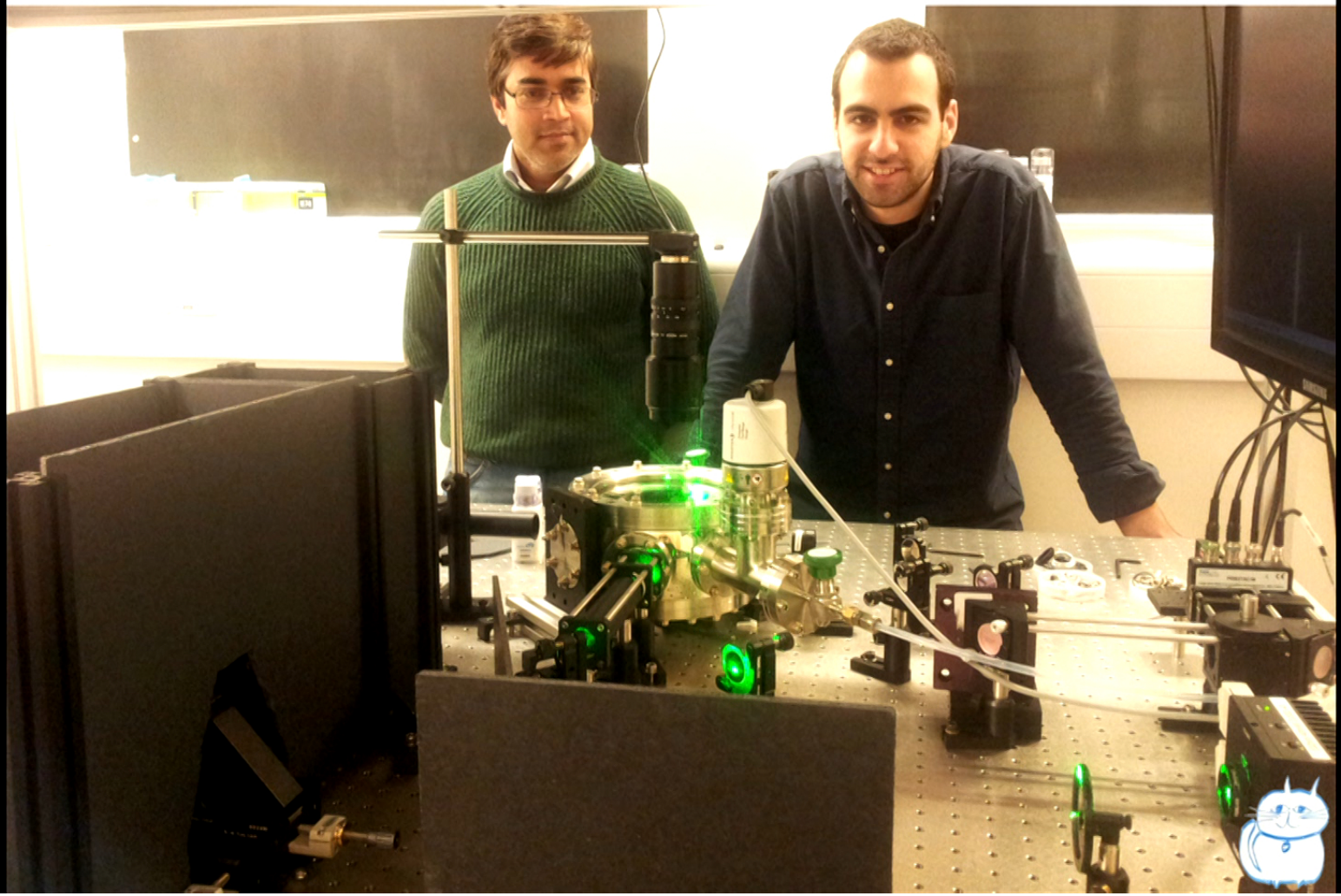
Single atom superposition: not a cat state



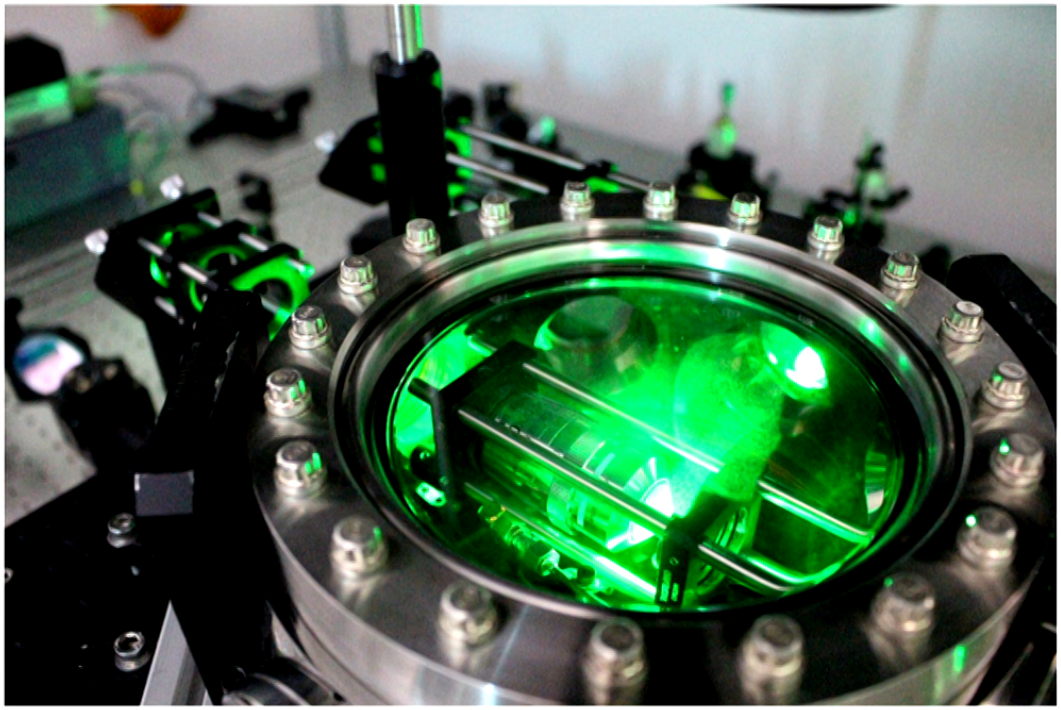
Our experiment: optically levitated nanodiamond

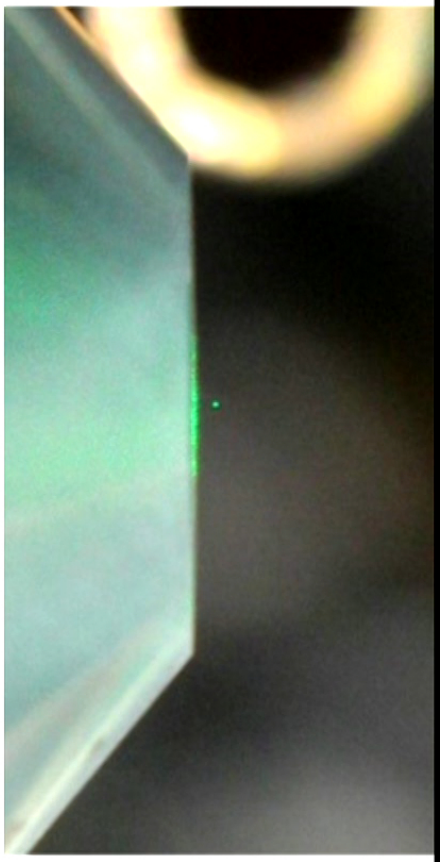


Our experiment: optically levitated nanodiamond

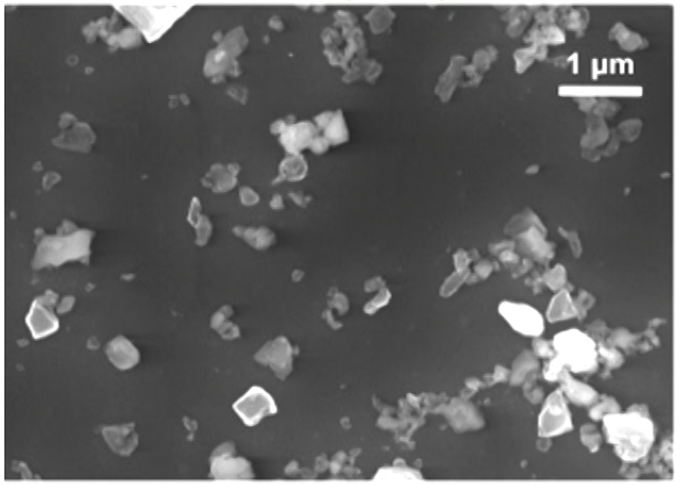


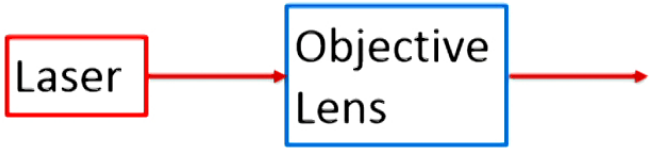
Our experiment: optically levitated nanodiamond

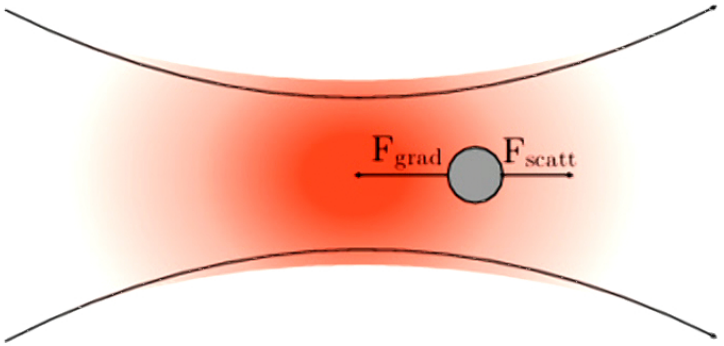


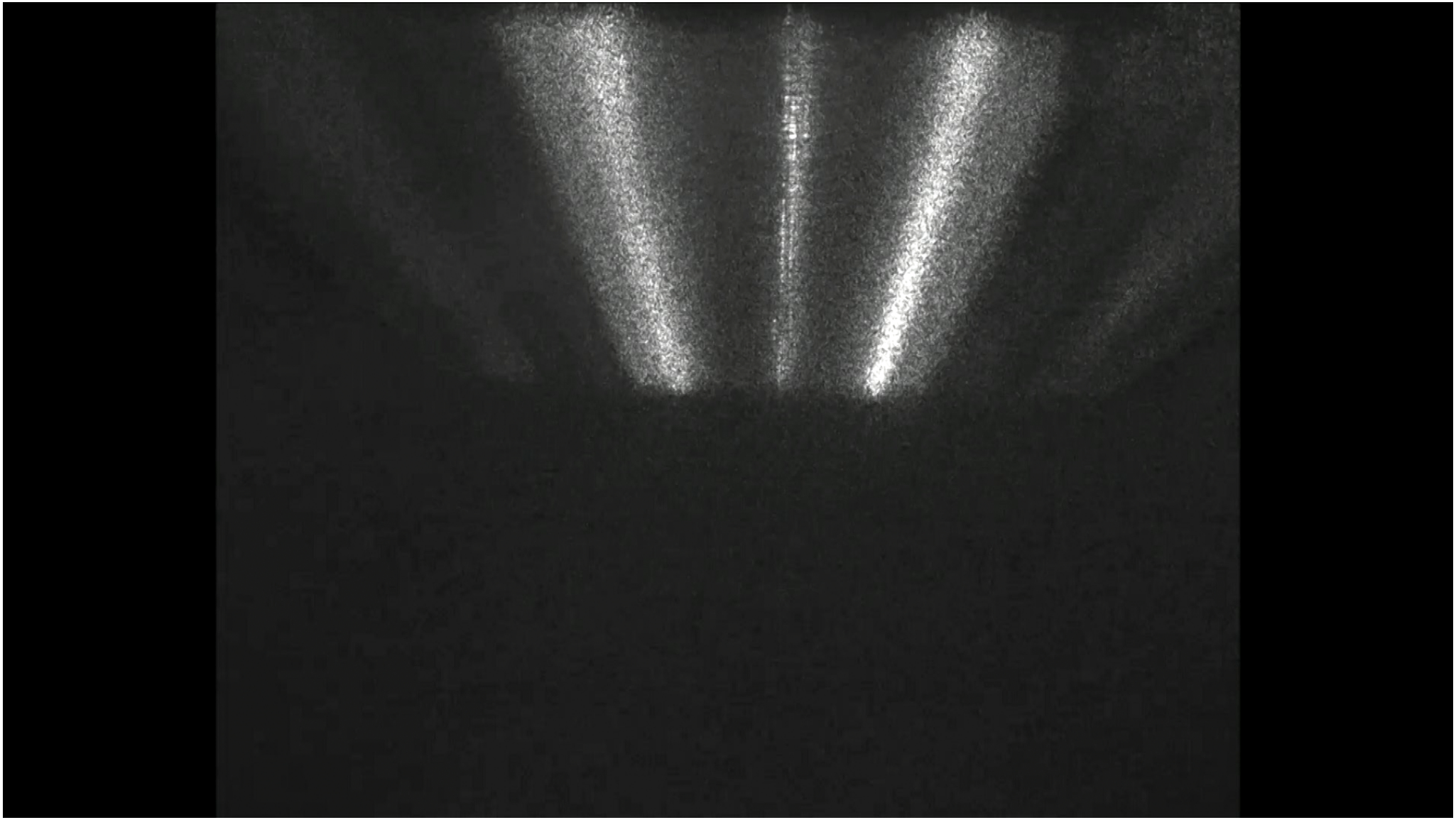


Optical tweezers:
Single beam optical trap

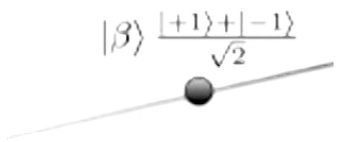








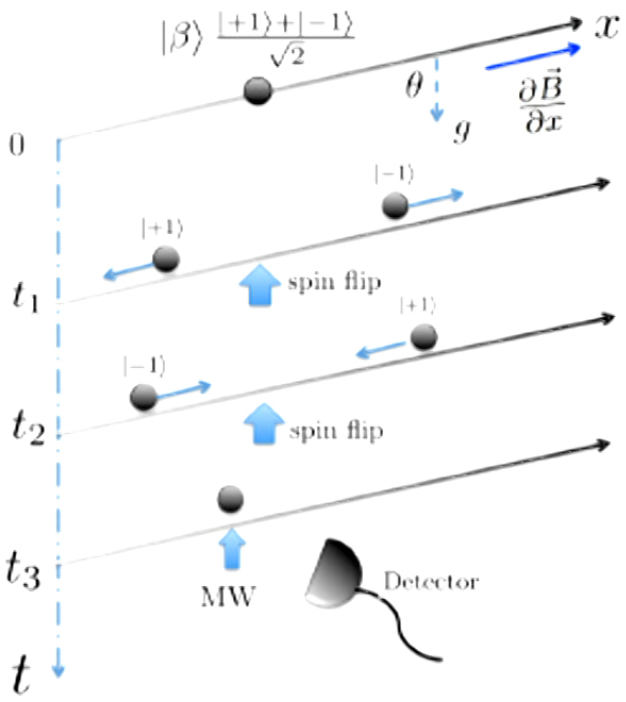
Our proposal: drop a nanodiamond containing a spin



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 & GWM, arXiv:1810.07045 (2018)
- JS Pedernales, GWM & MB Plenio, arXiv:1906.00835 (2019)

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

Our proposal: drop a nanodiamond containing a spin



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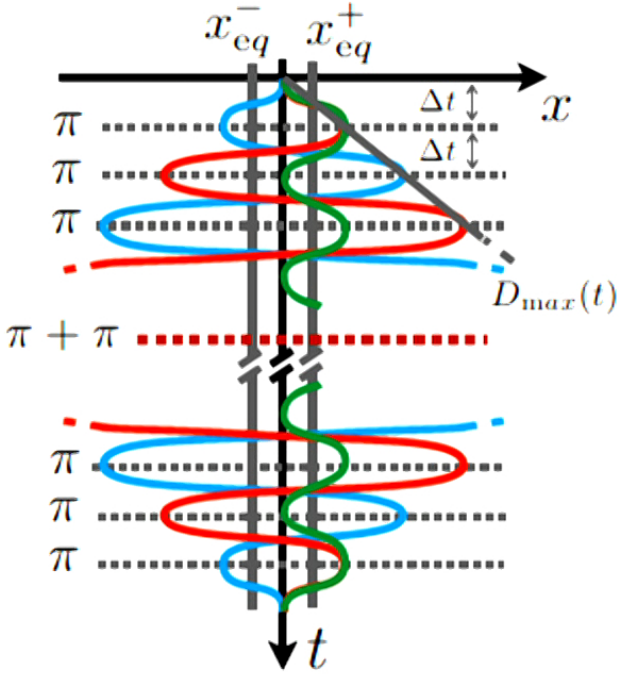
$$H = \frac{\hat{p}^2}{2m} - g_{\mathrm{NV}}\mu_B \frac{\partial B}{\partial x}\hat{S}_z\,\hat{x} + mg\cos\theta\hat{x}$$

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

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

Our proposal: drop a nanodiamond containing a spin



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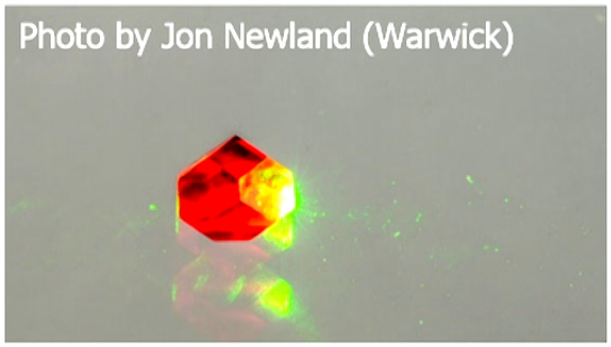
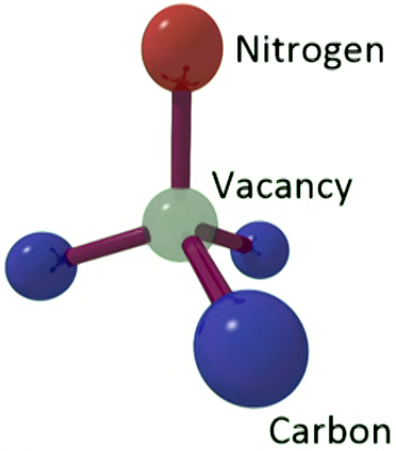
- RJ Marshman... S Bose, arXiv:1807.10830 (2018)
- S Bose & GWM, arXiv:1810.07045 (2018)
- JS Pedernales, GWM & MB Plenio, arXiv:1906.00835 (2019)

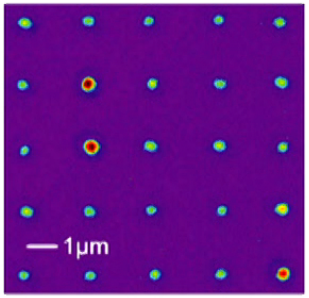
Decoherence:

- Spin decoherence
- Electric charges
- Gas atoms
- Blackbody radiation
- Rotation of microdiamond
- Casimir force
- Vibrations and tilt

Nitrogen-vacancy (NV^-) centres in diamond

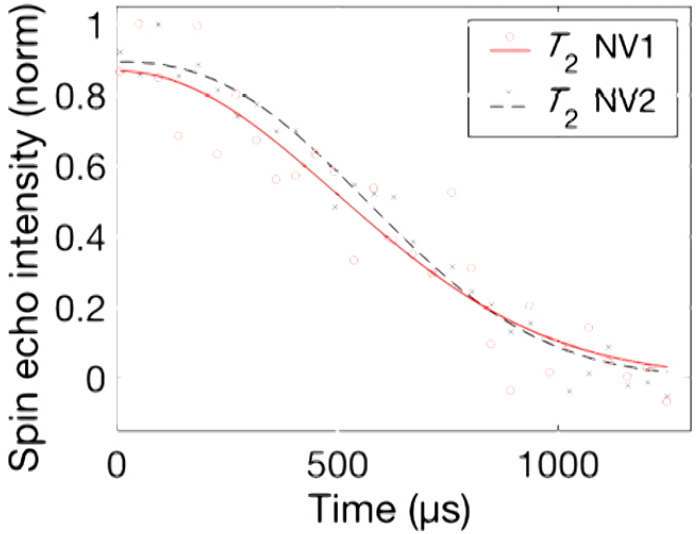


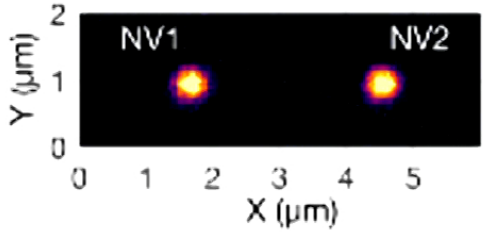




Y-C Chen et al, Optica 6, 662 (2019)

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



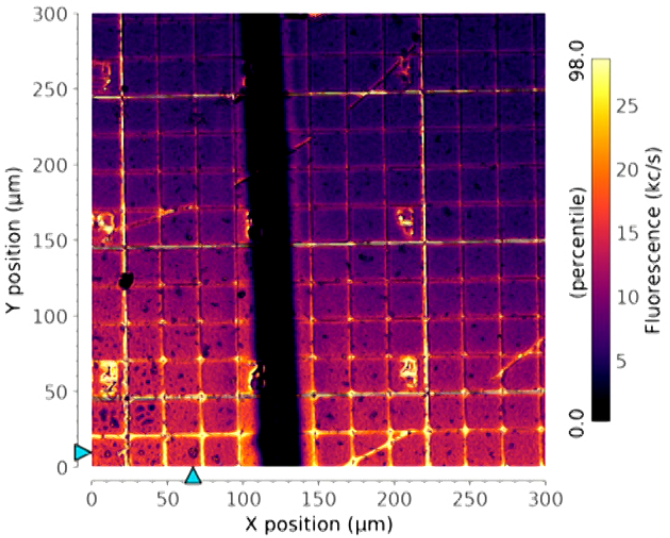


C.J. Stephen, B.L. Green, Y.N.D. Lekhai, L. Weng, P. Hill, S. Johnson, A.C. Frangeskou, P.L. Diggle, M.J. Strain, E. Gu, M.E. Newton, J.M. Smith, P.S. Salter & G.W. Morley, Physical Review Applied 12, 064005 (2019)

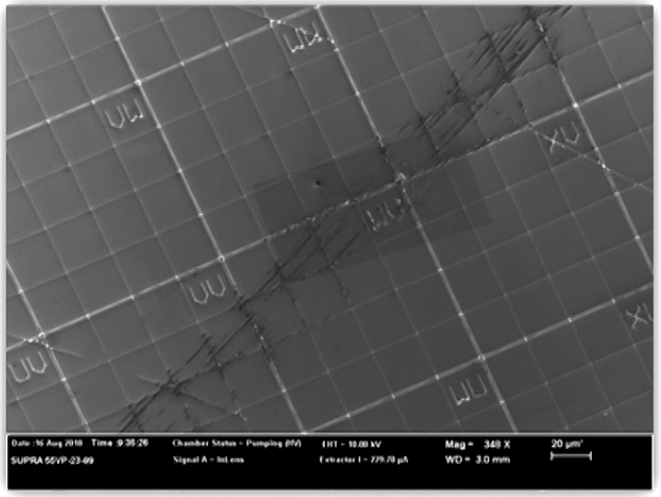
Guy Stimpson

A solution: more pure diamonds

Scanning confocal microscopy



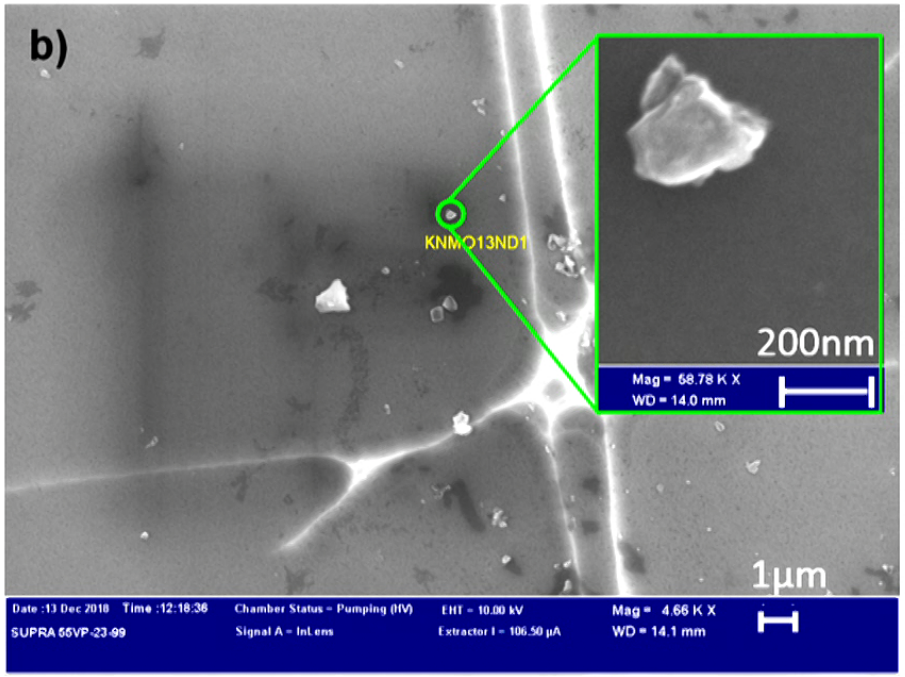
Scanning Electron Microscopy (SEM)



Guy Stimpson

A solution: more pure diamonds

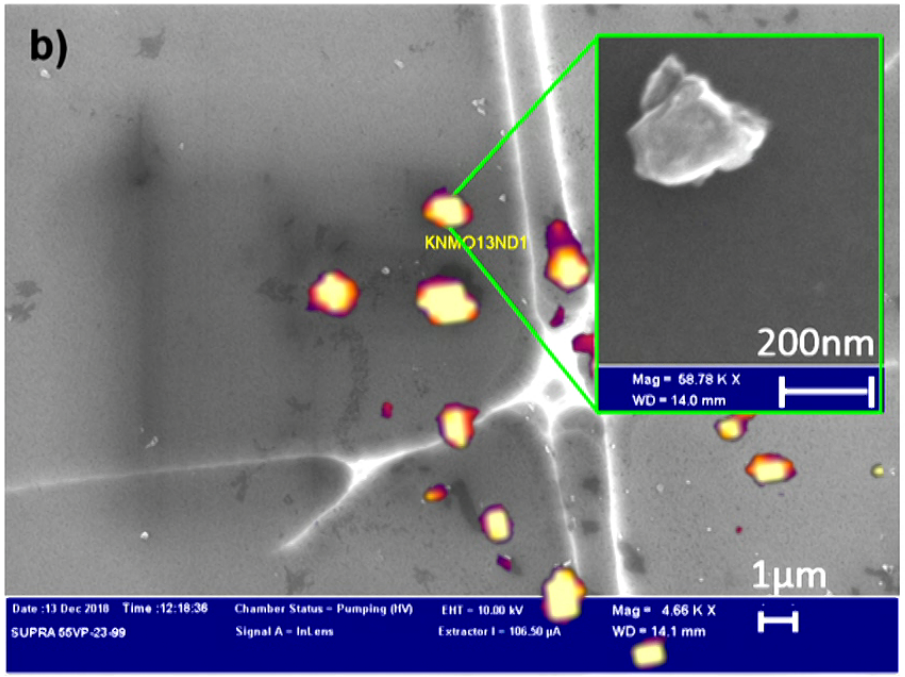
Scanning Electron Microscopy (SEM)



Guy Stimpson

A solution: more pure diamonds

Scanning confocal microscopy & Scanning Electron Microscopy (SEM)



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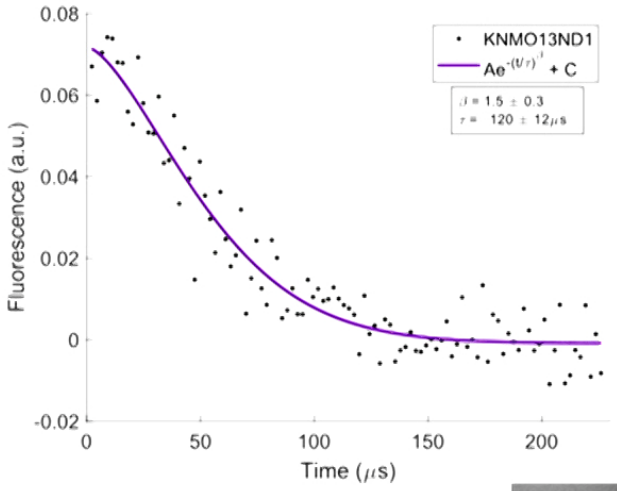
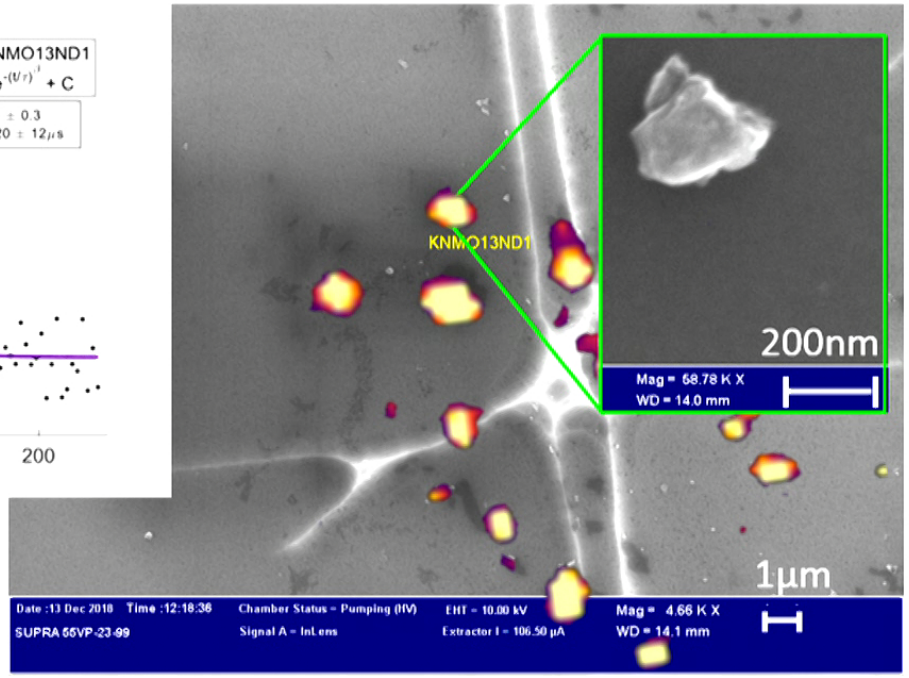
A solution: more pure diamonds

Scanning confocal microscopy & Scanning Electron Microscopy (SEM)

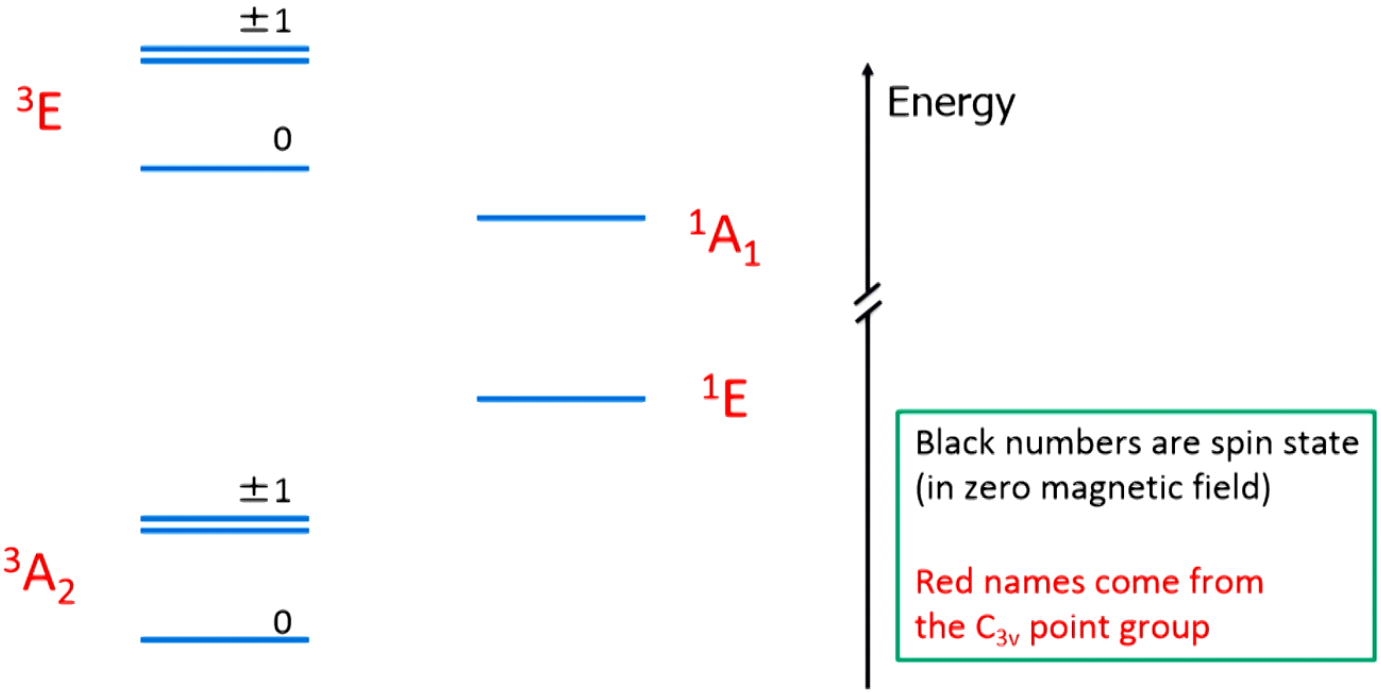




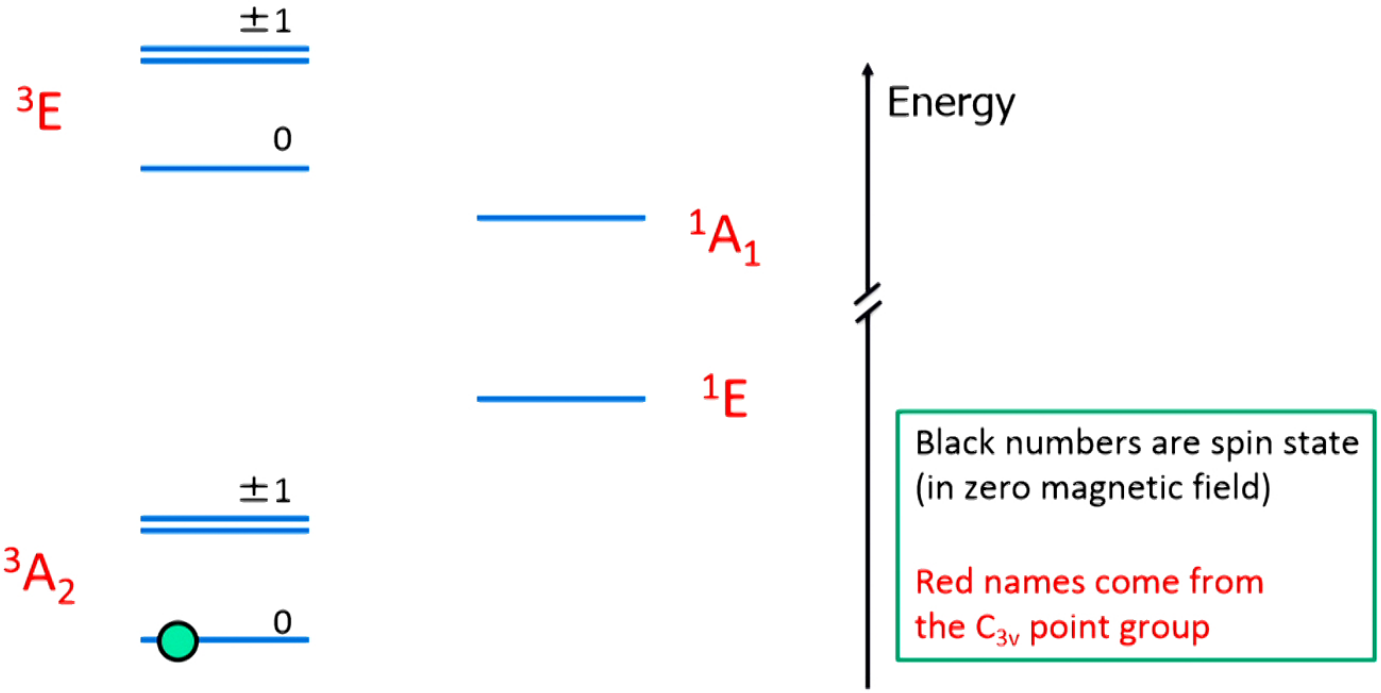
$T_2 = 120\ \mu s$

Gavin W Morley, Indefinite Causal Structure, PI, 11th December 2019

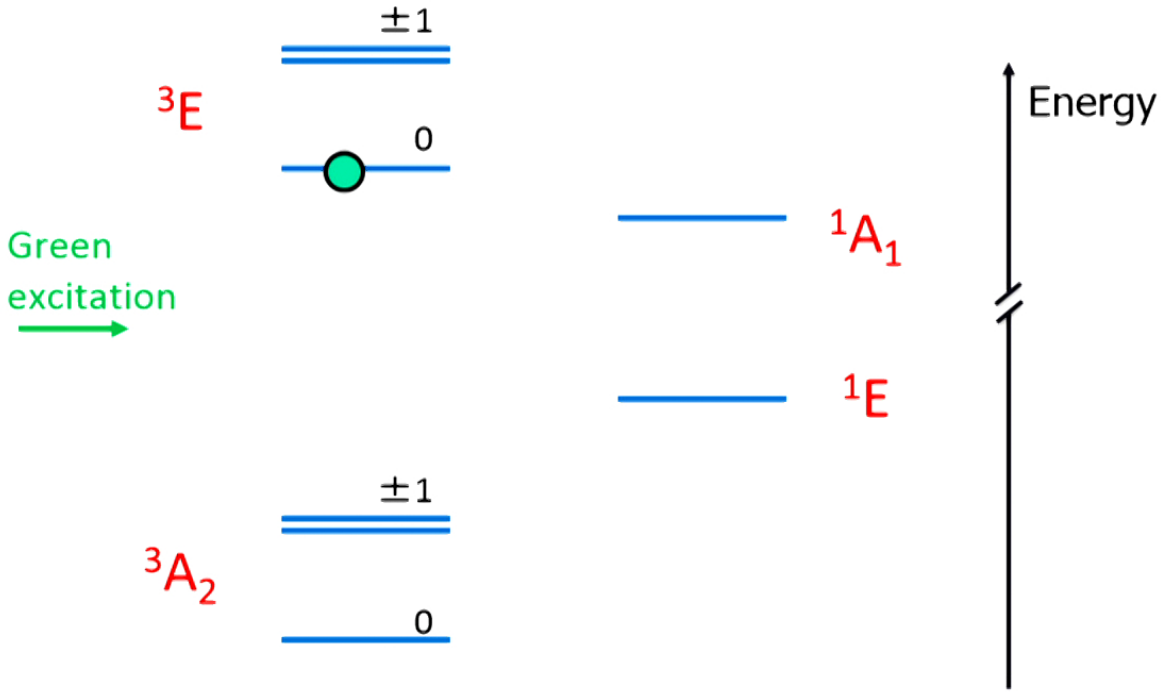
Nitrogen-vacancy (NV^-) energy levels



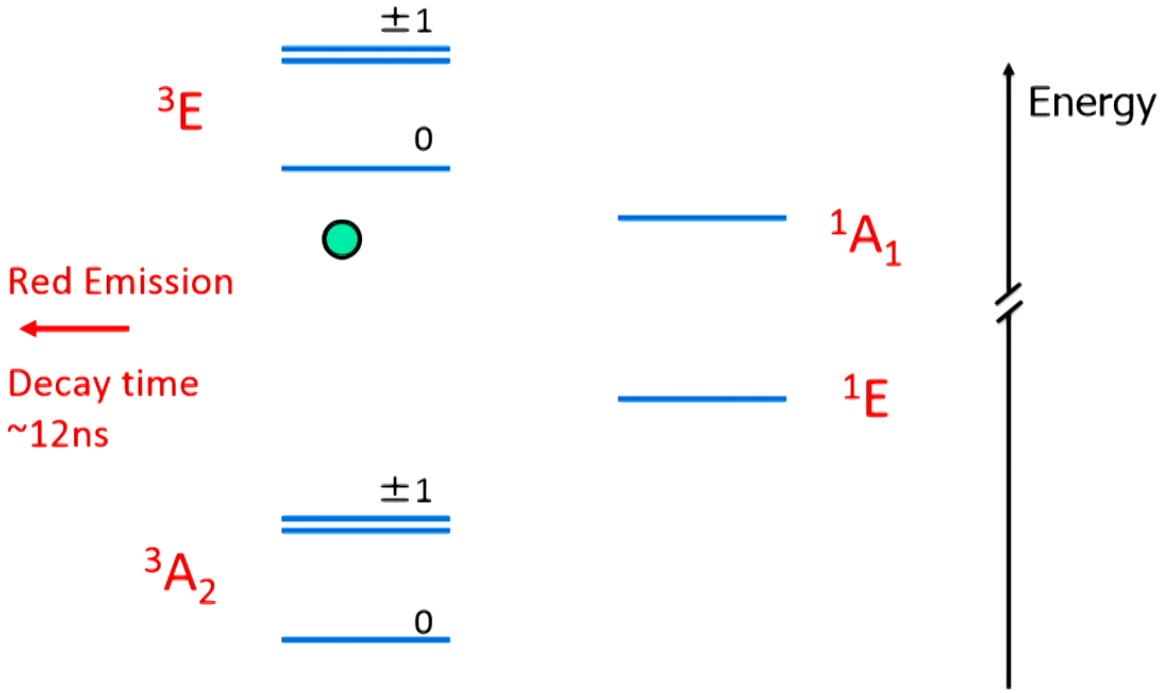
Nitrogen-vacancy (NV^-) energy levels



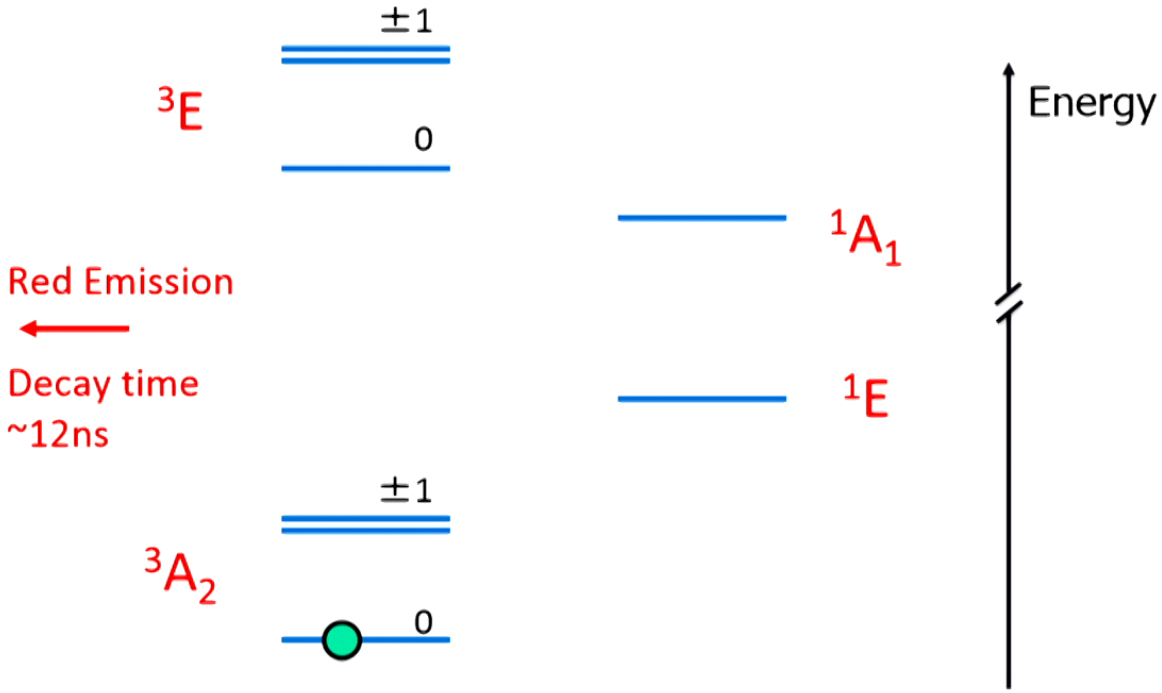
Nitrogen-vacancy (NV^-) energy levels: excite



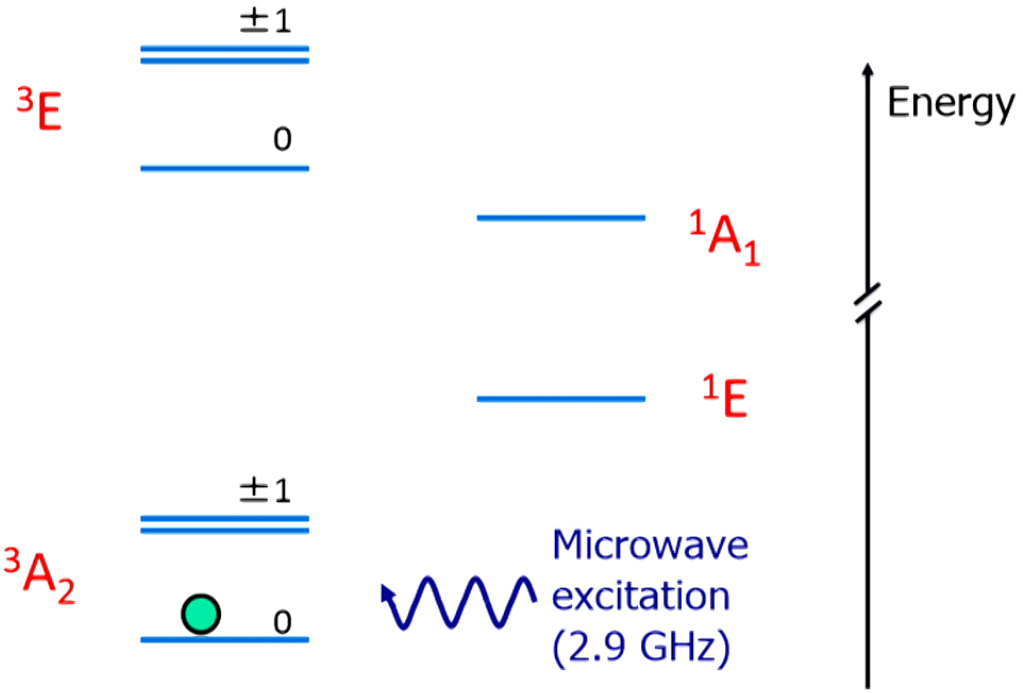
Nitrogen-vacancy (NV^-) energy levels: florescence



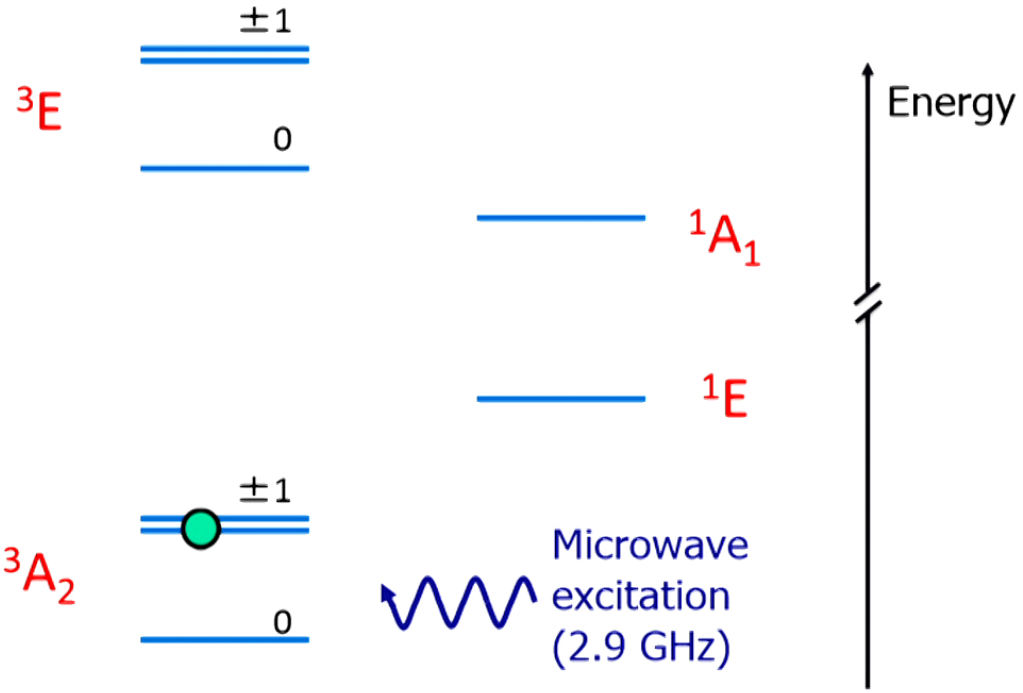
Nitrogen-vacancy (NV^-) energy levels: florescence



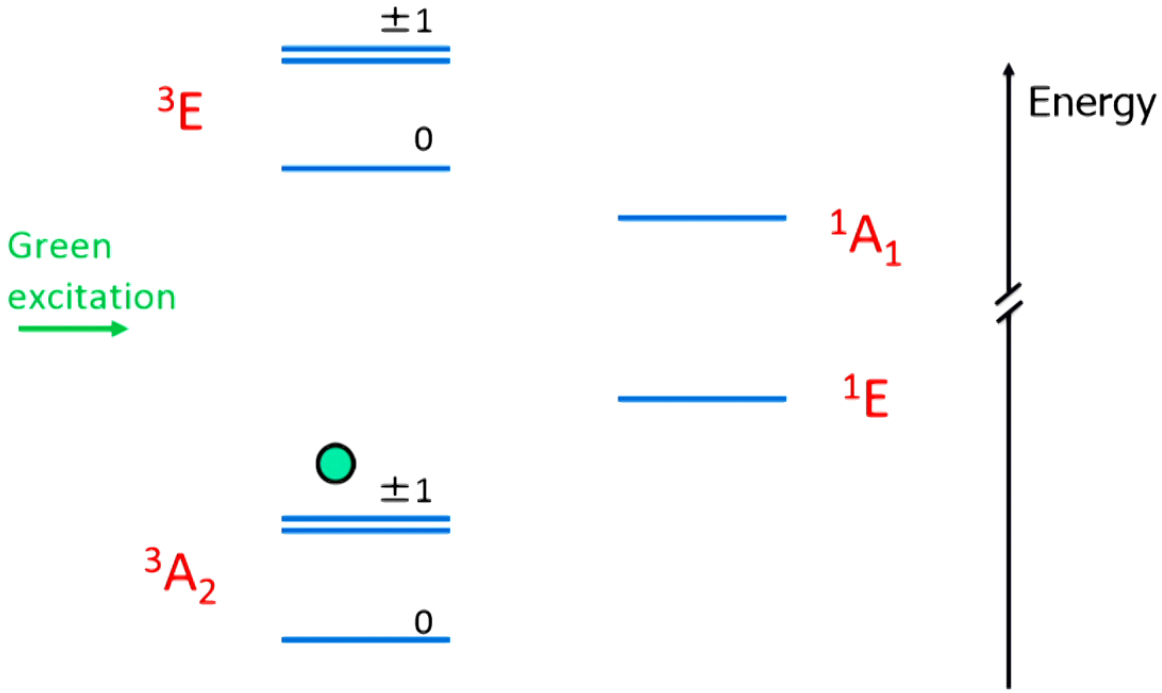
Nitrogen-vacancy (NV^-) energy levels: microwaves



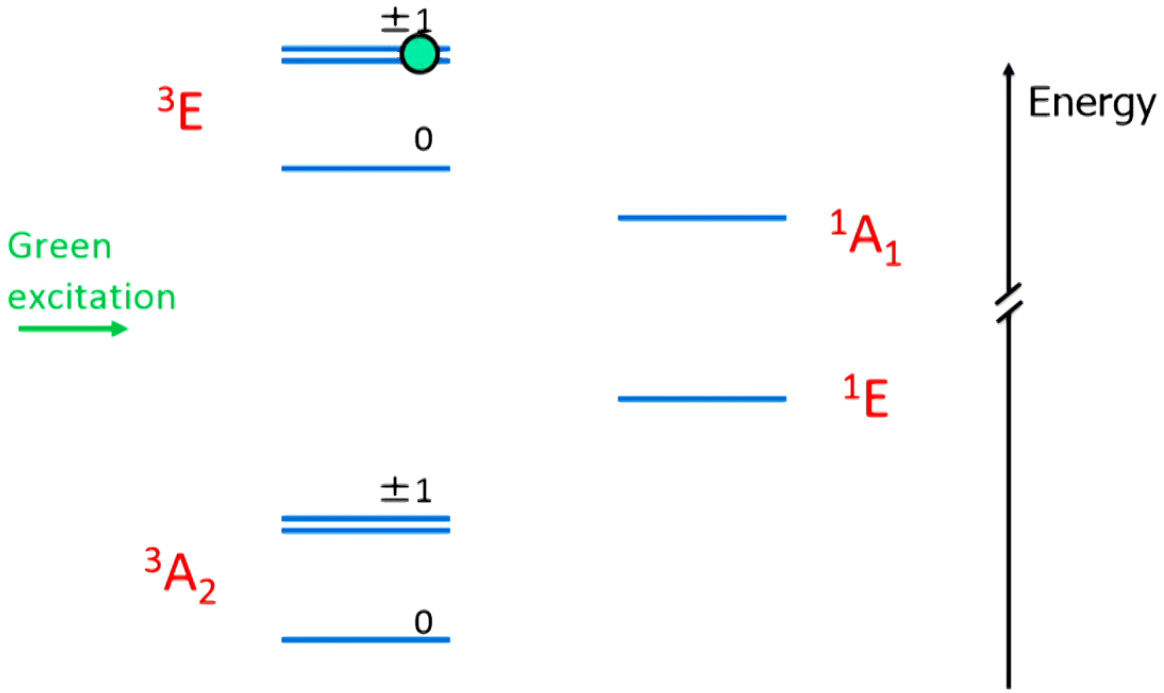
Nitrogen-vacancy (NV^-) energy levels: microwaves



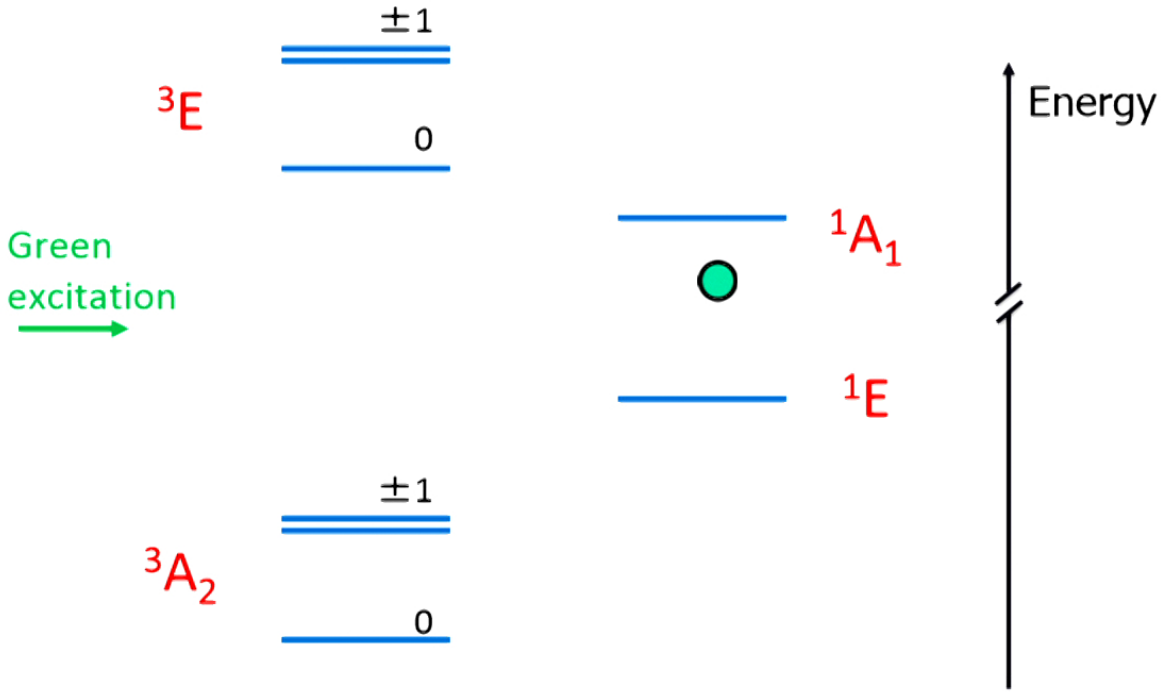
Nitrogen-vacancy (NV^-) energy levels: dark state



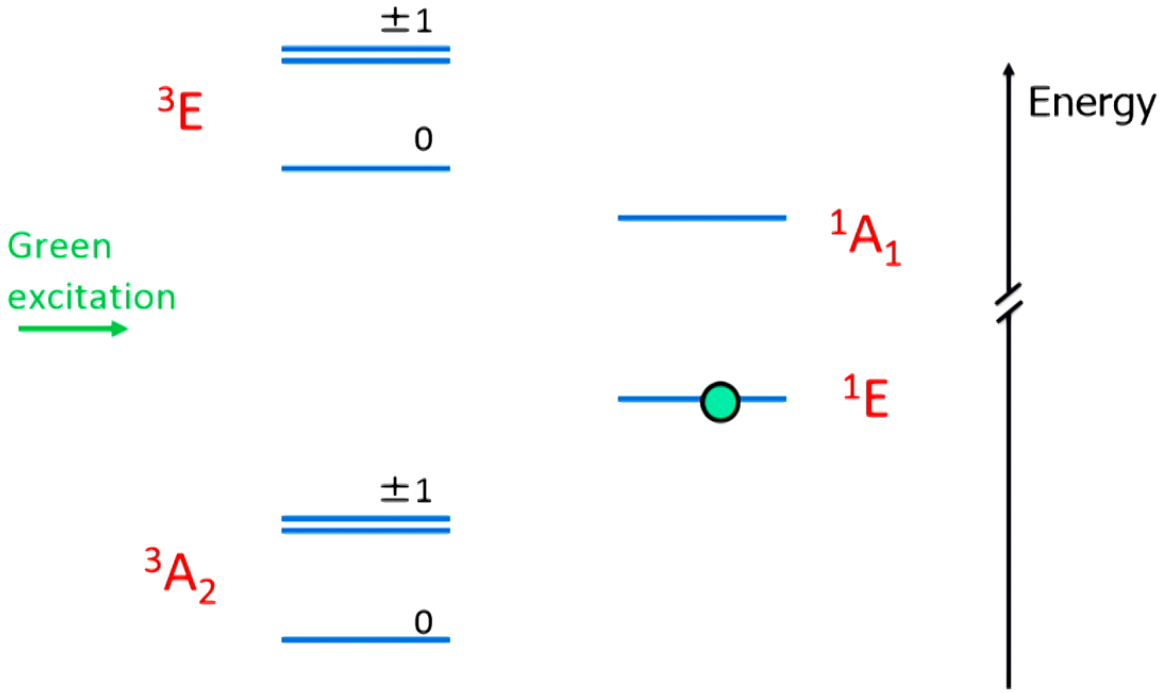
Nitrogen-vacancy (NV^-) energy levels: dark state



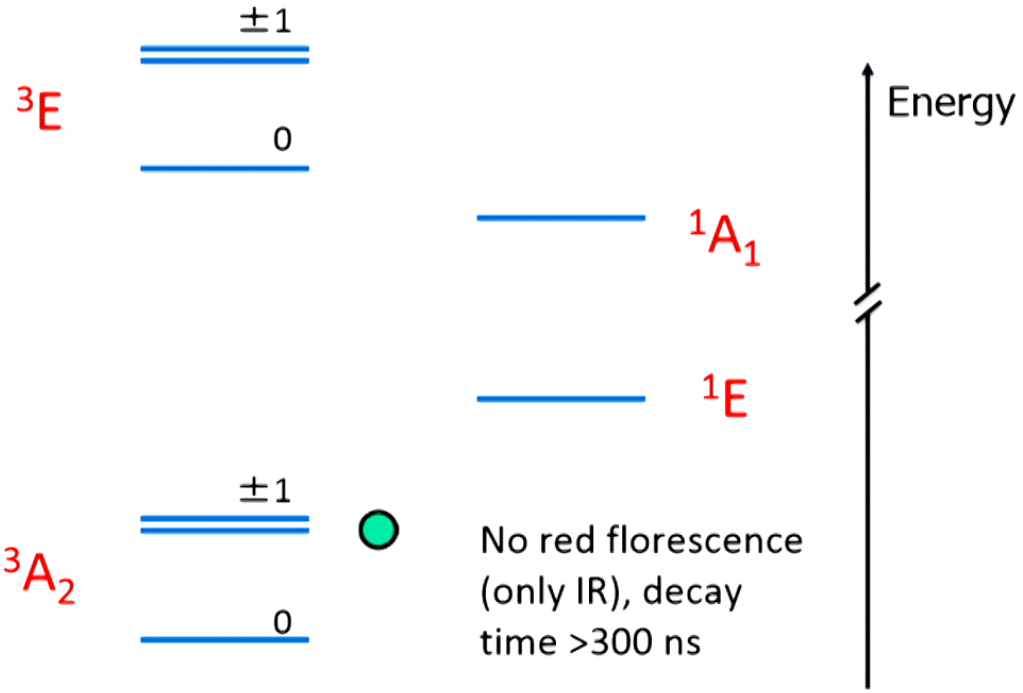
Nitrogen-vacancy (NV^-) energy levels: dark state



Nitrogen-vacancy (NV^-) energy levels: dark state



Nitrogen-vacancy (NV^-) energy levels



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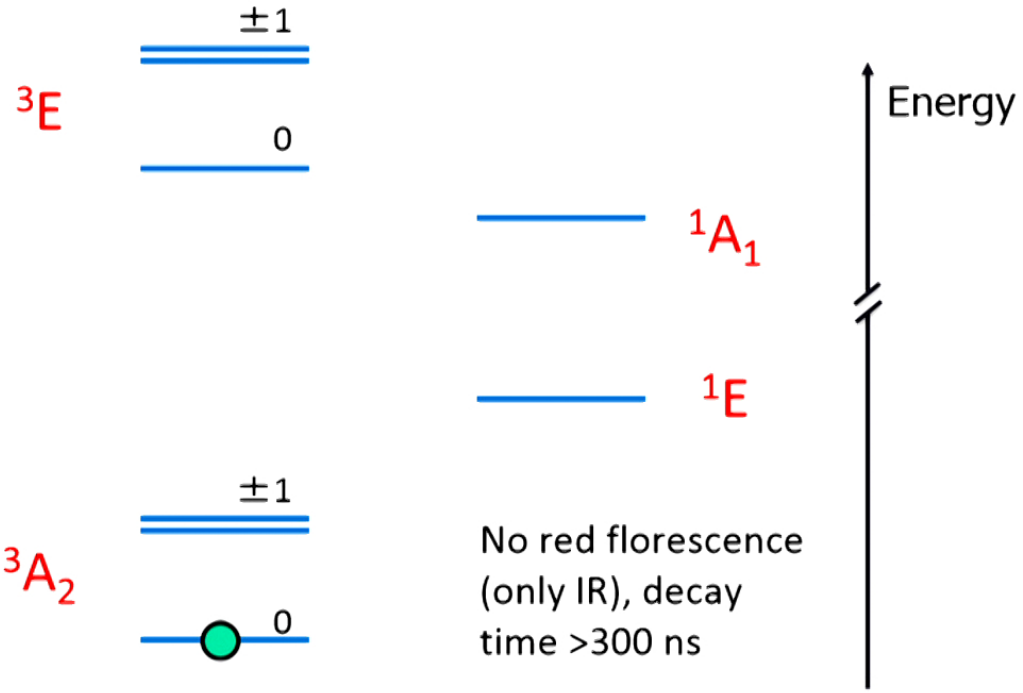
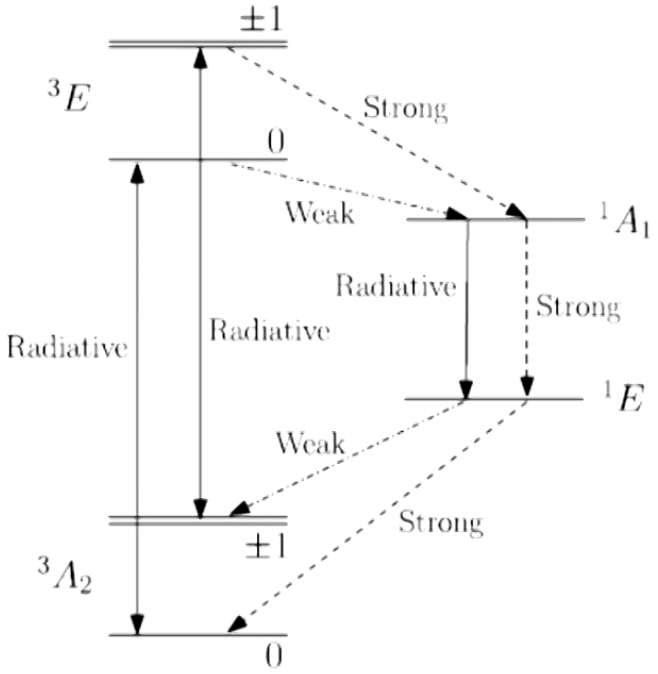


Nitrogen-vacancy (NV^-) energy levels



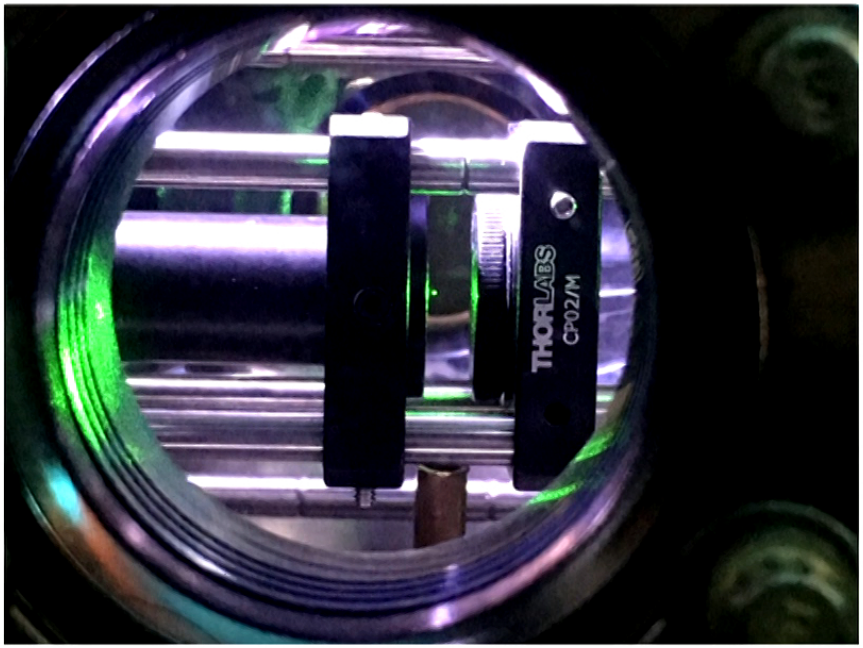
Green excitation →

1. Spin polarization
2. Spin-dependent florescence

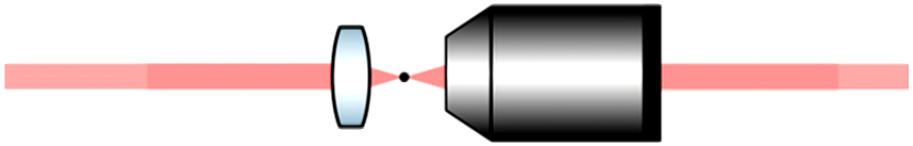
Optically-levitated nanodiamond

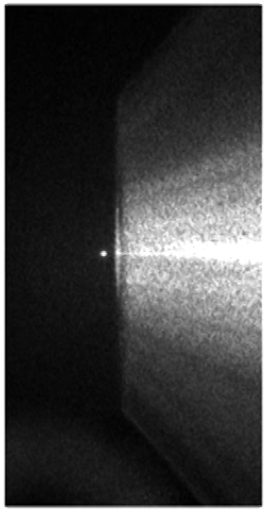
Our experiments: - Commercial nanodiamonds overheat

- Our pure nanodiamonds don't



Need high vacuum e.g. $<10^{-6}$ mbar





Other groups over 5 mbar:

- LP Neukirch, E von Haartman, JM Rosenholm & AN Vamivakas, Nat Photon 9, 653 (2015)

- TM Hoang, J Ahn, J Bang & T Li, Nat Comms 7, 12250 (2016)

(1 mbar ~ 1 torr ~ 0.01 psi ~ 100 Pa ~ 0.001 atmospheres)

Levitating nanodiamonds in air

- Berlin: atmospheric pressure,
A Kuhlicke, AW Schell, J Zoll & O Benson, APL **105**, 073101 (2014)

- Paris: 10^{-2} mbar,
T Delord, L Nicolas, L Schwab & G Hétet, NJP **19**, 033031 (2017)

- University College London: Peter Barker's group

- ICFO: 10^{-2} mbar,
GP Conangla, AW Schell, RA Rica & R Quidant, Nano Lett **18**, 3956 (2018).

Ion traps

- Pittsburgh: 10^{-7} mbar,
J-F Hsu, P Ji, CW Lewandowski & B D'Urso, Sci Rep **6**, 30125 (2016)

- Macquarie: 10^{-6} mbar,
MC O'Brien, S Dunn, JE Downes & J Twamley, APL **114**, 053103 (2019)

Magnetic traps

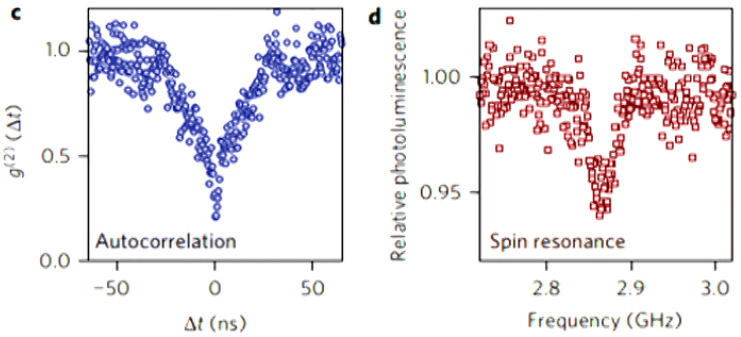
- Rochester: 1064 nm, >5 mbar,
LP Neukirch… & AN Vamivakas, Nat Photon **9**, 653 (2015)

- Purdue: 1550 nm, >10 mbar
TM Hoang, J Ahn, J Bang & T Li, Nat Comms **7**, 12250 (2016)

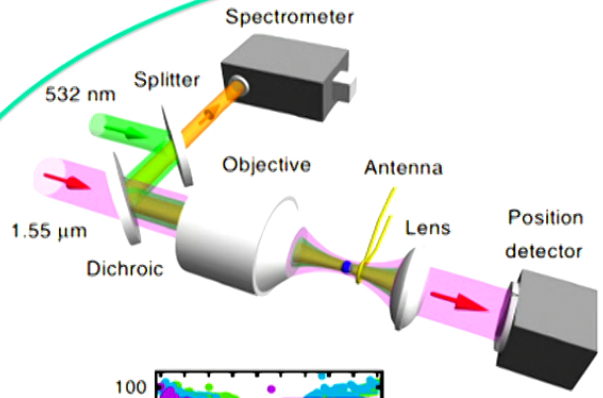
Optical traps

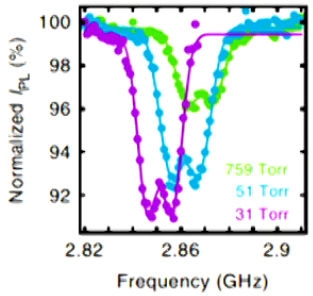
Levitating nanodiamonds: optical trap

Rochester: 1064 nm, >5 mbar,
LP Neukirch, E von Haartman, JM Rosenholm & AN Vamivakas, Nat Photon **9**, 653 (2015)



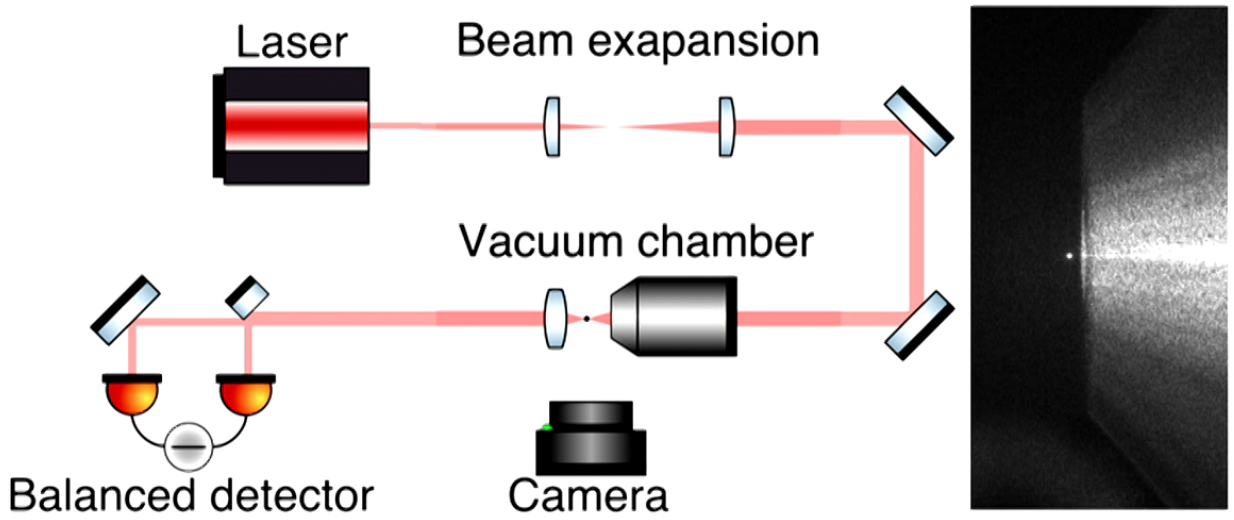
460 mbar atmospheric pressure





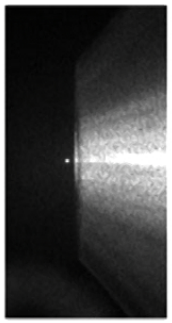
Purdue: 1550 nm, >10 mbar
TM Hoang, J Ahn, J Bang & T Li, Nat Comms **7**, 12250 (2016)

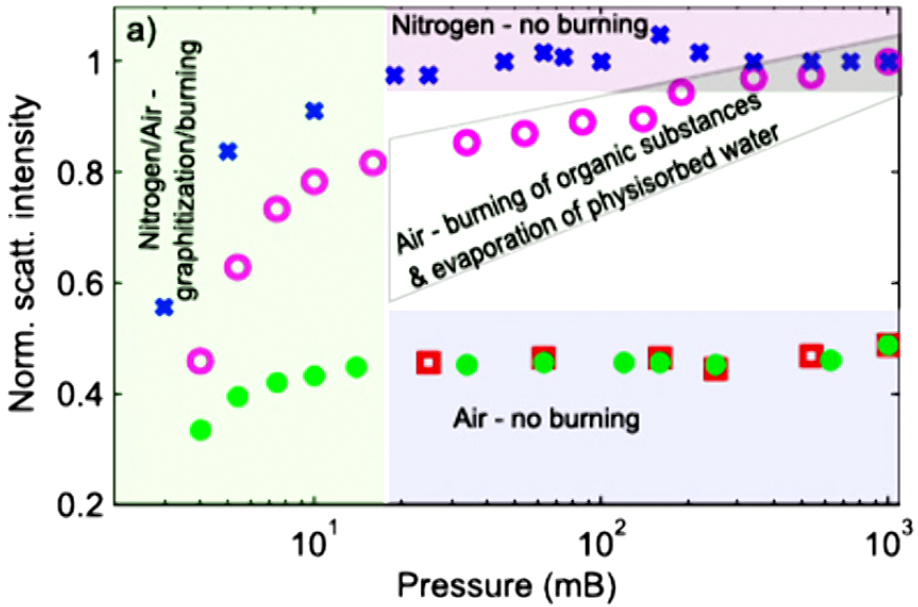
Our levitating nanodiamonds



Levitating nanodiamonds can graphitize

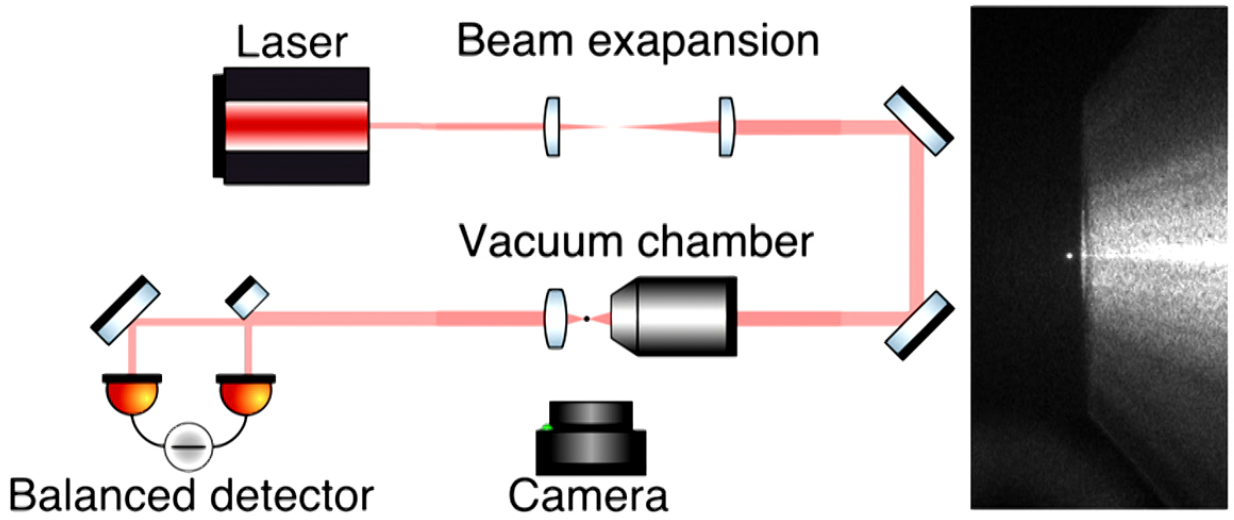
300 mW
trap
power



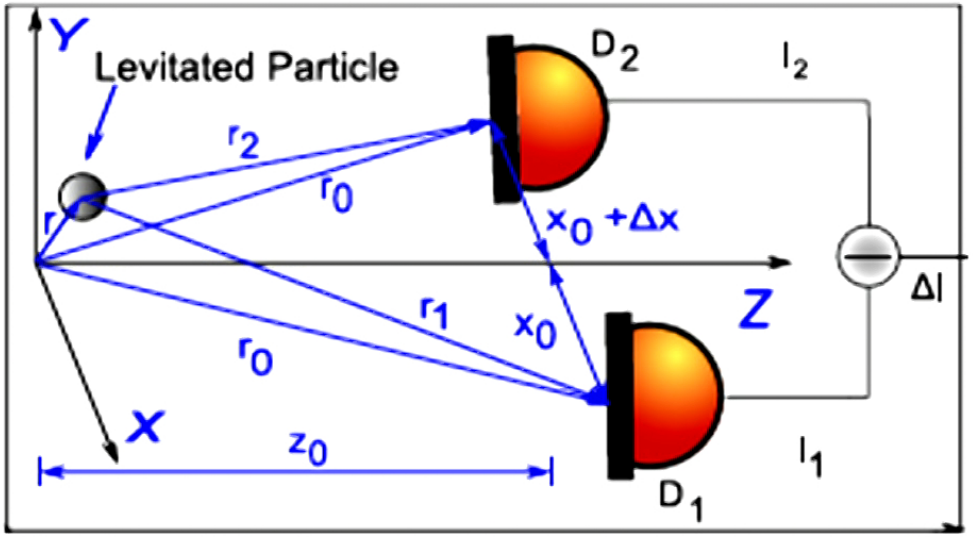


ATMA Rahman *et al.*, Scientific Reports **6**, 21633 (2016)

Our setup

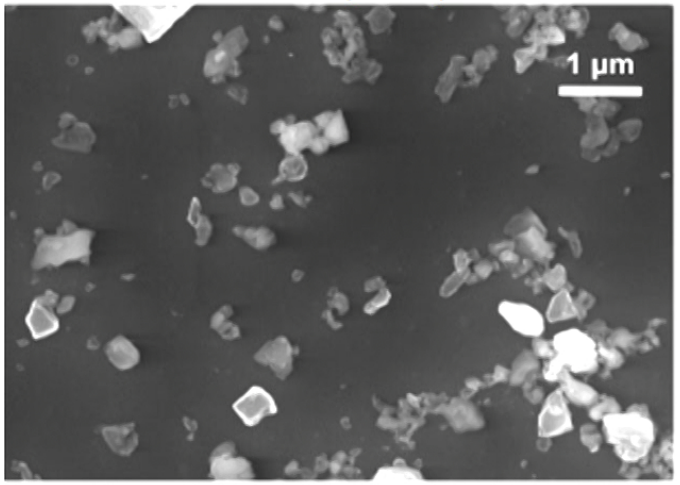

Laser
Beam exapansion
Vacuum chamber
Balanced detector
Camera

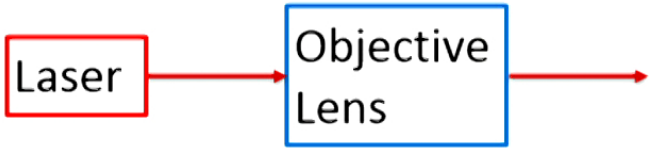
Analytical model for interferometric balanced detection

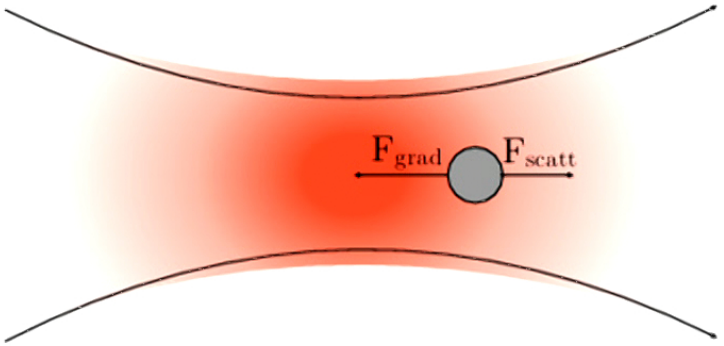


ATM Anishur Rahman, AC Frangeskou, PF Barker & GW Morley, Review of Scientific Instruments **89**, 023109 (2018)

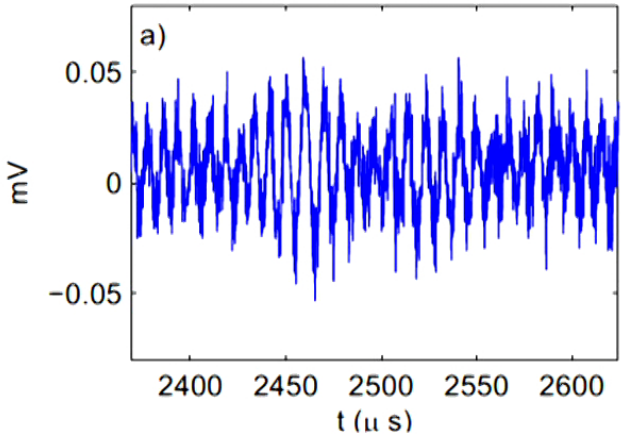
Optical tweezers:
Single beam optical trap







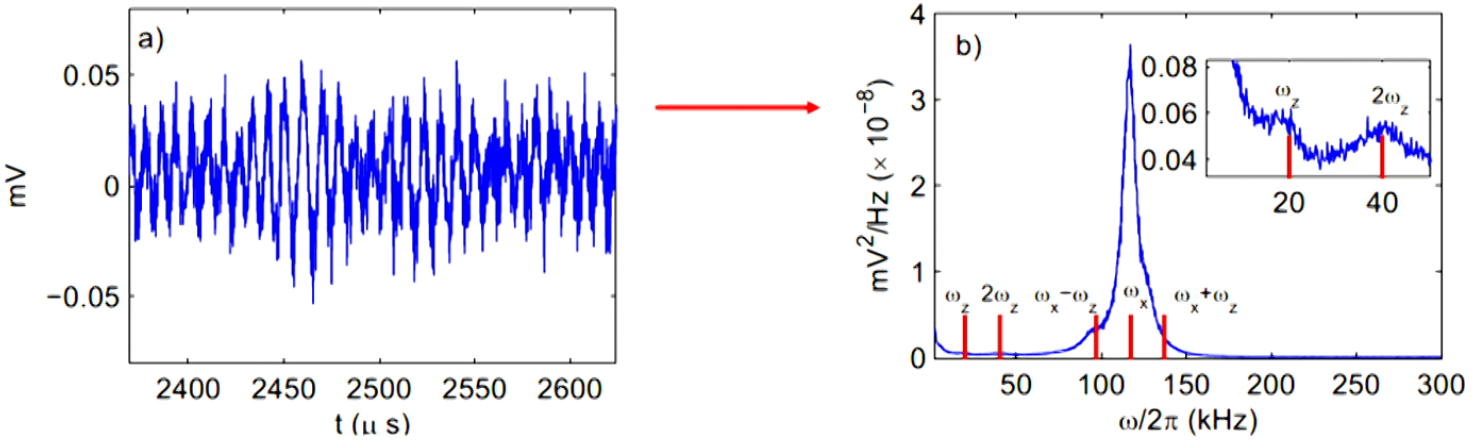
Oscillations



$$m\ddot{x}(t) + m\Gamma_0\dot{x}(t) + m\omega_0^2 x(t) = f_B(t),$$

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

Brownian thermometry

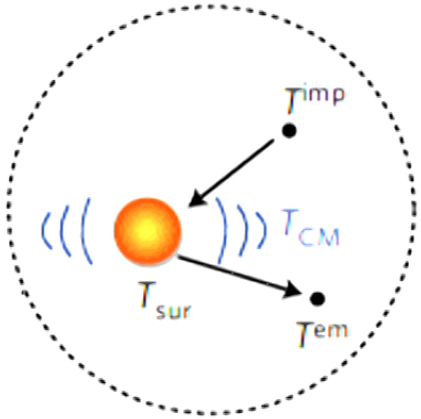


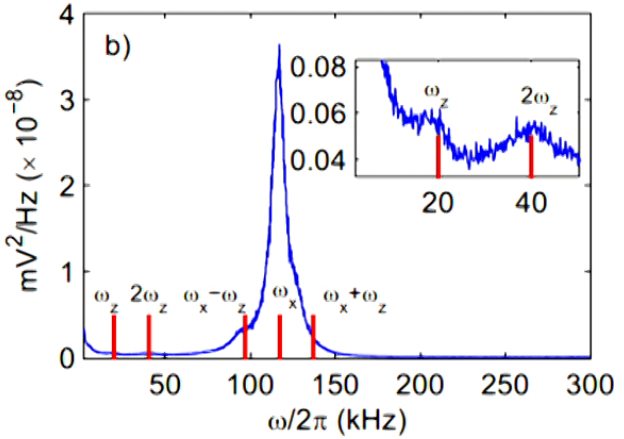
$$m\ddot{x}(t) + m\Gamma_0\dot{x}(t) + m\omega_0^2 x(t) = f_B(t),$$

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

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

Brownian thermometry



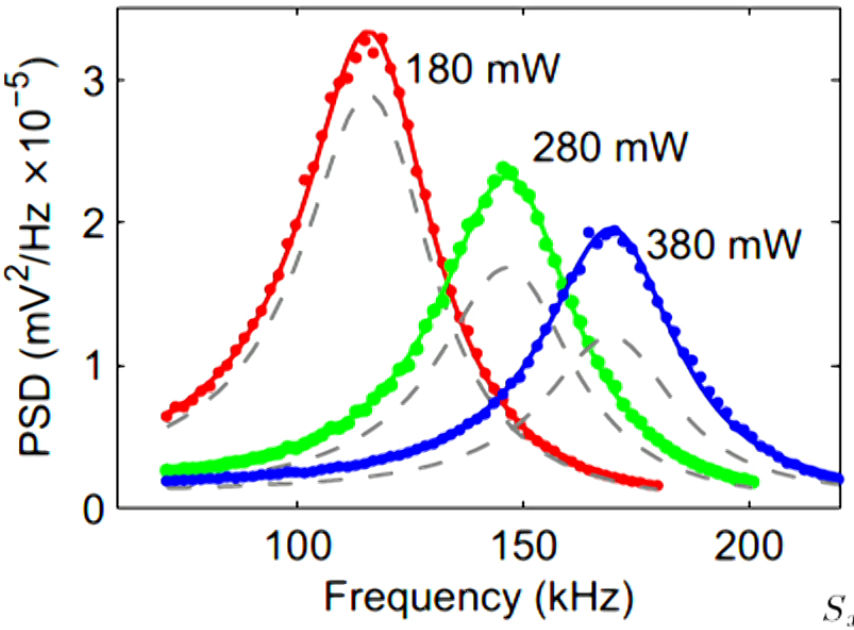


J Millen, T Deesuwan, P Barker & J Anders, Nature Nanotechnology **9**, 425 (2014)

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

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

Levitating nanodiamonds heating up

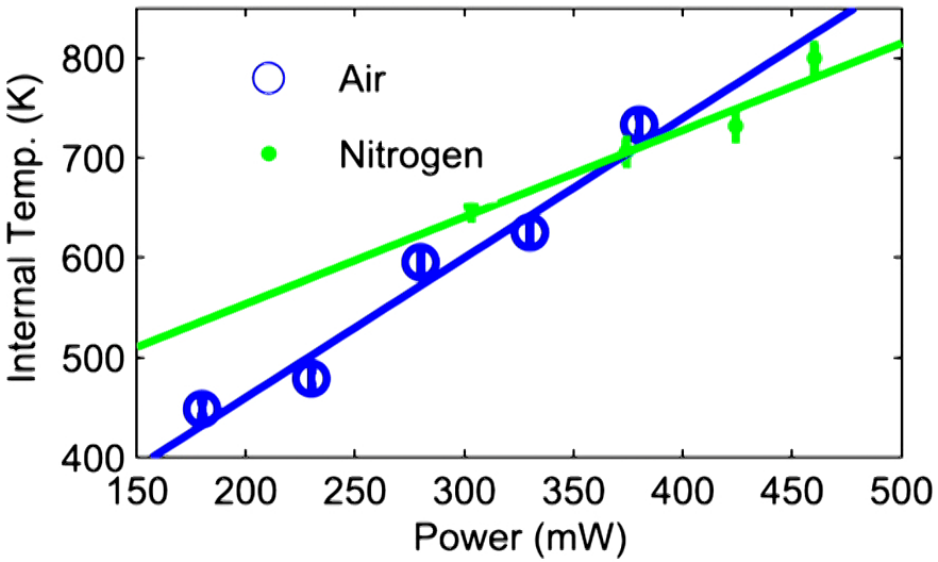


20 mbar

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

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

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).

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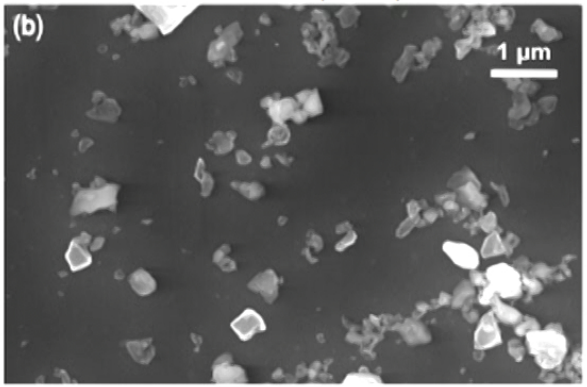


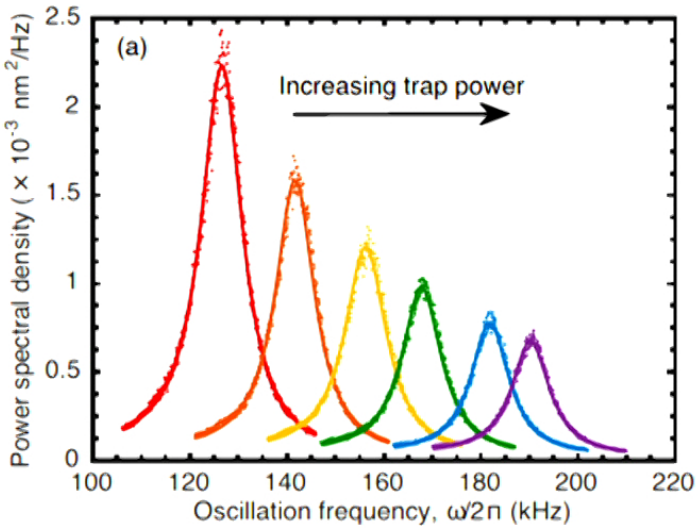
120 ppb nitrogen impurities

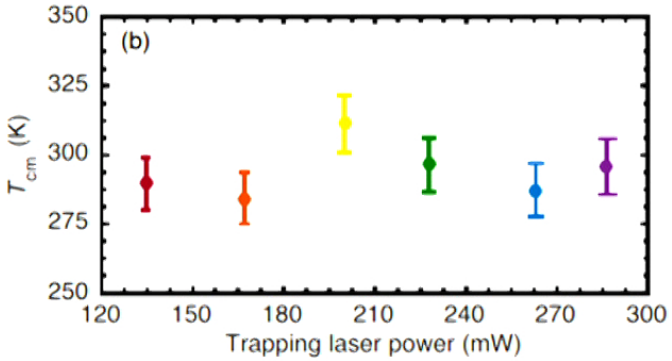
Milling by Ollie Williams' group, Cardiff

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 diamonds

4 mbar





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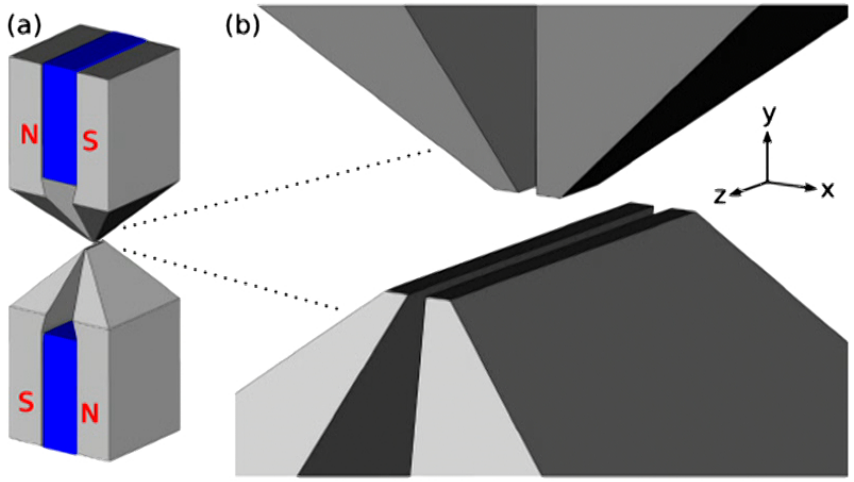
AC Frangeskou, ATMA Rahman, L Gines, S Mandal, OA Williams, PF Barker & GW Morley, New Journal of Physics, 20, 043016 (2018).

Improved proposal: magnetic trap



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

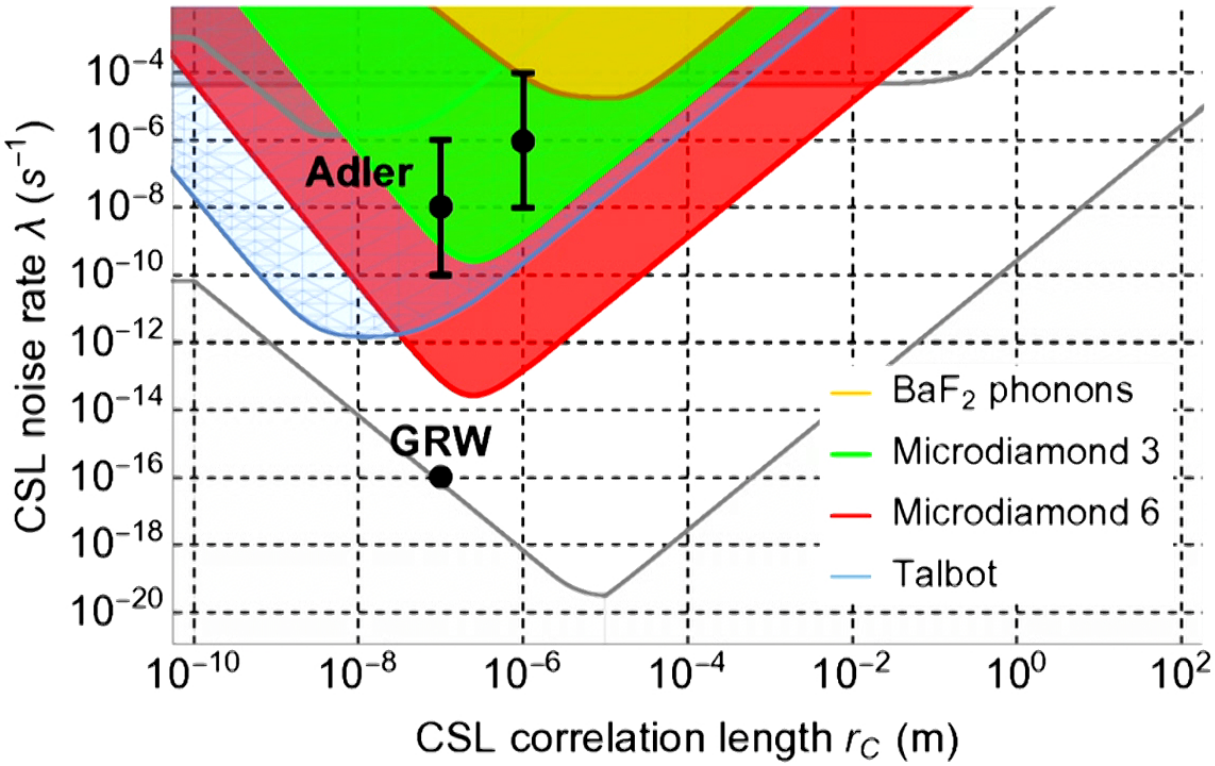
S Bose & GW Morley, arXiv:1810.07045 (2018)
JS Pedernales, GW Morley & MB Plenio, arXiv:1906.00835 (2019)

Macroscopic Quantum Superpositions (MaQS) Project proposal

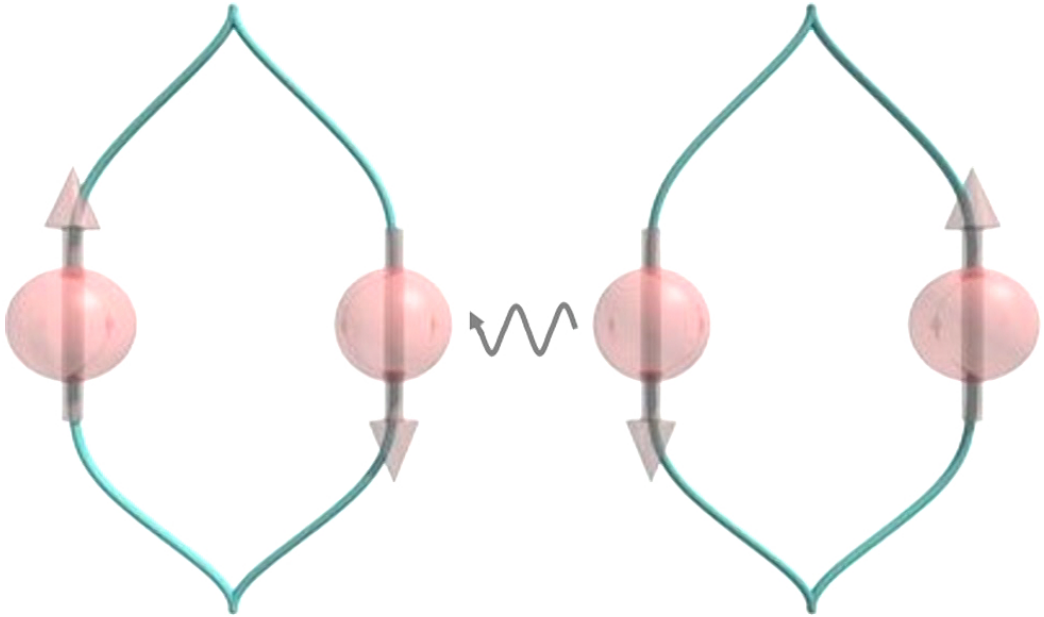
https://MaQSphysics.com

MaQS Workshop,
April 2019

Macroscopicity



Does gravity permit a quantum superposition?



S Bose, A Mazumdar, GW Morley, H Ulbricht, M Toroš, M Paternostro, A Geraci, P Barker, MS Kim & G Milburn, PRL 119, 240401 (2017)

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

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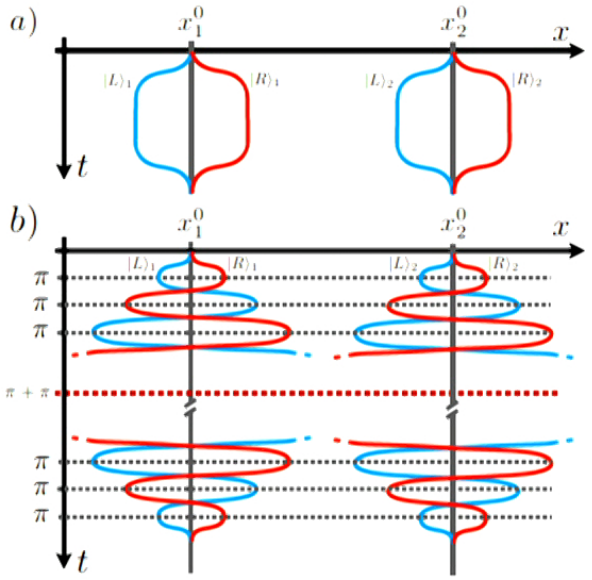

JS Pedernales, GWM & MB Plenio, arXiv:1906.00835 (2019)

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Conclusion

- Levitated microdiamonds could test the macroscopic limit of quantum mechanics
- High purity diamond helps
- Test if gravity permits a quantum superposition