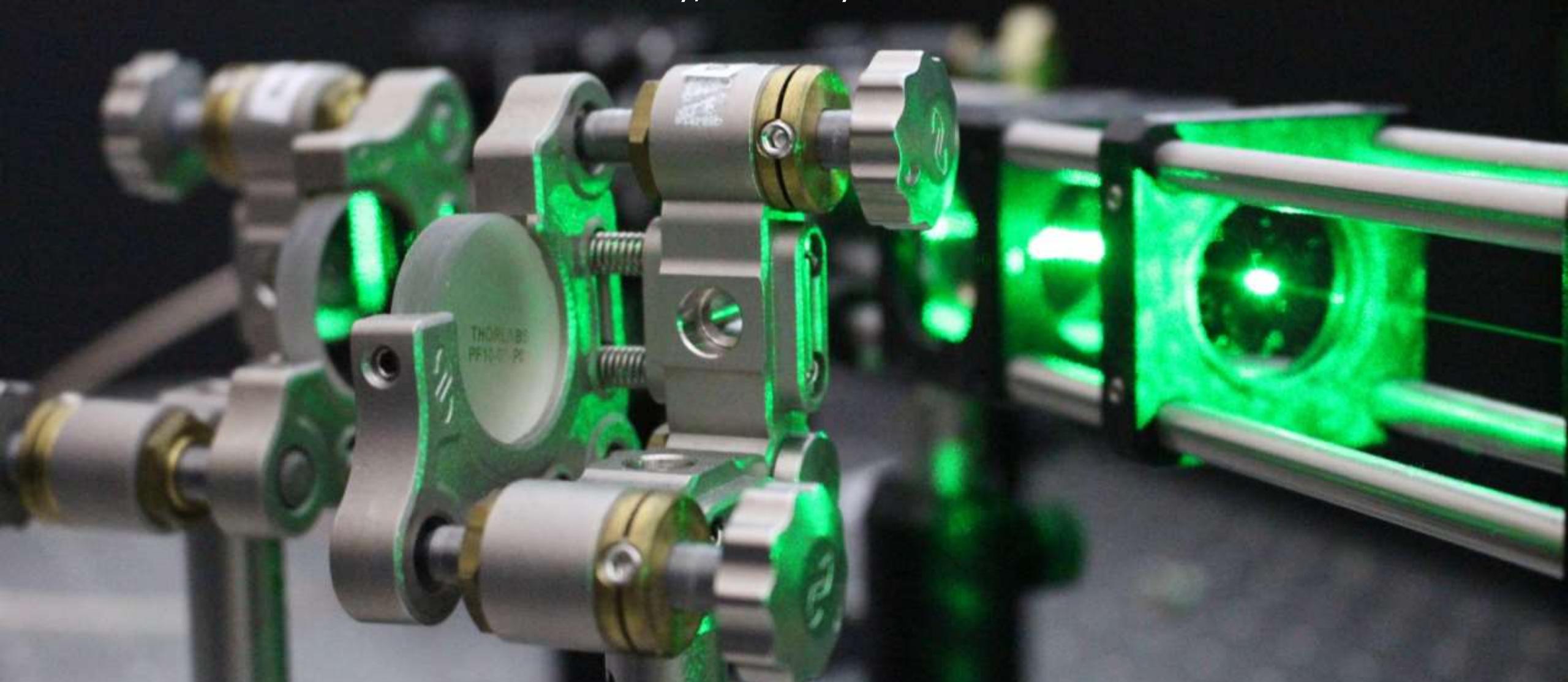


Levitating nanodiamond experiments: towards a test of quantum gravity

Gavin W Morley, University of Warwick



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Warwick University: Angelo Frangeskou, Colin Stephen, Anis Rahman (now UCL), Ben Green, Ben Breeze, Guy Stimpson, Yashna Lekhai, Rajesh Patel, Ben Wood, James March, Lingraj Kumar

Groningen: Anupam Mazumdar

Southampton: Hendrik Ulbricht, Marko Toroš

Queen's University Belfast: Mauro Paternostro

Northwestern: Andrew Geraci

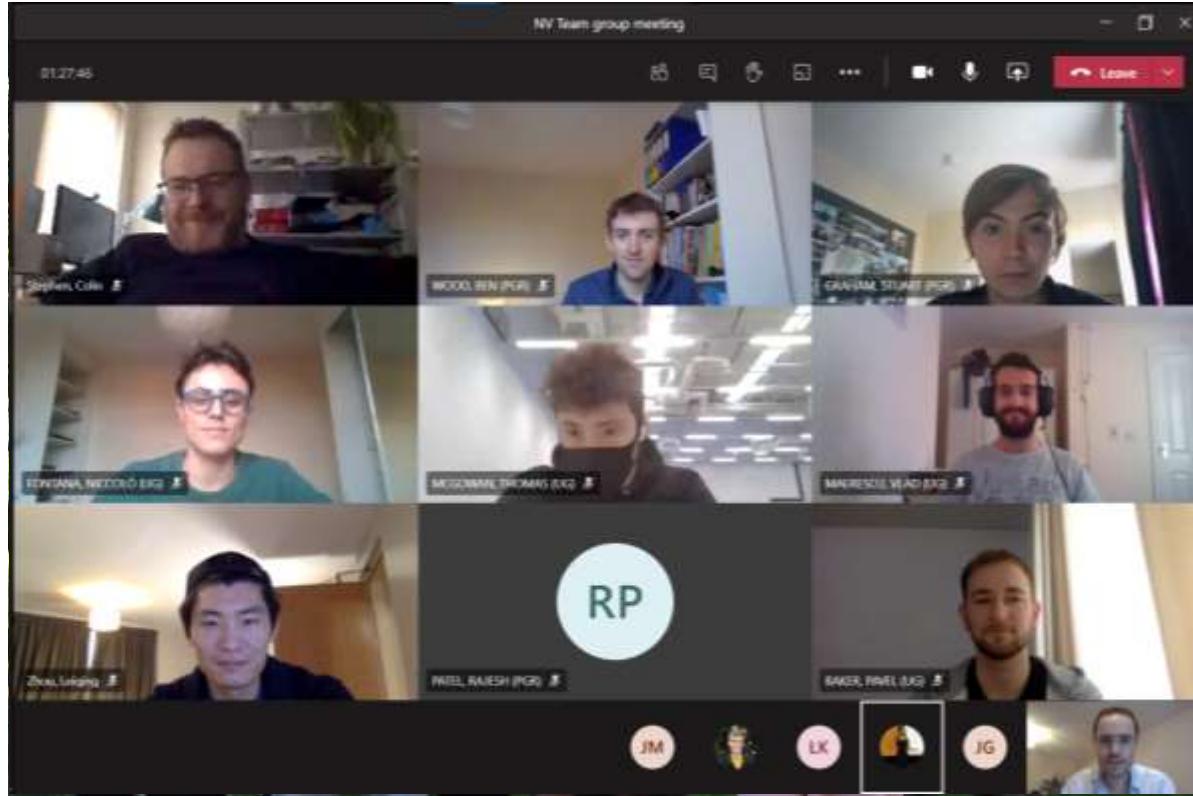
Queensland: Gerard Milburn

Ulm: Julen Pedernales, Martin Plenio

Cardiff University: Laia Gines, Soumen Mandal & Oliver Williams

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

Imperial College London: Chuanqi Wan, Myungshik Kim



Engineering and
Physical Sciences
Research Council





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

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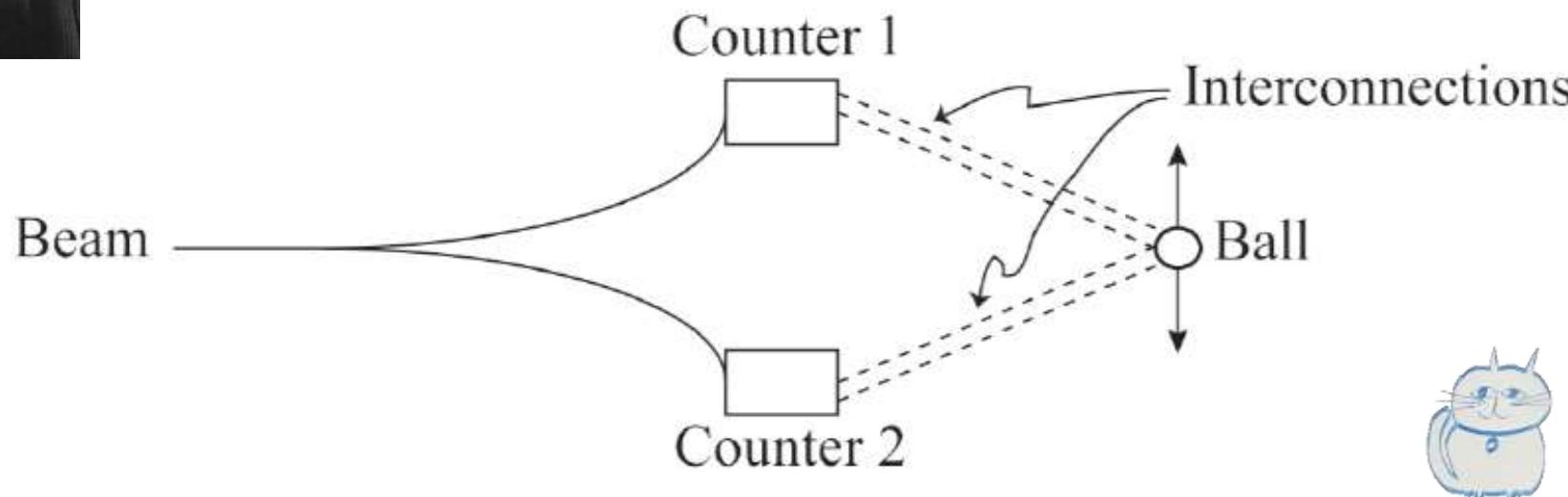
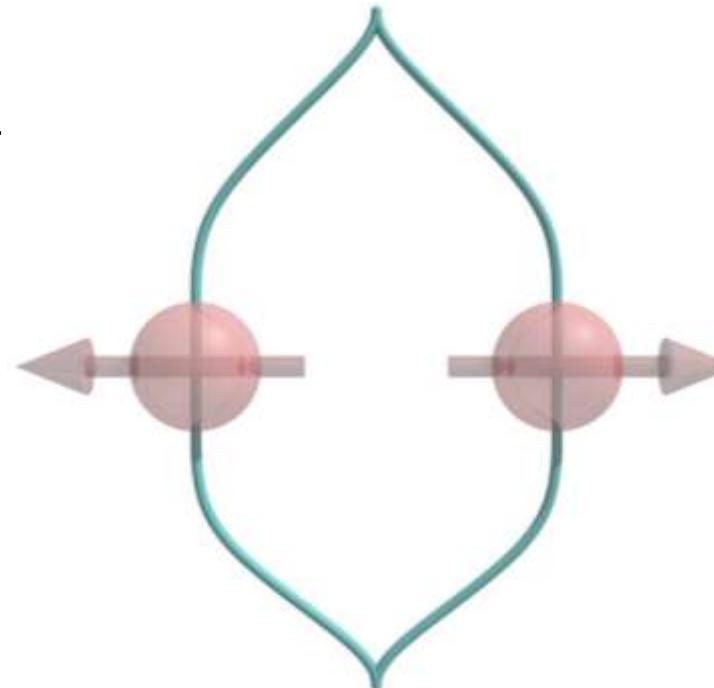
$$|\Psi_{cat}\rangle = \frac{1}{\sqrt{2}}\left(|\text{cat in box}\rangle + |\text{empty box}\rangle\right)$$



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

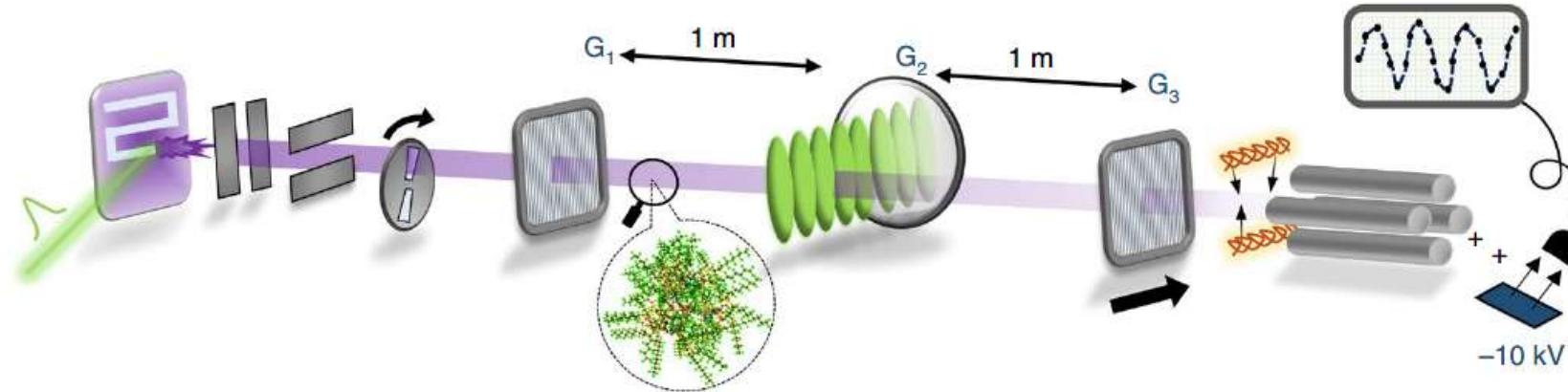


Richard Feynman
CM DeWitt, D Rickles (eds), The role
of gravitation in physics: report from
the 1957 Chapel Hill Conference,
page 250, Published 2011

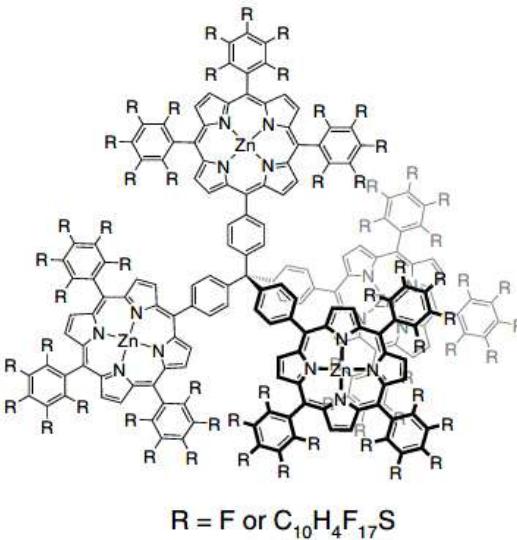


What is the gravitational effect
from a mass in a spatial superposition?

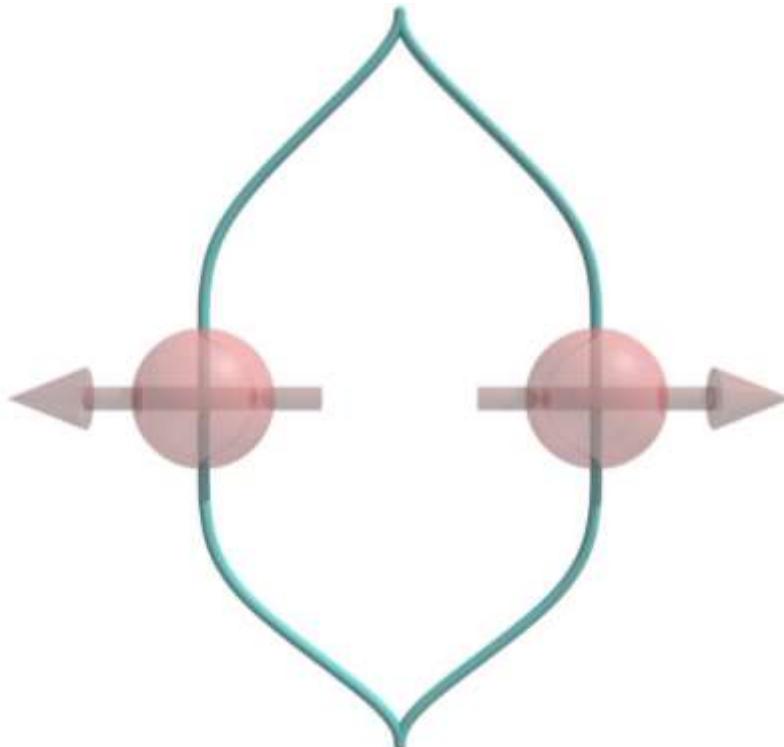
The most macroscopic spatial superposition so far



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... & GWM, arXiv:2105.02105 (2021)

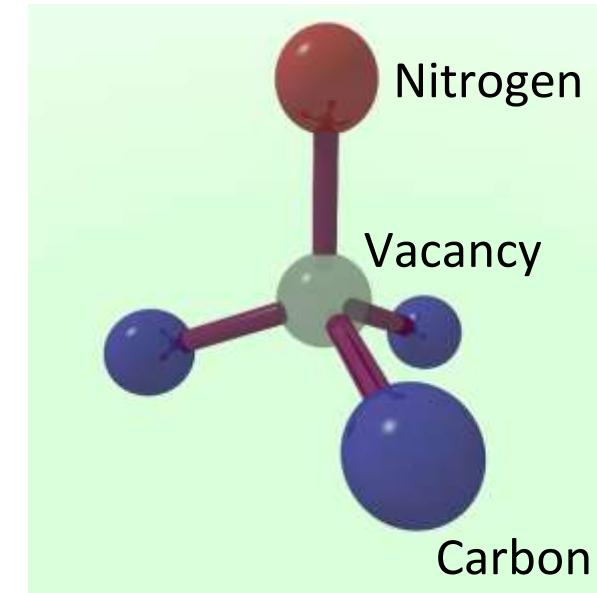
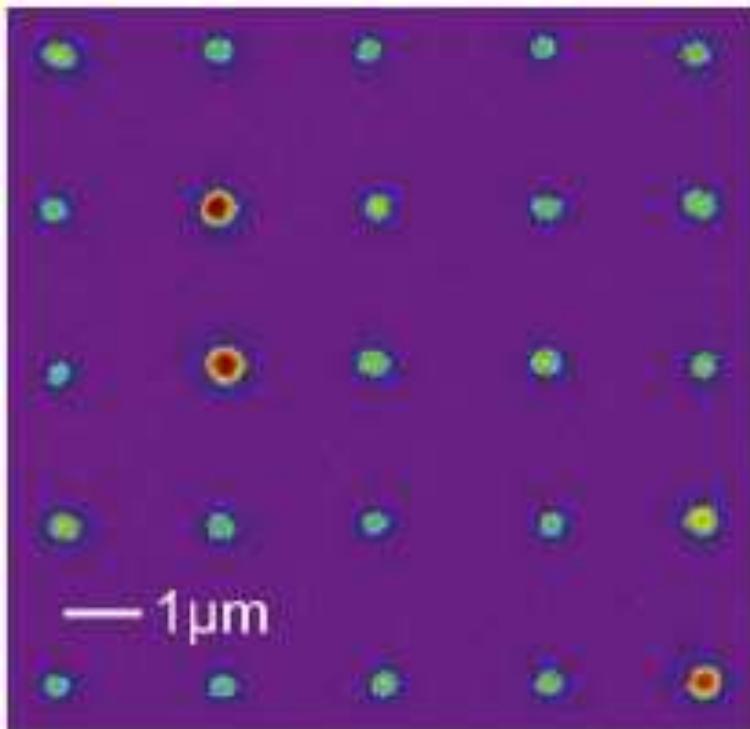
From other groups:

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



Nitrogen-vacancy (NV^-) centres in diamond

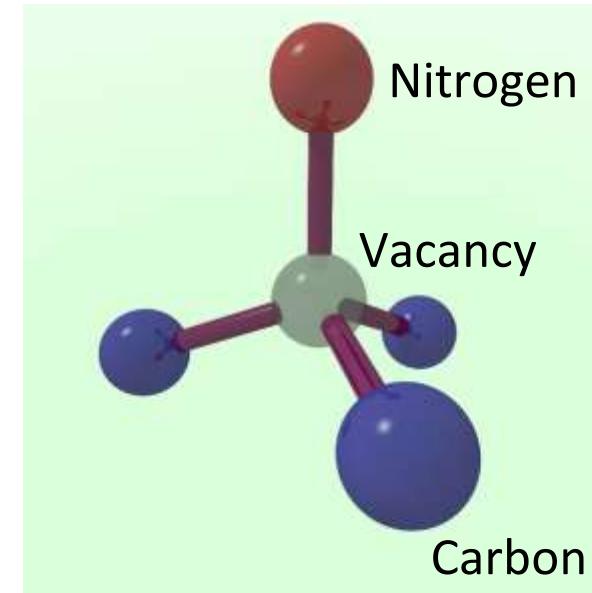
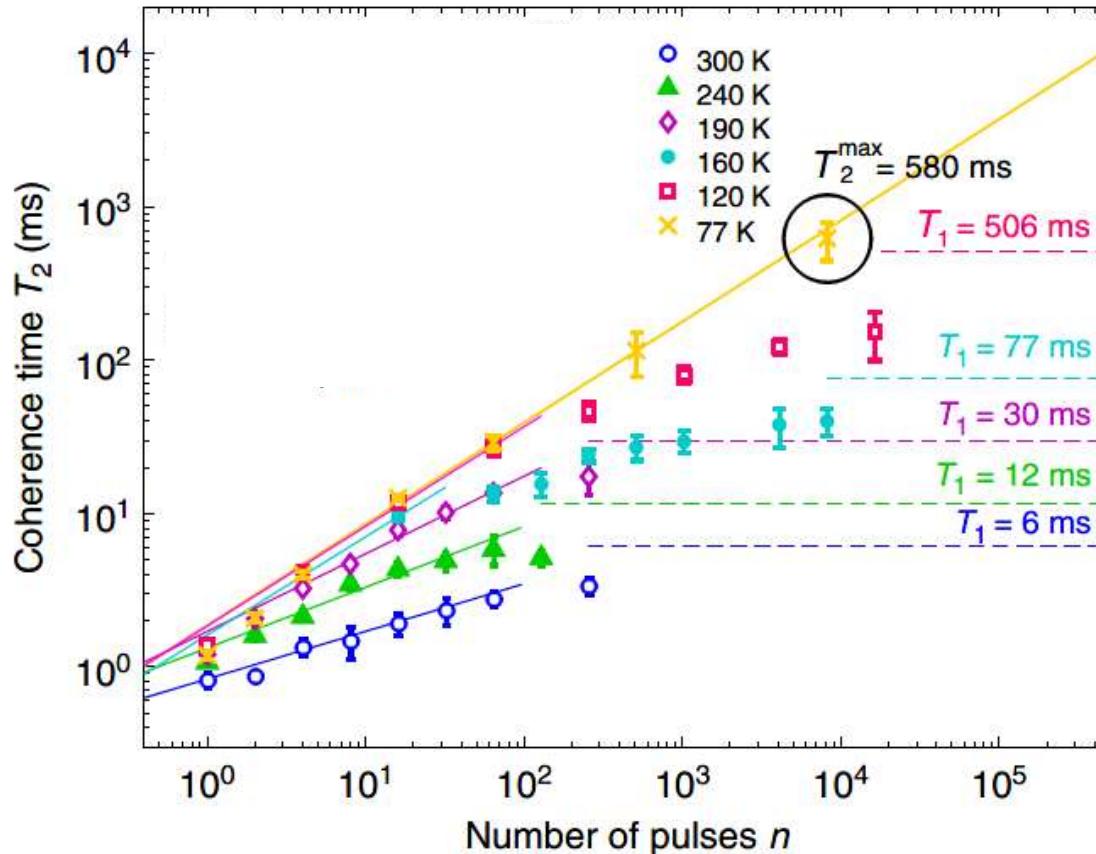
Photo by Jon Newland (Warwick)



Y-C Chen... & JM Smith Nat Photon 11, 77 (2017)
CJ Stephen... & GWM, PR Applied 12, 064005 (2019)
Y-C Chen... & JM Smith, Optica 6, 662 (2019)



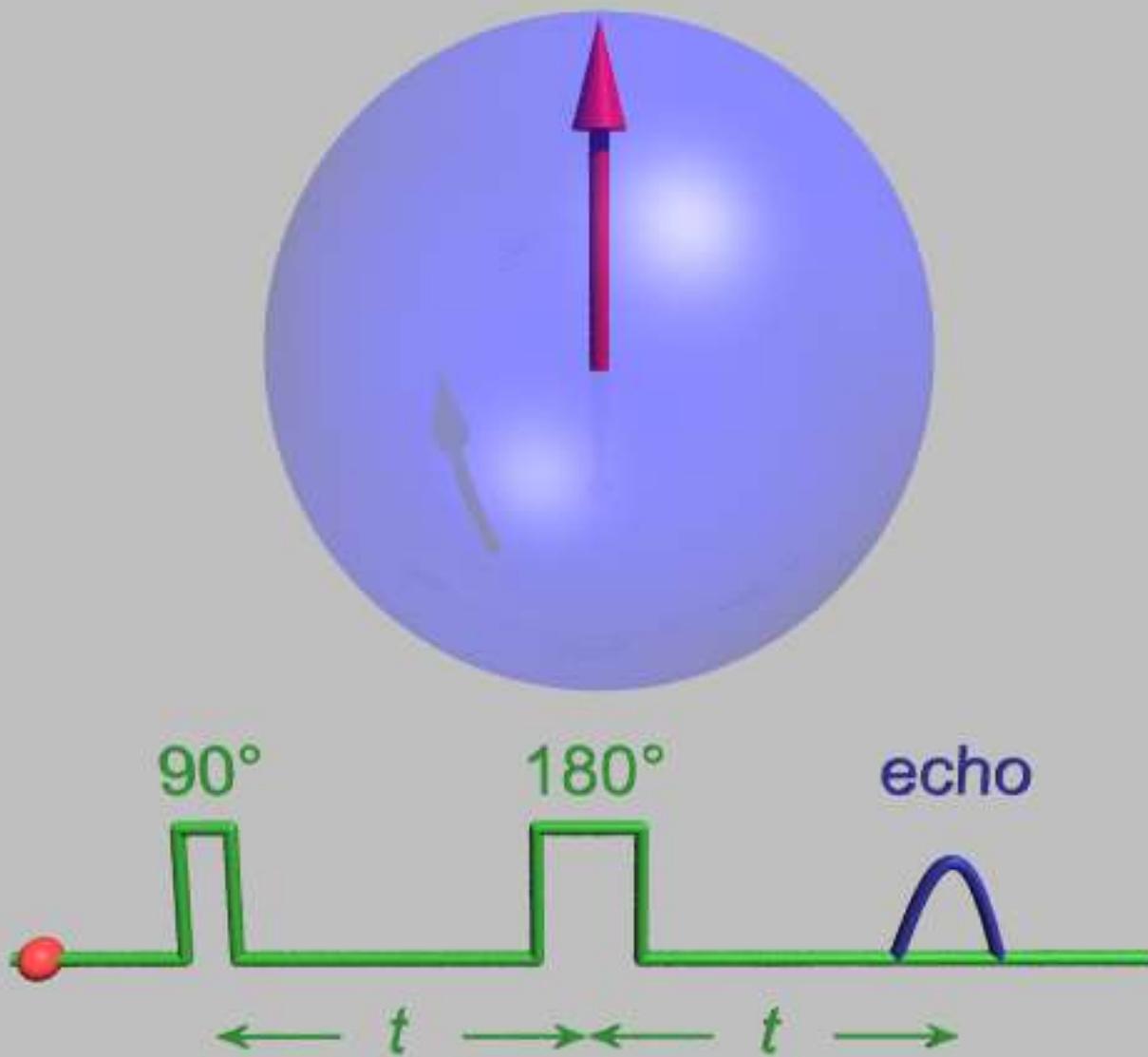
Nitrogen-vacancy (NV^-) centres in bulk diamond



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



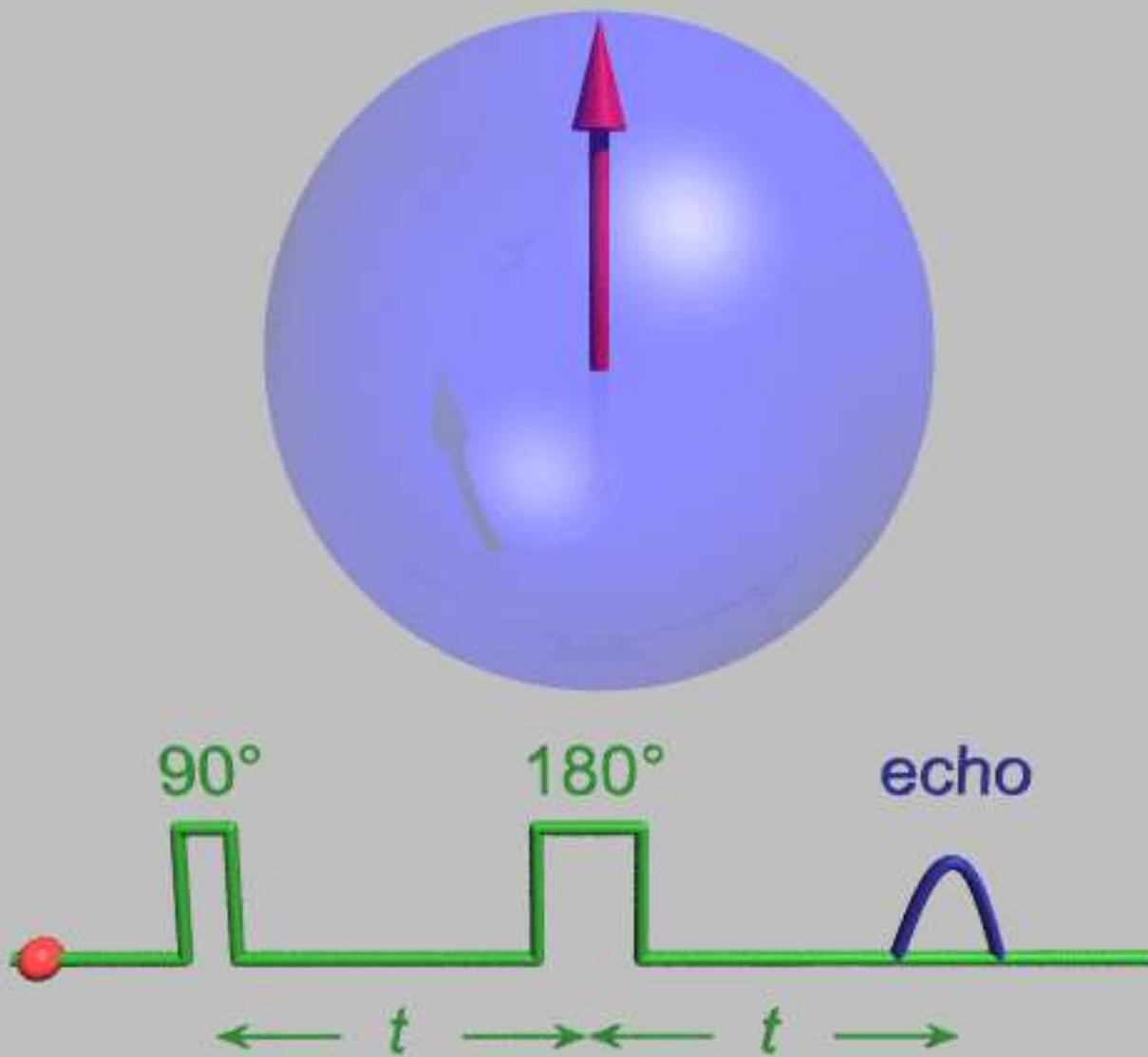
Spin echo



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



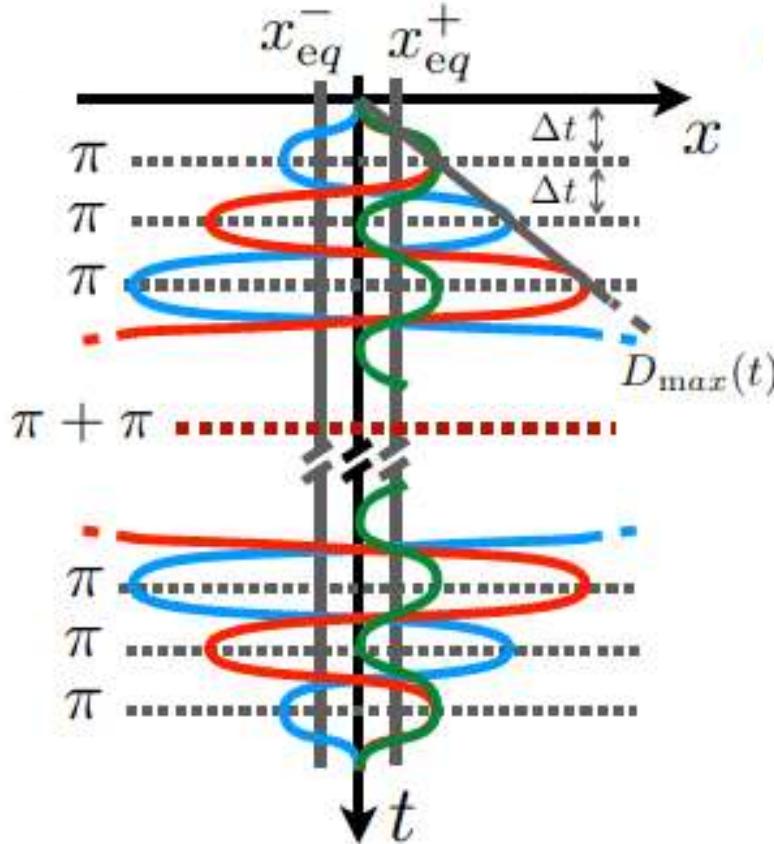
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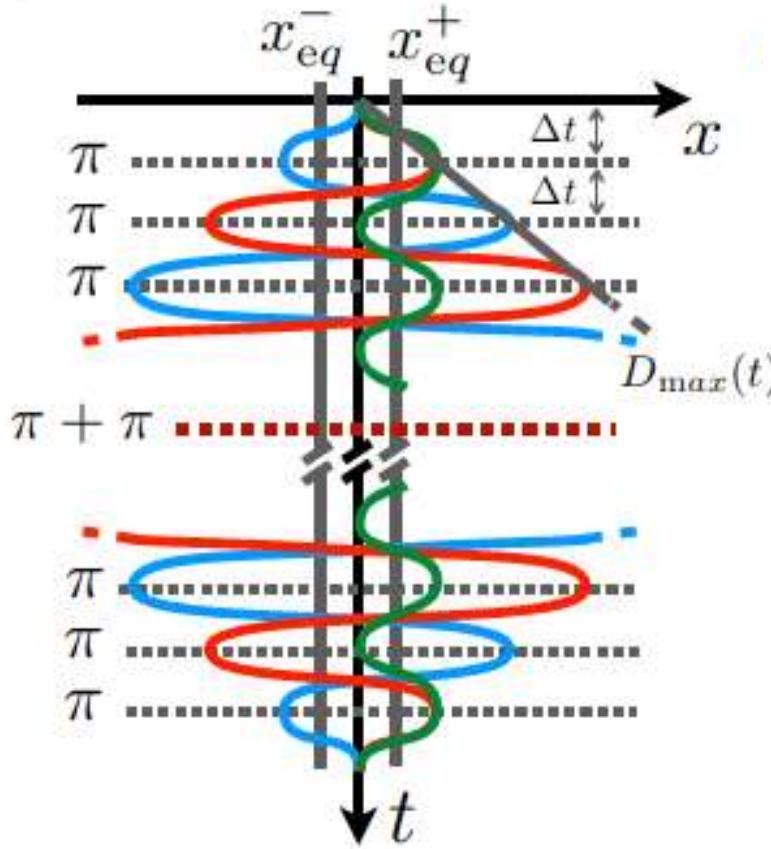


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- C Wan... & MS Kim, PRL **117**, 143003 (2016)
- S Bose... & G Milburn, PRL **119**, 240401 (2017)
- JS Pedernales, GWM & MB Plenio, PRL **125**, 023602 (2020)
- BD Wood... & GWM, arXiv:2105.02105



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- JS Pedernales, GWM & MB Plenio, PRL **125**, 023602 (2020)
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Decoherence:

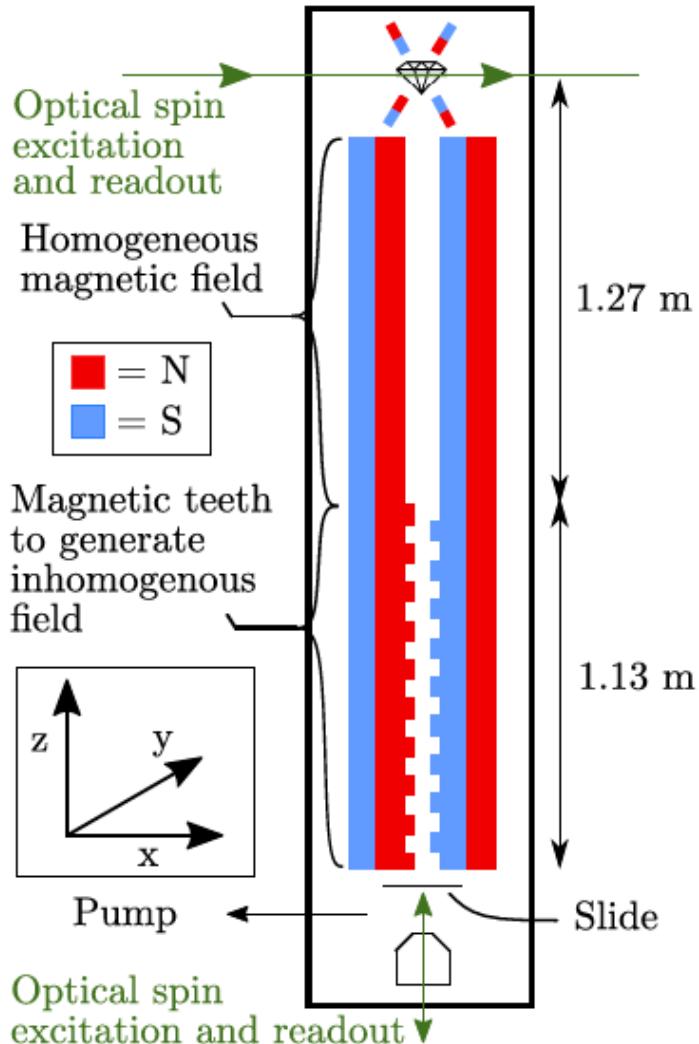
- Spin decoherence
- Electric charges
- Gas atoms
- Blackbody radiation
- Rotation of nanodiamond
- Casimir force
- Vibrations and tilt



Our proposal: drop a nanodiamond containing a spin



Ben Wood



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- JS Pedernales, GWM & MB Plenio, PRL **125**, 023602 (2020)
- BD Wood, GA Stimpson, JE March, YND Lekhai, CJ Stephen, BL Green, AC Frangeskou, L Ginés, S Mandal, OA Williams, S Bose & GWM, arXiv:2105.02105

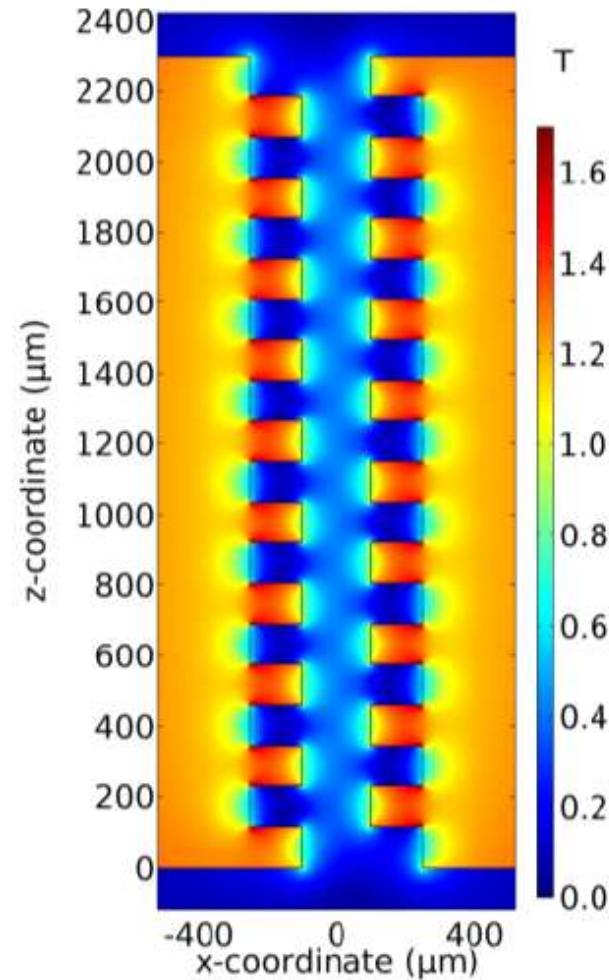
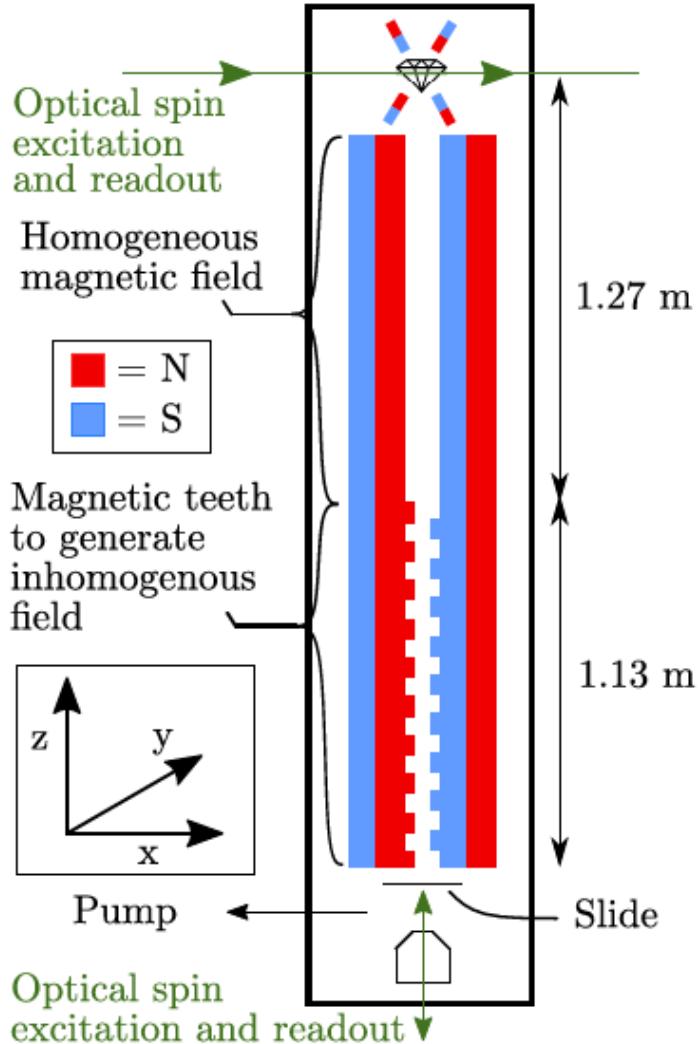


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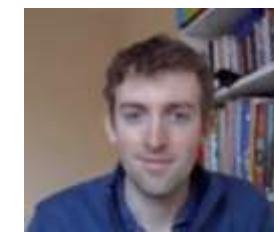


Ben Wood

BD Wood... & GWM,
arXiv:2105.02105

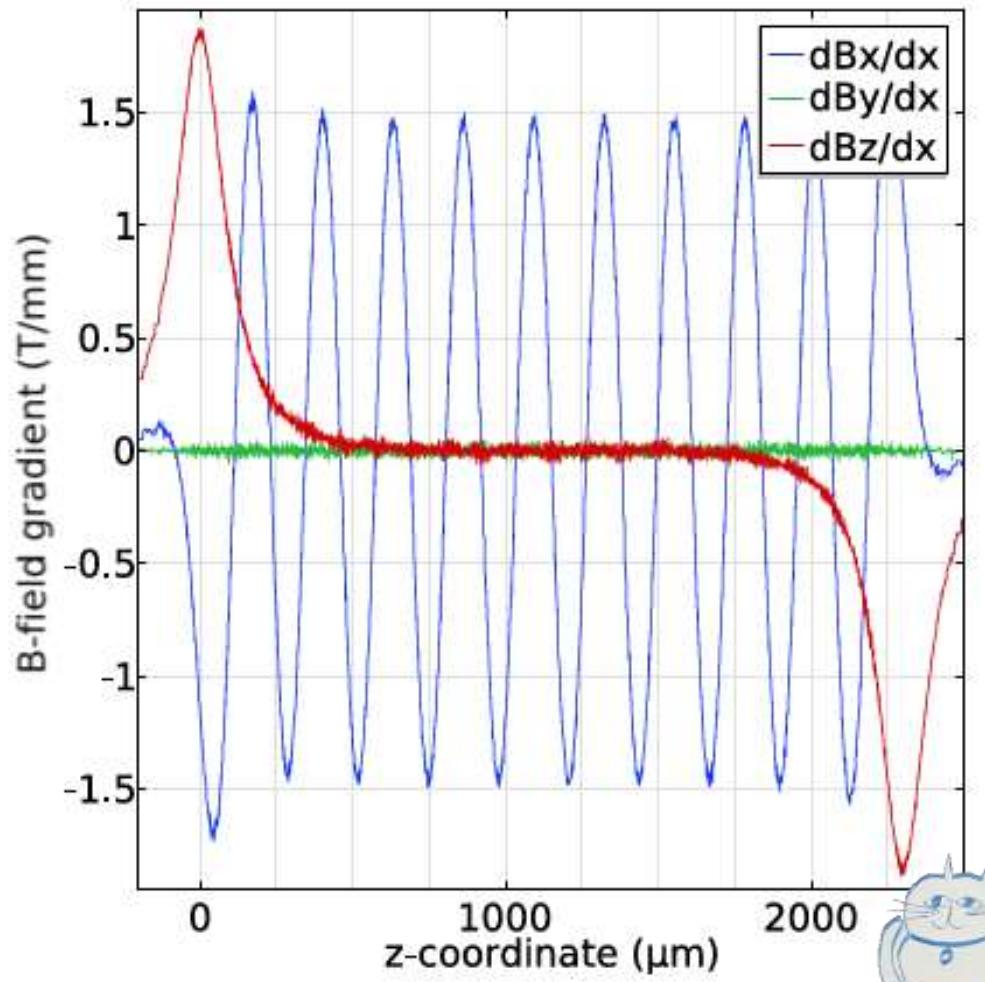
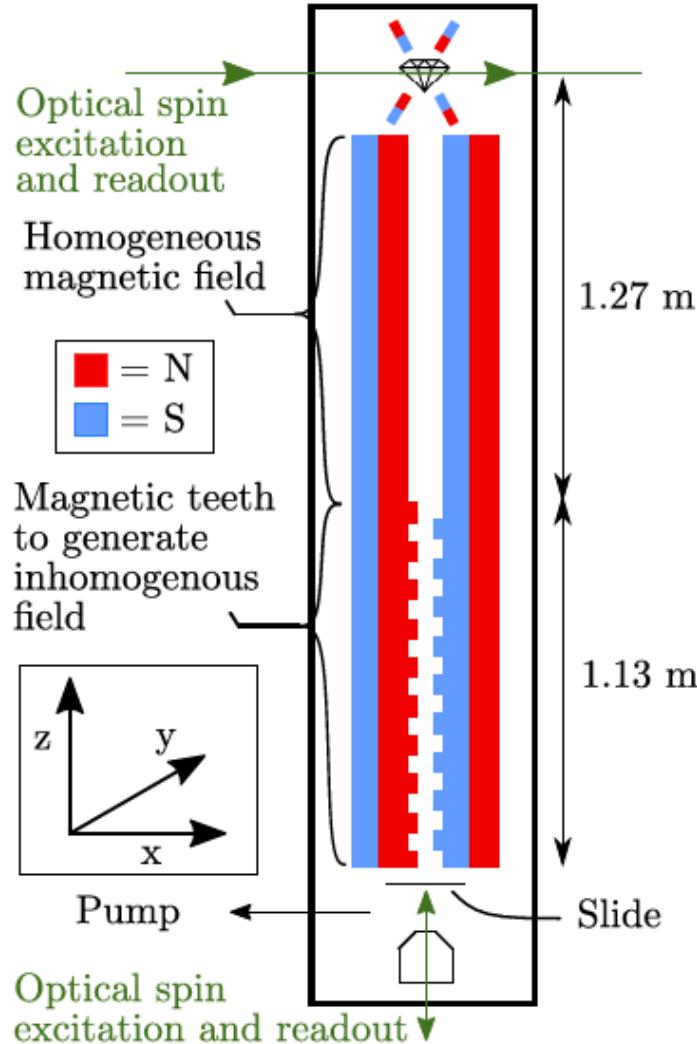


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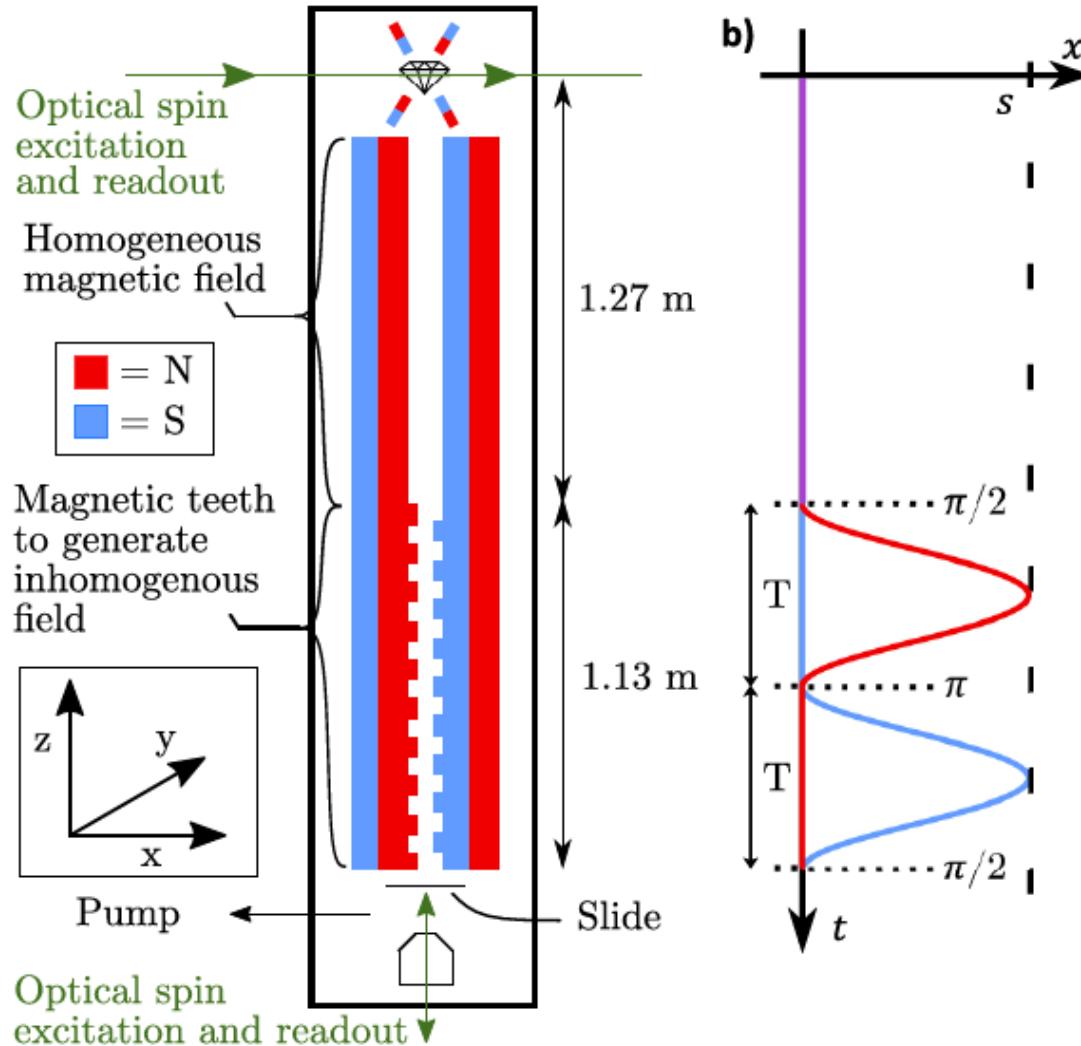


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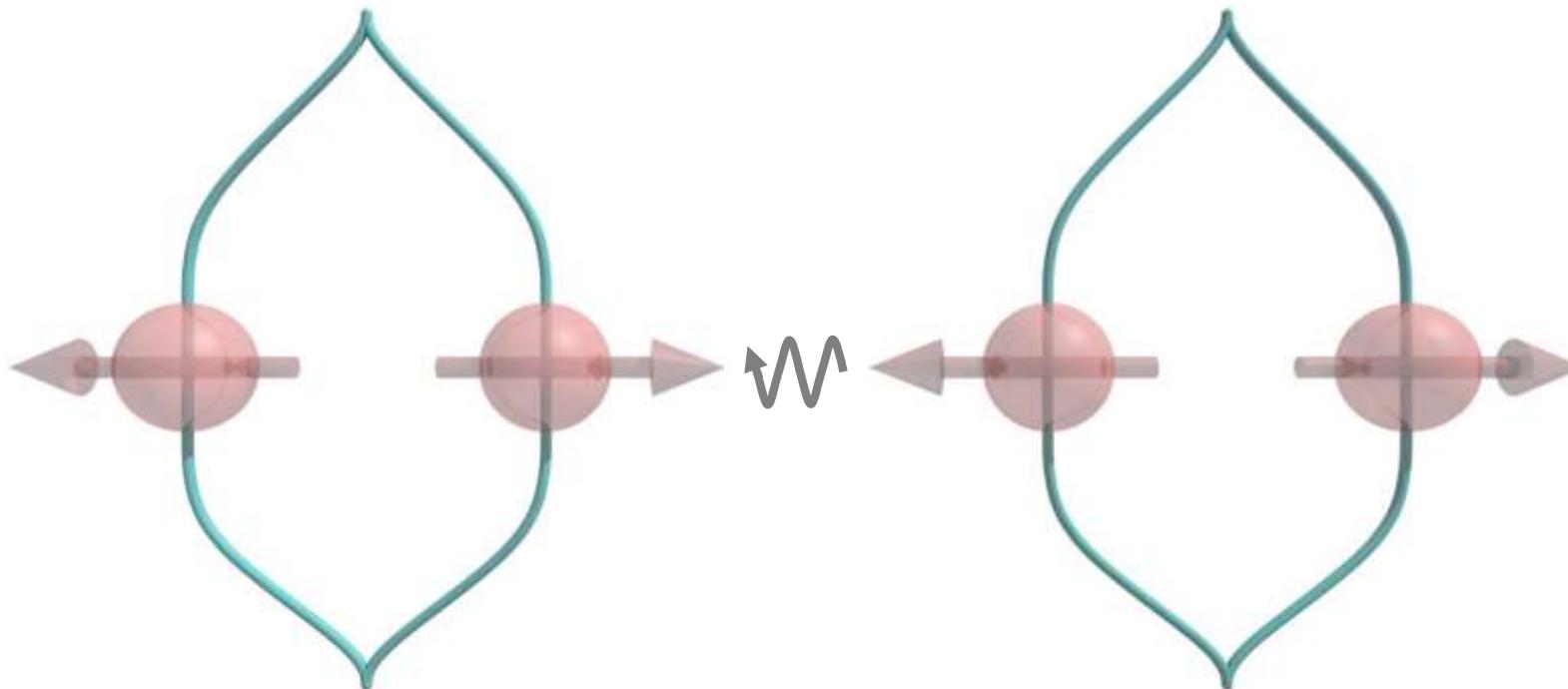


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BD Wood... & GWM,
arXiv:2105.02105



Can gravitational effects be in a quantum superposition?



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

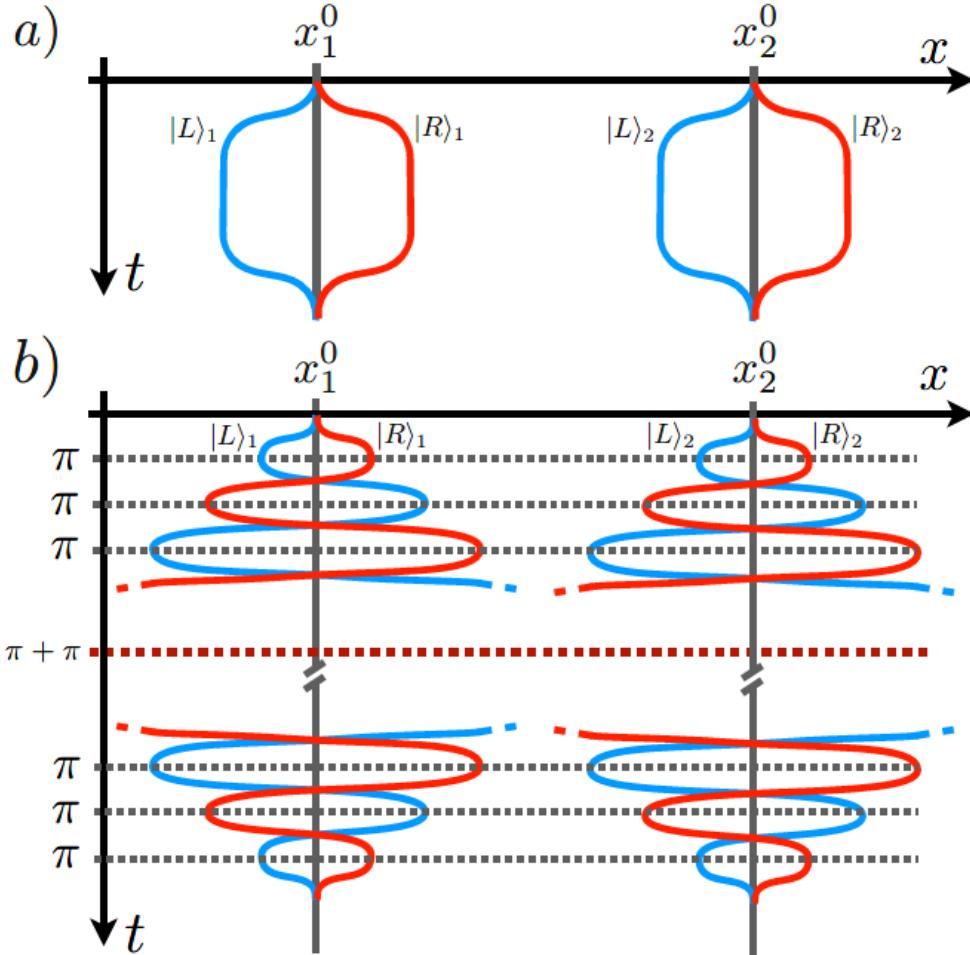
C Marletto & V Vedral, PRL 119, 240402 (2017)

$\Delta x \sim 250 \mu\text{m}$

Closest
approach $\sim 200 \mu\text{m}$

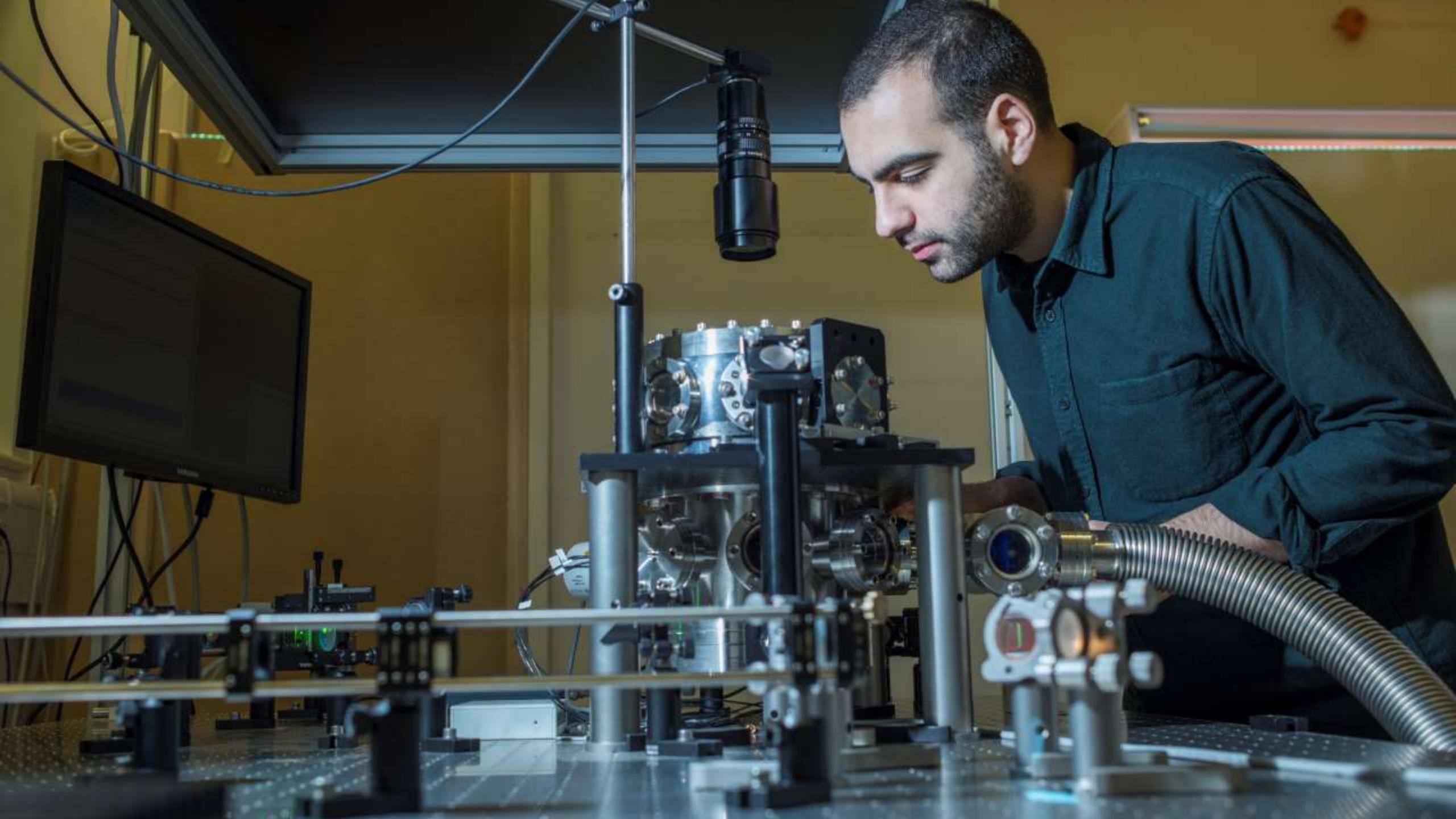


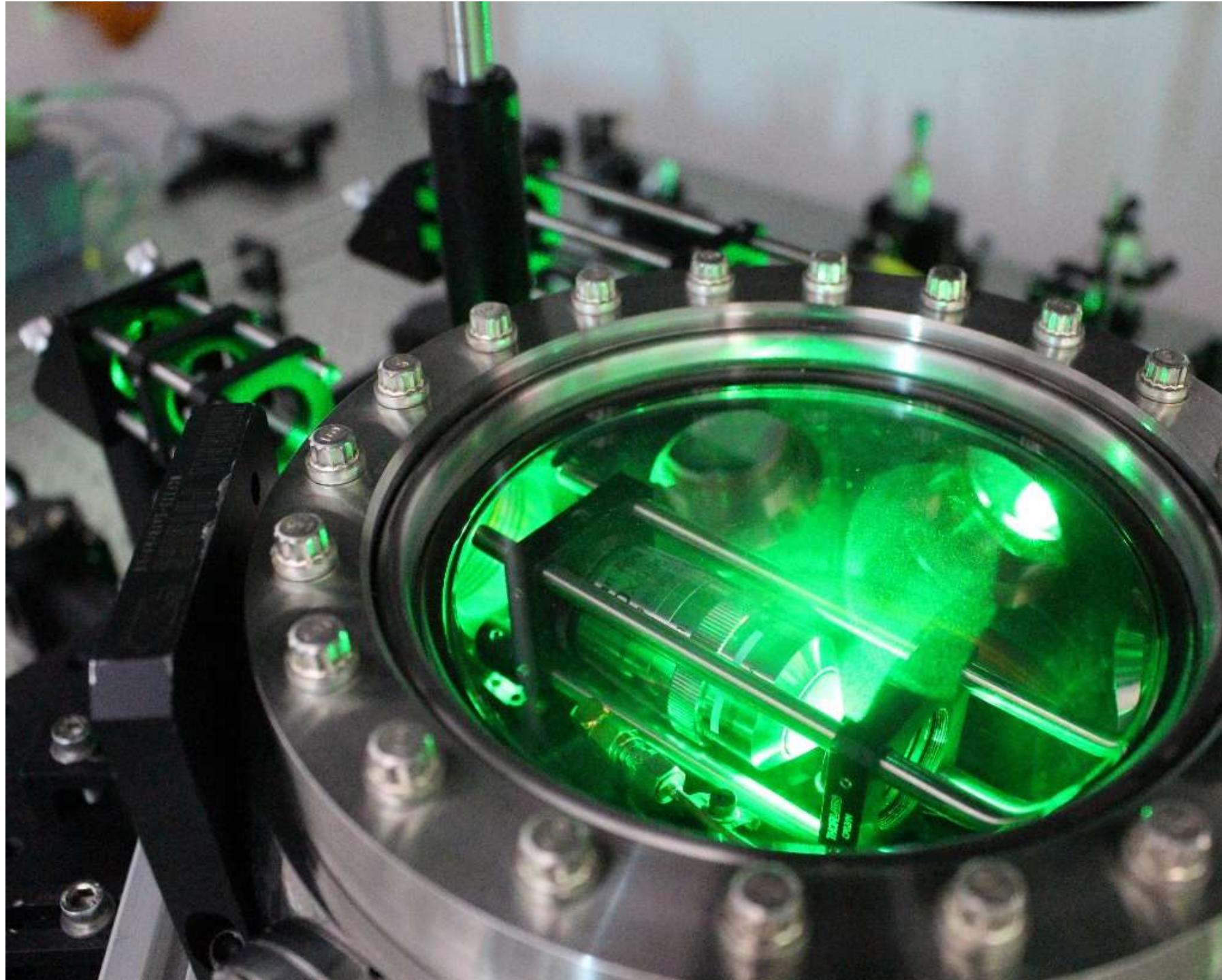
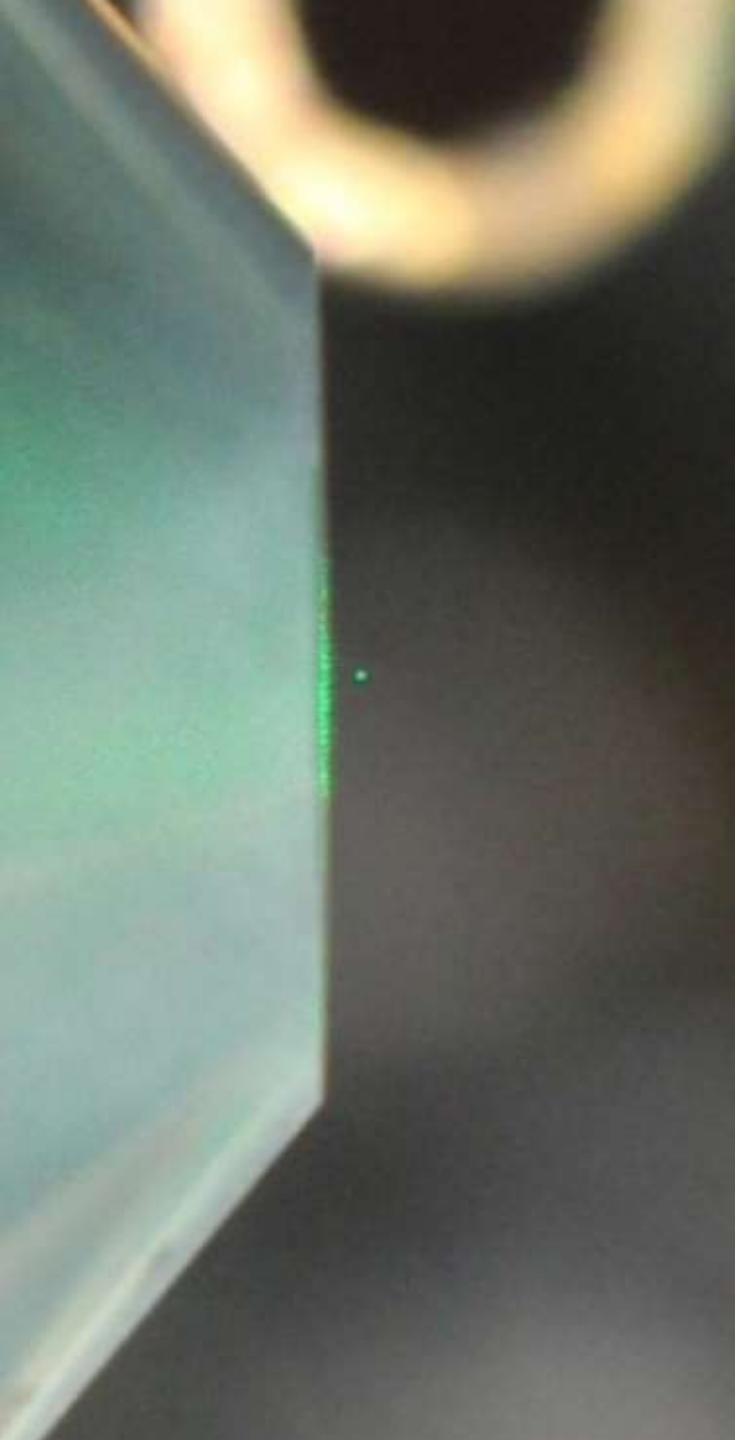
Our proposal: drop a nanodiamond containing a spin



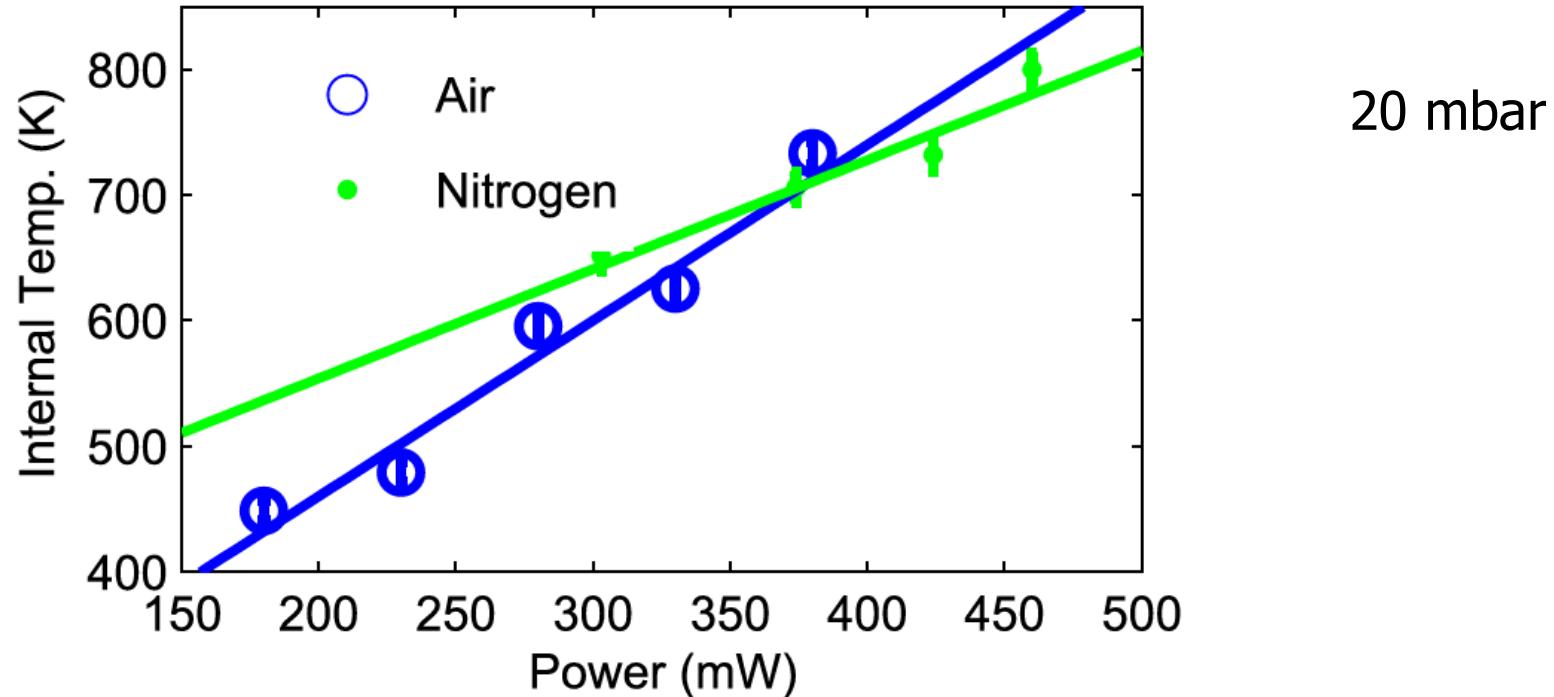
JS Pedernales, GWM & MB
Plenio, PRL **125**, 023602
(2020), arXiv:1906.00835







Levitating nanodiamonds overheating

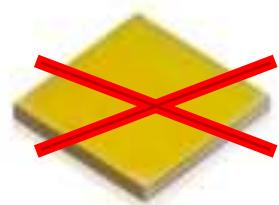


20 mbar

ATMA Rahman, AC Frangeskou, MS Kim, S Bose, GWM & PF Barker, Scientific Reports **6**, 21633 (2016)



A solution: more pure diamonds



150 ppm nitrogen
impurities

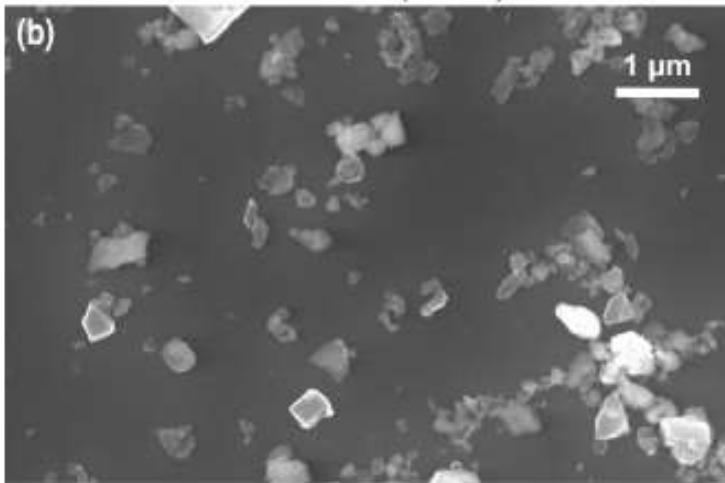


120 ppb nitrogen
impurities

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

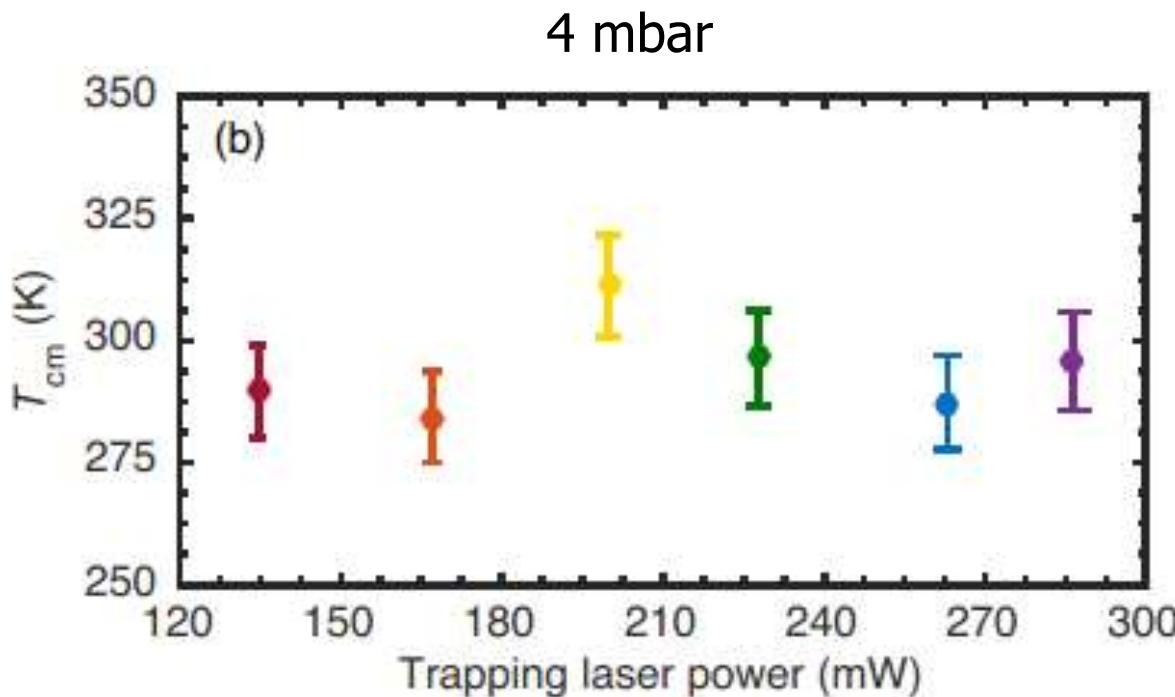
Milling by Ollie
Williams' group,
Cardiff



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



A solution: more pure diamonds



Still need a
magnetic trap to
have internal
temperature $\sim 5\text{K}$

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

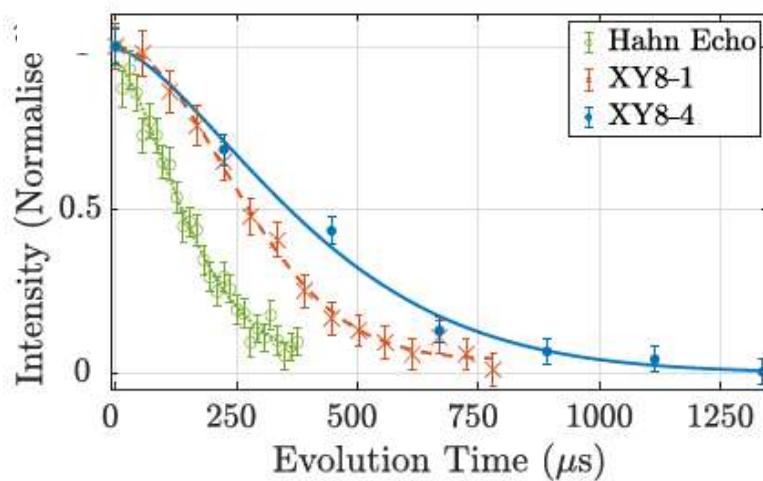


Guy Stimpson



A solution: more pure diamonds

Scanning Electron Microscopy (SEM)

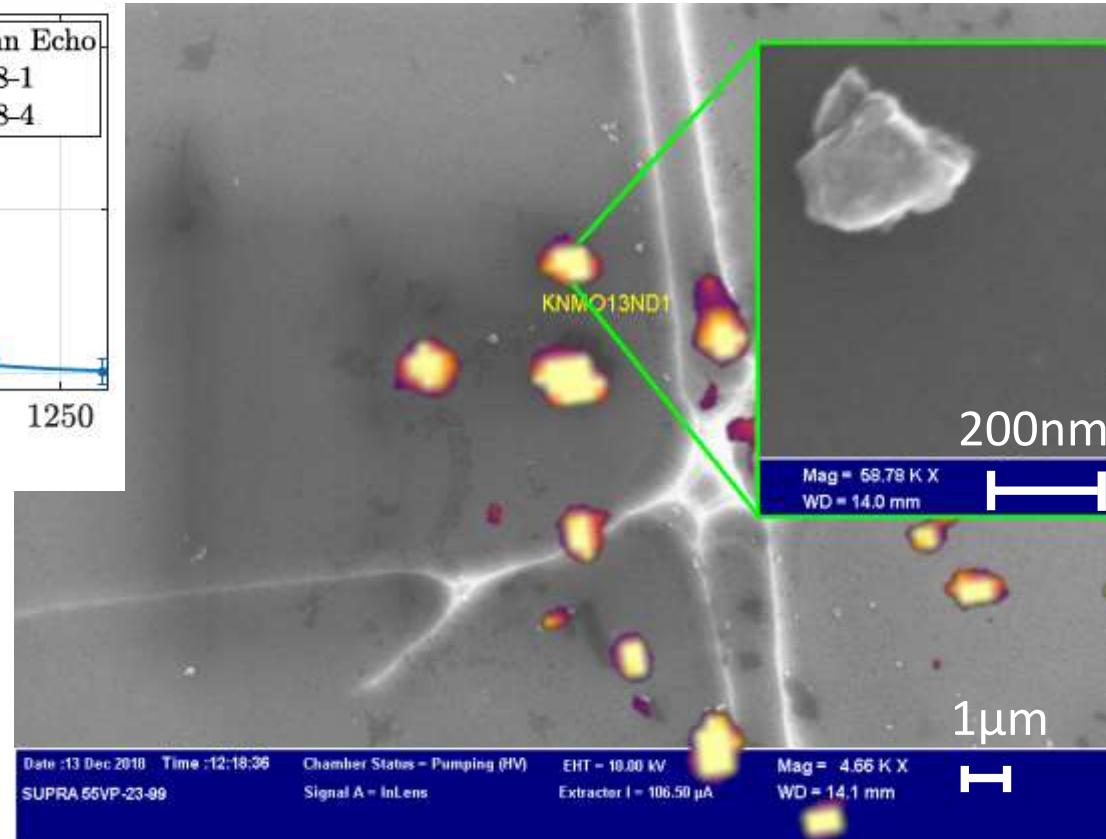


$$T_2 \text{ Hahn echo} = 177 \mu\text{s}$$

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

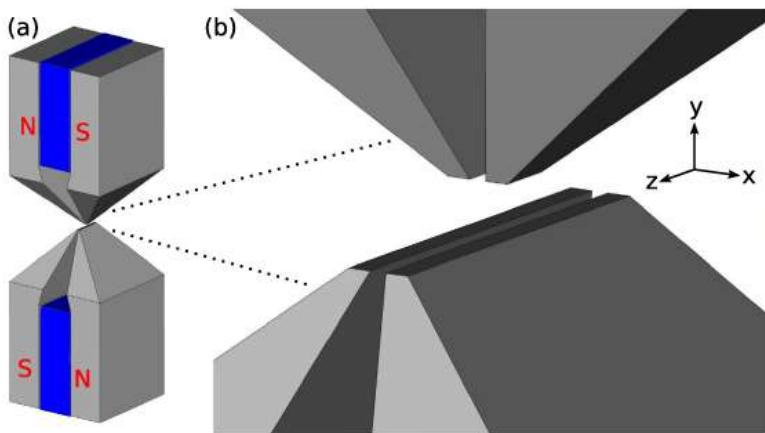


Ben
Wood

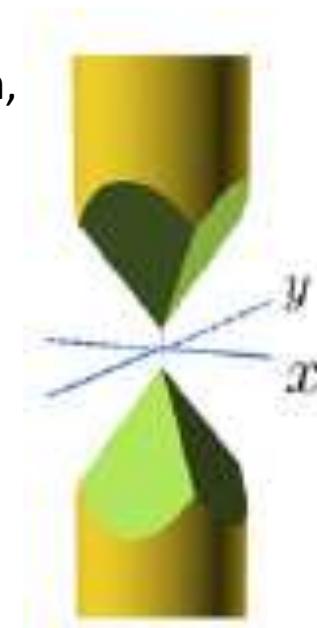


Magnetic traps for nanodiamonds

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)



Diamond spatial superposition roadmap

1. Levitating nanodiamonds

- J-F Hsu... & B D'Urso, *Sci Rep* **6**, 30125 (2016)
- MC O'Brien... & J Twamley, *APL* **114**, 053103 (2019)
- Gabriel Hetet's ion trap work

2. Spatial superposition in a trap

- M Scala... & S Bose, *PRL* **111**, 180403 (2013)

3. + free flight

- C Wan... & MS Kim, *PRL* **117**, 143003 (2016)

4. + magnetic teeth with cryostat and two-lobe dynamic decoupling

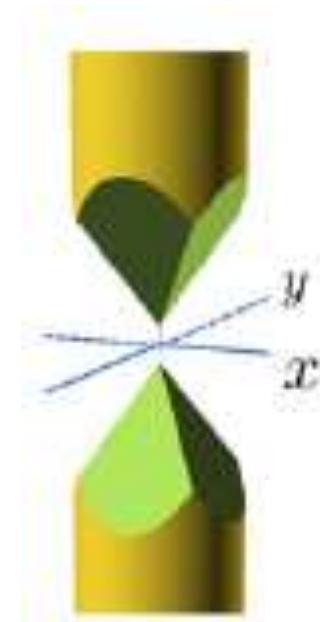
- BD Wood... & GWM, arXiv:2105.02105 (2021)

5. + many lobes of dynamic decoupling

- JS Pedernales, GWM & MB Plenio, *PRL* **125**, 023602 (2020)

6. Two diamonds entangled with gravity

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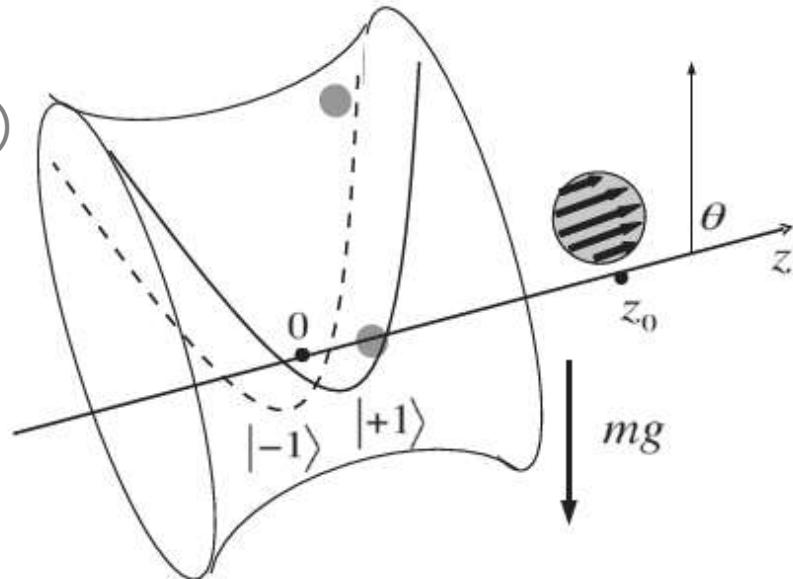
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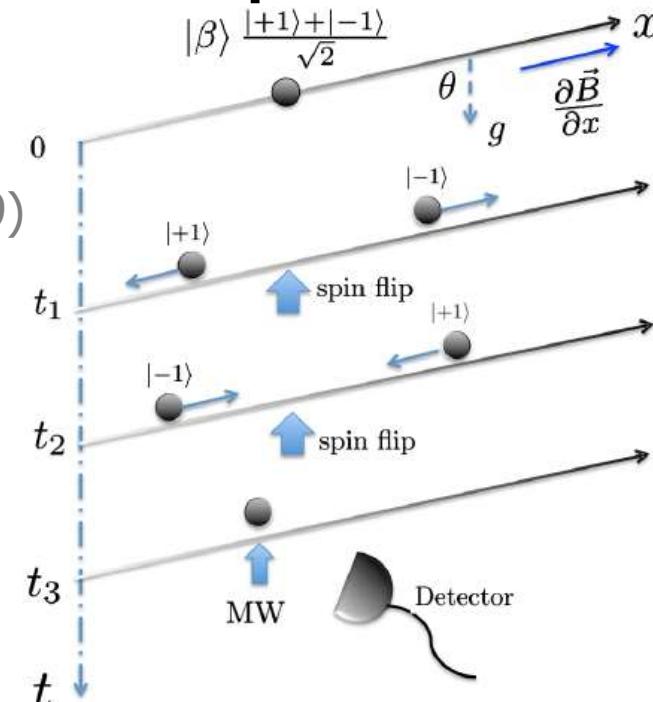
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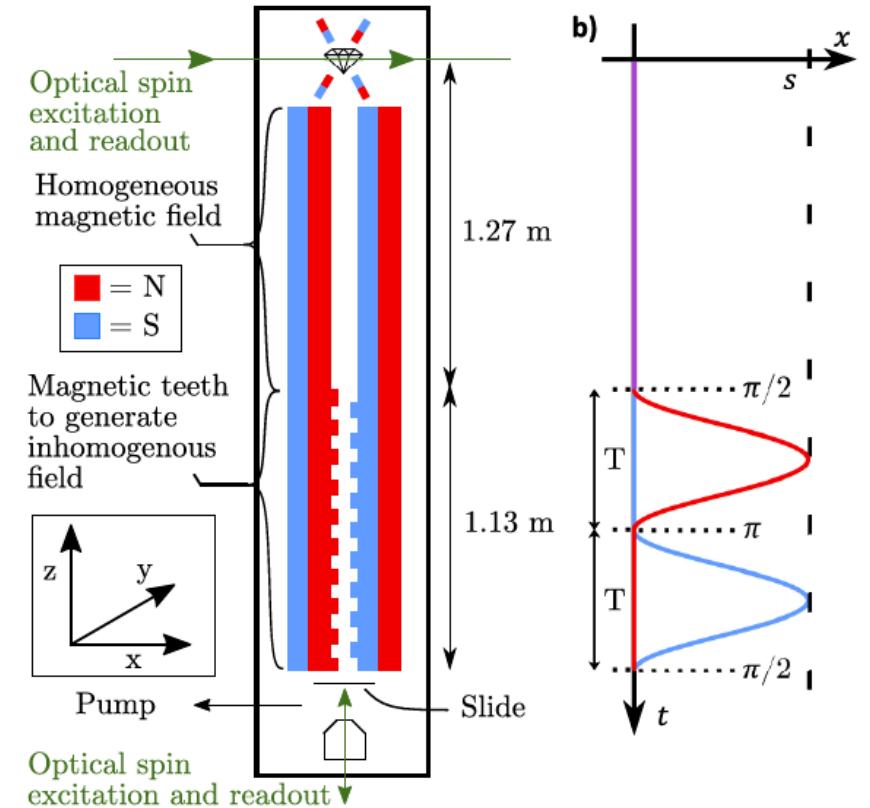
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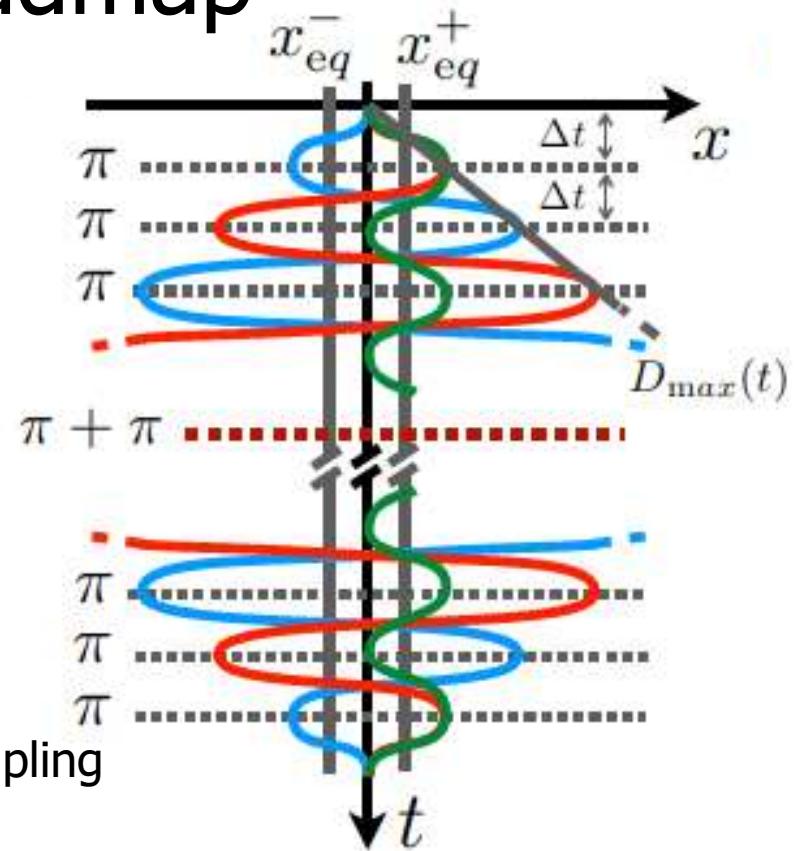
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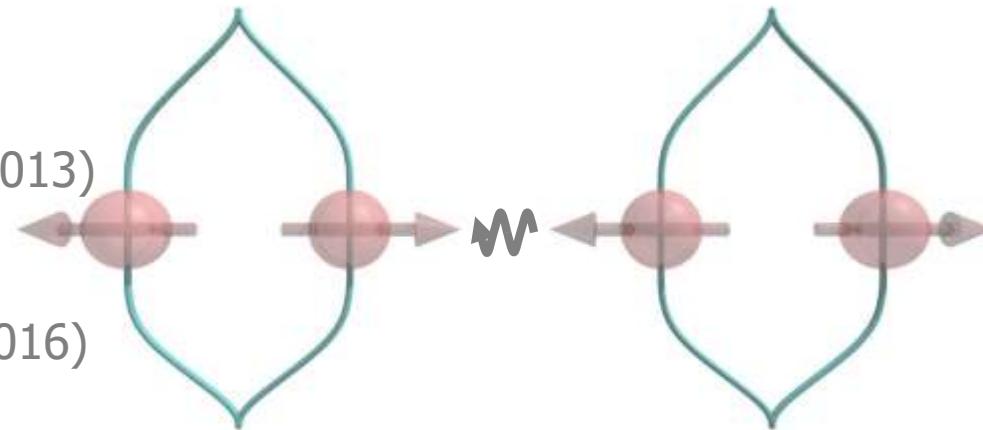
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Conclusions

- Dropping levitated nanodiamonds could test quantum gravity
- Purer nanodiamonds don't heat up in an optical trap at 4 mbar, and have long-lived spin coherence

