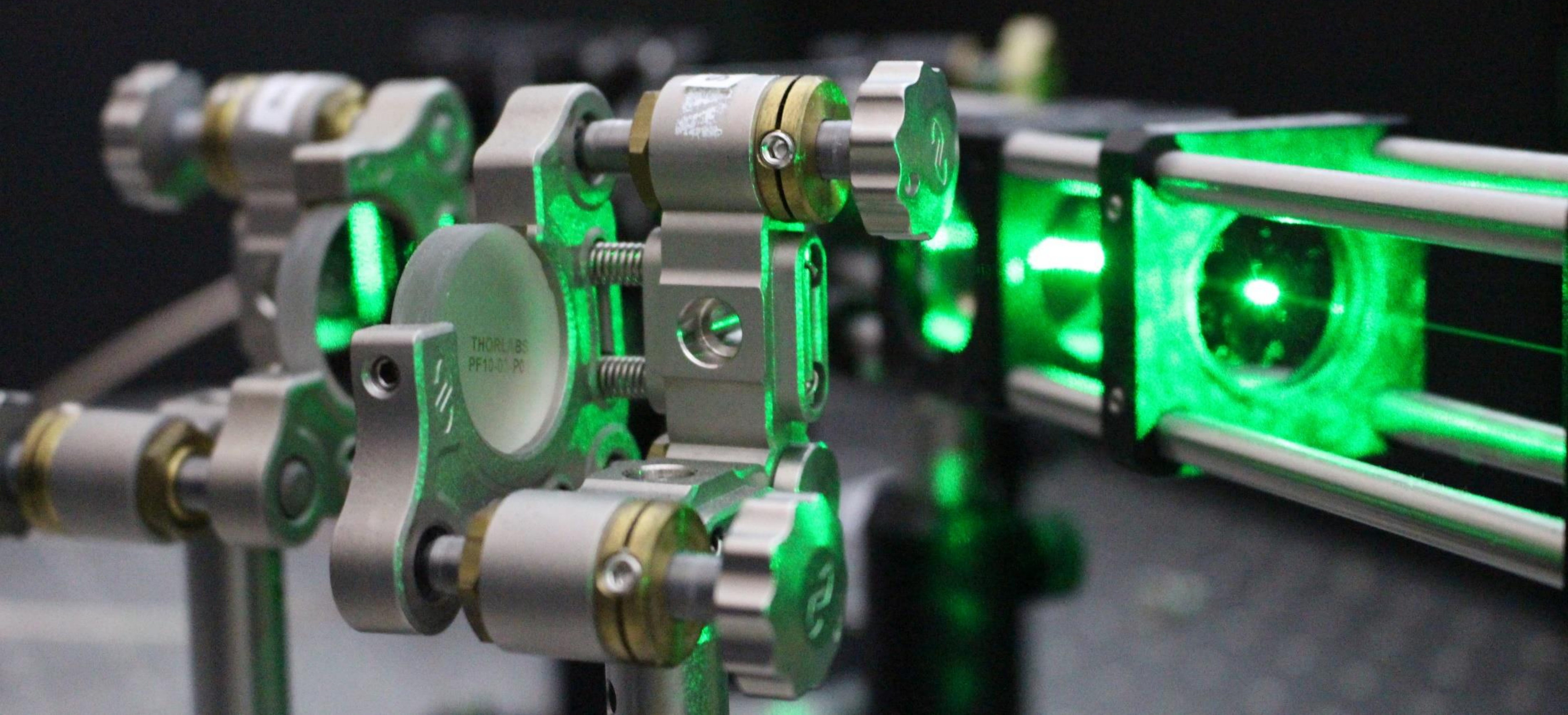
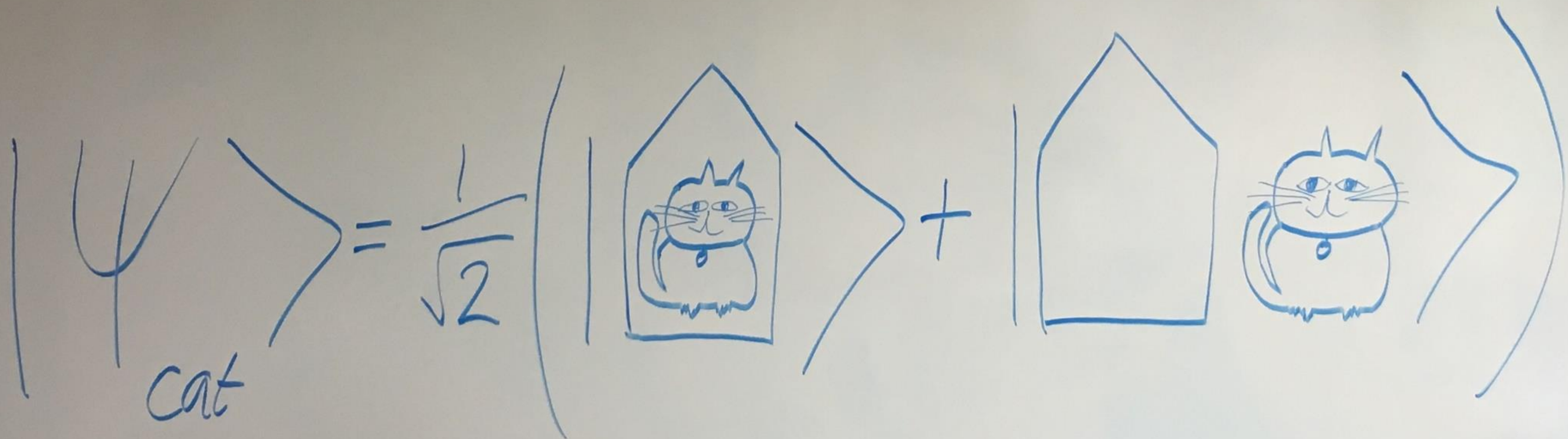
WP2: Macroscopic quantum superpositions for physics beyond the standard model (MaQS)

Gavin W Morley, University of Warwick



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

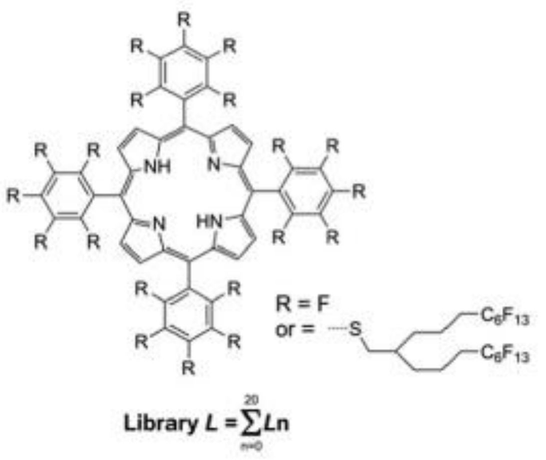
$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|L\rangle + |R\rangle\right)$$

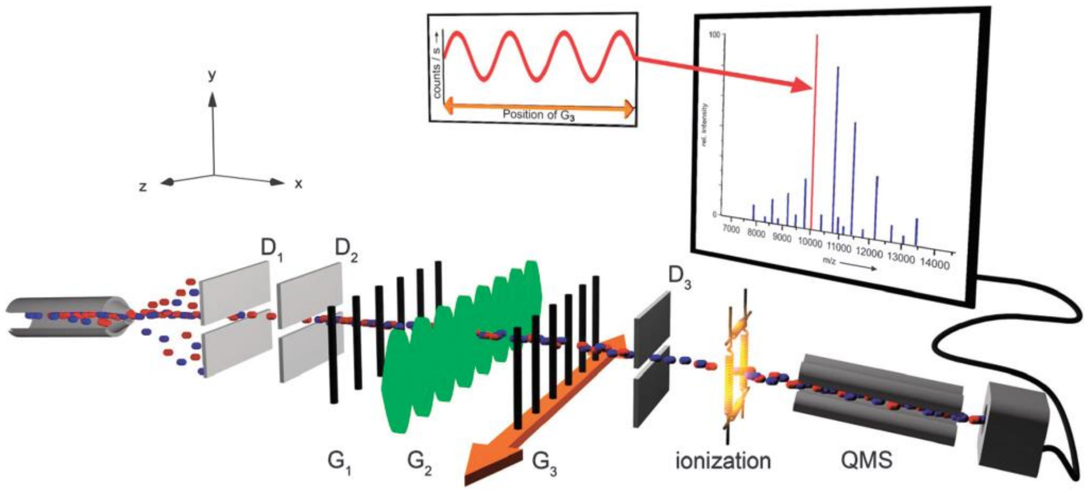


Science goal:

What is the most macroscopic spatial superposition possible?

Most macroscopic spatial superposition so far





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

Outline

- Science goals
- Deliverables and plan of work for six years
  - Where is the work happening, what internal infrastructure?
  - Strengths and weaknesses
- Coordinator, team and experience plus internal work package governance
- Budget and potential modifications
- International landscape
- Dedicated work package workshop
- Opportunities for new members to join
- Overlaps with other WPs
- Conclusion

Science goals

Most macroscopic superposition?

Spontaneous wavefunction collapse?

Search for dark matter, quantum gravity, short-range forces, GUP

Plan of work

- Levitated 10-1000 nm particle (10^5 – 10^{11} atoms) put in a spatial superposition:

Subpackage 1: Silica spheres
Subpackage 2: Diamonds containing NV^- centres

- More massive objects with smaller superposition distance

Subpackage 3: Clamped oscillators

- Theory underpins everything

Subpackage 4: Theory

Deliverables: SP1 Silica spheres

Lead: Hendrik Ulbricht, Southampton. Experiments in Southampton and Oxford

Per 1 (Years 1-2):

D1: Implement low-noise electronics with high-precision timing for switching the trap

D2: Reach the lowest ever centre-of-mass (CM) temperatures for nanoparticles

D3: CM cooling followed by free-fall experiments and wavefunction expansion studies

D4: Build ion trap for non-interferometric tests of CSL heating with 1 μm silica (Oxford)

Per 2 (Year 3):

D5: CM cooling and free flight with an optical grating applied within the trap

D6: Quantum non-demolition pulsed position measurements for levitated nanoparticles

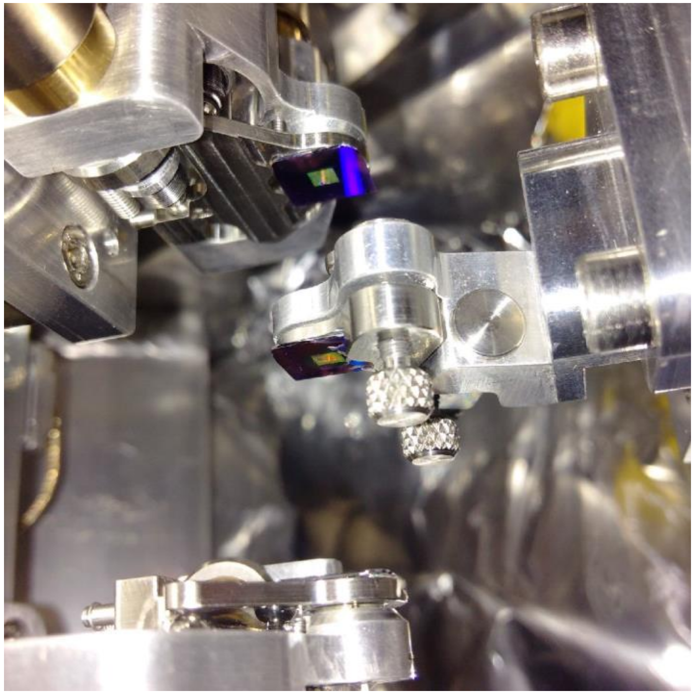
Per 3 (Years 4-6):

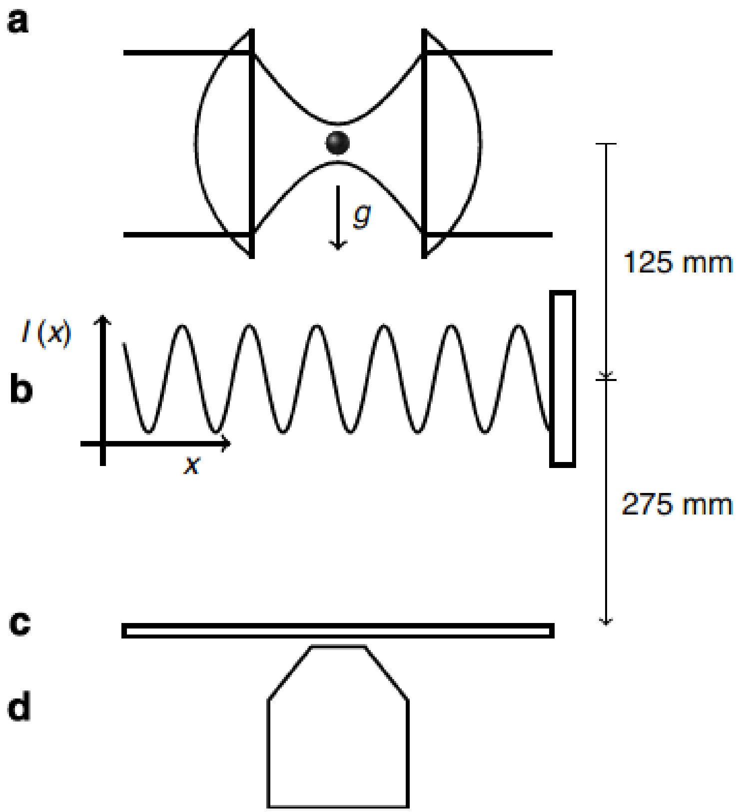
D7: Measure spatial superposition of 10-100 nm silica spheres with small superposition distance

D8: 30 cm free-fall with silica spheres and implementation of Talbot interferometer

Deliverables: SP1 Silica spheres

Lead: Hendrik Ulbricht, Southampton. Experiments in Southampton and Oxford





James Bateman, Stefan Nimmrichter, Klaus Hornberger & Hendrik Ulbricht, Nature Communications, 5, 4788 (2014)

Deliverables: SP2 Diamonds with spin

Lead: Peter Barker, UCL. Experiments in UCL and Warwick

Per 1 (Years 1-2):

D9: Trapping and CM cooling in linear Paul trap of 100 nm diamonds with NV^- centres

D10: Build & test magnetogravitational (MG) trap for 1 μm diamonds with NV^- centres

Per 2 (Year 3):

D11: Install an inhomogeneous magnet into the Paul trap

D12: Cool the internal temperature of the diamonds to 8 K in the MG trap

D13: Implement active damping of vibrations and tilt following LIGO work

Per 3 (Years 4-6):

D14: In-trap Ramsey interferometry of 100 nm diamonds using linear Paul trap

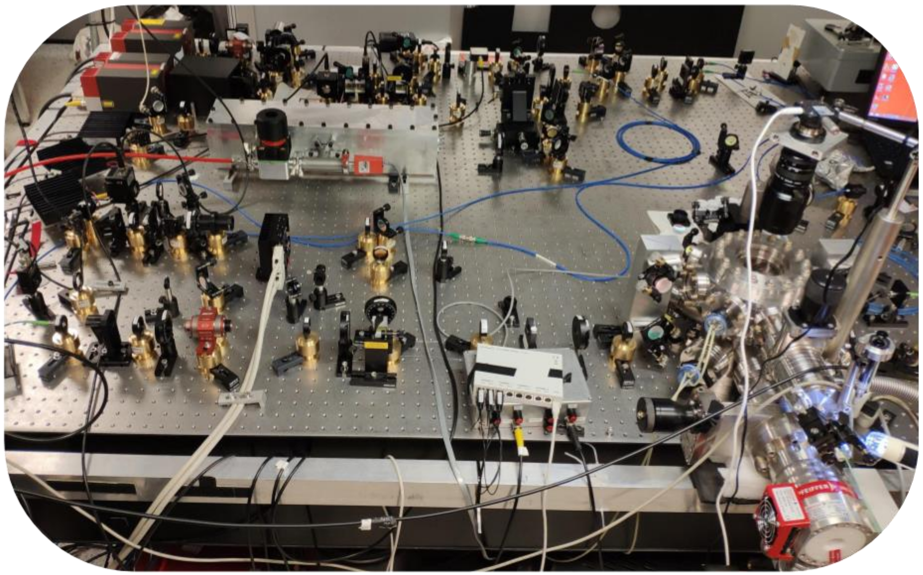
D15: Charge neutralisation and free fall from the Paul trap

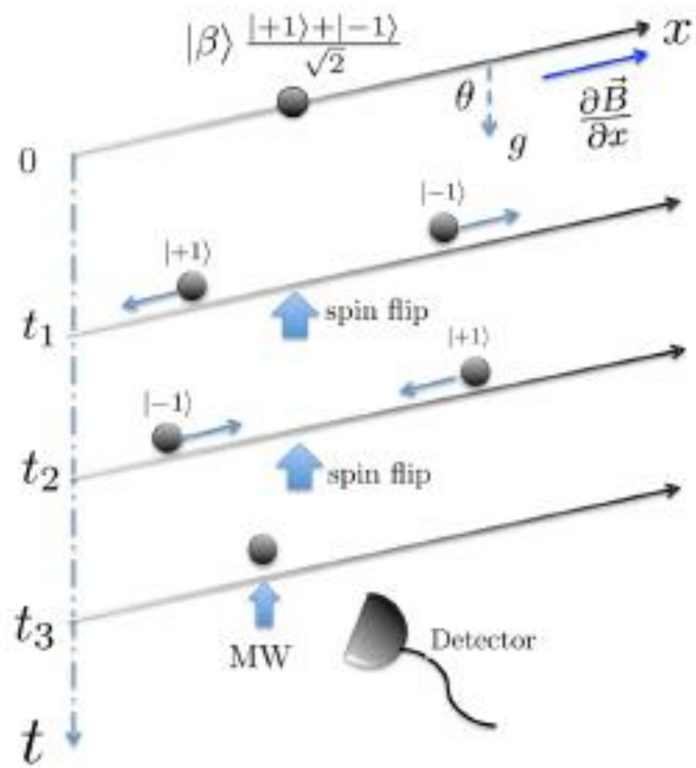
D16: Charge neutralisation in the MG trap

D17: Create small spatial superposition in MG trap

Deliverables: SP2 Diamonds with spin

Lead: Peter Barker, UCL. Experiments in UCL and Warwick





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)

Deliverables: SP3 Clamped oscillators

Lead: Michael Vanner, Imperial

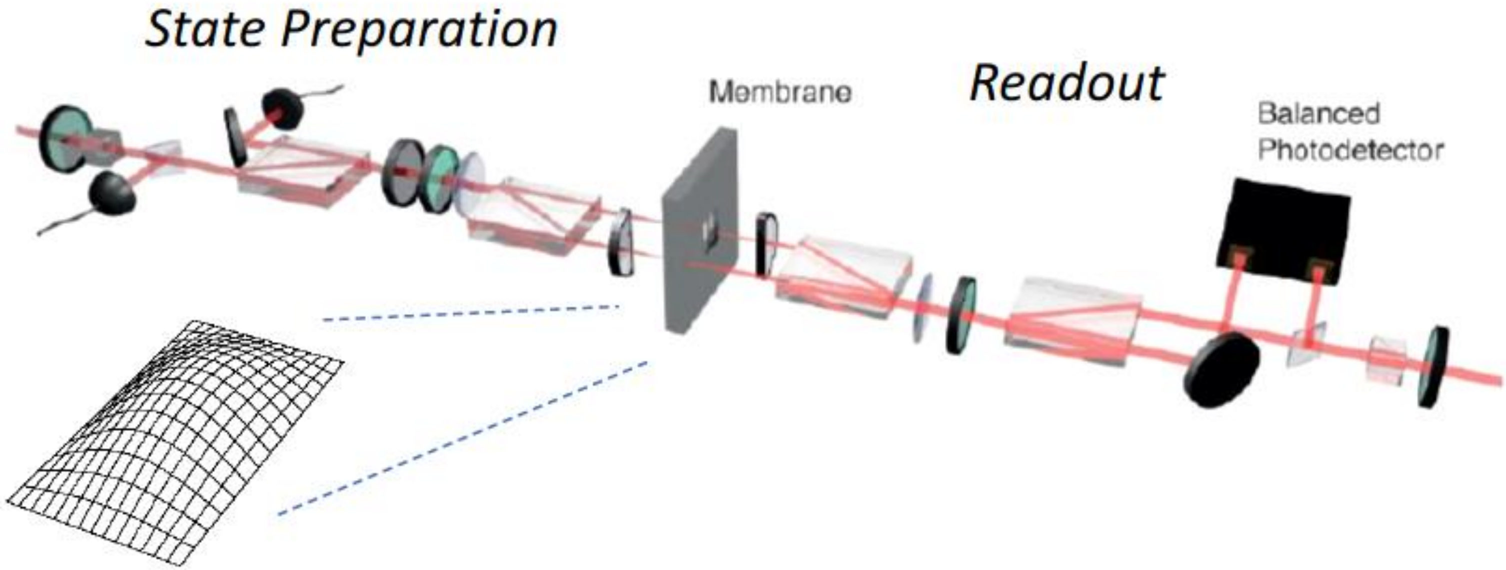
Per 1 (Years 1-2):
D18: Generate and observe mechanical interference fringes at low thermal occupations

Per 2 (Year 3):
D19: Experimentally observe an optomechanical geometric phase / revivals

Per 3 (Years 4-6):
D20: Use the geometric phase to more strongly test GUP

Deliverables: SP3 Clamped oscillators

Lead: Michael Vanner, Imperial



£2M state-of-the-art lab under construction at Imperial

Deliverables: SP4 Theory

Lead: Sougato Bose, UCL

Per 1 (Years 1-2):

D21: Theory of quantum sensing in optomechanical interferometry

D22: Identify system specs for the detection of dark matter and neutrinos

D23: Design hybrid system: atomic ion coupled to ion-trapped nanoparticle

D24: Design optomechanical short-range force tests in unexplored regimes

D25: Design proposal to test relativistic effects in quantum mechanics

Per 2 (Year 3):

D26: Self-consistent description of non-eqm. mesoscopic QM including CSL

D27: Extend our gravitational wave detector proposals

D28: Improve simulations and proposals for macroscopic superpositions

Per 3 (Years 4-6):

D29: Study of models with very light scalar fields using QFT methods

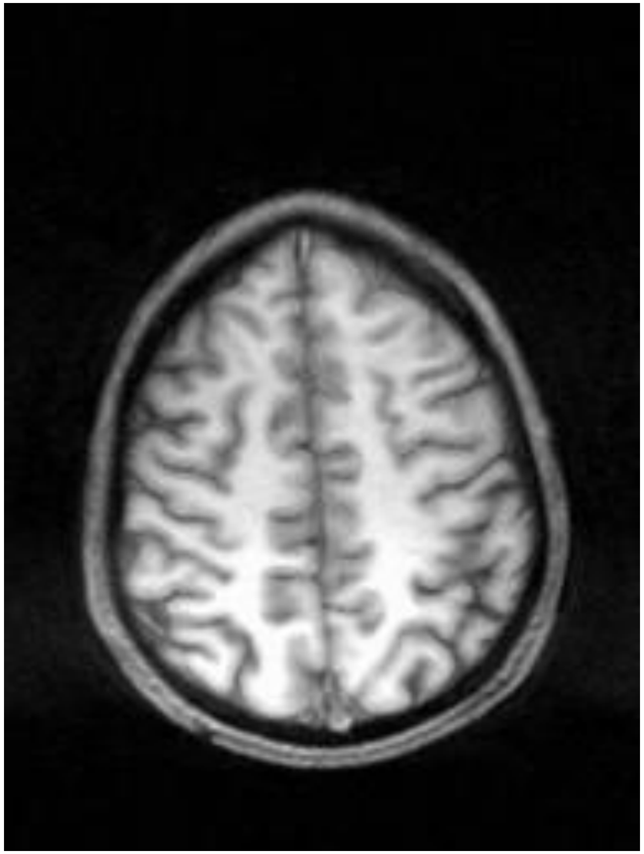
Deliverables: SP4 Theory

Lead: Sougato Bose, UCL

Per 1 (Years 1-2):
D21: Animesh Datta (Warwick)
D22: Paul Harrison (Warwick)
D23: Andrew Steane (Oxford)
D24: John March-Russell (Oxford)
D25: Myungshik Kim (Imperial)

Per 2 (Year 3):
D26: Mauro Paternostro
D27: Haixing Miao (Birmingham)
D28: Sougato Bose (UCL)

Per 3 (Years 4-6):
D29: Xavier Calmet (Sussex)



Strengths and weaknesses

Strengths:

- Results come with or without spontaneous collapse
- Leverages investment in three QT Hubs
- Many years of work by us to propose this work
- Community already working together

Weakness:

- We haven't made a spatial superposition yet

→ Address this with multiple experimental approaches

Meet the team

Management team (re-evaluates plans for years 3-6):
Gavin Morley (coordinator), Clare Burrage, Sheila Rowan, John March-Russell, Hendrik Ulbricht, Peter Barker, Michael Vanner & Sougato Bose

Full team:
Michael Vanner & Myungshik Kim (Imperial), Hendrik Ulbricht & Alexander Belyaev (Southampton) Mauro Paternostro (QUB), Peter Barker, Tania Monteiro, Chamkaur Ghag & Sougato Bose (UCL), Gary Barker, Yorck Ramachers, Paul Harrison, Animesh Datta & Gavin Morley (Warwick), Andrew Steane, Christopher Foot, Hans Kraus & John March-Russell (Oxford), James Bateman (Swansea), Xavier Calmet (Sussex), Haixing Miao (Birmingham), James Millen (KCL), Clare Burrage & Pierre Verlot (Nottingham), Oliver Williams & Sean Giblin (Cardiff), Sheila Rowan & Giles Hammond (Glasgow), Andreas Nunnenkamp (Cambridge), Kishan Dholakia (St Andrews) and Michael Hartmann (Heriot Watt)

Meet the team: EPSRC people

Management team:

Gavin Morley (coordinator), Clare Burrage, Sheila Rowan, John March-Russell, Hendrik Ulbricht, Peter Barker, Michael Vanner & Sougato Bose

Full team:

Michael Vanner & Myungshik Kim (Imperial), Hendrik Ulbricht & Alexander Belyaev (Southampton) Mauro Paternostro (QUB), Peter Barker, Tania Monteiro, Chamkaur Ghag & Sougato Bose (UCL), Gary Barker, Yorck Ramachers, Paul Harrison, Animesh Datta & Gavin Morley (Warwick), Andrew Steane, Christopher Foot, Hans Kraus & John March-Russell (Oxford), James Bateman (Swansea), Xavier Calmet (Sussex), Haixing Miao (Birmingham), James Millen (KCL), Clare Burrage & Pierre Verlot (Nottingham), Oliver Williams & Sean Giblin (Cardiff), Sheila Rowan & Giles Hammond (Glasgow), Andreas Nunnenkamp (Cambridge), Kishan Dholakia (St Andrews) and Michael Hartmann (Heriot Watt)

Team experience

Review paper: A. Bassi *et al.*, RMP **85**, 471 (2013).

Proposals for macroscopic superpositions

M. R. Vanner *et al.*, PNAS **108**, 16182 (2011).
M. Scala *et al.*, PRL **111**, 180403 (2013).
M. R. Vanner *et al.*, PRL **110**, 010504 (2013).
J. Bateman *et al.*, Nat. Commun. **5**, 4788 (2014).
M. Bahrami *et al.*, PRL **112**, 210404 (2014).
C. Wan *et al.*, PRL **117**, 143003 (2016).
S. Bose *et al.*, PRL **119**, 240401 (2017).
D. Branford *et al.*, PRL **121**, 110505 (2018).
R. J. Marshman *et al.*, arXiv:1807.10830 (2018).

Experiments towards macroscopic superpositions

M. Rashid *et al.*, PRL **117**, 273601 (2016).
P. Z. G. Fonseca *et al.*, PRL **117**, 173602 (2016).
J. Vovrosh *et al.*, JOSAB **34**, 1421 (2017).
A. C. Frangeskou *et al.*, NJP **20**, 043016 (2018).

Budget

Per 1 (Years 1-2) costs £3.9M

Experimental work totalling £2.4M

- eight PDRAs (£1.6M)
- equipment (£600k)
- consumables (£100k)
- travel (£40k)
- technician time (£70k)

Theory work totalling £840k

- four PDRAs (£800k)
- travel (£40k)

PI time for the 31 team members

- £700k

£5.8M

Correspondingly £1.9M for **Per 2** (Year 3): buy last equipment

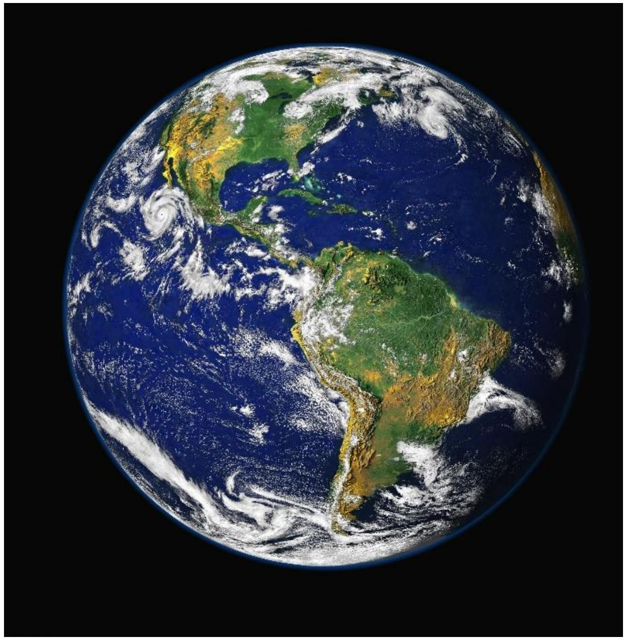
Per 3 (Years 4-6) then costs £4.8M.

International landscape

Molecular beams are current leaders but with limited potential: Vienna

Levitated nanoparticles: multiple groups in EU and USA but no coordinated project for creating superpositions

Clamped oscillators: multiple groups in EU and USA but we take advantage of quantum measurement tools



Dedicated workpackage workshop

1. Informal meeting tomorrow in Oxford to discuss science and progress the 4-pager: all welcome
2. International conference 1st April in Imperial organised by Myungshik Kim

Opportunities for new members

Please ask us!

Overlap with other workpackages

WP3: AION needs low vibration and low tilt

Other dark matter searches

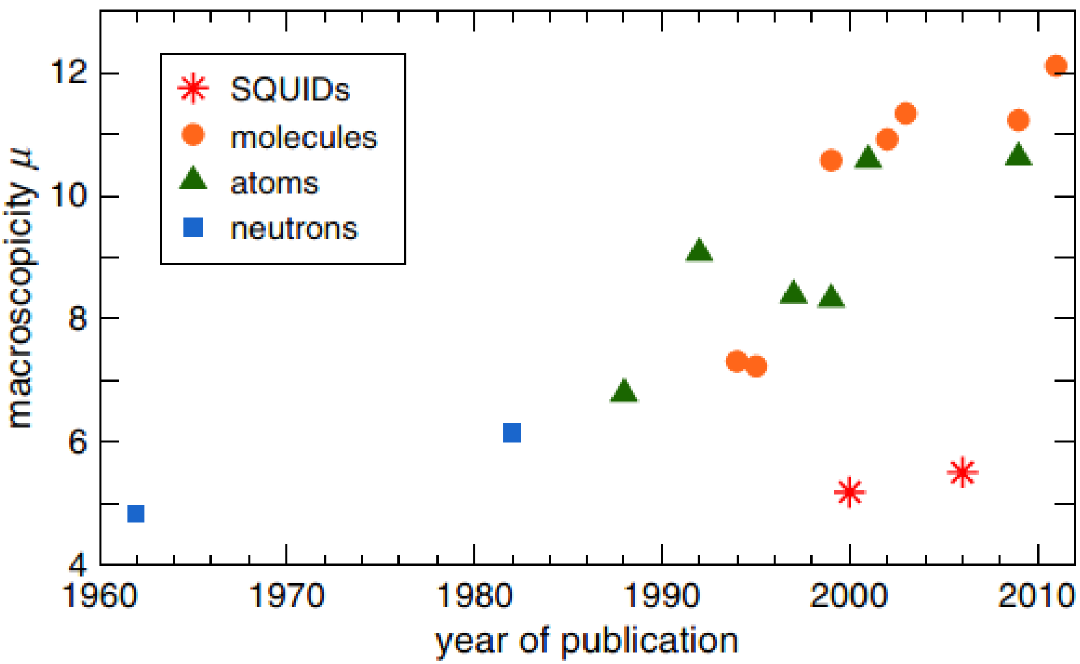
Conclusion

Let's search for the most macroscopic spatial superposition

$\mu \sim 28$

Macroscopicity

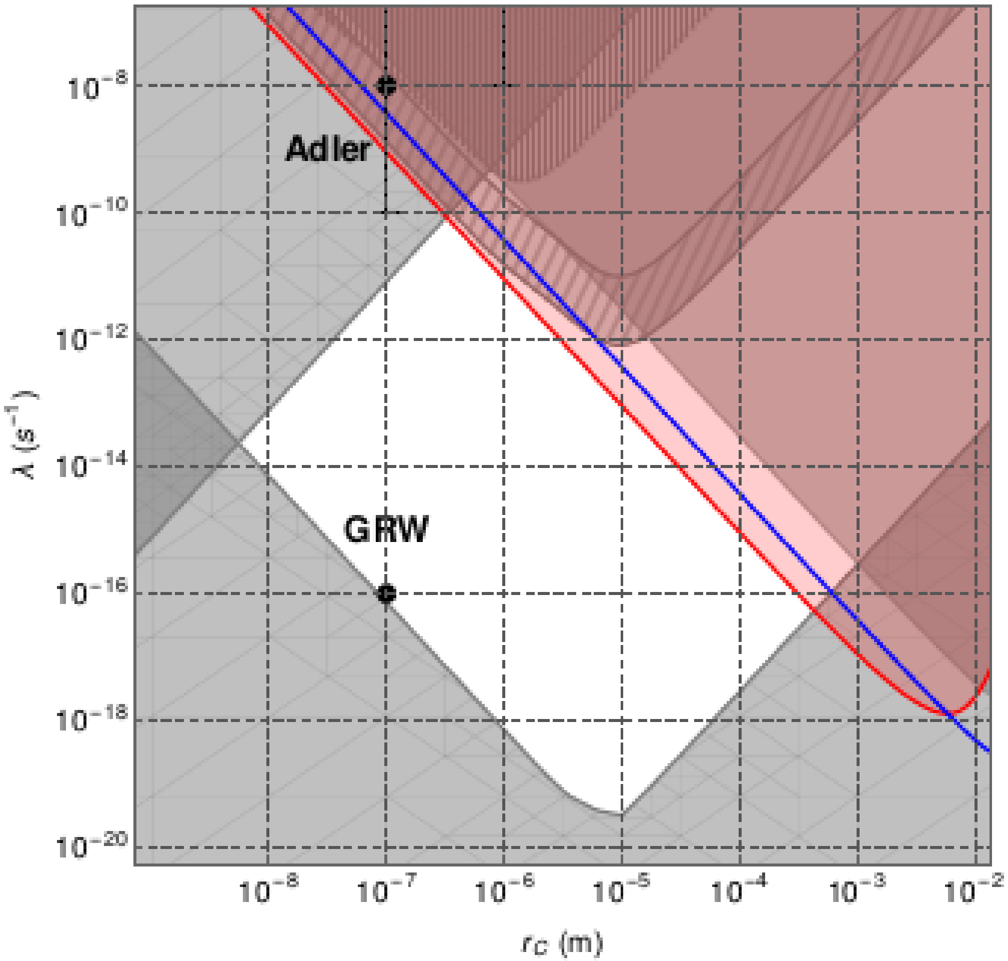
$$\mu \approx \log_{10}\left[\left(\frac{M}{m_e}\right)^2 \frac{t}{1\ \mathrm{s}}\right]$$



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)

UK groups seeking macroscopic superpositions