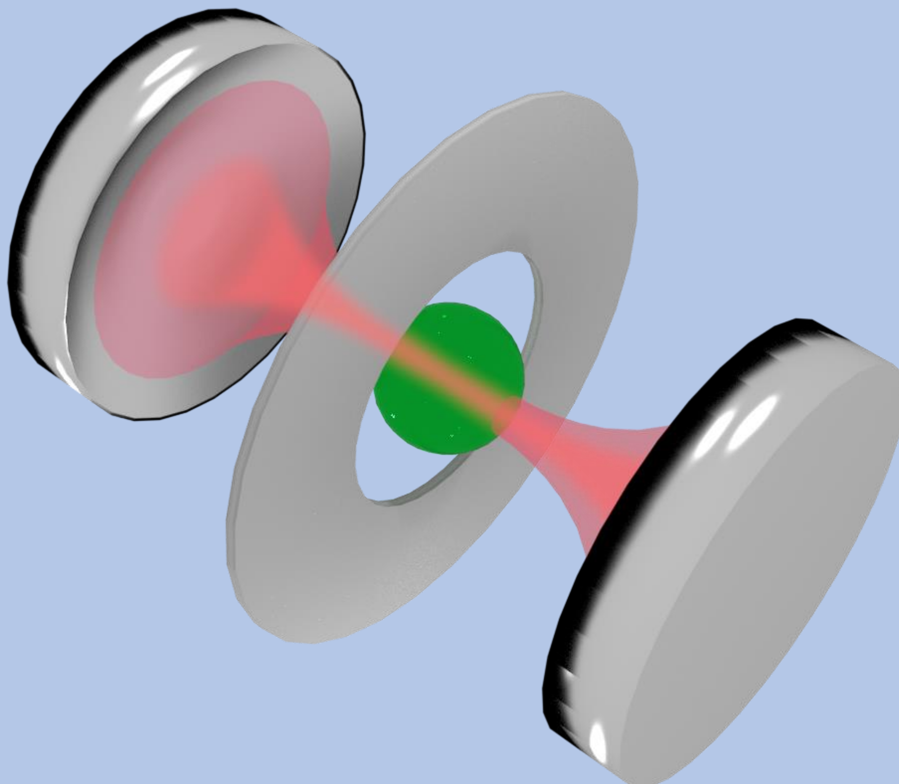
Hybrid Macroscopic Quantum Systems



不破 麻里亜

2020年1月12日

東京大学
THE UNIVERSITY OF TOKYO

さきがけ PRESTO

MACROSCOPIC QUANTUM MACHINES

Outline

Self Introduction

↓

Nakamura-Usami Lab Introduction

↓

My Levitation Project

Outline

Self Introduction

Nakamura-Usami Lab Introduction

My Levitation Project

Self Introduction

9. 2016　Receive PhD from University of Tokyo
Prof. Akira Furusawa's laboratory

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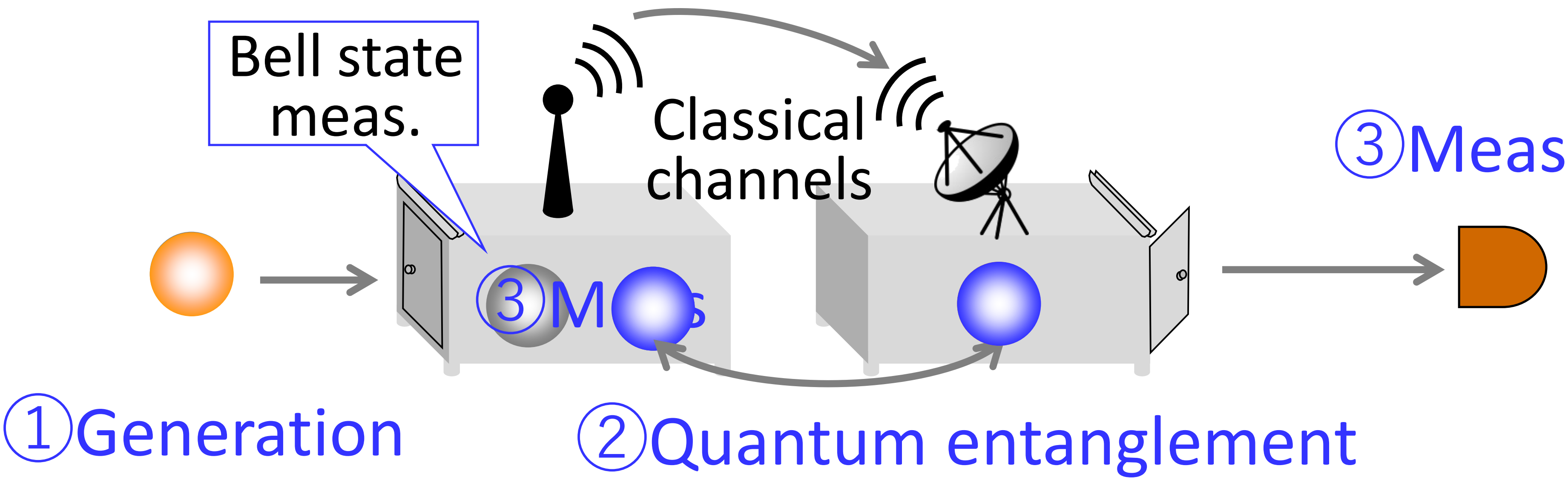
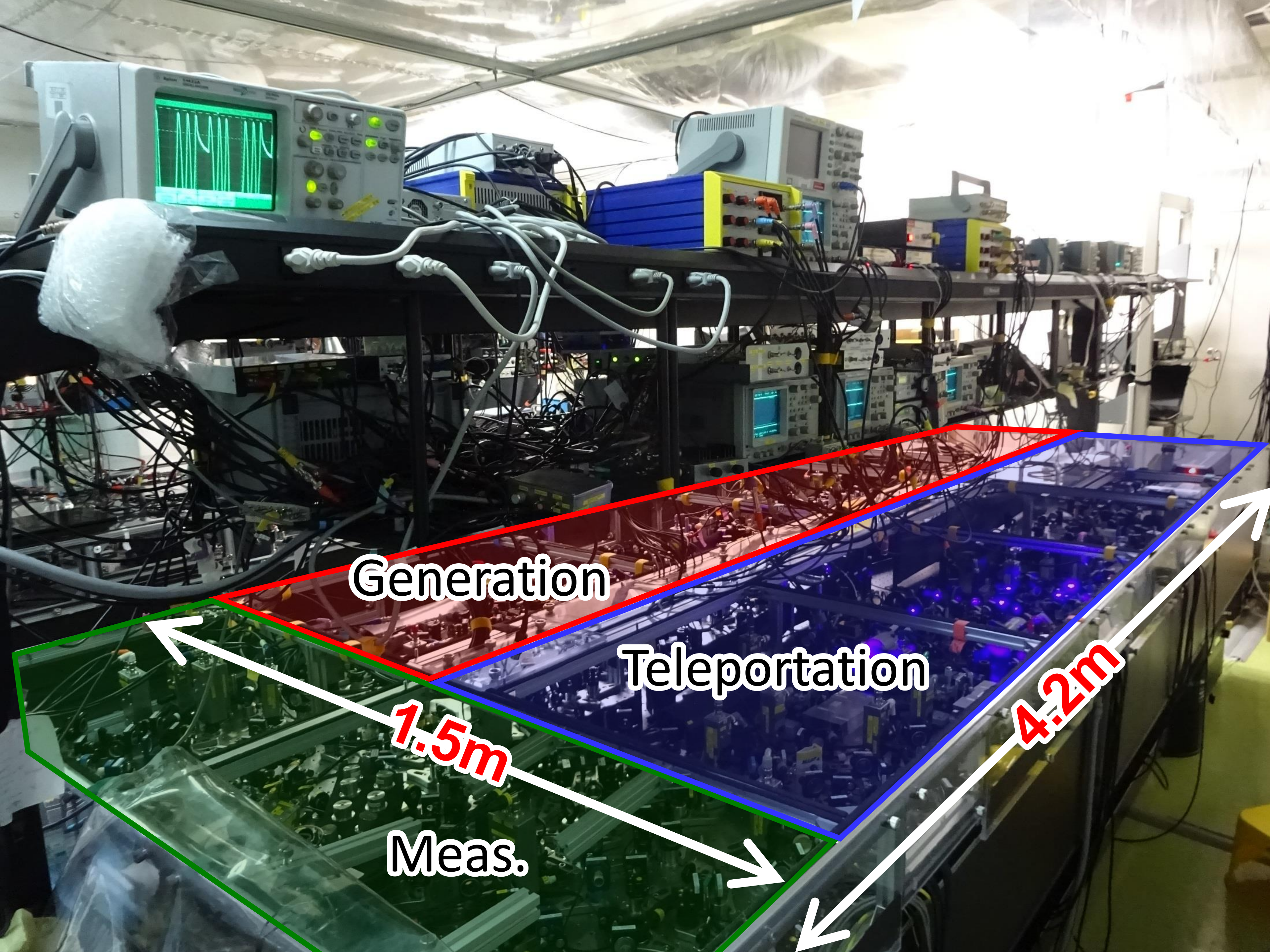


Quantum teleportation


Generation
Teleportation
Meas.
1.5m
4.2m

Over **500** mirrors, **8** cavities, **13** interferometers

Self Introduction

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THE UNIVERSITY OF TOKYO

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Leuch's Division, Prof. C. Marquardt

MAX-PLANCK-GESELLSCHAFT

Self Introduction

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Arakawa-Iwamoto laboratory

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MAX-PLANCK-GESELLSCHAFT

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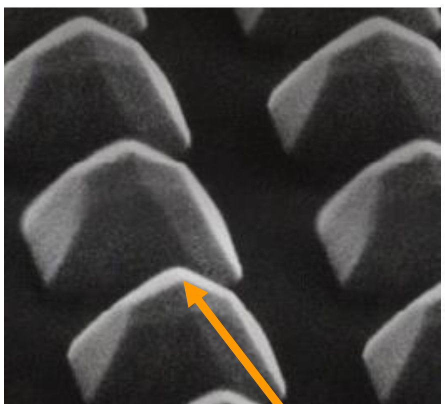
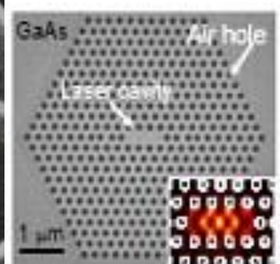
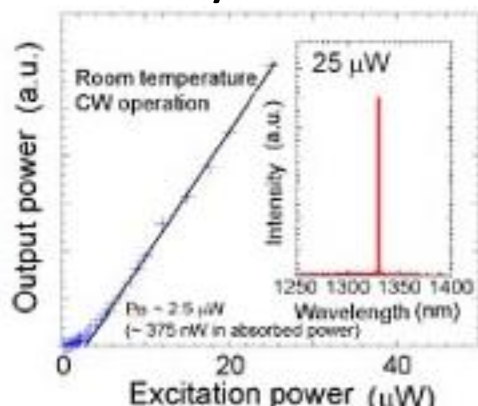
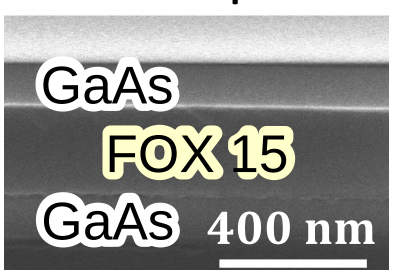
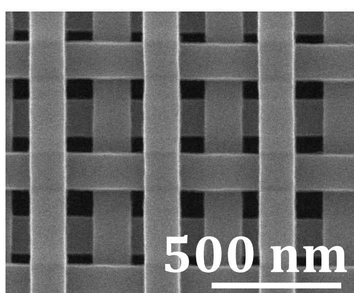


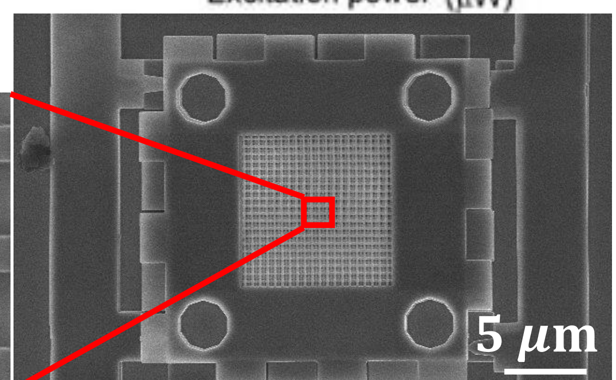
InAs quantum dots











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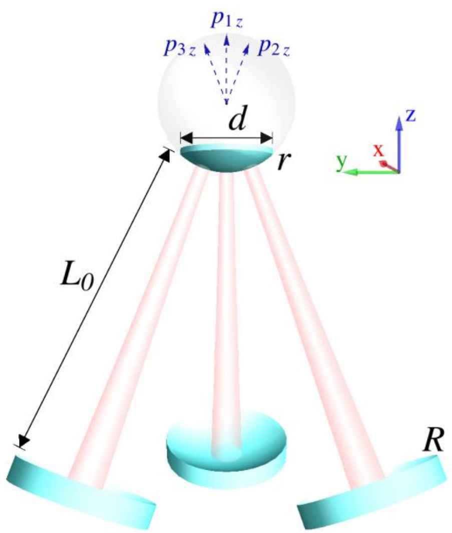
9. 2017 CQC2T Quantum Optic's laboratory
Ping Koy's laboratory



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INSTITUTE OF INDUSTRIAL SCIENCE · THE UNIVERSITY OF TOKYO

Australian National University

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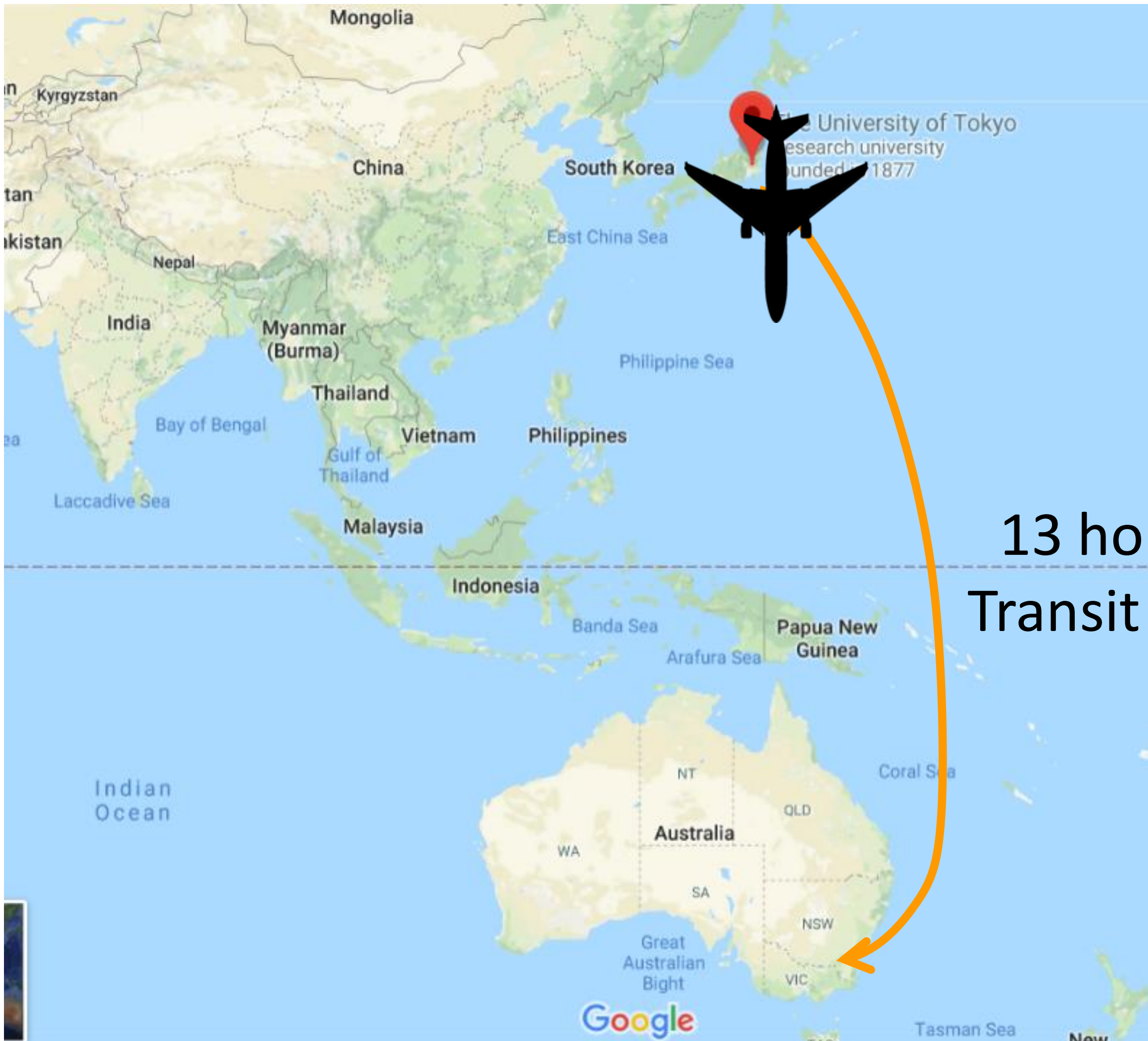


13 hours flight
Transit at Sydney

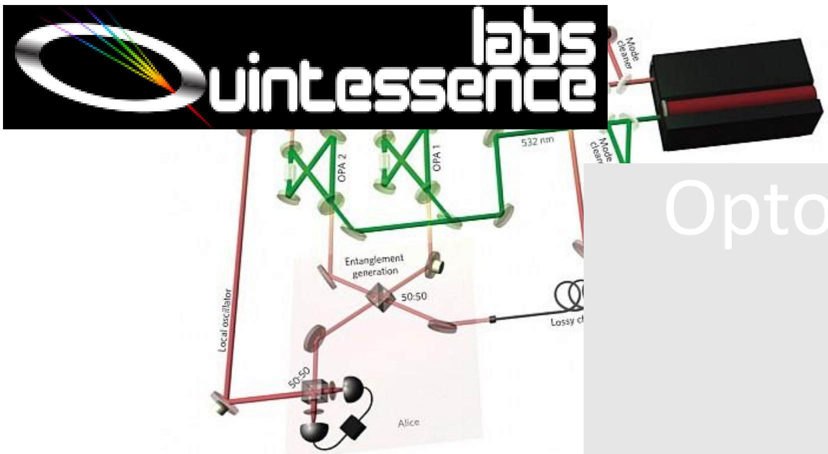
Australian
National
University

Canberra

Australian National University

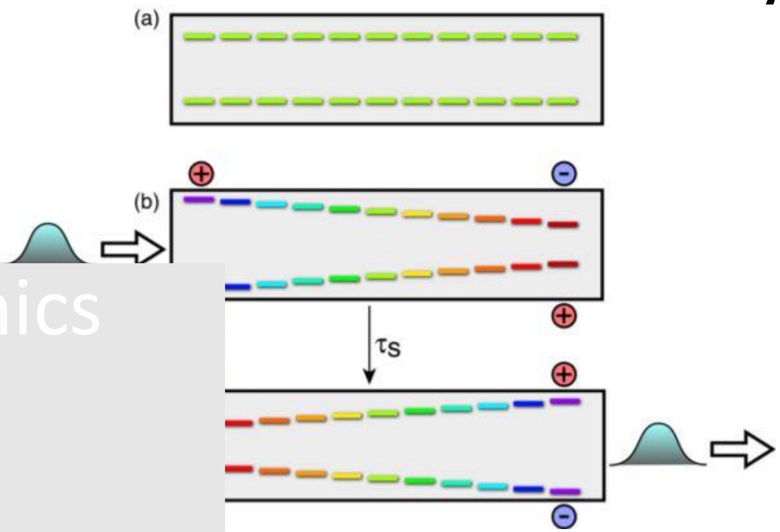
Ping Koy Lab

Quantum Information Random Number Generator

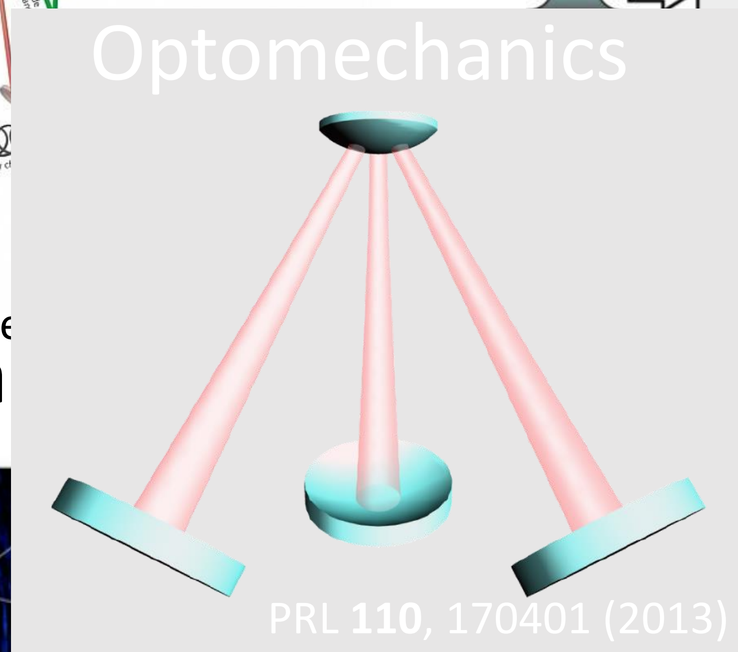


Appl. Phys. Le

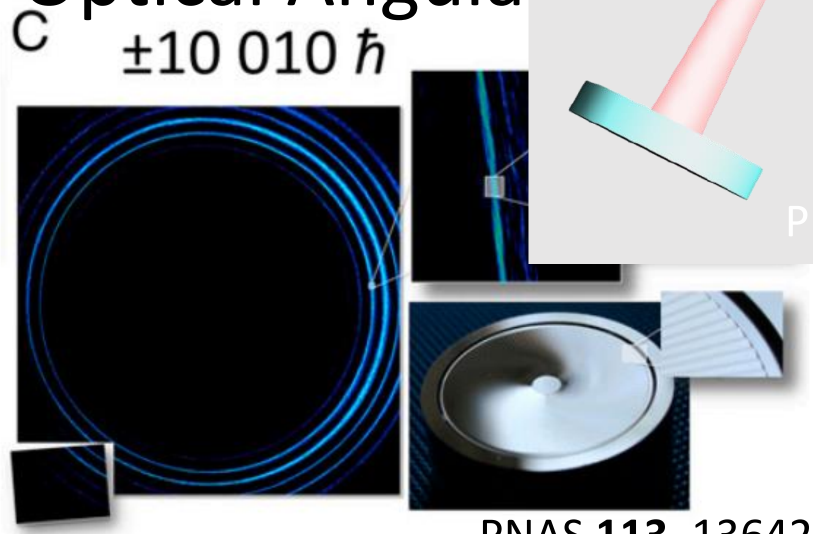
Gradient Echo Memory



Nature **461**, 241 (2009)

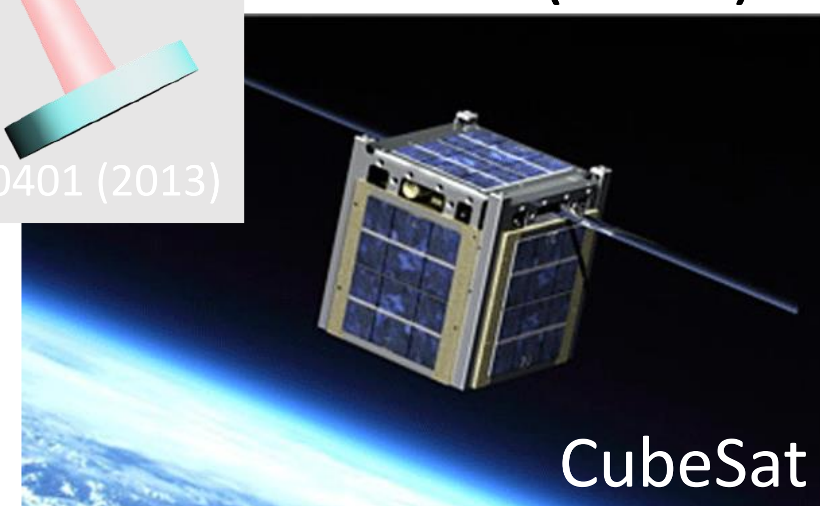


Optical Angula



PNAS **113**, 13642 (2016)

Material (TMD)



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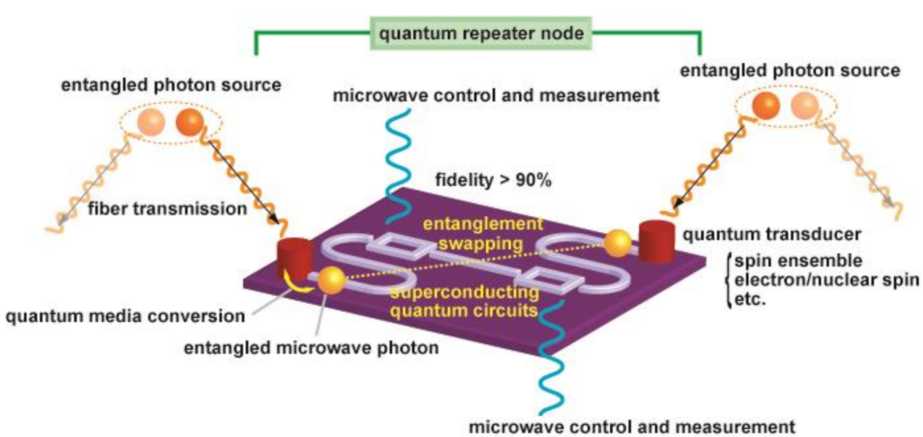
Nakamura-Usami Laboratory



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Australian National University

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Nakamura-Usami Lab Introduction

My Levitation Project

Quantum Information Physics & Engineering Lab @ UTokyo

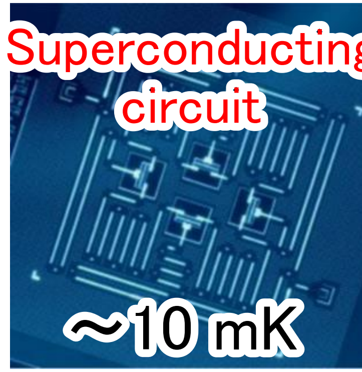
様々な量子系で「巨視的量子状態」の実現を目指してます

http://www.qc.rcast.u-tokyo.ac.jp/

Quantum System Candidates

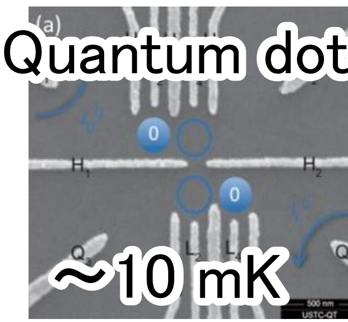
10GHz
T = 0.5K

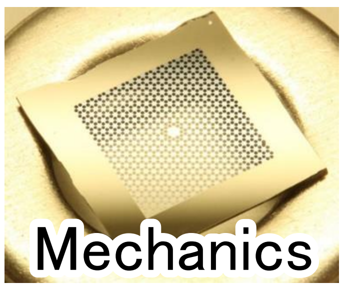
1µm = 300THz
T = 14,000K

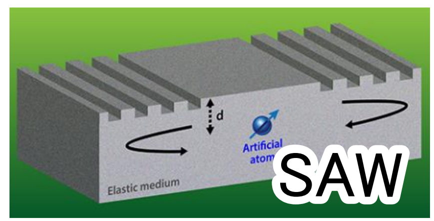


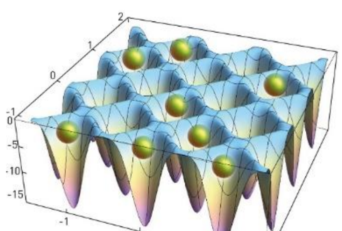
- ✓ Good coherence
- ✓ Advanced control
- ✓ Precise measurement
- ✓ Integration

(Requires Fridge)

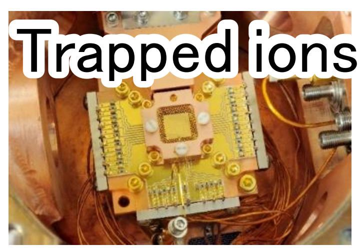


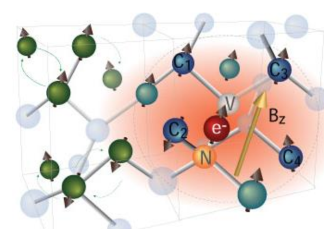






Neutral atoms





NV centers

- ✓ Long distance Communication

(Room T operation)

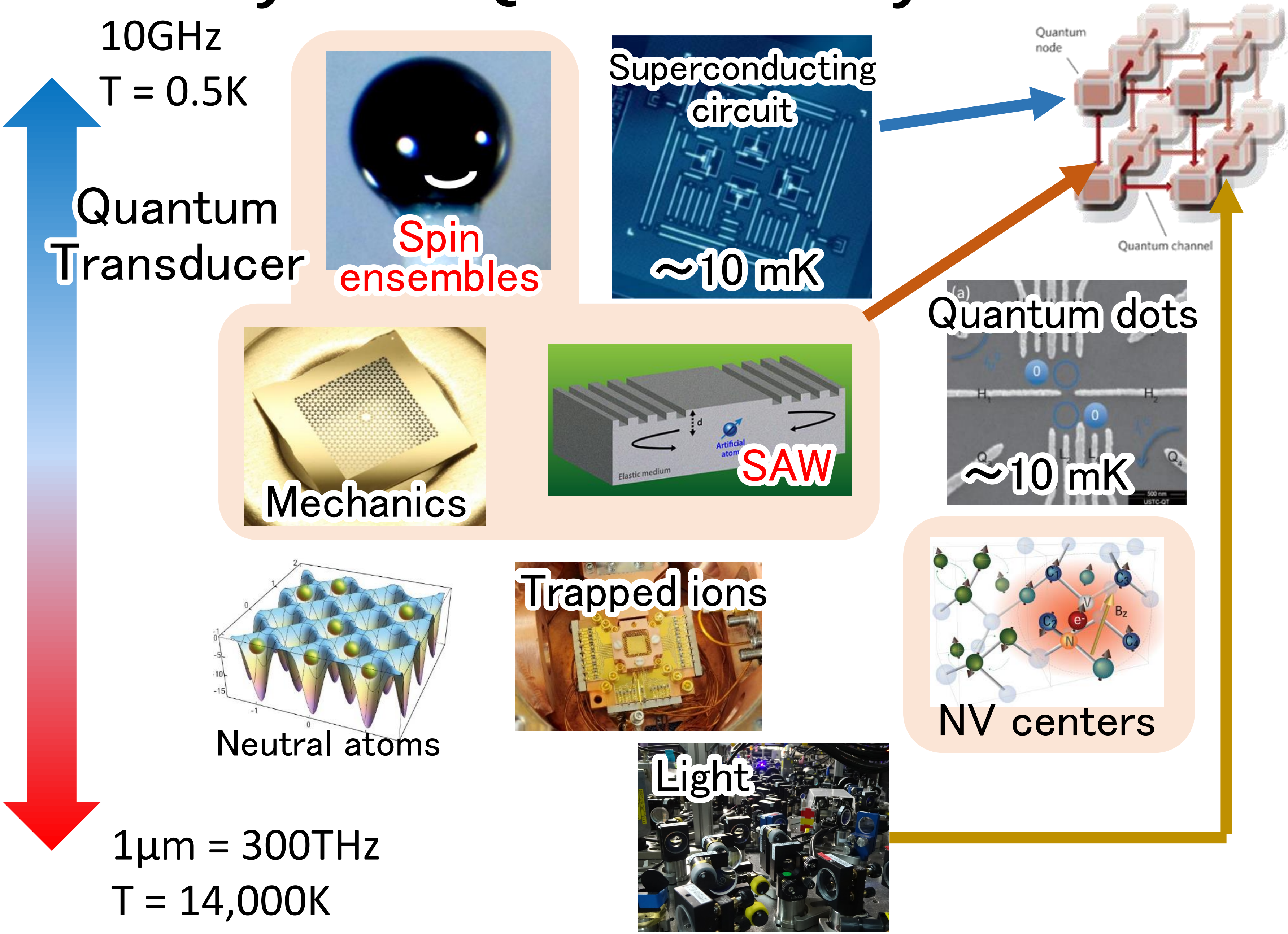
$$E_{\mathrm{MW}} = \hbar\omega_{\mathrm{MW}}$$

$$E_{\mathrm{opt}} = \hbar\omega_{\mathrm{opt}}$$

$$\frac{E_{\mathrm{opt}}}{E_{\mathrm{MW}}} = \left(\frac{1.5\,\mu\mathrm{m}}{3\,\mathrm{cm}}\right)^{-1} = 20{,}000$$

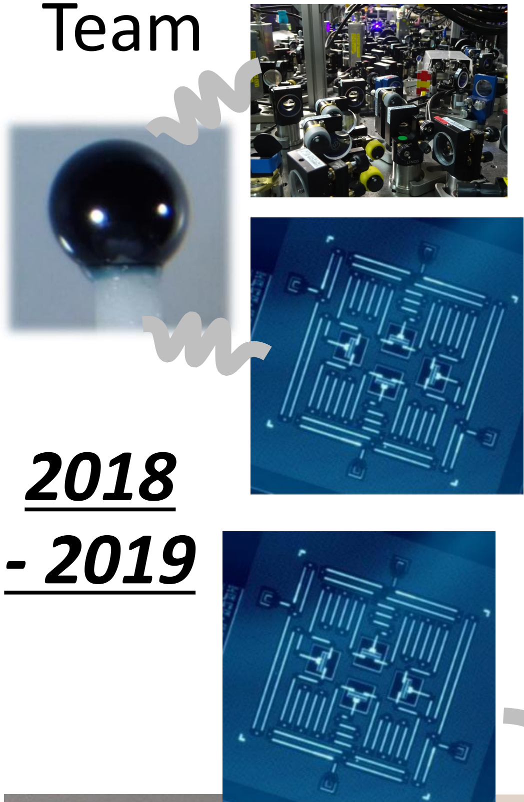
How to fill the big gap in energy?

Hybrid Quantum Systems



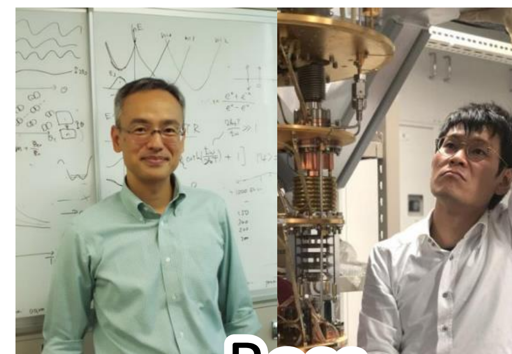
Hybrid Quantum Systems

Magnon Team



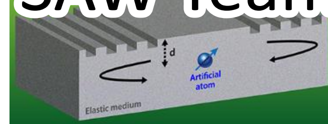
2018

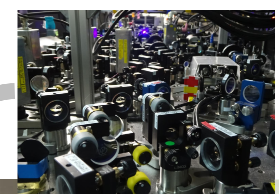
- 2019

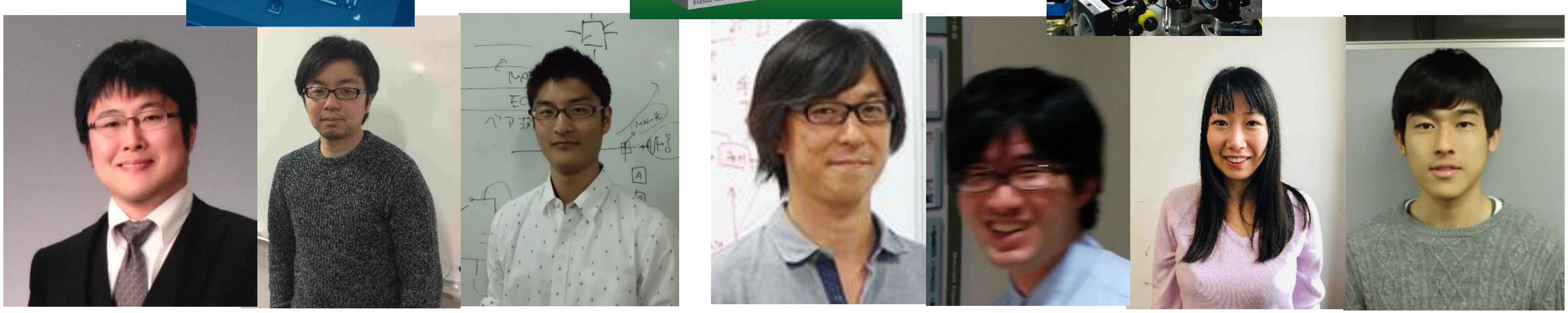


Boss

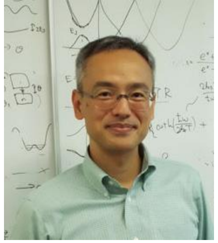
SAW Team



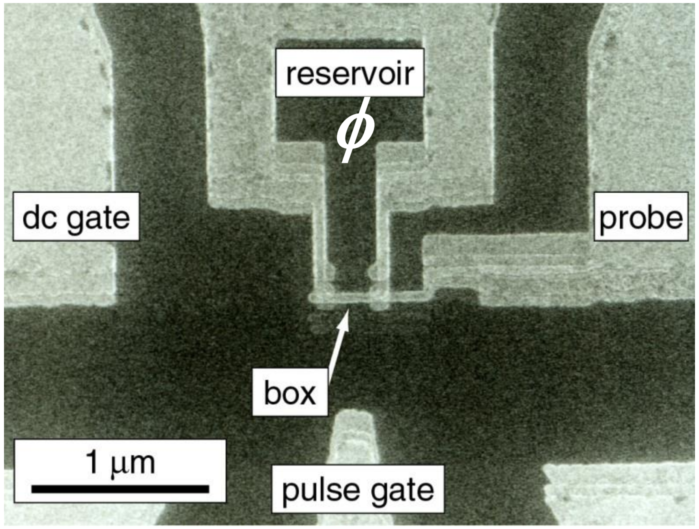


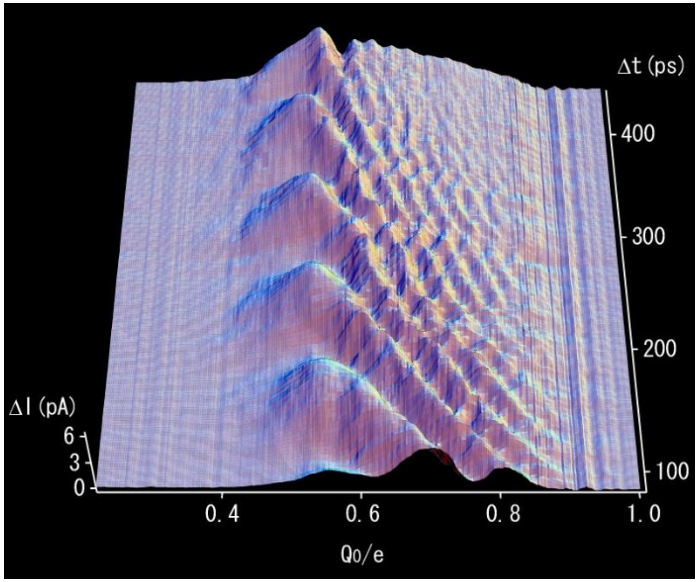


Superconducting qubit



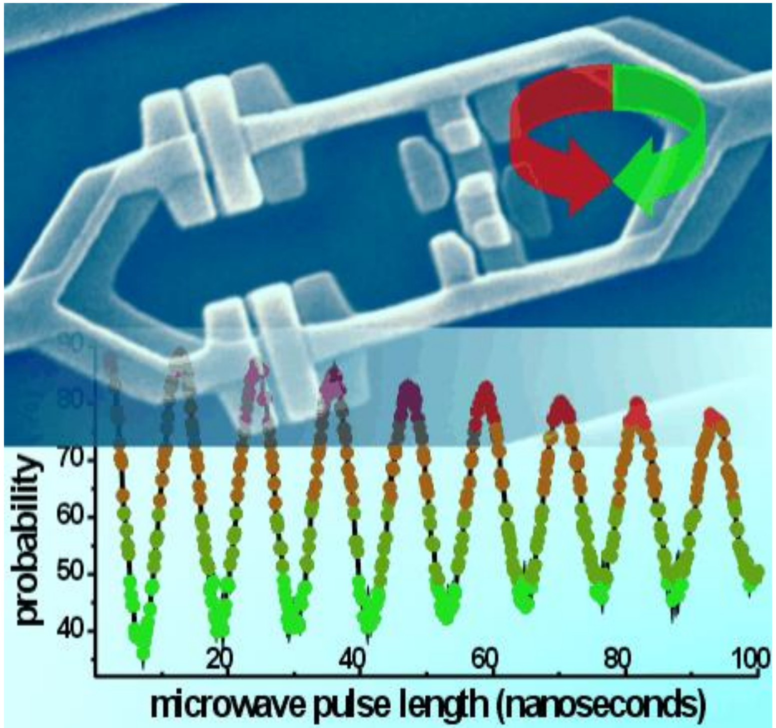
Charge qubit





Nakamura, Pashkin, Tsai, Nature (1999)

Flux qubit



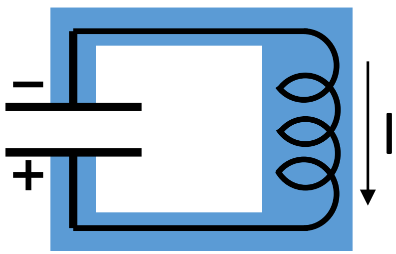
Chiorescu, Nakamura, Harmans, Mooij, Science (2003)

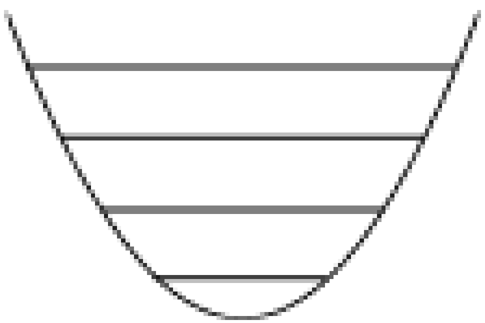
$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

Superposition between $|0\rangle$ and $|1\rangle$

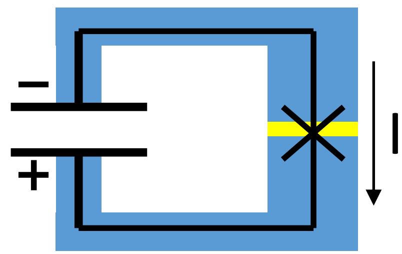
Atom and artificial atom

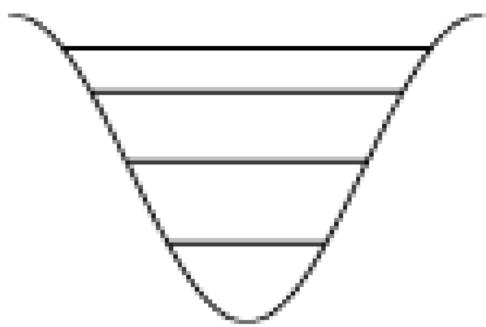
LC resonator



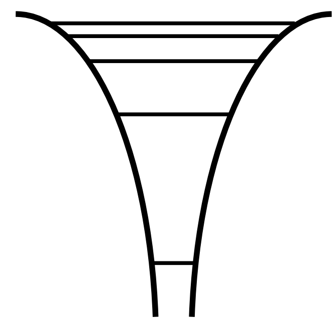


Superconducting qubit
= artificial atom
~mm

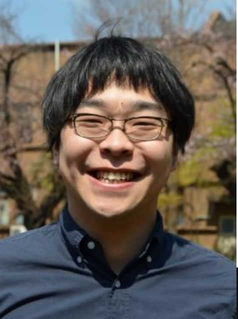




Atom
~ Å

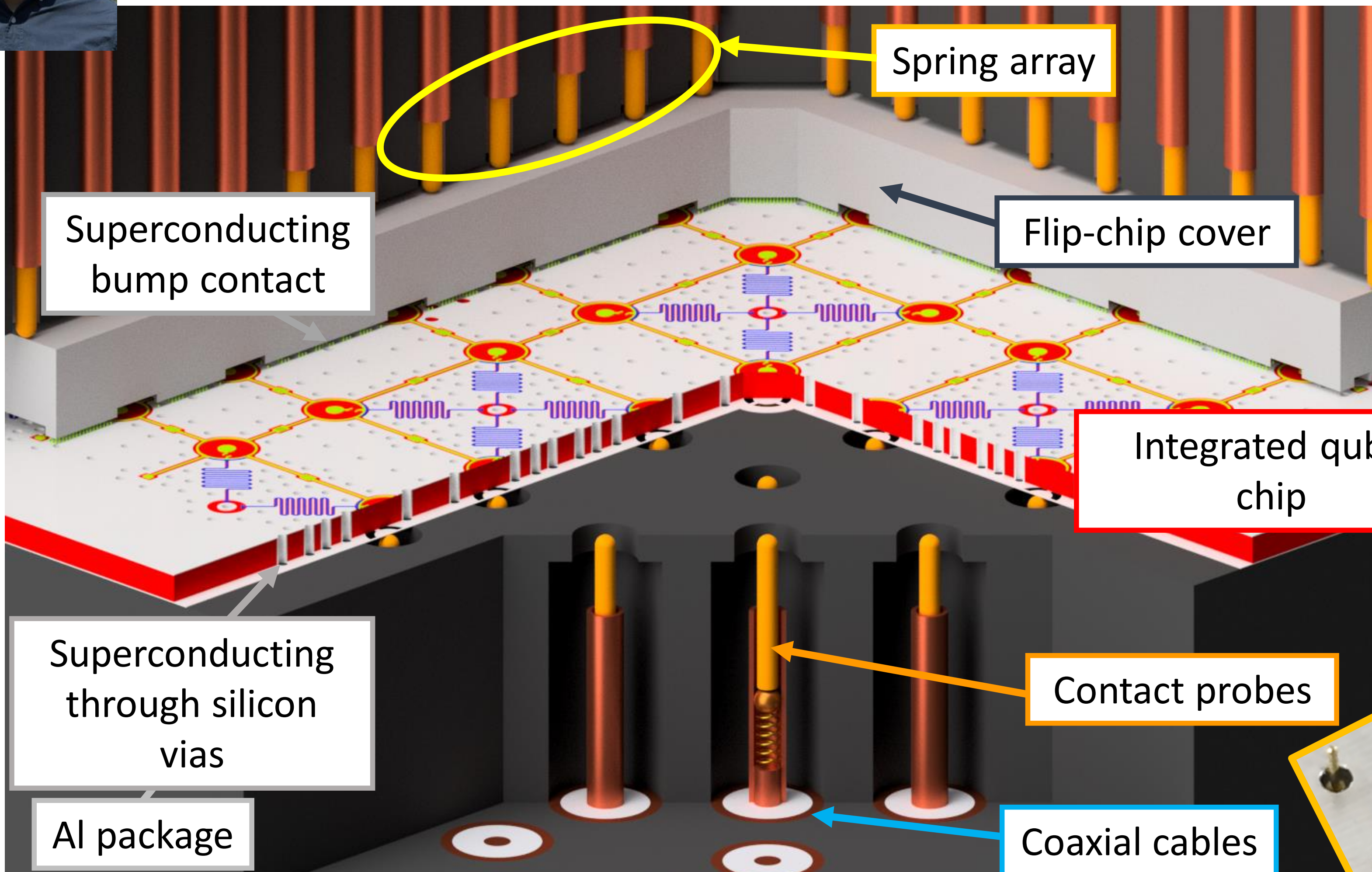


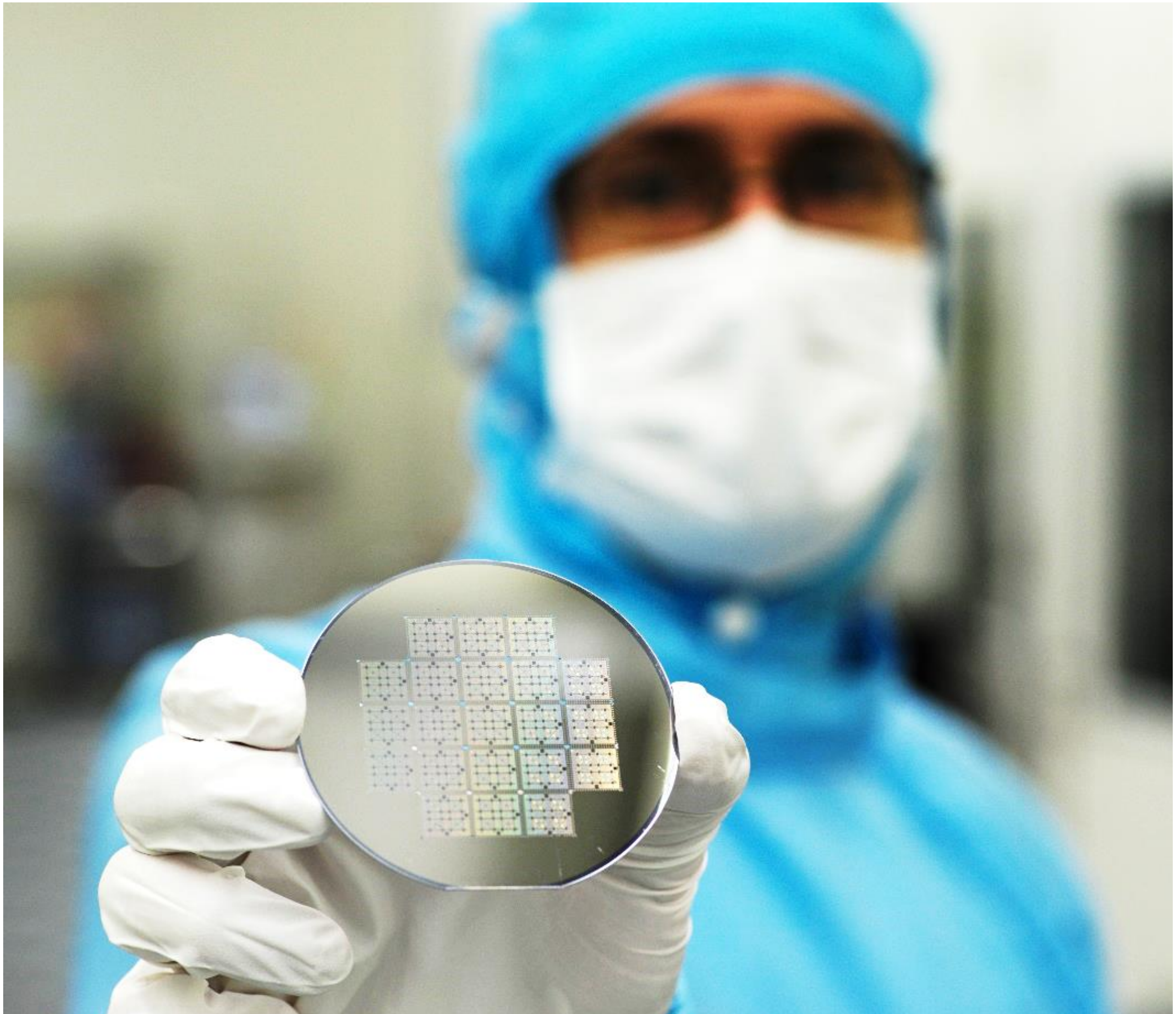
- Low dissipation
- Strong nonlinearity
- Large dipole moment



Package with 3D wiring

玉手　＠QUATUO 2019





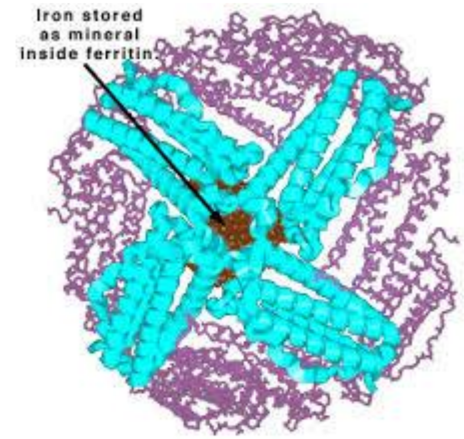
L. Szikszai

Macroscopic quantum tunneling in spin systems

VOLUME 68, NUMBER 20 PHYSICAL REVIEW LETTERS 18 MAY 1992

Macroscopic Quantum Tunneling in Magnetic Proteins

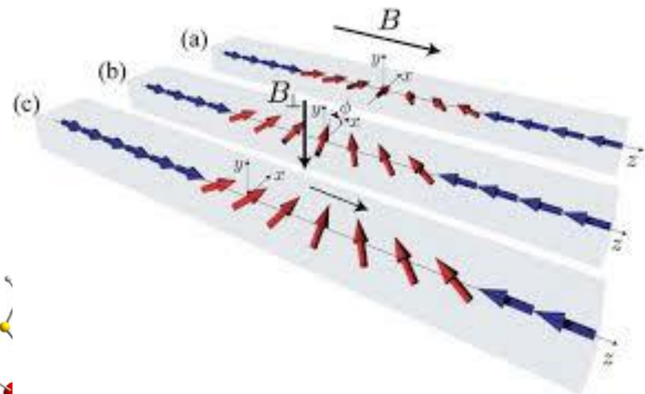
D. D. Awschalom,[1] J. F. Smyth,[1] G. Grinstein,[2] D. P. DiVincenzo,[2] and D. Loss[2]
[1]*Department of Physics, University of California, Santa Barbara, California 93106*
[2]*IBM Research Division, IBM T. J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598*
(Received 13 February 1992)



VOLUME 72, NUMBER 5 PHYSICAL REVIEW LETTERS 31 JANUARY 1994

Macroscopic Quantum Tunneling of a Domain Wall in a Ferromagnetic Metal

Gen Tatara and Hidetoshi Fukuyama
Department of Physics, University of Tokyo, 7-3-1 Hongo, Tokyo 113, Japan
(Received 6 July 1993)

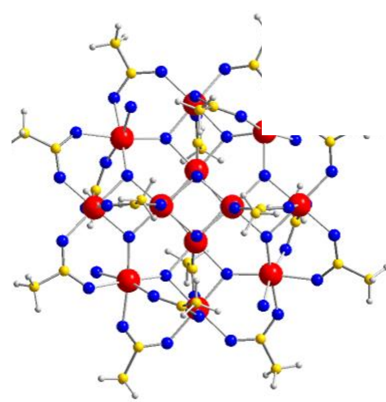


Science 1999

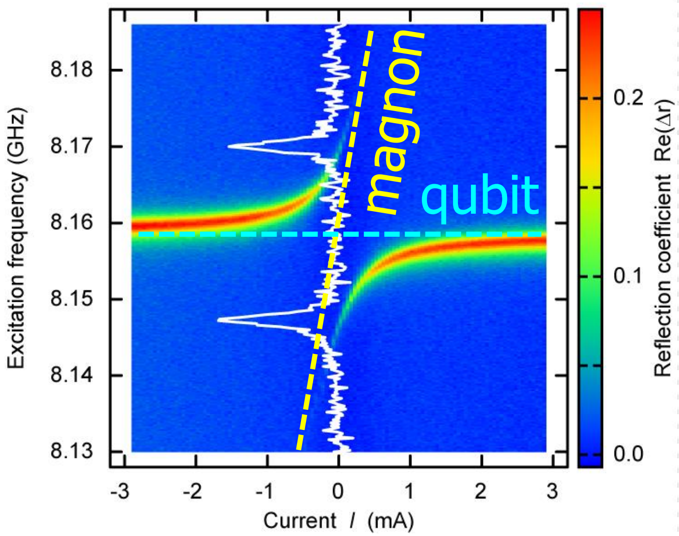
REPORTS

Quantum Phase Interference and Parity Effects in Magnetic Molecular Clusters

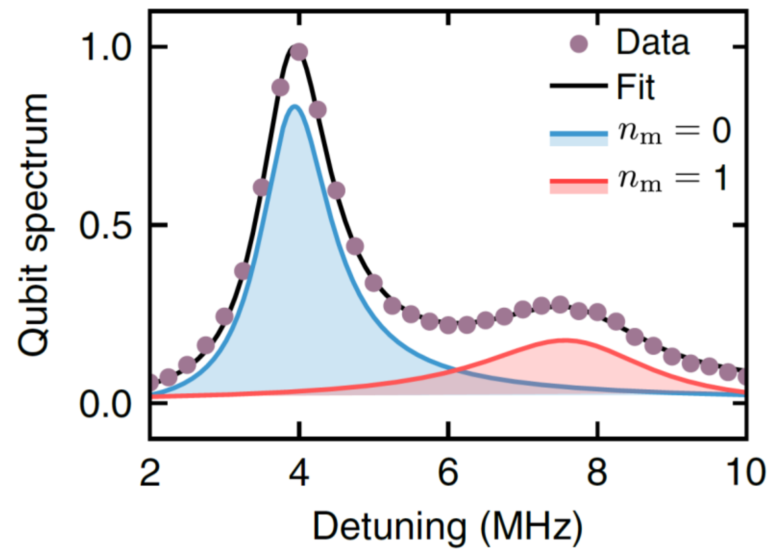
W. Wernsdorfer[1]* and R. Sessoli[2]



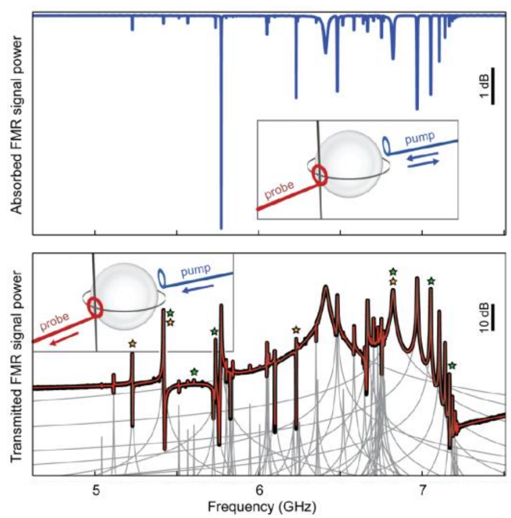
YIG Magnon Project



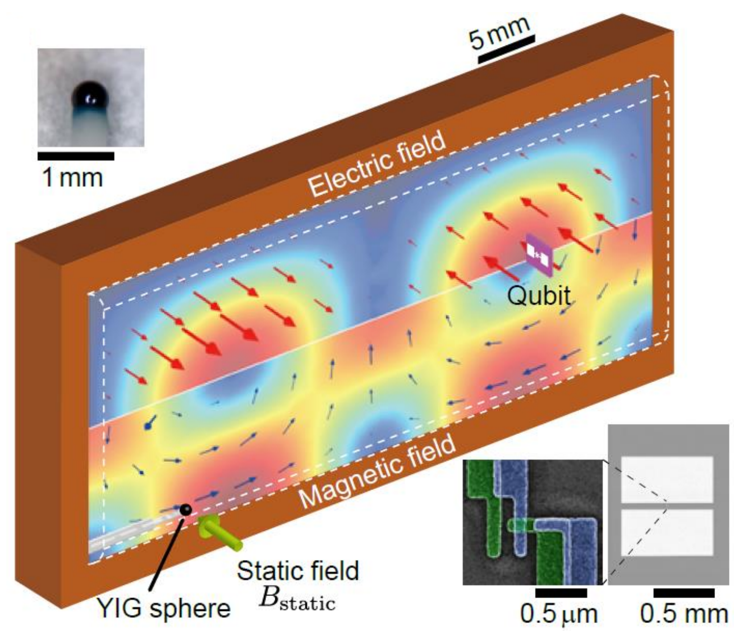
Vaccum Rabi splitting



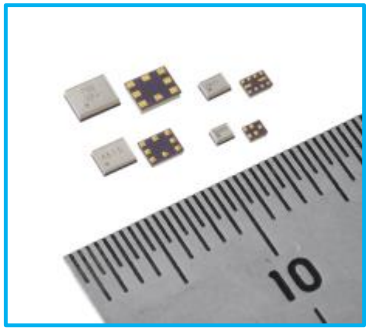
Single shot magnon detection



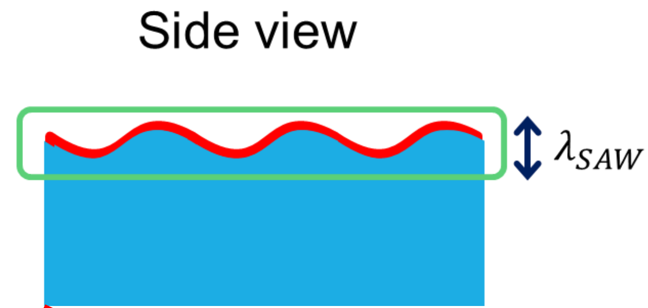
Resonant magnetic induction tomography

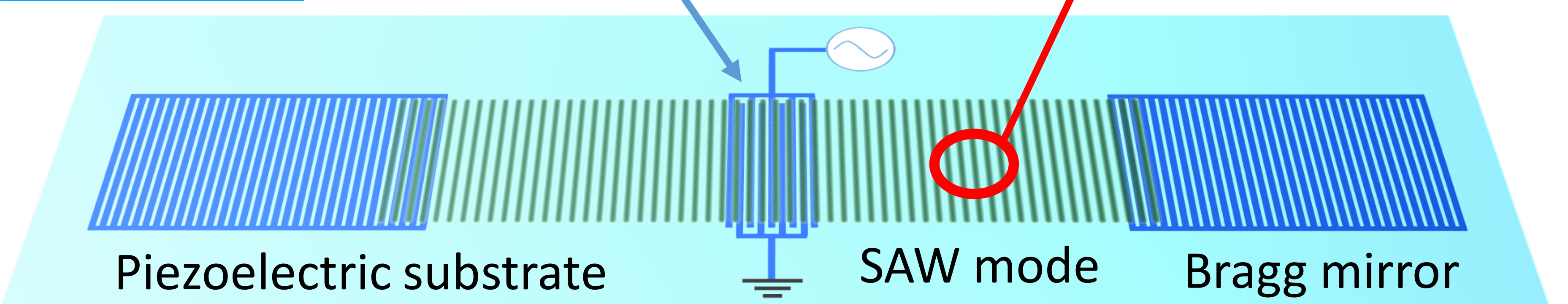


Surface acoustic waves



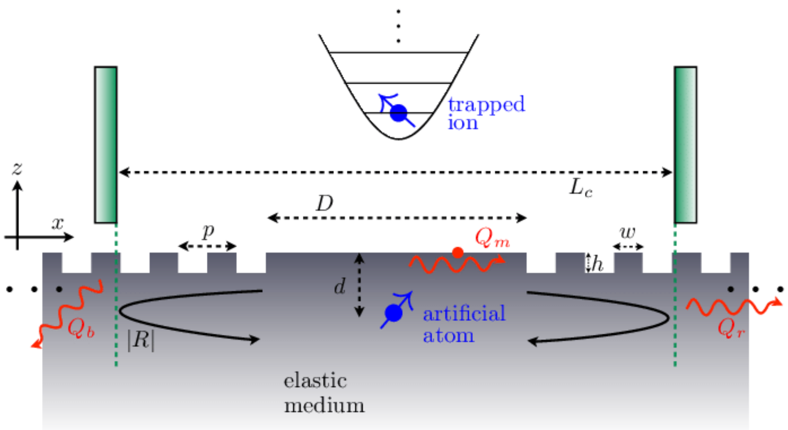
Filters, sensors, etc.

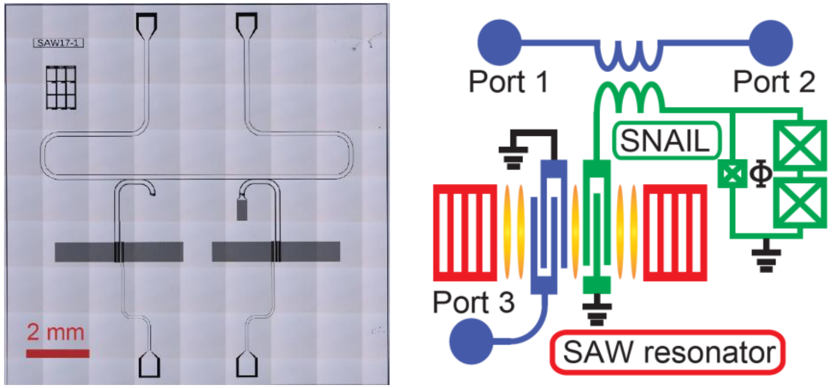




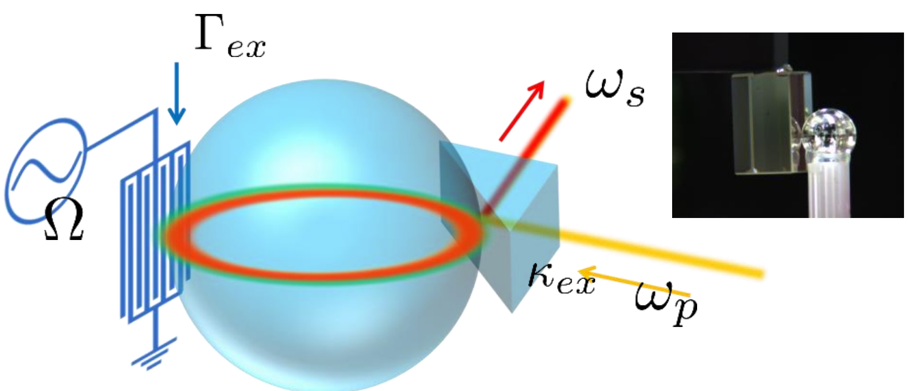
- Small sound velocity — compact device
- Surface mode — small mode volume
- Low loss — Q〜1,000,000
- High frequency — ω/2π 〜 GHz
- Piezoelectric — strong coupling with E-field
- Photoelastic coupling — possible strong coupling with light

SAW Transducer Project

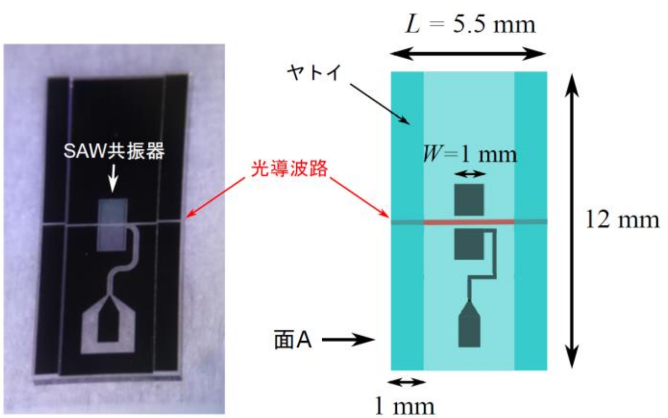




Single photon strong
SAW-microwave coupling
$C \sim 10^3$



Tripple resonance
SAW-optical coupling
$C = 6.3 \times 10^{-4}$



On chip waveguide
SAW-optical coupling
$C = 6.8 \times 10^{-5}$

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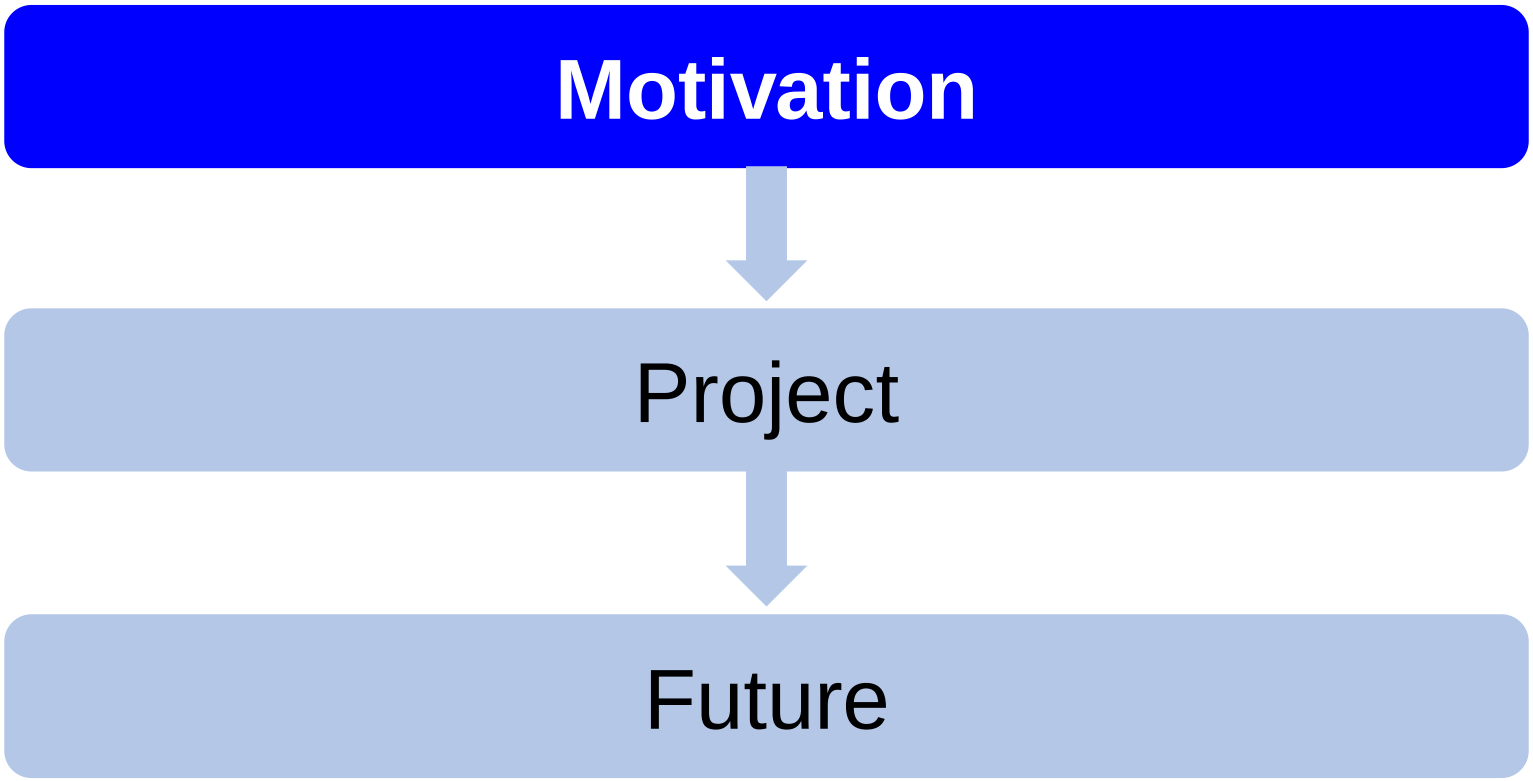
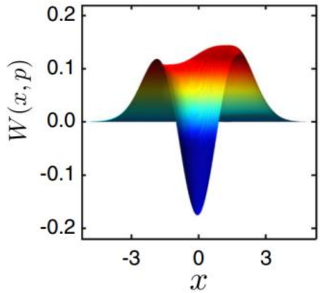


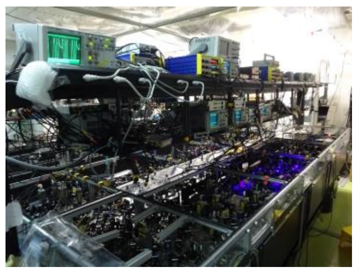
Initial Motivation of Project

Quantum Optics

Source State generation



Communi-cation Operations



Readout Measurement

○ Room temperature

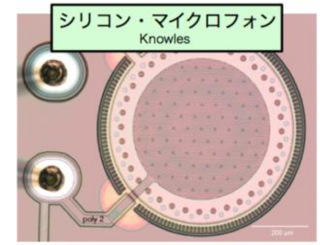
✕ Nonlinearity

×

Mechanics

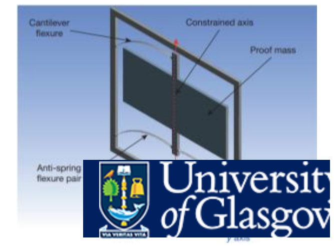
Semiconductor MEMS

knowles



Measurement

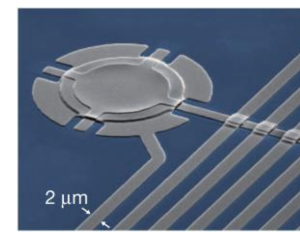
Tidal cycle $\sim \mu$Hz



Nature **531**, 614 (2016)

Superconducting circuits $\sim$GHz

NIST



Nature **475**, 359 (2011)

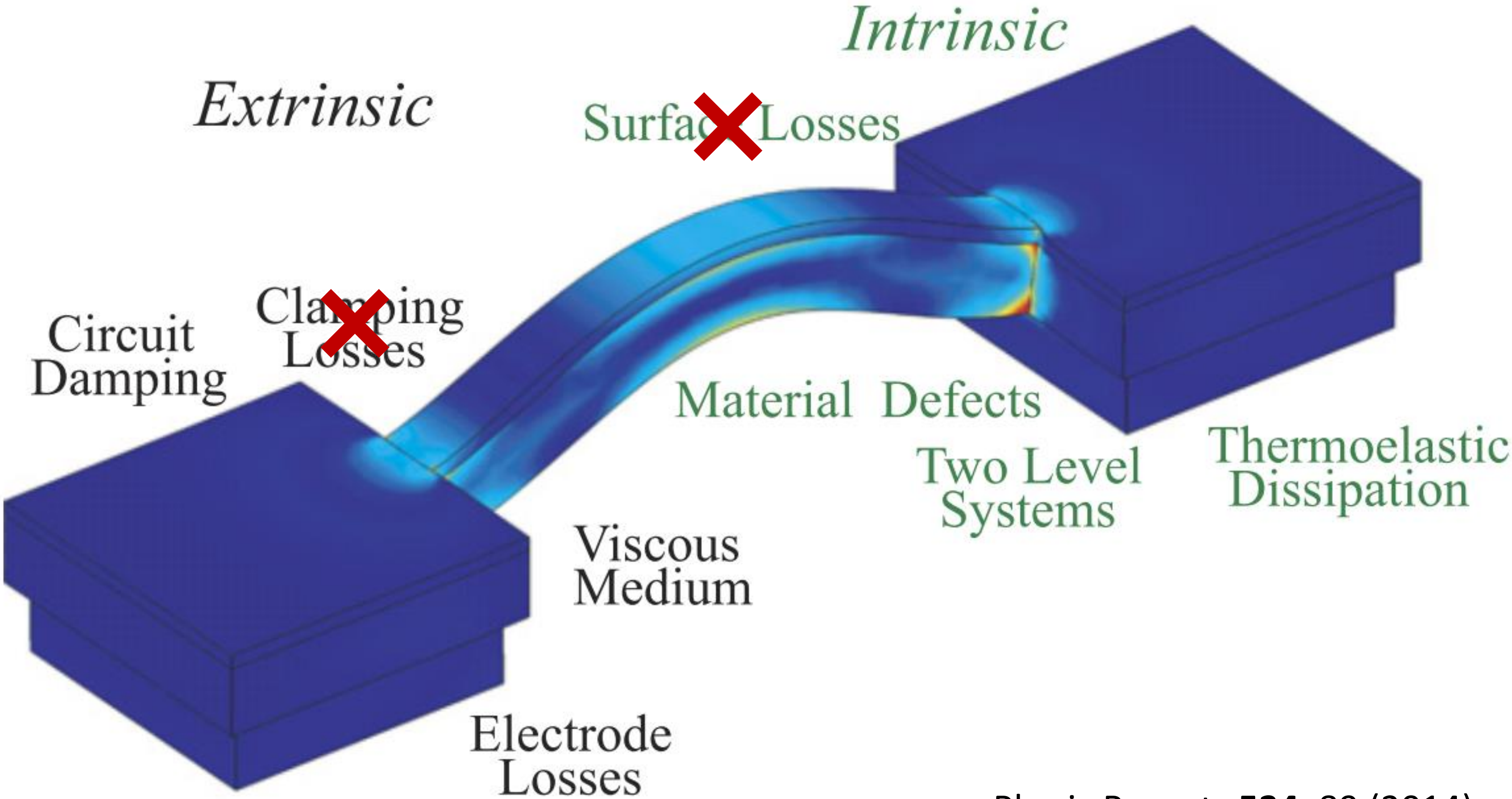
✕ Needs cooling

○ Nonlinearity

Towards novel photonic quantum industry

Dissipations in Oscillators

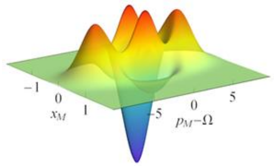
Due to surface to volume ratio $Q \propto \sqrt[3]{V}$

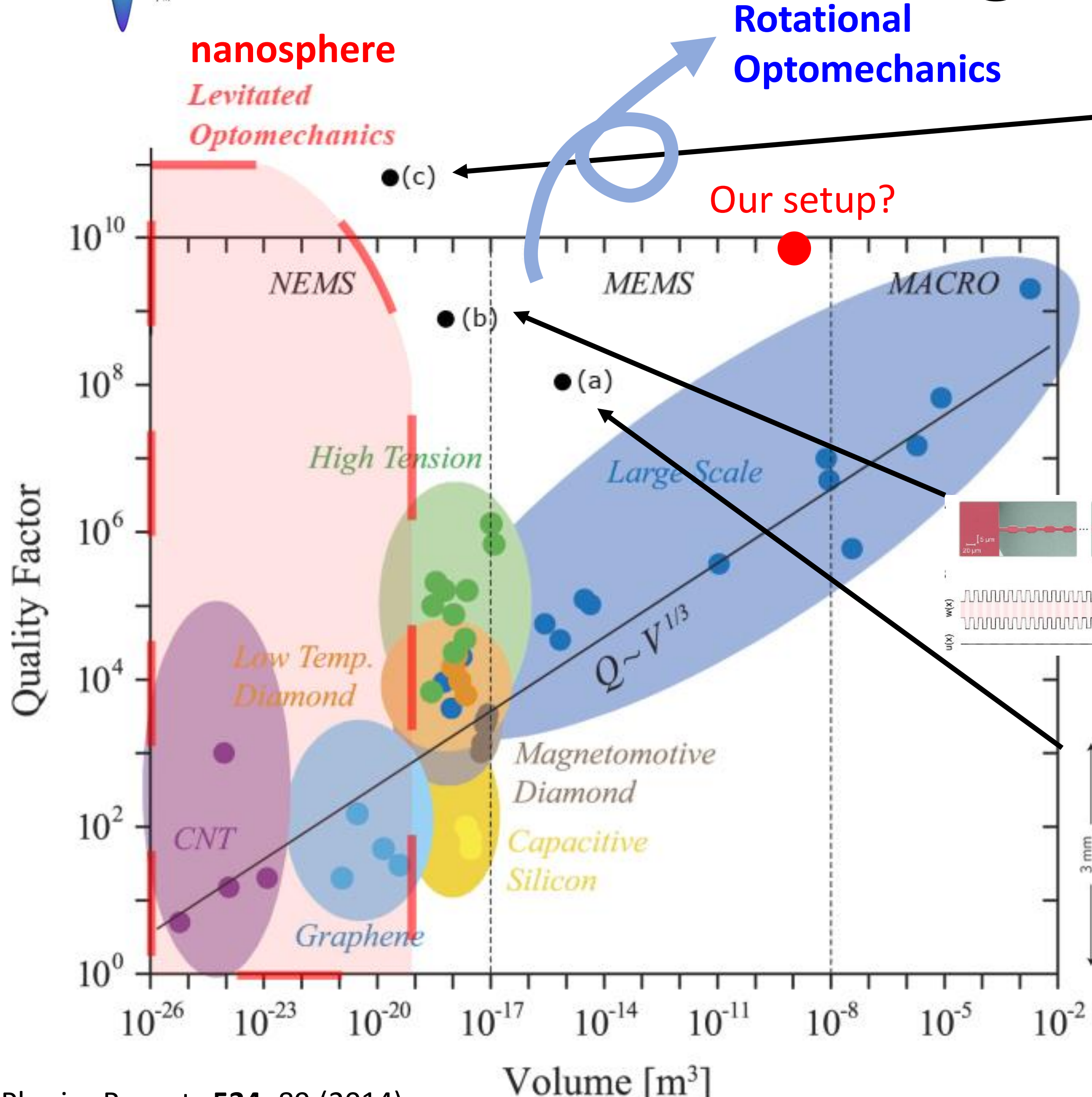


Physic Reports **534**, 89 (2014)

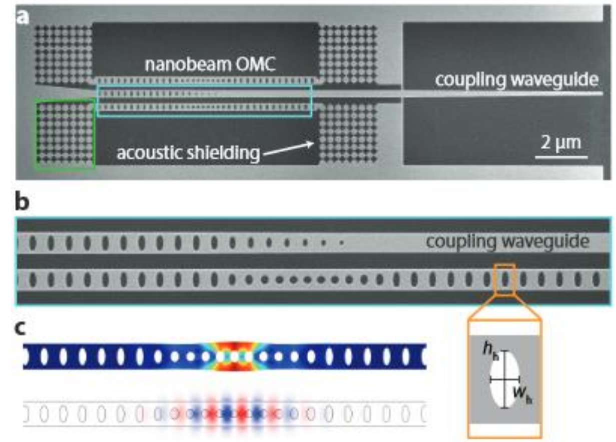
Levitation allows gas damping limited mechanical oscillators

ace Towards High Q-factor

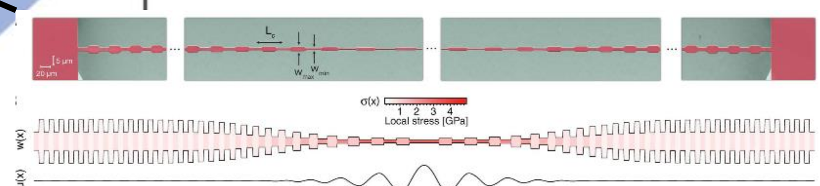




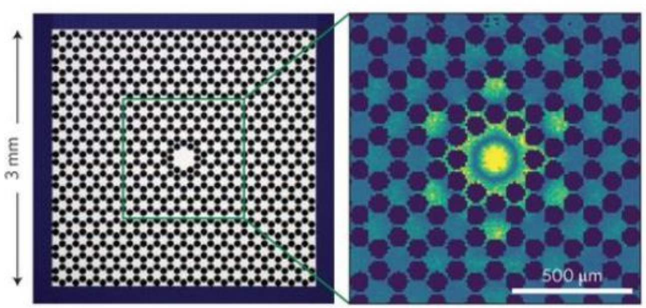
Physics Reports **534**, 89 (2014)



arXiv:1901.04129 [cond-mat]



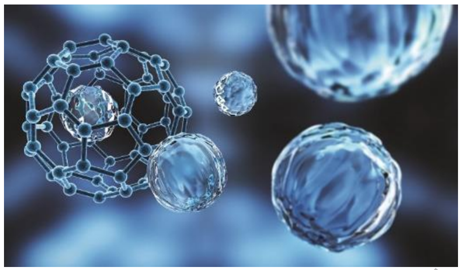
Science **18**, 764 (2018)



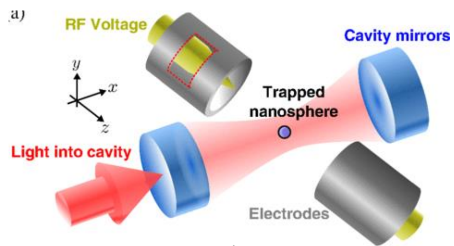
Nat. Nanotech. **12**, 776 (2017)

Levitation and Physics

Biology
Eg. Drug delivery



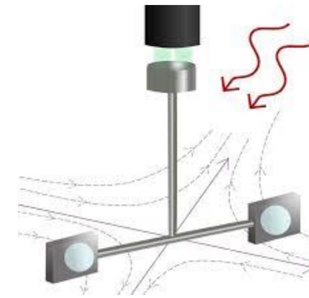
Quantum optomechanics



Spintronics

齊藤研HP

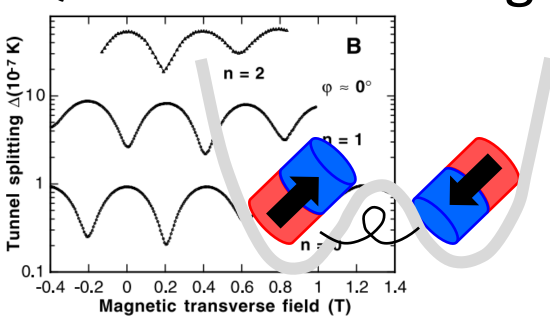
Gravitational wave detection



small

Large

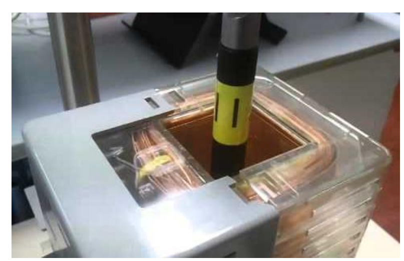
Quantum Tunneling



Science **284**, 133 (1999)

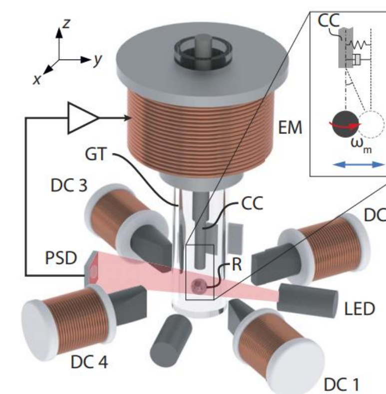
Magnetometry

Solid state physics experiment



Suspended tortional pendulum

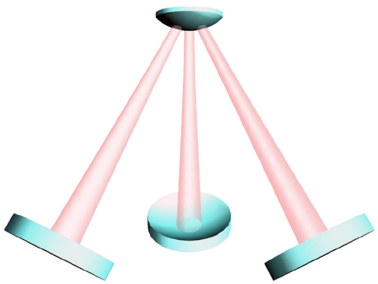
Magnetic rotor



Sci. Adv. **4**, e1701519 (2018)

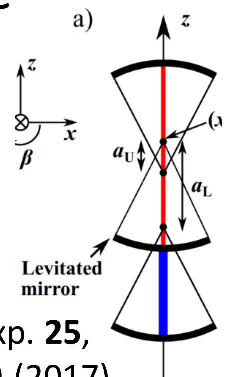
Types of Levitation

Macroscopic > µm
Radiation pressure



PRL **111**, 183001 (2013)

Australian National University

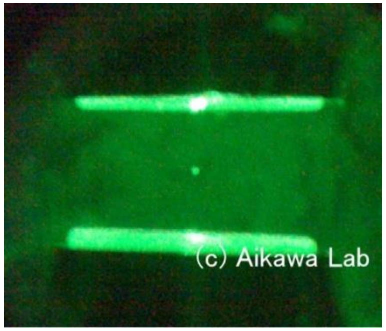


Op. Exp. **25**, 13799 (2017)

東京大学 THE UNIVERSITY OF TOKYO

Microscopic < µm
Optical tweezers

Tokyo Tech

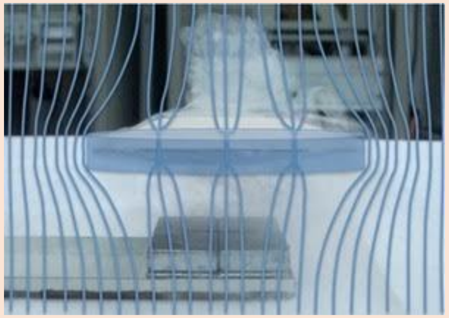


Bell Laboratories

Nat. Phys. **9**, 806 (2013)

✕ Heating　　◯ Room temperature

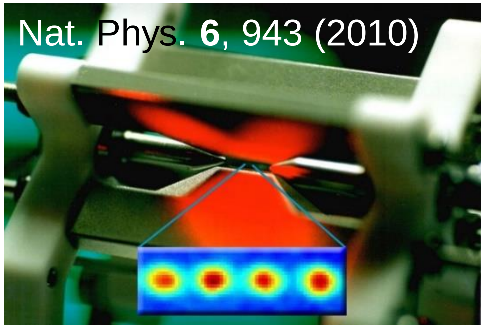
Meissner, flux pinning



◯ Stable, no heating

✕ Cryogenic

Paul trap



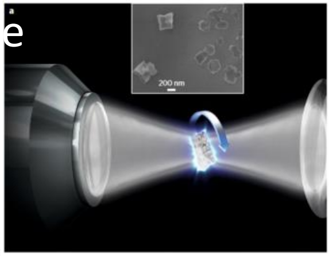
✕ Micro motion

◯ Room temperature

Levitations Around the World

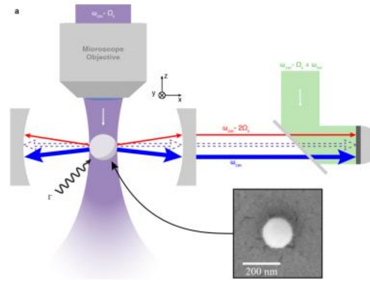
Graphene

UCL



2017, φ = 200 nm, $T \sim \mathrm{mK}$

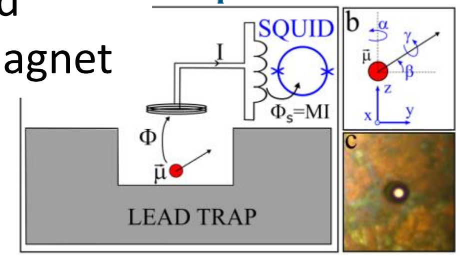
SiO_2



2019, φ = 200 nm, $n_\mathrm{p} < 1$

Nd magnet

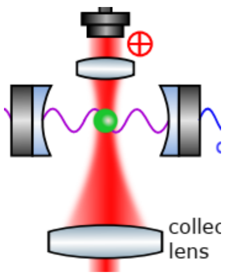
UNIVERSITY OF Southampton



2019, φ = 27 μm, $Q \sim 10^7$

SiO_2

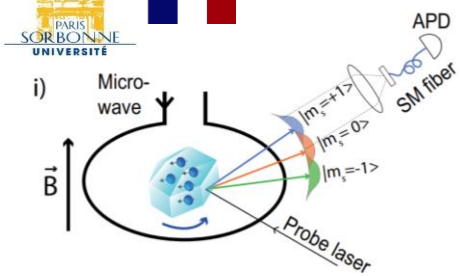
ICFO The Institute of Photonic Sciences



2018, φ ~ 100 nm, $n \sim 2000$

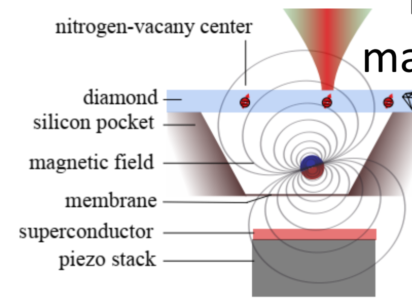
PARIS SORBONNE UNIVERSITÉ

NV center

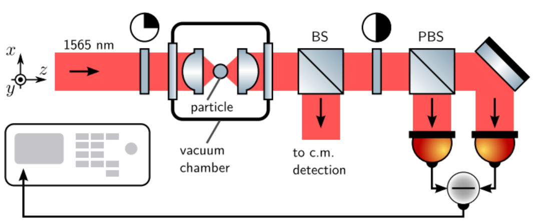


2019, φ = 15 μm, $Q \sim 67$

Nd magnet

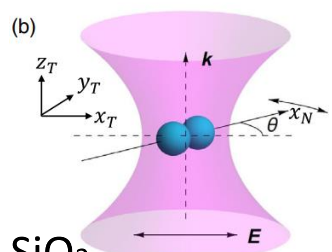


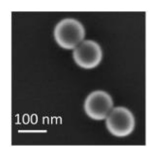
2019, φ ~ 20 μm, $Q \sim 10^6$



SiO_2 ETH zürich

2018, φ ~ 100 nm, ω~1 GHz

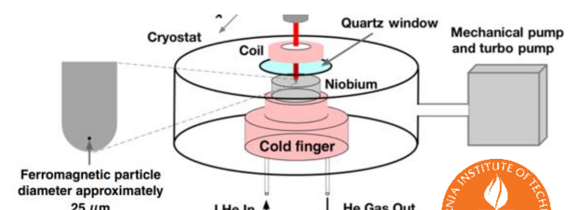




PURDUE UNIVERSITY

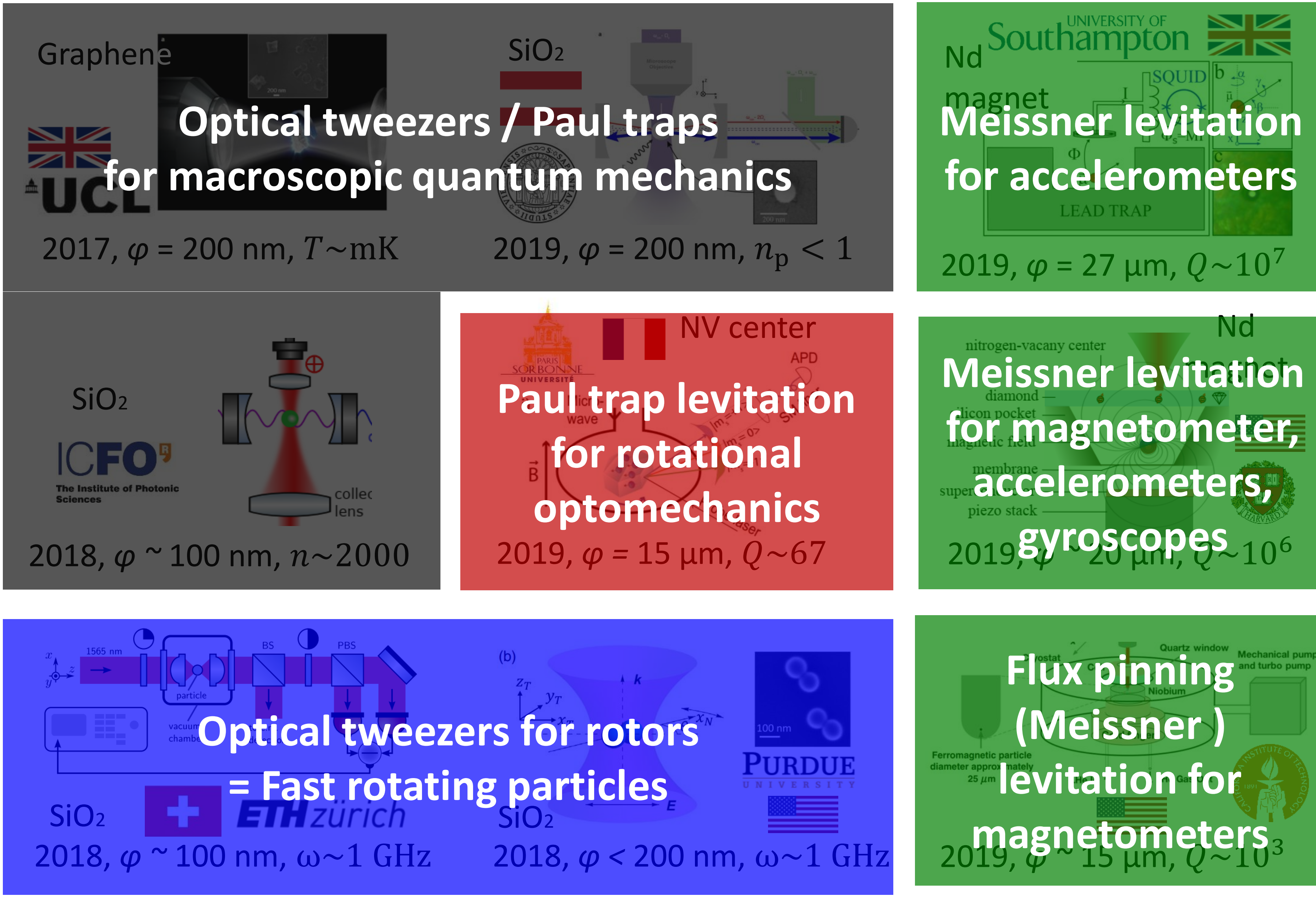
SiO_2

2018, φ < 200 nm, ω~1 GHz



2019, φ ~ 15 μm, $Q \sim 10^3$

Levitations Around the World



Magnonics with YIGs

Yttrium iron garnet (YIG) $Y_3Fe_5O_{12}$

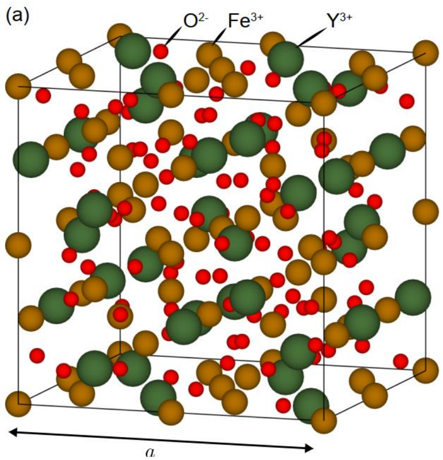
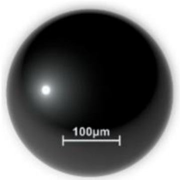


図 : 久富博論（2019）

- ✓ Electron spins affect ferromagnetism
- ✓ High spin density for insulator
  $2.1 \times 10^{22}\ \mu_B/\mathrm{cm}^3 \gg 10^{16} - 10^{18} \mu_B/\mathrm{cm}^3$
- ✓ Long spin coherence time: 1 MHz
- ✓ High quality crystals commercially available;



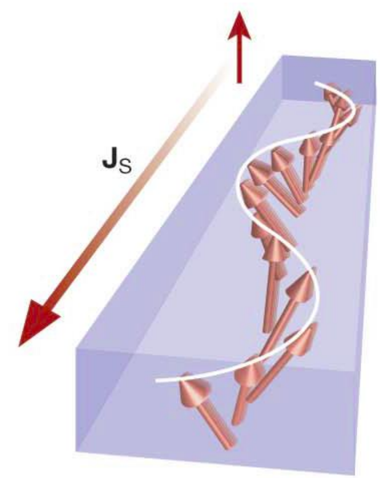
Microwave oscillators

CANDOX Corporation

Optical isolators

FDK Corporation

Spintronics

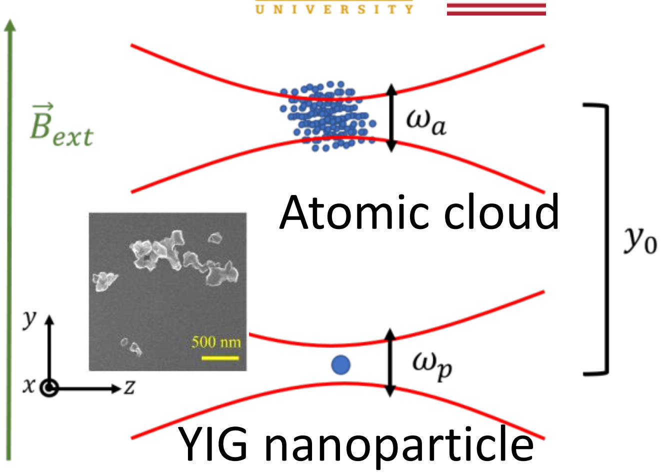


Kajiwara et al.
Nature 2010

Levitation of YIG Soft Ferromagnets

(p) = proposal

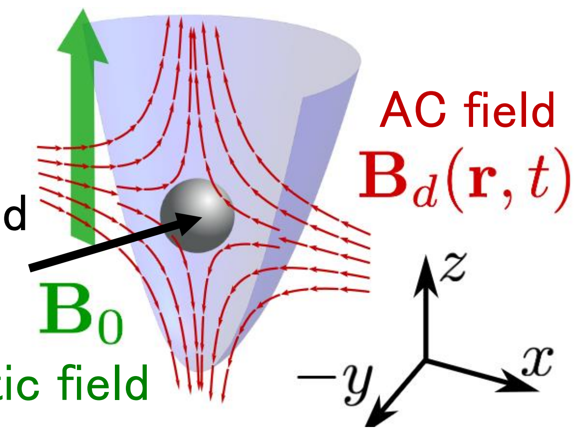
PURDUE UNIVERSITY



[quant-ph] arXiv:1910.05371

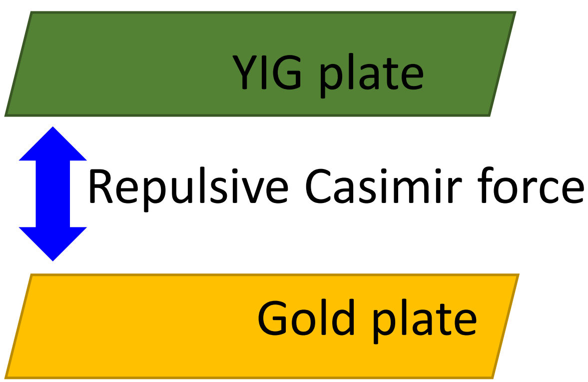
2019 Optical tweezer levitation

universität innsbruck



[quant-ph] arXiv:1907.04039

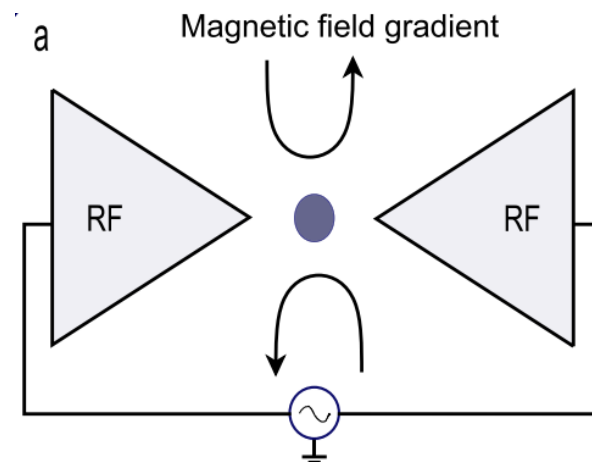
2019 Ground state cooling (p)



HYOGO UNIVERSITY OF HEALTH SCIENCES

Journal of Applied Physics **111**, 074304 (2012)

2012 Long lasting MEMS (p)



φ~20 nm

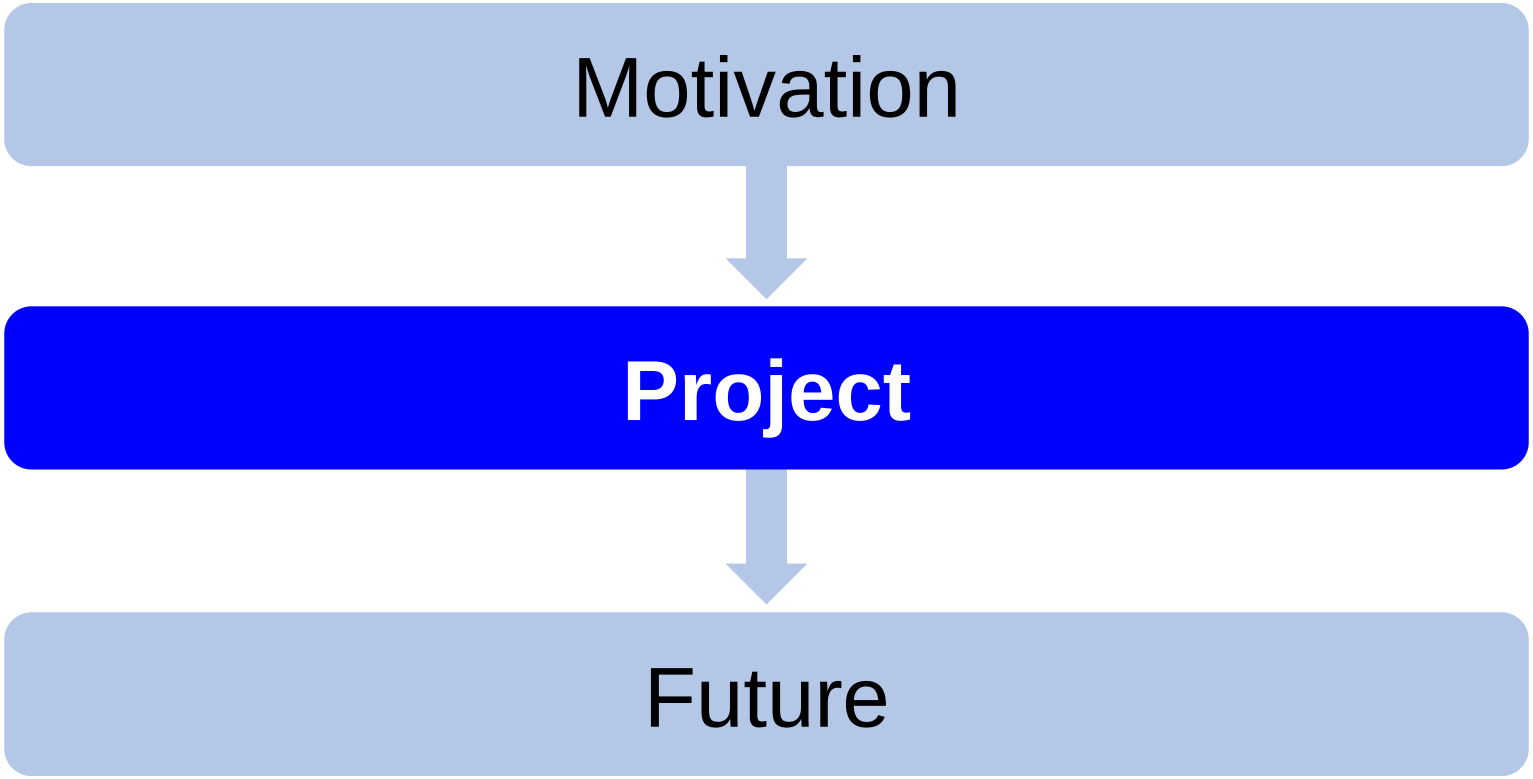
Paul trap

UCL

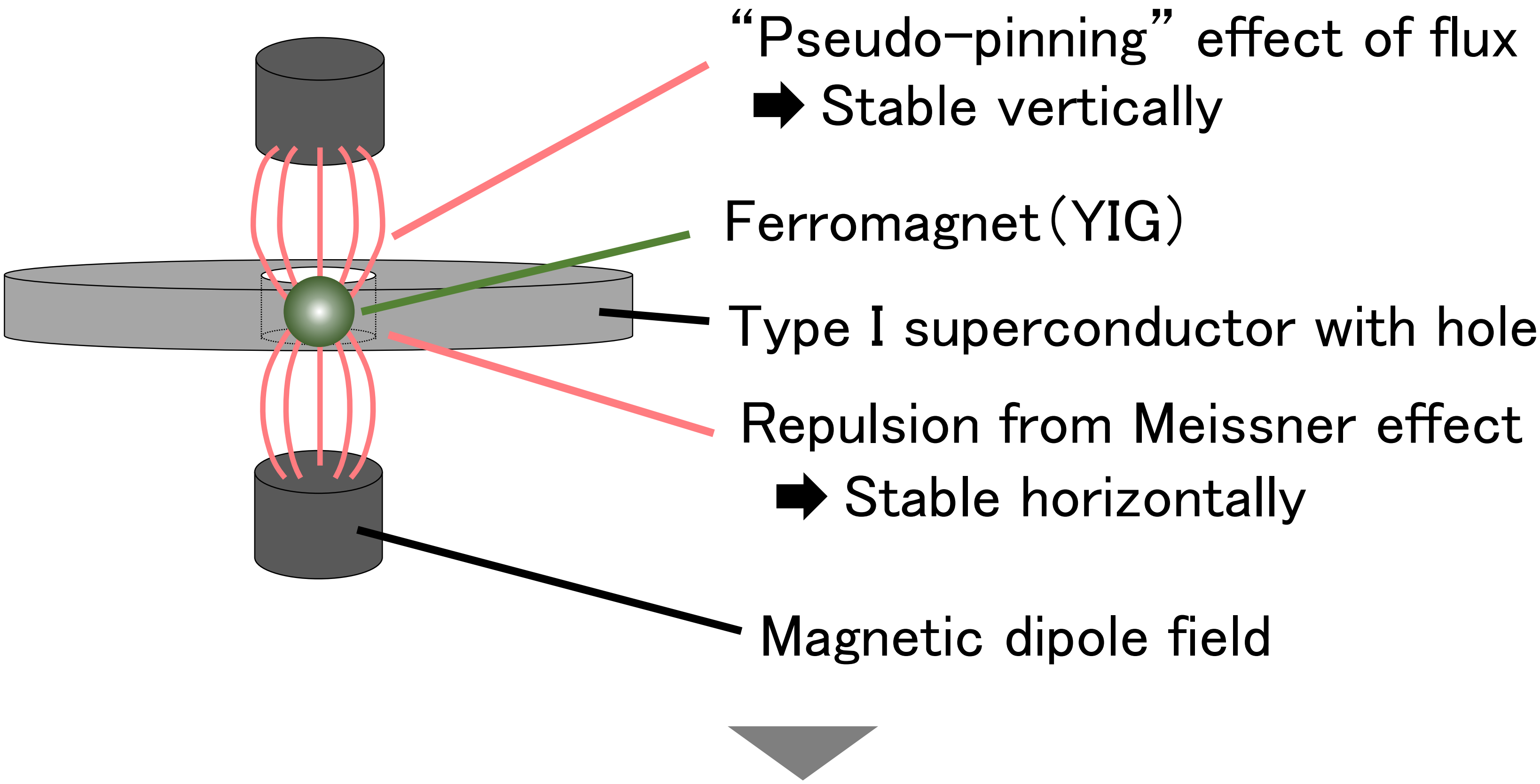
New J. Phys. **21**, 113011 (2019)

2019 Cat state generation (p)

My Levitation Project



Overview of Our Project



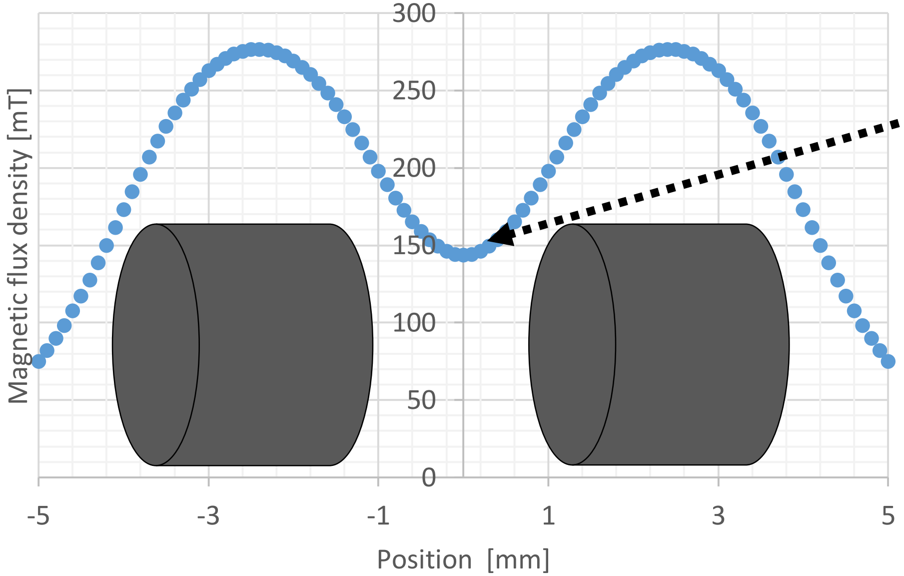
First levitation of **high Q insulating soft magnet**

Goal: Utilize conservation of angular momentum, spins

Rotational optomechanics, Magnetometers, Accelerometers

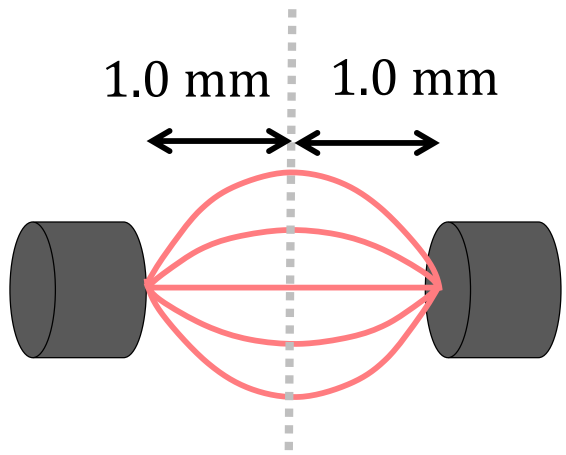
Magnetic Trap Simulations

Dipole trap from 2 magnets



Magnetic flux diverges

Faster spread when aspect ratio close to 1:1

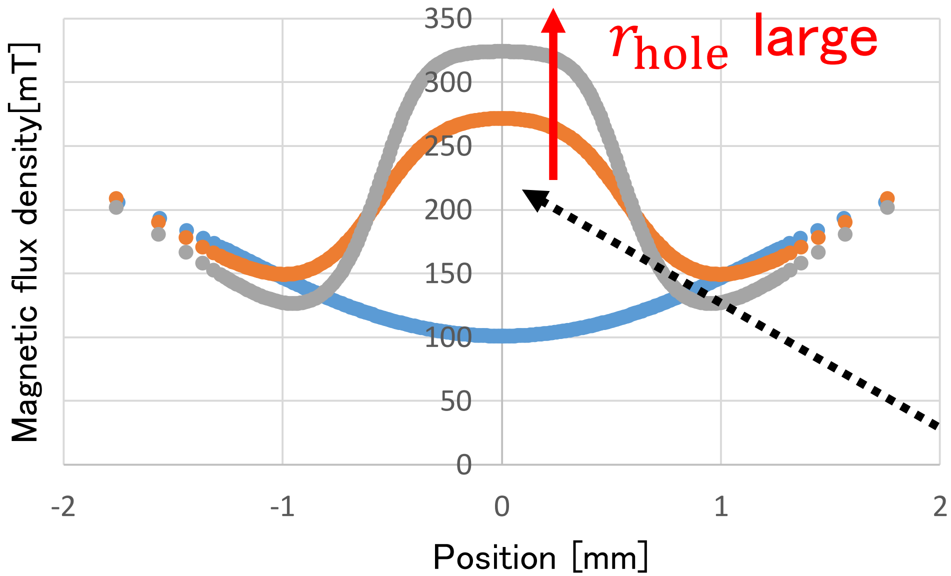


Nd magnets 380 mT

$\varphi = 3.0\ \mathrm{mm}, h = 3.0\ \mathrm{mm}$

Magnetic Trap Simulations

Dipole trap from 2 magnets + superconducting disk w/ hole

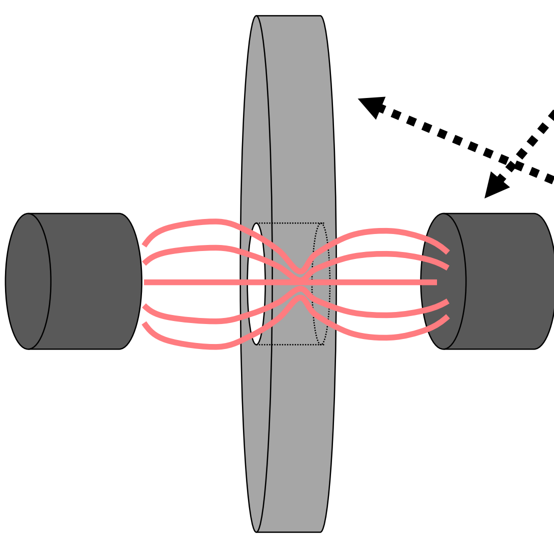


$r_{\mathrm{hole}} = 0.30$ mm

$r_{\mathrm{hole}} = 0.35$ mm

No superconductor

Magnetic flux squeezed

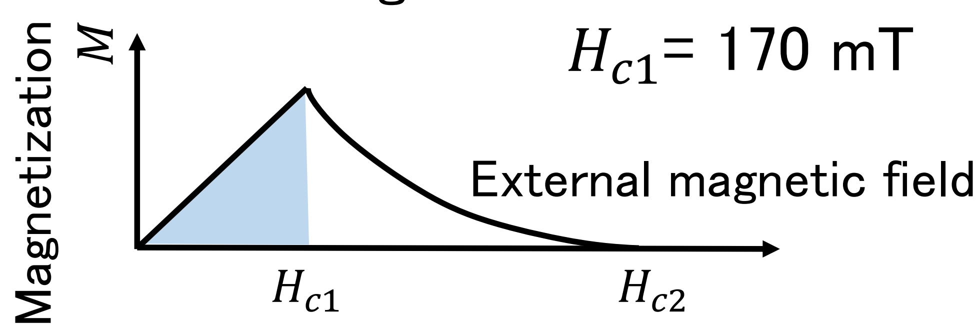


Nd magnets 380 mT

$\varphi = 3.0$ mm, $h = 3.0$ mm

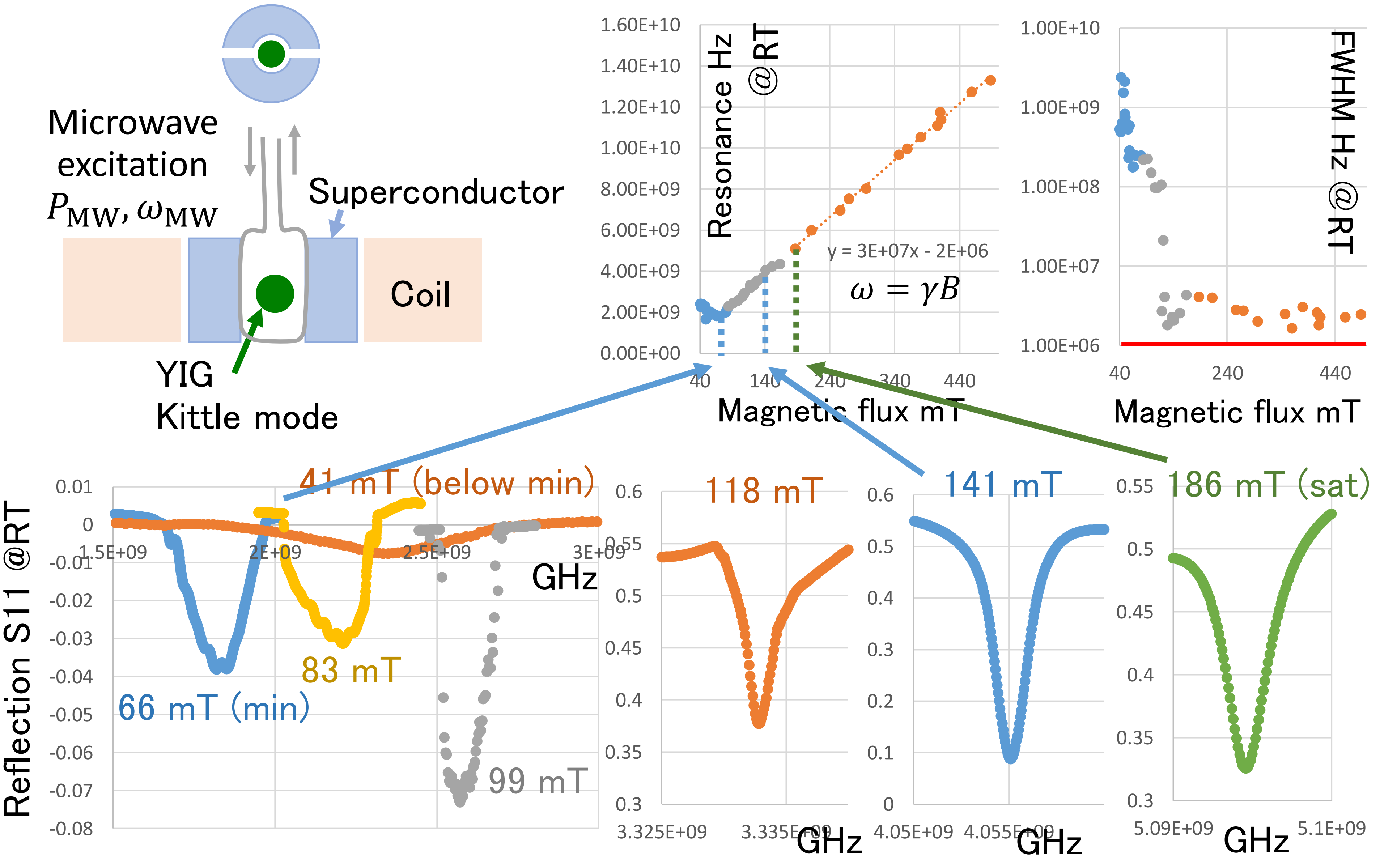
Nb Critical magnetic field

H_{c1} = 170 mT

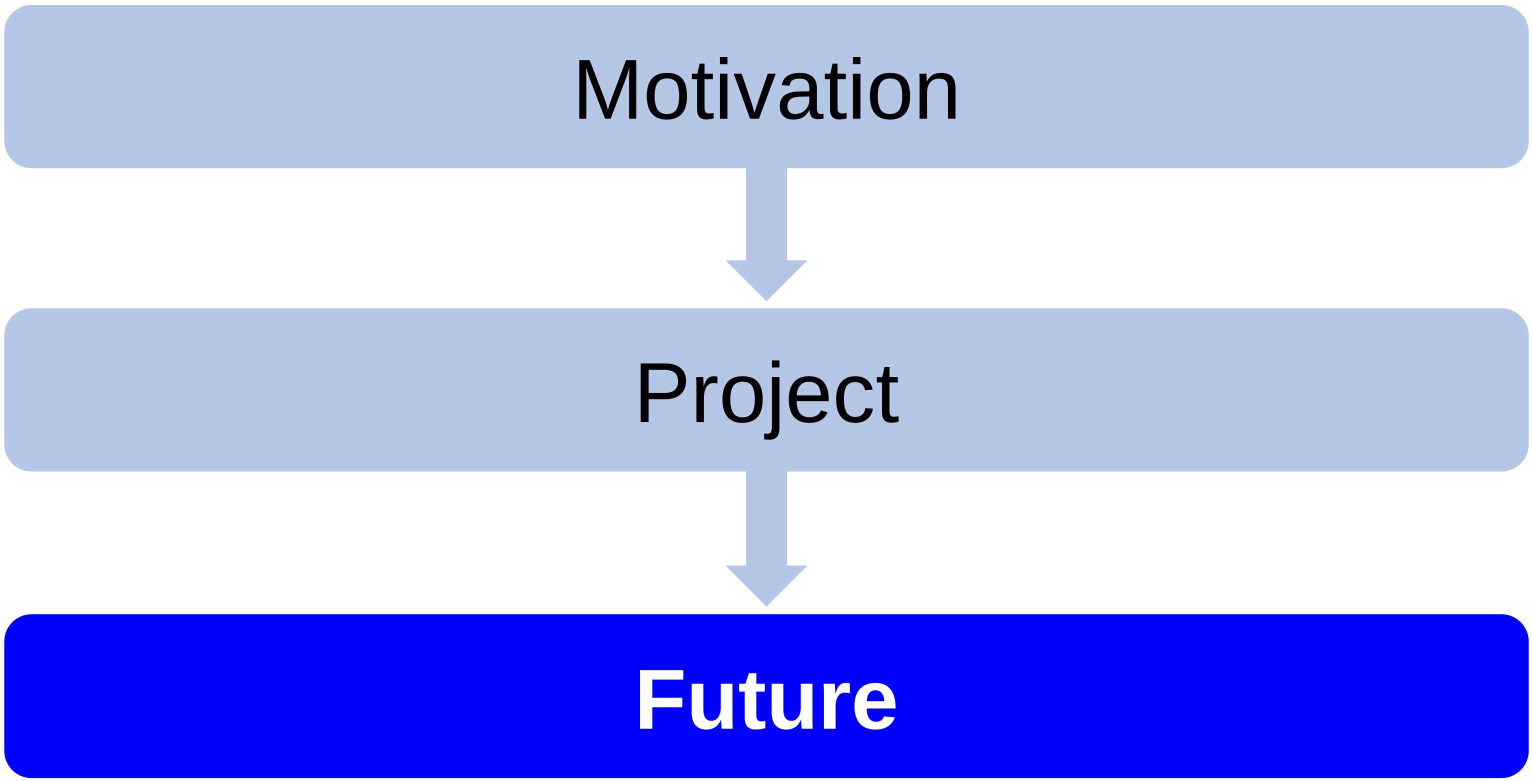


Accessing Internal Degrees of Freedom

Insert single coil from slit to read FMR



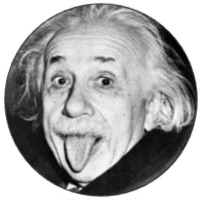
My Levitation Project

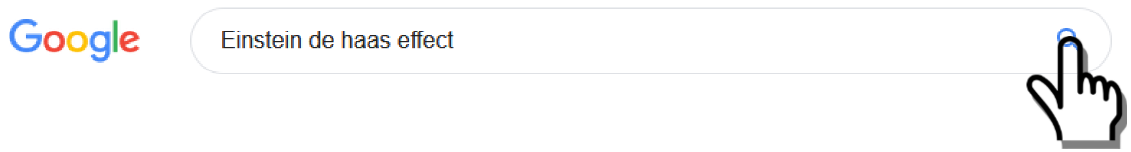


Einstein de Hass Effect

1915 Einstein & de Haas using Fe Torsional pendulum

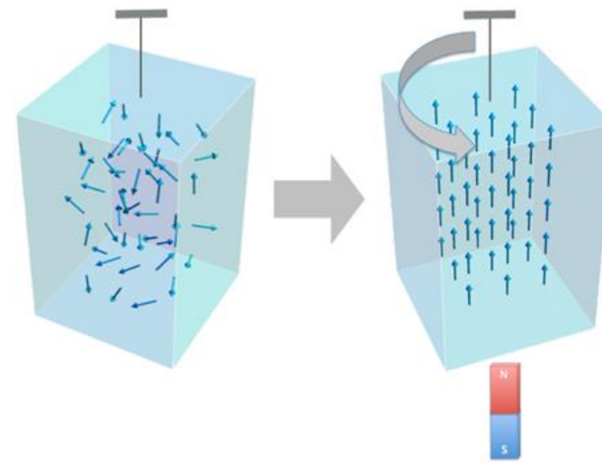
"Experimental proof of the existence of Ampere's molecular currents"



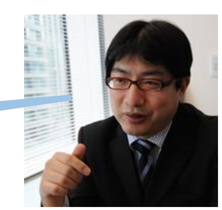
Ferromagnet

AC magnetic field



Front. Phys. 3:54 (2015)

MEMS for spintronics!

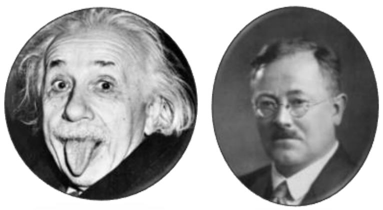


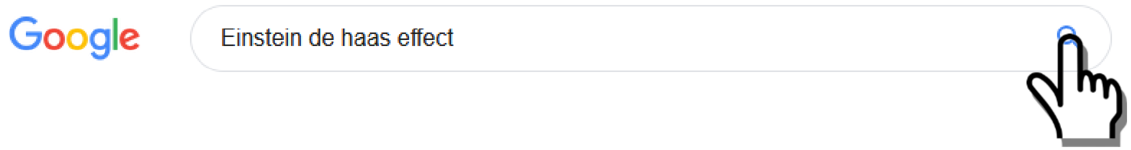
https://www.youtube.com/watch?v=5S54yz7r-3w

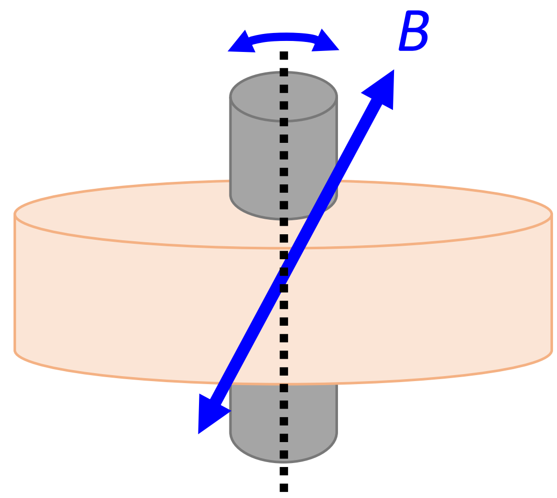
Einstein de Hass Effect

1915 Einstein & de Haas using Fe Torsional pendulum

"Experimental proof of the existence of Ampere's molecular currents"



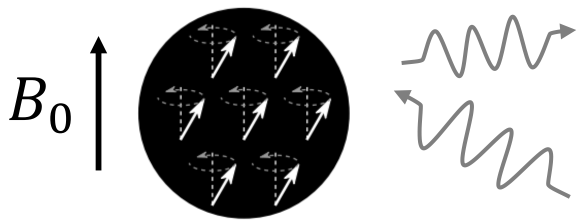




https://www.youtube.com/watch?v=5S54yz7r-3w

Youtube videos are not Einstein de Haas effects!

How Much Rotation?



Decay $\Gamma \sim 1$ MHz

Microwave $\omega = \gamma B$

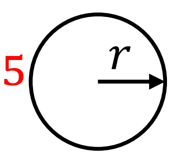
Equation of motion in ideal case

$$I\ddot{\omega} = \underline{N\hbar/\Gamma}$$

N magnons continuous excitation

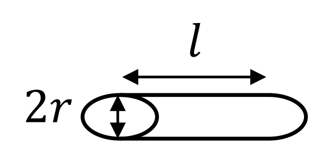
➡ Uniform acceleration $\omega(t) = \frac{N\hbar}{I\Gamma} t^2 \propto N r^{-5} t^2$

Sphere moment of inertia $\mathrm{I} = \frac{2}{5} m r^2 = \frac{8\pi}{15} \rho r^5$

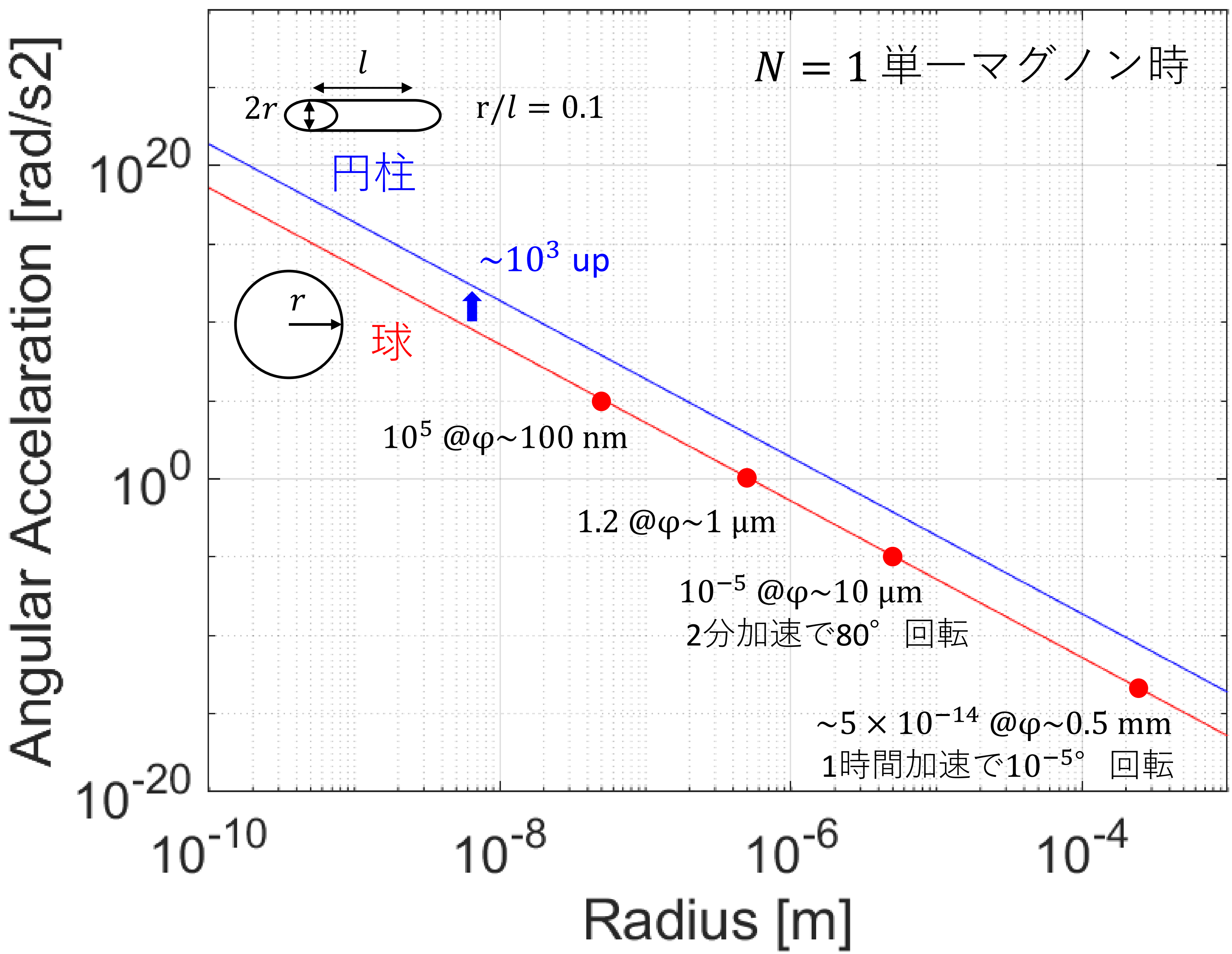


Rod moment of inertia $\mathrm{I} = \frac{1}{12} m(3r^2 + l^2) = \frac{\pi}{12} \rho \alpha^2 (3\alpha^2 + 1) l^5$

$\alpha = r/l$



➡ **Q. Quantization of rotation (N=1)?**



N = 1 単一マグノン時
l
2r
r/l = 0.1
円柱
~10^3 up
r
球
10^5 @φ~100 nm
1.2 @φ~1 µm
10^−5 @φ~10 µm
2分加速で80° 回転
~5 × 10^−14 @φ~0.5 mm
1時間加速で10^−5° 回転
Angular Acceleration [rad/s2]
10^20
10^0
10^-20
10^-10
10^-8
10^-6
10^-4
Radius [m]

Coupling of Internal and External

[quant-ph] arXiv:1907.04039

$$\hat{H} = \omega_x \hat{b}^\dagger \hat{b} + \omega_m \hat{s}^\dagger \hat{s} + \omega_p \hat{a}^\dagger \hat{a}$$

Center of mass — Magnon — Acoustic

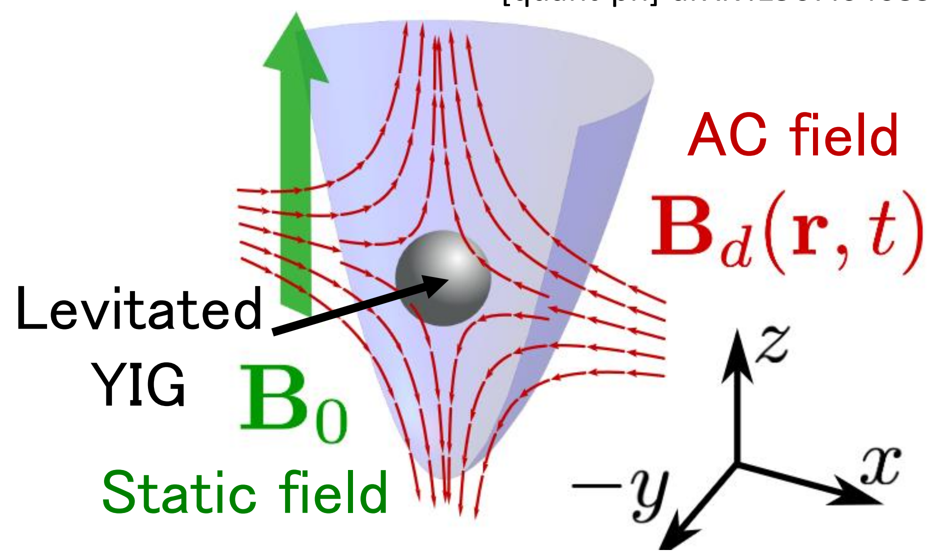
Resonant

$$+g(\hat{s}^\dagger \hat{a} + \hat{a}^\dagger \hat{s})$$

Magneto−elastic

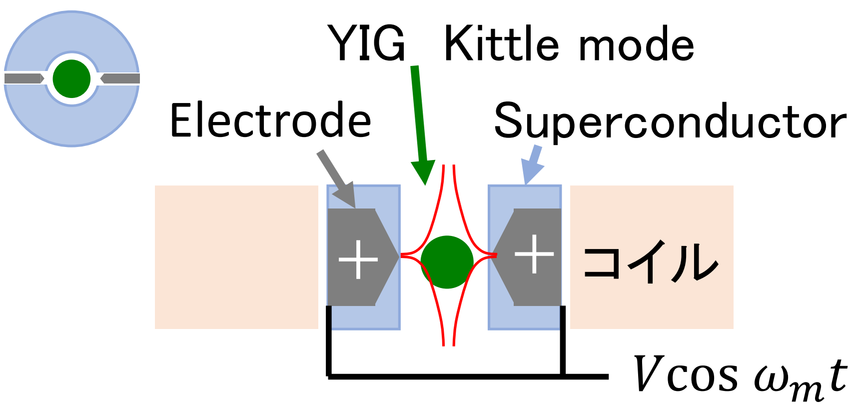
$$+G_x \cos \omega_d t\, (\hat{s}^\dagger + \hat{s})(\hat{b}^\dagger + \hat{b})$$

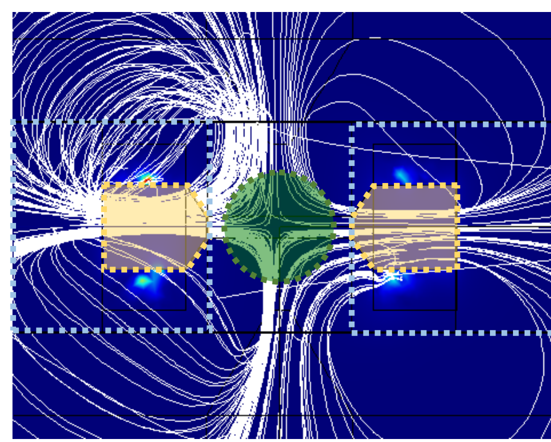
Center of mass motion coupled to magnons through acoustic modes



Cooling and control of motion through magnons

Insert electrodes through slit to create quadrupole field

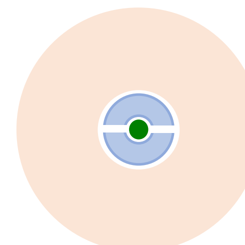




Problems and Future Prospects

Summary

	1st Generation		2nd Generation
Apply magnetic field	Magnet	➡	Coil
Shape of superconductor	Disk with hole	➡	Add slit



Problems to solve

✓ Build 2nd generation setup

Q. Other interesting future goals with levitation?

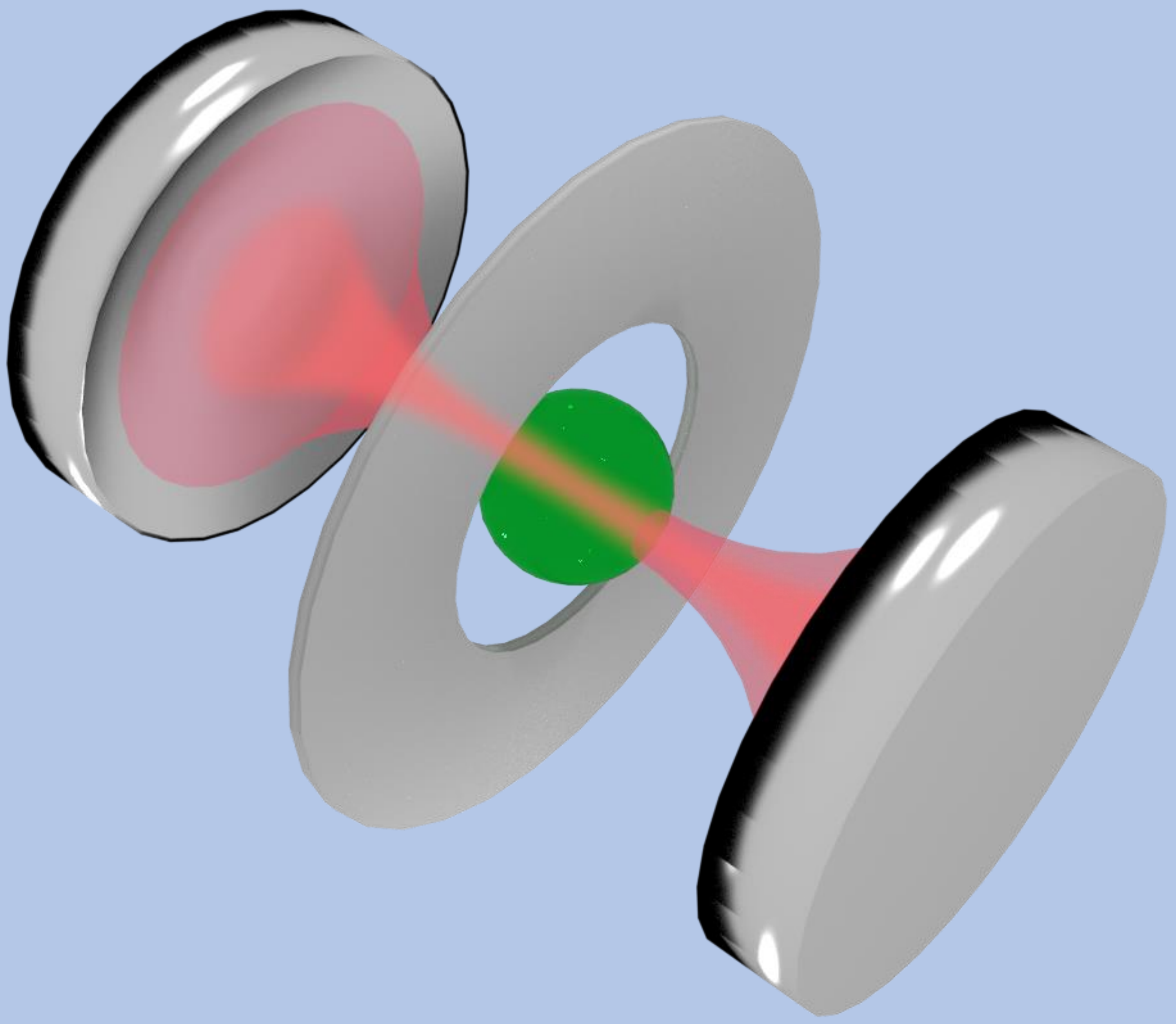
Q. Good readout scheme? Currently light will be used

Q. How to shape Nb without degrading H_{c1}?

Q. How to obtain smaller μm sized YIG spheres?

Future goal: Control of external motion through internal magnons

Thank You for Your Attention



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