Physics Frontiers with Quantum Science and Technology
University of Tokyo, Mar 9 – 10, 2022

Mesoscopic physics and quantum sensing

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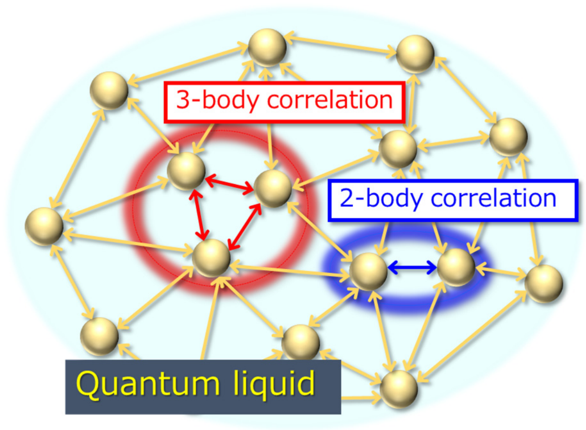
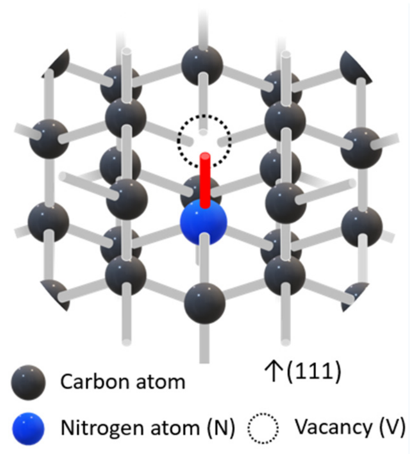
Outline

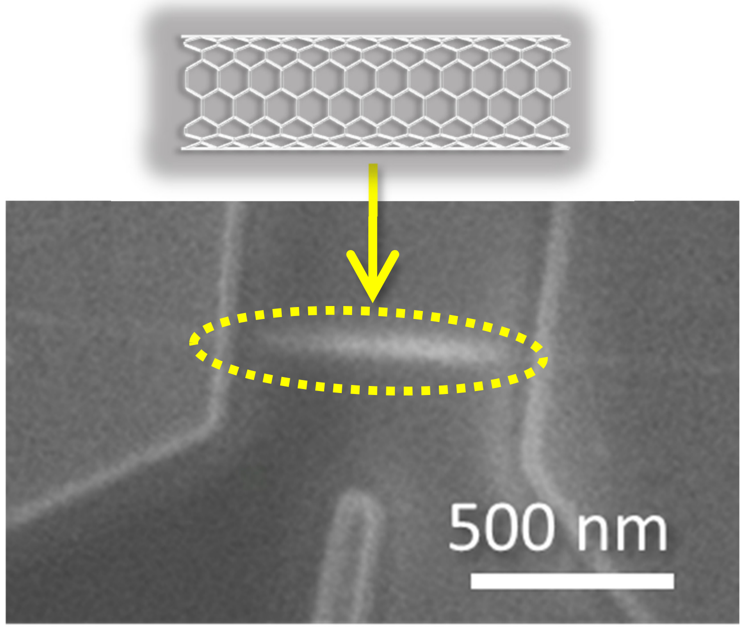
- What is mesoscopic physics?
- Correlations in quantum liquid
  - Quantum liquid
  - Kondo effect in quantum dot
  - Detection of correlation
- Quantum spin microscope
  - New tool for mesoscopic physics





What is

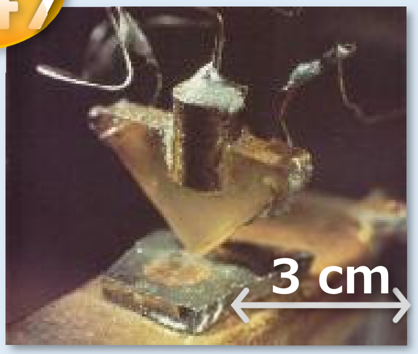
Mesoscopic Physics ?



Physics On-chip

Electronics = To play with electrons

1947



First transistor

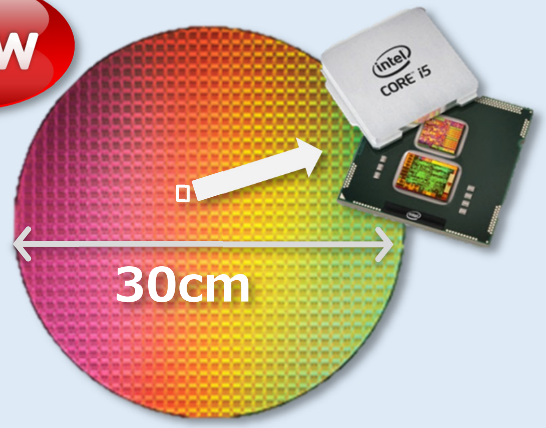
http://smithsonianchips.si.edu/augarten/i2.htm

1958

First Integrated Circuit

https://en.wikipedia.org/wiki/Integrated_circuit

Now



Billion transistors in a chip

<u>Great progress</u>

Material science

Nanotechnology

→

<u>New research field</u>

mesoscopic physics (nanophysics)

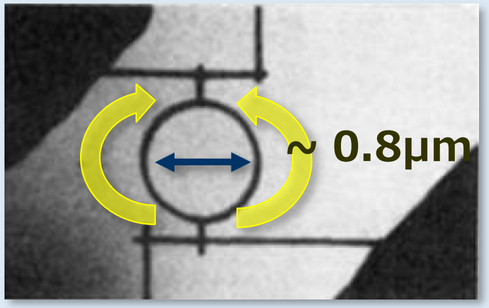
Mesoscopic System

Solid-state device where quantum mechanics manifests itself.

1980's- Stage for fundamental physics

Example

✓Electron interference
✓Single electron transistor
etc.



Webb *et al.* PRL 54, 2696 (1985)

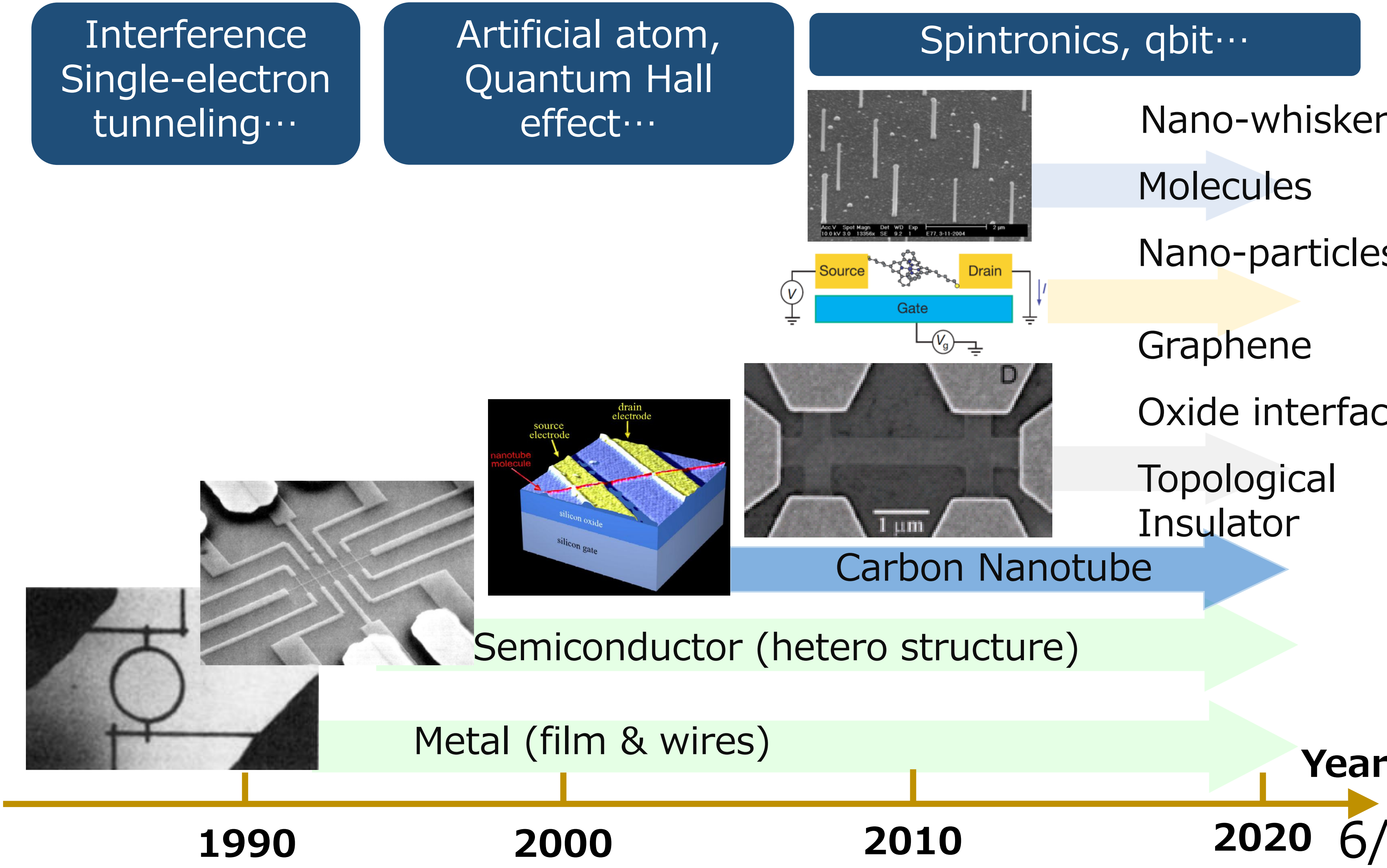
Charge
Spin
Phase
Coherence
Interaction
…

- Quantum computing
- Exotic materials — nanotube, graphene, topological…
- MEMS — micro-electromechanical systems
- Spintronics
- etc.

✓ Degree of freedom in the design

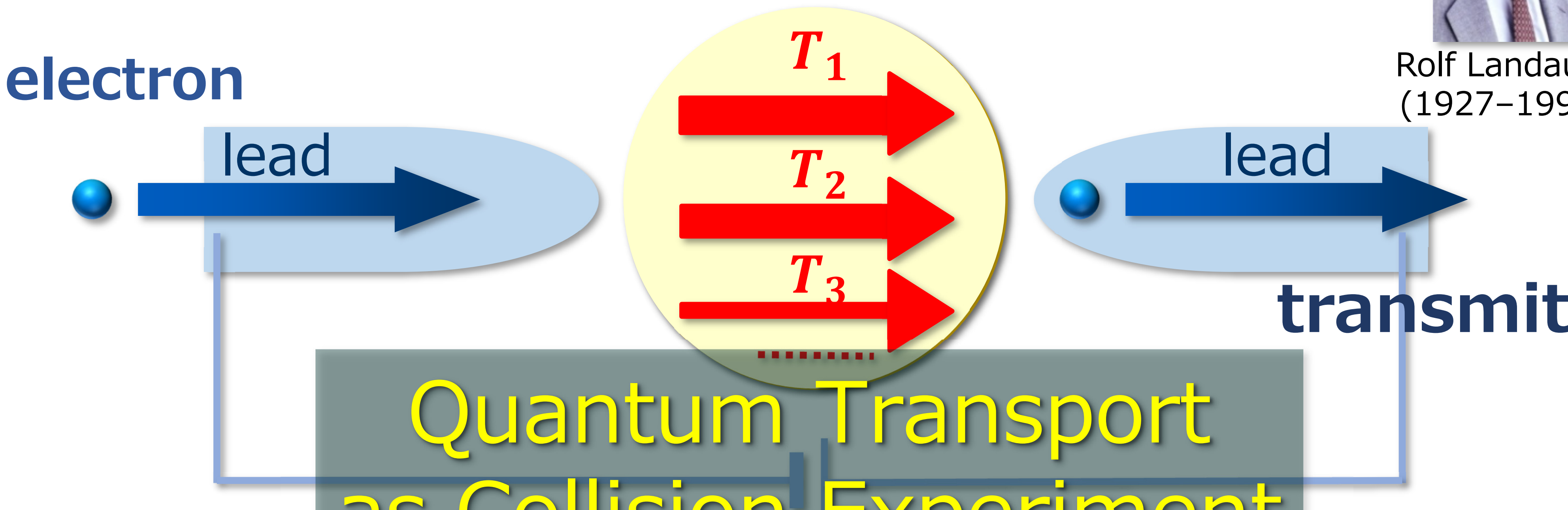
✓ Controllability

Stages for Mesoscopic Physics



"Conductance is Transmission."

Rolf Landauer (1927–1999)



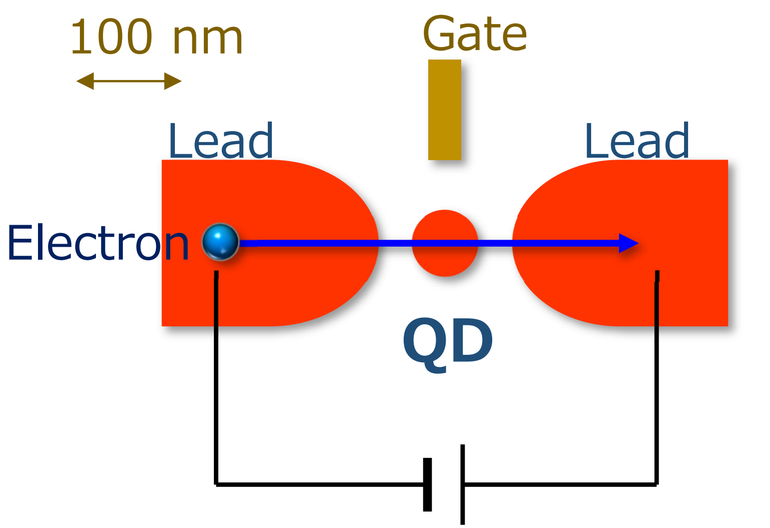
Quantum Transport as Collision Experiment

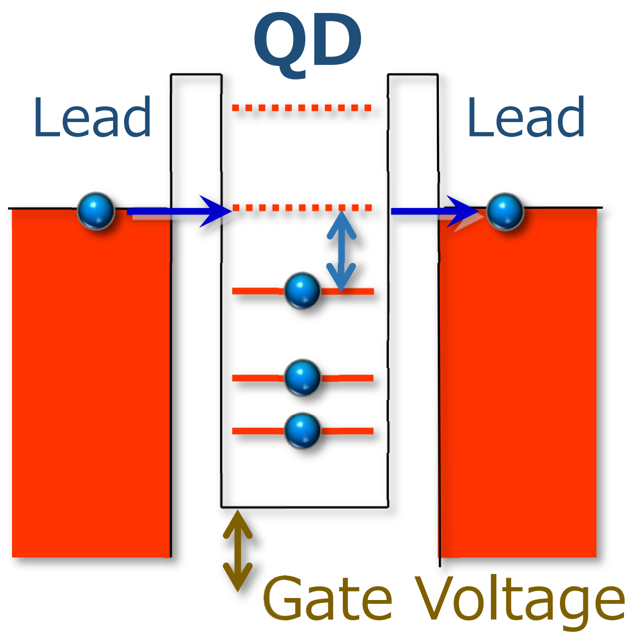
Landauer formula

$$G = \frac{2e^2}{h} \sum_n T_n \qquad \frac{2e^2}{h} \sim (12.9\ \mathrm{k\Omega})^{-1}$$

Enable us to study electronic properties of a single quantum system (interference, single-level transport, Kondo physics⋯).

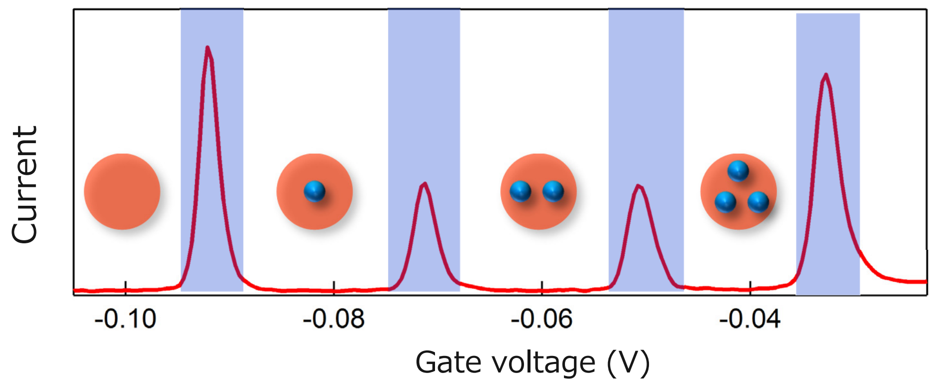
Quantum Dot (=Artificial Atom)





Electron droplet
↓
Charging effect & Confinement
↓
Discrete energy levels in QD.
# of electrons in QD is fixed.

Electron can pass QD only when the level coincides with those of the leads.

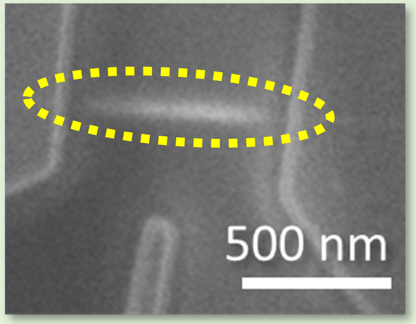


Thought experiments realized

Many-body interaction, Entanglement, Quantum computation, Spintronics, Quantum materials (graphene, topological materials, etc.), non-equilibrium ...

Quantum Dot (artificial atom)

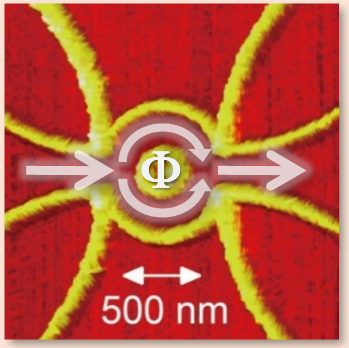
Particle nature



J. Phys. Soc. Jpn. **73,** L3235 (2004); *Phys. Rev. Lett.* **106**, 176601 (2011); **118**, 196803 (2017); **121**, 247703 (2018); *Nature Phys.* **12**, 230 (2016); *Nature Comm.* **12,** 3233 (2021).

Electron Interferometer

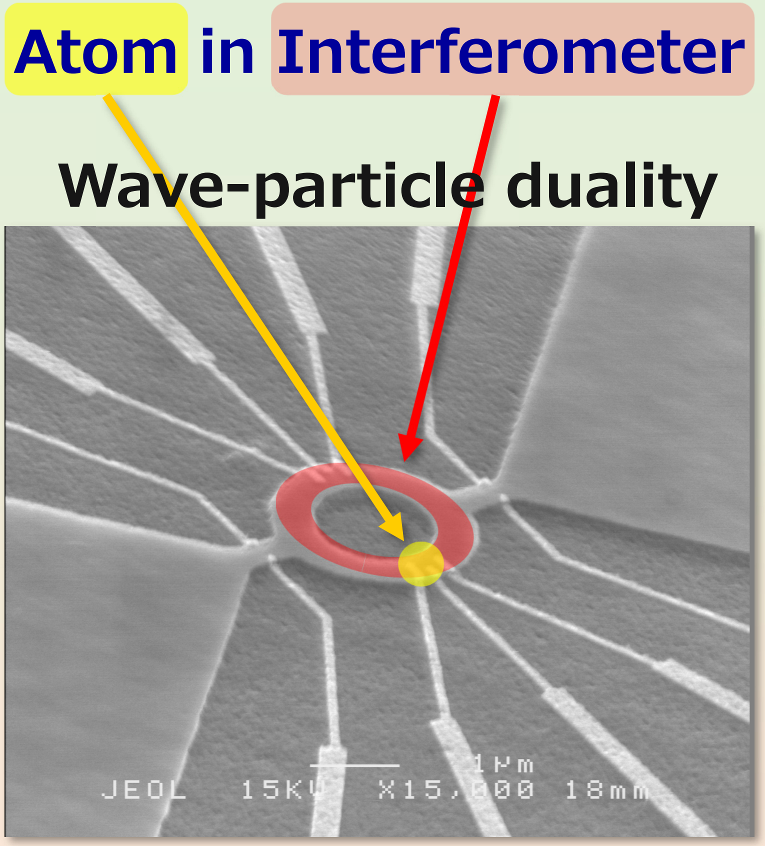
Wave nature



J. Phys. Soc. Jpn. **71,** L2094 (2002); *Phys. Rev. Lett.* **104,** 080602 (2010); *Phys. Rev.* B **79,** 161306 (R) (2009); **83,** 155431 (2011); *Physica* E **42,** 1091 (2010).

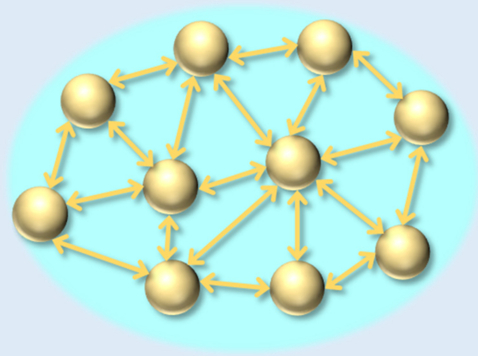
Atom in Interferometer

Wave-particle duality



Phys. Rev. Lett. **88,** 256806 (2002); **92,** 176802 (2004); **95,** 066801 (2005); Phys. Rev. B **68,** 235304 (2003); **70,** 035319 (2004); **73,** 195329 (2006).

Correlations in quantum liquid



T. Hata *et al.*, *Nature Comm.* **12,** 3233 (2021).

Experiment

T. Hata, T. Arakawa, S.-H. Lee (Osaka Univ.)
M. Ferrier, R. Deblock (Univ. Paris-Saclay, CNRS)

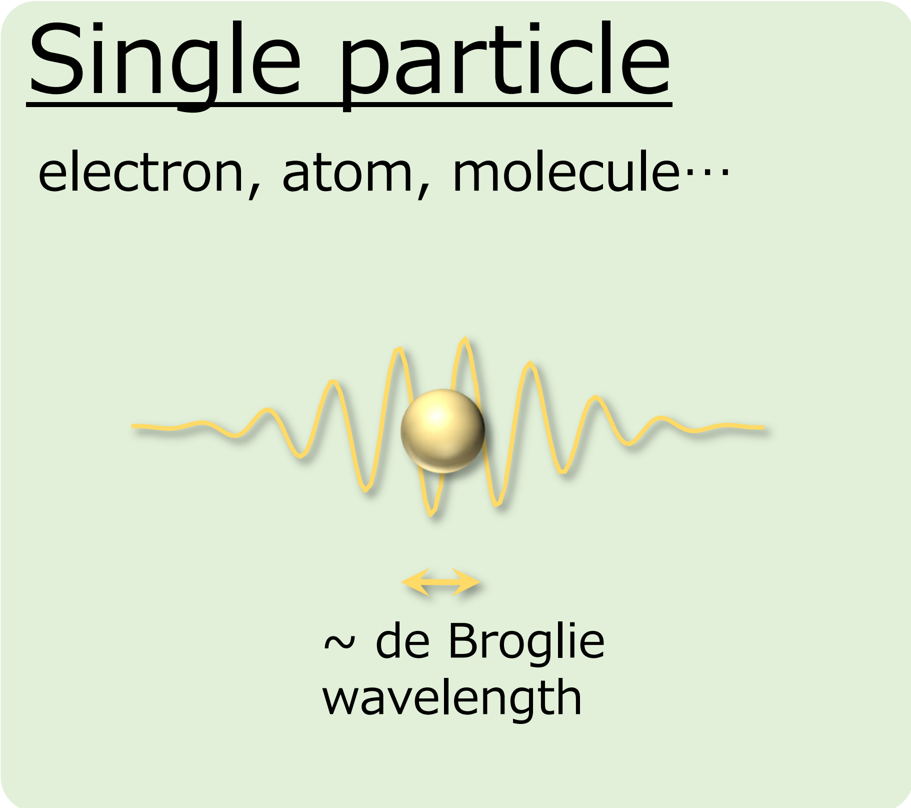
Theory

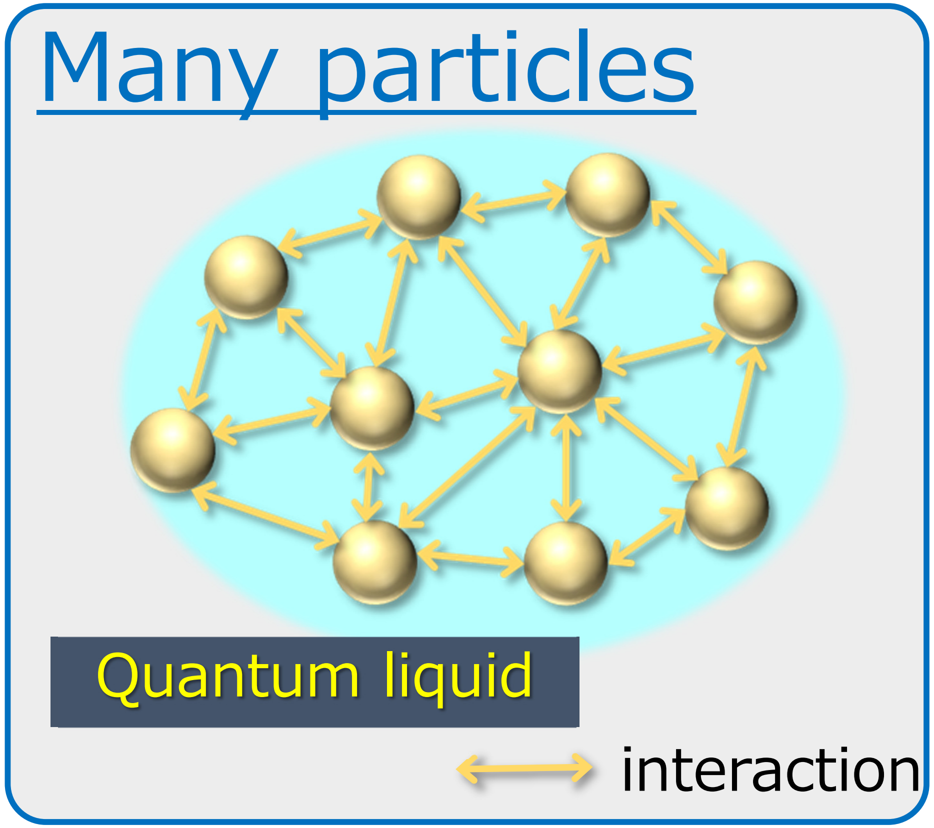
R. Sakano (ISSP, Univ. of Tokyo)

Y. Teratani, A. Oguri (Osaka City Univ.)

Special thanks to: R. Delagrange (Univ. Paris-Saclay, CNRS)

Quantum liquid



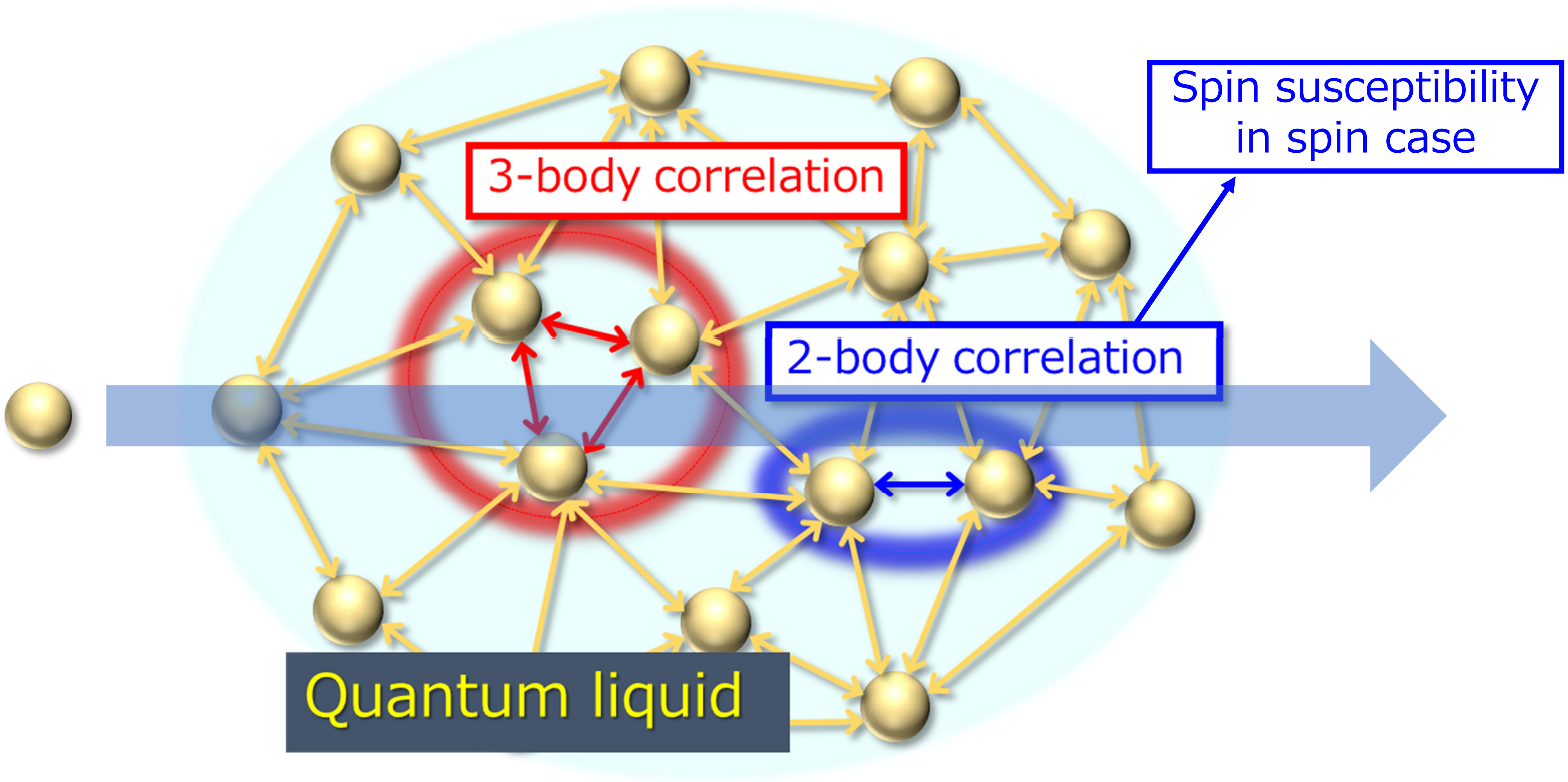


Quantum liquid: Essentially different from a single particle (liquid He, BEC, superconductor ···).

This work: Kondo-correlated quantum liquid

Many-body correlations

Idea: Detect "liquidness" by making it non-equilibrium.

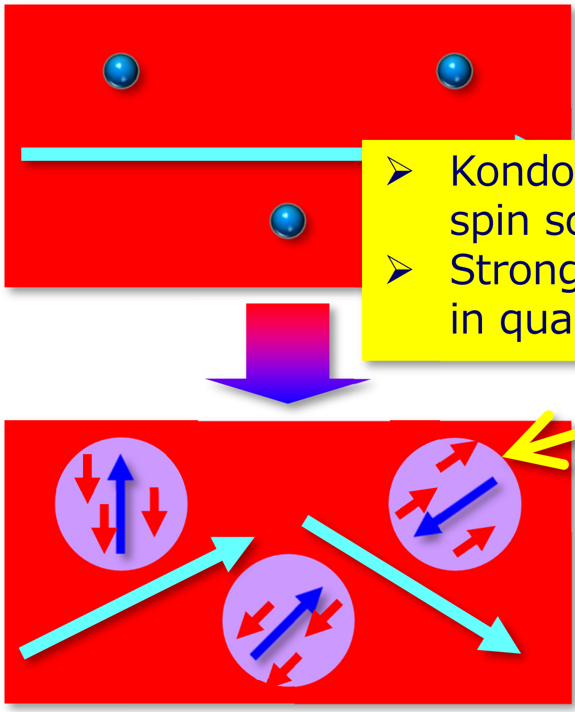


Kondo effect 1964

J. Kondo 1930-

Magnetic impurity in metals

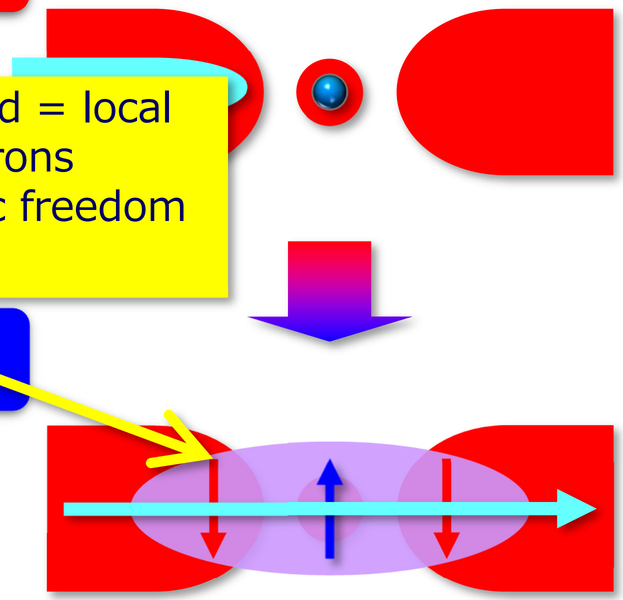
High T



Low T

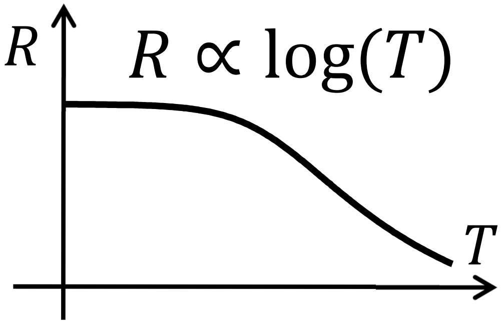
Quantum dot (QD)

High T

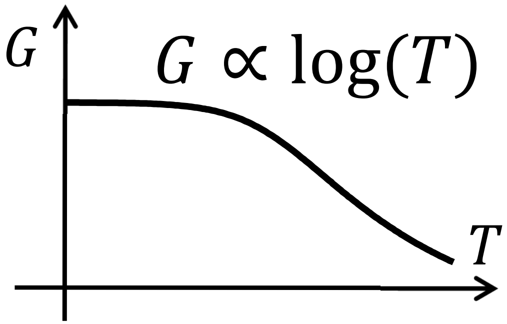


Low T

- Kondo state = Quantum liquid = local spin screened by many electrons
- Strong analogy to asymptotic freedom in quark physics

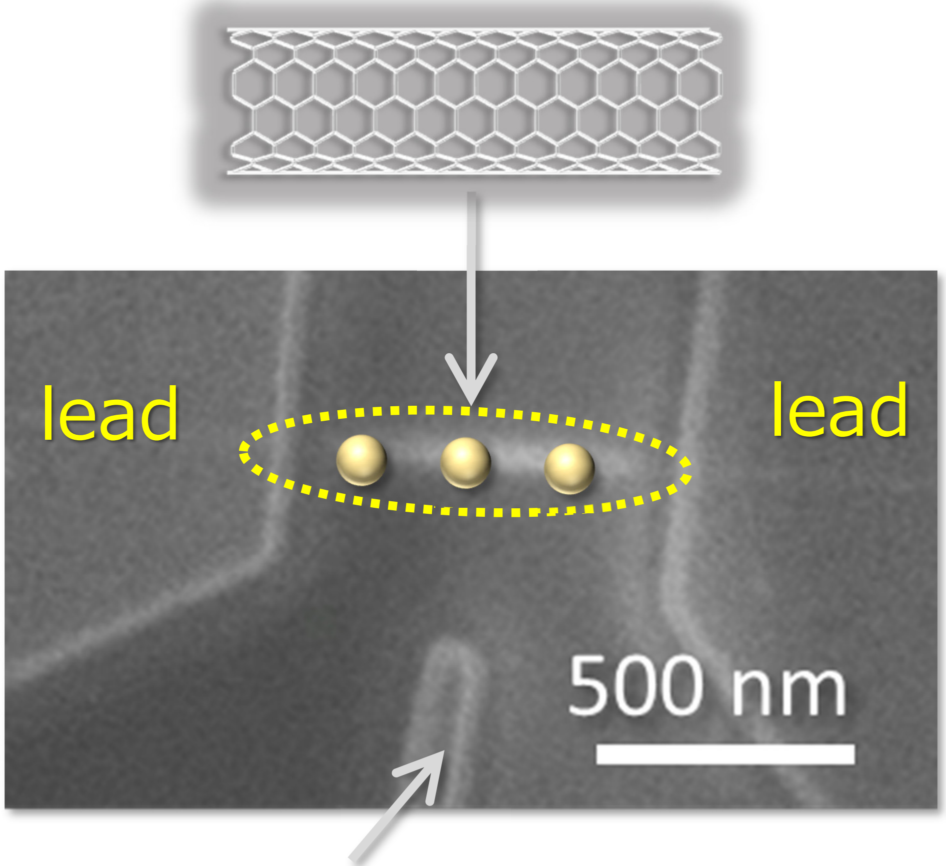


Kondo effect in QD: Goldhaber-Gordon *et al.* Nature **391,** 156 (1998); Cronenwett *et al.,* Science **281,** 540 (1998); Schmid *et al.* Physica B 256-258, 182 (1998). van der Wiel *et al.,* Science **289,** 2105 (2000).



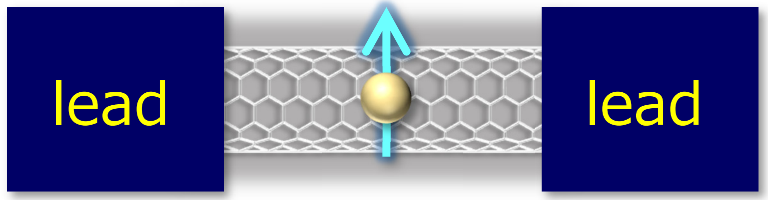
Create quantum liquid in QD

Carbon nanotube QD

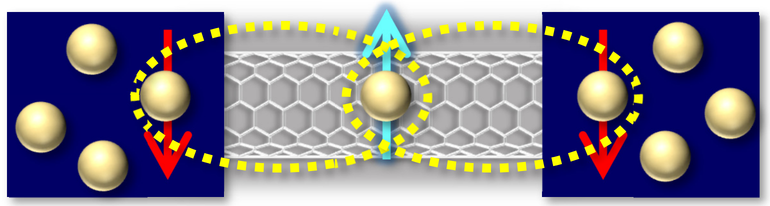


gate electrode
to tune # of electrons in QD

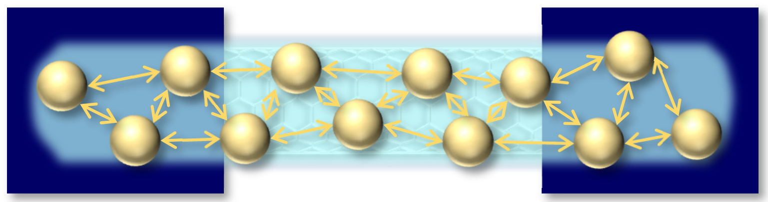
(1) Confine a single electron in QD



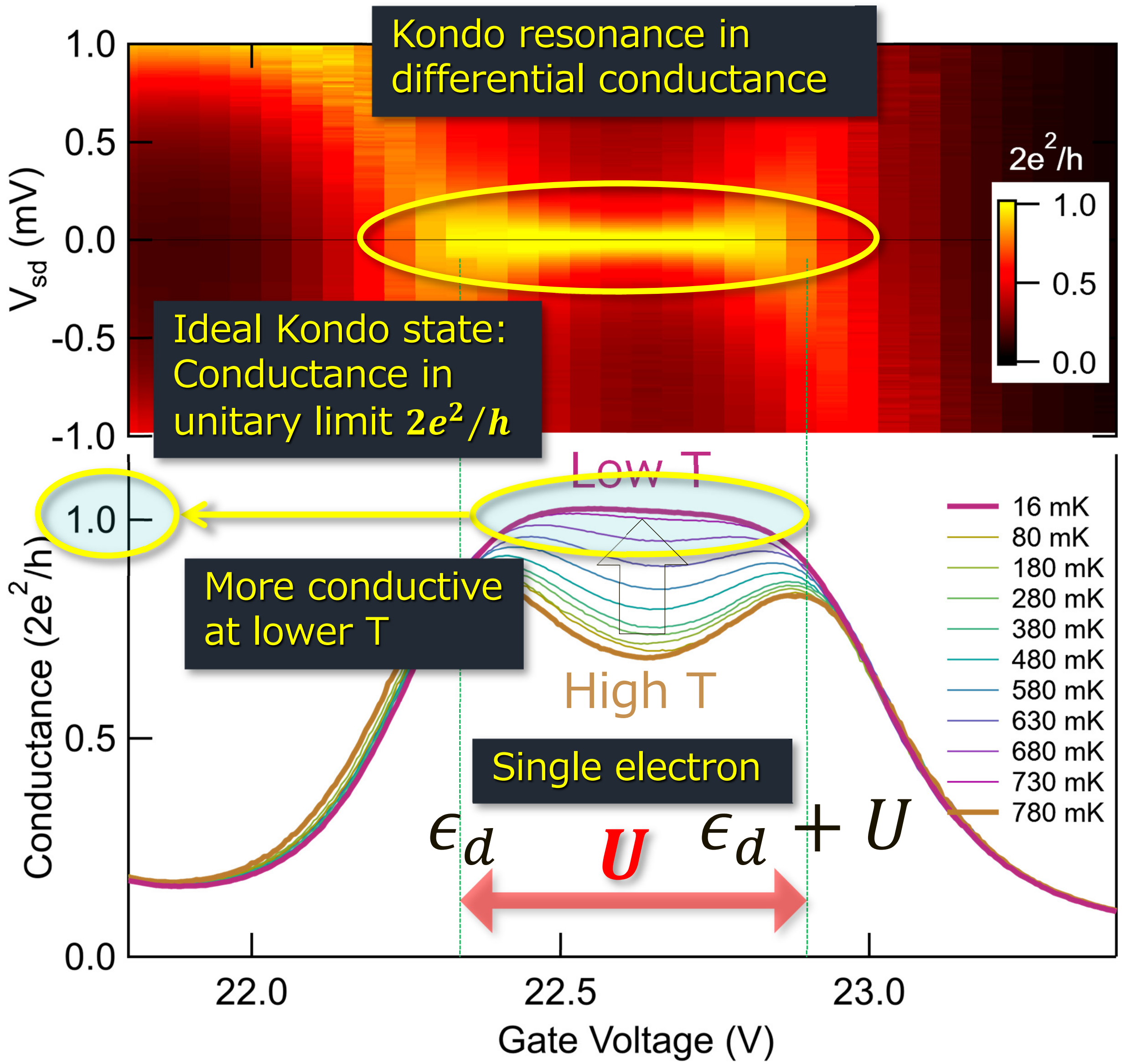
(2) Kondo screening caused by conduction electrons

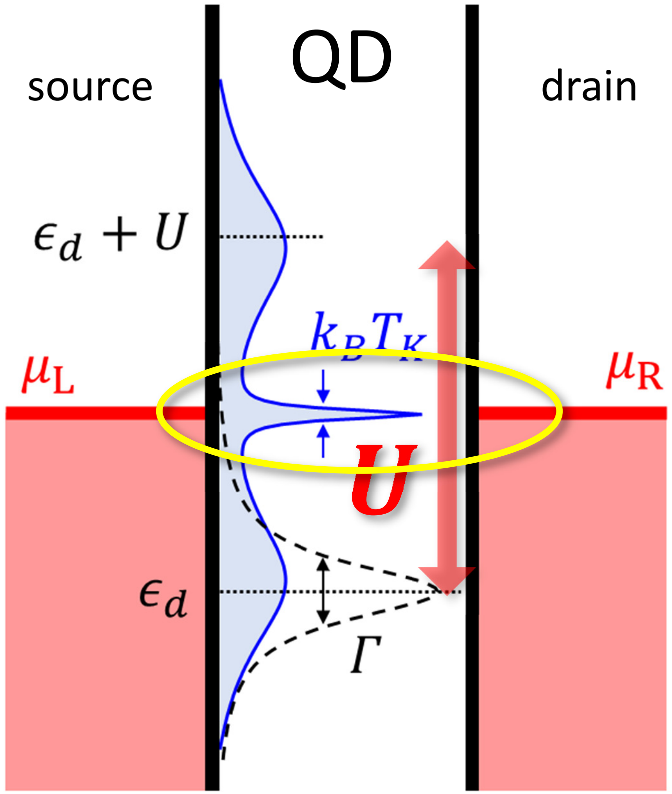


(3) Quantum liquid formed



Ideal Kondo state realized





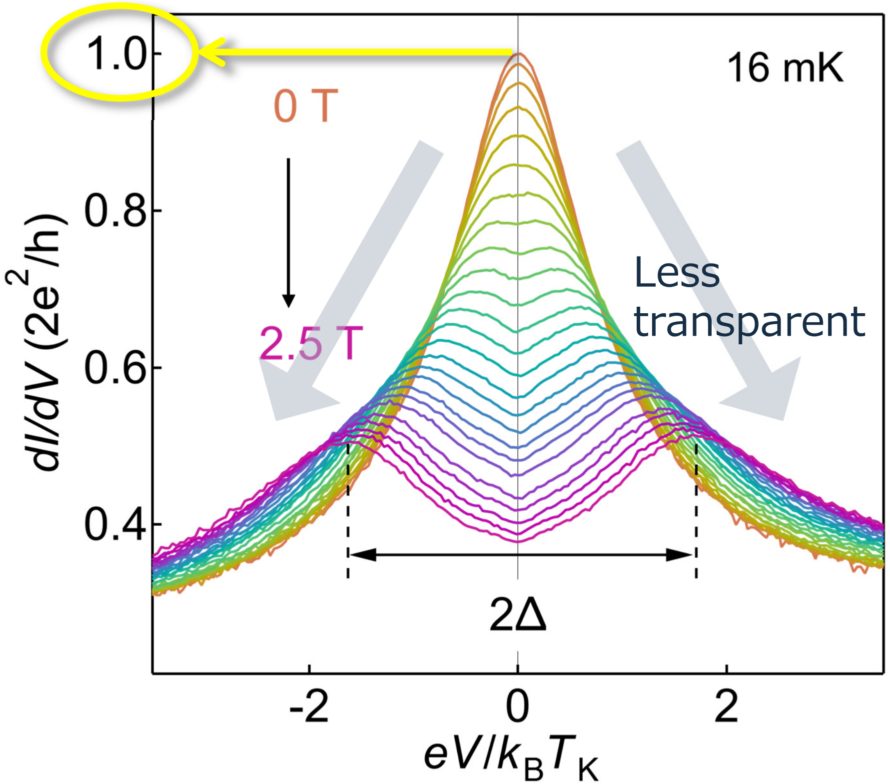
Ferrier, KK, *et al.*, *Nature Phys.* **12**, 230 (2016).

20-years mystery

PHYSICAL REVIEW B **95**, 165404 (2017)

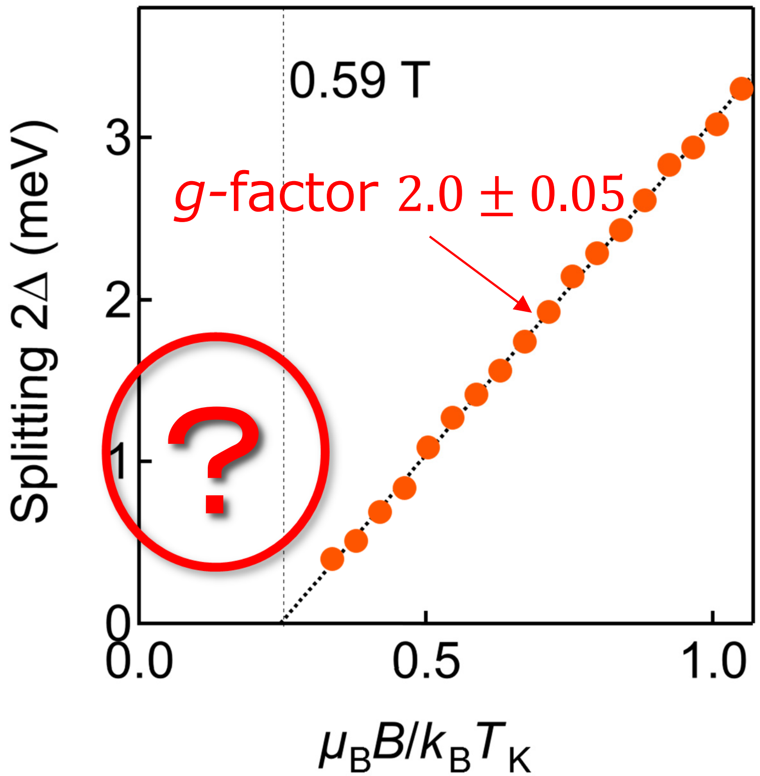
At which magnetic field, exactly, does the Kondo resonance begin to split? A Fermi liquid description of the low-energy properties of the Anderson model

Michele Filippone,[1] Cătălin Paşcu Moca,[2,3] Jan von Delft,[4] and Christophe Mora[5]



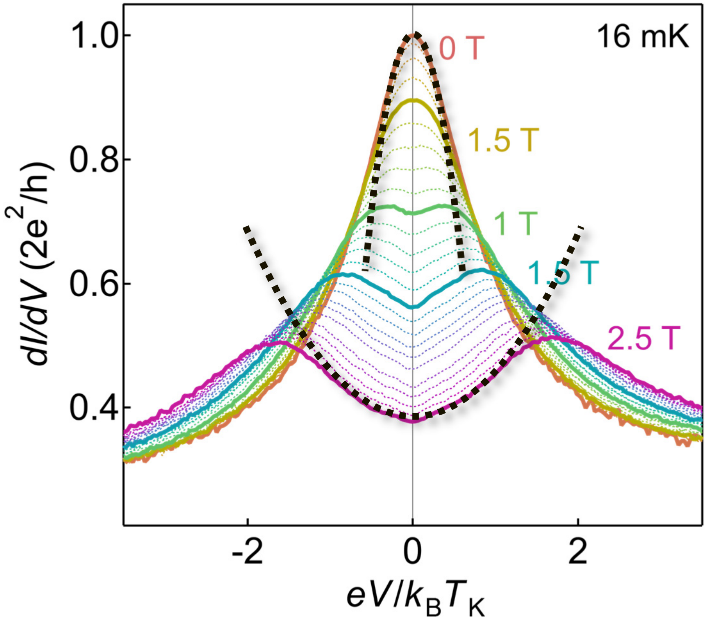
At electron-hole symmetry

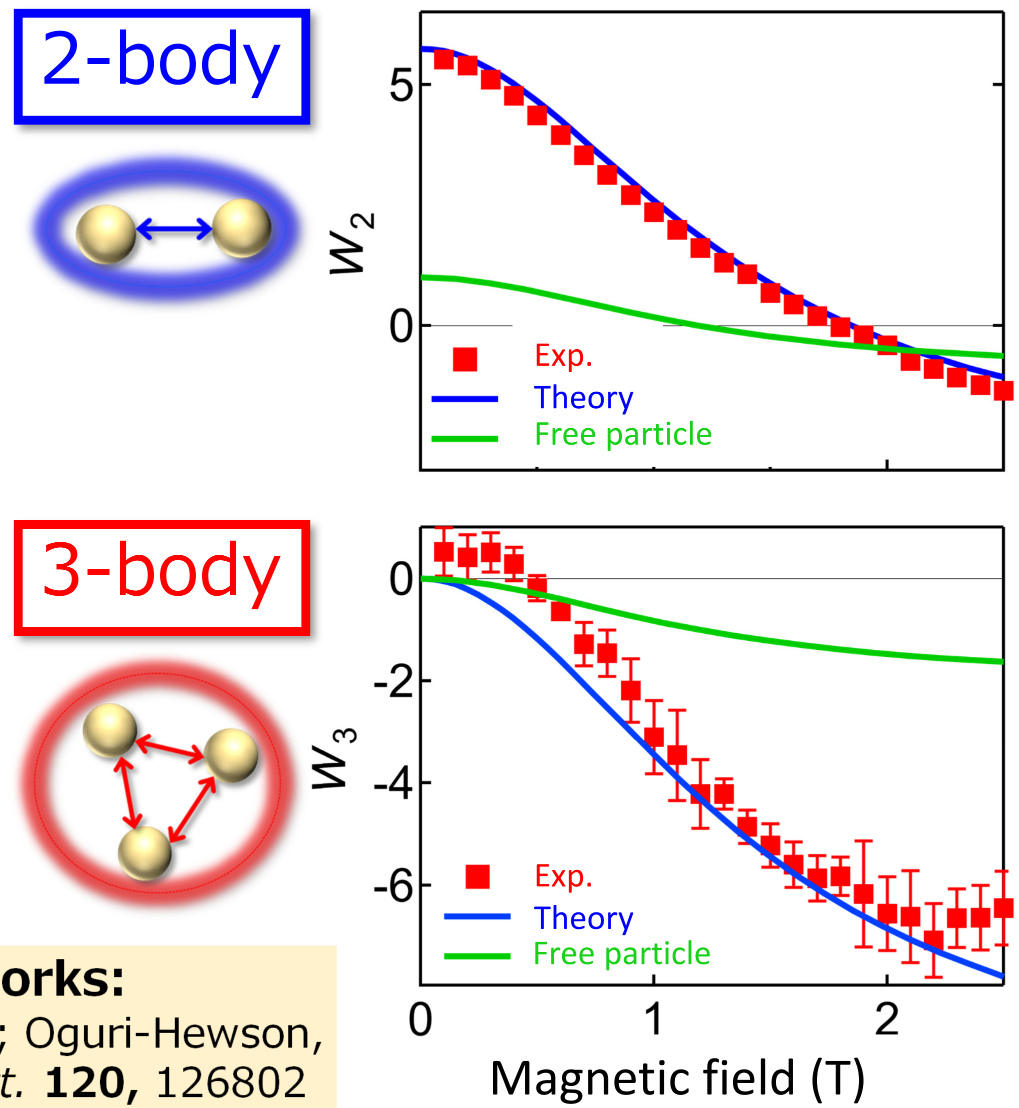
NOT a simple Zeeman splitting



Correlations

$$\frac{dI}{dV} = G_0 - \alpha_V \left(\frac{eV}{k_B T_K}\right)^2 + \cdots$$



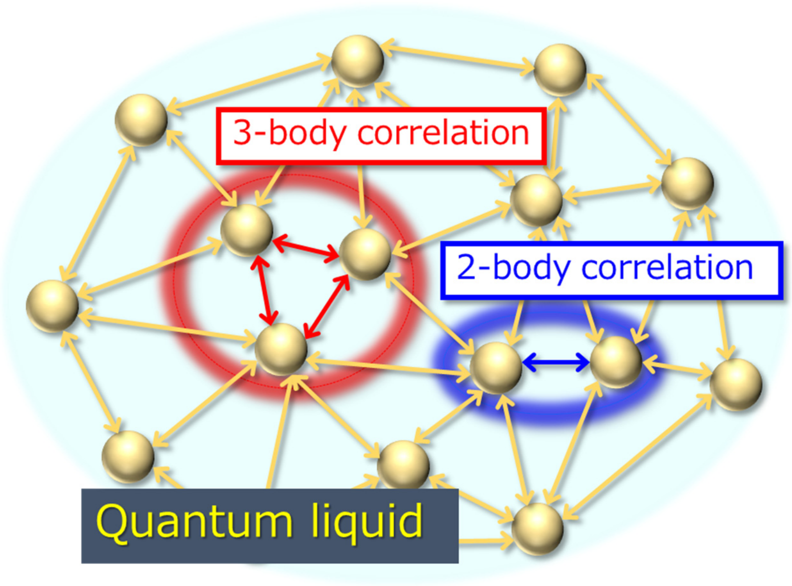


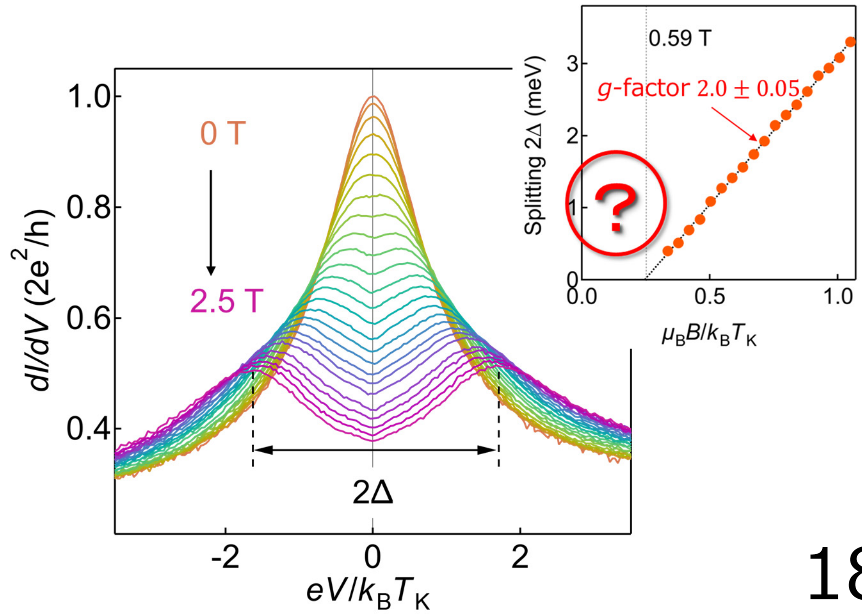
Analysis according to the theoretical works:
Filippone *et al. Phys. Rev.* B **98,** 075404 (2018); Oguri-Hewson, *Phys. Rev.* B **97,** 035435 (2018); *Phys. Rev. Lett.* **120,** 126802 (2018); Teratani et al. *Phys. Rev.* B **102,** 165106 (2020); Teratani-Sakano-Oguri, *Phys. Rev. Lett.* **125,** 216801 (2020).

Short summary

Hata *et al.*, *Nature Comm.* **12,** 3233 (2021).

- First detection of 3-body correlations in quantum liquids
- Solved 20-years mystery of Kondo splitting
- Step toward more complex quantum many-body systems in non-eq. regime





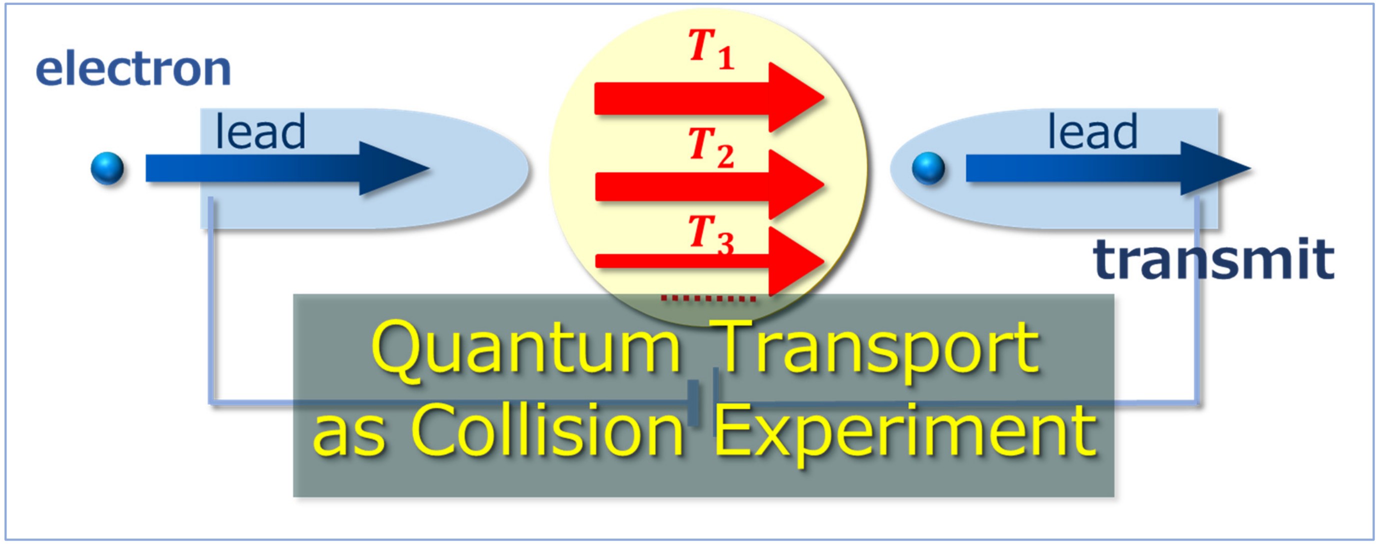
Quantum spin microscope

Kento Sasaki (Assist. Prof.)
Kensuke Ogawa (M2)
Moeta Tsukamoto (M2)
Shunsuke Nishimura (M1)
Shuji Ito (M1)
@U. Tokyo 2020-

Dr. Sasaki has been working with Dr. E. Abe for several years in his Ph.D. course.

Why new quantum sensor ?

Landauer approach only allows us to observe electric charge in conducting systems.

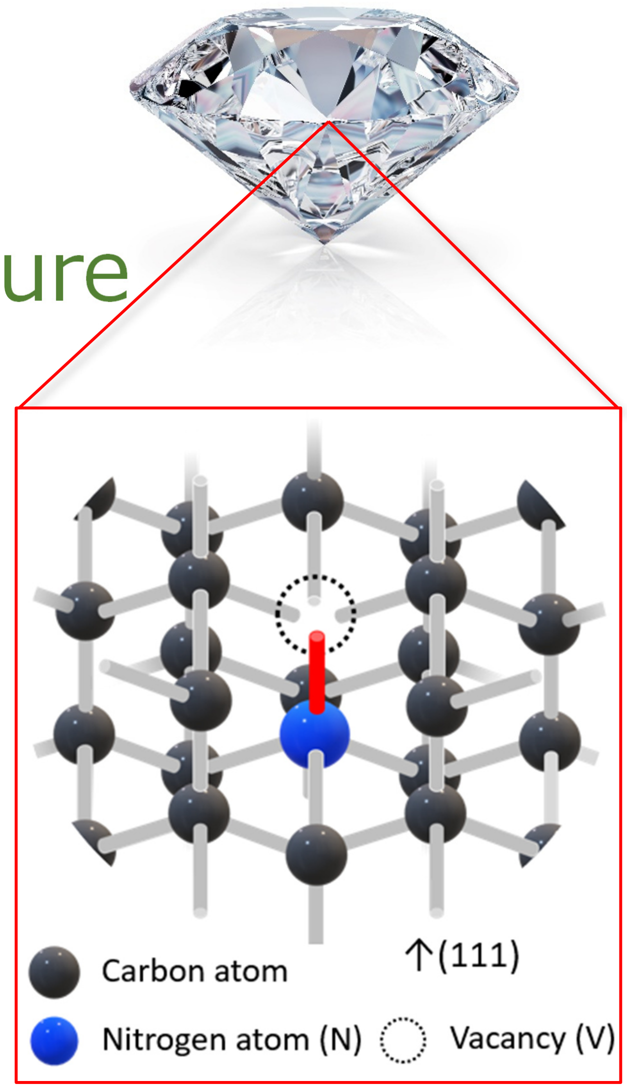


How about others?

insulators, magnetism, spin, heat···

Diamond quantum sensor

NV (nitrogen-vacancy) center
= Atomic size sensitive sensor
for magnetic field* & temperature



New tool for meso. physics

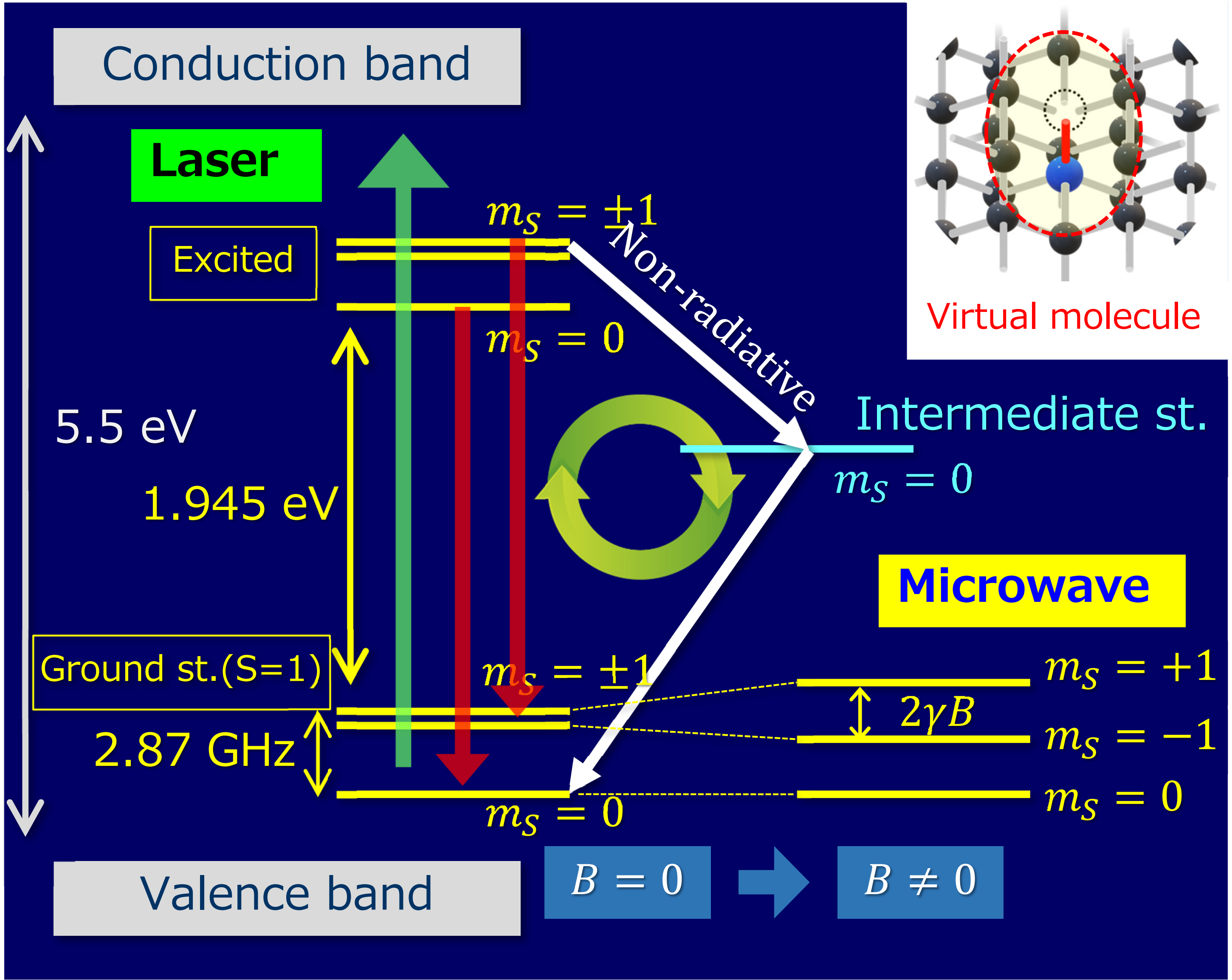
- Non-eq.: heat & spin current
- Nano-magnetism
- Topological edge states
- Phase transitions
- Superconducting vortex …

At the atomic level in real time

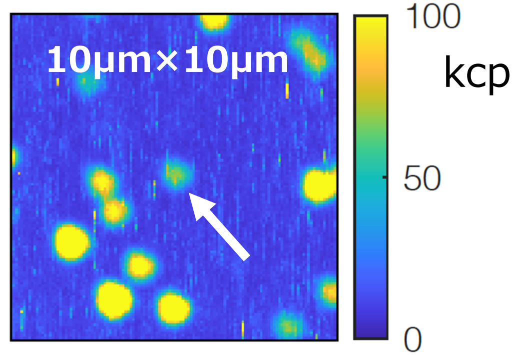
***Proposal:** Maze *et al., Nature* **455,** 644 (2008); Degen, *Appl. Phys. Lett.* **92,** 243111 (2008); Taylor *et al.*, *Nature Phys.* **4**, 810 (2008); Balasubramanian *et al., Nature* **455,** 648 (2008).

ODMR optically detected magnetic resonance

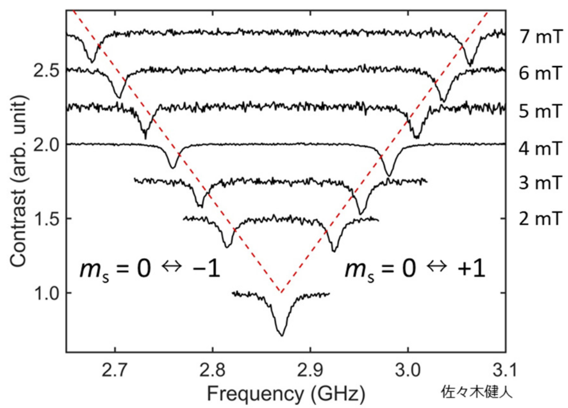
Quantum sensors = use quantum mechanics to achieve ultra-high sensitivity



PL from single defect
K. Sasaki

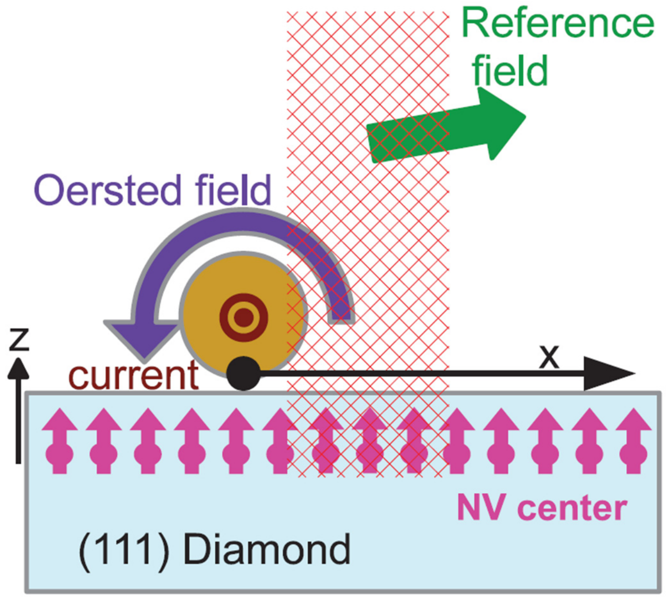


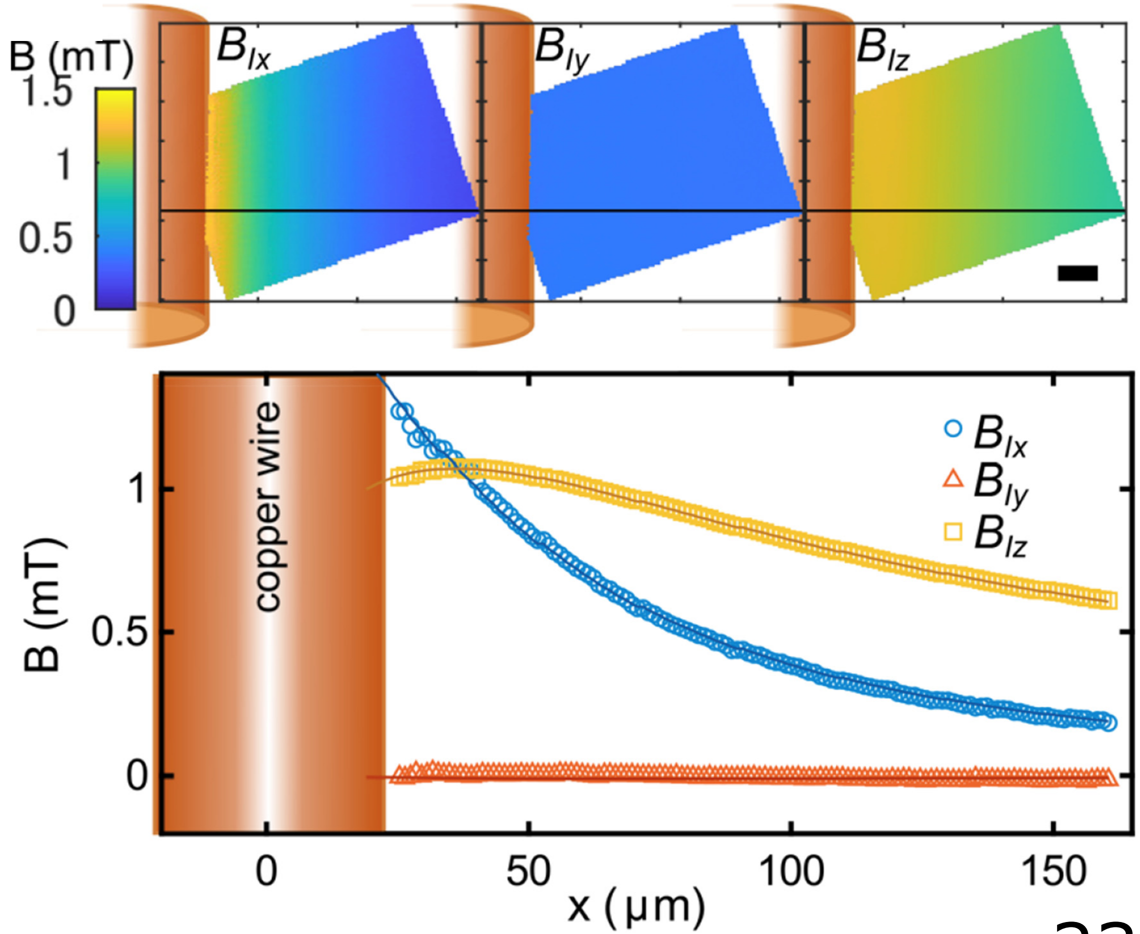
ODMR spectra
K. Sasaki



Vector magnetometry

Detect 1 μT in 1 μm cf. geomagnetism ~ 30 μT



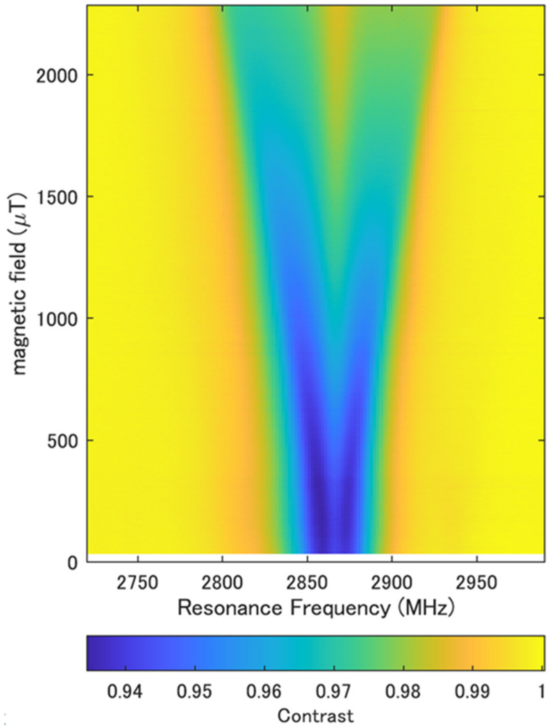


With Hatano group in TITECH
M. Tsukamoto, K. Ogawa, H. Ozawa, T. Iwasaki, M. Hatano, K. Sasaki, and K. Kobayashi, Appl. Phys. Lett. **118,** 264002 (2021).

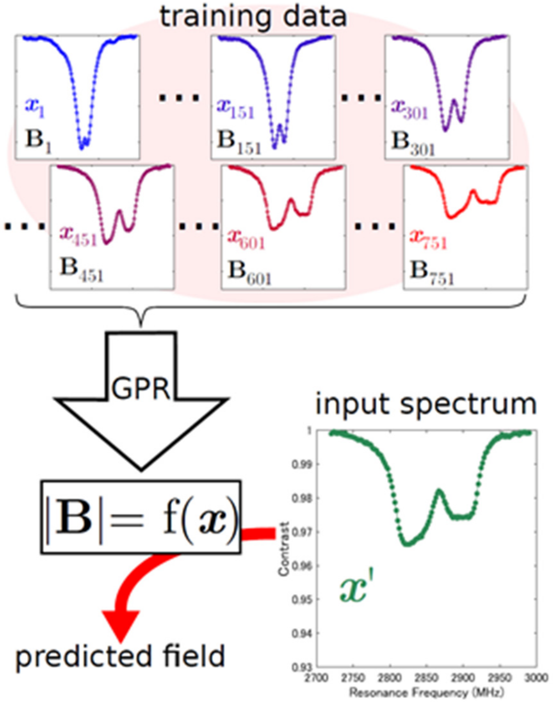
Machine-learning enhancement

First successful combination between quantum sensing and model-free machine learning Tsukamoto *et al.* arXiv:2202.00380.

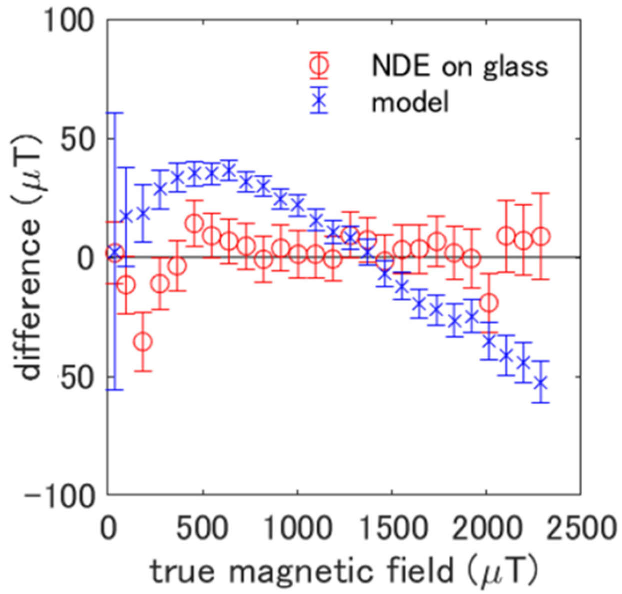
Precisely obtain ODMR spectra



Gaussian process regression

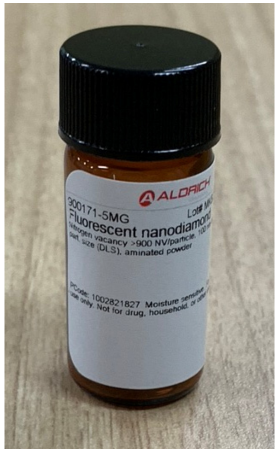


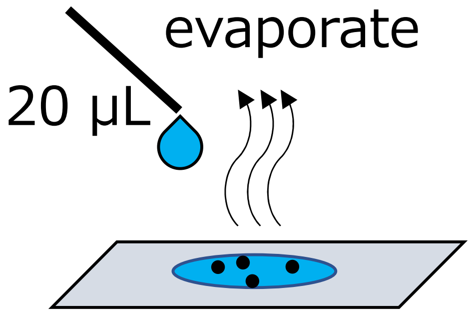
Model-free method is more accurate than physical model



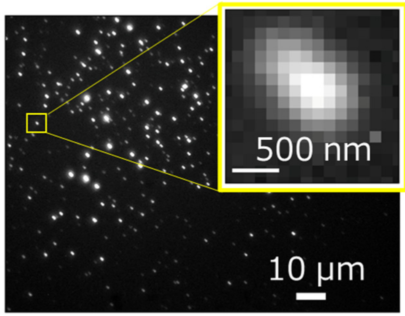
Quantum thermography

Detect 0.1 K in 1 µm

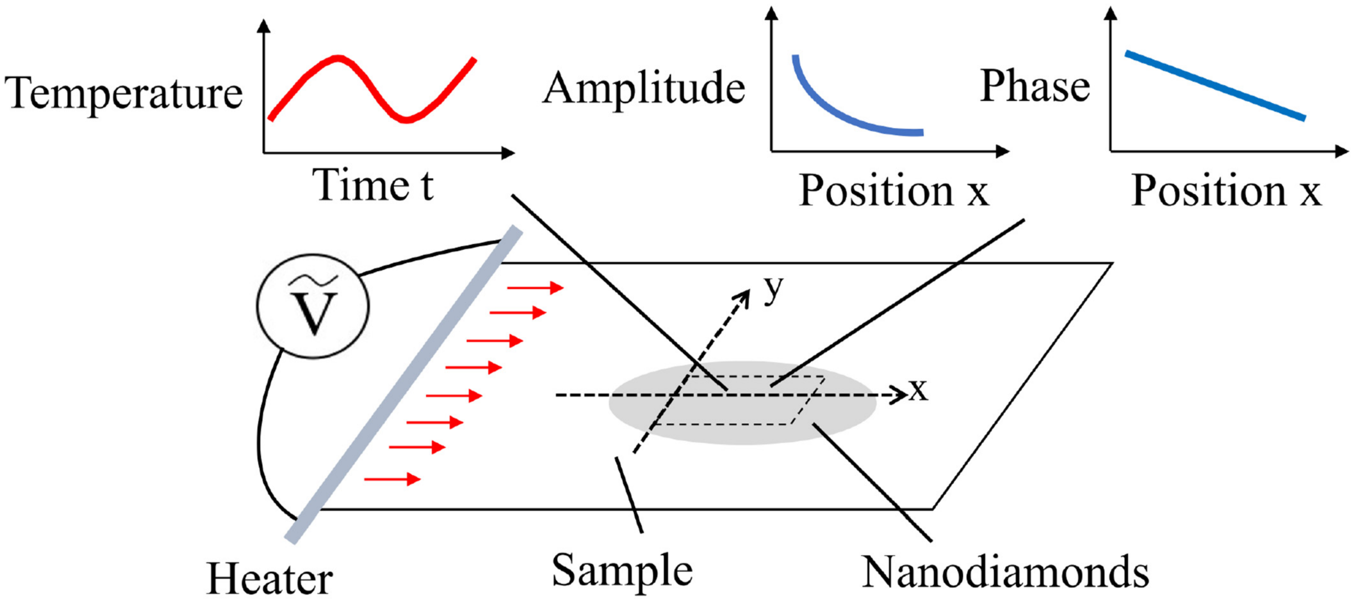




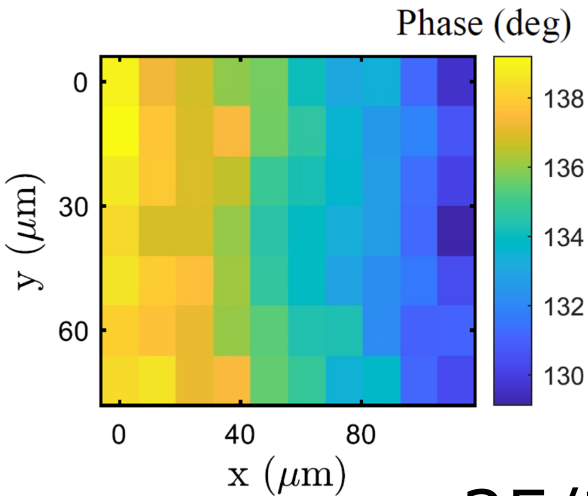
Nano-diamond



Ogawa *et al. submitted.*



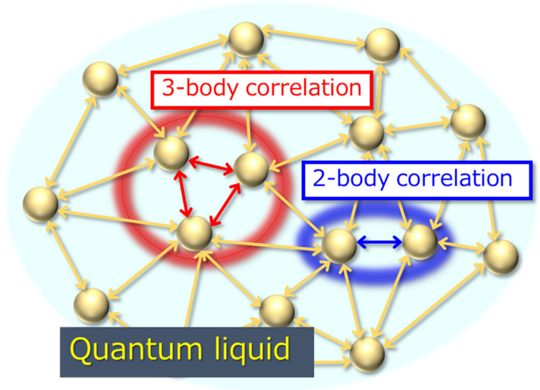
Imaging of heat flow



Conclusion

Correlation in quantum liquids

T. Hata *et al.*, *Nature Comm.* **12,** 3233 (2021).



Quantum spin microscope

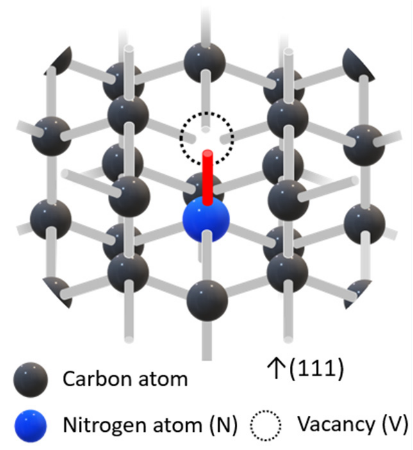
[*B*-field imaging] Tsukamoto *et al., APL* **118,** 264002 (2021).

[Machine learning] Tsukamoto *et al.* arXiv:2202.00380.

[Thermography] Ogawa *et al. submitted.*

[Efficient spin readout] Nakamura *et al. submitted.*

[Floquet engineering] Nishimura *et al. in preparation.*



Acknowledgements: T. Hata, T. Arakawa, S.-H. Lee (Osaka Univ.), M. Ferrier, R. Deblock (Univ. Paris-Saclay, CNRS), R. Sakano (ISSP, Univ. of Tokyo), Y. Teratani, A. Oguri (Osaka City Univ.), M. Tsukamoto, K. Ogawa, K. Sasaki, Y. Ashida (U. Tokyo), Y. Ozawa, T. Iwasaki, M. Hatano (Titech).

Financial support: JSPS KAKENHI Grant (No. JP19H05826, No. JP19H00656).