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Quantum Technologies for Advanced Sensors and Computers

ART 020: Quantum Technologies for Armament Systems

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Center for Quantum Science & Engineering
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Quantum Technologies for Advanced Sensors and Computers

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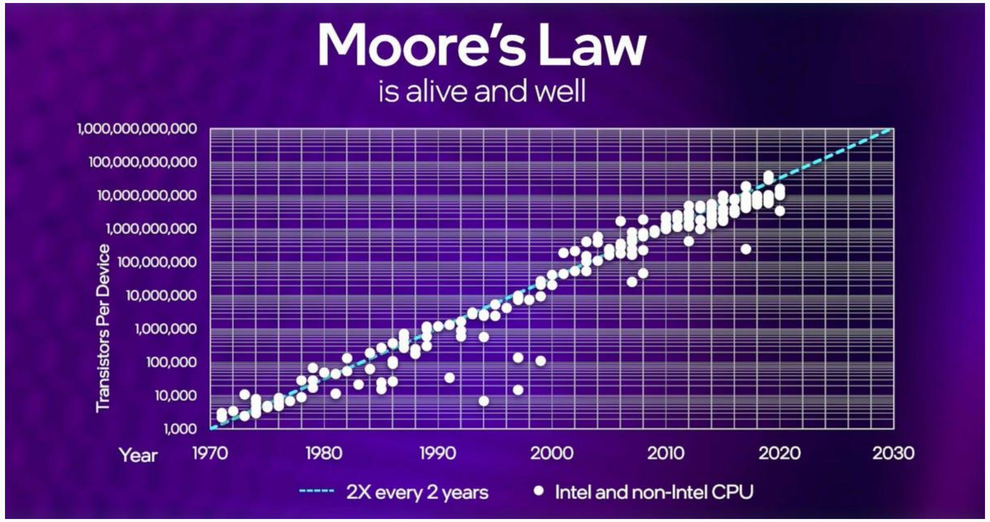
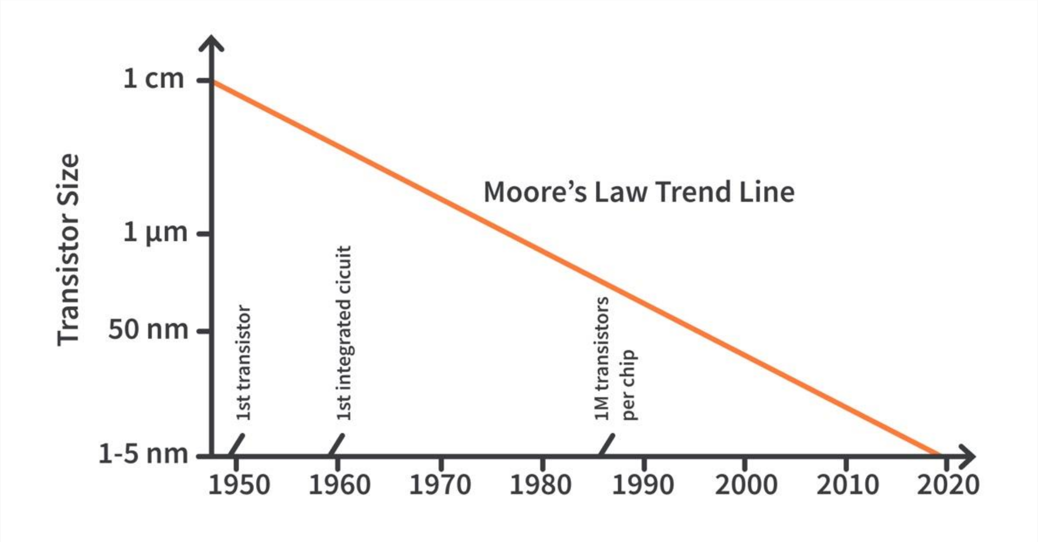
Outline

- Introduction: Quantum Science and Quantum Technologies
- I. Atomic Gyroscope
- II. Graphene Interferometer
- III. Optical Ising Machine
- Conclusion

Why Quantum?

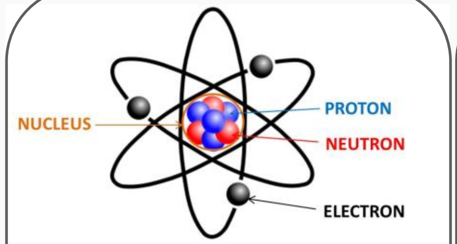
- Conventional technologies become incapable of addressing some big challenges
- The number of transistors on a chip doubles every two years. Will this continue? What happens if the size of the transistor is too small?
- At small (nano or few-atom) scales, classical physics no longer accurately describes the behavior of particles.
- Quantum Mechanics is the fundamental law for understanding the physical world.





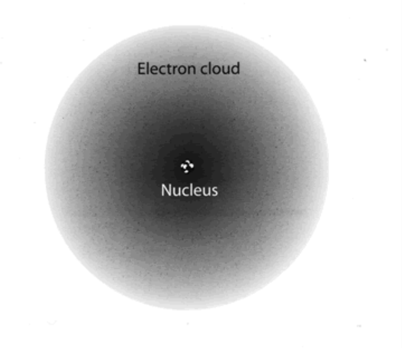
Strangeness in the quantum realm

- **Particle-wave duality**: both particle-like and wave-like
- **Quantum superposition**: both 0 and 1, both dead and alive
- **Quantum entanglement**: spooky action at a distance

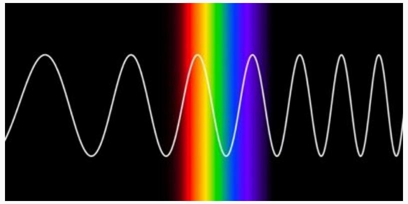


electrons

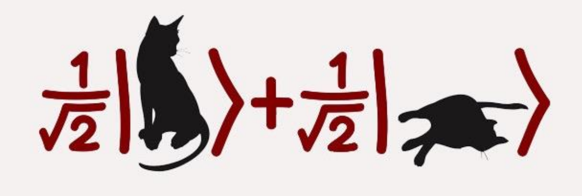
photons



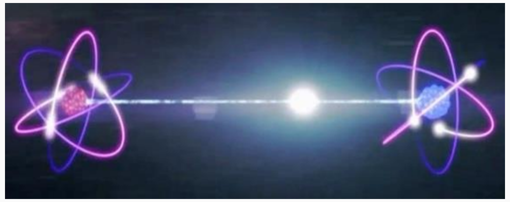
Matter waves



Light waves



Quantum superposition



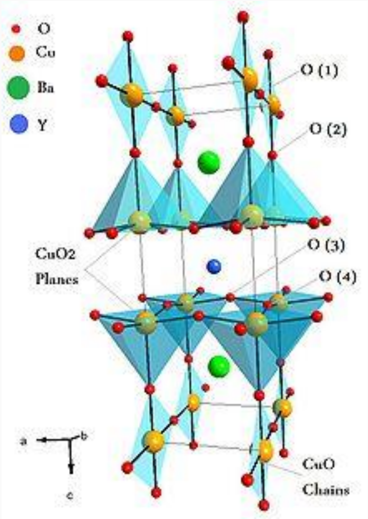
Quantum entanglement

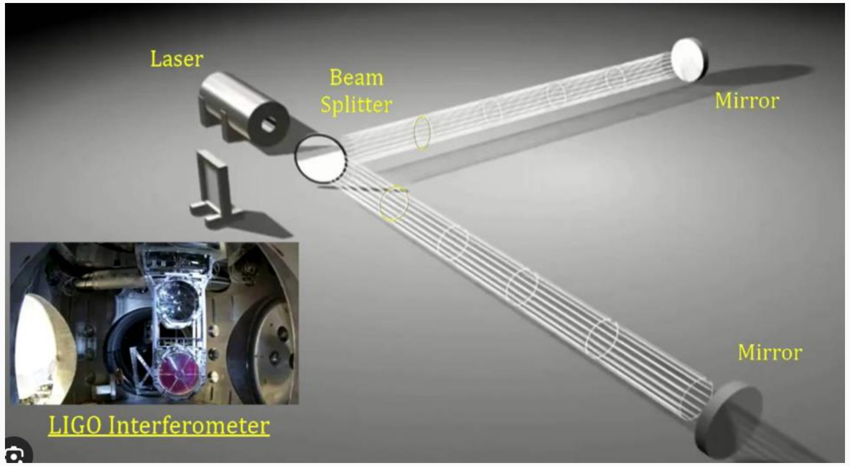
It is the strangeness that opens up new technological possibilities.

Quantum Technology: addressing big challenges

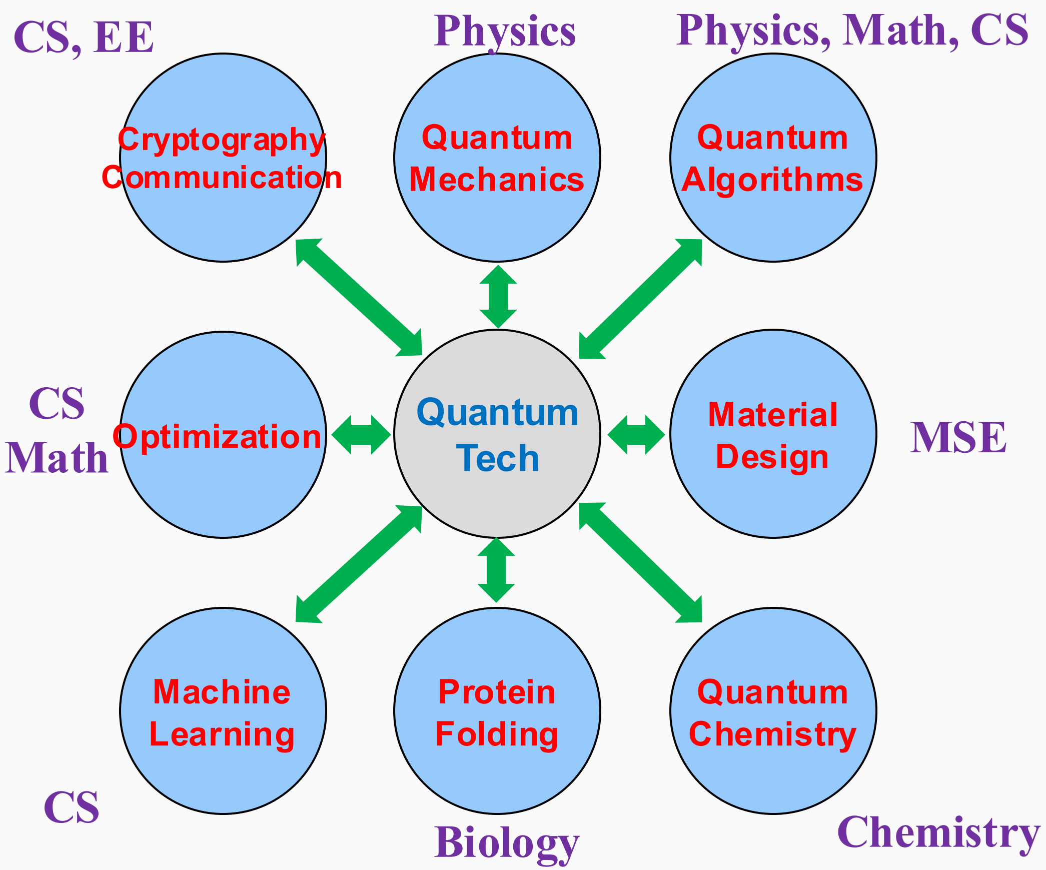
Applying basic principles of quantum mechanics for transformative technological applications:

- Solving NP-hard optimization problems, e.g., traveling salesman problem
- Simulating strongly correlated many-body quantum systems, e.g., high temperature superconductivity
- Sensing extremely weak signals, e.g., dark matter, gravitational waves, etc.
- …





Quantum Tech Race



US: National Quantum Initiative Act
EU: Quantum Flagship Initiative
UK: National Quantum Technologies Program
China: Quantum Experiments at Space Scale

and more

ART-020 subtasks: quantum-enhanced sensors and computers

➢ **Atomic gyroscope for rotation sensing**

C. Qu, C.-H. Li, Y. P. Chen, S. Stringari, Physics Review A (2023)

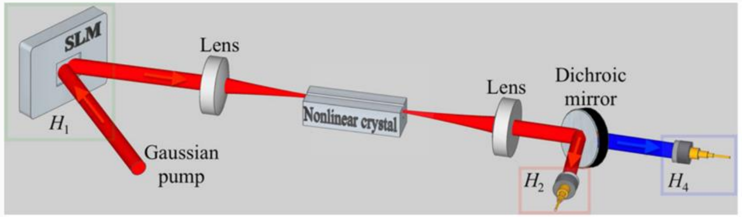
➢ **Graphene interferometer for magnetic field sensing**

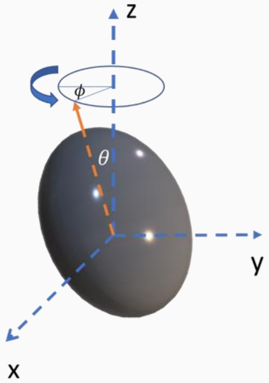
Z. Tang et al., IEEE Open Journal of Nanotechnology (2023)

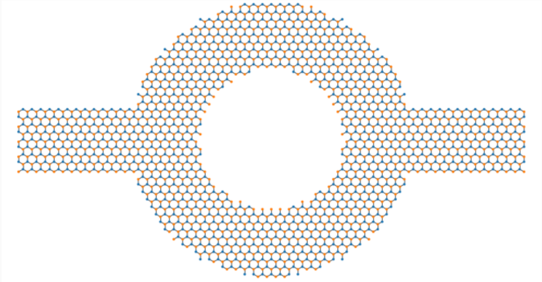
C. Osuala, Z. Tang, S. Strauf, E.H. Yang, C. Qu, Materials Science & Engineering B (2023)

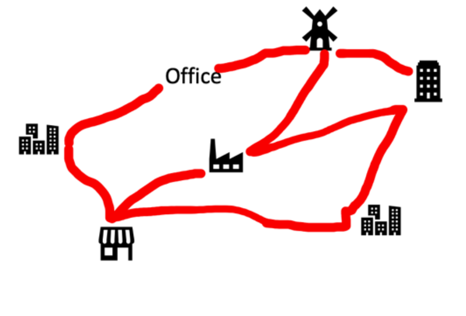
➢ **Optical Ising machine for optimization problems**

S. Kumar, Z. Li, T. Bu, C. Qu, Y. Huang, Communications Physics (2023)





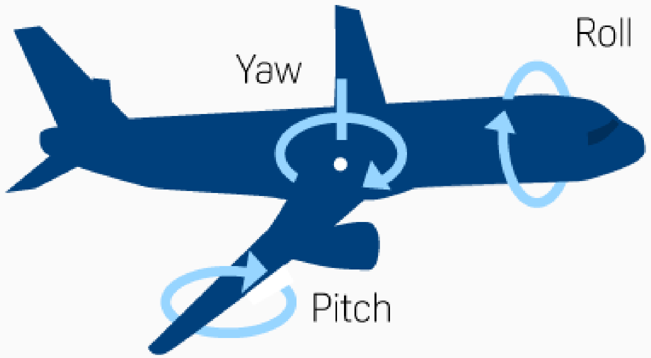


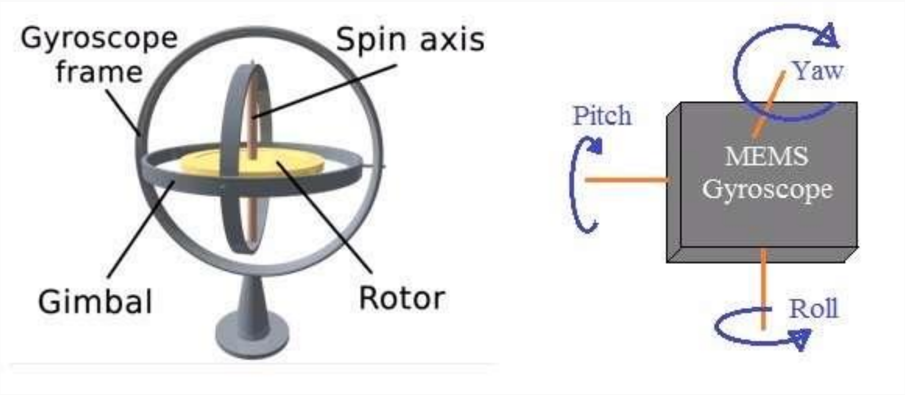


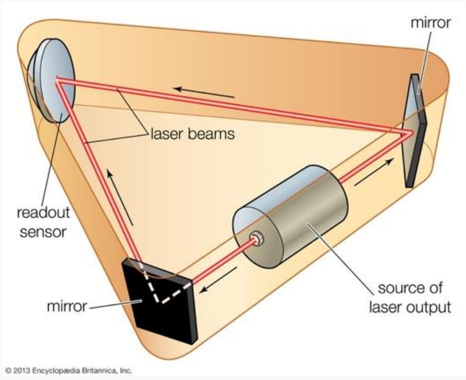
Gyroscopes

- Gyros are vital for the successful implementation of the next generation of precision-guided weapons and surveillance apparatus

- Small
- Robust
- Inexpensive
- Tactical grade performance

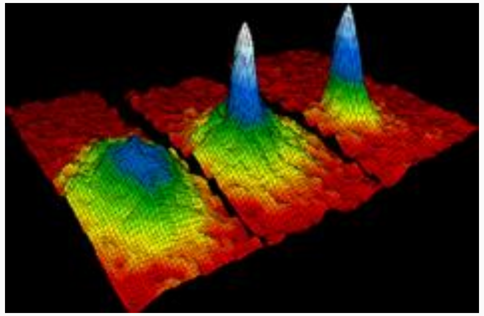






Matter-wave gyroscopes?

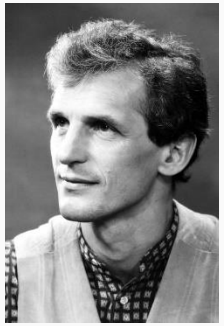
Ultracold atomic gases and Bose-Einstein condensation



2001

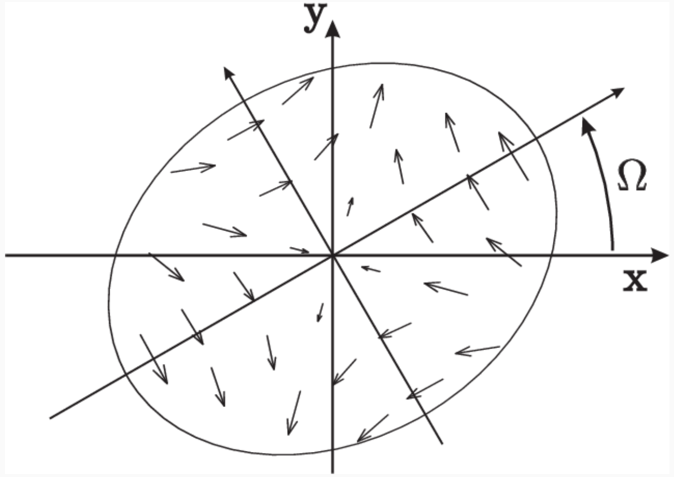
Cornell
(JILA)

Wieman
(JILA)



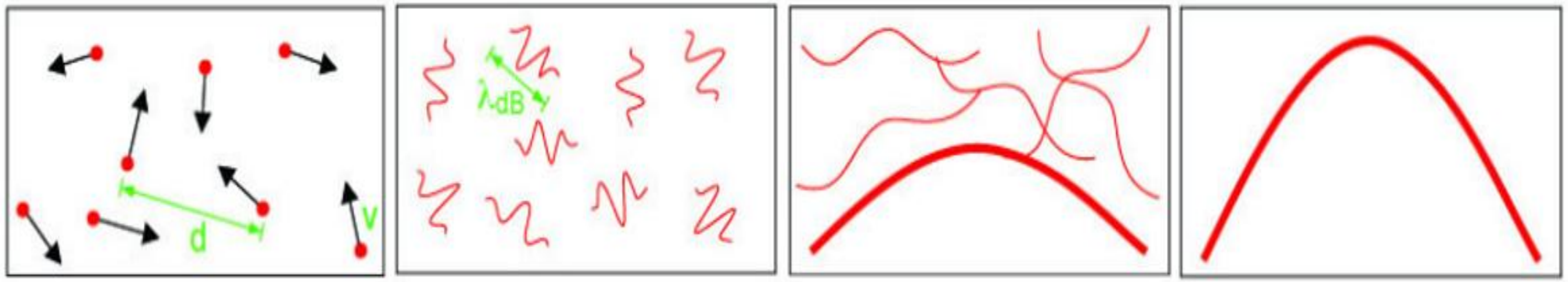
Ketterle
(MIT)

Irrotational Velocity flow



Vortex-free rotating BEC

de-Broglie wavelength $\lambda_{dB} = h/p$

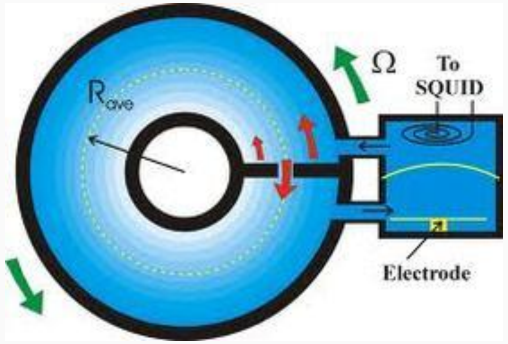


Billiard balls | Wave packets | Wave overlap | Giant matter wave

figure: Ketterle

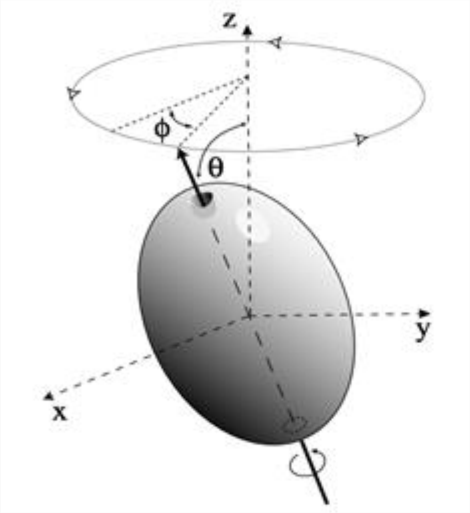
Atomic gyroscopes

Rotating Superfluid



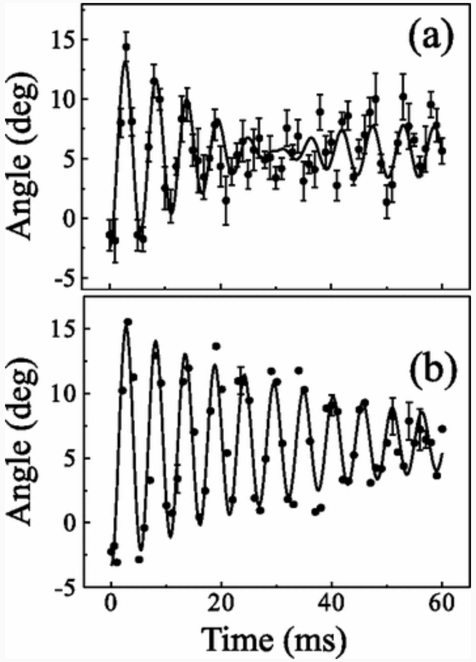
- Richard Packard et al. UC-Berkeley (1980s)
- Josephson effect with liquid ^{4}He and ^{3}He
- **Many quanta of circulation**

Harmonically trapped BEC



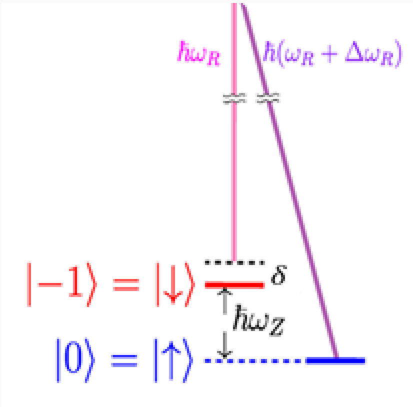
- S. Stringari, PRL (2001)
- Mesoscopic quantum system
- **A single quantized vortex** can have visible effects on the global motion of the condensate

Experiment



- C. Foot group, PRL (2003)
- Fig: angle θ projected to the x-z plane

Synthetic rotational field for ultracold neutral atoms



Two-photon Raman transition → Synthetic spin-orbit-coupling

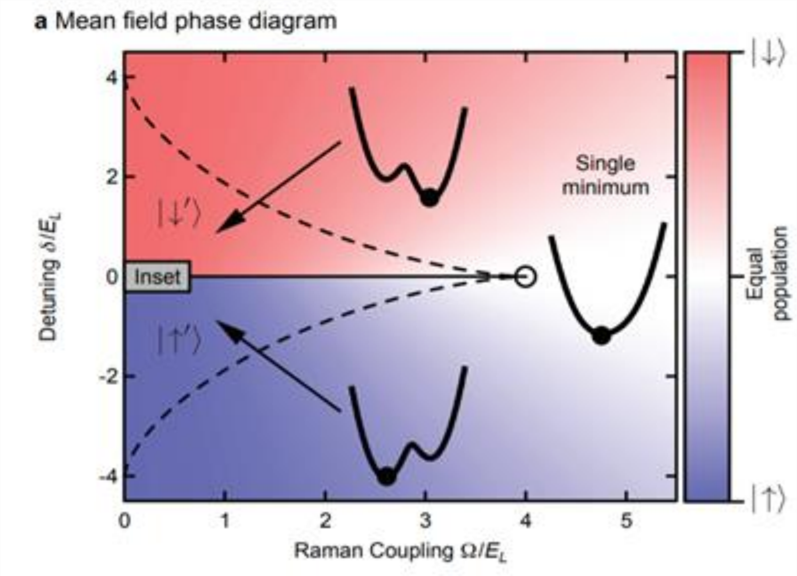
$$H \approx \frac{[p_x - \hbar k_{\min}(\Omega, \delta)]^2}{2m^*}$$

Position-dependent detuning

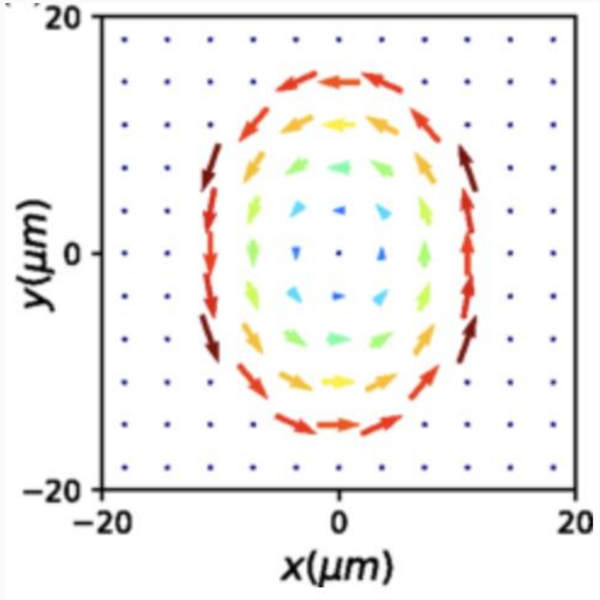
$$\delta = \delta(y)$$

Synthetic rotational field

$$\vec{\omega}_{rot} \sim \frac{\partial k_{min}(y)}{\partial y} \hat{z}$$



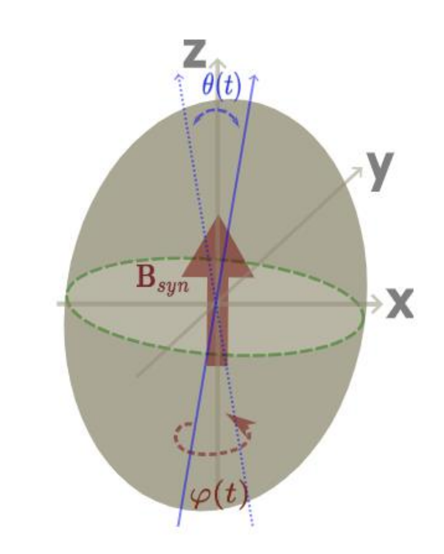
I. Spielman group, Nature (2011)

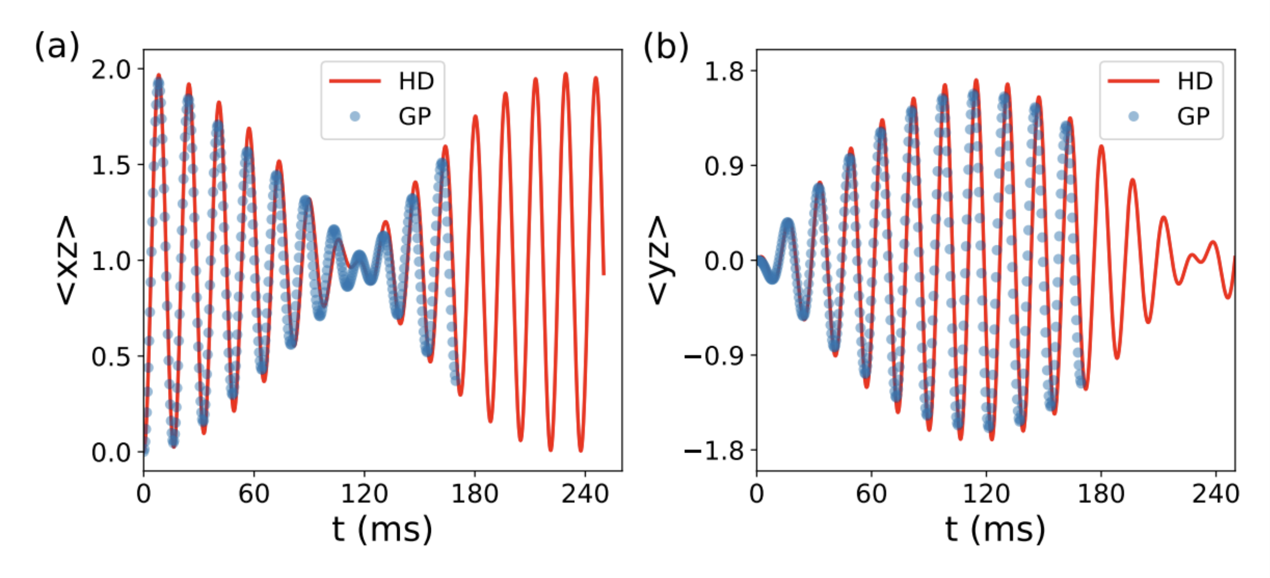


C. Qu and S. Stringari, PRL (2018)

Atomic gyroscopes

Tilting the condensate away from the symmetric axis → Scissors mode in the vertical plane exhibits a precession due to the rotational velocity field





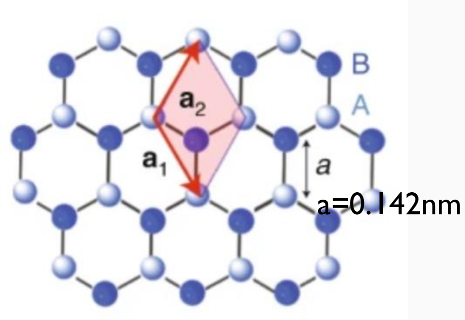
This realizes an atomic gyroscope (without the generation of vortex)

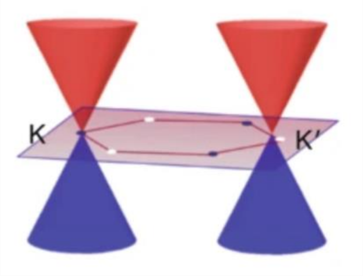
Optimal precession occurs when the two original modes are degenerate

C. Qu, C.-H. Li, Y. P. Chen, S. Stringari, Physics Review A (2023)

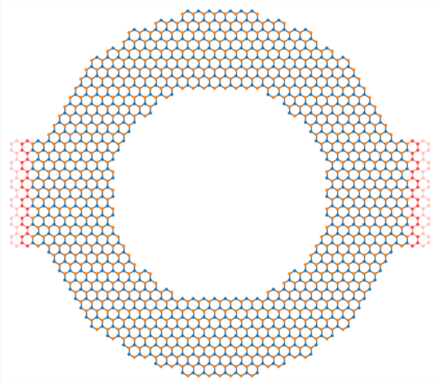
Graphene

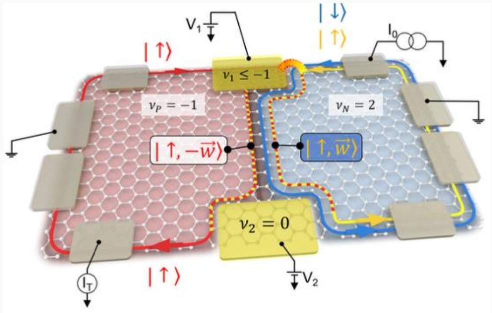
- Atomically thin monolayer structure with exceptional properties
- Compelling contender for next-generation compact and high-performance electronic devices
- Promising testbed for the field of electron quantum optics (beam splitters, Mach-Zehnder interferometer)
- Manipulation of the charge, spin, valley, and twist degrees of freedom for quantum information processing



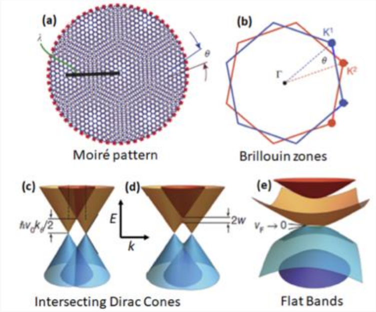


Graphene ring





Jo et al., PRL (2021)

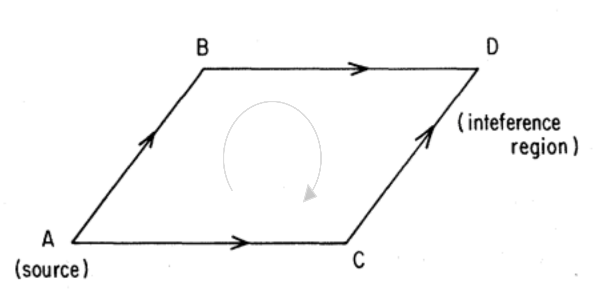


Cao et al., Nature (2019)

Graphene Aharonov-Bohm interferometer

Instead of studying a graphene gyroscope under rotation, we apply a magnetic field to study the Aharonov-Bohm oscillation

In a rotating frame

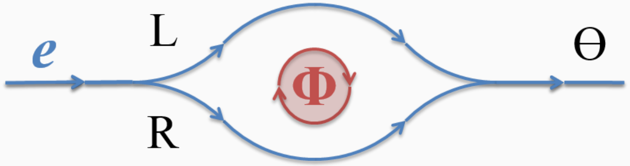


$$\phi_{ACD} - \phi_{ABD} = (2m/\hbar) \int \vec{\omega} \cdot d\vec{\sigma}$$

mathematically equivalent

J. Sakurai, PRD (1980)

In a magnetic field

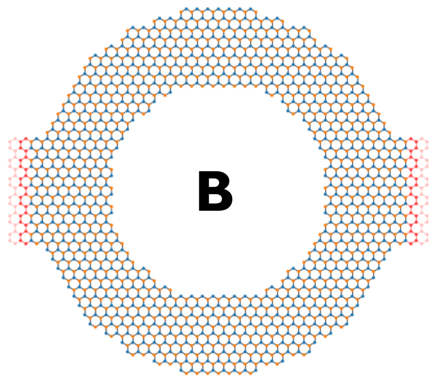


$$\phi_{ACD} - \phi_{ABD} = (e/\hbar c) \oint \vec{A} \cdot d\vec{s} = (e/\hbar c) \int \vec{B} \cdot d\vec{\sigma}$$

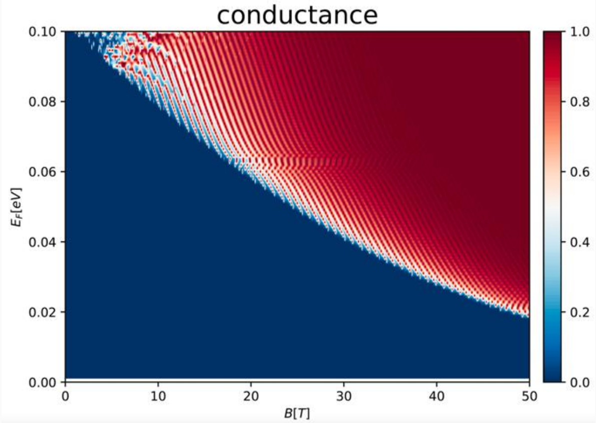
Quantum transport in a magnetic field

Graphene ring

Left lead

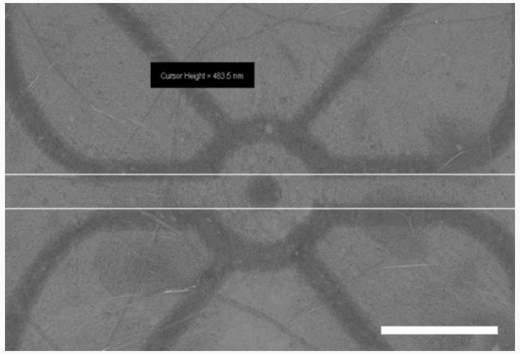


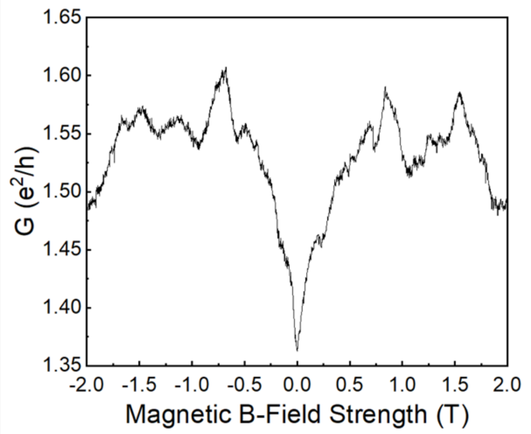
Right lead

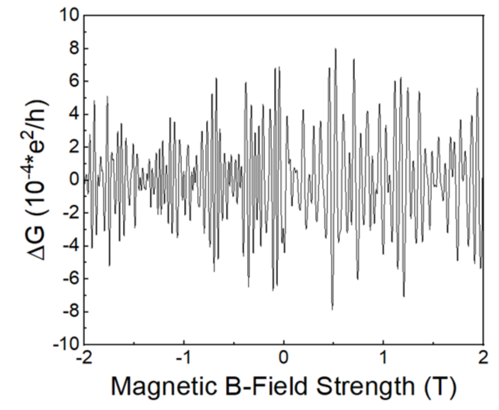


Aharonov-Bohm oscillation in CVD graphene

Experiment (Z. Tang, S. Chen, A. Sakar, S. Strauf, E.H. Yang)



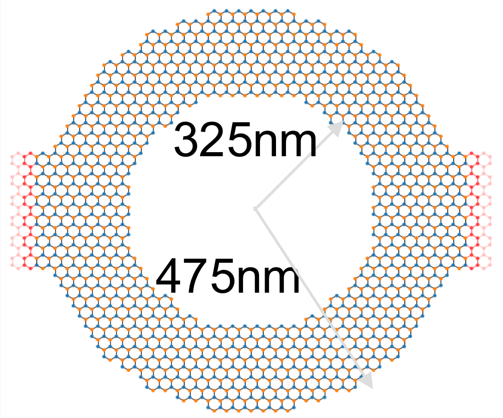


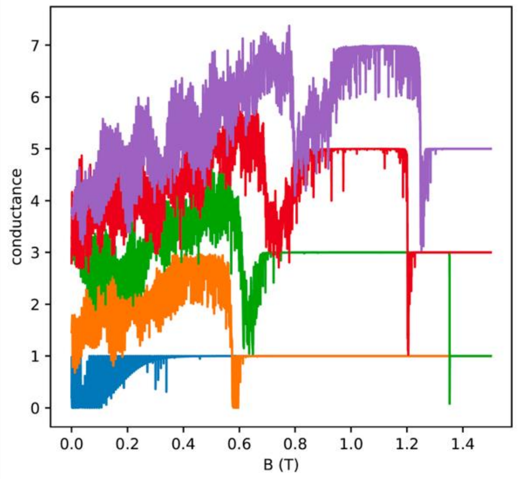


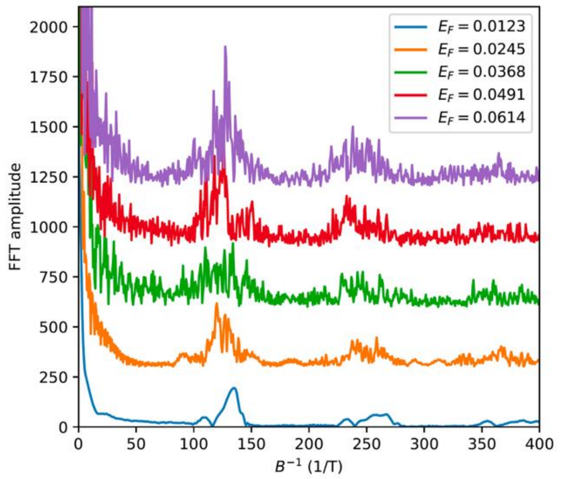
- Z. Tang, S. Chen, A. Sakar, C. Osuala, S. Strauf, G. Hader, T. Chou, A. Cummings, C. Qu, E.H. Yang, IEEE NANO conference (2023)
- Z. Tang, C. Osuala, S. Chen, G. Hader, A. Cummings, S. Strauf, C. Qu, E.H. Yang, under review (2023)

Simulation (C. Osuala, C. Qu)

Fourier transformation

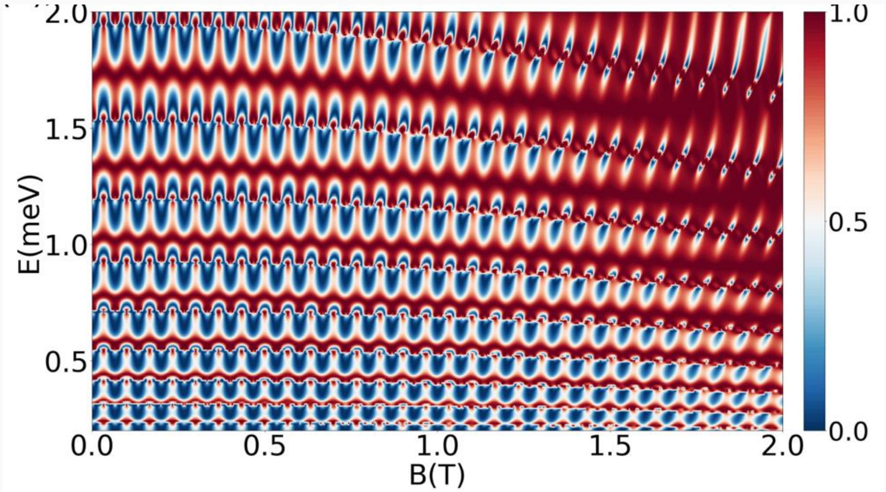


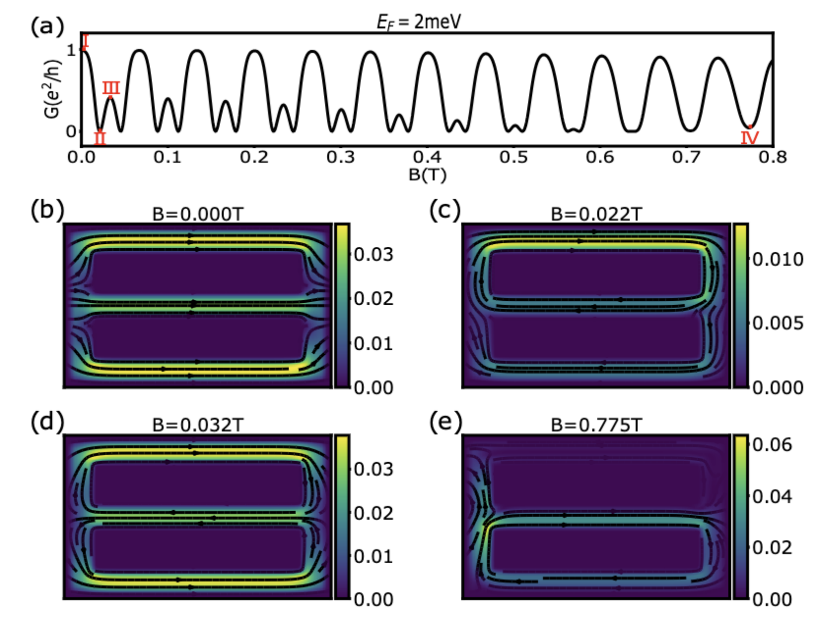




- Magnetic field
- Fermi energy
- Leads position
- Ring size
- Spin-orbit coupling
- Side gate potentials
- Defects
- Finite temperature

AB oscillation in multi-path graphene interferometer





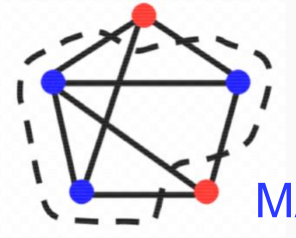
Electron matter wave diffraction grating

Some channels may be blocked at larger B field

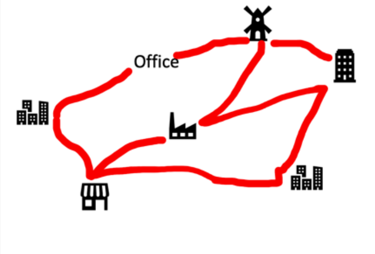
C. Osuala, Z. Tang, S. Strauf, E.H. Yang, C. Qu, Materials Science & Engineering B (2023)

Optimization problems

Solving an **optimization problem** is usually equivalent to finding the **ground state** of a spin-model



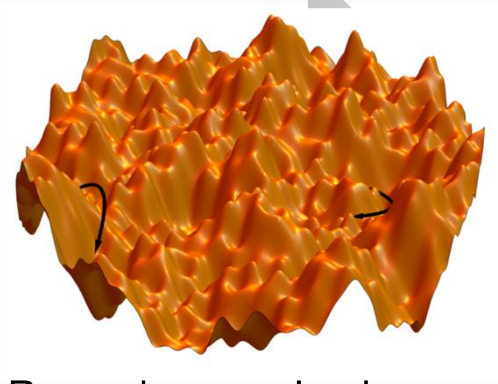
MAX-cut



TSP

$$H = -\sum_{i,j} J_{ij}\sigma_i\sigma_j$$

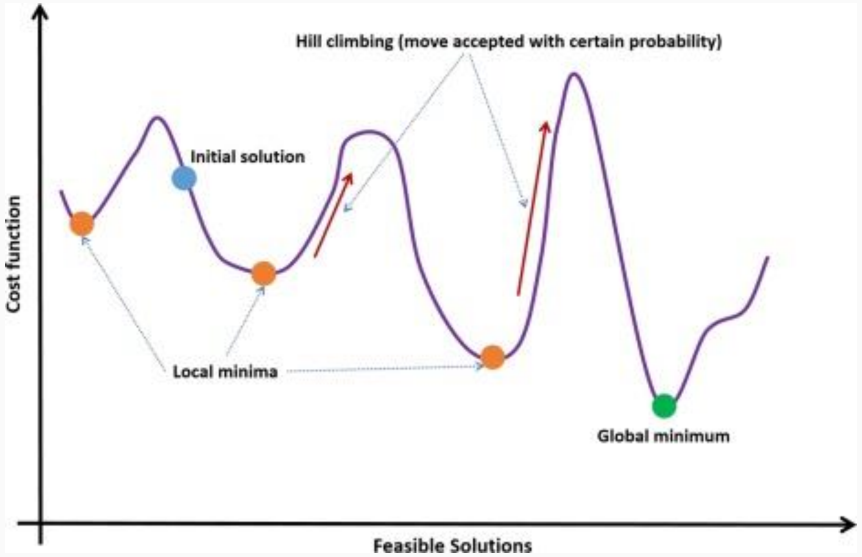
if random



Rugged energy landscape
⟶ complexity

2021 NP ⟶ Giorgio Parisi (spin glass)

Simulated annealing with Metropolis hasting algorithm



Randomly choose one spin to flip

- If energy decreases, accept the flip;
- If energy increases, reject it with certain probability (to escape local minimum)

Ising machine

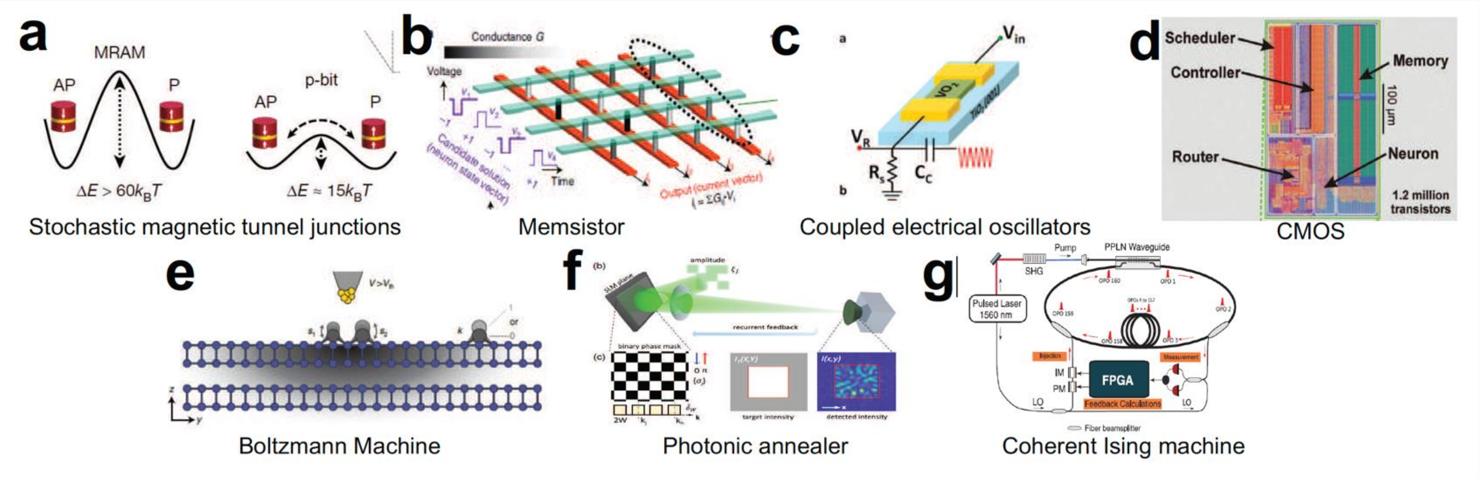
Calculating the total energy in each step can be **computationally expensive** for a large system size

Ising machine: Hardware solvers of combinatorial optimization problems

Many physical systems have been proposed to realize an Ising machine

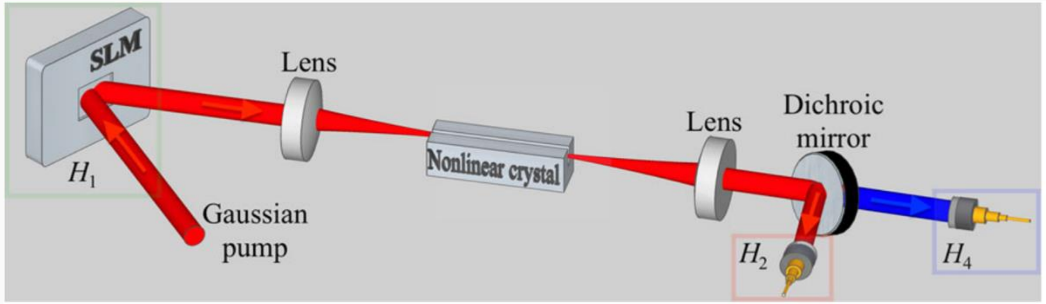
Among them, **optical Ising machine** is particularly attractive

- ✓ Parallelism
- ✓ Lower energy consumption
- ✓ Operation at the speed of light



Mohseni, McMahon, Byrnes, Nature Review Physics (2022)

Nonlinear optical Ising machine



S. Kumar, H. Zhang, Y.-P. Huang, Commun. Phys. (2020)

- Nonlinear crystal to generate four-body interaction

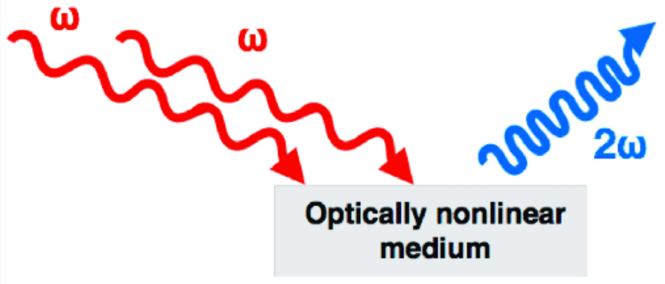
- Fully connected Ising model

- large scale: can encode millions of spins

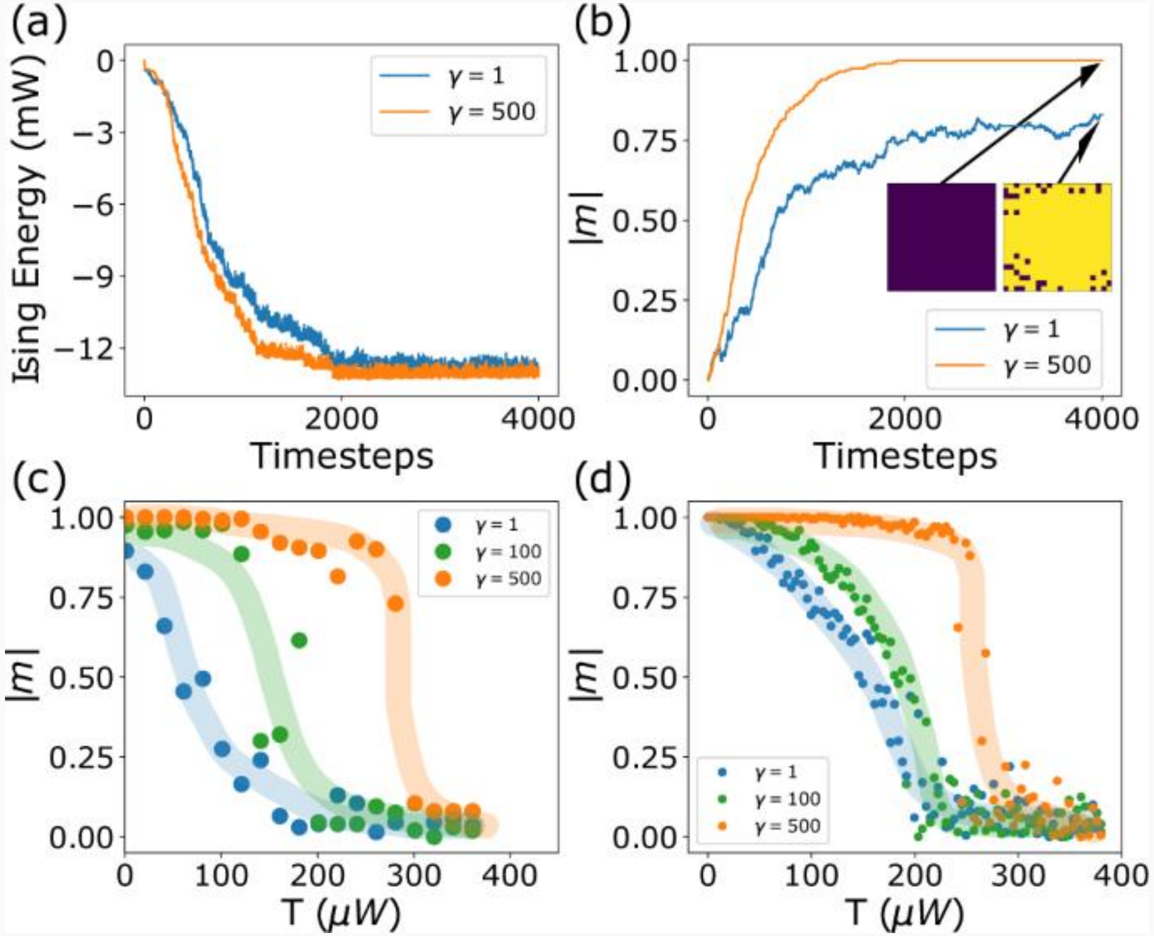
- Optical speed-up: directly measuring light intensity as the two-body and four-body total energies. It avoids the computation of matrix vector multiplication.

$$H = -\sum_{i,j} J_{ij}\sigma_i\sigma_j - \gamma \sum_{i,j,s,r} K_{ijsr}\sigma_i\sigma_j\sigma_s\sigma_r$$

4-body spin interaction from nonlinear optics



Distinct phase transitions in the nonlinear optical Ising machine



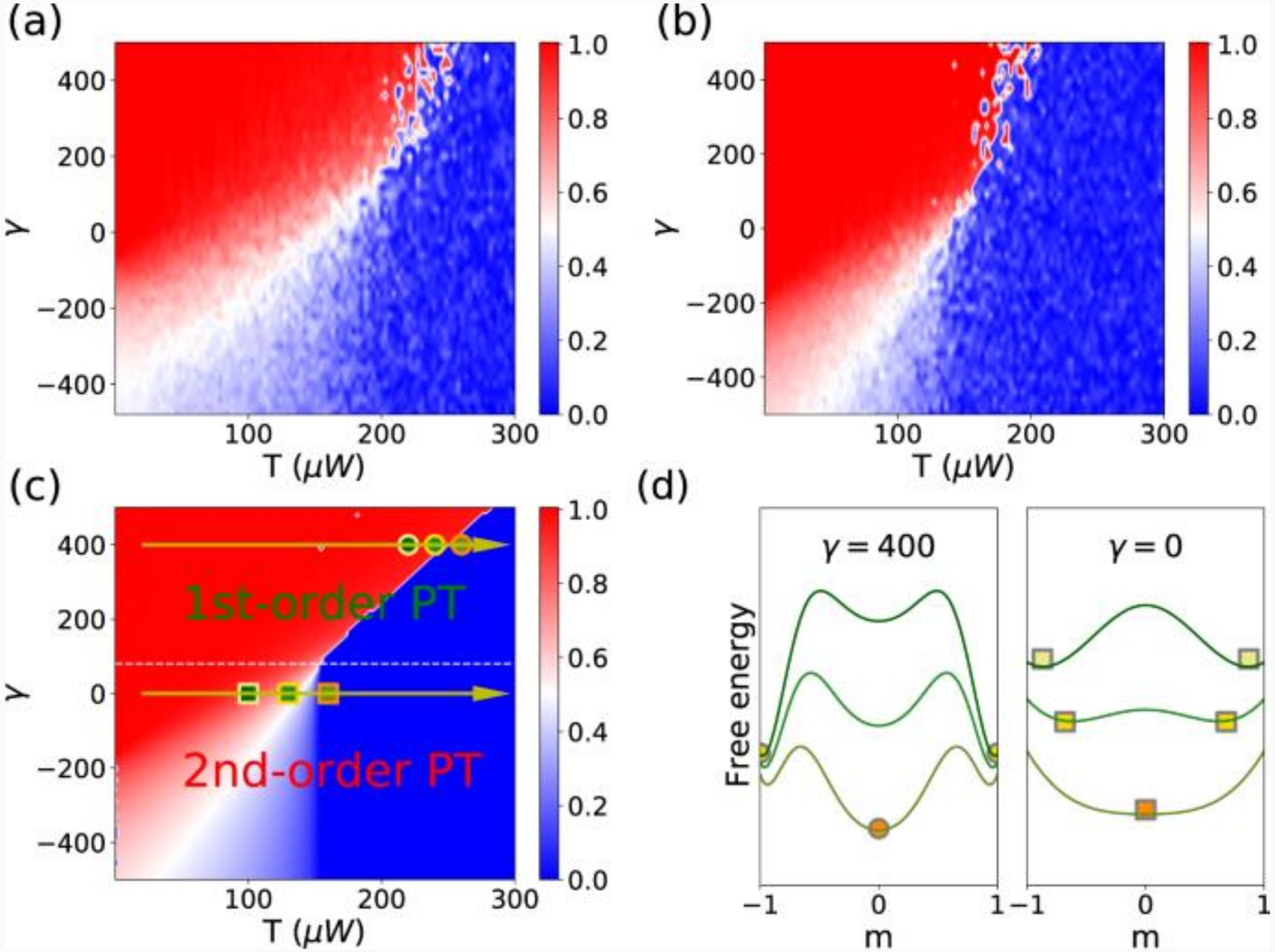
Experiment: S. Kumar, T. Bu, Y. Huang

$$H = -\sum_{i,j} J_{ij}\sigma_i\sigma_j - \gamma \sum_{i,j,s,r} K_{ijsr}\sigma_i\sigma_j\sigma_s\sigma_r$$

Depending on the ratio of the four-body and two-body spin interaction coefficients, the magnetization either drops to zero gradually or abruptly as the increase of temperature

S. Kumar, Z. Li, T. Bu, C. Qu, Y. Huang, Communications Physics (2023)

Distinct phase transitions in the nonlinear optical Ising machine



Theory: Z. Li, C. Qu

Similar behavior was observed in numerical simulation

Developed a mean-field theory to understand the phase diagram

- 1st order phase transition
- 2nd order phase transition

S. Kumar, Z. Li, T. Bu, C. Qu, Y. Huang, Communications Physics (2023)

Conclusion

➢ **Atomic gyroscope for rotation sensing**

C. Qu, C.-H. Li, Y. P. Chen, S. Stringari, Physics Review A (2023)

➢ **Graphene interferometer for magnetic field sensing**

Z. Tang et al., IEEE Open Journal of Nanotechnology (2023)

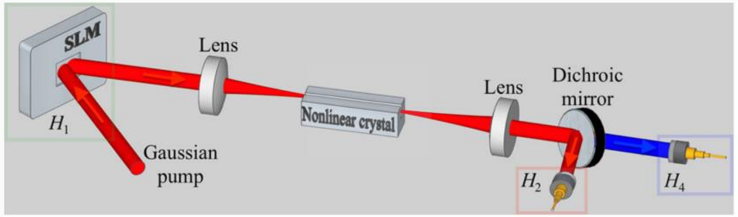
C. Osuala, Z. Tang, S. Strauf, E.H. Yang, C. Qu, Materials Science & Engineering B (2023)

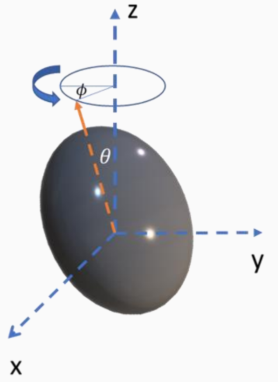
➢ **Optical Ising machine for optimization problems**

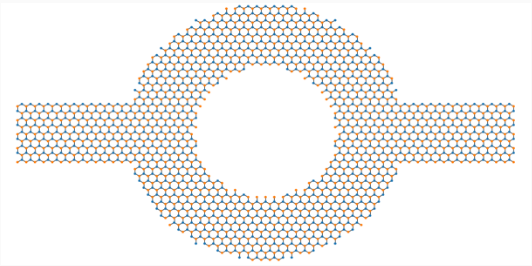
S. Kumar, Z. Li, T. Bu, C. Qu, Y. Huang, Communications Physics (2023)

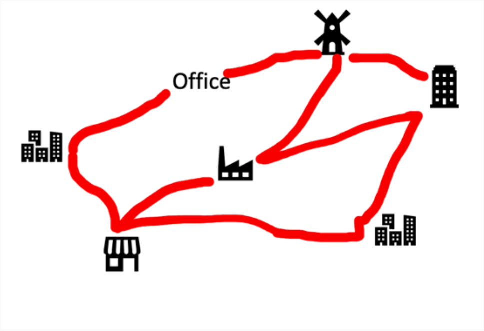
ART-020: Quantum Technologies for Armament Systems

sub-tasks: quantum-enhanced sensors and computers









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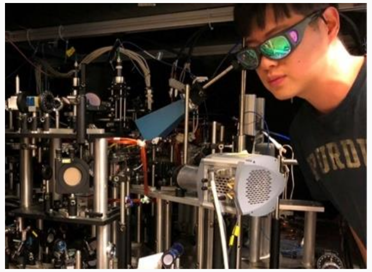
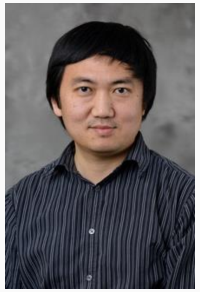
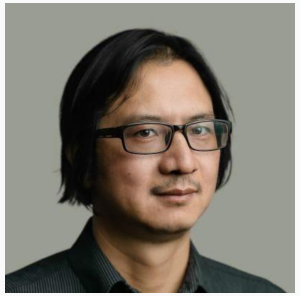
  - Zitao Tang (Stevens)
  - Stefan Strauf (Stevens)
  - E.H. Yang (Stevens)
- **Optical Ising machine**
  - Zhaotong Li (Stevens)
  - Santosh Kumar (Stevens)
  - Yuping Huang (Stevens)





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Thanks for your attention

Thank you

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