Dynamical Condensation of Exciton-Polaritons
– New Quantum liquid and Application to Quantum Emulator –

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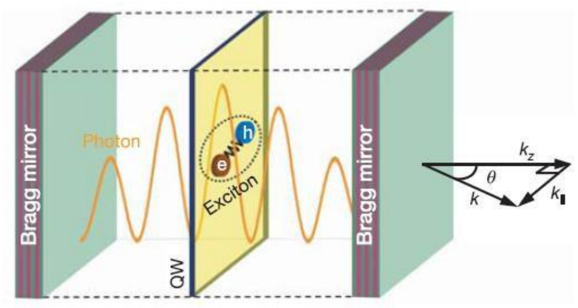
Introduction to microcavity Exciton-Polariton



Polariton is bosonic quasi-particle formed by a strong coupling of excitons and photon in a semiconductor cavity.

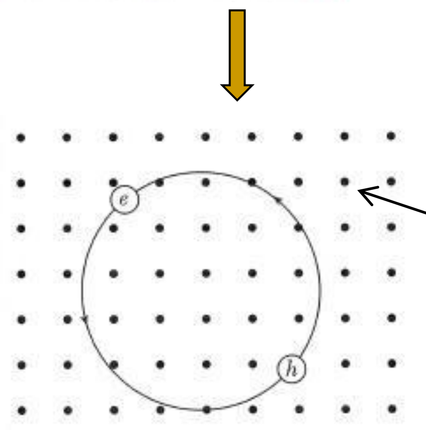
Exciton is bosonic quasi-particle formed by the bound electron –hole pair in quantum wells.

Wave Function

$$\psi(x_e, x_h) = \psi(r)\, exp(iK \cdot R)/\sqrt{V}$$

Total Energy

$$E(K,n) = E_g - \varepsilon_{exc,n} + \frac{\hbar^2 K^2}{2M}$$



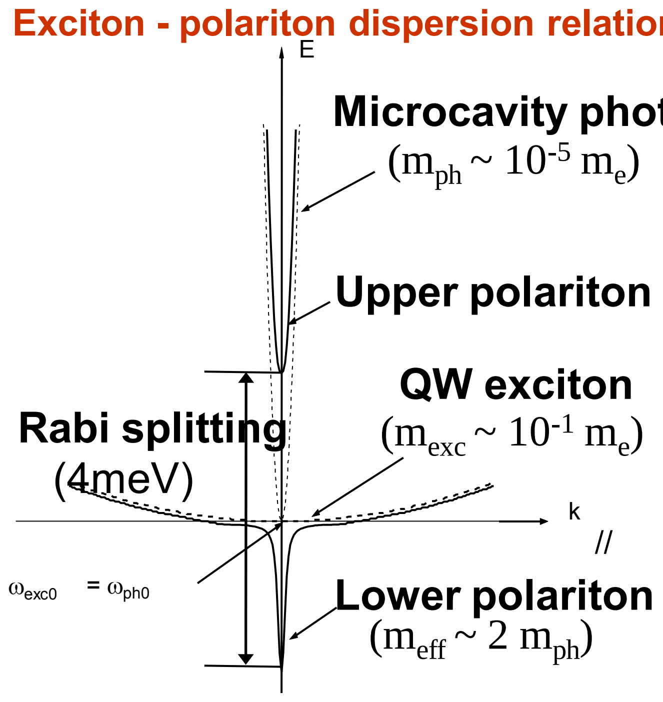
crystal lattice

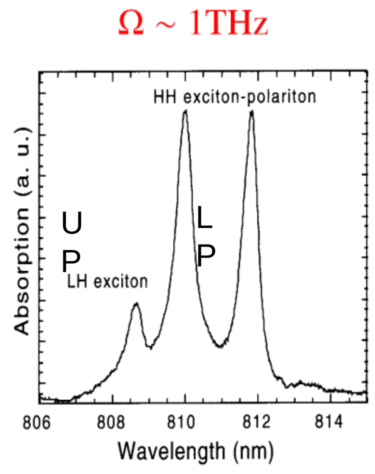
e ⇨ electron (negative charge)
h ⇨ hole: vacant orbital left by electron (positive charge)

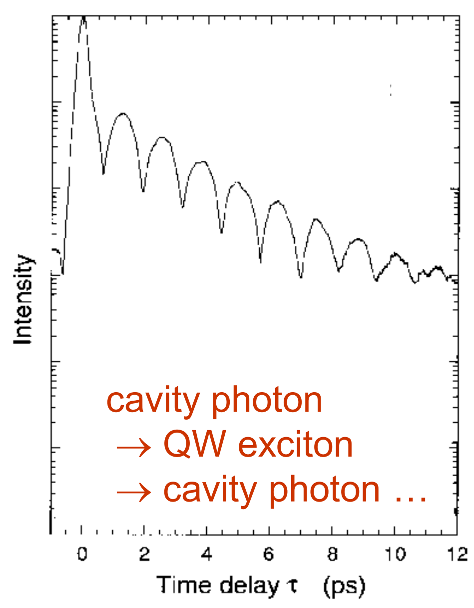
Semiconductor Cavity QED in Strong Coupling Regime – Dressing Excitons with Electromagnetic Vacuum Field –

Exciton - polariton dispersion relation

$$\hat{\mathcal{H}} = \hbar\omega_p \hat{a}^+\hat{a} + \hbar\omega_e \hat{c}^+\hat{c} + \hbar\Omega\left(\hat{a}^+\hat{c} + \hat{a}\hat{c}^+\right) + \hat{\mathcal{H}}_{NL}$$







C. Weisbuch et al., Phys. Rev. Lett. 69, 3314 (1992) S. Jiang et al., Appl. Phys. Lett. 73, 3031 (1998)

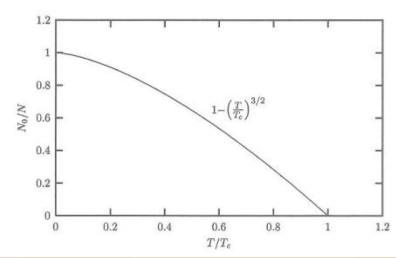
Bose-Einstein Condensation

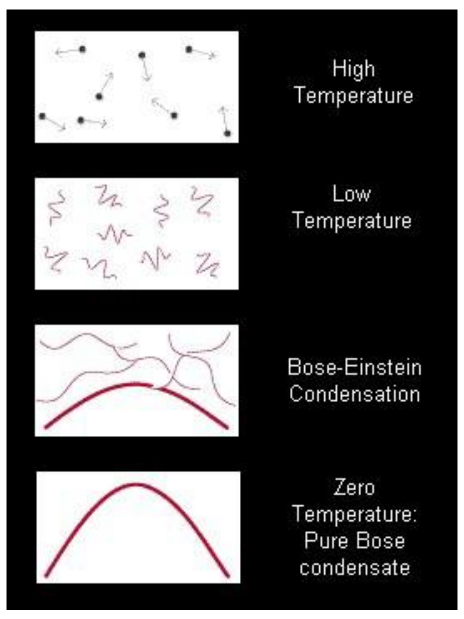
Boson: Particles that can occupy the same quantum state with the same energy and it follows Bose-Einstein statistics:

$$f_{BE}(\varepsilon) = \frac{1}{\exp\{(\varepsilon - \mu)/kT\} - 1}$$

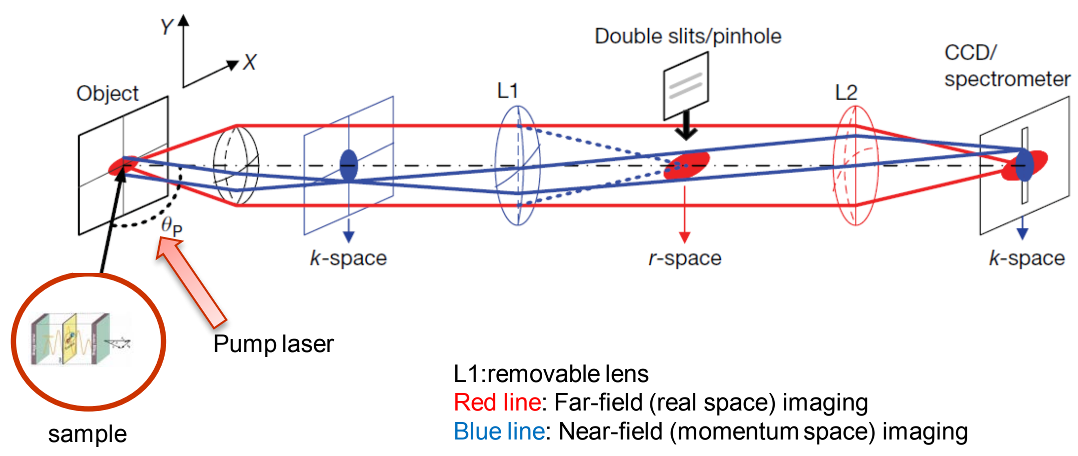
BEC phenomenon occurs

$$N_0 = N\left[1 - \left(\frac{T}{T_c}\right)^{3/2}\right]$$



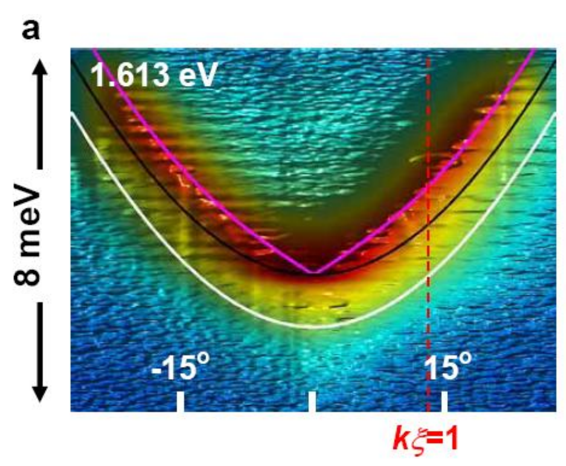


Experiment Setup



C.W. Lai et al. Nature **450**, 529-532 (22 November 2007)

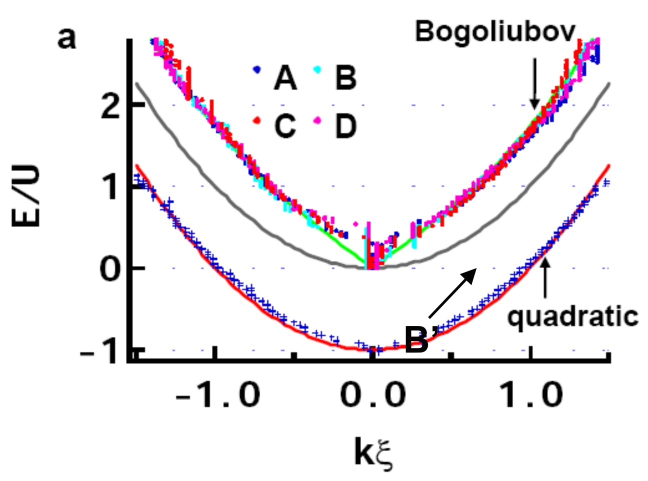
Bogoliubov Excitation Spectrum S. Utsunomiya et al., to be published in Nature Physics



White line : Single particle dispersion

Black line : $E = \dfrac{p^2}{2m}$

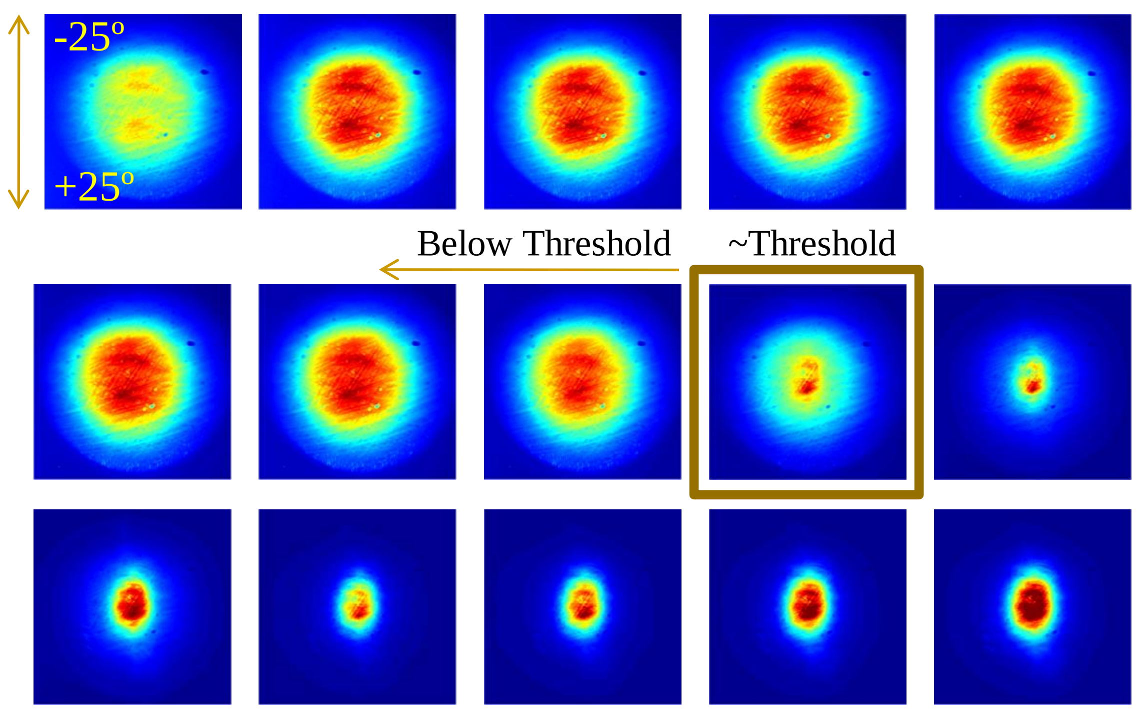
Pink line : Bogoliubov theory (polariton-polariton interaction) $E = \dfrac{p^2}{2m} + UN_0$



A : Δ = 1.4meV, p/p_{th} = 4
B : Δ = 0.82meV, p/pth = 8
B' : Δ = 0.82meV, p/pth = 0.0001
C : Δ = 4.2meV, p/pth = 4
D : Δ = -0.23meV, p/pth = 24

Far Field Pattern (momentum space distribution)

Thermal Polaritons ➔ aspect ratio~1:1 (isotropic) **50 × 50 degrees (Δk=7.5 × 10⁴ cm⁻¹)**

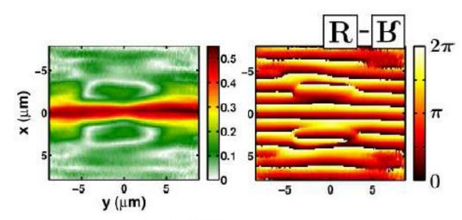


Modeling of exciton-polariton condensates - quantized vortex dynamics

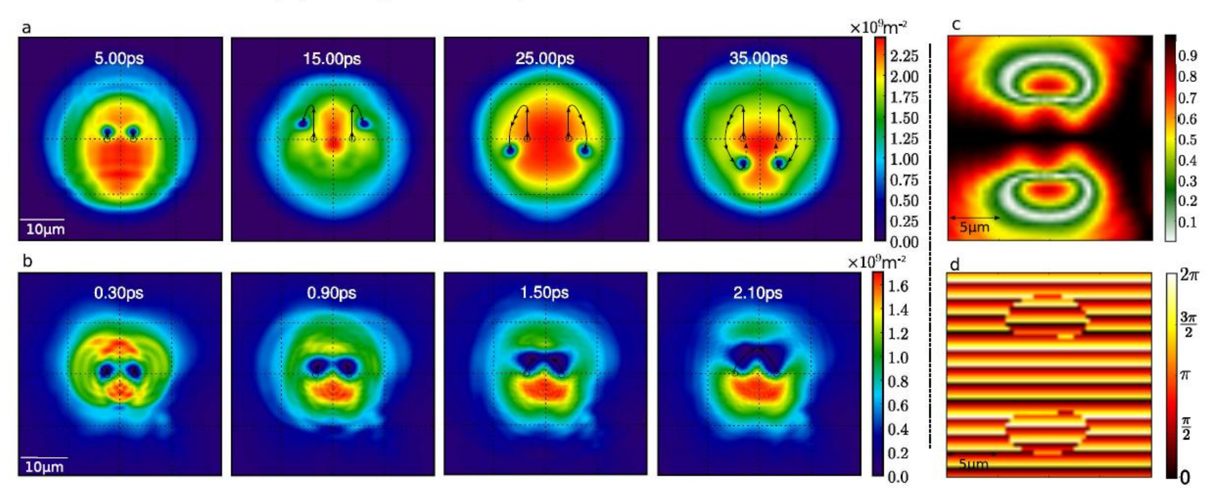
MD Fraser et.al. NJP **11** 113048 (2009)
G Roumpos et.al. arXiv:1005.1897v1 (2010)

- Dissipative polariton condensate requires new model to describe its features
- Demonstrated to closely match experiments
- Prediced new stable vortex states
- Being used to design real polariton laser devices

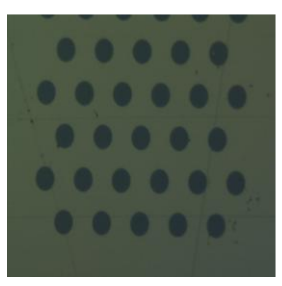
First experimental observation of vortex-antivortex pairs (Stanford)



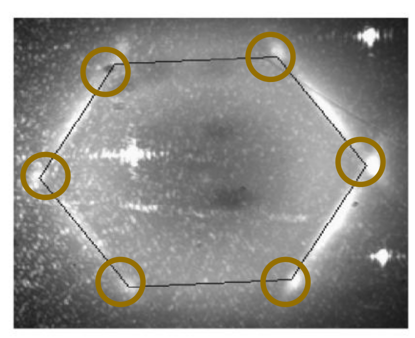
Numerical reconstruction of vortex pair dynamics (a) in a conservative system and (b) in a dissipative polariton condensate. The numerical fringe visibility (c) and phase profile (d) assuming the vortex motion in (b) closely match experimental measurements above



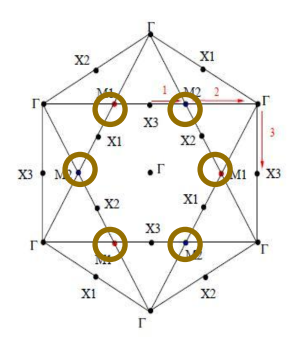
The formation of a new kind of vortex lattices in triangular lattice potentials



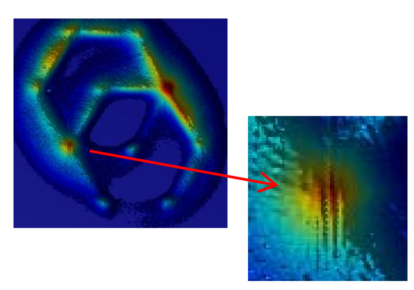
2-dimensional periodic potential by deposited thin metal patterns



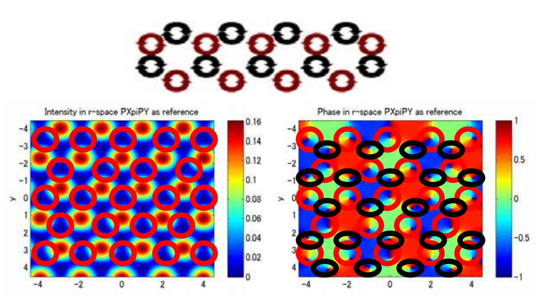
Observed meta-stable condensation at M-points



Brillouin Zones



Inteference indicates the existance of coherence between M1 points.



Experimental results indicates the existence of the new kind of vortex lattices. Vortex and anti-vortex stands like hexagonal lattices as seen above.

A Bose-Einstein Condensate Computer

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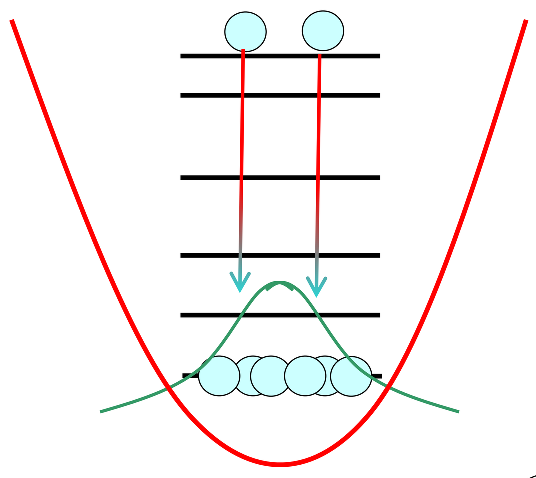
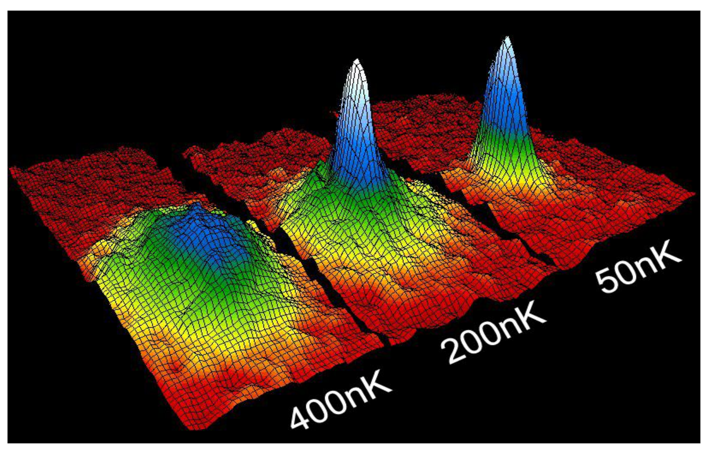
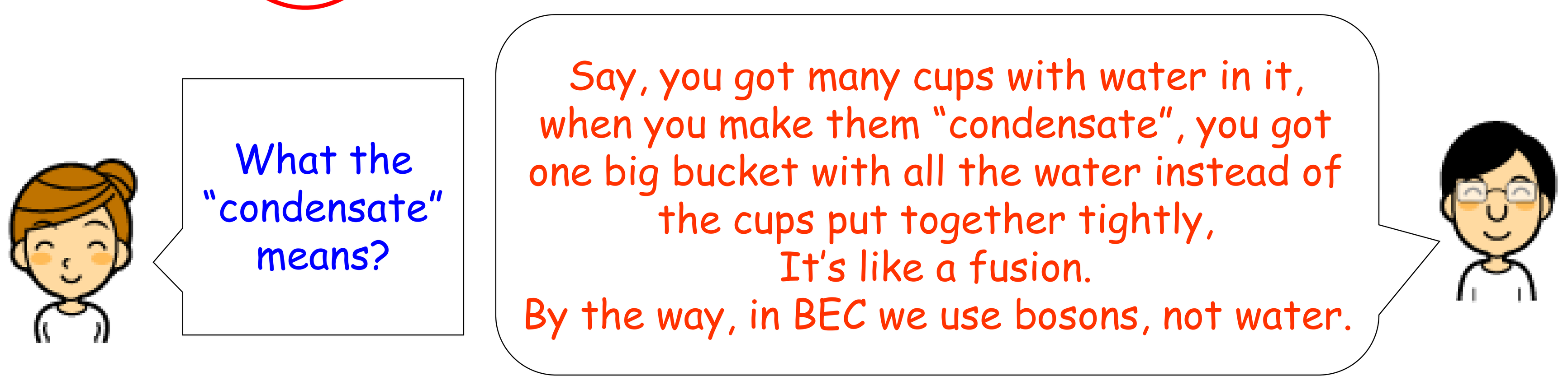
National Institute of Informatics, and E. L. Ginzton Laboratory, Stanford University

What's BEC?

In a BEC, the system has a large concentration of particles in the system ground state. In bosonic final state stimulation, the transition rate is enhanced by a factor N+1, given N particles in the final state, Bosonic particles have an enhanced cooling rate.



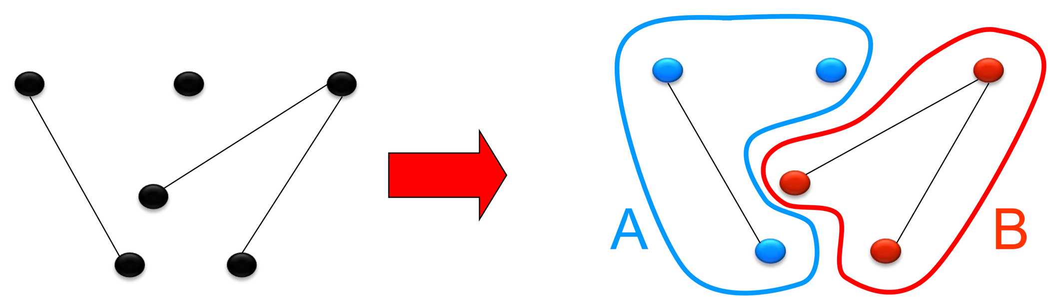


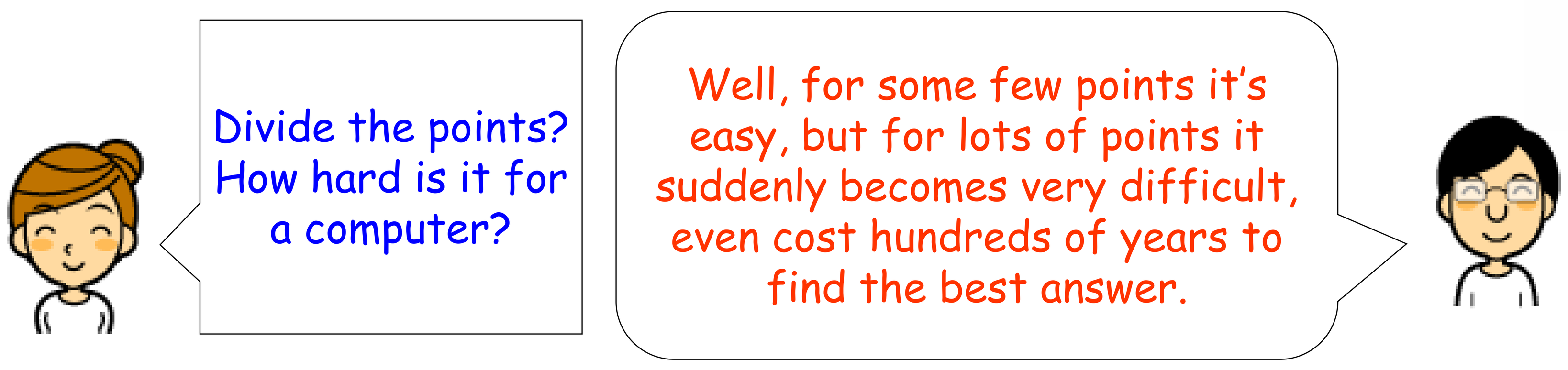


Example of computational problem

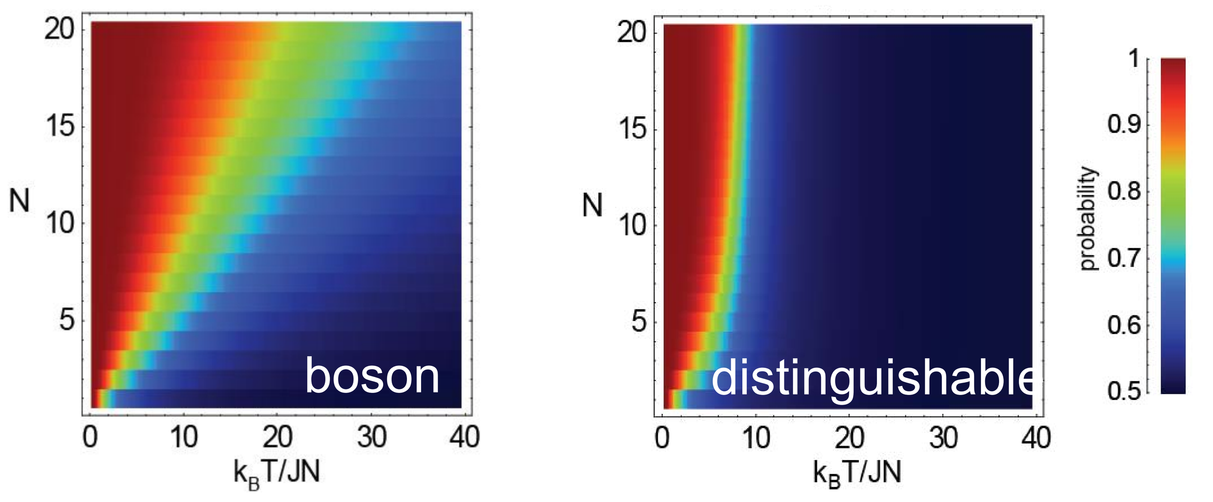
The Graph Partitioning Problem(GPP)

Given 2*N* points with arbitrary connections between them, divide the points into two groups (A and B) of *N* points, minimizing the number of connections between them. Any kind of NP-complete problem can be formulated as GPP.

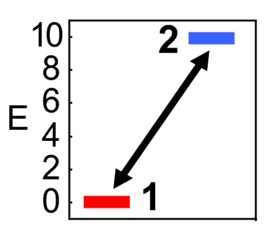


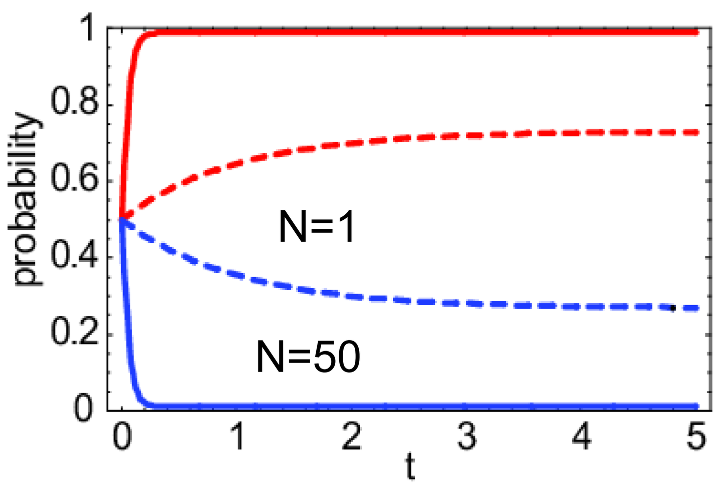


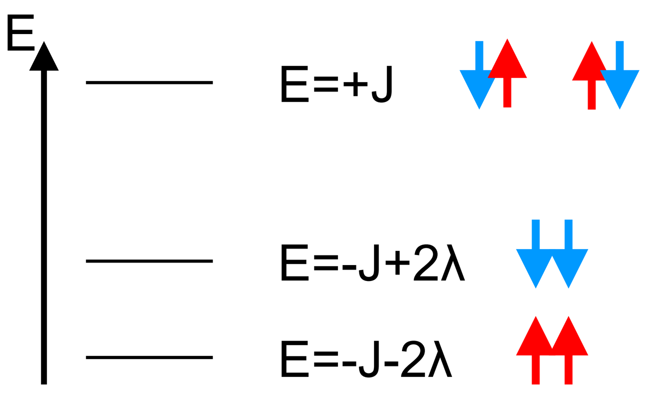
Cooling to thermal equilibrium

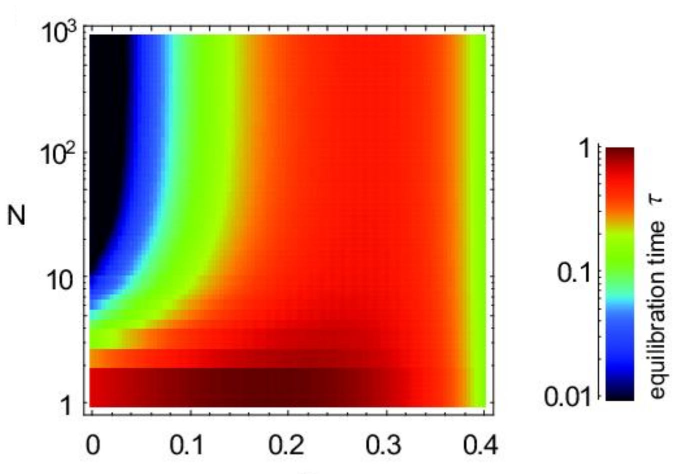


2 level system







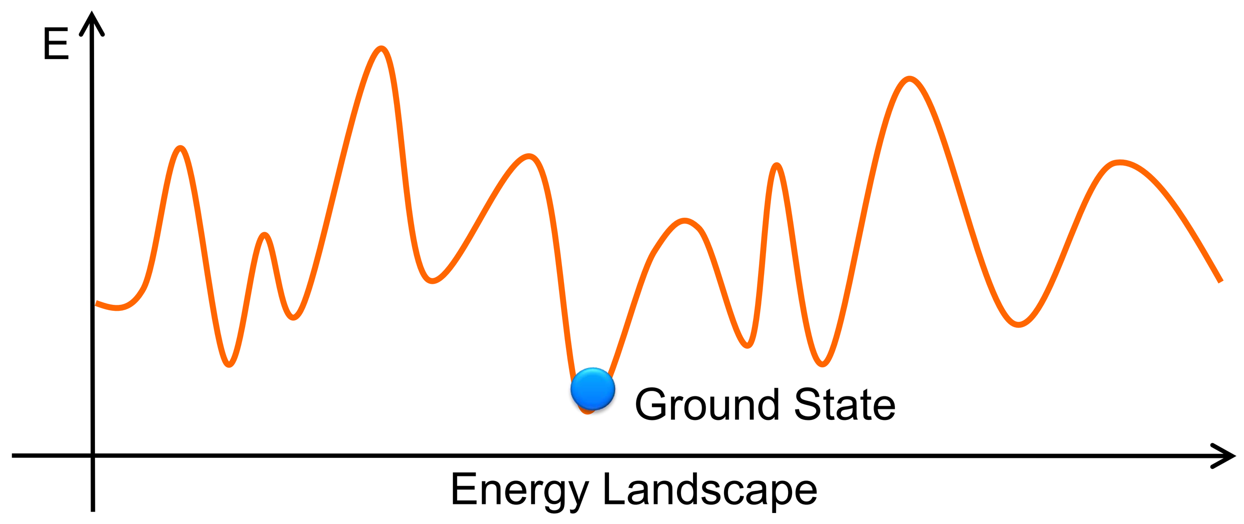


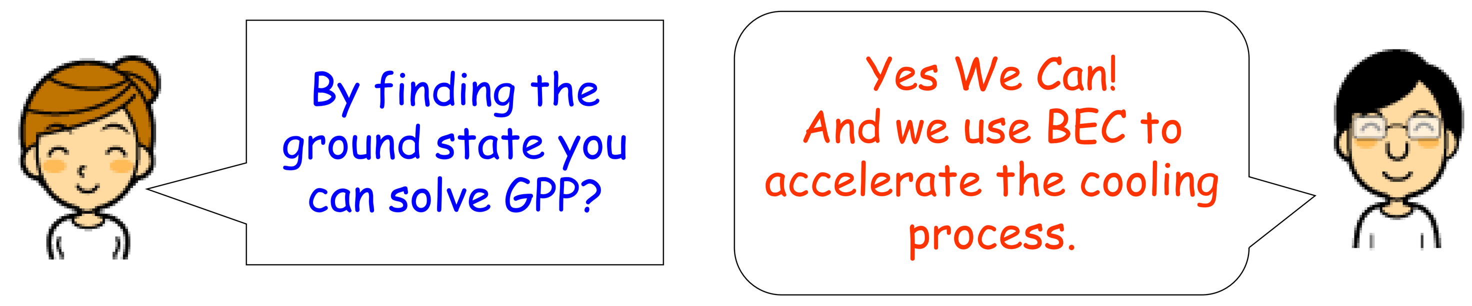
Conclusions

- Bosons speed up the equilibriation time of the Ising model by final state stimulation. An enhanced ground state population is present due to bosonic statistics.
- Introducing quantum coherence an interesting direction for future study.

How is this useful for computation?

Problem like Graph Partitioning Problem(GPP) can be formulated as a cost minimization problem.

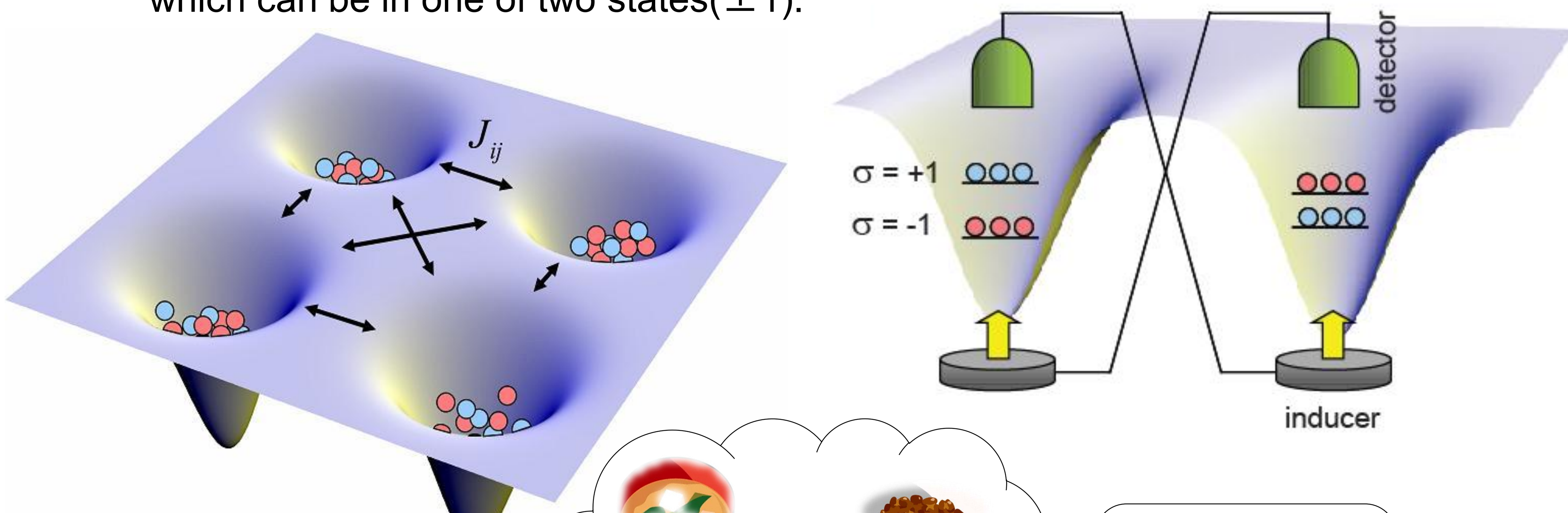


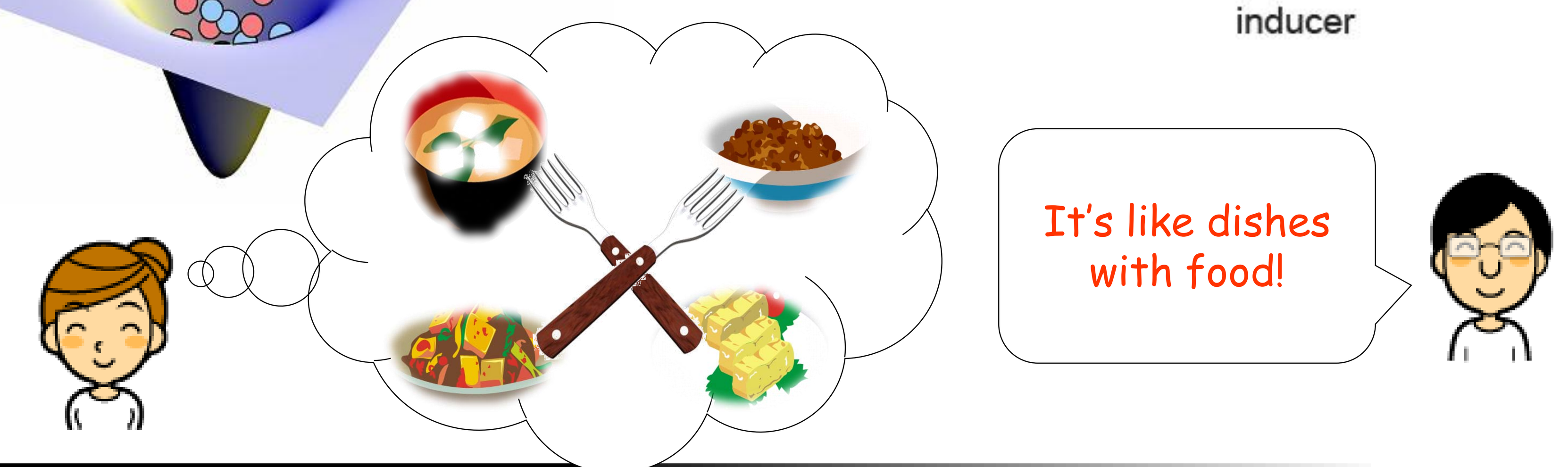


Device idea

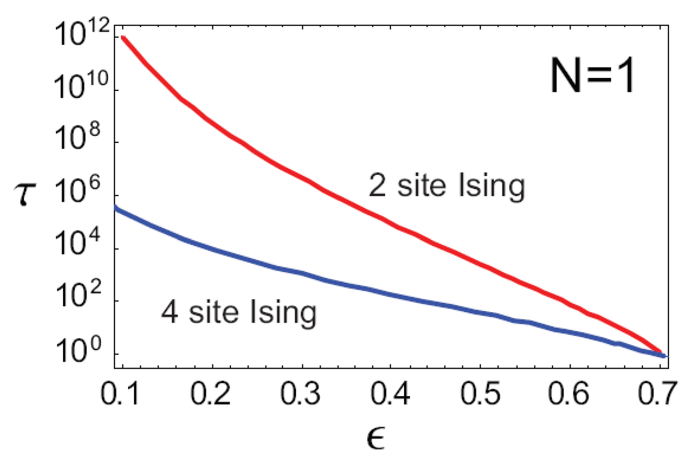
Each site is correspondent to a point in the given GPP, and has N bosons, each of which can be in one of two states(±1).

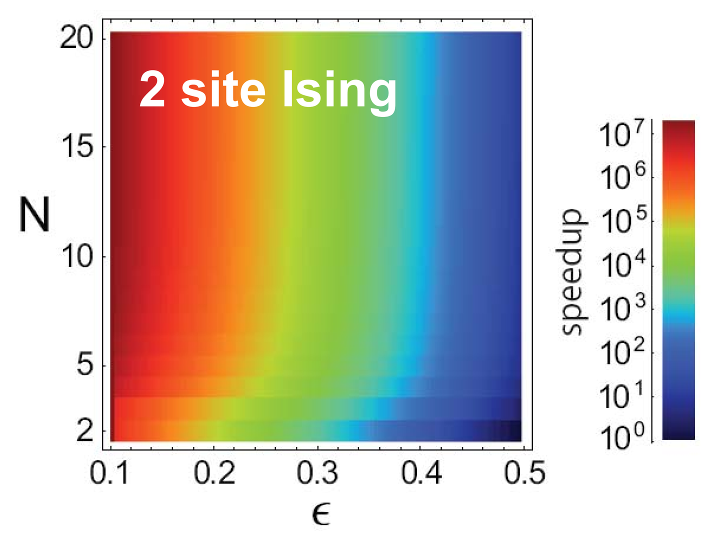
Interactions between sites are modified externally via feedback loop



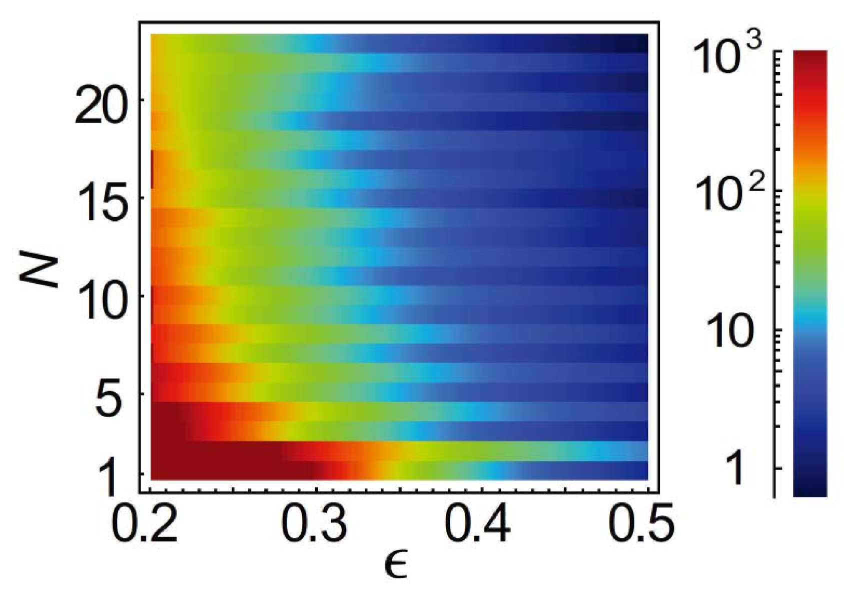


Direct Ising model simulation

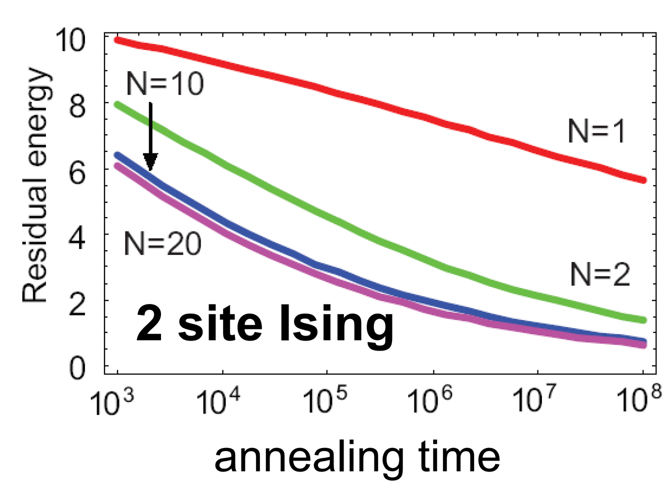




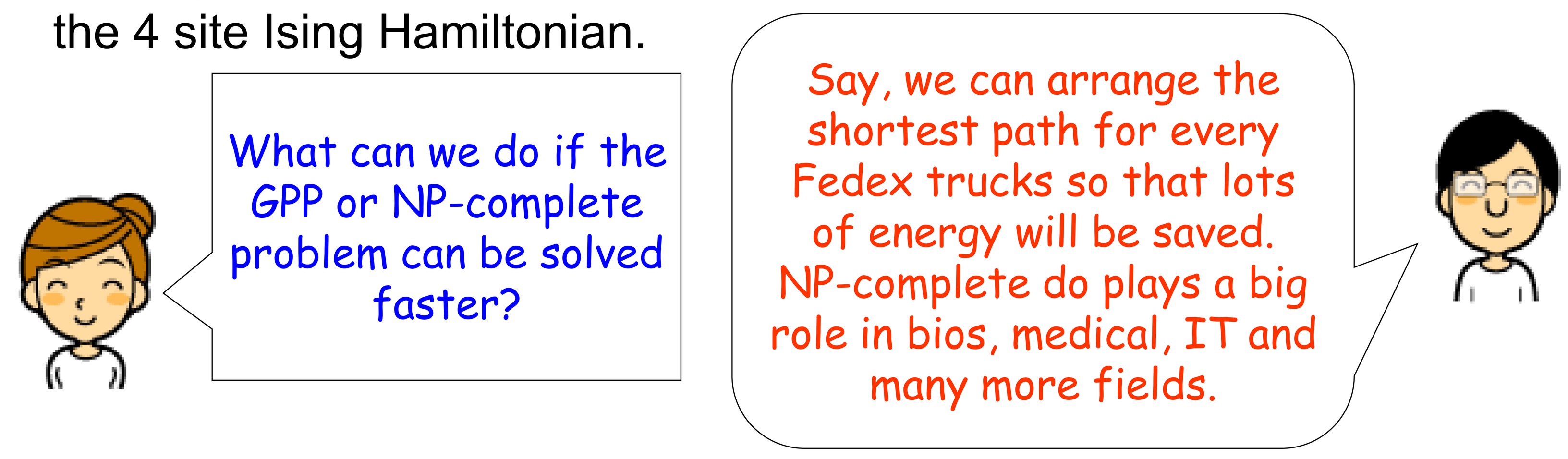
Increasing boson number increases equilibration speed for both 2 and 4 site Ising models.



The equilibration time for the 4 site Ising Hamiltonian.



Increasing boson number N reduces residual energy for the same annealing time.



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