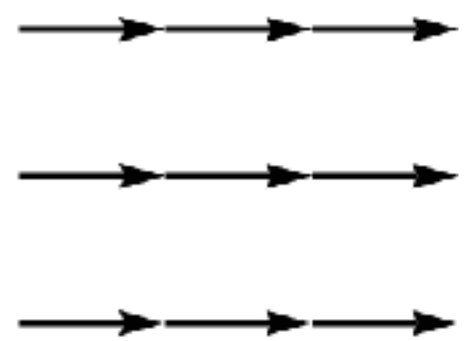
Utrecht University

Floquet Superconductor in Holography



Takaaki Ishii (Utrecht)

arXiv:1804.06785 [hep-th] w/ Keiju Murata

11 June 2018, Nonperturbative QCD Paris

Motivations

Holography in time dependent systems

To understand nonequilibrium phenomena from nonlinear dynamics in holographic theory.

e.g.) QGP, quench, thermalization

Condensed matter ideas

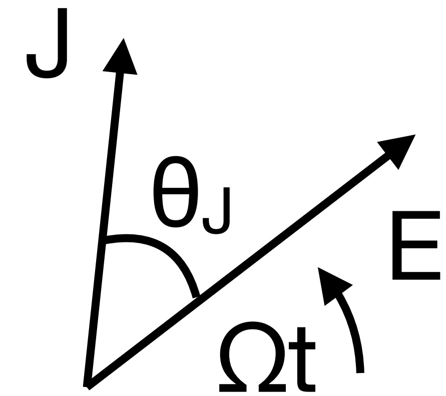
Apply time dependent perturbation (laser-pulse)
→ nonequilibrium states.

e.g.) ARPES, superconductivity enhancement

We consider rotating electric field

$$E_x + iE_y = Ee^{i\Omega t}$$

$$J_x + iJ_y = Je^{i\Omega t + i\theta_J}$$



In gauge potential $A_x + iA_y = Ae^{i\Omega t} \quad (A \equiv iE/\Omega)$

We include this rotating electric field to a holographic model of superconductivity (SC).

c.f.) Linear polarization: $E_x = E\cos(\Omega t),\ E_y = 0$

Rotating sources in holography

Complex scalar with phase rotation

[Biasi-Carrecedi-Mas-Musso-Serantes]

c.f.) Spontaneous phase rotation: Boson star

[Astefanesei-Radu, Buchel-Liebling-Lehner]

D3/D7+rotating cpx scalar: Chiral magnetic effect

[Hoyos-O'Bannon-Nishioka]

D3/D7+rotating electric field for Weyl semimetal

[Hashimoto-Kinoshita-Murata-Oka]

[↑Murata's talk]

Gauge/gravity duality

Gravity		**Field (gauge) theory**
Classical gravity in curved spacetime (AdS)	↔	Large-N of strongly interacting field theory
Local symmetry	↔	Global symmetry
Field	↔	Operator O_Δ
Nonnormalizable mode	↔	Source of O_Δ
Normalizable mode	↔	VEV of O_Δ

Holographic superconductor(/superfluid)

Gravity		**Field (gauge) theory**
U(1) gauge field	↔	U(1) global symmetry and/or external $U(1)_{em}$
Complex scalar	↔	Cooper pair
Nontrivial scalar solution despite trivial scalar boundary condition	↔	Spontaneous symmetry breaking

Simplest model

[Hartnoll-Herzog-Horowits]

Abelian Higgs model in AdS4 black hole geometry
↔ 2+1D field theory in finite temperature

$$S = \int d^4x\sqrt{-g}\left(-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - |D_\mu\Psi|^2 + 2|\Psi|^2\right)$$

$$ds^2 = \frac{1}{z^2}\left(-f(z)dt^2 + \frac{dz^2}{f(z)} + dx^2 + dy^2\right)$$

Introduce chemical potential $A_t(z) = \mu - \rho z + \cdots$

Ψ eq: $\Psi'' - \left(\frac{2}{z} - \frac{f'}{f}\right)\Psi' - \frac{1}{f}\left(\frac{m^2}{z^2} - \frac{A_t^2}{f}\right)\Psi = 0$

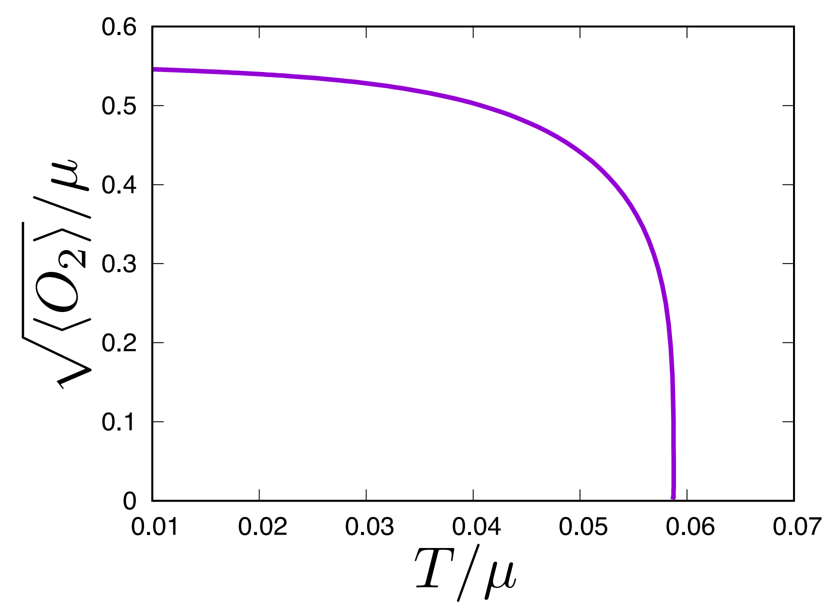
High temperature: $\Psi(z) = 0$

Spontaneous condensation

$$\Psi'' - \left(\frac{2}{z} - \frac{f'}{f}\right)\Psi' - \frac{1}{f}\left(\frac{m^2}{z^2} - \frac{A_t^2}{f}\right)\Psi = 0$$

This has $\Psi(z) \neq 0$ solution in low temperature

= spontaneous condensation <O>



Features as superconductivity:

Infinite DC conductivity, mass gap Δ~<O>

Our setup

$$S = \int d^4x\sqrt{-g}\left(-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - |D_\mu\Psi|^2 + 2|\Psi|^2\right)$$

Ansatz: $A_t(z),\ \Psi(z),\ A_x + iA_y = b(z)e^{i\Omega t}$

With this rotating ansatz, (z,t) variables separate.

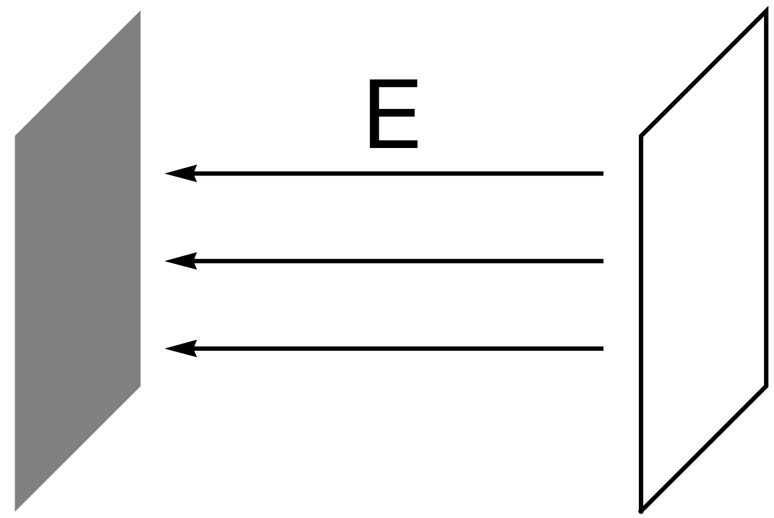
→ EOM reduces to ODEs rather than PDEs

$$\mathcal{L} = -\frac{1}{2}A_t'^2 + \frac{f}{2}|b'|^2 - \frac{\Omega^2}{2f}|b|^2 + \frac{1}{z^2}\left[f\psi'^2 + \left(|b|^2 - \frac{2}{z^2} - \frac{A_t^2}{f}\right)\psi^2\right]$$

Ψ eq: $\Psi'' - \left(\frac{2}{z} - \frac{f'}{f}\right)\Psi' - \frac{1}{f}\left(\frac{m^2}{z^2} - \frac{A_t^2}{f} + |b|^2\right)\Psi = 0$

Holographic steady state

BH is heat bath. (No metric backreaction.)



There is a steady flux flow to BH.

Constant flux in the holographic direction:

$$b \to b e^{i\theta} : \; J_\theta = \frac{if}{2}(b^* b' - b^{*\prime} b), \quad \partial_z J_\theta = 0$$

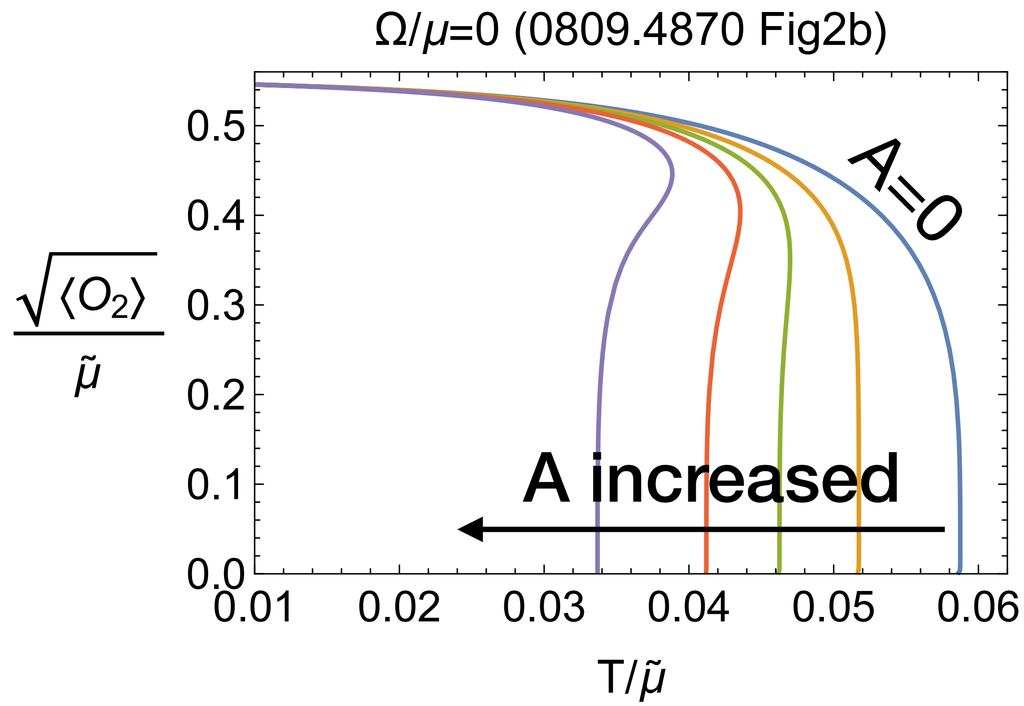
This gives Joule heating: $q = \Omega J_\theta = \vec{E} \cdot \vec{J}$

Review: Ω=0 case

Corresponds to a constant gauge potential.

[Basu-Mukherjee-Shieh, Herzog-Kovtun-Son]

In our setup, $(E,\Omega)\to 0$ with $|A|=E/\Omega$ fixed.

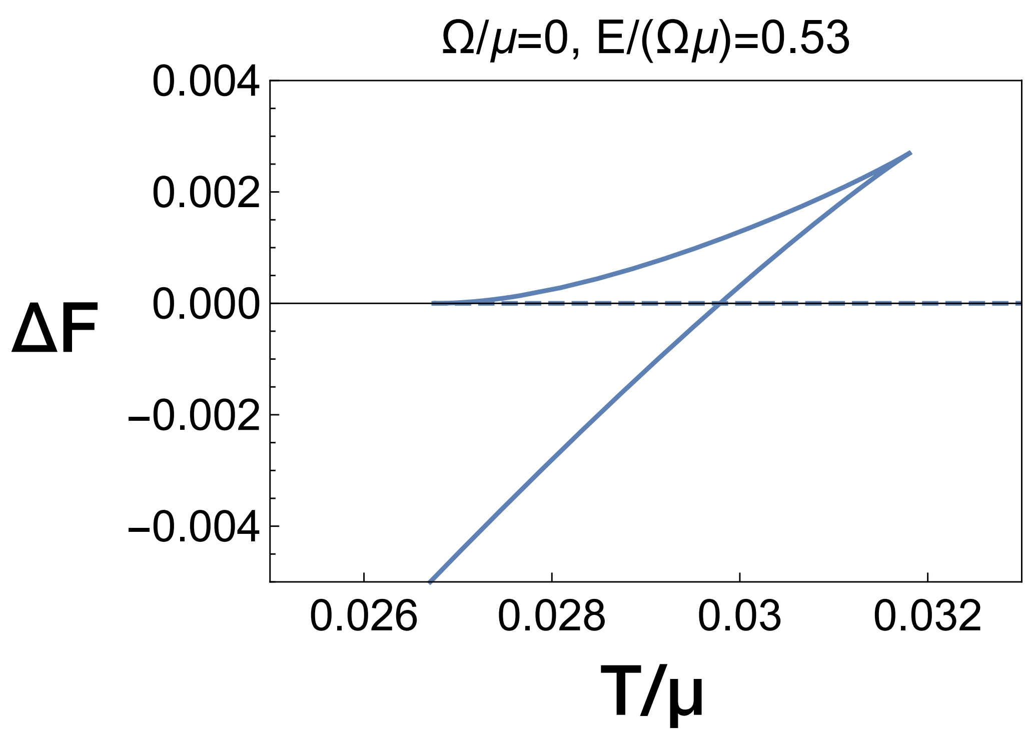


As A is increased, phase transition becomes 1st order.

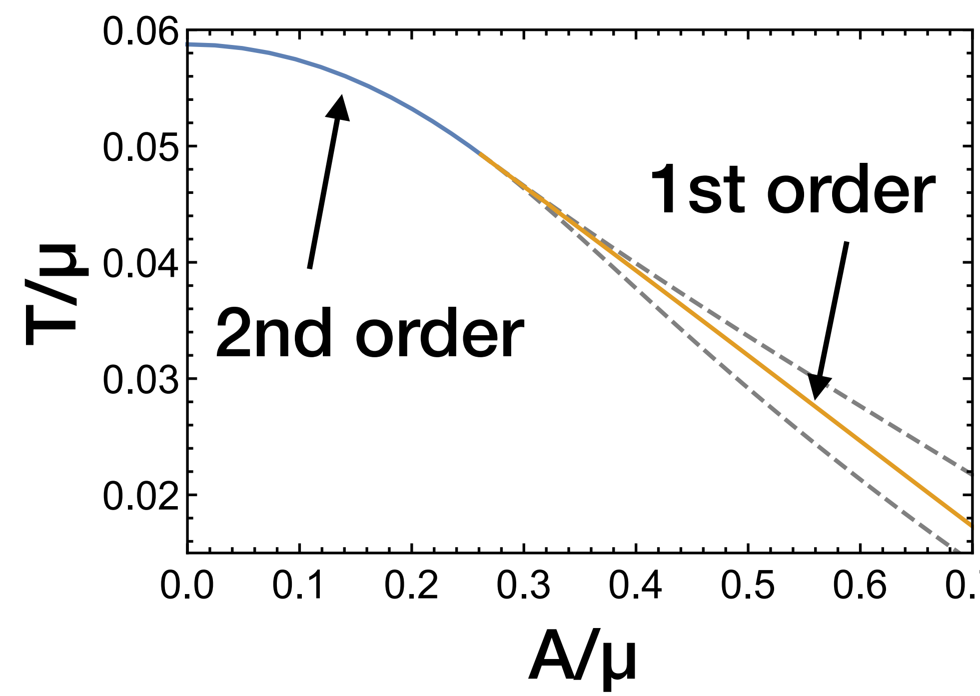
To calculate phase transition

Evaluate free energy, which is well-defined at Ω=0.

$$F_{\Omega=0} = -\frac{S_{\text{on-shell}}}{V} = -\frac{1}{2}\left(\mu\rho + \vec{A}\cdot\vec{J}\right) - \int \frac{dz}{z^2}\left(|b|^2 - \frac{A_t^2}{f}\right)\Psi^2$$

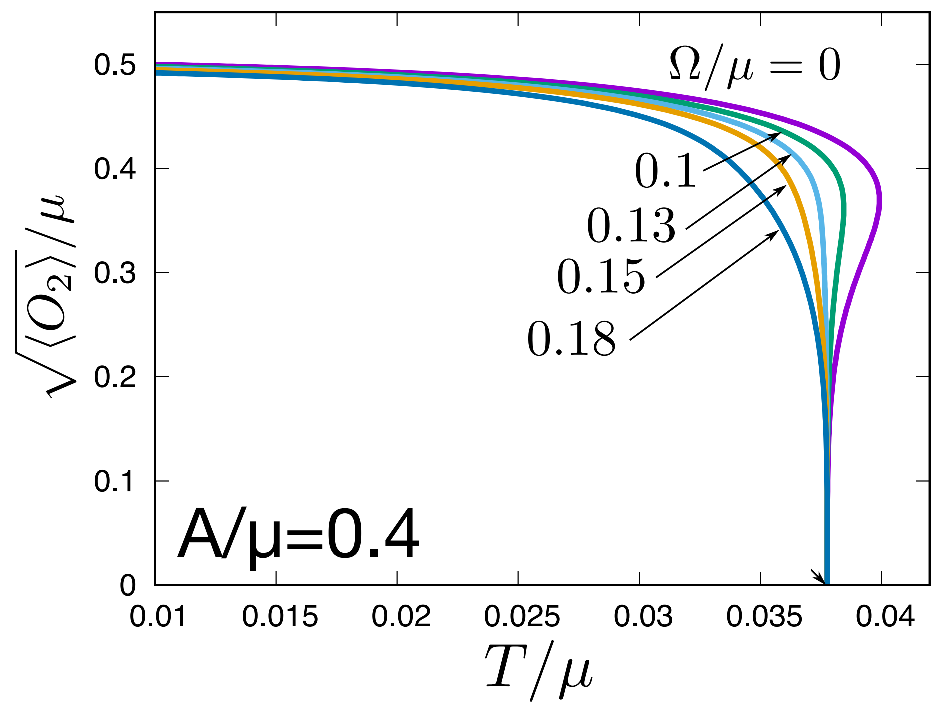


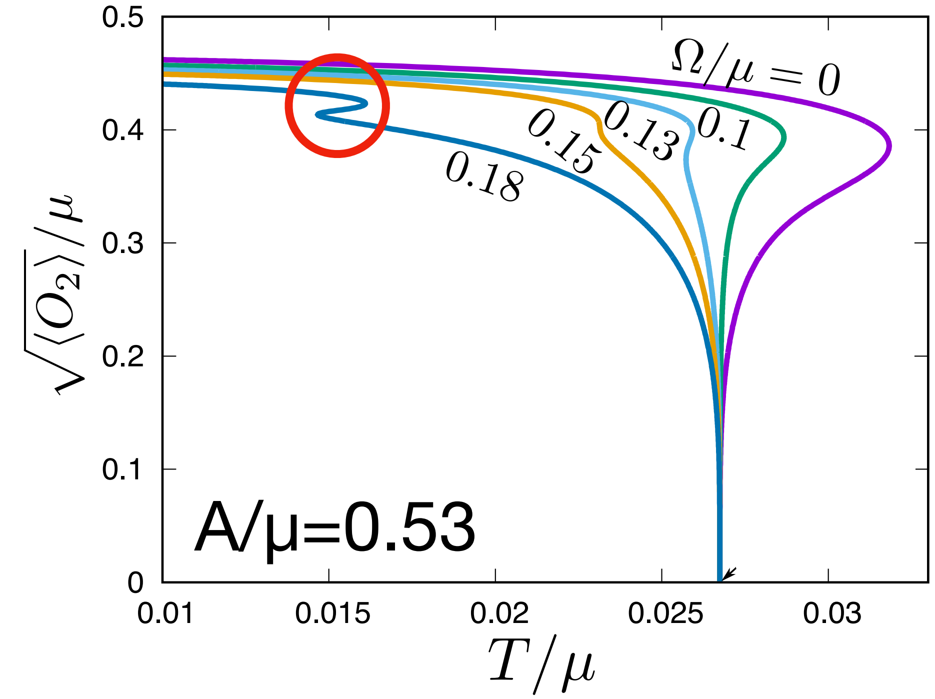
Example of F for 1st order phase transition



A(=E/Ω) dependence of Tc

When Ω>0

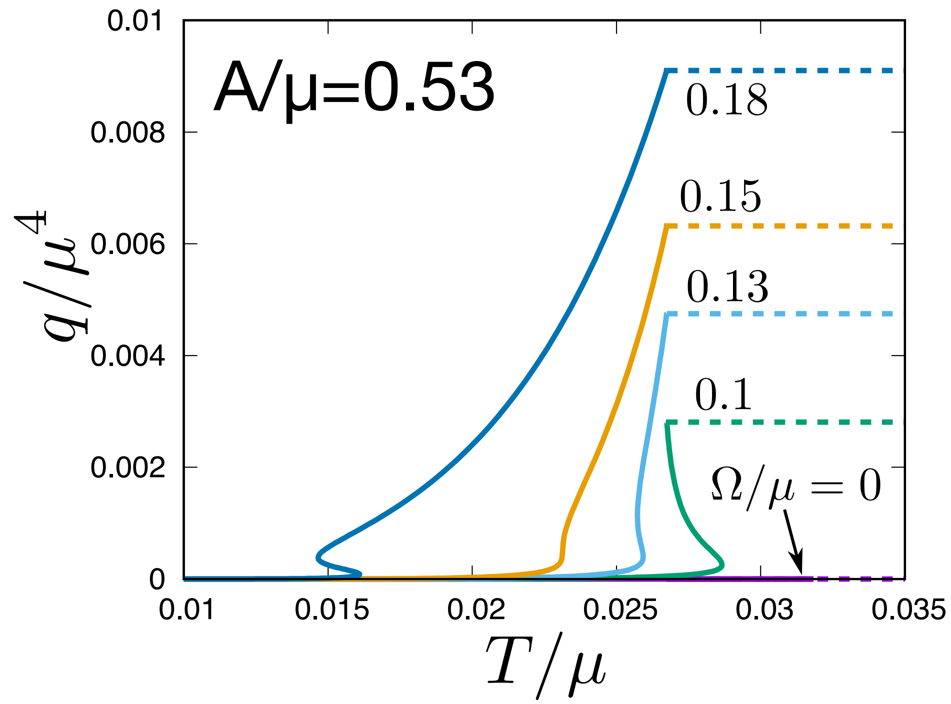


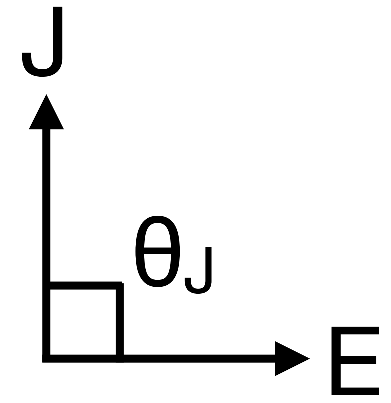


Larger Ω pushes back normal-to-SC phase transition (which is 1st order because of A) to 2nd order.

At large A and Ω, the condensate is multivalued inside the SC phase: 1st order (phase) transition

E and J get out of phase



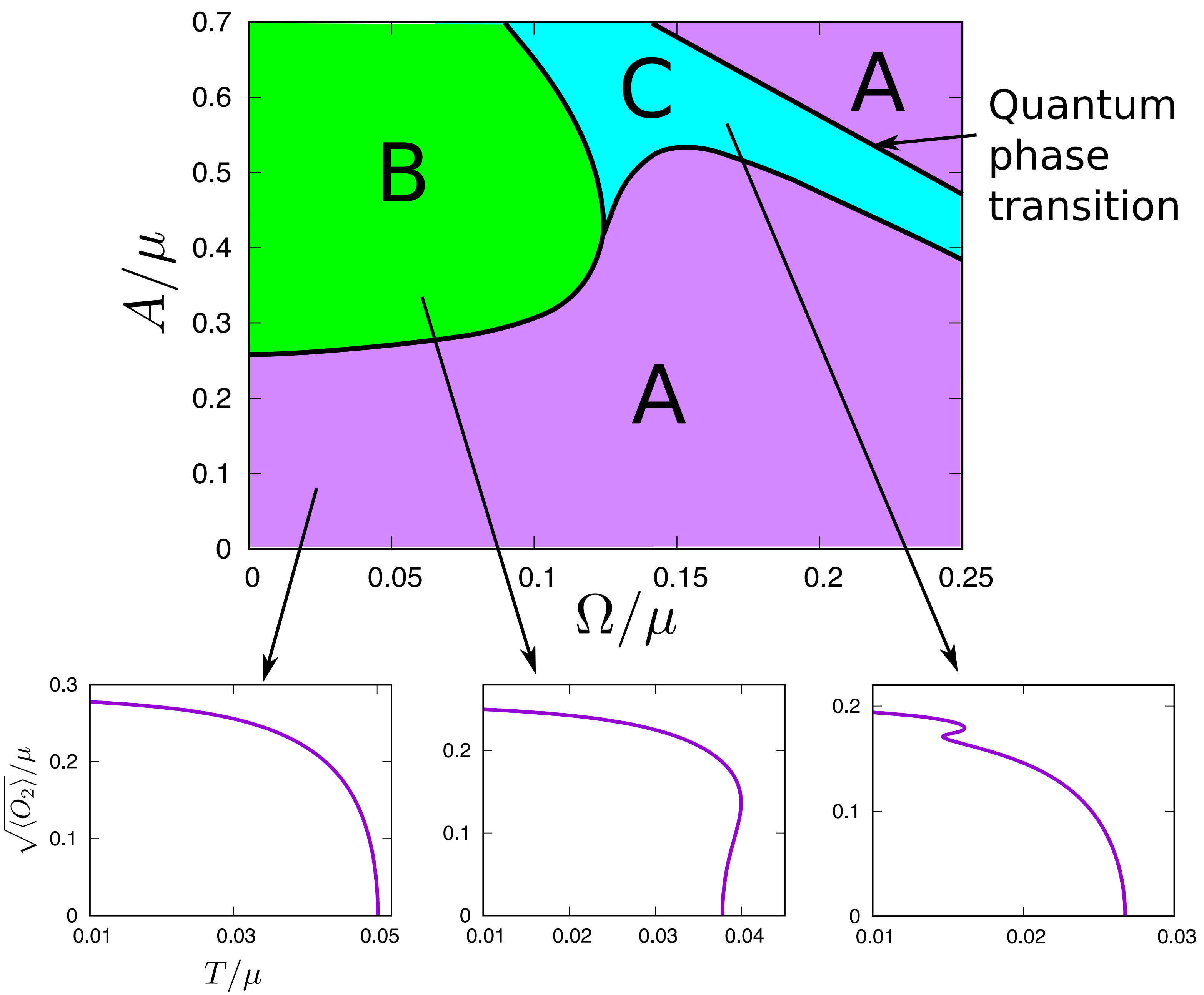


$$q = \vec{E} \cdot \vec{J}$$

Joule heating q is suppressed in the SC phase, consistent with the suppression of normal current.

This means that E and J are 90 degrees out of phase, consistent with the London equation.

Phase diagram



Ω=0 phase transition revisited

Free energy can be given in variational form

$$\delta S_{\text{on-shell}} = \int_\partial d^3x \left(\rho\delta\mu + \vec{J}\cdot\delta\vec{A}\right)$$

$$\Rightarrow \quad dF_{\Omega=0} = -\rho d\mu - \vec{J}\cdot d\vec{A}$$

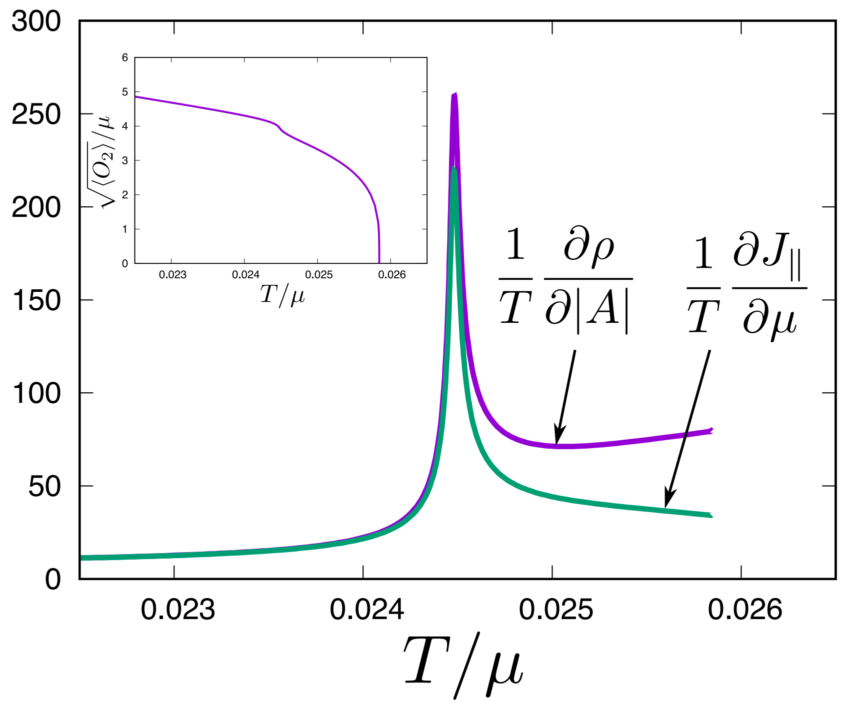
Integrability of dF is satisfied when Ω=0:

$$\frac{\partial\rho}{\partial\vec{A}} = \frac{\partial\vec{J}}{\partial\mu}, \quad \frac{\partial}{\partial\vec{A}}\times\vec{J} = 0$$

Maxwell construction: $F_{\Omega=0} = -\int \rho d\mu = -\int \vec{J}\cdot d\vec{A}$

Free energy for Ω≠0?

Integrability for ρ(μ,A), J(μ,A) is violated if Ω≠0.



Violation is larger in the region q is **not** small.

No dF exists which satisfies $dF = -\rho d\mu - \vec{J}\cdot d\vec{A}$

Why?

$$\delta S_{\text{on-shell}} = \delta s_b + \delta s_h$$

$$\delta s_b = \int d^3x \left[\rho\delta\mu + \vec{J}\cdot\delta\vec{A} - (q/\Omega)\delta(\Omega t)\right]$$

$$\delta s_h = \int d^3x \, [\Omega \, \mathrm{Im}(b^*\delta b)_{\text{horizon}} + (q/\Omega)\delta(\Omega t)]$$

AdS/CFT dictionary Derive the field theory quantity from δs_b. Horizon is included as ingoing wave condition rather than δs_h.

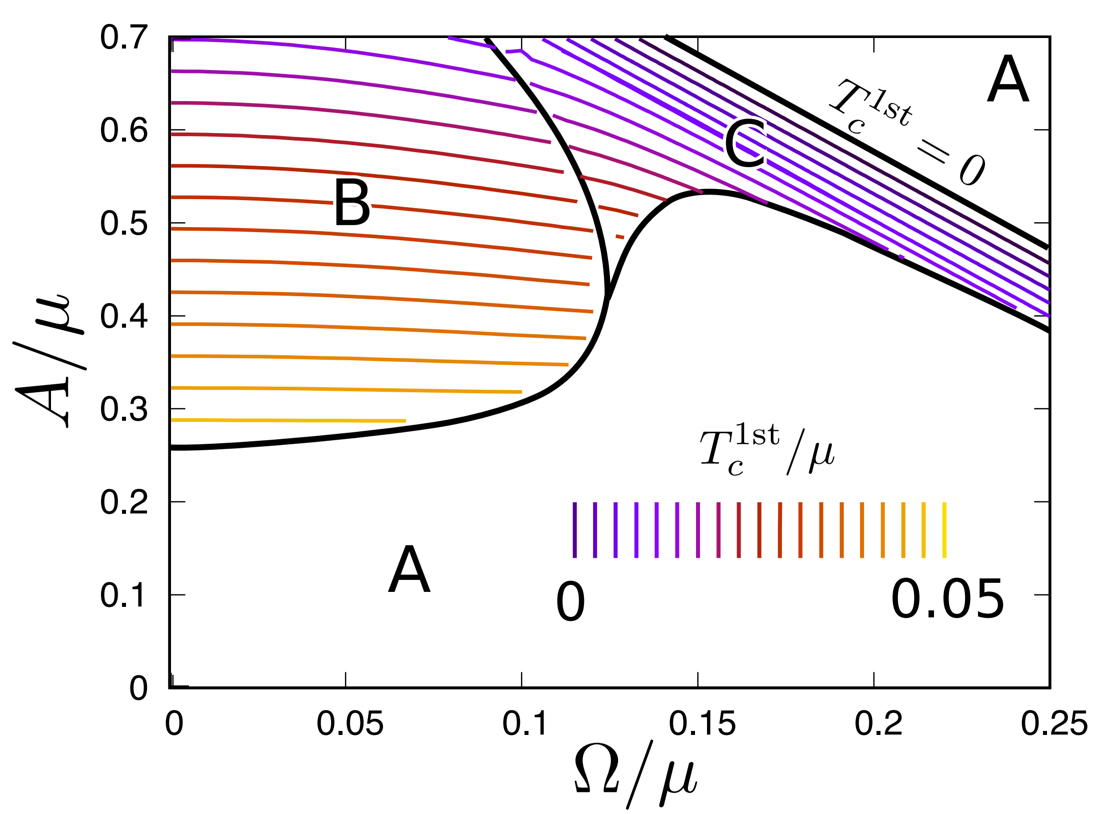
But δs_b does not behave as dF because of δs_h.

Therefore dF is not given by $-\delta s_b$.

Phase transition temperature

To reasonably estimate the temperature of the 1st order transition, we try

$$F := \int \rho d\mu$$



2nd order transition temperature in region A is not shown here.

Measurement of Microwave-Enhanced Energy Gap in Superconducting Aluminum by Tunneling*

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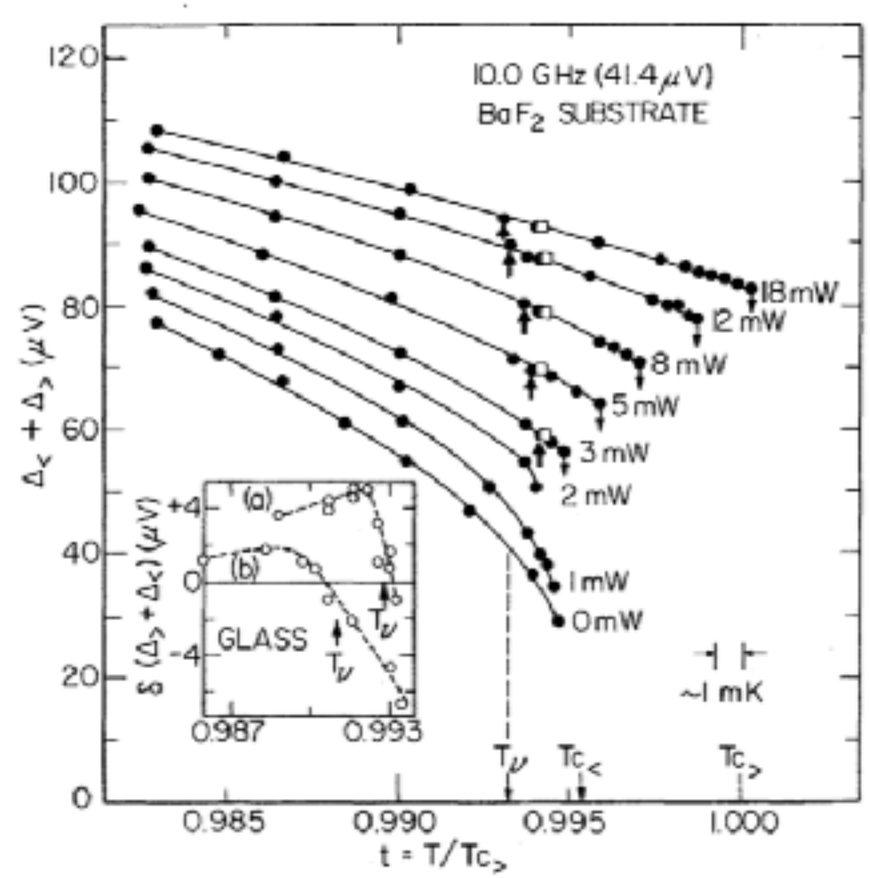
(Received 7 February 1977)

Al–Al_2O_3–Al tunnel junctions were used to measure large increases in the energy gap of superconducting aluminum films in the presence of 10–GHz microwave radiation. When

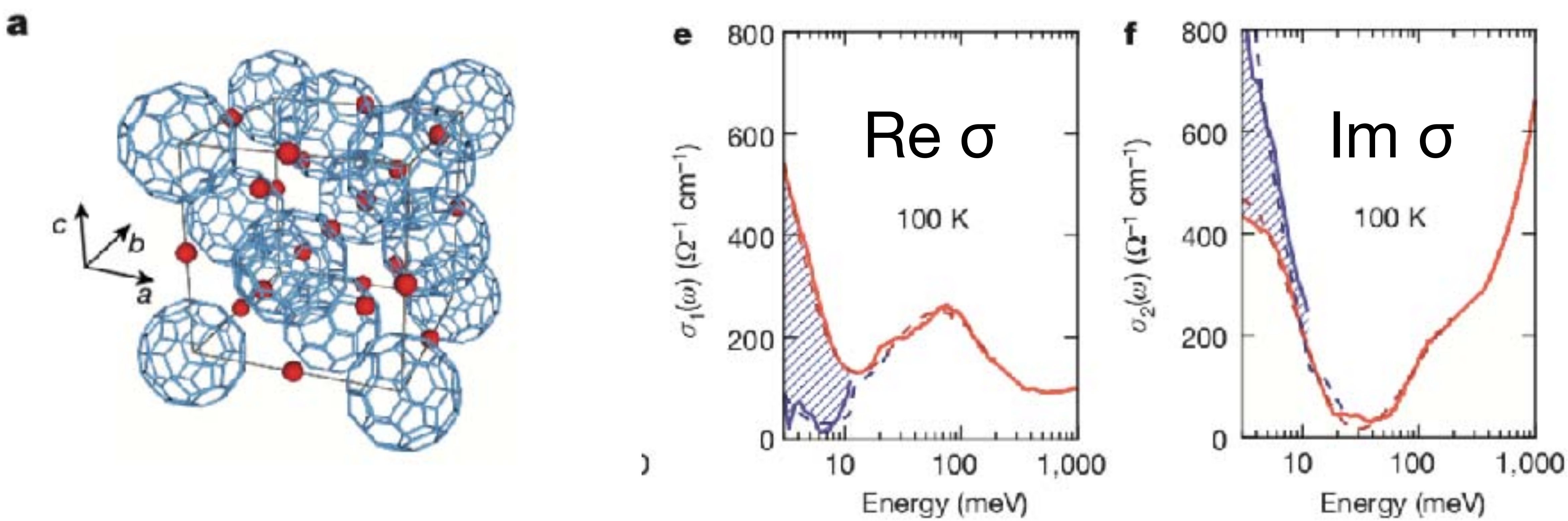


LETTER

doi:10.1038/nature16522

Possible light-induced superconductivity in K_3C_{60} at high temperature

M. Mitrano[1], A. Cantaluppi[1,2], D. Nicoletti[1,2], S. Kaiser[1], A. Perucchi[3], S. Lupi[4], P. Di Pietro[3], D. Pontiroli[5], M. Riccò[5], S. R. Clark[1,6,7], D. Jaksch[7,8] & A. Cavalleri[1,2,7]



LETTER

doi:10.1038/nature13875

Nonlinear lattice dynamics as a basis for enhanced superconductivity in $YBa_2Cu_3O_{6.5}$

R. Mankowsky[1,2,3]*, A. Subedi[4]*, M. Först[1,3], S. O. Mariager[5], M. Chollet[6], H. T. Lemke[6], J. S. Robinson[6], J. M. Glownia[6], M. P. Minitti[6], A. Frano[7], M. Fechner[8], N. A. Spaldin[8], T. Loew[7], B. Keimer[7], A. Georges[4,9,10] & A. Cavalleri[1,2,3,11]

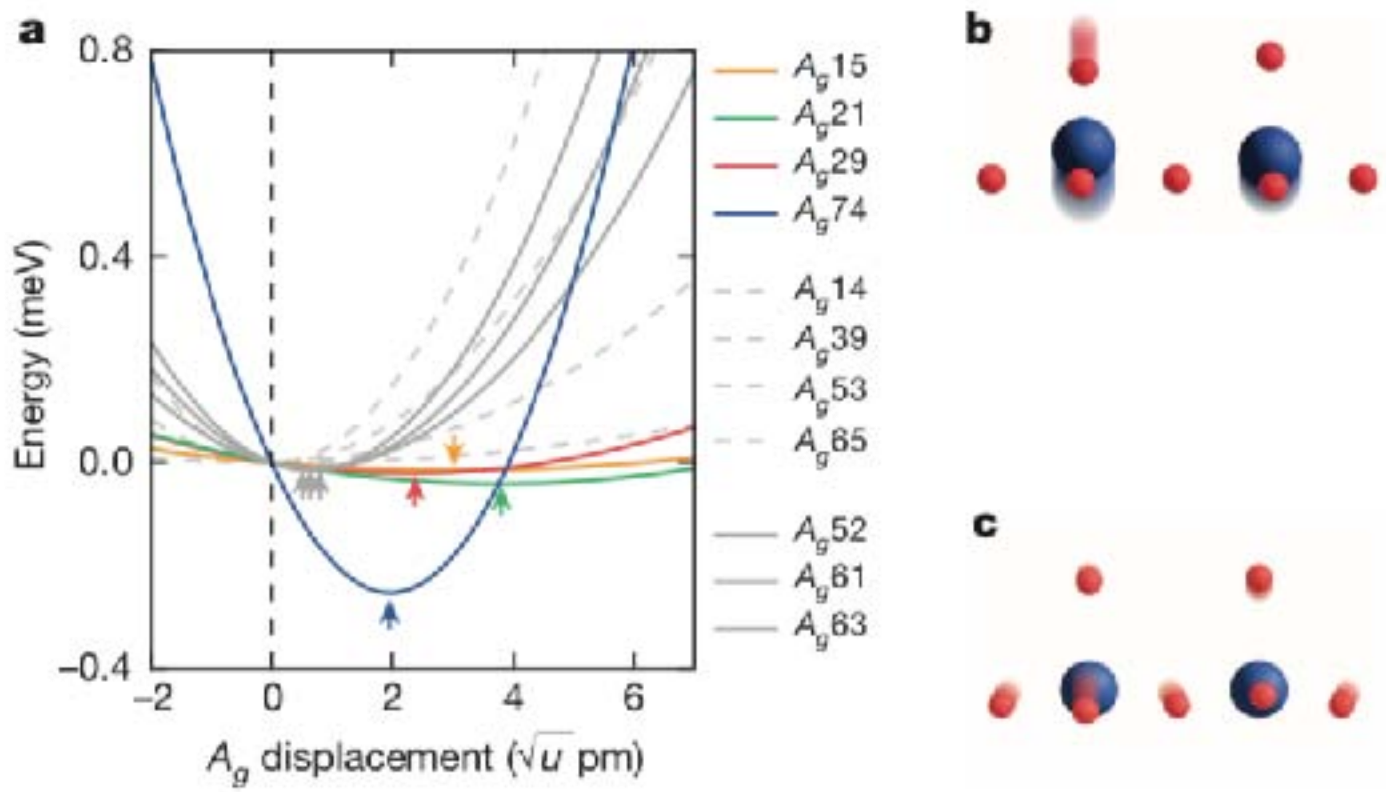


Figure 3 | First-principles calculations of cubic coupling between 11 A_g modes and the driven B_{1u} mode. **a**, Energy potentials of all A_g modes for a

Summary

We applyed a rotating electric field a to holographic superconducting model and constructed a superconducting steady state.

Nonequilibrium "thermodynamics" (free energy) for quantifying phase transition is challenging.

Future plan

Vortex formation, turbulence, boson star.

How to enhance SC, lattice structure.