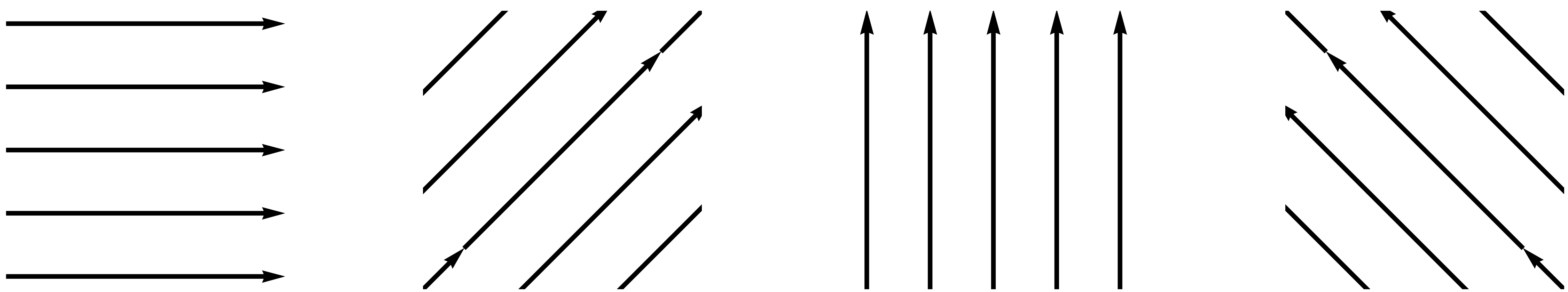
Utrecht University

Floquet Superconductor in Holography



Takaaki Ishii (Utrecht)

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

4 July 2018, HoloQuark2018 @ Santiago de Compostela

Motivations

Holography in time dependent systems

Nonequilibrium phenomena, nonlinear dynamics

e.g.) QGP, quench, thermalization

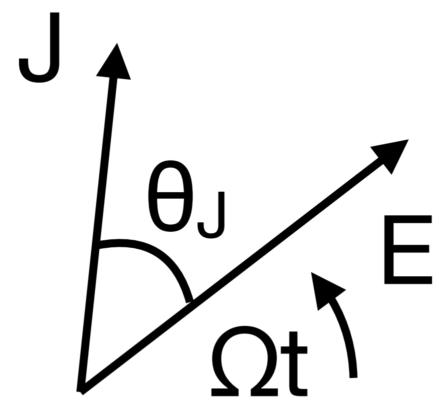
Condensed matter in real world

Driving, laser-pulse, nonequilibrium states

e.g.) ARPES, superconductivity enhancement

Rotating electric field

We apply a circularly polarized electric field



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

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

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

Amplitude is fixed, only direction changes: $|\vec{E}| = |E|$

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

Rotating holography

Complex scalar with phase rotation $\phi \sim \phi_0 e^{i\Omega t} + \cdots$

[Biasi-Carrecedi-Mas-Musso-Serantes]

c.f.) Spontaneous rotation: Boson star

[Astefanesei-Radu, Buchel-Liebling-Lehner]

D3/D7+rotating cpx scalar for CME

[Hoyos-O'Bannon-Nishioka]

D3/D7+rotating electric field $A_x + iA_y = A(z)e^{i\Omega t}$

[Hashimoto-Kinoshita-Murata-Oka]

↑Murata's talk

Review: holographic superconductor

The simplest probe model in Sch-AdS4 BH:

[Hartnoll-Herzog-Horowits]

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

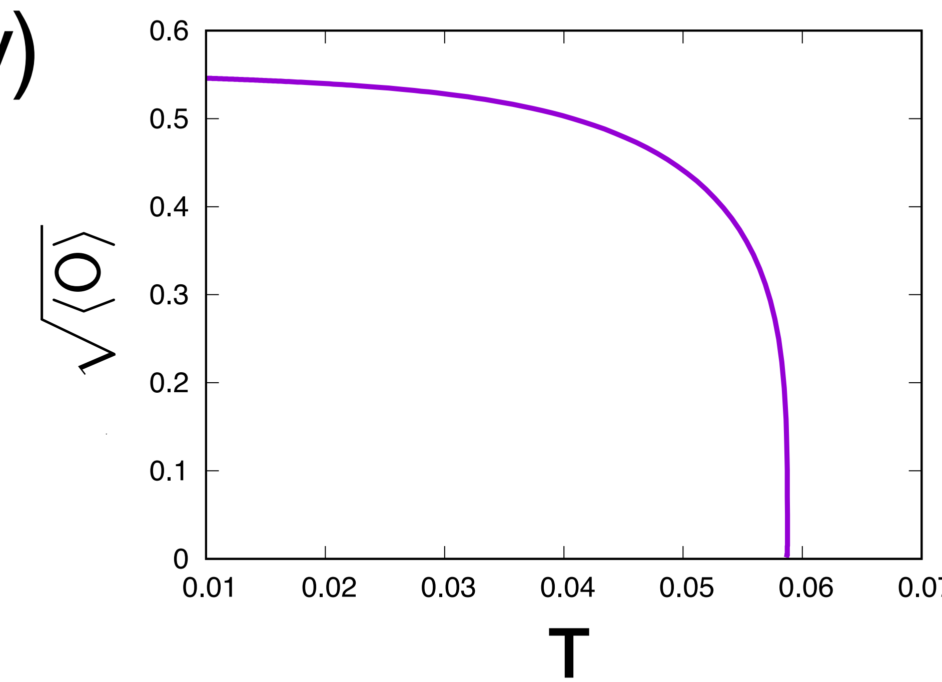
$$ds^2 = \frac{1}{z^2} \left(-f(z)dt^2 + \frac{dz^2}{f(z)} + dx^2 + dy^2 \right)$$

U(1) charge (we use μ=1 today)

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

Spontaneous condensation

$$\Psi(z) = \psi_2 z^2 + \cdots \neq 0$$



We add the rotating gauge field

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

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

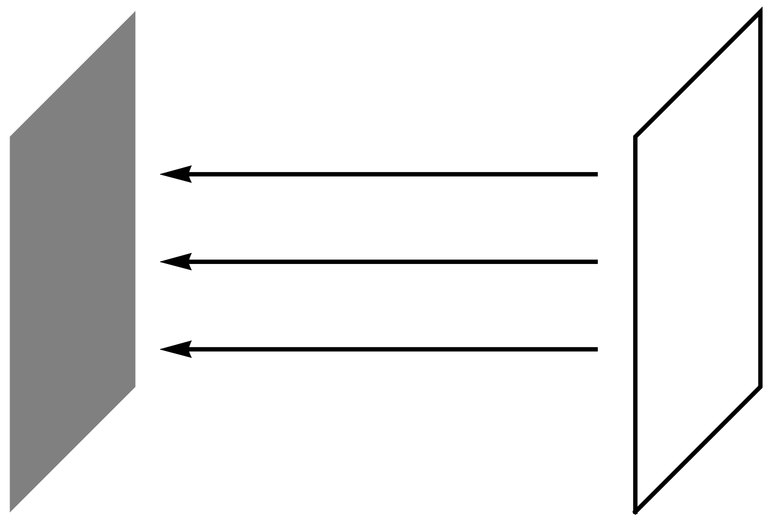
Then time dependence disappears: we get ODEs.

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

Source and current in $A_{x,y}$: $b(z) = A + Jz + \cdots$

Holographic steady state

BH is like heat bath in probe models



Conserved flux (in the holographic direction)

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

This gives Joule heating for normal conductor

$$q = \Omega J_\theta = \vec{E} \cdot \vec{J}$$

Review: Ω=0

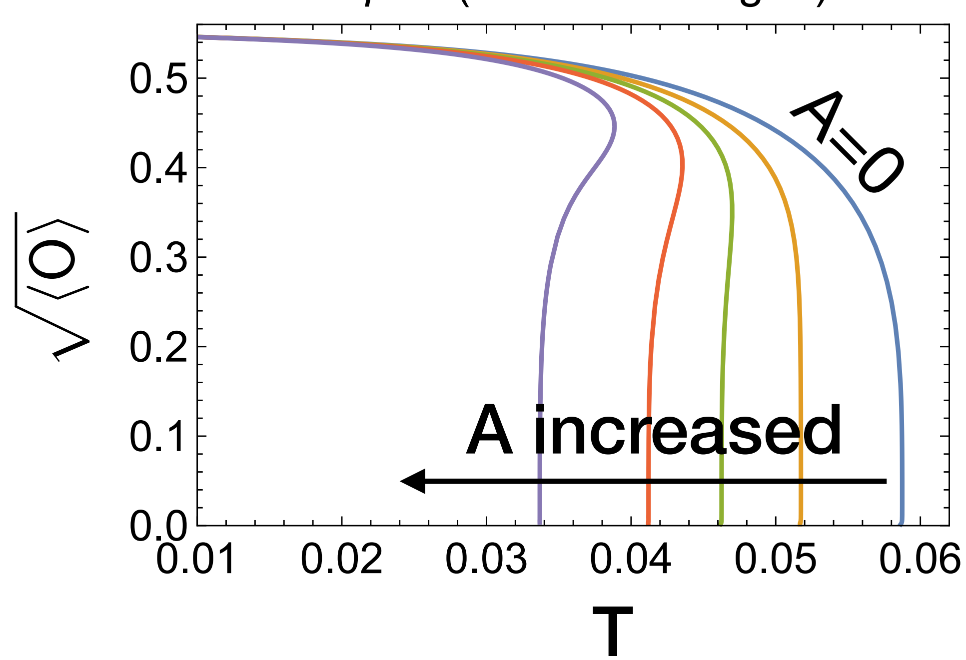
This is constant gauge potential for superfluid velocity.

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

In our setup: (E,Ω)→0 with A=E/Ω fixed

Phase transition changes from 2nd to 1st order.

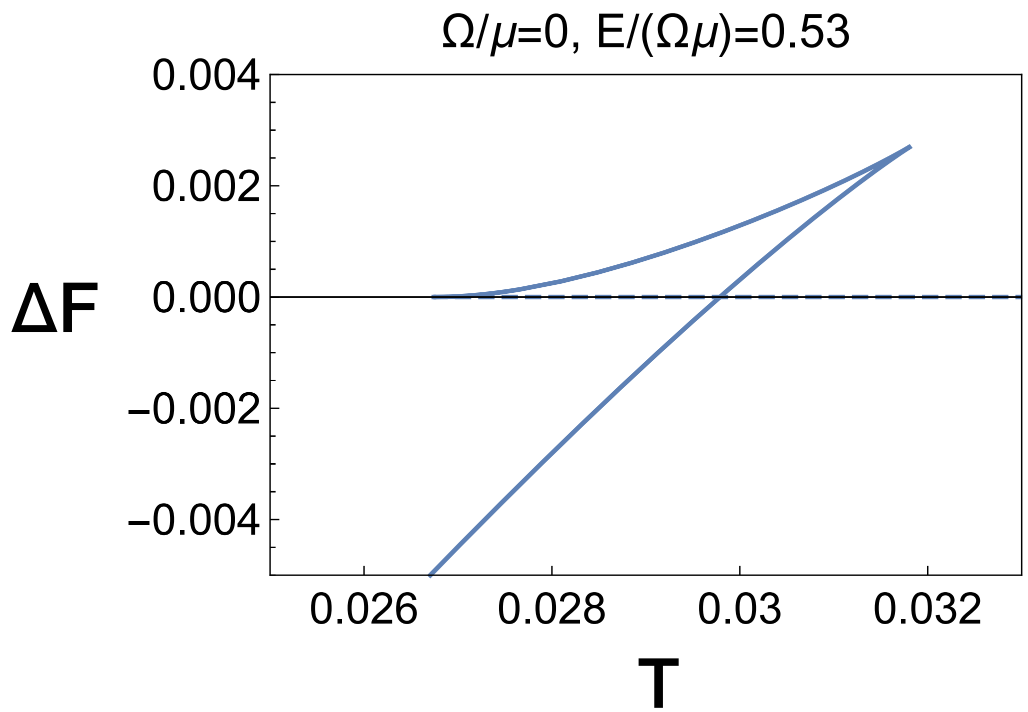
Ω/μ=0 (0809.4870 Fig2b)



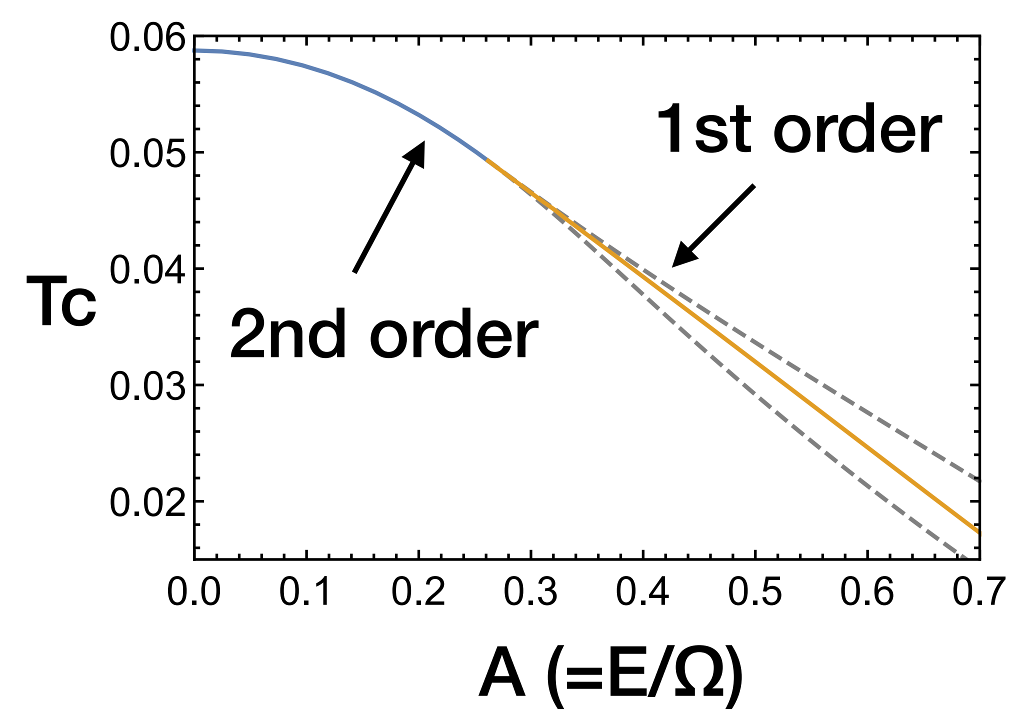
Free energy for Ω=0

"Free energy is the minus of on-shell action."

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

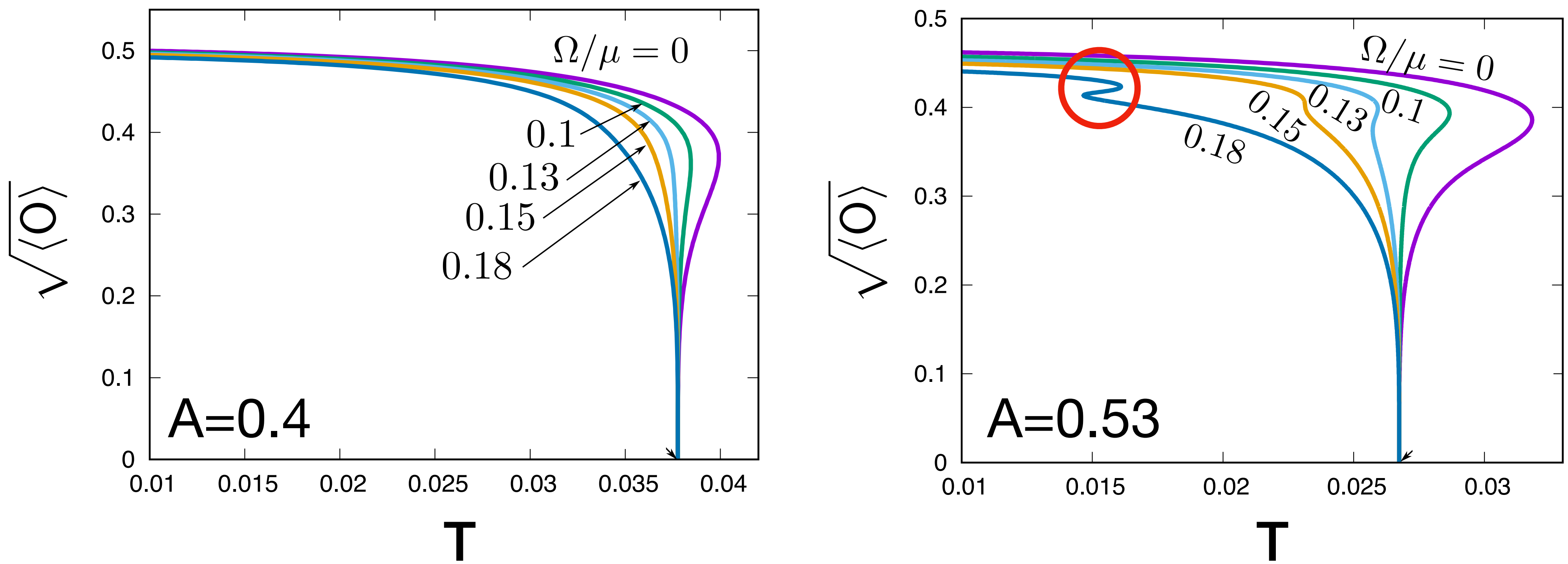


"Swallow tail" for 1st order PT



Tc always decreases

When Ω≠0

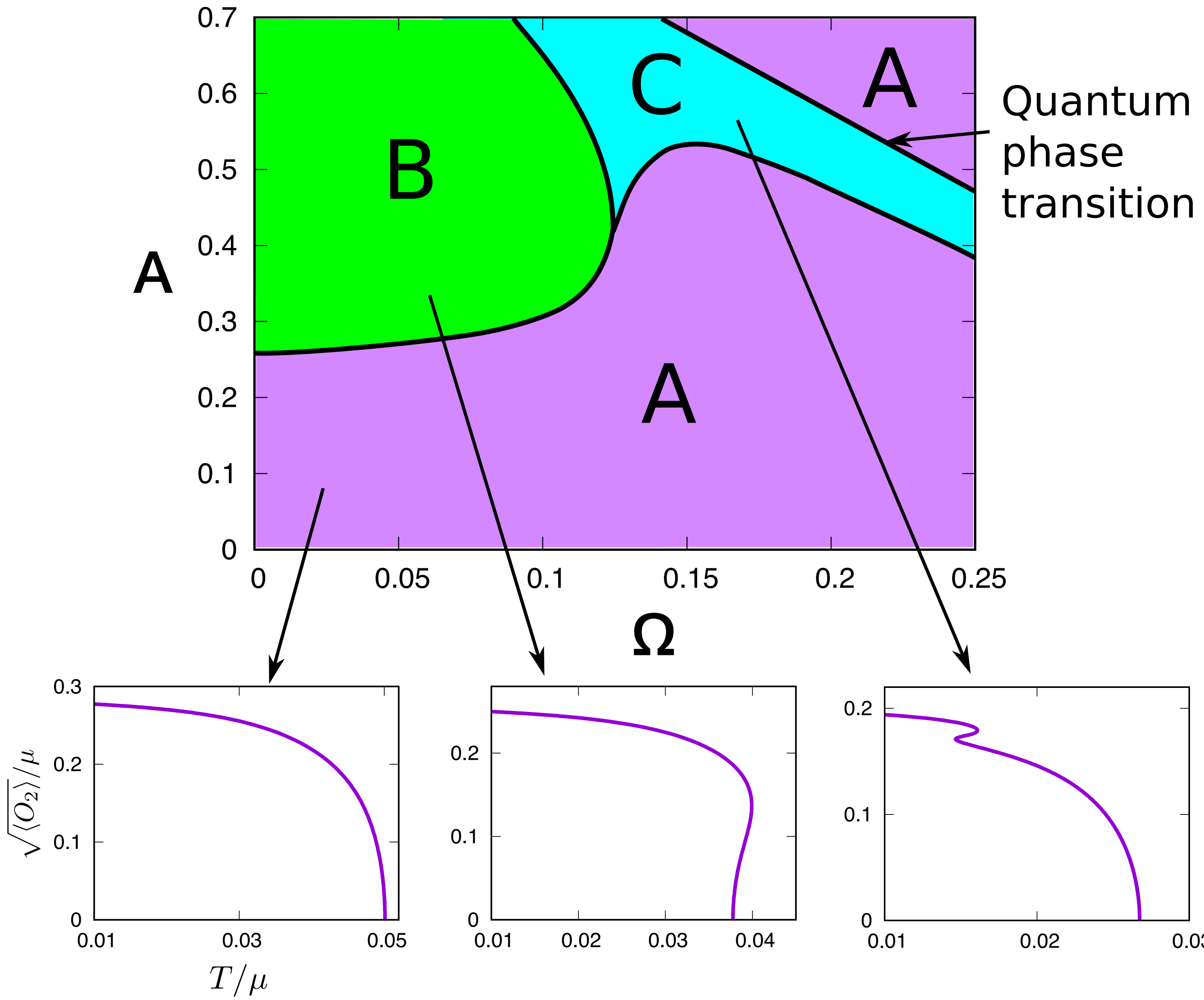


Normal-to-SC transition is pushed back to 2nd order.

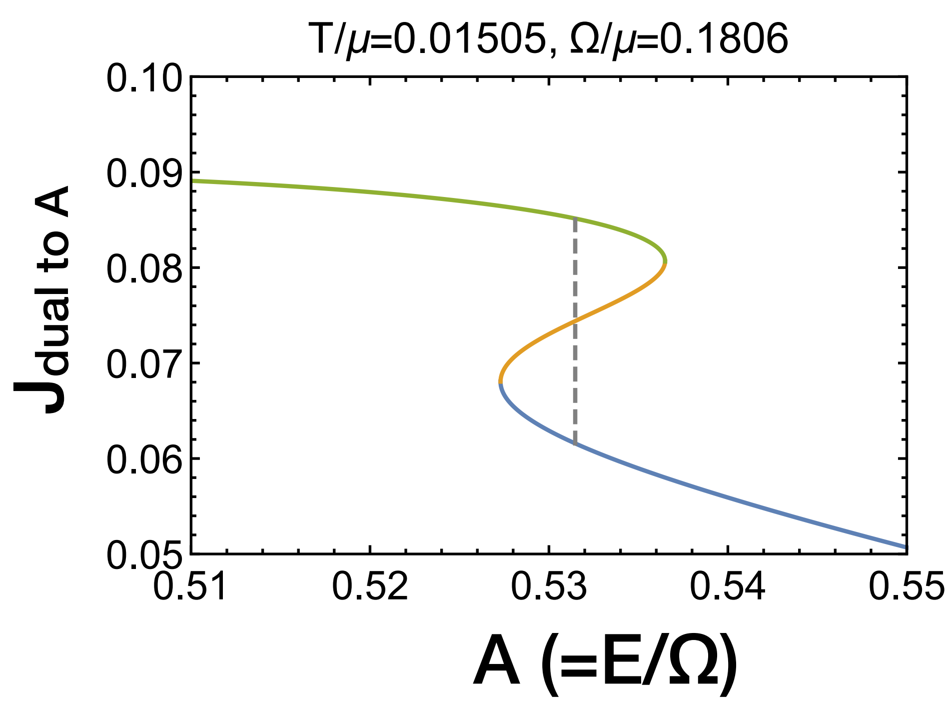
There appears spinodal structure inside the SC phase.

This indicates 1st order (phase) transition.

Phase diagram



Evaluate phase transition when Ω≠0?



Order parameters will "jump" in the spinodal region.

Where do they actually jump?

Can I use Maxwell construction (aka "equal area law")?

Ω=0 revisited

Free energy can be given in the 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 is satisfied: $\dfrac{\partial \rho}{\partial \vec{A}} = \dfrac{\partial \vec{J}}{\partial \mu}, \quad \dfrac{\partial}{\partial \vec{A}} \times \vec{J} = 0$

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

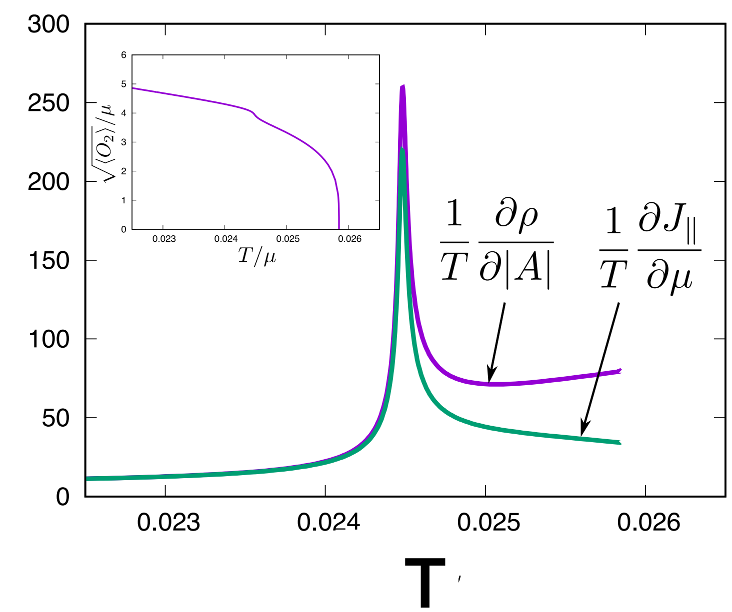
Free energy for Ω≠0?

Do we have nonequilibrium thermodynamics in which there is dF satisfying $dF = -\rho d\mu - \vec{J}\cdot d\vec{A} + \cdots$?

A: No

Integrability is violated:

$$\frac{\partial \rho}{\partial \vec{A}} \neq \frac{\partial \vec{J}}{\partial \mu}, \qquad \frac{\partial}{\partial \vec{A}} \times \vec{J} \neq 0$$



The violation is small when the Joule heating q is small.

Is anything wrong with our sources/vevs?

AdS/CFT dictionary revisited

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

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

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

Real-time AdS/CFT dictionary

Field theory quantities are derived from δs_b.

We have $A_t(z) = \mu - \rho z + \cdots$ $b(z) = A + Jz + \cdots$

Then δs_b is not an integrable dF because of δs_h.

So there is difficulty

AdS/CFT dictionary gives how to calculate VEVs (ρ,J,...) in nonequilibrium ...from δs_b. We believe it.

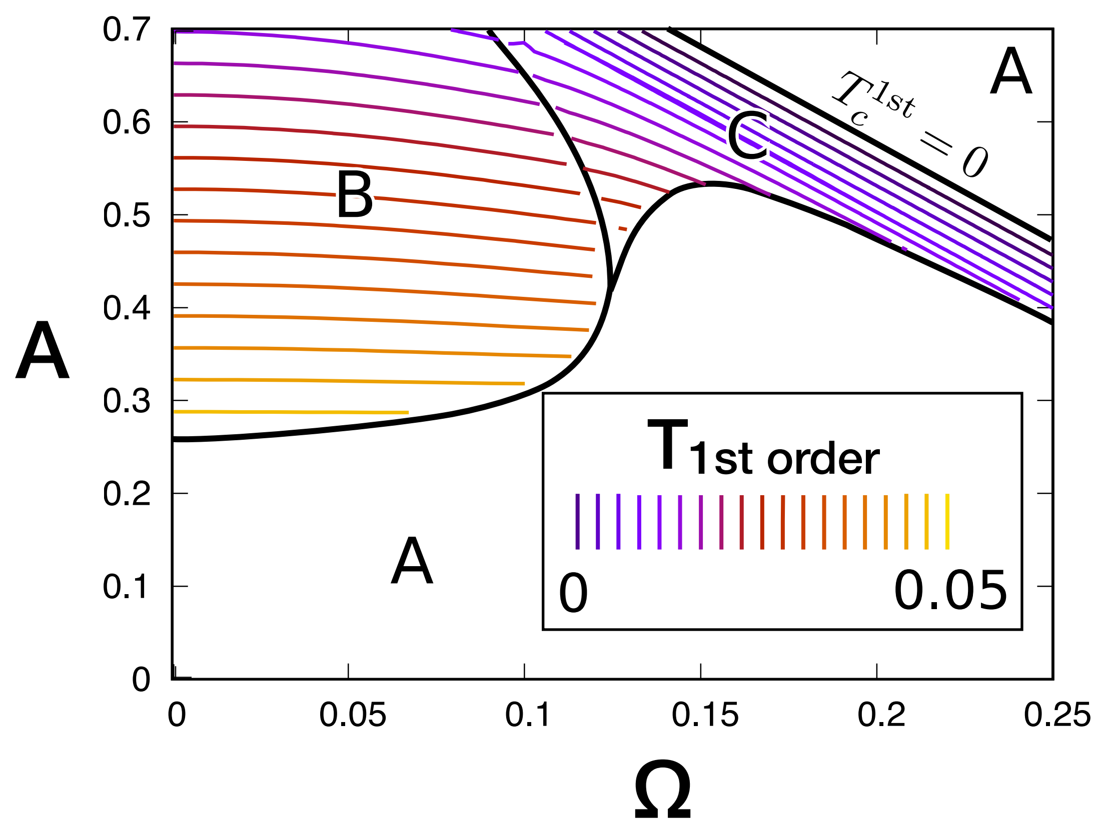
Then we do not have integrable dF for nonequilibrium steady solutions.

Should we have defined (ρ,J,...) such that we had $dF = -\rho d\mu - \vec{J}\cdot d\vec{A} + \cdots$? Probably No.

But anyway we can estimate $T_{1st\ order}$

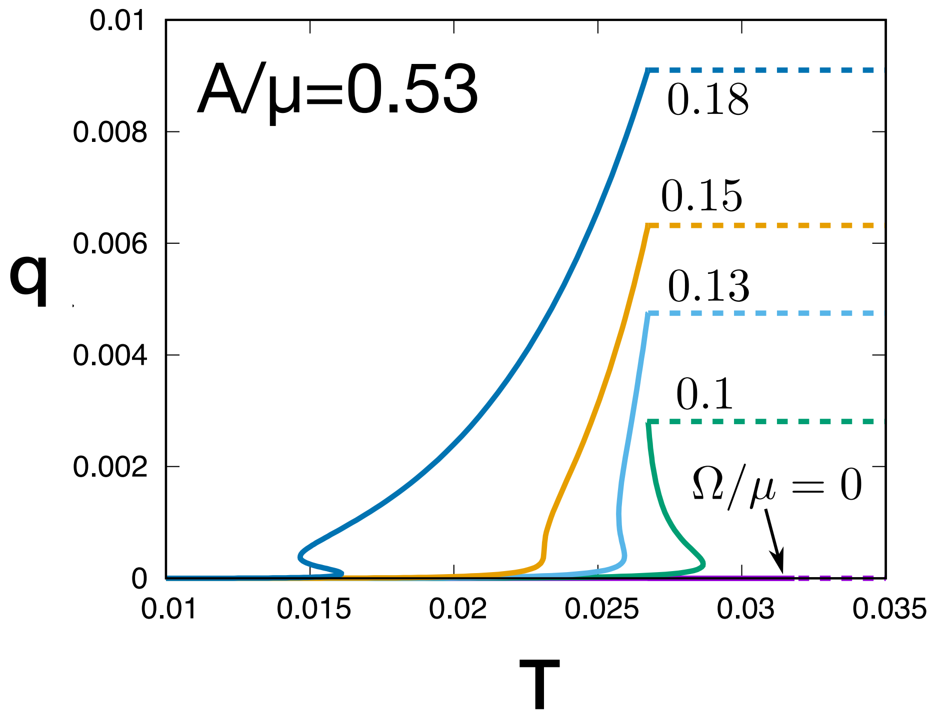
We employ a reasonable choice realizing the "swallow tail" for 1st order phase transition

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

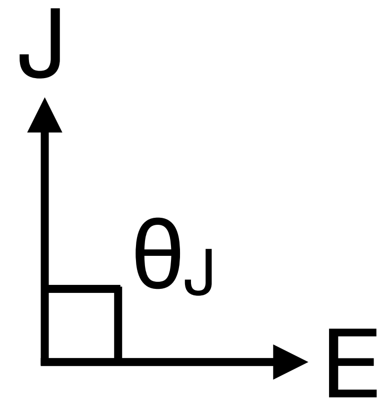


(2nd order Tc in region A is not shown)

Current: E and J get out of phase



$$q = \vec{E} \cdot \vec{J} \to 0$$



Joule heating is suppressed: no Ohm's law

Instead we have E⊥J: London equation

Discussion

Superconductivity enhancement is one of our motivations.

But in our results Tc for superconducting phase transition is always lowered by the electric field.

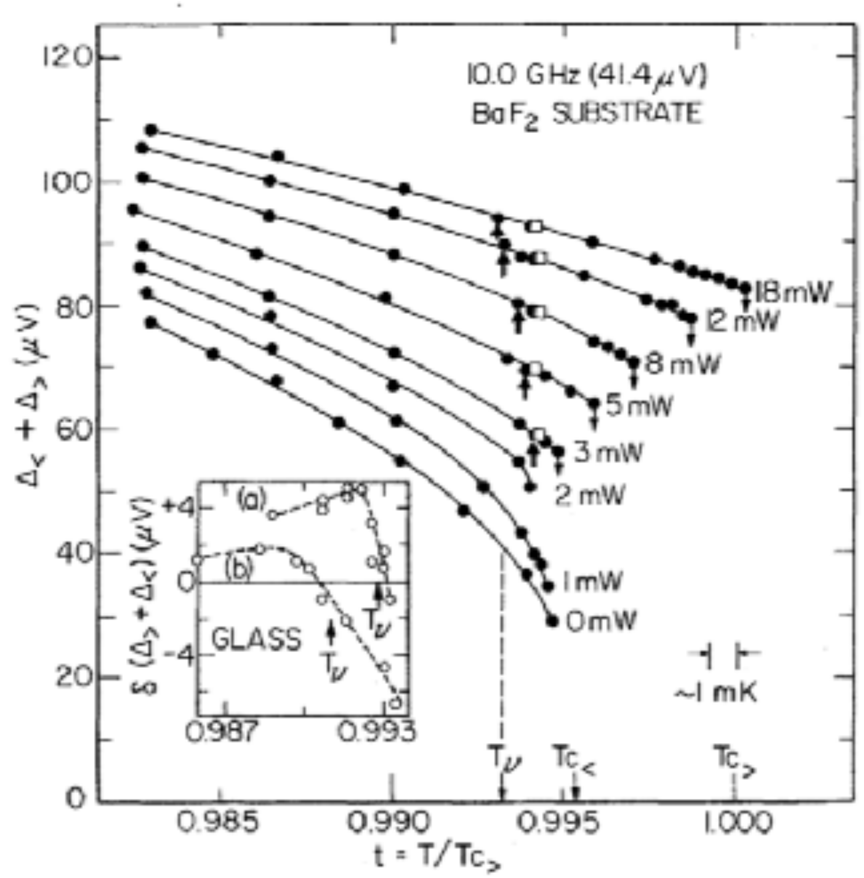
This might be due to our model being too simple.

What will/can/need to be done?

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

Tom Kommers and John Clarke
Department of Physics, University of California, and Materials and Molecular Research Division, Lawrence Berkeley Laboratory, Berkeley, California 94720
(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

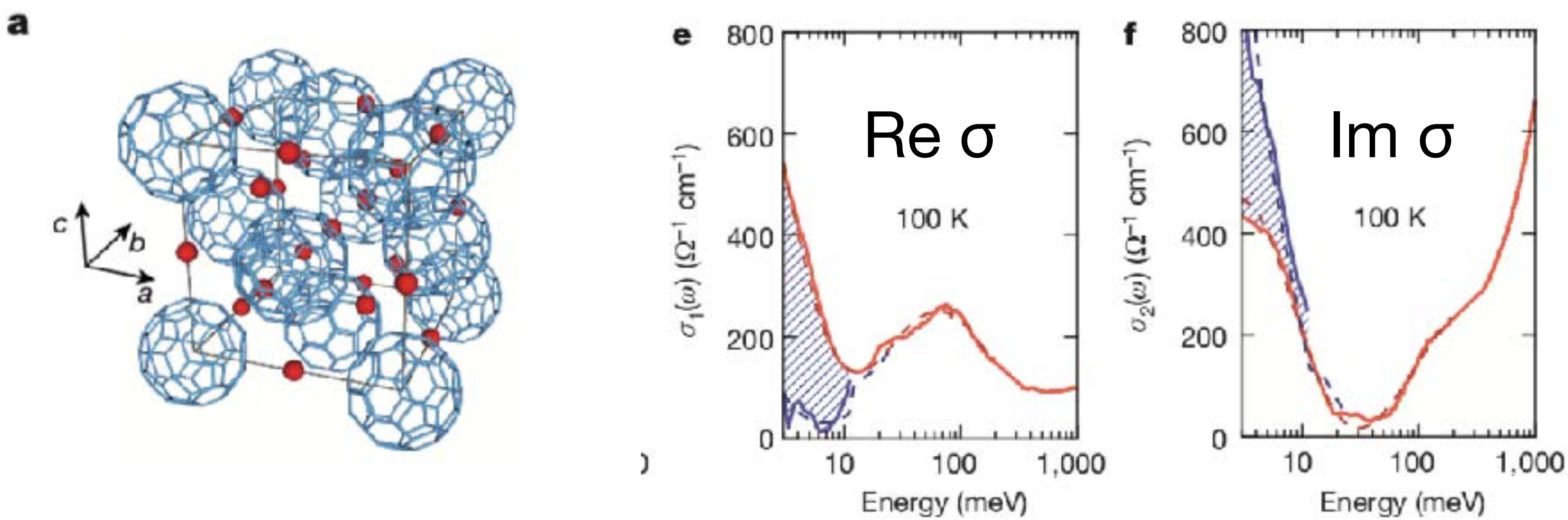


LETTER

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]

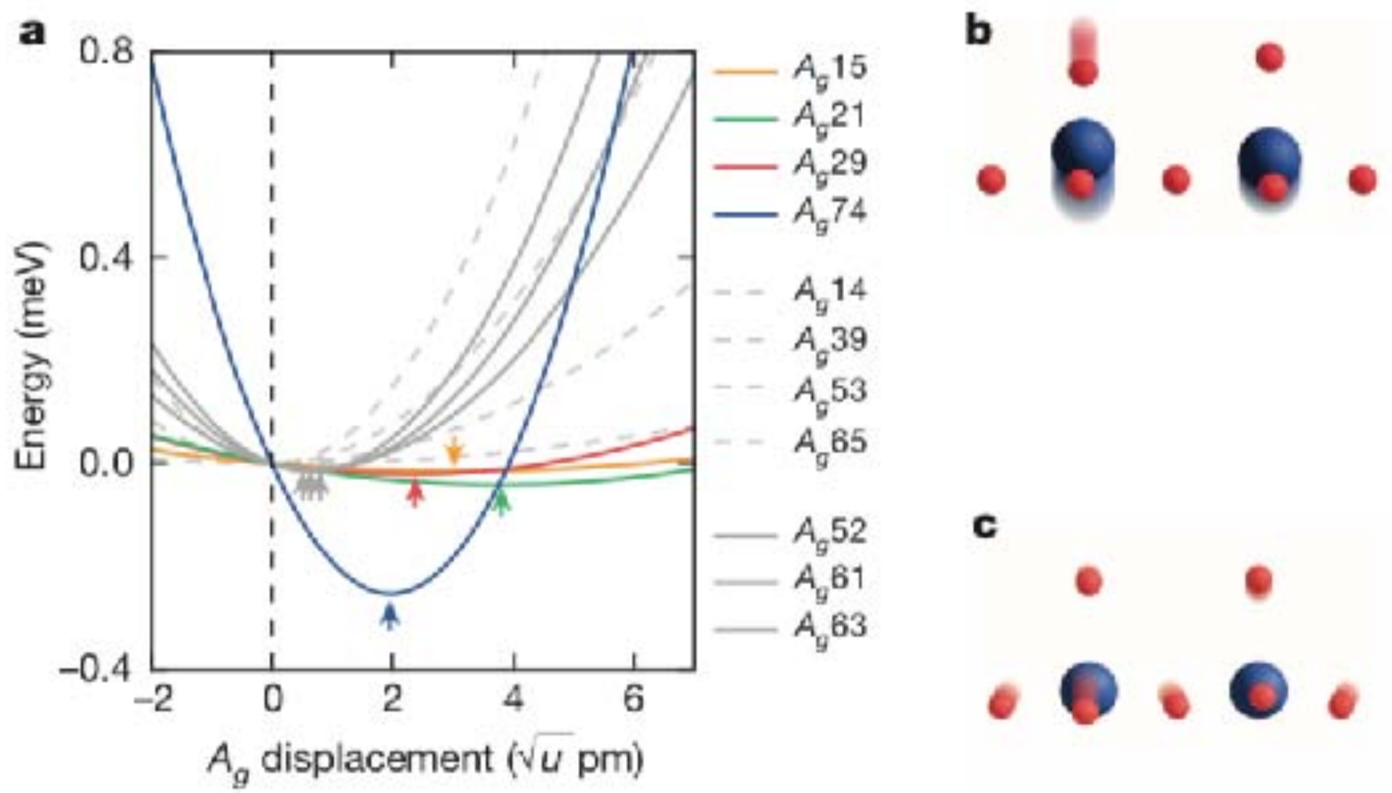


Figure 3 | First-principles calculations of cubic coupling between 11 A_g modes and the driven B_{1u} mode. **a**, Energy potentials of all A_g modes for a

Summary

We applied a rotating electric field to holographic superconductors.

We obtained steady state solutions.

We discussed nonequilibrium "thermodynamics."

Many things to do before HoloQuark2020

backreaction, photon stars; vortex formation, turbulence; SC enhancement, lattices, ...