Hybridization and enhancement processes in quasi-two-dimensional superconductors

Zachary M. Raines

Ph.D. Defense

April 22nd, 2019

CMTC

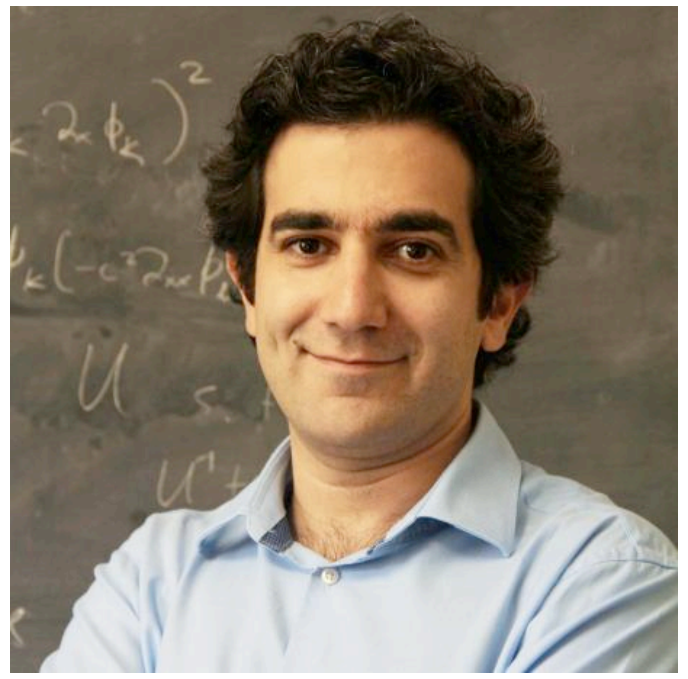
University of Maryland 1856

Joint Quantum Institute

Collaborators

Victor Galitski

Mohammad Hafezi



Valentin Stanev

Andrew Allocca

Jonathan Curtis

Works in this dissertation

Chapter 2

- **ZMR**, Stanev, V. G. & Galitski, V. M., *Enhancement of superconductivity via periodic modulation in a three-dimensional model of cuprates*. Phys. Rev. B 91, 184506 (2015).

- **ZMR**, *Phase pinning and interlayer effects on competing orders in cuprates*. arXiv:1809.06879

Chapter 3

- **ZMR**, Stanev, V. G. & Galitski, V. M., *Hybridization of Higgs modes in a bond-density-wave state in cuprates*. Phys. Rev. B 92, 184511 (2015).

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- Curtis, J. B., **ZMR**, Allocca, A. A., Hafezi, M. & Galitski, V. M., *Cavity Quantum Eliashberg Enhancement of Superconductivity*. In Press, PRL.

Chapter 5

- Allocca, A. A., **ZMR**, Curtis, J. B. & Galitski, V. M. *Cavity superconductor-polaritons*. Phys. Rev. B 99, 020504(R), (2019).

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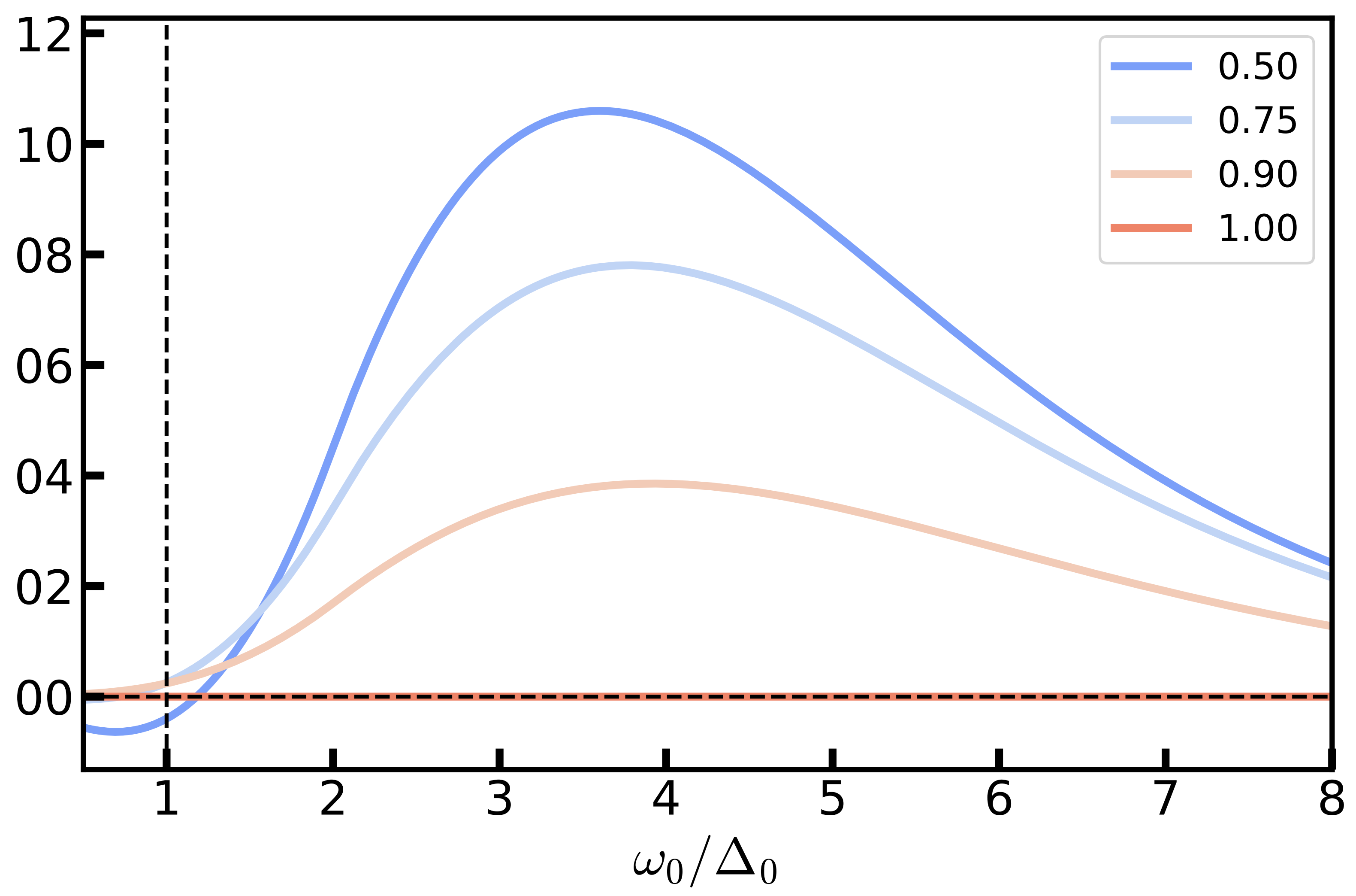
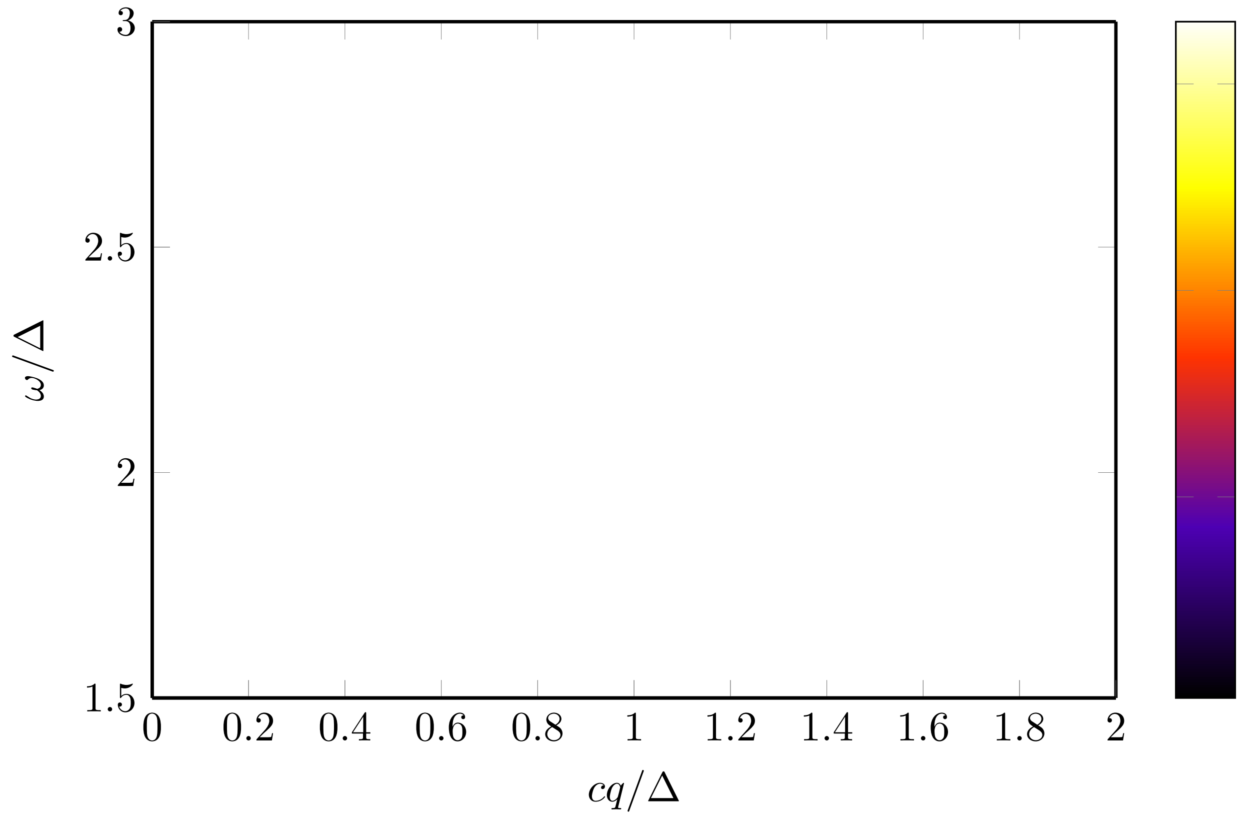
Chapter 5

Preview

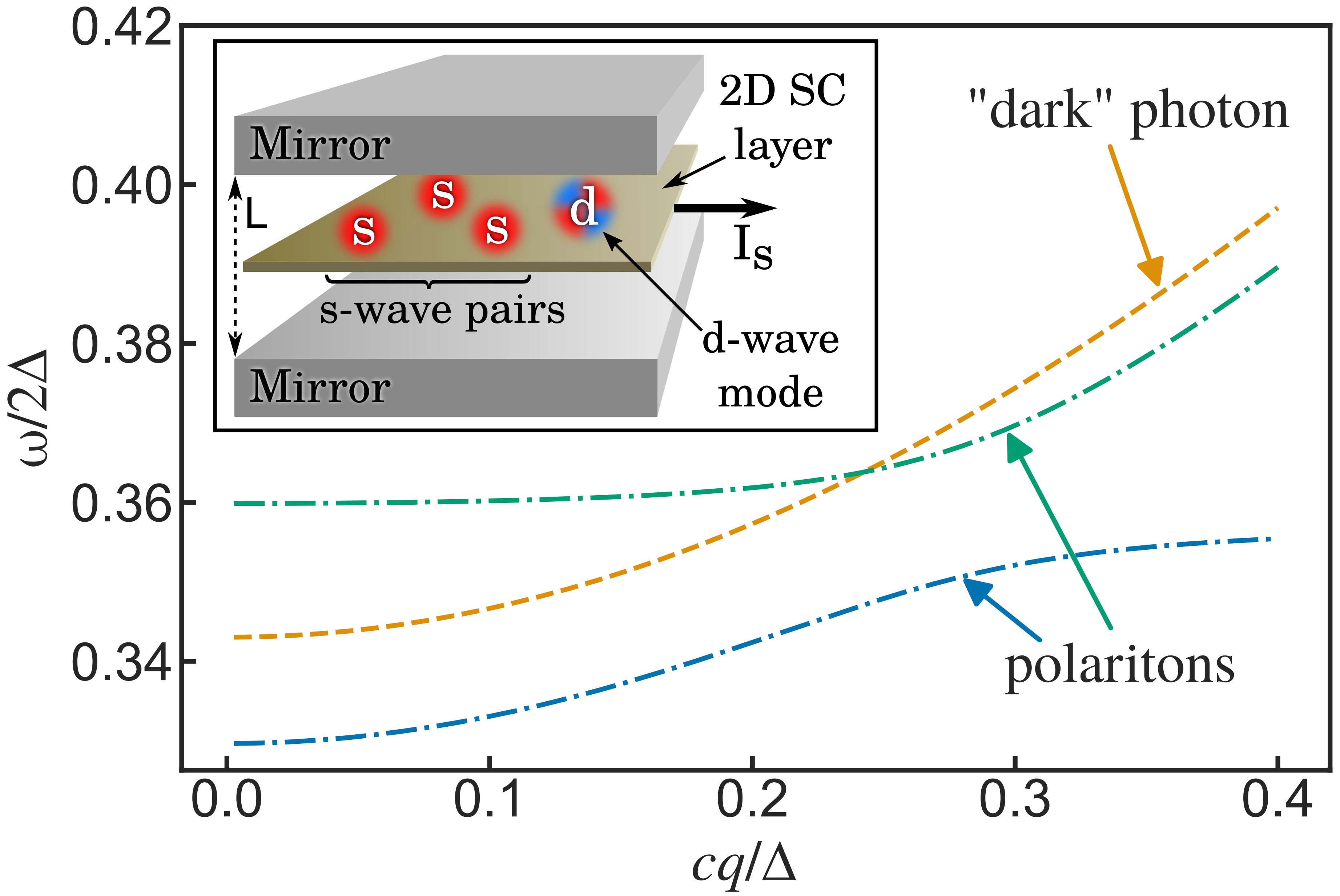


Cavity enhancement of superconductivity



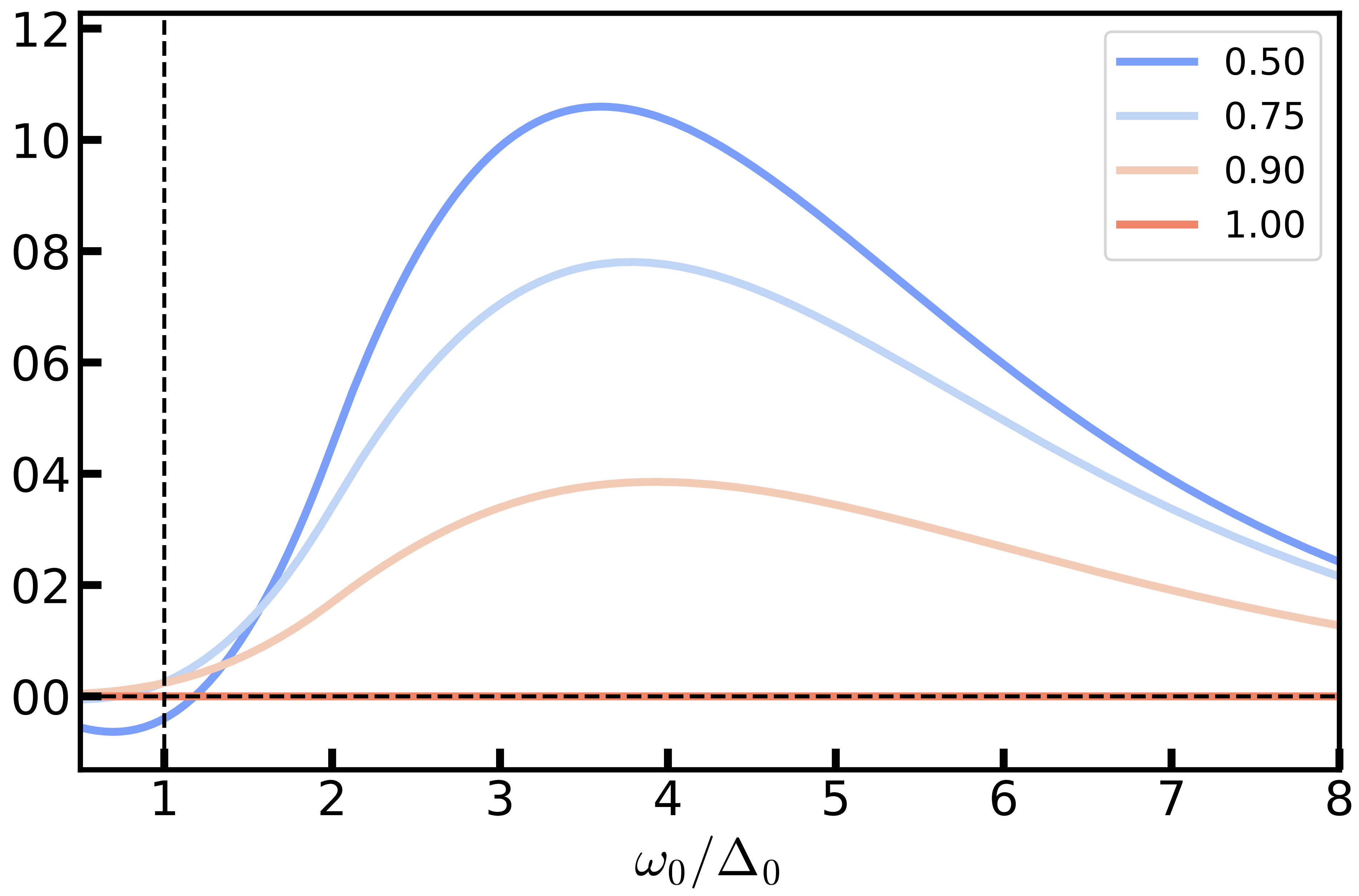
Higgs Polaritons

Bardasis-Schrieffer Polaritons



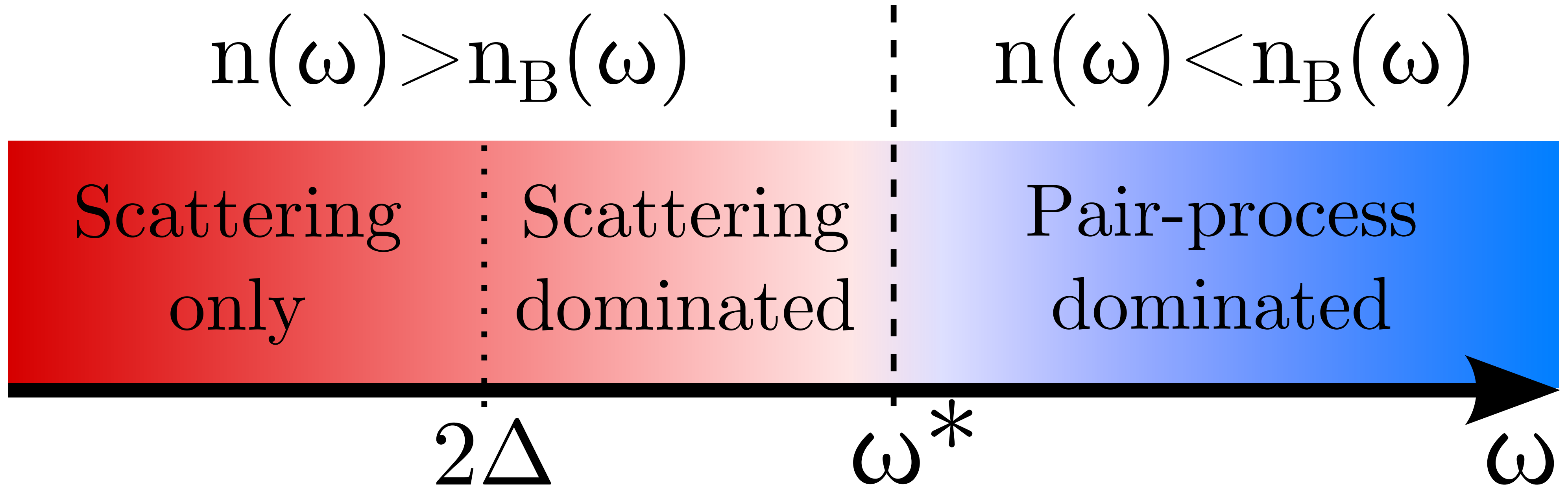
Coupling superconductors to cavity photons allows us to investigate interesting problems

Preview



Cavity enhancement of superconductivity

Superconductivity can be enhanced by coupling to a suitably engineered photonic cavity

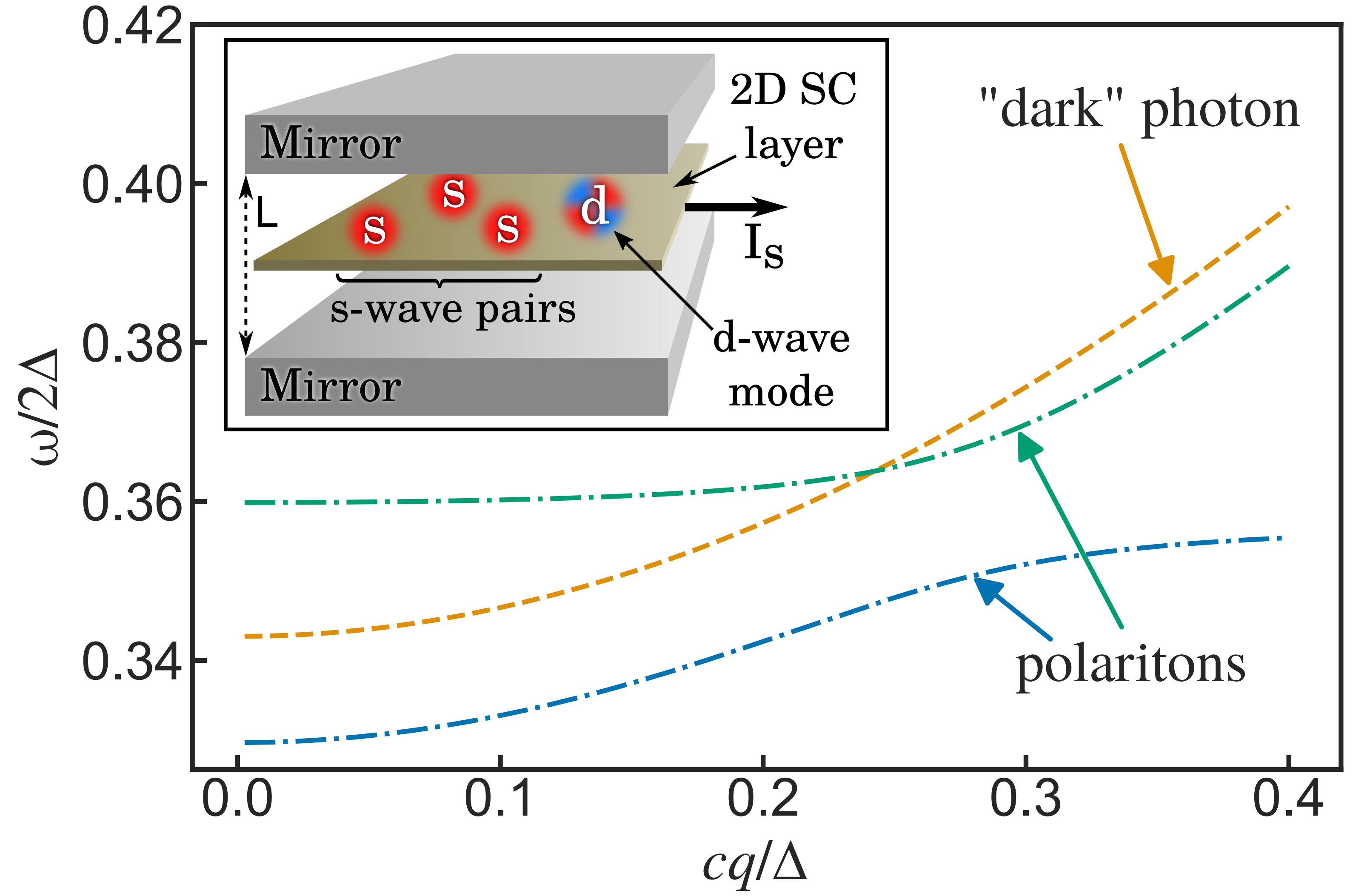


Preview

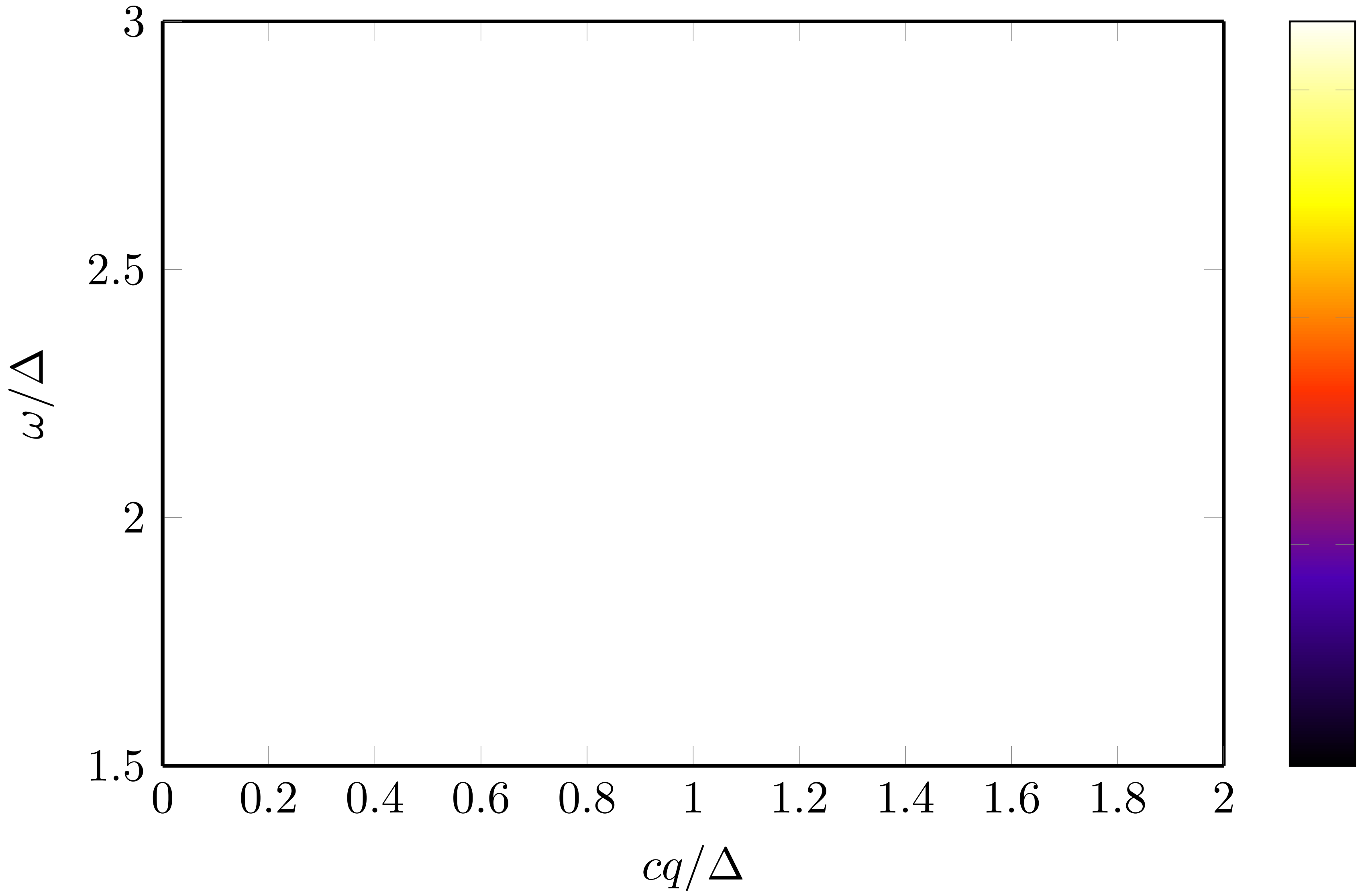
A cavity with a supercurrent-bearing superconductor can host hybrid excitations formed from *photons* and the superconductor's *collective modes*

Condensation of these objects may allow for the realization of interesting new states at high temperatures

Bardasis-Schrieffer Polaritons



Higgs Polaritons



Outline

- **Chapter 4 - Cavity Quantum Eliashberg Enhancement of Superconductivity**
    - Curtis, J. B., **ZMR**, Allocca, A. A., Hafezi, M. & Galitski, V. M. In Press, PRL.
- **Chapter 5 - Cavity superconductor-Polaritons**
    - Allocca, A. A., **ZMR**, Curtis, J. B. & Galitski, V. M., Phys. Rev. B 99, 020504(R), (2019).
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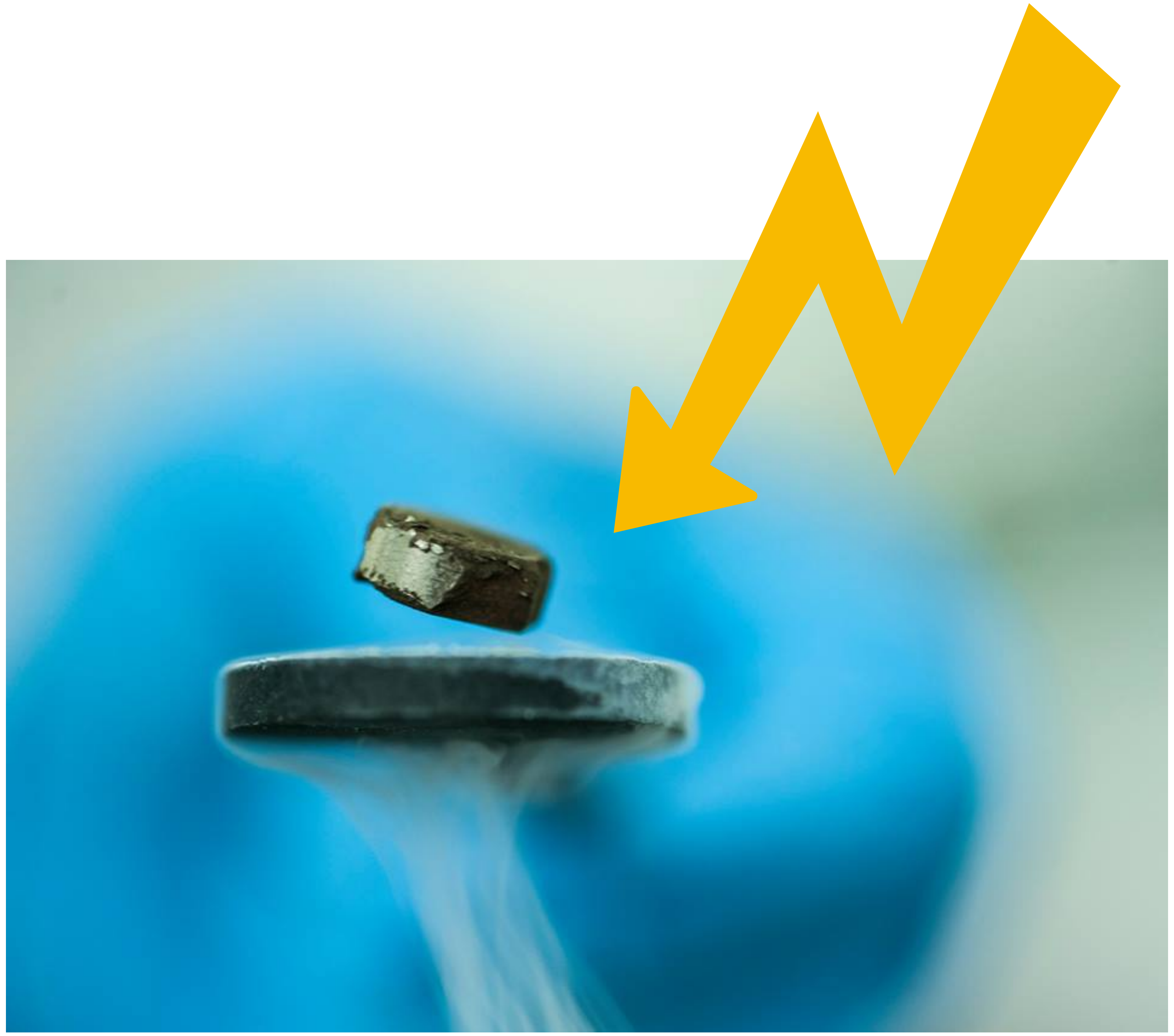
What happens to a superconductor under microwave irradiation?



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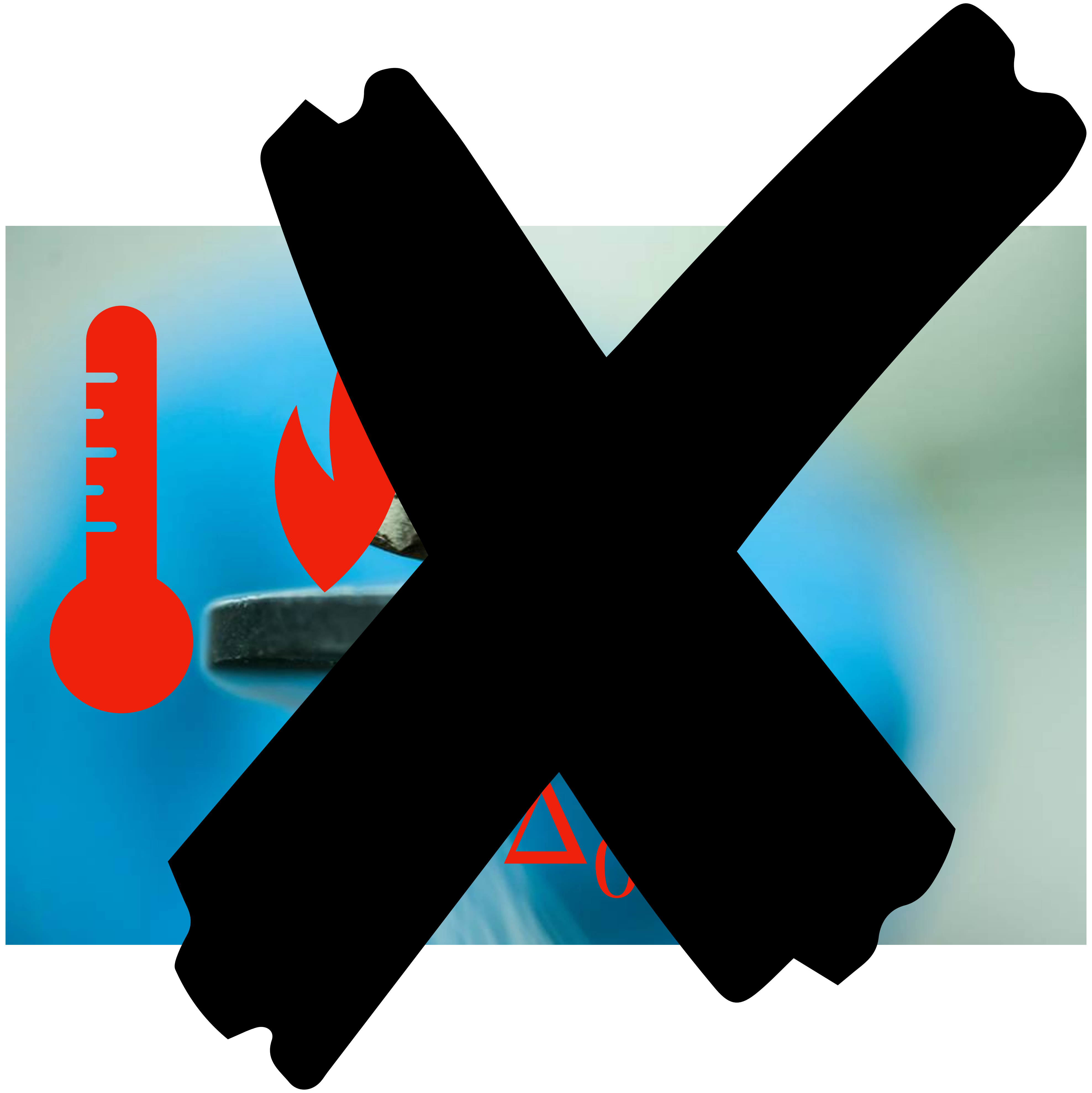


?

What happens to a superconductor under microwave irradiation?

PHYSICAL REVIEW B VOLUME 20, NUMBER 3 1 AUGUST 1979

Measurements of microwave-enhanced superconductivity in aluminum strips

J. A. Pals and J. Dobben
Philips Research Laboratories, Eindhoven, The Netherlands

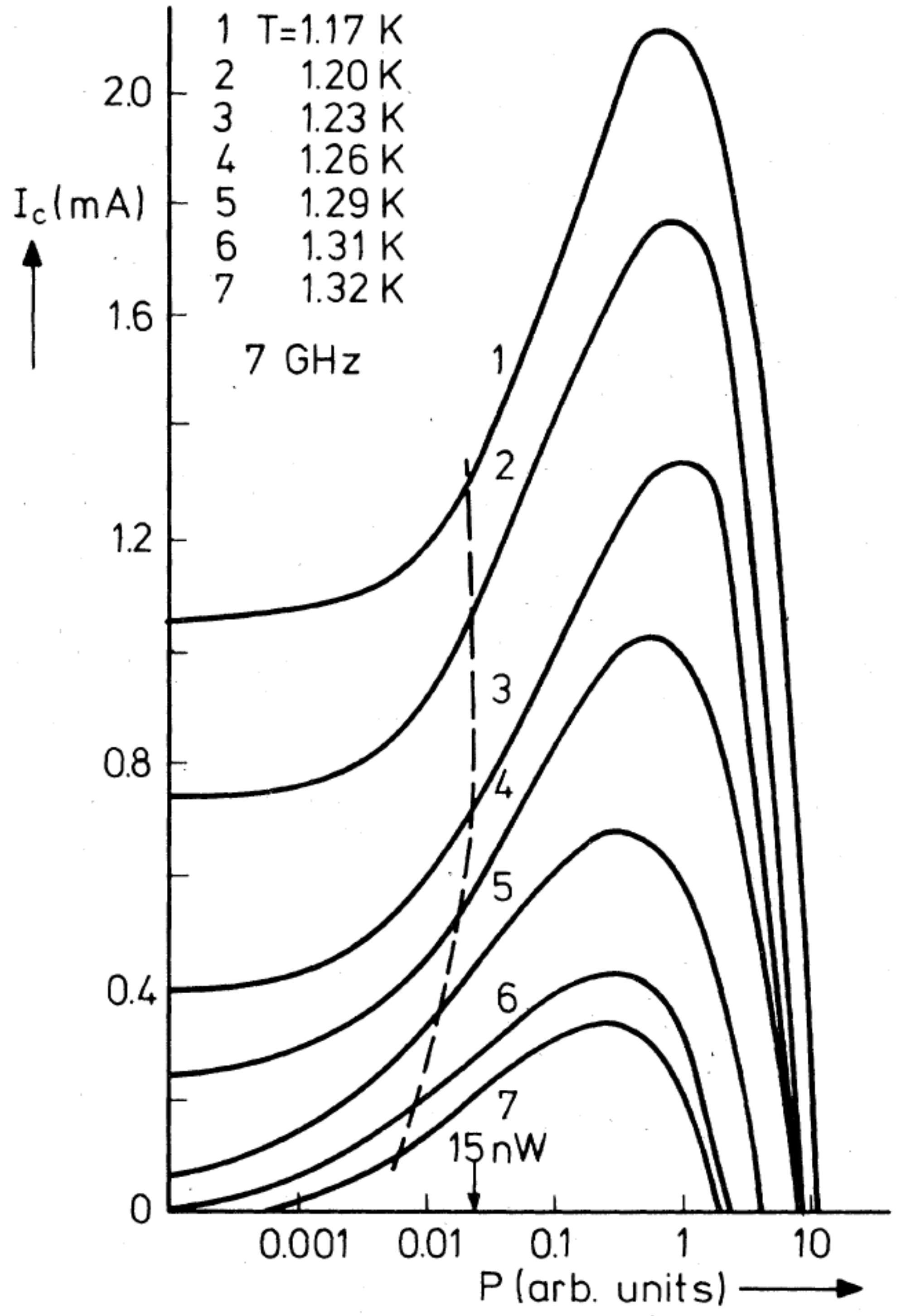


FIG. 2. Critical current I_c as a function of 7 GHz microwave power P with the temperature T of the helium bath

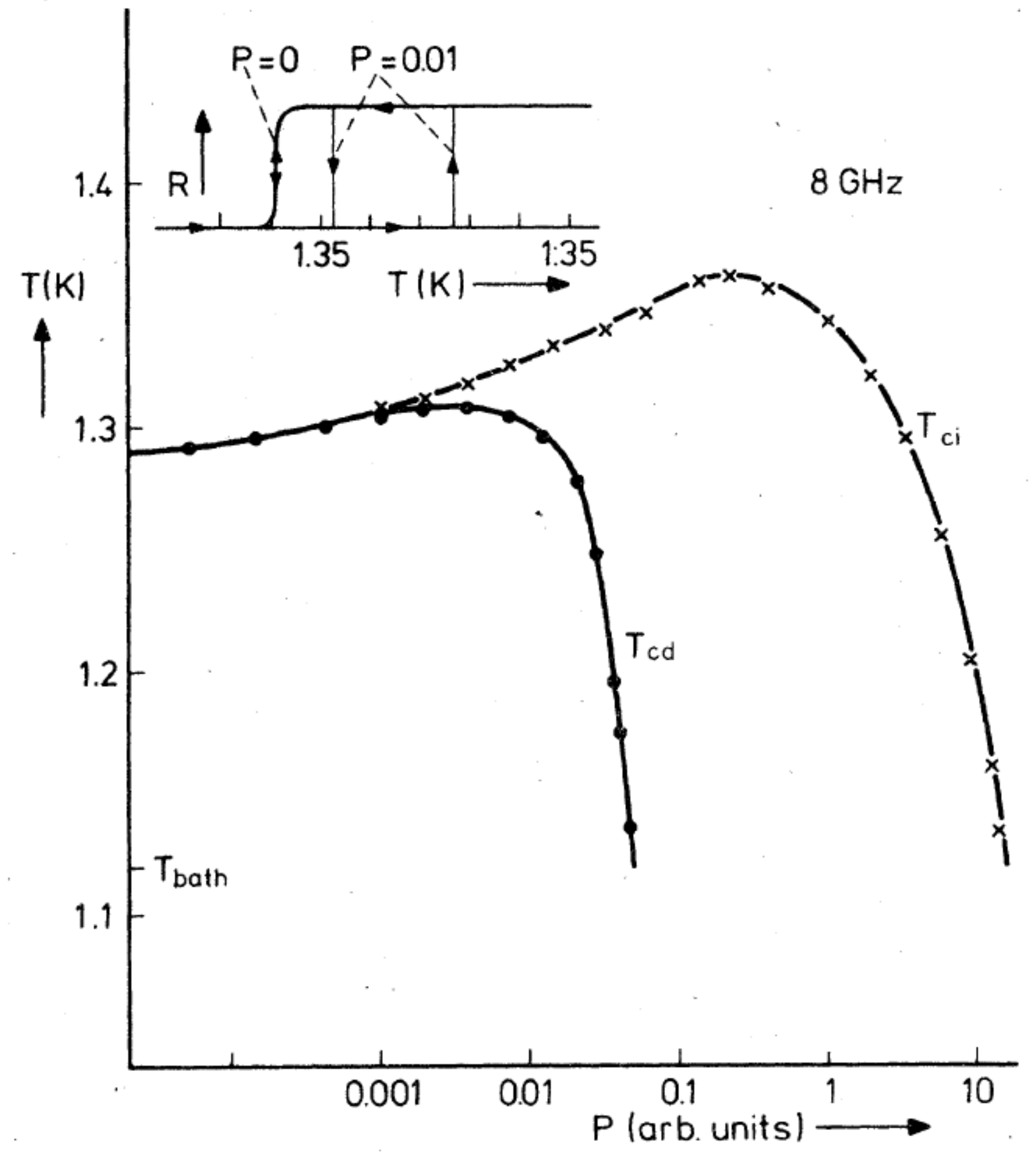


FIG. 12. Measured critical temperatures T_{ci} for increasing temperature and T_{cd} for decreasing temperature as a function of microwave power P. In the inset we have plotted the

MICROWAVE-ENHANCED CRITICAL SUPERCURRENTS IN CONSTRICTED TIN FILMS

A. F. G. Wyatt, V. M. Dmitriev,* W. S. Moore, and F. W. Sheard
Physics Department, Nottingham University, Nottingham, England
(Received 8 April 1966)

PHYSICAL REVIEW VOLUME 155, NUMBER 2 10 MARCH 1967

Behavior of Thin-Film Superconducting Bridges in a Microwave Field

A. H. Dayem and J. J. Wiegand
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received 4 October 1966)

- Enhancement of superconductivity is experimentally observed under microwave irradiation in certain parameter regimes

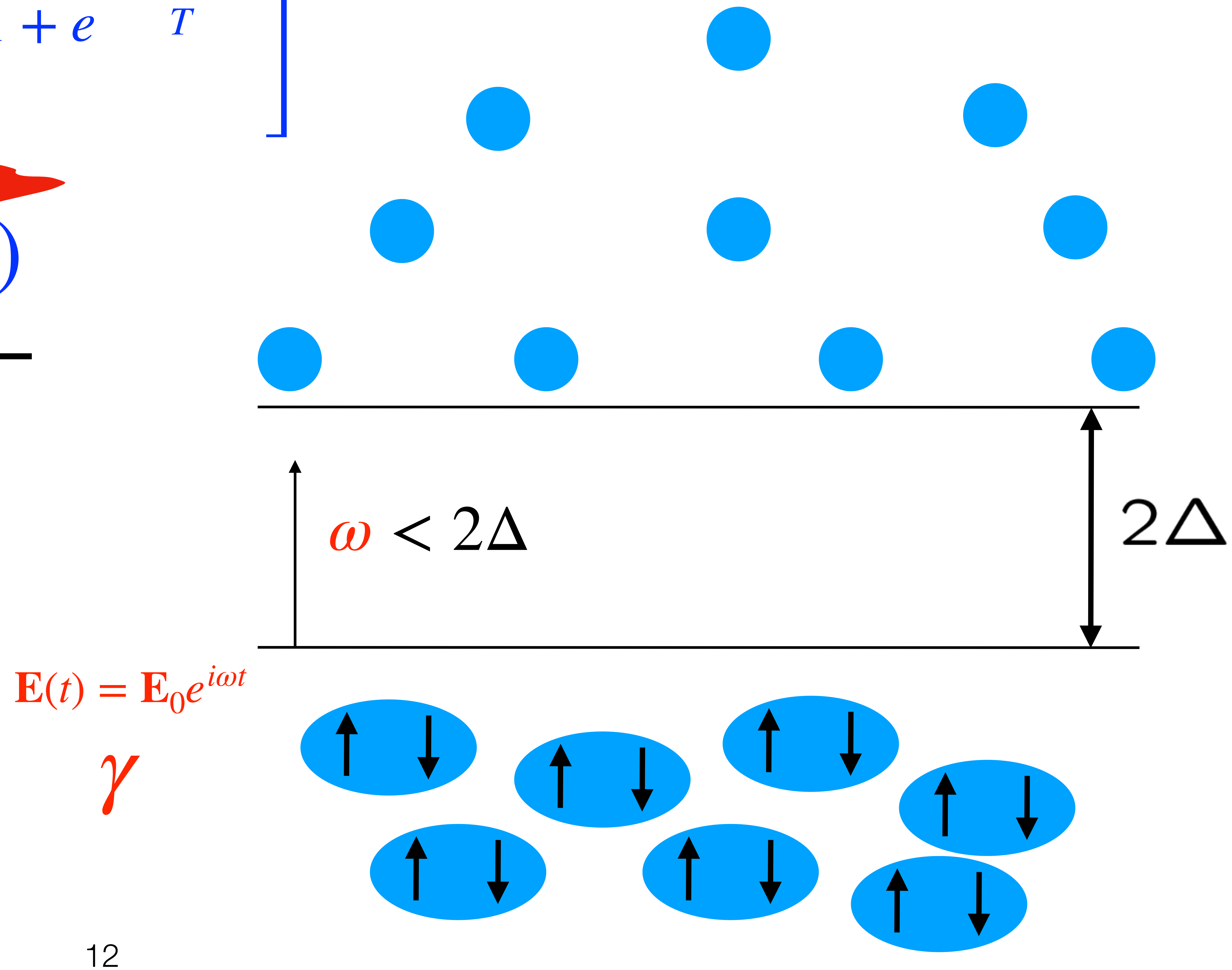
Microwave stimulation of Superconductivity

The Eliashberg effect

$\tilde{n}$

$$n_F(\epsilon) = \left[1 + e^{\frac{\sqrt{\epsilon^2+\Delta^2}}{T}}\right]^{-1}$$

$$\frac{1}{g} = \int_{\mathbf{k}} \frac{1 - 2n_F(\sqrt{\xi_{\mathbf{k}}^2+\Delta^2}, T)}{\sqrt{\xi_{\mathbf{k}}^2 + \Delta^2}}$$



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Klapwijk, T. M., Bergh, J. N. V. D. & Mooij, J. E. J. Low Temp. Phys 26, 385-405 (1977).

Chang, J.-J. & Scalapino, D. J. J. Low Temp. Phys. 29, 477-485 (1977).

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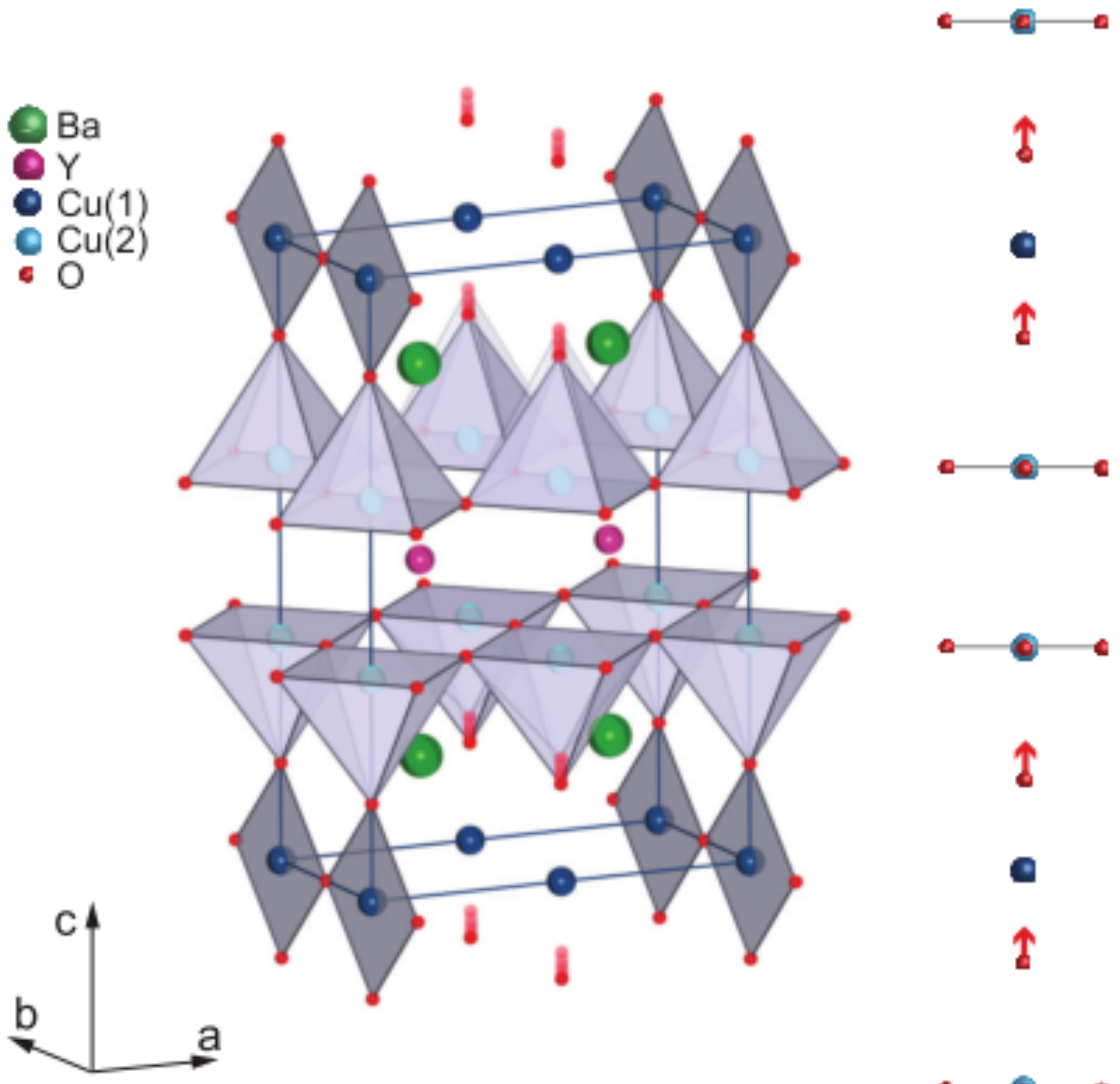
Renewed interest in light induced enhancement of superconductivity



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. P. Minitti[6], A. Frano[7], M. Fechner[8], N. A. Spaldin[8], T. Loew...

Light-Induced Superconductivity in a Stripe-Ordered Cuprate

D. Fausti,[1,2]*†‡ R. I. Tobey,[2]†§ N. Dean,[1,2] S. Kaiser,[1] A. Dienst,[2] M. C. Hoffmann,[1] S. Pyon,[3] T. Takayama,[3] H. Takagi,[3,4] A. Cavalleri[1,2]*

One of the most intriguing features of some high-temperature cuprate superconductors is the interplay between one-dimensional "striped" spin order and charge order, and superconductivity. We used mid-infrared femtosecond pulses to transform one such stripe-ordered compound, nonsuperconducting $La_{1.675}Eu_{0.2}Sr_{0.125}CuO_4$, into a transient three-dimensional superconductor. The emergence of coherent interlayer transport was evidenced by the prompt appearance of a Josephson plasma resonance in the c-axis optical properties. An upper limit for the time scale needed to form the superconducting phase is estimated to be 1 to 2 picoseconds, which is significantly faster than expected. This places stringent new constraints on our understanding of stripe order and its relation to superconductivity.

PHYSICAL REVIEW B **90**, 100503(R) (2014)

Optically induced superconductivity in striped $La_{2-x}Ba_xCuO_4$ by polarizatio... in the near infrared

D. Nicoletti,[1,*] E. Casandruc,[1] Y. Laplace,[1] V. Khanna,[1,2,3] C. R. Hunt,[1,4] S. Kaiser,[1] S. S. ...
J. P. Hil...
[1]*Max Planck Institute for the Stru...*
[2]*Diamond Light Source, C...*
[3]*Department of Physics, Clarendon La...*
[4]*Department of Physics, University o...*
[5]*Condensed Matter Physics and Materials Science D...*
(Received 27 April 2014; revised manuscri...

nature materials | ARTICLES
PUBLISHED ONLINE: 11 MAY 2014 | DOI: 10.1038/NMAT3963

Optically enhanced coherent transport in $YBa_2Cu_3O_{6.5}$ by ultrafast redistribution of interlayer coupling

W. Hu[1†], S. Kaiser[1†], D. Nicoletti[1†], C. R. Hunt[1,2†], I. Gierz[1], M. C. Hoffmann[1], M. Le Tacon[3], T. Loew[3], B. Keimer[3] and A. Cavalleri[1,4]*

PHYSICAL RE...

Optically induced coherent transport far above T_c in underdoped $YBa_2Cu_3O_{6+\delta}$

S. Kaiser,[1,*] C. R. Hunt,[1,4] D. Nicoletti,[1] W. Hu,[1] I. Gierz,[1] H. Y. Liu,[1] M. Le Tacon,[2] T. Loew,[2] D. Haug,[2] B. Keimer,[2] and A. Cavalleri[1,3,†]
[1]*Max Planck Institute for the Structure and Dynamics of Matter, Hamburg, Germany*
[2]*Max Planck Institute for Solid State Research, Stuttgart, Germany*
[3]*Department of Physics, Oxford University, Clarendon Laboratory, Oxford, United Kingdom*
[4]*Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA*
(Received 18 March 2014; revised manuscript received 25 April 2014; published 30 May 2014)

c.f. Chapter 2

Renewed interest in light induced enhancement of superconductivity

PRL **118**, 087002 (2017) PHYSICAL REVIEW LETTERS week ending 24 FEBRUARY 2017

Theory of Laser-Controlled Competing Superconducting and Charge Orders

M. A. Sentef,[1,*] A. Tokuno,[2,3] A. Georges,[2,3,4] and C. Kollath[5]
[1]*Max Planck Institute for the Structure and Dynamics of Matter, Center for Free Electron Laser Science, 22761 Hamburg, Germany*
[2]*Centre de Physique Théorique, École Polytechnique, CNRS, 91128 Palaiseau Cedex, France*
[3]*Collège de France, 11 place Marcelin Berthelot, 75005 Paris, France*
[4]*Department of Quantum Matter Physics, University of Geneva, 24 Quai Ernest-Ansermet, 1211 Geneva 4, Switzerland*
[5]*HISKP, University of Bonn, Nussallee 14-16, D-53115 Bonn, Germany*
(Received 14 November 2016; published 21 February 2017)

PHYSICAL REVIEW B **93**, 195139 (2016)

Light-induced enhancement of superconductivity via melting of competing bond-density wave order in underdoped cuprates

Aavishkar A. Patel and Andreas Eberlein
Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
(Received 23 February 2016; revised manuscript received 30 April 2016; published 19 May 2016)

PHYSICAL REVIEW B **91**, 104507 (2015)

Redistribution of phase fluctuations in a periodically driven cuprate superconductor

R. Höppner,[1] B. Zhu,[1] T. Rexin,[1] A. Cavalleri,[2,3] and L. Mathey[1,4]
[1]*Zentrum für Optische Quantentechnologien and Institut für Laserphysik, Universität Hamburg, 22761 Hamburg, Germany*
[2]*Max Planck Institute for the Structure and Dynamics of Matter, Hamburg, Germany*
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[4]*The Hamburg Centre for Ultrafast Imaging, Luruper Chaussee 149, Hamburg 22761, Germany*
(Received 22 November 2014; revised manuscript received 21 January 2015; published 11 March 2015)

PHYSICAL REVIEW B **91**, 184506 (2015)

Enhancement of superconductivity via periodic modulation in a three-dimensional model of cuprates

Zachary M. Raines and Valentin Stanev
Joint Quantum Institute and Condensed Matter Theory Center, Department of Physics, University of Maryland, College Park, Maryland 20742-4111, USA
Victor M. Galitski
Joint Quantum Institute and Condensed Matter Theory Center, Department of Physics, University of Maryland, College Park, Maryland 20742-4111, USA and School of Physics, Monash University, Melbourne, Victoria 3800, Australia
(Received 18 February 2015; published 8 May 2015)

Dynamical Cooper pairing in non-equilibrium electron-phonon systems

Michael Knap,[1] Mehrtash Babadi,[2] Gil Refael,[2] Ivar Martin,[3] and Eugene Demler[4]
[1]*Department of Physics, Walter Schottky Institute, and Institute for Advanced Study, Technical University of Munich, 85748 Garching, Germany*
[2]*Institute for Quantum Information and Matter, Caltech, Pasadena, CA 91125, USA*
[3]*Materials Science Division, Argonne National Laboratory, Argonne, IL 60439, USA*
[4]*Department of Physics, Harvard University, Cambridge MA 02138, USA*
(Dated: January 26, 2016)

PHYSICAL REVIEW B **94**, 214504 (2016)

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(Received 20 July 2016; revised manuscript received 10 October 2016; published 8 December 2016)

PHYSICAL REVIEW B **92**, 184511 (2015)

Hybridization of Higgs modes in a bond-density-wave state in cuprates

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Phase pinning and interlayer effects on competing orders in cuprates

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(Dated: September 20, 2018)

arXiv:1809.06879

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

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RAPID COMMUNICATIONS

PHYSICAL REVIEW B **90**, 100503(R) (2014)

Optically induced superconductivity in striped $La_{2-x}Ba_xCuO_4$ by polarization-selective excitation in the near infrared

D. Nicoletti,[1,*] E. Casandruc,[1] Y. Laplace,[1] V. Khanna,[1,2,3] C. R. Hunt,[1,4] S. Kaiser,[1] S. S. Dhesi,[2] G. D. Gu,[5] J. P. Hill,[5] and A. Cavalleri[1,3,†]
[1]*Max Planck Institute for the Structure and Dynamics of Matter, Hamburg, Germany*
[2]*Diamond Light Source, Chilton, Didcot, Oxfordshire, United Kingdom*
[3]*Department of Physics, Clarendon Laboratory, University of Oxford, Oxford, United Kingdom*
[4]*Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA*
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PHYSICAL REVIEW B **89**, 184516 (2014)

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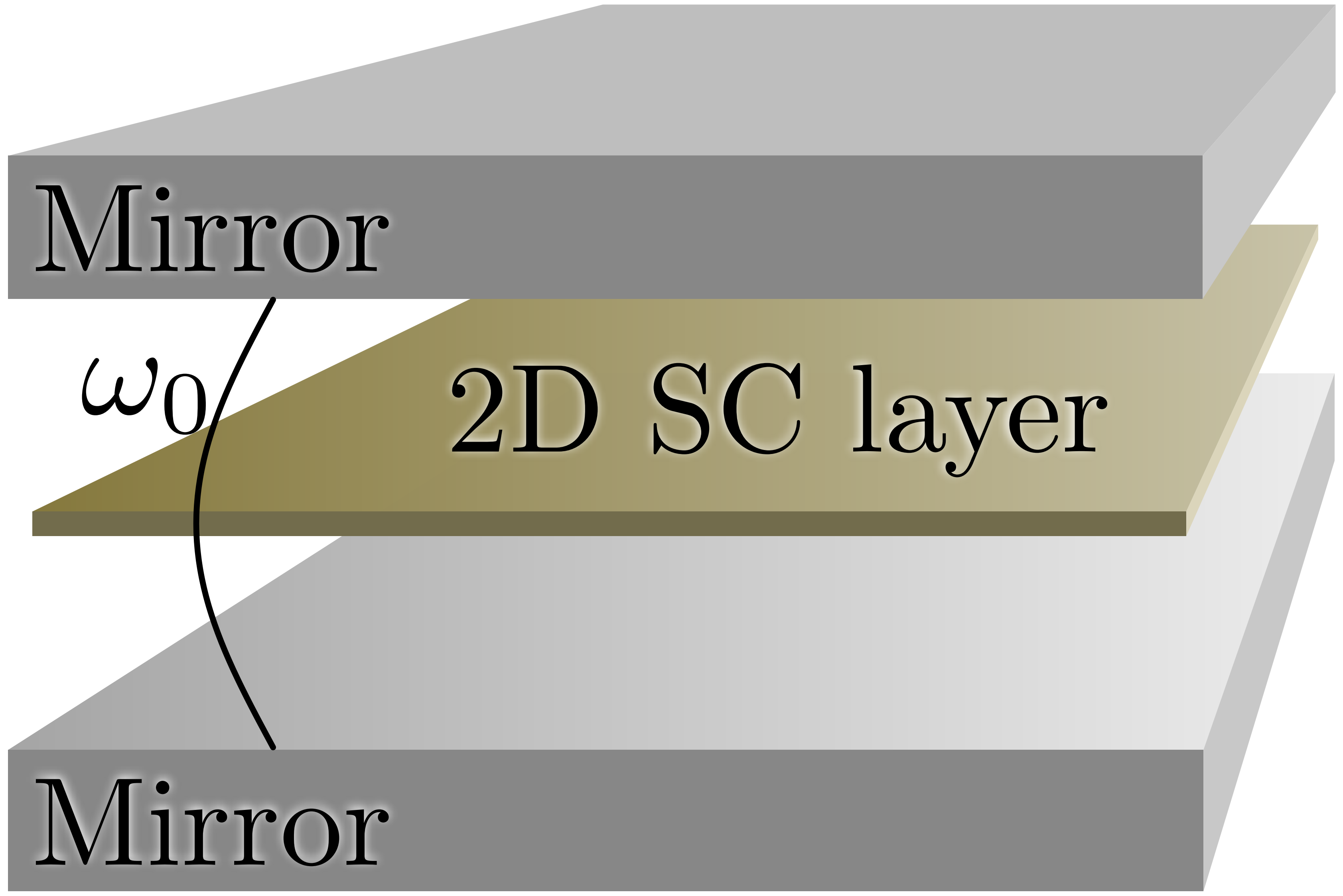
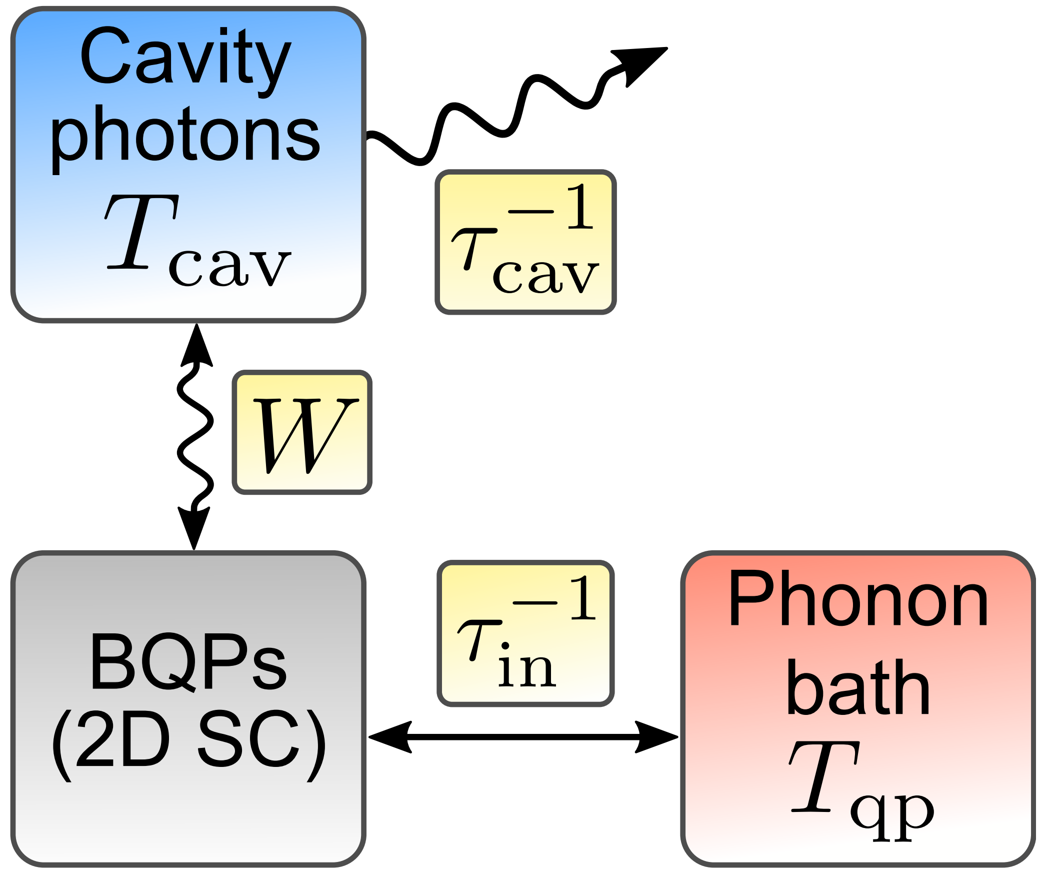
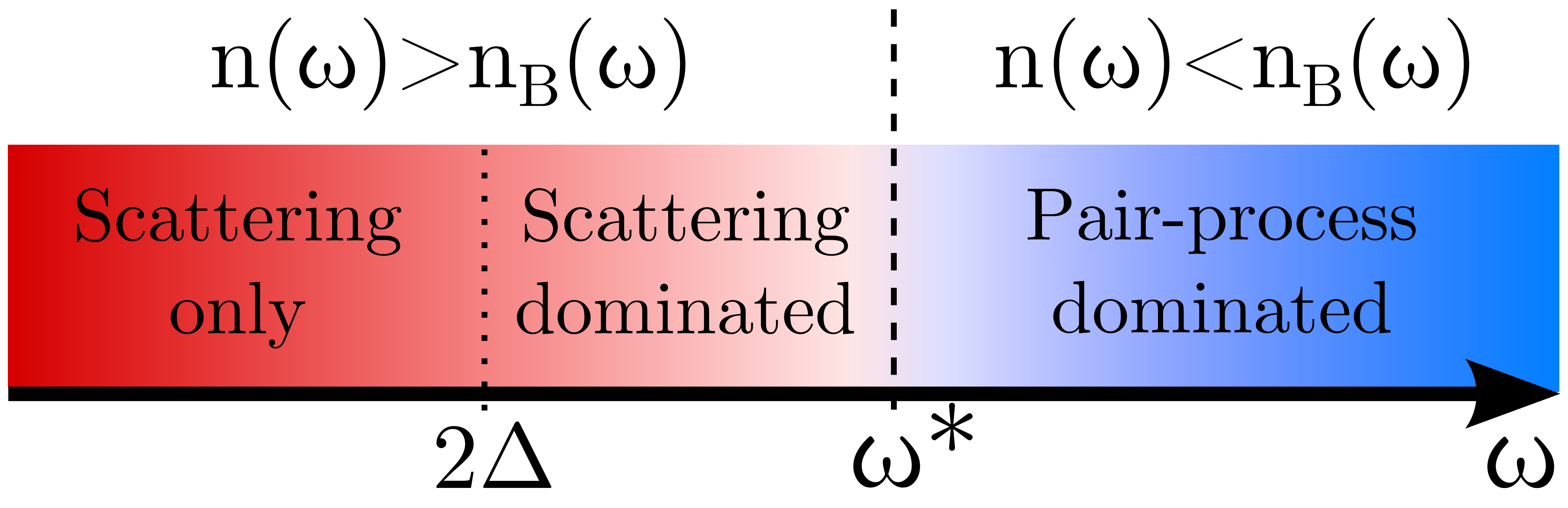
(Received 18 March 2014; revised manuscript received 25 April 2014; published 30 May 2014)

Enhancement in the absence of microwaves





- The basic idea is to replace microwave irradiation with a coupling to (lossy) cavity photons
    - The finite size gap of these electrons allows the nature of the effect to be tuned
- The electronic system is not driven



arXiv:1805.01482

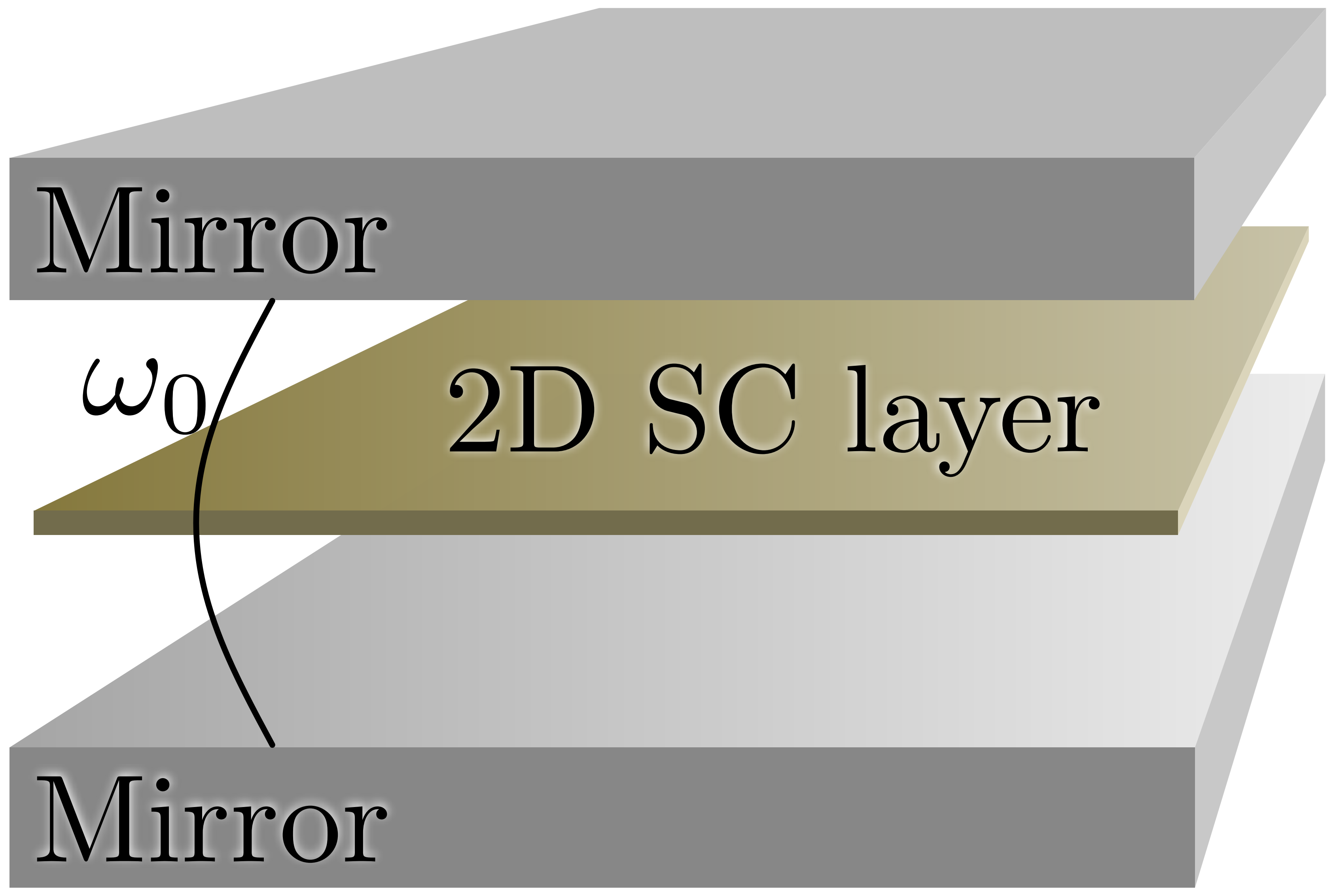
Photonic cavities: important properties for us

- Gapped photons due to finite size quantization

- This allows photon energies to be tuned into resonance with gapped solid state processes

- Tailoring of the wave functions allows for stronger light-matter coupling

$$\omega_q = \sqrt{c^2\left[q^2 + \left(\frac{n\pi}{L}\right)^2\right]} \sim mc^2 + \frac{q^2}{2m}$$



Kinetic equation treatment

Boltzmann Equation

$$\frac{\partial n}{\partial t} = \mathscr{I}_{\text{cav}}[n] - \frac{n - n_F}{\tau_{\text{in}}}$$

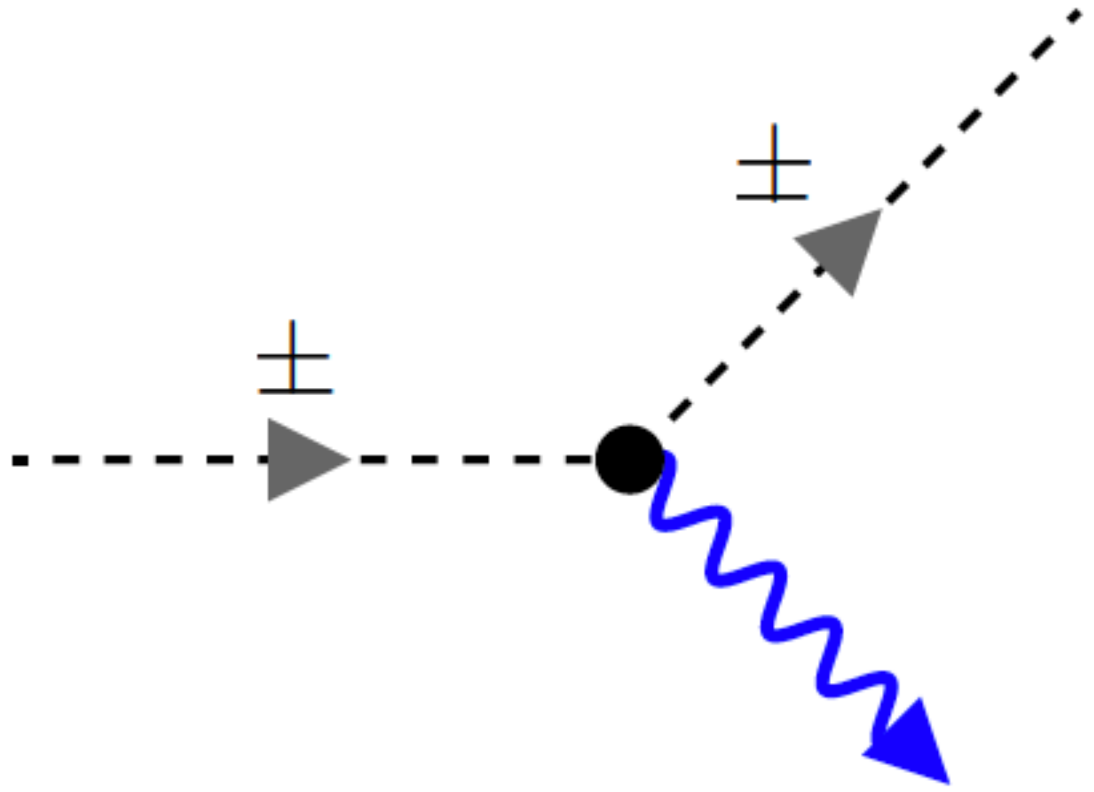
$$\frac{1}{g} = \int_{\mathbf{k}} \frac{1 - 2n\left(\sqrt{\xi_{\mathbf{k}}^2 + \Delta^2}, T\right)}{\sqrt{\xi_{\mathbf{k}}^2 + \Delta^2}}$$

- We can calculate the effect of the cavity through the modification of the fermionic occupation function
- The occupation function can be obtained from the Boltzmann equation with the collision integral at one loop order

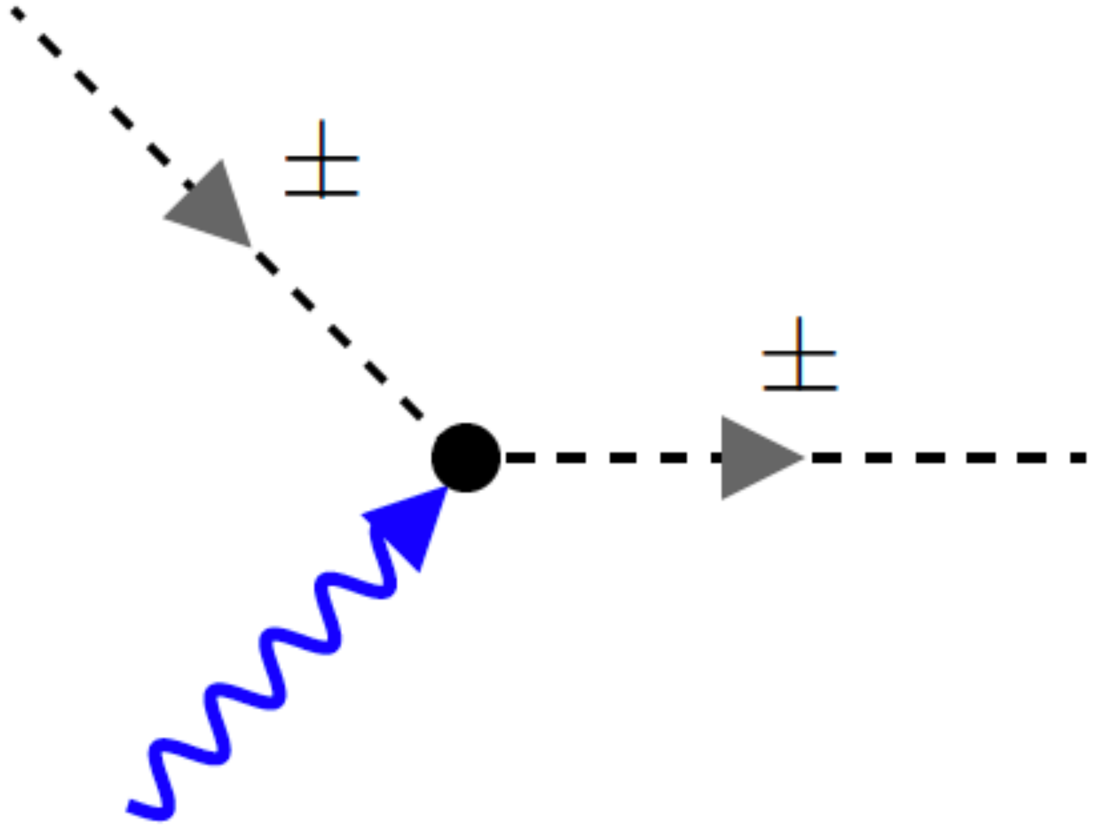
arXiv:1805.01482

Types of scattering terms

Relaxation



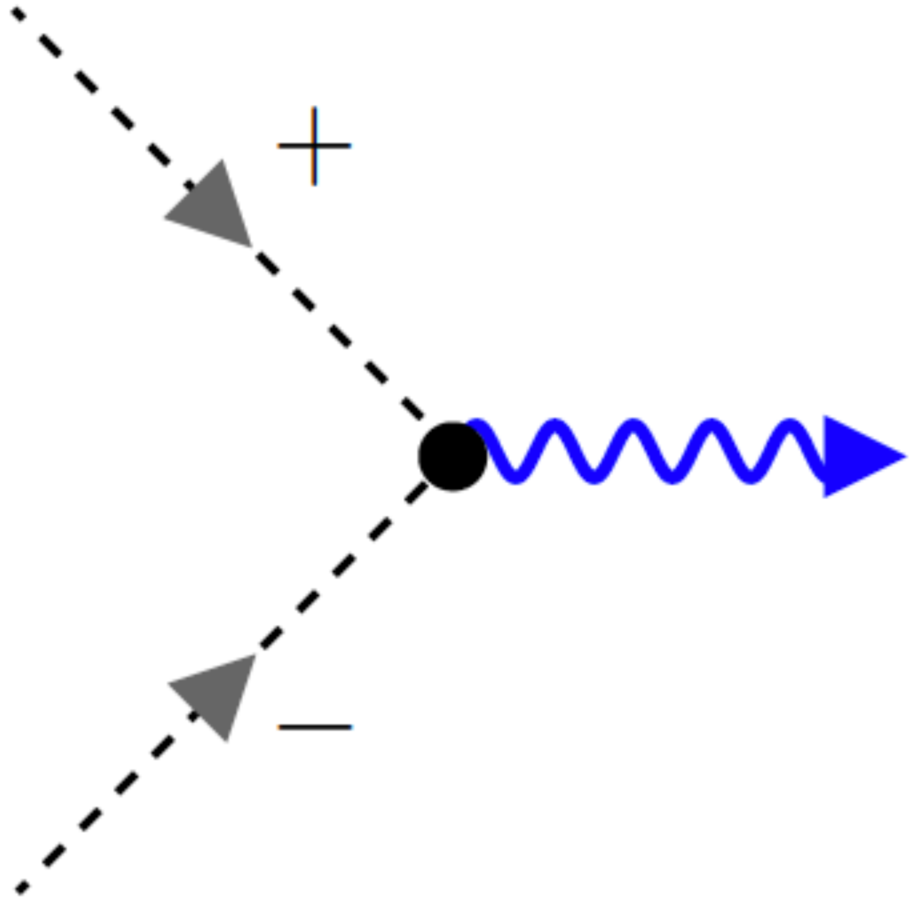
Photoexcitation



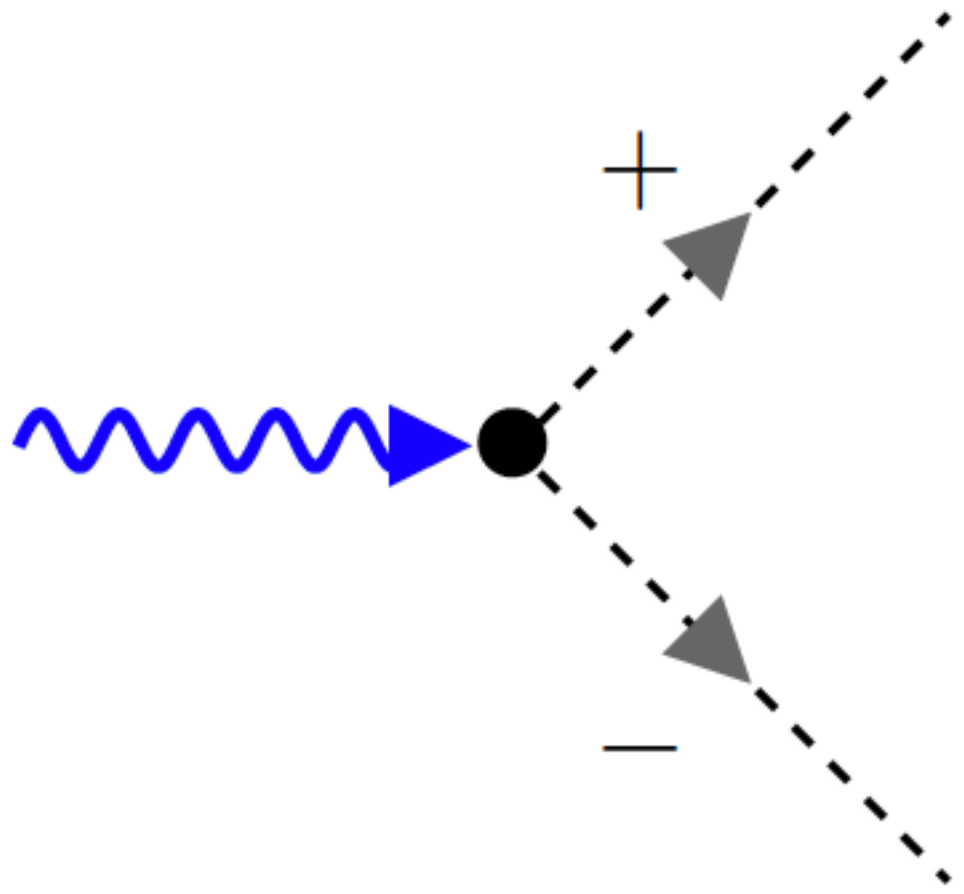
In equilibrium, these terms cancel due to detailed balance

We concern ourselves with non-equilibrium processes

$$\omega_0 \sim 2\Delta$$



Pair recombination



Pair breaking

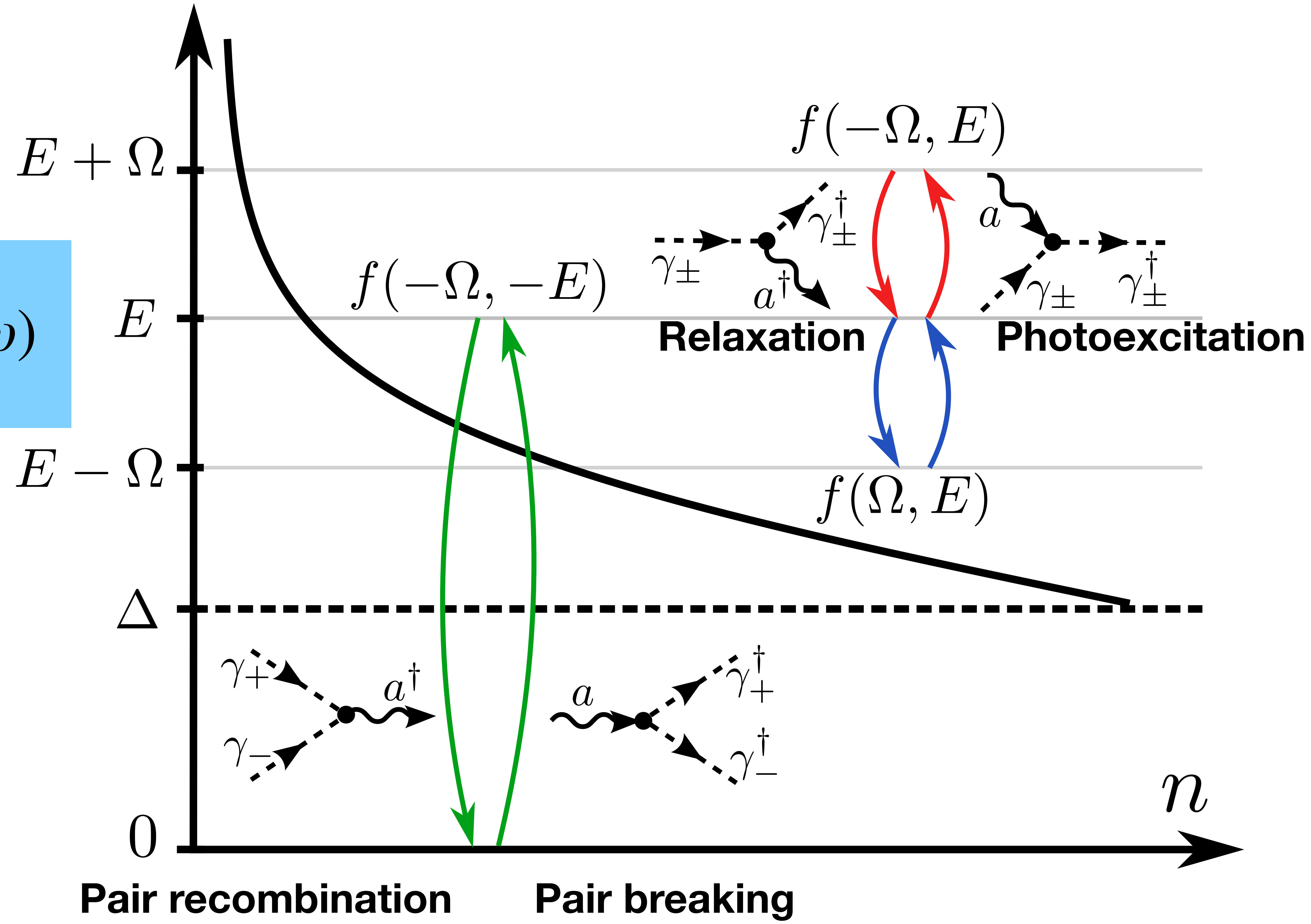
Types of scattering terms

- Each processes enters as a term in the collision integral

$$\delta n(\epsilon) = \tau_{\text{in}} \int_0^\infty d\omega\; S(\omega)\Big(n_B(\omega, T_{\text{qp}}) - N(\omega)\Big)\, I_\epsilon^{\text{el}}(\omega)$$

$$I_\epsilon^{el}(\omega) = f(\Omega, E) + f(-\Omega, E) - f(-\Omega, -E)$$

$$\delta n^{\text{conv.}}(\epsilon, \omega) = \frac{\alpha D |\mathbf{A}_\omega|^2}{\gamma c} I_\epsilon^{\text{el}}(\omega)$$



Cavity Quantum Eliashberg Effect

Conventional

$$\delta\Delta^{\text{conv.}}(\omega) = \frac{\alpha D |\mathbf{A}_\omega|^2}{c} Y^{\text{el}}(\omega)$$

Fluctuation

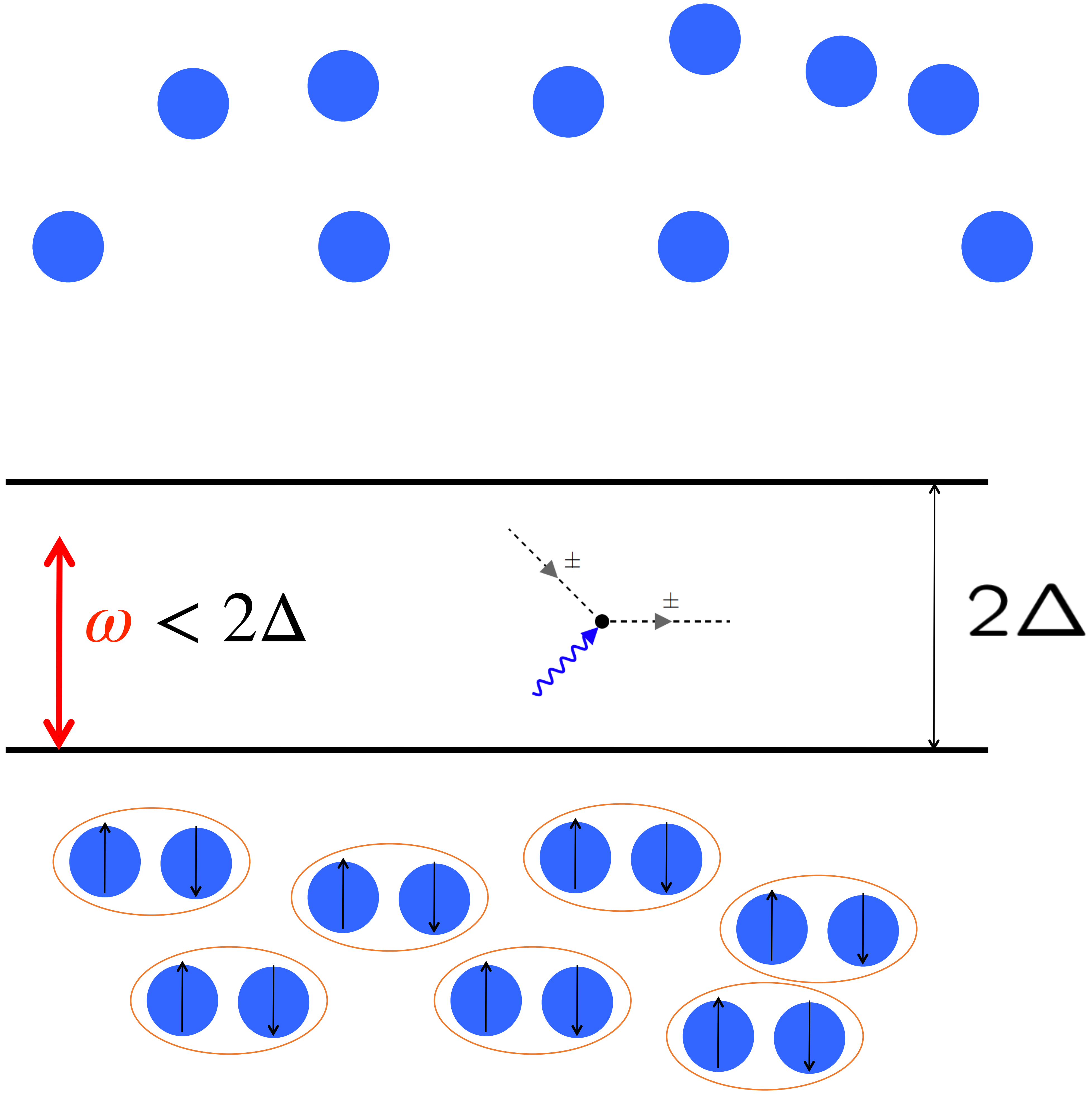
$$\delta\Delta = \int_0^\infty d\omega \; S(\omega)\Big(n_B(\omega, T_{\text{qp}}) - N(\omega)\Big) \, Y^{\text{el}}(\omega)$$

- The total effect is a weighted sum determined by the photon occupation and spectral function

$$S(\omega) = \frac{\alpha D}{c} \sum_{\mathbf{q}} \frac{2\pi c^2}{\omega_q} \mathscr{A}_q(\omega) \sum_{\alpha, i \in \{x,y\}} \left| \epsilon^i_{\mathbf{q},\alpha}\left(\frac{L}{2}\right) \right|^2$$

Cavity properties

Mechanisms for enhancement



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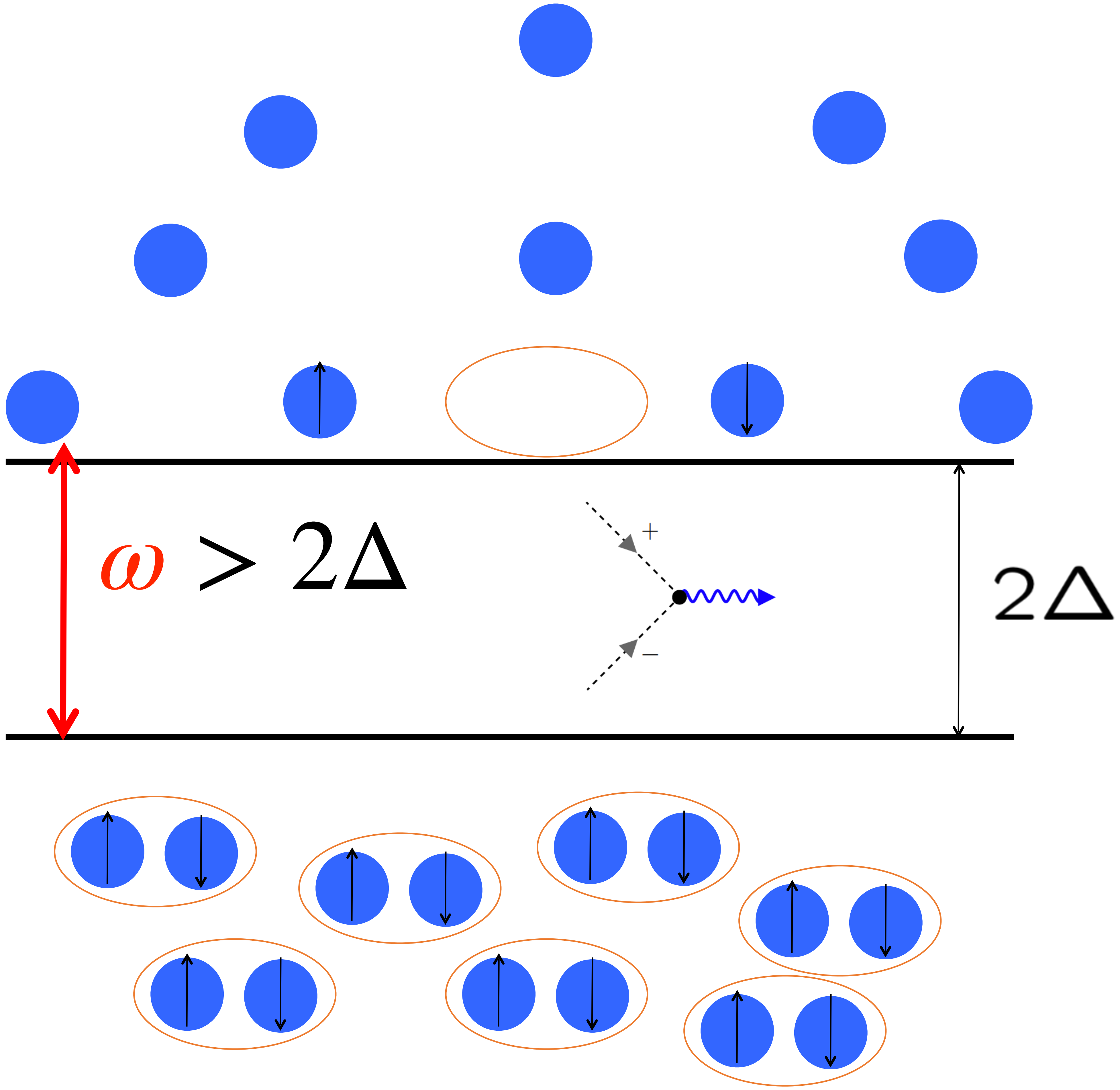
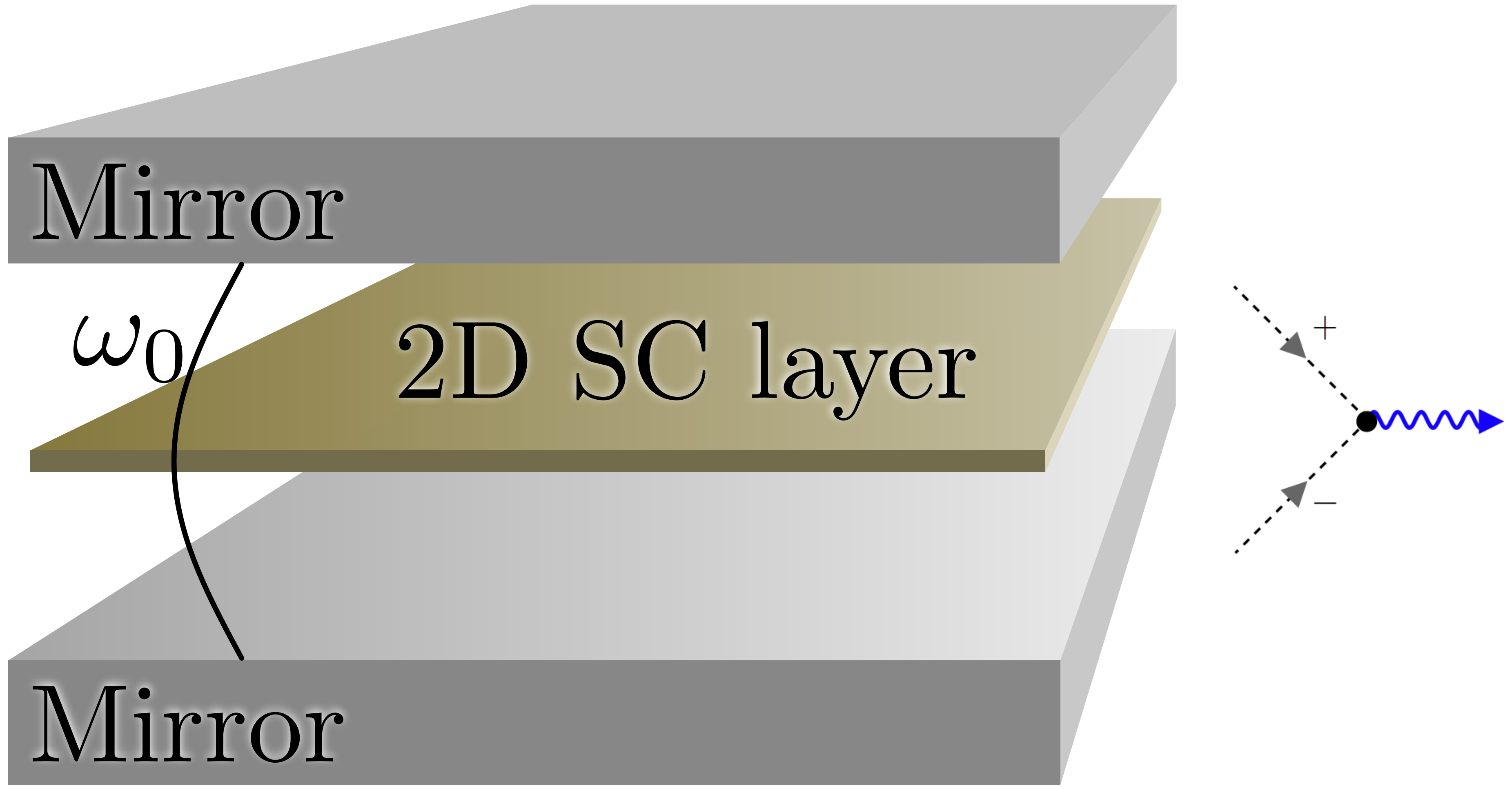
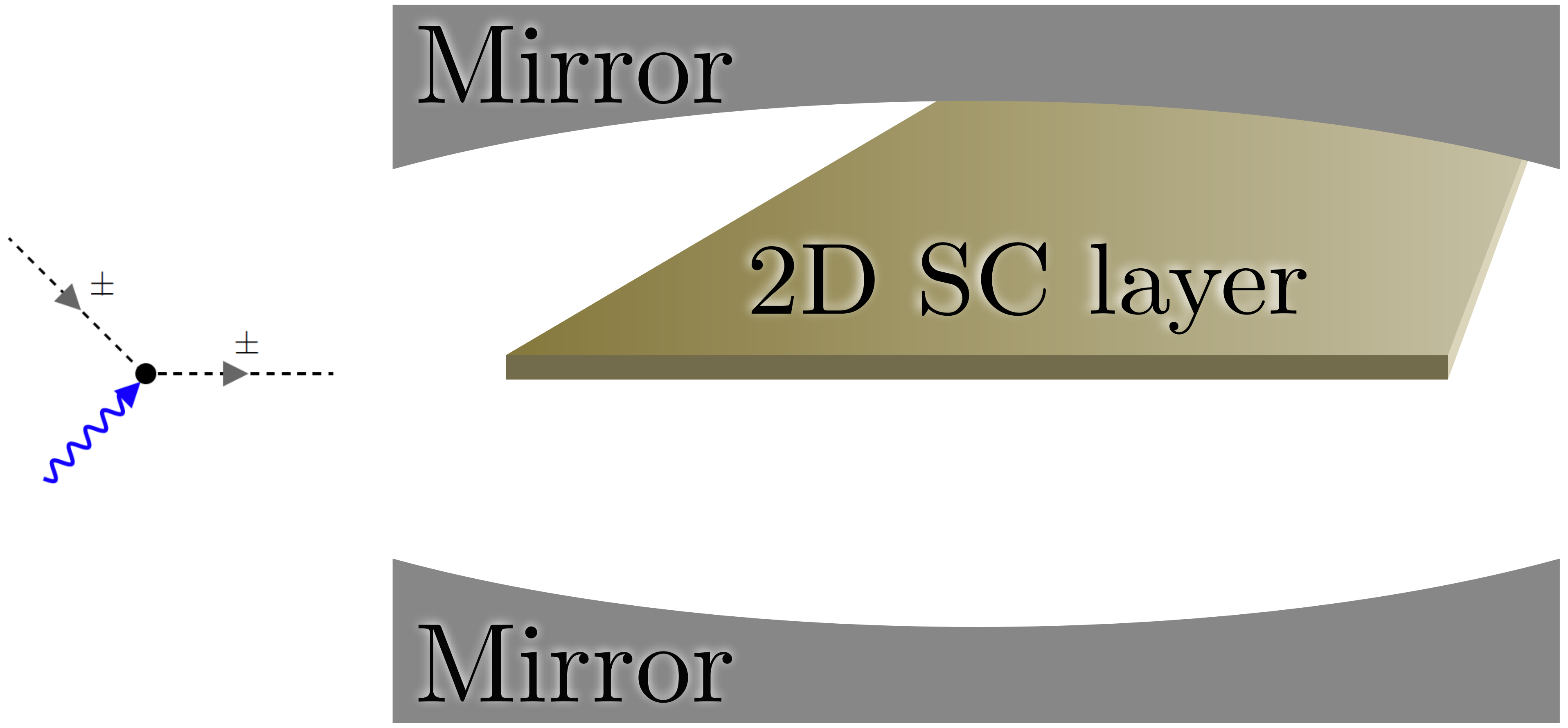
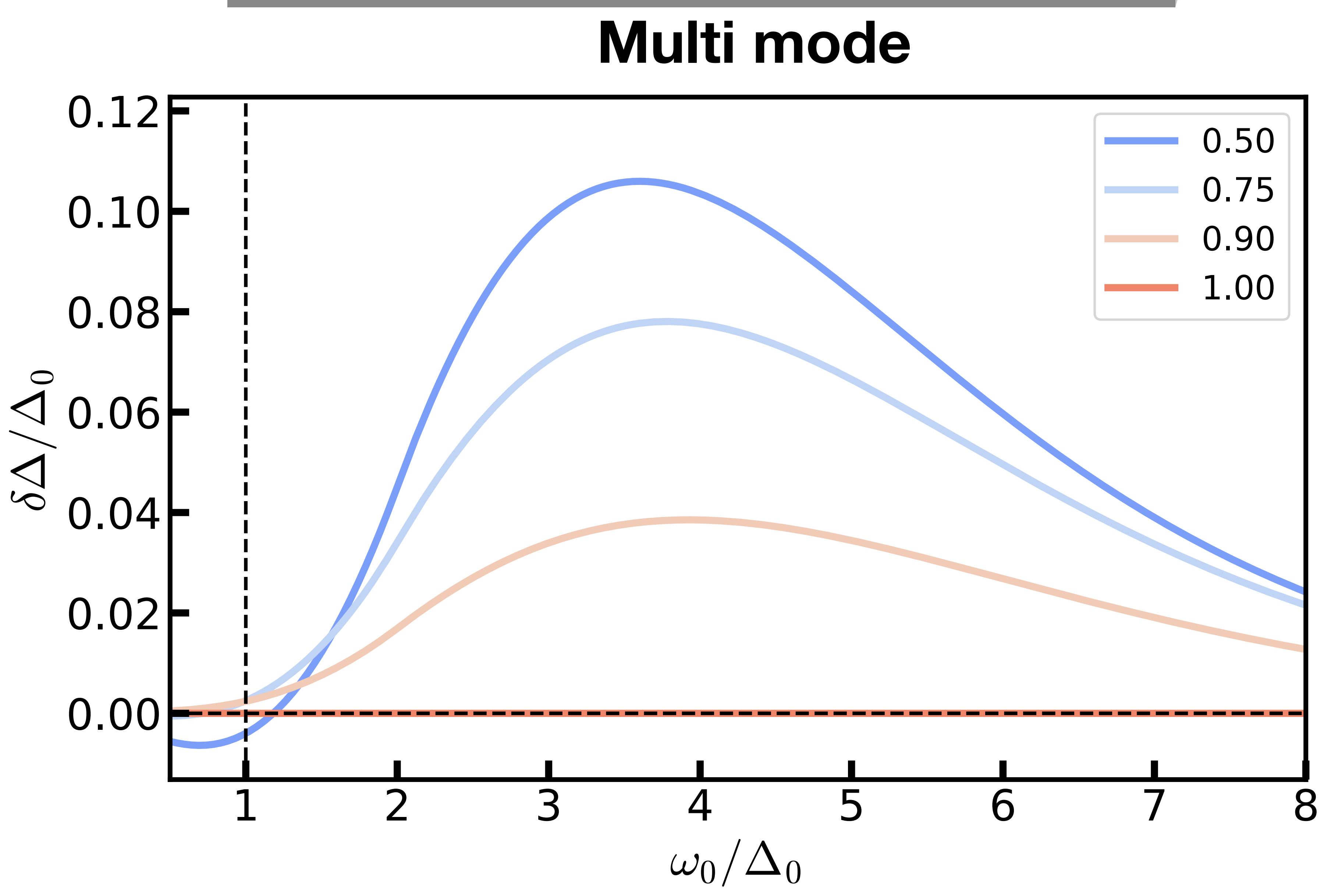


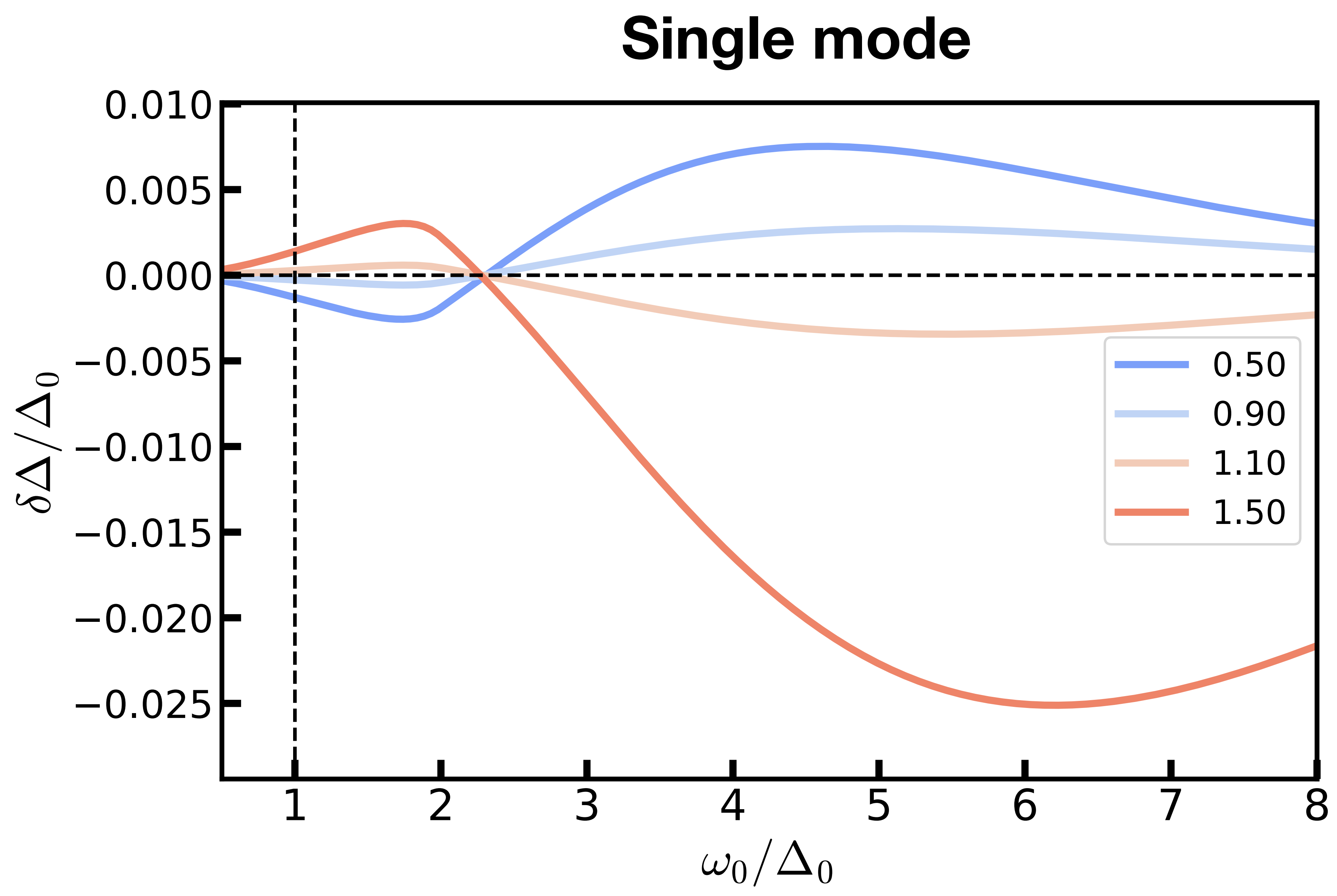
arXiv:1805.01482

Results for two cases

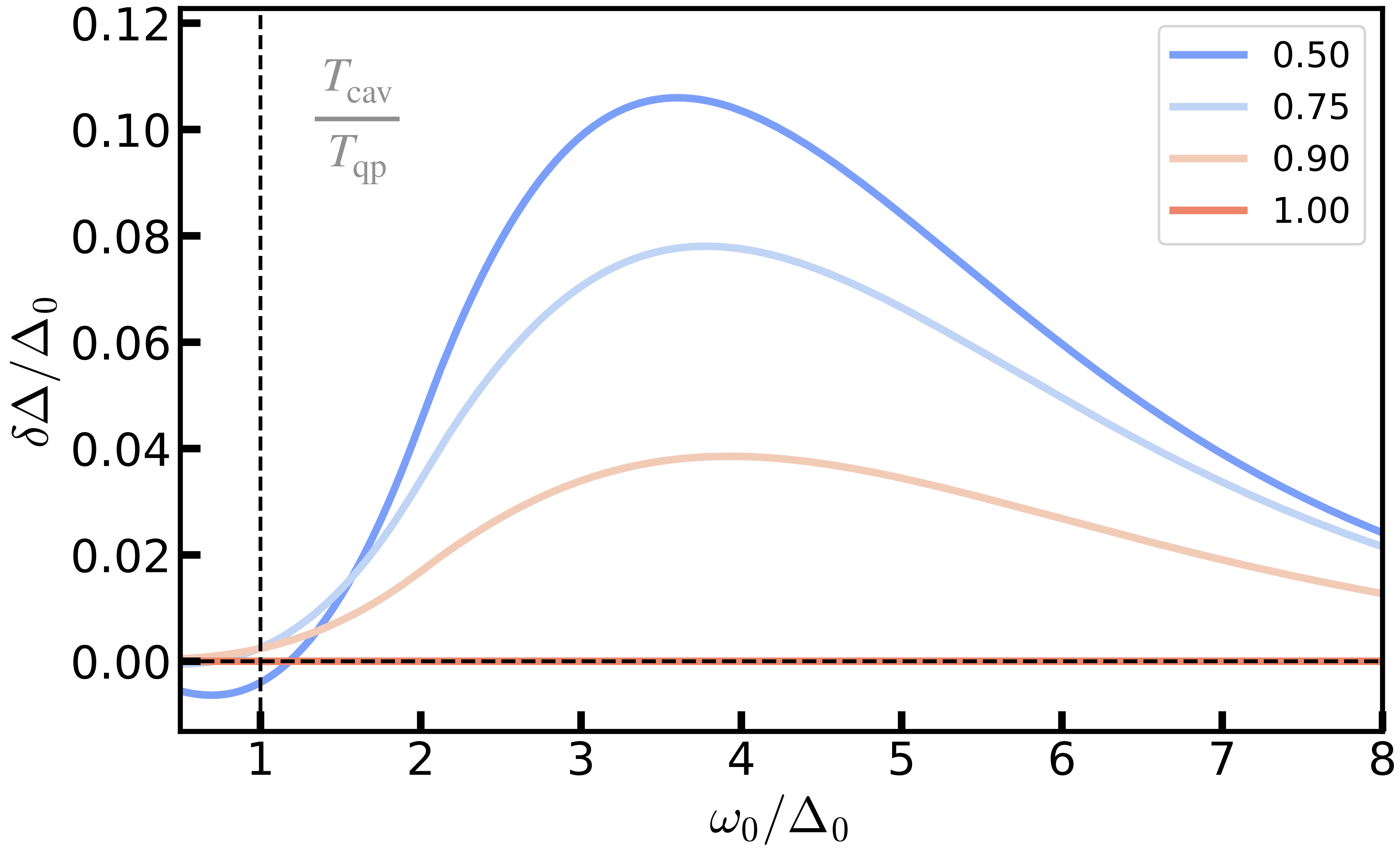


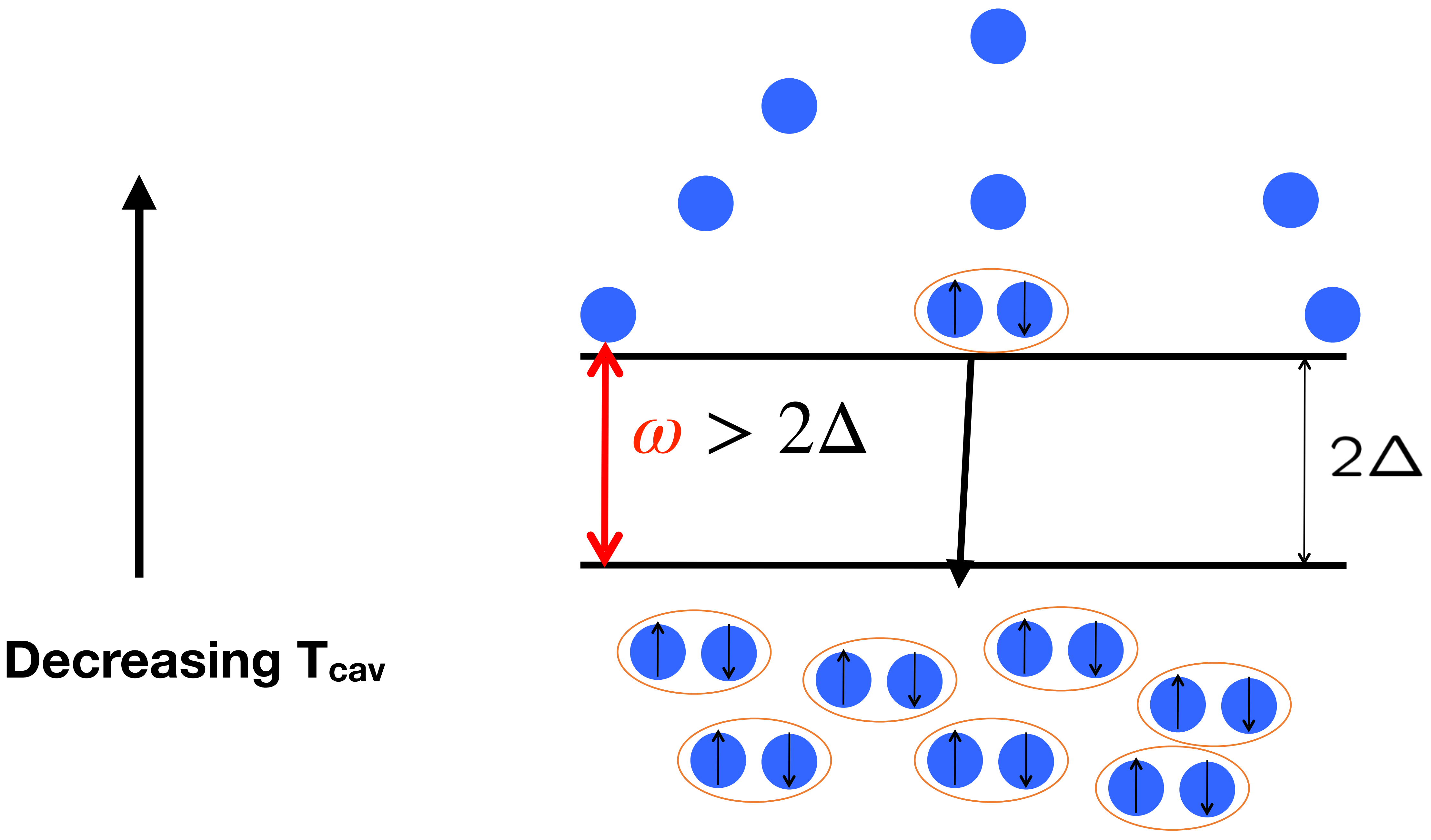






Multi mode enhancement

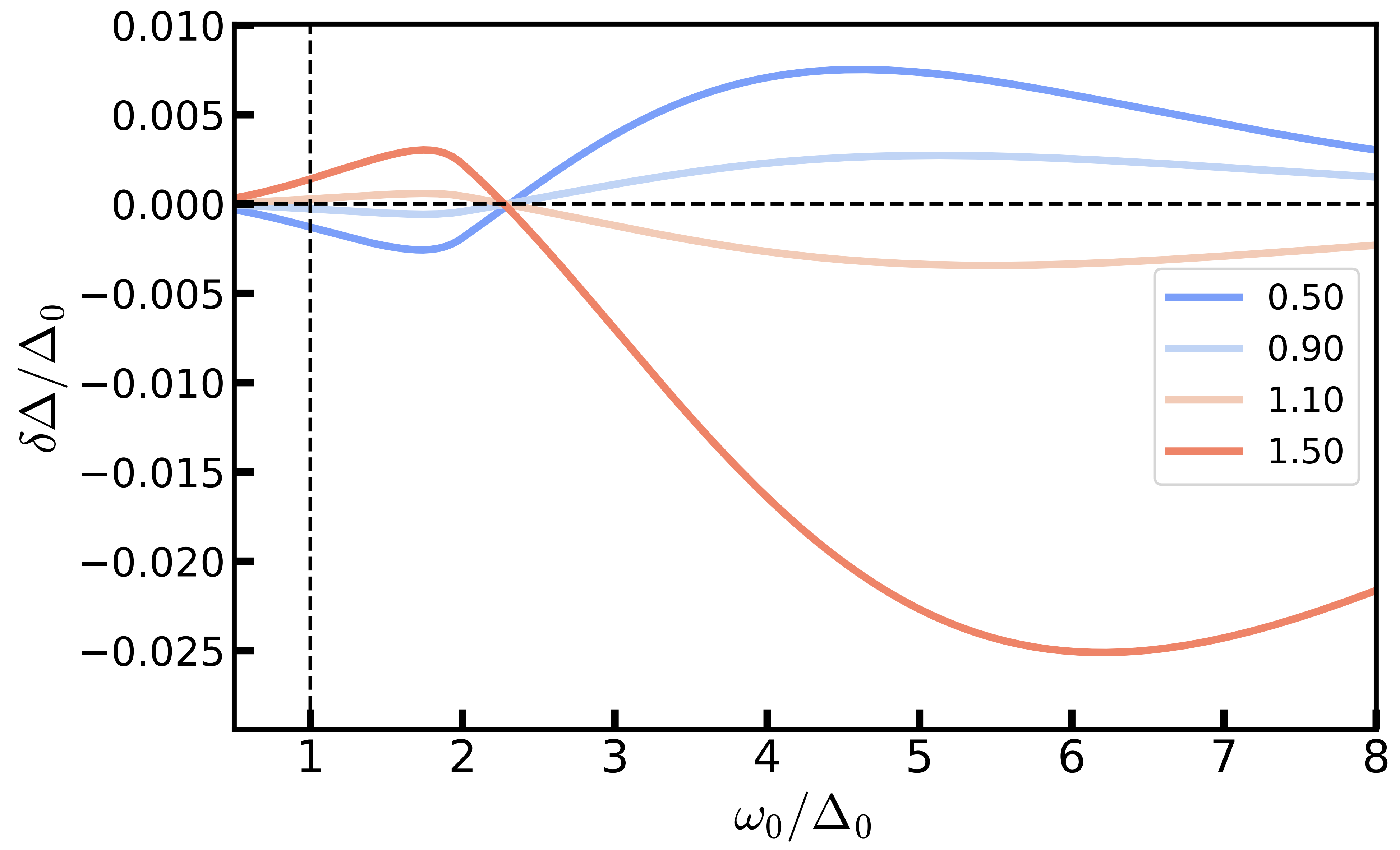




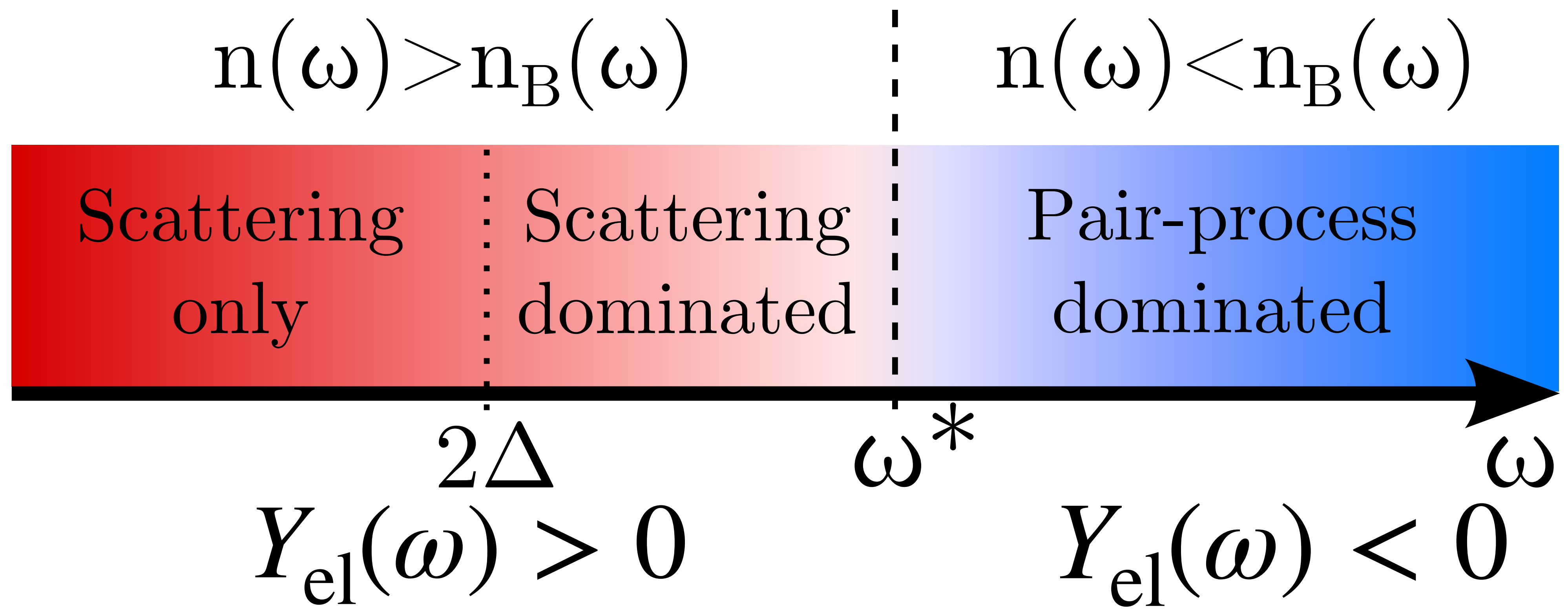
- The enhancement effect is dependent on the resonant frequency of the cavity
- Presented here are the results for an illustrative case of photons at temperature T_{cav} in a multi-mode cavity
- Enhancement happens via recombination for photons at a *lower* energy density

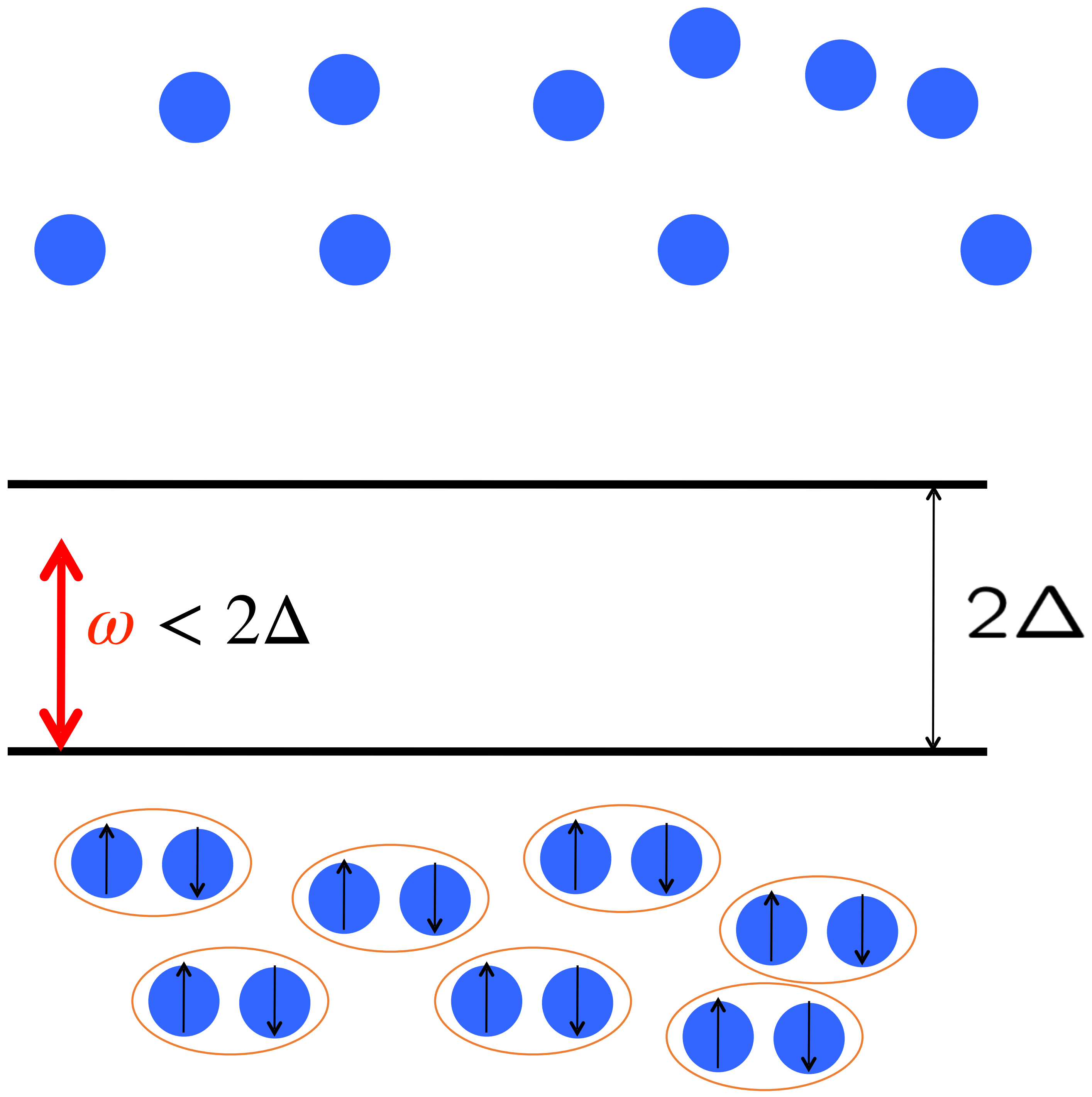
arXiv:1805.01482

Single mode enhancement



- Enhancement happens for photons at a *higher* energy density





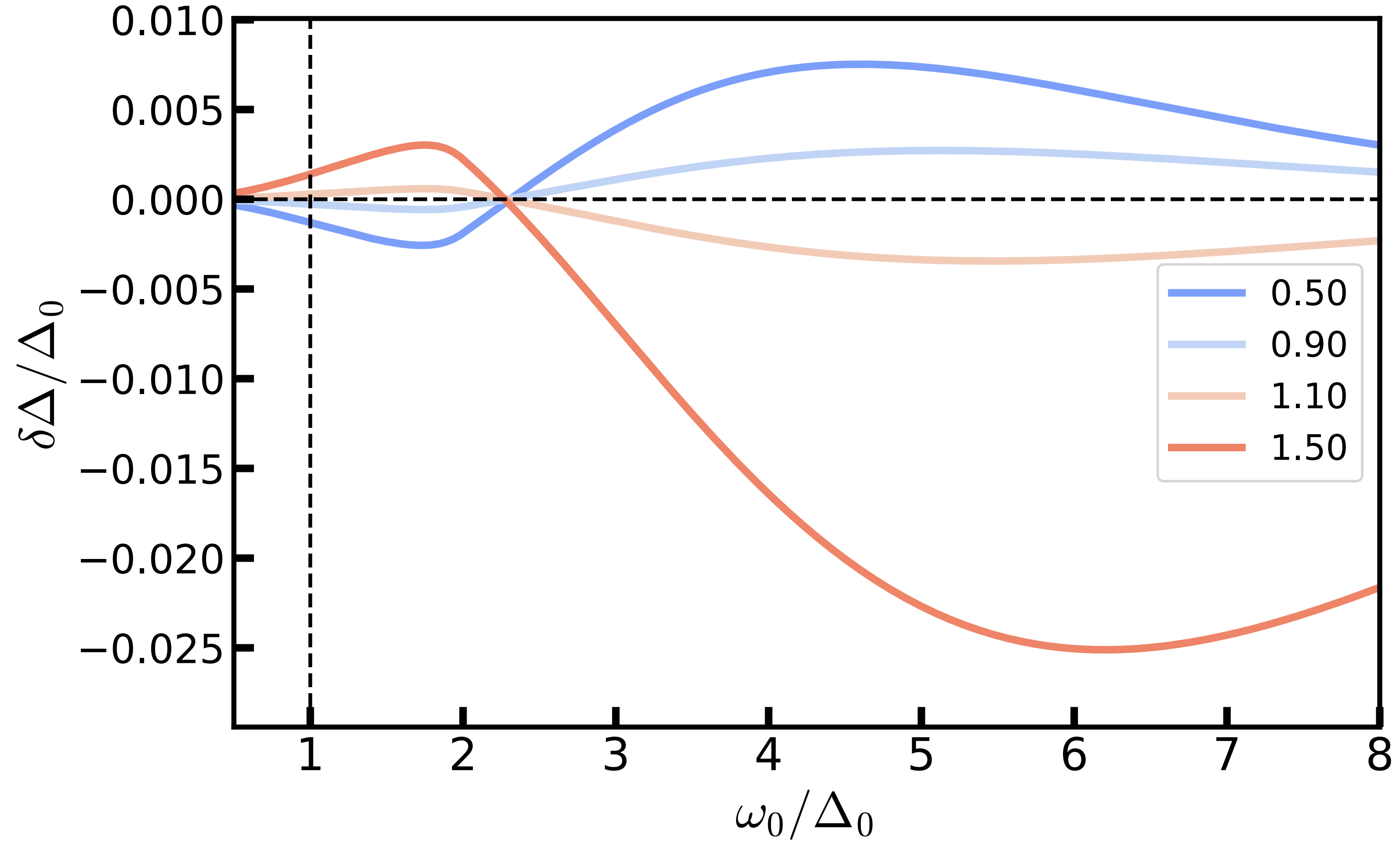
Cavity Eliashberg Effect

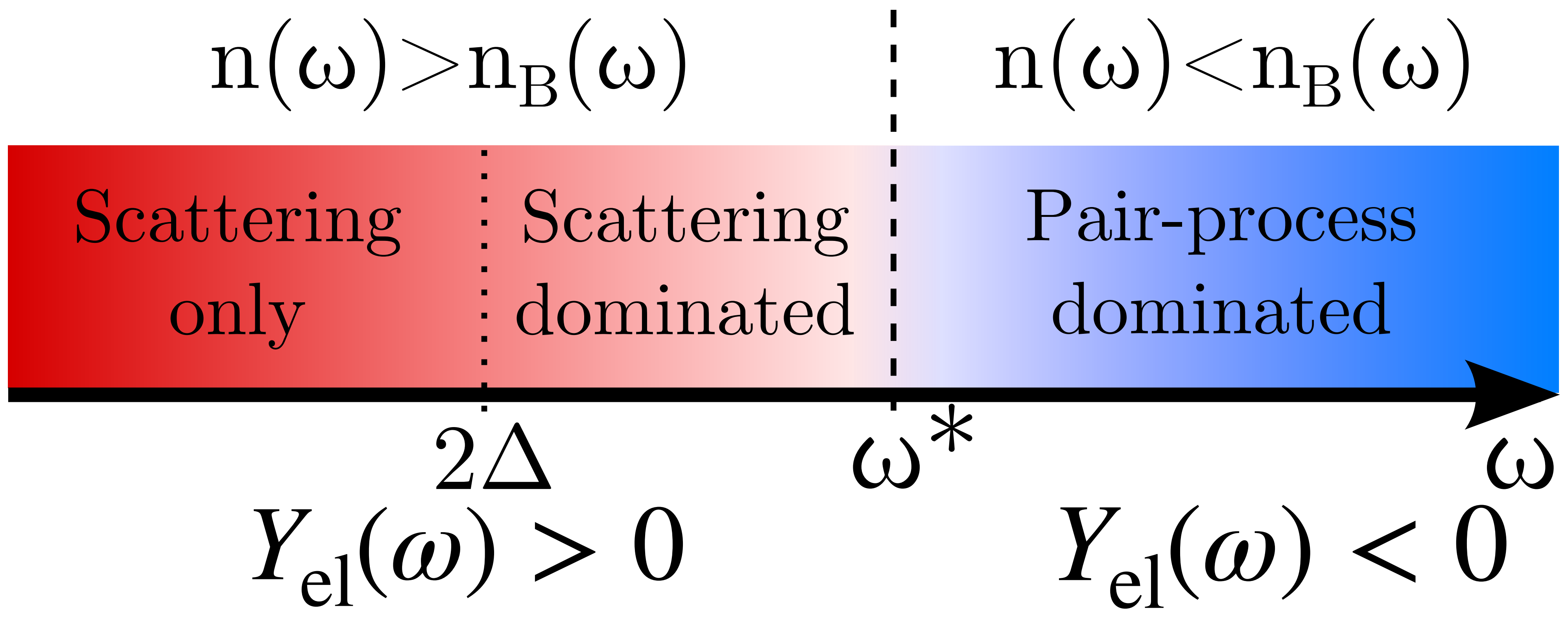
Related to the photon distribution function

Related to the Fermionic distribution function

$$\delta\Delta = \int_0^\infty d\omega\ S(\omega)\Big(n_B(\omega, T_{\rm qp}) - N(\omega)\Big)Y^{\rm el}(\omega)$$

Related to the cavity geometry





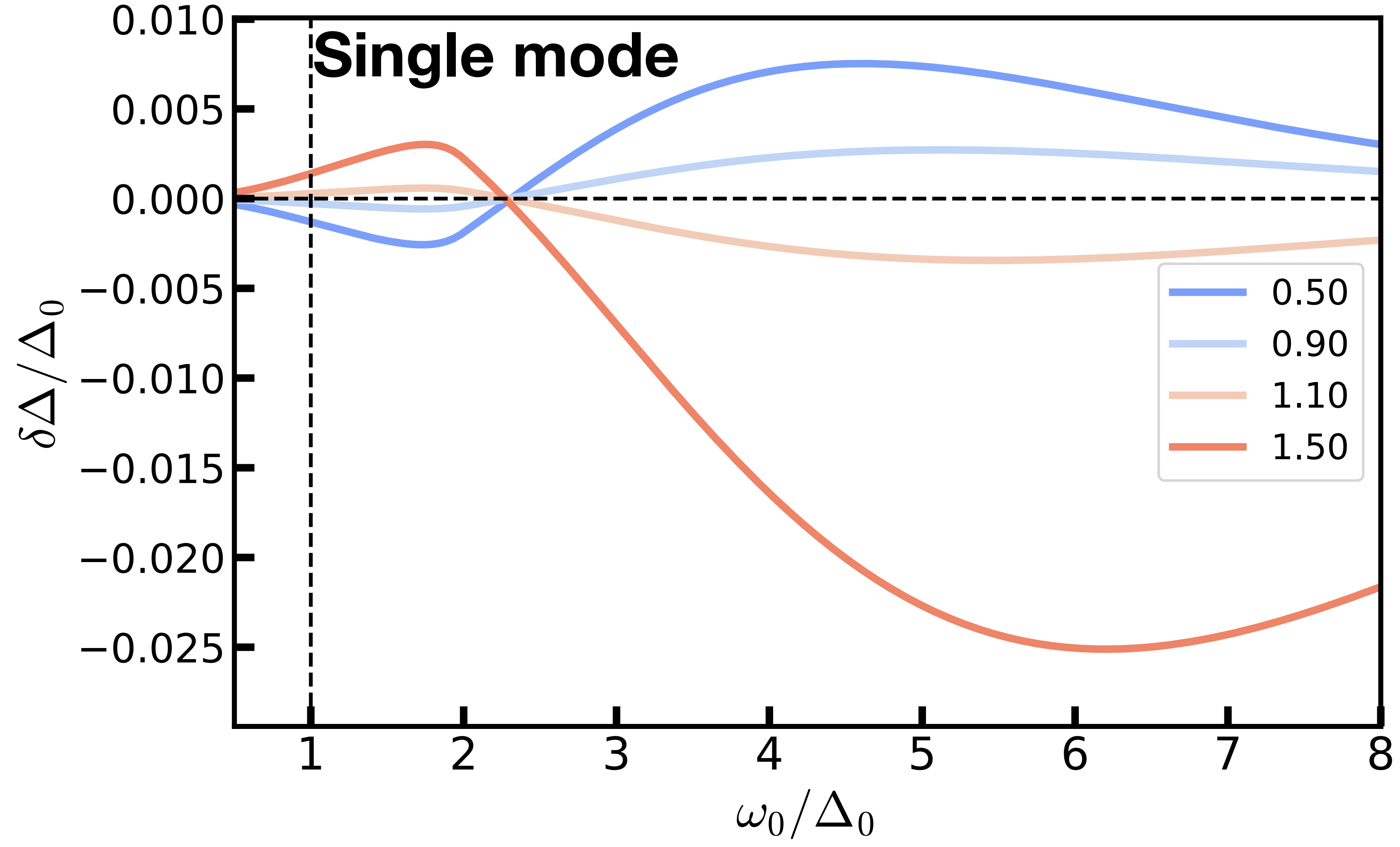
- In general there is a maximum frequency where pair processes lead to suppression in the traditional effect
- This can be remediated by making the photon reservoir ‘colder’ in this frequency range

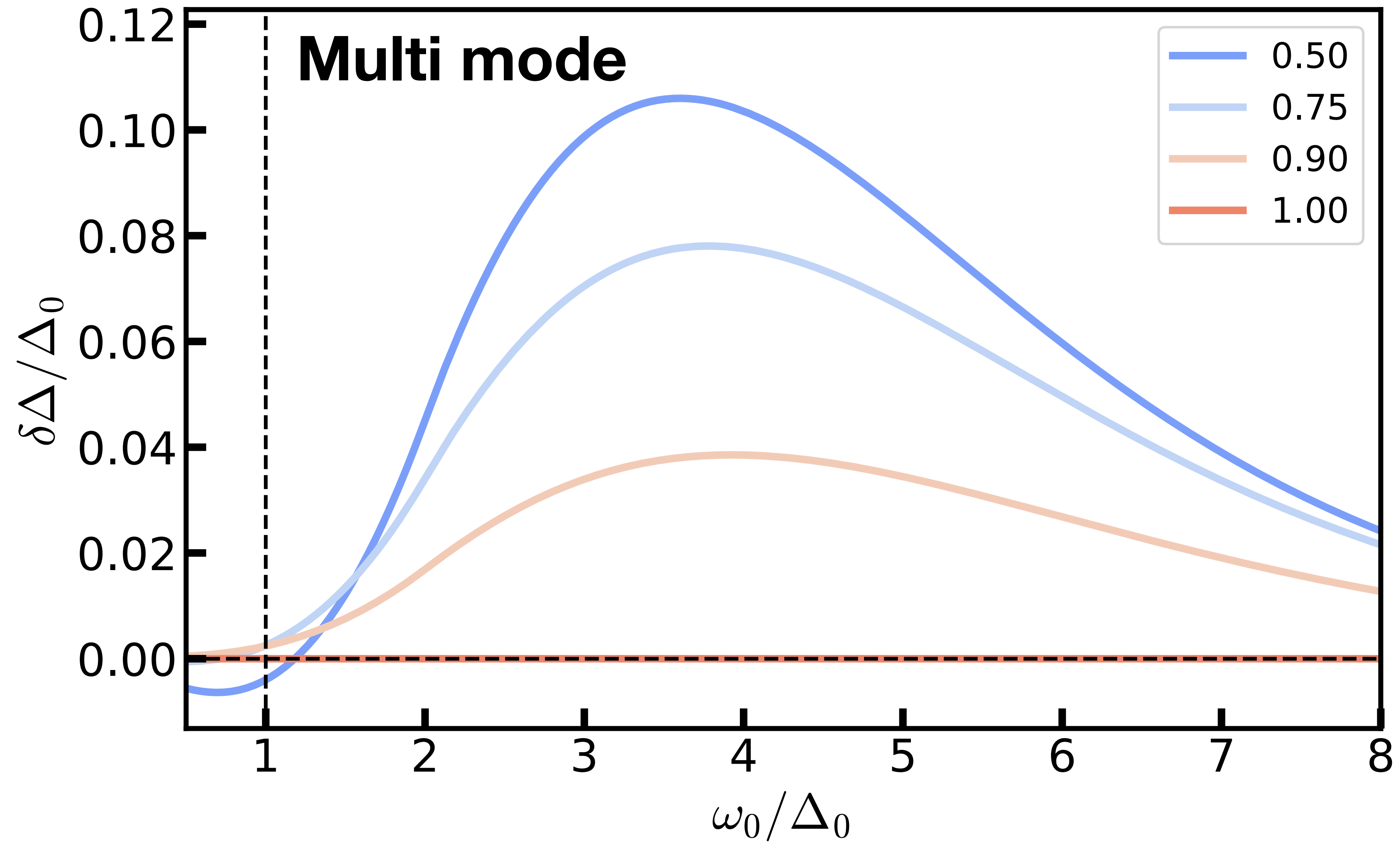
Cavity Eliashberg Effect: Summary

In general form

$$\delta\Delta = \int_0^\infty d\omega\ S(\omega)\frac{\mathcal{N}(\omega) - \mathcal{B}(\omega)}{2}Y^{\mathrm{el}}(\omega)$$

- Superconductivity can be enhanced by engineering of a coupled photon reservoir
- Our result is applicable for *a general cavity distribution and spectrum*
- Results can be modified based upon
  - **Cavity geometry**
  - **Photon occupation** relative to **Fermionic system**





Outline

- **Chapter 4 - Cavity Quantum Eliashberg Enhancement of Superconductivity**
  - Curtis, J. B., **ZMR**, Allocca, A. A., Hafezi, M. & Galitski, V. M. In Press, PRL.
- **Chapter 5 - Cavity superconductor-Polaritons**
  - Allocca, A. A., **ZMR**, Curtis, J. B. & Galitski, V. M., Phys. Rev. B 99, 020504(R), (2019).
  - **ZMR**, Allocca, A. A. & Galitski, V. M., *Cavity Higgs-Polaritons*. In Preparation (2019).

Cavity exciton-polaritons

Letter | Published: 29 August 2010

Spontaneous formation and optical manipulation of extended polariton condensates

E. Wertz, L. Ferrier, D. D. Solnyshkov, R. Johne, D. Sanvitto, A. Lemaître, I. Sagnes, R. Grousson, A. V. Kavokin, P. Senellart, G. Malpuech & J. Bloch

Nature Physics **6**, 860–864 (2010) | Download Citation

Vol 443|28 September 2006|**doi:10.1038/nature05131** nature

ARTICLES

Bose–Einstein condensation of exciton polaritons

J. Kasprzak[1], M. Richard[2], S. Kundermann[2], A. Baas[2], P. Jeambrun[2], J. M. J. Keeling[3], F. M. Marchetti[4], M. H. Szymańska[5], R. André[1], J. L. Staehli[2], V. Savona[2], P. B. Littlewood[4], B. Deveaud[2] & Le Si Dang[1]

PRL **110,** 196406 (2013) PHYSICAL REVIEW LETTERS week ending 10 MAY 2013

From Excitonic to Photonic Polariton Condensate in a ZnO-Based Microcavity

Feng Li,[1,2] L. Orosz,[3] O. Kamoun,[4] S. Bouchoule,[5] C. Brimont,[4] P. Disseix,[3] T. Guillet,[4] X. Lafosse,[5] M. Leroux,[1] J. Leymarie,[3] M. Mexis,[4] M. Mihailovic,[3] G. Patriarche,[5] F. Réveret,[3] D. Solnyshkov,[3] J. Zuniga-Perez,[1] and G. Malpuech[3]

[1]*CRHEA-CNRS, Rue Bernard Gregory, 06560 Valbonne, France*

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[3]*Institut Pascal, PHOTON-N2, Clermont Université, CNRS and Université Blaise Pascal, 24 Avenue des Landais, 63177 Aubière cedex, France*

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(Received 20 December 2012; revised manuscript received 1 February 2013; published 10 May 2013)

VOLUME 69, NUMBER 23 PHYSICAL REVIEW LETTERS 7 DECEMBER 1992

Observation of the Coupled Exciton-Photon Mode Splitting in a Semiconductor Quantum Microcavity

C. Weisbuch,[(a)] M. Nishioka,[(b)] A. Ishikawa, and Y. Arakawa

Research Center for Advanced Science and Technology, University of Tokyo, 4-6-1 Meguro-ku, Tokyo 153, Japan

(Received 12 May 1992)

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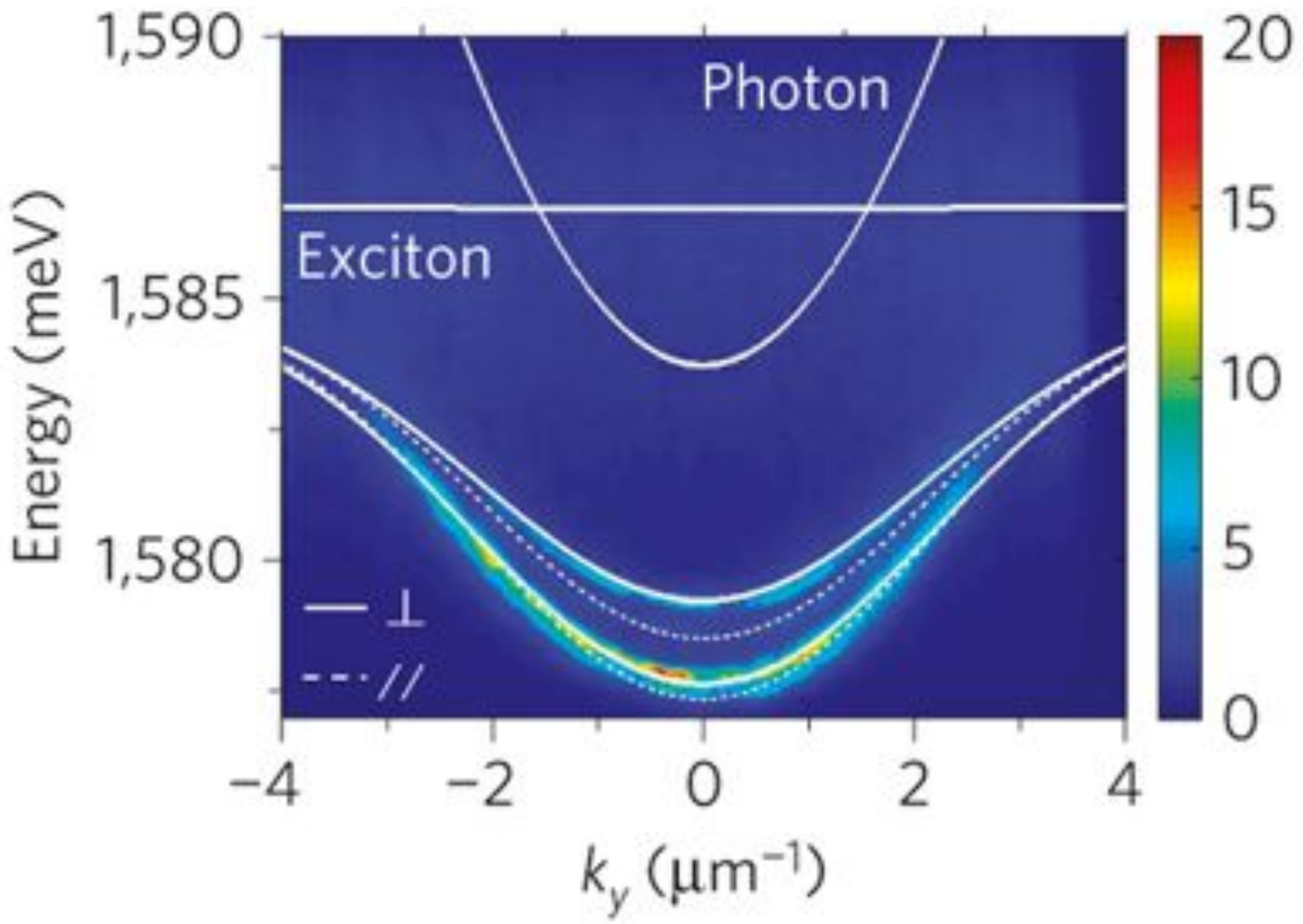

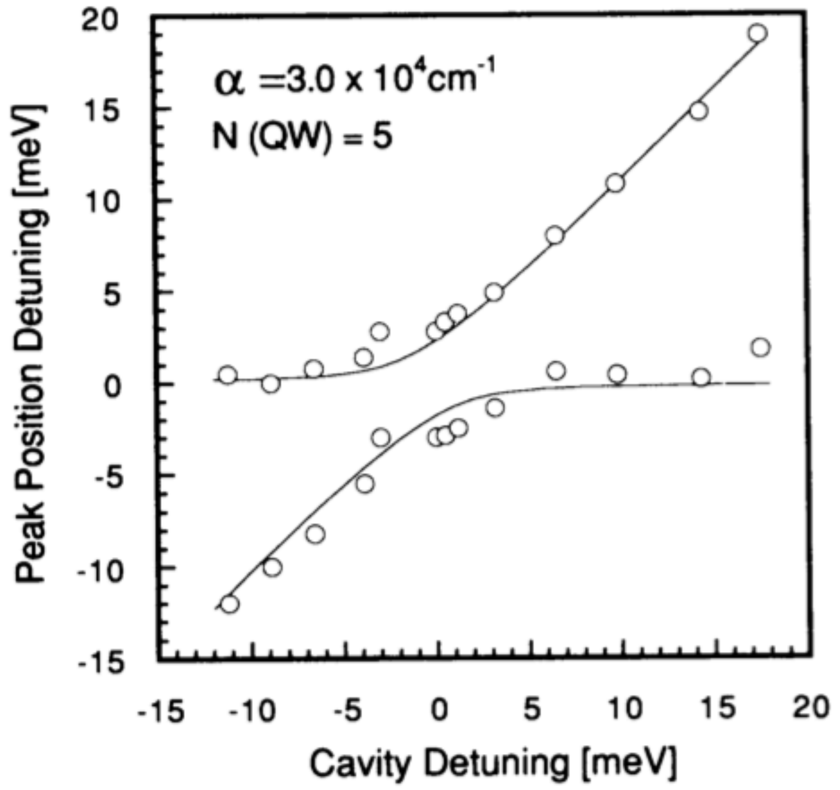

FIG. 3. Reflectivity peak positions as a function of cavity detuning for a five-quantum-well sample at $T = 5$ K. The theoretical fit is obtained through a standard multiple-interference analysis of the DBR–Fabry-Pérot–quantum-well structure.

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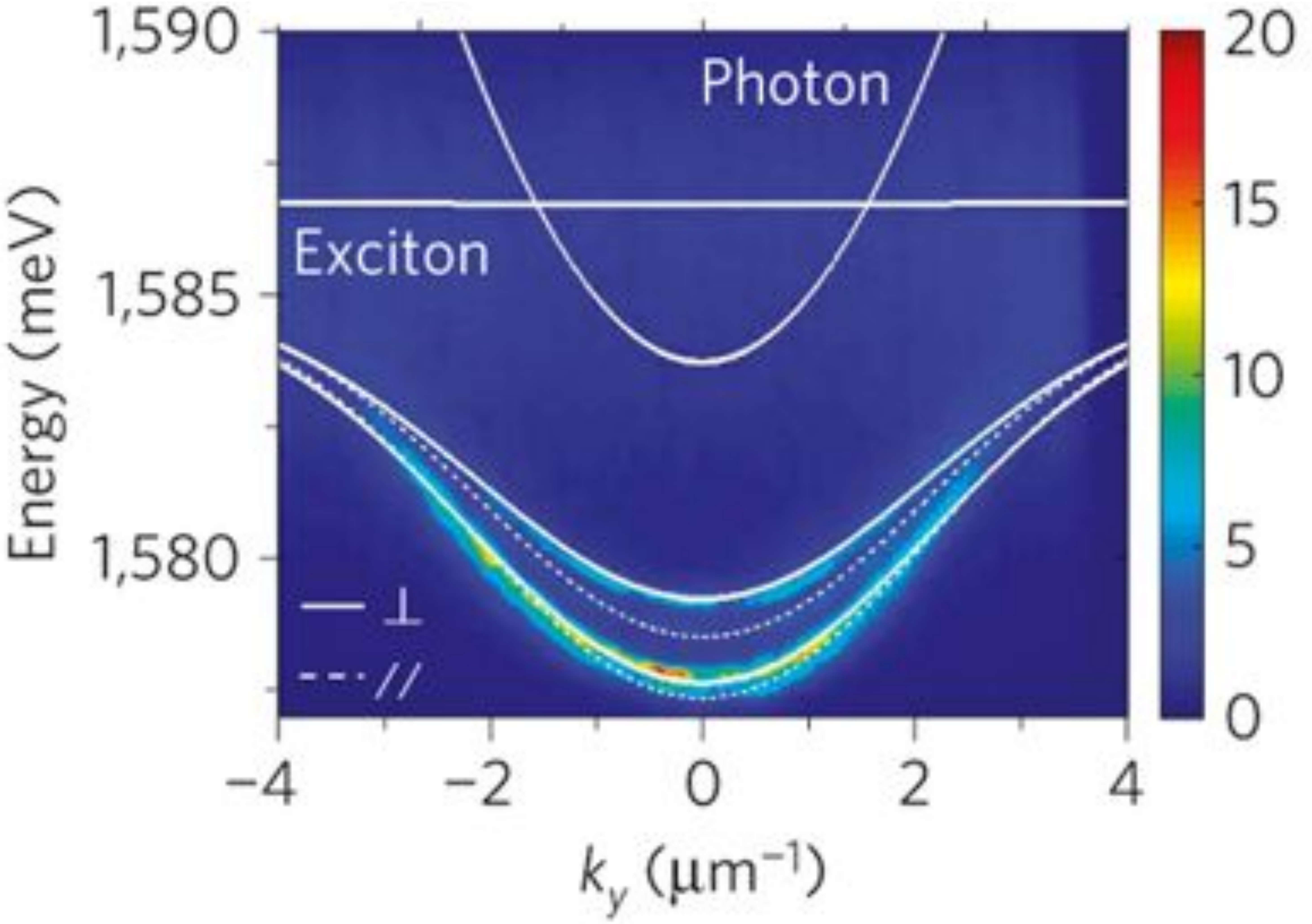
(Received 12 May 1992)

Cavity exciton-polaritons



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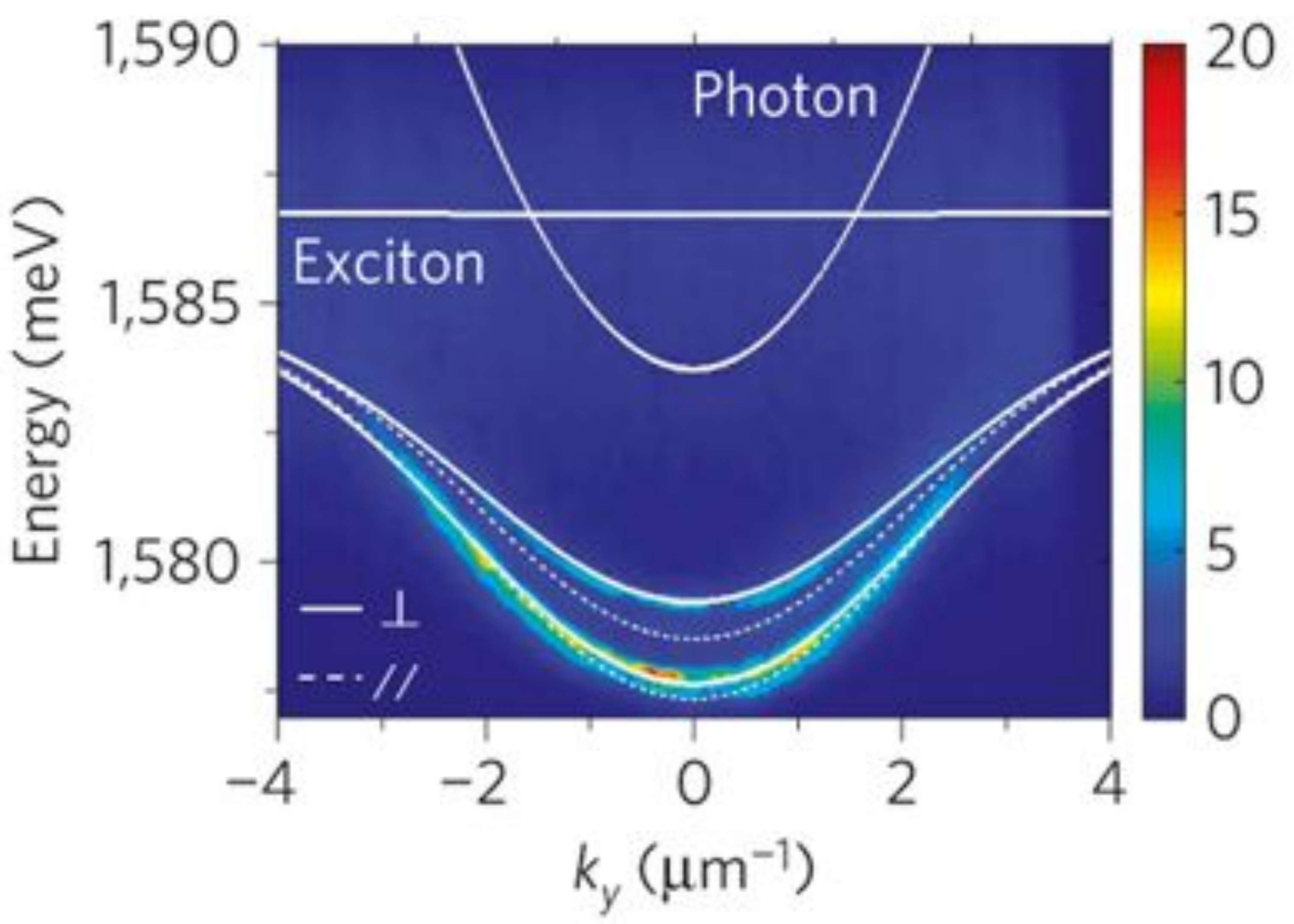
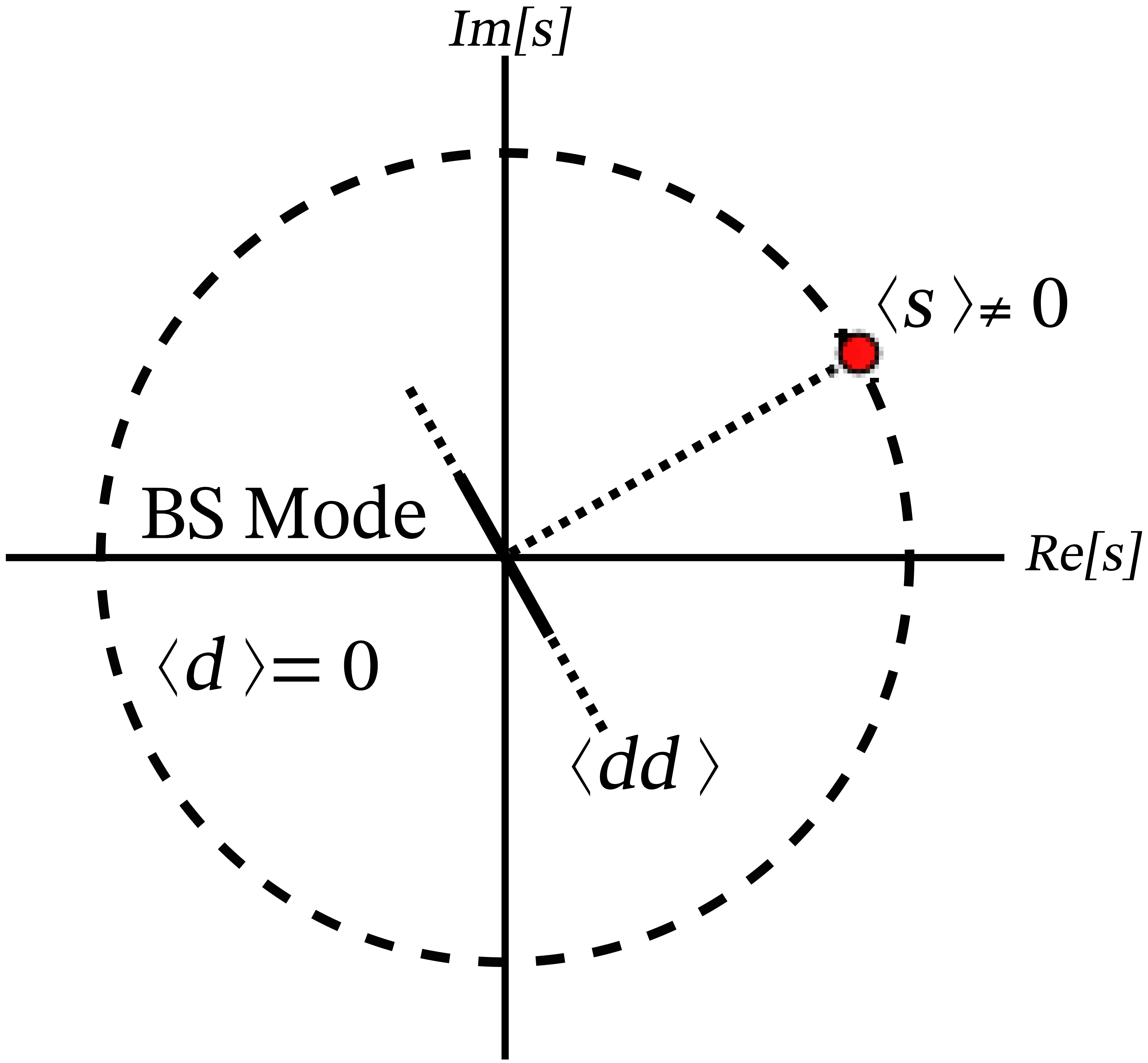


$$H = \begin{pmatrix} \Omega_{\text{exc}} & g \\ g & \omega_{\mathbf{q}} \end{pmatrix}$$

- Exciton-polaritons have been studied for 60 years — Hopfield Phys. Rev. 112, 1555-1567 (1958).
- The physics can be qualitative well described by a theory of coupled bosons
- Not only can polaritonic states be formed, but condensation is observed up to room temperature in some cases — Plumhof et al. Nature Materials 13, 247-252 (2014).

Bardasis-Schrieffer Polaritons

~ a superconductor exciton-polariton



Phys. Rev. B 99, 020504(R)

The Bardasis-Schrieffer mode

PHYSICAL REVIEW VOLUME 121, NUMBER 4 FEBRUARY 15, 1961

Excitons and Plasmons in Superconductors*

A. BARDASIS AND J. R. SCHRIEFFER
University of Illinois, Urbana, Illinois

(Received October 13, 1960)

$$V(\mathbf{k},\mathbf{k}') = \sum_{\Gamma} g_{\Gamma} f_{\Gamma}(\mathbf{k}) f_{\Gamma}(\mathbf{k}') \simeq g_s + g_d f_d(\mathbf{k}) f_d(\mathbf{k}')$$

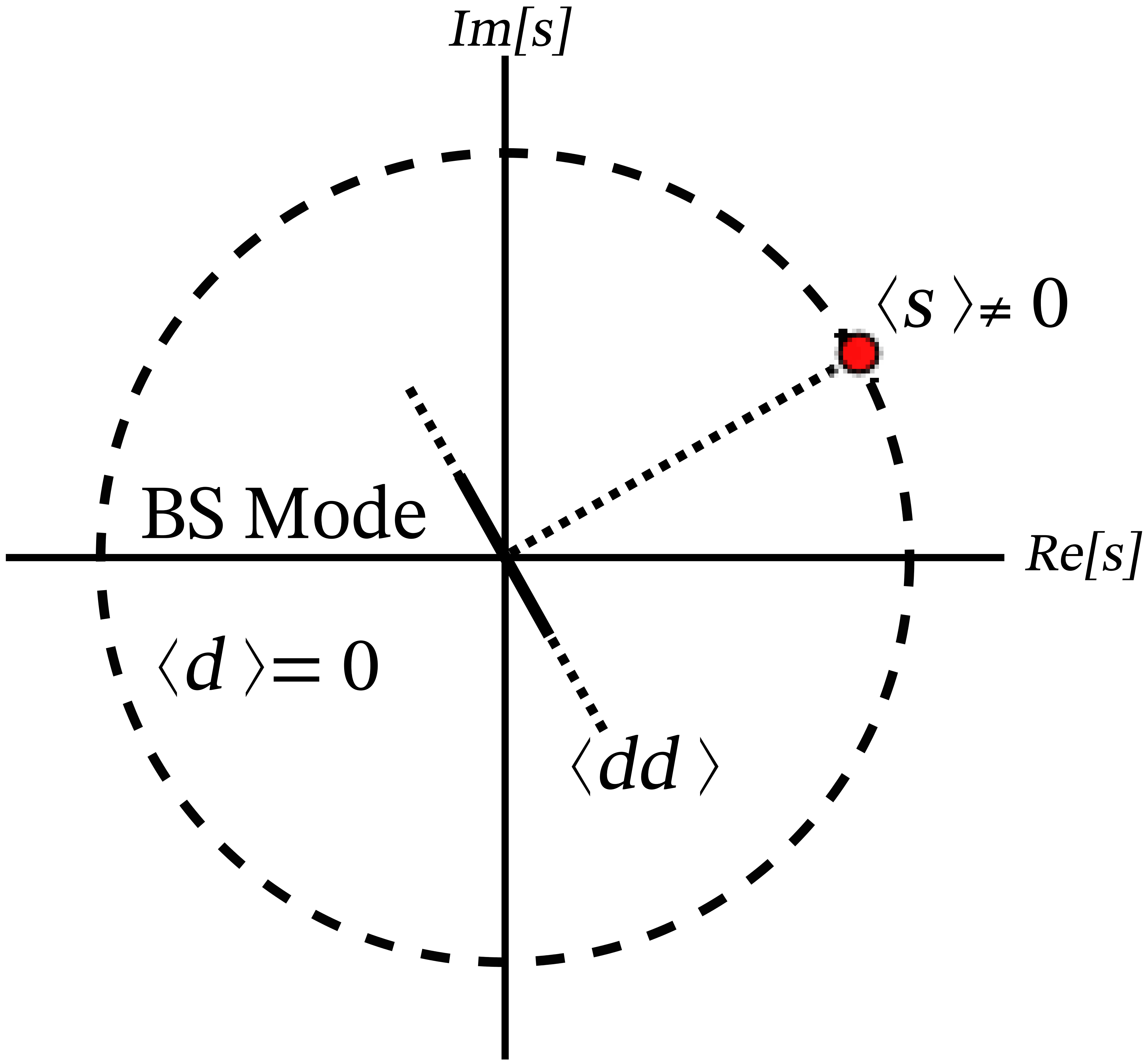
$$\mathscr{L} = \frac{1}{g_s}|s|^2 + \frac{1}{g_d}d^2 + \sum_i \bar{\psi}_i\left(i\omega_n + \xi_{\mathbf{k}} + s + d f_d(\mathbf{k})\right)\psi$$

Higher angular momentum channel

$$\langle s \rangle = \Delta_0$$
$$\langle d \rangle = 0$$

$$\langle d_{-q} d_q \rangle \propto \left(\omega_m^2 + \Omega_{\mathrm{BS}}^2(\mathbf{q})\right)^{-1}$$

The closest analog to excitons in a superconductor



See Also

*e.g. Maiti, S. & Hirschfeld, P. J. Phys. Rev. B **92**, 094506 (2015).*

Effective bosonic theory of coupled modes

$$S_{\text{eff}} = \frac{1}{2\beta} \sum_q (d_{-q}, A_{\alpha,-q}) \underbrace{\begin{pmatrix} D^{-1}_{\text{BS},q} & g_{\beta,q} \\ g^*_{\alpha,q} & D^{-1}_{\alpha\beta,q} \end{pmatrix}}_{\mathscr{D}^{-1}} \begin{pmatrix} d_q \\ A_{\beta,q} \end{pmatrix}$$

Bardasis-Schrieffer

Photon

Two polarizations = Two modes

- We want to obtain a Hamiltonian description like in the exciton-polariton case

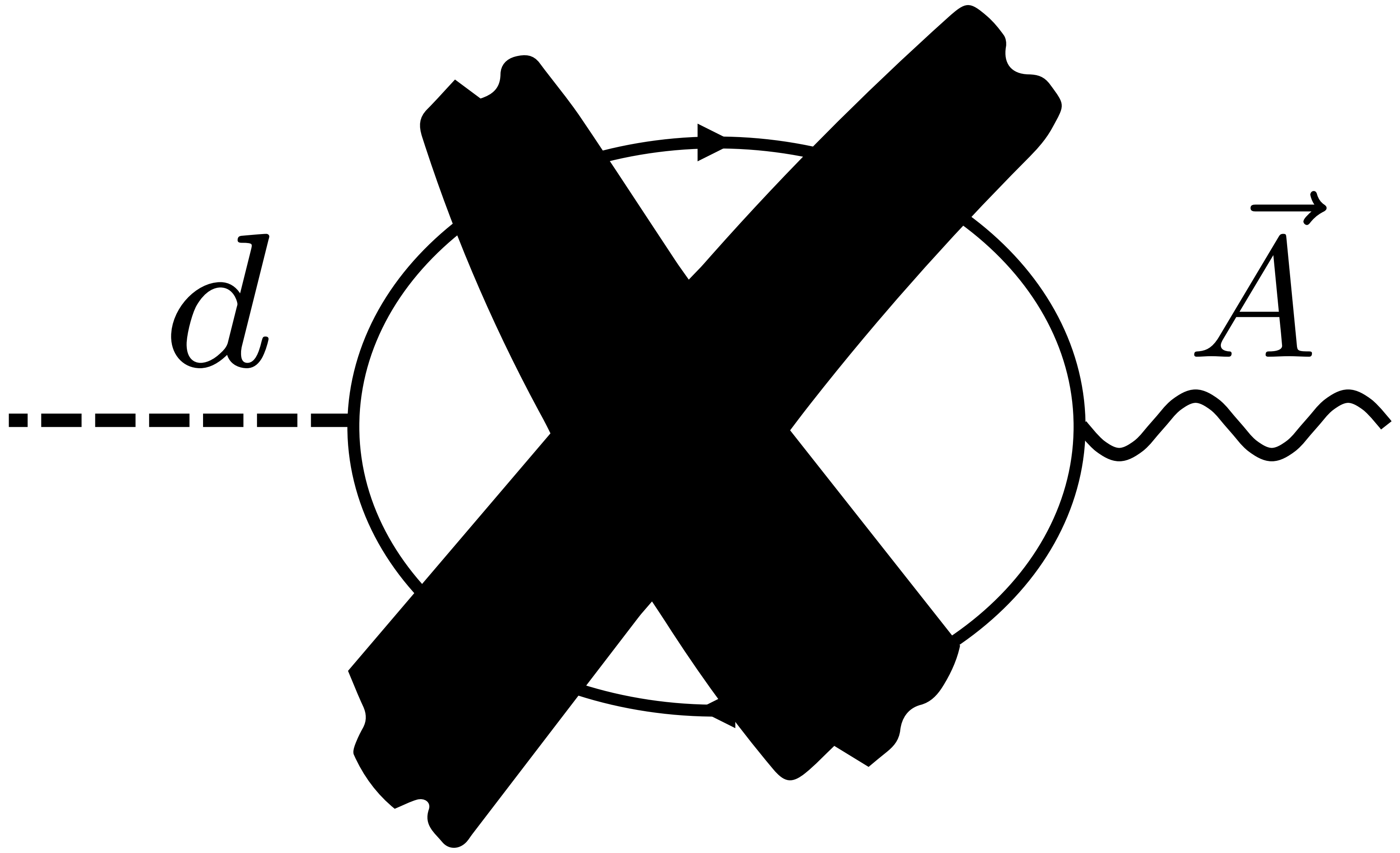
$$d_q \propto b_q + \bar{b}_{-q} \qquad A_{\alpha,q} \propto a_{\alpha,q} + \bar{a}_{\alpha,-q}$$

- Of particular importance is the hybridization term g
  - This is due to quasiparticles

$$S_{\text{eff}} \approx \frac{1}{\beta} \sum_q \left(\bar{b}_q, \bar{a}_{\alpha,q}\right) \left(-i\Omega_m + \check{H}^{\text{eff}}_{\mathbf{q}}\right) \begin{pmatrix} \bar{b}_{-q} \\ \bar{a}_{\beta,-q} \end{pmatrix}$$

A recurring theme: vanishing linear coupling

$$g = \sum_{\mathbf{k},q} \sum_{\alpha,\alpha'} \frac{n_F(E^{\alpha}_{\mathbf{k}}) - n_F(E^{\alpha'}_{\mathbf{k}})}{i\Omega_m - (E^{\alpha}_{\mathbf{k}} - E^{\alpha'}_{\mathbf{k}})} \left(-e\mathbf{v}_{\mathbf{k}} \cdot \mathbf{A}_q \hat{\tau}_0\right)_{\alpha,\alpha'} \left(f_d(\mathbf{k})\tau_2\right)_{\alpha',\alpha} = 0$$

$g =$ 

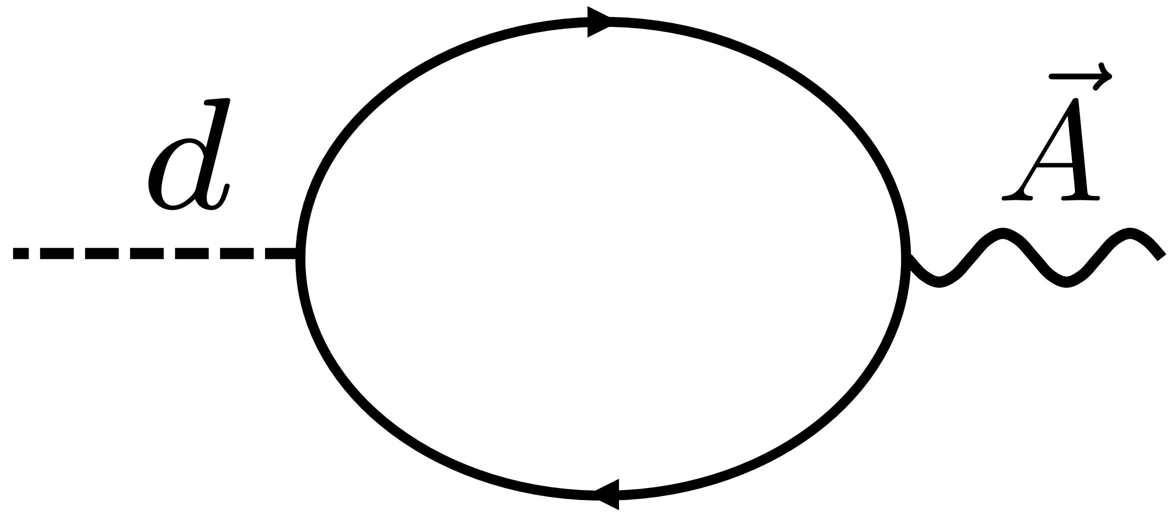
$$\longrightarrow = \hat{G} = \begin{pmatrix} G & F \\ F^{\dagger} & -G^T \end{pmatrix}$$

Nambu Matrix Green's Function

- The coupling between the BS mode and photons vanishes at **q** = 0
- Due to
  - vanishing overlap of matrix elements (current and SC vertices)
  - rotational symmetry (d-wave form factor)
  - inversion symmetry (velocity operator)

Moor, A., Volkov, A. F. & Efetov, K. B. Phys. Rev. Lett ***118****, 047001 (2017).*

Condensate flow induced coupling

$g =$ 

Nambu Green's Function

$$\longrightarrow = \hat{G} = \begin{pmatrix} G & F \\ F^{\dagger} & -G^{T} \end{pmatrix}$$

- Condensate flow has two important effects on the system
  - The energy acquires a doppler shift term from the superfluid velocity
  - A new current vertex coupling to the gauge field arises (proportional to the superfluid velocity)

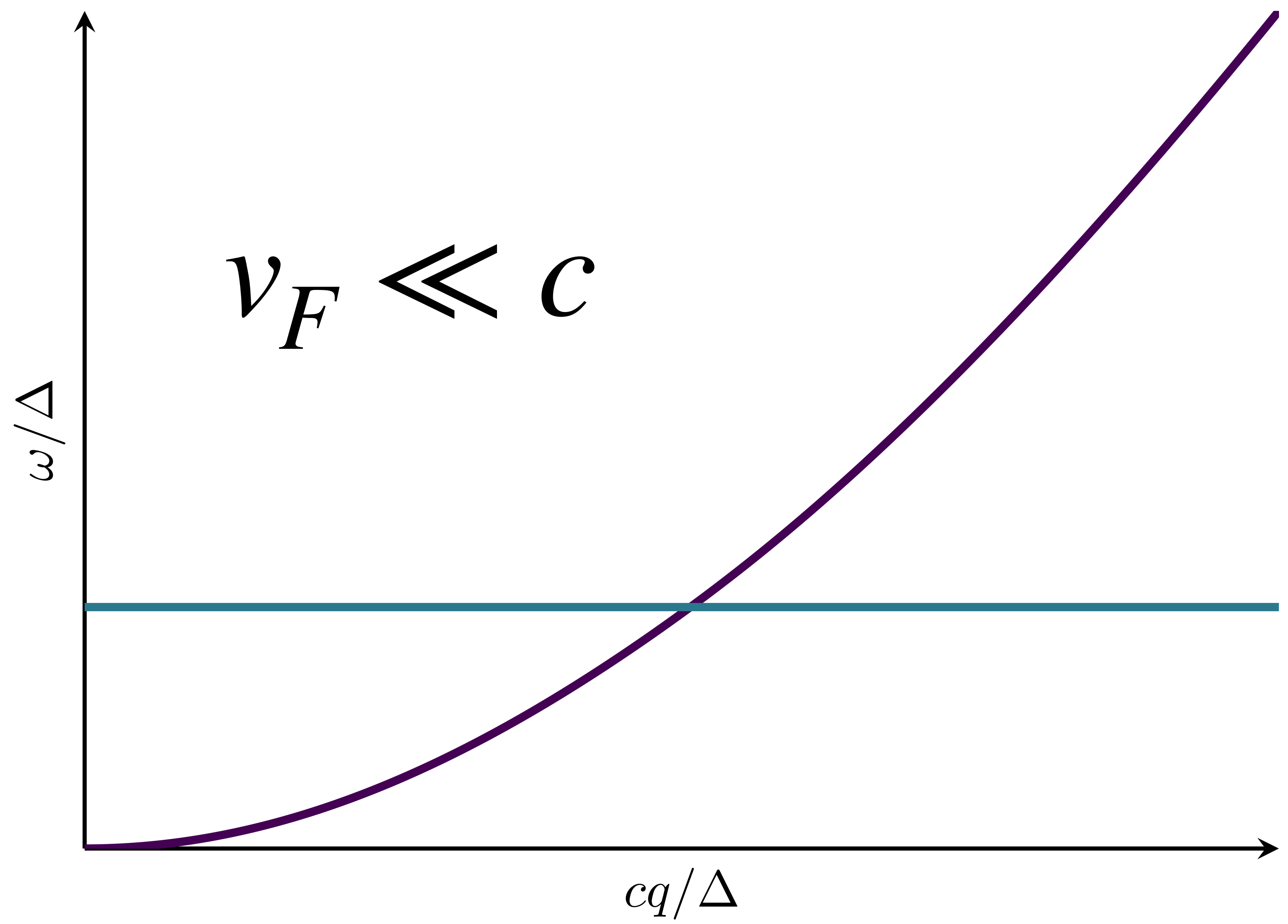
$$\xi_k \rightarrow \xi_k + \frac{m}{2} v_S^2 + \vec{k} \cdot \vec{v}_S$$

$$S_{\psi-A} \rightarrow \frac{1}{\beta} \sum_{k,q} \bar{\Psi}_{k+\frac{q}{2}} \left(-e\vec{v}_k\, \hat{\tau}_0 - e\vec{v}_S\, \hat{\tau}_3\right) \cdot \vec{A}_q \Psi_{k-\frac{q}{2}}$$

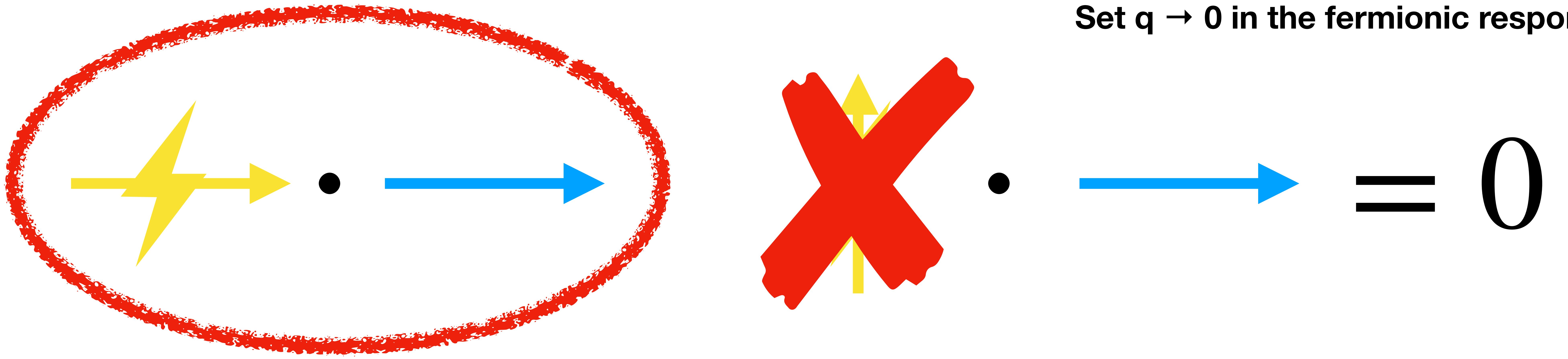
Phys. Rev. B 99, 020504(R)

Effective **Hamiltonian** bosonic theory of coupled modes

$$\check{H}_q^{\text{eff}} = \begin{pmatrix} \Omega_{\text{BS}} & g & 0 \\ g^* & \omega_q + \Pi^S & 0 \\ 0 & 0 & \omega_q \end{pmatrix},$$



Set q → 0 in the fermionic response

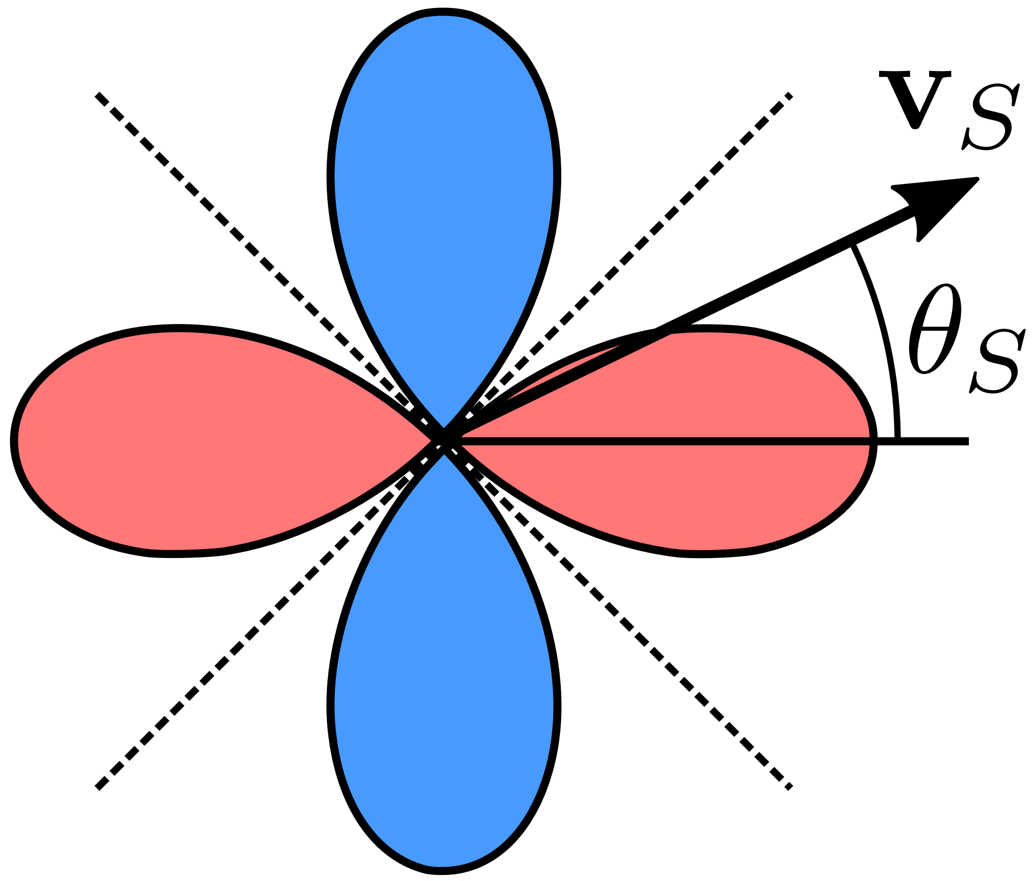


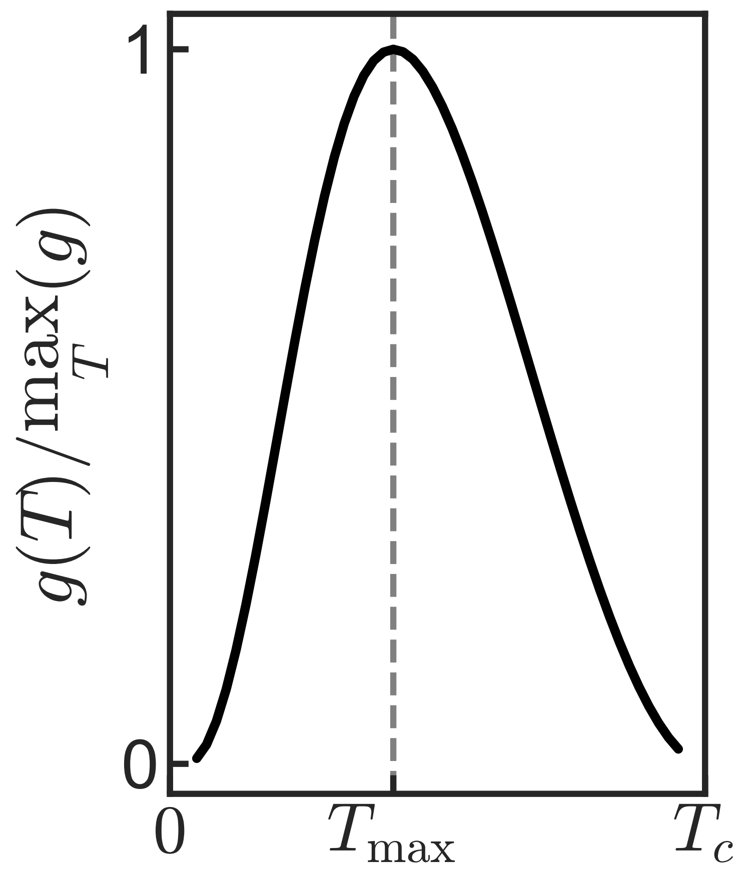
These form approximately decoupled polarizations

Effective **Hamiltonian** bosonic theory of coupled modes

$$\check{H}_q^{\text{eff}} = \begin{pmatrix} \Omega_{\text{BS}} & g & 0 \\ g^* & \omega_q + \Pi^S & 0 \\ 0 & 0 & \omega_q \end{pmatrix},$$

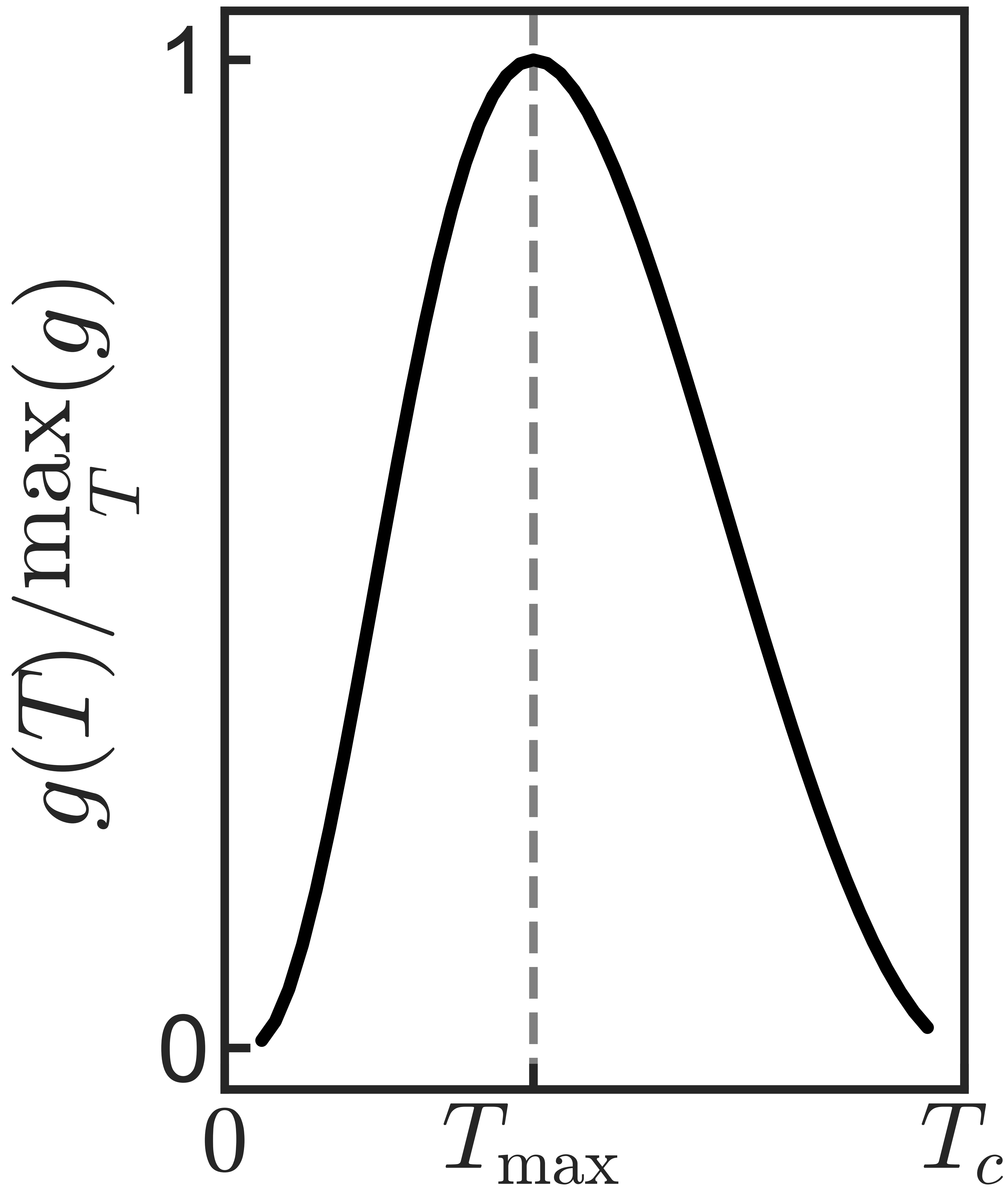
Shift of photon branch





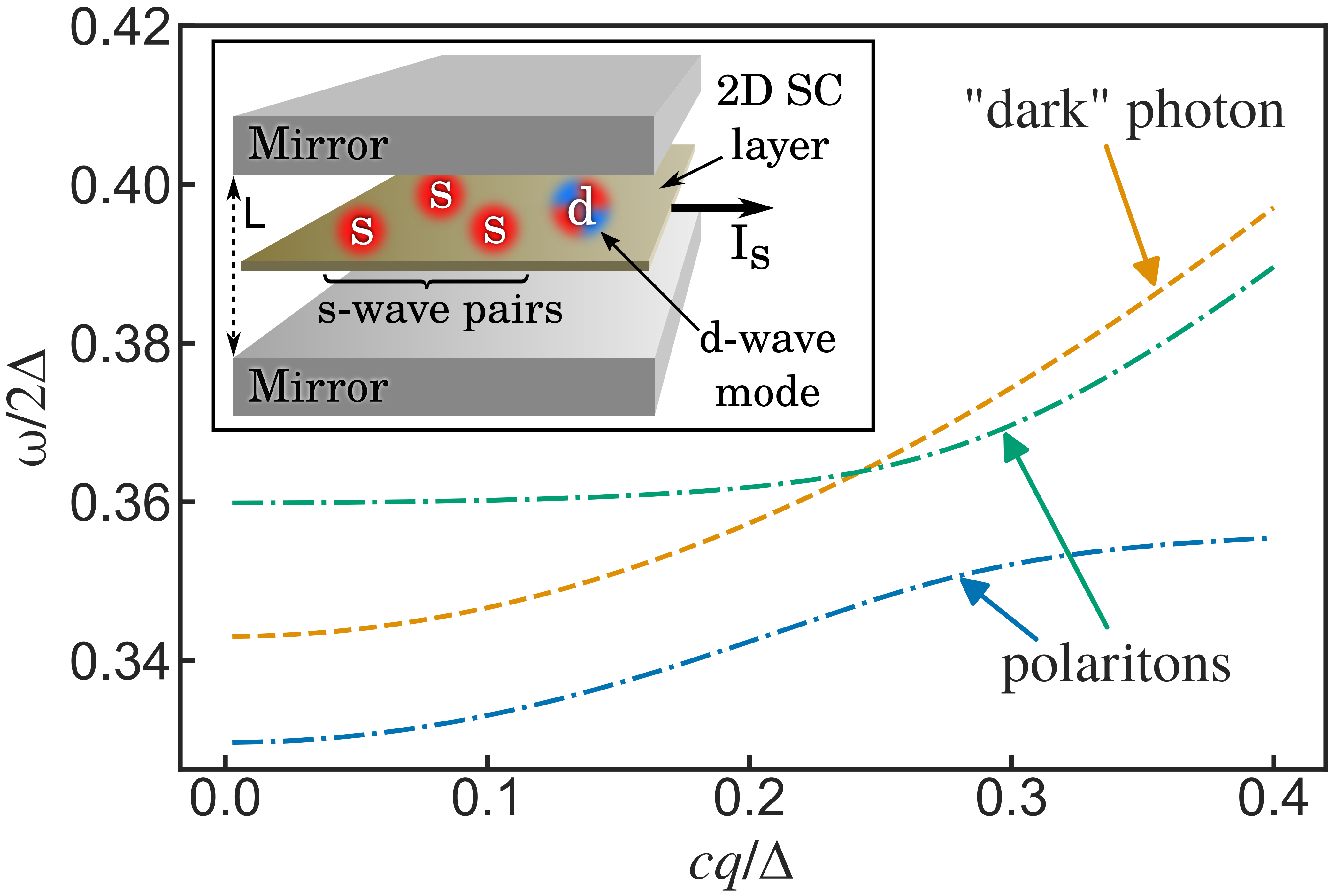
- Within the low-energy theory the Hamiltonian separates into two sectors
- A single purely photonic mode: *the 'dark' photon*
- A hybrid collective mode-photon sector: the Bardasis-Schrieffer polaritons

Effective **Hamiltonian** bosonic theory of coupled modes

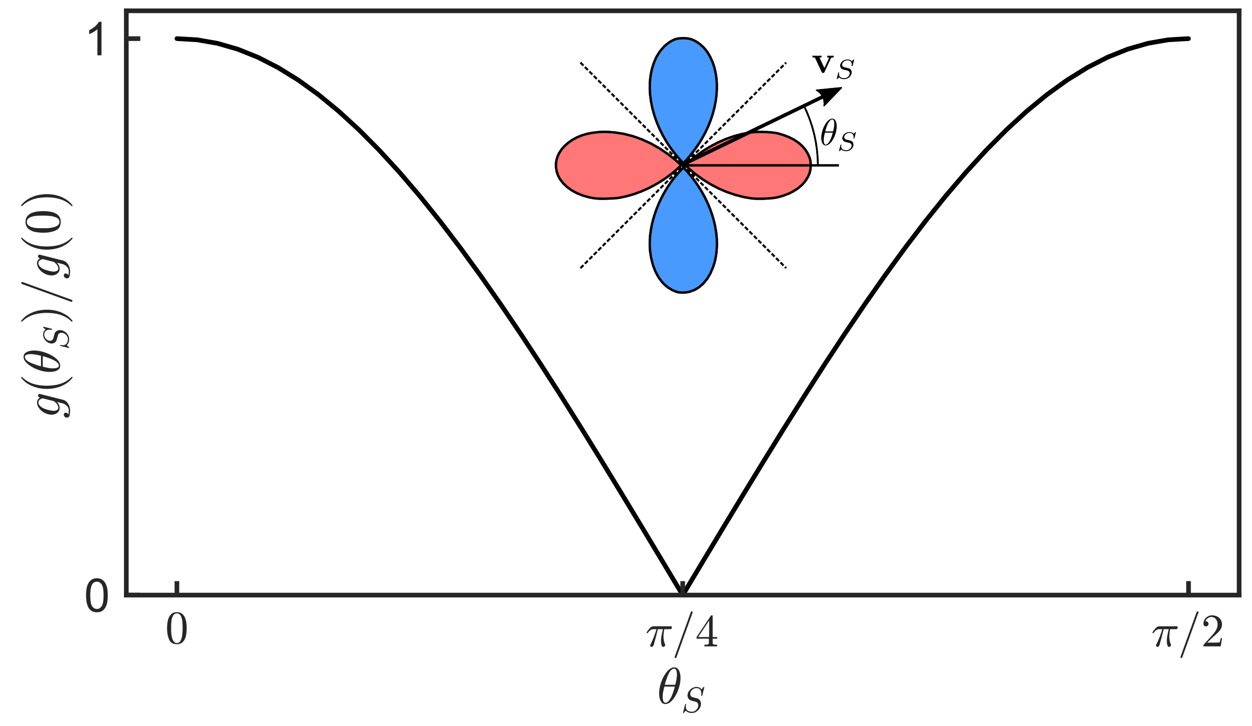


- Coupling is due to quasi-particles
- This leads to an intermediate temperature where coupling is maximized

Bardasis-Schrieffer Polaritons

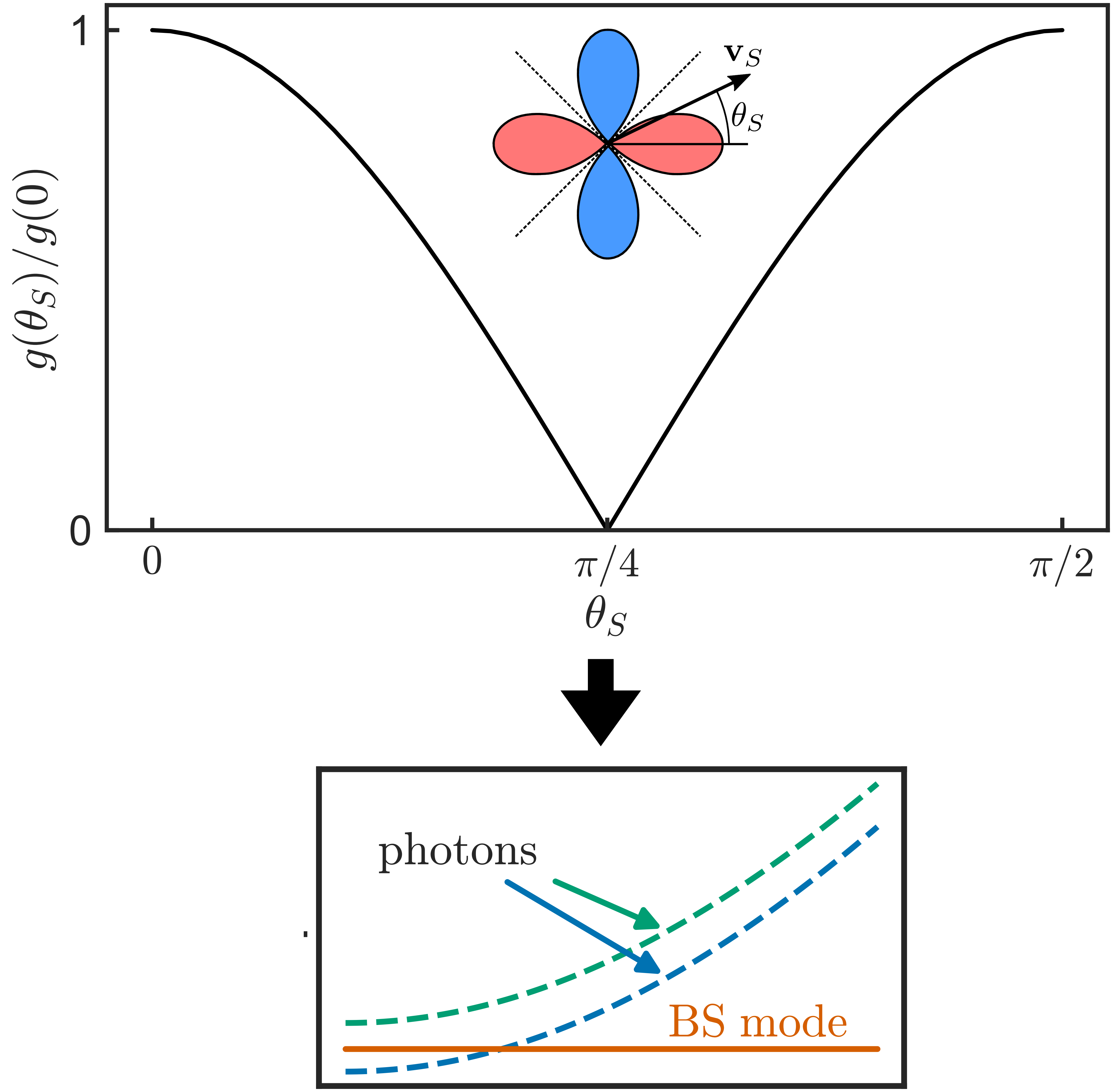


- Both the polariton bands and the ‘dark’ photon can be observed in the bosonic dispersion



arXiv:1807.06601

Angular dependence



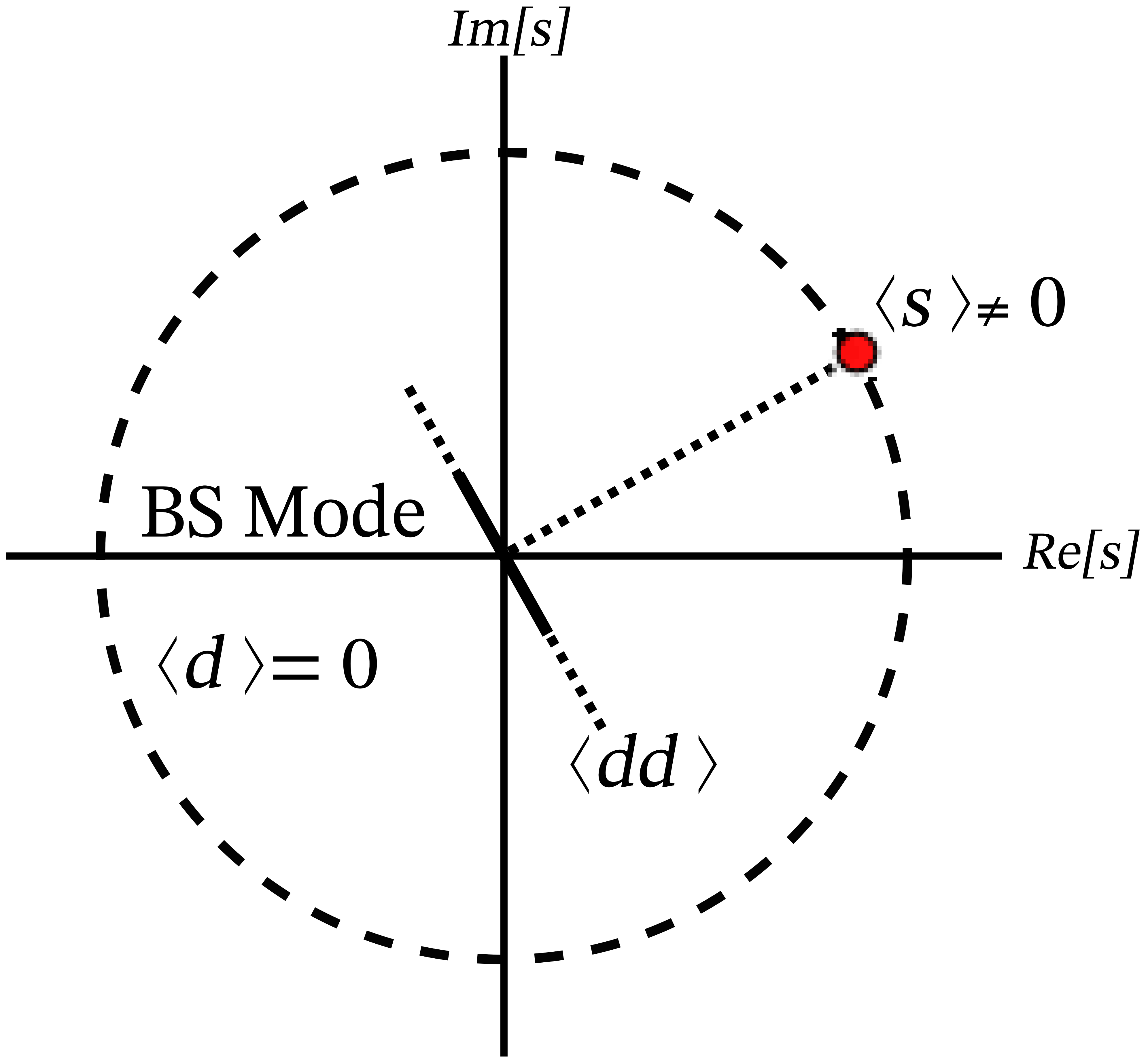
- The form of the coupling allows the strength of the hybridization to be modified *in situ* by changing the direction of the supercurrent

- The modes exactly decouple at $\theta=\pi/4$ (the nodes of the d-wave form factor)

Phys. Rev. B 99, 020504(R)

Non-equilibrium s+id superconductivity

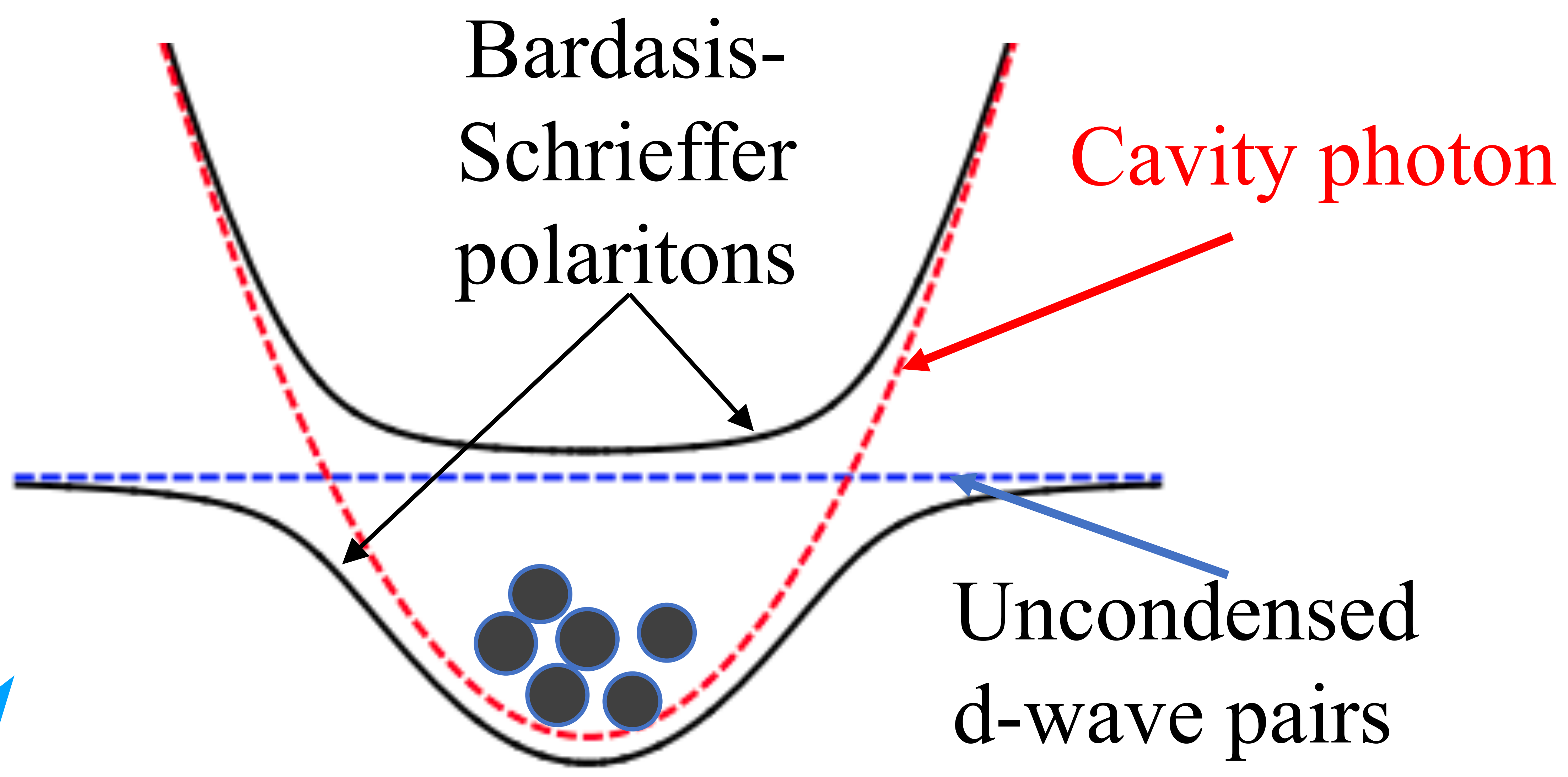
- Due to finite overlap with the BS mode, coherent population of the lower polariton branch would induce a non-equilibrium s±id state
- This is due to the phase relation implied by the BS mode



Phys. Rev. B 99, 020504(R)

Non-equilibrium s+id superconductivity

- In analogy with exciton-polariton condensation, we conjecture that it may be possible for Bardasis Schrieffer-polaritons to condense
  - Residual interaction arise from qua terms
  - Thermalization time from physics of orde Δ
  - Decay time of order cavity decay rate
- Such condensation could represent and transient non-equilibrium s±id state



excite polaritons

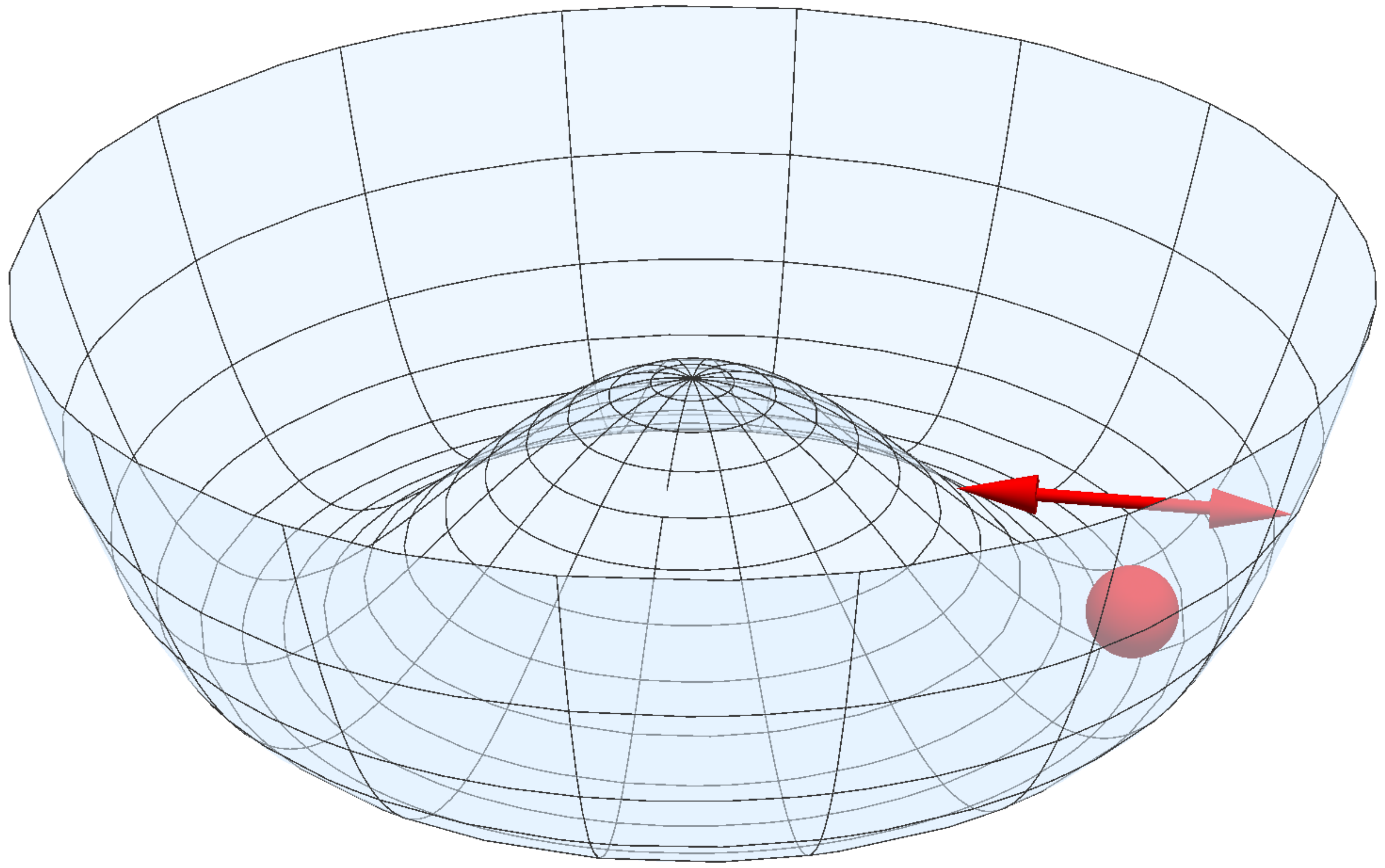
Polaritons Equilibrate	Transient State	Polaritons Decay • • •

ground state

Phys. Rev. B 99, 020504(R)

Higgs-Polaritons

~ a collective mode-polariton



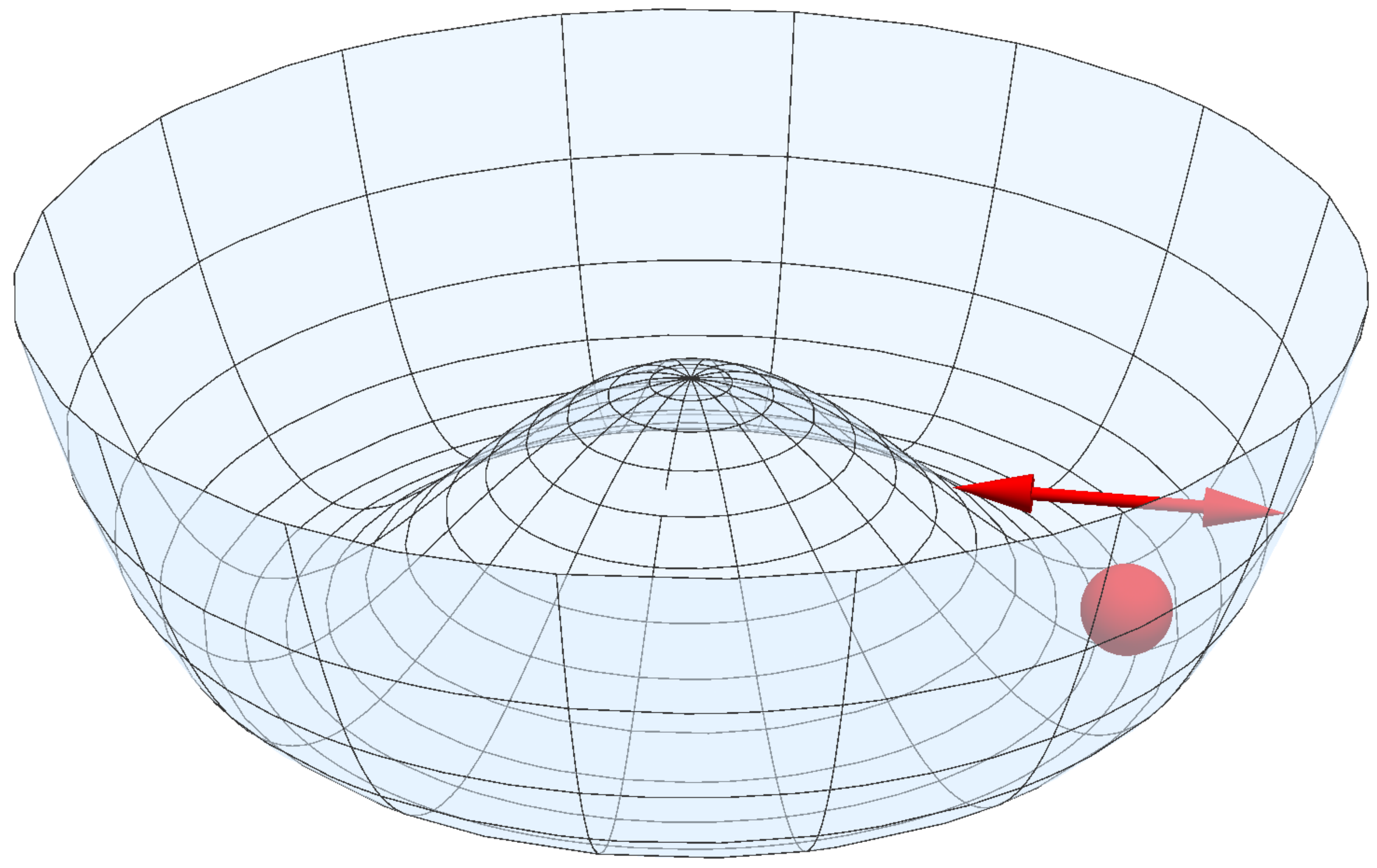
Coupling the Higgs mode to light

$$|\Delta(q,\Omega)| = \Delta_0 + \delta\Delta(q,\Omega)$$

$$\Omega_{\mathrm{Higgs}} = 2\Delta_0$$

- The Higgs mode is the amplitude mode of the superconducting order parameter

- In general, photons do not couple to the Higgs mode of a superconductor as it has no charge or dipole moments.



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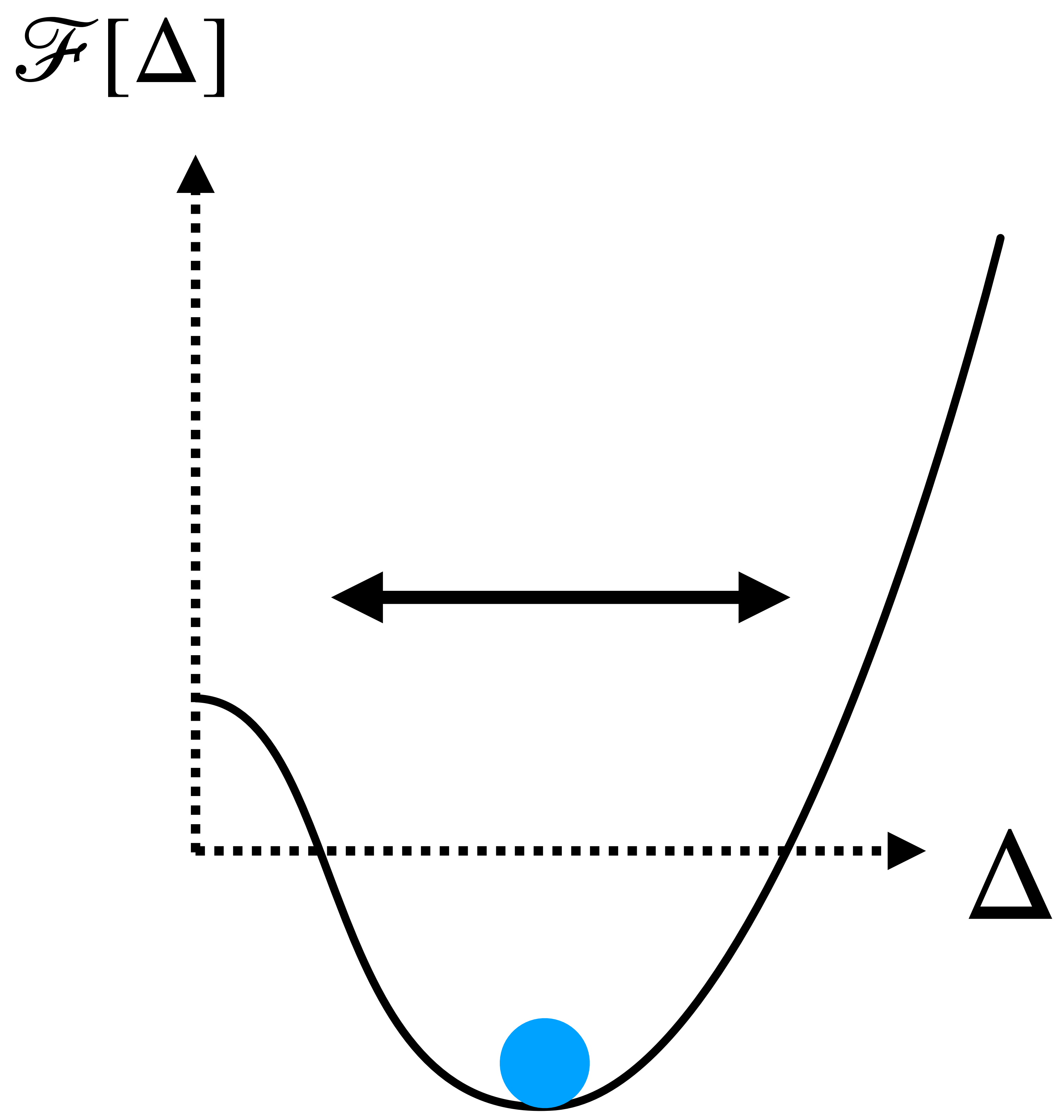


Linear coupling to the Higgs mode

System	Higgs-photon coupling?
Clean	$= 0$
Supercurrent	$= 0$
Disorder & Supercurrent	$\neq 0$

Moor, A., Volkov, A. F. & Efetov, K. B., Phys. Rev. Lett 118, 047001 (2017).
Nakamura, S. et al. Infrared activation of Higgs mode by supercurrent injection in a superconductor NbN. arXiv (2018).

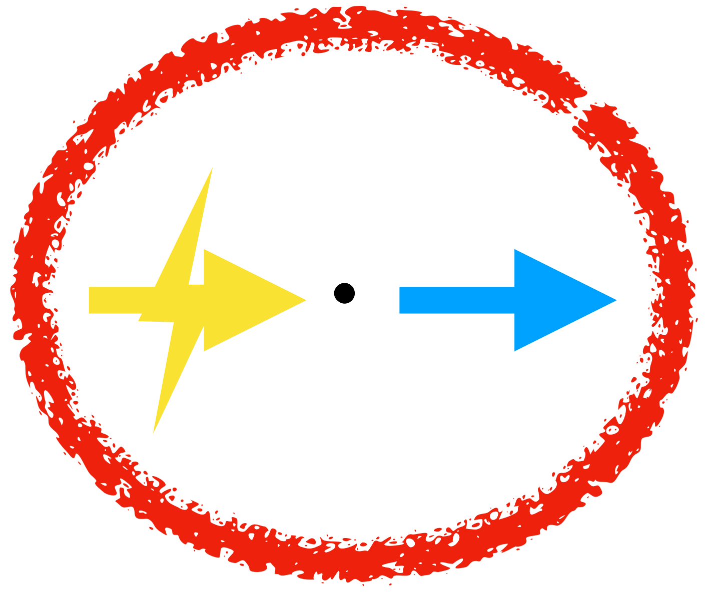
Effective bosonic theory of coupled modes

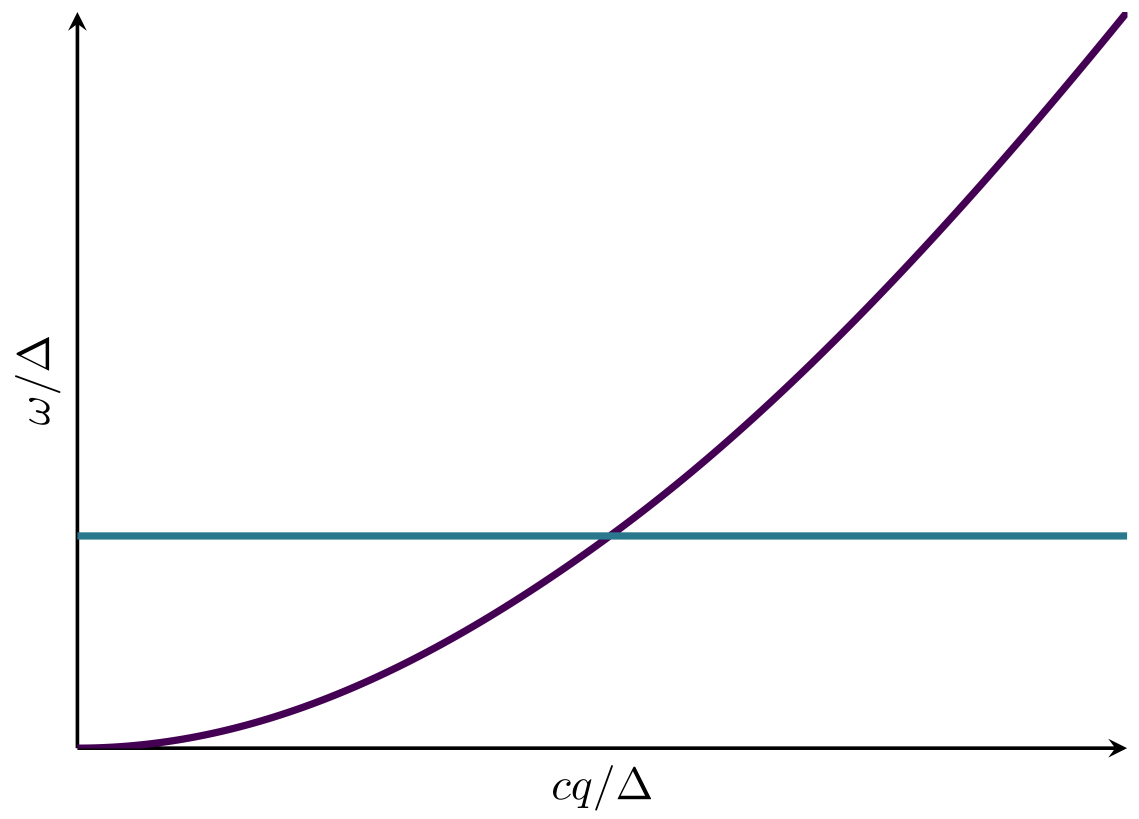
Higgs

$$[\hat{G}^R]^{-1}(\omega, \mathbf{q}) = \begin{pmatrix} -\frac{2\nu}{\lambda} - \Pi_h^R(\omega) & g^R(\omega) \\ g^R(\omega) & D^{-1}(\omega, \mathbf{q}) - \Pi_A^R(\omega) \end{pmatrix}$$

$$g^R \propto v_s$$

Photon





Hybrid Modes

$$\det\left\{[G^R]^{-1}(\omega_{\mathbf{q}}, \mathbf{q})\right\} = 0$$

Spectral Function

$$\mathscr{A}(\omega, \mathbf{q}) = -\frac{1}{2\pi i}\,\mathrm{tr}\left[\hat{G}^R(\omega, \mathbf{q}) - \hat{G}^A(\omega, \mathbf{q})\right]$$

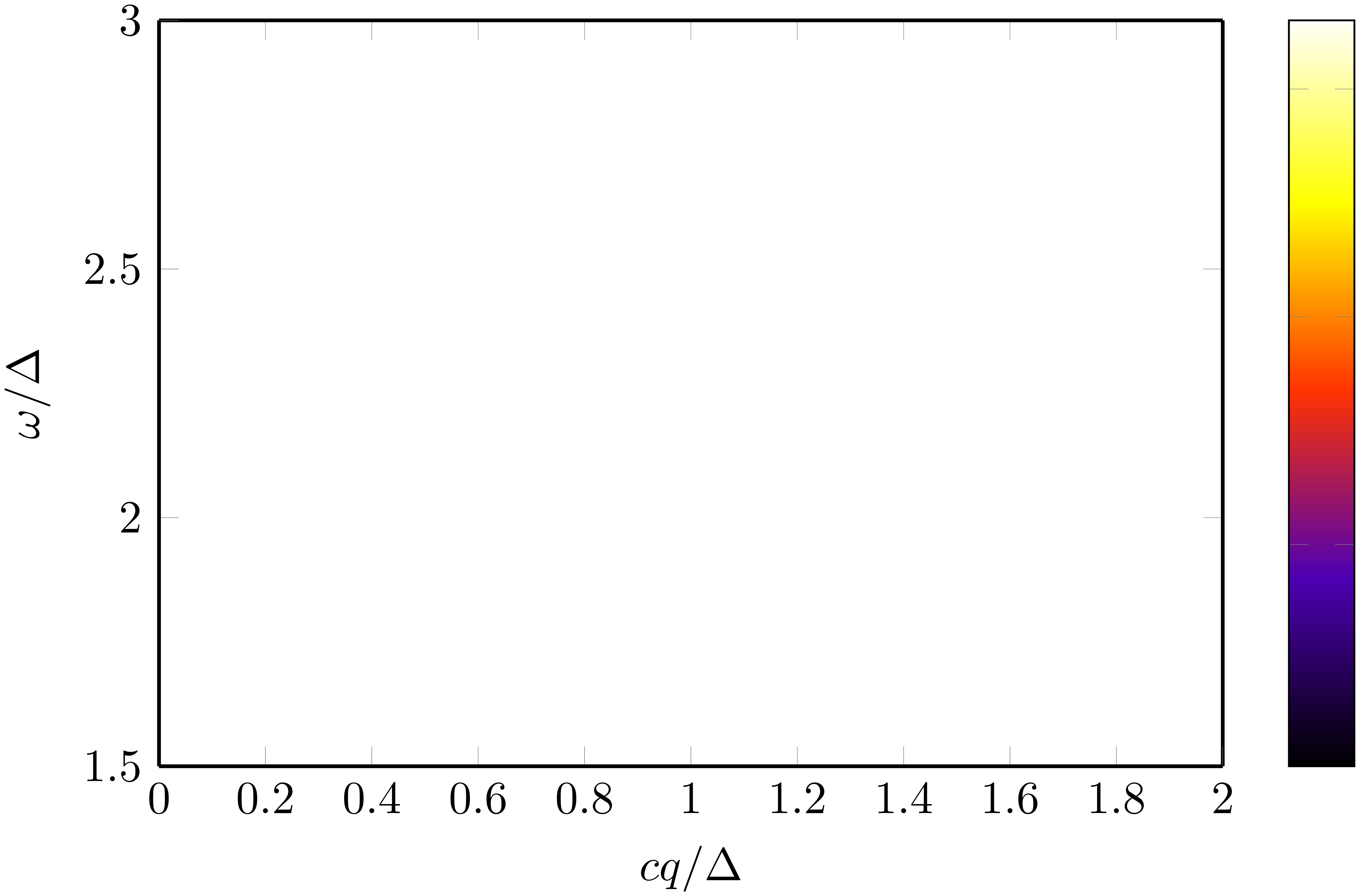
Effective bosonic theory of coupled modes

- Undamped excitation
  - δ - function at mode energy
- Damped excitation
  - Lorentzian at mode energy

Spectral Function

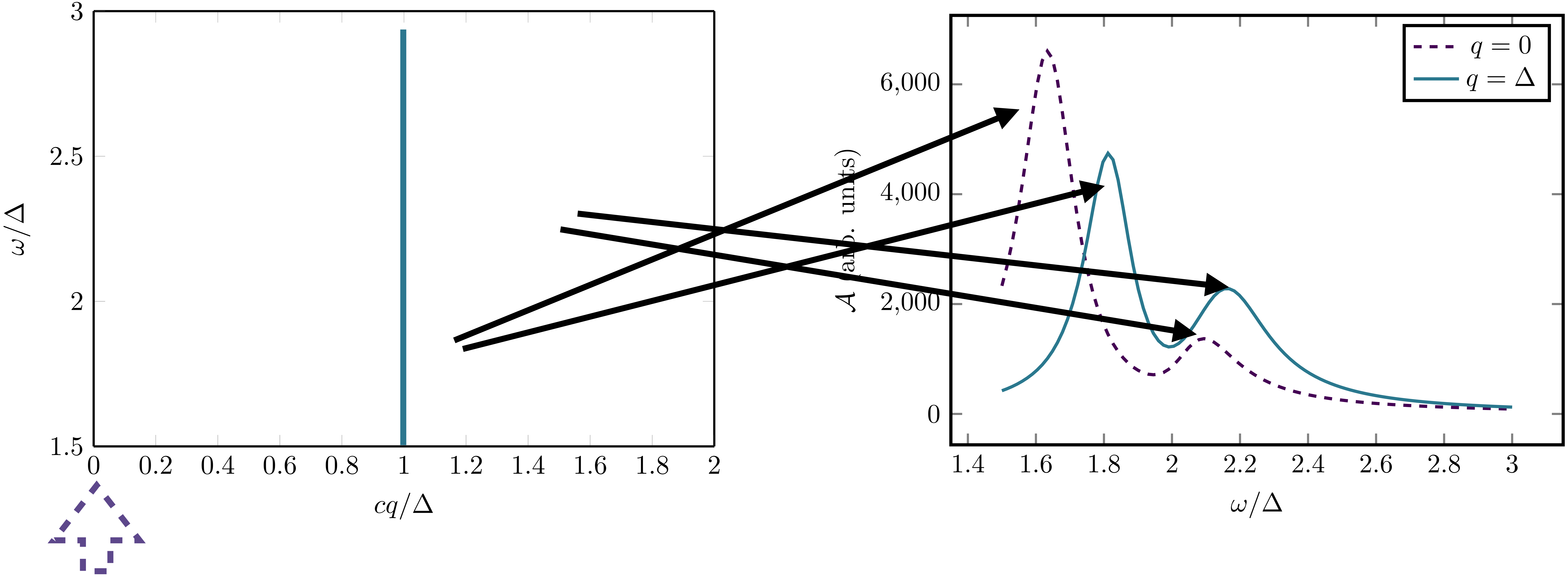
$$\mathscr{A}(\omega, \mathbf{q}) = -\frac{1}{2\pi i}\,\mathrm{tr}\left[\hat{G}^R(\omega, \mathbf{q}) - \hat{G}^A(\omega, \mathbf{q})\right]$$

Polariton Spectral function



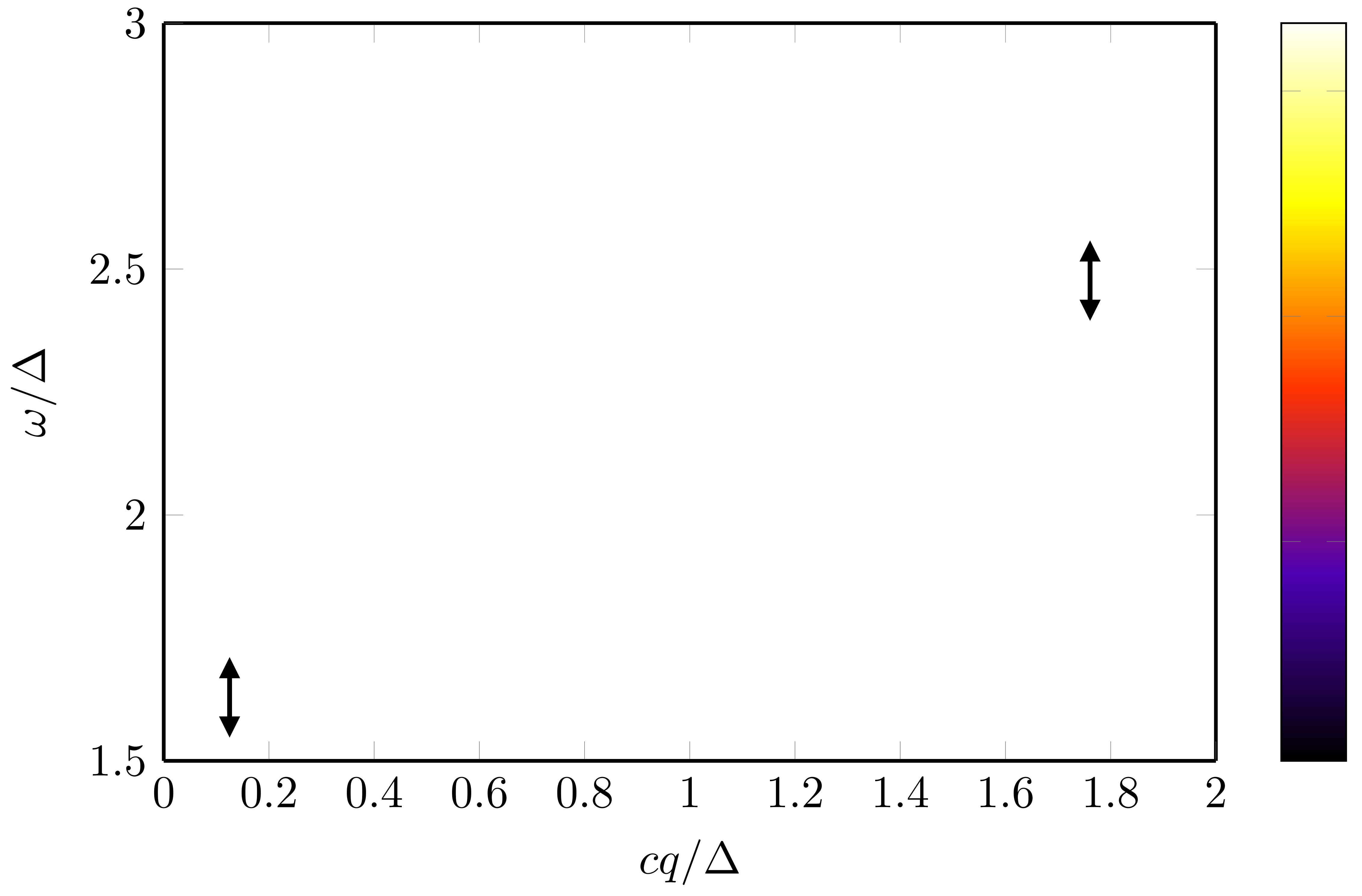
Polariton Spectral function

$$\mathscr{A} = -\frac{1}{2\pi i}\,\mathrm{tr}\left[G^R - G^A\right]$$



Damping of the Higgs Polariton

- There are two competing effects here
  - the Higgs mode is damped by its coupling to the two particle continuum
  - but, the hybridization pushes lower branch down into the gap



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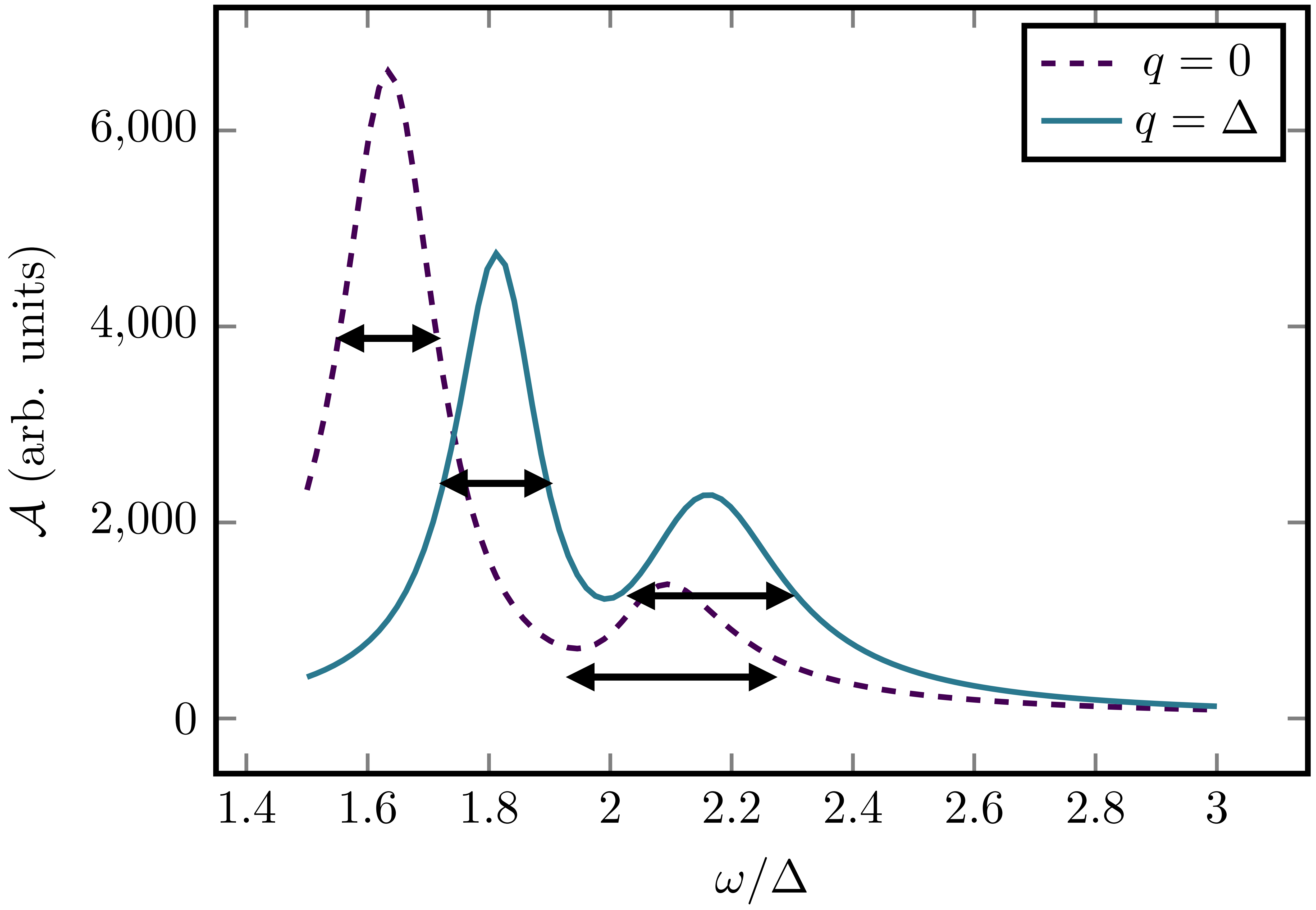
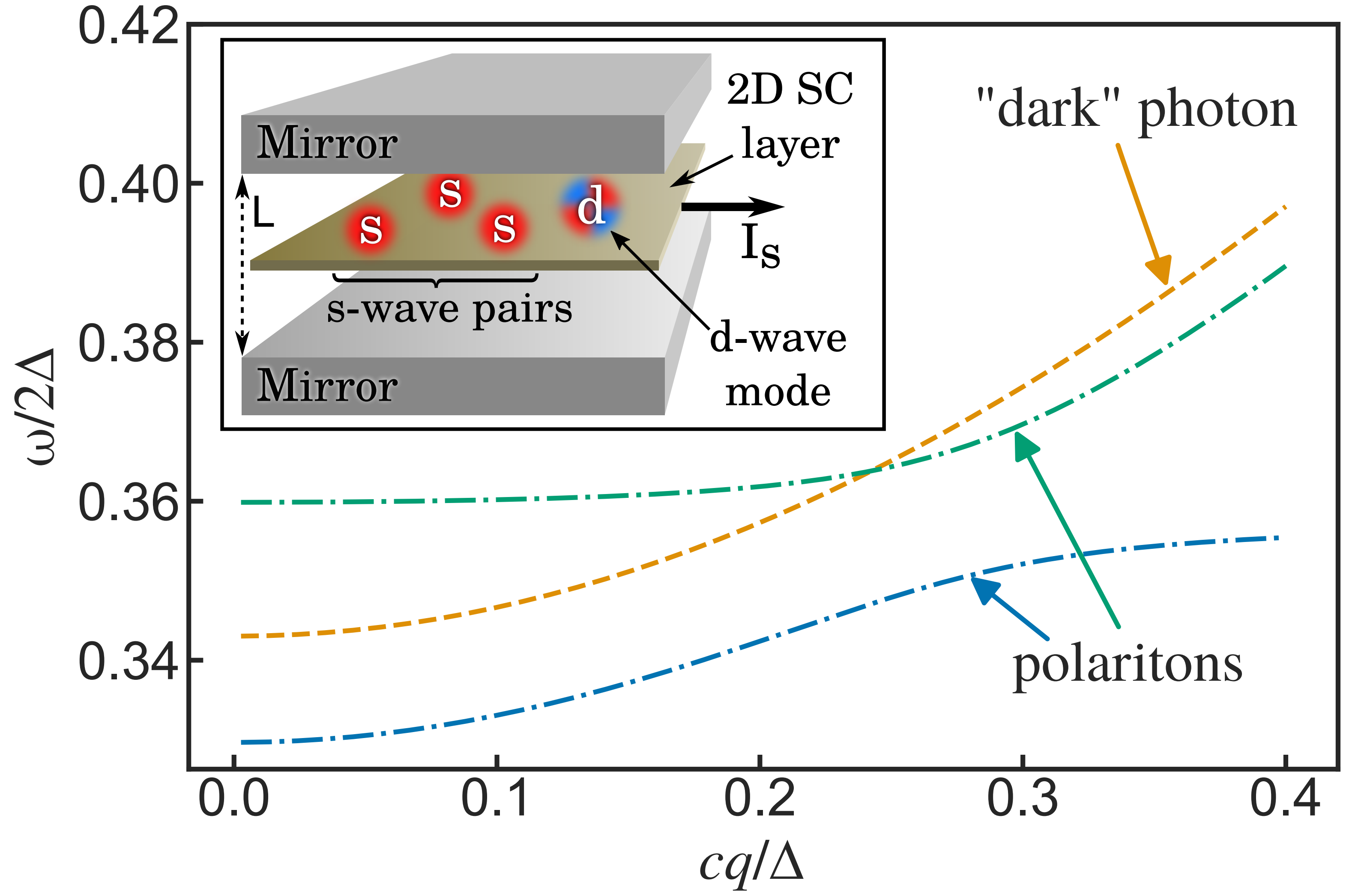
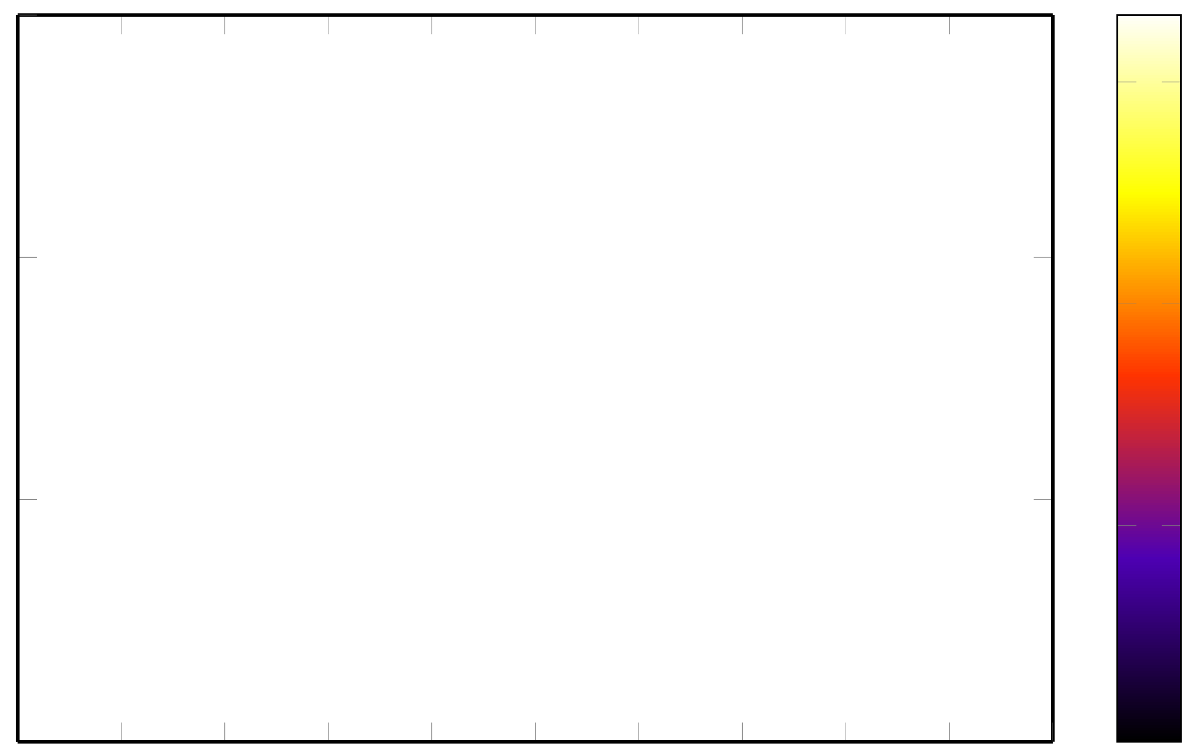


Cavity superconductor polaritons

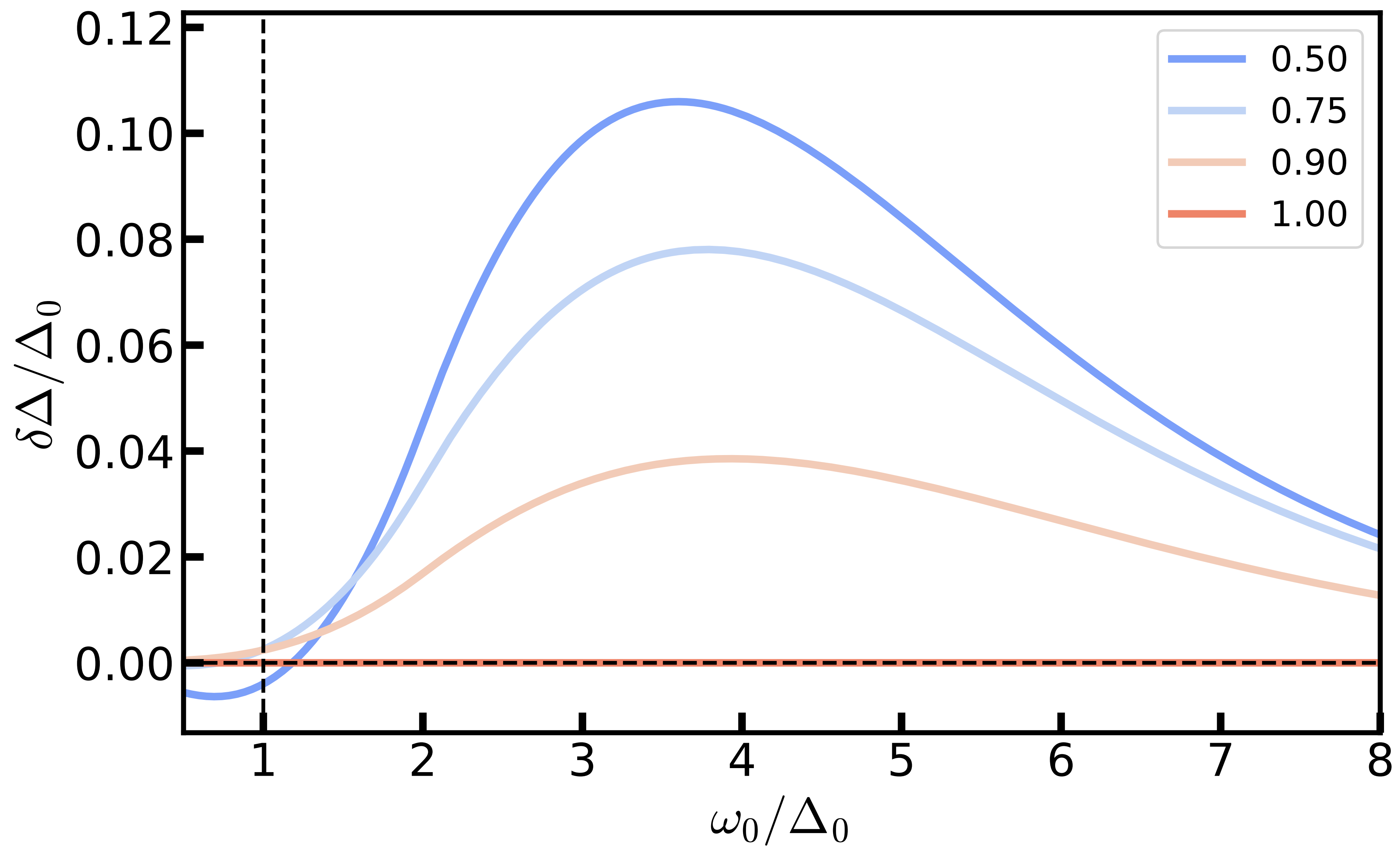
- Cavity photons can hybridize with the collective mode of a superconductor to form well defined hybrid excitations - *cavity superconductor-polaritons*
  - We have demonstrated this construction with two collective modes
    - The Higgs Mode
    - The Bardasis-Schrieffer Mode

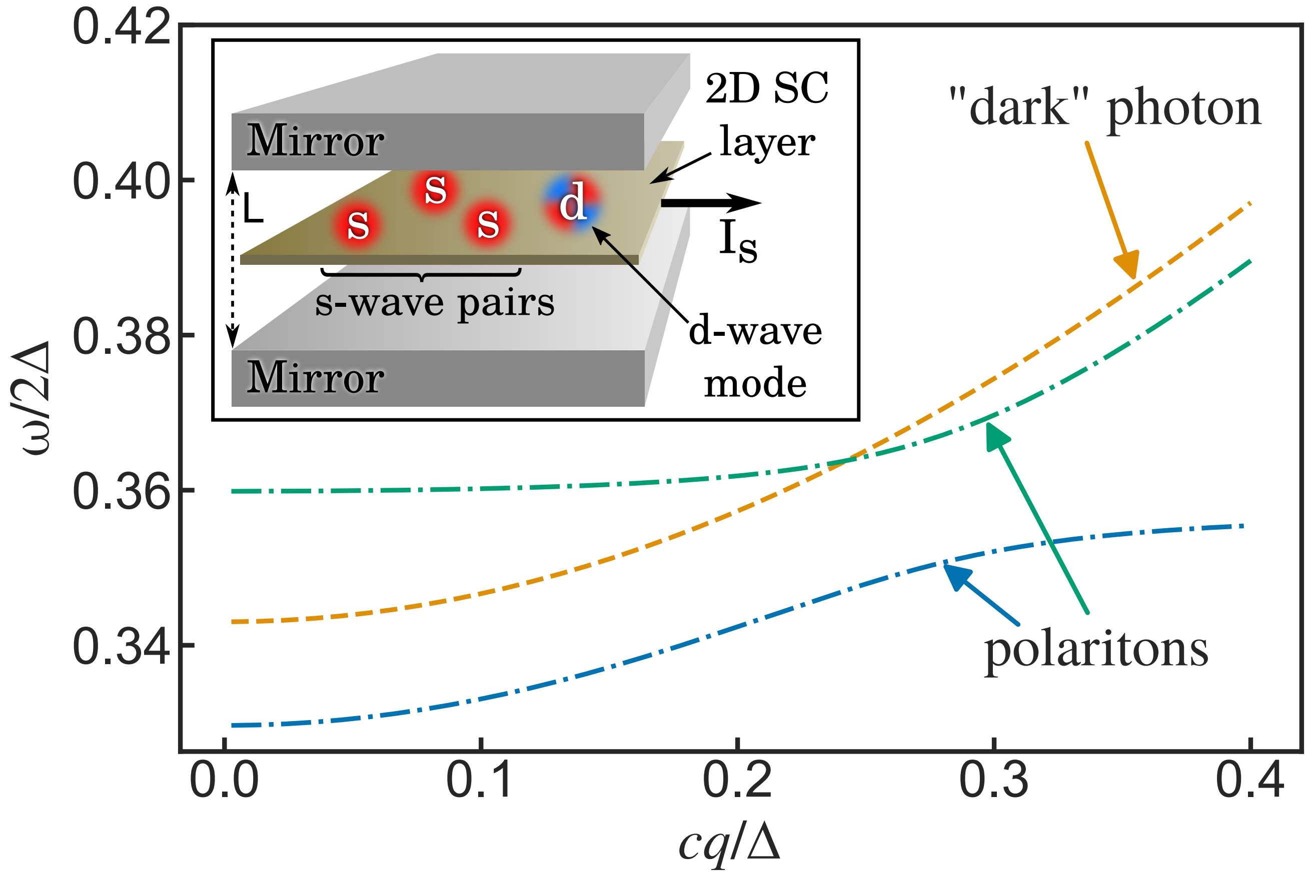


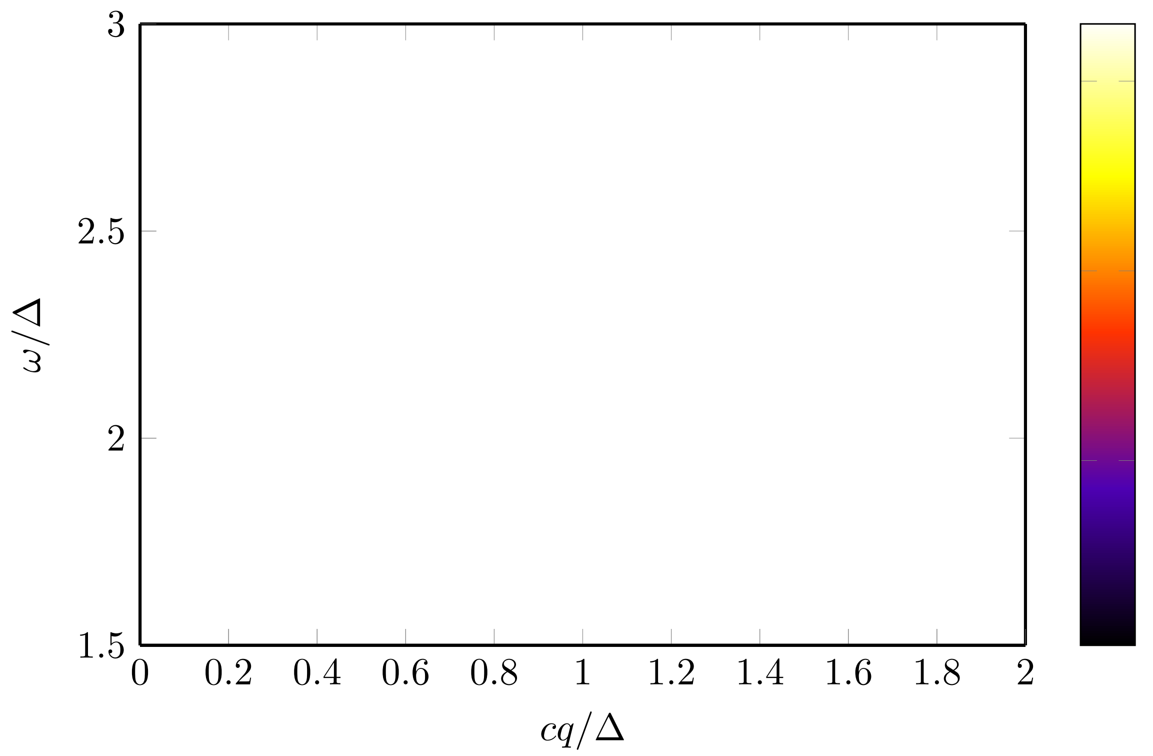


Summary

- **Chapter 4 - Cavity Quantum Eliashberg Enhancement of Superconductivity**
    - A superconductor placed in a properly resonant photonic cavity can be enhanced by engineering of the photonic distribution function (**arXiv:1805.01482**)
- **Chapter 5 - Cavity superconductor-Polaritons**
    - Bardasis-Schrieffer (BS) polaritons can be formed by tuning the cavity frequency to the BS frequency *and could form a non-equilibrium s±id state* (**Phys. Rev. B 99, 020504(R)**)
    - The Higgs mode of a disordered superconductor can be hybridized with light in the present of a supercurrent and can lead to polariton formation







Thank you!