

Flatiron Institute
Center for Computational Quantum Physics
Quantum Cavities and Excitonic Insulators
Workshop

New York, New York, July 8-12, 2019

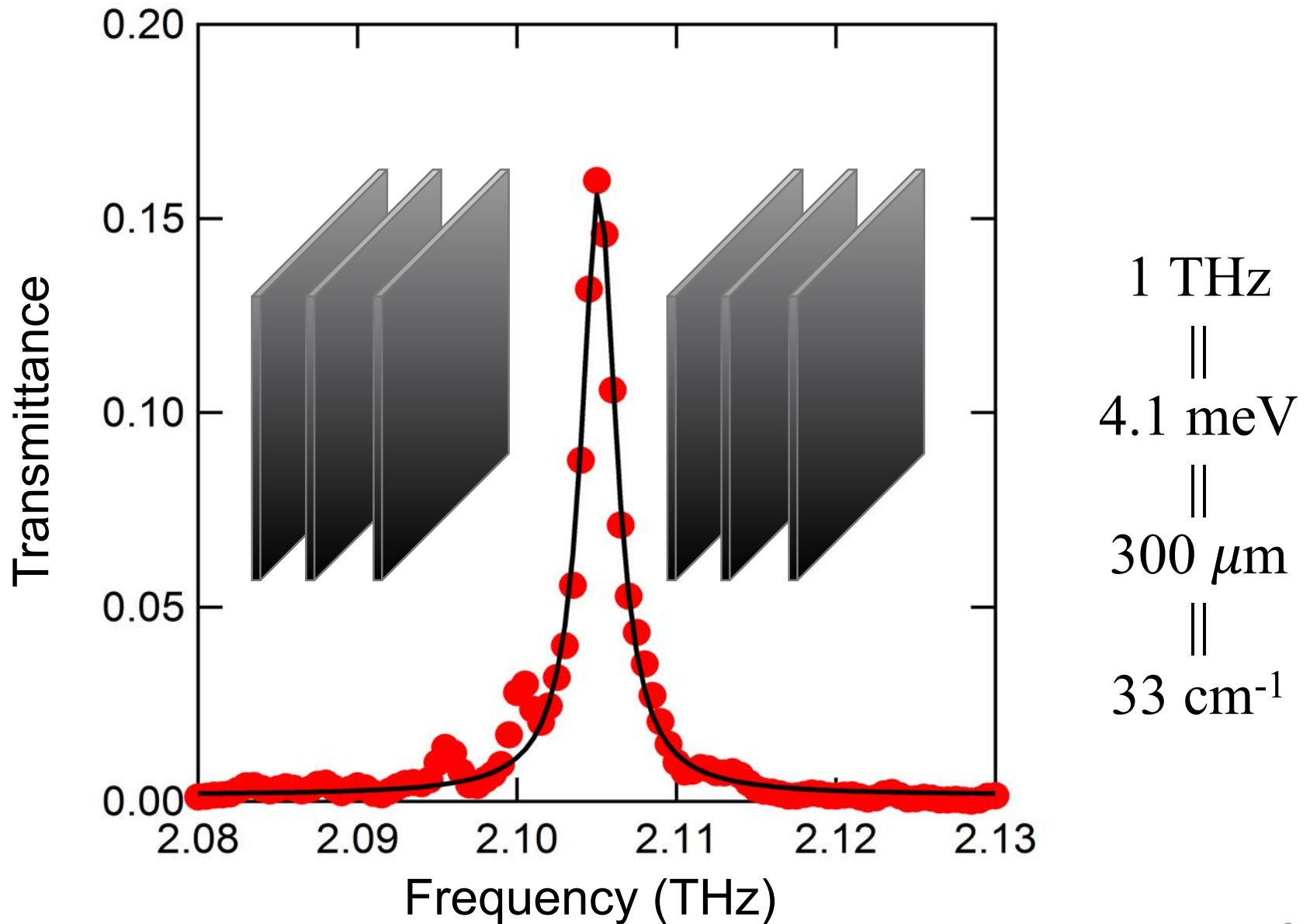
**Ultrastrong Light-Matter Coupling in
High- Q THz Cavities**

Junichiro Kono

*Departments of Electrical & Computer Engineering, Physics & Astronomy,
and Materials Science & NanoEngineering,
Rice University, Houston, Texas, U.S.A.*



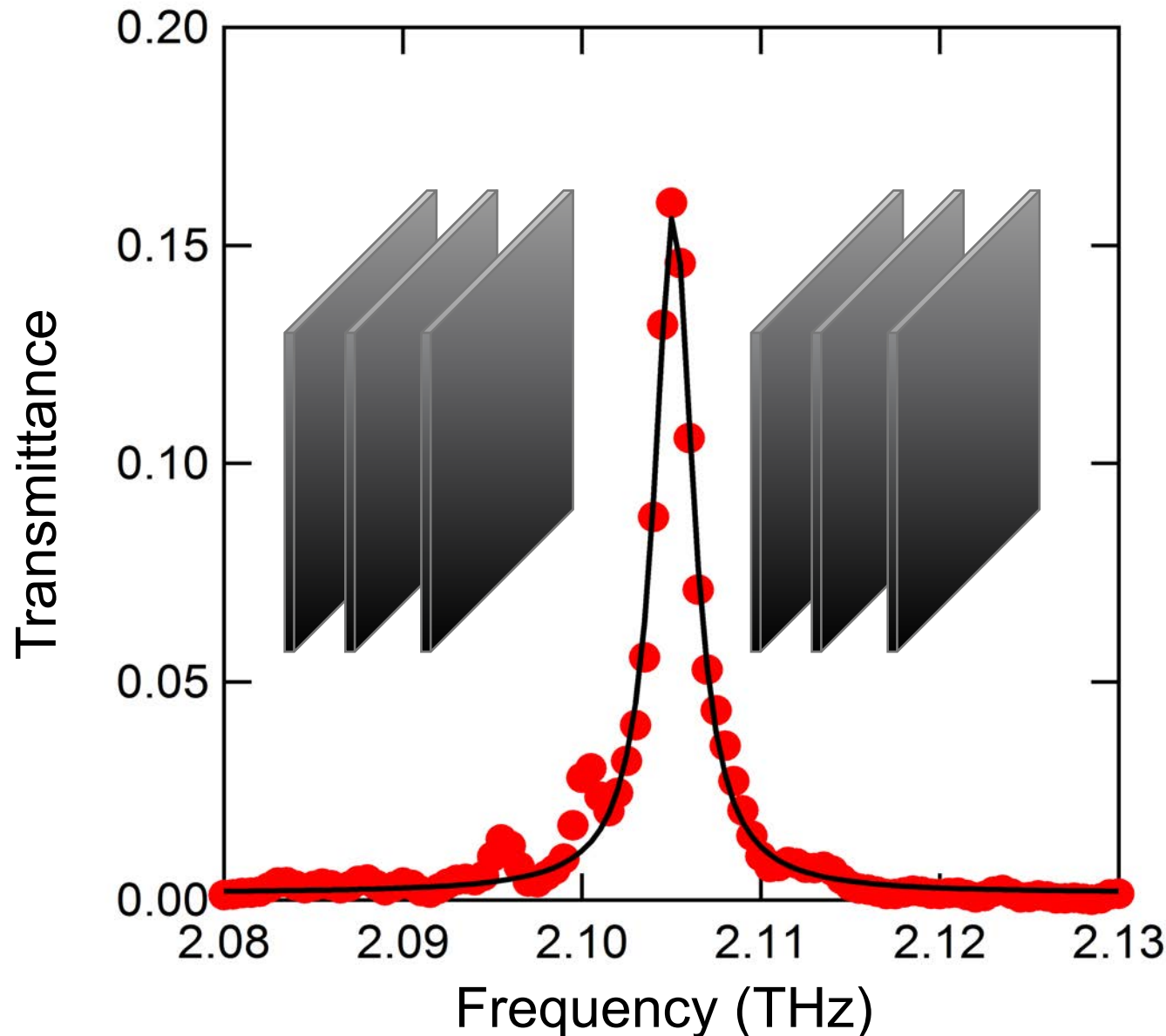
High-Q THz Cavity



$$\kappa/2\pi \sim 2.5 \text{ GHz}, \omega_0/2\pi \sim 2.5 \text{ THz}$$



$$Q \sim 10^3$$



$$\tau_{\text{cav}} \sim 70 \text{ ps}$$

$$F \sim 100$$

$$1 \text{ THz}$$



$$4.1 \text{ meV}$$

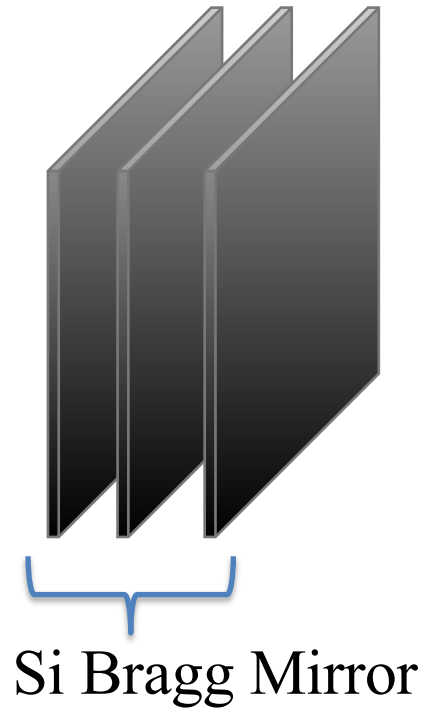
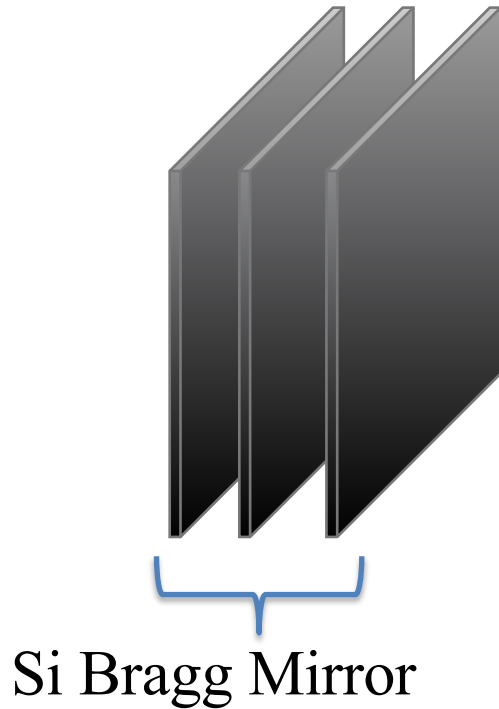


$$300 \mu\text{m}$$



$$33 \text{ cm}^{-1}$$

1D THz Photonic-Crystal Cavity



$$n_{\text{Si}} = 3.42$$

$$n_{\text{vac}} = 1$$

THz 'Cavity Lab' for Materials

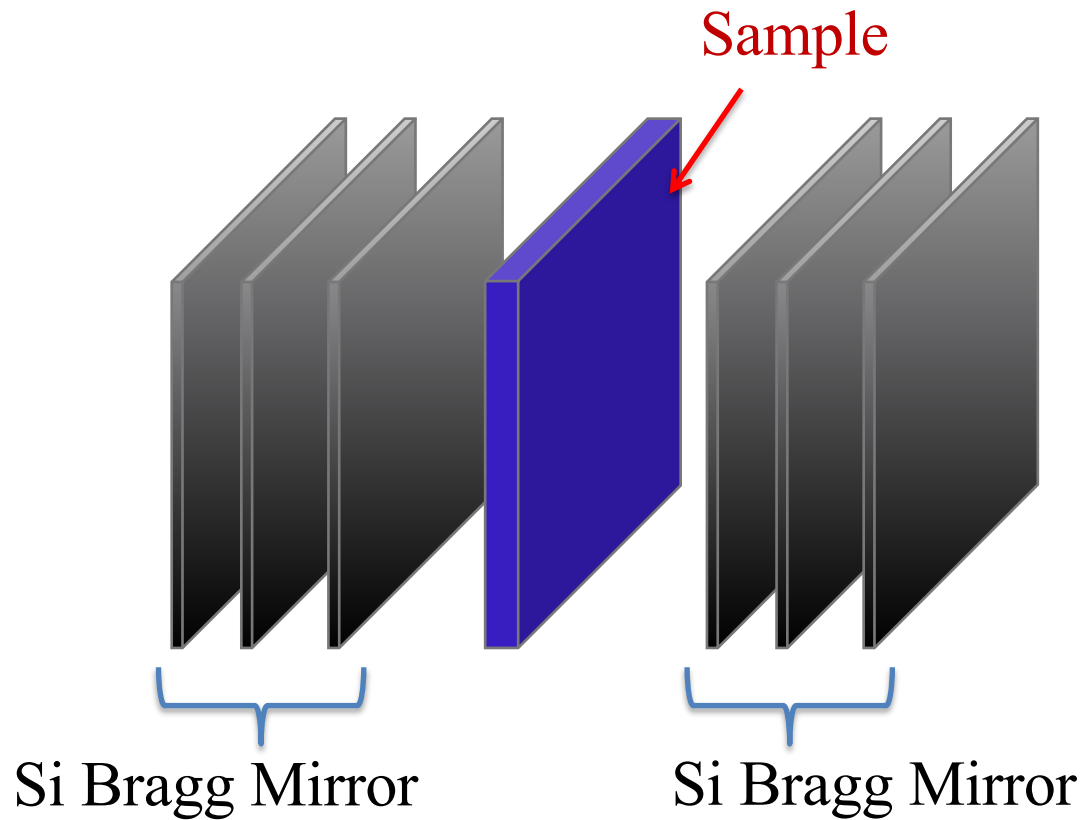


Si Bragg Mirror

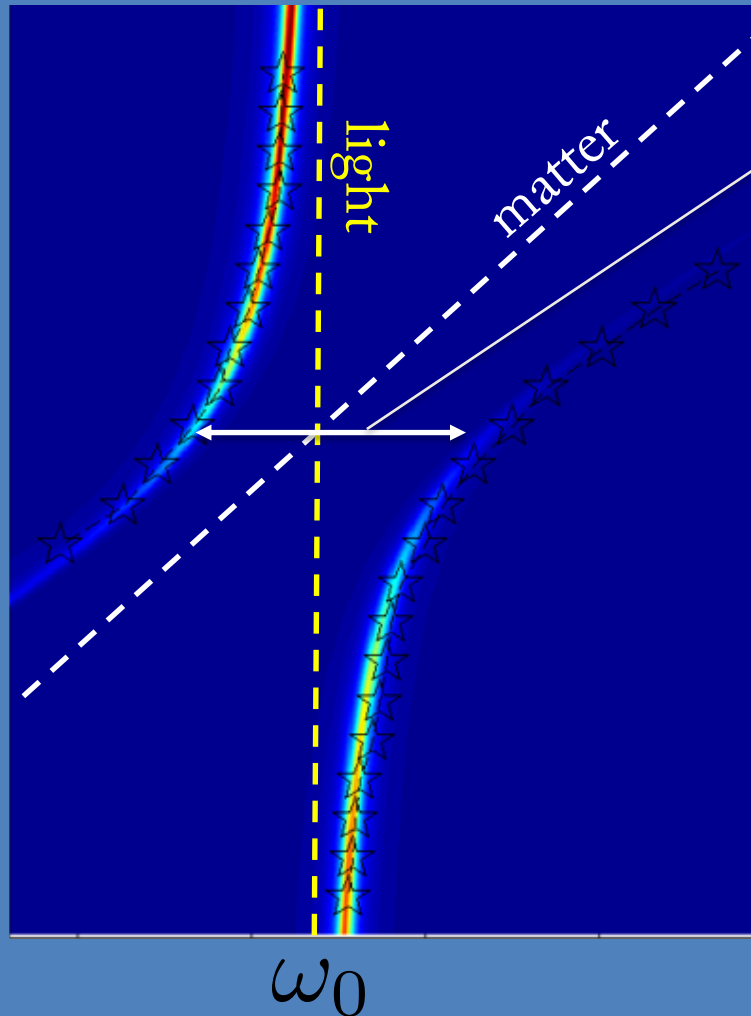


Si Bragg Mirror

THz 'Cavity Lab' for Materials



Ultrastrong Light-Matter Coupling



$2g$: vacuum Rabi splitting

g : coupling rate

ω_0 : resonance frequency

Ordinary Regime:

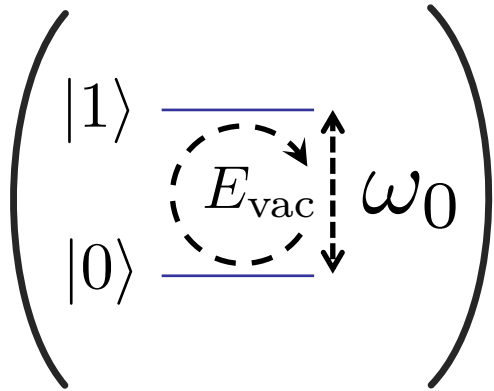
$$\omega_0 \gg g$$

Ultrastrong Coupling (USC):

~~$$\omega_0 \gg g$$~~

Ultrastrong Coupling Regime (and why THz?)

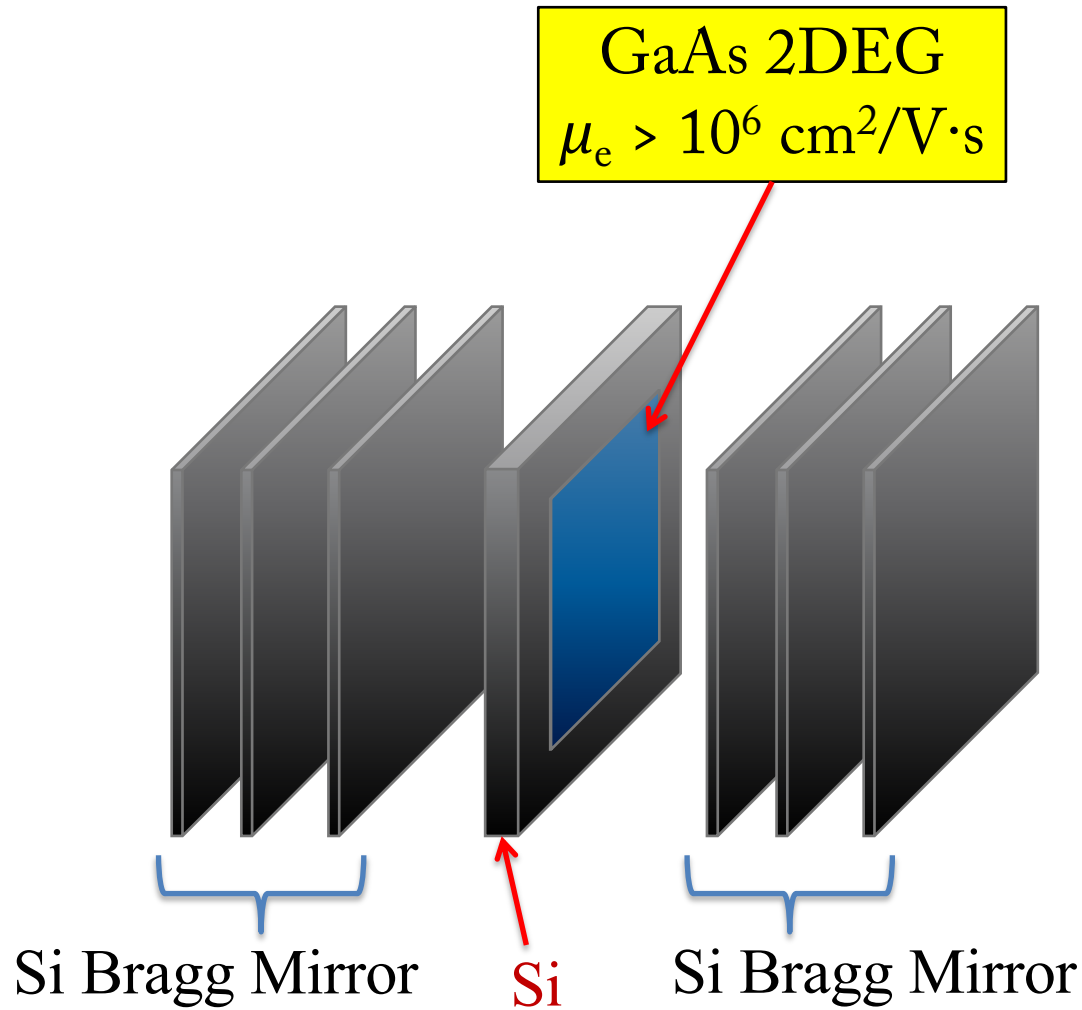
$$g > 0.1\omega_0$$



$$\frac{g}{\omega_0} = \frac{|\mu_{01} E_{\text{vac}}|}{2\hbar\omega_0} = \frac{|\mu_{01}|}{\sqrt{2\varepsilon_0\hbar\omega_0 V_0}}$$

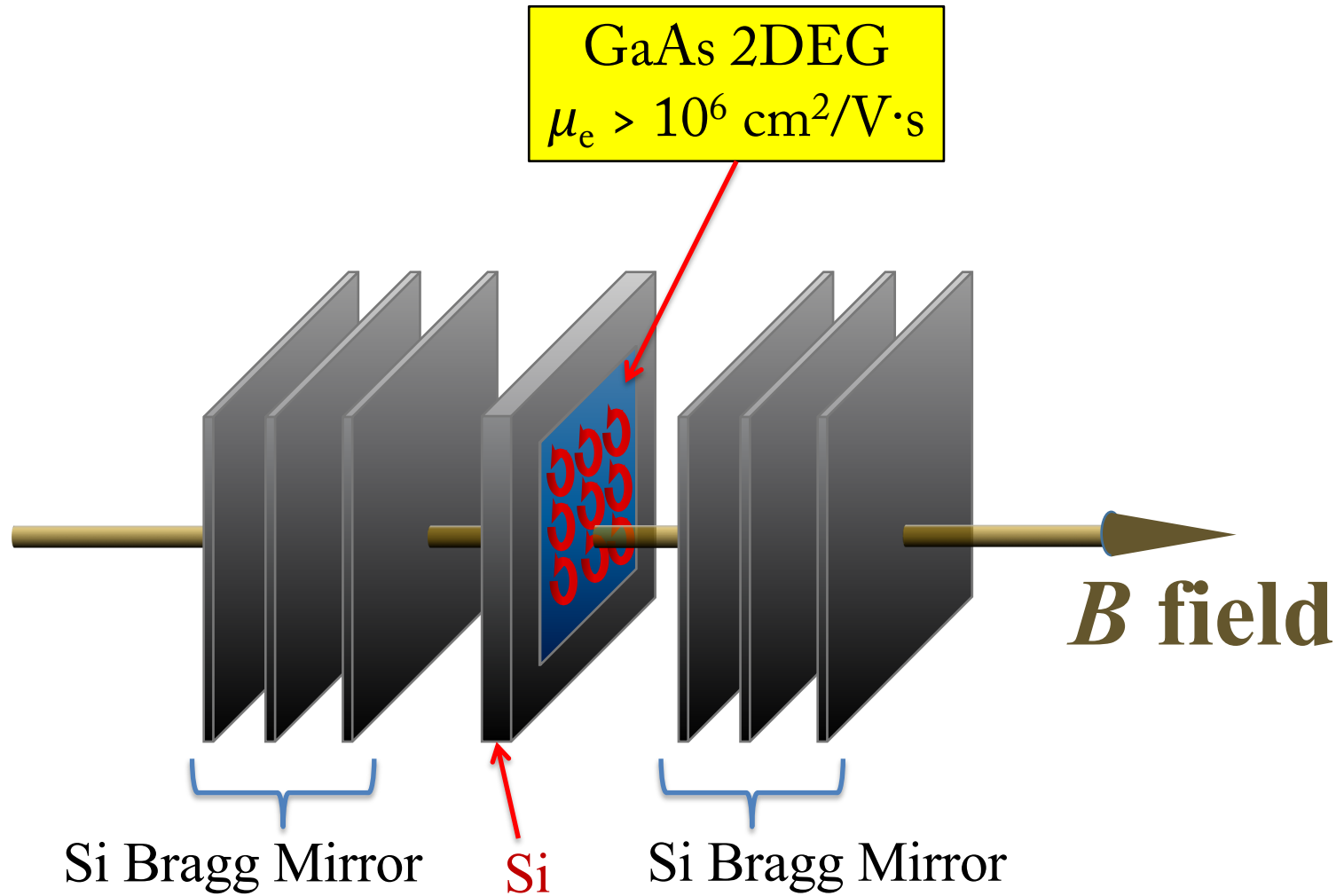
Large μ_{01} & Small ω_0

- Breakdown of the rotating-wave approximation (RWA)
→ Bloch-Siegert shift
- Diamagnetic (A^2) term becomes non-negligible
- Nonclassical ground state properties (Ciuti *et al.*, 2005)
- Possibility of the Dicke superradiant phase transition



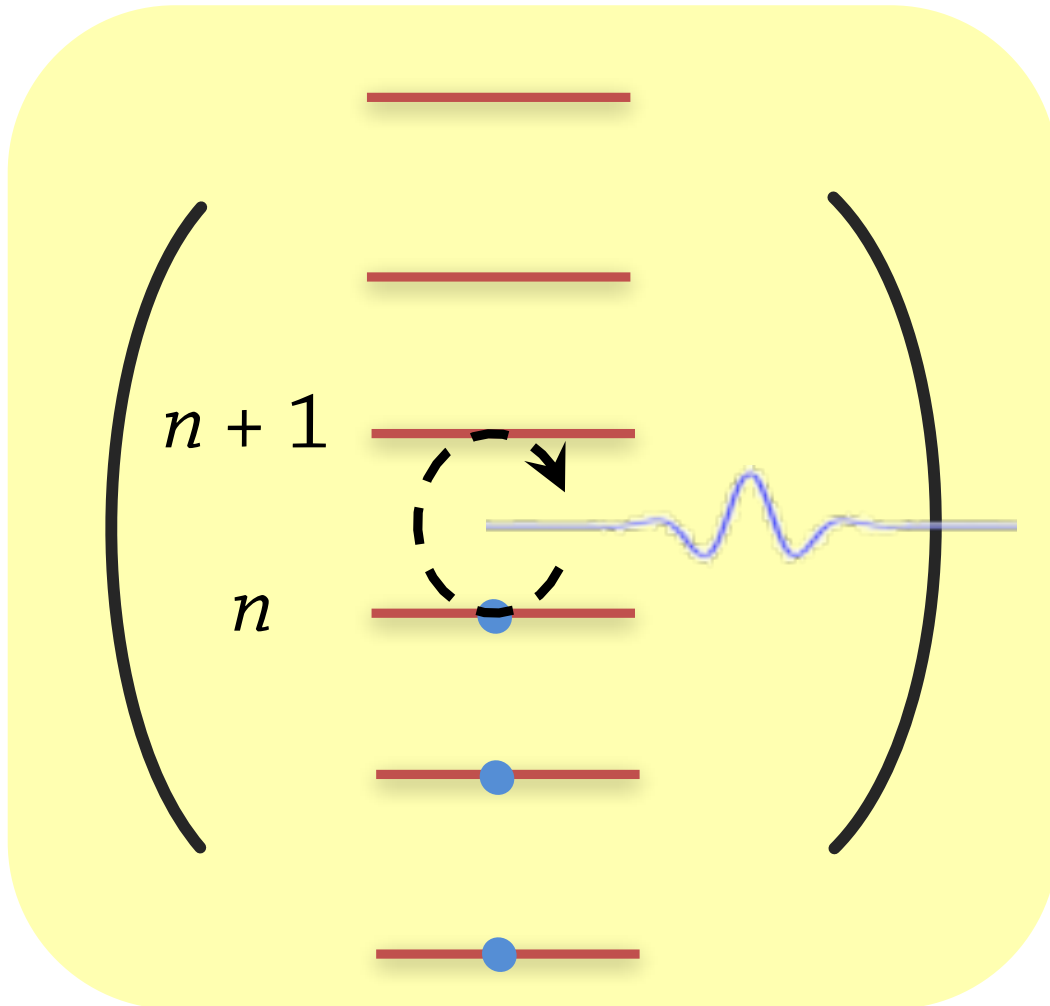
Q. Zhang *et al.*, *Nature Physics* **12**, 1005 (2016)

X. Li *et al.*, *Nature Photonics* **12**, 324 (2018)



Q. Zhang *et al.*, *Nature Physics* **12**, 1005 (2016)
X. Li *et al.*, *Nature Photonics* **12**, 324 (2018)

Landau-Quantized 2D Electrons in the Integer QH Regime in a High-Q THz Cavity

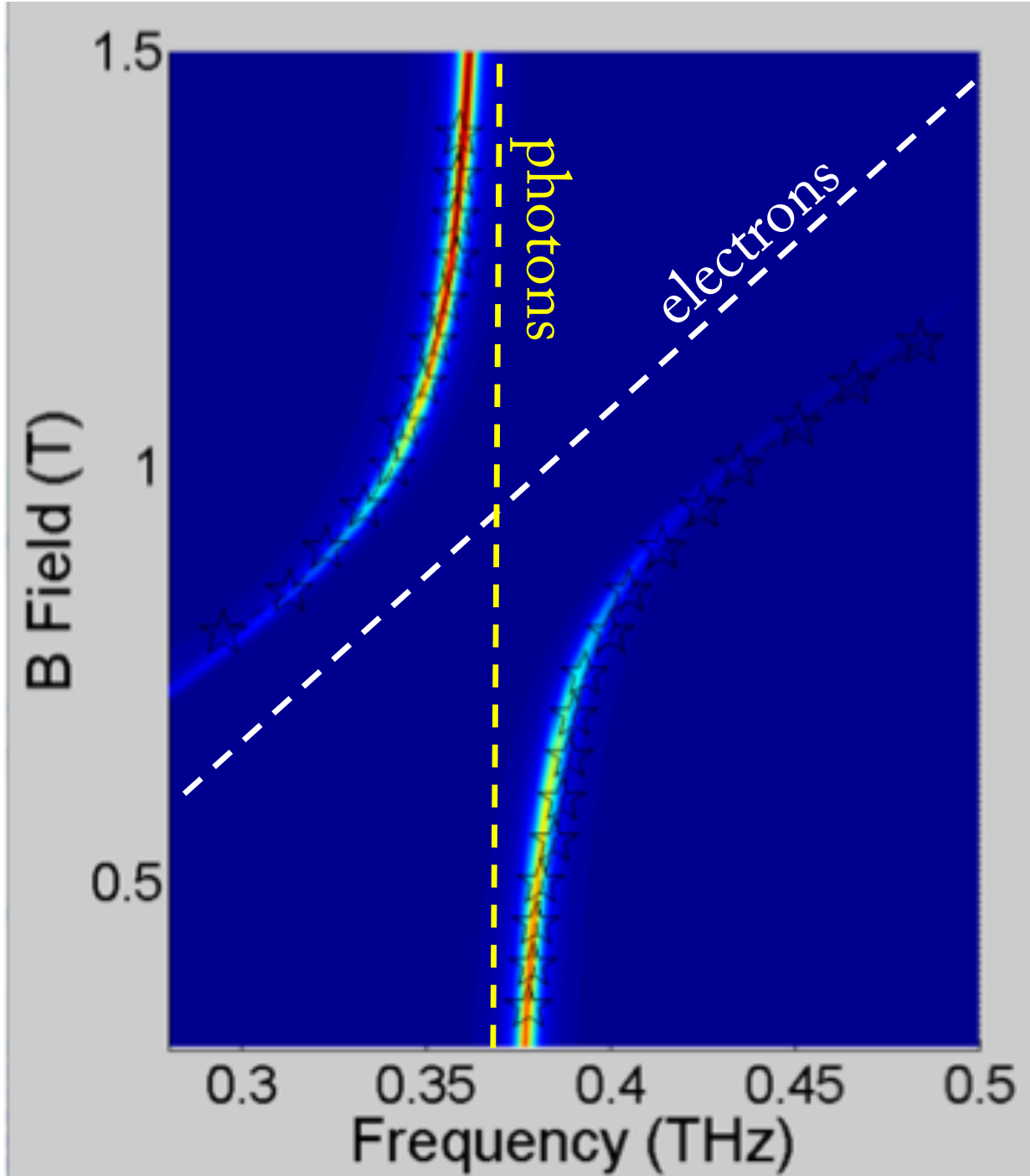


Landau levels

$$\varepsilon_n = \left(n + \frac{1}{2} \right) \hbar \omega_c$$

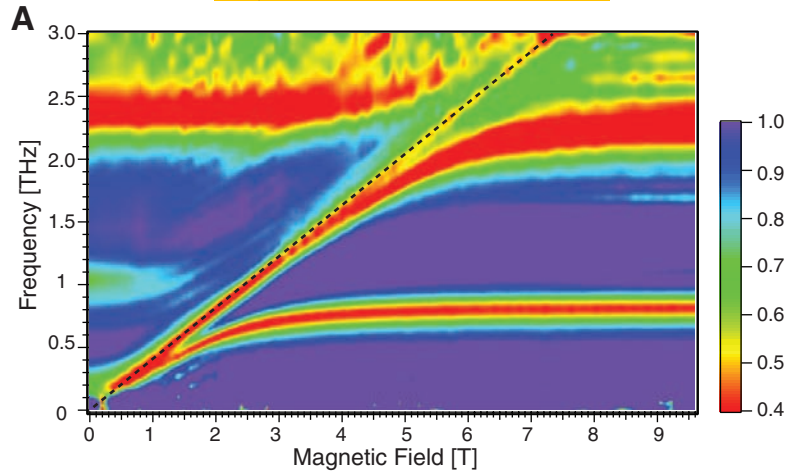
$$\omega_c = \frac{eB}{m^*}$$

$$n = 0, 1, 2, \dots$$

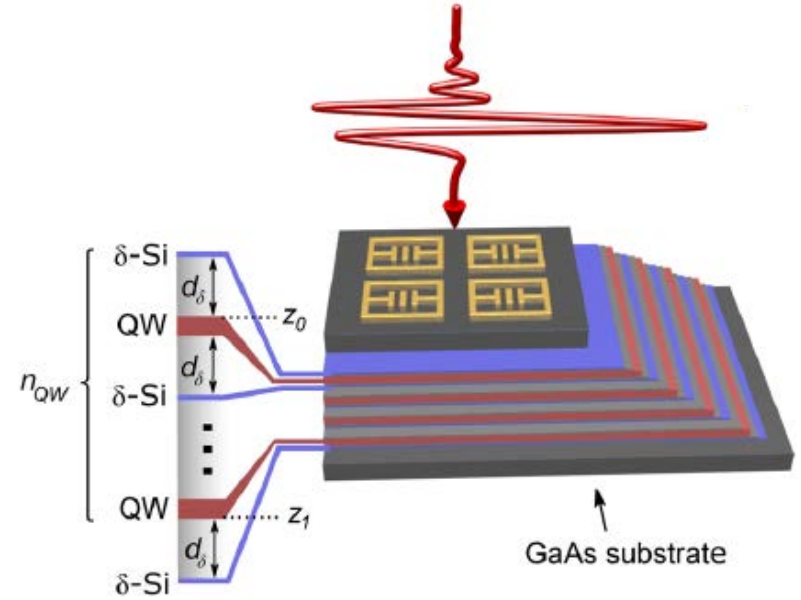


Prior Experimental Work: Cyclotron Resonance

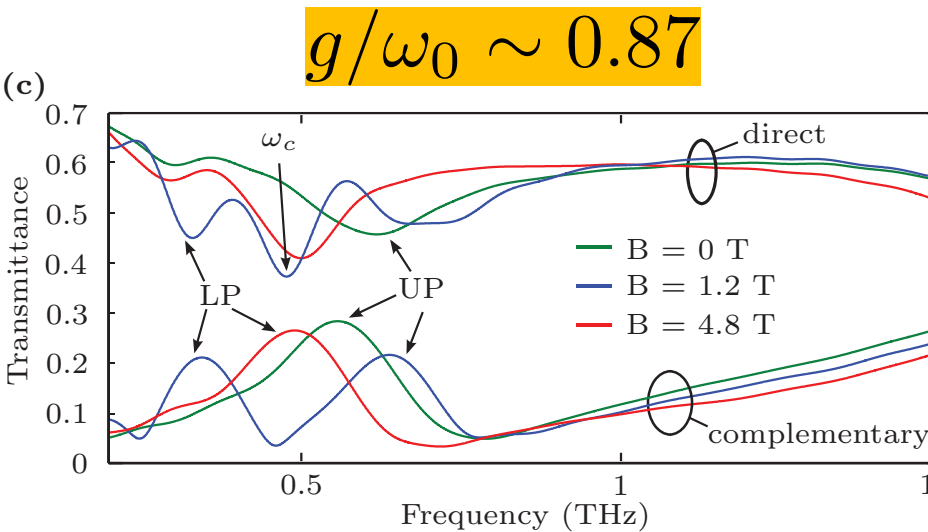
$$g/\omega_0 \sim 0.58$$



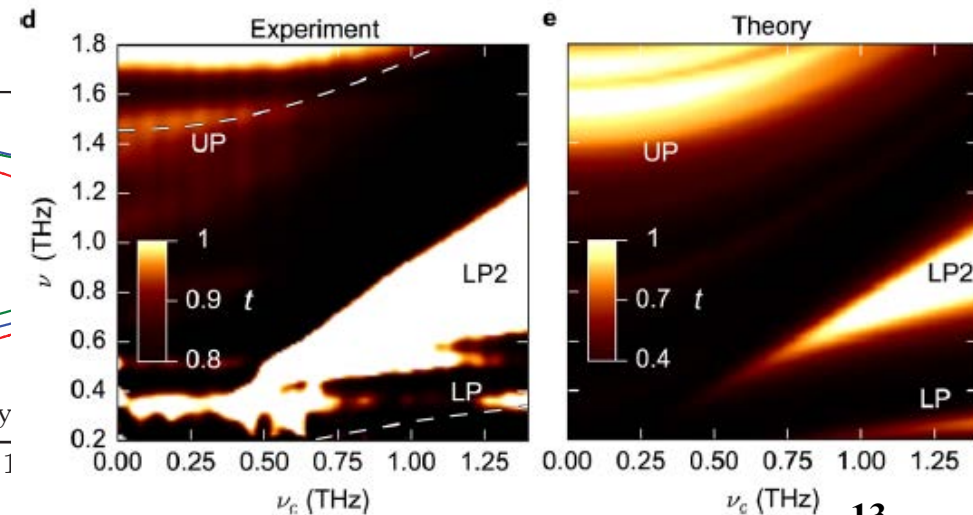
G. Scalari *et al.*, Science **335**, 1323 (2012)



$$g/\omega_0 \sim 1.43$$



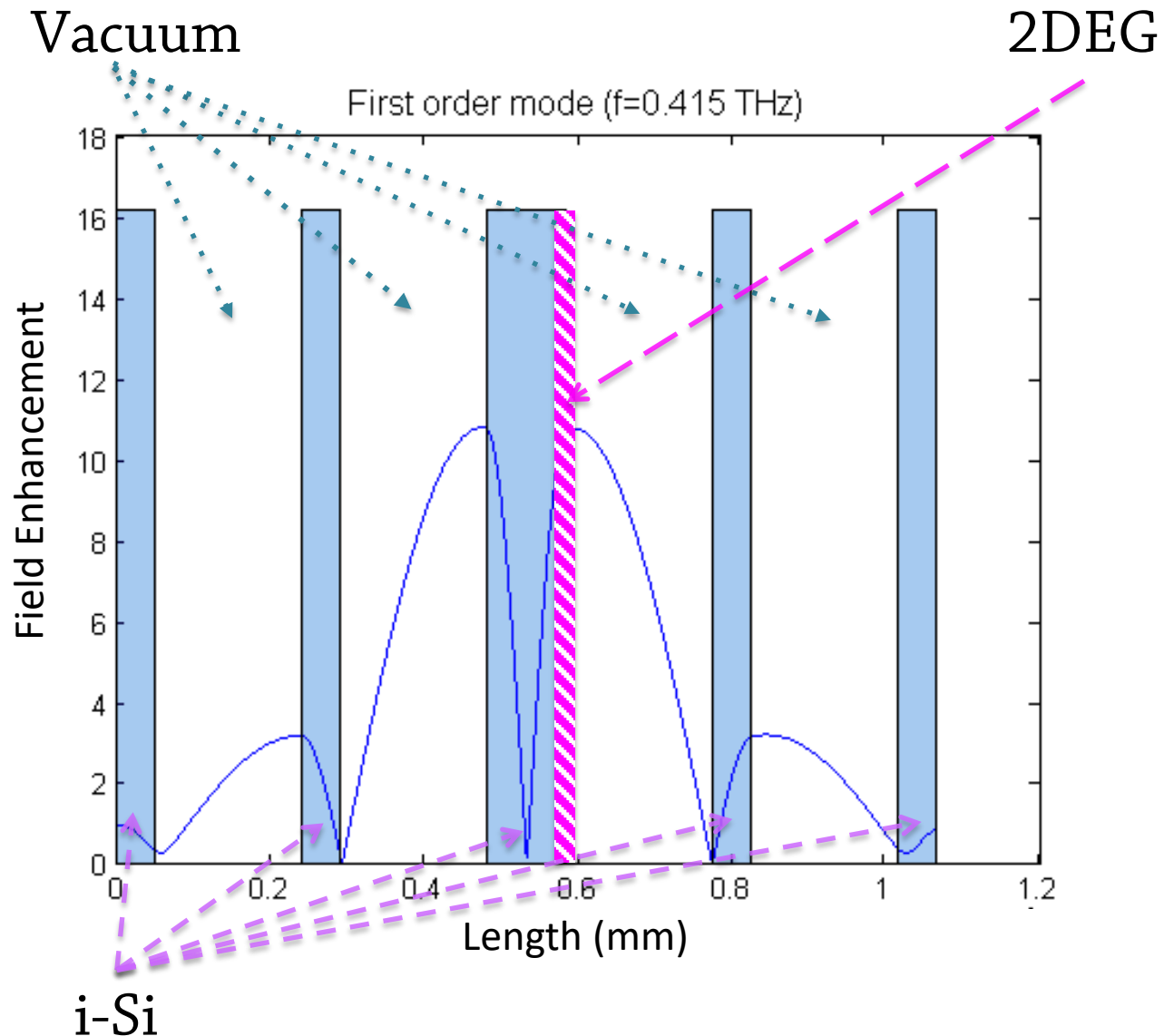
$$g/\omega_0 \sim 0.87$$



C. Maissen *et al.*, Phys. Rev. B **90**, 205309 (2014)

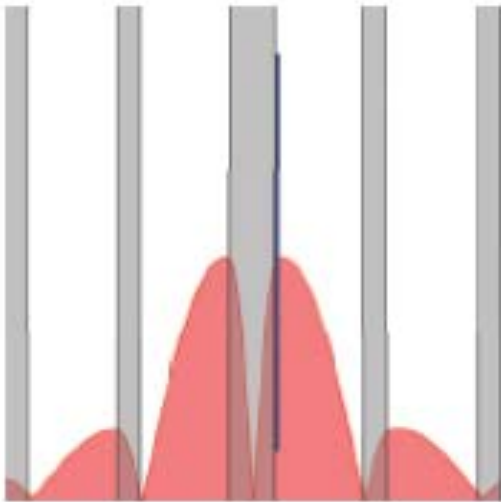
A. Bayer *et al.*, Nano Lett. **17**, 6340 (2017)

1D Photonic-Crystal Cavity

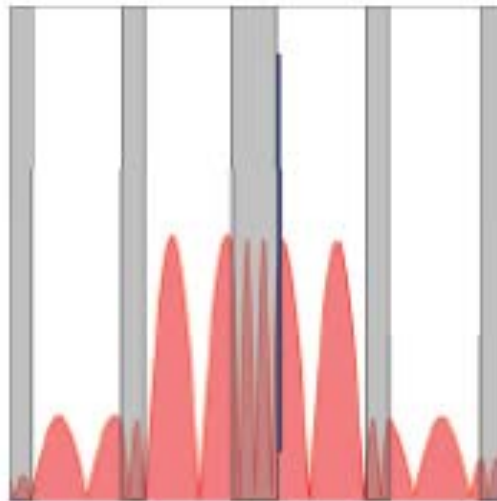


1D Photonic-Crystal Cavity

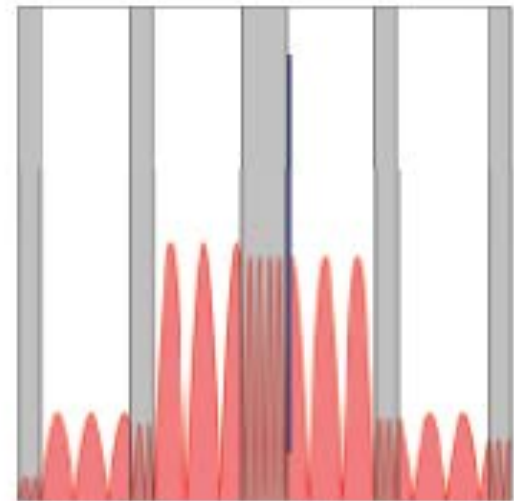
First mode



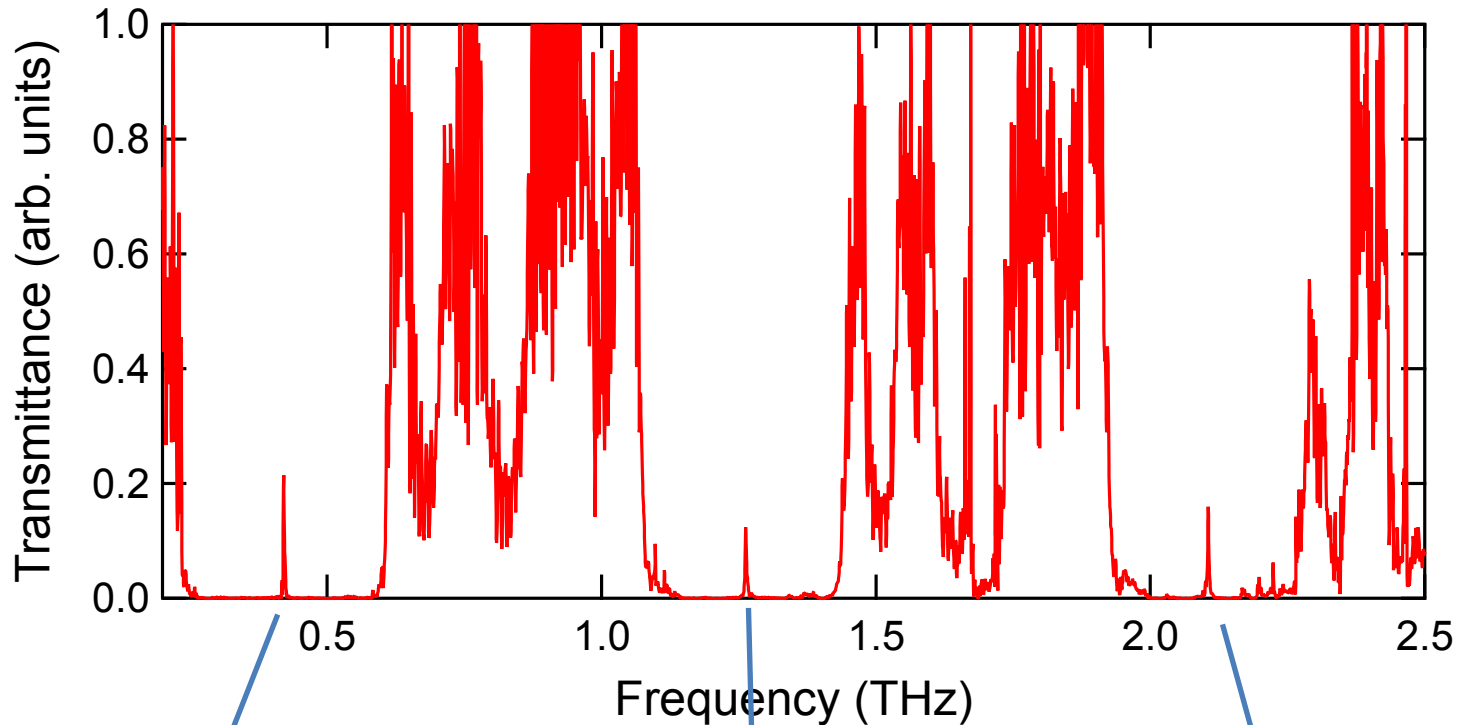
Second mode



Third mode

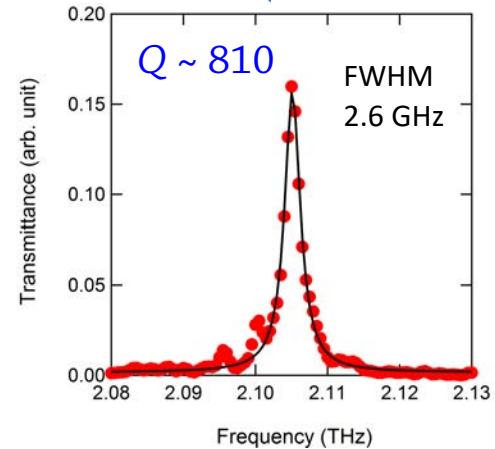
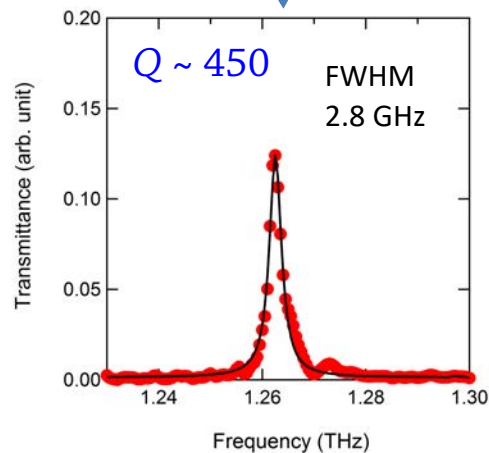
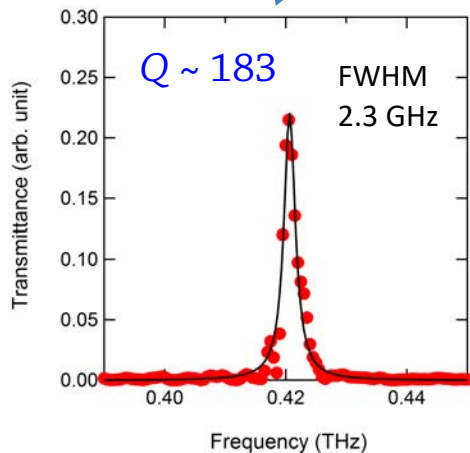


1D THz Photonic-Crystal Cavity



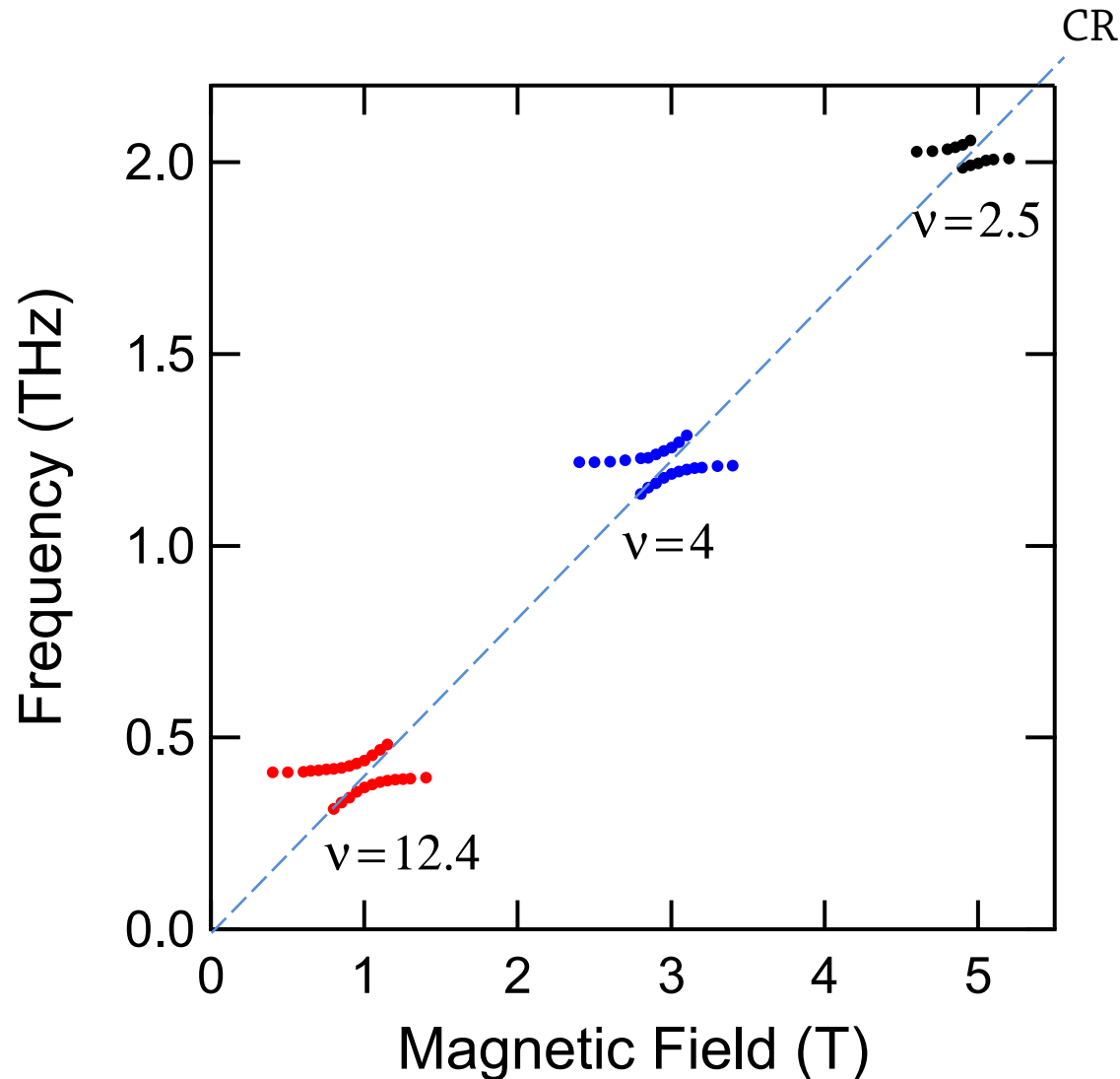
$T = 300 \text{ K}$

500 ps
time window



Theoretical
limit $\sim 1 \text{ GHz}$
for this cavity
design

Hybridization of Cyclotron Resonance with THz Photonic Cavity Modes

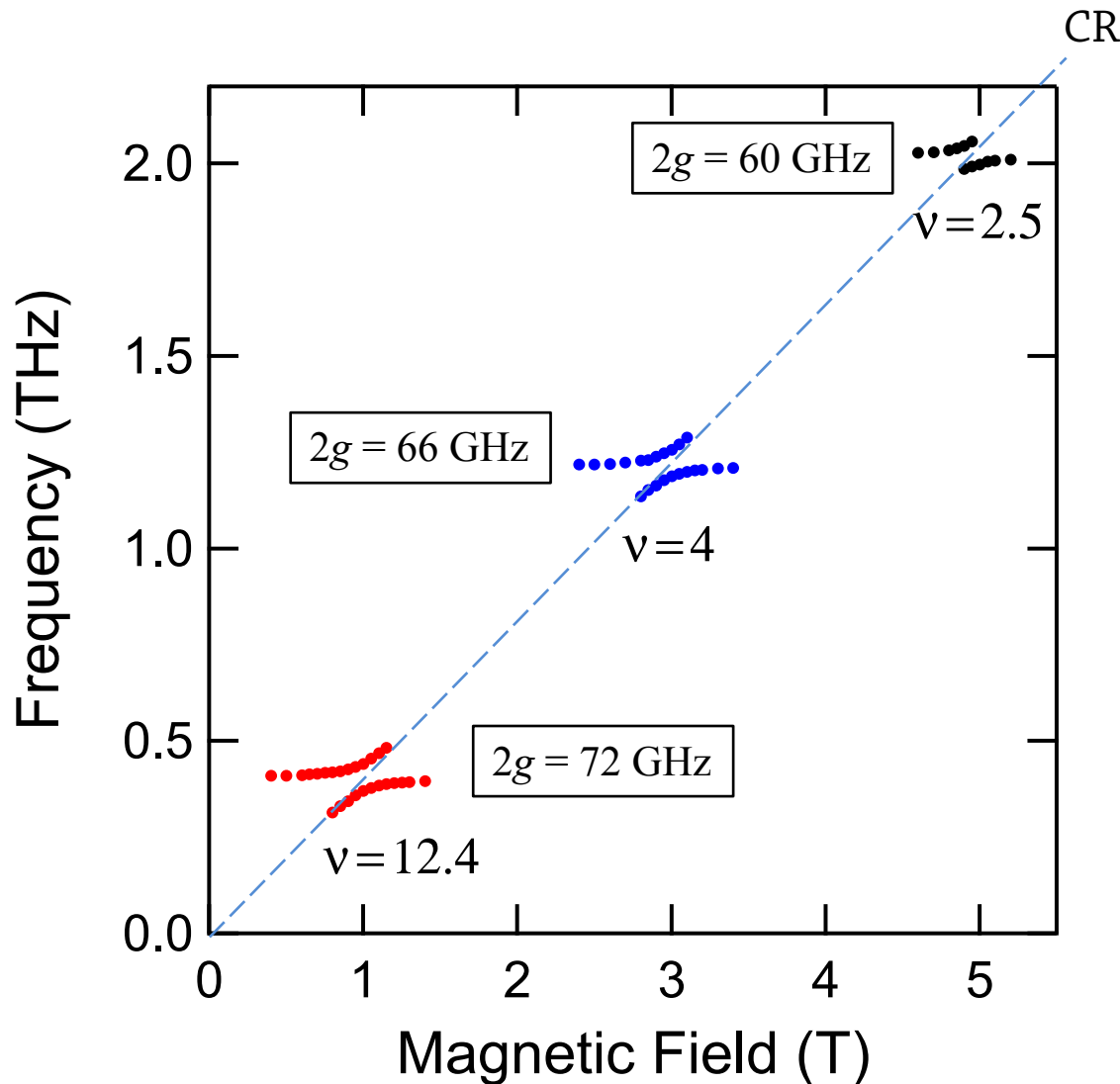


Landau-level
filling factor:

$$\nu = \frac{h n_e}{e B}$$

Magnetic Field Dependence of Vacuum Rabi Splitting

Theory: D. Hagenmüller, S. De Liberato, and C. Ciuti, *Phys. Rev. B* **81**, 235303 (2010)



$$2g = dE_{\text{vac}} \sqrt{\frac{n_e}{v}}$$

$$d = e\ell_0 \sqrt{v}$$

$$\ell_0 = \sqrt{\frac{\hbar}{eB}} = \sqrt{\frac{\hbar}{m^* \omega_c}}$$

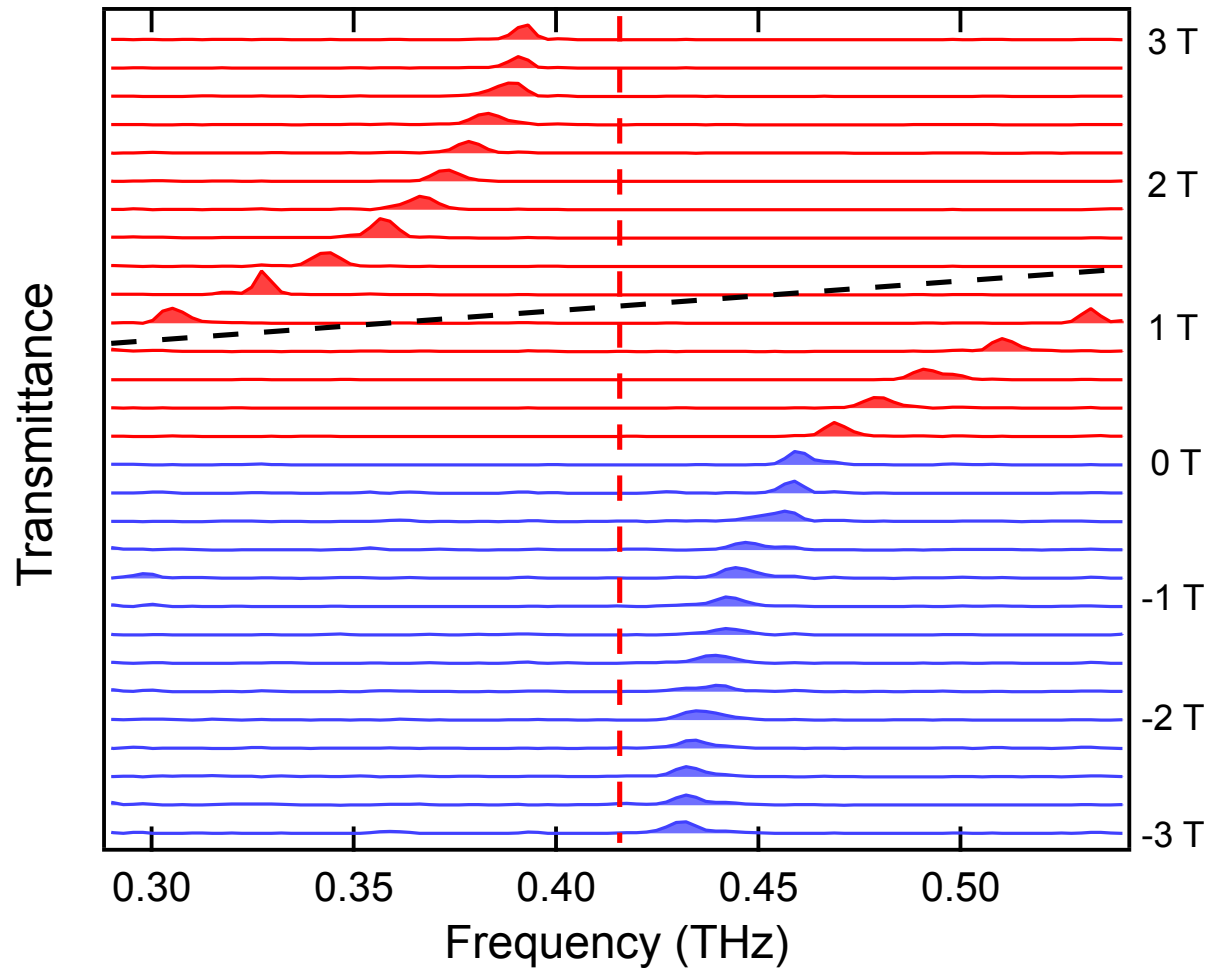
$$E_{\text{vac}} = \sqrt{\frac{\hbar \omega_c}{\epsilon L_z S}}$$



$$2g = e\hbar \sqrt{\frac{n_e}{m^* \epsilon L_z S}}$$

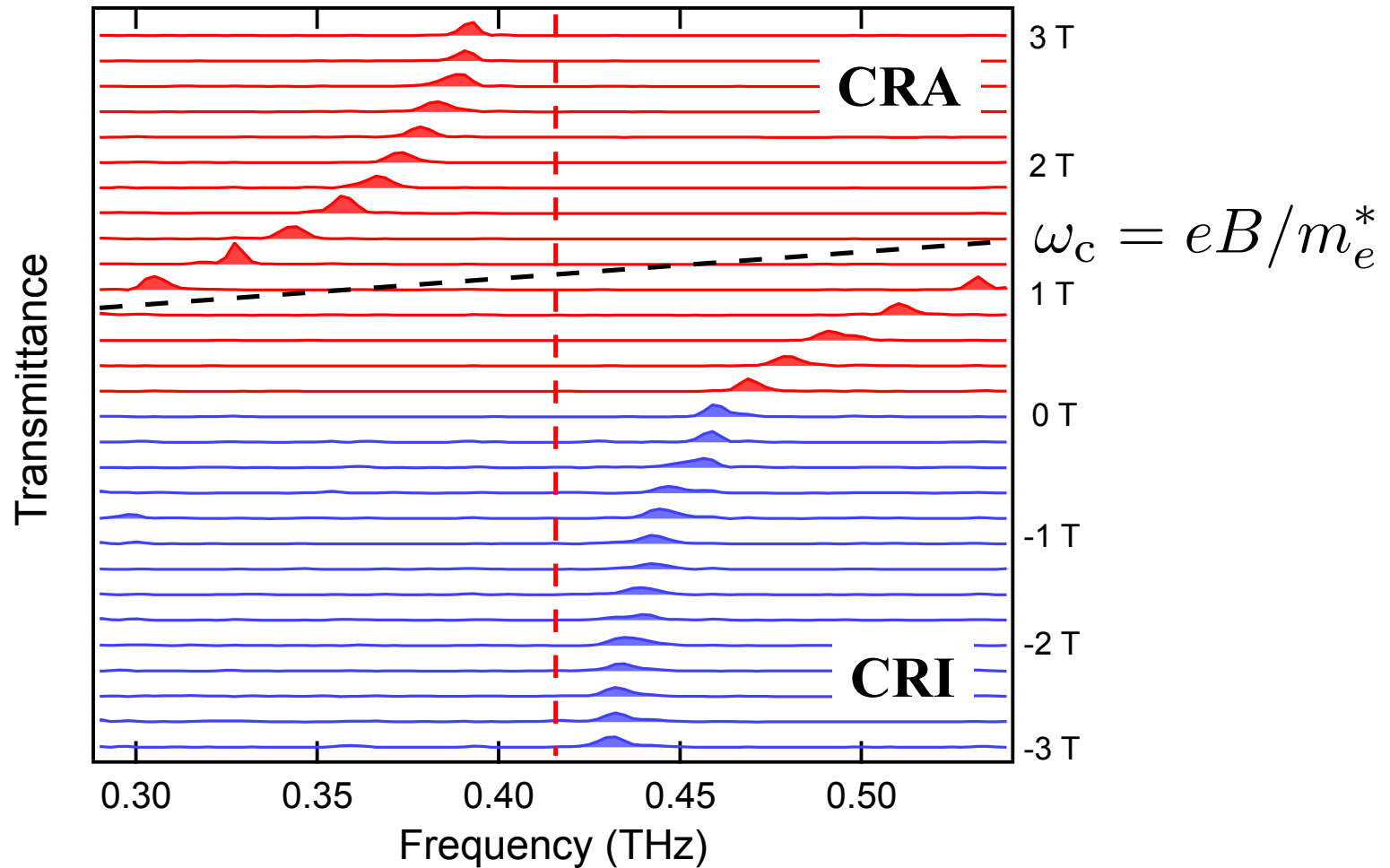
No explicit B dependence ¹⁸

Landau Polaritons (Experimental Data!)

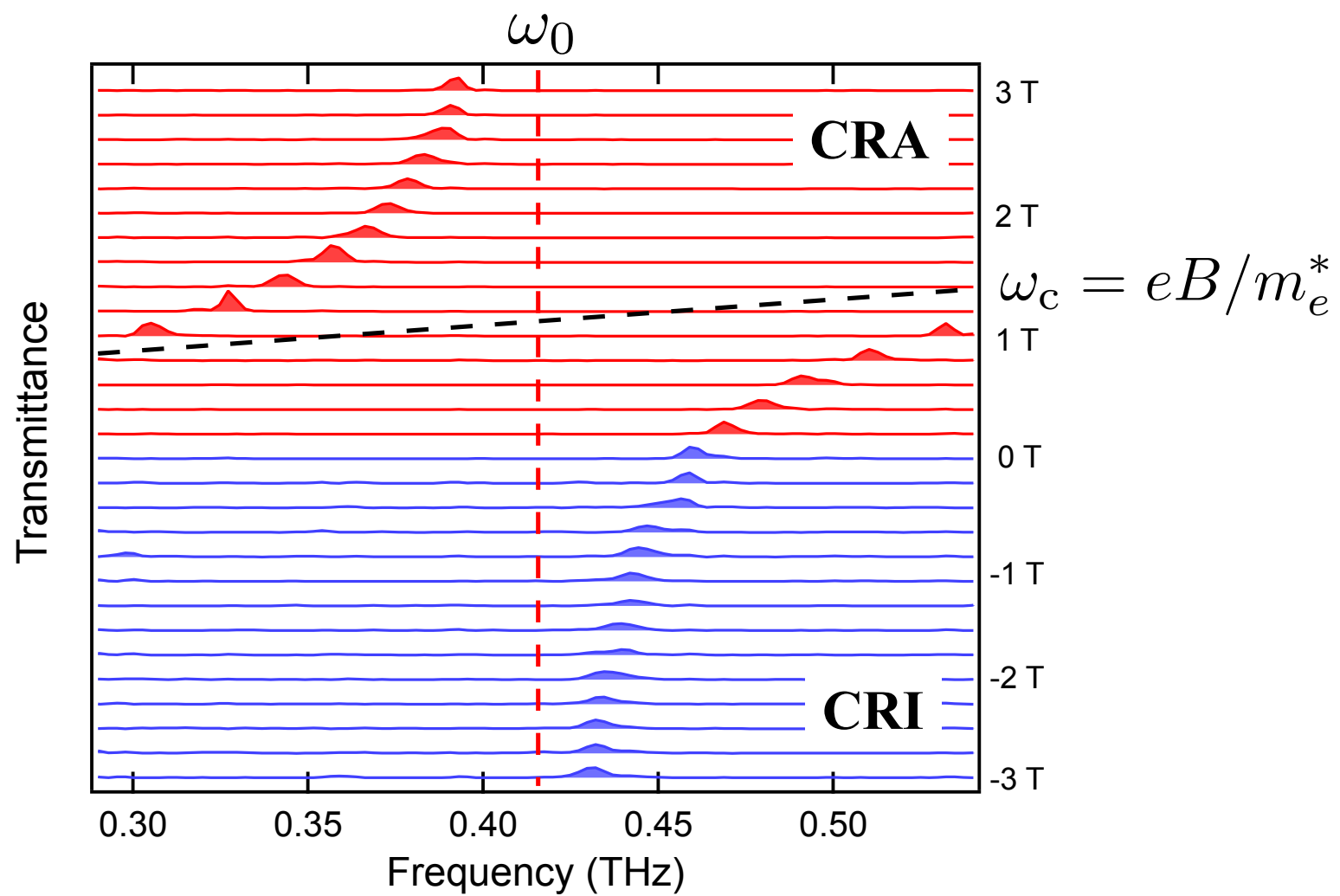


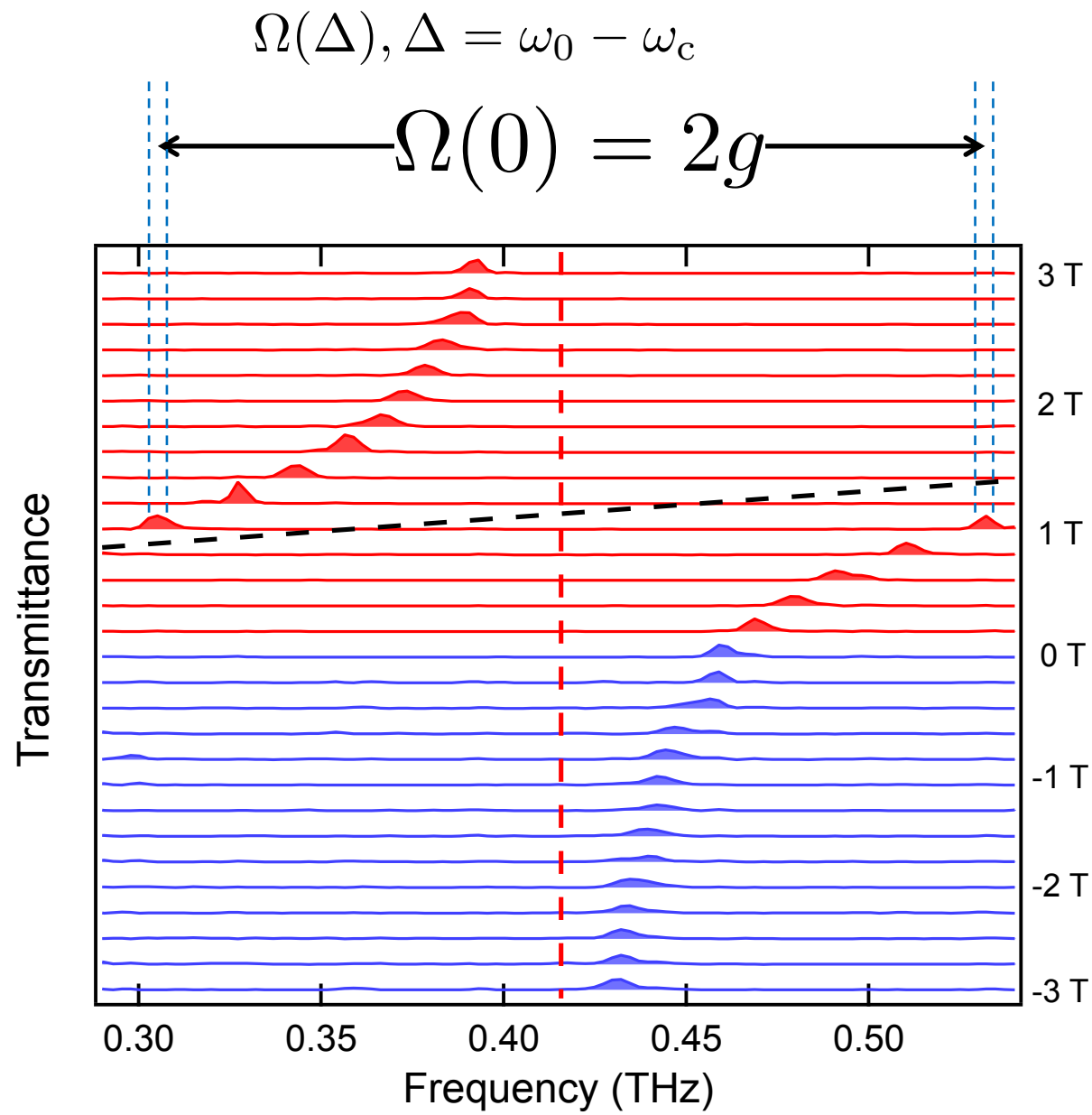
X. Li *et al.*, *Nature Photonics* **12**, 324 (2018)

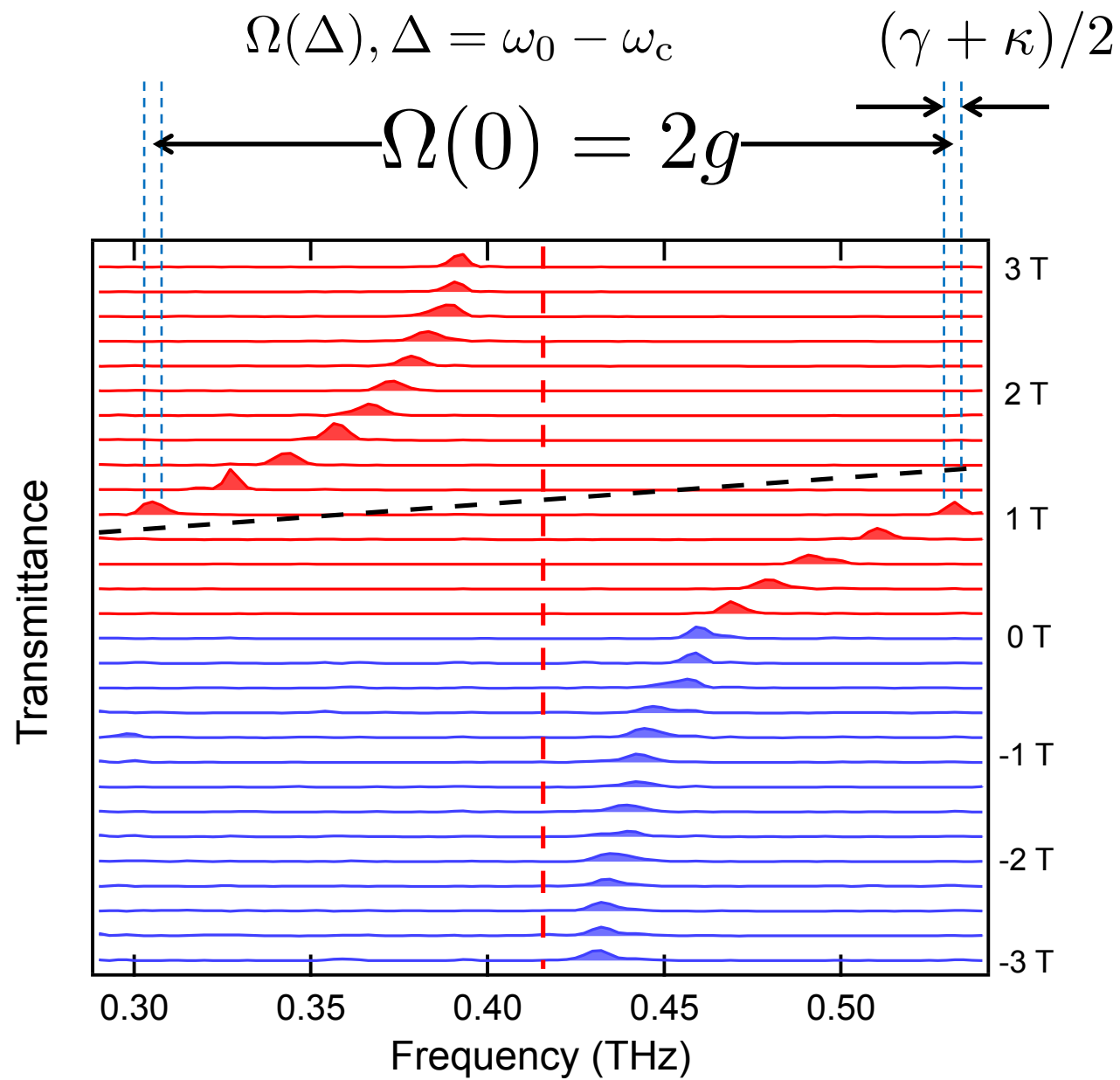
CRA = Cyclotron Resonance Active

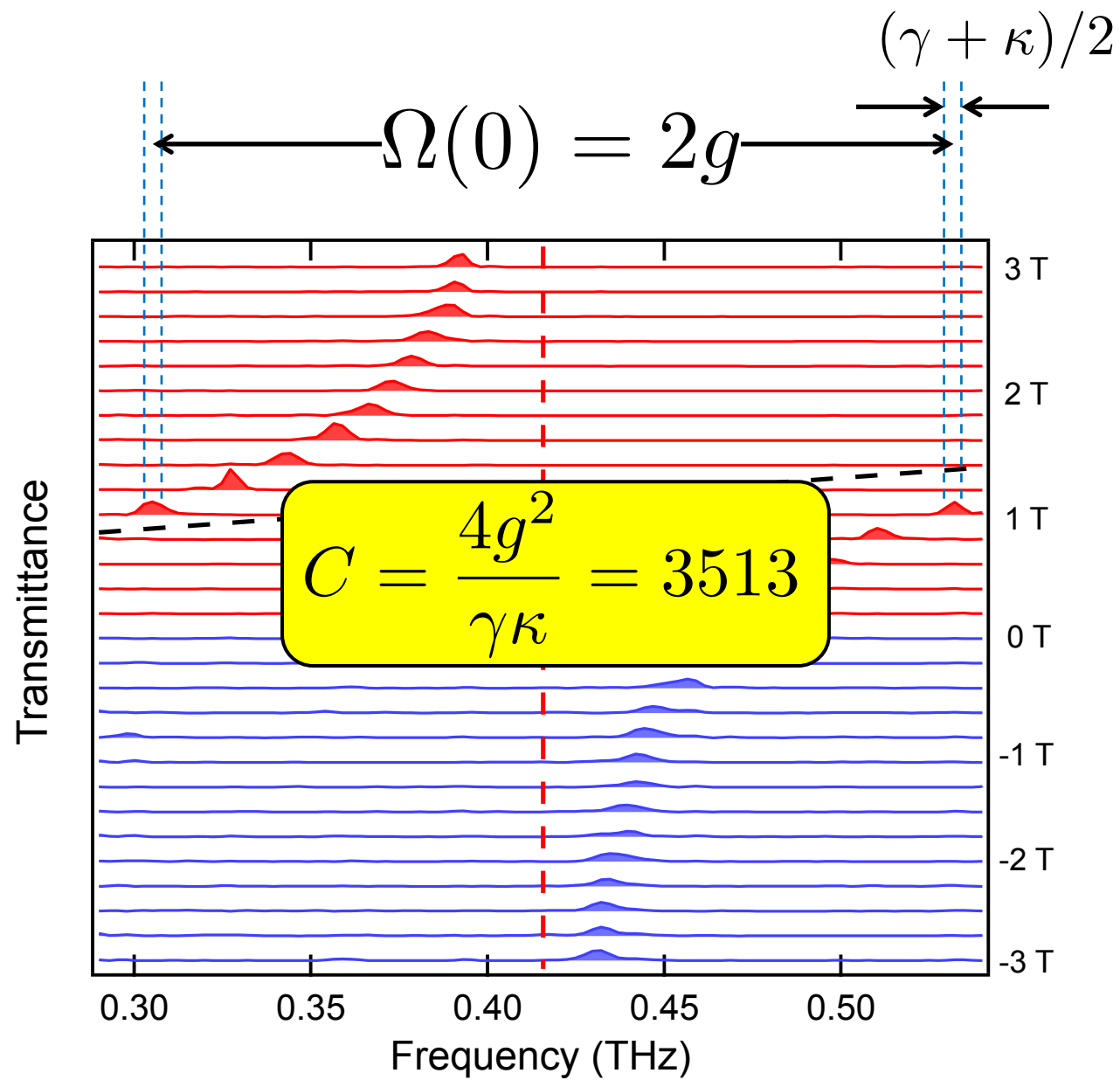


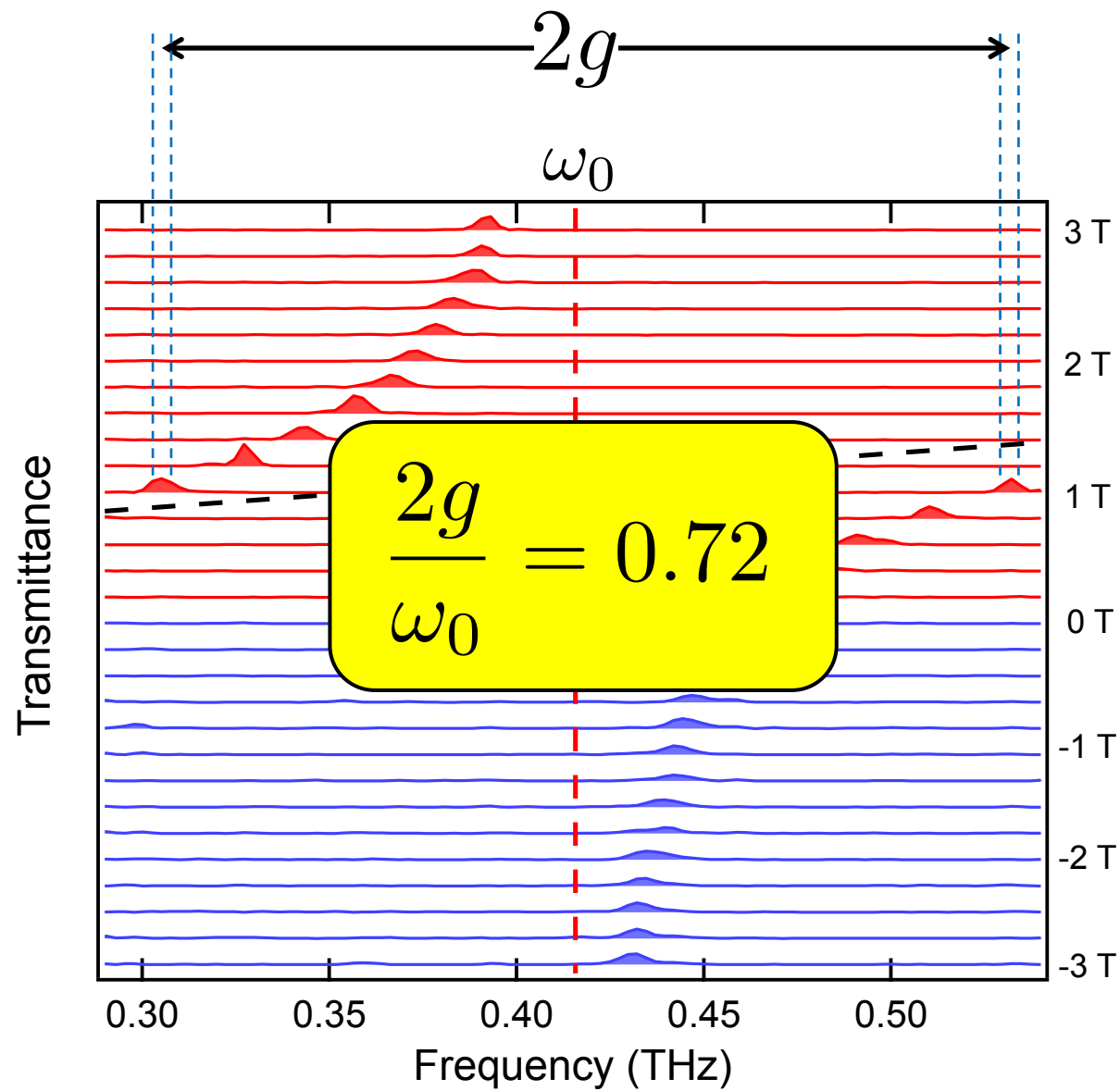
CRI = Cyclotron Resonance Inactive

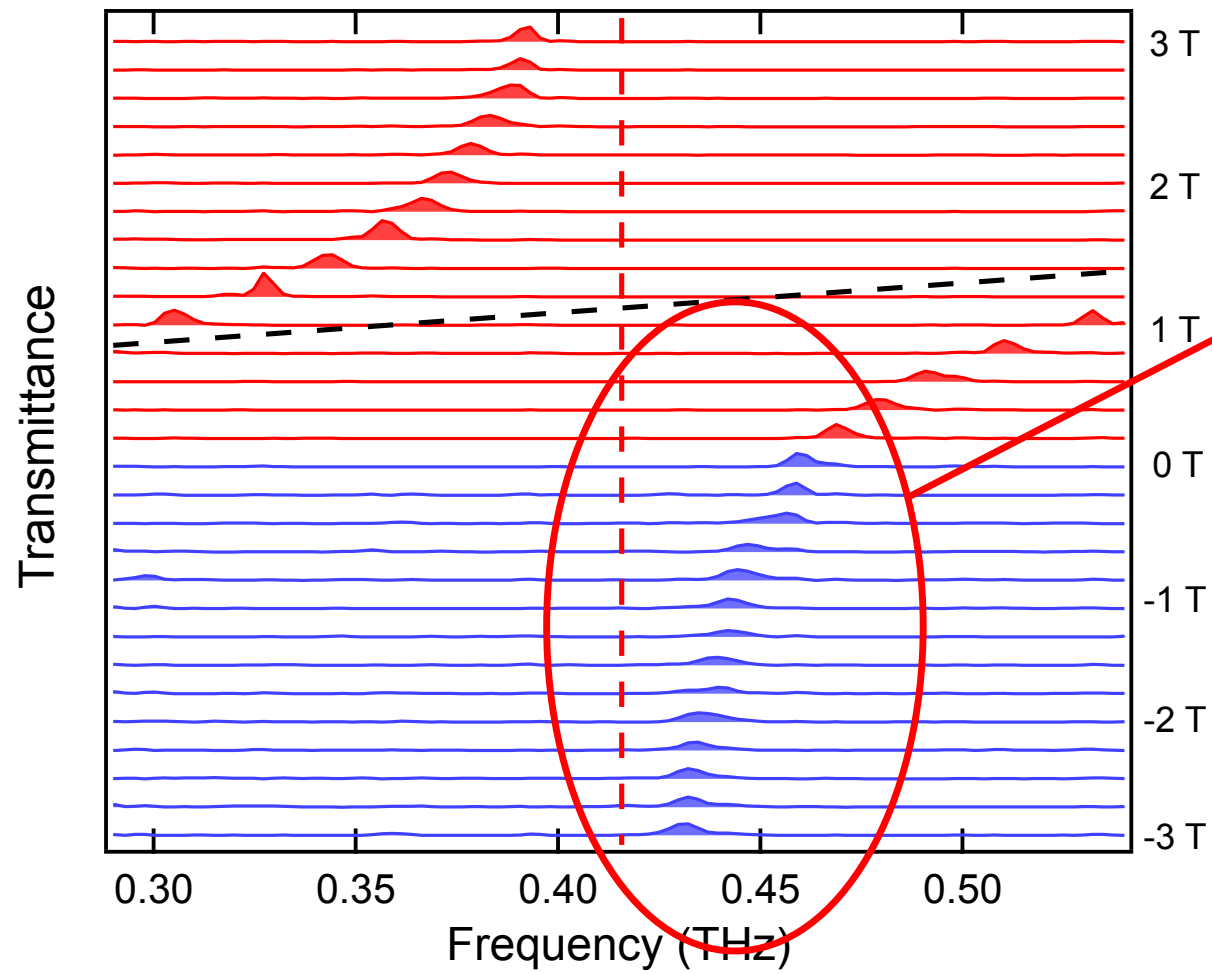


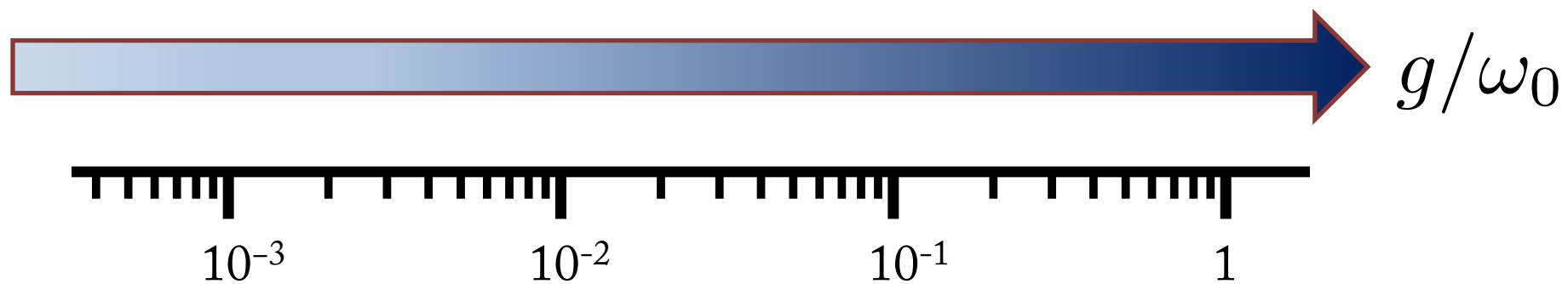
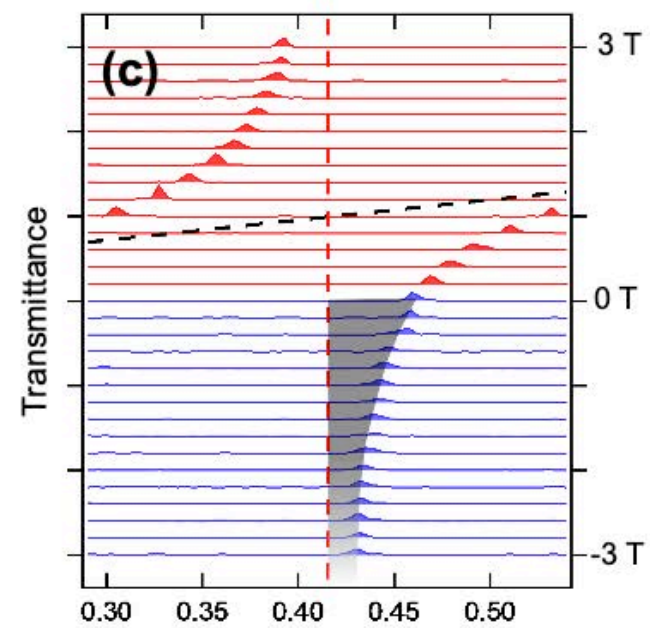
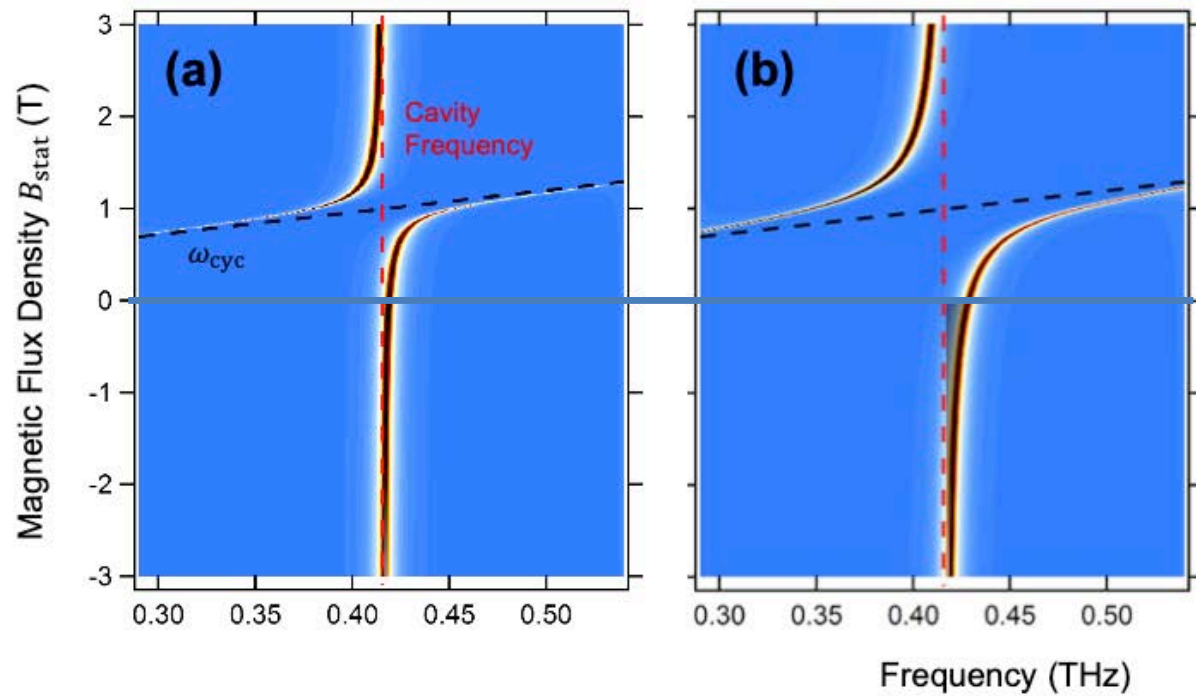






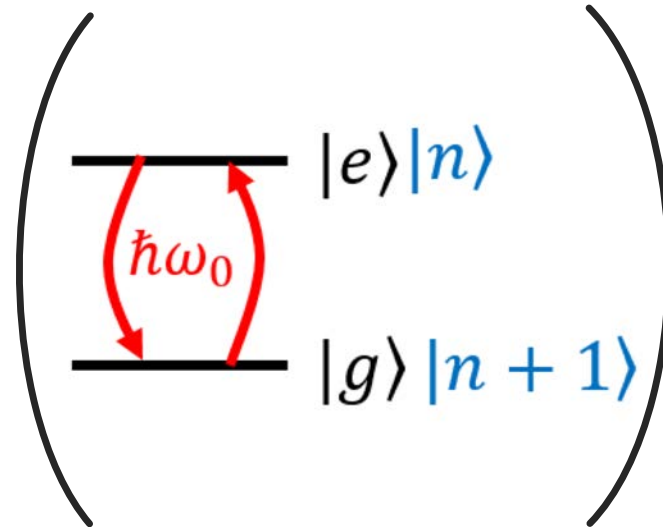






Jaynes-Cummings Model

$$\hat{H}_{\text{JC}} = \underbrace{\frac{1}{2}\hbar\omega_0\hat{\sigma}_z}_{\text{matter}} + \underbrace{\hbar\omega_c\hat{a}^\dagger\hat{a}}_{\text{light}} + \underbrace{\hbar g(\hat{\sigma}_+\hat{a} + \hat{\sigma}_-\hat{a}^\dagger)}_{\text{interaction}}$$



2-level atom in a cavity

Ultrastrong Coupling Regime

$$g > 0.1\omega_0$$

Breakdown of the RWA: counter-rotating terms
must be kept → **Bloch-Siegert shift**

PHYSICAL REVIEW

Magnetic Resonance for Nonrotating Fields

F. BLOCH AND A. SIEGERT*

Department of Physics, Stanford University, Stanford University, California

(Received January 19, 1940)

Ultrastrong Coupling Regime

$$g > 0.1\omega_0$$

Breakdown of the RWA: counter-rotating terms
must be kept $\rightarrow$ **Bloch-Siegert shift**

$$\begin{aligned}\hat{H} = & \frac{1}{2}\hbar\omega_0\hat{\sigma}_z + \hbar\omega_c\hat{a}^\dagger\hat{a} \\ & + \hbar g \left(\underbrace{\hat{\sigma}_+\hat{a} + \hat{\sigma}_-\hat{a}^\dagger}_{\text{co-rotating terms}} + \underbrace{\hat{\sigma}_-\hat{a} + \hat{\sigma}_+\hat{a}^\dagger}_{\text{counter-rotating terms}} \right)\end{aligned}$$

Ultrastrong Coupling Regime

$$g > 0.1\omega_0$$

Breakdown of the RWA: counter-rotating terms
must be kept → **Bloch-Siegert shift**

$$\begin{aligned}\hat{H} = & \frac{1}{2}\hbar\omega_0\hat{\sigma}_z + \hbar\omega_c\hat{a}^\dagger\hat{a} \\ & + \hbar g \left(\underbrace{\hat{\sigma}_+\hat{a} + \hat{\sigma}_-\hat{a}^\dagger}_{\text{co-rotating terms}} + \underbrace{\hat{\sigma}_-\hat{a} + \hat{\sigma}_+\hat{a}^\dagger}_{\text{counter-rotating terms}} \right) \\ & + \underbrace{\eta(\hat{a} + \hat{a}^\dagger)(\hat{a} + \hat{a}^\dagger)}_{\text{A}^2 \text{ term}} \quad (\eta \propto g^2)\end{aligned}$$

Theory of Landau Polaritons in the Ultrastrong Coupling Regime

$$\hat{H} = \hat{H}_{\text{CR}} + \hat{H}_{\text{cav}} + \hat{H}_{\text{int}} + \hat{H}_{A^2}$$

$$\hat{H}_{\text{CR}} = \hbar\omega_c \hat{\beta}_0^\dagger \hat{\beta}_0$$

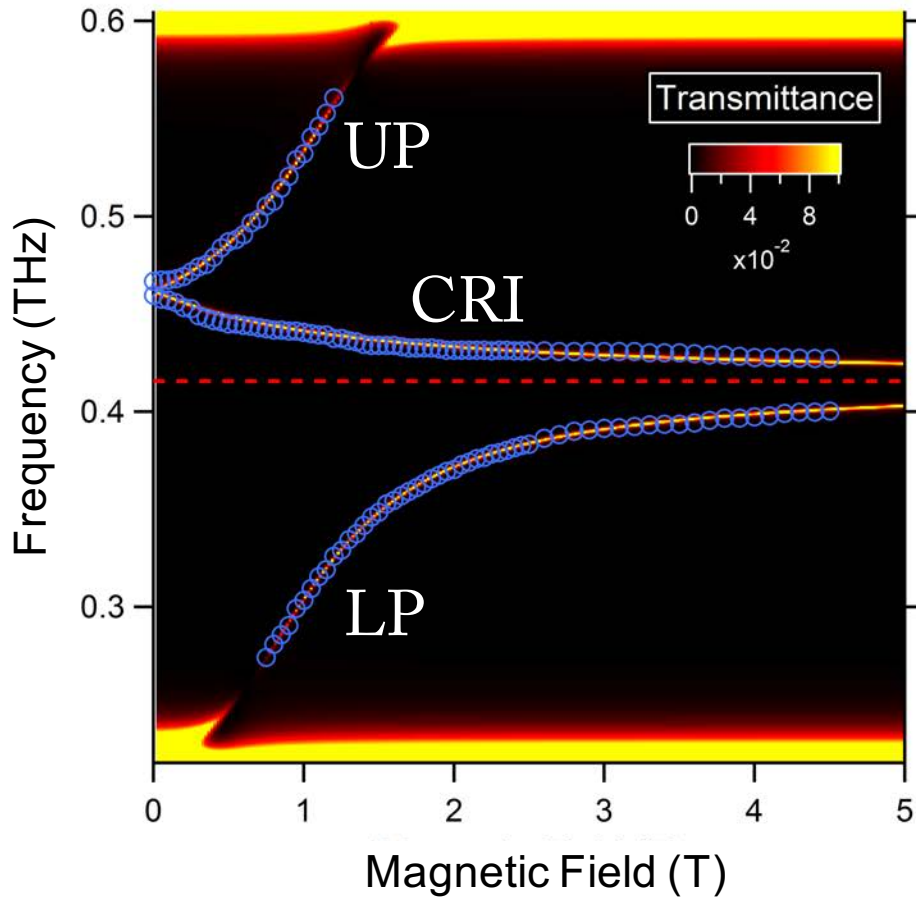
$$\hat{H}_{\text{cav}} = \sum_{n_z=1}^{\infty} \sum_{\xi=\pm} \hbar\omega_{\text{cav}}^{n_z} \hat{a}_{n_z,\xi}^\dagger \hat{a}_{n_z,\xi}$$

$$\hat{H}_{\text{int}} = \sum_{n_z=1}^{\infty} i\hbar g_{n_z} \left[\hat{\beta}_0^\dagger (\hat{a}_{n_z,+} + \hat{a}_{n_z,-}^\dagger) - \hat{\beta}_0 (\hat{a}_{n_z,-} + \hat{a}_{n_z,+}^\dagger) \right]$$

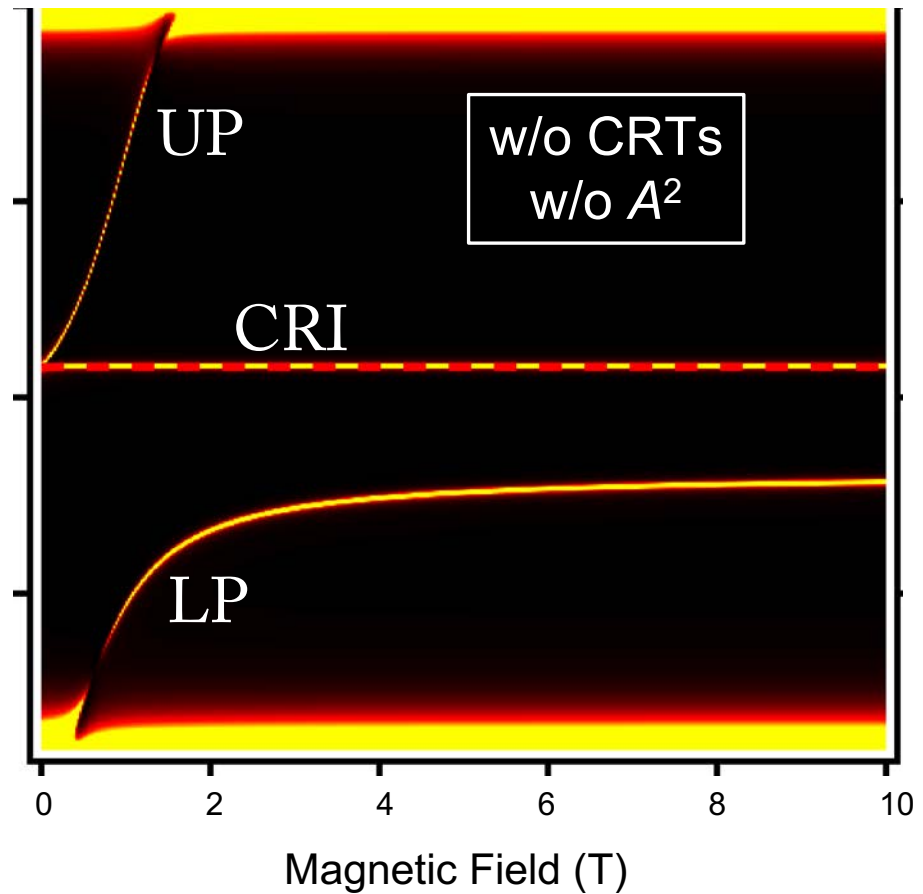
$$\hat{H}_{A^2} = \sum_{n_z=1}^{\infty} \sum_{n'_z=1}^{\infty} \frac{\hbar g_{n_z} g_{n'_z}}{\omega_c} (\hat{a}_{n_z,-} + \hat{a}_{n_z,+}^\dagger) (\hat{a}_{n'_z,+} + \hat{a}_{n'_z,-}^\dagger)$$

by **Motoaki Bamba (Osaka Univ.):** **arXiv:1901.06749**

Experiment

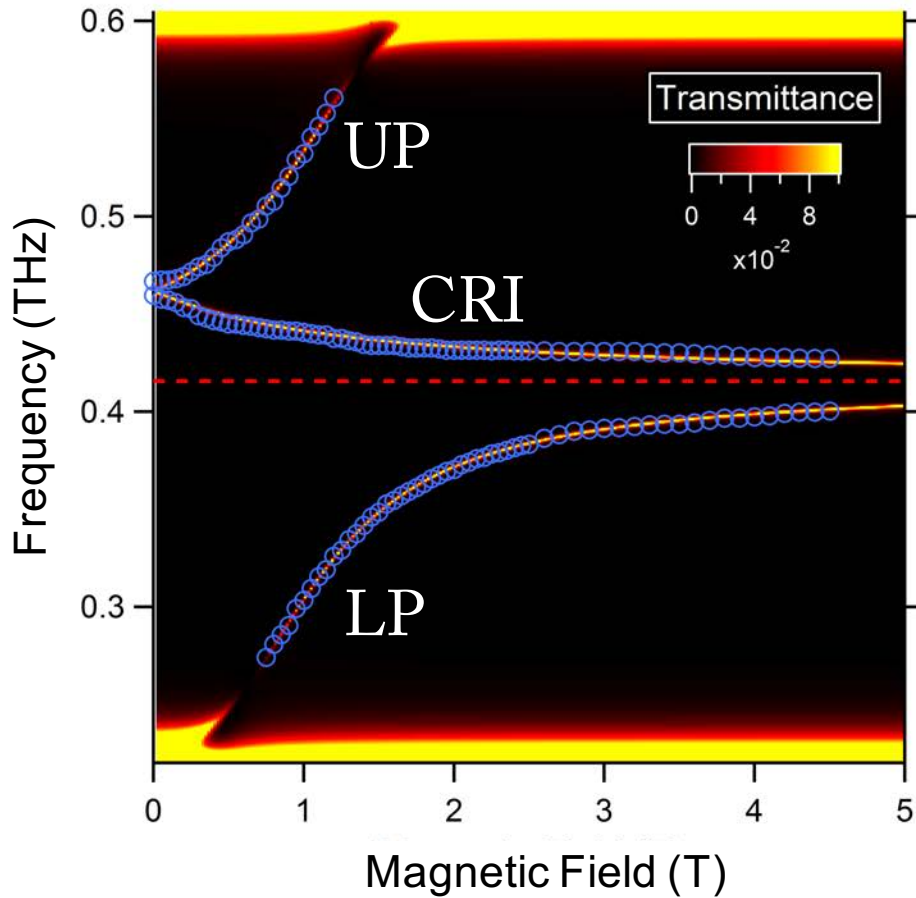


Theory

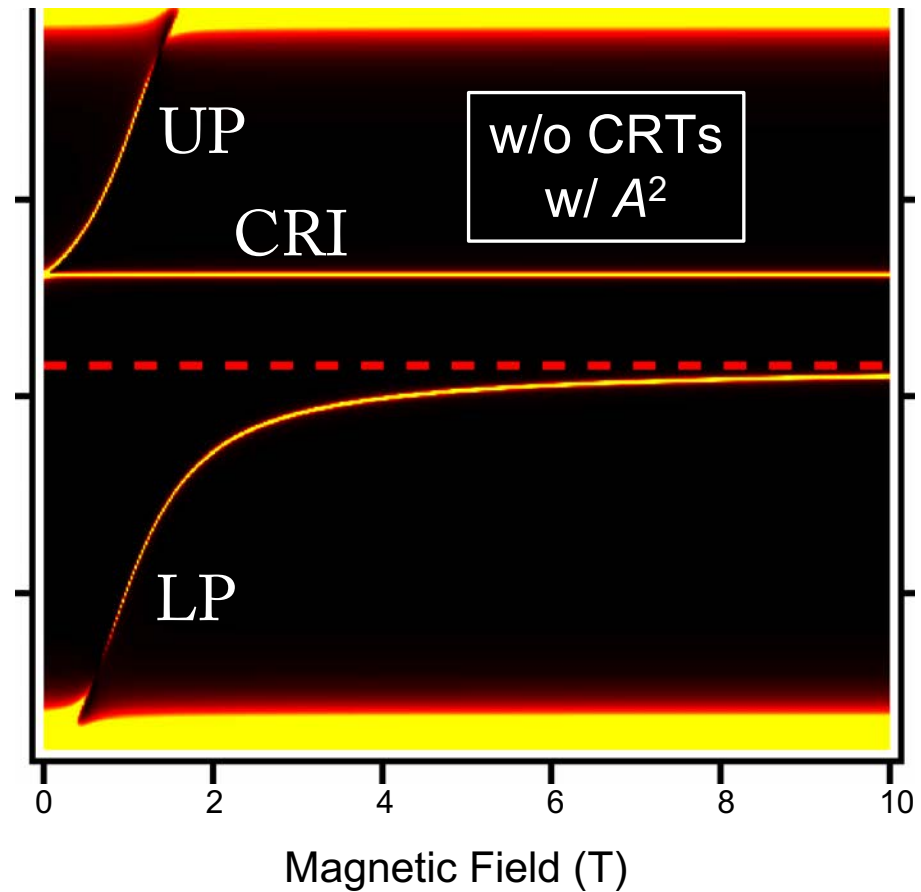


UP: upper polariton
CRI: cyclotron resonance inactive
LP: lower polariton

Experiment

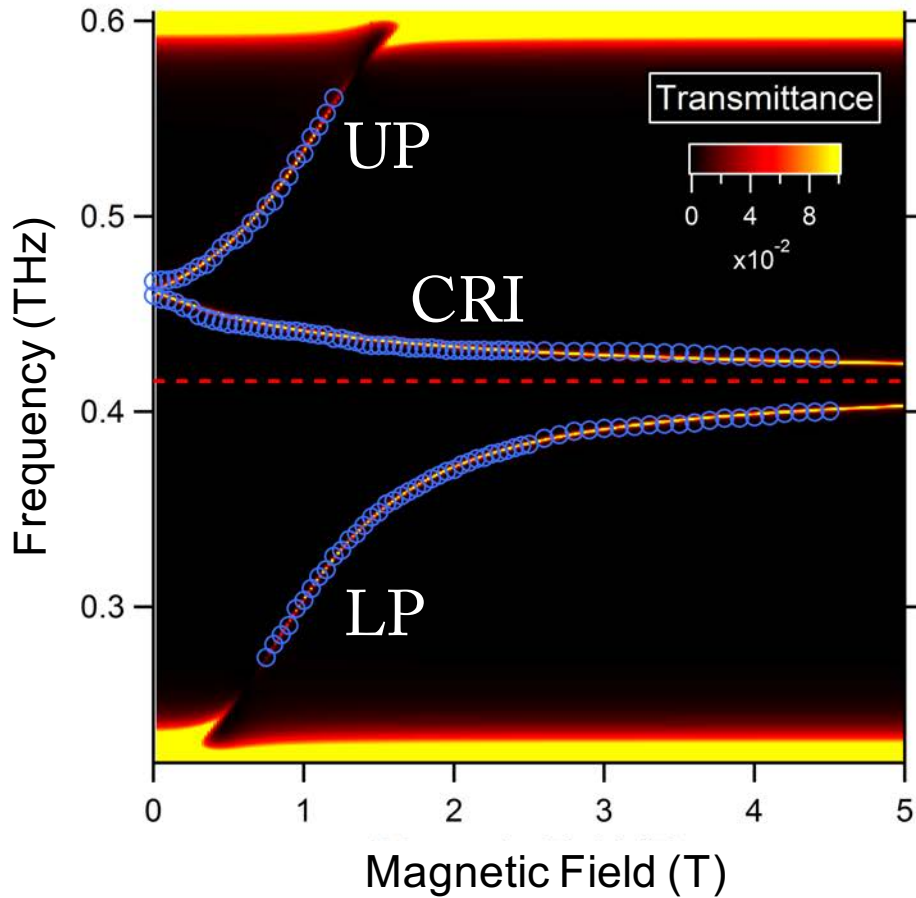


Theory

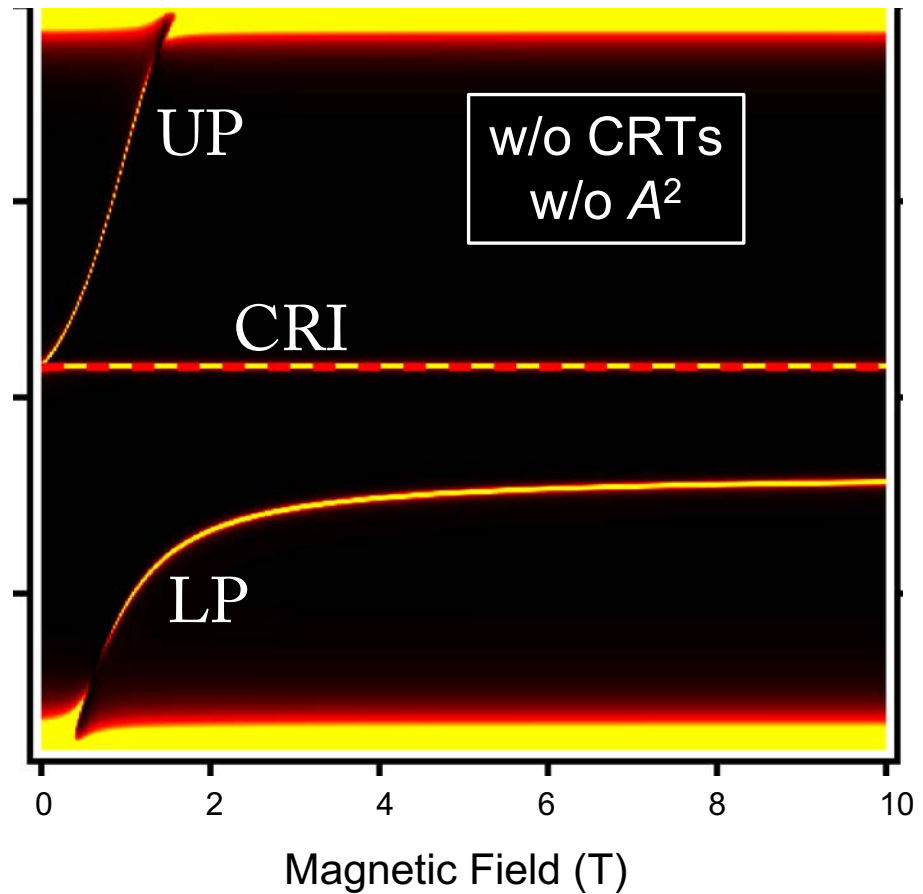


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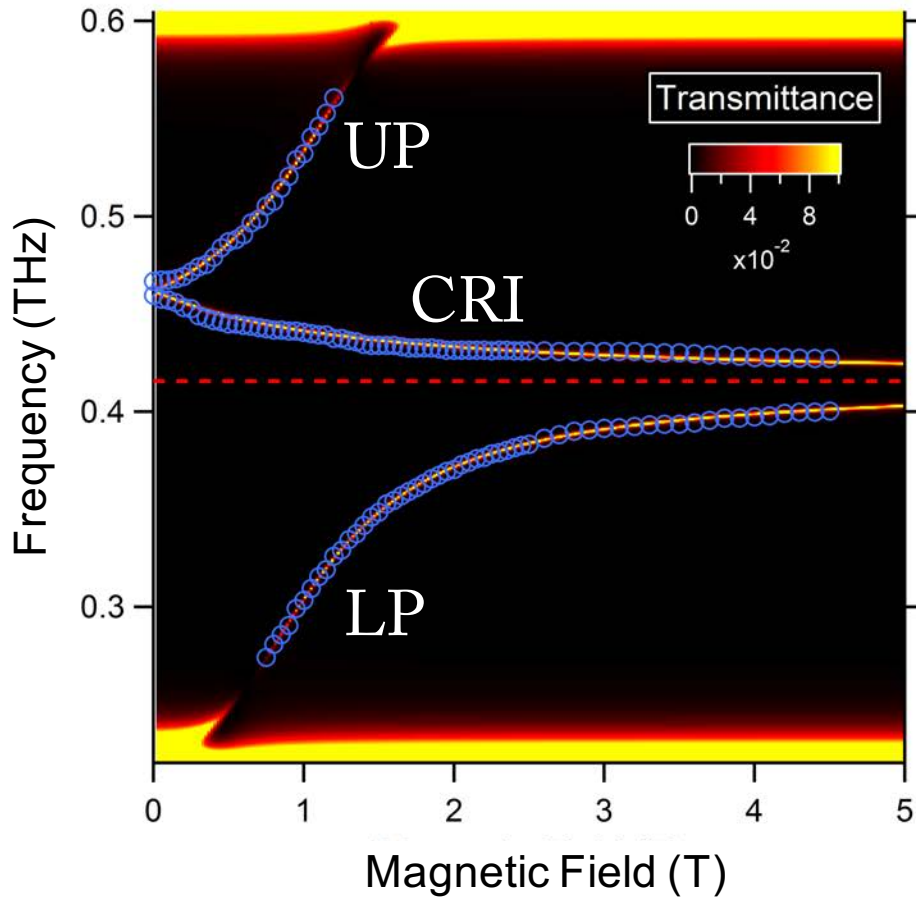


Theory

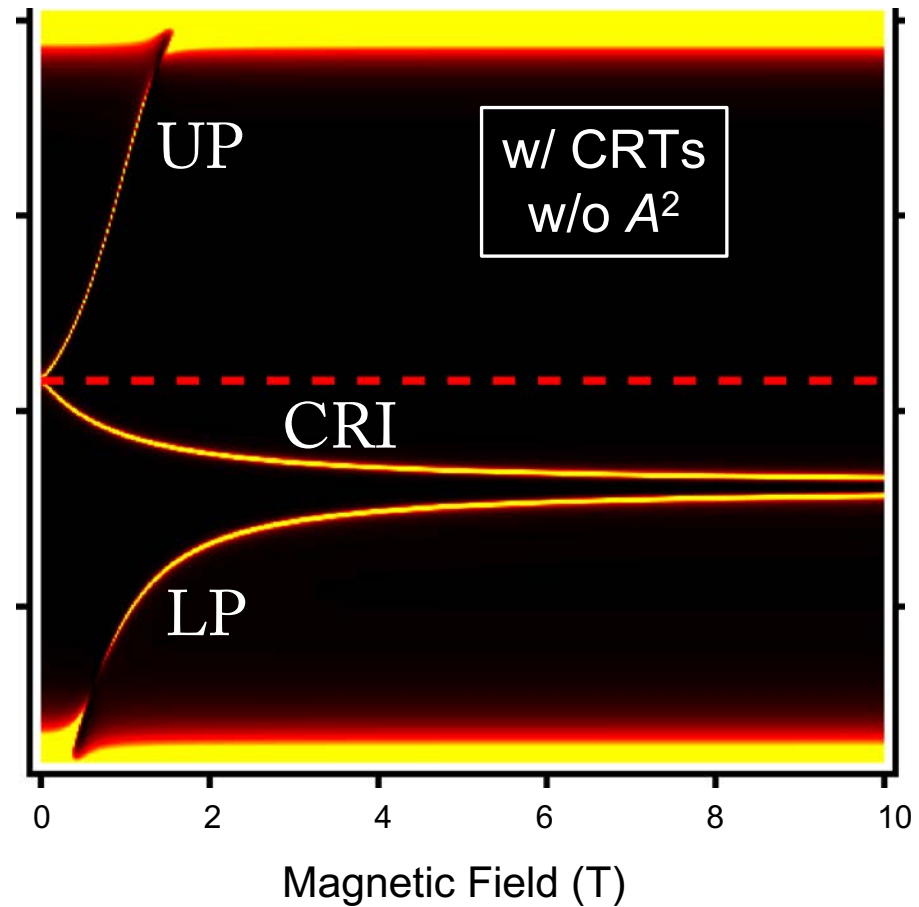


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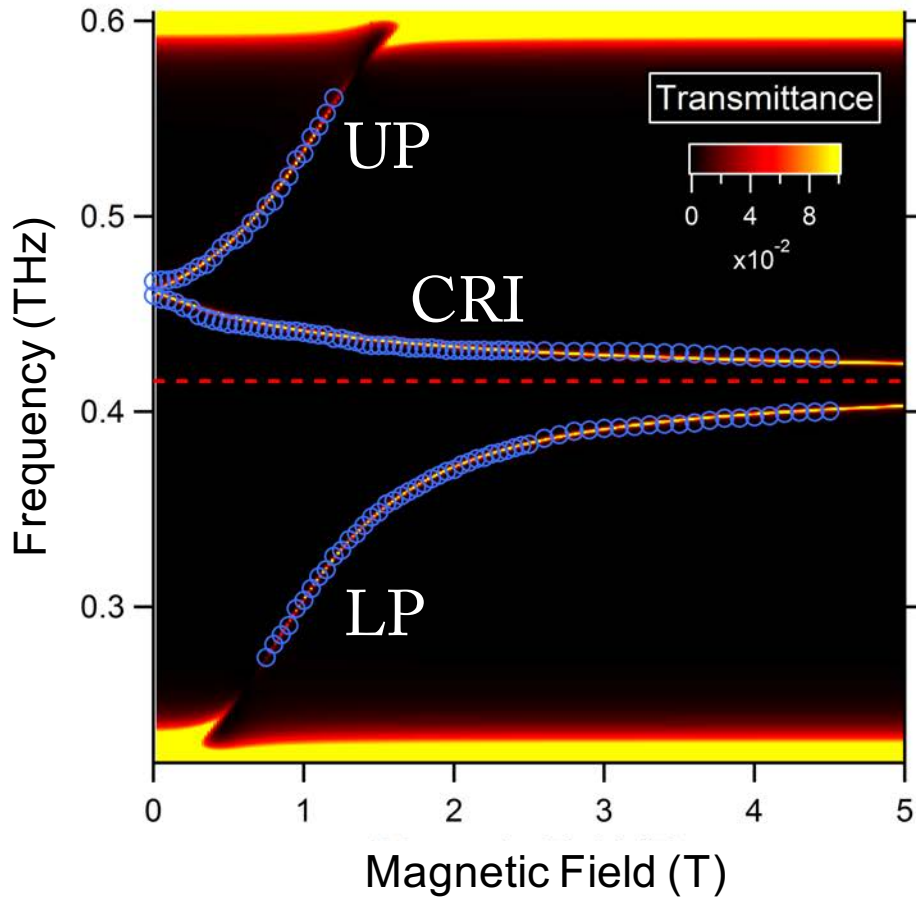


Theory

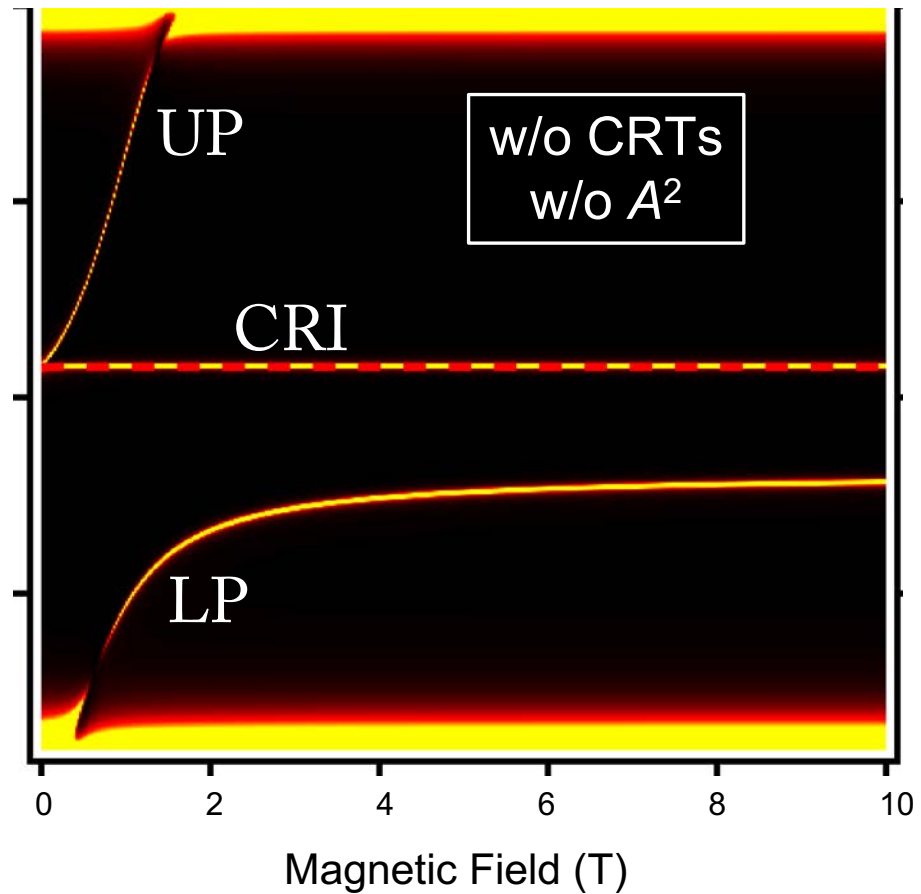


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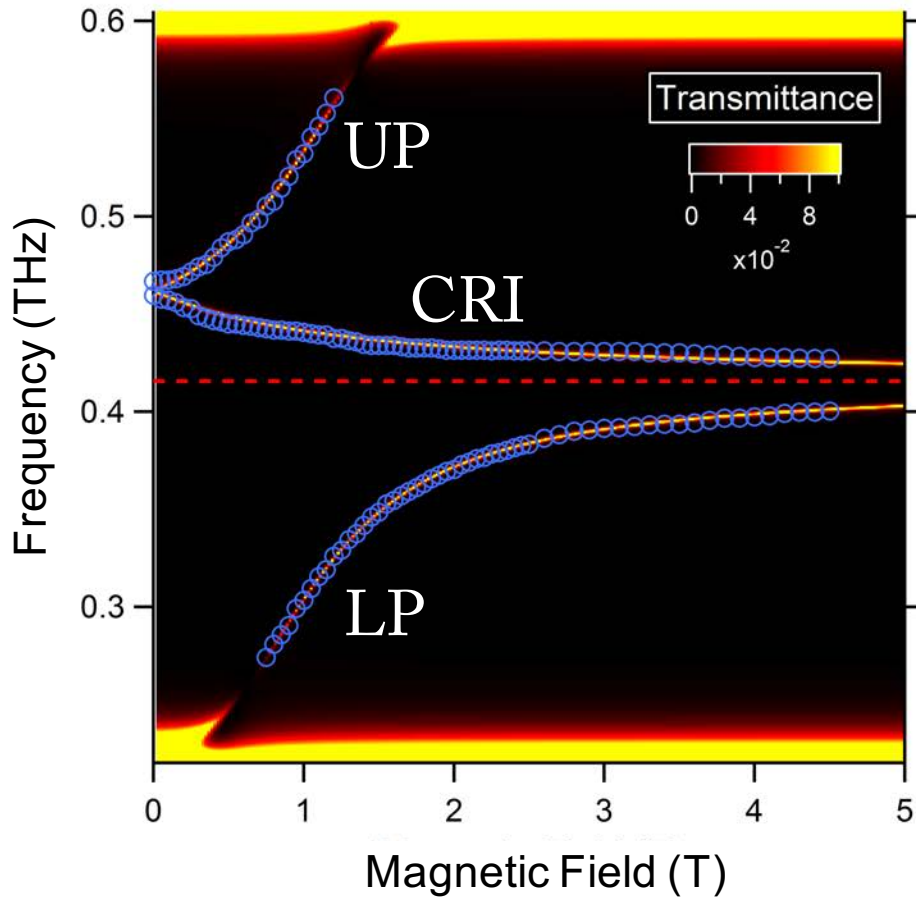


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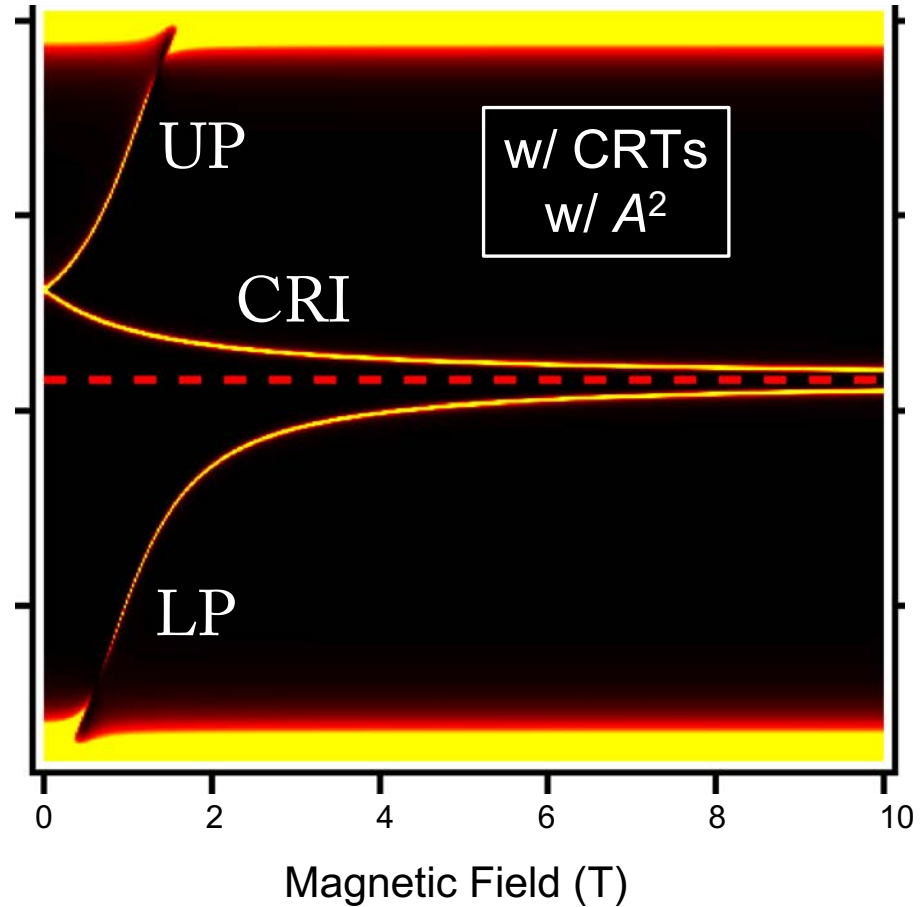


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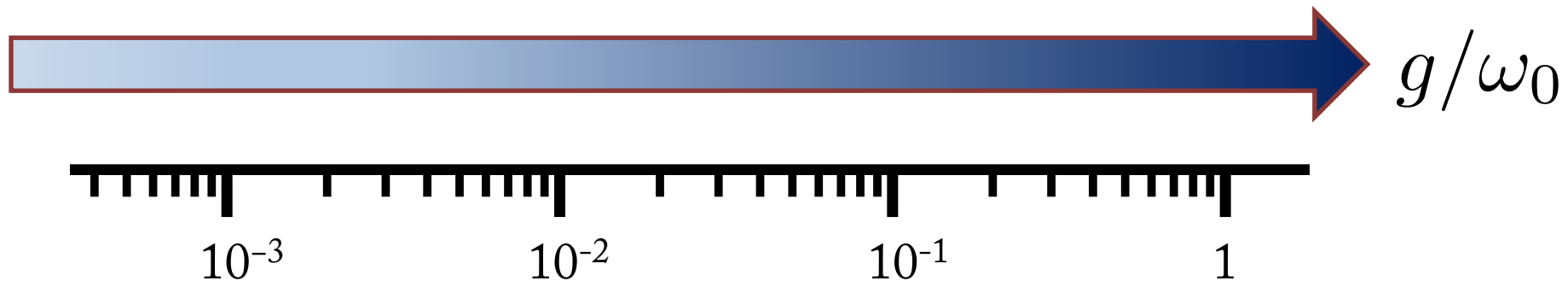
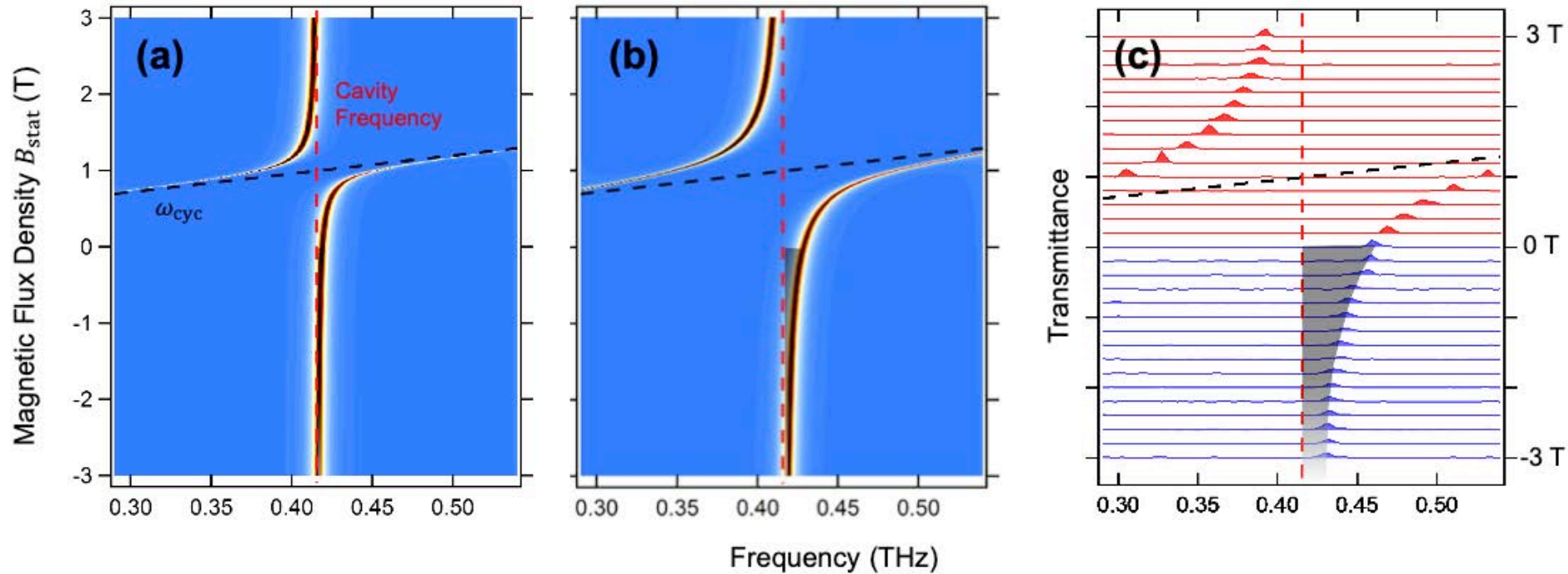


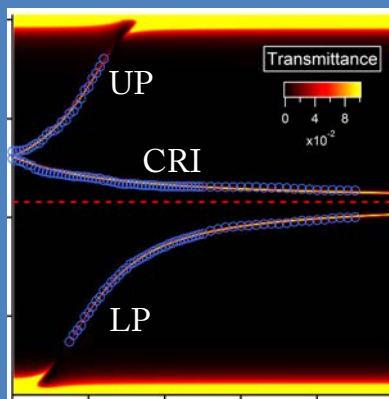
Theory



UP: upper polariton
CRI: cyclotron resonance inactive
LP: lower polariton

The vacuum Bloch-Siegert shift appears *only* on the CRI side *only* in the USC regime.





Summary (Part I)

THz Cavity QED

We have developed high-Q THz cavities that are

easy to fabricate

usable for studying a variety of materials

compatible with low T & high B

Landau polaritons in a high-mobility 2DEG revealed

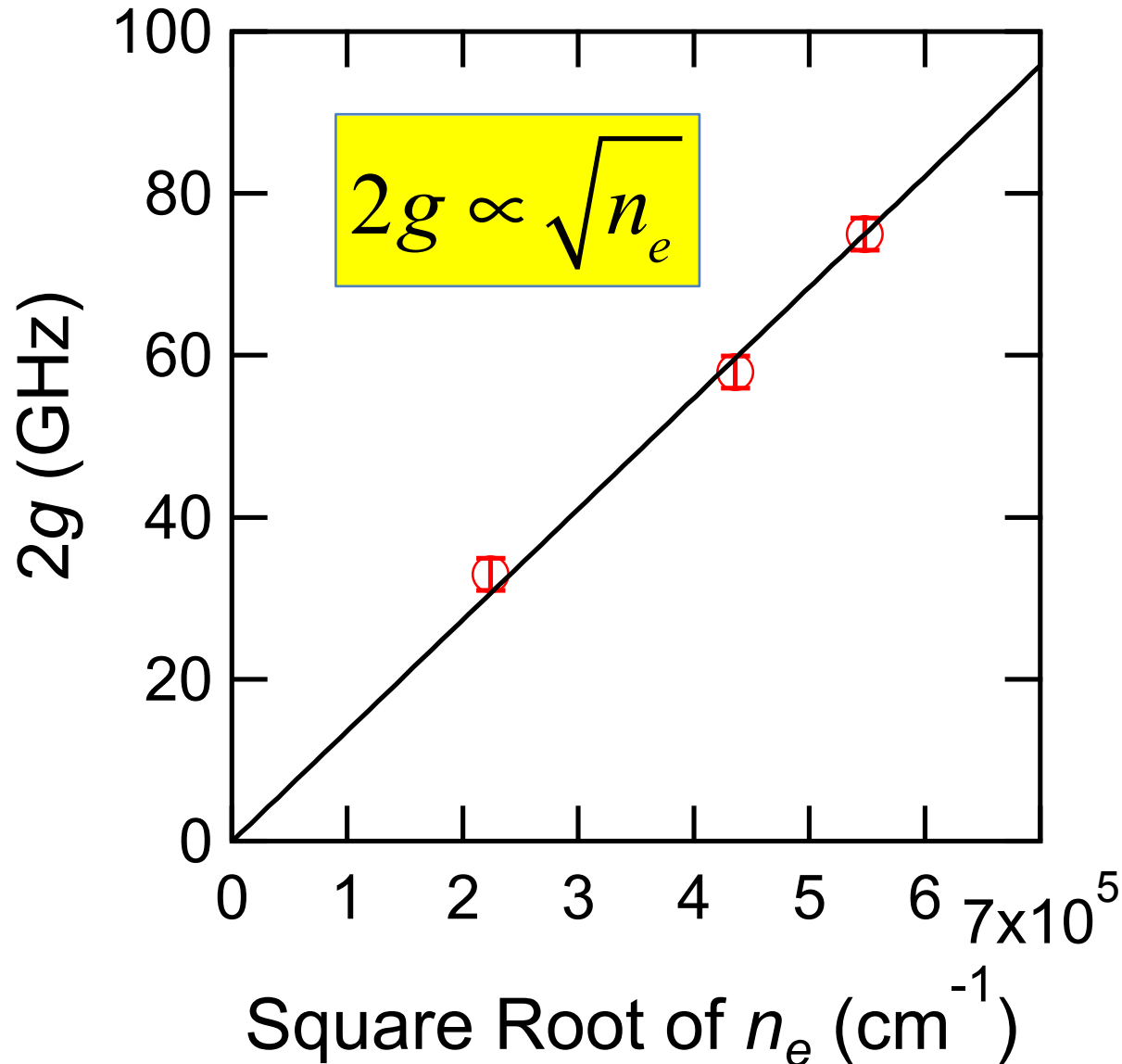
coherent THz-light/matter coupling $\rightarrow$ Landau polaritons

ultrastrong coupling with a record-high cooperativity ($> 3.5 \times 10^2$)

vacuum Bloch-Siegert shift (distinguished from the A^2 shift),
coming from the counter-rotating terms in the Hamiltonian

**THz Cavity QED = THz Strong-Field Physics + THz
Quantum Optics + THz Condensed Matter Physics**

Density (n_e) Dependent Vacuum Rabi Splitting, $2g$: *Cooperative* Light-Matter Coupling



Dicke Cooperativity:

Many-Body Enhancement of Coupling

The Tavis-Cummings (or Dicke) Hamiltonian

$$\hat{H}_{\text{int}} = \sum_{j=1}^N \hbar g (\hat{\sigma}_{j,+} \hat{a} + \hat{\sigma}_{j,-} \hat{a}^{\dagger})$$

$$\hat{b} \equiv \frac{1}{\sqrt{N}} \sum_{j=1}^N \hat{\sigma}_{j,-}, \quad \hat{b}^{\dagger} \equiv \frac{1}{\sqrt{N}} \sum_{j=1}^N \hat{\sigma}_{j,+}$$

$$\Rightarrow \hat{H}_{\text{int}} = \boxed{\sqrt{N} \hbar g} (\hat{b}^{\dagger} \hat{a} + \hat{b} \hat{a}^{\dagger})$$

The Dicke Superradiant Phase Transition

$$g > \omega_0$$

On the Superradiant Phase Transition for Molecules in a Quantized Radiation Field: the Dicke Maser Model

KLAUS HEPP

Physics Department, ETH, Zürich, 8049 Switzerland

AND

ELLIOTT H. LIEB*

Mathematics Department, MIT, Cambridge, Mass. 02139, USA

Ann. Phys. **76**, 360 (1973)

Phase Transition in the Dicke Model of Superradiance*

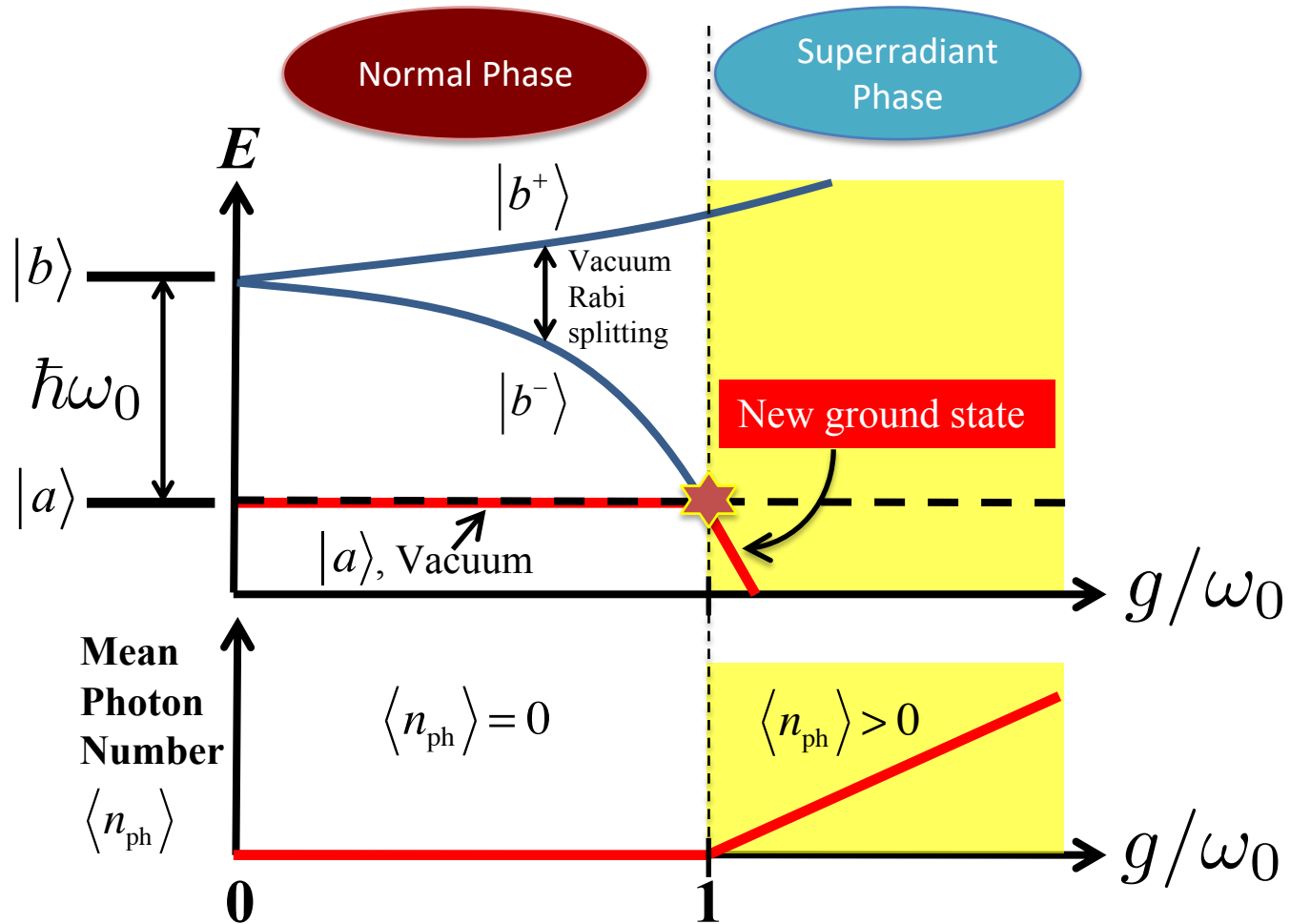
Y. K. Wang and F. T. Hioe

Institute for Fundamental Studies, Department of Physics and Astronomy, The University of Rochester, Rochester, New York 14627
(Received 10 October 1972)

Phys. Rev. A **7**, 831 (1973)

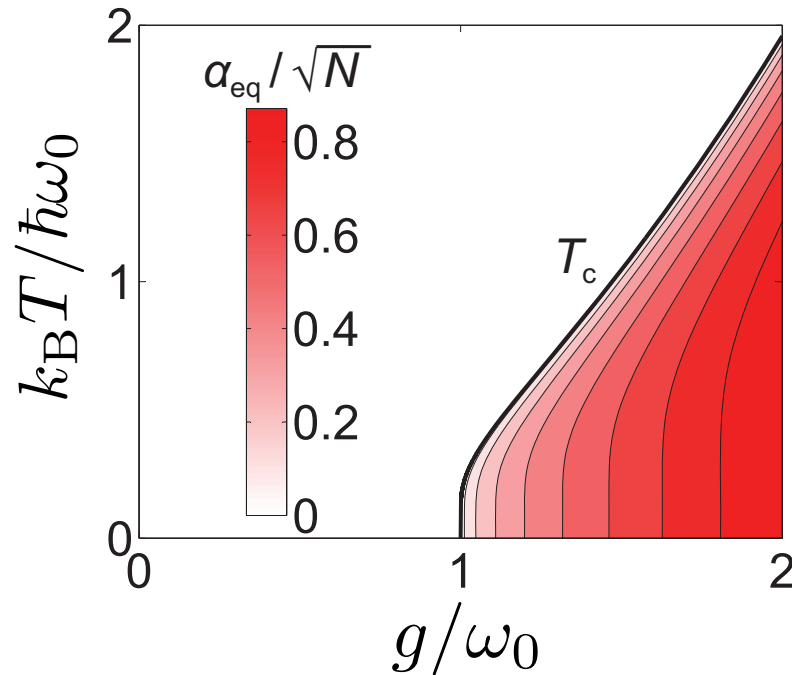
The Dicke Superradiant Phase Transition

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The Dicke Superradiant Phase Transition

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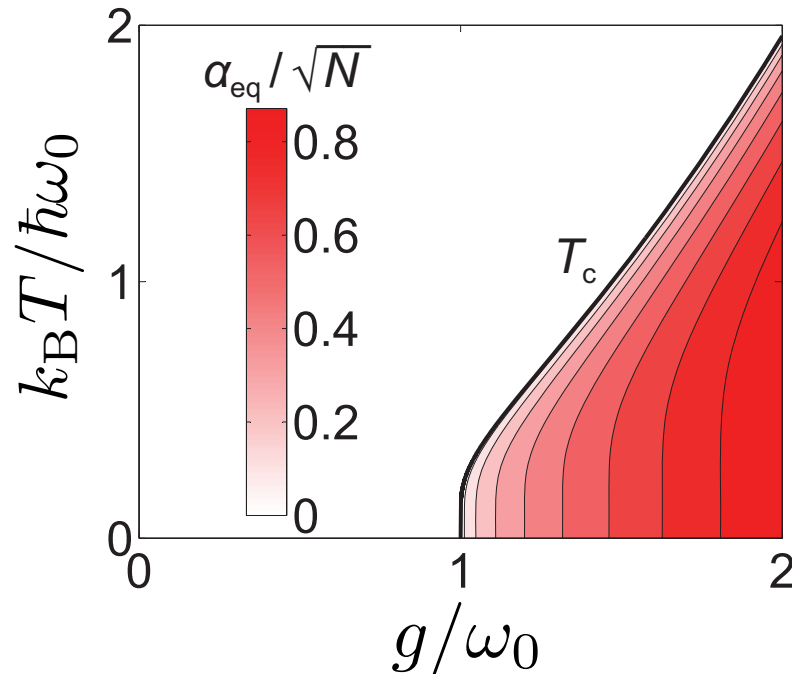


K. Hepp & E. H. Lieb, *Ann. Phys.* **76**, 360 (1973)

Y. K. Wang & F. T. Hioe, *Phys. Rev. A* **7**, 831 (1973)

The Dicke Superradiant Phase Transition

$$g > \omega_0$$



K. Hepp & E. H. Lieb, *Ann. Phys.* **76**, 360 (1973)

Y. K. Wang & F. T. Hioe, *Phys. Rev. A* **7**, 831 (1973)

Quantum Phase Transition

- C. Emary & T. Brandes, *Phys. Rev. E* **67**, 066203 (2003); *Phys. Rev. Lett.* **90**, 044101 (2003)
- F. Dimer *et al.*, *Phys. Rev. A* **75**, 013804 (2007)
- P. Nataf & C. Ciuti, *Nat. Commun.* **1**, 72 (2010)
- J. Larson & E. K. Irish, *J. Phys. A* **50**, 174002 (2017)

No-Go Theorem for the Dicke Phase Transition (?)

Phase Transitions, Two-Level Atoms, and the A^2 Term

K. Rzażewski* and K. Wódkiewicz*

*Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627, and
Institute of Theoretical Physics, Warsaw University, 00-681, Warsaw, Poland*

and

W. Żakowicz

Institute of Nuclear Research, 00-681, Warsaw, Poland

(Received 11 June 1975)

We show that the presence of the recently discovered phase transition in the Dicke Hamiltonian is due entirely to the absence of the A^2 terms from the interaction Hamiltonian.

Phys. Rev. Lett. **35**, 432 (1975)

Dicke Superradiant Phase Transition: Ongoing Debate

PHYSICAL REVIEW A

VOLUME 17, NUMBER 4

APRIL 1978

Are super-radiant phase transitions possible?

J. M. Knight, Y. Aharonov,^{*} and G. T. C. Hsieh

VOLUME 93, NUMBER 8

PHYSICAL REVIEW LETTERS

week ending
20 AUGUST 2004

First-Order Superradiant Phase Transitions in a Multiqubit Cavity System

Chiu Fan Lee^{*} and Neil F. Johnson[†]

Coulomb interactions, gauge invariance, and phase transitions of the Dicke model

J. Phys.: Condens. Matter **19** (2007) 295213 (8pp)

Jonathan Keeling¹

PHYSICAL REVIEW A **90**, 063825 (2014)

Stability of polarizable materials against superradiant phase transition

Motoaki Bamba^{*} and Tetsuo Ogawa

PRL **112**, 073601 (2014)

PHYSICAL REVIEW LETTERS

week ending
21 FEBRUARY 2014



Elimination of the A-Square Problem from Cavity QED

András Vukics,^{1,*} Tobias Grieser,² and Peter Domokos¹

Dicke Superradiant Phase Transition: Ongoing Debate

Phys. Rev. A **98**, 053819 (2018)

Breakdown of gauge invariance in ultrastrong-coupling cavity QED

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Atominstitut, TU Wien, 1040 Vienna, Austria and*

²*School of Physics and Astronomy, University of Southampton, Southampton, SO17 1BJ, United Kingdom*

Nat. Commun. **10**, 499 (2019)

Gauge ambiguities in QED: Jaynes-Cummings physics remains valid in the ultrastrong-coupling regime

Adam Stokes* and Ahsan Nazir[†]

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Oxford Road, Manchester M13 9PL, United Kingdom*

Nat. Phys., to appear (2019); arXiv:1809.08749

Resolution of Gauge Ambiguities in Ultrastrong-Coupling Cavity QED

Omar Di Stefano,¹ Alessio Settineri,² Vincenzo Macrì,¹ Luigi
Garziano,¹ Roberto Stassi,¹ Salvatore Savasta,^{1,2,*} and Franco Nori^{1,3}

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³*Physics Department, The University of Michigan, Ann Arbor, Michigan 48109-1040, USA*

Dicke Superradiant Phase Transition: Ongoing Debate

arXiv:1905.11227

Cavity QED of Strongly Correlated Electron Systems: A No-go Theorem for Photon Condensation

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⁶*Department of Physics, The University of Texas at Austin, Austin, TX 78712, USA*

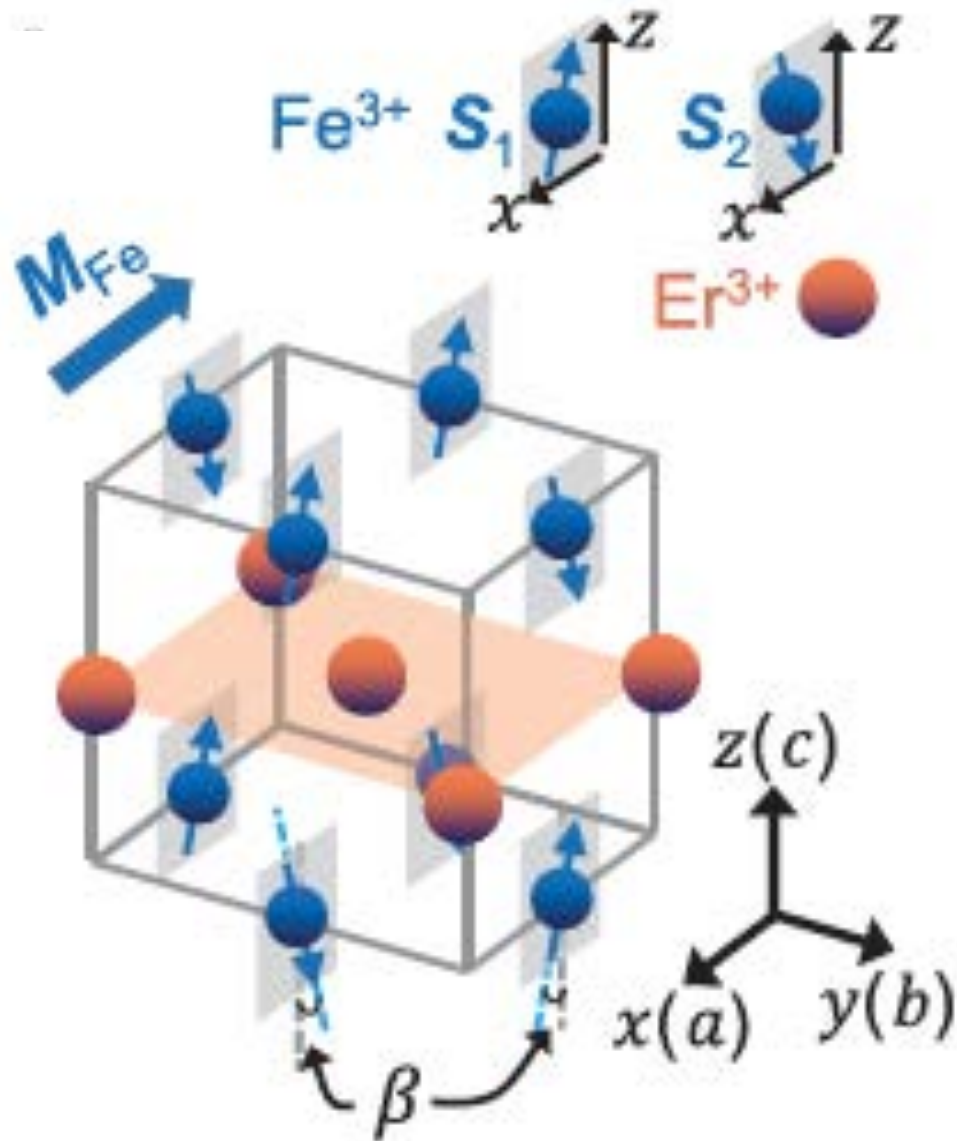
Are super-radiant phase transitions possible?

J. M. Knight, Y. Aharonov,* and G. T. C. Hsieh

It appears, therefore, that we cannot rule out phase transitions based on magnetic-dipole interactions. A realization of this possibility might consist of a cavity with a constant magnetic field in the z direction. The magnitude of the field would be chosen so that the Larmor frequency is resonant with a mode of the cavity having its magnetic field in the y direction. This system would be well described by the Hamiltonian¹⁹

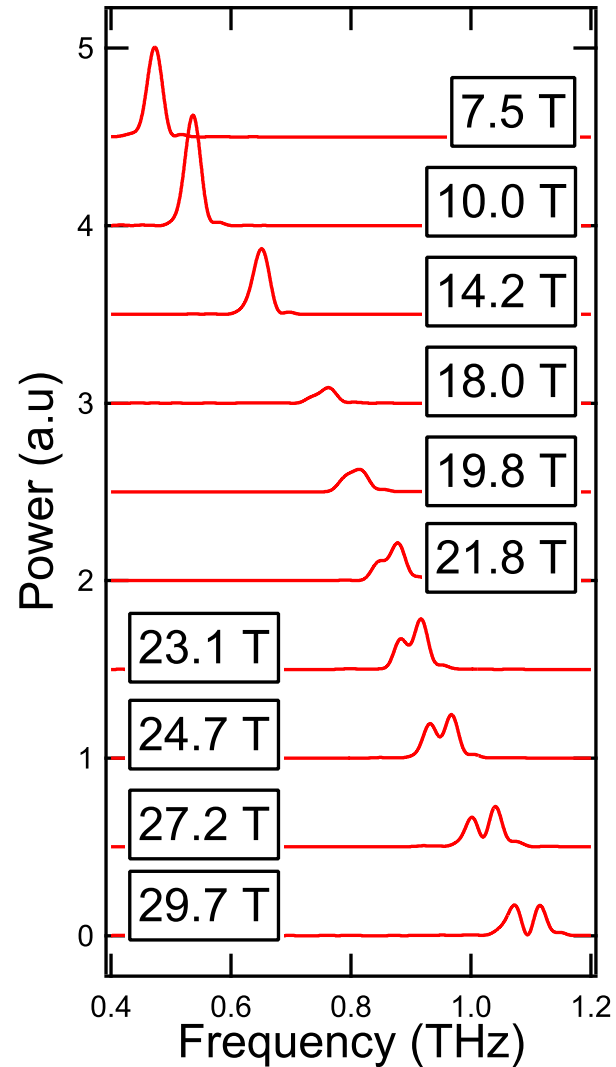
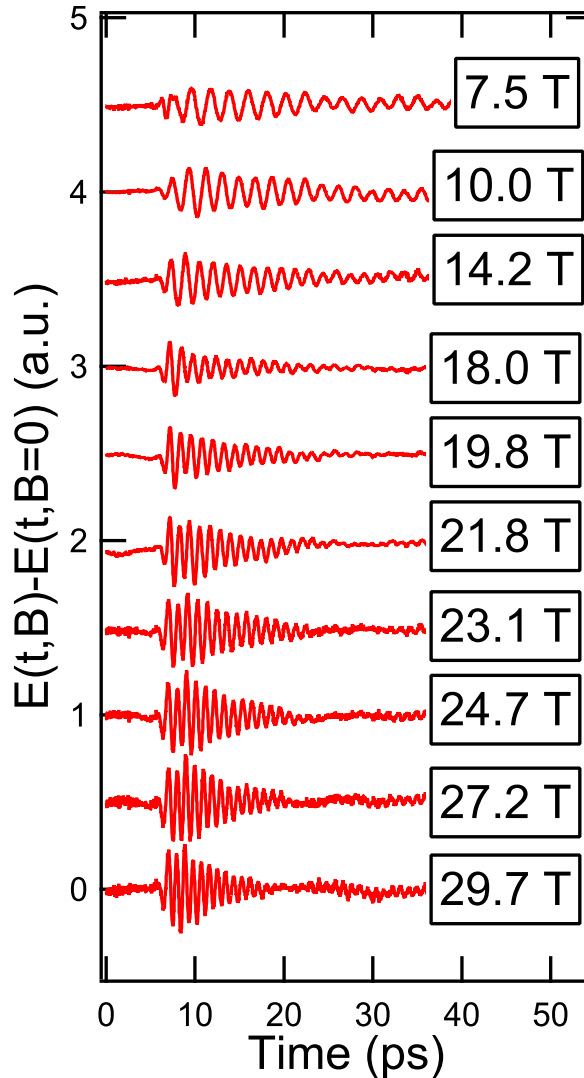
$$H = \hbar\omega_L \left(\sum_j \sigma_j^{(z)} + a^\dagger a \right) + i\xi(a - a^\dagger) \sum_j \sigma_j^{(y)}, \quad (46)$$

which is of the Dicke form, and which is obtained from the fundamental Hamiltonian without making any approximations which violate gauge invari-

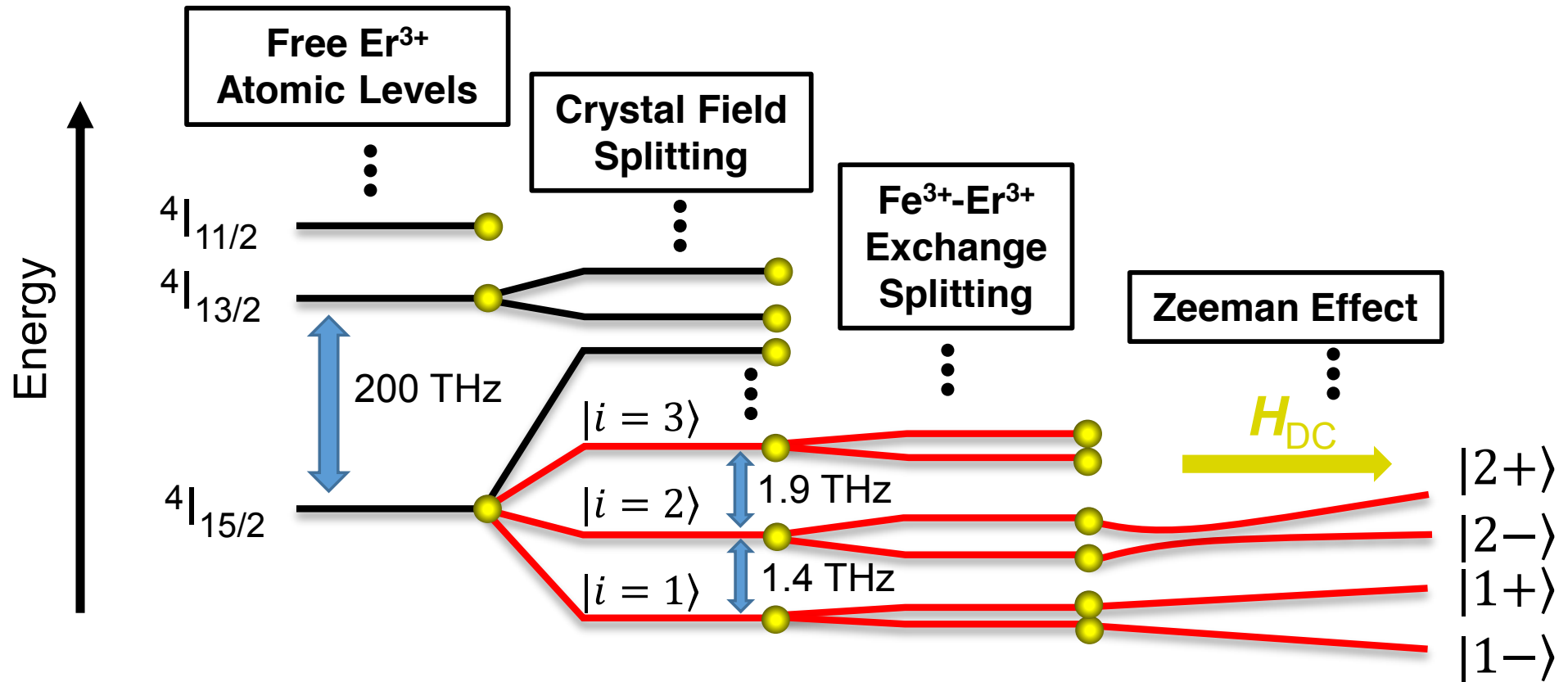


X. Li *et al.*, *Science*
361, 794 (2018)

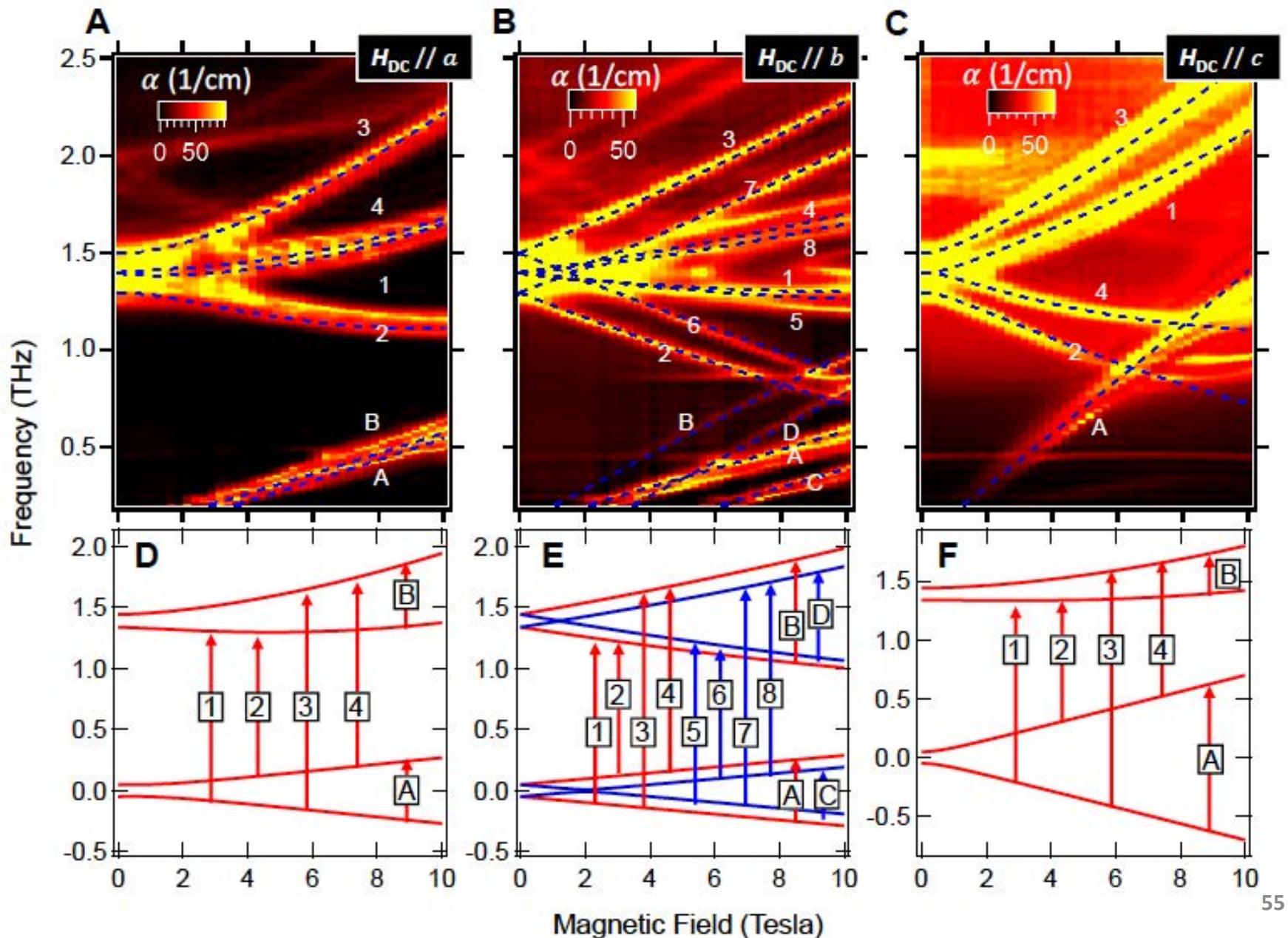
Coherent THz Magnon Excitation



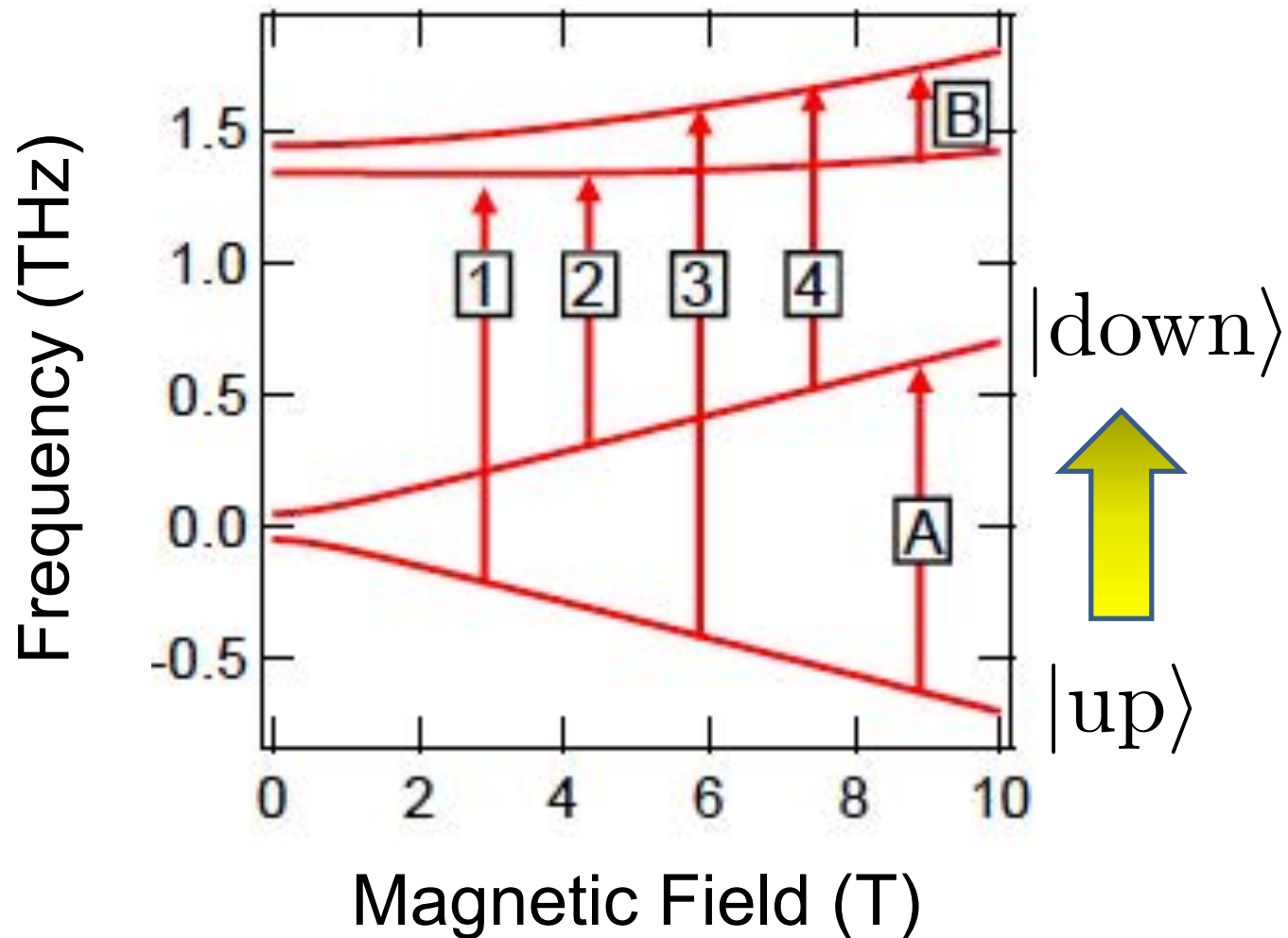
Energy Levels of Er^{3+} in ErFeO_3



Energy Levels of Er^{3+} in ErFeO_3

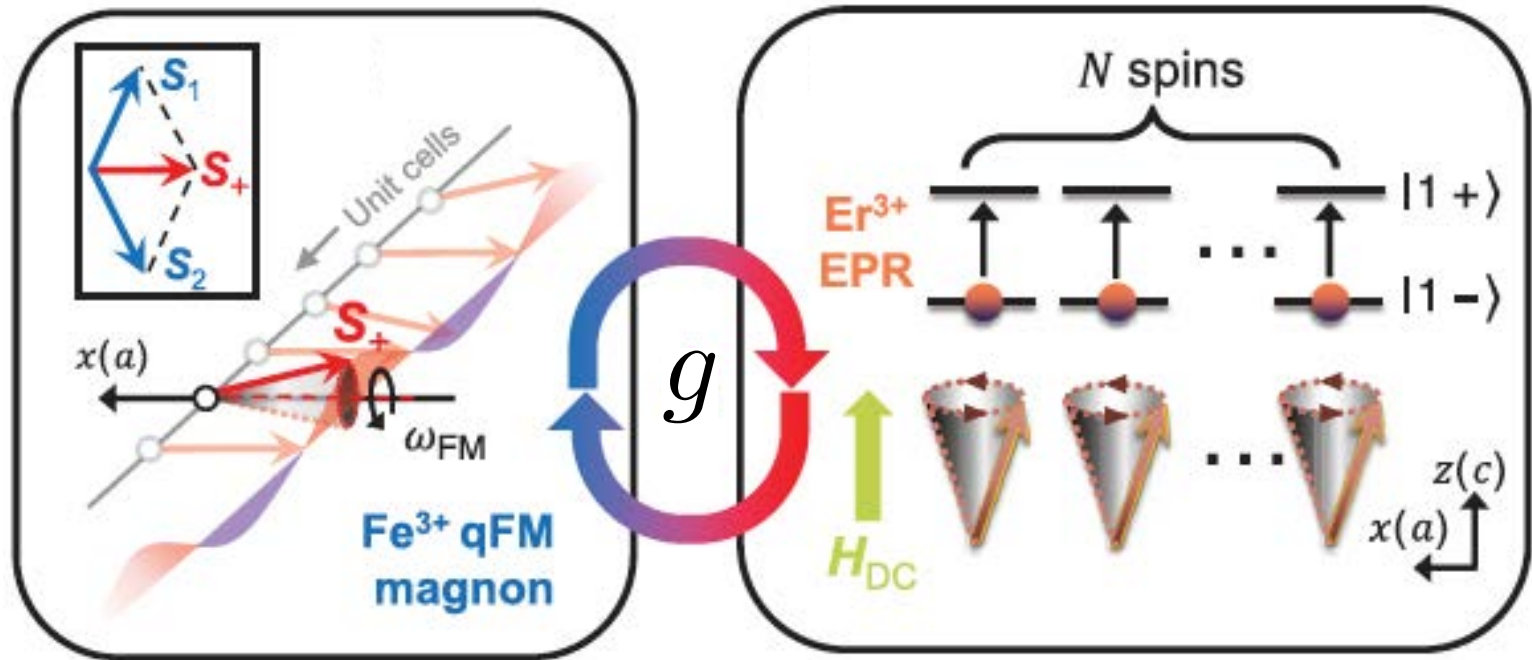


Energy Levels of Er^{3+} in ErFeO_3



Cooperative & Ultrastrong Er-Fe Exchange Interaction: Dicke Physics without Light

ErFeO₃

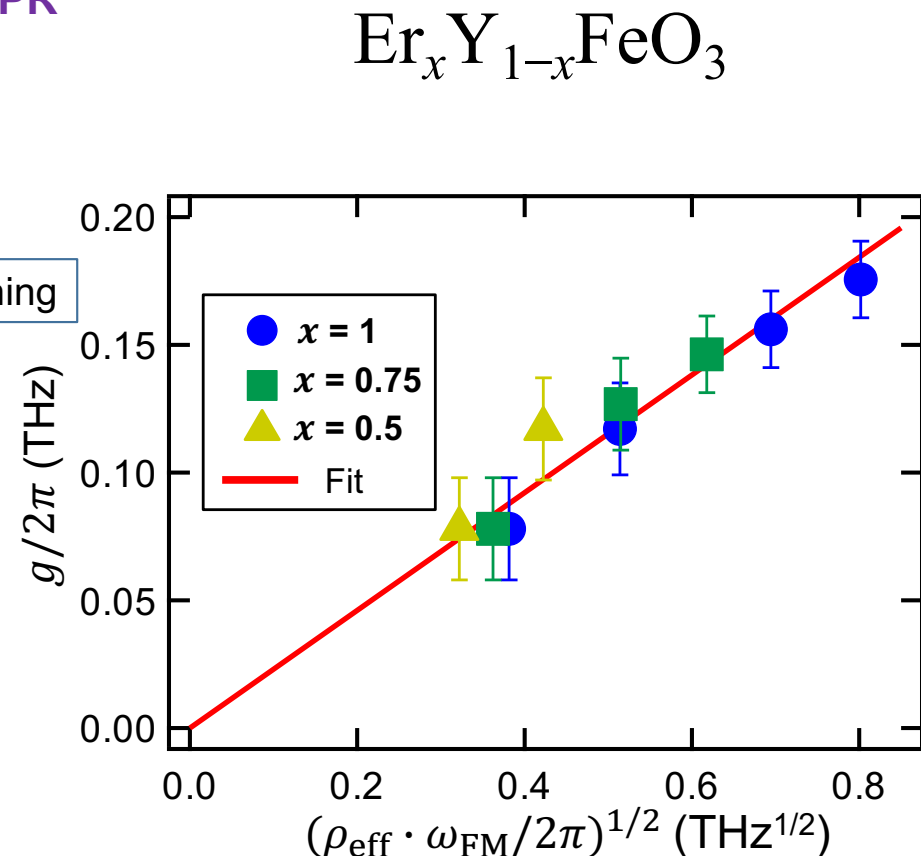
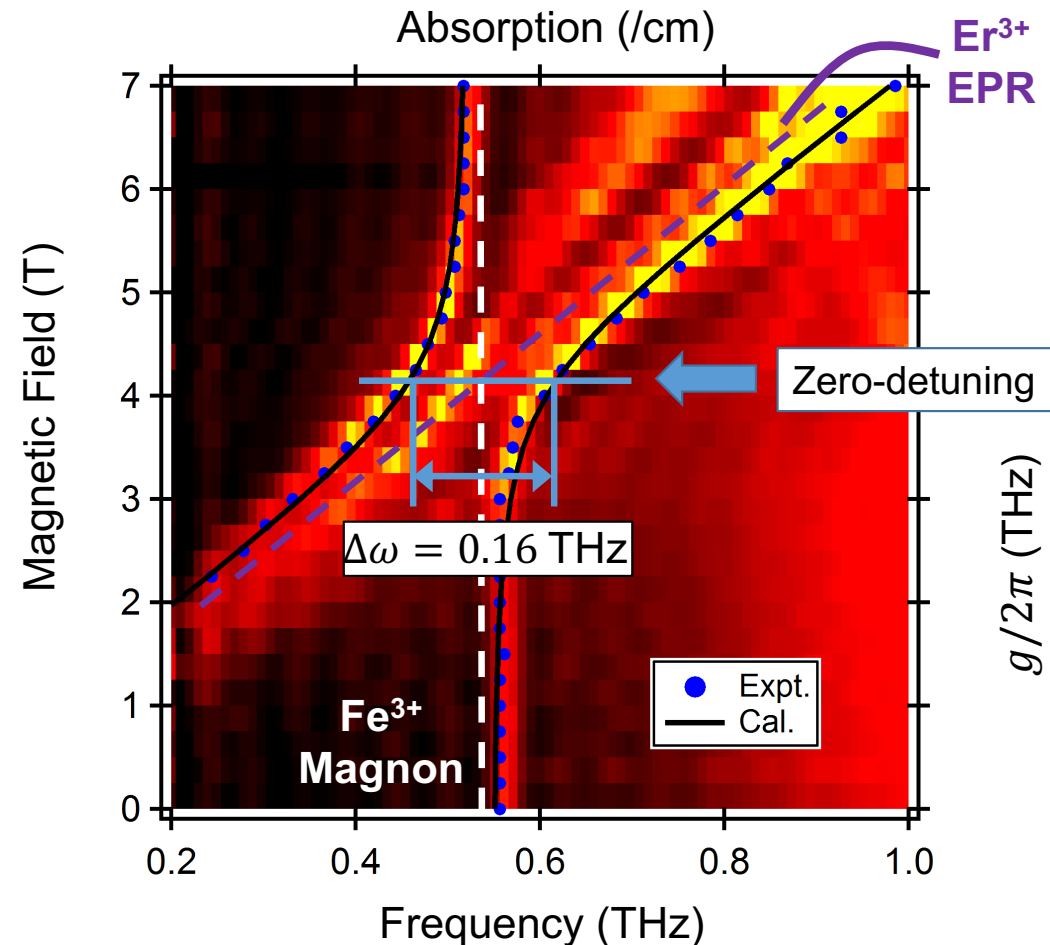


$$\hat{H}_{\text{Fe-Er}} = \sum_{l=1}^{N_{\text{UC}}} [J_1 \hat{\mathbf{R}}_l \cdot \hat{\mathbf{S}}_{2l-1} + J_2 \hat{\mathbf{R}}_l \cdot \hat{\mathbf{S}}_{2l} + \mathbf{D}_1 \cdot (\hat{\mathbf{R}}_l \times \hat{\mathbf{S}}_{2l-1}) + \mathbf{D}_2 \cdot (\hat{\mathbf{R}}_l \times \hat{\mathbf{S}}_{2l})]$$

➔ $\hat{\mathcal{H}}_{\text{Fe-Er,dynamic}} = i\hbar g \left(\hat{b}^\dagger + \hat{b} \right) \left(\hat{a}^\dagger - \hat{a} \right)$ **No A^2 term!**

Cooperative & Ultrastrong Er-Fe Exchange Interaction: Dicke Physics without Light

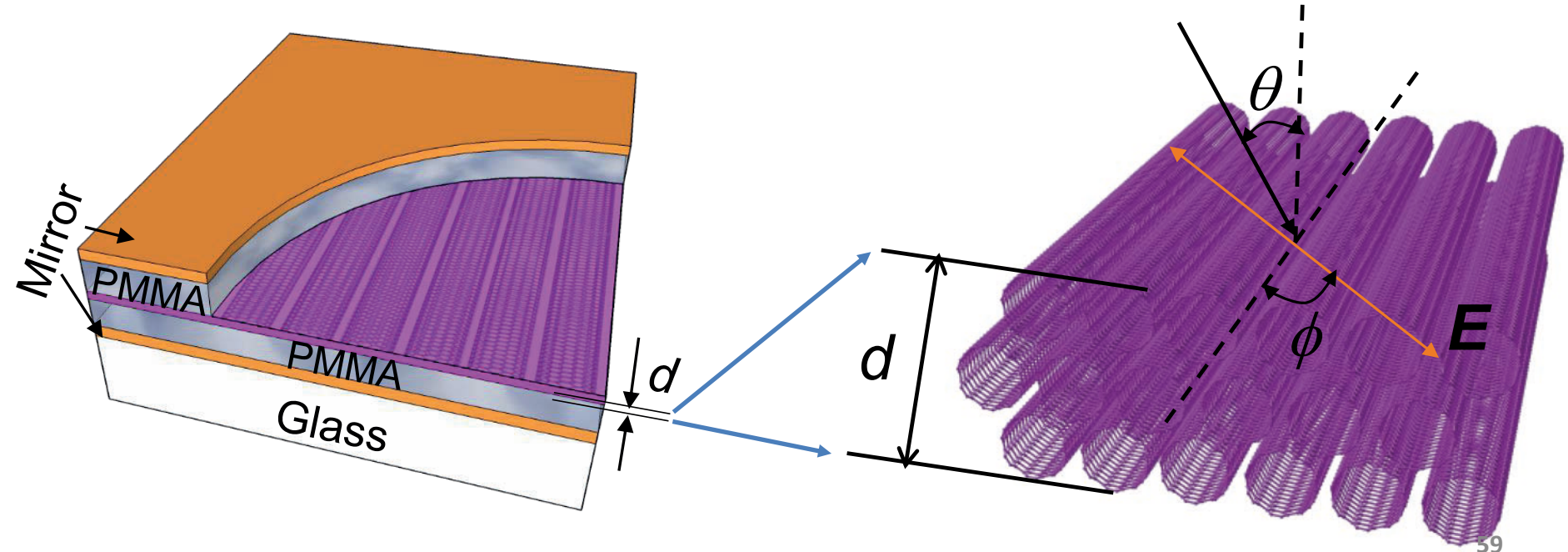
X. Li *et al.*, *Science* **361**, 794 (2018)



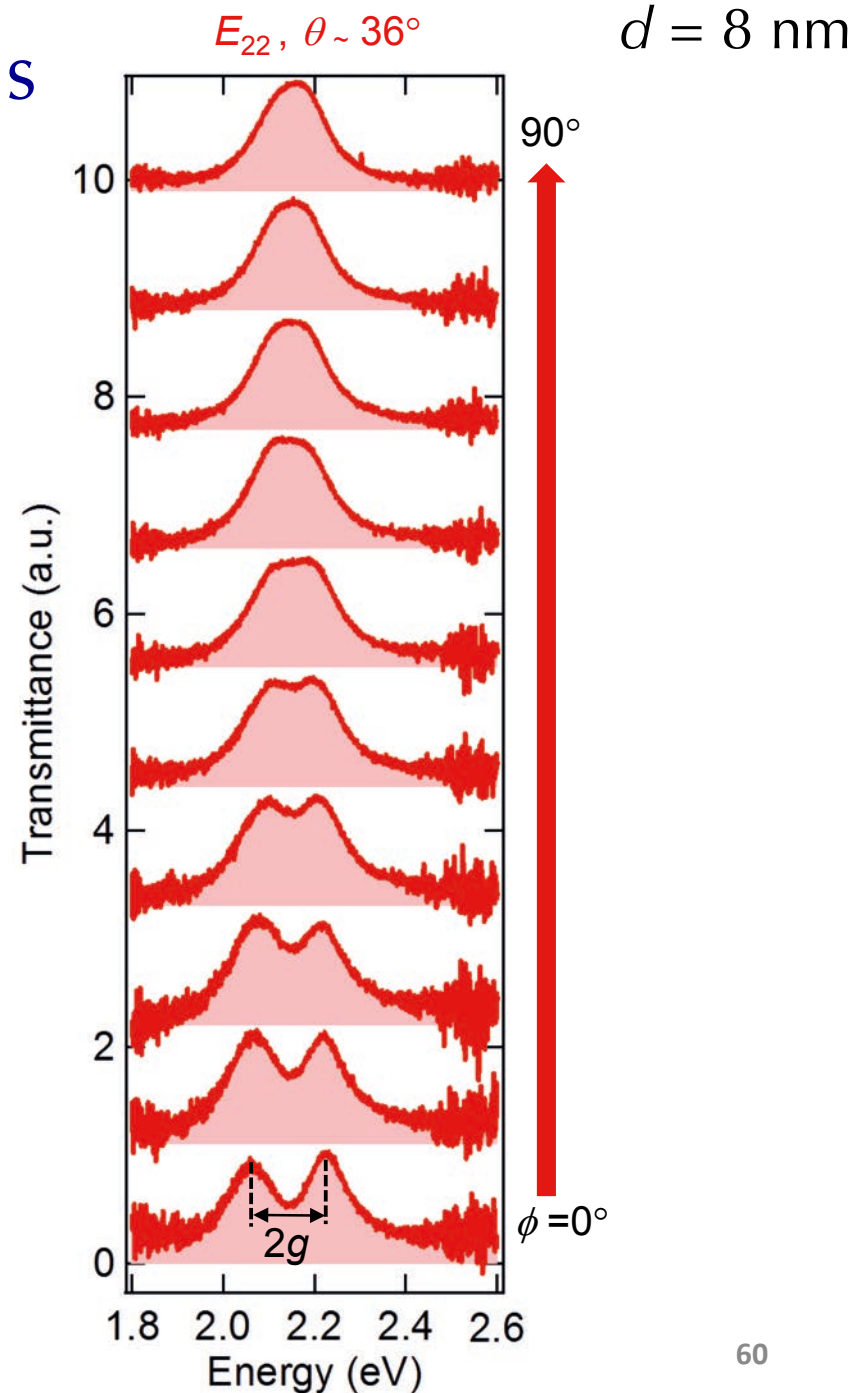
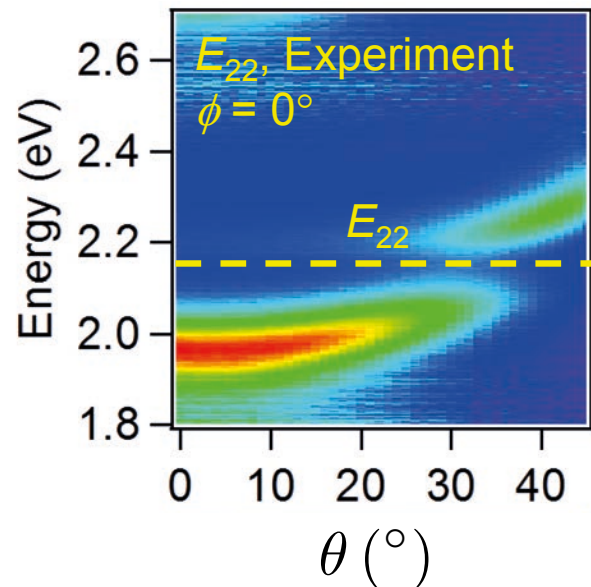
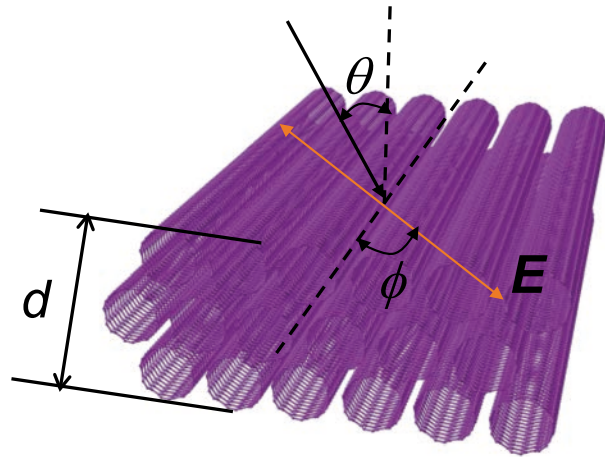
Continuous transition between weak and ultrastrong coupling through exceptional points in carbon nanotube microcavity exciton-polaritons

Weilu Gao ¹, Xinwei Li¹, Motoaki Bamba ^{2,3} and Junichiro Kono ^{1,4,5*}

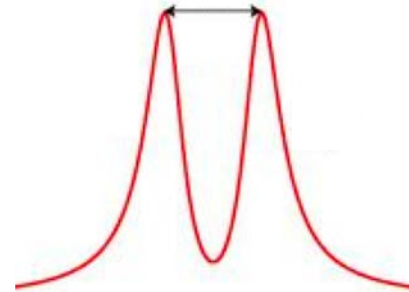
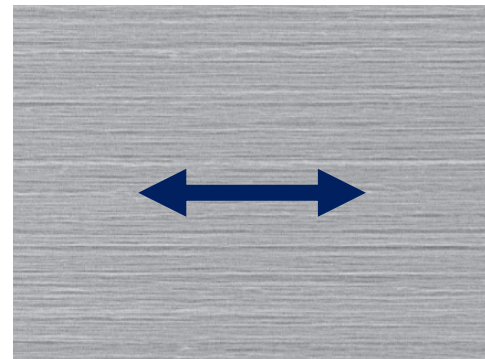
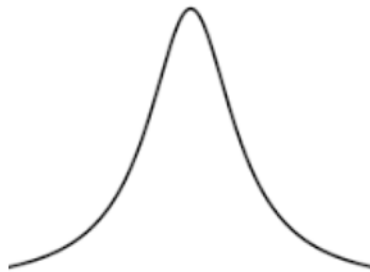
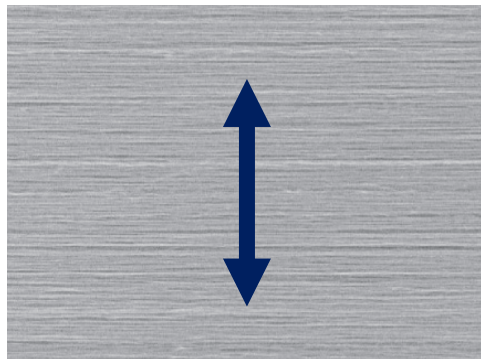
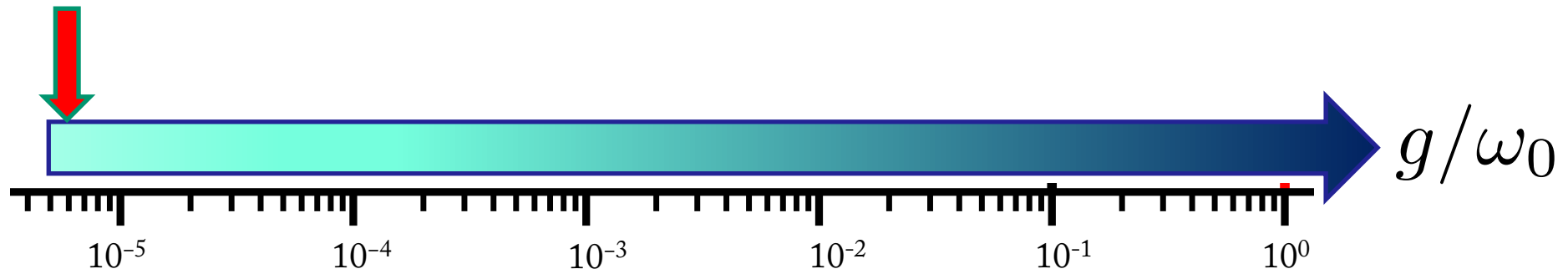
Nature Photonics **12**, 362 (2018)



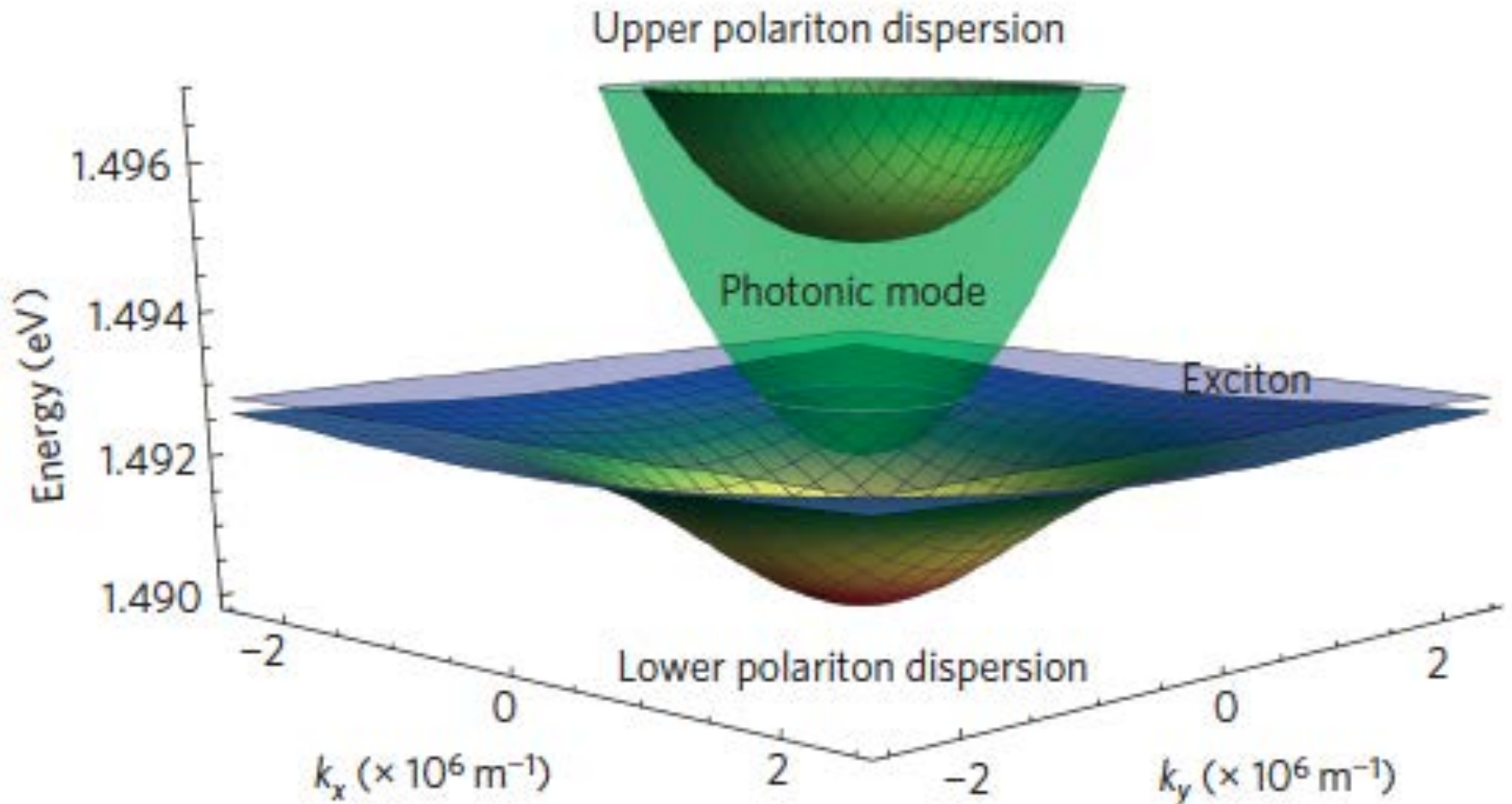
Microcavity Exciton Polaritons in Aligned (6,5) SWCNTs



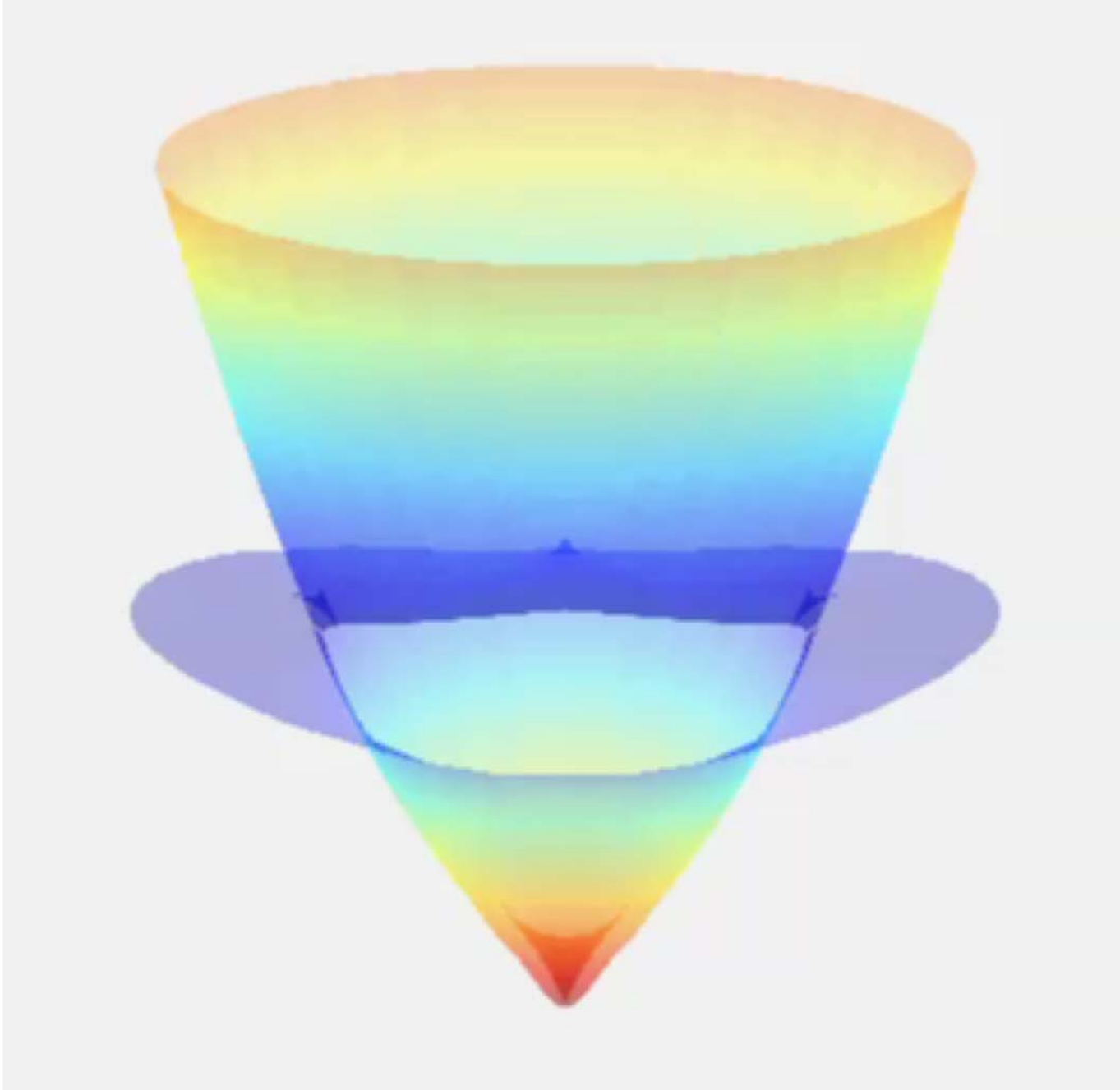
Continuous Transition Between Weak and Ultrastrong Coupling



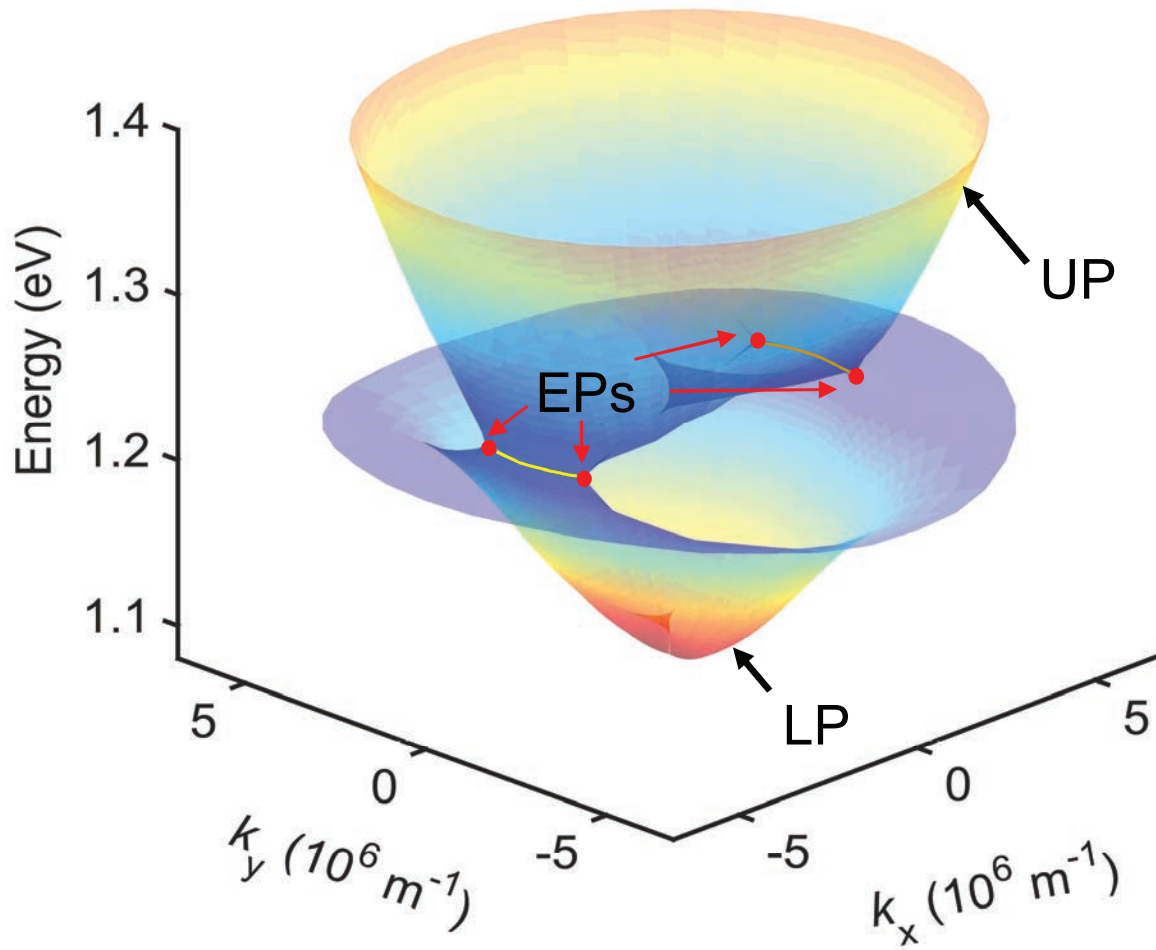
Microcavity Exciton Polaritons



D. Sanvitto & S. Kéna-Cohen, *Nat. Materials* **15**, 1061 (2016)



Polariton Dispersion



Appearance of Exceptional Points in Open or Dissipative Systems

Theory by Motoaki Bamba (Osaka Univ.)

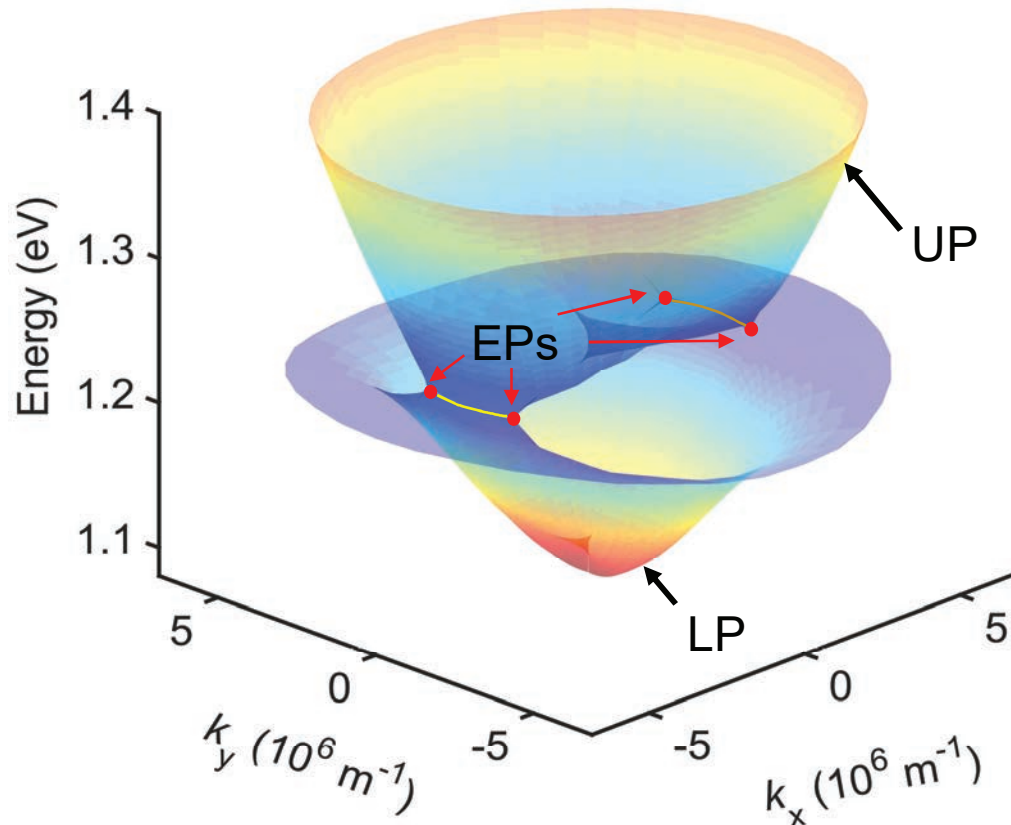
Quantum Langevin equations:

$$-i\omega\hat{b}(\omega) = -i(\omega_{\text{exc}} - i\gamma/2)\hat{b}(\omega) - ig\hat{a}(\omega) - \sqrt{\gamma}\hat{b}_{\text{in}}$$

$$-i\omega\hat{a}(\omega) = -i(\omega_{\text{cav}} - i\kappa/2)\hat{a}(\omega) - ig\hat{b}(\omega) - \sqrt{\kappa_1}\hat{a}_{\text{in1}} - \sqrt{\kappa_2}\hat{a}_{\text{in2}}$$

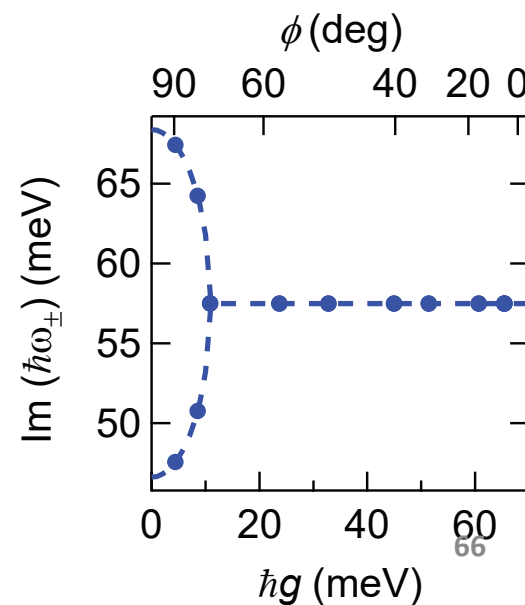
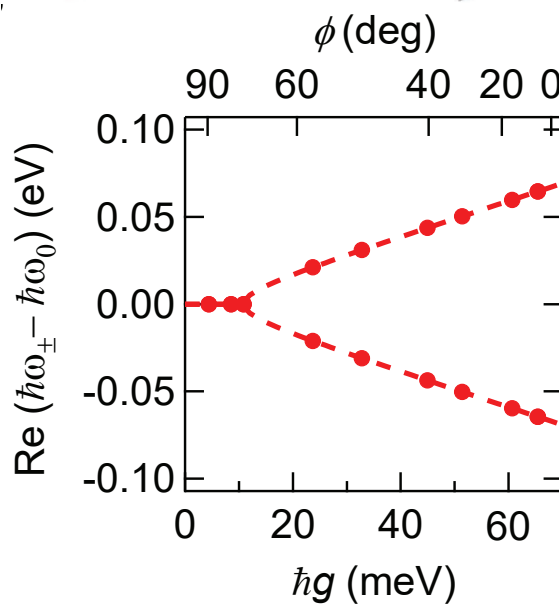
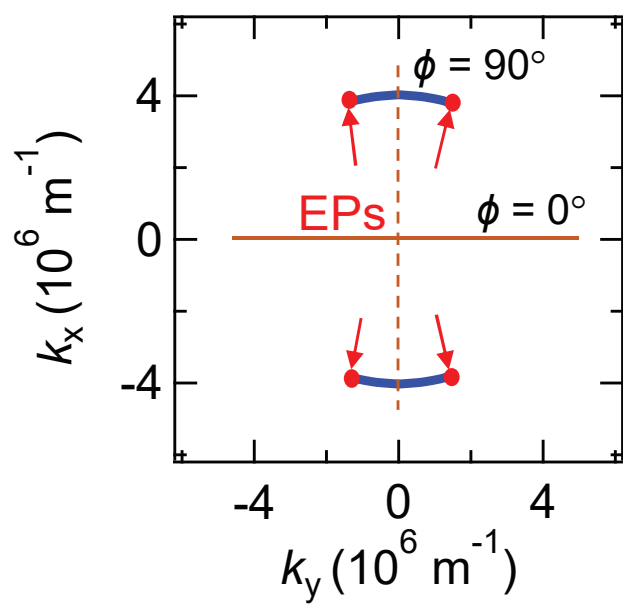
$$\omega_{\pm} = \frac{1}{2}(\omega_{\text{exc}} + \omega_{\text{cav}}) - \frac{i(\gamma + \kappa)}{4} \pm \sqrt{g^2 + \left(i\frac{(\kappa - \gamma)}{4} + \frac{(\omega_{\text{exc}} - \omega_{\text{cav}})}{2} \right)^2}$$

$$|\kappa - \gamma|/4 > g(\theta, \phi) \rightarrow \text{coalescence}$$



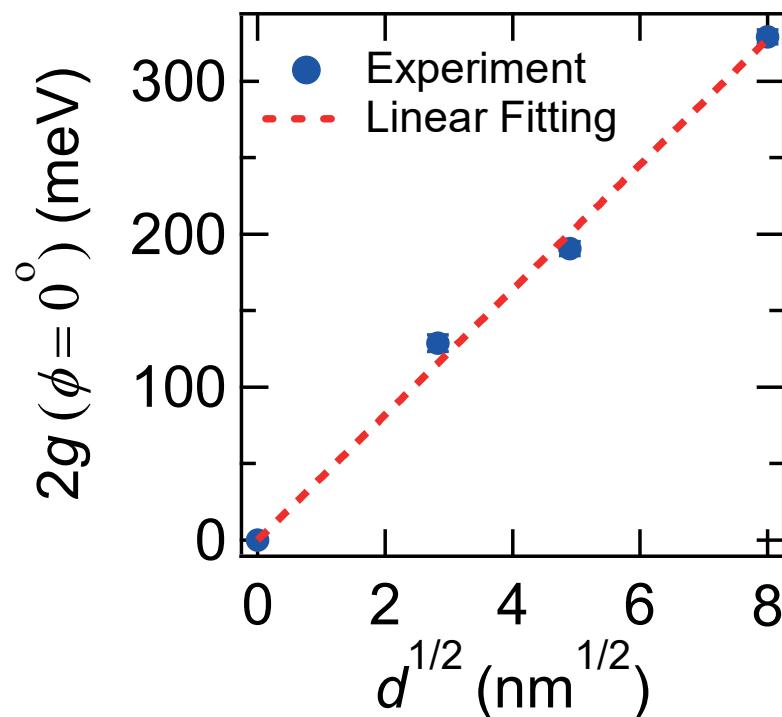
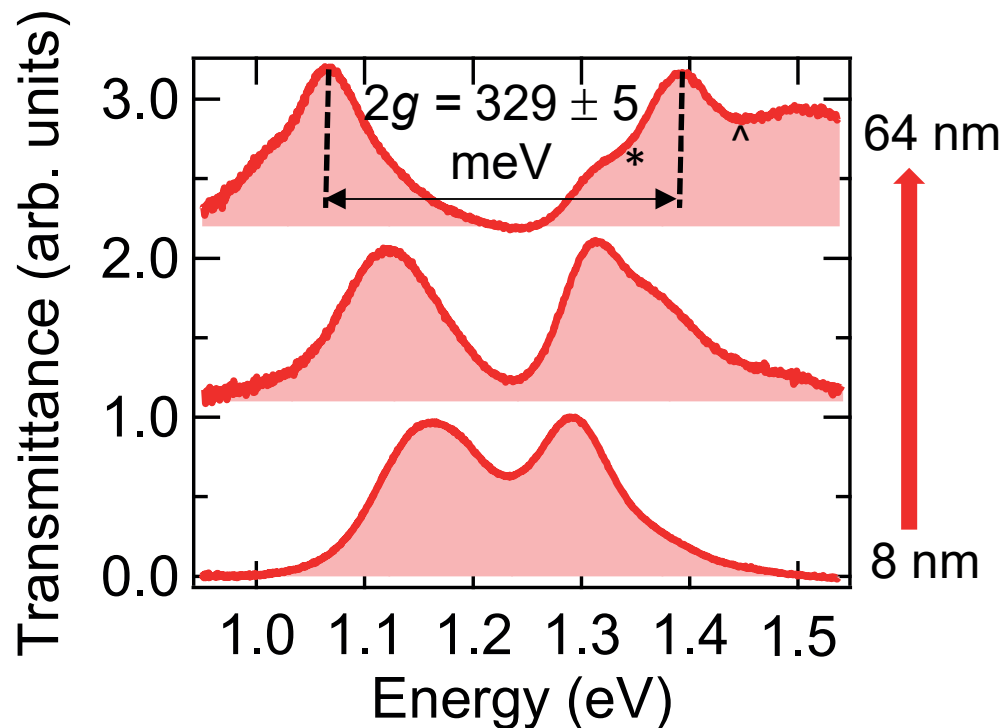
EP:
exceptional
points

$$|\kappa - \gamma| > g$$



Cooperatively Enhanced Ultrastrong Coupling of 1D Excitons with Cavity Photons

$$g/\omega_0 = 0.13$$



Cooperative & Ultrastrong Light-Matter / Matter-Matter Coupling

Conclusions

1. High- Q THz cavities combine many-body condensed matter physics and cavity-based strong-field physics
2. ErFeO_3 provides a novel environment in which to study ultrastrong coupling physics without light
3. Microcavity exciton polaritons in aligned carbon nanotubes exhibit continuous tunability from weak to ultrastrong

Cavity QED in Condensed Matter Systems

Quantum Optics Inspired Many-Body Condensed Matter Physics

Sci. Adv. 4, 6969 (2018)

Cavity quantum-electrodynamical polaritonically enhanced electron-phonon coupling and its influence on superconductivity

M. A. Sentef^{1*}, M. Ruggenthaler¹, A. Rubio^{1,2}

Phys. Rev. Lett. 122, 133602 (2019)

Cavity-mediated electron-photon superconductivity

Frank Schlawin¹, Andrea Cavalleri^{1,2} and Dieter Jaksch¹

Phys. Rev. Lett. 122, 017401 (2019)

Superradiant Quantum Materials

Giacomo Mazza^{1,2,*} and Antoine Georges^{2,3,1,4}

Cavity QED in Condensed Matter Systems

Quantum Optics Inspired Many-Body Condensed Matter Physics

Phys. Rev. Lett. 122, 167002 (2019)

Cavity Quantum Eliashberg Enhancement of Superconductivity

Jonathan B. Curtis,^{1,2,*} Zachary M. Raines,^{1,2} Andrew A. Allocca,^{1,2} Mohammad Hafezi,¹ and Victor M. Galitski^{1,2}

Phys. Rev. B 99, 085116 (2019)

Manipulating quantum materials with quantum light

Martin Kiffner^{1,2}, Jonathan Coulthard², Frank Schlawin², Arzhang Ardavan², and Dieter Jaksch^{2,1}

Coworkers

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K. Yoshioka, *Yokohama National University, Japan*

D. Turchinovich, *University of Duisburg-Essen, Germany*

J. D. Watson, S. Fallah & M. J. Manfra, *Purdue University, U.S.A.*

W. Pan and J. L. Reno, *Sandia National Laboratories, U.S.A.*

N. Yuan, M. Xiang, K. Xu, Z. Jin, W. Ren, G. Ma & S. Cao, *Shanghai University, China*

M. Bamba, *Osaka University, Japan*

Experiments

Samples

Theory