SPICE WORKSHOP ON QUANTUM SPINOPTICS

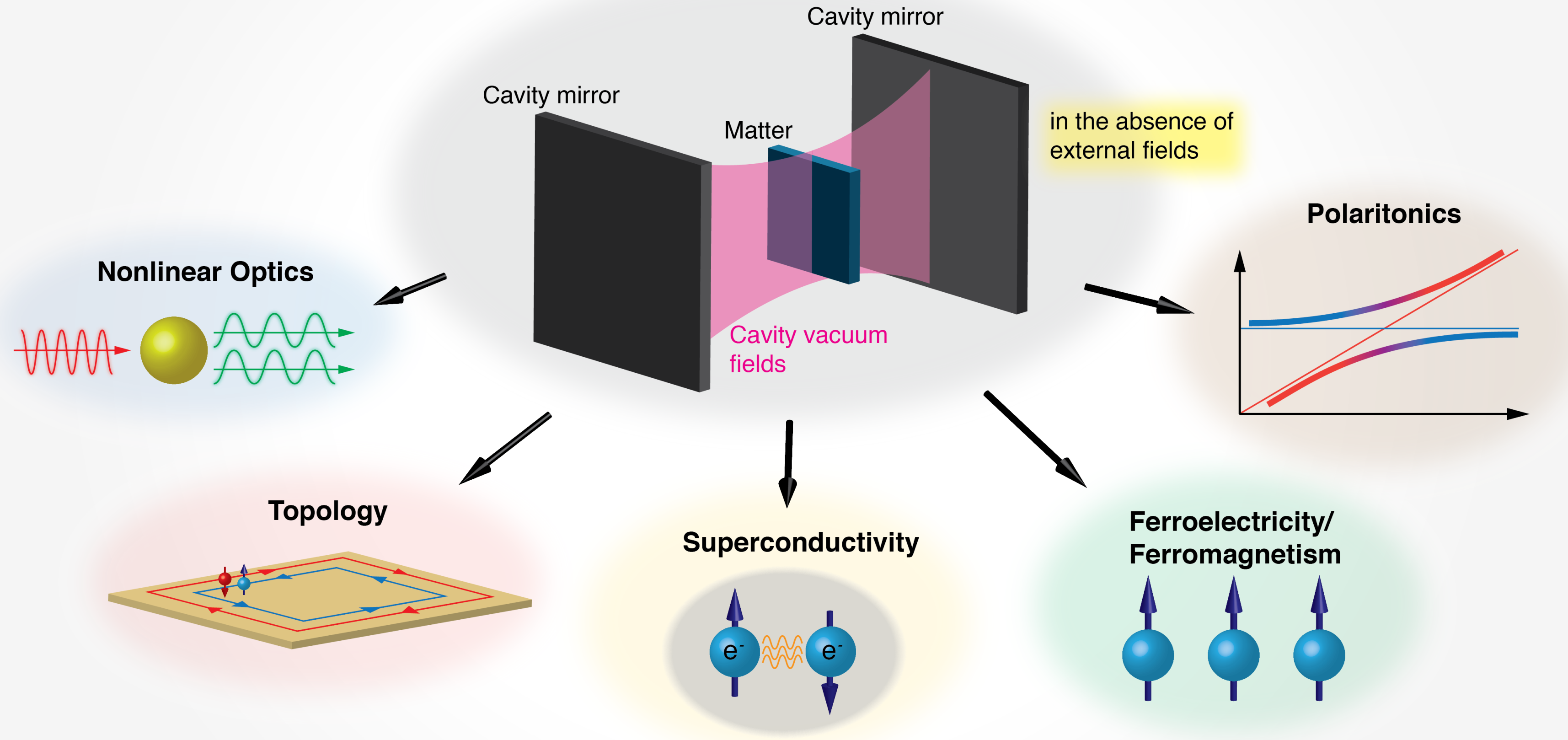
WASEM MONASTERY, INGELHEIM, GERMANY

SIMULATING DICKE PHYSICS WITH SPIN-MAGNON COUPLING IN RARE EARTH ORTHOFERRITES

JUNICHIRO KONO, RICE UNIVERSITY

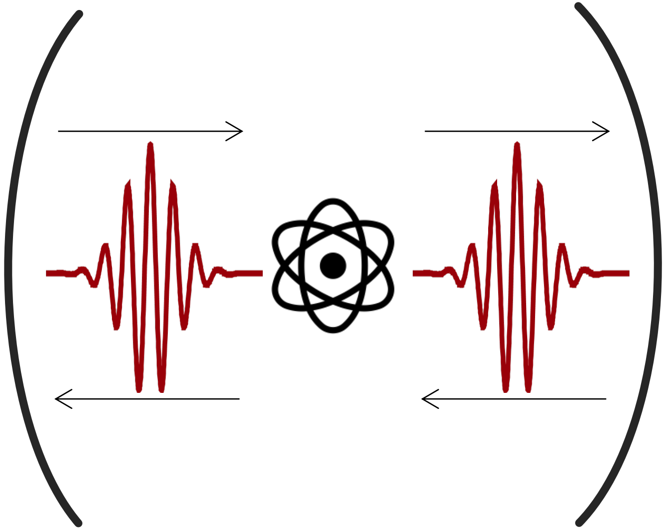
JUNE 13, 2023

Cavity vacuum-driven materials



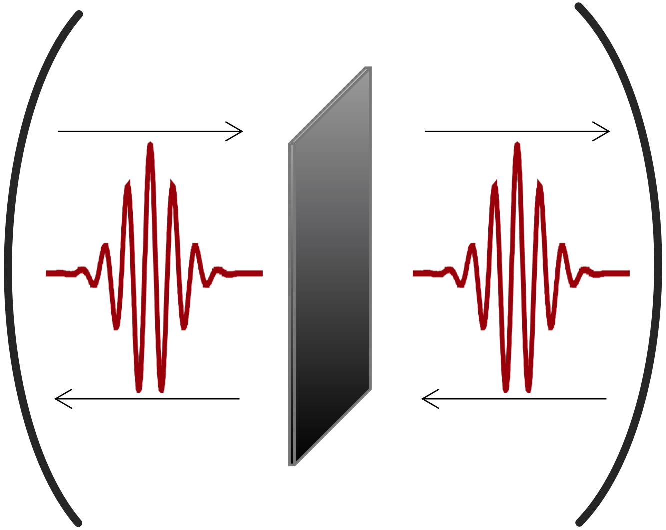
Cavity Quantum Electrodynamics (C-QED)

The interaction of an atom with quantized light



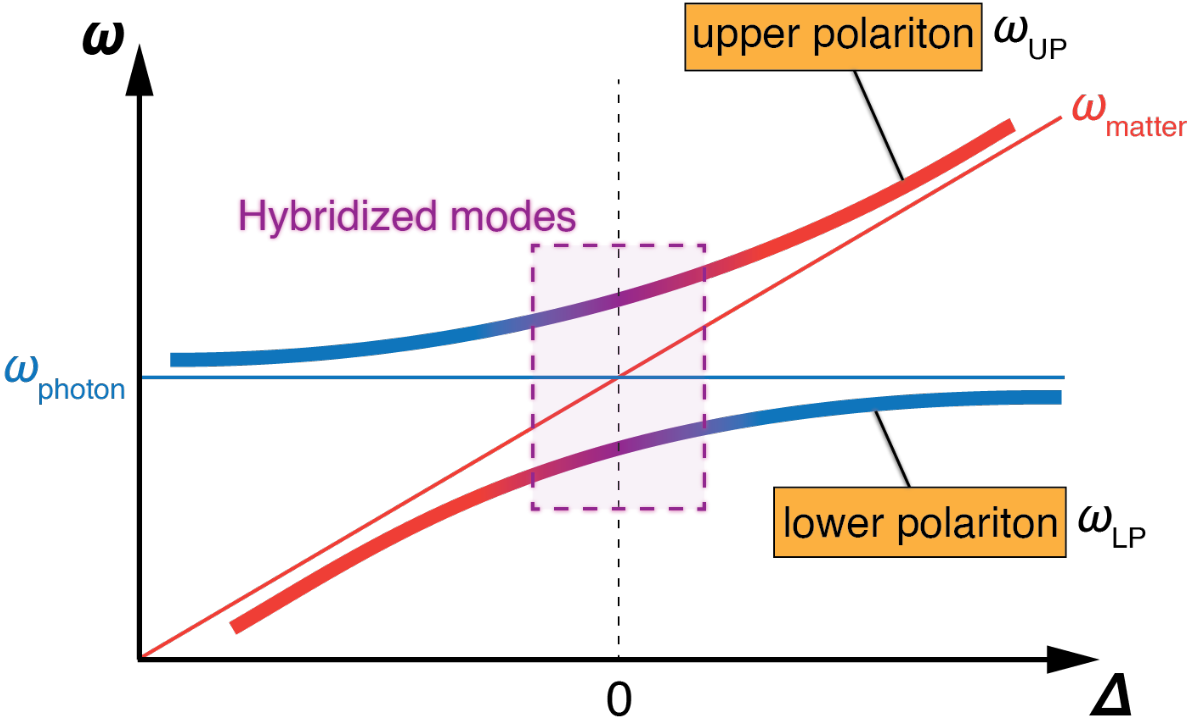
Condensed Matter Cavity QED

The interaction of a solid with quantized light



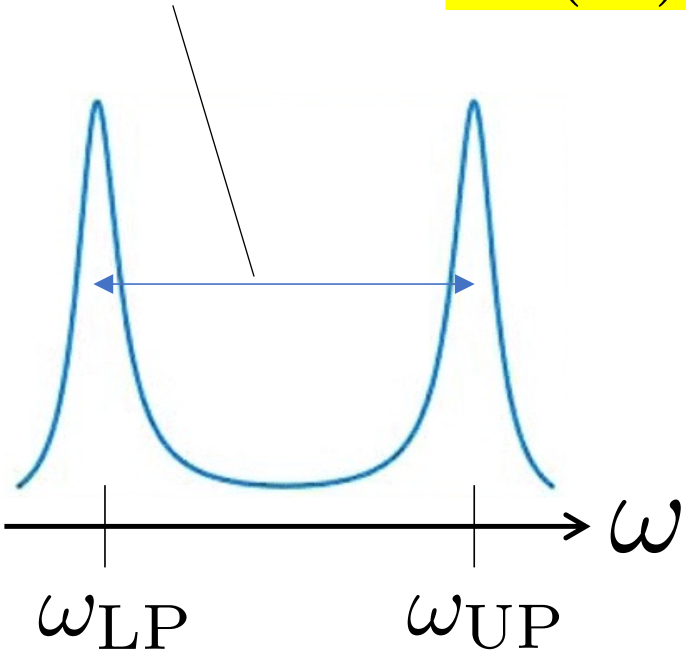
Large dipole moments + cooperativity → Strong & ultrastrong light-matter coupling

<u>Anticrossing</u> (or avoided crossing) is a hallmark of strong coupling.

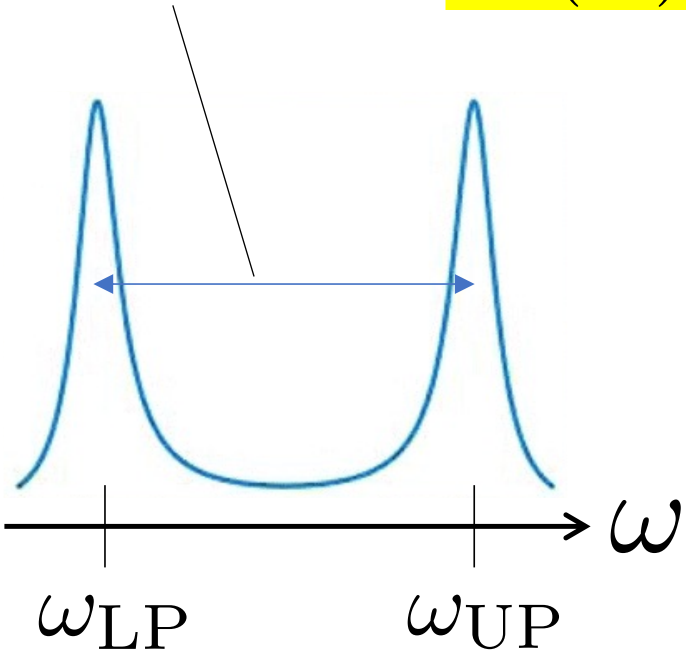


$$\Delta = \omega_{\mathrm{matter}} - \omega_{\mathrm{photon}}$$: detuning

Rabi splitting: $\Omega_n(\Delta) = \sqrt{4g^2(n+1) + \Delta^2}$



Rabi splitting: $\Omega_n(\Delta) = \sqrt{4g^2(n+1) + \Delta^2}$

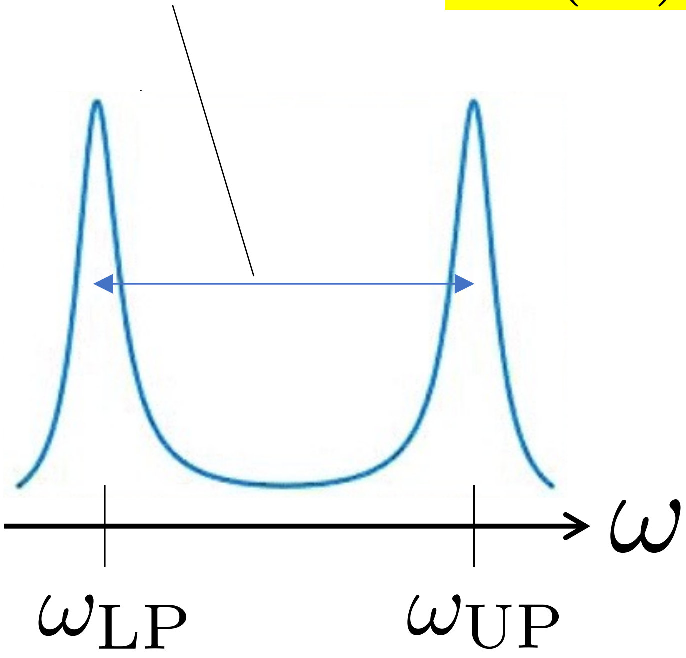


g : coupling rate

Δ : detuning

n : number of photons

Rabi splitting: $\Omega_n(\Delta) = \sqrt{4g^2(n+1) + \Delta^2}$



g : coupling rate

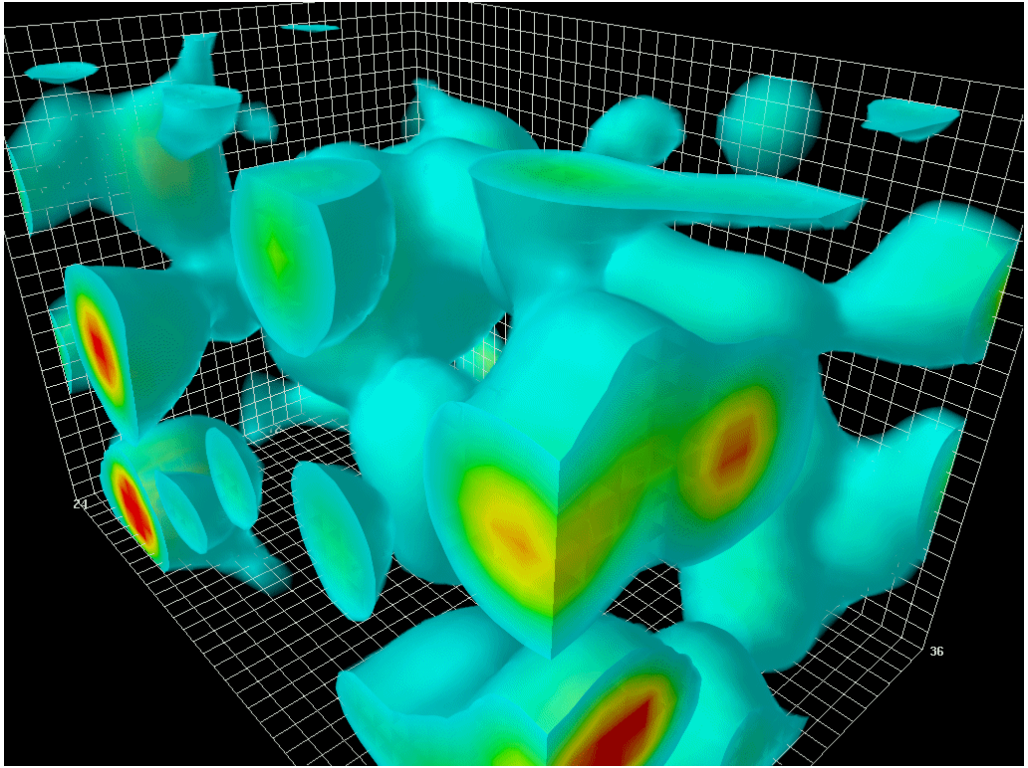
Δ : detuning

n : number of photons

On-resonance vacuum Rabi splitting: $\Omega_0(0) = 2g$

$\Delta = 0$ $\quad$ $n = 0$

The vacuum is not empty – it contains virtual photons that come into and out of existence.



Derek Leinweber, www.physics.adelaide.edu.au

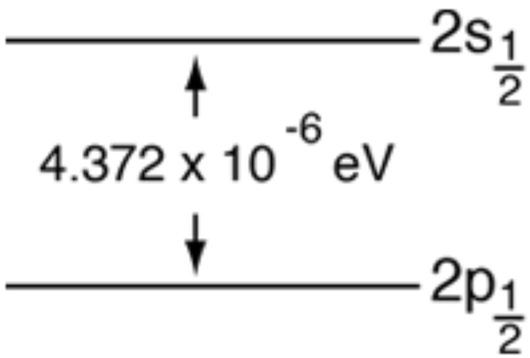
Zero-point energy:

$$E = \frac{1}{2}\hbar\omega$$

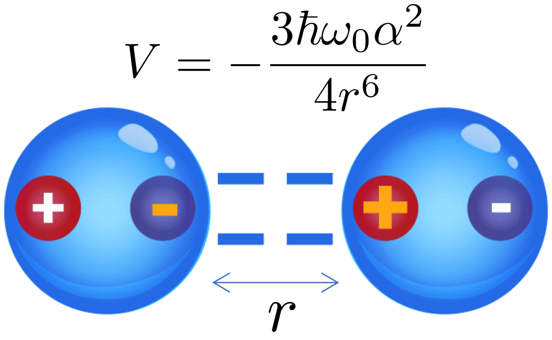
Spectral energy density:

$$\rho_{\mathrm{vac}}(\omega) = \frac{\hbar\omega^3}{2\pi^2 c^3}$$

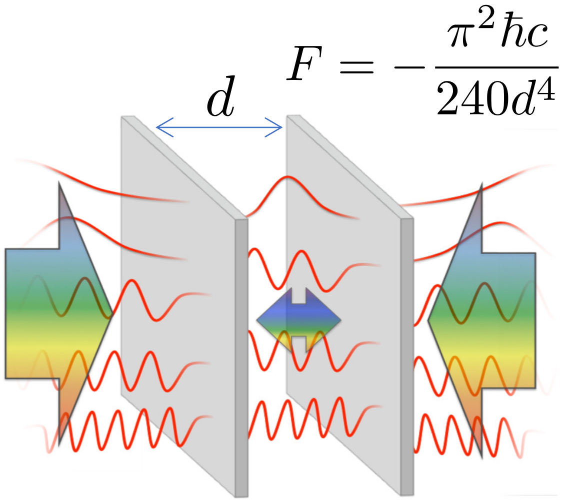
Zero-point field effects are usually miniscule.



http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/lamb.html



https://gamesmartz.com/definitions?definition=7172&Van-der-Waals-force=



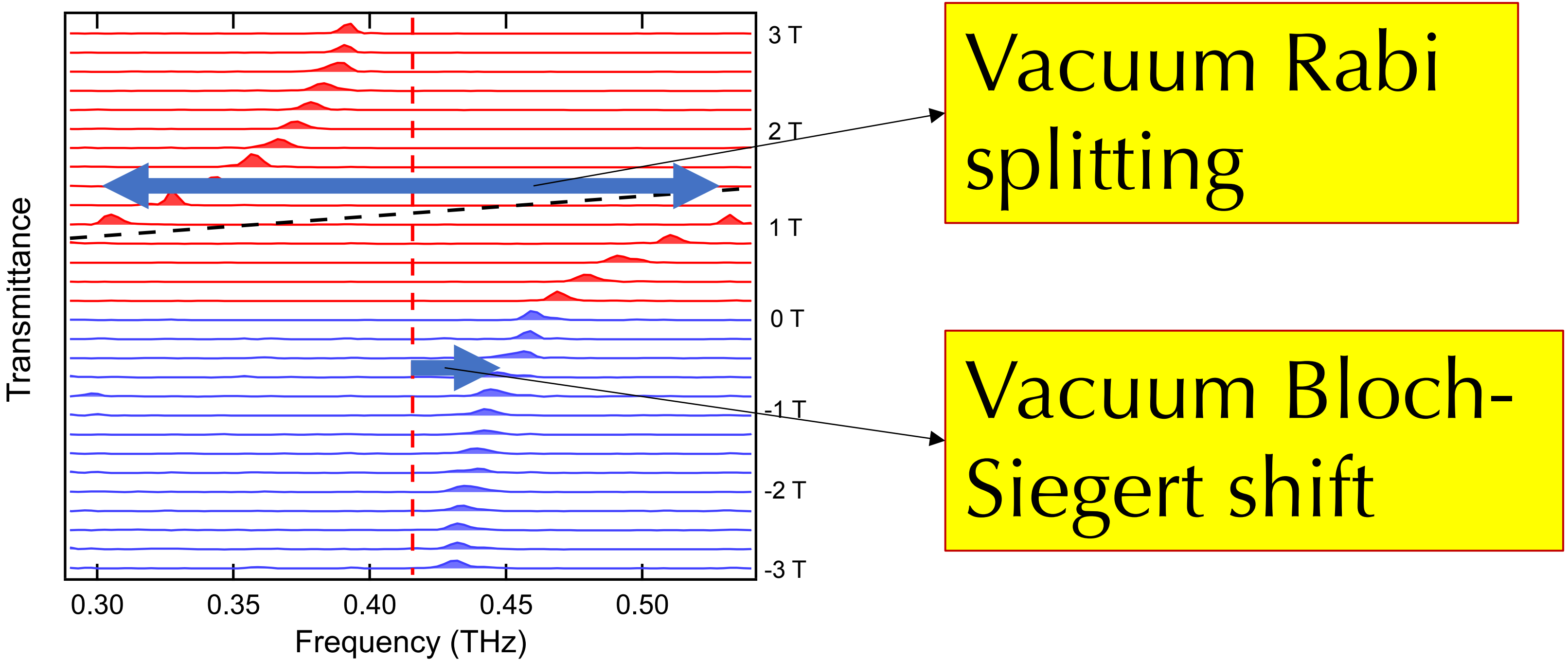
https://www.degruyter.com/document/doi/10.1515/nanoph-2020-0425/html

The Lamb shift

The van der Waals force

The Casimir Effect

Extremely large, unambiguous vacuum-field effects have been recently observed.



X. Li *et al.*, Nature Photonics **12**, 324 (2018)
T. Makihara *et al.*, Nature Communications **12**, 3115 (2021)

The Question of the Day

Can we use cavity-enhanced vacuum fields to modify and control materials properties?

For example,

1. Can we modify electrical conductivity with vacuum photons (*lightless* photoconductivity)?

2. Can we increase the transition temperature of a superconductor by placing it in a cavity?

3. Can we modify the topology of an electronic band using circularly polarized cavity vacuum fields?

4. Can we create or destroy phases of matter using engineered vacuum fields?

There are so many stimulating theory papers!

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

M. A. Sentef[1]*, M. Ruggenthaler[1], A. Rubio[1,2]

Cavity-Mediated Electron-Photon Superconductivity

Frank Schlawin,[1,*] Andrea Cavalleri,[1,2] and Dieter Jaksch[1]

Quantum Electrodynamical Bloch Theory with Homogeneous Magnetic Fields

Vasil Rokaj,[1,*] Markus Penz,[1] Michael A. Sentef,[1] Michael Ruggenthaler,[1] and Angel Rubio[1,2,†]

Cavity quantum electrodynamical Chern insulator: Towards light-induced quantized anomalous Hall effect in graphene

Xiao Wang,[1] Enrico Ronca,[2] and Michael A. Sentef[2,*]

Manipulating quantum materials with quantum light

Martin Kiffner,[1,2] Jonathan R. Coulthard,[2] Frank Schlawin,[2] Arzhang Ardavan,[2] and Dieter Jaksch[2,1]

Quantum Electrodynamic Control of Matter: Cavity-Enhanced Ferroelectric Phase Transition

Yuto Ashida*

Superradiant Quantum Materials

Giacomo Mazza[1,2,*] and Antoine Georges[2,3,1,4]

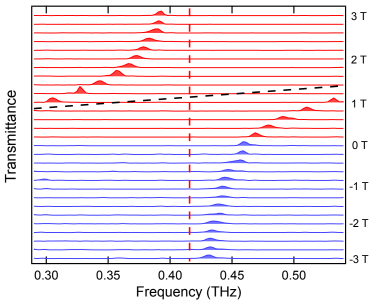
Cavity Higgs polaritons

Zachary M. Raines,[1,2,*] Andrew A. Allocca,[1,2] Mohammad Hafezi,[1] and Victor M. Galitski[1,2]

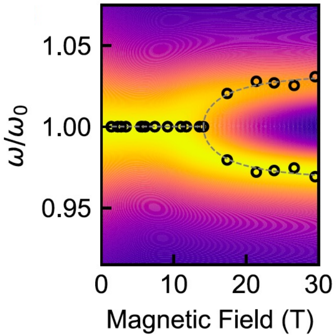
Cavity Quantum Eliashberg Enhancement of Superconductivity

Jonathan B. Curtis,[1,2,*] Zachary M. Raines,[1,2] Andrew A. Allocca,[1,2] Mohammad Hafezi,[1] and Victor M. Galitski[1,2]

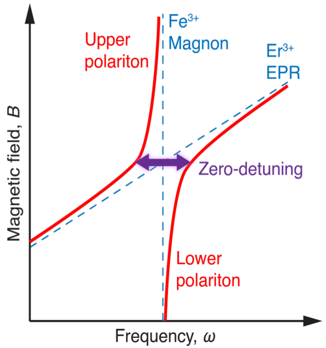
Experimental Condensed Matter Cavity QED Platforms



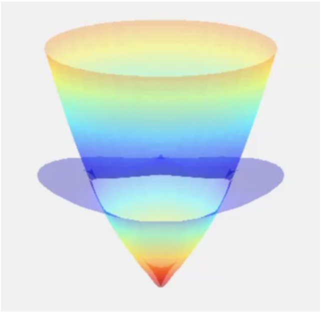
Landau polaritons
Nat. Phys. (2016);
Nat. Photon. (2018)



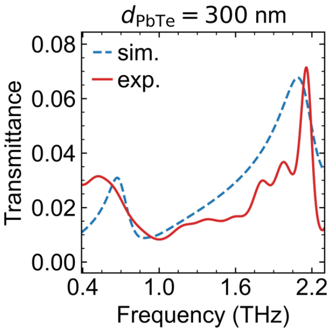
Magnon-polaritons
Phys. Rev. Research (2023)



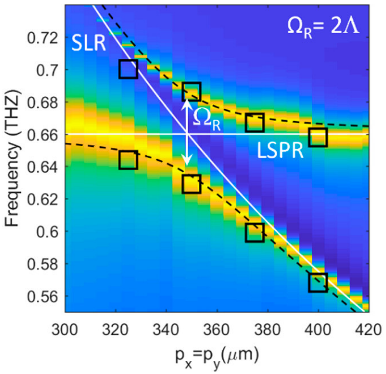
Spin-magnon & magnon-magnon coupling
Science (2018);
Nat. Commun. (2021)



Exciton-polaritons in carbon nanotubes
Nat. Photon. (2018)

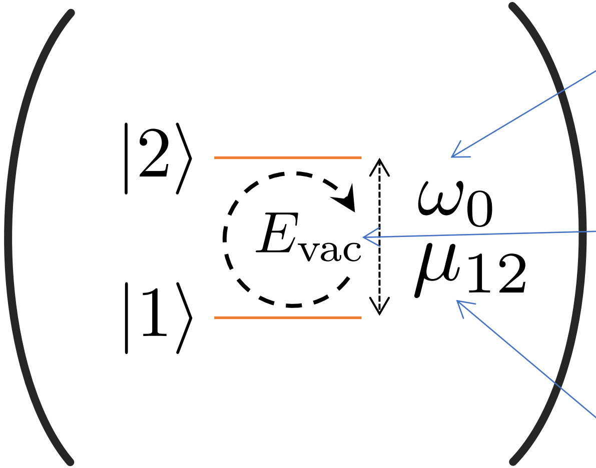


Phonon-polaritons
unpublished



Plasmon-plasmon coupling
Nano Lett. (2022)

The coupling strength, g, depends on V_m and μ_{12}.



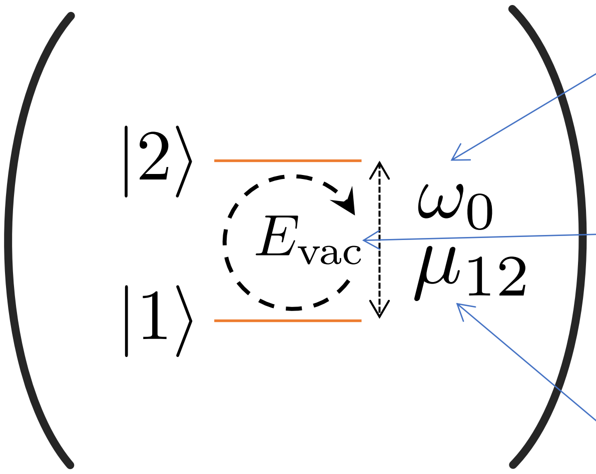
Resonance (or transition) frequency

$$E_{vac} = \sqrt{\frac{\hbar\omega_0}{2\varepsilon_r\varepsilon_0 V_m}}$$: Vacuum fluctuation field

Mode volume

Dipole moment

The coupling strength, g, depends on V_m and μ_{12}.



Resonance (or transition) frequency

$$E_{vac} = \sqrt{\frac{\hbar\omega_0}{2\varepsilon_r\varepsilon_0 V_m}}$$

: Vacuum fluctuation field

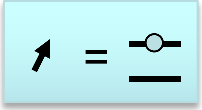
Mode volume

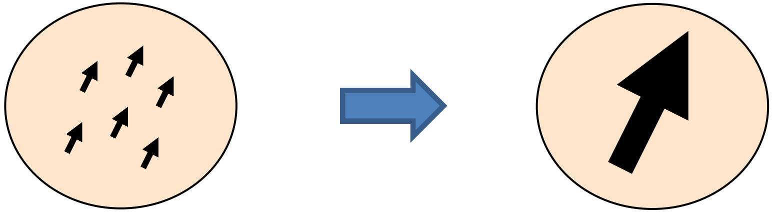
Dipole moment

$$g = \frac{|\mu_{12} E_{vac}|}{\hbar}$$

N atoms can cooperatively enhance the coupling strength as $g \propto \sqrt{N}$.

Dicke cooperativity





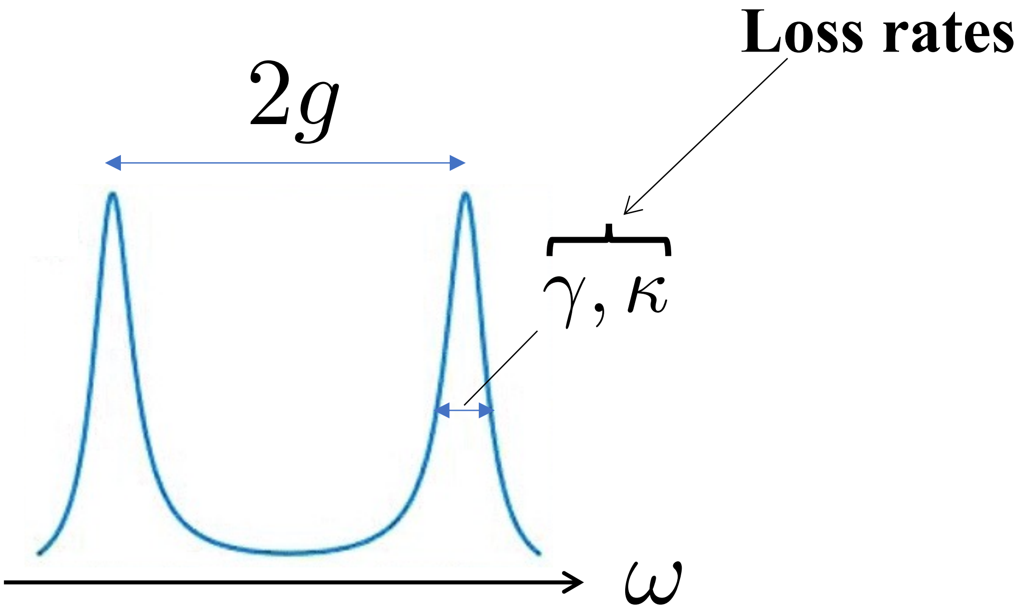
$$g_0 \rightarrow g = \sqrt{N} g_0$$

Single-atom case **_N_-atom case**

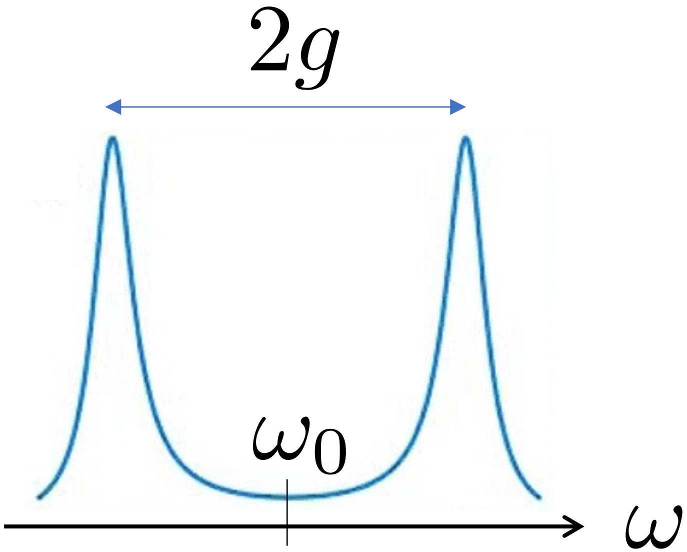
Dicke (1954); Tavis & Cummings (1968)

The strong coupling regime arises when the coupling rate is higher than all loss rates.

$$C \equiv \frac{4g^2}{\gamma\kappa} > 1$$



The Ultrastrong Coupling (USC) Regime



Reviews of Modern Physics **91**, 025005 (2019)

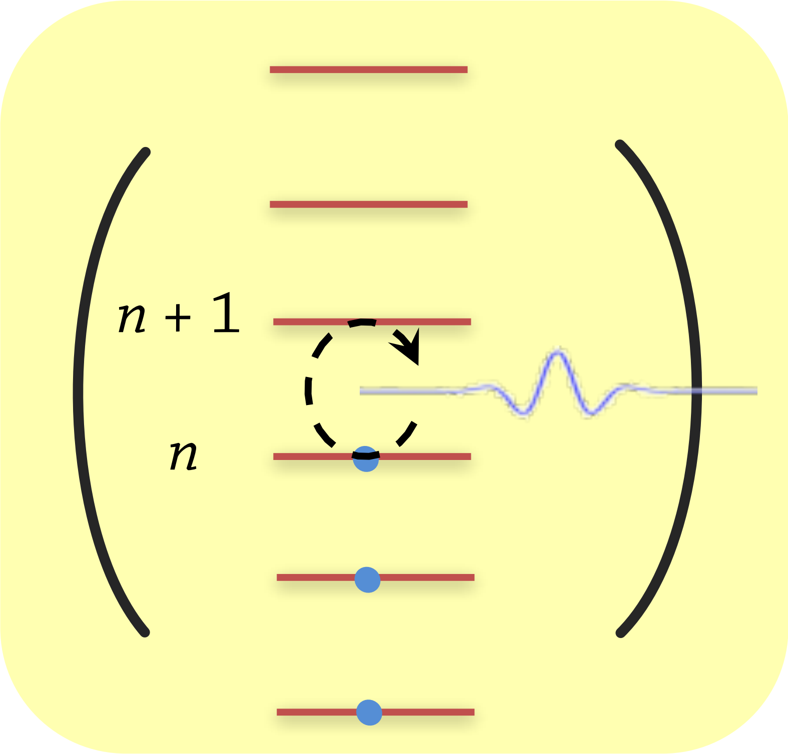
$$g \sim \omega_0$$

Outline

1. **Landau polaritons in quantum Hall systems**
2. Spin-photon ultrastrong coupling in a paramagnet
3. Spin-magnon ultrastrong coupling in an antiferromagnet
4. Summary and outlook

RICE
Unconventional Wisdom

Landau polaritons emerge as a result of strong coupling of 2D electrons in *B* with THz cavity photons.



Landau levels

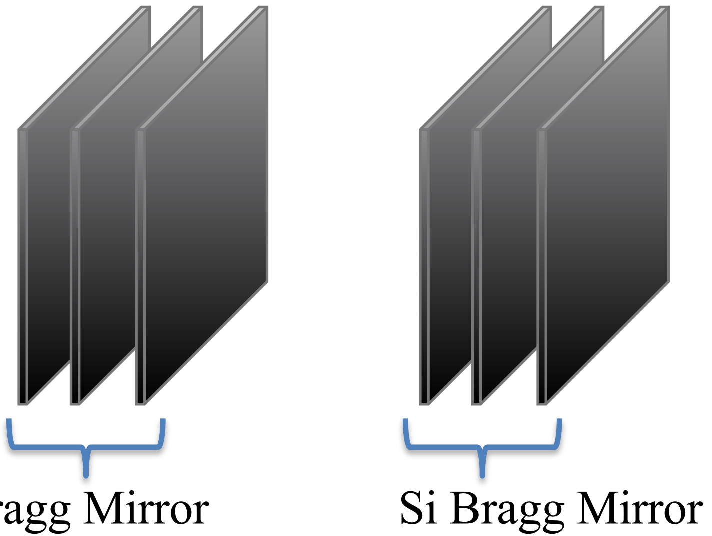
$$\varepsilon_n = \left(n + \frac{1}{2}\right)\hbar\omega_c$$

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

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

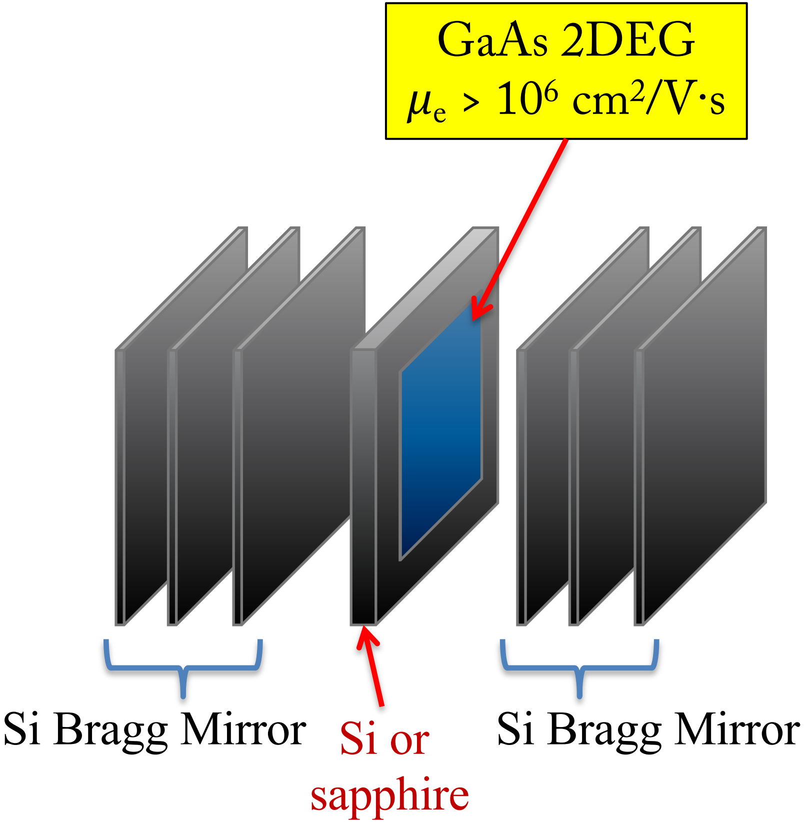
See, e.g., G. Scalari, J. Faist *et al.*, Science **335**, 1323 (2012)

1D THz Photonic-Crystal Cavity

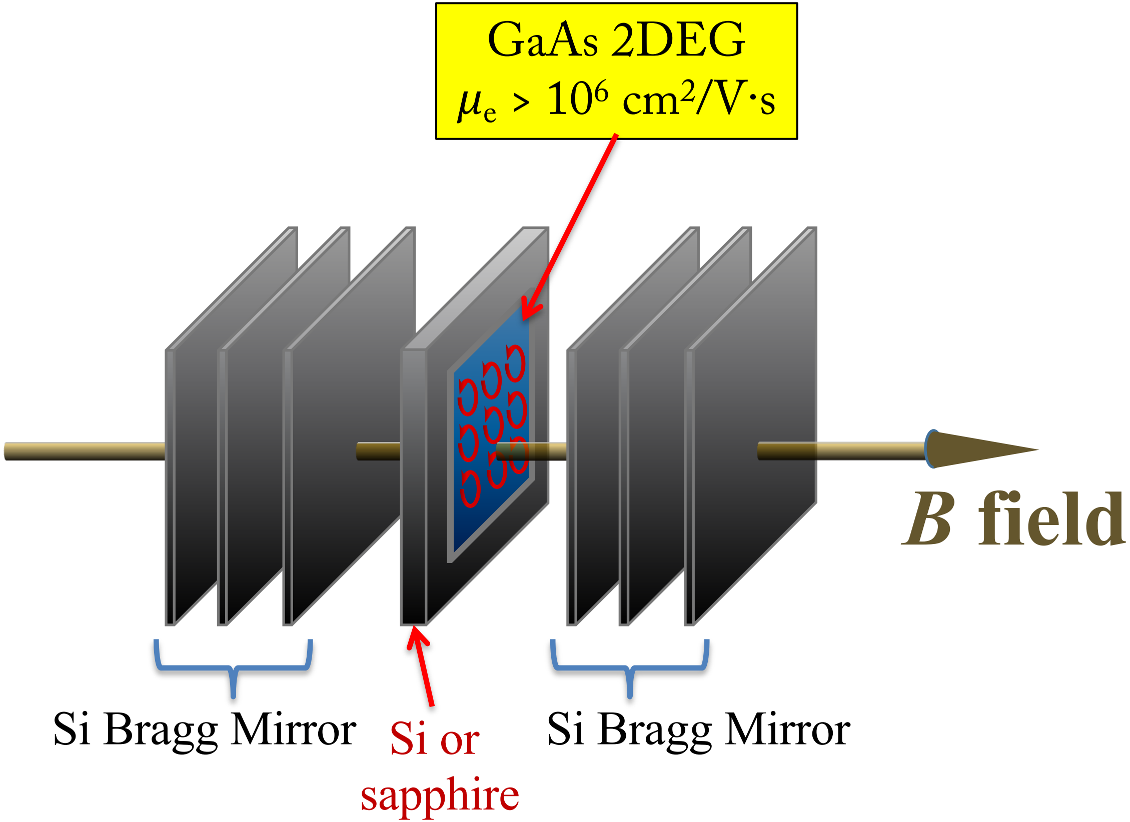


$$n_{\mathrm{Si}} = 3.42$$
$$n_{\mathrm{vac}} = 1$$

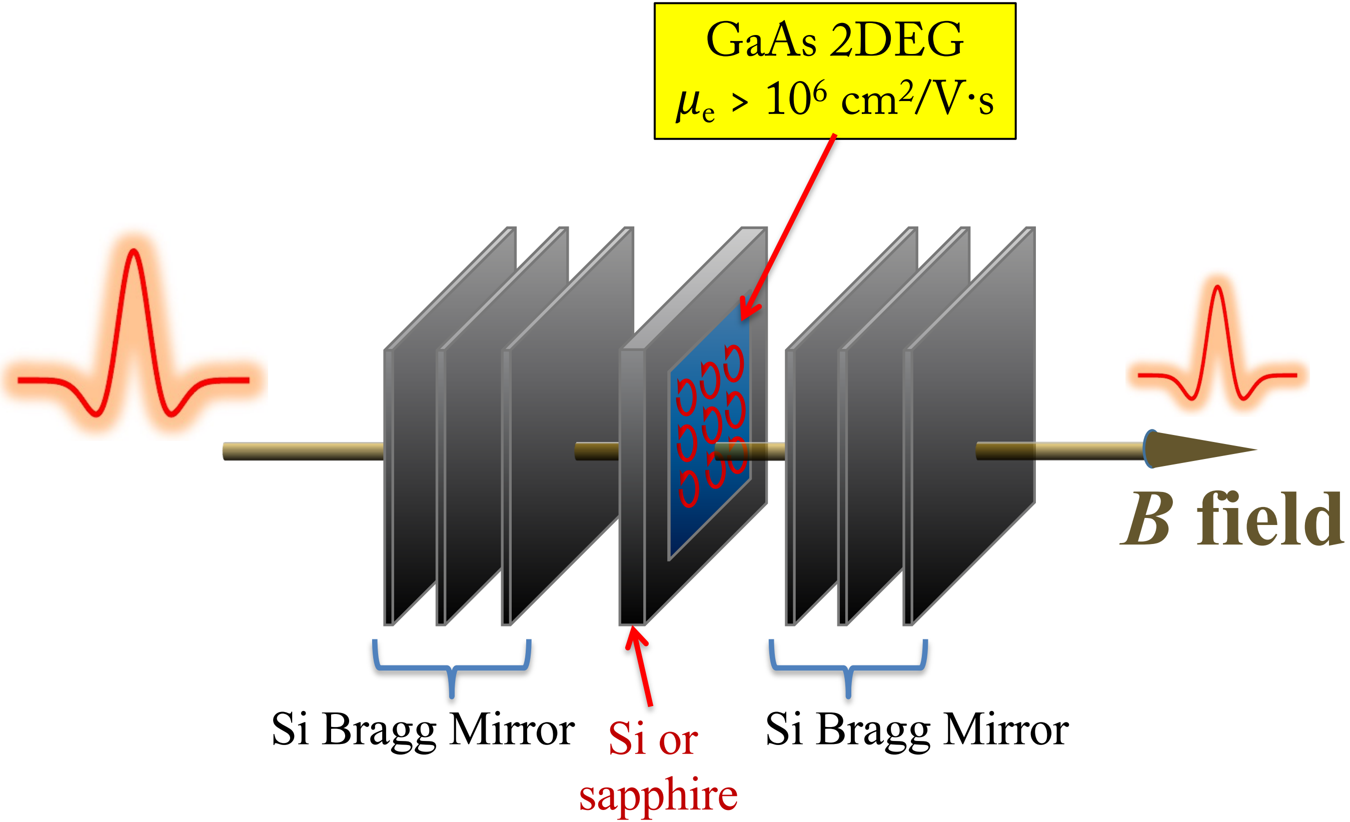
Q. Zhang *et al.*, Nature Physics **12**, 1005 (2016)



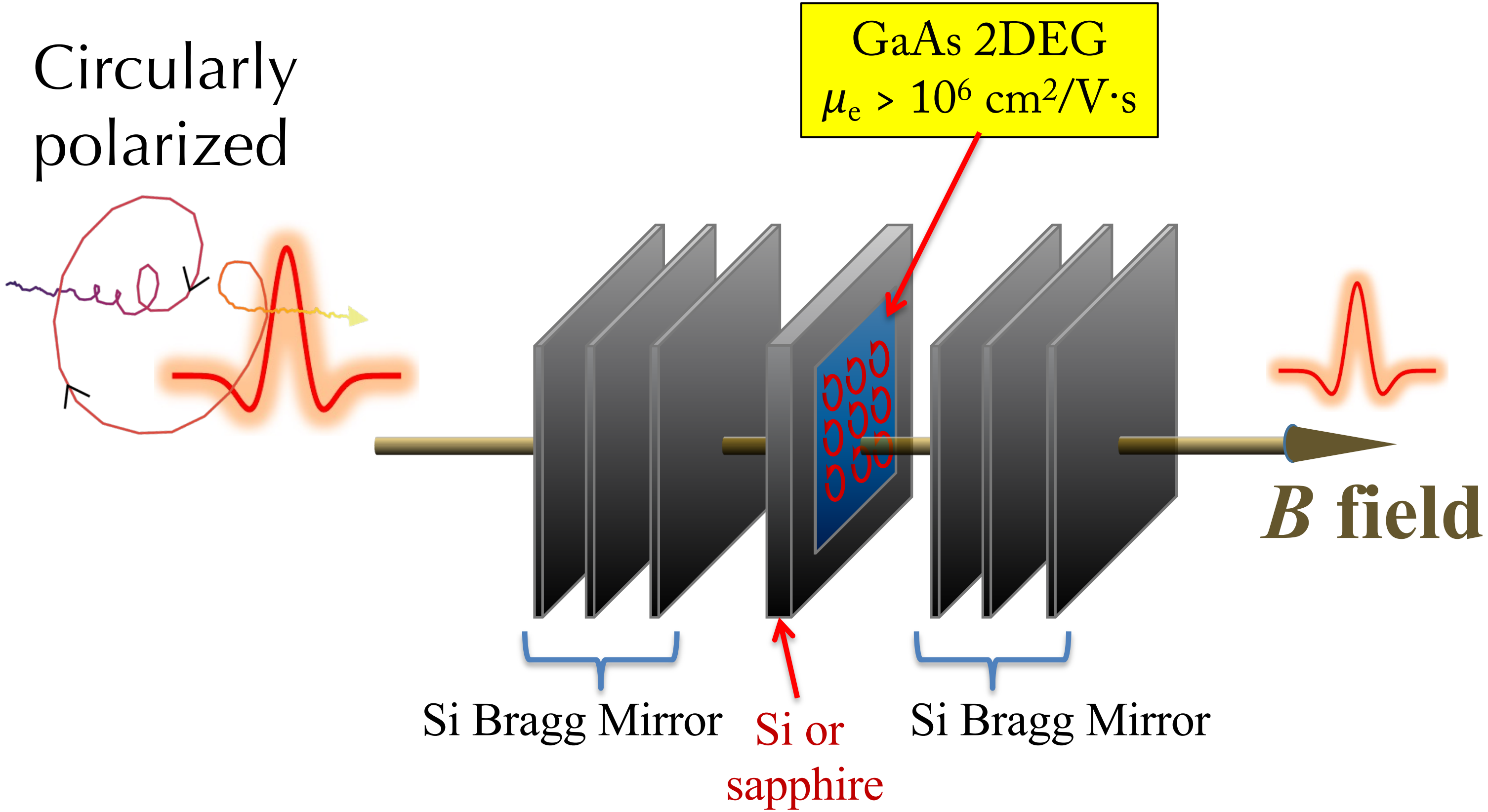
Q. Zhang *et al.*, Nature Physics **12**, 1005 (2016)



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

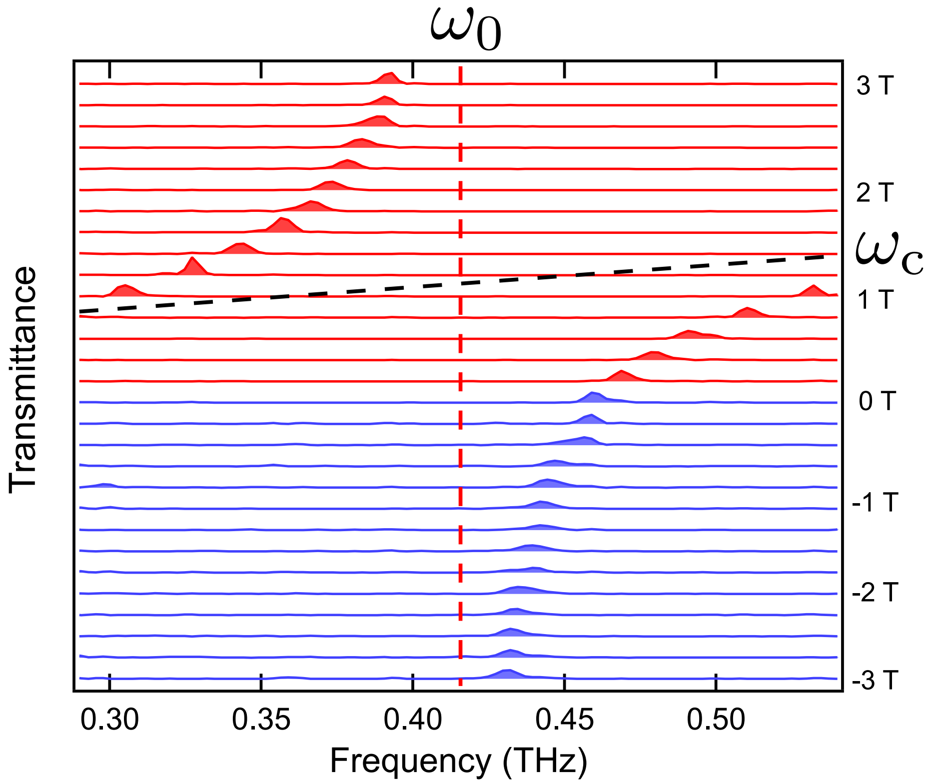


Q. Zhang *et al.*, Nature Physics **12**, 1005 (2016)

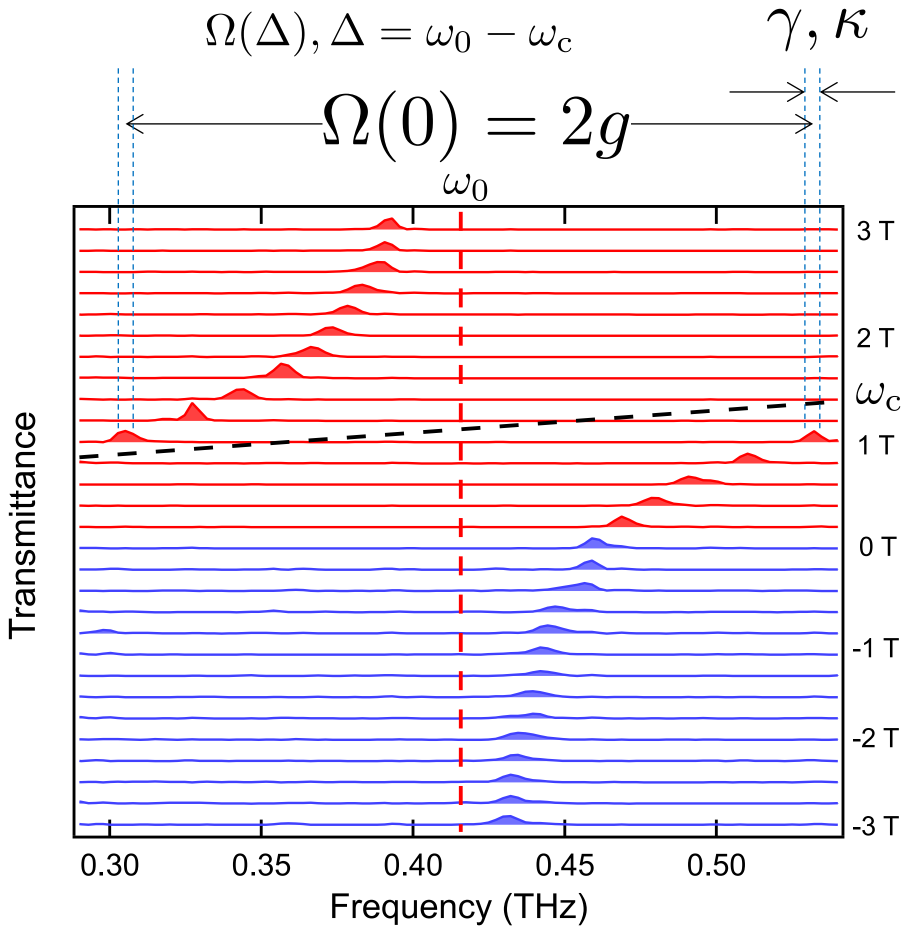


Q. Zhang *et al.*, Nature Physics **12**, 1005 (2016)

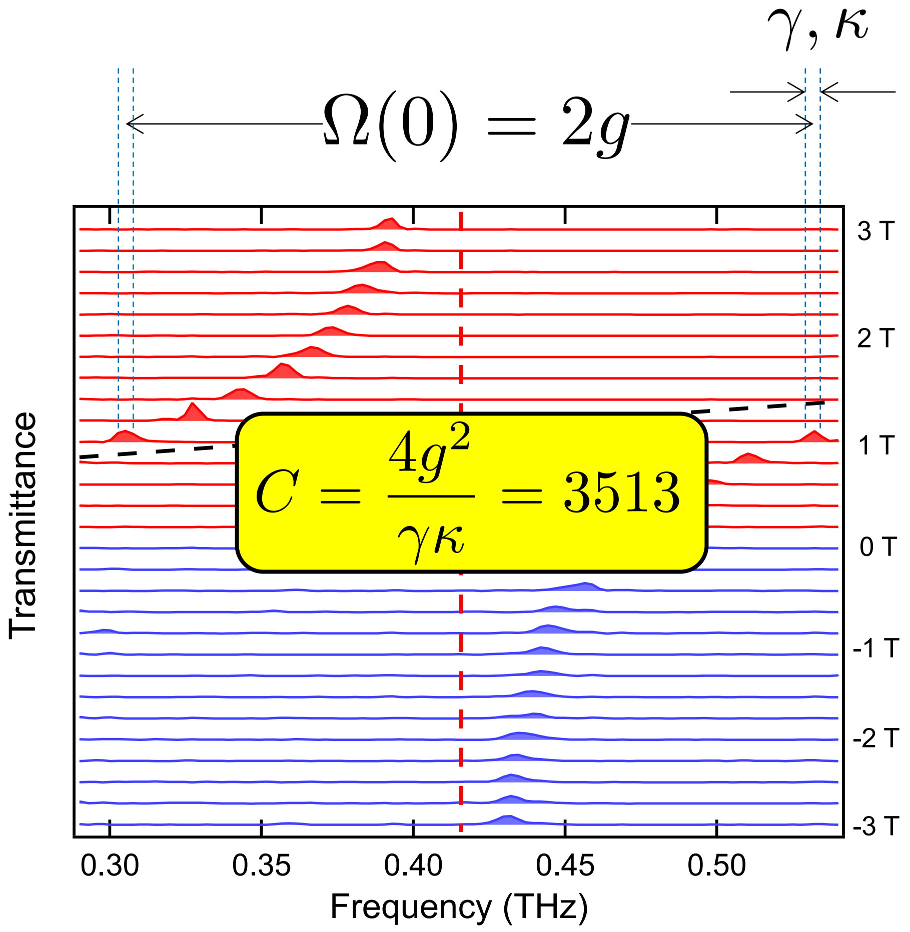
Landau Polaritons (Experimental Data)



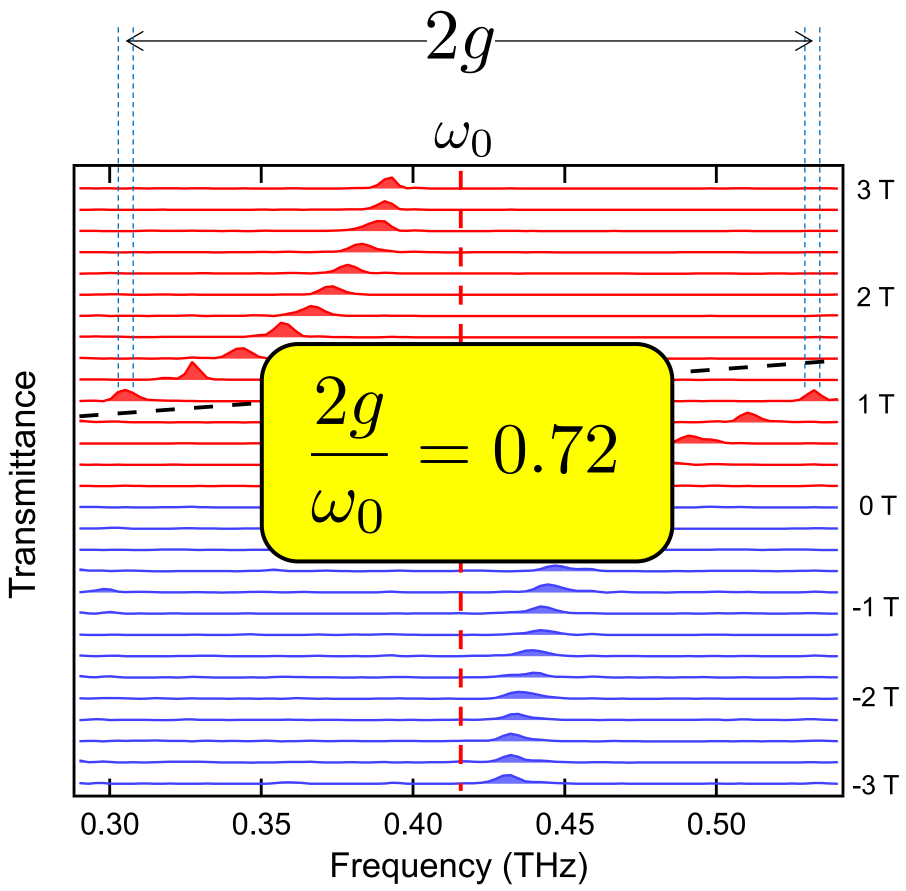
X. Li *et al.*, Nature Photonics **12**, 324 (2018)



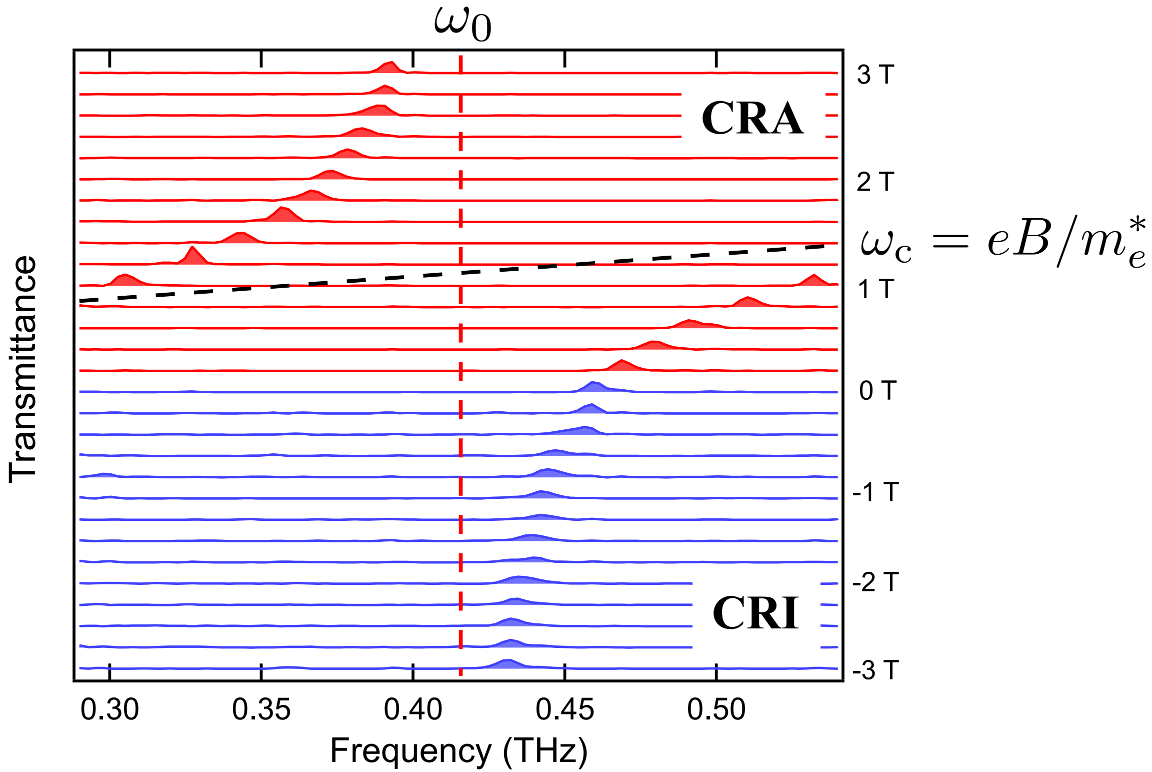
$\Omega(\Delta), \Delta = \omega_0 - \omega_c$
γ, κ
$\Omega(0) = 2g$
ω_0
ω_c
3 T
2 T
1 T
0 T
-1 T
-2 T
-3 T
Transmittance
0.30
0.35
0.40
0.45
0.50
Frequency (THz)



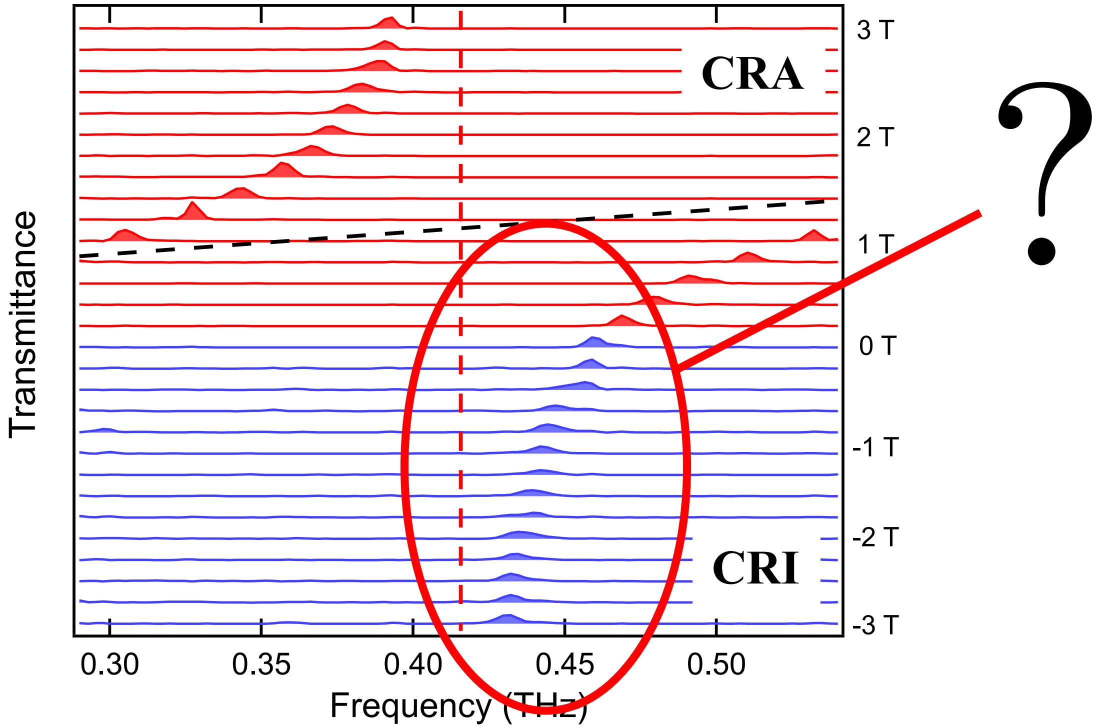
γ, κ
$\Omega(0) = 2g$
$C = \frac{4g^2}{\gamma\kappa} = 3513$
Transmittance
3 T
2 T
1 T
0 T
-1 T
-2 T
-3 T
0.30
0.35
0.40
0.45
0.50
Frequency (THz)


$2g$
ω_0
3 T
2 T
1 T
0 T
-1 T
-2 T
-3 T
Transmittance
0.30
0.35
0.40
0.45
0.50
Frequency (THz)
$\frac{2g}{\omega_0} = 0.72$

CRA = Cyclotron Resonance Active



CRI = Cyclotron Resonance Inactive


CRA
CRI
?
3 T
2 T
1 T
0 T
-1 T
-2 T
-3 T
Transmittance
0.30
0.35
0.40
0.45
0.50
Frequency (THz)

Jaynes-Cummings Model

one atom interacting with a single photonic mode

$$\hat{H}_{\text{J-C}} = \frac{1}{2}\hbar\omega_0\hat{\sigma}_z + \hbar\omega_c\hat{a}^\dagger\hat{a} + \hbar g(\hat{\sigma}_+\hat{a} + \hat{\sigma}_-\hat{a}^\dagger)$$

matter light interaction

Breakdown of the RWA: counter-rotating terms must be kept → Bloch-Siegert shift (1940)

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

Breakdown of the RWA: counter-rotating terms must be kept → Bloch-Siegert shift (1940)

$$\hat{H} = \frac{1}{2}\hbar\omega_0\hat{\sigma}_z + \hbar\omega_c\hat{a}^\dagger\hat{a}$$

$$+\hbar g(\underbrace{\hat{\sigma}_+\hat{a} + \hat{\sigma}_-\hat{a}^\dagger}_{\text{co-rotating terms}} + \underbrace{\hat{\sigma}_-\hat{a} + \hat{\sigma}_+\hat{a}^\dagger}_{\text{counter-rotating terms}})$$

$$\underbrace{+D(\hat{a} + \hat{a}^\dagger)(\hat{a} + \hat{a}^\dagger)}_{\text{A}^2 \text{ term}} \quad (D \propto g^2)$$

Theory of Landau Polaritons in the Ultrastrong Coupling Regime

by Motoaki Bamba

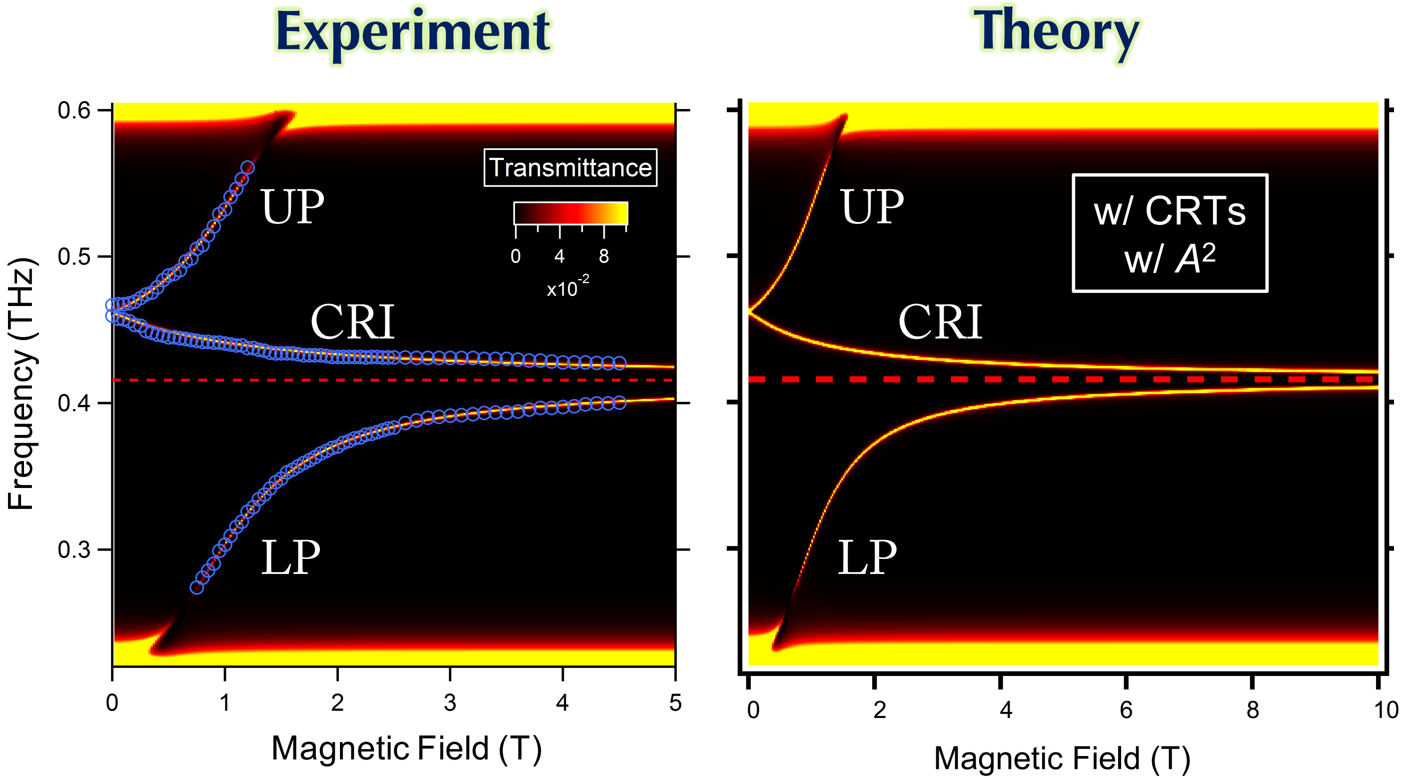
$$\hat{H} = \hat{H}_{\mathrm{CR}} + \hat{H}_{\mathrm{cav}} + \hat{H}_{\mathrm{int}} + \hat{H}_{A^2}$$

$$\hat{H}_{\mathrm{CR}} = \hbar\omega_{\mathrm{c}}\hat{\beta}_0^{\dagger}\hat{\beta}_0$$

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

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

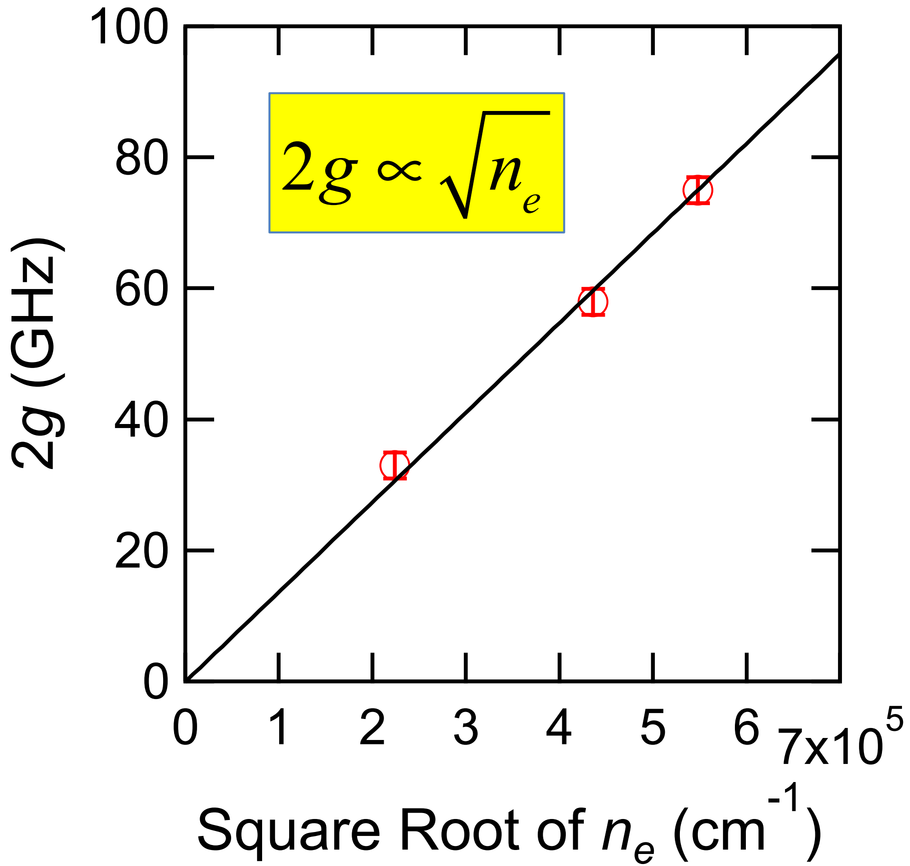
$$\hat{H}_{A^2} = \sum_{n_z=1}^{\infty}\sum_{n_z'=1}^{\infty}\frac{\hbar g_{n_z}g_{n_z'}}{\omega_{\mathrm{c}}}(\hat{a}_{n_z,-} + \hat{a}_{n_z,+}^{\dagger})(\hat{a}_{n_z',+} + \hat{a}_{n_z',-}^{\dagger})$$



Nature Photonics **12**, 324 (2018)

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

We have clearly observed Dicke cooperativity.



Outline

1. Landau polaritons in quantum Hall systems
2. **Spin-photon ultrastrong coupling in a paramagnet**
3. Spin-magnon ultrastrong coupling in an antiferromagnet
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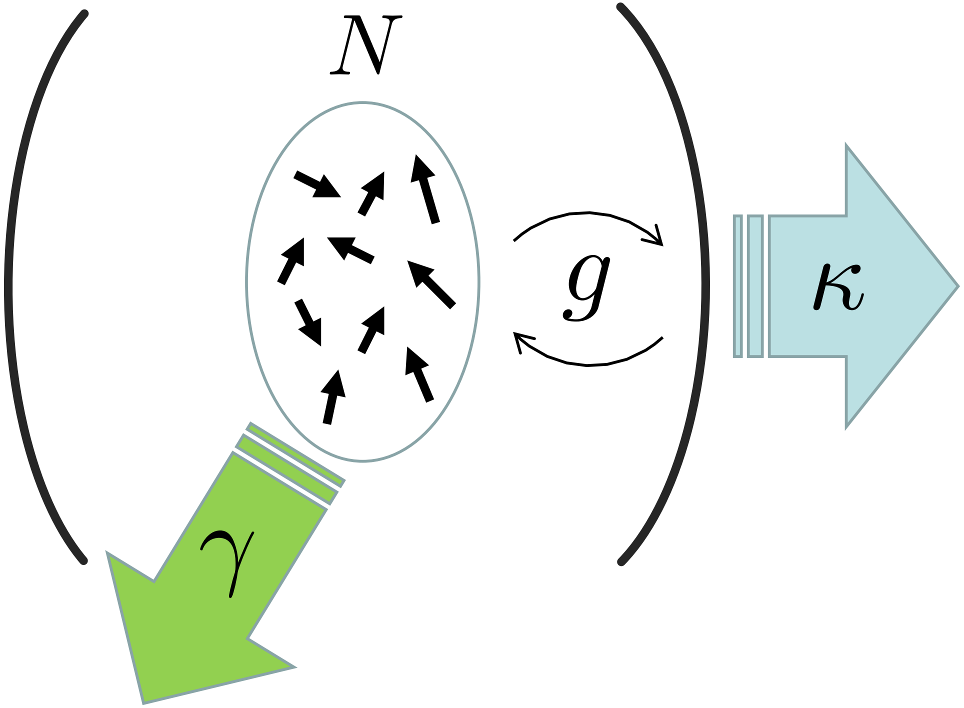
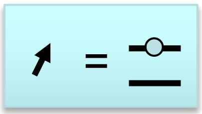
RICE
Unconventional Wisdom

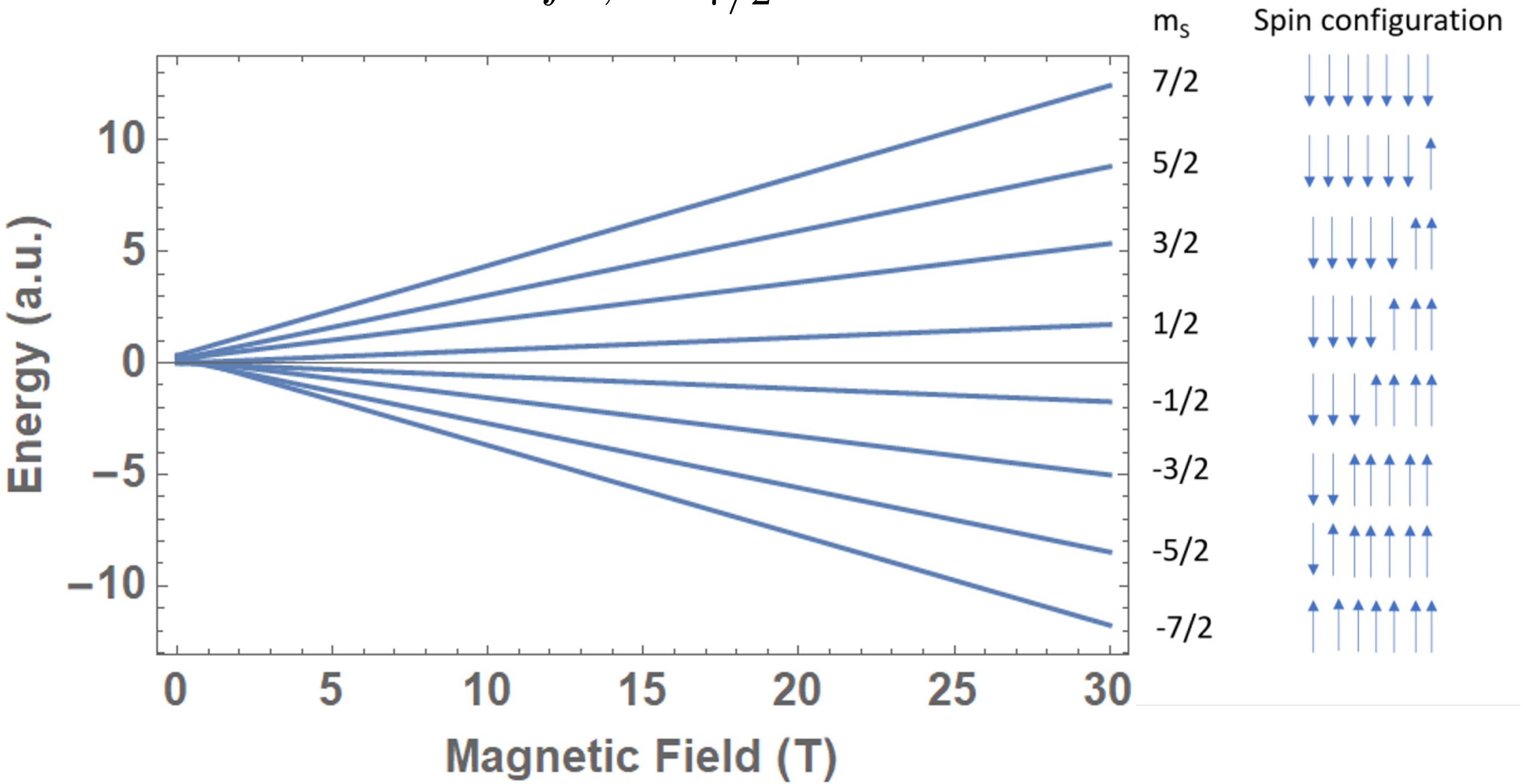
An ensemble of paramagnetic spins in a single-mode cavity represents the Dicke model in condensed matter.





Gd^{3+} Ions in $Gd_3Ga_5O_{12}$ (GGG) in a Magnetic Field

$$4f^7,\ ^8S_{7/2}$$



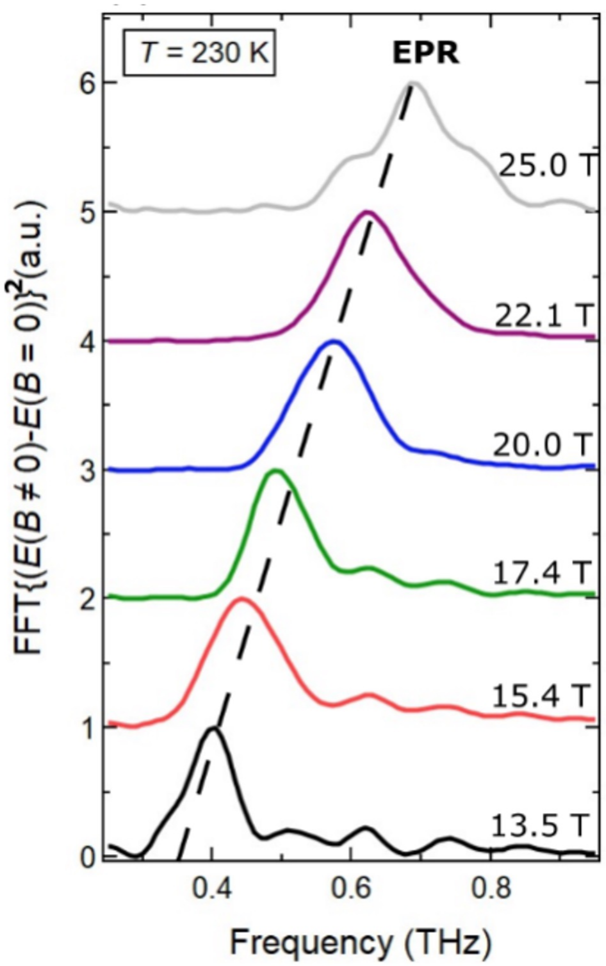
Ga^{3+} spins exhibit a single electron paramagnetic resonance (EPR) mode.

$$^8S_{7/2}:\ J = S = 7/2,\ L = 0$$

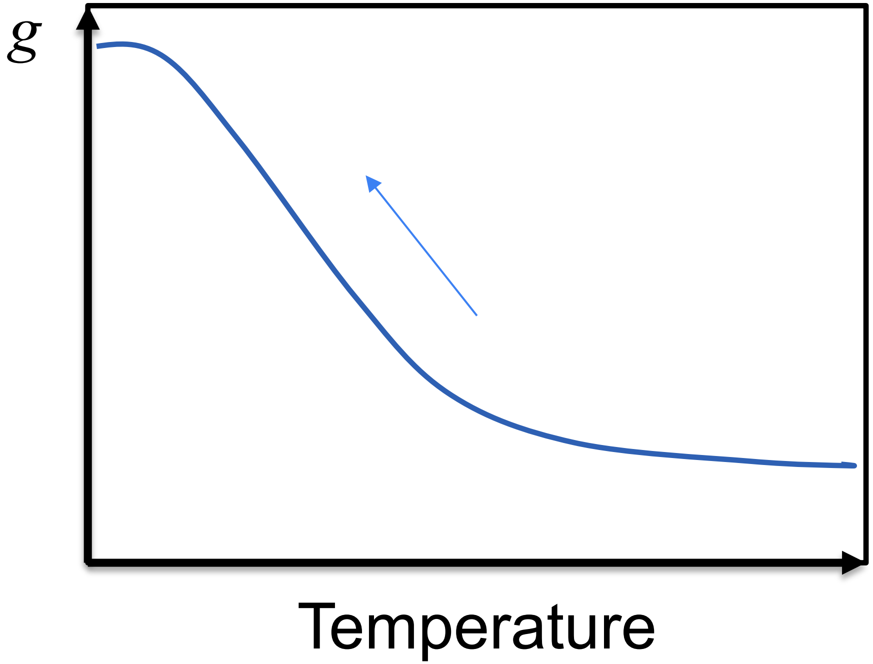
$$g(JLS) = \frac{3}{2} + \frac{1}{2}\left[\frac{S(S+1) - L(L+1)}{J(J+1)}\right] = 2$$

$$M = \frac{N}{V} g(JLS)\mu_B J B_J \left(\frac{g(JLS)\mu_B \mu_0 J H}{k_B T}\right)$$

$$B_J : \text{Brillouin function}$$

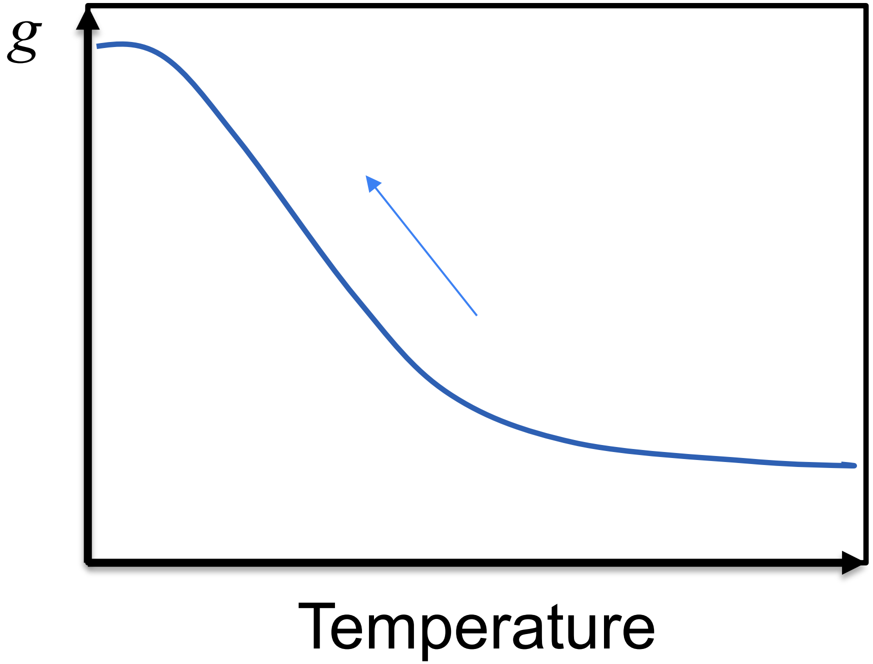


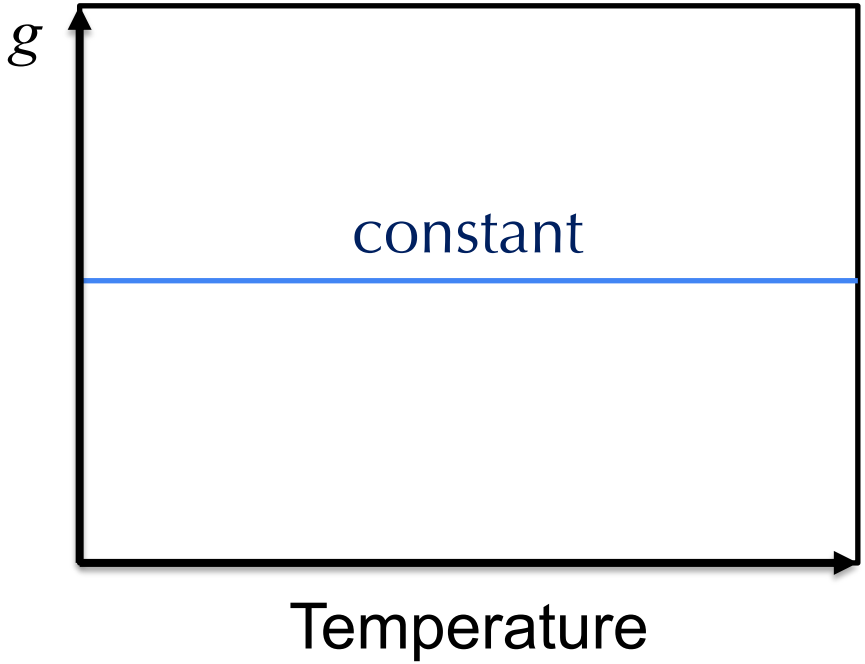
Spin-Boson Coupled System (Dicke model)



Spin-Boson Coupled System
(Dicke model)

Boson-Boson Coupled System
(Hopfield model)



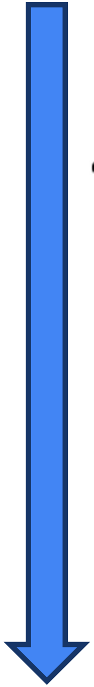


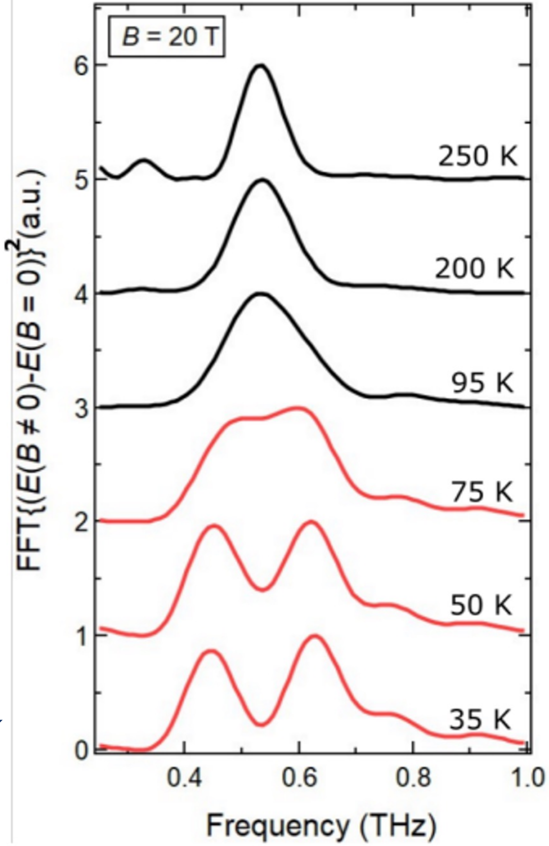
The THz-EPR coupling exhibits USC at low *T* and high *B*.

Weak coupling

Strong coupling

Ultrastrong coupling





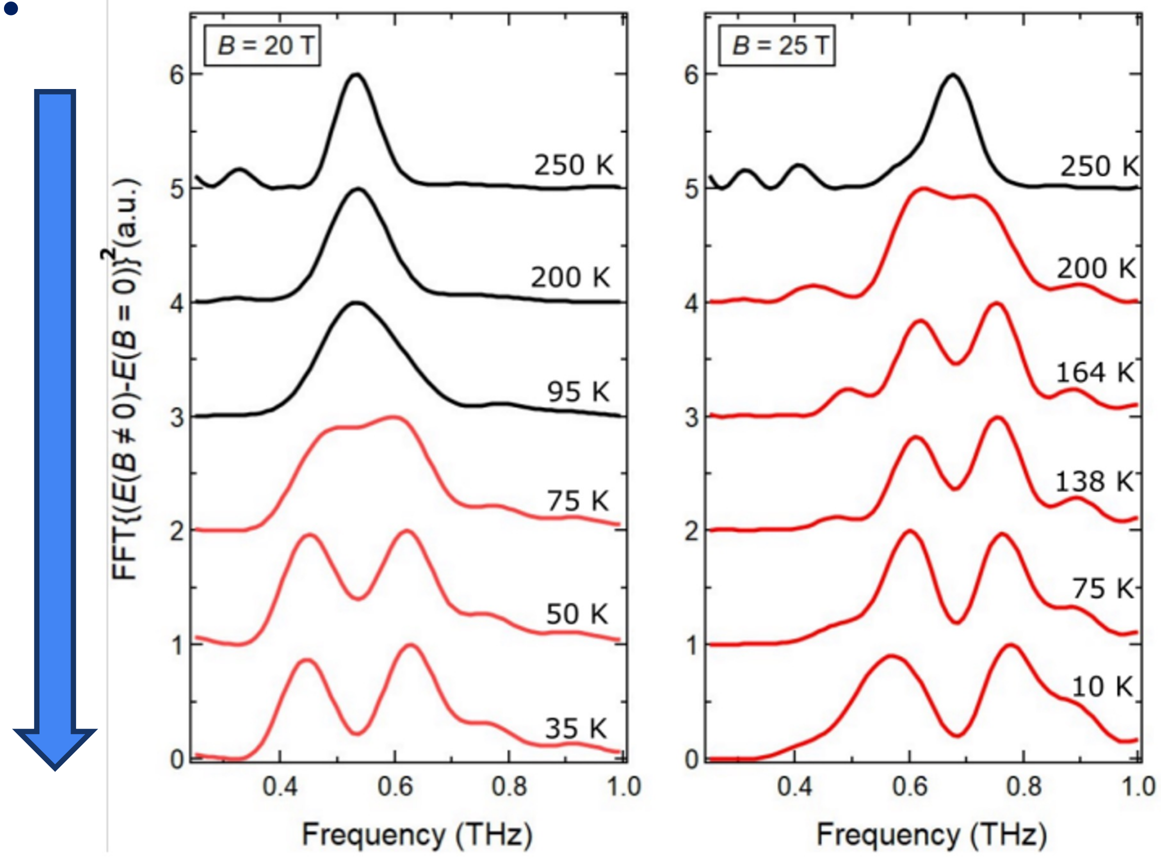
$$\omega_\pm = \omega_0 - \frac{i(\gamma+\kappa)}{2} \pm \sqrt{g^2 - \left(\frac{\kappa-\gamma}{4}\right)^2}$$

The THz-EPR coupling exhibits USC at low *T* and high *B*.

Weak coupling

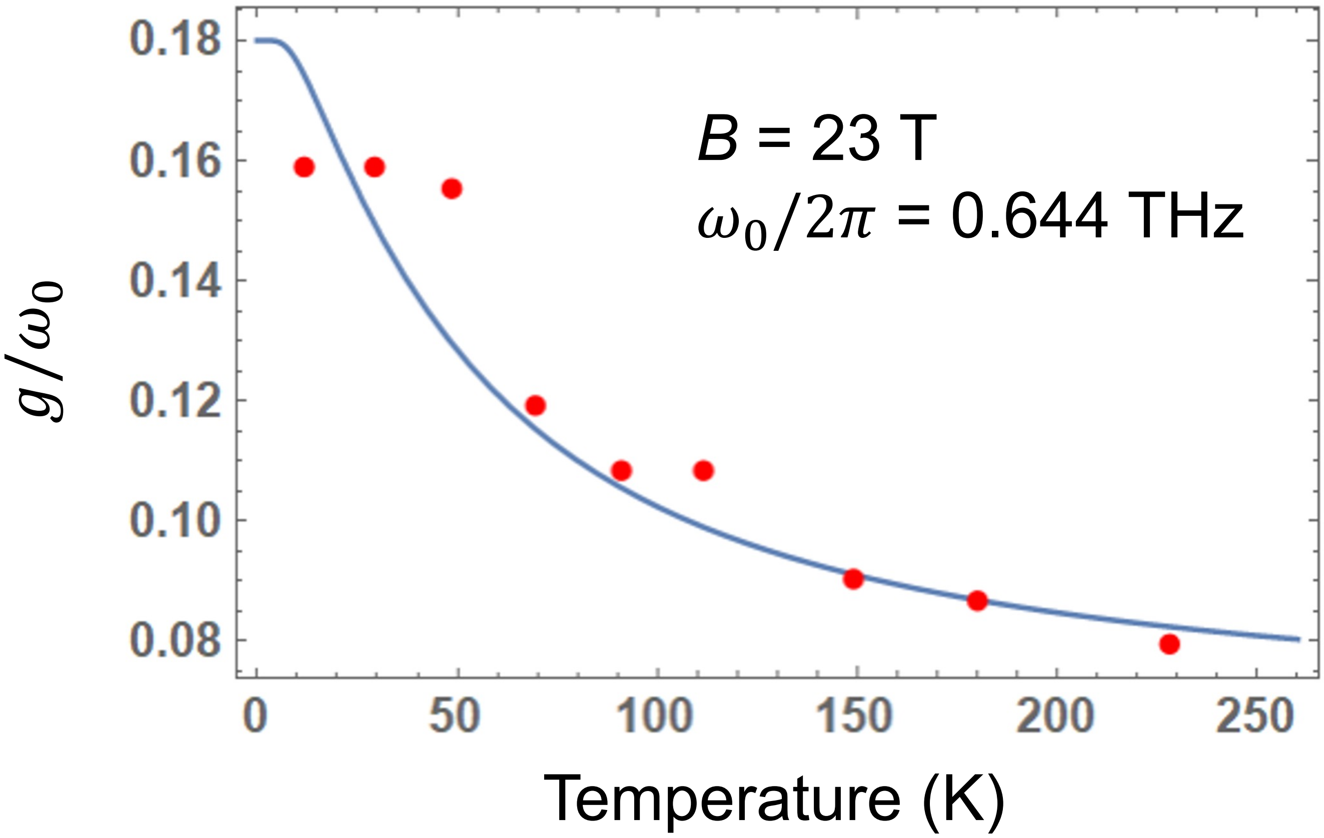
Strong coupling

Ultrastrong coupling



$$\eta = 0.23$$

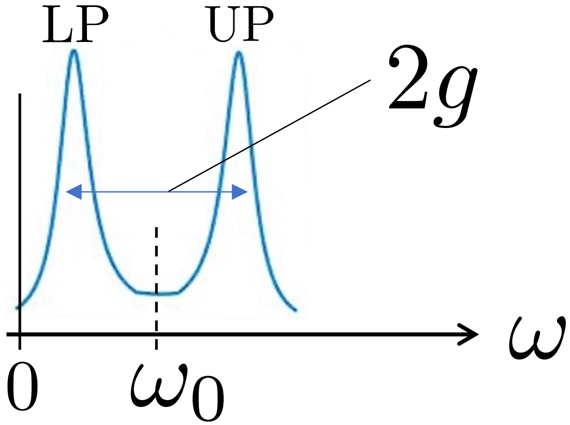
The coupling strength increased with decreasing temperature.



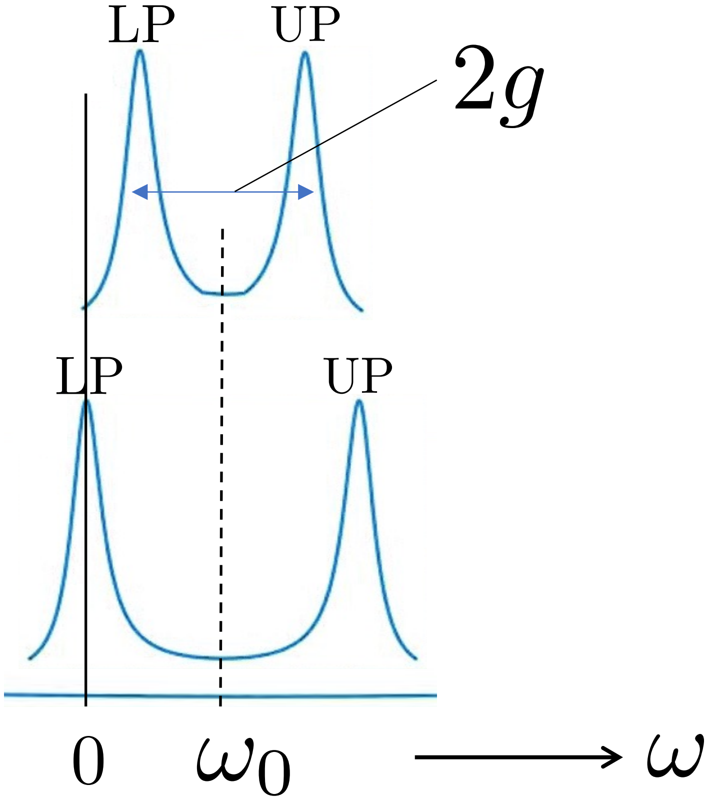
Outline

1. Landau polaritons in quantum Hall systems
2. Spin-photon coupling in a paramagnet
3. **Spin-magnon ultrastrong coupling in an antiferromagnet**
4. Summary and outlook

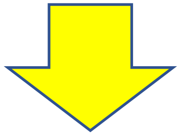
RICE
Unconventional Wisdom



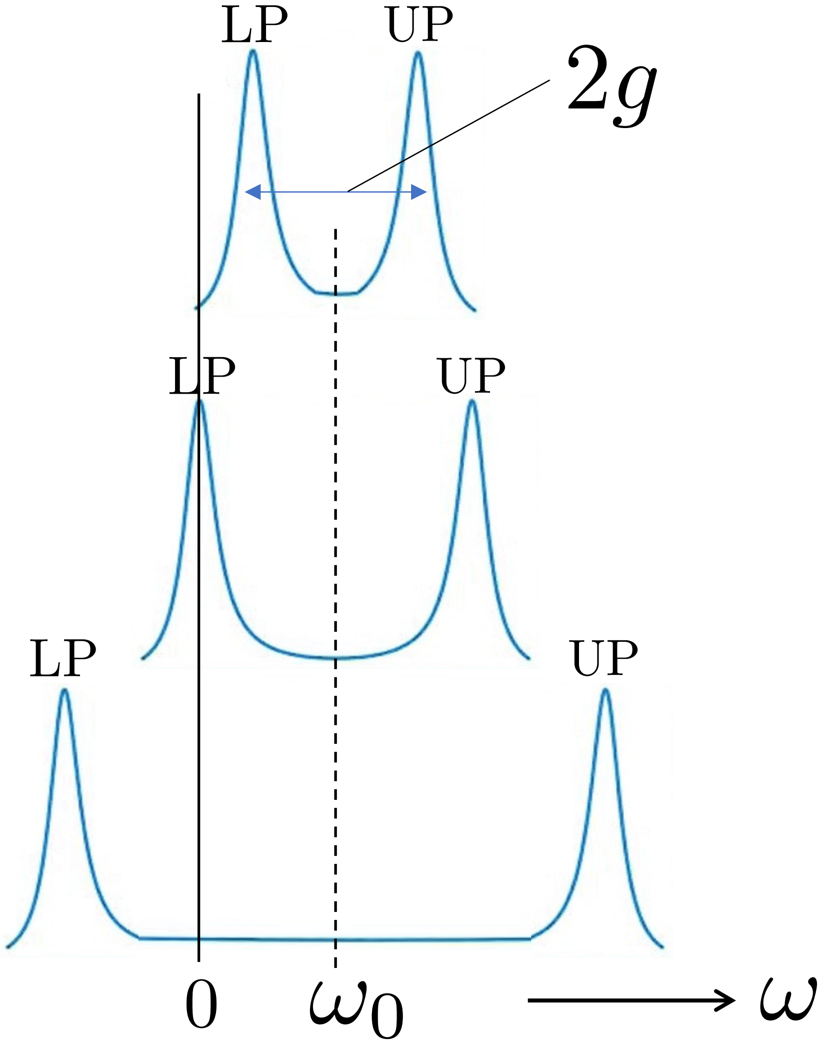
$$g < \omega_0$$



$$g < \omega_0$$



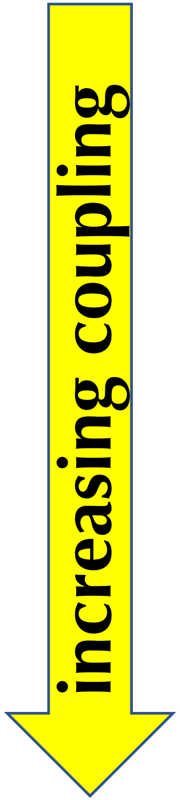
$$g = \omega_0$$



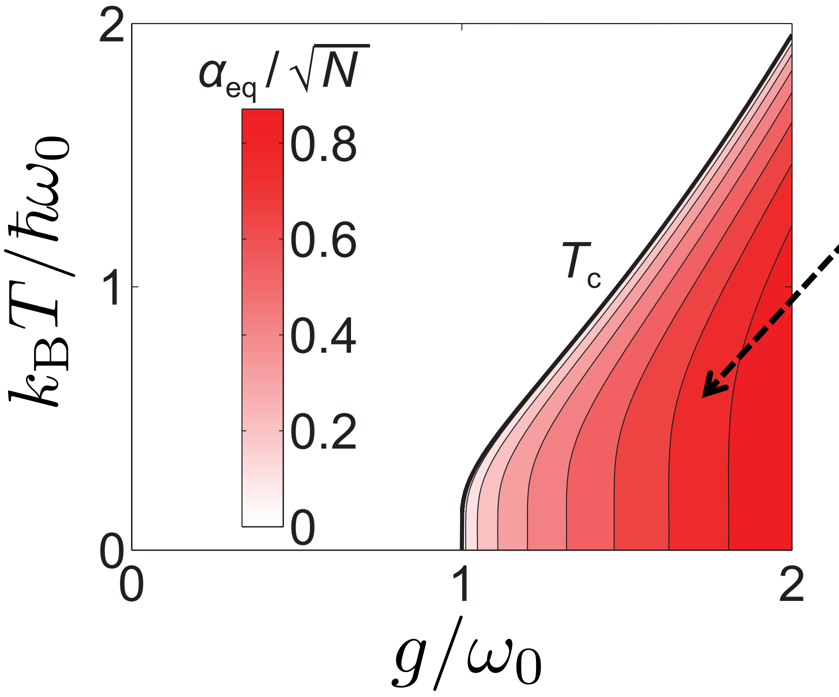
$$g < \omega_0$$

$$g = \omega_0$$

$$g > \omega_0$$



There is a new ground state at low enough *T* and large enough *g* (the Dicke superradiant phase transition: SRPT).

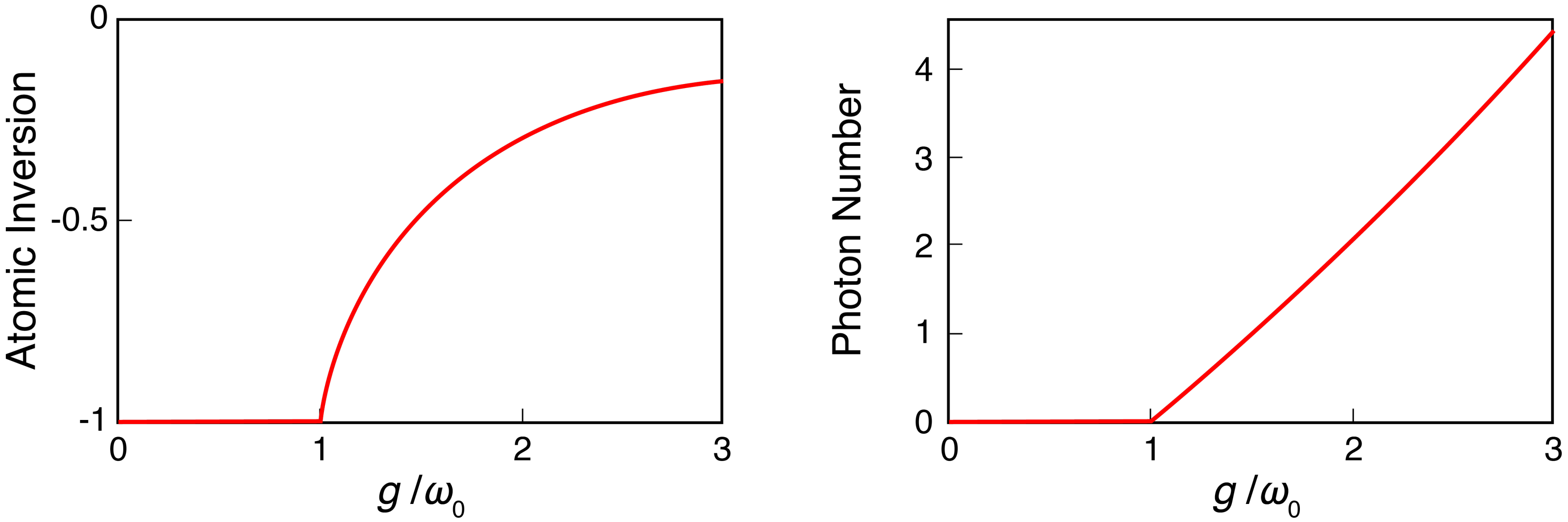


The superradiant (SR) phase

$$\omega_{\text{atom}} = \omega_{\text{photon}} \equiv \omega_0$$

K. Hepp & E. H. Lieb, Annals of Physics **76**, 360 (1973)

There are two order parameters in the SRPT (a.k.a. photon condensation).



$T = 0$

C. Emary & T. Brandes, Physical Review E **67**, 066203 (2003); Physical Review Letters **90**, 044101 (2003)
F. Dimer *et al.*, Physical Review A **75**, 013804 (2007)
P. Nataf & C. Ciuti, Nature Communications **1**, 72 (2010)
J. Larson & E. K. Irish, Journal of Physics A **50**, 174002 (2017)

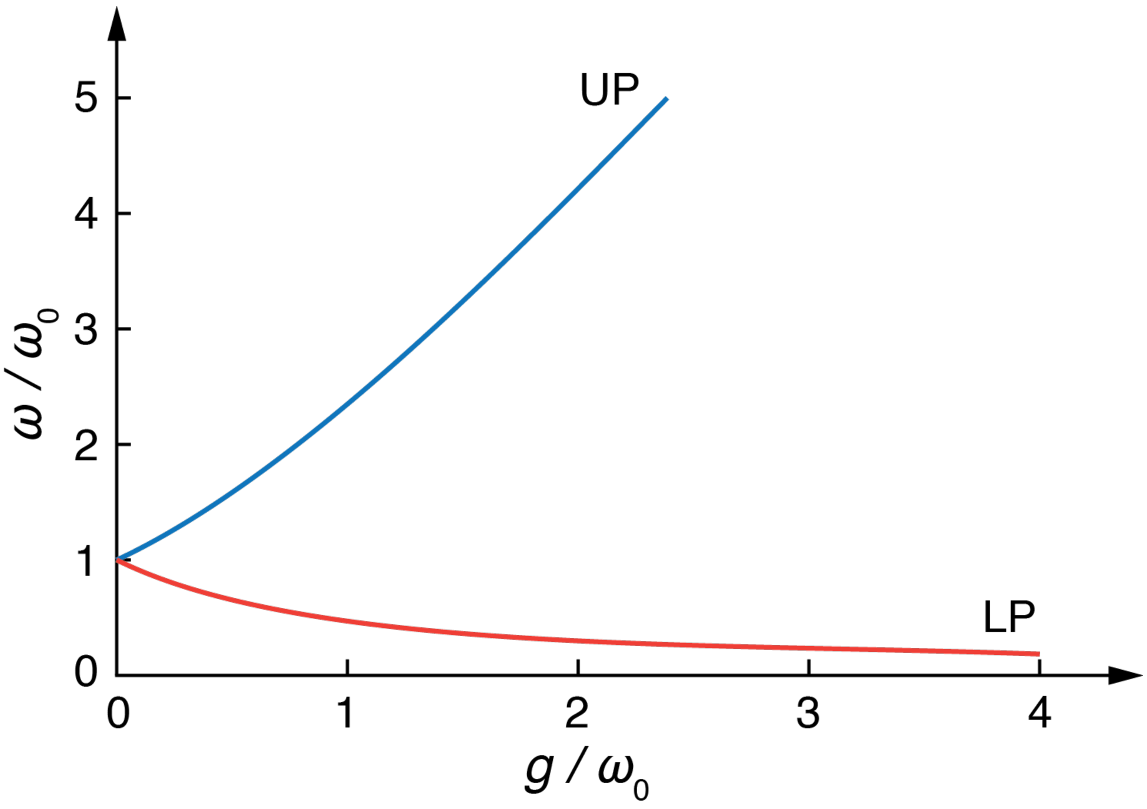
No-Go Theorem for the SRPT

K. Rzazewski *et al.*, Physical Review Letters **35**, 432 (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.

$$\frac{\mathbf{p}^2}{2m} \to \frac{(\mathbf{p}+e\mathbf{A})^2}{2m} = \frac{\mathbf{p}^2}{2m} + \frac{e}{m}\mathbf{A}\cdot\mathbf{p} + \frac{e^2}{2m}\mathbf{A}^2$$

No-Go Theorem for the SRPT



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 Keeling[1]

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 Grießer,[2] and Peter Domokos[1]

Dicke Superradiant Phase Transition: Ongoing Debate

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

Breakdown of gauge invariance in ultrastrong-coupling cavity QED

Daniele De Bernardis[1], Philipp Pilar[1], Tuomas Jaako[1], Simone De Liberato[2], and Peter Rabl[1]

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

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

Adam Stokes[*] and Ahsan Nazir[†]

Nat. Phys. **15**, 803 (2019)

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]

Dicke Superradiant Phase Transition: Ongoing Debate

Phys. Rev. B **100**, 121109 (2019)

Cavity quantum electrodynamics of strongly correlated electron systems: A no-go theorem for photon condensation

G. M. Andolina,[1,2] F. M. D. Pellegrino,[3,4] V. Giovannetti,[5] A. H. MacDonald,[6] and M. Polini[2]

Phys. Rev. Lett. **123**, 207402 (2019)

Rashba Cavity QED: A Route Towards the Superradiant Quantum Phase Transition

Pierre Nataf,[1] Thierry Champel,[1] Gianni Blatter,[2] and Denis M. Basko[1]

Phys. Rev. Lett. **125**, 257604 (2020)

Superradiant Phase Transition in Electronic Systems and Emergent Topological Phases

Daniele Guerci,[1,2] Pascal Simon,[2] and Christophe Mora[1]

Dicke Superradiant Phase Transition: Ongoing Debate

Phys. Rev. B **102**, 125137 (2020)

Theory of photon condensation in a spatially varying electromagnetic field

G. M. Andolina,[1,2,*] F. M. D. Pellegrino,[3,4,*] V. Giovannetti,[5] A. H. MacDonald,[6] and M. Polini[7,8,2]

Phys. Rev. B **105**, 245304 (2022)

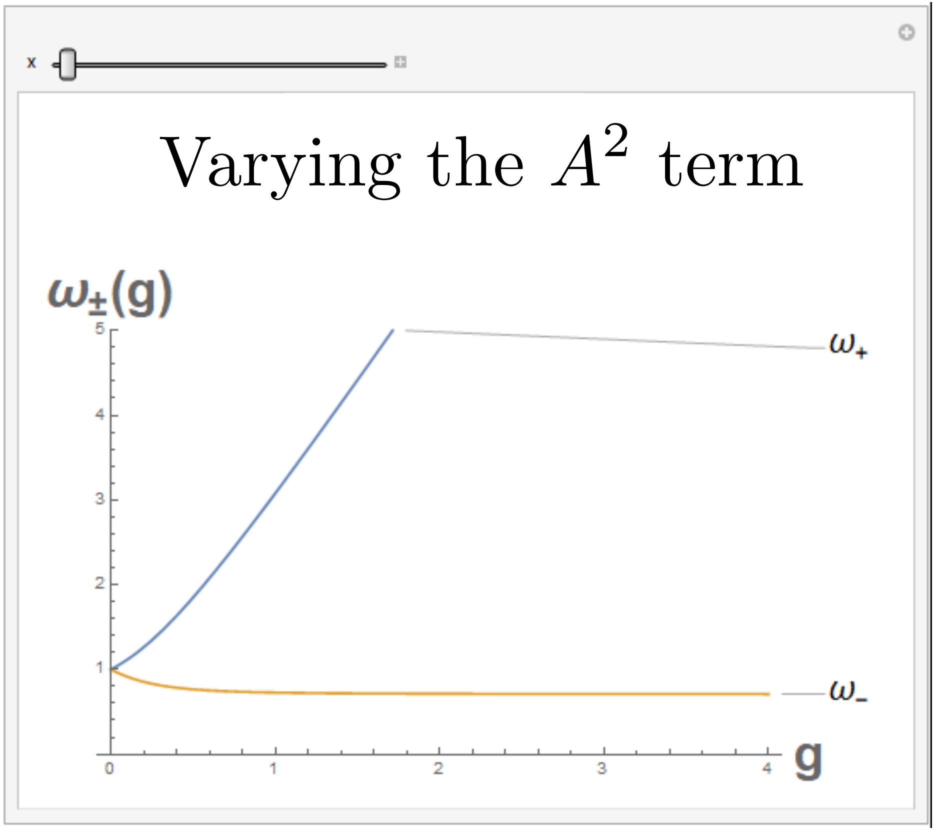
Superradiant quantum phase transition for Landau polaritons with Rashba and Zeeman couplings

Guillaume Manzanares, Thierry Champel, Denis M. Basko, and Pierre Nataf

Euro. Phys. J. Plus **137**, 1348 (2022)

A non-perturbative no-go theorem for photon condensation in approximate models

G.M. Andolina,[1,2,3] F.M.D. Pellegrino,[4,5] A. Mercurio,[6,*] O. Di Stefano,[6] M. Polini,[7,8,2] and S. Savasta[6]


x
Varying the A^2 term
$\omega_{\pm}(g)$
5
4
3
2
1
0
1
2
3
4
g
ω_+
ω_-

Phys. Rev. A. **17**, 1454 (1978)

Are super-radiant phase transitions possible?

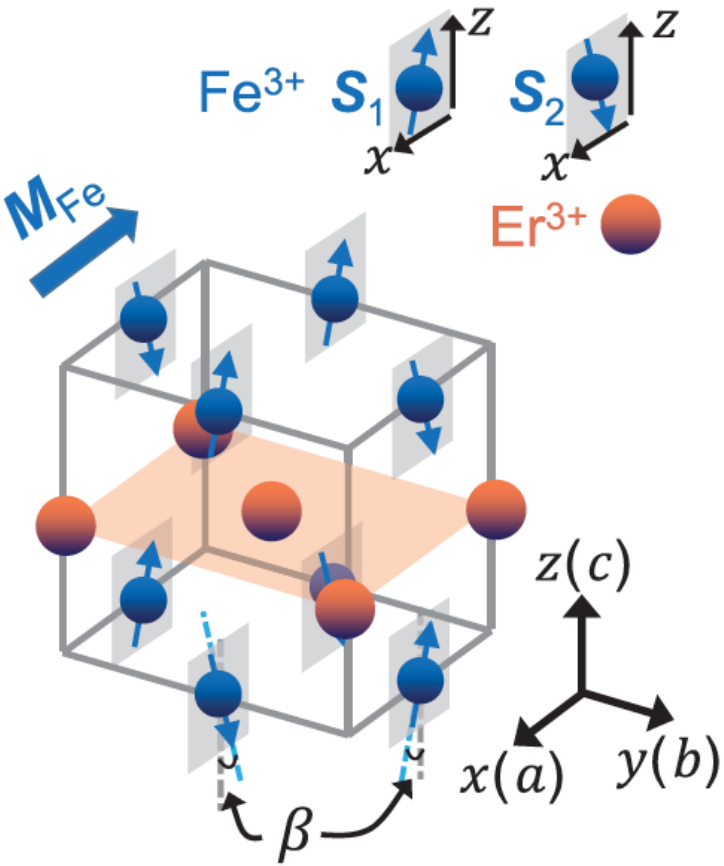
J. M. Knight, Y. Aharonov,* and G. T. C. Hsieh

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 Hamiltonian[19]

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

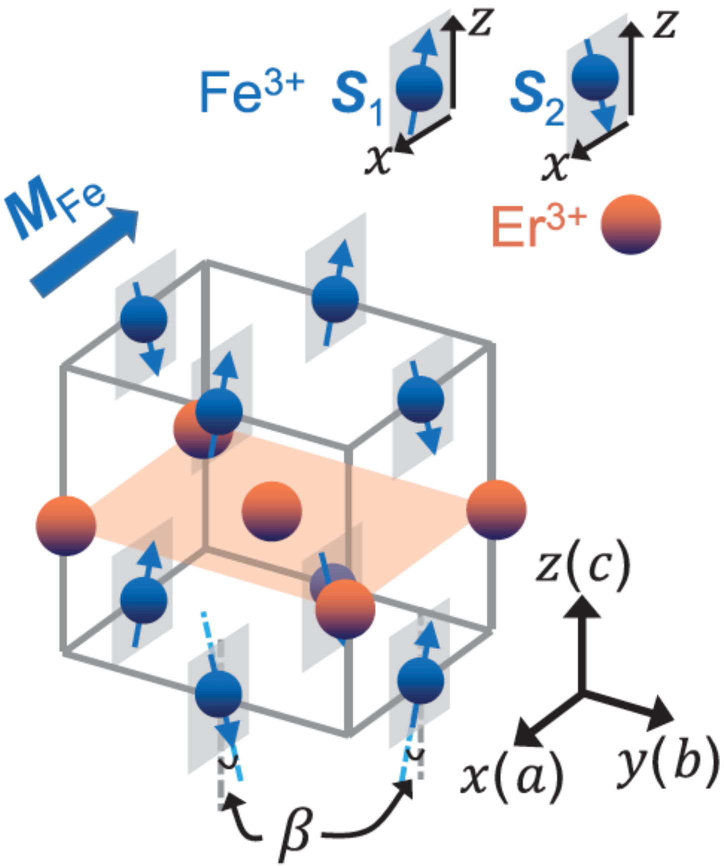
which is of the Dicke form, and which is obtained from the fundamental Hamiltonian without making any approximations which violate gauge invari-

$ErFeO_3$

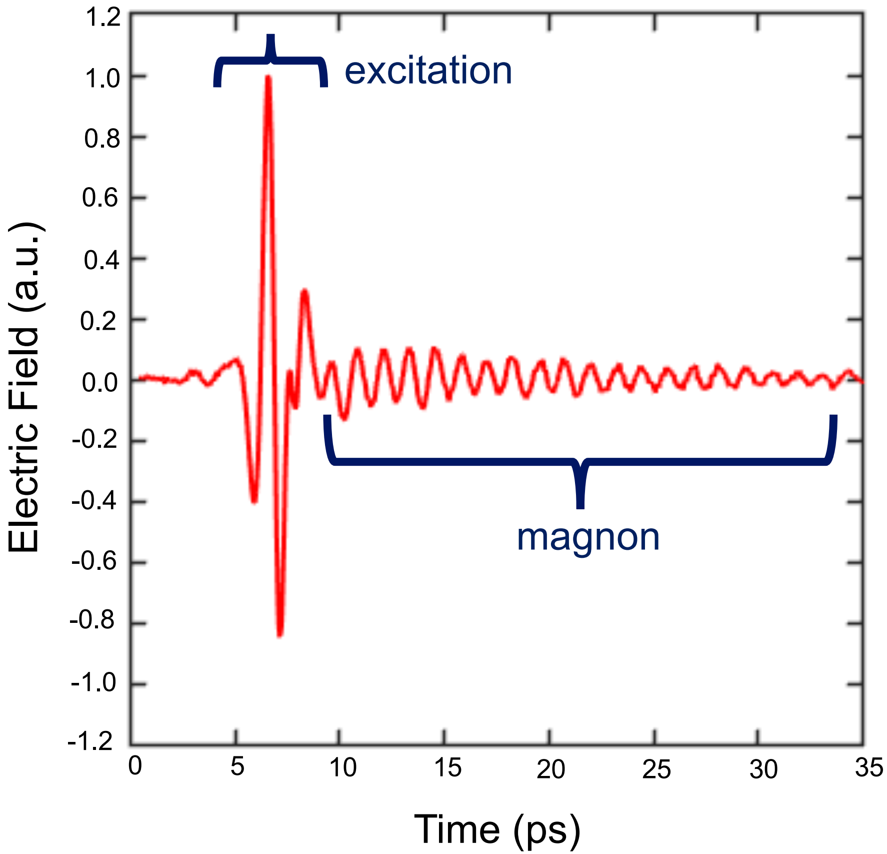


Fe^{3+} → antiferromagnetically ordered (T_N = 650 K)
Er^{3+} → paramagnetic (> 4 K)

$ErFeO_3$

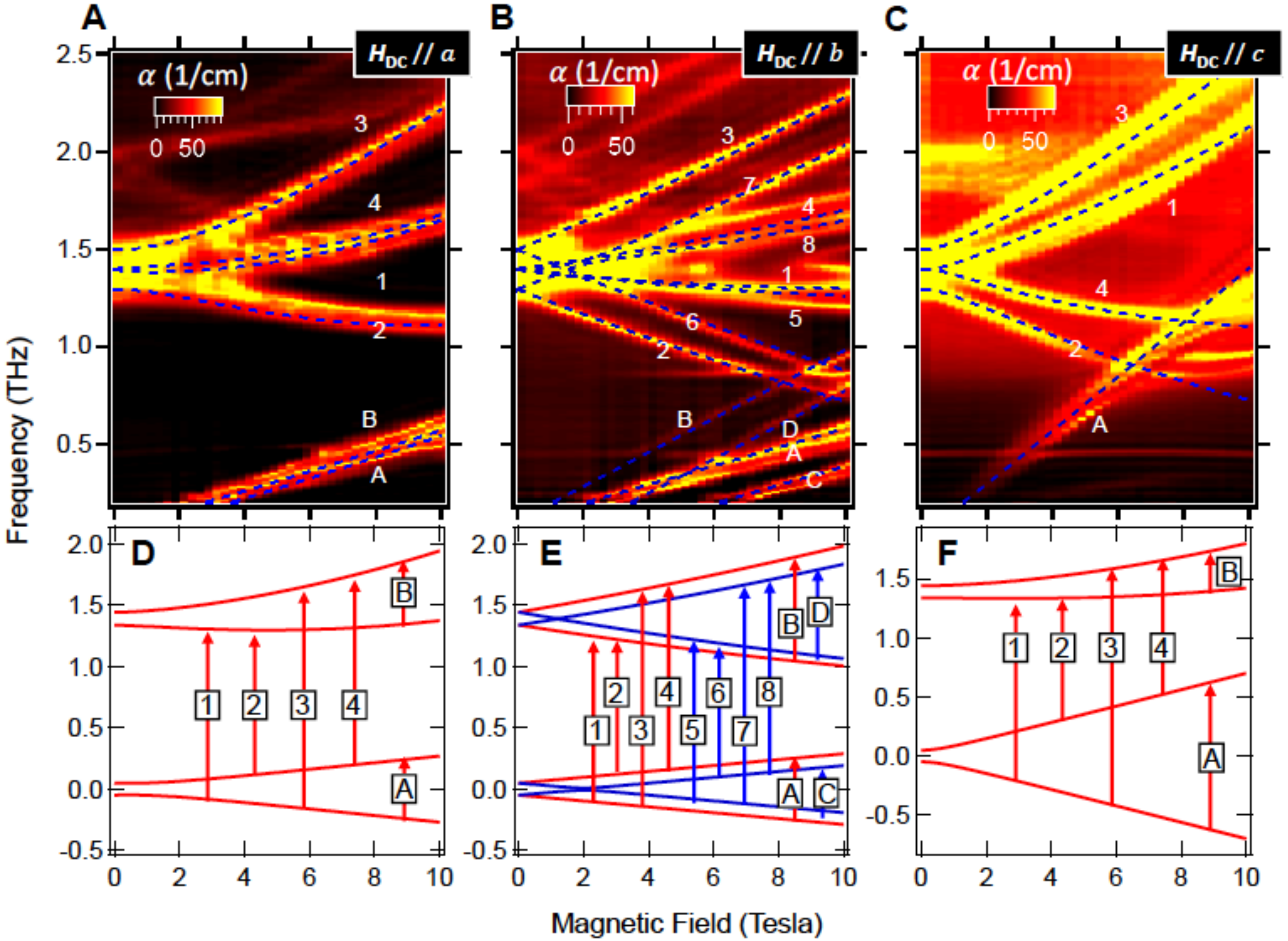


$RFeO_3$ exhibits long-lived coherent THz magnons due to ordered Fe spins.

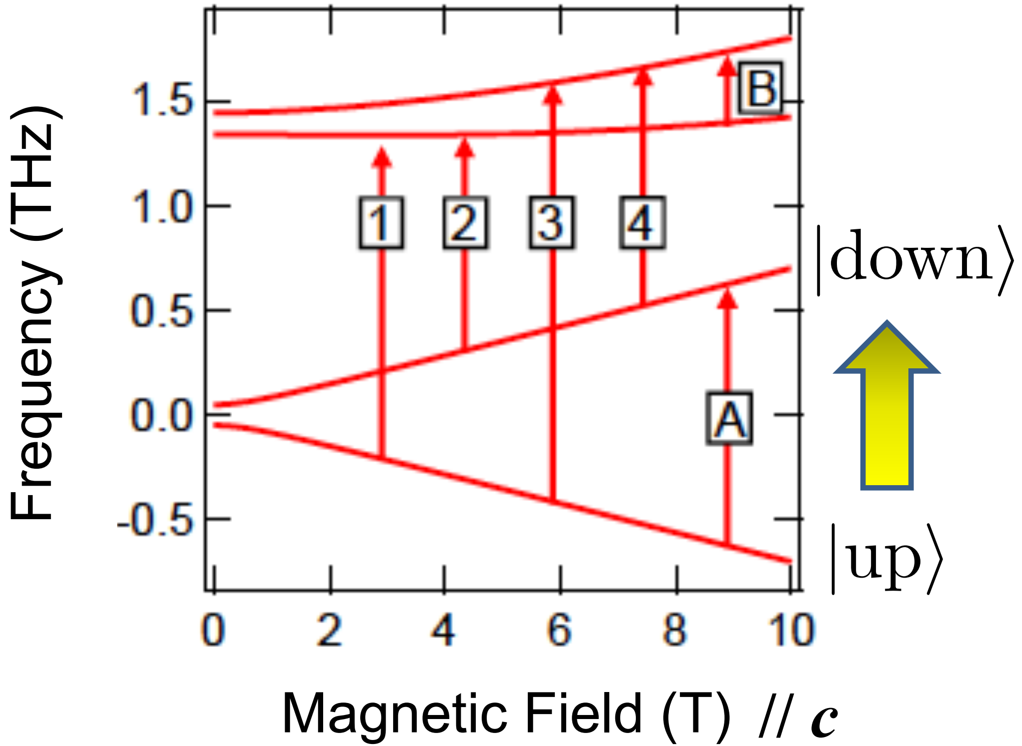


Crystal Field Transitions of Er^{3+} in $ErFeO_3$

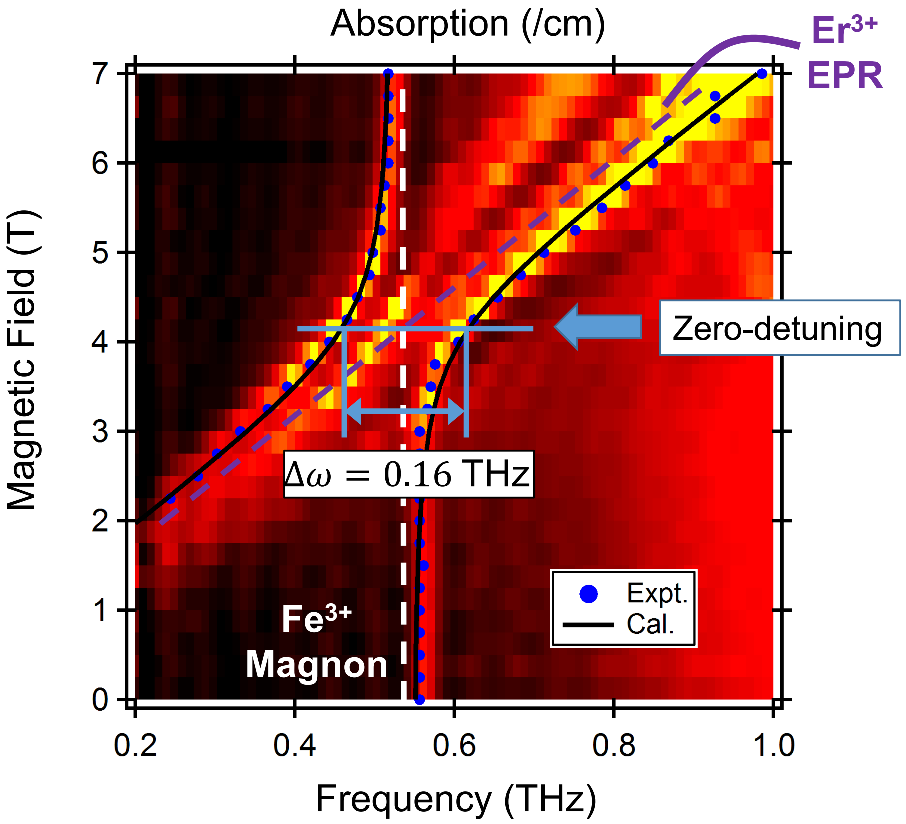
$4f^{11},\ {}^4I_{15/2}$



The electron paramagnetic resonance (EPR) of Er^{3+} is observed at low *T*.

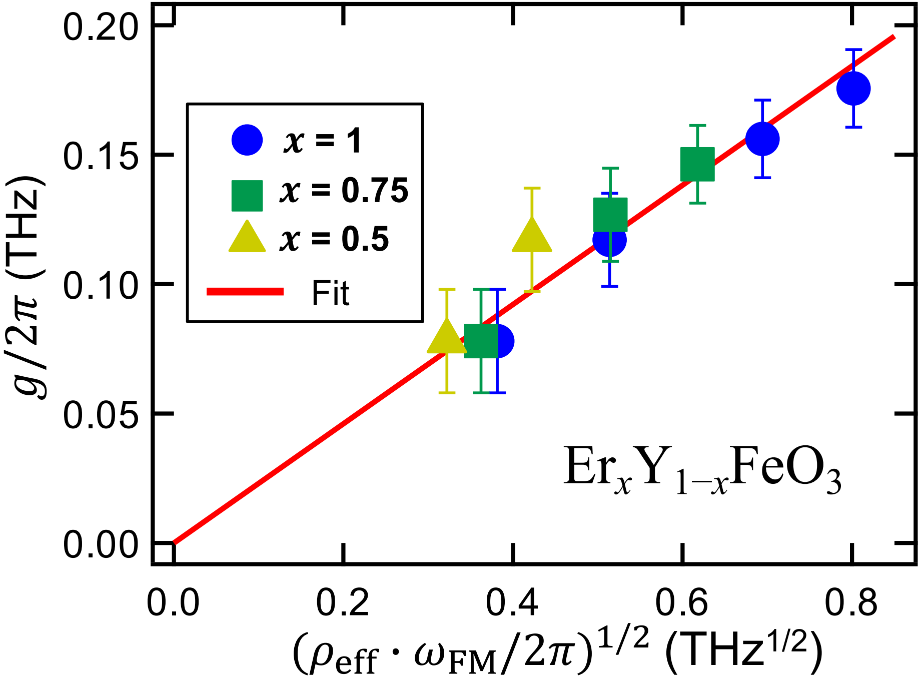


The Fe^{3+} magnon and Er^{3+} EPR show avoided crossing with a huge vacuum Rabi splitting.



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

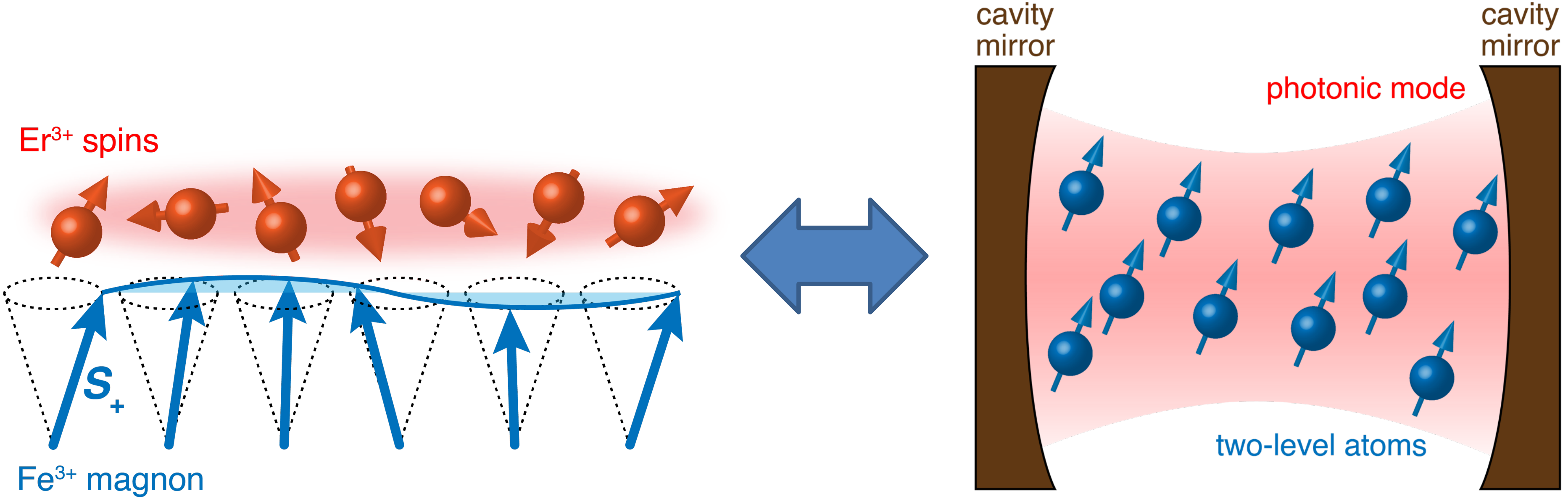
The Fe^{3+} magnon – Er^{3+} EPR coupling is cooperative.



$g \propto \sqrt{N_{\mathrm{spin}}}$

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

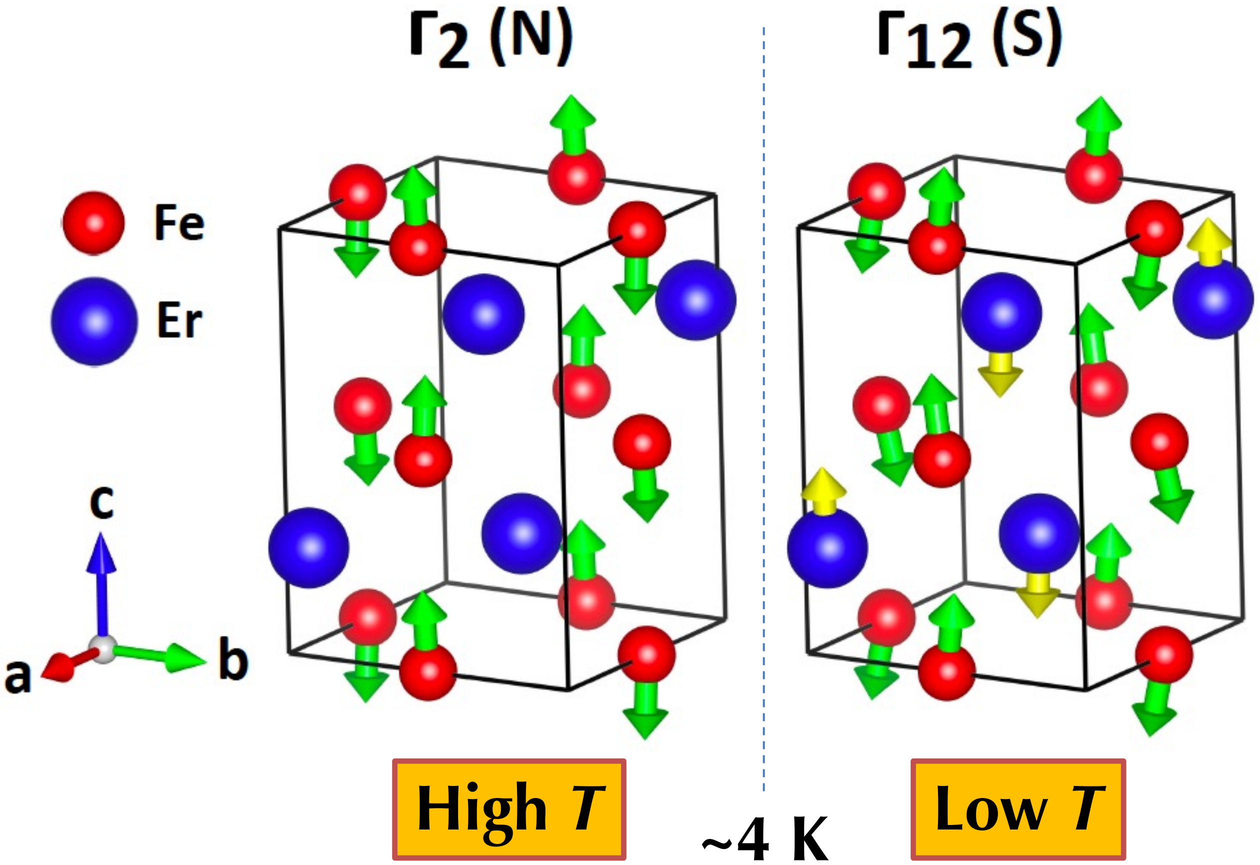
Spin–magnon ultrastrong coupling in $ErFeO_3$ simulates atom–photon ultrastrong coupling.



Science **361**, 794 (2018)

$ErFeO_3$

N. Marquez Peraca *et al.*, arXiv:2302.06028



Extended Dicke Model for Spin-Magnon Coupling

M. Bamba *et al.*, Communications Physics **5**, 3 (2022)

$$\hat{\mathcal{H}} \approx \sum_{K=0,\pi} \hbar\omega_K \hat{a}_K^\dagger \hat{a}_K + E_x \hat{\Sigma}_x^+ + \sum_{\xi=x,y,z} \mathfrak{g}_\xi^{\mathrm{Er}} \mu_{\mathrm{B}} B_\xi^{\mathrm{DC}} \hat{\Sigma}_\xi^+ + \frac{8 z_{\mathrm{Er}} J_{\mathrm{Er}}}{N} \hat{\boldsymbol{\Sigma}}^{\mathrm{A}} \cdot \hat{\boldsymbol{\Sigma}}^{\mathrm{B}}$$
$$+ \frac{2\hbar g_x}{\sqrt{N}} (\hat{a}_\pi^\dagger + \hat{a}_\pi) \hat{\Sigma}_x^+ + \frac{\mathrm{i}2\hbar g_y}{\sqrt{N}} (\hat{a}_0^\dagger - \hat{a}_0) \hat{\Sigma}_y^+ + \frac{\mathrm{i}2\hbar g_z}{\sqrt{N}} (\hat{a}_\pi^\dagger - \hat{a}_\pi) \hat{\Sigma}_z^-$$
$$+ \frac{2\hbar g_y'}{\sqrt{N}} (\hat{a}_\pi^\dagger + \hat{a}_\pi) \hat{\Sigma}_y^- + \frac{2\hbar g_z'}{\sqrt{N}} (\hat{a}_0^\dagger + \hat{a}_0) \hat{\Sigma}_z^+ .$$

Multi-mode, **anisotropic** Dicke Hamiltonian + **Nearest-neighbor Er-Er exchange interaction**

Extended Dicke Model for Spin-Magnon Coupling

M. Bamba *et al.*, Communications Physics **5**, 3 (2022)

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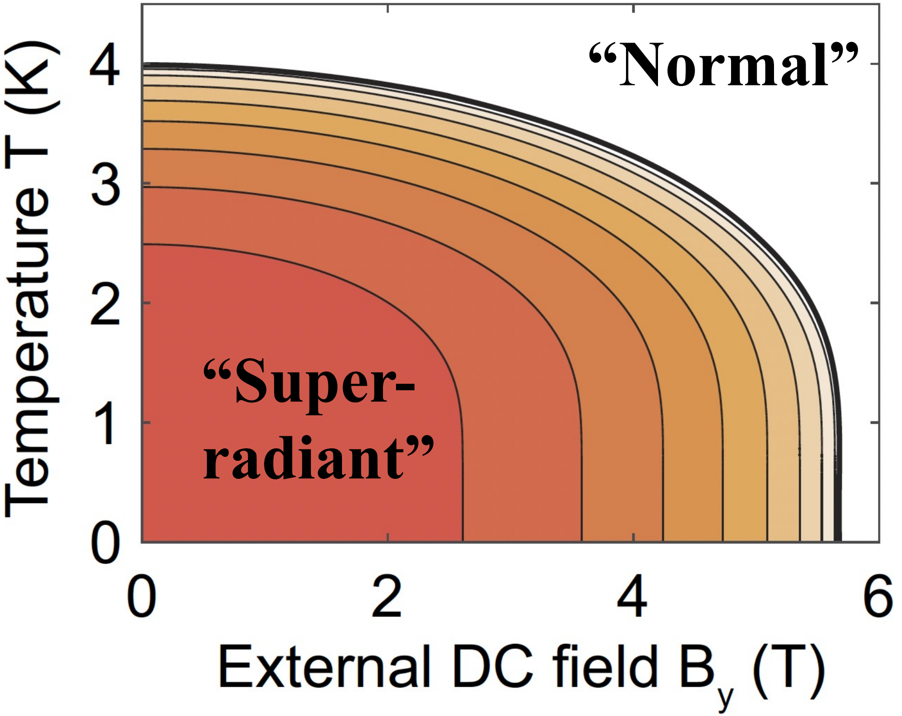
Multi-mode, **anisotropic** Dicke Hamiltonian + **Nearest-neighbor Er-Er exchange interaction**

No A^2 term!

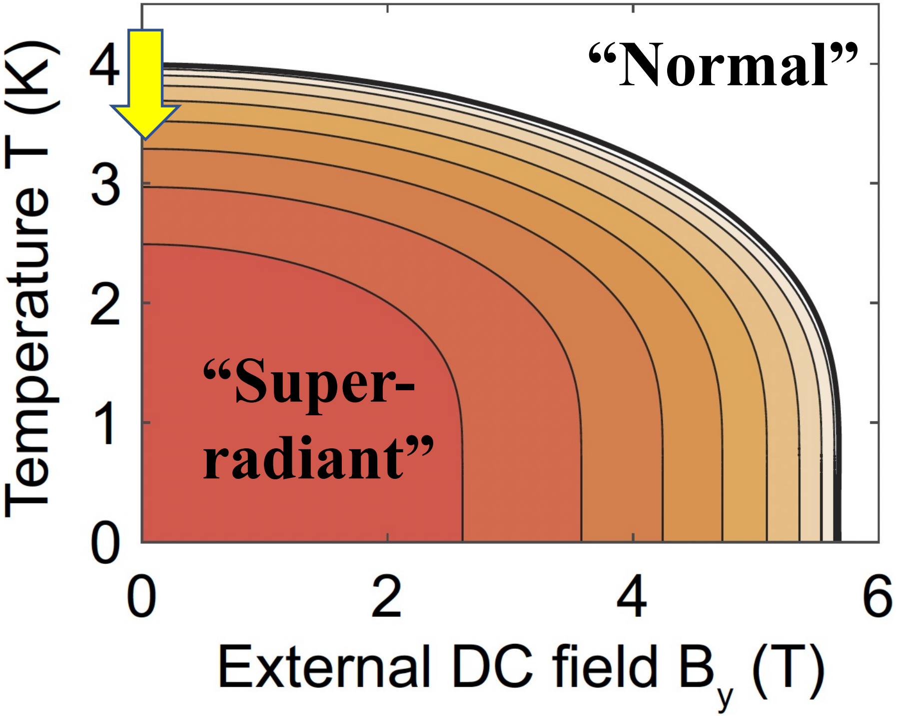
Magnonic Superradiant Phase Transition in $ErFeO_3$

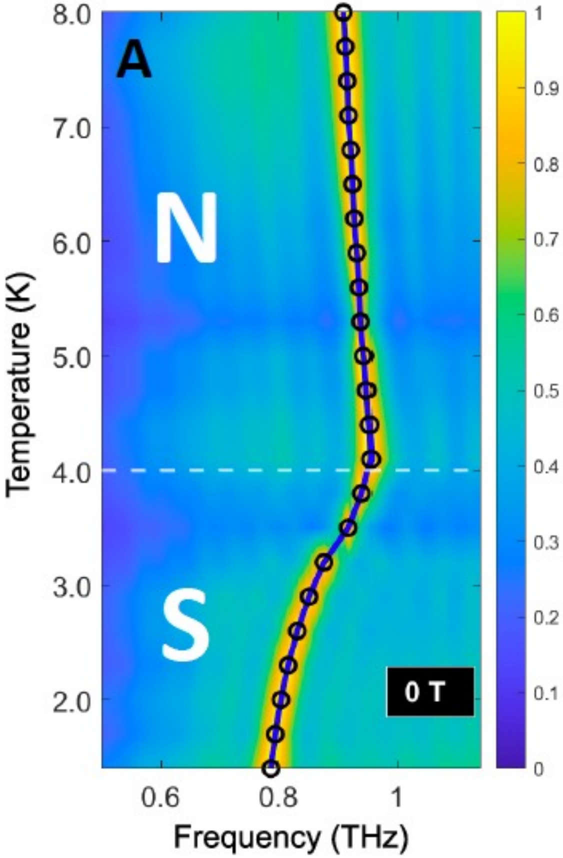


Communications Physics
5, 3 (2022)

Phase diagram based on the <u>extended Dicke model</u>

We have mapped out the low-temperature phase diagram of $ErFeO_3$ through THz magnetospectroscopy.





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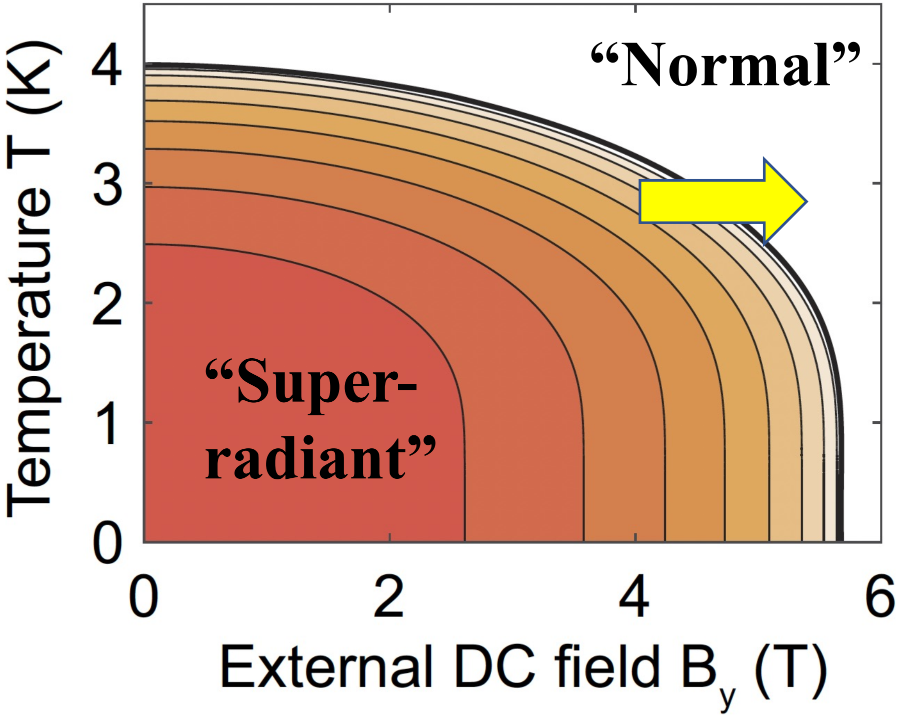

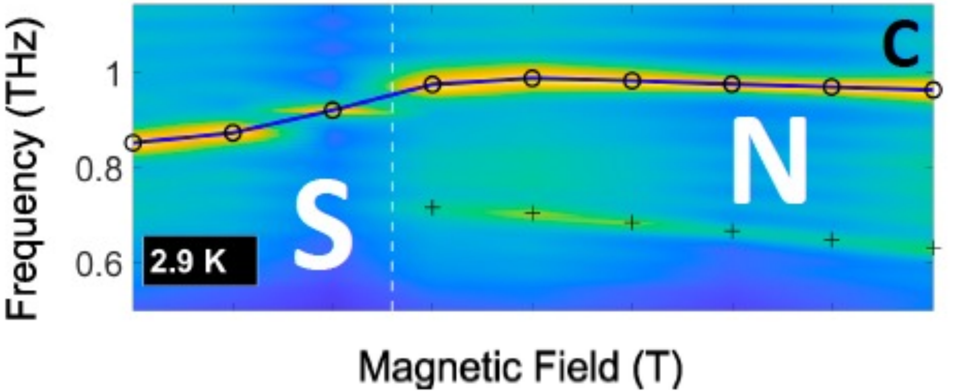

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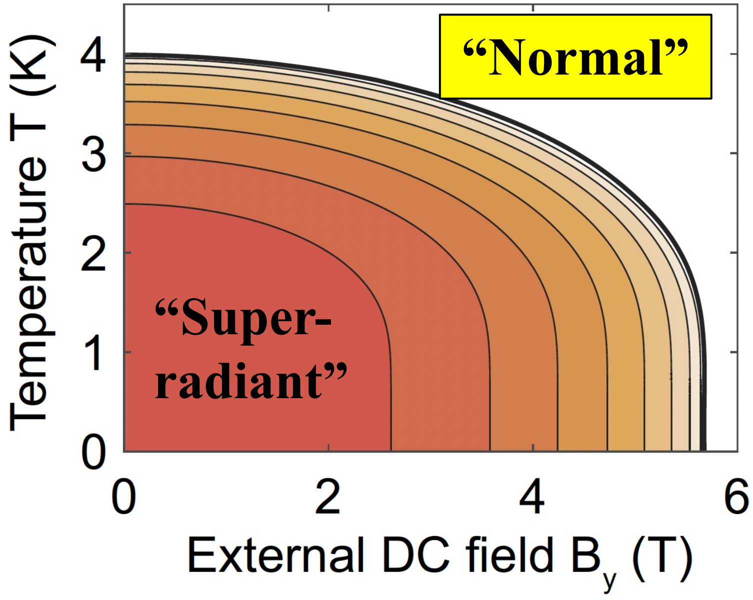

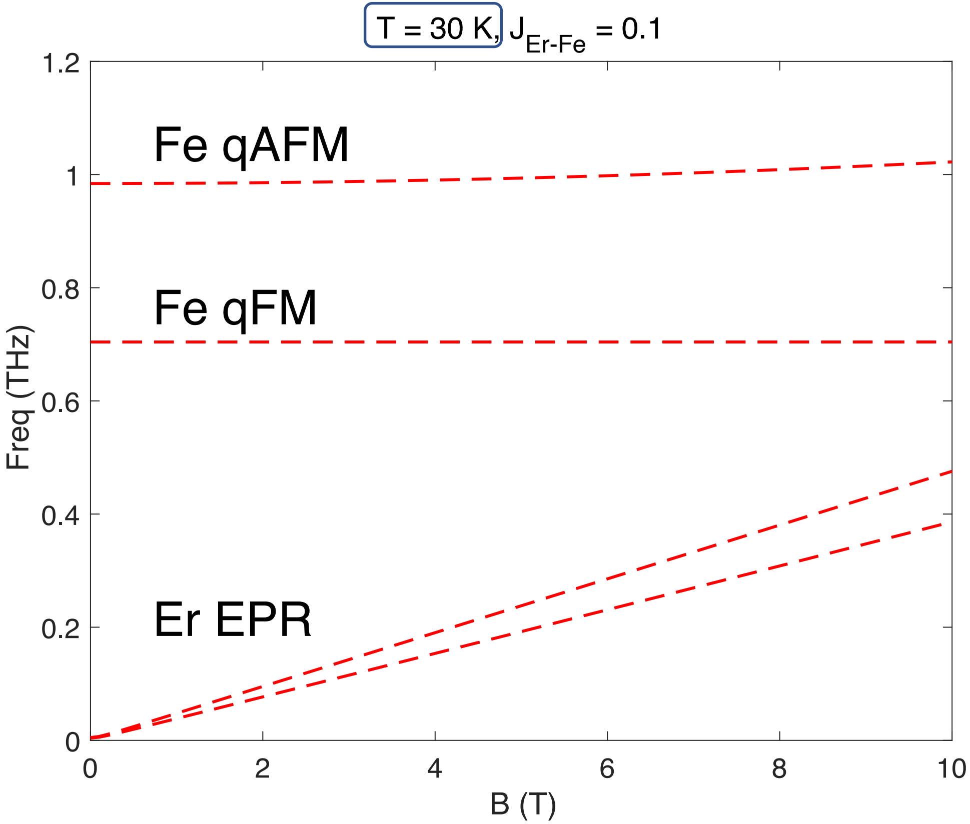

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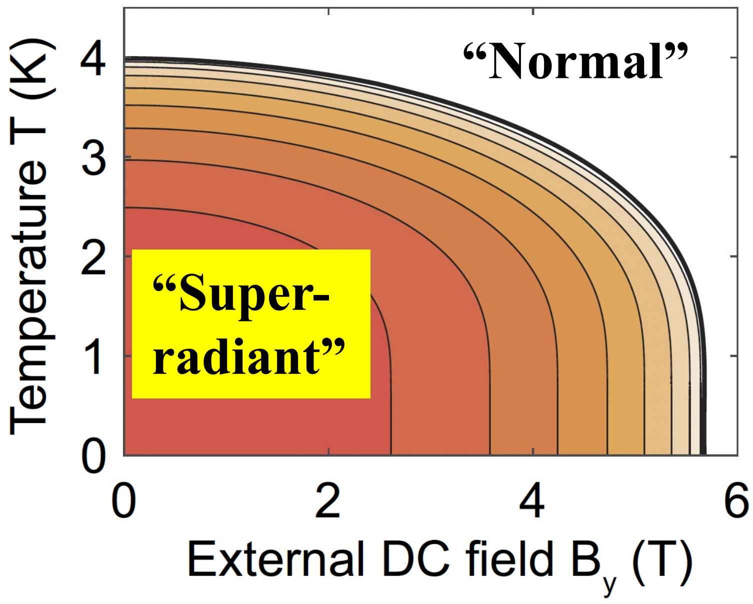
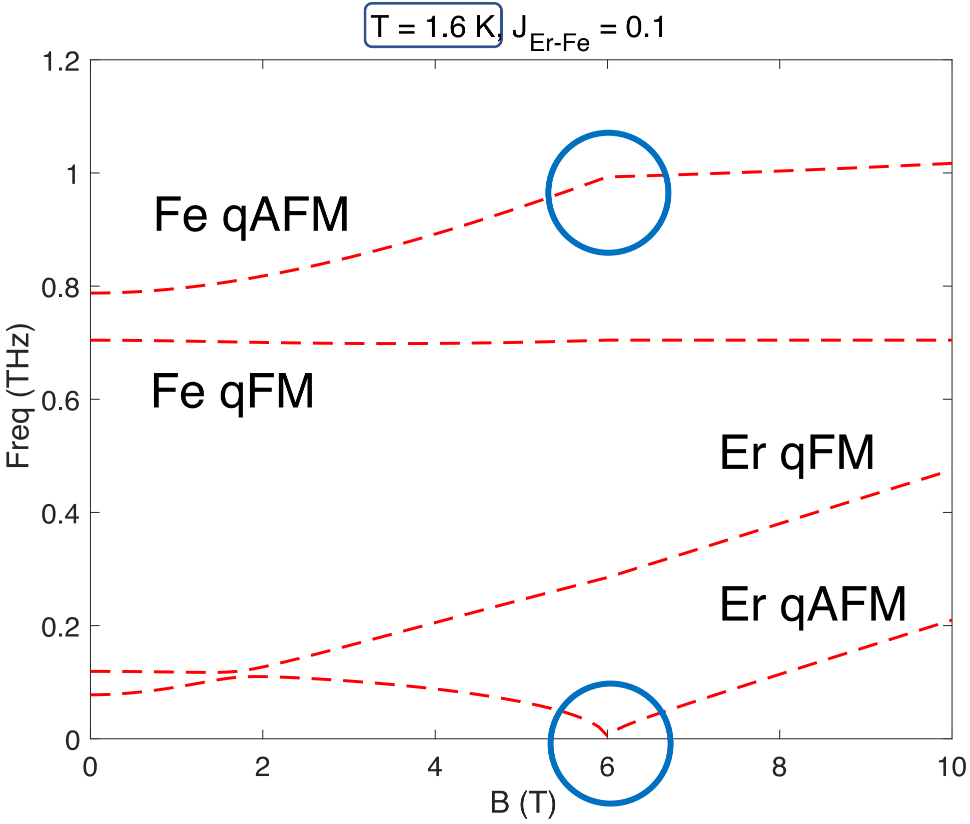
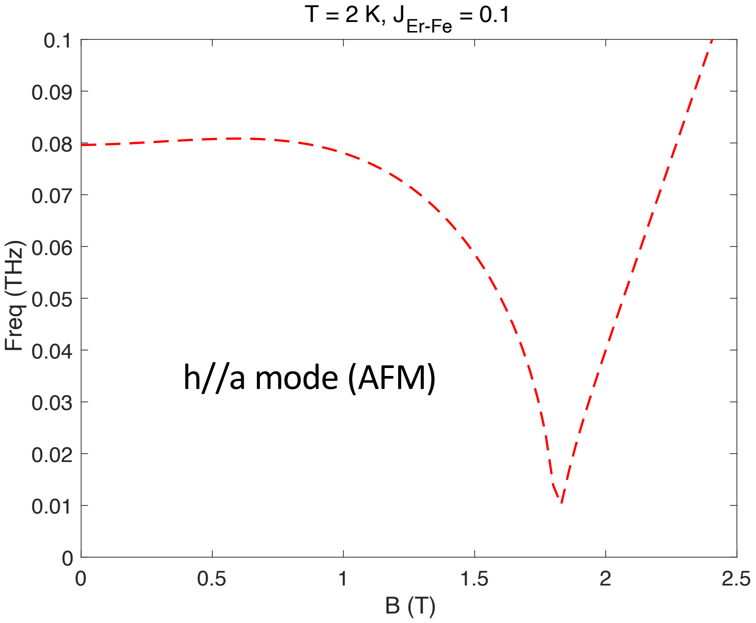
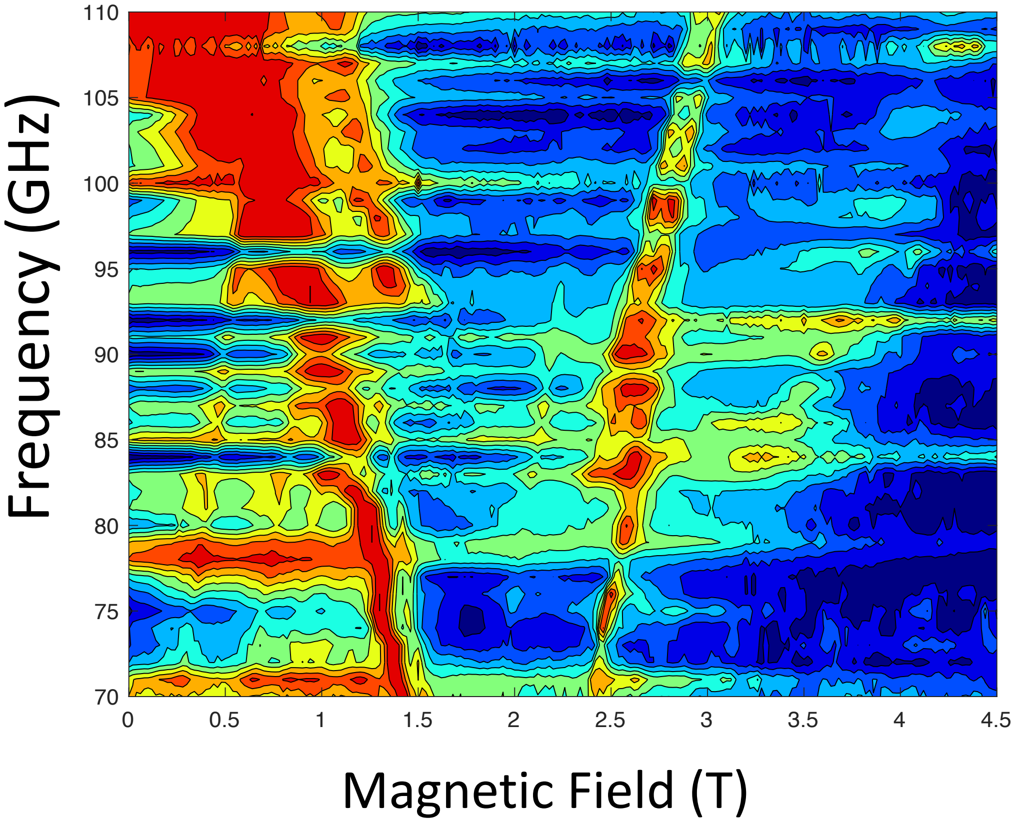




GHz Magnetospectroscopy at a Low Temperature

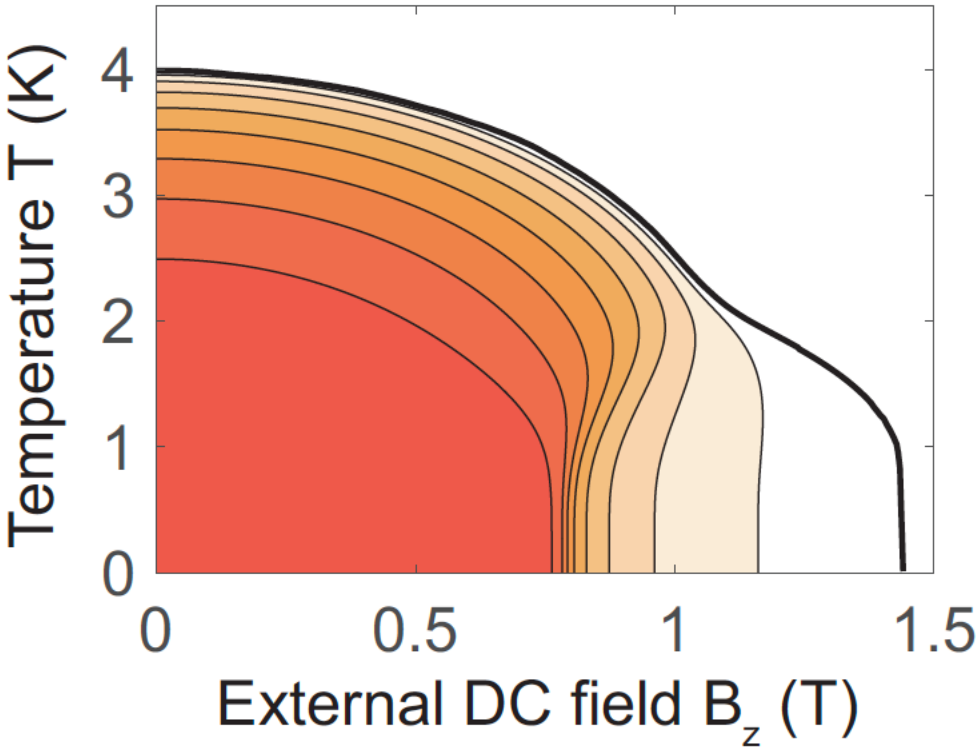




D. Kim *et al.*, unpublished

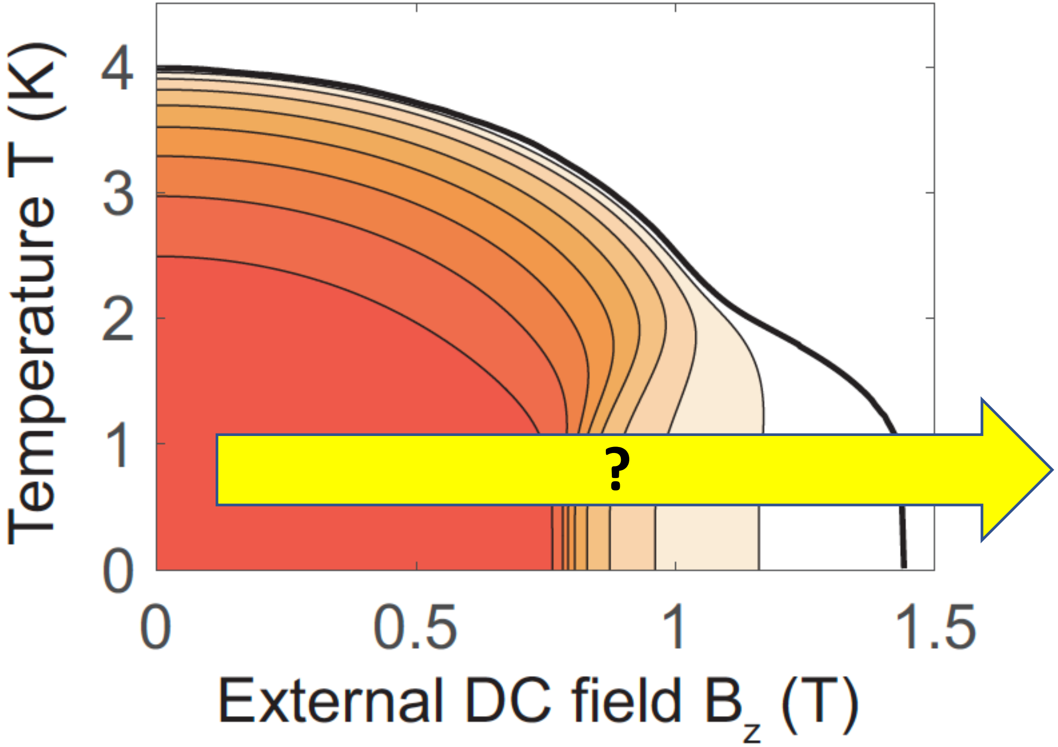
Phase Diagram When *B* // *z*

M. Bamba *et al.*, Communications Physics **5**, 3 (2022)

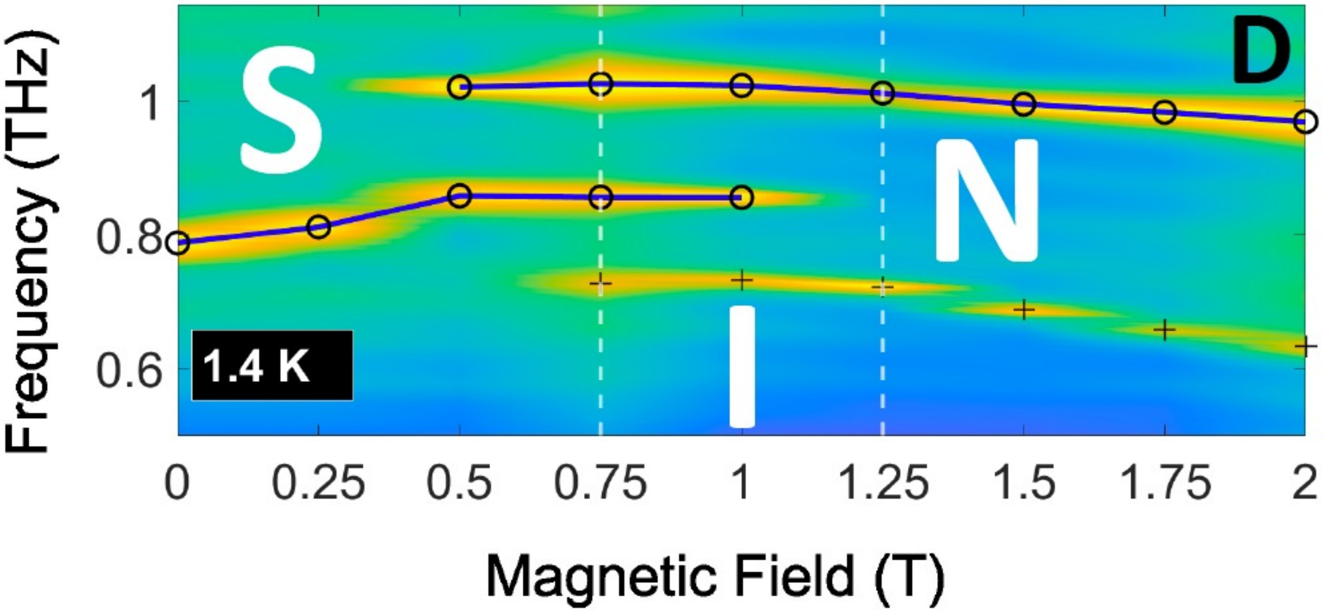


Phase Diagram When *B* // *z*

M. Bamba *et al.*, Communications Physics **5**, 3 (2022)



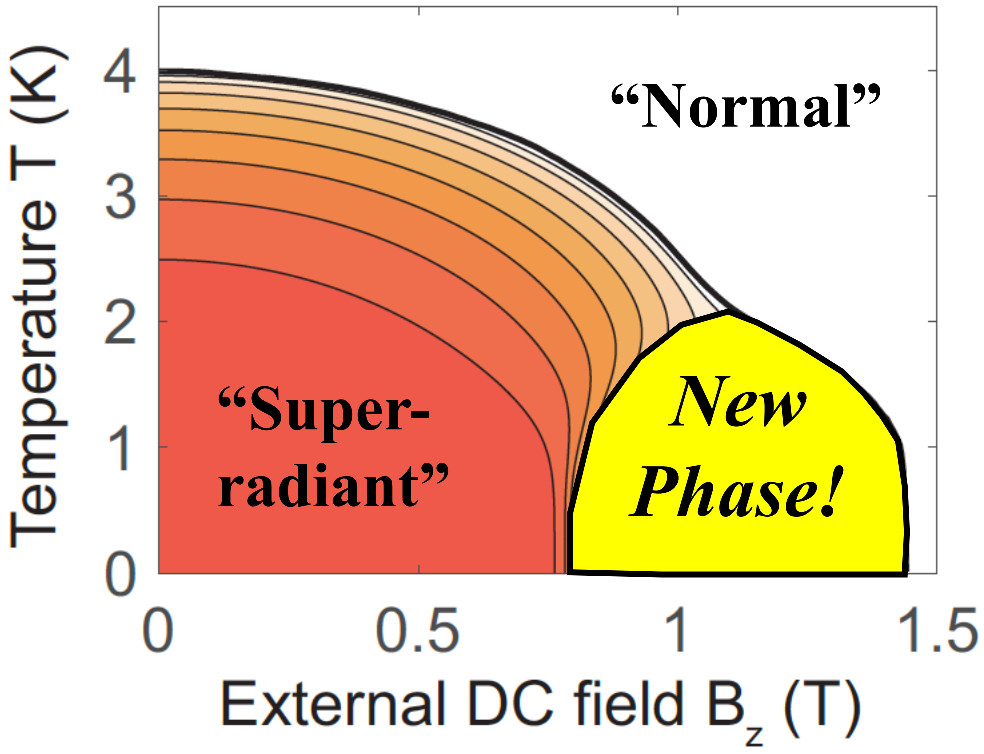
THz Magnetospectroscopy for B // z



N. Marquez Peraca *et al.*, arXiv:2302.06028

A New Phase Beyond SRPT When *B* // *z*

arXiv:2302.06028



A new phase beyond the superradiant phase transition description emerged!

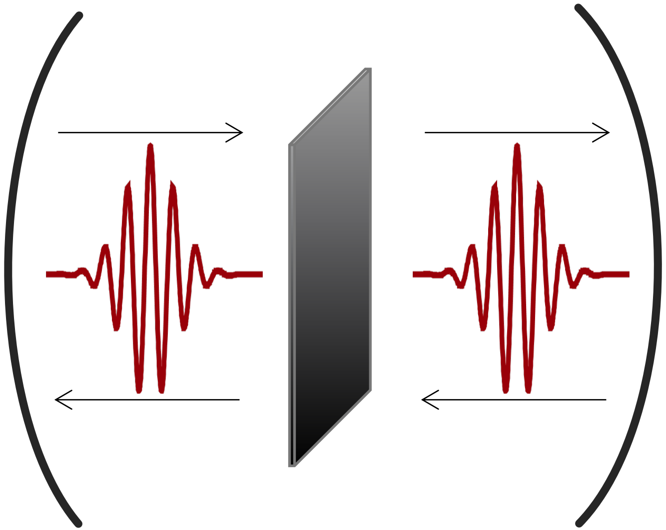
Outline

1. Landau polaritons in quantum Hall systems
2. Spin-photon ultrastrong coupling in a paramagnet
3. Spin-magnon ultrastrong coupling in an antiferromagnet
4. **Summary and outlook**

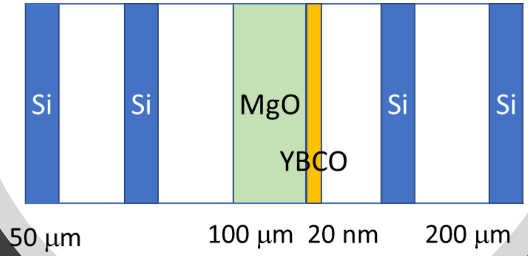
RICE
Unconventional Wisdom

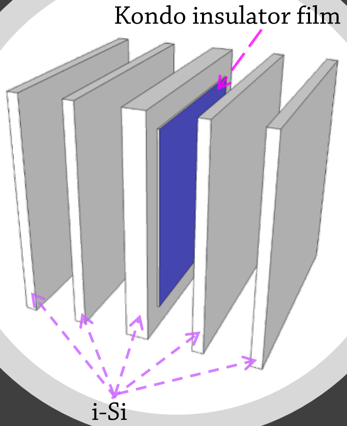
Cavity QED in Solids

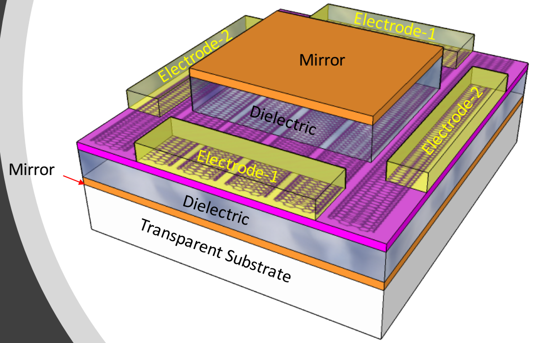
The marriage of quantum optics and condensed matter physics



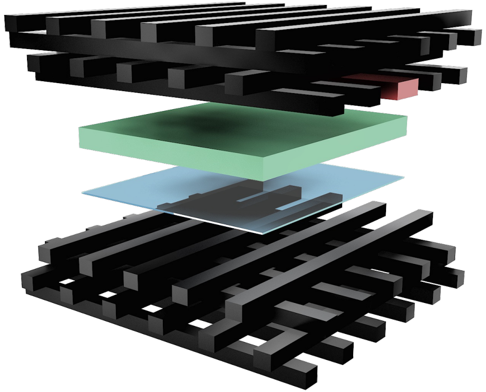
1. Large dipole moments → Ultrastrong light-matter coupling
2. Many electrons → Cooperative enhancement of coupling
3. Hybridization of matter with vacuum, or *zero-point*, fields
4. Nonintuitive modifications and control of materials by cavity photons







Designing novel cavities



ON-GOING

Probing superconductors, ferromagnets/antiferromagnets, carbon nanotubes, graphene, strongly correlated materials, … in cavities

Co-workers & Sponsors

Fuyang Tay, Dasom Kim, Nicolas Marquez Peraca, Hongjing Xu, Elijah Kritzell, Xinwei Li, Manu Manjappa & Andrey Baydin

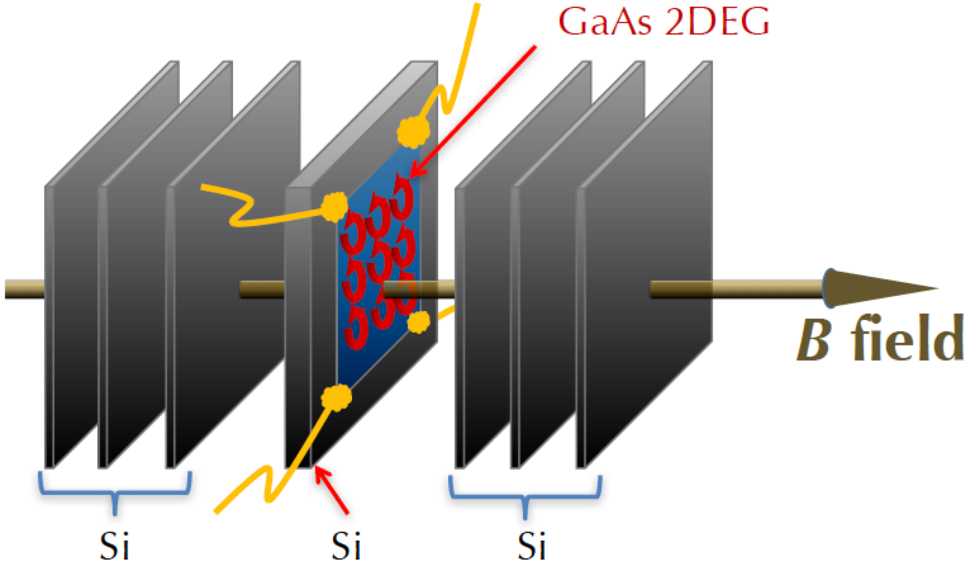
N. Yuan, M. Xiang, K. Xu, Z. Jin, W. Ren, G. Ma & S. Cao

Motoaki Bamba, Katsu Yoshioka, Ikufumi Katayama & Jun Takeda

David Hagenmüller

Shuang Liang, Geoff Gardener & Michael Manfra

Lightless photoconductivity: probing the influence of vacuum fluctuations on electronic transport in a cavity.



See also:

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- D. Hagenmüller *et al.*, Physical Review Letters **119**, 223601 (2017); Physical Review B **97**, 205303 (2018).
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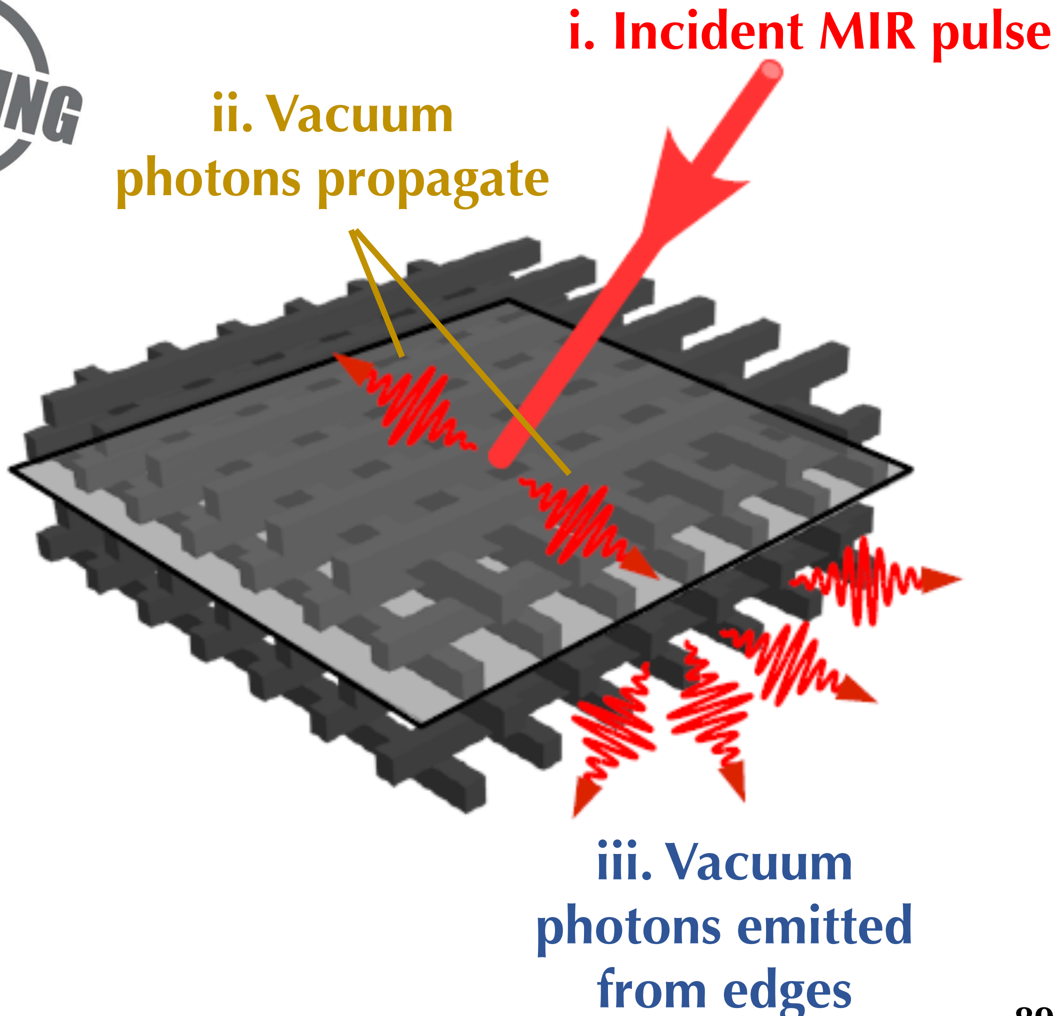
Quantum vacuum radiation: generating real photons out of vacuum via a quantum quench.

ON-GOING



Theory:

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- D. Hagenmüller, Physical Review B **93**, 235309 (2016).