Unlocking All Regimes of Light-Matter Interactions for Next-Generation Quantum Technologies

NAS Board on Physics and Astronomy
Spring 2025 Meeting

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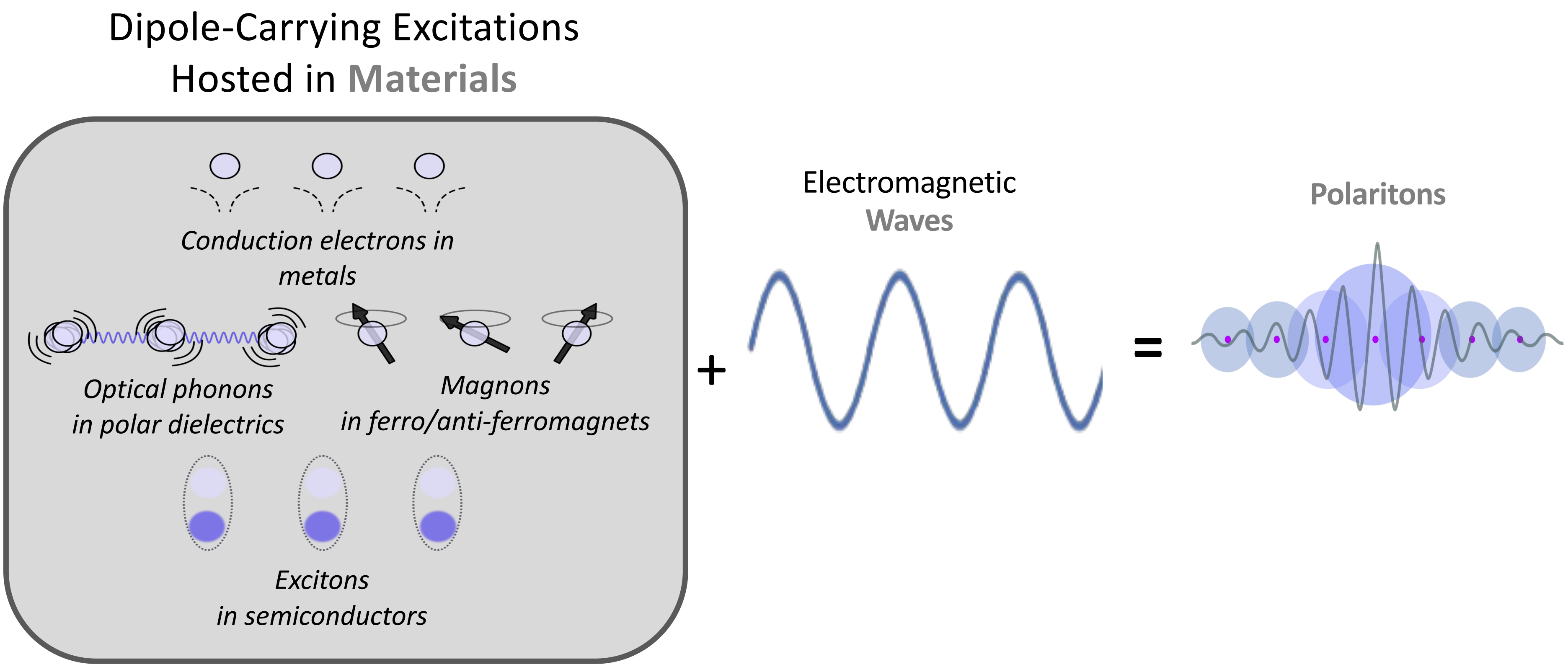
May 1, 2025

UF | Electrical & Computer Engineering
UNIVERSITY *of* FLORIDA

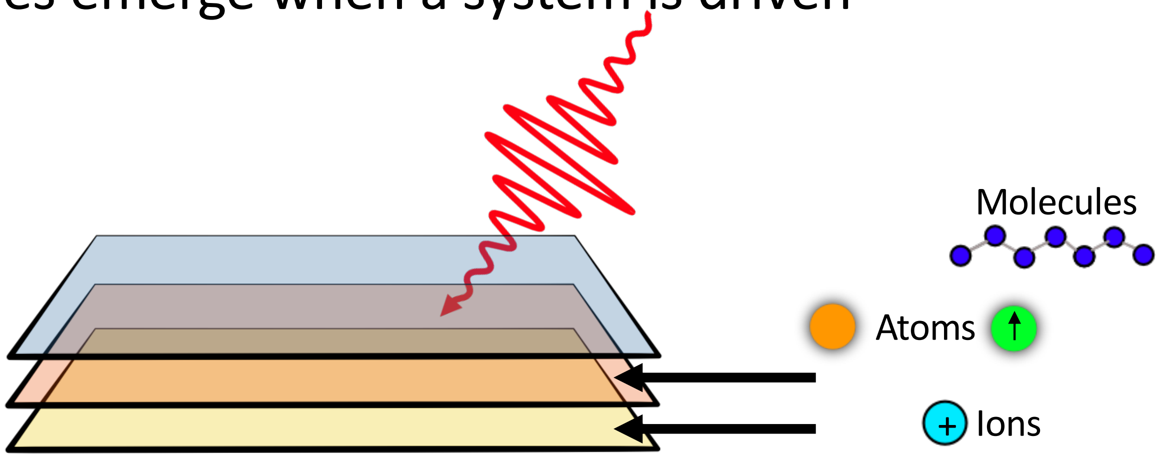
Engineering **Photons** in a Medium



Material-Driven Approach to Extreme Light-Matter Interactions

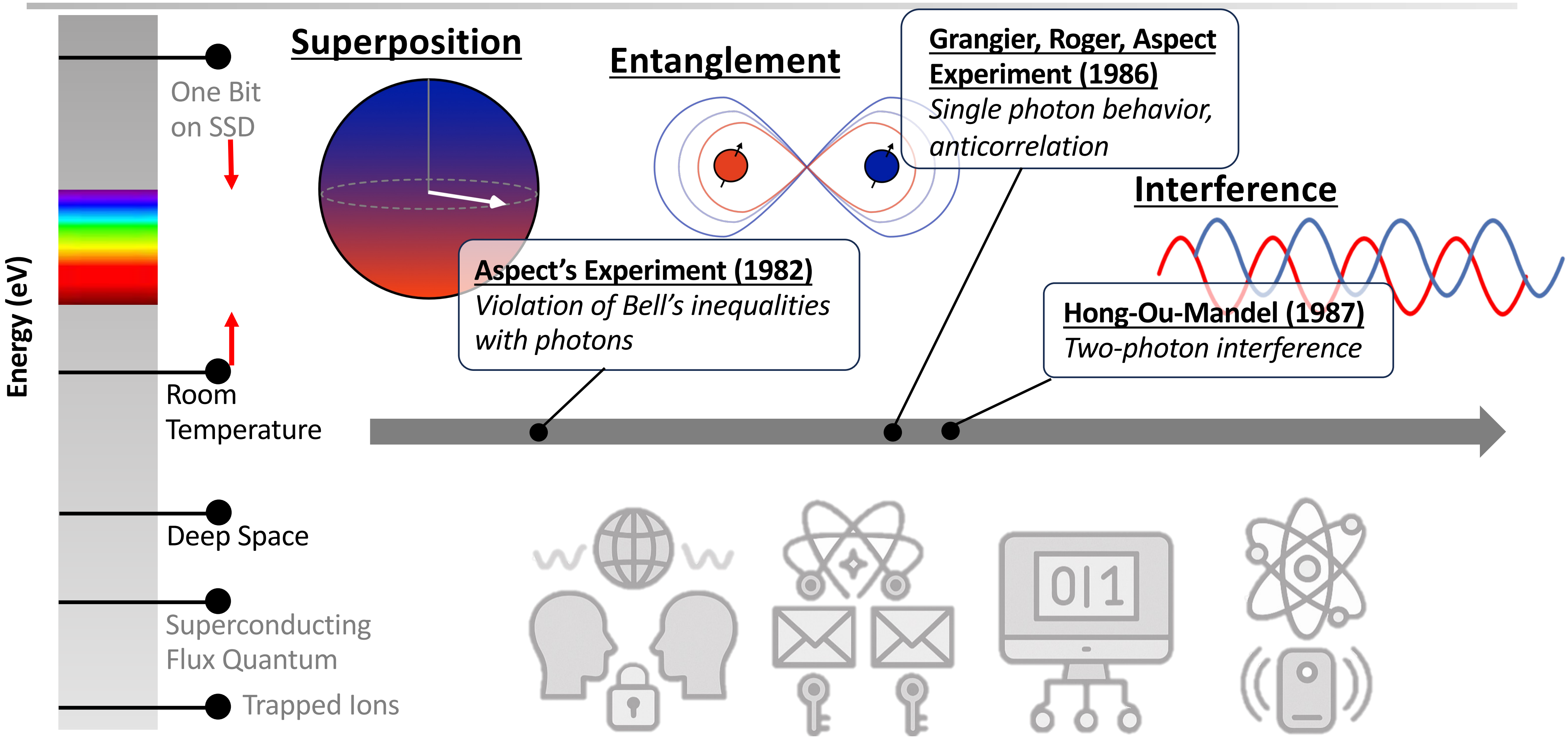
- Can material-driven photon engineering unlock new regimes of light–matter interactions?
- What new opportunities emerge when a system is driven out of equilibrium?

>1500 energetically stable 2D
>100 experimentally isolated



J. Zhou et al. *Scientific Data* 6, 86 (2019).

Why Light?



https://quantumcomputinginc.com/

Light-Matter Interaction Regimes

Weak Coupling	Strong Coupling (SC)		Ultra SC	Deep SC
$g \ll \kappa, \gamma$	g>>κ, γ	$g/\omega \lesssim 0.01$	$g/\omega \gtrsim 0.1$	$g/\omega \approx 1$

Adopted from
A. F. Kockum, …F. Nori. *Nat. Rev. Phys.* 1, 19-20 (2019).

Purcell Effect

Quantum Rabi Oscillations

Higher-Order and Non-Perturbative Effects

- Ultralow-threshold lasers
- Single-photon sources

Quantum 1.0 Technologies

Light-Matter Interaction Regimes

Weak Coupling	Strong Coupling (SC)		Ultra SC	Deep SC
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Purcell Effect

- Ultralow-threshold lasers
- Single-photon sources

Quantum 1.0 Technologies

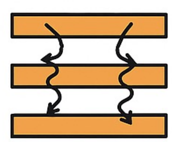
Quantum Rabi Oscillations

Higher-Order and Non-Perturbative Effects

Harnessing the *Quantumness* of Light

Quantum 2.0

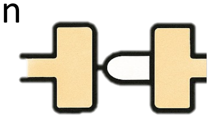
- Deterministic photon-photon interactions
- Nonlinearity at single-photon level



Polaritons

Ciuti, C., Bastard, G. & Carusotto,
Phys. Rev. B **72**, 115303 (2005).

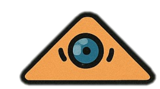
- Quantum vacuum emission



SC circuits

Niemczyk, T. et al. *Nat. Phys.* **6**, 772 (2010).
Forn-Díaz, P. et al. *Phys. Rev. Lett.* **105**, 237001 (2010).

- Virtual photon engineering
- Light-matter decoupling

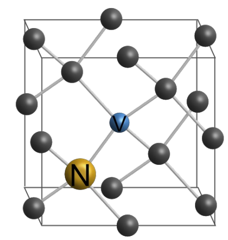


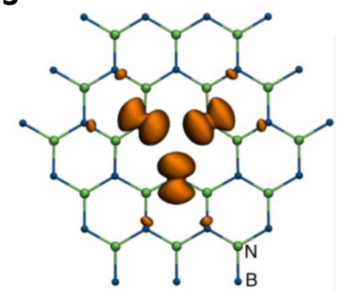
Quantum dots

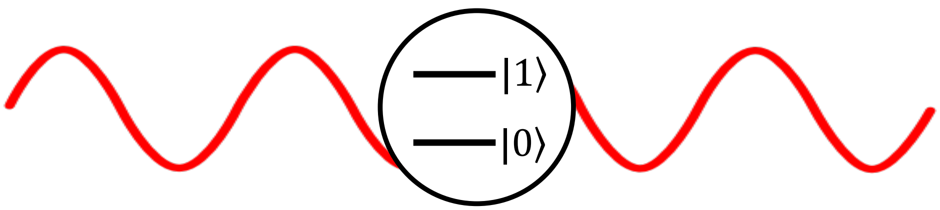
Anappara, A. A. et al. *Phys. Rev. B* **79**, 201303 (2009).

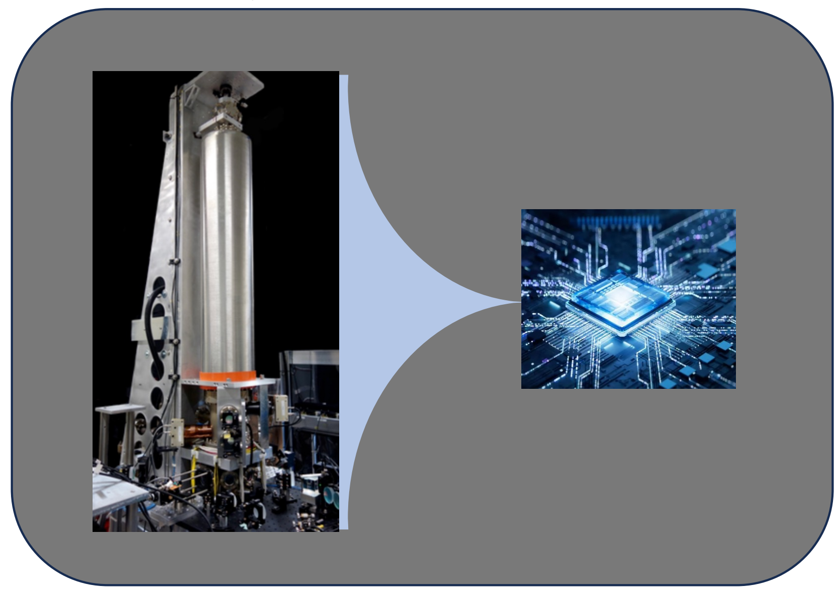
Cavity Quantum Electrodynamics (QED)

Atom-like systems
In solid-state





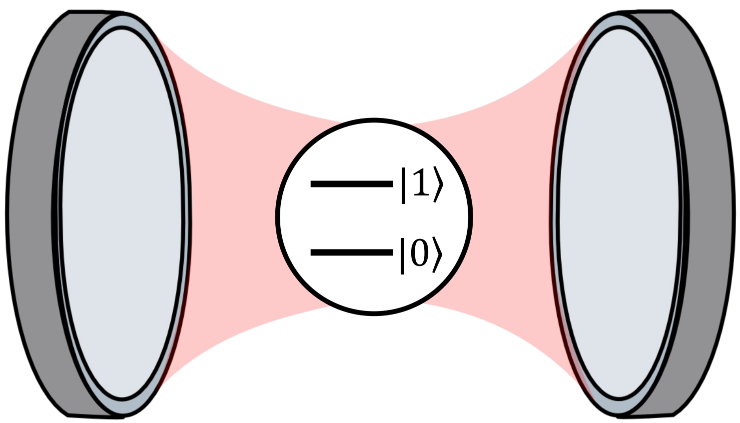




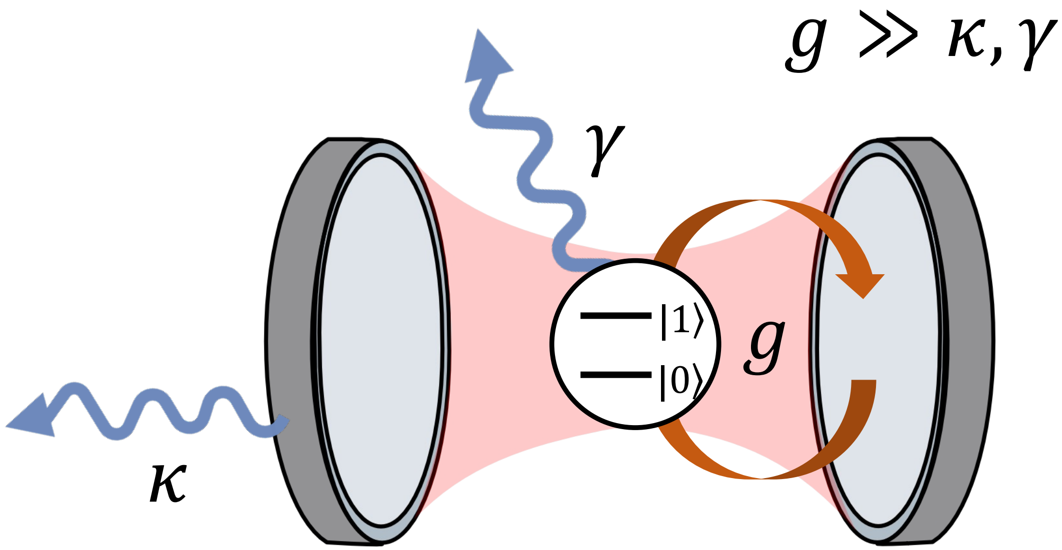
Fine structure constant

$$\boldsymbol{\alpha} \approx \frac{\mathbf{1}}{\mathbf{137}}$$

Cavity Quantum Electrodynamics (QED)

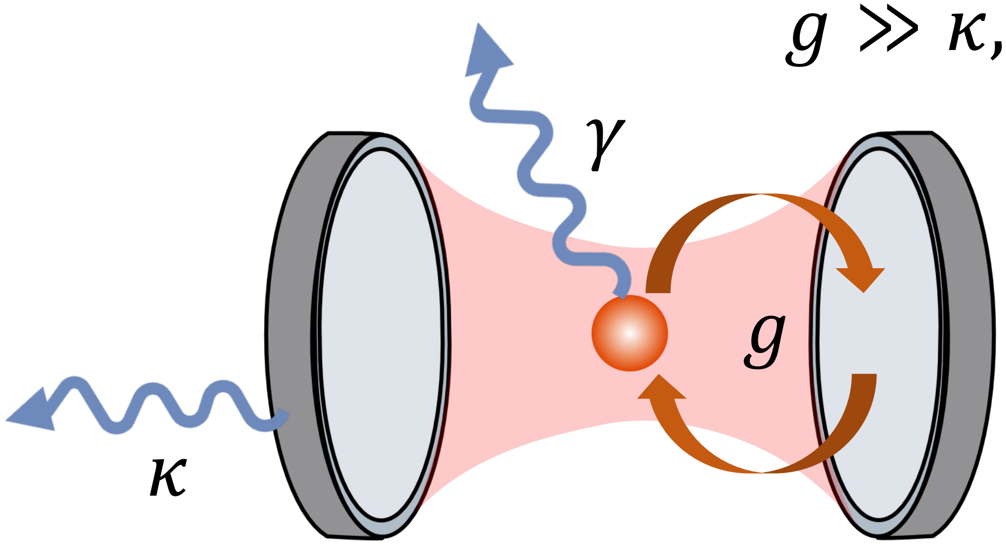


Cavity QED

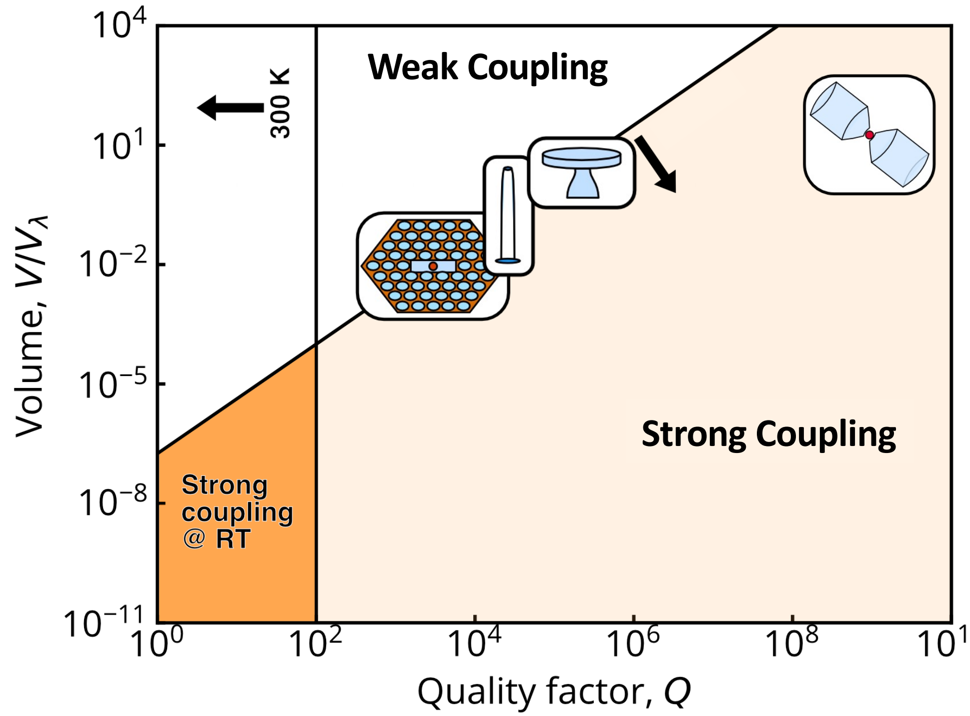


Cavity QED

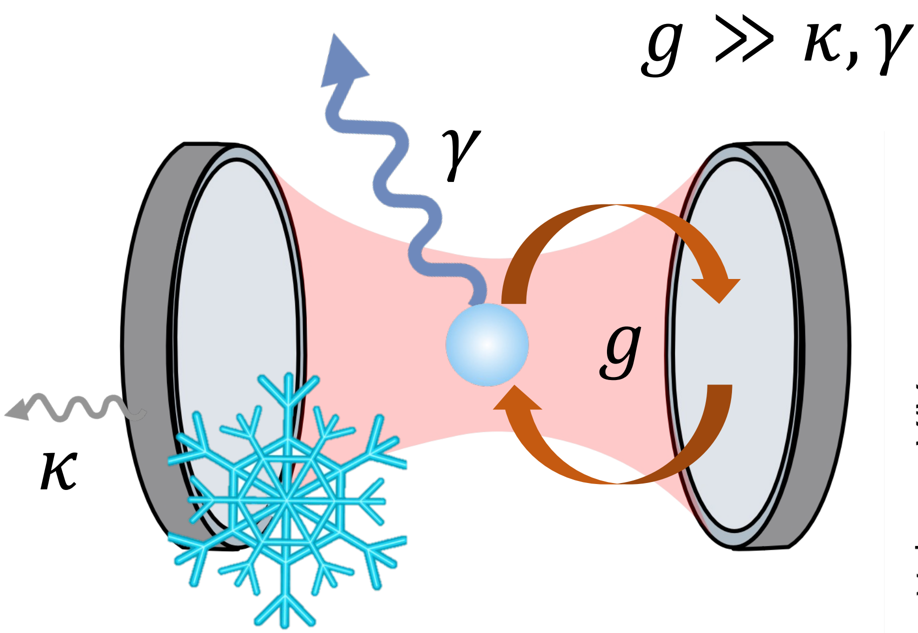
$$g \gg \kappa, \gamma$$



Adopted from
R. Chikkaraddy, …,J. Baumberg. Nature 535, 127-130 (2016).



Cavity QED



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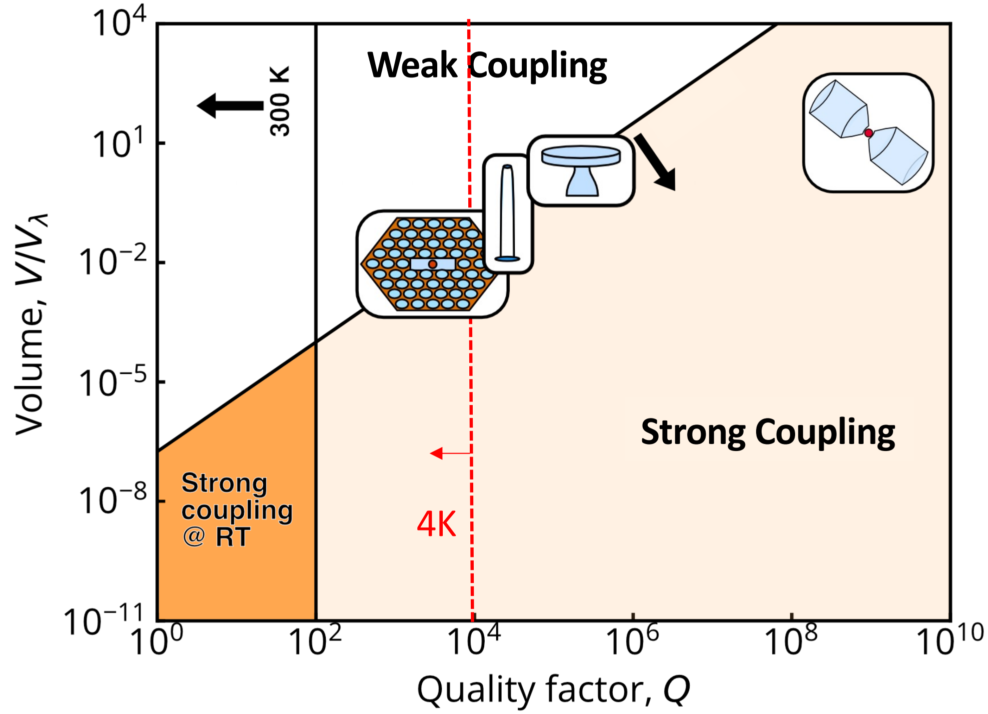
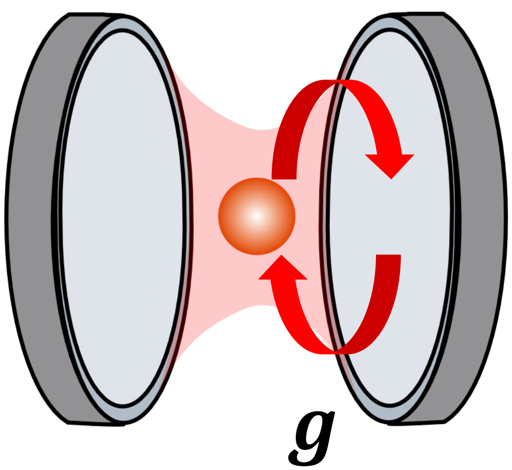
R. Chikkaraddy, …,J. Baumberg. Nature 535, 127-130 (2016).



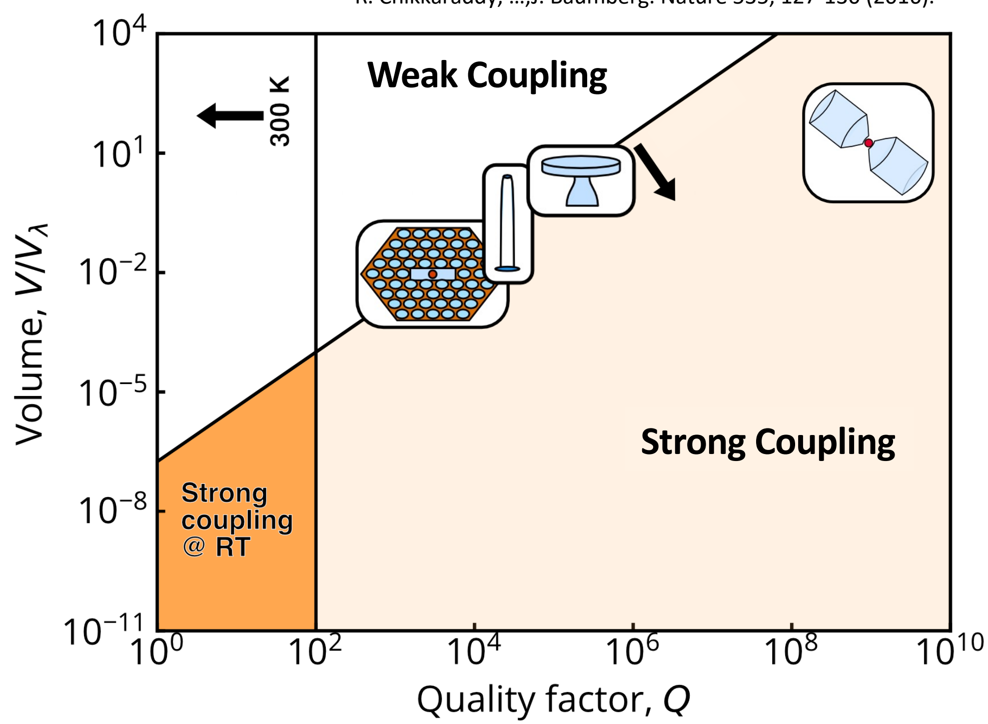
Cavity QED

$$g \gg \kappa, \gamma$$

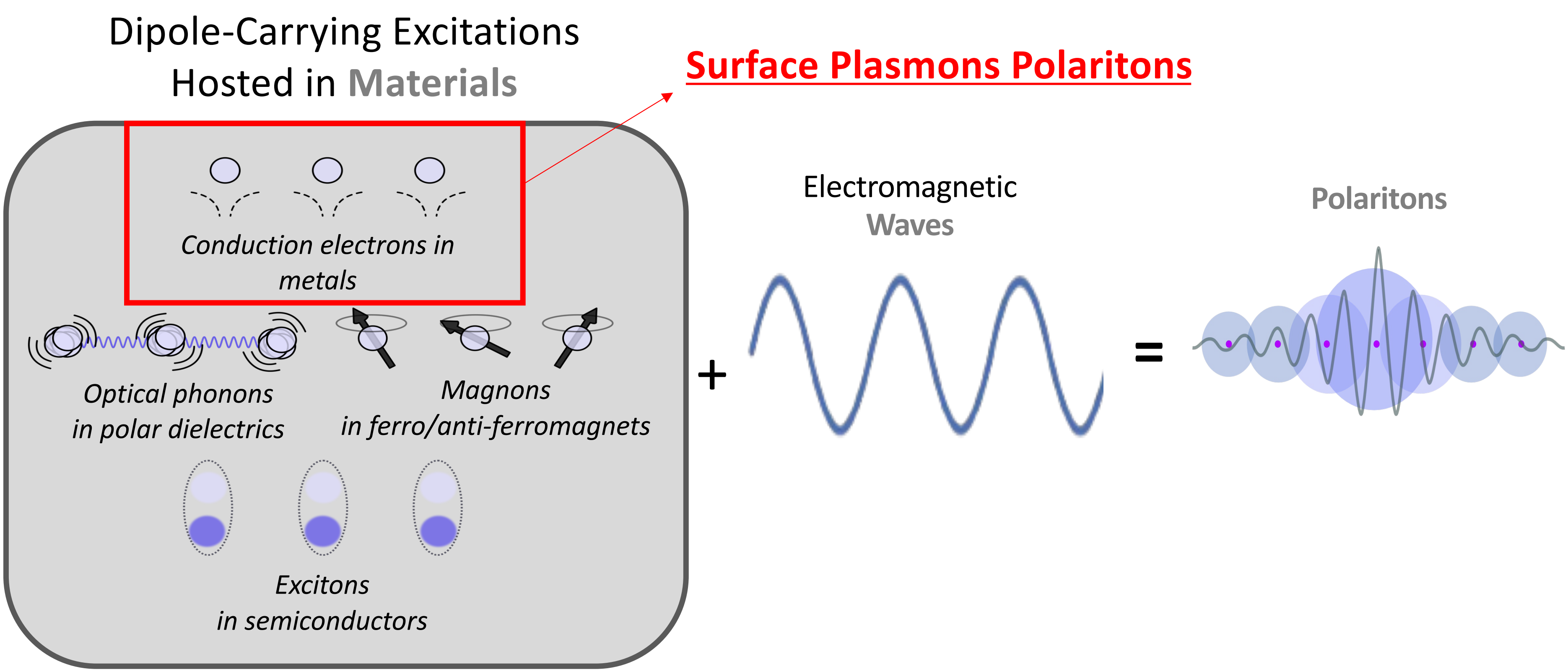
$$g \propto \frac{1}{\sqrt{V}}$$



Adopted from
R. Chikkaraddy, …,J. Baumberg. Nature 535, 127-130 (2016).

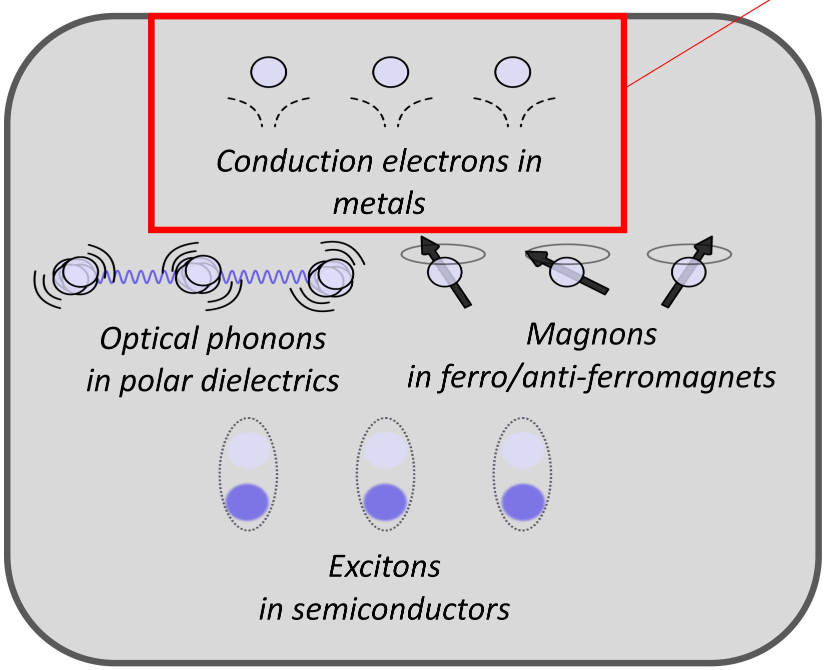


Engineering Photons in a Medium

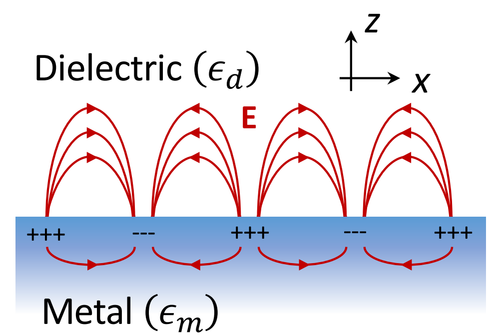


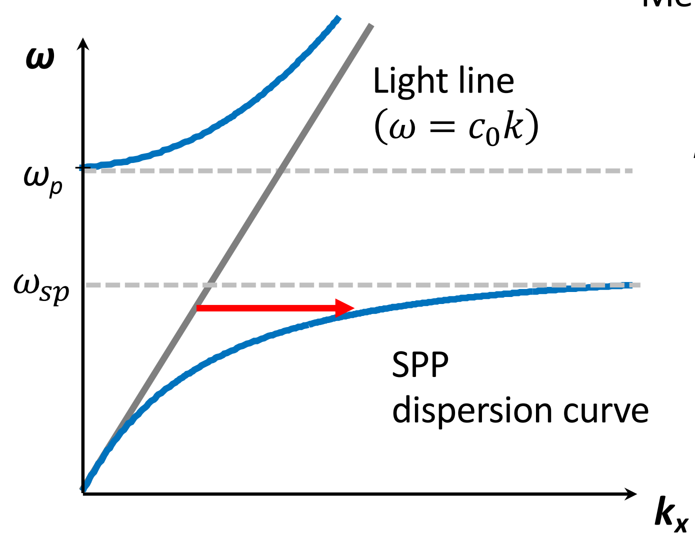
Surface Plasmon Polaritons (SPPs)

Dipole-Carrying Excitations
Hosted in **Materials**



Surface Plasmons Polaritons

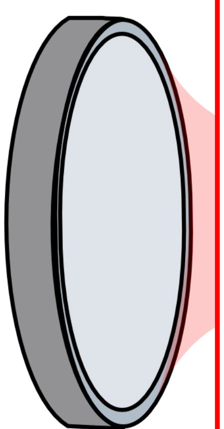


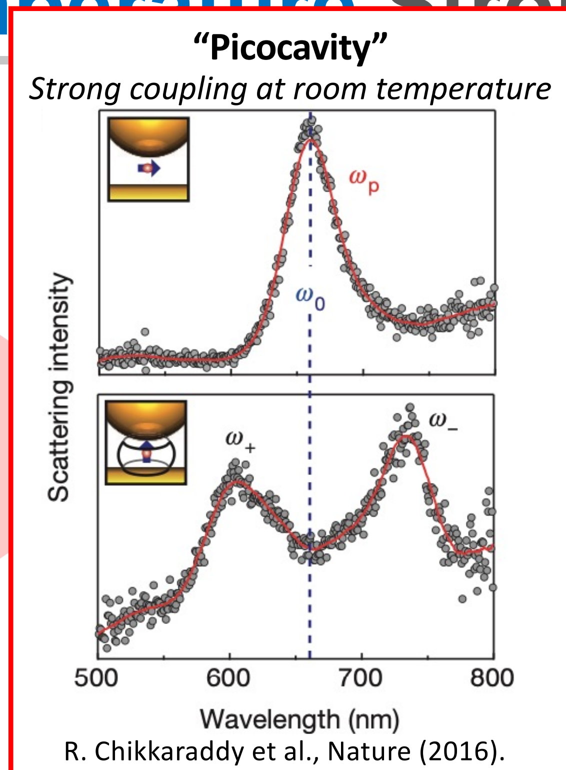


$$k_x = \frac{\omega}{c}\sqrt{\frac{\epsilon_m \epsilon_d}{\epsilon_m + \epsilon_d}}$$

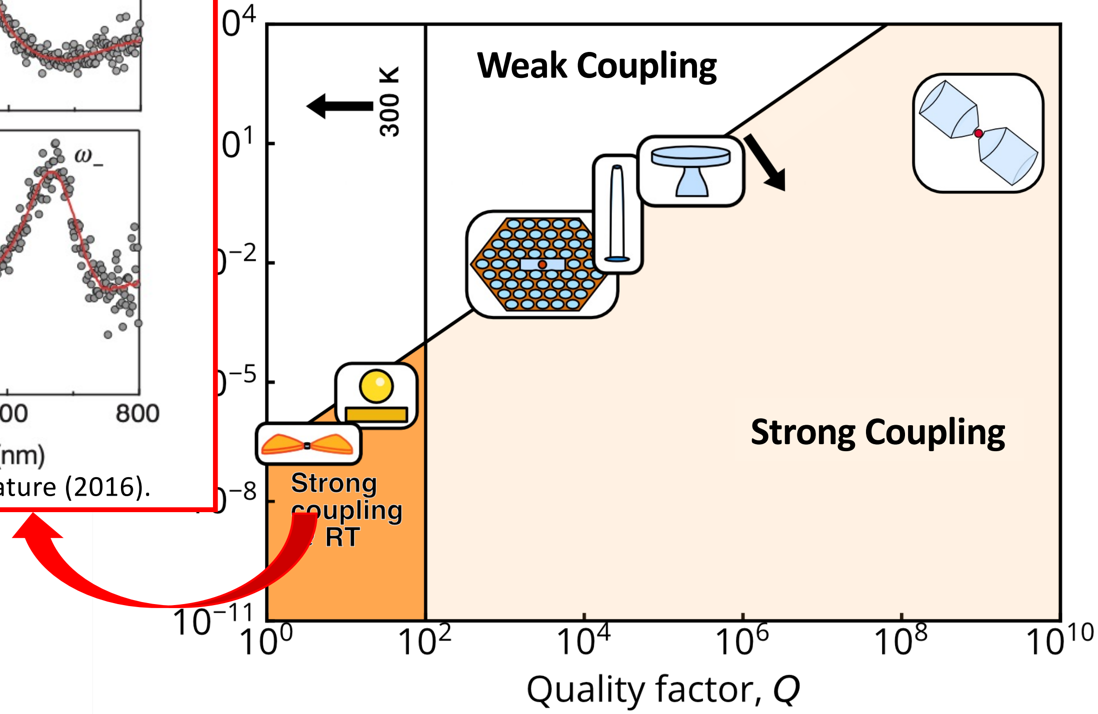
Room-Temperature Strong Coupling

$$g \propto \frac{1}{\sqrt{V}}$$





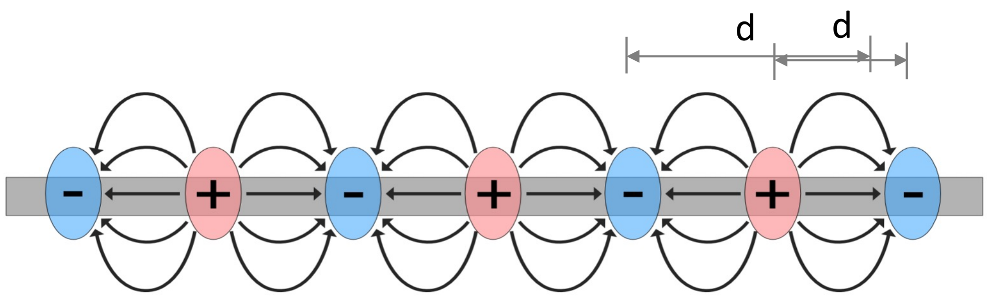
Adopted from
R. Chikkaraddy, …,J. Baumberg. Nature 535, 127-130 (2016).



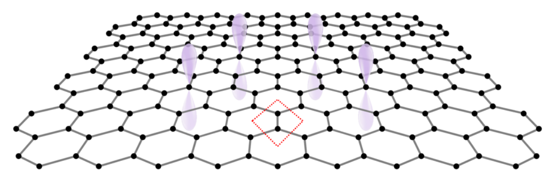
Flatland Plasmonics for Low Loss and Higher Confinement

Oscillation frequency depends on restoring force

$\omega \propto \sqrt{K} \leftarrow$ 'spring' constant



$K \propto \frac{1}{d}$

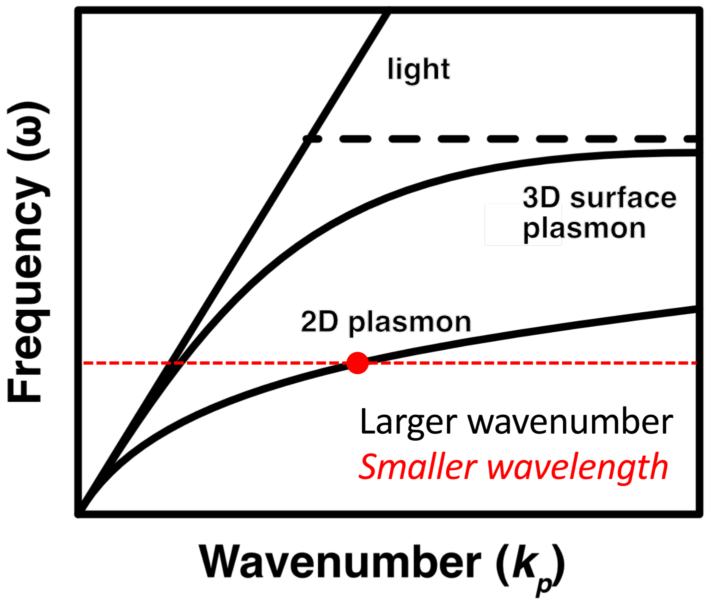


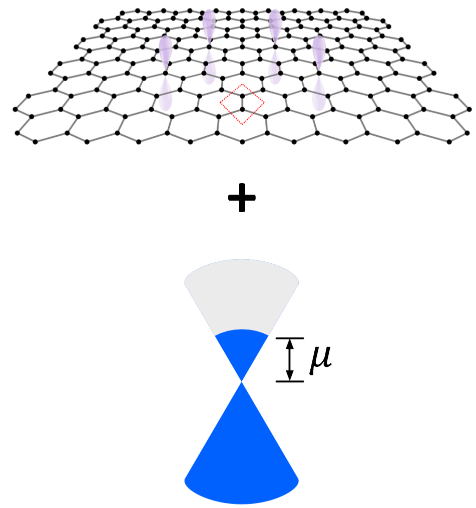
Graphene is an ultimate limit of this trend.

Thinner metallic layer → Smaller wavelength

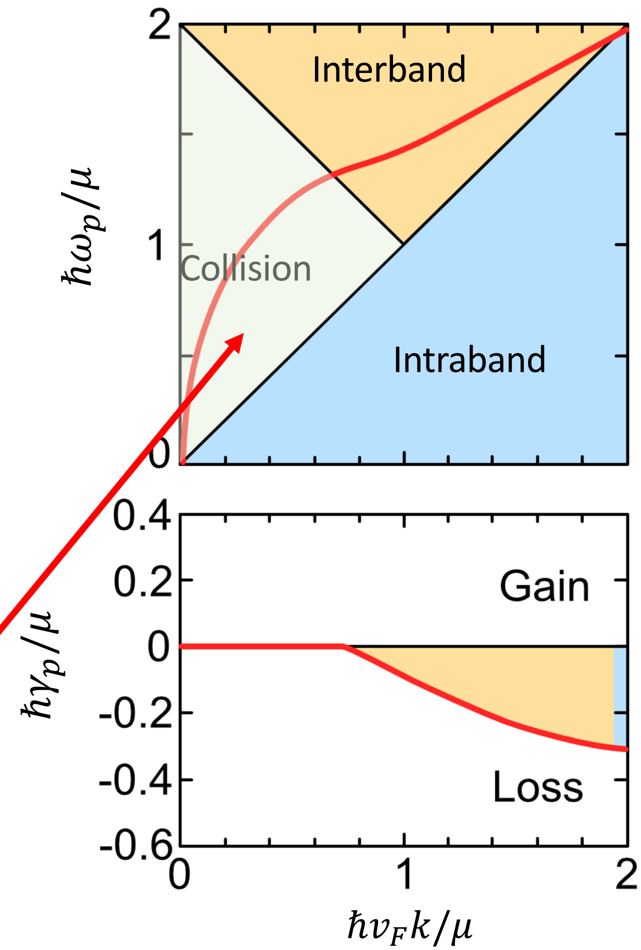
V. Brar, et al. *Nano Lett*. 14, 3876–3880 (2014).
M. Jablan, et al. *PRB* (2009).
V. Brar, et al. *Nano Lett*. 13, 2541-2547 (2013).

Plasmon Excitations Bound on 2D





2D Dirac Plasmons



$$L_k = \frac{\pi\hbar^2}{e^2} \times \frac{1}{E_F} \times \frac{1}{W}$$

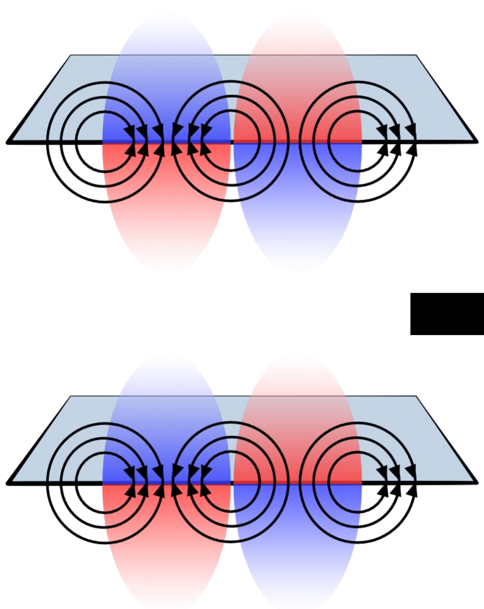
Vs.

$$L_{k,3D} = \frac{3\pi^2\hbar^2}{2e^2} \times \frac{1}{E_F} \times \frac{1}{W} \times \frac{1}{k_F\delta}$$

Gate-**Tunable**
Loss-less Region

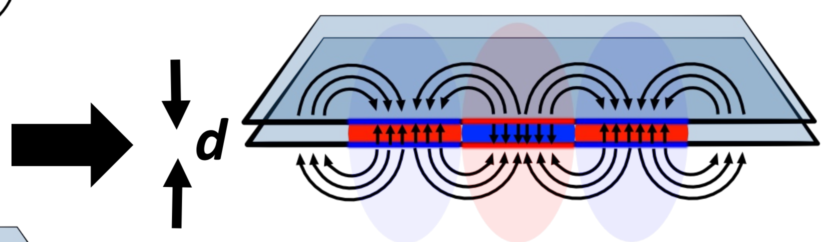
Yoon, Hosang, et al. *Philos. Trans. Royal Soc. A. (2014).*

Acoustic Plasmons – Extreme Confinement



$$\omega = \sqrt{\frac{e^2 E_F}{2\epsilon\pi\hbar^2} k_p}$$

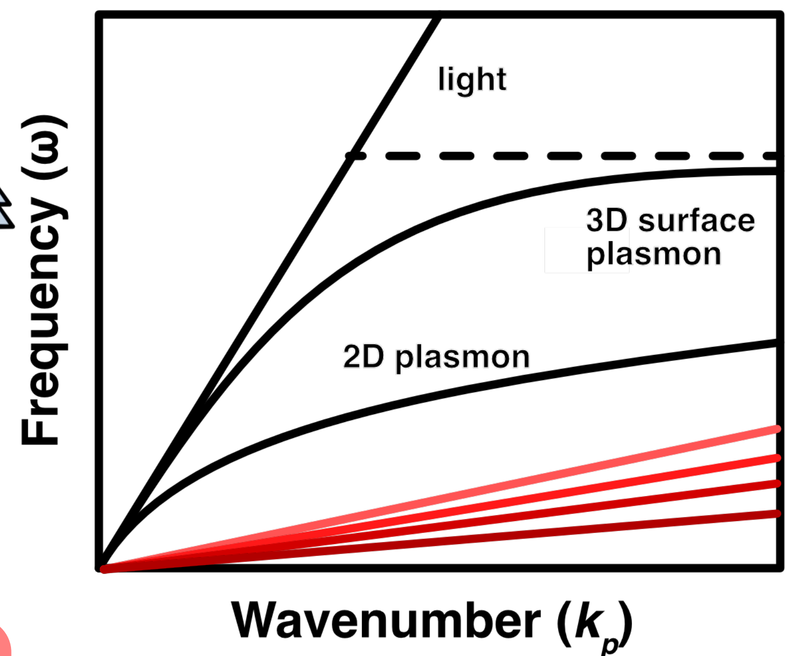
Layered 2D conductors



$$\omega = k_p \sqrt{\frac{e^2 E_F d}{\epsilon\pi\hbar^2}}$$

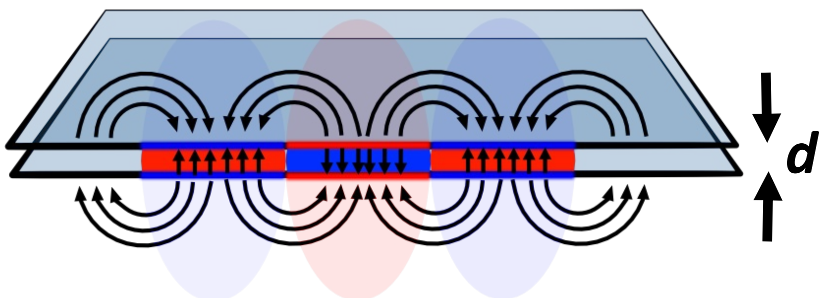
$\boldsymbol{d}$ → one atom thick

"Ultimate mode volume limit"

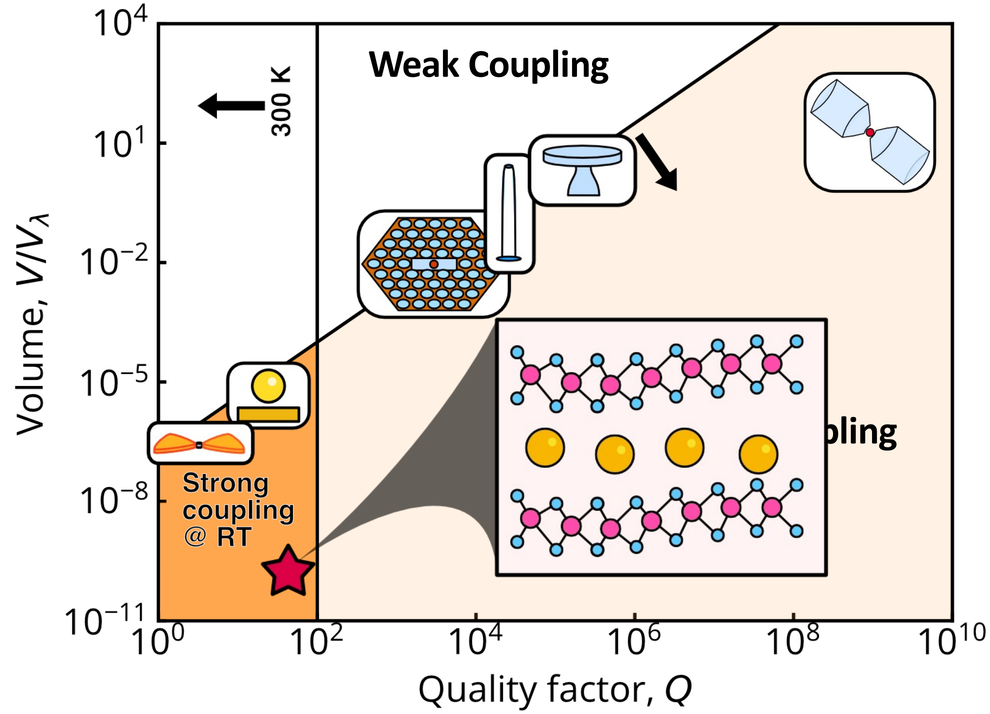


Scalable RT Quantum Technology Platform

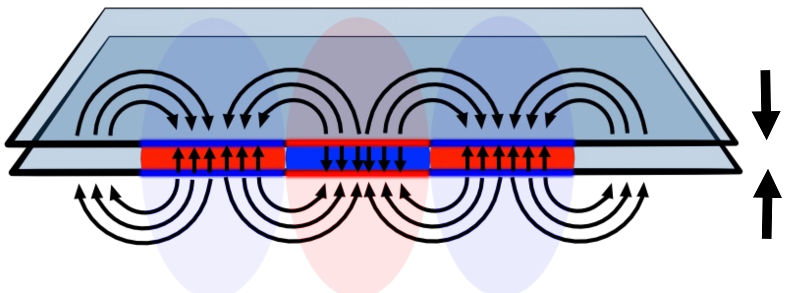
"Ultimate mode volume limit"



Emitter-Cavity architecture entirely constructed from 2D systems

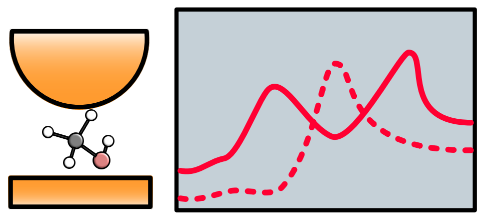


Nonlocality at the Atomic Scale

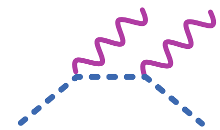


Gateway to
New Quantum
Optical Phenomena

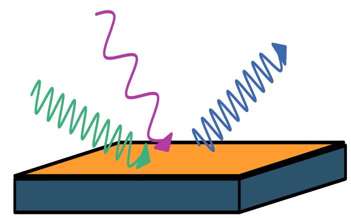
Single-Molecule Chemistry
Quantum Chemistry



Higher order processes of QED

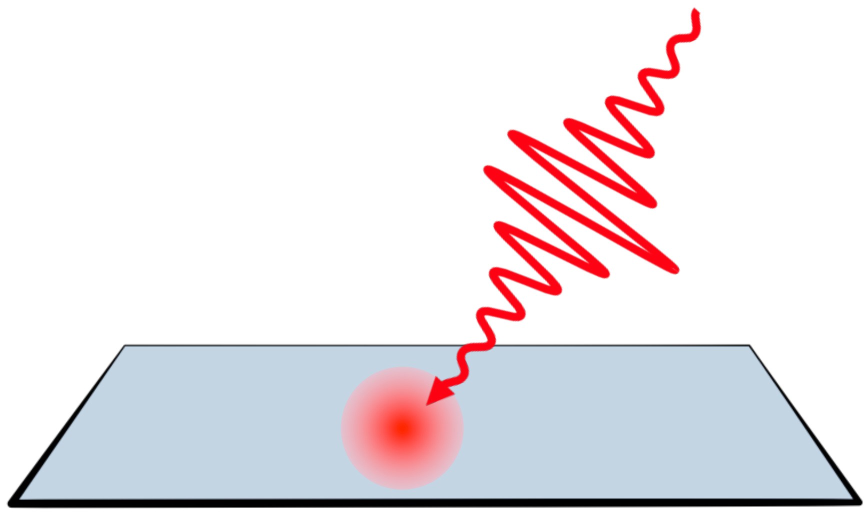


Two-plasmon emission process

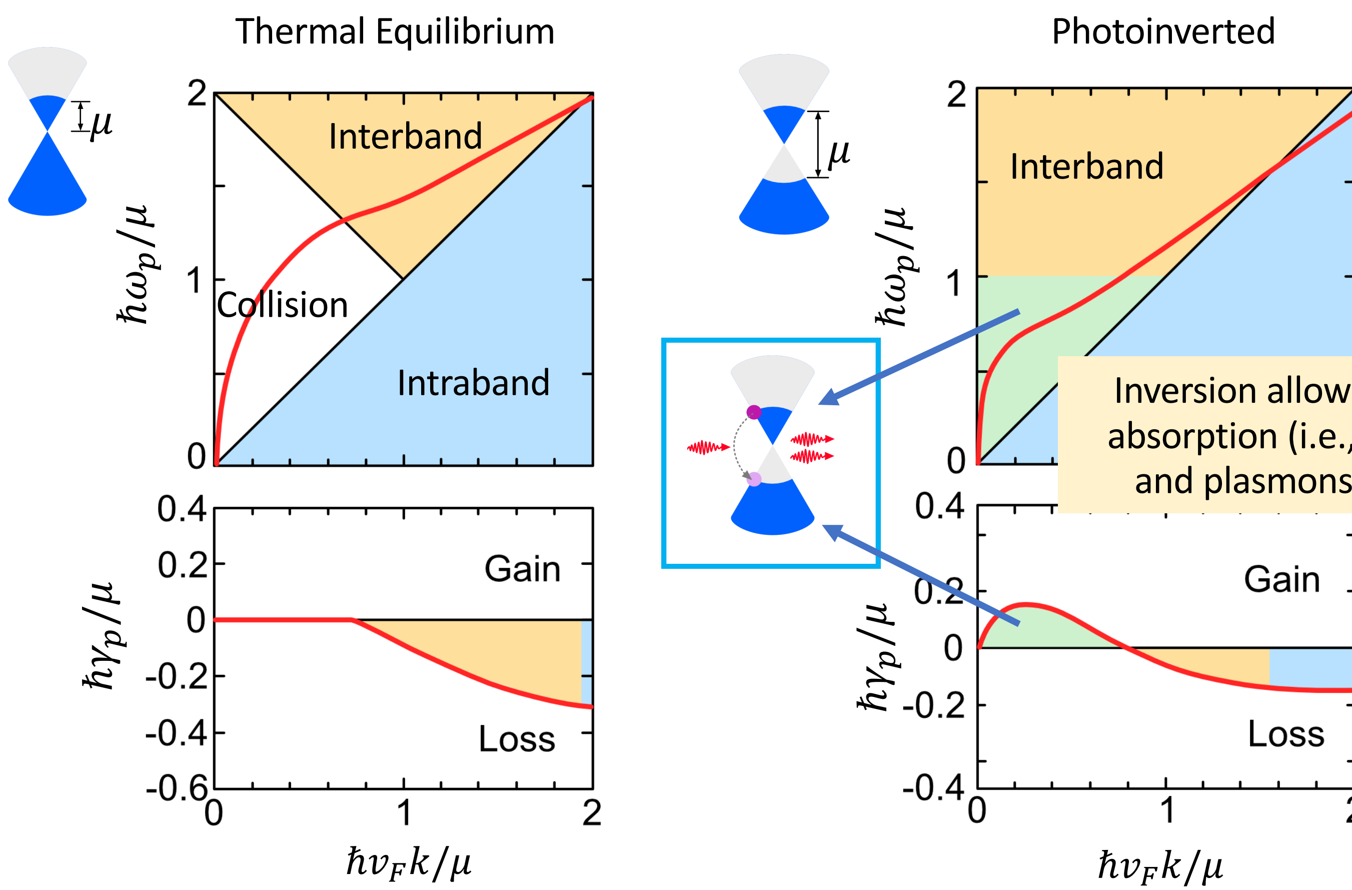


Sensitive probes of electron dynamics

Materials Driven Out Of Equilibrium

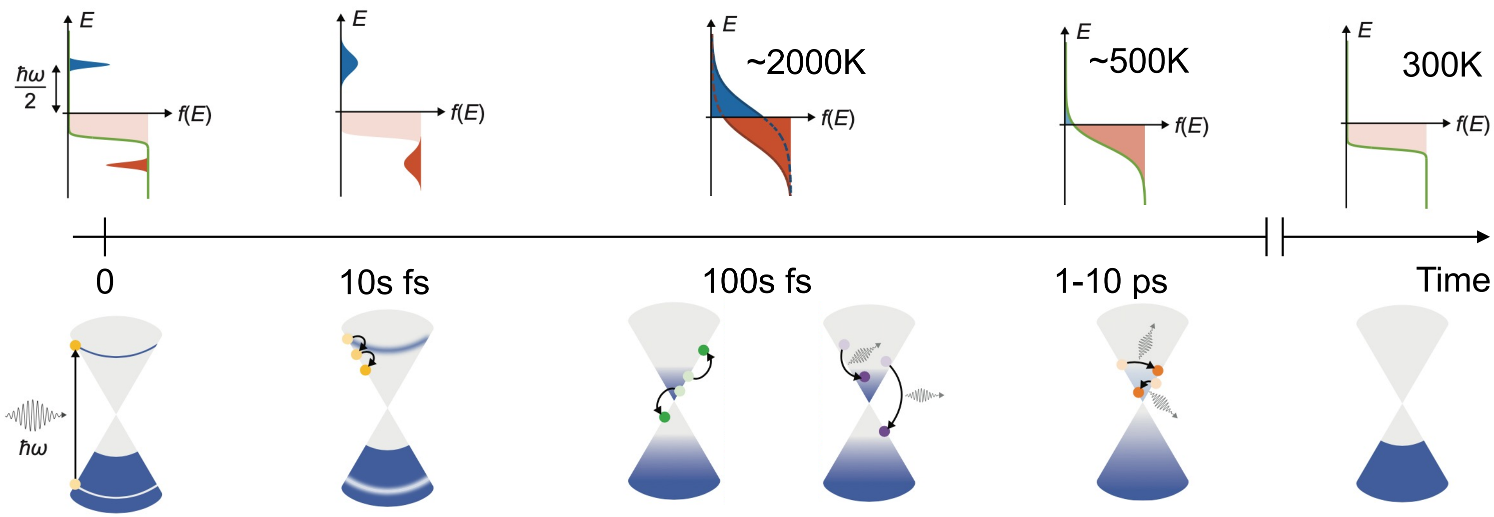


From Mitigating Loss to Generating Gain



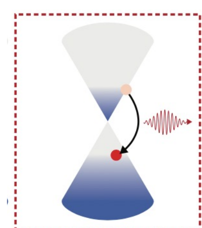
Inversion allows a reversal process of absorption (i.e., stimulated emission), and plasmons can experience **gain**

Plasmon Emission, Overlooked Decay Pathway

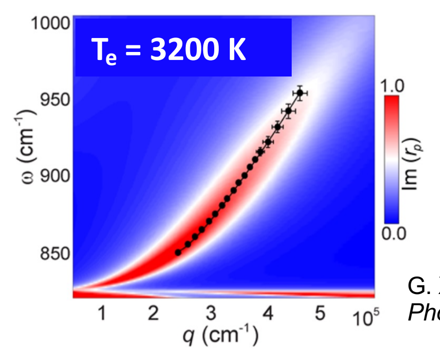


Theoretically predicted, but experimentally overlooked decay pathway!

F. Rana et al. *PRB* (2010).
J. M. Hamm et al. *PRB* (2016).
F. A. Page et al. *PRB* (2015).



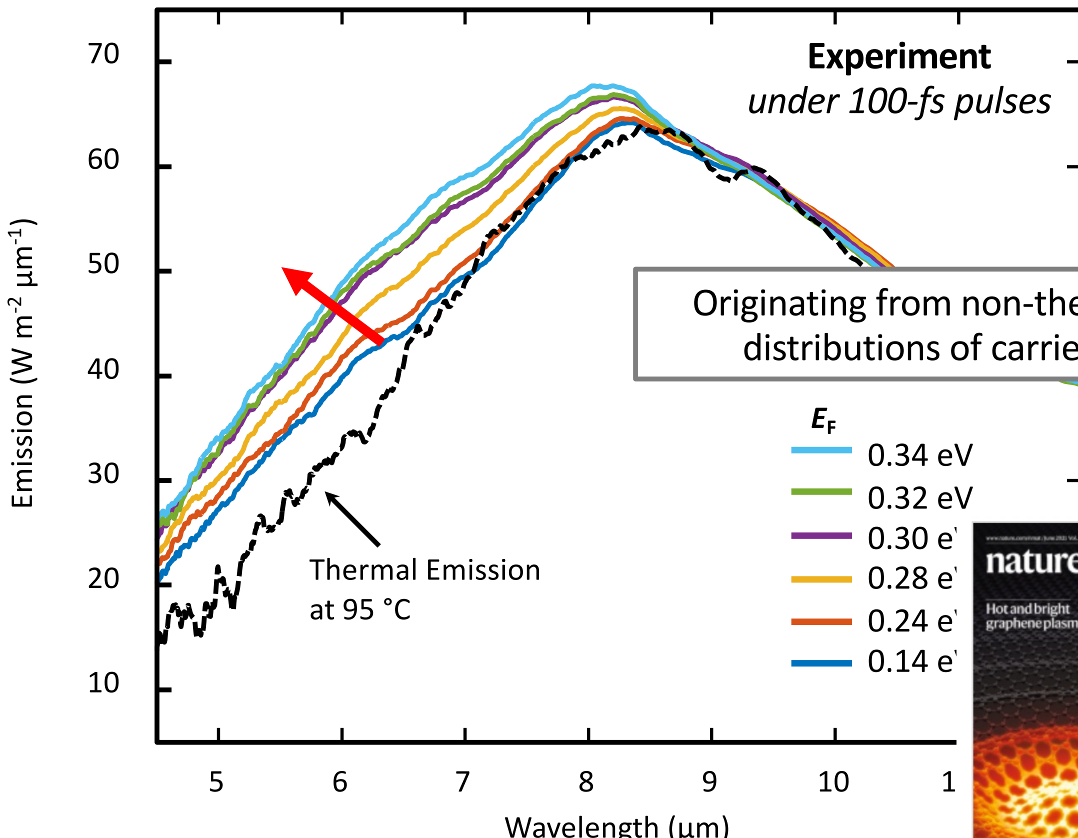
Plasmon Emission



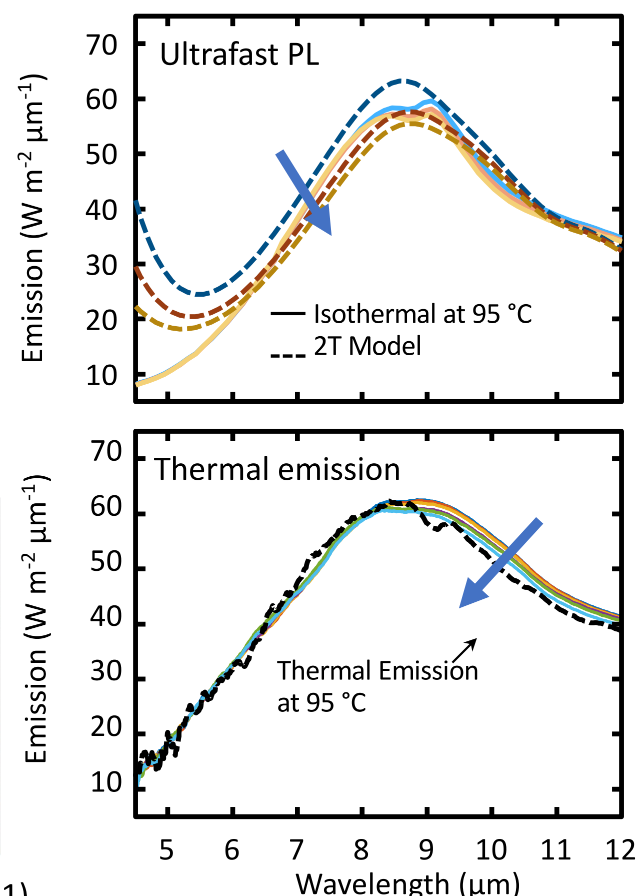
G. X. Ni et al. *Nat. Photonics* (2016).

S. A. Jensen et al. *Nano Lett.* (2014).
I. Gierz, *Nat. Mater.* (2013).
L. M. Malard et al. *N. J. Phys.* (2013).
B. Y. Sun et al. *PRB* (2012).
M. Breusing et al. *PRB* (2011).
A. Tomadin et al. *Sci. Adv.* (2018).

"Hot Plasmons Make Graphene Shine"

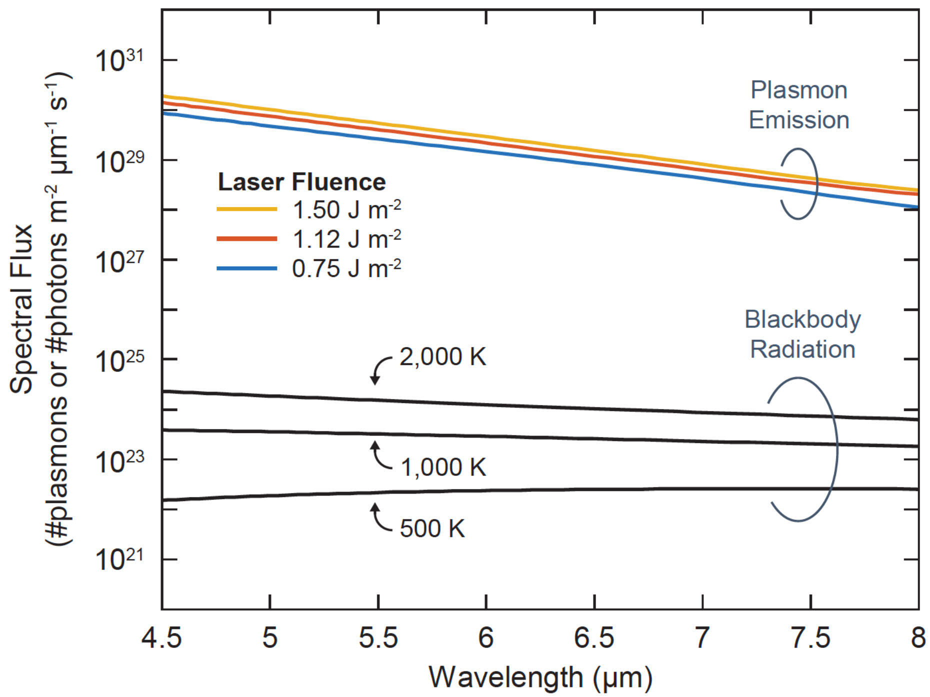


Planckian Emission Mechanisms



L. Kim et al. *Nat. Mat.* (2021).

Bright Emission Through Hot Plasmons

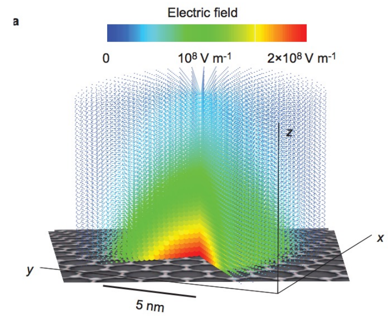


Spontaneous Emission of Photons vs. Plasmons

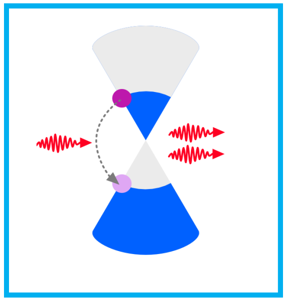
- Several orders of magnitude higher flux than blackbody radiation at several 1000s of Kelvins

L. Kim et al. *Nat. Mater.* (2021).

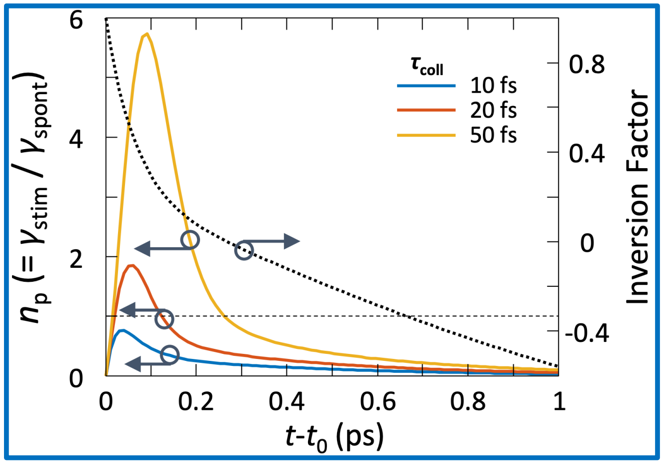
Coherent Amplification of Plasmons



V. Apalkov and M. Stockman. *Light: Science & Applications* (2014).

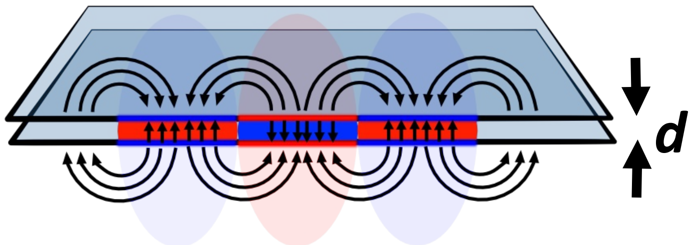


- mid-IR **nanolasers**
- Coherent amplification of graphene plasmons



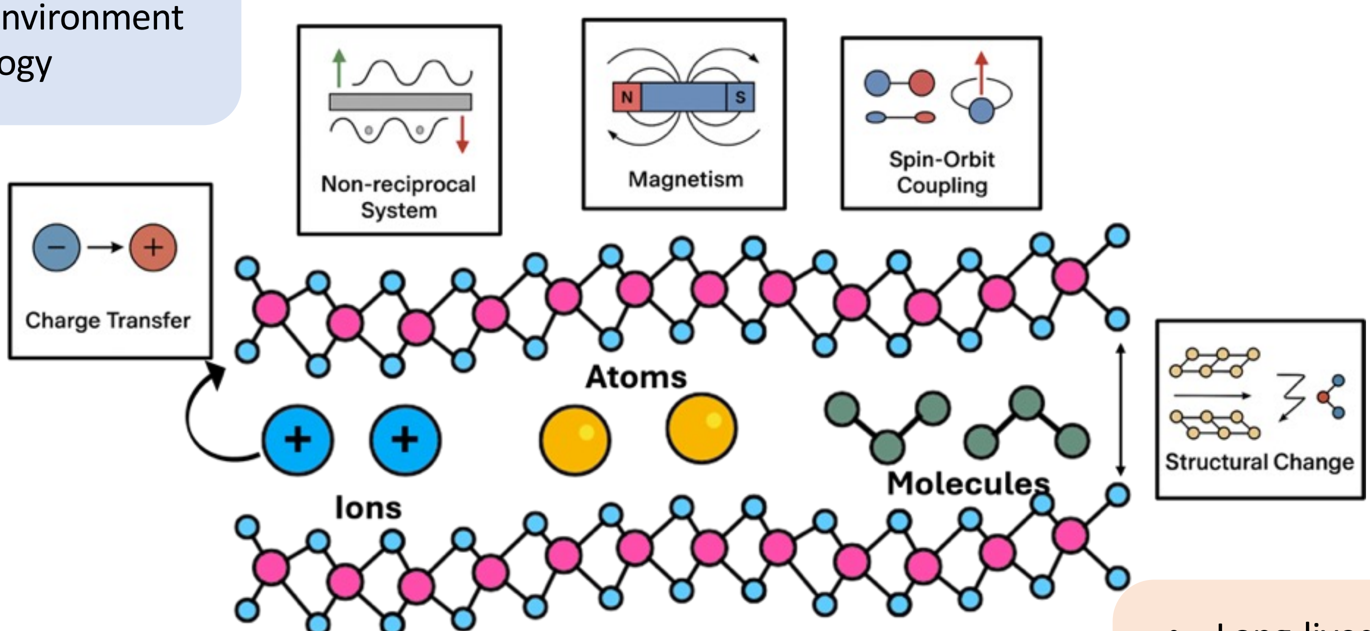
L. Kim et al. *Nat. Mat.* (2021).

Materials-driven ***amplification*** *without* an external gain medium



Plasmonic Metamaterials via Intercalation

- Carrier density
- Dielectric environment
- Band topology

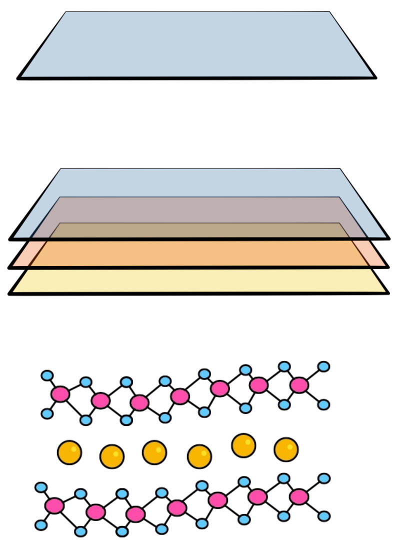


- Long-lived plasmons
- Coherent amplification, gain
- Ultrafast control
- Extreme confinement

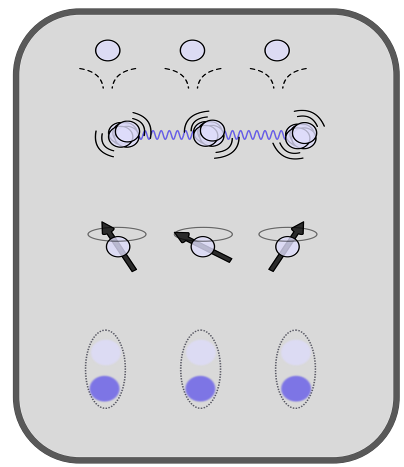
SUMMARY

From Materials to Momentum in Quantum Technology

Materials are the enablers of discovery



Materials Engineering With Atomic Precision



Photonic quasiparticle Engineering

- Reaching all regimes of light-matter interactions
- Unlocking phenomena previously out of reach