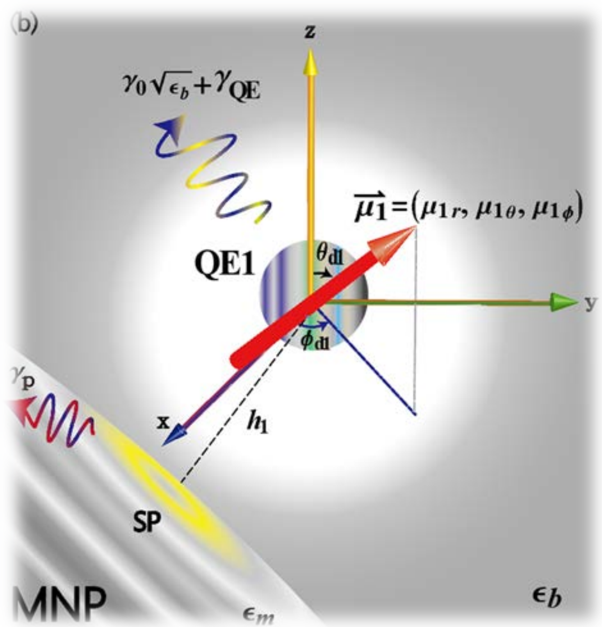
points of quantum emitters coupled to nanoparticle surface plasmons

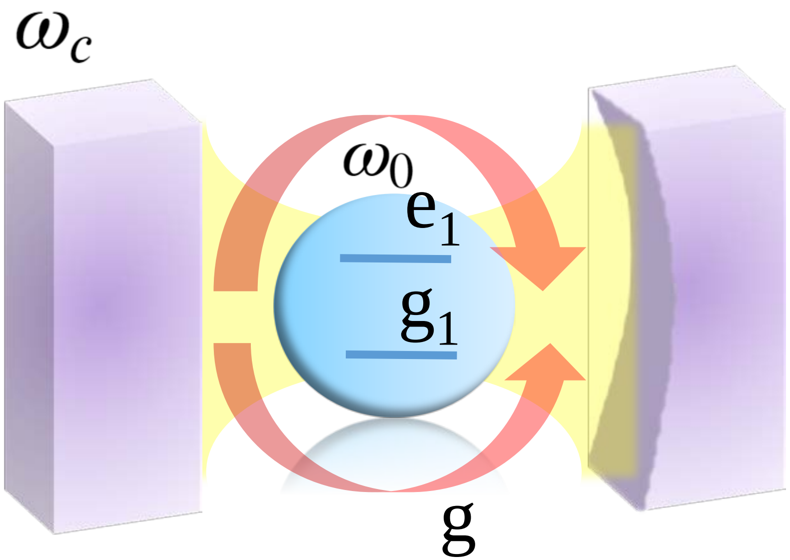
Po-Chen Kuo, Neill Lambert, Adam Miranowicz ,
Hong-Bin Chen, Guang-Yin Chen, Yueh-Nan Chen,
and Franco Nori



Outline

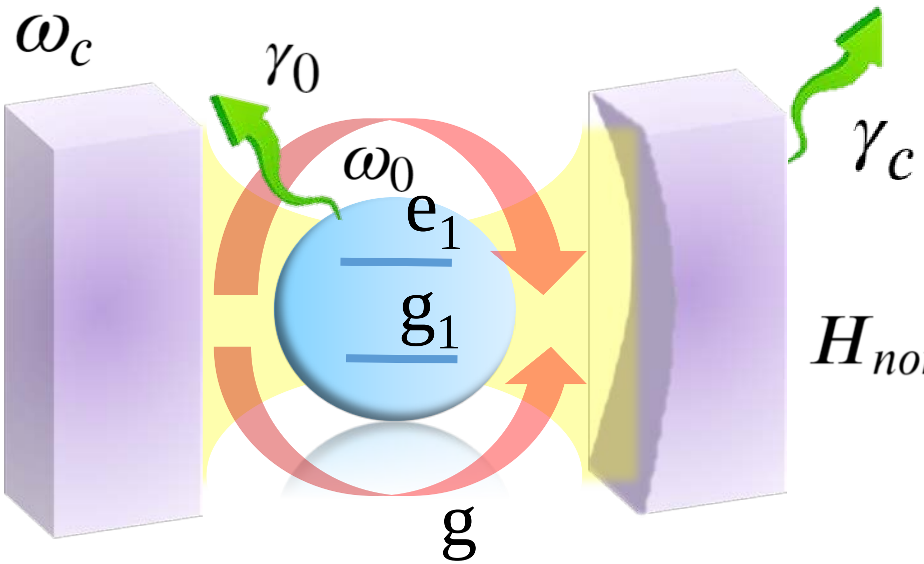
- Exceptional point (EP) and Diabolic-point (DP)
- Localized surface plasmon (LSP)
- Quantum emitter (QE) coupled to LSP
  - Single-QE & a nanoparticle (NP)
  - Multi-QE & a nanoparticle (NP)
- Detection of EP by power spectrum
- Conclusion

Hermitian and Non-Hermitian system



Hermitian

$$H = \begin{pmatrix} \omega_0 & g \\ g & \omega_c \end{pmatrix}$$



Non-Hermitian

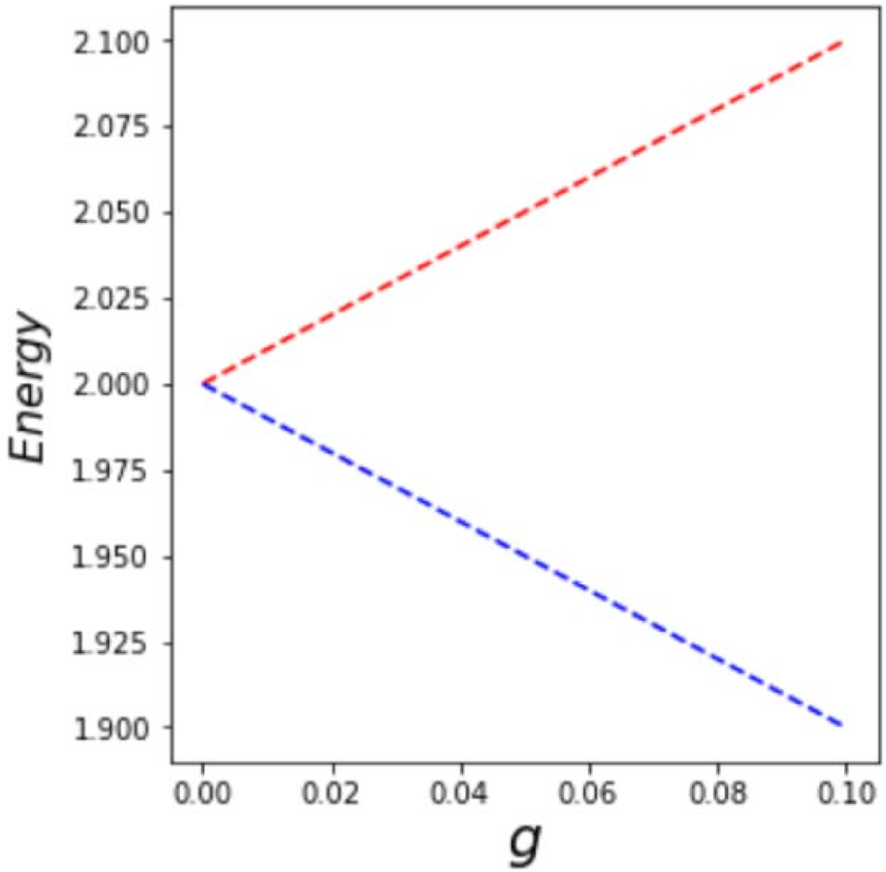
$$H_{non} = \begin{pmatrix} \omega_0 - i\frac{\gamma_0}{2} & g \\ g & \omega_c - i\frac{\gamma_c}{2} \end{pmatrix}$$

Exceptional point (EP)

Hermitian

$$H = \begin{pmatrix} \omega_0 & g \\ g & \omega_c \end{pmatrix}$$

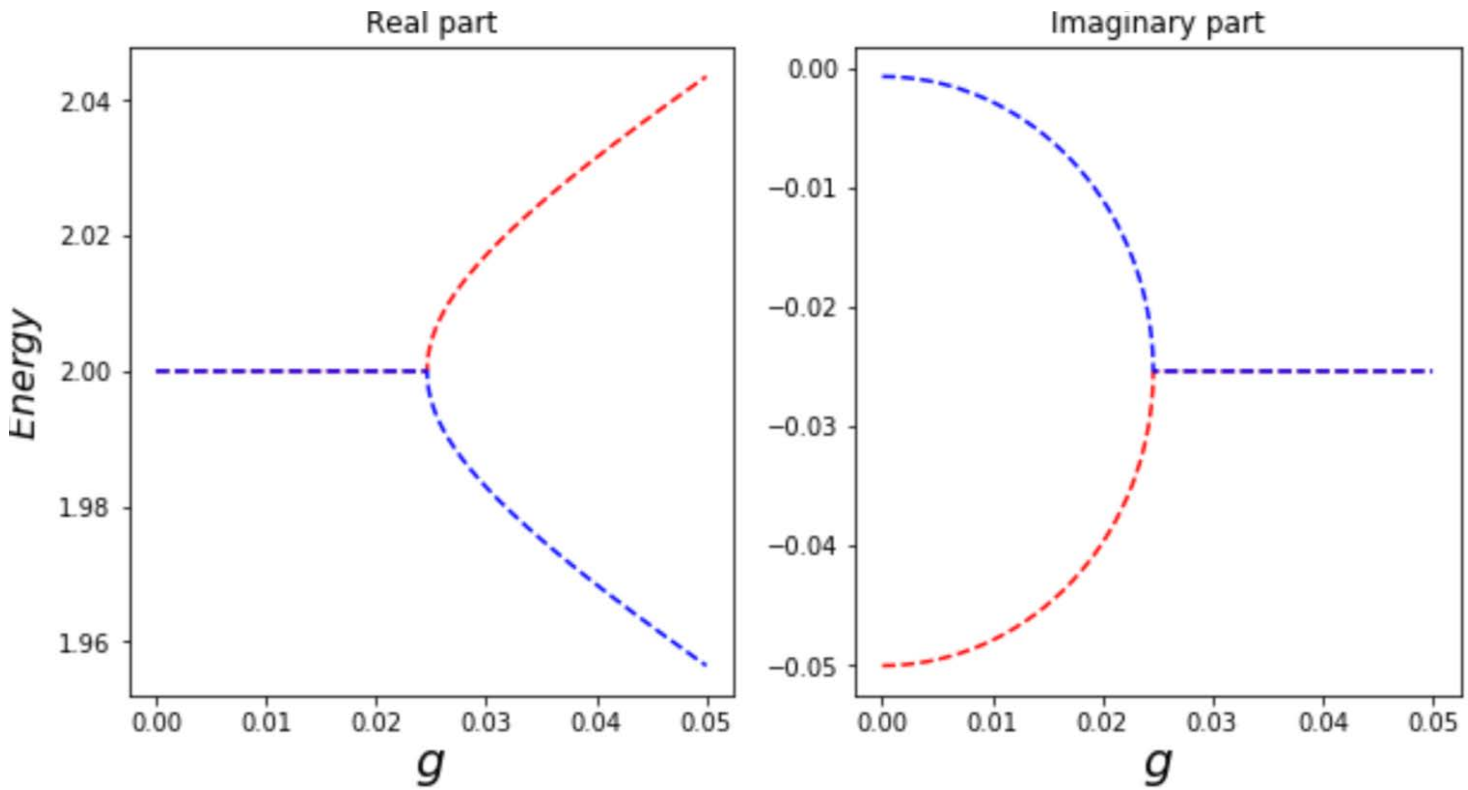
$$\omega_0 = 2eV \; \omega_c = 2eV$$



Exceptional point (EP)

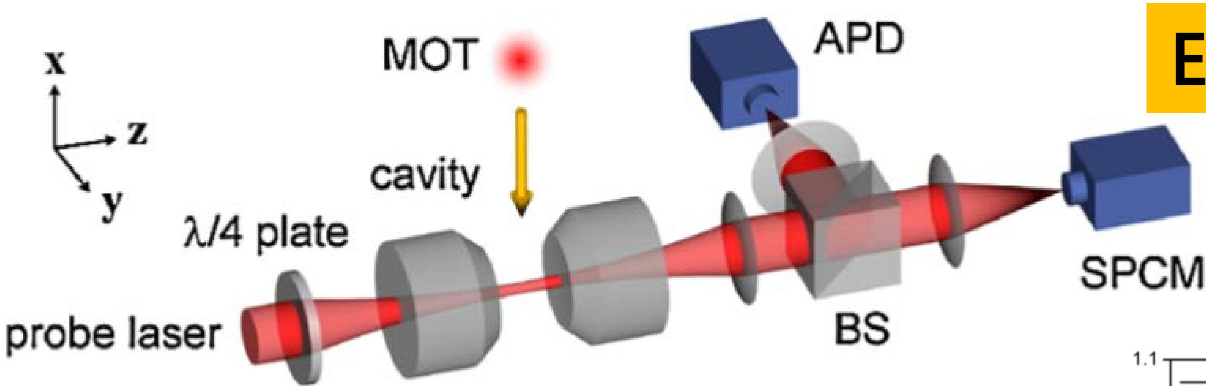
Non-Hermitian

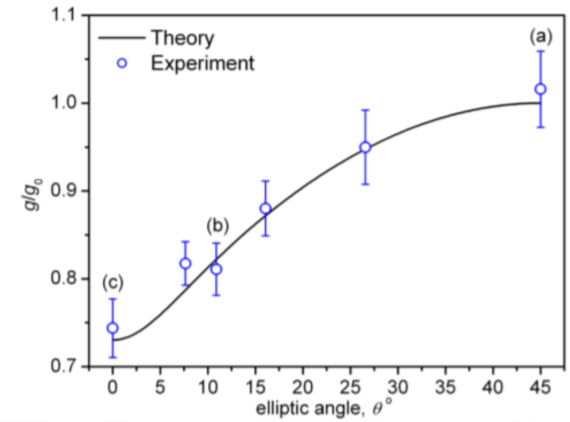
$$H_{non} = \begin{pmatrix} \omega_0 - i\frac{\gamma_0}{2} & g \\ g & \omega_c - i\frac{\gamma_c}{2} \end{pmatrix}$$



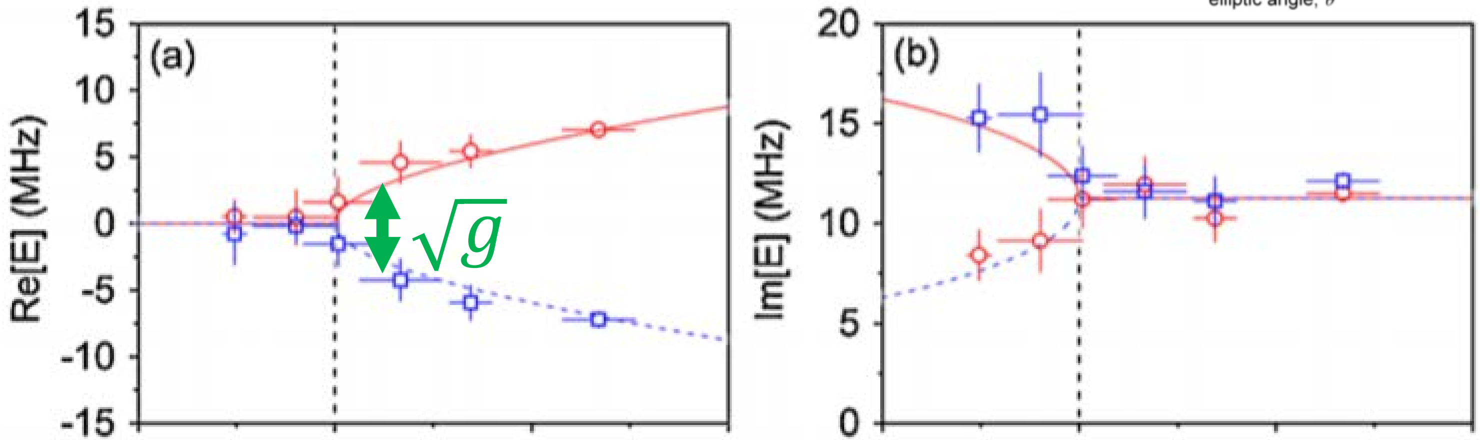
Exceptional point

Sensing

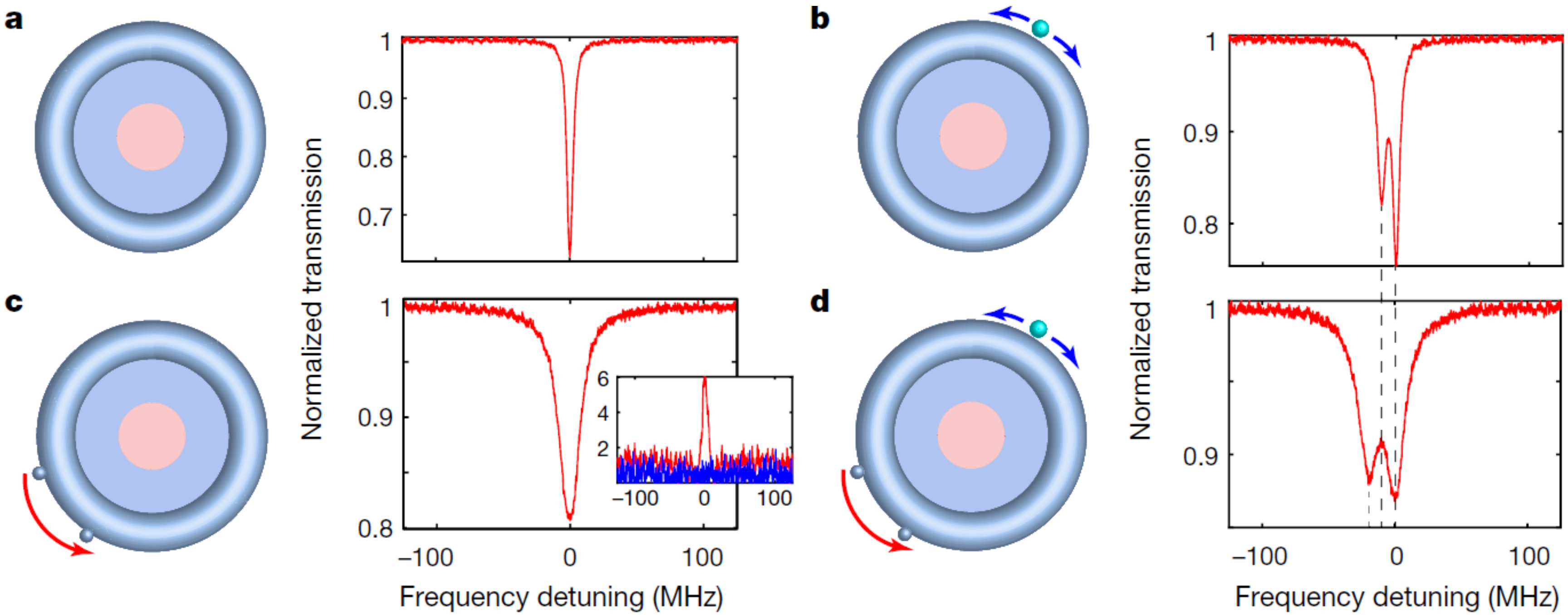


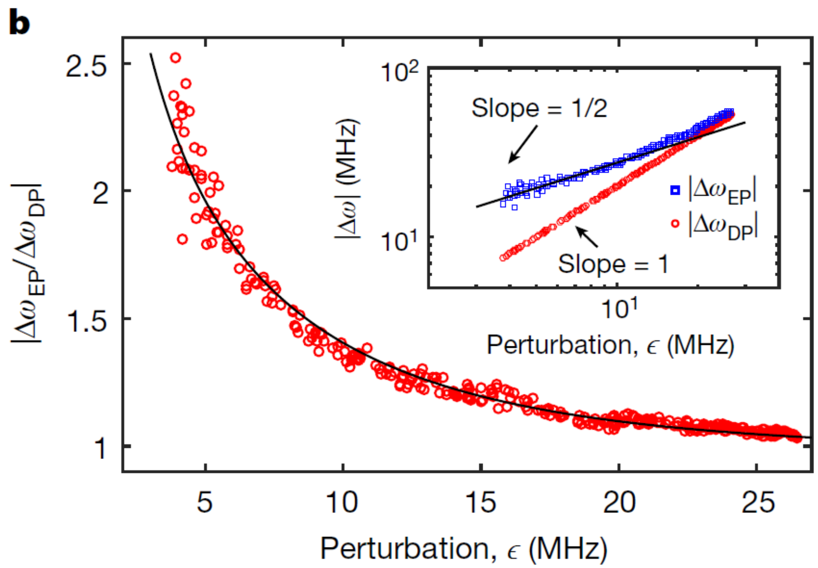


$$H' = \hbar \begin{bmatrix} \omega_a - i\gamma_a & g \\ g & \omega_c - i\gamma_c \end{bmatrix}$$

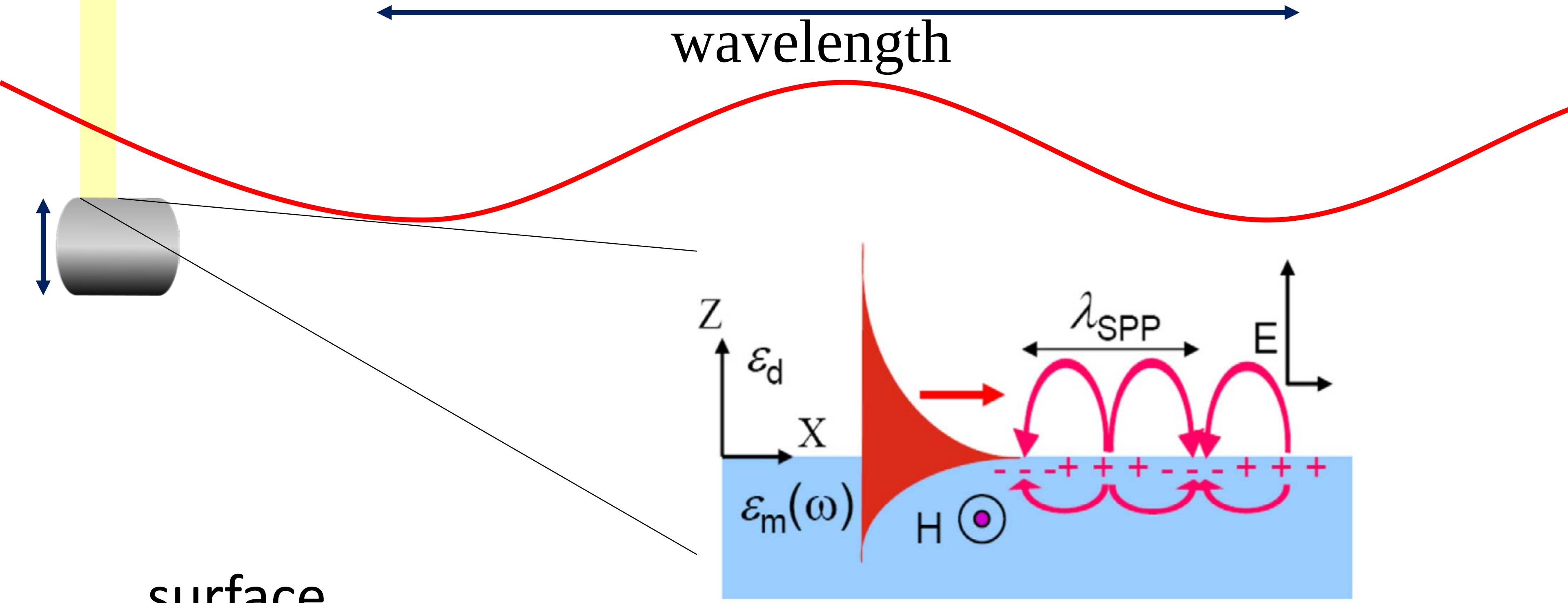


Youngwoon Choi. Phys. Rev. Lett. **104**, 153601


a
b
c
d
Normalized transmission
1
0.9
0.8
0.7
6
4
2
−100
0
100
Frequency detuning (MHz)

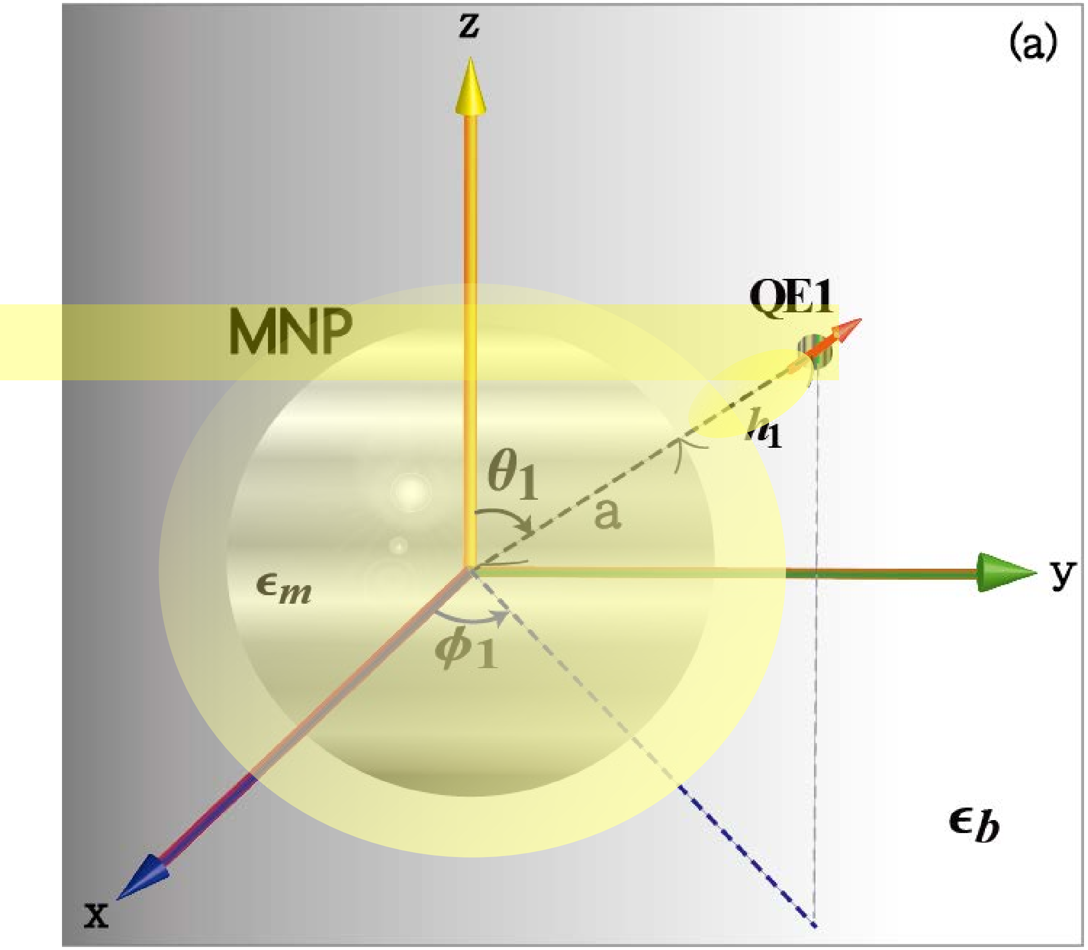

b
2.5
2
1.5
1
$|\Delta\omega_{EP}/\Delta\omega_{DP}|$
5
10
15
20
25
Perturbation, ϵ (MHz)
10^2
10^1
$|\Delta\omega|$ (MHz)
Slope = 1/2
Slope = 1
$|\Delta\omega_{EP}|$
$|\Delta\omega_{DP}|$
Perturbation, ϵ (MHz)

surface plasmons (SP)



surface plasmon polaritons (SPP)

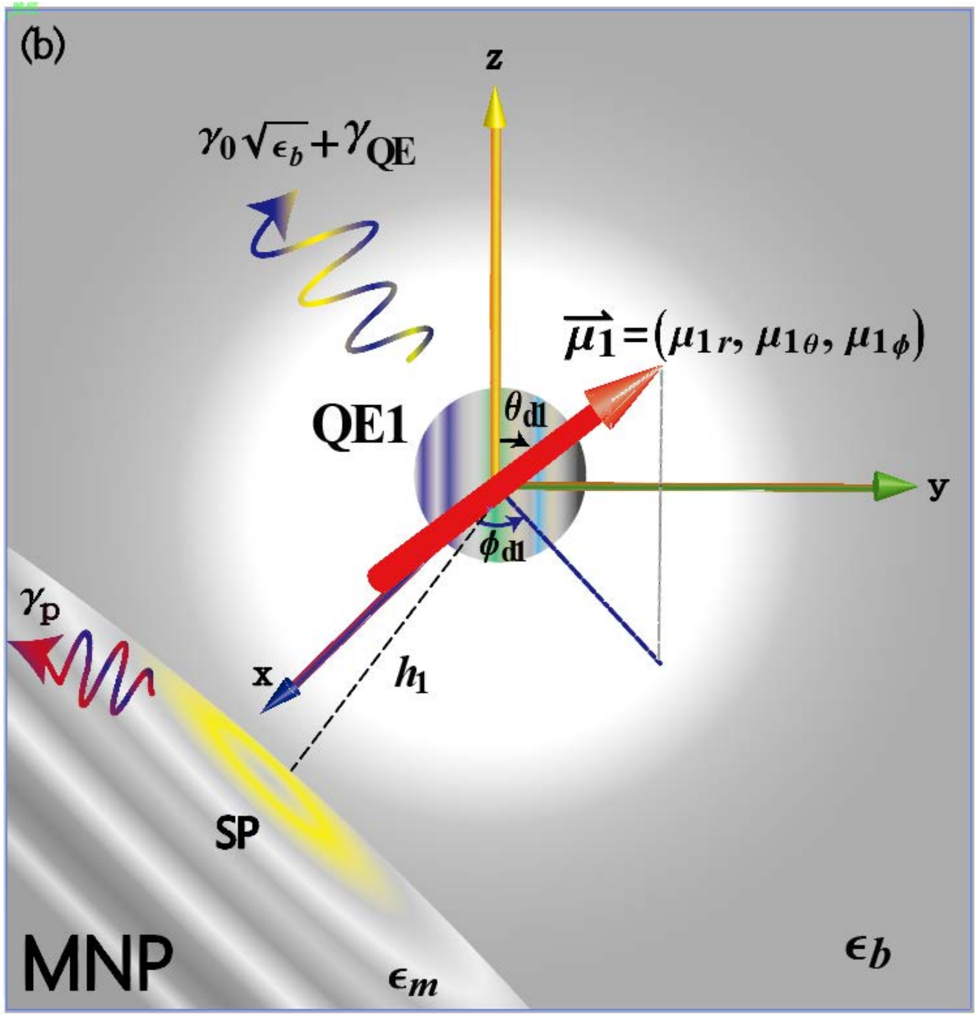
- confinement of the electromagnetic field
- Enhancement of light matter interaction



$$\hbar\left[\omega_0 - i\left(\frac{\gamma_{QE}}{2}\right)\right]\sigma_{e_1,e_1}$$

$$+\int d^3\vec{r}\int_0^\infty d\omega\hbar\omega\hat{f}^\dagger(\vec{r},\omega)\hat{f}(\vec{r},\omega)$$

$$-\int_0^\infty d\omega\left[\vec{\mu_1}\cdot\left(\hat{E}(\vec{r},\omega)\sigma_+^{(1)} + H.c.\right)\right]$$



$$-\int_0^\infty d\omega\left[\vec{\mu_1}\cdot\left(\hat{E}(\vec{r},\omega)\sigma_+^{(1)}+H.c.\right)\right]$$

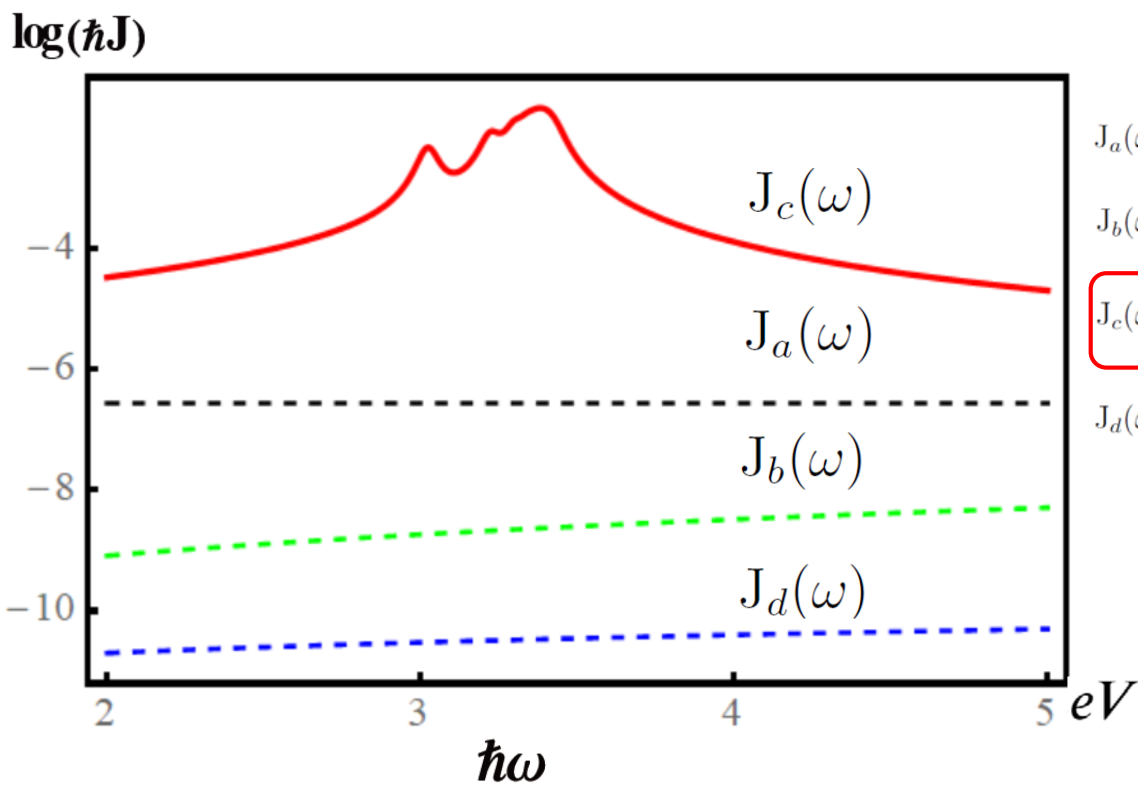
$$\hat{E}(\vec{r},\omega)=i\sqrt{\frac{\hbar}{\pi\epsilon_0}}\frac{\omega^2}{c^2}\int d^3\vec{r_1}\sqrt{\epsilon^I(\vec{r_1},\omega)}\widehat{G}(\vec{r},\vec{r_1},\omega)\hat{f}(\vec{r_1},\omega)$$

$$\nabla\times\nabla\times\widehat{G}(\vec{r},\vec{r_1},\omega)-\frac{\omega^2}{c^2}\epsilon(\vec{r},\omega)\widehat{G}(\vec{r},\vec{r_1},\omega)=\mathbf{I}\delta(\vec{r},\vec{r_1})$$

$$\tilde{G}^{(11)}_{es(r,R)}=\begin{pmatrix} G_{es}^{(rr)} & G_{es}^{(r\theta)} & G_{es}^{(r\phi)} \\ G_{es}^{(\theta r)} & G_{es}^{(\theta\theta)} & G_{es}^{(\theta\phi)} \\ G_{es}^{(\phi r)} & G_{es}^{(\phi\theta)} & G_{es}^{(\phi\phi)} \end{pmatrix}$$

$$H.\psi \Rightarrow \dot{C}_1(t) = -\int_0^t dt_1 \int_0^\infty d\omega J(\omega) e^{i(\omega_0-\omega)(t-t_1)} C_1(t_1)$$

$$\mathrm{J}(\omega) \approx \mathrm{J}_a(\omega) + \mathrm{J}_b(\omega) + \mathrm{J}_c(\omega) + \mathrm{J}_d(\omega)$$

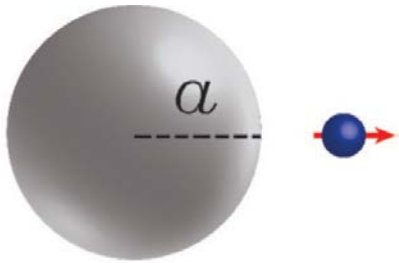


$$\mathrm{J}_a(\omega) = \frac{\gamma_0\sqrt{\epsilon_b}}{2\pi}$$

$$\mathrm{J}_b(\omega) = \frac{\gamma_0\epsilon_b^{3/2}\omega^2(a+h_1)^2}{8\pi c^2\mu_1^2}(\mu_{1\theta}^2 + \mu_{1\phi}^2)$$

$$\mathrm{J}_c(\omega) = \sum_{n=0}^{\infty} \frac{g_{nr}^2(\mu_1) + g_{n\theta}^2(\mu_1) + g_{n\phi}^2(\mu_1)}{\pi} \frac{\gamma_p/2}{(\omega-\omega_n)^2 + (\gamma_p/2)^2}$$

$$\mathrm{J}_d(\omega) = \sum_{\eta=0}^{\infty} \frac{g_{\eta\theta}^2(\mu_1) + g_{\eta\phi}^2(\mu_1)}{\pi} \frac{\gamma_p}{\omega^2 + \gamma_p^2},$$

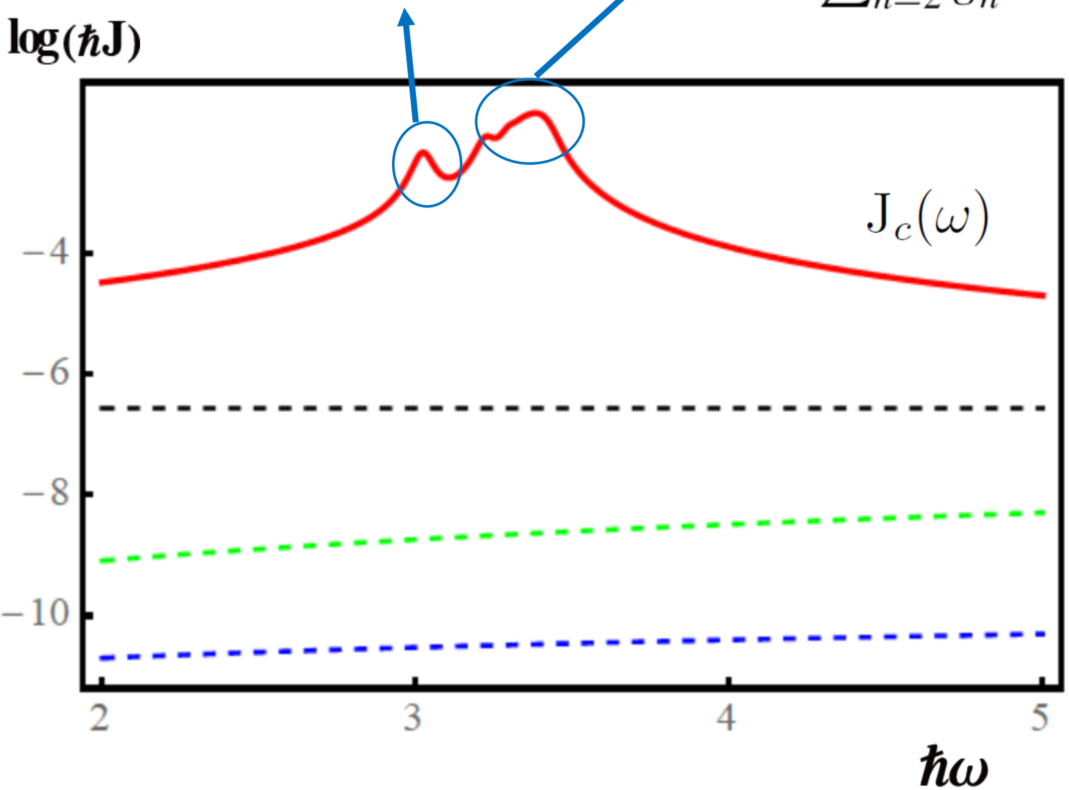


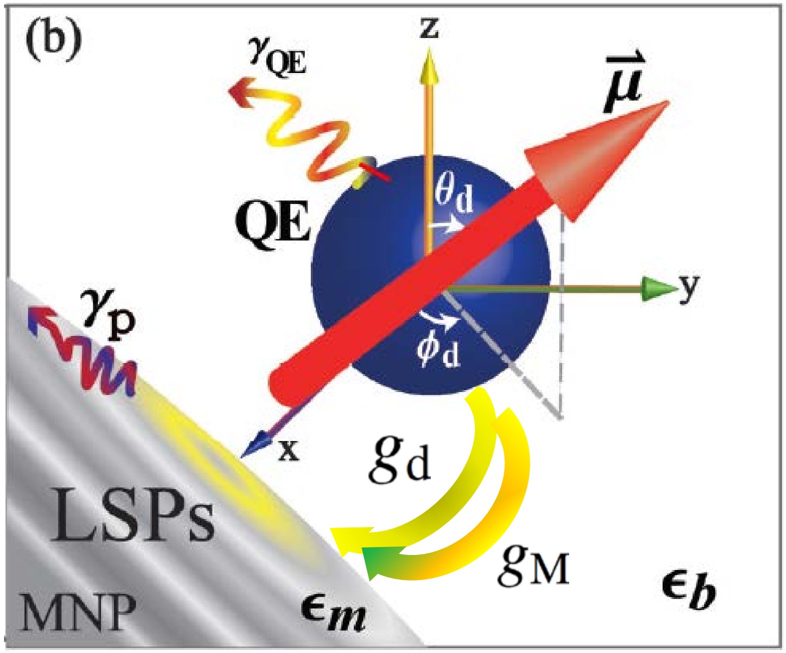
$$J(\omega) \approx \sum_{n=0}^{\infty} \frac{g_n^2}{\pi} \frac{\gamma_p/2}{(\omega-\omega_n)^2 + (\gamma_p/2)^2}$$

$$\omega_n = \omega_p/\sqrt{\epsilon_\infty + \epsilon_d(n+1)/n}$$

$$\omega_d = \omega_1$$

$$\omega_M = \frac{\sum_{n=2}^{\infty} \omega_n g_n^2}{\sum_{n=2}^{\infty} g_n^2}$$





$$\hat{H}_{3\times3} = \begin{bmatrix} \omega_0 - i\frac{\gamma_{QE}}{2} & g_d & g_M \\ g_d & \omega_d - i\frac{\gamma_p}{2} & 0 \\ g_M & 0 & \omega_M - i\frac{\gamma_p}{2} \end{bmatrix}$$

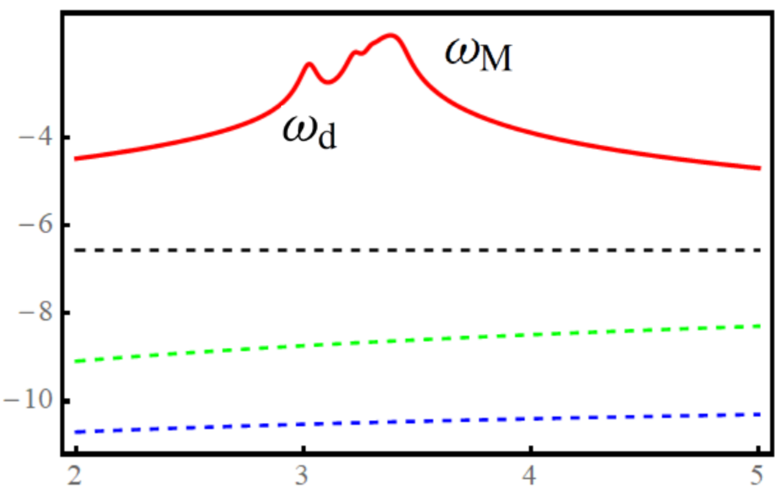
$$g_d = g_1$$

$$g_M^2 = \sum_{n=2}^{\infty} g_n^2$$

$$g_n^2 = \sum_{\alpha=r,\theta,\phi} g_{n\alpha}^2$$

$$g_{nr}^2 = \mu_r^2 (n+1)^2 f_n(\omega_n)$$

$$g_{n\theta(\phi)}^2 = \mu_{\theta(\phi)}^2 \sum_{m=0}^{n} \mathcal{D}_{nm}\left[m P_n^m(0)\right]^2 f_n(\omega_n)$$

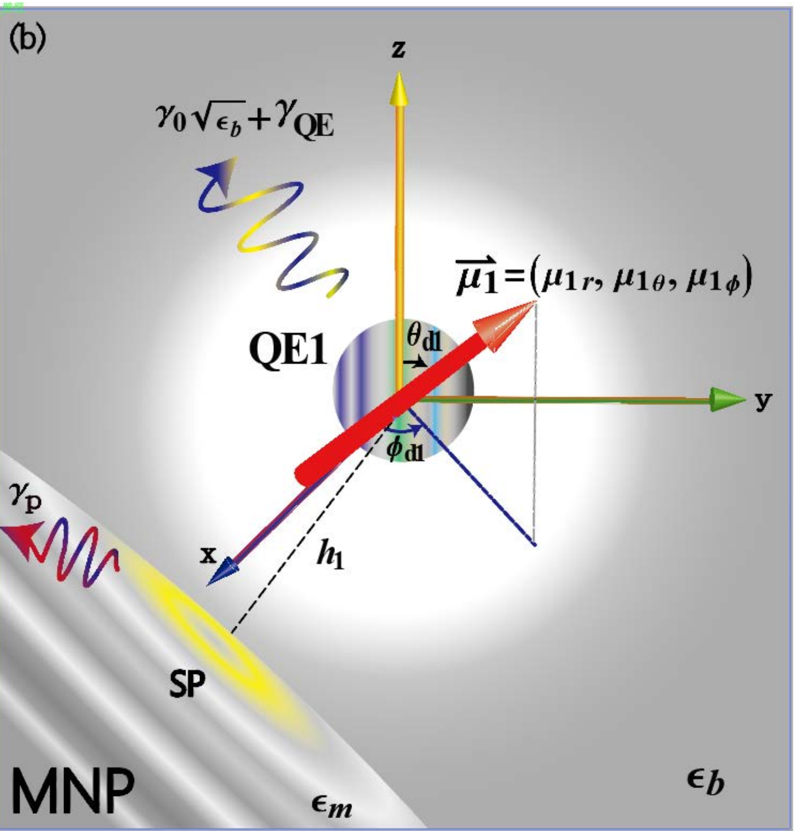


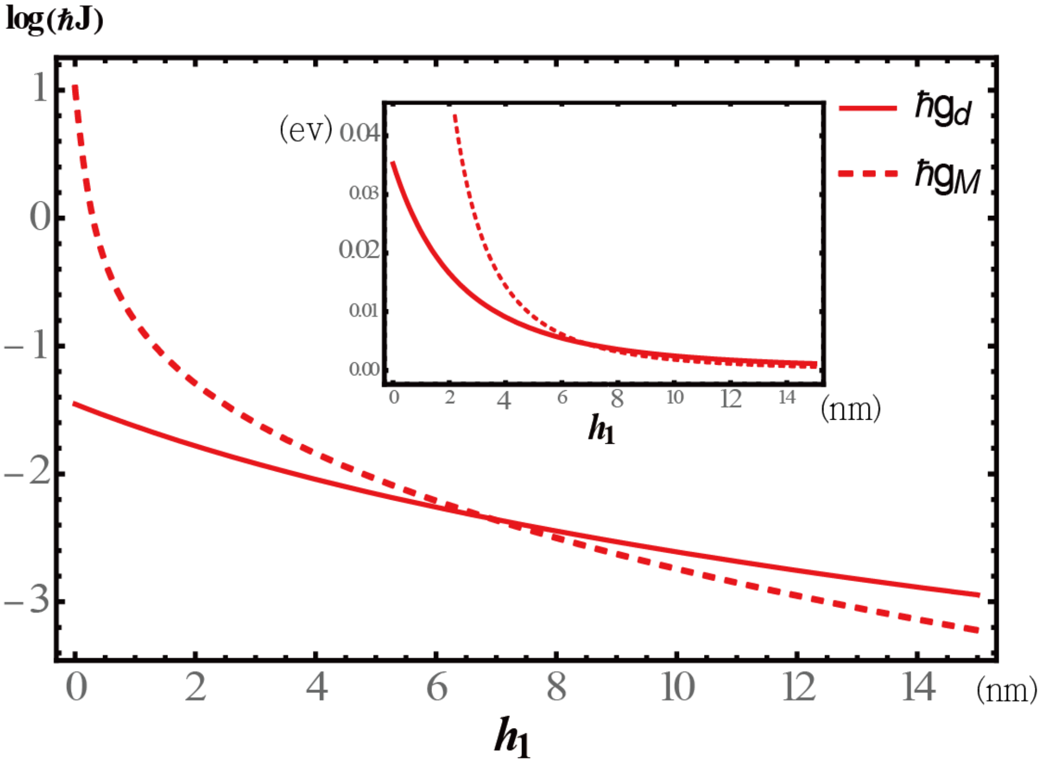
$$g_n^2 = \sum_{\alpha=r,\theta,\phi} g_{n\alpha}^2$$

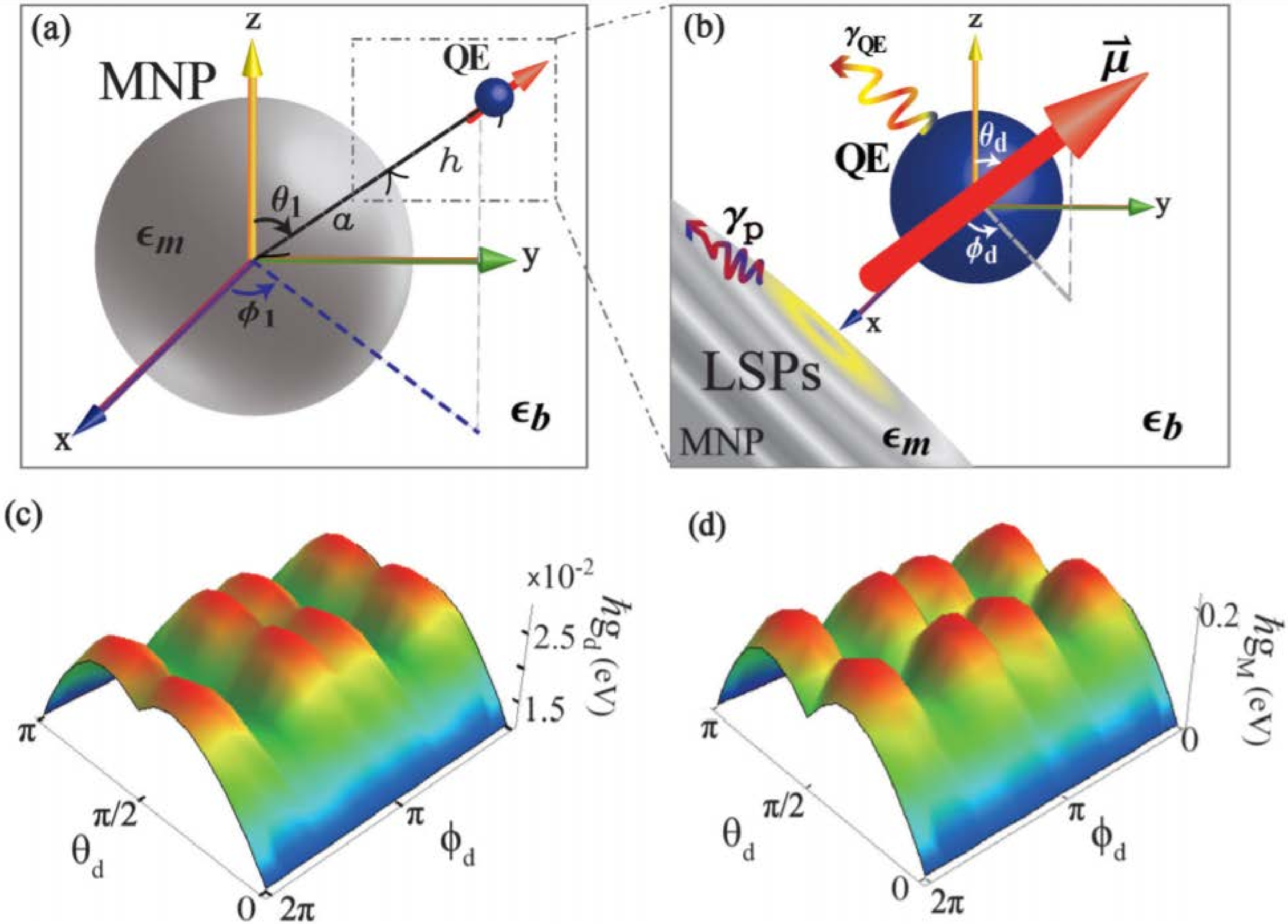
$$g_{nr}^2 = \mu_r^2 (n+1)^2 f_n(\omega_n)$$

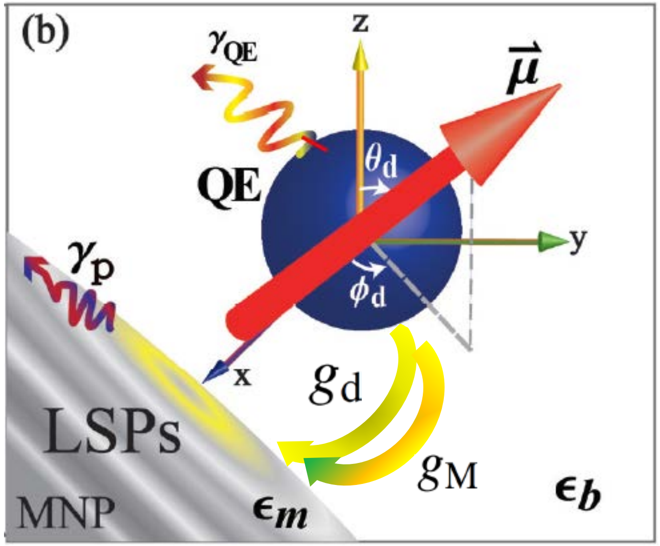
$$g_{n\theta(\phi)}^2 = \mu_{\theta(\phi)}^2 \sum_{m=0}^{n} \mathcal{D}_{nm}\left[m P_n^m(0)\right]^2 f_n(\omega_n)$$

$$f_n(\omega_n) = \frac{a^{2n+1}}{(a+h)^{2n+4}}\left(1+\frac{1}{2n}\right)\frac{\omega_p}{4\pi\epsilon_0\hbar}\left(\frac{\omega_n}{\omega_p}\right)^3$$





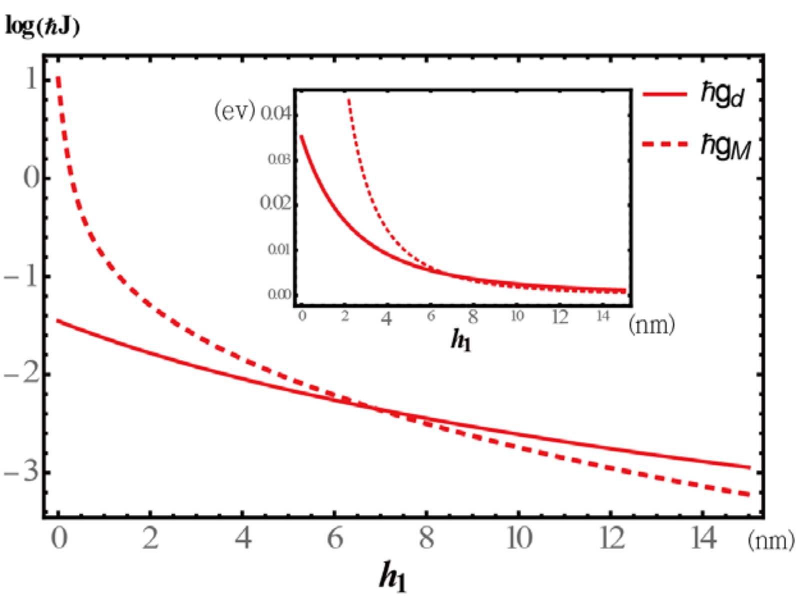

(a)
z
MNP
QE
h
θ_1
α
ϵ_m
y
ϕ_1
x
ϵ_b
(b)
γ_{QE}
z
$\vec{\mu}$
QE
θ_d
y
γ_p
ϕ_d
x
LSPs
MNP
ϵ_m
ϵ_b
(c)
$\times 10^{-2}$
$\hbar g_d$ (eV)
2.5
1.5
π
π/2
θ_d
0
2π
π
ϕ_d
(d)
0.2
$\hbar g_M$ (eV)
0
π
π/2
θ_d
0
2π
π
ϕ_d



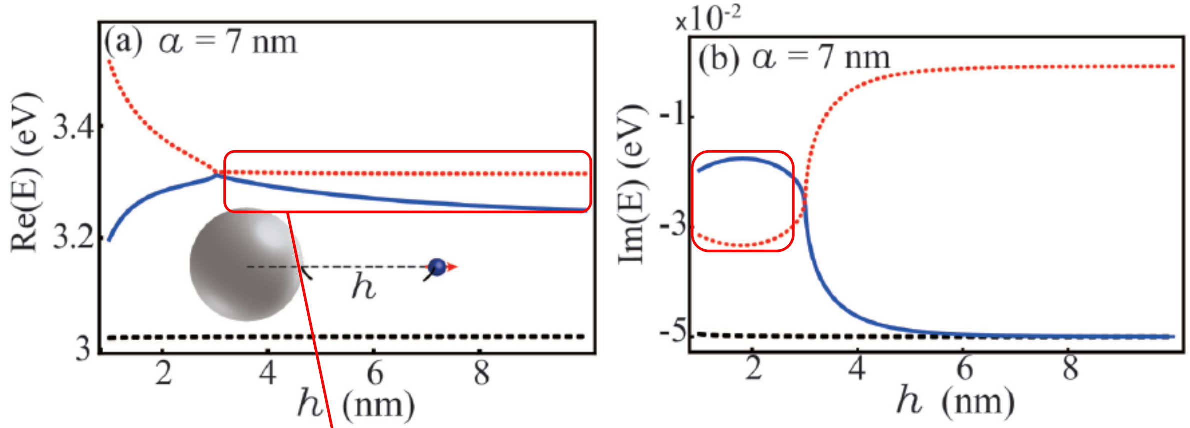
$$\hat{H}_{3\times3} = \begin{bmatrix} \omega_0 - i\frac{\gamma_{QE}}{2} & g_d & g_M \\ g_d & \omega_d - i\frac{\gamma_p}{2} & 0 \\ g_M & 0 & \omega_M - i\frac{\gamma_p}{2} \end{bmatrix}$$

$$\hat{H}_{2\times2} = \begin{bmatrix} \omega_0 - i\frac{\gamma_{QE}}{2} & g_M \\ g_M & \omega_M - i\frac{\gamma_p}{2} \end{bmatrix}$$

$$g_M = (\gamma_p - \gamma_{QE})/4$$



$$\hat{H}_{3\times3} = \begin{bmatrix} \omega_0 - i\frac{\gamma_{QE}}{2} & g_d & g_M \\ g_d & \omega_d - i\frac{\gamma_p}{2} & 0 \\ g_M & 0 & \omega_M - i\frac{\gamma_p}{2} \end{bmatrix}$$



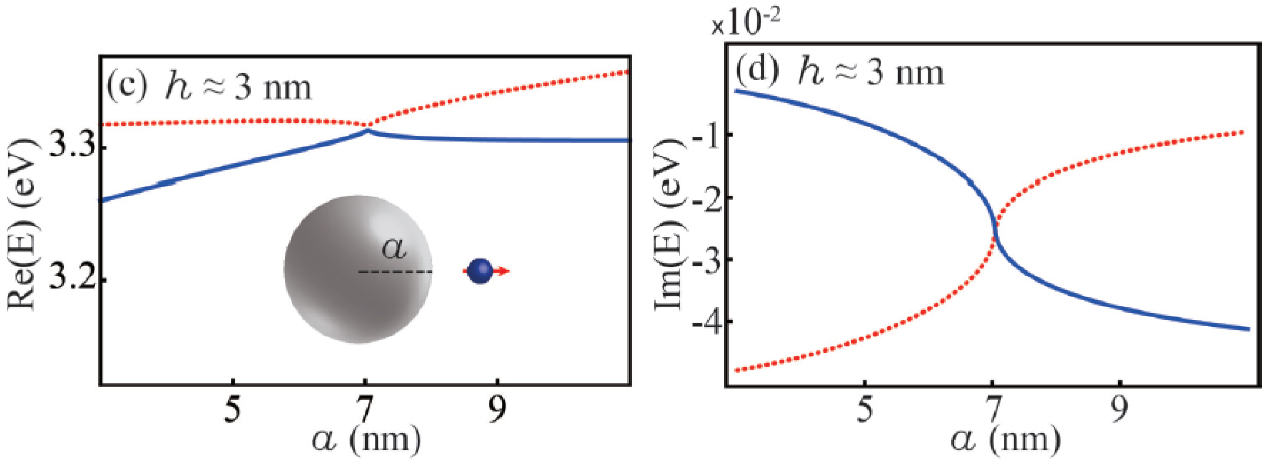
$$\Delta E = \frac{-\sqrt{3}i[u^2 + p(\omega_d, g_d)^{2/3} - 48g_d^2]}{12p(\omega_d, g_d)^{1/3}}$$

$$p(\omega_d, g_d) = 144g_d^2(2\omega_{d\triangle} + i\gamma_\triangle) + iu^3 + 12q(\omega_d, g_d)$$

$$q(\omega_d, g_d) = -96g_d^4(\gamma_\triangle^2 - 10i\gamma_\triangle\omega_{d\triangle} + 2\omega_{d\triangle}^2) - 3\gamma_\triangle g_d^2u^3 - 768g_d^6,$$

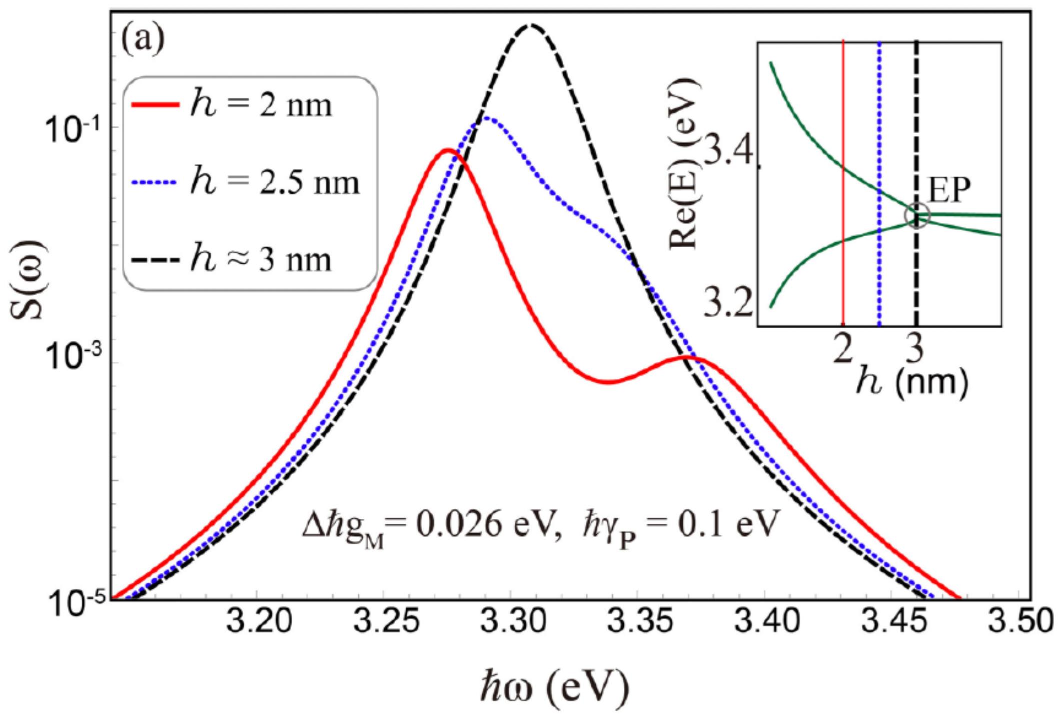
$u = \gamma_\triangle + 4i\omega_{d\triangle}$, $\omega_{d\triangle} = \omega_d - \omega_0$, and $\gamma_\triangle = \gamma_p - \gamma_{QE}$

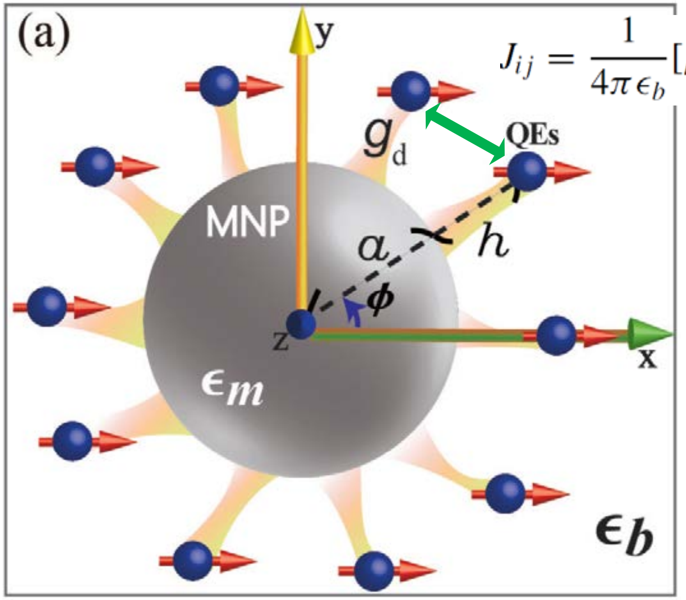
$$\hat{H}_{3\times 3} = \begin{bmatrix} \omega_0 - i\frac{\gamma_{\mathrm{QE}}}{2} & g_{\mathrm{d}} & g_{\mathrm{M}} \\ g_{\mathrm{d}} & \omega_{\mathrm{d}} - i\frac{\gamma_{\mathrm{p}}}{2} & 0 \\ g_{\mathrm{M}} & 0 & \omega_{\mathrm{M}} - i\frac{\gamma_{\mathrm{p}}}{2} \end{bmatrix}$$



$$\hat{H}_{3\times 3} = \begin{bmatrix} \omega_0 - i\frac{\gamma_{\mathrm{QE}}}{2} & g_{\mathrm{d}} & g_{\mathrm{M}} \\ g_{\mathrm{d}} & \omega_{\mathrm{d}} - i\frac{\gamma_{\mathrm{P}}}{2} & 0 \\ g_{\mathrm{M}} & 0 & \omega_{\mathrm{M}} - i\frac{\gamma_{\mathrm{P}}}{2} \end{bmatrix}$$

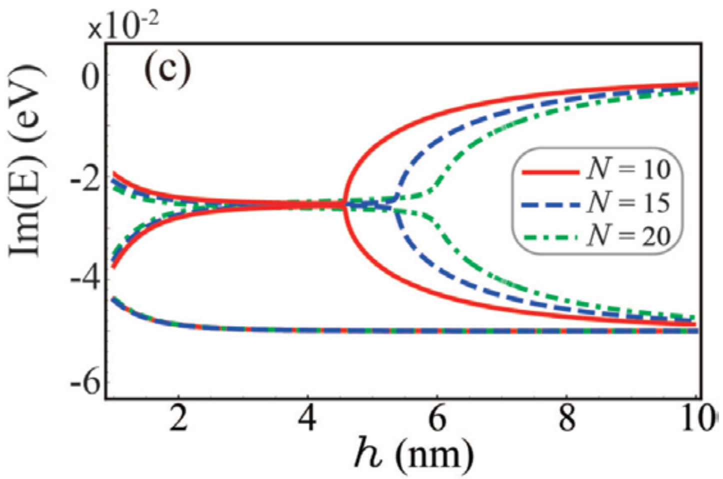
$$S(\omega) = \frac{1}{\pi}\mathrm{Re}\int_0^\infty d\tau \langle \hat{\sigma}_+^{(1)}(0)\hat{\sigma}_-^{(1)}(\tau)\rangle e^{i\omega\tau}$$

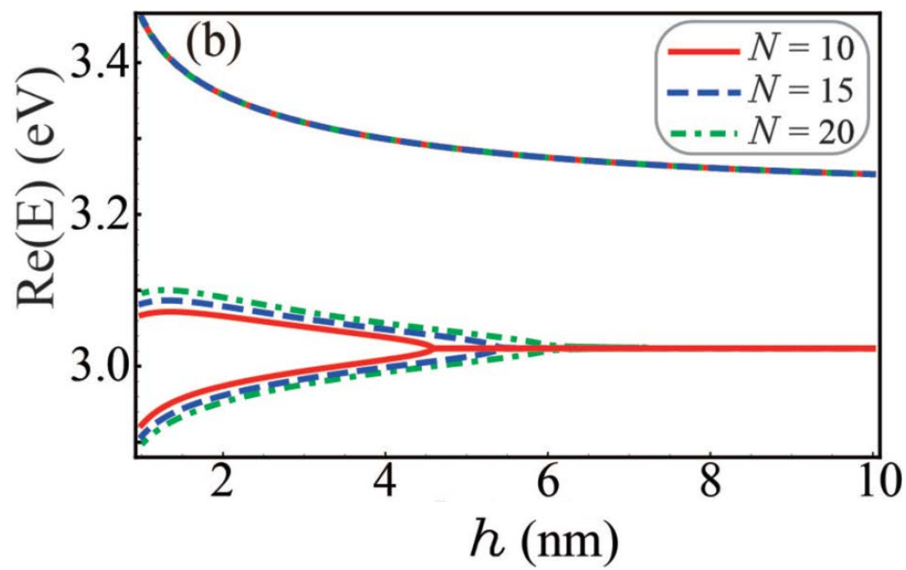


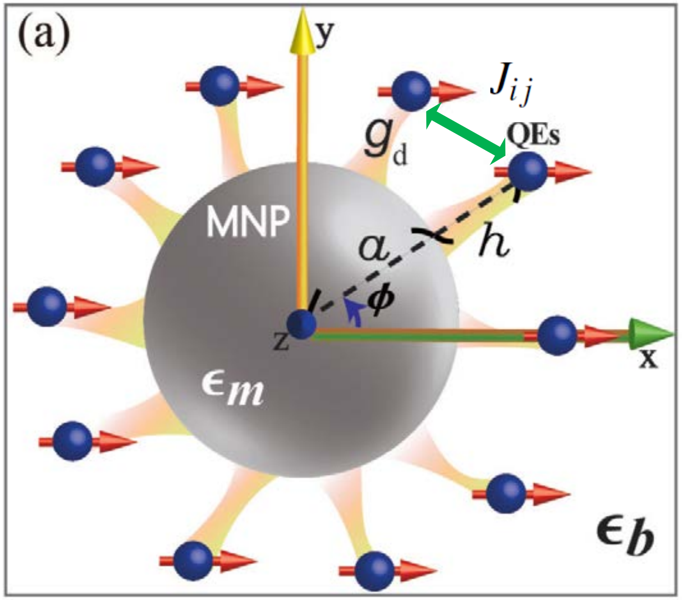


$$J_{ij} = \frac{1}{4\pi\epsilon_b}[\vec{\mu}_i \cdot \vec{\mu}_j/|\vec{r}_{ij}|^3 - 3(\vec{\mu}_i \cdot \vec{r}_{ij})(\vec{\mu}_j \cdot \vec{r}_{ij})/|\vec{r}_{ij}|^5]$$

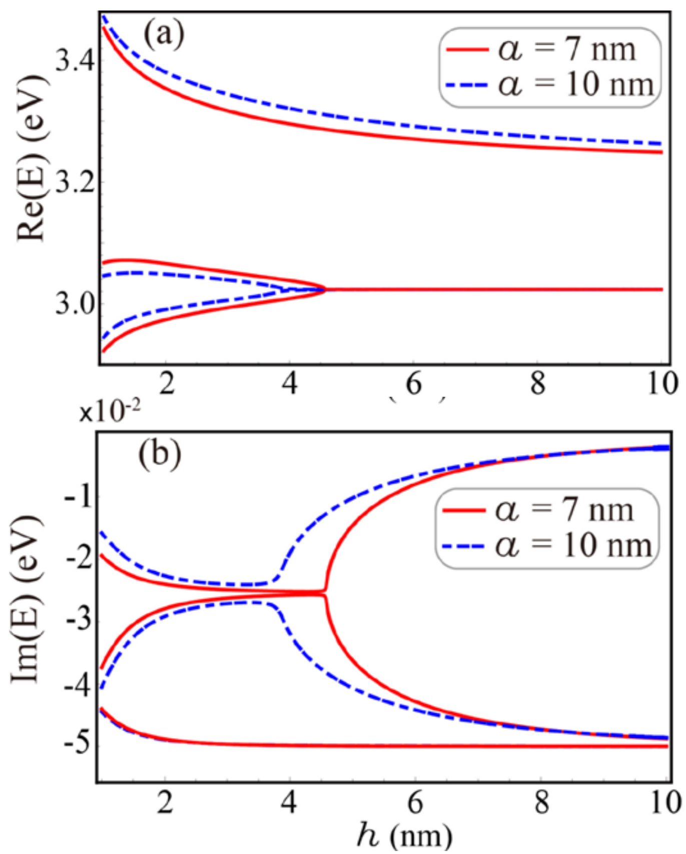
$$H_{3\times3} = \begin{bmatrix} \omega_0 - i\frac{\gamma_{QE}}{2} & g_d & g_M \\ g_d & \omega_d - i\frac{\gamma_p}{2} & 0 \\ g_M & 0 & \omega_M - i\frac{\gamma_p}{2} \end{bmatrix}$$

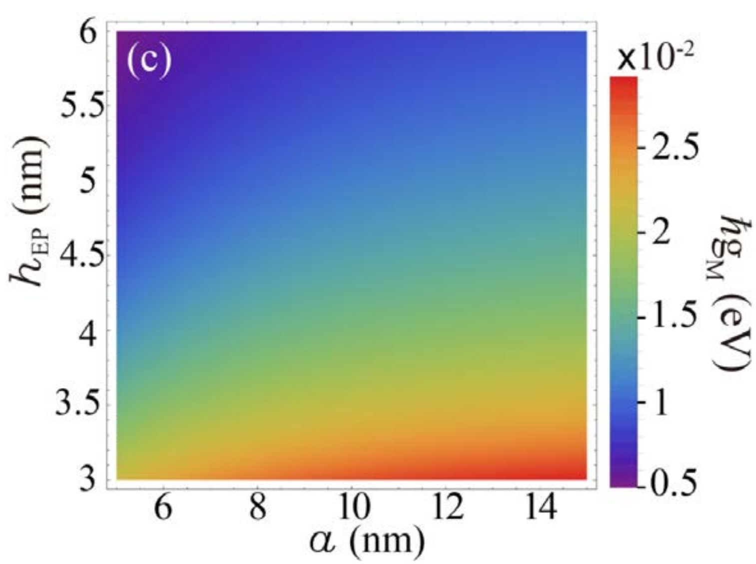


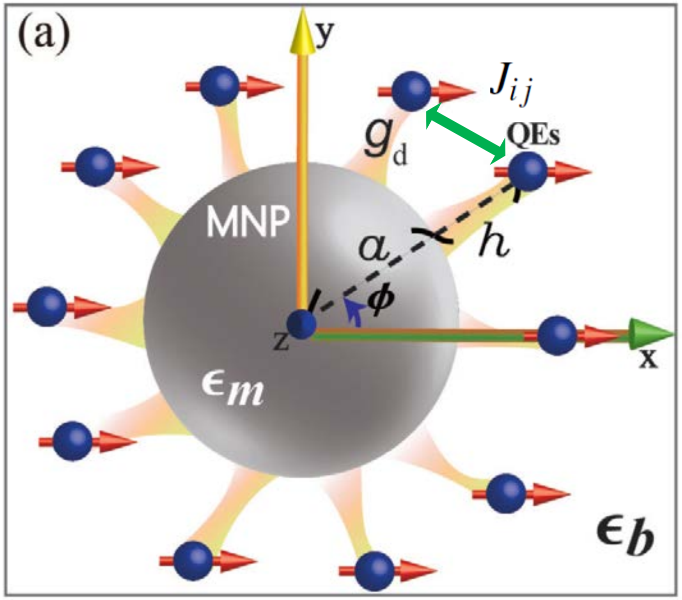




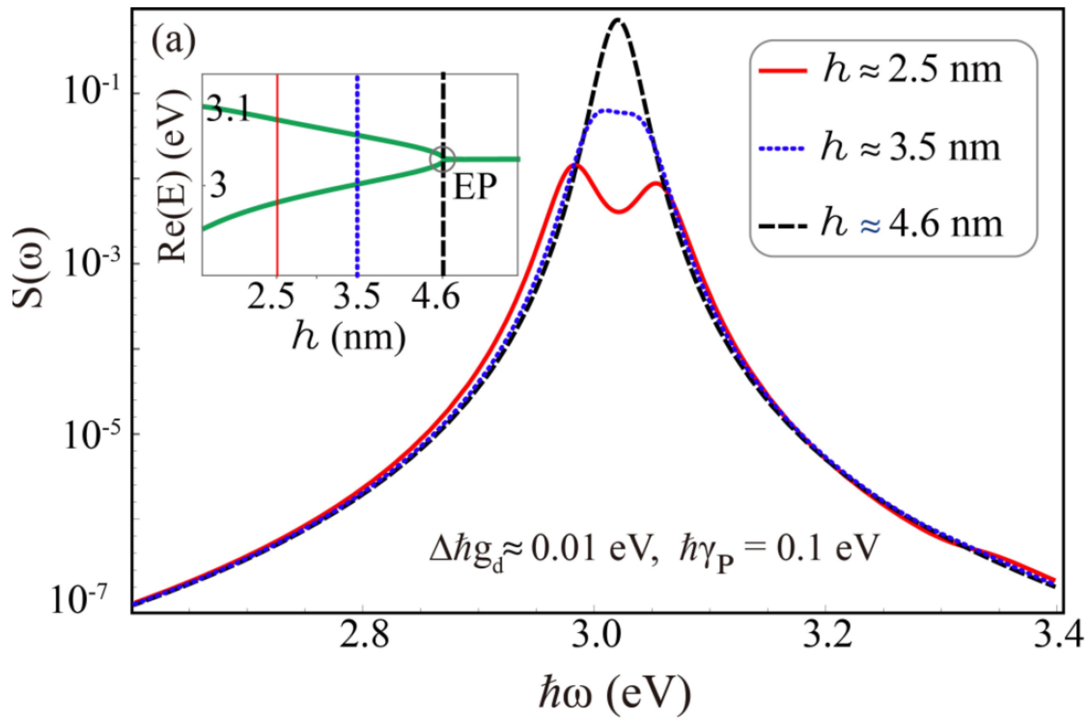
$$H_{3\times 3} = \begin{bmatrix} \omega_0 - i\frac{\gamma_{QE}}{2} + \delta_J & \sqrt{N}g_d & g_M \\ \sqrt{N}g_d & \omega_d - i\frac{\gamma_p}{2} & 0 \\ g_M & 0 & \omega_M - i\frac{\gamma_p}{2} \end{bmatrix}$$



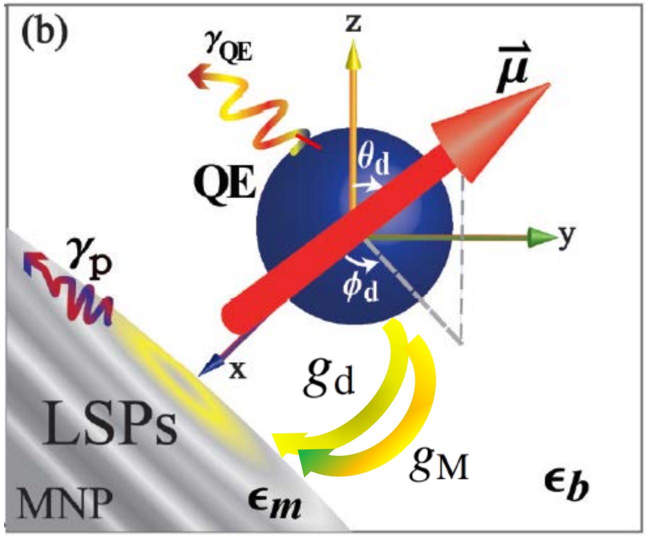


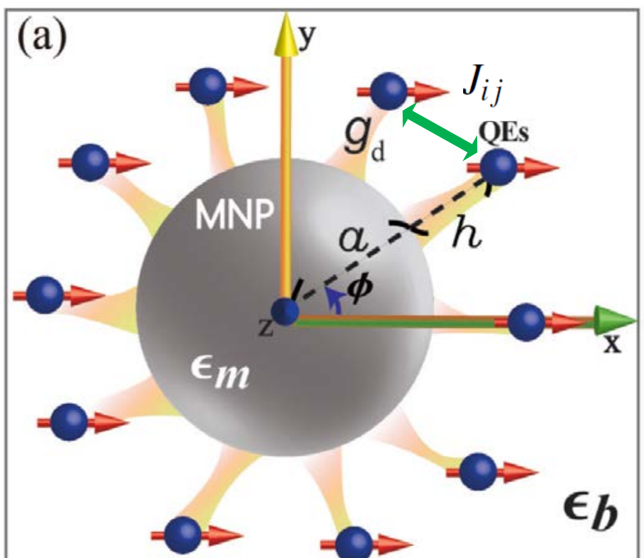


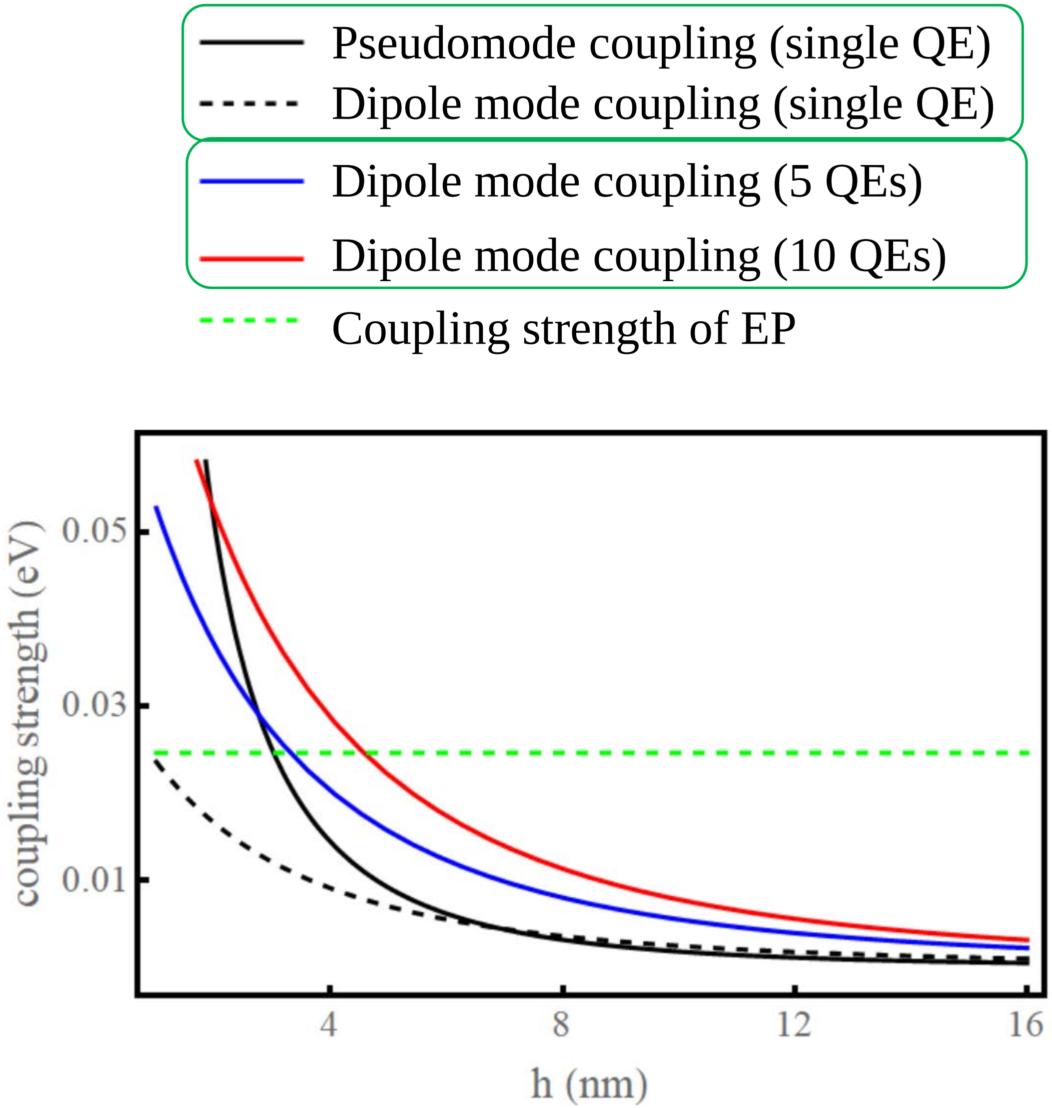
$$H_{3\times3} = \begin{bmatrix} \omega_0 - i\frac{\gamma_{\mathrm{QE}}}{2} + \delta_{\mathrm{J}} & \sqrt{N} g_{\mathrm{d}} & g_{\mathrm{M}} \\ \sqrt{N} g_{\mathrm{d}} & \omega_{\mathrm{d}} - i\frac{\gamma_{\mathrm{p}}}{2} & 0 \\ g_{\mathrm{M}} & 0 & \omega_{\mathrm{M}} - i\frac{\gamma_{\mathrm{p}}}{2} \end{bmatrix}$$



$$S(\omega) = \frac{1}{\pi}\mathrm{Re}\int_0^\infty d\tau \langle \hat{\sigma}_+^{(c)}(0)\hat{\sigma}_-^{(c)}(\tau)\rangle e^{i\omega\tau}$$


(b)
γ_{QE}
z
$\vec{\mu}$
QE
θ_d
y
γ_p
ϕ_d
x
g_d
LSPs
g_M
ϵ_b
MNP
ϵ_m


(a)
y
J_{ij}
g_d
QEs
MNP
a
h
ϕ
z
x
ϵ_m
ϵ_b


Pseudomode coupling (single QE)
Dipole mode coupling (single QE)
Dipole mode coupling (5 QEs)
Dipole mode coupling (10 QEs)
Coupling strength of EP
coupling strength (eV)
0.05
0.03
0.01
4
8
12
16
h (nm)

Thanks for listening !!