QUANTUM RESPONSE OF PLASMONIC SYSTEMS

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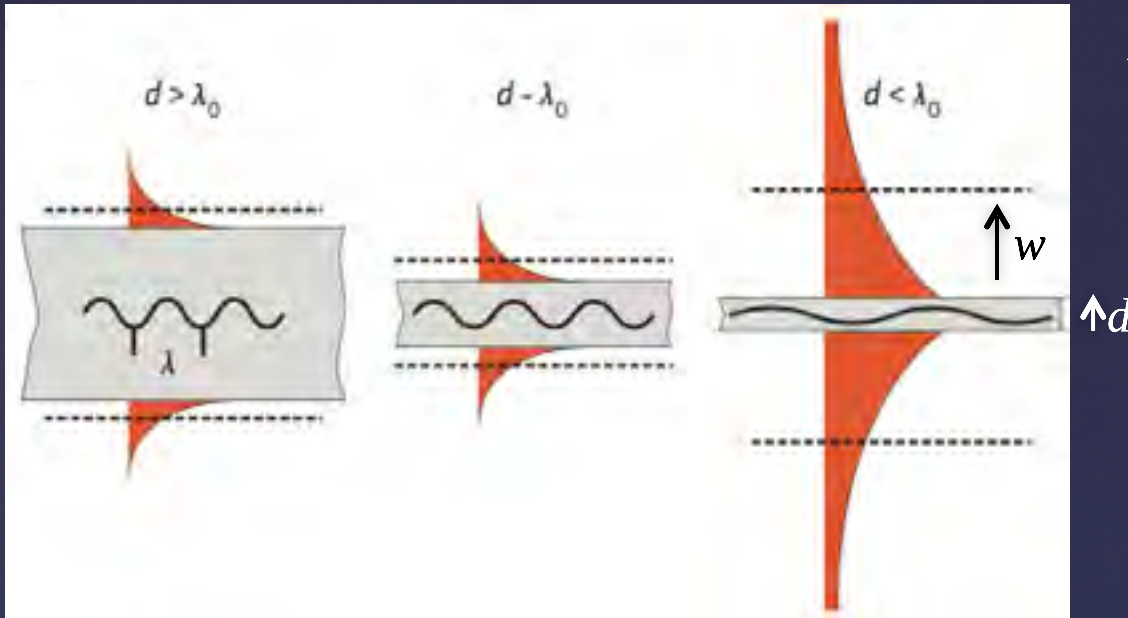
INTRODUCTION

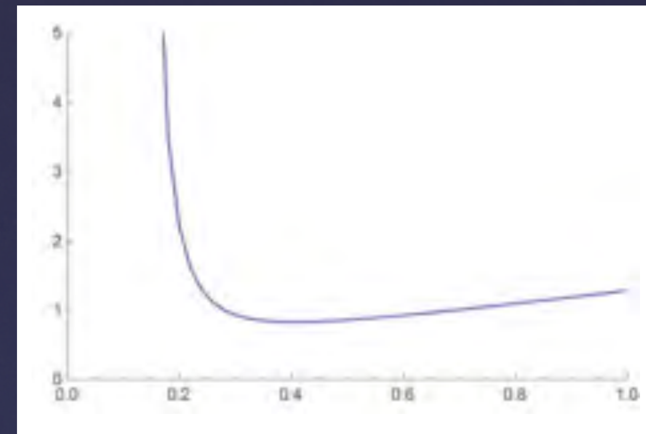
By how much can I squeeze light spatially?

OREGON ZOO

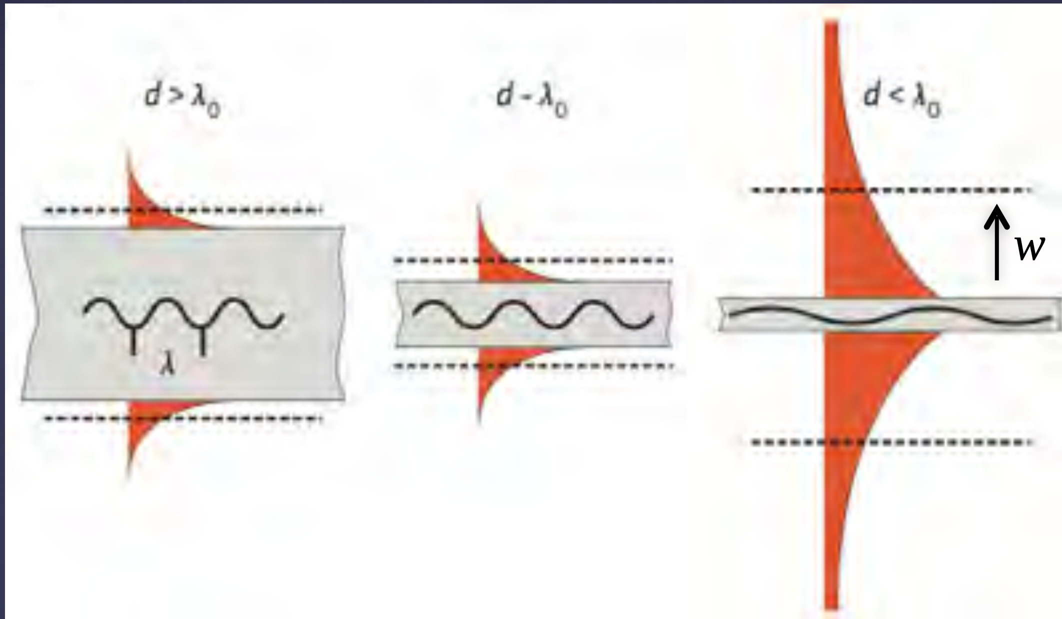
The 'Squishing of the Squash'



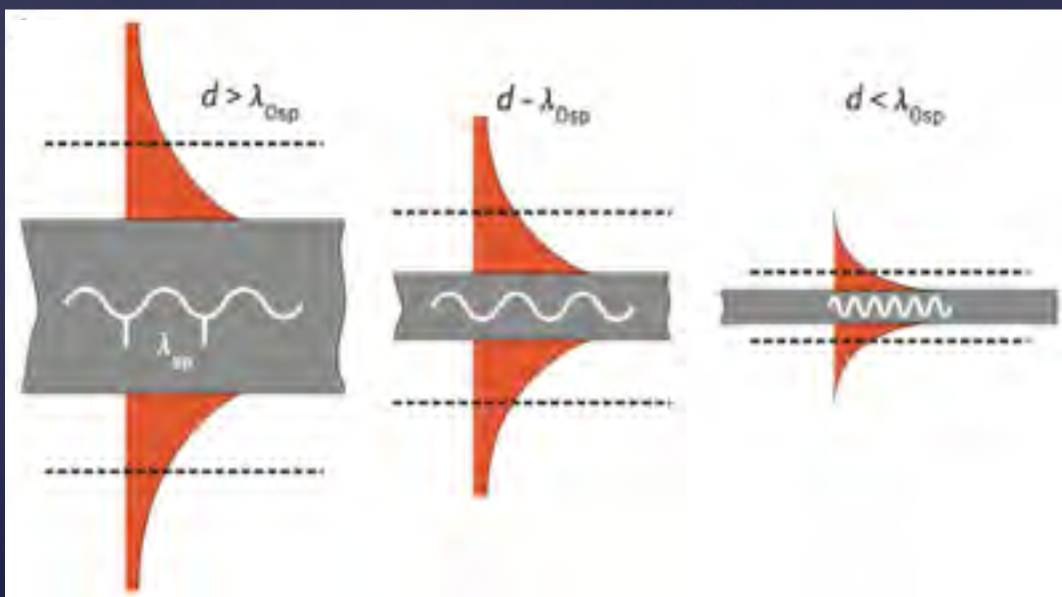
w/λ_0



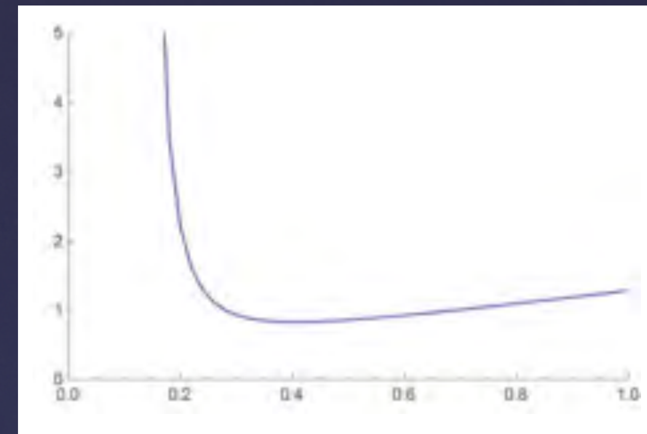
d/λ_0



d

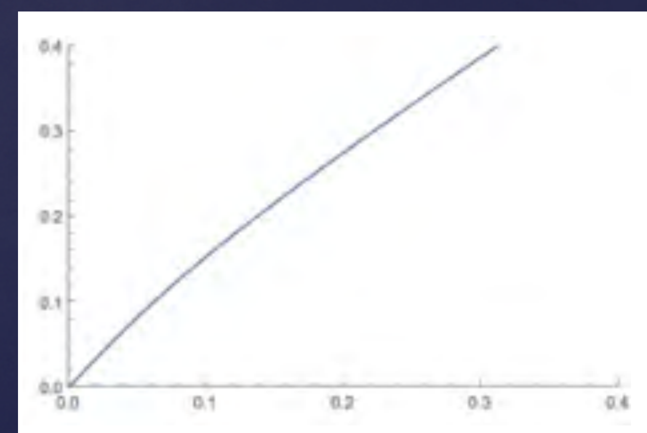


w/λ_0

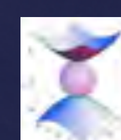


d/λ_0

w/λ_0



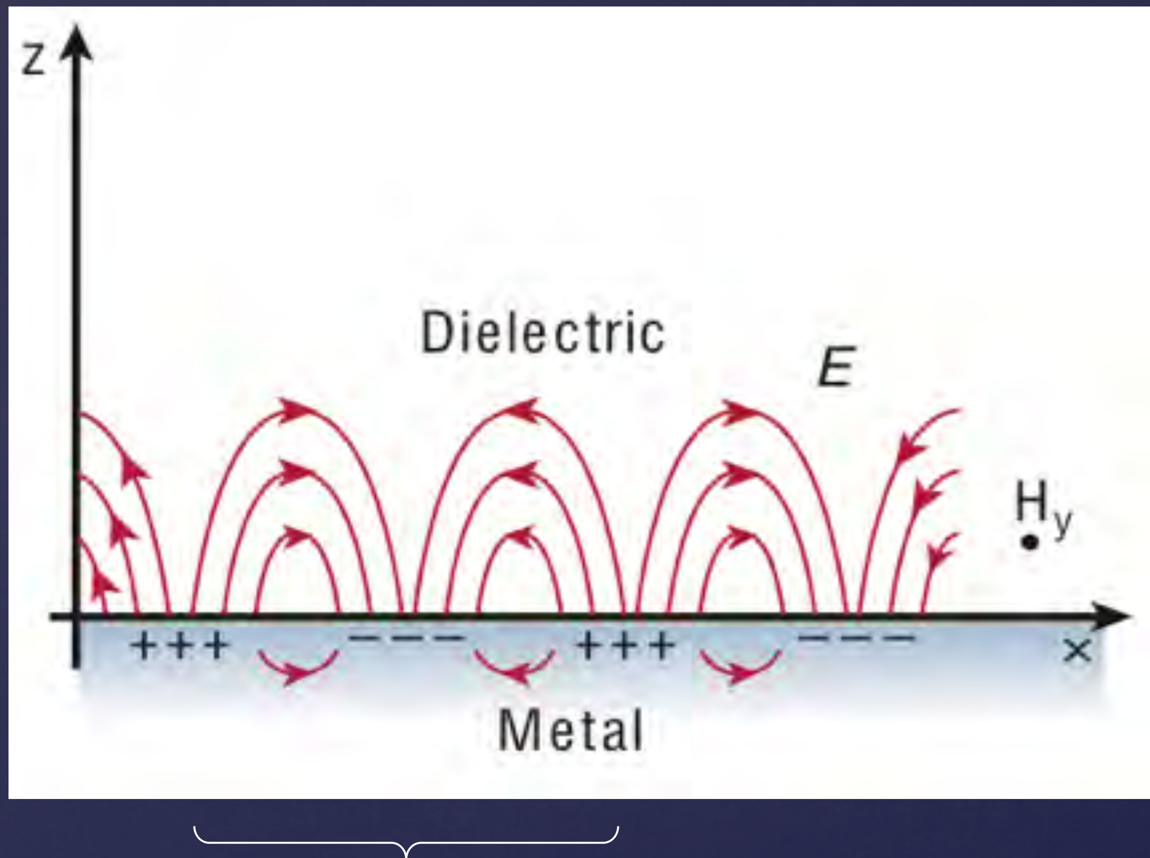
d/λ_0



Gramotnev and Bozhevolnyi, Nat. Phot. 4, 83 (2010)

Takahara et al., Opt. Lett. 22, 475 (1997)

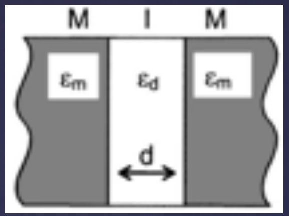
Surface plasmon polariton



$\lambda_{\sigma\pi}$

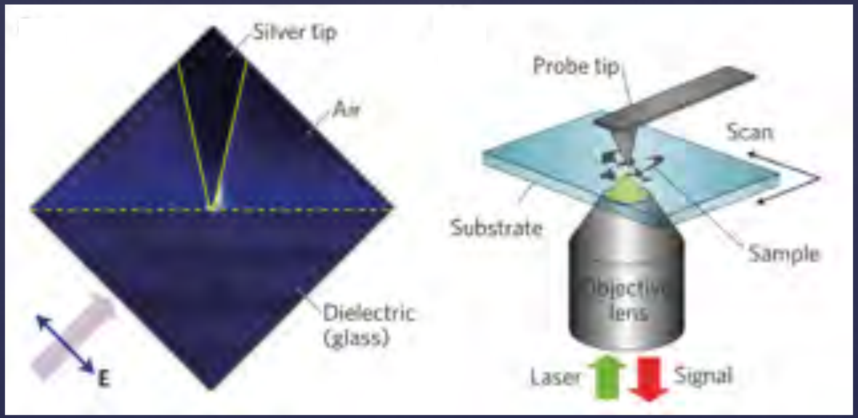
Barnes, Dereux and Ebbesen, Nature 424, 824 (2003)

Applications

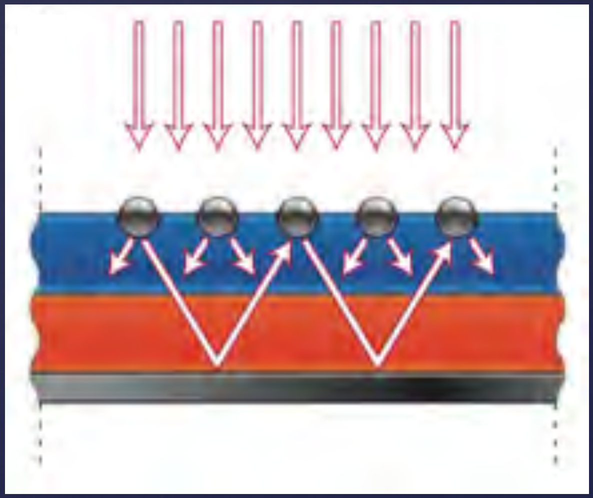


Takahara, Plasmonic Nanoguides and Circuits (2009)

Zia et al., J. Opt. Soc. Am. A 21, 2442 (2004)

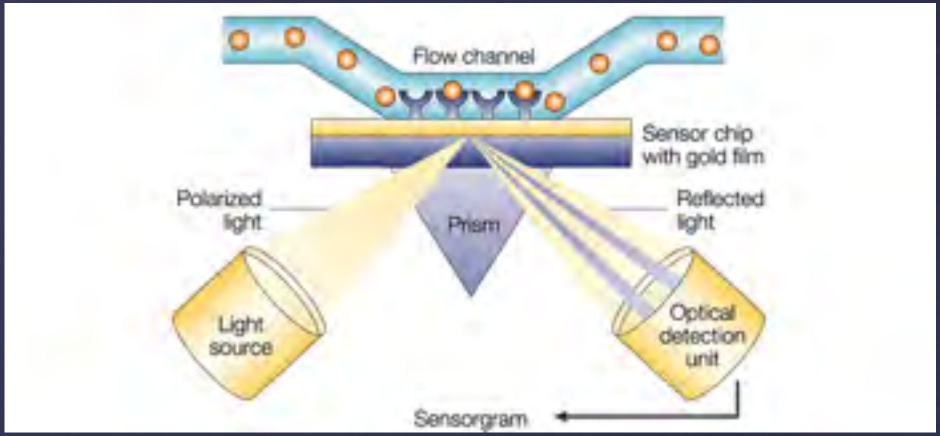


Kawata et al., Nature Phot. 3, 388 (2009)



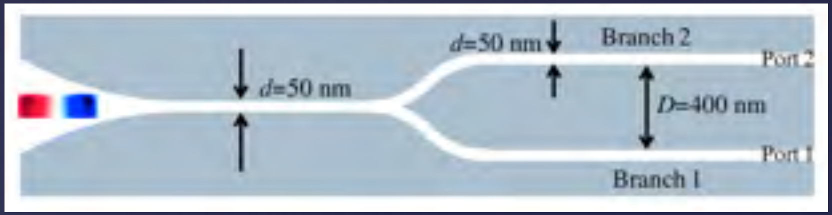
Atwater and Polman, Nature Mat. 9, 205 (2010)

More applications



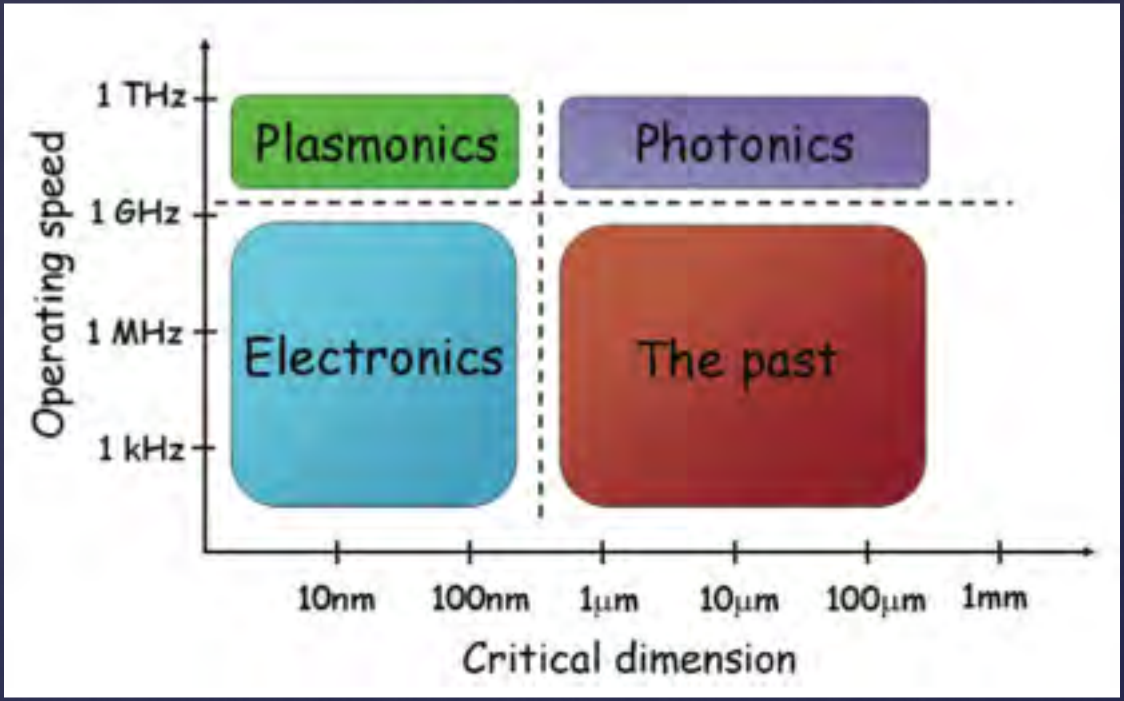
J. N. Anker et al., Nature Mat. 7, 442 (2008)

e.g. BIACORE, Dynamic Biosensors, Attana AB etc.



Gramotnev and Bozhevolnyi,
Nature Phot. 4, 83 (2010)

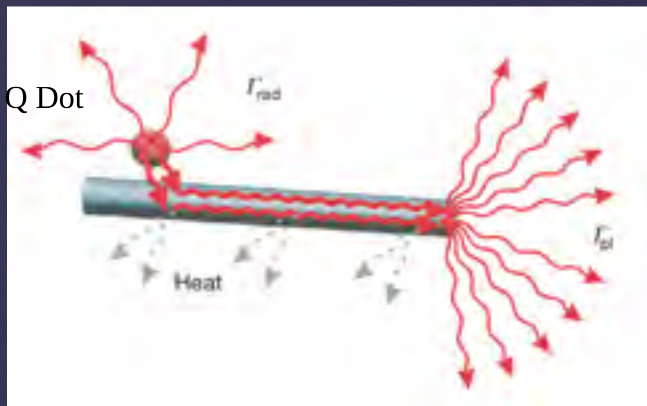
Technology perspective



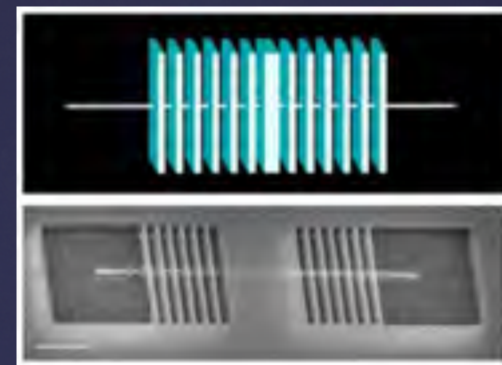
Zia et al., Materials Today 9, 20 (2006)

Single-photon sources

Enhancement of light-matter interaction



Akimov et al., Nature 450, 402 (2007)



de Leon et al., PRL 108, 226803 (2012)

waveguide

$g \propto 1/\sqrt{A_{eff}}$

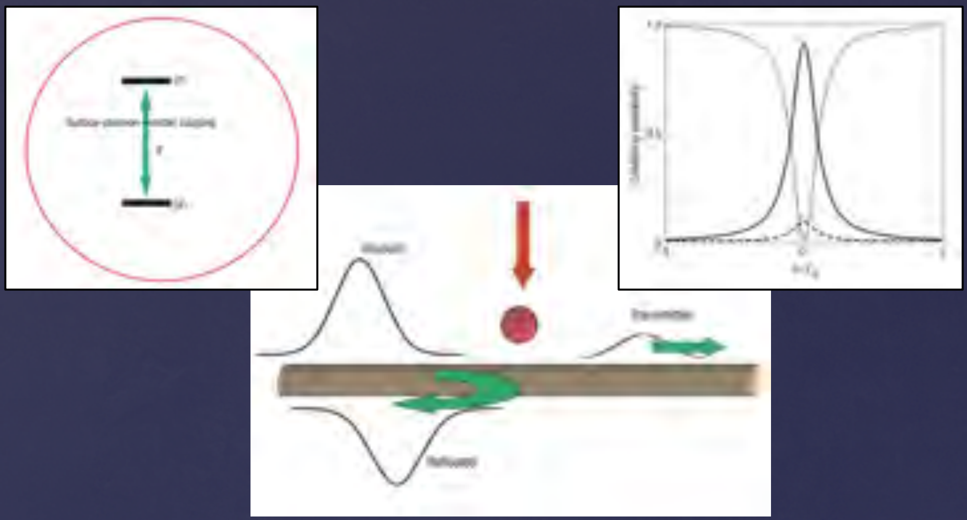
cavity

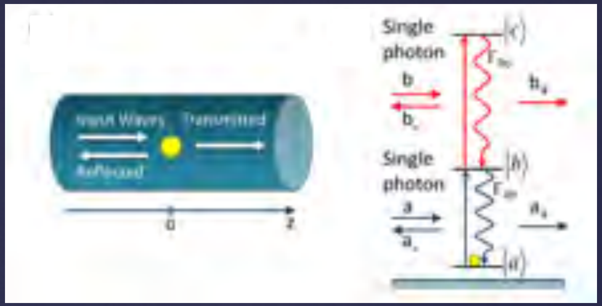
$g \propto 1/\sqrt{V_{eff}}$

Purcell effect $P \propto \frac{Q}{V}$

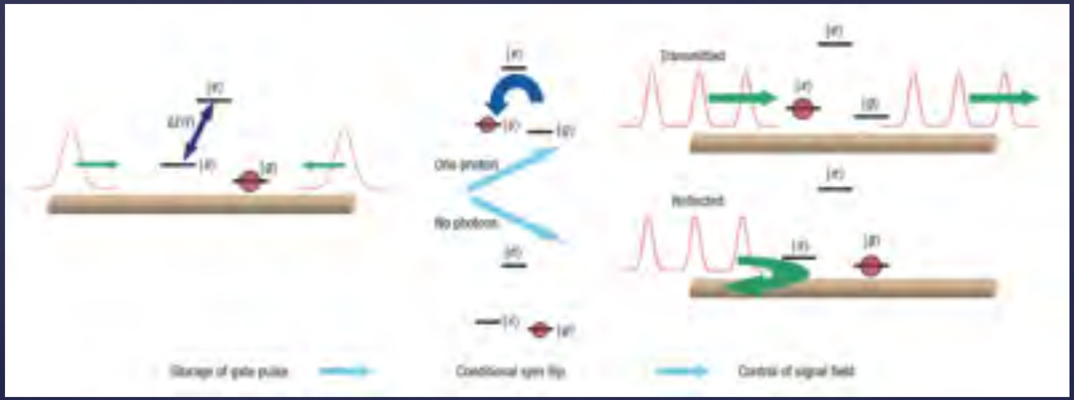
dielectric: $P \lesssim 1$ metal wire: $P \gtrsim 100$ metal cavity: $P \gtrsim 200$

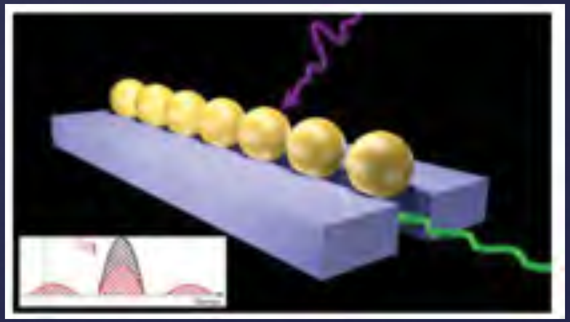
Single-photon switches





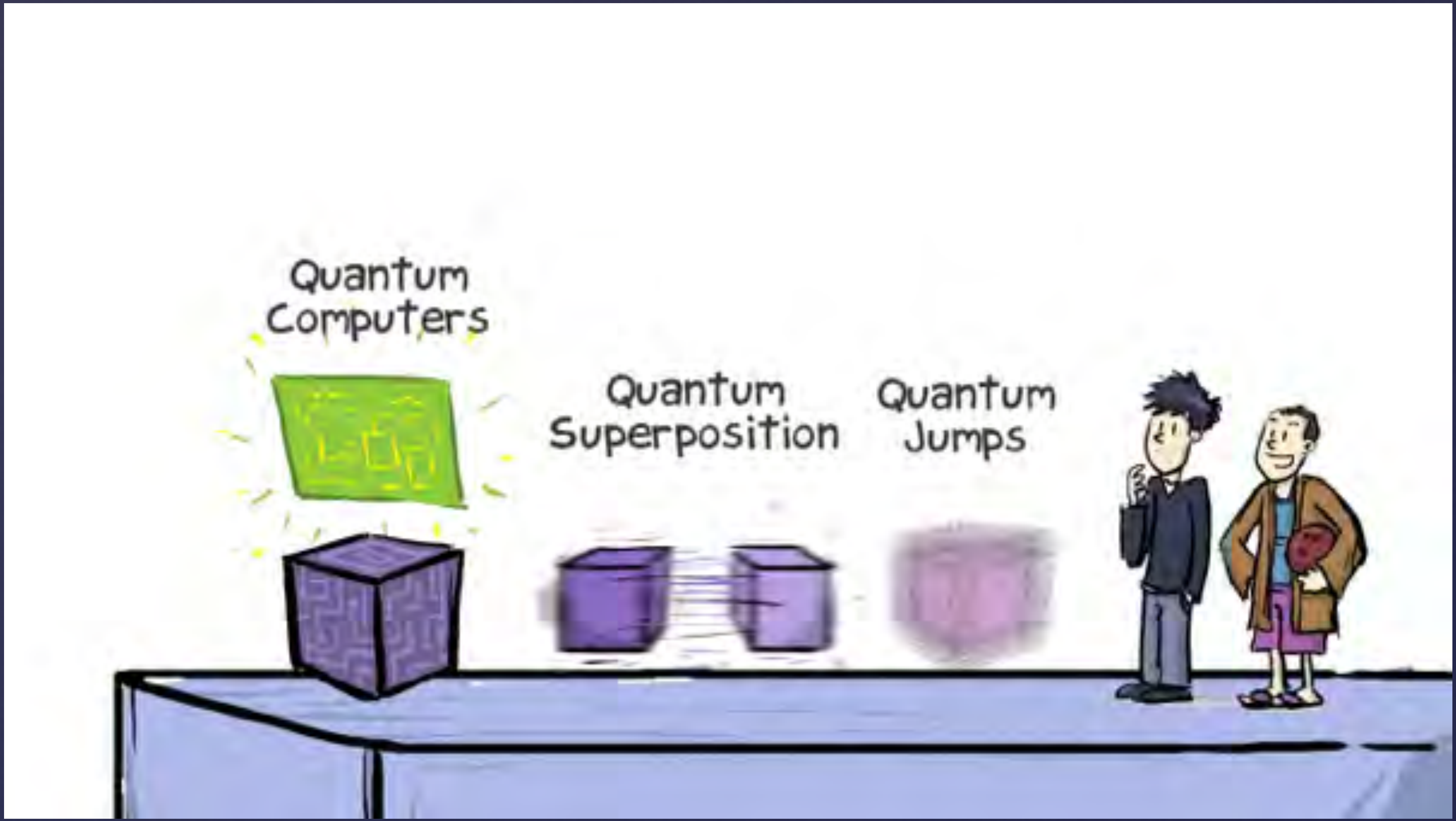
Kolchin et al., PRL 106, 113601 (2011)





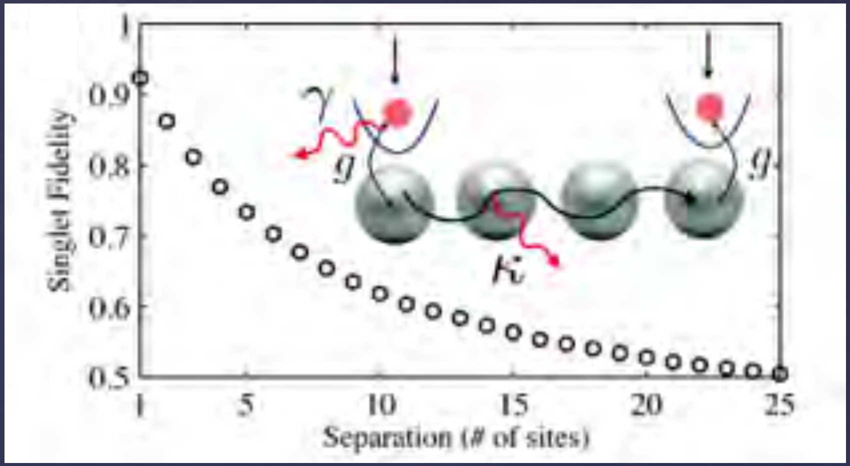
Frank, PRB 85, 195463 (2012)

Chang et al., Nature Phys. 3, 807 (2007)

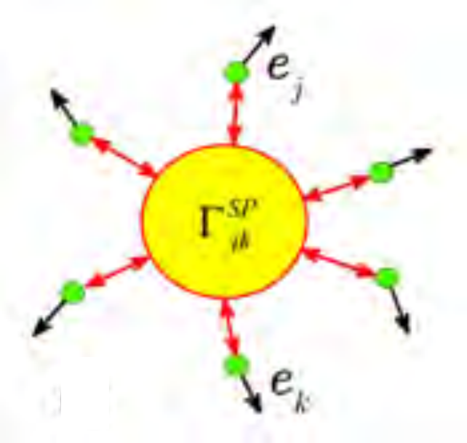


& Quantum Communication, Quantum Sensing…

Many-body quantum dynamics and simulation at nanoscale



Gullans et al., PRL 109, 235309 (2012)



Pustovit and Shahbazyan, PRB 82, 075429 (2010)

and more!

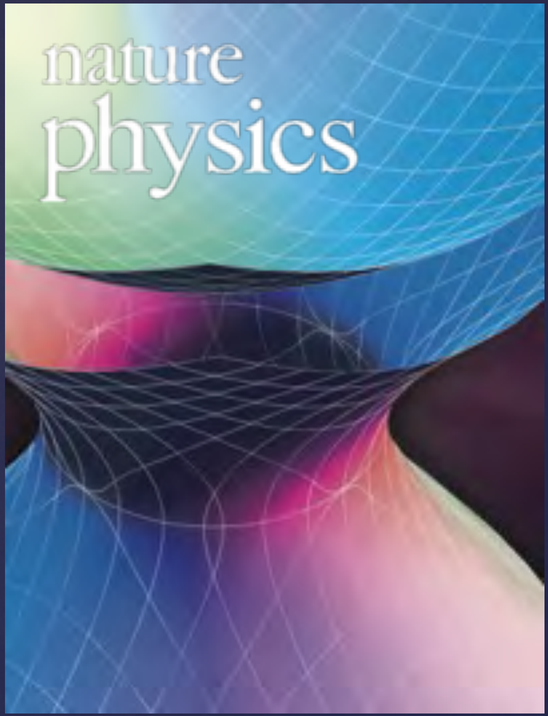

nature physics
REVIEW ARTICLE

Quantum plasmonics

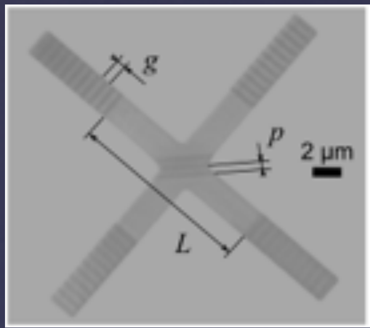
M. S. Tame[1*], K. R. McEnery[1,2], Ş. K. Özdemir[3], J. Lee[4], S. A. Maier[1*] and M. S. Kim[2]

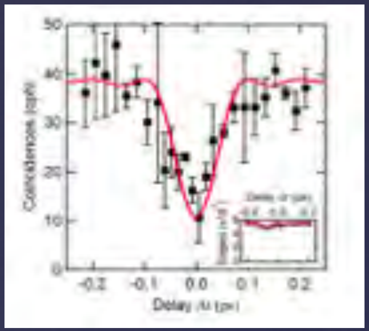
Quantum plasmonics is a rapidly growing field of research that involves the study of the quantum properties of light and its interaction with matter at the nanoscale. Here, surface plasmons—electromagnetic excitations coupled to electron charge density waves on metal-dielectric interfaces or localized on metallic nanostructures—enable the confinement of light to scales far below that of conventional optics. We review recent progress in the experimental and theoretical investigation of the quantum properties of surface plasmons, their role in controlling light-matter interactions at the quantum level and potential applications. Quantum plasmonics opens up a new frontier in the study of the fundamental physics of surface plasmons and the realization of quantum-controlled devices, including single-photon sources, transistors and ultra-compact circuitry at the nanoscale.

Tame et al., Nature Phys. 9, 329 (2013)



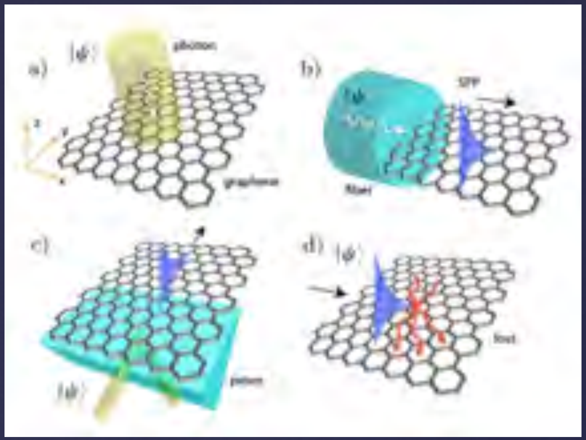
Quantum plasmonics





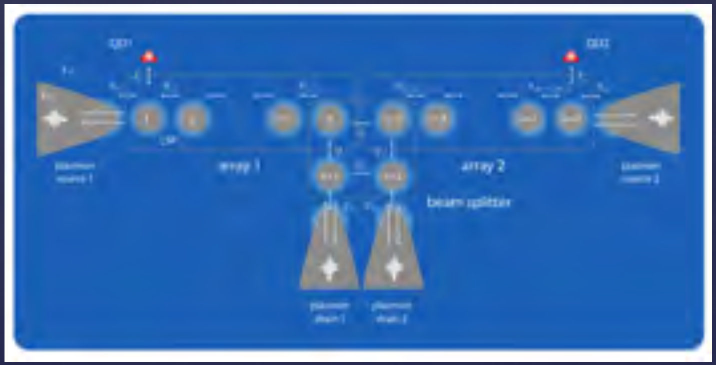
Plasmonic Hong-Ou-Mandel (e)

Di Martino et al., PR App. 1, 034004 (2014)



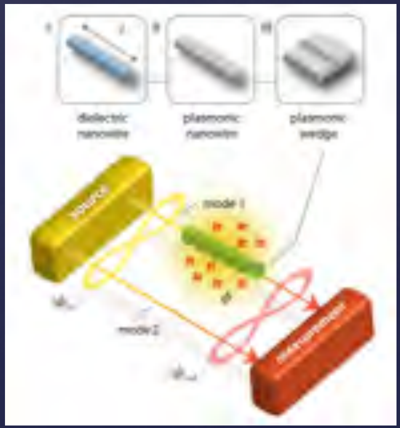
Loss-tolerant propagation in graphene (t)

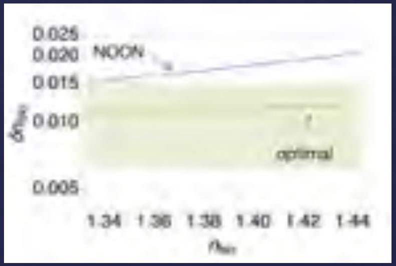
Hanson et al., Phys. Rev. A 92, 013828 (2015)



Robust-to-loss entanglement generation (t)

Lee et al., New J. Phys. 15, 083017 (2013)

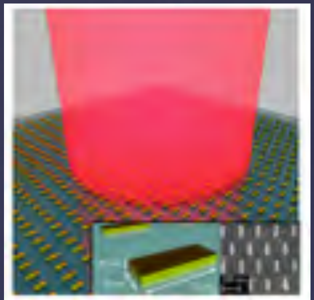


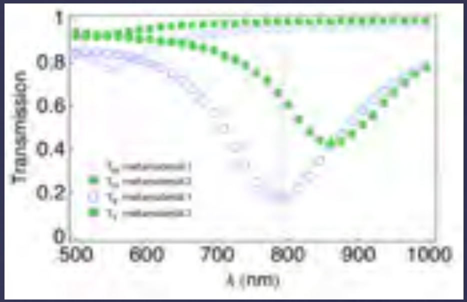


Quantum plasmonic sensing (t)

Lee et al. arXiv: 1601.00173 (2016)

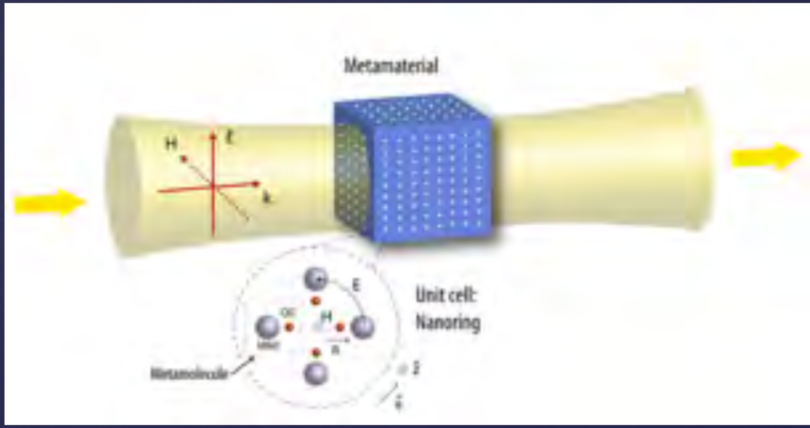
Quantum plasmonics





Entanglement distillation using a plasmonic metamaterial (e)

Asano et al., Scientific Reports (2015)



Quantum plasmonic metamaterials (t)

McEnery et al., PRA 89, 013822 (2014)

1. LOSS-TOLERANT PROPAGATION

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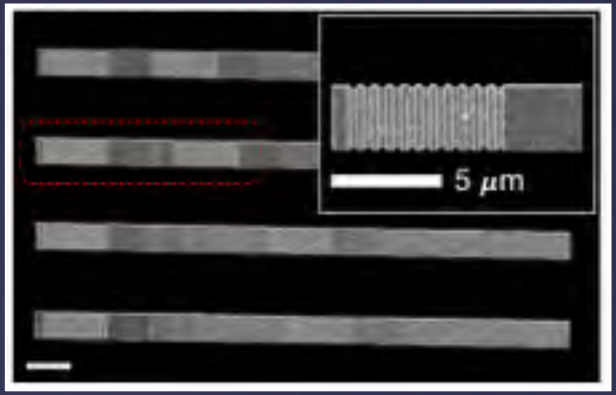

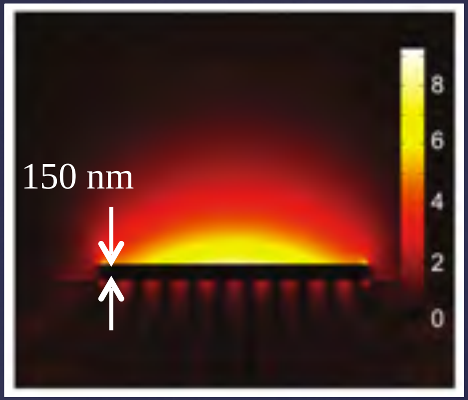

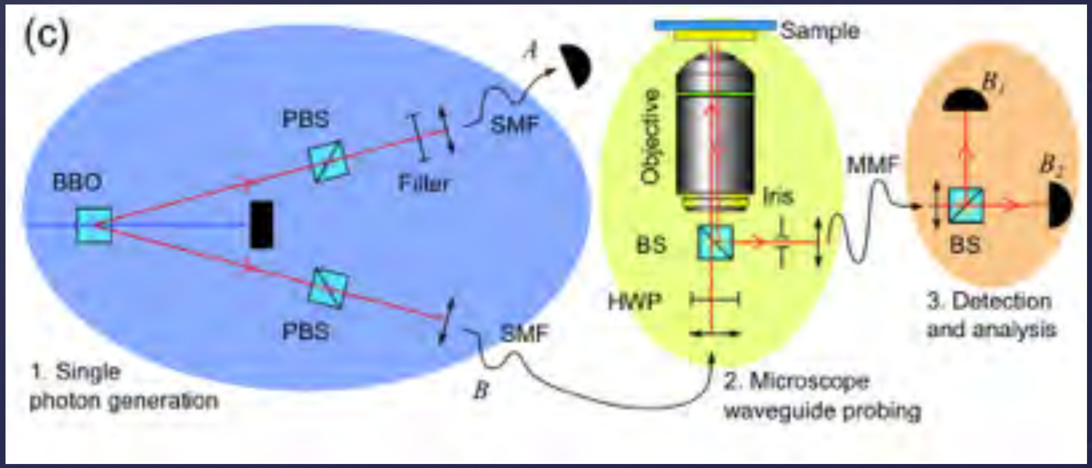

Di Martino et al., Nano Lett. 12, 2504 (2012)

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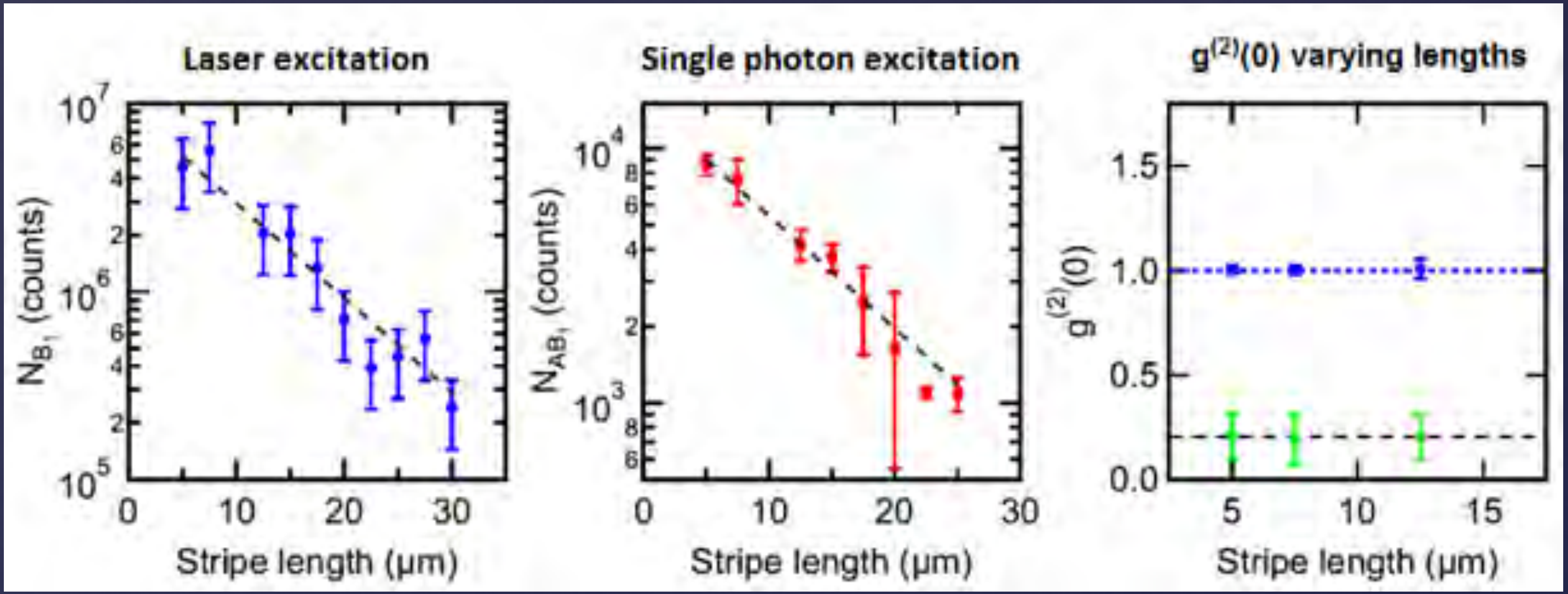

Di Martino et al., Nano Lett. 12, 2504 (2012)

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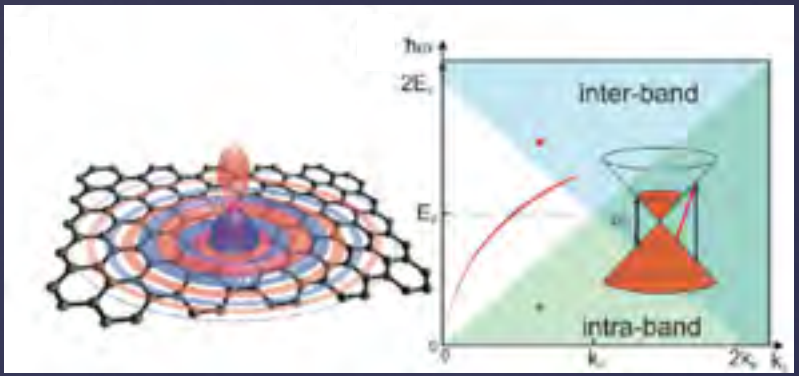
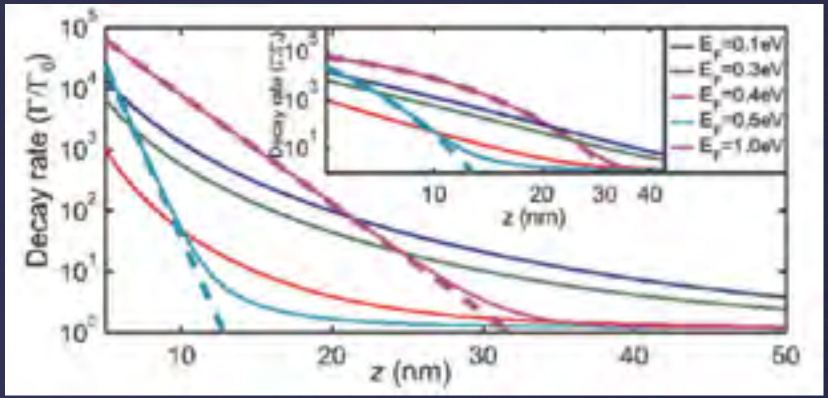
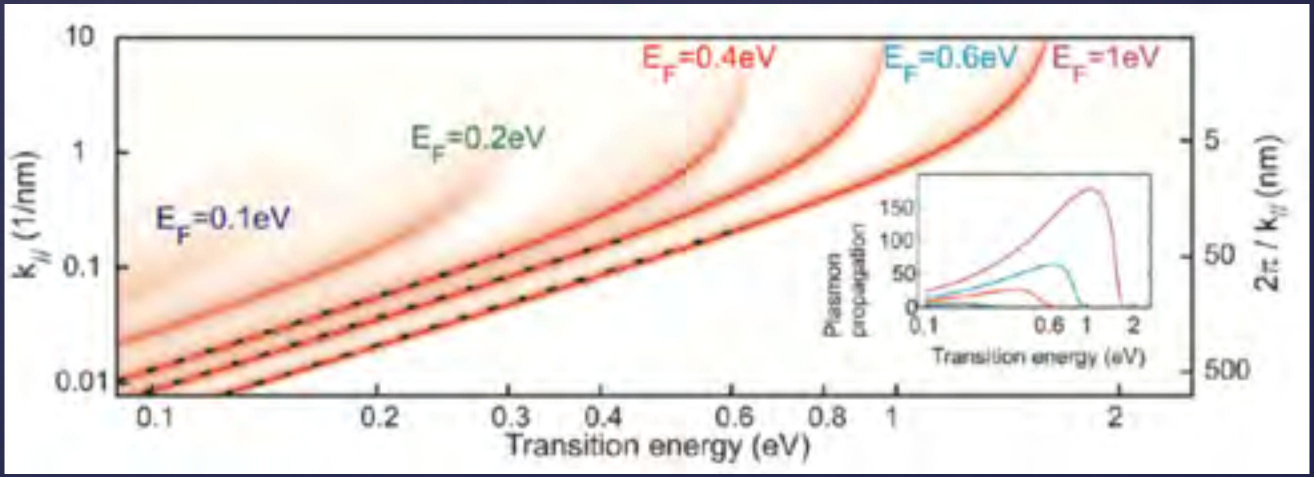
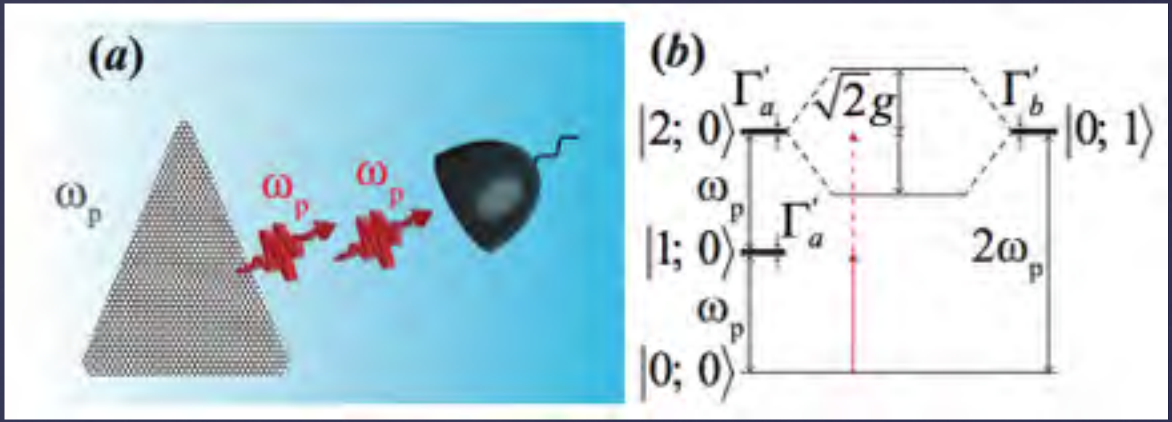




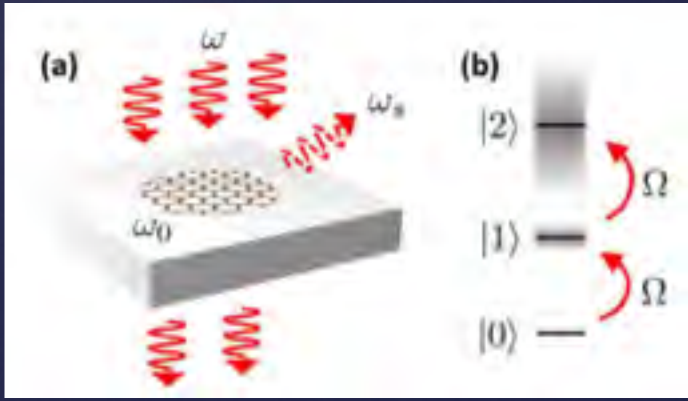


Koppens et al., NL 11, 3370 (2011)

1. LOSS-TOLERANT PROPAGATION



Manzoni et al., NJP 17, 083031 (2015)



Jablan and Chang, PRL 114, 236801 (2015)

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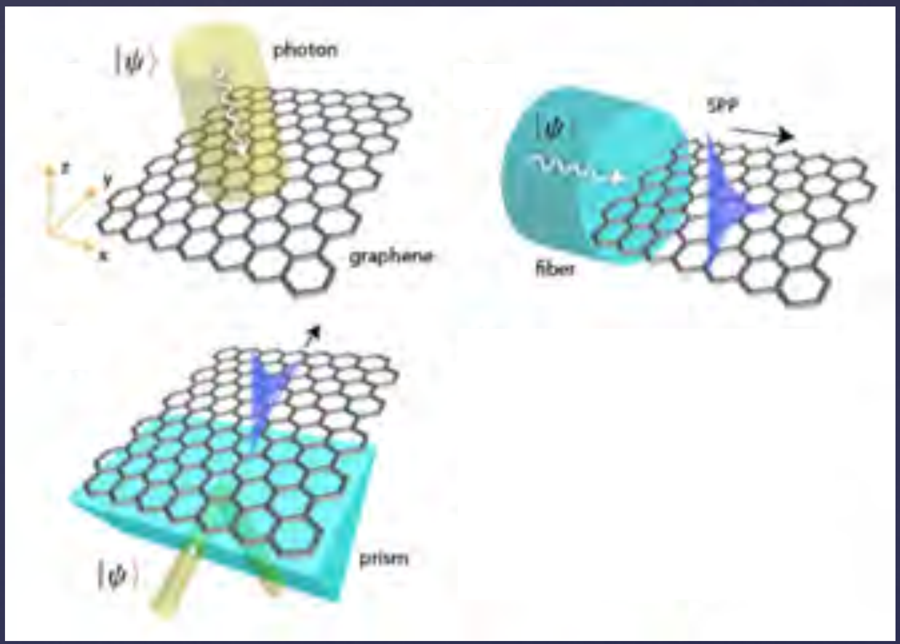
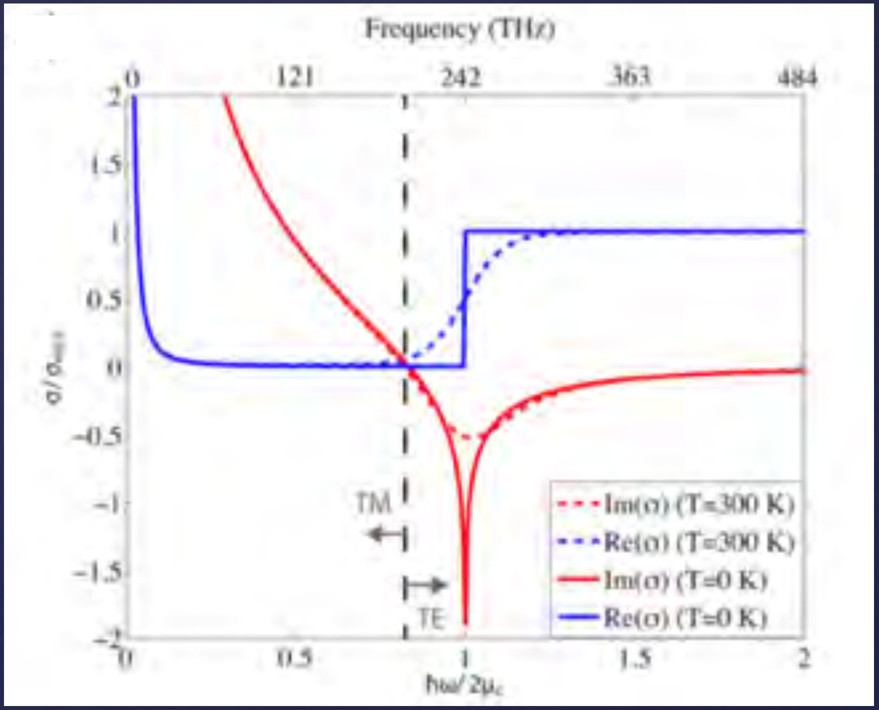


$$\sigma(\omega) = \frac{ie^2 k_B T}{\pi\hbar^2(\omega + i\Gamma)}\left(\frac{\mu_c}{k_B T} + 2\ln(e^{-\frac{\mu_c}{k_B T}} + 1)\right) + \frac{ie^2(\omega + i\gamma)}{\pi\hbar^2}\int_0^\infty \frac{f_d(-\varepsilon) - f_d(\varepsilon)}{(\omega + i\gamma)^2 - 4(\varepsilon/\hbar)^2}d\varepsilon$$



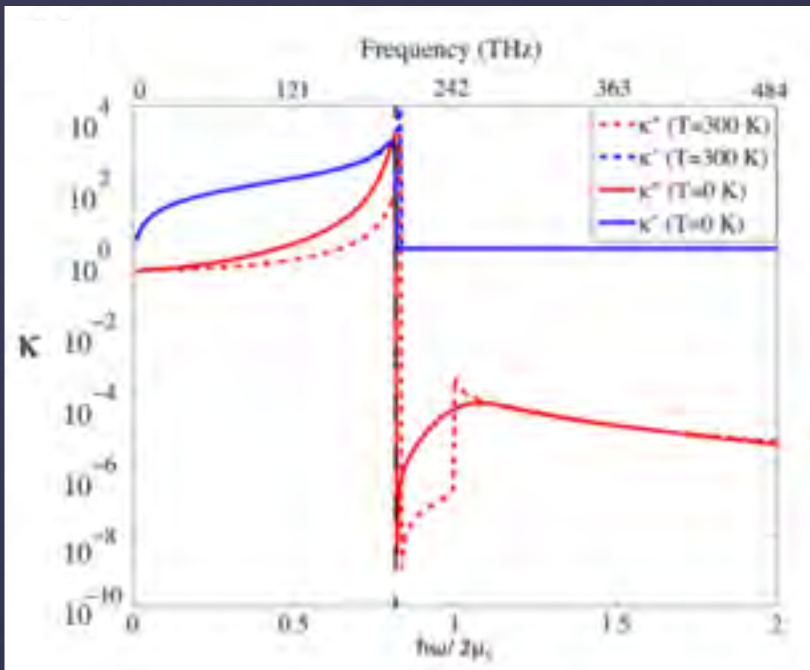
$$k^{\mathrm{TM}} = k_x^{\mathrm{TM}} = k_0\sqrt{\varepsilon_r\left(1 - \left(\frac{2}{\sigma\eta}\right)^2\right)},$$

$$k^{\mathrm{TE}} = k_x^{\mathrm{TE}} = k_0\sqrt{\varepsilon_r\left(1 - \left(\frac{\sigma\eta}{2}\right)^2\right)},$$

$$k_0 = \omega_k/c_0 \quad \eta = \sqrt{\mu_0\mu_r/\varepsilon_0\varepsilon_r}$$

Hanson et al., Phys. Rev. A 92, 013828 (2015)

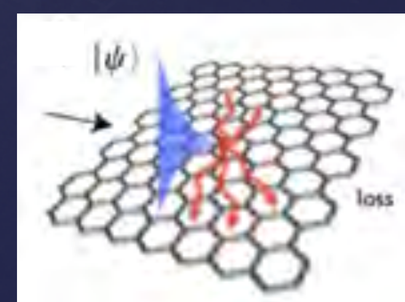
1. LOSS-TOLERANT PROPAGATION



$$\hat{\mathbf{A}}^{\mathrm{TE/TM}}_{\mathrm{SPP}}(\mathbf{r},t) = \frac{1}{2\pi}\int d\omega \sqrt{\frac{\hbar}{2\varepsilon_0 W v_g \omega N^{\mathrm{TE/TM}}}} \times \phi^{\mathrm{TE/TM}}(z,\omega)e^{-i\omega(t-x/v_g)}\hat{b}(\omega) + \mathrm{H.c.}$$

$$\hat{b}_{\mathrm{out}}(\omega,x) = e^{ik_x x}\hat{b}_{\mathrm{out}}(\omega) + i\sqrt{2k_0\kappa''(\omega)}\int_0^x dx' e^{ik_x(x-x')}\hat{c}(\omega,x')$$

$$\kappa = k_x/k_0 = \kappa' + i\kappa''$$



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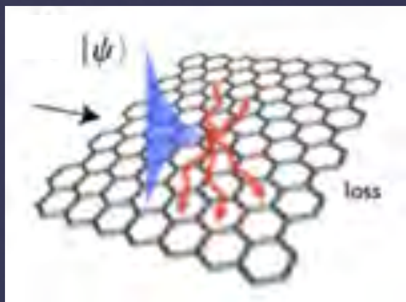
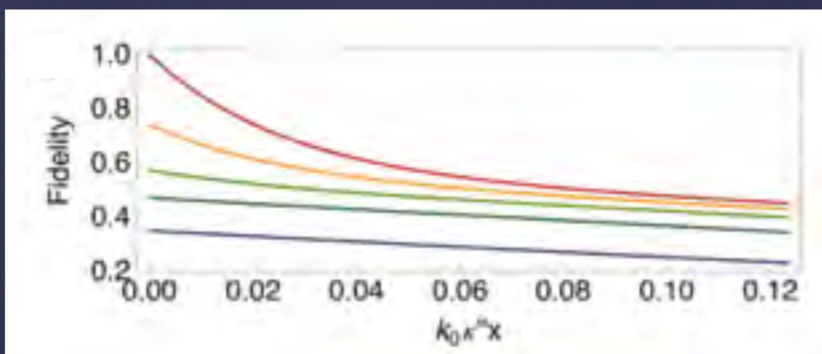


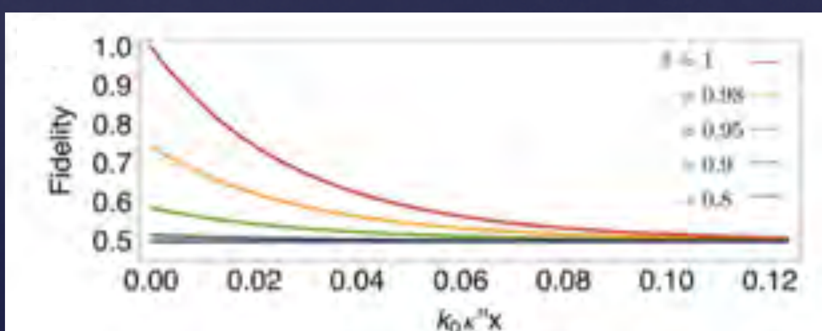
$$|\Psi\rangle_{\mathrm{in}} = N(|\alpha\rangle + |-\alpha\rangle)$$

$$|\pm\alpha\rangle \;= \exp[-|\alpha|^2/2] \sum_{n=0}^{\infty} (\pm\alpha)^n/\sqrt{n!}|n\rangle$$

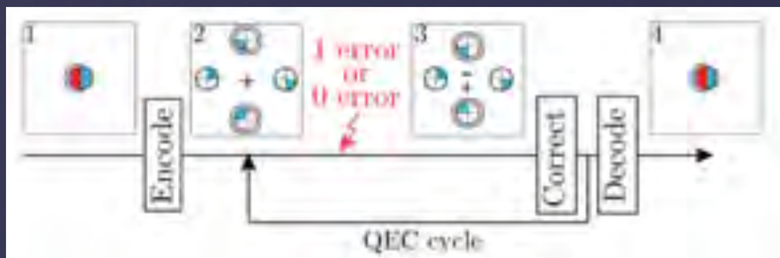
$$F \;=\; \langle\psi|\hat{\rho}|\psi\rangle$$



$\alpha = 3$

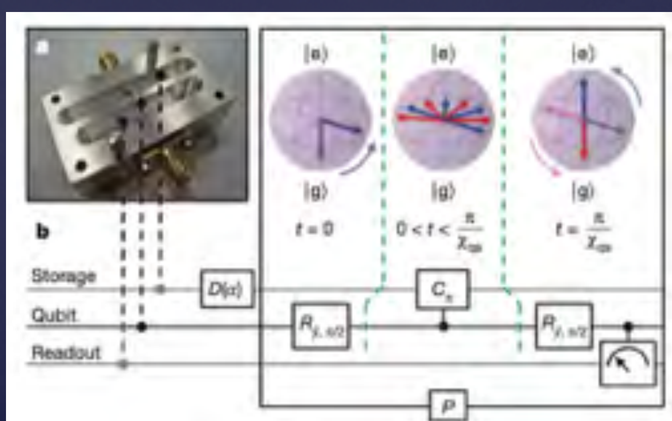


1. LOSS-TOLERANT PROPAGATION



Leghtas et al., PRL 111, 120501 (2013)
Mirrahimi et al., NJP 16, 045014 (2014)

Sun et al., Nature 511, 444 (2014)



$$|\bar{0}_\pm\rangle = \frac{1}{\sqrt{N_\pm}}(|\alpha\rangle \pm |-\alpha\rangle),$$
$$|\bar{1}_\pm\rangle = \frac{1}{\sqrt{N_\pm}}(|i\alpha\rangle \pm |-i\alpha\rangle),$$

$$N_\pm = 2(1 \pm e^{-2|\alpha|^2})$$

$$|\Psi\rangle = c_0|\bar{0}_+\rangle + c_1|\bar{1}_+\rangle$$

$$|c_0|^2 + |c_1|^2 = 1$$

1. LOSS-TOLERANT PROPAGATION

$$|\Psi\rangle = c_0|\bar{0}_+\rangle + c_1|\bar{1}_+\rangle$$

$$|c_0|^2 + |c_1|^2 = 1$$

Encode

$$\hat{\rho} \rightarrow \hat{\rho}' = \Delta P \hat{\rho}_{jump} + (1 - \Delta P)\hat{\rho}_{no-jump}$$

Loss

$$|\bar{0}_+\rangle\langle\bar{0}_+| \rightarrow \Delta P|\bar{0}_-\rangle\langle\bar{0}_-| + (1 - \Delta P)|\bar{0}_{+,\Delta t}\rangle\langle\bar{0}_{+,\Delta t}|$$
$$|\bar{1}_+\rangle\langle\bar{1}_+| \rightarrow \Delta P|\bar{1}_-\rangle\langle\bar{1}_-| + (1 - \Delta P)|\bar{1}_{+,\Delta t}\rangle\langle\bar{1}_{+,\Delta t}|$$

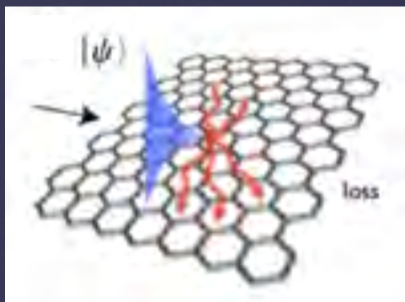
$$|\bar{0}_{\pm,\Delta t}\rangle = \frac{1}{\sqrt{N_{\pm,\Delta t}}}(|\alpha e^{-\gamma\Delta t/2}\rangle \pm |-\alpha e^{-\gamma\Delta t/2}\rangle),$$
$$|\bar{1}_{\pm,\Delta t}\rangle = \frac{1}{\sqrt{N_{\pm,\Delta t}}}(|i\alpha e^{-\gamma\Delta t/2}\rangle \pm |-i\alpha e^{-\gamma\Delta t/2}\rangle)$$

$$\hat{P} = e^{i\pi \hat{a}^\dagger \hat{a}} = \sum_n e^{i\pi n}|n\rangle\langle n|$$ →

$$\langle\bar{0}_+|\hat{P}|\bar{0}_+\rangle = \langle\bar{1}_+|\hat{P}|\bar{1}_+\rangle = +1$$
$$\langle\bar{0}_-|\hat{P}|\bar{0}_-\rangle = \langle\bar{1}_-|\hat{P}|\bar{1}_-\rangle = -1$$

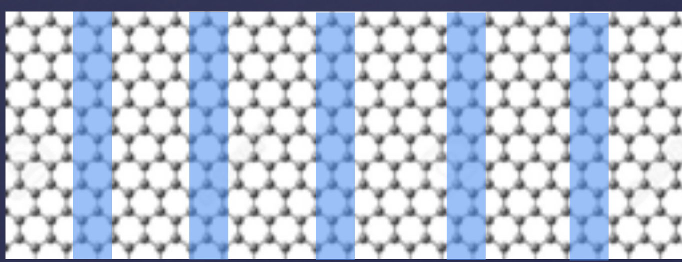
Parity check

1. LOSS-TOLERANT PROPAGATION

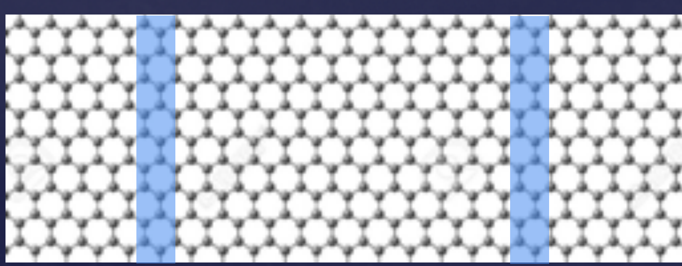


Ideal case parity check is every $\Delta x \ll (2k_0\kappa''|\alpha|^2)$ m

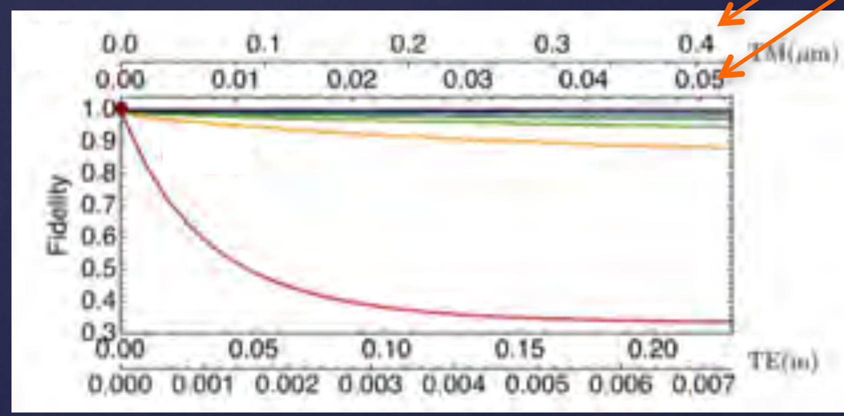
p=1



p=0.5



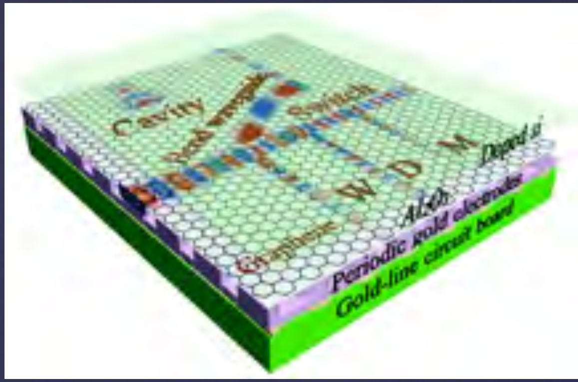
1500 nm
810 nm



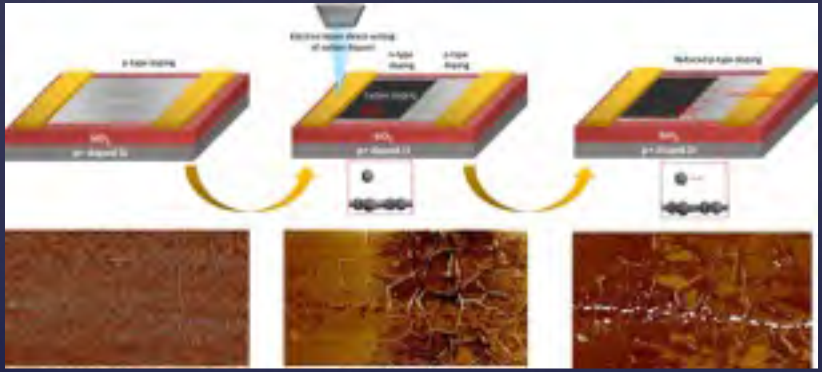
$\alpha = 3$

Fidelity averaged over Bloch sphere

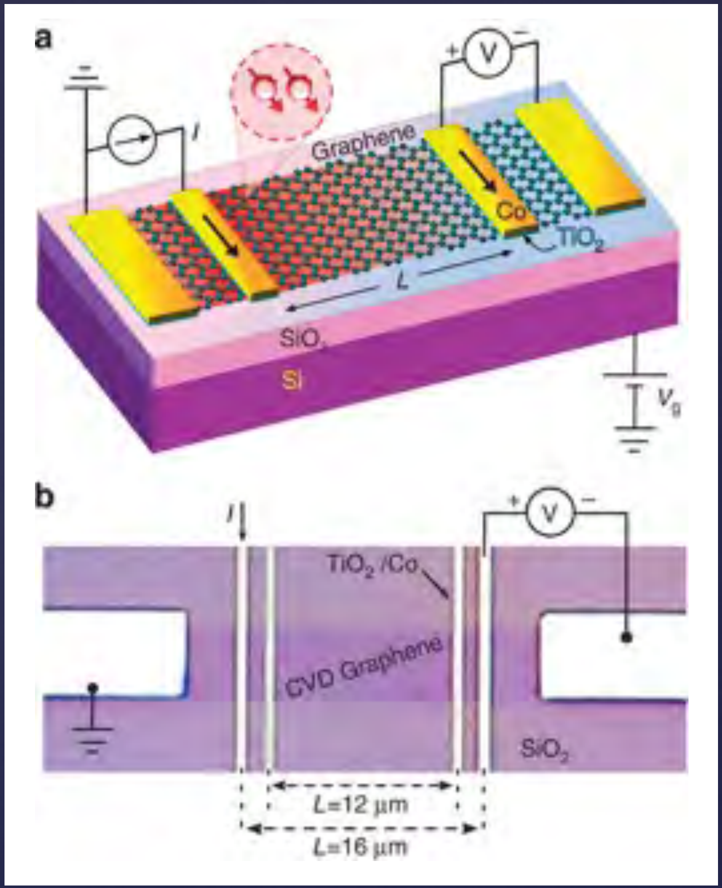
1. LOSS-TOLERANT PROPAGATION



Chen et al., Nanoscale 7, 10912 (2015)



Kim et al., Nanoscale 7, 14946 (2015)

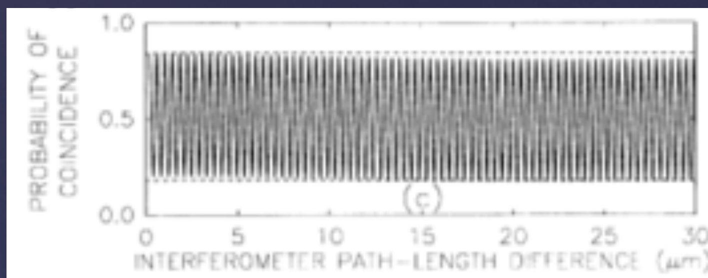


Kamalakar et al., Nat. Comm. 6, 6766 (2015)

2. QUANTUM PLASMONIC SENSING

2. QUANTUM PLASMONIC SENSING

Caves, PRD 23, 1693 (1981)



N=2

$$|\psi_{\text{in}}\rangle = \frac{1}{\sqrt{2}}\left(|N0\rangle + |0N\rangle\right)_{12}$$

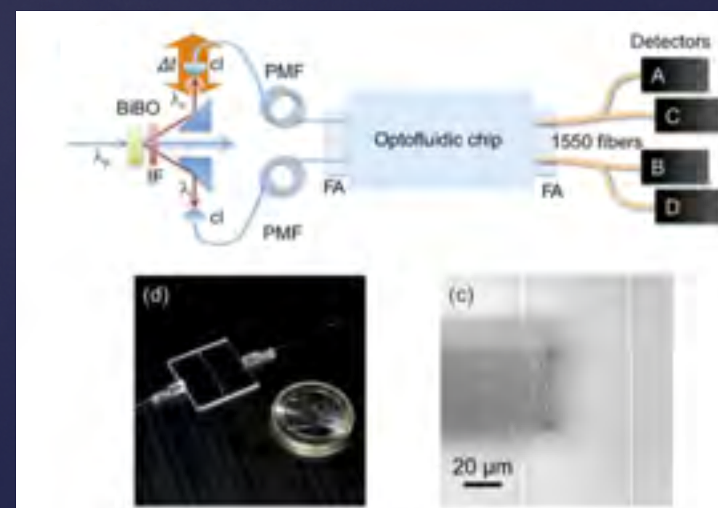
Rarity et al., PRL 65, 1348 (1990)

Lee et al., J. Mod. Opt. 49, 2325 (2002)

Giovannetti et al., Science 306, 1330 (2004)

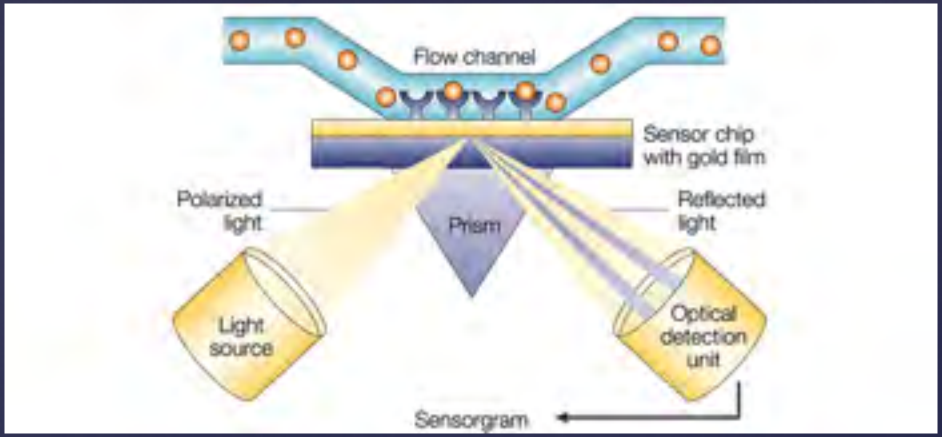
Nagata et al., Science 316, 5825 (2007) N=4

Demkowicz-Dobrzanski et al.,
Prog. Opt. 60, 345 (2015)



Crespi et al., APL 100, 233704 (2012)

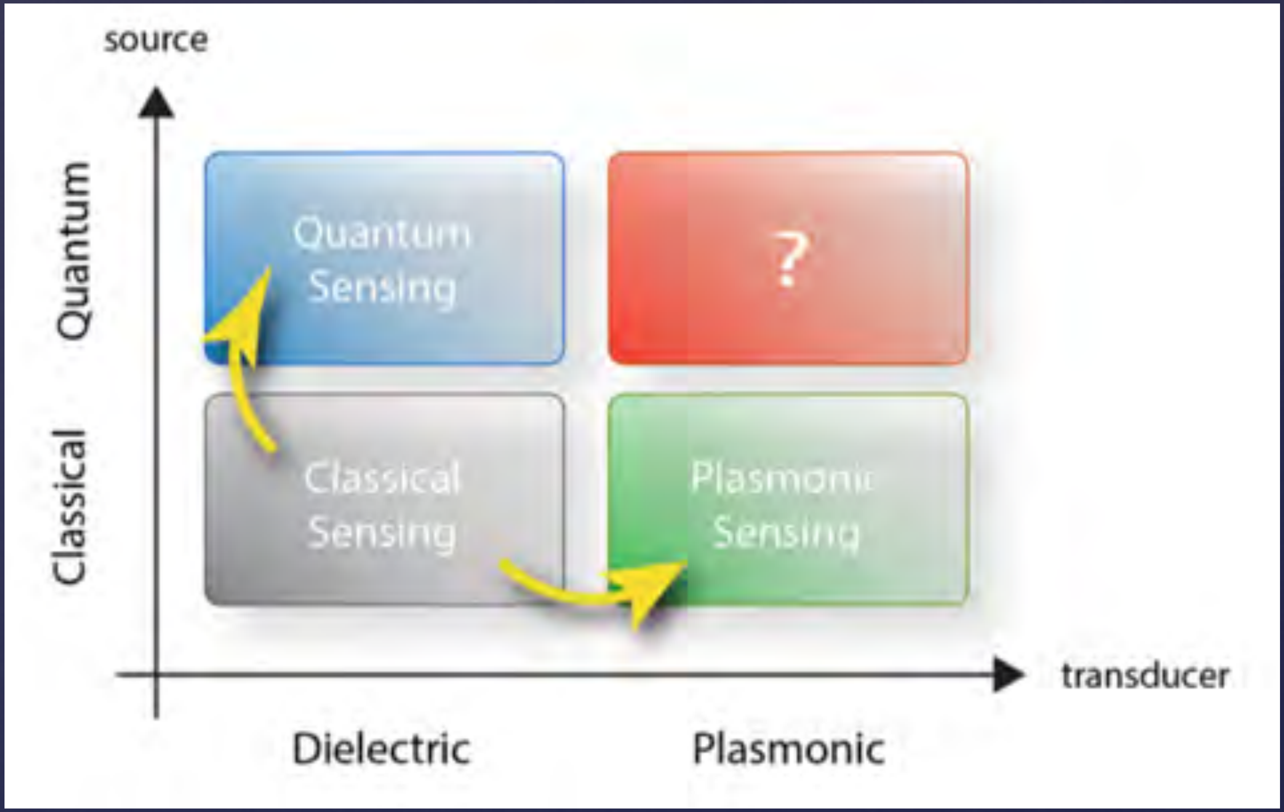
2. QUANTUM PLASMONIC SENSING



J. N. Anker et al., Nature Mat. 7, 442 (2008)

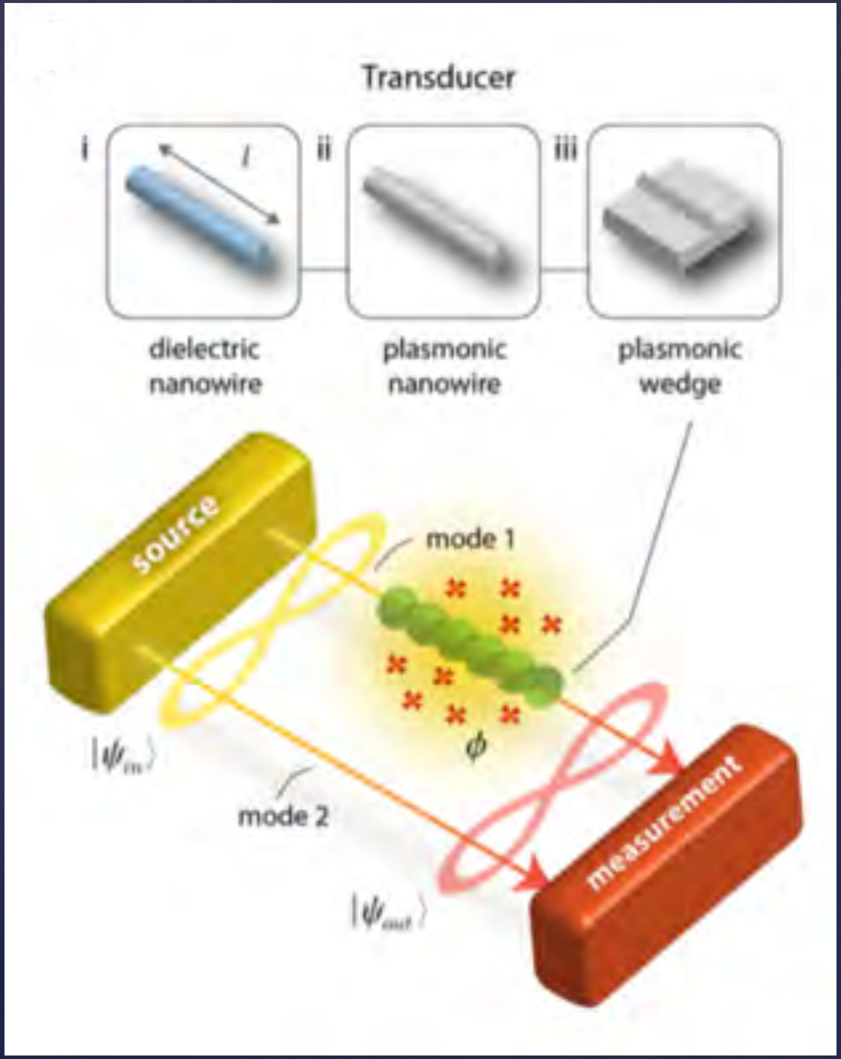
e.g. BIACORE, Dynamic Biosensors, Attana AB etc.

2. QUANTUM PLASMONIC SENSING

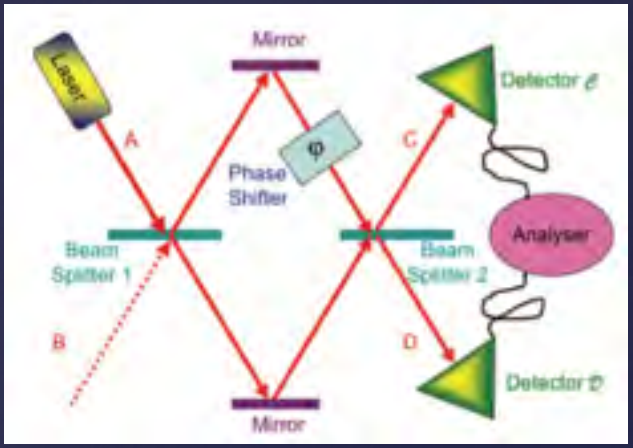


Lee et al. arXiv: 1601.00173 (2016)

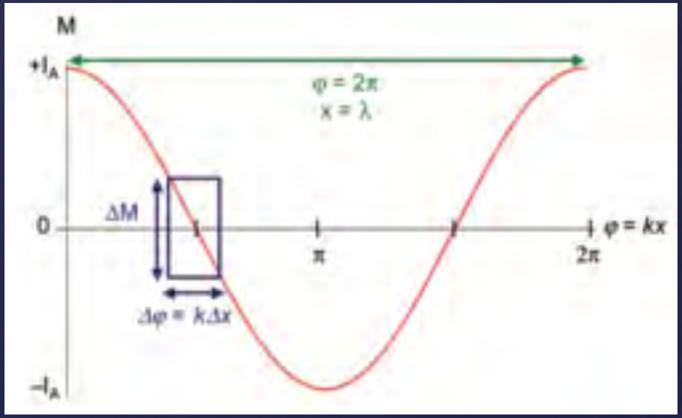
2. QUANTUM PLASMONIC SENSING



Dowling, Contem. Phys. 49, 125 (2008)



$$M(\varphi) \equiv I_{\mathrm{D}} - I_{\mathrm{C}} = I_{\mathrm{A}} \cos(\varphi)$$



2. QUANTUM PLASMONIC SENSING

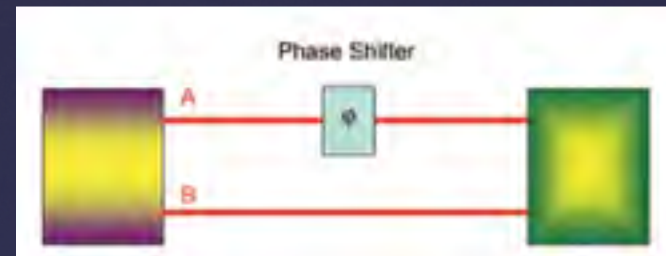
1. Source (fixed number of photons N)

(i) Classical:

$$|\alpha\rangle_A |0\rangle_B \xrightarrow{\text{BS}} \left|\frac{\alpha}{\sqrt{2}}\right\rangle_A \left|\frac{\alpha}{\sqrt{2}}\right\rangle_B \qquad |\alpha|^2 = N$$

(ii) Quantum:

$$|\text{N00N}\rangle = \frac{1}{\sqrt{2}}(|N\rangle_A |0\rangle_B + |0\rangle_A |N\rangle_B)$$



source measurement

2. Phase ϕ picked up in mode A

3. Measurement

(i) Classical: beamsplitter (BS) on modes, then measurement of intensity difference $M = I_B - I_A$ →

→ minimum resolution $\delta\phi^{(\text{SNL})} = 1/\sqrt{N}$

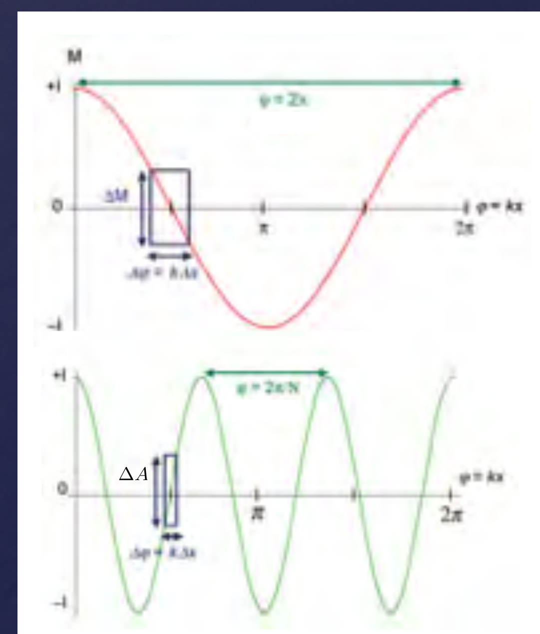
'shot noise' limit

(ii) Quantum: measurement of operator

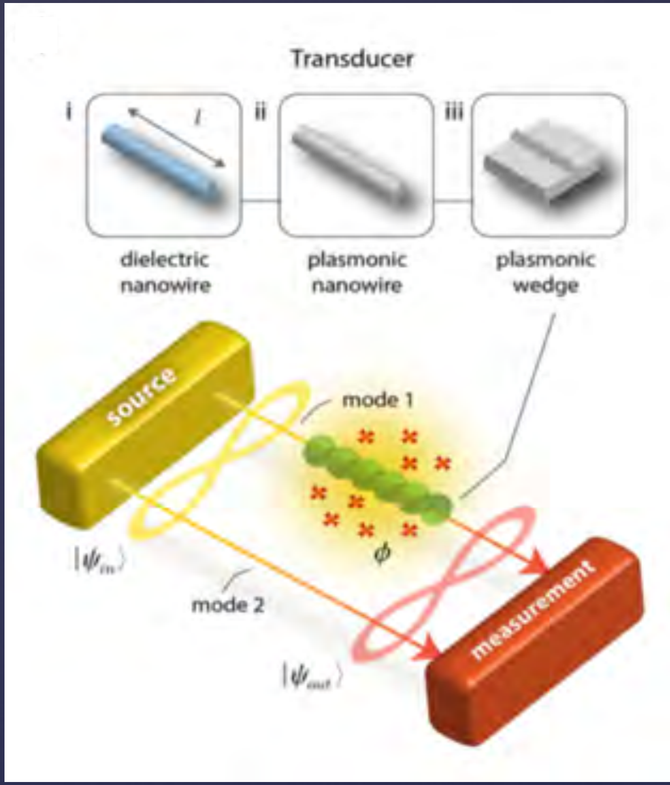
$$\hat{A} = |0, N\rangle\langle N, 0| + |N, 0\rangle\langle 0, N|$$ →

→ minimum resolution $\delta\phi^{(\text{HL})} = 1/N$

'Heisenberg' limit

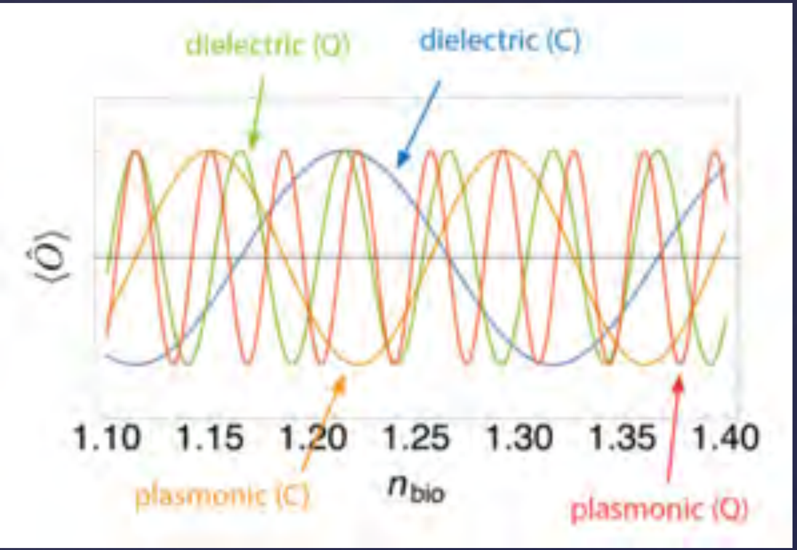


2. QUANTUM PLASMONIC SENSING



nanowire
l = 4um
λ_0 = 810 nm
r = 50 nm

N=4

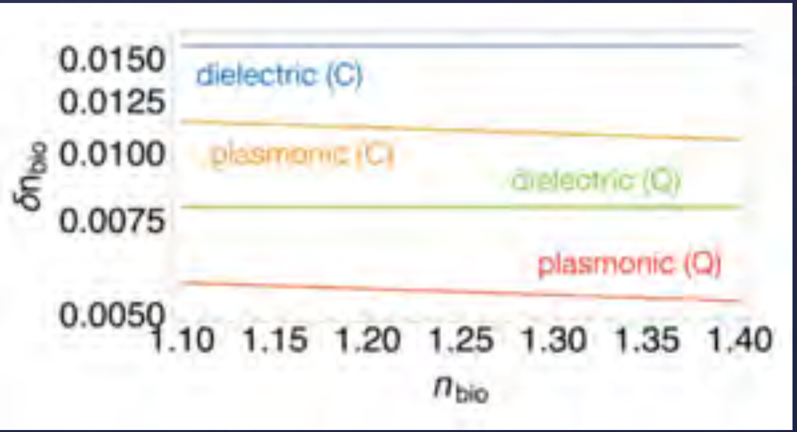


Minimum resolution

$$\delta n_{bio} = \frac{\Delta \hat{O}}{|\partial \langle \hat{O} \rangle / \partial n_{bio}|}$$

$$\phi(n_{bio}) = \beta(n_{bio}) \times l$$

$$\Delta \hat{O} = (\langle \hat{O}^2 \rangle - \langle \hat{O} \rangle^2)^{1/2}$$



2. QUANTUM PLASMONIC SENSING

- When loss is included the NOON state is no longer optimal
- Neither is the measurement operator A

Optimal states

$$|\psi_{\rm in}\rangle = \sum_{n=0}^{N} c_n |n, N-n\rangle$$

for some set of coefficients c_n depending on loss

Dorner et al., PRL 102, 040403 (2009)

Optimal measurement

Hard to find but we can use the following relation:

$$\delta\phi = F_Q^{-1/2}$$

F_Q – Fisher information

(amount of info about ϕ that state contains)

and use

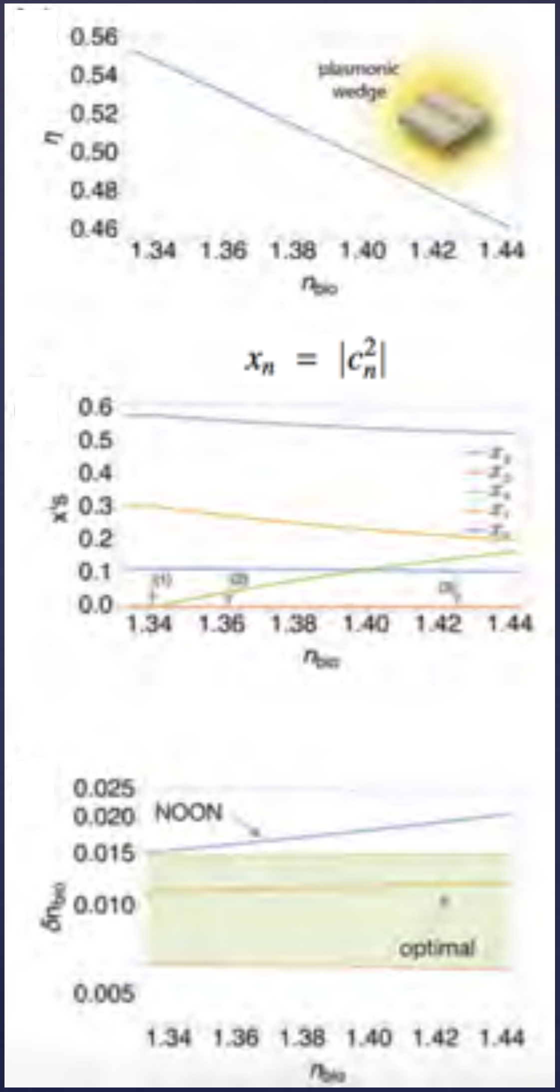
$$\delta n_{\rm bio} = \delta\phi \left| \frac{\partial\phi}{\partial n_{\rm bio}} \right|^{-1}$$

depends on medium (dielectric or plasmonic)

depends on state and measurement

$\partial\phi/\partial n_{\rm bio}$ $(= l \times \partial\beta/\partial n_{\rm bio})$

2. QUANTUM PLASMONIC SENSING



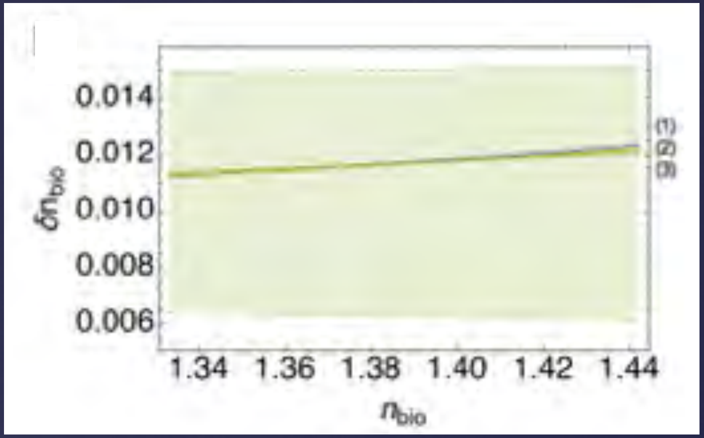
l = 4um

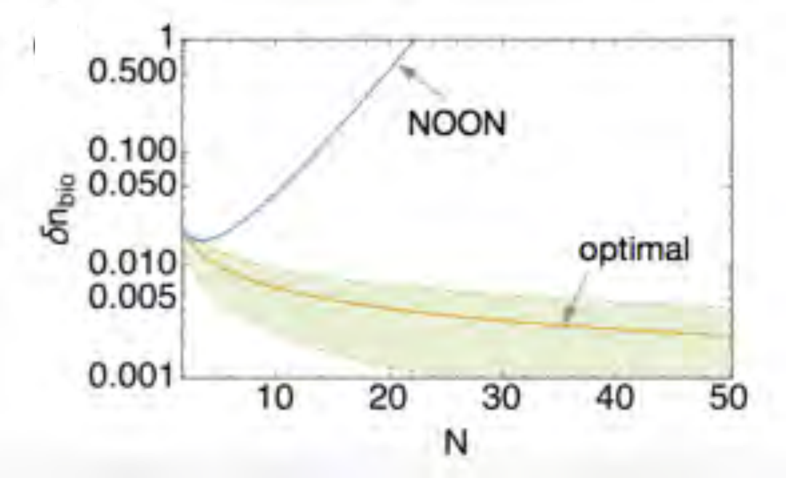
λ_0 = 810 nm

h = 50 nm

SNL (SIL)

HL

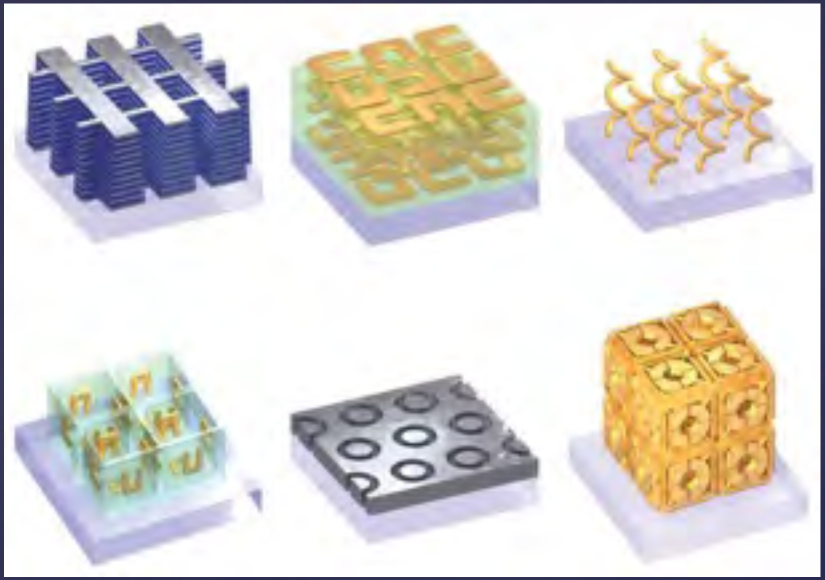




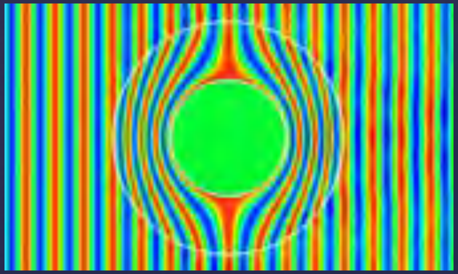
Quantum plasmonic sensing is useful for highly photosensitive material of which only a small quantity is available

3. ENGINEERED METAMATERIALS

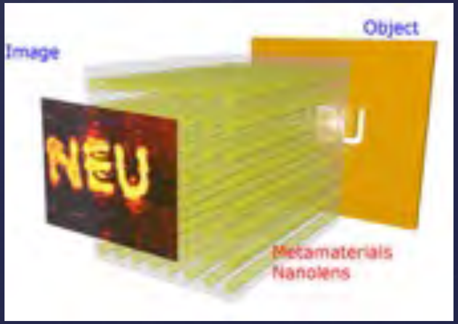
3. ENGINEERED METAMATERIALS



Soukoulis and Wegener, Nat. Phot. 5, 523 (2011)

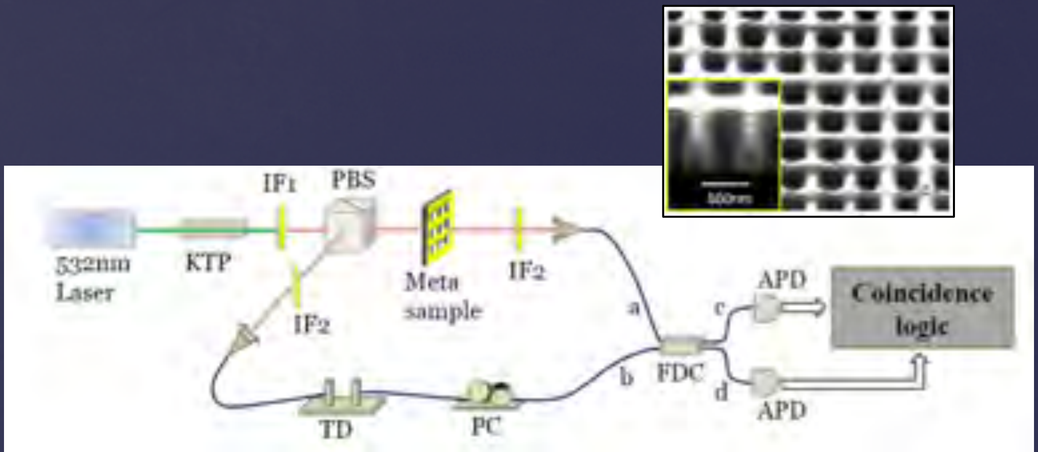


Cai et al., Nat. Phot. 1, 224 - 227 (2007)

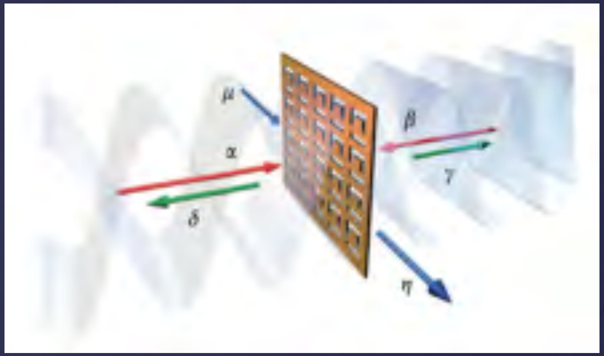


Casse et al., APL 96, 023114 (2010)

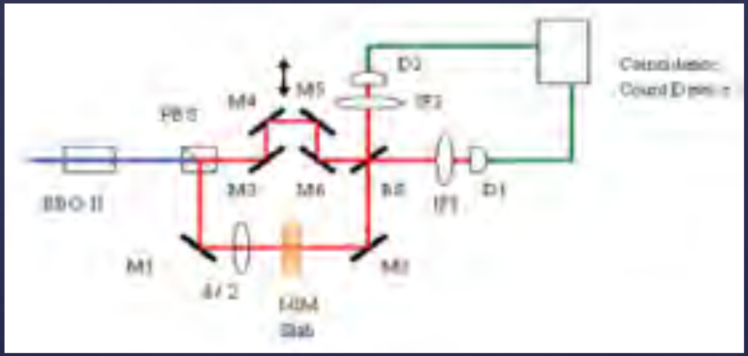
Quantum optical metamaterials



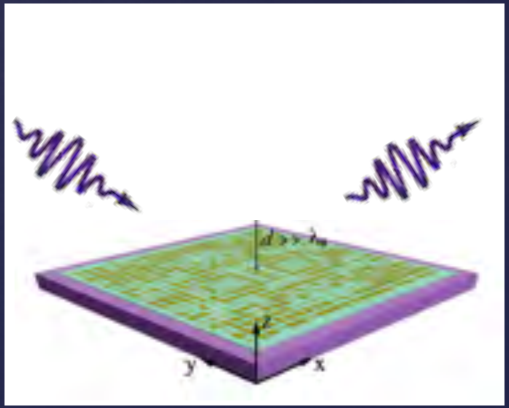
Wang et al., Opt. Exp. 20, 5213 (2012)



Roger et al., Nat. Comm. 6, 7031 (2015)

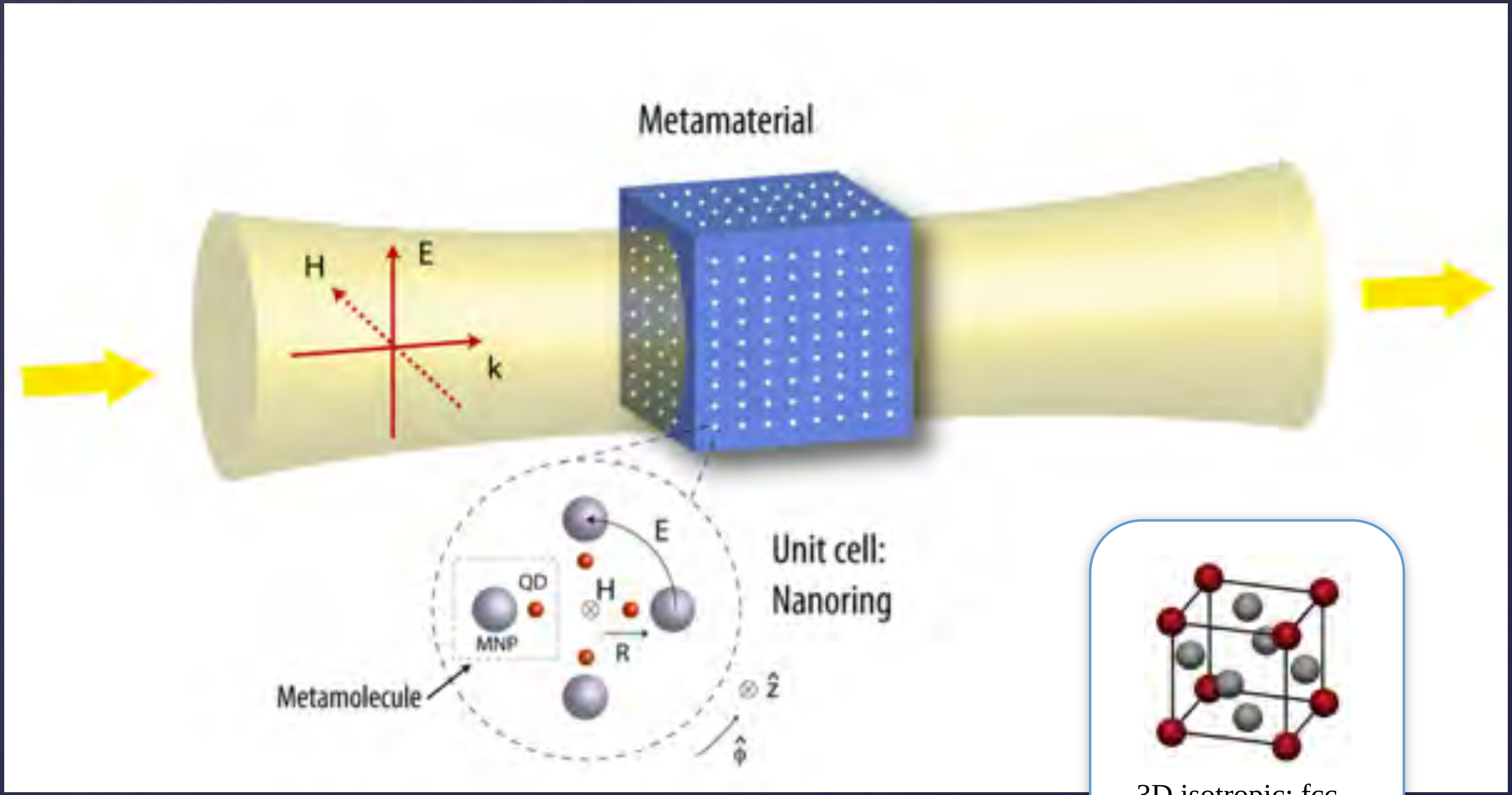


Zhou et al., PRA 85, 023841 (2012)



Jha et al., PRL 115, 025501 (2015)

Quantum optical metamaterials

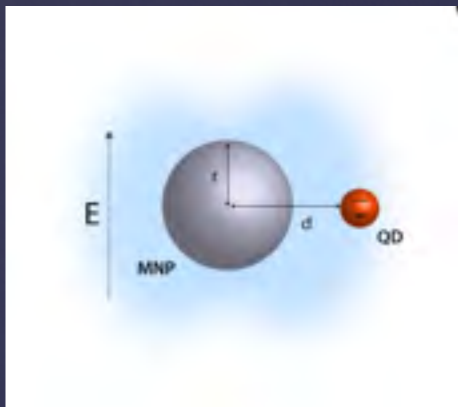


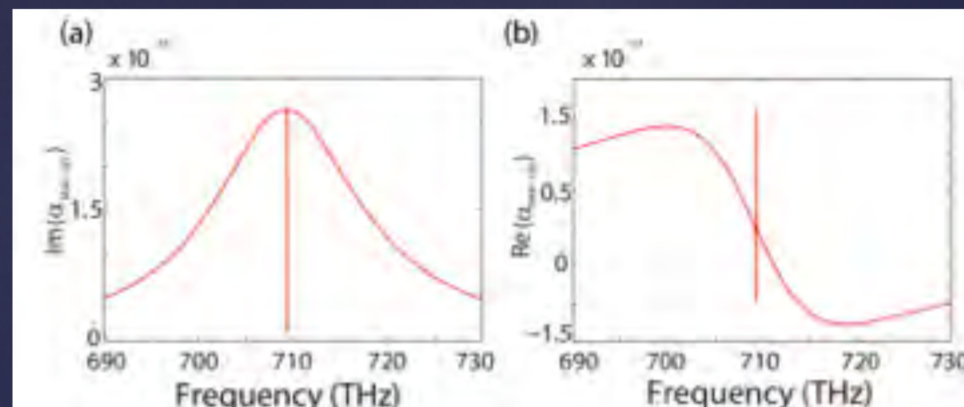
McEnery et al., PRA 89, 013822 (2014)

3D isotropic: fcc

Quantum optical metamaterials

Zhang, Govorov and Bryant, PRL 97, 146804 (2006)
Ridolfo et al., PRL 105, 263601 (2010)
Waks and Sridharan, PRA 82, 043845 (2010)





$$\hat{H} = \hat{H}_0 + \hat{H}_{int} + \hat{H}_{drive}$$

$$\hat{H}_0 = \hbar\omega_0 \hat{a}^\dagger \hat{a} + \hbar\omega_x \hat{\sigma}^\dagger \hat{\sigma},$$

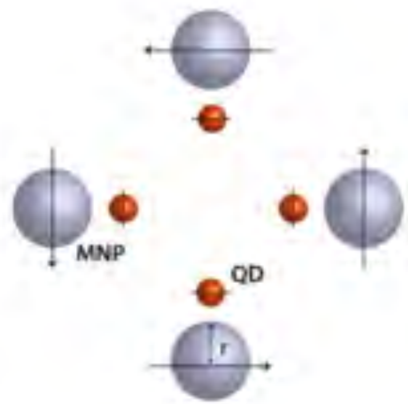
$$\hat{H}_{int} = i\hbar g(\hat{\sigma}^\dagger \hat{a} + \hat{\sigma}\hat{a}^\dagger),$$

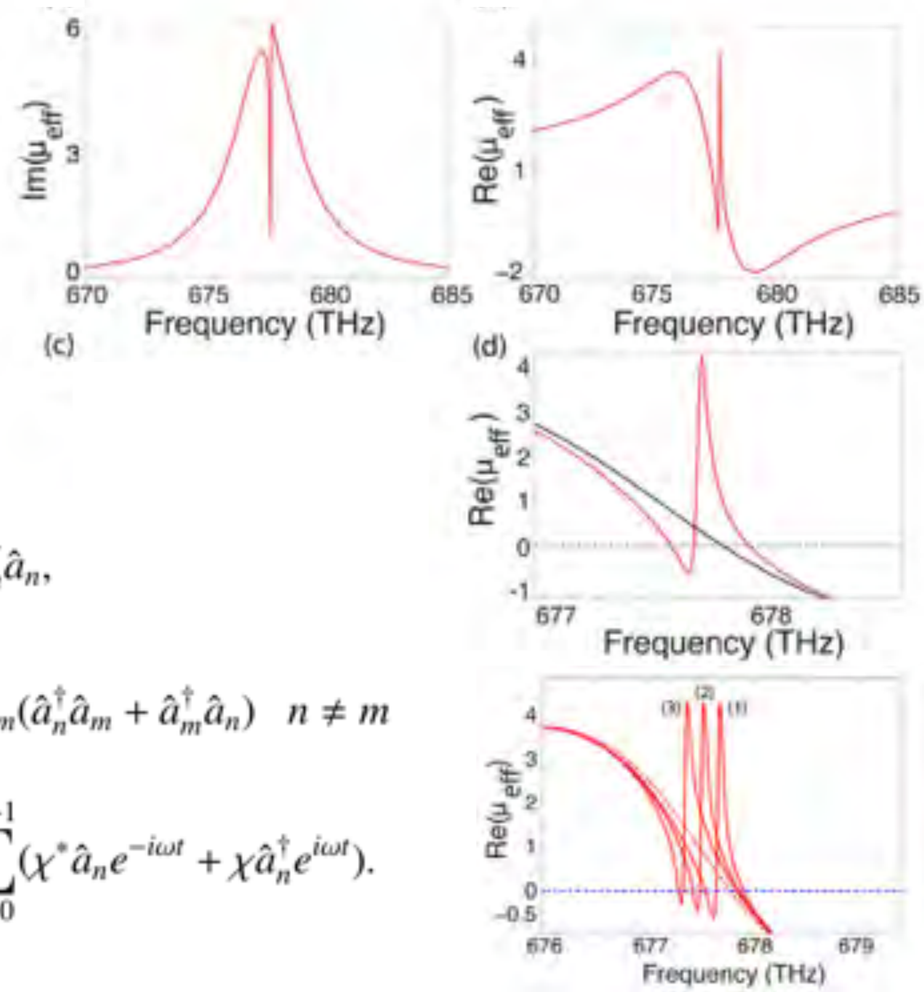
$$\hat{H}_{drive} = -E_0\mu(\hat{\sigma}e^{-i\omega t} + \hat{\sigma}^\dagger e^{i\omega t}) - E_0(\chi^* \hat{a} e^{-i\omega t} + \chi \hat{a}^\dagger e^{i\omega t})$$

$$g = \frac{S\mu}{d^3}\sqrt{\frac{3\eta r^3}{4\pi\epsilon_0\hbar}}$$

$$\chi = -i\epsilon_b\sqrt{12\eta\epsilon_0\pi\hbar r^3}$$

Quantum optical metamaterials





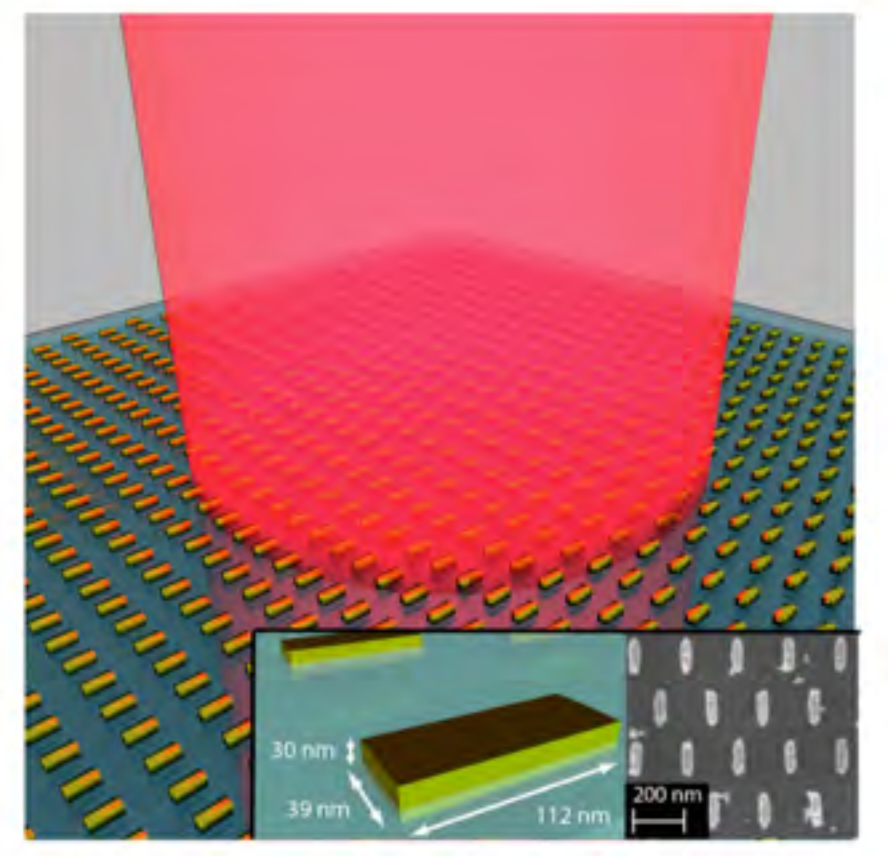
$$\hat{H}_0 = \sum_{n=0}^{N-1} \hbar\omega_0 \hat{a}_n^\dagger \hat{a}_n,$$

$$\hat{H}_{int} = \sum_{n,m=0}^{N-1} \hbar J_{nm}(\hat{a}_n^\dagger \hat{a}_m + \hat{a}_m^\dagger \hat{a}_n) \quad n \neq m$$

$$\hat{H}_{drive} = -E_0 \sum_{n=0}^{N-1} (\chi^* \hat{a}_n e^{-i\omega t} + \chi \hat{a}_n^\dagger e^{i\omega t}).$$

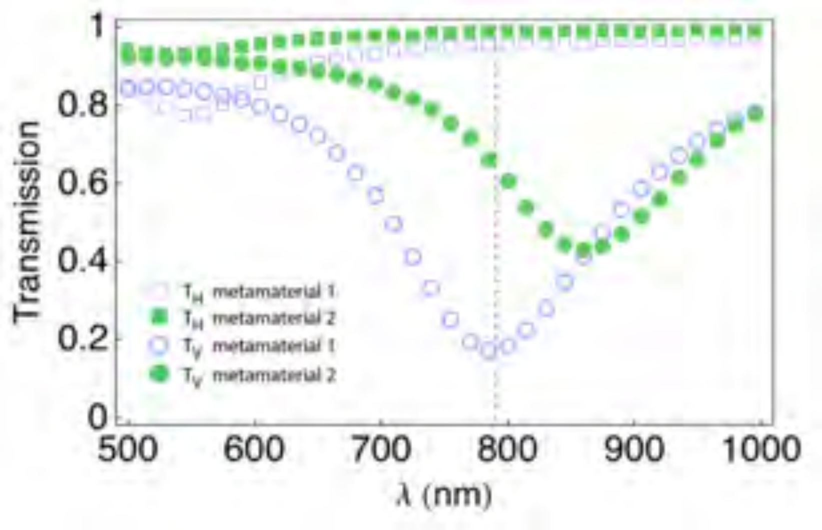
Zeng et al., PRA 84, 033834 (2011)

Quantum optical metamaterials



Asano et al., Sci. Rep. 5, 18313 (2015)

beam size ~90 μm

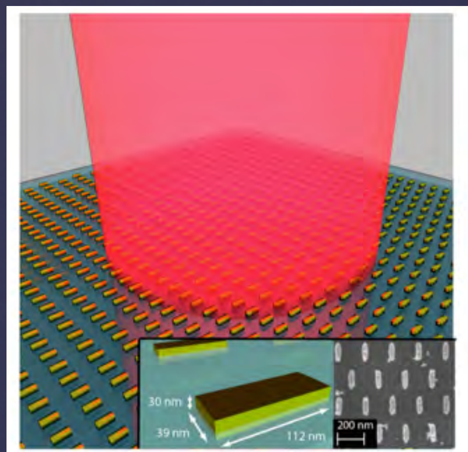


Quantum optical metamaterials

Bohren and Huffman,
‘Absorption and scattering of light by small particles’ (1983)

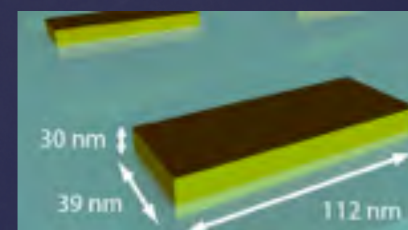
Polarizability of individual nanorod:

$$\alpha_{ii} = \frac{\pi}{8} w z \ell \frac{\epsilon_m - \epsilon_d}{3\epsilon_d + 3L_{ii}(\epsilon_m - \epsilon_d)}$$



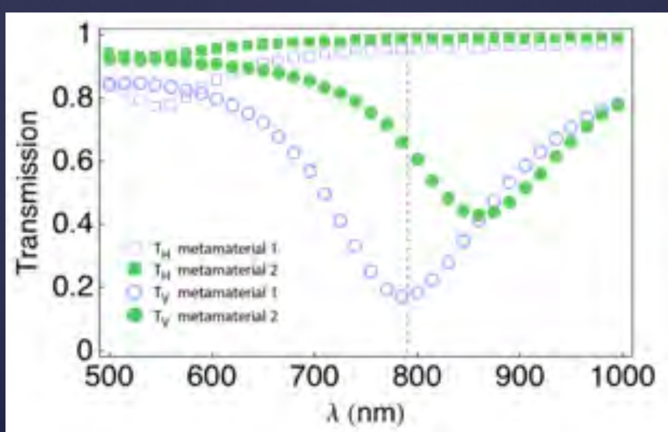
z

w



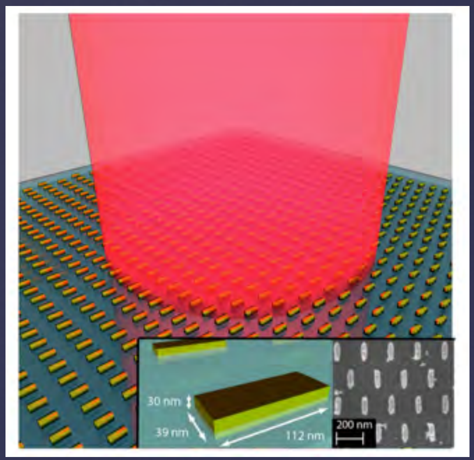
l

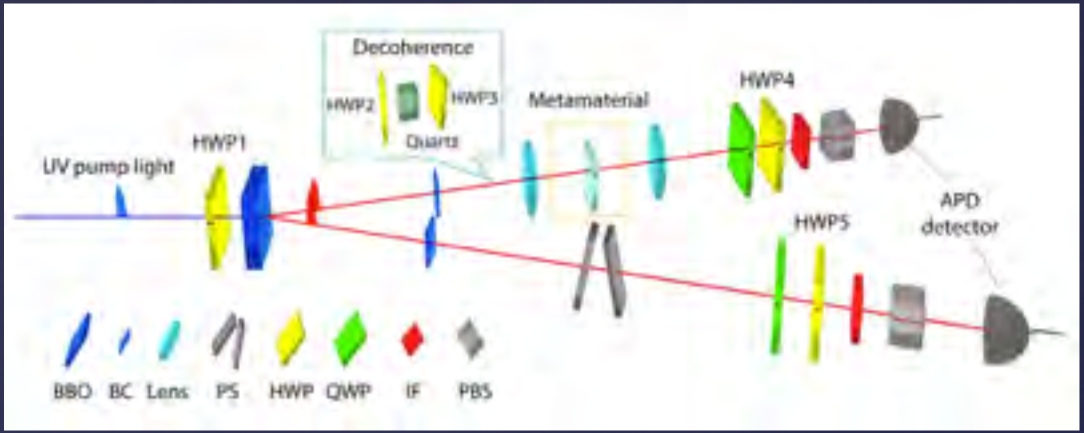
L_{ii} – shape factor

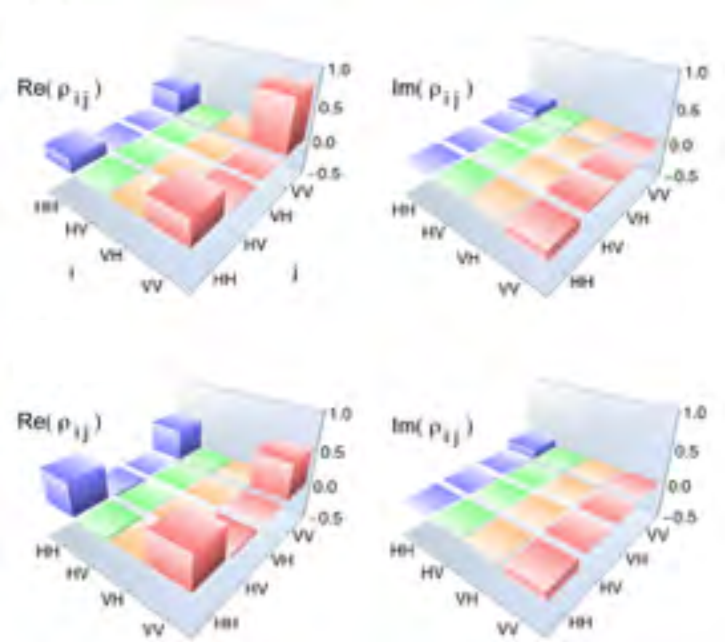


$$\mathbf{T} = \begin{pmatrix} T_{xx} & 0 \\ 0 & T_{yy} \end{pmatrix} = \begin{pmatrix} 1 - \dfrac{j\mu_0 \pi f c}{d_x d_y} \dfrac{\alpha_{xx}}{1 - C_{xx}\alpha_{xx}} & 0 \\ 0 & 1 - \dfrac{j\mu_0 \pi f c}{d_x d_y} \dfrac{\alpha_{yy}}{1 - C_{yy}\alpha_{yy}} \end{pmatrix}$$

Quantum optical metamaterials







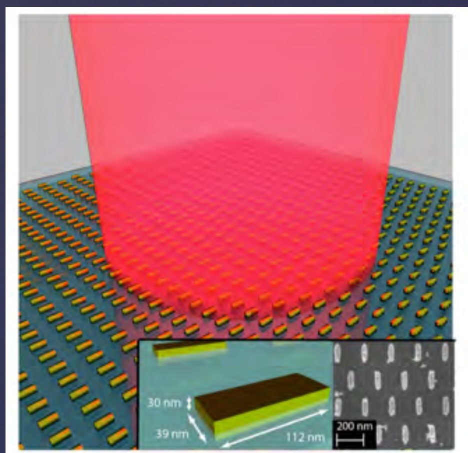
before

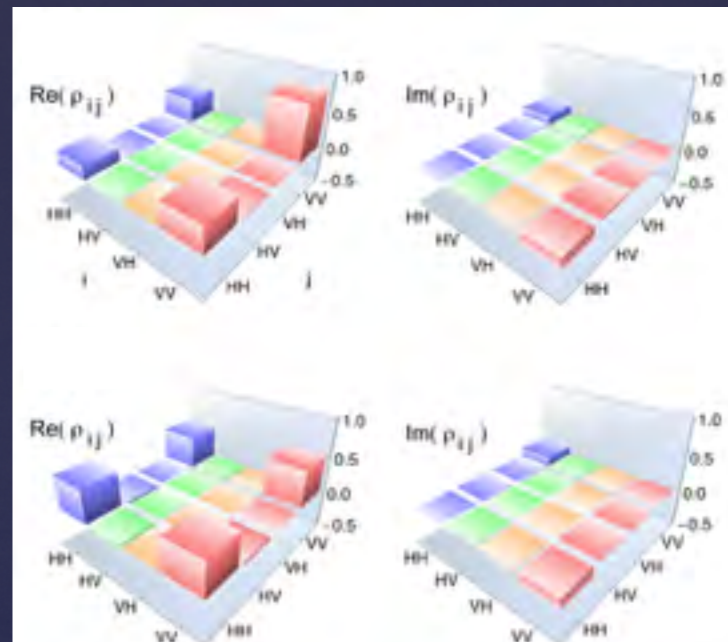
after

Entanglement distillation of
non-maximally entangled states:

$$|\Phi_\varepsilon\rangle = \frac{1}{\sqrt{1+\varepsilon^2}}\left(\varepsilon|H\rangle|H\rangle + |V\rangle|V\rangle\right)$$

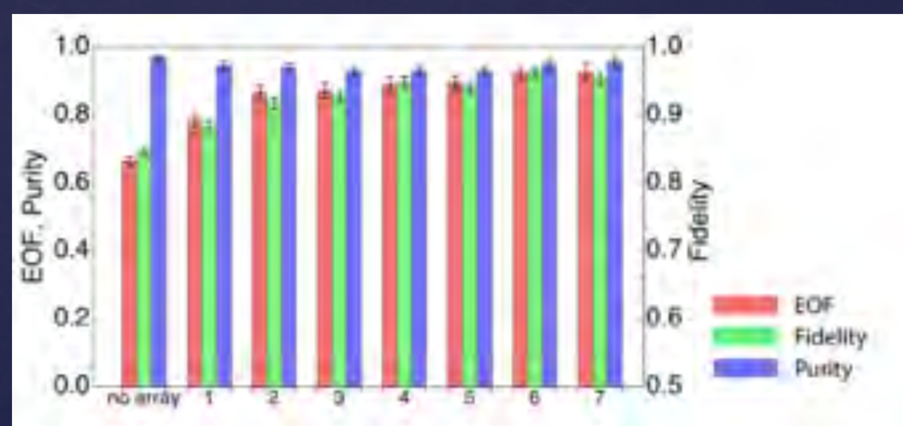
Quantum optical metamaterials





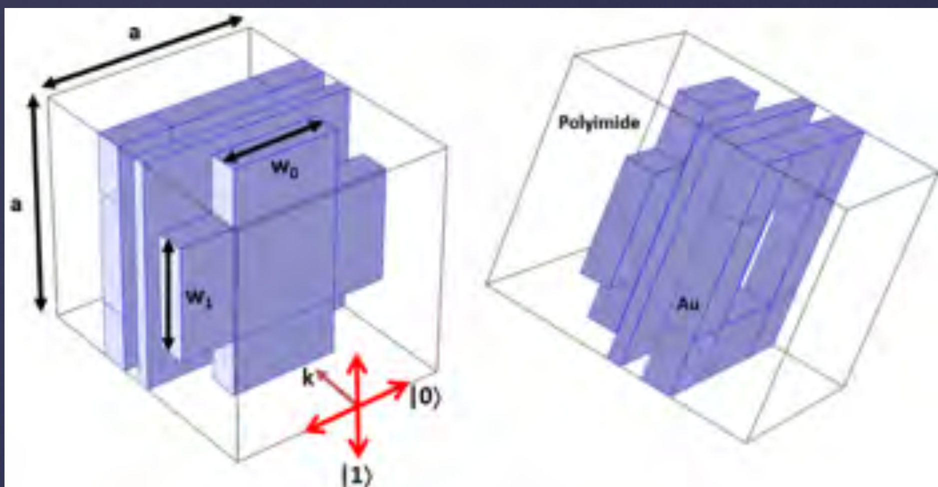
before

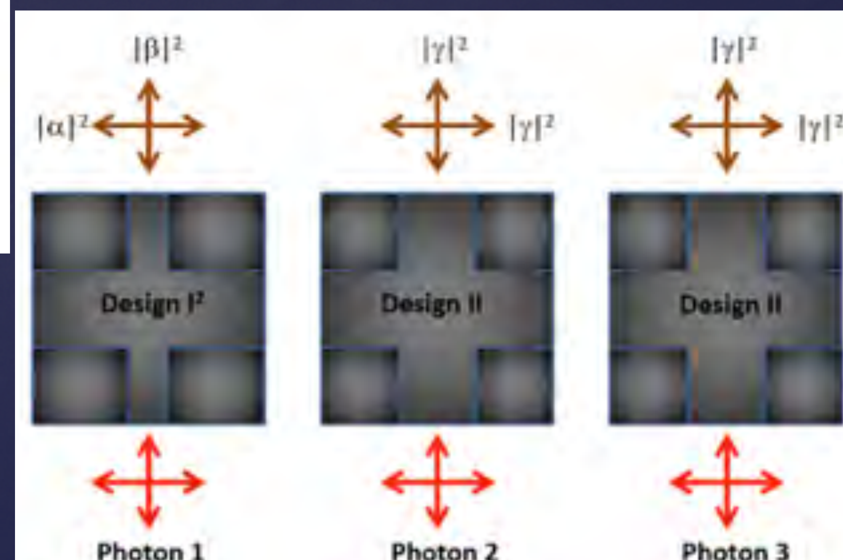
after



Quantum optical metamaterials

Abdullah al Farooqui et al., Opt. Exp. 23, 17941 (2015)





$$|\Phi_3\rangle = \alpha|1\rangle_1|0\rangle_2|0\rangle_3 + \beta(|0\rangle_1|1\rangle_2|0\rangle_3 + |0\rangle_1|0\rangle_2|1\rangle_3)$$

Collaborative network

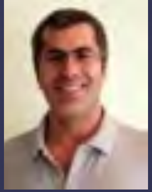
Changhyoup Lee

Changsuk Noh

Dimitris Angelakis

CQT Centre for Quantum Technologies

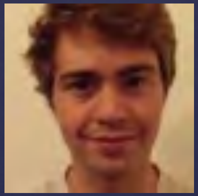
Imperial College London



Sahin Ozdemir

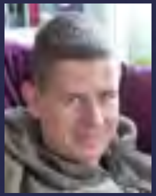
Washington
WASHINGTON·UNIVERSITY·IN·ST·LOUIS

Jinhyoung Lee



Frederik Dieleman

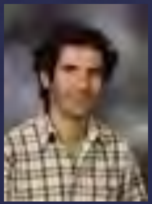
Myungshik Kim



Stefan Maier

Takashi Yamamoto & Motoki Asano

大阪大学
OSAKA UNIVERSITY



Durdu Guney

MichiganTech

Martin Wegener & Muriel Bechu

KIT
Karlsruhe Institute of Technology

QUANTUM RESPONSE OF PLASMONIC SYSTEMS

MARK TAME

University of KwaZulu-Natal, South Africa

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National Research Foundation

NIThеP National Institute for Theoretical Physics

CSIR our future through science