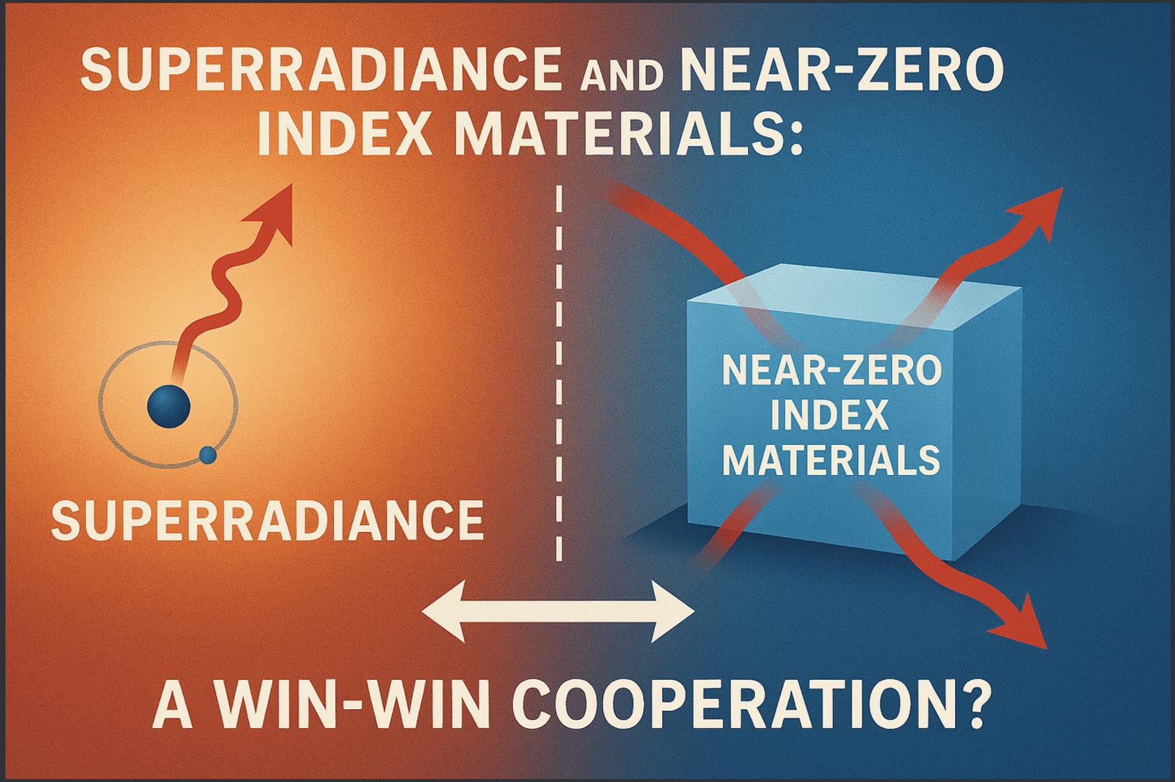
Prompt: “Can you create a picture illustrating the title "superradiance and near-zero index materials: a win win cooperation?"?” Copilot October 6th 2025



Superradiance and near-zero refractive index materials: a win-win cooperation?

21st Rencontres du Vietnam, Quy Nhon

October 8th 2025

Slides available on simple request

M. Lobet,
O. Melo, A. Debacq, L. Vertchenko, S. Nelson, D. Guney, E. Mazur

HARVARD VE RI TAS

NISM Namur Institute of Structured Matter

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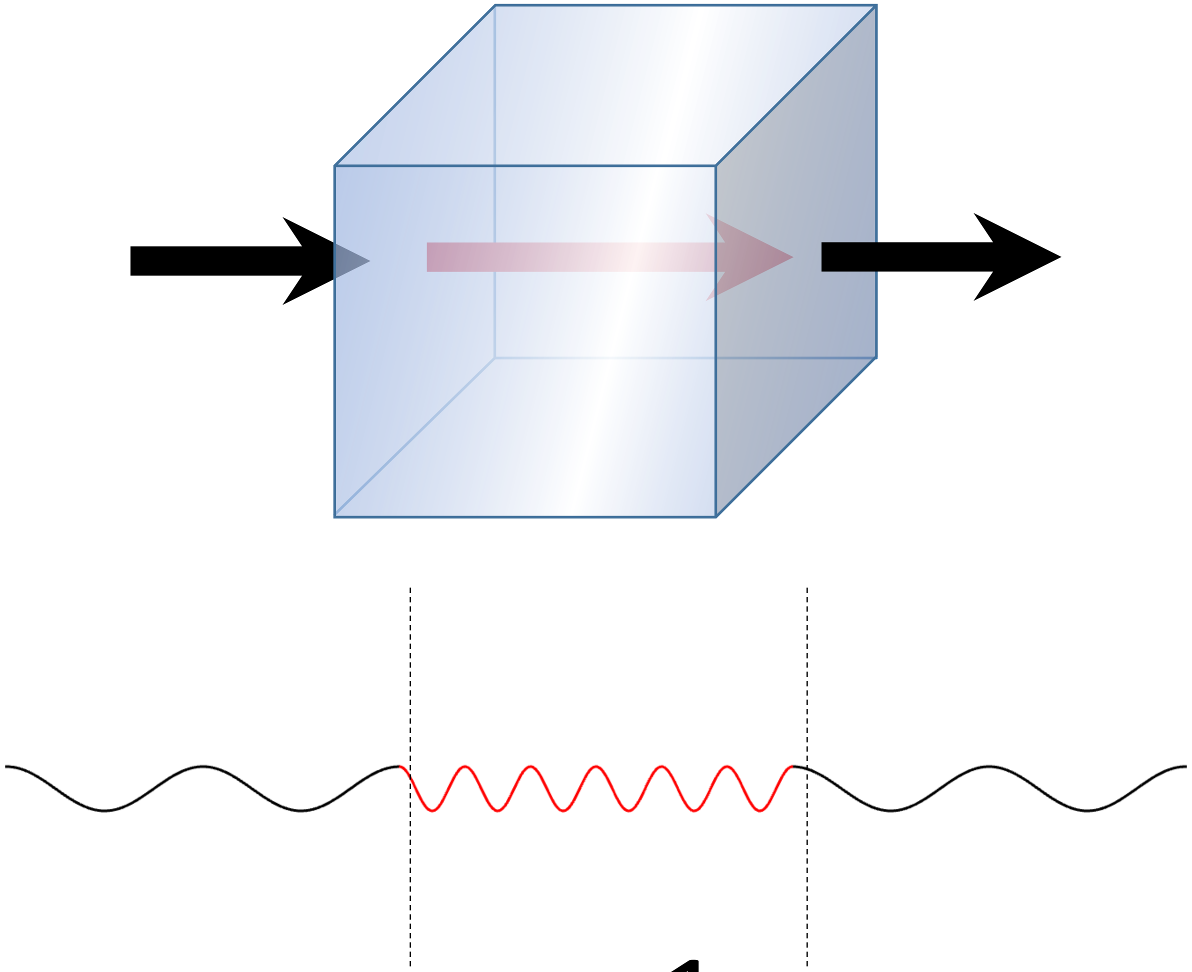
MLTeam Michaël Lobet Research Team

UNIVERSITÉ DE NAMUR

What are near-zero index media?

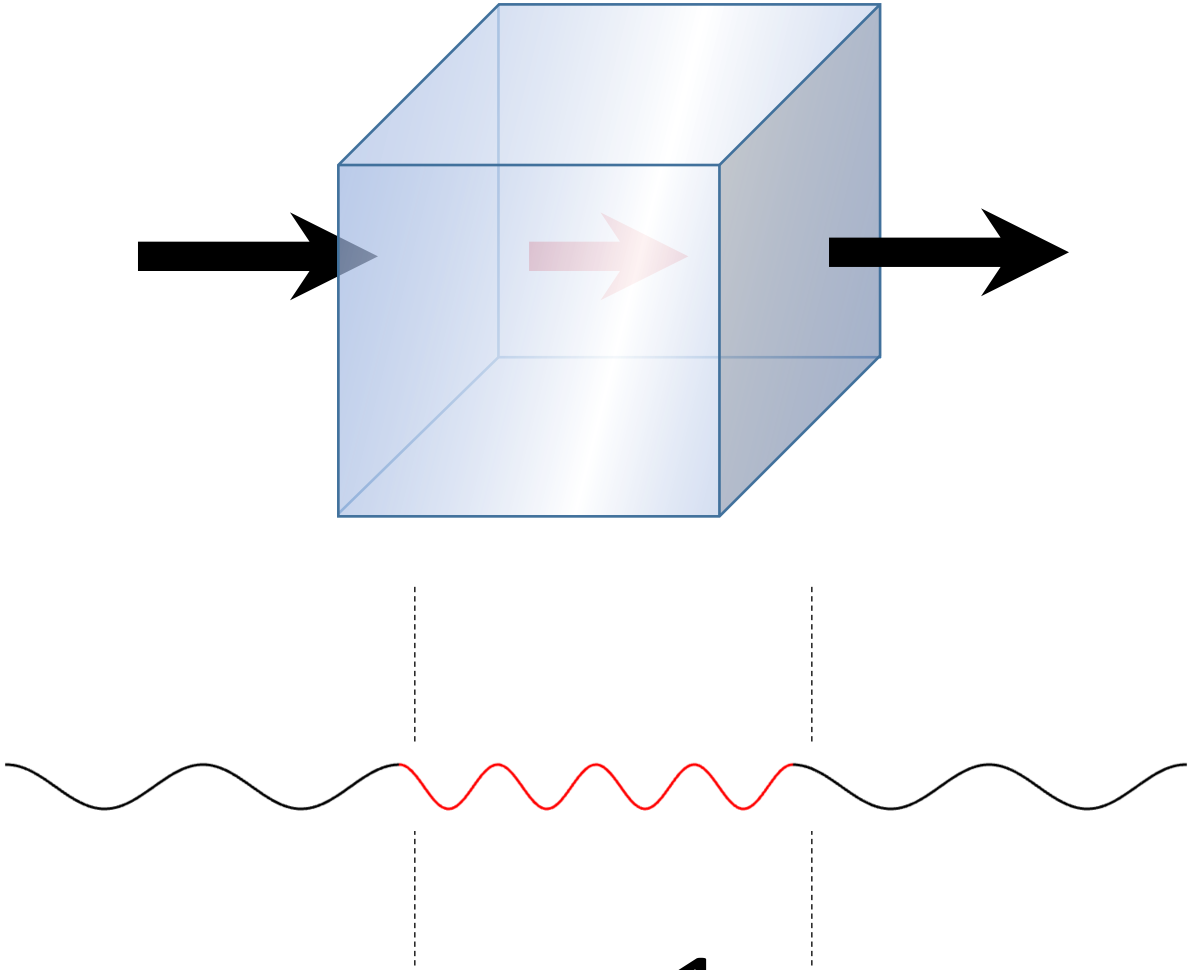
Introduction: NZI media



$n > 1$

Introduction: NZI media

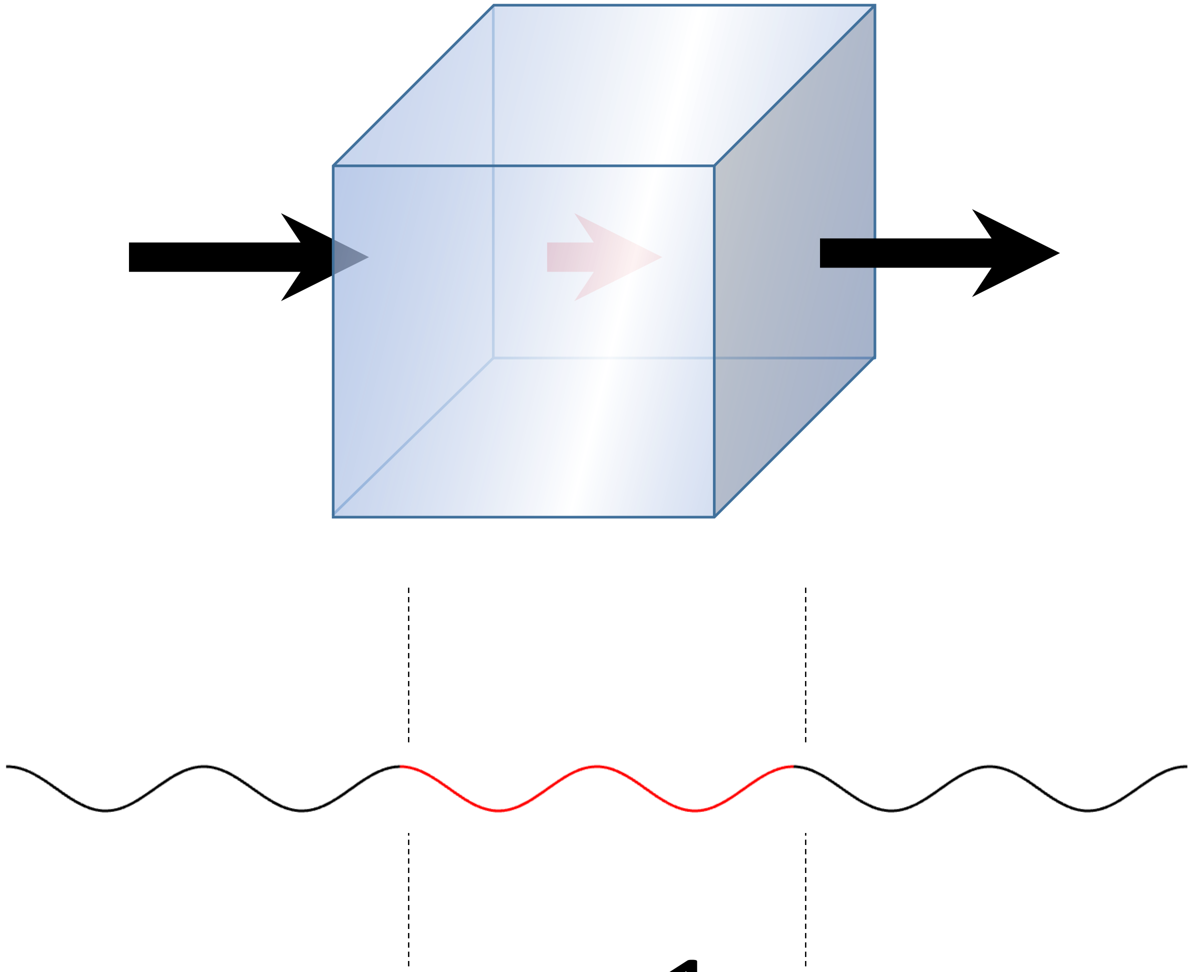
As the index **decreases**, the effective wavelength **increases**.



$n > 1$

Introduction: NZI media

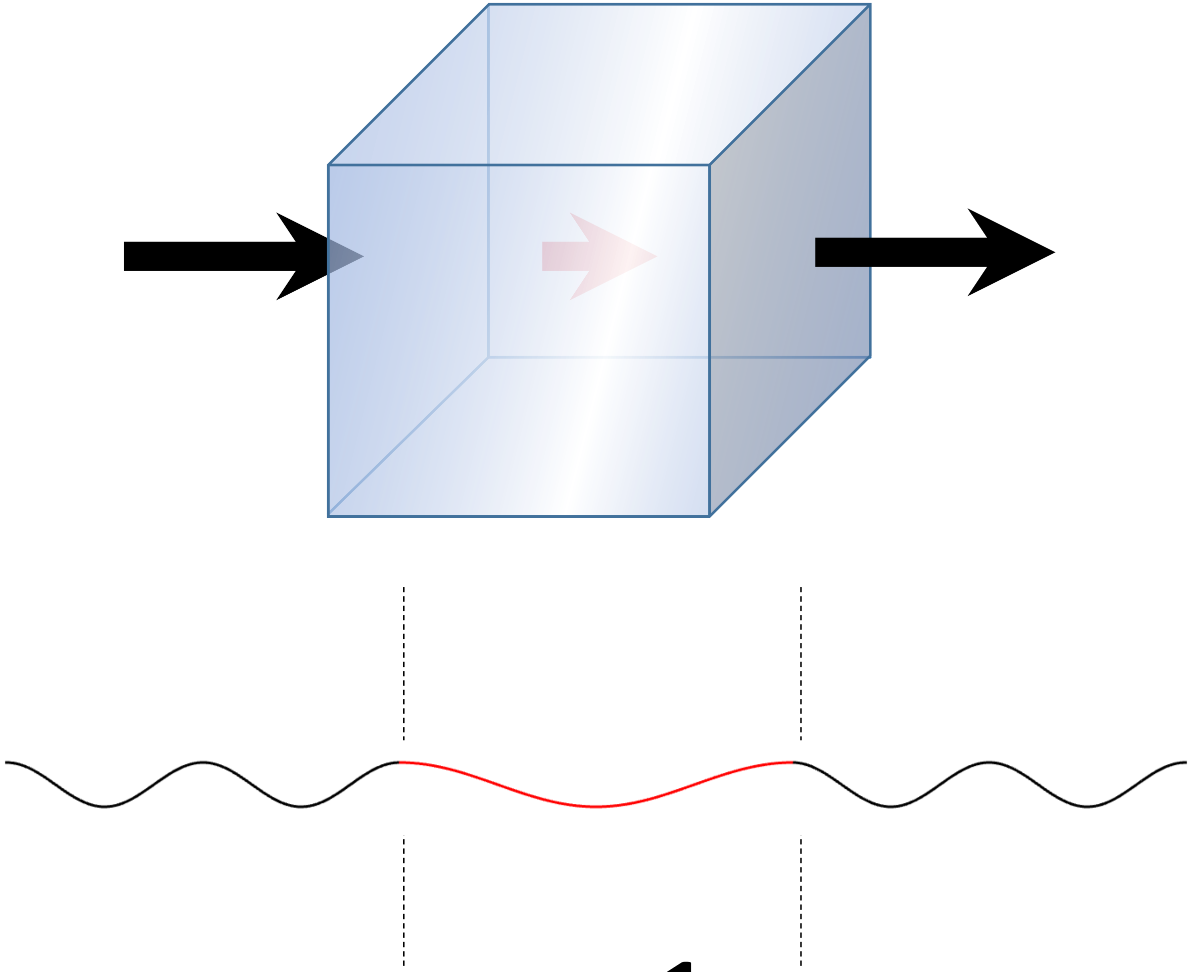
As the index **decreases**, the effective wavelength **increases**.



$n = 1$

Introduction: NZI media

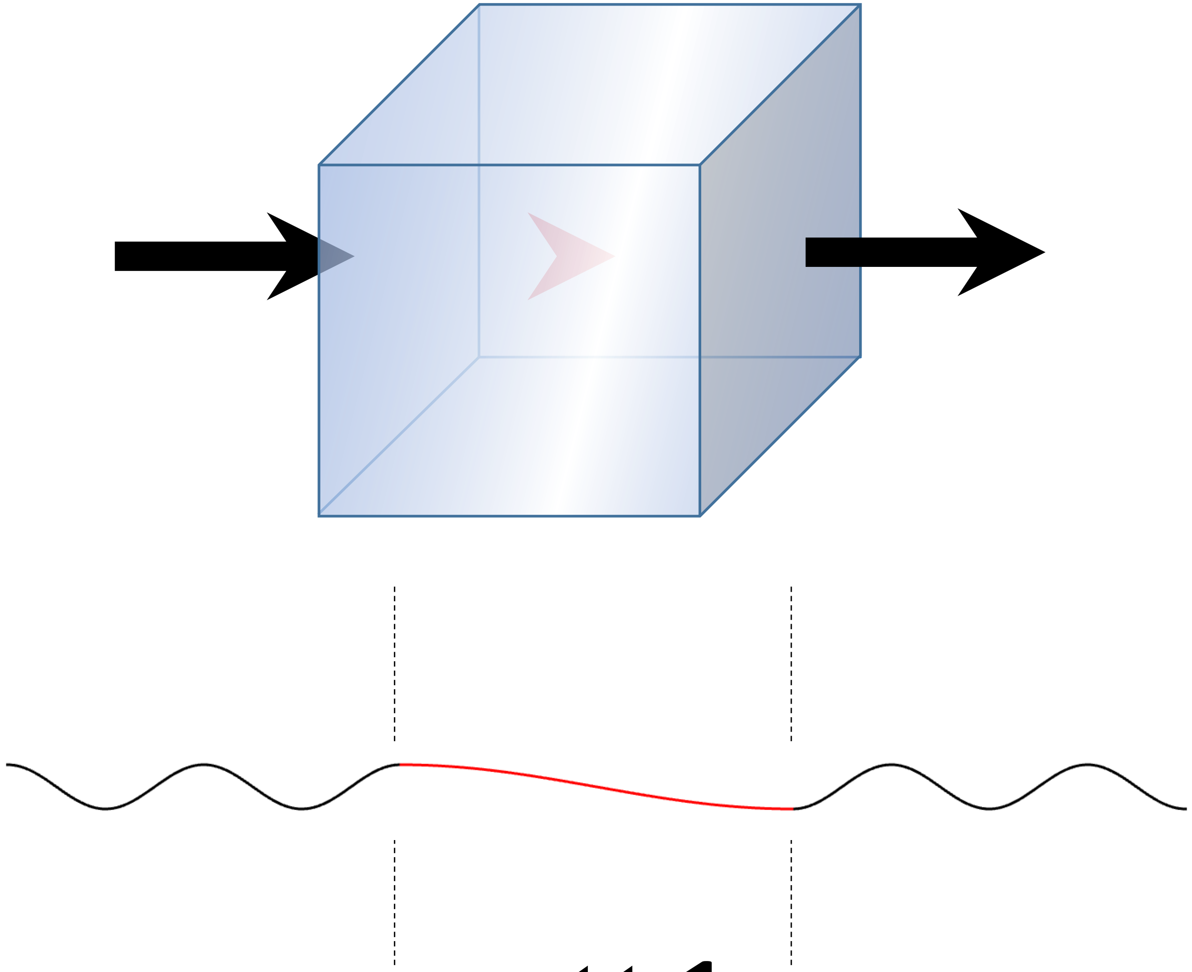
As the index **decreases**, the effective wavelength **increases**.



$n < 1$

Introduction: NZI media

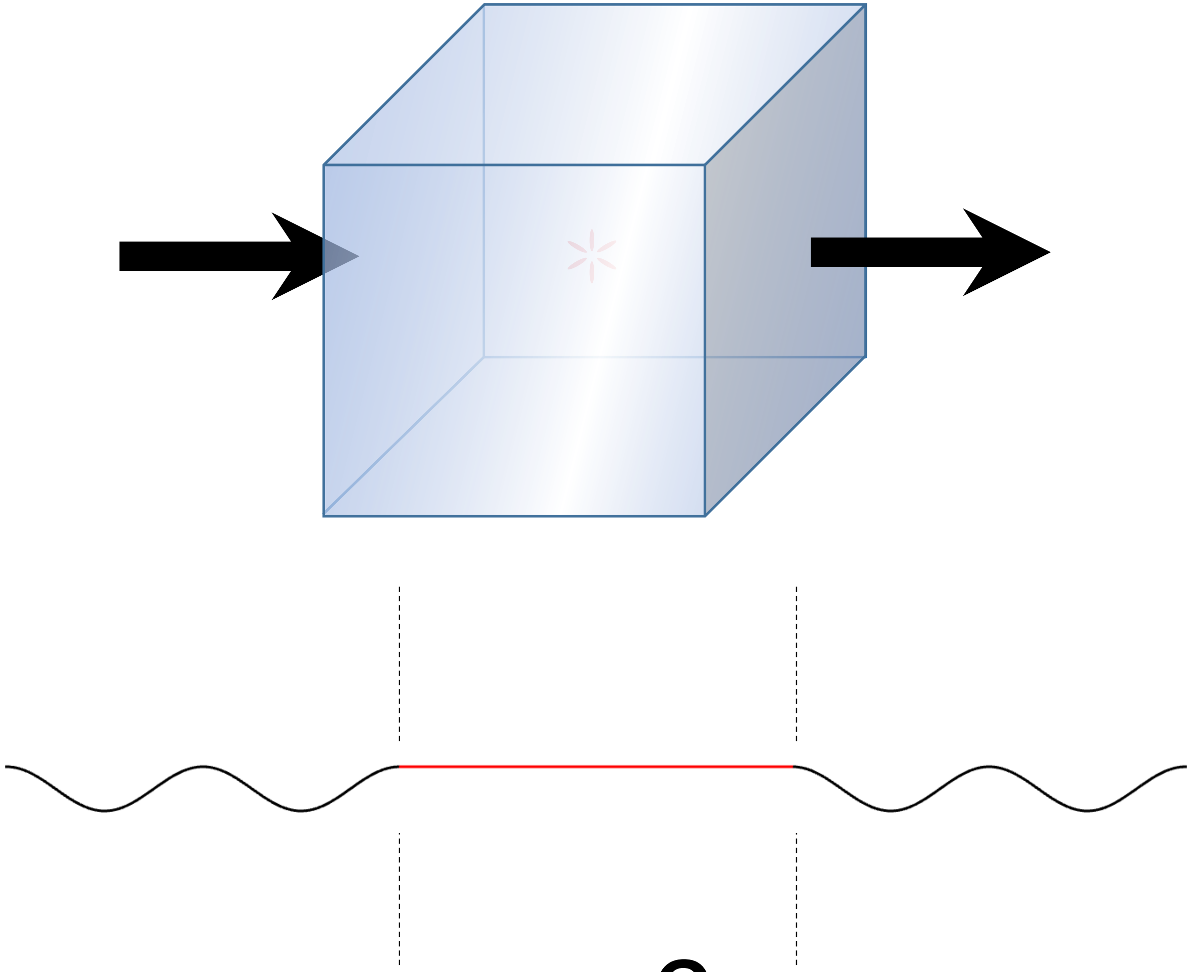
As the index **decreases**, the effective wavelength **increases**.



$n \ll 1$

Introduction: NZI media

As the index **decreases**, the effective wavelength **increases**.



$$n = 0$$

NZI properties

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$$\lambda = \frac{\lambda_0}{n}$$

∞ (λ) 0 (n)

Infinite wavelength

$$k = \frac{\omega n}{c}$$

0 (k) 0 (n)

Zero k vector

Lobet, M.. *et al.* Momentum considerations inside near-zero index materials. *Light Sci Appl* **11**, 110 (2022).

$$v = f\lambda$$

∞ (v) ∞ (λ)

Infinite phase velocity

$$\phi = ikx$$

0 (φ) 0 (k)

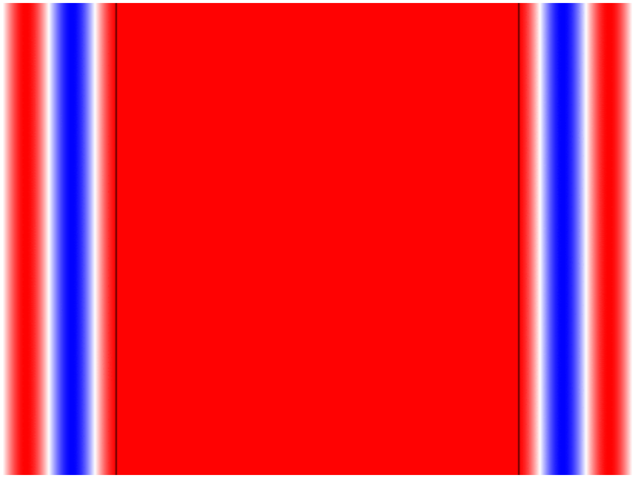
Zero phase change

$$\vec{E} = \vec{E}_0 e^{-i\omega t}$$

Interestingly: no diffraction and no Doppler effect occur in NZI

NZI properties

Air $(n = 1)$ NZIM $(n = 0)$ Air $(n = 1)$



Zero *k* vector

Infinite wavelength

Infinite phase velocity

Zero phase change

Introduction: NZI media

Introducing 3 classes

$$n = \sqrt{\varepsilon\mu}$$

$\varepsilon \rightarrow 0$
ENZ

ε and $\mu \rightarrow 0$
EMNZ

$\mu \rightarrow 0$
MNZ

Lobet, Michaël, et al. "Fundamental radiative processes in near-zero-index media of various dimensionalities." *ACS Photonics* 7.8 (2020): 1965-1970.

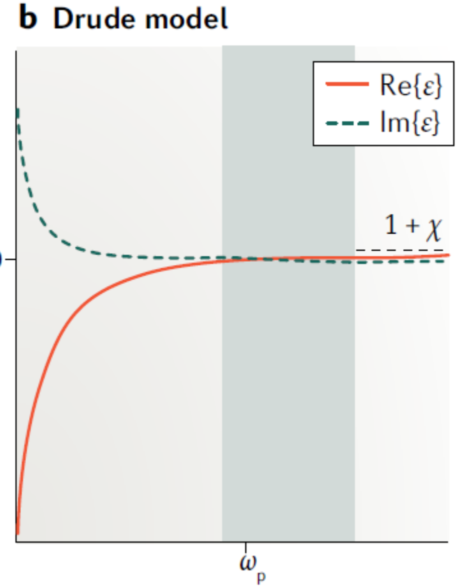
Lobet, Michaël, et al. "New horizons in near-zero refractive index photonics and hyperbolic metamaterials." *ACS photonics* 10.11 (2023): 3805-3820.

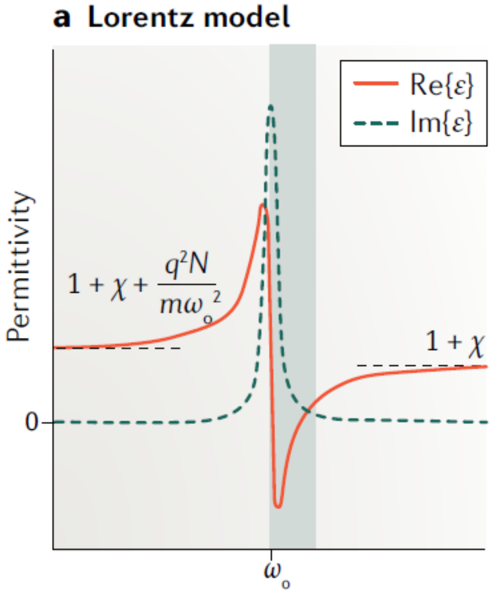
How can we make NZI media?

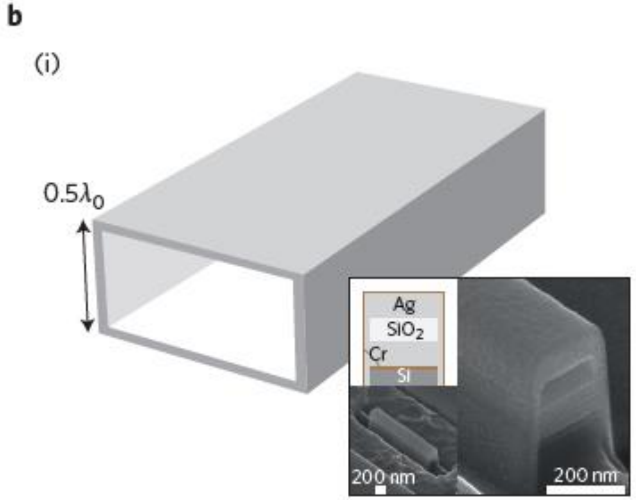
$$\varepsilon_{Drude}(\omega) = 1 - \frac{\omega_p^2}{\omega^2 - i\gamma\omega}$$

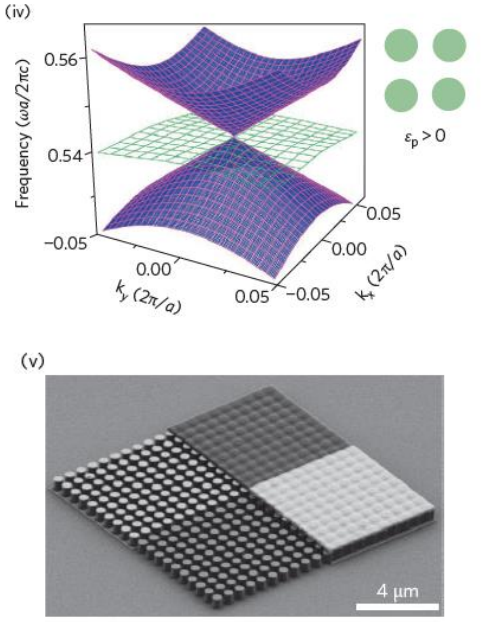
At ω_p, $\varepsilon \to 0$

$$\varepsilon_{Lorentz}(\omega) = \varepsilon_\infty + \frac{\omega_p^2}{\omega_0^2 - \omega^2 - i\gamma\omega}$$









Drude/Lorentz materials

See Kinsey or Liberal/Engheta reviews

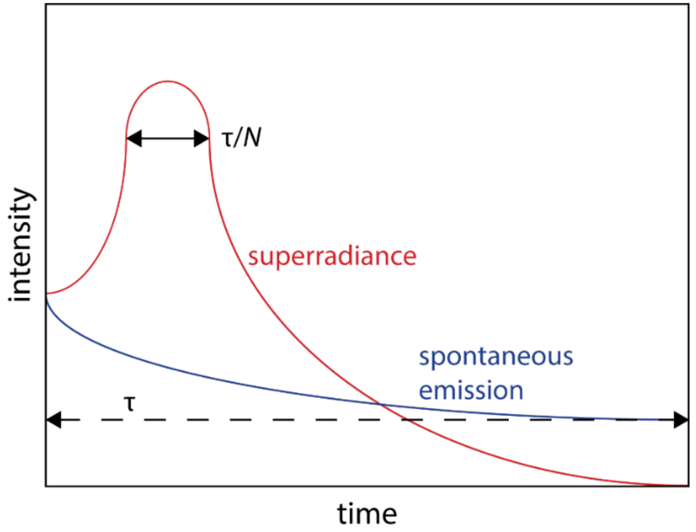
Waveguides at cut-off

See Engheta/Polman works

Photonic crystals (Dirac cone MM)

See Mazur/CT Chan works

How can it be useful for superradiance?



M. Gross and S. Haroche, *Phys. Rep.* (1982)

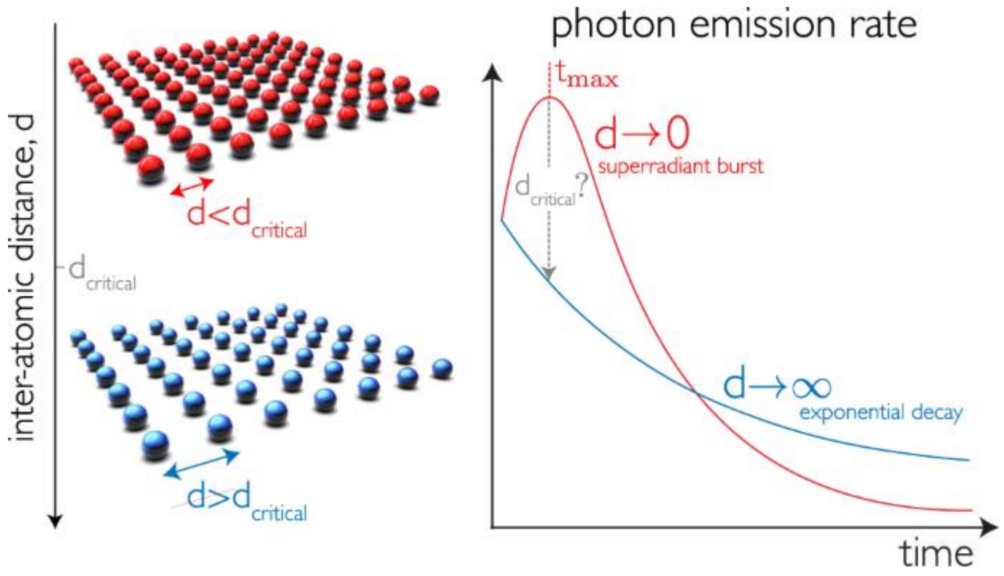
Dicke superradiance

✓ ***It's a near-field interaction***

All emitters need to be within
1 λ from each other

$$\Leftrightarrow kr < \lambda$$

Need to adjust precisely r, the
inter-emitter spacing



S. Masson and A. Asenjo-Garcia, *Nat. Com.* (2022)

Limitations
- Small number of atoms/emitters
- Small spatial extent

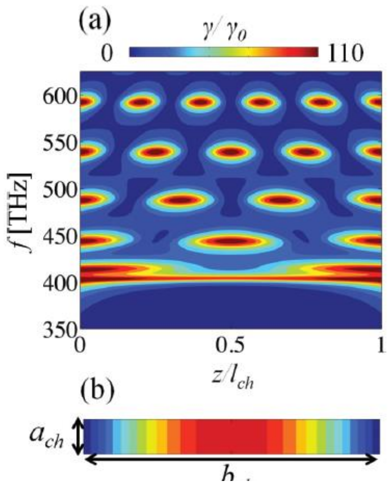
Our approach

$$0 \longleftarrow n\frac{2\pi}{\lambda_0}r = kr < \lambda = \frac{\lambda_0}{n} \longrightarrow \infty$$

As small as possible | *As big as possible*

✓ Use metamaterials? → Use Near-Zero Refractive Index (NZI) materials! (No phase change $\Delta\varphi \rightarrow 0$)

Literature review



PHYSICAL REVIEW B **87**, 201101(R) (2013)

Enhanced superradiance in epsilon-near-zero plasmonic channels

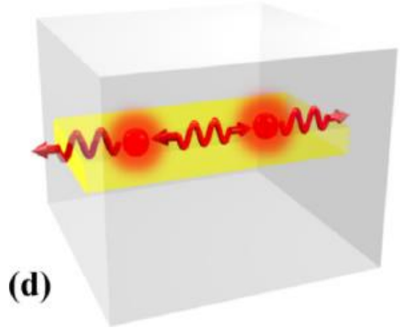
Romain Fleury and Andrea Alù*

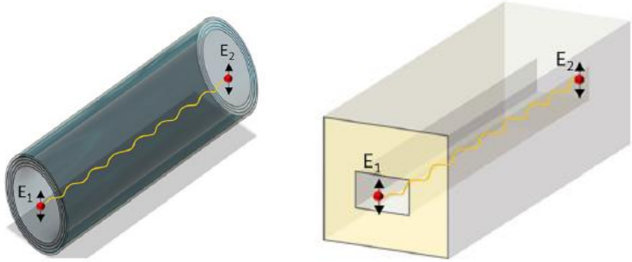
1D ENZ: Enhanced spontaneous emission

Vol. 24, No. 23 | 14 Nov 2016 | OPTICS EXPRESS 26696

Controlling collective spontaneous emission with plasmonic waveguides

YING LI AND CHRISTOS ARGYROPOULOS*

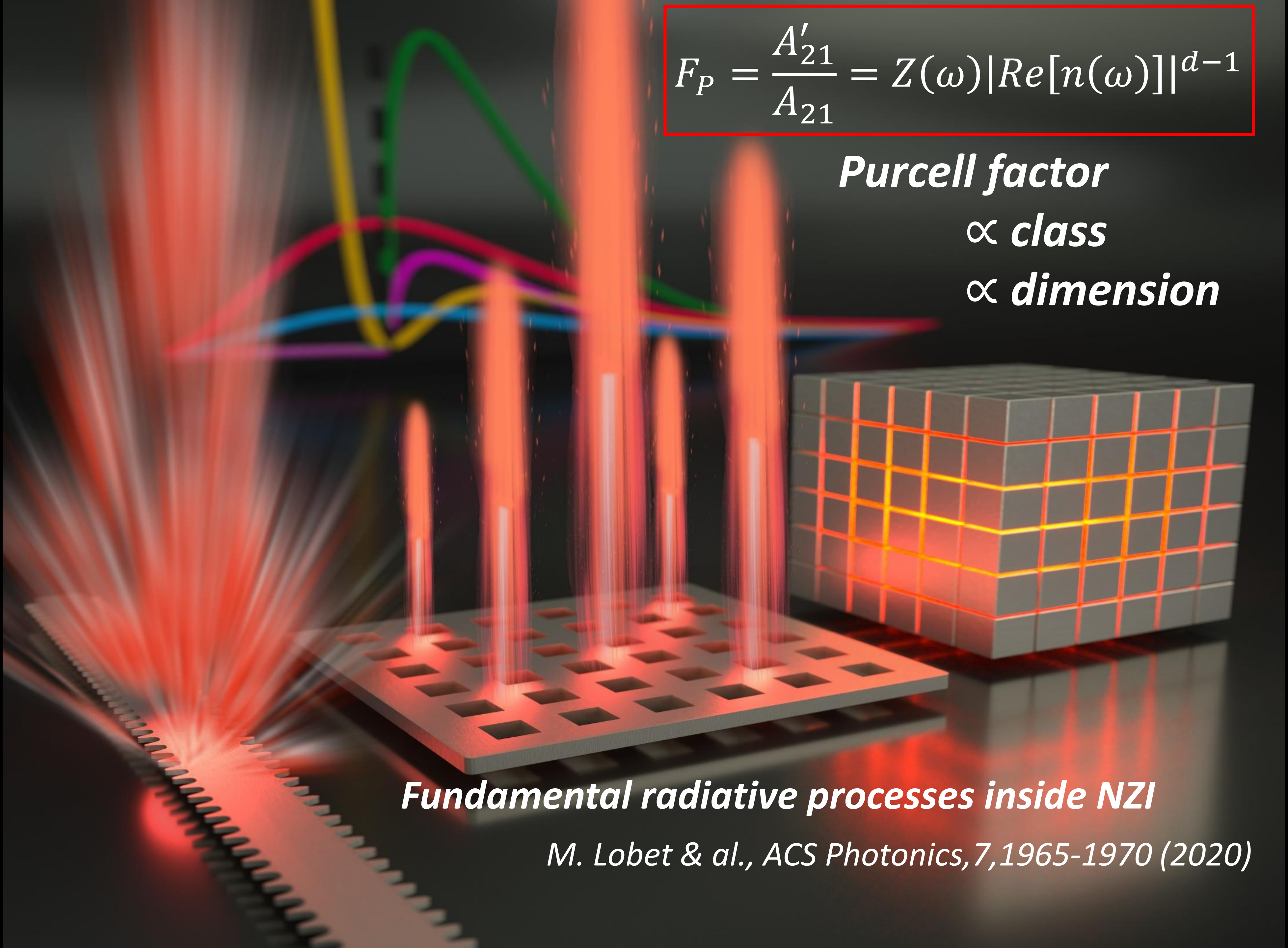




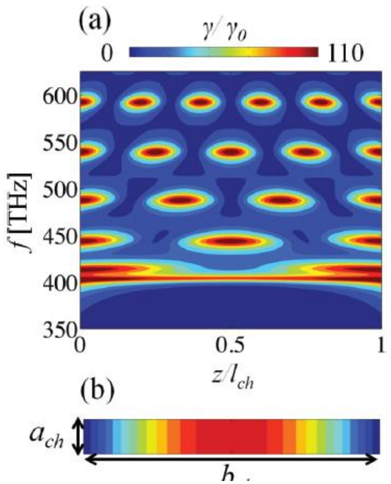
Qubit–qubit entanglement mediated by epsilon-near-zero waveguide reservoirs

Ibrahim Issah and Humeyra Caglayan[a)]

Appl. Phys. Lett. **119**, 221103 (2021)


$F_P = \frac{A'_{21}}{A_{21}} = Z(\omega)|Re[n(\omega)]|^{d-1}$
Purcell factor
∝ class
∝ dimension
Fundamental radiative processes inside NZI
M. Lobet & al., ACS Photonics,7,1965-1970 (2020)

Literature review



PHYSICAL REVIEW B **87**, 201101(R) (2013)

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1D ENZ: Enhanced spontaneous emission

! Losses !

Vol. 24, No. 23 | 14 Nov 2016 | OPTI

Controlling collective spontaneous emission with plasmonic waveguides

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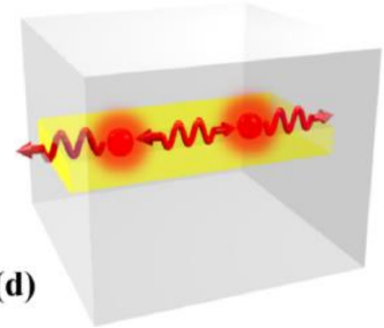
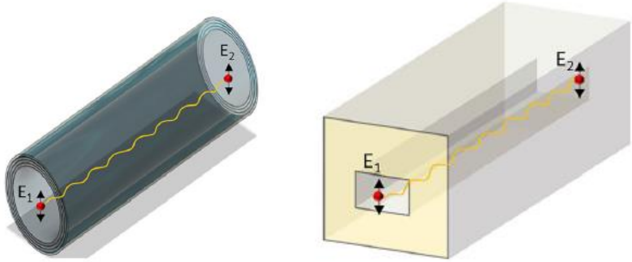


(d)



Qubit–qubit entanglement mediated by epsilon-near-zero waveguide reservoirs

Ibrahim Issah and Humeyra Caglayan[a)]

Appl. Phys. Lett. **119**, 221103 (2021)

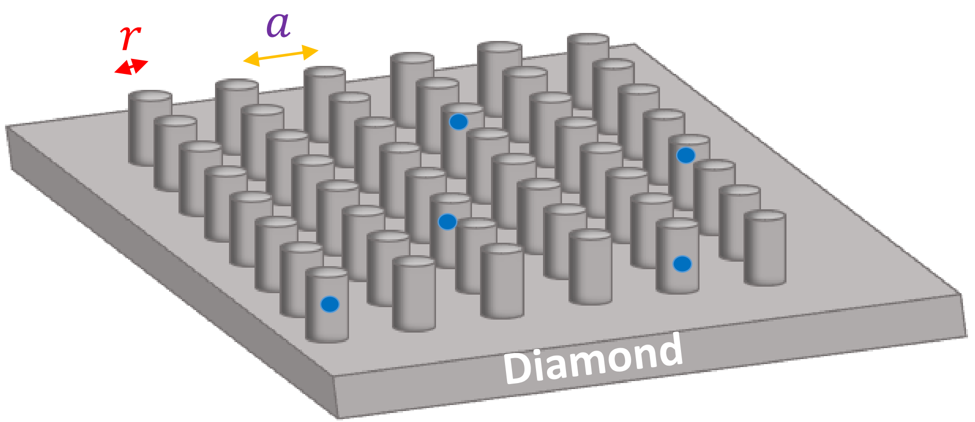
Design of NZI platforms

→ All-dielectric

→ Visible

→ Suitable for quantum optics

2D ENZ diamond platform with SiV centers



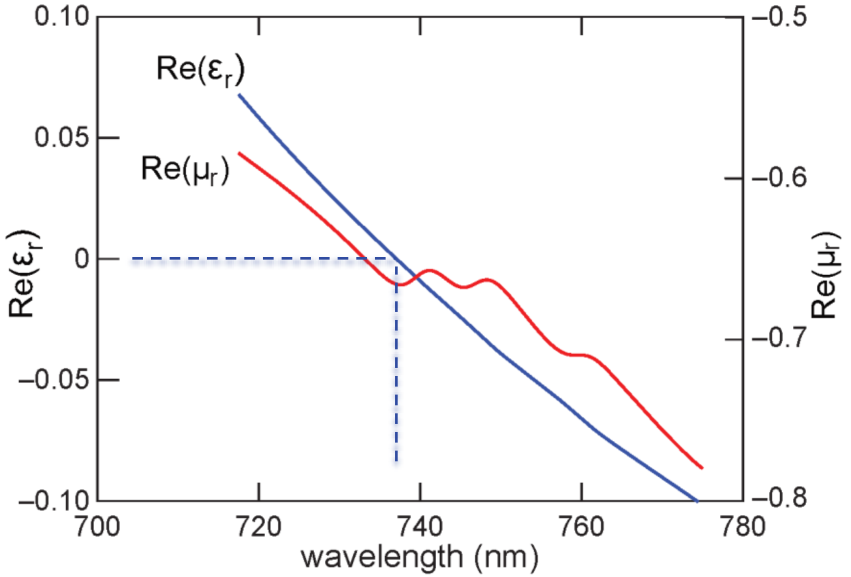
(emitters operating at 737 nm)

Tuning a and r such that:

$\varepsilon \to 0$ at 737 nm

$\mu \to 0$ at 737 nm

Near-Zero crossing

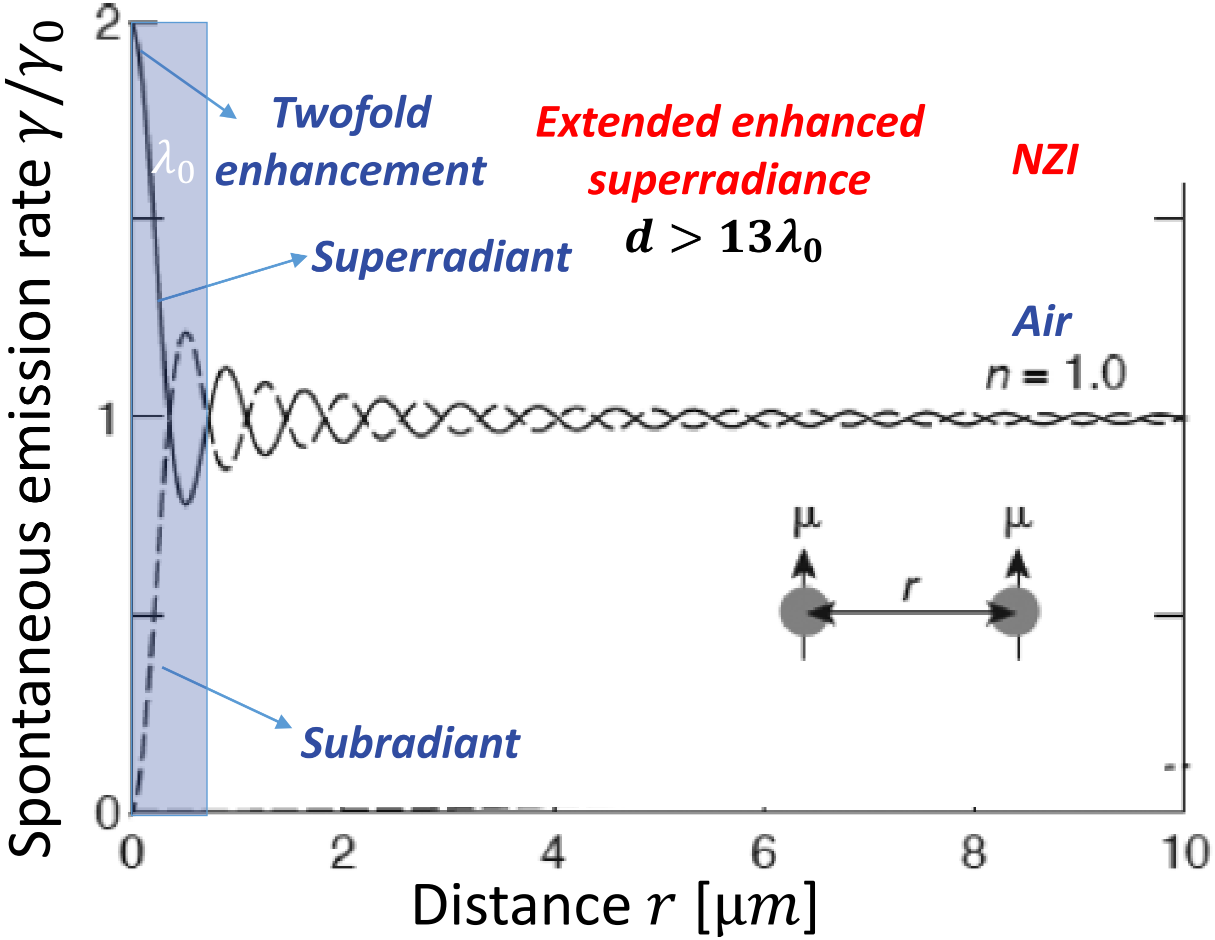


- ✓ O. Mello et al., Appl. Phys. Lett. 120, 061105 (2022)
- ✓ O. Mello et al., *Light: Sci & App.* 14.1, 300 (2025).

How does it help for superradiance?

Dicke superradiance for two two-level system in NZI

Spontaneous emission rate $$\gamma_{\pm} = \gamma_0 \left[1 \pm \frac{3}{2}\left(\frac{\sin(kr)}{kr} + \frac{\cos(kr)}{(kr)^2} - \frac{\sin(kr)}{(kr)^3}\right)\right]$$



- ✓ O. Mello et al., Appl. Phys. Lett. 120, 061105 (2022)
- ✓ O. Mello et al., *Light: Sci & App.* 14.1, 300 (2025).

Emission from randomly positioned N dipoles

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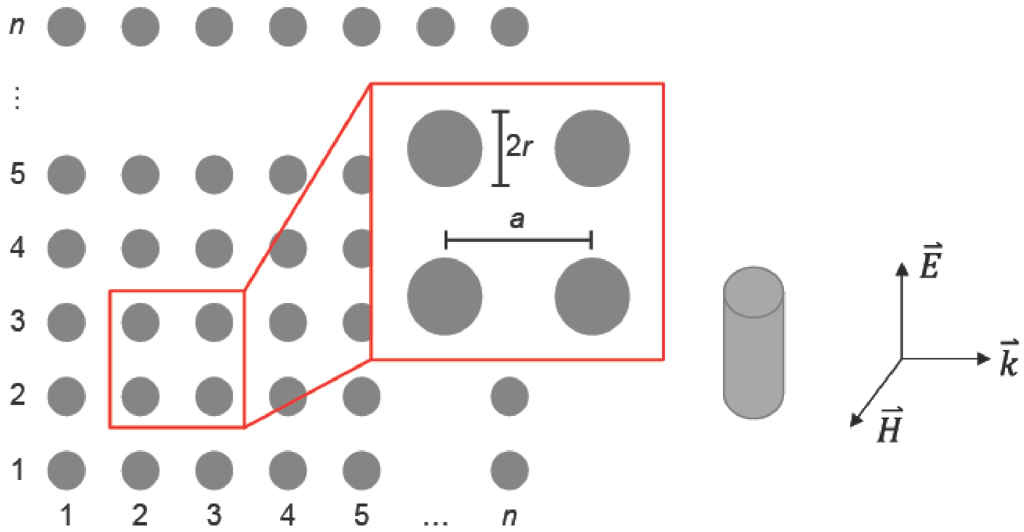
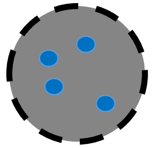
What if we increase the number of emitters?

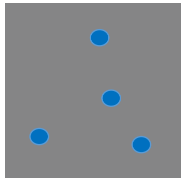
Coherent emission from N dipoles?



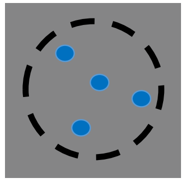
3 situations



Emitters randomly distributed inside diamond ***pillars***



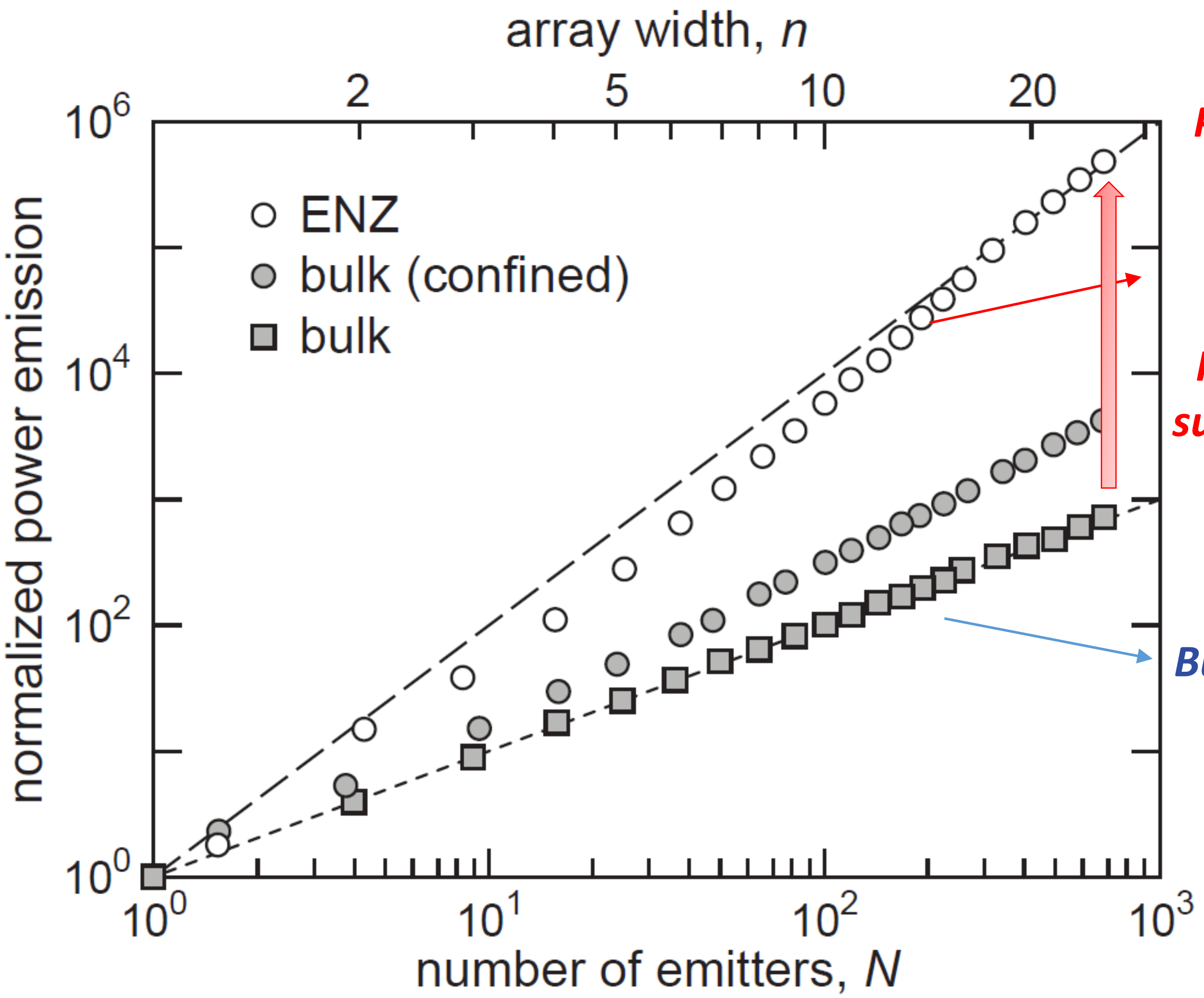
Emitters randomly distributed inside ***bulk*** diamond



Emitters randomly distributed inside ***confined bulk*** diamond

✓ O. Mello et al., Appl. Phys. Lett. 120, 061105 (2022)

Emission from randomly positioned N dipoles



Power enhancement

$P_{rad} \propto N^2$

Hallmark of superradiance

Bulk: incoherent

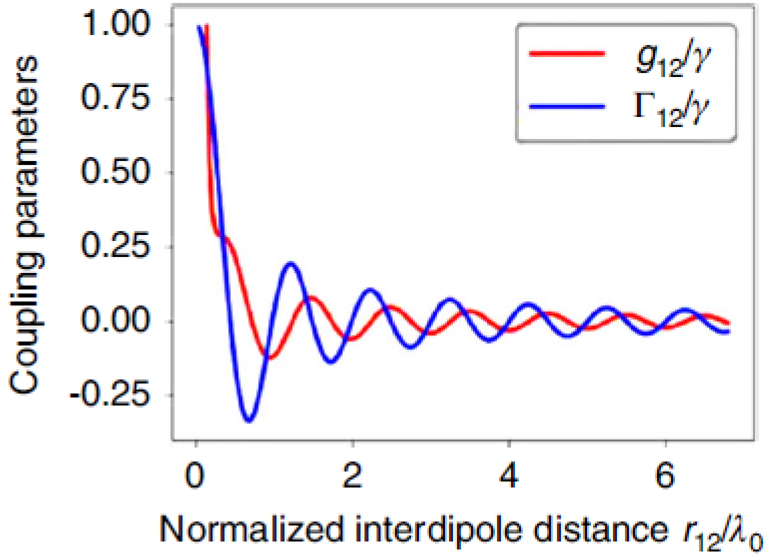
$P_{rad} \propto N$

✓ O. Mello et al., Appl. Phys. Lett. 120, 061105 (2022)

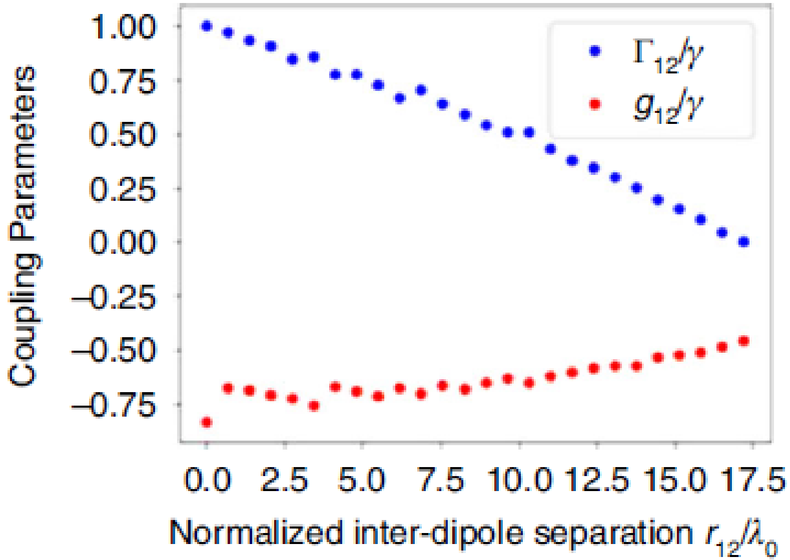
Entanglement properties in the MNZ platform

Dipole-dipole coupling term

$$g_{ij} = \frac{2\omega_j^2}{\hbar\varepsilon_0 c^2} d_i \mathrm{Re}\left[\overleftrightarrow{G}(r_i, r_j, \omega_j)\right] d_j^*$$



Free space



MNZ metamaterial

Having a $\Gamma_{12} \gg g_{12}$ is ideal for attaining a large transient concurrence

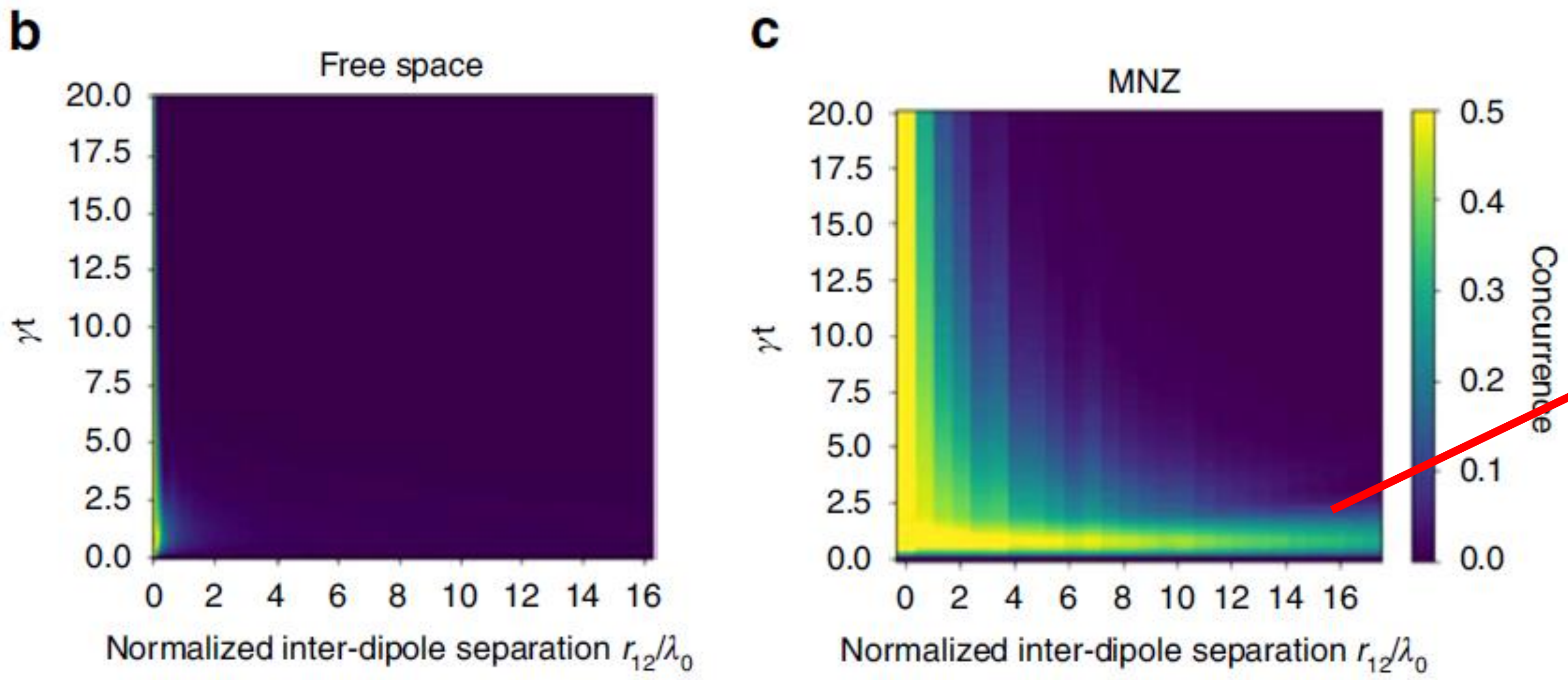
✓ O. Mello et al., *Light: Sci & App.* 14.1, 300 (2025).

Entanglement properties in the MNZ platform

Concurrence [Wouters PRL 1998]

$$C = \frac{1}{2}\sqrt{\left(e^{-(\gamma+\Gamma_{12})t} - e^{-(\gamma-\Gamma_{12})t}\right)^2 + 4e^{-2\gamma t}\sin^2(2g_{12}t)}$$

Transient concurrence



$C = 0.35$
$at\ r_{12} = 17\lambda_0$ i.e. 12.5µm

→ 10x ENZ plasmonic waveguide

Robust entanglement

✓ O. Mello et al., *Light: Sci & App.* 14.1, 300 (2025).

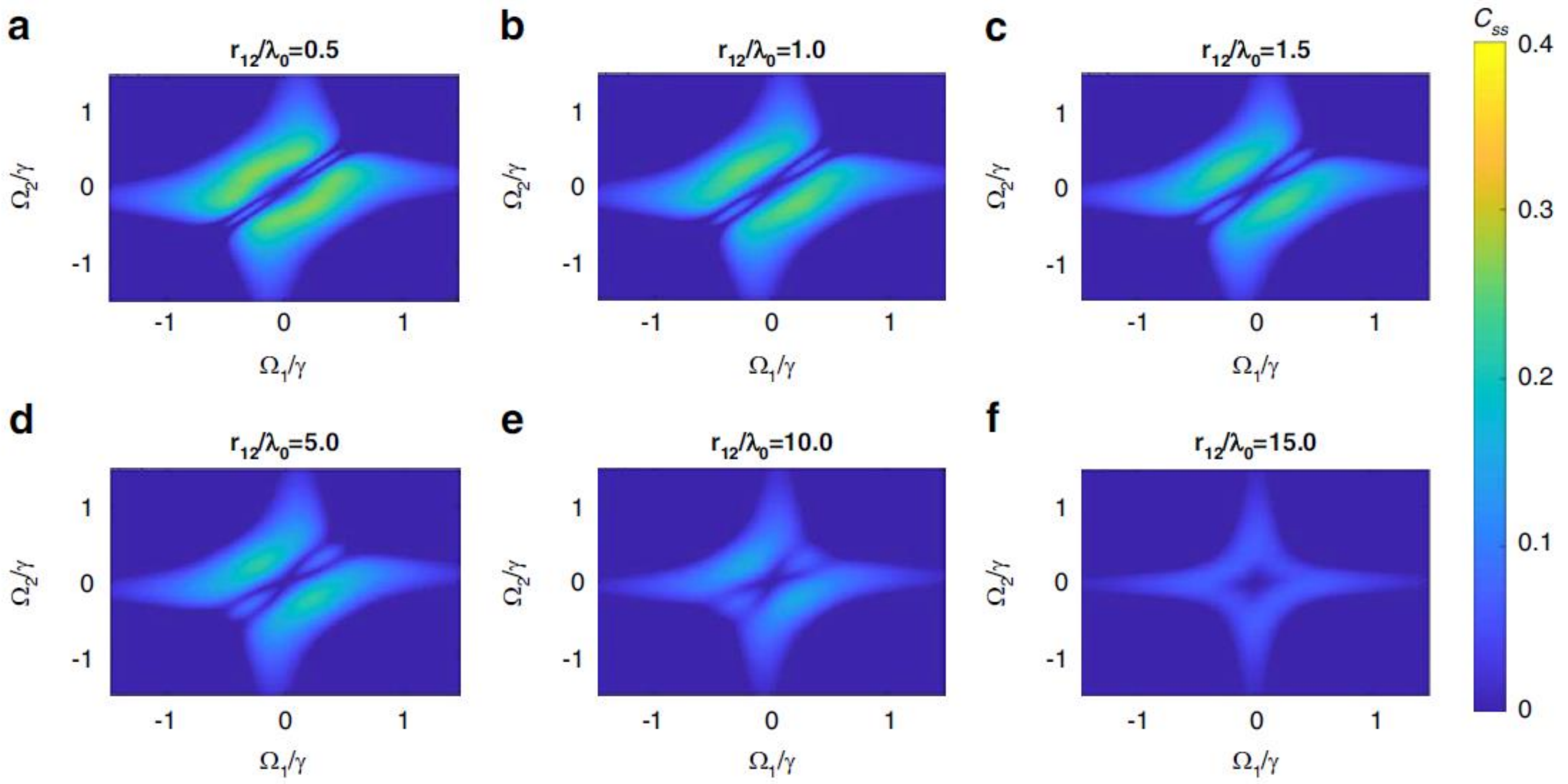
Entanglement properties in the MNZ platform

Steady-state concurrence

Add pumping

$$V = -\sum_{i=1}^{2} \hbar \left(\Omega_i e^{-i\Delta_i t} \sigma_i^\dagger + \Omega_i^* e^{i\Delta_i t} \sigma_i \right)$$

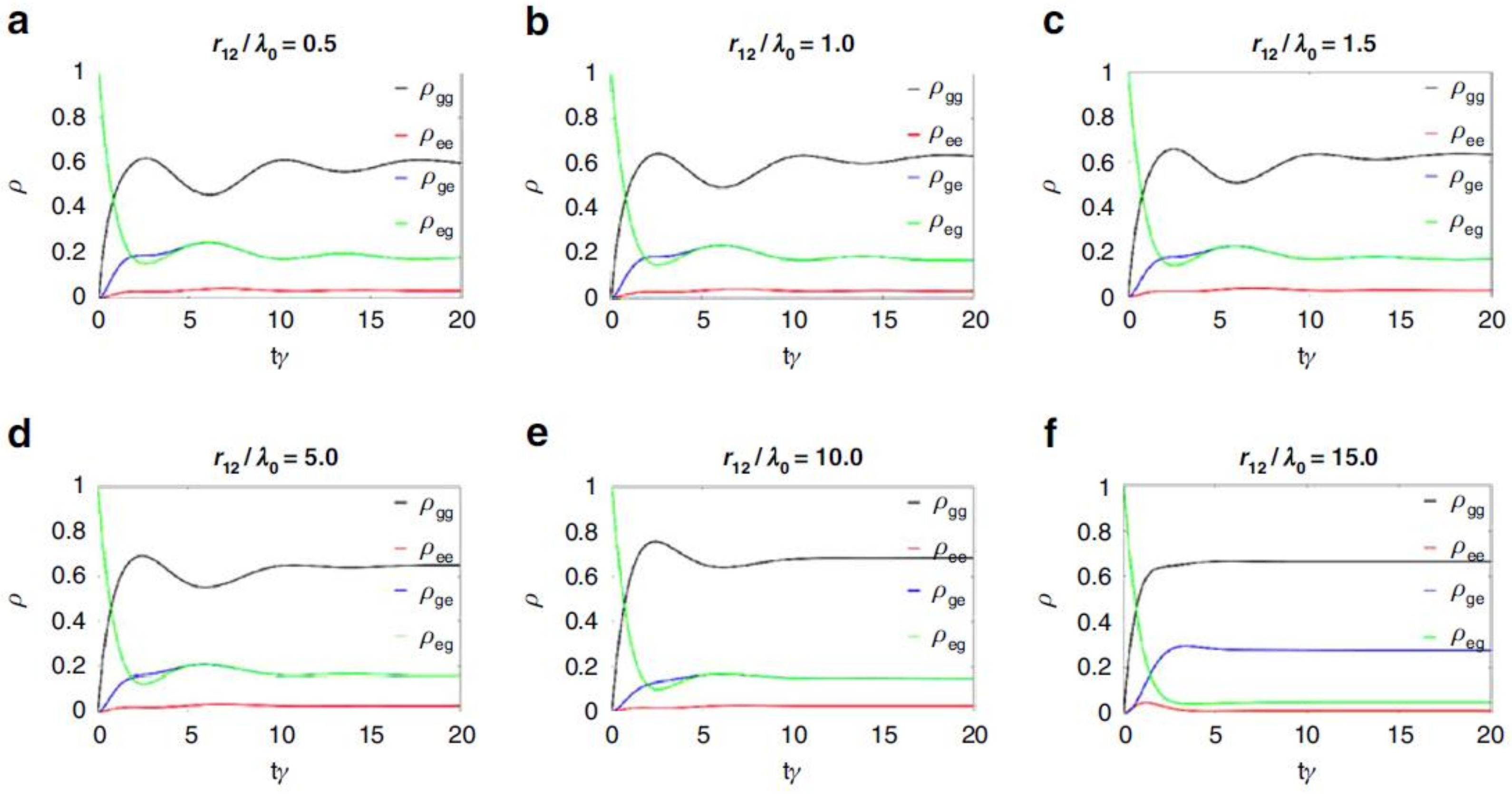
+ solve time evolution of density matrix



One order of magnitude enhancement in the entanglement range compared to ENZ plasmonic waveguide

Entanglement properties in the MNZ platform

Time evolution of the probabilities for the basis states

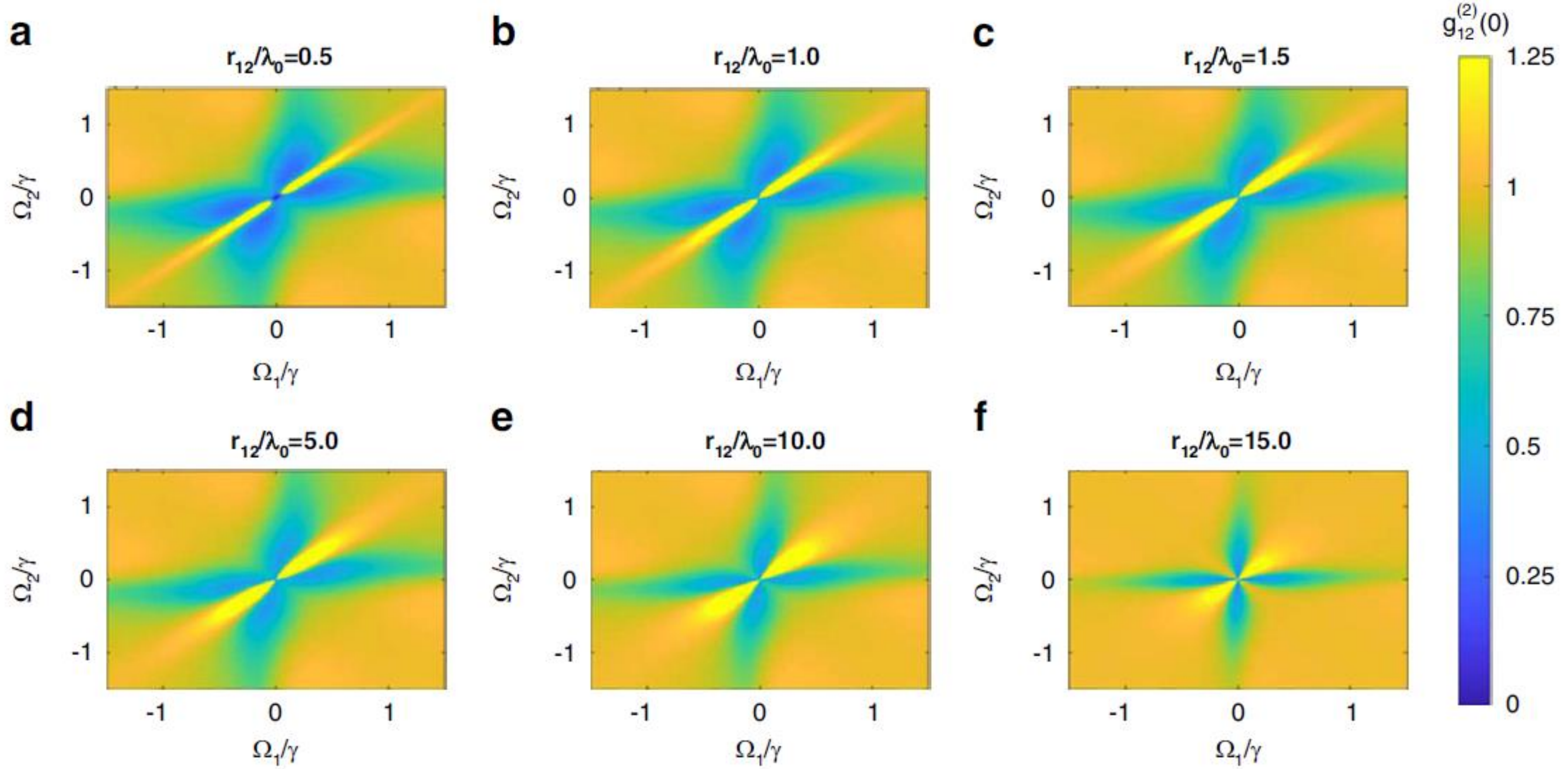


Steady state at $\gamma t = 20$

Entanglement properties in the MNZ platform

Photon–photon intensity correlations at zero-time delay

$$g^{(2)}_{12}(0) = \frac{\langle \sigma_1^\dagger \sigma_2^\dagger \sigma_2 \sigma_1 \rangle}{\langle \sigma_1^\dagger \sigma_1 \rangle \langle \sigma_2^\dagger \sigma_2 \rangle} = \frac{\rho_{ee}}{(\rho_{eg} + \rho_{ee})(\rho_{ge} + \rho_{ee})}$$



High C, small $g^2_{12}(0)$

With the increasing separation between the quantum emitters, the parameter space for antibunching shrinks as expected.

Transitions from bunching to antibunching ($g^2_{12}(0) = 0$, correlated with entanglement) depending on the values of Rabi frequencies Ω_1, Ω_2

Superradiance and near-zero refractive index materials: a win-win cooperation?

Yes!

That would be hype

Yes, maybe, if we can prove it experimentally

That's about trust

Acknowledments

O. Melo

L. Vertchenko

S. Nelson

D. Guney

E. Mazur

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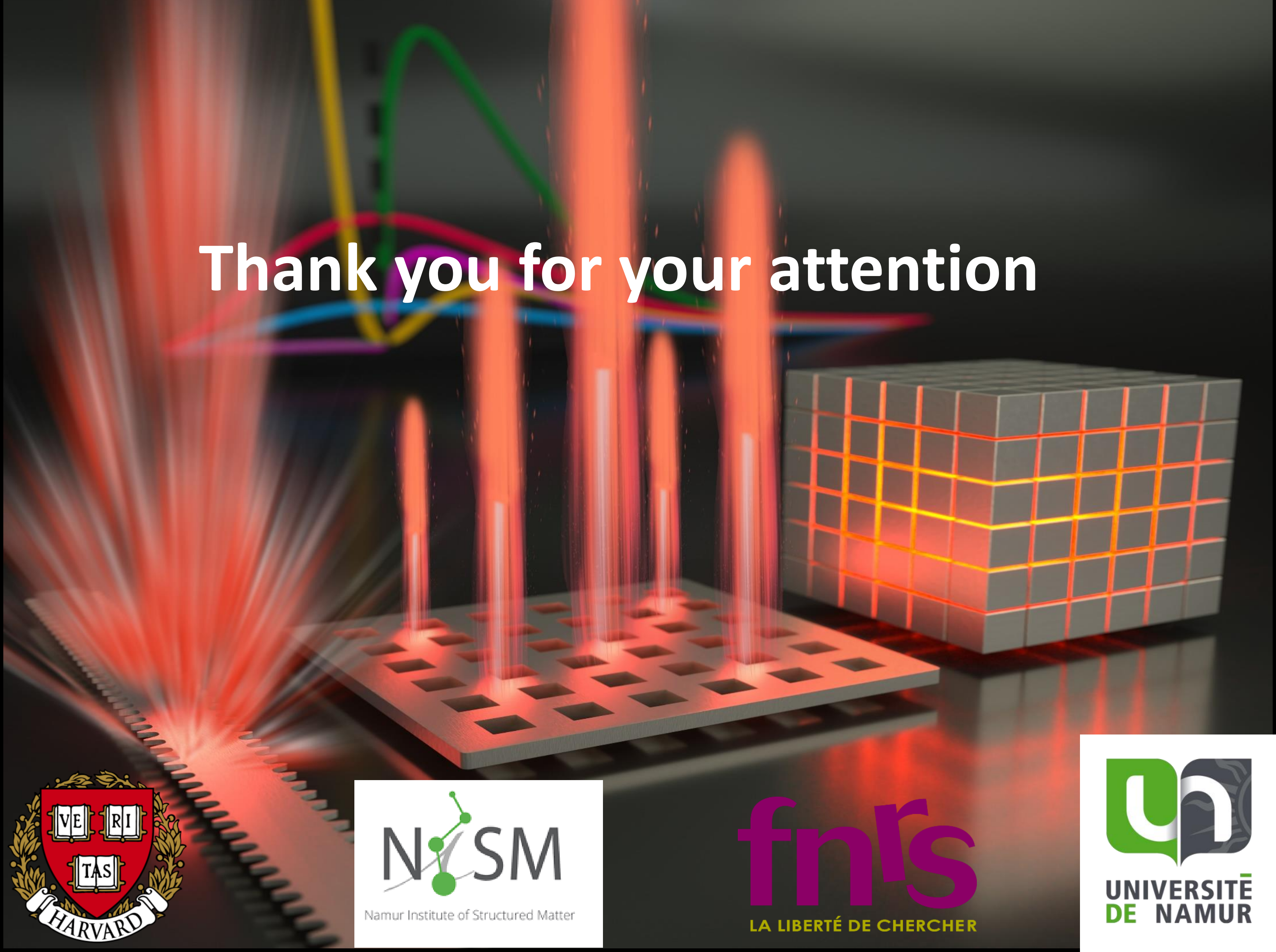
Thank you for your attention



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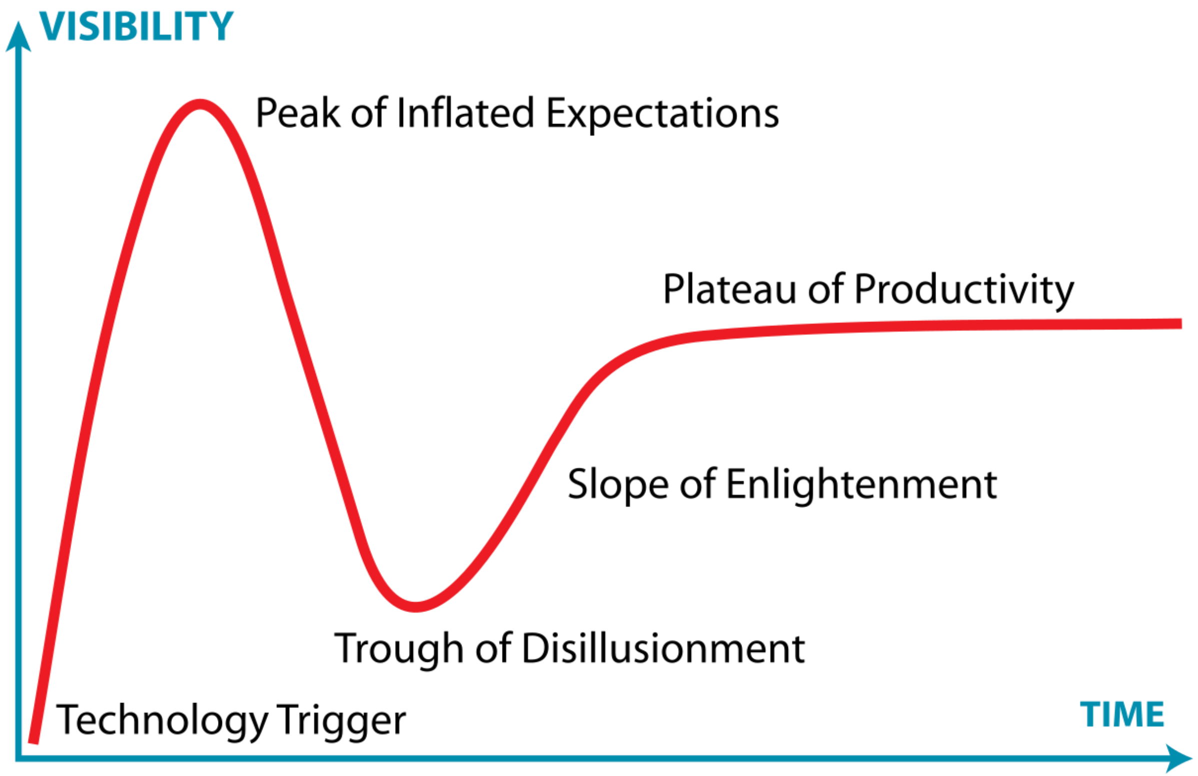
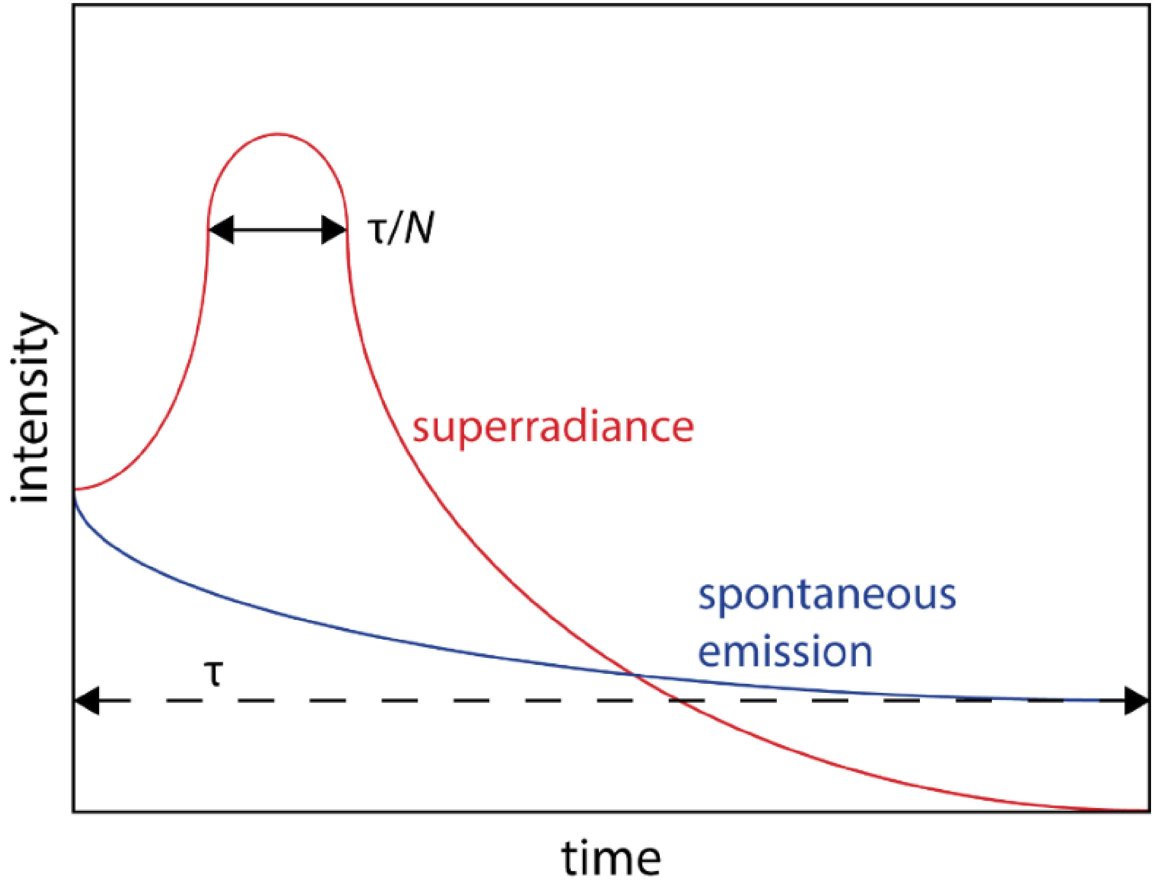
Made with Copilot October 7th

Conclusions

- ✓ 2D ENZ low loss metamaterial platform compatible for quantum optics
- ✓ High degree of superradiance for distance greater than $13\lambda_0$
- ✓ Power enhancement over 3 orders of magnitude higher than bulk for large arrays with N^2 scaling

Conclusions

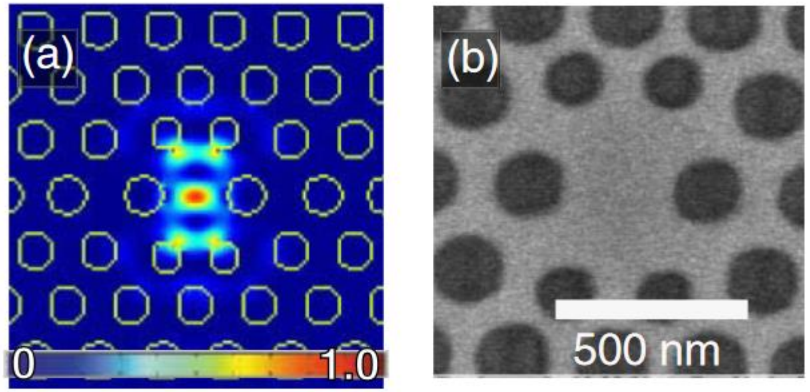




Literature review

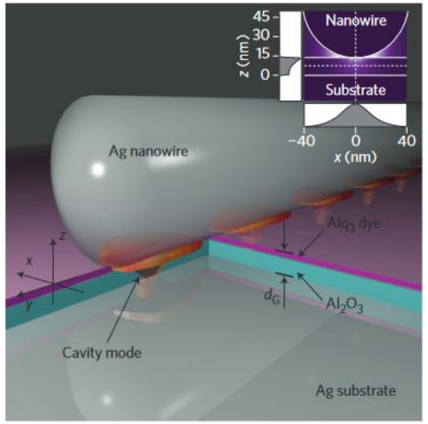
Strategies

✓ Use photonic crystals

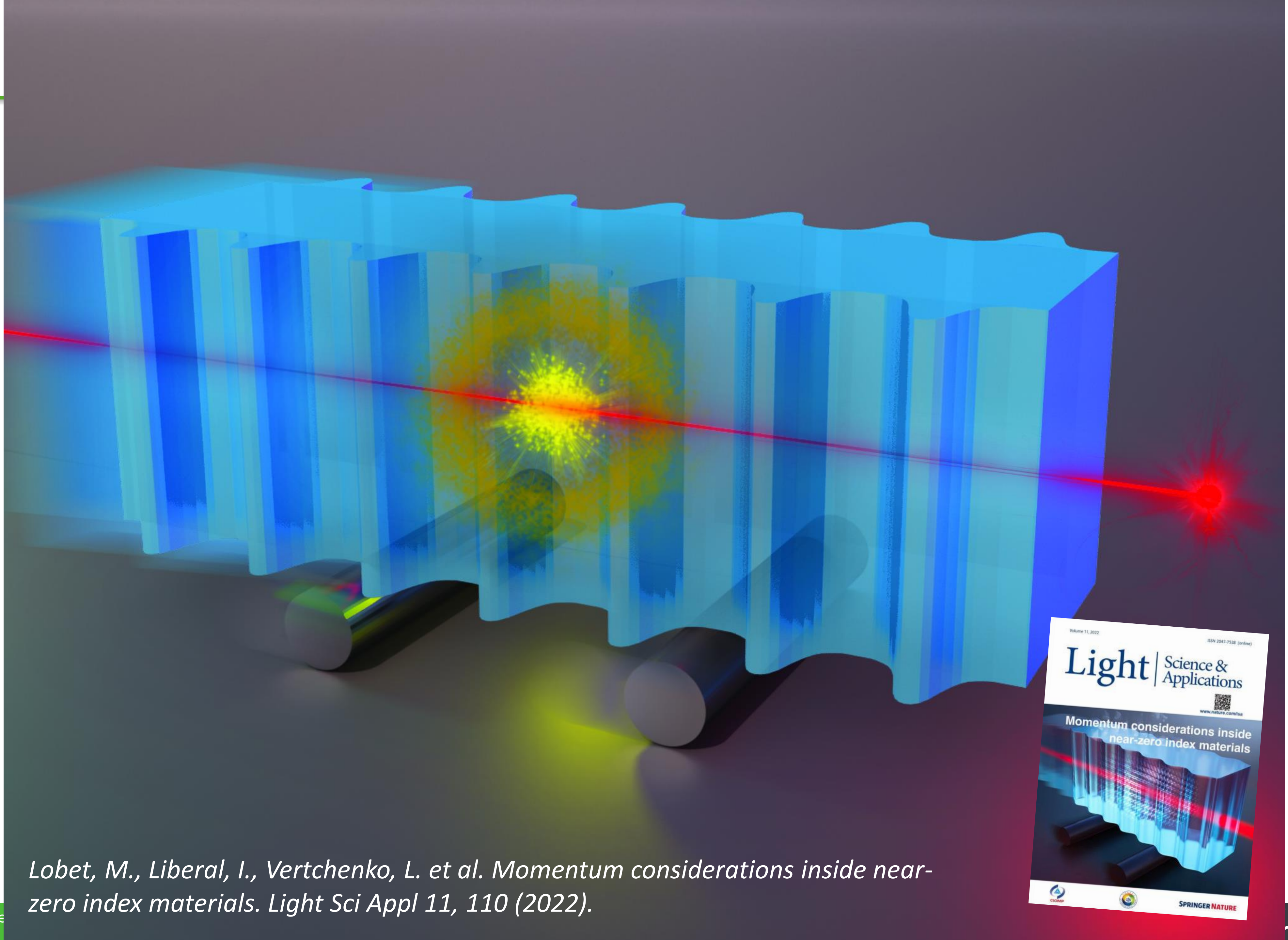


D. Englund, ..., J. Vuckovic , *PRL.* (2005)

✓ Use (plasmonic) cavities



K. Russel, ... E. Hu ,
Nat. Phot. (2012)



Lobet, M., Liberal, I., Vertchenko, L. et al. Momentum considerations inside near-zero index materials. Light Sci Appl 11, 110 (2022).

Applications of near-zero index materials

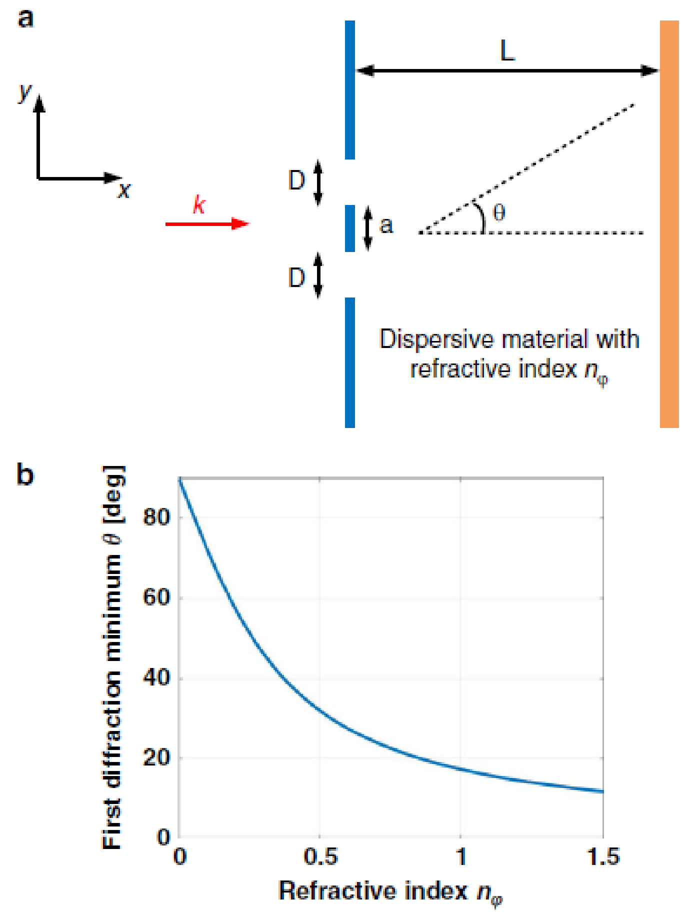


Fig. 3 Young double-slit experiment within dispersive material. **a** EM wave with ***k*** wavevector is sent on a double-slit with slit width *D* at a distance *L* from an observing screen. The distance between the slits is *a*. **b** First diffraction minimum as a function of refractive index. Wavelength is set to 500 nm for a separation width of $a = 800$ nm

$$\tan(\theta) = \frac{\lambda_0}{2a|n_\varphi|}$$

$$I(y) = \frac{I_0}{2} \frac{\sin^2\left(\frac{\pi D y}{\lambda L}\right)}{\left(\frac{\pi D y}{\lambda L}\right)} \left[1 + \cos\left(\frac{2\pi a y}{\lambda L}\right)\right]$$

Applications of near-zero index materials

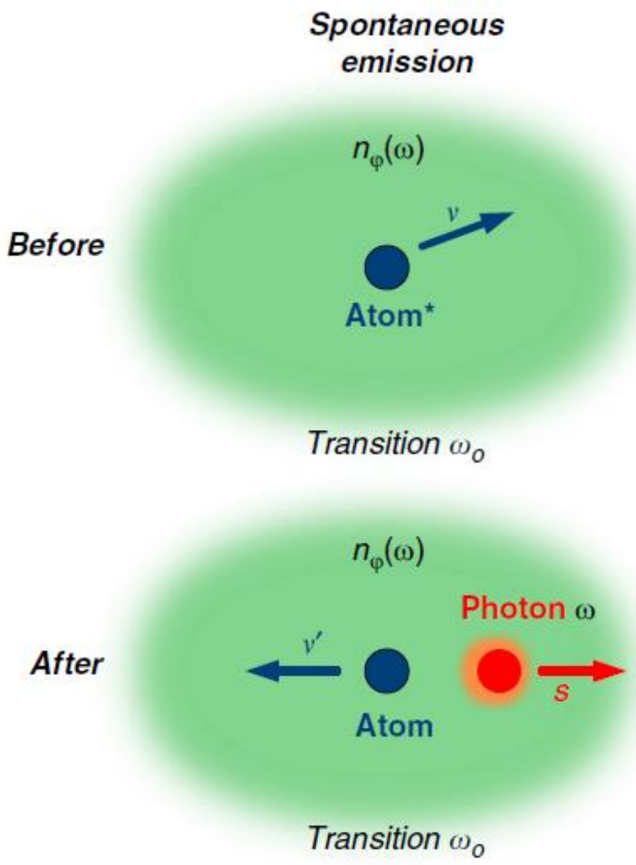


Fig. 1 Schematic of the spontaneous emission process inside NZI materials of refractive index $n_\varphi(\omega)$ (green background). An atom (blue) moves around at a velocity v (v') before (after) spontaneous emission process. A photon (red) is being emitted after the excited atom relaxed in its ground state, in direction ***s***

In the non-relativistic approximation[41], conservation of energy for the spontaneous emission process implies

$$\frac{mv^2}{2} + \hbar\omega_0 = \frac{mv\prime^2}{2} + \hbar\omega \quad (7)$$

while the conservation of linear momentum can be expressed as

$$m\boldsymbol{v} = m\boldsymbol{v}\prime + \hbar\boldsymbol{k} \quad (8)$$

with $\boldsymbol{k} = \left[n_\varphi(\omega)\frac{\omega}{c}\right]\boldsymbol{s}$, **s** being an unit vector pointing in the direction of the emitted photon and $-\hbar\boldsymbol{k}$ is the recoil momentum of the atom. As is well known from classical physics, the frequency of the emitted light, as it appears to the moving atom, is increased due to the Doppler shift. The Doppler shift formula can be deduced as[42,43]

$$\omega = \omega_0\left[1 + \frac{n_\varphi(\omega)}{c}v\cos\theta\right] \quad (9)$$

where θ is the angle between $\boldsymbol{v}$ and **s**. In general, $\hbar\boldsymbol{k}$ is not solely the momentum of the emitted photon, but corresponds to the total momentum transferred from the atom to both the emitted photon and the medium[6].

Applications of near-zero index materials

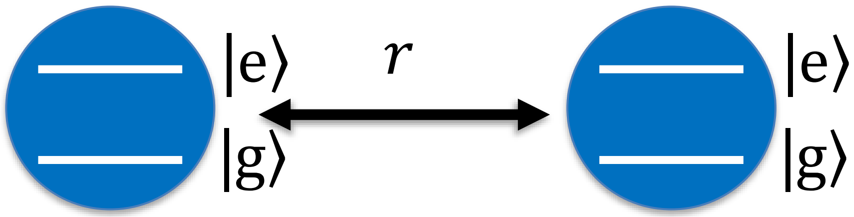
quantization in the dielectric[illegible]. Both approaches yield to the conclusion that the recoil momentum is the canonical momentum:

$$p_C = n_\varphi(\omega_0)\frac{\hbar\omega_0}{c} \tag{10}$$

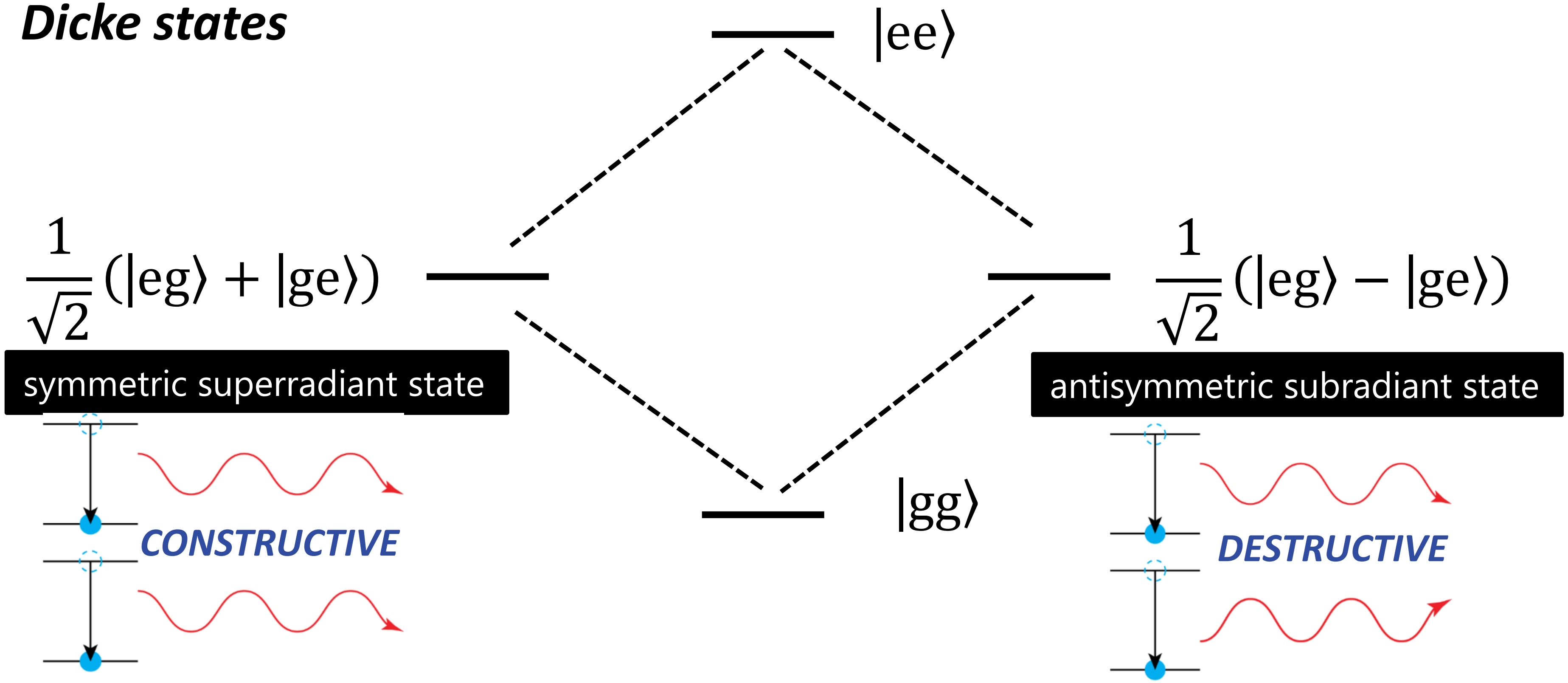
Consequently, the recoil momentum vanishes inside NZI materials. Moreover, the Doppler shift perceived by the atom also vanishes as the phase refractive index goes to zero (Eq. (9)). This extinction of the Doppler shift can be understood as a continuous transition between inverse Doppler effect occurring in negative index materials[44–46]

Dicke superradiance for two two-level system

Analytical model



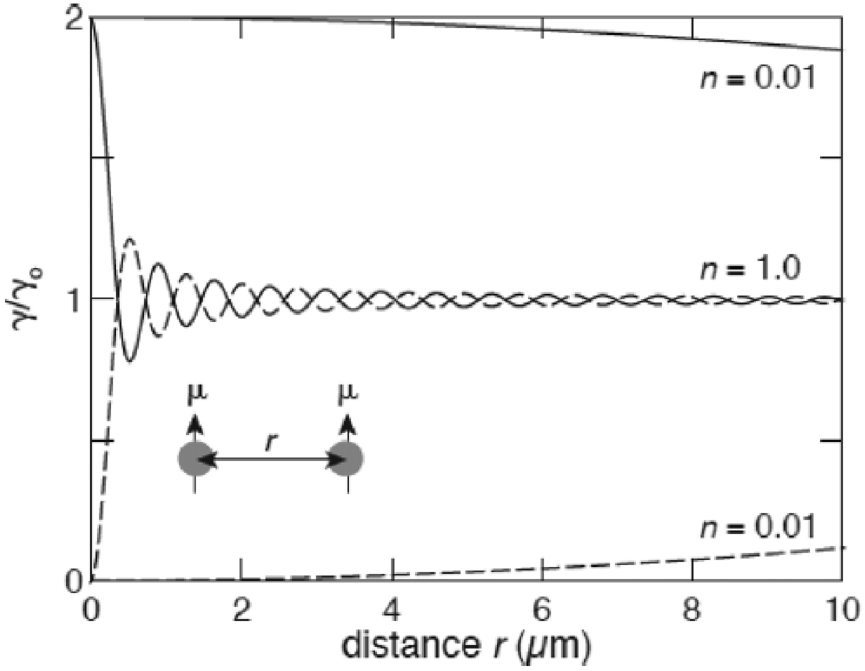
Dicke states



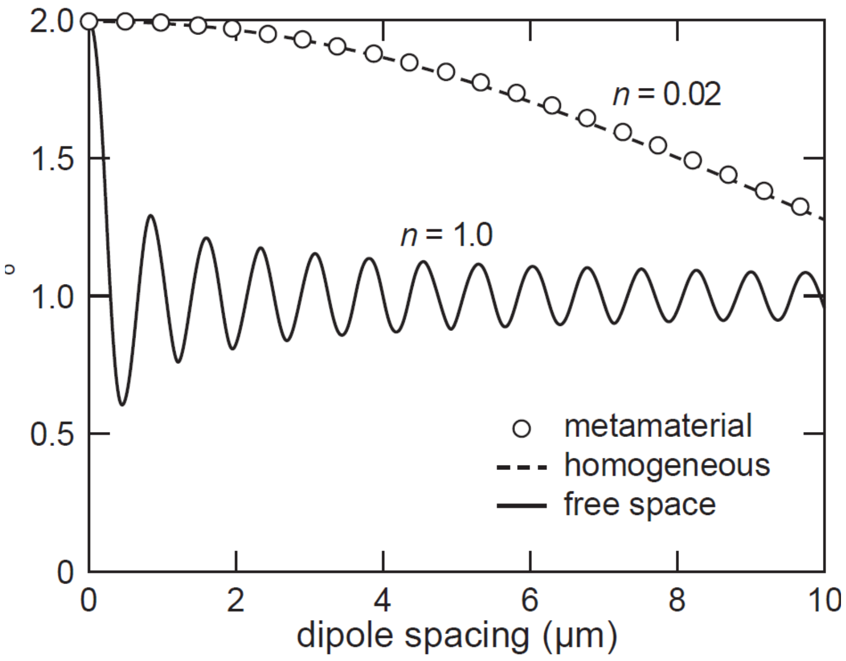
Dicke superradiance for two two-level system in 2D ENZ

Spontaneous emission rate

Two-atom decay rate
Homogeneous NZI
(*Analytical model*)

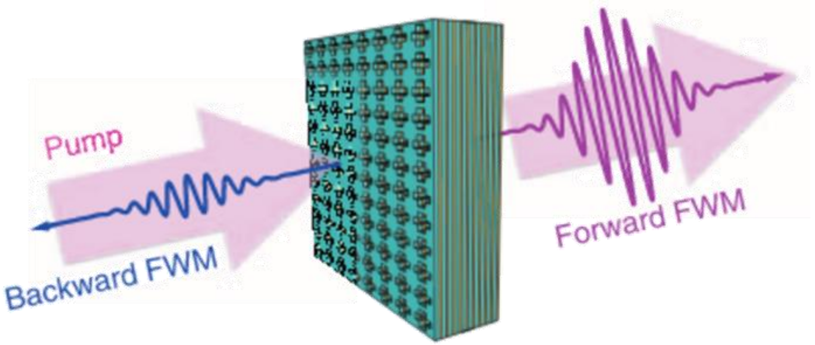


Two-atom decay rate
2D ENZ diamond platform SiV centers
(*COMSOL simulations*)



Applications of near-zero index materials

Nonlinear phase matching

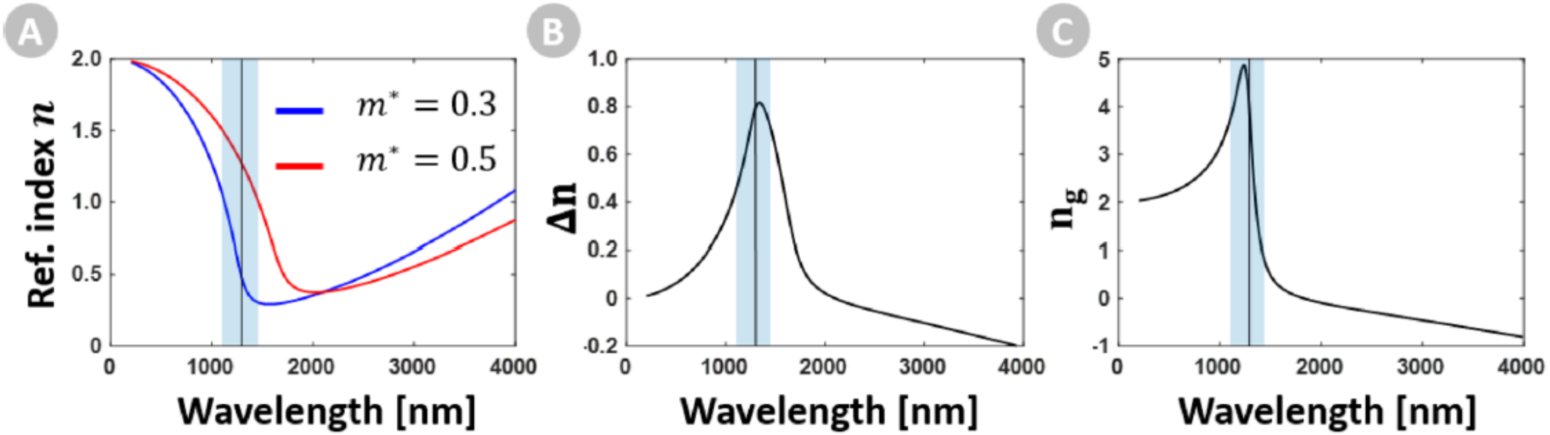


H. Suchowski et al, Science, vol. 342, 2013

Nonlinear optics

$$n_2 = \frac{3\chi^{(3)}}{4n_0\Re[n_0]\epsilon_0 c}$$

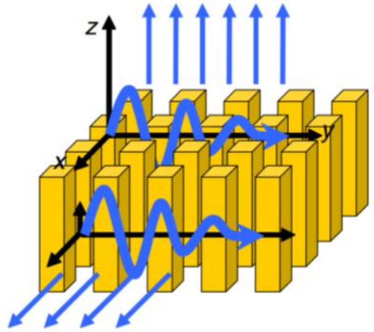
M. Zahirul Alam et al, Science, vol. 352, 2016



M. Lobet *et al,* ACS Photonics, 10, 3805–3820 (2023).

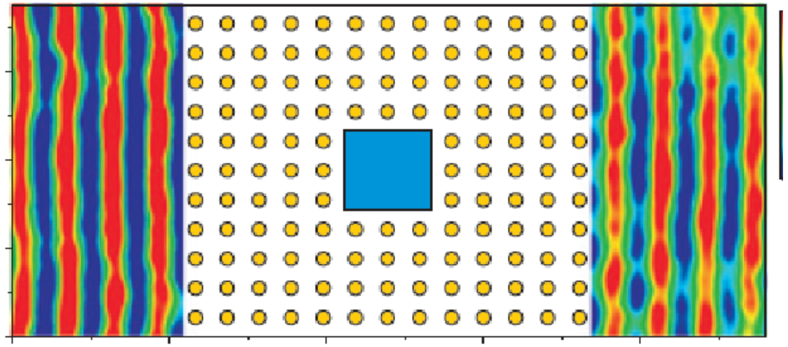
Applications of near-zero index materials

Beam steering



M. Memarian et al, Nature Comm., vol. 6, 2015

Cloaking



X.Q. Huang et al, Nature Materials, vol. 10, 2011

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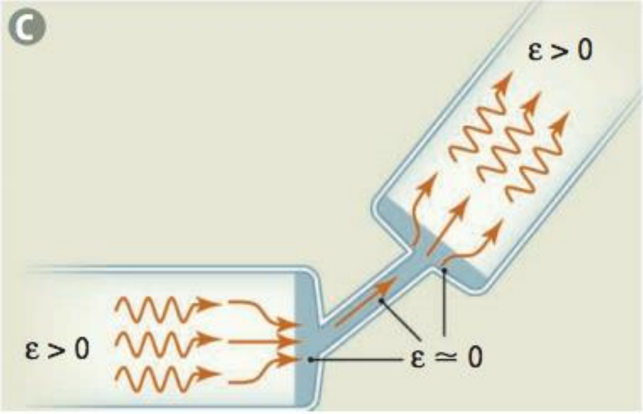
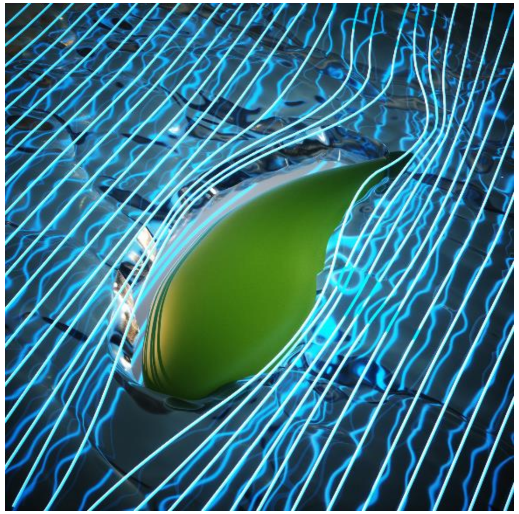
Supercoupling



M. Silveirinha & N. Engheta, PRL 97, 2006 / PRB 76, 2007 / N. Engheta, Science, vol. 340, 2013

Ideal fluid



I. Liberal , PNAS, 2020

Applications of near-zero index materials

$$\mathbf{S} = \mathbf{S}_R + i\mathbf{S}_I = \frac{1}{2}\mathbf{E} \times \mathbf{H}^*$$

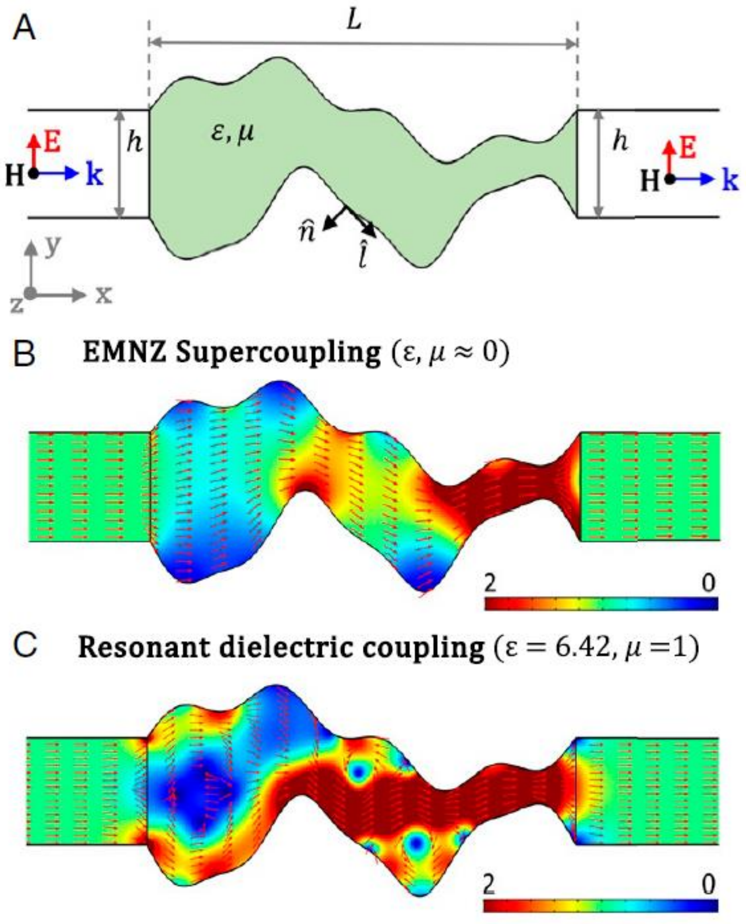
$$\nabla \cdot \mathbf{S} = -\frac{\omega}{2}\left[\left(\varepsilon_0\varepsilon'' |\mathbf{E}|^2 + \mu_0\mu'' |\mathbf{H}|^2\right) + i\left(\varepsilon_0\varepsilon' |\mathbf{E}|^2 - \mu_0\mu' |\mathbf{H}|^2\right)\right].$$

→ 0 Incompressible

$$\nabla \times \mathbf{S} = \frac{1}{2}\left[(\mathbf{H}^* \cdot \nabla)\mathbf{E} - (\mathbf{E} \cdot \nabla)\mathbf{H}^* + \mathbf{E}(\nabla \cdot \mathbf{H}^*) - \mathbf{H}^*(\nabla \cdot \mathbf{E})\right].$$

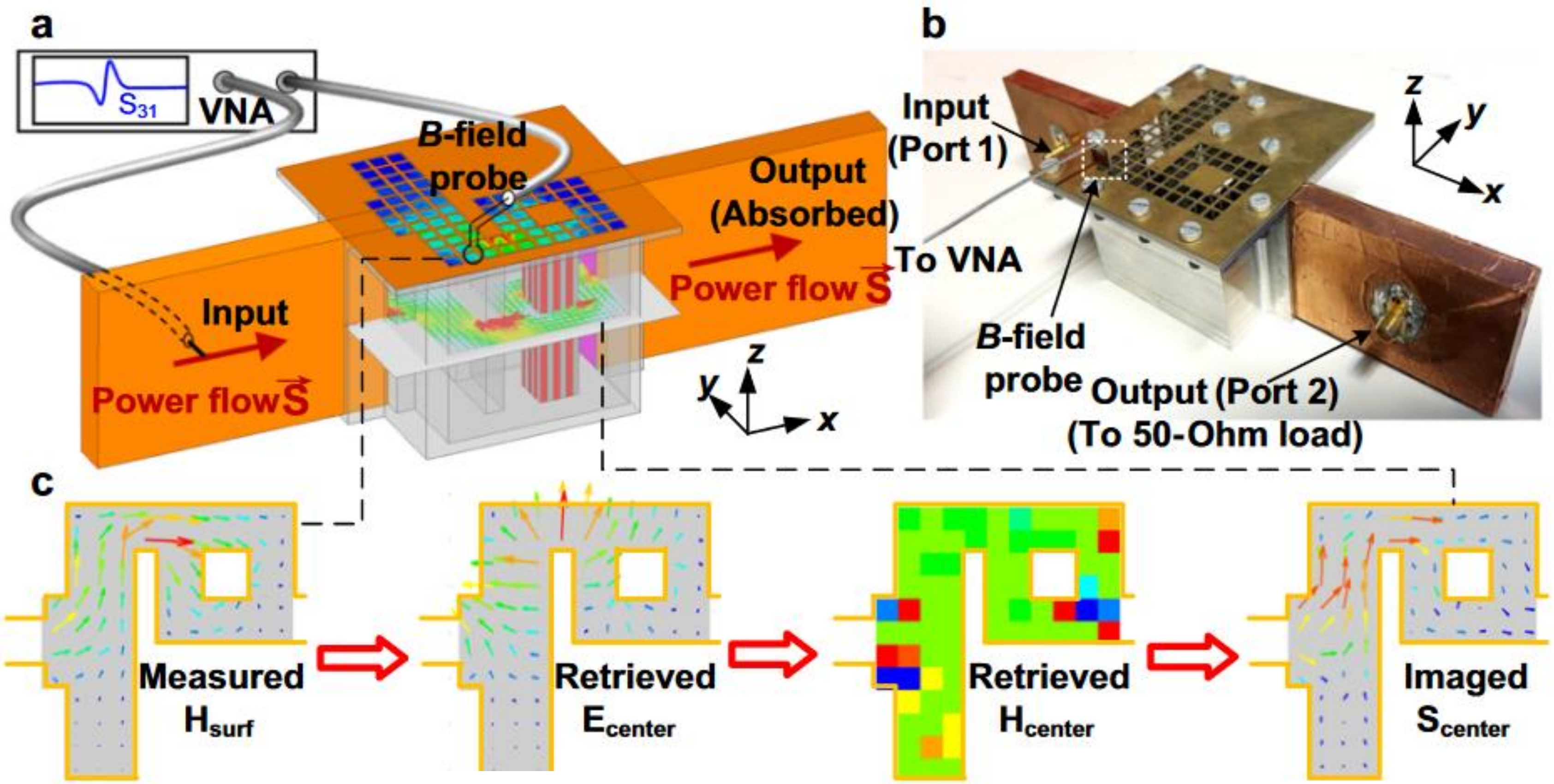
→ 0 for TM fields in ENZ materials

Irrotational → No vortex



I. Liberal , PNAS, 2020

Applications of near-zero index materials



$$\mathbf{E}(x,y,0)=\frac{i\omega\mu_0 h}{\pi}\mathbf{H}(x,y,\frac{h}{2})\times\hat{\mathbf{z}}.\quad \mathbf{H}(x,y,0)=\frac{1}{i\omega\mu_0}\nabla_{xy}\times\mathbf{E}(x,y,0).\quad \mathbf{S}_R(x,y,0)=\frac{1}{2}\mathrm{Re}[\mathbf{E}(x,y,0)\times\mathbf{H}(x,y,0)].$$

H. Li & al. Nature Communications 13 (2022)

Applications of near-zero index materials

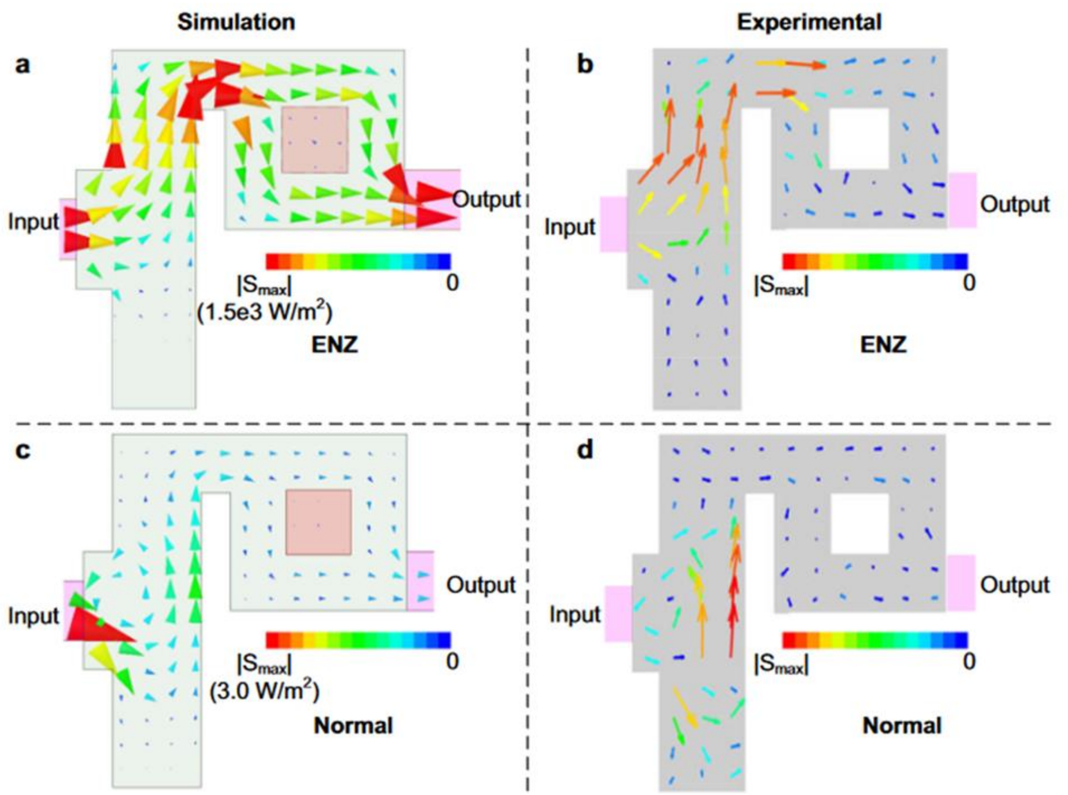
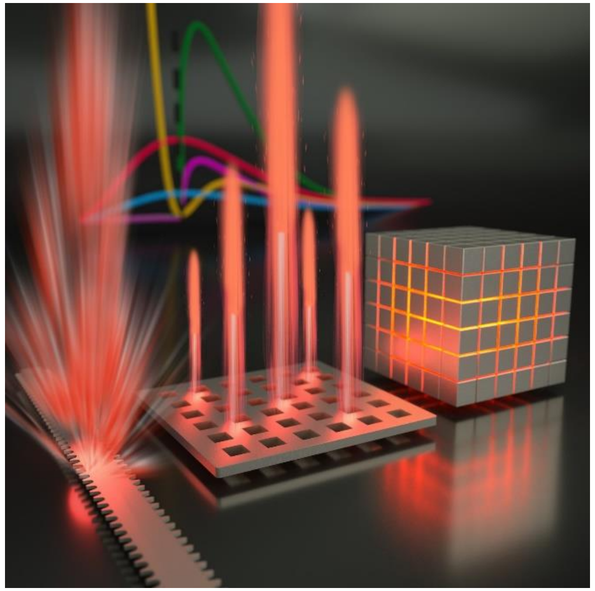


Fig. 3 | Simulated and experimental observation of the power flow within doped ENZ and normal media. **a**, **b** the simulated and experimentally imaged power flow of the doped ENZ medium at 3.06 GHz, **c**, **d** the simulated and experimentally reconstructed power flow of the normal medium with the same dielectric particle but the operating frequency at 3.9 GHz.

H. Li & al. Nature Communications 13 (2022)

Applications of near-zero index materials

Modified fundamental radiative processes



M. Lobet , ACS Photonics, 2020

Applications of near-zero index materials

$$\varepsilon(\omega) = \mu(\omega) = \frac{\omega^2 - \omega_Z{}^2 + 2i\omega\Gamma}{\omega^2 - \omega_r{}^2 + 2i\omega\Gamma}$$

(No losses)

$\omega_r = 0.1\omega_Z$