Light-matter interactions with photonic quasiparticles

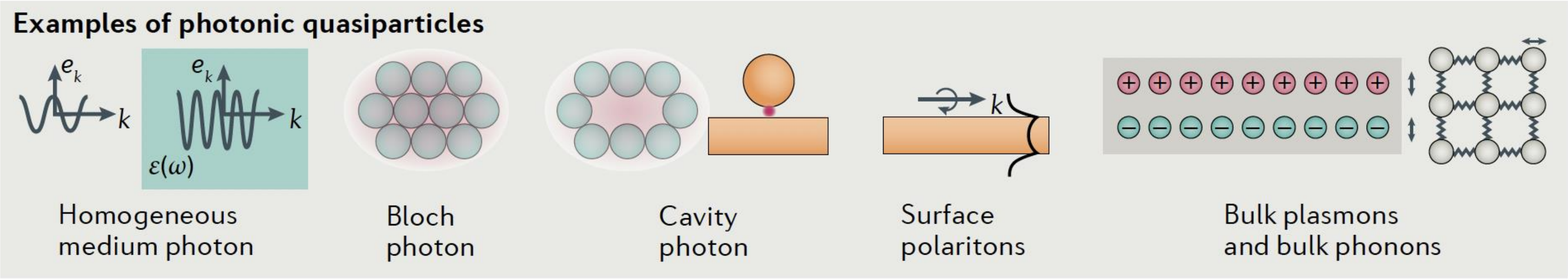
Nick Rivera

Massachusetts Institute of Technology

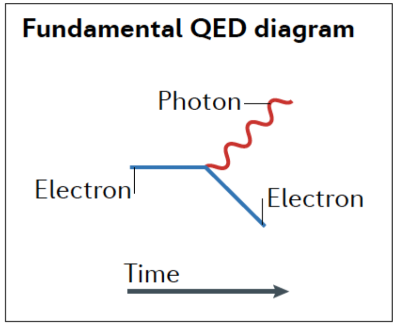
https://nrivera.scripts.mit.edu/nhr

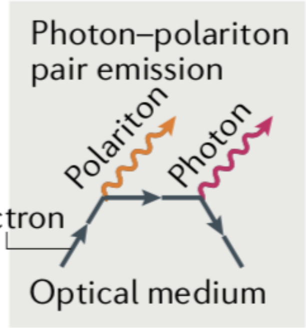
Outline

Photonic quasiparticles

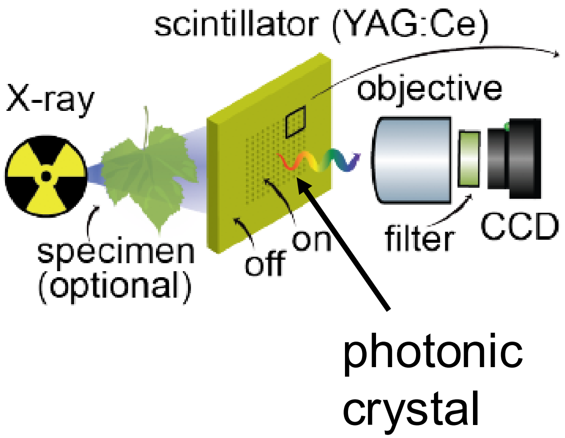


New light-matter interactions based on photonic quasiparticles

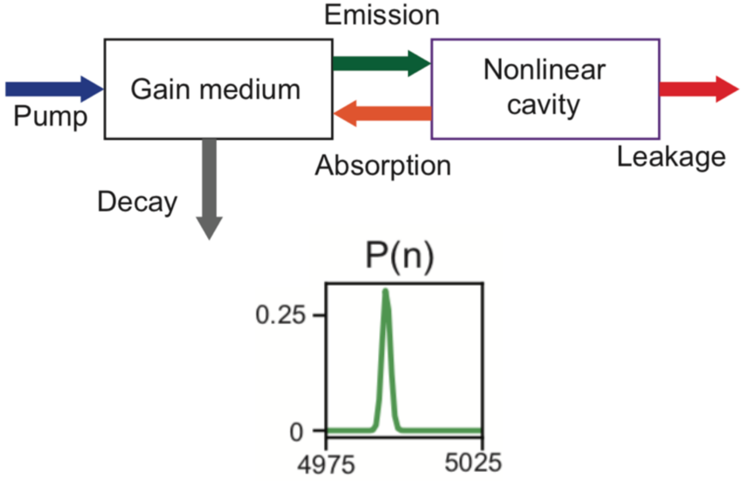




New particle detectors based on photonic quasiparticle interactions

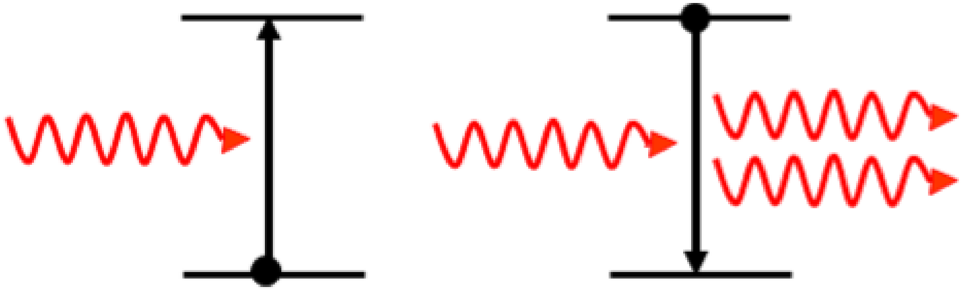


Using photonic quasiparticle nonlinearities to generate macroscopic Fock states

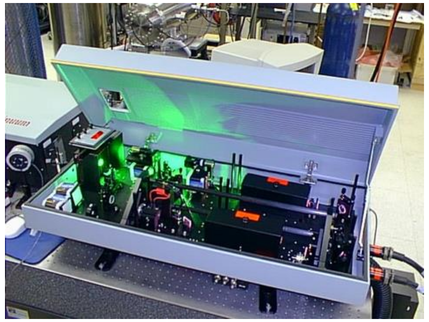


Light-matter interactions

Working definition: electronic transitions (bound and free electrons) leading to absorption, emission, or scattering of the photon.



Lasers

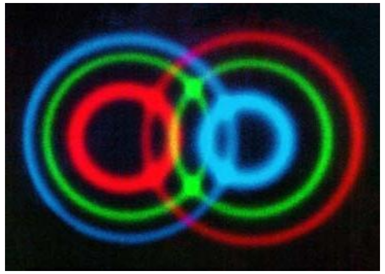


LEDs

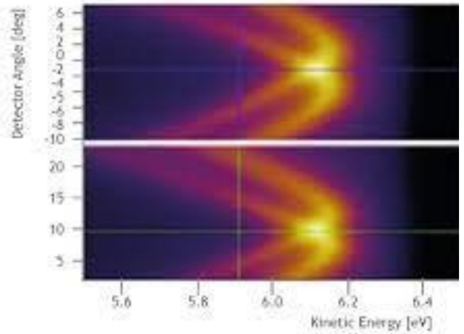
Solar cells

Detectors

Quantum light



Spectroscopy



Particle detection

Limitations of light-matter interactions

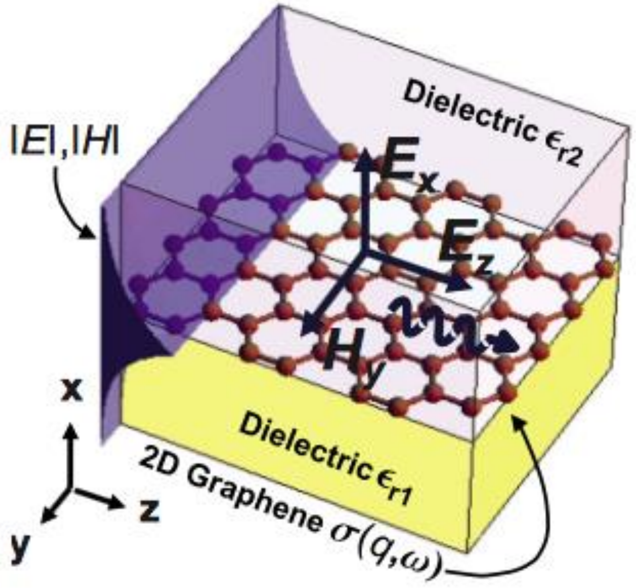
The interactions are *very weak*, are largely described at leading order.

- Coupling strength: α
- Ratio of atomic size to optical wavelength: $ka = 2\pi a/\lambda$
- Scale of applied field to internal field: $E_{\rm ext}/E_0$

All of these together, strongly limit the diversity of allowed interactions.

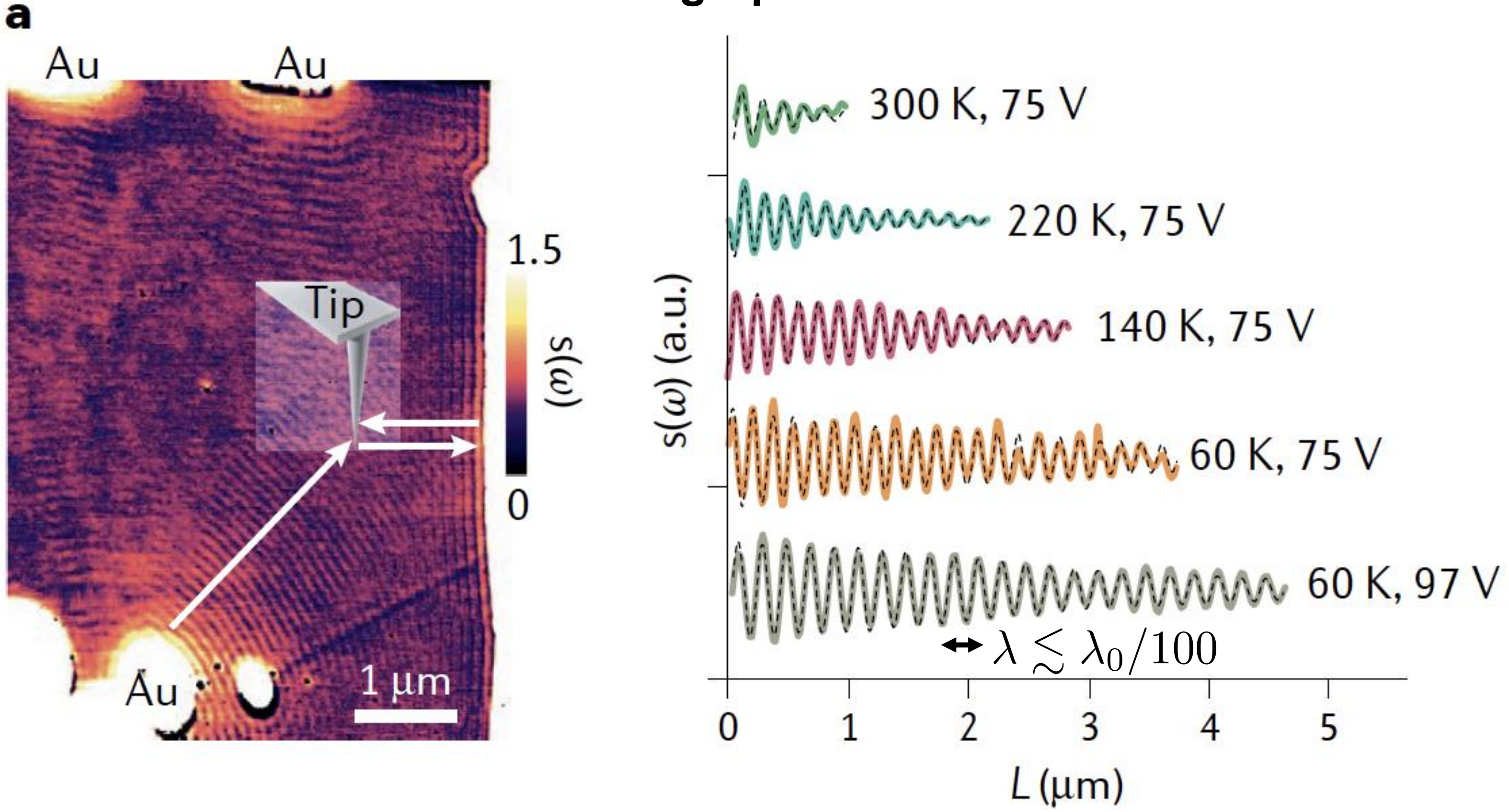
- Neglect "multipole" decays [dipole approx.]
- Neglect "multiphoton" decays [first-order QED approx.]
- Neglect nonlinear phenomena [first-order external field approx.]

Collective excitations in solids challenge these limitations



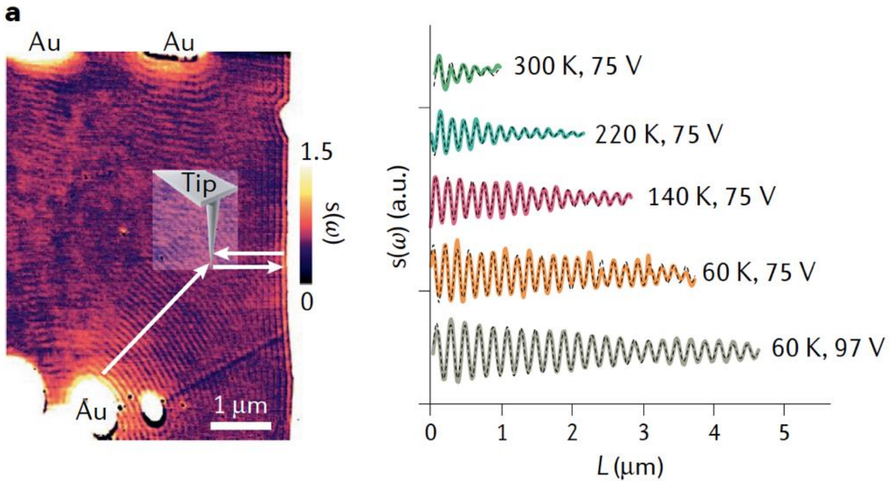
Jablan *et al. PRB* (2009).

Plasmons in graphene

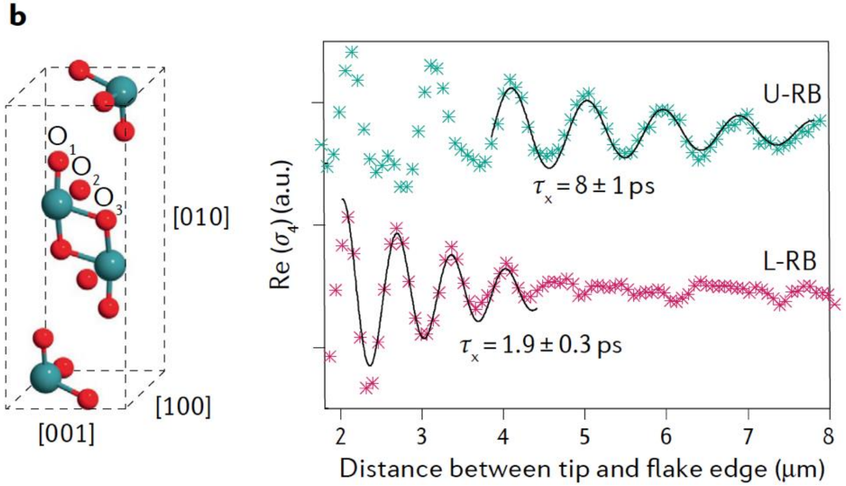


Ni *et al*. *Nature* (2018).

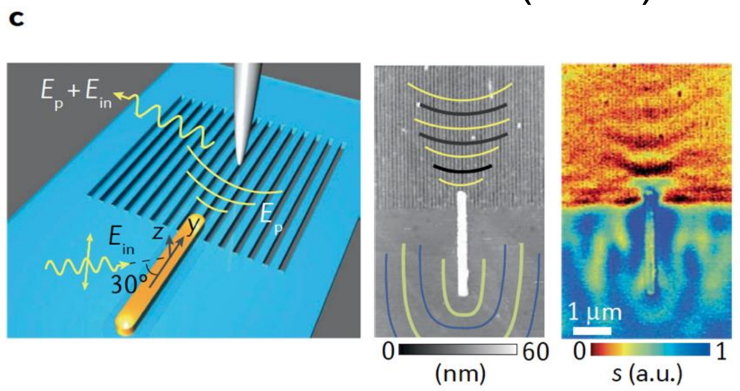
Collective excitations: like photons but with very different linear properties



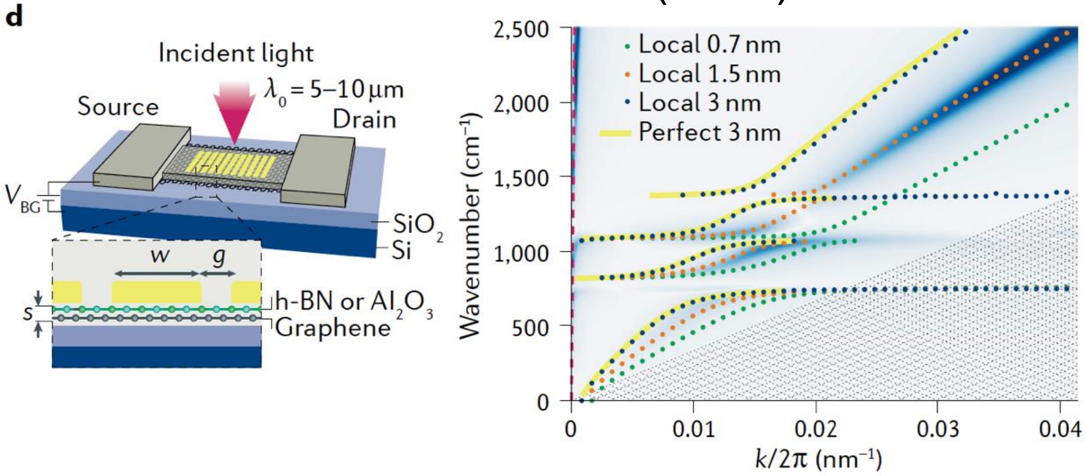
Ni *et al*. *Nature* (2018).



Ma *et al*. *Nature* (2018).



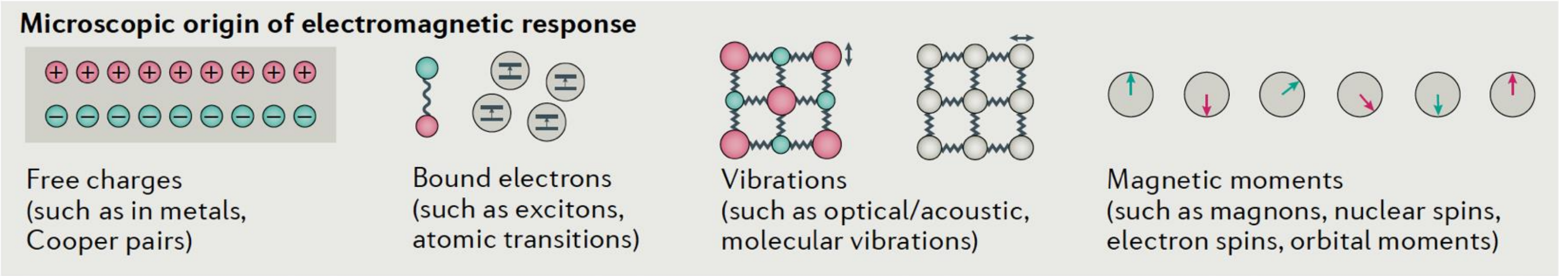
Li *et al*. *Science* (2018).



Iranzo *et al*. *Science* (2018).

- *Wavelength* – >100x smaller
- *Polarization* – often circular
- *DOS* – very high
- *Mode volume* – very small

Photonic quasiparticles (PQPs) as quantized solutions to Maxwell equations



Rivera & Kaminer. *Nature Reviews Physics* (2020).

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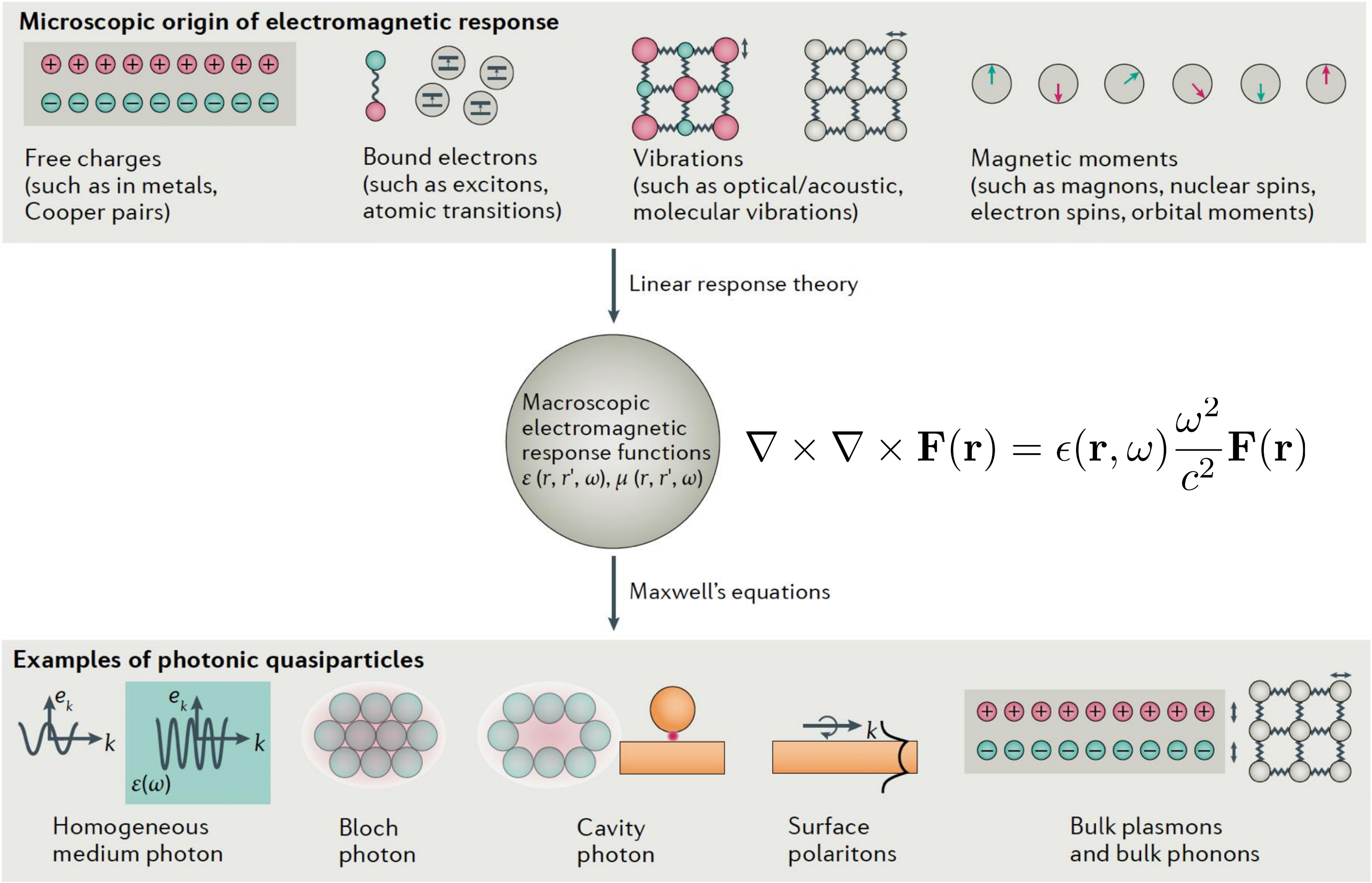


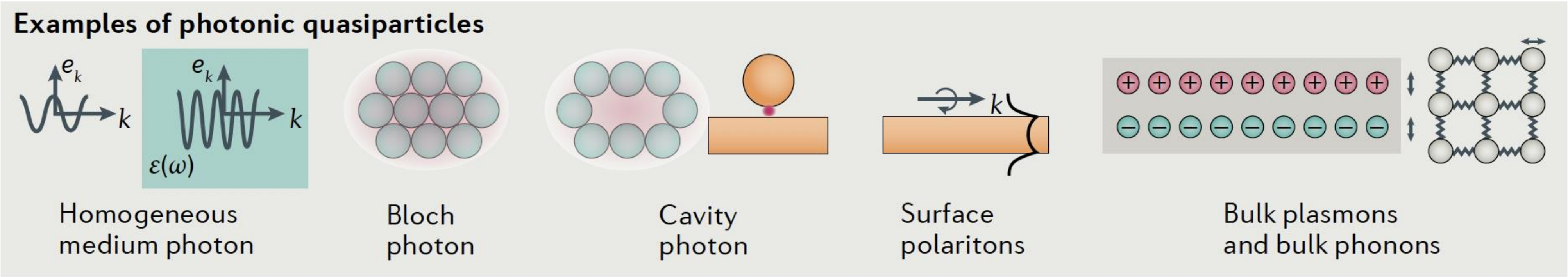
$$\nabla \times \nabla \times \mathbf{F}(\mathbf{r}) = \epsilon(\mathbf{r}, \omega)\frac{\omega^2}{c^2}\mathbf{F}(\mathbf{r})$$

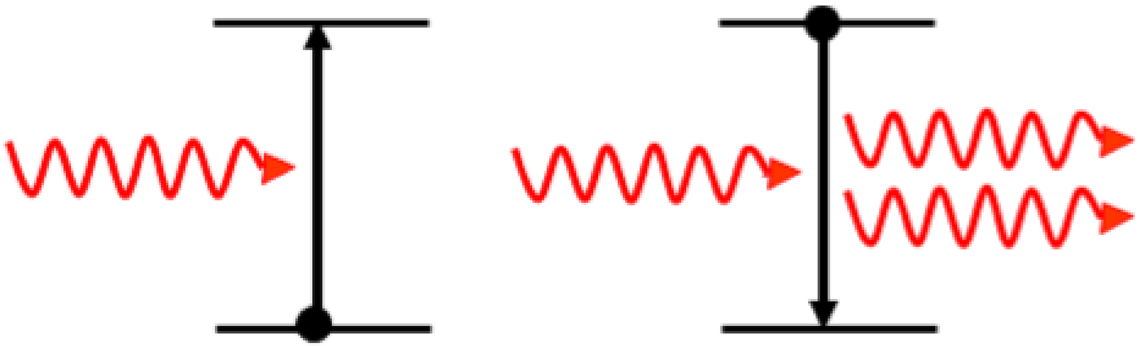
Quantized PQP field:

$$\mathbf{E}(\mathbf{r}) = i\sum_n \sqrt{\frac{\hbar\omega_n}{2\epsilon_0}}(\mathbf{F}_n(\mathbf{r})a_n - \text{h.c.})$$

Rivera & Kaminer. *Nature Reviews Physics* (2020).

Light-matter interactions with photonic quasiparticles





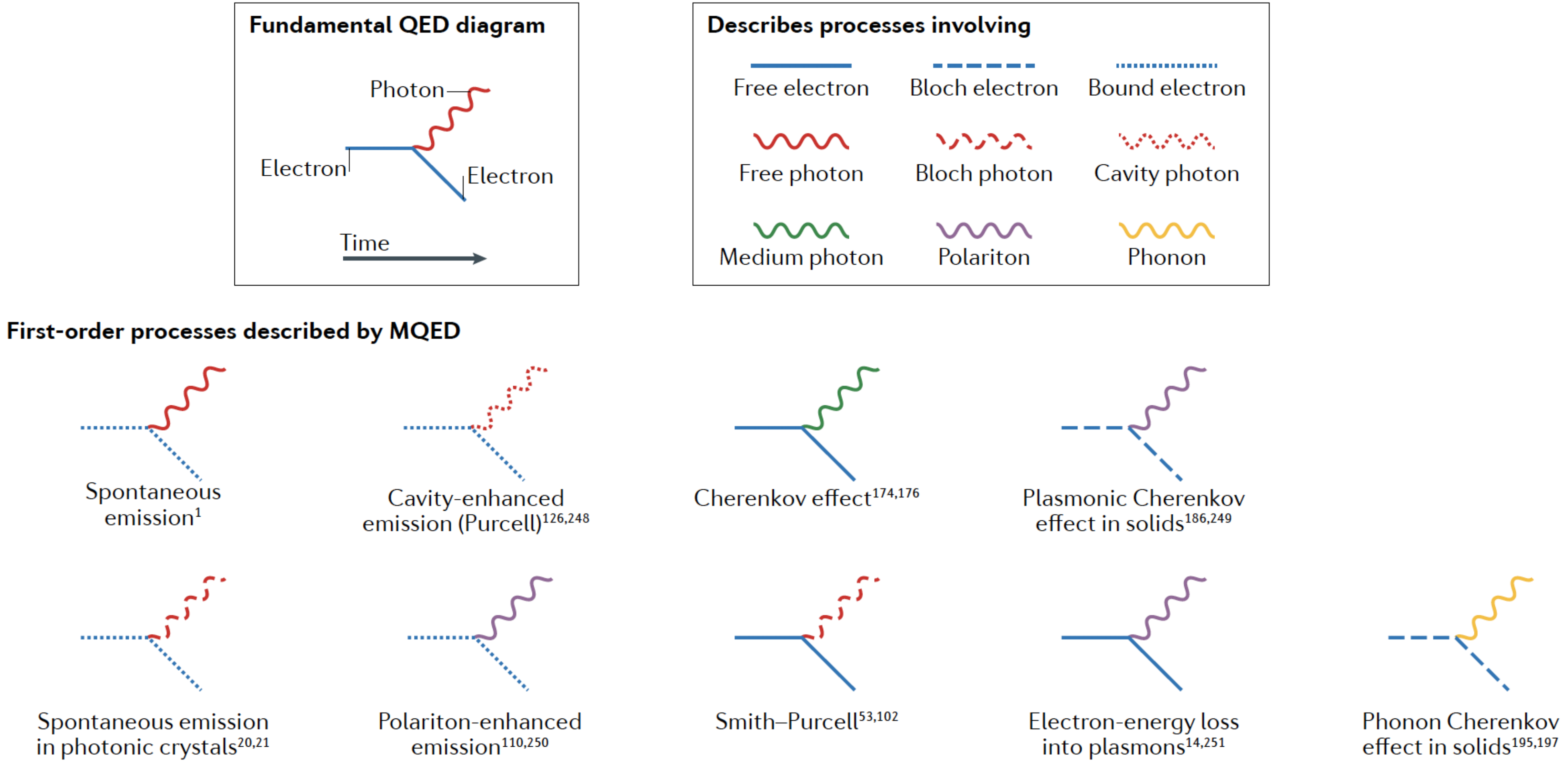
What happens when an excited electron interacts electro-magnetically with photonic quasiparticles?

Rivera & Kaminer. *Nature Reviews Physics* (2020).

Elementary processes of light-matter interaction between electrons and photonic quasiparticles

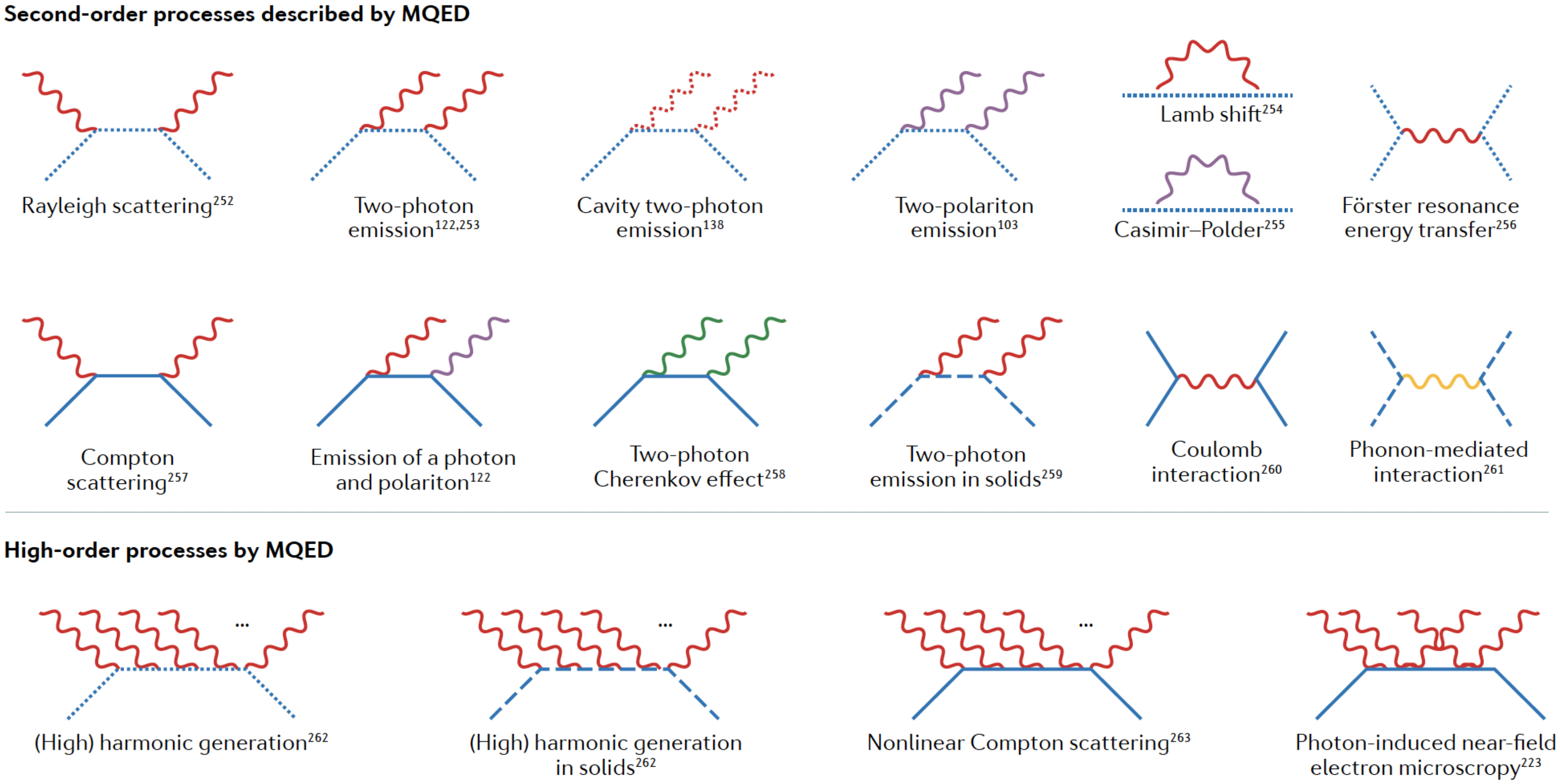
Rivera*, Kaminer*, *et al. Science* (2016), **Rivera** *et al. Proc. Nat. Acad. Sci.* (2017),
Rivera *et al. Nature Physics* (2019), **Rivera** *& Kaminer. Nature Reviews Physics* (2020).

Describing light-matter interactions with photonic quasiparticles



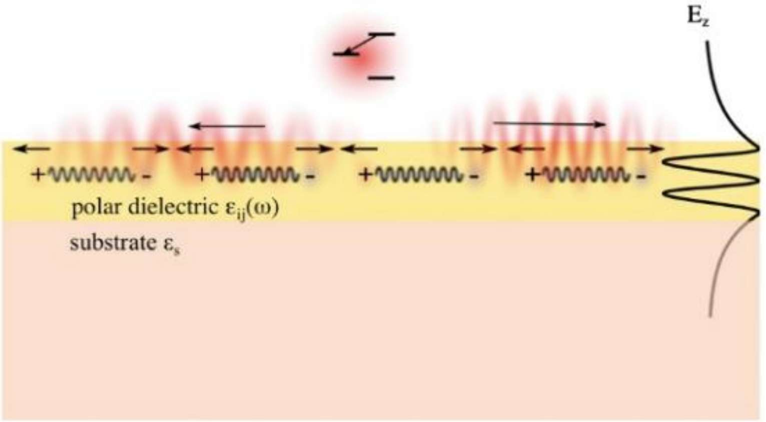
Rivera & Kaminer. *Nature Reviews Physics* (2020).

Describing light-matter interactions with photonic quasiparticles



Rivera & Kaminer. *Nature Reviews Physics* (2020).

Higher-order processes can also be made dominant, like two-photon decay



n-polariton emission rate:

$$\Gamma(nE1) \sim \alpha^n \eta^{3n} (ka)^{2n} \omega_0$$

Rivera *et al. PNAS* (2017).

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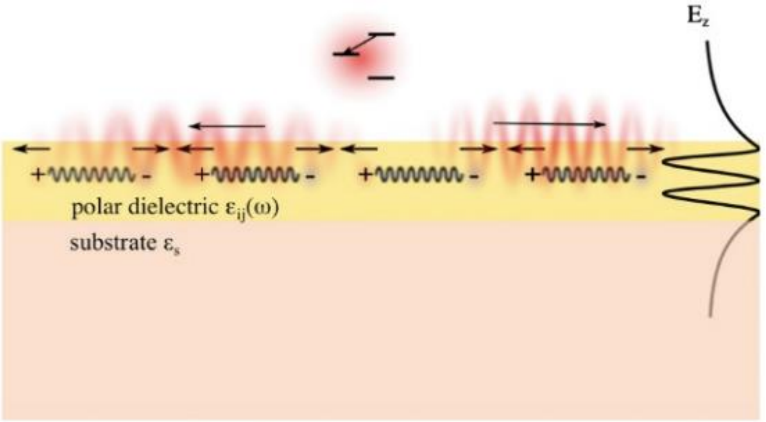

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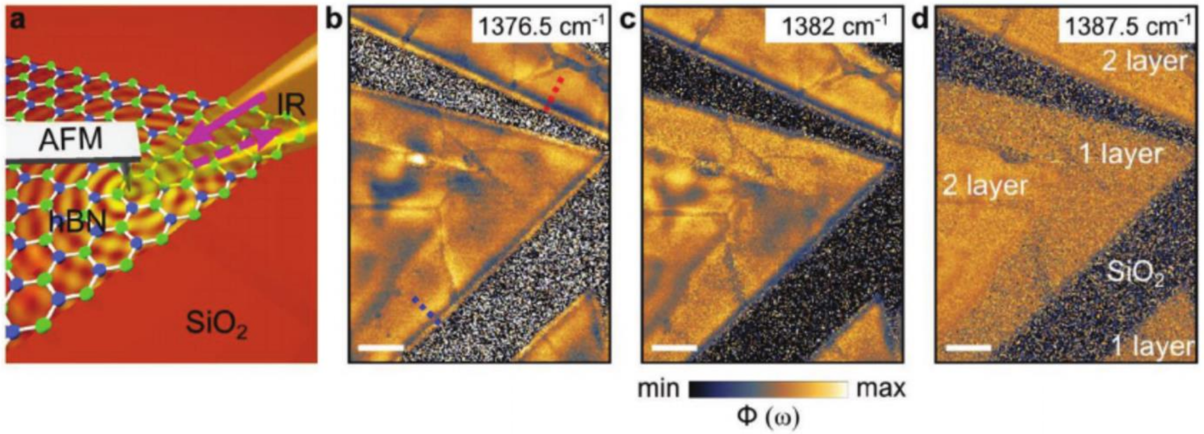
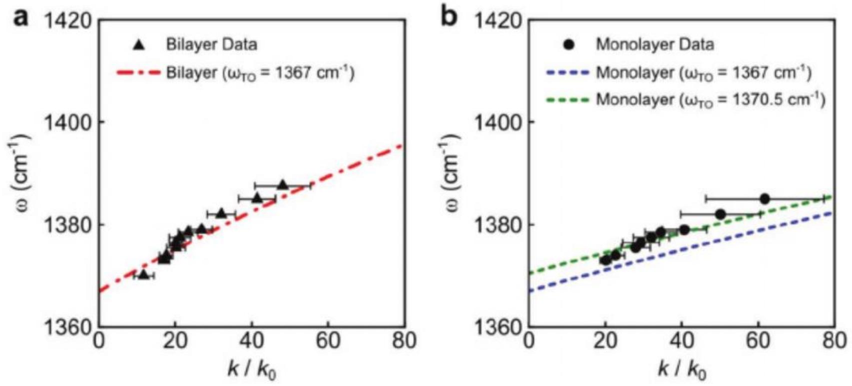
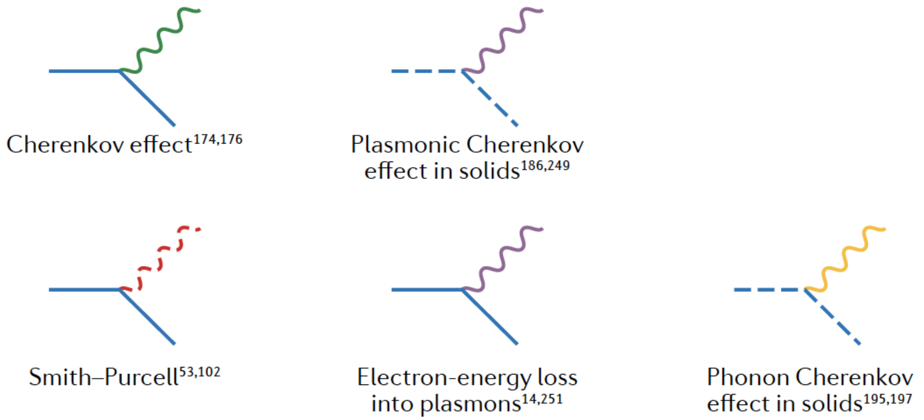




Predictions: **Rivera** *et al. Nano Lett*. (2019).
Observations: Dai, Fang, **Rivera**, *et al. Adv. Mat.* (2019).
Li *et al. Nature Materials* (2021).
[collabs. with P. Narang (Harvard), D. Basov (Columbia)]

New physics in free-electron light-matter interactions with photonic quasiparticles



Rivera & Kaminer, *Nat. Rev. Phys. (2020)*

[for even more, see free-electron quantum optics collaboration with Prof. Ido Kaminer (Technion)]

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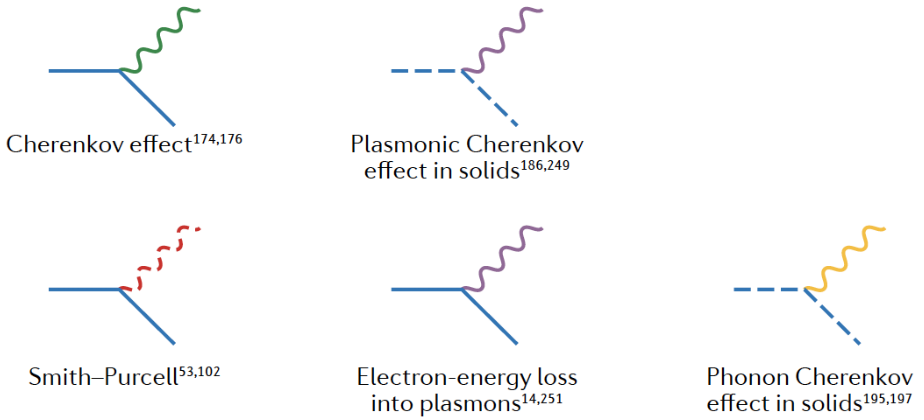

Rivera & Kaminer, *Nat. Rev. Phys. (2020)*

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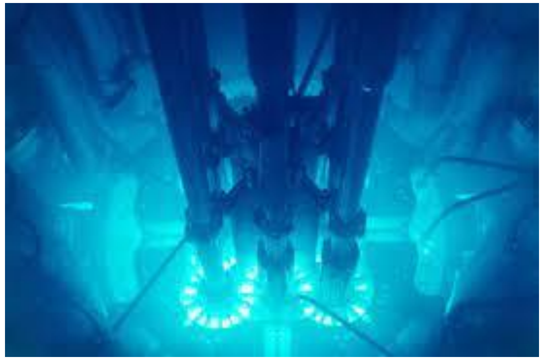
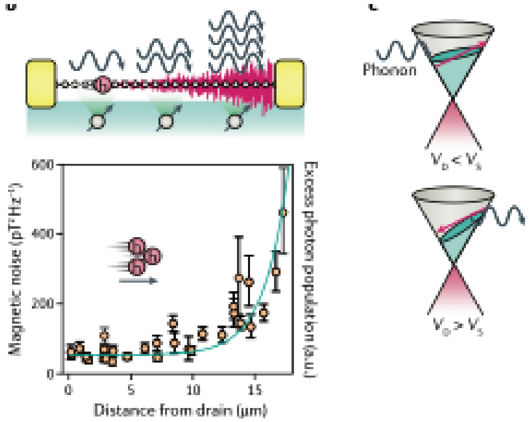
Cherenkov radiation, with and without PQPs



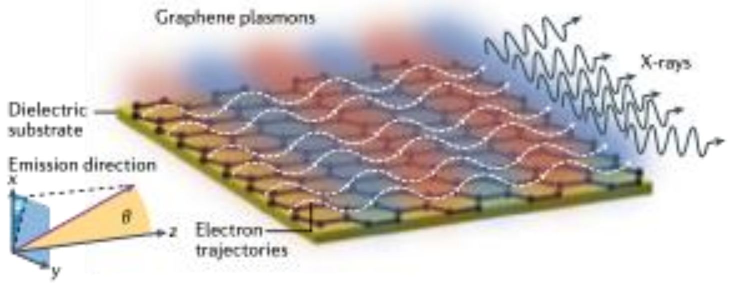
Cherenkov effect



Andersen *et al.*, *Science* (2019)

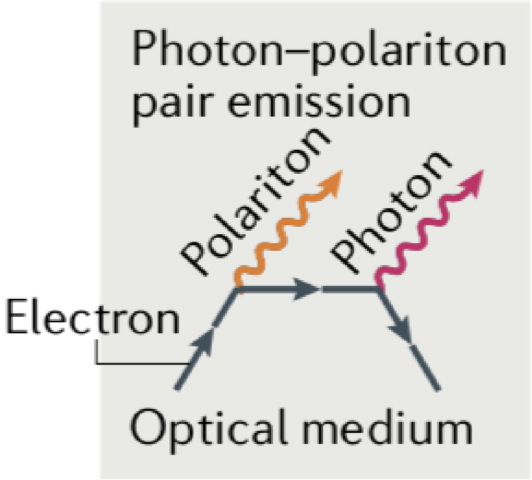
Free-electron X-ray sources, with and without PQPs

Synchrotron



Wong *et al.*, *Nature Photonics* (2016)

Two-photon emission by a free electron into an X-ray and a polariton



$$\omega_{\mathrm{ph}} = \omega_{\mathrm{pol}} \frac{\beta n(\omega_{\mathrm{pol}}) \cos\theta_{\mathrm{pol}} - 1}{1 - \beta \cos\theta_{\mathrm{ph}}}$$

Enables simultaneous emission of an (entangled) polariton/X-ray photon pair

Rivera *et al.*, *Nature Physics* (2019).

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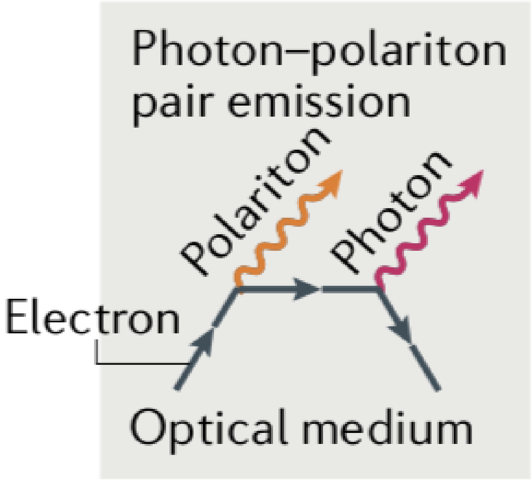

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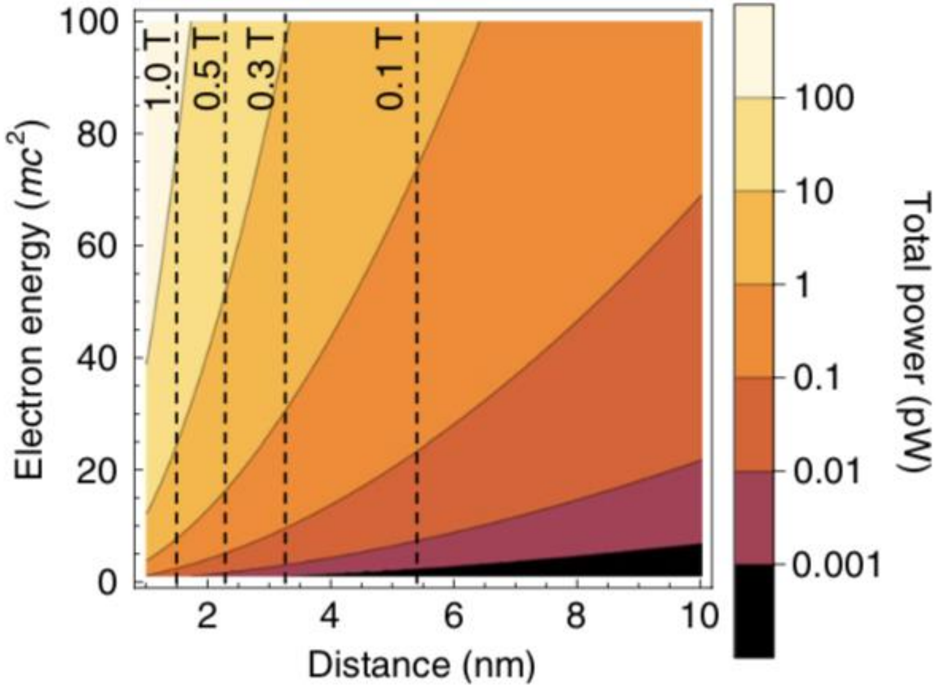
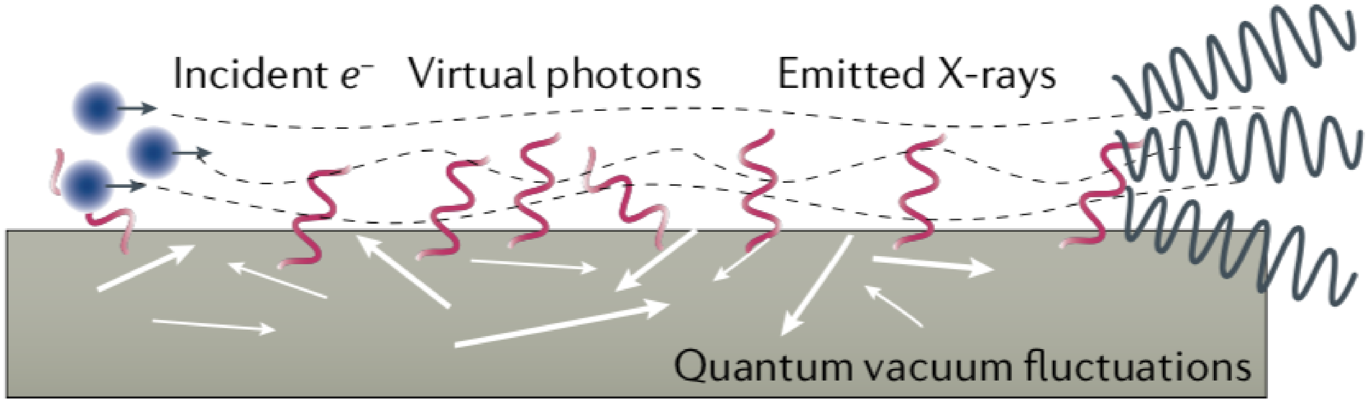


Power comparable to synchrotron radiation in a Tesla-scale field

Rivera *et al.*, *Nature Physics* (2019).

The two-photon emission is strong, due to strong nanoscale vacuum forces

$$P = \frac{e^4\gamma^2(4-\beta^2)}{24\pi\epsilon_0 m^2 c^3}\langle 0|\mathbf{E}^2|0\rangle$$ **[Larmor's formula]**



This TPE can be equivalently calculated as radiation by an accelerated charge, which comes from a vacuum (Casimir-like) fluctuating force from zero-point fluctuations of the photonic quasiparticle (here, plasmons).

Rivera *et al.*, *Nature Physics* (2019).

New particle detectors (scintillators) based on photonic quasiparticle interactions

Roques-Carmes***, Rivera*** *et al. A general framework for scintillation in nanophotonics. arXiv: 2110:11492.*

Charles Roques-Carmes

Scintillators: an application of light-matter interactions with photonic quasiparticles

Core phenomenon

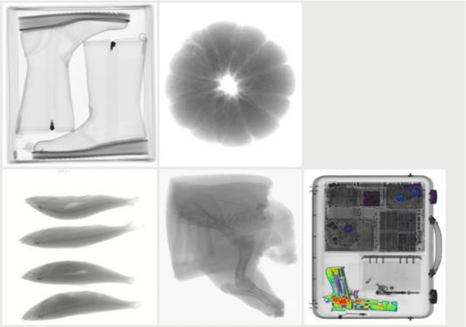
Ionizing radiation (e^-, X, γ)

Photons

Application domains

Medical imaging

Non-destructive testing

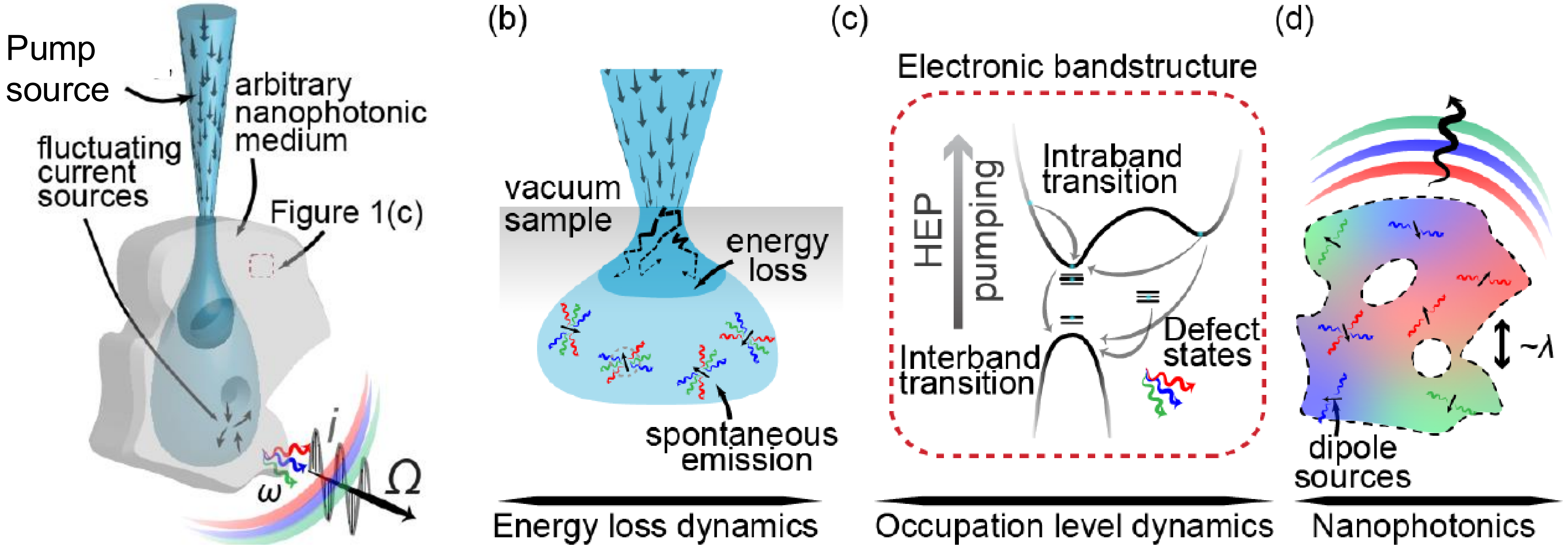


Radiation monitoring

Electron microscopy

A tantalizing prospect: enhancing scintillation brightness with nanophotonic control over the density of states – but it's complicated!

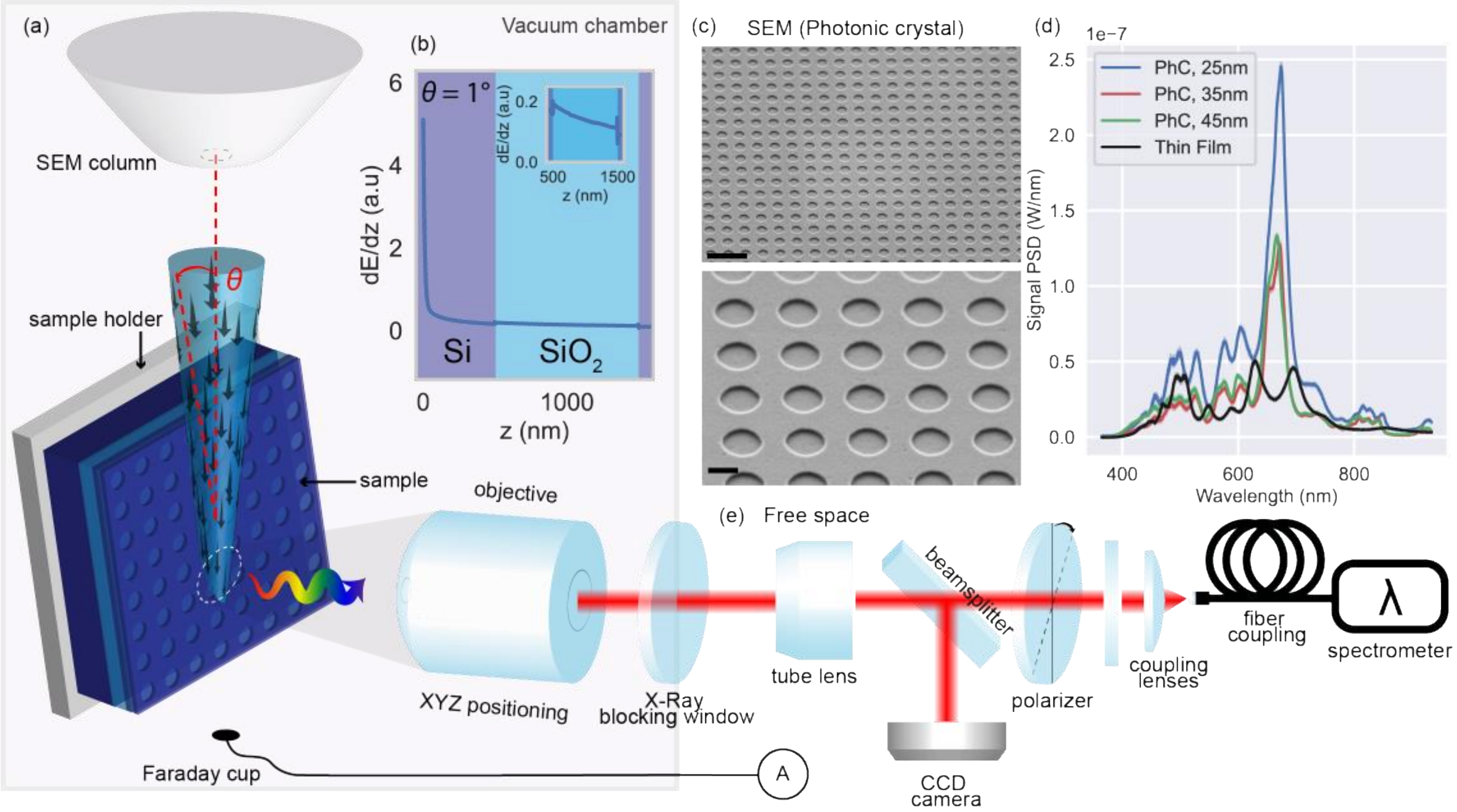
The process of scintillation, from end-to-end



Roques-Carmes*, **Rivera*** *et al. arXiv: 2110:11492*

[One of the main contributions: general framework to calculate nanophotonic scintillation]

Nanophotonic-enhanced scintillation induced by electron bombardment



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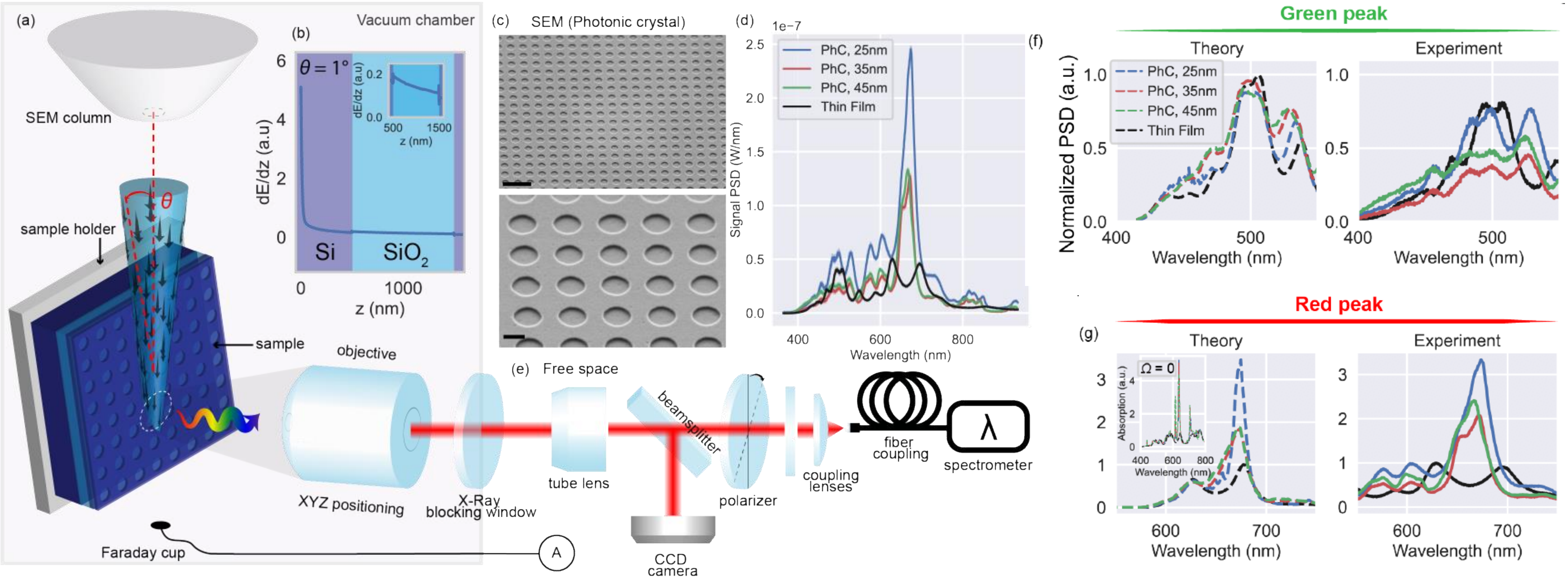
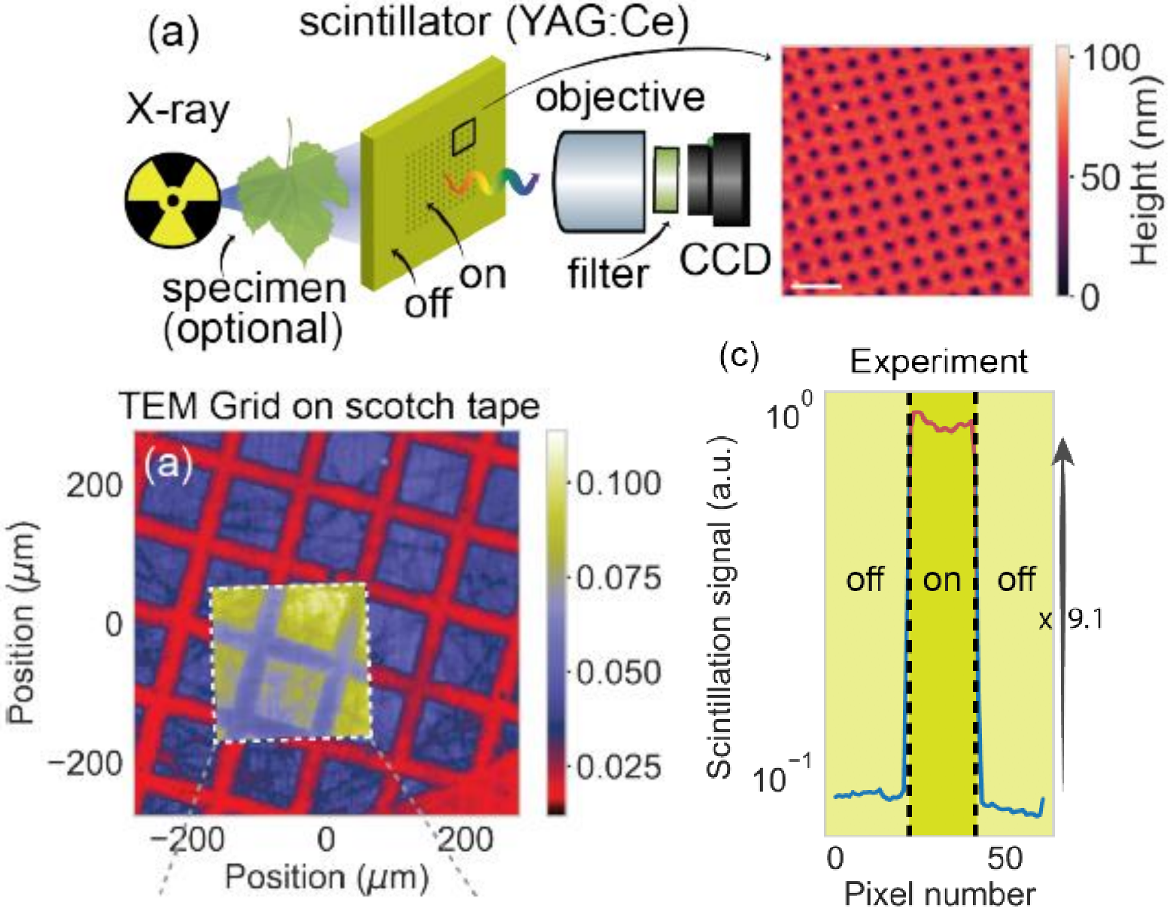


Roques-Carmes*, **Rivera*** *et al. arXiv: 2110:11492*

Nanophotonic-enhanced scintillation induced by X-ray bombardment



Roques-Carmes*, **Rivera*** *et al. arXiv: 2110:11492*

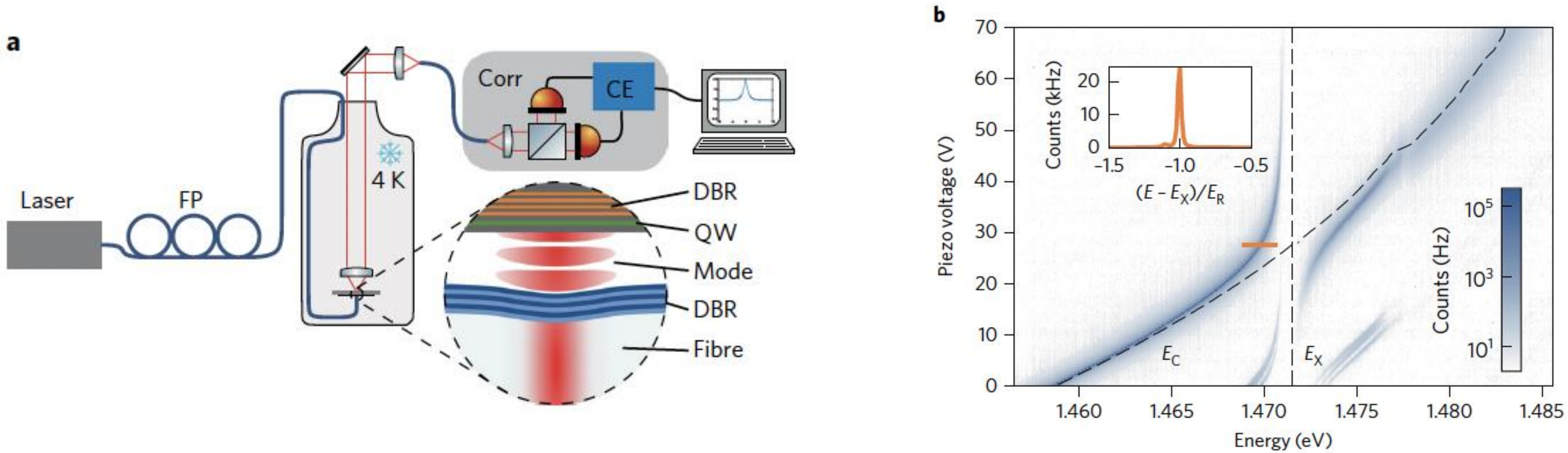
- Real-world example
  - Patterned photonic crystal into an X-ray scintillator
  - Put it into a micro-CT machine and look at light from patterned vs. unpatterned region

- **10x brighter image** from the patterned region

Optical nonlinearities and preparation of macroscopic optical Fock states

Rivera *et al. Macroscopic condensation of photon noise in sharply nonlinear dissipative systems. In preparation.*

Photonic quasiparticles can also have (much) stronger optical nonlinearities



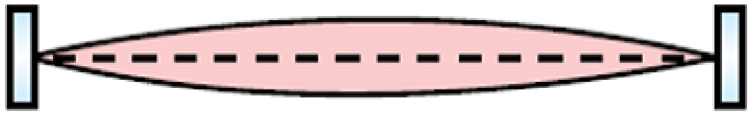
Such systems realize a Kerr Hamiltonian

$$H_{\mathrm{Kerr}}/\hbar = \omega_{\mathrm{LP}}(p^\dagger p + \beta p^{\dagger 2} p^2)$$

where $\beta \sim 10^{-5}$. Compare to expected value $\chi^{(3)}(\pi\hbar c/\epsilon_0\lambda^4) \lesssim 10^{-8}$ (GaAs).

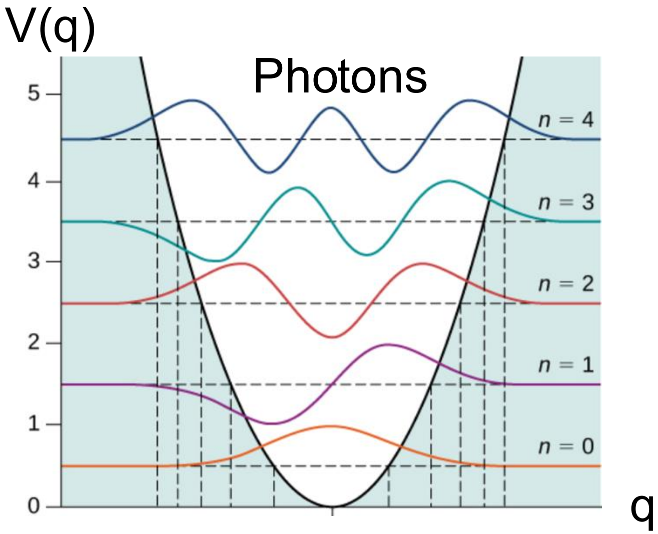
Dissipative Kerr physics in exciton-polaritons
Imamoglu *et al.* Physical Review Letters (1997).
Fink *et al.* Nature Physics (2018).
Delteil & Fink *et al.* Nature Materials (2019).

Using strong nonlinearities to generate macroscopic Fock states of radiation

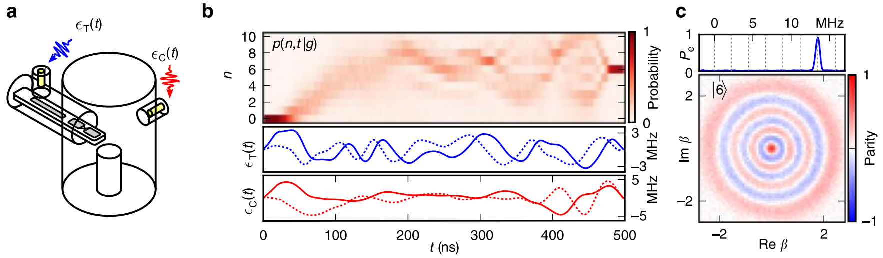


$$A(z,t) = 2\sqrt{\frac{\hbar\omega}{\epsilon_0 V}}\sin(kz)q$$

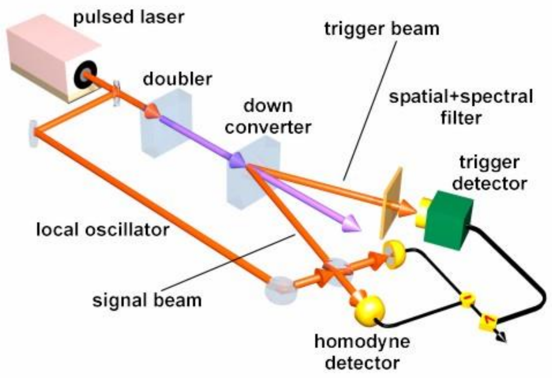
$$a^\dagger a|n\rangle = n|n\rangle$$



How Fock states are generated



Heeres *et al. Nat. Comm.* (2017).



Lvovsky, PRL (2001),
Bimbard *Nat. Phot.* (2010).

Fock states are the most fundamental states of light, and yet extremely difficult to produce

- Few mechanisms naturally selecting Fock
- Fragile in presence of loss

Two steps to producing macroscopic Fock states of radiation

(1) Construct a special nonlinear (intensity-dependent) dissipation

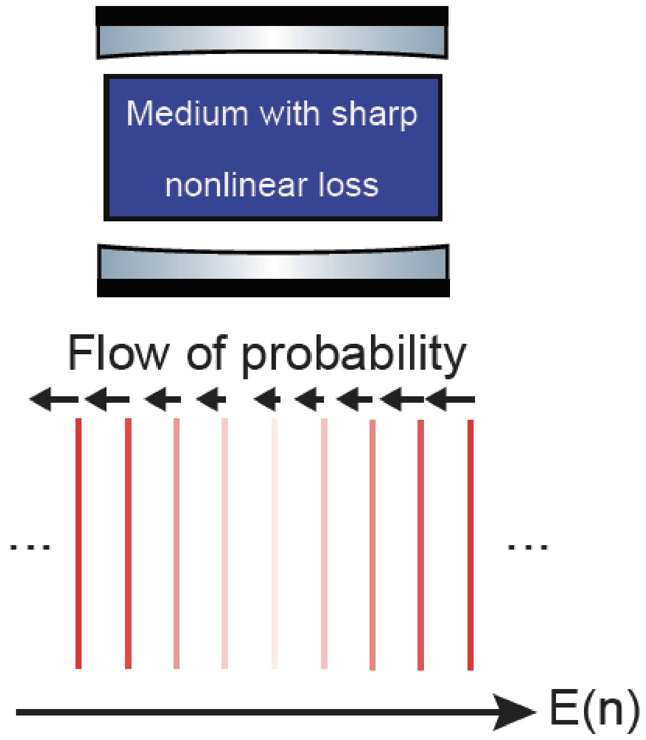
- Time-dependent solution of master equation: quantum light states will evolve into a Fock state **transiently** (or close, sub-Poissonian approximation)

(2) Incorporate a gain medium into (1) [now it's a laser]

- **Steady-state** solution of master equation: Fock state or close approximation

Dissipative preparation of large Fock states

Starting point: decay of light in a cavity with an embedded nonlinear medium.
The effect of the NL medium will be to induce an intensity-dependent dissipation.



Effect of decay on the photon probabilities?

$$\dot{p}(n) = -L(n)p(n) + L(n+1)p(n+1)$$

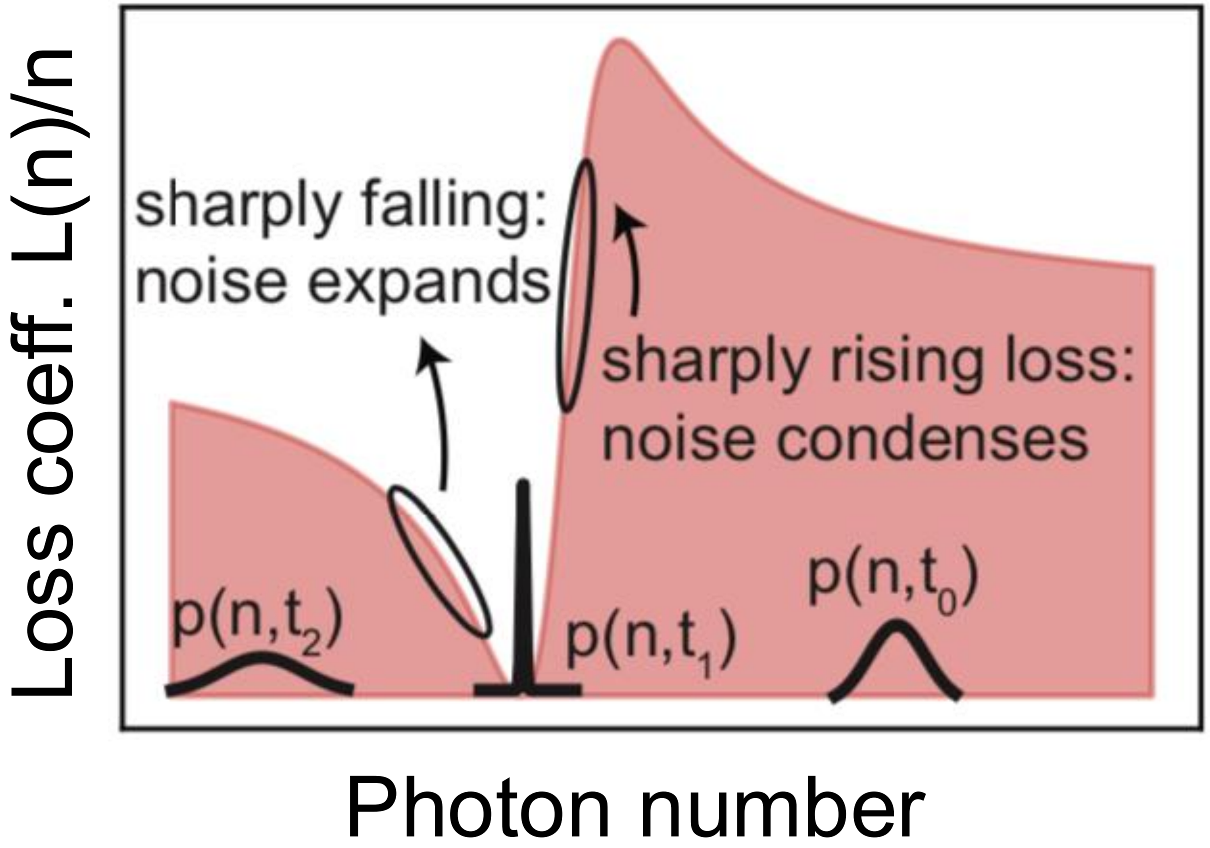
Rate of transition in which n photons becomes n-1

Rate of transition in which n+1 photons becomes n

[master equation for probabilities]

Rivera *et al. Macroscopic condensation of photon noise in sharply nonlinear dissipative systems. In preparation.*

A nonlinear interaction that naturally produces Fock states of light



Dynamics of first two cumulants:

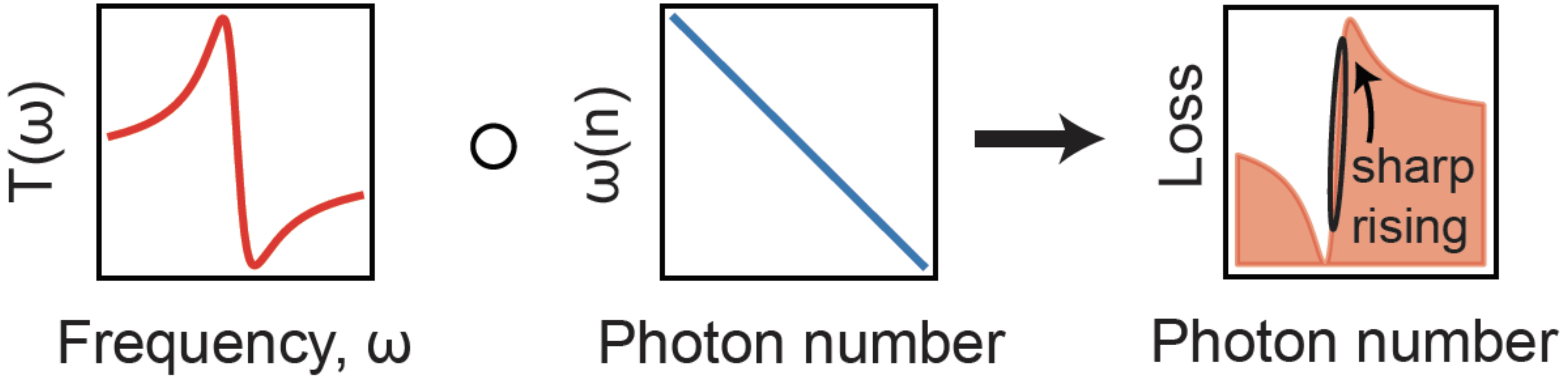
$$\dot{n} = -L(n)$$
$$(\dot{\Delta n})^2 = L(n) - 2(dL/dn)(\Delta n)^2$$

Photon noise drops relative to mean:

$$dL/dn(\Delta n)^2 > L(n)$$

Rivera *et al. Macroscopic condensation of photon noise in sharply nonlinear dissipative systems. In preparation.*

How to create such a nonlinear loss?



$$\frac{d\kappa}{dn} = \frac{d\kappa}{d\omega}\frac{d\omega}{dn} \sim \beta/\gamma$$

[Sharper transmission & stronger NL, yield stronger effect]

A physical picture of what's happening:

- As light leaks out, intensity changes
- As intensity changes, index & mode freq. changes [Kerr effect]
- Variation of mode frequency relative to mirror freq. changes loss

An explicit construction of nonlinear loss

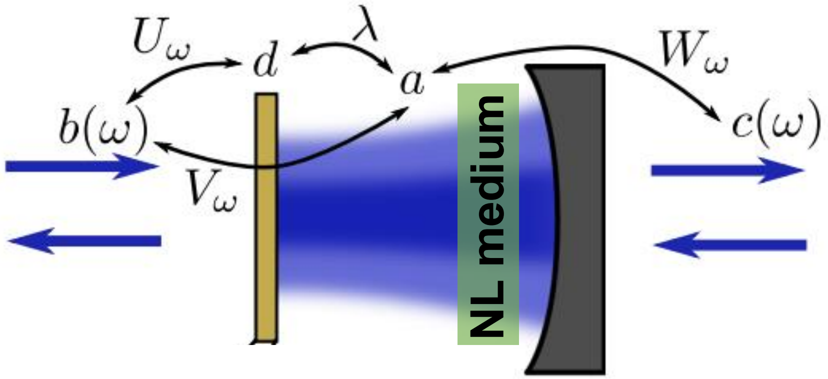


Image source: Cernotik *et al.* PRL (2019).

$$H/\hbar = H_a + \omega_d d^\dagger d + \left(\lambda a d^\dagger + \lambda^* a^\dagger d\right) + \sum_k \omega_k b_k^\dagger b_k + \sum_k \left(g_k a b_k^\dagger + g_k^* a^\dagger b_k\right) + \sum_k \left(v_k d b_k^\dagger + v_k^* d^\dagger b_k\right).$$

Rivera *et al. In preparation.*

An explicit construction of nonlinear loss

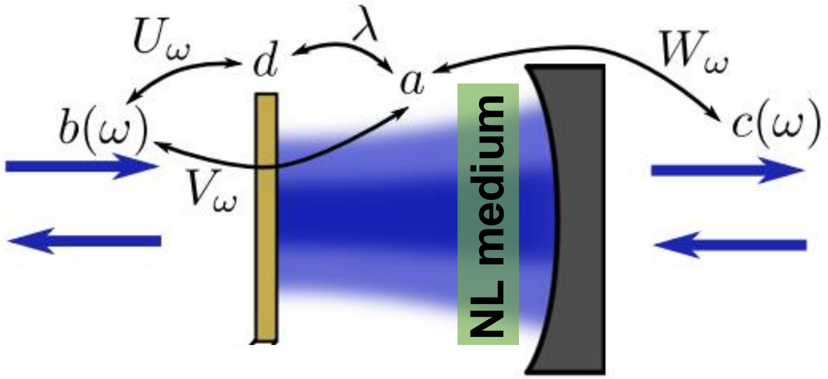


Image source: Cernotik *et al.* PRL (2019).

$$H/\hbar = H_{\mathrm{a}} + \omega_d d^\dagger d + \left(\lambda a d^\dagger + \lambda^* a^\dagger d\right) + \sum_k \omega_k b_k^\dagger b_k$$
$$+ \sum_k \left(g_k a b_k^\dagger + g_k^* a^\dagger b_k\right) + \sum_k \left(v_k d b_k^\dagger + v_k^* d^\dagger b_k\right).$$

Master equation for an anharmonic oscillator coupled to a frequency-dependent loss.

$$\dot{\rho}_{ad} = -i[H_{ad}/\hbar, \rho_{ad}] + (X^\dagger X \rho_{ad} + \rho_{ad} X^\dagger X - 2X\rho_{ad}X^\dagger).$$

$$X = \sqrt{\kappa} a + \sqrt{\gamma} d$$

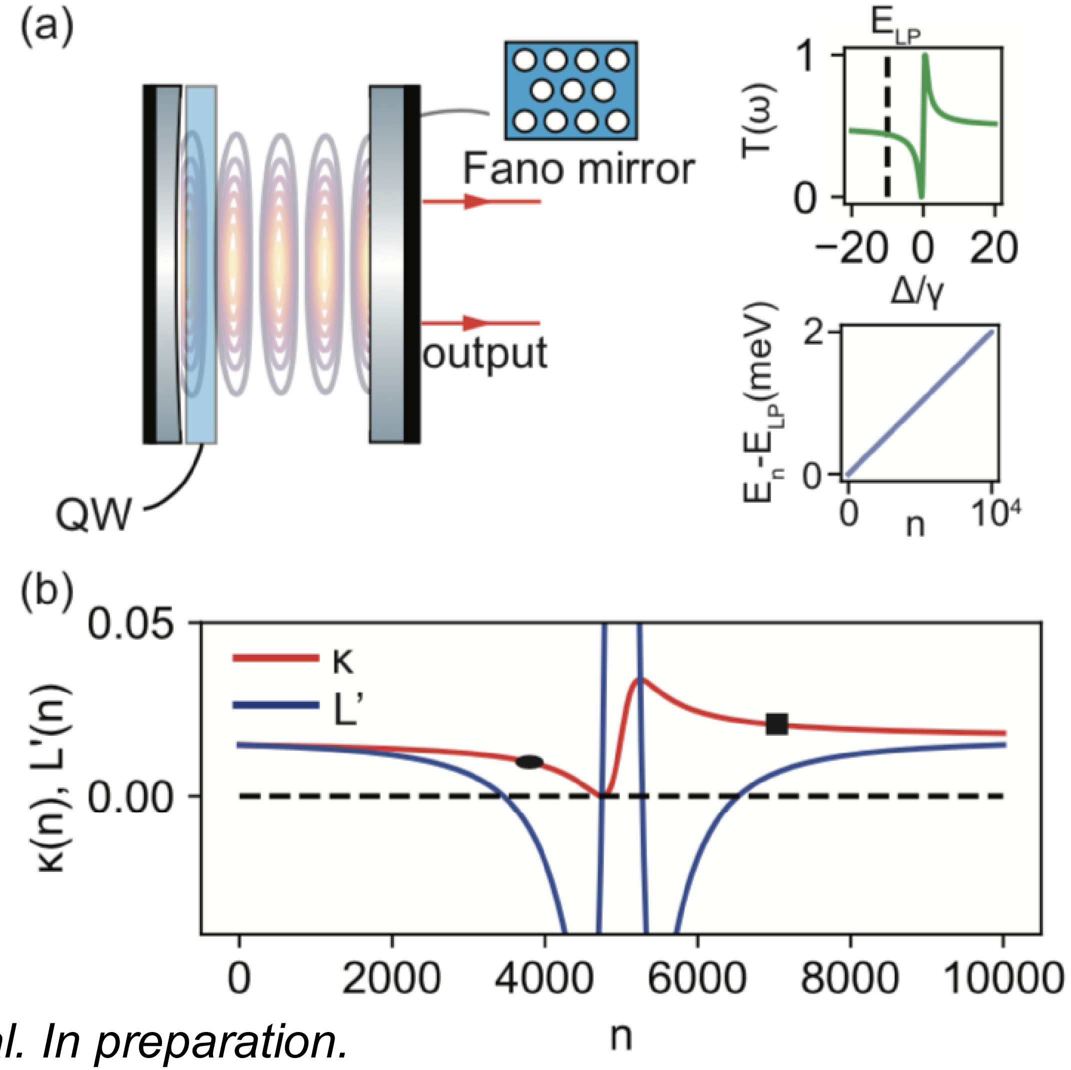
adiabatic elimination of mirror mode (*d*)

$$\dot{\rho}_{n,n} = -n\left(\kappa - 2\mathrm{Re}\left[\frac{G_+G_-}{i(\omega_d - \omega_{n,n-1}) + \gamma/2}\right]\right)\rho_{n,n} +$$
$$(n+1)\left(\kappa - 2\mathrm{Re}\left[\frac{G_+G_-}{i(\omega_d - \omega_{n+1,n}) + \gamma/2}\right]\right)\rho_{n+1,n+1},$$

$$L(n+1)$$

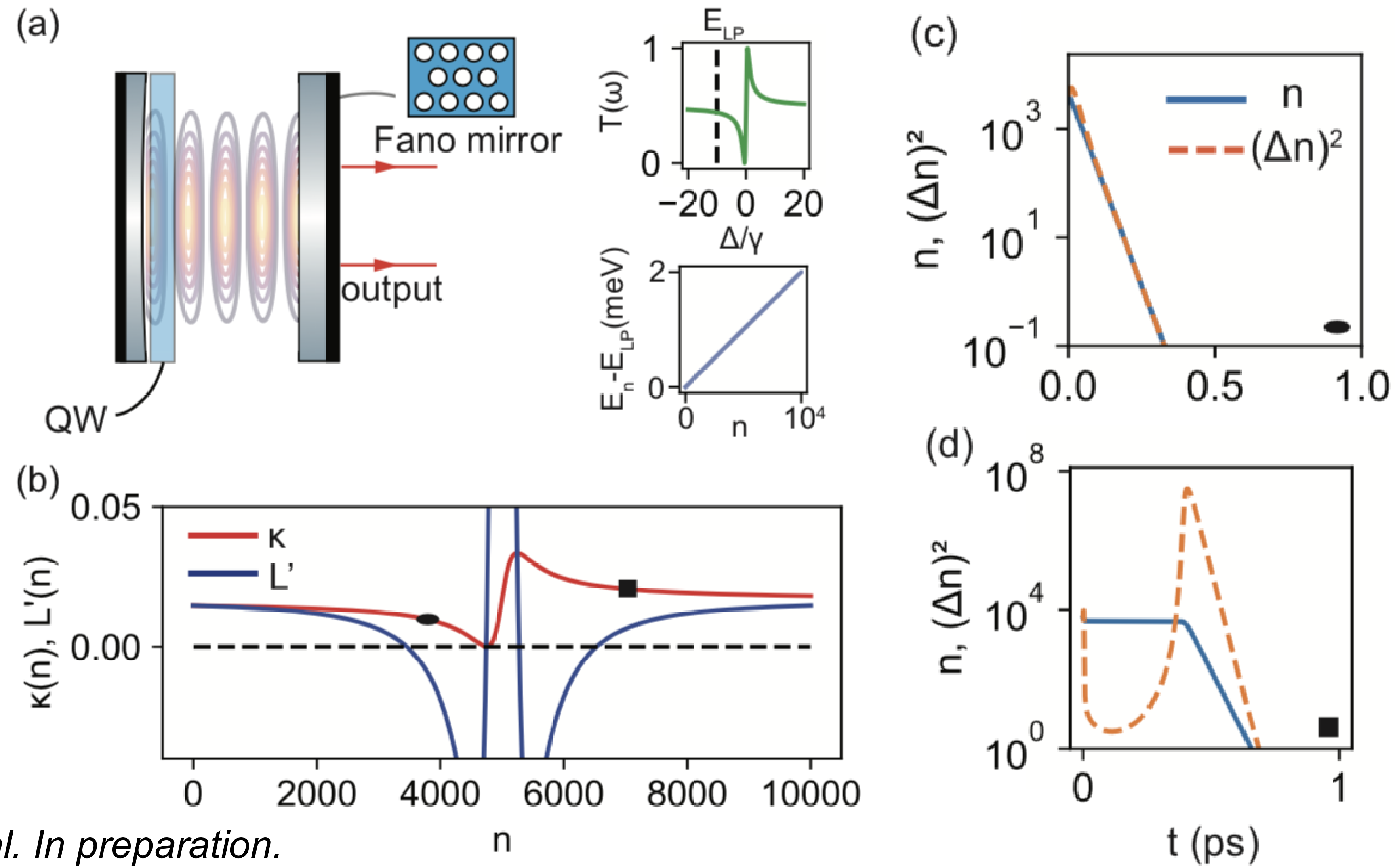
Rivera *et al. In preparation.*

Nearly complete condensation of optical photon noise using this nonlinearity



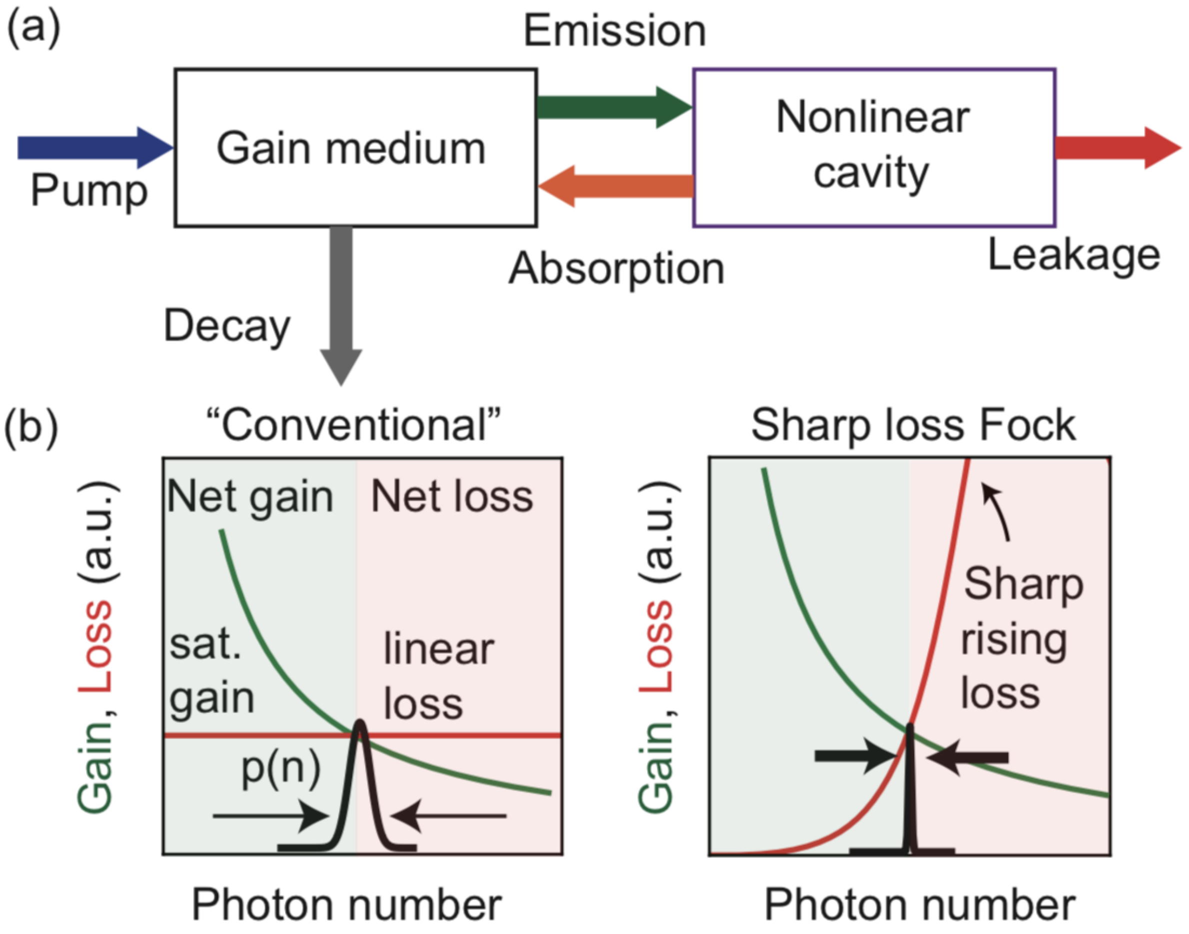
Rivera *et al. In preparation.*

Nearly complete condensation of optical photon noise using this nonlinearity



Rivera *et al. In preparation.*

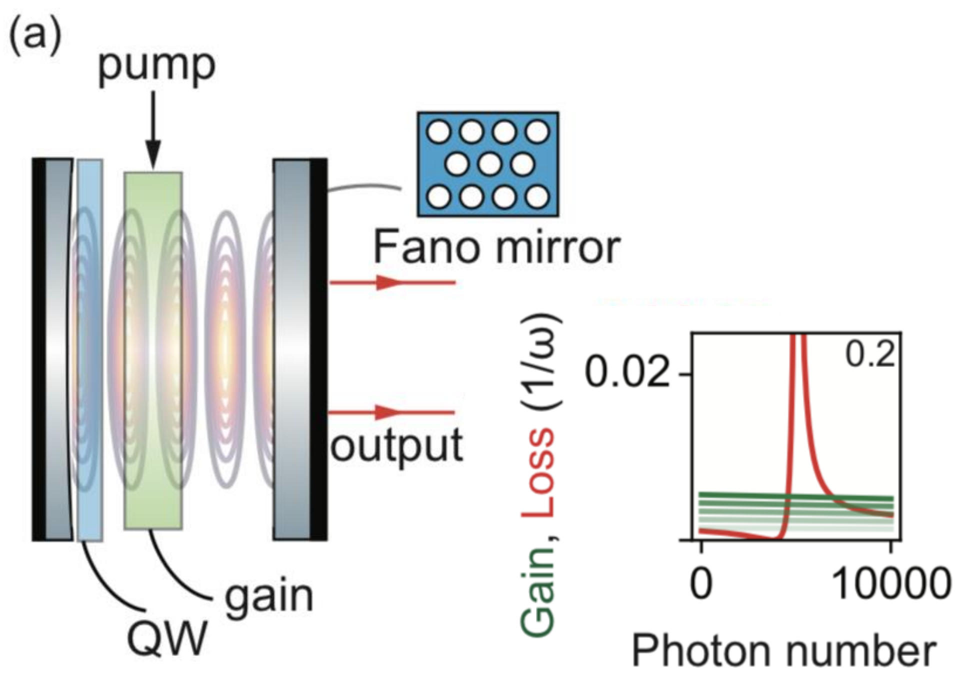
This nonlinear interaction enables a new kind of laser emitting Fock states



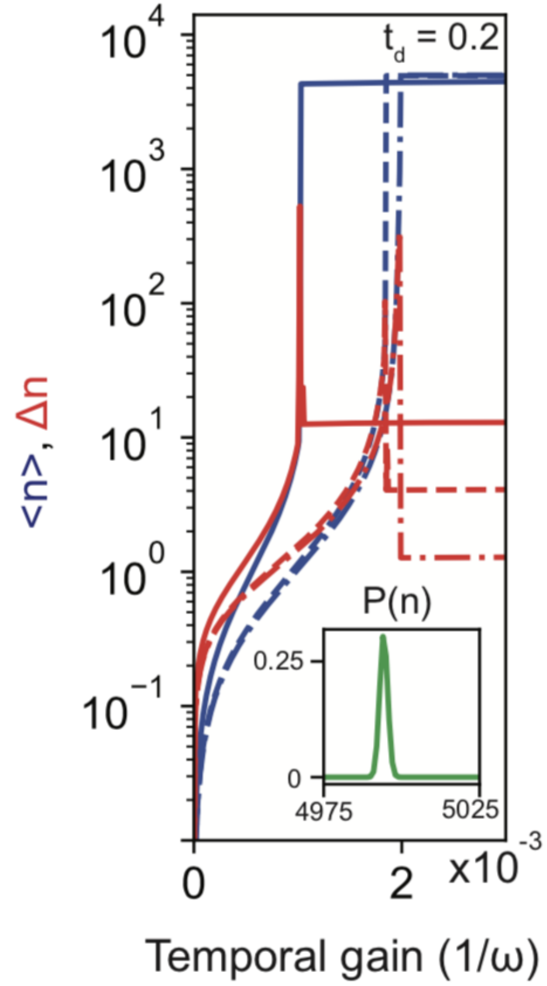
Rivera *et al. In preparation.*

Characteristics of an optical Fock laser

Schematic



Input-output curves



Rivera *et al. In preparation.*

Condensation of optical noise in the deeply macroscopic regime?

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Yannick Salamin (MIT postdoc)

Supplementary slides

Macroscopic QED as a technique to study light-matter coupling in dissipative systems

Rivera*, Kaminer*, *et al. Science* (2016), **Rivera** *et al. Proc. Nat. Acad. Sci.* (2017),
Rivera *et al. Nature Physics* (2019), **Rivera** *& Kaminer. Nature Reviews Physics* (2020).

Confining light on wavelength scales to control light-matter interaction

- Many of the applications above: light is a *plane wave*, with energy delocalized over a volume $\gg \lambda^3$.

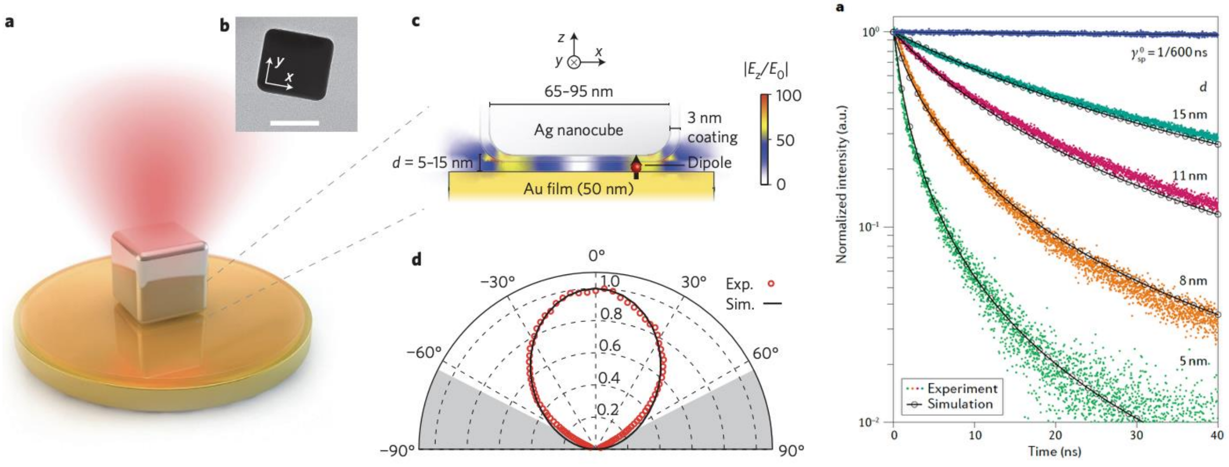
- **The interactions are *very weak*, and are largely lowest-order (e.g., in coupling strength, atomic size, field strength)**

- A promising "way out" is nanophotonics
  - Controlling & confining light with polarizable media with spatial variations on the scale of λ (*nanophotonics*), we can enhance the interactions.

  - Intuitively: changing basic properties of the photon (soln. to Maxwell)

Confining light on wavelength scales to control light-matter interaction

- Many of the applications above: light is a *plane wave*, with energy delocalized over a volume $\gg \lambda^3$.
- By controlling light with polarizable media with spatial variations on the scale of λ (*nanophotonics*), we can enhance the interactions.
- Very representative: Purcell effect
- **Still, the interactions are *very weak*, and are largely lowest-order (e.g., in coupling strength, atomic size, field strength)**



Akselrod *et al. Nature Photonics* (2014).

$$\Gamma_{fi} = \frac{3}{4\pi^2} \frac{Q}{(V/\lambda_0^3)} |\hat{\mathbf{d}}_{fi} \cdot \mathbf{u}(\mathbf{r})|^2 \Gamma_0,$$

Relation to textbook EM field quantization

Table 1 | **Levels of quantization of the electromagnetic field**

Type of medium	Vector potential	Conditions on vector potential
Vacuum	$\sum_{\mathbf{k},\varepsilon_{\mathbf{k}}}\sqrt{\frac{\hbar}{2\varepsilon_0\omega_{\mathbf{k}}V}}\left(e^{i\mathbf{k}\cdot\mathbf{r}-i\omega_k t}\varepsilon_{\mathbf{k}}a_{\mathbf{k},\varepsilon_{\mathbf{k}}}+e^{-i\mathbf{k}\cdot\mathbf{r}+i\omega_k t}\varepsilon^*_{\mathbf{k}}a^\dagger_{\mathbf{k},\varepsilon_{\mathbf{k}}}\right)$	$\mathbf{k}\cdot\varepsilon_{\mathbf{k}}=0;\omega_{\mathbf{k}}=ck$
Homogeneous, lossless, non-dispersive, isotropic	$\sum_{\mathbf{k},\varepsilon_{\mathbf{k}}}\sqrt{\frac{\hbar}{2\varepsilon_0\omega_{\mathbf{k}}n^2V}}\left(e^{i\mathbf{k}\cdot\mathbf{r}-i\omega_k t}\varepsilon_{\mathbf{k}}a_{\mathbf{k},\varepsilon_{\mathbf{k}}}+e^{-i\mathbf{k}\cdot\mathbf{r}+i\omega_k t}\varepsilon^*_{\mathbf{k}}a^\dagger_{\mathbf{k},\varepsilon_{\mathbf{k}}}\right)$	$\mathbf{k}\cdot\varepsilon_{\mathbf{k}}=0;\omega_{\mathbf{k}}=ck/n$
Inhomogeneous, lossless, non-dispersive, anisotropic	$\sum_n\sqrt{\frac{\hbar}{2\varepsilon_0\omega_n}}\left(\mathbf{F}_n(\mathbf{r})e^{-i\omega_n t}a_n+\mathbf{F}^*_n(\mathbf{r})e^{i\omega_n t}a^\dagger_n\right)$	$\nabla\times\nabla\times\mathbf{F}_n(\mathbf{r})=\boldsymbol{\varepsilon}(\mathbf{r})\frac{\omega_n^2}{c^2}\mathbf{F}_n(\mathbf{r});$ $\int d^3r\,\mathbf{F}^*_n\cdot\boldsymbol{\varepsilon}(\mathbf{r})\cdot\mathbf{F}_n=1$
Inhomogeneous, lossless, weakly dispersive, anisotropic	$\sum_n\sqrt{\frac{\hbar}{2\varepsilon_0\omega_n}}\left(\mathbf{F}_n(\mathbf{r})e^{-i\omega_n t}a_n+\mathbf{F}^*_n(\mathbf{r})e^{i\omega_n t}a^\dagger_n\right)$	$\nabla\times\nabla\times\mathbf{F}_n(\mathbf{r})=\varepsilon(\mathbf{r},\omega_n)\frac{\omega_n^2}{c^2}\mathbf{F}_n(\mathbf{r});$ $\frac{1}{2\omega_n}\int d^3r\,\mathbf{F}^*_n(\mathbf{r})\cdot\frac{d(\omega^2\boldsymbol{\varepsilon}(\mathbf{r},\omega))}{d\omega}\Big\|_{\omega_n}\cdot\mathbf{F}_n(\mathbf{r})=1$
Inhomogeneous, lossy, dispersive, isotropic, local	$\sqrt{\frac{\hbar}{\pi\varepsilon_0}}\int_0^\infty d\omega\int d^3r'\frac{\omega}{c^2}\sqrt{\mathrm{Im}\,\varepsilon(\mathbf{r}',\omega)}$ $(\mathbf{G}(\mathbf{r},\mathbf{r}',\omega)\mathbf{f}(\mathbf{r}',\omega)e^{-i\omega t}+\mathbf{G}^*(\mathbf{r},\mathbf{r}',\omega)\mathbf{f}^\dagger(\mathbf{r}',\omega)e^{i\omega t})$	$\left(\nabla\times\nabla\times-\varepsilon(\mathbf{r},\omega)\frac{\omega^2}{c^2}\right)\mathbf{G}(\mathbf{r},\mathbf{r}',\omega)=\delta(\mathbf{r}-\mathbf{r}')I$
Inhomogeneous, lossy, dispersive, anisotropic, non-local	$\sqrt{\frac{\hbar}{\pi\varepsilon_0}}\int_0^\infty d\omega\int d^3r'\frac{\omega}{c^2}\sqrt{\mathrm{Im}\,\boldsymbol{\varepsilon}(\mathbf{r},\mathbf{r}',\omega)}$ $(\mathbf{G}(\mathbf{r},\mathbf{r}',\omega)\mathbf{f}(\mathbf{r}',\omega)e^{-i\omega t}+\mathbf{G}^*(\mathbf{r},\mathbf{r}',\omega)\mathbf{f}^\dagger(\mathbf{r}',\omega)e^{i\omega t})$	$\left(\nabla\times\nabla\times-\int d^3r'\,\boldsymbol{\varepsilon}(\mathbf{r},\mathbf{r}',\omega)\frac{\omega^2}{c^2}\right)\mathbf{G}(\mathbf{r},\mathbf{r}',\omega)=\delta(\mathbf{r}-\mathbf{r}')I$

Rivera & Kaminer. *Nat. Rev. Phys.* (2020).

Additional details on the general framework for nanophotonic scintillation & experiments

Roques-Carmes***, Rivera*** *et al. A general framework for scintillation in nanophotonics. arXiv: 2110:11492.*

A general framework for describing nanophotonic scintillators

- Time-scale separation leads to an approximate non-equilibrium distribution

- Spectral & angular density of emitted light in scintillation

$$\frac{dP^{(i)}}{d\omega d\Omega} = \frac{\omega^2}{8\pi^2\epsilon_0 c^3}\int d\mathbf{r}' \frac{E_j^{*(i)}(\mathbf{r}',\mathbf{r},\omega)}{\left|\mathbf{E}_{\text{inc}}^{(i)}(\mathbf{r}',\mathbf{r},\omega)\right|}\frac{E_k^{(i)}(\mathbf{r}',\mathbf{r},\omega)}{\left|\mathbf{E}_{\text{inc}}^{(i)}(\mathbf{r}',\mathbf{r},\omega)\right|} S_{jk}(\mathbf{r}',\omega)$$

[specified by Maxwell solutions]

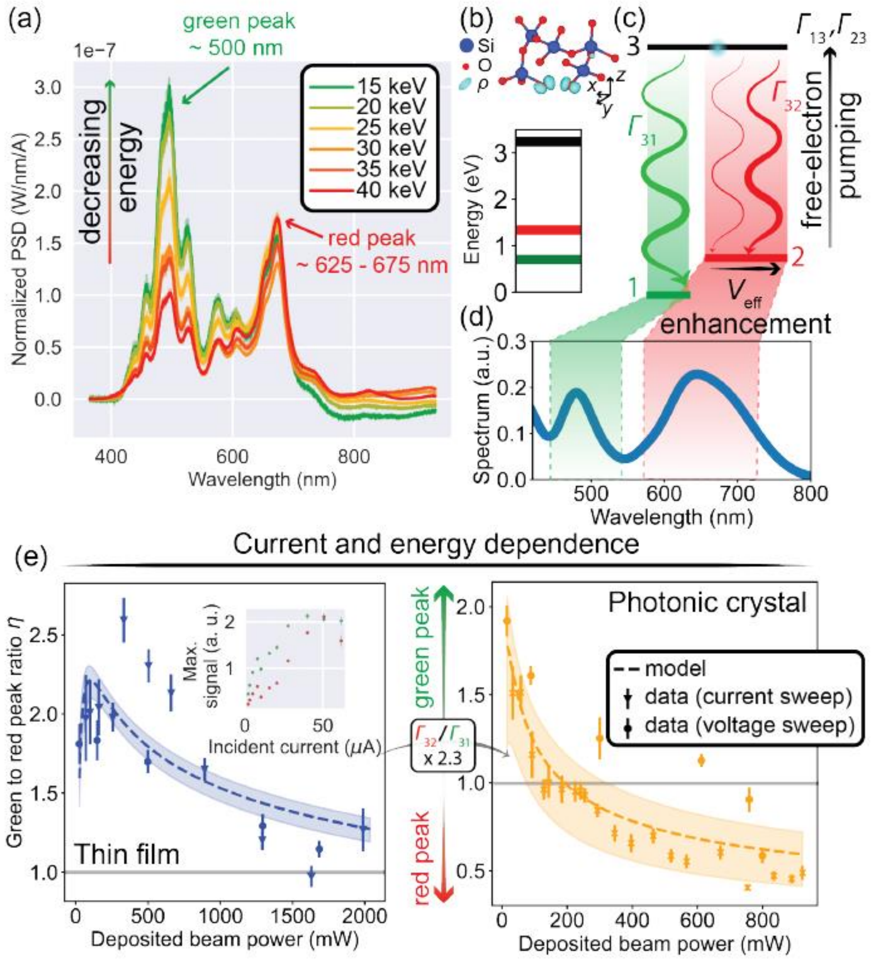
$$S_{jk}(\mathbf{r_1},\mathbf{r}_2,\omega) \sim \langle J_j^-(\mathbf{r}_1,\omega)J_k^+(\mathbf{r}_2,\omega)\rangle$$

[specified by microscopics: energies, matrix elements, occupations]

- Some similarity to description of thermal radiation (but non-equilibrium electrons require more

Roques-Carmes*, **Rivera*** *et al. arXiv: 2110:11492*

Out-of-equilibrium physics of defects controlled by nanophotonics

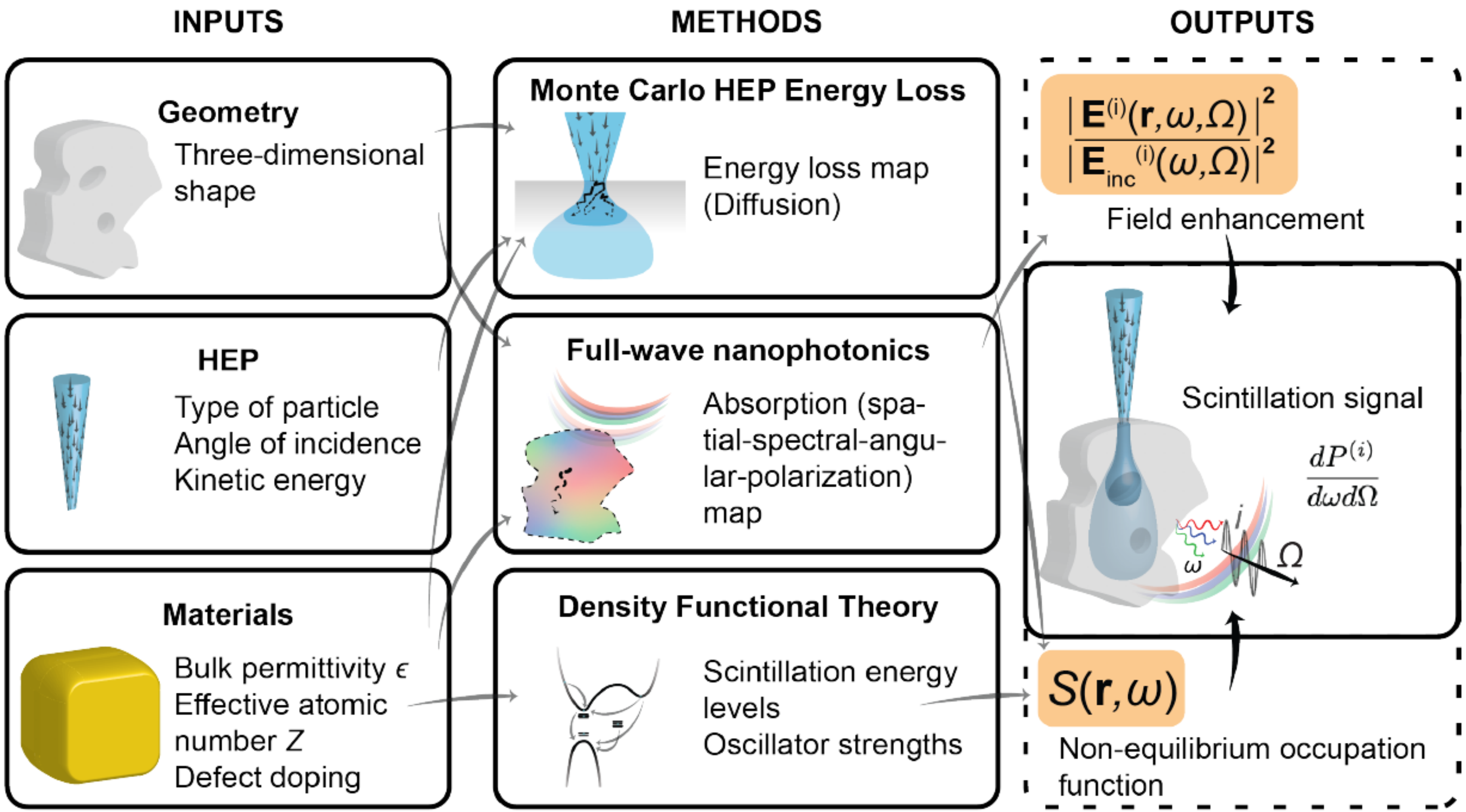


- Beyond predicting "nanophotonic" features the framework also, accounts for features requiring microscopics+nanophotonics
  - Nonlinear dependence of emission on pump + "cross-over" from green to red
    - 3-level dynamics of self-trapped holes

$$
\begin{cases}
\frac{dp_1}{dt} = -\Gamma_{13}\, p_1(1-p_3) + \Gamma_{31}\, p_3(1-p_1) \\
\frac{dp_2}{dt} = -\Gamma_{23}\, p_2(1-p_3) + \Gamma_{32}\, p_3(1-p_2) \\
\frac{dp_3}{dt} = \Gamma_{13}\, p_1(1-p_3) - \Gamma_{31}\, p_3(1-p_1) \\
\qquad\quad +\Gamma_{23}\, p_2(1-p_3) - \Gamma_{32}\, p_3(1-p_2)
\end{cases}
$$

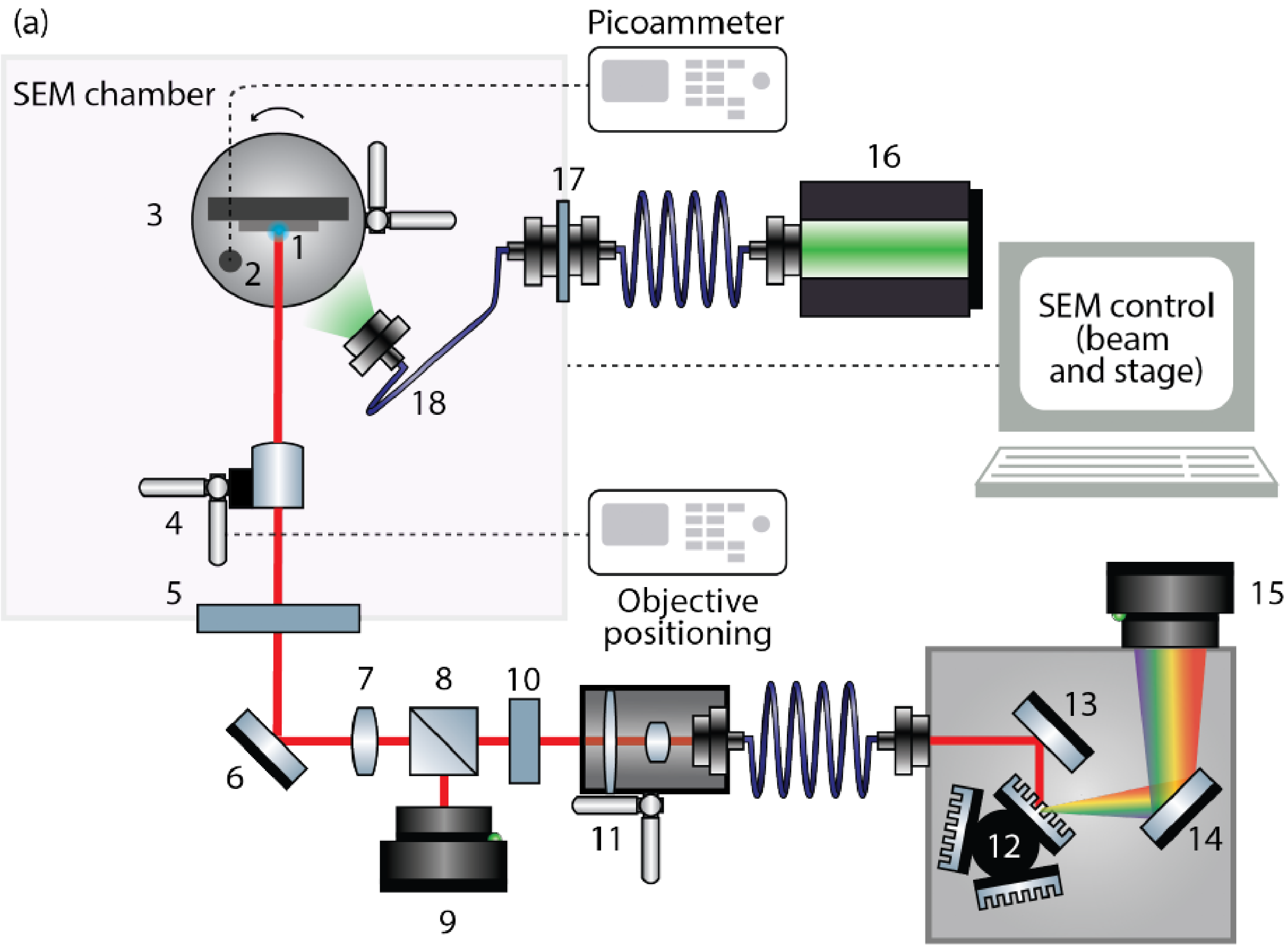
Roques-Carmes*, **Rivera*** *et al. arXiv: 2110:11492*

The end-to-end numerical pipeline for nanophotonic scintillation, summarized



Roques-Carmes*, **Rivera*** *et al. arXiv: 2110:11492.*

Electron-beam scintillation setup



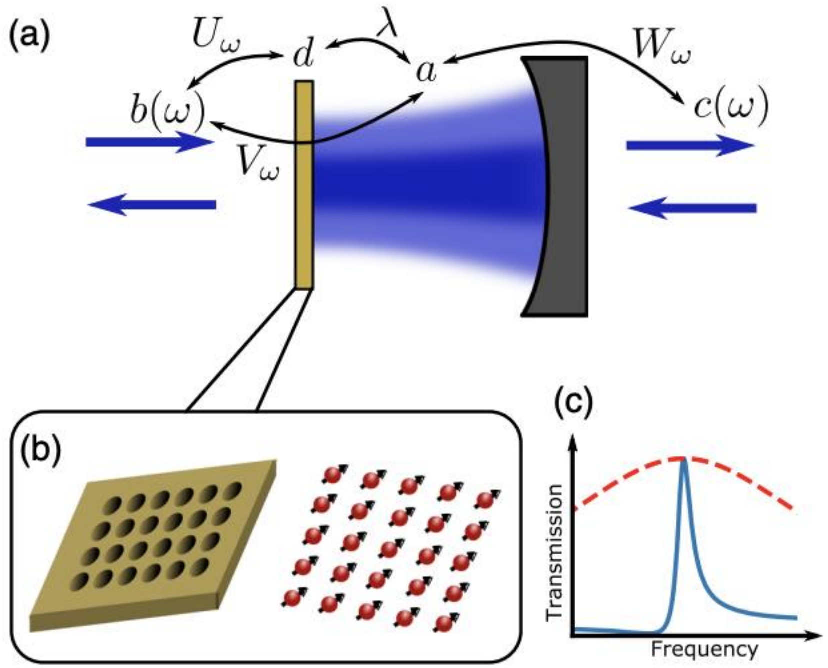
Roques-Carmes*, **Rivera*** *et al. arXiv: 2110:11492.*

Theory of nonlinear lasers and transient Fock state generation

Rivera *et al. Macroscopic condensation of photon noise in sharply nonlinear dissipative systems. In preparation.*

A “microscopic model” of nonlinear loss

Inspiration: Cernotik *et al. PRL* (2019).



$$H/\hbar = H_a + \omega_d d^\dagger d + (\lambda a d^\dagger + \lambda^* a^\dagger d) + \sum_k \omega_k b_k^\dagger b_k$$
$$+ \sum_k \left(g_k a b_k^\dagger + g_k^* a^\dagger b_k\right) + \sum_k \left(v_k d b_k^\dagger + v_k^* d^\dagger b_k\right).$$

Rivera *et al. In preparation.*

- Could we find the posited dynamics resulting from the exact description of a system?
  - Need a quantum optical model (Lindblad theory) of a frequency-dependent reflector.
- Compared to Cernotik *et al*.: we consider the case of an *anharmonic* oscillator undergoing dissipation, as would be from inserting a nonlinear medium.
- Model of Fano resonance (asymmetric scattering lineshape; great recent interest [see Zhen *et al. Nat. Rev. Mat.* (2016)])

Lindbladian for an anharmonic oscillator coupled to a frequency-dependent loss

- When two systems (*a*,*d*) are coupled to the same reservoir, the jump/transition operator in the Lindbladian describing loss couples

$$\dot{\rho}_{ad} = -i[H_{ad}/\hbar, \rho_{ad}] + (X^\dagger X \rho_{ad} + \rho_{ad} X^\dagger X - 2X\rho_{ad}X^\dagger).$$

$$X \equiv \sqrt{\kappa}a + \sqrt{\gamma}d,$$

- In the adiabatic limit, where *d* (mirror mode) decays much faster than the round-trip time, we adiabatically eliminate *d* from Liouvillian
  - This enables us to find an EOM for *a*
  - Also verified numerically ("exactly")

$$\begin{aligned}\dot{\rho} = &-\kappa(a^\dagger a\rho + \rho a^\dagger a - 2a\rho a^\dagger) \\ &+ \sum_{n=0}^{\infty} \frac{nG_+G_-}{i(\omega_d - \omega_{n,n-1}) + \gamma} T_{n,n}\rho \\ &+ \sum_{n=0}^{\infty} \frac{n(G_+G_-)^*}{-i(\omega_d - \omega_{n,n-1}) + \gamma} \rho T_{n,n} \\ &+ \sum_{m,n=0}^{\infty} \frac{\sqrt{m(n+1)}(G_+G_-)^*}{-i(\omega_d - \omega_{n+1,n}) + \gamma} T_{m-1,m}\rho T_{n+1,n} \\ &+ \sum_{m,n=0}^{\infty} \frac{\sqrt{m(n+1)}(G_+G_-)}{i(\omega_d - \omega_{m,m-1}) + \gamma} T_{m-1,m}\rho T_{n+1,n},\end{aligned}$$

$$\begin{aligned}\dot{\rho}_{n,n} = &-n\left(\kappa - 2\mathrm{Re}\left[\frac{G_+G_-}{i(\omega_d - \omega_{n,n-1}) + \gamma/2}\right]\right)\rho_{n,n} + \\ &(n+1)\left(\kappa - 2\mathrm{Re}\left[\frac{G_+G_-}{i(\omega_d - \omega_{n+1,n}) + \gamma/2}\right]\right)\rho_{n+1,n+1},\end{aligned}$$

Rivera *et al. In preparation.*

Description of the nonlinear loss in terms of a number-dependent Langevin forces

- We can associate a Langevin equation with the density matrix equation

$$\dot{T}_{n,n} = -L_n T_{n,n} + L_{n+1} T_{n+1,n+1} + F_{n,n}$$

- Which, from the Einstein relation: $2\langle D_{\mu\nu}\rangle = \frac{d}{dt}\langle A_\mu A_\nu\rangle - \langle A_\mu D_\nu\rangle - \langle D_\mu A_\nu\rangle$ implies

$$2\langle D_{n,n}\rangle = \langle L(n)\rangle = \langle n\kappa(n)\rangle$$

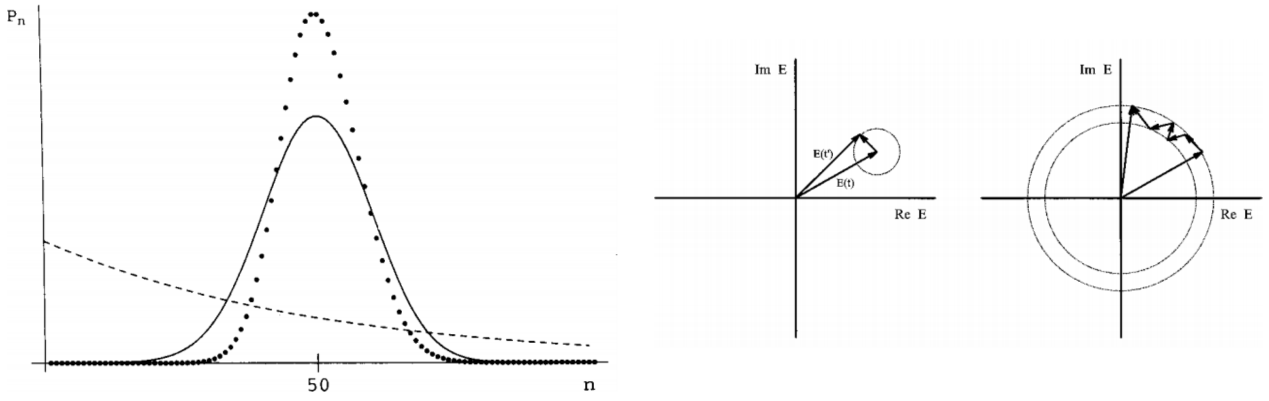
- This is then converted to a Langevin equation for the photon number

$$\dot{n} = -\kappa(n)n + F_n \quad \text{with} \quad \begin{aligned} &\langle F_n(t)\rangle = 0 \\ &\langle F_n(t)F_n(t')\rangle = \langle L(n)\rangle \delta(t-t') \end{aligned}$$

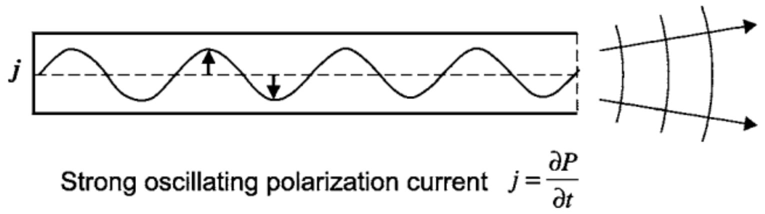
- Advantage of Langevin: easy to get moments, noise spectrum (corresponds to a common experimental observable), especially with important classes of gain (solid-state & semiconductor lasers)

Rivera *et al. In preparation.*

Relation to “textbook” quantum laser theory, e.g., of Lamb & Scully



Glauber, *Nobel Lecture* (2005)



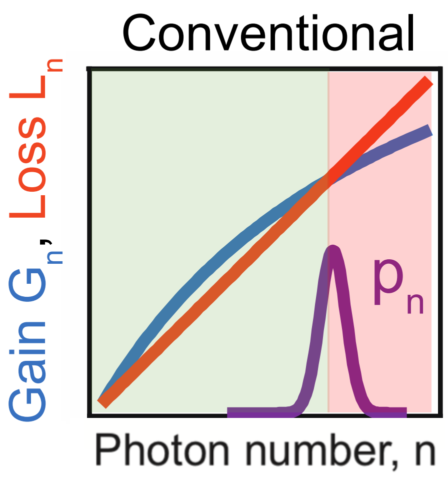
- “Textbook result”
  - “De-phased” coherent states (well-beyond threshold)
- Here, saturation comes from photon NL rather than gain
  - Here, we develop a new quantum theory of these “nonlinear lasers”
  - Covers many more cases than presented here

Relation to "textbook" quantum laser theory, e.g., of Lamb & Scully

- Dynamics of the resonator photon probability distribution p_n can be shown to follow a rate equation

$$\dot{p}_n = G_n p_{n-1} - (L_n + G_{n+1})p_n + L_{n+1}p_{n+1}.$$

- Textbook case of the quantum optics of a laser:
  - $R_{emit}(n-1 \rightarrow n) = \frac{An}{1+n/n_s} = Gn,$
  - $R_{loss}(n \rightarrow n-1) = \kappa n = Ln$



$$\Delta n = \left(1 - G_{\langle n\rangle+1}/L_{\langle n\rangle+1}\right)^{-1/2}$$

- Key to the "coherent" state: "negative feedback" from atomic saturation (as intensity increases, gain decreases)

Infinite-order nonlinearities and Fock-state lasing in the deep-strong coupling regime of QED

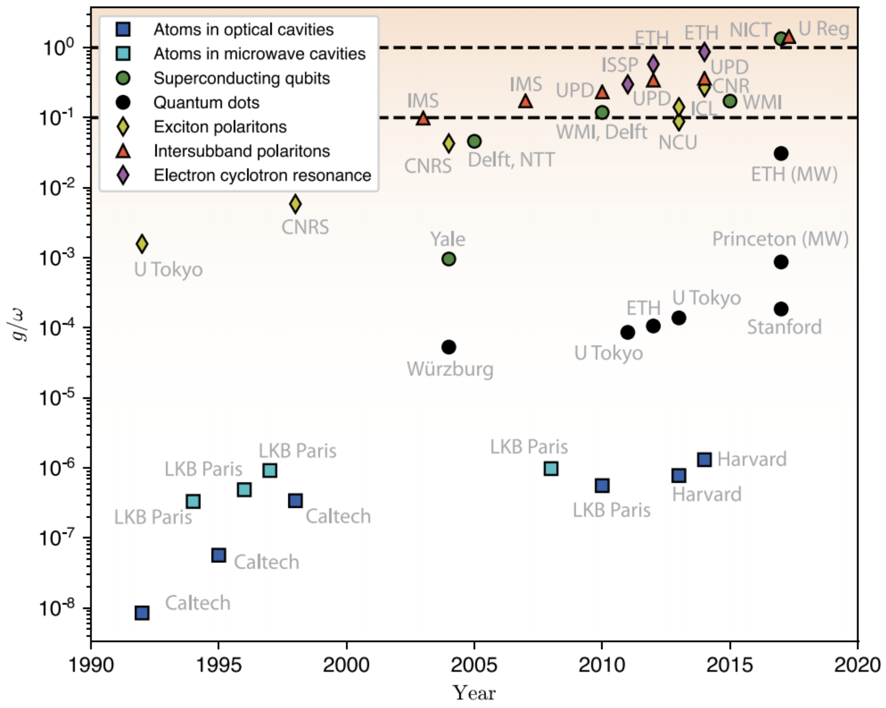
Rivera *et al. Infinite-order nonlinearities and Fock-state lasing in the deep-strong coupling regime of QED.*

These effects may also be realized using exotic new excitations in cavity QED

TLS coupled to a cavity

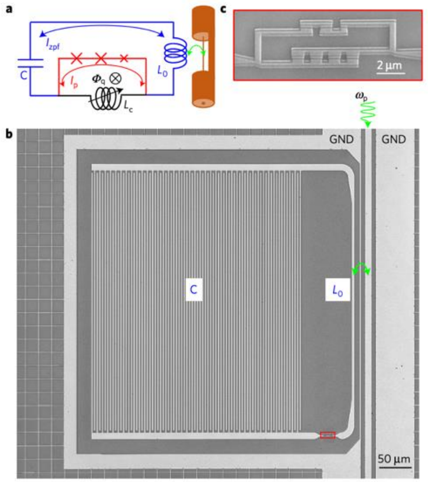
$$H_R = \left(\frac{\hbar\omega_0}{2}\sigma_z + \frac{\hbar\lambda}{2}\sigma_x \right) + \hbar\omega a^\dagger a + \hbar\tilde{g}\sigma_x(a + a^\dagger)$$

Deep-strong coupling (DSC) regime (coupling >> bare energies)

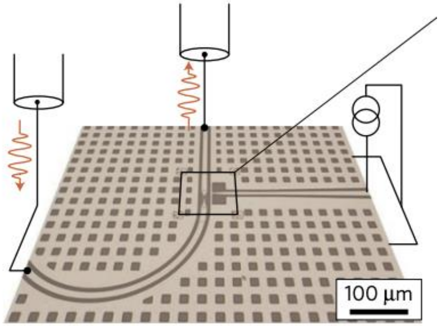


Forn-Díaz, *et al. Rev. Mod. Phys.* (2019).

Devoret, *et al. Ann. Phys.* (2007).

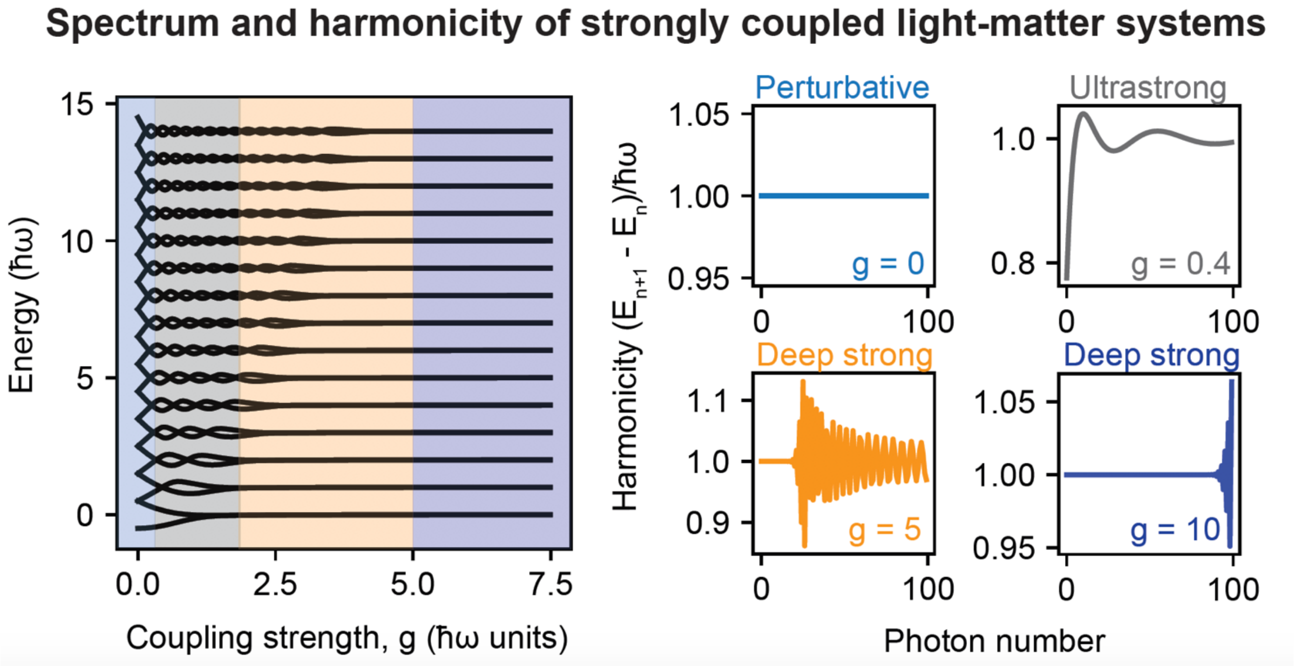


Forn-Díaz, *et al.* *Nat. Phys.* (2017).



Yoshihara, *et al.* *Nat. Phys.* (2017).

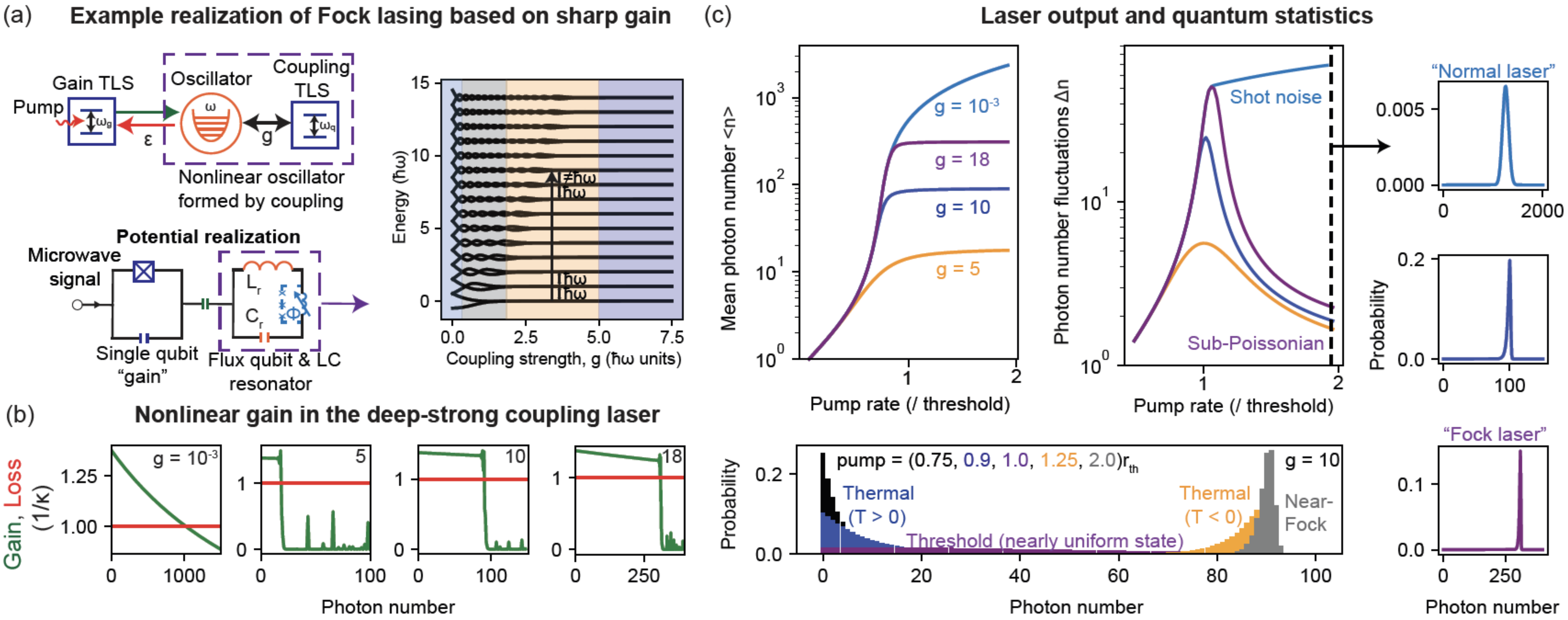
An extremely high-order nonlinearity arising from a TLS coupling to a cavity



- The eigenstates are an effective photon (DSC photon) with a pseudo-spin

$$E_{n\sigma} = \hbar\omega\left(n + \frac{1}{2}\sigma e^{-2|g|^2} L_n(4|g|^2)\right) \qquad |n,\sigma\rangle = \frac{1}{\sqrt{2}}\left(D^\dagger|+x,n\rangle + \sigma D|-x,n\rangle\right)$$

These form the basis for a Fock maser, for example, with sharp NL gain



Stimulated emission of DSC photons

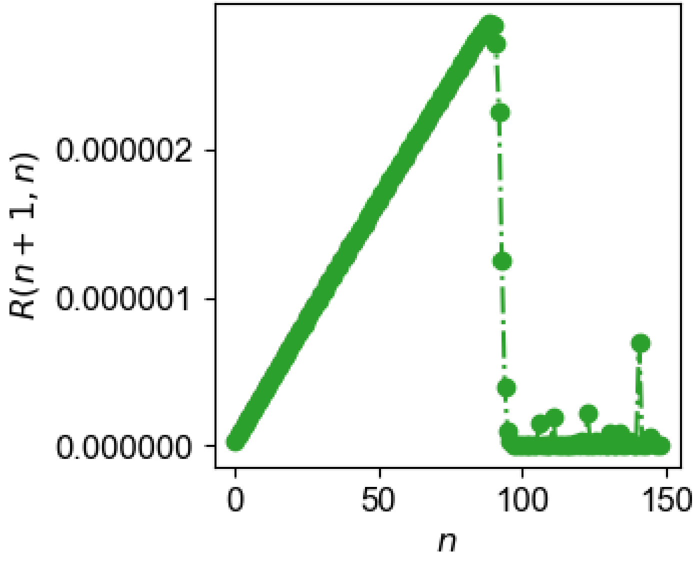
- Consider an ancillary TLS coupled to the field of the DSC photon through the JC interaction: $\epsilon\sigma_{x,\text{em}}(a + a^{\dagger})$

- The stimulated emission rate is found to be:

$$R^{(\epsilon)}_{(n+1)\sigma',n\sigma} \approx \frac{2r_a\epsilon^2(n+1)}{\Gamma^2 + 4\epsilon^2(n+1) + \Delta^2_{n+1}}\delta_{\sigma,\sigma'}$$

- Notice the similarity to textbook laser physics:

$$\chi = -\frac{i\chi_0\gamma[\gamma - i(\omega-\nu)]}{\gamma^2(1 + I/I_s) + (\omega-\nu)^2} .$$



Gain dynamics of a laser based on emission into DSC photons

- For the photon probabilities p(*n*) of having *n* photons:

$$\dot{p}_n = G_n p_{n-1} - (L_n + G_{n+1})p_n + L_{n+1}p_{n+1}$$

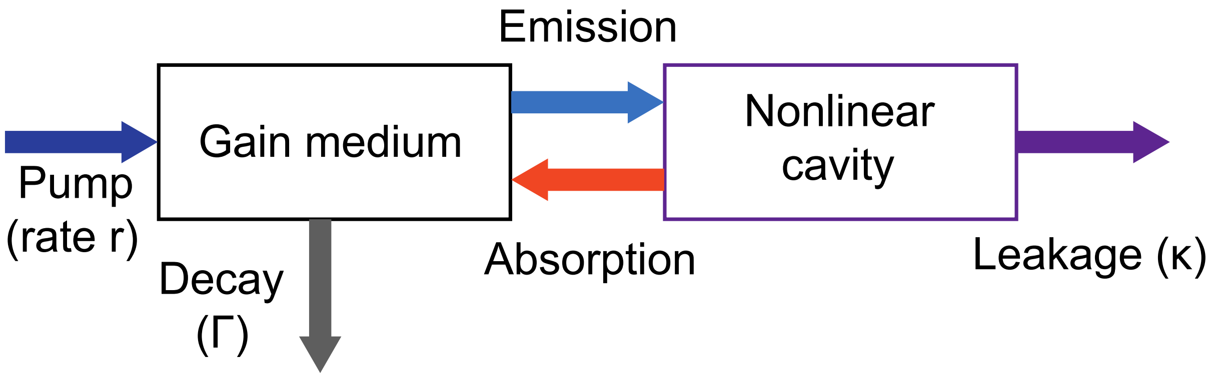
- Which, for our problem, reads

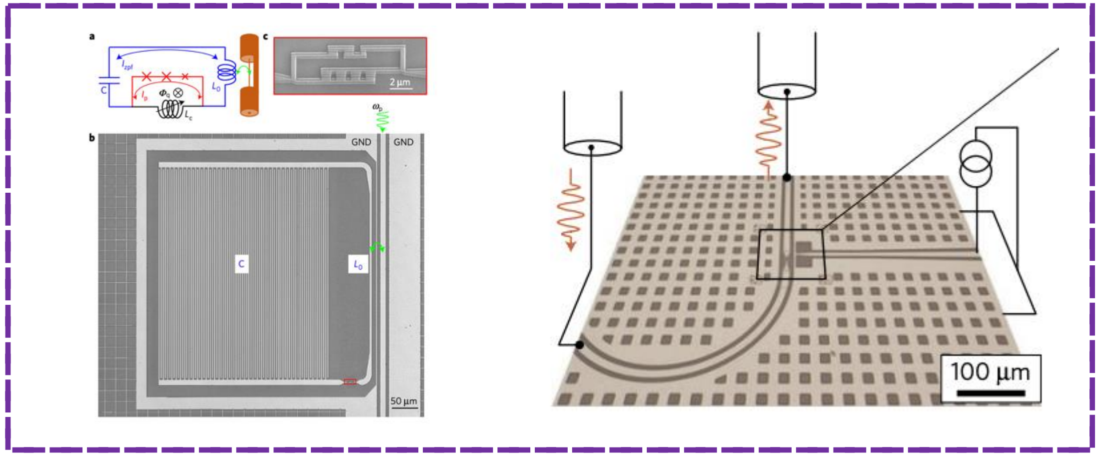
$$\dot{\rho}_{nn} = \frac{2rn\epsilon^2}{\Gamma^2 + F(n)}\rho_{n-1,n-1} - \left(\frac{2r(n+1)\epsilon^2}{\Gamma^2 + F(n+1)} + \kappa n\right)\rho_{nn} + \kappa(n+1)\rho_{n+1,n+1}$$

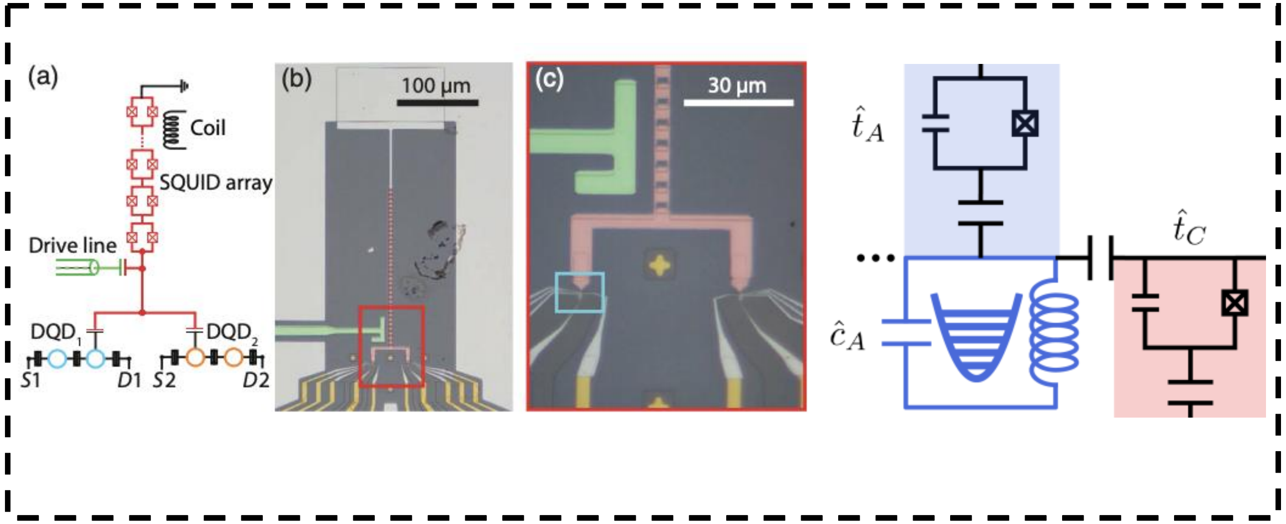
- where the nonlinearity $F(n) = 4n\epsilon^2 + \frac{1}{4}\omega^2 e^{-4g^2}(L_n(4g^2) - L_{n-1}(4g^2))^2$

- The steady-state solution is: $\rho_n = \frac{1}{Z}\prod_{m=1}^{n} \frac{2r\epsilon^2/\kappa}{\Gamma^2 + F(m)}$

Paths to experimental realization





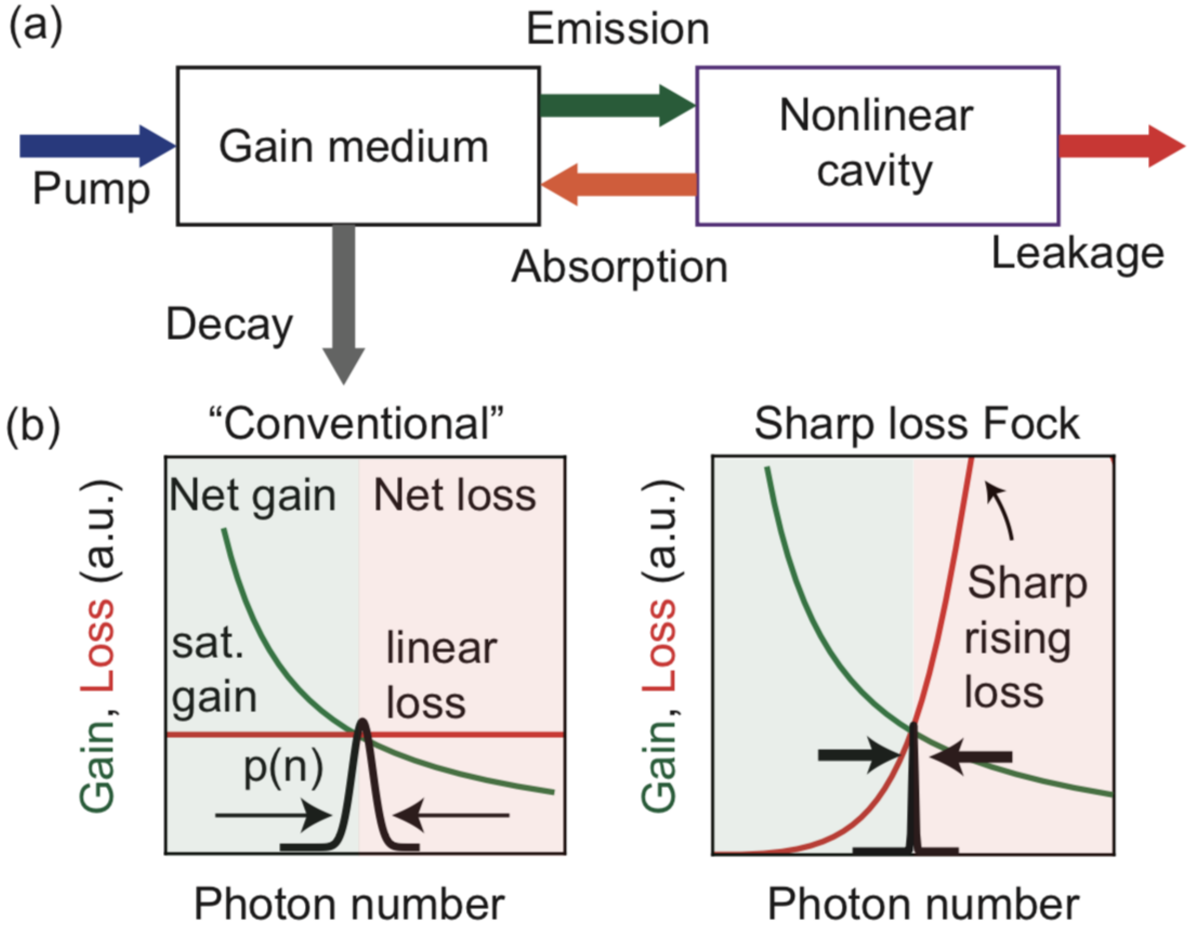


- A key realization from previous slide: “gain” can be provided by a single emitter,
  - a repeatedly pumped qubit
  - or multiple emitters, such as microwave-active molecules

Condensation of optical noise in the macroscopic regime

Rivera *et al. Macroscopic condensation of photon noise in sharply nonlinear dissipative systems. In preparation.*

Noise properties of lasers with nonlinear dissipation



- Presence of saturable gain adds terms to master eqn. (Lamb, Scully)

$$\dot{p}_n = G_n p_{n-1} - (L_n + G_{n+1}) p_n + L_{n+1} p_{n+1}.$$

- Admits steady-state solution:

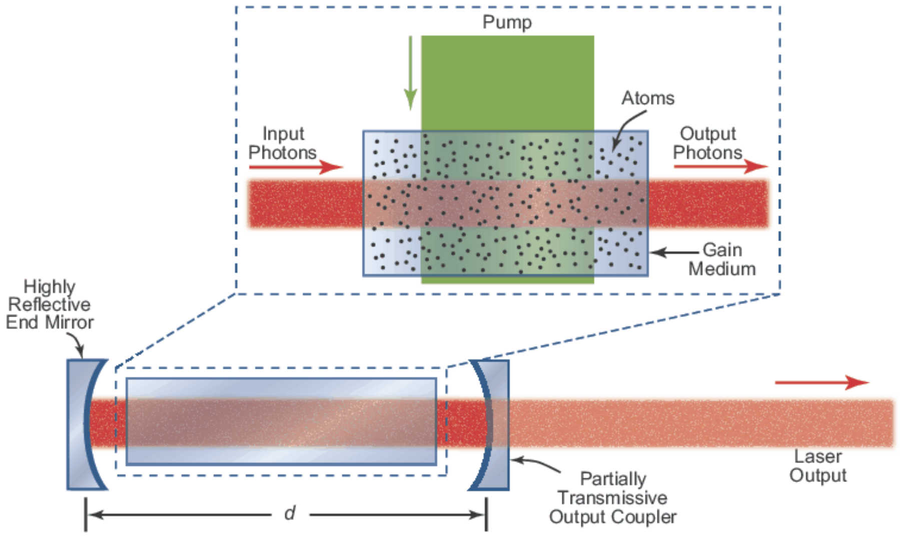
$$p_n = \frac{1}{Z} \prod_{m=1}^{n} \frac{G_m}{L_m}$$

- Noise given by

$$\Delta n = \left(1 - G_{\langle n \rangle + 1} / L_{\langle n \rangle + 1}\right)^{-1/2}$$

Rivera *et al. In preparation.*

Condensation of optical noise in the macroscopic regime?



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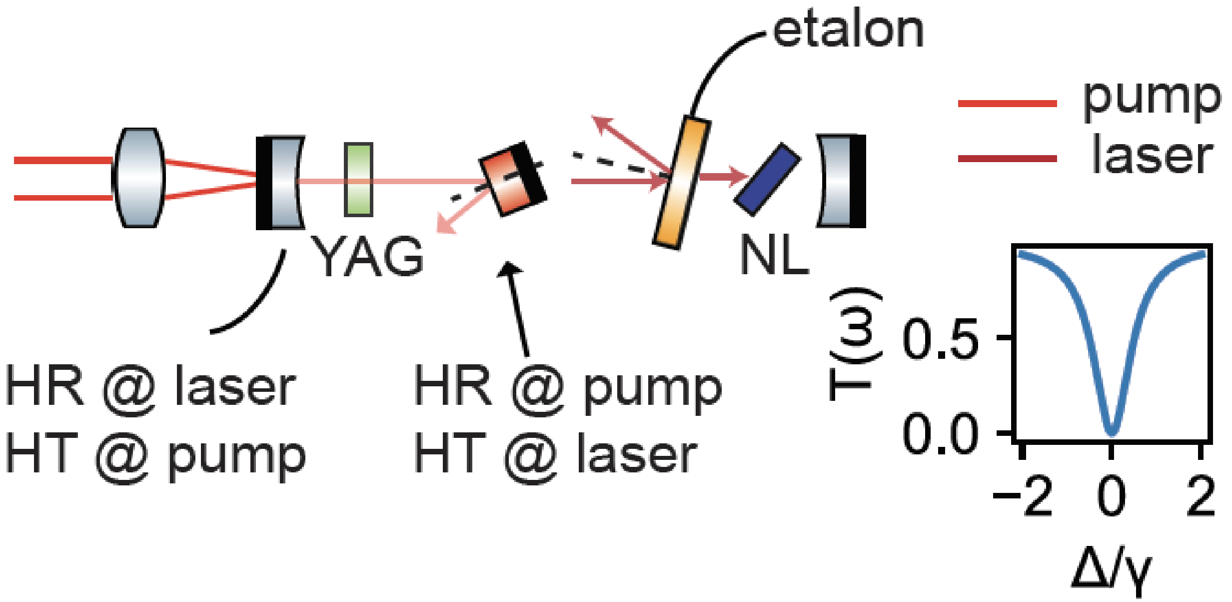


How would sharp loss affect existing devices, e.g., a "garden-variety" laser?

Condensation of optical noise in the macroscopic regime?

- Master eq. for probabilities corresponds to a Langevin equation for the photon number $\dot{n} = -\kappa(n)n + F_n.$ with F_n an operator-valued, Langevin force with statistical properties dictated by the Einstein relation (FDT)

$$\langle F_n(t) \rangle = 0$$

$$\langle F_n(t) F_n(t') \rangle = \langle L(n) \rangle \delta(t - t')$$

- Combining this with a description of the inversion a la Lax, we have:

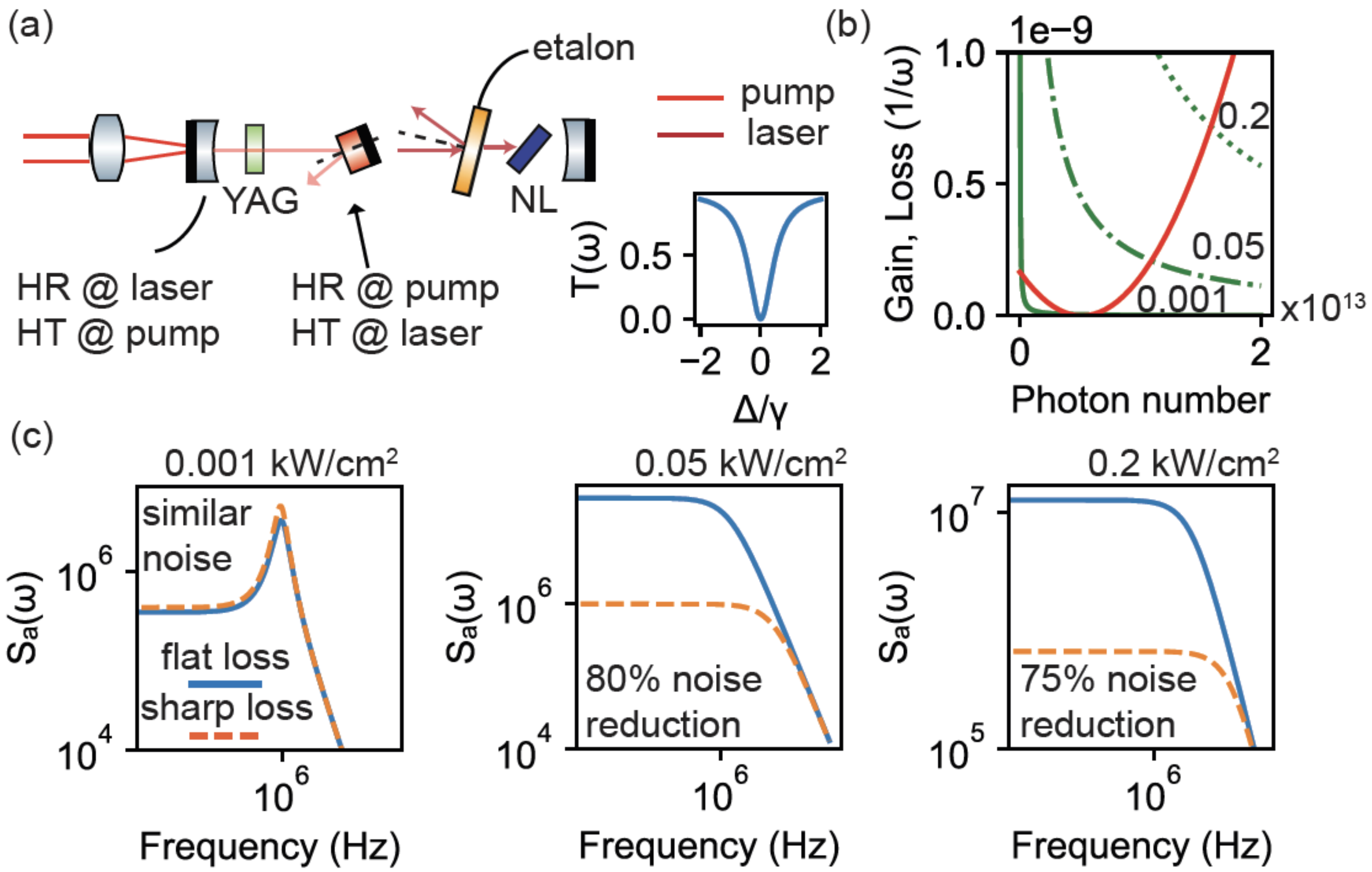
$$\dot{n} = (R_{\mathrm{sp}} S - \kappa(n))n + F_n$$

$$\dot{S} = \Lambda - (\gamma_{||} + R_{\mathrm{sp}} n)S + F_S$$

$$\begin{pmatrix} \delta \dot{S} \\ \delta \dot{n} \end{pmatrix} = \begin{pmatrix} -\left(\gamma_{||} + R_{\mathrm{sp}} \langle n \rangle\right) & -R_{\mathrm{sp}} \langle S \rangle \\ R_{\mathrm{sp}} \langle n \rangle & -\kappa'(\langle n \rangle)\langle n \rangle \end{pmatrix} \begin{pmatrix} \delta S \\ \delta n \end{pmatrix} + \begin{pmatrix} F_S \\ F_n \end{pmatrix}$$

Rivera *et al. In preparation.*

Condensation of optical noise in the macroscopic regime?



Spectrum of number fluctuations

$$S_a(\omega) = \frac{1}{\pi}\langle \delta n^\dagger(\omega)\delta n(\omega)\rangle$$

related to overall noise via

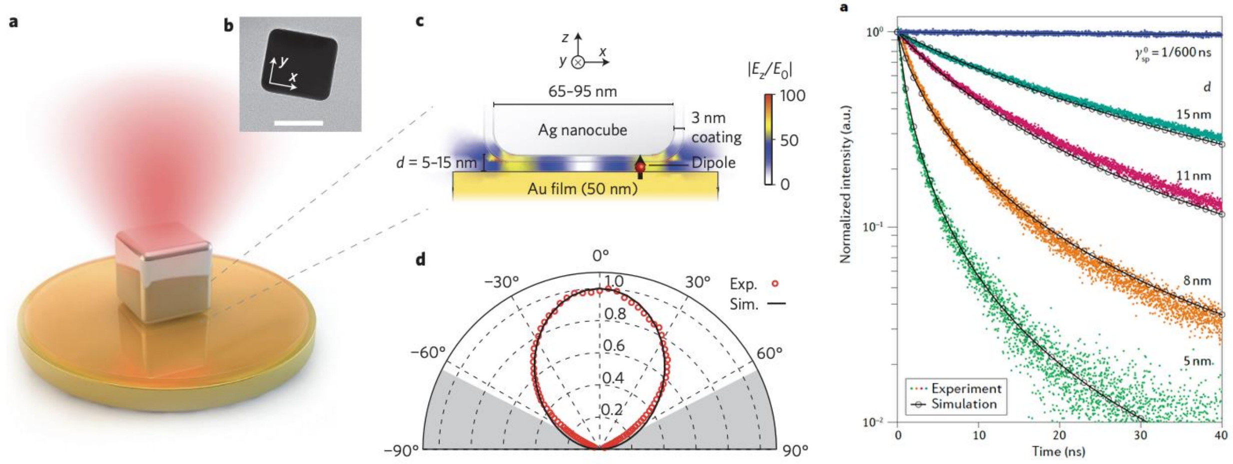
$$(\Delta n)^2 = \int_0^\infty d\omega\ S_a(\omega)$$

Note: incomplete condensation because the NL here is weak, but we still get a fairly strong effect due to inclusion of a very sharp freq.-dependent element.

Rivera *et al. In preparation.*

Confining light on wavelength scales to control light-matter interaction

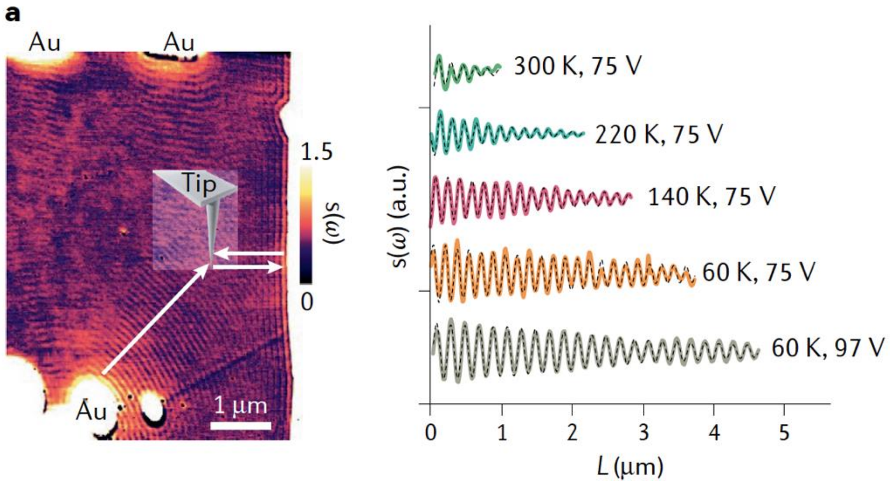
- Many of the applications above: light is a *plane wave*, with energy delocalized over a volume $\gg \lambda^3$.
- By controlling light with polarizable media with spatial variations on the scale of λ (*nanophotonics*), we can enhance the interactions.
- Very representative: Purcell effect
- **Still, the interactions are *very weak*, and are largely lowest-order (e.g., in coupling strength, atomic size, field strength)**



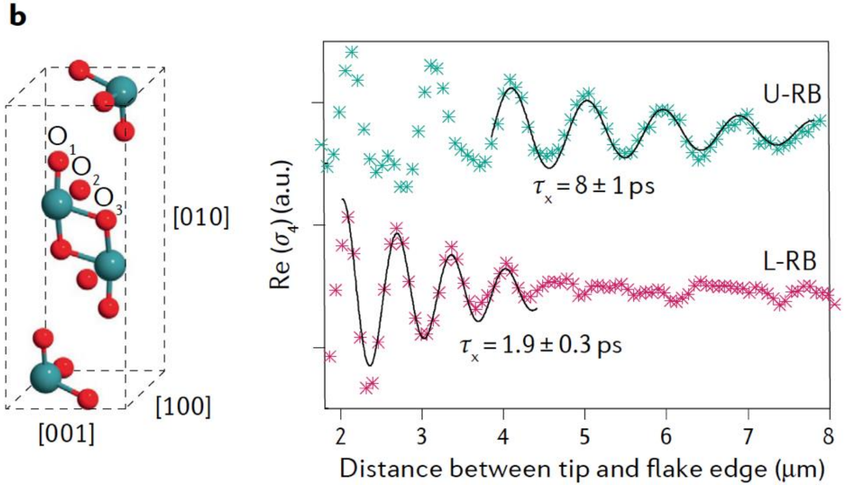
Akselrod *et al. Nature Photonics* (2014).

$$\Gamma_{fi} = \frac{3}{4\pi^2} \frac{Q}{(V/\lambda_0^3)} \left|\hat{\mathbf{d}}_{fi} \cdot \mathbf{u}(\mathbf{r})\right|^2 \Gamma_0,$$

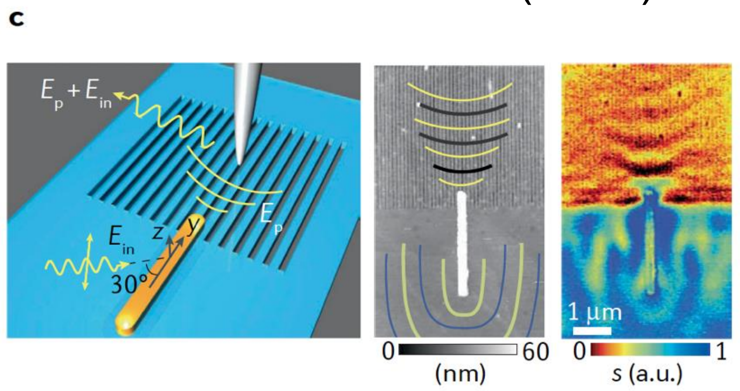
Collective excitations as generalized photons, or photonic quasiparticles



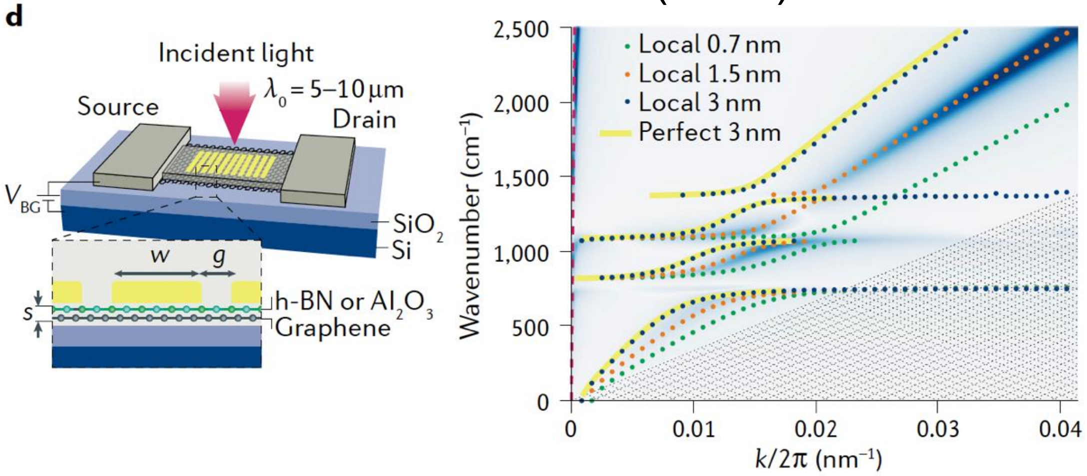
Ni *et al.* *Nature* (2018).



Ma *et al.* *Nature* (2018).



Li *et al.* *Science* (2018).



Iranzo *et al.* *Science* (2018).

Can be used in many of the same ways as photons, but very different linear properties:

- *Wavelength* – >100x smaller
- *Polarization* – often circular
- *DOS* – very high
- *Mode volume* – very small

Outline

1. Intro to light-matter interactions and photonic quasiparticles

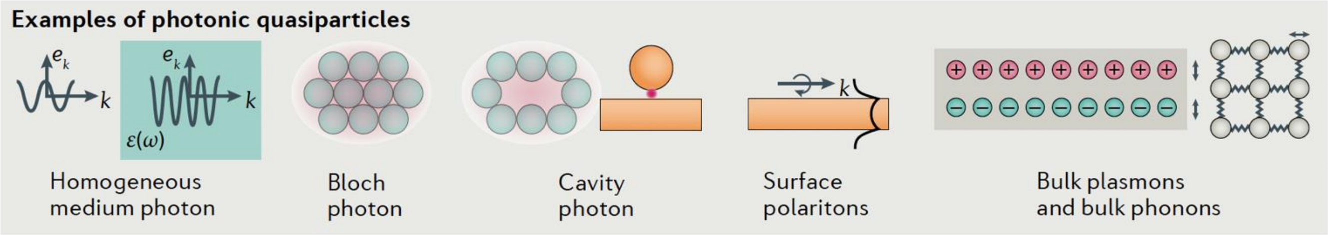
2. Systematic study of elementary processes of light-matter interactions with photonic quasiparticles

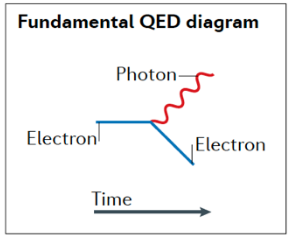
3. An application of enhancing light-matter interactions – novel high-energy particle detectors based on scintillators

4. Photonic quasiparticle nonlinearities, new nonlinear dissipative phenomena, and large optical Fock state generation

Putting it all together

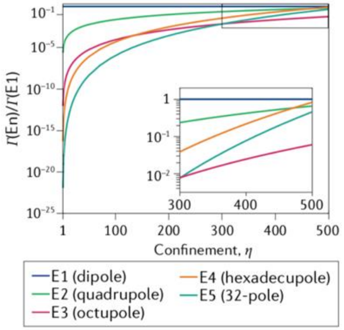
Light-matter interactions with photonic quasiparticles

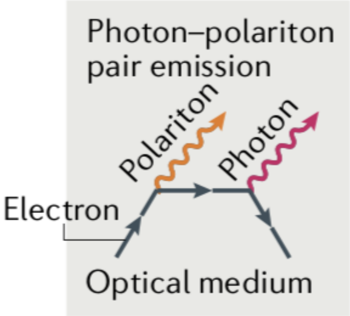


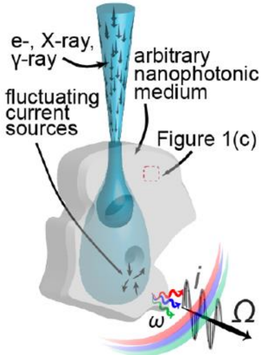


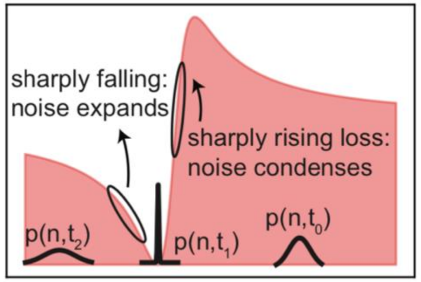
Interactions arising from linear properties

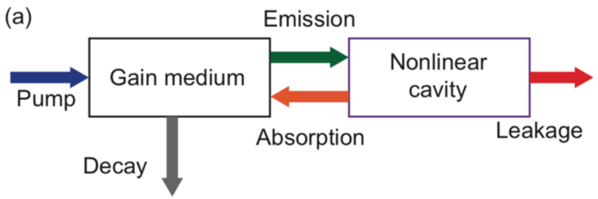
& nonlinear properties







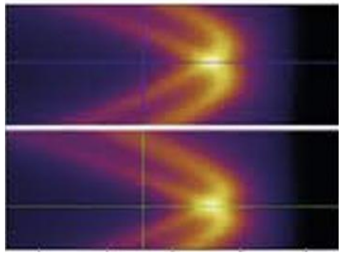




Some potential applications of these interactions

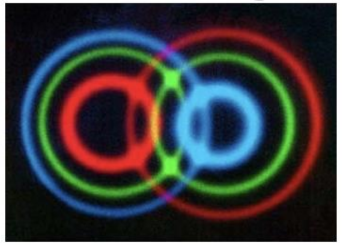
Detectors

Spectroscopy



Particle detection

Quantum light



Lasers