Large suppression of quantum fluctuations at the nanoscale

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A bit of history…

Haroche and Wineland in 2012.

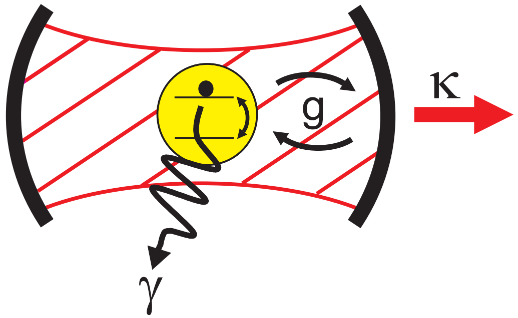
Preparation, Cooling, and Spectroscopy of

W. Neuhauser, M. Hohenstatt, and P.E. Toschek

Institut für Angewandte Physik der Universität
D-6900 Heidelberg, Fed. Rep. of Germany
and

H.G. Dehmelt

Physics Department, University of Washington
Seattle, WA 98195, USA



Certainly the most desirable conditions of experiments, to which an atomic physicist could ever aspire under the viewpoint of clarity and simplicity, include the preparation of a single, well-localized atomic particle. The realization of

H. Walther, et al. (eds.), Laser Spectroscopy IV (Springer-Verlag, Berlin Heidelberg 1979)

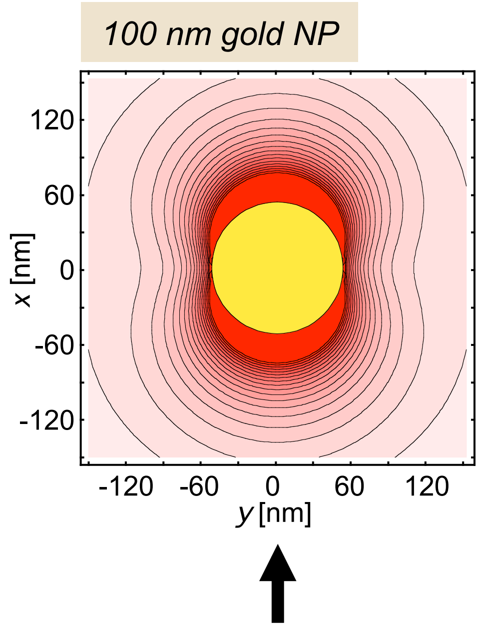
Fluorescence enhancement or quenching?

field enhancement

$$S_o \propto \eta_o |\mathbf{E}_o|^2, \quad \eta_o = \frac{\gamma_r^o}{\gamma_t^o}, \quad \gamma_t^o = \gamma_r^o + \gamma_{nr}^o$$

$$S \propto \eta |\mathbf{E}|^2$$

quantum efficiency
(radiation efficiency)



decay rates

antenna efficiency

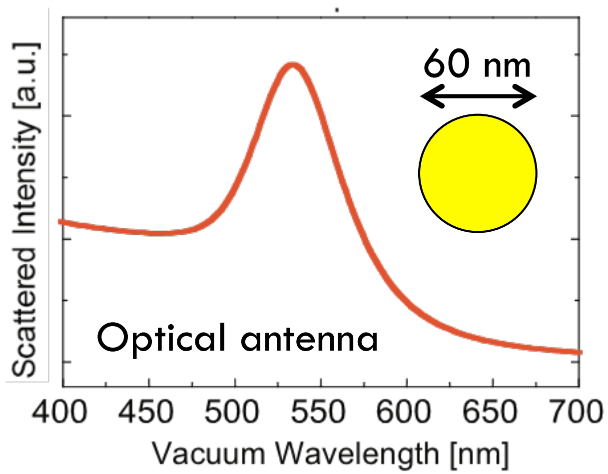
$$\eta = \frac{\gamma_r}{\gamma_t} = \frac{\eta_o}{(1-\eta_o)\frac{\gamma_r^o}{\gamma_r} + \frac{\eta_o}{\eta_a}}, \quad \eta_a = \frac{\gamma_r}{\gamma_r + \gamma_{nr}}$$

$$\gamma_t = \gamma_r + \gamma_{nr}^o + \gamma_{nr}$$

$$\frac{|\mathbf{E}|^2}{|\mathbf{E}_o|^2} \approx \frac{\gamma_r}{\gamma^o}$$

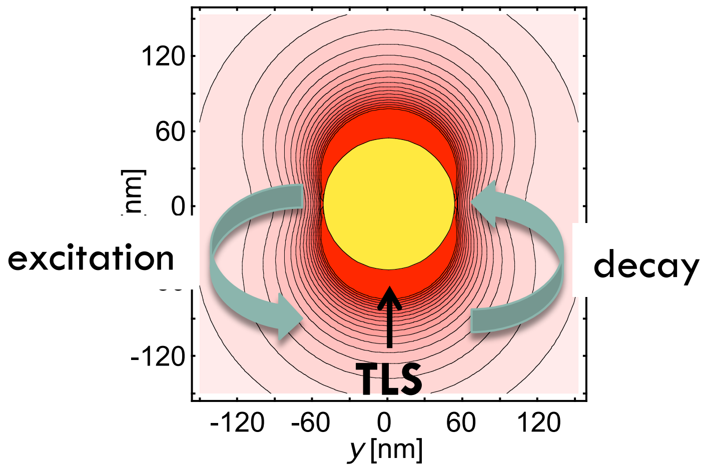
S. Kühn, et al, Phys. Rev. Lett. 97, 017402 (2006), P. Anger, et al. Phys. Rev. Lett. 96, 113002 (2006)

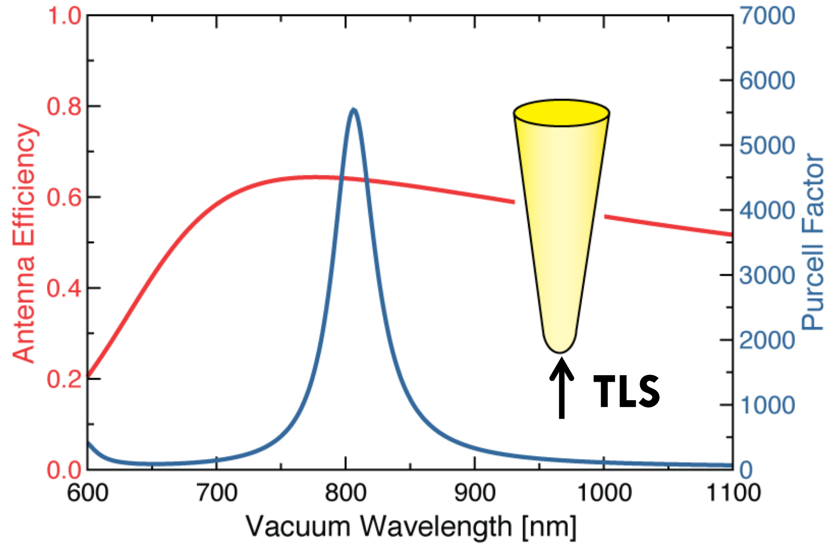
Enhancing quantum emitters



Strong enhancement with a high antenna efficiency

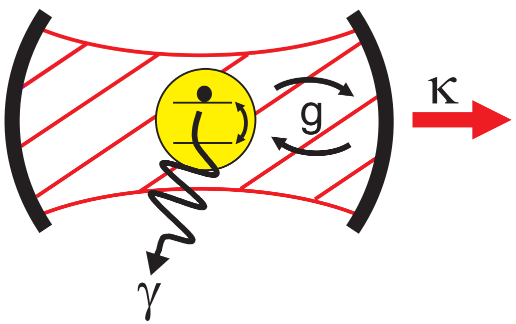
$$\eta_{\mathrm{a}} = \frac{P_{\mathrm{rad}}}{P_{\mathrm{rad}} + P_{\mathrm{abs}}} \approx 1$$





M. Agio, Nanoscale 4, 692 (2012) and references therein

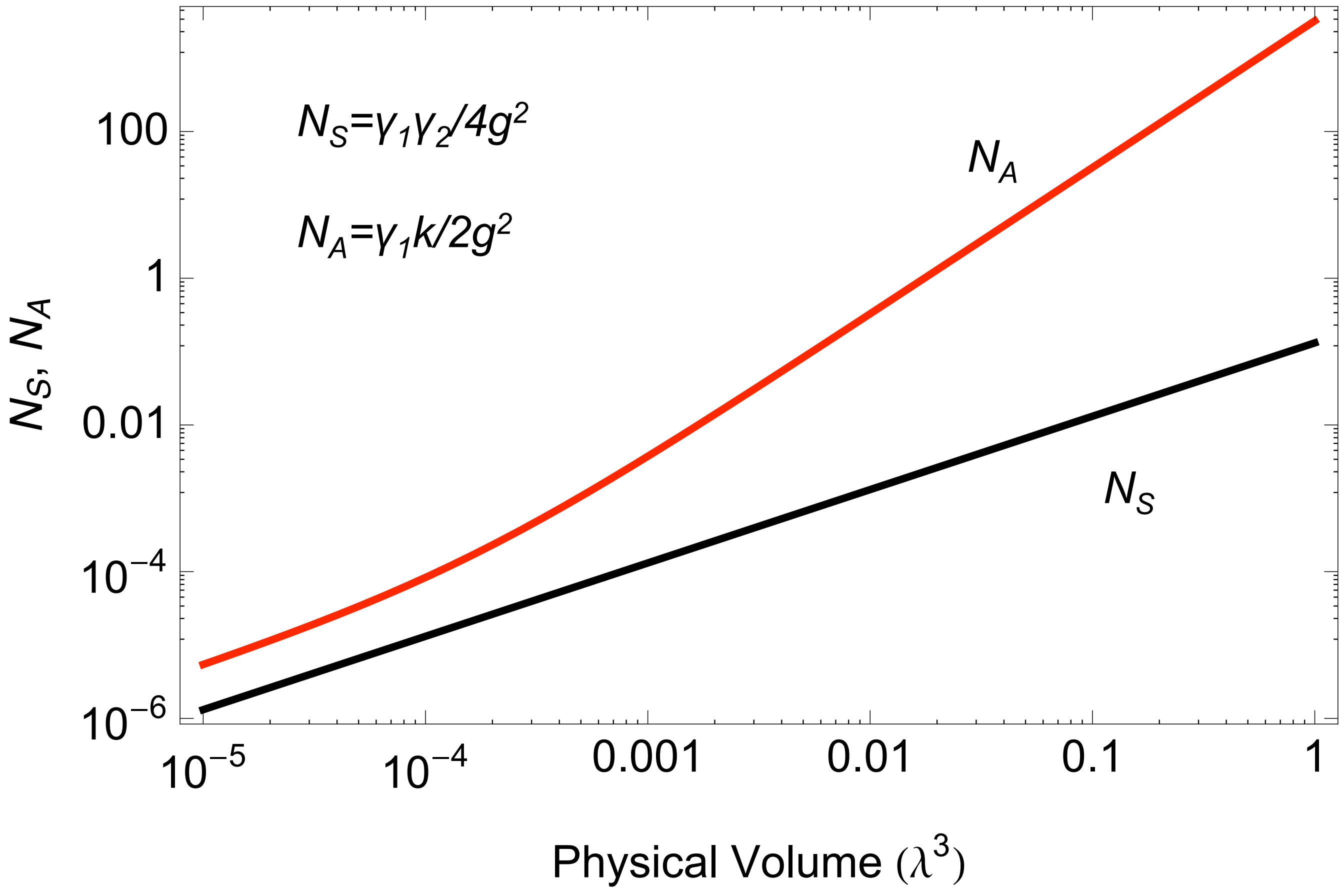
Critical parameters



(g,k,γ)=(34,2,1.25) MHz

(g,k,γ)=(97,48,-) GHz

… ?



Critical photon number (N_S) (black curve) and critical atomic number (N_A) (red curve) as a function of the cavity volume. The calculation was performed assuming dephasing times T_2=100 fs and T_1 =2.7 ns at λ =740 nm.

X.-W. Chen, A. Mohammadi, A. Ghasemi, M. Agio, Mol. Phys. 111, 3003 (2013)

Scattered electric field operator

Nanostructure + Two-level emitter dynamics: macroscopic QED

$$\hat{\mathbf{E}}(\mathbf{r},\omega) = i\sqrt{\frac{\hbar}{\pi\varepsilon_0}\frac{\omega^2}{c^2}}\int \mathrm{d}^3\mathbf{r}'\sqrt{\varepsilon''(\mathbf{r}',\omega)}\mathbf{G}(\mathbf{r},\mathbf{r}',\omega)\hat{\mathbf{f}}(\mathbf{r}',\omega)$$

Heisenberg equations of motion (Markovian and rotating wave approx)

$$\hat{E}_i^{(+)}(\mathbf{r},t) = |g_i(\mathbf{r})|e^{\imath\phi_i(\mathbf{r})}\hat{\sigma}(t), \quad \propto \quad \hat{\sigma} = |g\rangle\langle e|$$

QE coherence

where the complex electric field amplitude

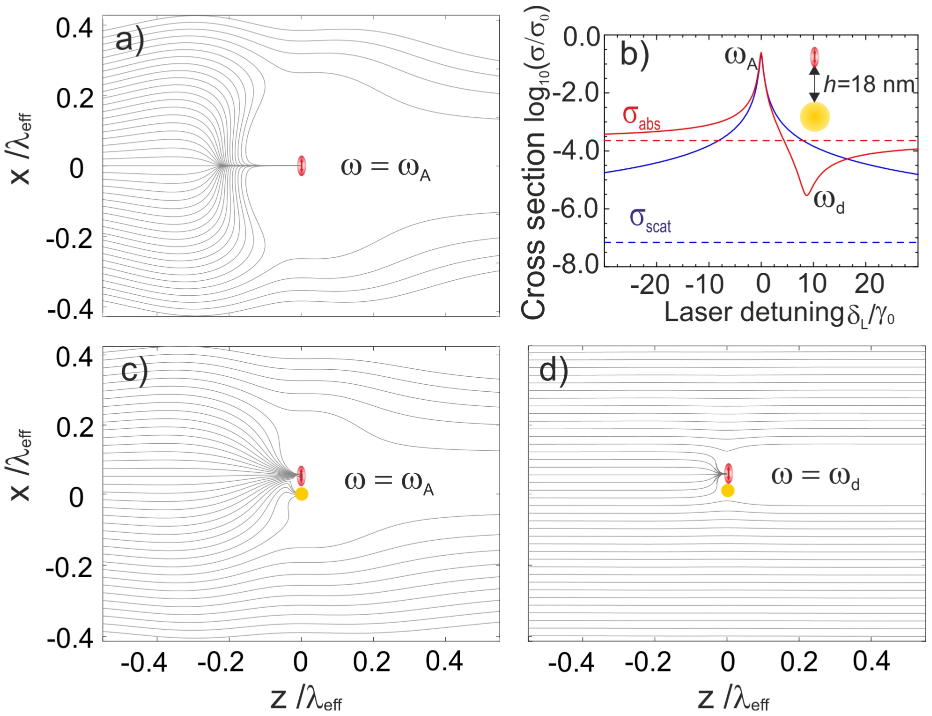
$$g_i(\mathbf{r}) = \frac{\mathcal{P}}{\pi\varepsilon_0}\int_0^\infty \mathrm{d}\omega\,\frac{\omega^2}{c^2}\frac{\mathrm{Im}\{G_{ij}(\mathbf{r},\mathbf{r}_\mathrm{E},\omega)\}d_j}{\omega_\mathrm{E}-\omega} + \imath\frac{\omega_\mathrm{E}^2}{\varepsilon_0 c^2}\mathrm{Im}\{G_{ij}(\mathbf{r},\mathbf{r}_\mathrm{E},\omega_\mathrm{E})\}d_j.$$

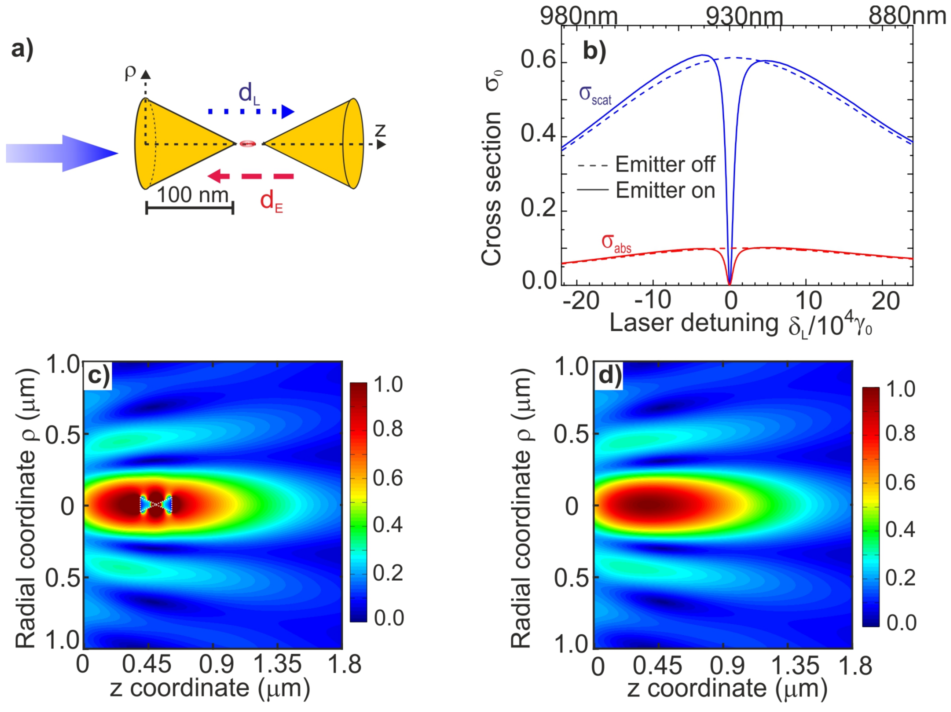
Green's tensor

Dung H.T., Knöll L., Welsch D.-G., Phys. Rev. A 64, 013804 (2000)

Coherent coupling effects

Beyond: Weak excitation, Rate equations, Classical light





X.-W. Chen, V. Sandoghdar, M. Agio, Phys. Rev. Lett. 110, 153605 (2013)

What is squeezed light?

Quantum electromagnetic field quadrature

$$E(\bar{r},t) = E^{+}(\bar{r},t) + E^{-}(\bar{r},t) \quad \textit{satisfying} \quad \left[E^{+}(\bar{r},t), E^{-}(\bar{r},t)\right] = 2C$$

Or more general, as a combination of both parts with a phase

$$E_{\theta}(\bar{r},t) = E^{+}(\bar{r},t)e^{i\theta} + E^{-}(\bar{r},t)e^{-i\theta}$$

Then a squeezed state of light corresponds to such that: $\left\langle \Delta E_{\theta}^{2}(\bar{r},t) \right\rangle < C$

Normal ordering → $\left\langle E^{-}E^{-} \ldots E^{+}E^{+} \right\rangle$

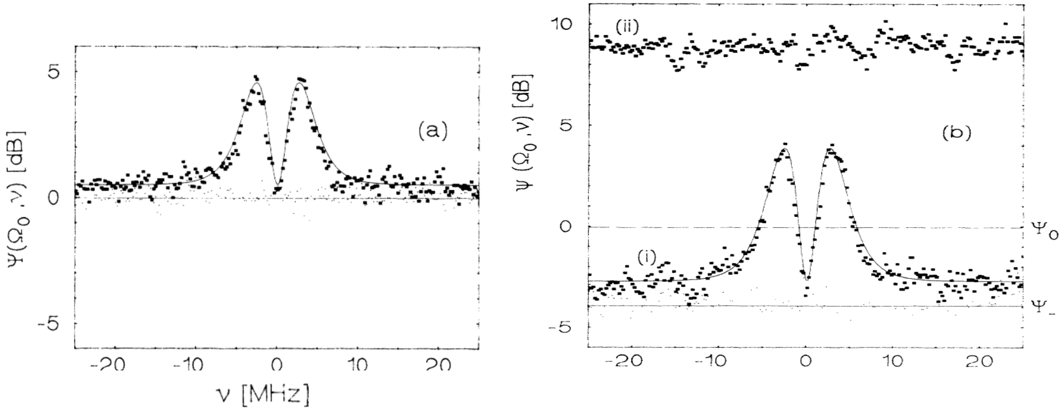
Or alternatively, since $\left\langle \Delta E_{\theta}^{2}(\bar{r},t) \right\rangle = C + \left\langle : \Delta E_{\theta}^{2}(\bar{r},t) : \right\rangle$

$$\boxed{\left\langle : \Delta E_{\theta}^{2}(\bar{r},t) : \right\rangle < 0}$$

Scully, M.O., Zubairy, M.S., Quantum Optics (Cambridge Univ. Press, 1997)

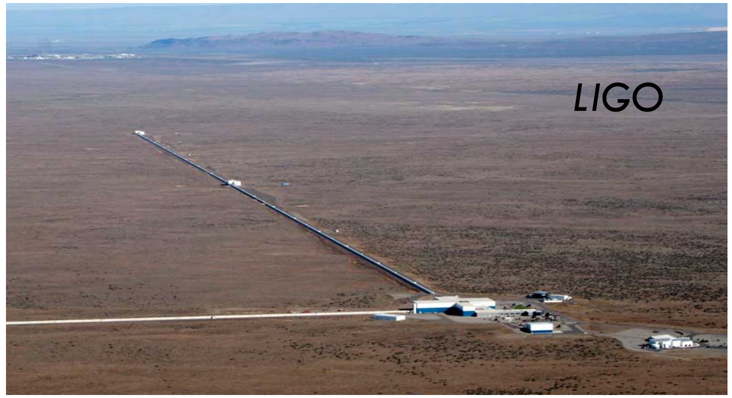
Applications of squeezed light

Spectroscopy



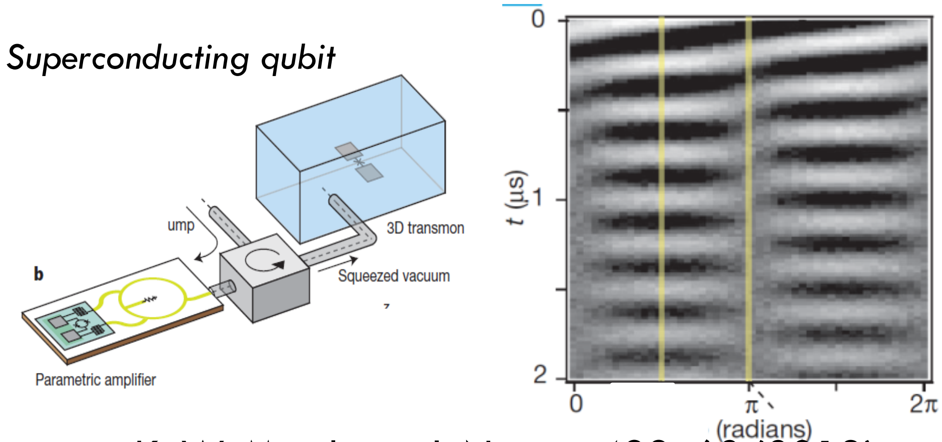
Polzik, E. S. et al, PRL 68, 3020 (1992)
Surpass standard quantum limit in sensitivity

Quantum interferometry



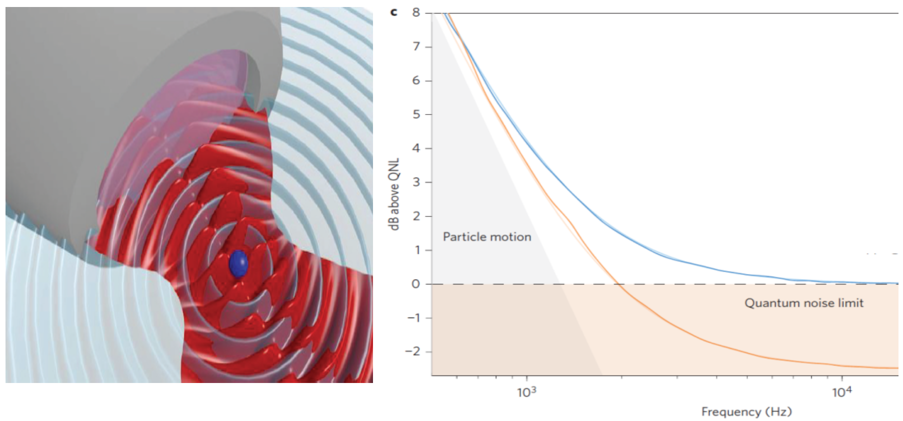
Aasi, J. et al. Nat. Photon. 7, 613 (2013)
Detection of gravitational waves

Quantum light-matter interactions



K. W. Murch et al, Nature 499, 62 (2013)
Reduction of emitter coherence decay

Quantum imaging

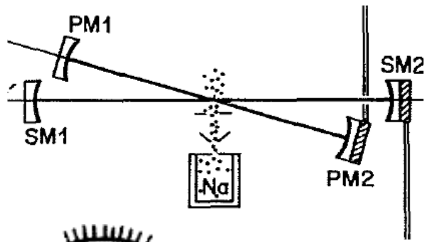


M. A. Taylor et al, Nat. Photon. 7, 229 (2013)
Quantum enhanced biological measurements

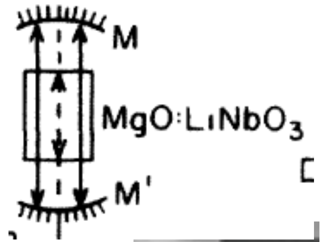
Sources of squeezed light

Cavity assisted

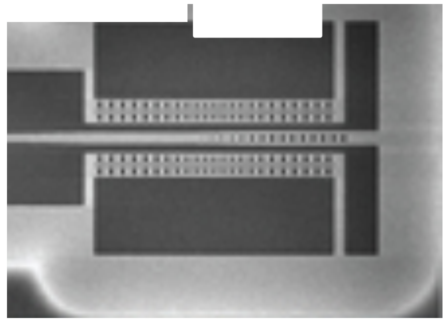
Four wave-mixing (cloud of Na atoms):
Slusher, R., et al, Phys. Rev. Lett. *55*, 2409 (1985)



Parametric down conversion (nonlinear crystal):
Wu, L. A., et al., Phys. Rev. Lett. *57*, 2520 (1986)



Optomechanics (Si chip microresonator+waveguide):
Safavi-Naeini, A. H., et al., Nature 500, 185 (2013)



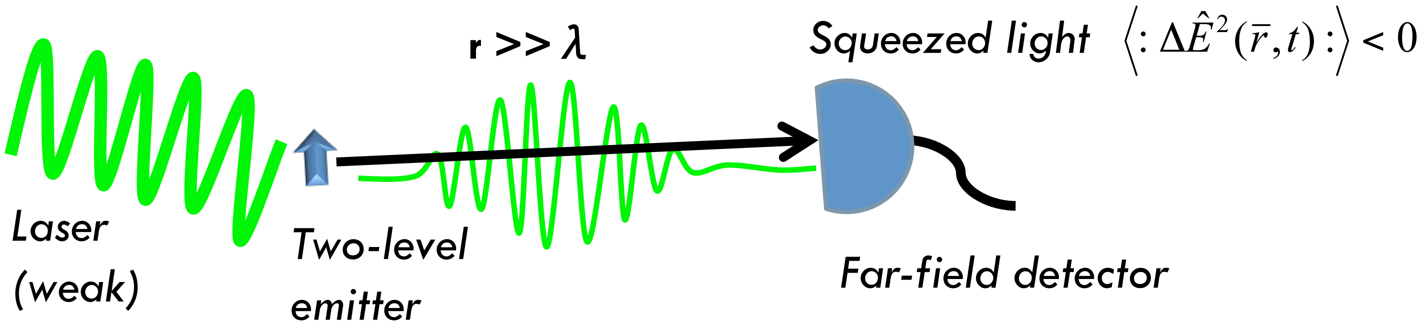
Free space

Resonance Fluorescence:
Walls, D. F. & Zoller, P., Phys. Rev. Lett. *47*, 709 (1981)

Review: Walls, D. F., Nature 306, 141 (1983)

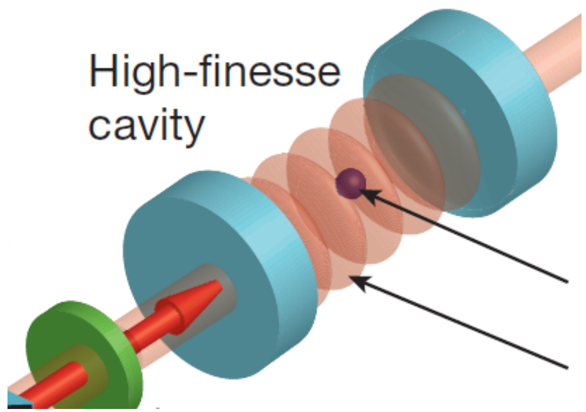
Resonance fluorescence in vacuum

Resonance fluorescence in free space:
Walls, D. F. & Zoller, P., Phys. Rev. Lett. 47, 709 (1981)



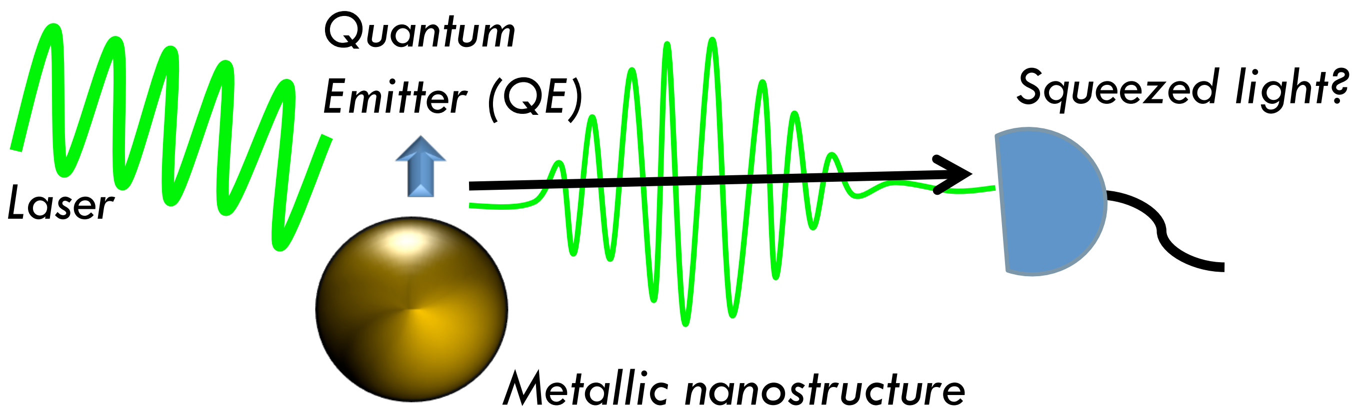
Challenging measurement at the single-emitter level: small signal intensity and collection efficiency

Only verified with the assistance
of a high-Q cavity at MPQ:
Ourjoumtsev, A., et al., Nature 474, 623 (2011)



Nanoscale hybrid source of squeezed light

Could nanostructures assist squeezed light generation?



Nanoscale hybrid systems:

- *Explore novel solid-state sources of squeezed-light*
- *Operation at the single-photon intensity level*
- *Applications for integrated systems with single QEs: enhanced nonclassical spectroscopy, imaging, and multipartite entanglement.*

Squeezed light generation

$$\langle : [\Delta \hat{E}_i(\mathbf{r}, t)]^2 : \rangle = |g_i(\mathbf{r})|^2 \, \langle : [\Delta \hat{\sigma}_{\phi_i}]^2(t) : \rangle$$

$$= 2|g_i(\mathbf{r})|^2 \left[\underbrace{\langle \hat{\sigma}^\dagger(t)\hat{\sigma}(t)\rangle - |\langle \hat{\sigma}(t)\rangle|^2}_{\text{Positive term}} - \underbrace{\mathrm{Re}\left(e^{\imath 2\phi_i(\mathbf{r})}\langle \hat{\sigma}(t)\rangle^2\right)}_{\text{Coherence fluctuations (Phase-dependent)}} \right]$$

Positive term

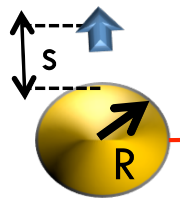
Coherence fluctuations
(Phase-dependent)

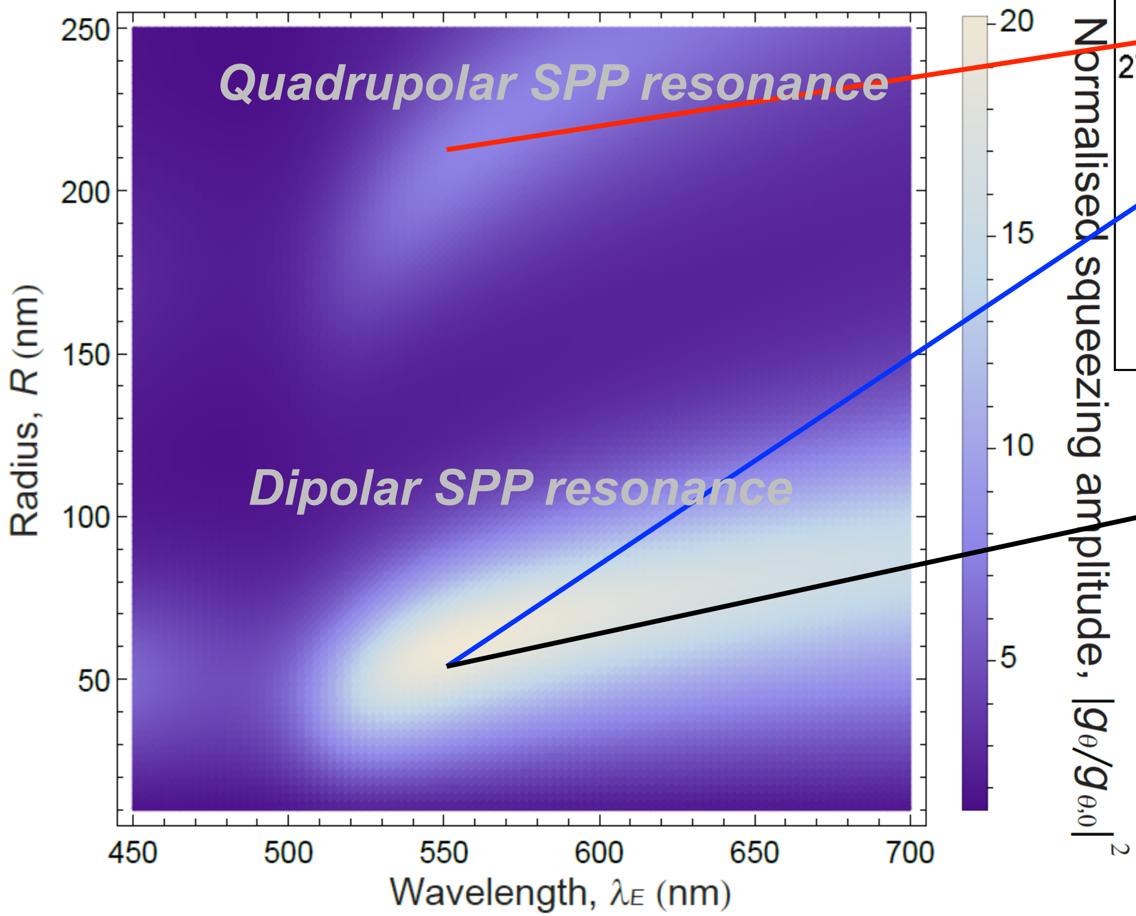
- *If* $\langle : [\Delta \hat{\sigma}_{\phi_i}]^2(t) : \rangle$ *<0 → Squeezed light*

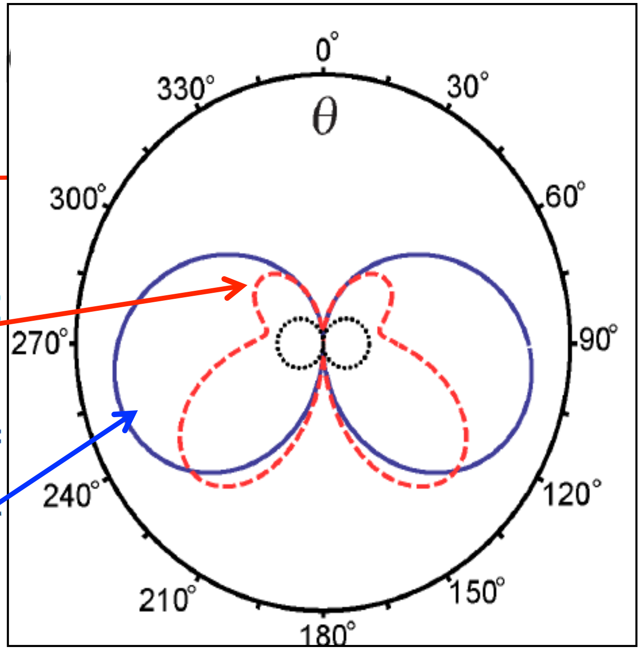
- *Effect of nanostructure*
  - → *Emitter coherence dynamics* $\gamma \quad \Omega \quad \delta$
  - → ϕ_i *, Phase shift*
  - → $|g_i|^2$*, Enhancement*

Squeezing amplitude in the far-field

$$\langle : [\Delta \hat{E}_i(\mathbf{r},t)]^2 : \rangle = |g_i|^2 \langle : [\Delta \hat{\sigma}_{\phi_i}]^2(t) : \rangle$$







20 times compared to free space

Control the direction and enhance the squeezing amplitude

Boundaries for squeezing

$$\langle : [\Delta \hat{E}_i(\mathbf{r}, t)]^2 : \rangle = |g_i|^2 \langle : [\Delta \hat{\sigma}_{\phi_i}]^2(t) : \rangle \leq 0$$

For the steady state conditions: $z^2 \leq (1 + \delta^2)$

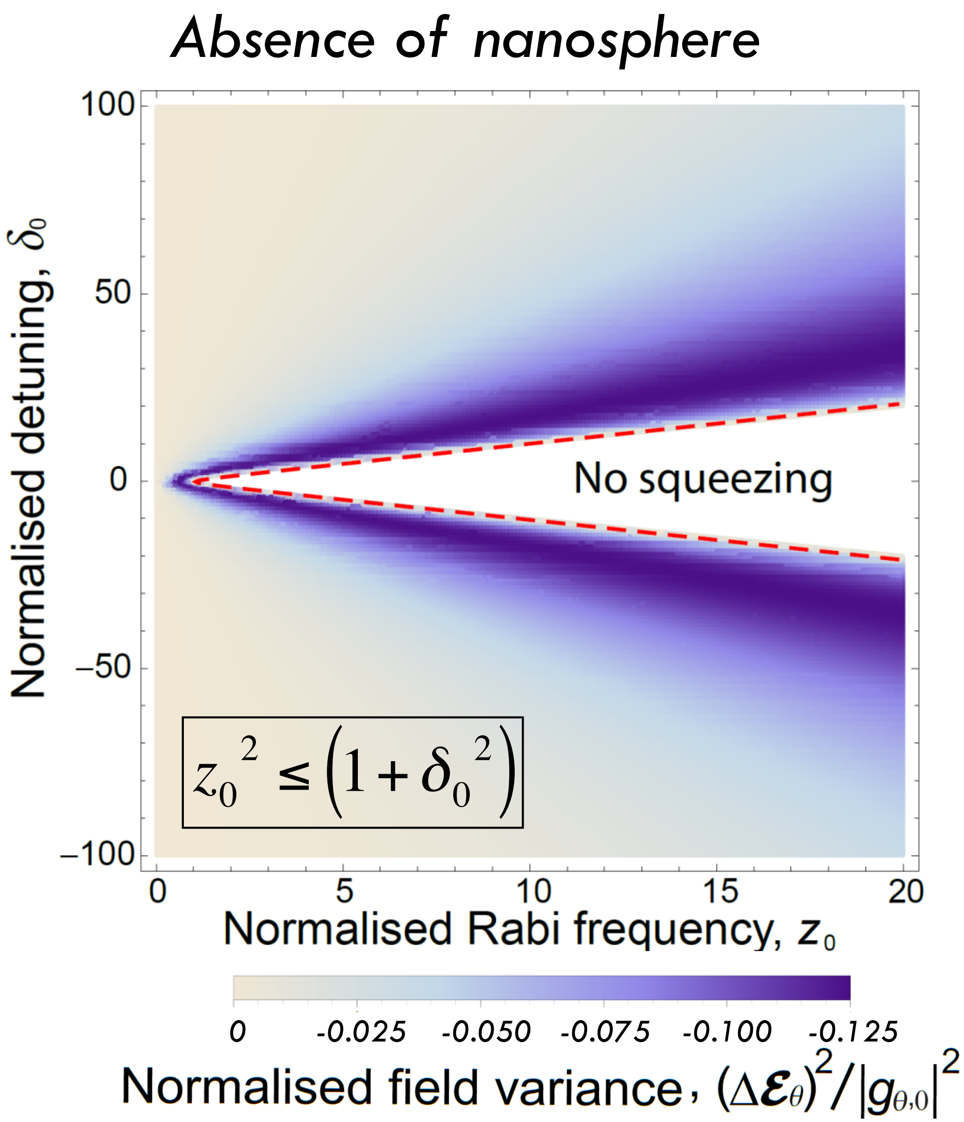
(for a QE, pure dephasing: $\gamma^* = 0$ *)*

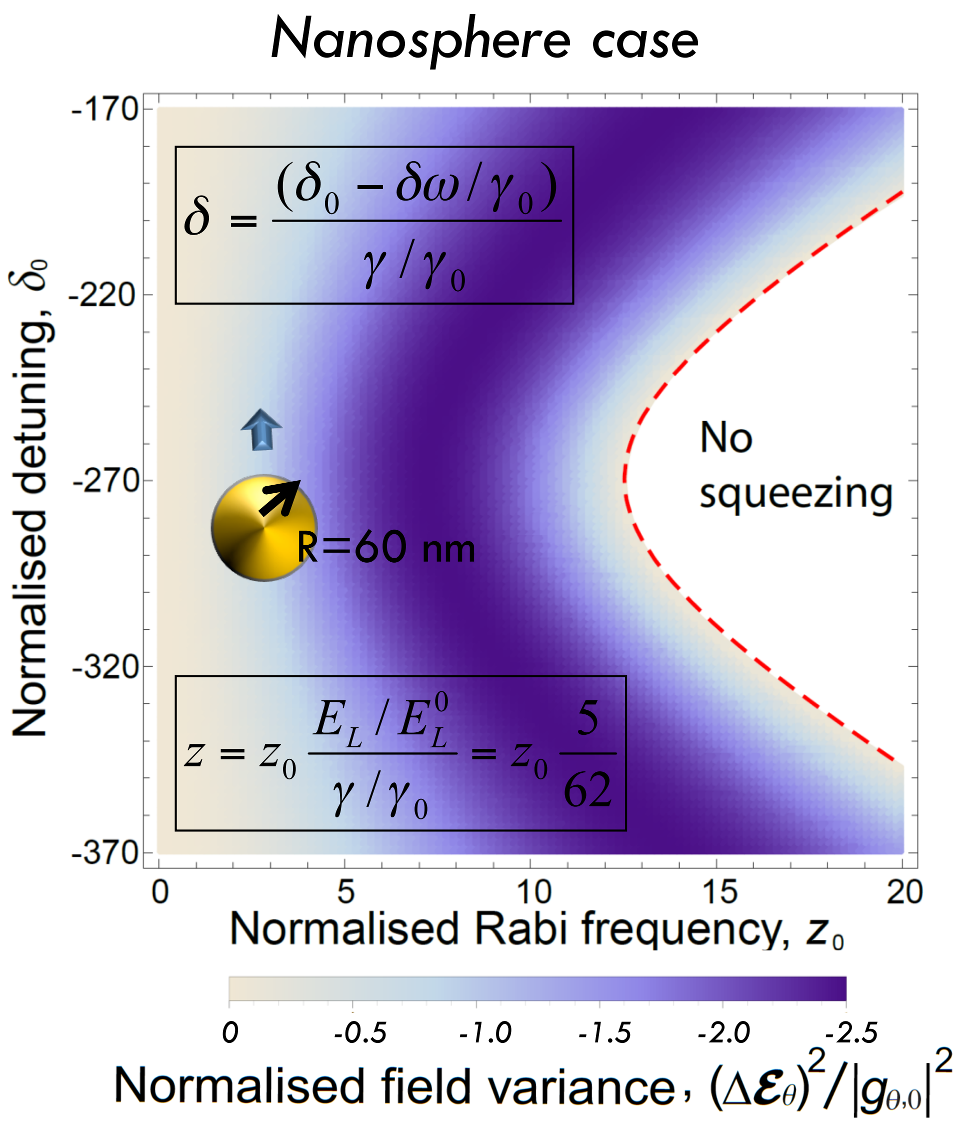
Normalized Rabi freq. $z = \sqrt{2}|\Omega| / \gamma$

Normalized detuning $\delta = 2\delta_L / \gamma$

The effective driving field should be sufficiently weak to generate squeezed light

Free space versus nanoparticle





Wider range of detuning and driving conditions generating squeezed light

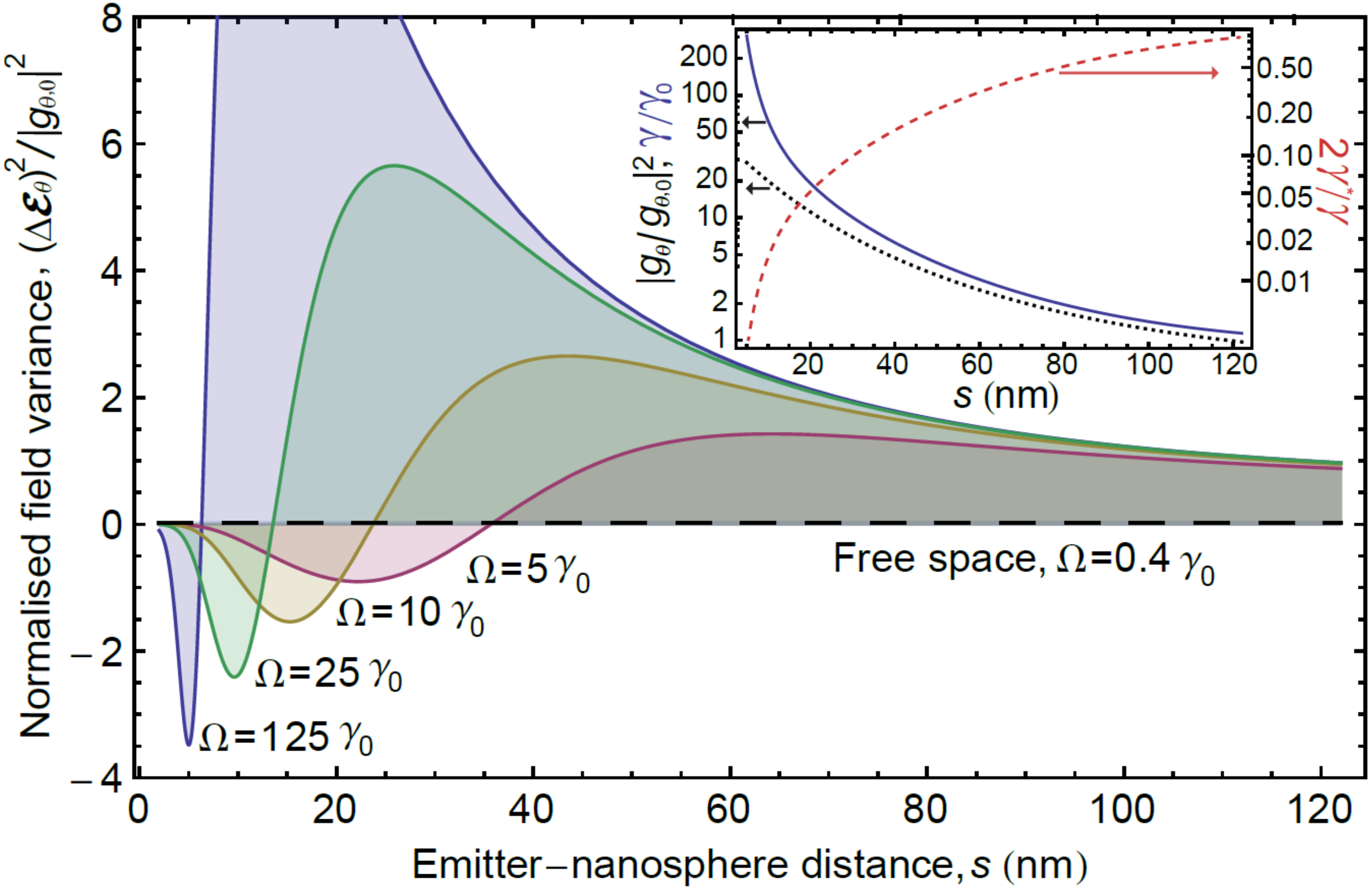
The role of dephasing

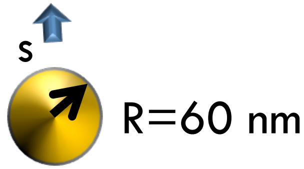
$$\langle : [\Delta\hat{\sigma}_{\phi_i}]^2(t) : \rangle < 0$$

$$z^2 \leq \left(1+\delta^2\right)\left(\frac{1-x}{1+x}\right) \rightarrow x = \frac{2\gamma^*}{\gamma} < 1 \rightarrow \gamma > 2\gamma^*$$

The emitter should be partially coherent in order to generate squeezed light

The role of a nanostructure



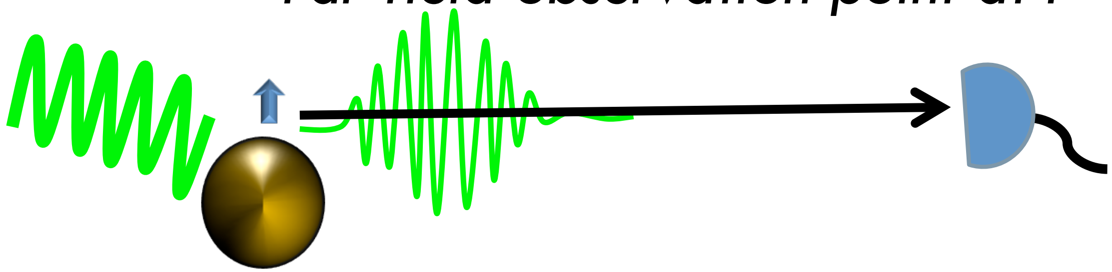


$2\gamma^*=\gamma_0$

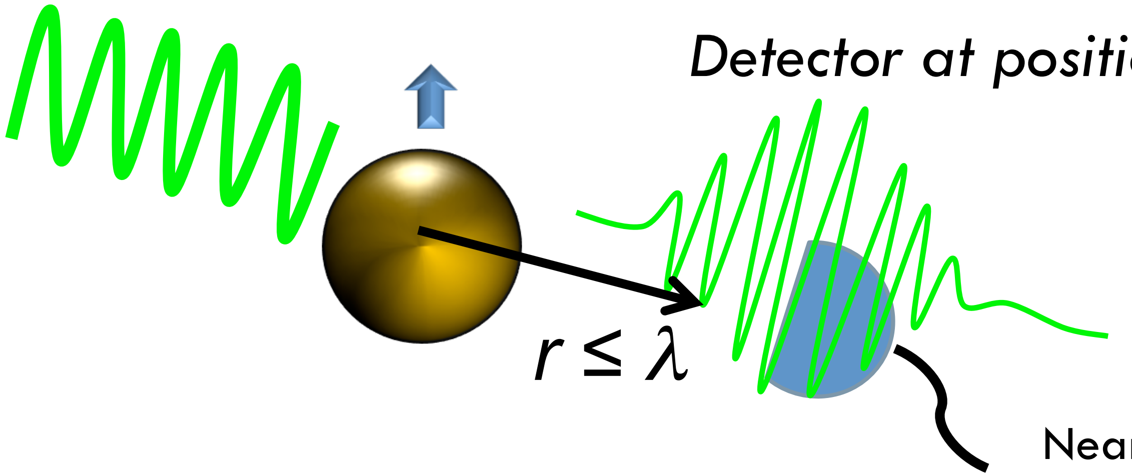
A nanostructure may assist the creation squeezed light in emitters, which do not generate squeezing in free space

Squeezing in the near field

Far-field observation point at r >> λ

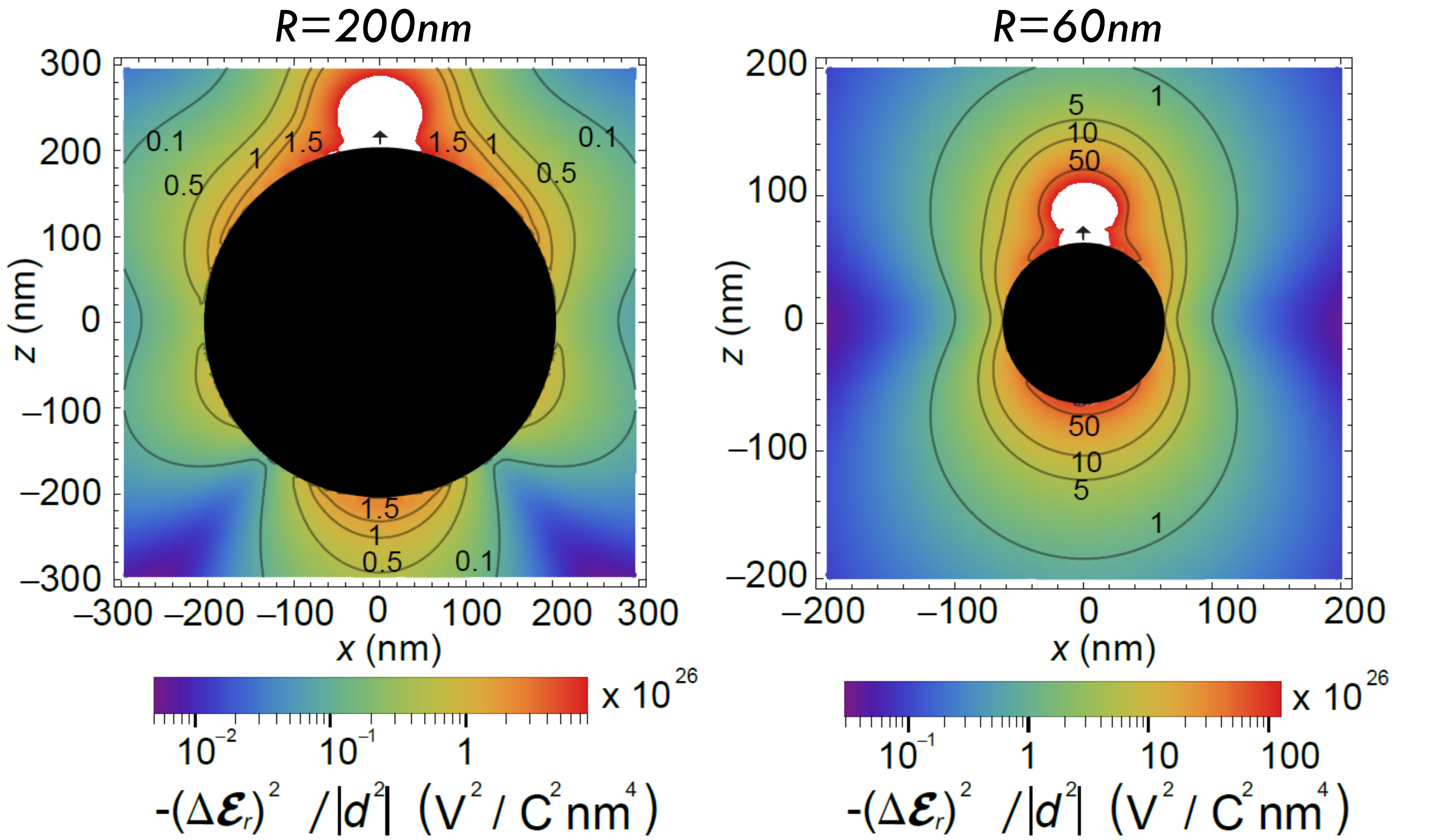


Sub-λ near fields: further enhance and manipulate squeezing



Near field microscopy (SNOM, etc…)

Near field maximum degree of squeezing



A factor 30 larger for the small nanoshere compared to the large one, and 10^9 respect to the far field case

Conclusions

- QE & nanostructures: nanoscale source of squeezed light
- Significantly enhance the degree of squeezing with respect to free space
- Increase driving and detuning boundaries for generating squeezing
- Overcome the effect of pure dephasing
- Extend the control of squeezed light at the nanoscale

Diego Martín Cano, Harald R. Haakh, Karim Murr, Mario Agio
"Large suppression of quantum fluctuations of light from a single emitter by an optical nanostr."
Phys. Rev. Lett. 113, 263605 (2014)

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Diego Martin Cano

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Karim Murr

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