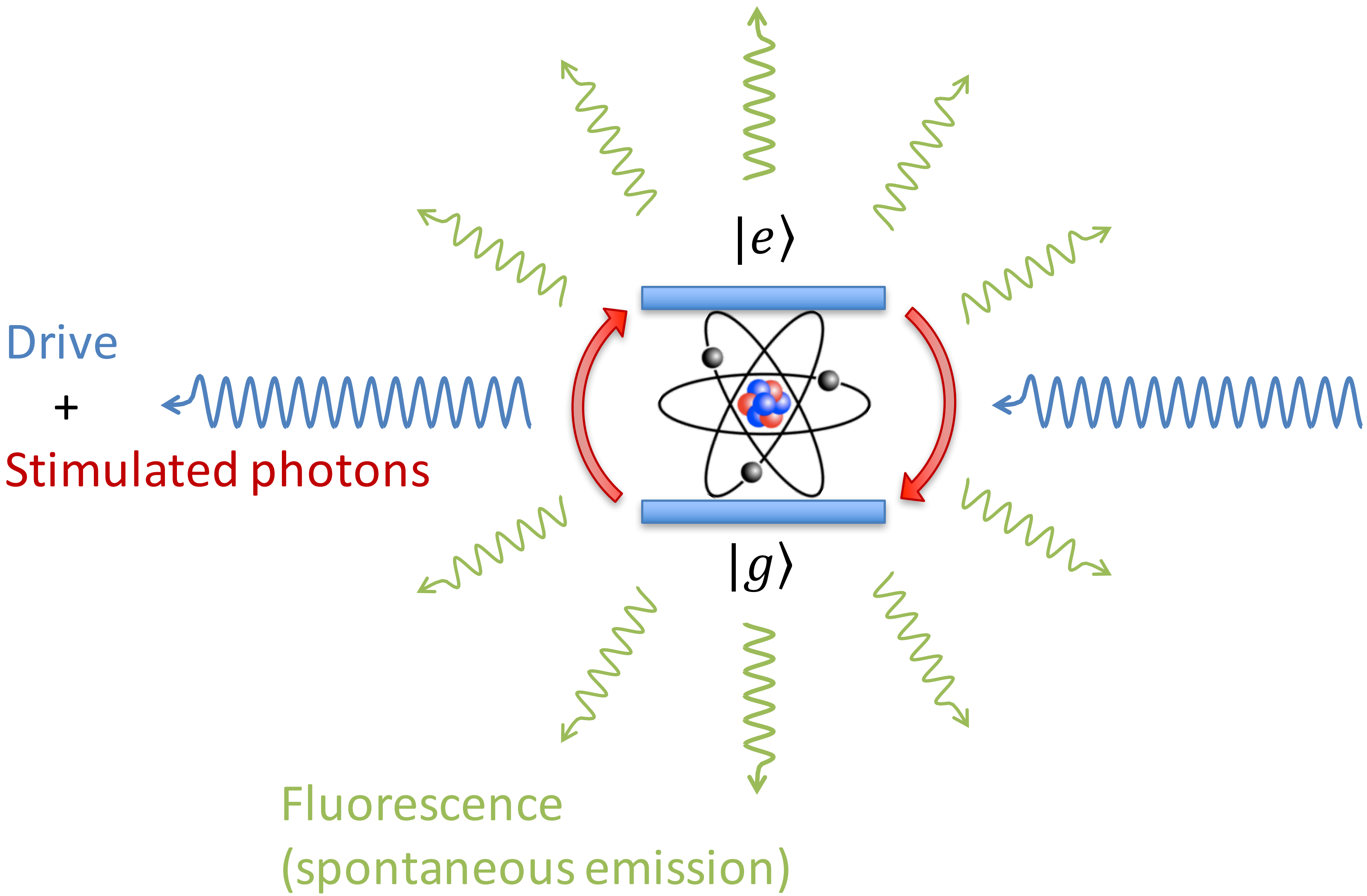
STIMULATED EMISSION AND MICROWAVE ROUTER WITH A SUPERCONDUCTING QUBIT

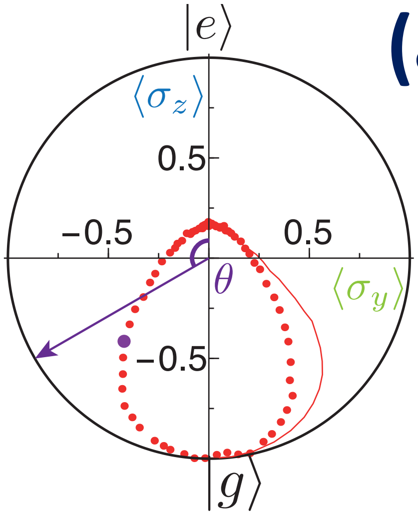
Sébastien Jezouin

Quantum Electronics Group
CNRS – Ecole Normale Supérieure, Paris, France

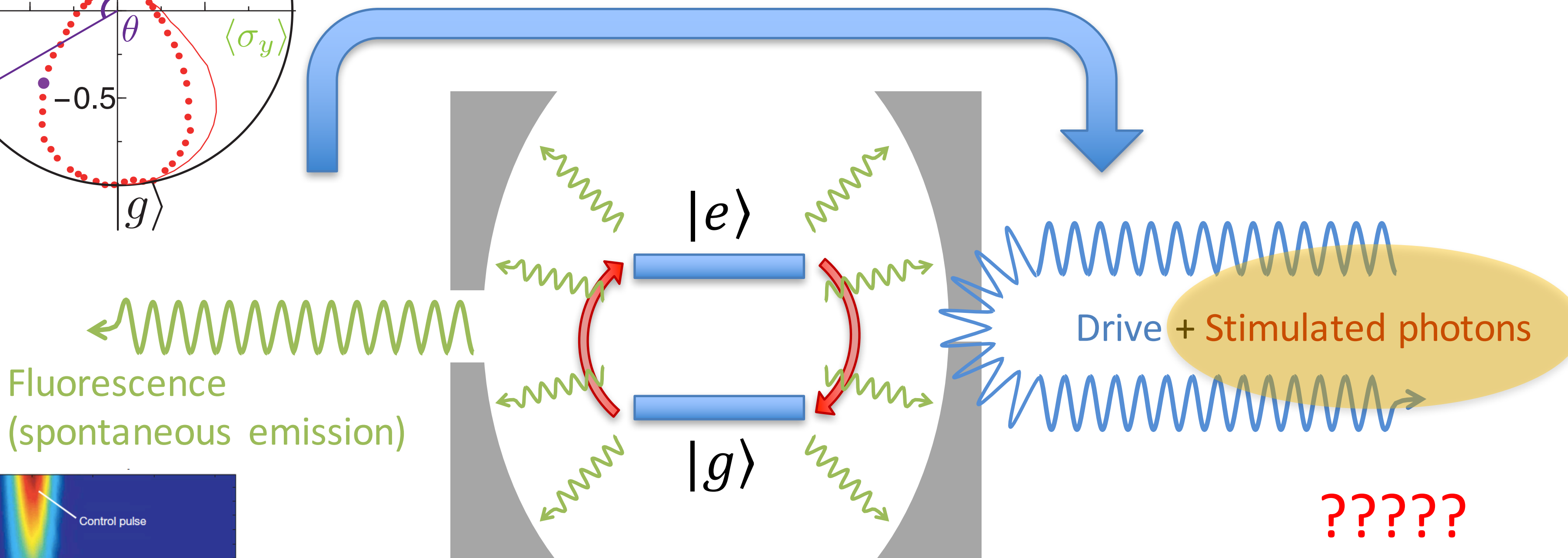
RESONANT EXCITATION OF AN ATOM



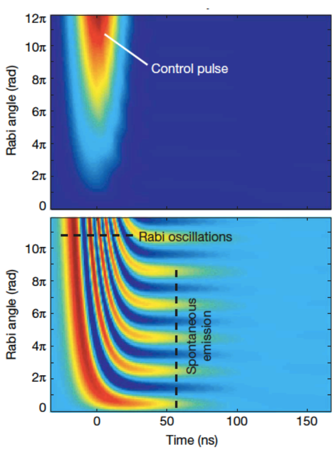
RESONANT EXCITATION OF AN (artificial) ATOM in CAVITY QED



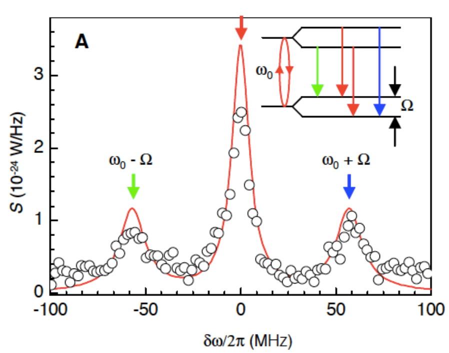
Campagne, Jezouin PRL 2016



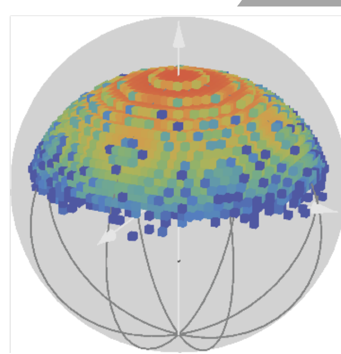
?????



Houck, Nature 2007

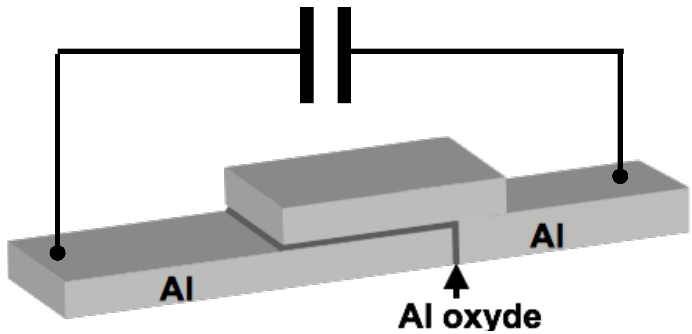


Astafiev, Science 2010

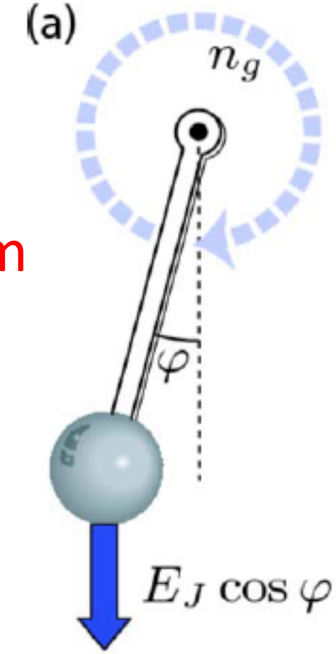


Campagne, PRX 2016

SUPERCONDUCTING (TRANSMON) QUBIT



Quantum Rotor



Josephson junction

with large capacitive shunt

$$\hat{H} = 4E_c(\hat{n} - n_g)^2 - E_J \cos \hat{\varphi}$$

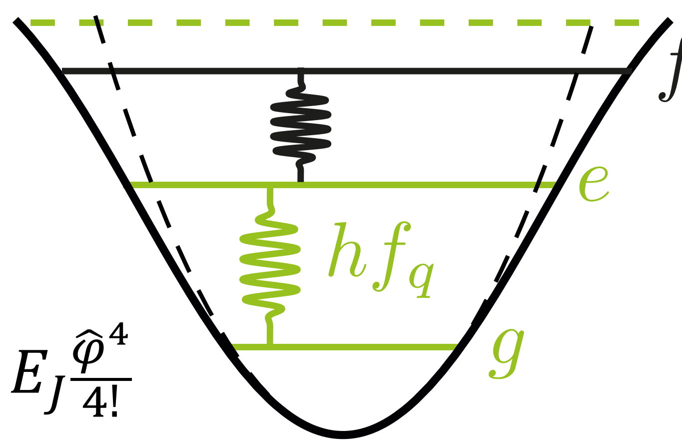
Charging energy $e^2/2C$

Number of Cooper pairs

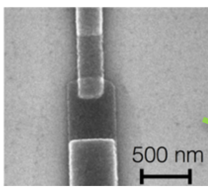
Supercondu-cting phase

$$\boxed{E_J \gg E_c}$$

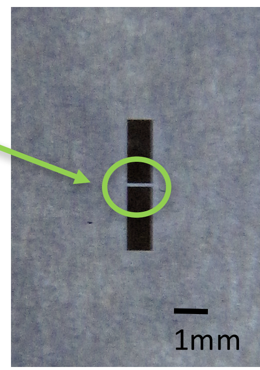
$$\hat{H} \approx 4E_c \hat{n}^2 + E_J \frac{\hat{\varphi}^2}{2} - E_J \frac{\hat{\varphi}^4}{4!}$$



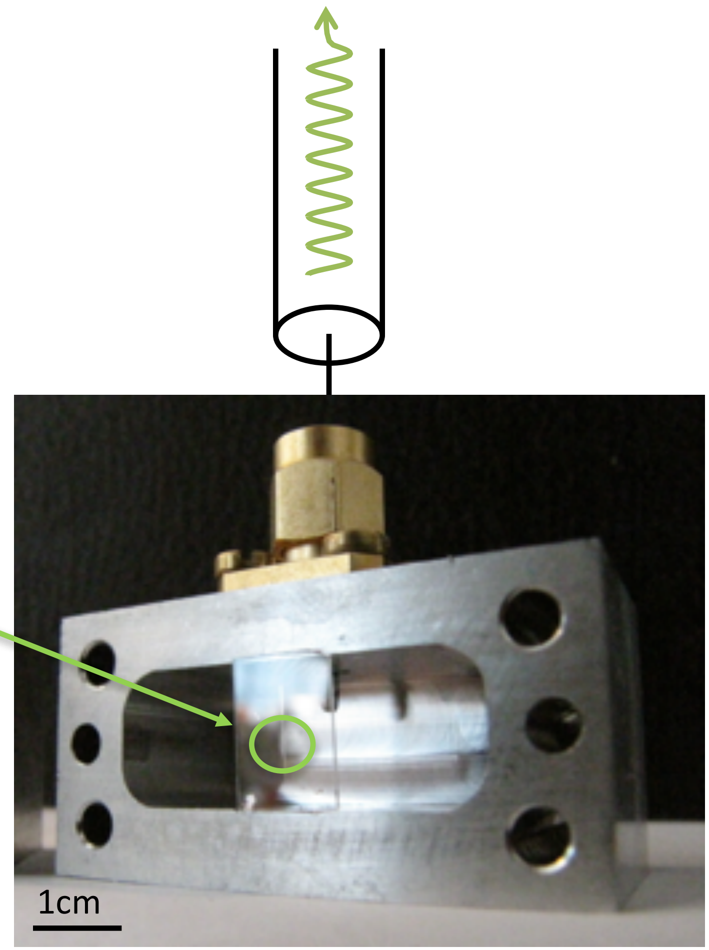
3D TRANSMON QUBIT



Non-linear,
lossless
element…



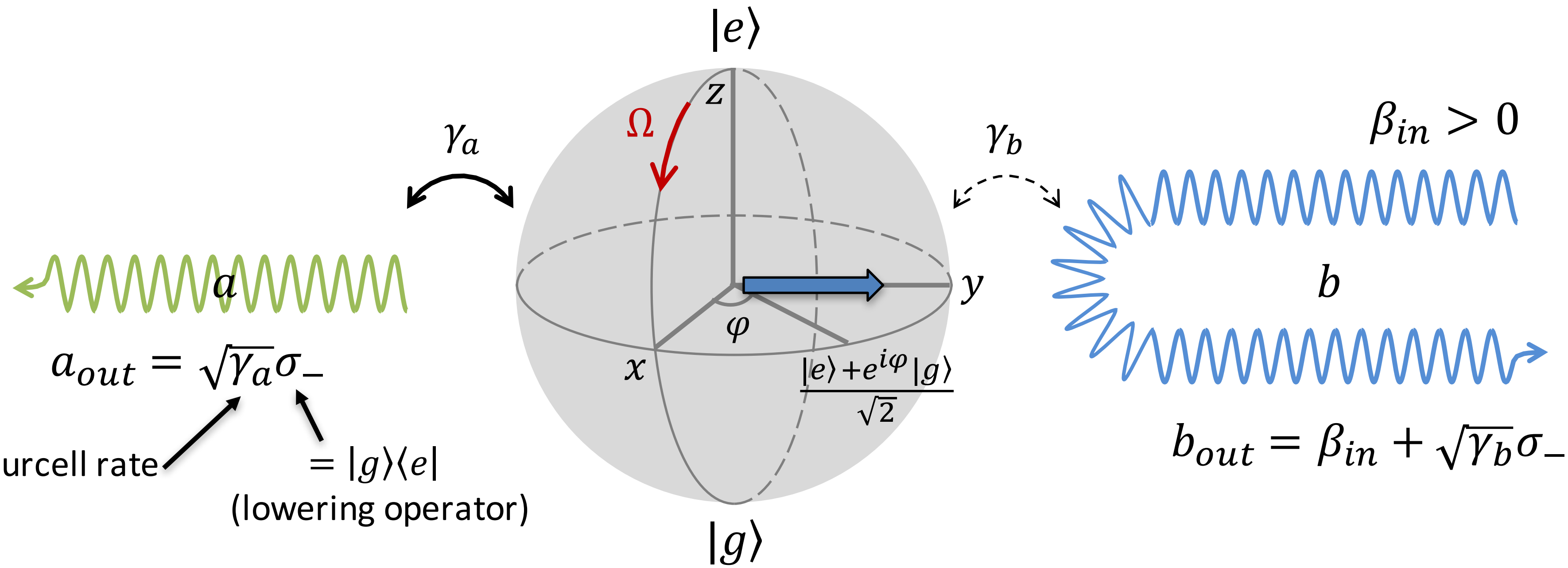
…strongly
(dipole) coupled…



… to a 3D cavity resonant mode

f_q = 7.09 GHz
f_c = 7.91 GHz
χ = 33 MHz
κ = 0.77 MHz
T_1 = 1.95 μs
T_2 = 2.95 μs

MEASURING THE STIMULATED PHOTONS ?



THE NOISE IS THE SIGNAL !

$$\langle a_{out}^+ a_{out}\rangle = \gamma_a \langle \sigma_+ \sigma_- \rangle$$

$$= \gamma_a \frac{1 + z(t)}{2}$$

Spontaneous emission

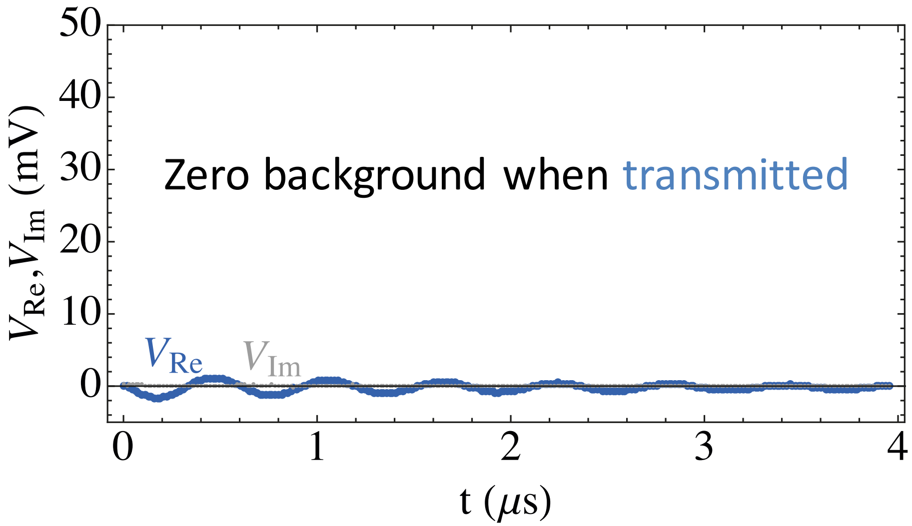
$$\langle b_{out}^+ b_{out}\rangle = \beta_{in}^2 + \gamma_b \langle \sigma_+ \sigma_- \rangle + 2\sqrt{\gamma_b}\beta_{in}\mathrm{Re}\langle \sigma_- \rangle$$

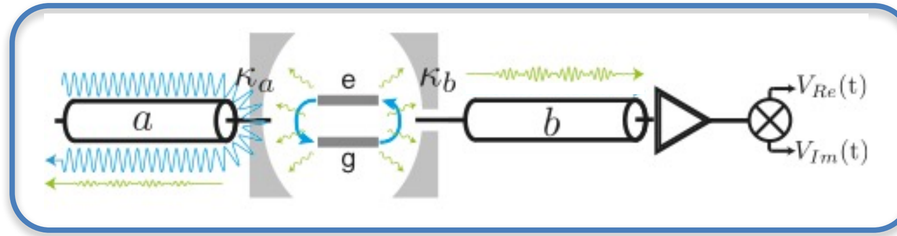
$$= \beta_{in}^2 + \gamma_b \frac{1 + z}{2} + \frac{\Omega}{2} x$$

Photon flux in the drive

Stimulated emission

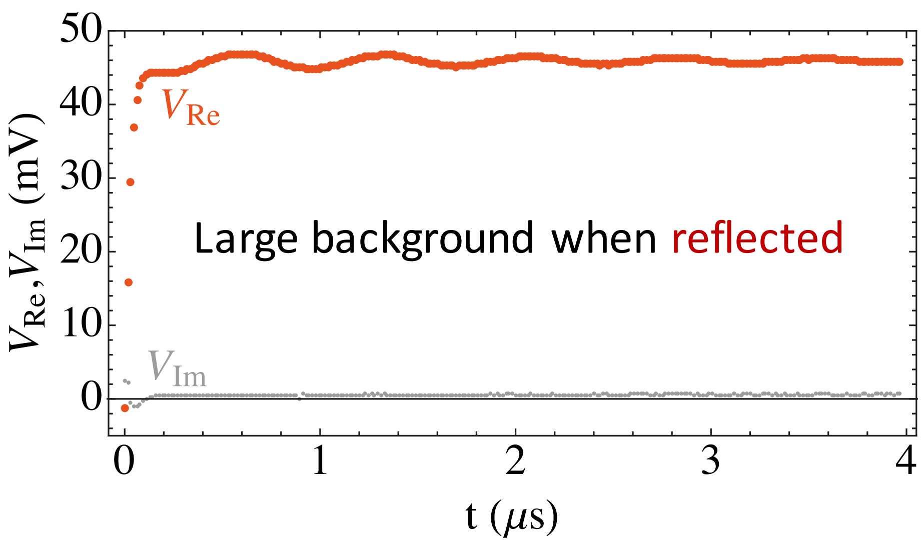
HETERODYNE MEASUREMENT

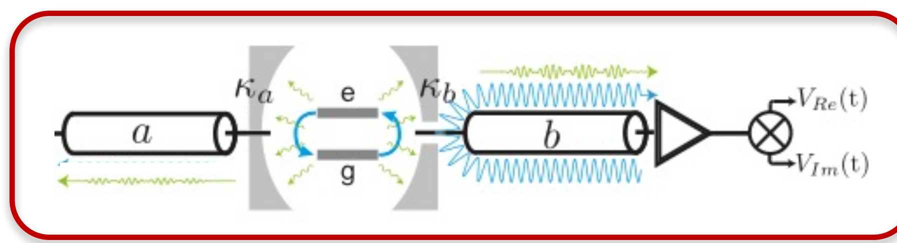




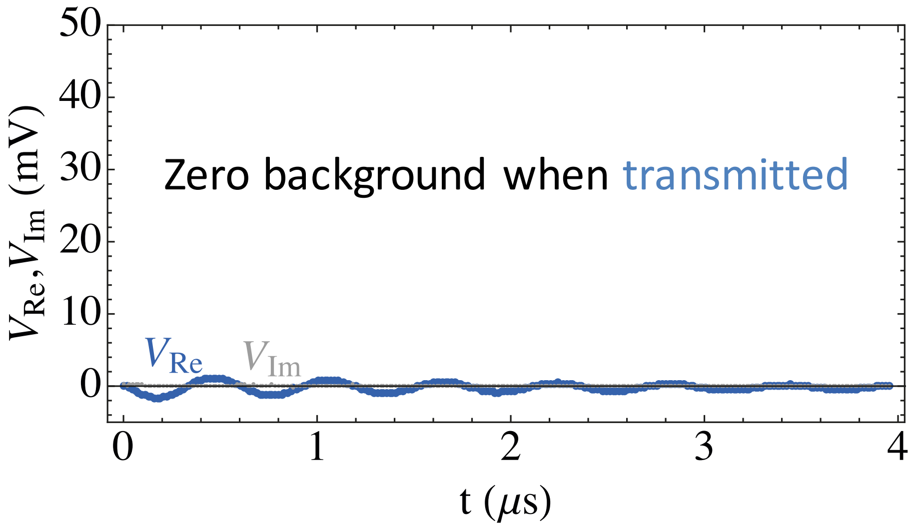
$$\langle b_{out} \rangle \propto \overline{V_{\mathrm{Re}}} + i\overline{V_{\mathrm{Im}}}$$

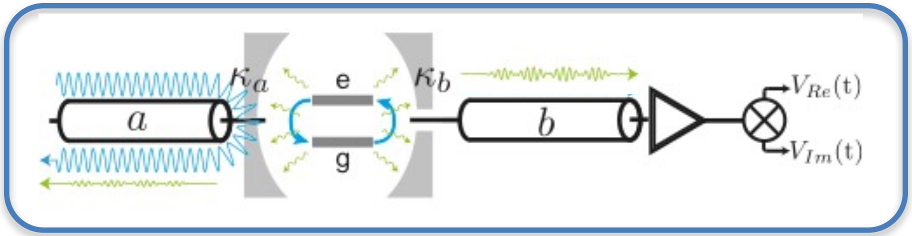
$$\langle b_{out} \rangle = \beta_{in} + \frac{\sqrt{\gamma_b}}{2} x(t)$$

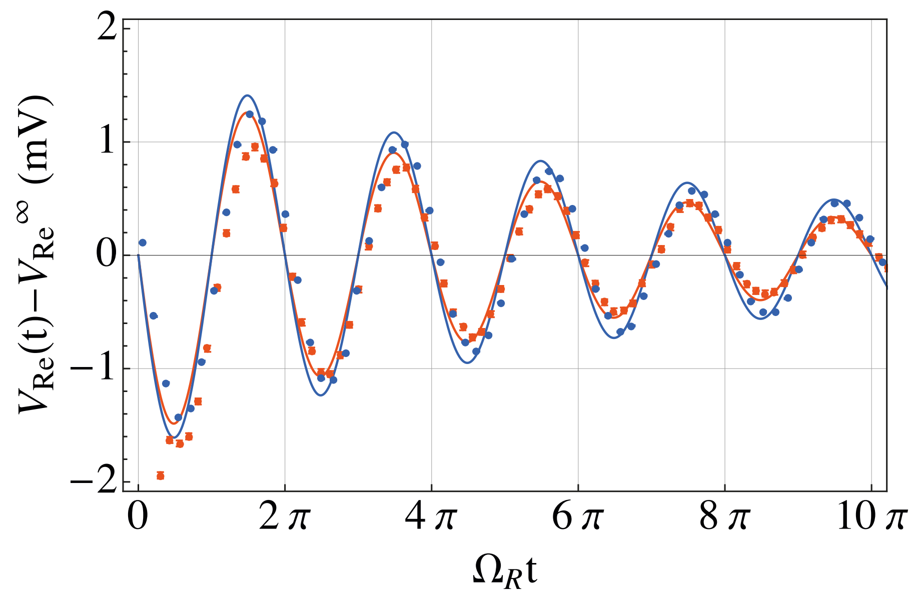


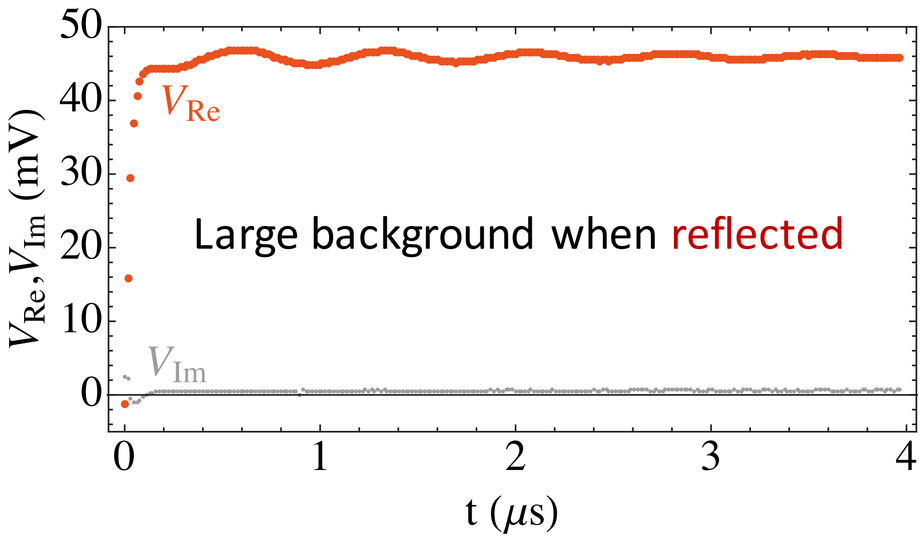


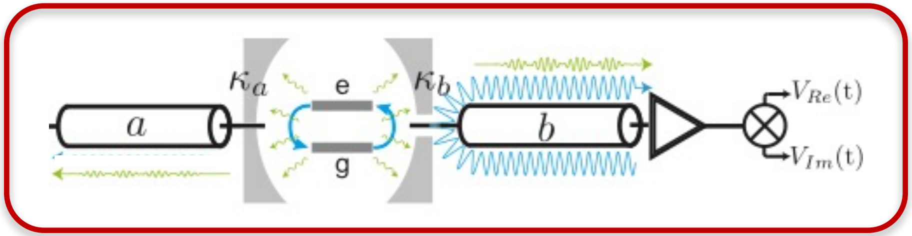
HETERODYNE MEASUREMENT



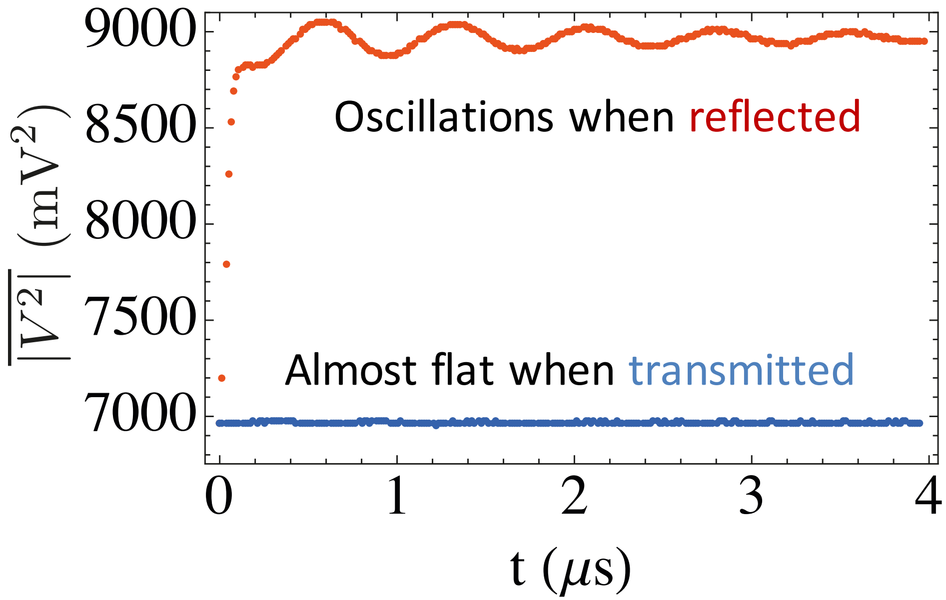


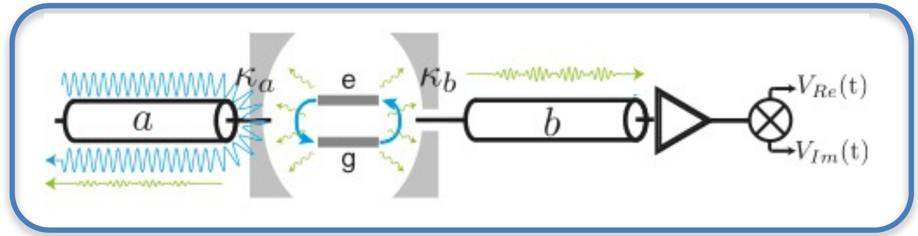






PHOTON RATE MEASUREMENT

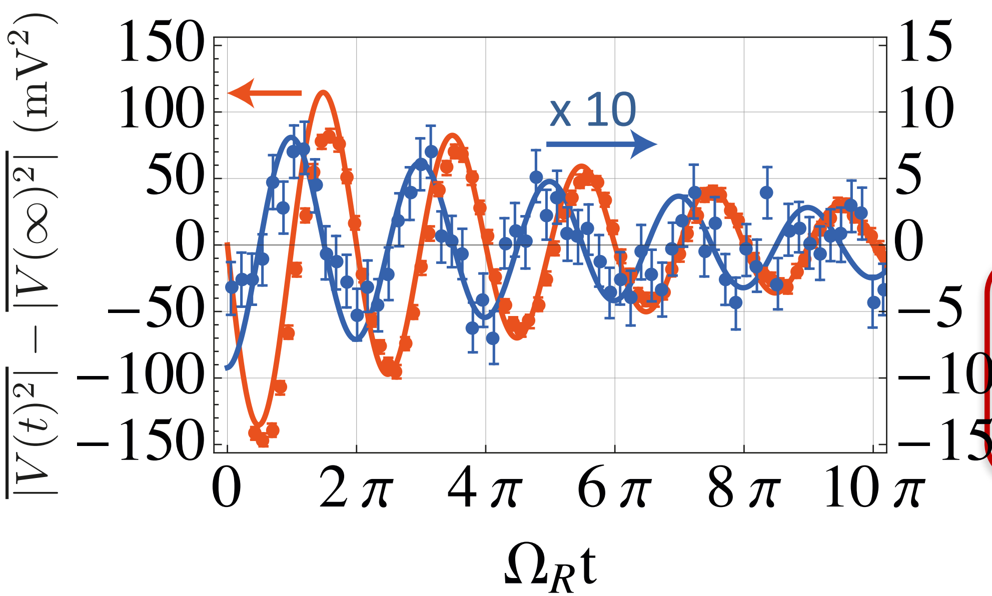


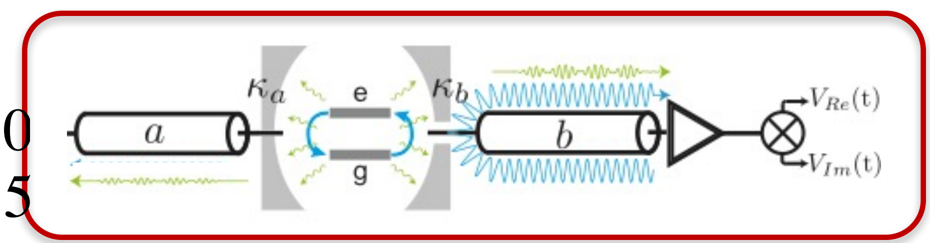


$$\langle b_{out} \rangle \propto \overline{V_{\mathrm{Re}}} + i\overline{V_{\mathrm{Im}}}$$

$$\langle b_{out}^{+} b_{out} \rangle \propto \overline{|V|^2} = \overline{V_{\mathrm{Re}}}^2 + \overline{V_{\mathrm{Im}}}^2$$

$$\langle b_{out}^{+} b_{out} \rangle = \beta_{in}^2 + \gamma_b \frac{1 + z(t)}{2} + \frac{\Omega}{2} x(t)$$



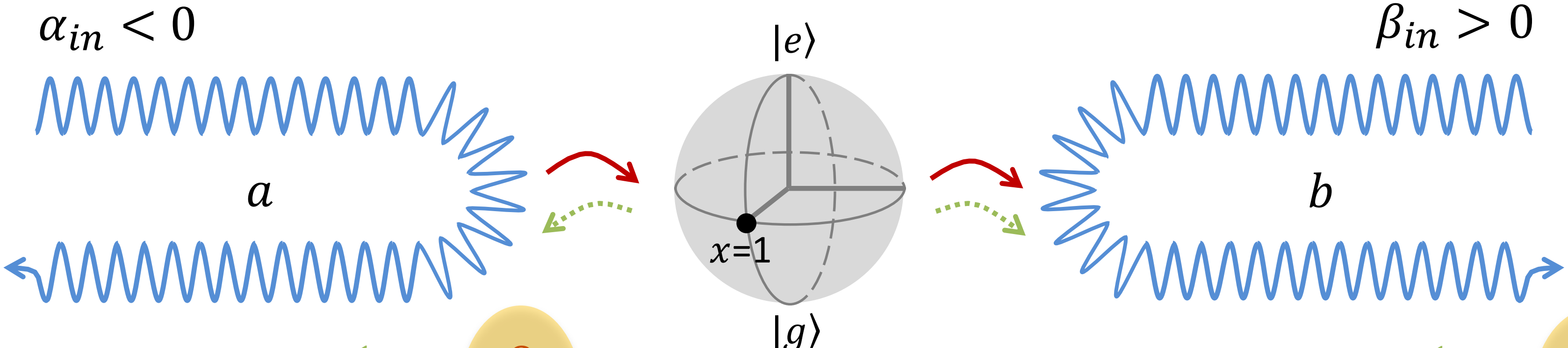


ENERGY TRANSFER ACROSS THE QUBIT

Add a 2nd drive to freeze the qubit

$$\sqrt{\gamma_a}\alpha_{in} + \sqrt{\gamma_b}\beta_{in} = 0$$

$\alpha_{in} < 0$ $\beta_{in} > 0$



$$\langle a_{out}^{+} a_{out} \rangle = \alpha_{in}^{2} + \gamma_a \frac{1+z}{2} - \frac{\Omega}{2} x$$

$$\langle b_{out}^{+} b_{out} \rangle = \beta_{in}^{2} + \gamma_b \frac{1+z}{2} + \frac{\Omega}{2} x$$

Energy transfer from port a to port b, although the local field is zero !

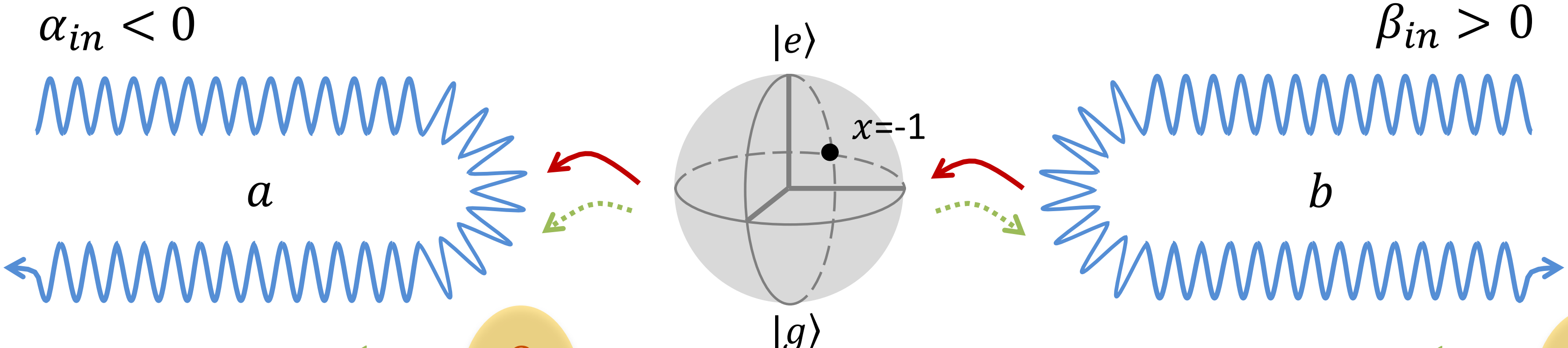
ENERGY TRANSFER ACROSS THE QUBIT

Add a 2nd drive to freeze the qubit

$$\sqrt{\gamma_a}\alpha_{in} + \sqrt{\gamma_b}\beta_{in} = 0$$

$\alpha_{in} < 0$

$\beta_{in} > 0$



$$\langle a_{out}^{+} a_{out} \rangle = \alpha_{in}^2 + \gamma_a \frac{1+z}{2} - \frac{\Omega}{2} x$$

$$\langle b_{out}^{+} b_{out} \rangle = \beta_{in}^2 + \gamma_b \frac{1+z}{2} + \frac{\Omega}{2} x$$

Energy transfer from port a to port b, although the local field is zero !

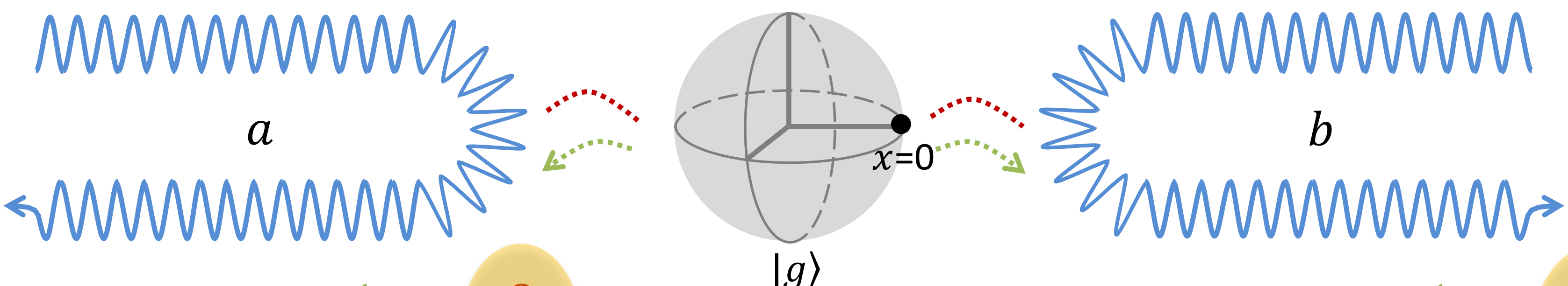
ENERGY TRANSFER ACROSS THE QUBIT

Add a 2nd drive to freeze the qubit

$$\sqrt{\gamma_a}\alpha_{in} + \sqrt{\gamma_b}\beta_{in} = 0$$

$\alpha_{in} < 0$

$\beta_{in} > 0$



$$\langle a_{out}^{+} a_{out} \rangle = \alpha_{in}^2 + \gamma_a \frac{1+z}{2} - \frac{\Omega}{2} x$$

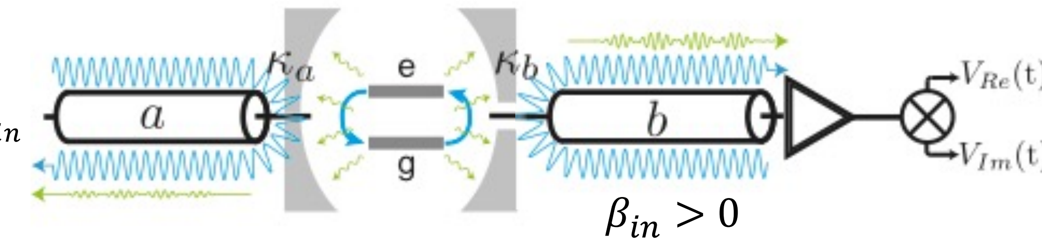
$$\langle b_{out}^{+} b_{out} \rangle = \beta_{in}^2 + \gamma_b \frac{1+z}{2} + \frac{\Omega}{2} x$$

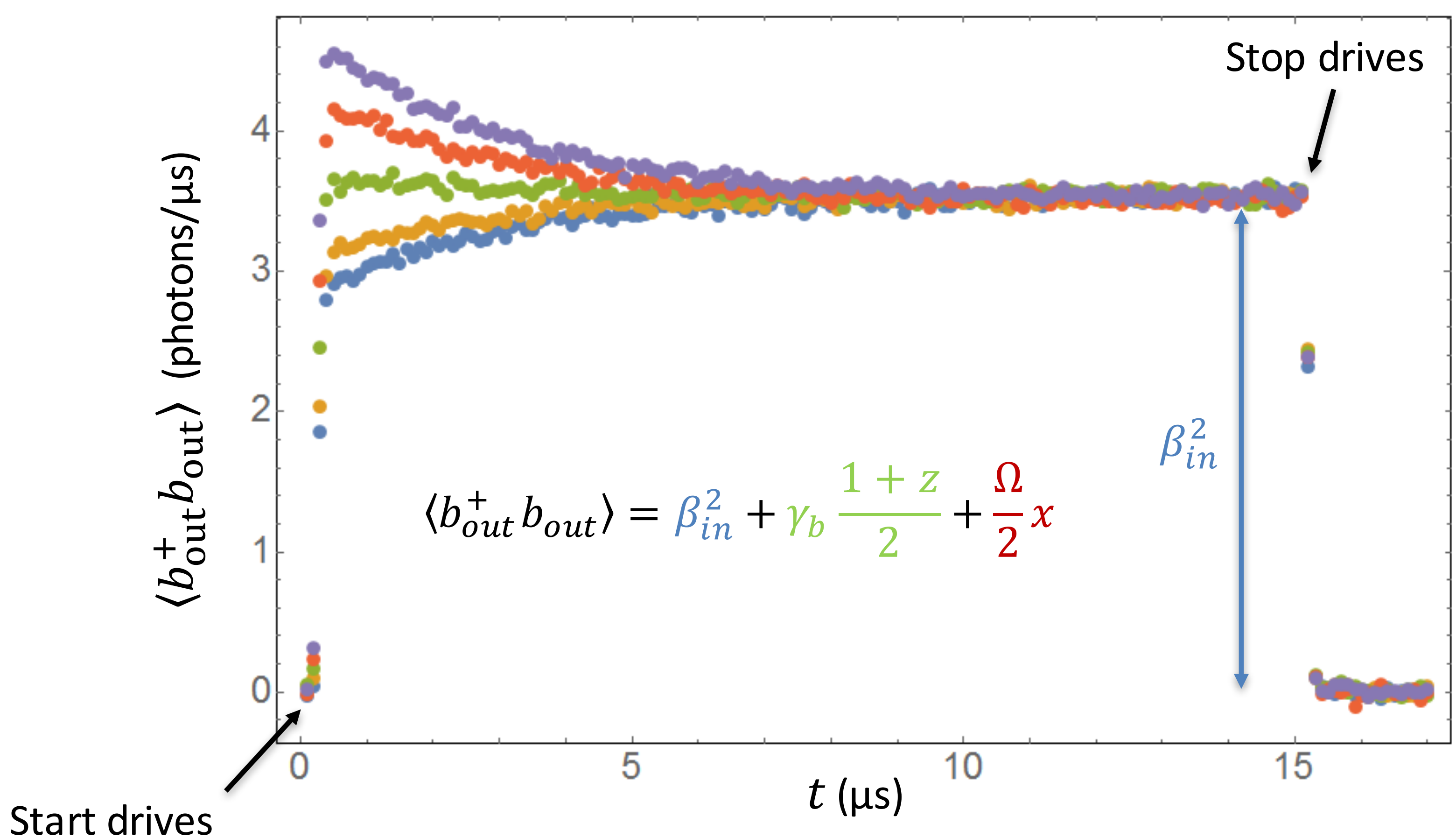
Energy transfer from port a to port b, although the local field is zero !
& phase dependent

PHASE DEPENDENCE OF STIMULATED EMISSION

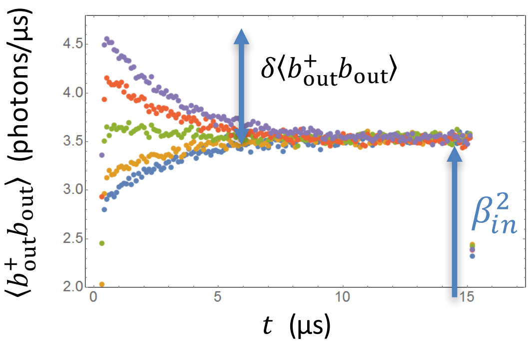
Prepare qubit in
$$\frac{|e\rangle + e^{i\varphi}|g\rangle}{\sqrt{2}}$$

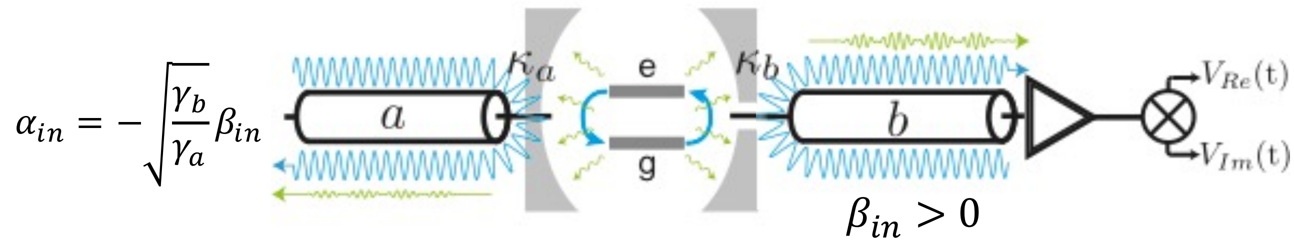
$$\alpha_{in} = -\sqrt{\frac{\gamma_b}{\gamma_a}}\beta_{in}$$

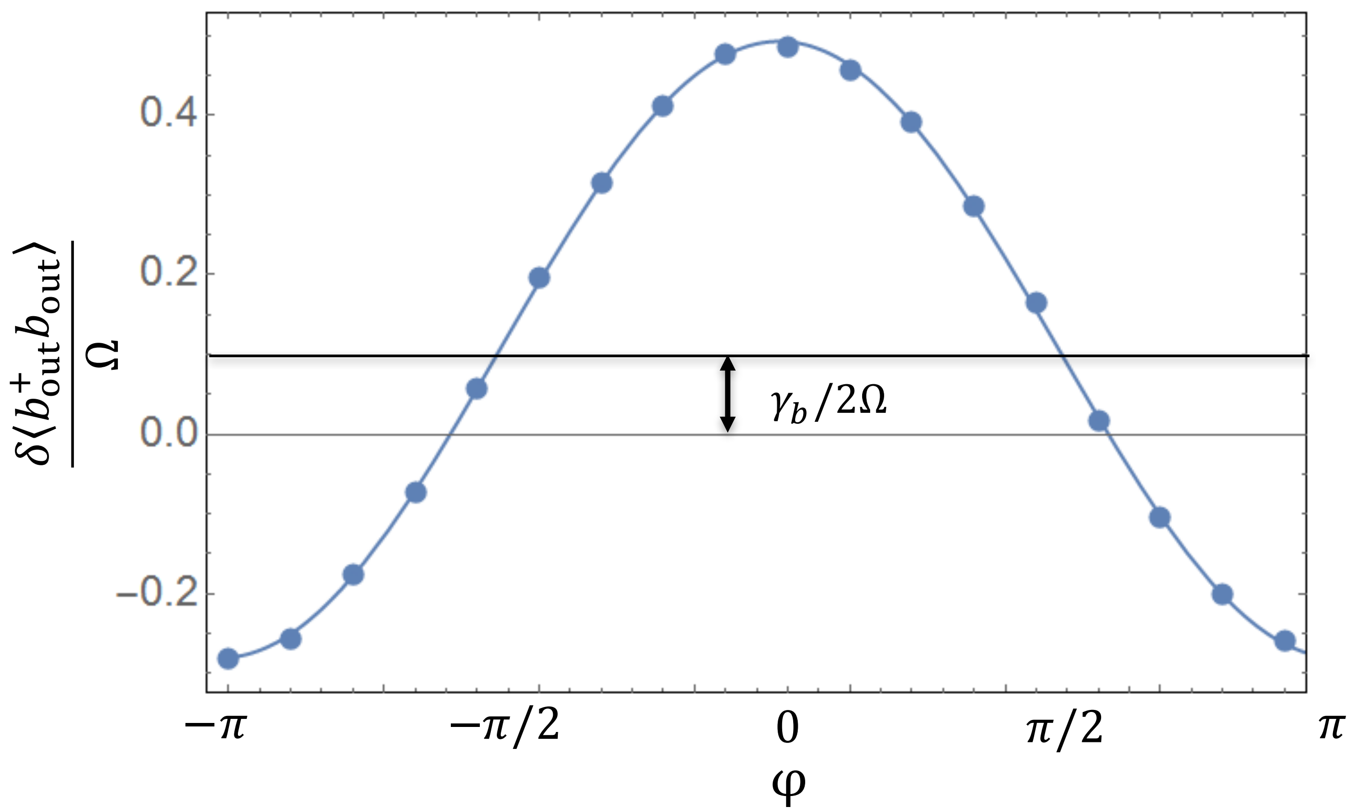




PHASE DEPENDENCE OF STIMULATED EMISSION

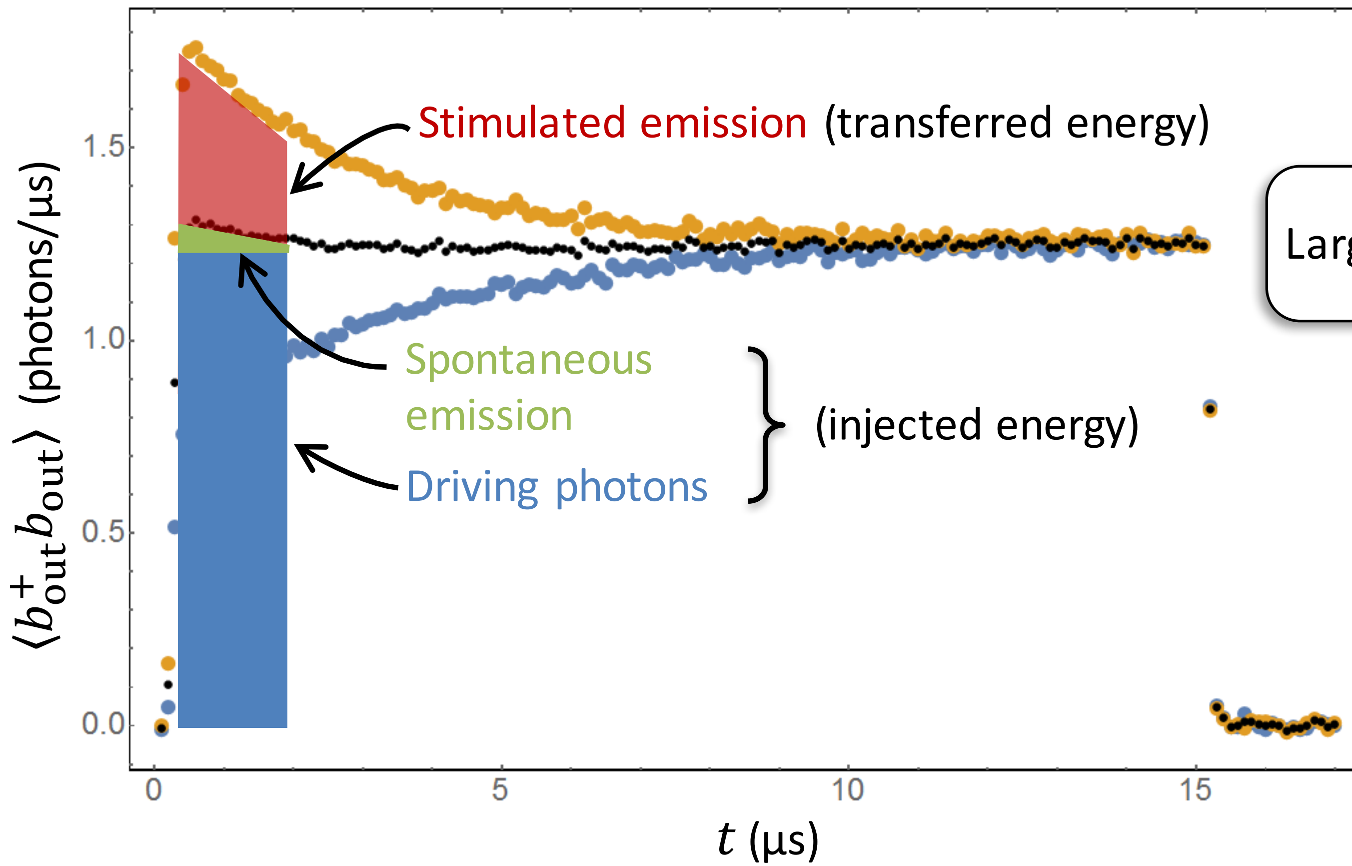






TRANSFERRED vs INJECTED ENERGY

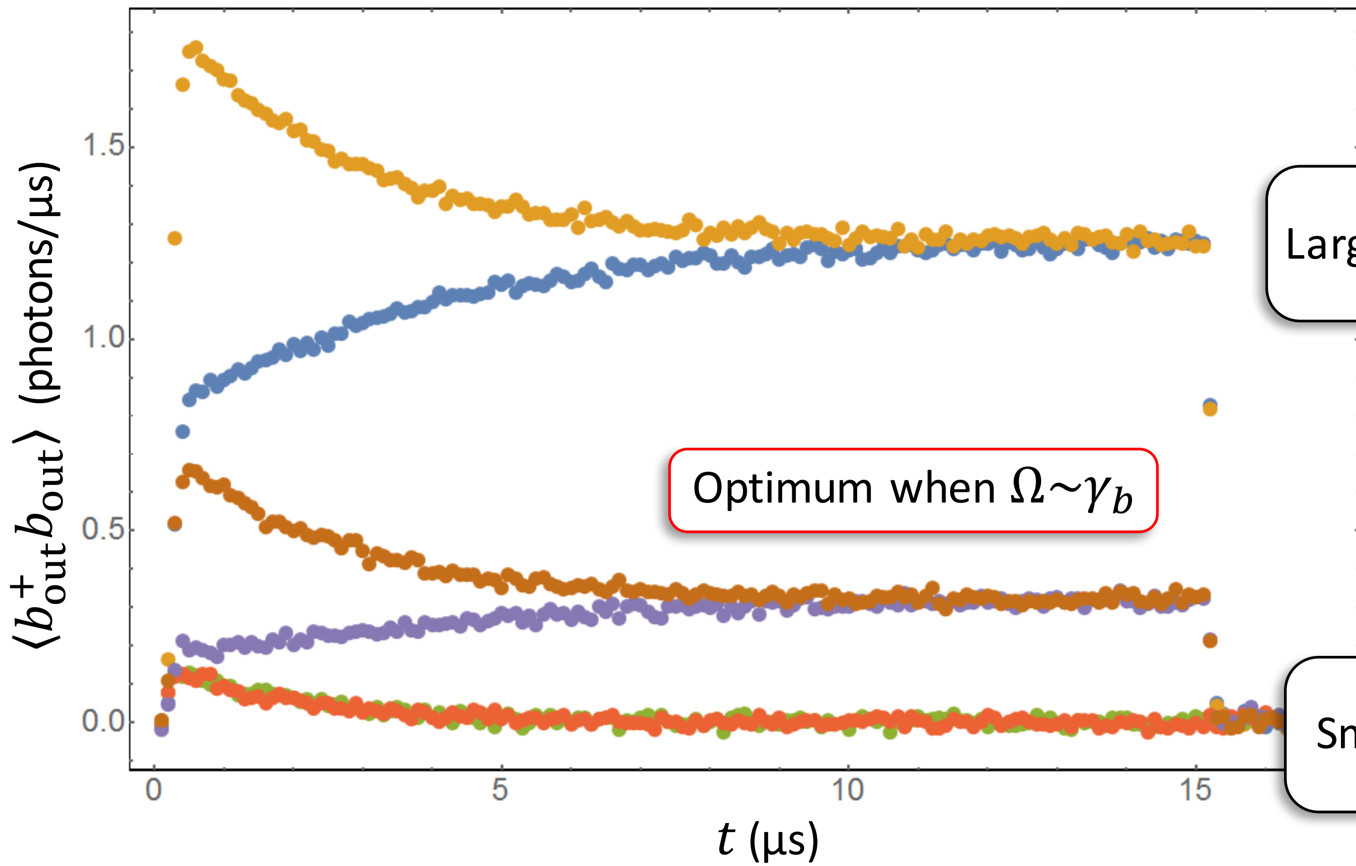
Preparation in : $\frac{|e\rangle \pm |g\rangle}{\sqrt{2}} (x = \pm 1)$ $\Rightarrow$ $\langle b_{out}^{+} b_{out} \rangle_{\pm} = \beta_{in}^2 + \gamma_b \frac{1+z}{2} \pm \frac{\Omega}{2} x$



Large Ω : $\frac{\Omega}{\beta_{in}^2} \to 0$

TRANSFERRED vs INJECTED ENERGY

Preparation in : $\frac{|e\rangle \pm |g\rangle}{\sqrt{2}}(x = \pm 1)$ $\Rightarrow$ $\langle b_{out}^{+} b_{out} \rangle_{\pm} = \beta_{in}^{2} + \gamma_b \frac{1+z}{2} \pm \frac{\Omega}{2} x$



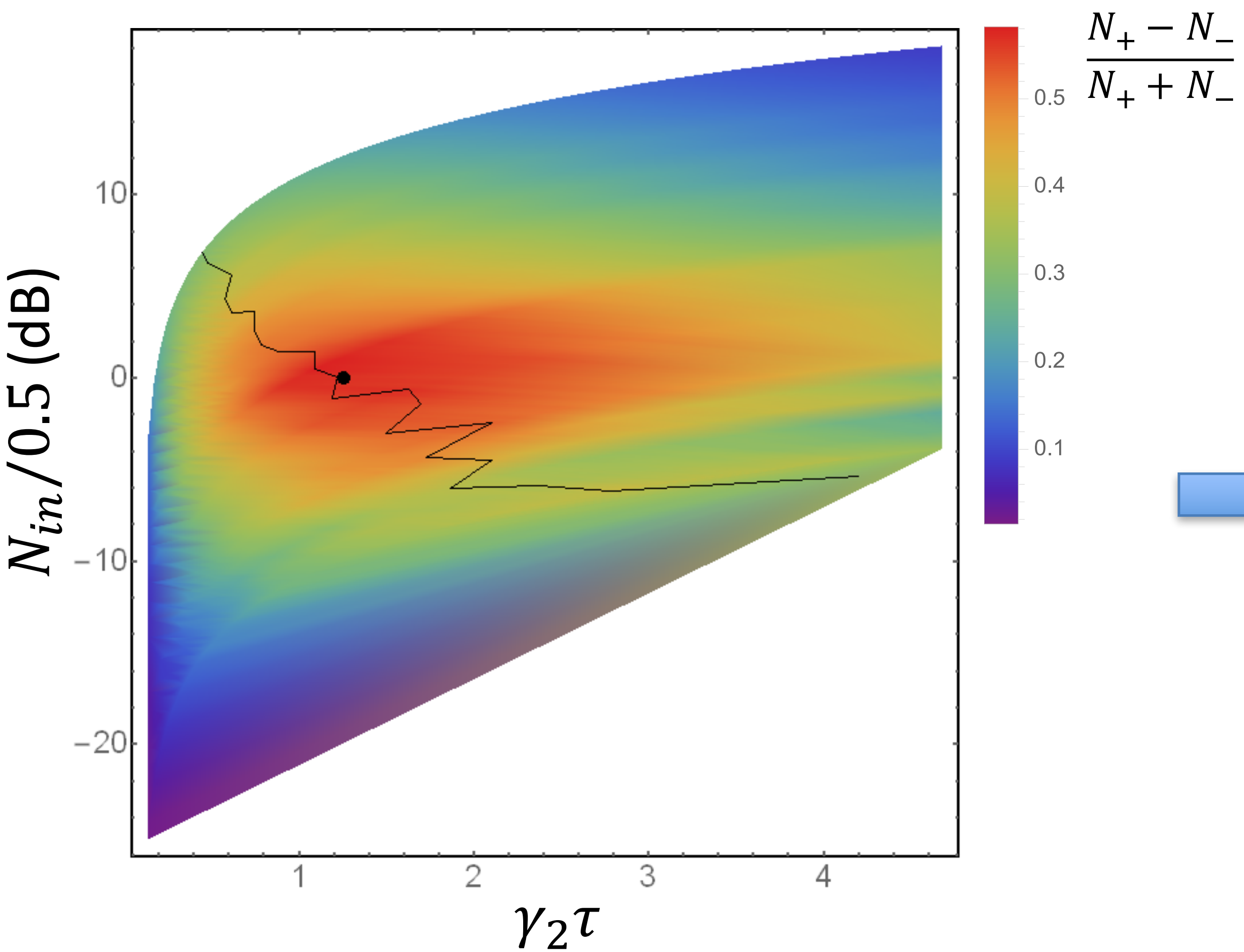
Large Ω : $\frac{\Omega}{\beta_{in}^{2}} \to 0$

Small Ω : $\frac{\Omega}{\gamma_b} \to 0$

ENERGY TRANSFER CONTRAST

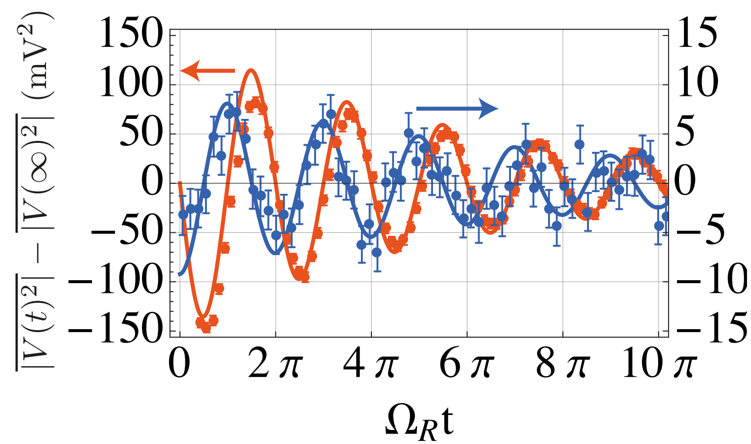
Drive during time τ and measure $N_{\pm} = \int_{-\infty}^{+\infty} \langle b_{out}^{+} b_{out} \rangle_{\pm}(t)\mathrm{d}t$

$$\langle b_{out}^{+} b_{out} \rangle_{\pm} = \beta_{in}^{2} + \gamma_b \frac{1+z}{2} \pm \frac{\Omega}{2} x$$



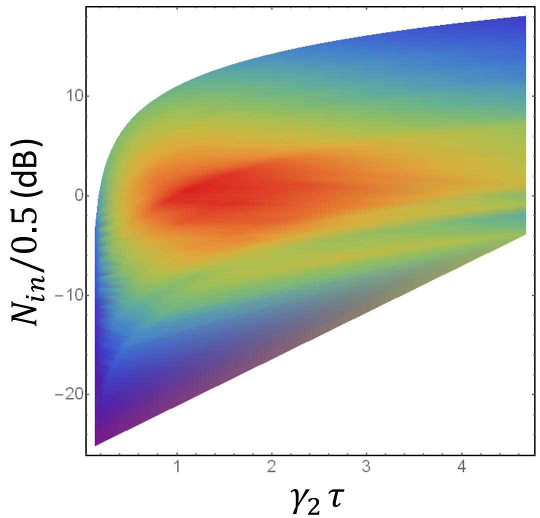
Up to 57%
(55% predicted)
of the drive energy
is transmitted

CONCLUSION



✓ The noise is the signal !

✓ Interplay between absorption & stimulated emission of different modes



- What about correlations in between those modes ?

- What about non-classical states ?

THANKS !

Philippe Campagne-Ibarcq (now CEA Saclay)

Institut Néel

Bogdan Reznychenko

Alexia Auffèves

Quantic - Theory

Pierre Six

Joachim Cohen

Rémi Azouit

Mazyar Mirrahimi

Pierre Rouchon

Alain Sarlette

MAIRIE DE PARIS

Agence Nationale de la Recherche ANR GIP

PSL RESEARCH UNIVERSITY