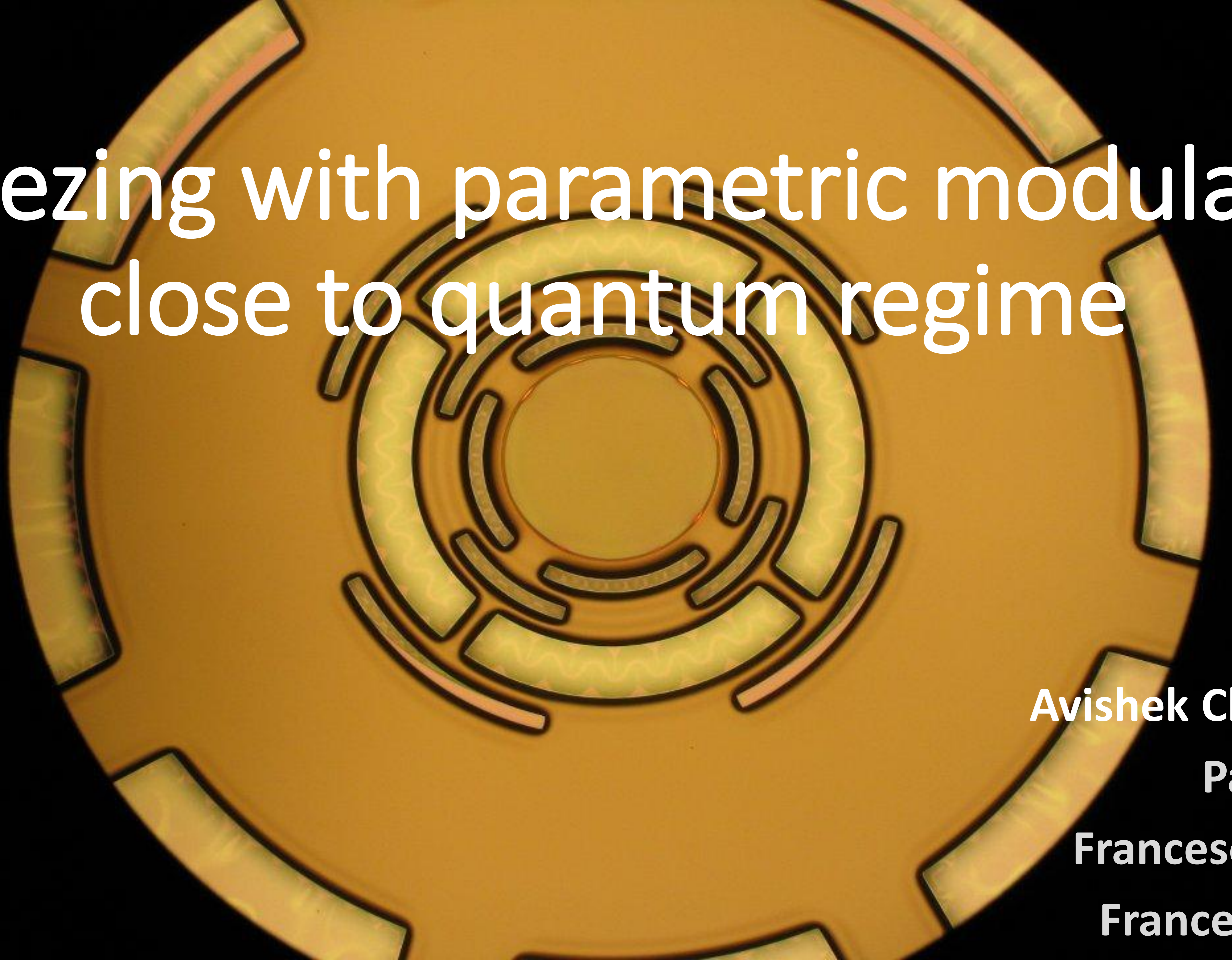
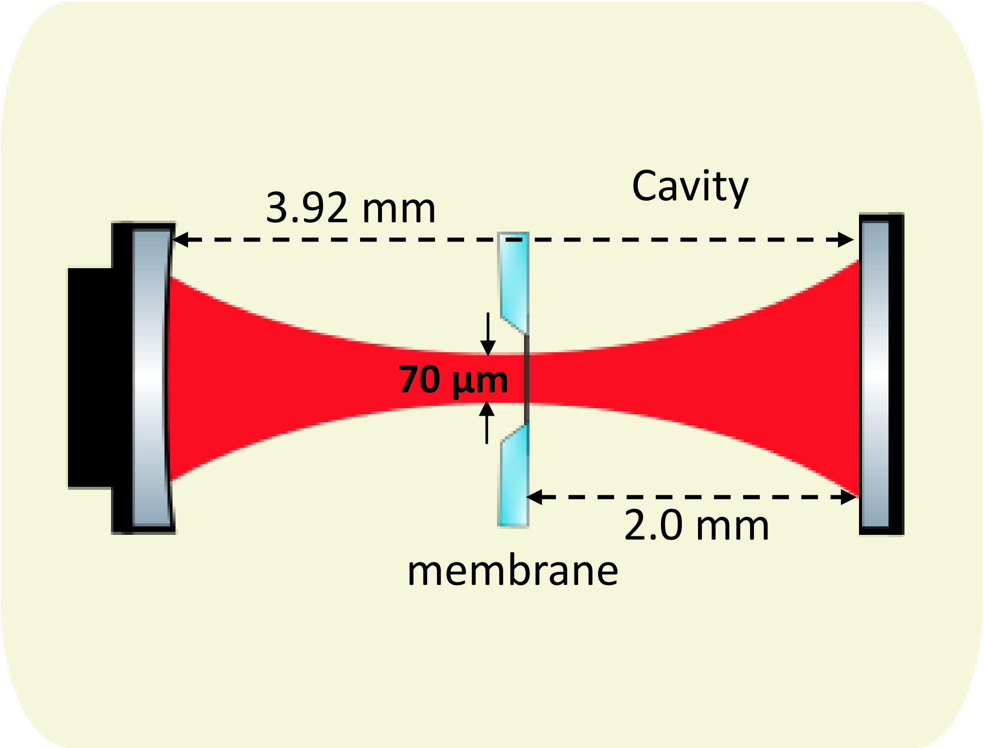
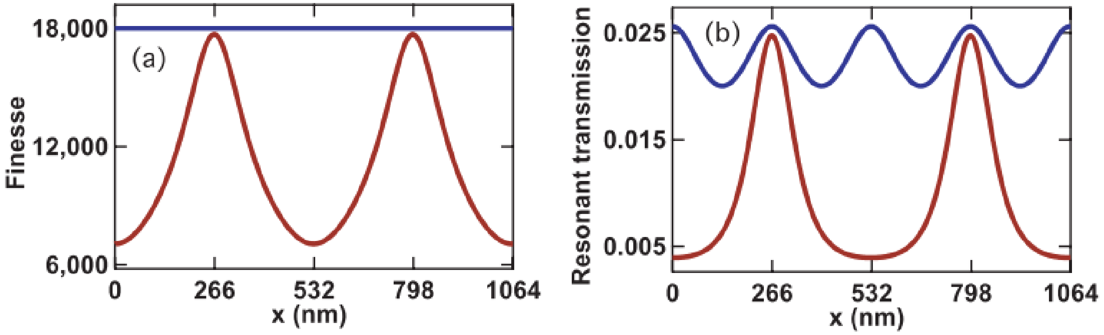


Squeezing with parametric modulation close to quantum regime

Avishek Chowdhury
Paolo Vezio
Francesco Marino
Francesco Marin

Cavity opto-mechanics: membrane in the middle



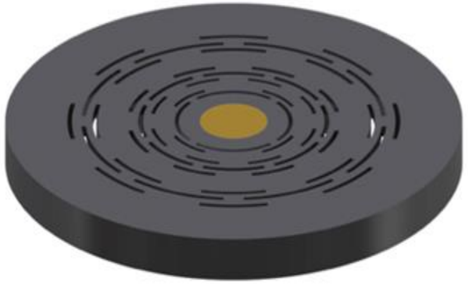


Jayich et al. NJP 10 (2008) 095008

Tunable finesse as a function of the membrane position

Cavity:

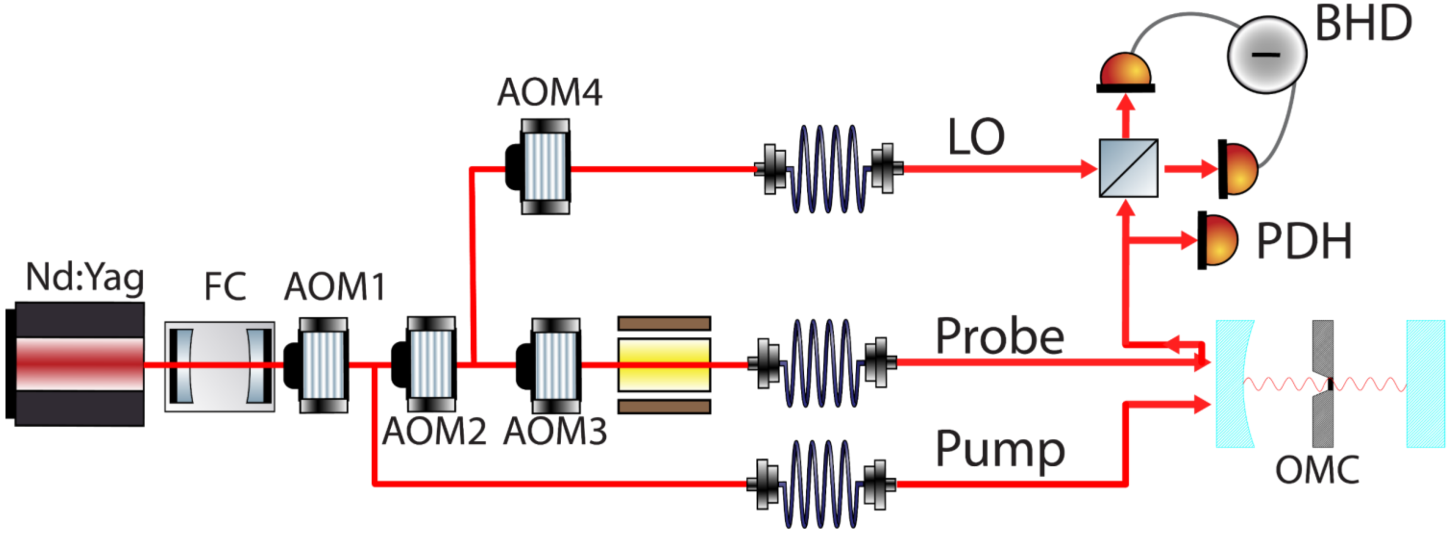
- Finesse ~ *20,000*
- Cavity linewidth ~ *1.9 MHz*

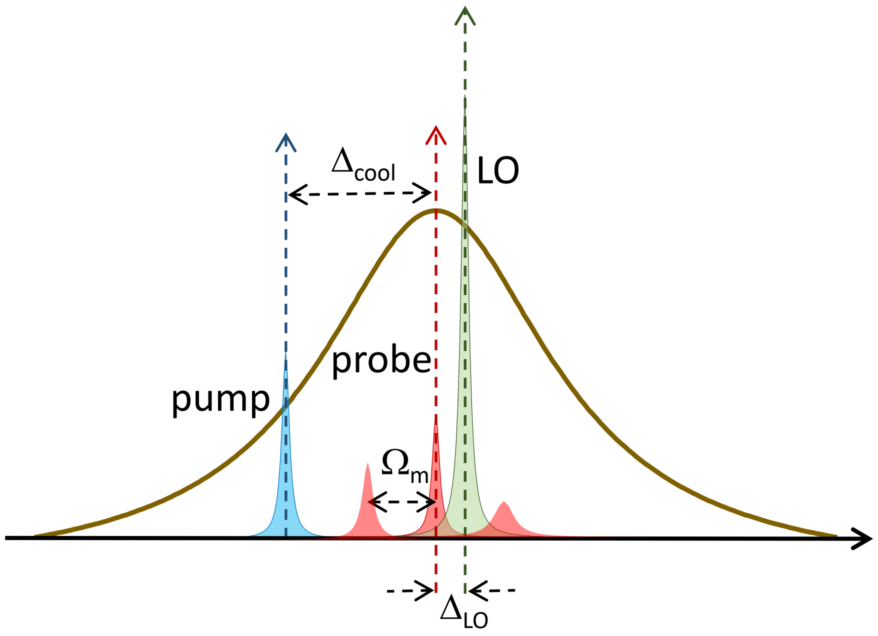


Membrane:

- Thickness ~ *100 nm*
- Diameter ~ *1.64 mm*
- $Q_{\text{cryogenic temp}}$ ~ 10^7

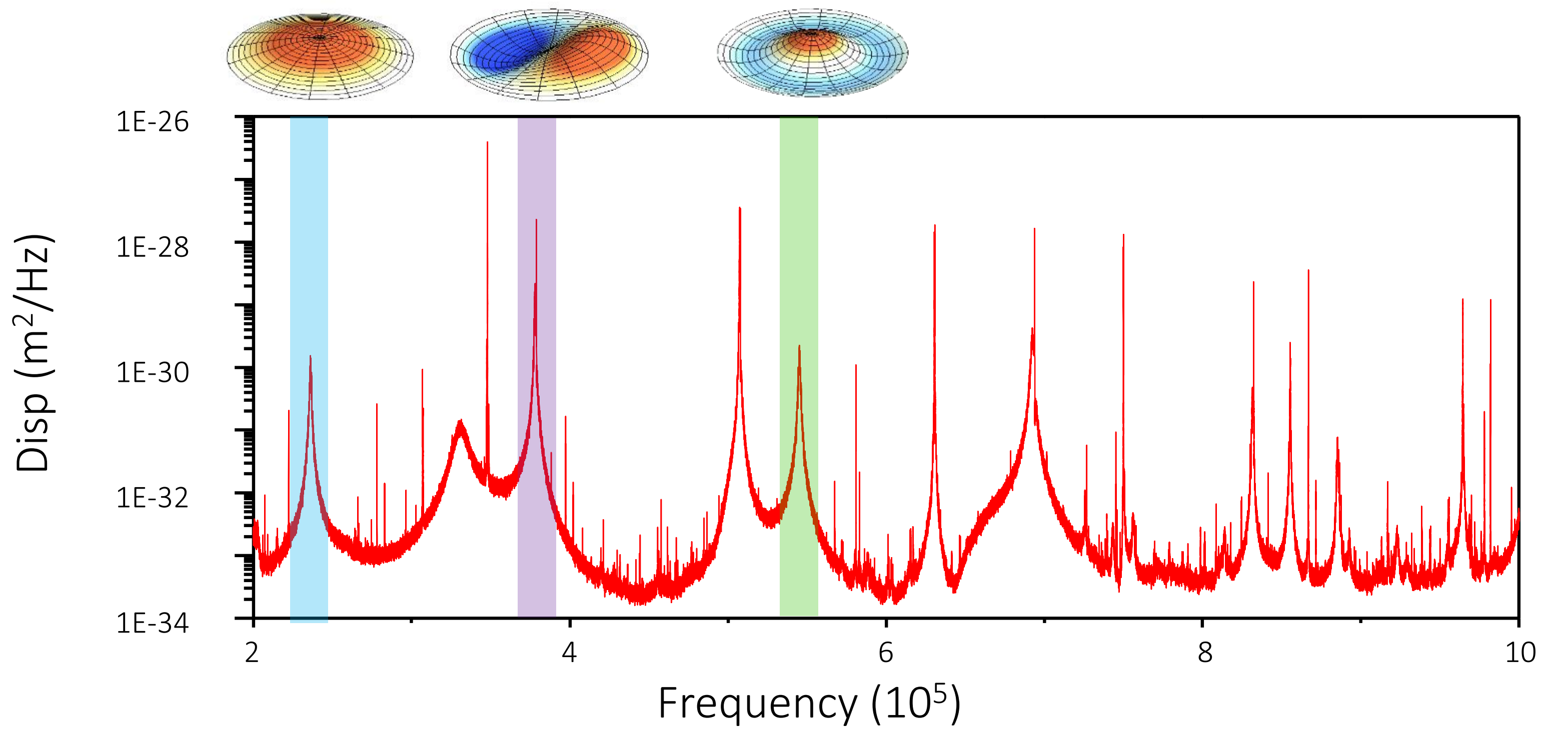
Simplified optical set-up

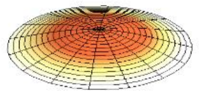




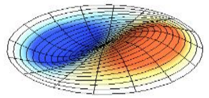
- ***Weak probe***: to detect the displacement of the mechanical mode, in resonance with the cavity.
- ***Strong pump***: detuned from the cavity, used to optically cool down the mechanical mode.
- ***LO beam***: Local Oscillator beam used to make heterodyne measurement on the mechanical mode.

Membrane modes: eigen-modes

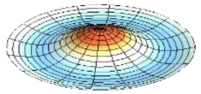




f_0 = 230 kHz, Q_0 = 7.8x10^6



f_0 = 370 kHz, Q_0 = 8.9x10^6

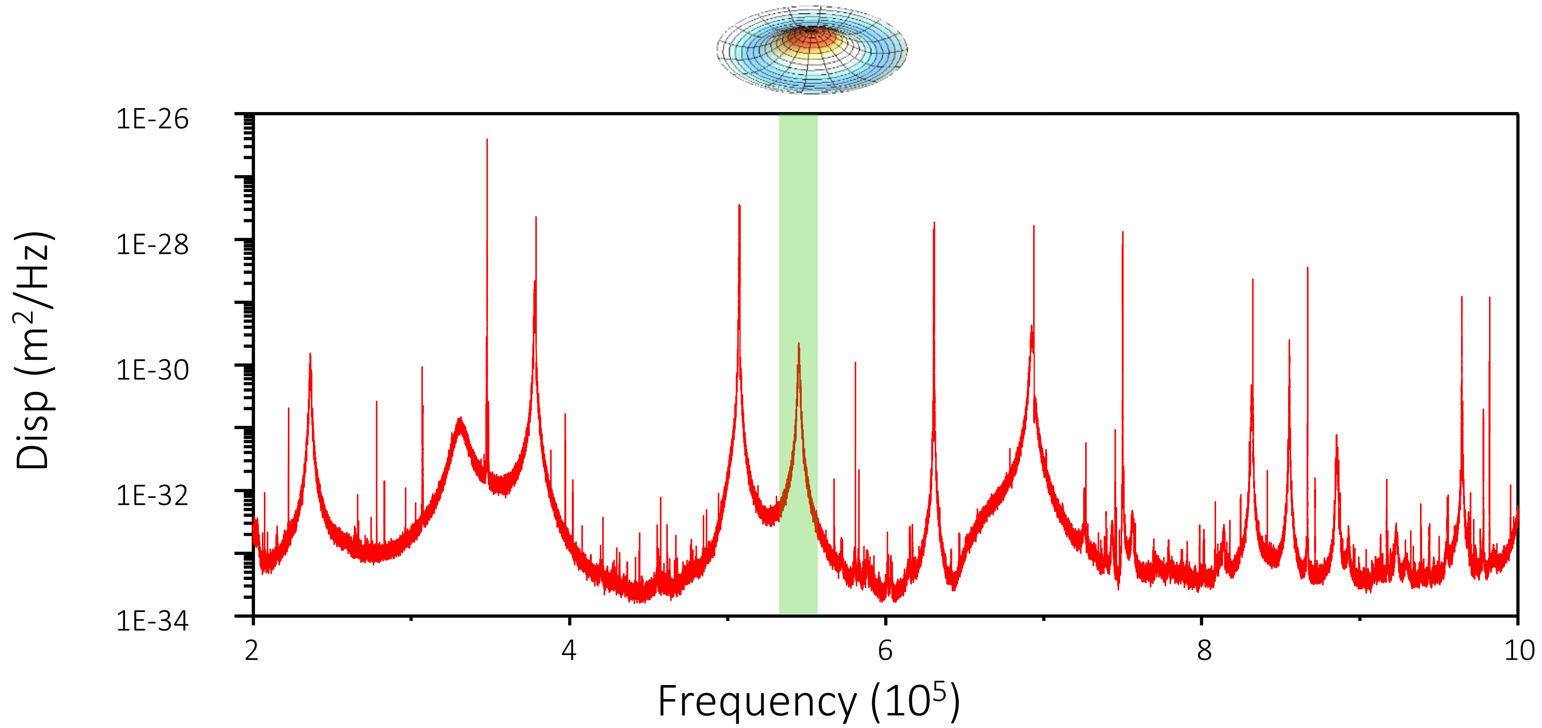


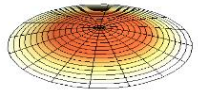
f_0 = 530 kHz, Q_0 = 6.4x10^6

Choice of the modes

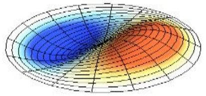
- Considerably high Q factor.
- High optomechanical coupling: highly dependent on the effective overlap between the laser beam and the membrane eigen mode.

Membrane modes: eigen-modes

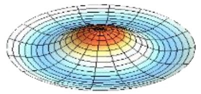




f_0 = 230 kHz, Q_0 = 7.8x10^6



f_0 = 370 kHz, Q_0 = 8.9x10^6



f_0 = 530 kHz, Q_0 = 6.4x10^6

We choose: Mode at 530 kHz

- Q factor: 6.4x10^6.
- With an optomechanical coupling g_0 ~ 5 Hz.

Cooling a mechanical mode

$$\delta\Omega_{\mathrm{m}}(\omega) = g^2 \frac{\Omega_{\mathrm{m}}}{\omega}\left[\frac{\Delta+\omega}{(\Delta+\omega)^2+\kappa^2/4} + \frac{\Delta-\omega}{(\Delta-\omega)^2+\kappa^2/4}\right]$$

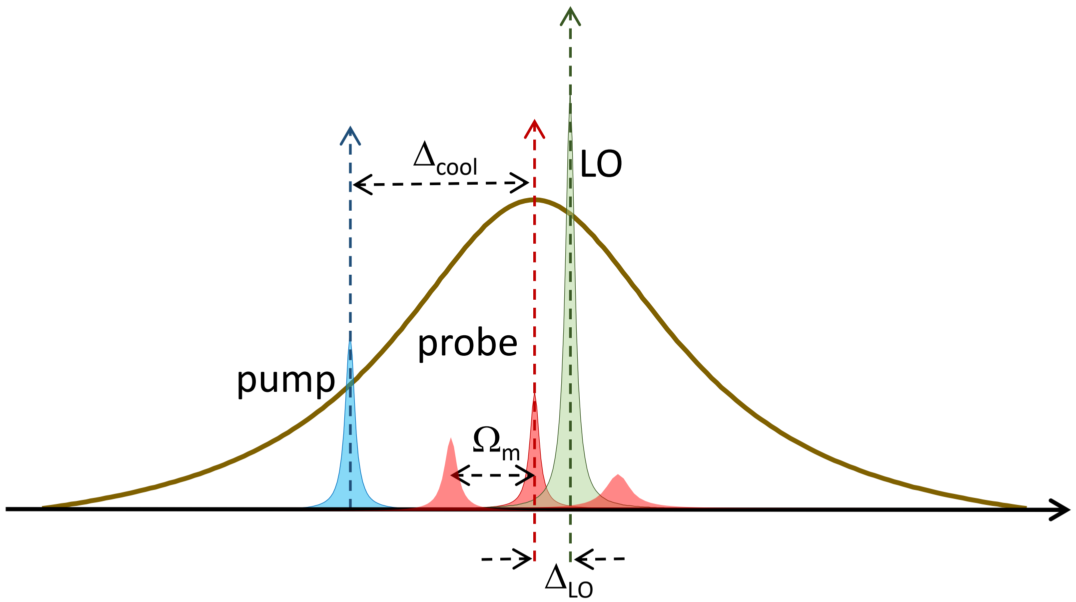
Optical Spring effect

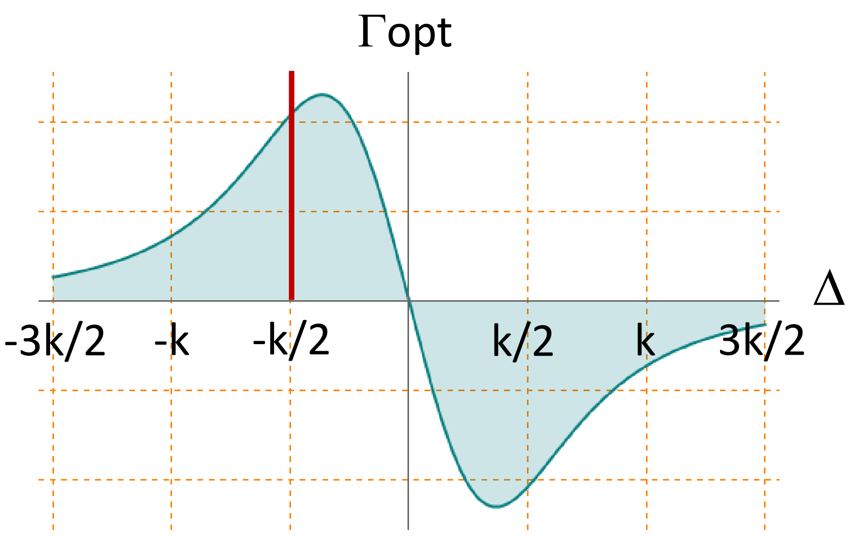
$$\Gamma_{\mathrm{opt}}(\omega) = g^2 \frac{\Omega_{\mathrm{m}}}{\omega}\left[\frac{\kappa}{(\Delta+\omega)^2+\kappa^2/4} - \frac{\kappa}{(\Delta-\omega)^2+\kappa^2/4}\right]$$

Damping of the mode ‘m’

$$g^2 = g_0^2 \bar{n}_{\mathrm{cav}}$$

Γopt ~ $f\,(n_{cav}, \Delta)$





In the bad cavity limit

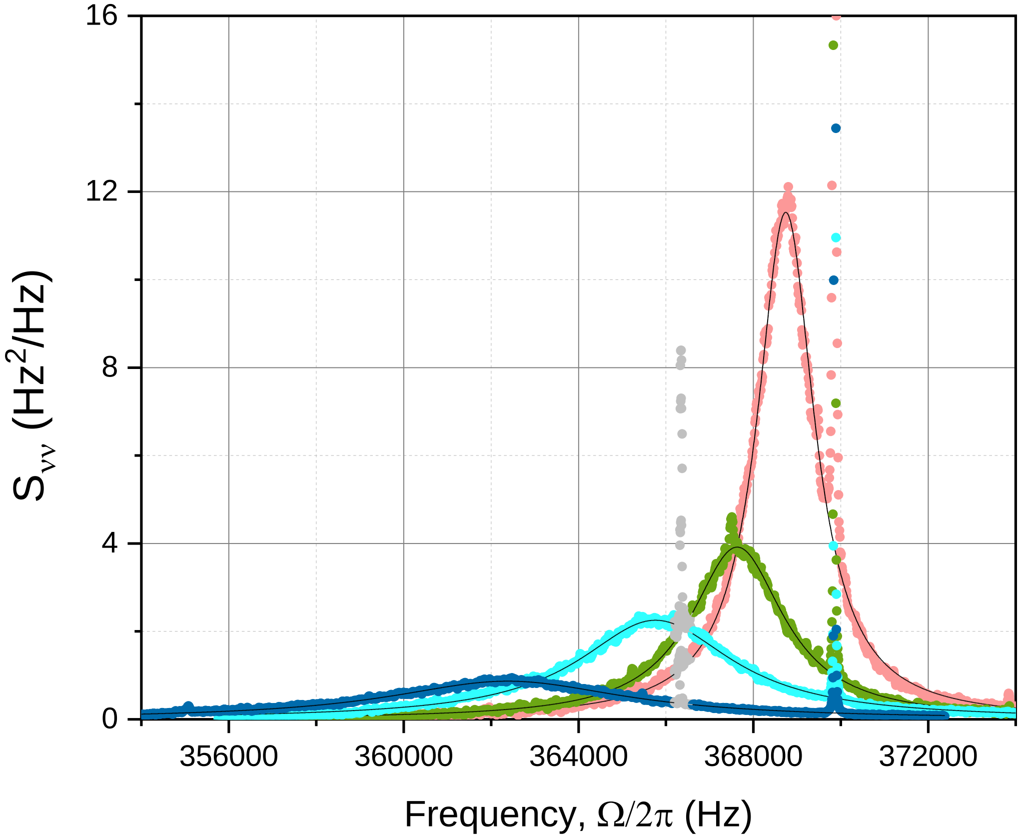
Cooling a mechanical mode

$$\Gamma_{\mathrm{opt}}(\omega) = g^2 \frac{\Omega_\mathrm{m}}{\omega}\left[\frac{\kappa}{(\Delta+\omega)^2+\kappa^2/4} - \frac{\kappa}{(\Delta-\omega)^2+\kappa^2/4}\right]$$

$\Delta \sim \kappa/2 = 1$ MHz

$$g^2 = g_0^2 \bar{n}_{\mathrm{cav}}$$

Cooling measurement relying on the measurement and calibration of motion induced scattering of light giving an average phonon occupancy $\langle n \rangle$

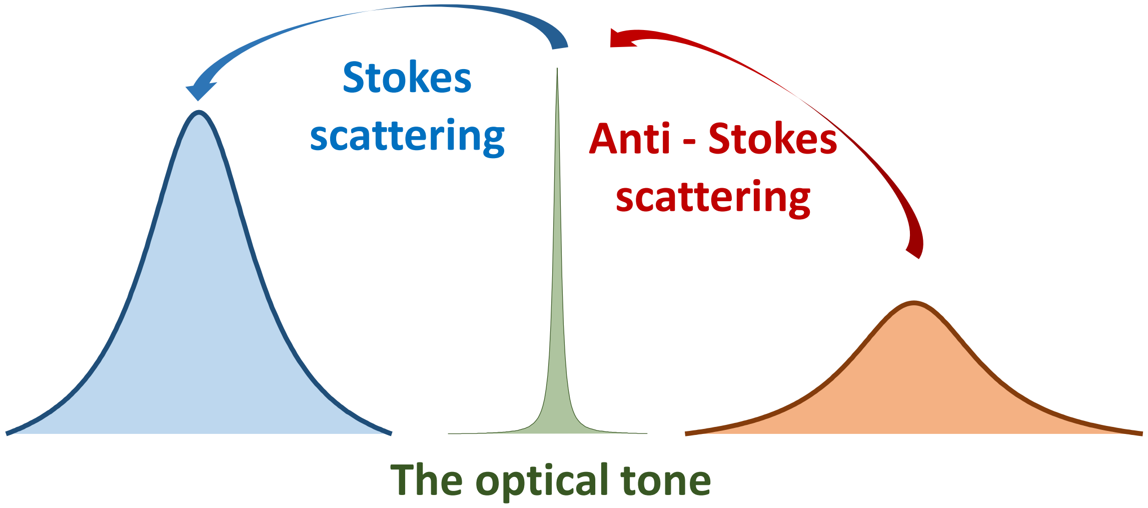


Quantum Sci. Technol. 4 (2019) 024007

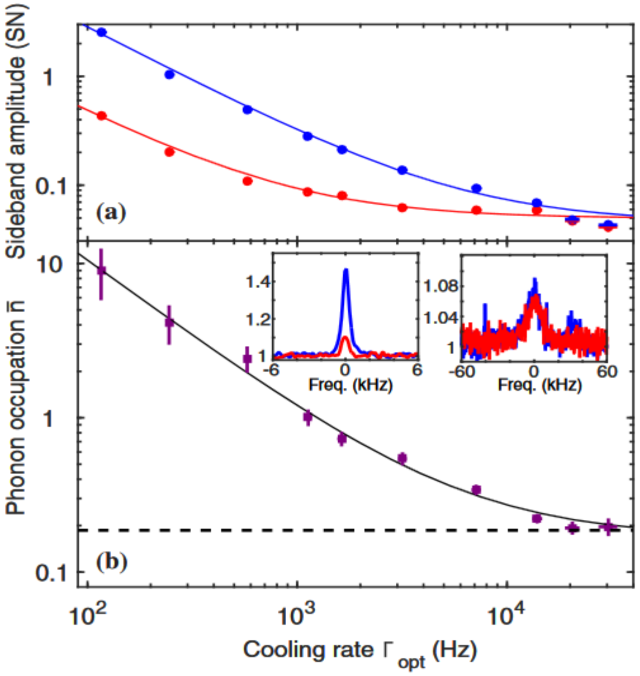
Quantum thermometry

- Ratio of Stokes and anti-Stokes sideband from the mechanical oscillator: $\frac{\langle n \rangle + 1}{\langle n \rangle}$

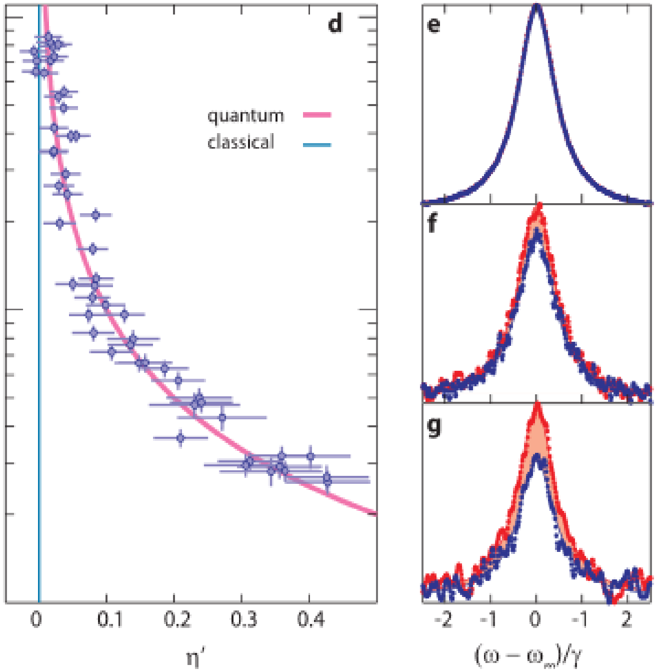
The scattering picture



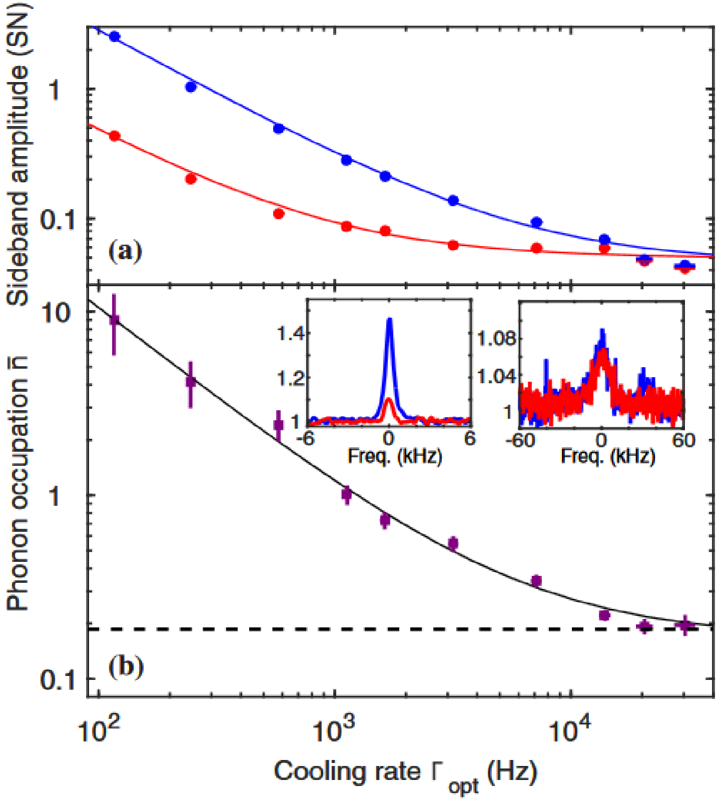
$$\text{Ratio} = \frac{\textit{Stokes rate}}{\textit{anti Stokes rate}} = \frac{\langle n \rangle + 1}{\langle n \rangle}$$



Regal, PRL 116, 063601 (2016)

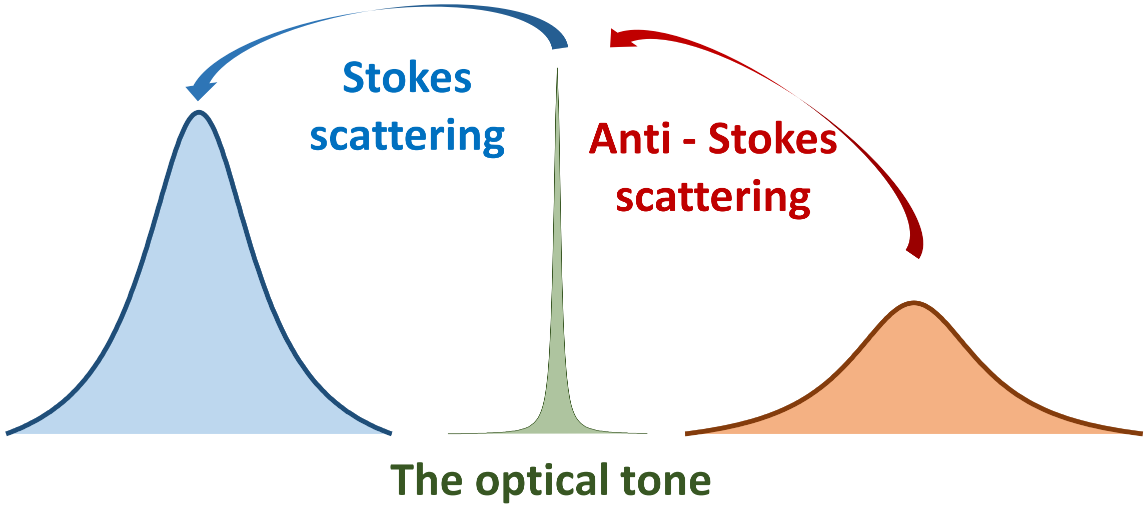


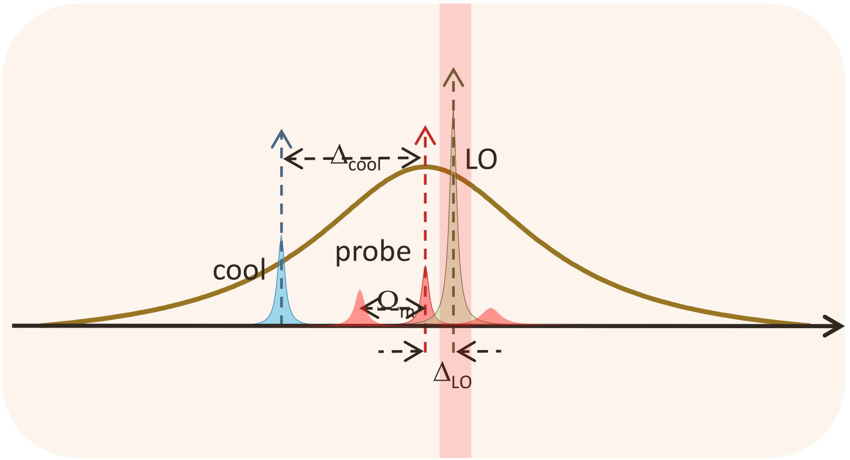
Painter, PRL 108, 033602 (2012)

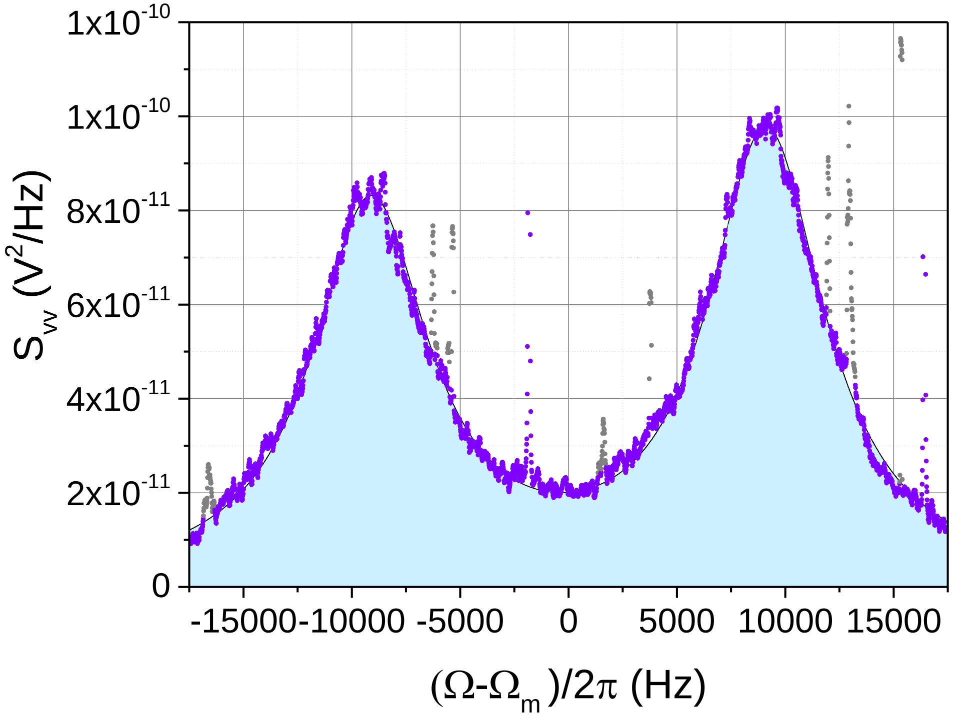


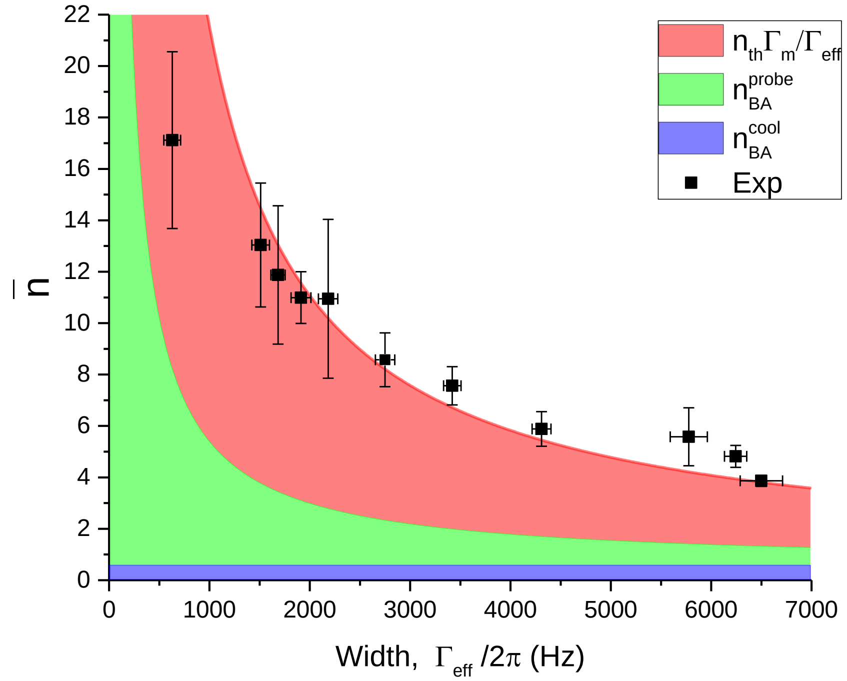
Regal, PRL 116, 063601 (2016)

The scattering picture









Quantum Sci. Technol. 4 (2019) 0240

Towards zero-point state

Lower bound to the position of SHO:

$$\Delta X\ \Delta Y \geq \frac{h}{2m_{eff}\Omega_m} = x_{ZPF}$$

Typical squeezing measurement: Measurement of noise in one quadrature -> Increase of noise in the other.

Already existing squeezing schemes:

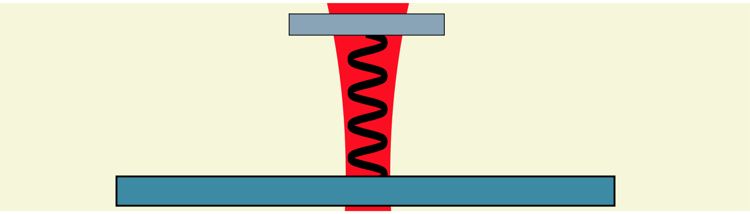
- Pulsed laser cooling of oscillator: ***requries short pulsed laser.***
- Squeezing via backaction evading measurements (BAE): ***requires motional state close to the quantum regime.***

Parametric squeezing

- No strict requirement on the starting occupation number of motional state.
- Experiments can be done in the ‘bad-cavity’ regime.

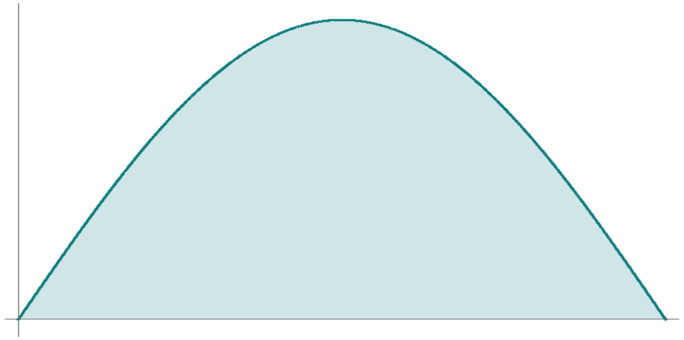
Parametric cooling of an oscillator

Modulation of spring constant at twice the resonant frequency

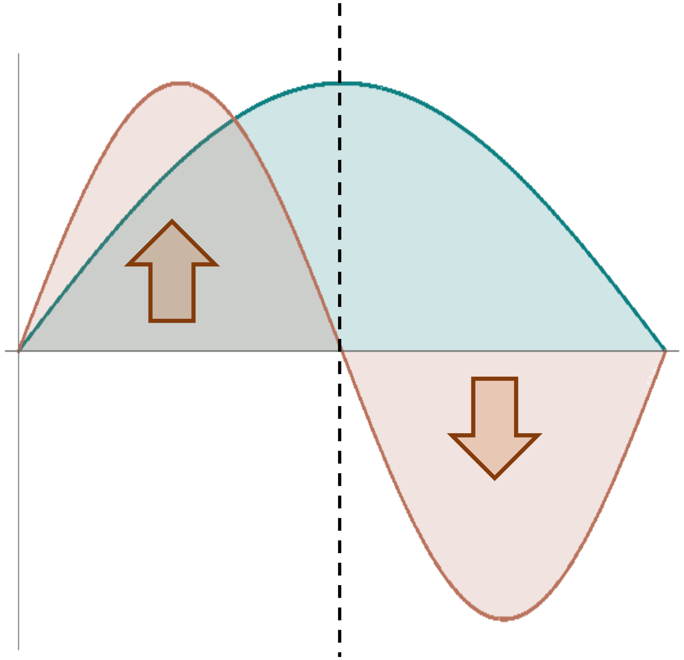


$$k(t) = k_0 + k_p(t)$$

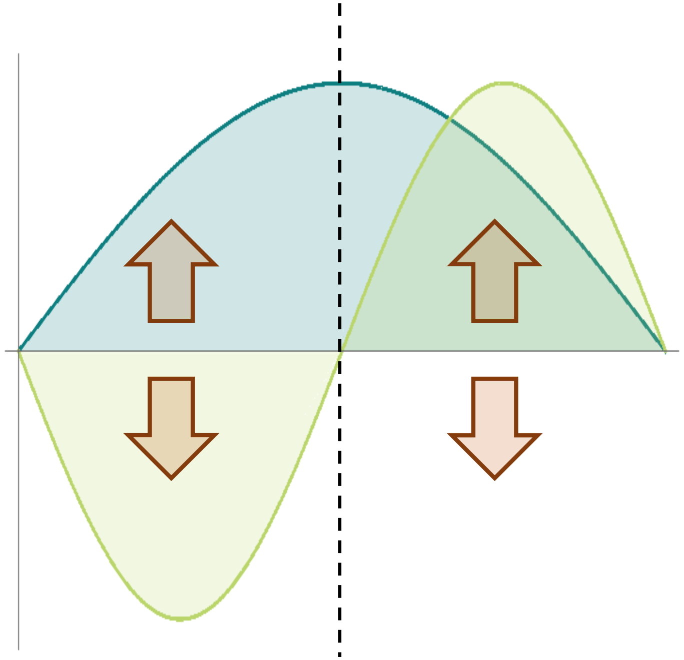
$k_0 \rightarrow intrinsic\ spring\ constant$
$k_p \sim Cos(2\pi f_0 t) \rightarrow parametric\ modulation$



Motion of a harmonic oscillator



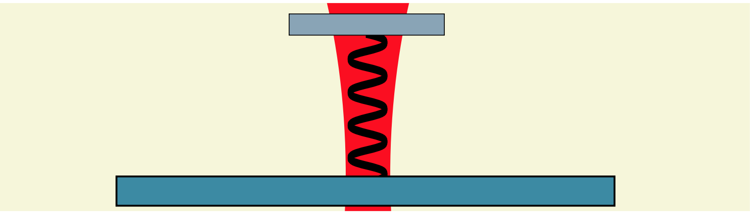
Parametric excitation @ $2f_0$



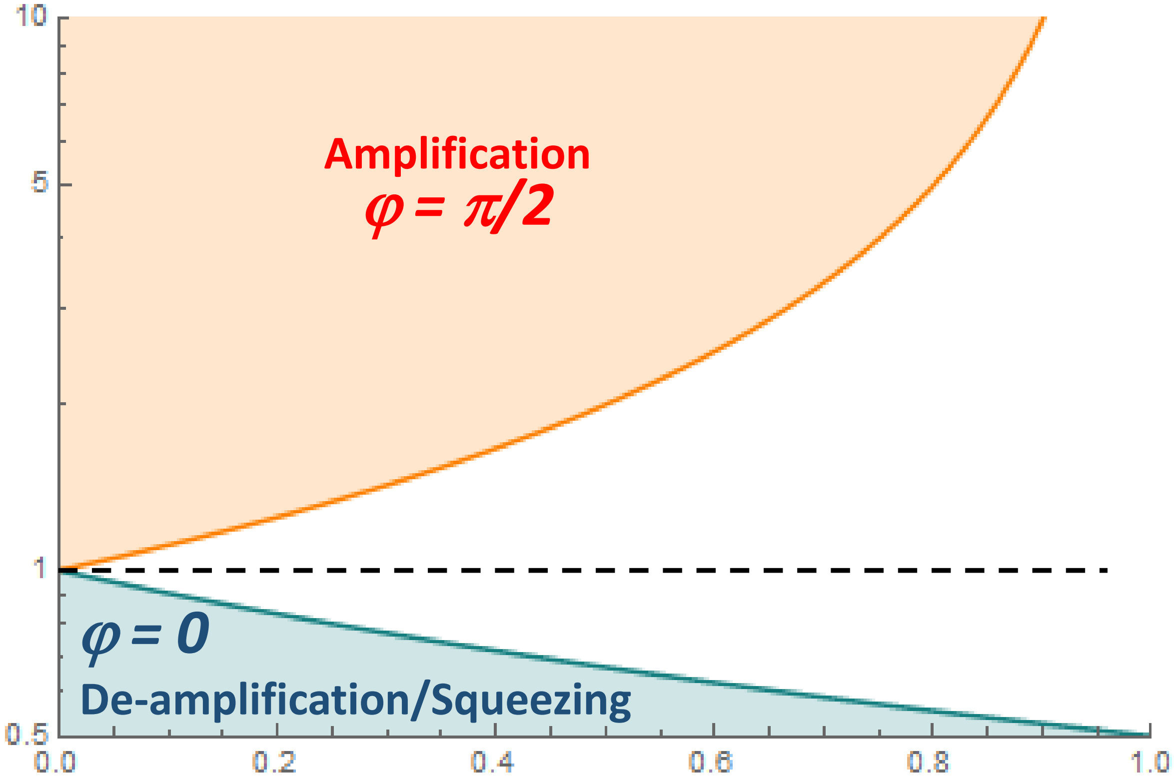
Parametric excitation @ $2f_0+\pi$

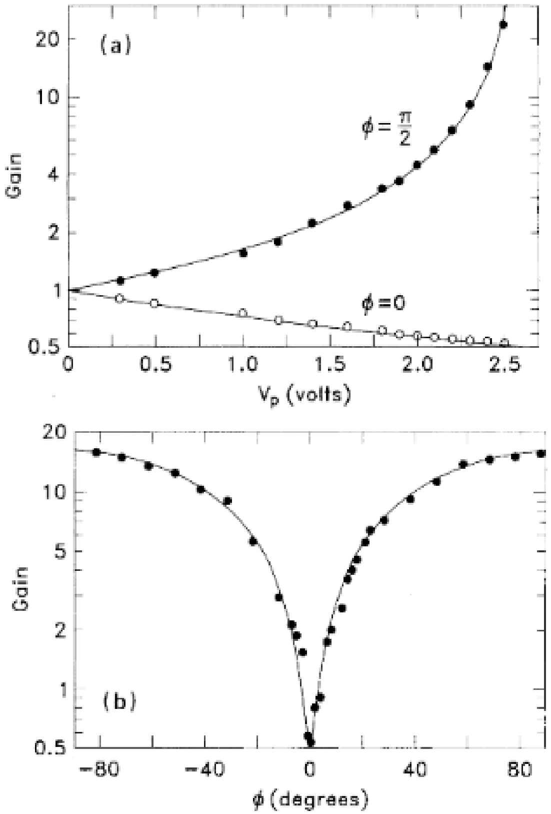
Parametric cooling of an oscillator

Modulation of spring constant at twice the resonant frequency



$$s(\varphi) = \left[\frac{Cos^2(\varphi)}{(1+P_{norm})^2} + \frac{Sin^2(\varphi)}{(1-P_{norm})^2}\right]^{1/2}$$

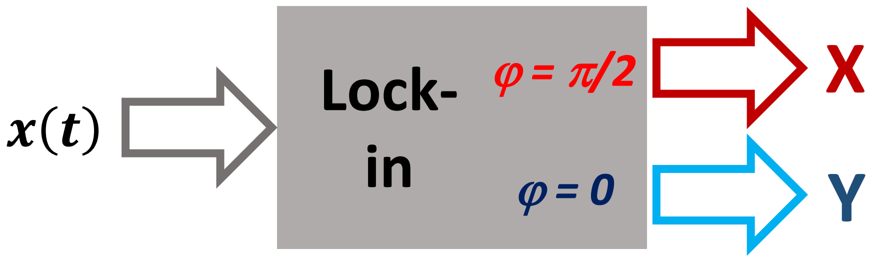


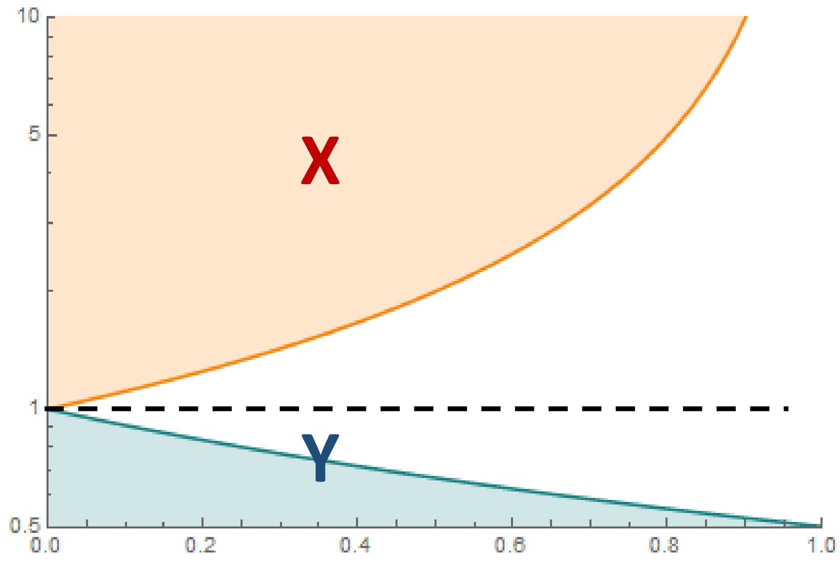


Rugar et al. PRL 67, 6 (1991)

Parametric cooling of an oscillator

$$x(t) = X\ Cos(2\pi f_0 t) + Y\ Cos(2\pi f_0 t)$$





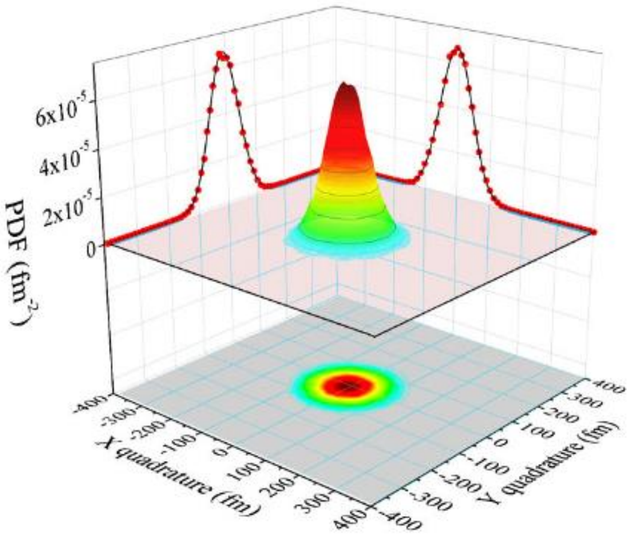
Squeezing the displacement in one quadrature while adding noise on the other:
Leads to thermal squeezing of a mechanical oscillator

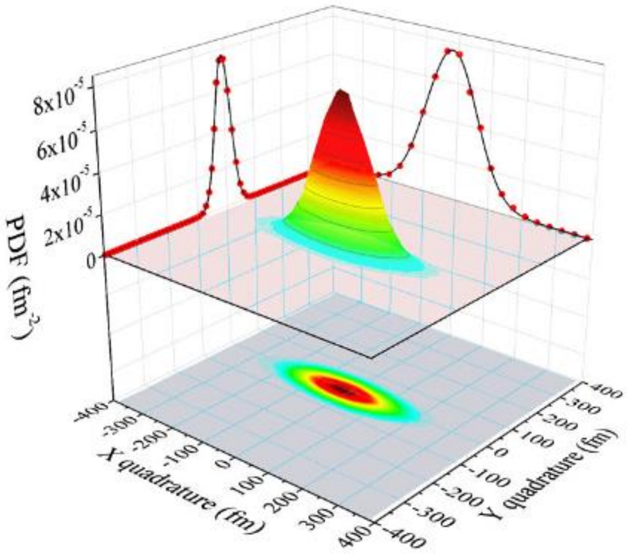
Parametric cooling of an oscillator

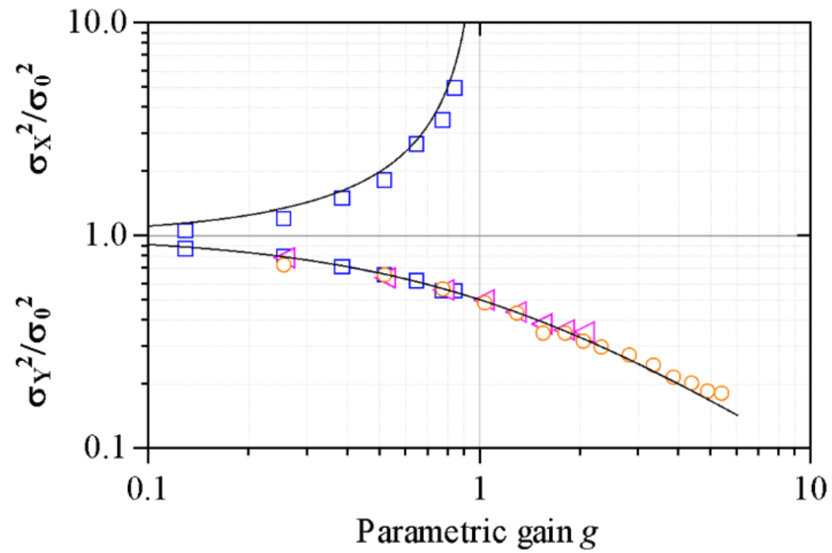
PRL 112, 023601 (2014) PHYSICAL REVIEW LETTERS week ending 17 JANUARY 2014

Squeezing a Thermal Mechanical Oscillator by Stabilized Parametric Effect on the Optical Spring

A. Pontin,[1,2] M. Bonaldi,[3,4] A. Borrielli,[3,4] F. S. Cataliotti,[5,6,7] F. Marino,[7,8] G. A. Prodi,[1,2] E. Serra,[1,9] and F. Marin[5,6,7,*]

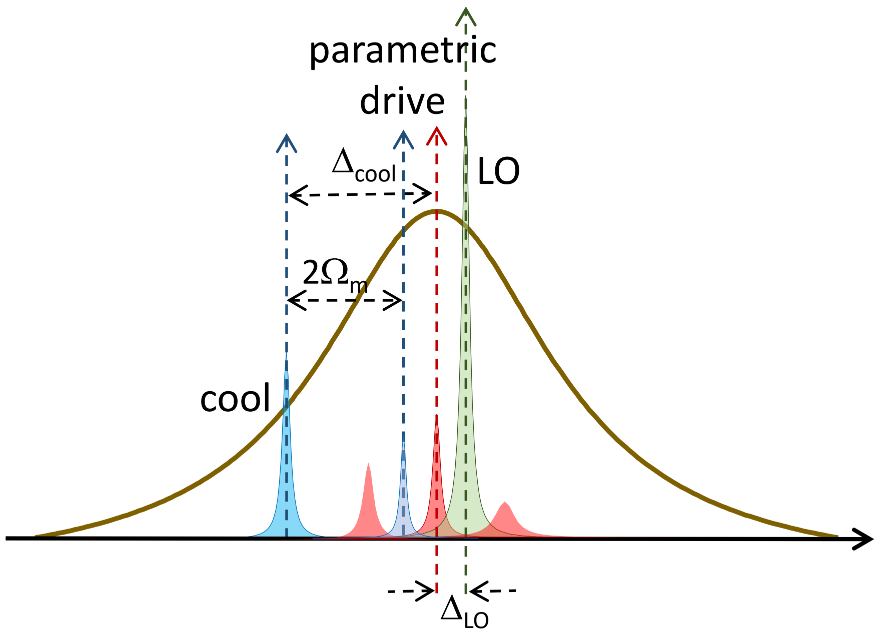


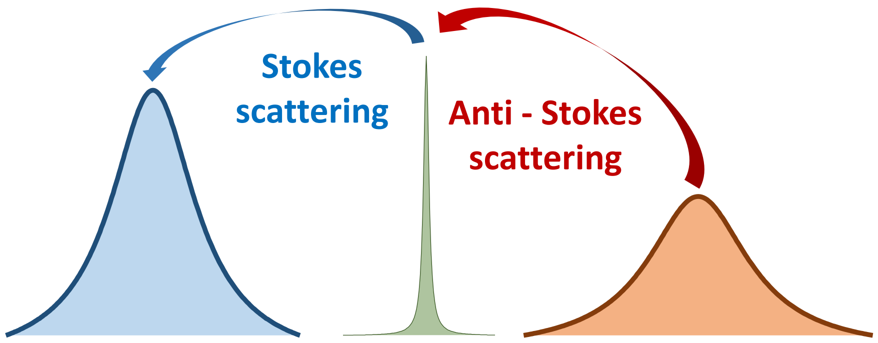




Squeezed thermal state

Parametric cooling close to the quantum regime

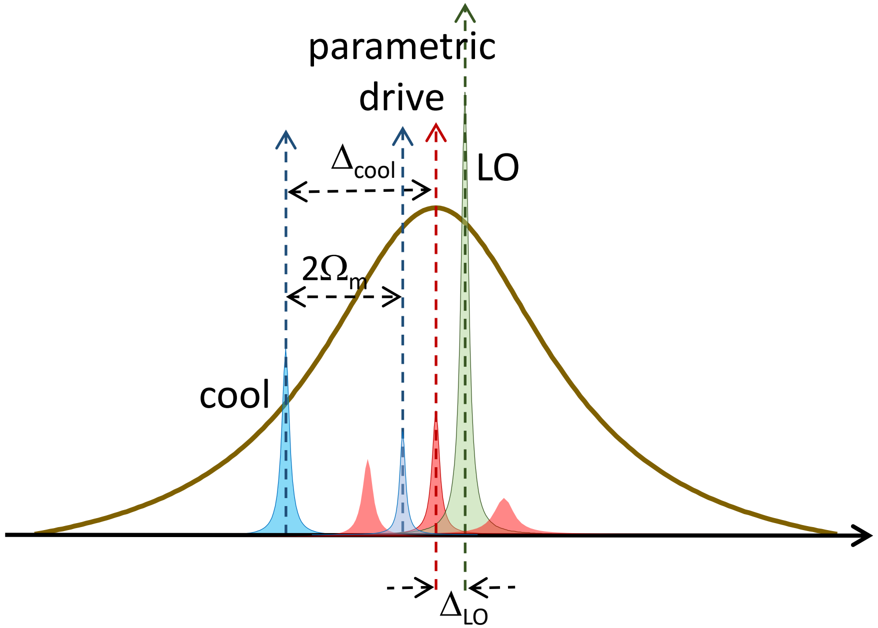


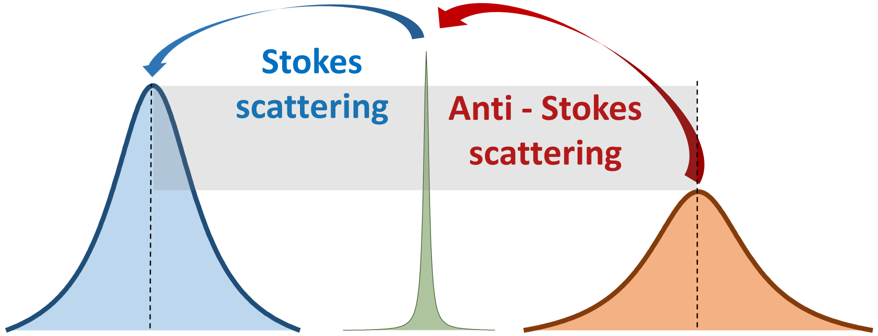


Weak parametric tone (@ $2\Omega_m$) added to the pump beam

$$I_{pump} = I_{cool} + I_{par}$$

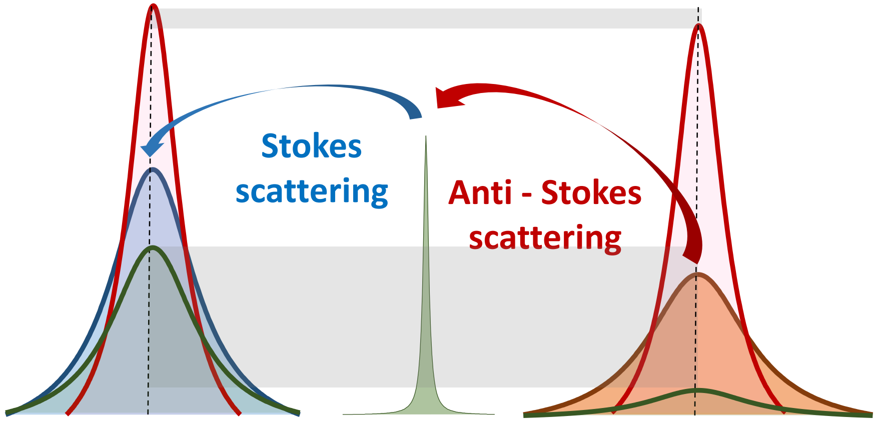
Parametric cooling close to the quantum regime



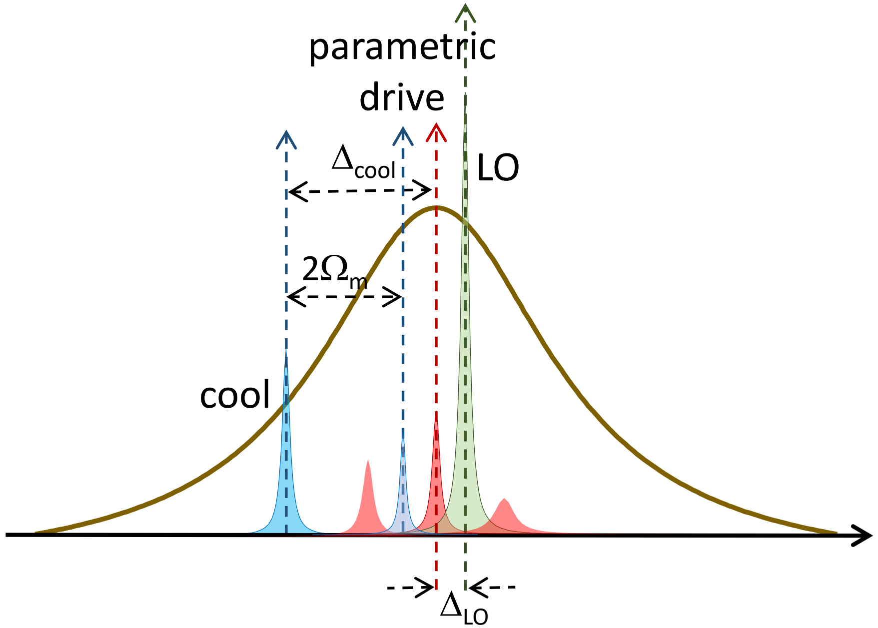


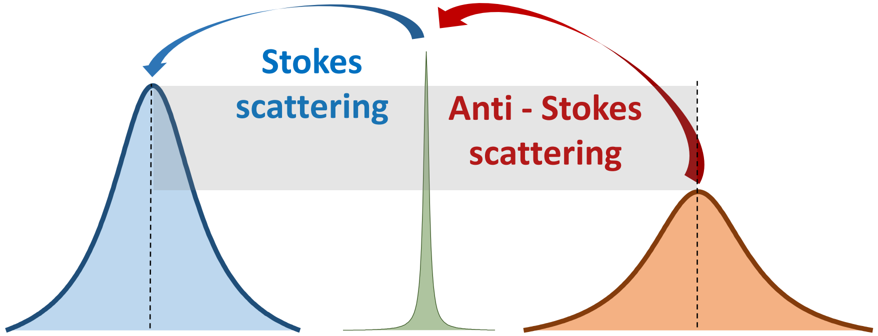
$$S_{anti-Stokes} = \frac{\Gamma_{opt}}{2}\left[\frac{\boldsymbol{n + s/2}}{\boldsymbol{\omega^2 + \left(\frac{\Gamma_-}{2}\right)^2}} + \frac{\boldsymbol{n - s/2}}{\boldsymbol{\omega^2 + \left(\frac{\Gamma_+}{2}\right)^2}}\right]$$

$$S_{Stokes} = \frac{\Gamma_{opt}}{2}\left[\frac{\boldsymbol{n + 1 - s/2}}{\boldsymbol{\omega^2 + \left(\frac{\Gamma_-}{2}\right)^2}} + \frac{\boldsymbol{n + 1 + s/2}}{\boldsymbol{\omega^2 + \left(\frac{\Gamma_+}{2}\right)^2}}\right]$$



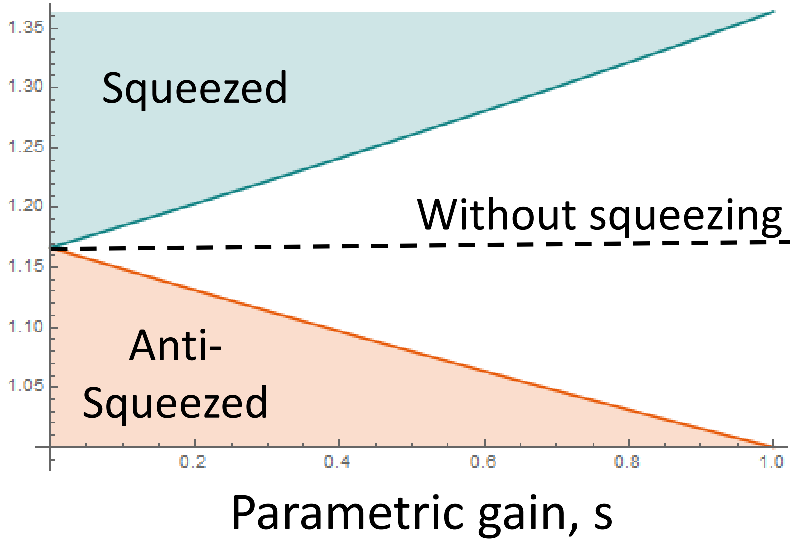
Parametric cooling close to the quantum regime

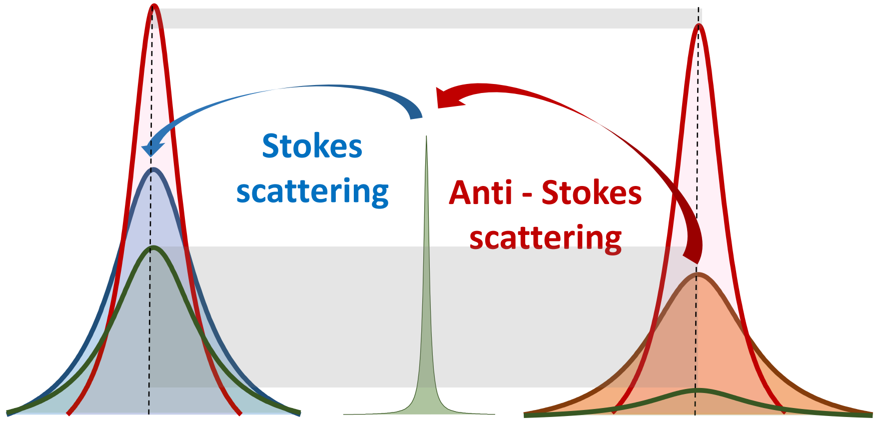




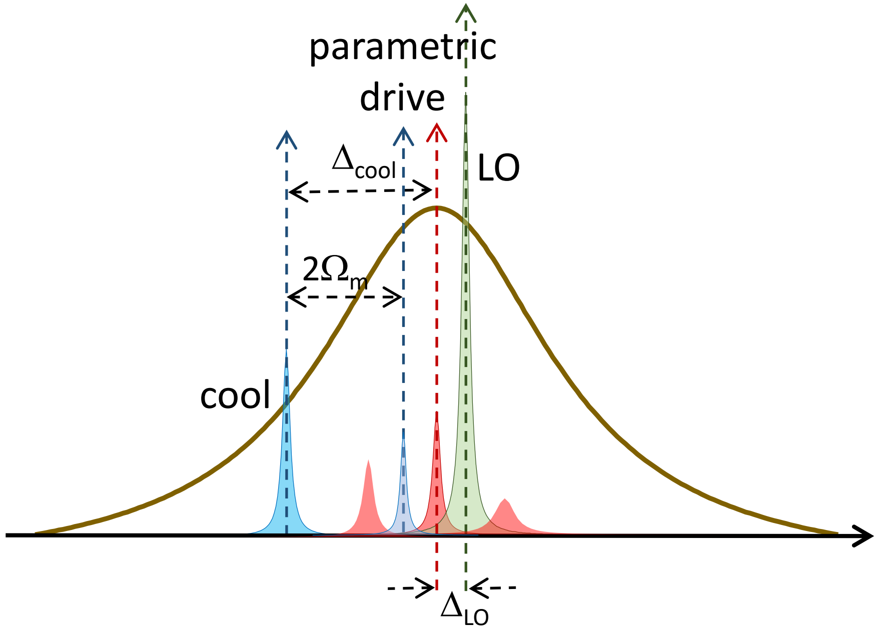
SB ratio, R_Y : $\dfrac{n+1+s/2}{n-s/2}$

SB ratio, R_X : $\dfrac{n+1-s/2}{n+s/2}$



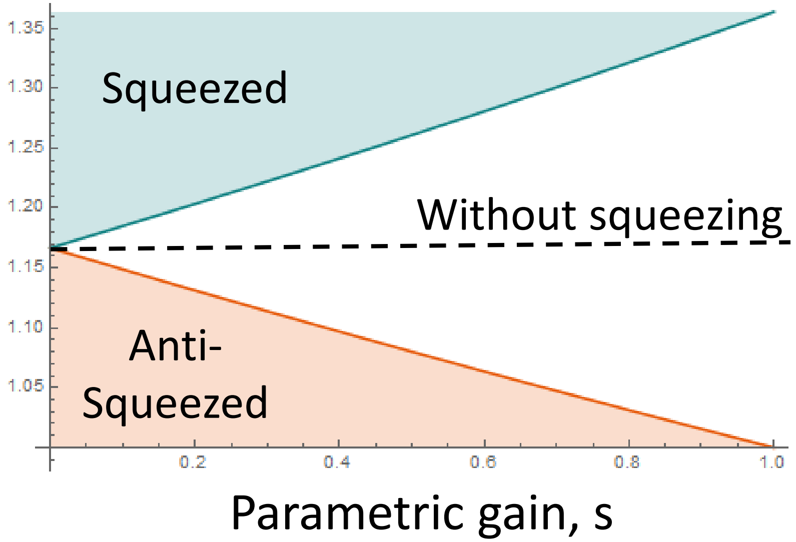


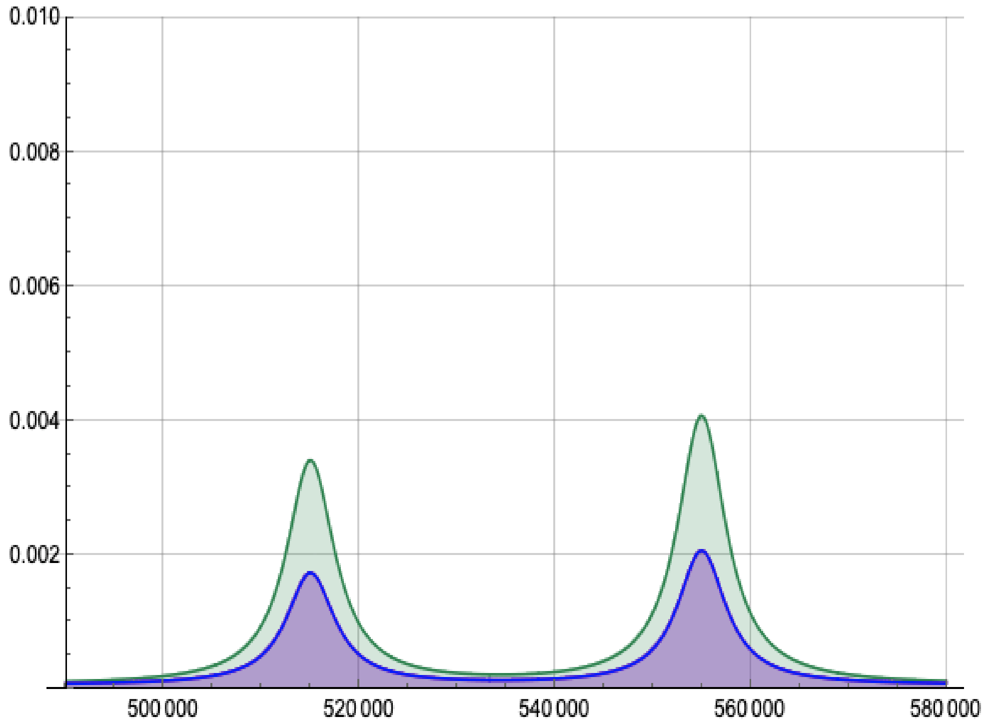
Parametric cooling close to the quantum regime



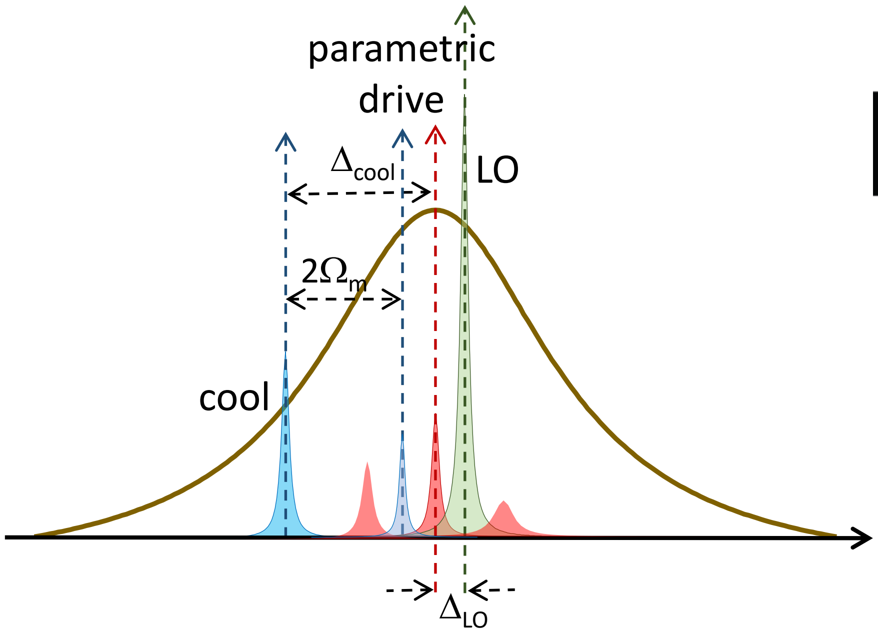
SB ratio, $\boldsymbol{R_Y}$: $\dfrac{n+1+s/2}{n-s/2}$

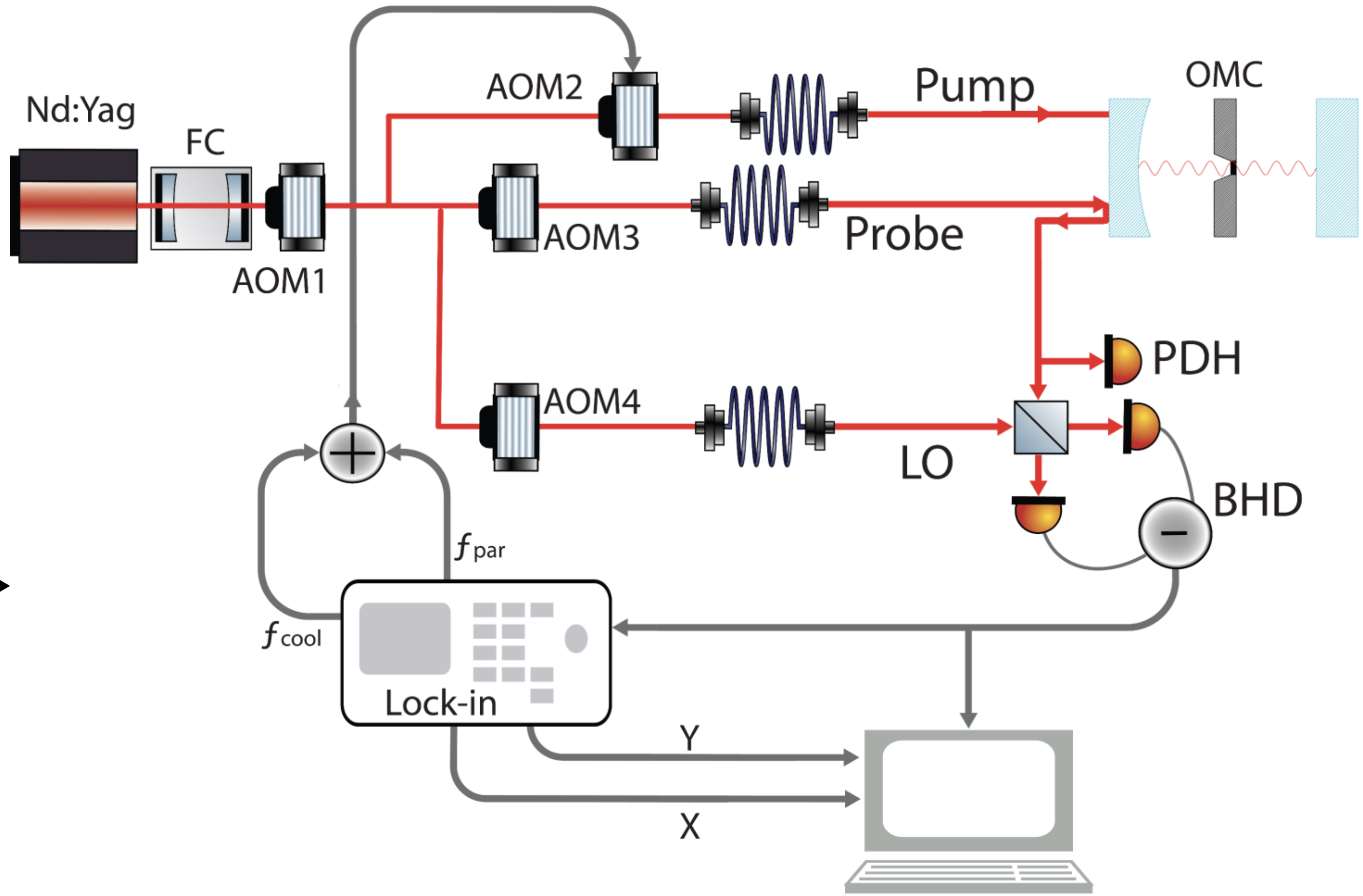
SB ratio, $\boldsymbol{R_X}$: $\dfrac{n+1-s/2}{n+s/2}$



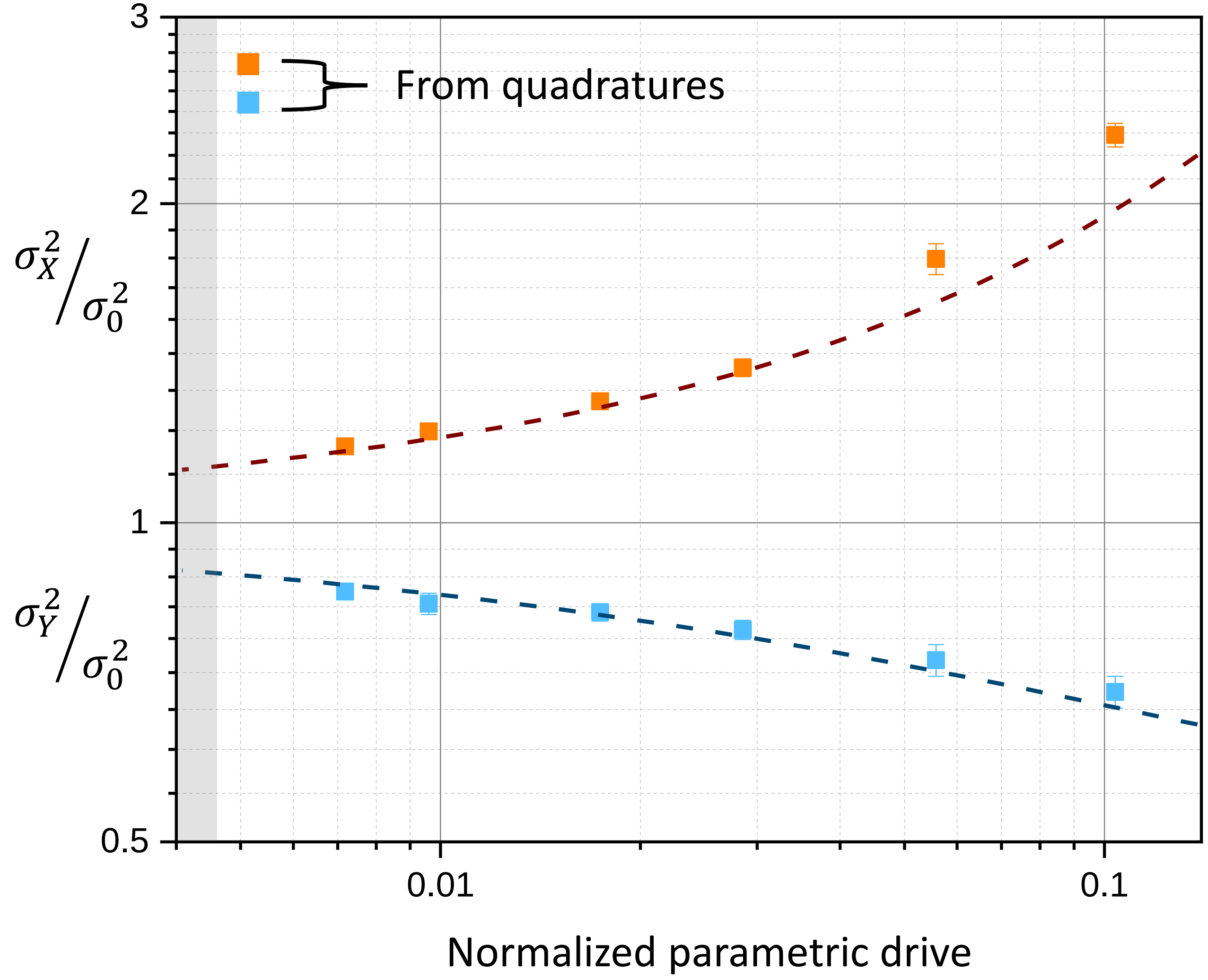


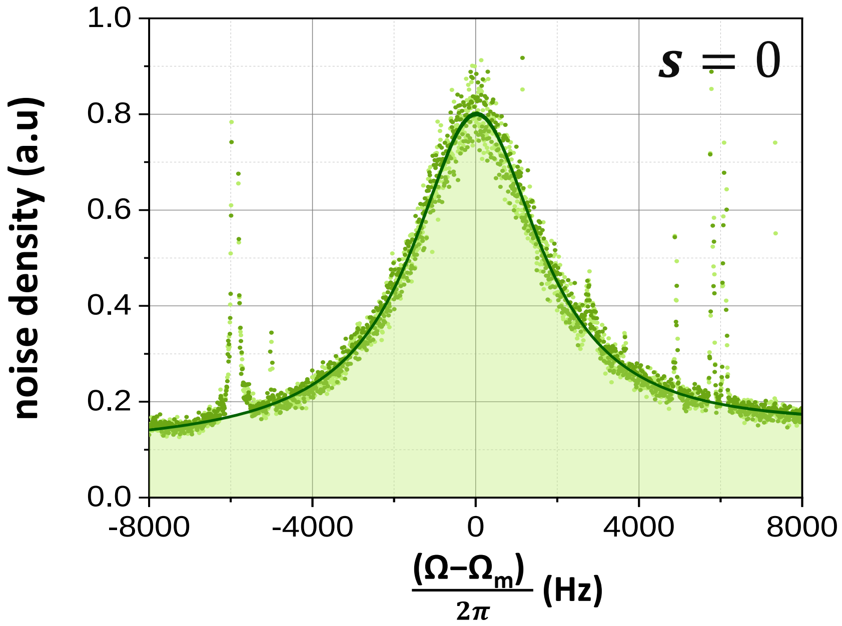
Parametric cooling: scheme





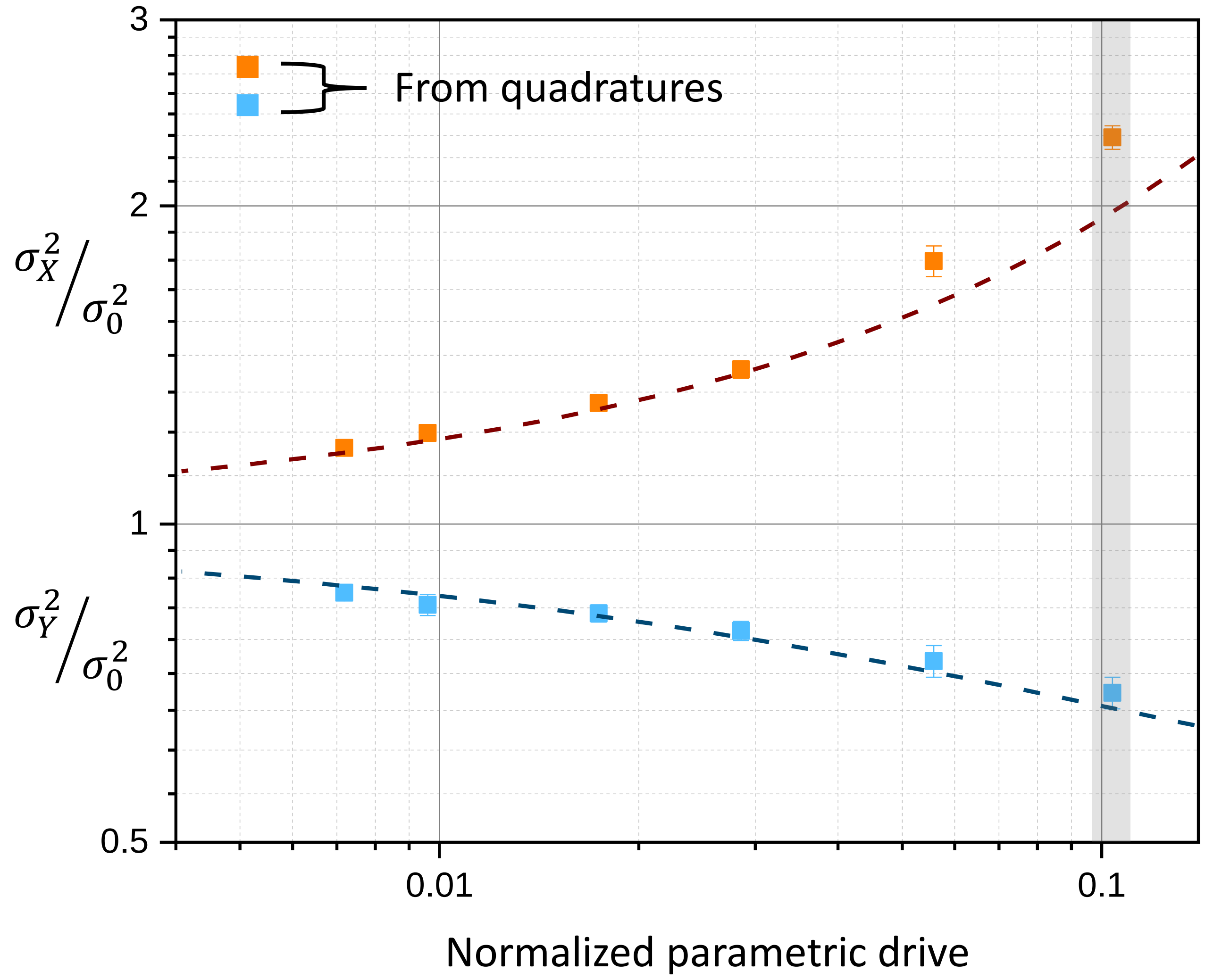
Expected variance of the quadratures



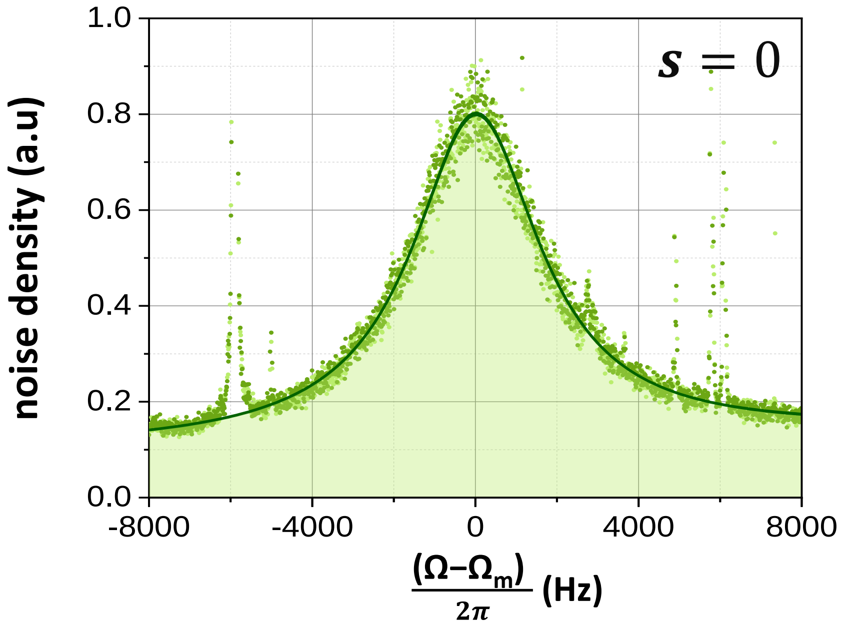


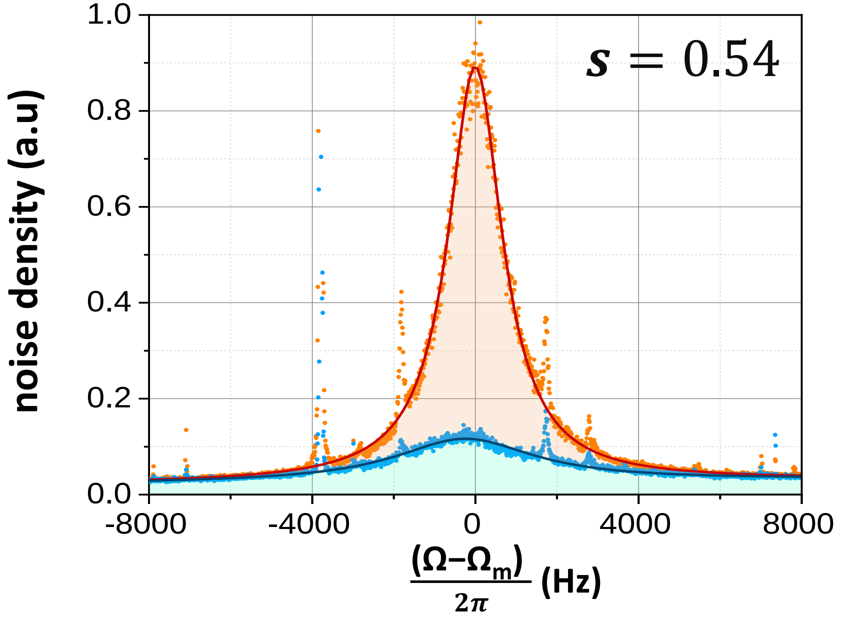
$$\sigma_X^2 = \frac{\sigma_0^2}{1-s} \qquad \sigma_Y^2 = \frac{\sigma_0^2}{1+s}$$

Expected variance of the quadratures



$$\sigma_X^2 = \frac{\sigma_0^2}{1-s} \qquad \sigma_Y^2 = \frac{\sigma_0^2}{1+s}$$

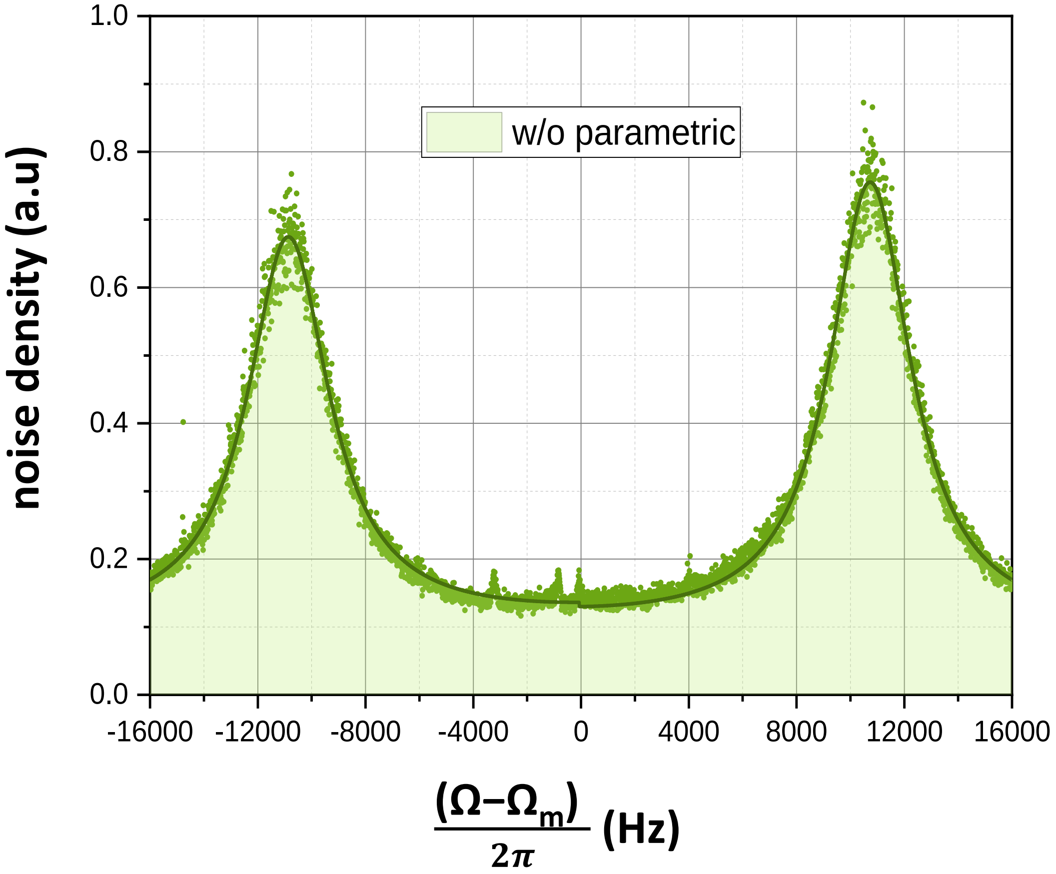




Variation of asymmetry of the quadratures

$$S_{tot} = \frac{\Gamma_{eff}}{2}\left[\frac{A_{left}}{(\omega - \Omega_{LO})^2 + \left(\frac{\Gamma_{eff}}{2}\right)^2} + \frac{A_{right}}{(\omega + \Omega_{LO})^2 + \left(\frac{\Gamma_{eff}}{2}\right)^2}\right]$$

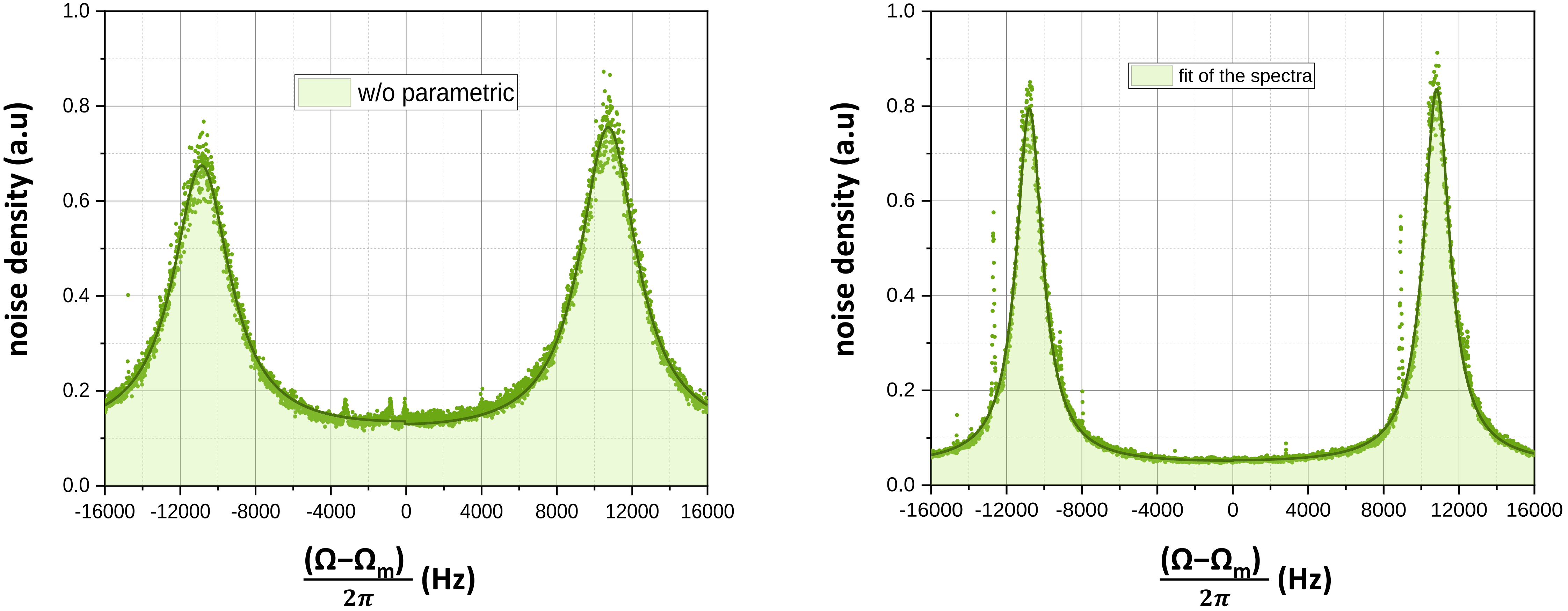
$s = 0$



Variation of asymmetry of the quadratures

$$S_{tot} = \left[\frac{\Gamma_X A^X_{left}}{(\omega - \Omega_{LO})^2 + \left(\frac{\Gamma_X}{2}\right)^2} + \frac{\Gamma_Y A^Y_{left}}{(\omega - \Omega_{LO})^2 + \left(\frac{\Gamma_Y}{2}\right)^2}\right] + \left[\frac{\Gamma_X A^X_{right}}{(\omega + \Omega_{LO})^2 + \left(\frac{\Gamma_X}{2}\right)^2} + \frac{\Gamma_Y A^Y_{right}}{(\omega + \Omega_{LO})^2 + \left(\frac{\Gamma_Y}{2}\right)^2}\right]$$

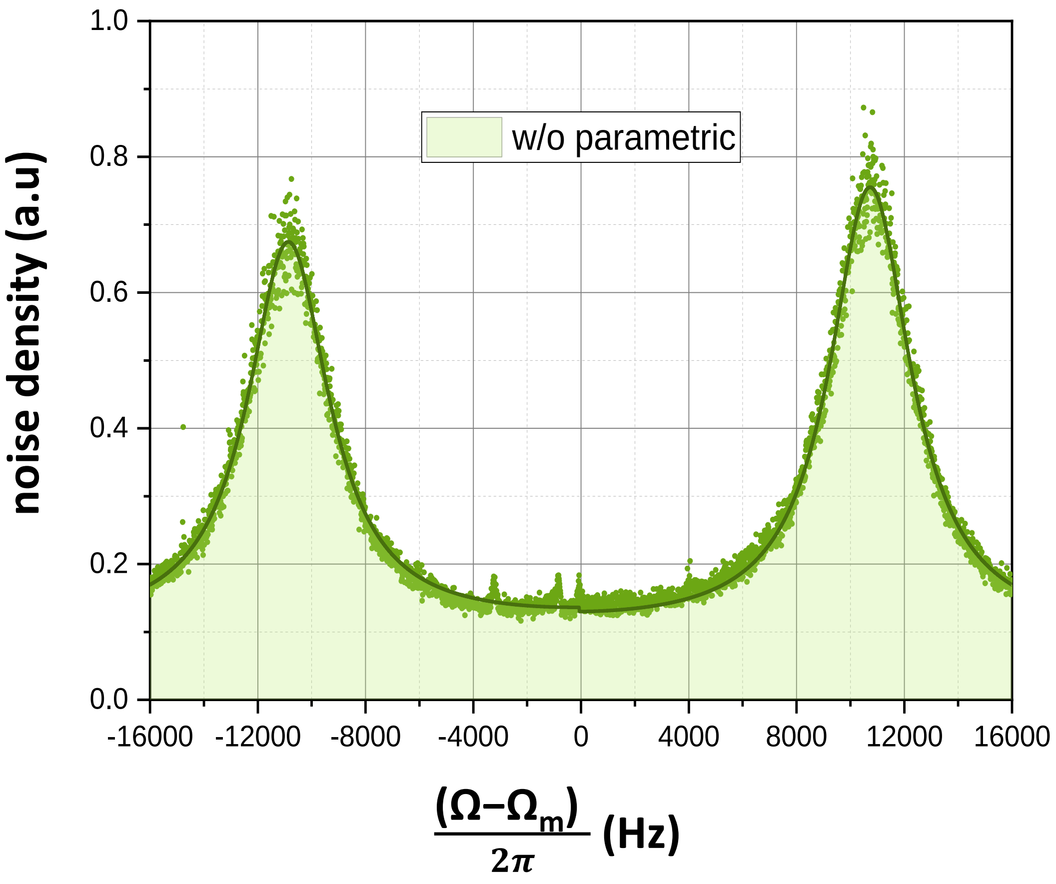
$s = 0$ $s = 0.54$



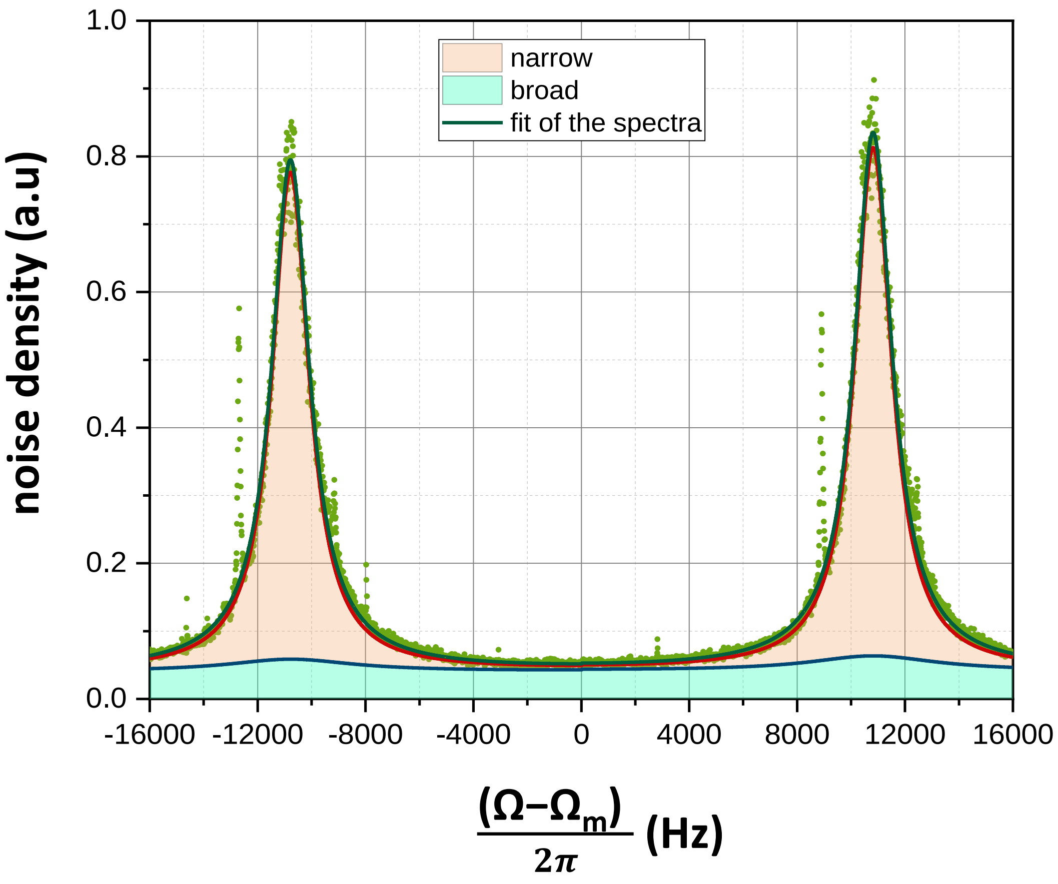
Variation of asymmetry of the quadratures

$$S_{tot} = \left[\frac{\Gamma_X A^X_{left}}{(\omega - \Omega_{LO})^2 + \left(\frac{\Gamma_X}{2}\right)^2} + \frac{\Gamma_Y A^Y_{left}}{(\omega - \Omega_{LO})^2 + \left(\frac{\Gamma_Y}{2}\right)^2} + \frac{\Gamma_X A^X_{right}}{(\omega + \Omega_{LO})^2 + \left(\frac{\Gamma_X}{2}\right)^2} + \frac{\Gamma_Y A^Y_{right}}{(\omega + \Omega_{LO})^2 + \left(\frac{\Gamma_Y}{2}\right)^2}\right]$$

$s = 0$



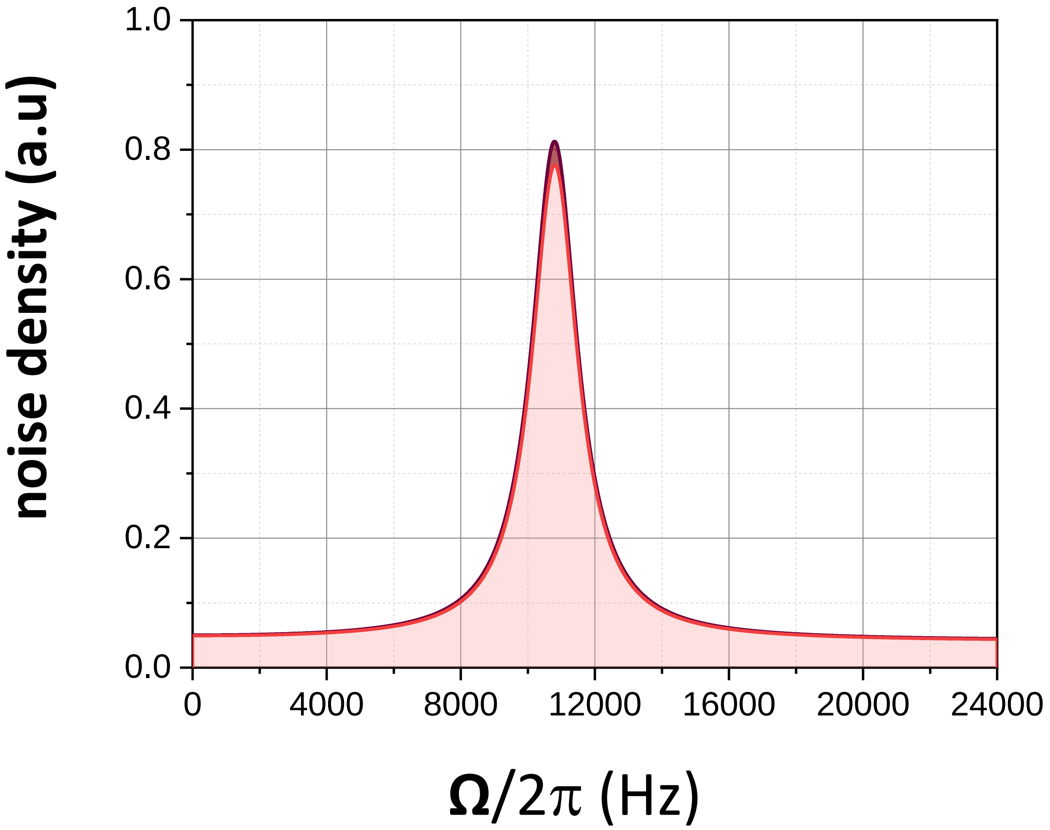
$s = 0.54$

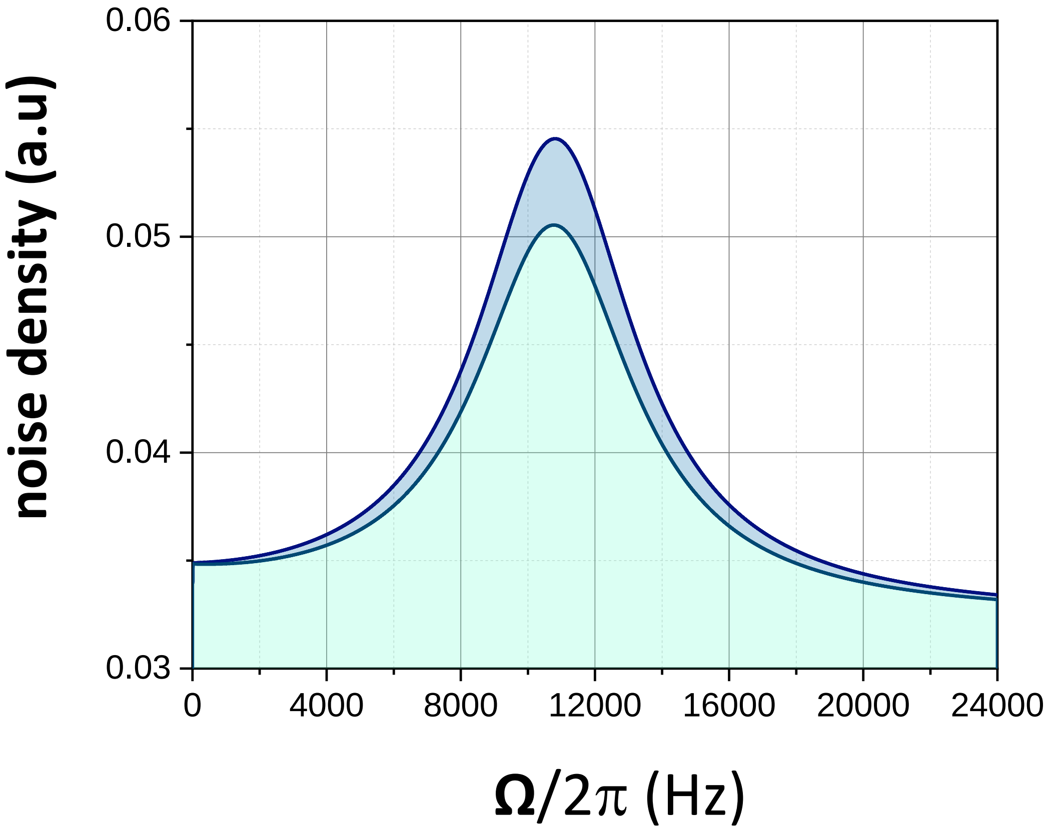


Variation of asymmetry of the quadratures

$$S_{tot} = \left[\frac{\Gamma_X A^X_{left}}{(\omega - \Omega_{LO})^2 + \left(\frac{\Gamma_X}{2}\right)^2} + \frac{\Gamma_Y A^Y_{left}}{(\omega - \Omega_{LO})^2 + \left(\frac{\Gamma_Y}{2}\right)^2} + \frac{\Gamma_X A^X_{right}}{(\omega + \Omega_{LO})^2 + \left(\frac{\Gamma_X}{2}\right)^2} + \frac{\Gamma_Y A^Y_{right}}{(\omega + \Omega_{LO})^2 + \left(\frac{\Gamma_Y}{2}\right)^2}\right]$$

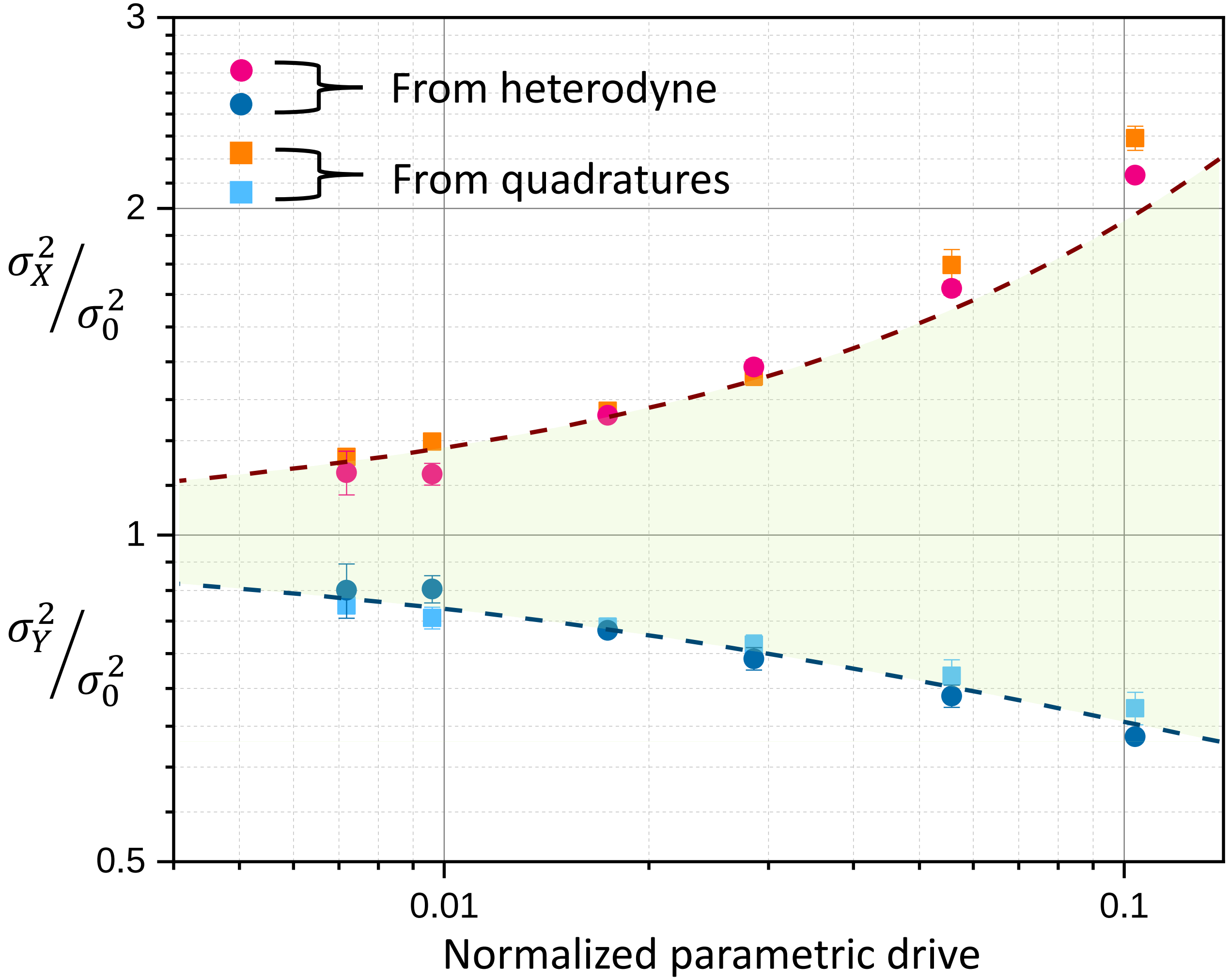
$$s = 0.54$$





Variation of asymmetry of the quadratures

$$S_{tot} = \left[\frac{\Gamma_X A^X_{left}}{(\omega - \Omega_{LO})^2 + \left(\frac{\Gamma_X}{2}\right)^2} + \frac{\Gamma_Y A^Y_{left}}{(\omega - \Omega_{LO})^2 + \left(\frac{\Gamma_Y}{2}\right)^2} + \frac{\Gamma_X A^X_{right}}{(\omega + \Omega_{LO})^2 + \left(\frac{\Gamma_X}{2}\right)^2} + \frac{\Gamma_Y A^Y_{right}}{(\omega + \Omega_{LO})^2 + \left(\frac{\Gamma_Y}{2}\right)^2}\right]$$



$$\Gamma_X = \Gamma_{eff}(1 - s)$$

$$\Gamma_Y = \Gamma_{eff}(1 + s)$$

$$\sigma_X^2 = \frac{\sigma_0^2}{1 - s}$$

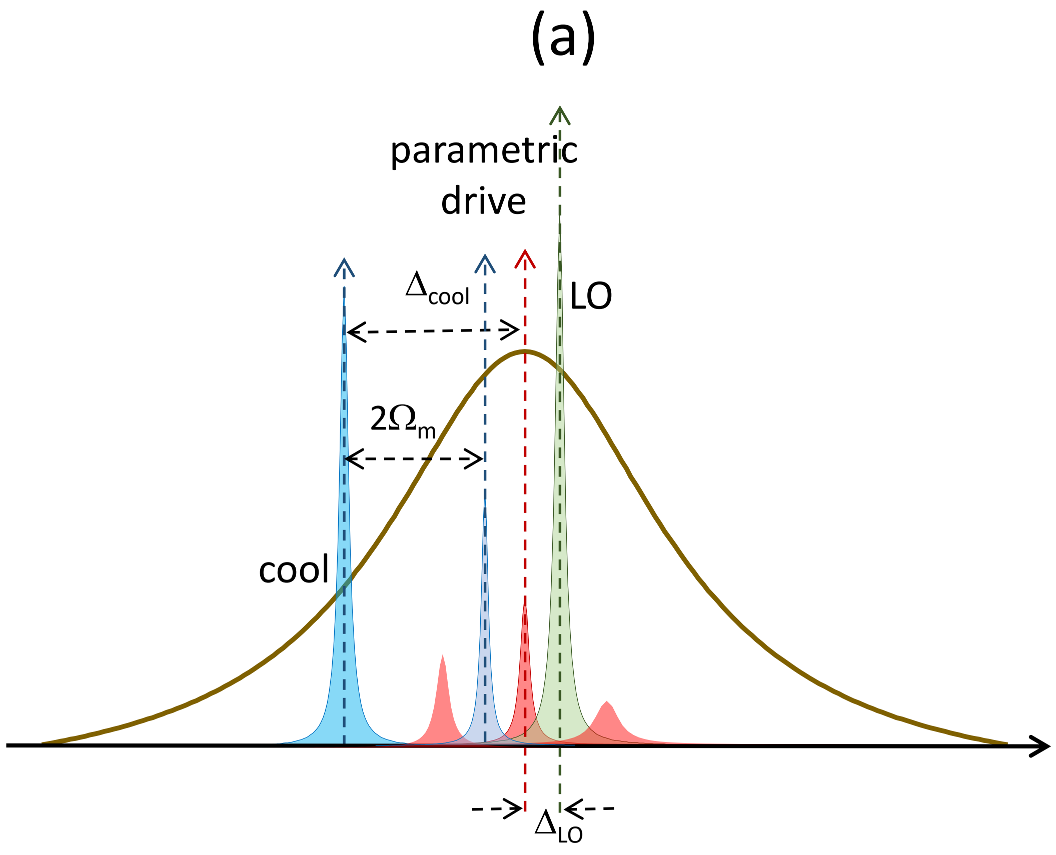
$$\sigma_Y^2 = \frac{\sigma_0^2}{1 + s}$$

Variation of asymmetry of the quadratures

$I_{pump} = I_{cool} + I_{par},$ where: $I_{par} = \alpha I_{pump}$

(a) $\boldsymbol{I_{pump} \uparrow}$ ***keeping*** $\boldsymbol{'\alpha'}$ ***constant***: $\boldsymbol{'s'}$ ***is constant***

(b) $I_{par} \uparrow$ *keeping* I_{pump} *constant*: $'s'$ *varies keeping* Γ_{eff} *constant*



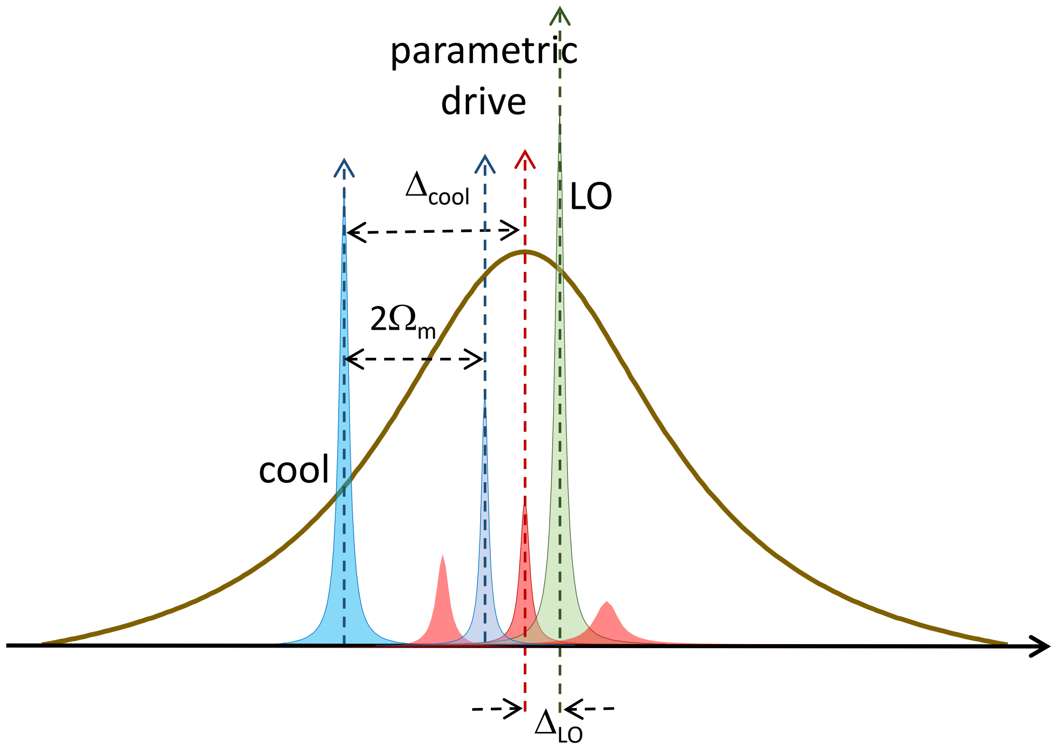
Variation of asymmetry of the quadratures

$I_{pump} = I_{cool} + I_{par},$ where: $I_{par} = \alpha I_{pump}$

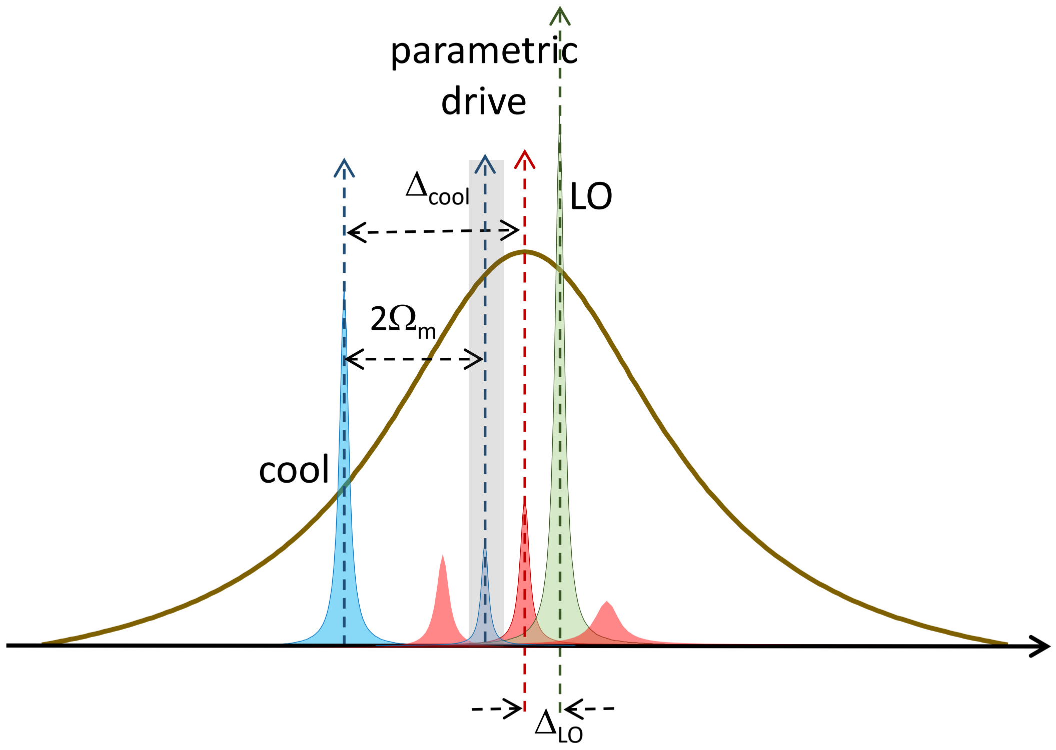
(a) $I_{pump} \uparrow$ *keeping* $'\alpha'$ *constant*: $'s'$ *is constant*

(b) $\boldsymbol{I_{par} \uparrow}$ ***keeping*** $\boldsymbol{I_{pump}}$ ***constant***: $\boldsymbol{'s'}$ ***varies keeping*** $\boldsymbol{\Gamma_{eff}}$ ***constant***

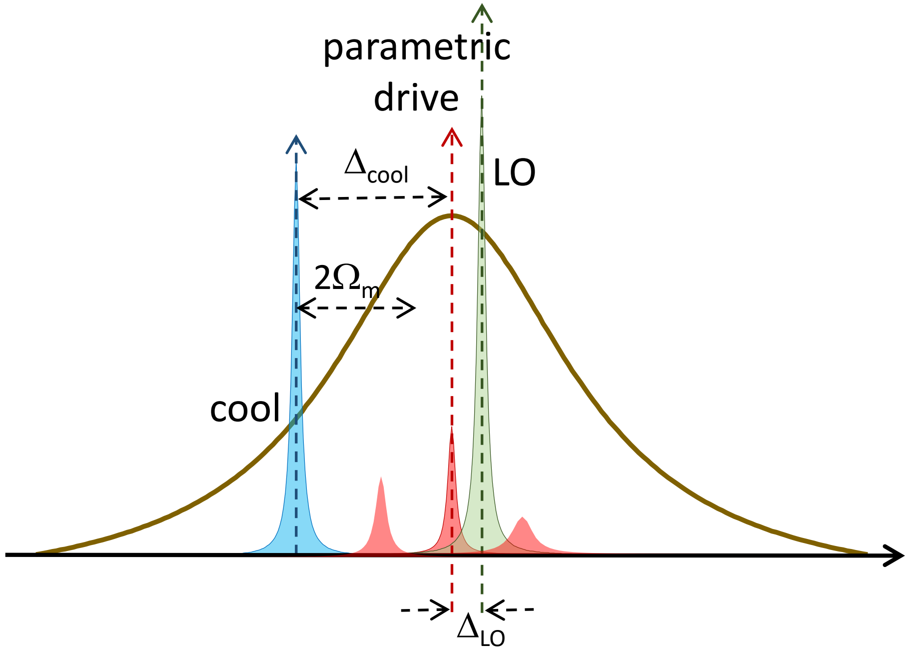
(a)



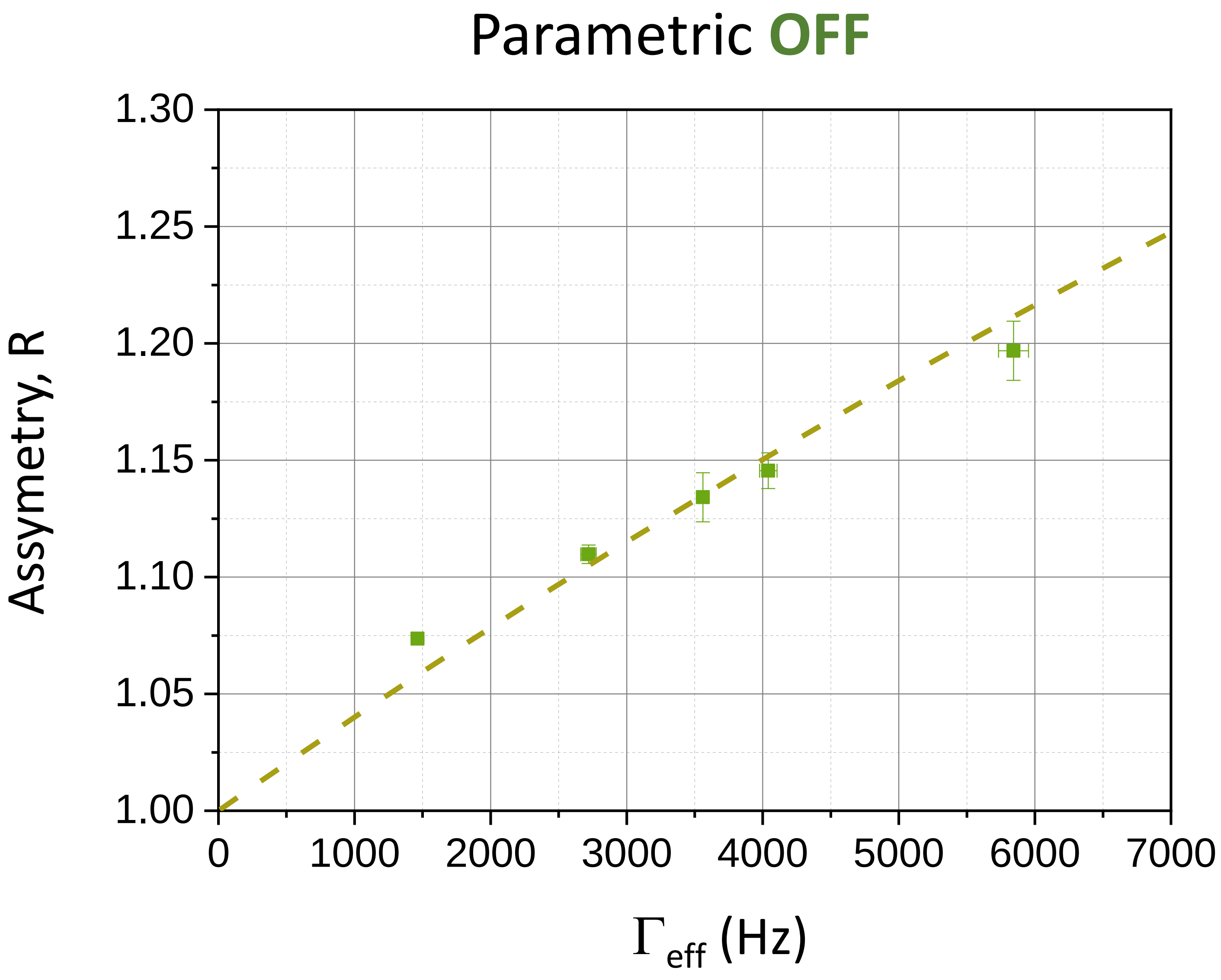
(b)



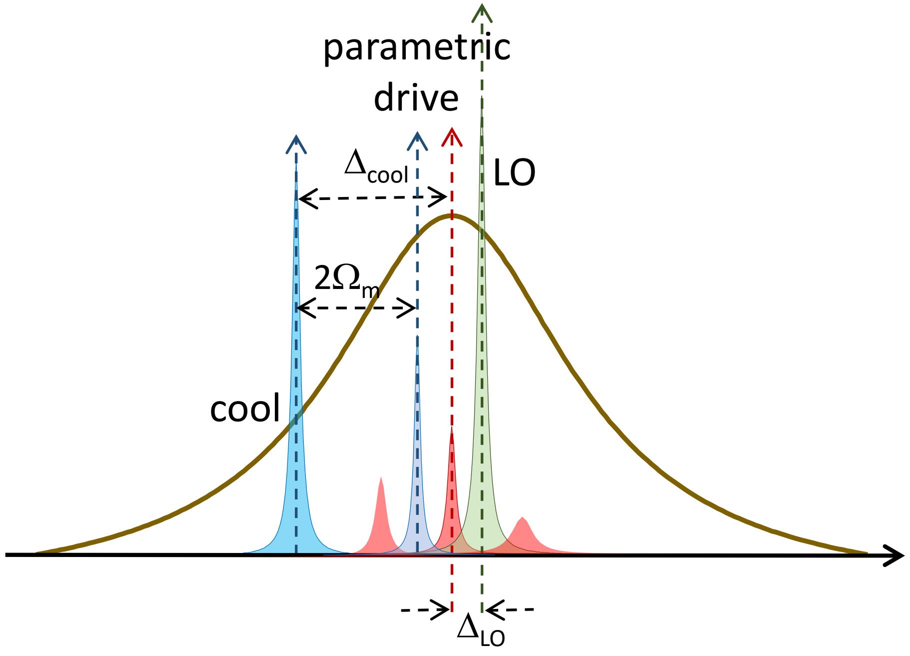
Asymmetry with pump power



SB ratio , R_0 : $\frac{n+1}{n}$



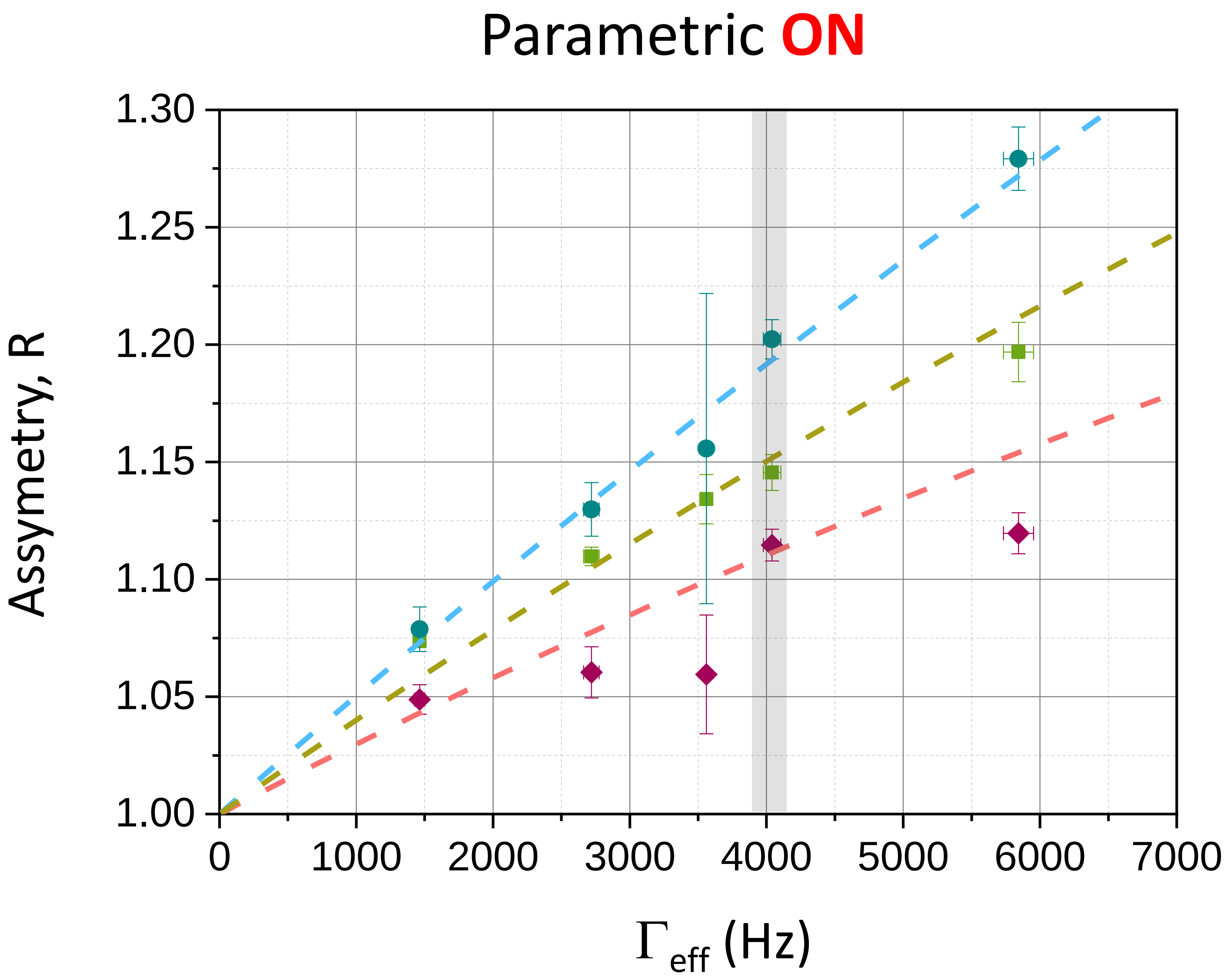
Asymmetry with pump power



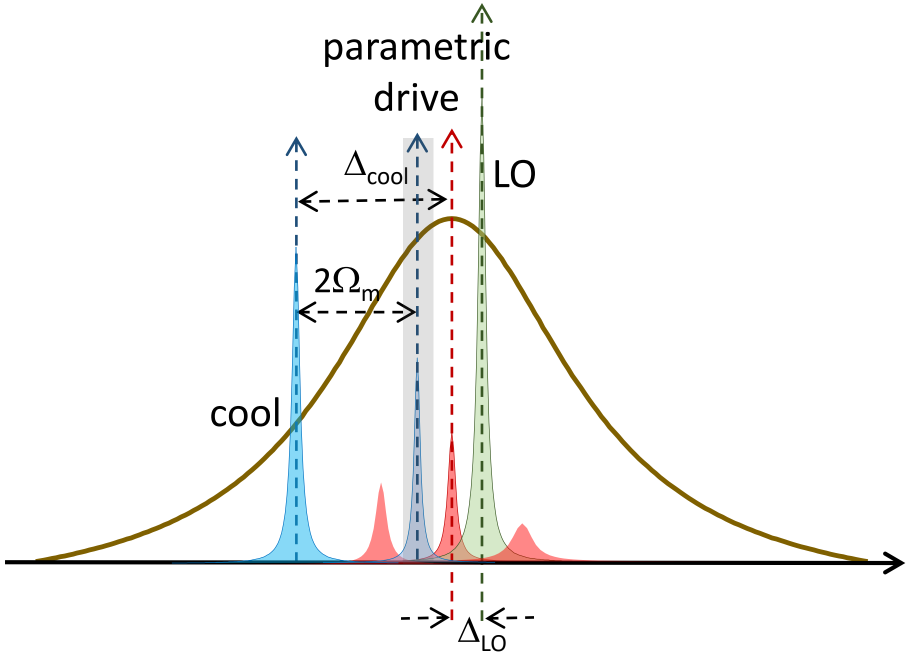
SB ratio , R_0 : $\frac{n+1}{n}$

SB ratio, R_+ : $\frac{n+1+s/2}{n-s/2}$

SB ratio, R_- : $\frac{n+1-s/2}{n+s/2}$



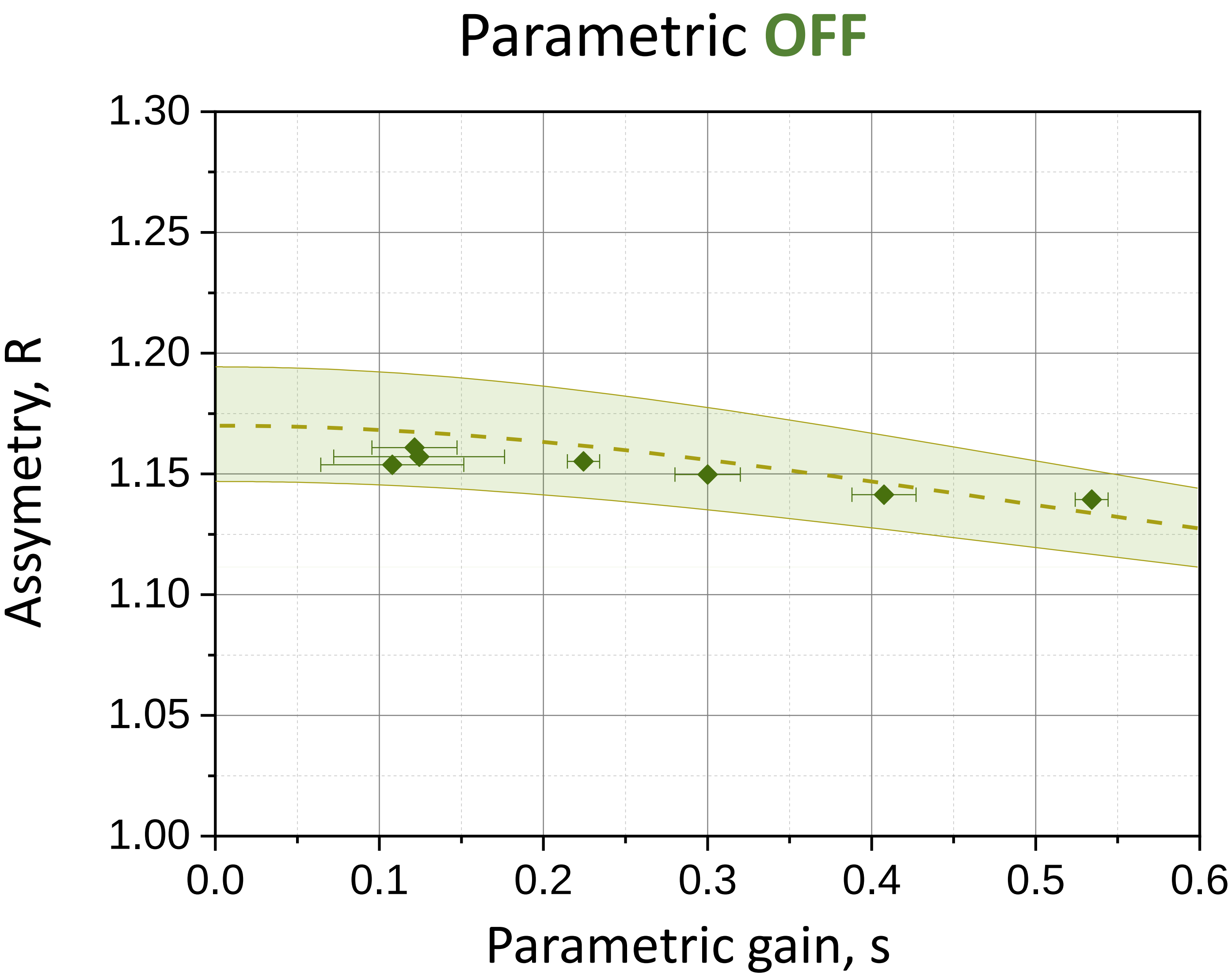
Asymmetry as a function of 's'



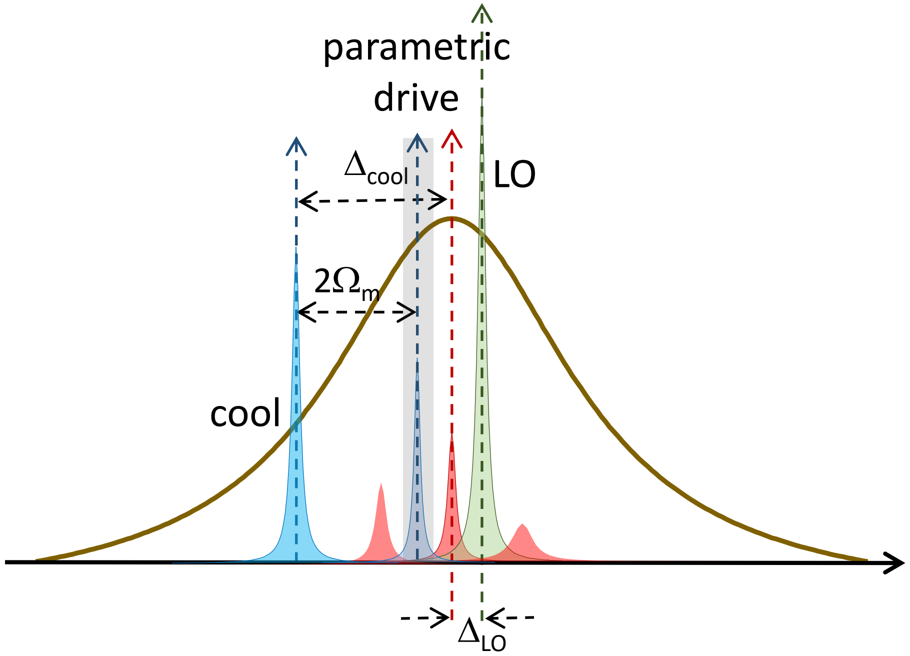
SB ratio , R_0 : $\dfrac{n+1}{n}$

SB ratio, R_+ : $\dfrac{n+1+s/2}{n-s/2}$

SB ratio, R_- : $\dfrac{n+1-s/2}{n+s/2}$



Asymmetry as a function of ‘s’



SB ratio , R_0 : $\dfrac{n+1}{n}$

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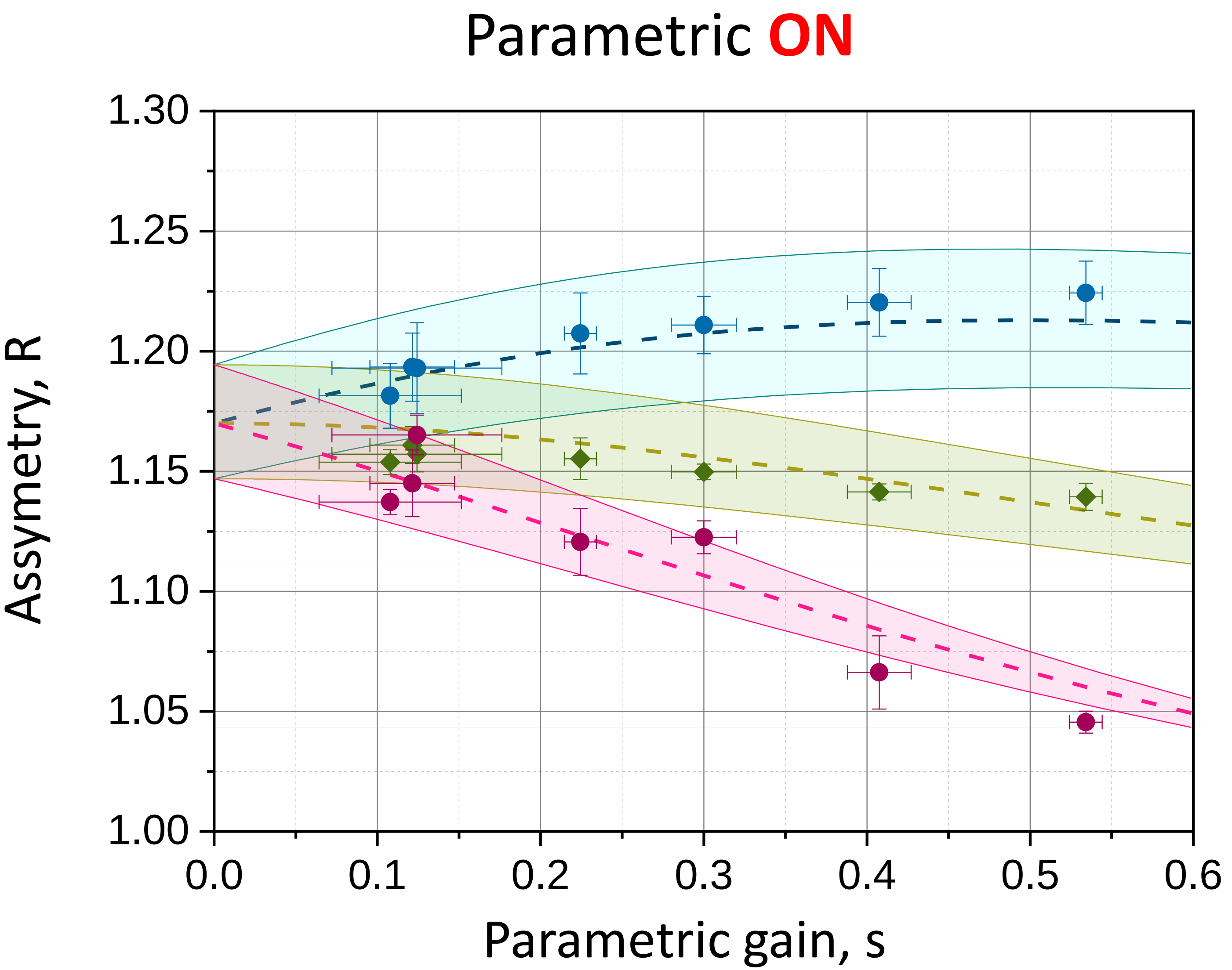
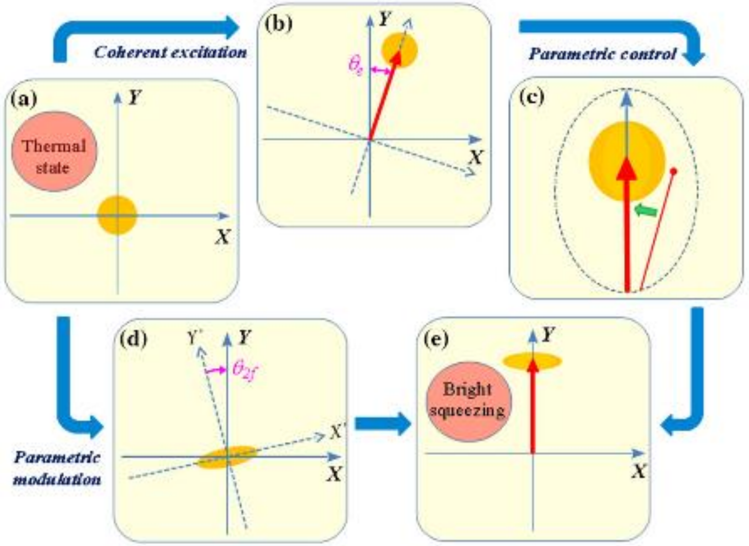
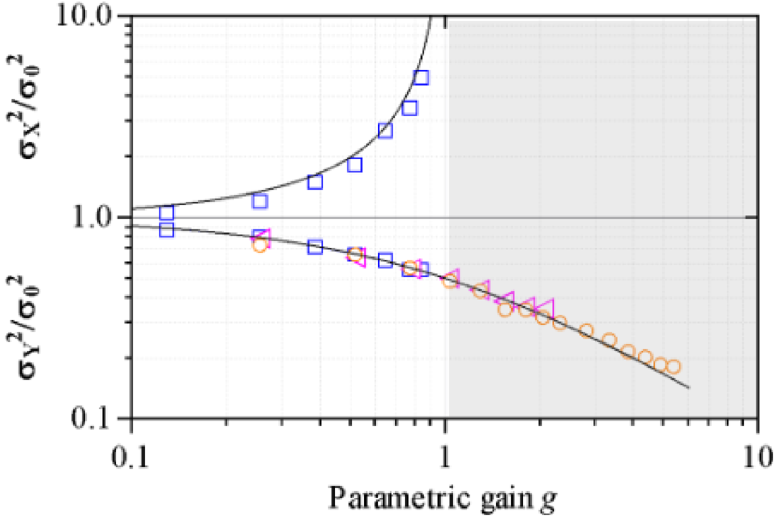
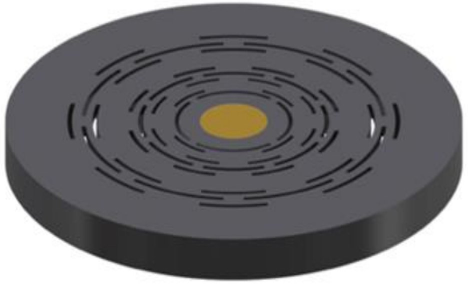


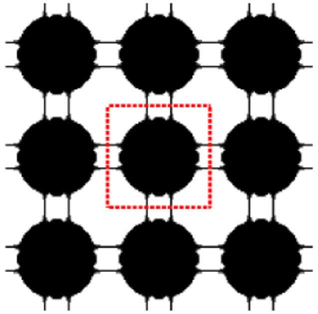
Perspectives

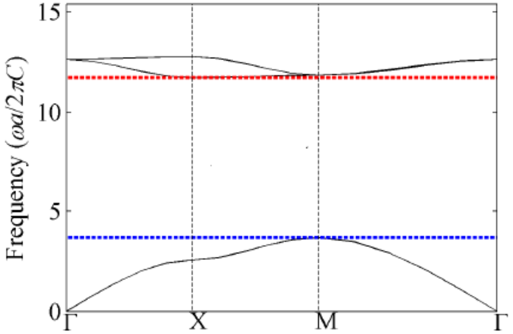




Parametric feedback control to realize squeezing below 3dB limit close to quantum regime







Q ~ 10^8

n~ 10

Quantum squeezing at room temperature

Thanks

Francesco Marin

Francesco Marino

Paolo Vezio

Massimo Calamai