Is delay always harmful to precision?

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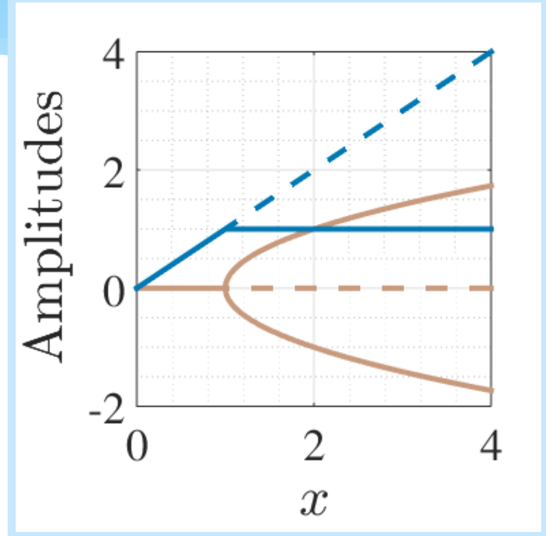
Outline

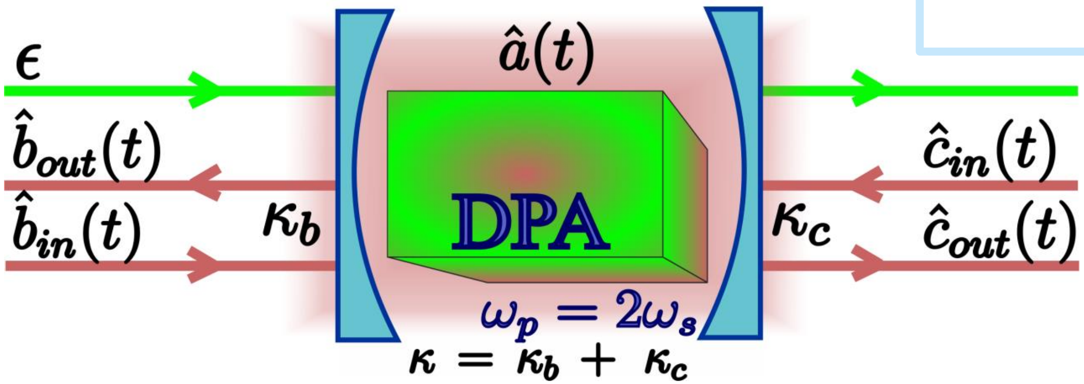
* Degenerate Parametric Amplifier
  * Classical dynamics
  * Squeezing characteristics
* DPA with time-delayed coherent feedback
  * Model
  * Squeezing spectrum
  * Change in the dynamics
  * Effects of loss

DPA dynamics & squeezing

- Classical dynamics:
  - Saturation of pump: threshold behaviour
  - Bifurcation of steady state solutions at $x = \frac{|\epsilon|}{\kappa} = 1$
- Quantum mechanical behaviour[1]:
  - Parametric pump approximation $(\epsilon = |\epsilon| e^{i\theta})$

$$\hat{H} = \hbar\Delta\hat{a}^\dagger\hat{a} + \frac{1}{2} i\hbar\left(\epsilon(\hat{a}^\dagger)^2 + \epsilon^*(\hat{a})^2\right)$$





[1]PRA, **30**:1386 (1984)

DPA dynamics & squeezing

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  * Saturation of pump: threshold behaviour
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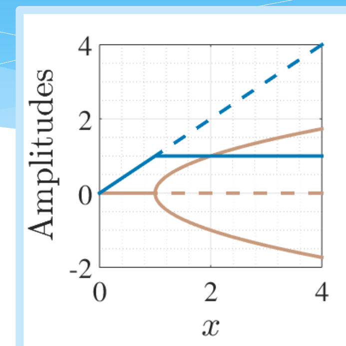
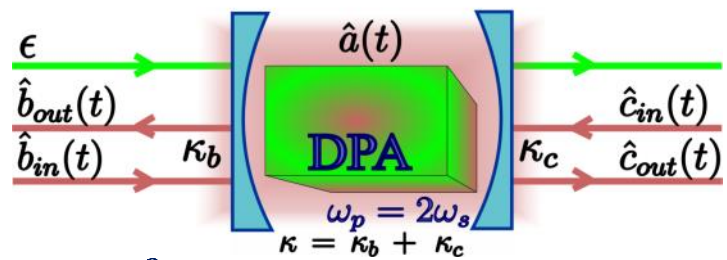


* Quantum mechanical behaviour[1]:
  * Parametric pump approximation $(\epsilon = |\epsilon| e^{i\theta})$

$$\hat{H} = \hbar\Delta\hat{a}^{\dagger}\hat{a} + \frac{1}{2} i\hbar\left(\epsilon\left(\hat{a}^{\dagger}\right)^2 + \epsilon^*(\hat{a})^2\right)$$



  * One-sided cavity quadrature variance:

$$\mathcal{X}_{out,\theta+\pi}(0) = \int \left\langle \widetilde{X}_{out,\theta'}(0), \widetilde{X}_{out,\theta'}(\nu') \right\rangle d\nu' = \frac{1}{4}\frac{(\kappa - |\epsilon|)^2}{(\kappa + |\epsilon|)^2}$$

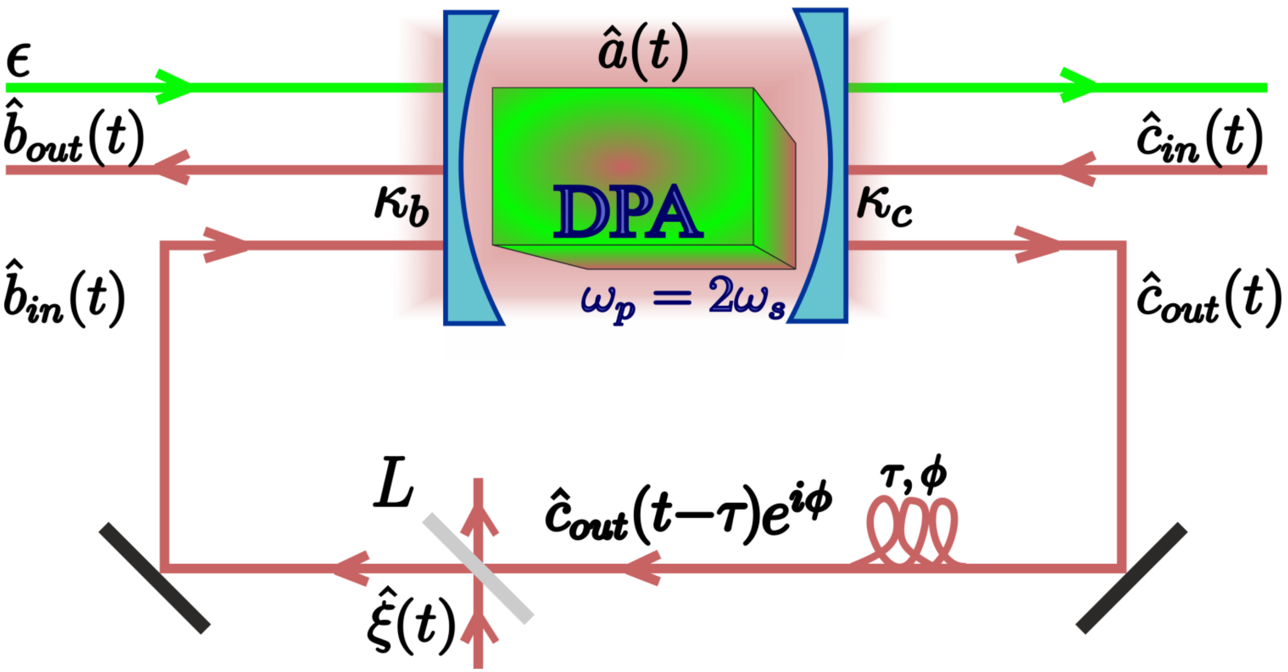
  * Symmetric cavity squeezing on resonance at threshold

$$\mathcal{X}_{out,\theta+\pi}(0) = \frac{1}{4}\frac{\kappa^2 + |\epsilon|^2}{(\kappa + |\epsilon|)^2}$$

[1]PRA, **30**:1386 (1984)

DPA & time-delayed coherent feedback

* Uncomplicated setup
  * Time-delay τ, overall phase-shift ϕ, overall loss, decoherence: $L, \hat{\xi}$



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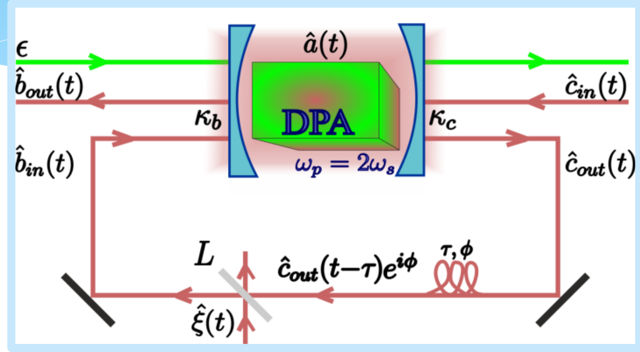


* Equation of motion of the subharmonic mode:

$$\frac{d\hat{a}}{dt} = i[\hat{H}, \hat{a}(t)] - \kappa\hat{a}(t) - \sqrt{2\kappa}\hat{a}_{in}(t) - e^{i\phi}k\hat{a}(t-\tau)$$

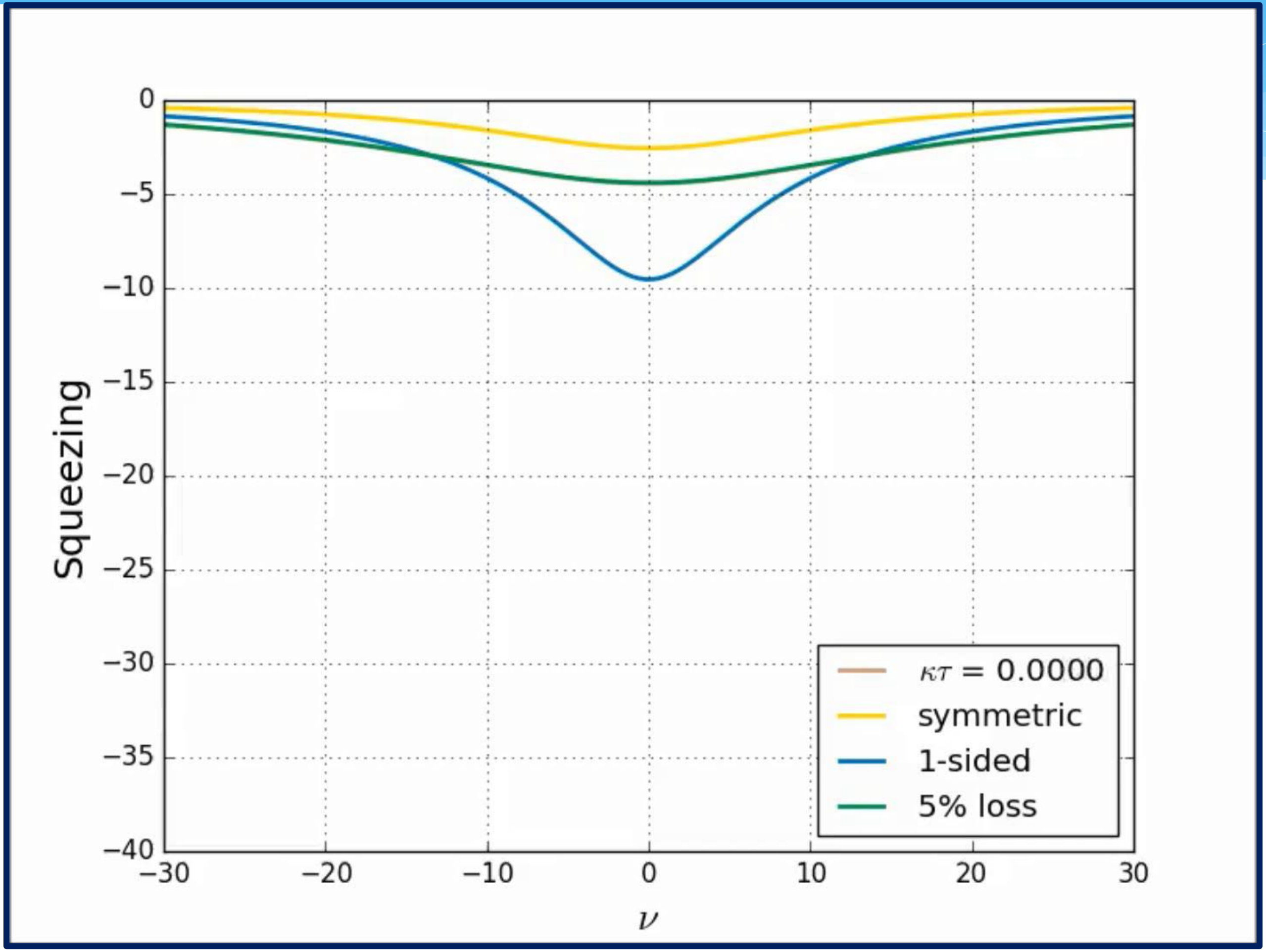
$$\hat{H} = \hbar\Delta\hat{a}^\dagger\hat{a} + \frac{1}{2}i\hbar\left(\epsilon\left(\hat{a}^\dagger\right)^2 + \epsilon^*(\hat{a})^2\right)$$

$$\kappa = \kappa_b + \kappa_c, k = 2\sqrt{\kappa_b\kappa_c(1-L)}$$

* Quadrature variance without delay:

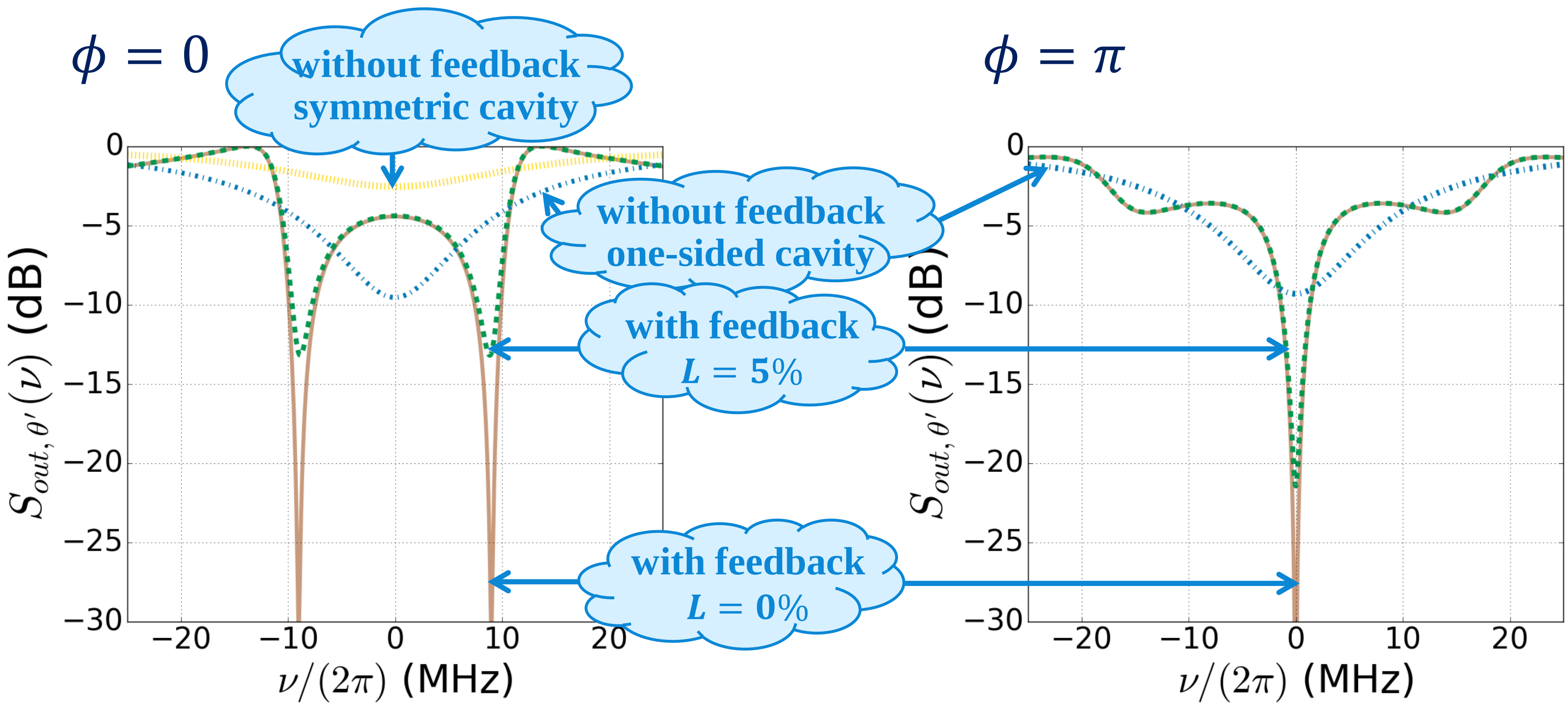
$$X_{out,\theta+\pi}(0) = \frac{1}{4}\frac{((\kappa + k\cos\phi) - |\epsilon|)^2}{((\kappa + k\cos\phi) + |\epsilon|)^2}$$

Emerging side-peaks



New setup with time-delay

- Transcendental equations
- Enhanced squeezing with feedback

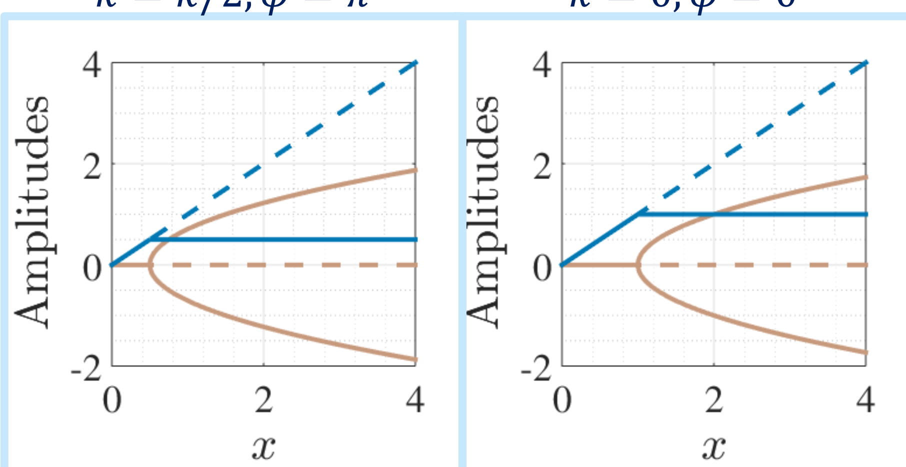


New setup with time-delay

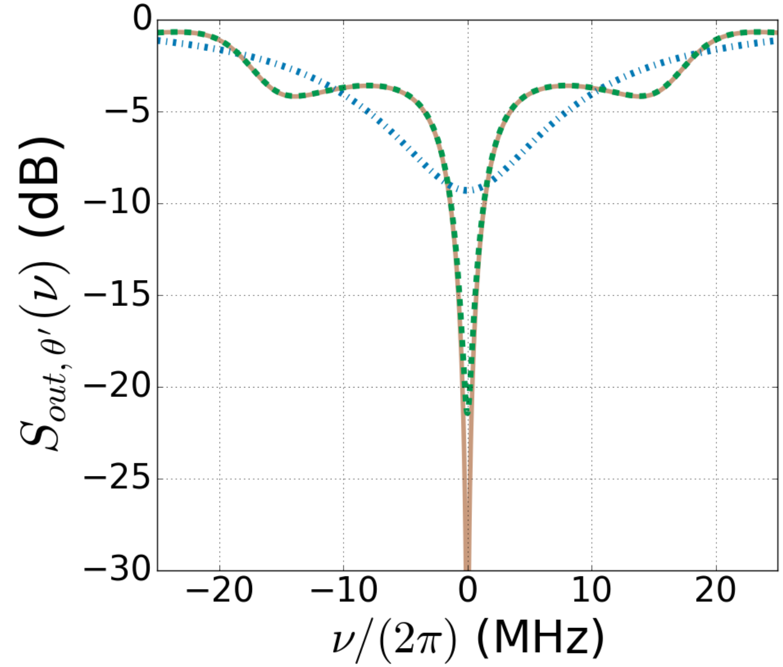
* Transcendental equations
* Enhanced squeezing with feedback
* Pyragas-type feedback:

$$\frac{d\hat{a}}{dt} = i[\hat{H}, \hat{a}(t)] - (\kappa - k)\hat{a}(t) - \sqrt{2\kappa}\hat{a}_{in}(t) +$$
$$+k\big(\hat{a}(t-\tau) - \hat{a}(t)\big)$$

$k = \kappa/2, \phi = \pi$ $\qquad$ $k = 0, \phi = 0$



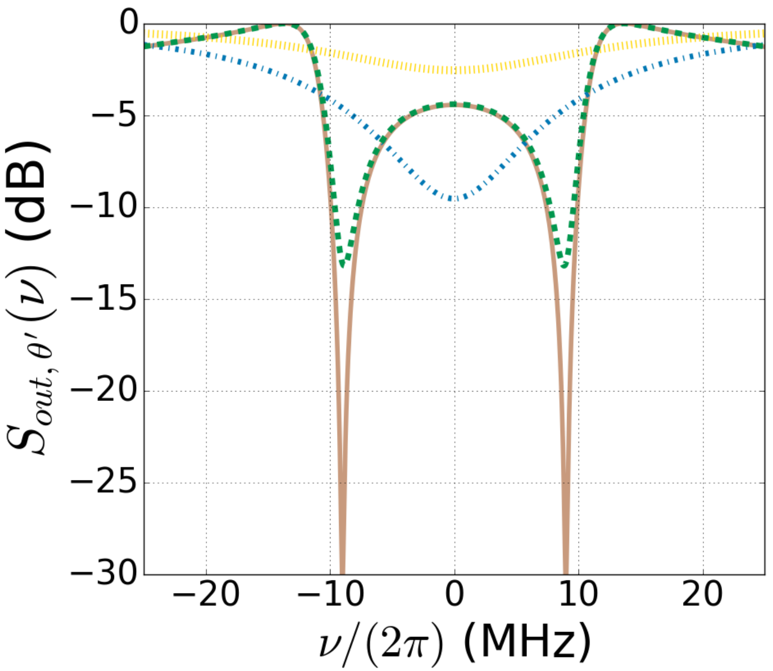
$\phi = \pi, \kappa_b = 0.93\kappa, |\epsilon| = 0.49\kappa,$
$\kappa\tau = 3, L = 0 \ \& \ 5\%$



New setup with time-delay

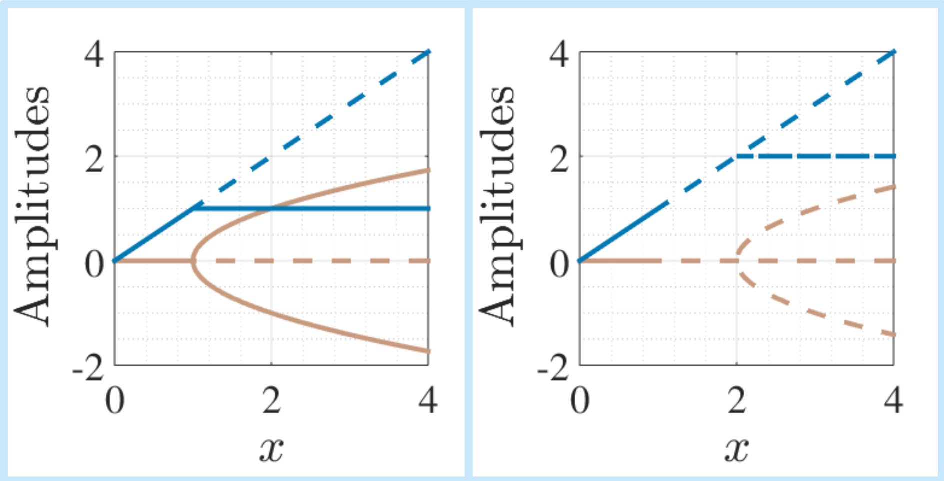
- Transcendental equations
- Enhanced squeezing with feedback

$$\phi = 0, \kappa_b = \kappa_c = 0.5\kappa, |\epsilon| = 0.5\kappa,$$
$$\kappa\tau = 2.3, L = 0 \ \& \ 5\%$$



- Limit cycle is reached on threshold
- Persistent oscillations with the characteristic frequency

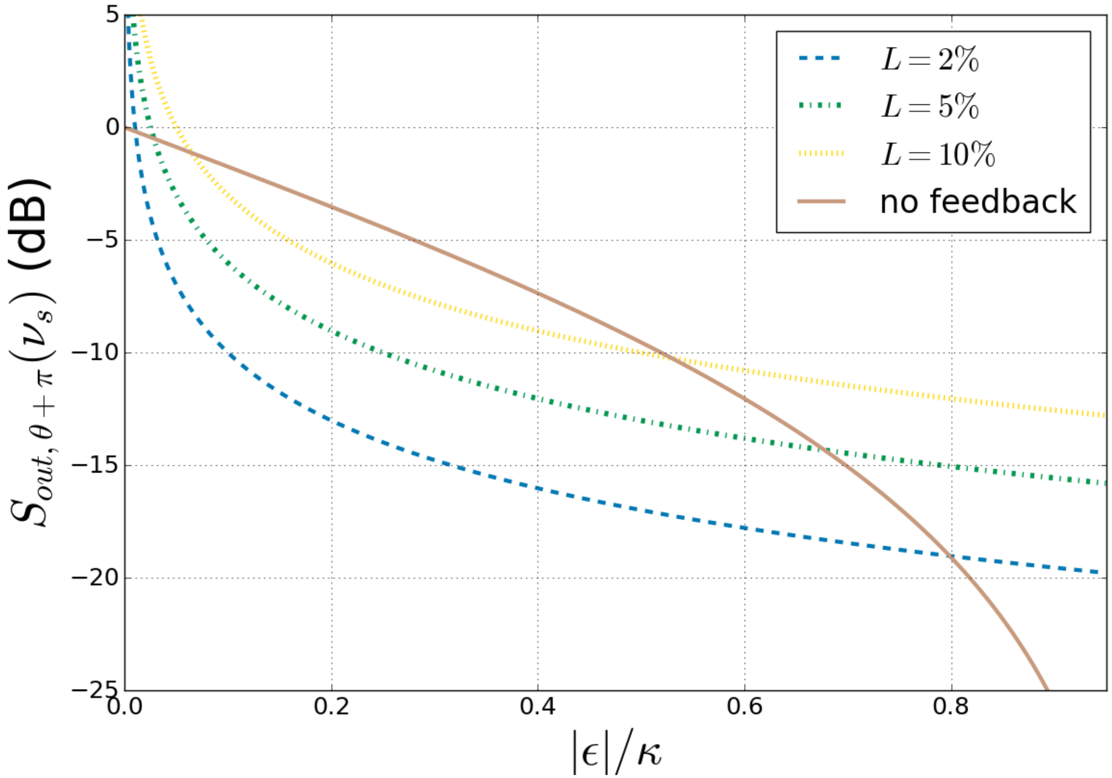
$k = 0, \phi = 0, \kappa\tau = 0$ $\quad$ $k = \kappa, \phi = 0, \kappa\tau = 1.57$



Effects of loss

* With loss wider range of tunability
* Quadrature variance at the critical point:

$$X_{out,\theta'}(\nu_{s,\Delta}) = \frac{1}{4}\frac{L\kappa_c}{|\epsilon_\Delta|}$$



Summary

* Coherent feedback:

  backaction-free way of enhancing useful quantum mechanical behaviours
* Time-delay:

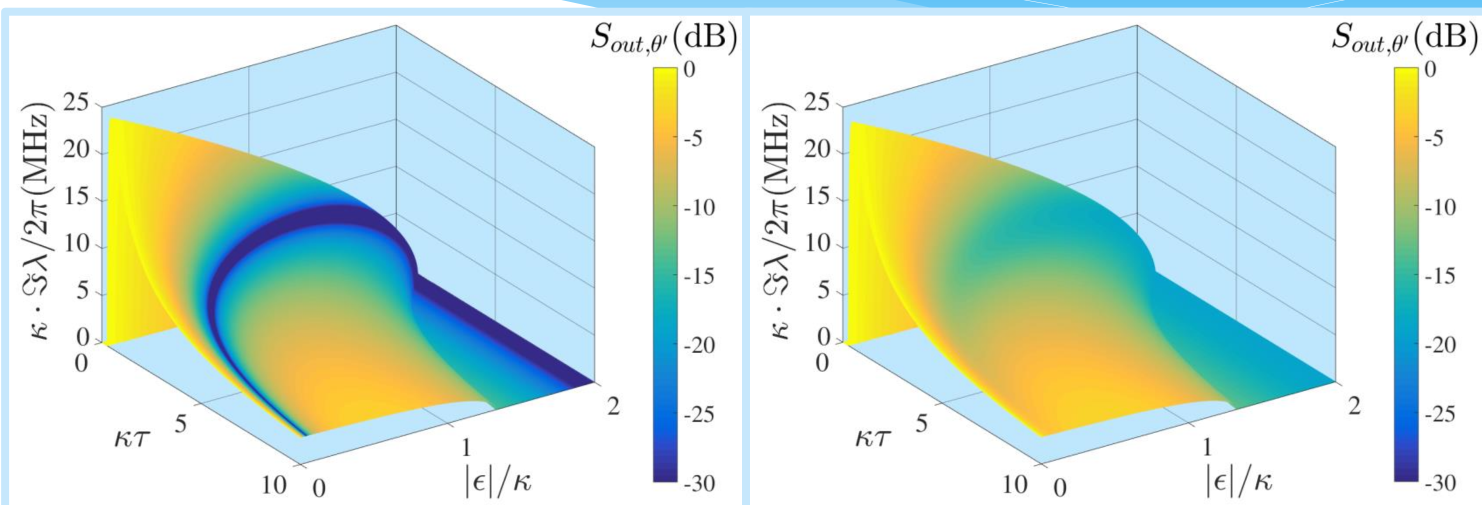
  tunable changes in the stability range
* Time-delayed one-loop setup with a DPA: enhanced squeezing
  * Improvement compared to previous feedback setups
  * On and off-resonant squeezing as well
  * Result of the changing dynamics of the system
* Loss in the feedback loop:
  * Decreased squeezing
  * BUT! higher tunability

Thank you for Your attention!

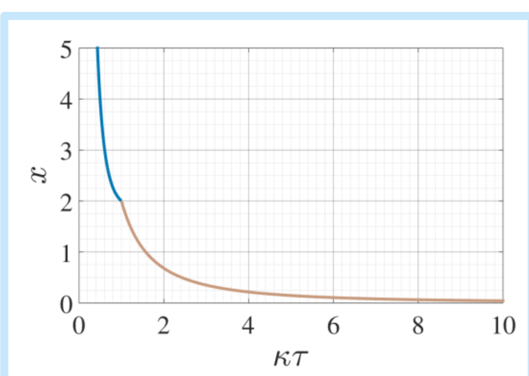
1 2 3 4 5 6 7 8 9 10 11 12
13 14 15 16

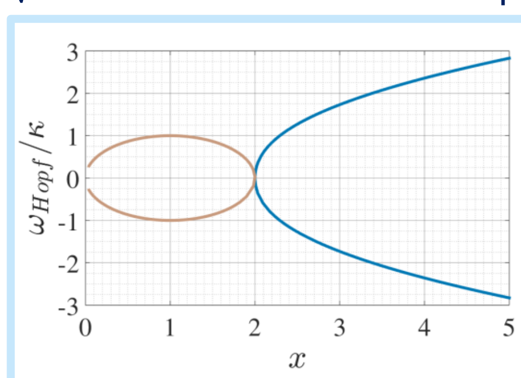
Thank you for Your attention!

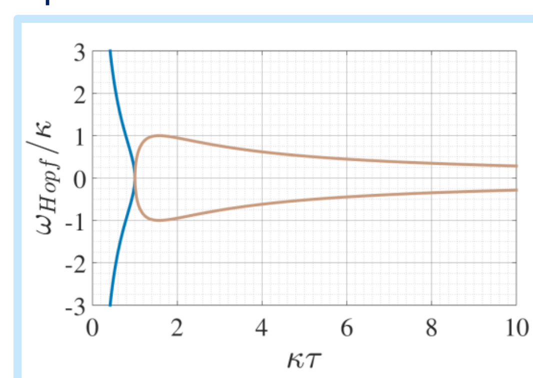
Characteristic frequency range



$$0 \le \nu_s \le \sqrt{|\epsilon|(2\kappa - |\epsilon|)}, 0 \le |\epsilon| \le \left|\kappa + k e^{i\phi}\right|$$



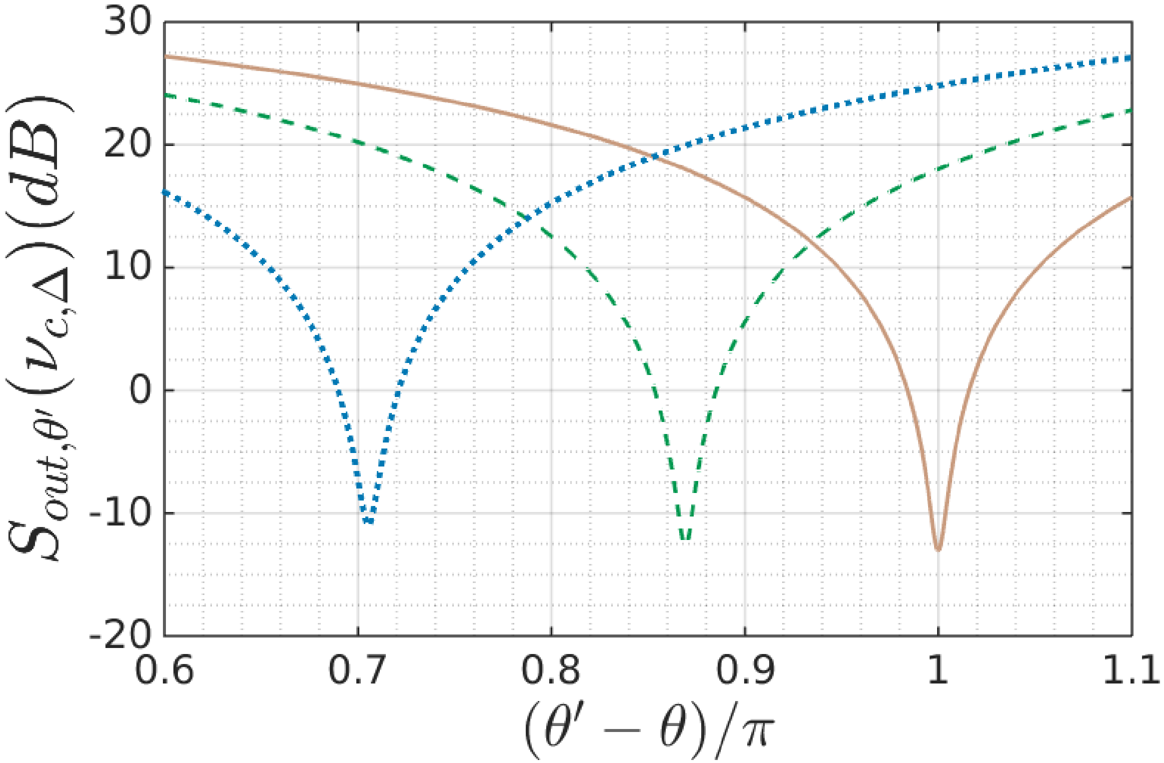




Detuning and quadrature angle

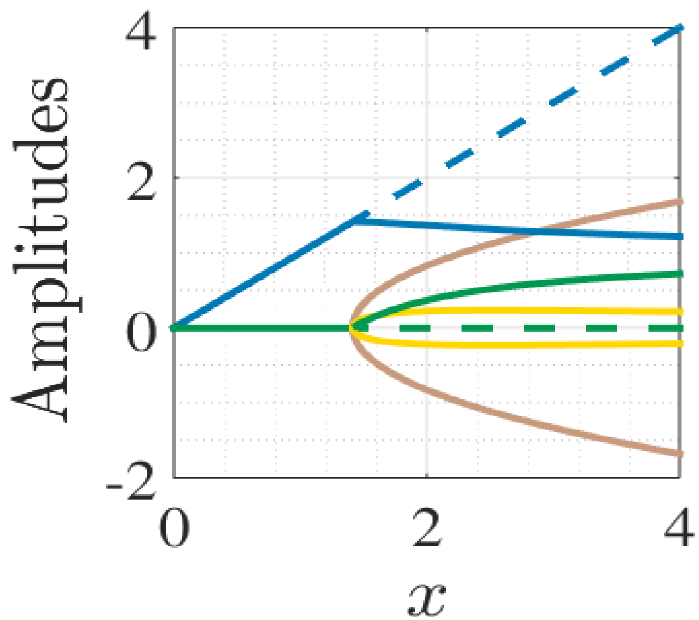
* Local oscillator phase:

$$\theta' = \theta - \pi + \arcsin\left(\frac{\Delta}{|\epsilon_\Delta|}\right)$$



$|\epsilon| = \frac{\kappa}{2}, \kappa_b = \kappa_c = \frac{\kappa}{2},$
$\kappa\tau = 2.418,$
$\nu_{c,\Delta} = 0.866\kappa,$
$L = 5\%,$
$\Delta = 0\ (solid),$
$0.1\kappa\ (dashed)$
$0.2\kappa\ (dotted)$

Effects of the phase shift



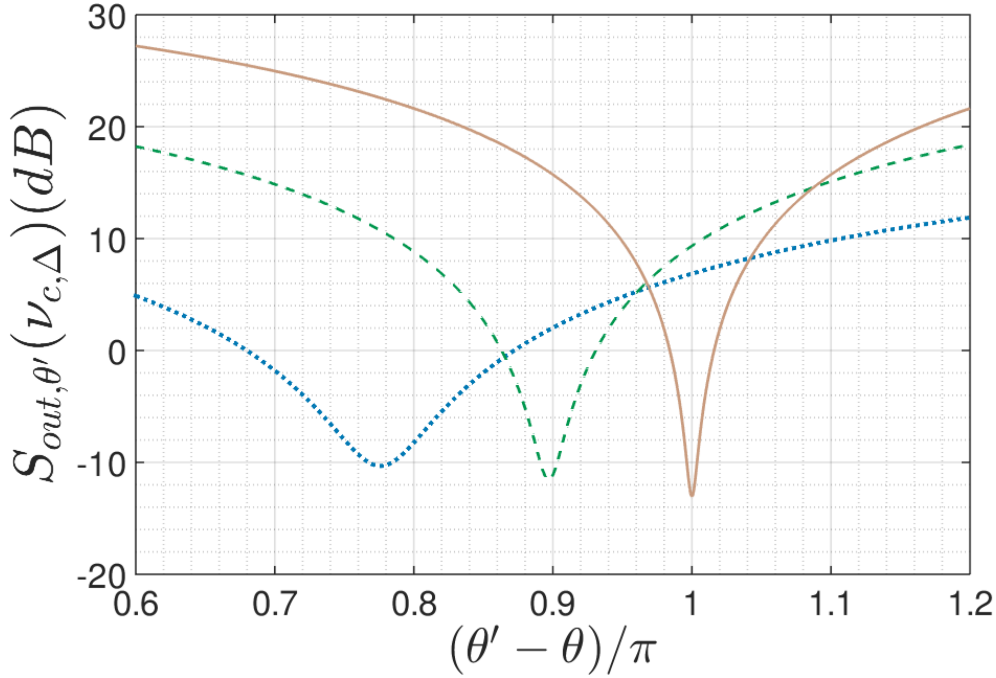
$k = \kappa, \phi = \pi/2$

ε_p: real (blue), imag (green)

ε: real (brown), imag (yellow)

$$|\epsilon| = \frac{\kappa}{2}, \kappa_b = \kappa_c = \frac{\kappa}{2}, \kappa\tau = 2.418, \nu_{c,\Delta} = 0.866\kappa,$$

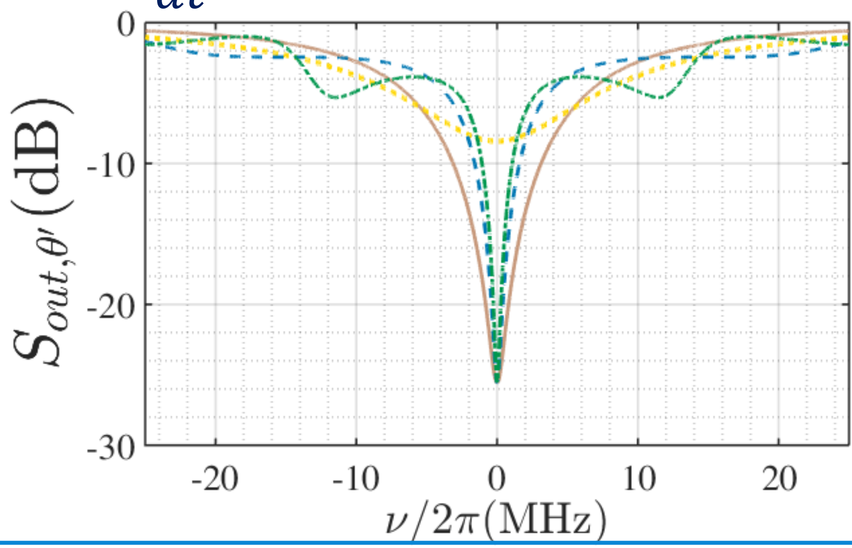
$$L = 5\%, \qquad \phi = -0.1\pi, 0.05\pi \ \& \ 0$$

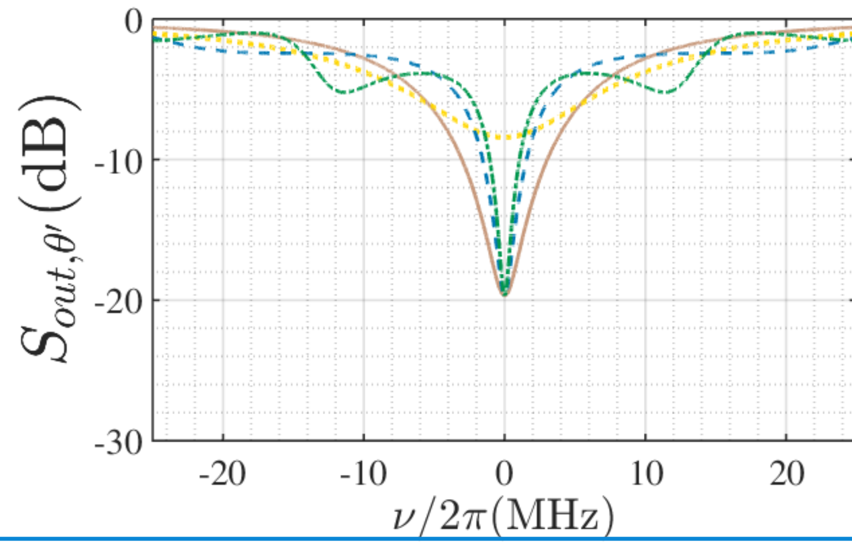


Pyragas-type feedback[1,2]

- Classical: Stabilizing unstable periodic orbitals
- Reordering of the equation of motion with $\phi = \pi$:

$$\frac{d\hat{a}}{dt} = i\left[\hat{H}, \hat{a}(t)\right] - (\kappa - k)\hat{a}(t) - \sqrt{2\kappa}\hat{a}_{in}(t) + k\big(\hat{a}(t-\tau) - \hat{a}(t)\big)$$

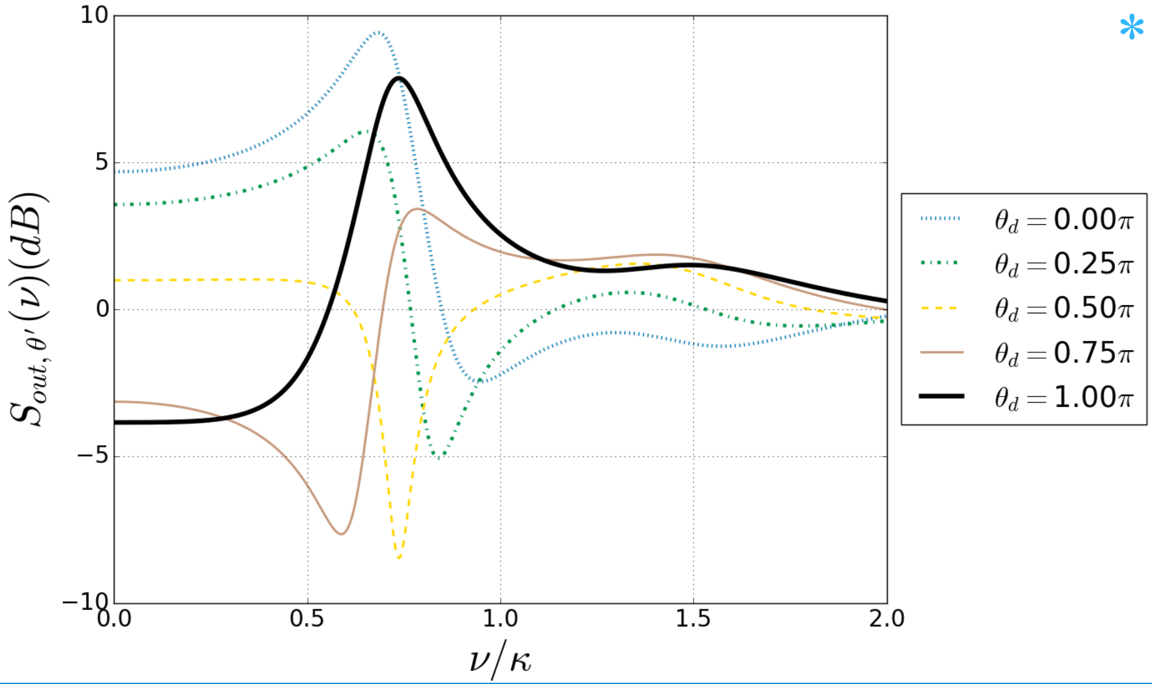




[1]PLA, **170**:421 (1992), [2]NJP **16**:065004 (2014),

Gravitational waves

* Adding π to the local oscillator phase in our case gives the required characteristics



* Frequency of the best squeezing: changing with the local oscillator phase
  * Lower frequencies: around $\theta' - \theta = 0$
  * Higher frequencies: around $\theta' - \theta = \pi$

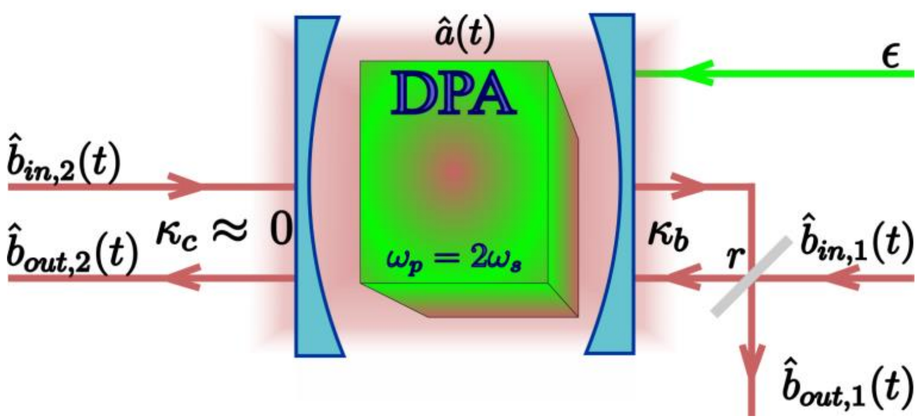
[1]PLA, **170**:421 (1992), [2]NJP **16**:065004 (2014),

Coherent feedback with DPA

* Single DPA
  * Feedback via beam splitter[1]
  * Enhanced, tunable squeezing at a given driving strength

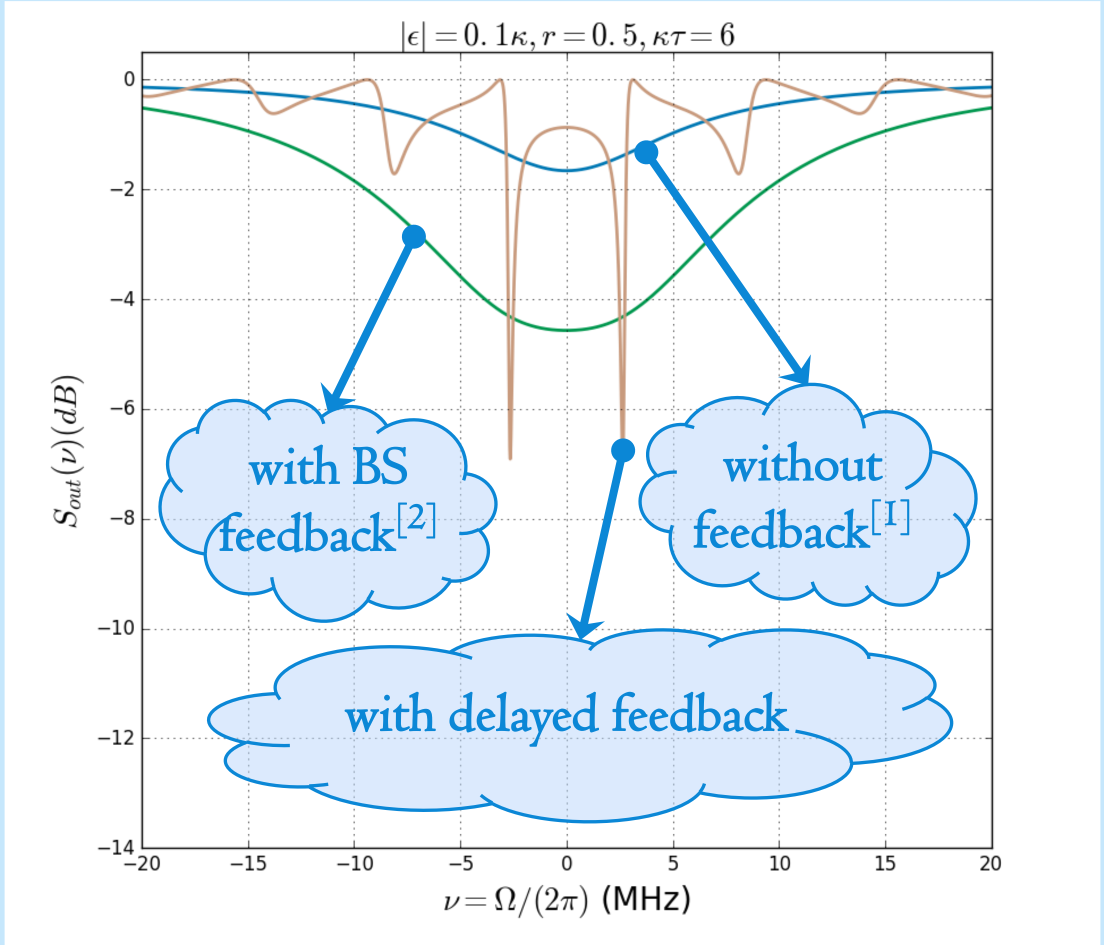
$$\mathcal{X}_{out,\theta+\pi}(0) = \frac{1}{4}\frac{(\kappa(r)-|\epsilon|)^2}{(\kappa(r)+|\epsilon|)^2}$$

  * Modified threshold
  * Experiment[2] agrees with theory[1]
  * BUT! Performance is limited
    * efficient $|\epsilon|$ range under 0.6κ
    * losses through the „perfectly reflecting mirror"



[1]PRA, **80**:042107 (2009), [2]IEEE Trans. Auto. Contr., **57**:2045 (2012)

Comparison with previous results[1,2]



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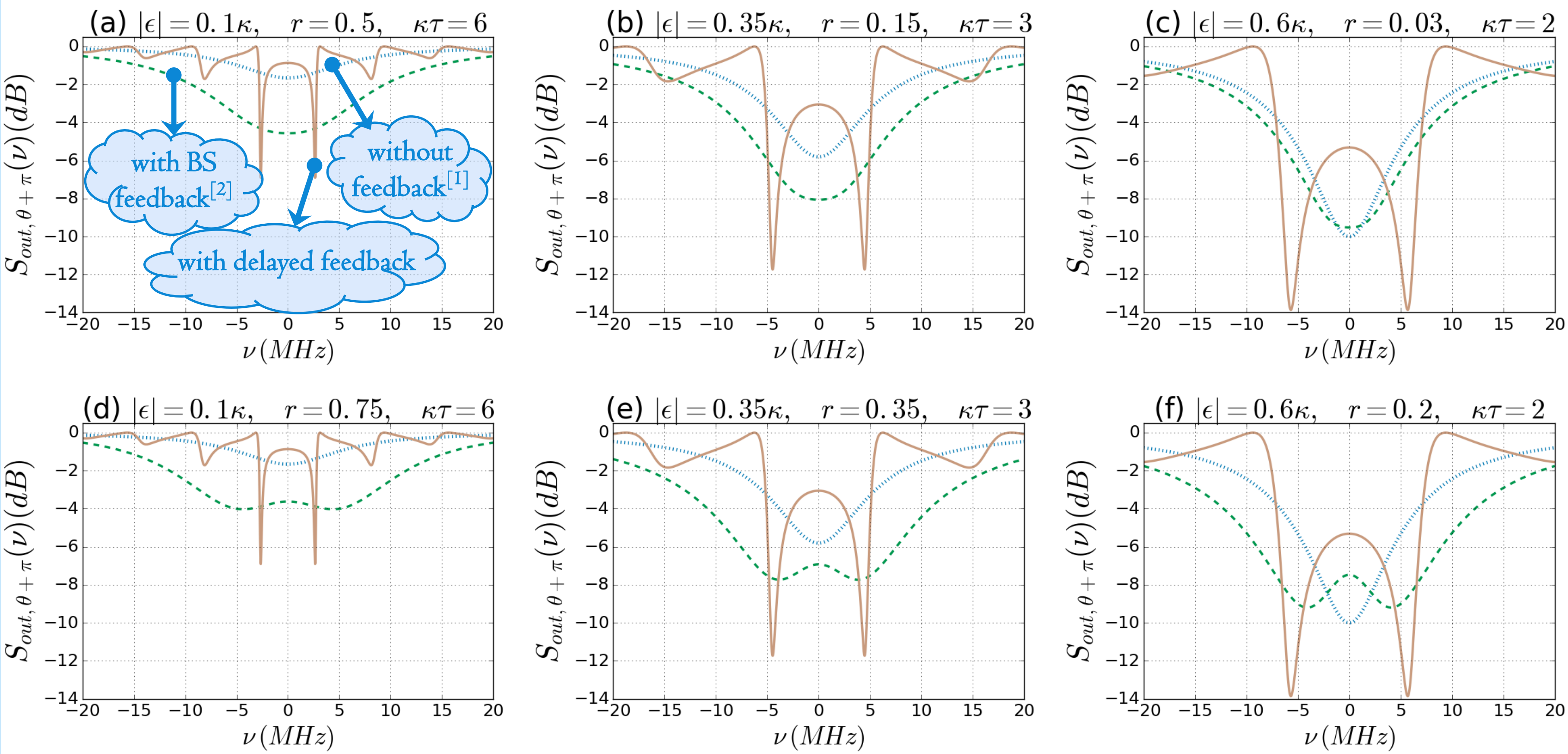

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New setup with time-delay

* Transcendental equations
* Enhanced squeezing with feedback
* Properties:
  * Best squeezing is on resonance
  * Effects of time-delay:
    * Narrower spectrum
    * Emerging small side-peaks
  * Perfect squeezing at stability change
    * Condition: $\kappa - k = |\epsilon_\Delta| = \sqrt{|\epsilon|^2 - \Delta^2}$
    * Local phase: $\theta' = \theta - \pi + \arcsin\left(\frac{\Delta}{|\epsilon_\Delta|}\right)$
    * Variance: $\mathcal{X}_{out,\theta'}(\nu_{s,\Delta}) = \frac{1}{4}\frac{L\kappa_c}{|\epsilon_\Delta|}$

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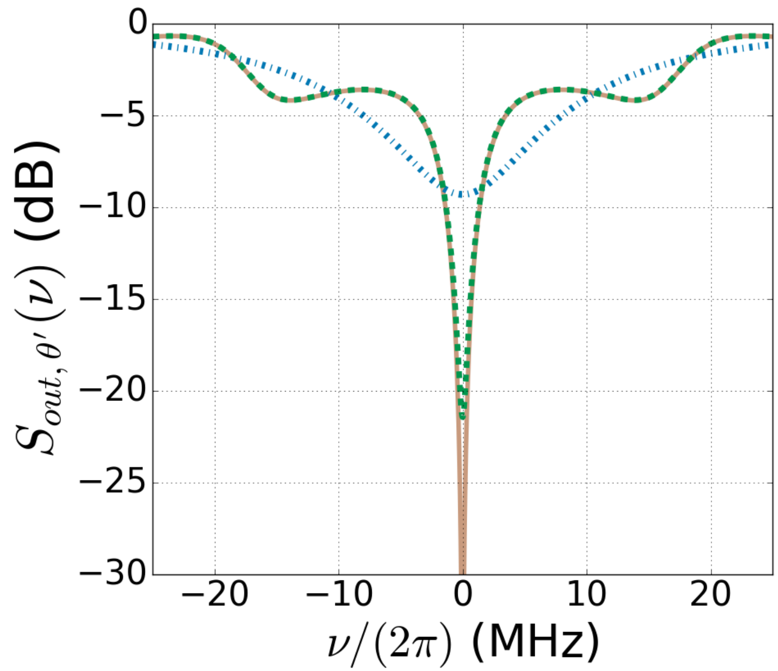

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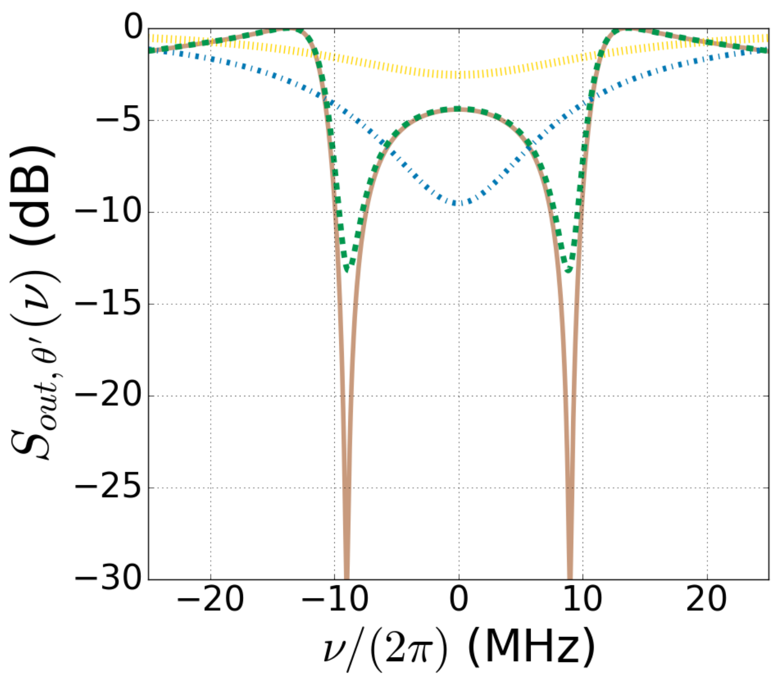

* Properties:
  * Best squeezing is off-resonant
  * Perfect squeezing at stability change
    * Local phase: $\theta' = \theta - \pi + \arcsin\left(\frac{\Delta}{|\epsilon_\Delta|}\right)$
    * Time-delay: $\tau_{s,n,\Delta} = \dfrac{\arccos\left(\frac{|\epsilon_\Delta|-\kappa}{k}\right)+2n\pi}{\nu_{s,\Delta}}$
    * Frequency: $\nu_{s,\Delta} = \pm\sqrt{k^2 - (|\epsilon_\Delta| - \kappa)^2}$
    * Variance: $\mathcal{X}_{out,\theta'}(\nu_{s,\Delta}) = \frac{1}{4}\frac{L\kappa_c}{|\epsilon_\Delta|}$

Classical analysis

* Originally: pitchfork bifurcation
* Time-delay: Changing stability of steady state solutions

  ↓

  Hopf bifurcation
* Imaginary eigenvalue becomes the frequency of persistent oscillations