Josephson parametric amplifiers for axion detection

JILA, U. of Colorado

Maxime Malnou
Daniel Palken
William F. Kindel
Konrad. W. Lehnert

NIST Boulder

Leila Vale
Gene Hilton

LLNL

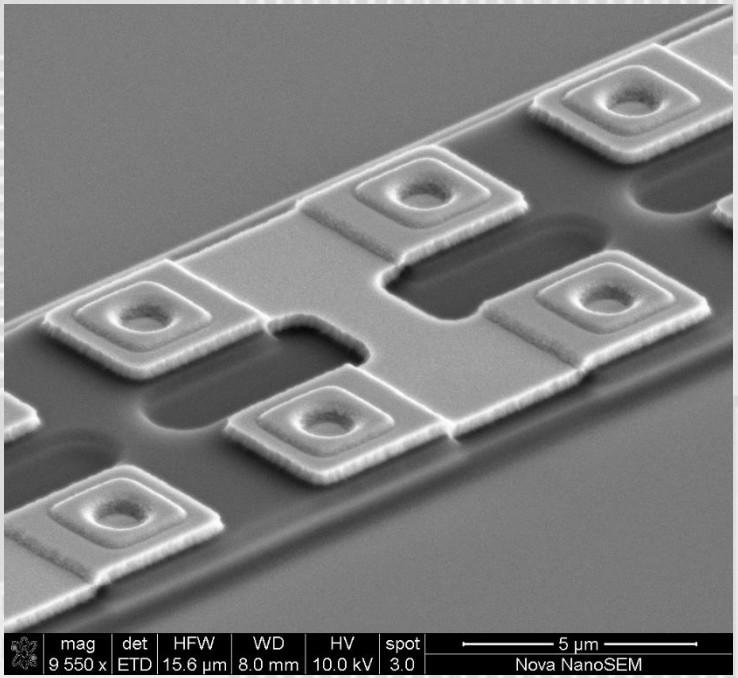
Timothy Shokair
Gianpaolo Carosi

UC Berkeley

Maria Simanovskaia
Samantha Lewis
Jaben Root
Saad Al Kenany
Nicholas Rapidis
Isabella Urdinaran
Karl van Bibber

Yale

Benjamin Brubaker
Kelly Backes
Ling Zhong
Sid Cahn
Steve Lamoreaux



Hypothetical axion: a light particle, cold and dense enough to contribute to dark matter

mechanism to resolve strong-CP problem (Peccei and Quinn)

associated particle (axion) is dark matter candidate

axion mass:

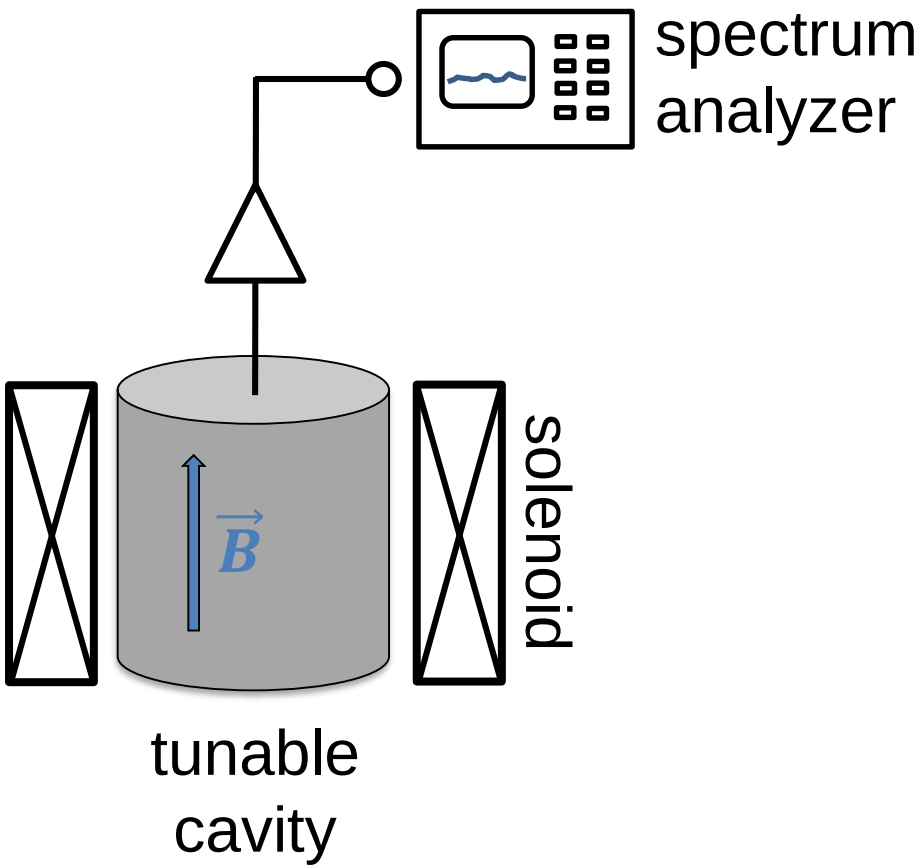
$1\ \mu\mathrm{eV} < \mathrm{m_a}c^2 < 1\ \mathrm{meV}$ → $250\ \mathrm{MHz} < \nu_\mathrm{a} < 250\ \mathrm{GHz}$

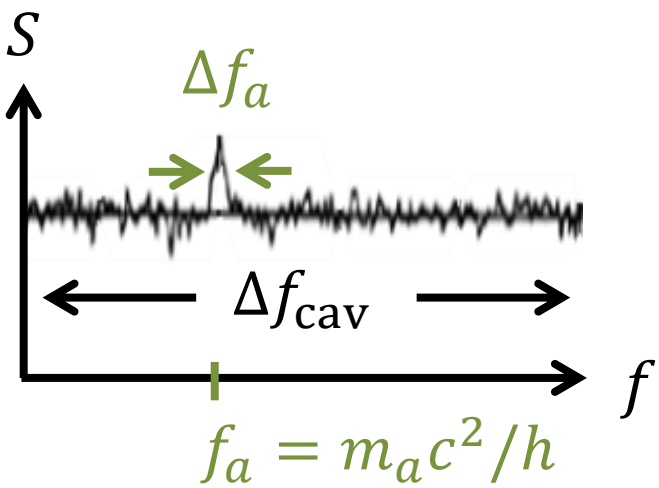
axion couples to EM field → creates microwave photons

Scan narrowband cavity to search for resonant axion to photon conversion (Sikivie 1983)

looking at an excess of photons in a microwave cavity

axion signal: $P_s \sim \omega_c B^2 V Q_L$





axion line narrower than cavity

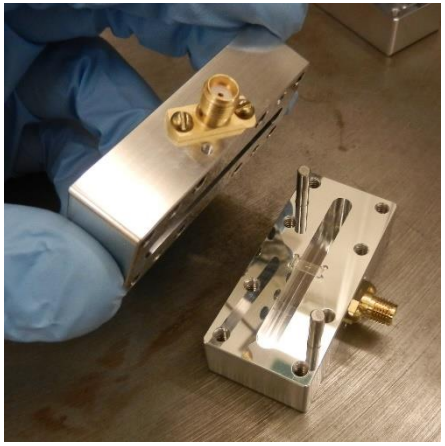
$$\frac{f_a}{\Delta f_a} \approx 10^6 \qquad \frac{f_{\mathrm{cav}}}{\Delta f_{\mathrm{cav}}} \approx 10^5$$

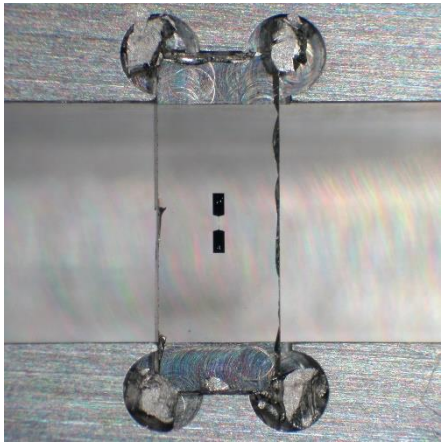
Detection of axions, quantum perspective

axion-photon conversion: $N_s \sim 10^{-3} - 10^{-6}$ photons

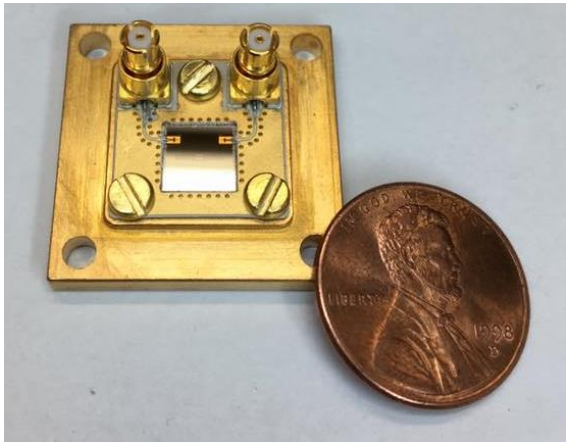
detection:

counting photons:
qubit

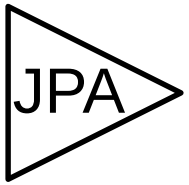




measuring a field:
microwave amplifier



Using a Josephson parametric amplifier



phase insensitive, quantum limited:

noise ≥1 photon

cavity vacuum fluctuations:
½ photon

amplifier added noise:
≥ ½ photon

SNR > 1 → $10^6 - 10^{12}$ independent measurements

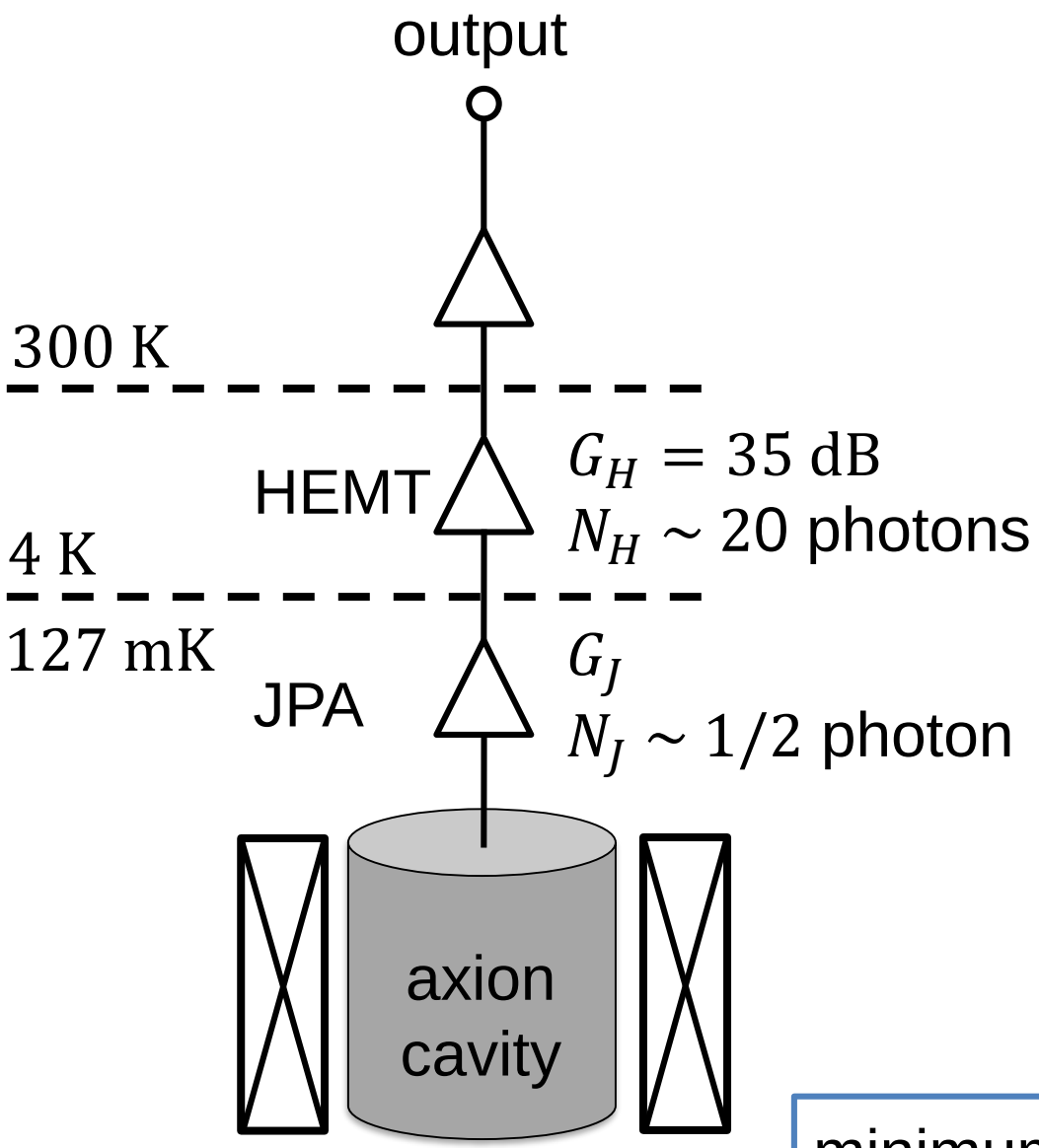
phase sensitive, squeezing:

accelerate axion scan rate

Josephson parametric amplifiers for axion detection

- Current JPA mode of operation
- Squeezing to enhance the axion scan rate
- Loss limitations

Reaching the quantum limit with a JPA



noise limited by JPA:

$$N_J > \frac{N_H}{G_J}$$

$$G_J > 20 \text{ dB}$$

axion cavity linewidth:

$\sim 500 \text{ kHz} < B_J$

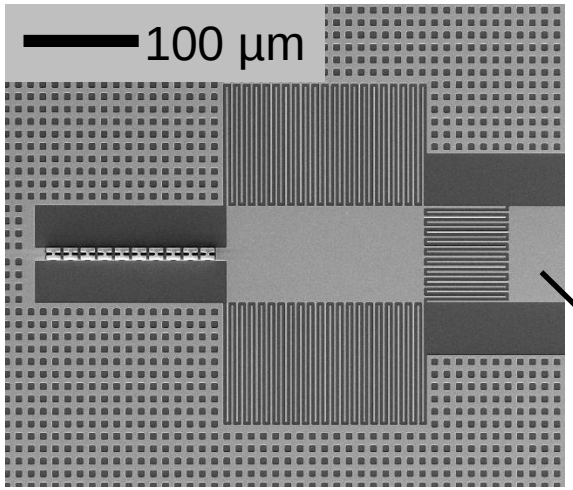
$$B_J > 2 \text{ MHz}$$

$(@G_J = 20 \text{ dB})$

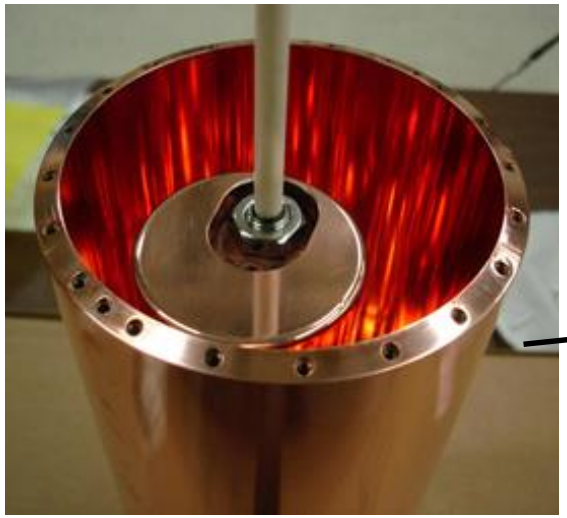
minimum: $\sqrt{G_J} * B_J = 20 \text{ MHz}$

Overview of the experiment and its integration

JPA (tunable)



Microwave Cavity (tunable)



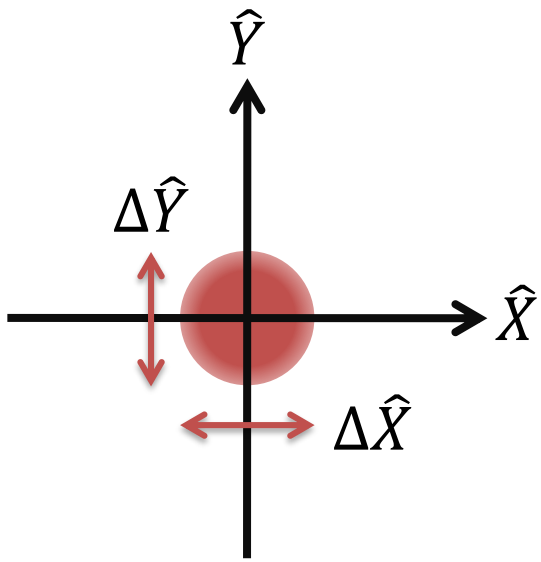
$^3He/^4He$ Dilution Refrigerator

9.4 Tesla, 10 Liter Magnet

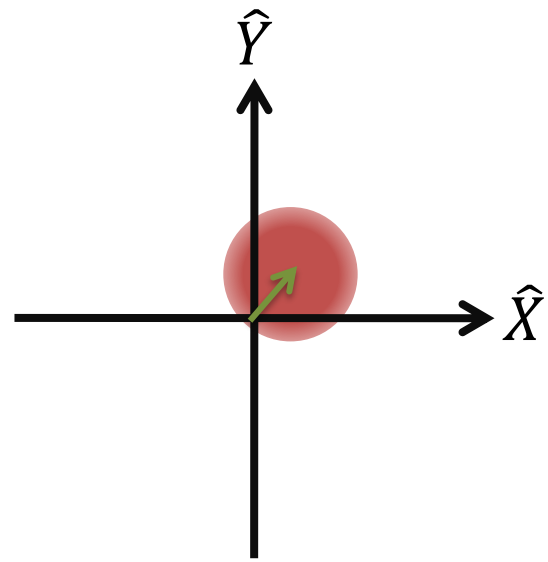
Axion search rate limited by fundamental sources of noise

amplifier measures cavity quadratures $\hat{X}$ and $\hat{Y}$

$$\hat{H}_{\text{cav}} = \hbar\omega_c\left(\hat{a}^\dagger\hat{a} + 1/2\right) = \hbar\omega_c\frac{\hat{X}^2 + \hat{Y}^2}{2} \qquad \left[\hat{X},\hat{Y}\right] = i \rightarrow \Delta\hat{X}\Delta\hat{Y} \geq \frac{1}{2}$$

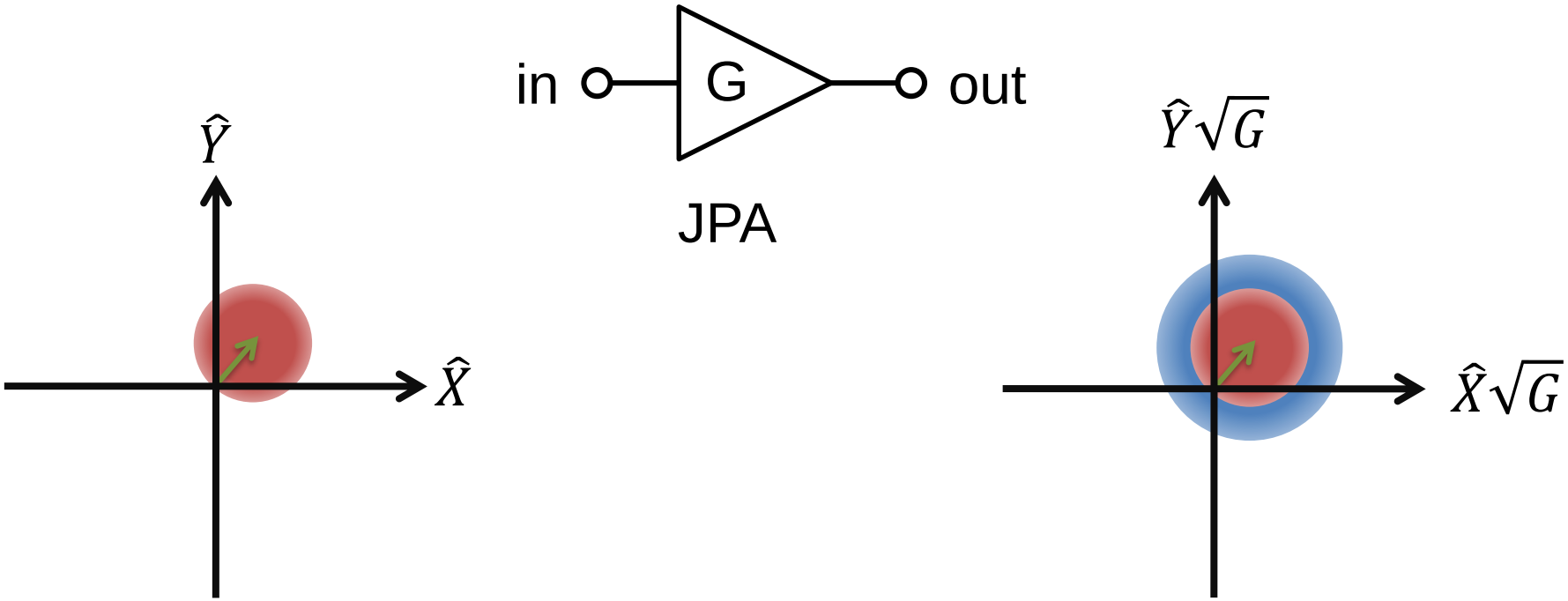


vacuum state



axion displaced state

Linear, phase-insensitive amplifiers must add noise



phase space volume not conserved → added noise

$$N_{\text{add}} \geq \frac{1}{2}$$

First near-quantum limited haloscope data

tunable: $4 - 6.5\ \mathrm{GHz}$

$\sqrt{G} * B = 31\ \mathrm{MHz}$ → $\mathrm{B} = 2.8\ \mathrm{MHz}$ @ $G = 21\ \mathrm{dB}$

added noise: 0.63 photons (@ $127\ \mathrm{mK}$)

↓

4.5 months data acquisition this year:
$100\ \mathrm{MHz}$ scanned @ $5.7 - 5.8\ \mathrm{GHz}$ (no axion)

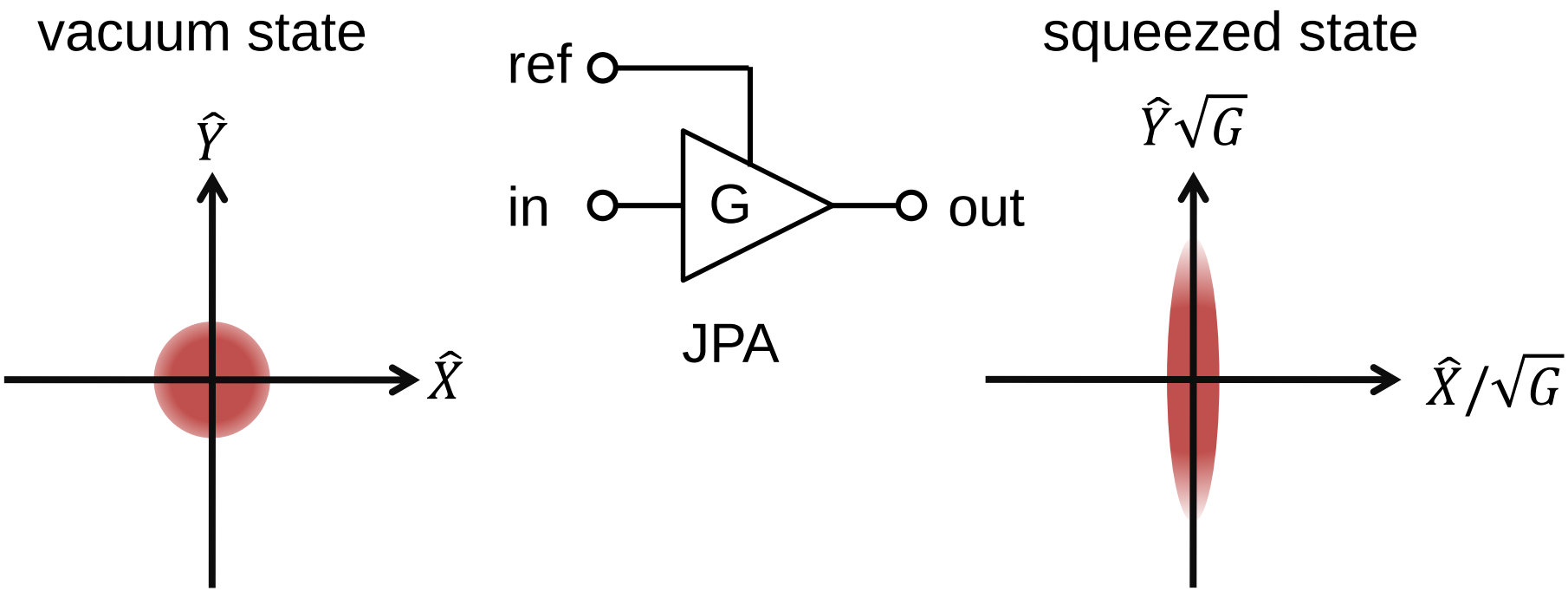
Brubaker et al. – arXiv (2016)
submitted to PRL

scan $4 - 12\ \mathrm{GHz}$ → 30 years (5 PhD student lifetimes) !!

Josephson parametric amplifiers for axion detection

- Current JPA mode of operation
- Squeezing to enhance the axion scan rate
- Loss limitations

Phase sensitive amplifier prepares a squeezed state

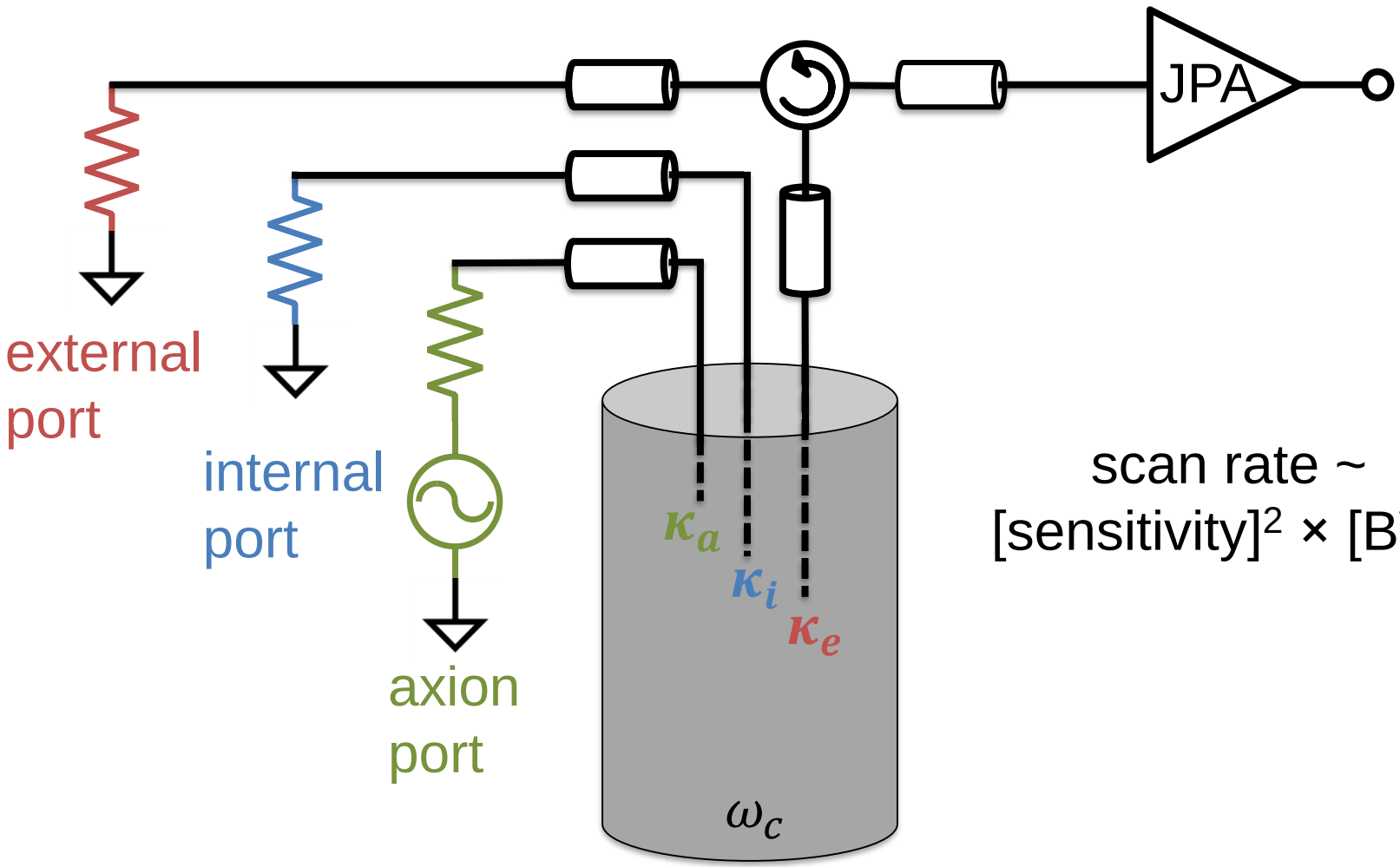


phase space volume conserved → no added noise

$$N_{\mathrm{add}} \geq 0$$

➡ use JPA to prepare cavity in squeezed state

Modeling the signal and noise



scan rate ~ [sensitivity]^2 × [BW]

axion cavity (tunable)

$Q_i = {}^{\omega_c}/_{\kappa_i} = 30{,}000$

$T = 127\ \mathrm{mK}$

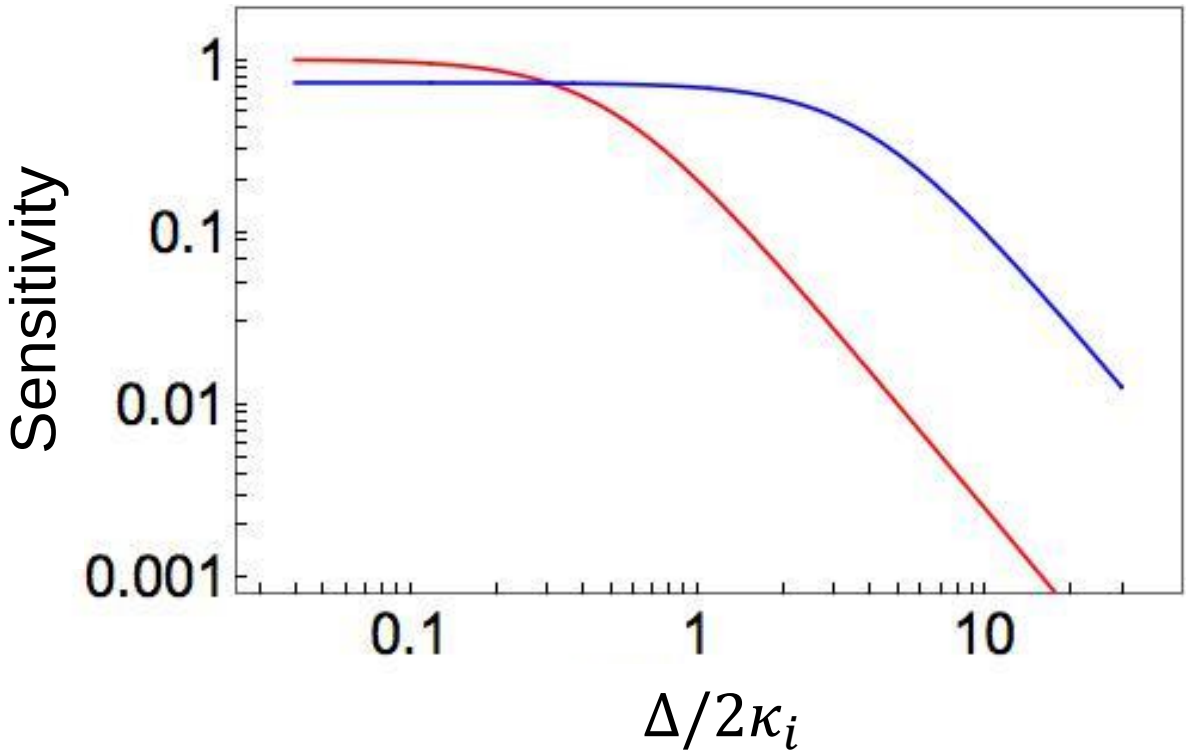
Benefit of squeezing

without squeezing:

$\kappa_i = \kappa_e$

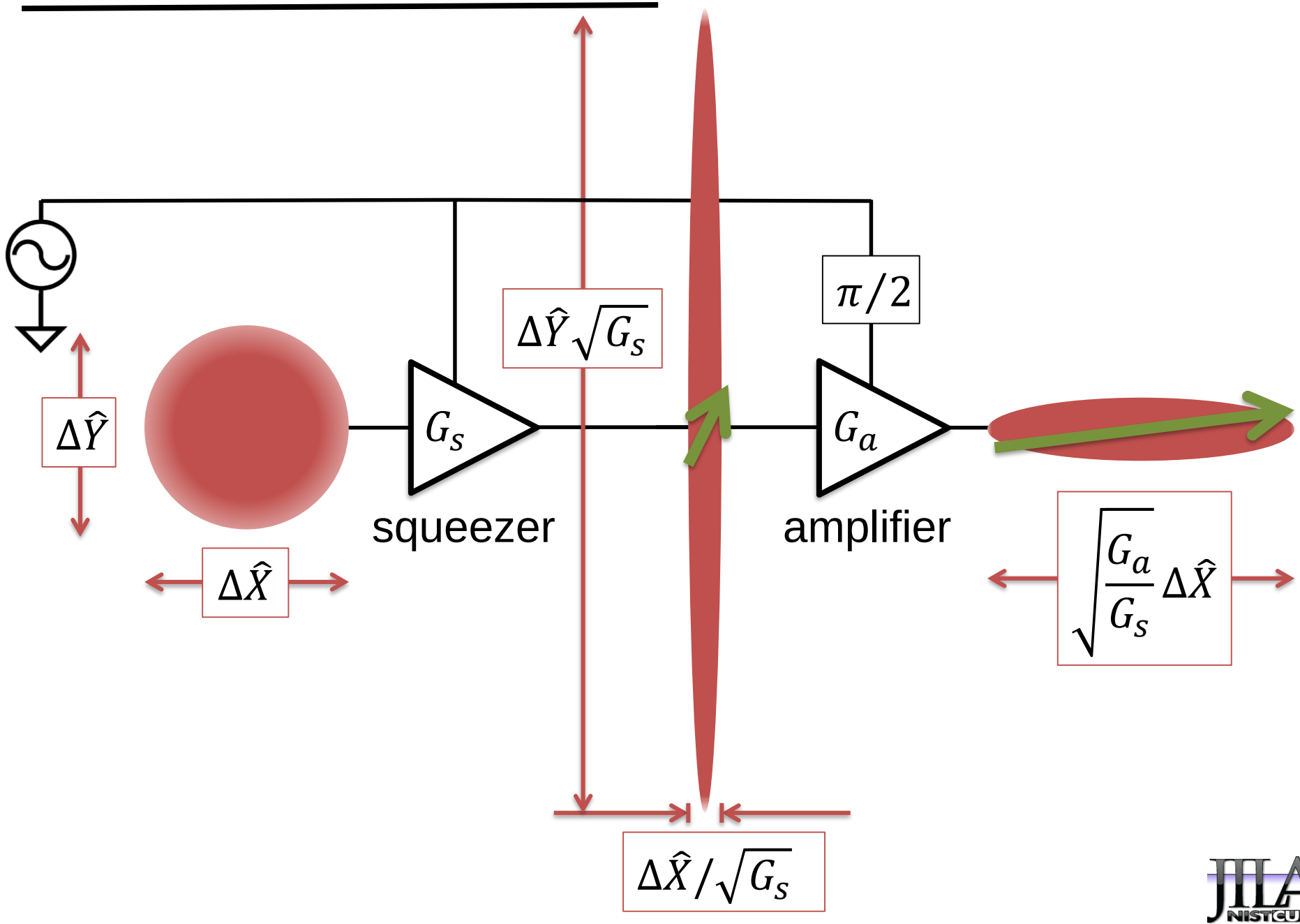
with squeezing:

$\kappa_i \ll \kappa_e$



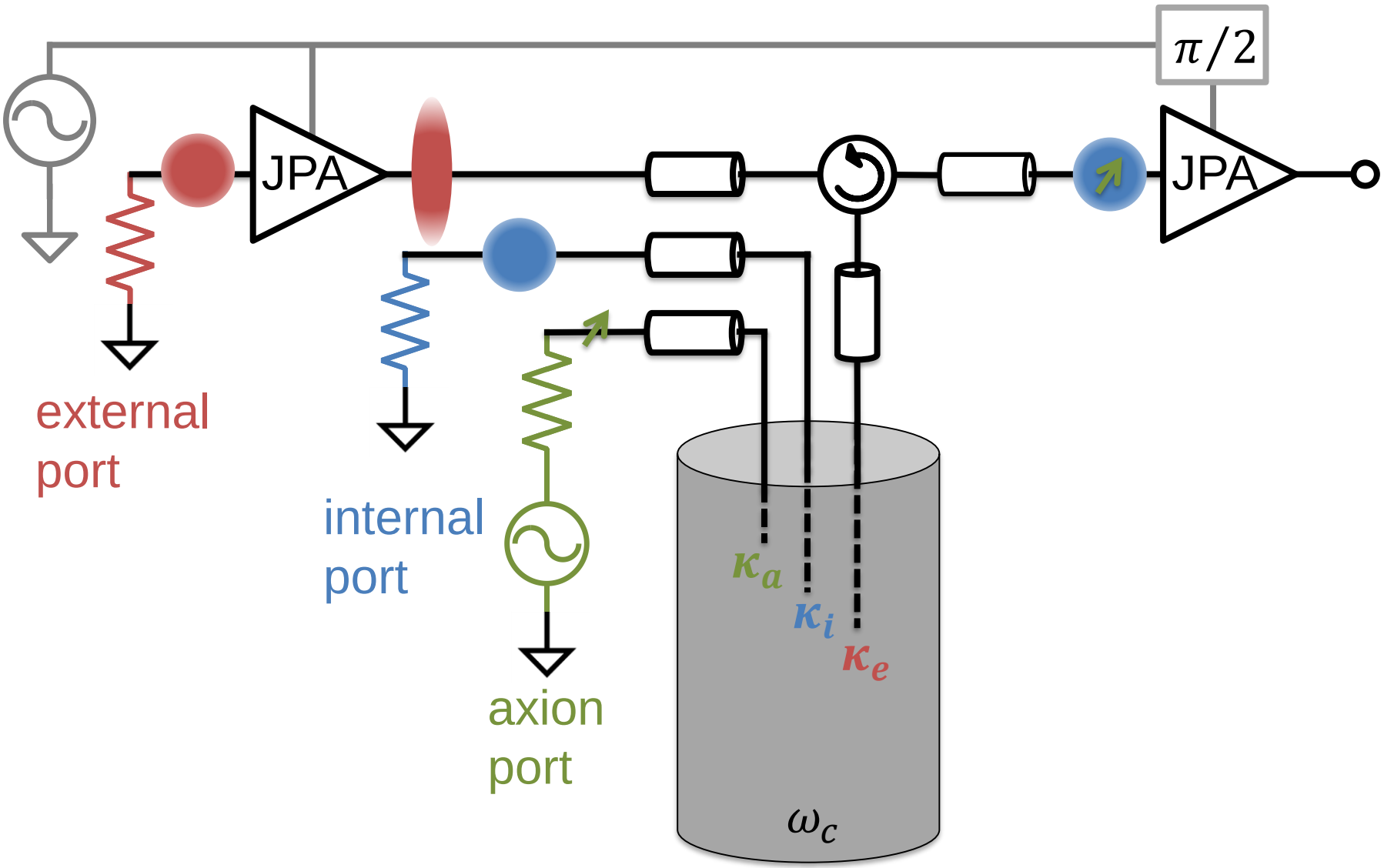
detuning: $\Delta = \omega - \omega_c$

Squeezing with a JPA



Zero detuning, critically coupled

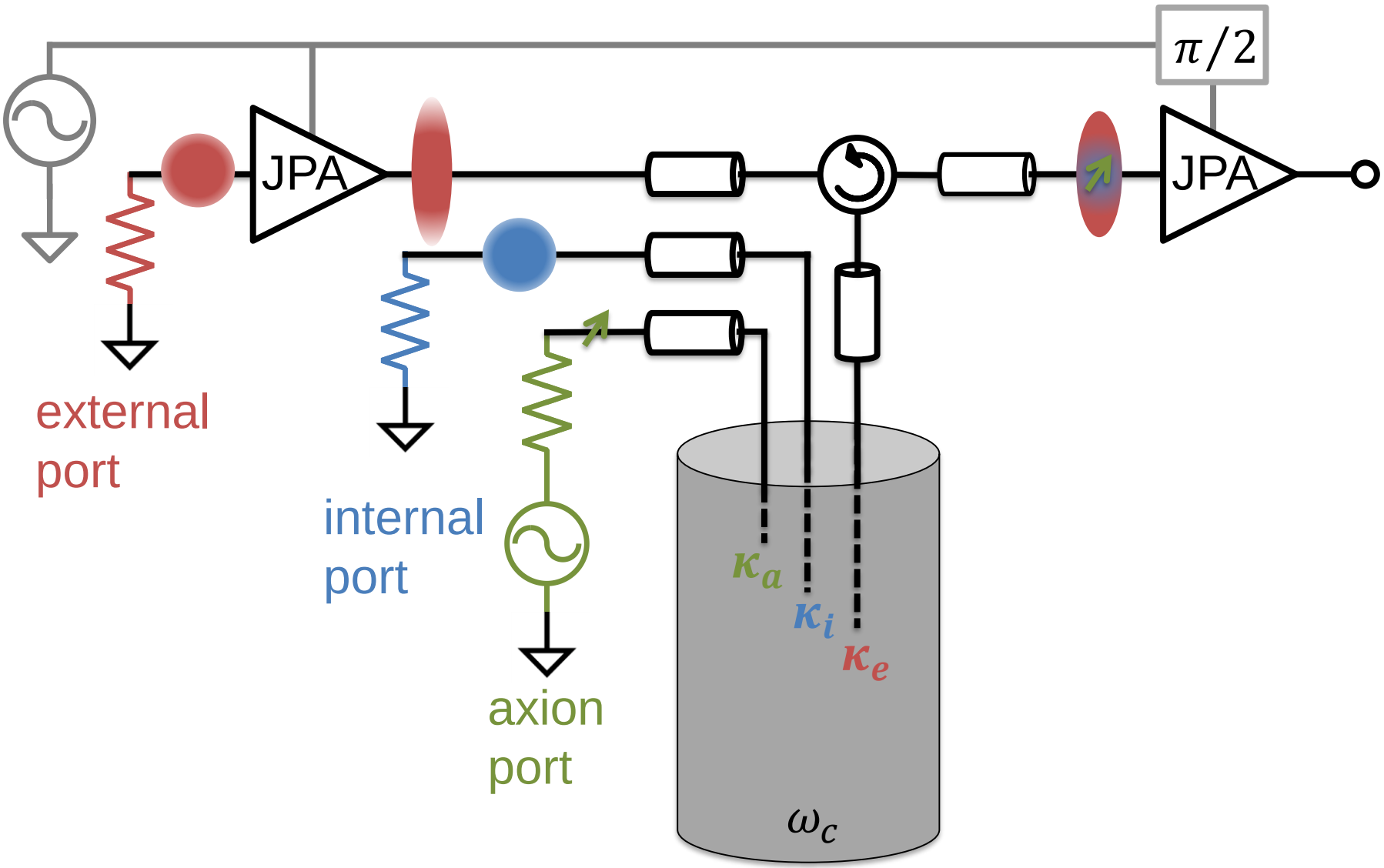
$\Delta = 0,\ \kappa_e = \kappa_i$



noise comes from internal port → squeezing does not help

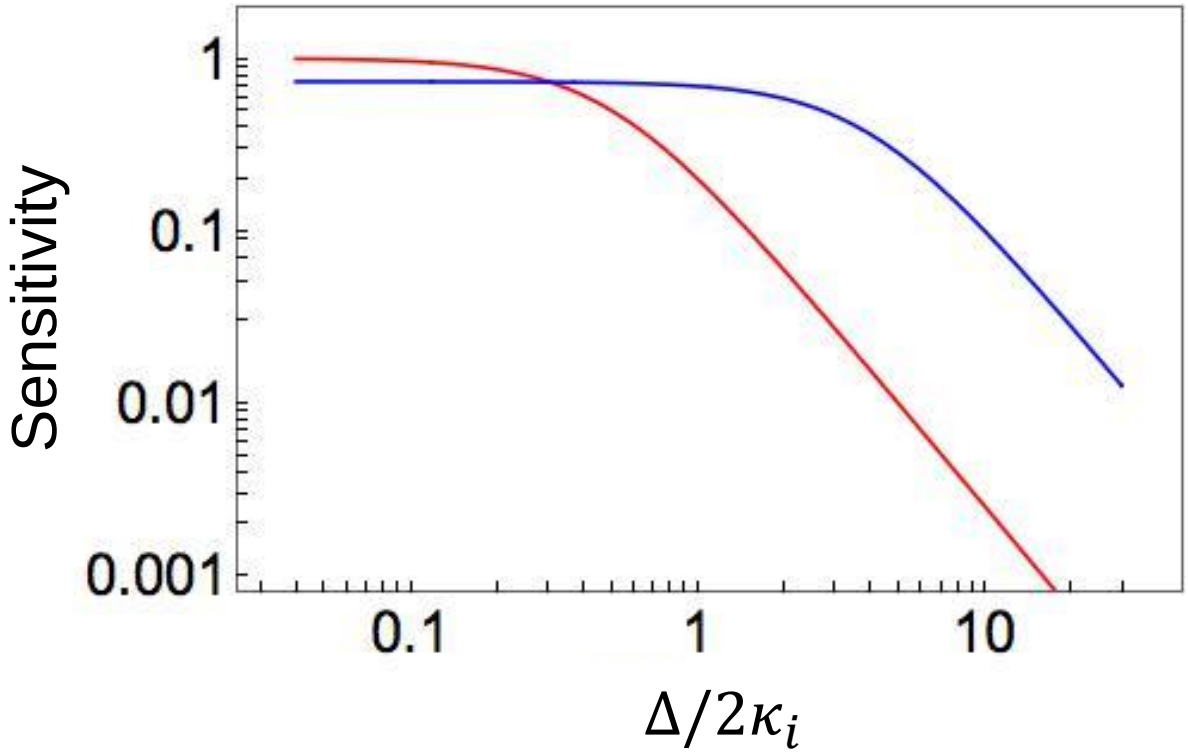
Large detuning, overcoupled

$\Delta \sim \kappa_e,\ \kappa_e \gg \kappa_i$



noise comes from external port → squeezing helps

Benefit of squeezing, revisited



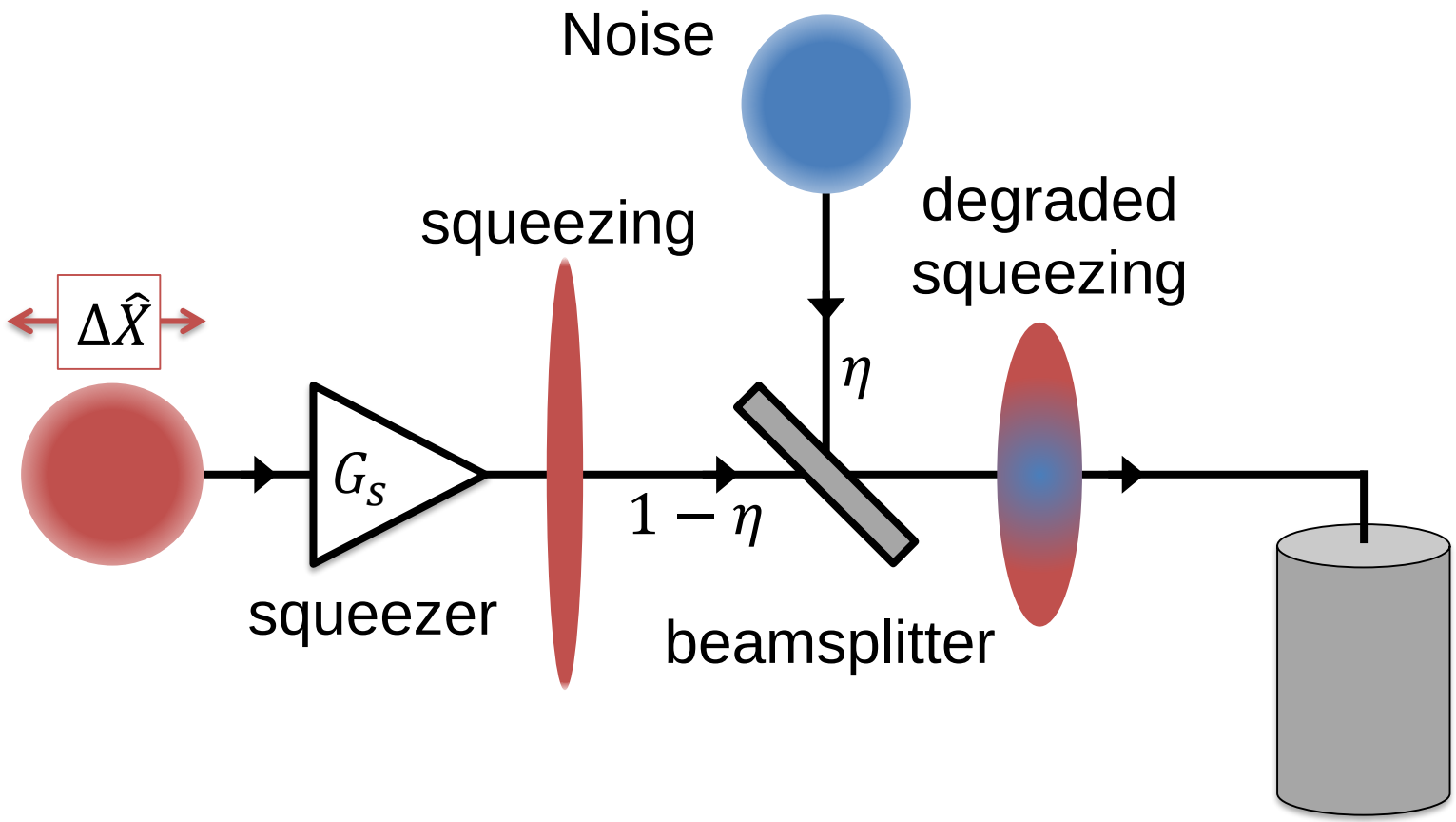
critically coupled ($\kappa_e = \kappa_i$) no squeezing

overcoupled ($\kappa_e \gg \kappa_i$) with squeezing

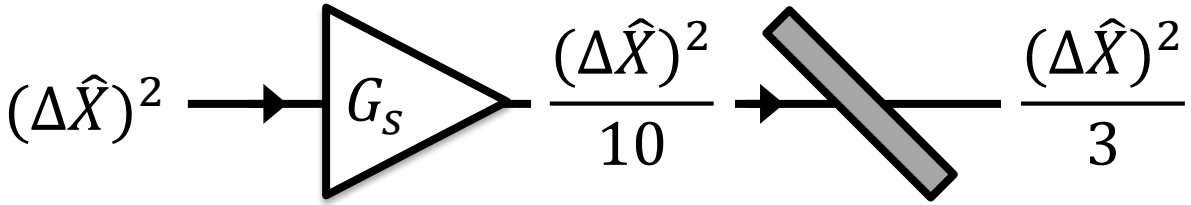
Josephson parametric amplifiers for axion detection

- Current JPA mode of operation
- Squeezing to enhance the axion scan rate
- **Loss limitations**

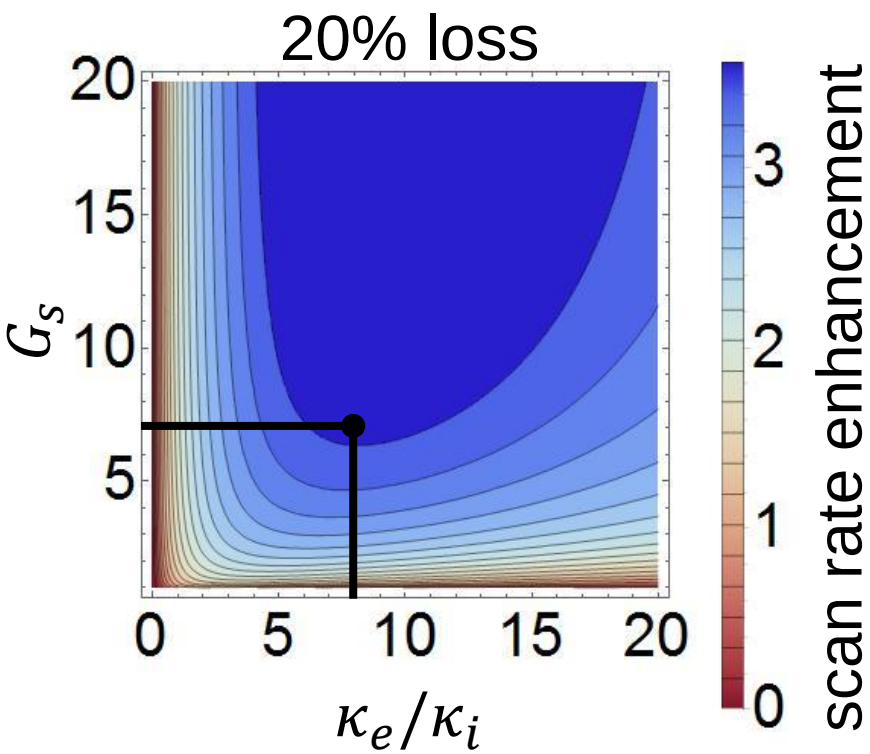
Losses between squeezer and amplifier

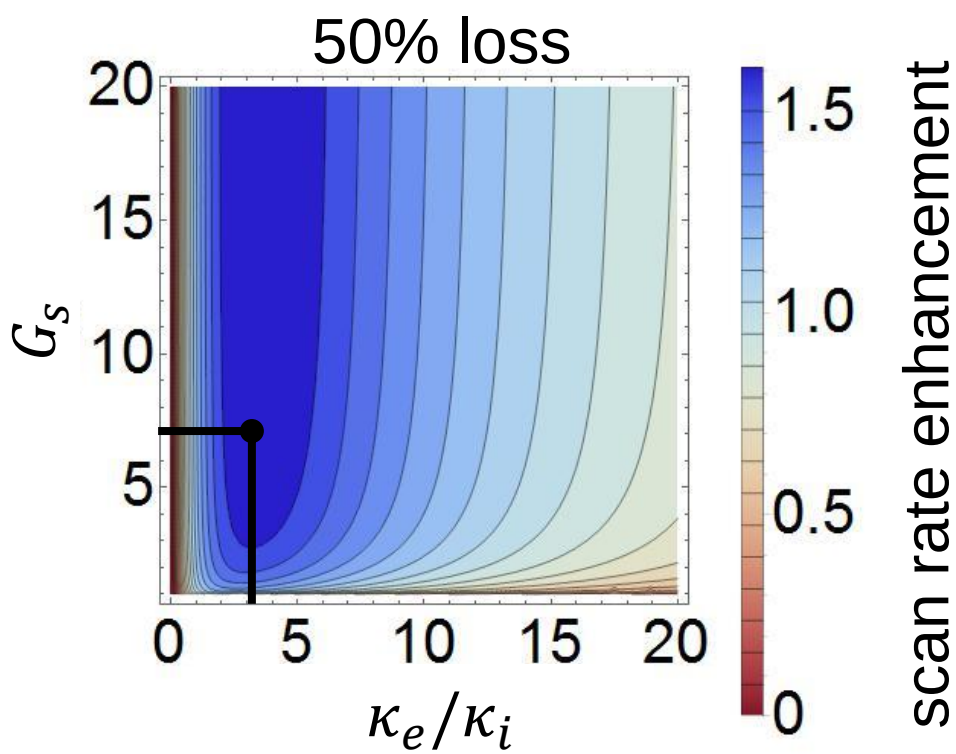


ex: $G_s = 10$ & loss $\eta = 20\%$



Effect of losses on the scan rate





20% loss: $G_s = 7$, $\kappa_e = 8\kappa_i$ scan rate x3.5

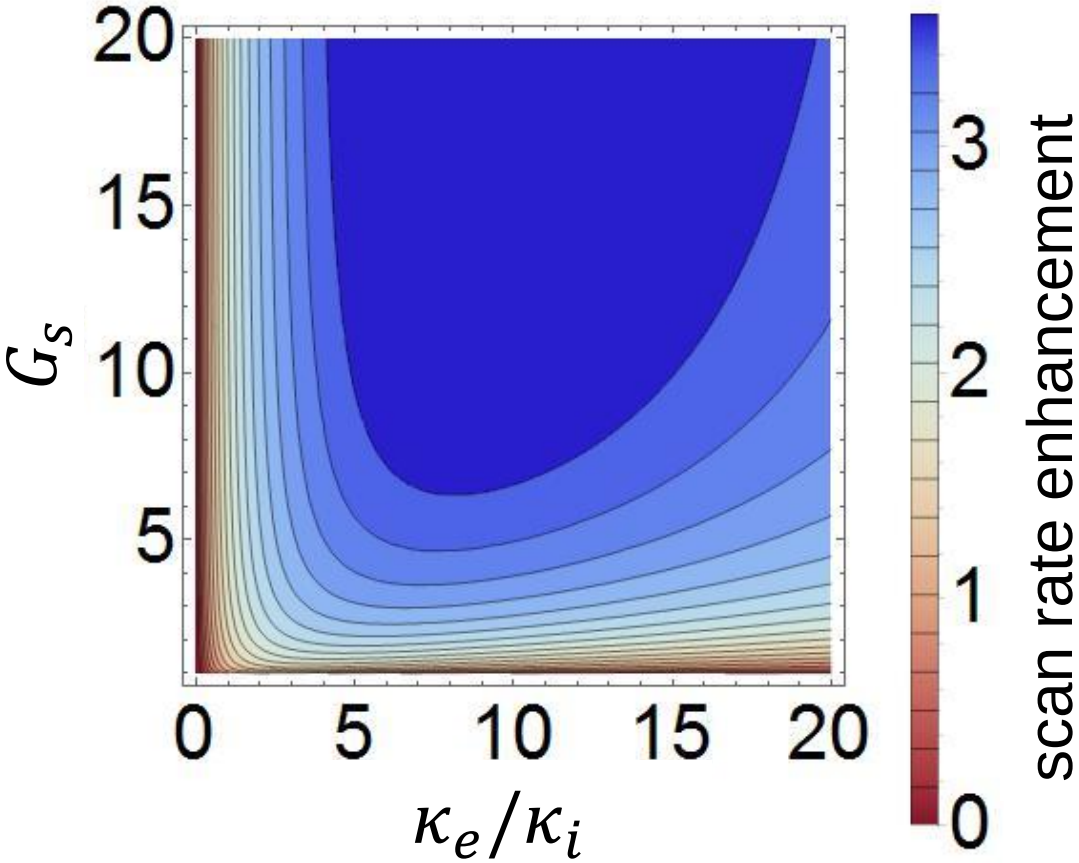
50% loss: $G_s = 7$, $\kappa_e = 3\kappa_i$ scan rate x1.5

Improvement to scan rate

80% microwave component efficiencies

3.5-fold increase in scan rate

2.5 yrs/GHz → 0.75 yrs/GHz (1.5 × KSVZ)



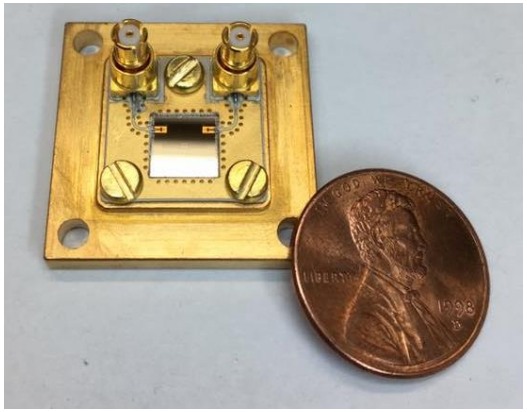
Conclusion - perspectives

JPA used for axion search:

quantum limited

$\mathrm{G} = 21\ \mathrm{dB}\ \&\ B = 2.8\ \mathrm{MHz}$

data acquired over $100\ \mathrm{MHz}\ @\ 5.7 - 5.8\ \mathrm{GHz}$

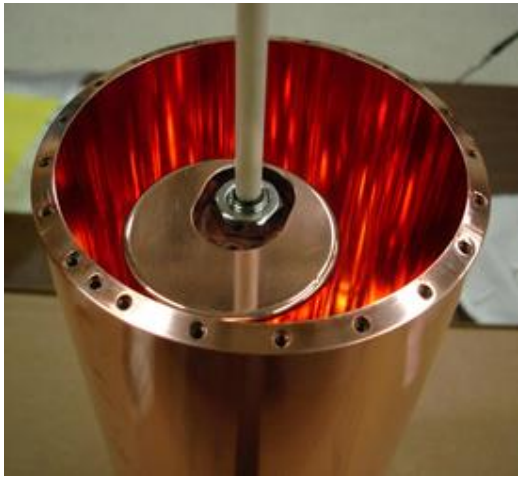


accelerate search with squeezing:

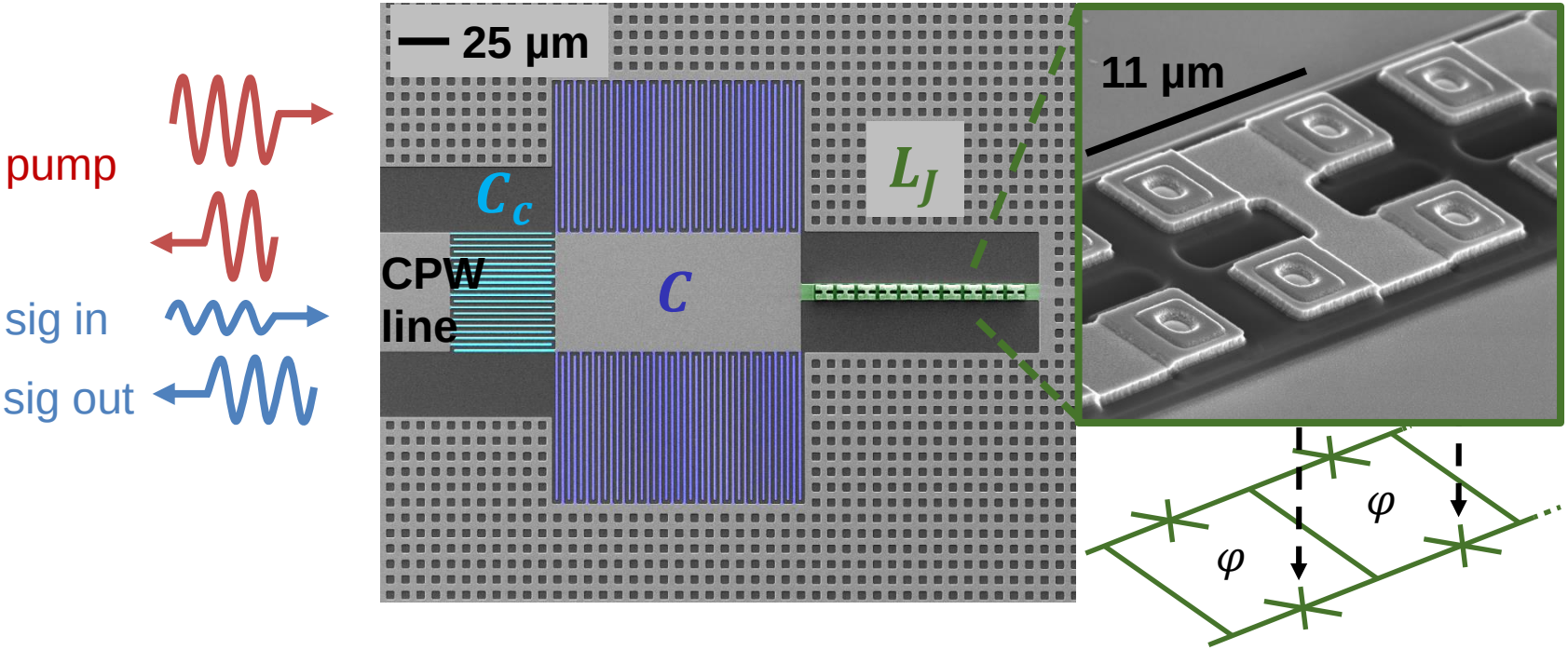
overcoupled with squeezing increases the scan rate

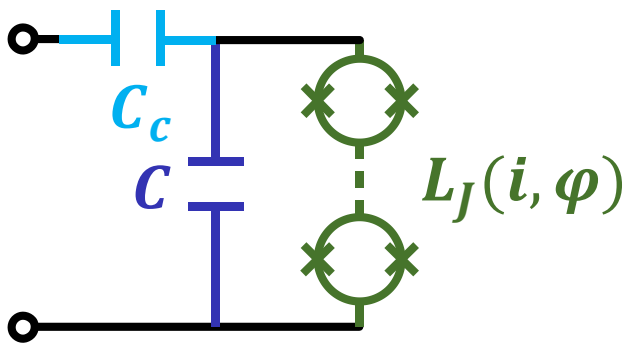
degraded by microwave losses

3.5 increase in scan rate with 20% of microwave losses



parametric amplification

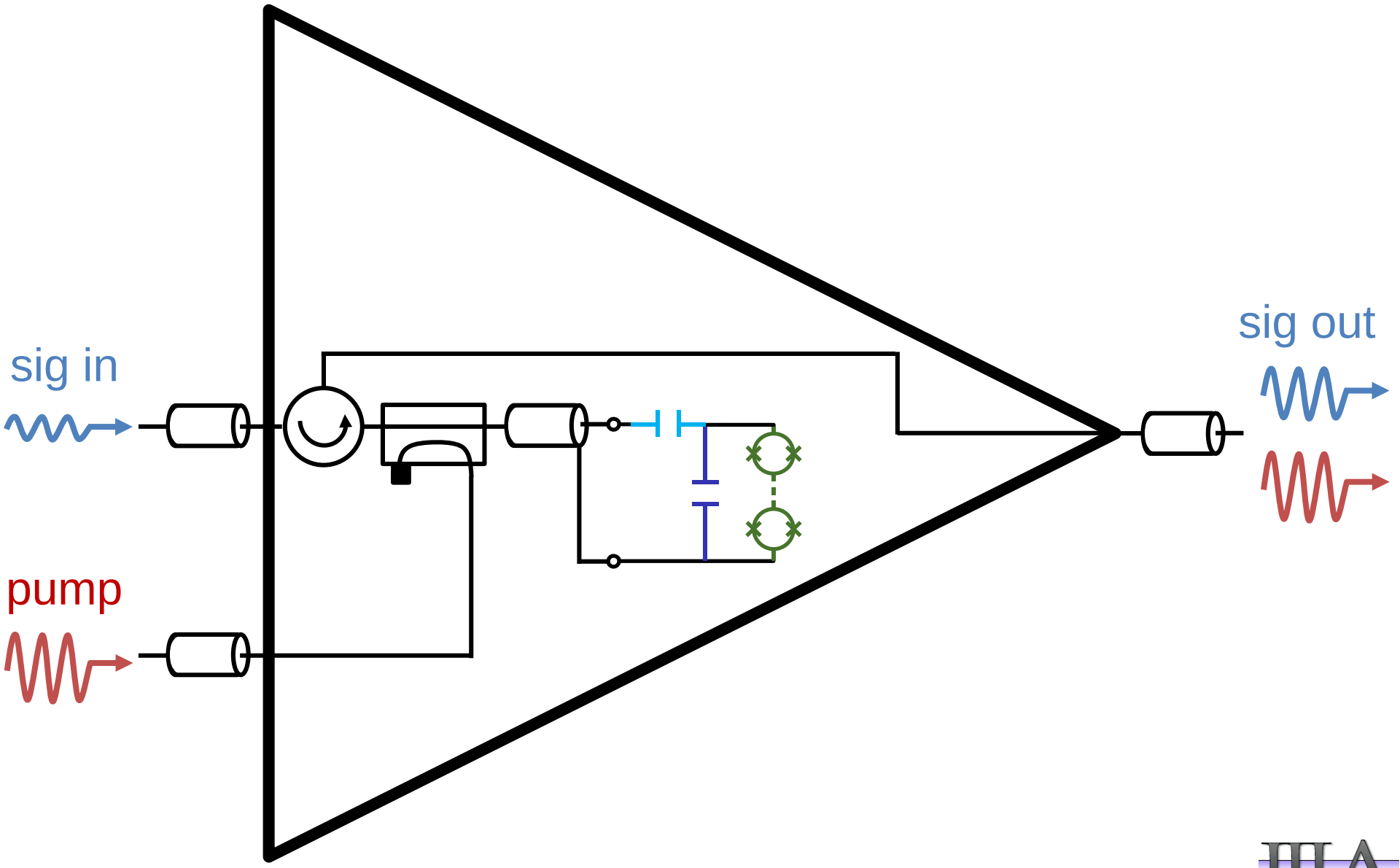




$$f_0 \approx \frac{1}{2\pi\sqrt{L_J(C + C_c)}}$$

$$B_J \approx \frac{\sqrt{L_J(C + C_c)^3}}{Z_0 C_c^2}$$

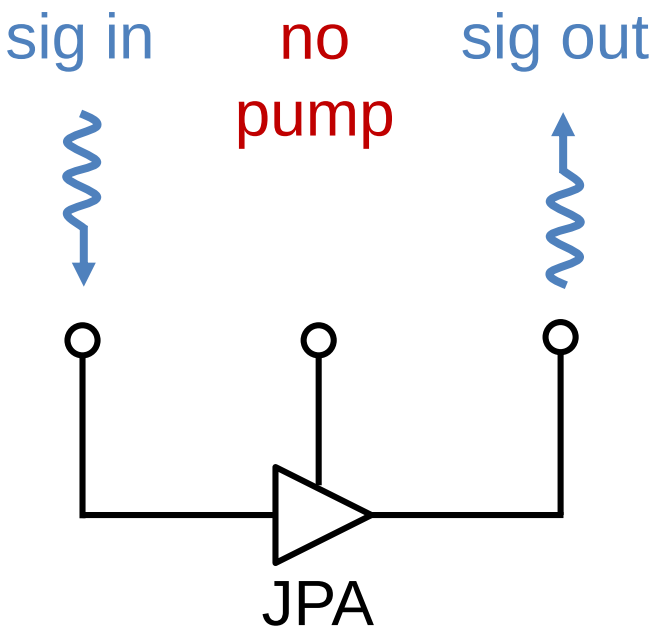
Josephson parametric amplifier

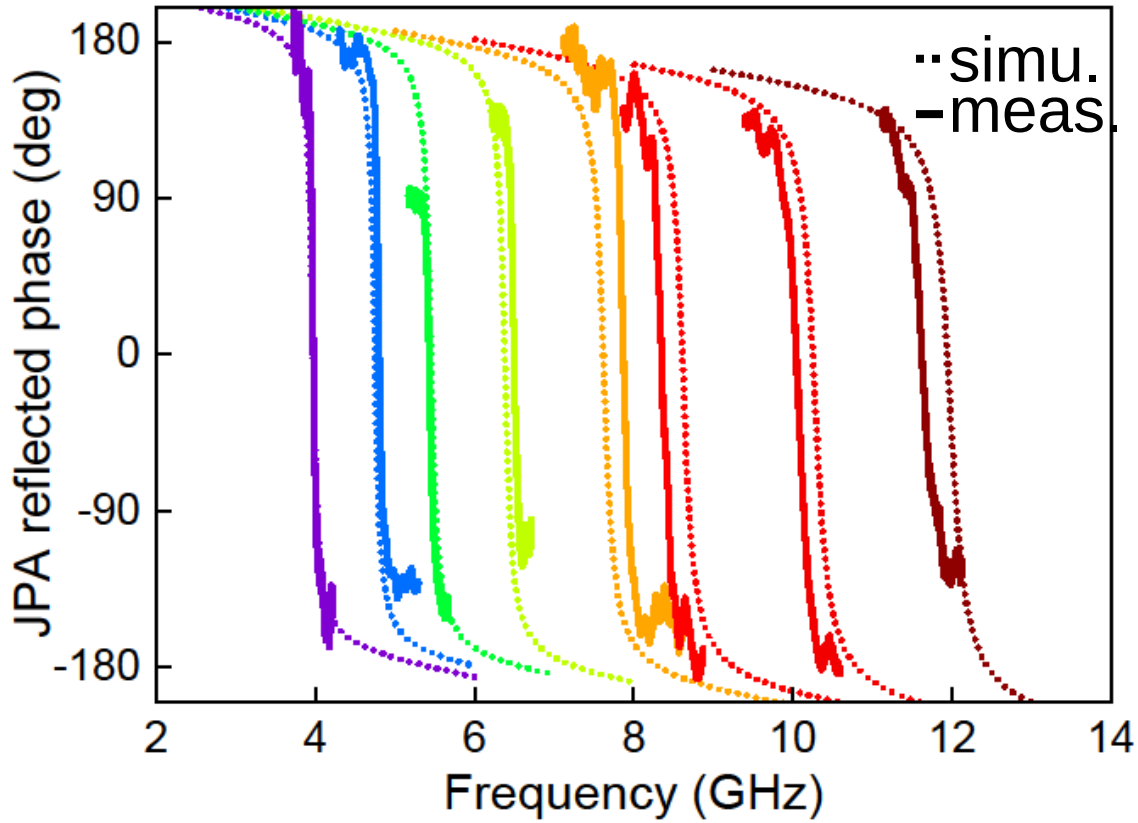


Fabricated JPAs

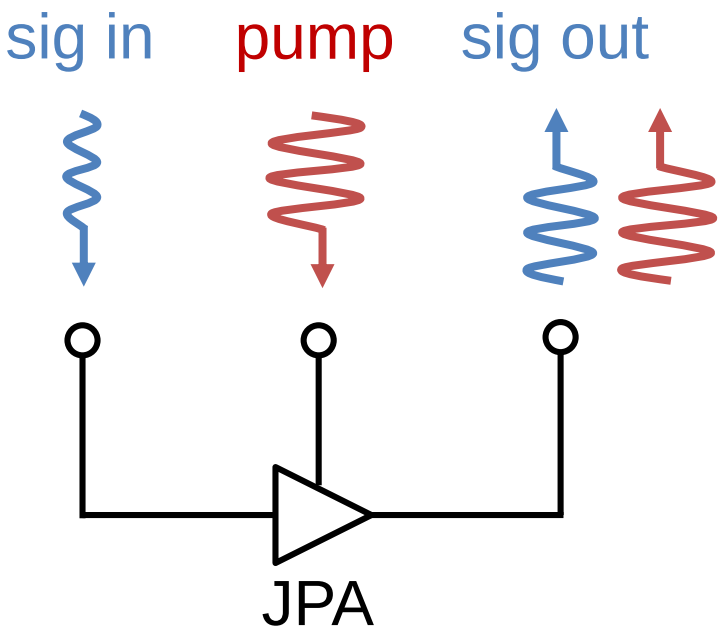
8 designs: $f_0 \in [4,12]\mathrm{GHz}$

f_0 @ 2π phase shift between sig in & sig out

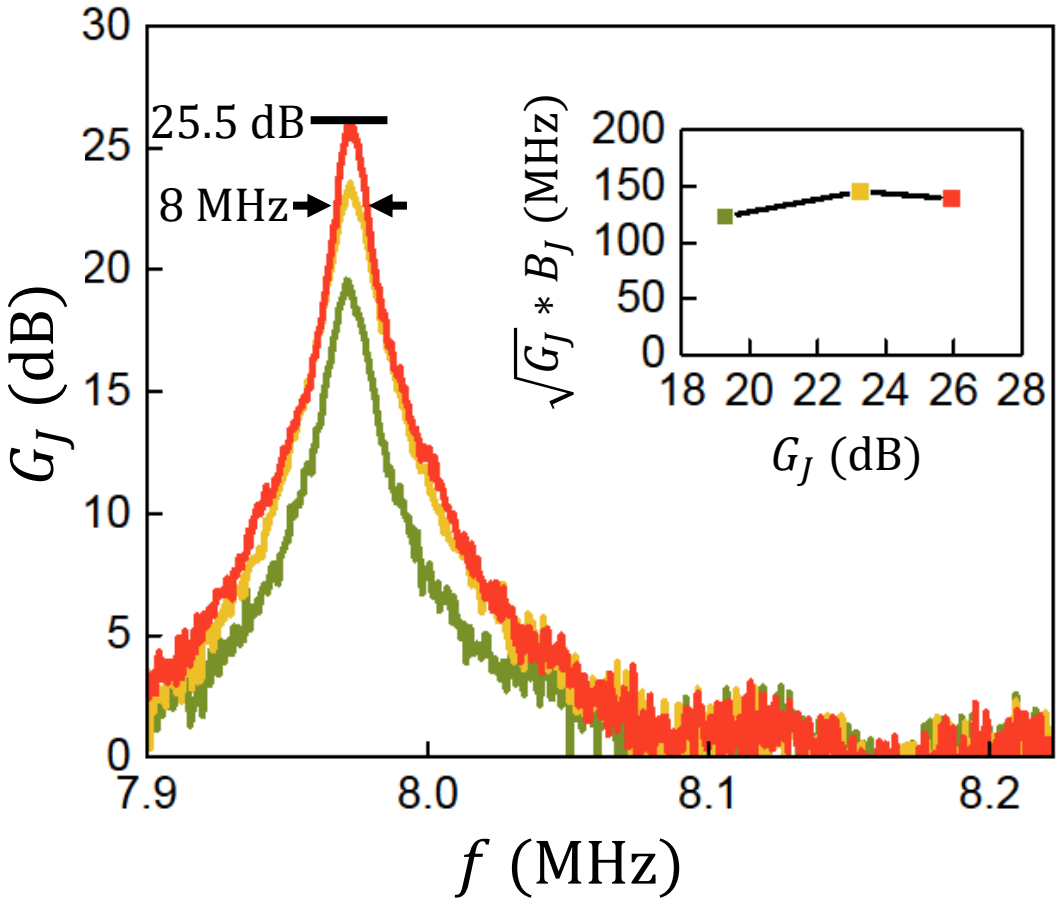




Gain and bandwidth

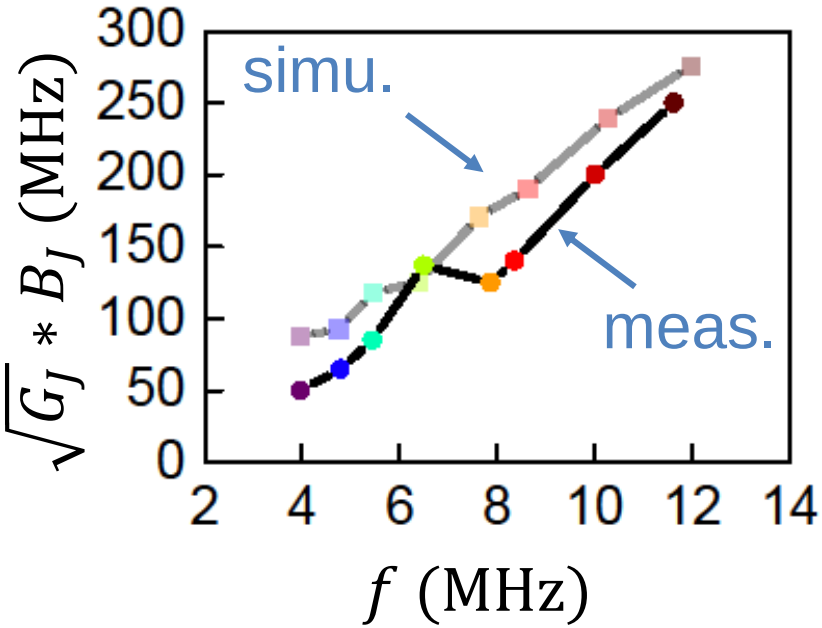


e.g. JPA G_J @ 7.97GHz:

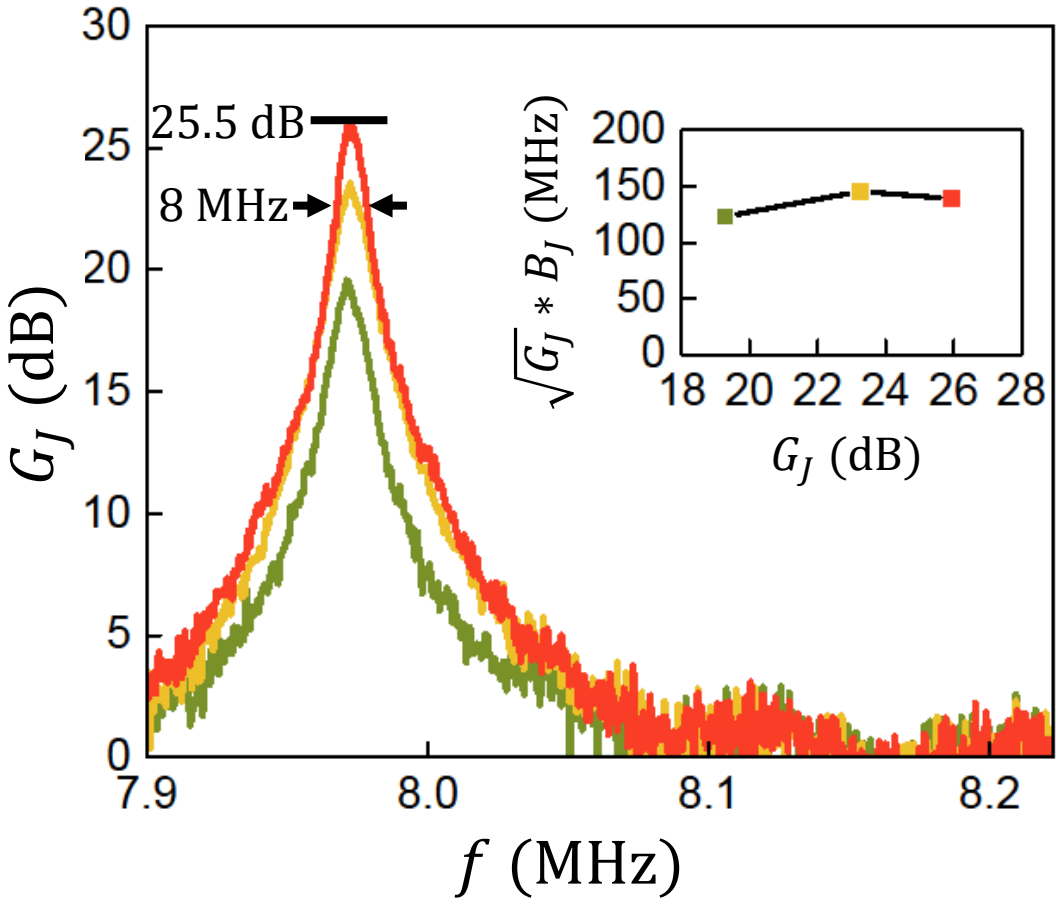


Gain and bandwidth

$\sqrt{G_J} * B_J$ for the 8 JPAs:



e.g. JPA G_J @ 7.97GHz:



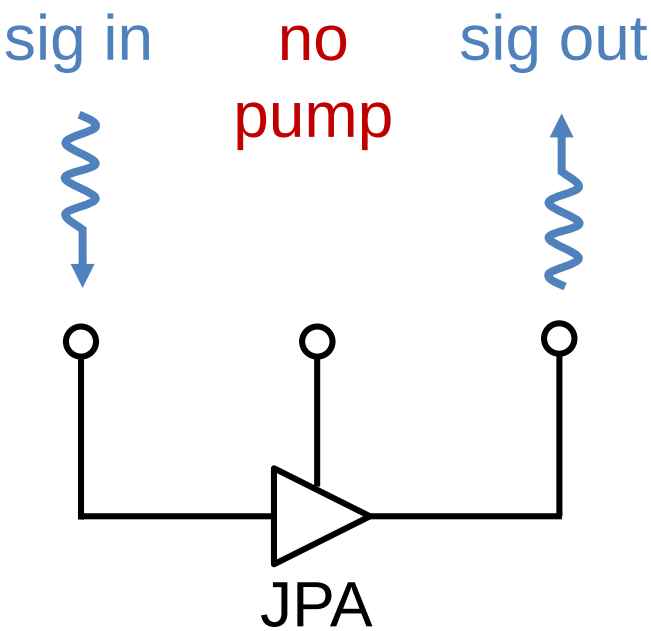
$$\sqrt{G_J} * B_J > 50 \text{ MHz}$$

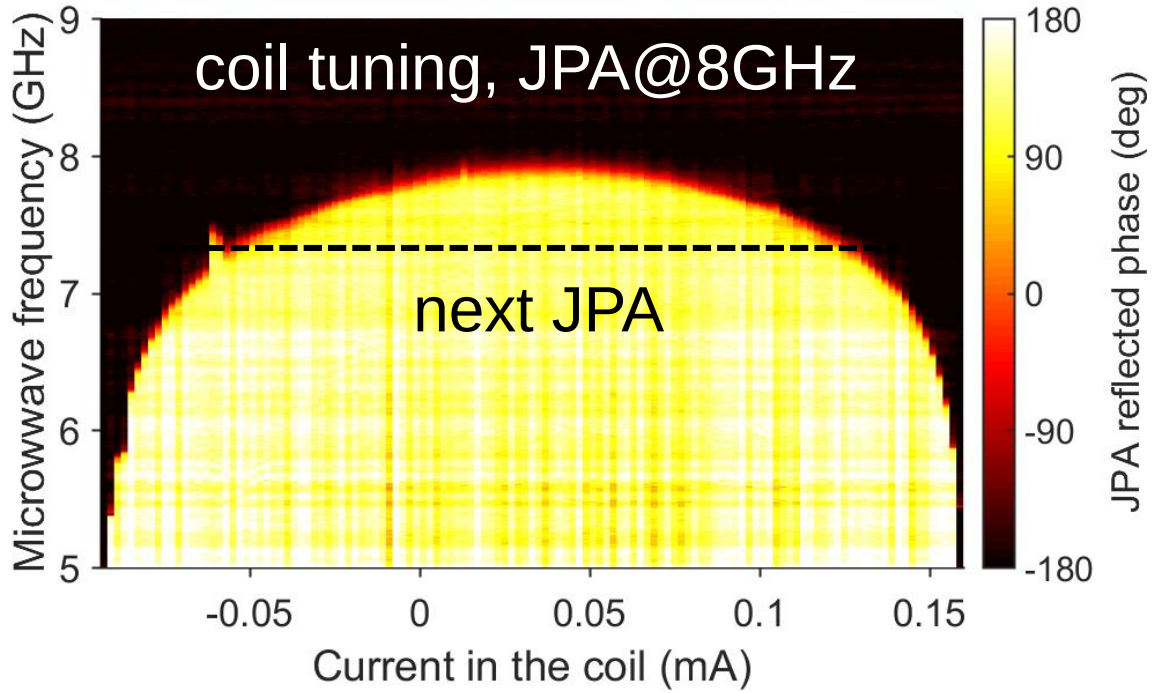
for each JPAs:

- G_J tunable between 20 and 30 dB
- $\sqrt{G_J} * B_J$ constant when the gain is tuned

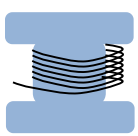
Frequency tuning with a coil

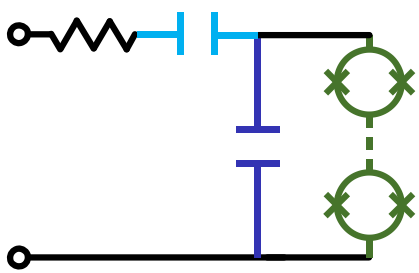
f_0 @ 2π phase shift between sig in & sig out

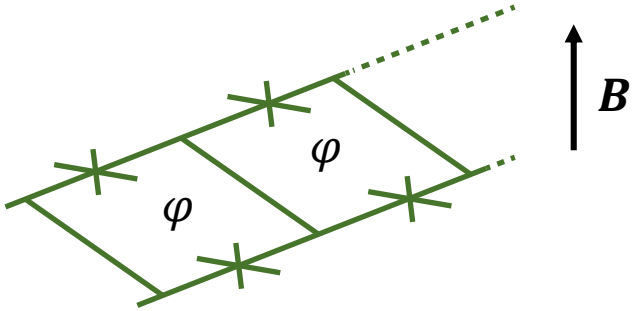




Coil

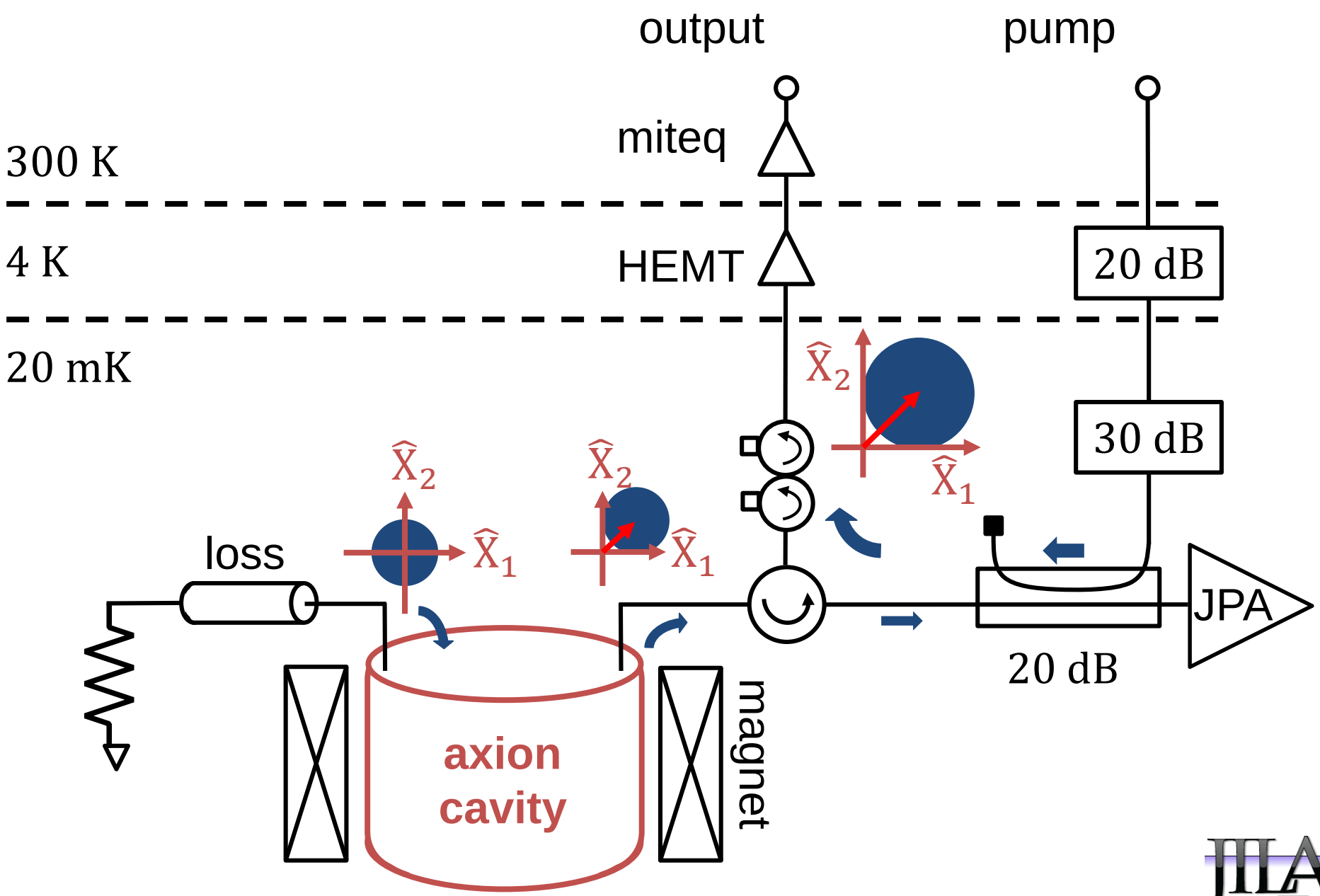






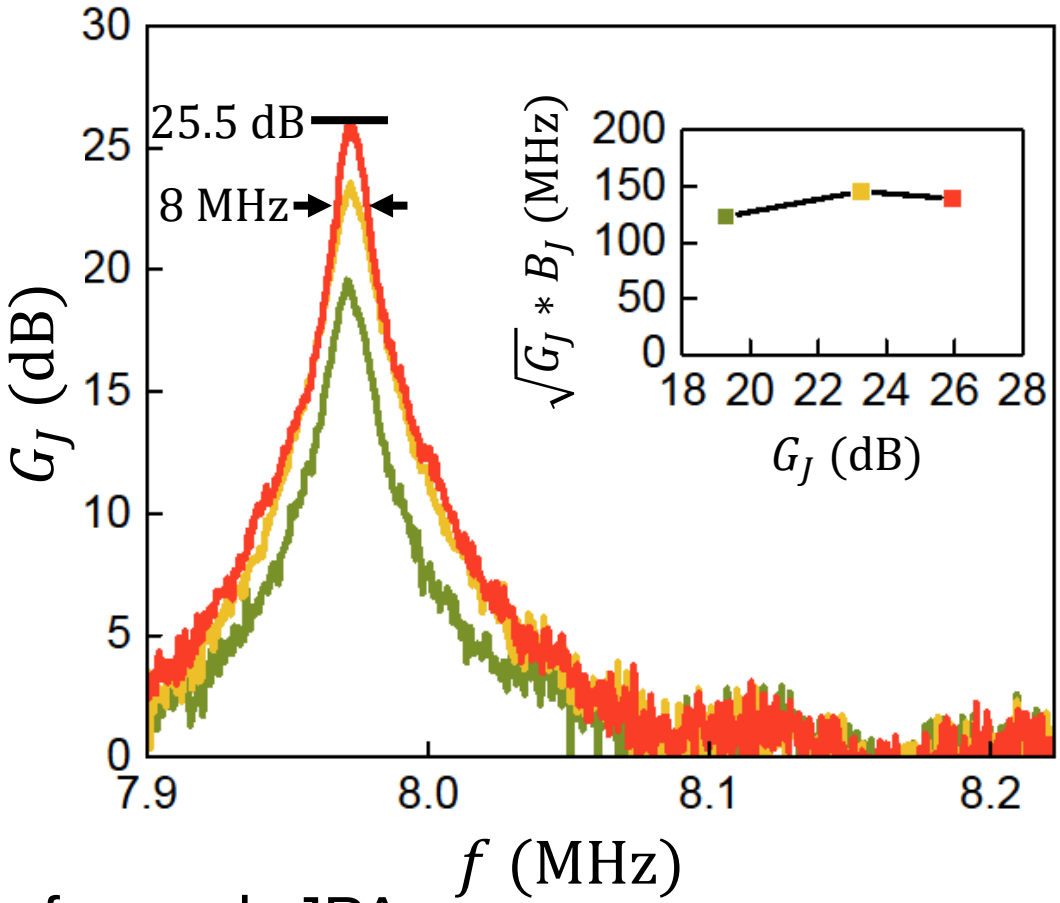
$$f_0 \propto \sqrt{\cos(\pi\,\varphi/\varphi_0)}$$

JPA integrated to the haloscope detector

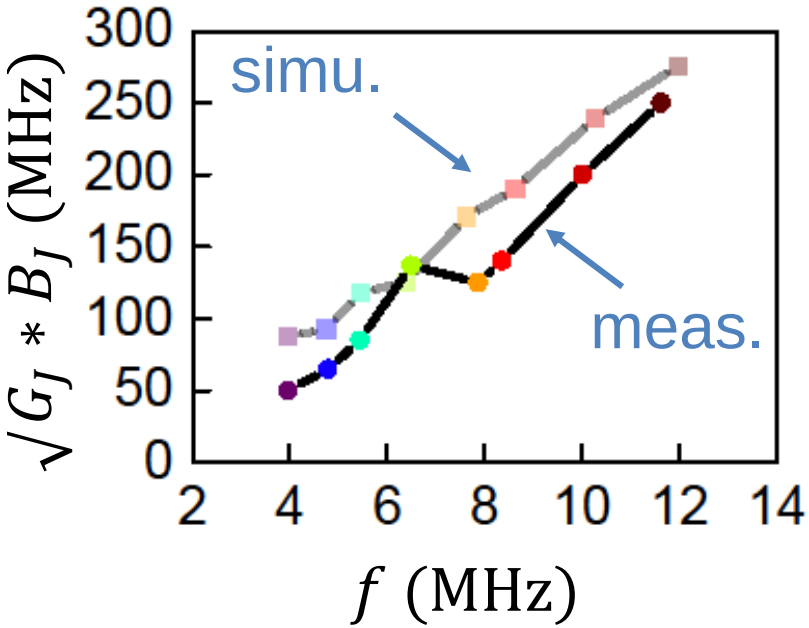


Gain and bandwidth

e.g. JPA G_J @ 7.97GHz:



$\sqrt{G_J} * B_J$ for the 8 JPAs:

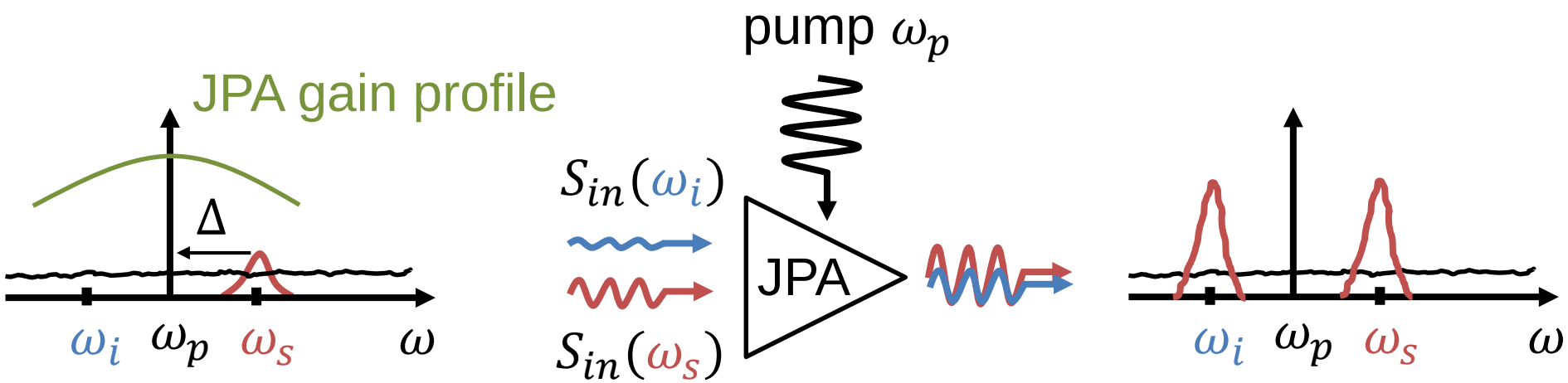


$$\sqrt{G_J} * B_J > 50 \text{ MHz}$$

for each JPAs:

- G_J tunable between 20 and 30 dB
- $\sqrt{G_J} * B_J$ constant when the gain is tuned

Phase insensitive amplification, quantum limited

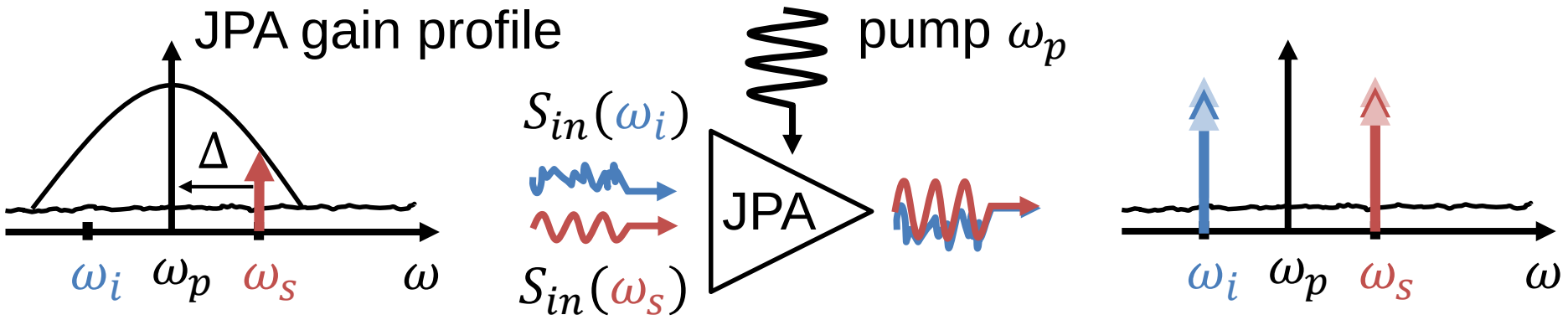


single sided signal
vacuum noise at
image frequency

$$S_{out} \approx G\,[S_{in}(\omega_s) + S_{in}(\omega_i)]$$

minimum added noise: $S_{in}(\omega_i) = \hbar\omega_i N_{\mathrm{add}}$ → $N_{\mathrm{add}} = 1/2$ photon

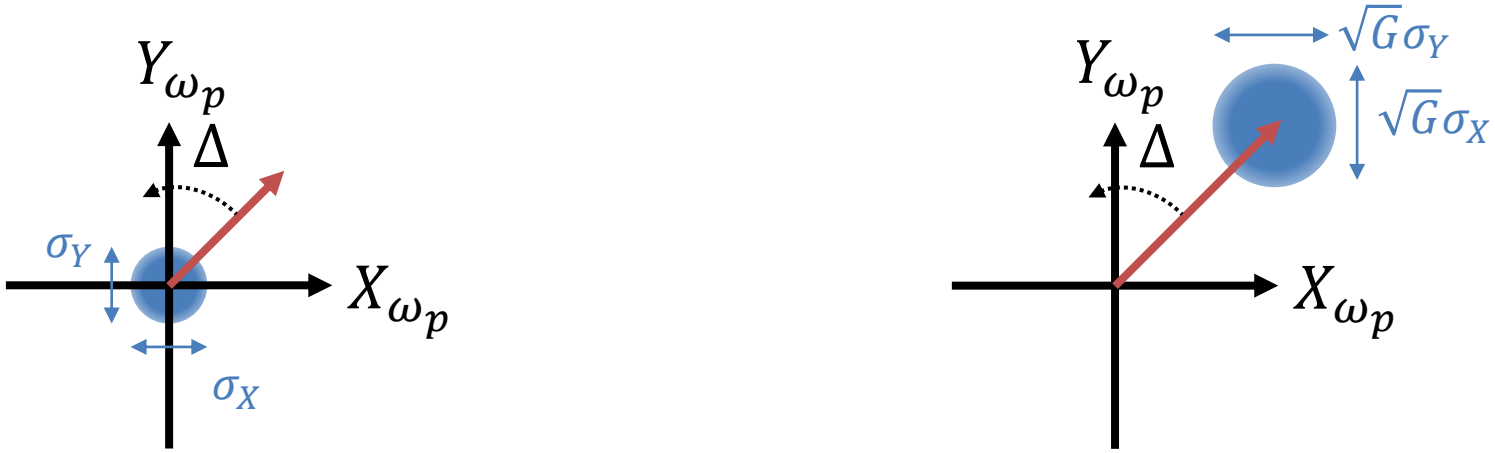
Phase insensitive amplification



pump rotating frame:

$$V_{\omega_p}(t) = X_{\omega_p}\cos(\omega_p t) + Y_{\omega_p}\sin(\omega_p t)$$

$$S_{out} \approx G\,[S_{in}(\omega_s) + S_{in}(\omega_i)]$$



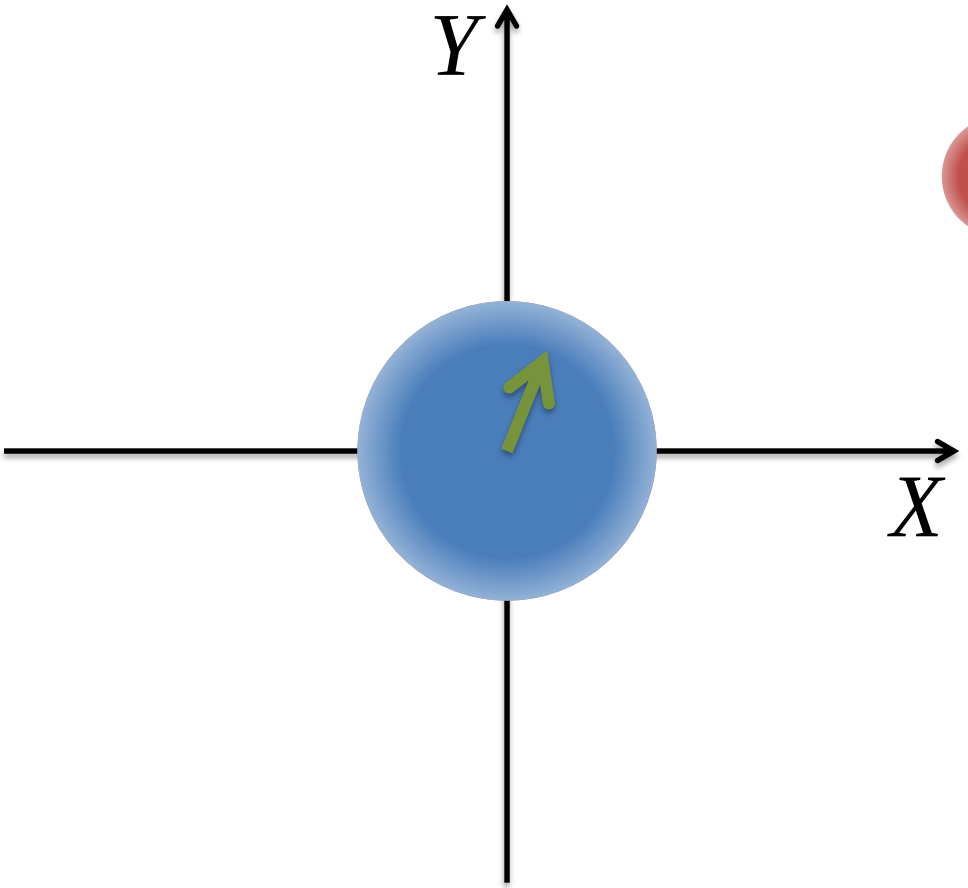
vacuum noise: $\sigma_X = \sigma_Y = 1/2$

added noise $= 1/2$

Fundamental limitation on sensitivity

$$H_{\omega_c} = \hbar\omega_c\left(aa^\dagger + 1/2\right) = \hbar\omega_c \frac{X^2 + Y^2}{2}$$

$$[X, Y] = i$$

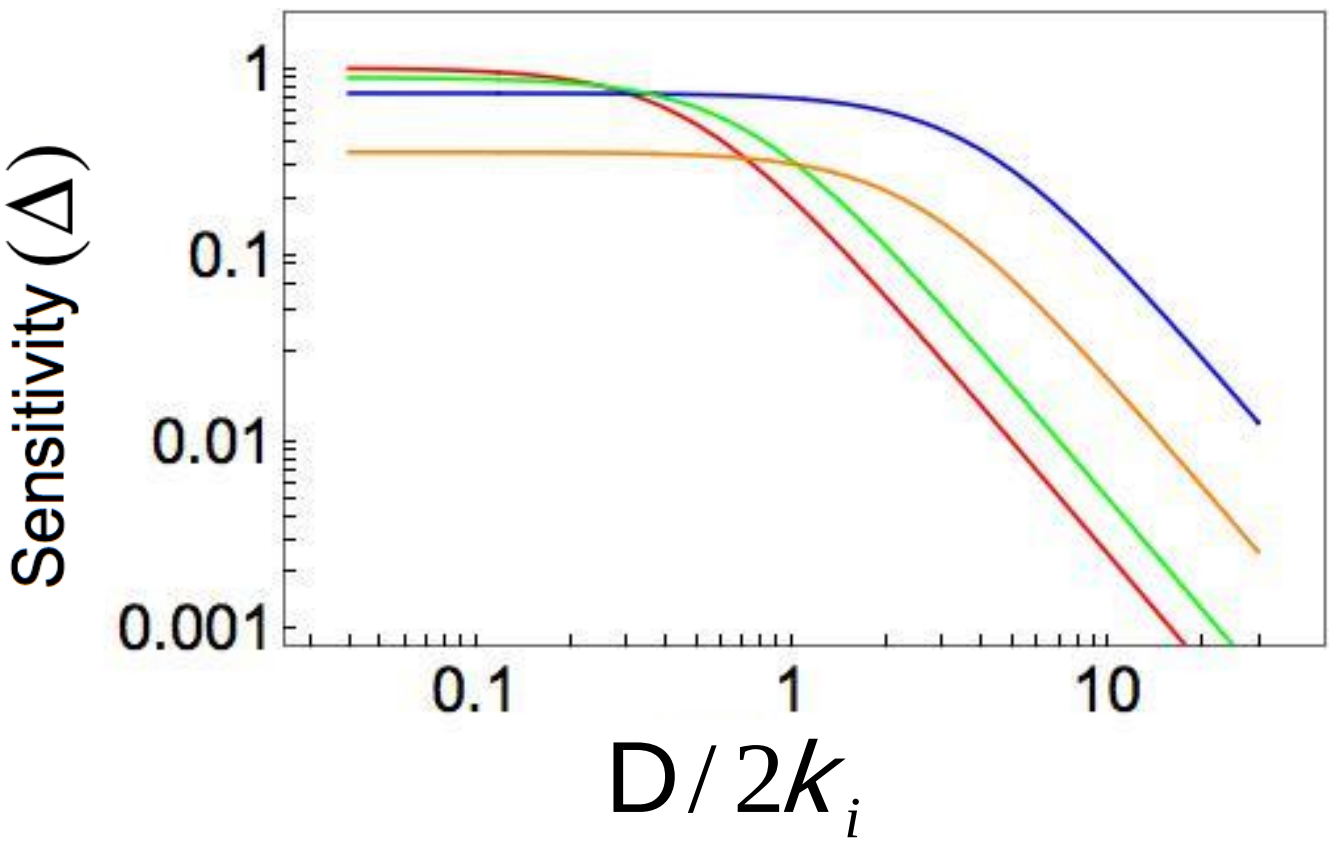


= internal port noise

= axion-induced signal

= external port noise

Squeezing benefit, four cases



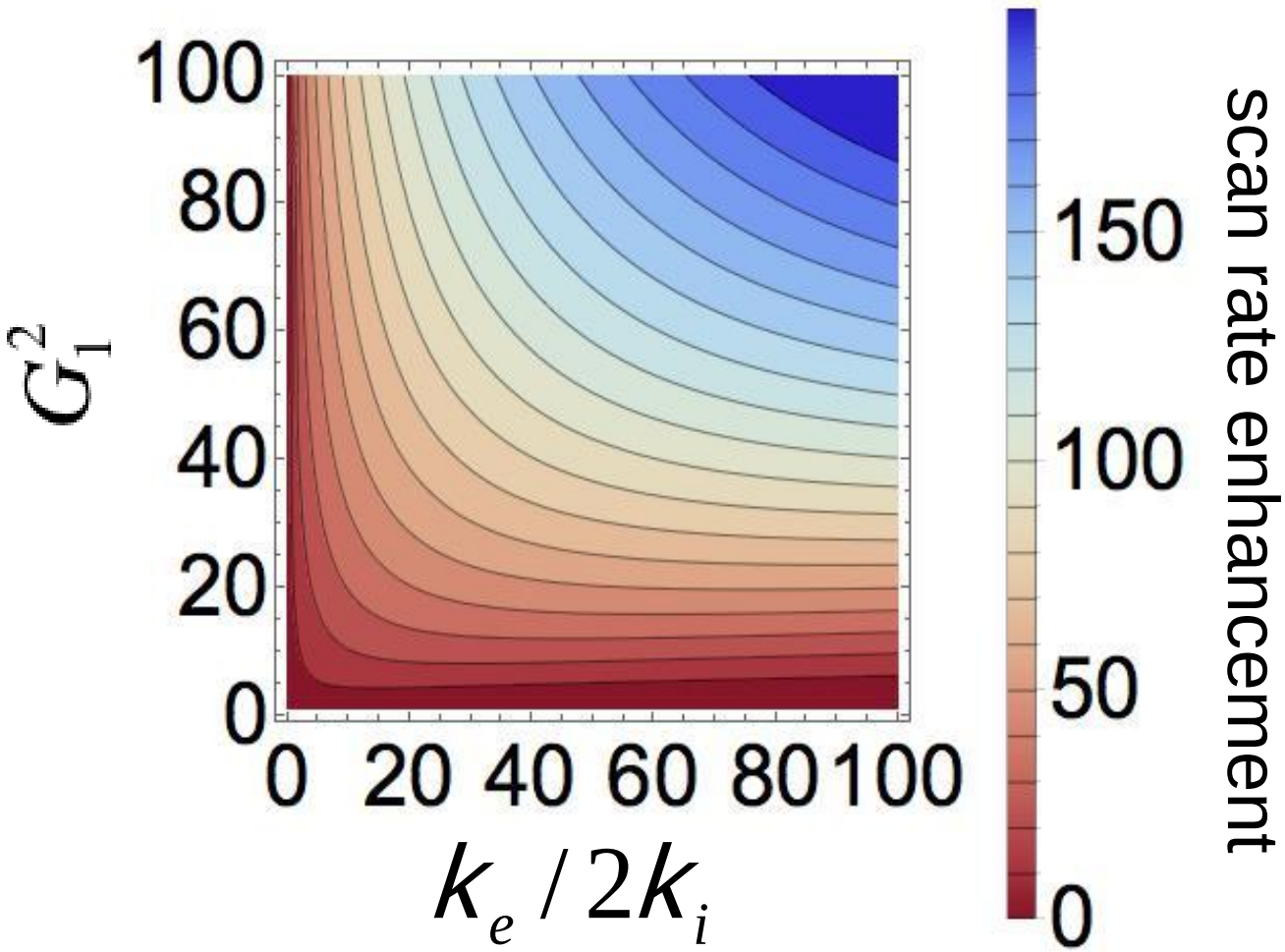
red = critically coupled, no squeezing

blue = strongly overcoupled, with squeezing

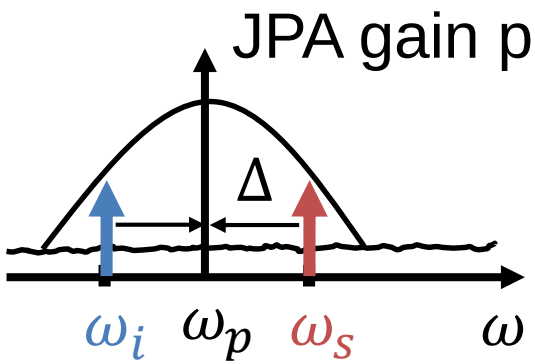
green = 2 × overcoupled, no squeezing

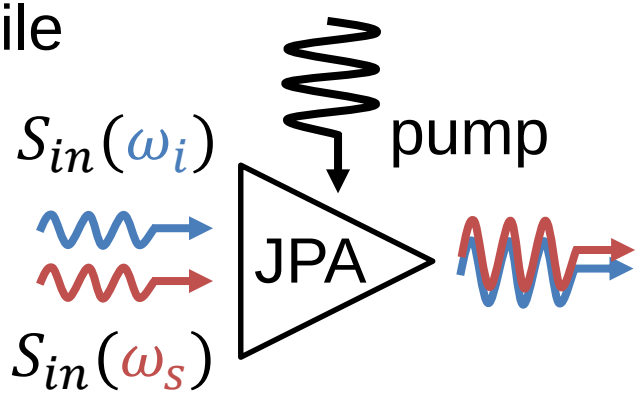
orange = strongly overcoupled, no squeezing

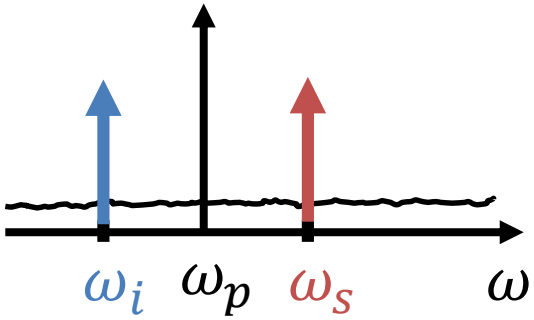
Scan rate enhancement, perfect efficiency



Phase sensitive amplification

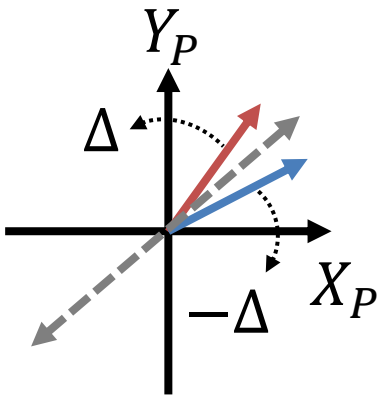


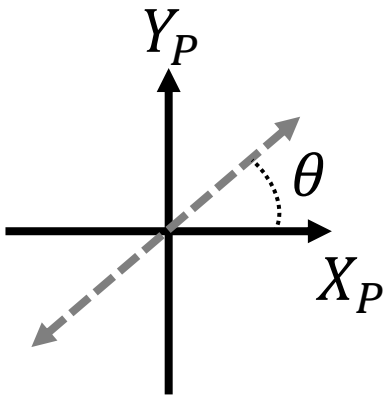


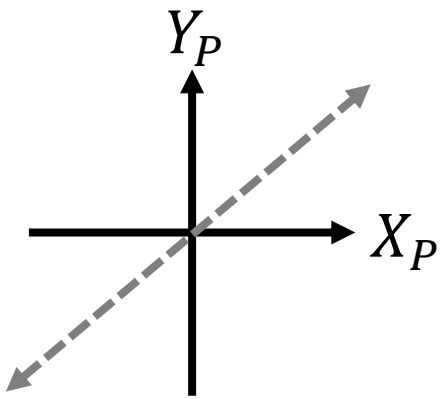


pump rotating frame:

$$S_{out} \approx 2G[1 + \cos(2\theta)]S_{in}$$

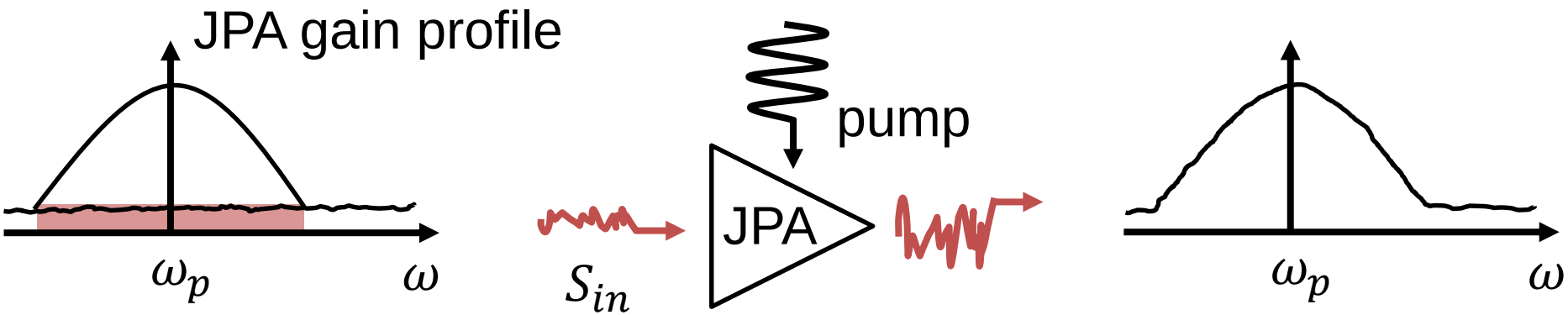






added noise = 0

Squeezing vacuum



pump rotating frame:

$$S_{out} \approx 2G[1 + \cos(2\theta)]S_{in}$$

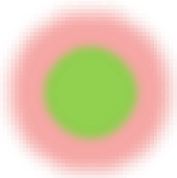
vacuum noise: $\sigma_X = \sigma_Y = 1/2$

squeezed noise

Quantum noise yields long search times

X_1 and X_2 don't commute with Hamiltonian or each other

$$S_d \rightarrow \frac{hf}{2} \qquad S_{\text{amp}} \rightarrow \frac{hf}{2}$$



noise variance: 1 quantum (photon)

axion energy: 10^{-3} – 10^{-4} photon

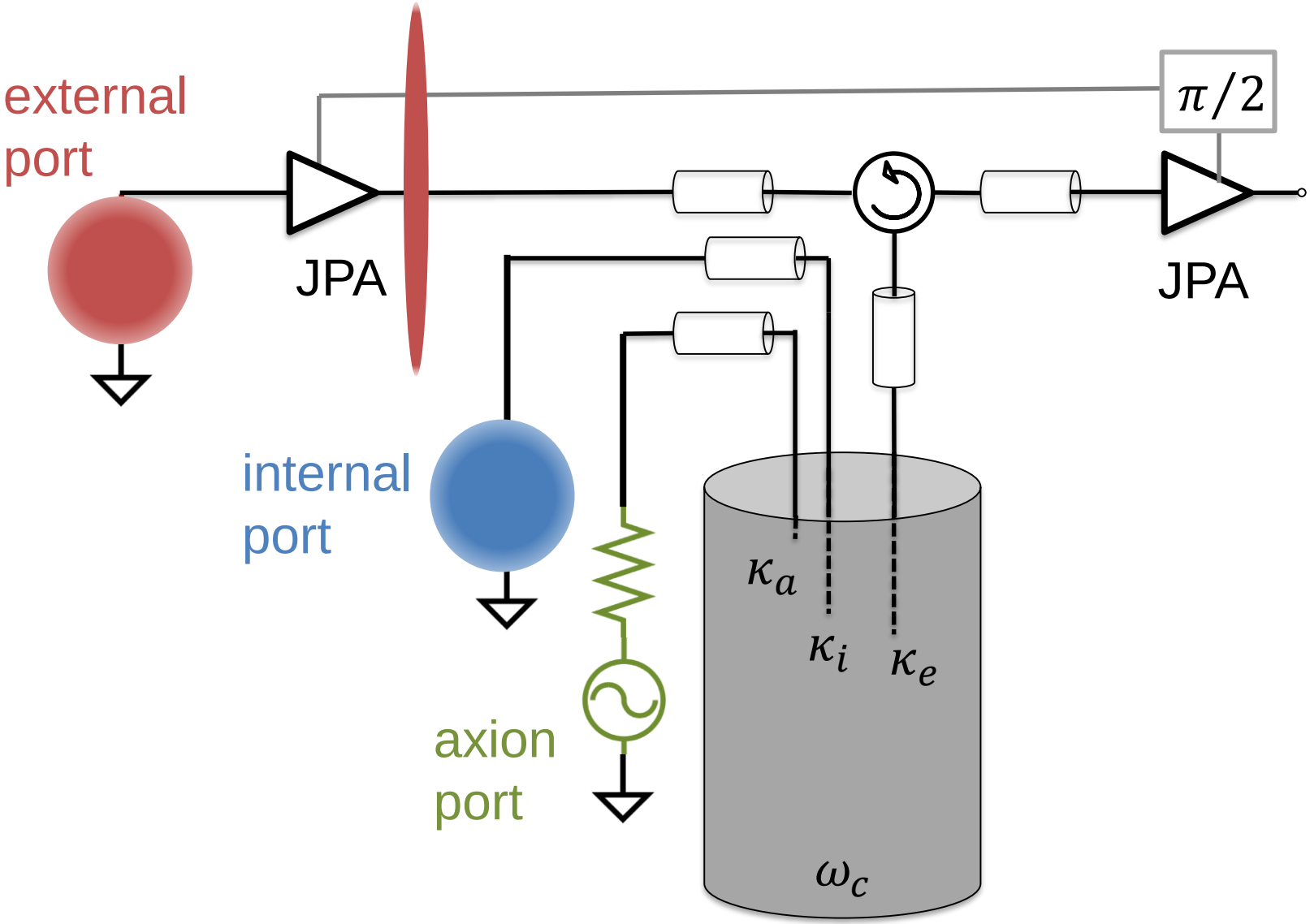
resolve signal in 10^6 – 10^8 averages

$$\frac{\delta S}{S} = \frac{1}{\sqrt{\Delta f_a \tau}}$$

τ ~ 3 minutes: each cavity resonance
~ 6 months: one octave

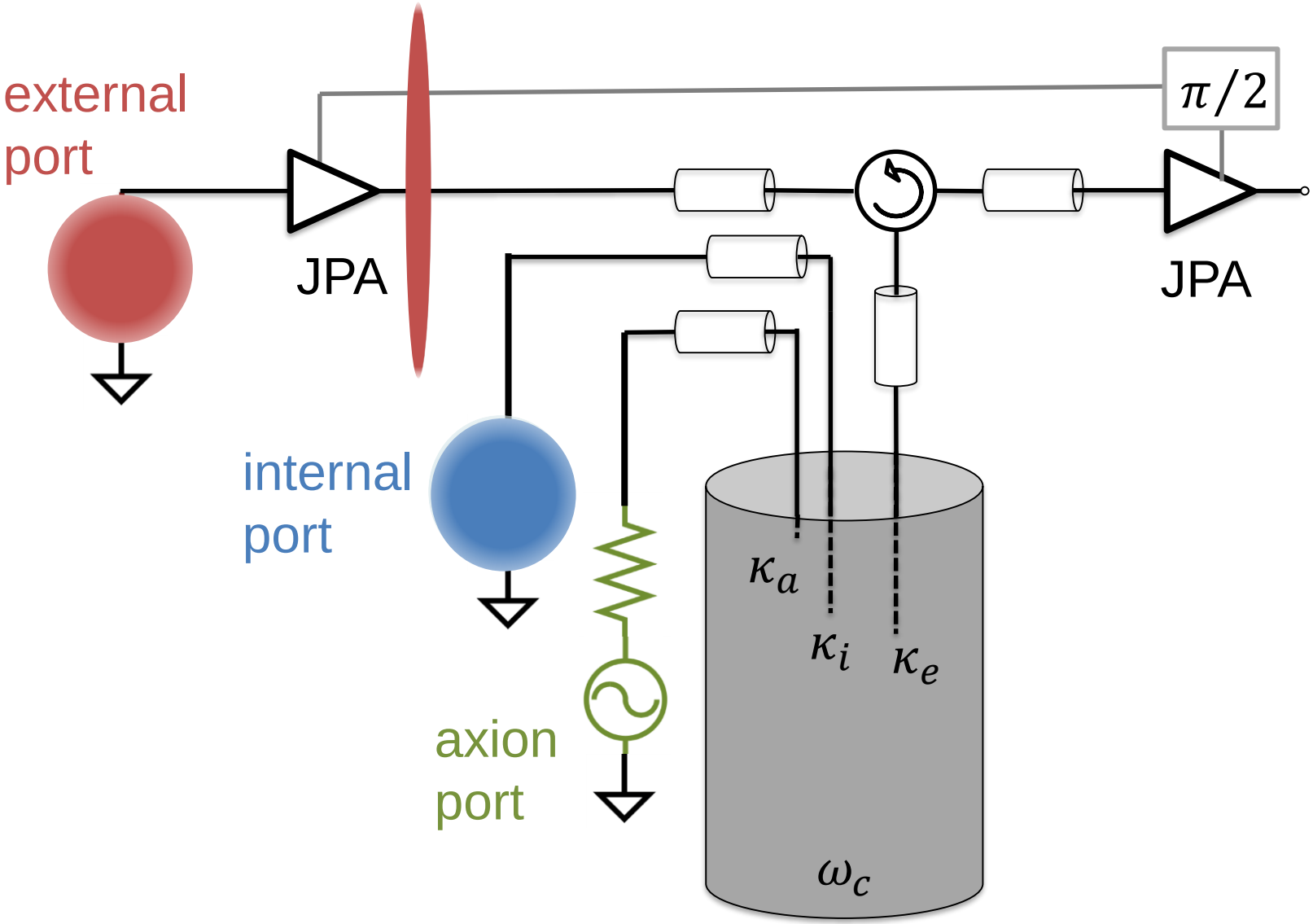
Critically coupled, zero detuning

$\kappa_e = \kappa_i, \Delta = 0$



Overcoupled, large detuning

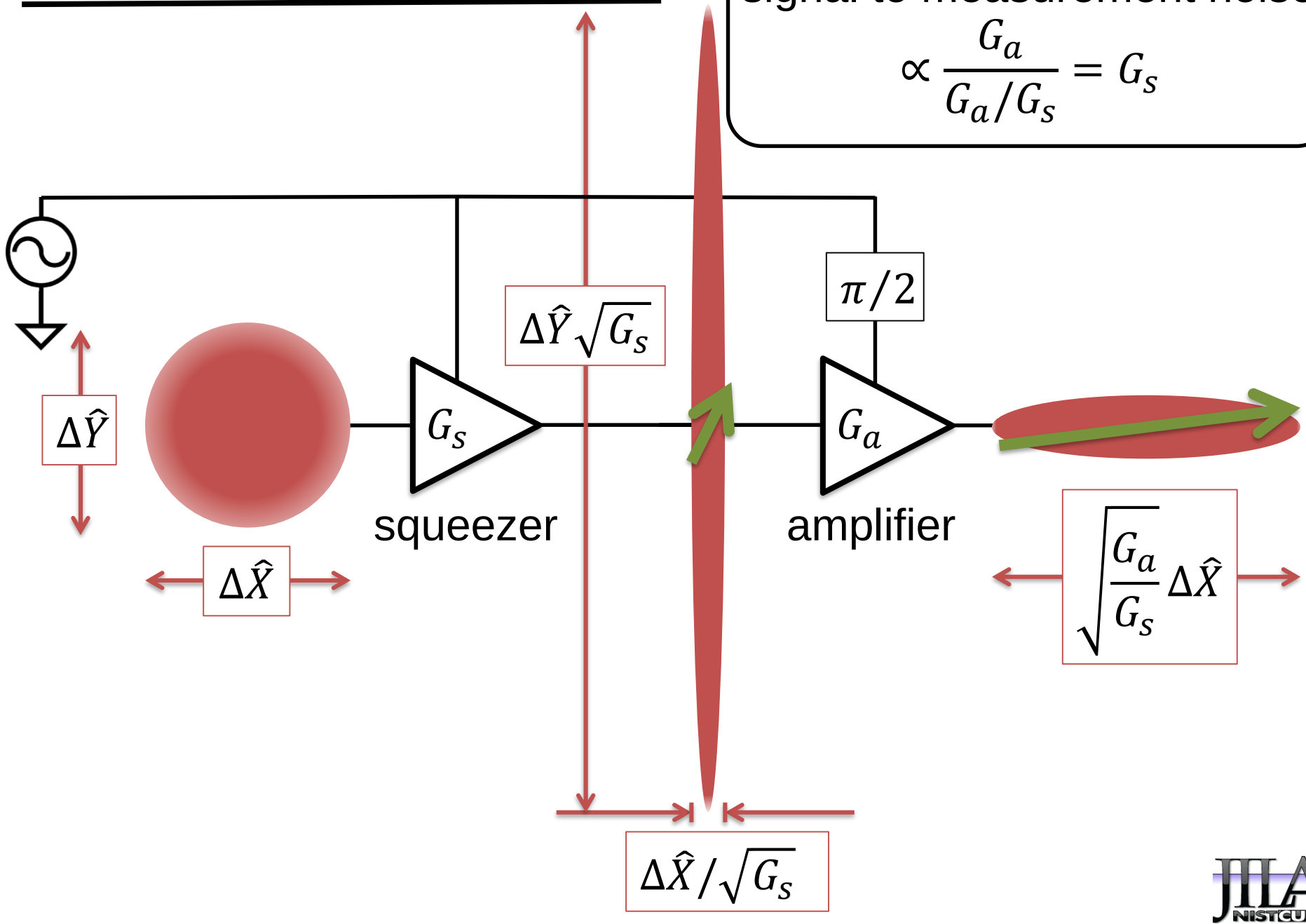
$\kappa_e \gg \kappa_i, \Delta \sim \kappa_e$



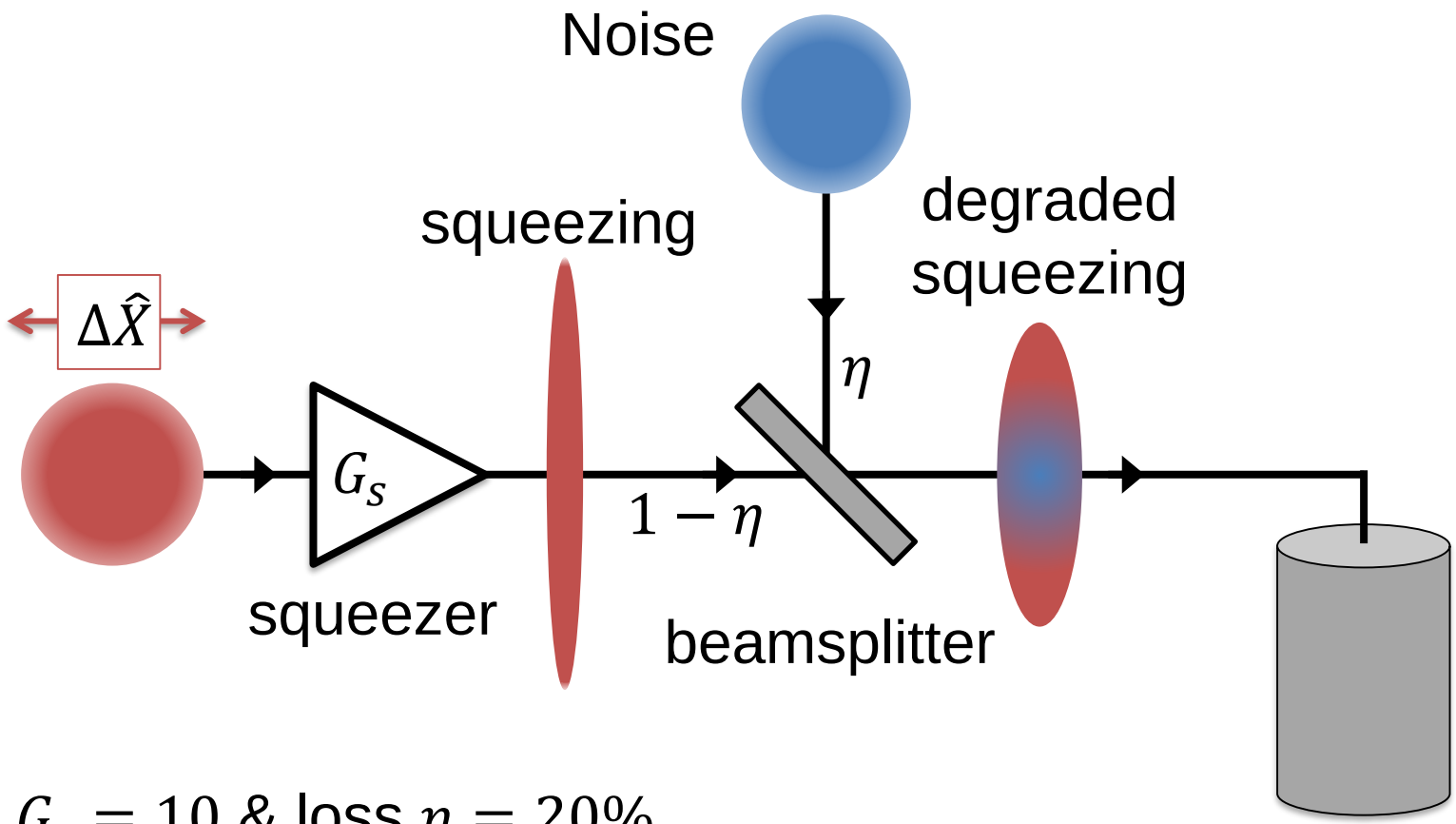
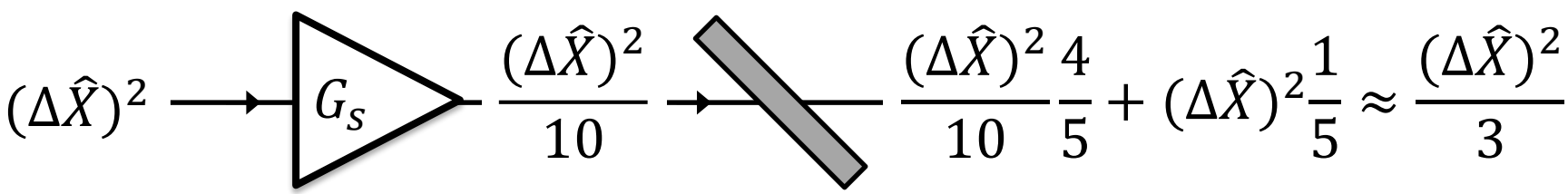
Squeezing with a JPA

signal to measurement noise

$$\propto \frac{G_a}{G_a/G_s} = G_s$$



Losses between squeezer and amplifier



ex: $G_s = 10$ & loss $\eta = 20\%$