Squeezed Light Spin Noise Spectroscopy

Vito Giovanni Lucivero

ICFO – The Institute of Photonic Sciences

IQIS 2015 - Monopoli

10 September 2015

Barcelona

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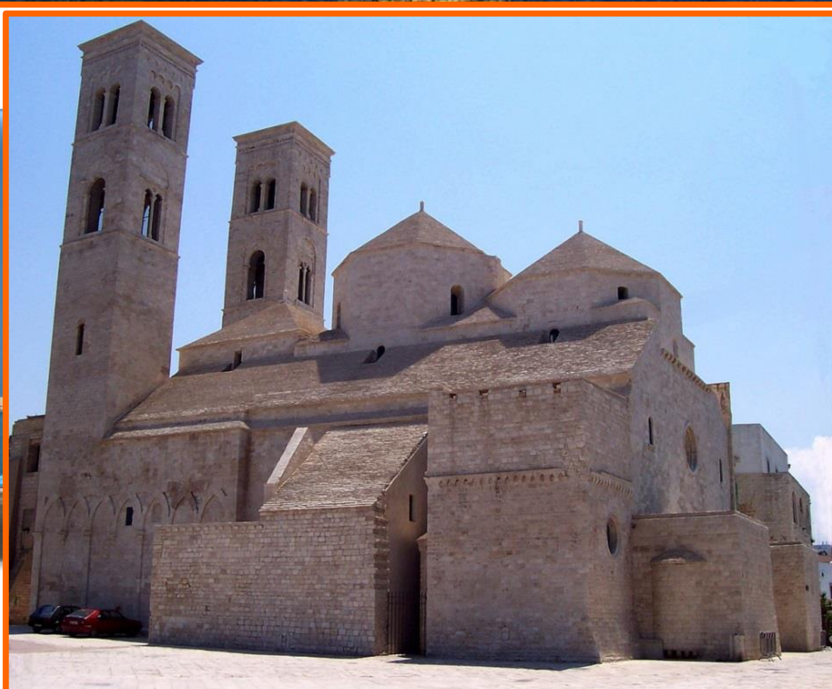


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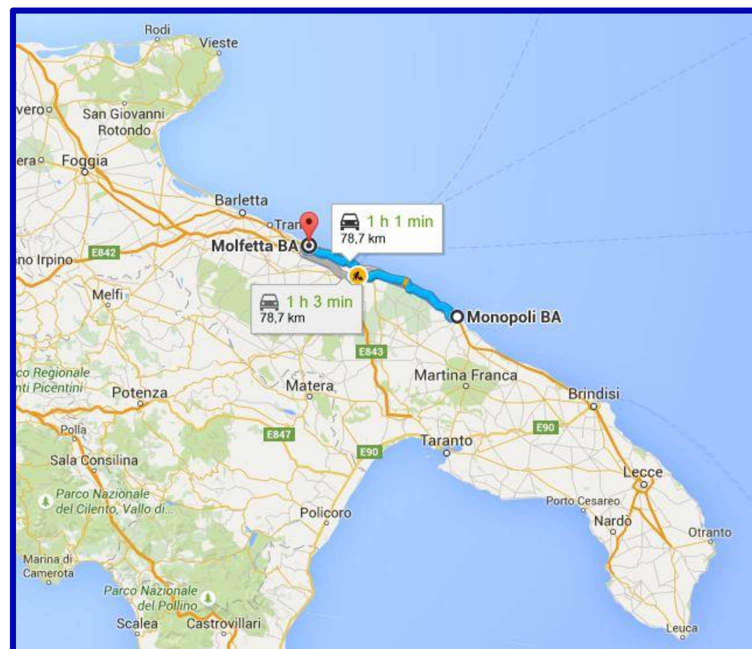

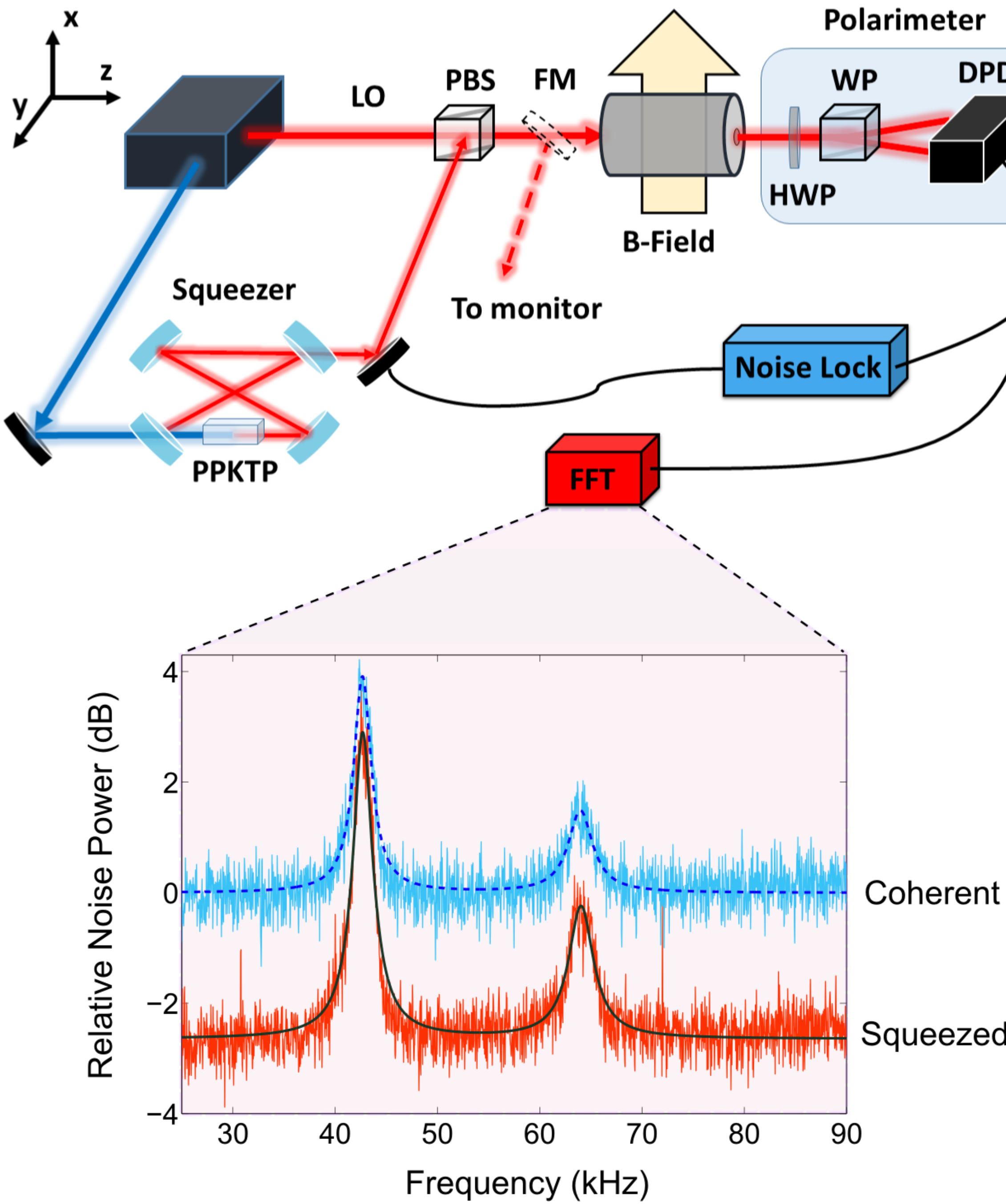

x
z
y
LO
PBS
FM
Polarimeter
WP
DPD
HWP
B-Field
To monitor
Squeezer
PPKTP
Noise Lock
FFT
Relative Noise Power (dB)
4
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30
40
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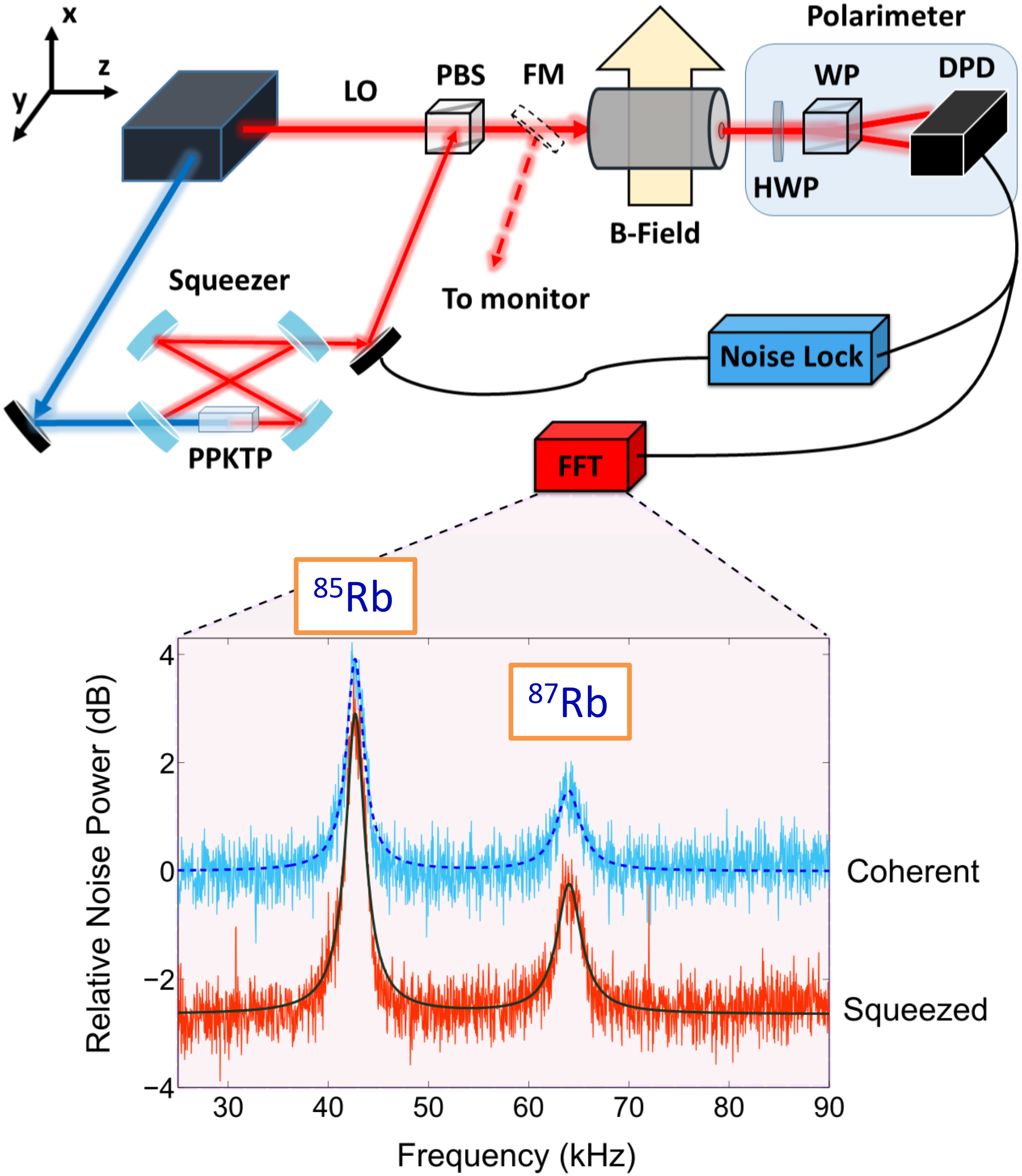
60
70
80
90
Frequency (kHz)
Coherent
Squeezed



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85Rb
87Rb
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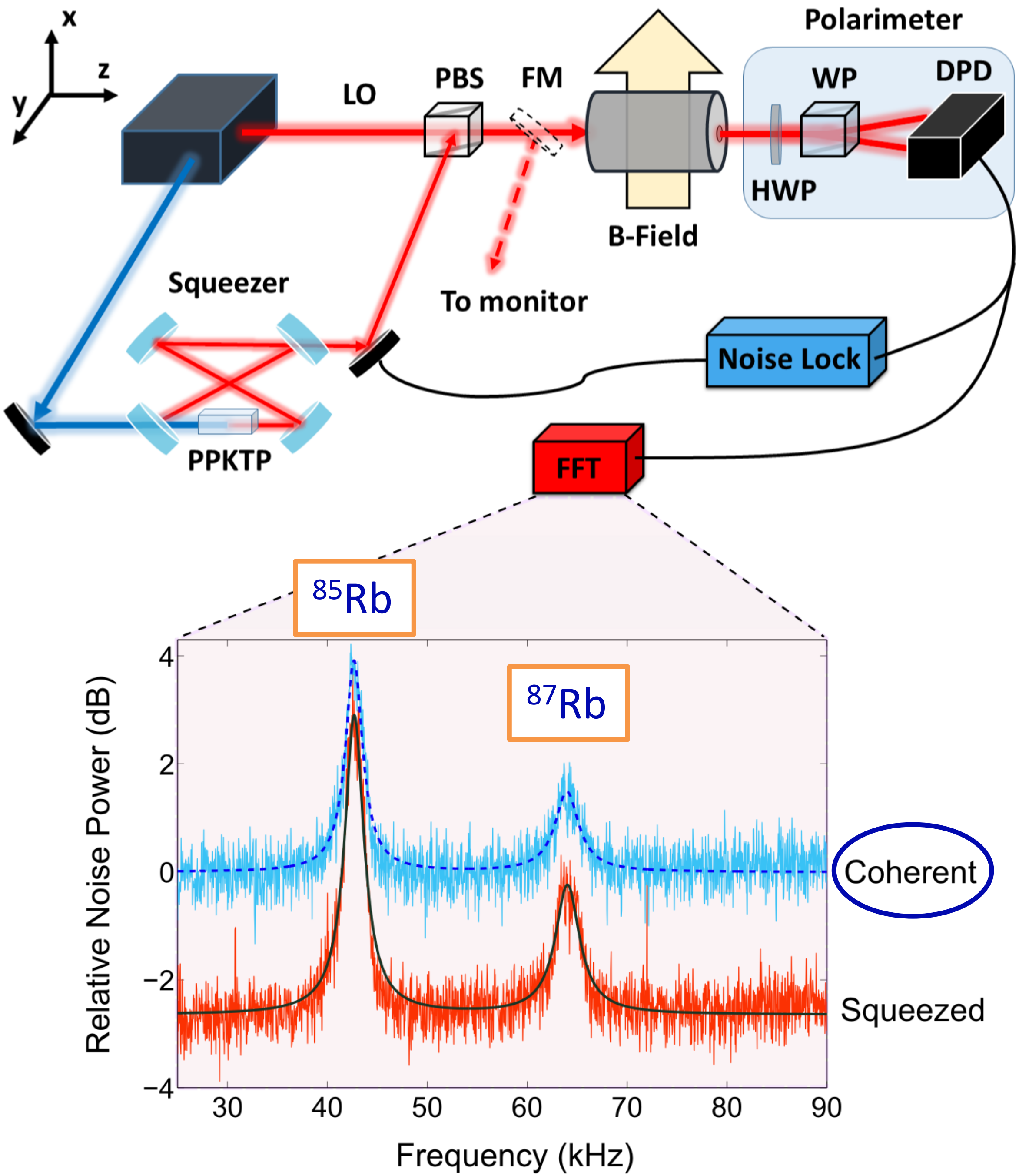

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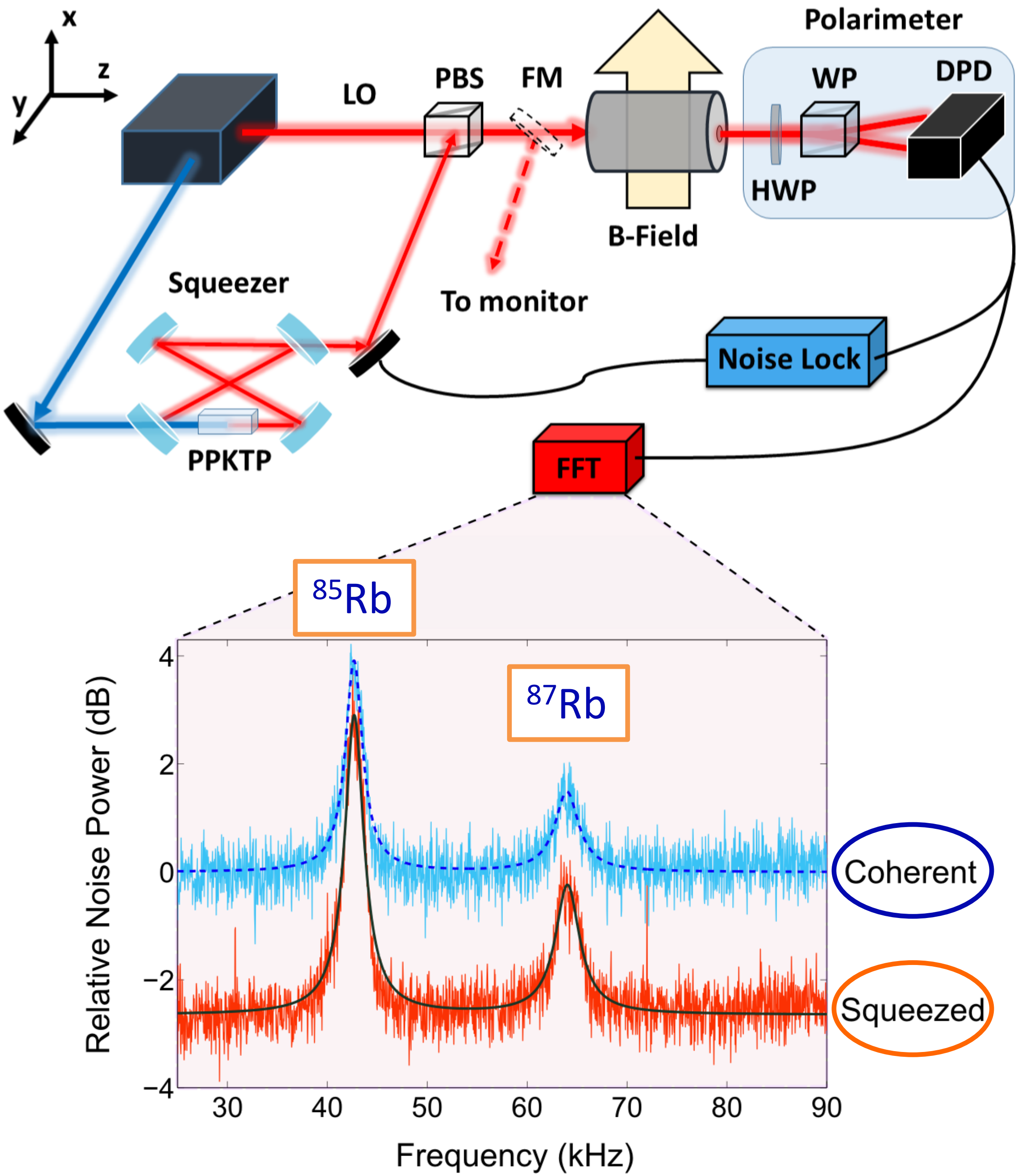
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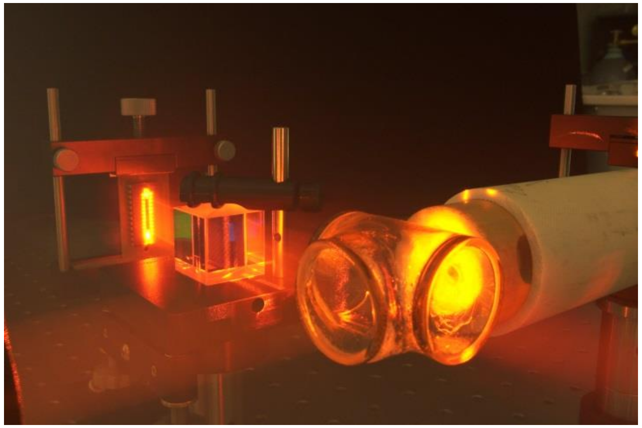
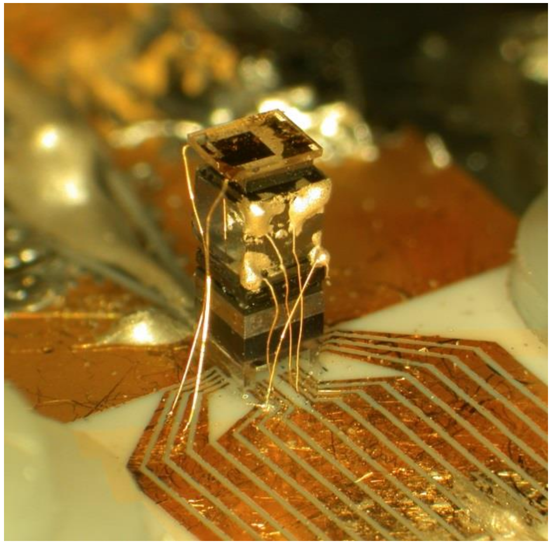
Open fundamental question:

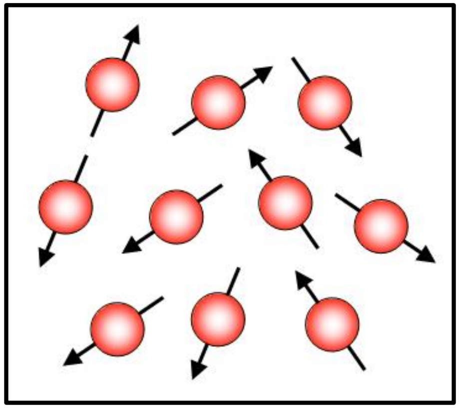
<u>Is it possible to apply squeezed light to precision measurements of high-density atomic ensembles?</u>



Optical magnetometers



Atomic clocks



Spin Noise Spectroscopy

Main fundamental noise sources:
atomic projection noise or by the *photon shot noise*

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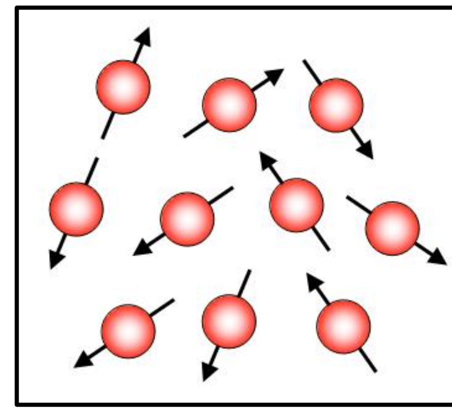


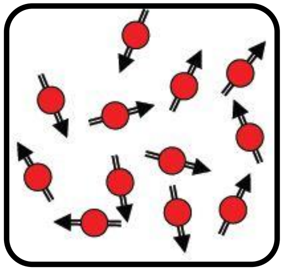
Optical magnetometers

Atomic clocks

Spin Noise Spectroscopy

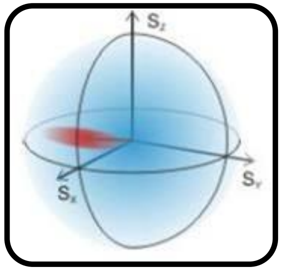
Here we show that we can improve a spin noise spectroscopy measurement via polarization squeezing!

Outline



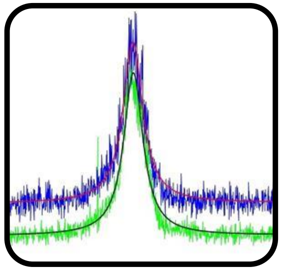
Spin Noise Spectroscopy (SNS)

- Faraday rotation based SNS



Polarization Squeezing

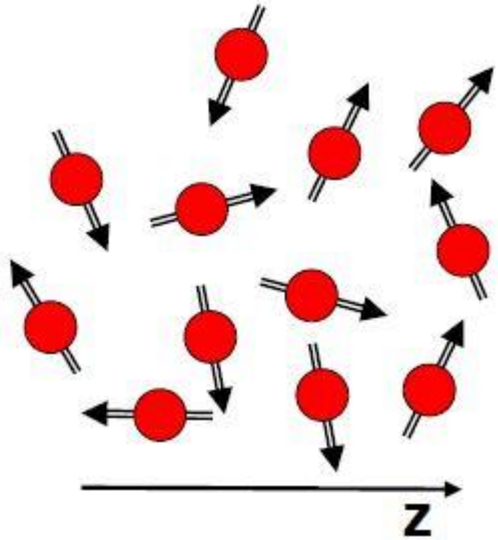
- Generation and detection



Squeezed Light SNS

- Experimental setup and results

Spin Noise Spectroscopy (SNS)



In thermal equilibrium the averaged value $< F_z(t) > = 0$

However fluctuations are present: $\sqrt{< [F_z(t)]^2 >} \sim\sqrt{N}$
Correlation function $< F_z(t)F_z(0) >$

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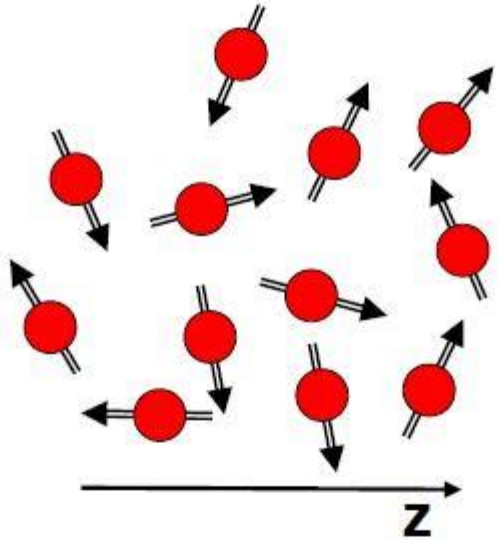

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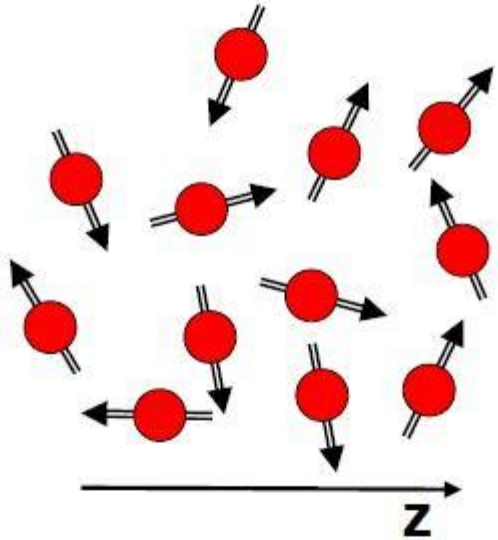

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- Spin noise spectroscopy (SNS) allows to measure the physical properties of an *unperturbed* state from its power spectrum

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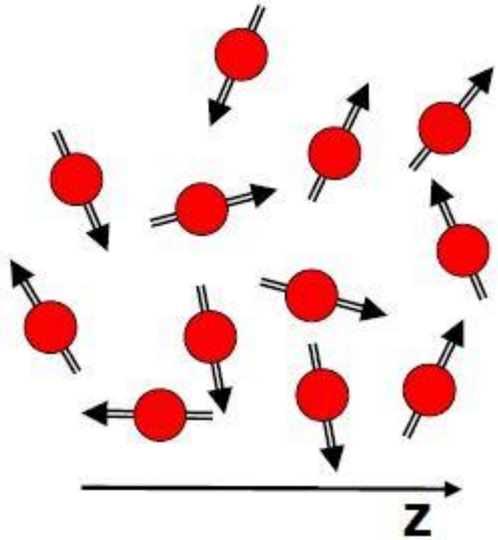

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FLUCTUATION – DISSIPATION THEOREM :

The power spectrum of fluctuations is proportional to the frequency response of the system to a small driving force

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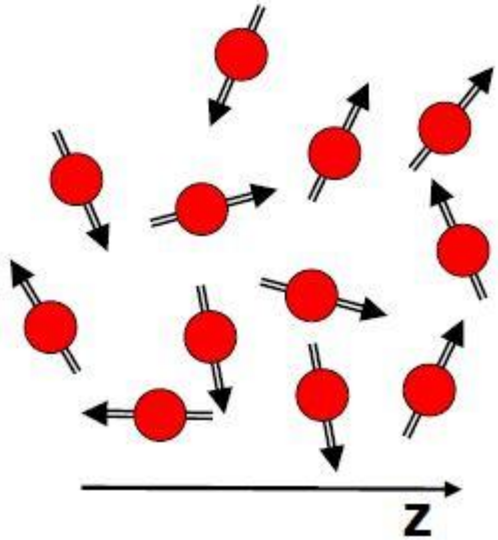

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IN PRINCIPLE:

Spin Noise Spectroscopy completely describes the spin system dynamics

Spin Noise Spectroscopy (SNS)

VOLUME 55, NUMBER 17 PHYSICAL REVIEW LETTERS 21 OCTOBER 1985

Nuclear-Spin Noise

Tycho Sleator and Erwin L. Hahn
Department of Physics, University of California, Berkeley, California 94720
and
Claude Hilbert and John Clarke
Department of Physics, University of California, Materials and Molecular Research Division, Lawrence Berkeley Laboratory, Berkeley, California 94720
(Received 12 August 1985)

The spectral density of Nyquist noise current in a tuned circuit coupled to a sample of nuclear spins has been measured at ^{4}He temperatures with a dc SQUID used as a rf amplifier. When the sample is in thermal equilibrium, a dip is observed in the spectral density at the Larmor frequency. For zero spin polarization, on the other hand, a bump in the spectral density is observed. This bump is due to temperature-independent fluctuations in the transverse component of magnetization, and represents spontaneous emission from the spins into the circuit.

First Approach:
Nuclear Magnetic Resonance techniques

Spectroscopy of spontaneous spin noise as a probe of spin dynamics and magnetic resonance

S. A. Crooker[1], D. G. Rickel[1], A. V. Balatsky[2] & D. L. Smith[2]

[1]*National High Magnetic Field Laboratory,* [2]*Theory Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

Nature 431, 49 (2004)

In the last decade:
Optical Faraday Rotation techniques

PHYSICAL REVIEW LETTERS week ending 18 NOVEMBER 2005

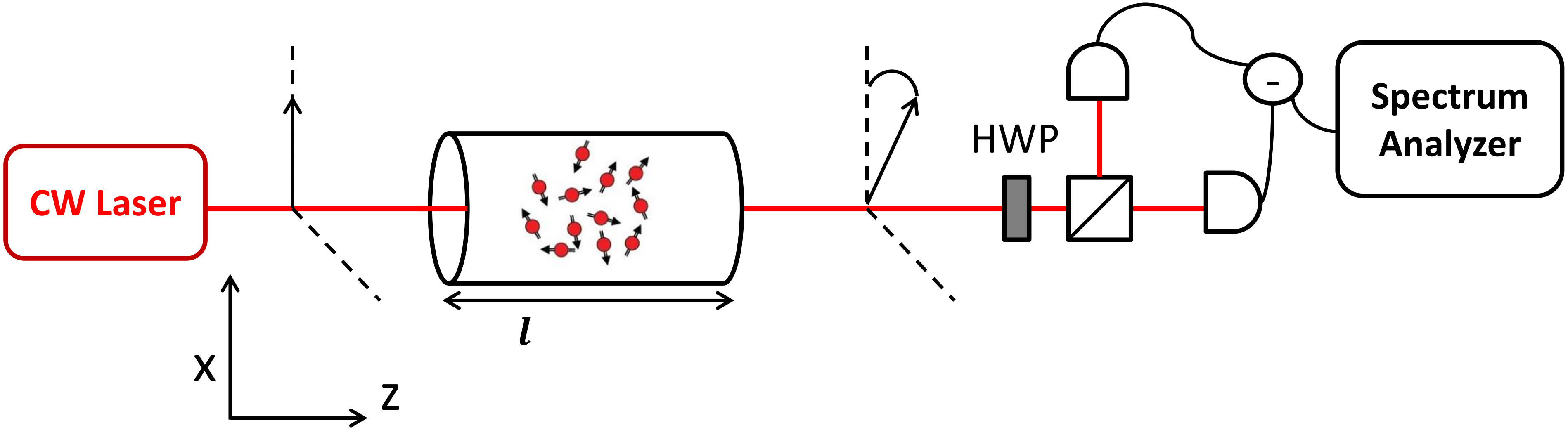
Spin Noise Spectroscopy in GaAs

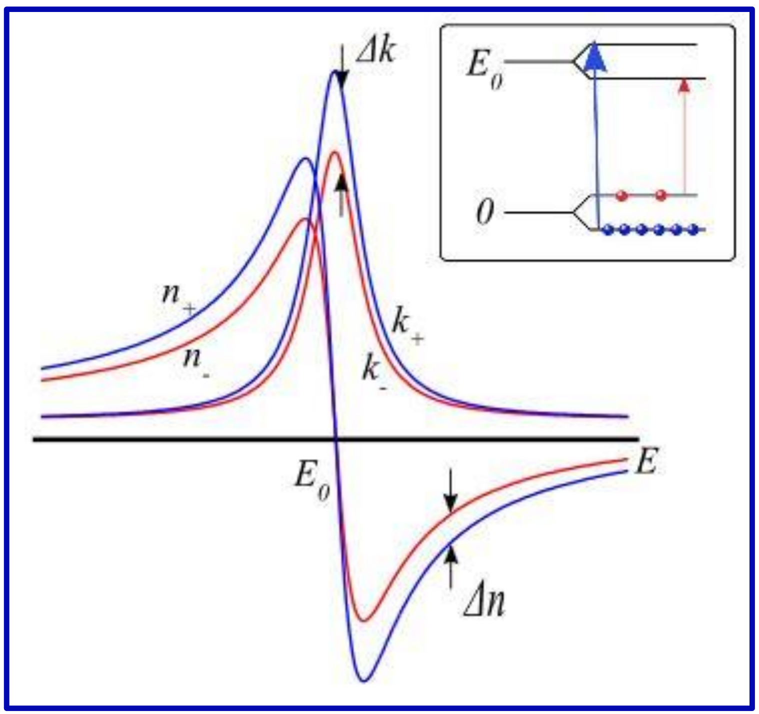
M. Oestreich, M. Römer, R. J. Haug, and D. Hägele
Institut für Festkörperphysik, Universität Hannover, Appelstraße 2, D-30167 Hannover, Germany
(Received 18 May 2005; published 17 November 2005)

We observe the noise spectrum of electron spins in bulk GaAs by Faraday-rotation noise spectroscopy. The experimental technique enables the undisturbed measurement of the electron-spin dynamics in semiconductors. We measure exemplarily the electron-spin relaxation time and the electron Landé g factor in n-doped GaAs at low temperatures and find good agreement of the measured noise spectrum with a theory based on Poisson distribution probability.

Review Articles: V. S. Zapasskii et al, Adv. Opt. Photon. 5, 131 (2013)
Hubner et al, Physica Status Solidi (b), 131 (2013)

Faraday rotation SNS





- Difference of population between the ground-state Zeeman sublevels turns into circular birefringence;

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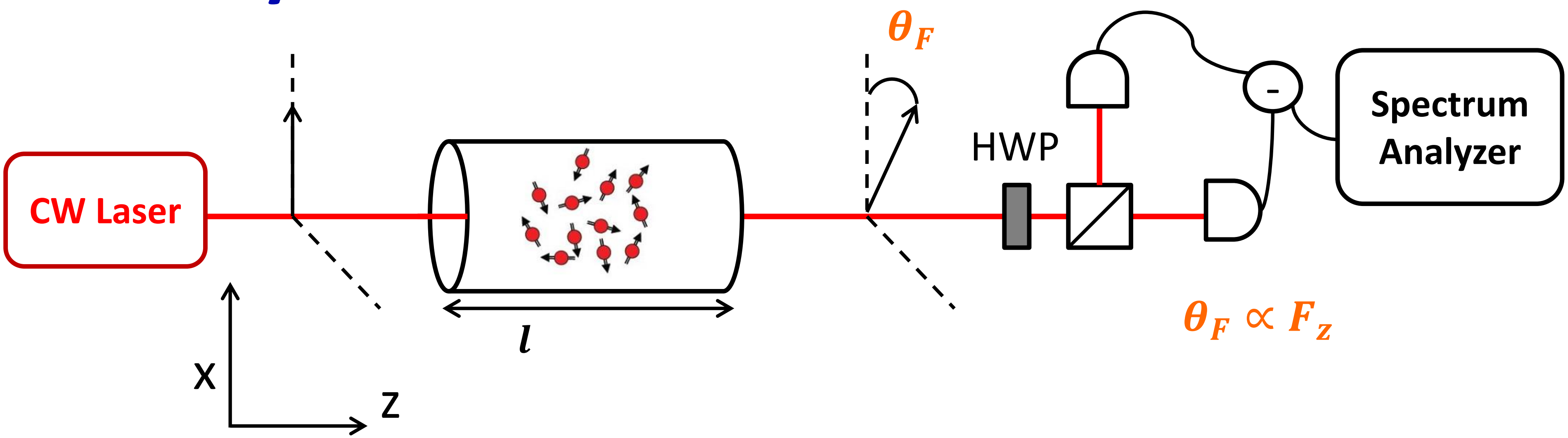
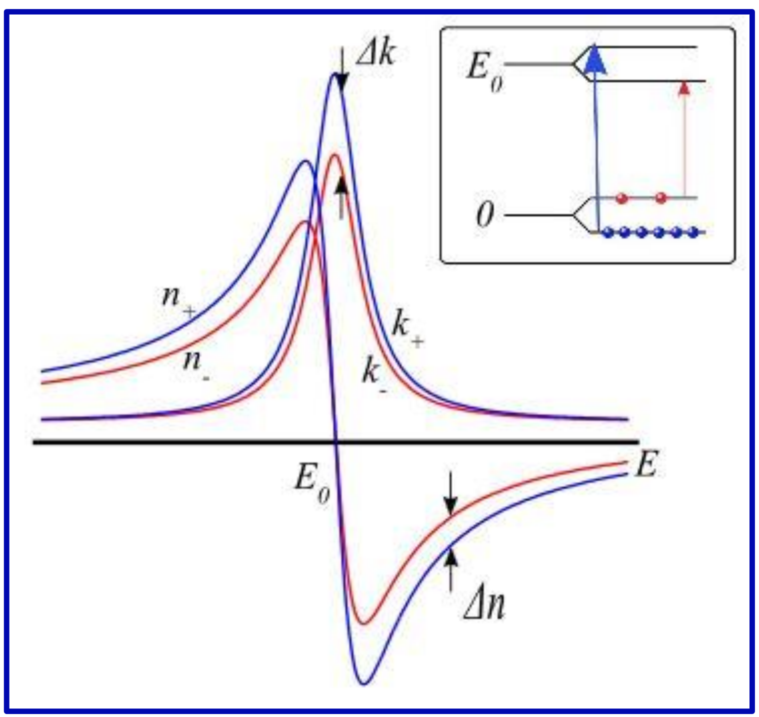
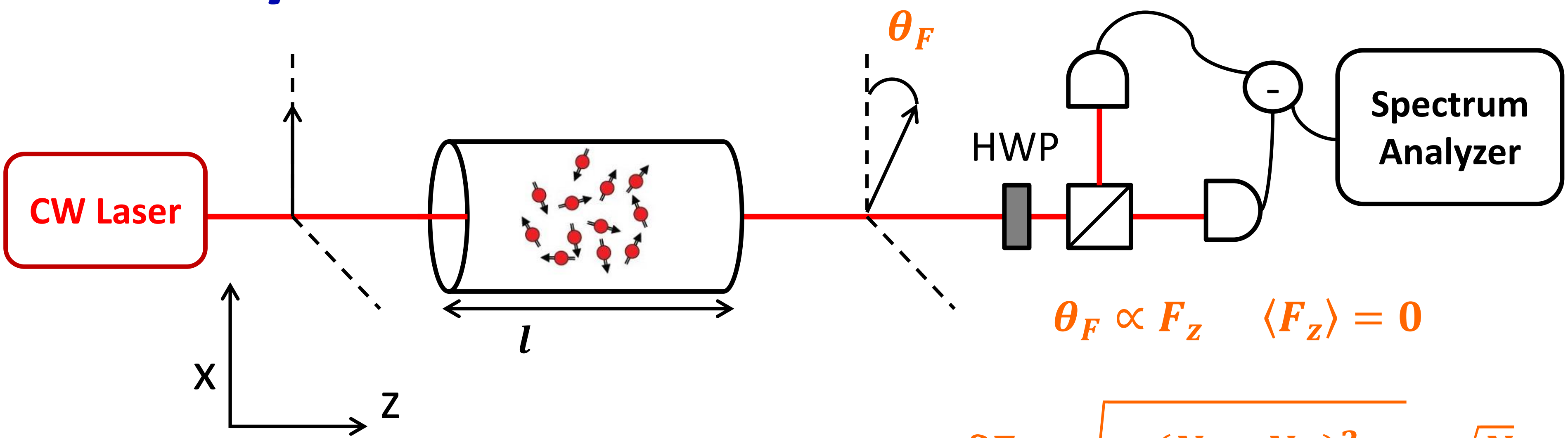




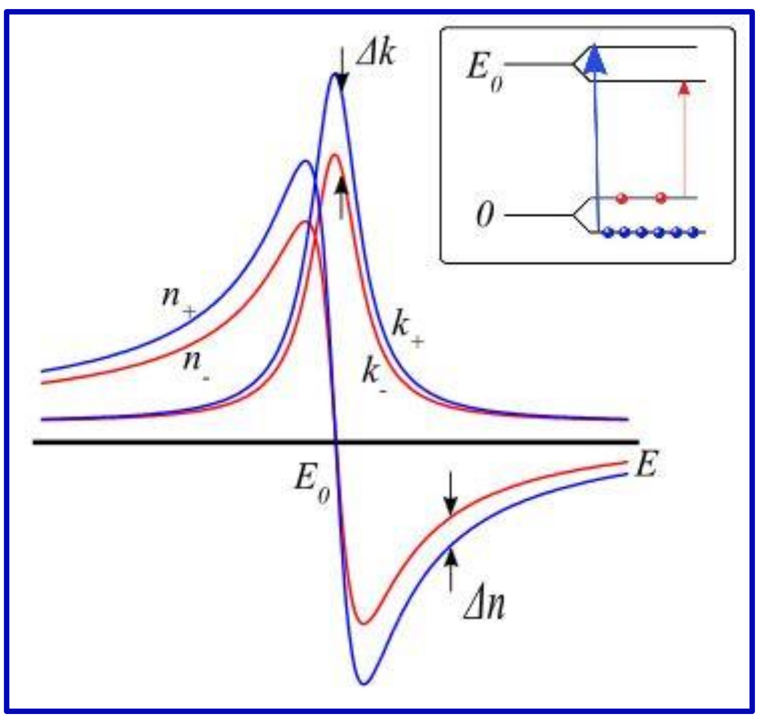
- Difference of population between the ground-state Zeeman sublevels turns into circular birefringence;
- Off-resonance probing of the atomic ensemble → rotation of the polarization plane

Faraday rotation SNS



$$\theta_F \propto F_z \qquad \langle F_z \rangle = 0$$

$$\delta F_z \sim \sqrt{< (N_+ - N_-)^2 >} = \sqrt{N}$$



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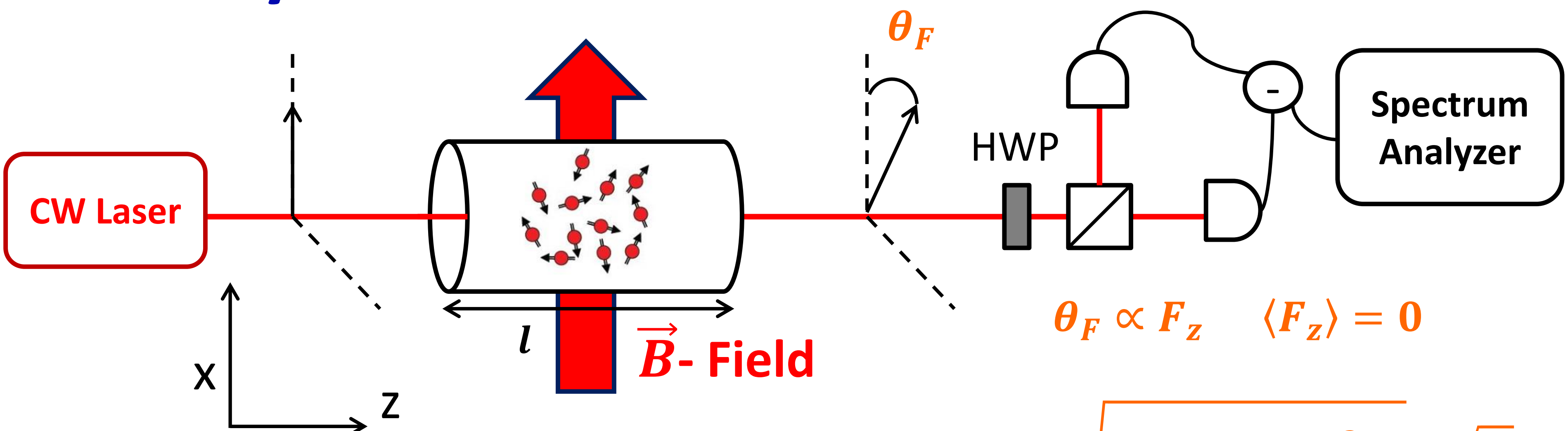

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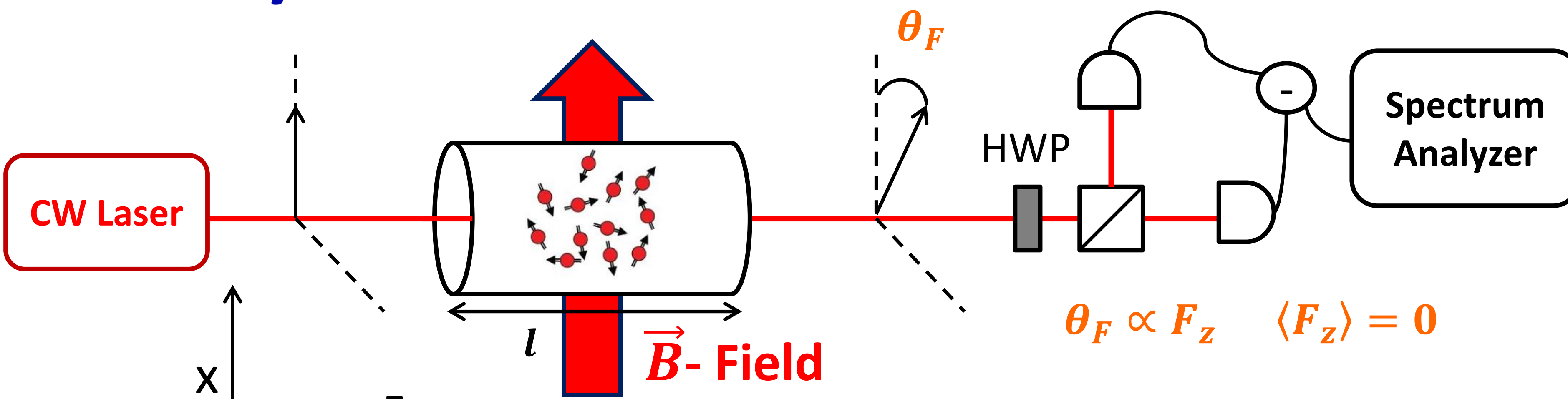

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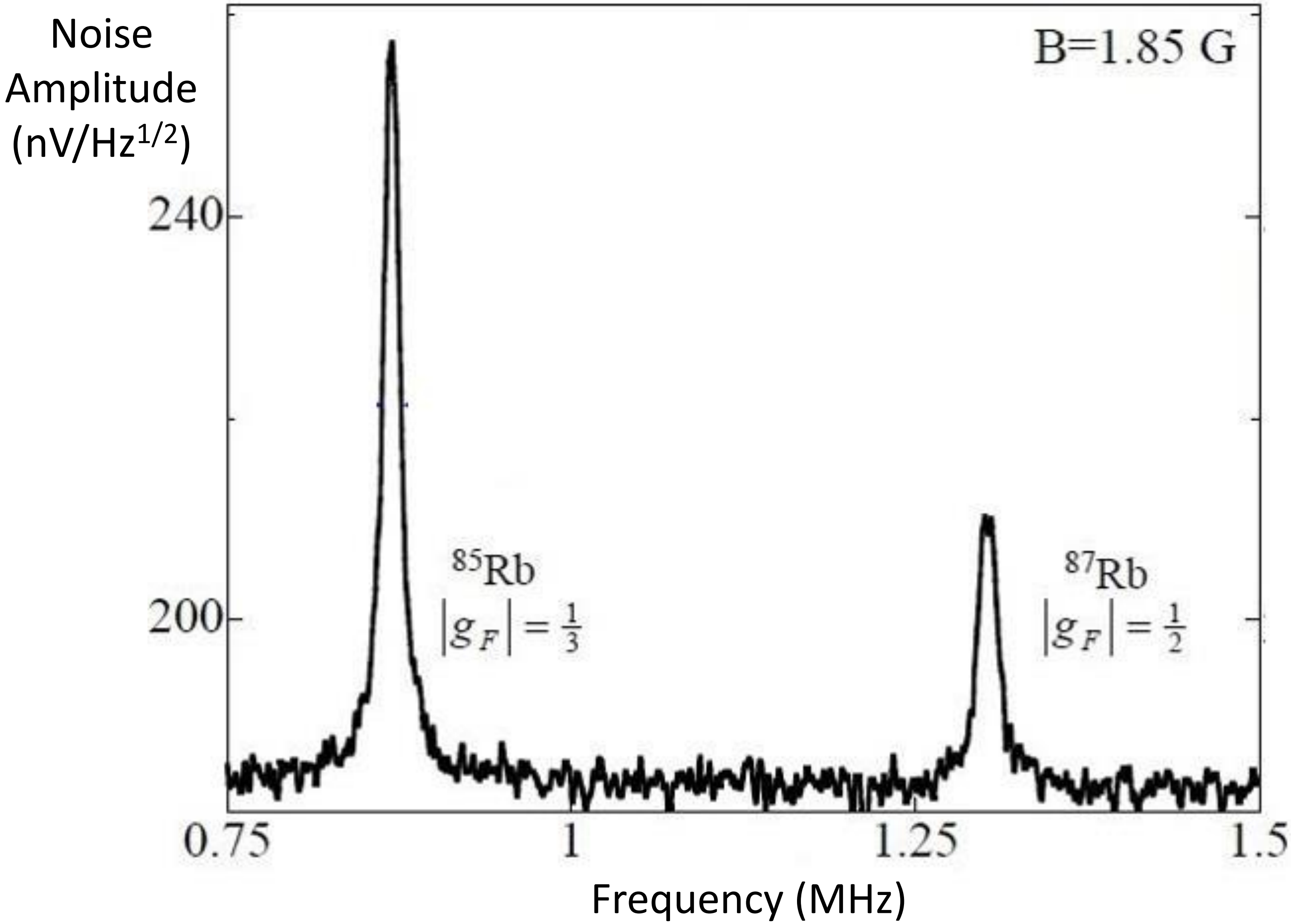
➡ Spin noise peak at the Larmor frequency in the power spectrum

Faraday rotation spin noise spectrum



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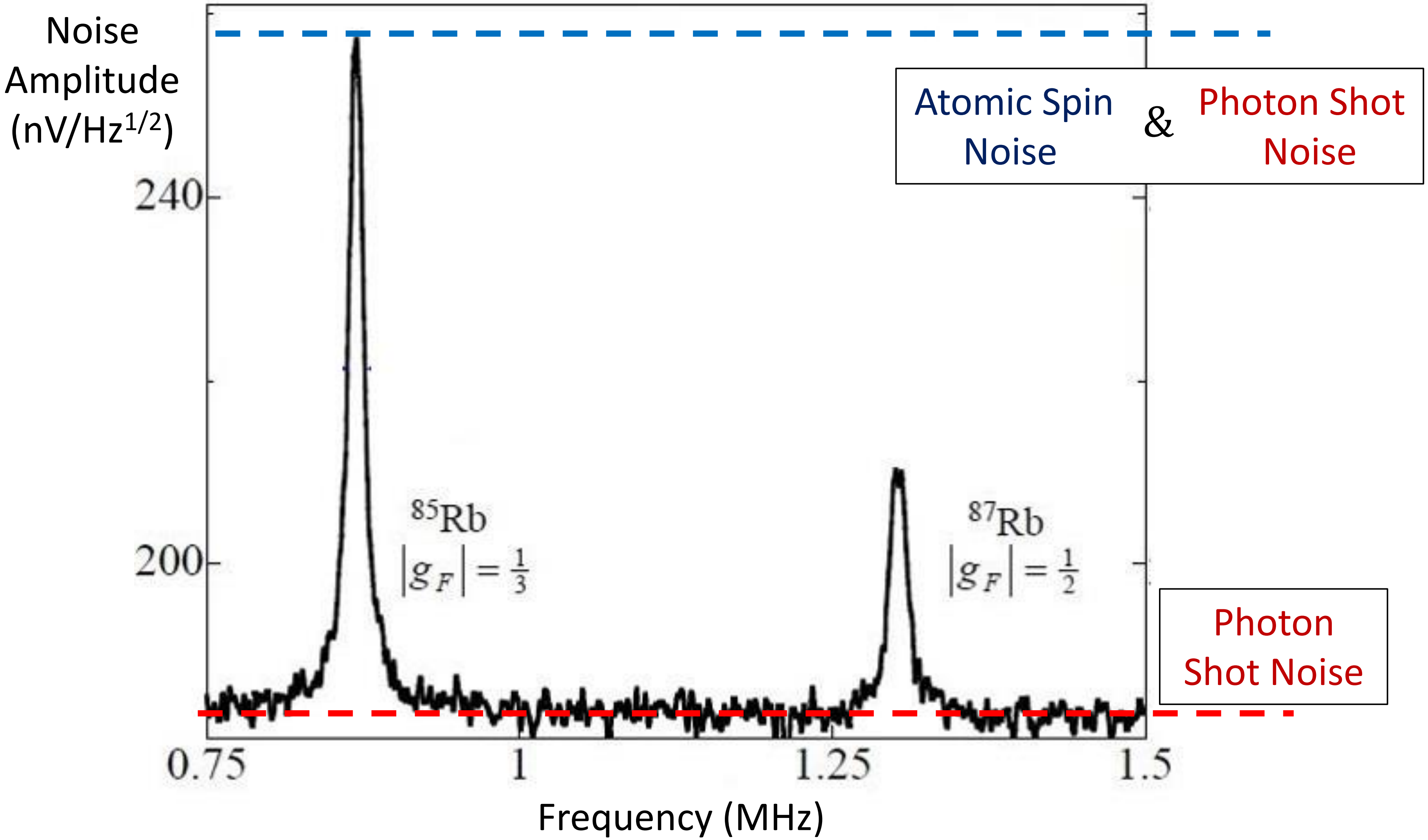

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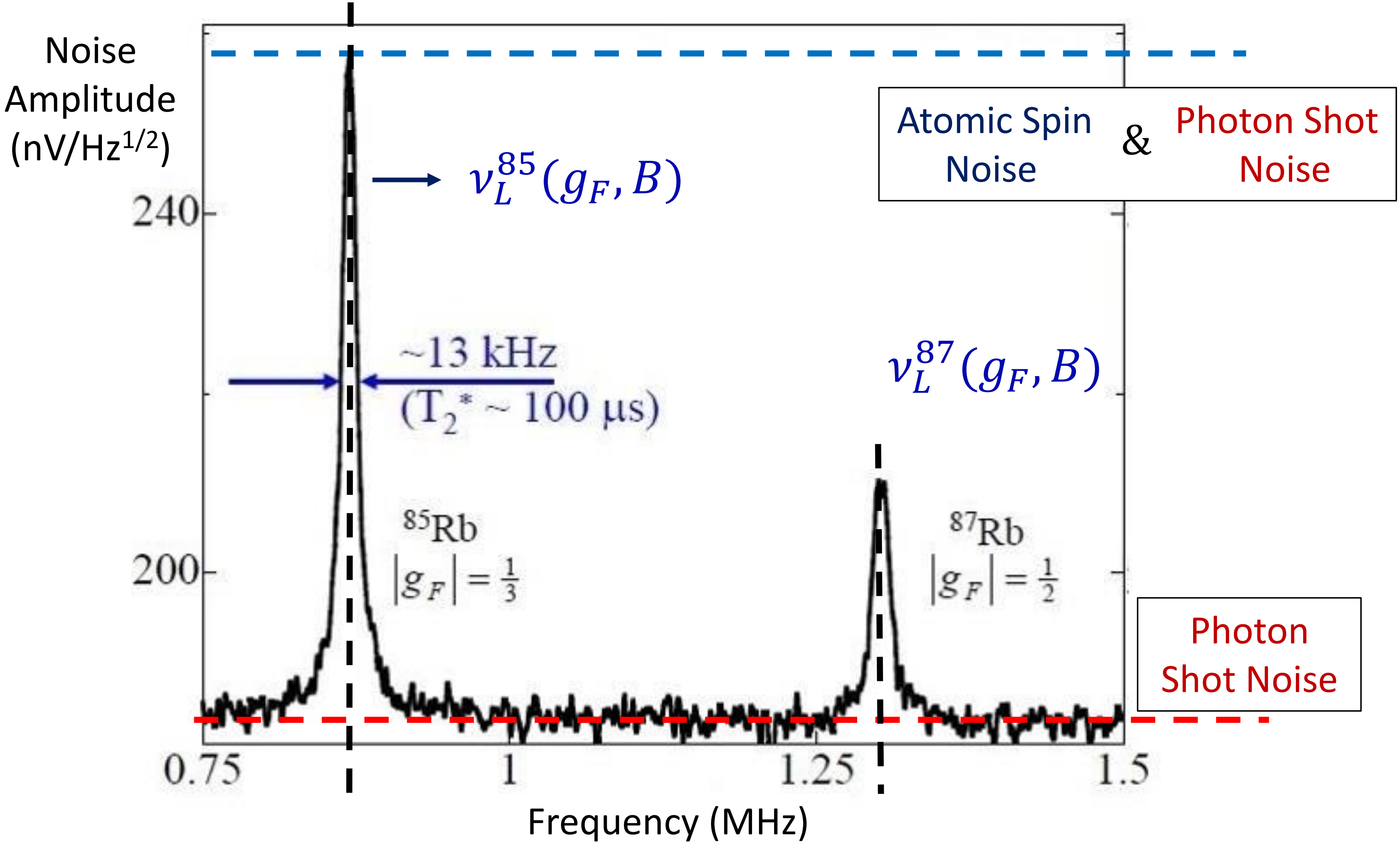

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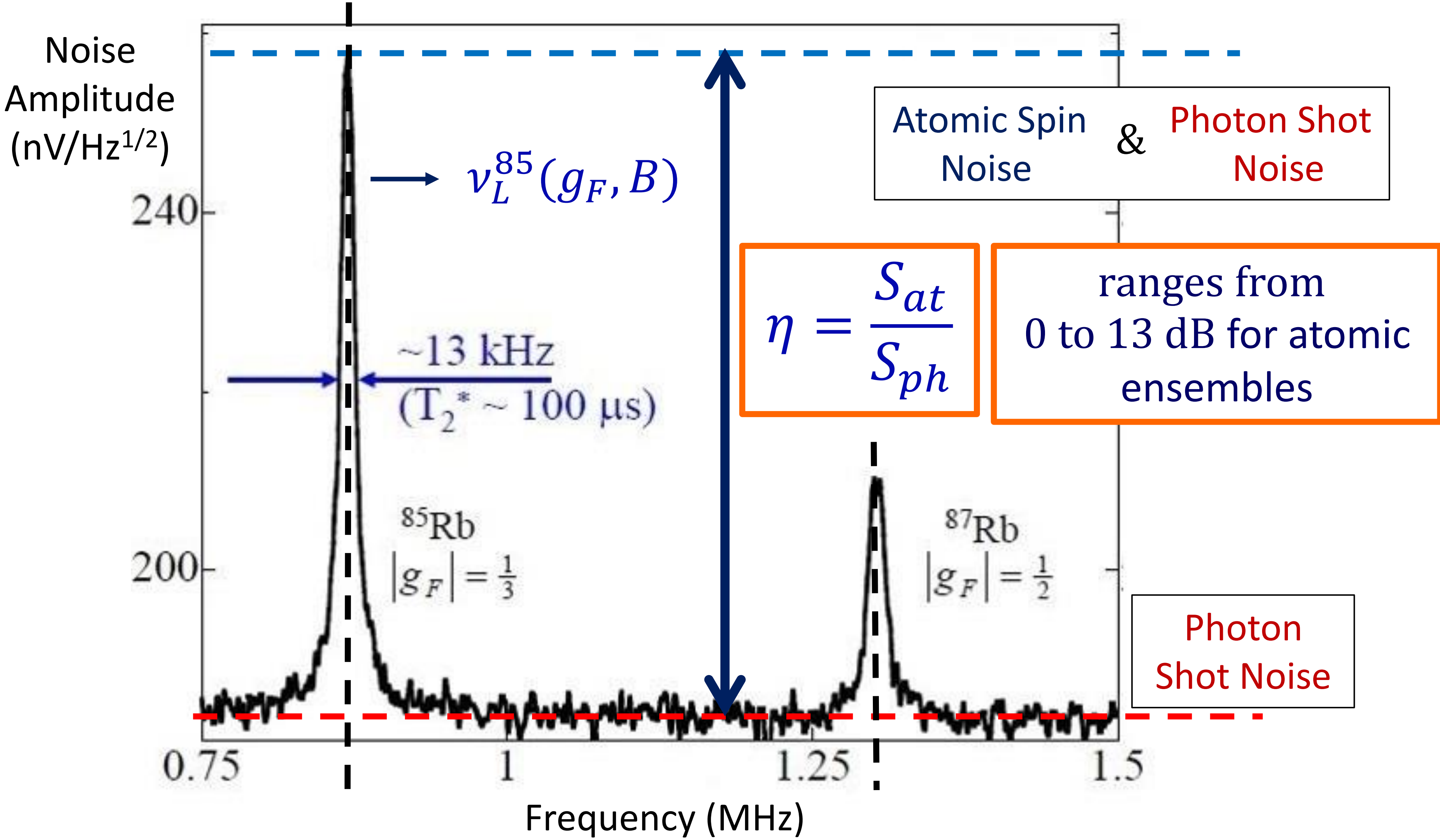

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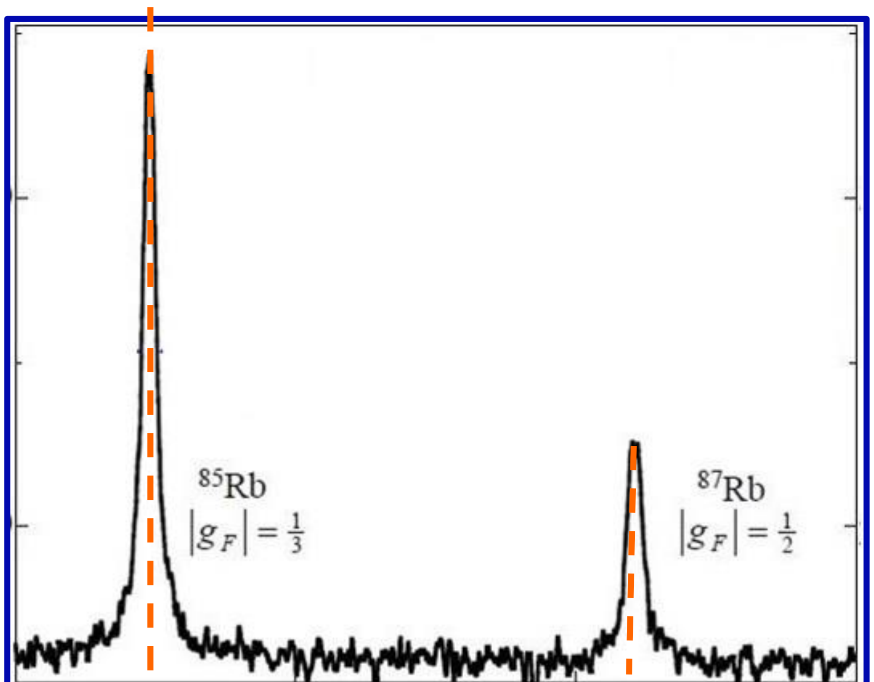
SNS Signal strength

$$S(v) = S_{ph} + \sum_{\iota\in\{85,87\}} S_{at}^{(i)} \frac{(\frac{\Delta\nu_i}{2})^2}{(\nu - \nu_L^{(i)})^2 + (\frac{\Delta\nu_i}{2})^2}$$



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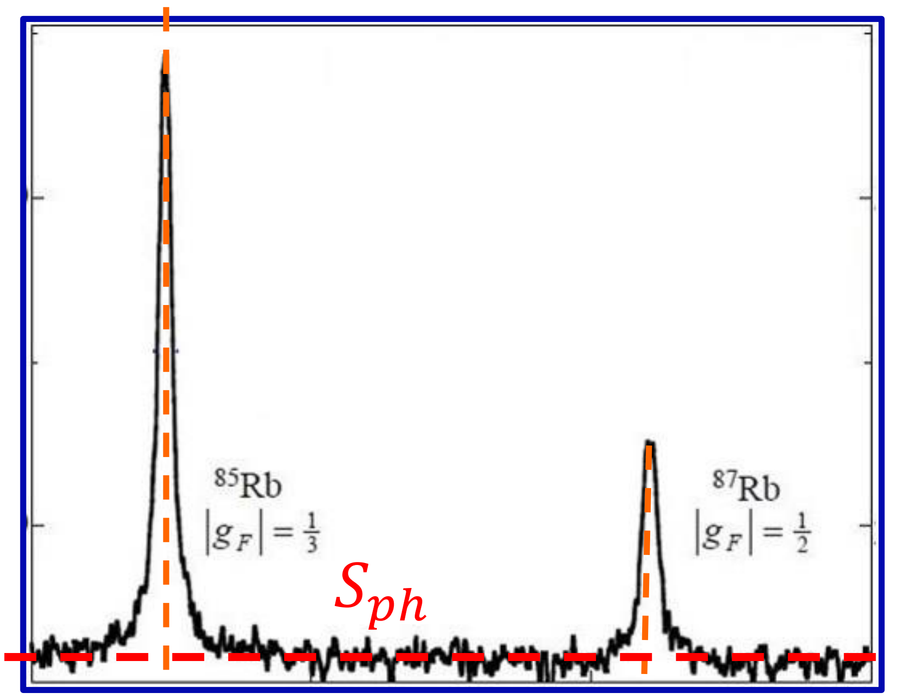

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$$\boxed{S_{ph} \propto P\xi^2}$$

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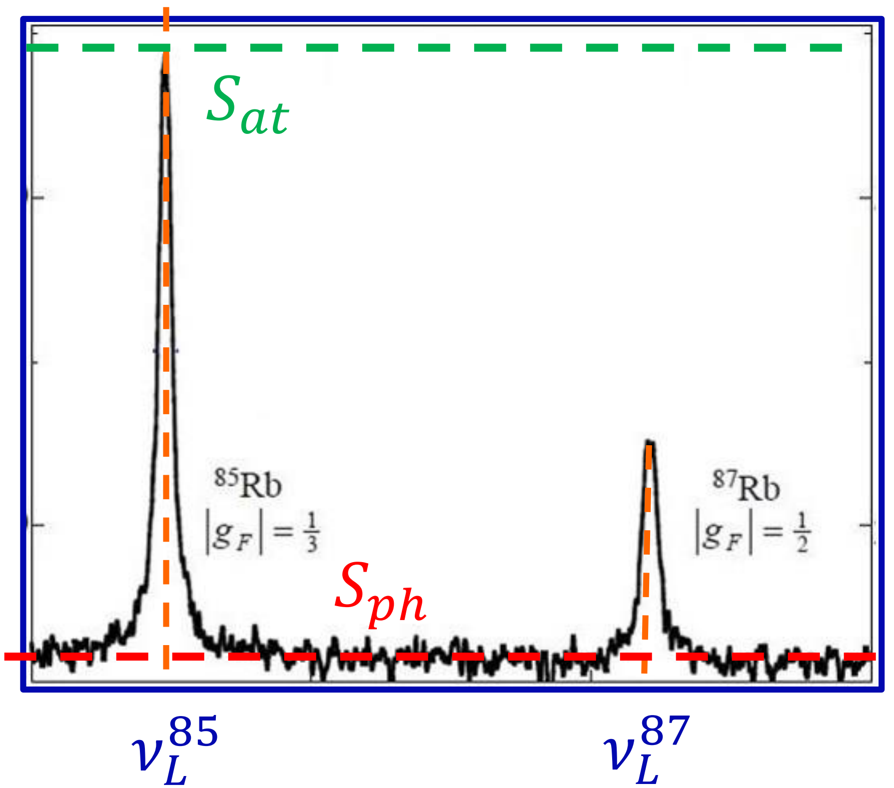

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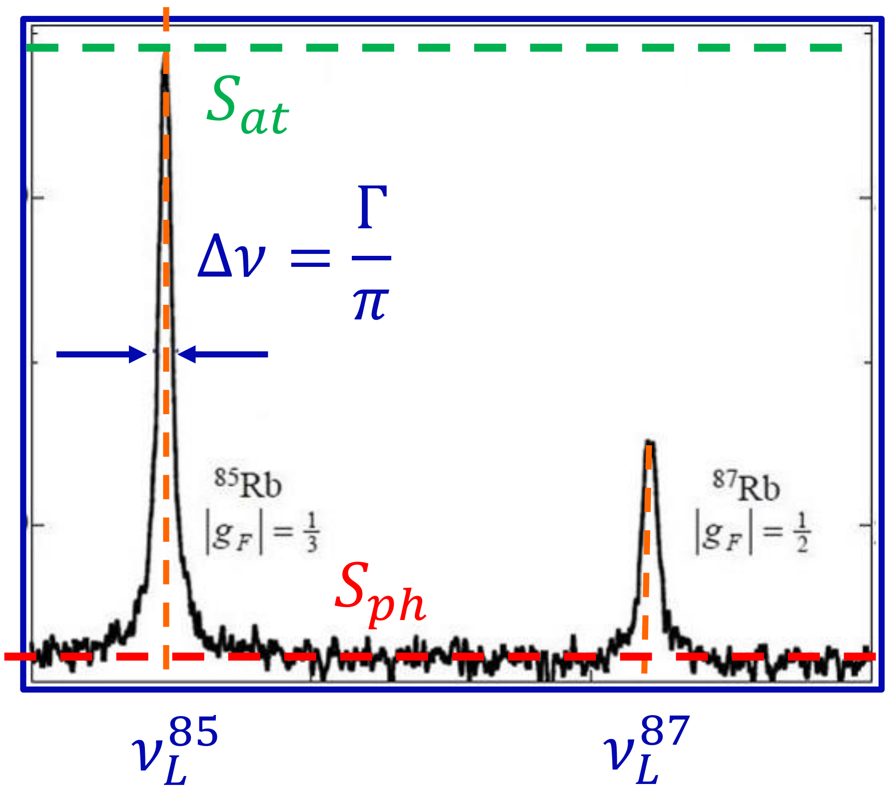

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$$\Gamma = \frac{1}{T_2} = \Gamma_0 + \alpha n + \beta P$$

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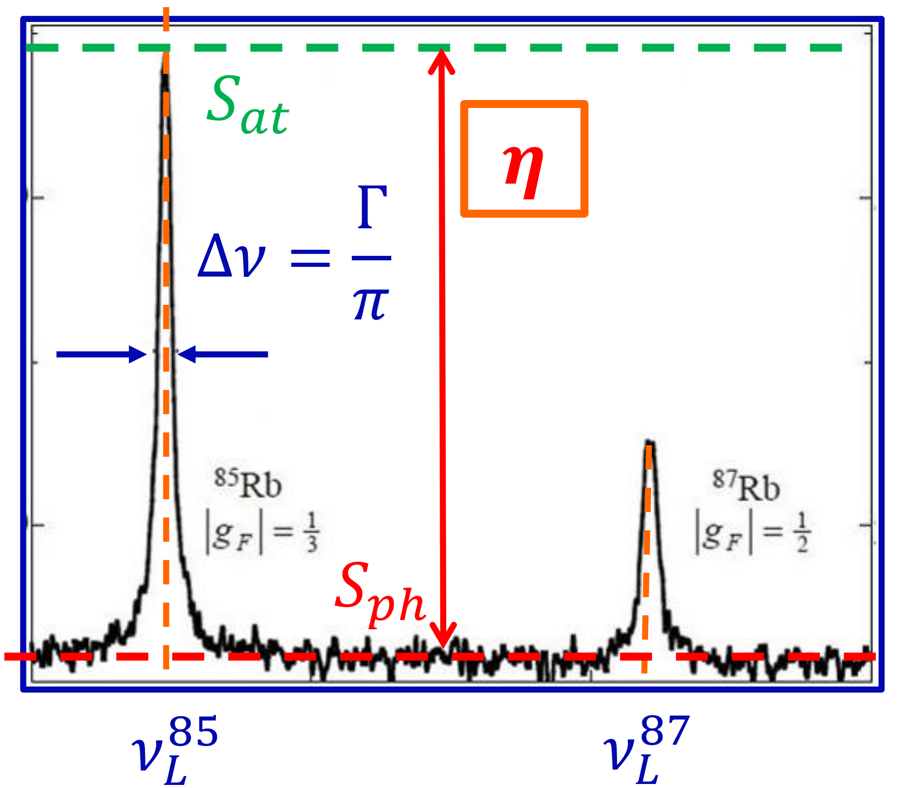

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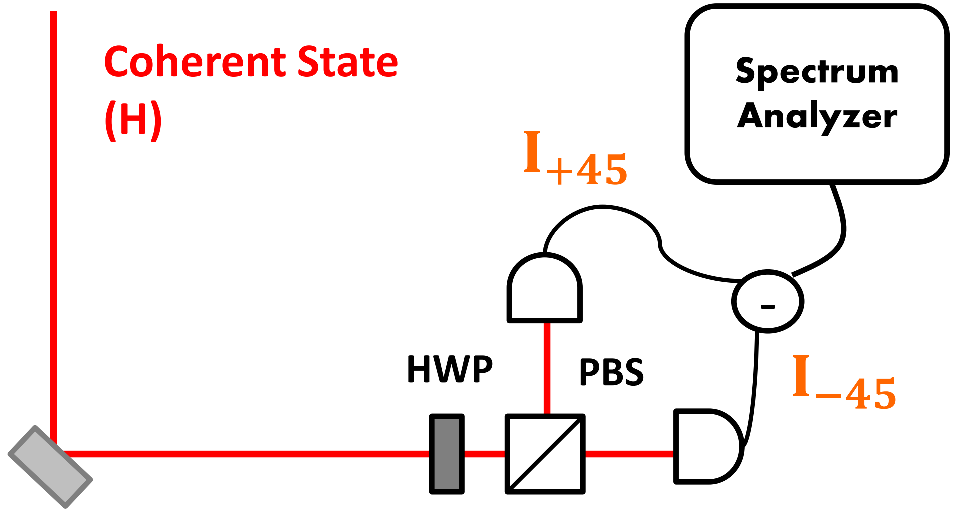
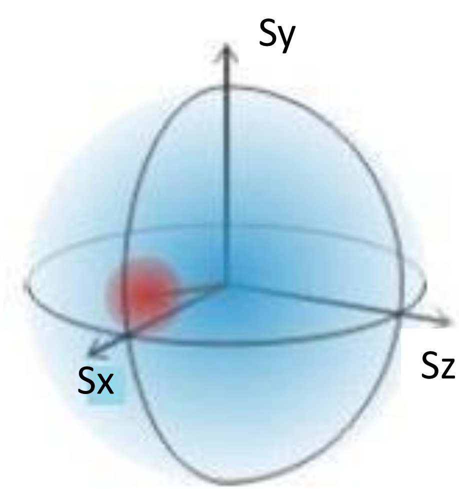
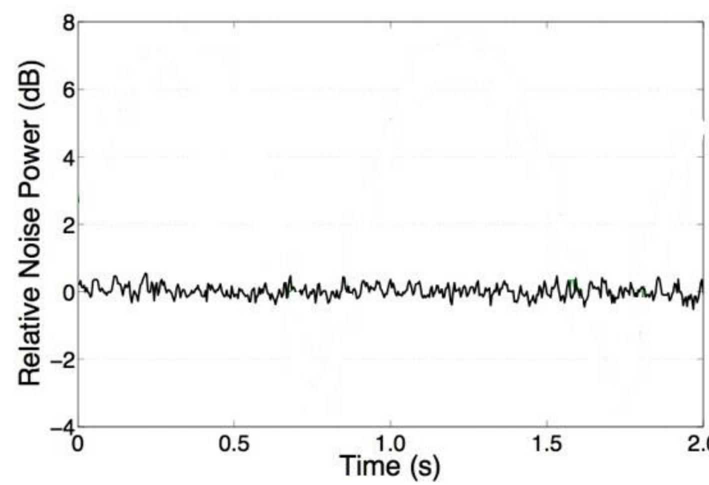
Polarization Squeezing



$$\hat{S}_y = I_{+45} - I_{-45}$$

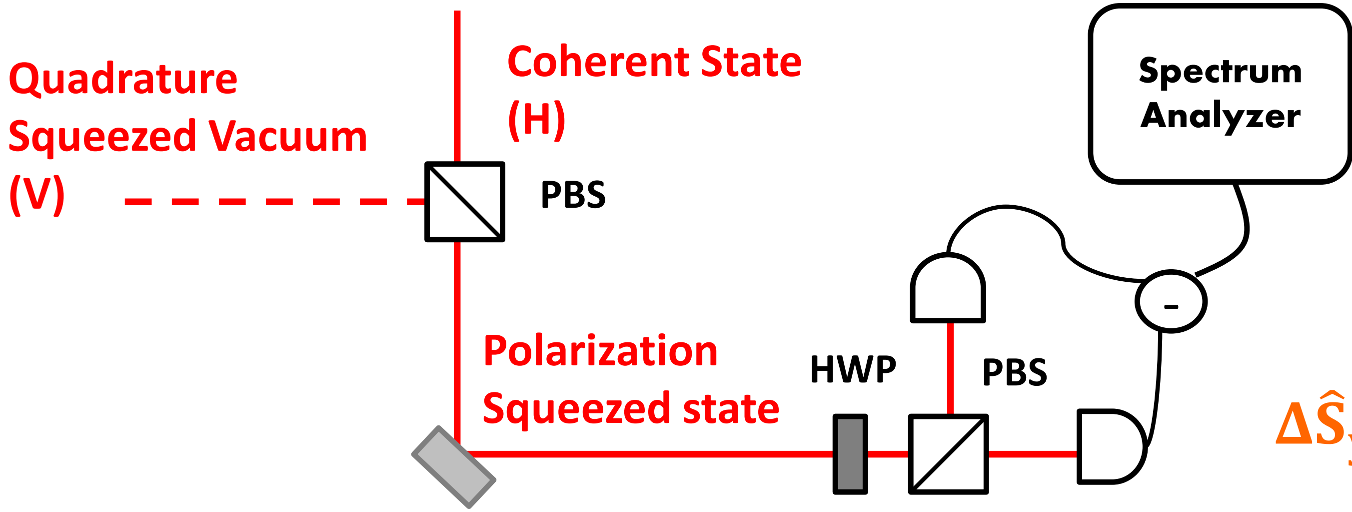
$$\Delta\hat{S}_y^{\,coh} \propto \sqrt{N_{ph}}$$





Polarization Squeezing

- Sub-shot noise measurements via polarization squeezing:



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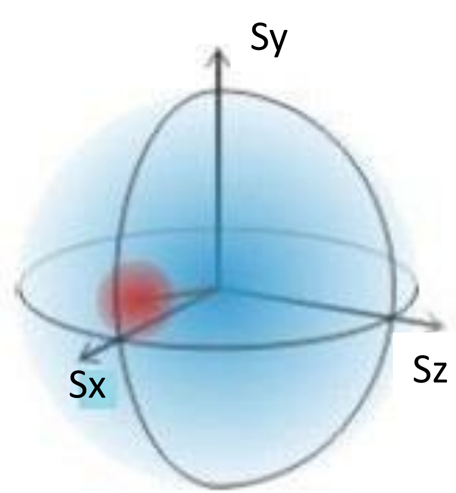

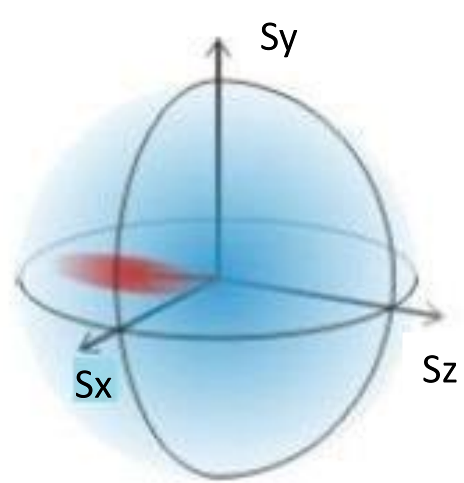

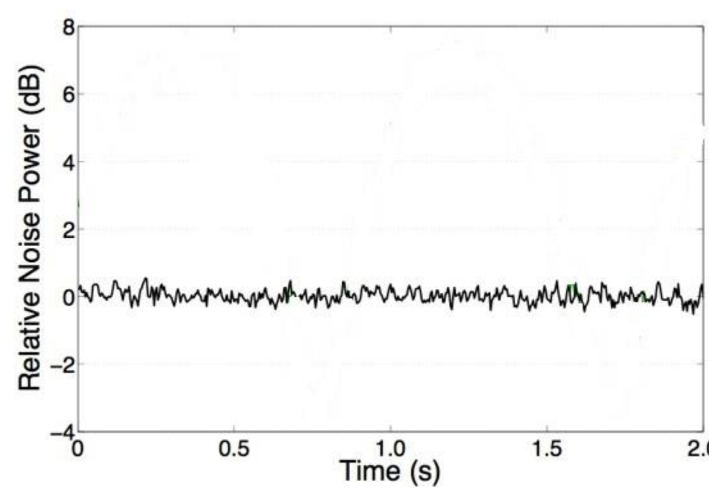

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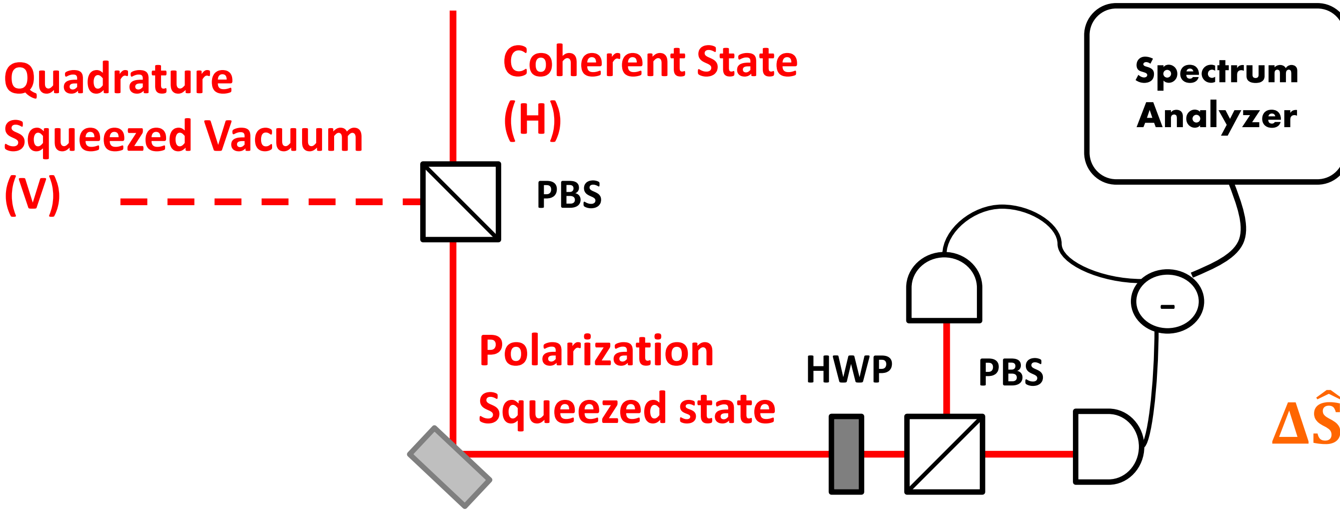

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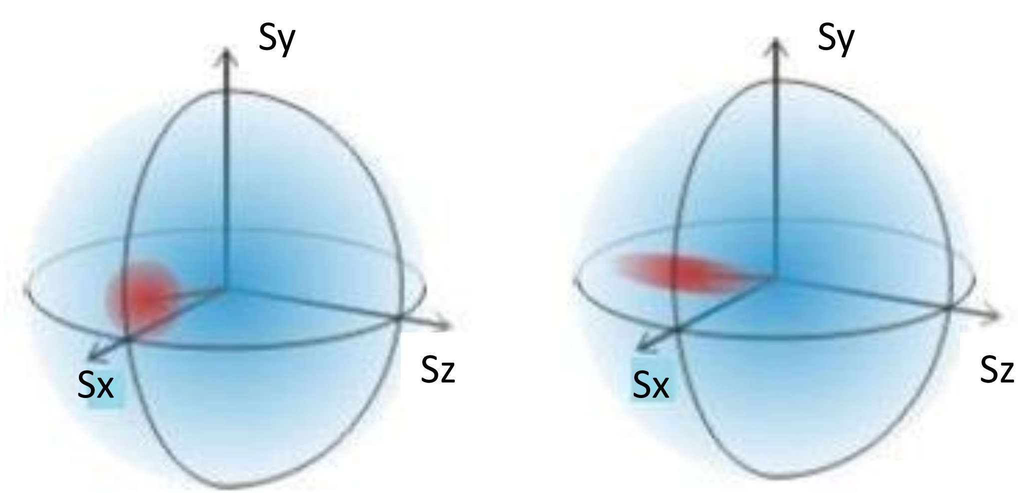
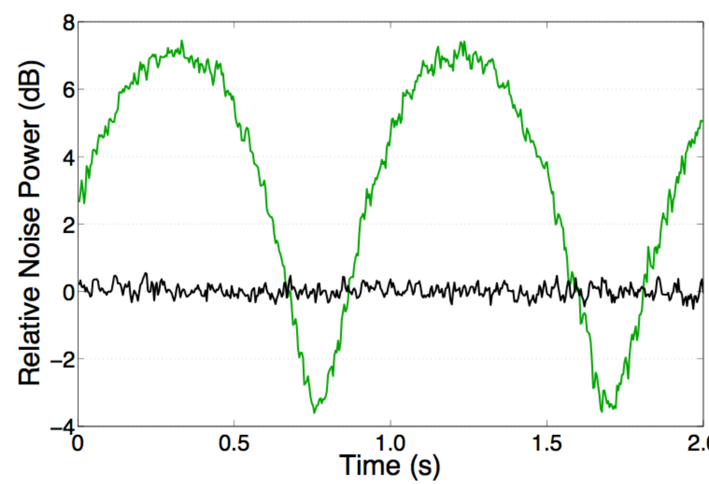
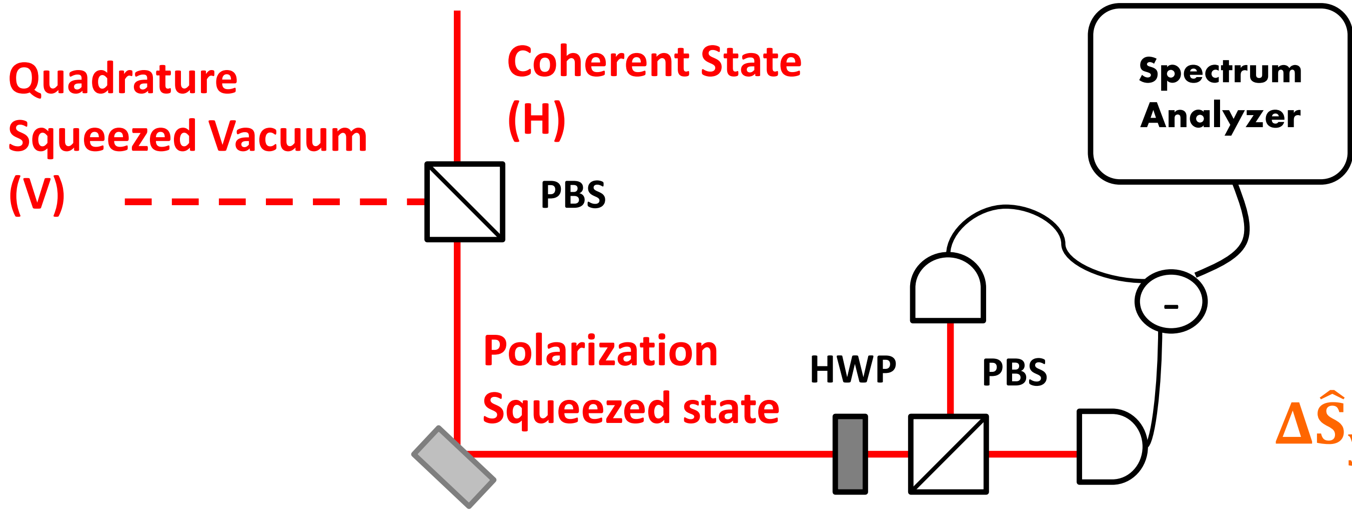
$$\Delta\hat{S}_y^{\,squeezed} < \Delta\hat{S}_y^{\,coh}$$





Polarization Squeezing

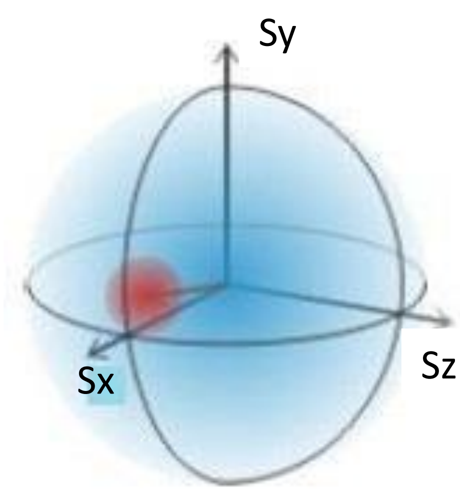
- Sub-shot noise measurements via polarization squeezing:

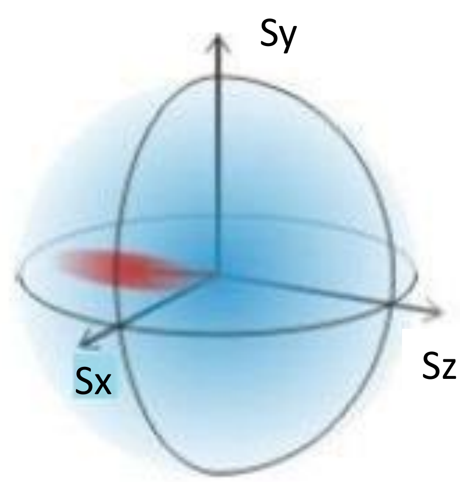


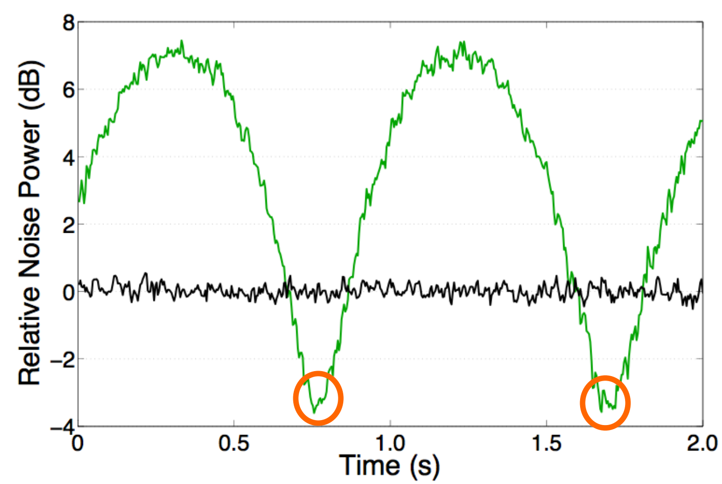
$$\hat{S}_y = I_{+45} - I_{-45}$$

$$\Delta\hat{S}_y^{\,coh} \propto \sqrt{N_{ph}}$$

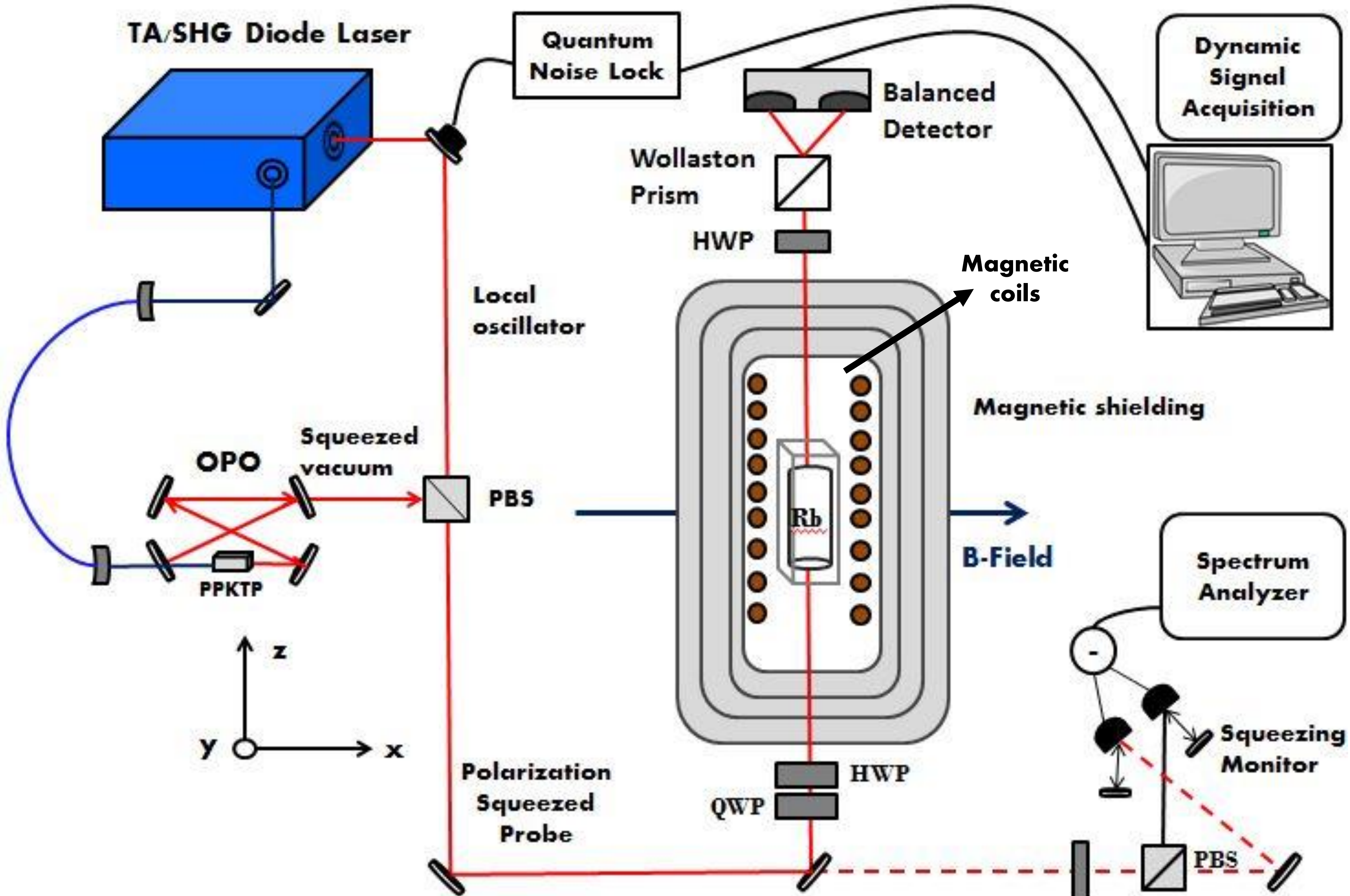
$$\Delta\hat{S}_y^{\,squeezed} < \Delta\hat{S}_y^{\,coh}$$







Squeezed Light SNS Setup



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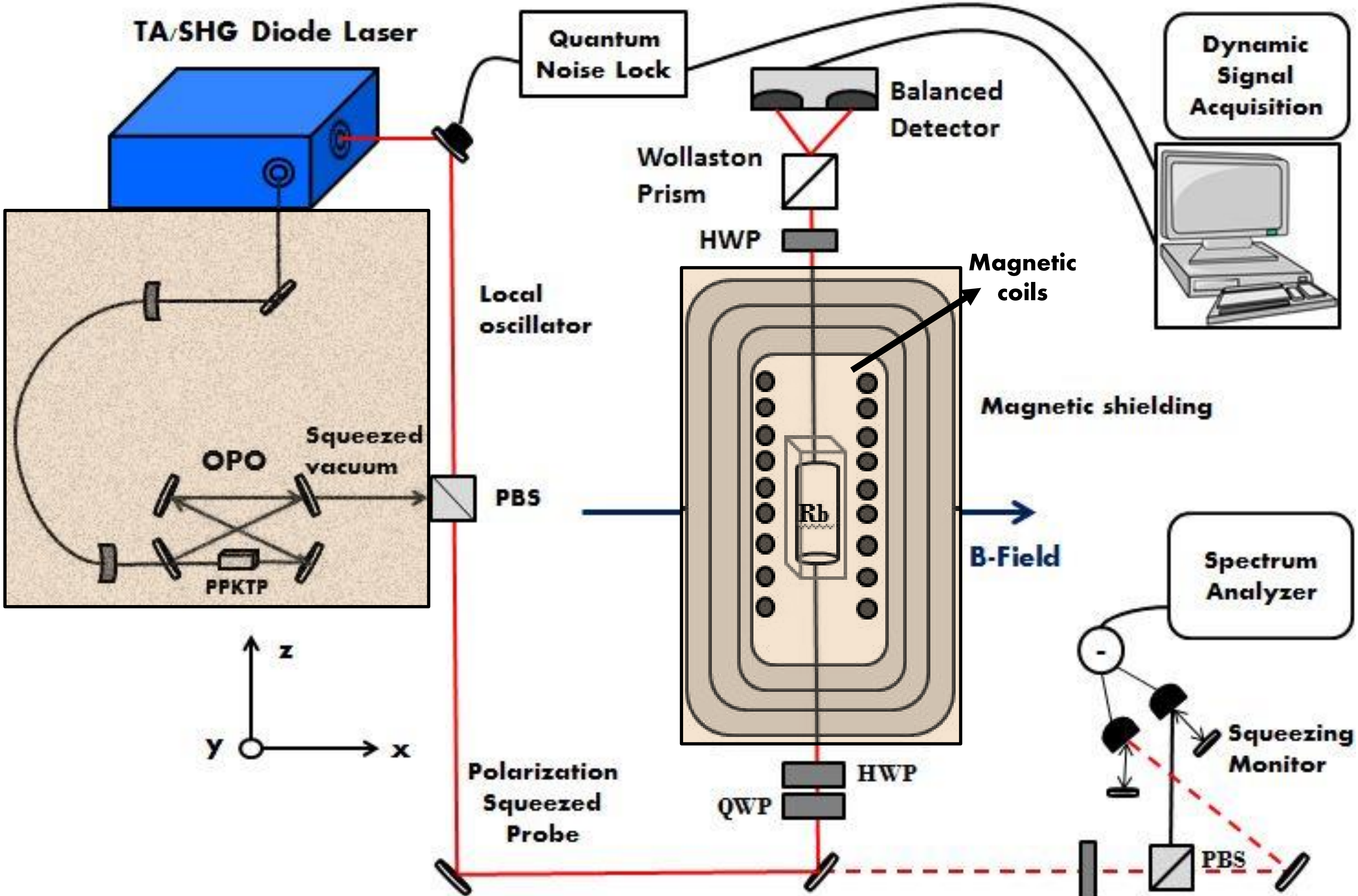

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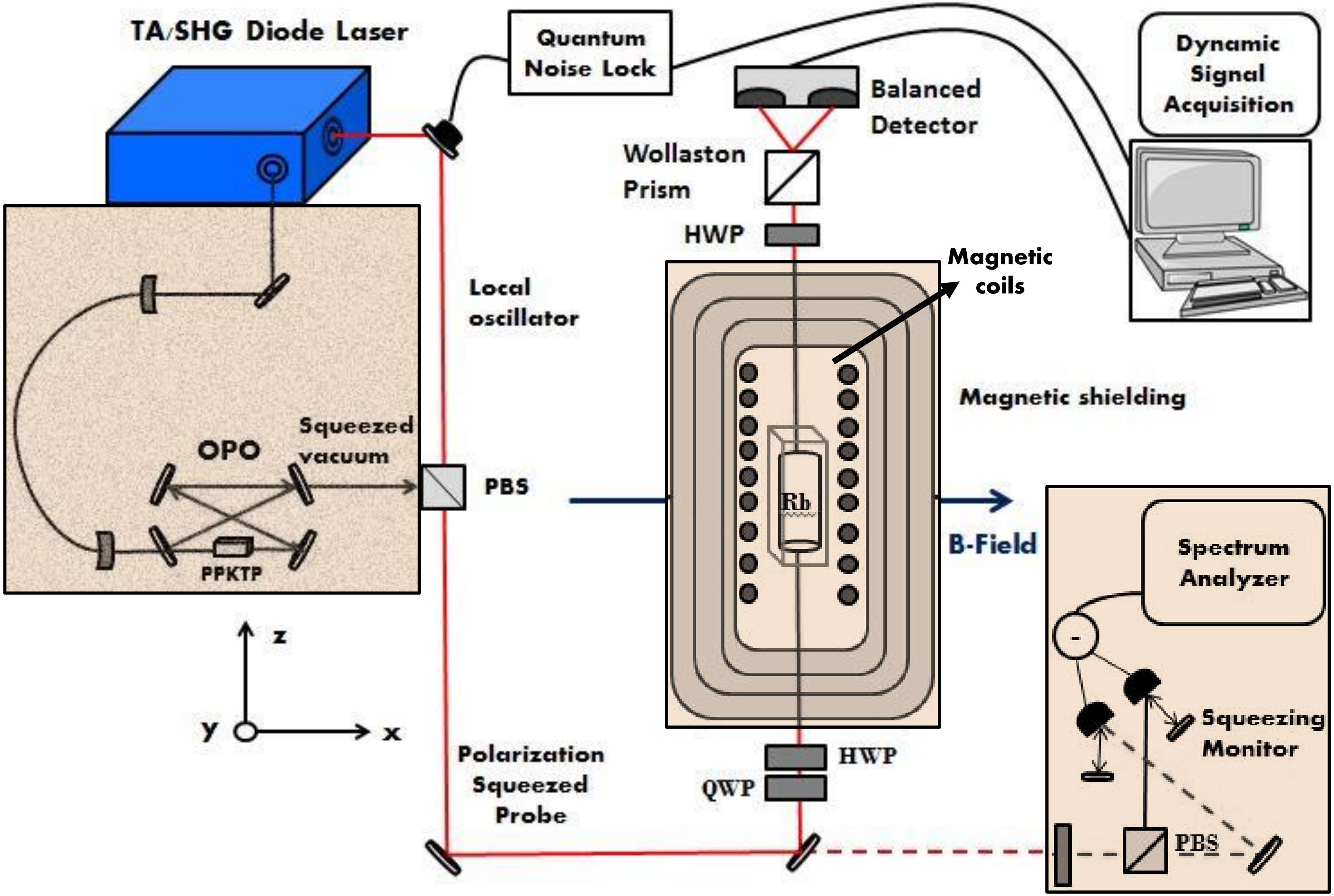
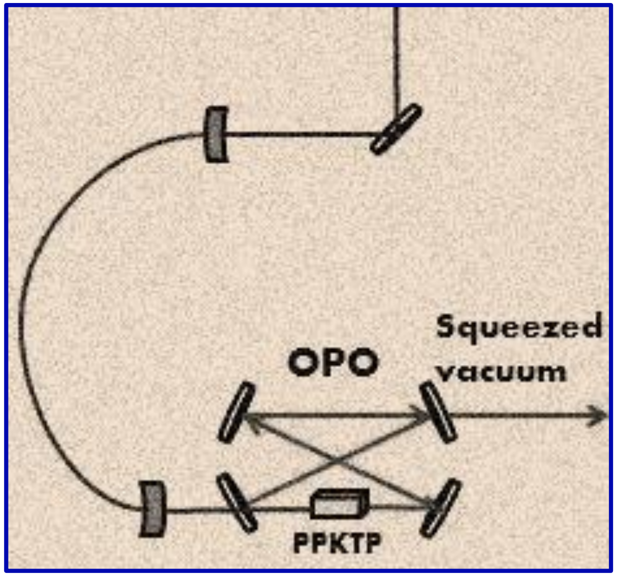
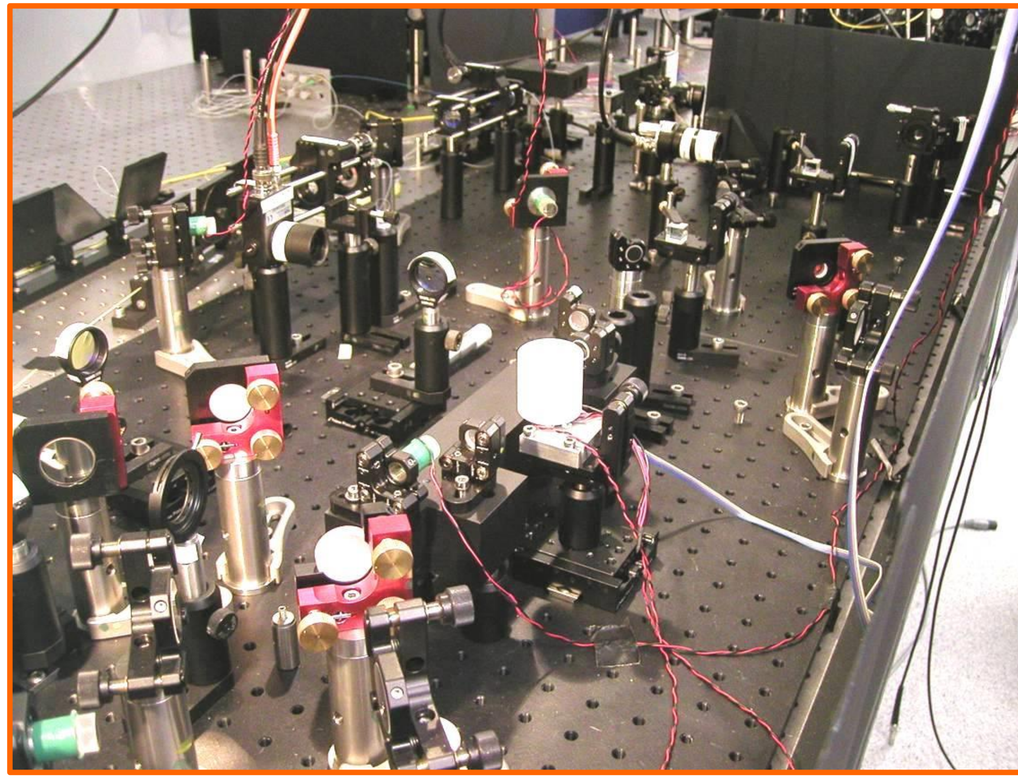


Squeezing Source





- ✓ Conventional SPDC source in OPO cavity bandwidth 8 MHz
- ✓ PPKTP crystal parametric gain up to 4.6

A. Predojević, Z. Zhai, J. M. Caballero, M. W. Mitchell Phys. Rev. A 78, 063820 (2008)
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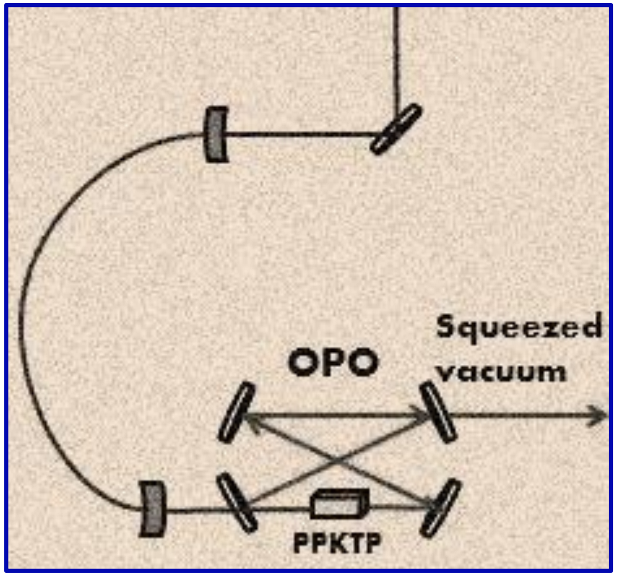

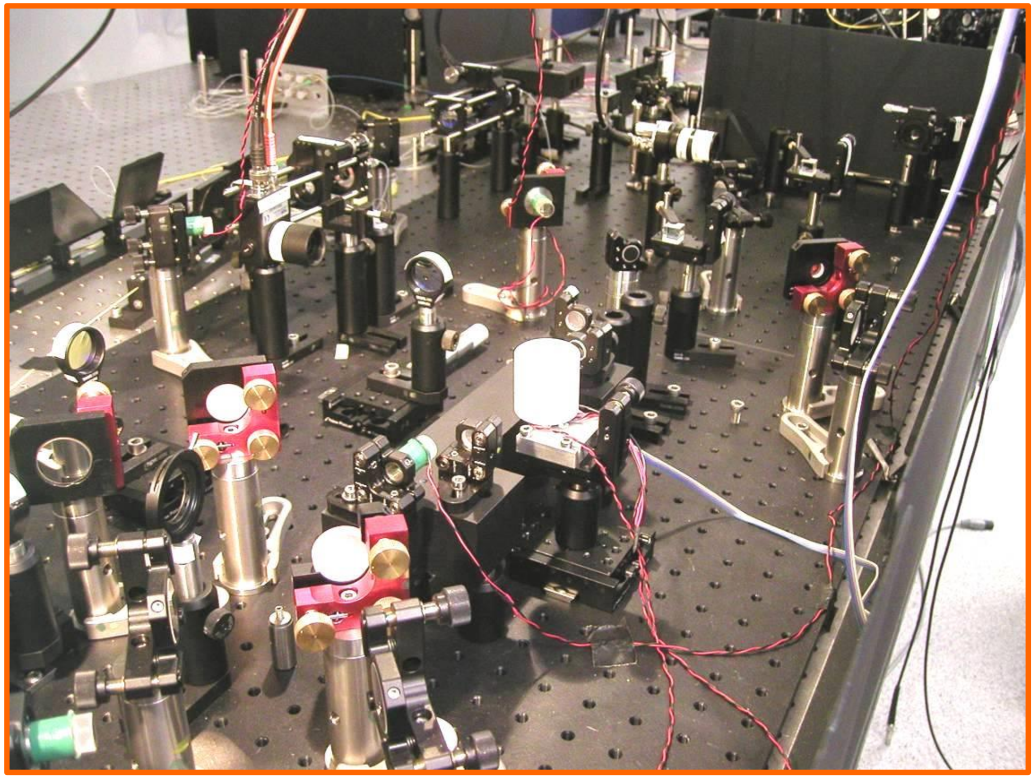

- ✓ Conventional SPDC source in OPO cavity bandwidth 8 MHz
- ✓ PPKTP crystal parametric gain up to 4.6
- ✓ Squeezing up to 3.2 dB of quantum noise suppression at a detuning of $\Delta = 20\ GHz$ from the D1 Line of Rb^{85}

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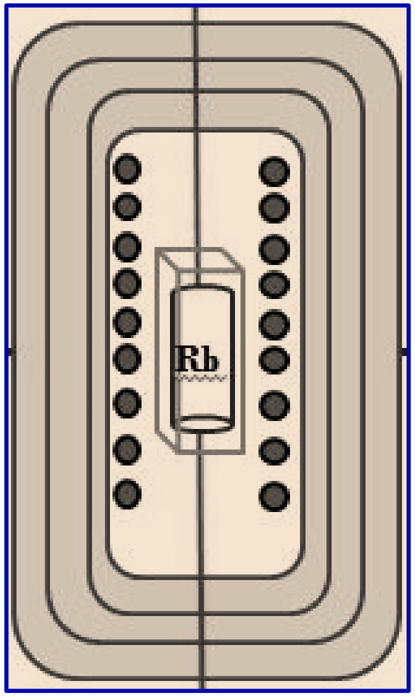
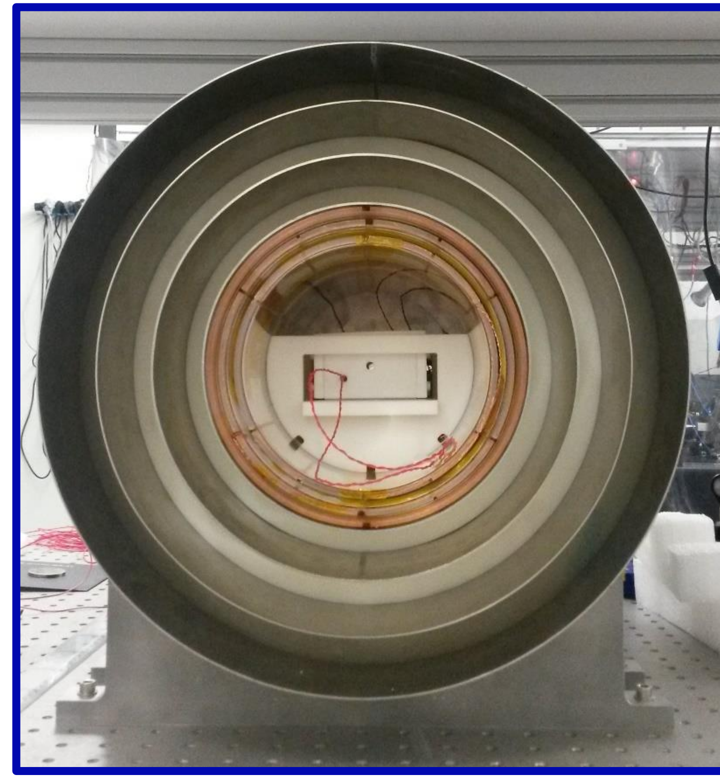
Magnetic Shielding and Atomic System





- ✓ Rb vapor cell with natural abundance & 100 Torr of N_2 buffer gas
- ✓ Temperature control up to 120 °C, high density up to $1.3*10^{13}$ cm^{-3}

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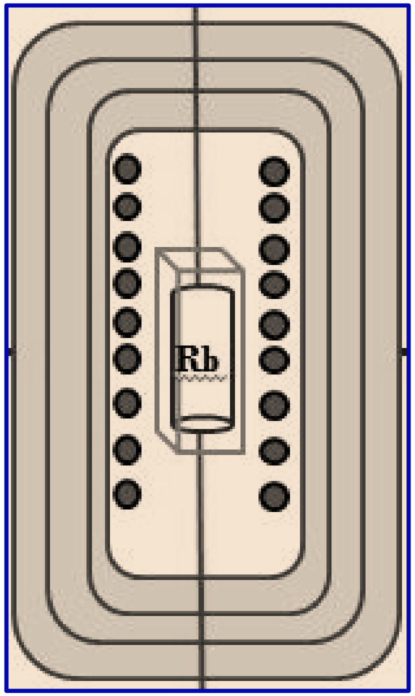
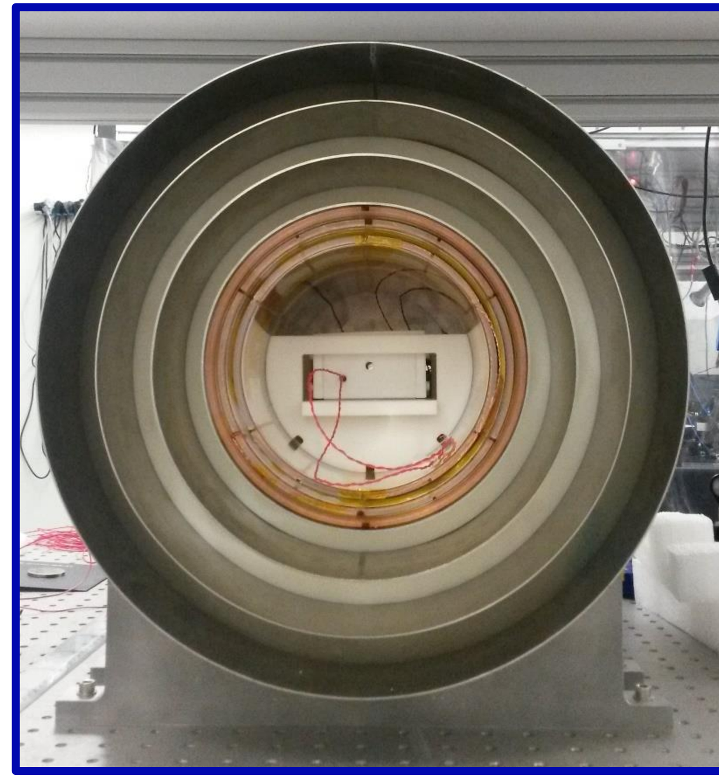
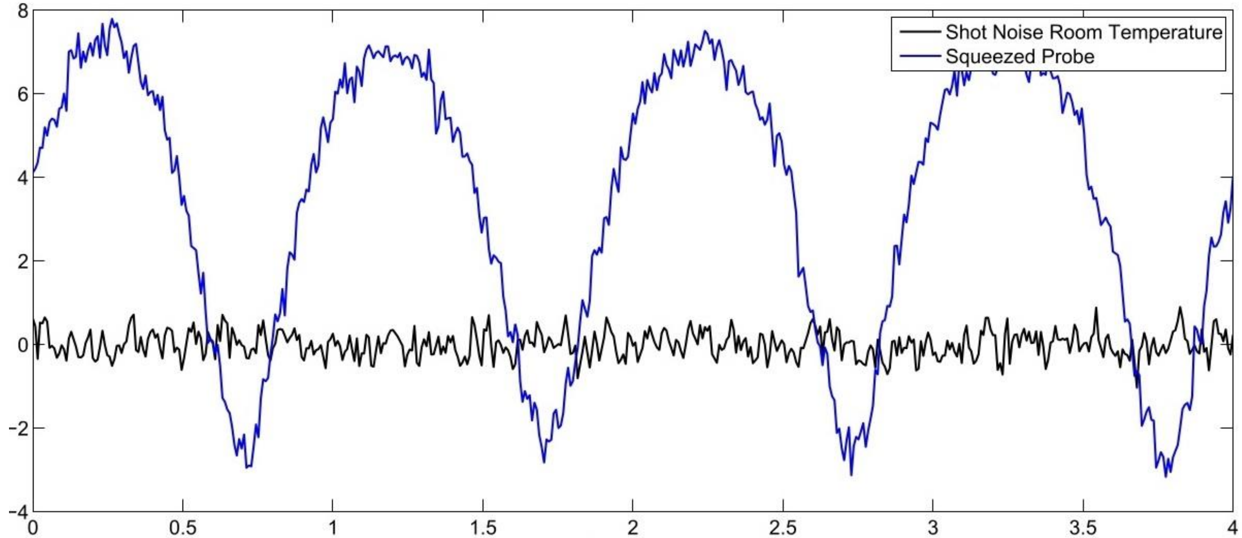




- ✓ Rb vapor cell with natural abundance & 100 Torr of N_2 buffer gas
- ✓ Temperature control up to 120 °C, high density up to $1.3*10^{13}$ cm^{-3}
- ✓ 3-axis DC-Fields & gradient coils in the beam propagation direction;
- ✓ 4 mu-metal layers in a cylindrical geometry (up to 10^6 efficiency);

Polarization Squeezing

Noise Suppression (dB)



Time (sec)

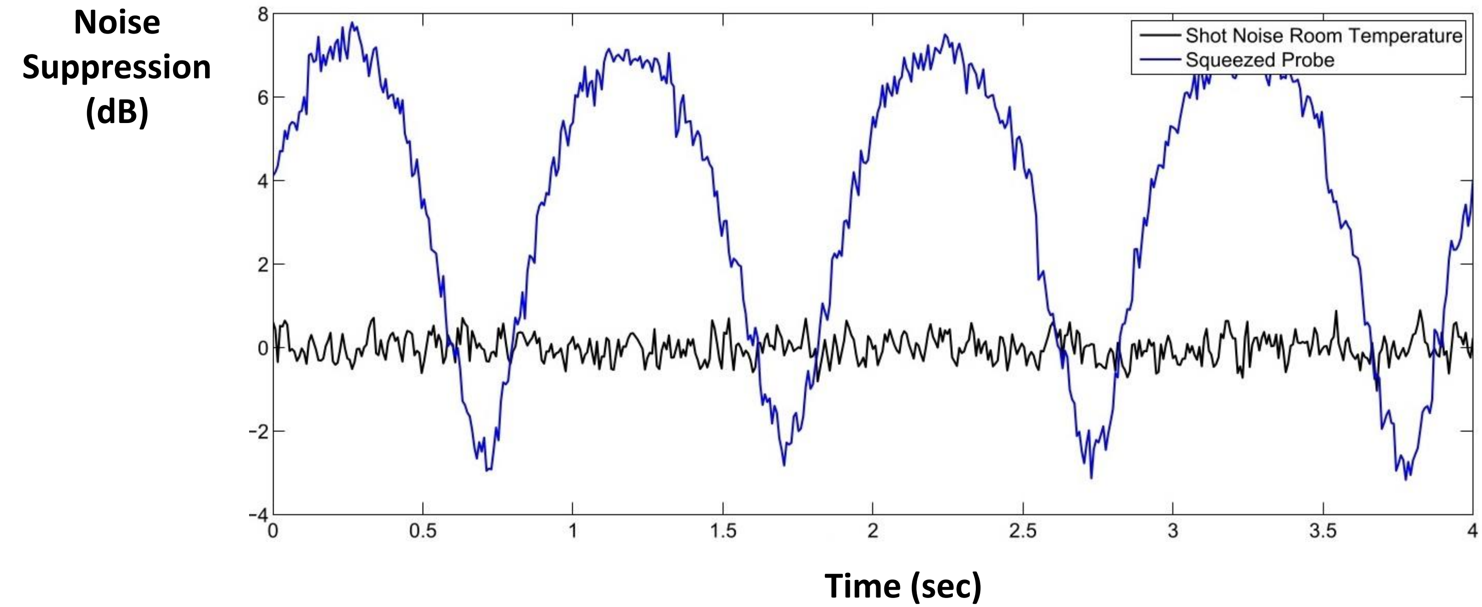
Before atomic interaction

-3.16 dB

<u>Room Temperature</u>

n = 1.3×10^{10} atoms/cm^3

Polarization Squeezing



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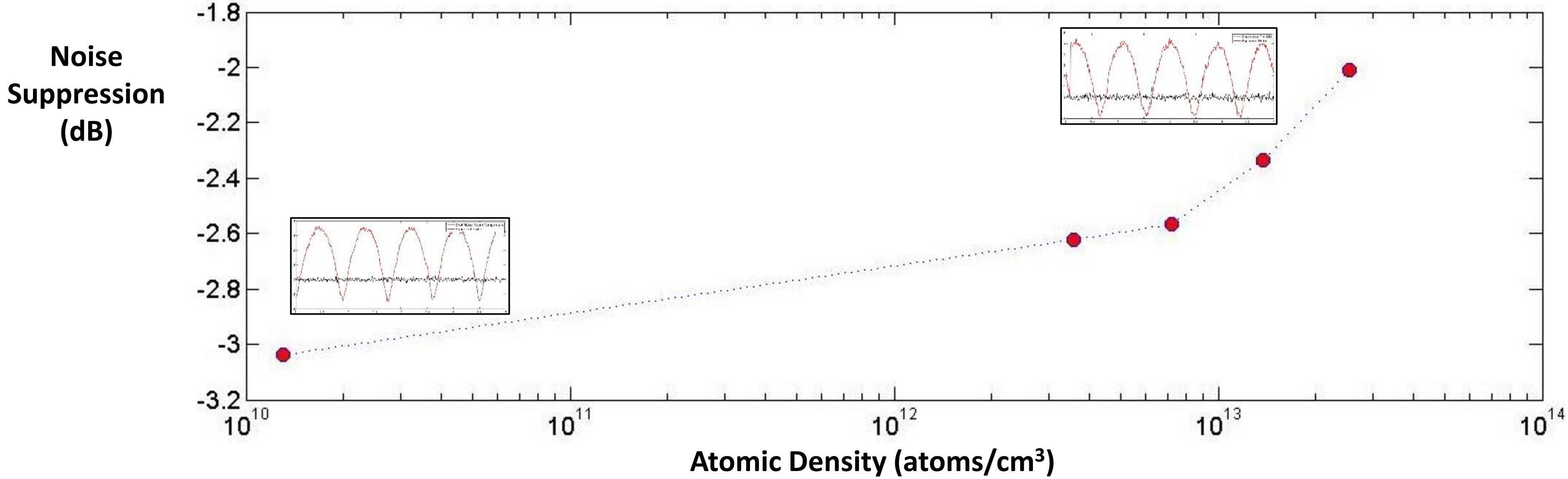
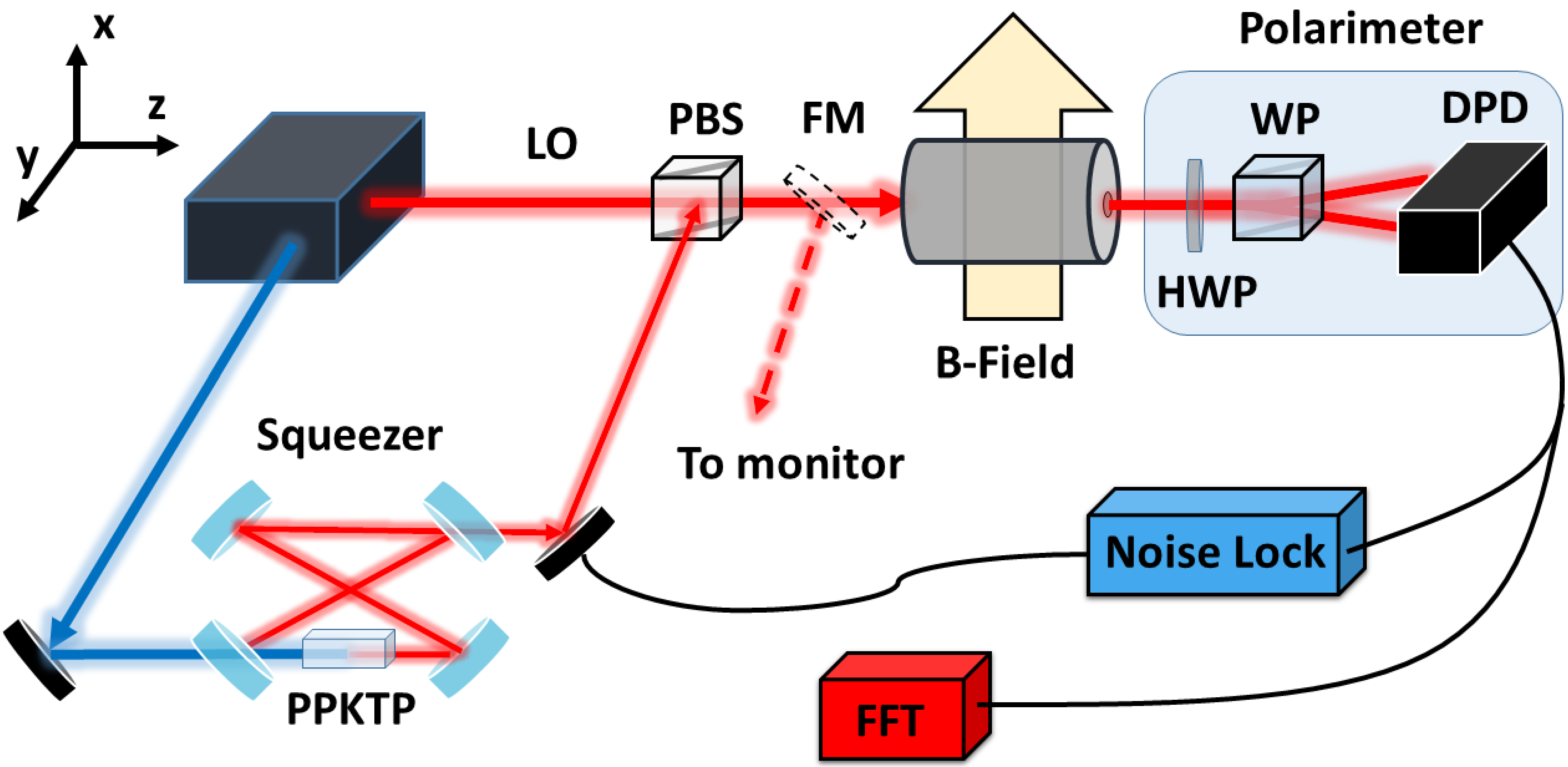


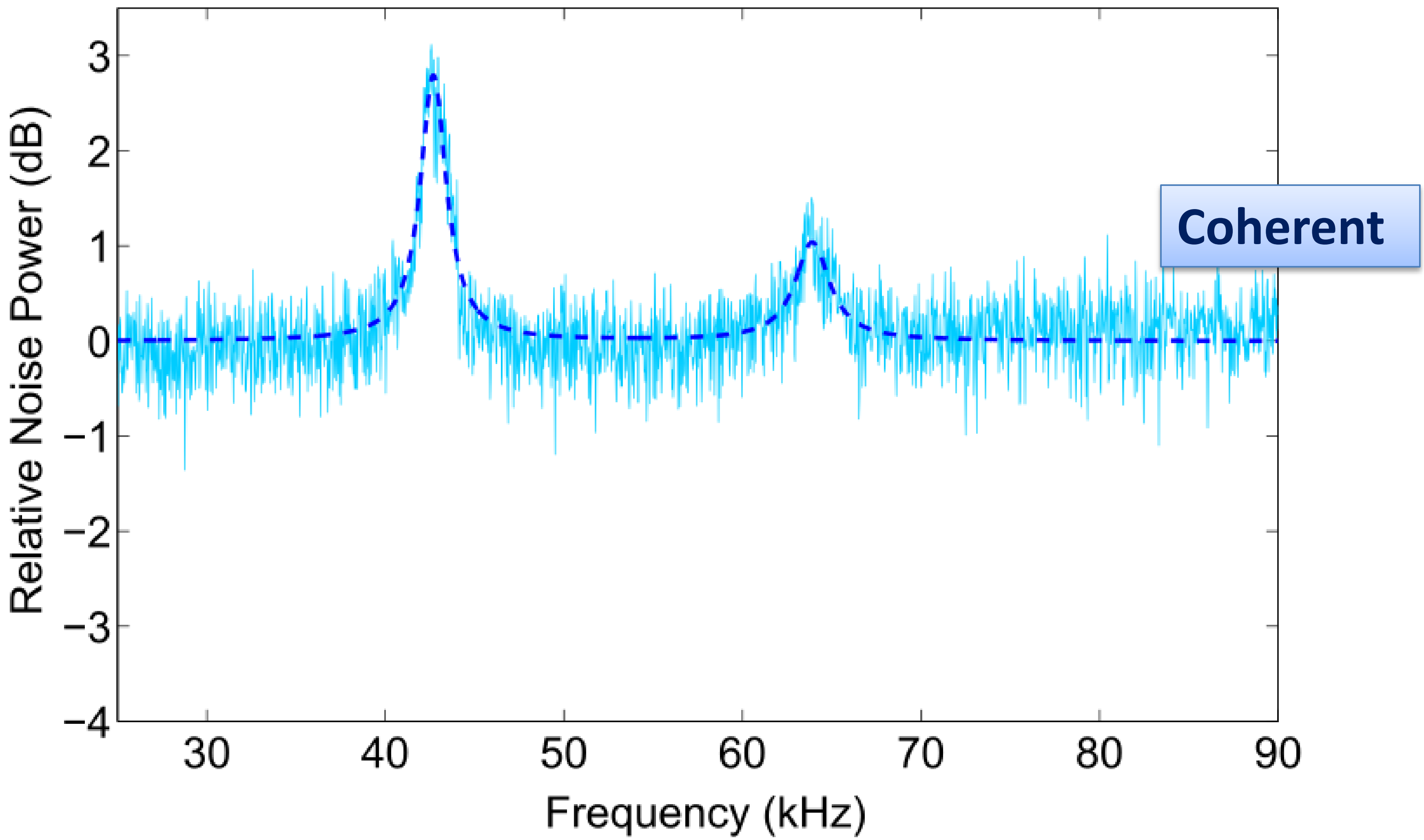
Squeezed-light SNS



“Squeezed-light spin noise spectroscopy” V. G. Lucivero et al. *ready for submission*

Squeezed-light SNS

$\boxed{B = 5.6\mu T}$



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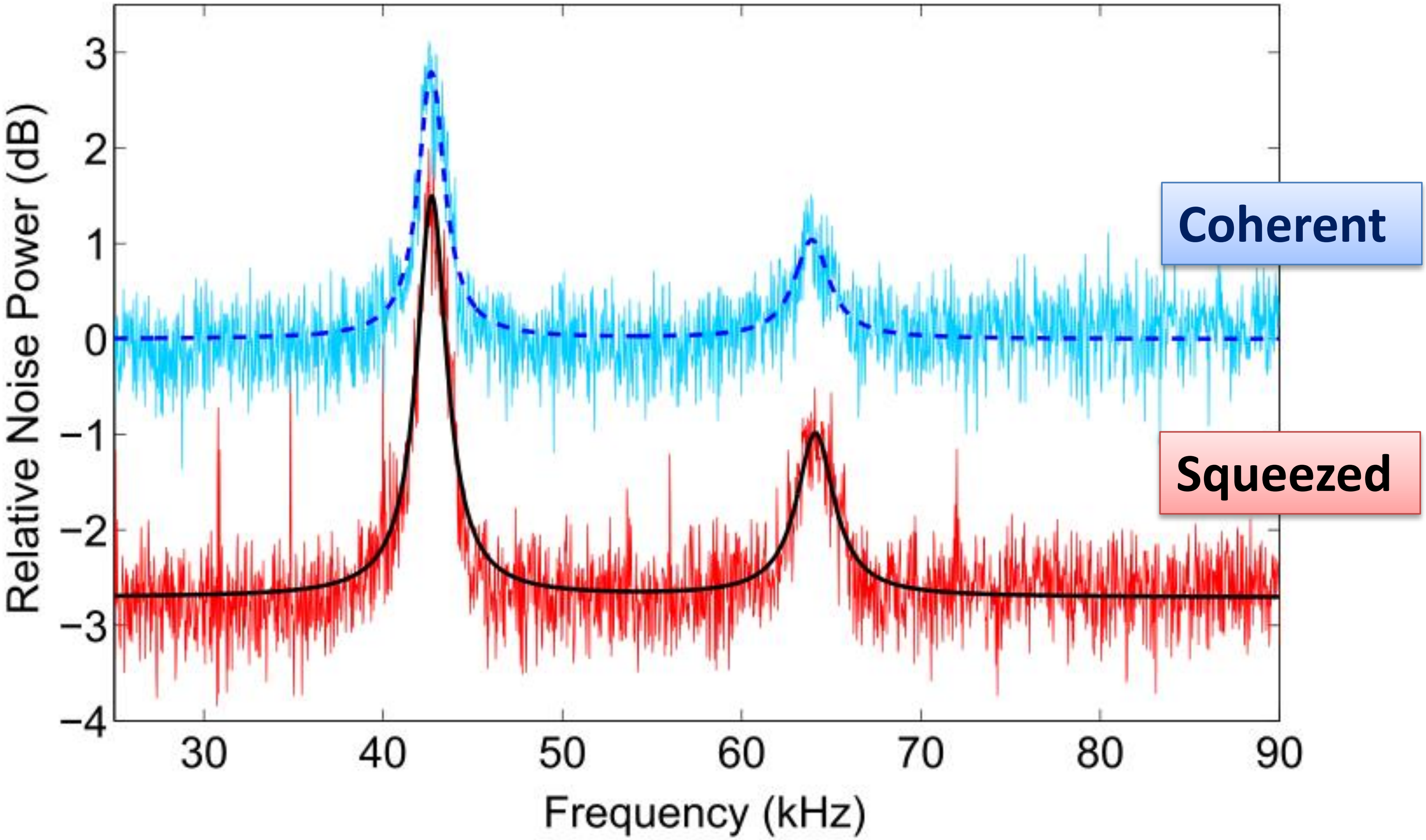
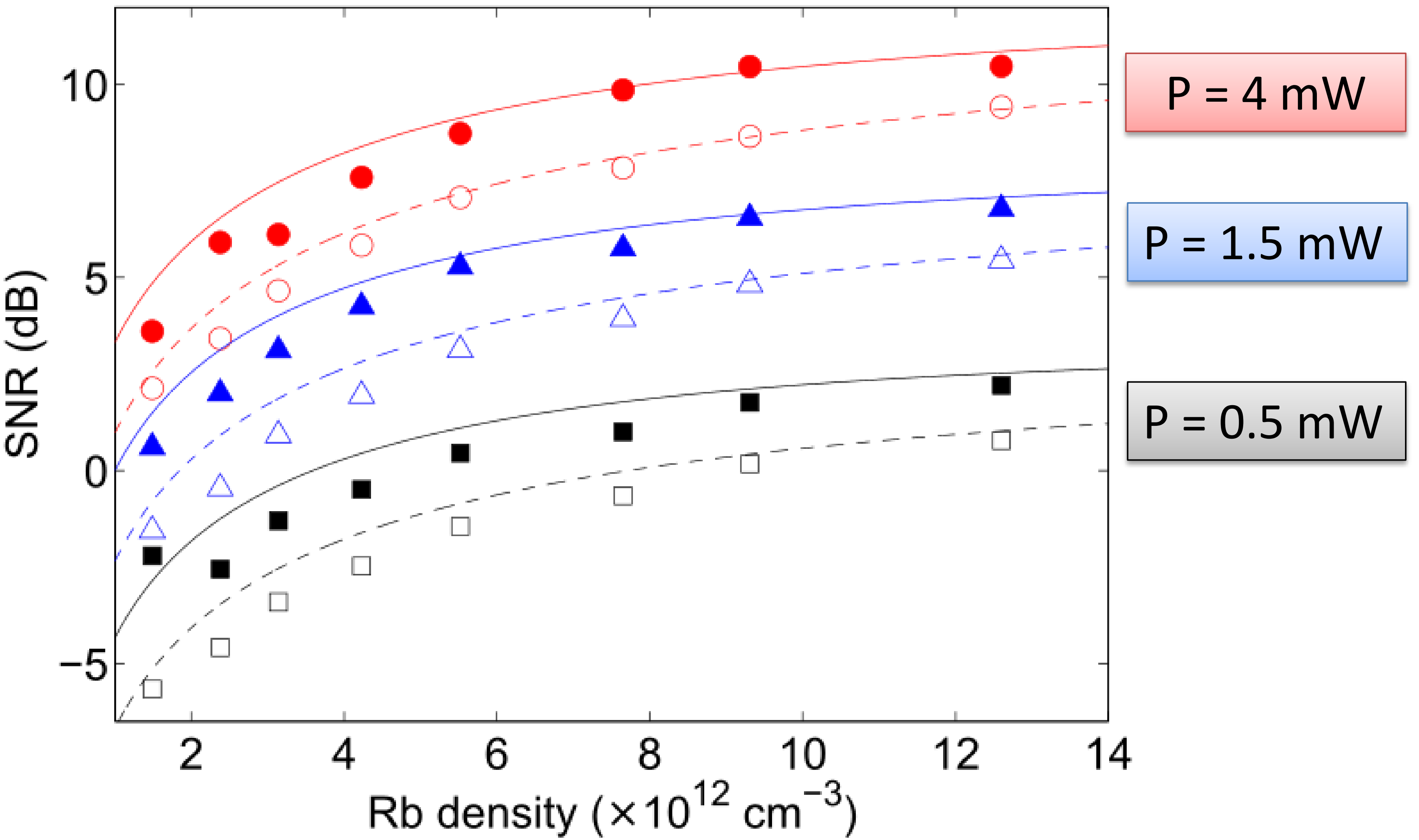


Improvement of η due to squeezing



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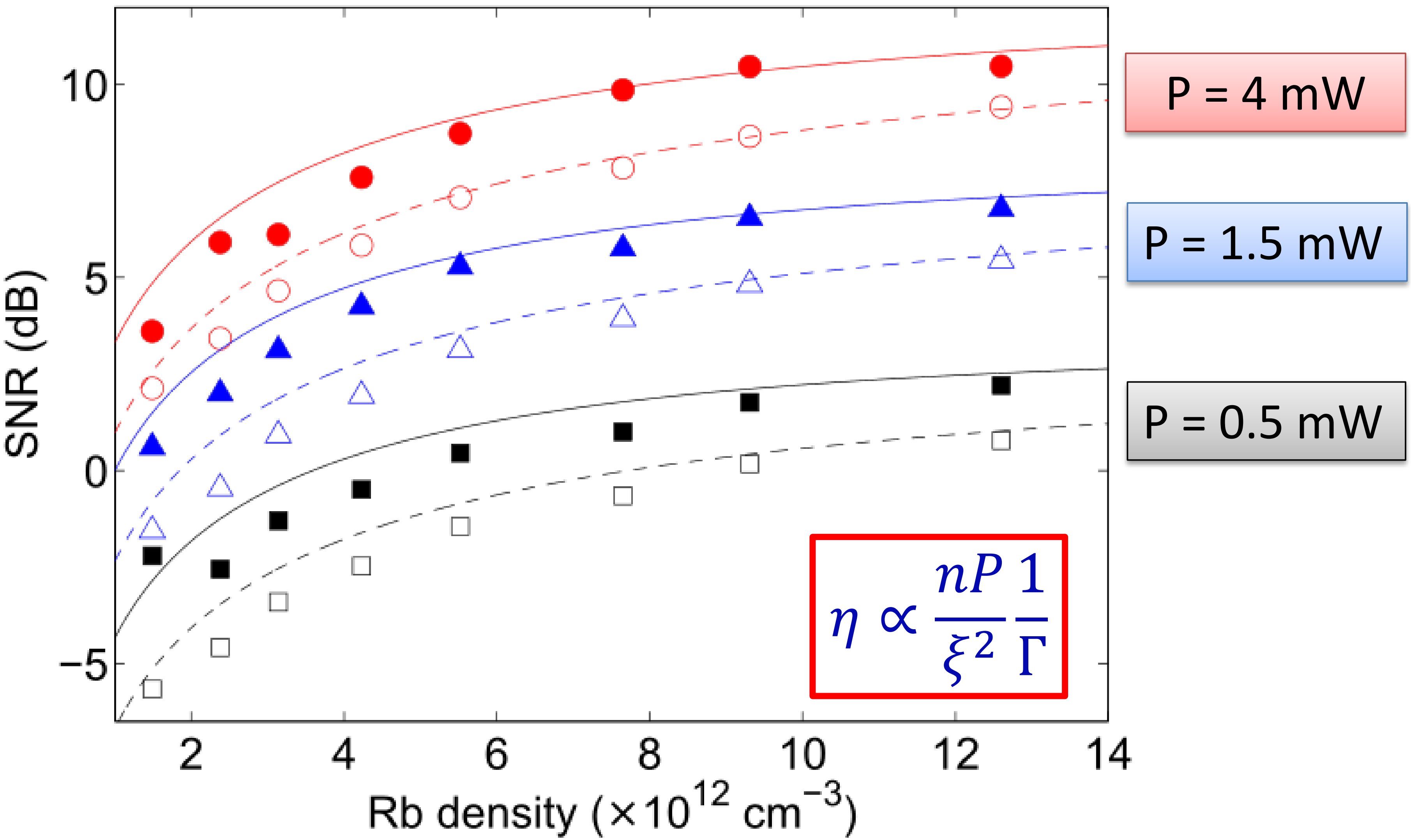
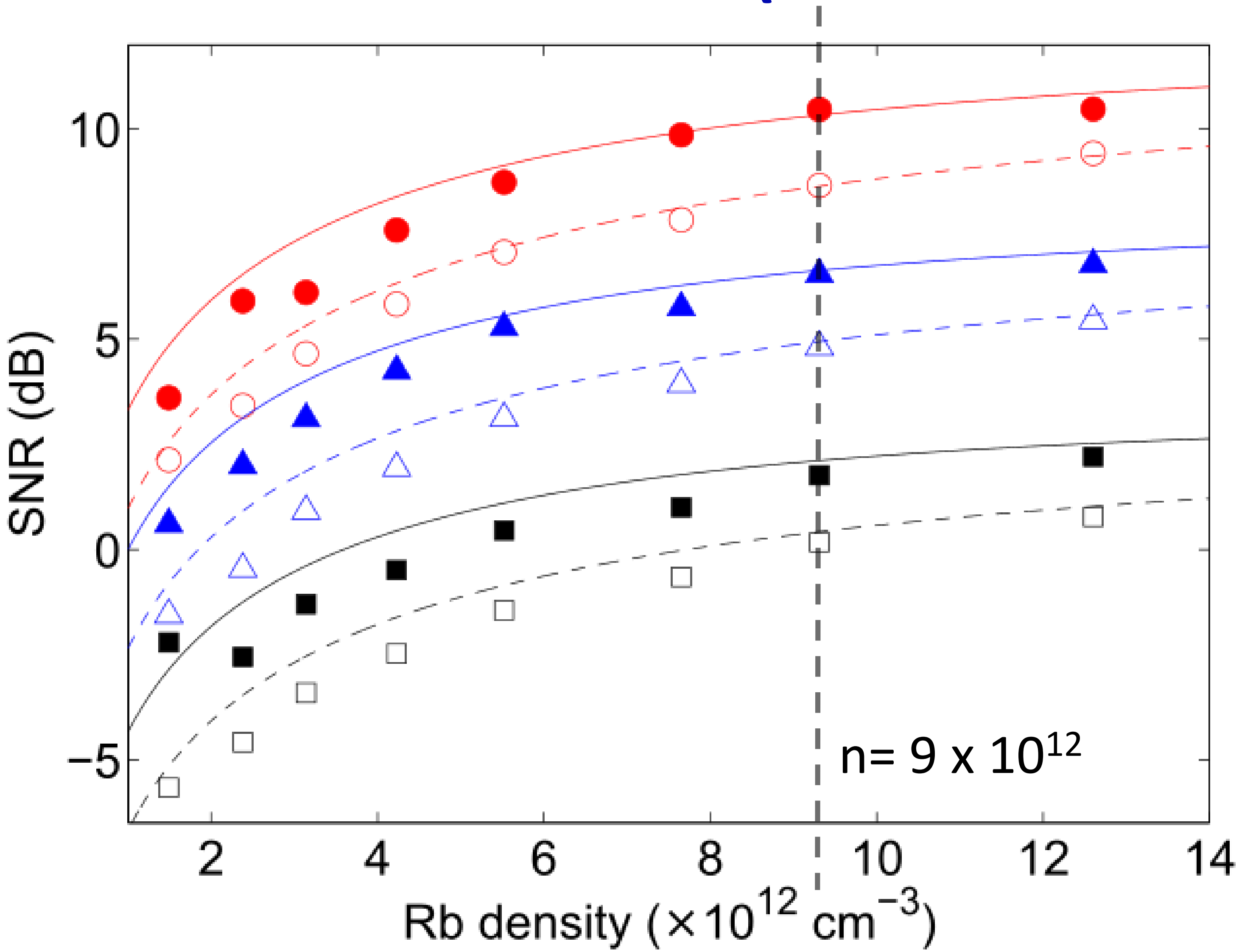


$$\eta \propto \frac{nP}{\xi^2}\frac{1}{\Gamma}$$

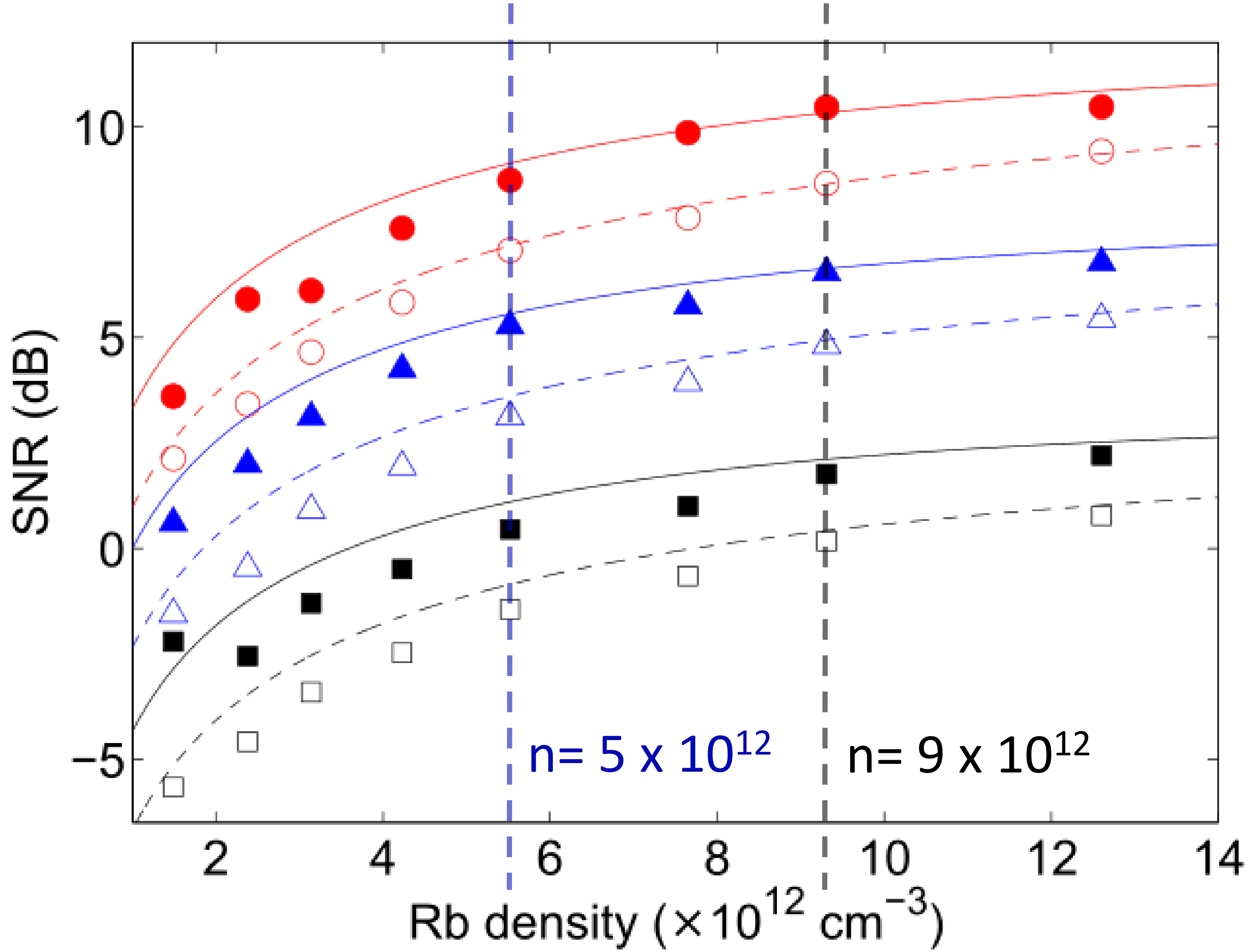
Quantum enhancement due to squeezing

from **2.7** dB(at n= 1.5 x 10^{12}) to **1.6 dB** (at n= 1.3 x 10^{13})

Disturbance reduction (due to collisions)

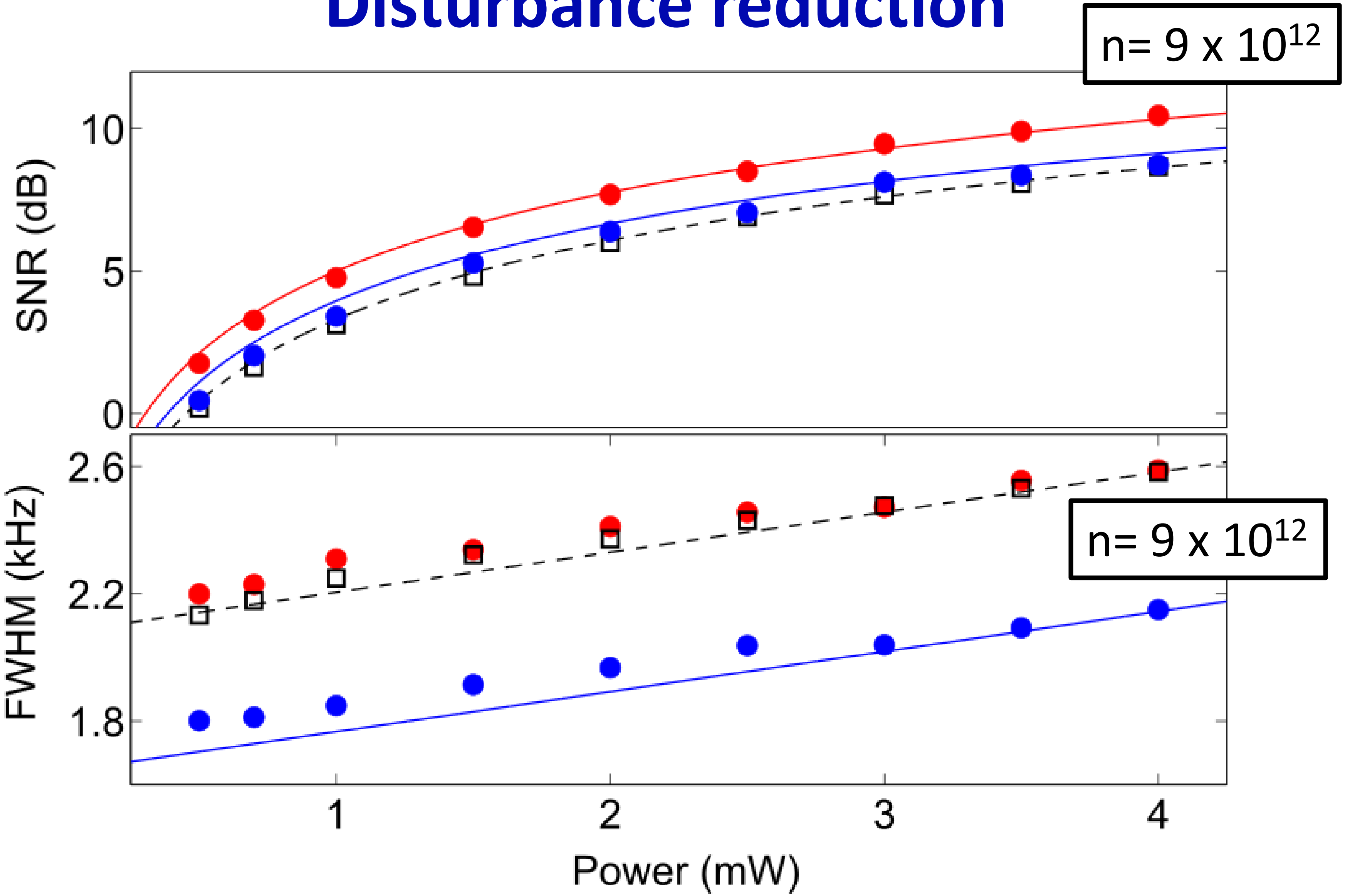


Disturbance reduction



The SNR with coherent is equal to the
SNR with squeezing at roughly twice the density

Disturbance reduction



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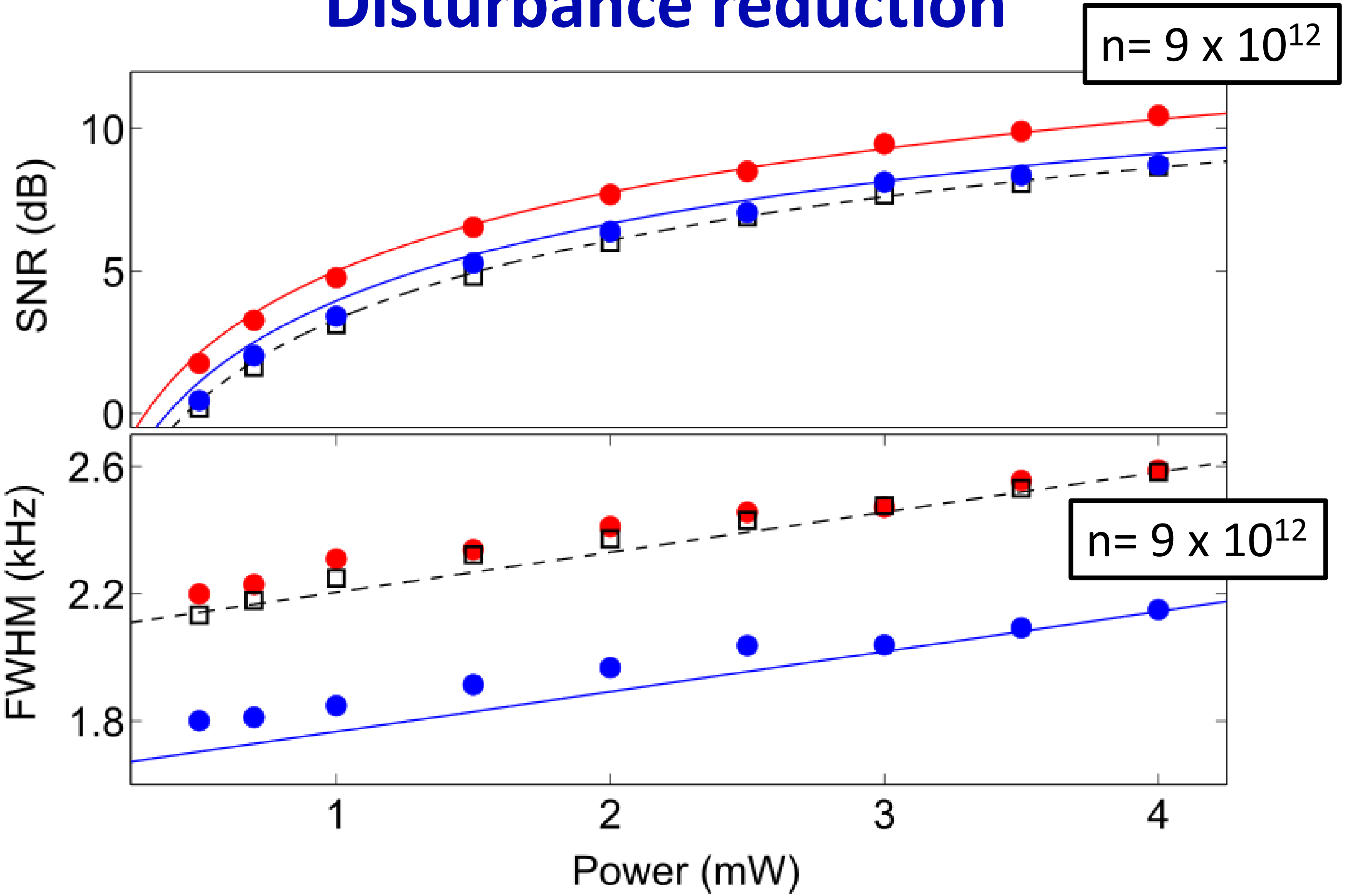
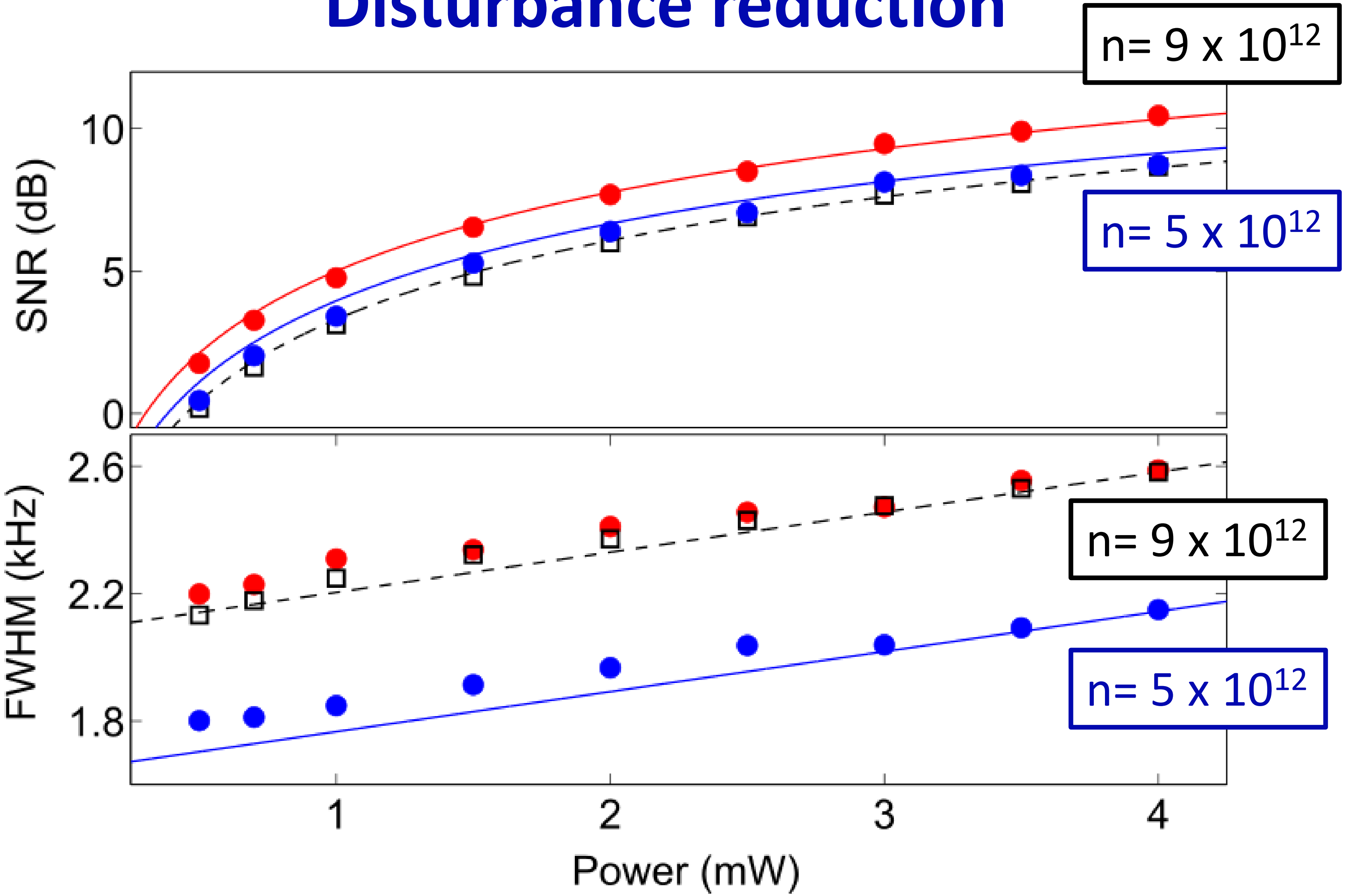


a) At constant disturbance squeezing enhances the SNR

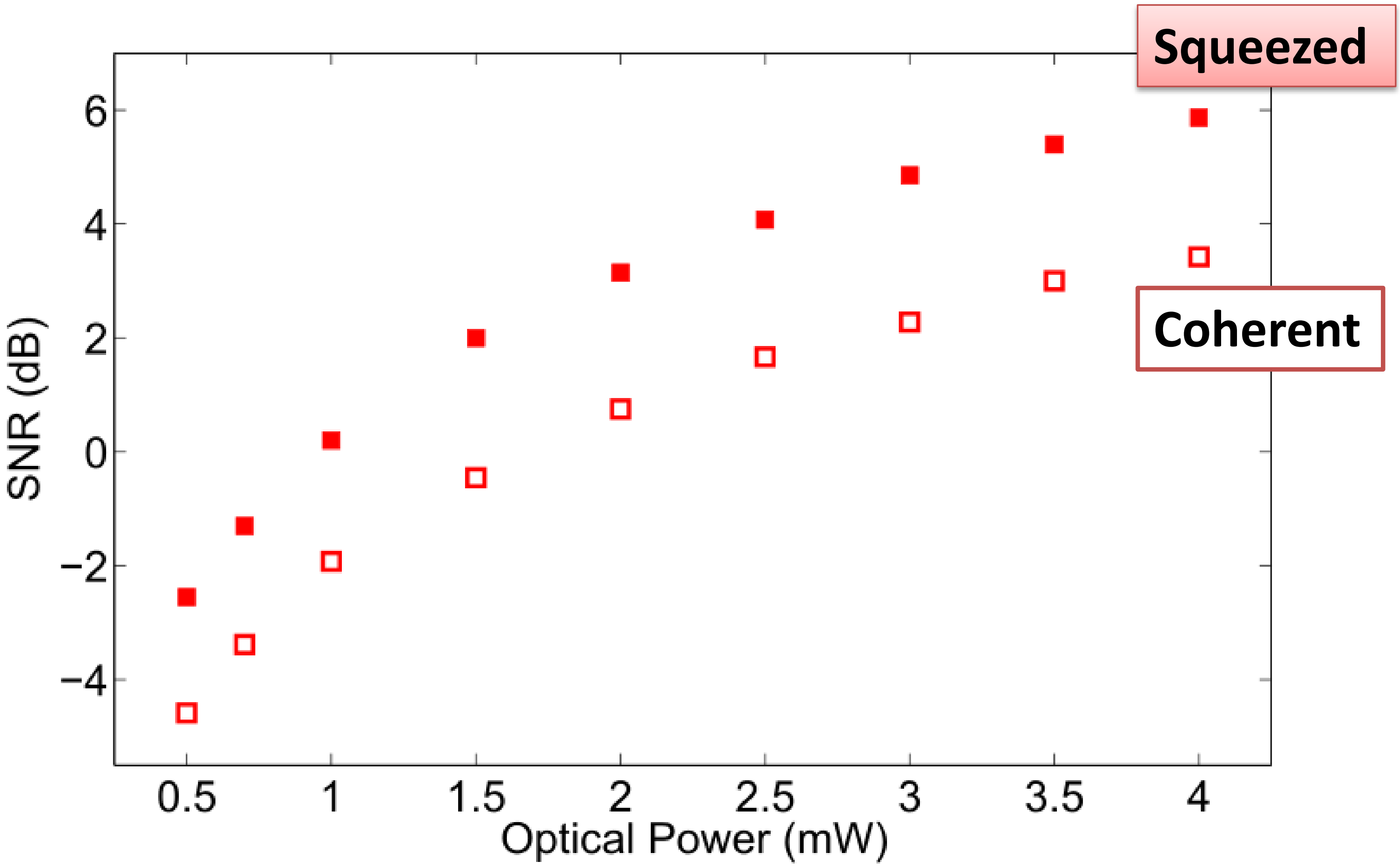
Disturbance reduction



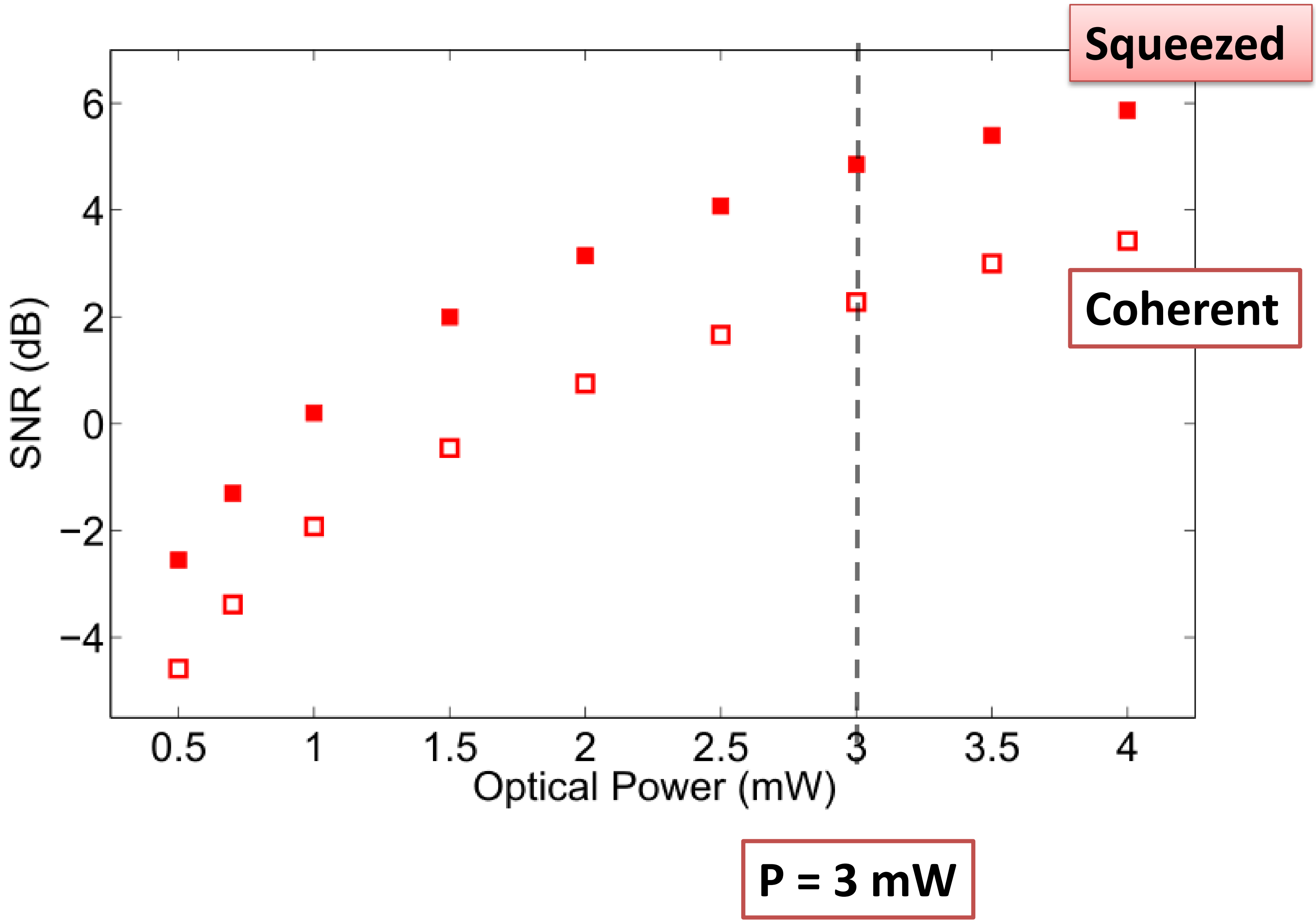
a) At constant disturbance squeezing enhances the SNR

b) At constant SNR squeezing reduces the disturbance

Disturbance reduction (due to absorption)



Disturbance reduction (absorption)



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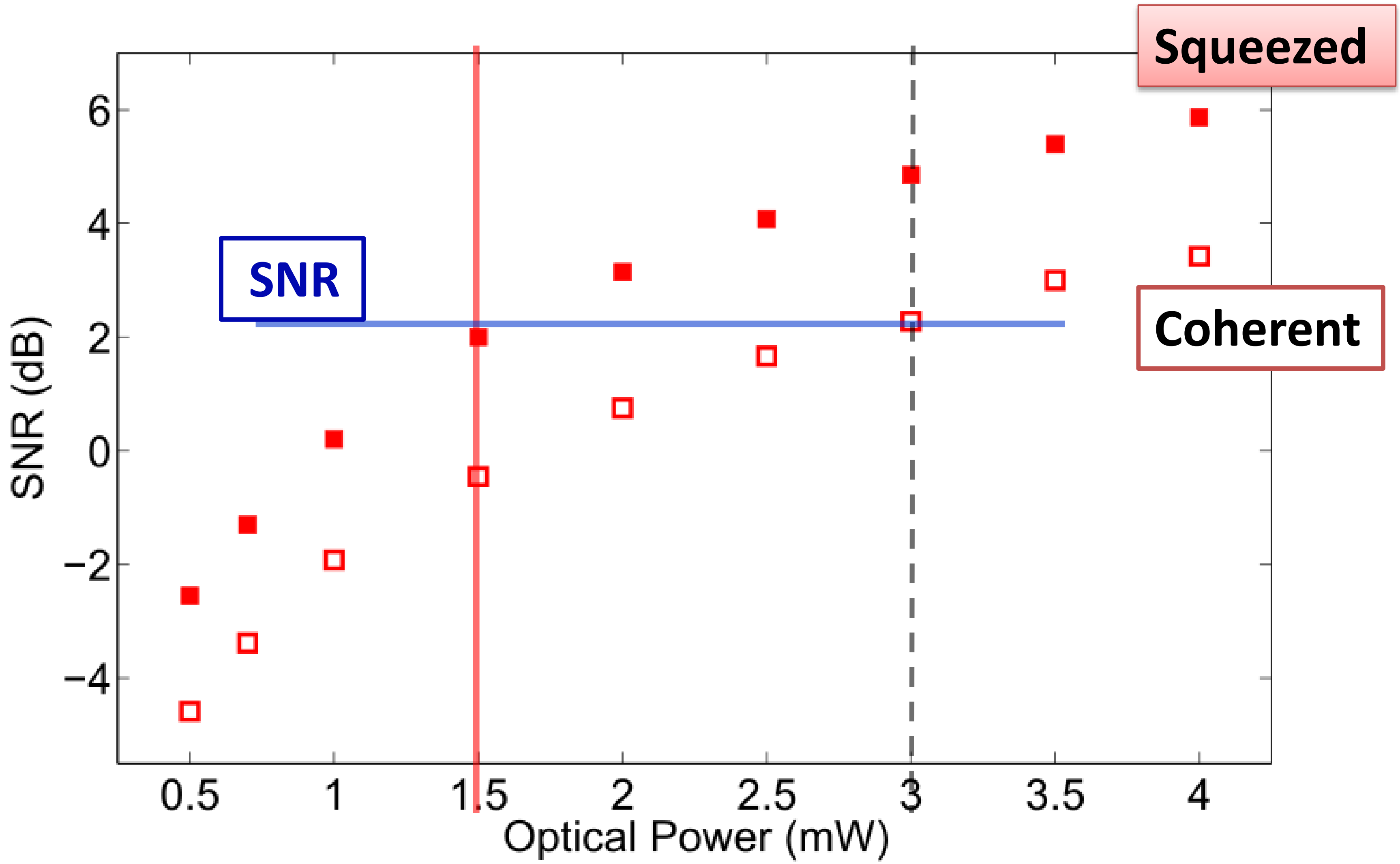
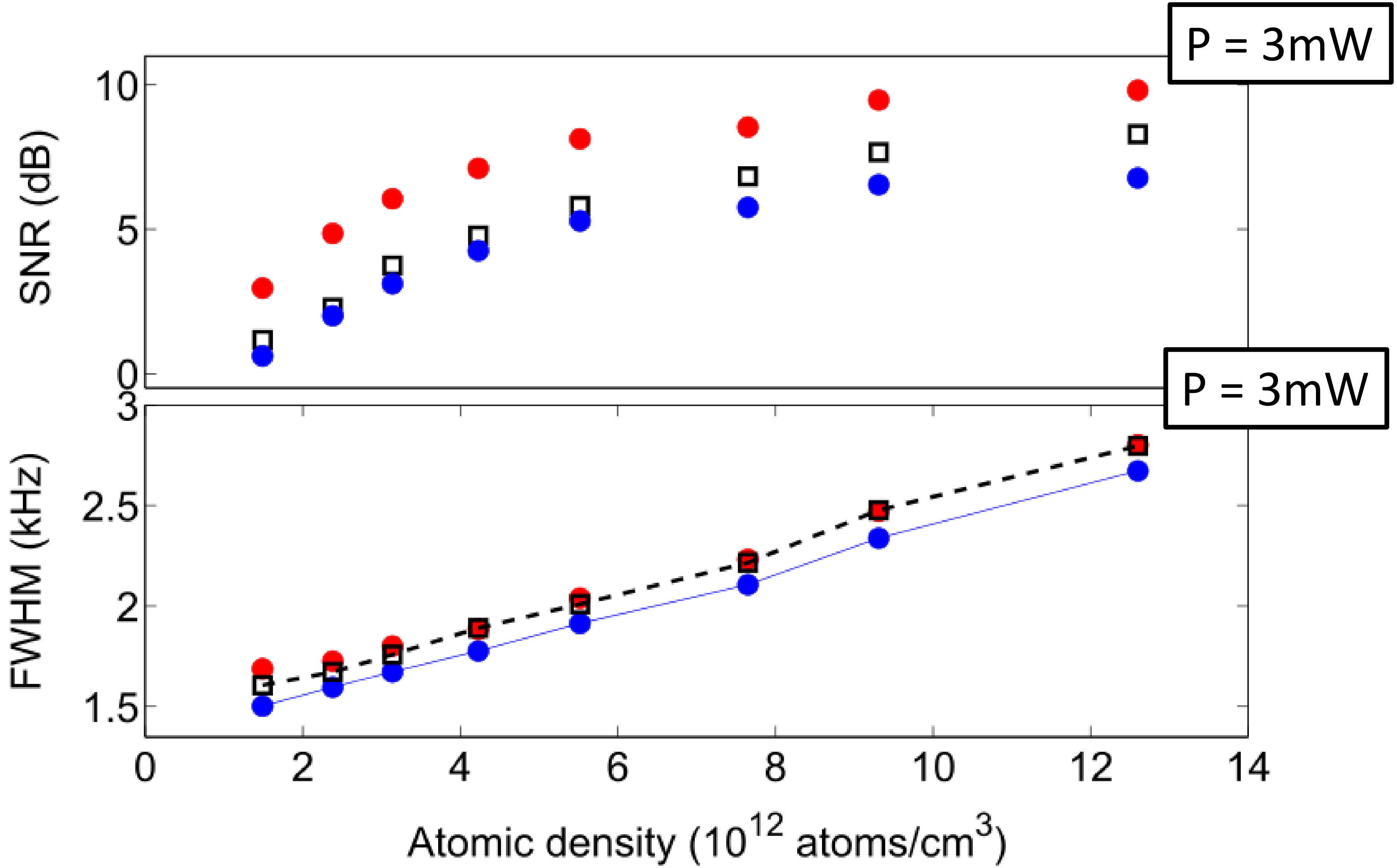


P = 1.5 mW

P = 3 mW

Disturbance reduction (absorption)



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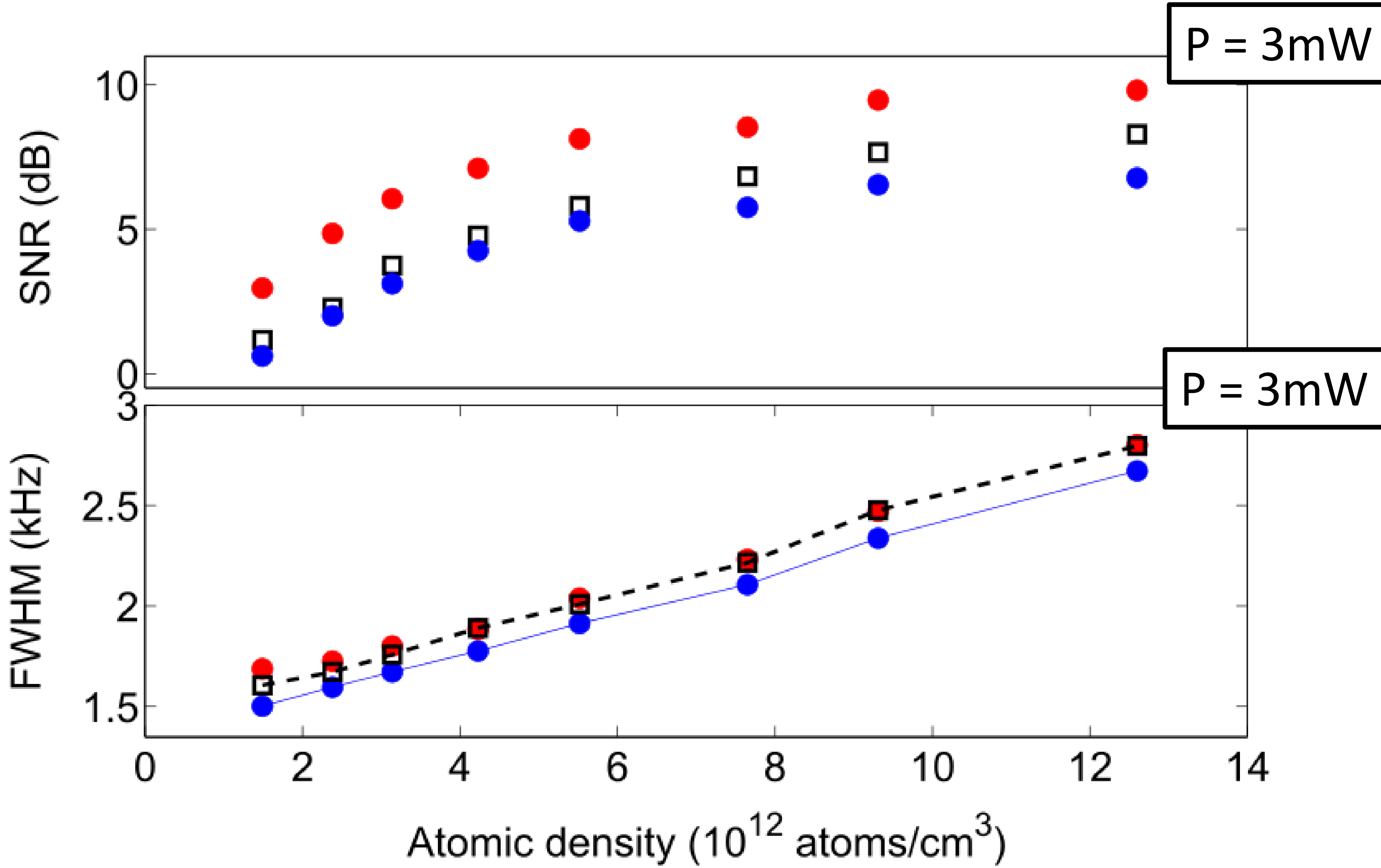

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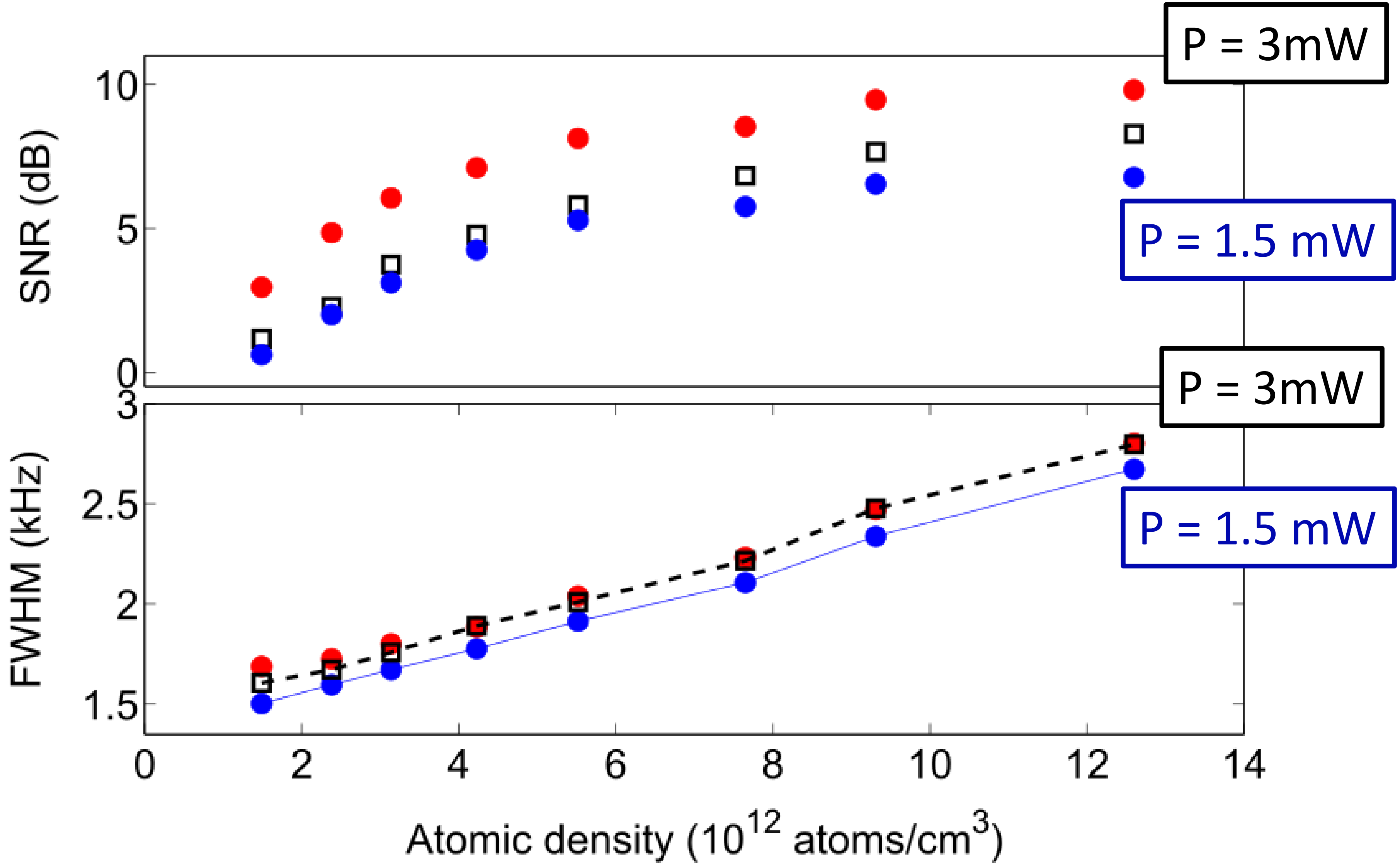
Disturbance reduction (absorption)



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"Shot-noise-limited magnetometer with sub-picotesla sensitivity at room temperature" V. G. Lucivero et al. Rev. Sci. Inst. 85, 113108 (2014)

"Squeezed-light spin noise spectroscopy" V. G. Lucivero et al. <u>*ready for submission*</u>

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