Squeezing vacuum with Rb atoms: quantum enhanced magnetometry and transient effects.

Eugeniy E. Mikhailov

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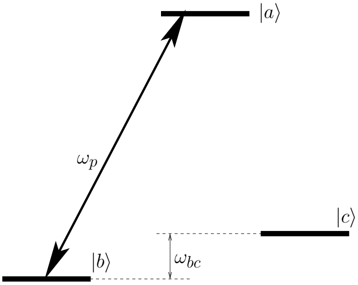
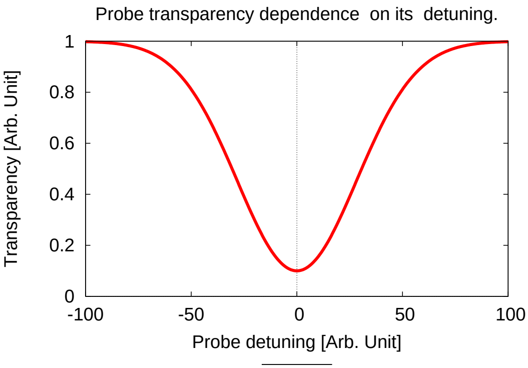
Helmholtz-Institut Mainz, November 2, 2018

About College of William and Mary

Electromagnetically Induced Transparency (EIT)





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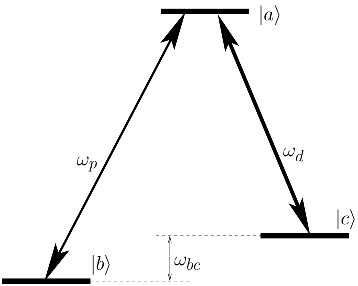

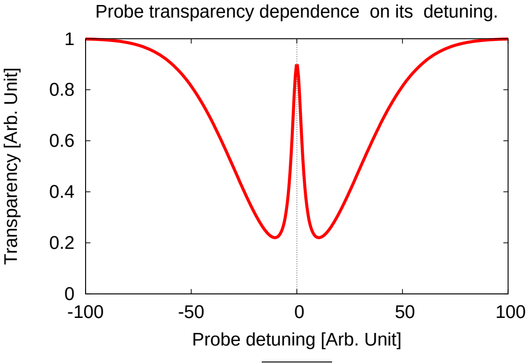

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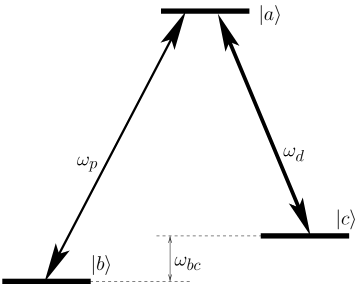
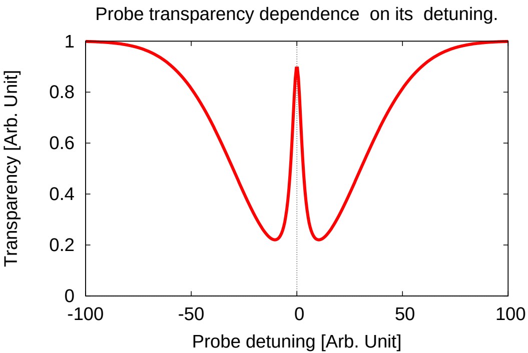
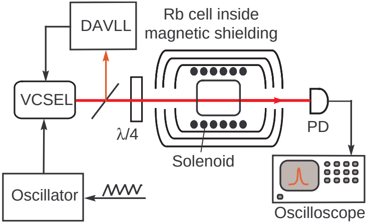


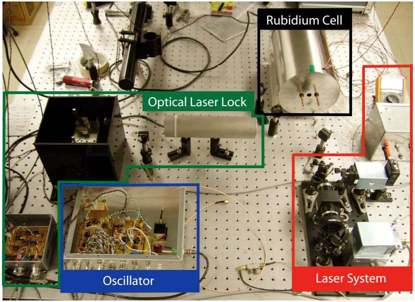


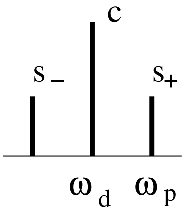
Coherent Population Trapping

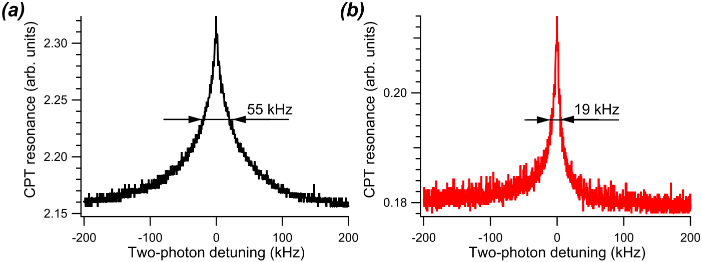
- Dark $|D\rangle = \Omega_d|b\rangle - \Omega_p|c\rangle$ and Bright $|B\rangle = \Omega_d|c\rangle + \Omega_p|b\rangle$ states
- resonance width ($\sim$ 10kHz) much smaller then natural line width

EIT observation

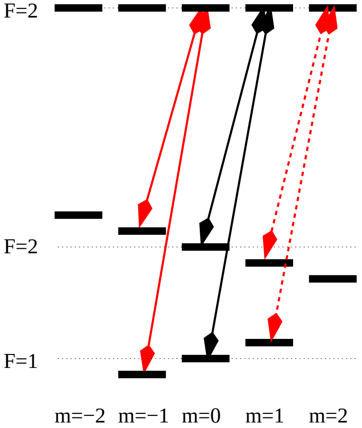


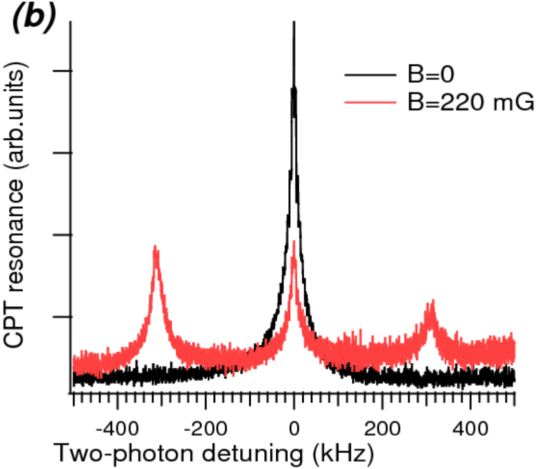




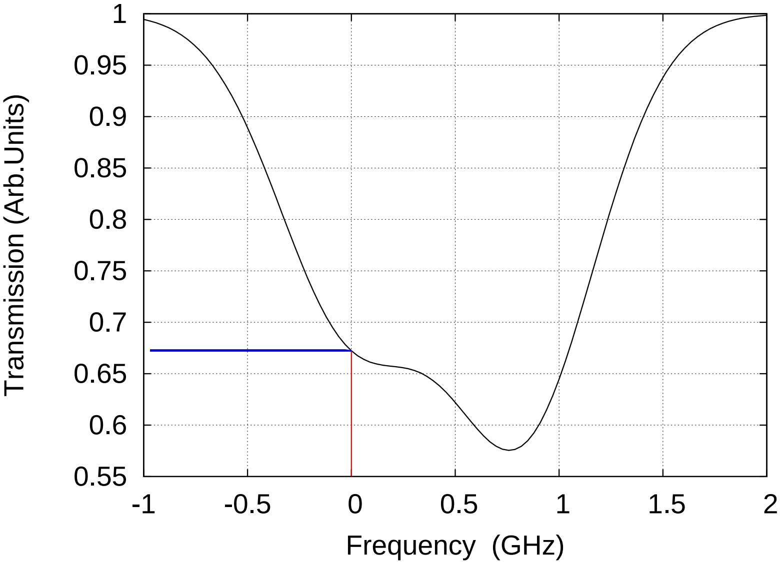


EIT with circularly polarized light





Phase noise to amplitude noise conversion



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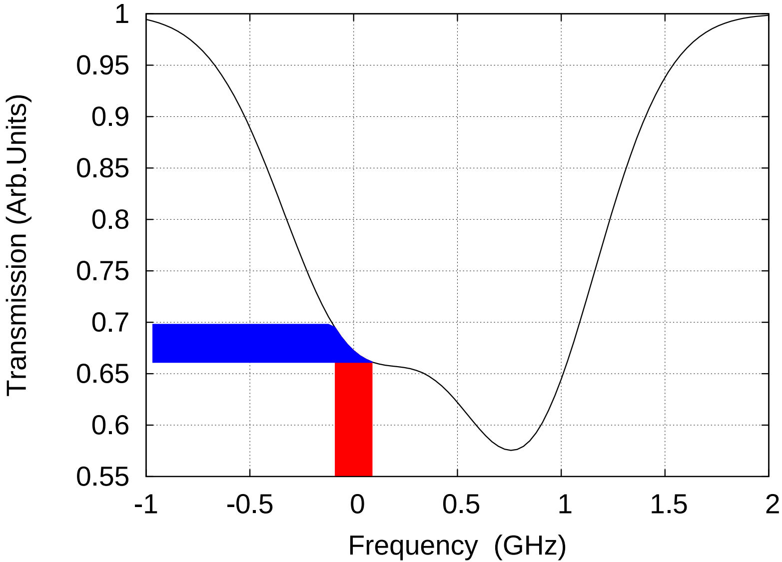
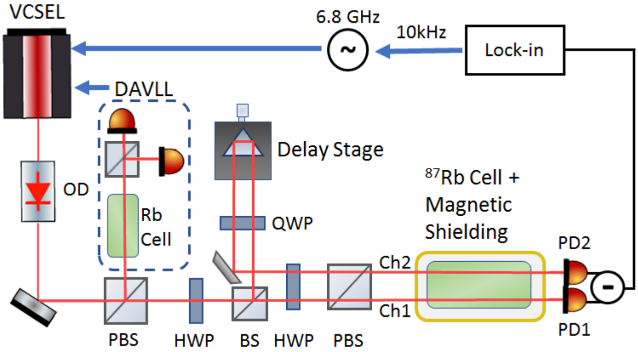


Transit Ramsey Electromagnetically Induced Transparency (TREIT)



Ravn M. Jenkins, Eugeniy E. Mikhailov, and Irina Novikova, “Transit Ramsey EIT resonances in a Rb vacuum cell”, arXiv:1807.10370, (2018).

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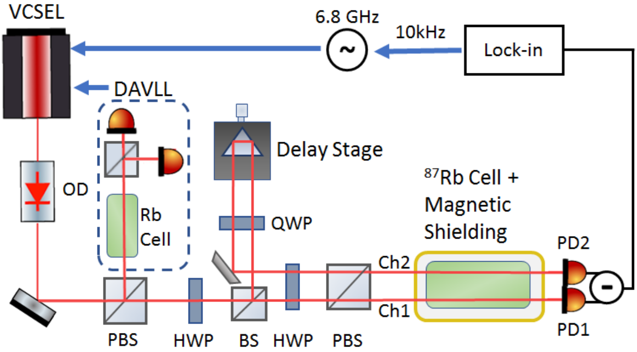

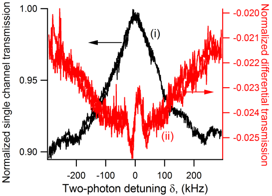

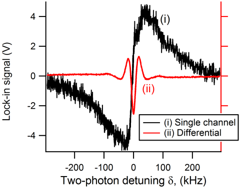

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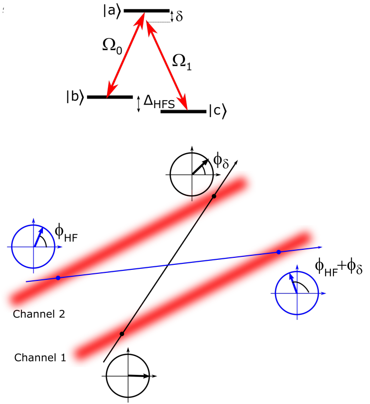
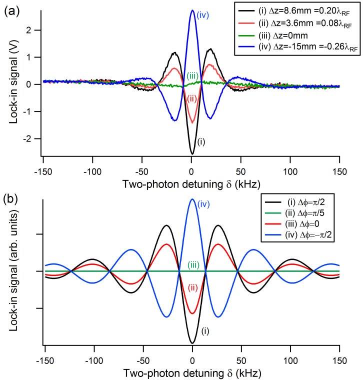
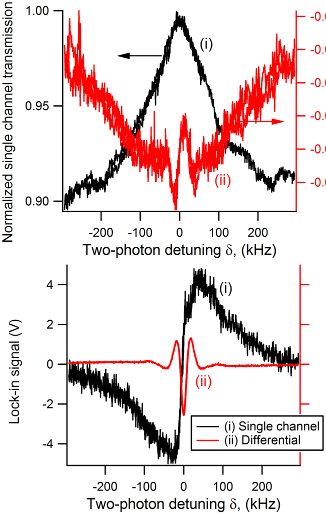
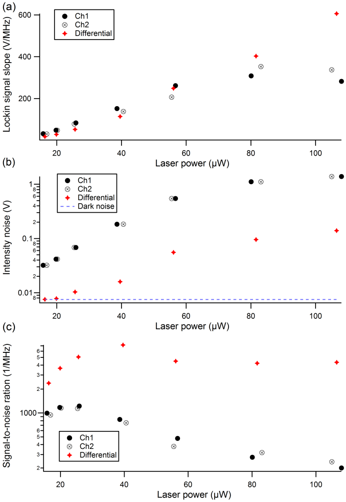
TREIT explanation





$$
\begin{aligned}
|D_1\rangle(t=\tau) &= (\Omega_1|b\rangle - e^{i\delta\cdot\tau}\Omega_0|c\rangle)/\Omega, \\
|D_2\rangle(t=\tau) &= (\Omega_1|b\rangle - e^{i\phi_{\mathrm{HF}}+i\delta\cdot\tau}\Omega_0|c\rangle)/\Omega, \\
\Delta I(\delta) &\propto \frac{|\Omega|^2}{\delta^2+\Gamma^2} e^{-2\Gamma t_{\mathrm{tr}}} \sin\phi_{\mathrm{HF}} \times \sin\left[\delta(2t_{\mathrm{tr}}+\tau) + \tan^{-1}(\delta/\Gamma)\right],
\end{aligned}
$$





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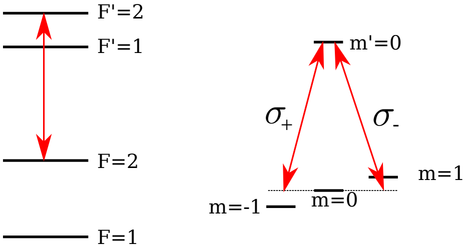
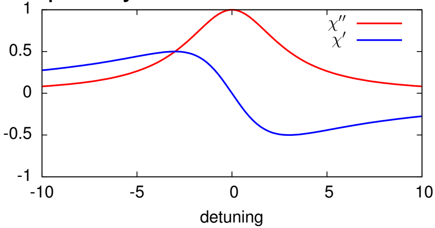
Optical magnetometer based on Faraday effect

^{87}Rb D_1 line



Susceptibility vs B



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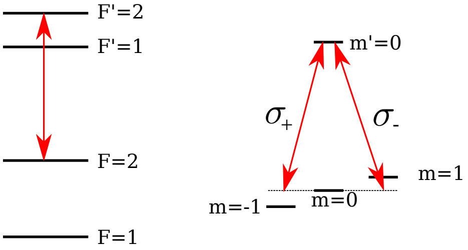

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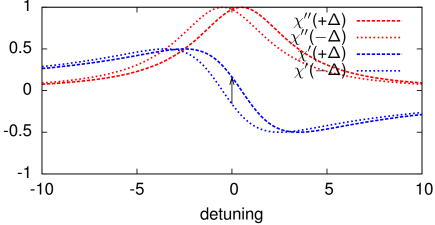

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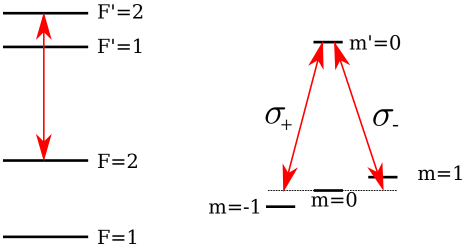

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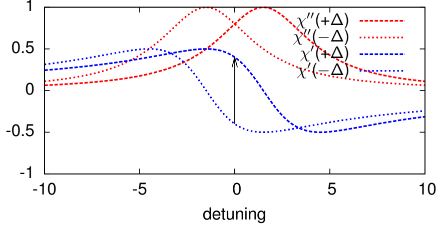

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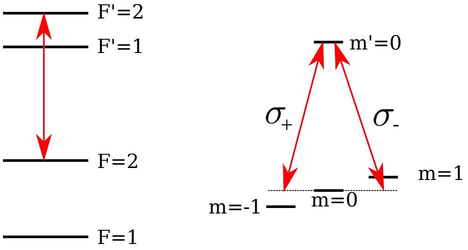

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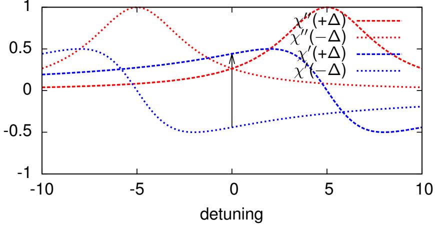

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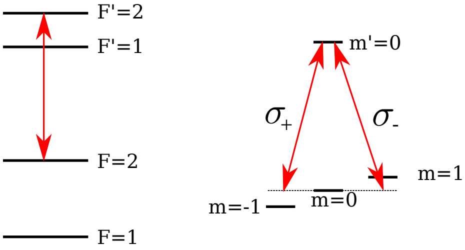

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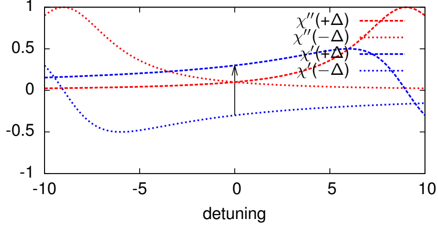

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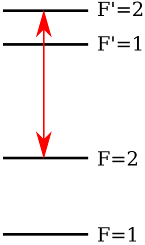
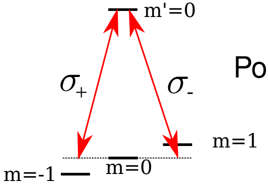
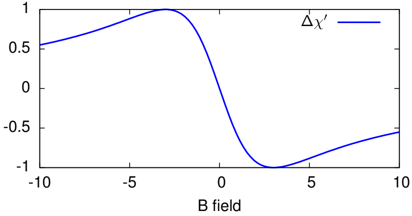




Polarization rotation vs B



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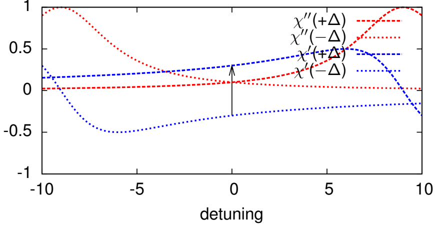
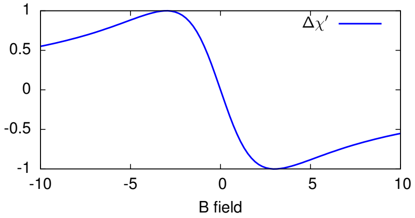
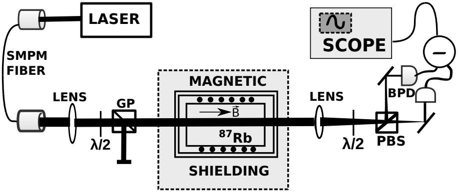


Optical magnetometer and non linear Faraday effect

Naive model of rotation

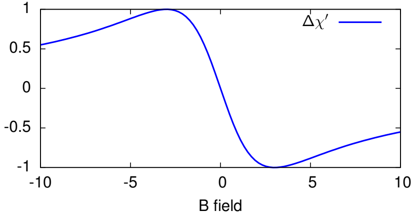


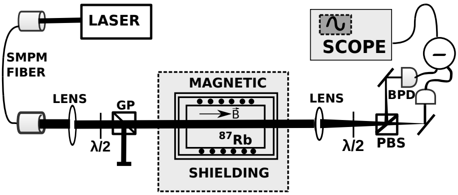


Experiment

Optical magnetometer and non linear Faraday effect

Naive model of rotation





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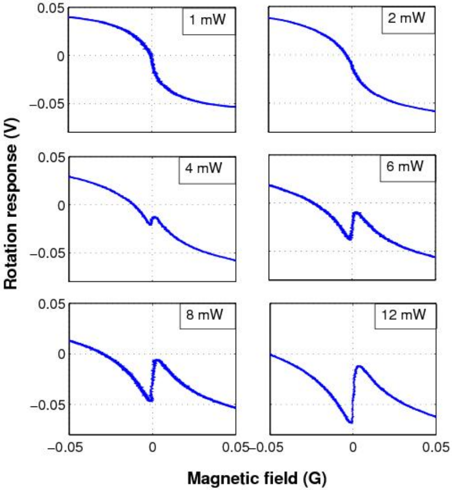
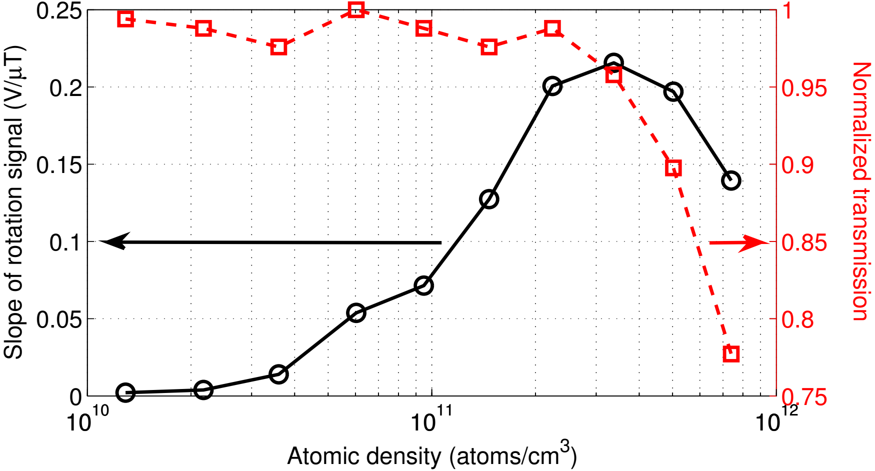
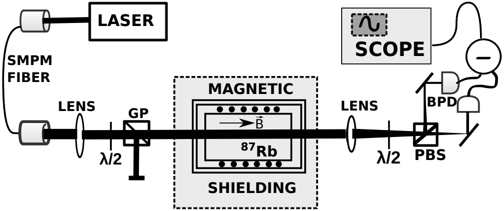
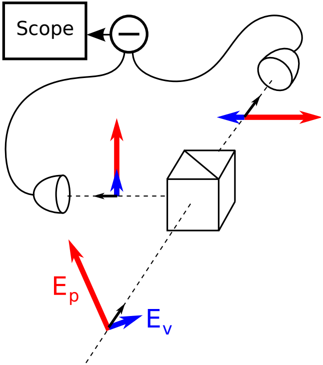


Magnetometer response vs atomic density



Shot noise limit of the magnetometer





$$S = |E_p + E_v|^2 - |E_p - E_v|^2$$

$$S = 4 E_p E_v$$

$$< \Delta S > \sim E_p < \Delta E_v >$$

Transition from classical to quantum field

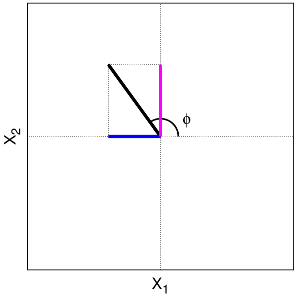
Classical analog

- Field amplitude a
- Field real part
  $X_1 = (a^* + a)/2$
- Field imaginary part
  $X_2 = i(a^* - a)/2$

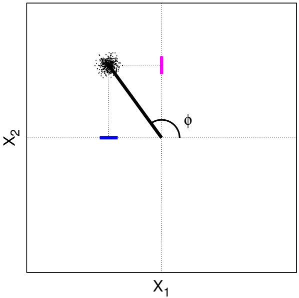
Quantum approach

- Field operator $\hat{a}$
- Amplitude quadrature
  $\hat{X}_1 = (\hat{a}^\dagger + \hat{a})/2$
- Phase quadrature
  $\hat{X}_2 = i(\hat{a}^\dagger - \hat{a})/2$

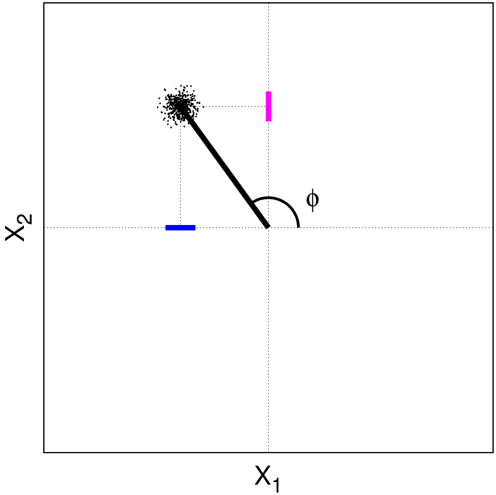
$$E(\phi) \;=\; |a|e^{-i\phi} = X_1 + iX_2$$



$$\hat{E}(\phi) \;=\; \hat{X}_1 + i\hat{X}_2$$



Quantum optics summary



Light consist of photons

- $\hat{N} = a^\dagger a$

Commutator relationship

- $[a, a^\dagger] = 1$
- $[X_1, X_2] = i/2$

Detectors measure

- number of photons $\hat{N}$
- Quadratures $\hat{X}_1$ and $\hat{X}_2$

Uncertainty relationship

- $\Delta X_1 \Delta X_2 \geq 1/4$

Heisenberg uncertainty principle and its optics equivalent

Heisenberg uncertainty principle

$\Delta p \Delta x \geq \hbar/2$

The more precisely the POSITION is determined, the less precisely the MOMENTUM is known, and vice versa

Heisenberg uncertainty principle and its optics equivalent

Heisenberg uncertainty principle

$\Delta p \Delta x \geq \hbar/2$

The more precisely the POSITION is determined, the less precisely the MOMENTUM is known, and vice versa

Optics equivalent

$\Delta \phi \Delta N \geq 1$

The more precisely the PHASE is determined, the less precisely the AMPLITUDE is known, and vice versa

Heisenberg uncertainty principle and its optics equivalent

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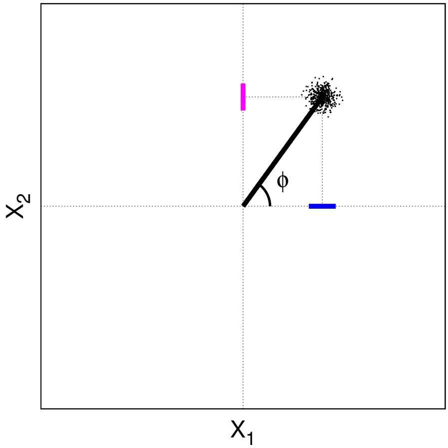
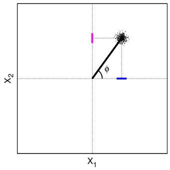
Optics equivalent strict definition

$\Delta X_1 \Delta X_2 \geq 1/4$

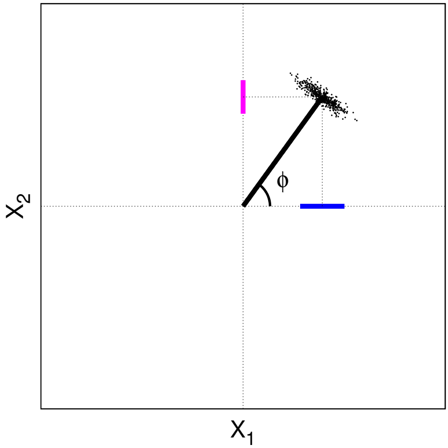
Squeezed quantum states zoo



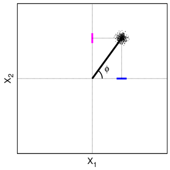
Unsqueezed coherent



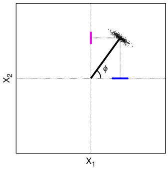
Squeezed quantum states zoo



Unsqueezed coherent



Amplitude squeezed



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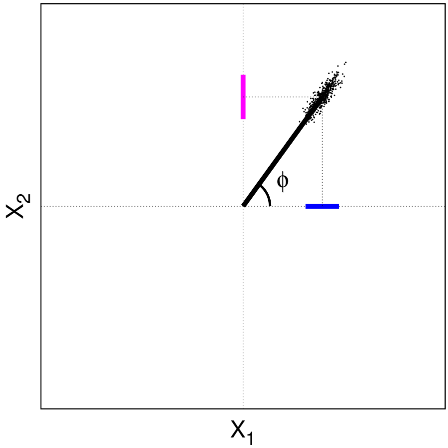

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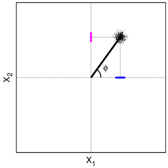

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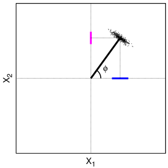
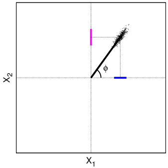
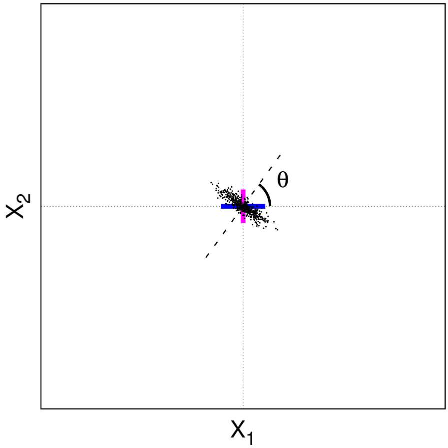


Phase squeezed



Squeezed quantum states zoo



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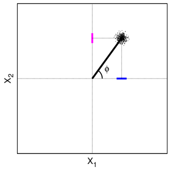

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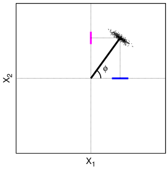
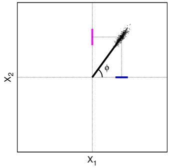
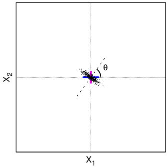


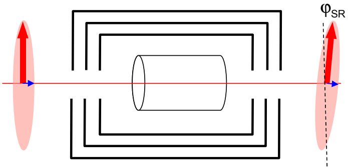
Phase squeezed

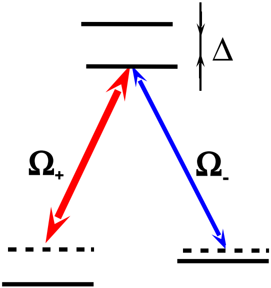


Vacuum squeezed



Self-rotation of elliptical polarization in atomic medium

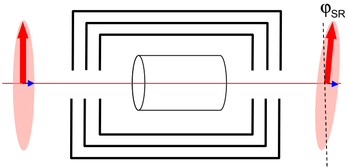


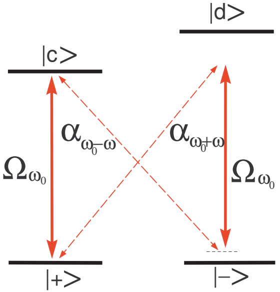


A. B. Matsko, I. Novikova, G. R. Welch, D. Budker, D. F. Kimball, and S. M. Rochester, PRA 66, 043815 (2002):
theoretical prediction of 4–6 dB noise suppression

$$a_{out} = a_{in} + \frac{igL}{2}(a_{in}^\dagger - a_{in})$$

Self-rotation of elliptical polarization in atomic medium





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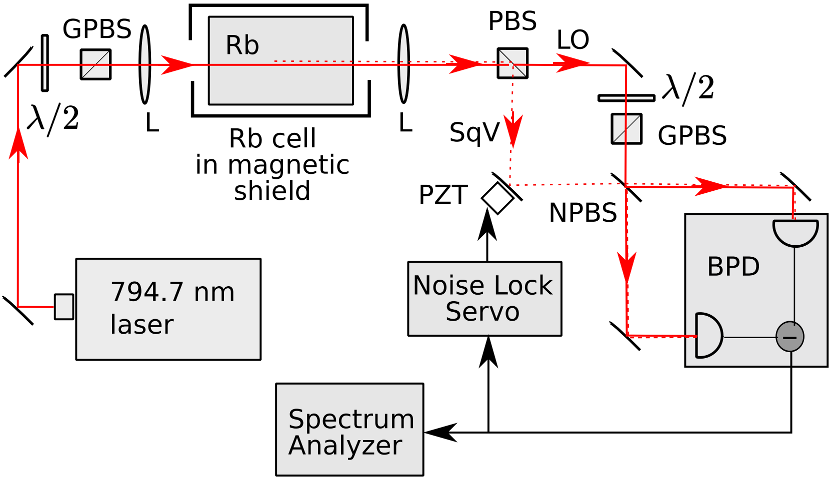
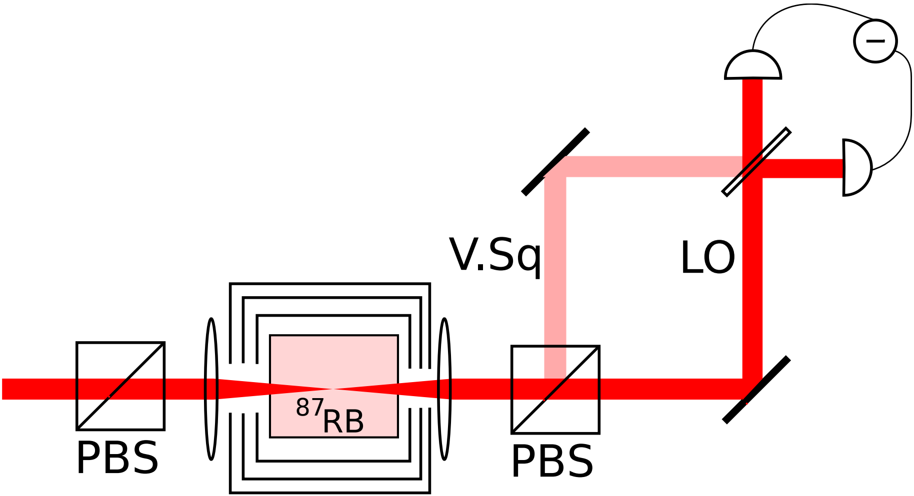
Setup

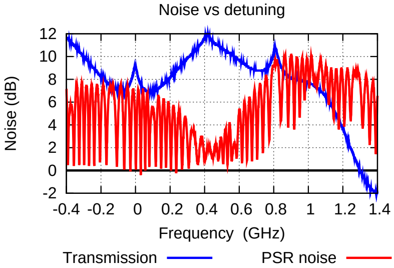

GPBS
Rb
PBS
LO
$\lambda/2$
$\lambda/2$
L
L
Rb cell
in magnetic
shield
SqV
GPBS
PZT
NPBS
BPD
794.7 nm
laser
Noise Lock
Servo
Spectrum
Analyzer

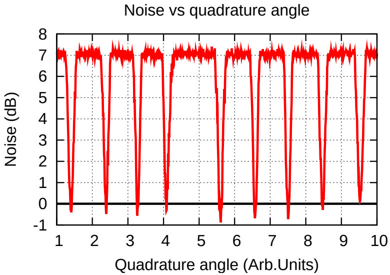
Setup



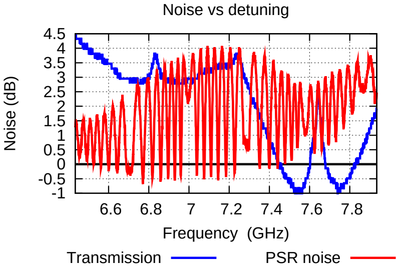
Noise contrast vs detuning in hot ^{87}Rb vacuum cell

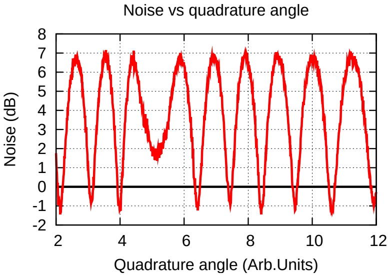
$F_g = 2 \rightarrow F_e = 1, 2$





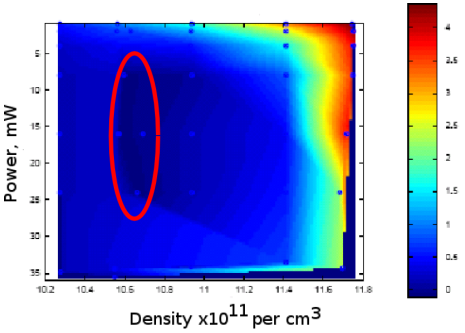
$F_g = 1 \rightarrow F_e = 1, 2$



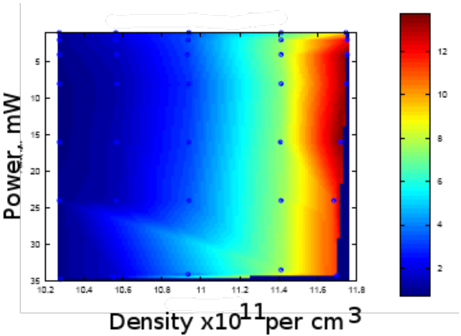


Squeezing region

Squeezing



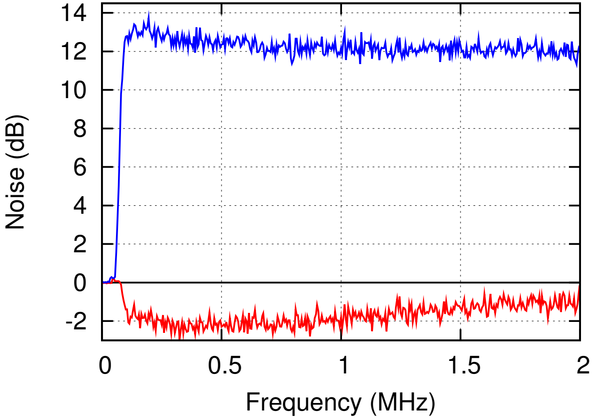
Anti-squeezing



Observation of reduction of quantum noise below the shot noise limit is corrupted by the excess noise due to atomic interaction with atoms.

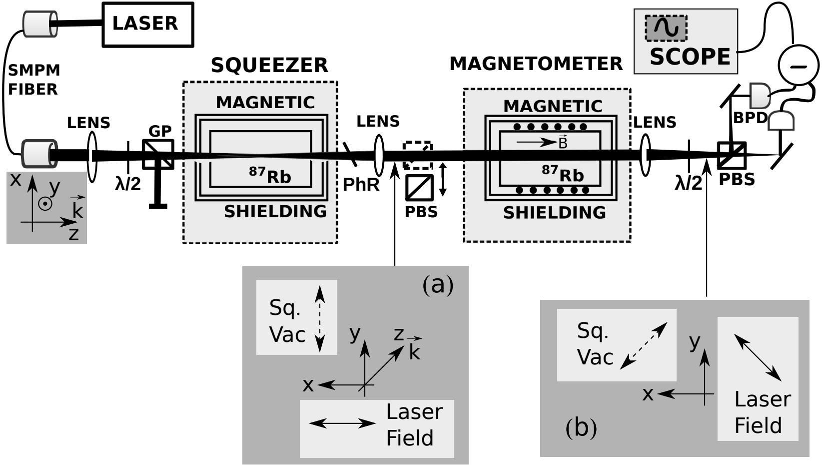
Maximally squeezed spectrum with ^{87}Rb

W&M team. ^{87}Rb $F_g = 2 \rightarrow F_e = 2$, laser power 7 mW, T=65° C



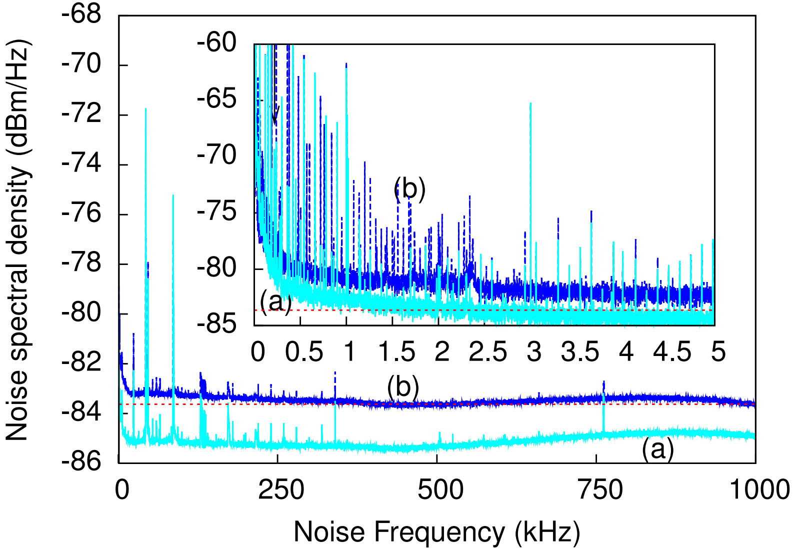
Lezama et.al report 3 dB squeezing in similar setup
Phys. Rev. A 84, 033851 (2011)

Squeezed enhanced magnetometer setup

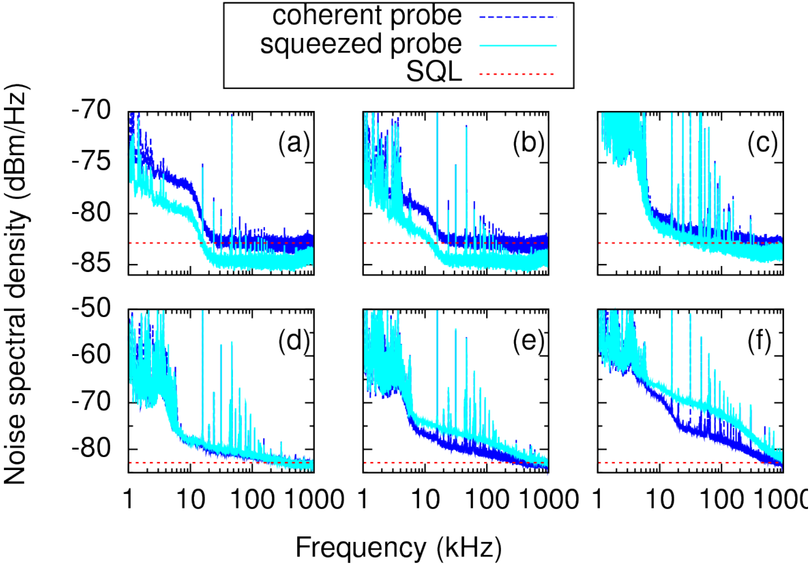


Note: Squeezed enhanced magnetometer was first demonstrated by Wolfgramm *et. al* Phys. Rev. Lett, **105**, 053601, 2010.

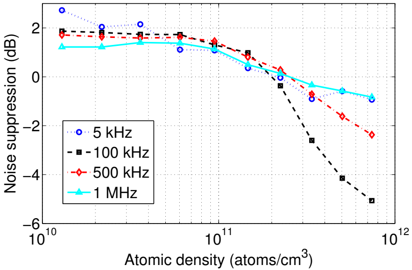
Magnetometer noise floor improvements



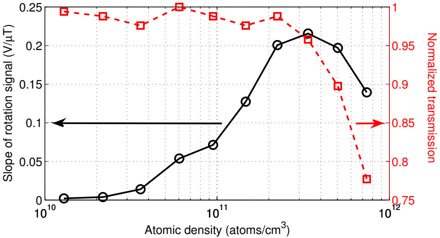
Magnetometer noise spectra



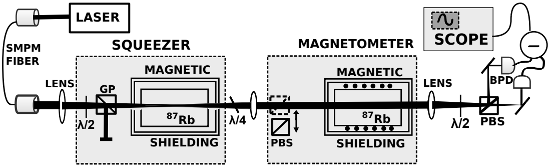
Noise suppression

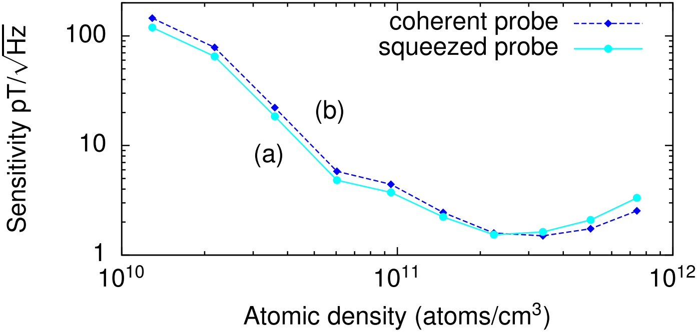


Response



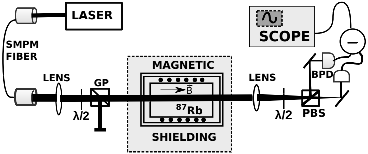
Magnetometer with squeezing enhancement

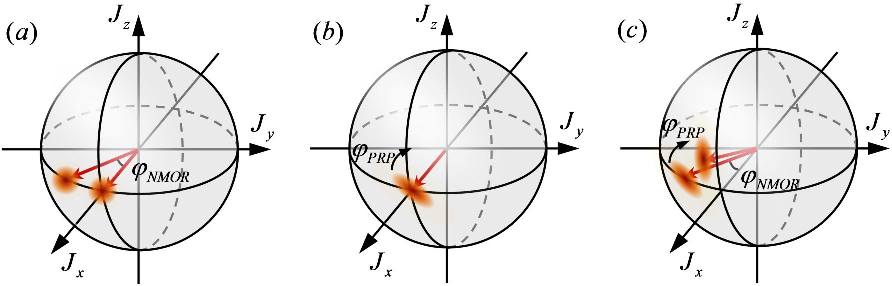




T. Horrom, et al. **PRA**, 86, 023803, (2012).

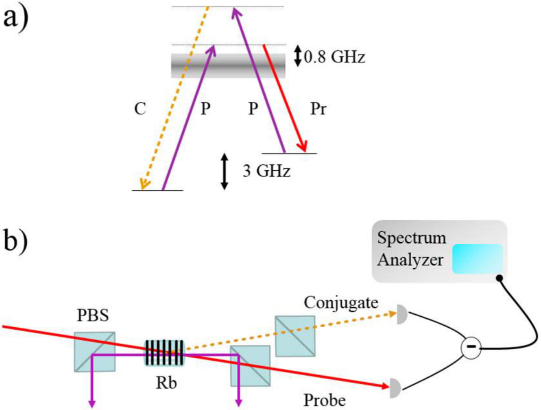
Self-squeezed magnetometry





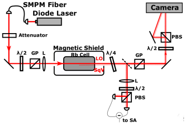
Irina Novikova, Eugeniy E. Mikhailov, Yanhong Xiao, "Excess optical quantum noise in atomic sensors", Phys. Rev. A, **91**, 051804(R), (2015)

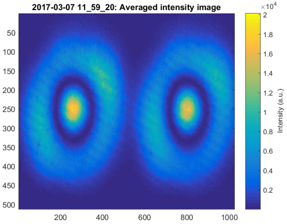
20 pT/$\sqrt{\text{Hz}}$ self-squeezed magnetometry with 4WM

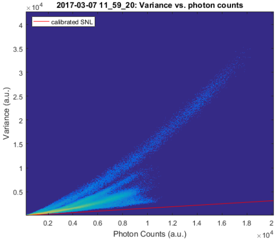


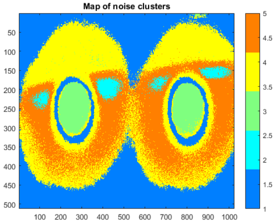
N. Otterstrom, R. C. Pooser, and B. J. Lawrie, “Nonlinear optical magnetometry with accessible in situ optical squeezing”, Optics Letters, **39**, Issue 22, pp. 6533-6536 (2014)

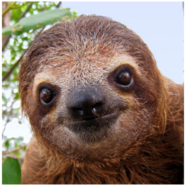
Quantum imaging effort: from owl to sloth

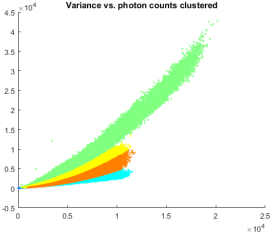












People

WM: Irina Novikova, Ravn M. Jenkins, Savannah Cuozzo, Austin Kalasky
Former members: George Denny, Melissa A. Guidry, Mi Zhang, Travis Horrom, Gleb Romanov, Demetrious Kutzke

Summary

- fully atomic squeezed enhanced magnetometer
  with sensitivity as low as 1 pT/$\sqrt{\text{Hz}}$
- superluminal squeezing propagation
  with $v_g \approx -7'000$ m/s $\approx -c/43'000$ or time advancement of 11 μS
- We were able to improve squeezing by multipass configuration
- Our squeezed state is a set of competing multimodes
- We are working on quantum modes extraction and imaging

Financial support by AFOSR, ARO, and NSF.