Interaction-based quantum metrology giving a scaling beyond the Heisenberg limit

Dr Rob Sewell

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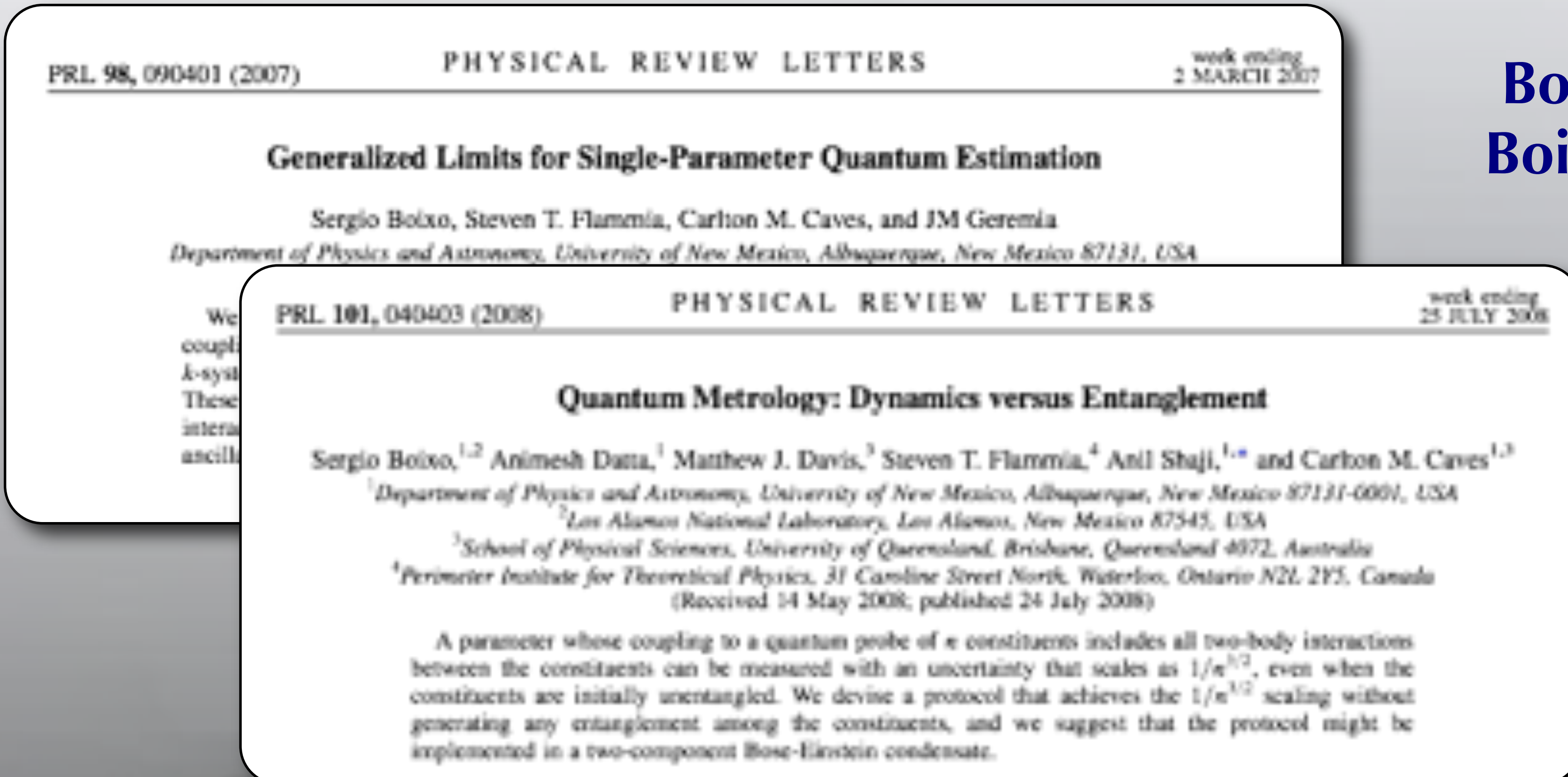
Nonlinear quantum metrology


PRL 98, 090401 (2007) PHYSICAL REVIEW LETTERS week ending 2 MARCH 2007

Generalized Limits for Single-Parameter Quantum Estimation

Sergio Boixo, Steven T. Flammia, Carlton M. Caves, and JM Geremia

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PRL 101, 040403 (2008) PHYSICAL REVIEW LETTERS week ending 25 JULY 2008

Quantum Metrology: Dynamics versus Entanglement

Sergio Boixo,[1,2] Animesh Datta,[1] Matthew J. Davis,[3] Steven T. Flammia,[4] Anil Shaji,[1,*] and Carlton M. Caves[1,3]

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A parameter whose coupling to a quantum probe of n constituents includes all two-body interactions between the constituents can be measured with an uncertainty that scales as $1/n^{3/2}$, even when the constituents are initially unentangled. We devise a protocol that achieves the $1/n^{3/2}$ scaling without generating any entanglement among the constituents, and we suggest that the protocol might be implemented in a two-component Bose-Einstein condensate.

Boixo *et al.* PRL 98, 090401 (2007)
Boixo *et al.* PRL 101, 040403 (2008)

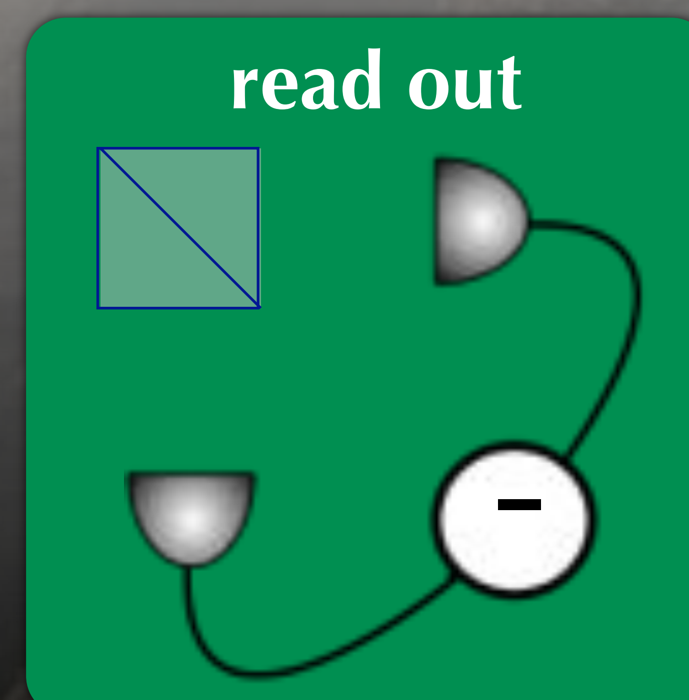
sensitivity

$$\delta\mathcal{X} \sim \frac{1}{N^{3/2}}$$

quantum probe

quantum system
X

$$H = \mathcal{X} N S_z$$



Nonlinear quantum metrology

Standard Quantum Limit

$$H = \mathcal{X} S_z$$

Signal $\sim N$

Noise $\sim \sqrt{N}$

Sensitivity

$$\delta\mathcal{X} \sim \frac{1}{\sqrt{N}}$$

Heisenberg Limit

$$H = \mathcal{X} S_z$$

Signal $\sim N$

Noise $\sim N^0$

Sensitivity

$$\delta\mathcal{X} \sim \frac{1}{N}$$

Nonlinear Quantum Metrology

$$H = \mathcal{X} N S_z$$

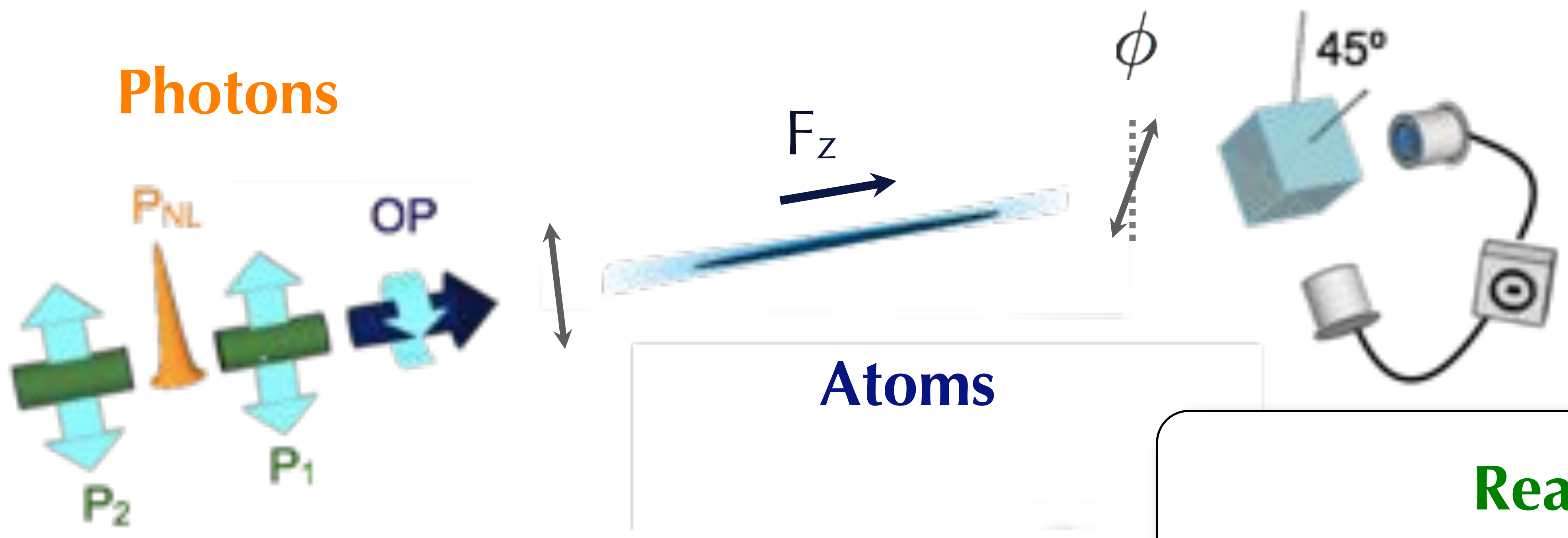
Signal $\sim N^2$

Noise $\sim \sqrt{N}$

Sensitivity

$$\delta\mathcal{X} \sim \frac{1}{N^{3/2}}$$

Experimental realisation



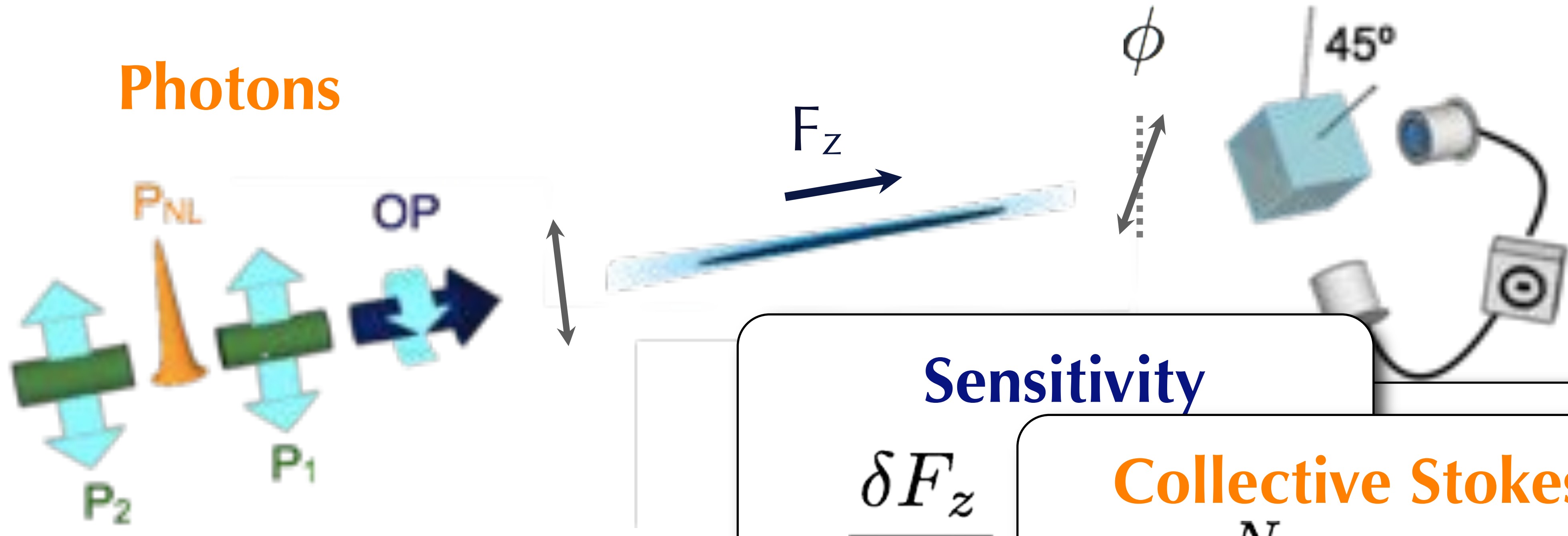
Read out
shot noise limited polarimetry

Photons
mode matched to atoms
detuning 0.4-1.5GHz
pulses 50ns-1μs long

Atoms
750,000 ^{87}Rb atoms at 25μK
10mm long, 25μm wide
optical density >50 (on resonance)

Nonlinear Faraday rotation / Faraday rotation

Photons



Sensitivity

$$\frac{\delta F_z}{\langle F_z \rangle}$$

Collective Stokes Operators

$$S_i \equiv \sum_{j=1}^{N_L} s_i^{(j)} \; ; \; \left\langle S_x^{(\mathrm{in})} \right\rangle = N_L$$

Nonlinear Hamiltonian

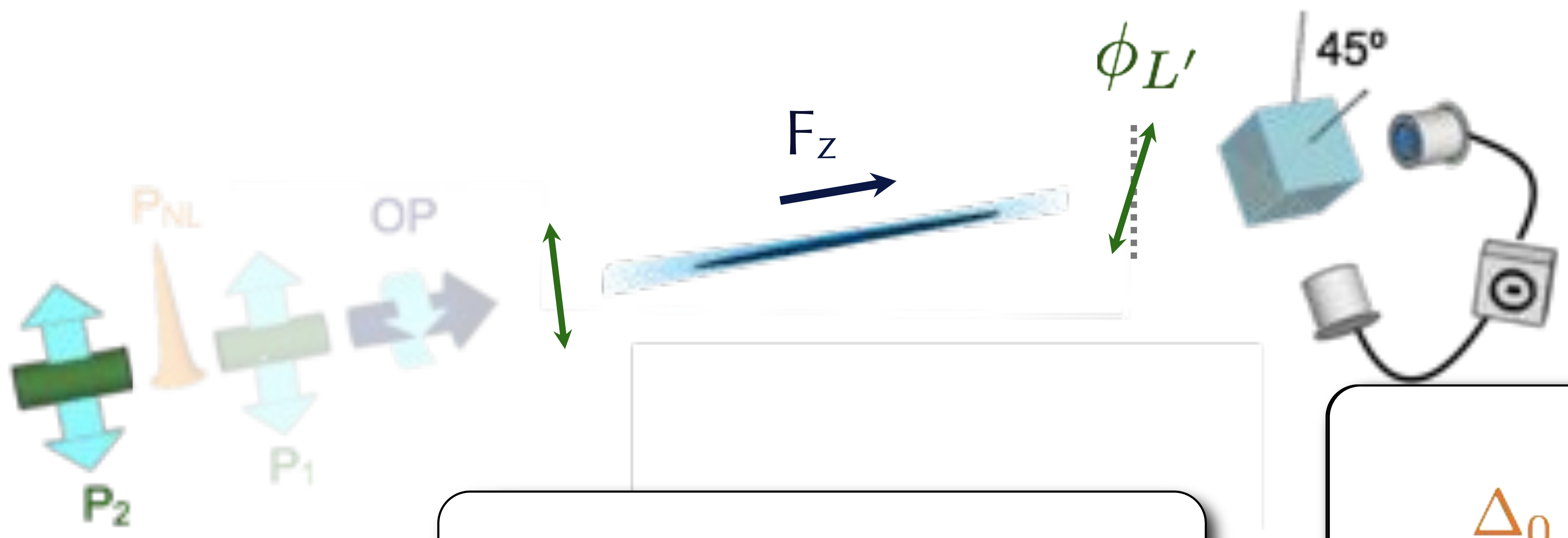
$$H = B(\Delta) N_L S_z F_z$$

Collective Spin Operators

$$F_i \equiv \sum_{j=1}^{N_A} f_i^{(j)} \; ; \left\langle F_z^{(\mathrm{in})} \right\rangle = N_A$$

Napolitano *et al.* NJP 12, 093016 (2010)

Damage



$$H_{NL} = B(\Delta) N_L S_z F_z$$

+462 … '=0

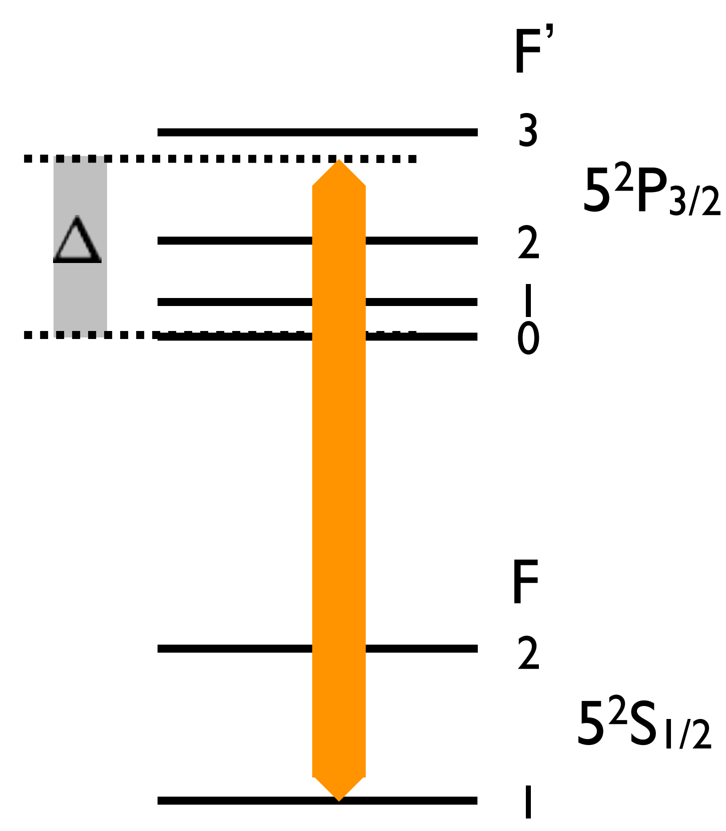
54…

~7 W/cm^2

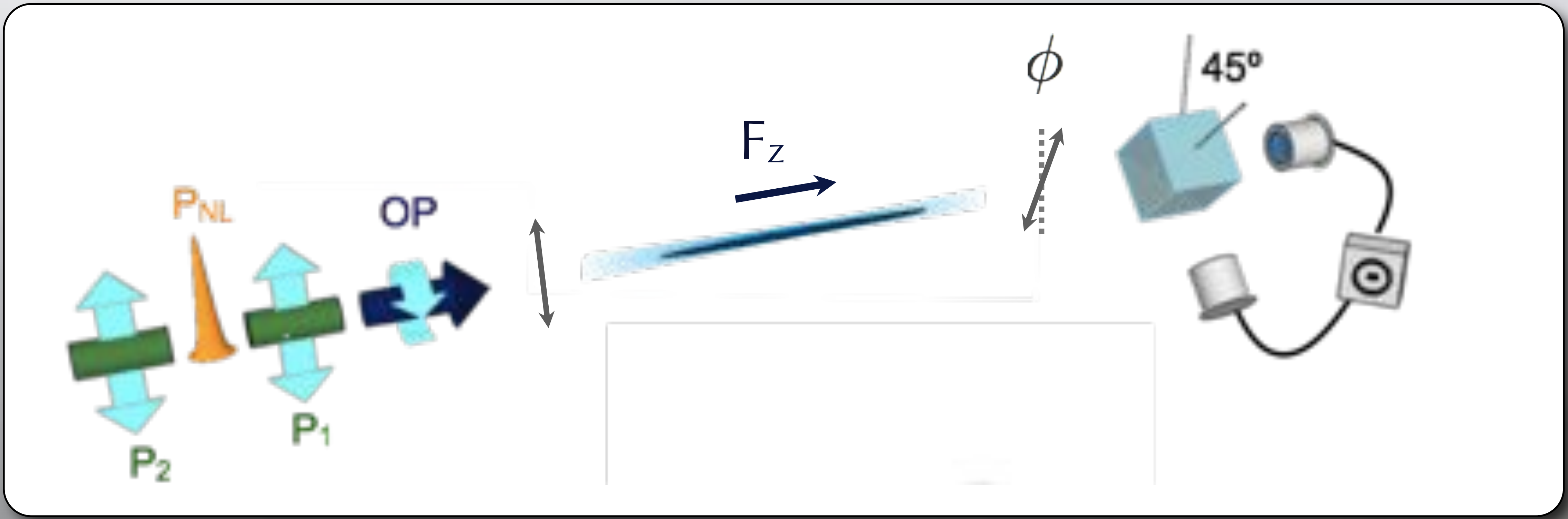
Damage to atomic state

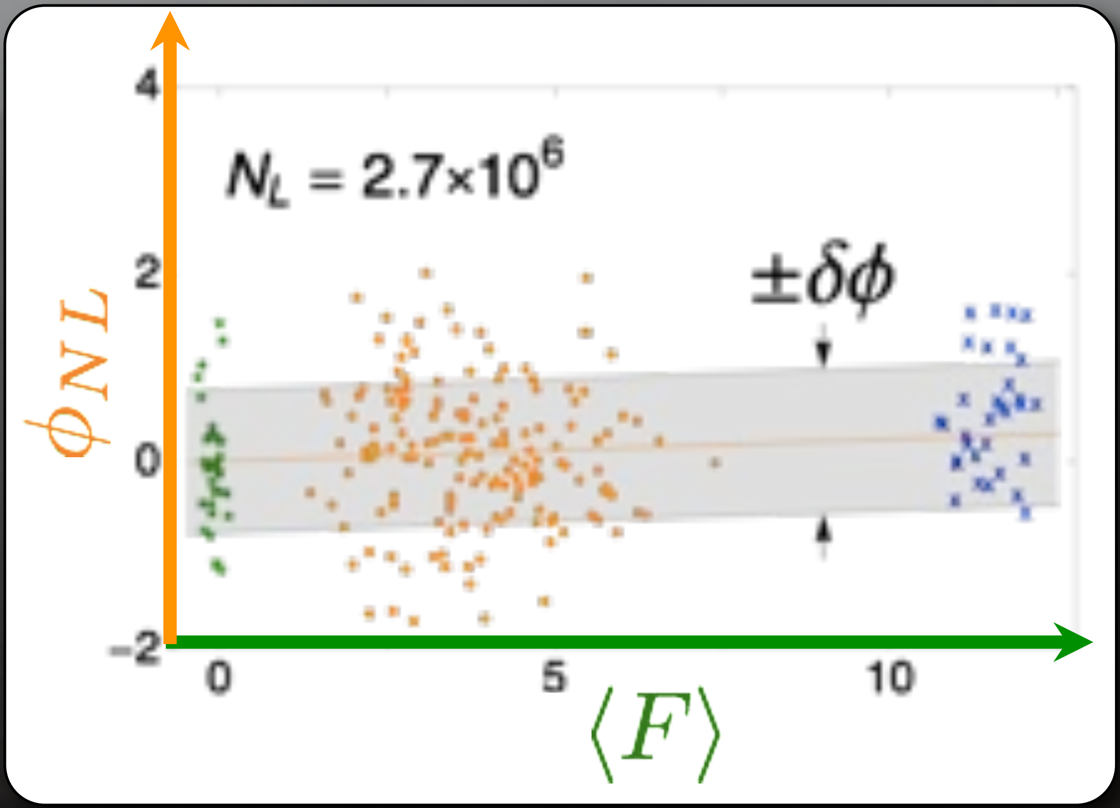
$$\eta = 1 - \frac{\phi_{L'}}{\phi_L}$$

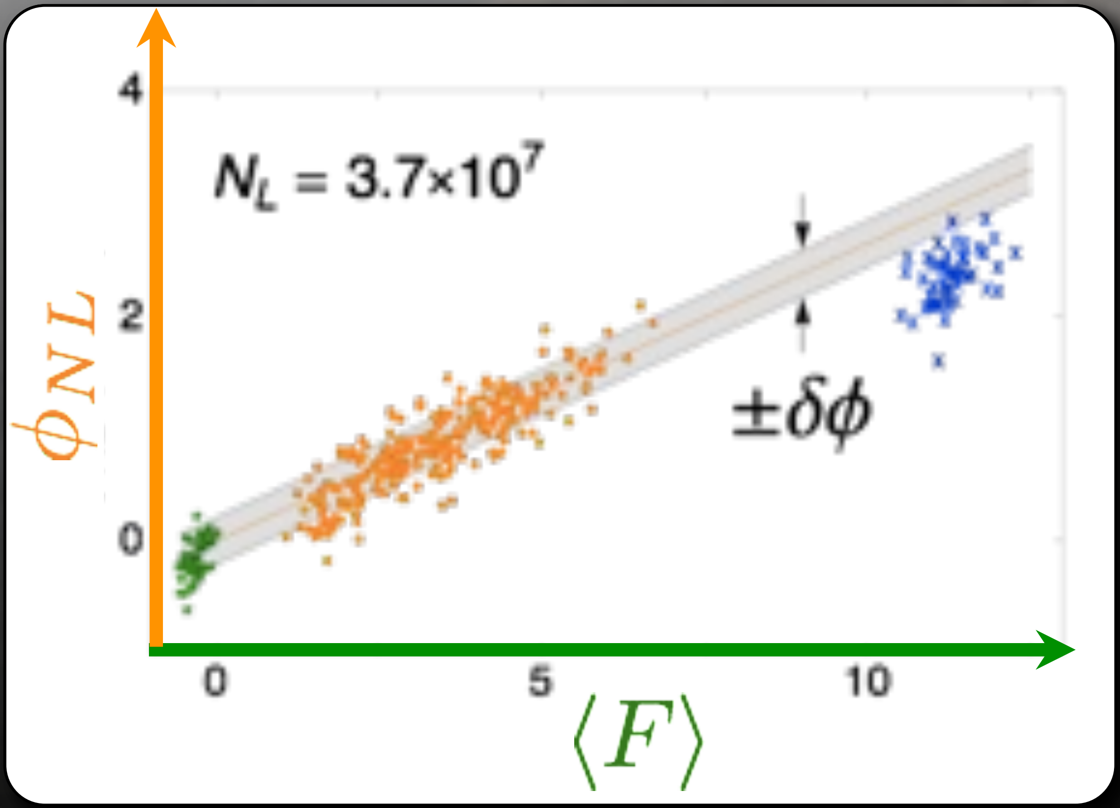
$$\Delta_0 = 462\,\mathrm{MHz}$$



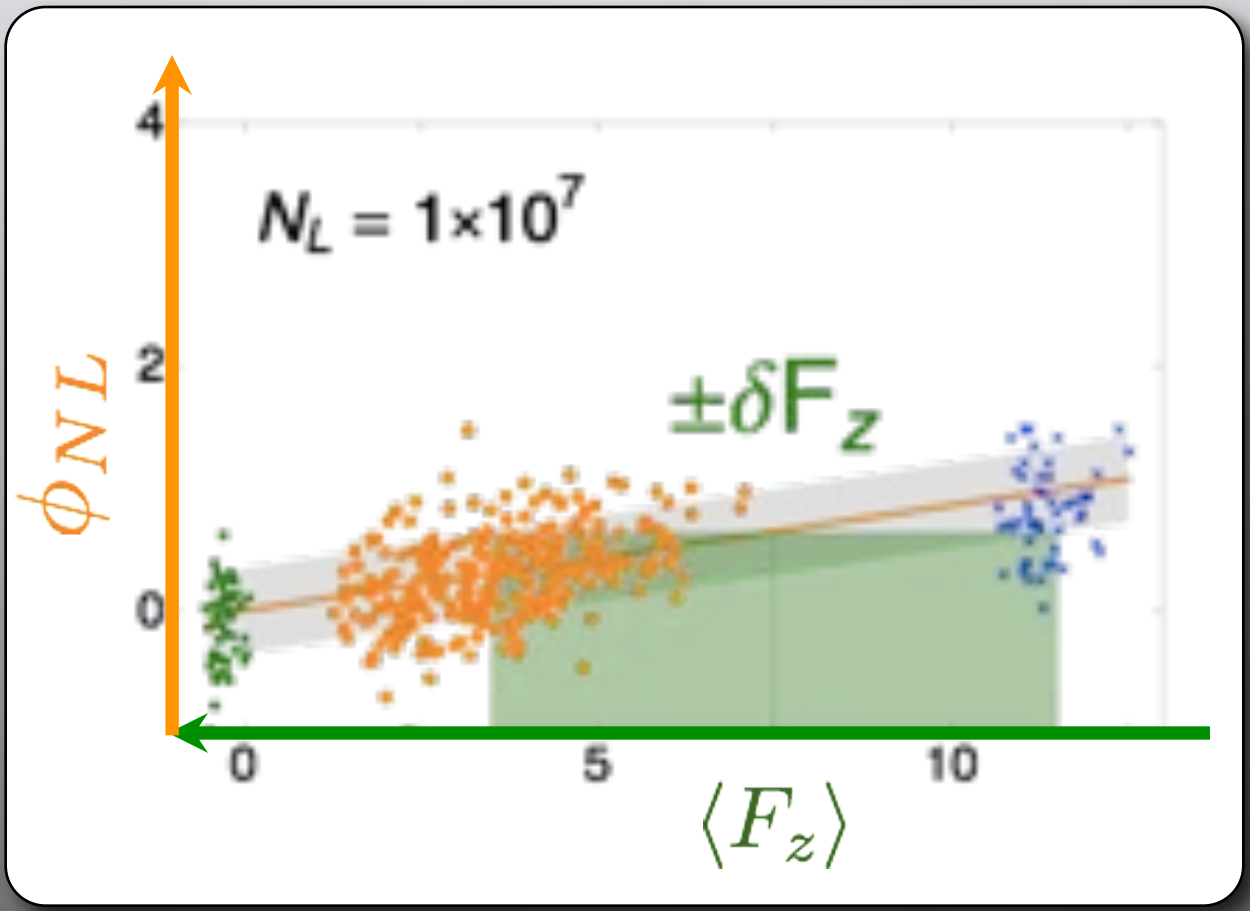
Calibration of nonlinear signal

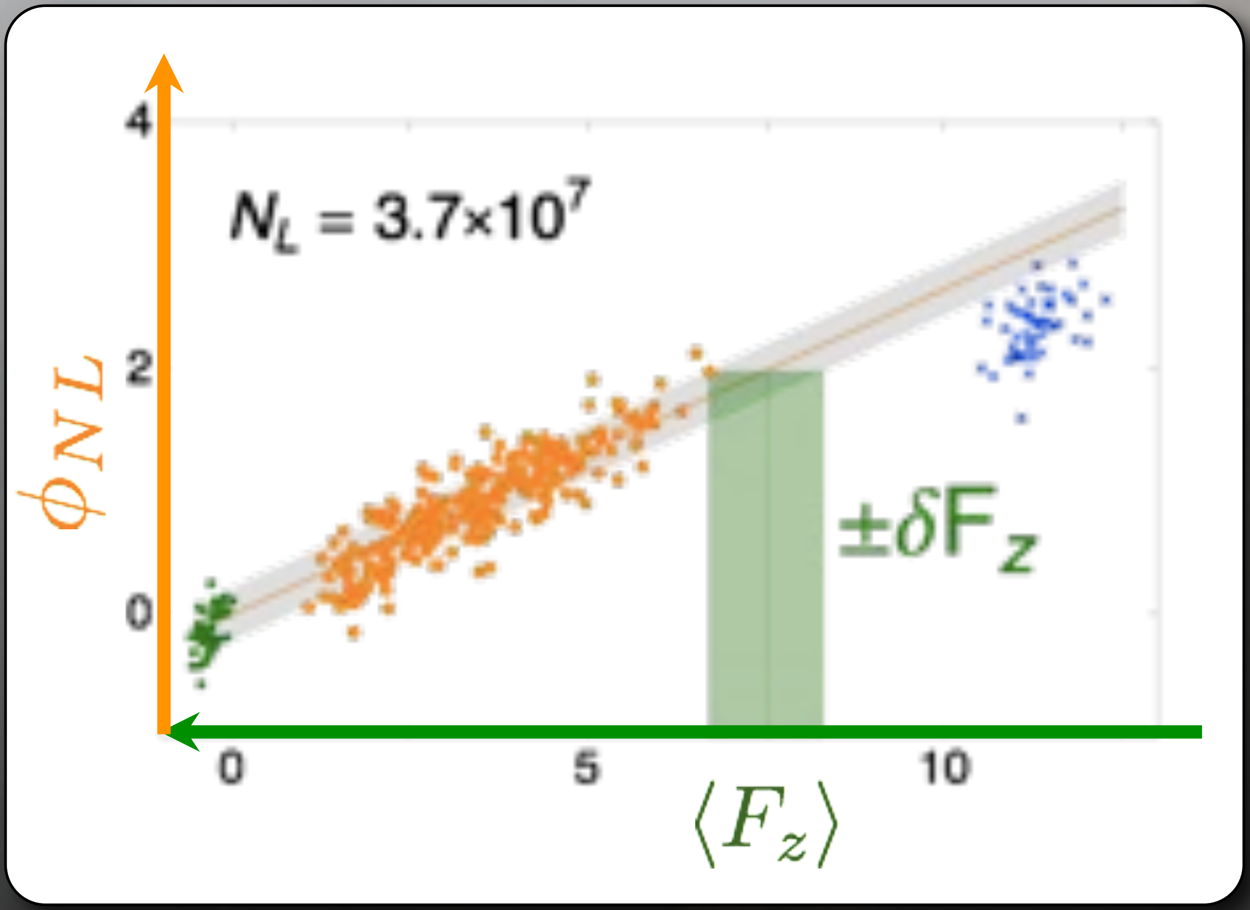




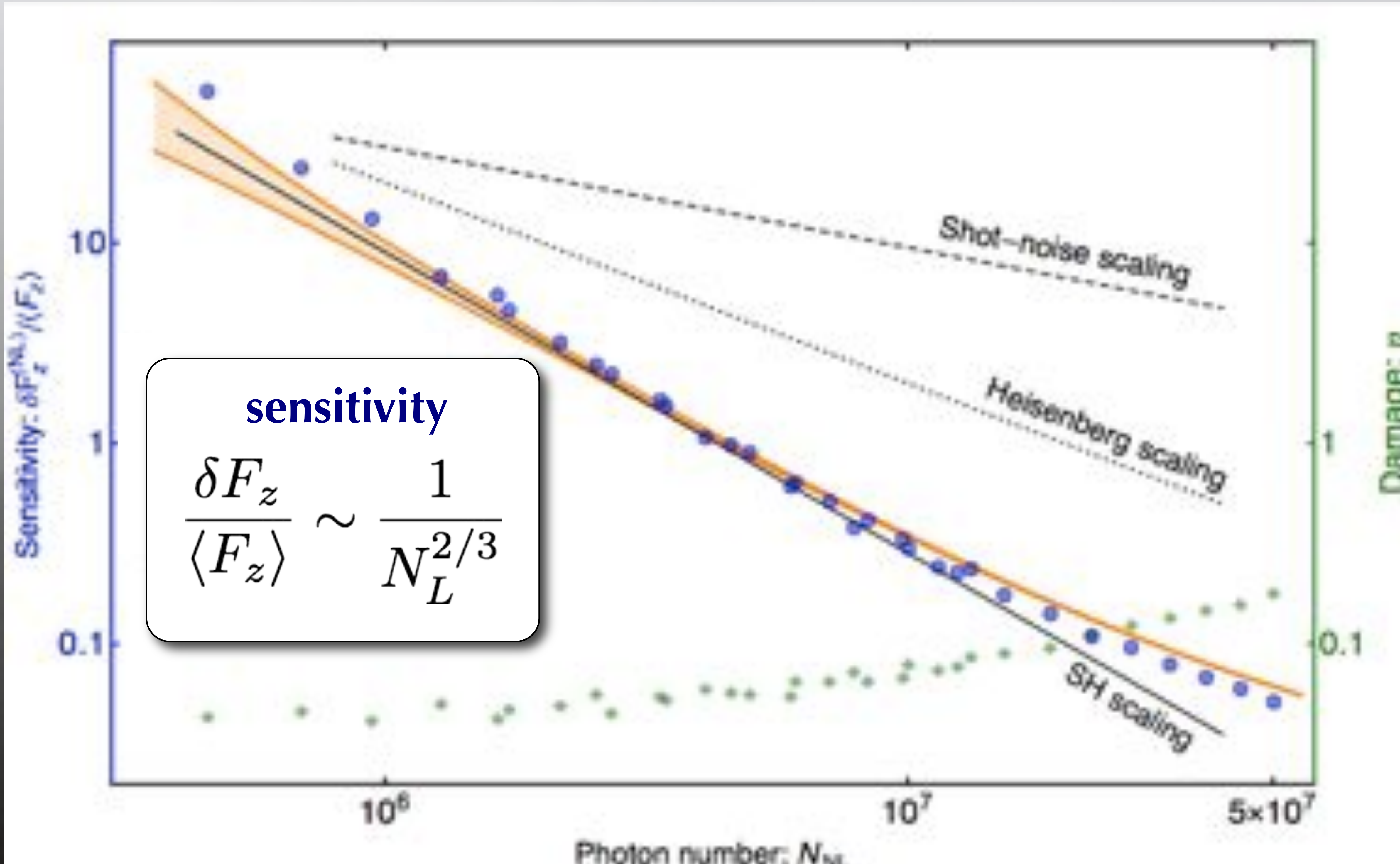


Calibration of nonlinear sensitivity





Better than Heisenberg scaling

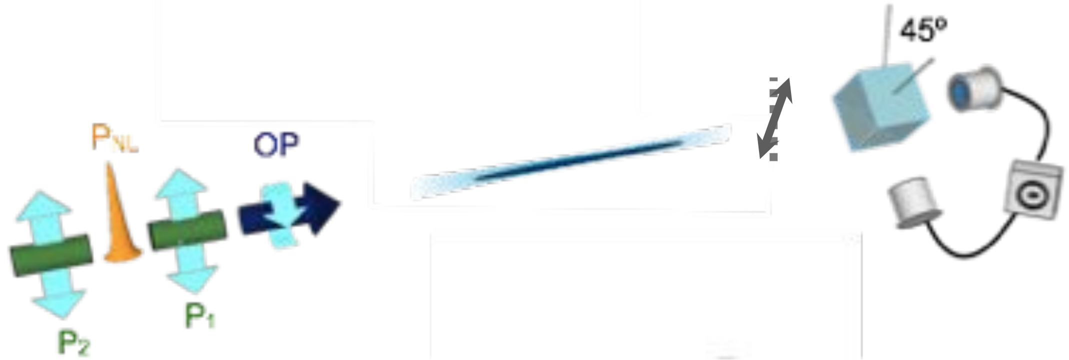


sensitivity

$$\frac{\delta F_z}{\langle F_z \rangle} \sim \frac{1}{N_L^{2/3}}$$

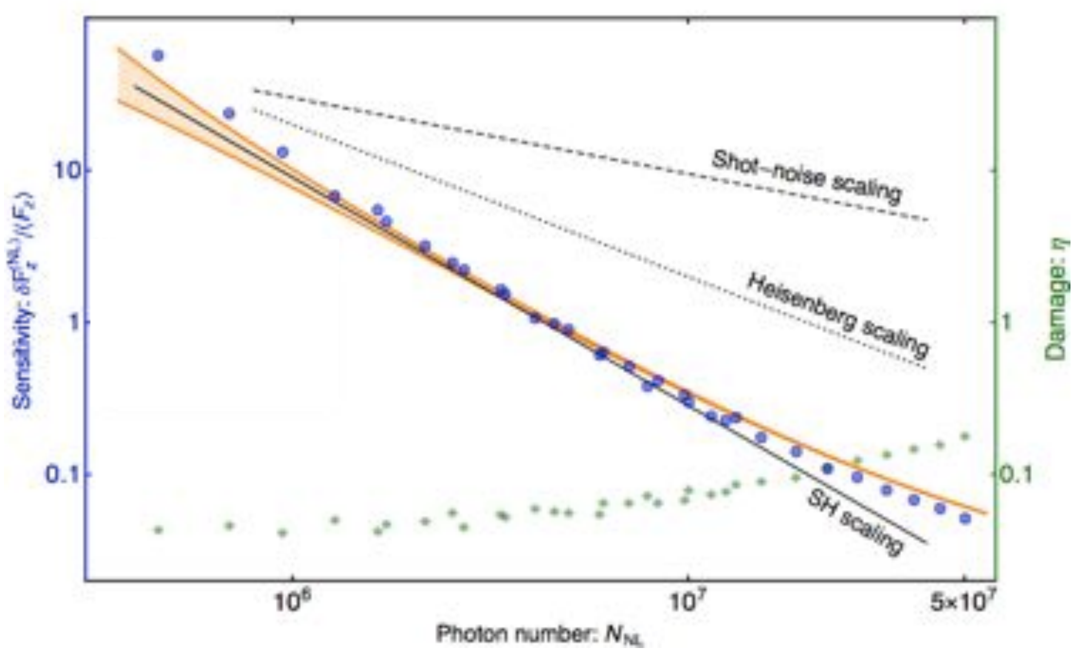
Conclusion

Quantum-limited nonlinear measurement of atomic spins



Interaction based enhancement of measured signal

Better than Heisenberg scaling of measurement sensitivity



M.Napoloitano, M.Koschorreck, B.Dubost, N.Behbood, R.J.S. & M.W.Mitchell, Nature 471, 486 (2011)

Quantum Metrology at ICFO

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EMALI

M. Koschorreck, M. Napolitano, B. Dubost, N. Behbood,
R.J. Sewell and M.W. Mitchell

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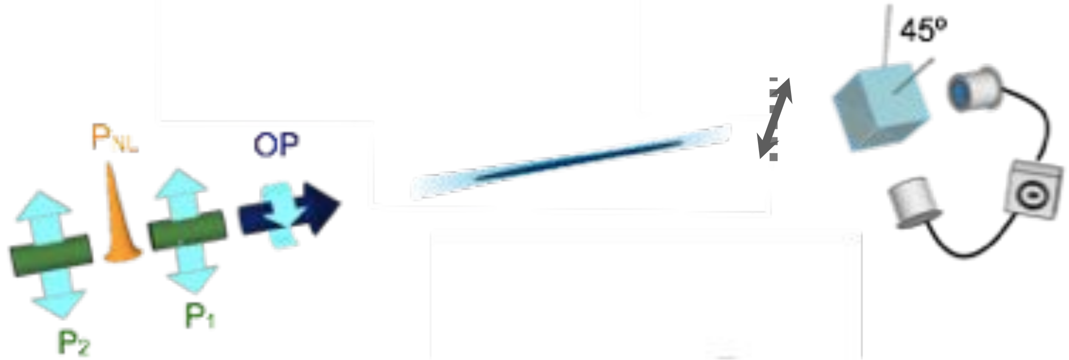
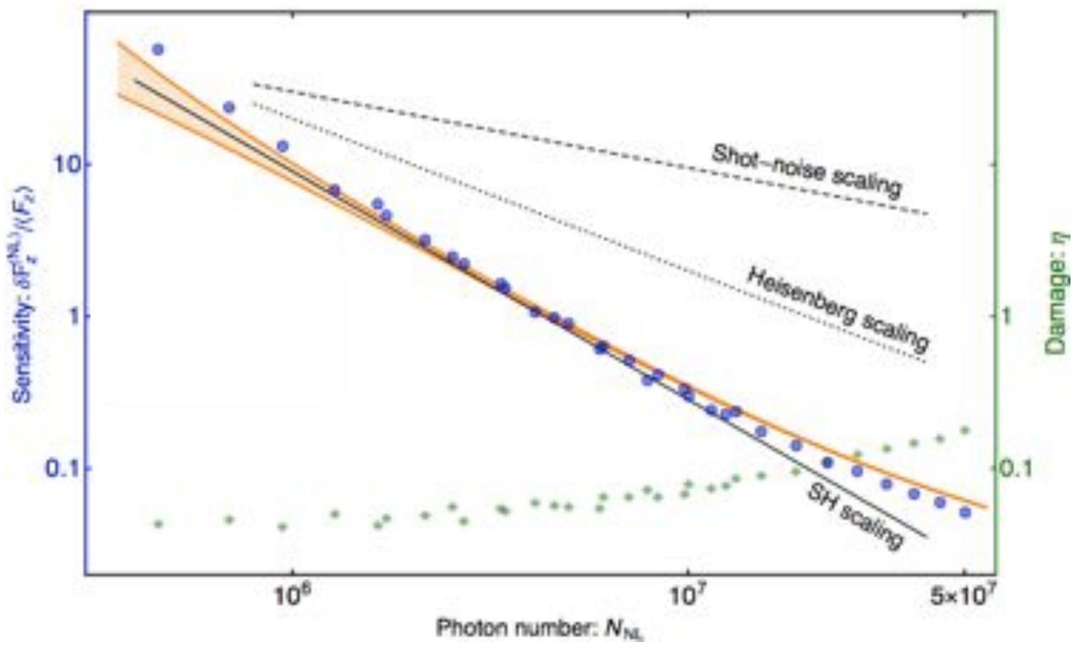
Quantum-limited nonlinear measurement of atomic spins



Interaction based enhancement of measured signal

Better than Heisenberg scaling of measurement sensitivity

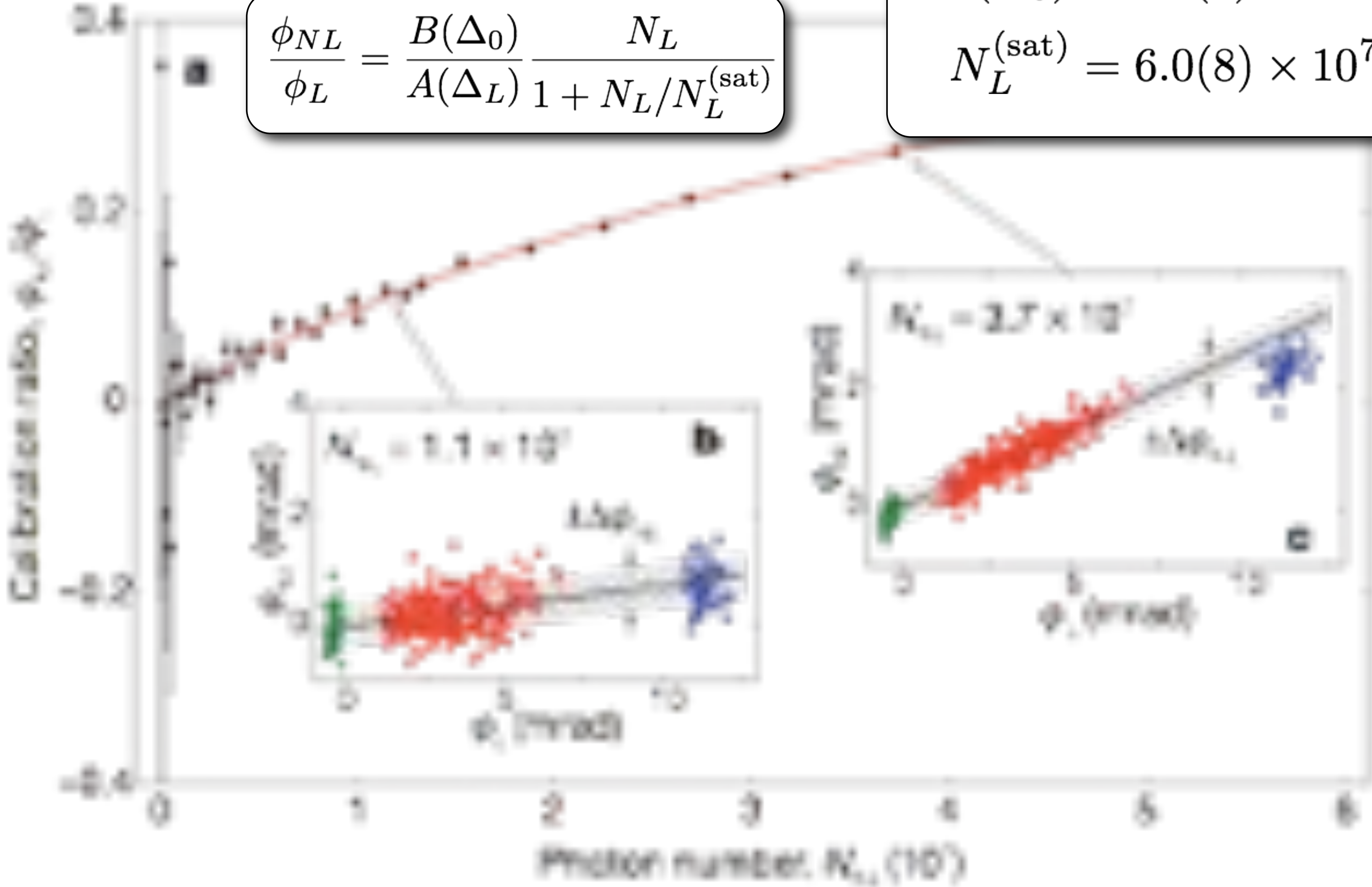


M.Napoloitano, M.Koschorreck, B.Dubost, N.Behbood, R.J.S. & M.W.Mitchell, Nature 471, 486 (2011)

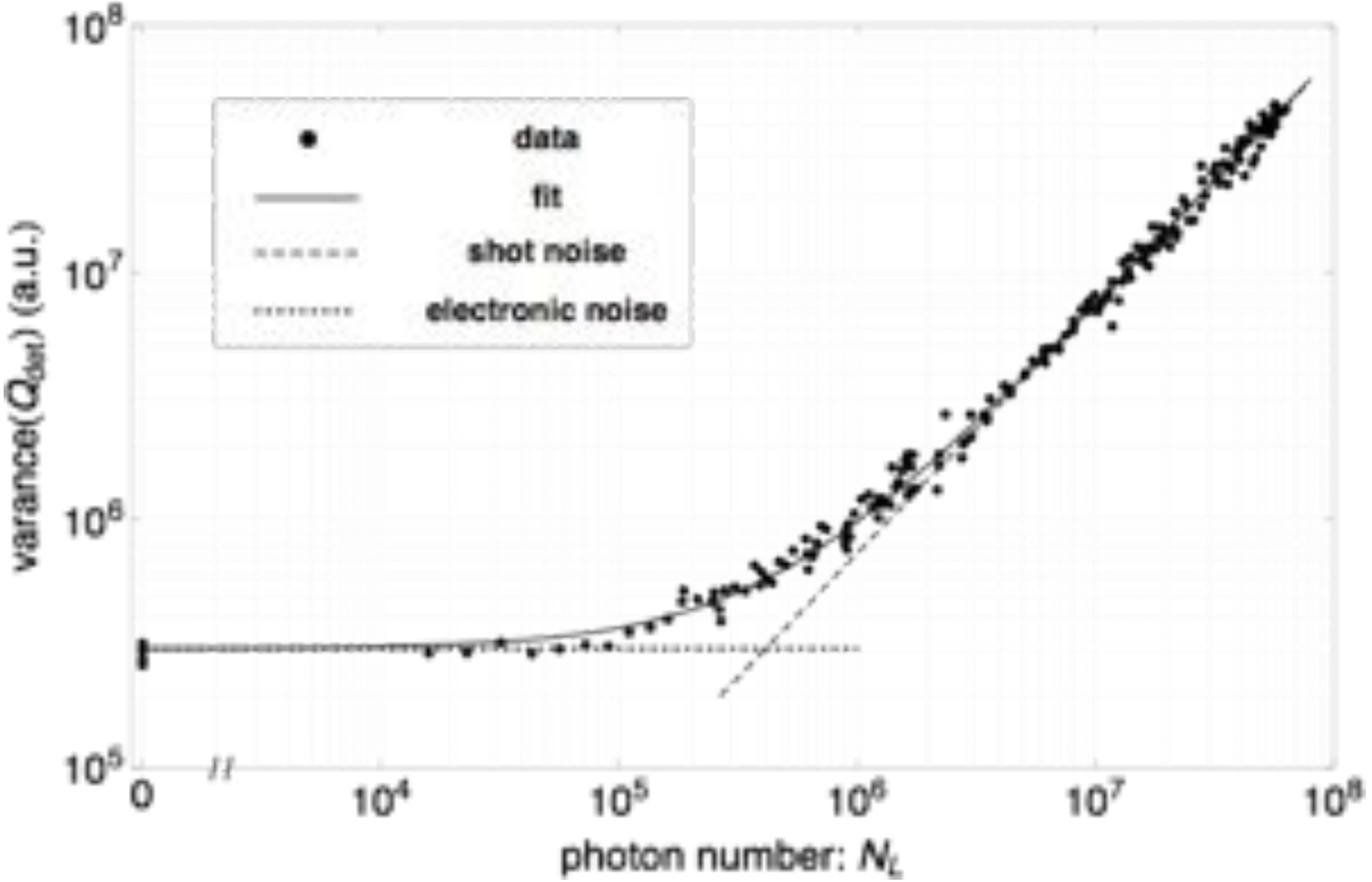
Calibration

$$\frac{\phi_{NL}}{\phi_L} = \frac{B(\Delta_0)}{A(\Delta_L)} \frac{N_L}{1 + N_L/N_L^{(\mathrm{sat})}}$$

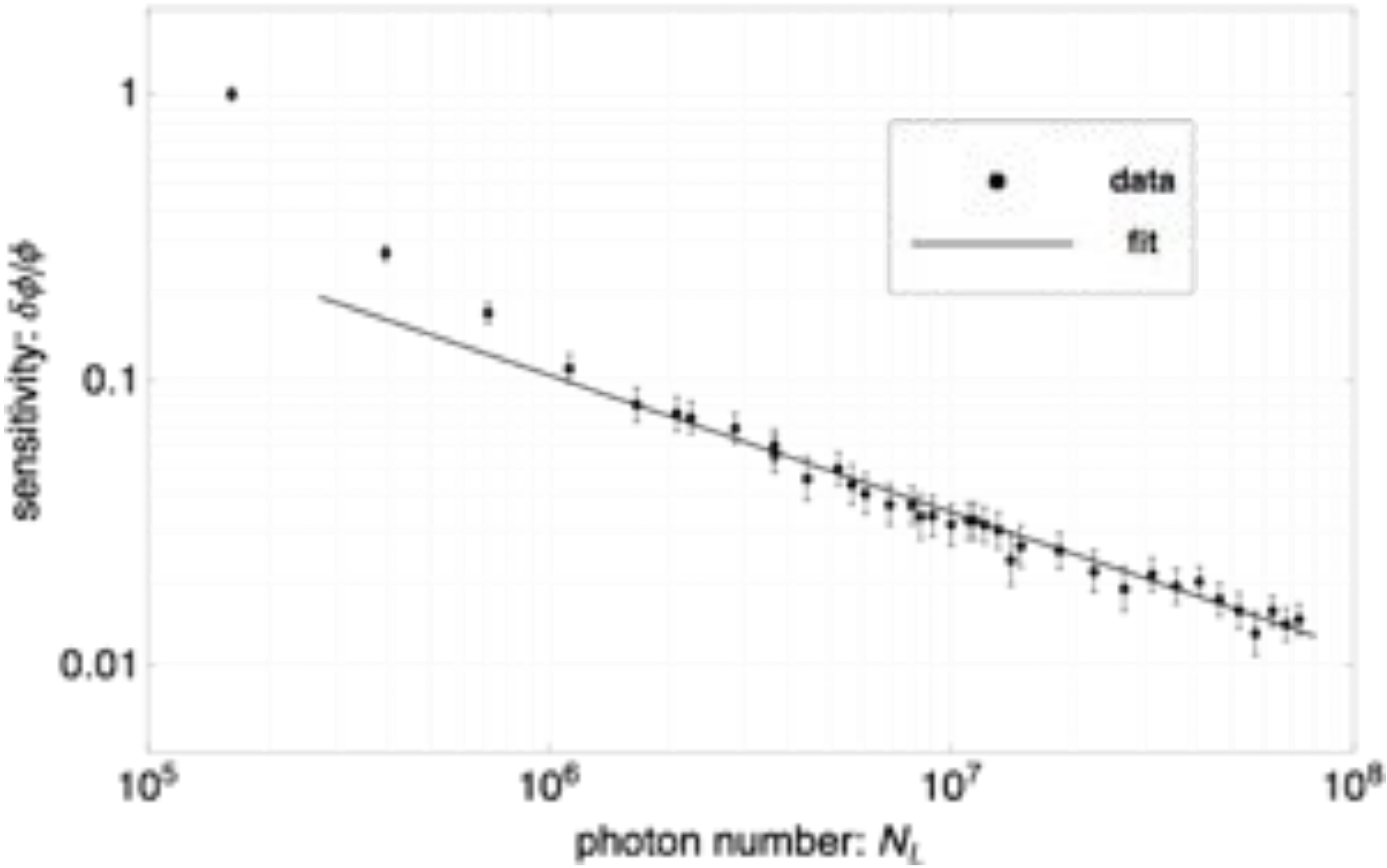
$$A(\Delta_L) = 3.1(1) \times 10^{-8}$$
$$B(\Delta_0) = 3.8(2) \times 10^{-16}$$
$$N_L^{(\mathrm{sat})} = 6.0(8) \times 10^{7}$$



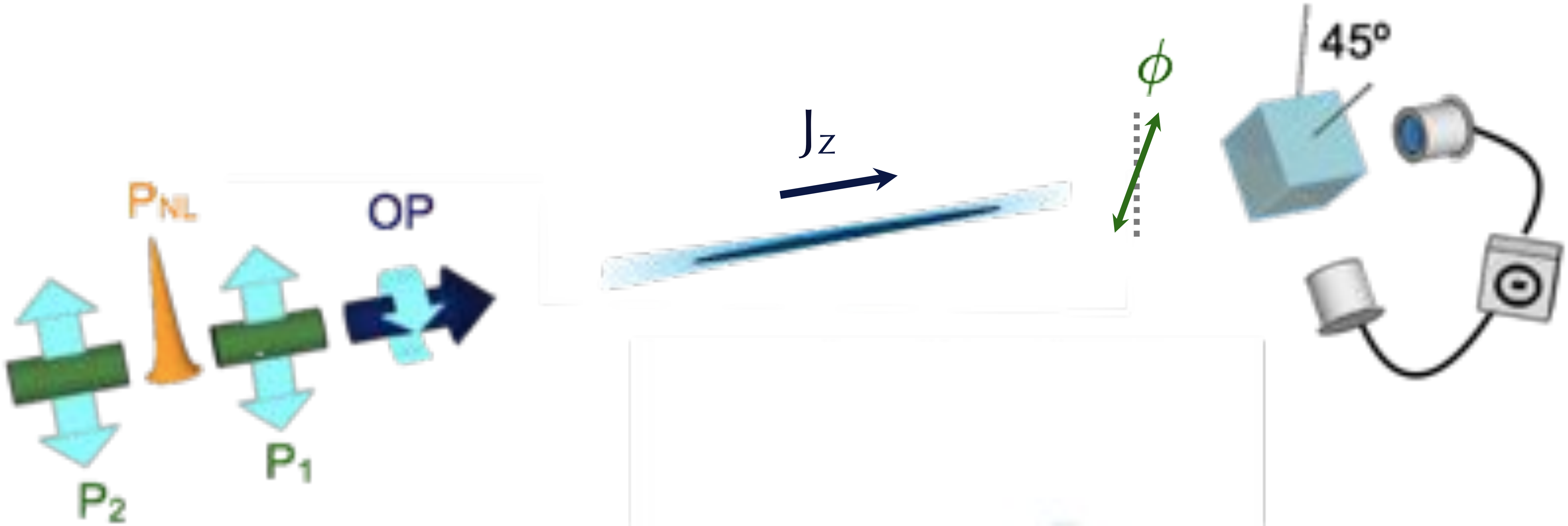
Shot-noise limited detection



Systematic linearity check



Effective Hamiltonian



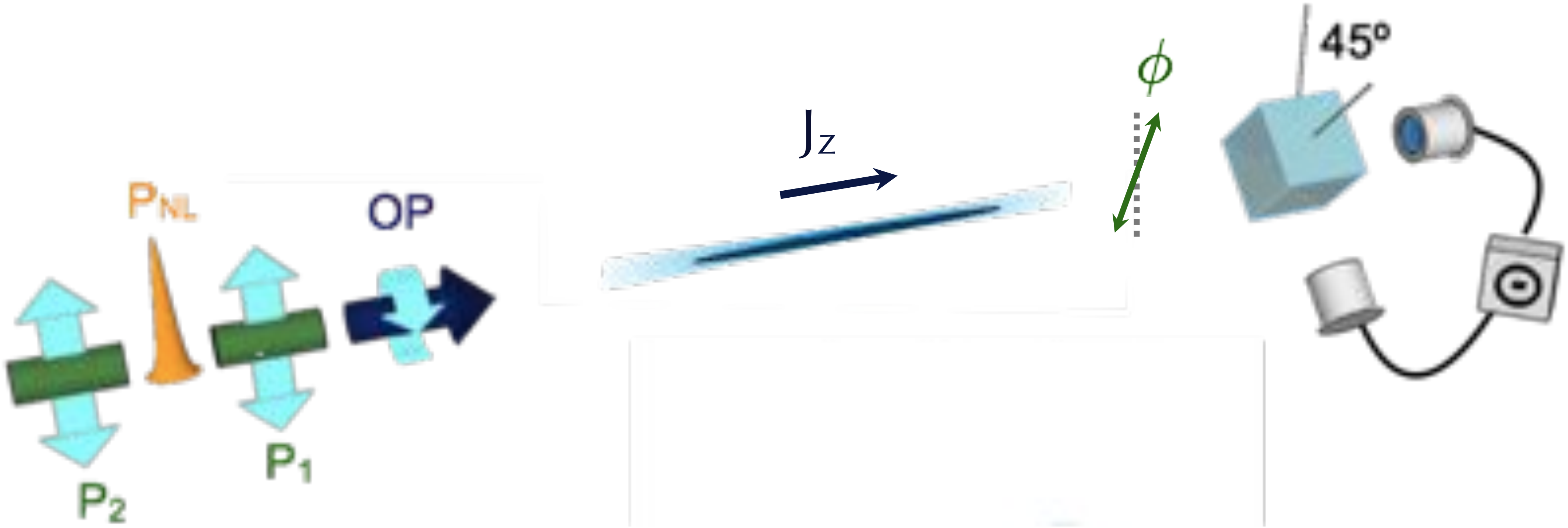
Pseudo-spin system

$$\mathbf{J} \equiv \sum_i \mathbf{j}^{(i)}$$

$$j_x \equiv \frac{1}{2}(f_x^2 - f_y^2) \qquad j_z \equiv \frac{1}{2} f_z$$

$$j_y \equiv \frac{1}{2}(f_x f_y + f_y f_x) \qquad j_0 \equiv \frac{1}{2}\frac{f_z^2}{2}$$

Effective Hamiltonian

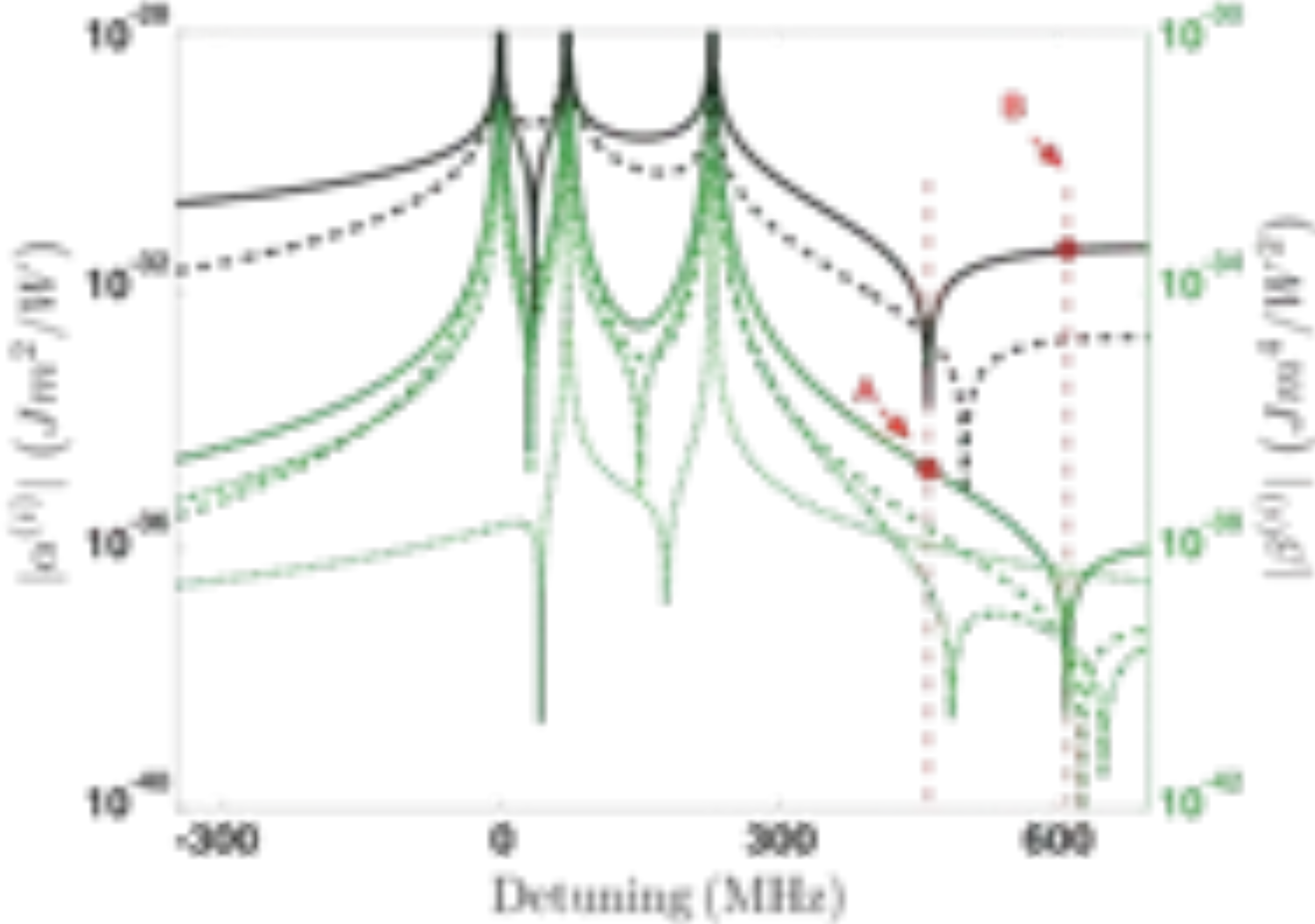


Full Hamiltonian

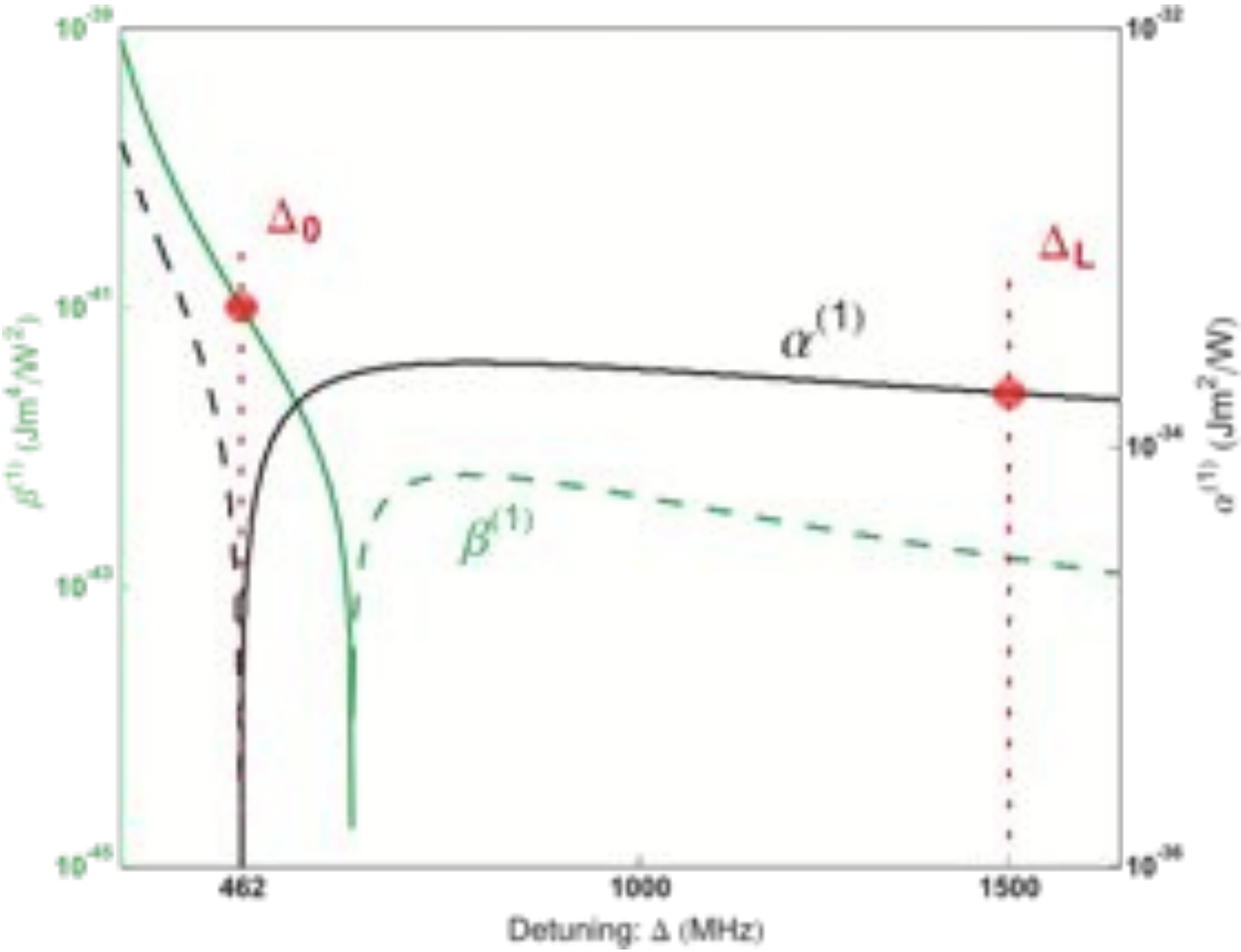
$$H_{\text{eff}}^{(2)} = \alpha^{(1)} S_z J_z + \alpha^{(2)} (S_x J_x + S_y J_y)$$

$$H_{\text{eff}}^{(4)} = \beta_J^{(0)} S_z^2 J_0 + \beta_N^{(0)} S_z^2 N_A$$
$$+ \beta^{(1)} S_0 S_z J_z + \beta^{(2)} S_0 (S_x J_x + S_y J_y)$$

Spectra of Hamiltonian terms



Experimental Working Point



Numerical Simulation