Ultra-sensitive atomic spin measurements with a nonlinear interferometer

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Mitchell Group

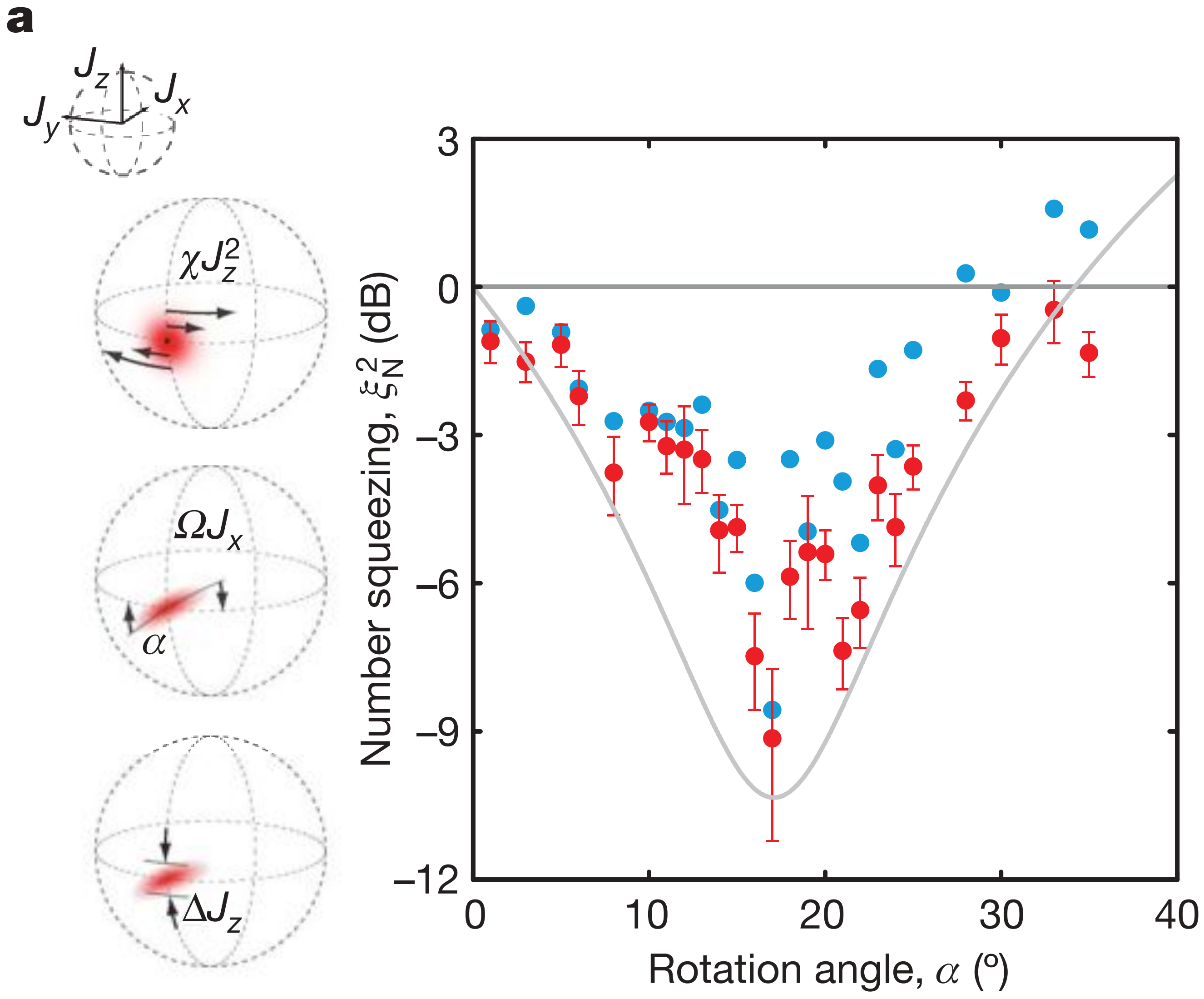
Berlin, 18 March 2014

Nonlinear interferometers

Matter-wave interferometer

atom-atom interactions
lead to nonlinear rotations
& spin squeezing

Gross, Nature 464, 1165 (2010)



Nonlinear interferometers

Nonlinear faraday rotation & optical magnetometry

nonlinear medium (atomic gas) gives rise to an enhanced rotation signal

Wojciechowski, PRA 81, 053420 (2010)

c.f. Budker group, Berkeley

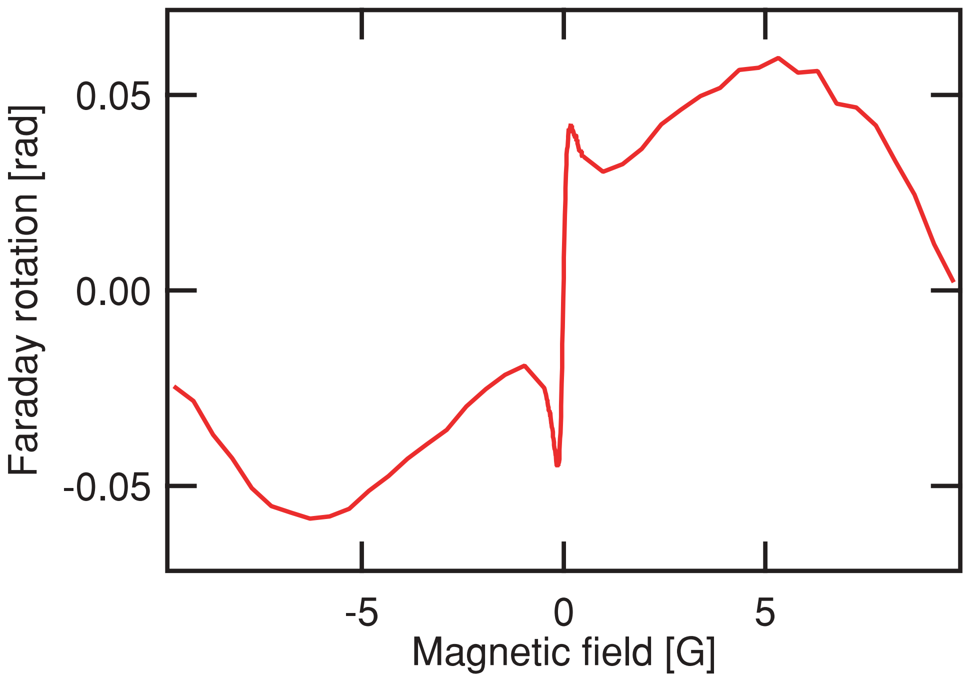
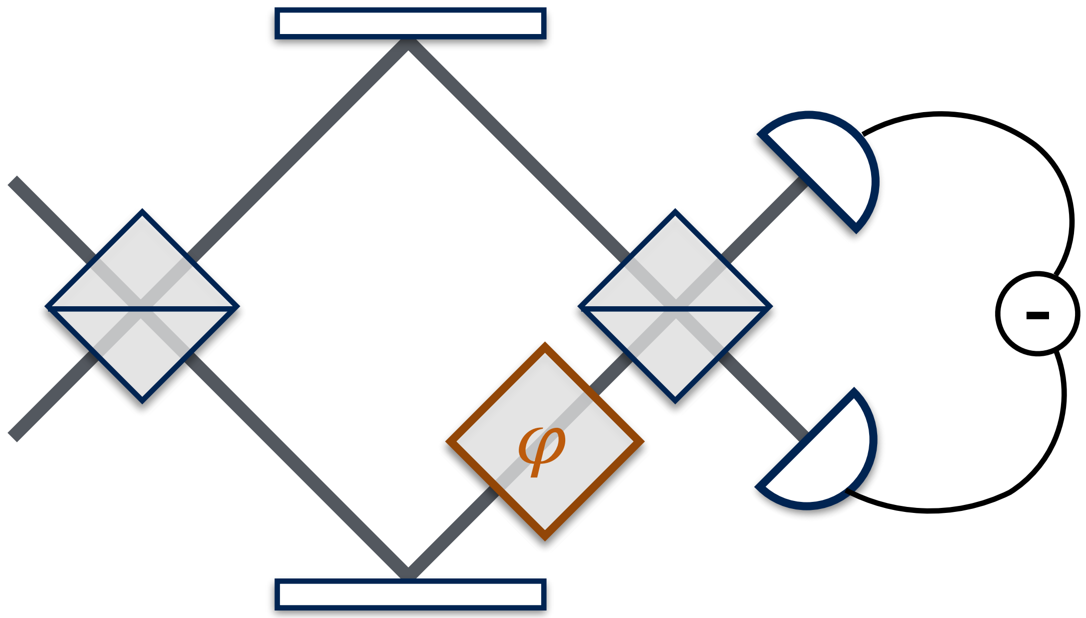
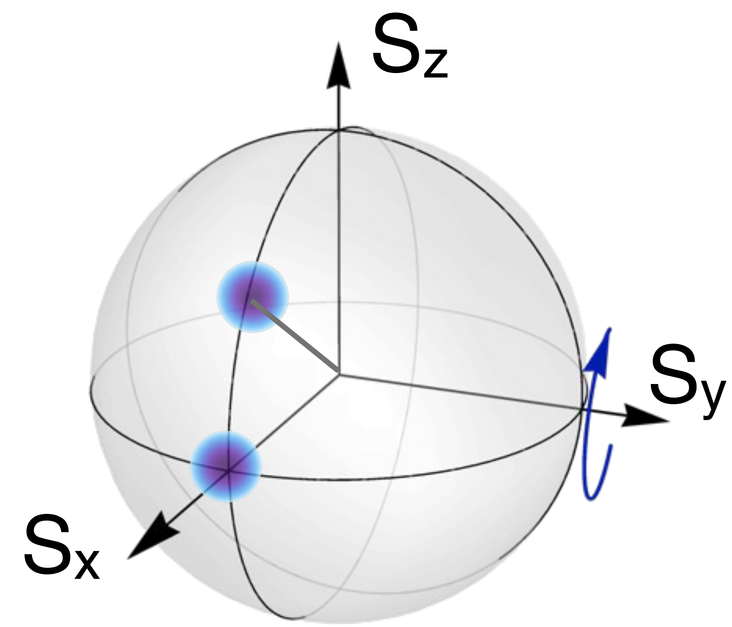


FIG. 2. (Color online) Linear (wide) and nonlinear (narrow) Faraday rotation resonances centered at $B = 0$. Signals were recorded at the time $\tau = 2$ ms after switching on the probing beam. The probe power is 64 μW. At that power the NFR resonance is substantially power broadened but is well visible in comparison with the LFR. The slope of the central part is $\approx$0,6 rad/G.

Linear interferometer





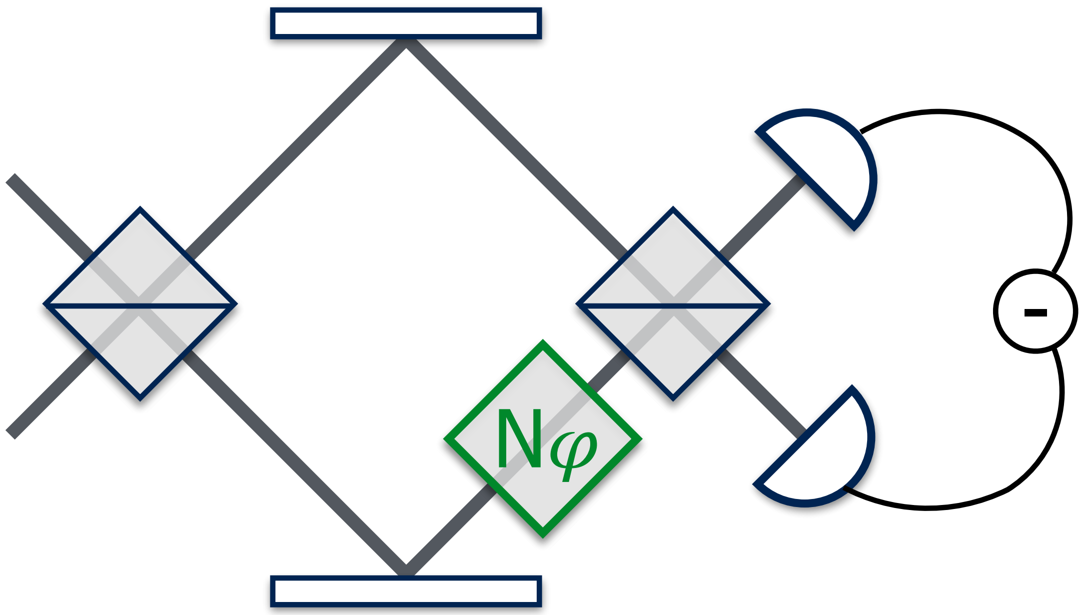
phase shift $\phi = \alpha J_y$

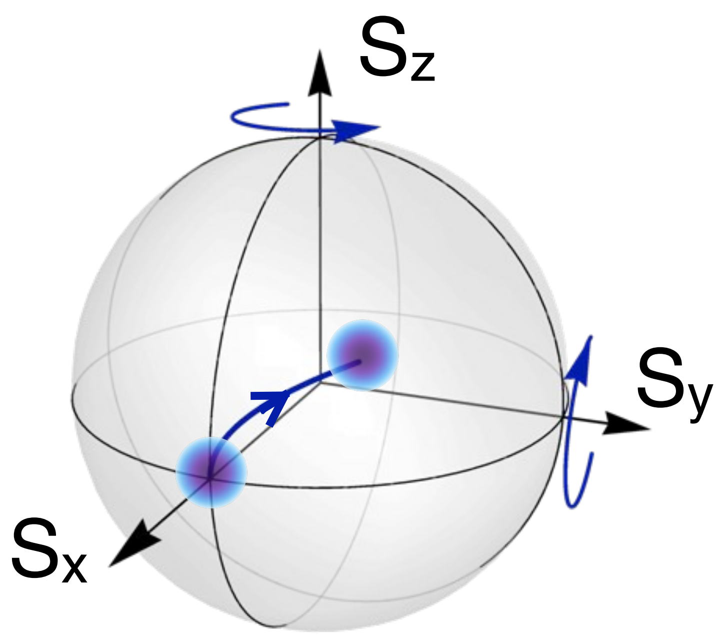
shot-noise $\Delta\phi = 1/\sqrt{N}$

sensitivity

$$\Delta J_y = \frac{\Delta\phi}{|\partial\phi/\partial J_y|} = \frac{1}{\alpha\sqrt{N}}$$

Nonlinear interferometer





phase shift $\phi = \beta N J_y$

shot-noise $\Delta\phi = 1/\sqrt{N}$

sensitivity

$$\Delta J_y = \frac{\Delta\phi}{|\partial\phi/\partial J_y|} = \frac{1}{\beta N^{3/2}}$$

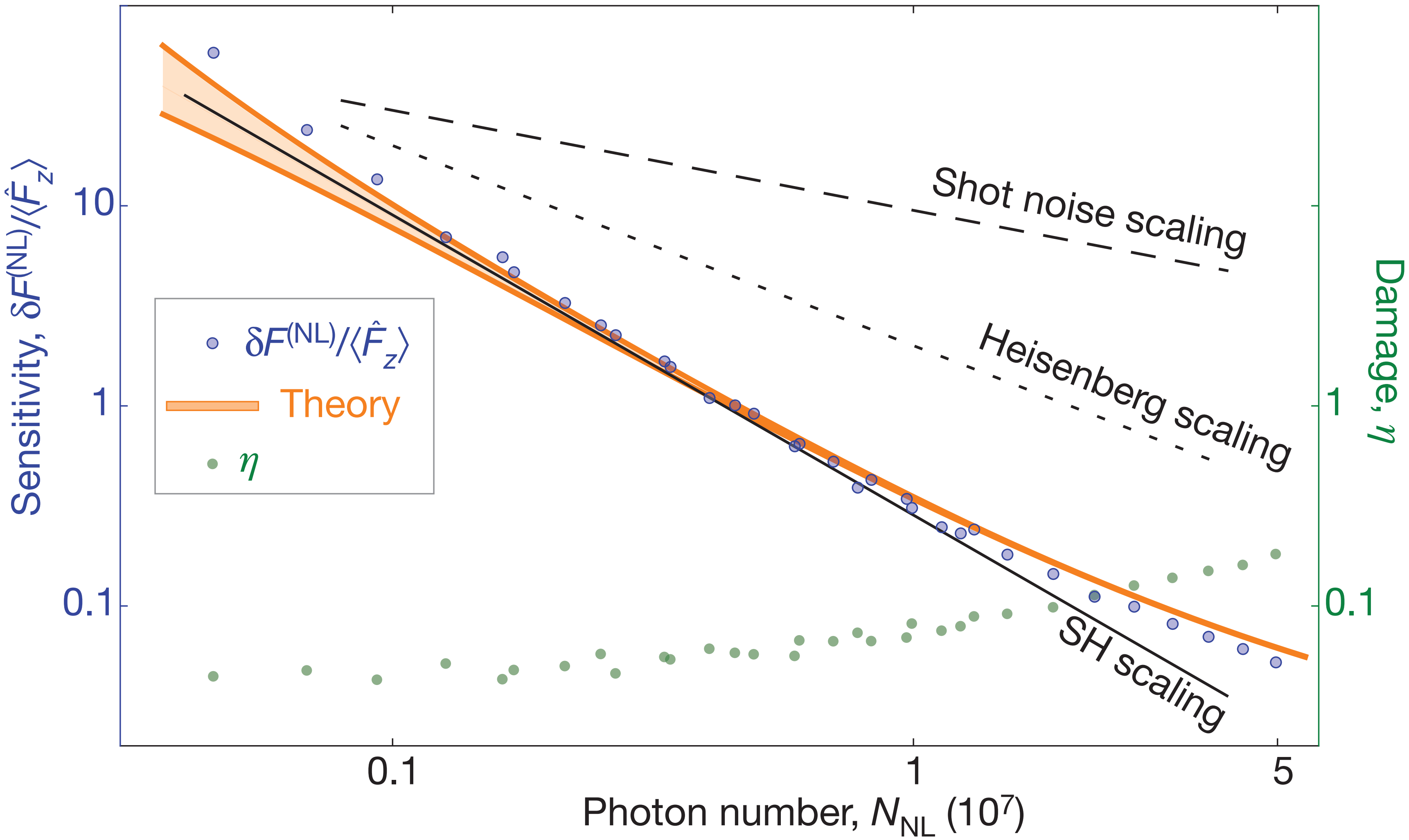
Can improved scaling give better sensitivity?

observed improved scaling

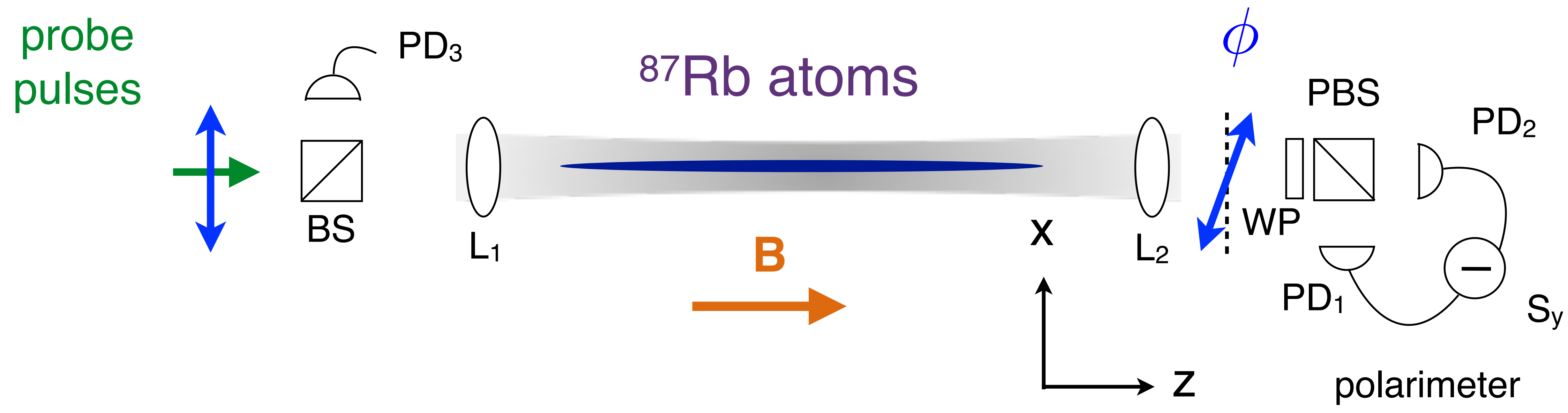
$$\Delta J \propto N^{-3/2}$$

did not continue to large N, nor give improved absolute sensitivity

Napolitano, Nature 486, 471 (2011)



Quantum atom-light interface



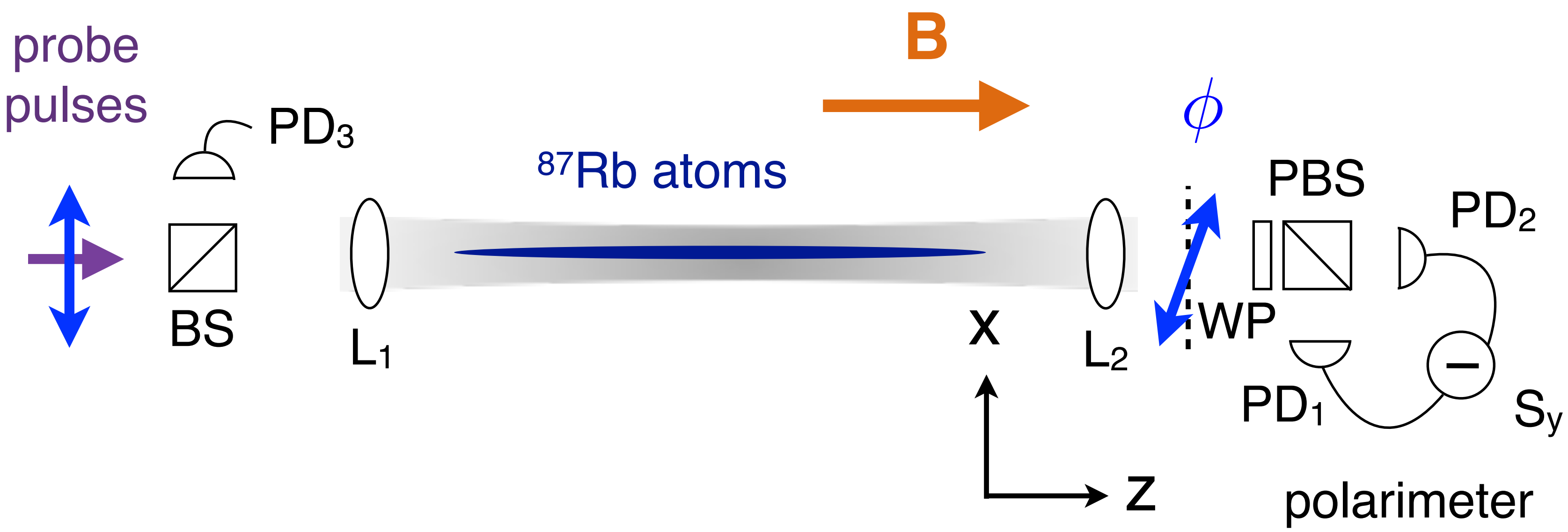
~10^6 ^{87}Rb atoms at 25μK
f=1 ground-state

1μs long pulses
linearly polarized
"mode matched" to atoms
0.7 GHz from D_2 line

[1] effective OD > 50
[2] Sensitivity 512 spins, < SQL
[3] QND measurement
[4] spin squeezing

1 Kubasik, et al. PRA 79, 043815 (2009)
2 Koschorreck, et al. PRL 104, 093602 (2010)
3 Koschorreck, et al. PRL 105, 093602(2010)
4 Sewell, et al. PRL 109, 253605 (2012)

Atom-light interaction



$$\tau H = G_1 S_z J_z + G_2 S_x J_x + \gamma B_z J_z$$

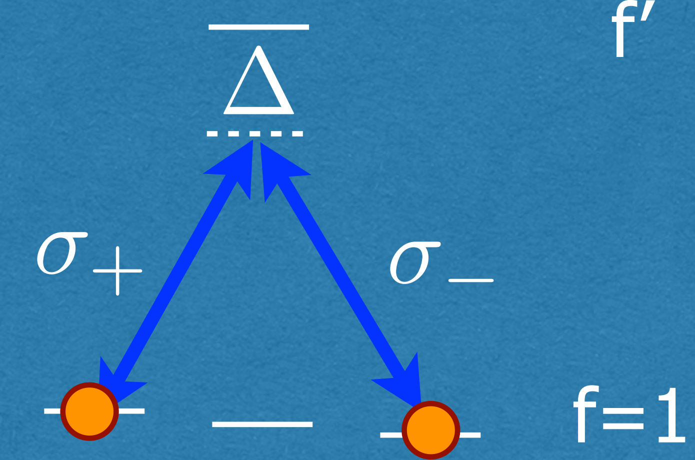
collective spin

$$J = \sum_{i=1}^{N_A} j^{(i)}$$

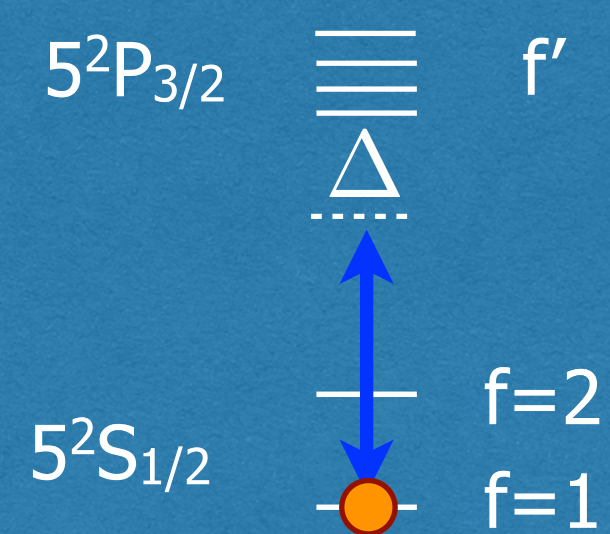
Stokes operators

$$S \equiv \sum_{i=1}^{N_L} s^{(i)}$$

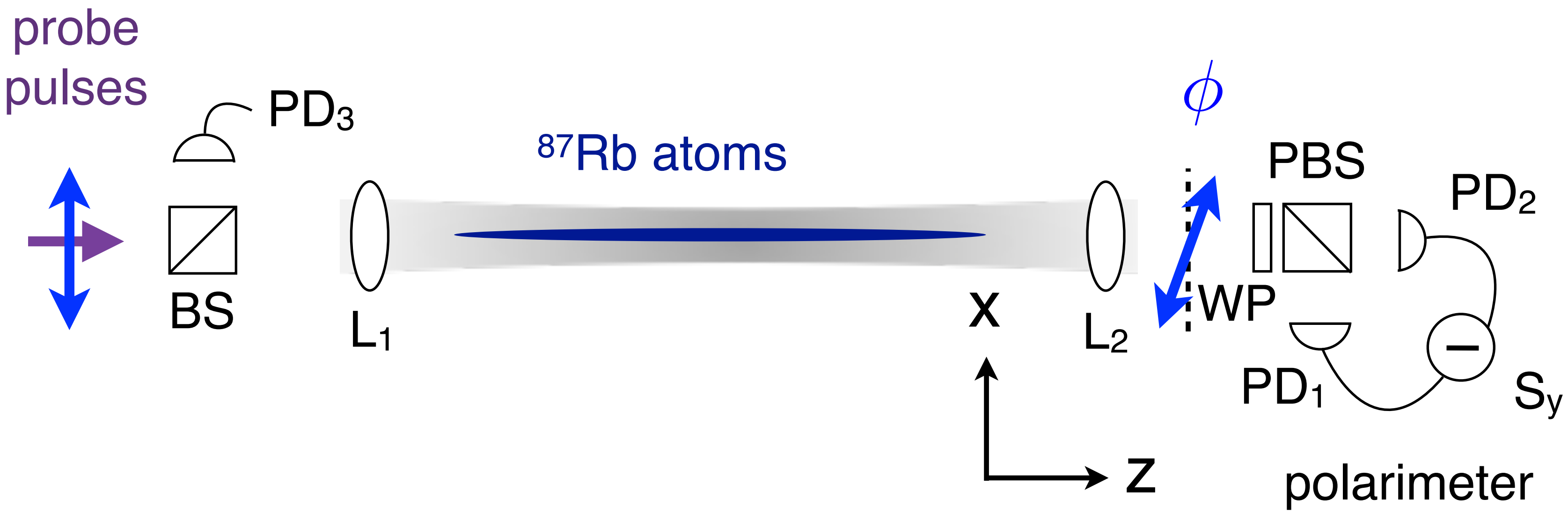
pseudo-spin



^{87}Rb D$_2$ line



Atom-light interaction



$$\tau H = G_1 S_z J_z + G_2 S_x J_x + \gamma B_z J_z$$

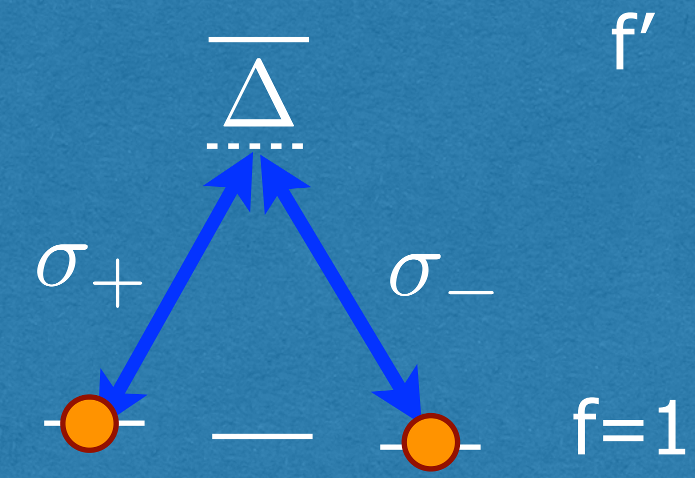
Faraday rotation

$$\phi = G_1 S_x J_z$$

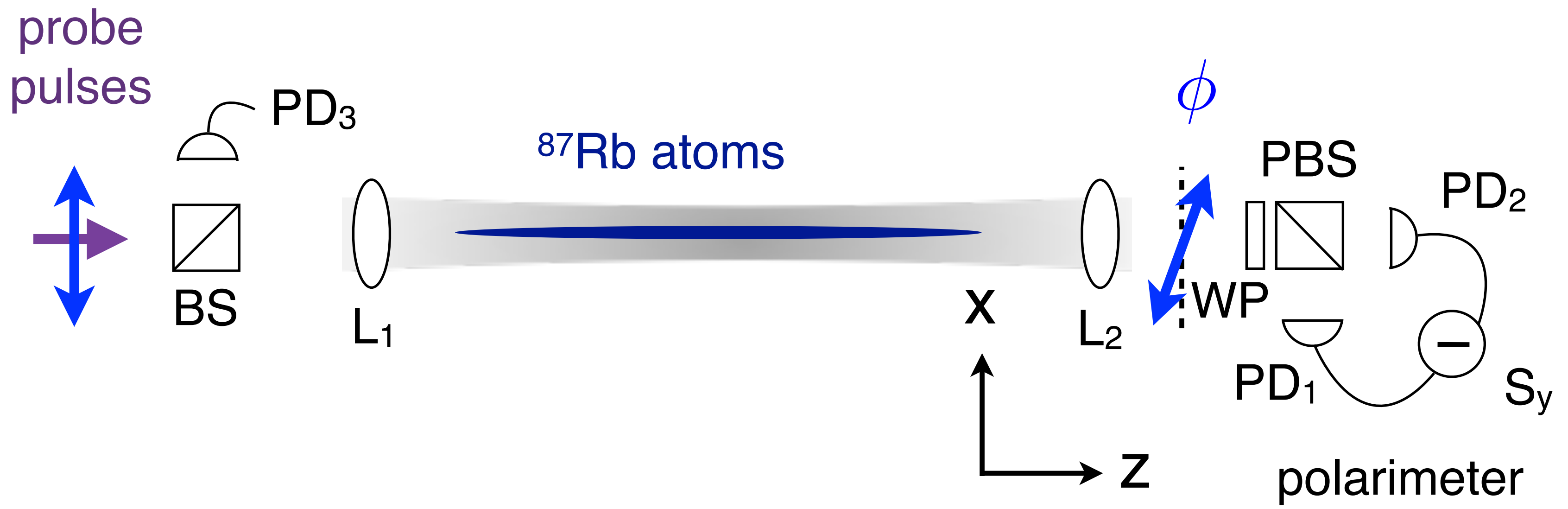
Larmor precession

$$J_y = \gamma B_z J_x$$

pseudo-spin



Atom-light interaction

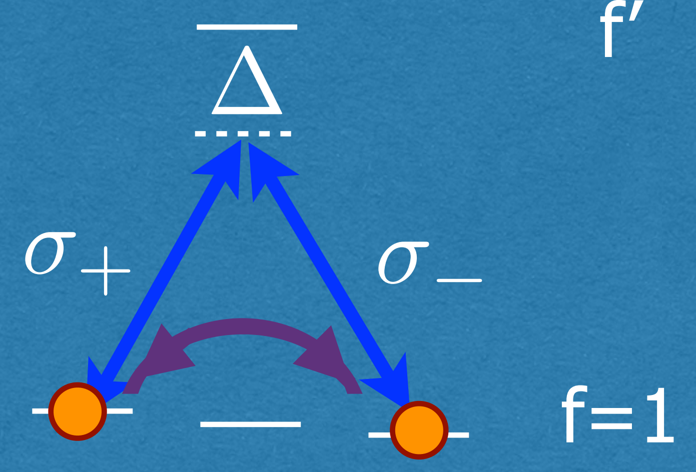


$$\tau H = G_1 S_z J_z + G_2 S_x J_x + \gamma B_z J_z$$

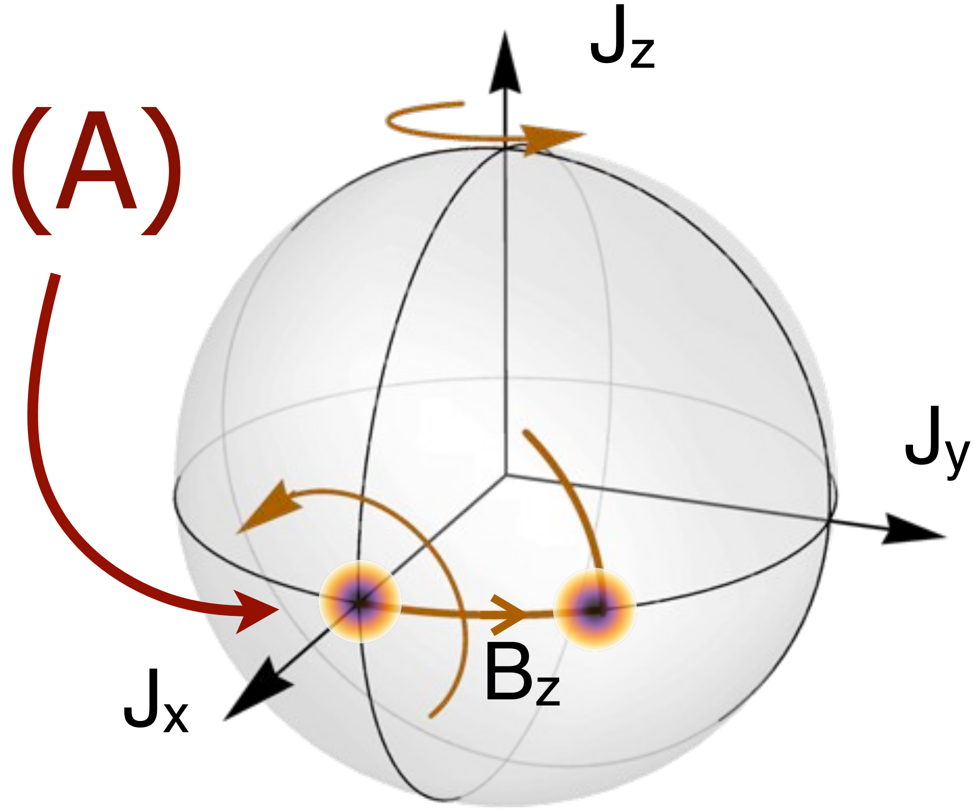
atomic birefringence

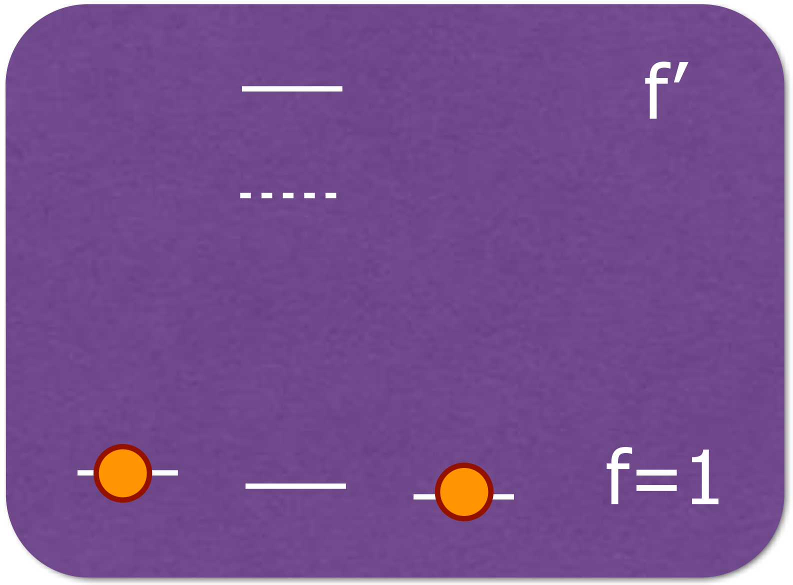
Raman transitions

pseudo-spin



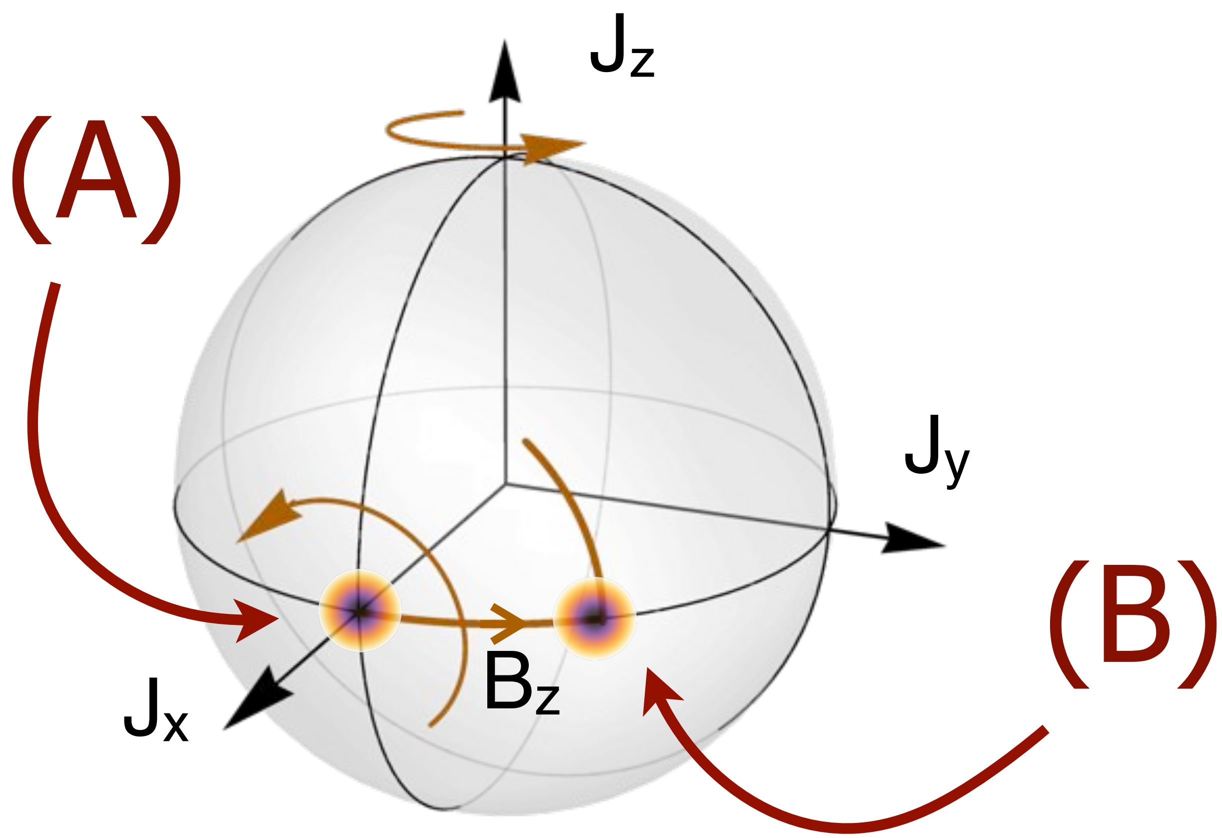
Atomic state

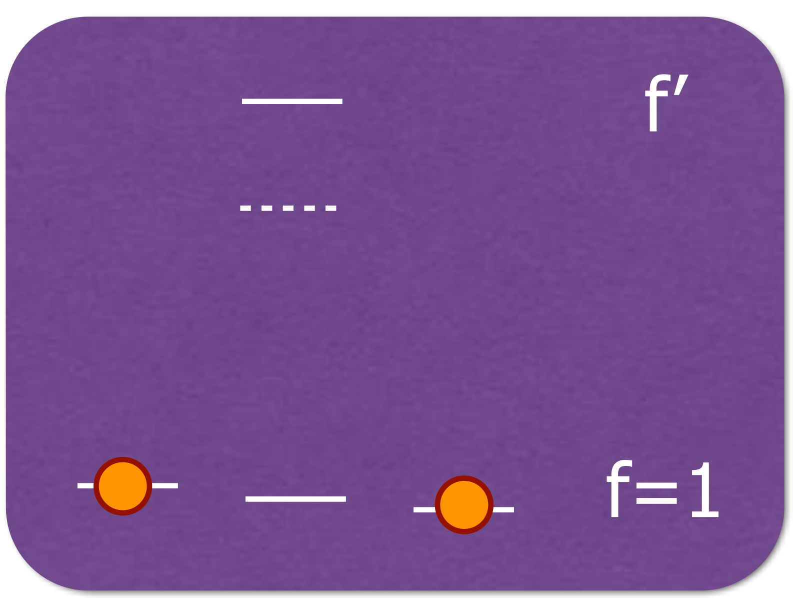




(A) input $J_x = N_A/2$ aligned state prepared via optical pumping

Atomic state rotates due to B-field



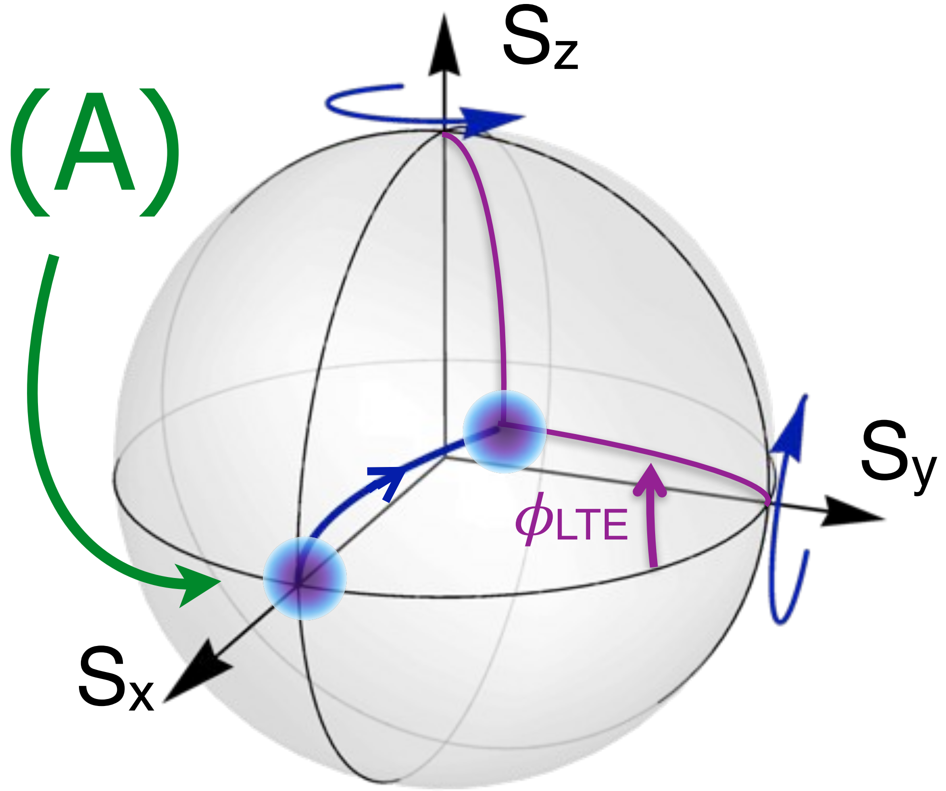


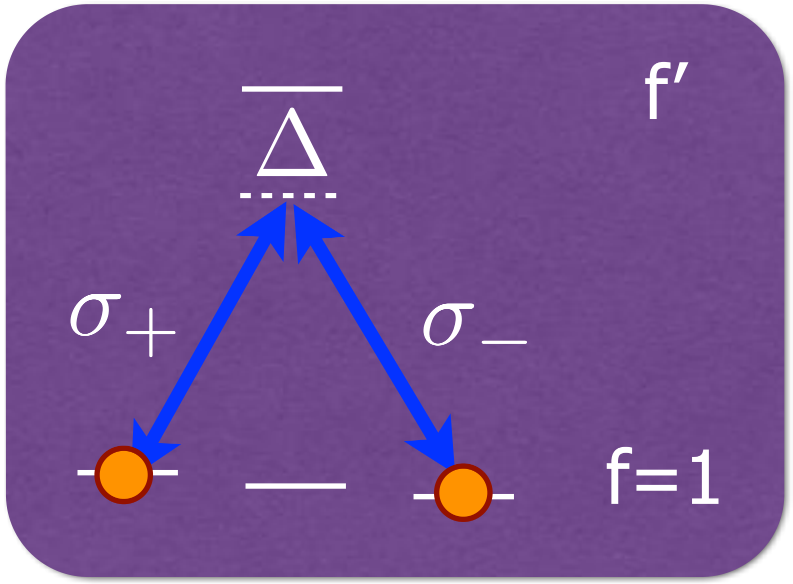
(A) input $J_x = N_A/2$ aligned state prepared via optical pumping

(B) B_z rotates collective atomic spin

$J_x \Rightarrow J_y \propto B_z$

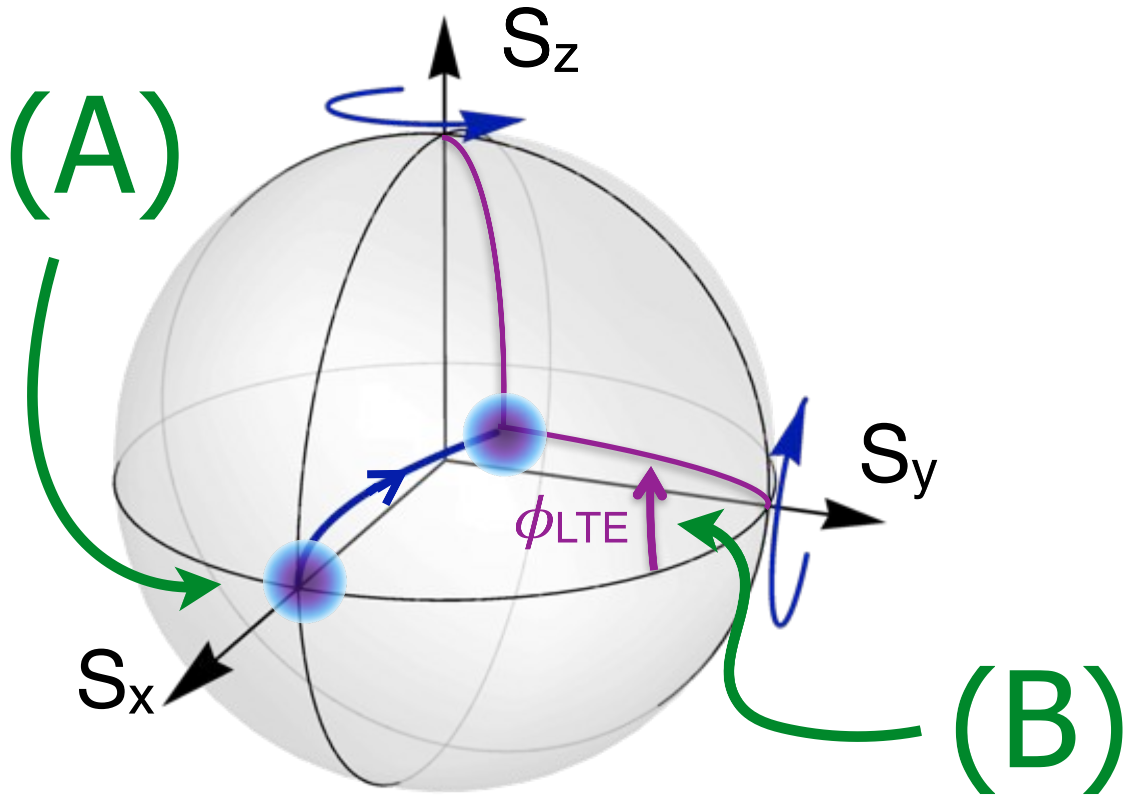
Read-out via optical birefringence

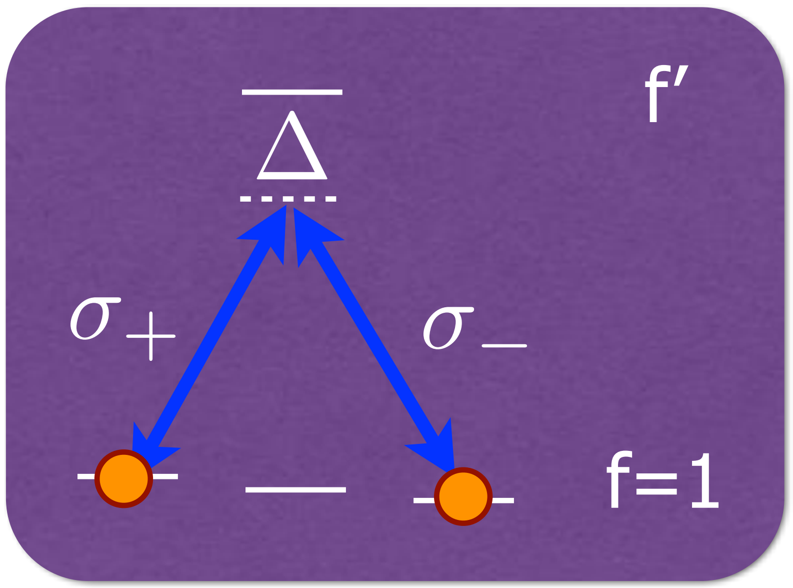




(A) input $S_x=N_L/2$ polarised optical pulse

Read-out via optical birefringence



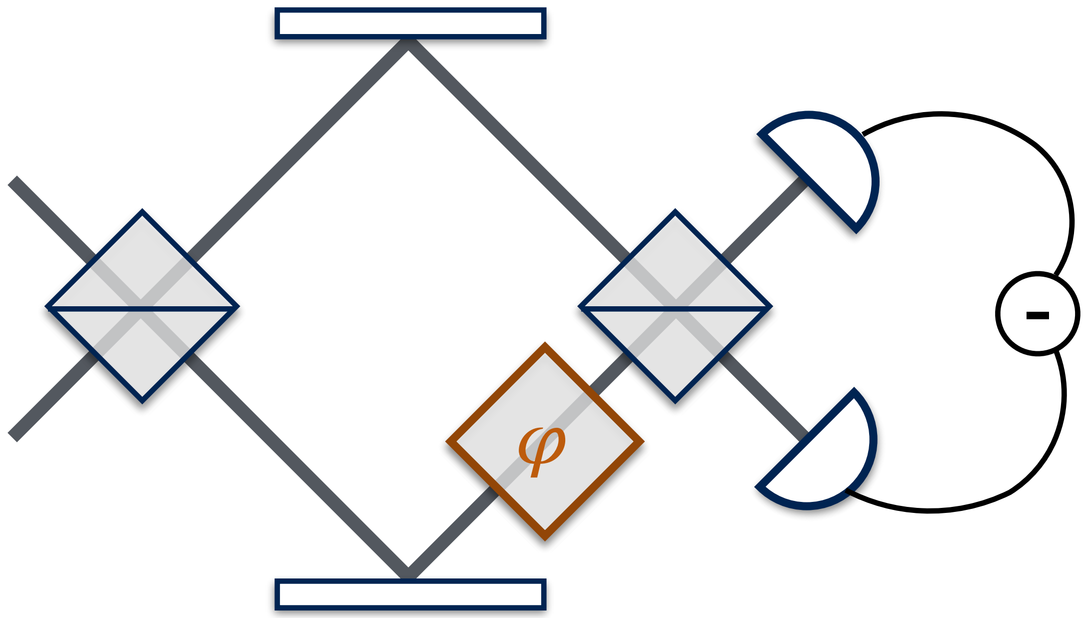


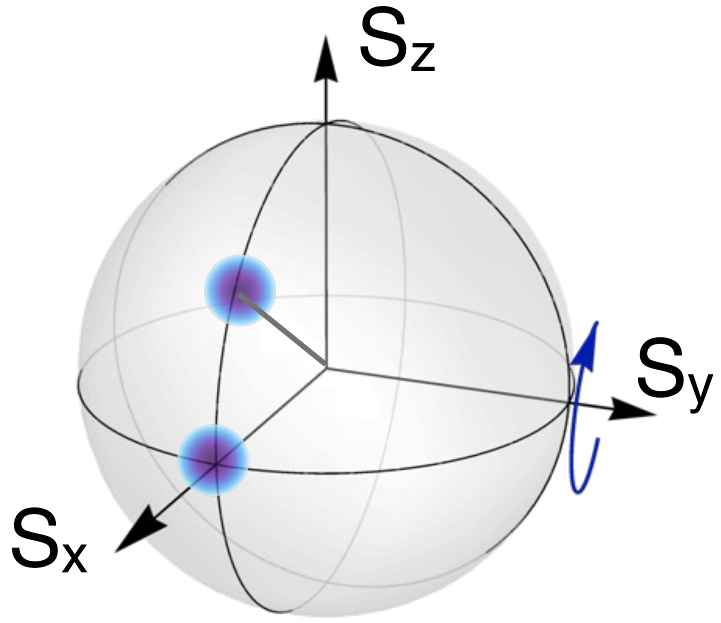
(A) input $S_x = N_L/2$ polarised optical pulse

(B) rotates $S_x \Rightarrow S_z \propto J_y$

(atomic birefringence)

Linear interferometer





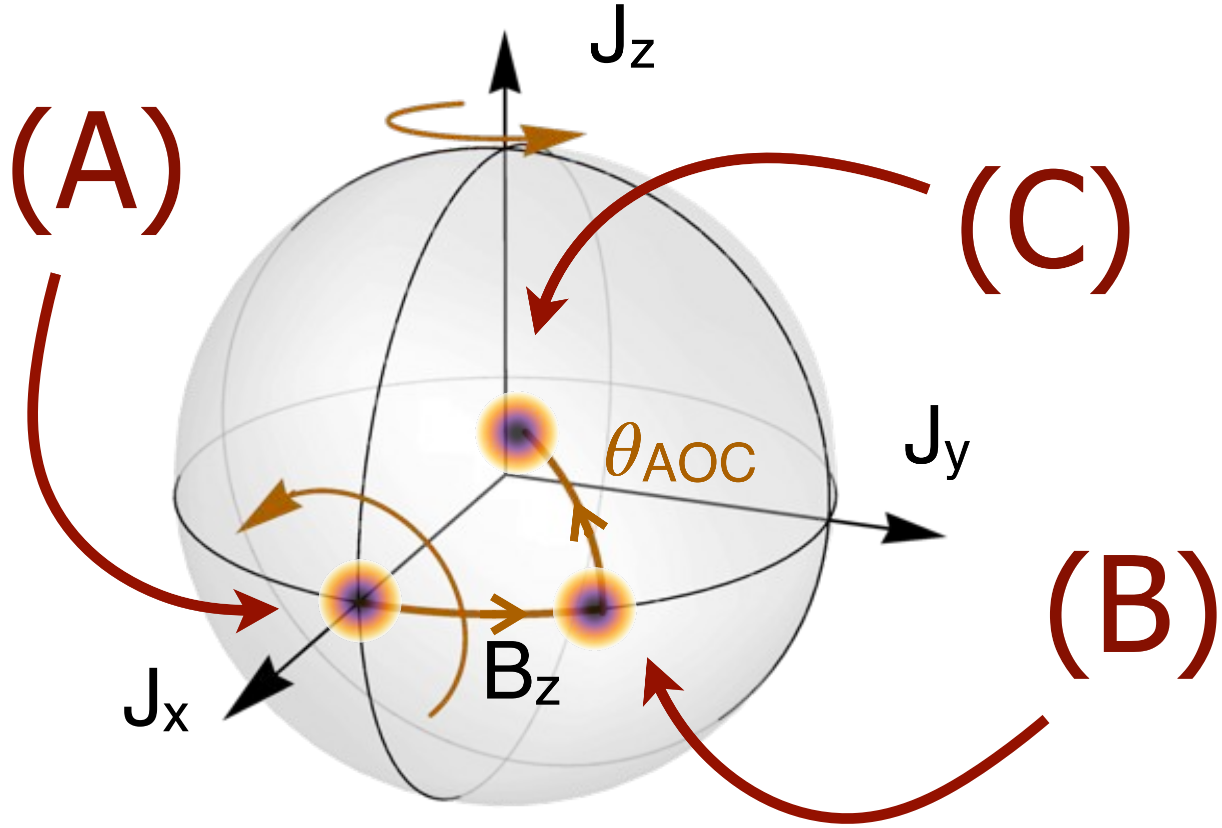
phase shift $\phi = G_2 J_y$

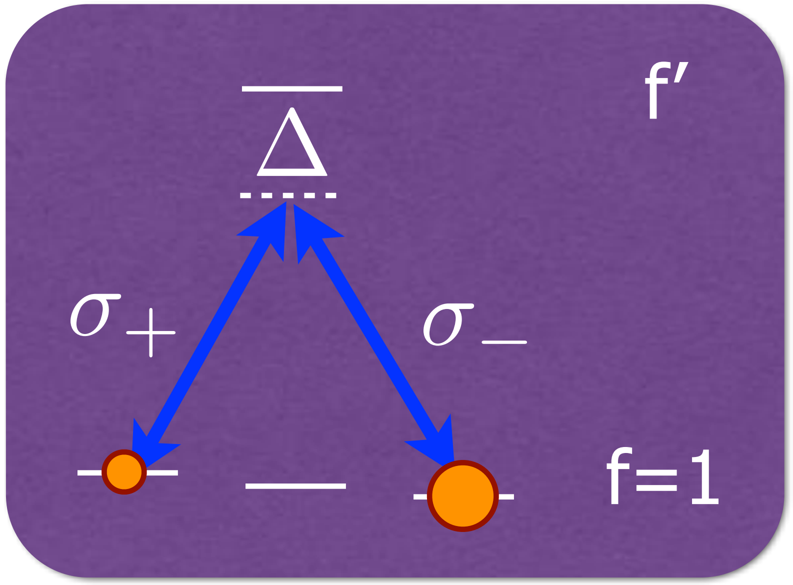
shot-noise $\Delta\phi = 4/\sqrt{N}$

sensitivity

$$\Delta J_y = \frac{4}{G_2}\frac{1}{\sqrt{N}}$$

Alignment-to-orientation conversion



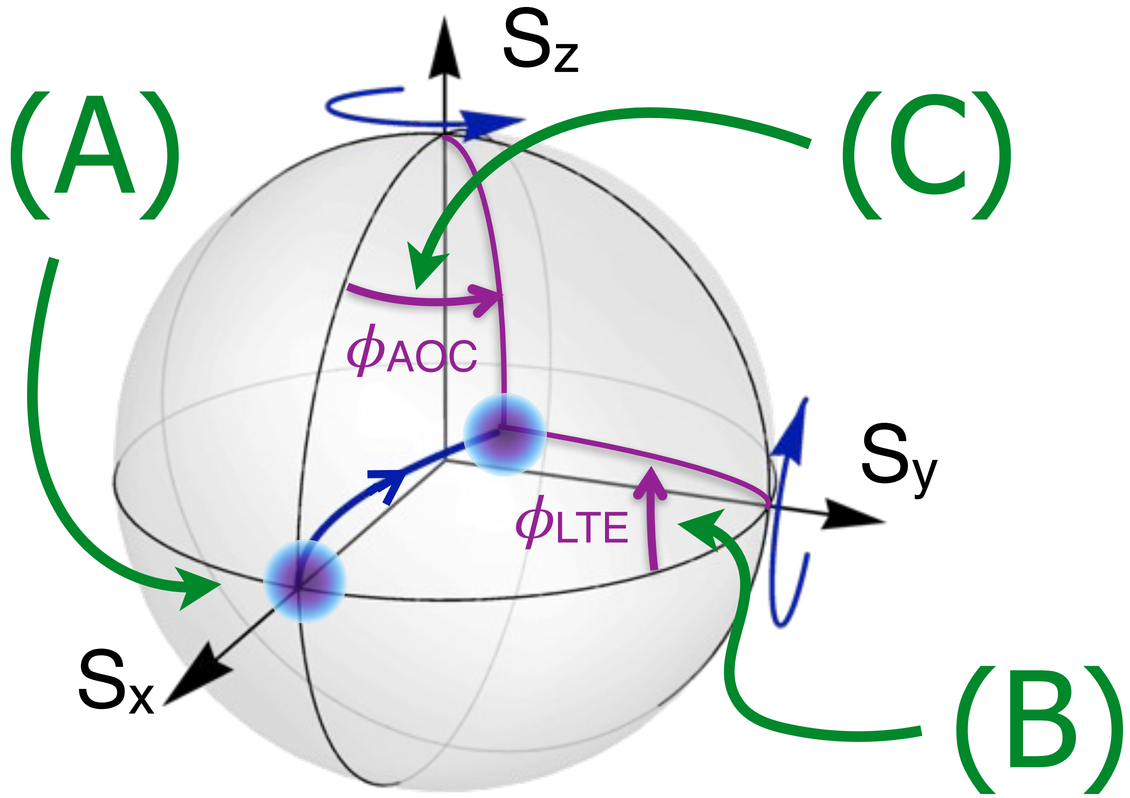


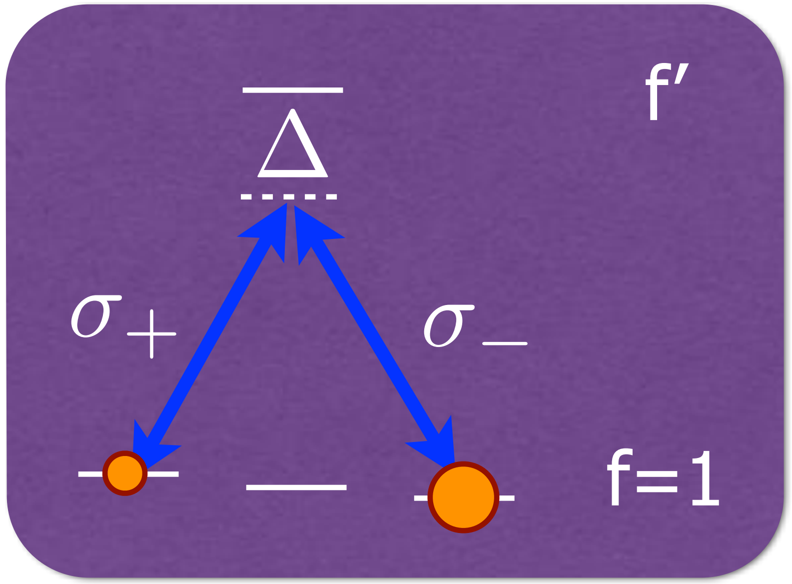
(A) input $J_x = N_A/2$ aligned state prepared via optical pumping

(B) B_z rotates collective atomic spin $J_x \Rightarrow J_y \propto B_z$

(C) probe pulses drive Raman transition $J_y \Rightarrow J_z \propto S_x$

Nonlinear Faraday rotation





(A) input $S_x = N_L/2$ polarised optical pulse

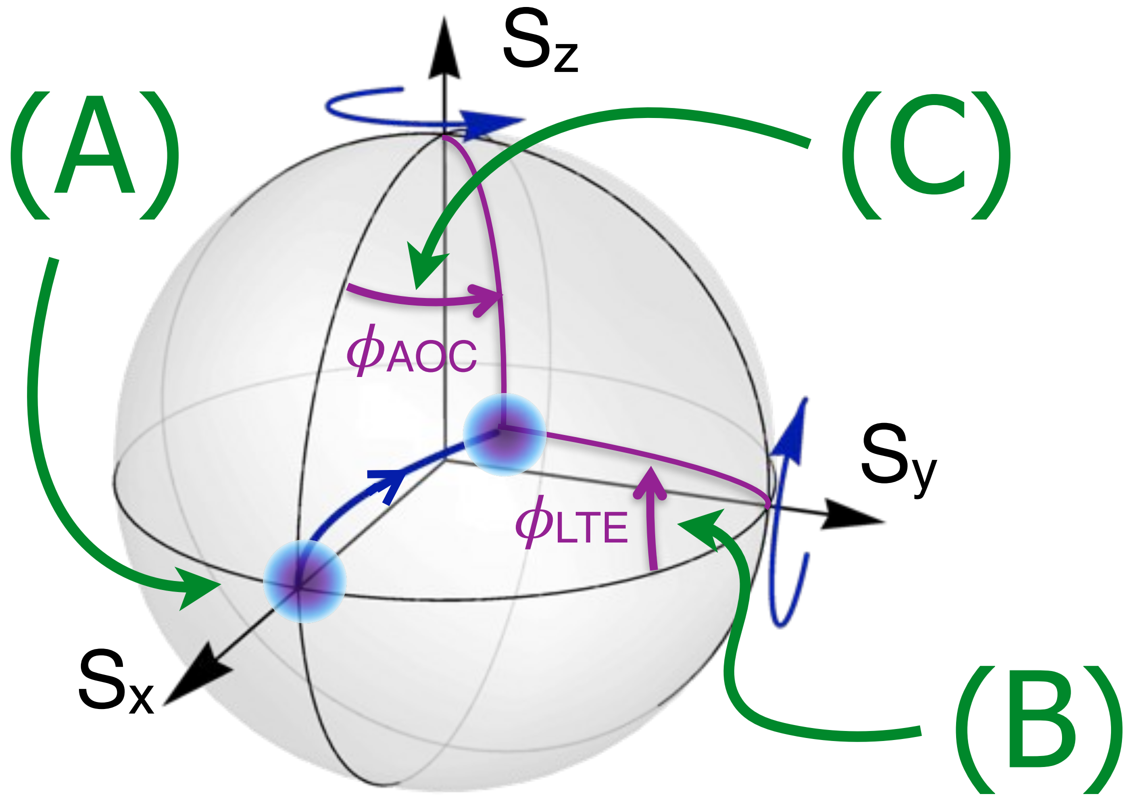
(B) rotates $S_x \Rightarrow S_z \propto J_y$

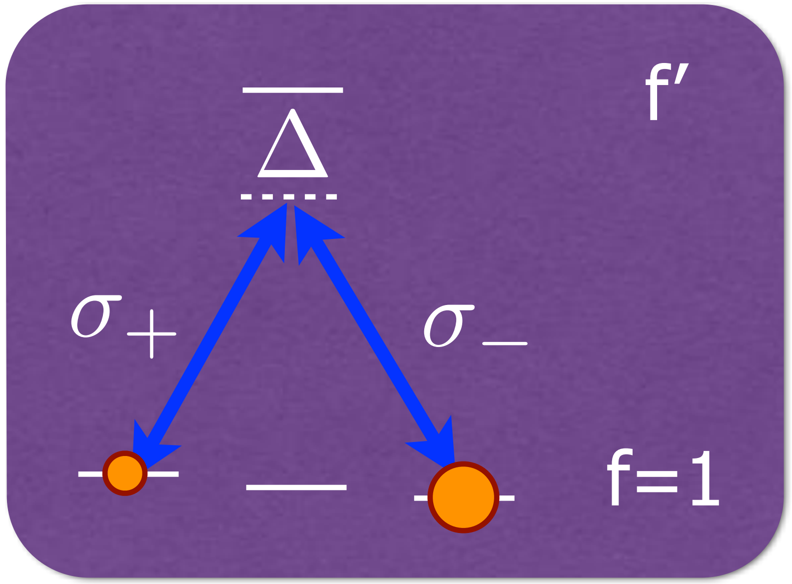
(atomic birefringence)

(C) rotates $S_x \Rightarrow S_y \propto J_z$

(Faraday rotation)

Nonlinear Faraday rotation





$J_y \Rightarrow J_z \propto S_x$

(A) input $S_x = N_L/2$ polarised optical pulse

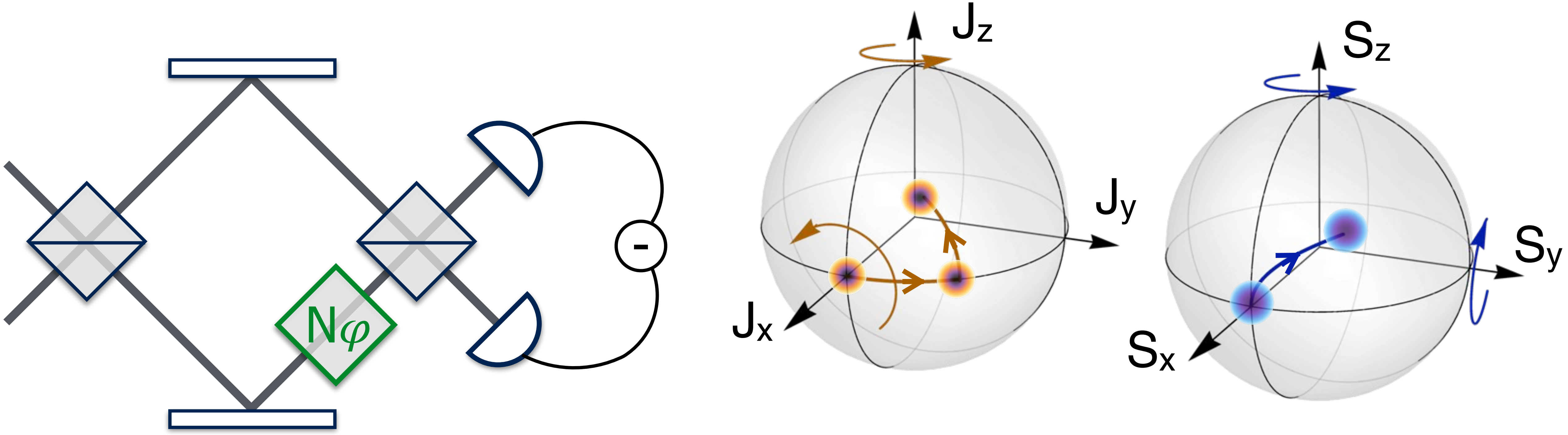
(B) rotates $S_x \Rightarrow S_z \propto J_y$

(atomic birefringence)

(C) rotates $S_x \Rightarrow S_y \propto J_z$

(Faraday rotation)

Nonlinear interferometer



phase shift $\phi = \frac{G_1 G_2}{4} N J_y$

shot-noise $\Delta\phi = 4/\sqrt{N}$

sensitivity

$$\Delta J_y = \frac{4}{G_1 G_2} \frac{1}{N^{3/2}}$$

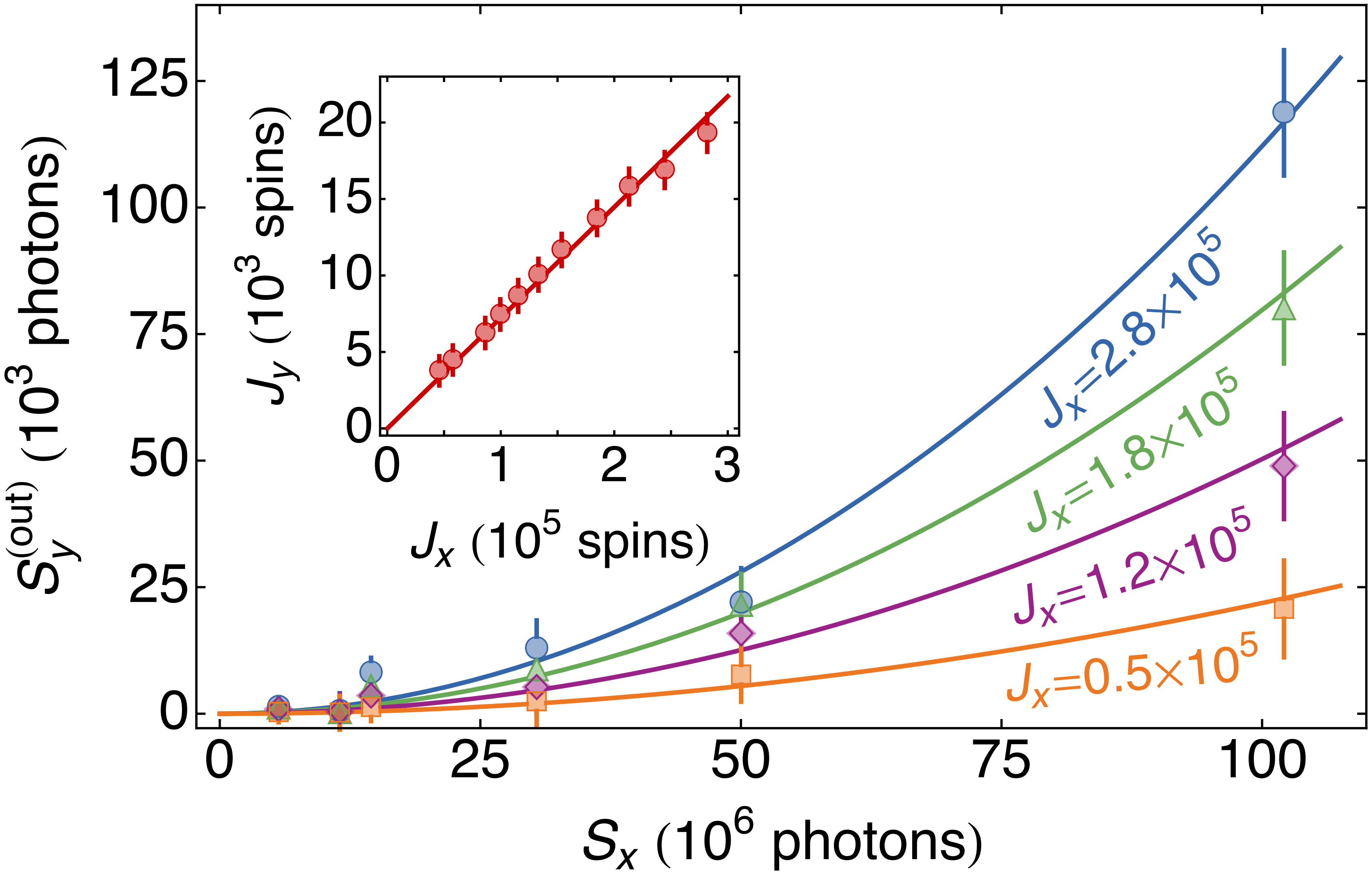
Nonlinear signal enhancement

signal from nonlinear Faraday rotation

$$S_y = \frac{G_1 G_2}{2} S_x^2 J_y$$

magnetometer read-out

$$J_y \propto B_z$$



Measurement sensitivity

sensitivity

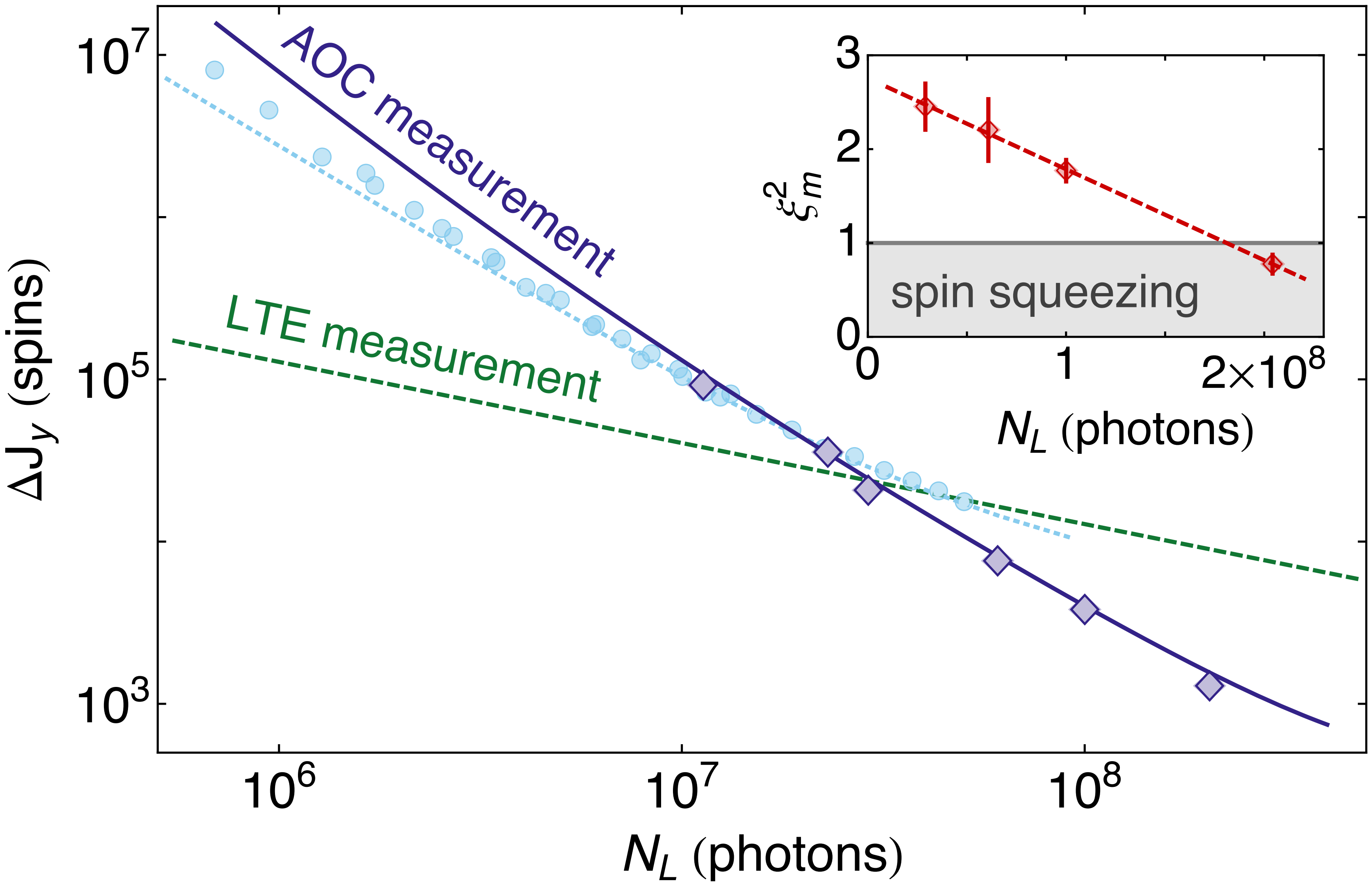
$$\Delta J_y = \frac{4}{G_1 G_2} \frac{1}{N^{3/2}}$$

$$\Delta J_y \simeq 10^3 \text{spins}$$

spin squeezing

$$\xi^2 = \frac{(\Delta K_\theta)^2 J_x}{2|J_x^{(\text{out})}|^2}$$

$$= 0.7$$



Measurement sensitivity

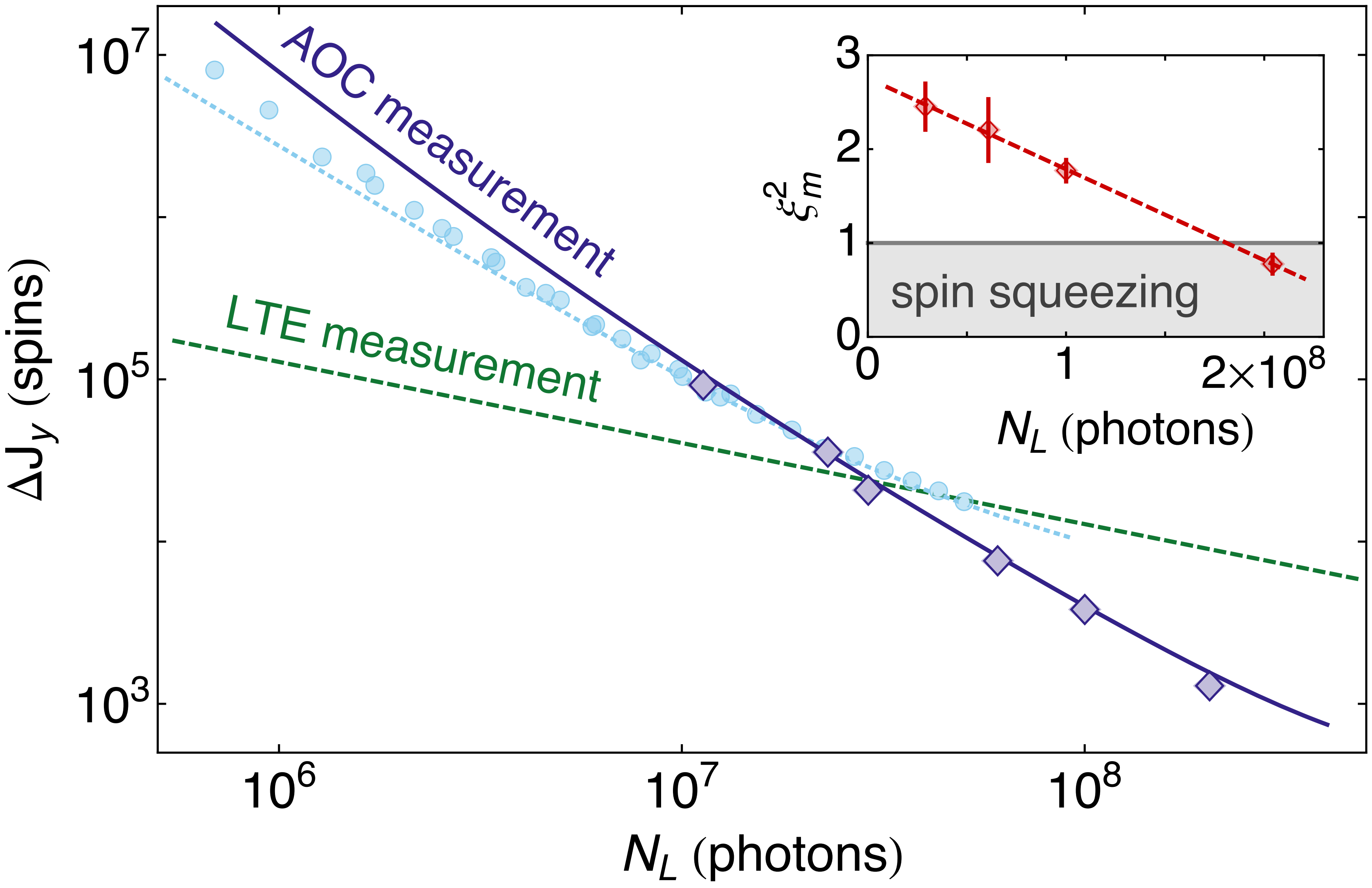
nonlinear read-out sensitivity

$$\Delta J_y = \frac{4}{G_1 G_2} \frac{1}{N^{3/2}}$$

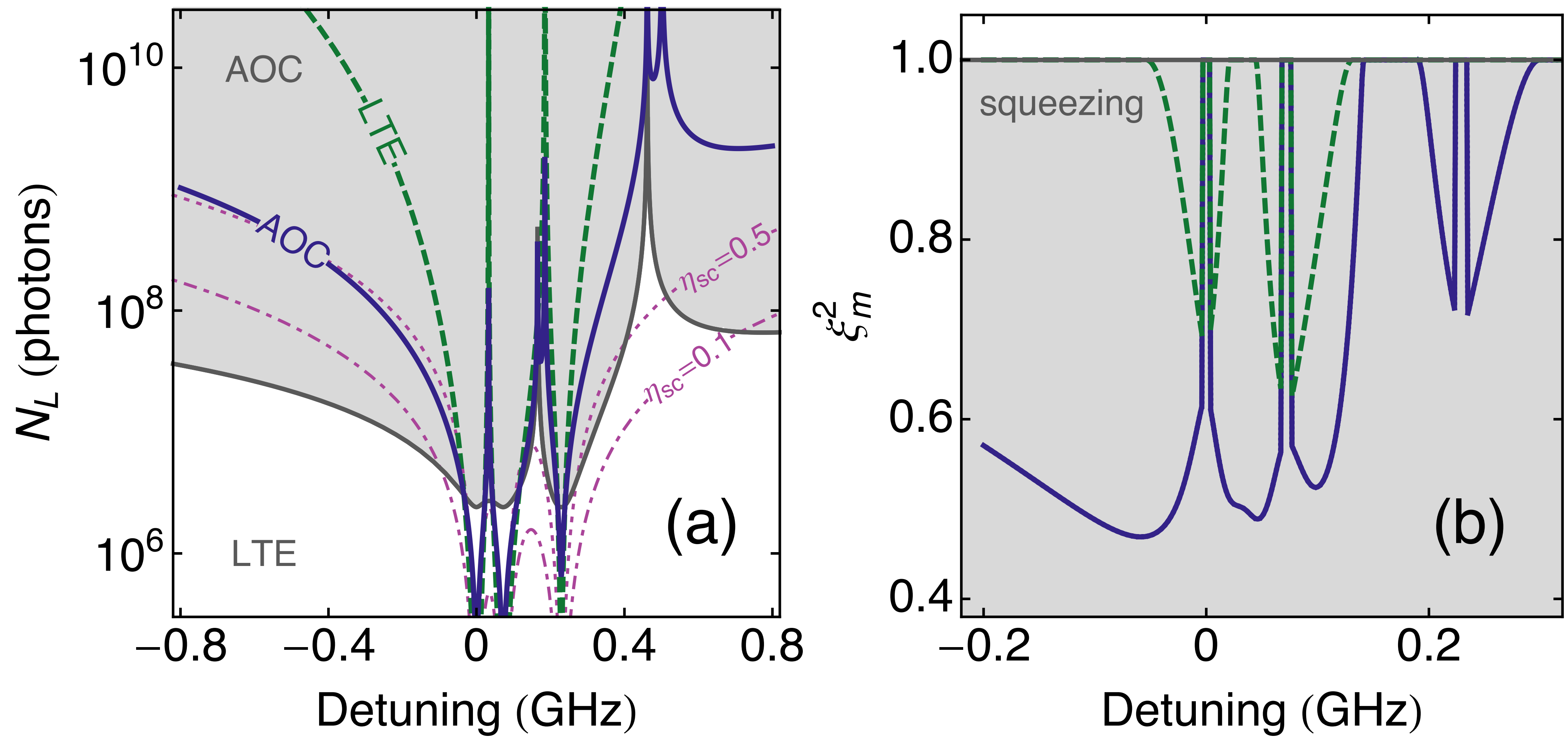
linear read-out sensitivity

$$\Delta J_y = \frac{4}{G_2} \frac{1}{\sqrt{N}}$$

crossover with N=3×10⁷ photons



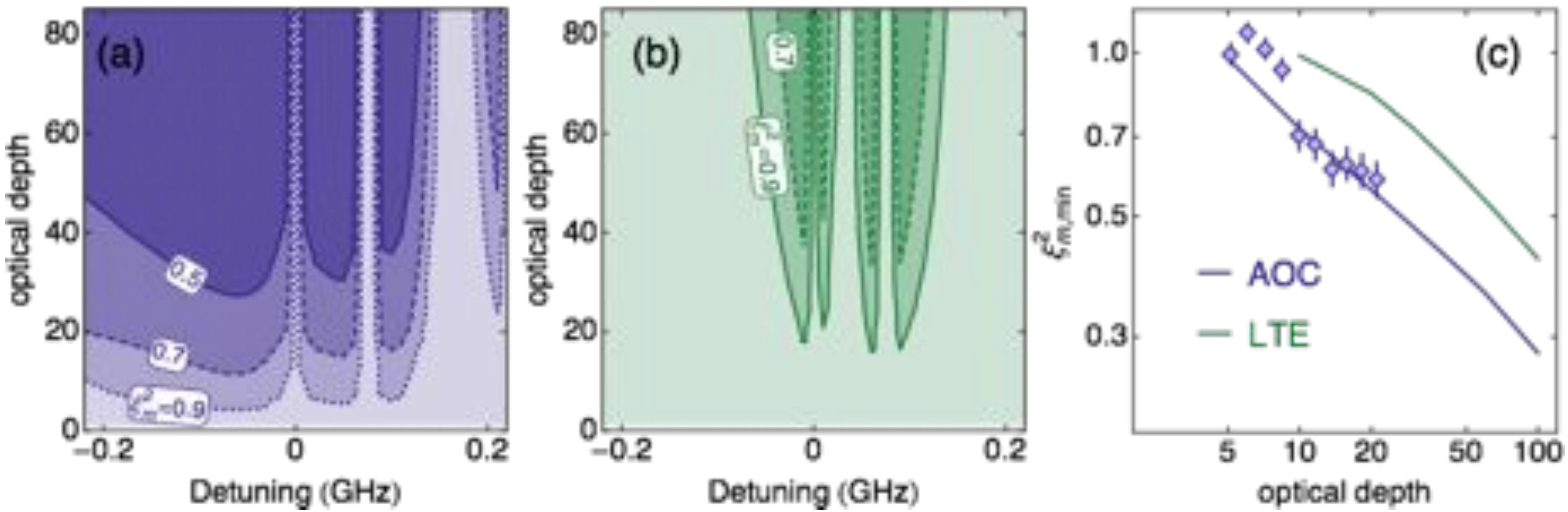
Nonlinear beats linear read-out



we optimise measurement sensitivity with respect to:

- probe detuning Δ
- probe power N (photon number)
- sample optical depth d_0 (atom number, interaction strength)

Nonlinear beats linear read-out



we optimise measurement sensitivity with respect to:

- probe detuning Δ
- probe power N (photon number)
- sample optical depth d_0 (atom number, interaction strength)

Can improved scaling give better sensitivity?

enhanced scaling

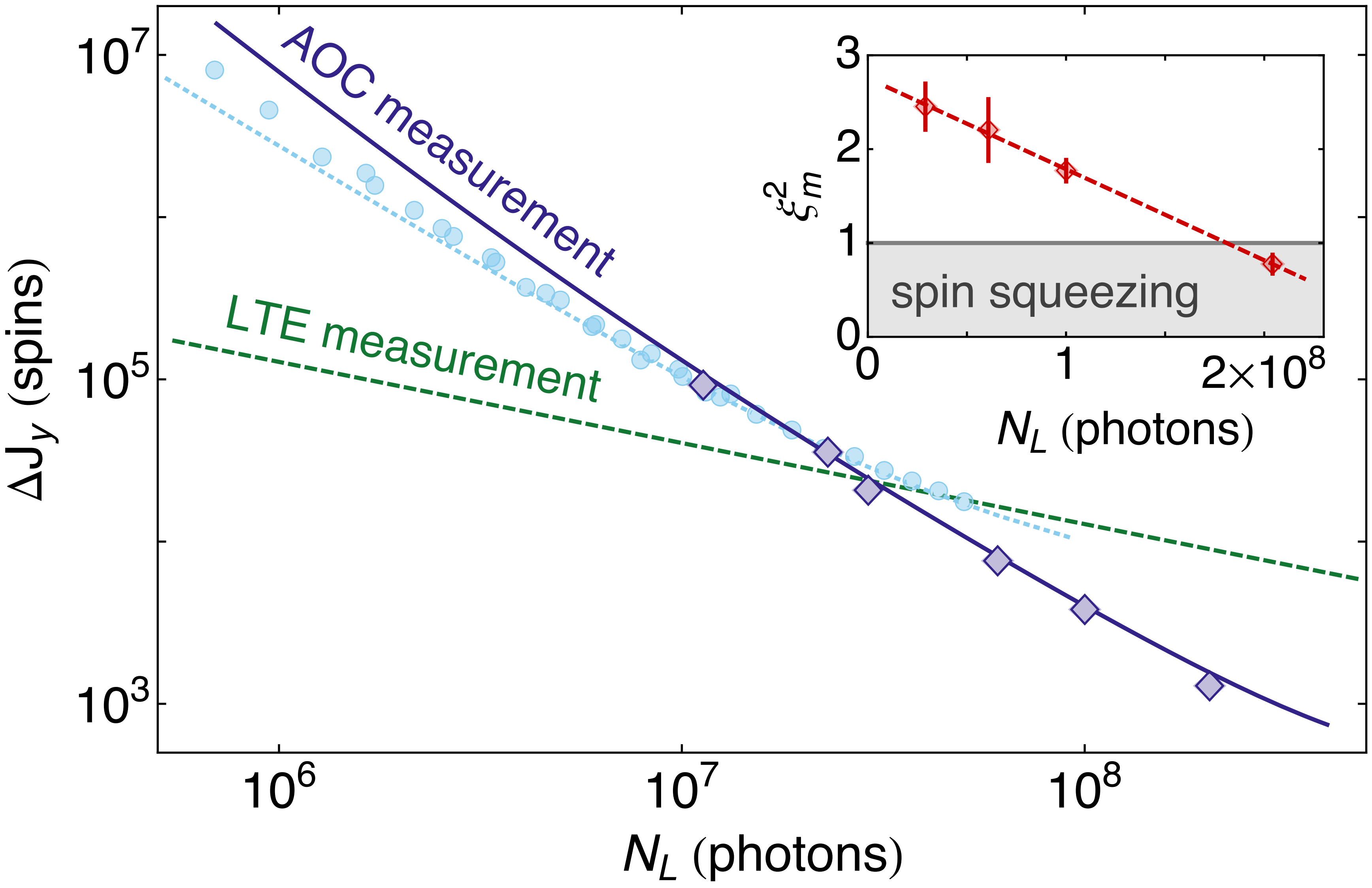
$$\Delta J_y \propto N^{-3/2}$$

metrologically significant

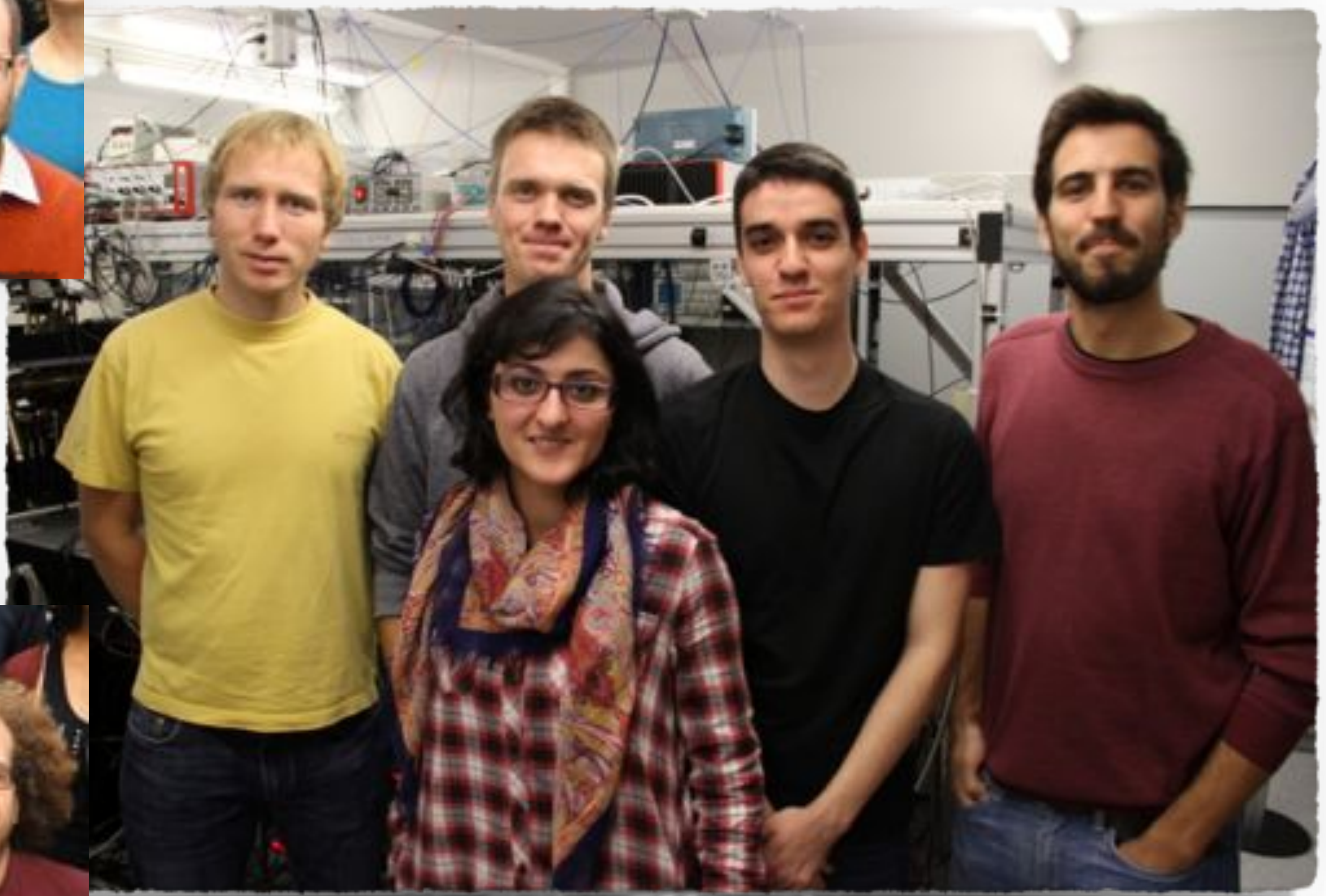
$$J_y \propto B_z$$

better absolute sensitivity

vs. (N, Δ, d_0)



Acknowledgments



RJS et al. arXiv: 1310.5889 (2013)

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