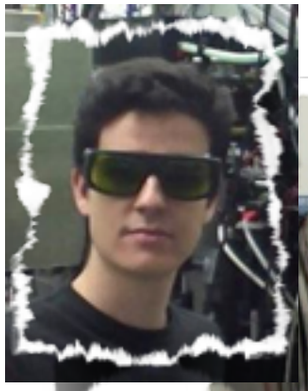
Super-Heisenberg scaling, spin squeezing & quantum nondemolition measurement of atomic spins

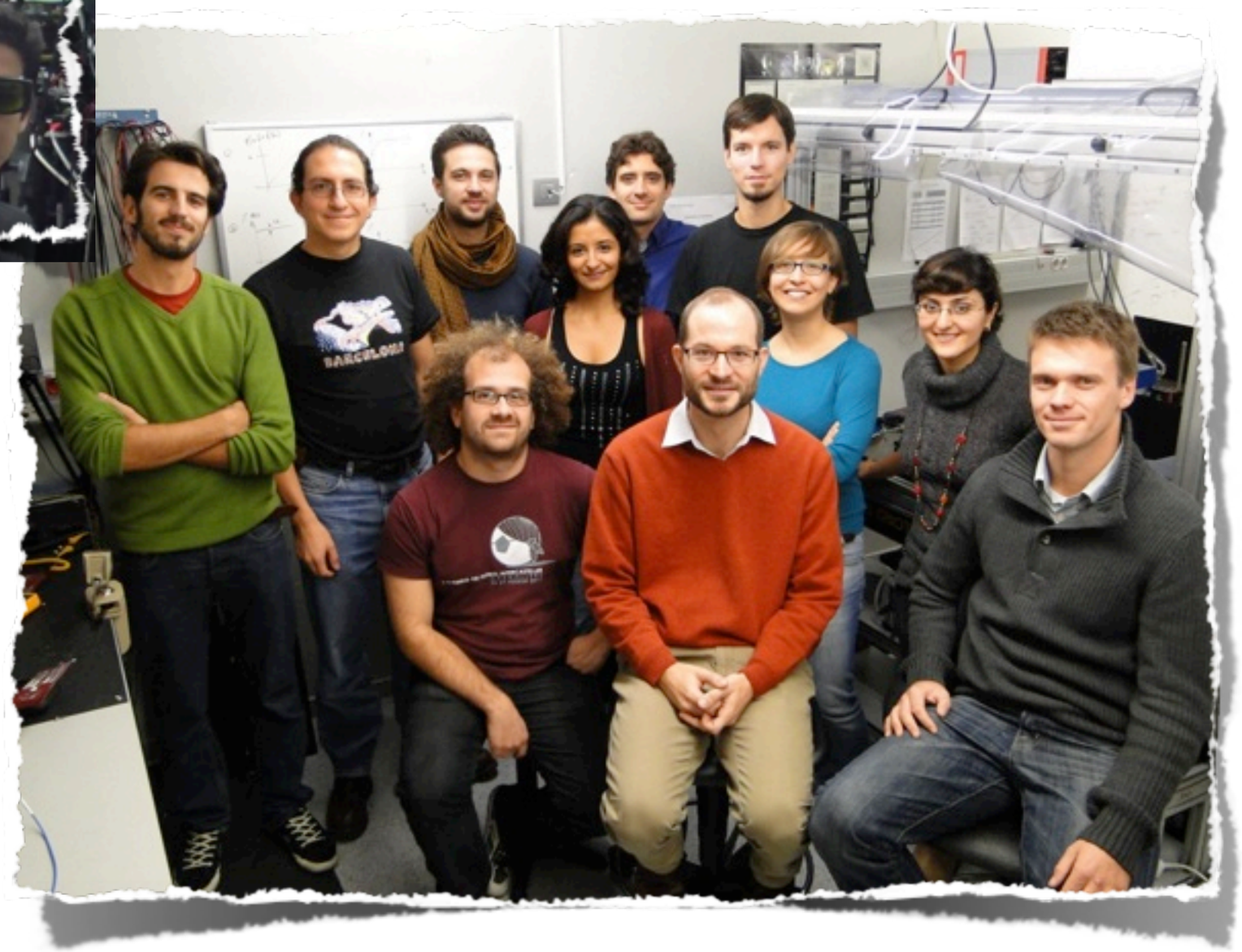
R.J.Sewell, M. Napolitano, M. Koschorreck, B. Dubost,
N. Behbood, G. Colangelo, F. Martin Ciurana,
M.W. Mitchell

QuAMP, Swansea
9 September 2013

Generalitat de Catalunya

Fundació Privada CELLEX





M. Koschorreck
(Cambridge)

R.J.S, M. Napolitano, G. Colangelo, N. Behbood,
F. Martin Ciurana & M.W. Mitchell*

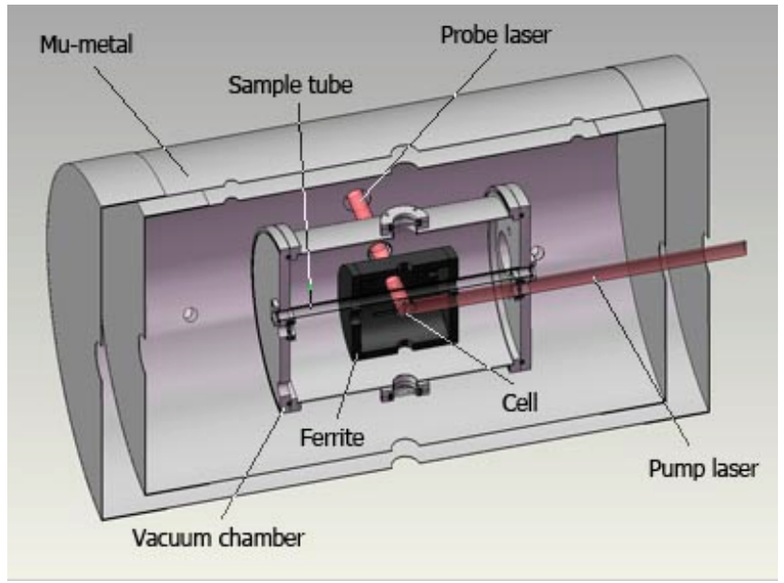
www.mitchellgroup.icfo.es

ICFO Institut de Ciències Fotòniques — MW Group

A subfemtotesla multichannel atomic magnetometer

I. K. Kominis*†, T. W. Kornack*, J. C. Allred‡ & M. V. Romalis*

** Department of Physics, Princeton University, Princeton, New Jersey 08544, USA*
‡ Department of Physics, University of Washington, Seattle, Washington 98195, USA

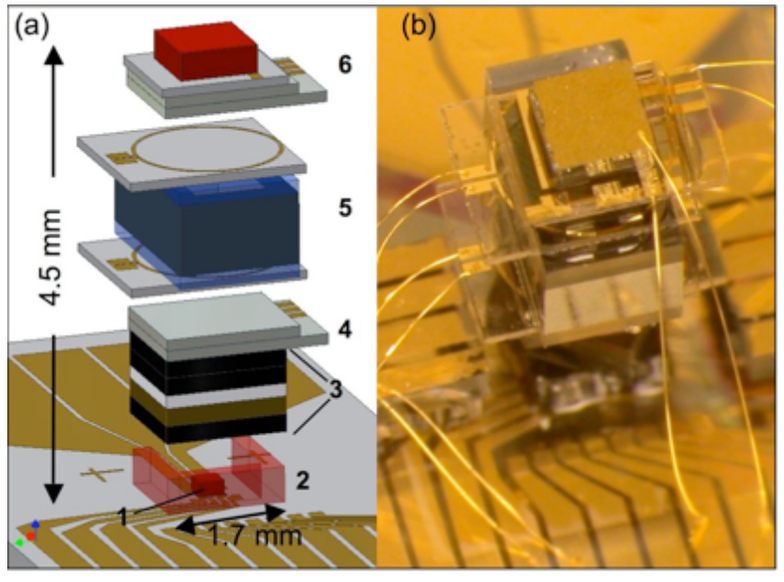


Kominis, Nature 422, 596 (2003)

Subpicotesla atomic magnetometry with a microfabricated vapour cell

VISHAL SHAH[1,2], SVENJA KNAPPE[1], PETER D. D. SCHWINDT[3] AND JOHN KITCHING[1]*

[1]National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305, USA
[2]Department of Physics, University of Colorado, Boulder, Colorado 80309, USA
[3]Sandia National Laboratories, MS 1082, PO Box 5800, Albuquerque, New Mexico 87185, USA
*e-mail: kitching@boulder.nist.gov

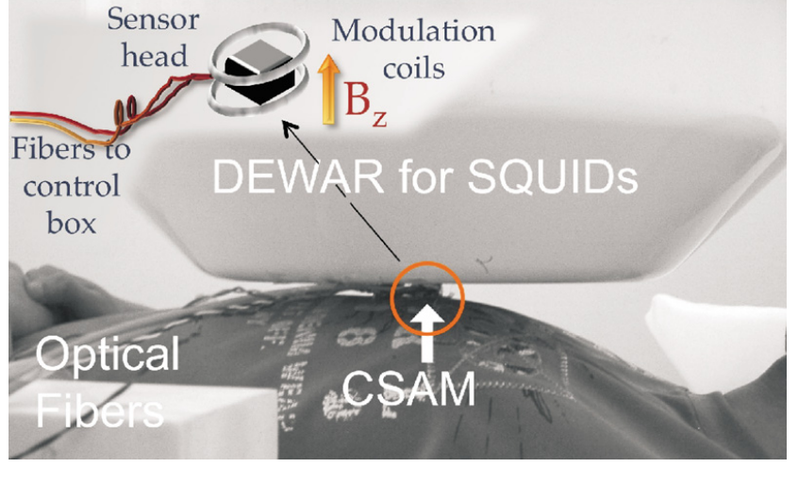


Shah, Nat. Phot. 1, 649 (2007)

Cross-validation of microfabricated atomic magnetometers with superconducting quantum interference devices for biomagnetic applications

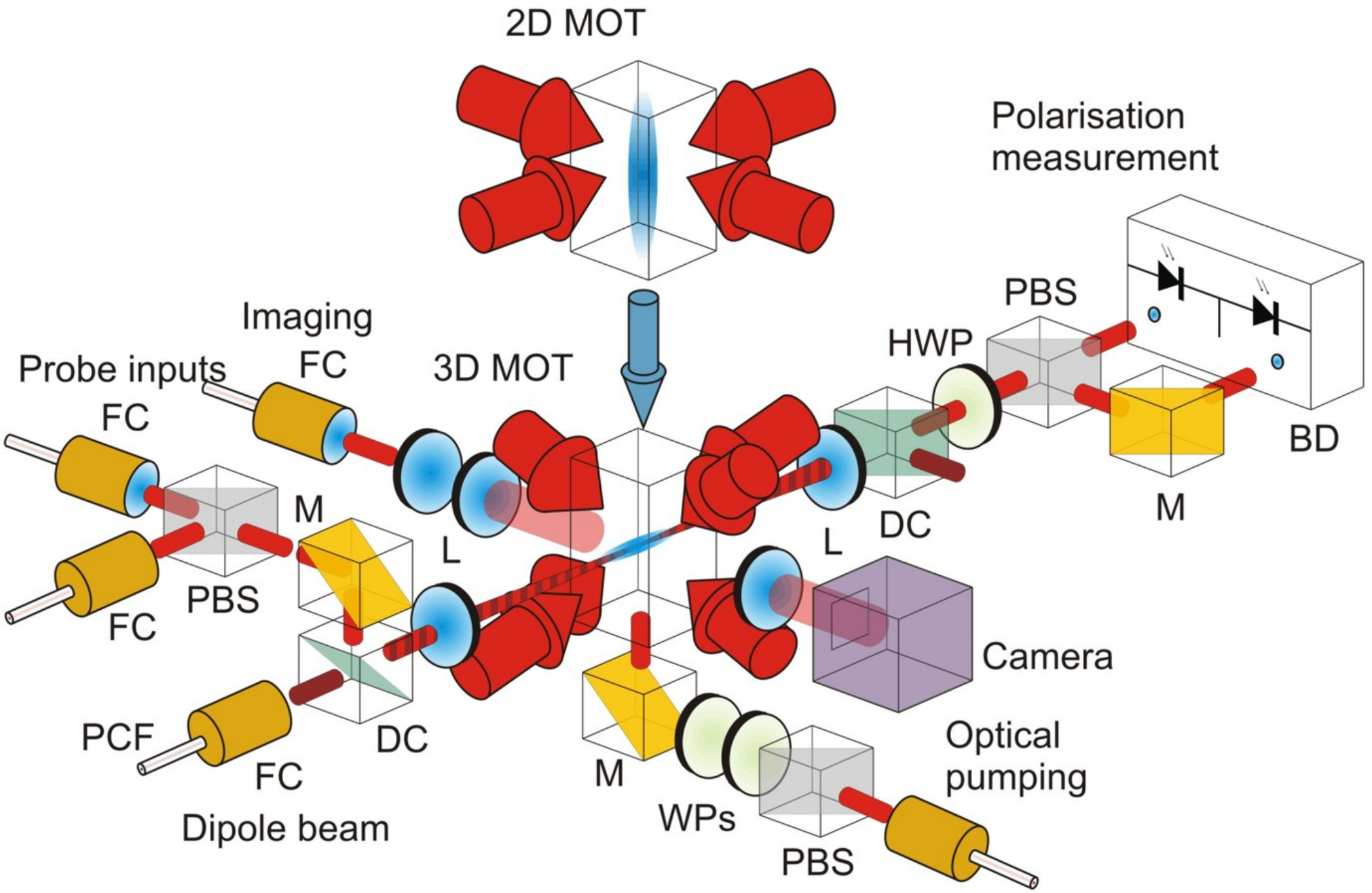
Svenja Knappe,[1,a)] Tilmann H. Sander,[2] Olaf Kosch,[2] Frank Wiekhorst,[2] John Kitching,[1] and Lutz Trahms[2]
[1]*NIST, Time and Frequency Division, 325 Broadway, Boulder, Colorado 80305, USA*
[2]*Physikalisch-Technische Bundesanstalt, Abbestr. 2-12, 10587 Berlin, Germany*

(Received 8 June 2010; accepted 27 August 2010; published online 28 September 2010)



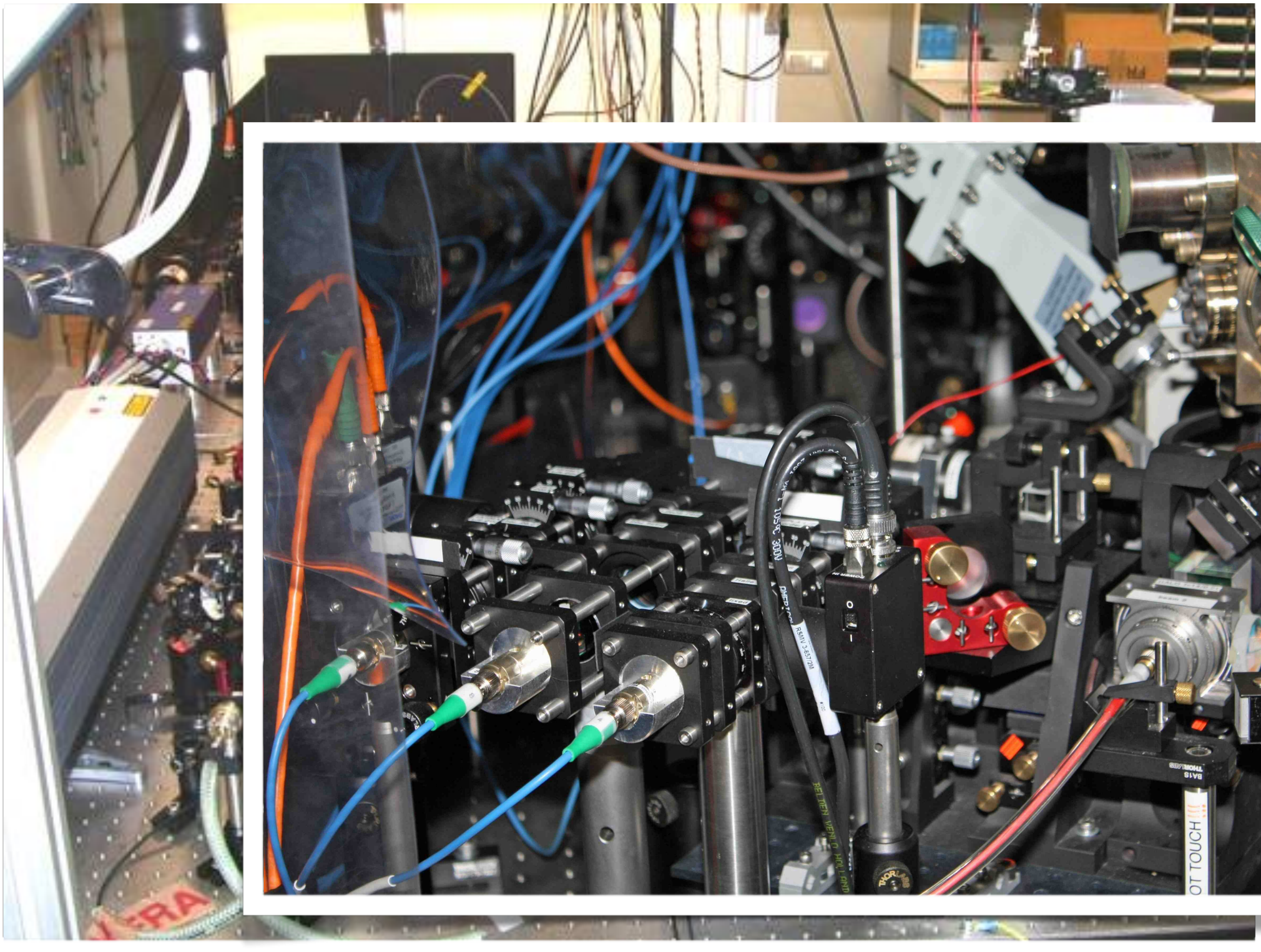
Knappe, APL 97, 133703 (2010)

Quantum atom-light interface

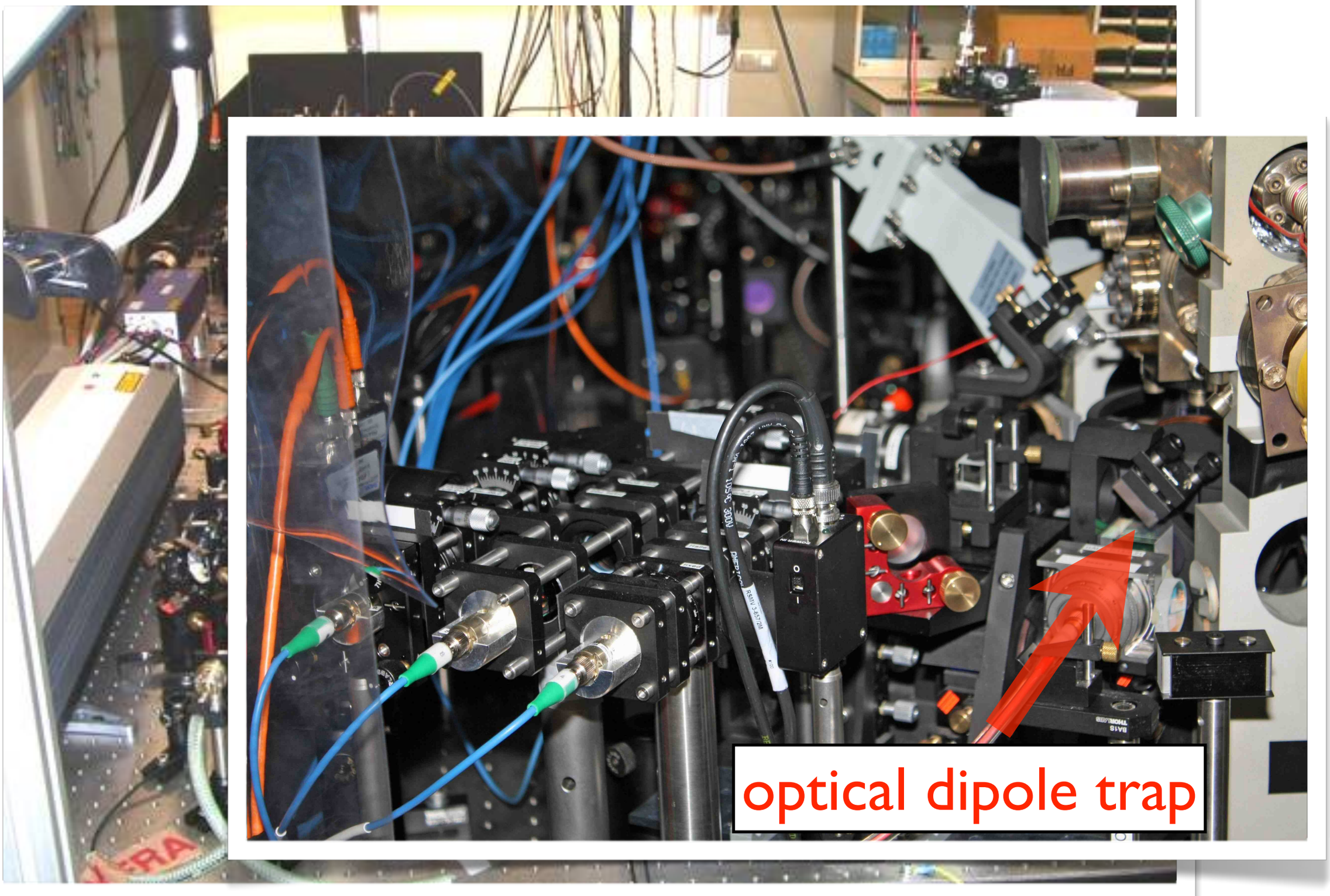


Quantum atom-light interface

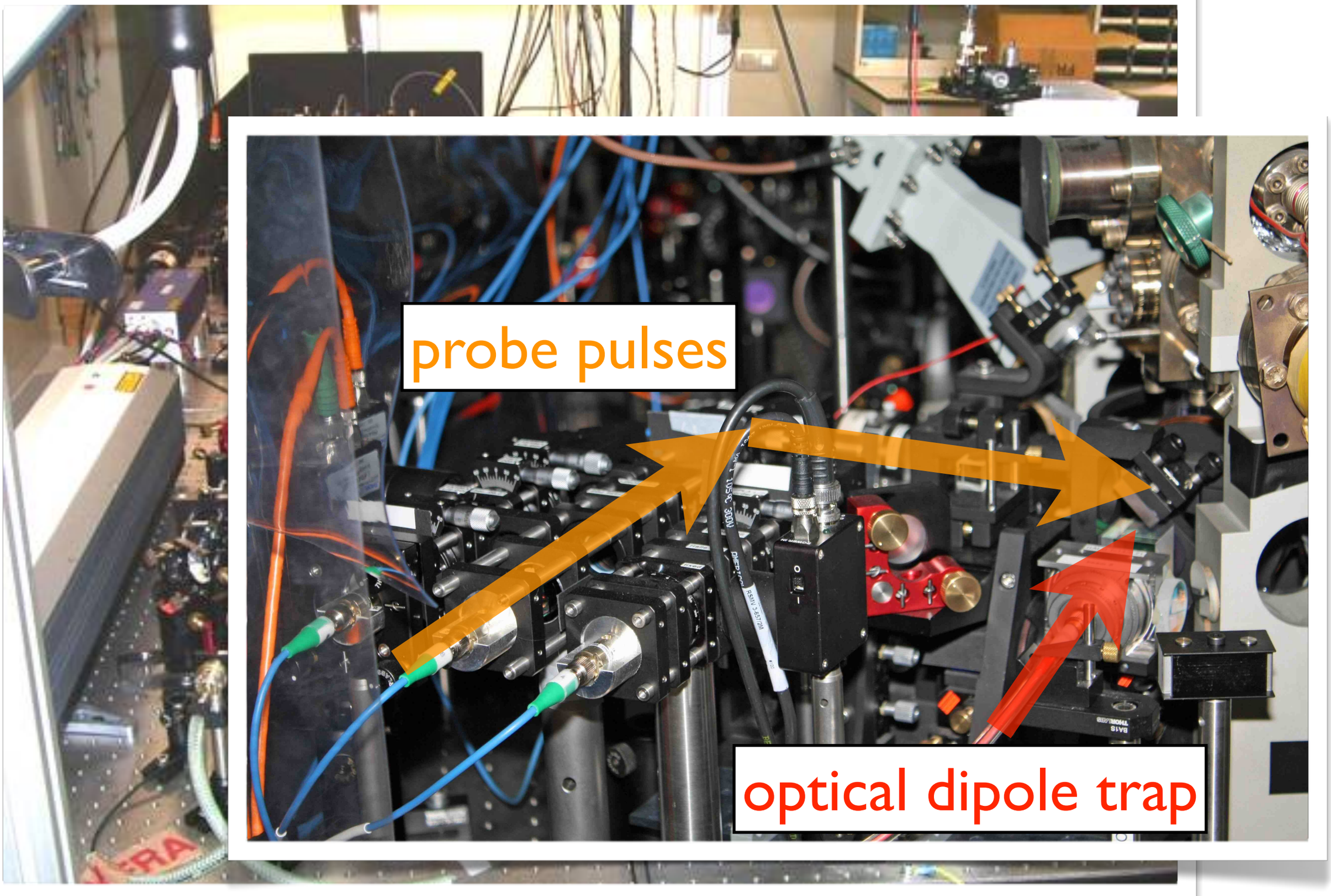
Quantum atom-light interface



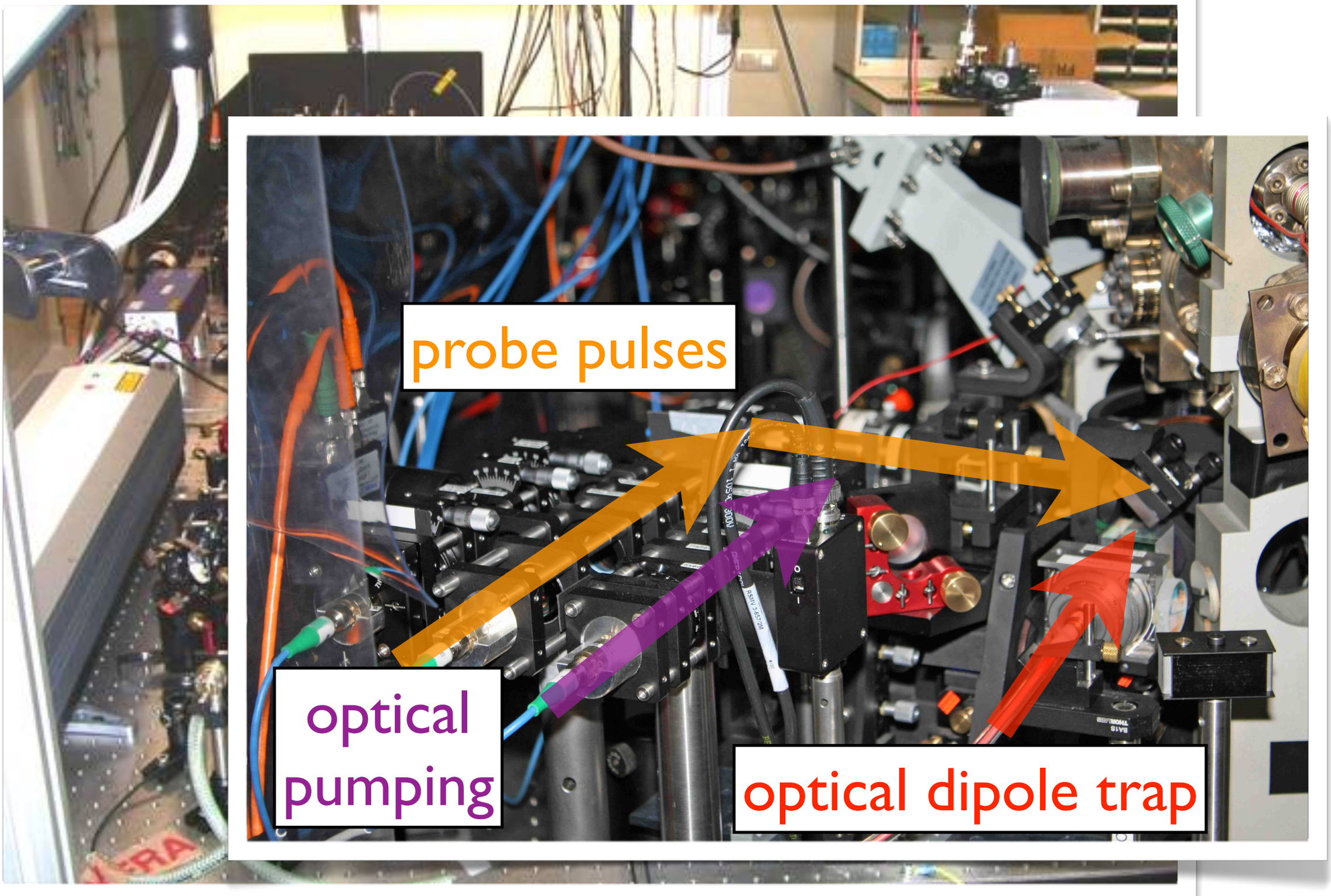
Quantum atom-light interface



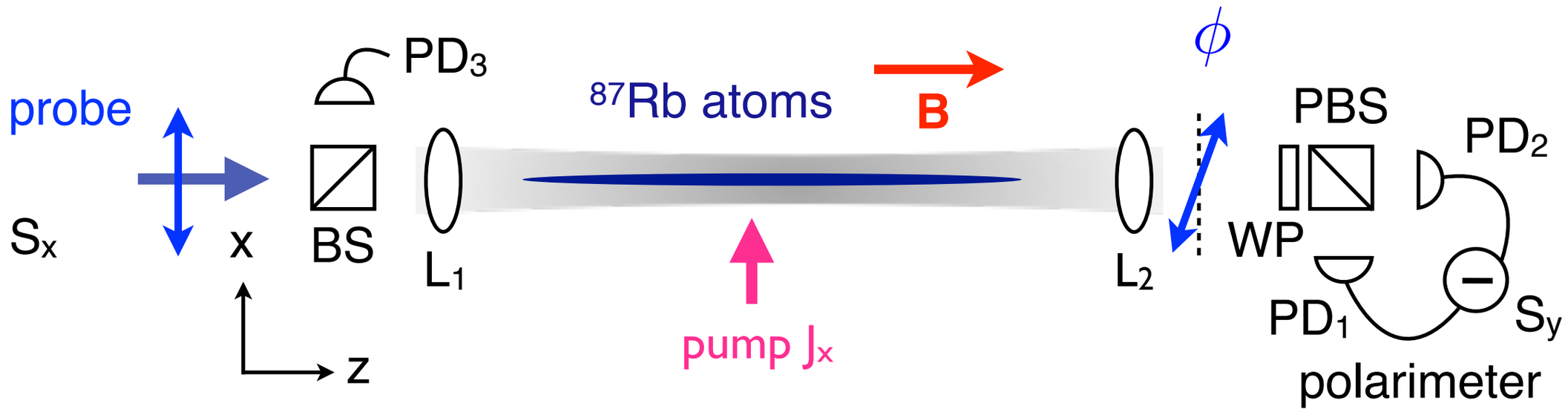
Quantum atom-light interface



Quantum atom-light interface



Quantum atom-light interface



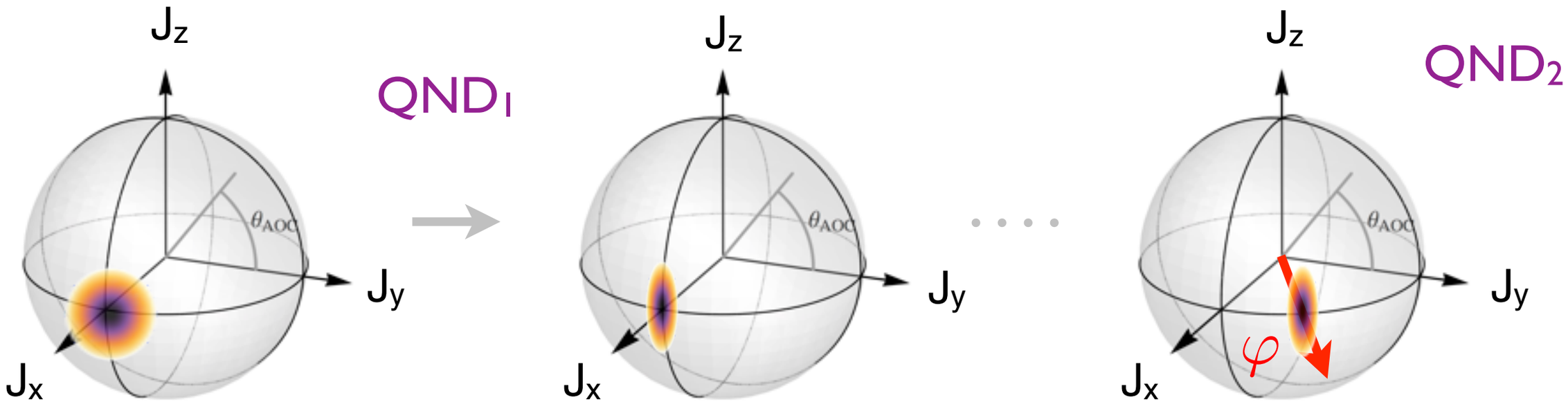
1μs long pulses
linearly polarized
"mode matched" to atoms
0.7 GHz from D_2 line

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

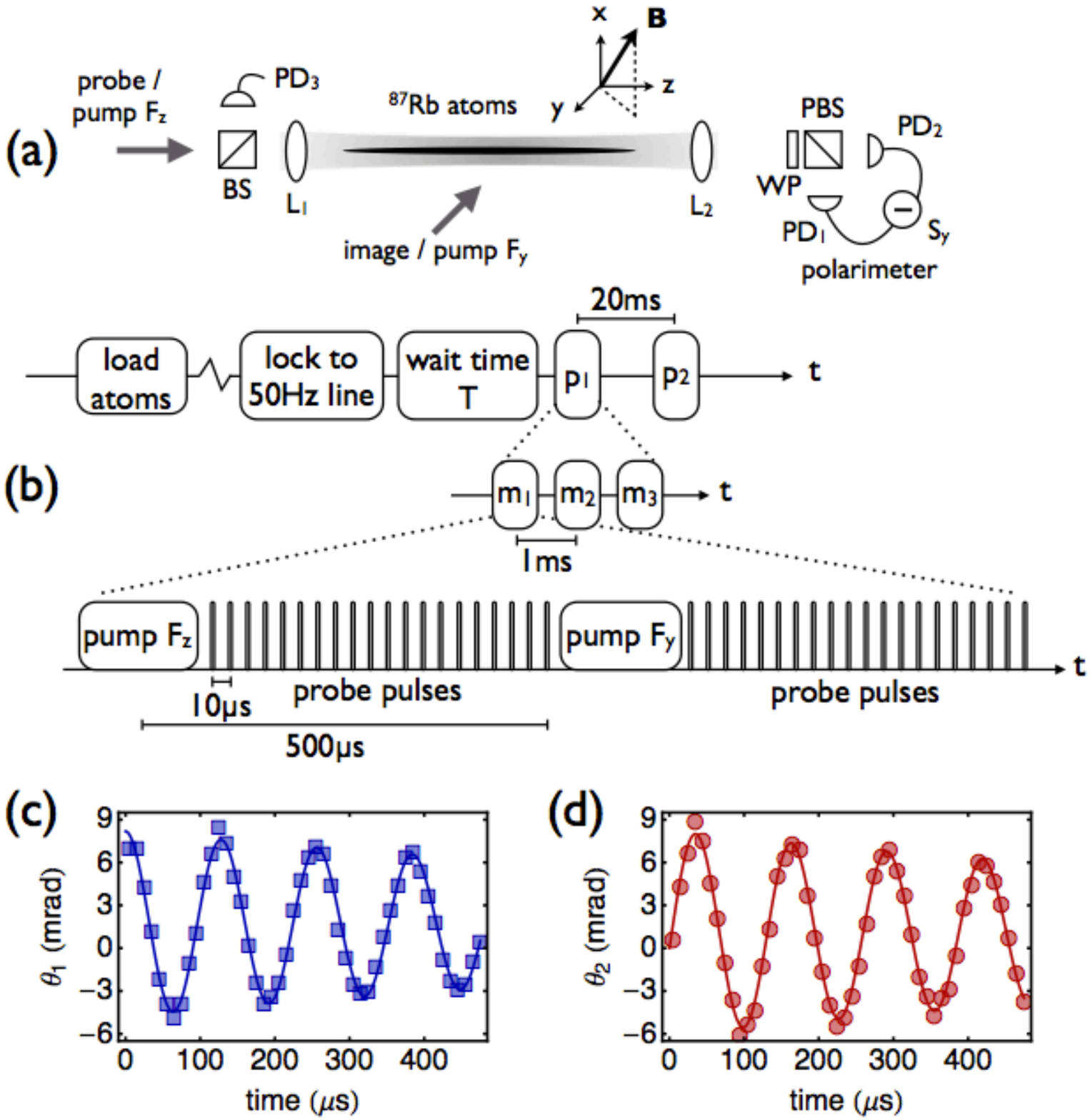
[1] effective OD > 50
[2] Sensitivity 512 spins, < SQL
[3] QND measurement
[4] spin squeezing

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)

Conditional spin squeezing

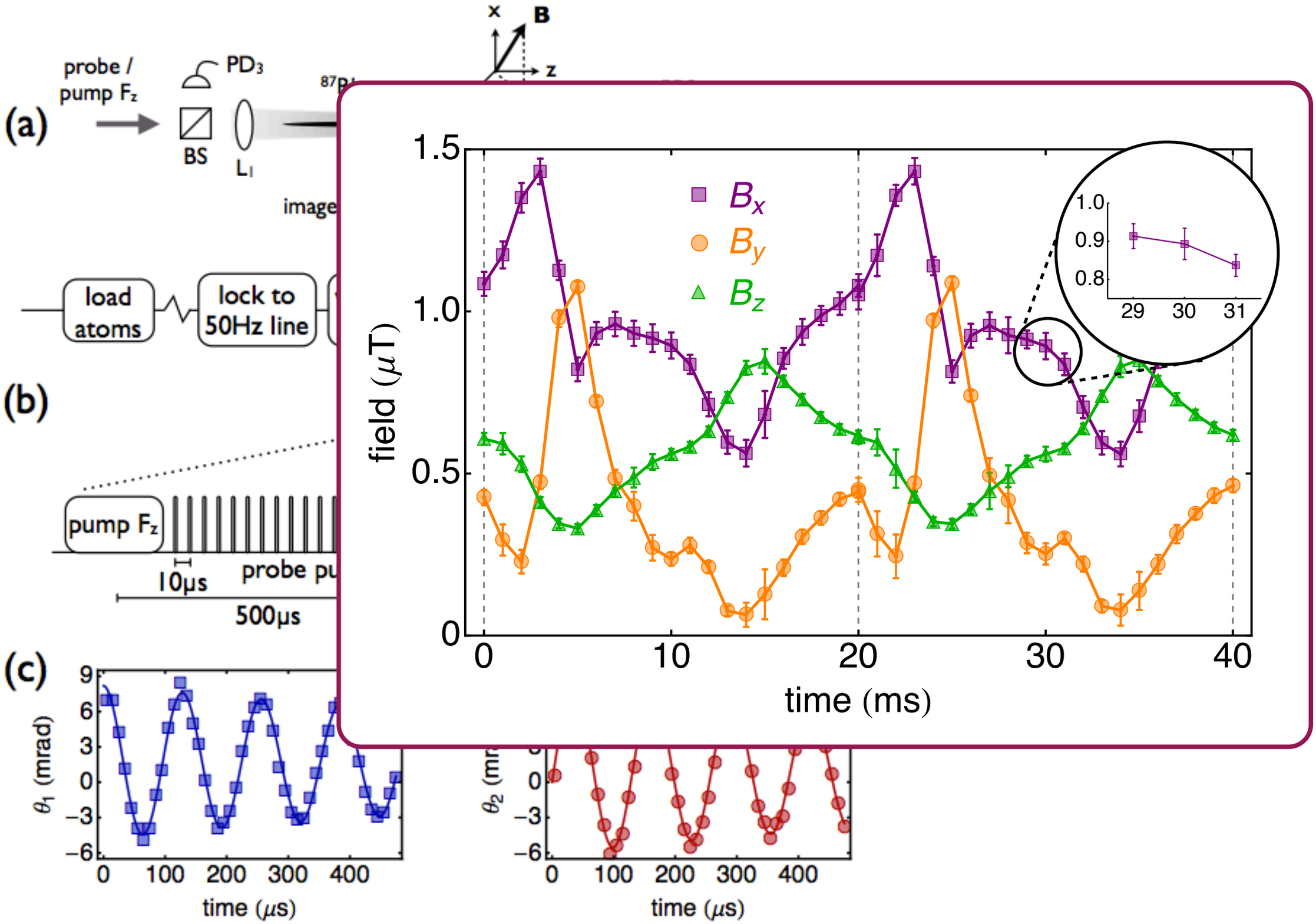


Non-demolition magnetic oscilloscope



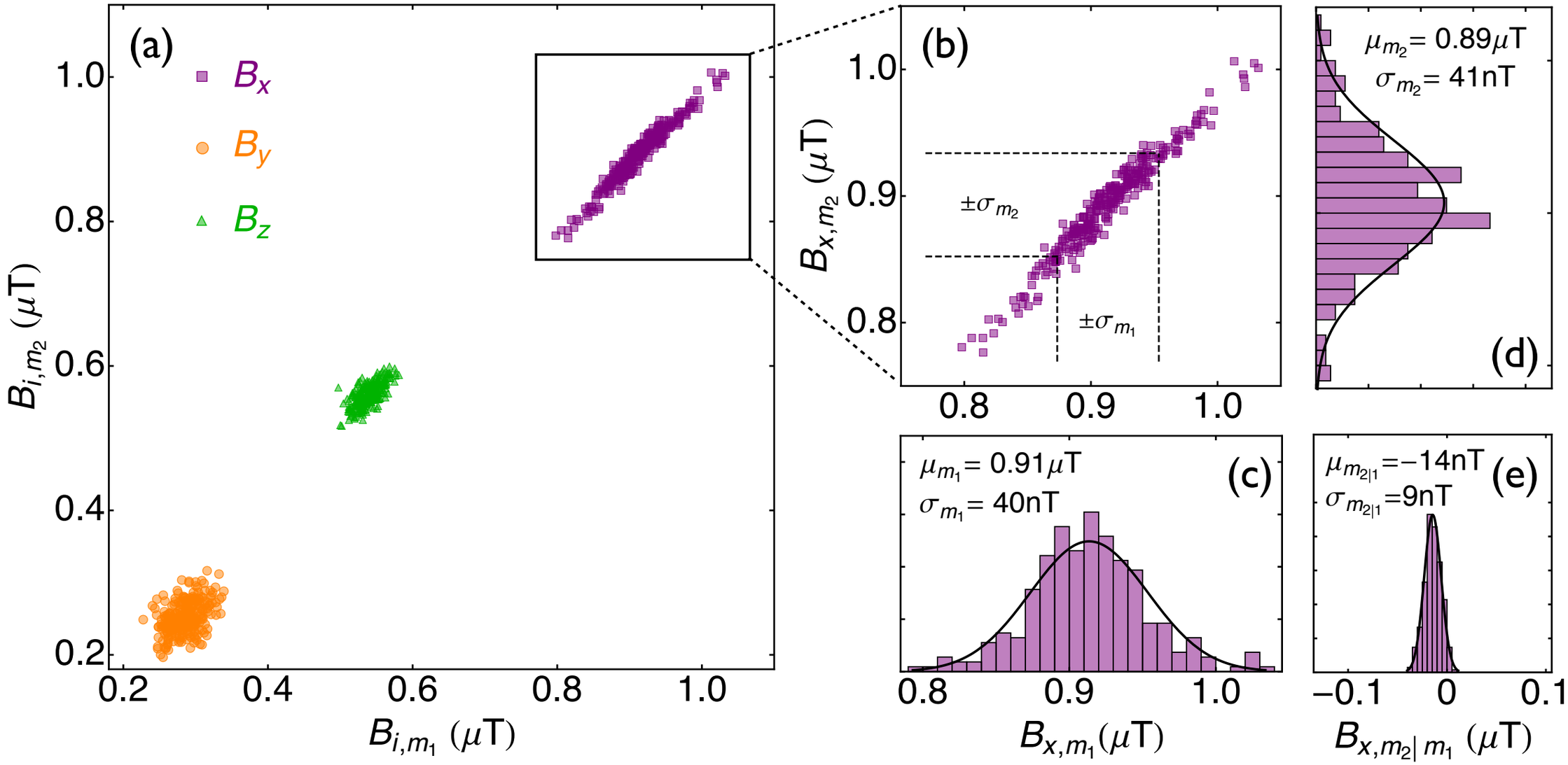
N. Bebood et al. APL102, 173504 (2013)

Non-demolition magnetic oscilloscope



N. Bebood et al. APL102, 173504 (2013)

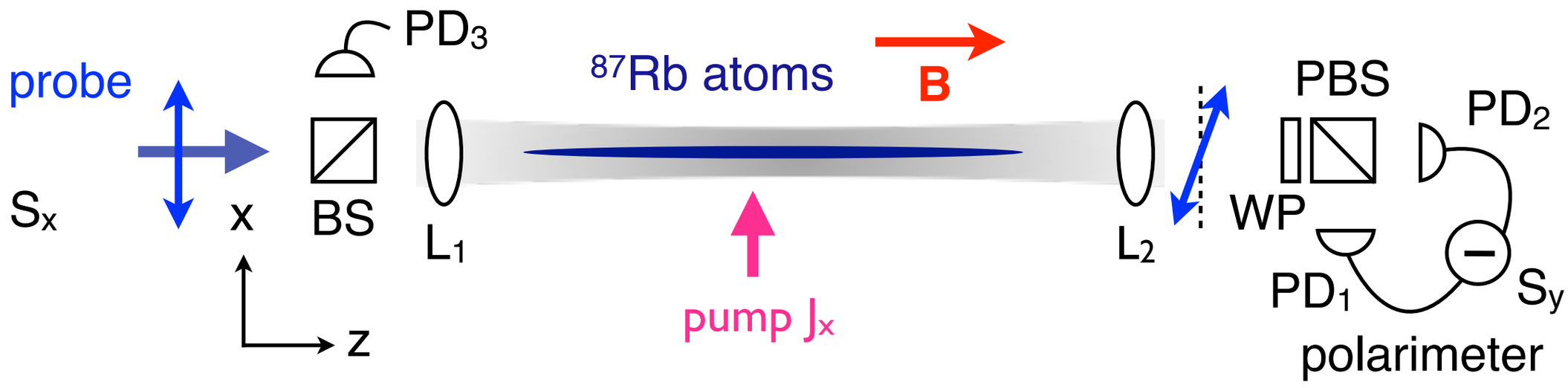
Non-demolition magnetic oscilloscope



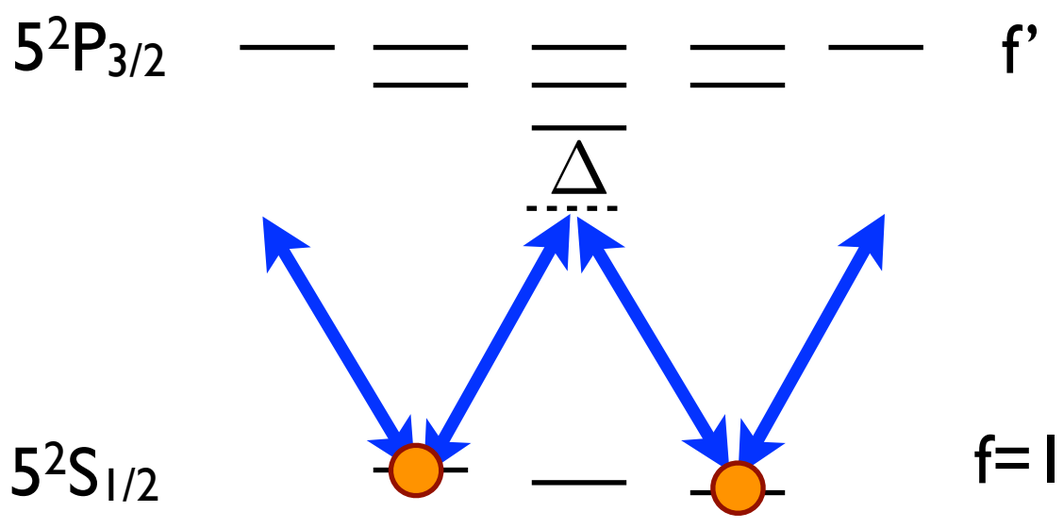
- background subtraction to 9 nT RMS
- entirely limited by environmental noise

N. Bebood et al. APL102, 173504 (2013)

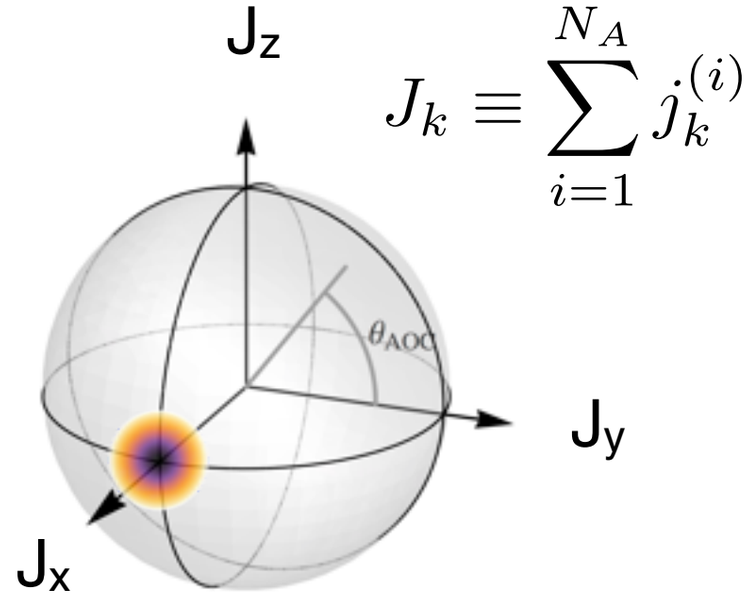
Atom-light interaction



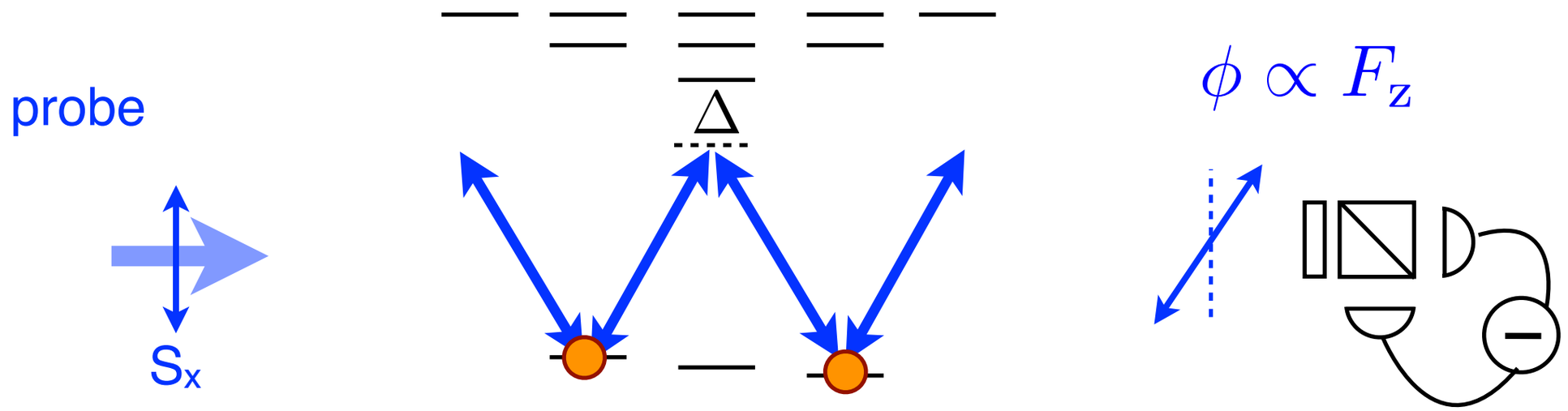
^{87}Rb D_2 line



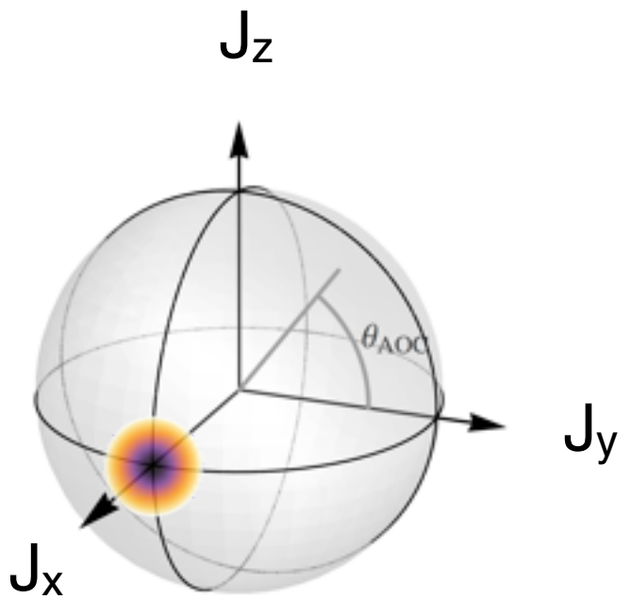
collective spin



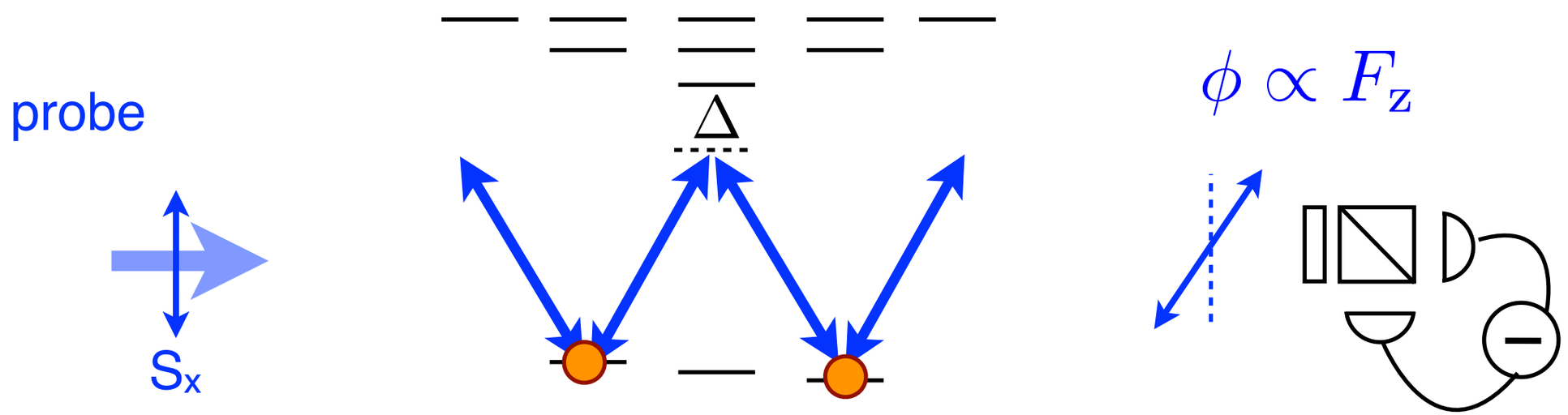
Atom-light interaction



$$H = \kappa_1 S_z J_z + \kappa_2 \left(S_x J_x + S_y J_y \right)$$

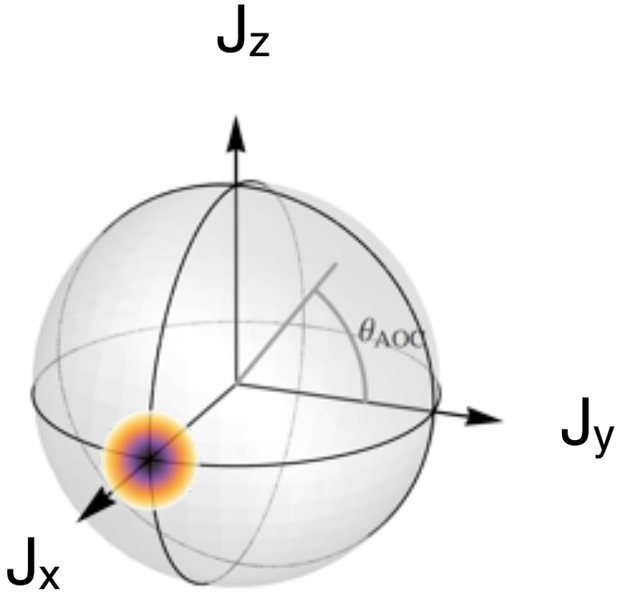


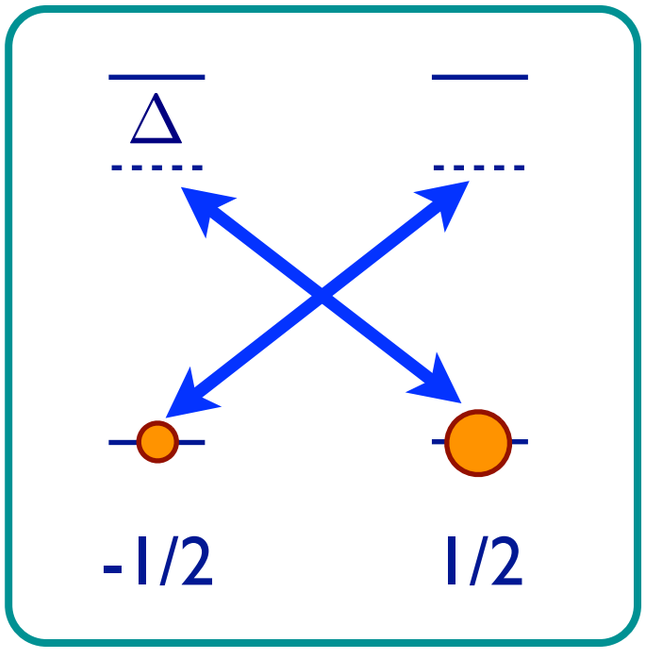
QND with spin-1/2 atoms



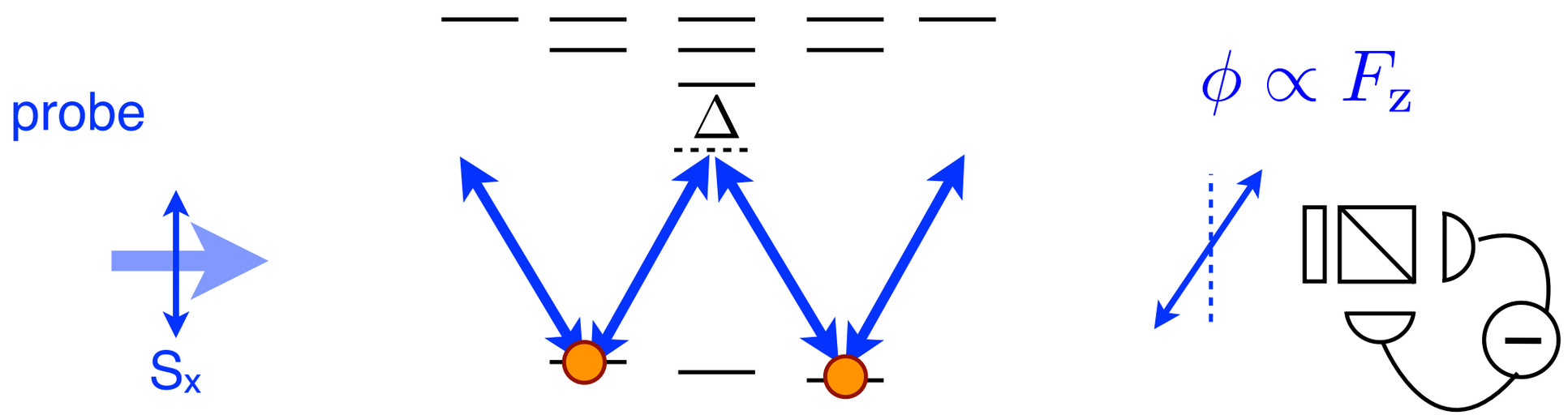
"QND"

$$H = \kappa_1 S_z J_z + \kappa_2 \left(S_x J_x + S_y J_y \right)$$



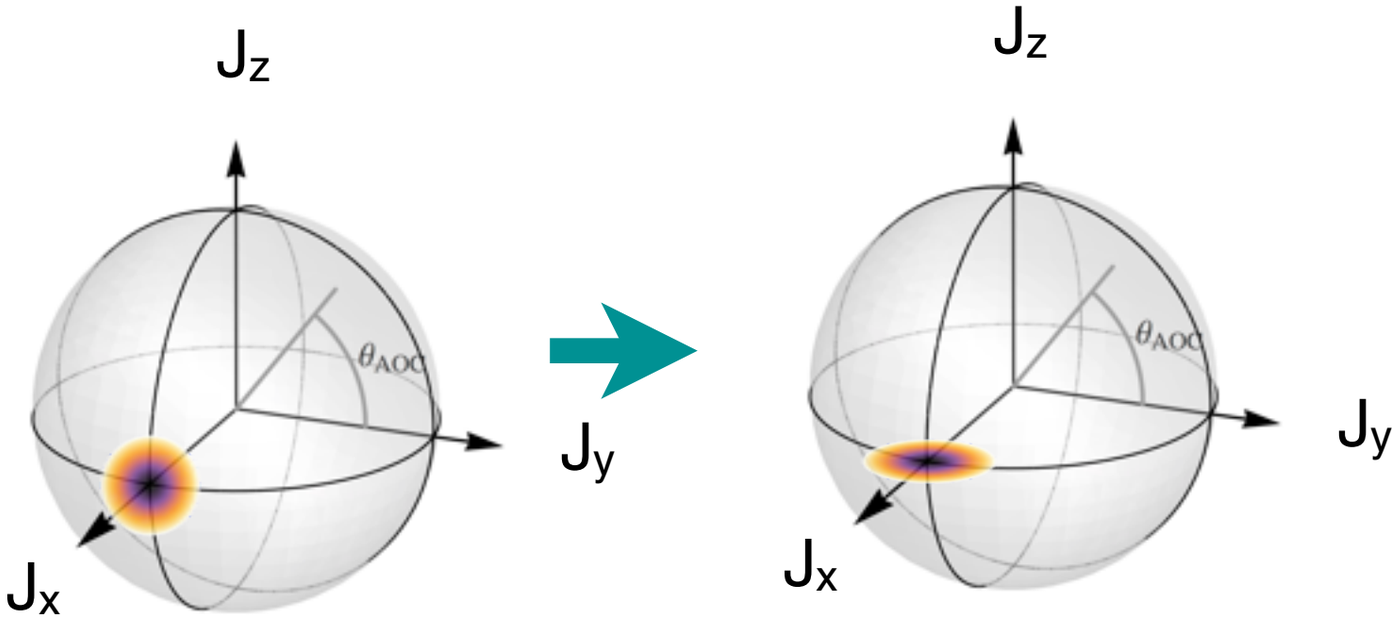


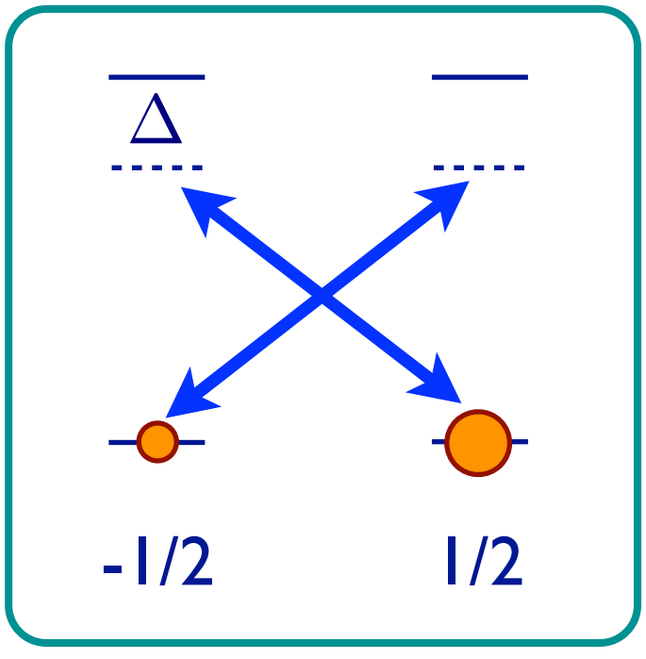
QND with spin-1/2 atoms



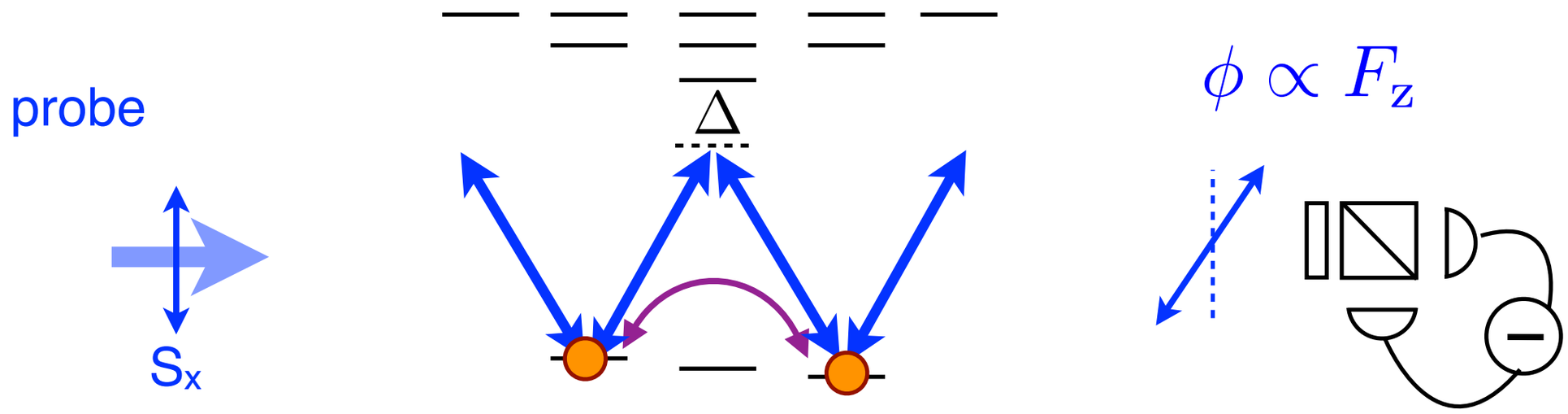
"QND"

$$H = \kappa_1 S_z J_z + \kappa_2 \left(S_x J_x + S_y J_y\right)$$



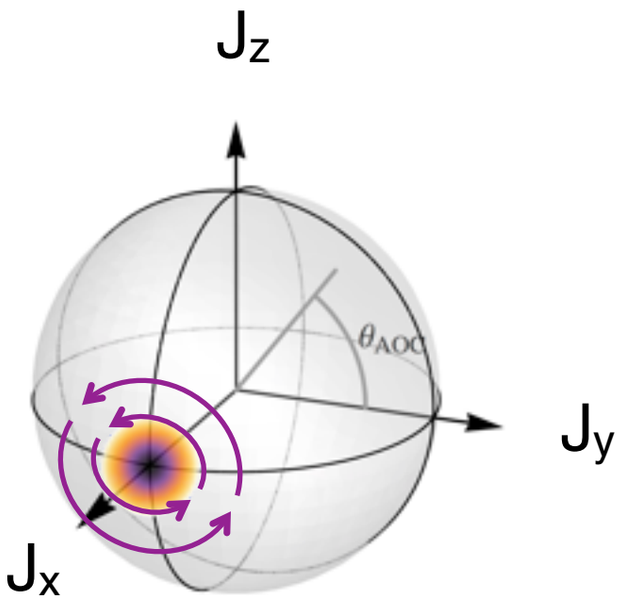


QND with large spin atoms



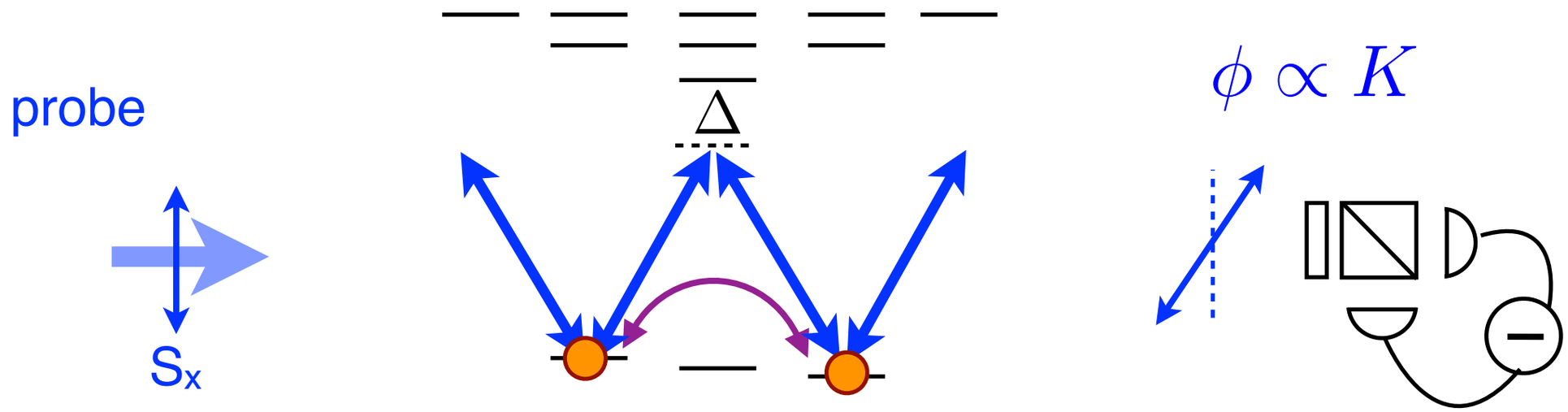
$$H = \kappa_1 S_z J_z + \kappa_2 \left(S_x J_x + S_y J_y \right)$$

tensorial light shift

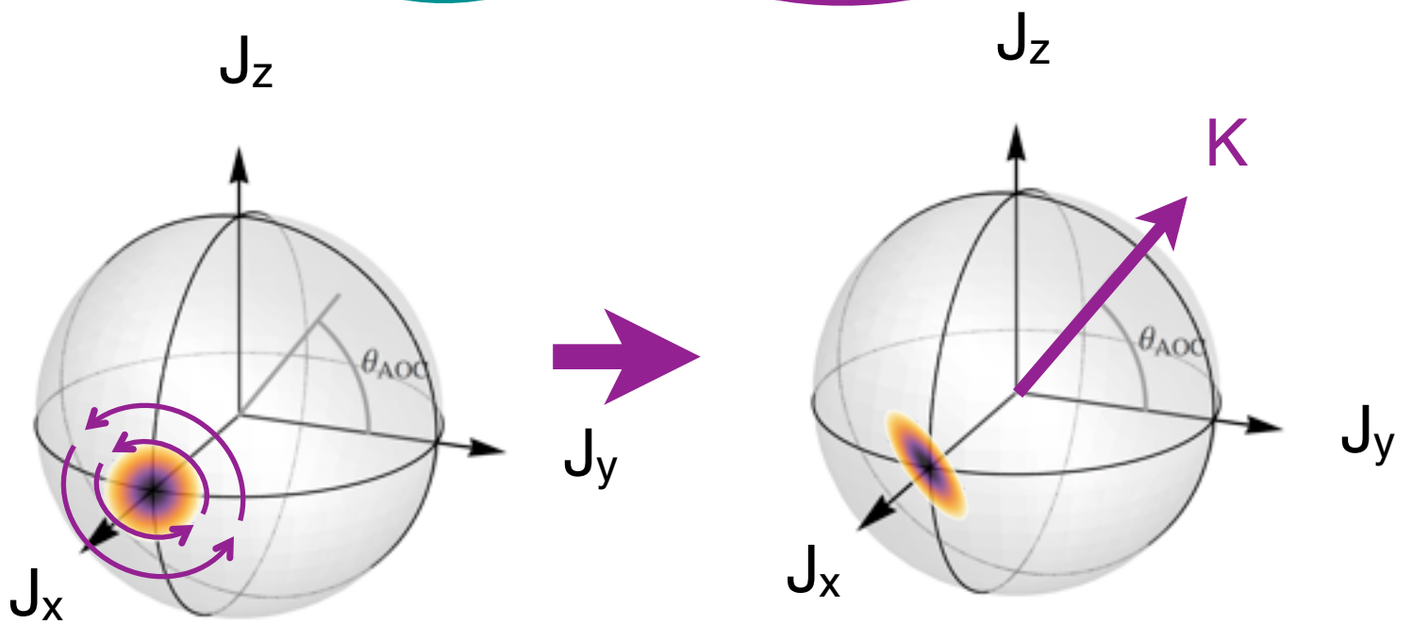


Koschorreck, et al. PRL 105, 093602(2010)

QND with large spin atoms



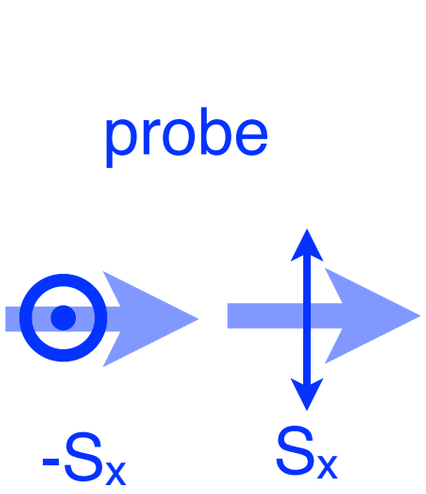
$$H = \kappa_1 S_z J_z + \kappa_2 \left(S_x J_x + S_y J_y \right)$$

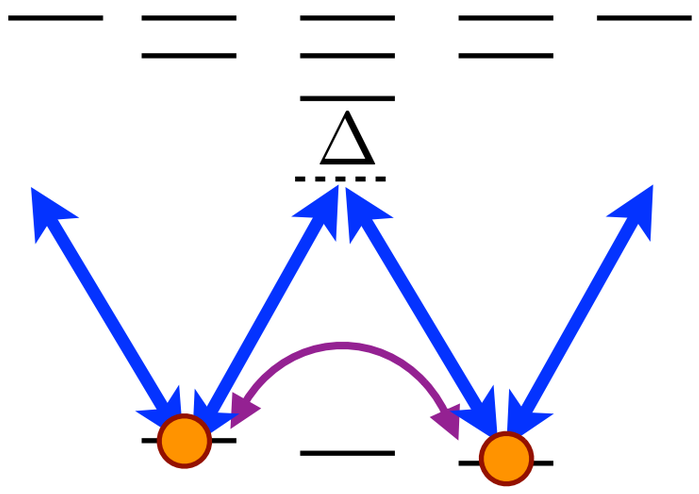


$$K = \cos\theta J_z + \sin\theta J_y$$
$$\theta = \kappa_2 S_x / 2$$

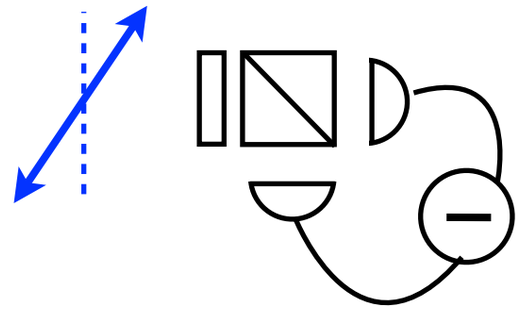
Koschorreck, et al. PRL 105, 093602(2010)

QND with large spin atoms

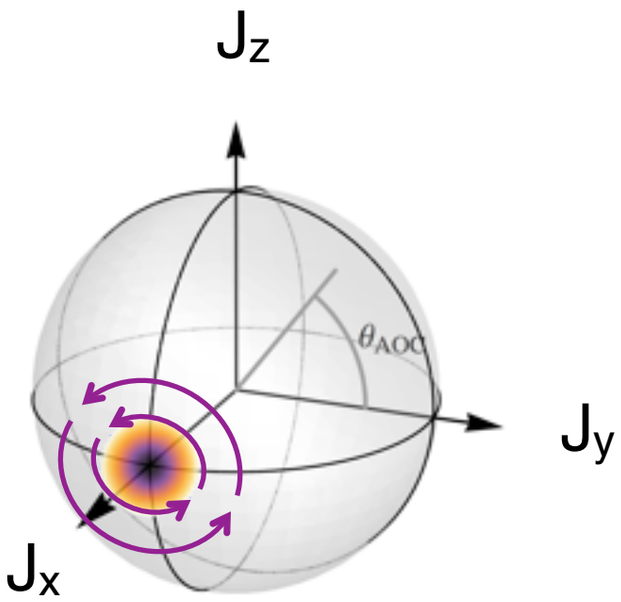




$\phi \propto K$

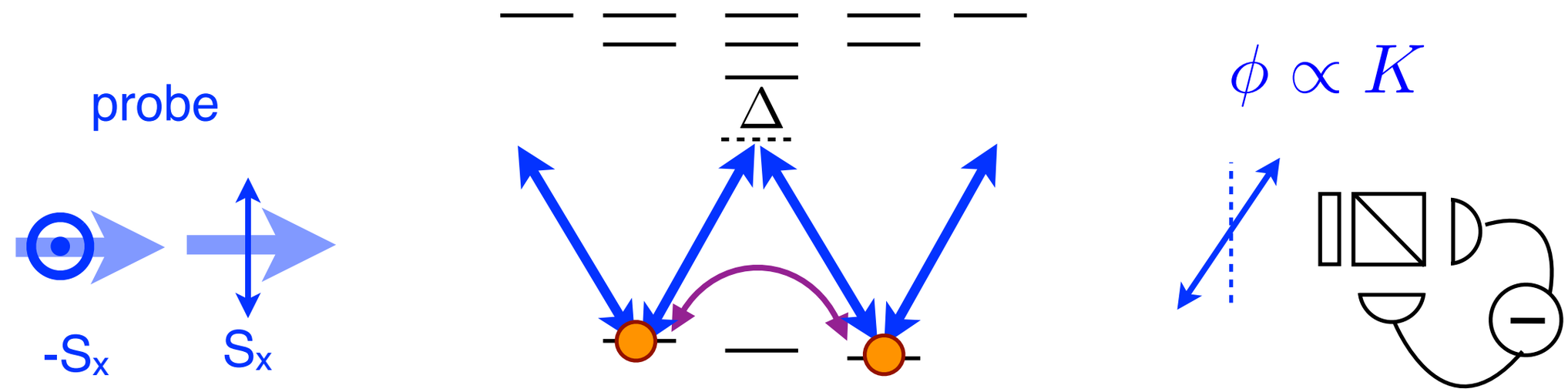


$$H = \kappa_1 S_z J_z + \kappa_2 \left(S_x J_x + S_y J_y \right)$$

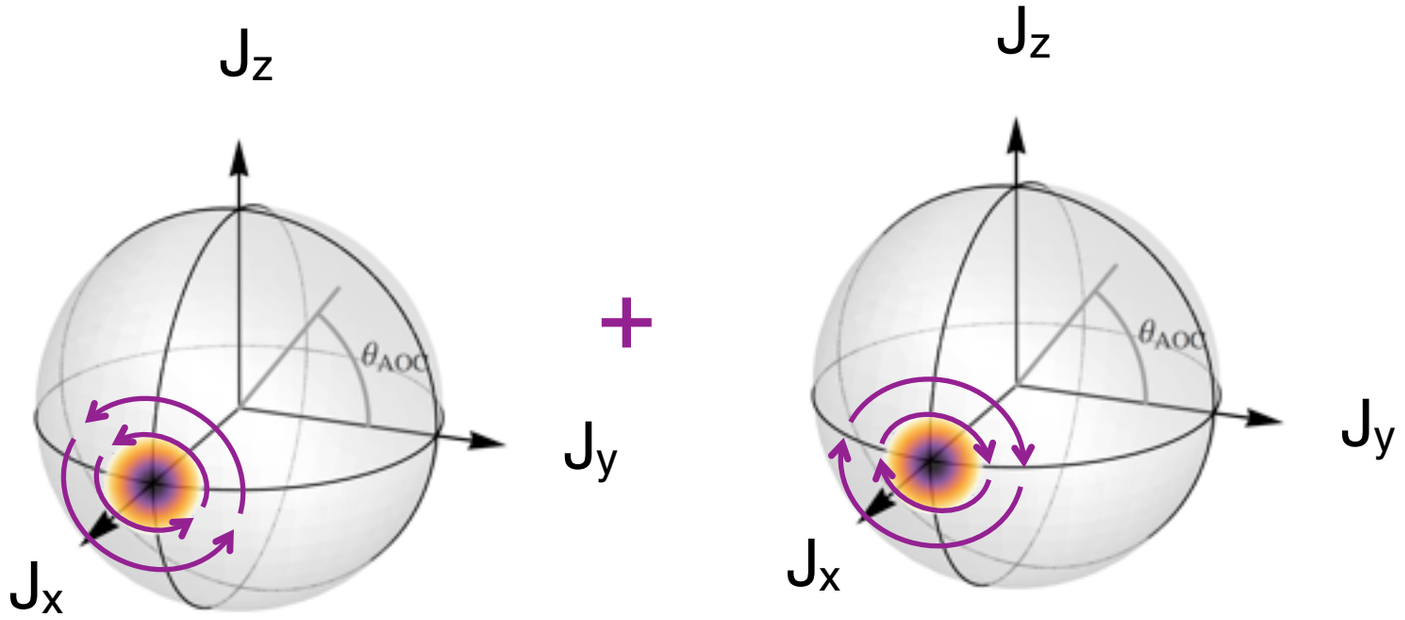


Koschorreck, et al. PRL 105, 093602(2010)

QND with large spin atoms

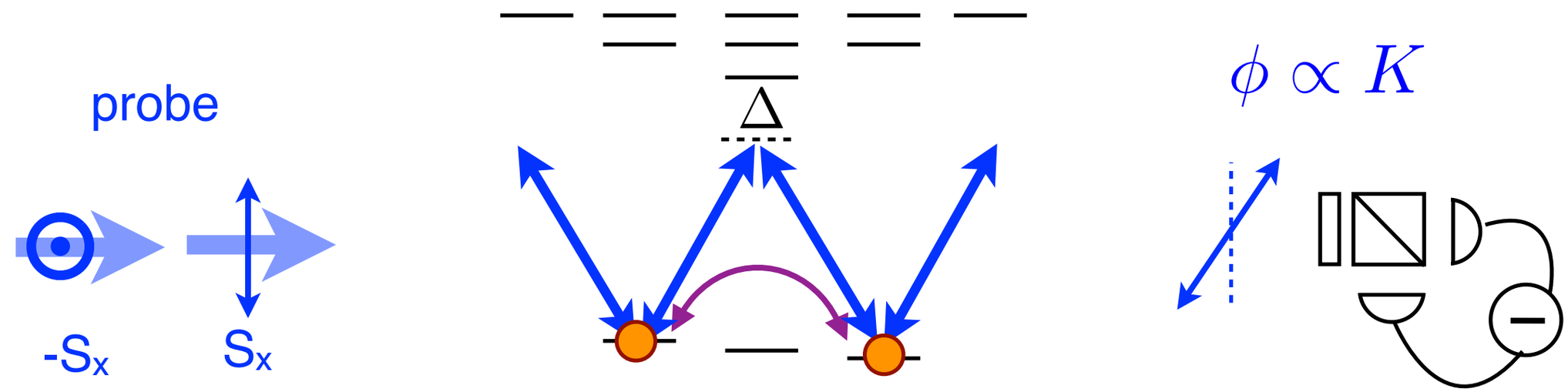


$$H = \kappa_1 S_z J_z + \kappa_2 \left(S_x J_x + S_y J_y \right)$$

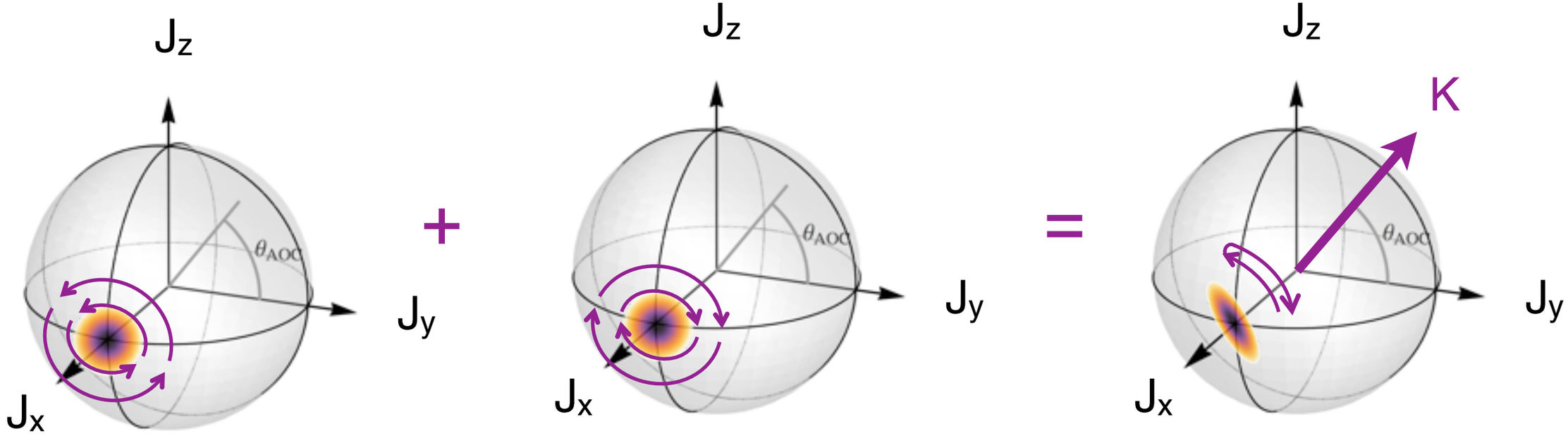


Koschorreck, et al. PRL 105, 093602(2010)

QND with large spin atoms

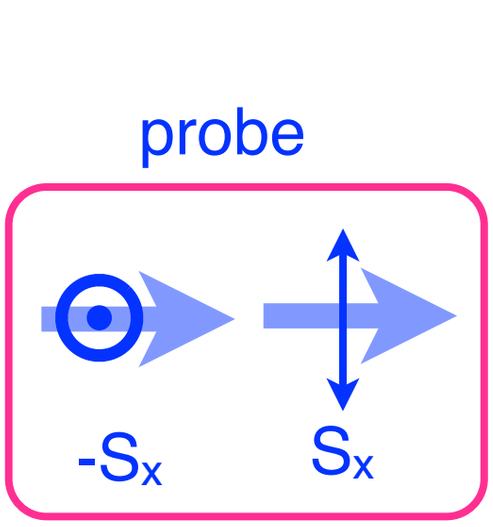


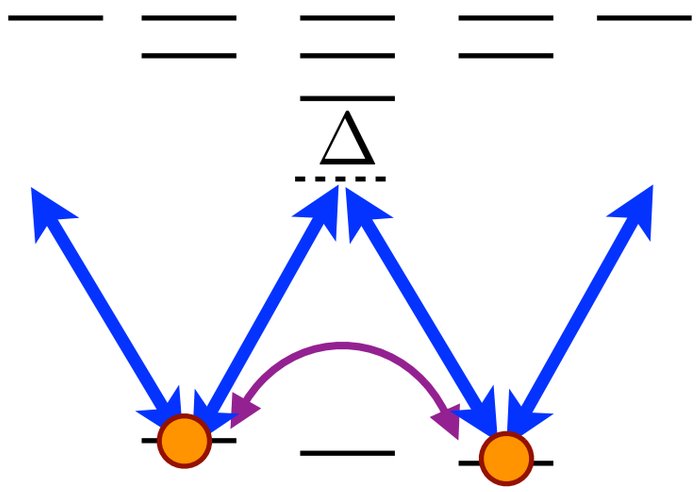
$$H = \kappa_1 S_z J_z + \kappa_2 \left(S_x J_x + S_y J_y \right)$$



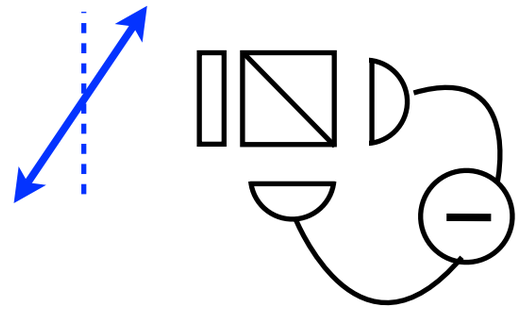
Koschorreck, et al. PRL 105, 093602(2010)

QND with large spin atoms

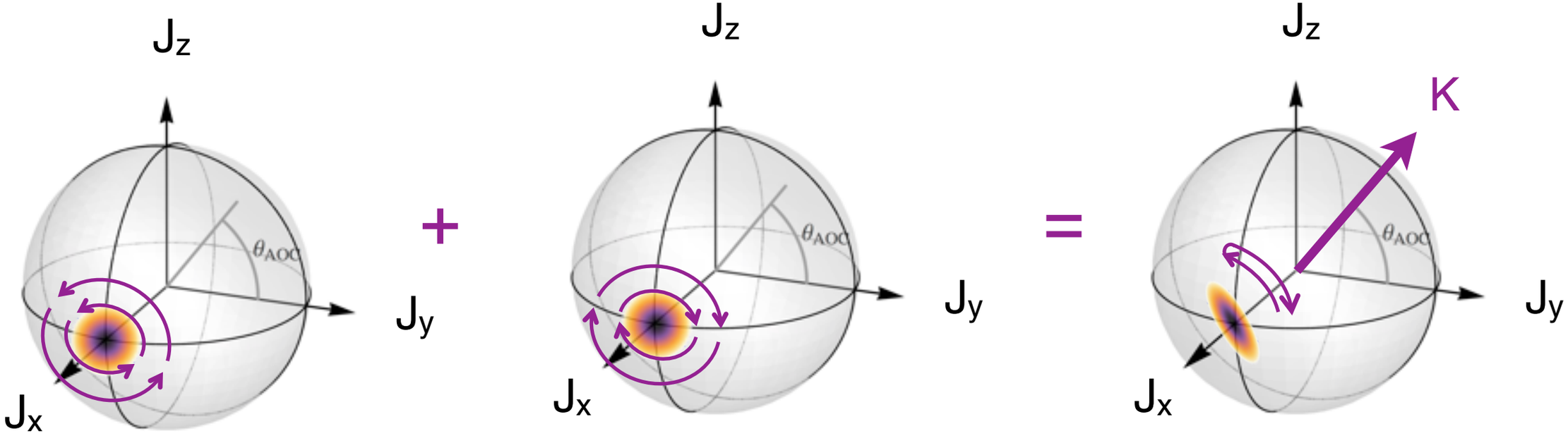




$$\phi \propto K$$

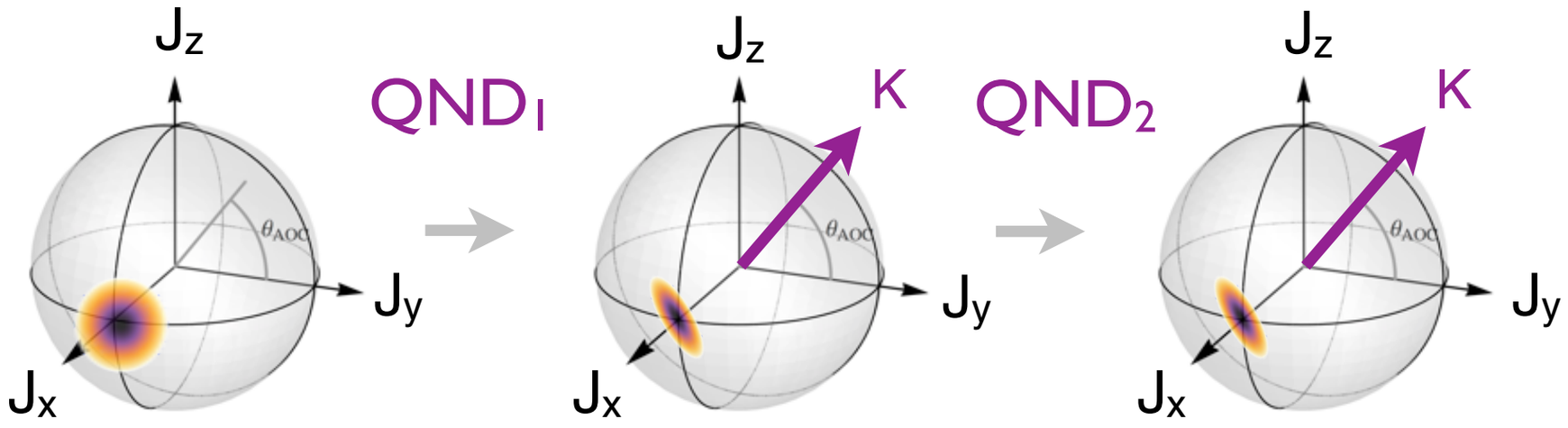


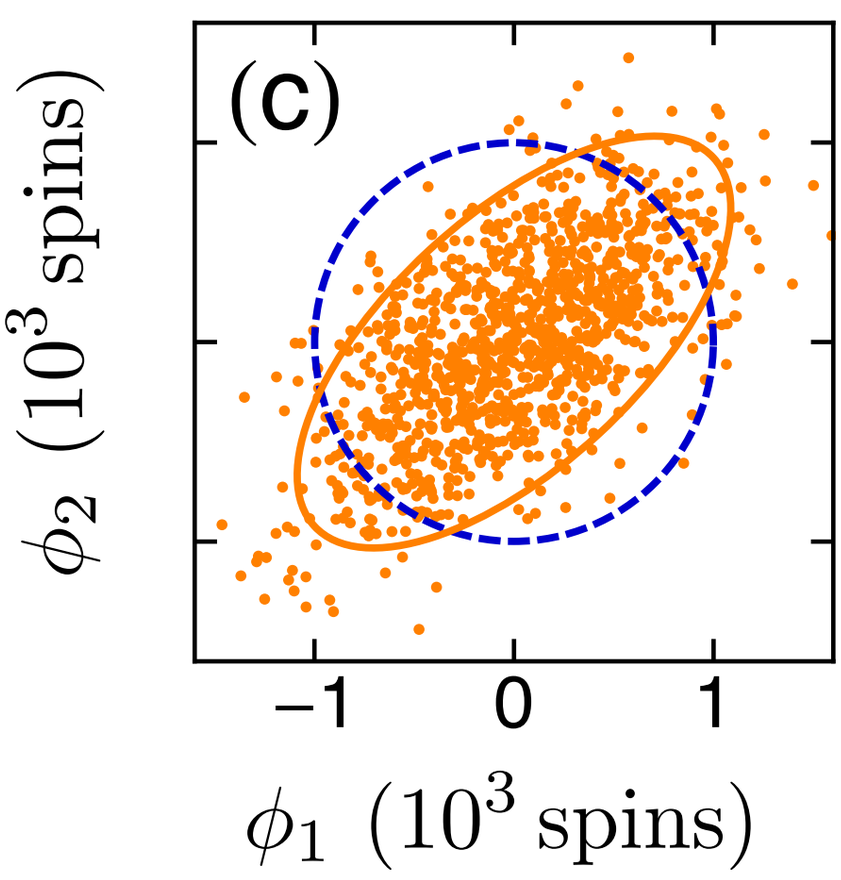
$$H = \kappa_1 S_z J_z + \kappa_2 \left(S_x J_x + S_y J_y \right)$$



Koschorreck, et al. PRL 105, 093602(2010)

Conditional noise reduction





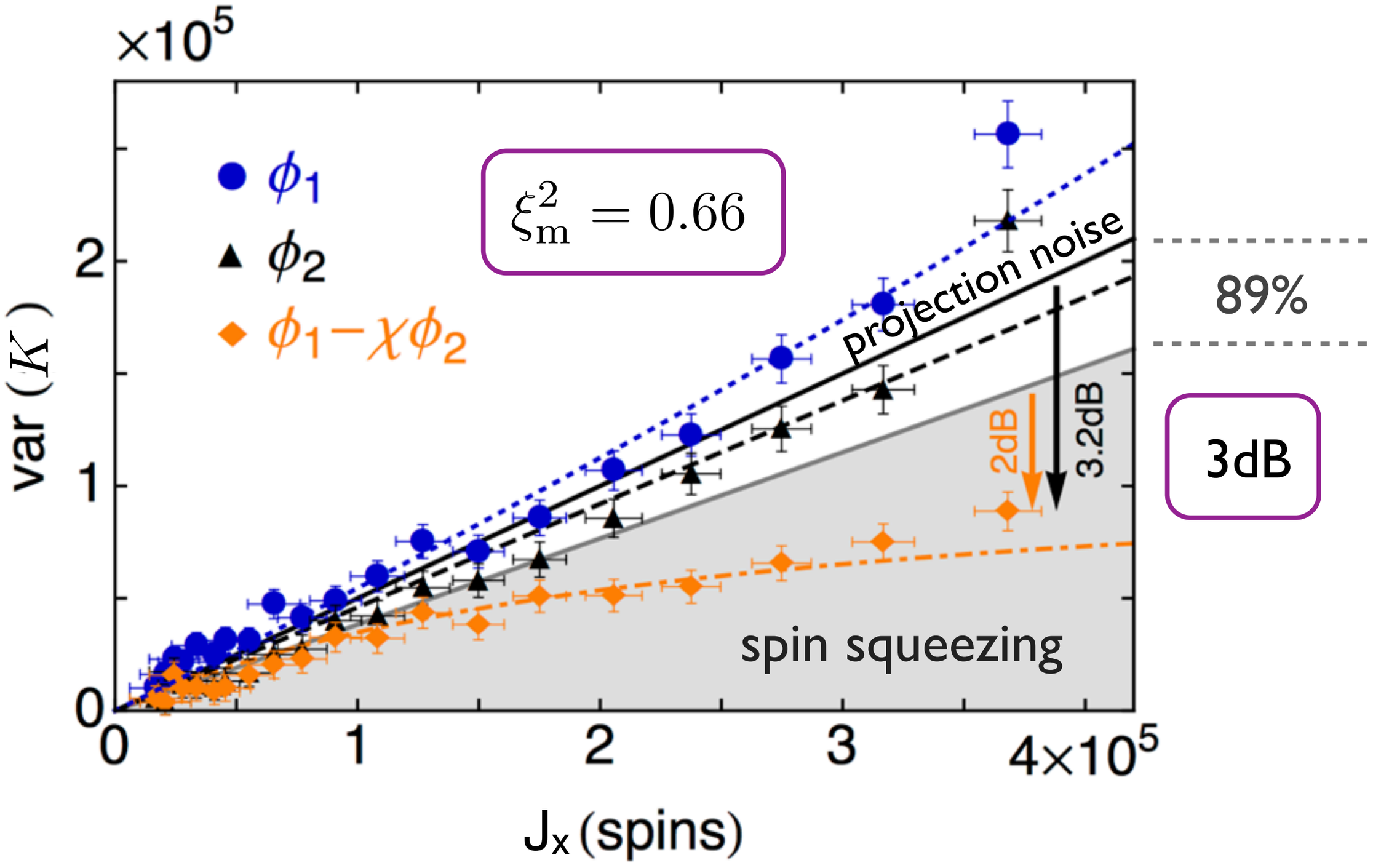
conditional variance

$$\mathrm{var}(K|\phi_1) \equiv \mathrm{var}(\phi_1 - \chi\phi_2)$$

$$\chi \equiv \frac{\mathrm{cov}(\phi_1, \phi_2)}{\mathrm{var}(\phi_1)}$$

R.J.S. et al. PRL 109, 253695 (2012)

Squeezing & entanglement

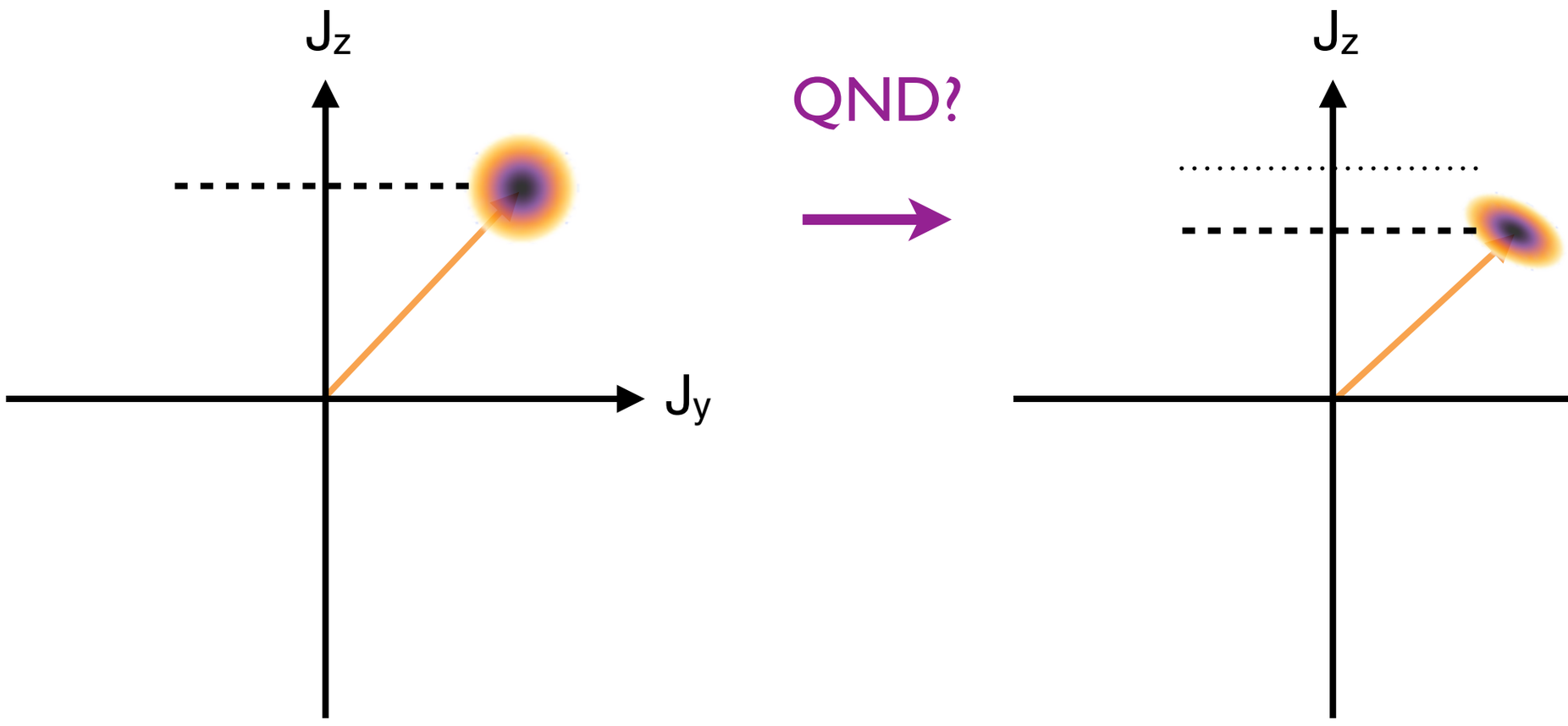


89%

3dB

R.J.S. et al. PRL 109, 253695 (2012)

QND measurement?

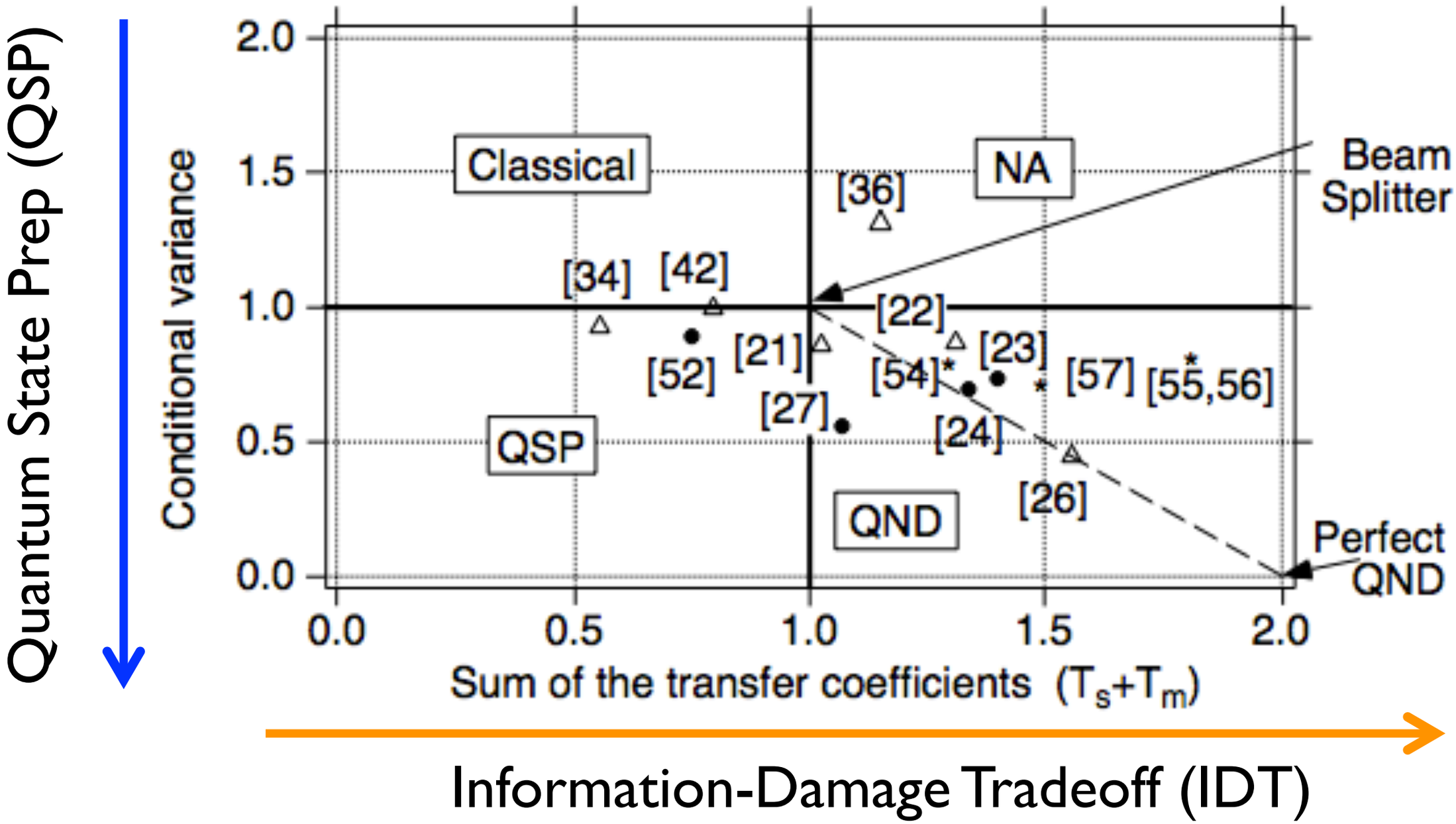


Grangier et al. Nature 396, 527 (1998)

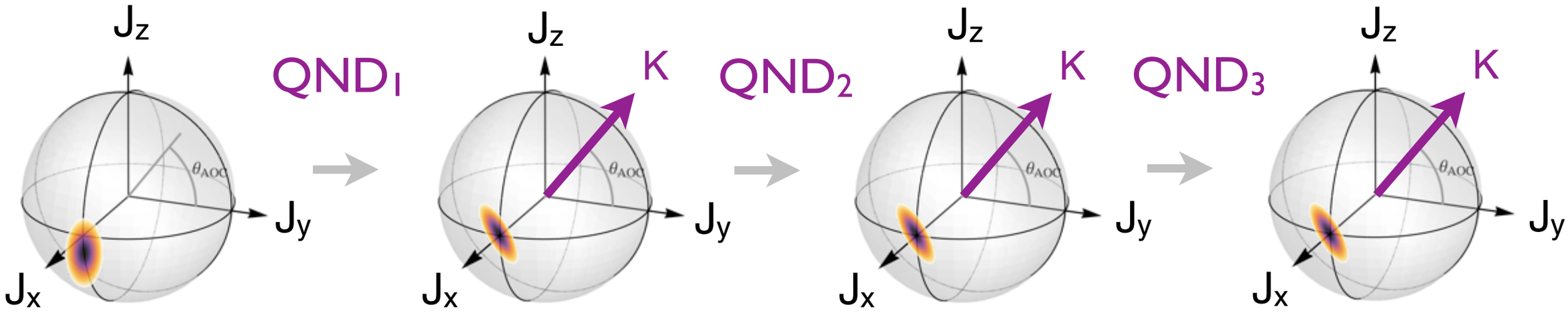
review article

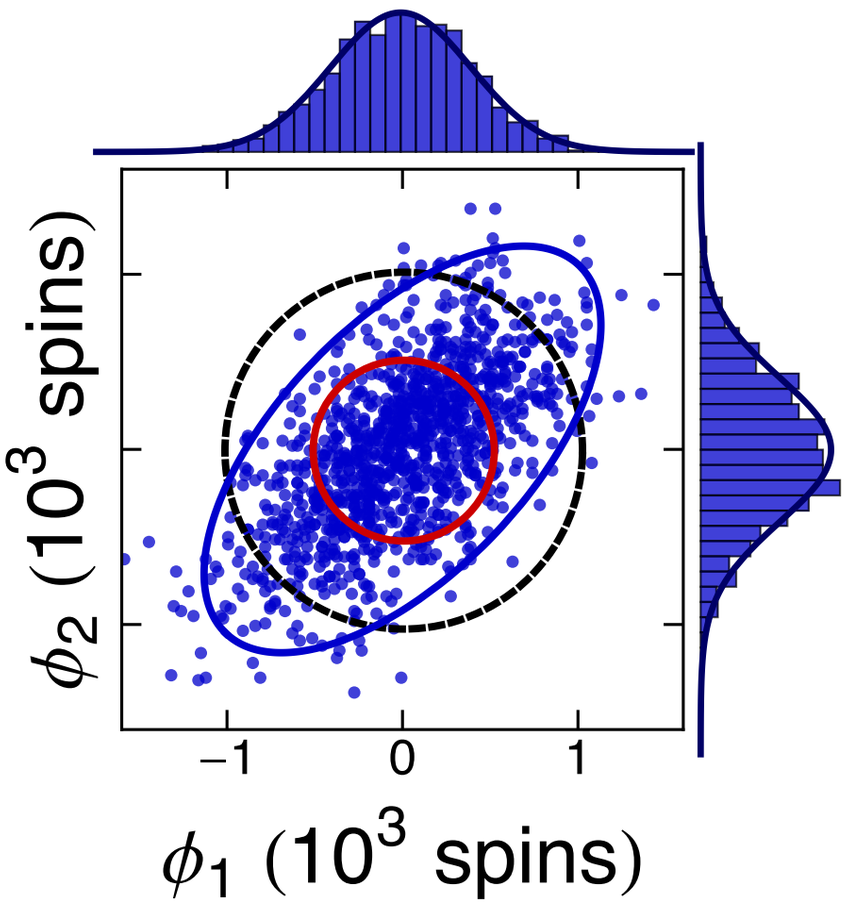
Quantum non-demolition measurements in optics

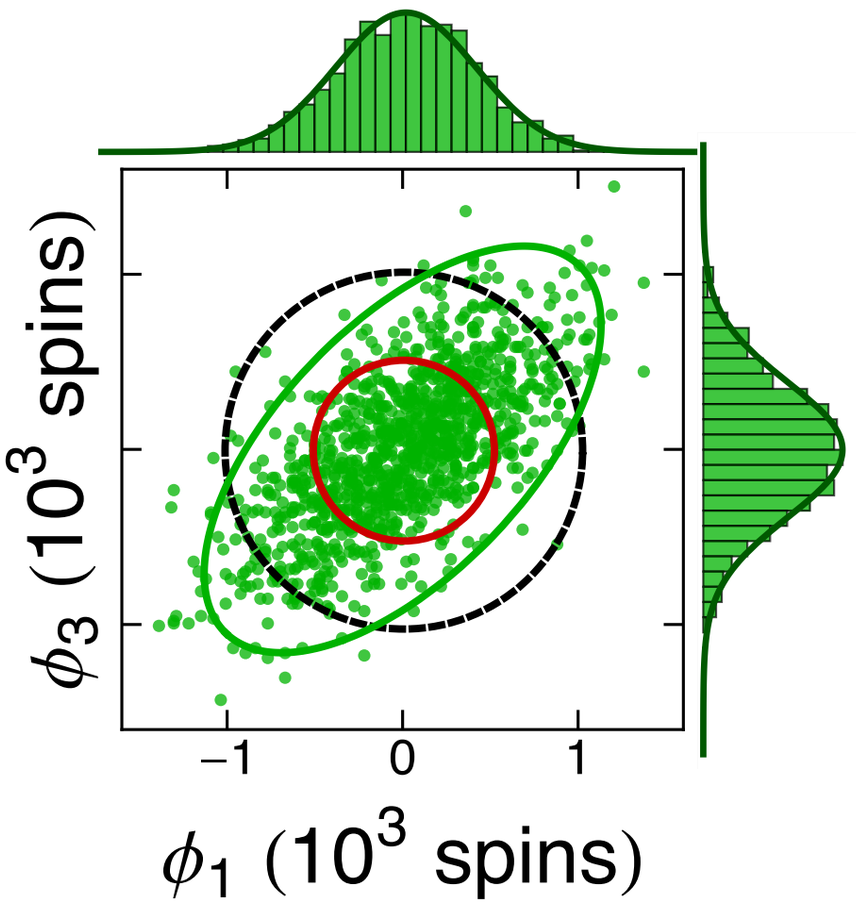
Philippe Grangier, Juan Ariel Levenson & Jean-Philippe Poizat



Repeated measurements

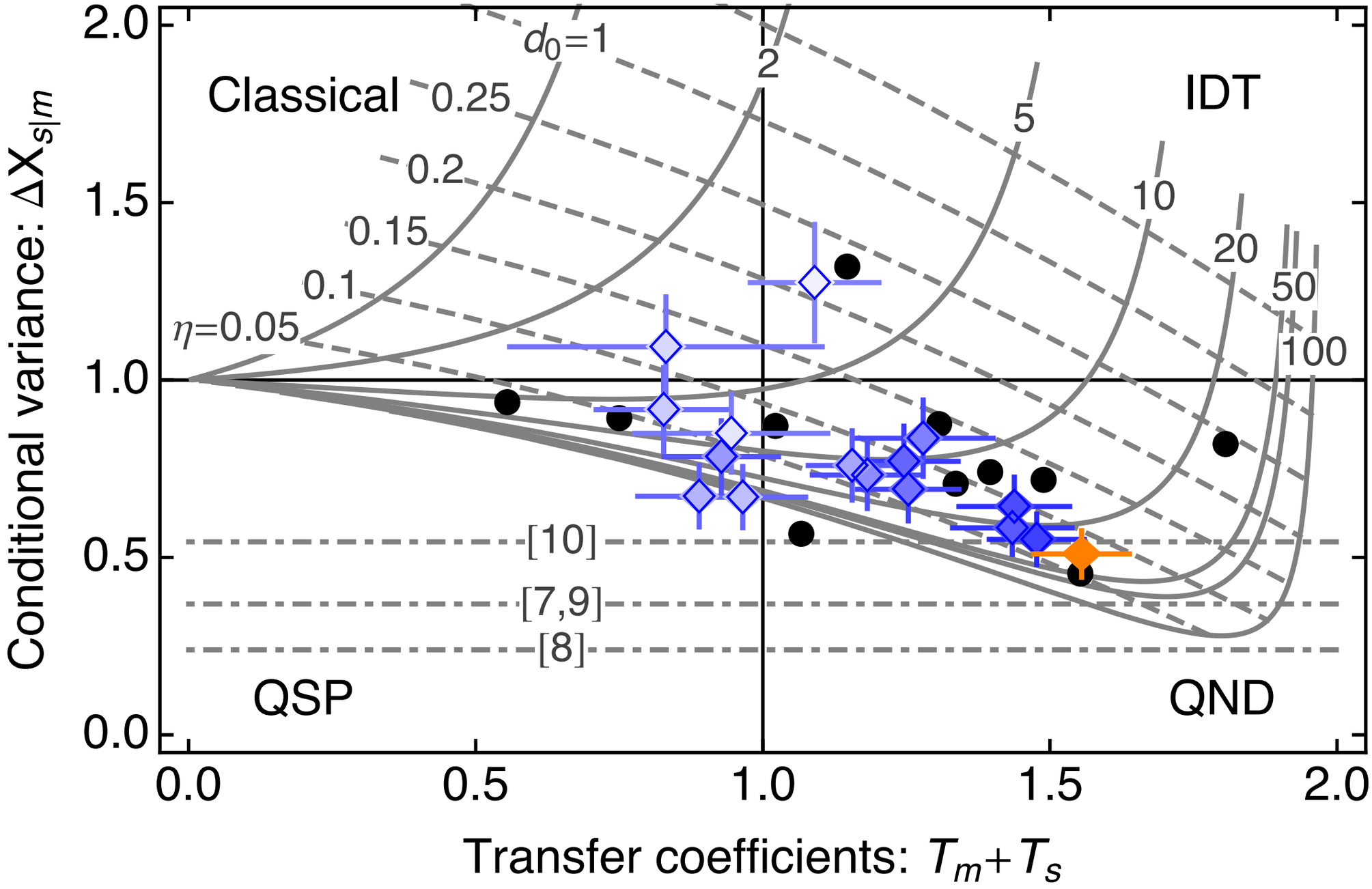






Mitchell et al. NJP 14, 085021 (2012)

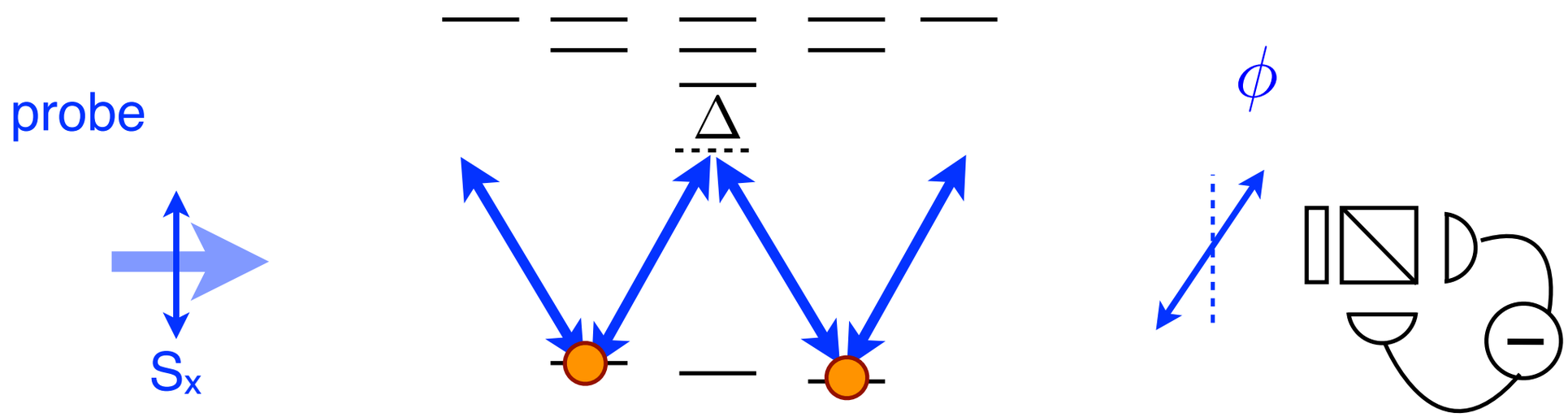
QND measurement of atomic spins

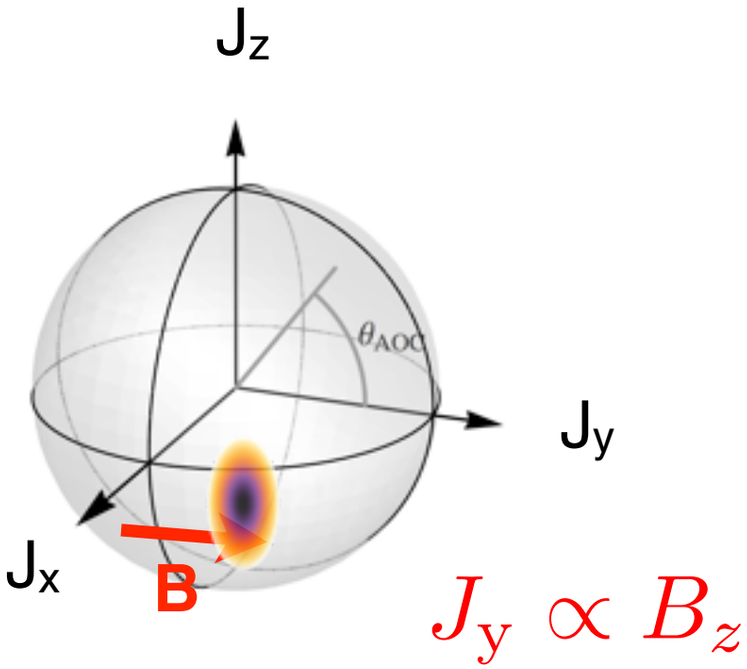


[7] Appel, Proc. Natl. Acad. Sci. USA 106, 10960 (2009)
[8] Schleier-Smith PRL 104, 073604 (2010)
[9] Chen PRL 106, 133601 (2011)
[10] Sewell PRL 109, 253605 (2012)

R.J.S. et al. Nat. Phot. 7, 517 (2013)

Quantum-enhanced magnetometry

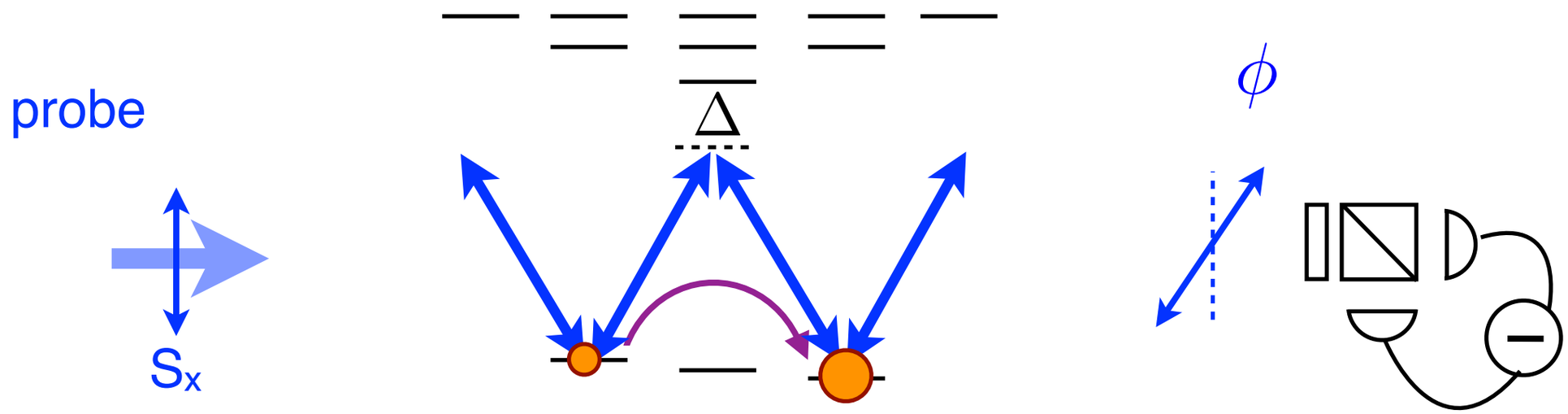


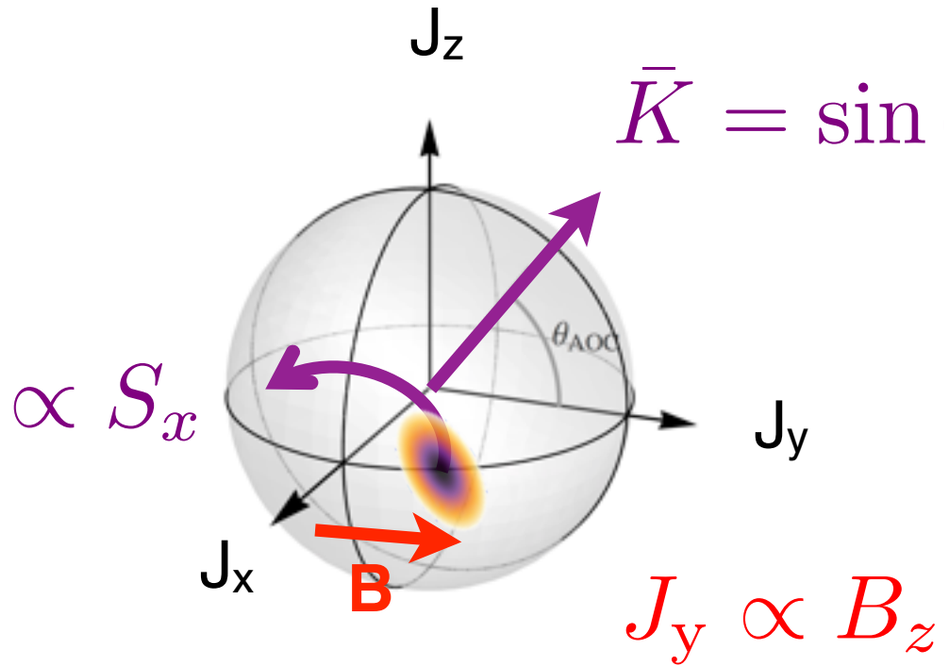


$$J_y \propto B_z$$

R.J.S. et al. PRL 109, 253695 (2012)

Quantum-enhanced magnetometry

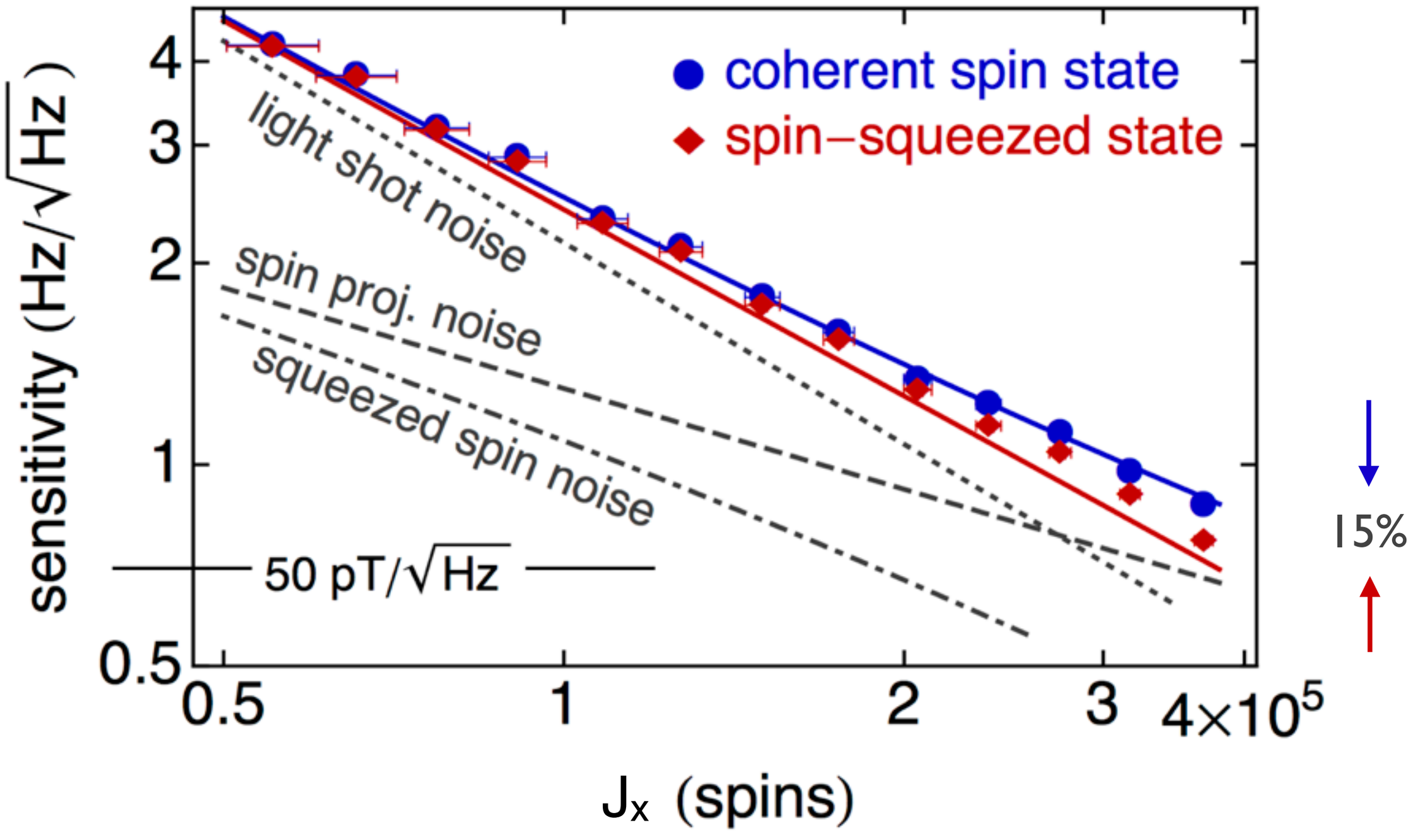




$$\theta \equiv \kappa_2 S_x/2$$

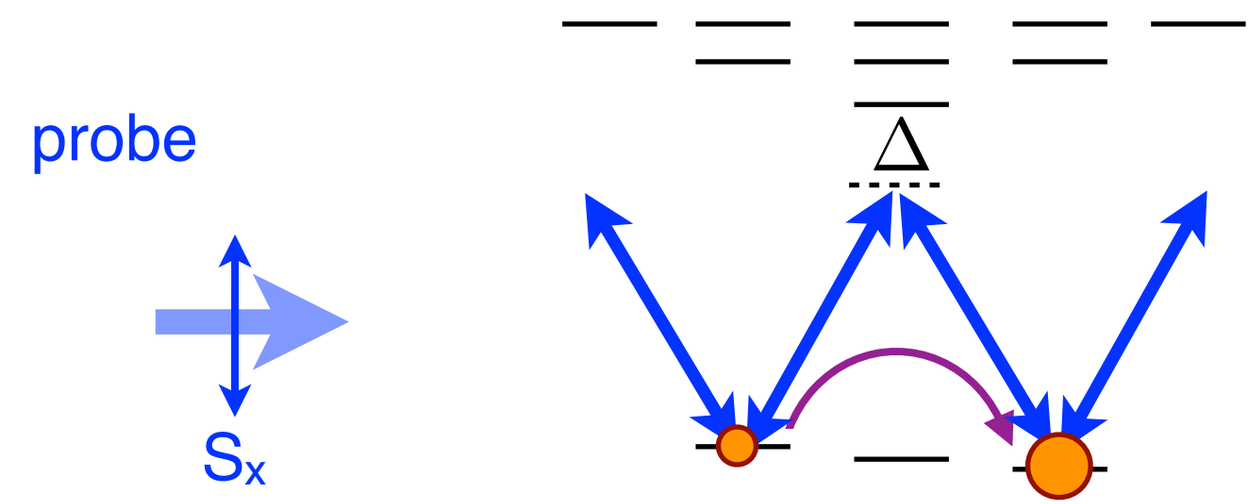
R.J.S. et al. PRL 109, 253695 (2012)

Quantum-enhanced magnetometry

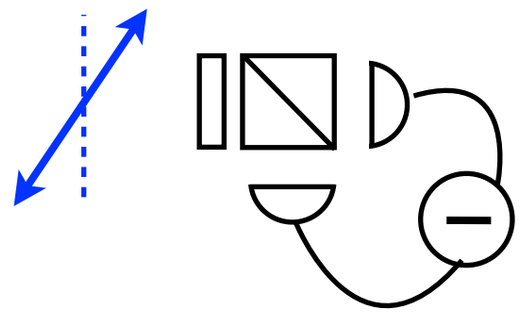


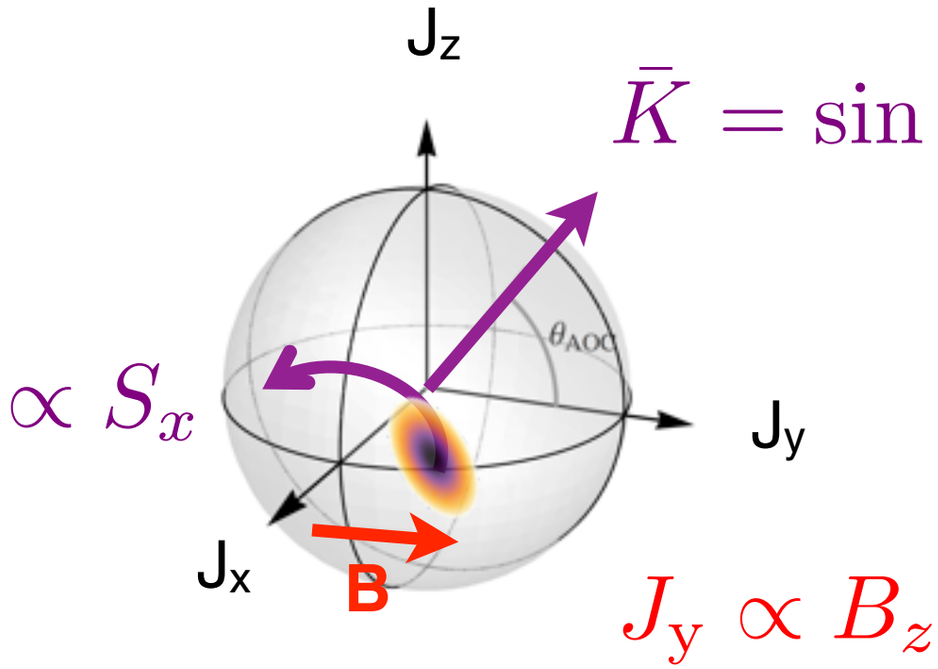
R.J.S. et al. PRL 109, 253695 (2012)

Quantum-enhanced magnetometry



$\bar{\phi} \propto \bar{J}_y$



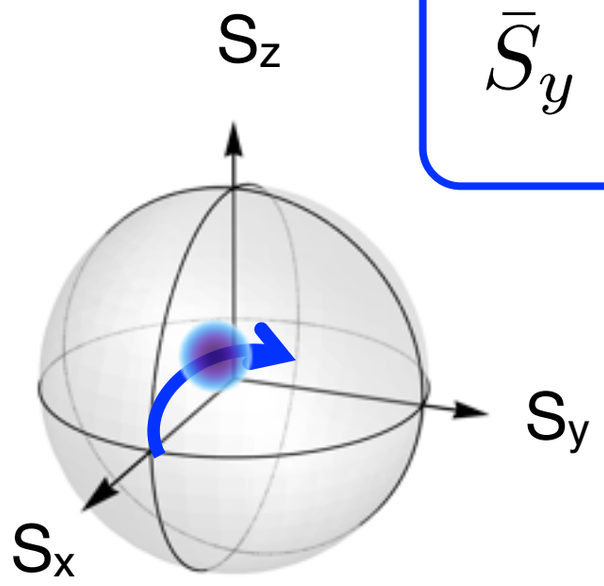


$\bar{K} = \sin\theta \bar{J}_y$

$\propto S_x$

$J_y \propto B_z$

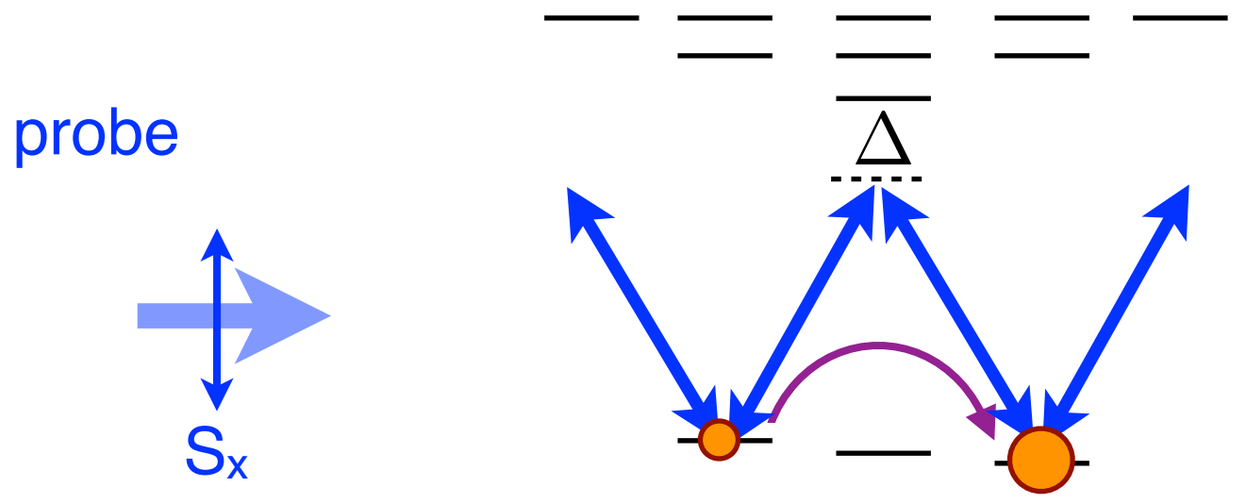
$\theta \equiv \kappa_2 S_x/2$



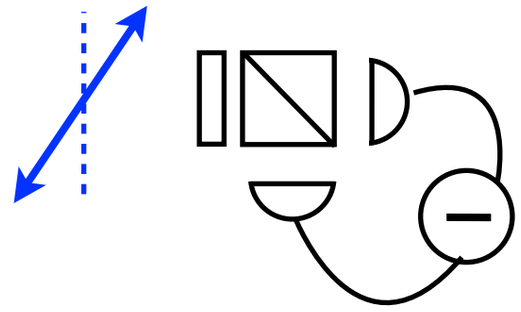
$$\bar{S}_y = \frac{\kappa_1 \kappa_2}{2} S_x^2 \bar{J}_y$$

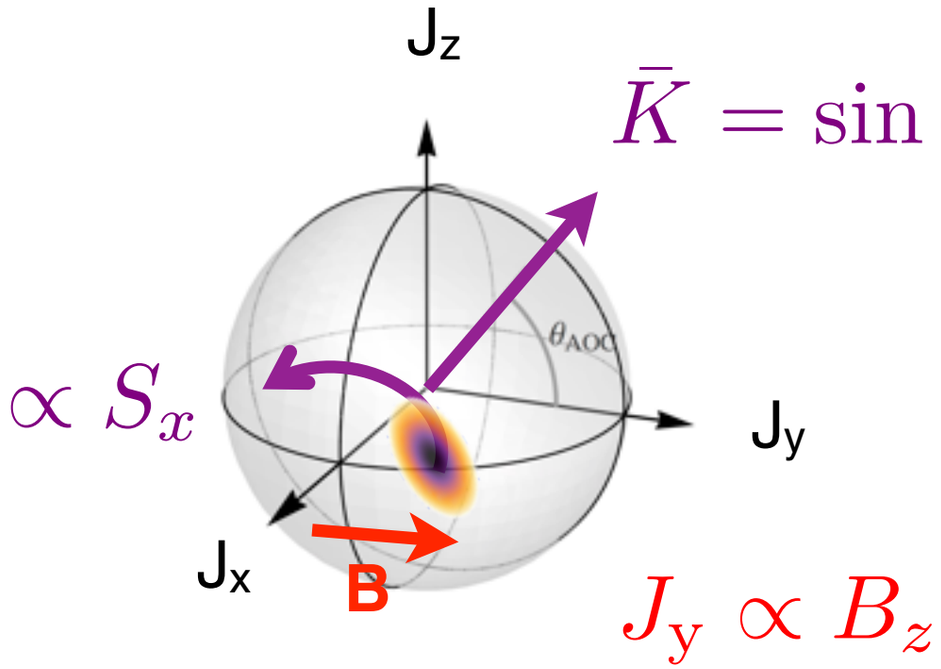
R.J.S. et al. PRL 109, 253695 (2012)

Nonlinear quantum metrology



$\bar{\phi} \propto \bar{J}_y$



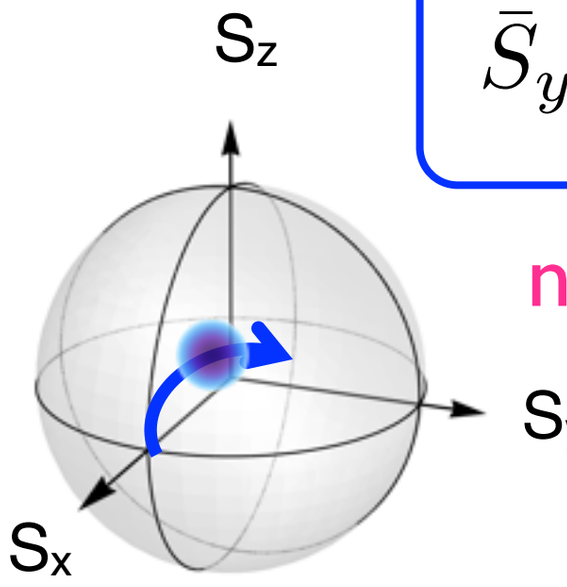


$\bar{K} = \sin\theta \bar{J}_y$

$\propto S_x$

$J_y \propto B_z$

$\theta \equiv \kappa_2 S_x/2$



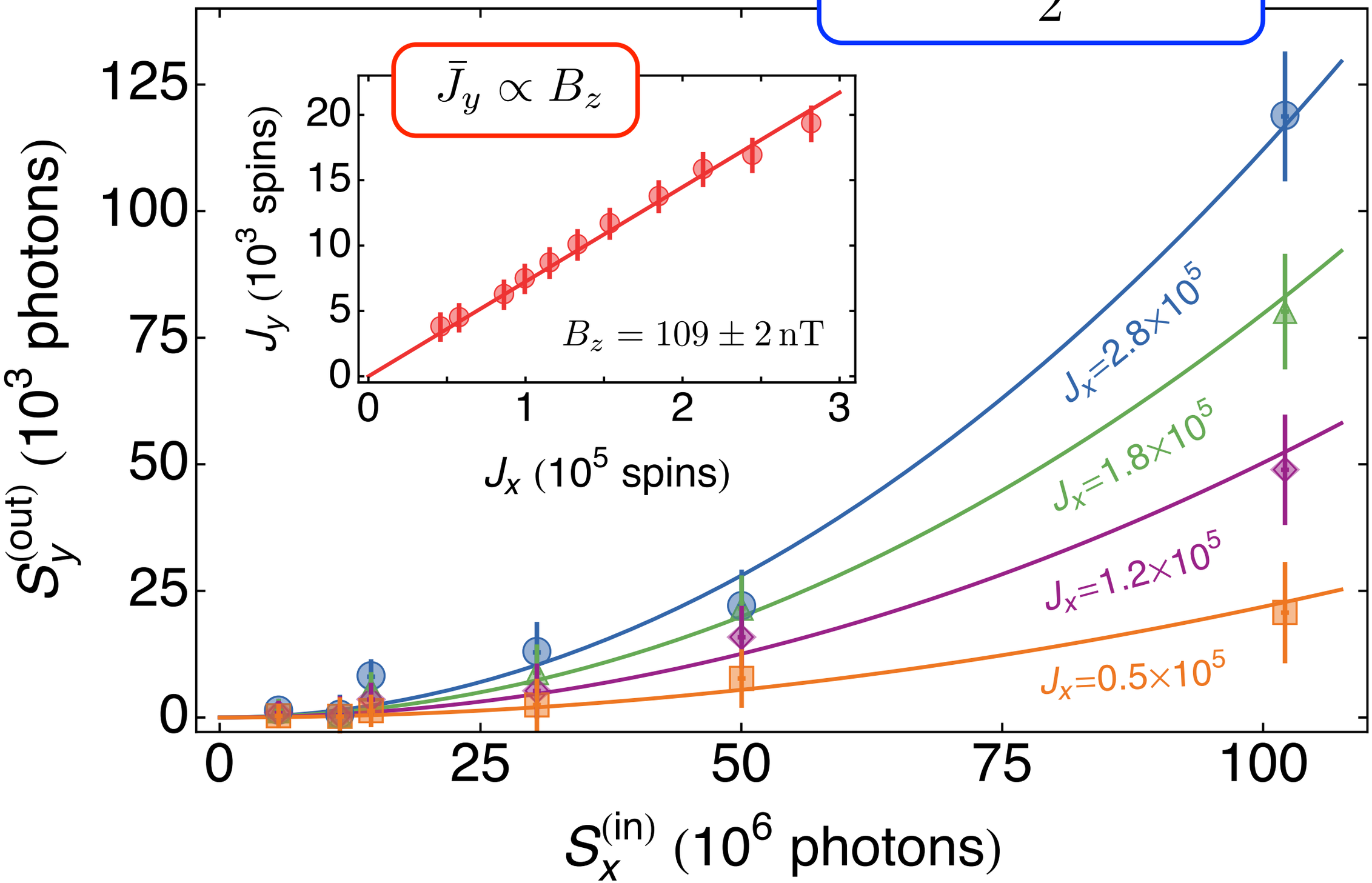
$$\bar{S}_y = \frac{\kappa_1 \kappa_2}{2} S_x^2 \bar{J}_y$$

nonlinear Faraday rotation

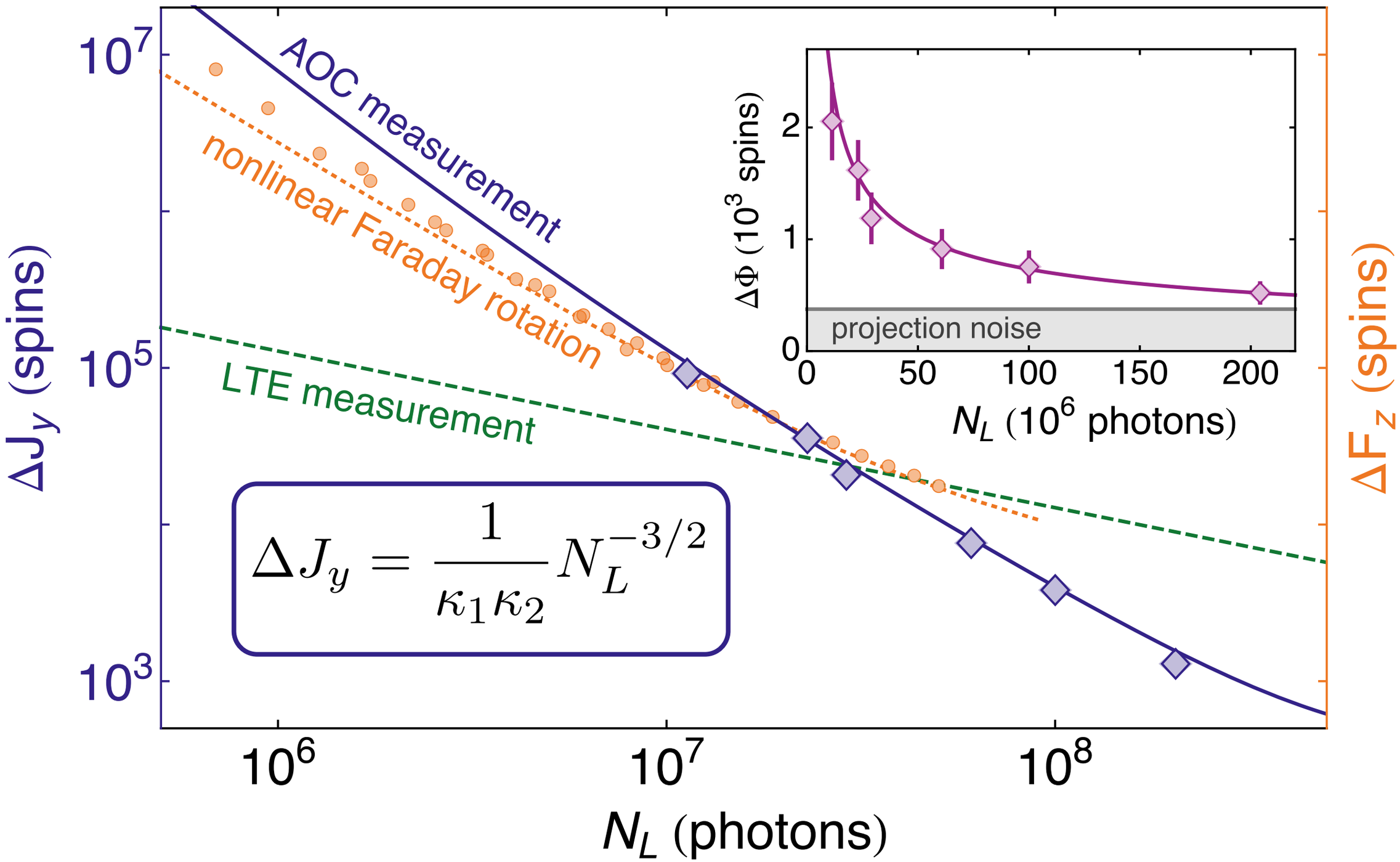
R.J.S. et al. PRL 109, 253695 (2012)

Nonlinear read-out

$$\bar{S}_y = \frac{\kappa_1 \kappa_2}{2} S_x^2 \bar{J}_y$$

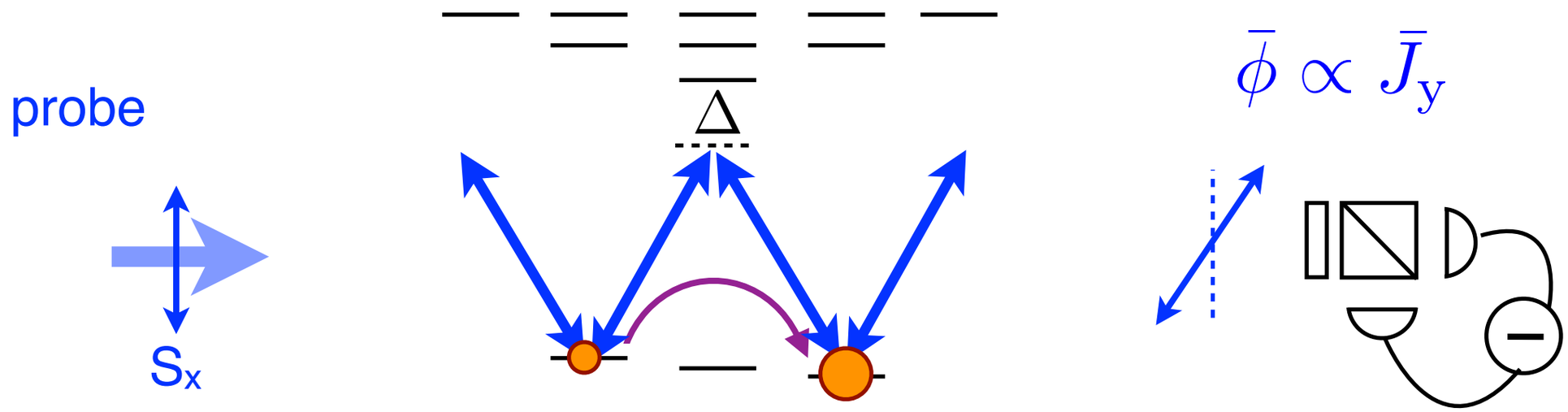


Super-Heisenberg scaling



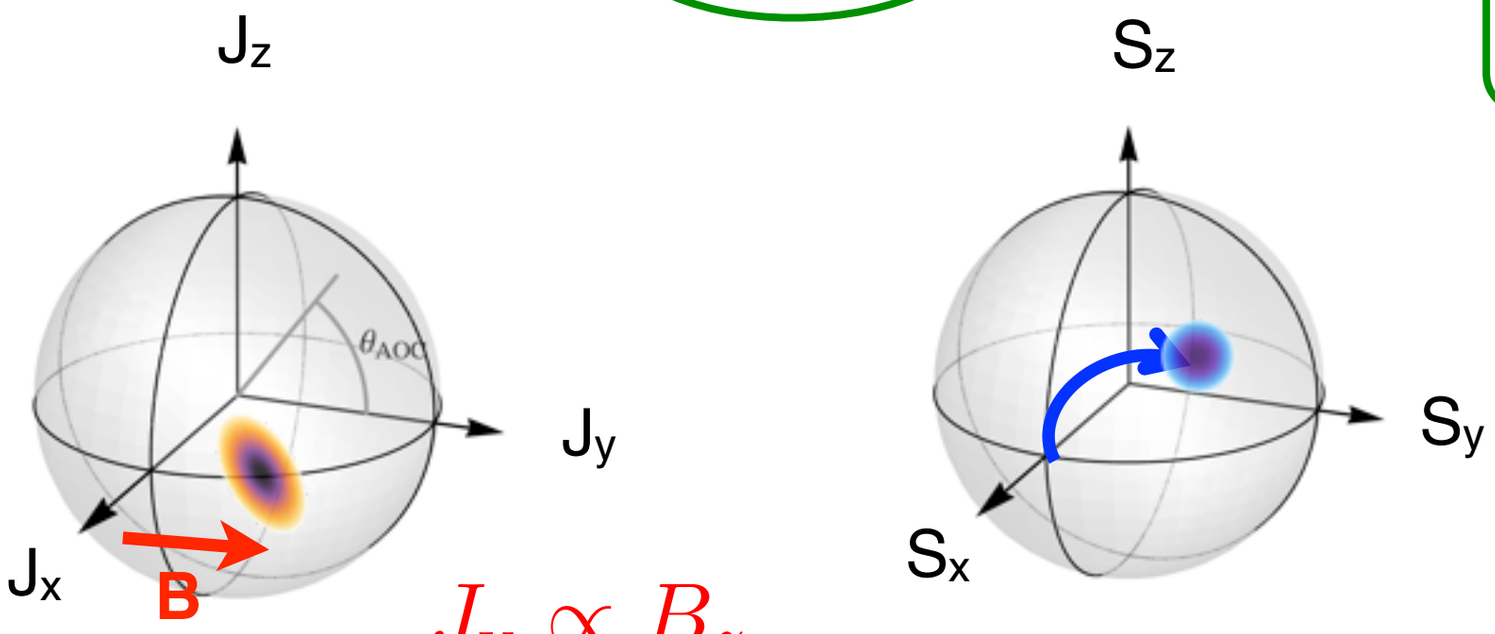
R.J.S. et al. submitted (2013)

Linear read-out



$$H = \kappa_1 S_z J_z + \kappa_2 \left(S_x J_x + S_y J_y \right)$$

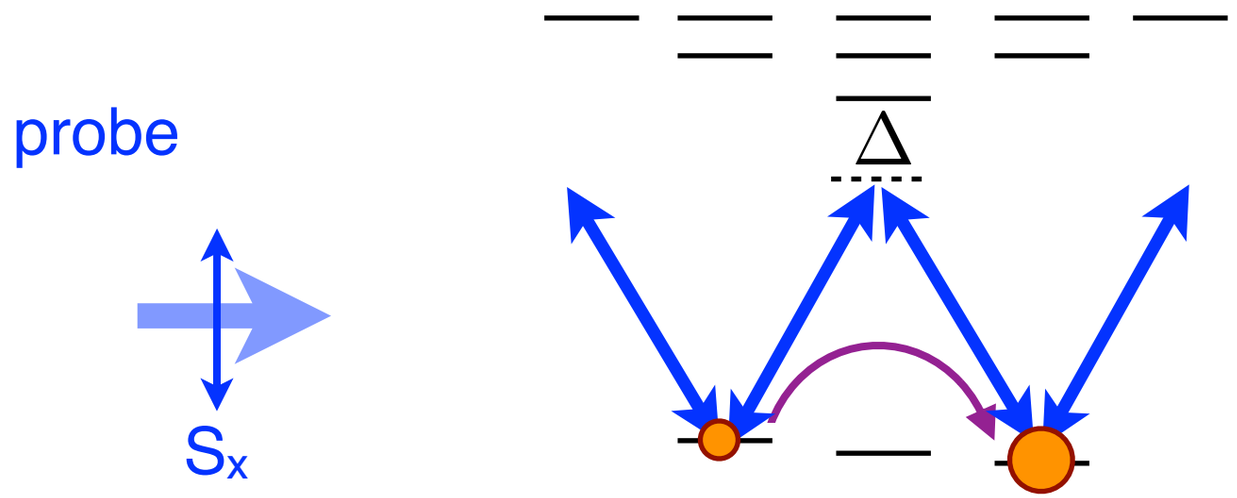
$$\bar{S}_z = \kappa_2 S_x \bar{J}_y$$



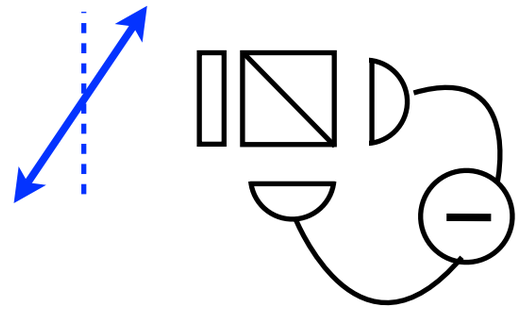
$$J_y \propto B_z$$

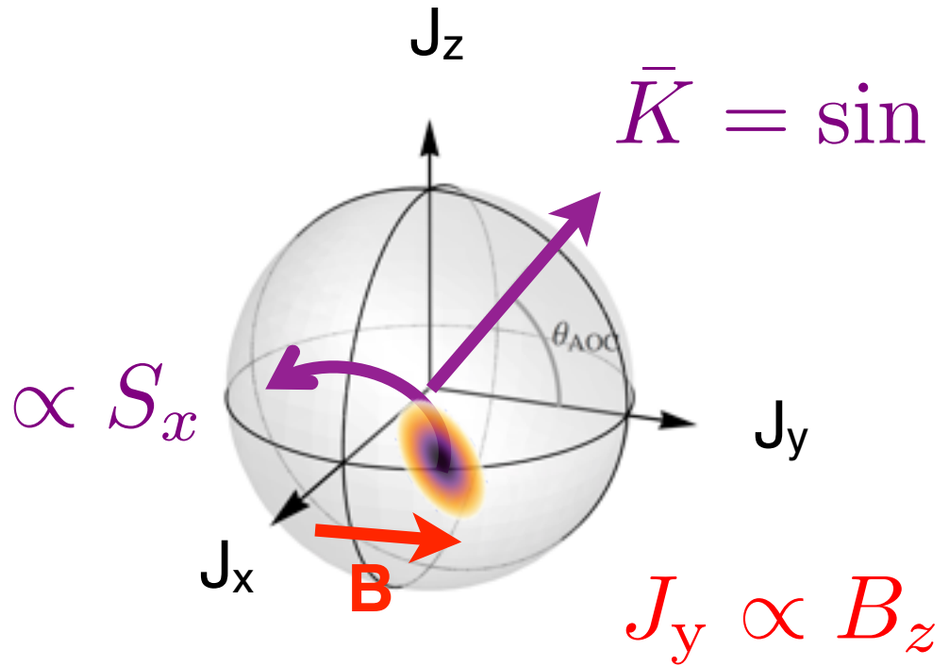
R.J.S. et al. submitted (2013)

Linear read-out



$\bar{\phi} \propto \bar{J}_{\mathrm{y}}$



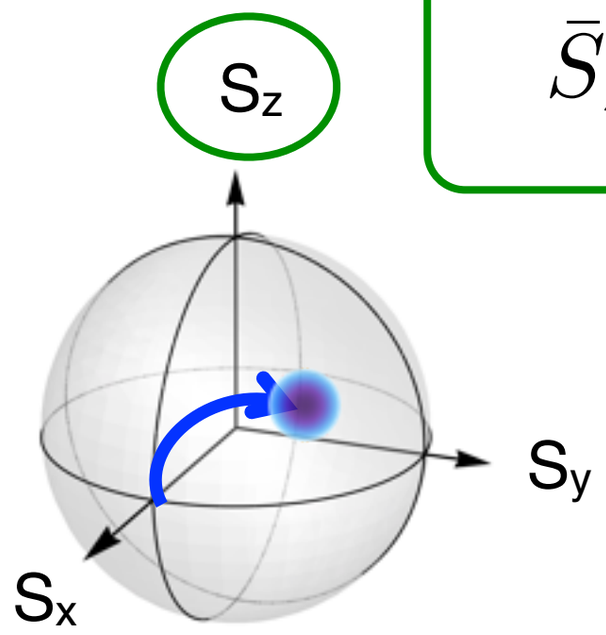


$\bar{K} = \sin\theta \bar{J}_{\mathrm{y}}$

$\propto S_x$

$J_{\mathrm{y}} \propto B_z$

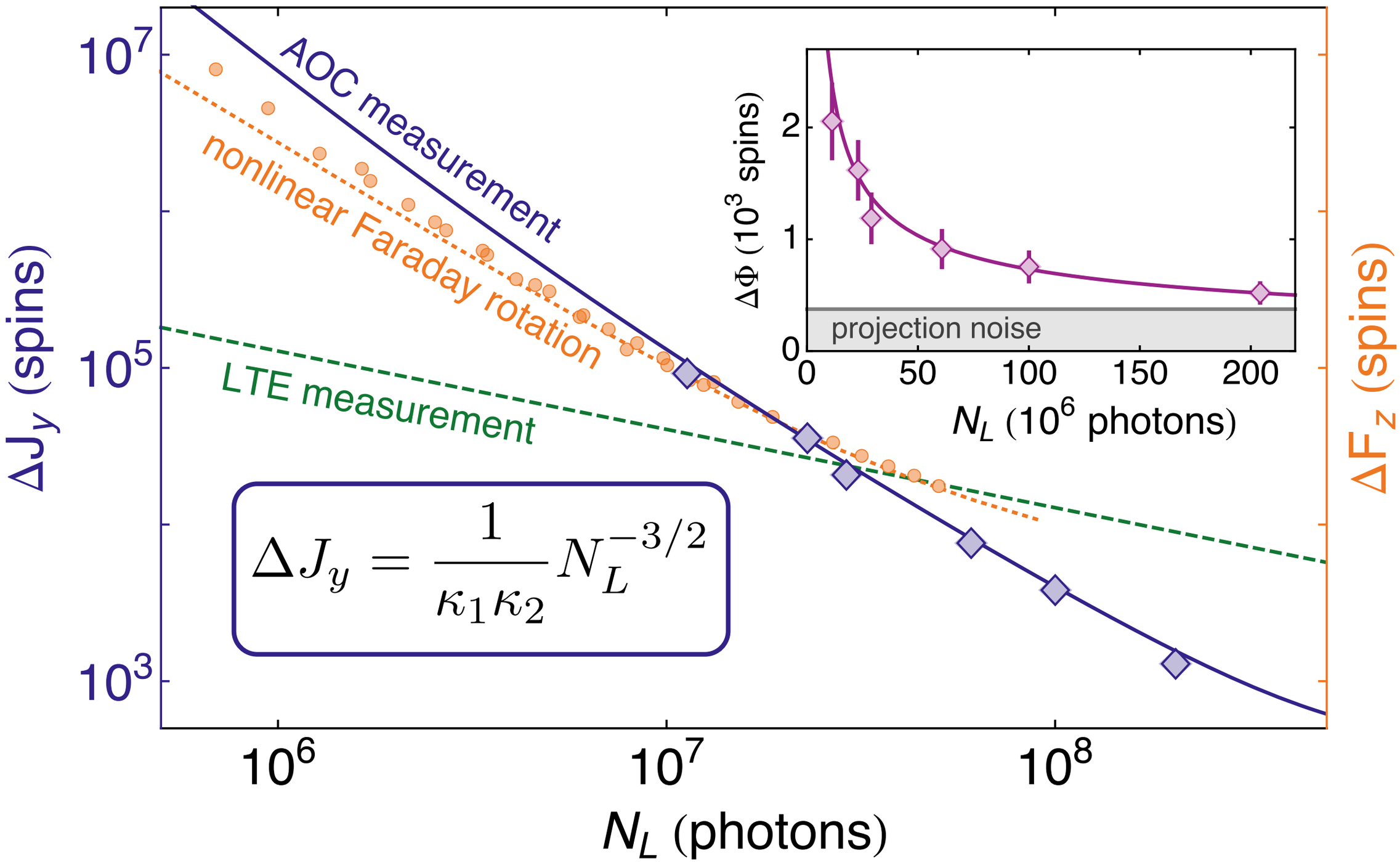
$\theta \equiv \kappa_2 S_x/2$



$\bar{S}_z = \kappa_2 S_{\mathrm{x}} \bar{J}_y$

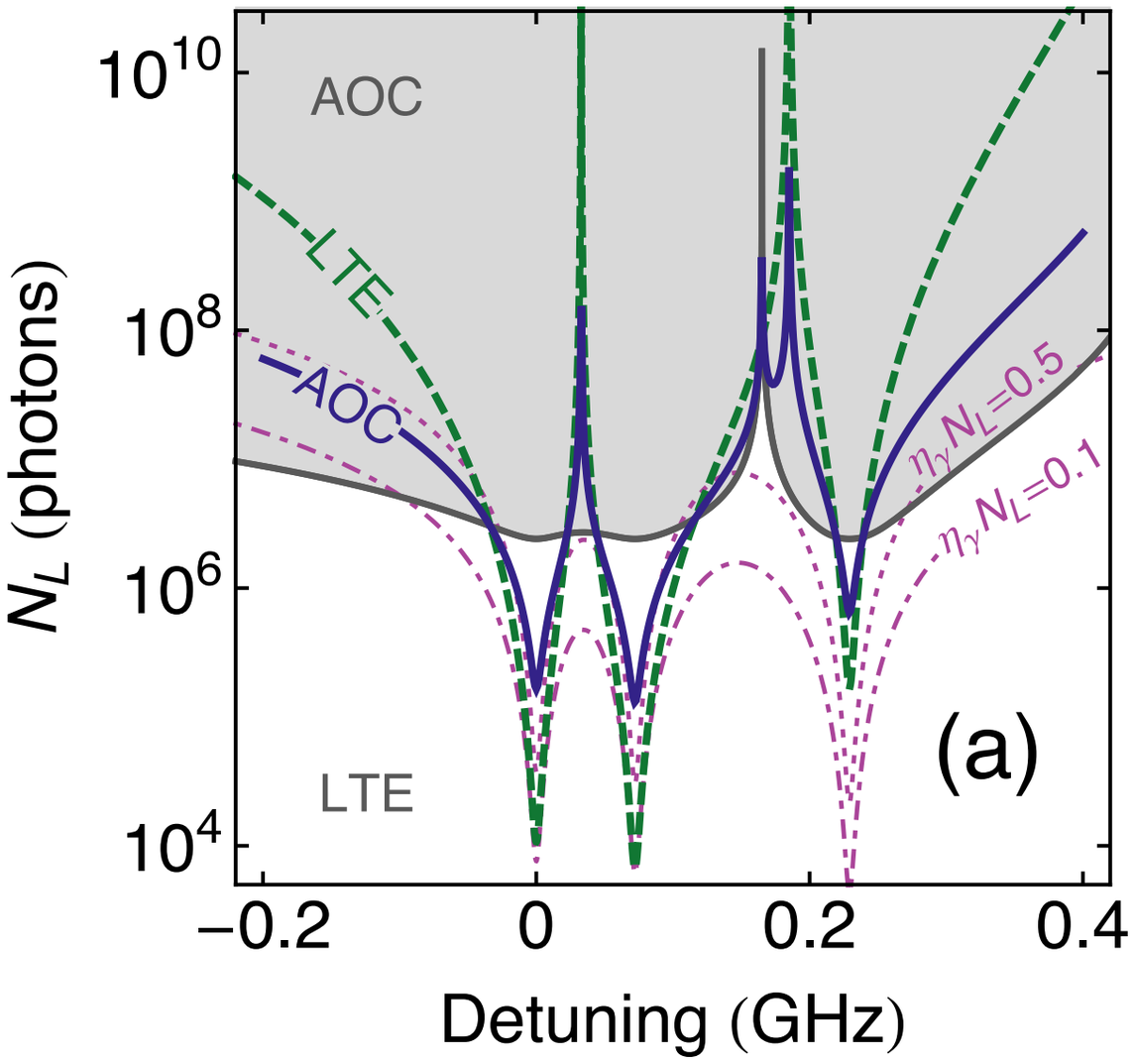
R.J.S. et al. submitted (2013)

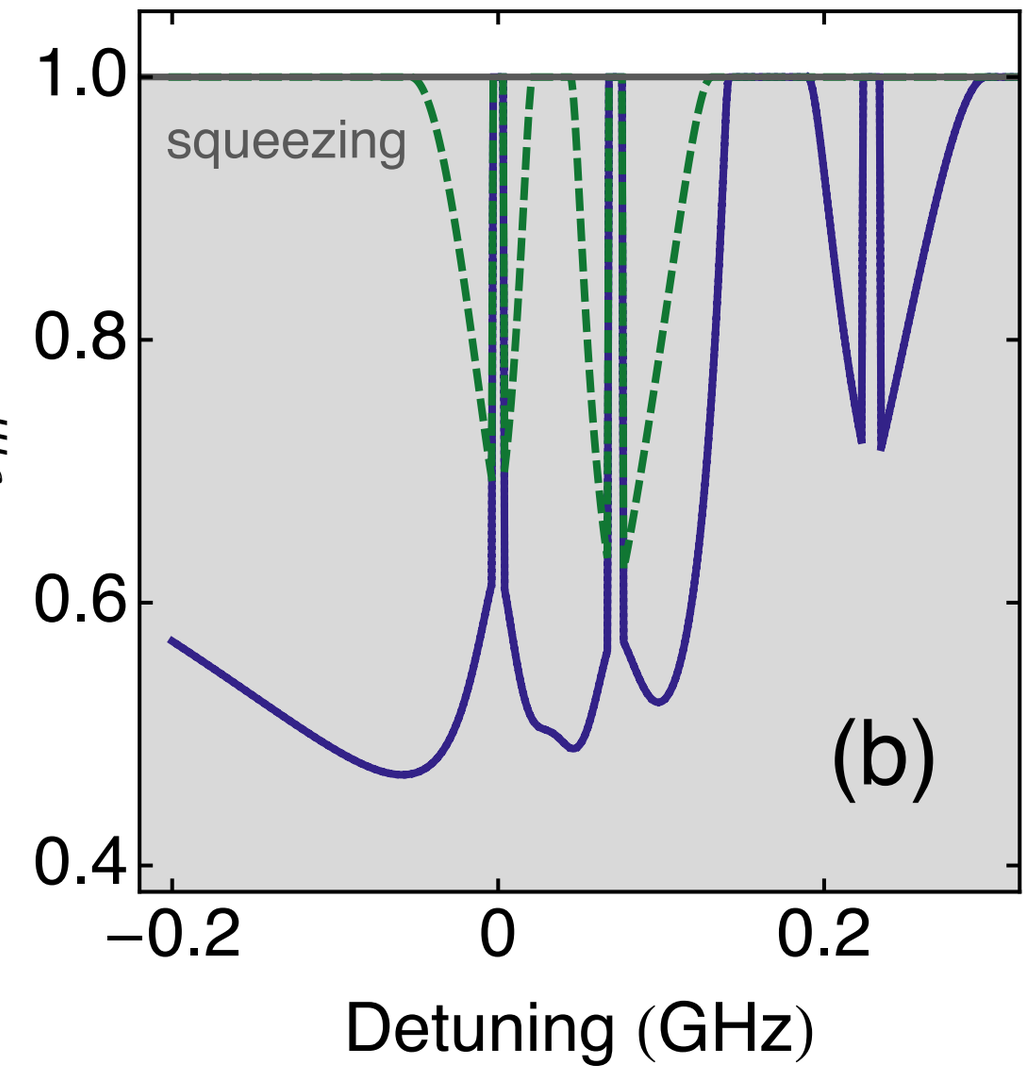
Super-Heisenberg scaling



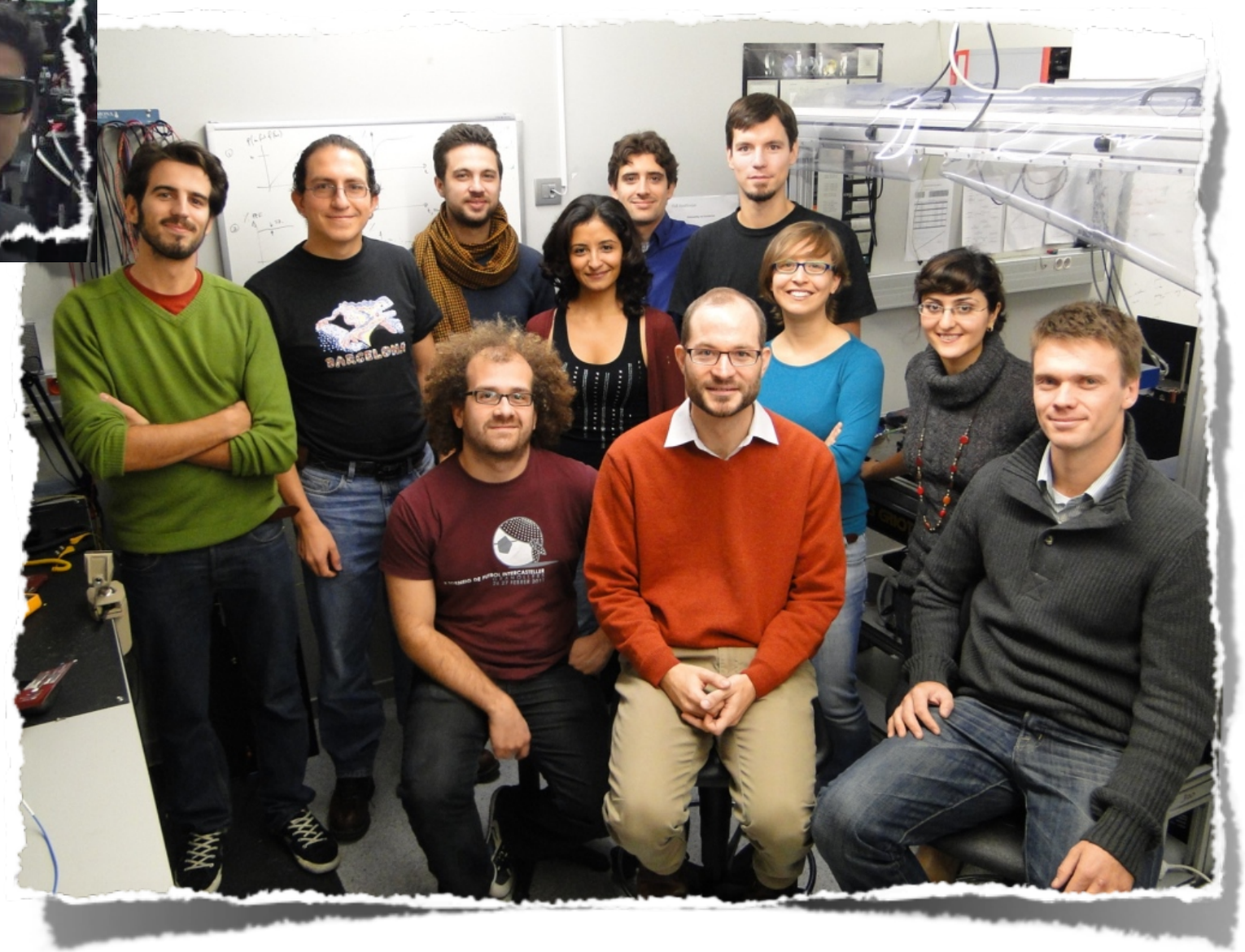
R.J.S. et al. submitted (2013)

Nonlinear beats linear readout





R.J.S. et al. submitted (2013)



M. Koschorreck
(Cambridge)

R.J.S, M. Napolitano, G. Colangelo, N. Behbood,
F. Martin Ciurana & M.W. Mitchell*

MINISTERIO DE CIENCIA E INNOVACIÓN
Generalitat de Catalunya
erc
MARIE CURIE ACTIONS
Fundació Privada CELLEX
icrea
Institució Catalana de Recerca i Estudis Avançats