Generation of a macroscopic spin singlet in cold atomic ensemble

Naeimeh Behbood[1], M. Napolitano[1], G. Colangelo[1], F. Martin Ciurana[1], G.Toth[2], R. J. Sewell[1], Morgan W. Mitchell[1,3]

[1]ICFO – Institute of Photonic Sciences
[2]Department of Theoretical Physics, Bilbao, Spain
[3]ICREA – Catalan Institution for Advanced Research

arXiv:1403.1964

Singlet state

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

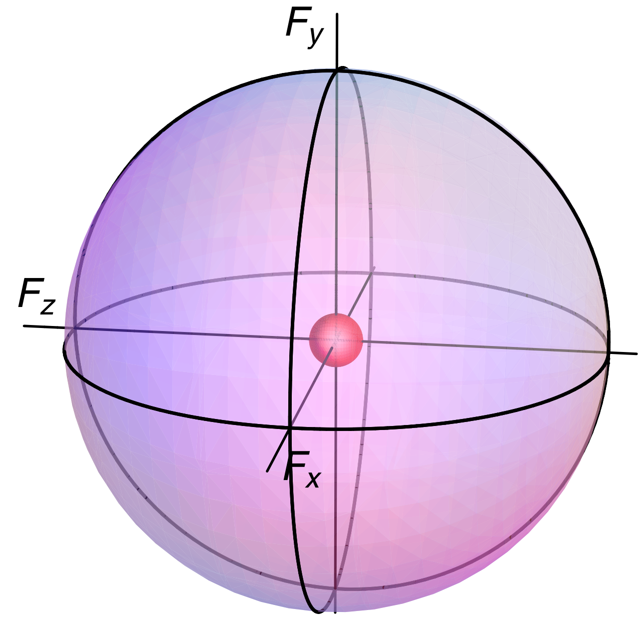
Zero spin $\mathbf{j} = \mathbf{0}$

No fluctuations $\Delta\mathbf{j} = \mathbf{0}$

What is a macroscopic spin singlet ?

<F> = 0

Var(F) = 0

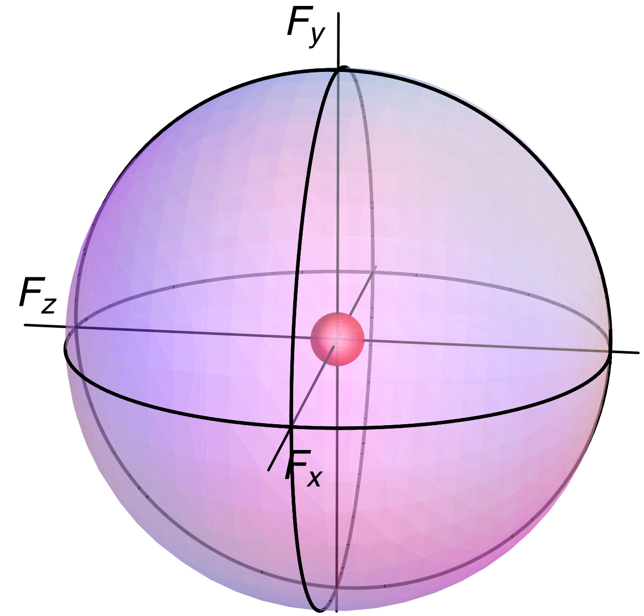


F is collective angular momentum

$$\mathbf{F} = \sum_{l=1}^{N_A} \mathbf{f}_l$$

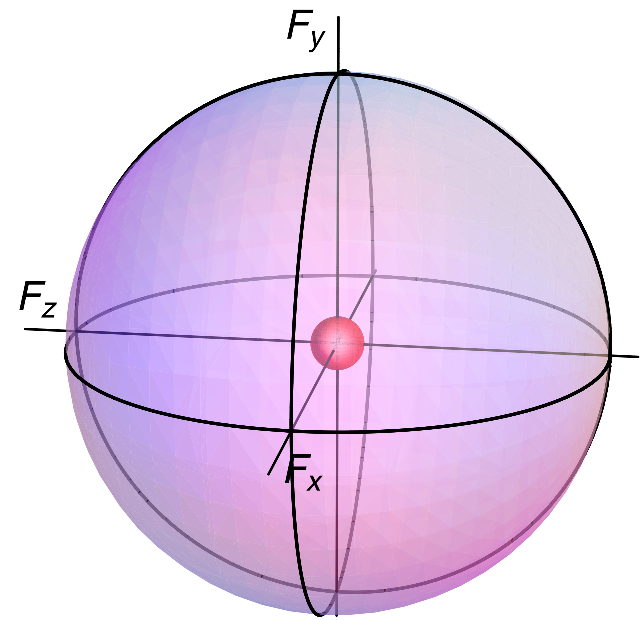
Doesn't the uncertainty principle forbid this ?

$$\delta F_x \delta F_z \geq \frac{1}{2}|\langle F_y \rangle| = 0$$



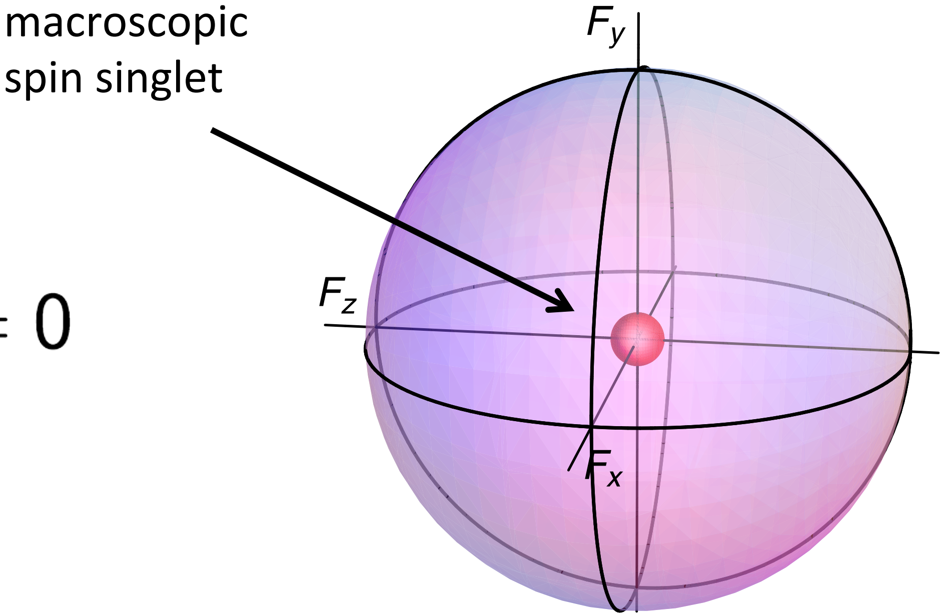
Doesn't the uncertainty principle forbid this ?

$$\delta F_x \delta F_z \geq \frac{1}{2}|\langle F_y \rangle| = 0$$



$$\delta F_x \delta F_y \geq 0$$
$$\delta F_y \delta F_z \geq 0$$
$$\delta F_z \delta F_x \geq 0$$

Doesn't the uncertainty principle forbid this ?



$$\delta F_x \delta F_z \geq \frac{1}{2}|\langle F_y \rangle| = 0$$

$$\delta F_x \delta F_y \geq 0$$
$$\delta F_y \delta F_z \geq 0$$
$$\delta F_z \delta F_x \geq 0$$

G. Toth, MWM, NJP **12** 053007 (2010)
Phys. Rev. A 87, 021601(R) (2013)

How do you know that you have made a MSS ?

spin squeezing parameter

$$\xi^2 \equiv \frac{\Delta F_x^2 + \Delta F_y^2 + \Delta F_z^2}{N_A f}$$

condition for squeezing

$$\xi^2 < 1$$

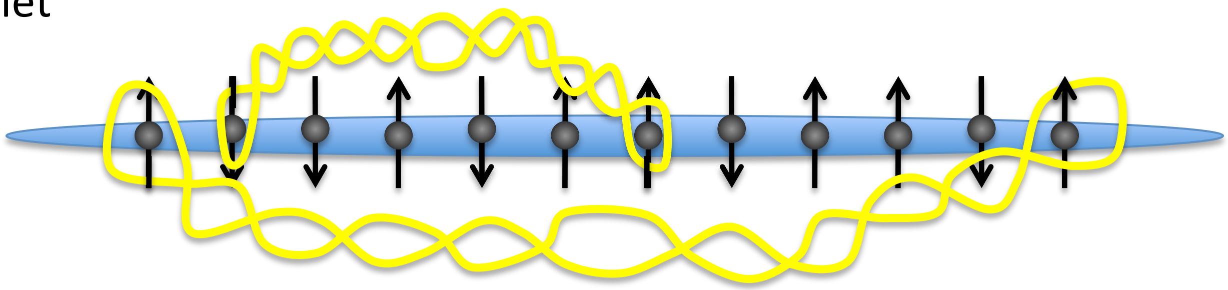
number of atoms in singlets

$$N_A(1 - \xi^2)$$

Vitagliano, Hyllus, Egusquiza and Tóth PRL (2011)
G. Toth, M. W. Mitchell, NJP **12** 053007 (2010)

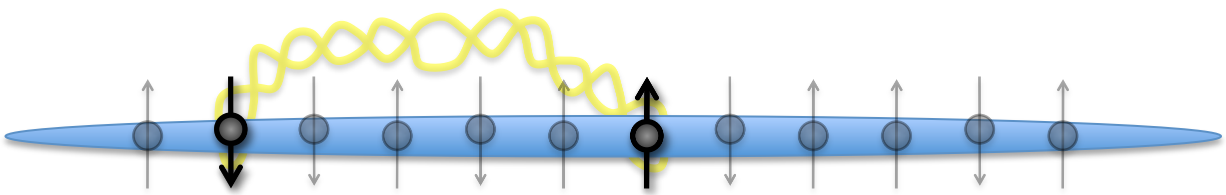
Motivation: Gradient magnetometry with singlets

Macro singlet



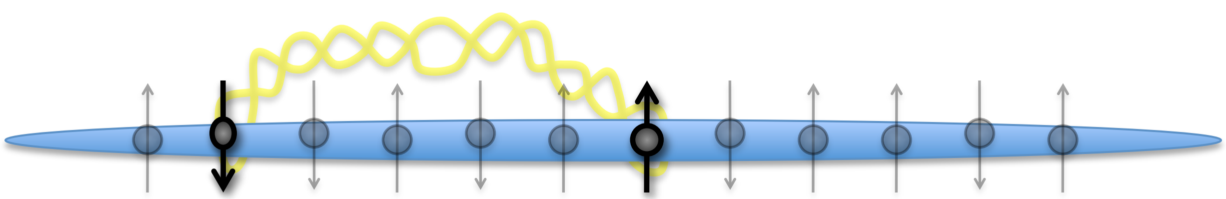
$|F|^2 = 0$

Uniform field : singlet -> singlet



$|F|^2 = 0$

Gradient field : singlet -> triplet



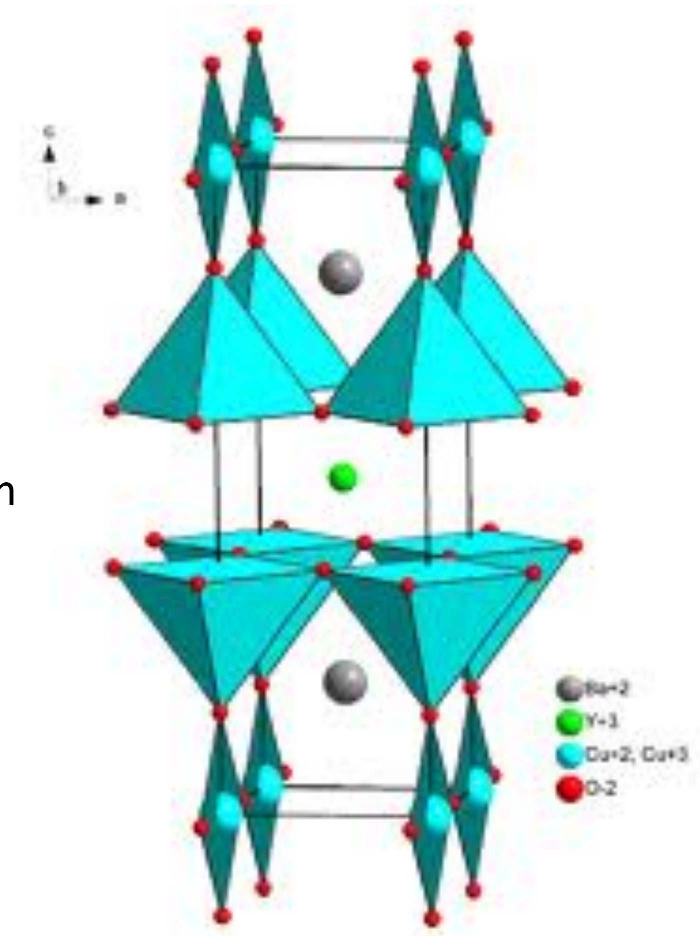
$|F|^2 > 0$

I. Urizar-Lanz, et al, Phys. Rev. A **88**, 013626 (2013)

Motivation

quantum spin correlations

Singlet as ground state of many spin model system



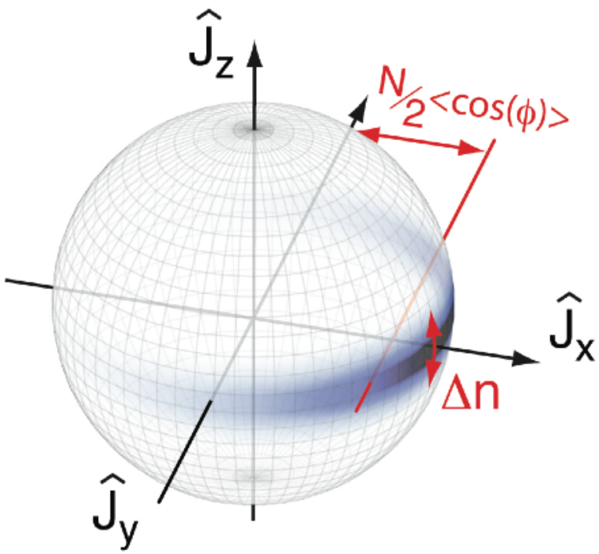
P. Hauke, et al, Phys. Rev. A, **87,** 021601(2013)

T. Iskhakov, et al, PRL **106,** 113602(2011)

Measurement-induced entanglement generation

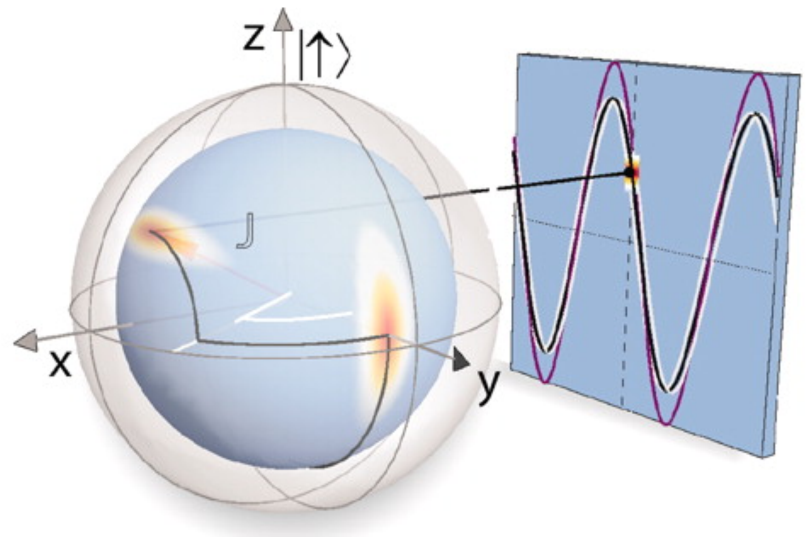
Spin squeezing by interactions

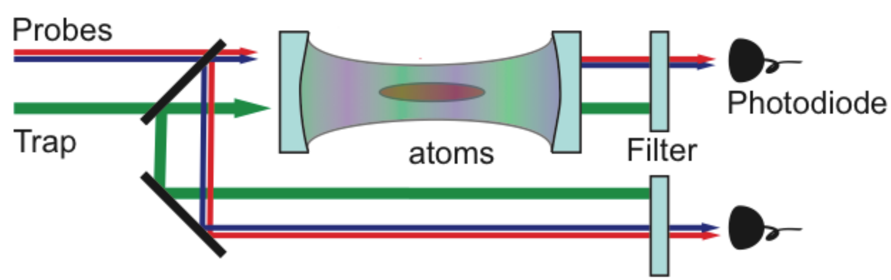
Oberthaler, Treutlein, Vuletic, Chapman, Klempt



Spin squeezing by measurement

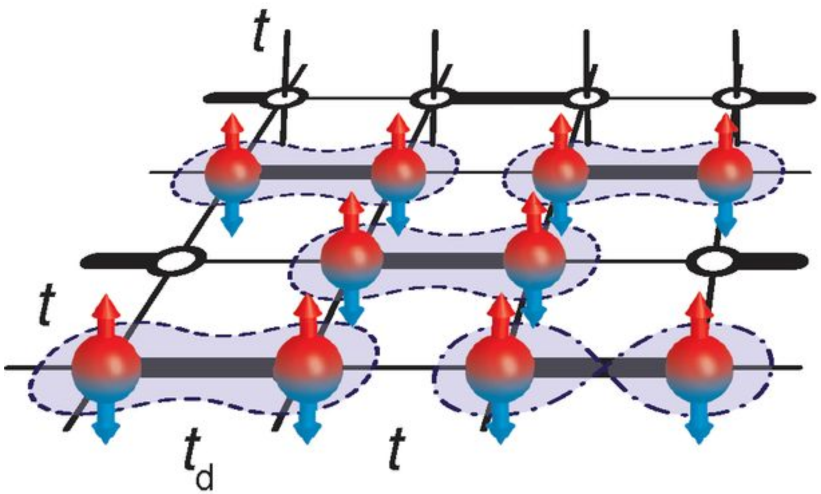
Kuzmich, Mabuchi, Polzik, Vuletic, Takahashi, Thompson, Mitchell



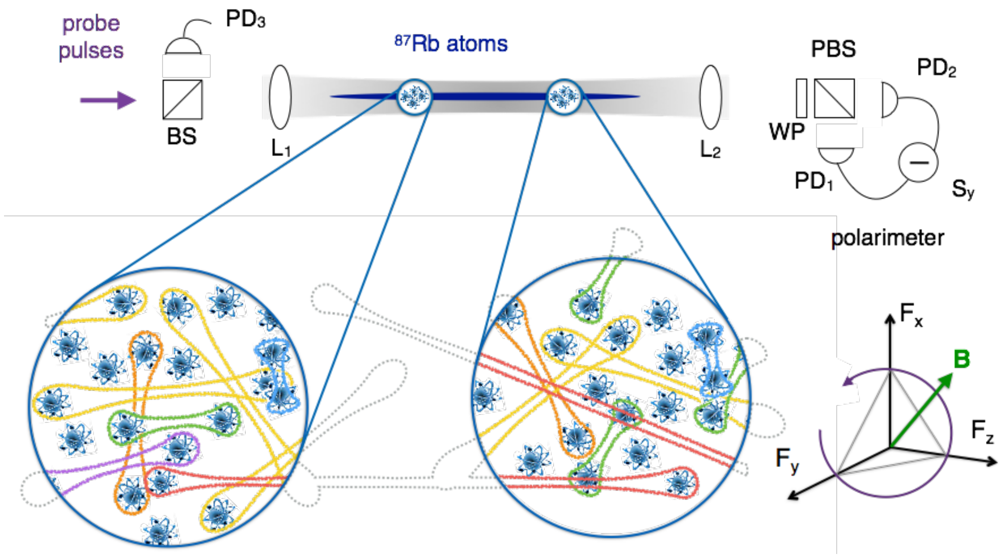


Measurement-induced entanglement generation

Spin singlets by interactions
Greiner, Esslinger



Spin singlets by measurement
This work.



How can you make a MSS ?

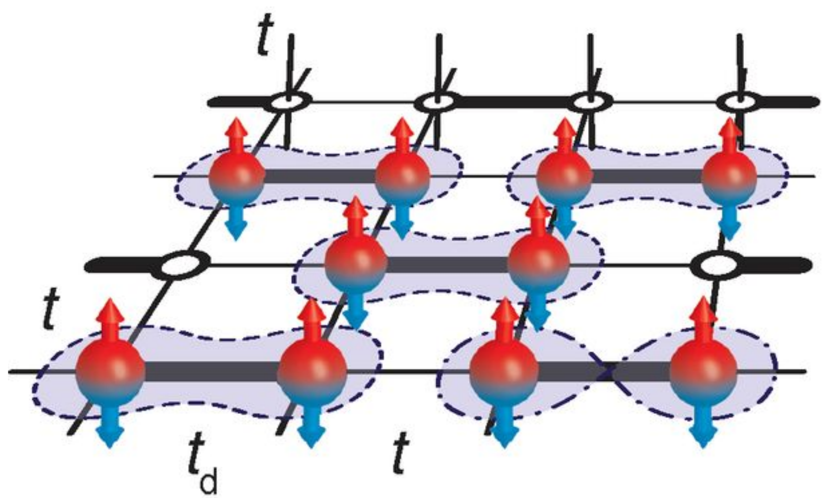
Quantum simulator approach :

Engineer anti-ferromagnet

Cool to ground state

D. Greif, et. al., Science, **340** 1307 (2013)

J. Simon et. al. , Nature, **472**, 307 (2011)



Measurement-based approach :

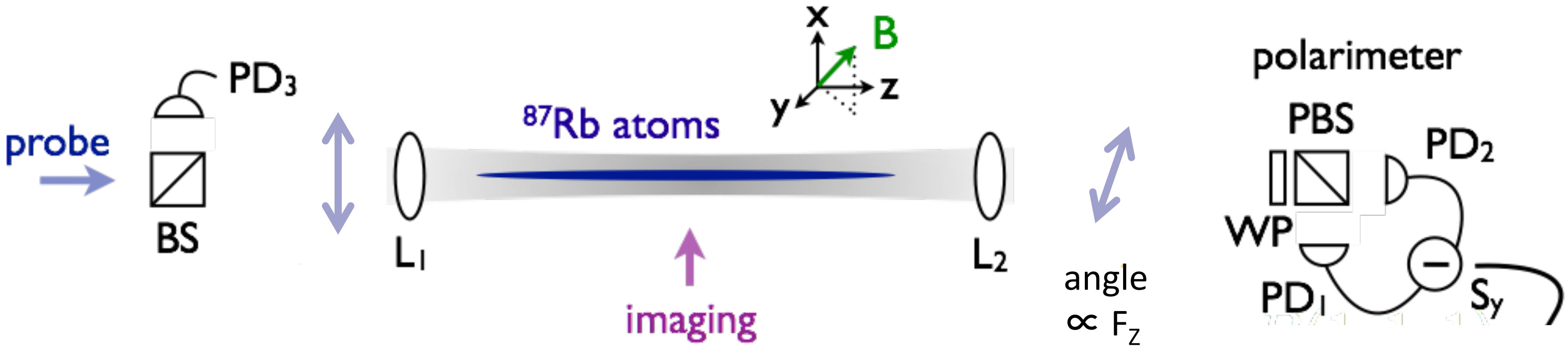
Quantum non-demolition measurements

Controlled rotations

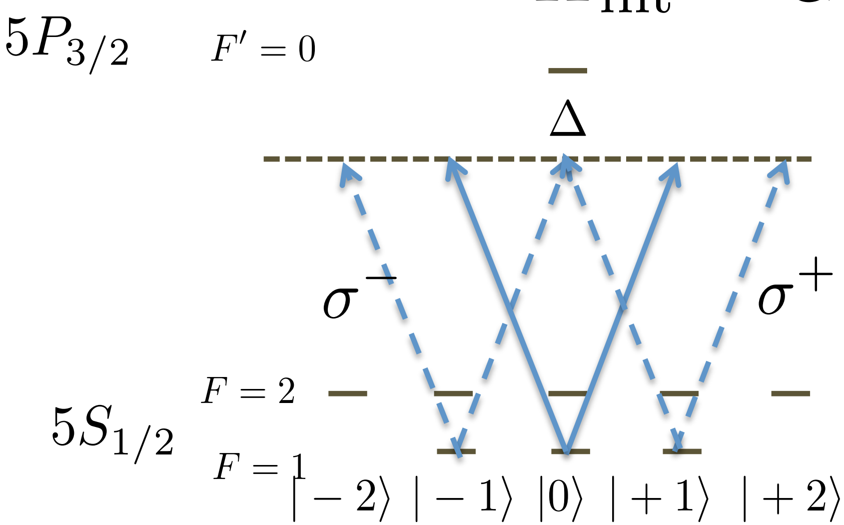
Vitagliano, Hyllus, Egusquiza and Tóth PRL (2011)

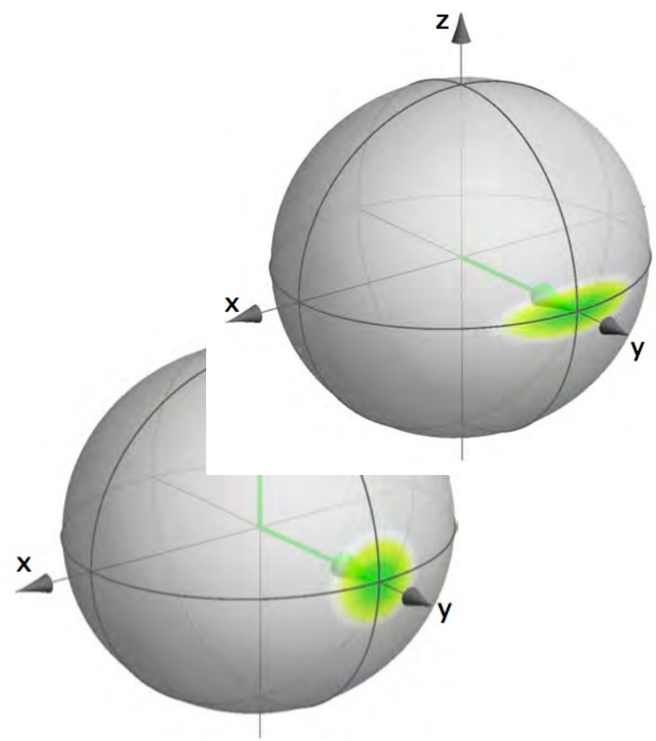
G. Toth, M. W. Mitchell, NJP **12** 053007 (2010)

QND measurement



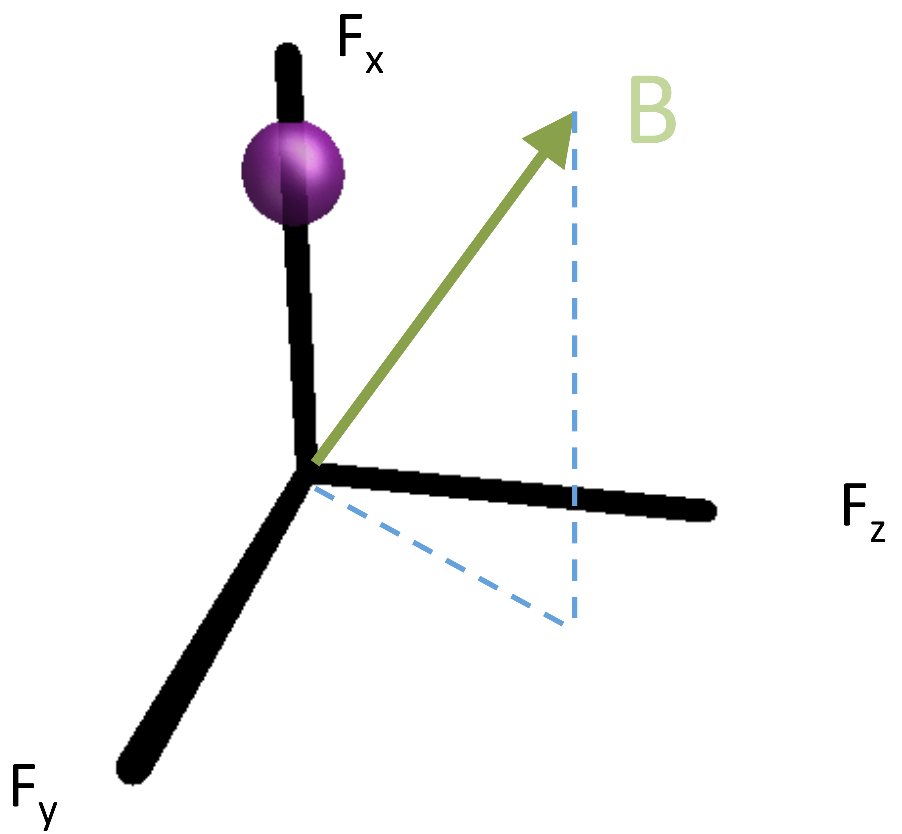
$$H_{\rm int} = G_1 S_z F_z$$





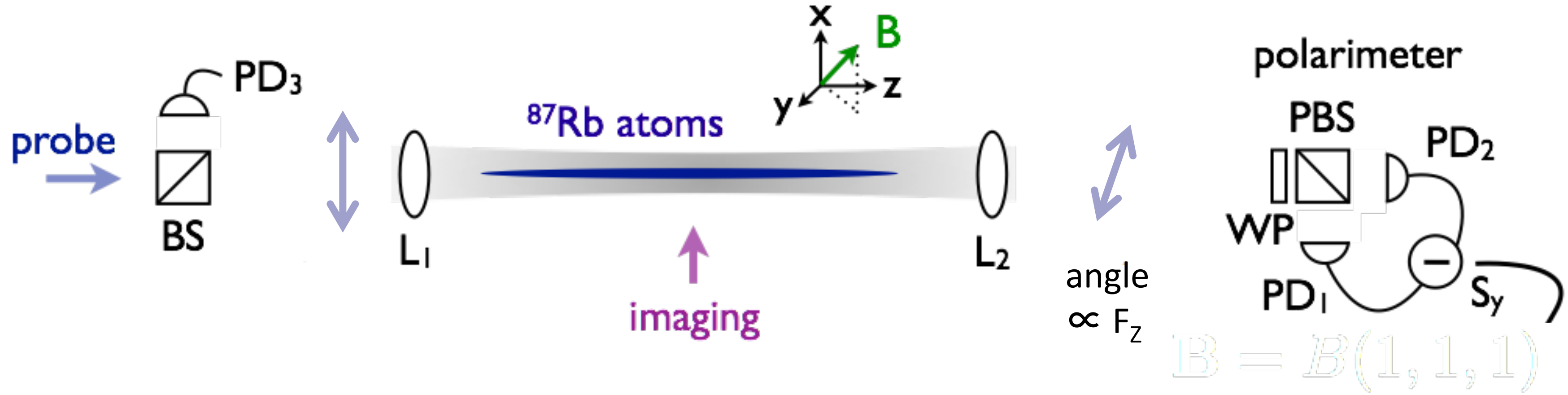
arXiv:1403.1964 (2014)

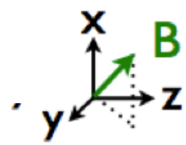
Stroboscopic probing

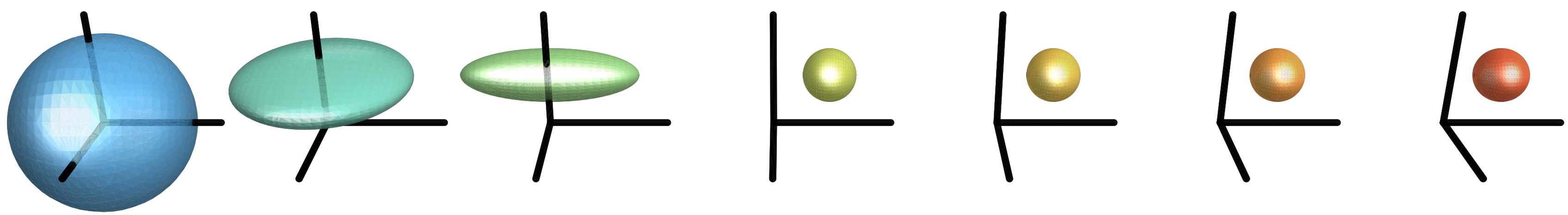


Behbood, APL 102, 173504 (2013)

Stroboscopic probing



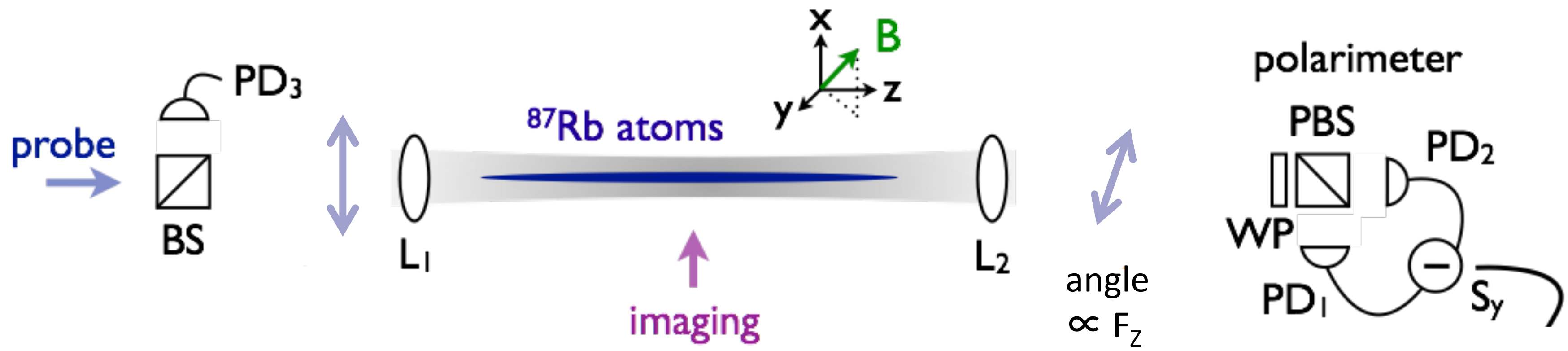




Behbood, APL 102, 173504 (2013)

arXiv:1403.1964 (2014)

Experimental system



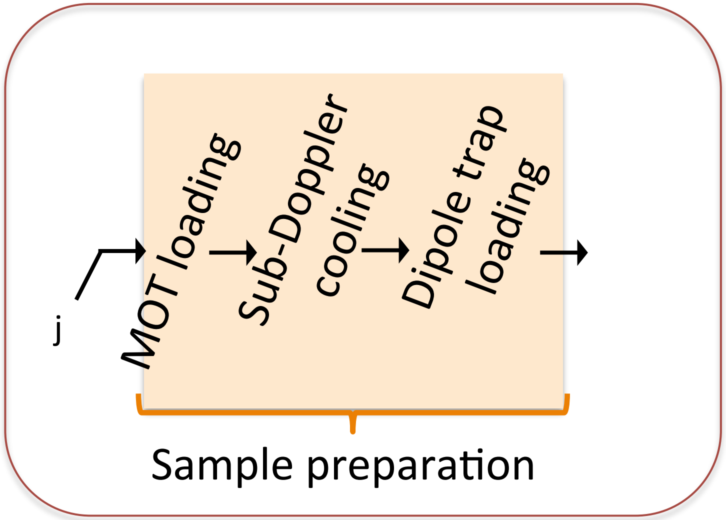
~10^6 ^{87}Rb atoms at 25μK
f=1 ground-state

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

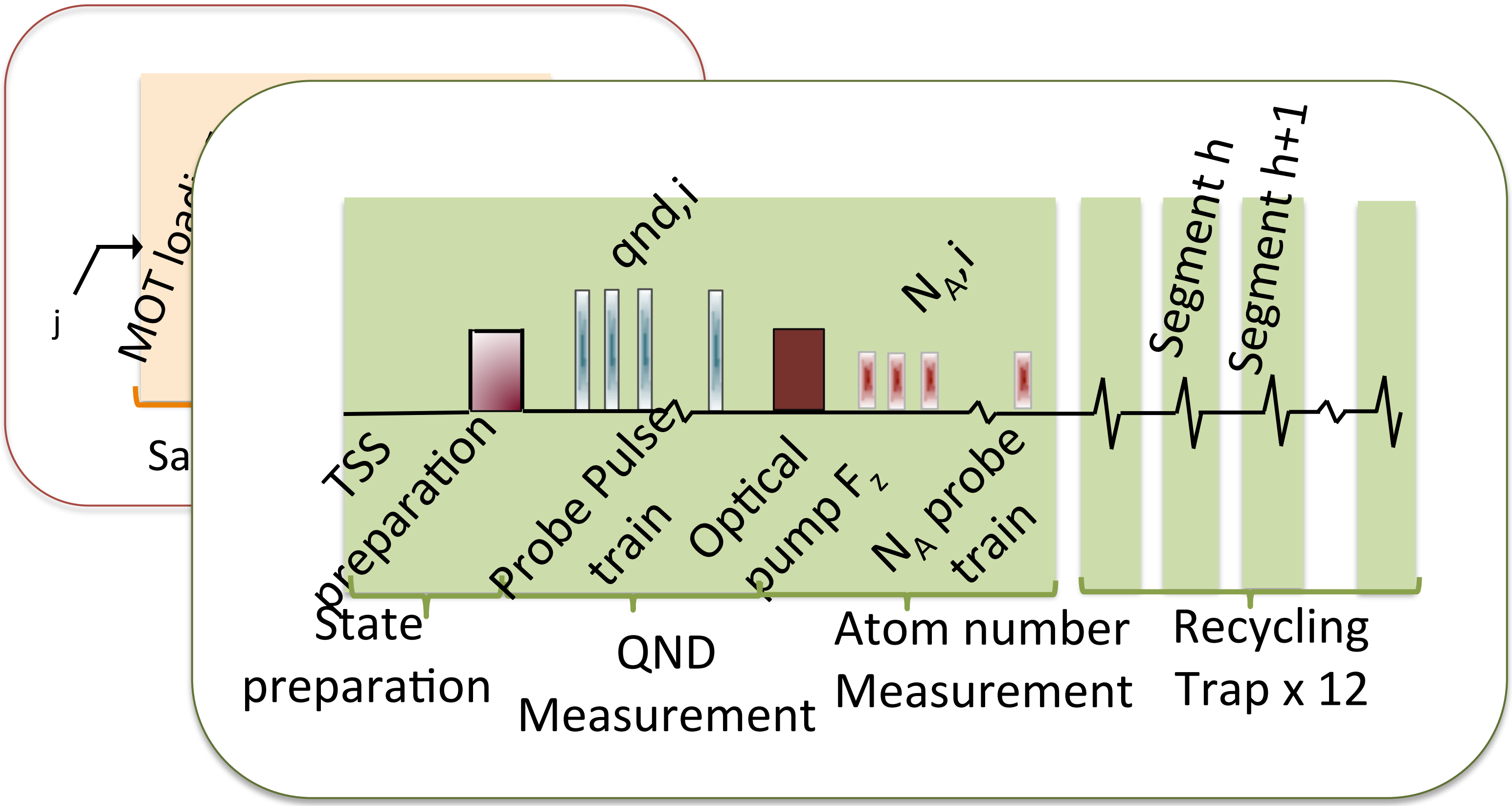
[1] effective OD > 50
[2] Sensitivity 512 spins, < SQL
[3] QND measurement
[4] spin squeezing

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)

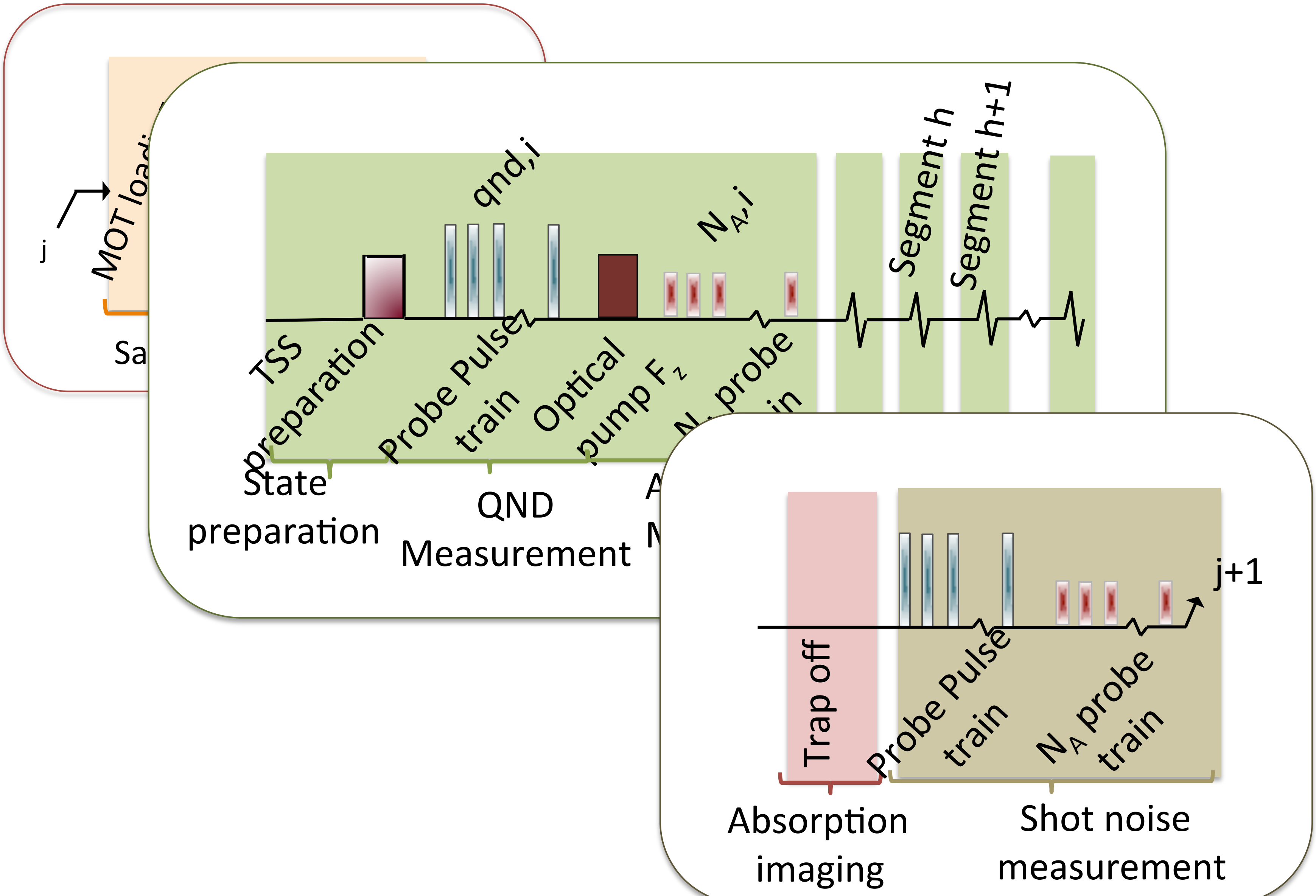
Experimental sequence



Experimental sequence

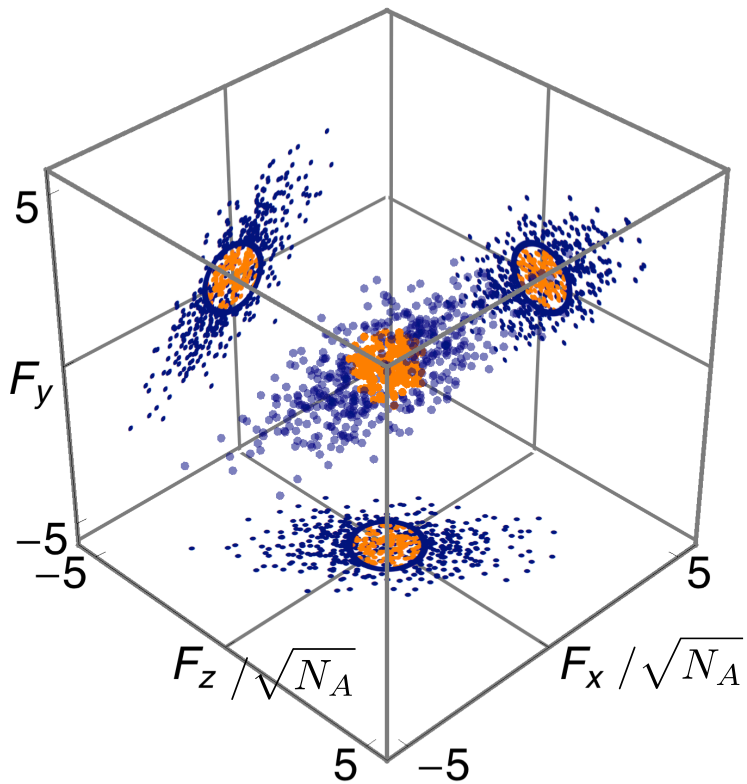


Experimental sequence

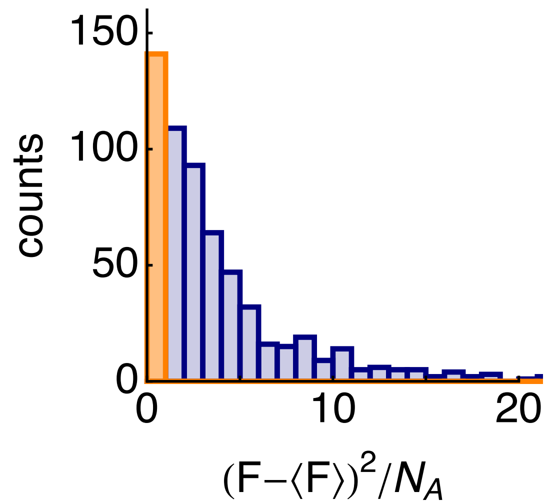


Vector non-demolition measurements

N_A=1.1x 10^6

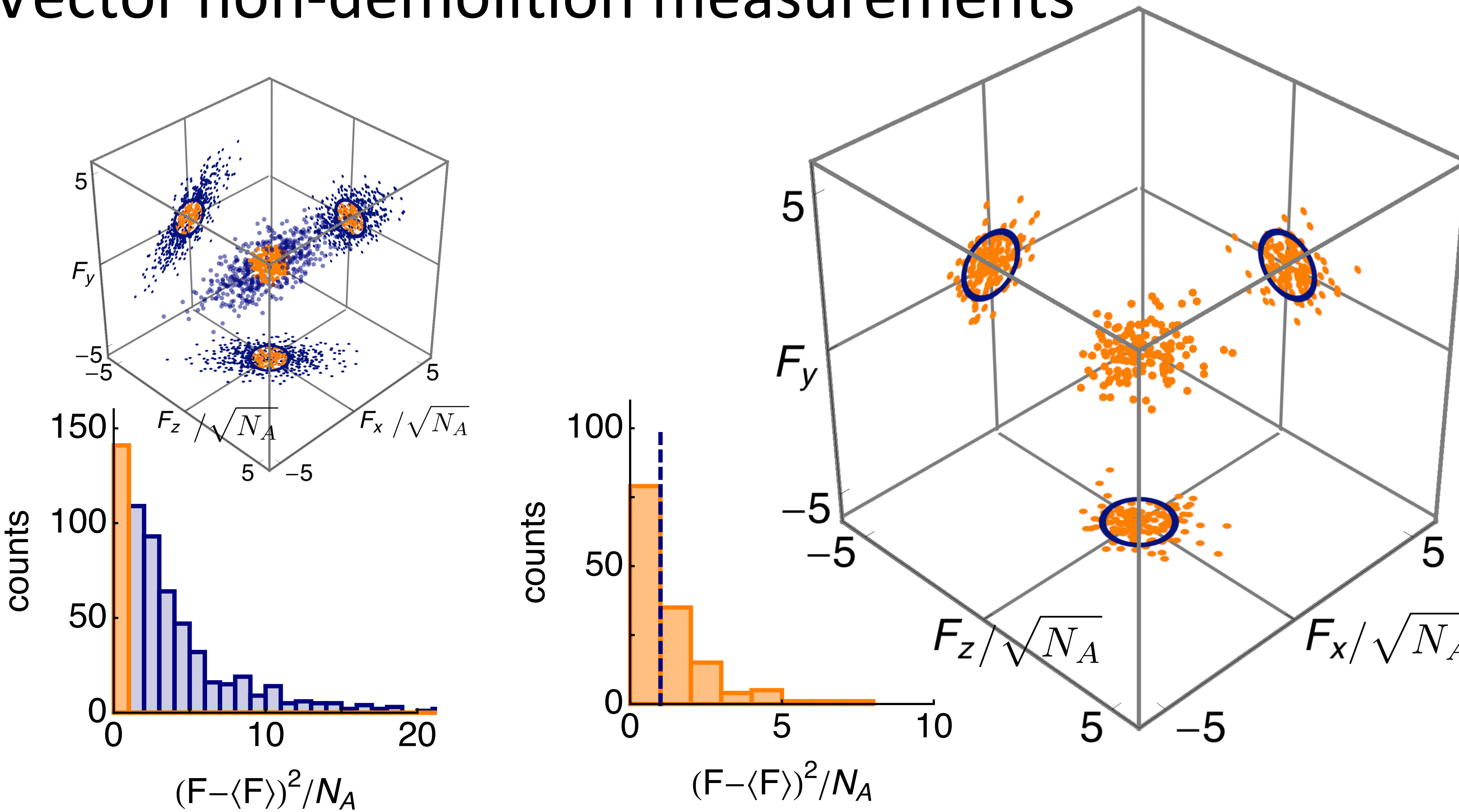


first vector measurement



arXiv:1403.1964

Vector non-demolition measurements

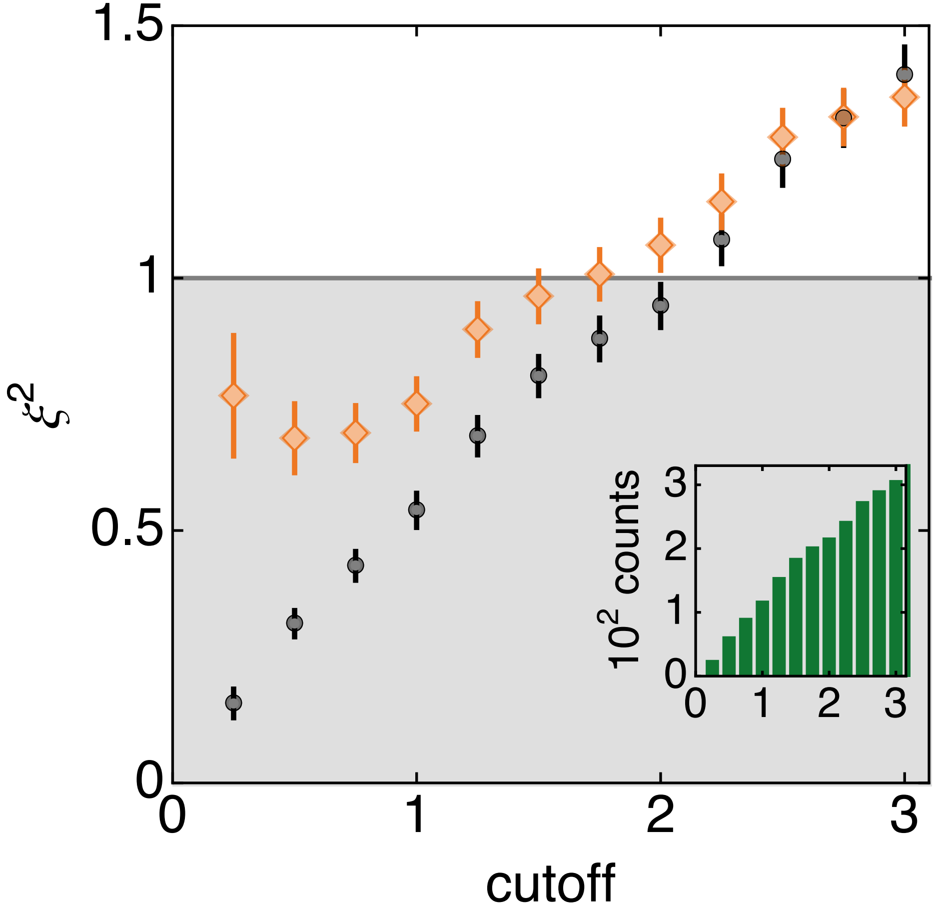


first vector measurement

second vector measurement

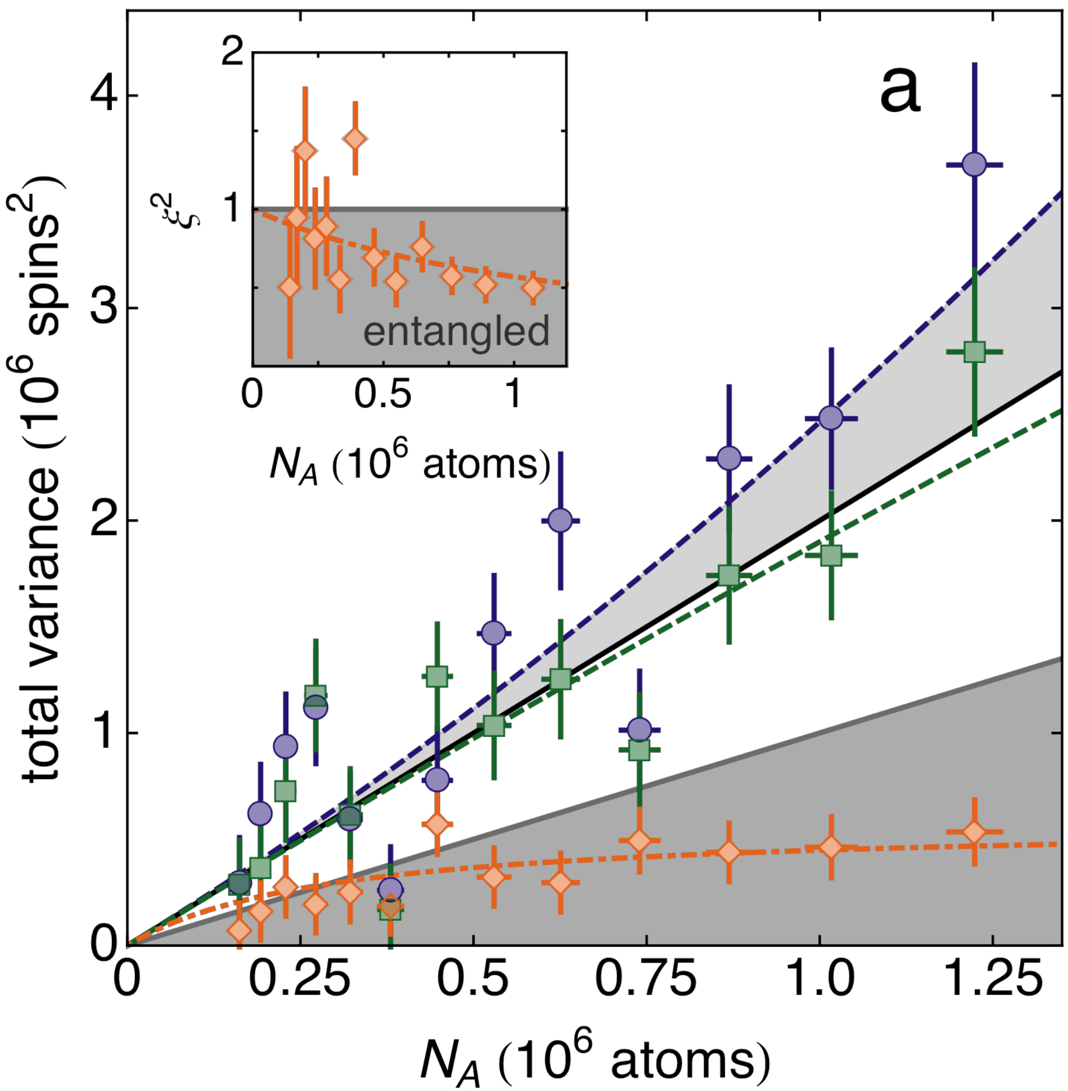
arXiv:1403.1964

Vector non-demolition measurements



arXiv:1403.1964

Quantifying squeezing by conditional variance



$(\Delta F)^2$ (1st measurement)

$(\Delta F)^2$ (2nd measurement)

standard quantum limit

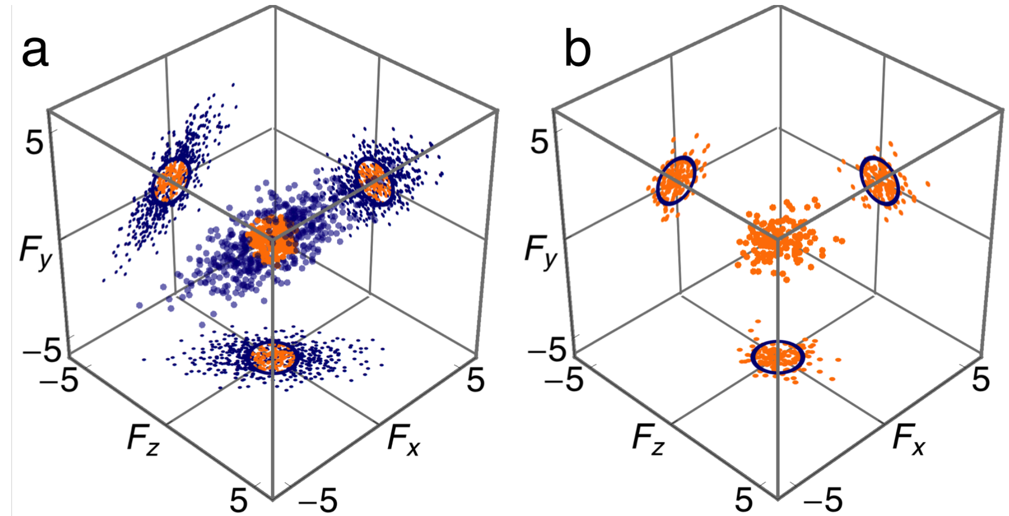
conditional variance

arXiv:1403.1964

Conclusions + Outlook

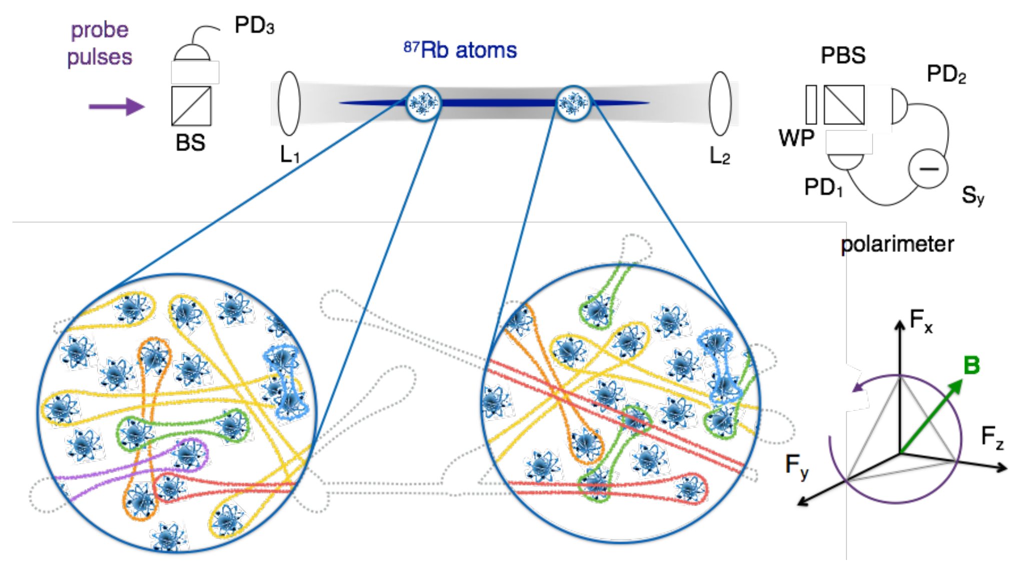
Vector non-destructive spin measurements

Macroscopic spin singlets
50 % singlet fraction



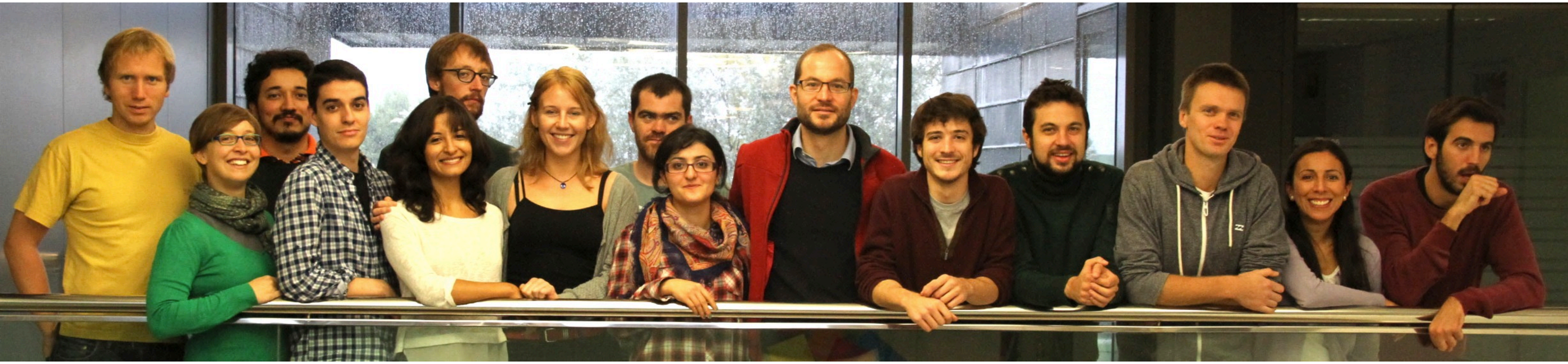
arXiv:1403.1964 (2014)

Next steps : Gradiometry

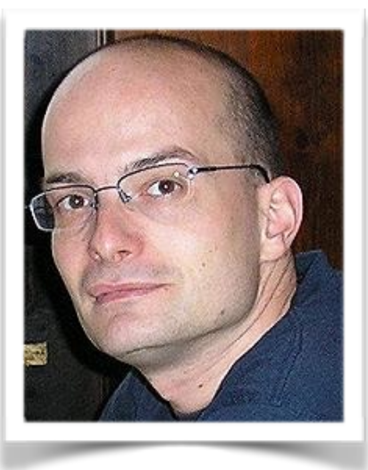


Thanks

Lukas Slodicka · Ricardo Jimenez · Simon Coop · Thomas Vanderbruggen · **Morgan Mitchell** · Gianvito Lucivero · Natali Martinez



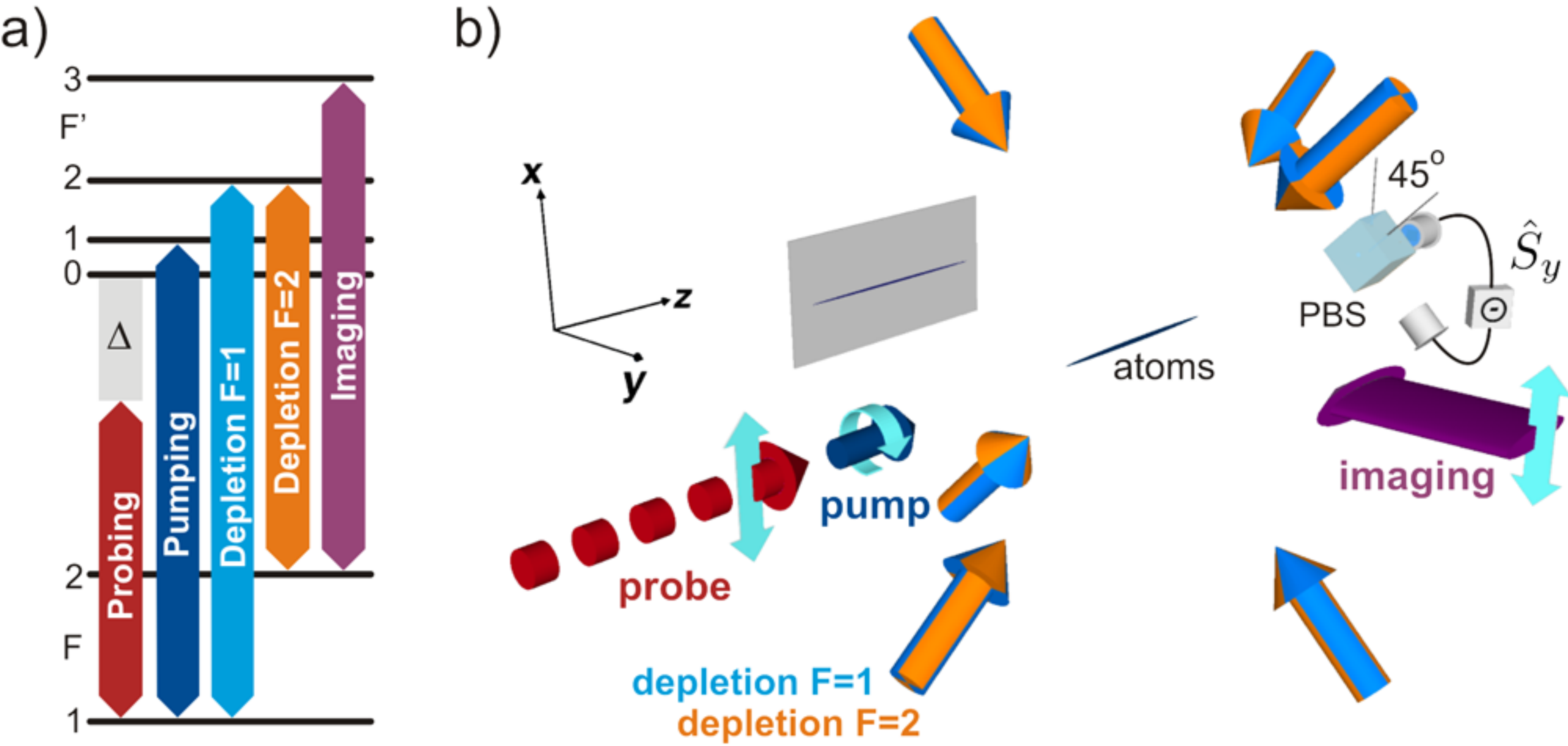
Federica Beduini · **Ferran Martin** · Silvana Palacios · Joanna Zielinska · **Mario Napolitano** · Gil Triginer · **Robert Sewell** · **Giorgio Colangelo**



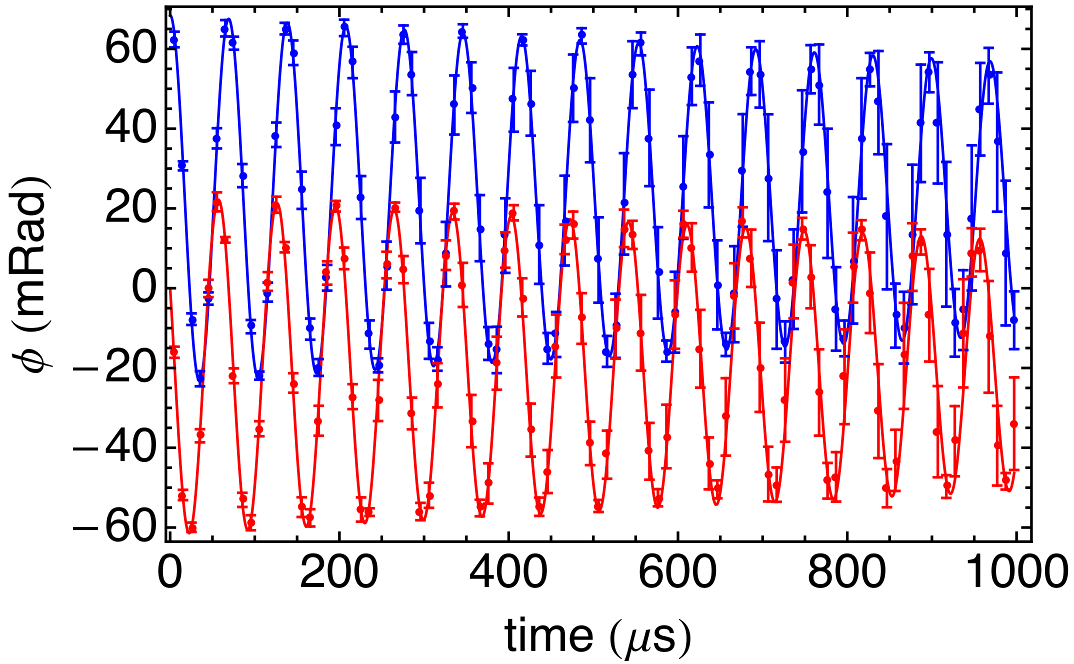
Geza Toth, and Iñigo Urizar Lanz, UPV

Thank You!

TSS preparation



Stroboscopic probing



Two orthogonal input coherent spin states

Extract vector field components and spin coherent time

Dephasing due to gradient fields

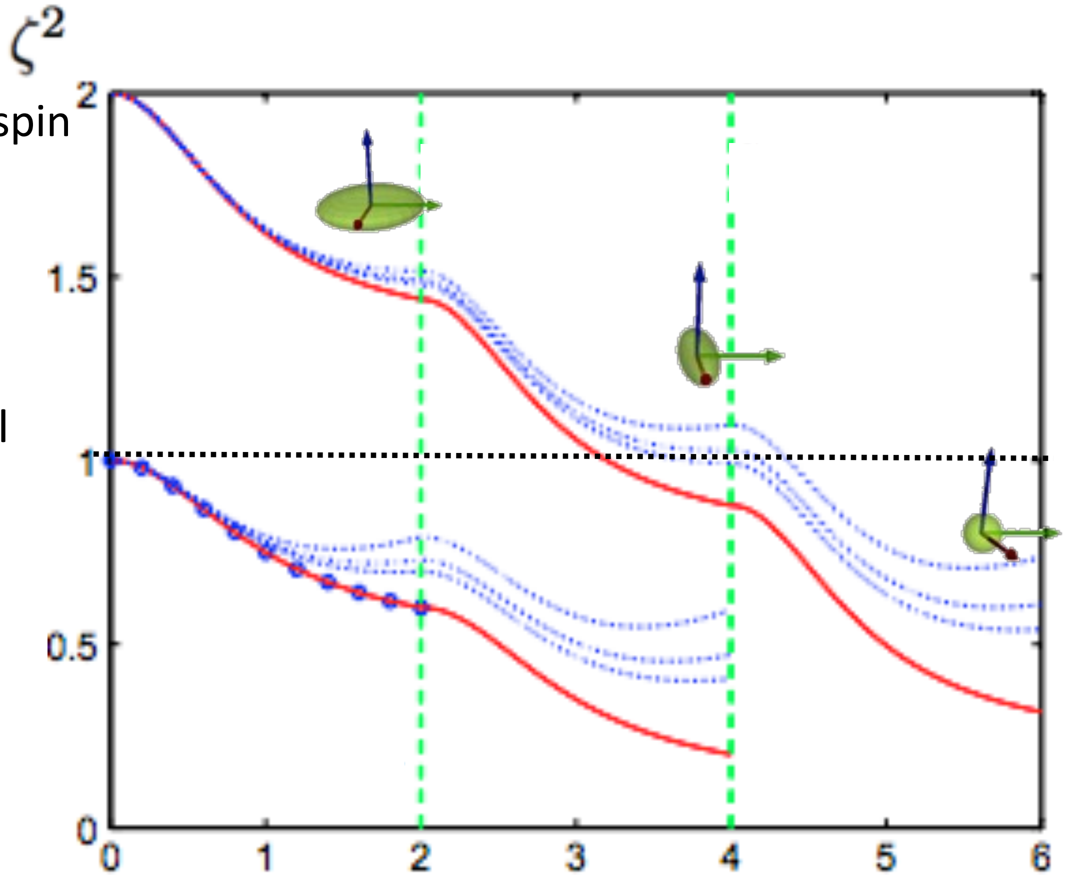
$$\theta_1(t) = \frac{G}{|B|^2}[B_z^2 + [B_x^2 + B_y^2]cos(\gamma|B|t)e^{t/T_2}F_z(0)$$

$$\theta_2(t) = \frac{G}{|B|^2}[B_y B_x(1 - cos(\gamma|B|t)e^{t/T_2}$$

$$+B_x|B|sin(\gamma|B|t)e^{t/T_2}]F_y(0)$$

Behbood, APL 102, 173504 (2013)

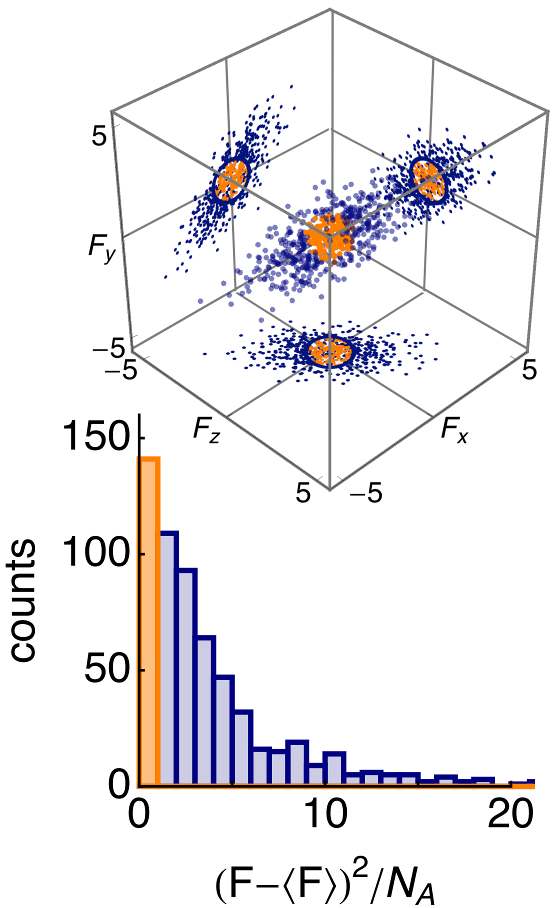
How well can this work ?



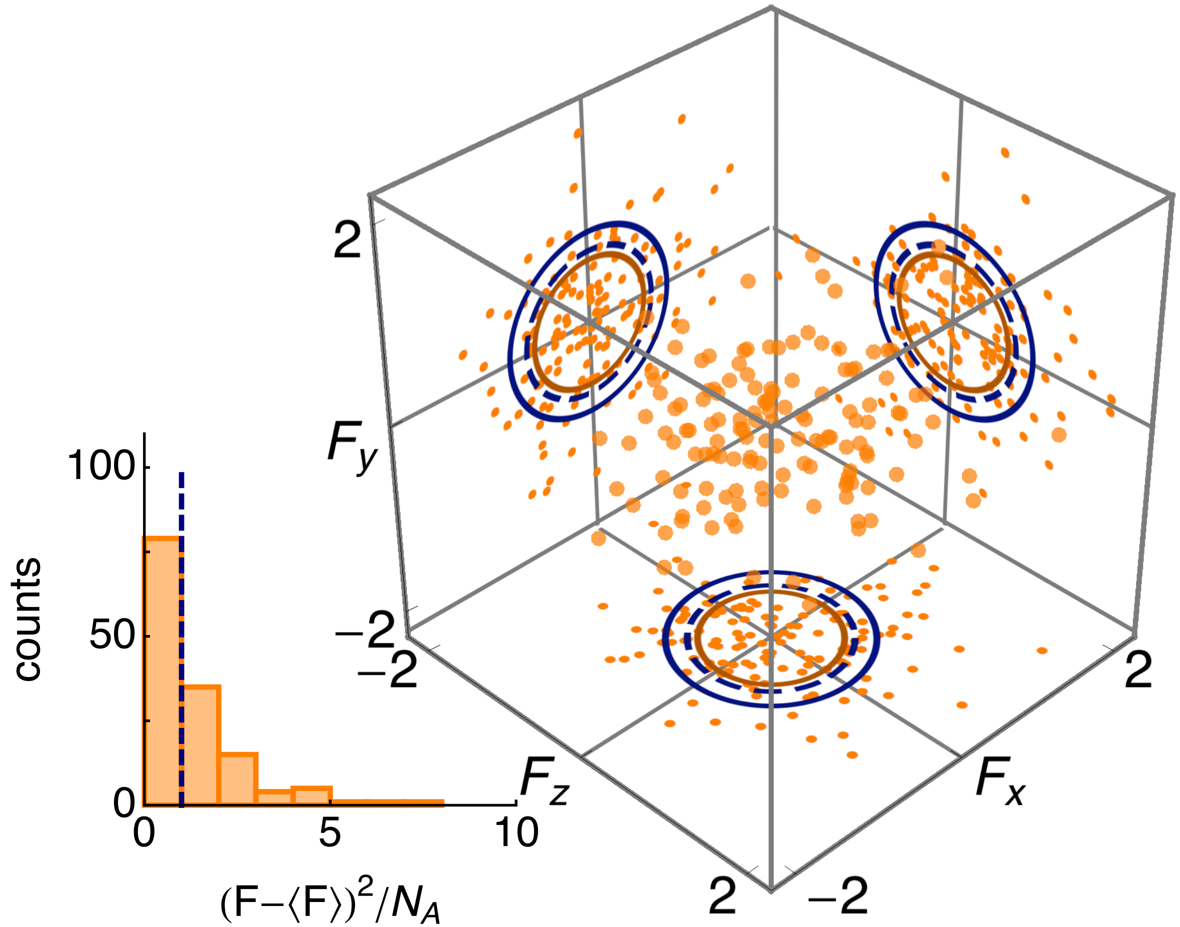
Generation of macroscopic singlet states in atomic ensembles

G. Toth, M. W. Mitchell, NJP **12** 053007 (2010)
Phys. Rev. A 87, 021601(R) (2013)

Vector non-demolition measurements



first vector measurement

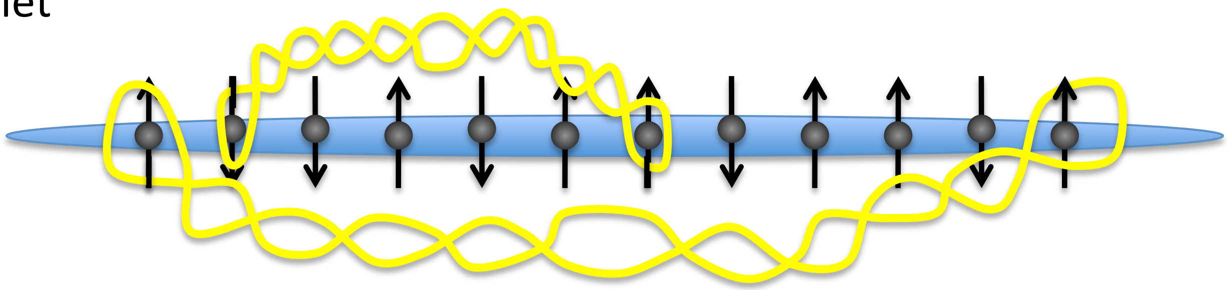


second vector measurement

arXiv:1403.1964

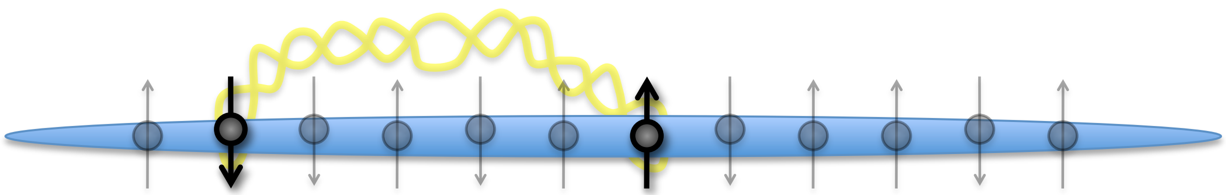
Motivation: Gradient magnetometry with singlets

Macro singlet



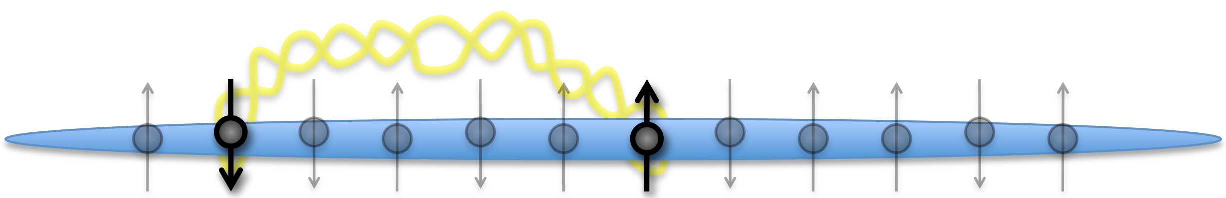
$|F|^2 = 0$

Uniform field : singlet -> singlet



$|F|^2 = 0$

Gradient field : singlet -> triplet



$|F|^2 > 0$

I. Urizar-Lanz, et al, Phys. Rev. A **88**, 013626 (2013)