Generation of a macroscopic singlet state in a cold atomic ensemble

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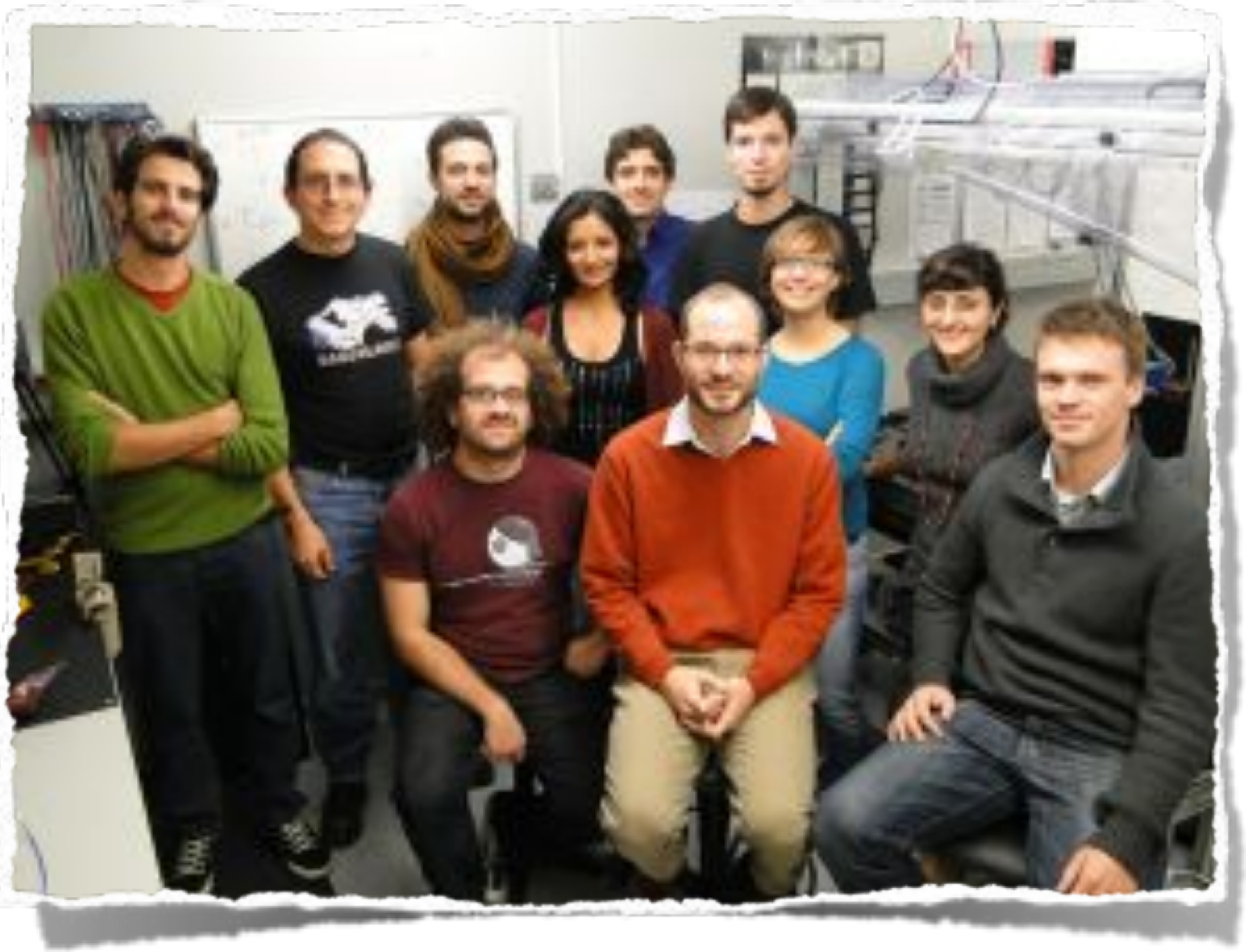
Bilbao, 10 March 2014

Singlet state project...



PEOPLE

N. Behbood, R.J.S,
F. Martin Ciurana,
G. Colangelo,
M.Napolitano,
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PLACES

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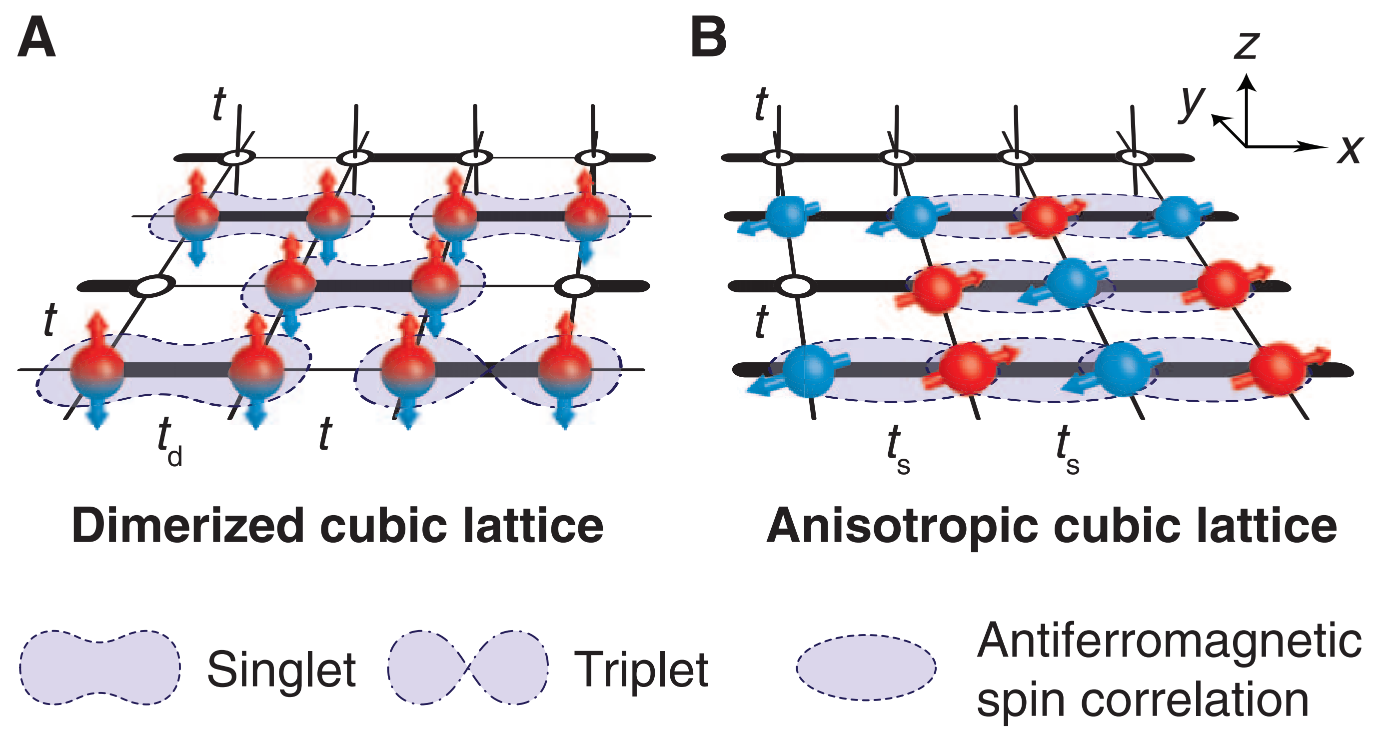
Simulating quantum magnetism

Short range quantum magnetism of ultra cold fermions in an optical lattice



Greif, Science 340, 1307 (2013)

nearest-neighbour spin correlations

low temperature & entropy

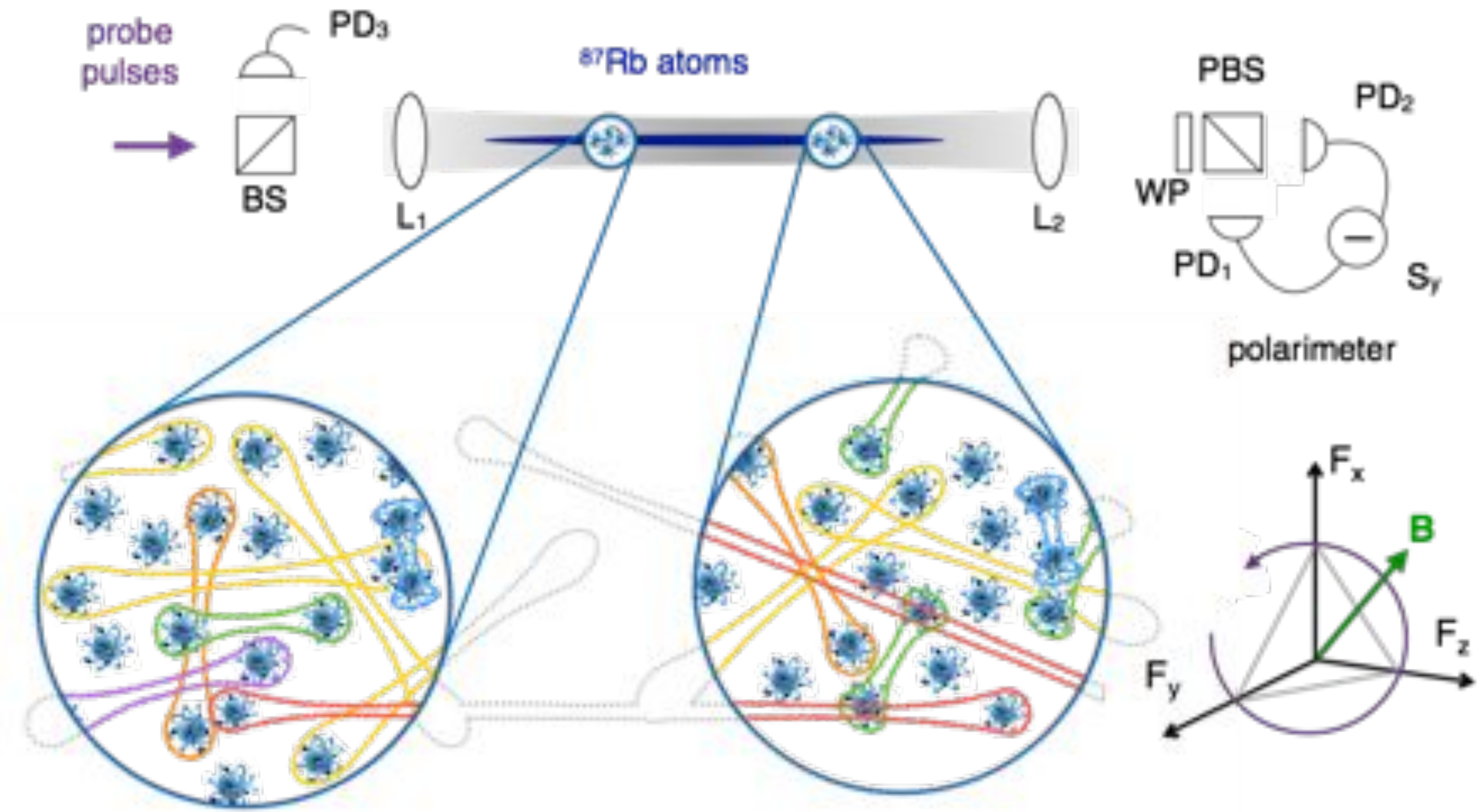
Simulating quantum magnetism

many problems in quantum simulators are characterised by <u>long-range</u> correlations, e.g. high-Tc superconductors & quantum Hall effects

classic example: quantum anti-ferromagnets, characterised by behaviours such as Néel ordering, valence bond solids, spin liquid phases, etc

open (& very difficult) experimental challenge, requiring very low temperatures, long time scales…

A different approach...



collective spin measurements directly generate long-range entanglement

A different approach...

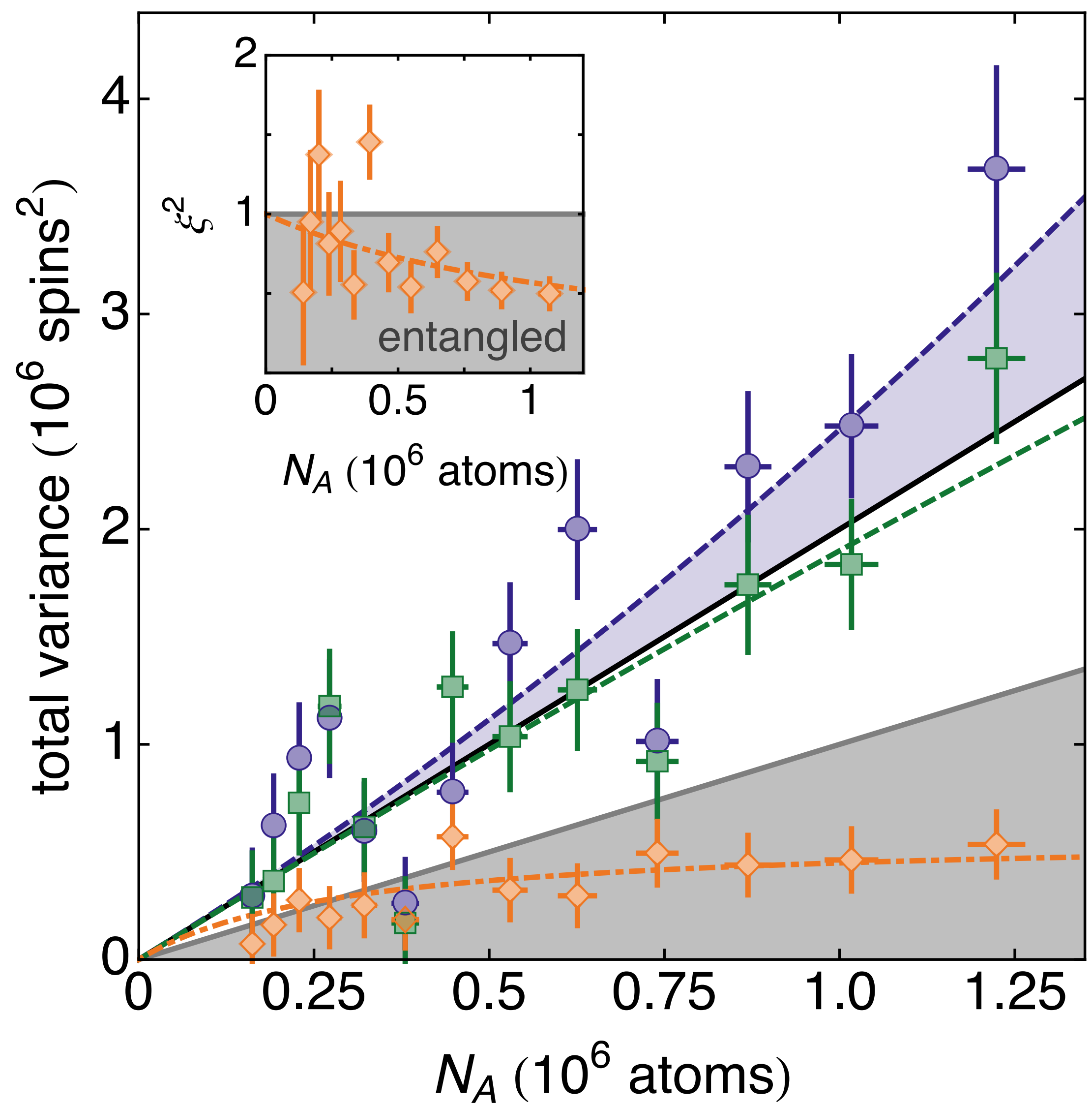
direct generation of
long-range entanglement

via quantum non-demolition (QND) measurement & spin squeezing

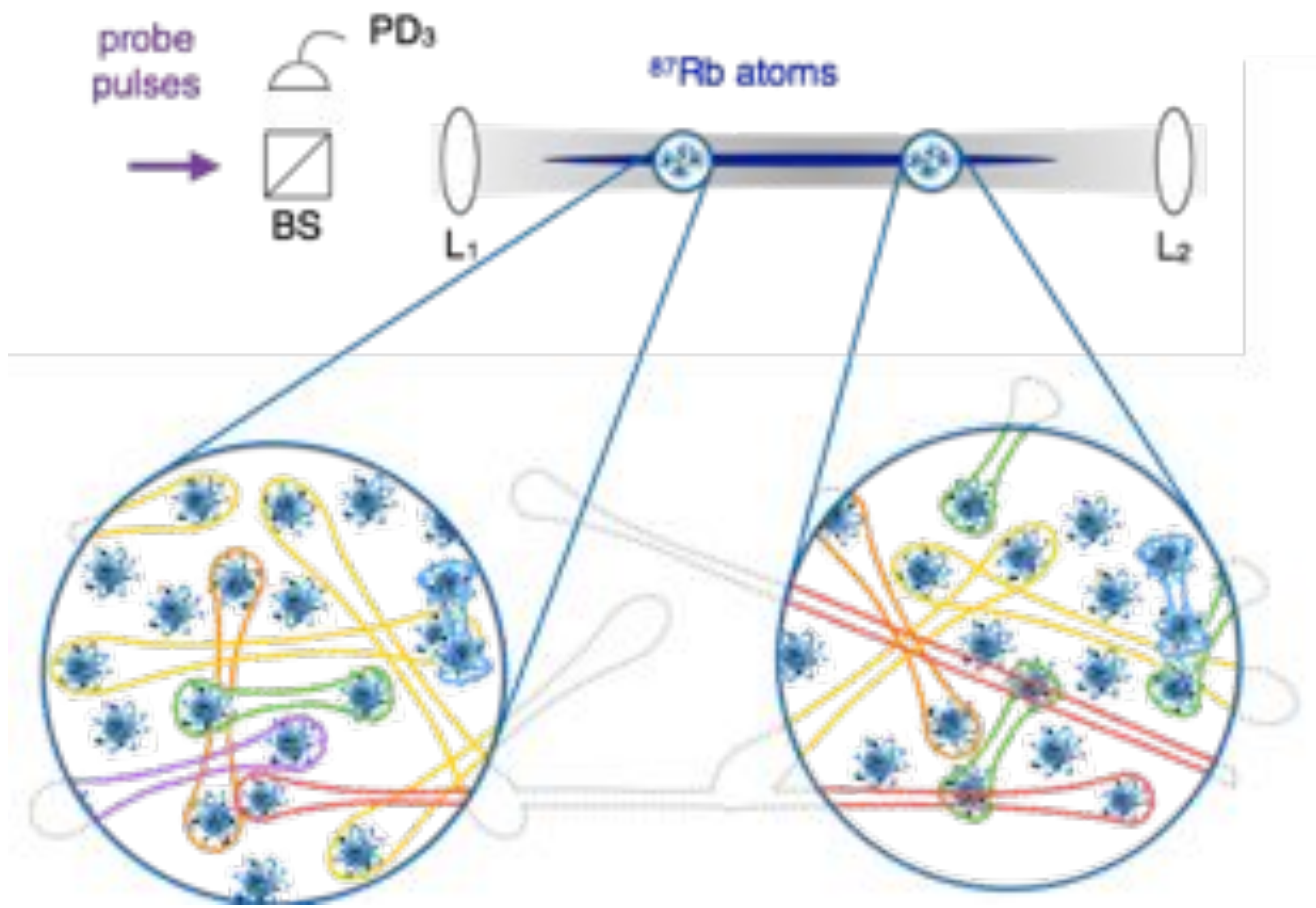
create a macroscopic singlet state (MSS)

Tóth, NJP 12, 053007 (2010)

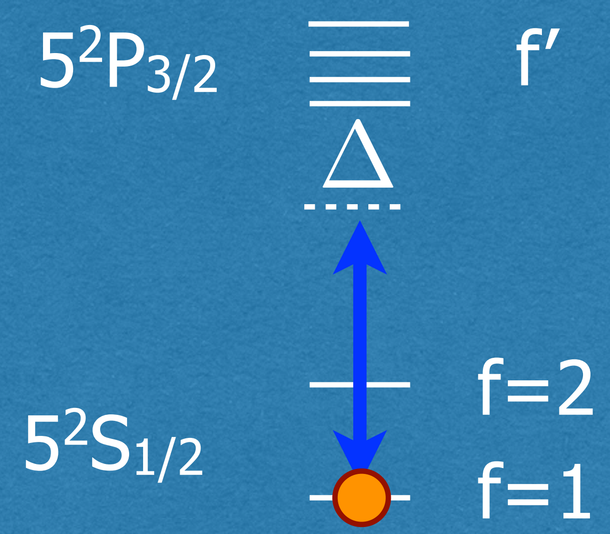
Behbood, arXiv:1403.1964 (2014)



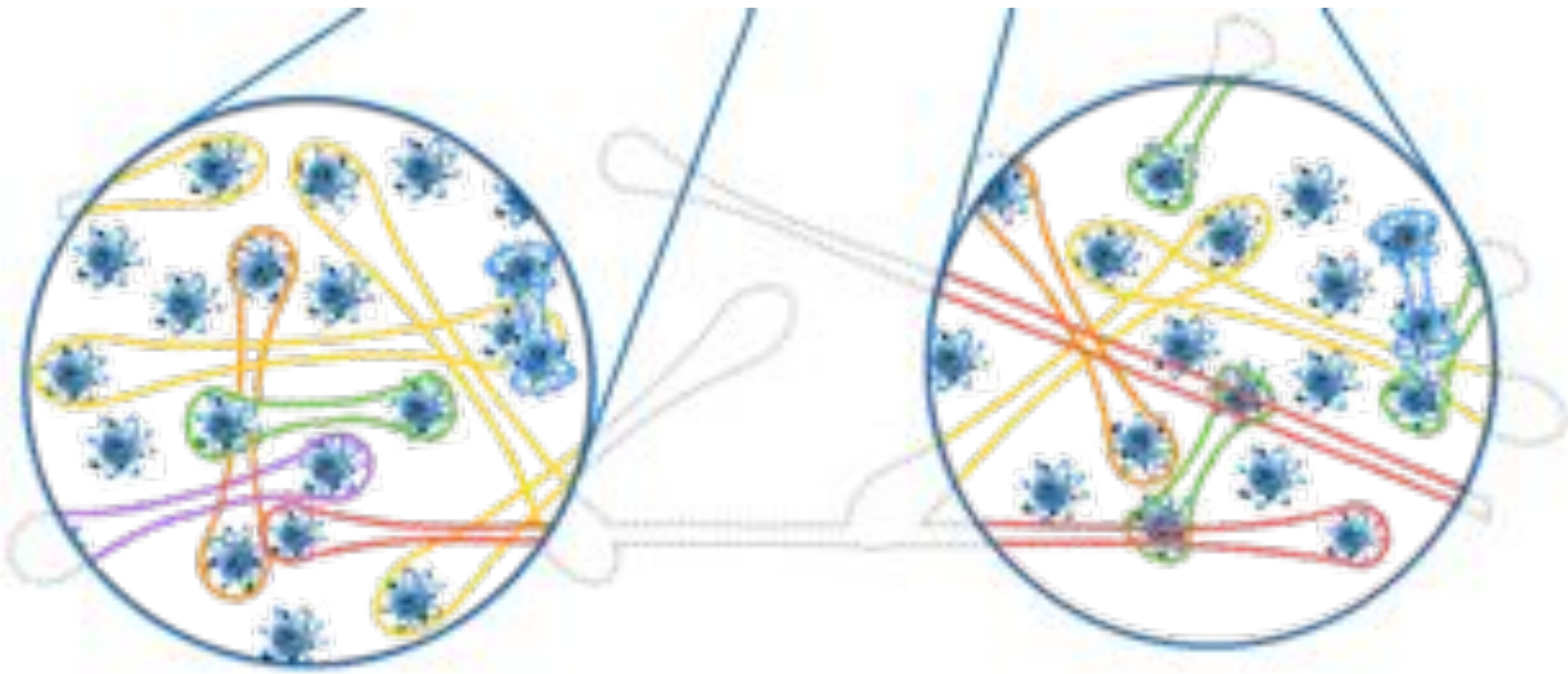
Quantum atom-light interface



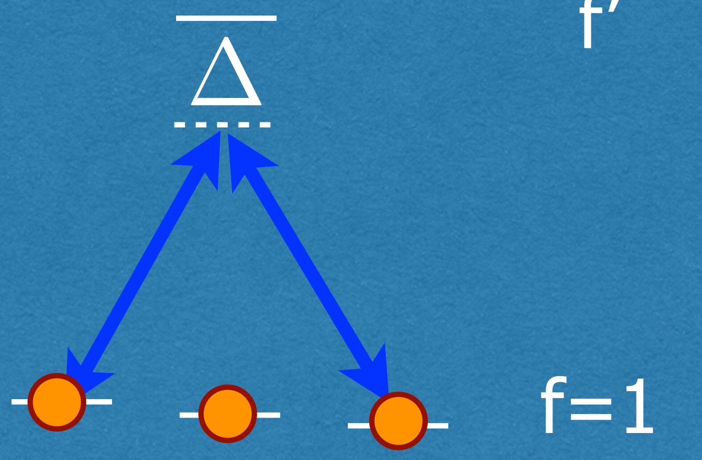
^{87}Rb D_2 line



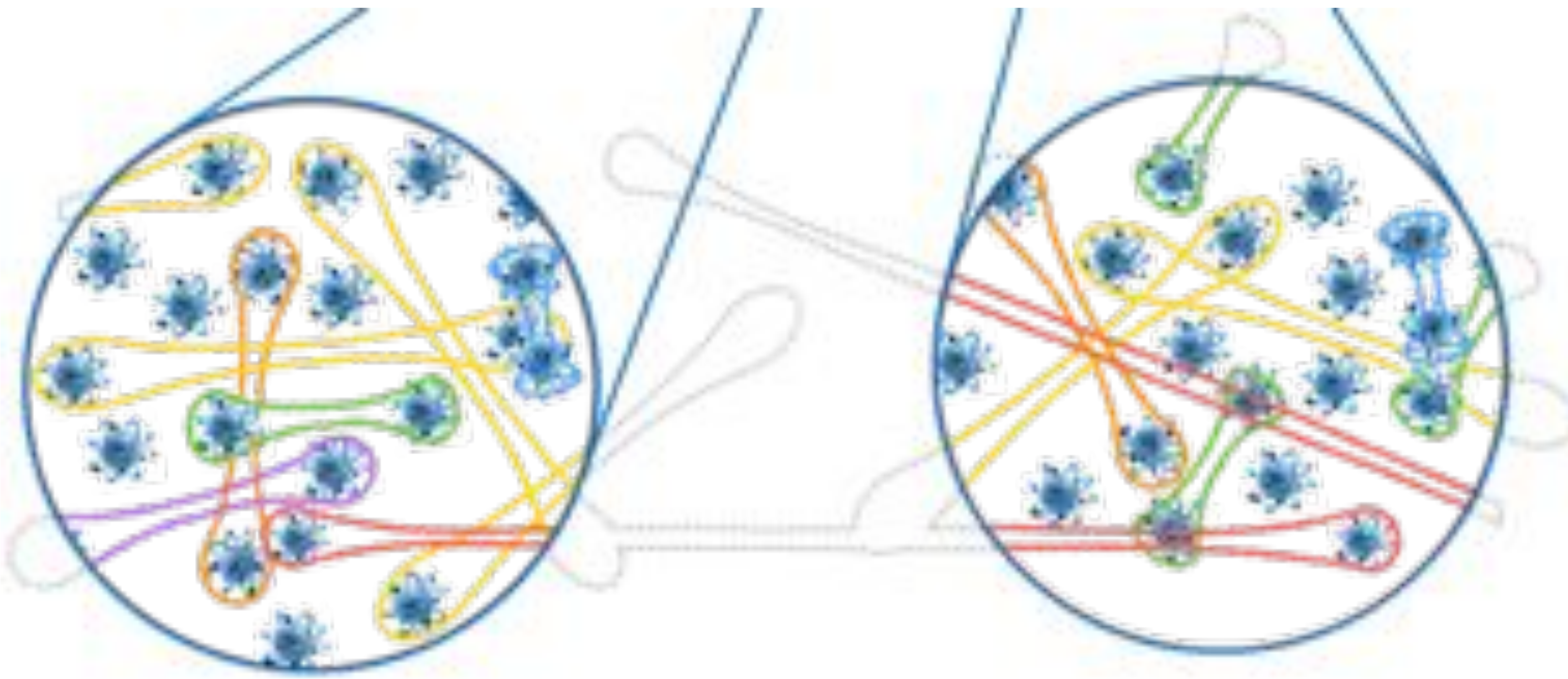
Collective atomic spin



spin-1 atoms



Collective atomic spin



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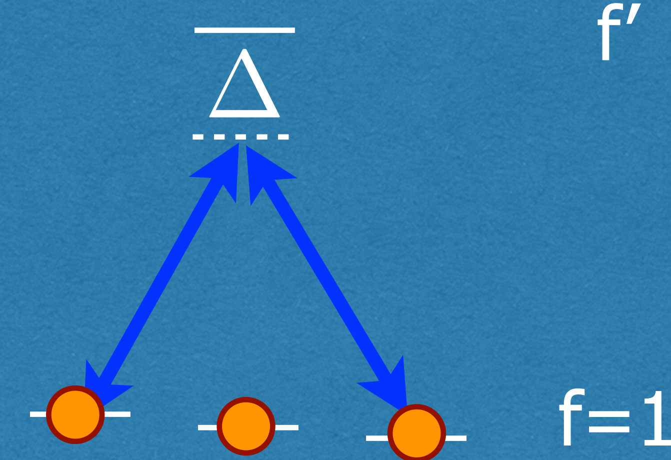
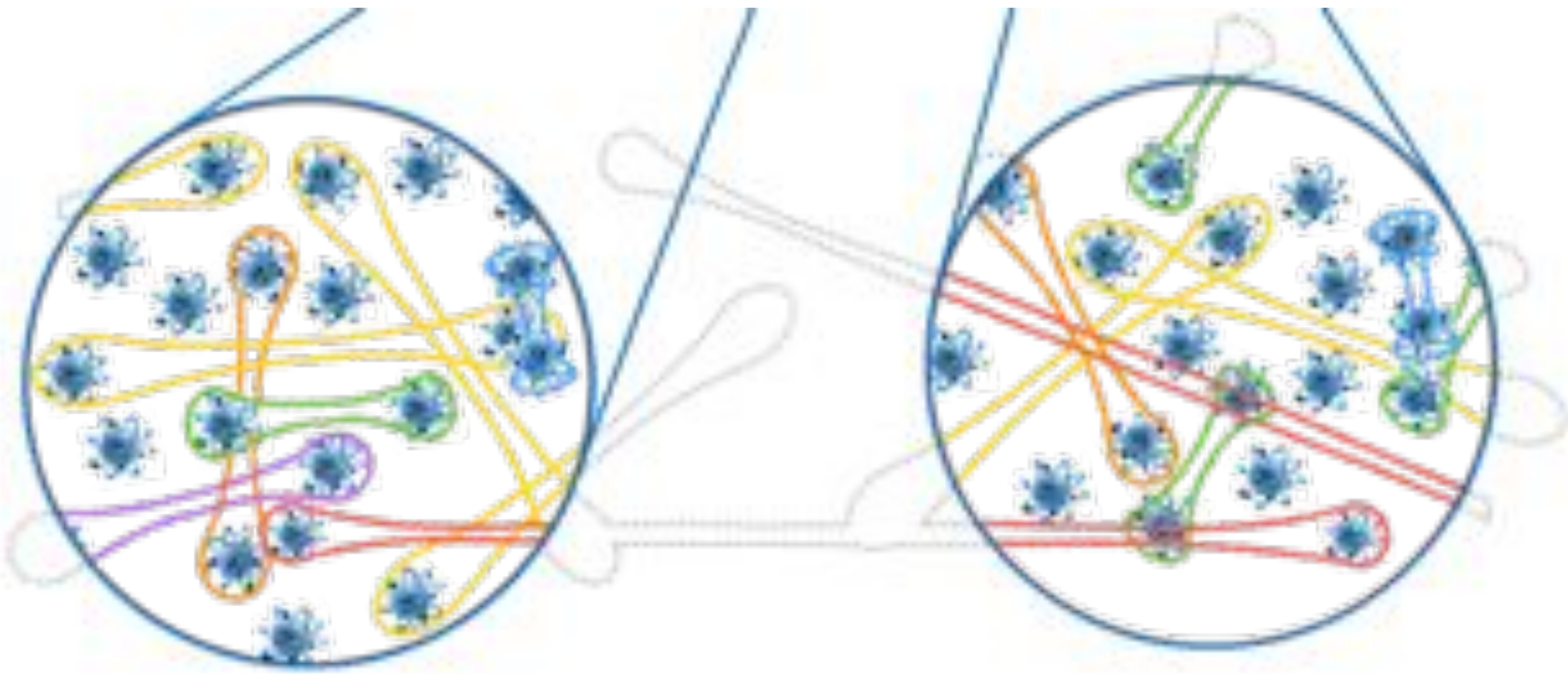


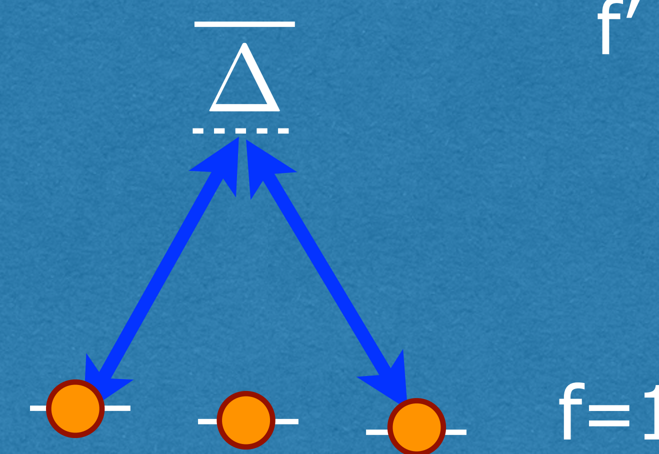
collective spin

$$F = \sum_{i=1}^{N_A} f^{(i)}$$

Thermal spin state



spin-1 atoms



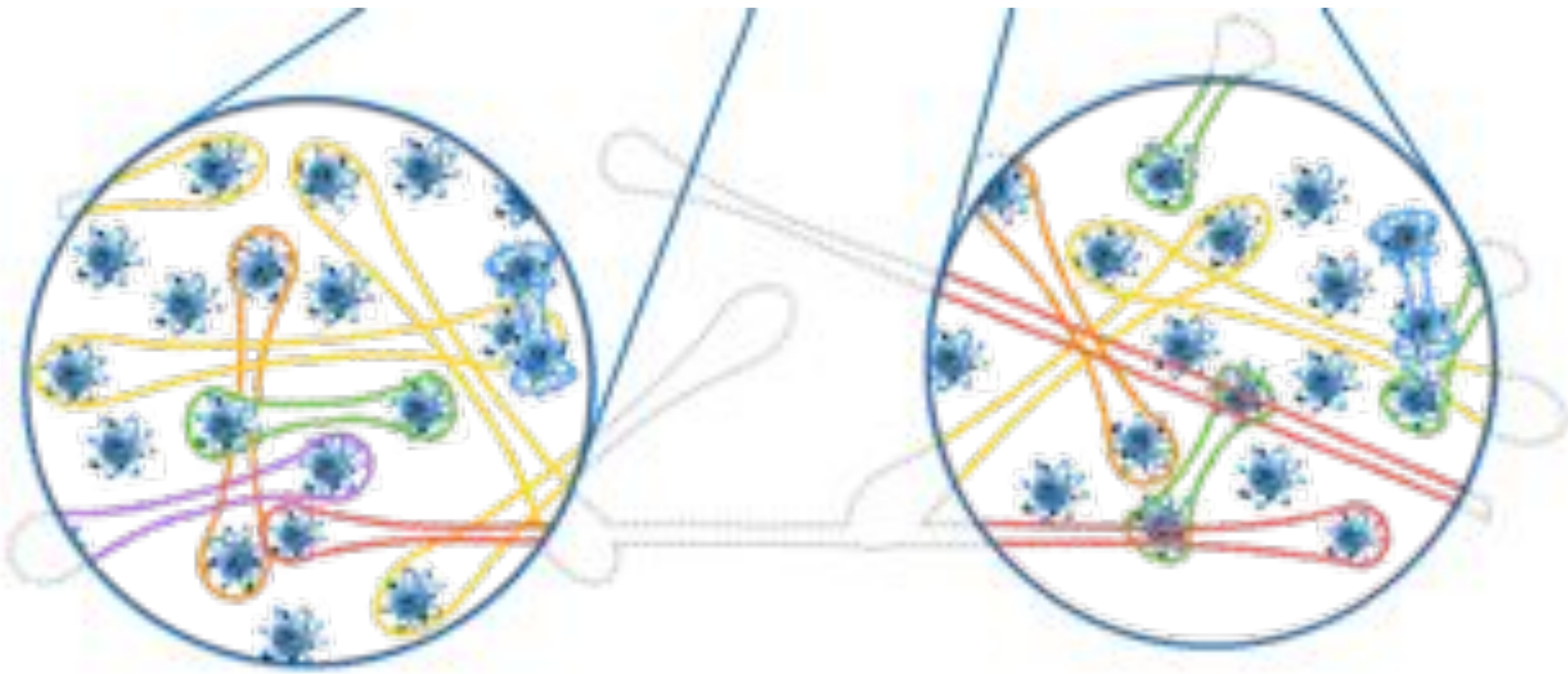
collective spin

$$F = \sum_{i=1}^{N_A} f^{(i)}$$

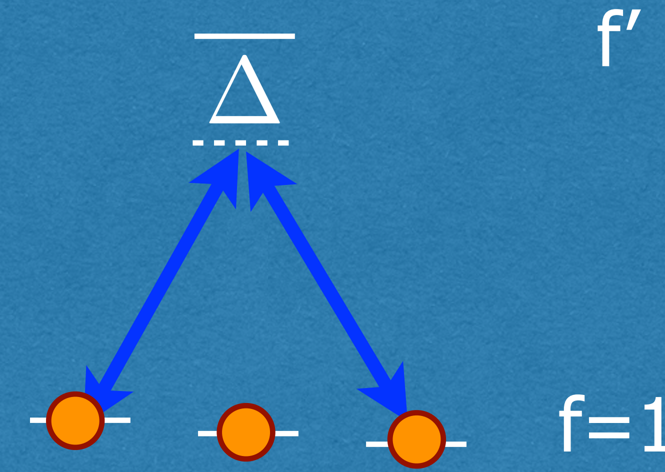
unpolarised $\Delta F_i \Delta F_j \geq |\langle F_k \rangle|/2 = 0$

uniform noise distribution $(\Delta F_i)^2 = (2/3) N_A$

Spin squeezing & entanglement



spin-1 atoms



collective spin

$$F = \sum_{i=1}^{N_A} f^{(i)}$$

standard quantum limit $\sum_i (\Delta F_i)^2 = f N_A$

entanglement witness $\xi^2 = (\Delta F_i)^2 / (f N_A)$

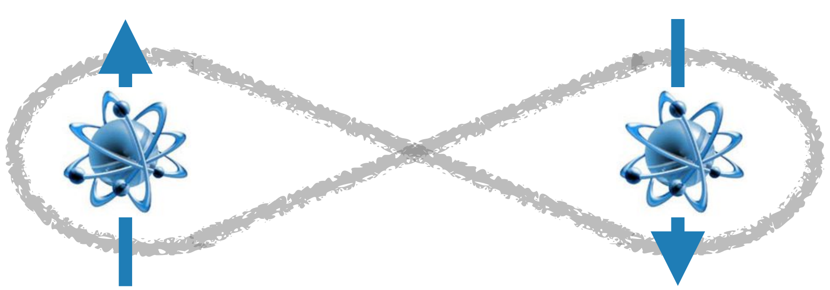
Spin singlet

singlet state

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

zero spin $\mathbf{f} = 0$

no fluctuations $\Delta\mathbf{f} = 0$



Macroscopic spin singlet

singlet state

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

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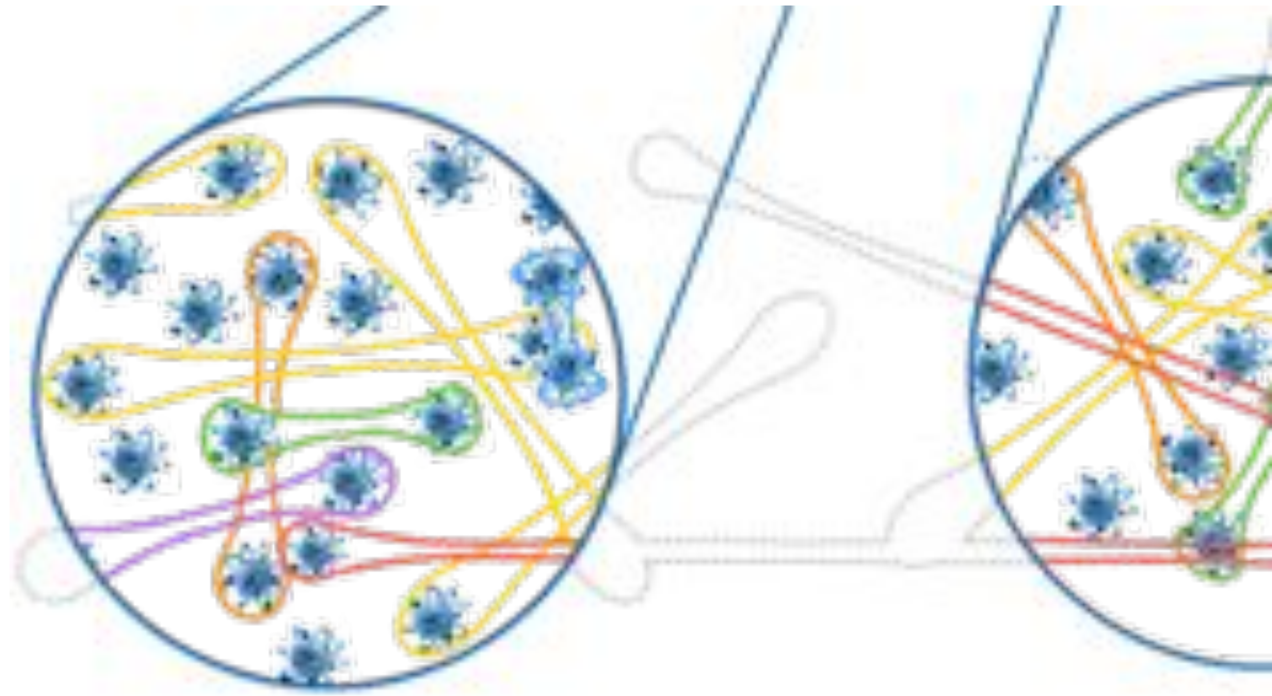
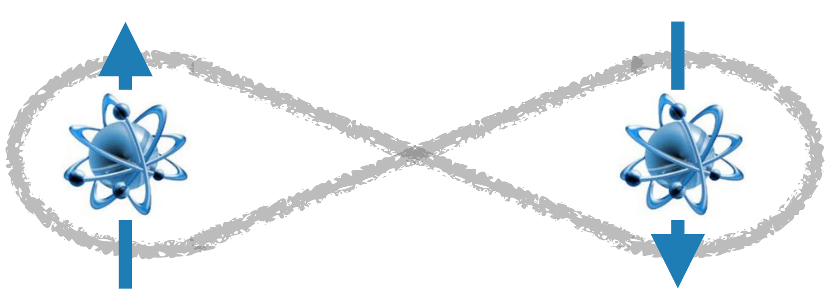




macroscopic singlet state

$$\mathbf{F} = 0$$

$$\Delta\mathbf{F} = 0$$

Macroscopic spin singlet

spin squeezing parameter

$$\xi^2 \equiv \sum_i (\Delta F_i)^2/(f N_A)$$

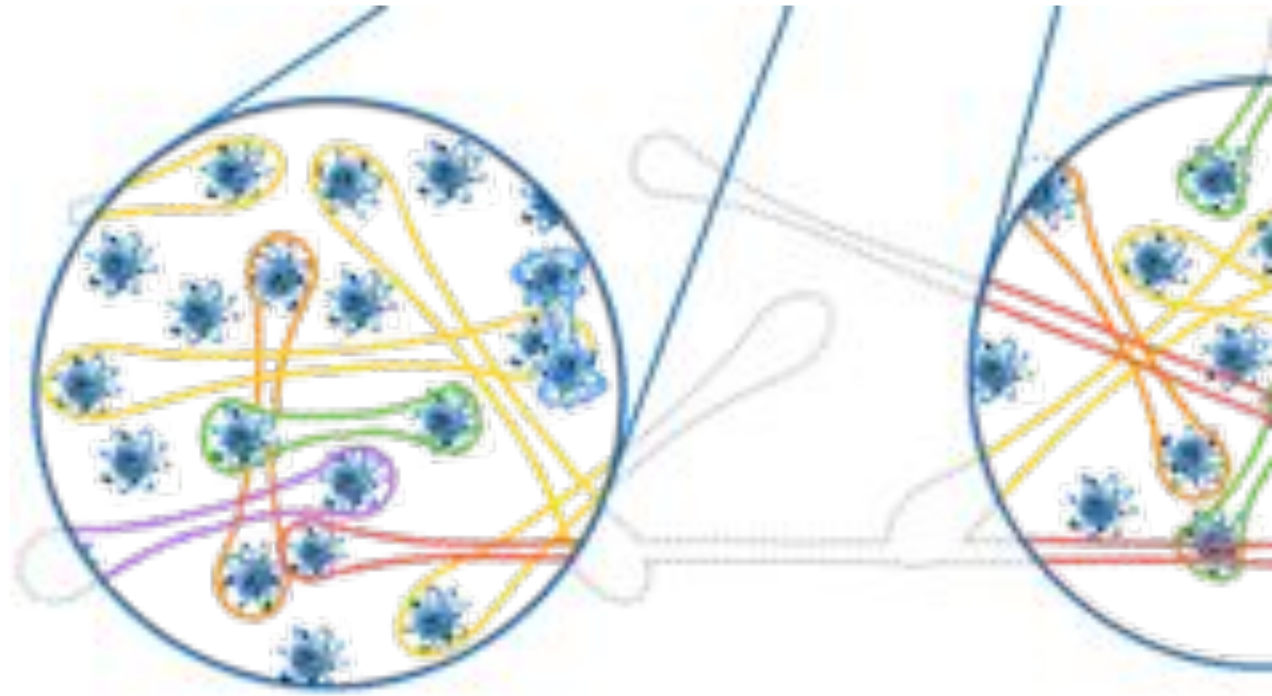
entanglement $\xi^2 < 1$

true singlet $\xi^2 \to 0$

entangled atoms

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

Tóth, NJP 12, 053007 (2010)



macroscopic singlet state

$$\mathbf{F} = 0$$

$$\Delta\mathbf{F} = 0$$

Macroscopic spin singlet

ground state of Heisenberg model with uniform coupling

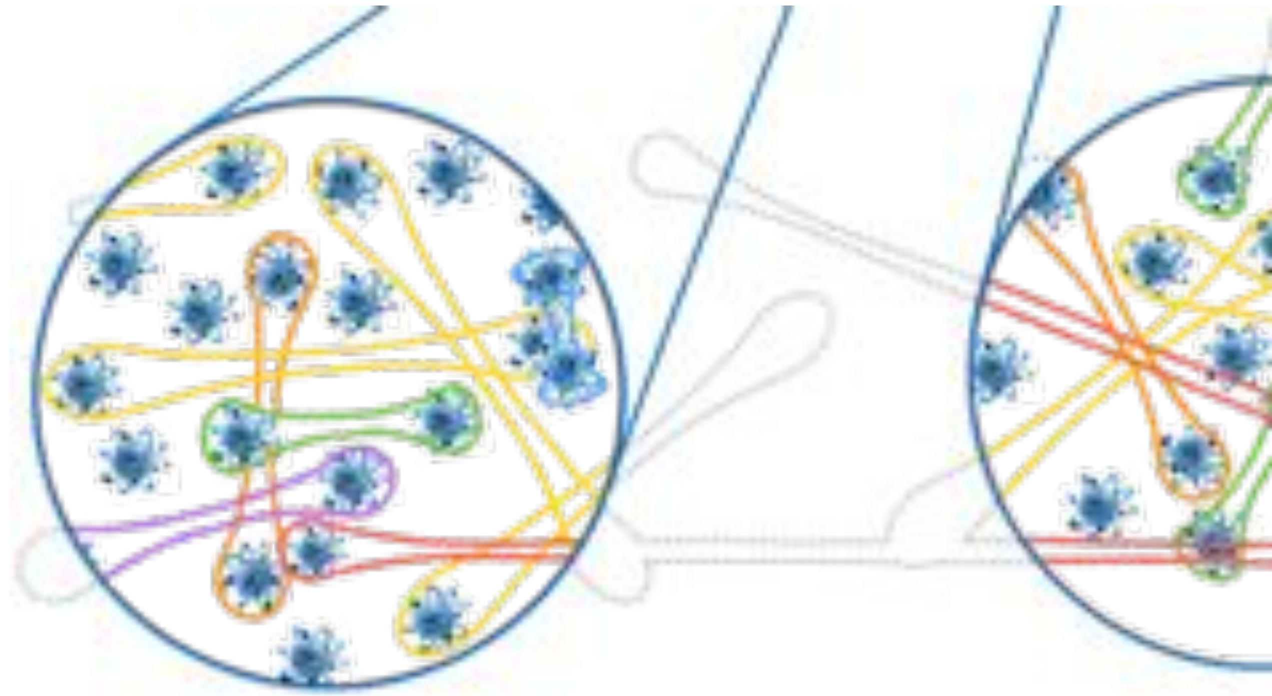
$$H = F_x^2 + F_y^2 + F_z^2$$

SU(2)-invariant

permutationally invariant

entanglement over many length scales

Tóth, NJP 12, 053007 (2010)

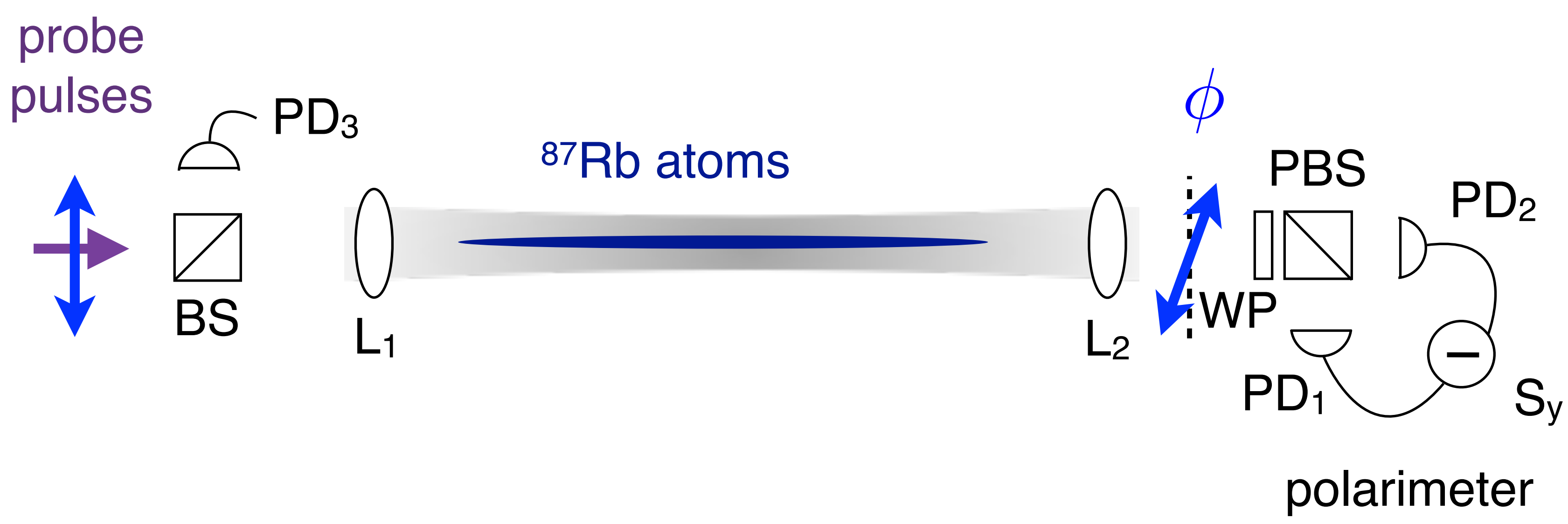


macroscopic singlet state

$$\mathbf{F} = 0$$

$$\Delta \mathbf{F} = 0$$

Quantum atom-light interface



collective spin

$$F \equiv \sum_{i=1}^{N_A} f^{(i)}$$

Stokes operators

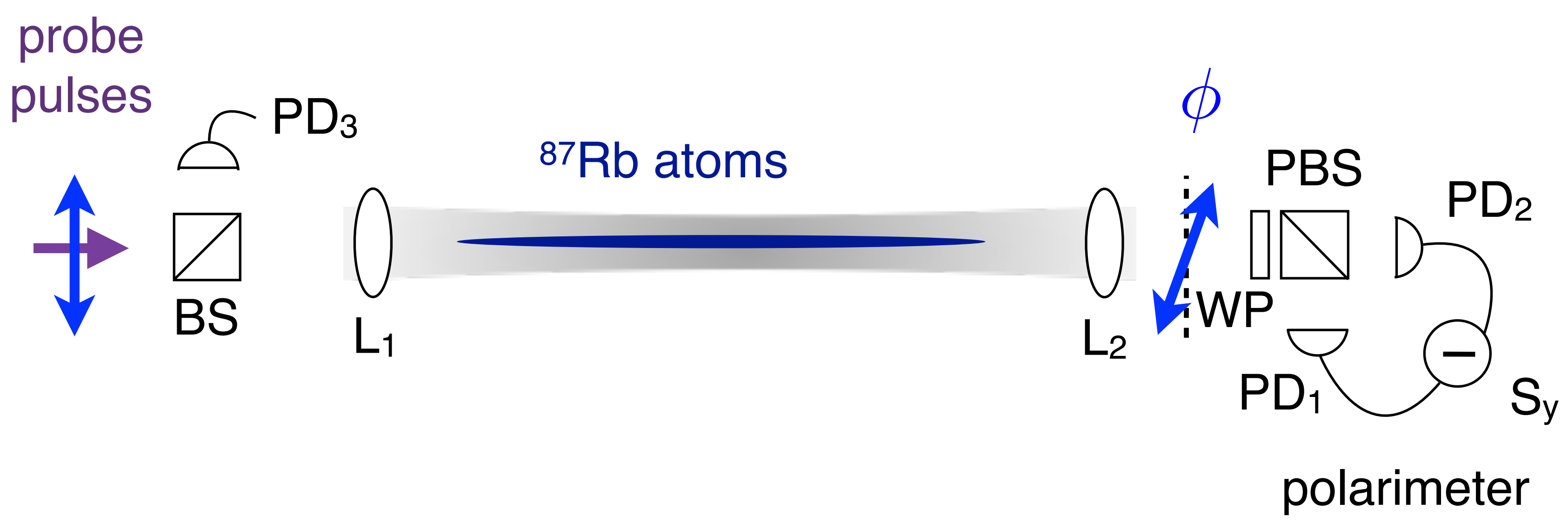
$$S \equiv \sum_{i=1}^{N_L} s^{(i)}$$

$$s_x = n_h - n_v$$
$$s_y = n_{\nearrow} - n_{\nwarrow}$$
$$s_z = n_r - n_l$$

quantum non-demolition interaction

$$\tau H = G_1 S_z F_z$$

Spin squeezing



Faraday rotation

$$\phi = \frac{S_y}{S_x} = G_1 F_z$$

signal-to-noise

$$\zeta = \frac{G_1^2 S_x^2 (\Delta F_z)^2}{(\Delta S_y)^2}$$

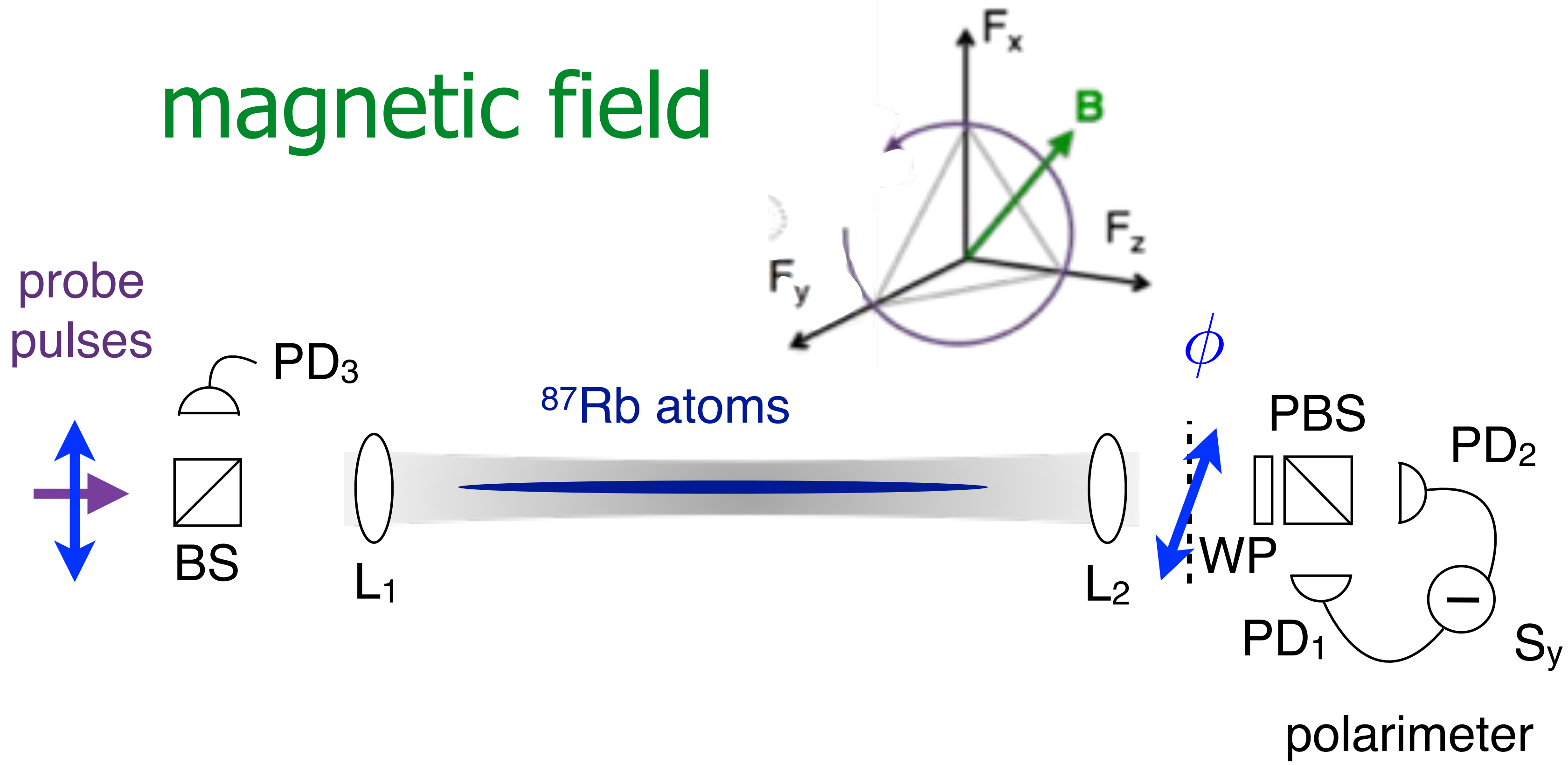
$$= \frac{2}{3} G_1^2 N_L N_A$$

spin squeezing

$$(\Delta F_z^{(\mathrm{out})})^2 = (\Delta F_z^{(\mathrm{in})})^2 / (1 + \zeta)$$

Stroboscopic probing

magnetic field



magnetic field

$$\mathbf{B} = B(1,1,1)$$

Larmor period

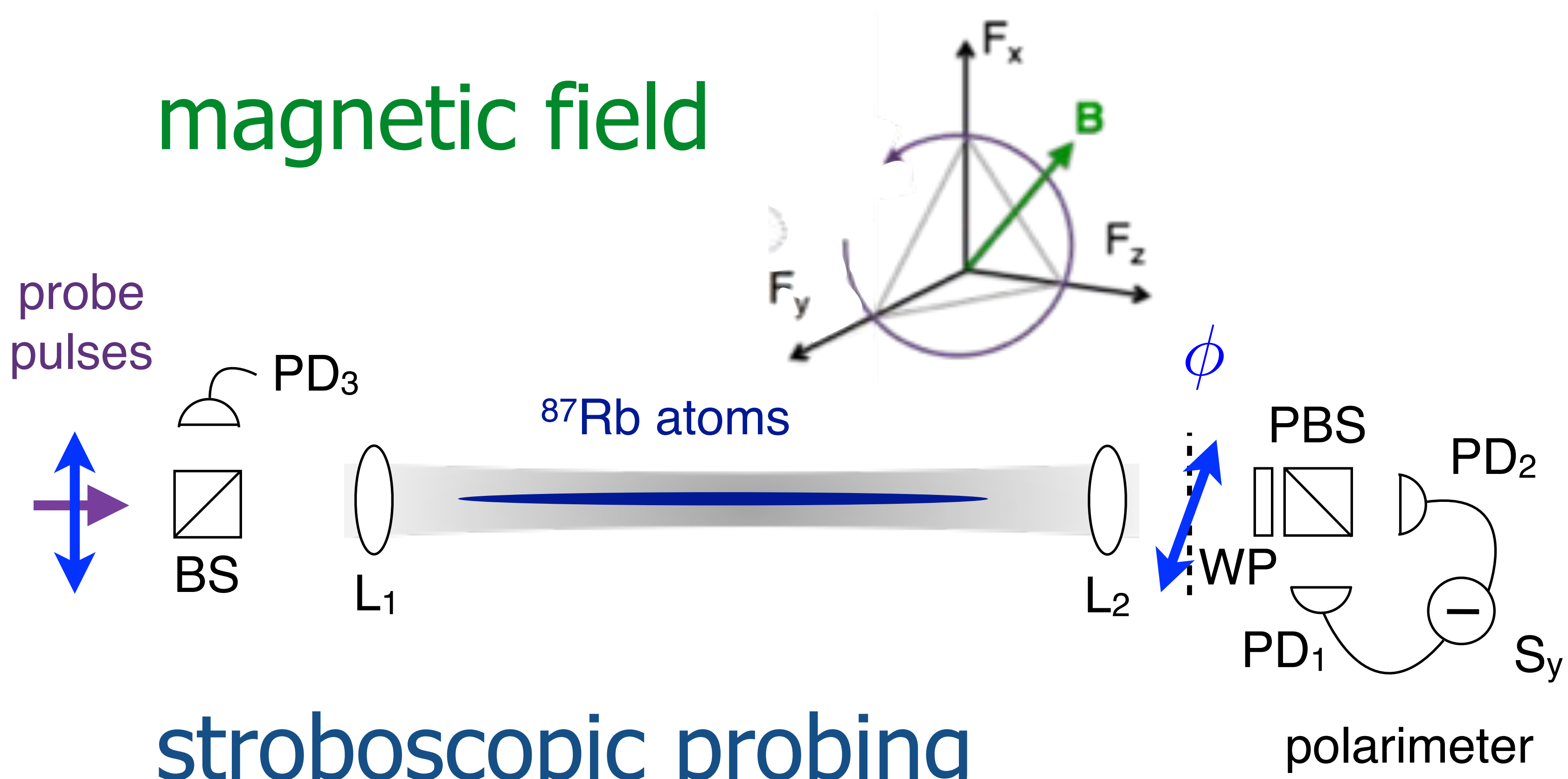
$$T_L = 2\pi/(\gamma B)$$

$$\gamma = \mu_B g_F/\hbar$$

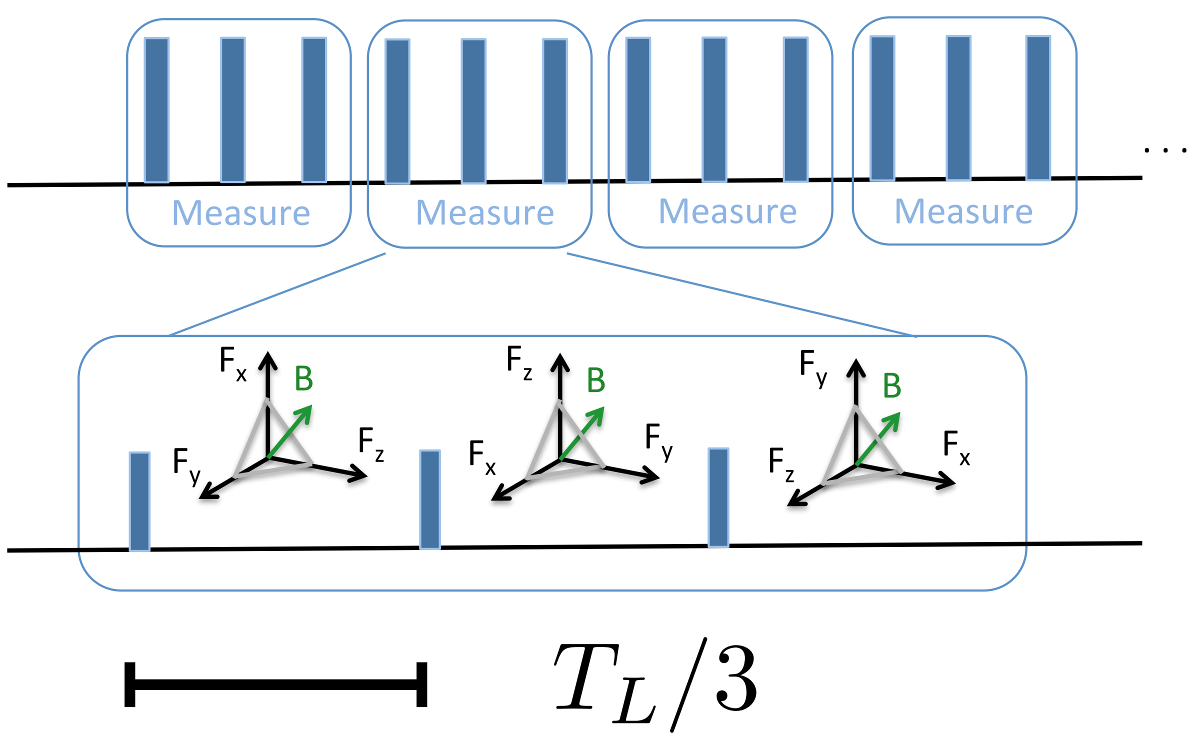
Behbood, PRL 111, 103601 (2013)

Stroboscopic probing

magnetic field



stroboscopic probing



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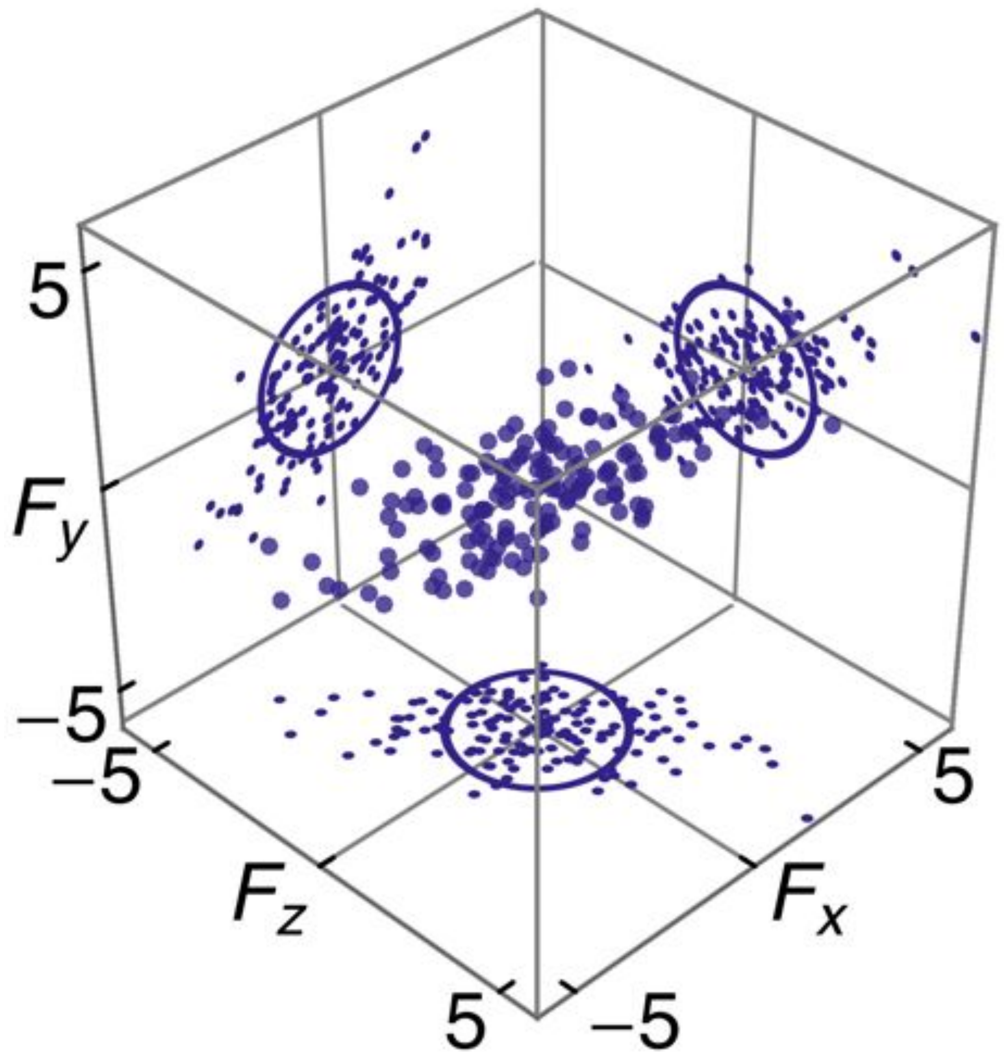
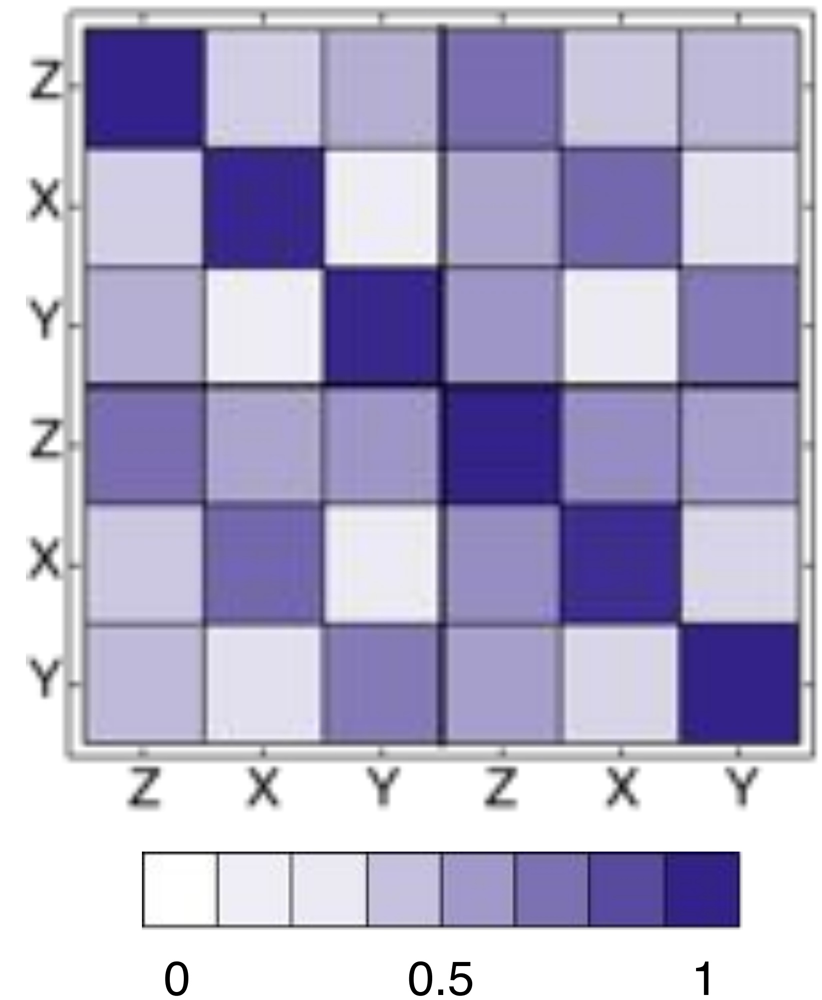
Behbood, PRL 111, 103601 (2013)

Spin state tomography

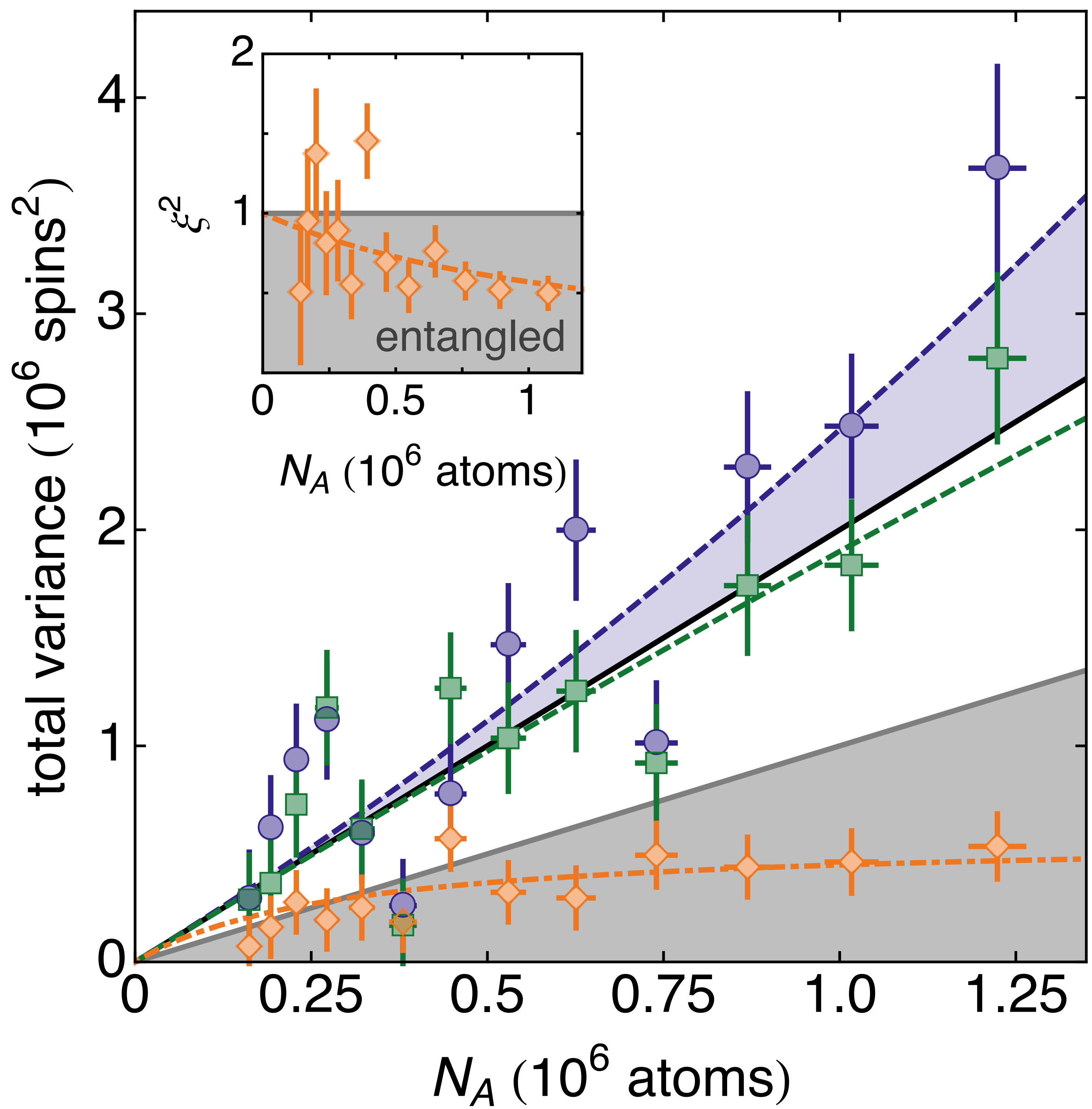




measurements $$F_i^{(m)} = \{F_z^{(1)}, F_x^{(1)}, F_y^{(1)}, F_z^{(2)}, \ldots\}$$

covariance $$\Gamma_{ij} = \tfrac{1}{2}\langle F_i F_j + F_j F_i\rangle - \langle F_i\rangle\langle F_j\rangle$$

Spin squeezing



total variance

$$\mathcal{V}_p = \mathrm{Tr}(\Gamma_p)$$

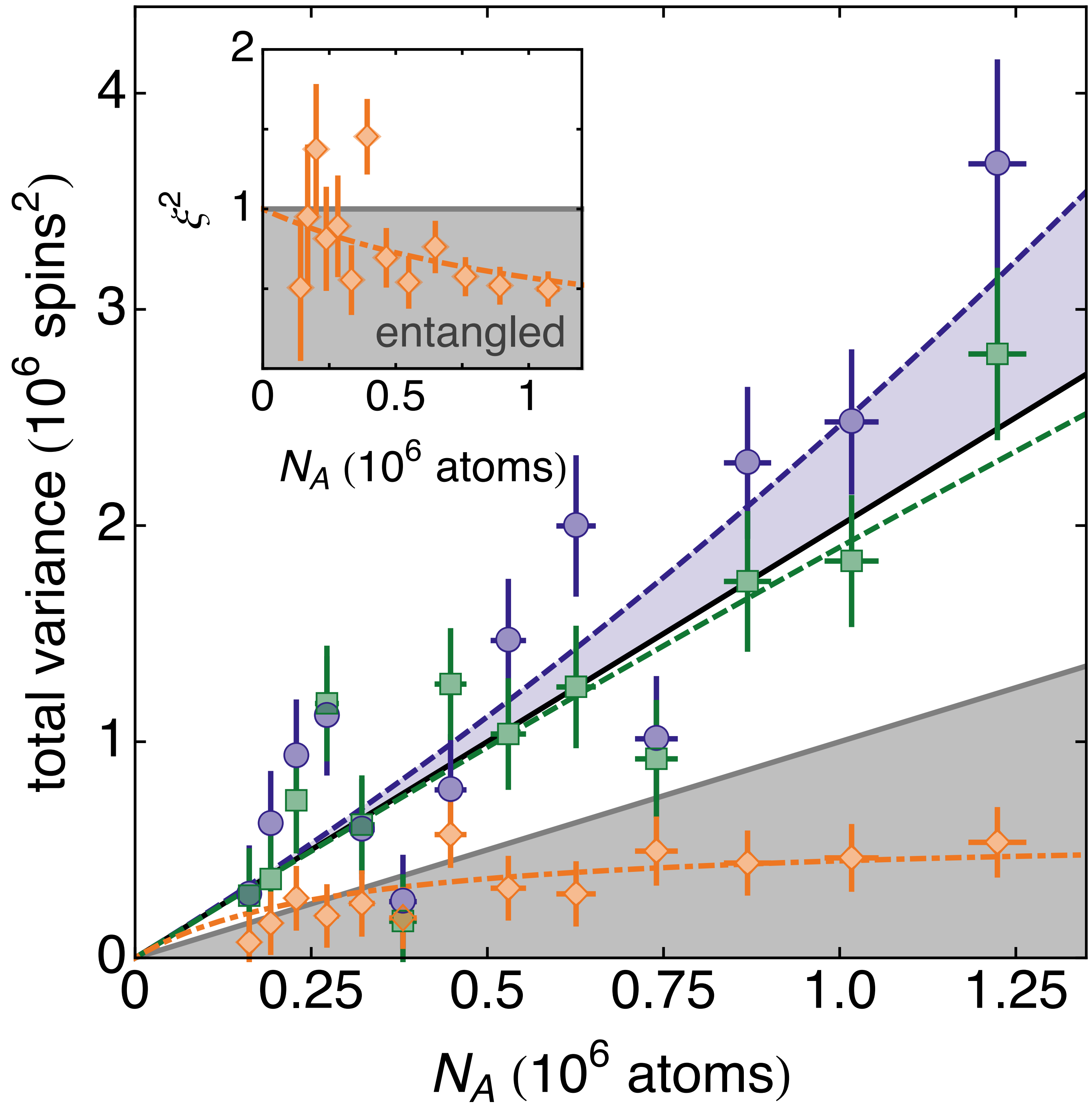
conditional covariance

$$\Gamma_{2|1} = \Gamma_2 - \Gamma_{2,1}\Gamma_1^{-1}\Gamma_{1,2}$$

spin squeezing

$$\xi^2 = \mathrm{Tr}(\Gamma_{2|1})/(fN_A)$$

Spin squeezing



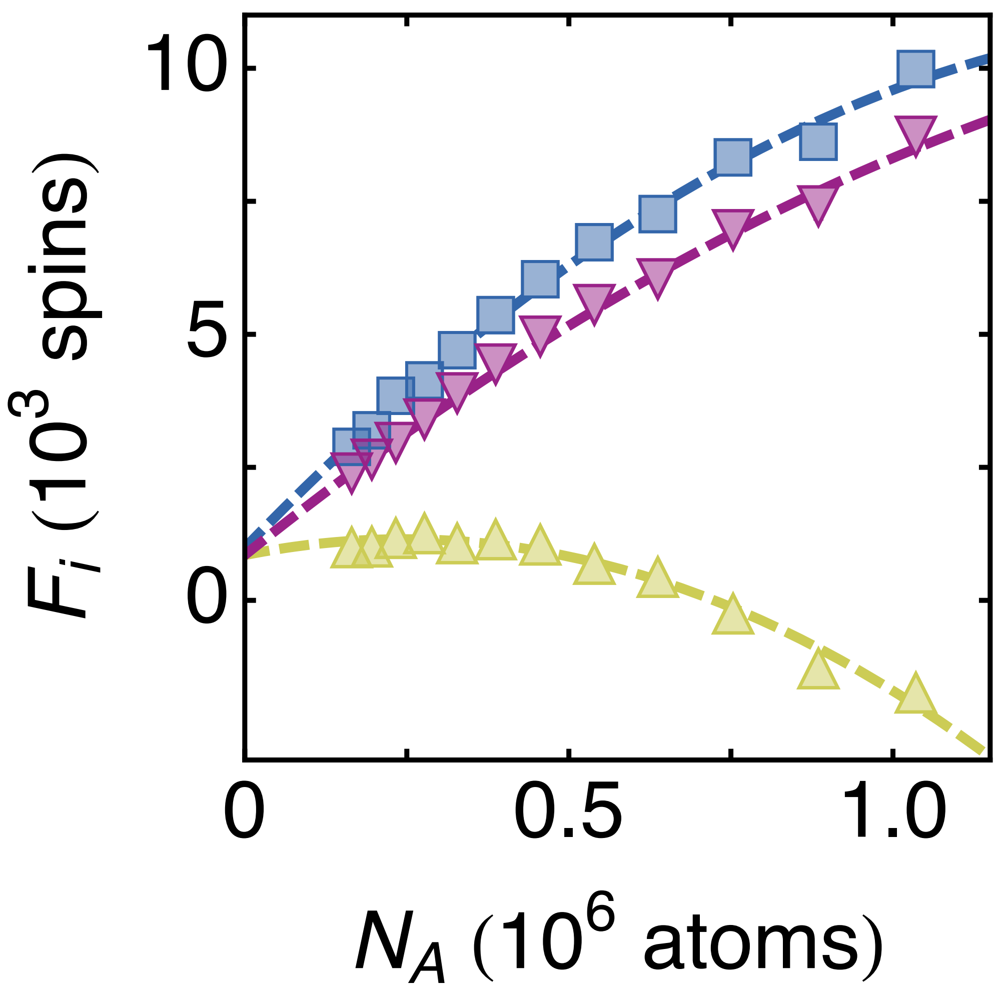
3dB spin squeezing

5.5×10^5 atoms
in the
entangled
singlet state

spin squeezing

$$\xi^2 = \mathrm{Tr}(\Gamma_{2|1})/(f N_A)$$

Unpolarised atoms

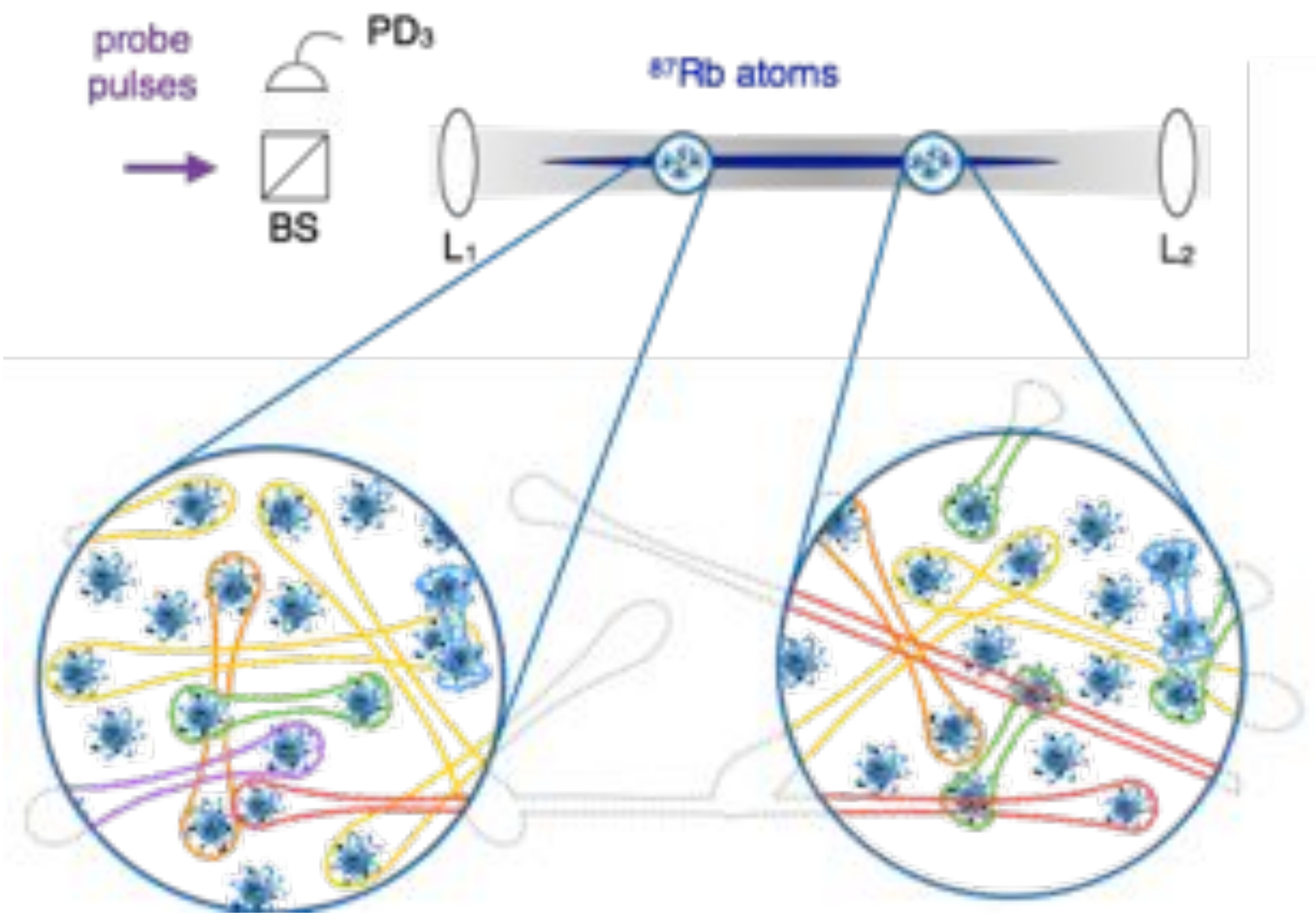


≪ 1% polarisation

in principle allow up to 20dB squeezing (much more than we can achieve)

$$\Delta F_i \Delta F_j \geq |\langle F_k \rangle|/2 = 0$$

Long-range entanglement



symmetric input state

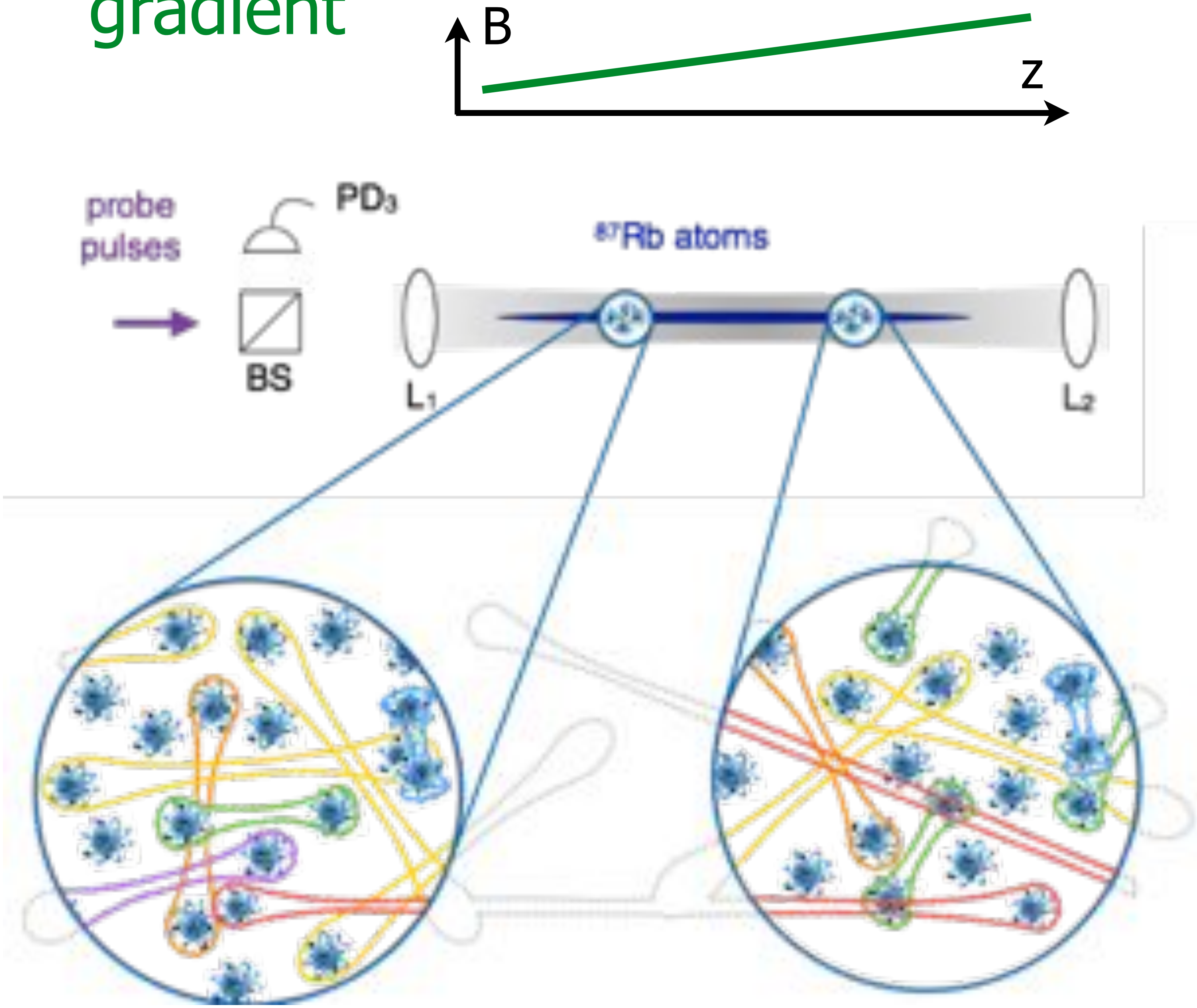
$$R = \rho^{\otimes N_A}$$

collective measurement

$$\tau H = G_1 S_z F_z$$

Decoherence

magnetic field gradient



singlet ⇒ triplet

spin flips

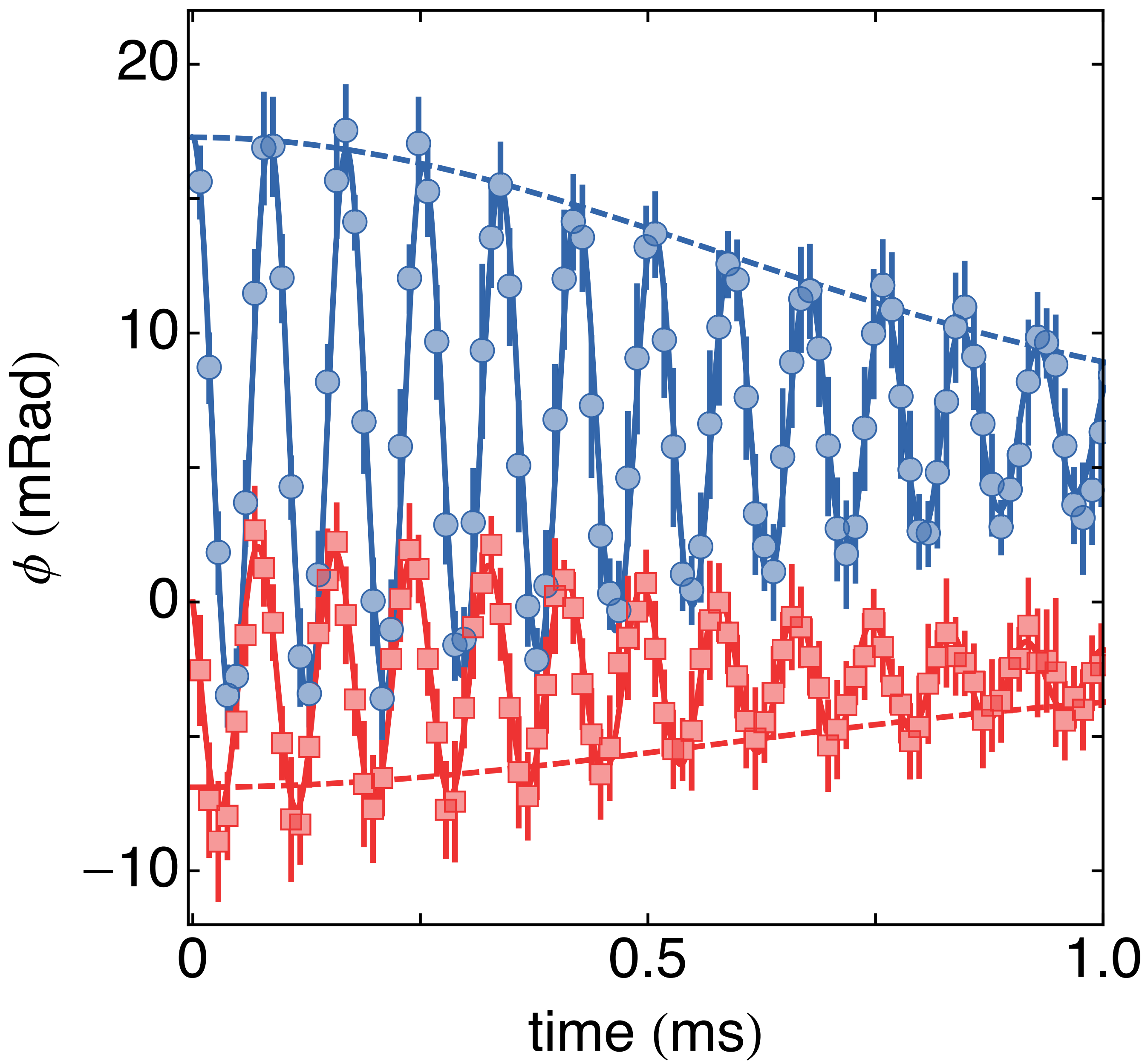
dephasing at a rate

$$\exp(-t^2/T_2^2)$$

$$1/T_2 = \sigma\gamma(\partial B/\partial z)$$

Urizar-Lanz, PRA 88, 013626 (2013)

Spin dephasing



input coherent spin state

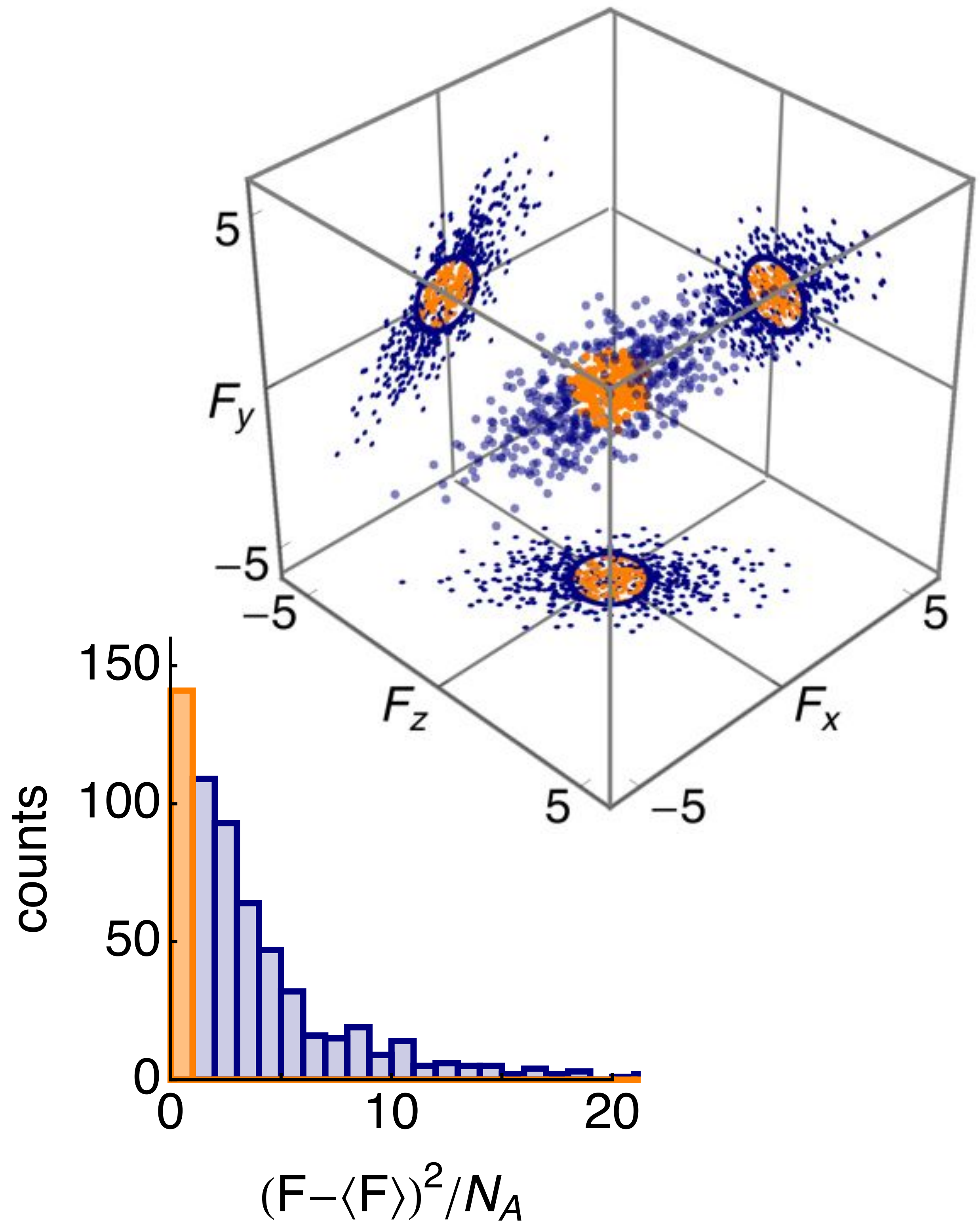
dephasing at a rate

$$\exp(-t^2/T_2^2)$$

$$1/T_2 = \sigma\gamma(\partial B/\partial z)$$

Behbood, APL 102, 173504 (2013)

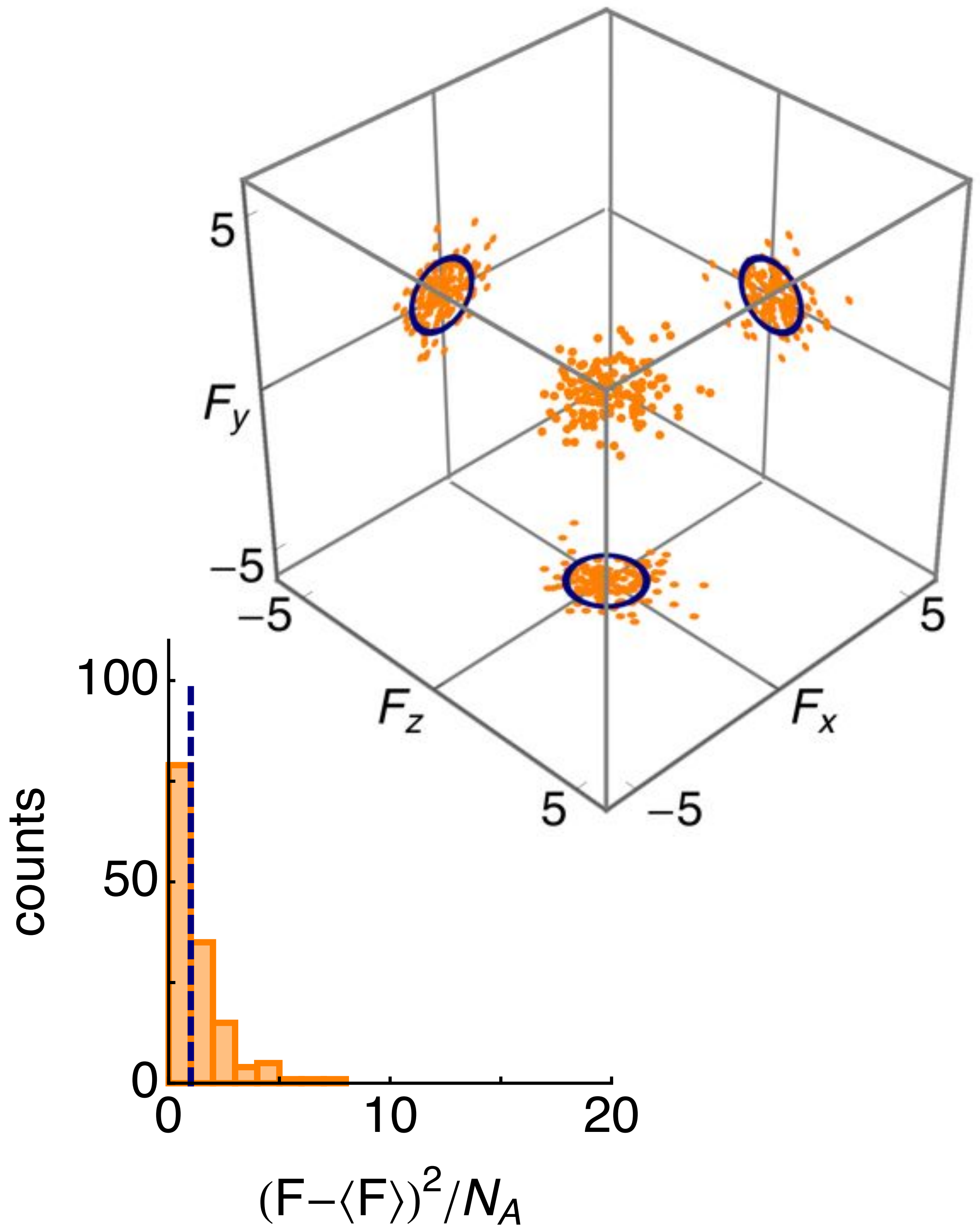
(Post-)select spin singlets



cutoff parameter

$$|\mathbf{F}^{(1)} - \langle \mathbf{F}^{(1)} \rangle| / N_A < C$$

(Post-)select spin singlets



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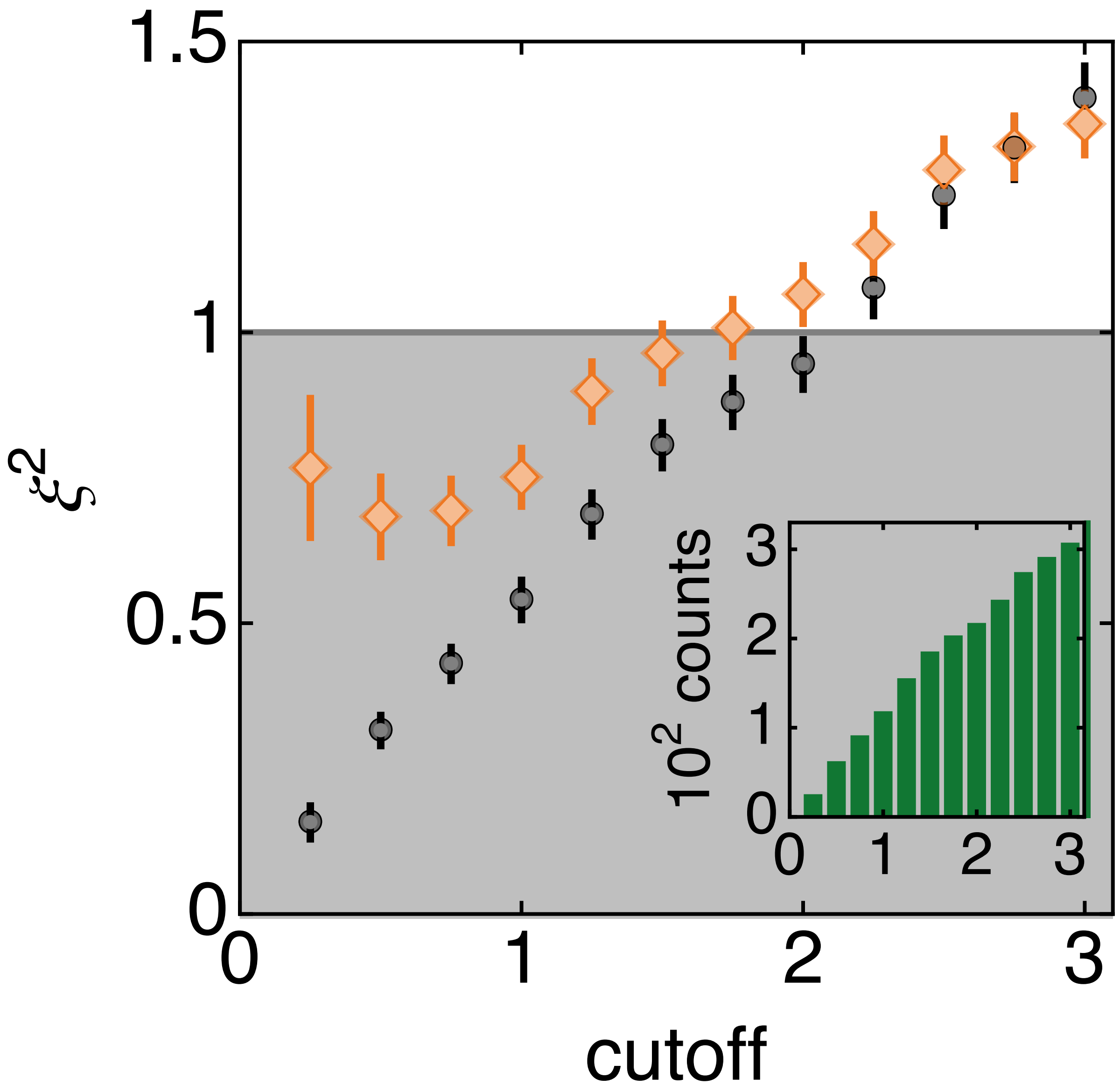
total variance

$$\mathcal{V}_p = \mathrm{Tr}(\Gamma_p)$$

(Post-)select spin singlets



cutoff parameter

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total variance

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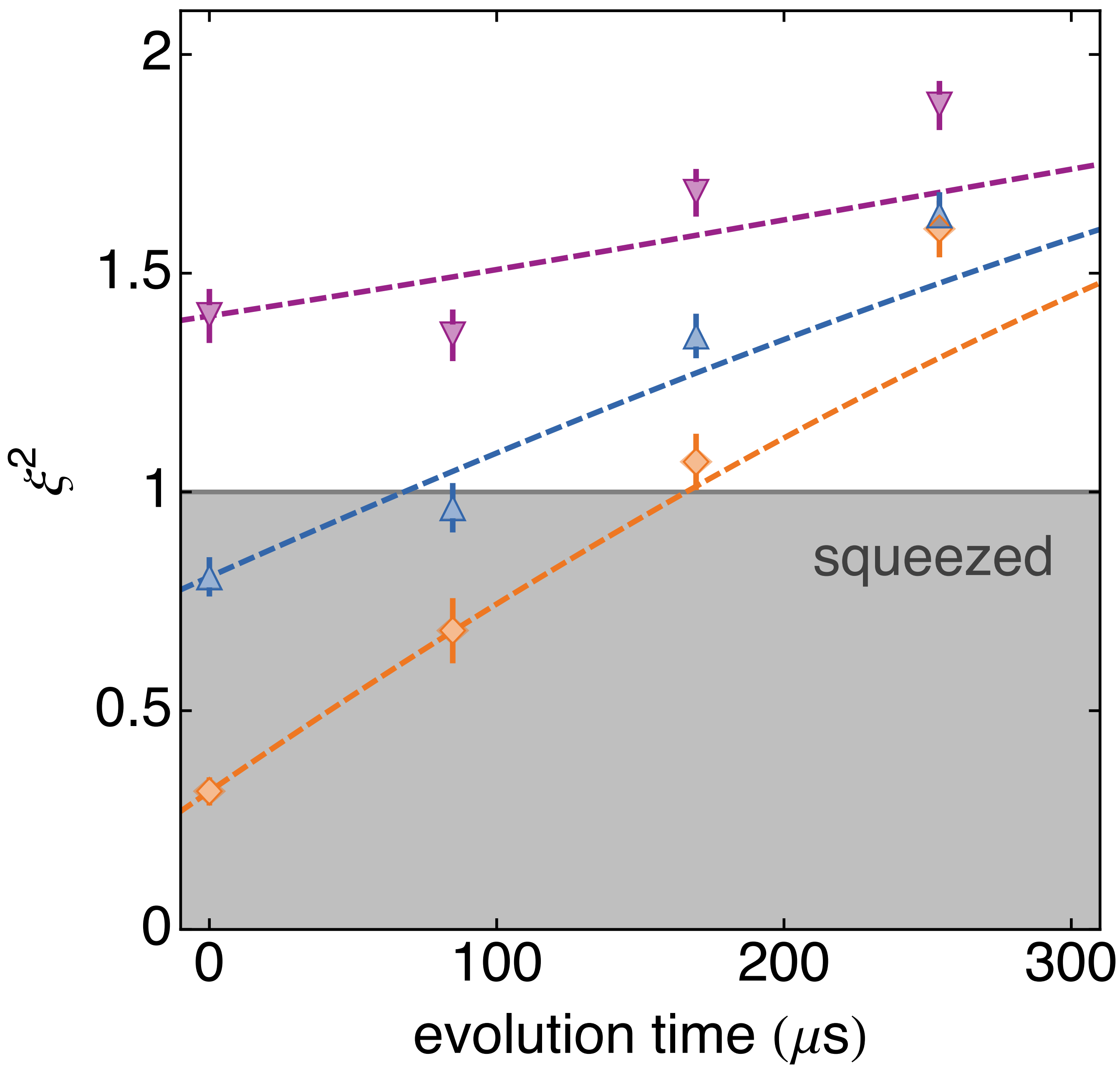
Decoherence



increase in total variance

$$\xi^2(t) \propto \left(1 - \exp(-t^2/T_2^2)\right)$$

$$1/T_2 = \sigma\gamma(\partial B/\partial z)$$

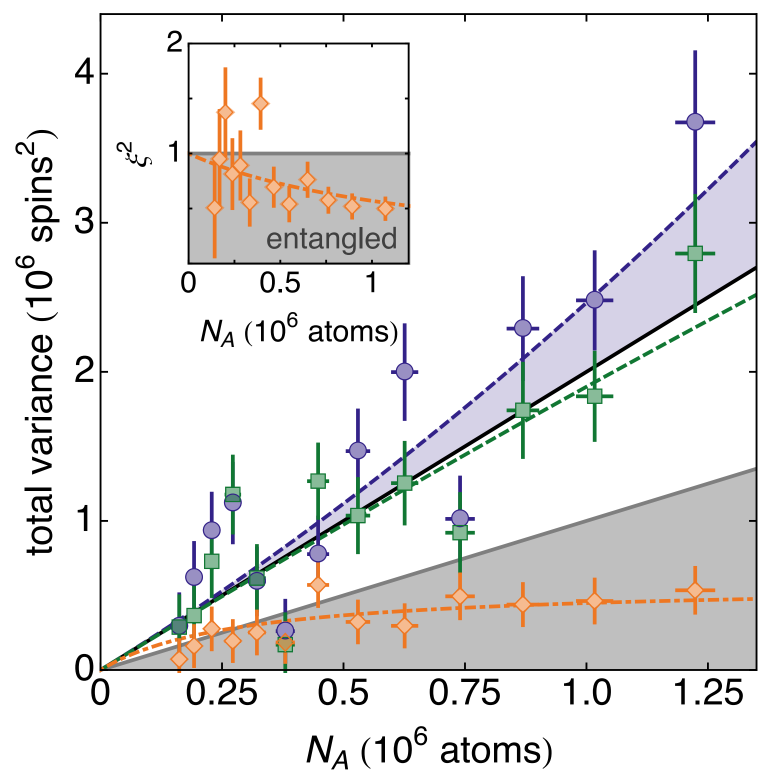
indirect evidence for long range entanglement

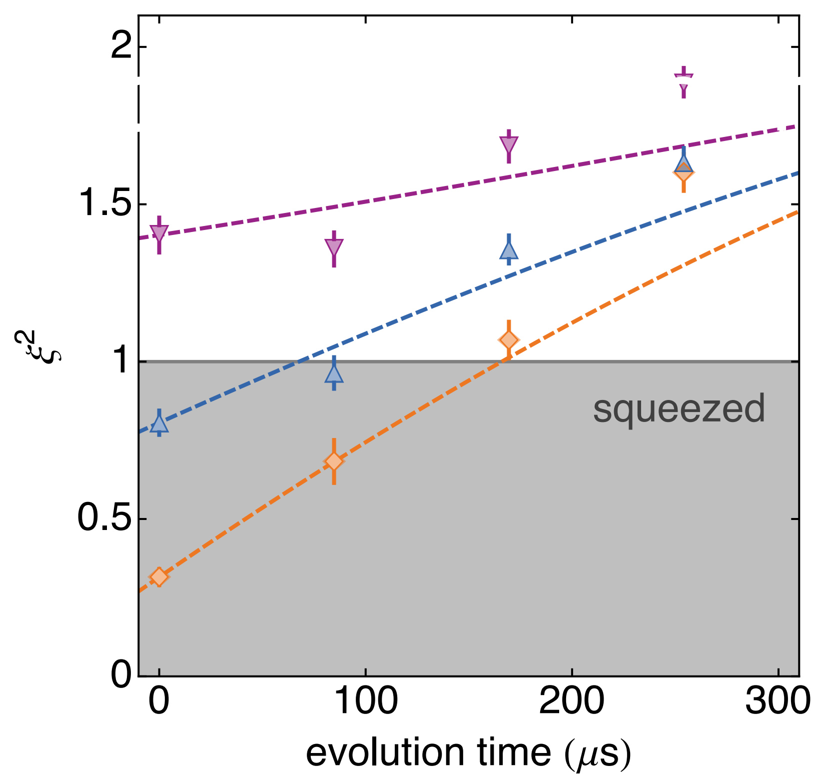
Macroscopic spin singlet

we have created a macroscopic singlet state by measurement-induced spin squeezing

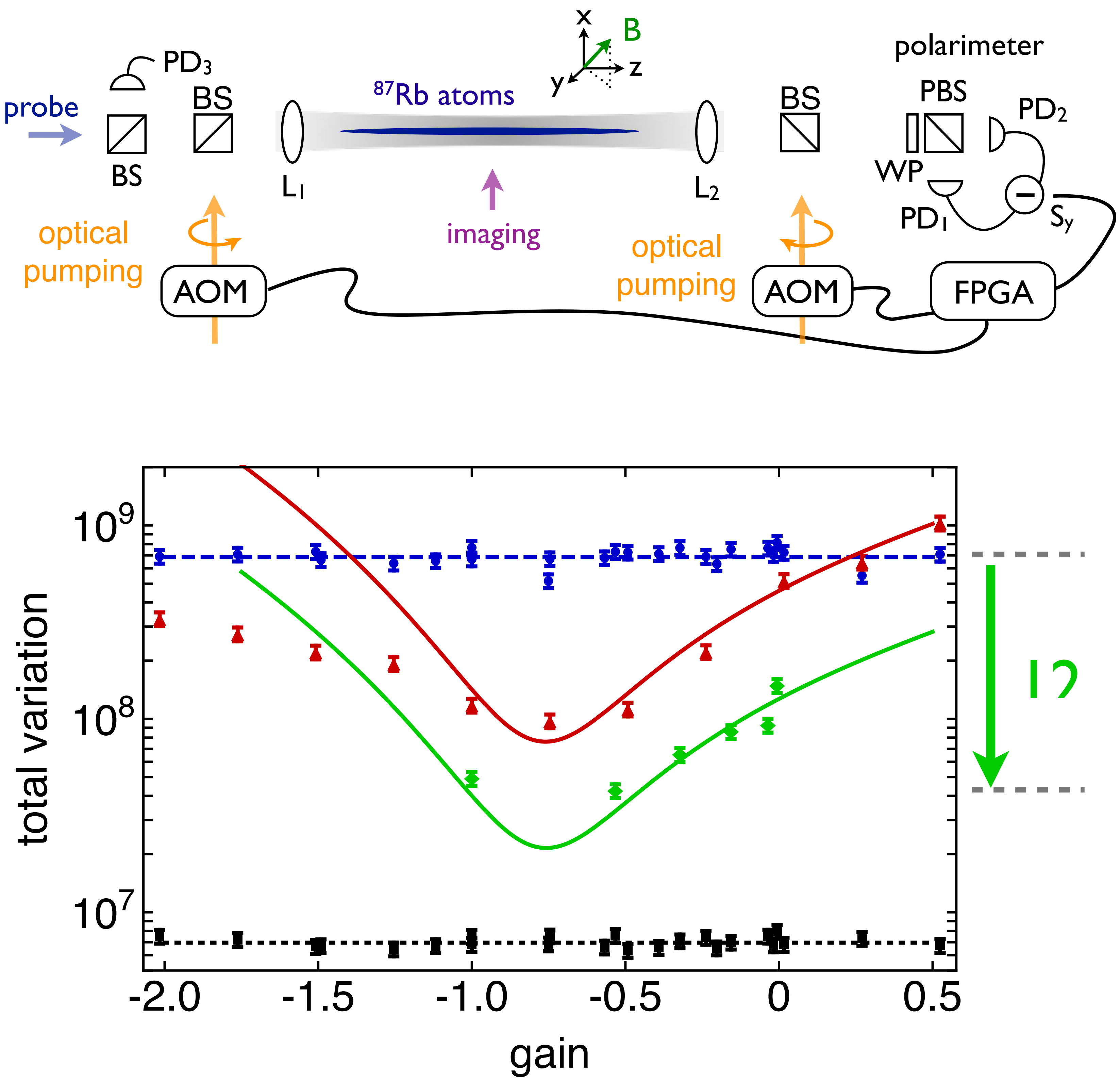
5.5×10^5 atoms in the entangled singlet state

evidence for long range entanglement





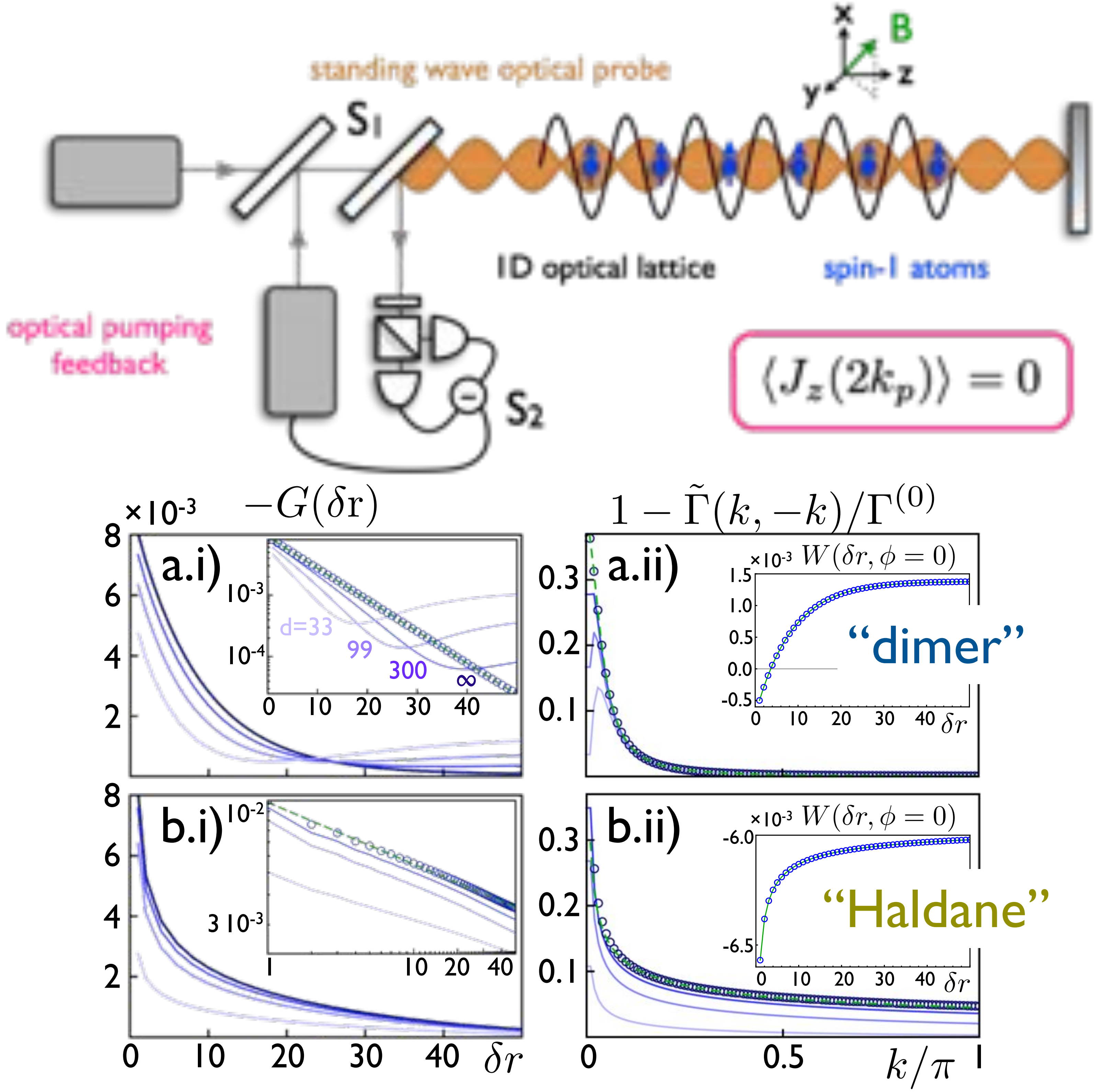
Feedback cooling



quantum control & feedback cooling

Behbood, PRL 111, 103601 (2013)

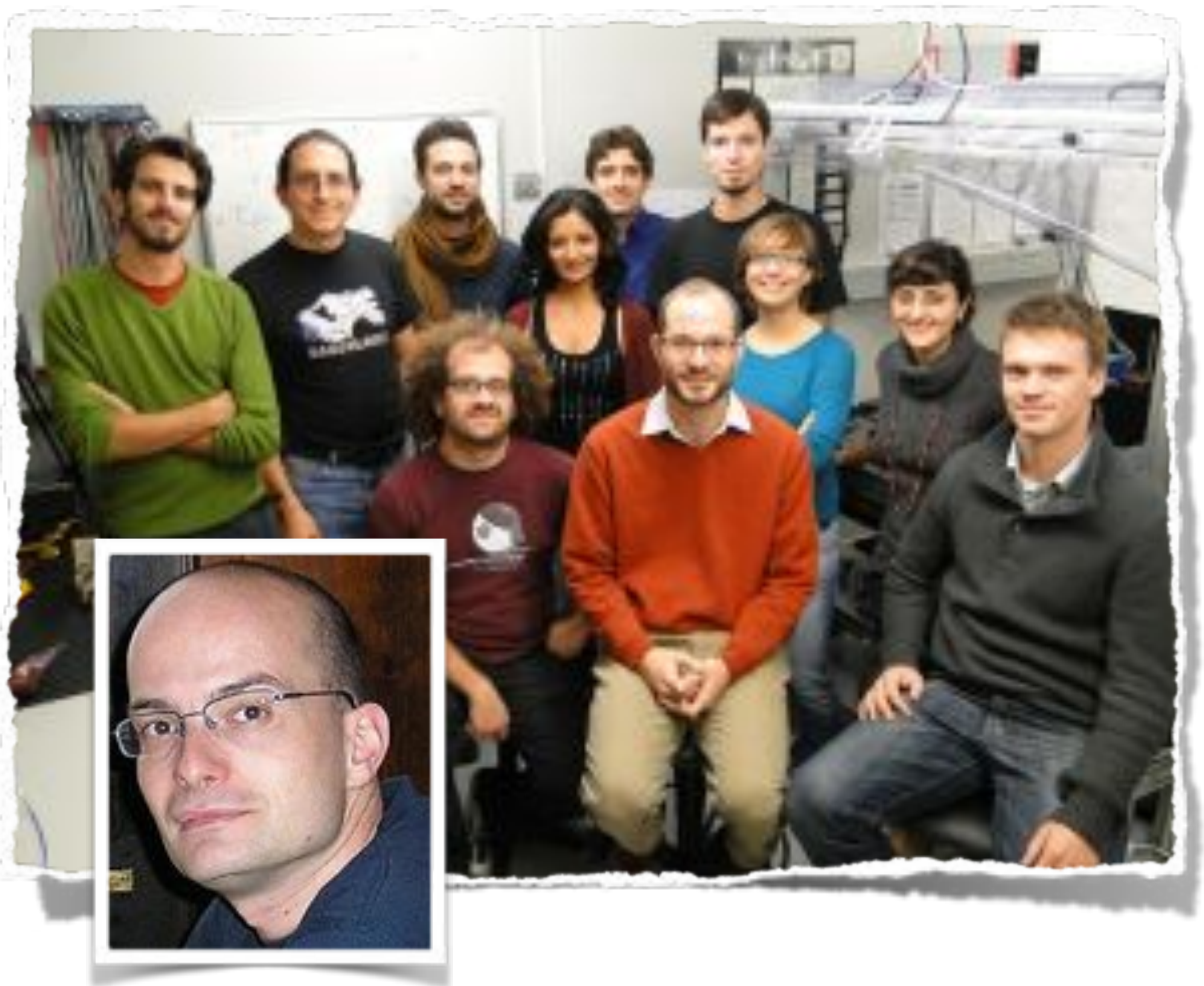
Quantum engineering



preparation of spatially structured quantum spin correlations

Hauke, PRA 87, 021601R (2013)

Acknowledgments



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MG roup itchell

MINISTERIO DE CIENCIA E INNOVACIÓN

Generalitat de Catalunya

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MARIE CURIE ACTIONS

Fundació Privada CELLEX

icrea
Institució Catalana de Recerca i Estudis Avançats

Thankyou

current work

Behbood, arXiv:1403.1964 (2014)

experiments

Behbood, PRL 111, 103601 (2013)

Behbood, APL 102, 173504 (2013)

theory

Tóth, NJP 12, 053007 (2010)

Urizar-Lanz, PRA 88, 013626 (2013)

Hauke, PRA 87, 021601R (2013)

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