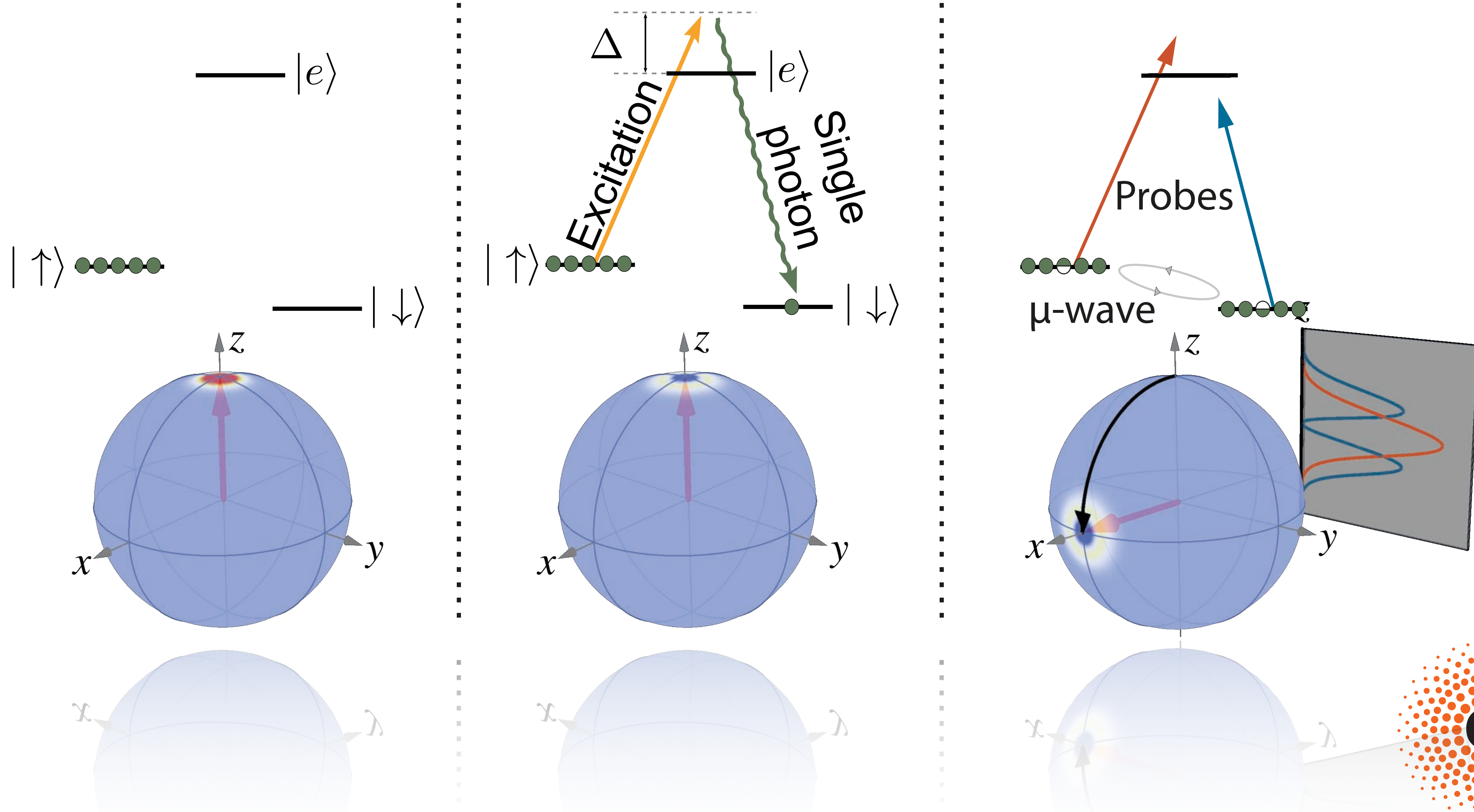

Quantum interference between a single spin excitation and a macroscopic atomic ensemble

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European Research Council
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QUANTOP

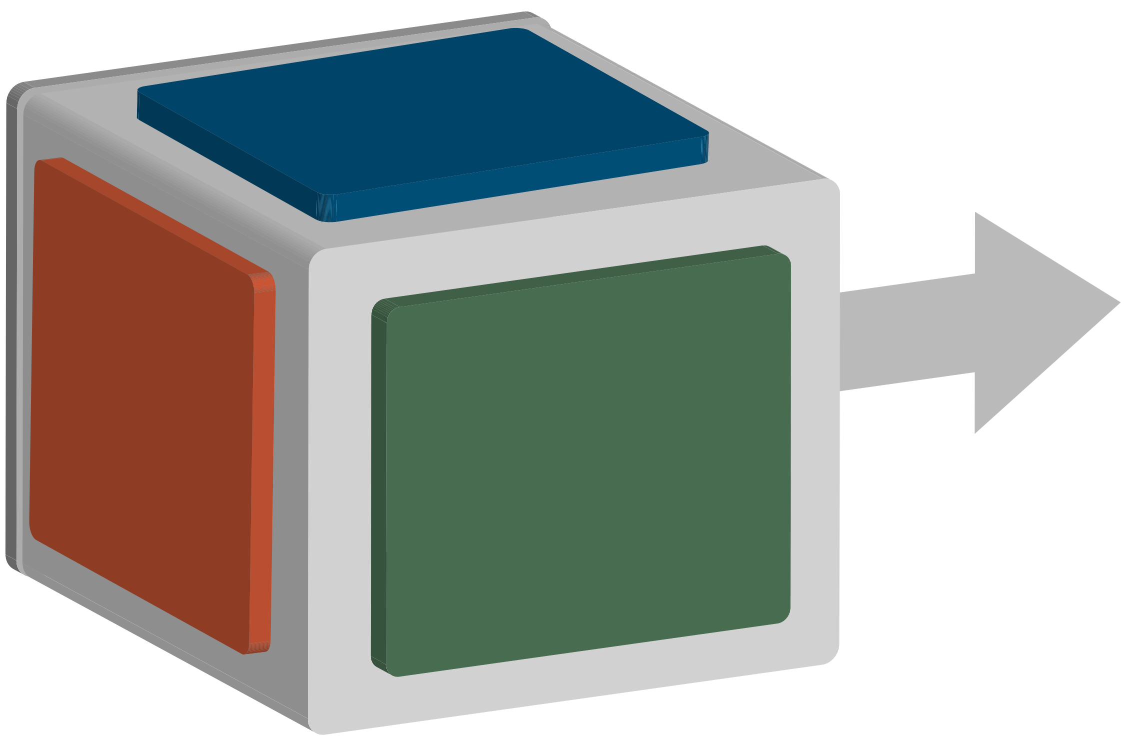
For quantum science we require on-demand and long lived quantum resources.

Quantum resources should be:

- On-demand.

- Distinct quantum.

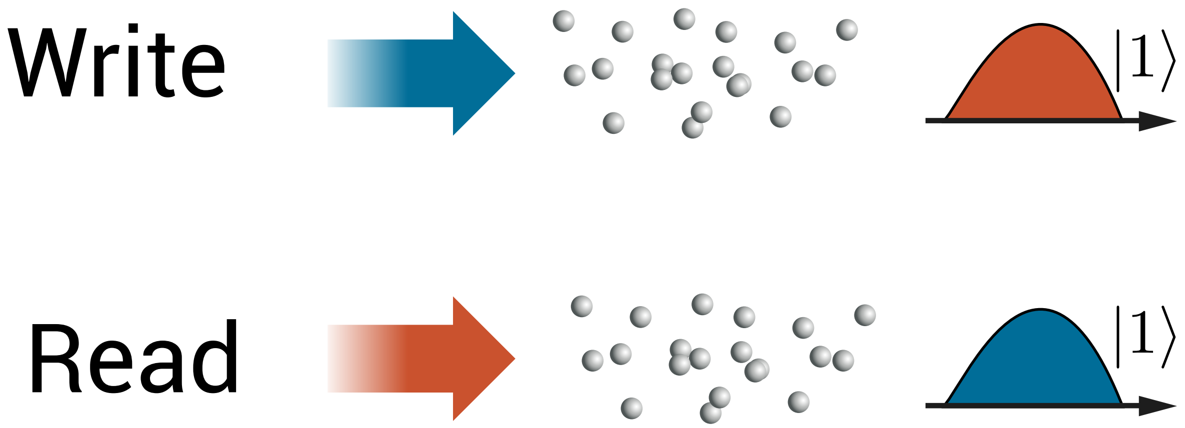
- Long lived.



Atom light interfaces have been based on either discrete or continuos approach.

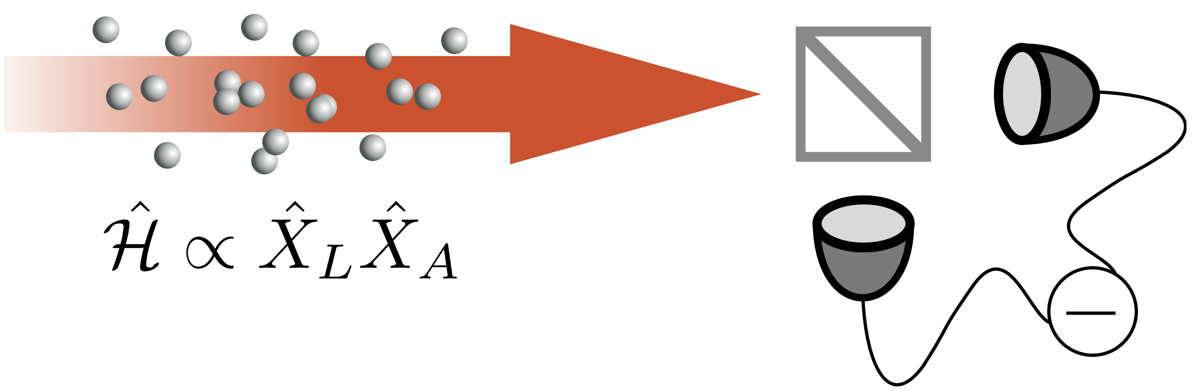
Discrete method uses:

- Fock states.
- Photon counting.



Continuous method uses:

- Gaussian states.
- Homodyne detection.



$$\hat{\mathcal{H}} \propto \hat{X}_L \hat{X}_A$$

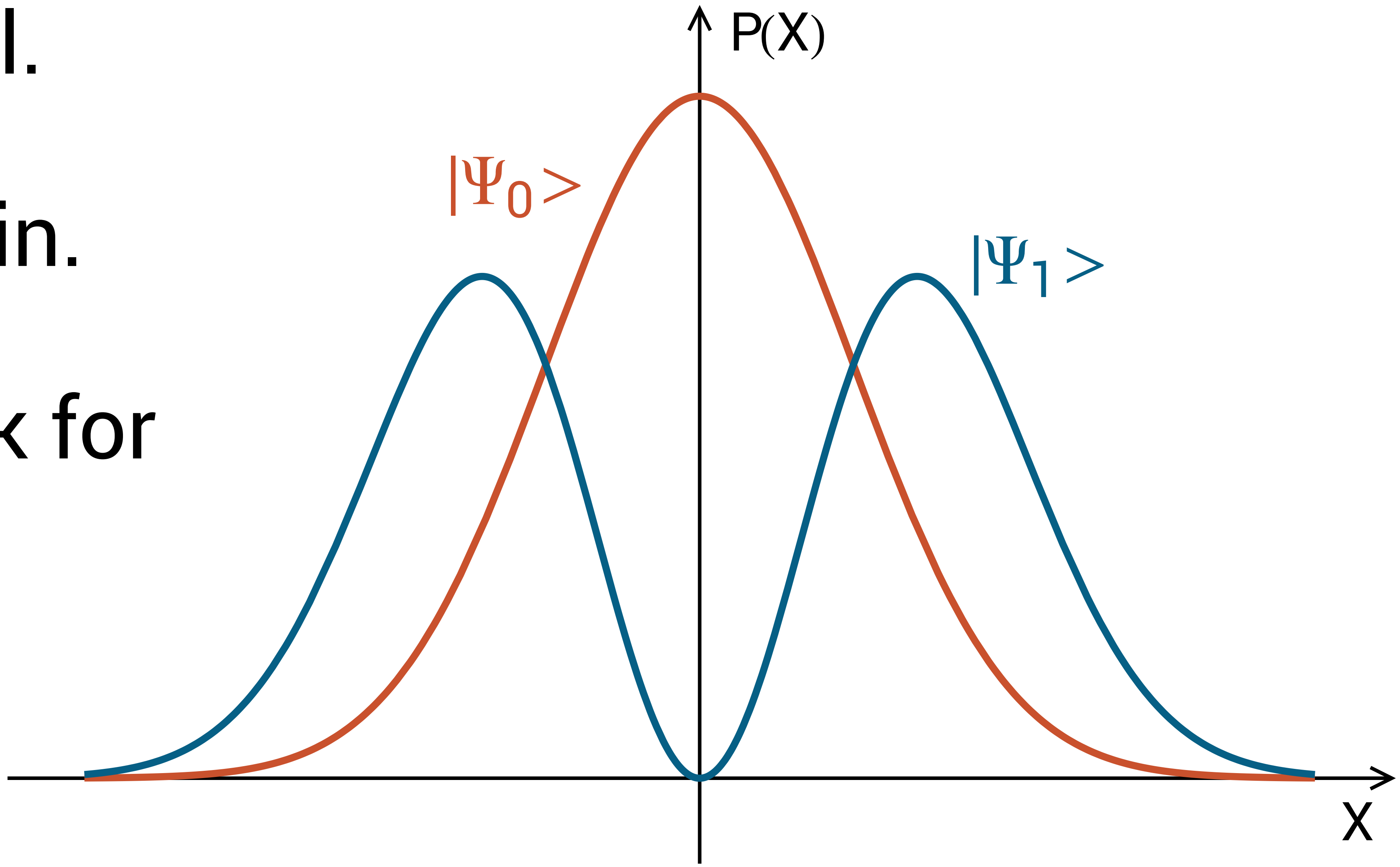
J. Kimble, Nature (2008)
K. Hammerer et al, RMP (2010)

We wil use a hybrid method combining discrete-continuous methods.

- Non-classical.

- Metrology gain.

- Building block for other states.



S. Christensen et al, NJP (2013)

Quantum state engineering in an atomic ensemble.

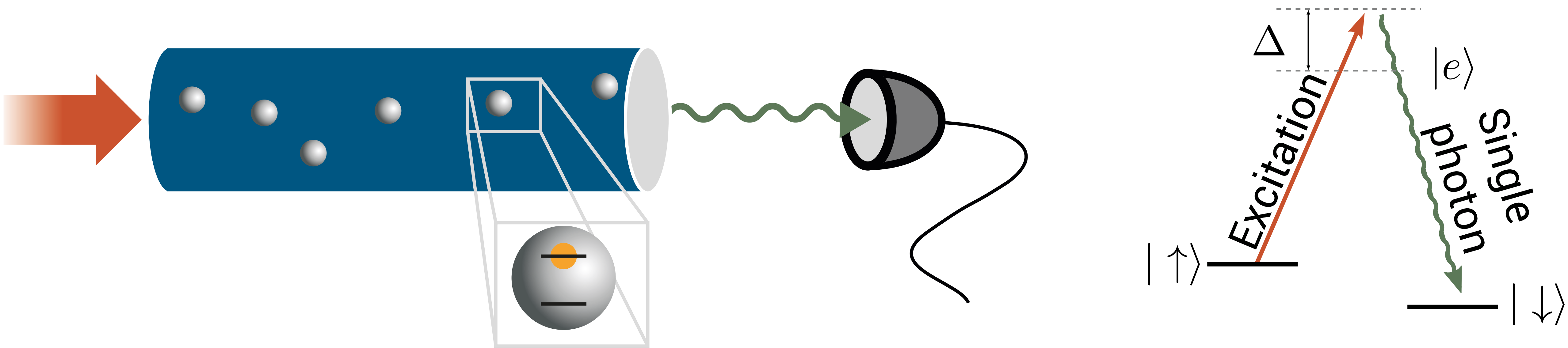
Collective single excitation state.

Atomic homodyne detection.

Experimental implementation.

Results and model.

The state of the atomic ensemble depends on the detection of a photon.



$$|\Psi_0\rangle \equiv |\uparrow\uparrow \ldots \uparrow\uparrow\rangle \xrightarrow{\text{Click}} |\Psi_1\rangle \equiv \frac{1}{\sqrt{N_\mathrm{a}}} \sum_{l=1}^{N_\mathrm{a}} |\uparrow\uparrow \ldots \uparrow \underbrace{\downarrow}_{l\text{-th atom}} \uparrow \ldots \uparrow\uparrow\rangle$$

L. Duan et al., Nature (2001)
S. Christensen et al, NJP (2013)

Rotating the states and measure the population difference.

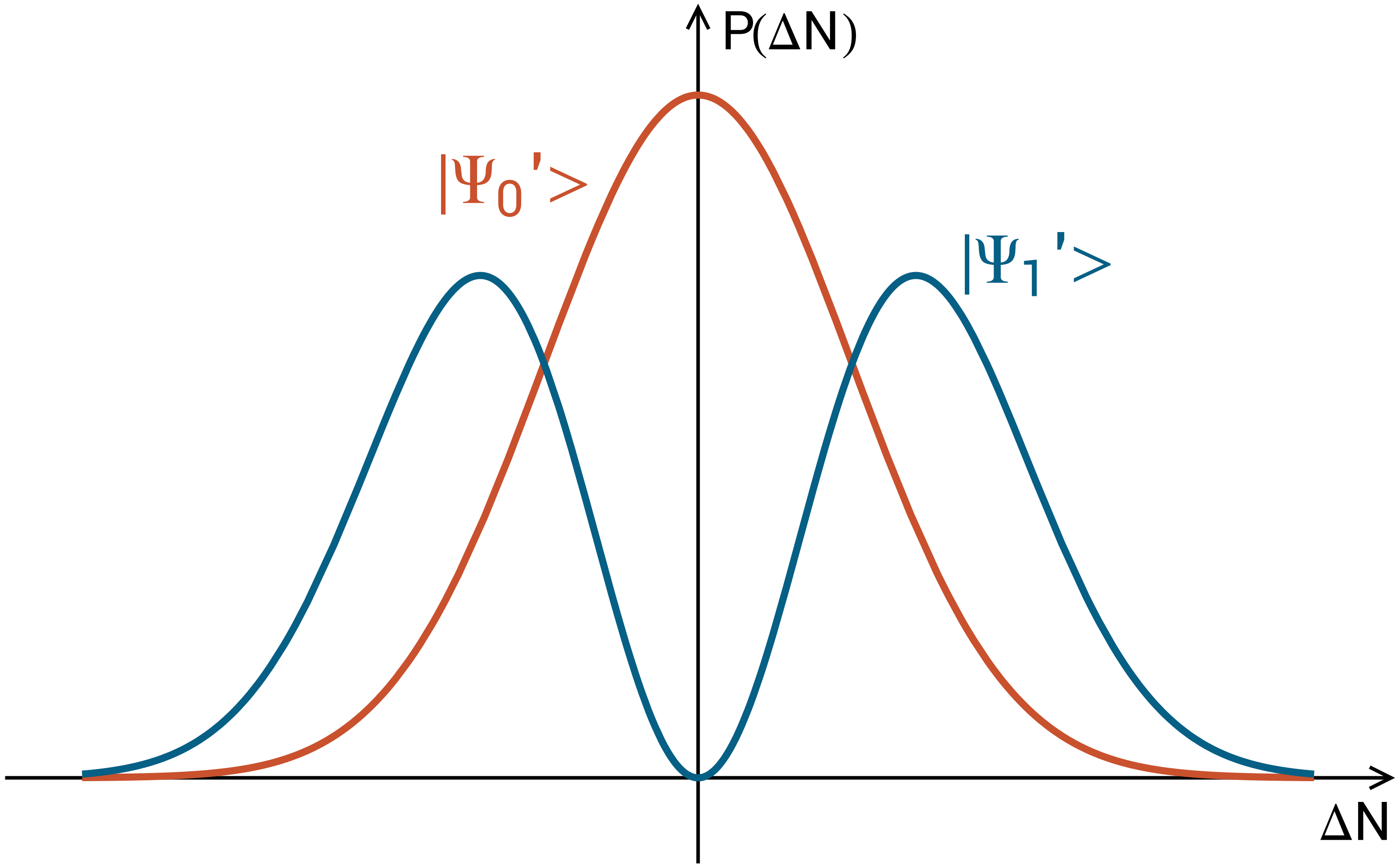
No click: $|\Psi_0'\rangle \equiv |\leftarrow\leftarrow \ldots \leftarrow\leftarrow\rangle$

Click: $|\Psi_1'\rangle \equiv \frac{1}{\sqrt{N_\mathrm{a}}} \sum_{l=1}^{N_\mathrm{a}} |\leftarrow\leftarrow \ldots \underbrace{\leftarrow \rightarrow \leftarrow}_{l\text{-th atom}} \ldots \leftarrow\leftarrow\rangle \, .$

- Non-Classical.

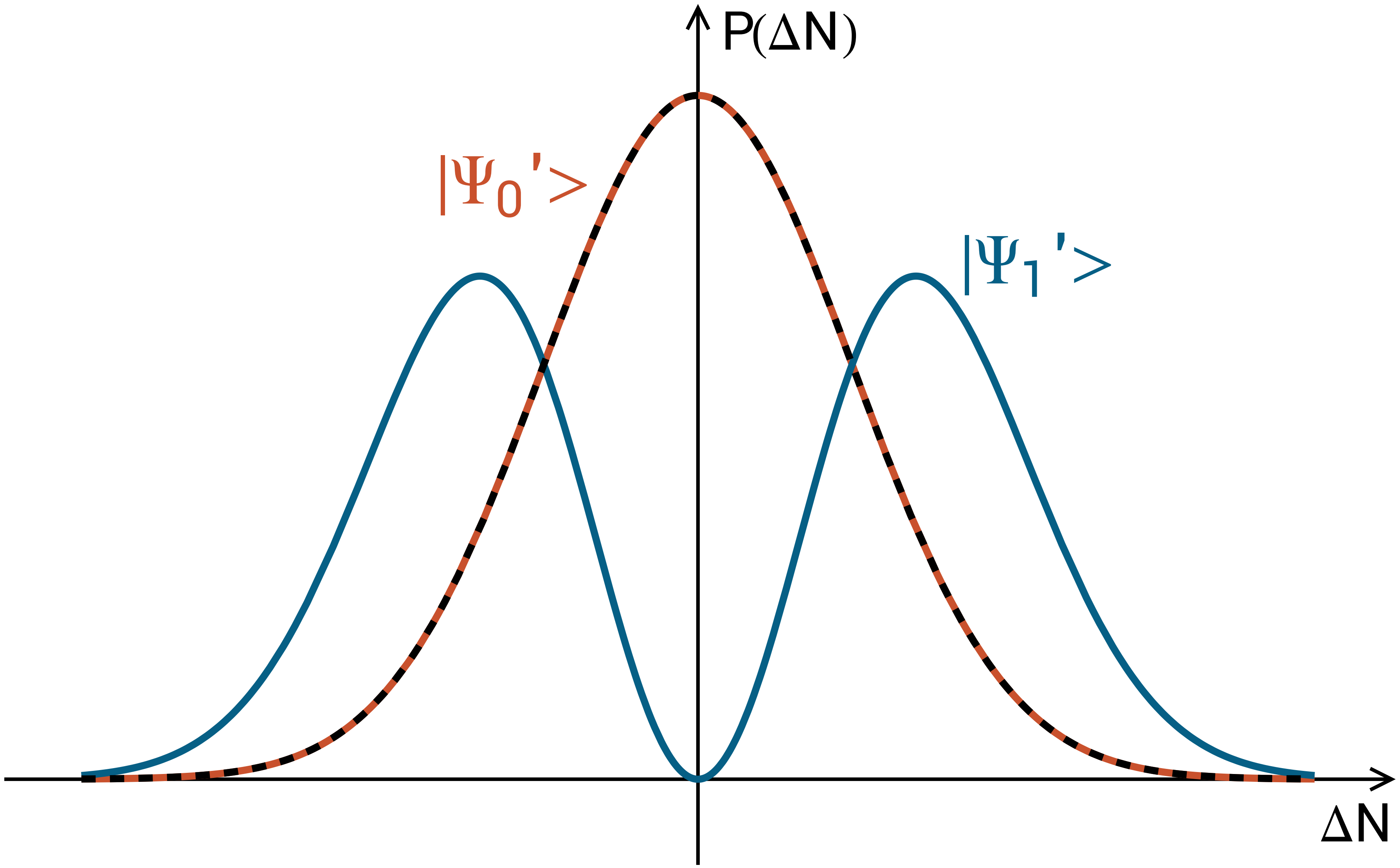
- Non-Gaussian

- Variance increase by a factor of 3.



S. Christensen et al., NJP (2013)

If a ***specific*** atom is flipped, no interference effect is observed.



S. Christensen et al., NJP (2013)

Homodyne detection allows to infer the quantum state.

Describing a state:

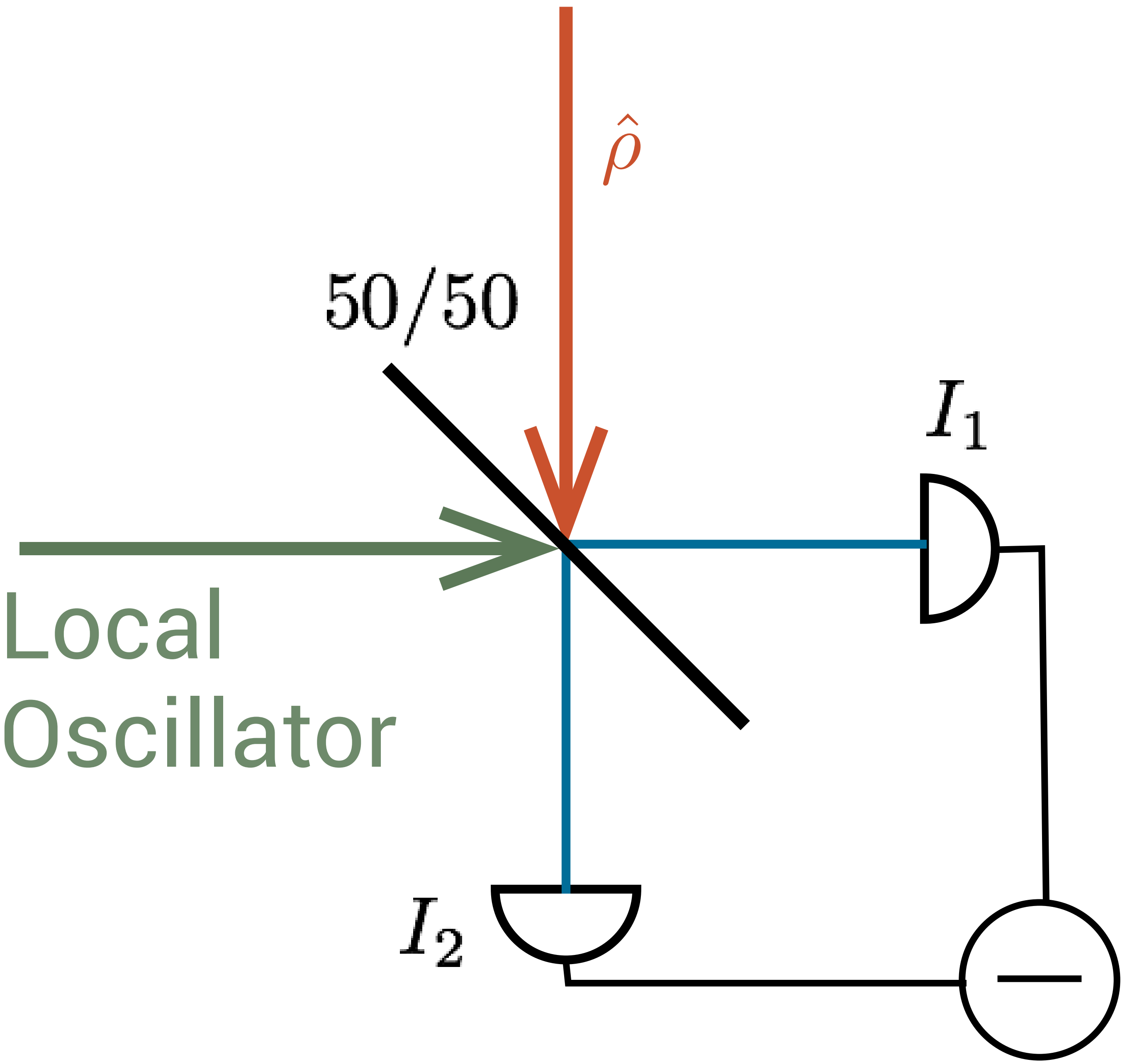
$$\hat{\rho} = ?$$

$$\hat{X}_L^\theta = \sin(\theta)\hat{X}_L + \cos(\theta)\hat{P}_L$$

$$[\hat{X}_L, \hat{P}_L] = i$$

Detection of a state:

$$\Delta I = I_1 - I_2 \propto \hat{X}_L^\theta \rightarrow \hat{\rho}$$

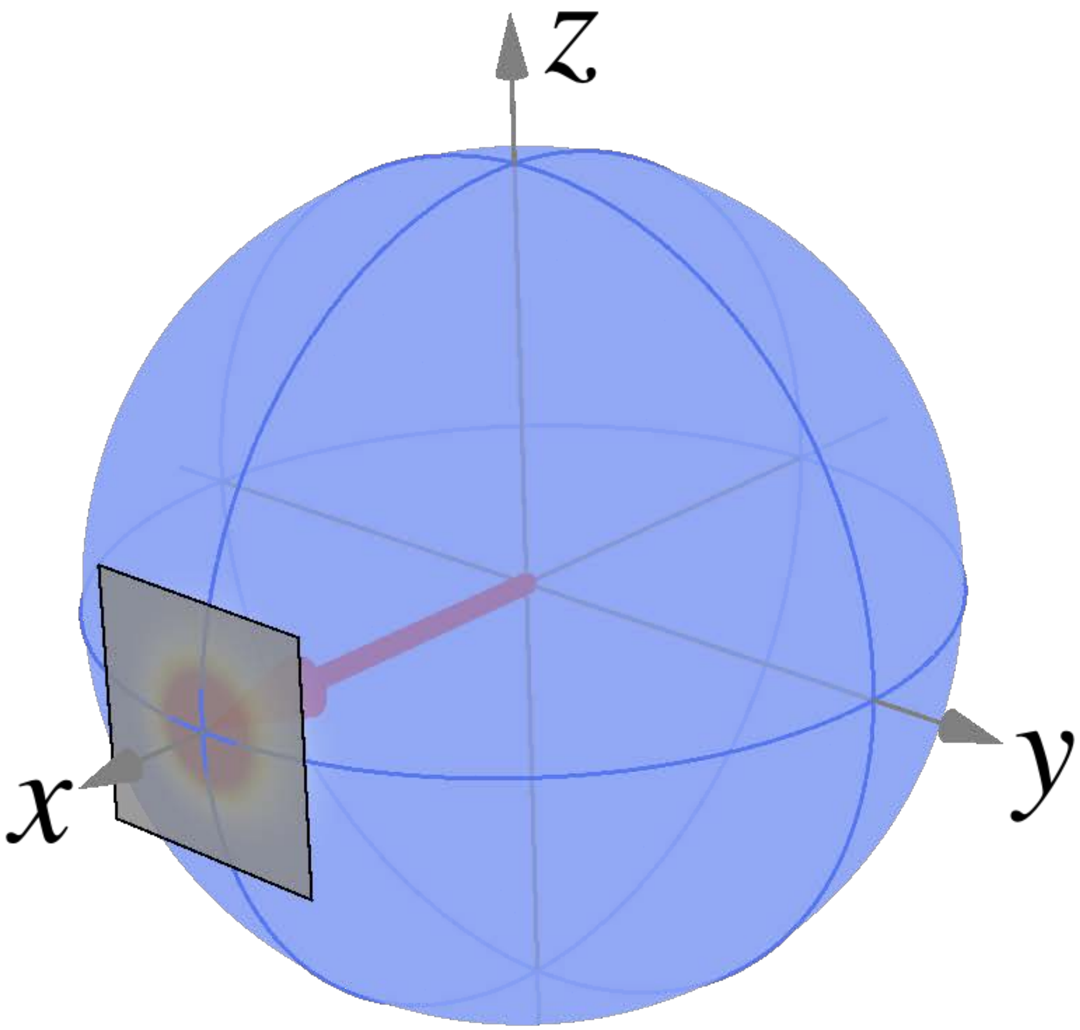


A. Lvovsky & M. Raymer, RMP (2009)

The atomic ensemble can be described by quadrature operators.

Adding each individual spin gives the total ensemble spin.

$$\hat{\boldsymbol{J}} = \sum_{l=1}^{N_a} \hat{\boldsymbol{j}}^{(l)}, \quad [\hat{J}_y, \hat{J}_z] = i\hat{J}_x$$



Large spin aligned to x-axis

$$\hat{X}_A = \frac{\hat{J}_y}{\sqrt{\langle J_x \rangle}}, \quad \hat{P}_A = \frac{\hat{J}_z}{\sqrt{\langle J_x \rangle}} \propto \Delta N,$$

$$[\hat{X}_A, \hat{P}_A] = i$$

A. Kuzmich & E. Polzik, PRL (2010)
T. Holstein & H. Primakoff, Phys. Rev. (1940)

Homodyne detection can also be done with atoms.

- LO: Atoms in $|\uparrow\rangle$

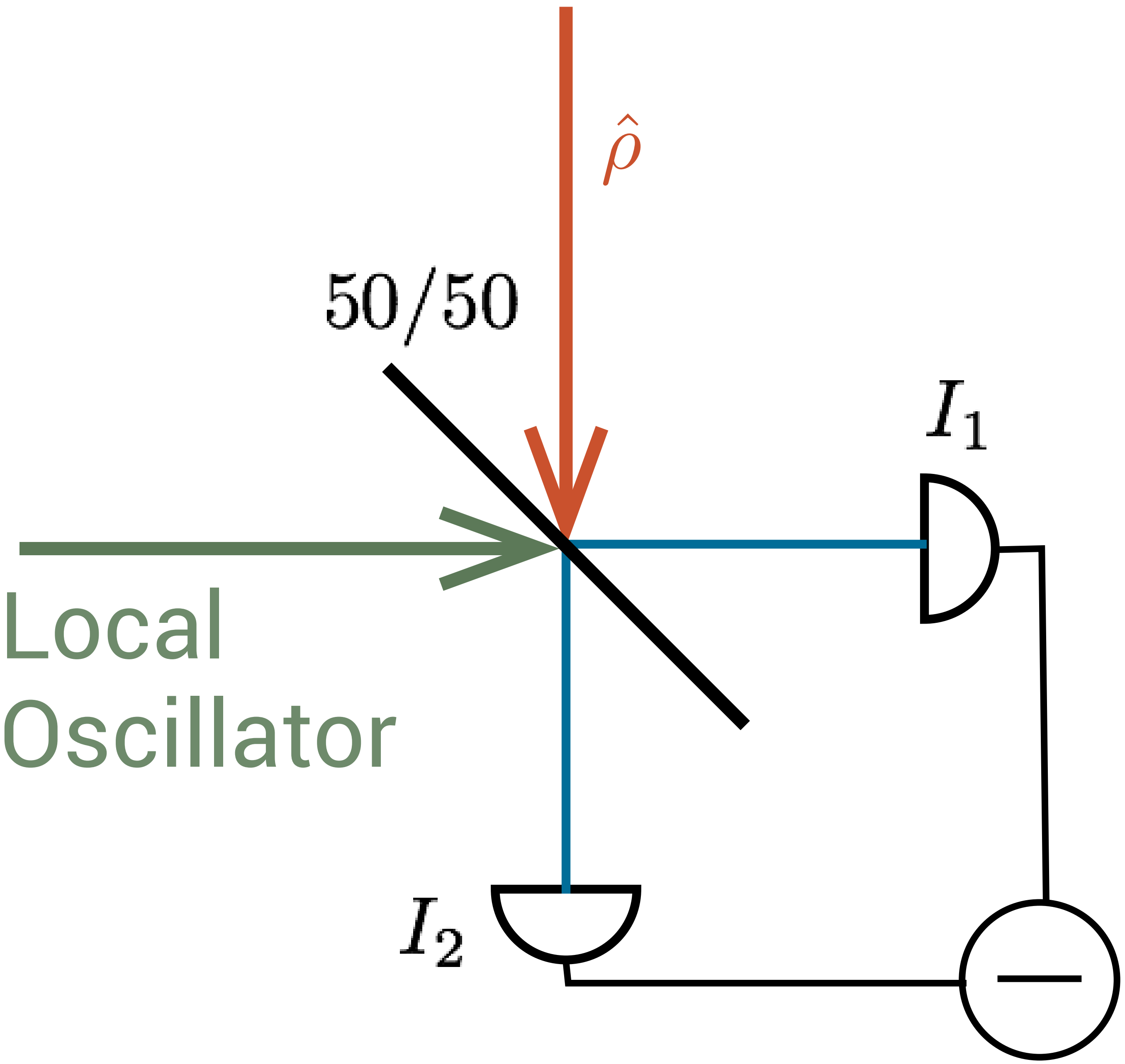
- Signal: Atom in $|\downarrow\rangle$

- 50/50: Microwave

$$|\downarrow\rangle \rightarrow |\rightarrow\rangle = \frac{|\uparrow\rangle - |\downarrow\rangle}{\sqrt{2}}$$

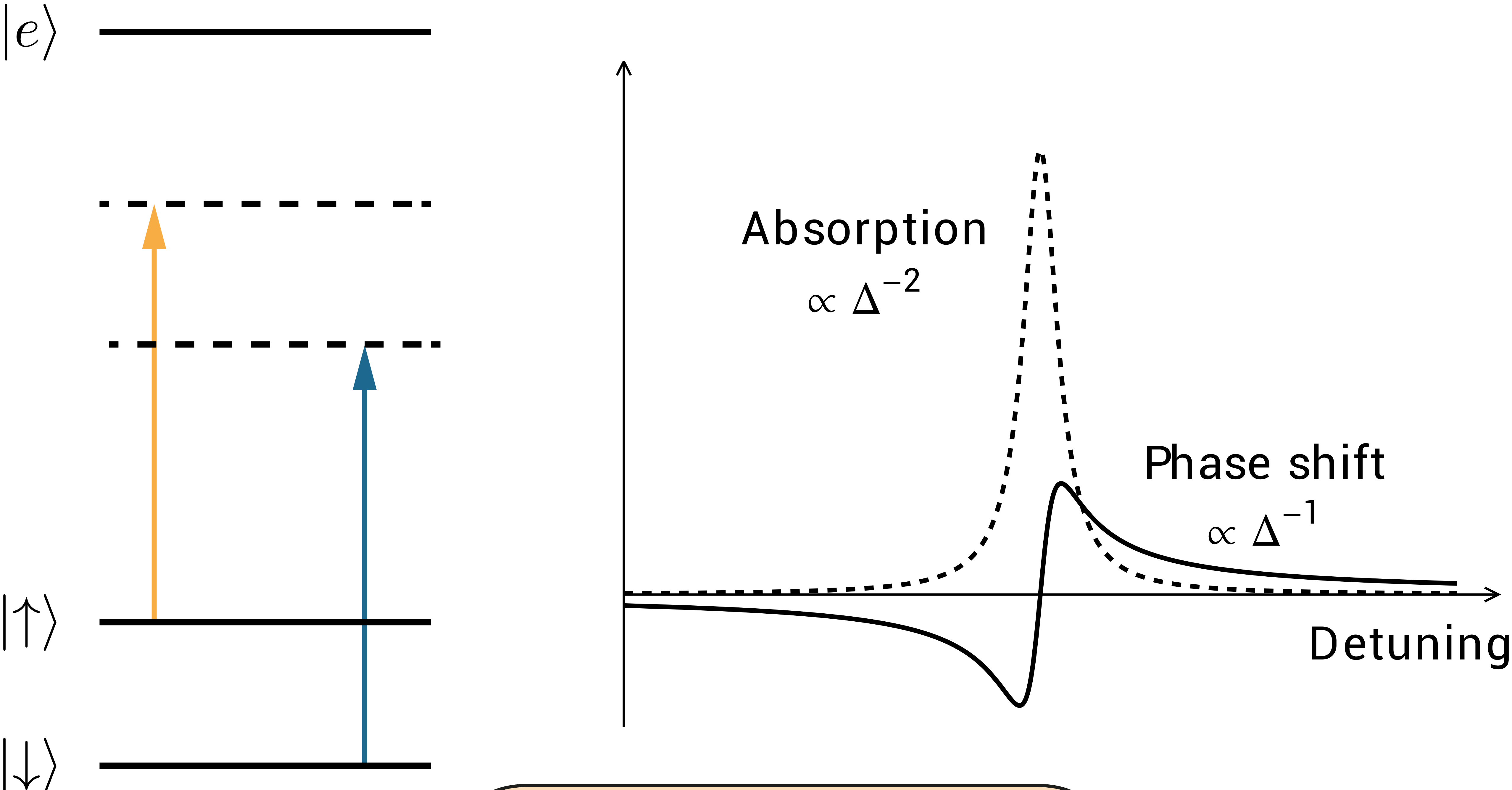
$$|\uparrow\rangle \rightarrow |\leftarrow\rangle = \frac{|\uparrow\rangle + |\downarrow\rangle}{\sqrt{2}}$$

- Measure: $\Delta N = N_\uparrow - N_\downarrow$



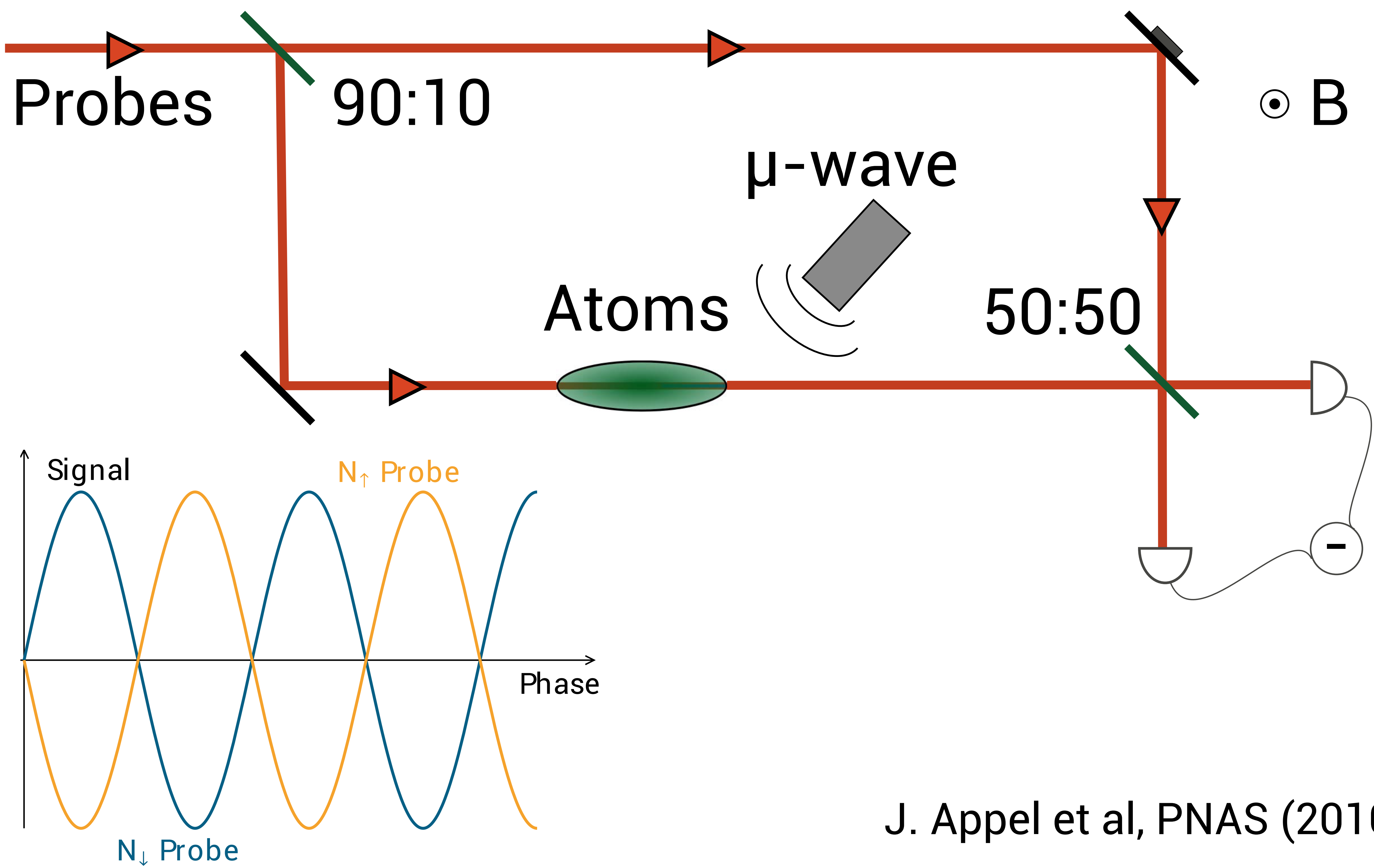
B. Juulsgaard et al., Nature (2001)
J. Appel et al, PNAS (2010)

Inferring the population from the phase allows to measure non-destructively.



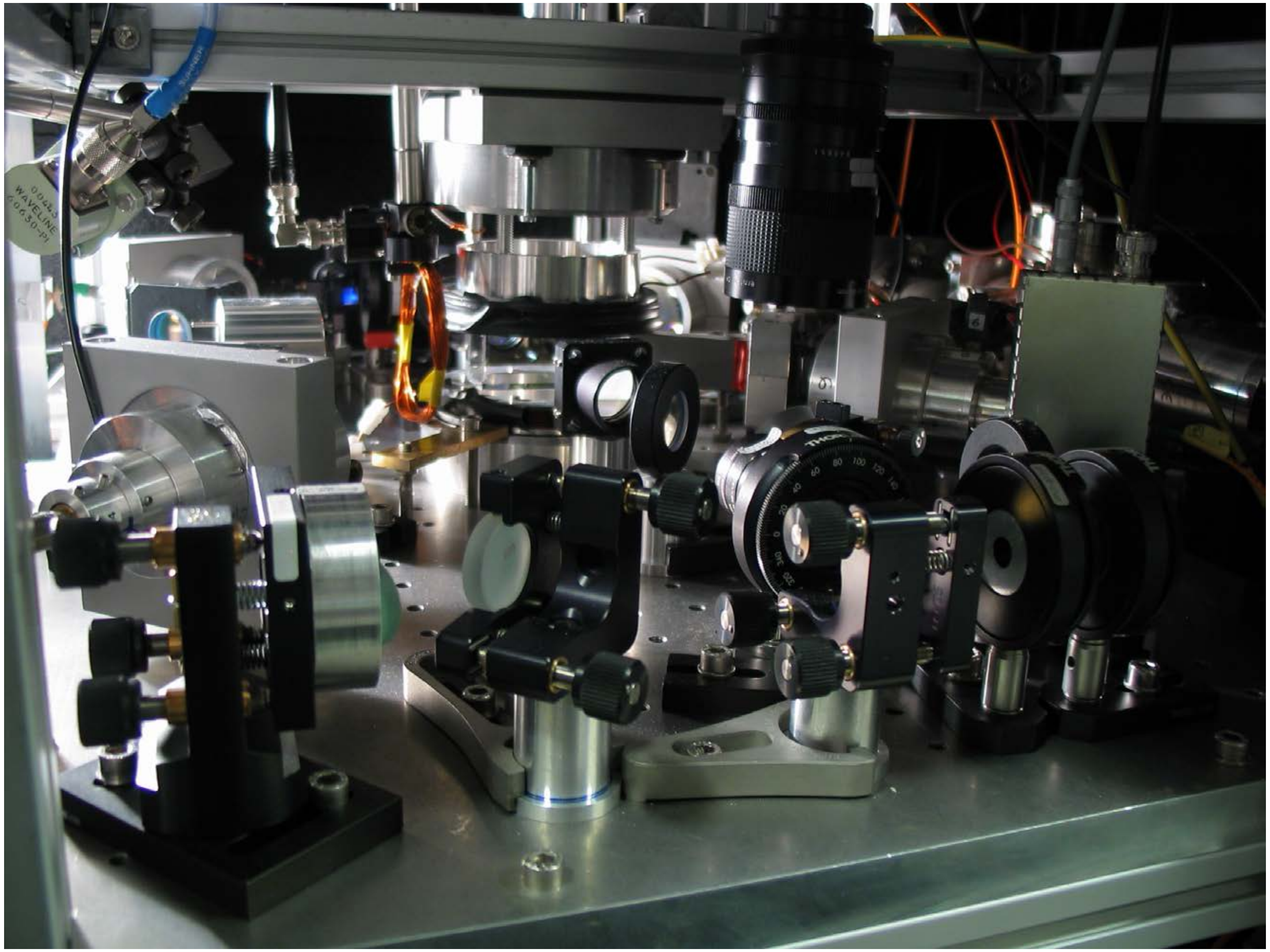
QND Measurement

The state dependent phase shift is measured with an interferometer.

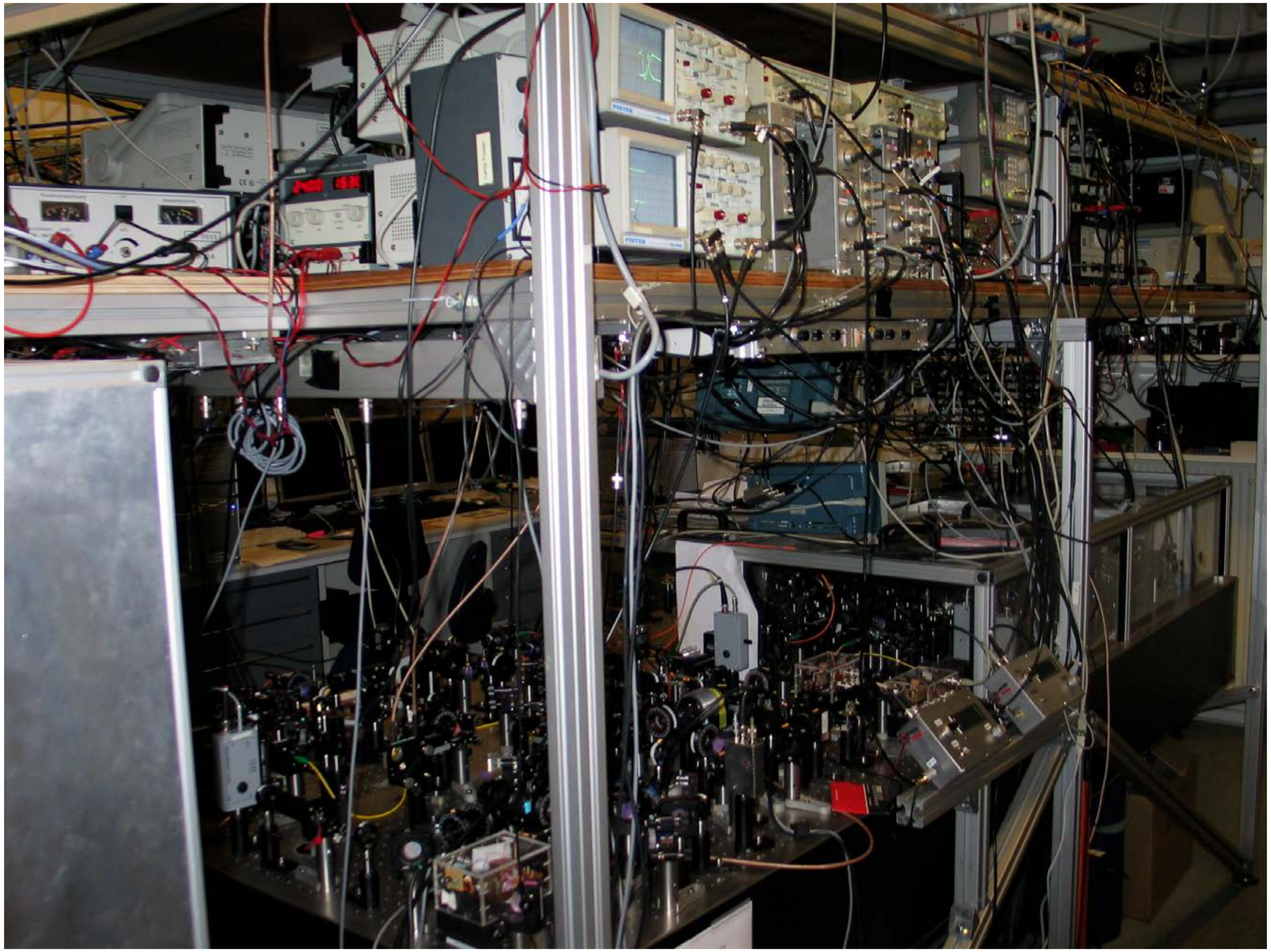


J. Appel et al, PNAS (2010)

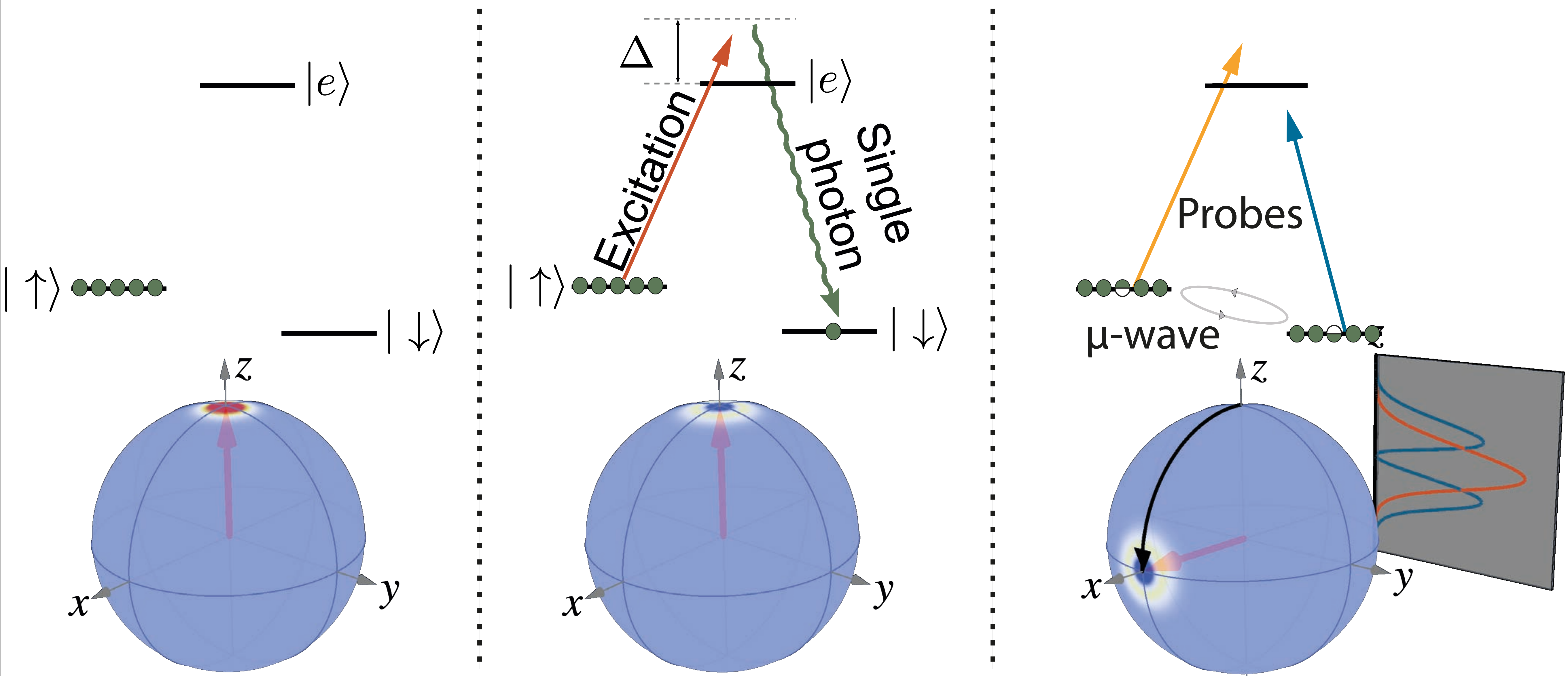
And it actually looks like this.



And it actually looks like this.

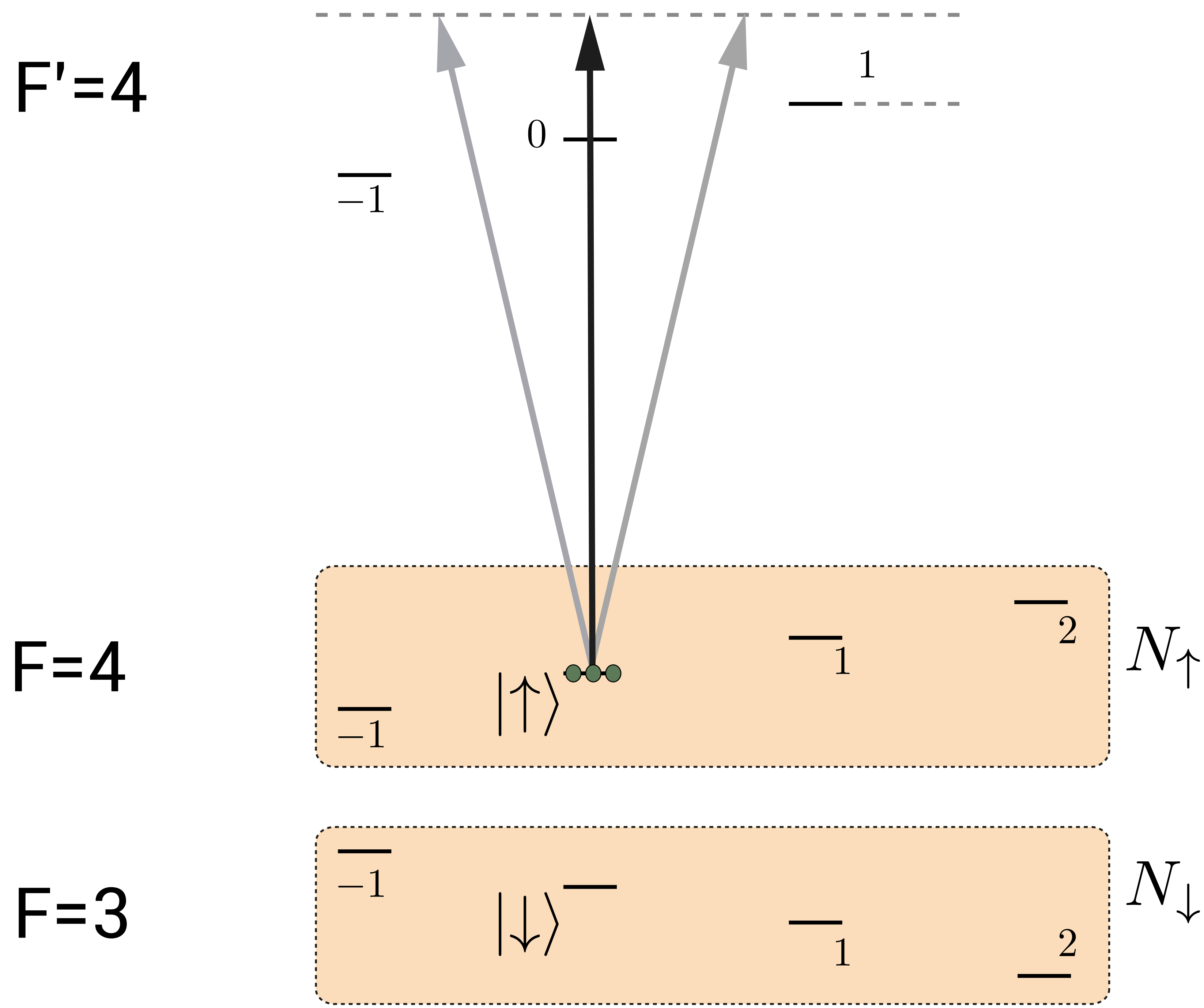


Single excitation state created via DLCZ protocol and detected by atomic homodyne.



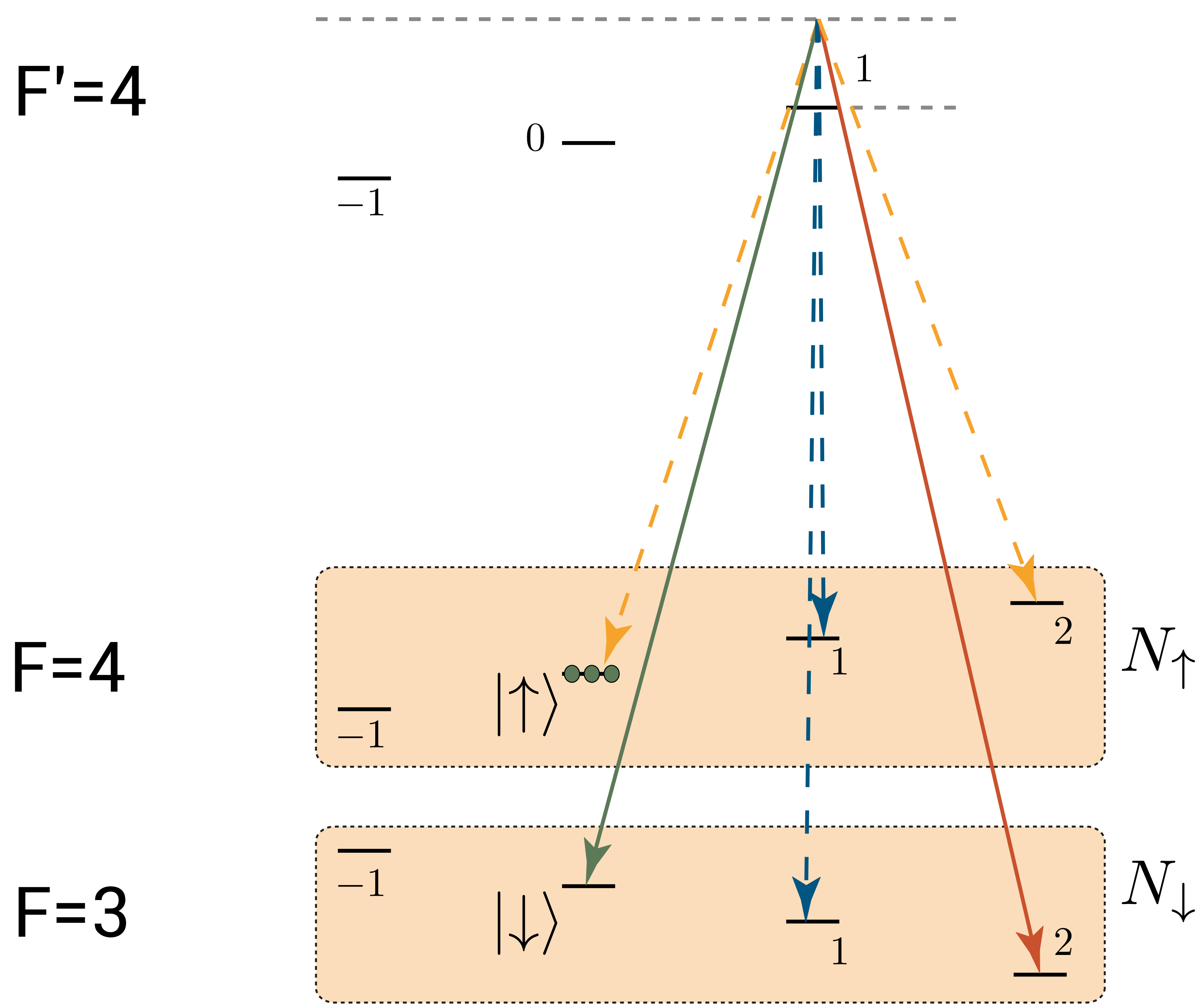
L. Duan et al, Nature (2001)
S. Christensen et al, NJP (2013)

A high magnetic bias field, polarisation and frequency filtering required.



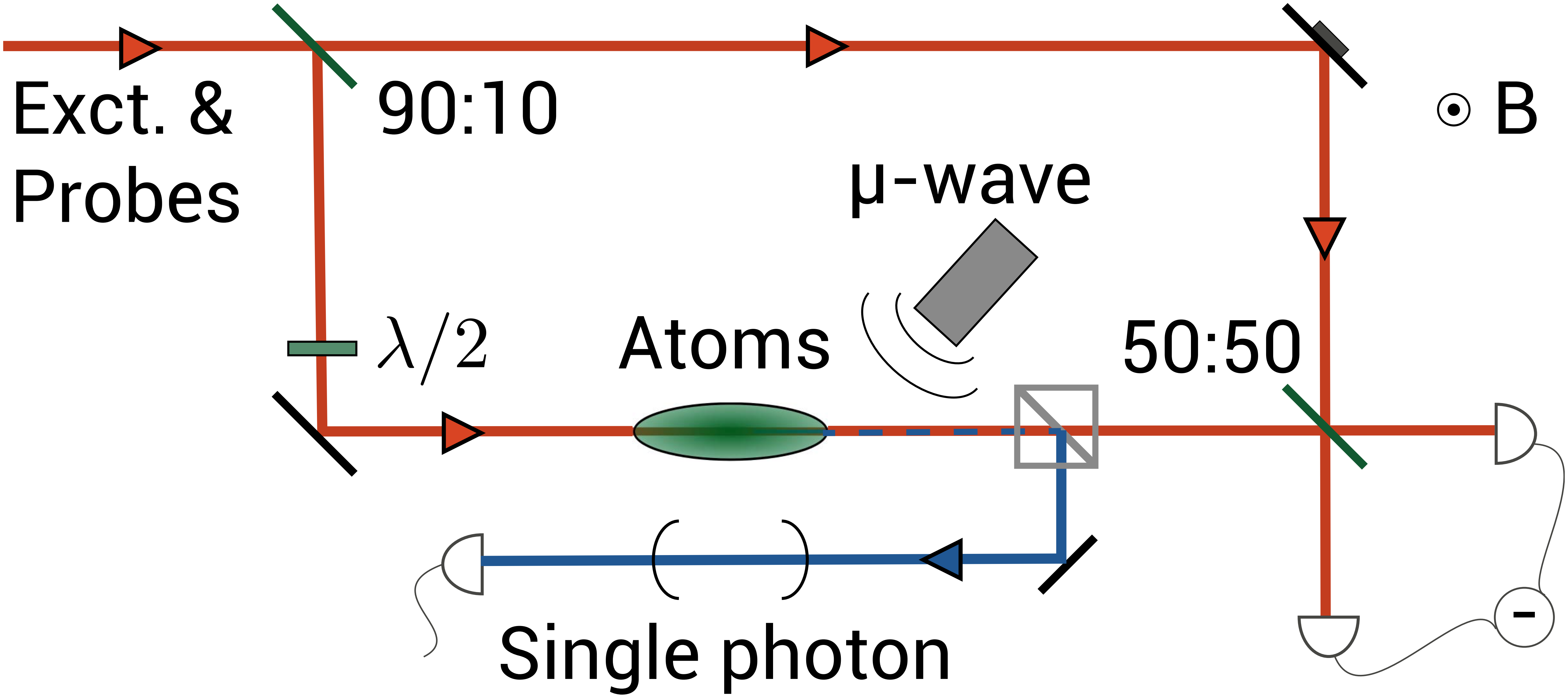
S. Christensen et al, NJP (2013)

A high magnetic bias field, polarisation and frequency filtering required.



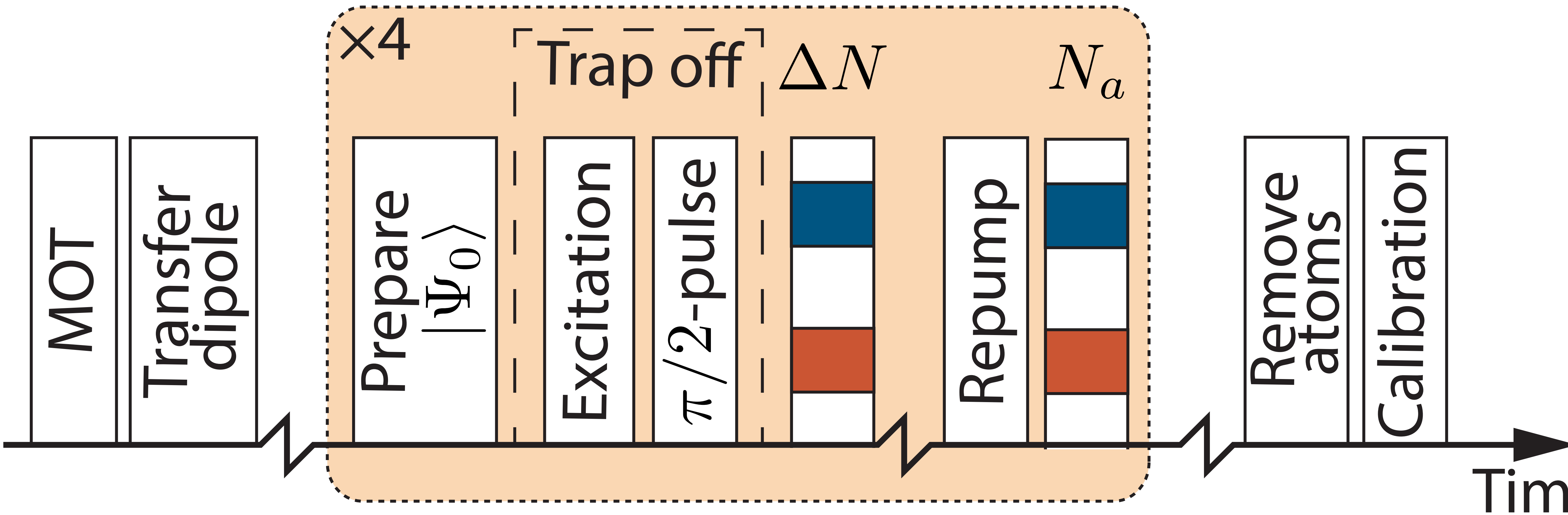
S. Christensen et al, NJP (2013)

We implement cavities and a polarising beam splitter to filter unwanted decays.



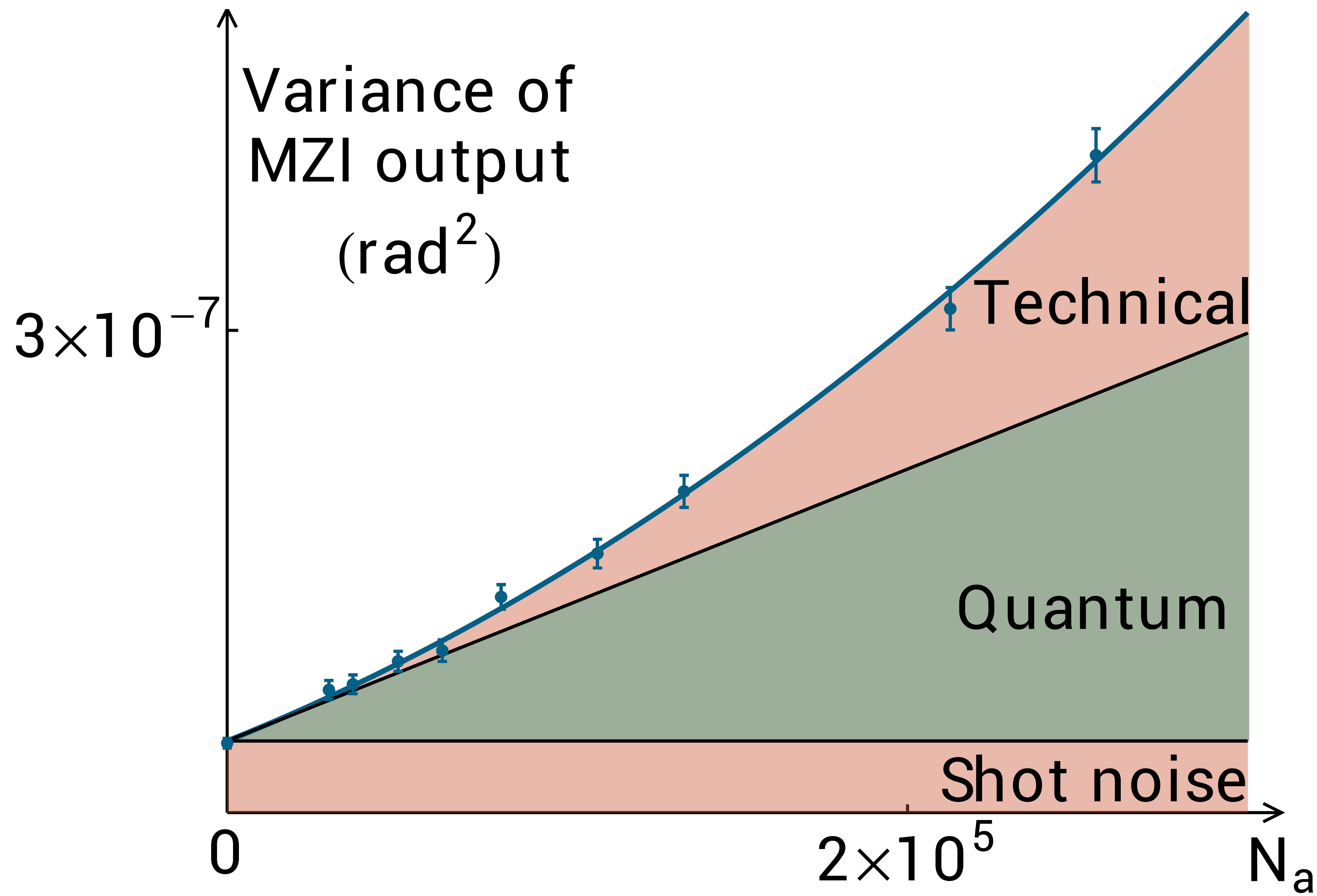
S. Christensen et al, arXiv (2013)

Reusing each MOT four times allows to measure for different atom numbers.



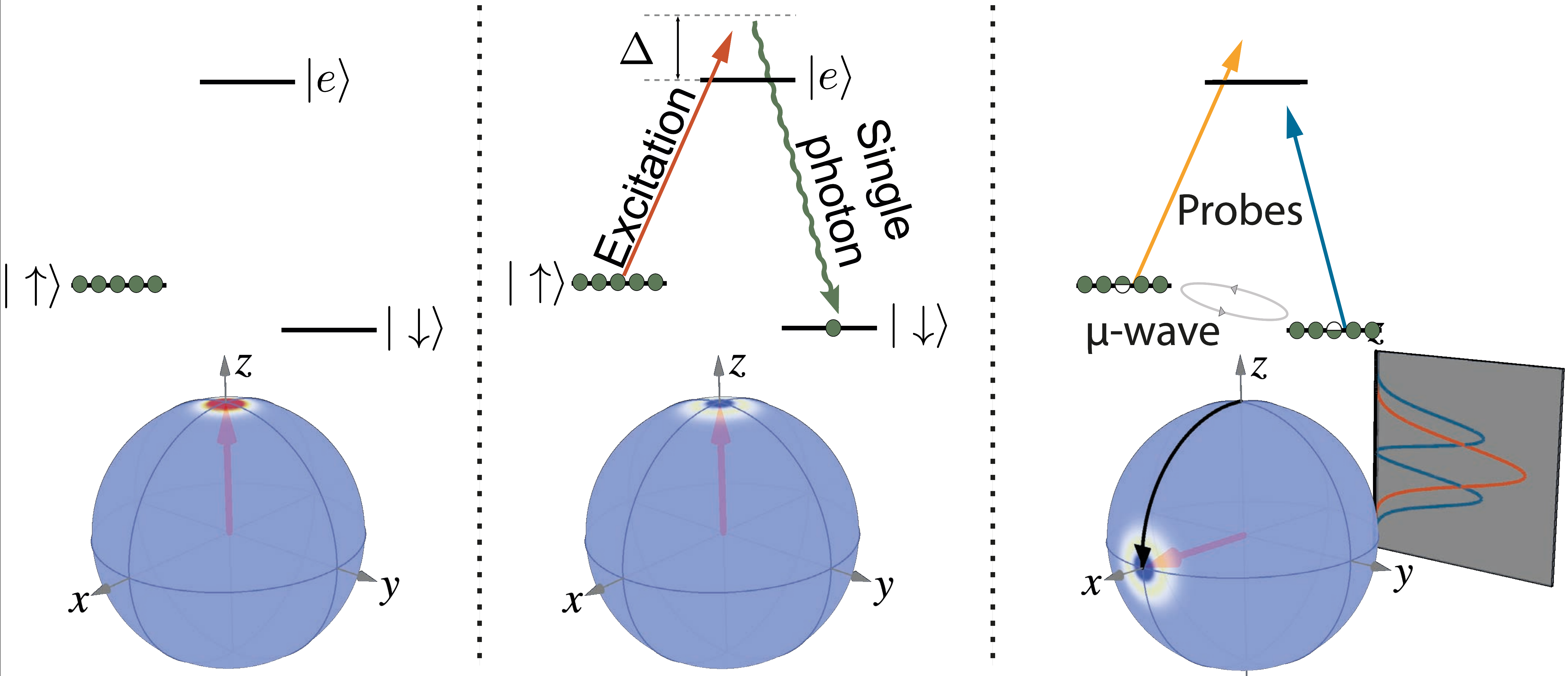
S. Christensen et al, arXiv (2013)

The atomic tomography method has a sensitivity beyond the projection noise.



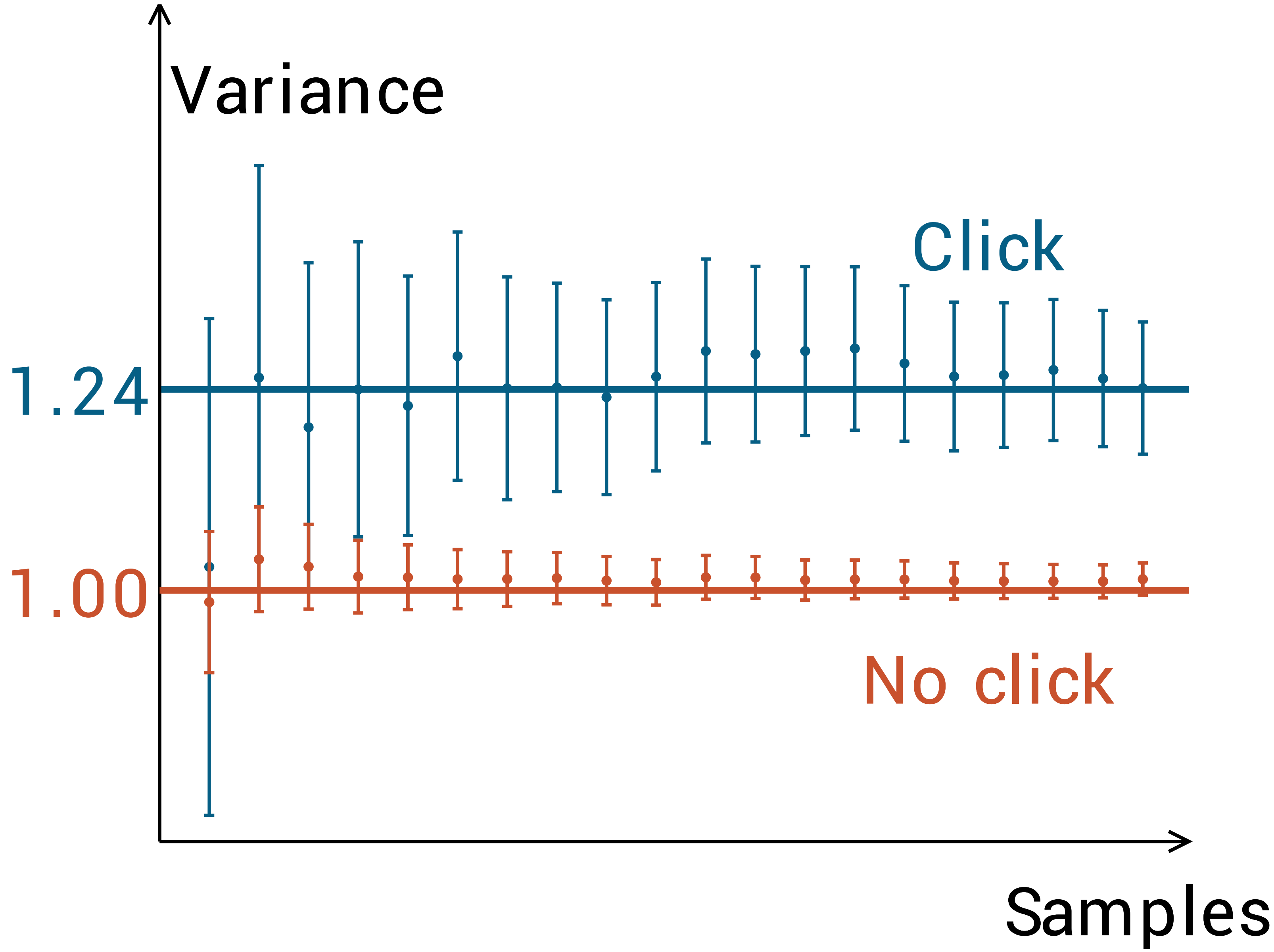
J. Appel et al, PNAS (2010)
S. Christensen et al, arXiv (2013)

Resolving the quantum noise we now turn to distinguishing the states of interest.



L. Duan et al, Nature (2001)
S. Christensen et al, NJP (2013)

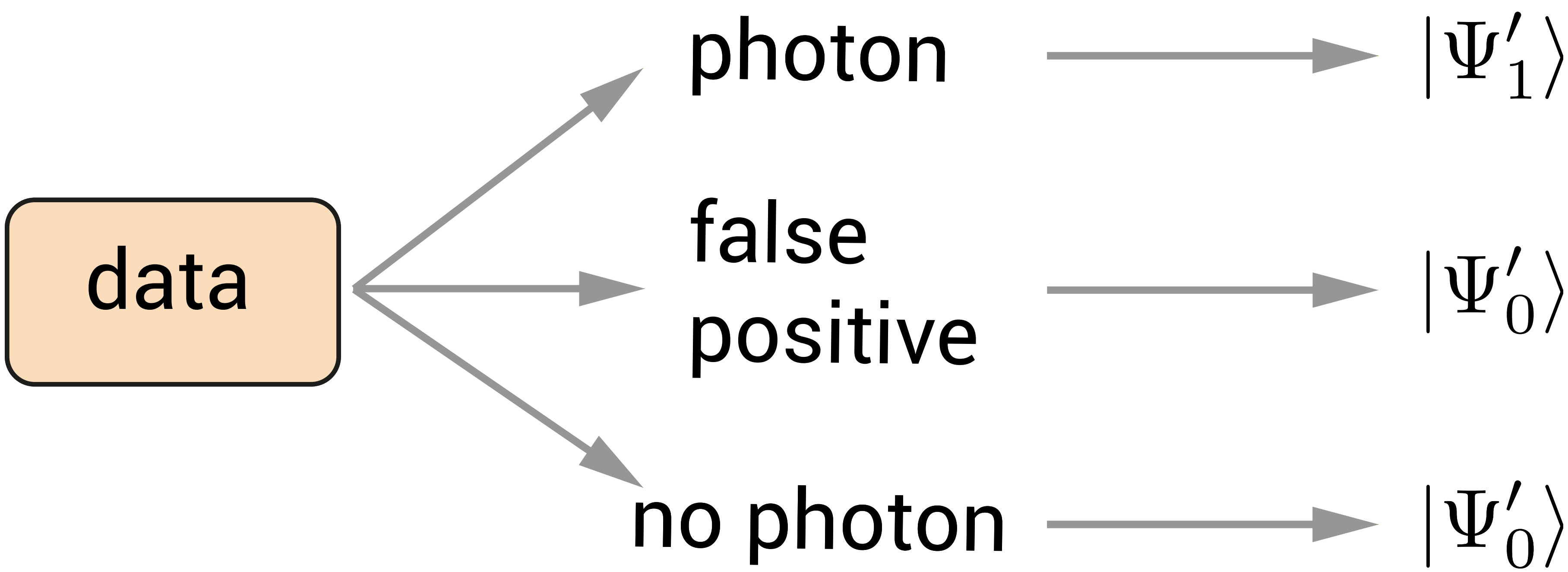
Conditioned on a click, a statistical significant variance increase is observed.



For pure state variance differ by a factor of three.

S. Christensen et al, arXiv (2013)

False positive events decrease the state purity.



False positives:
- Dark counts
- Bad decay
- Leakage photons

$$\hat{\rho} = p\,|\Psi'_1\rangle\langle\Psi'_1| + (1-p)\,|\Psi'_0\rangle\langle\Psi'_0|$$

$$p = p_{\mathrm{state}} = 0.38$$

S. Christensen et al, arXiv (2013)

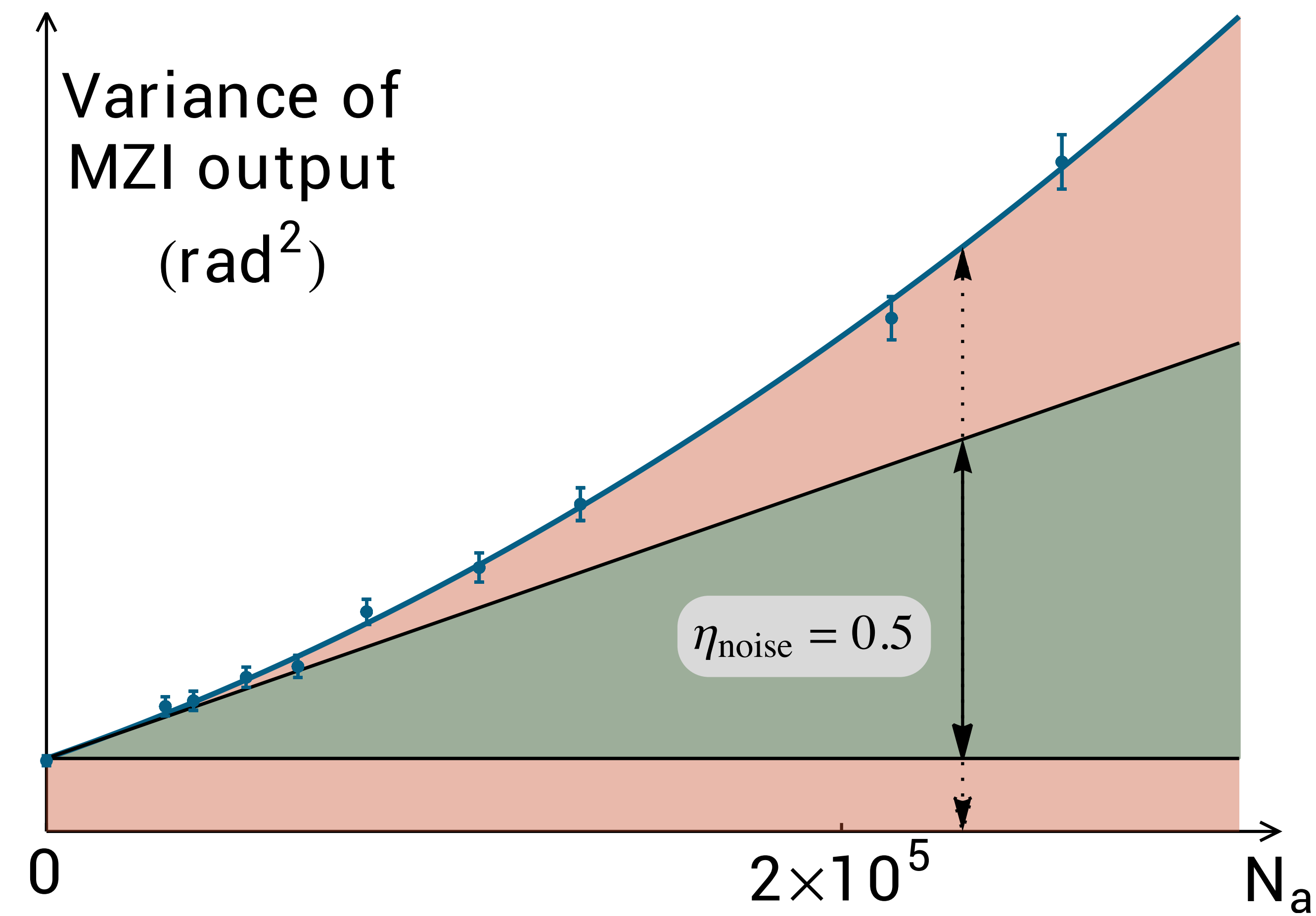
Model and experiment are in agreement.

Detection efficiency:

$$\eta_Q = \eta_{\text{noise}}\eta_{\text{other}} = 0.27$$

Mix with vacuum:

$$p_{\text{model}} = p_{\text{state}}\eta_Q = 0.10$$

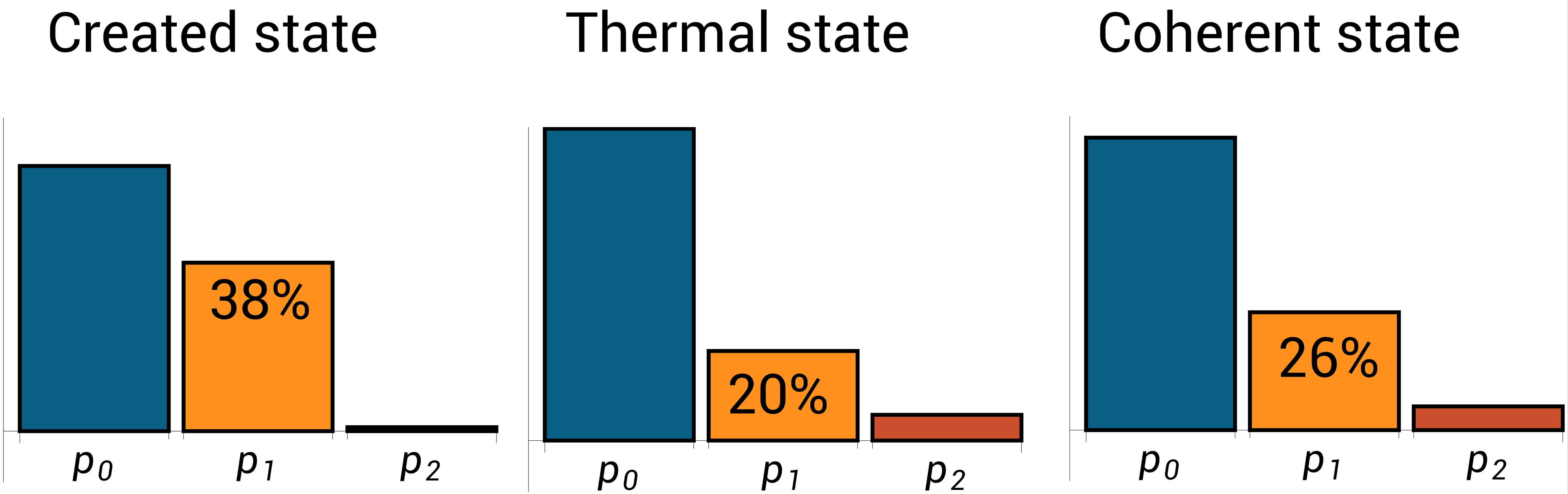


$$\hat{\rho} = p\,|\Psi_1'\rangle\langle\Psi_1'| + (1-p)\,|\Psi_0'\rangle\langle\Psi_0'|$$

$$\text{Model} : 1.20$$
$$\text{Observed} : 1.24 \pm 0.08$$

S. Christensen et al, arXiv (2013)

The probability of having one excitation is incompatible with other states.



S. Christensen et al, arXiv (2013)

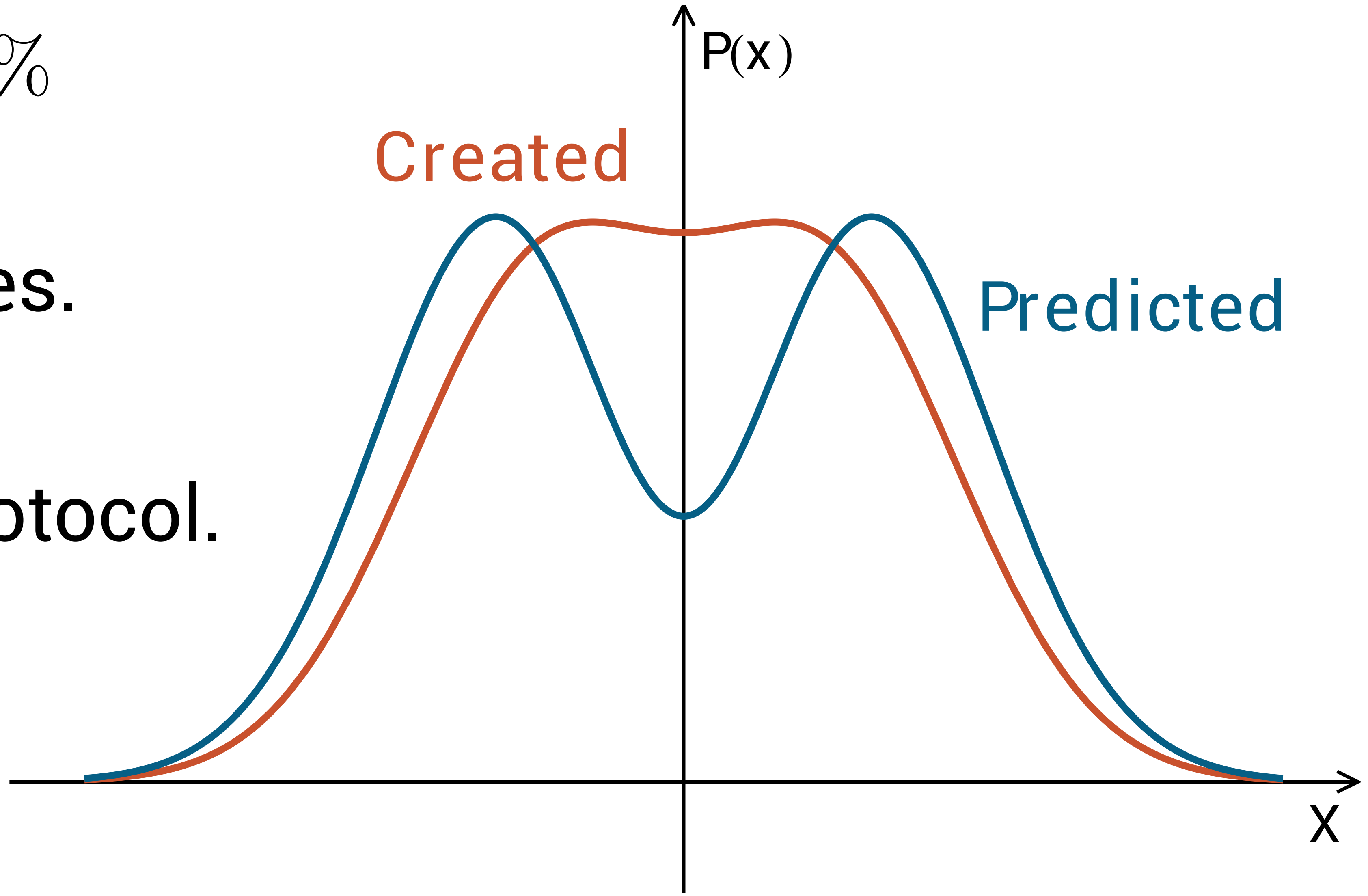
With technical improvements the creation of a non-classical states could be claimed.

- Improve filtering:

$$p_{\text{state}} = 38\% \rightarrow 70\%$$

- Schrödinger Cat states.

- Quantum repeater protocol.



S. Christensen et al, arXiv (2013)

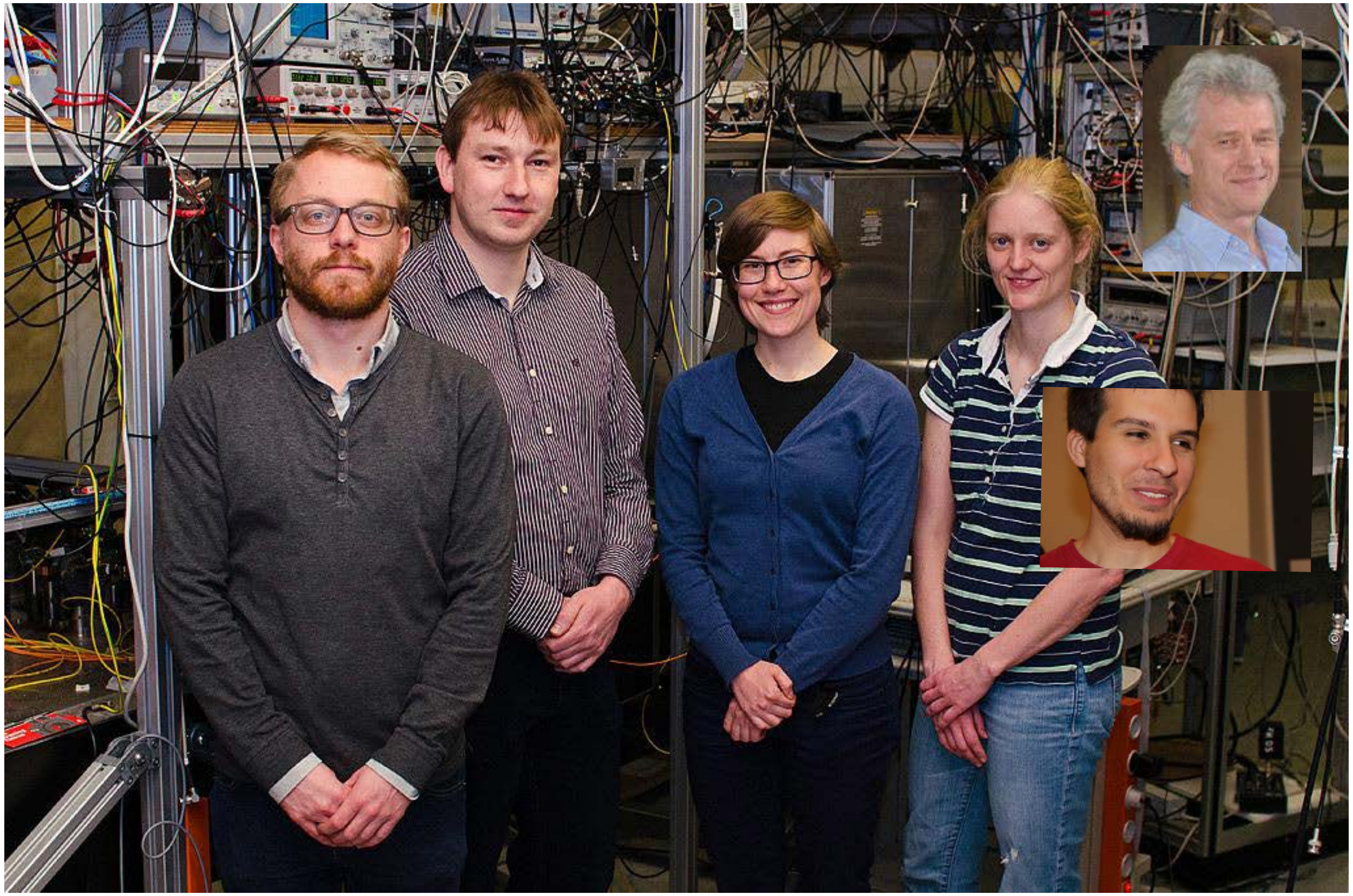
Quantum state engineering in an atomic ensemble.

Hybrid discrete-continuos method.

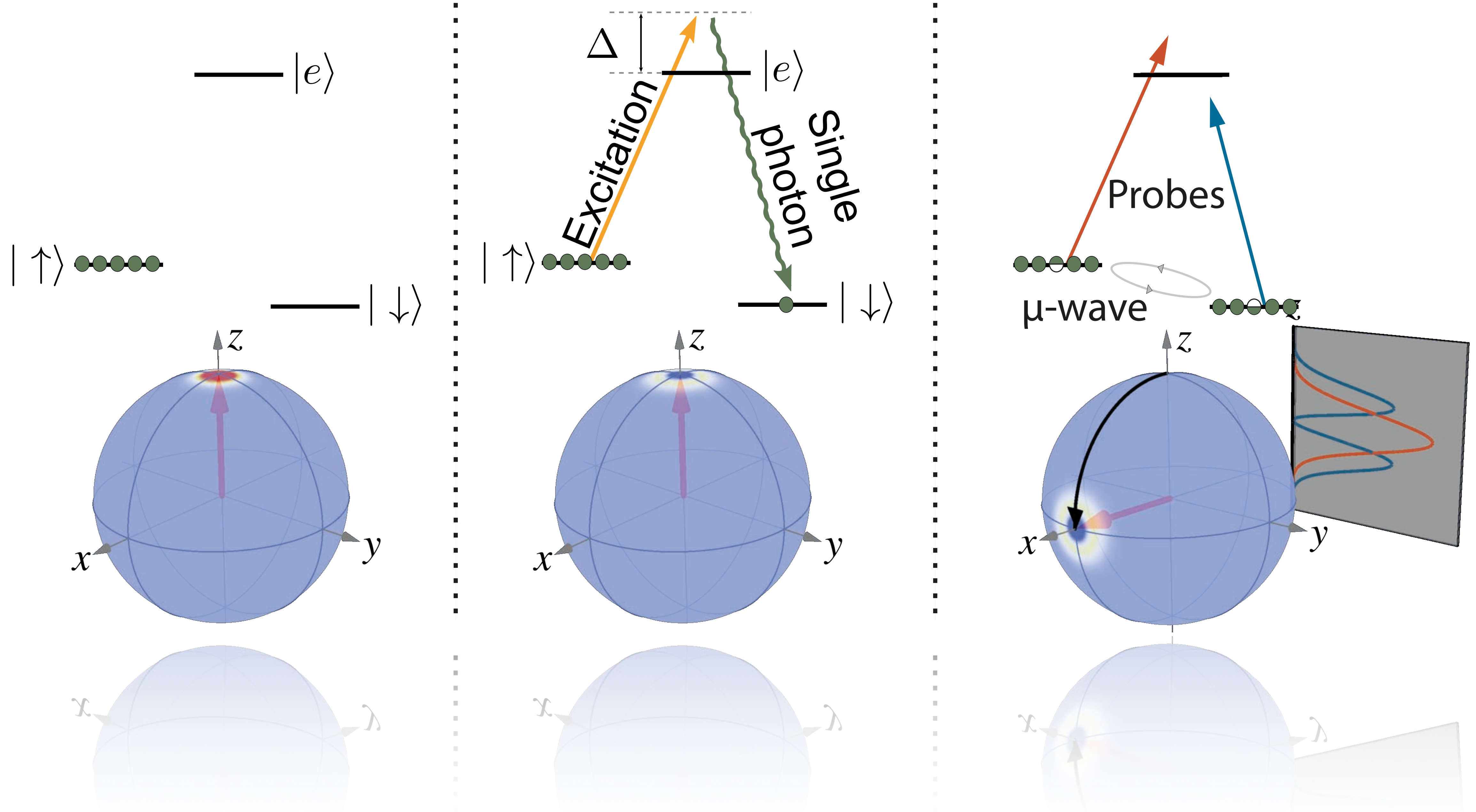
Atomic homodyne detection, for state characterisation.

A photon click leads to macroscopic alteration of a quantum state.

J. B. Beguin
H. L. Sørensen
E. Bookjans
J. H. Müller
J. Appel
E. Polzik



Niels Bohr Institute, University of Copenhagen



Thank you.

S. Christensen et al., NJP 15 015002 (2013)

S. Christensen et al. arxiv:1309.2514 (2013)

R. McConnell et al., PRA 88 063802 (2013)