Quantum Information, Decoherence-free Subspaces and a Michelson-Morley Test with Electrons

Hartmut Häffner, UC Berkeley

- Introduction

- Local detection of quantum correlations

- A Michelson-Morley test with electrons

- Conclusions

Quantum information

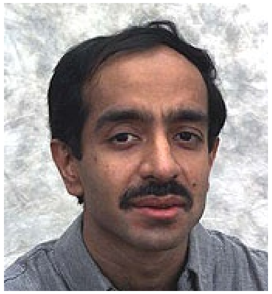
Solve Schrödinger equation for 300 interacting spins ?

Classical computation needs more bits than there are atoms in the universe.

➡ Quantum computers can solve certain tasks much more efficiently than classical computers.

Prominent examples:

- Factoring of large integers (P. Shor 1994)
- Search in an unsorted data base (L. Grover, 1997)
- ...



Quantum information

Schrödinger equation for 300 interacting spins.

Classical computation needs more bits than there are atoms in the universe.

➡ Quantum computers can solve certain tasks much more efficiently than classical computers.

In the mean time:

- Understand more about quantum mechanics
- Apply QIP to fundamental physics questions
- ...

Prominen

- Fa
- S
- ...

- Introduction to ion trap QIP

- Local detection of quantum correlations

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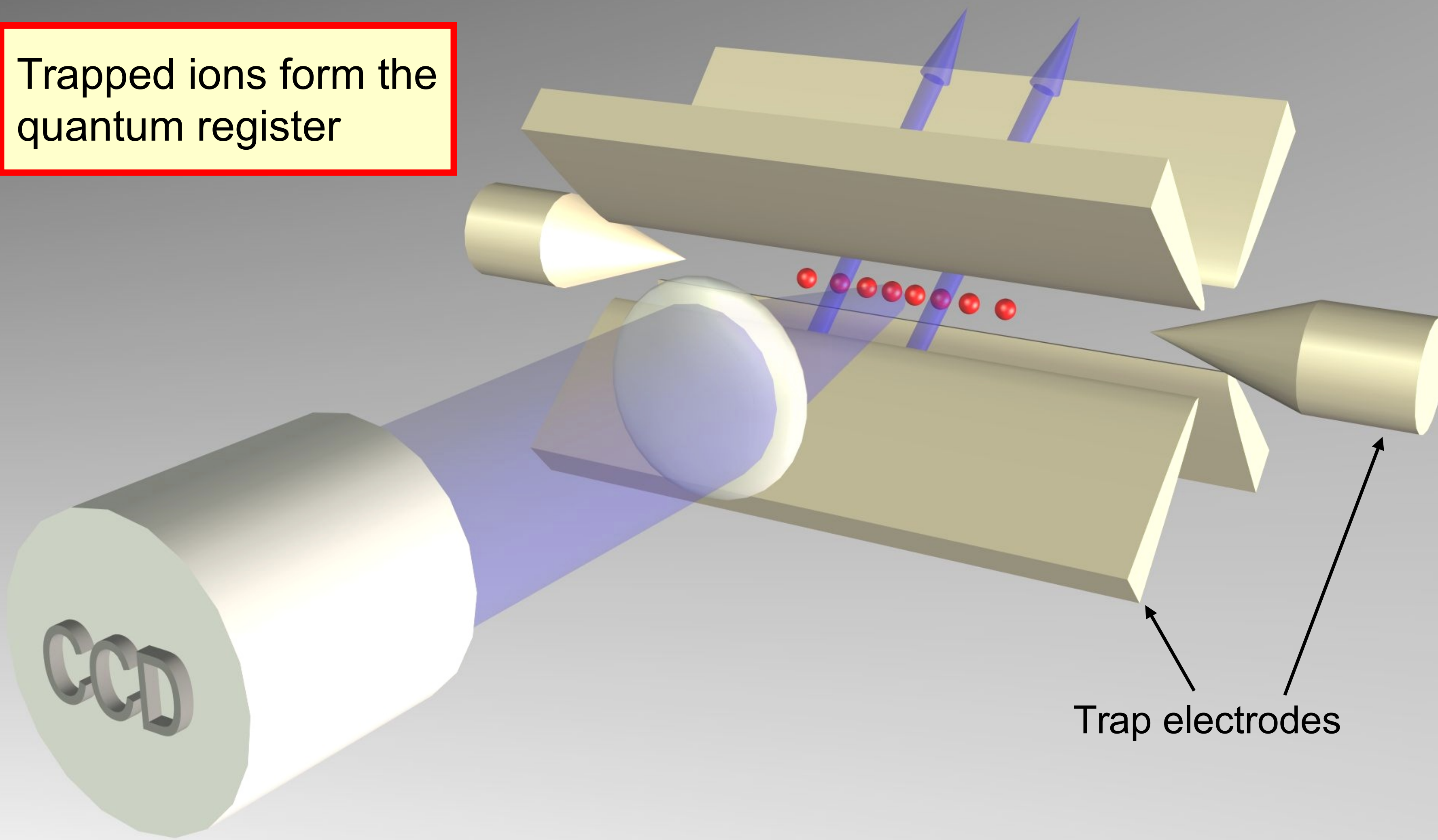
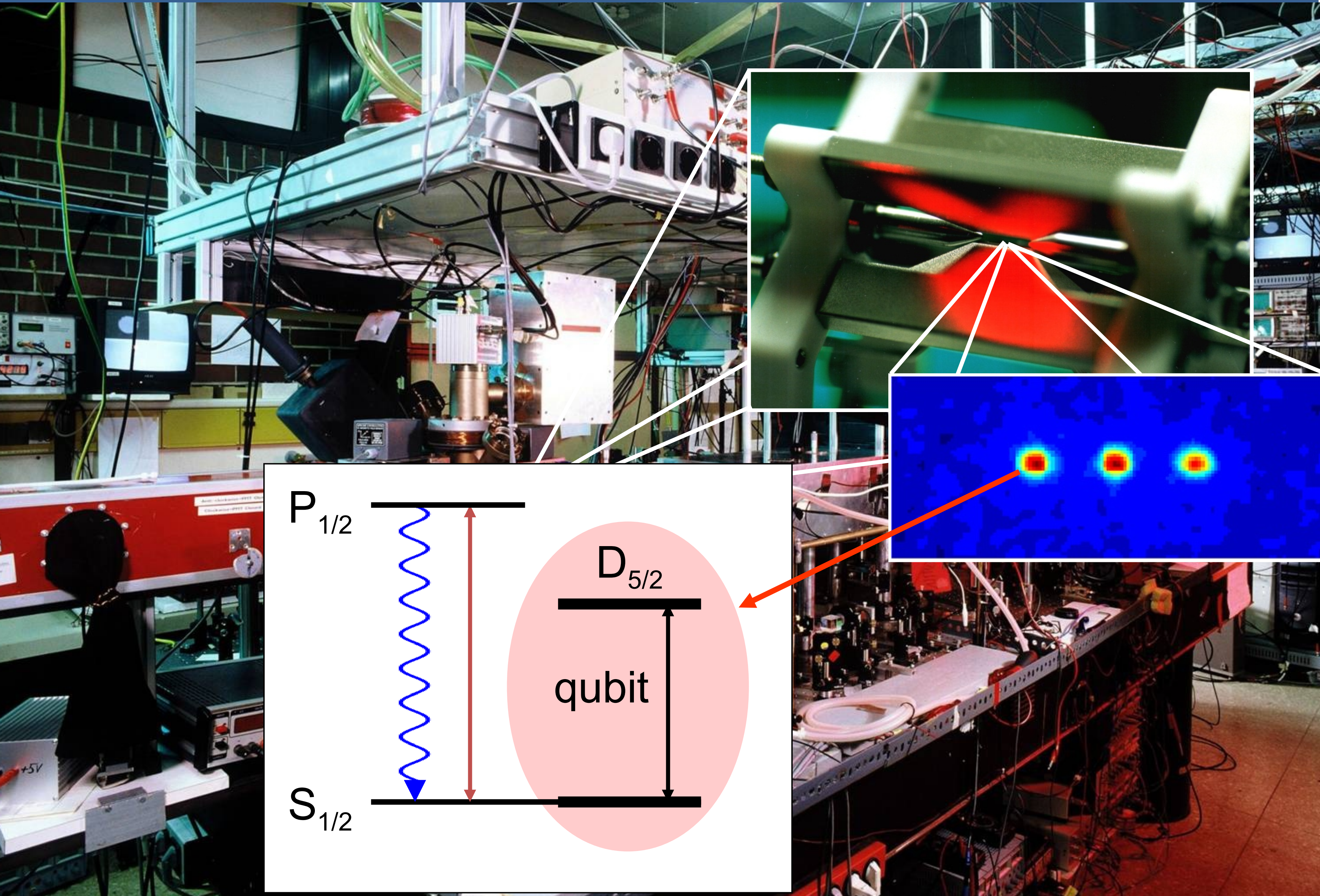
Ion trap quantum computing

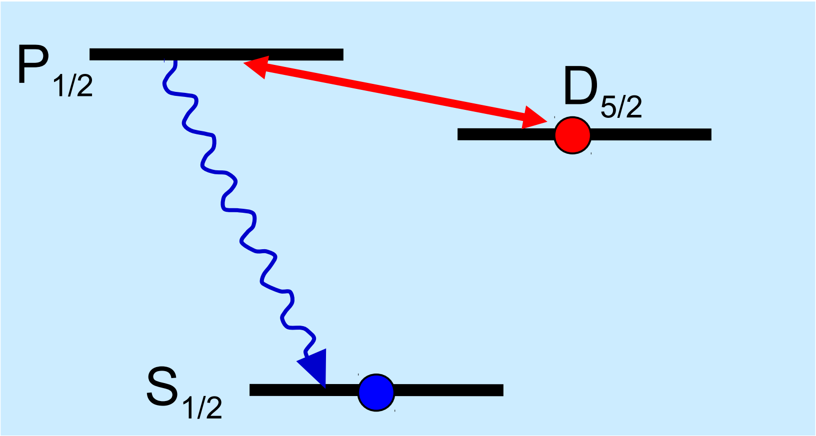
Trapped ions form the quantum register



The hardware

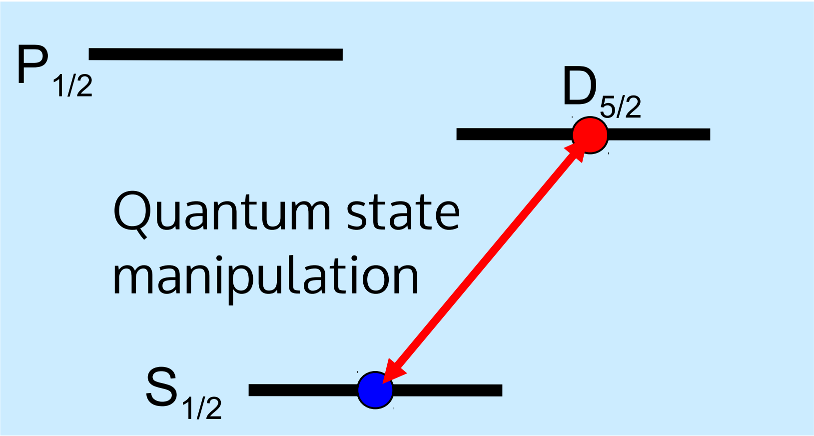


Experimental procedure



1. Initialization in a pure quantum state

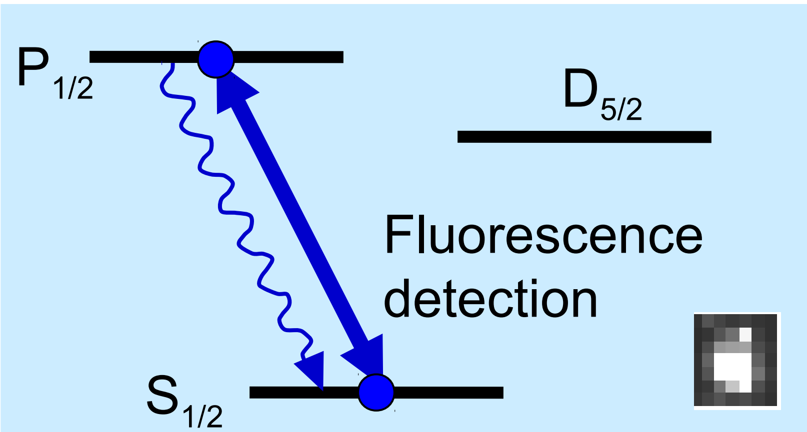
Experimental procedure



1. Initialization in a pure quantum state

2. Quantum state manipulation on $S_{1/2} – D_{5/2}$ transition

Experimental procedure

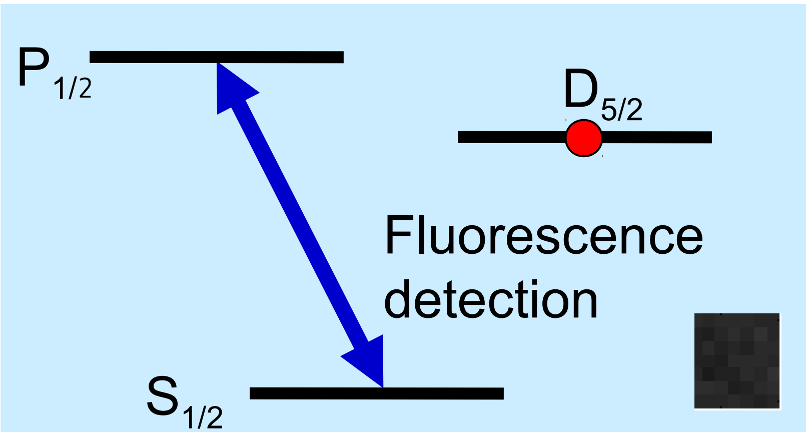


1. Initialization in a pure quantum state

2. Quantum state manipulation on $S_{1/2}$ – $D_{5/2}$ transition

3. Quantum state measurement by fluorescence detection

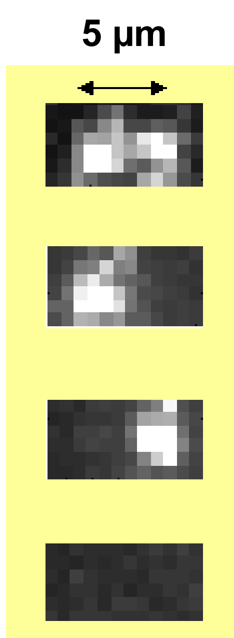
Experimental procedure



1. Initialization in a pure quantum state
2. Quantum state manipulation on $S_{1/2} - D_{5/2}$ transition
3. Quantum state measurement by fluorescence detection

<u>Two ions:</u>

Spatially resolved detection with CCD camera



$|SS\rangle$

$|SD\rangle$

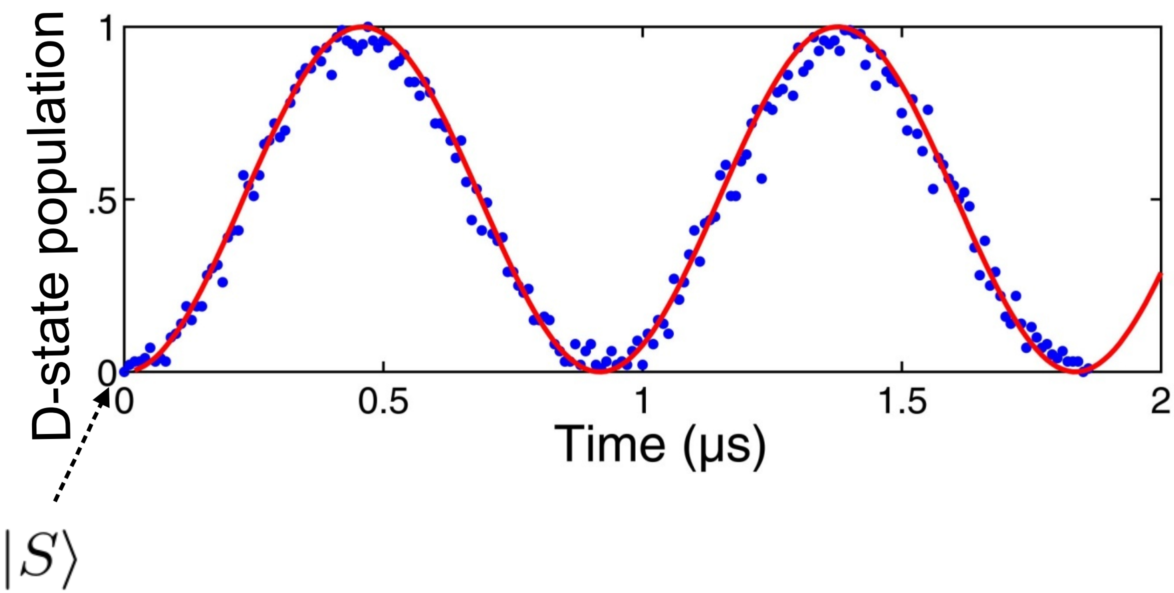
$|DS\rangle$

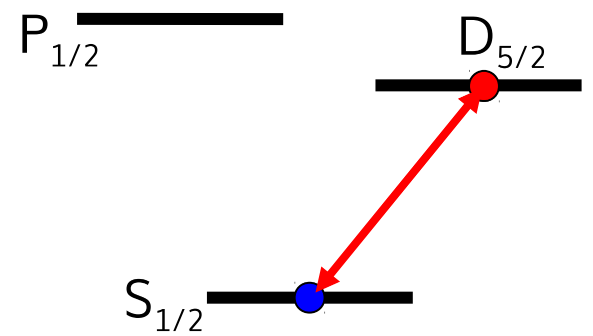
$|DD\rangle$

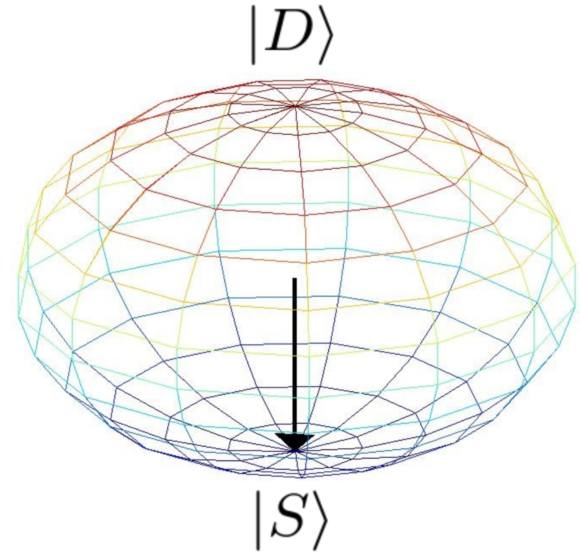
60 experiments / s

Repeat experiments 100-200 times

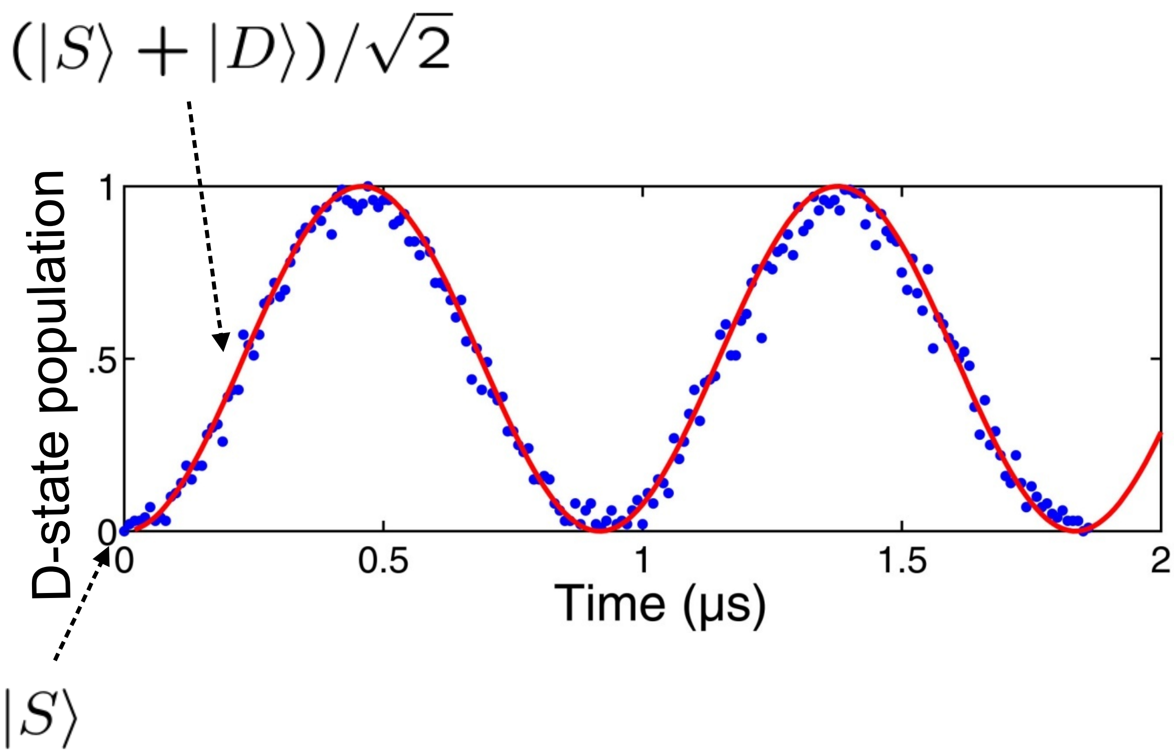
Single qubit gates

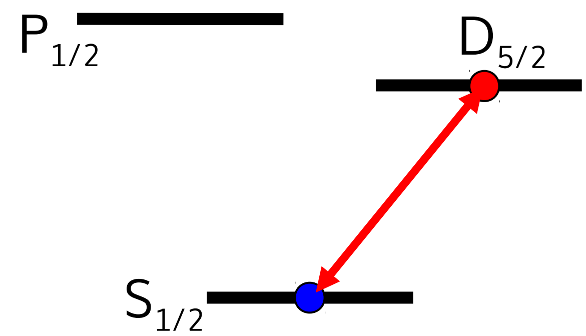


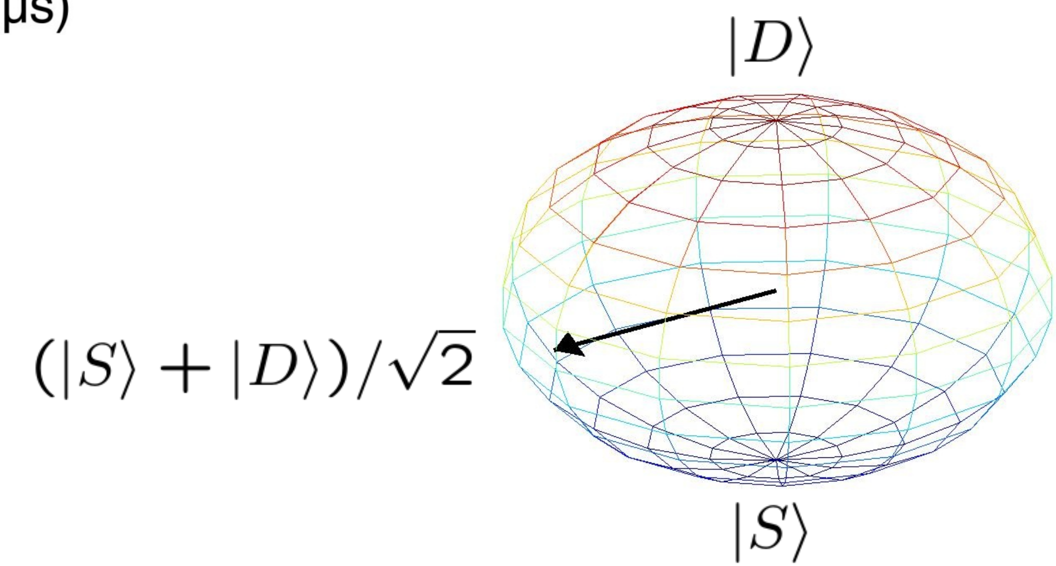




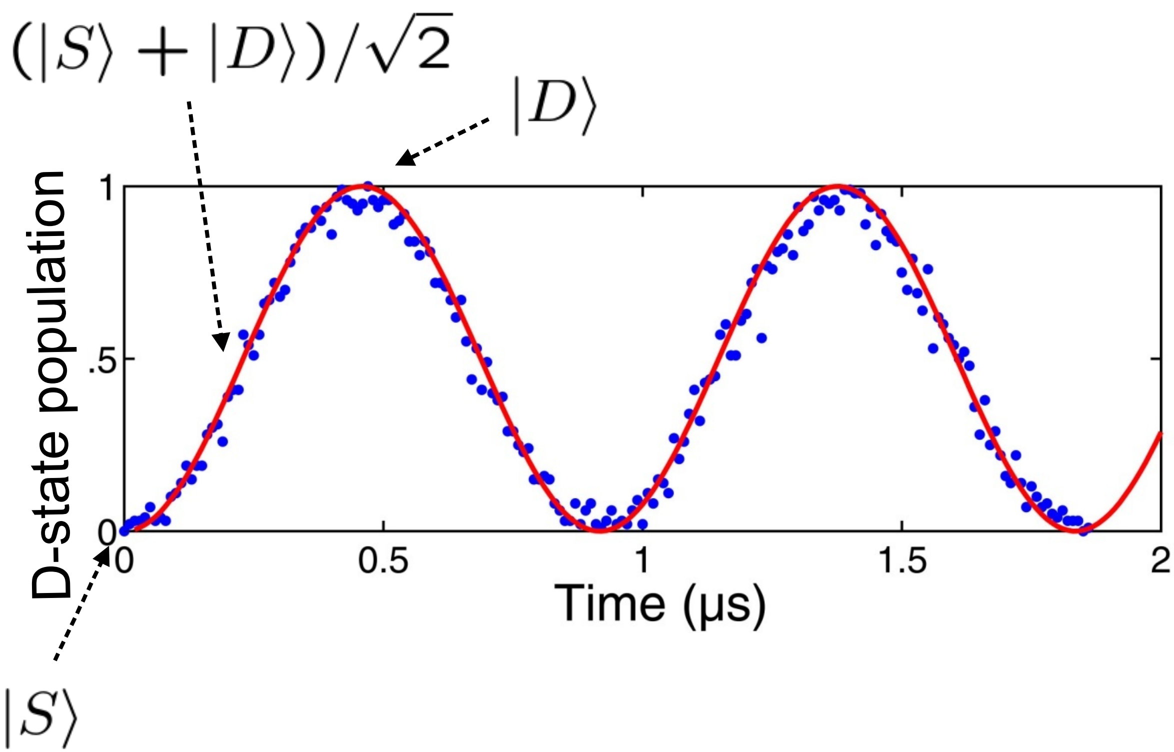
Single qubit gates

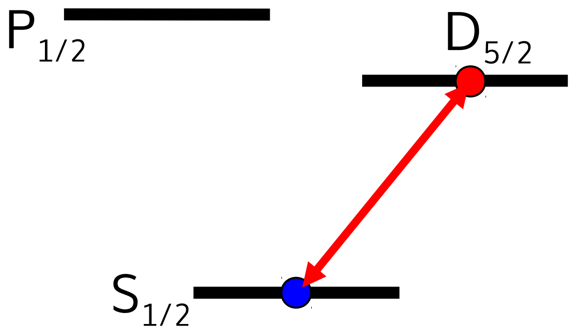


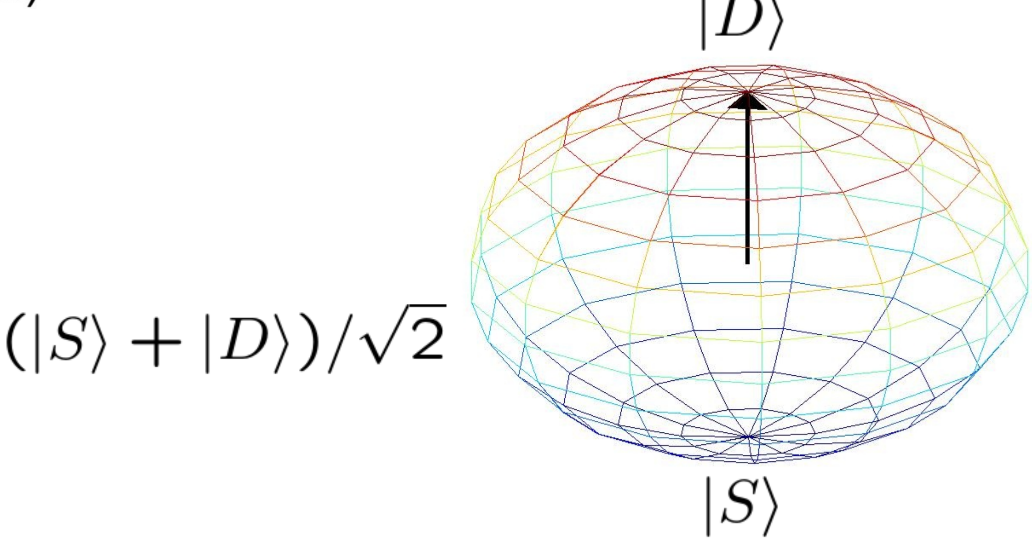




Single qubit gates

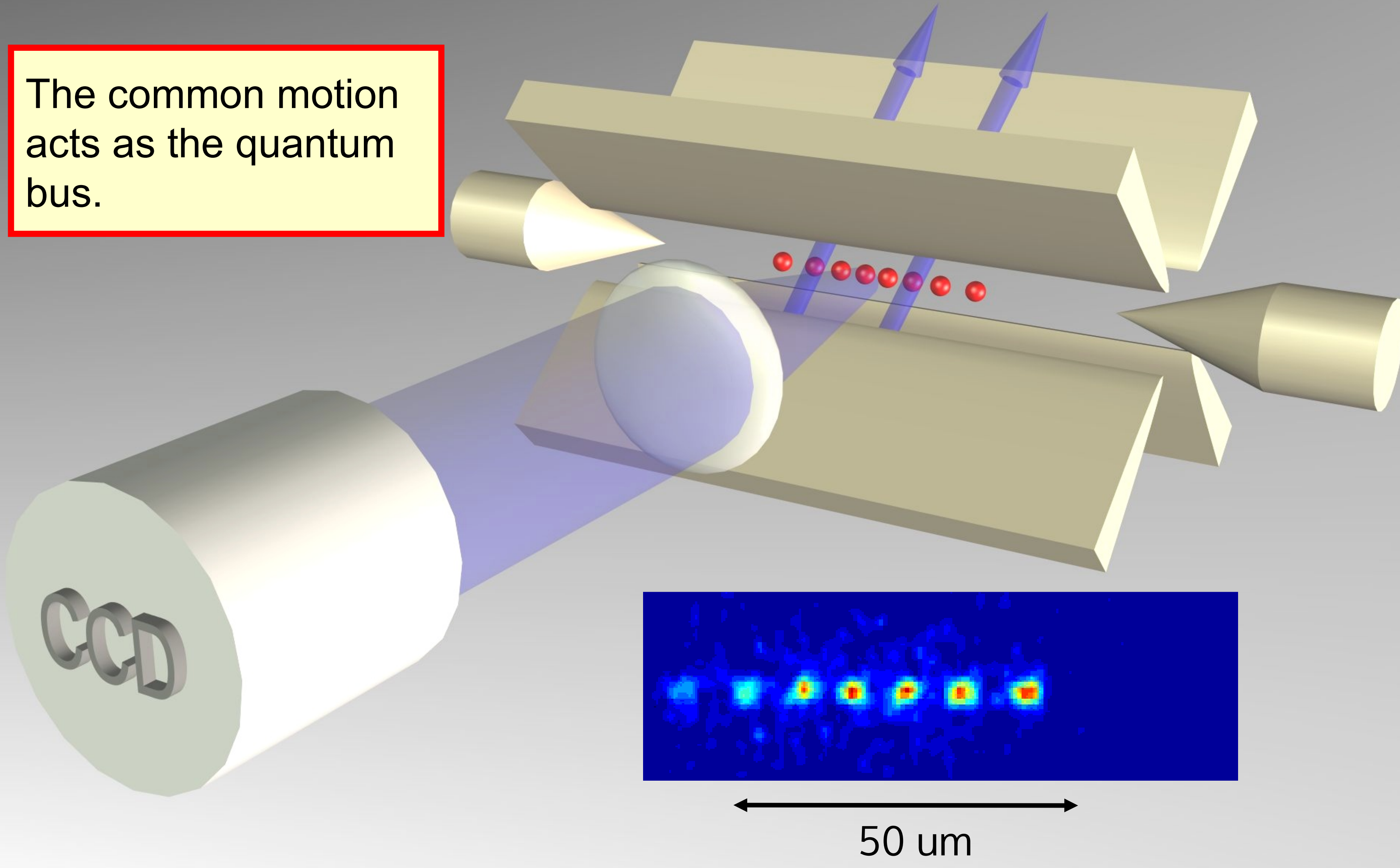




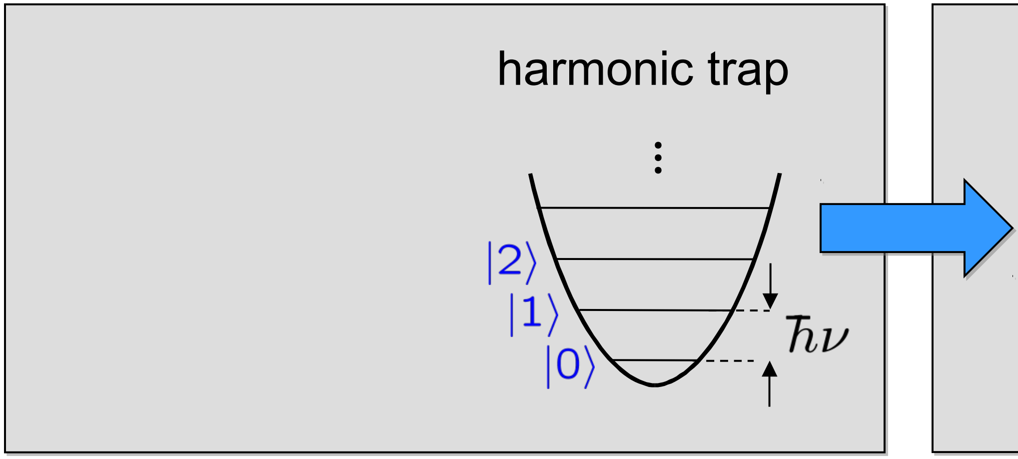


Having the qubits interact

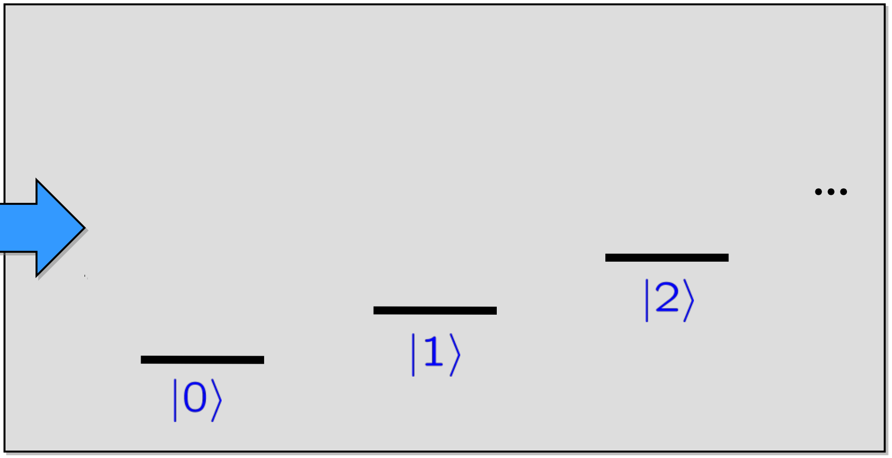
The common motion acts as the quantum bus.



Ion motion

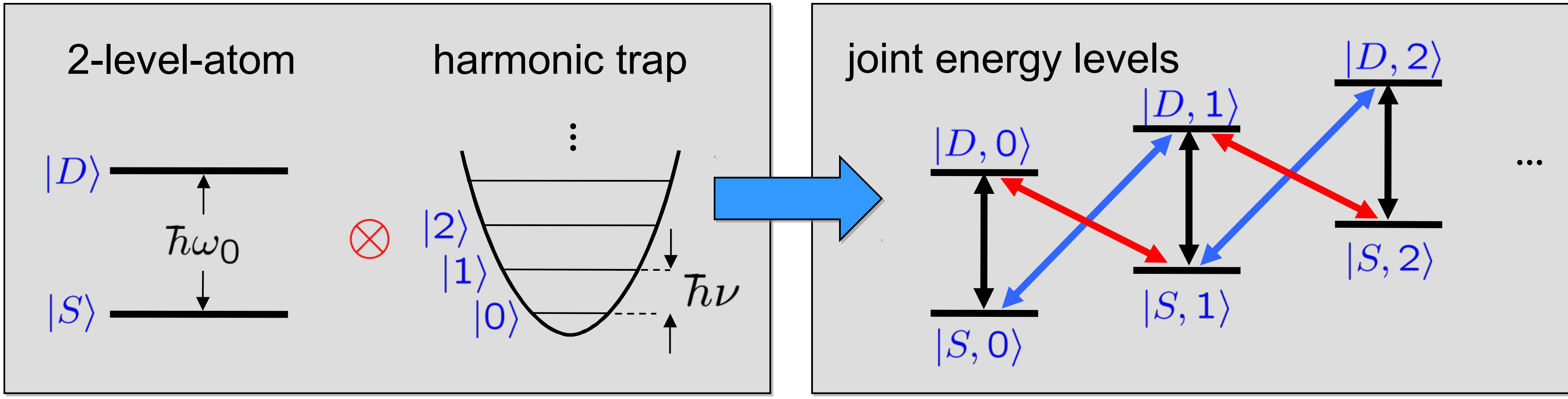


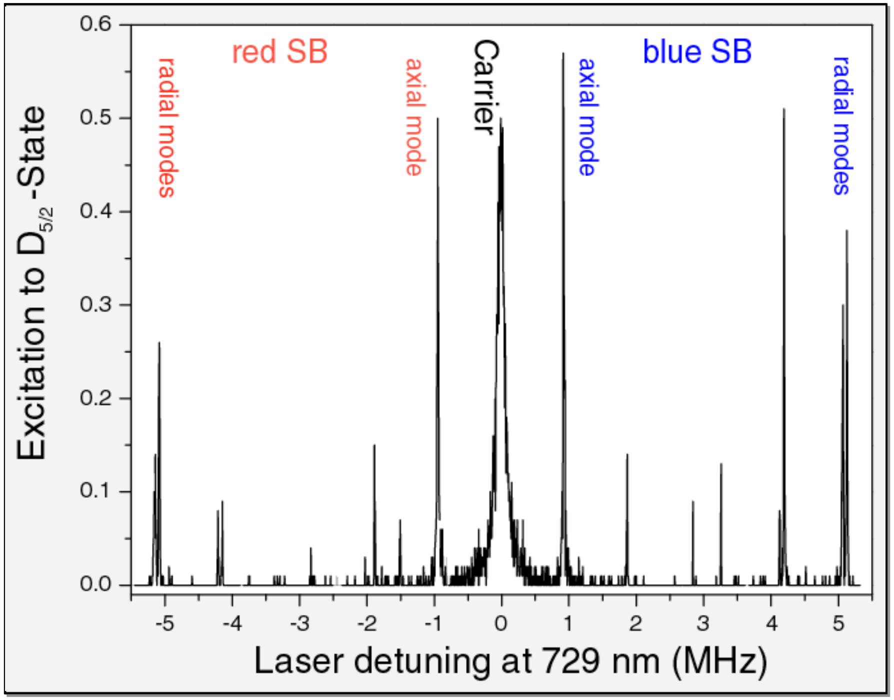
harmonic trap
$|2\rangle$
$|1\rangle$
$|0\rangle$
$\hbar\nu$



$|0\rangle$
$|1\rangle$
$|2\rangle$
...

Ion motion


2-level-atom
harmonic trap
$|D\rangle$
$\hbar\omega_0$
$|S\rangle$
$|2\rangle$
$|1\rangle$
$|0\rangle$
$\hbar\nu$
joint energy levels
$|D,0\rangle$
$|D,1\rangle$
$|D,2\rangle$
$|S,0\rangle$
$|S,1\rangle$
$|S,2\rangle$
...


red SB
blue SB
radial modes
axial mode
Carrier
axial mode
radial modes
Excitation to $D_{5/2}$ -State
Laser detuning at 729 nm (MHz)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
-5
-4
-3
-2
-1
0
1
2
3
4
5

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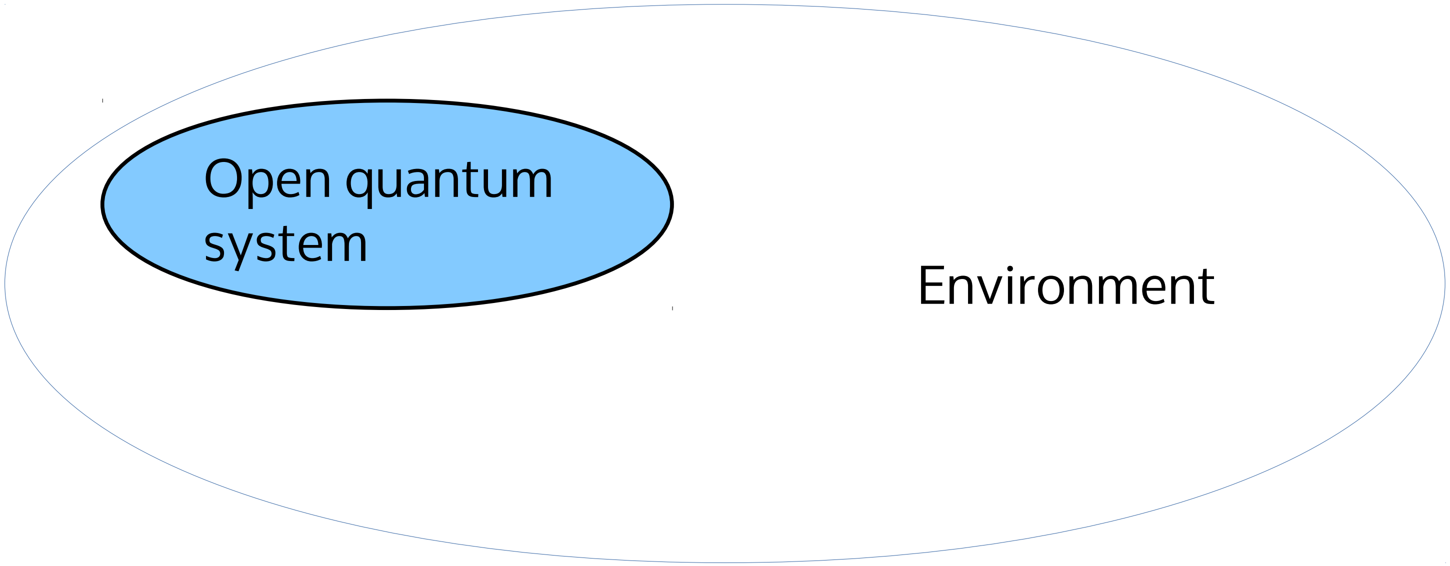
Local detection of quantum correlations

Given a quantum system, can you figure out whether it has quantum correlations with its environment ?



→ you can only control the open quantum system

Potential applications

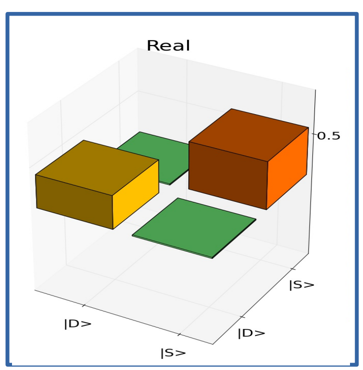
1. Study dynamics of quantum correlations

2. Characterize decoherence in QIP

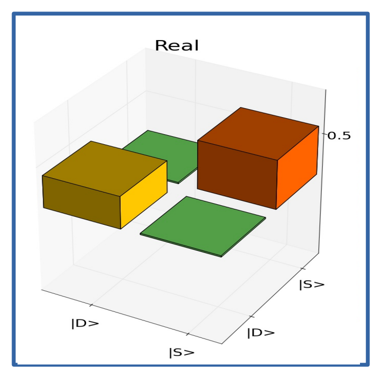
3. Study quantum correlations in quantum phase transitions

   - Clarify the role of entanglement during phase transitions
   - Detect phase transitions

4. How meaningful is the density matrix?



$\overset{?}{=}$



Local Detection Protocol

$$
\begin{tikzcd}
\rho(0) \arrow[r, "U_t"] \arrow[d, "\mathrm{Tr}_E"'] & \rho(t) \arrow[d, "\mathrm{Tr}_E"] \\
\rho_S(0) \arrow[r, "\Phi_t"] & \rho_S(t)
\end{tikzcd}
$$

Φ_t depends on:

- State of the environment
- Initial correlations between system and environment
- Standard assumption: no correlations

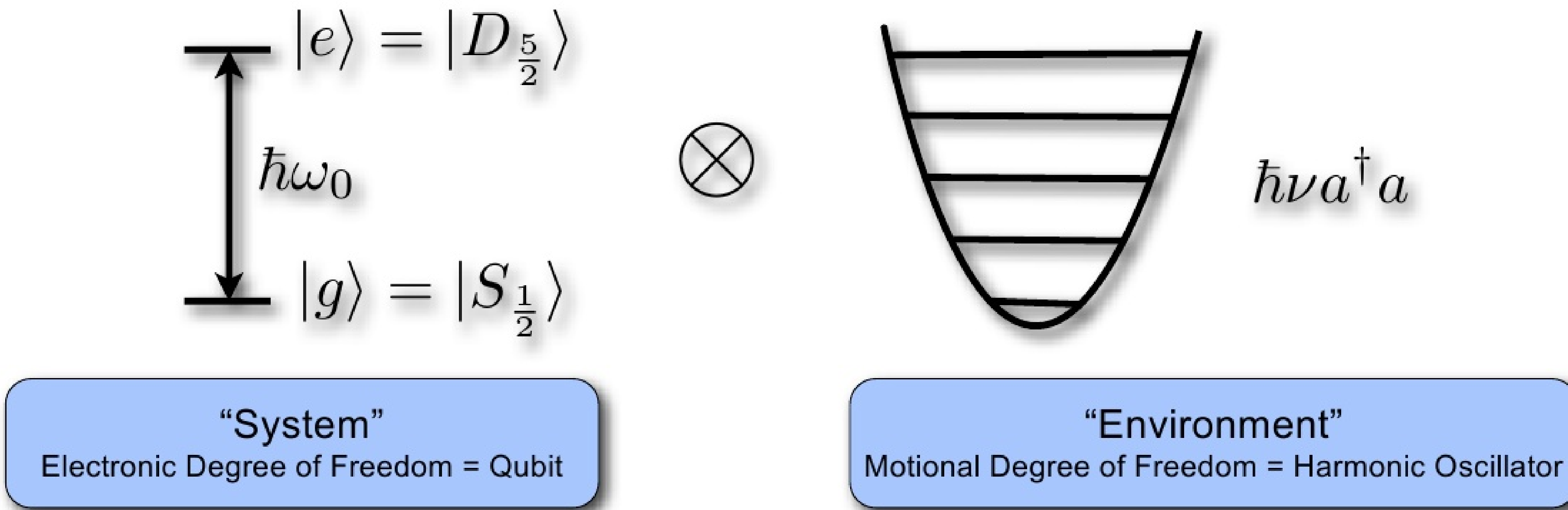
H.-P Breuer, Theory of Open Quantum Systems

Local Detection Protocol

$$
\begin{tikzcd}
\rho(0) \arrow[r, "U_t"] \arrow[d] \arrow[dddd, bend right=60, dotted, "\Phi \otimes \mathbb{I}"'] & \rho(t) \arrow[d] \\
\rho_S(0) \arrow[r, "\Phi_t"] & \rho_S(t) \\
= & \neq \\
\rho'_S(0) \arrow[r, "\Phi'_t"] & \rho'_S(t) \\
\rho'(0) \arrow[r, "U_t"] \arrow[u] & \rho'(t) \arrow[u]
\end{tikzcd}
$$

Gessner, Breuer, PRL 2011

Local detection of quantum correlations

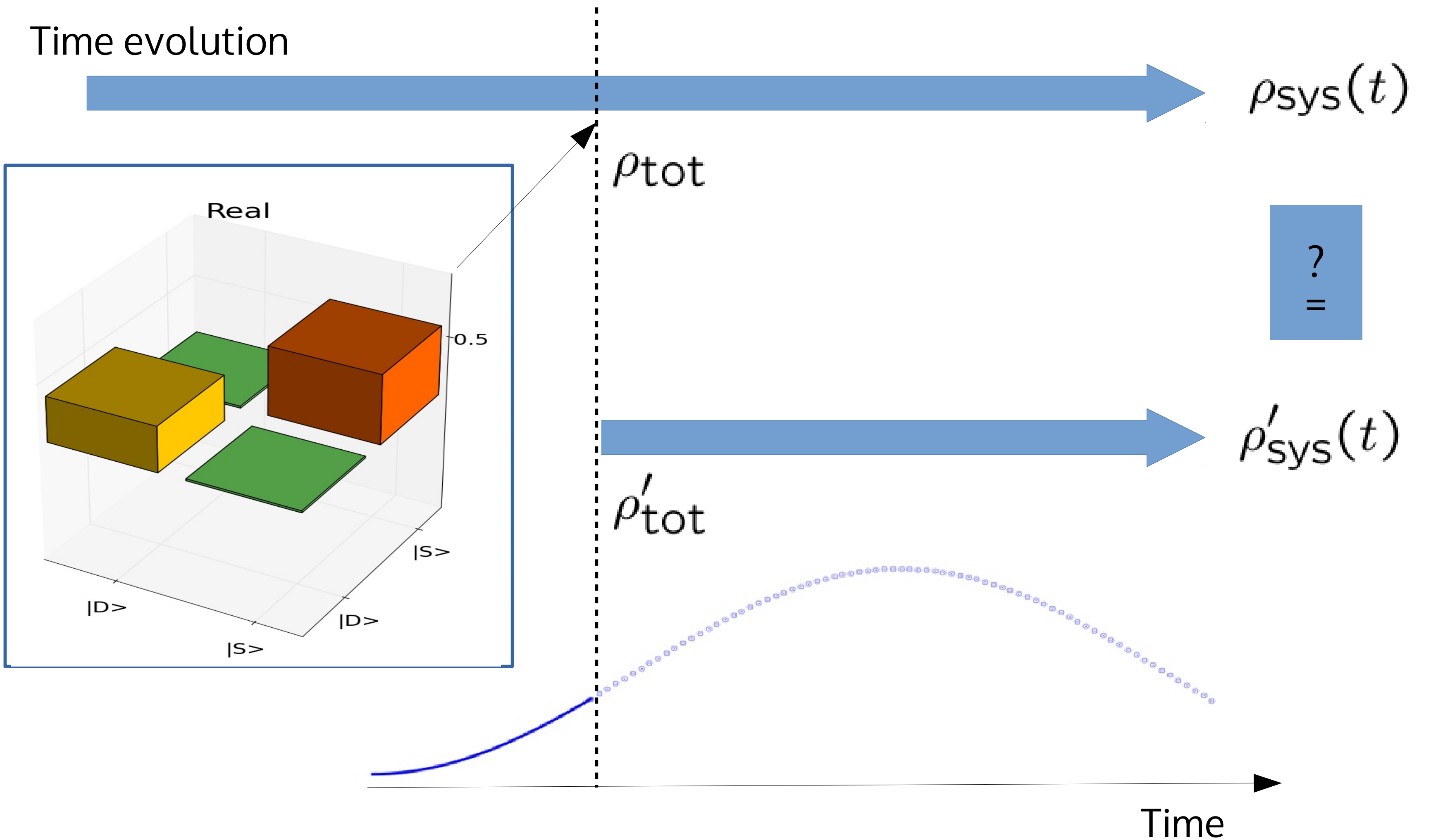


Open system – environment dynamics:

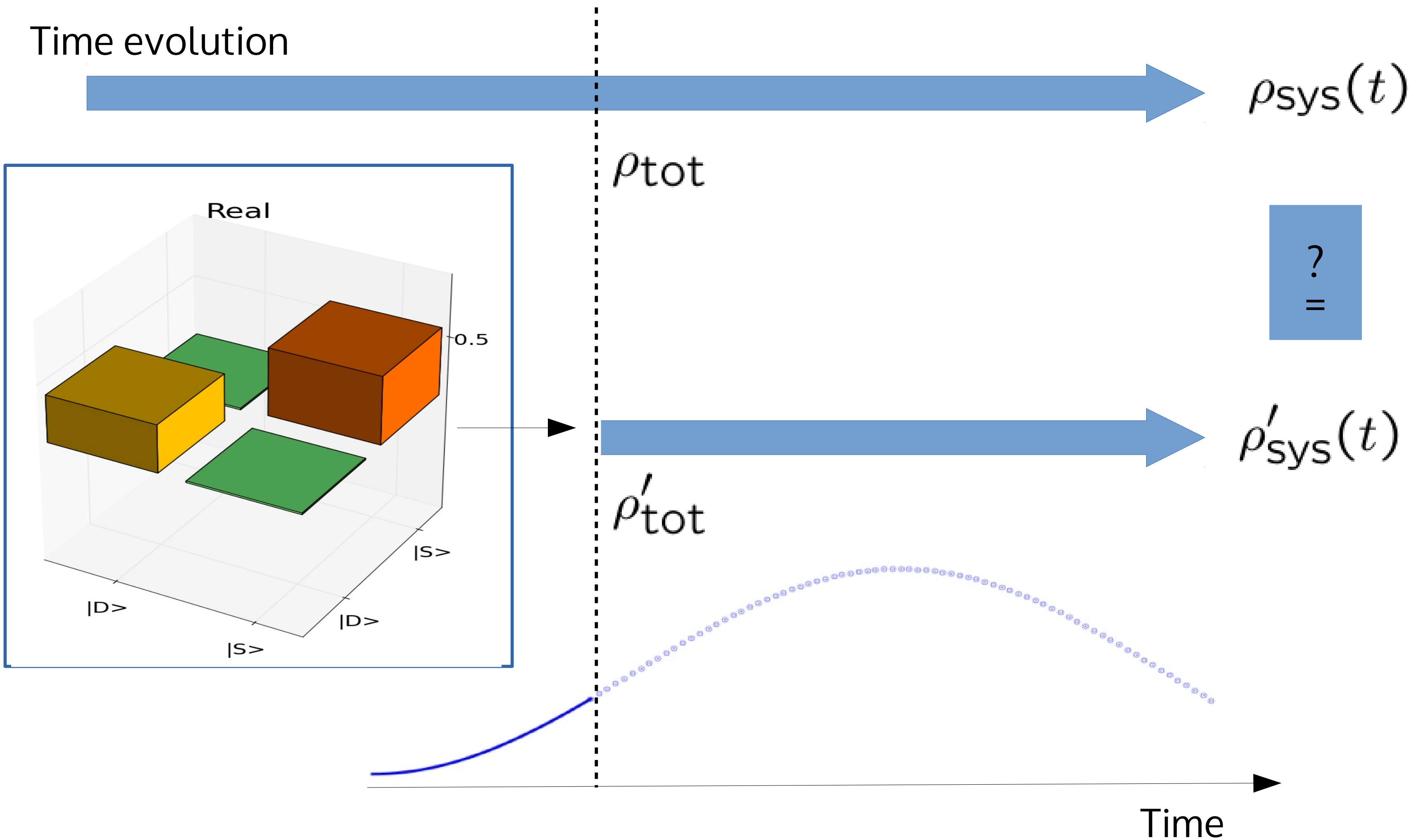
Blue sideband: $H = \sigma_+ a^\dagger + \sigma_- a$

M. Gessner *et al.*, Nature Phys. 10, 105 (2014).

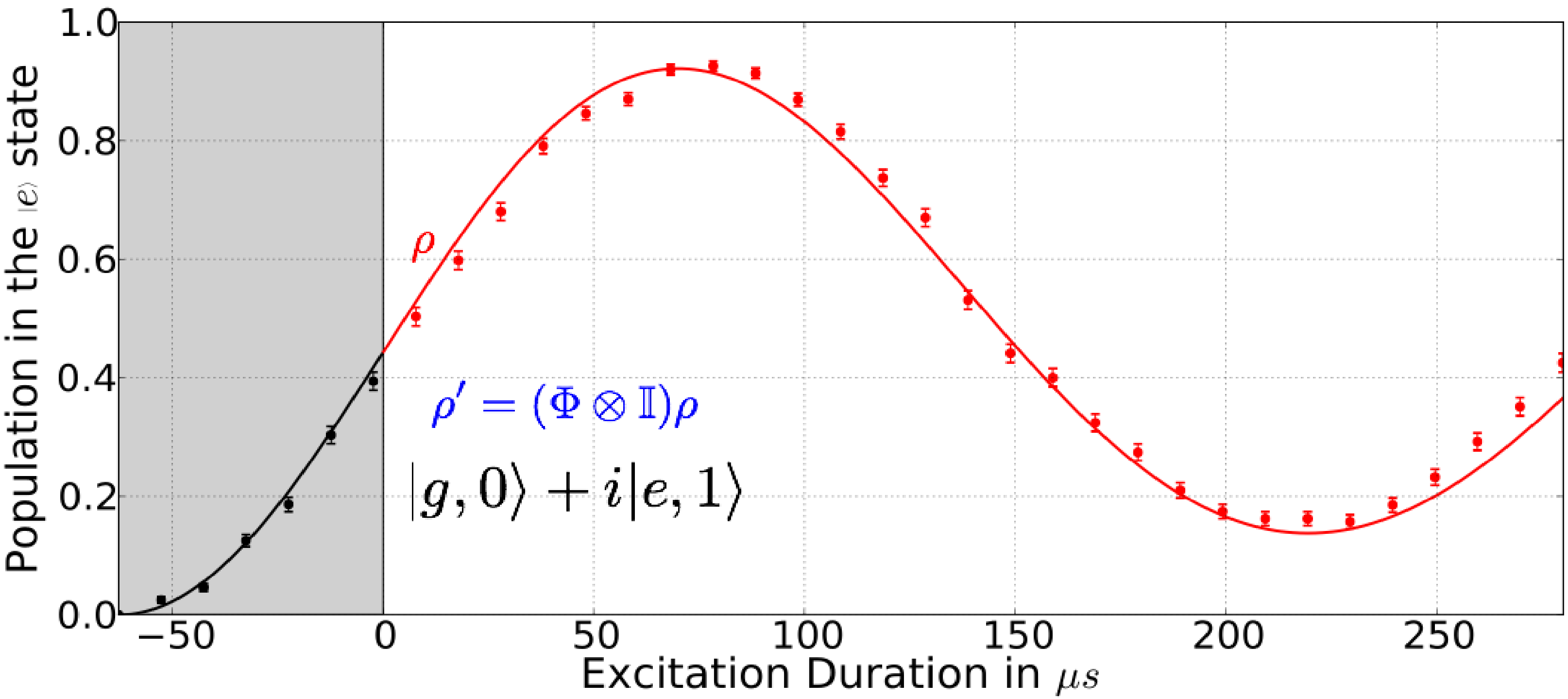
Local detection of quantum correlations

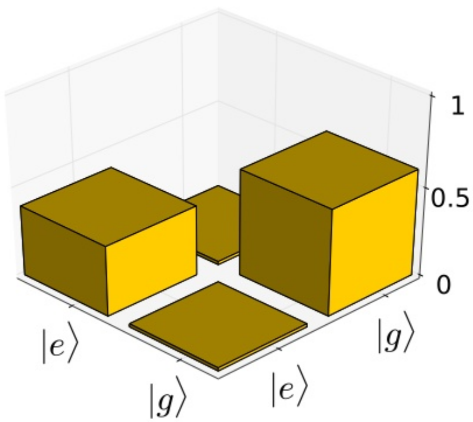


Local detection of quantum correlations

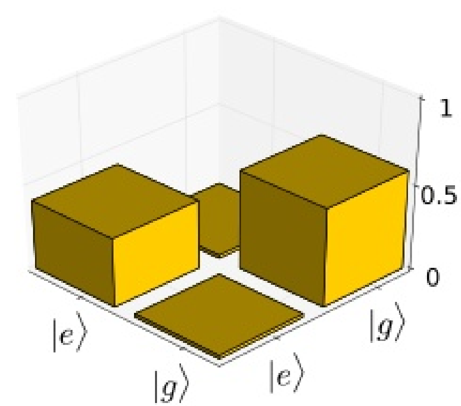


Local detection of quantum correlations

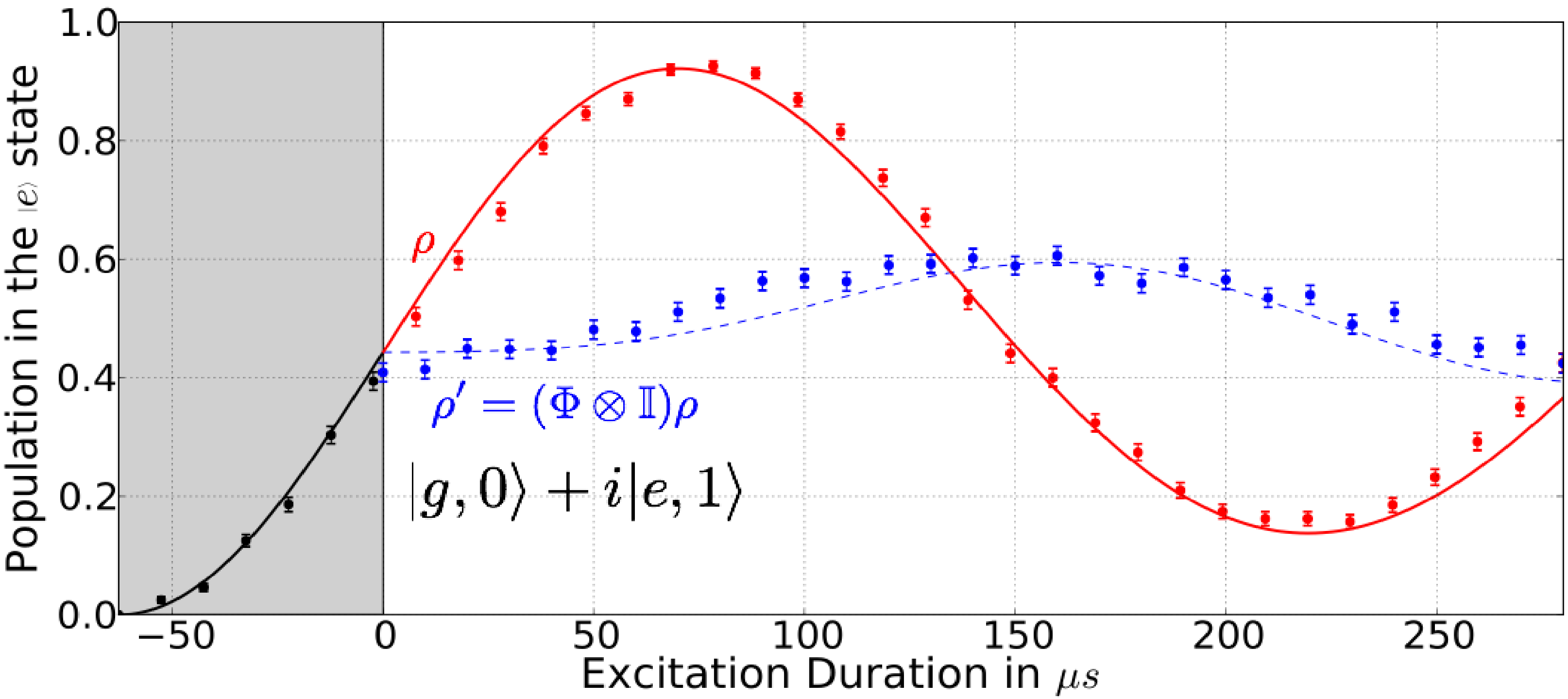


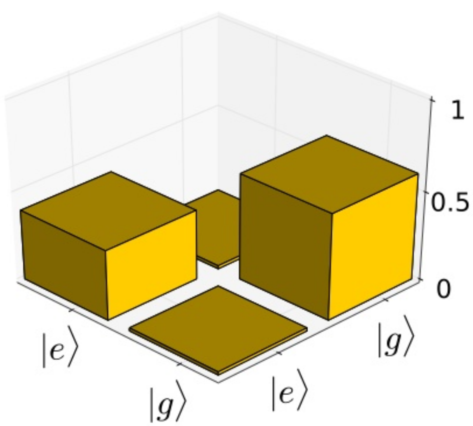


$\rho_S \quad = \quad \rho'_S$

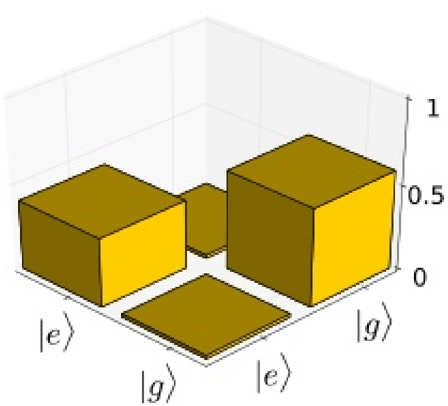


Local detection of quantum correlations



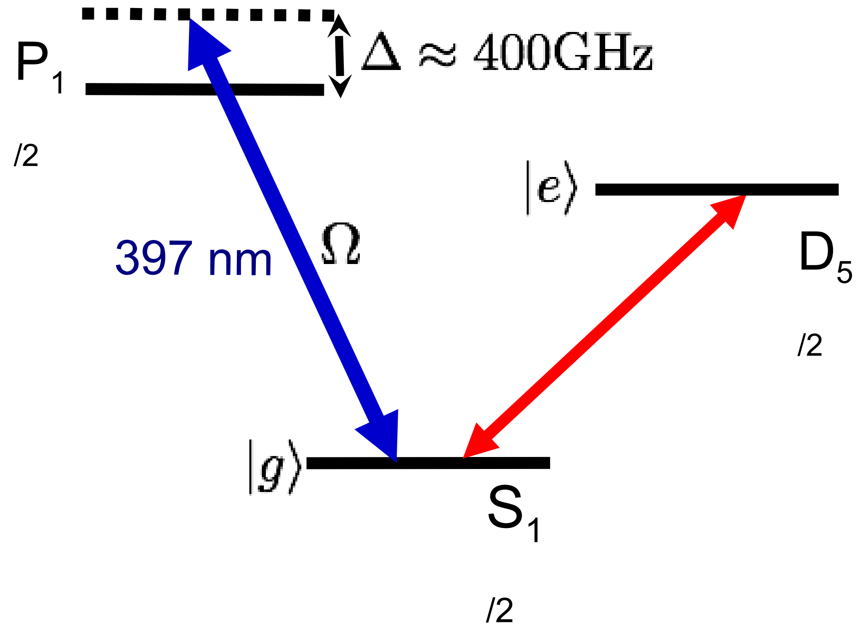


$$\rho_S \quad = \quad \rho'_S$$

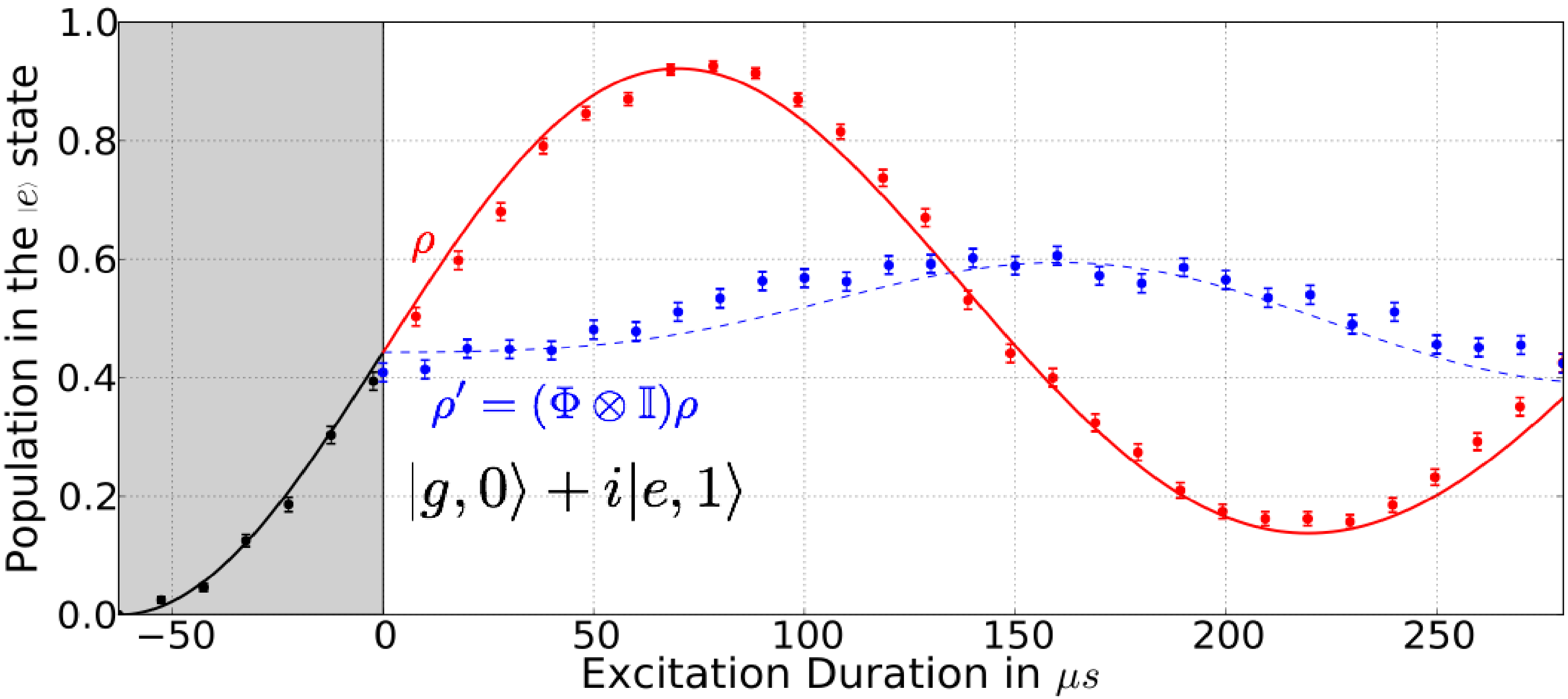


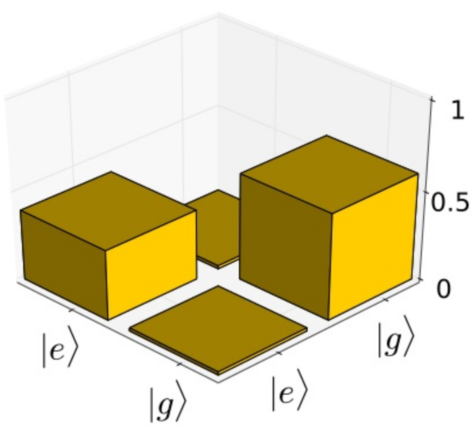
Dephasing Implementation

- AC Stark shift introduces a phase shift
- Averaging over interaction time removes coherence
- Populations, motion not affected



Local detection of quantum correlations





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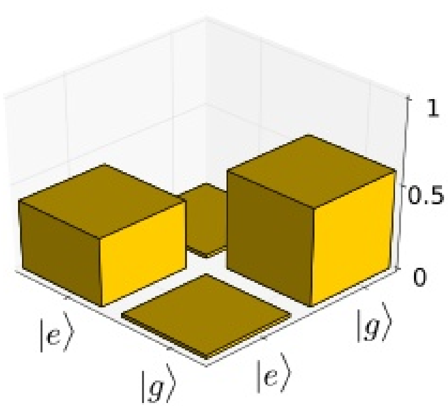
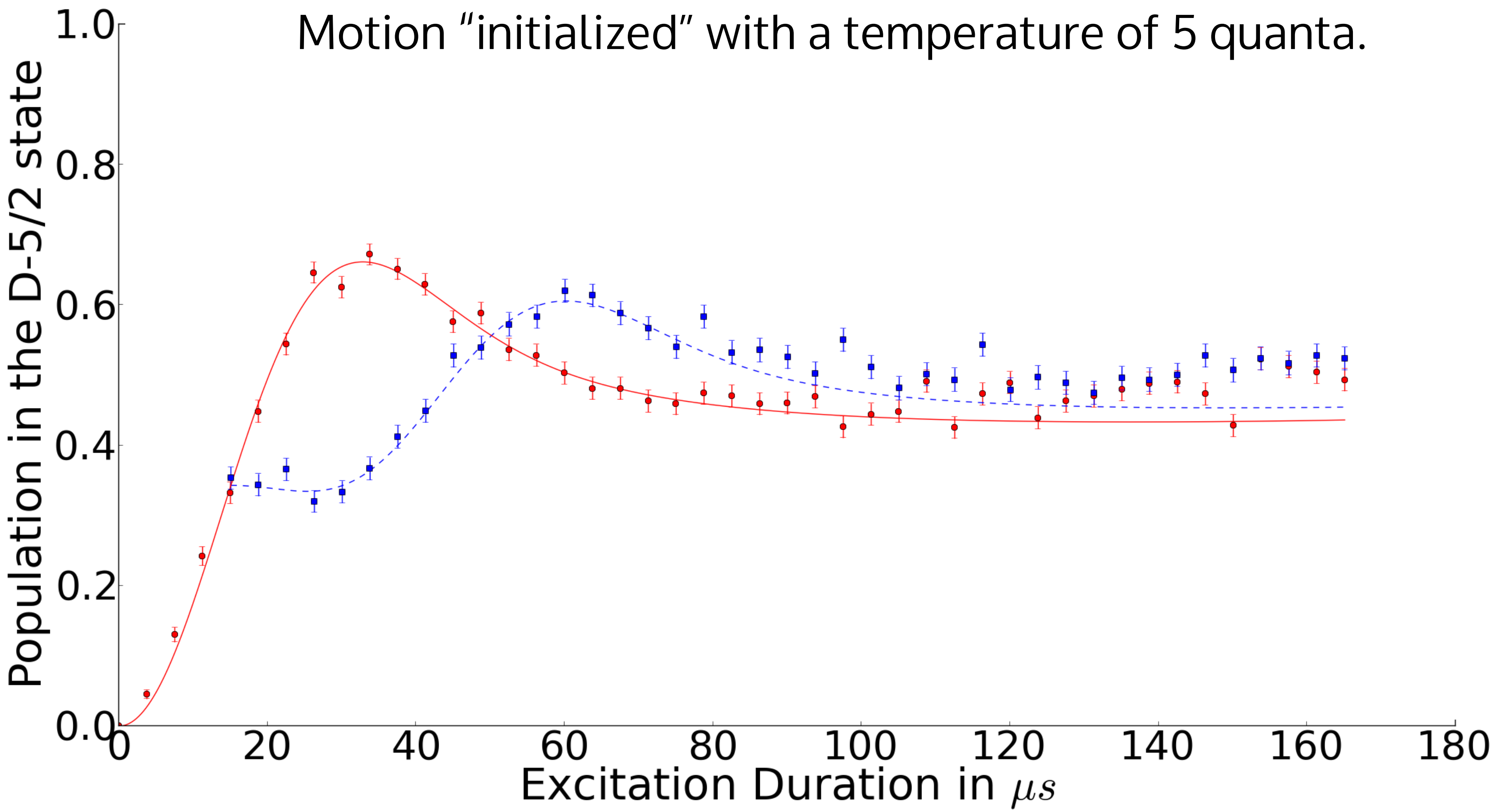


Detection of discord in the interesting case



M. Gessner *et al.*, Nature Phys. 10, 105 (2014).

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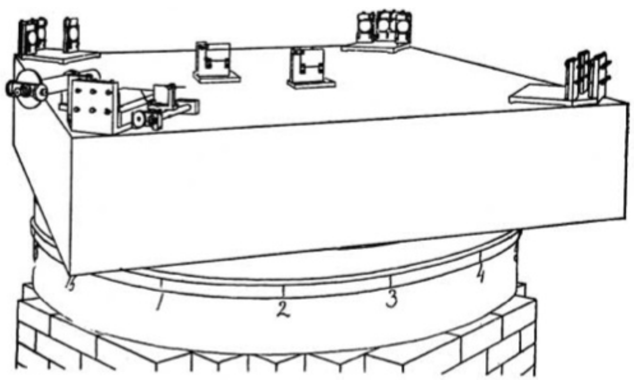
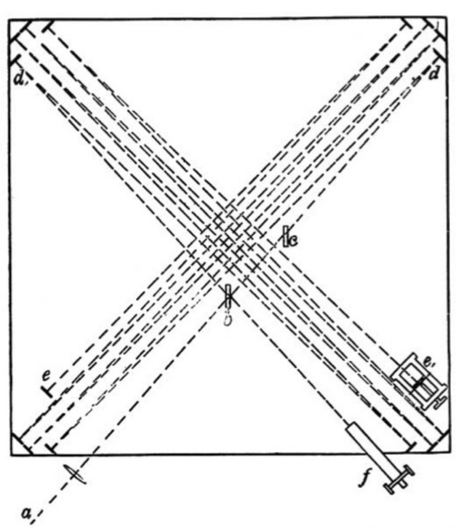
A most famous null experiment

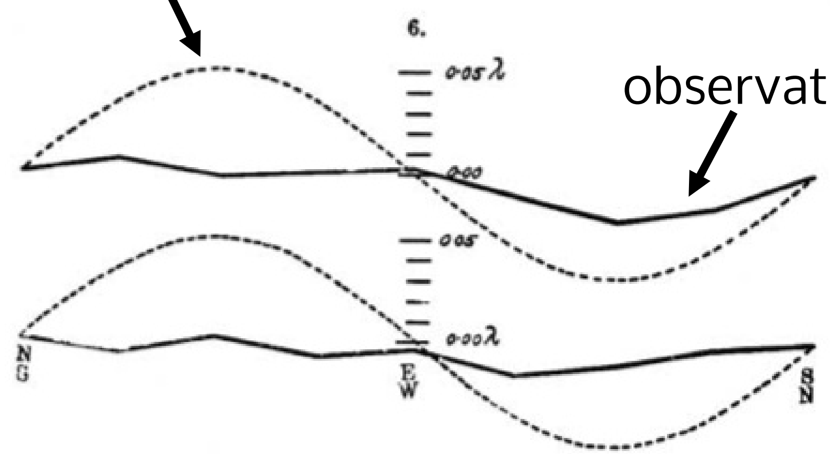
Test for an "aether".





expected fringe shift due to aether

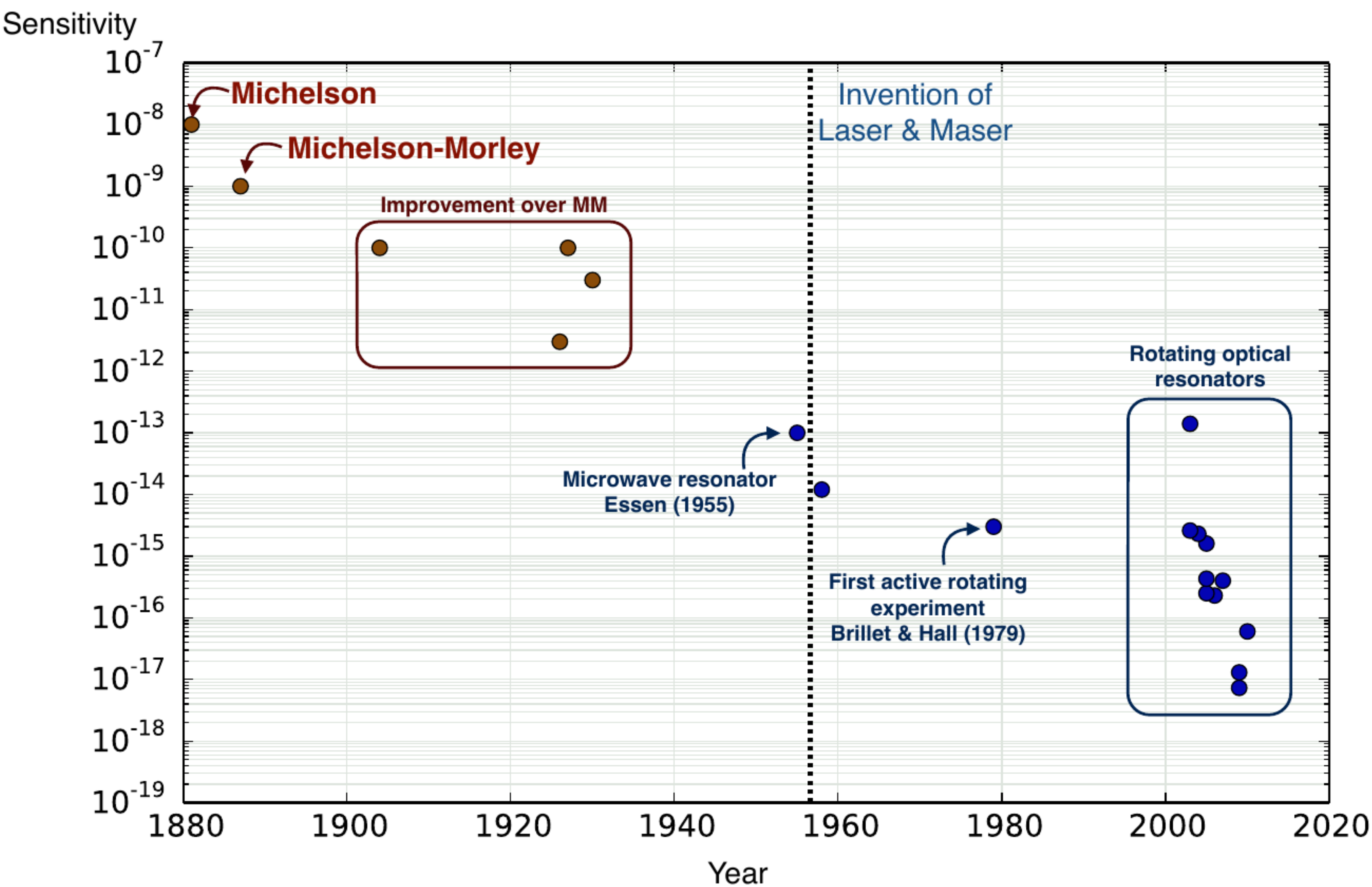
observation



Michelson-Morley experiment
confirms Lorentz symmetry to 10^{-9}

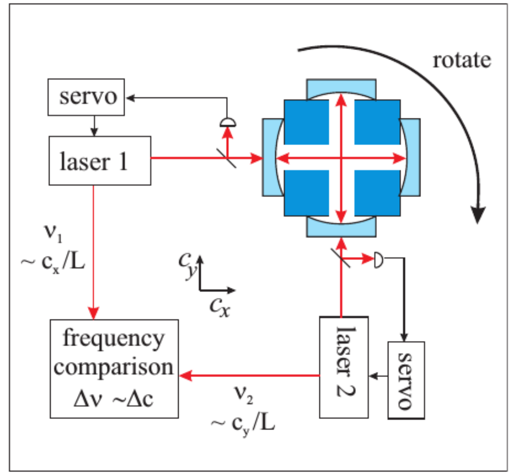
Michelson & Morley, Am. J. Science **34**, 427 (1887).

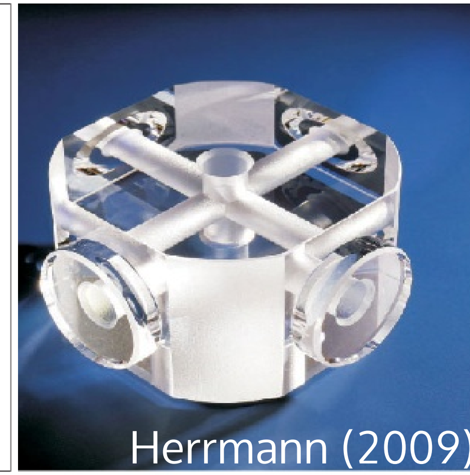
A most famous null experiment



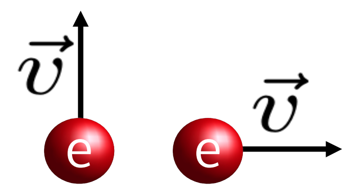
Lorentz-violating effects?

Modern Michelson-Morley experiments




Herrmann (2009)

Electrons
- maximum attainable speed is (not) "c"
- dependence of energy on direction of velocity



electron

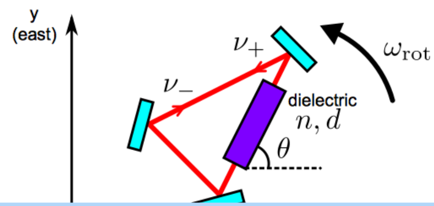
Others . . . .
- neutron, proton, neutrinos . . . .

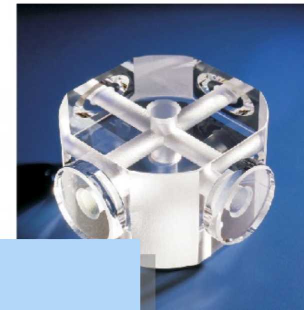
same energy?

Modern tests of Lorentz symmetry

Accelerator

Optical cavities

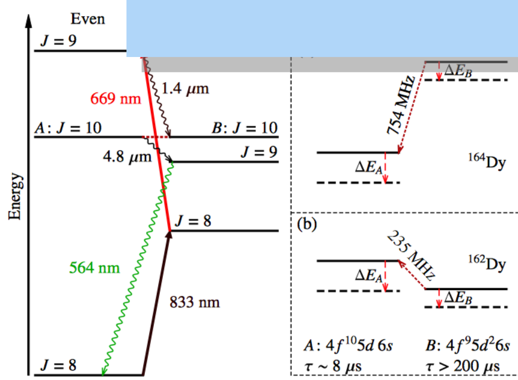




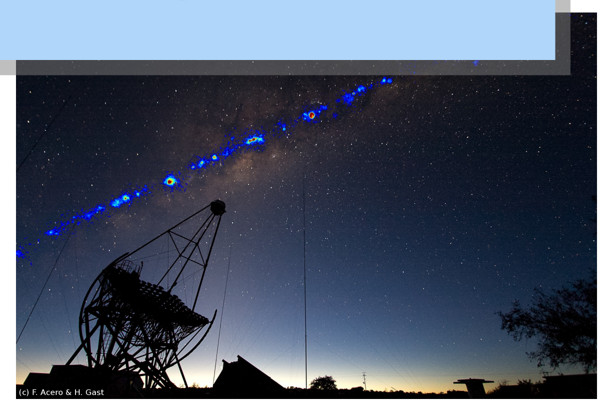
nn (2009)

This talk: New approach with electrons using quantum information techniques and decoherence free subspaces.

S

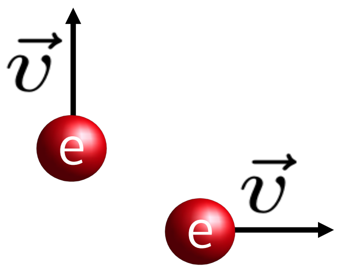


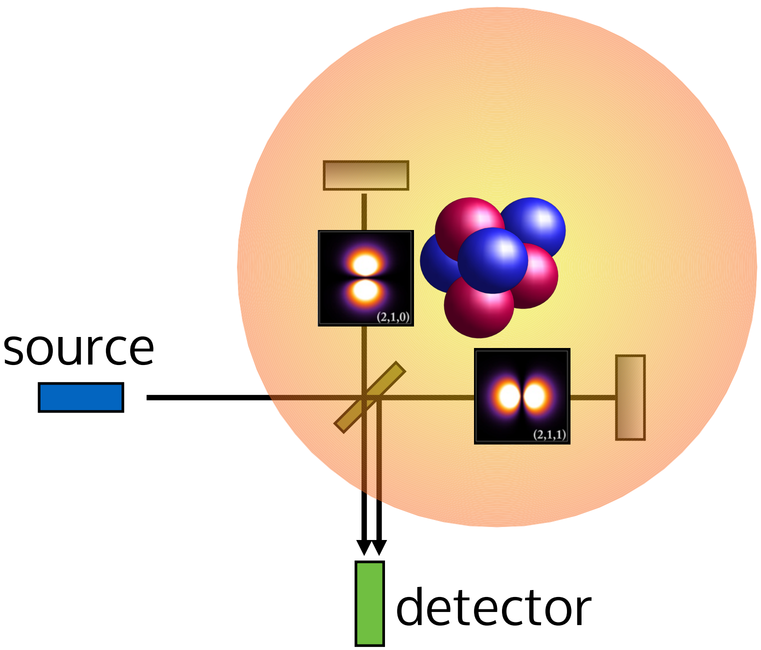
Hughes-Drever (1960/1961)
Hohensee (2013)



HESS telescope, Altschul (2006)

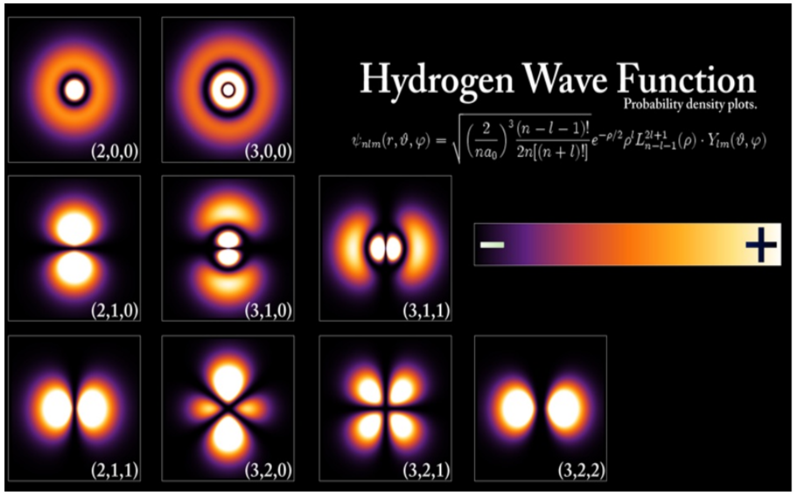
Interferometer with electrons?





Michelson interferometer

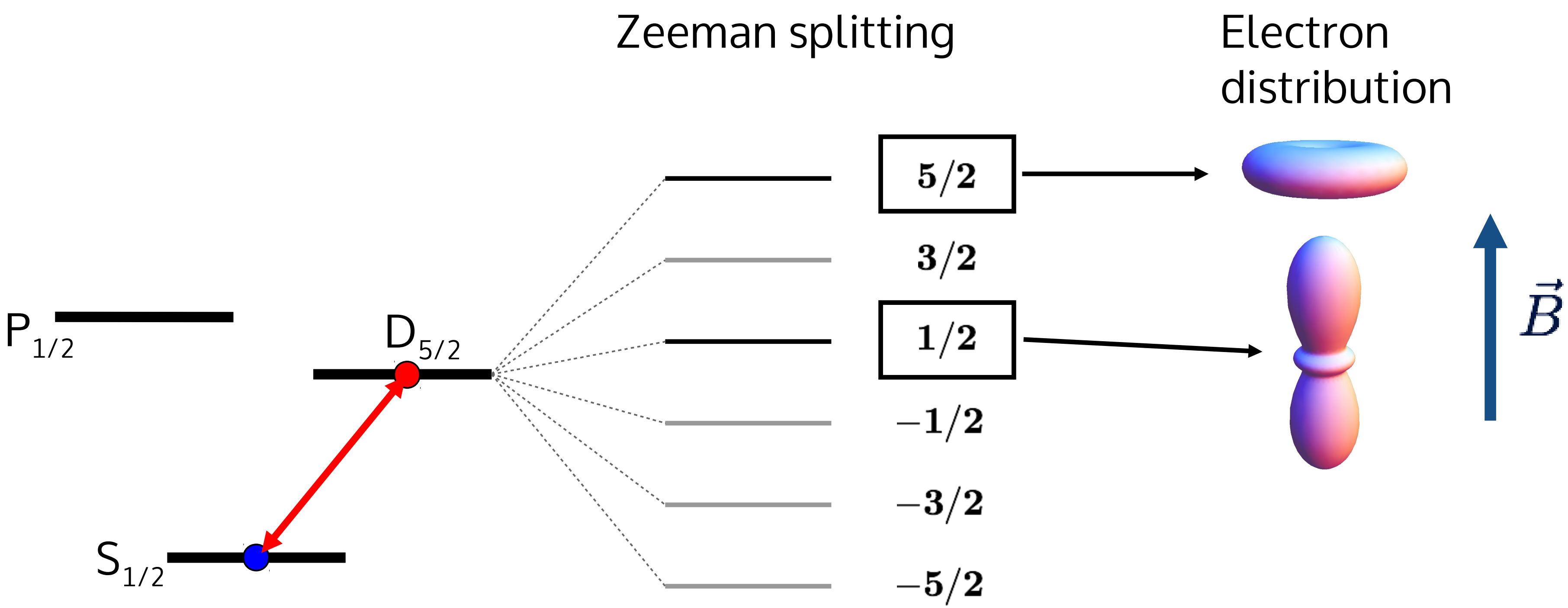
Use electrons trapped by nuclei



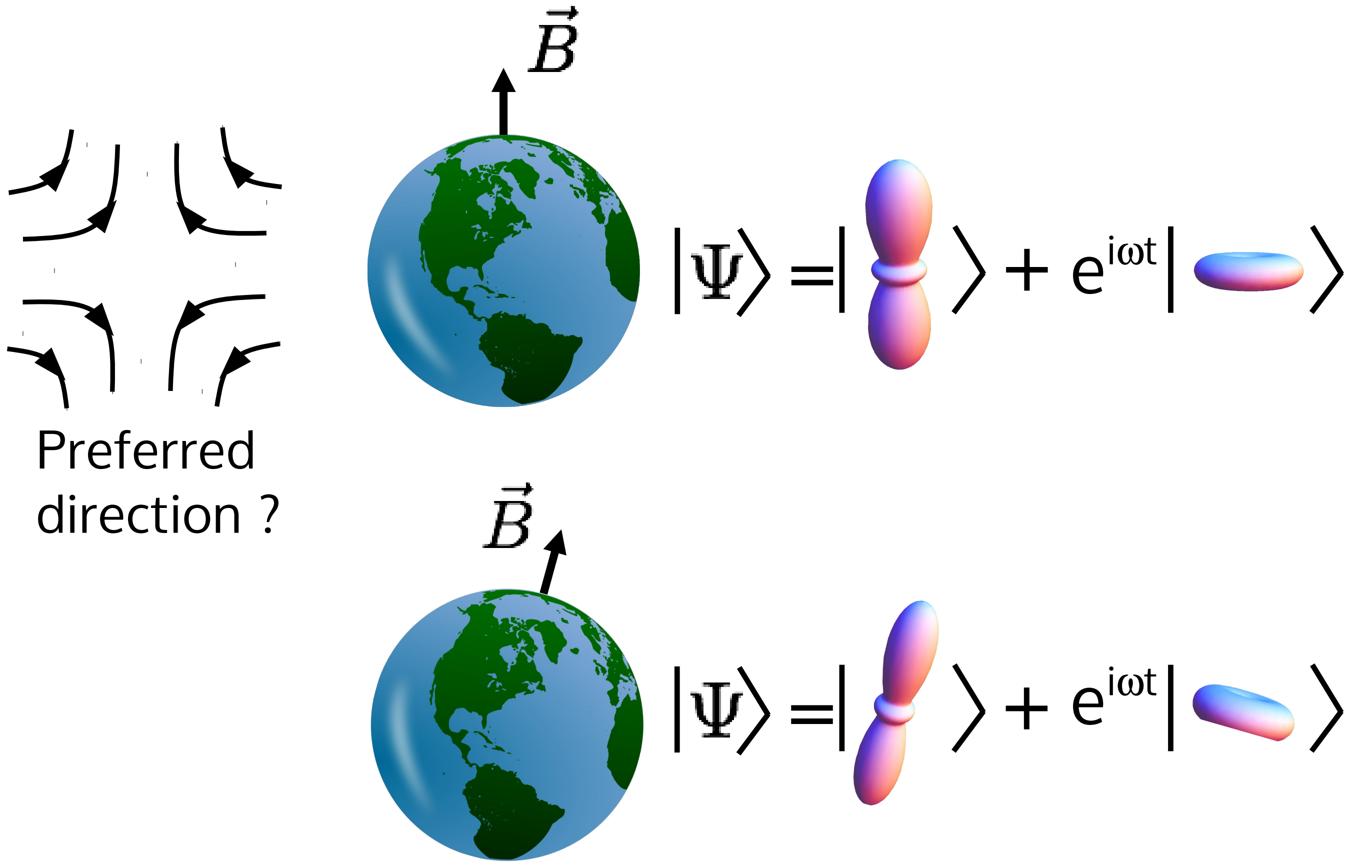
http://www.photonicquantum.info/Research/Hydrogen_Density_Plots.png

Interferometer with electrons?

Use the D-manifold of 40Ca+



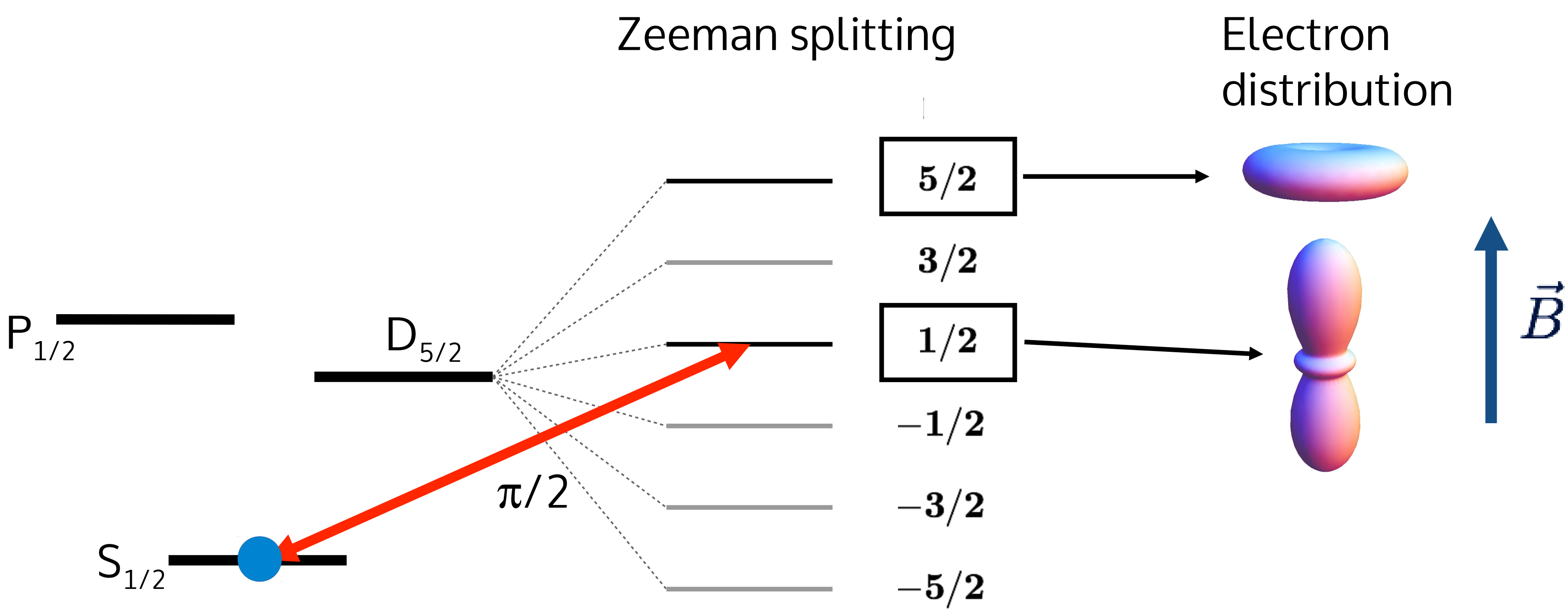
Measurement scheme



Lorentz violation → preferred direction

→ energy shift with the Earth's rotation

State preparation



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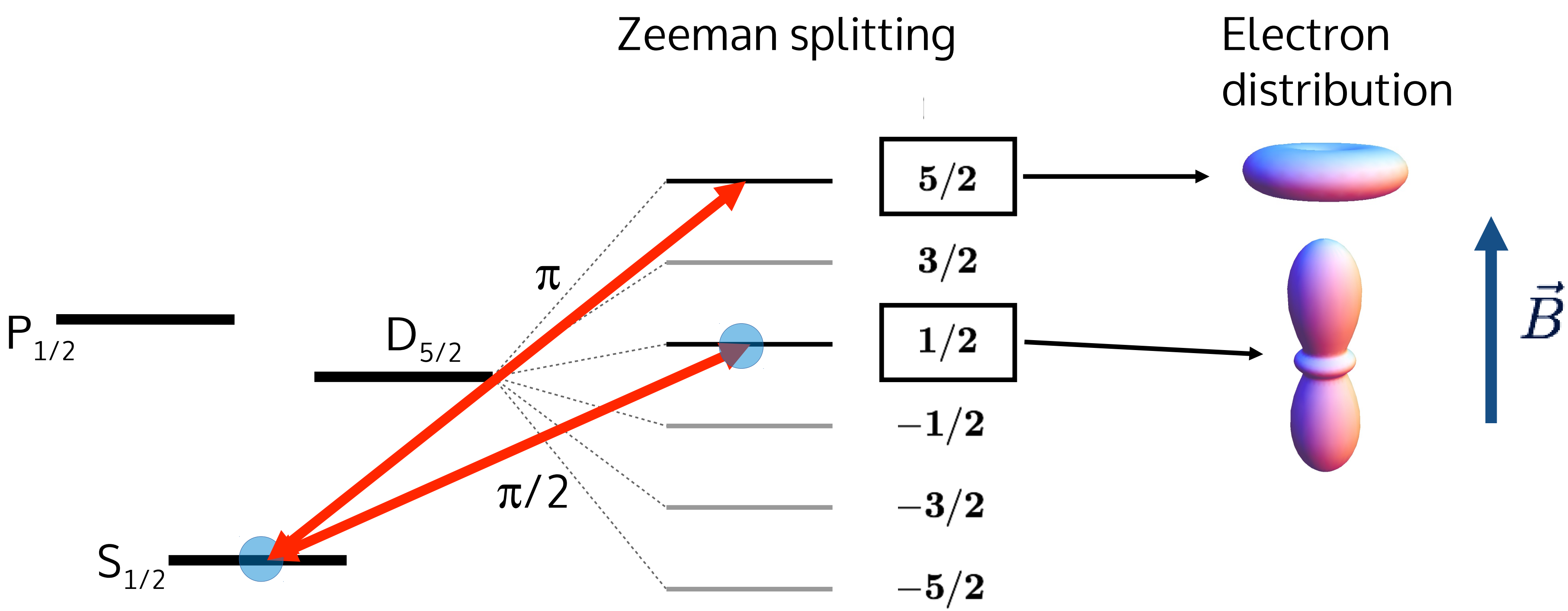
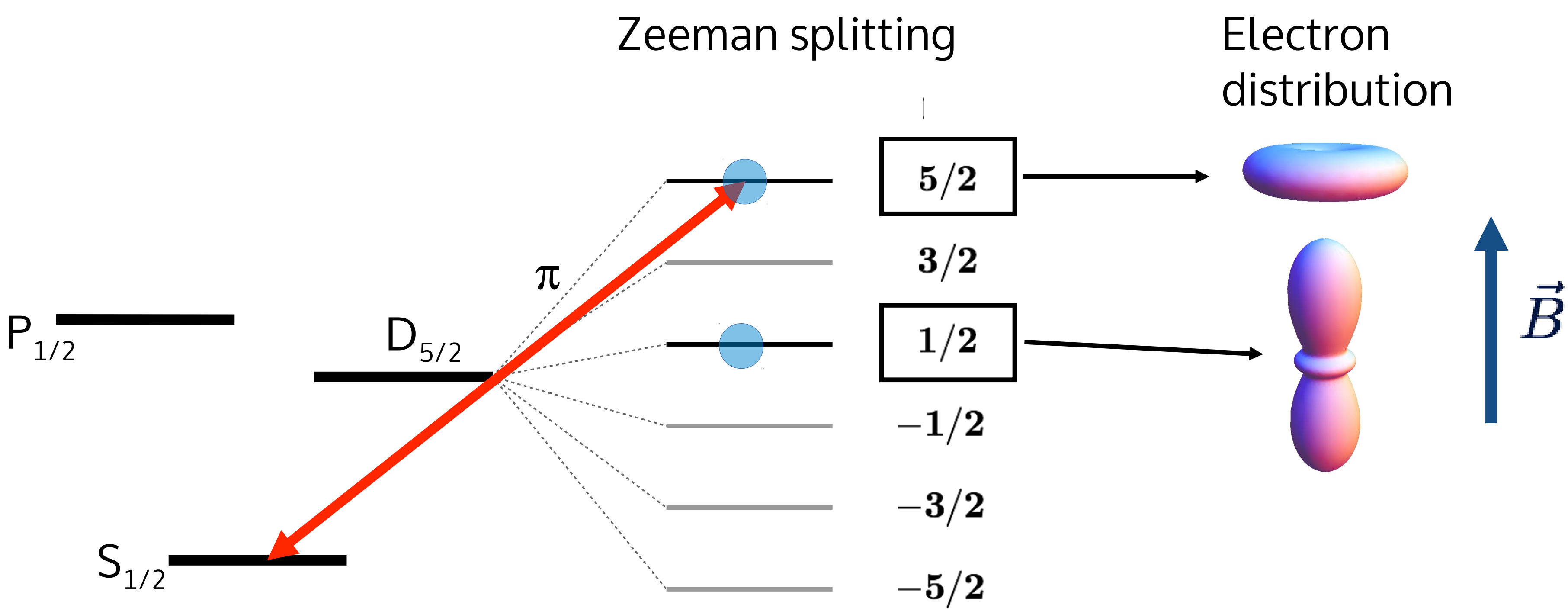
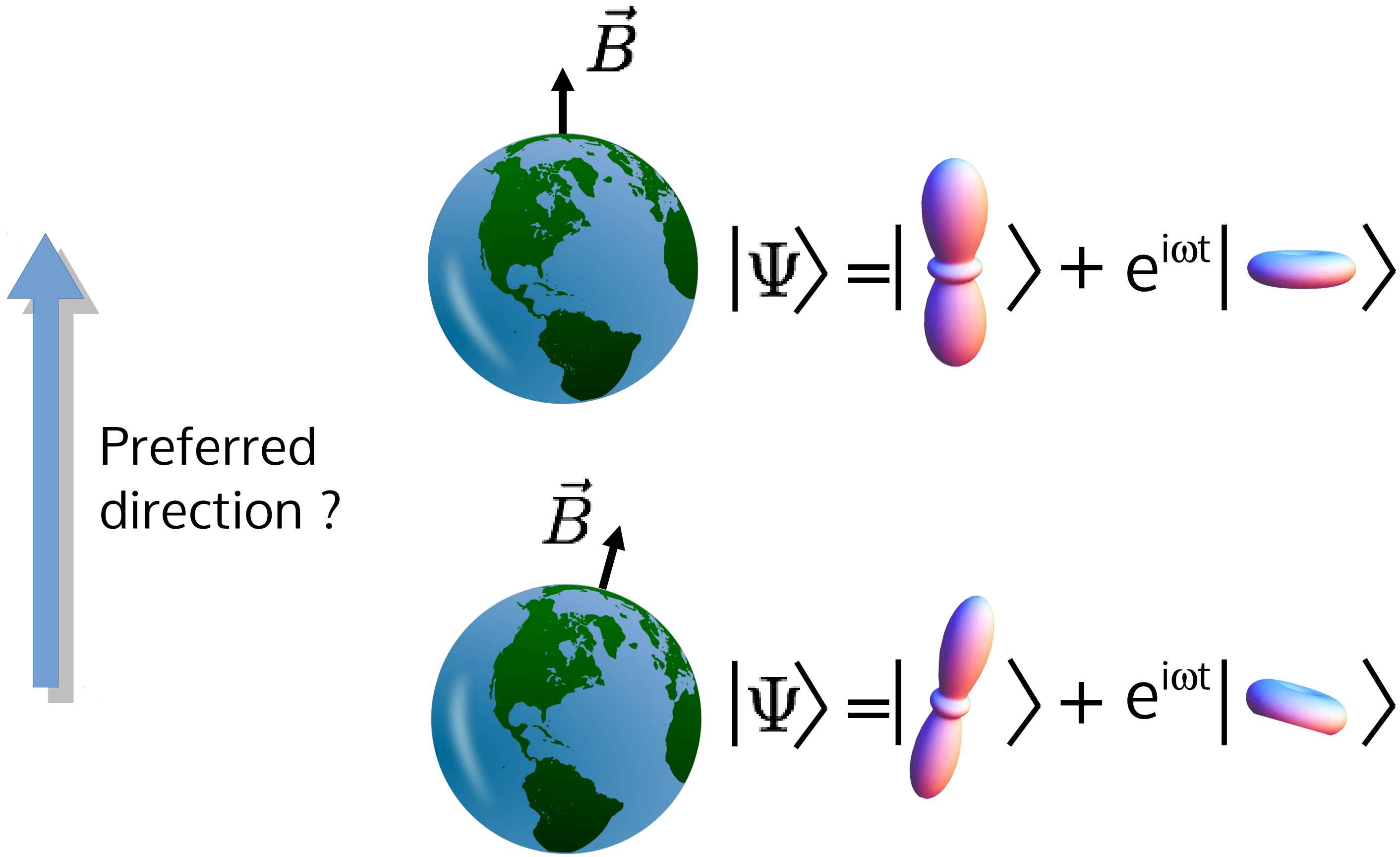


State preparation



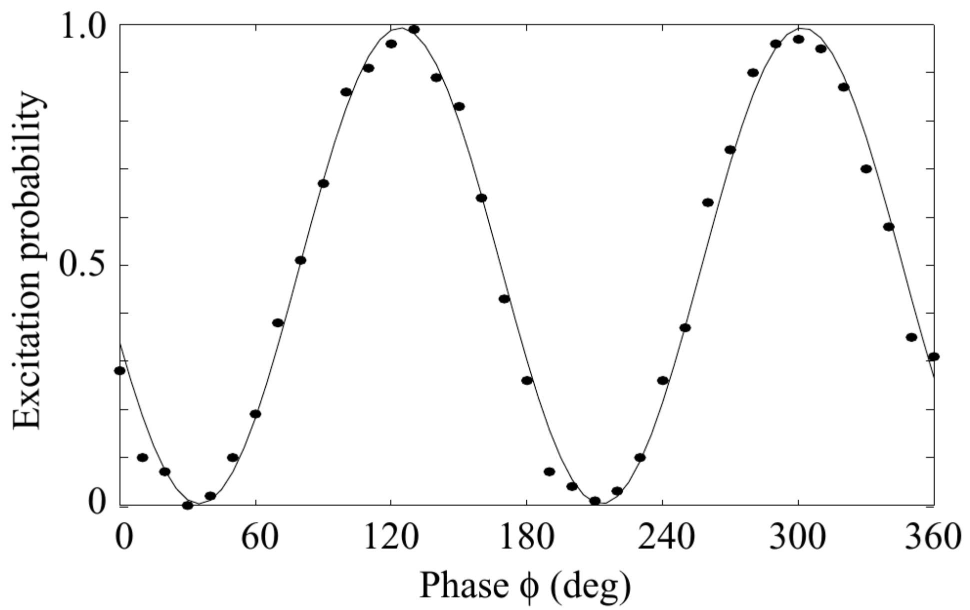
Measurement scheme



Lorentz violation → preferred direction

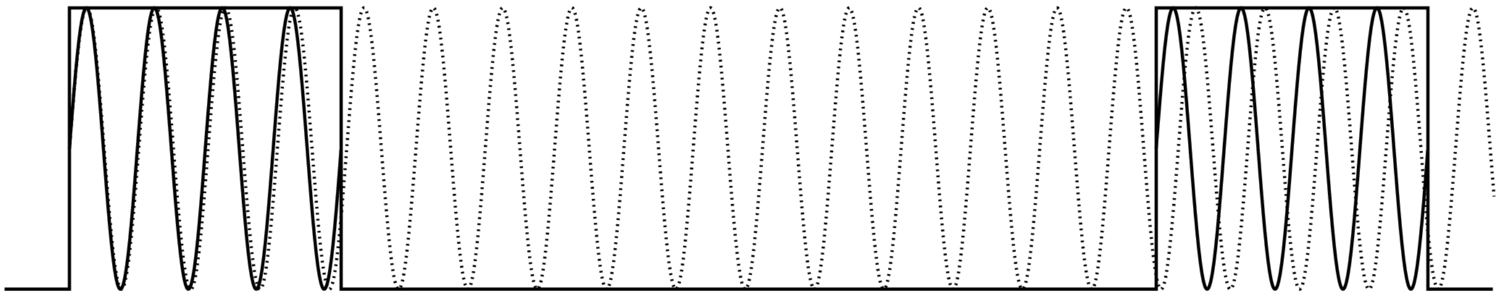
→ energy shift with the Earth's rotation

Read-out of the phase evolution

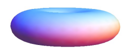


From: PhD thesis, Riebe 2005, Innsbruck

Magnetic dipole moment



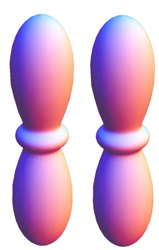
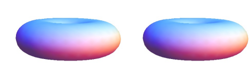
Decoherence-free subspace

$|\Psi\rangle = |$  $\rangle + e^{i\omega t}|$  $\rangle$

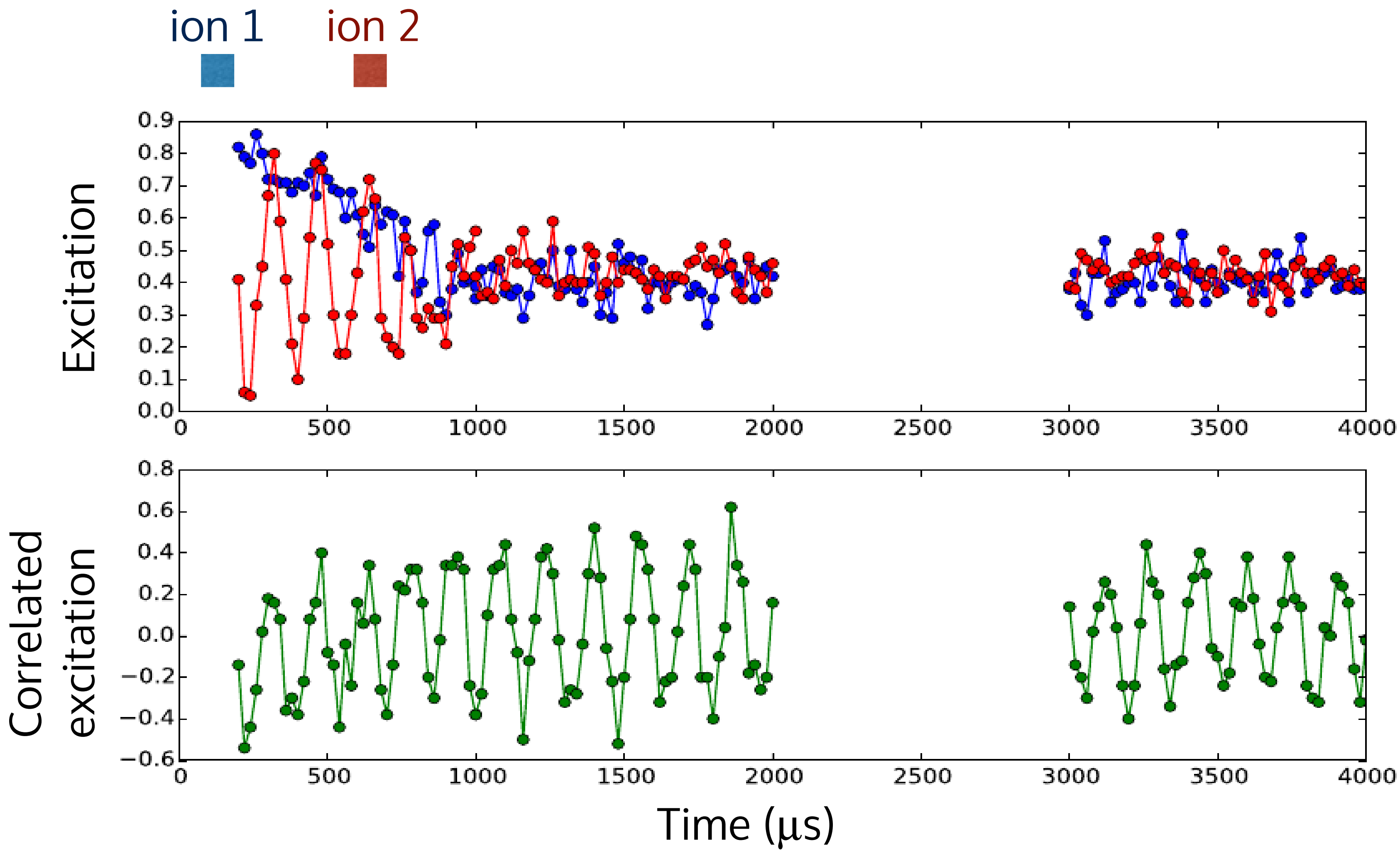
Problem: Zeeman effect swamps phase evolution

Use two ions:

$$|\Psi\rangle = |\overbrace{-1/2, 1/2}^{\mu_{eff}=0}\rangle + |\overbrace{-5/2, 5/2}^{\mu_{eff}=0}\rangle$$

$= |$  $\rangle + e^{i2\omega t}|$  $\rangle$

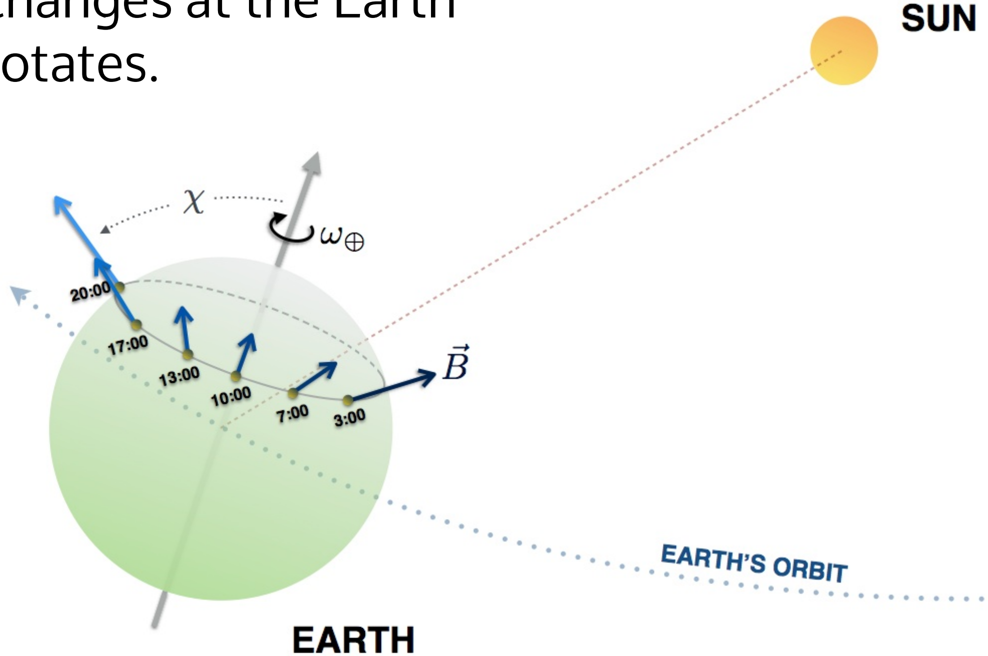
Decoherence-free subspace



Extends coherence by up to four orders of magnitude

Measurement scheme

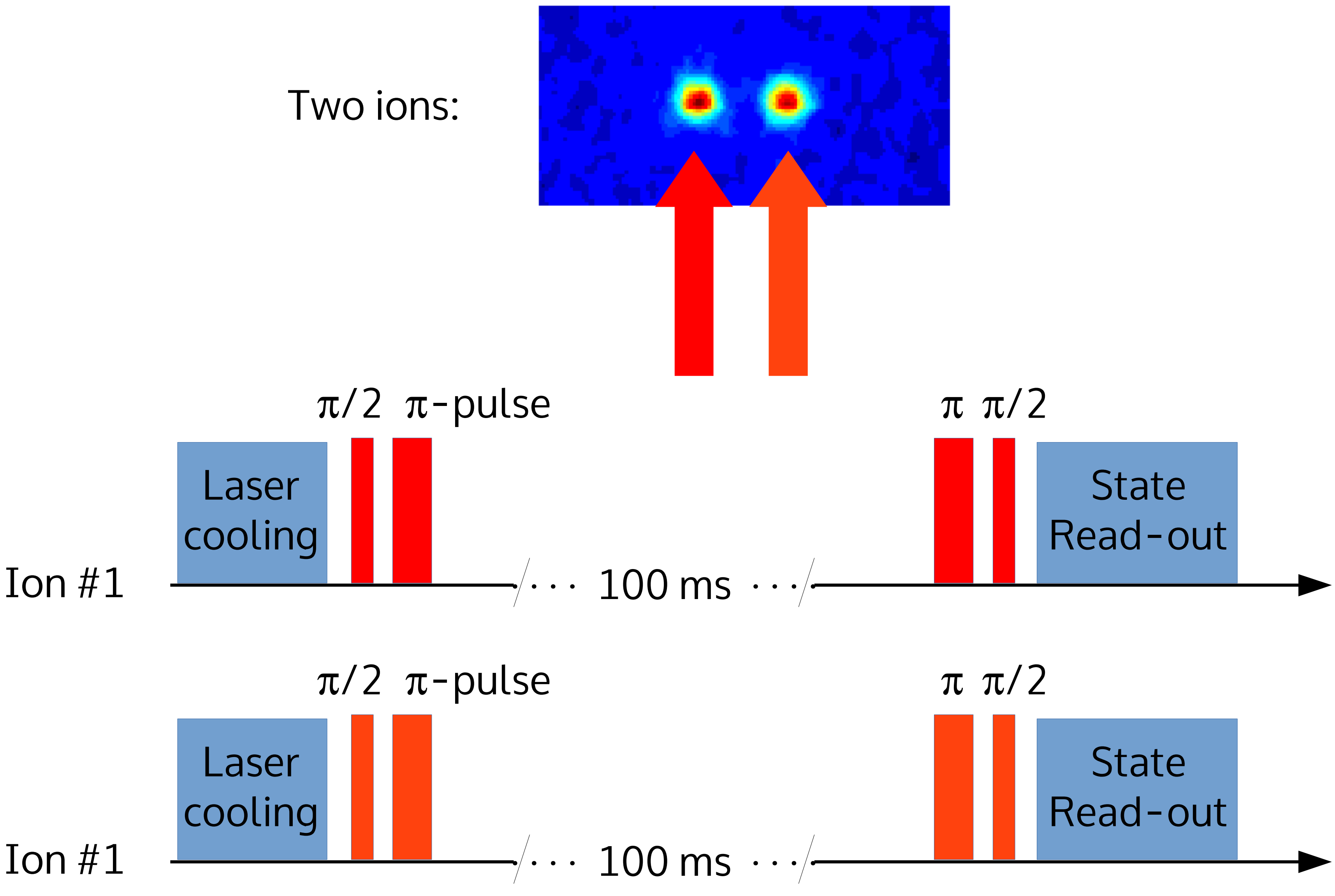
Magnetic field direction changes at the Earth rotates.



Electron wave-function rotates with respect to the Sun.

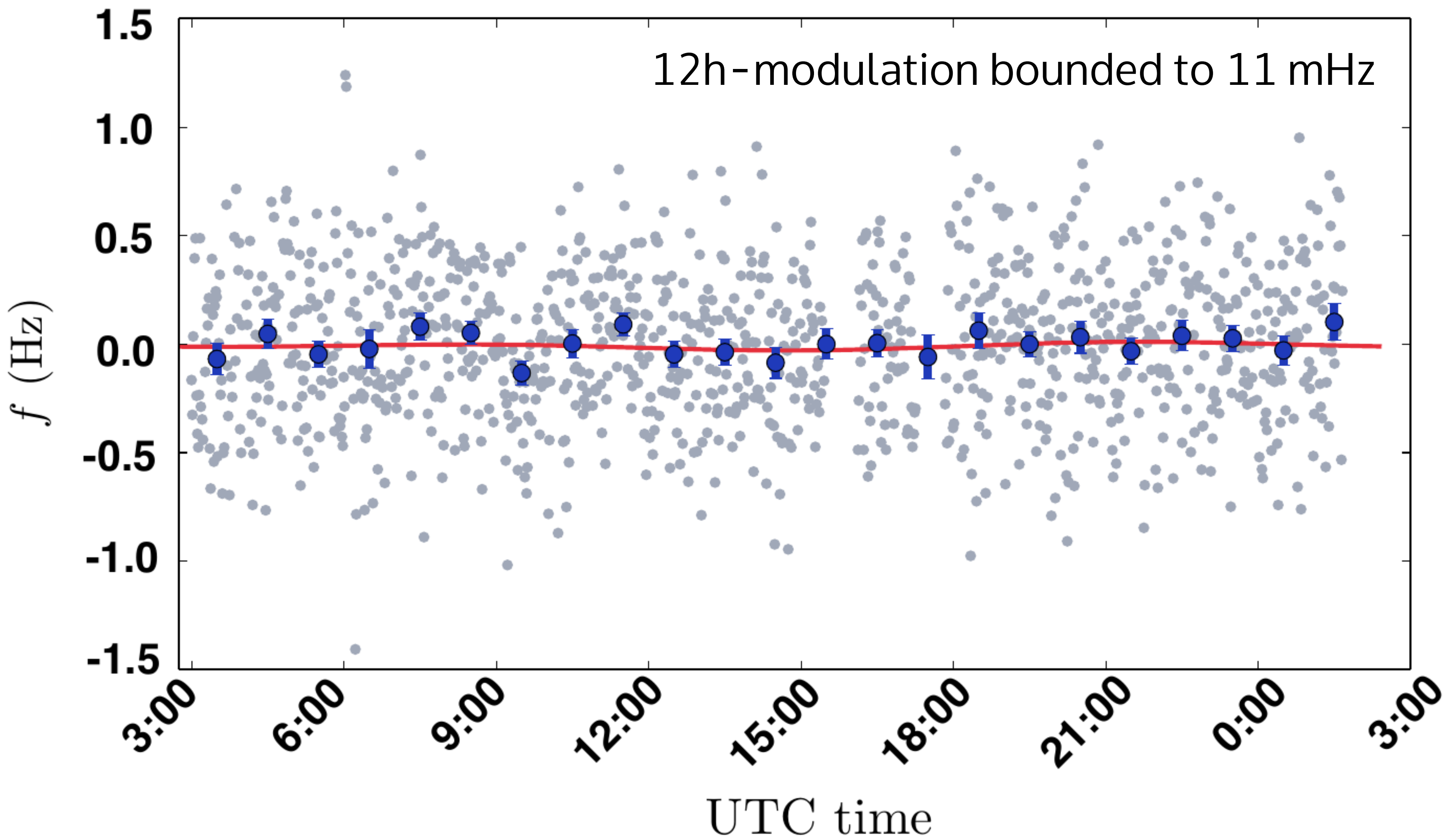
Lorentz-violation will modulate the energy shift correlated with the Earth's motion.

Measurement scheme



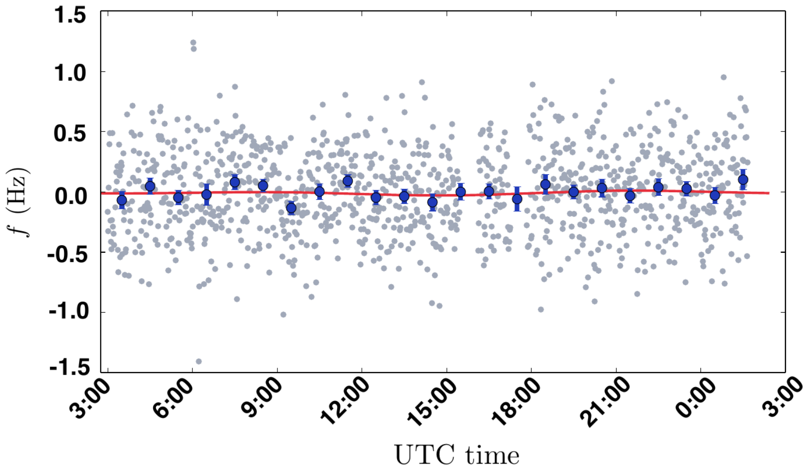
Data

Energy variations of a pair of $^{40}Ca^{+}$ ions on April 19th 2014



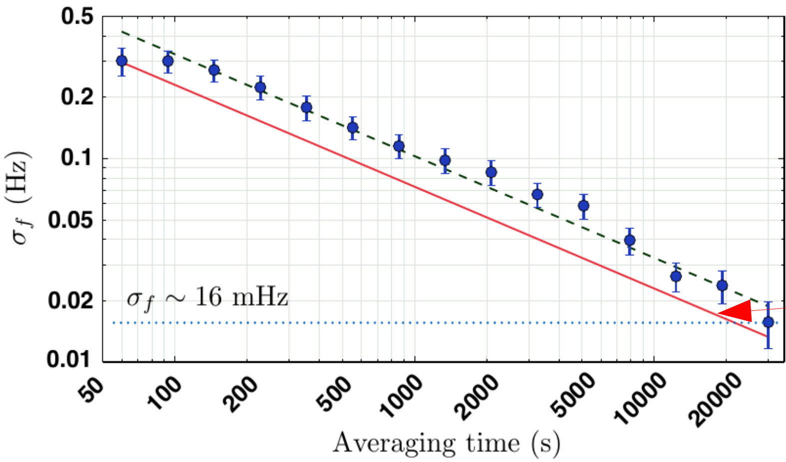
Results

Energy variations of a pair of $^{40}Ca^{+}$ ions on April 19th 2014



12h-modulation bounded to 11 mHz

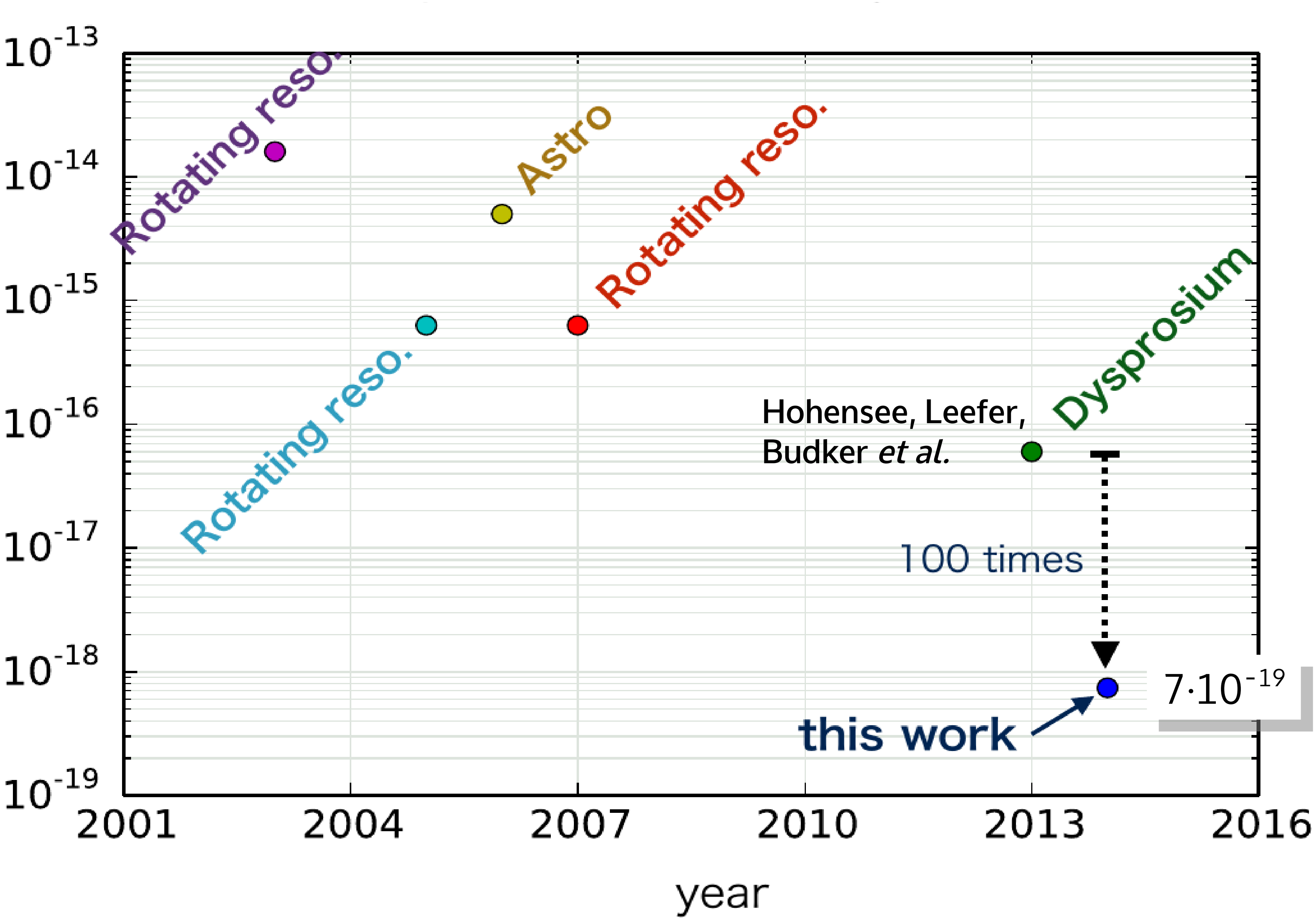
Error on the mean as a function of averaging time



Still averaging down, no signs of drifts

Expected quantum projection noise

Lorentz tests for the electron

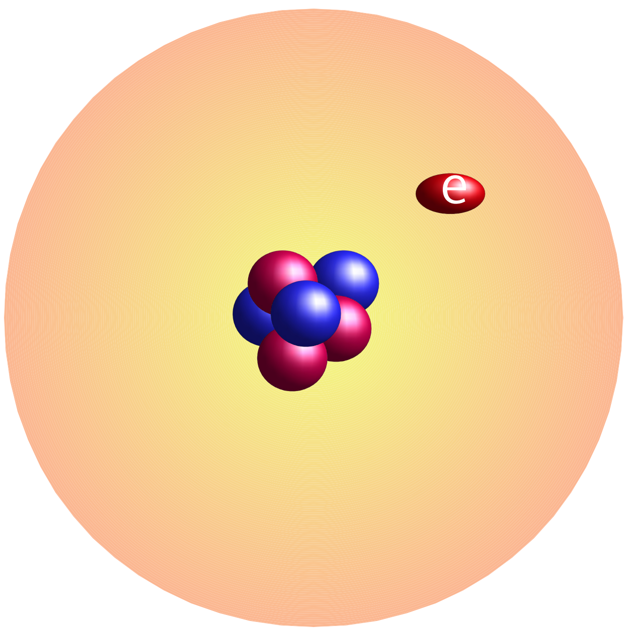


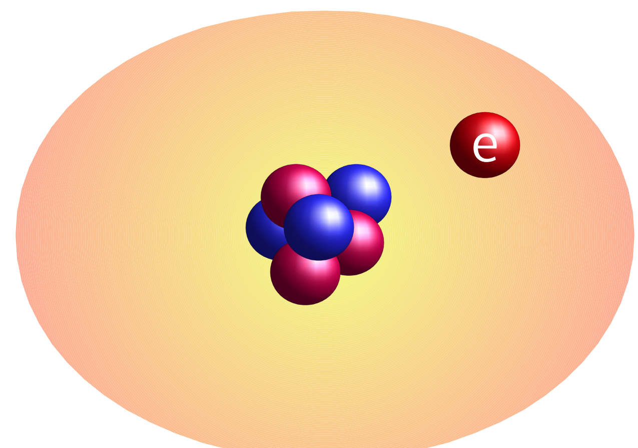
Interpretation

To analyze the experiment, we need to pick a reference.

Assumption: photon obeys Lorentz symmetry.
➡ any LI-signal is attributed to the electron

Or: electron obeys Lorentz symmetry
Coulomb potential asymmetric
➡ photon violates Lorentz symmetry

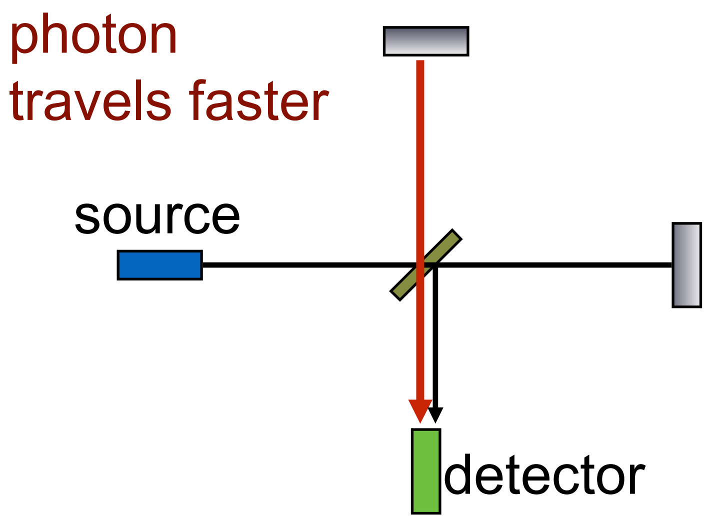


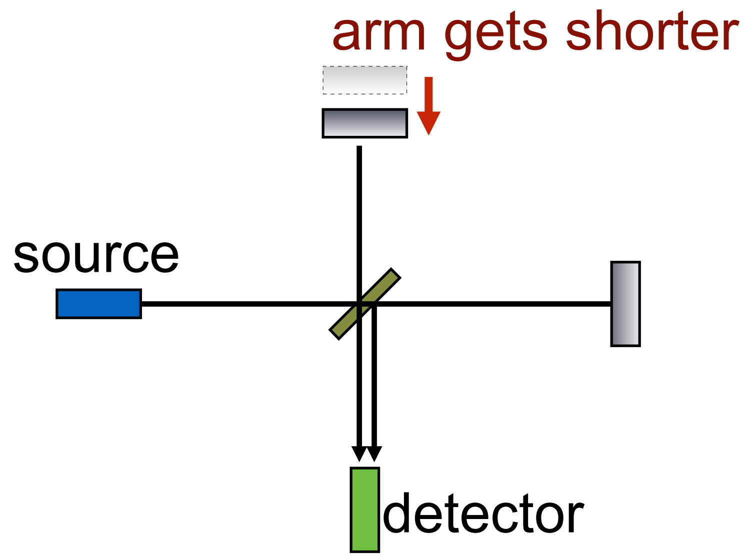


➡ We probe the difference between the electron and photon dispersion

Interpretation

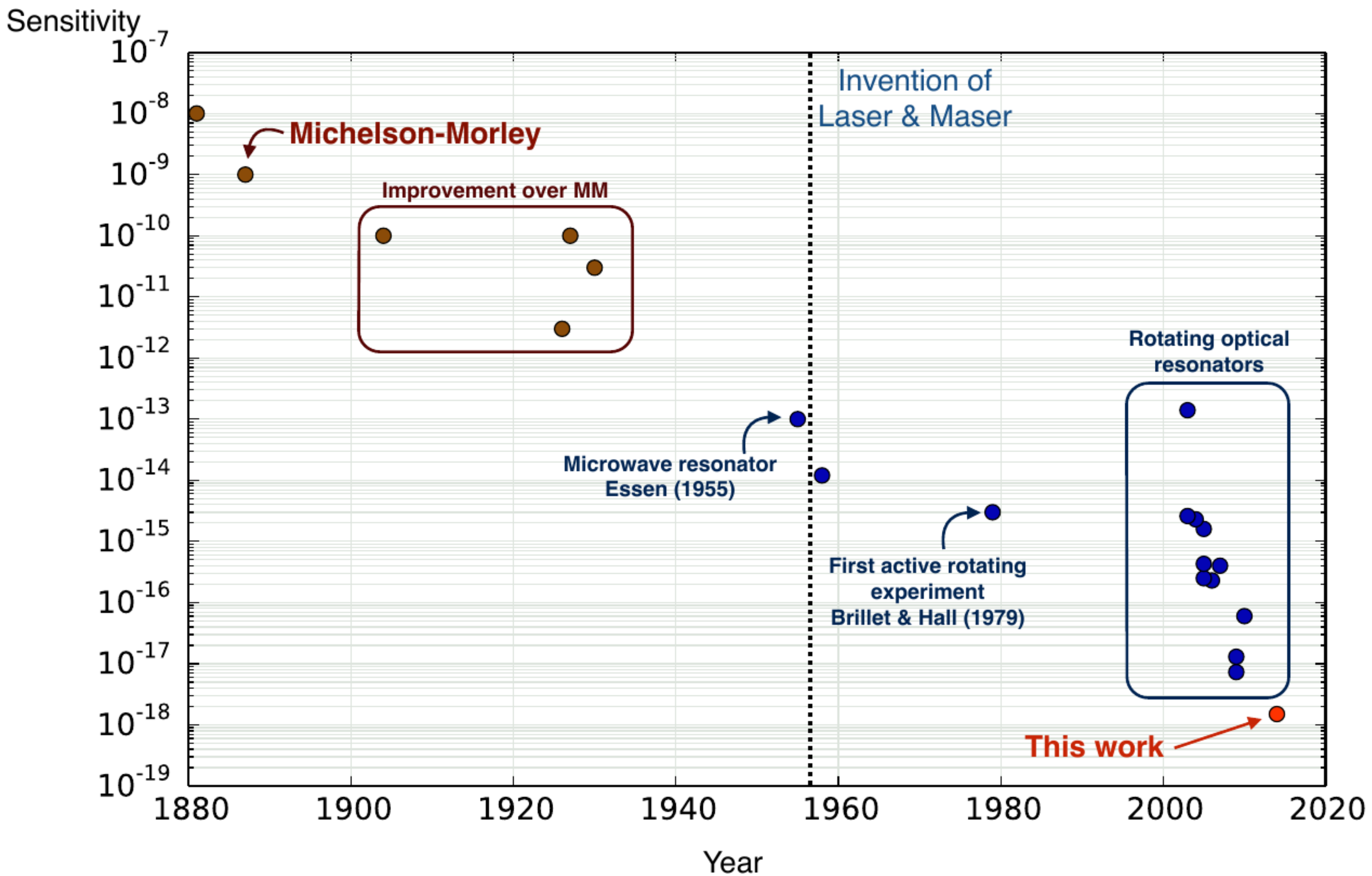
To analyze the experiment, we need to pick a reference.





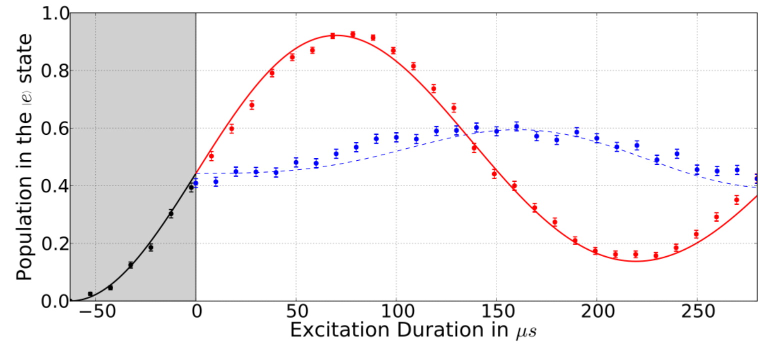
➡ Both experiments compare
the photon and the electron dispersion relation.

Lorentz invariance tests for light

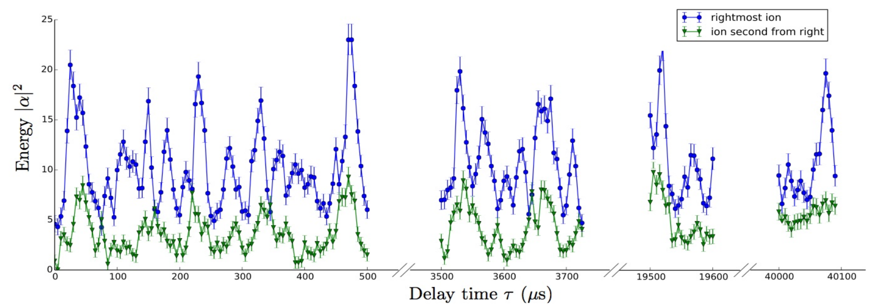


Summary

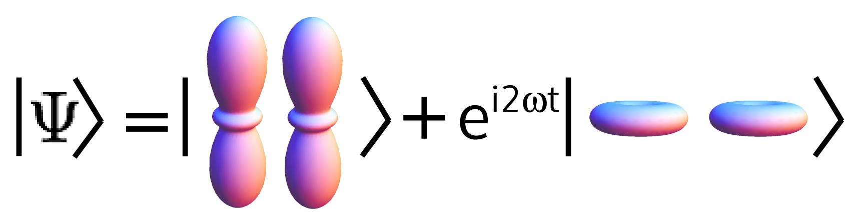
- Local Detection of Quantum Correlations



- Energy Transport in ion chains



- Michelson-Morley test with electrons confirms Lorentz symmetry at a level of $7{\cdot}10^{-19}$.



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