Quantum applications of ion trapping

Hartmut Häffner, UC Berkeley

1. Introduction to ion trapping
2. Quantum computing
3. Sources of decoherence
4. Scaling and quantum simulations
5. Quantum many-body physics
   and precision measurements

Plan

Lecture #1: Introduction
- Paul traps
- Laser ion-interaction

Lecture #2: Quantum computing
- Quantum gates
- Quantum state tomography

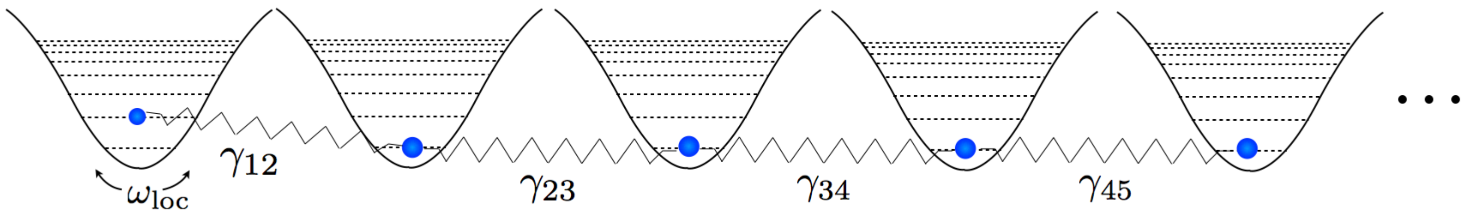
Lecture #3: Decoherence
- Qubit decoherence
- Scaling

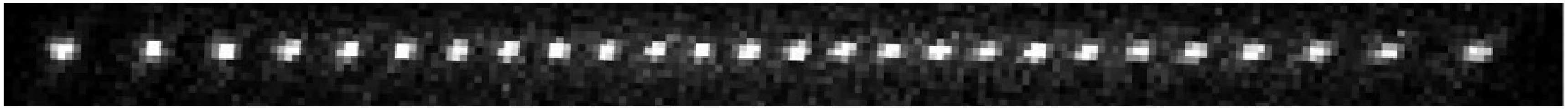
Lecture #4: Scaling and quantum simulation
- Scaling and anomalous heating
- Quantum simulation

Lecture #5: Applications
- Quantum many-body physics
- Precision measurements

Many-body physics

Oscillator chain of ions



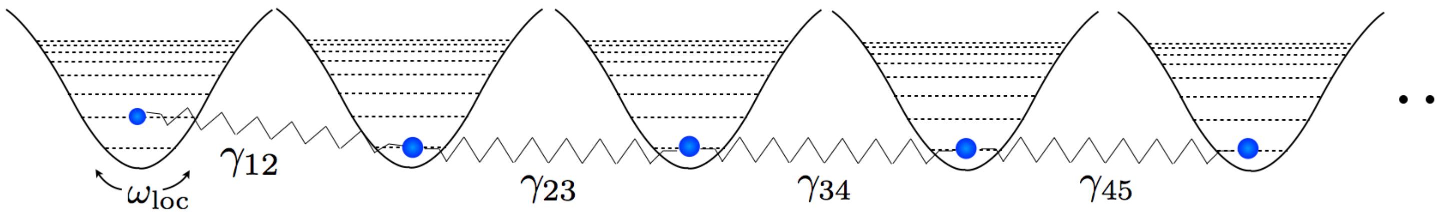


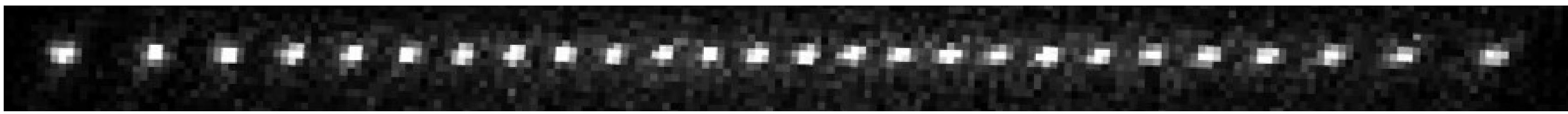
$$H = \hbar \sum \Delta_{\text{ion}} \sigma_i^z + \hbar \sum \omega_{\text{r},i} a_i^\dagger a_i + \sum t_{ij} \left(a_i^\dagger a_j + a_i a_j^\dagger \right)$$

$$+ \sum \lambda_i (\sigma_i^- a_i^\dagger + \sigma_i^+ a_i) + \sum \mu_i (\sigma_i^- + \sigma_i^+).$$

Many-body physics

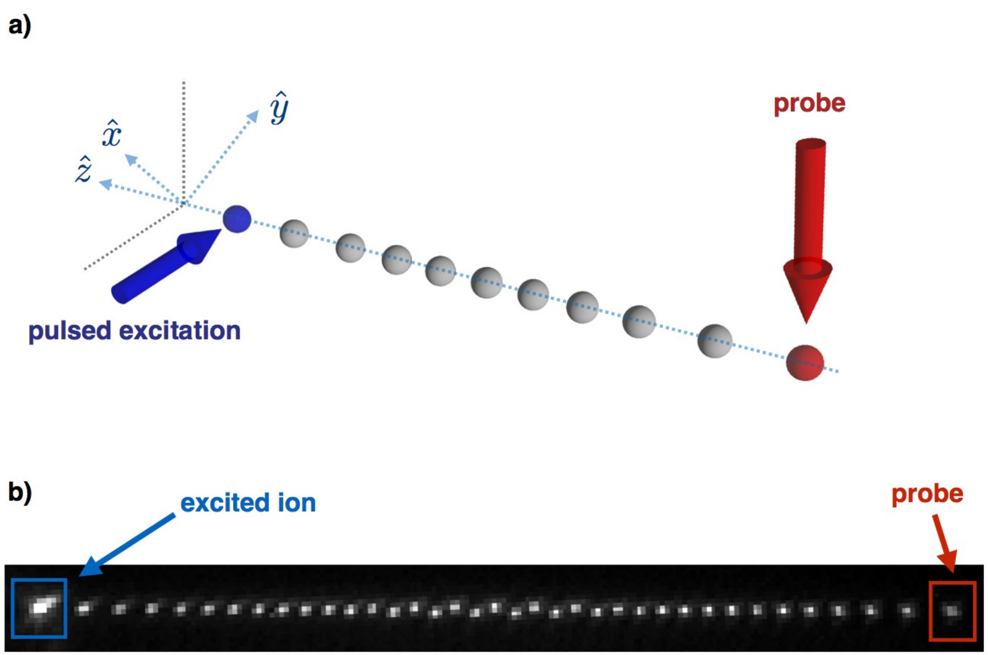
Oscillator chain of ions

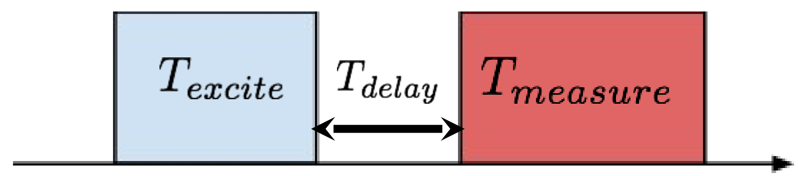




$$H = \hbar \sum \Delta_{\text{ion}} \sigma_i^z + \hbar \sum \omega_{\text{r},i} a_i^\dagger a_i + \sum \underbrace{t_{ij} \left(a_i^\dagger a_j + a_i a_j^\dagger \right)}_{\text{Coulomb interaction}}$$

Energy Transport in Ion Chains



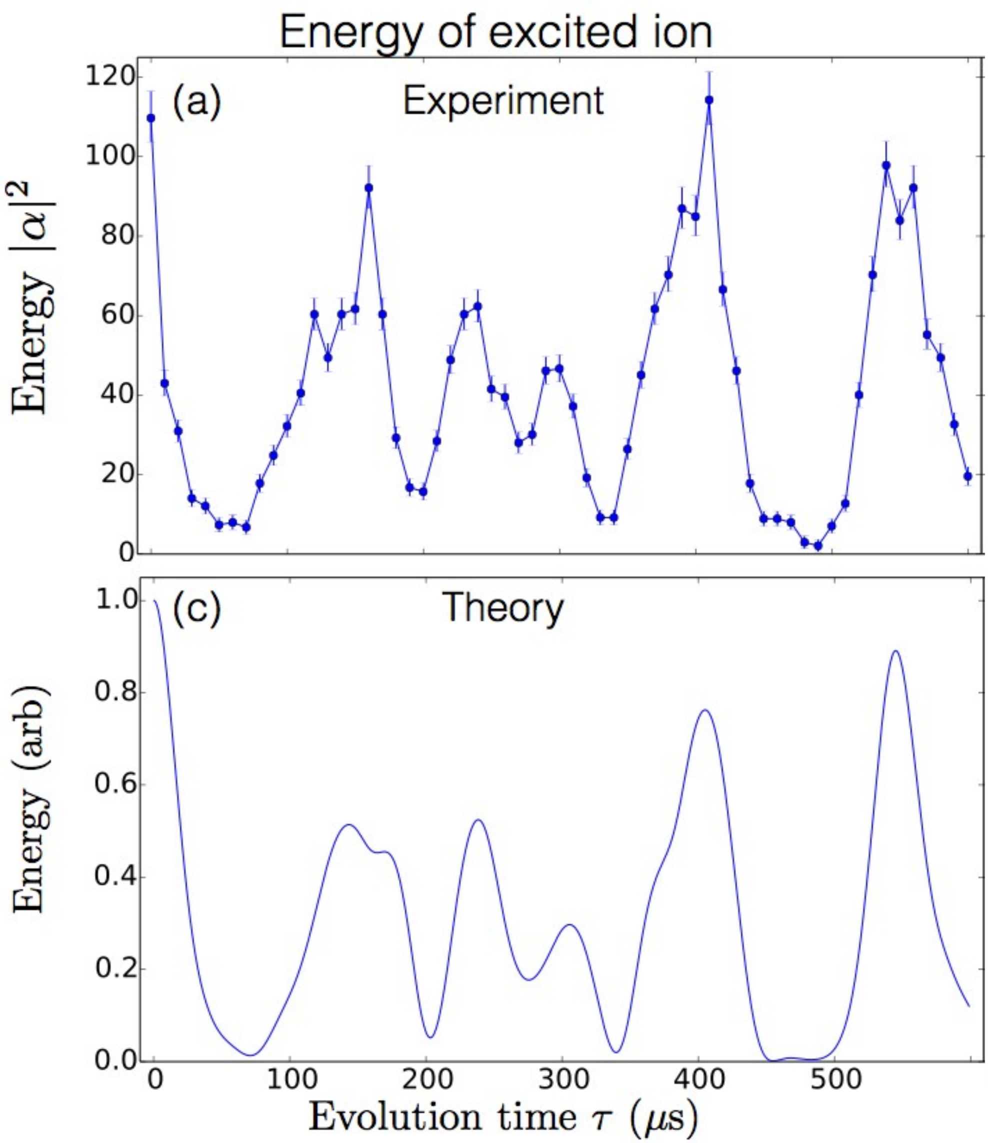


- Excite locally
- Let the system evolve
- Read out locally

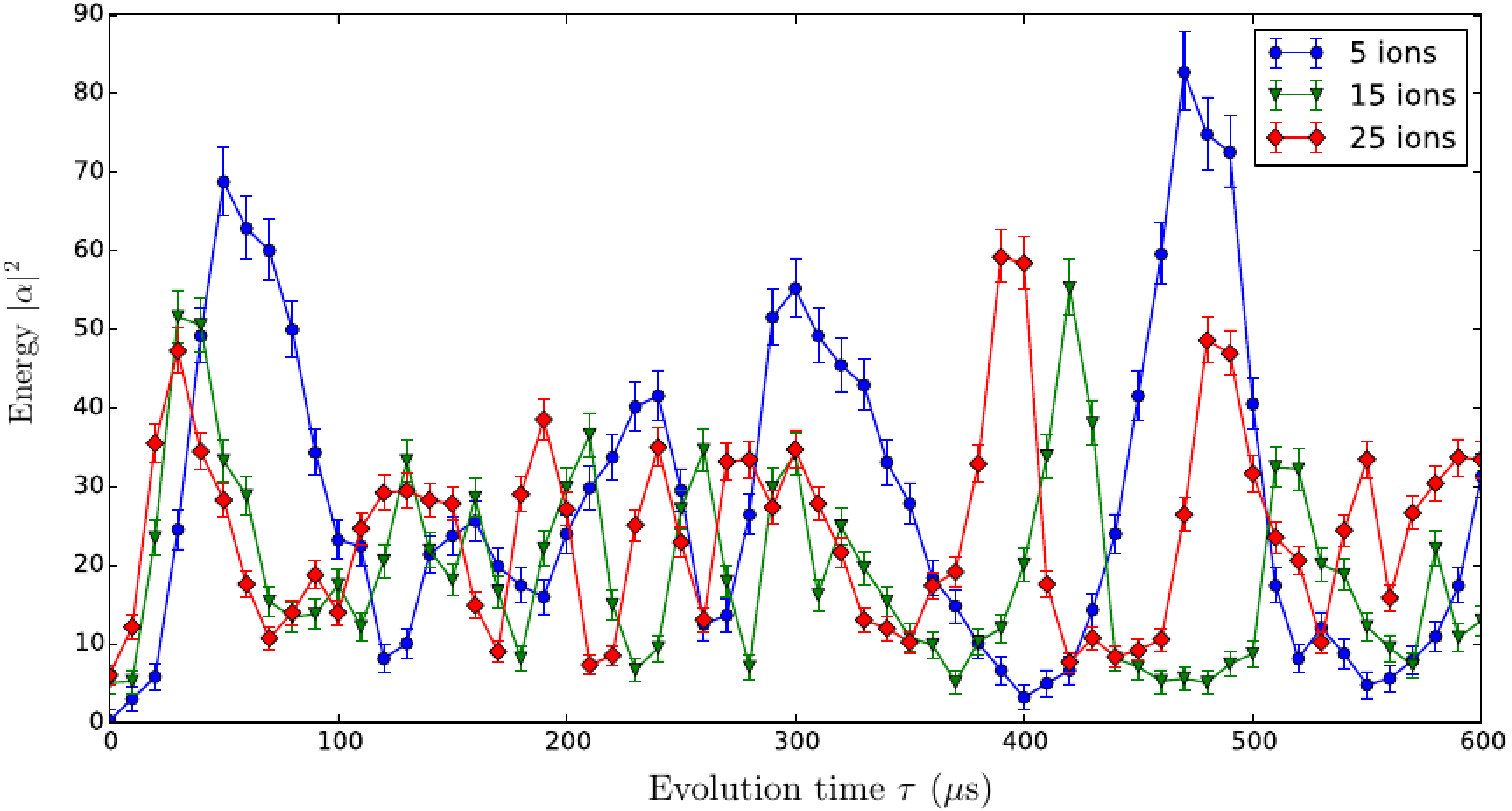
$$T_{\text{excite}} \ll T_{\text{coupling}}$$

$$T_{\text{measure}} \ll T_{\text{coupling}}$$

Theory vs Experiment for 5 ions

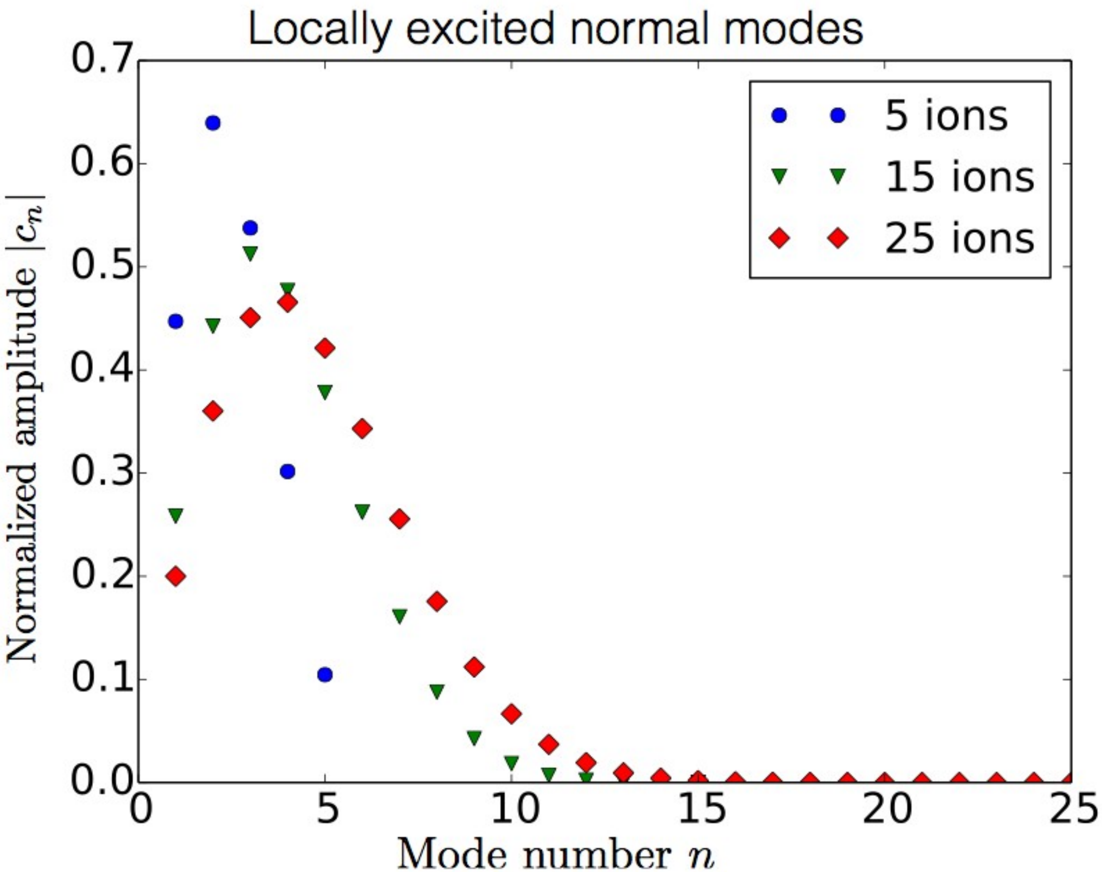


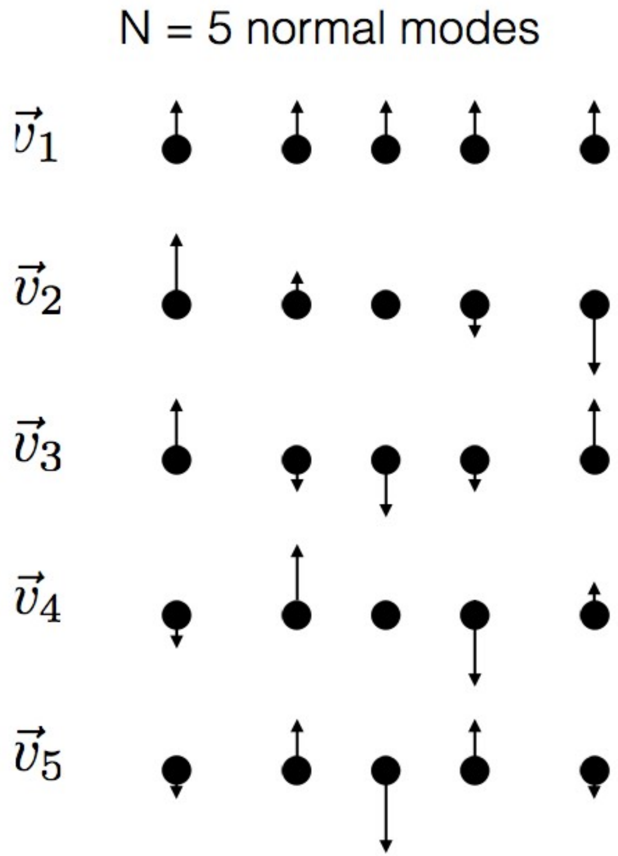
Ion number dependency



- Transport speed through the chain increases with the ion number

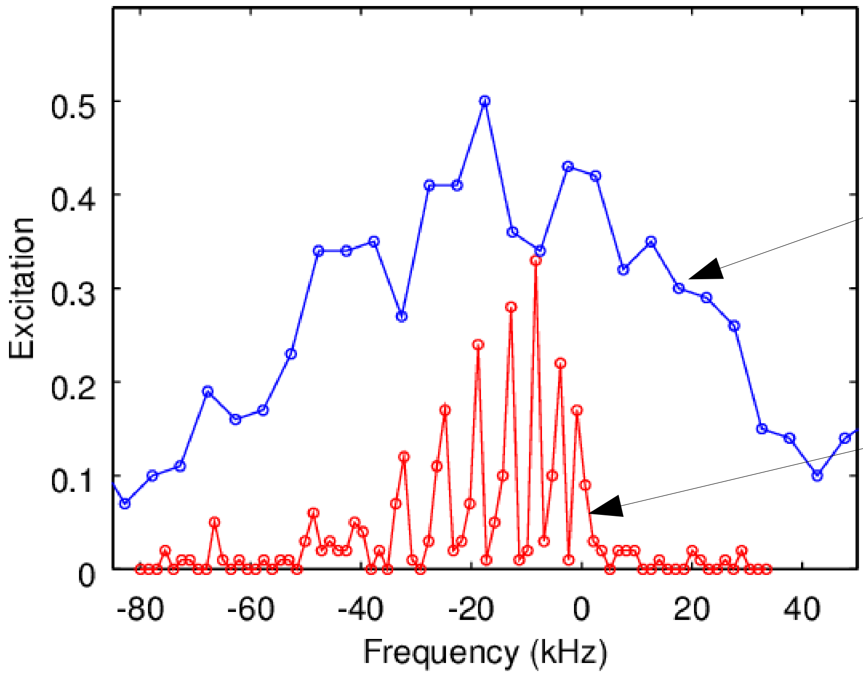
Normal Mode Decomposition





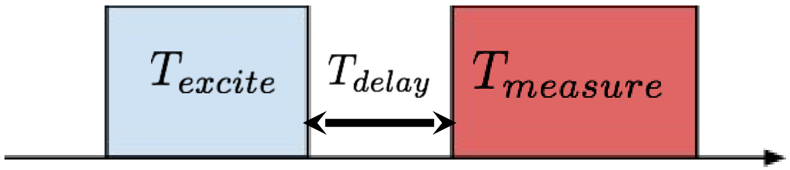
Key feature: all ions are in the same harmonic well

Energy Transport in Ion Chains



10 μs excitation

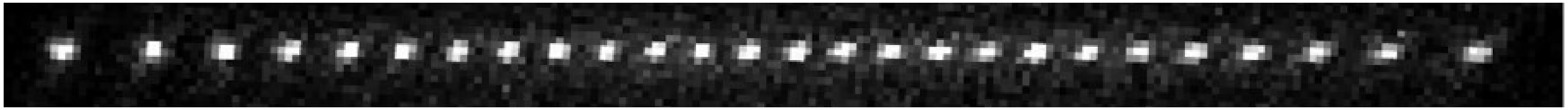
500 μs excitation

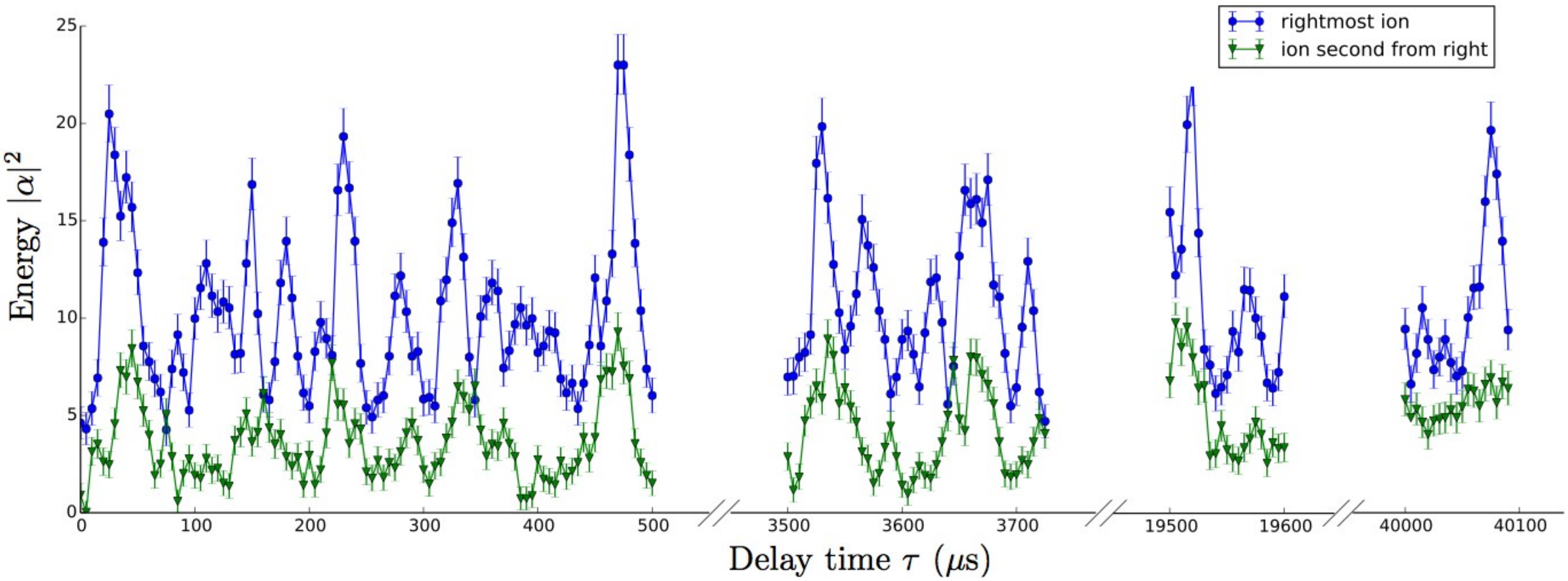


$$T_{\text{excite}} \ll T_{\text{coupling}}$$

$$T_{\text{measure}} \ll T_{\text{coupling}}$$

How closed is this (quantum) many-body system?

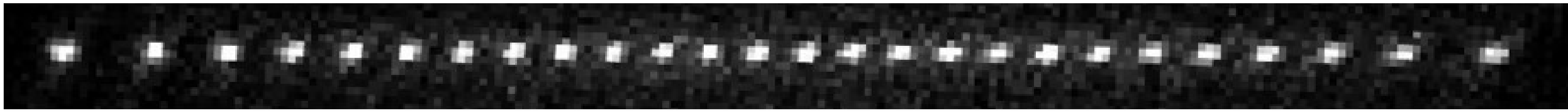




- Dynamics go on for very long time
- System well-isolated from the environment
- Add non-linearities in a controlled manner

Ramm *et al.*, NJP **16** 063062 (2014)

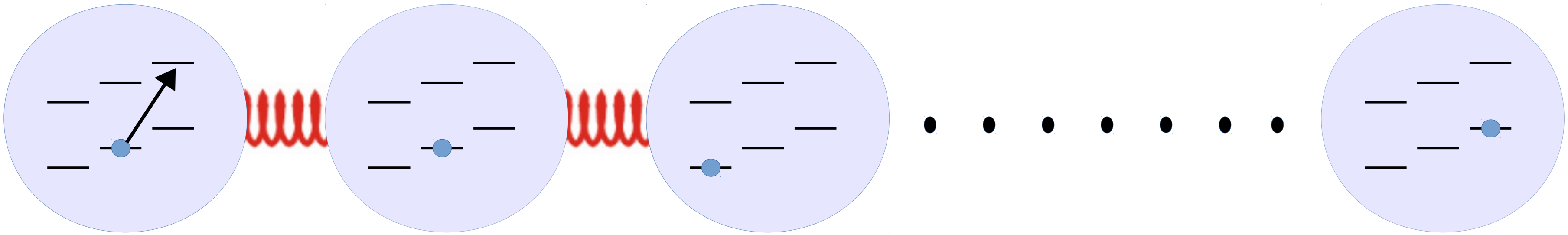
Extension to non-linear systems ?

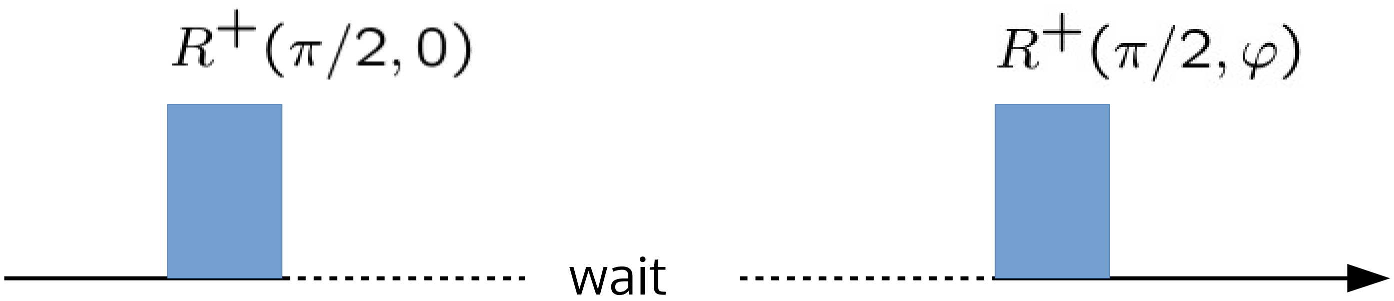


$$
\begin{aligned}
H \; = \; & \hbar \sum \Delta_{\text{ion}} \sigma_i^z + \hbar \sum \omega_{\text{r},i} a_i^\dagger a_i + \sum t_{ij} \left(a_i^\dagger a_j + a_i a_j^\dagger \right) \\
+ \; & \underbrace{\lambda_i (\sigma_i^- a_i + \sigma_i^+ a_i^\dagger)}_{\text{Blue sideband}}
\end{aligned}
$$

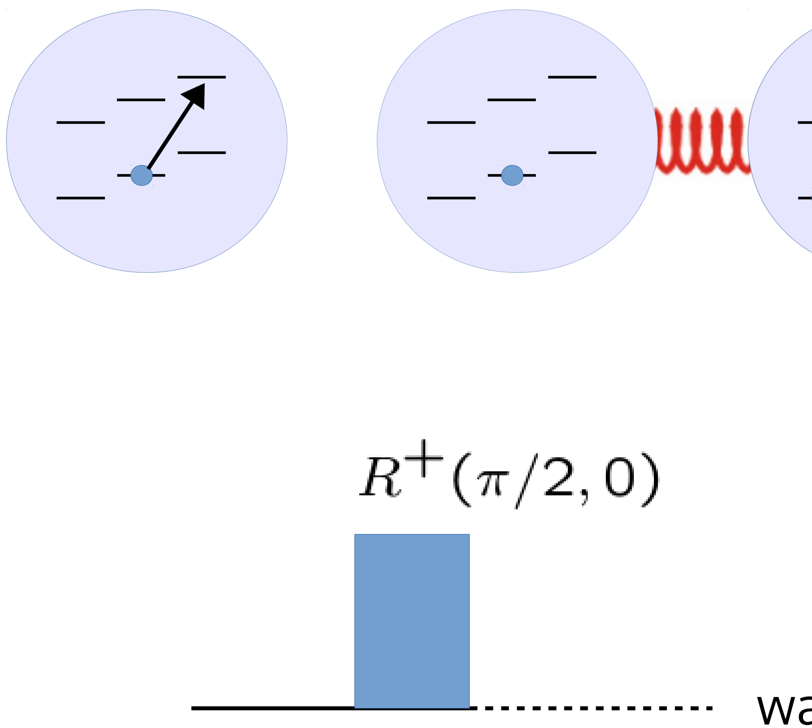
- How do quantum correlations propagate ?
- Study dynamics and equilibration in a closed system
- Spin-impurities in crystals, dissipation and decoherence, quantum phase transitions

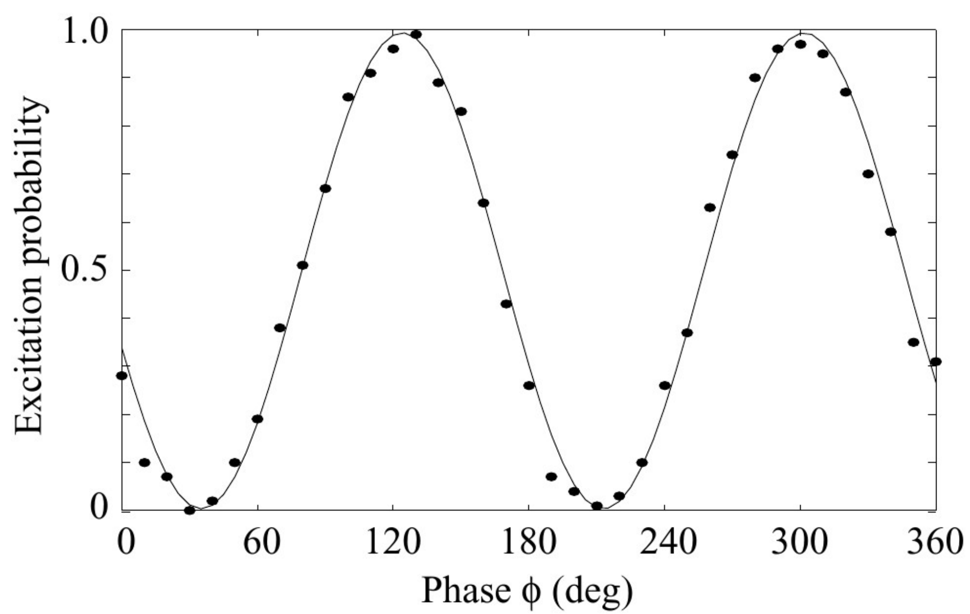
Generating and detecting quantum correlations





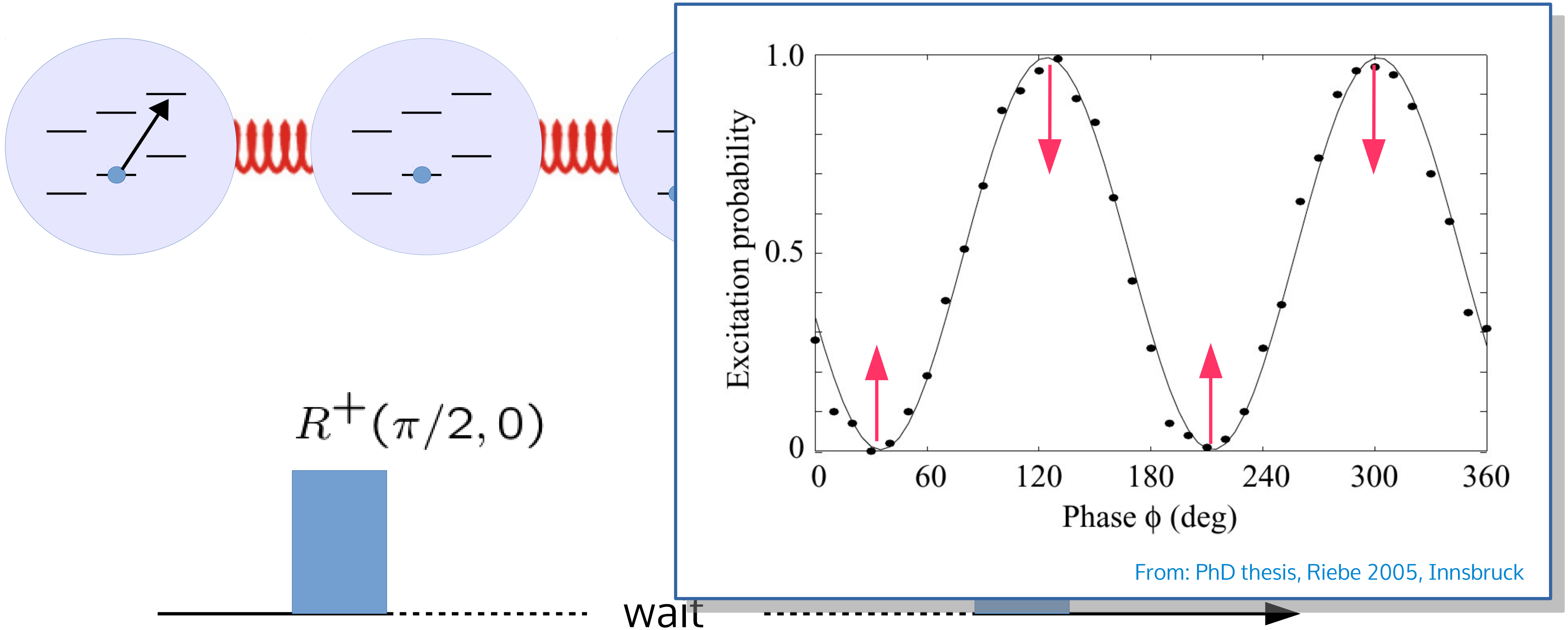
Generating and detecting quantum correlations





From: PhD thesis, Riebe 2005, Innsbruck

Generating and detecting quantum correlations



From: PhD thesis, Riebe 2005, Innsbruck

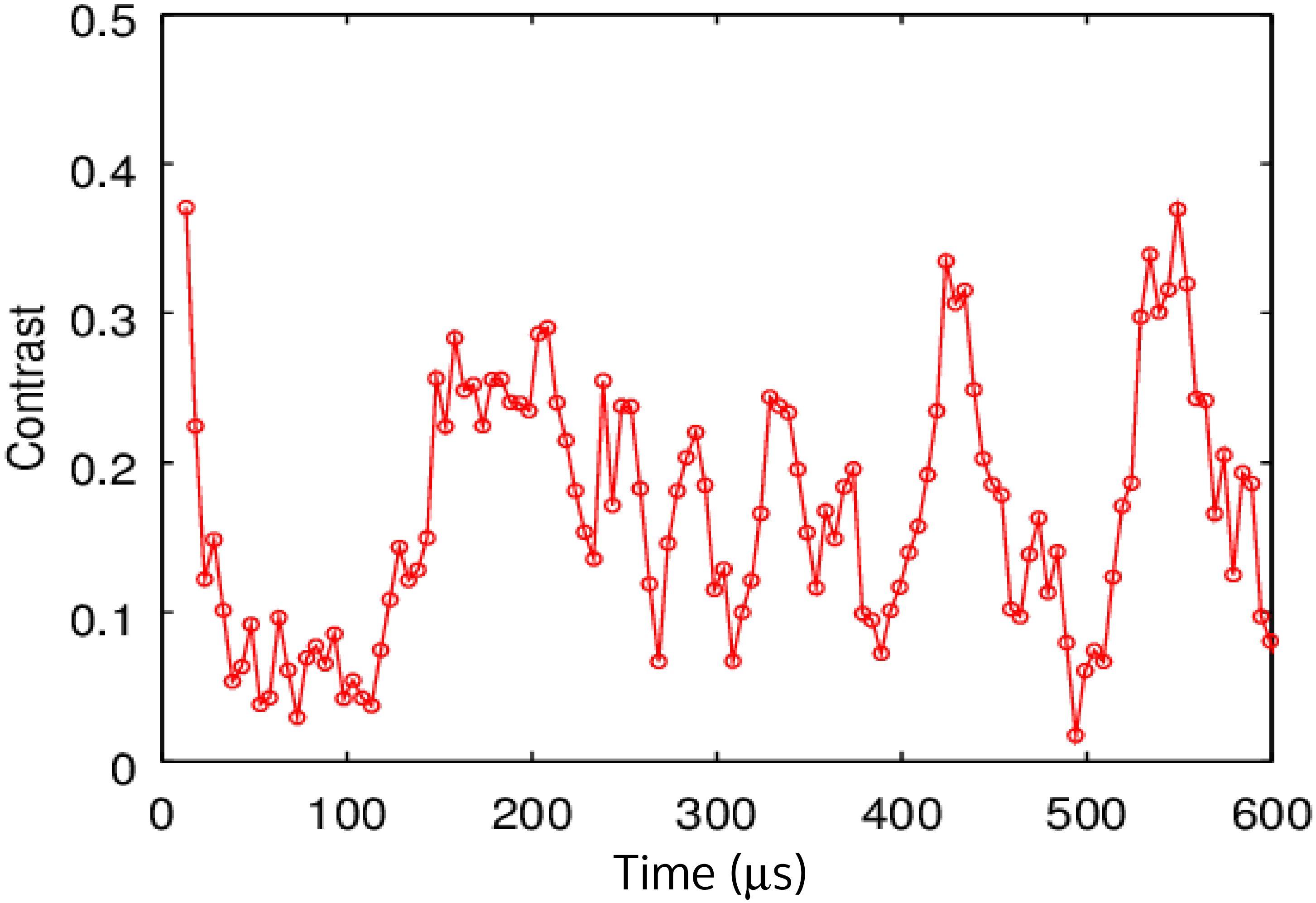
Phase contrast proves quantum correlations between the electronic state and the (local) motion of the ion.

Local detection of quantum correlations:

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

Dynamics of quantum correlations

Revivals of quantum correlations in a 35-ion chain



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High resolution spectroscopy

Optical frequency standards

Clock ions: Sr^+, Yb^+, Hg^+, Al^+,...

$$\frac{\delta\omega_0}{\omega_0} \approx 10^{-16}$$

Quantum information processing

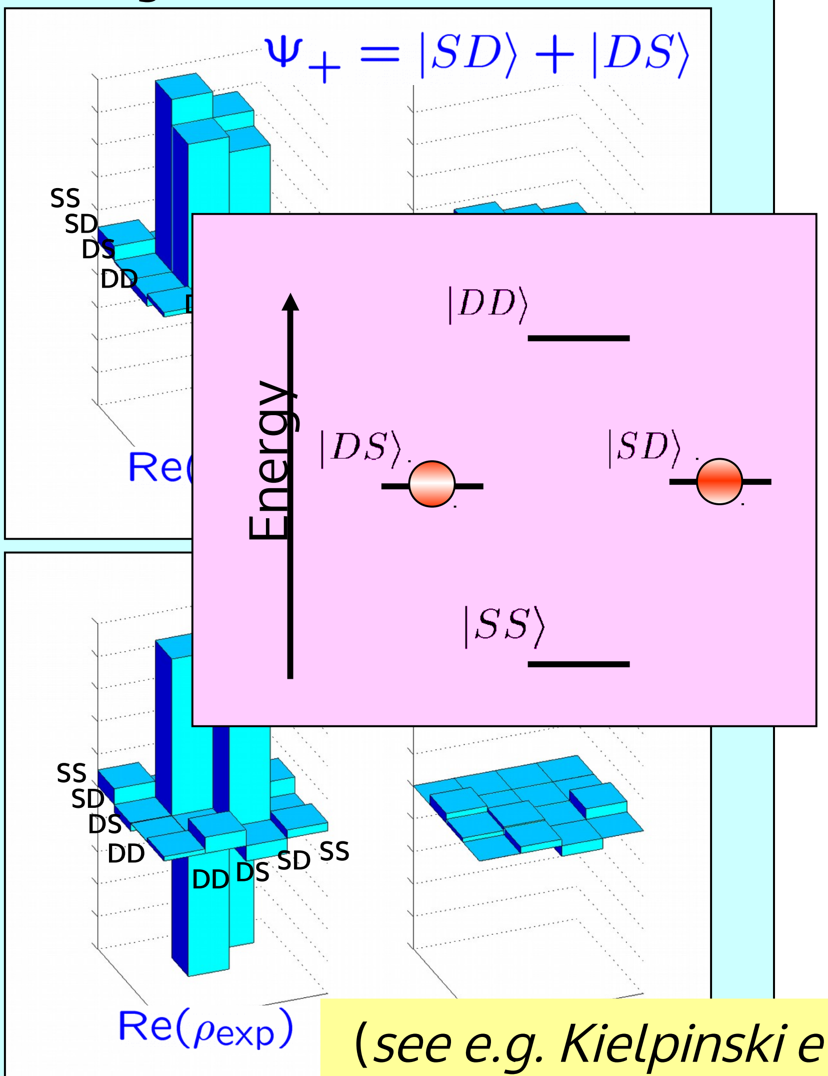
- perfect quantum control
- entanglement
- fundamental gates

Using entanglement to improve metrology

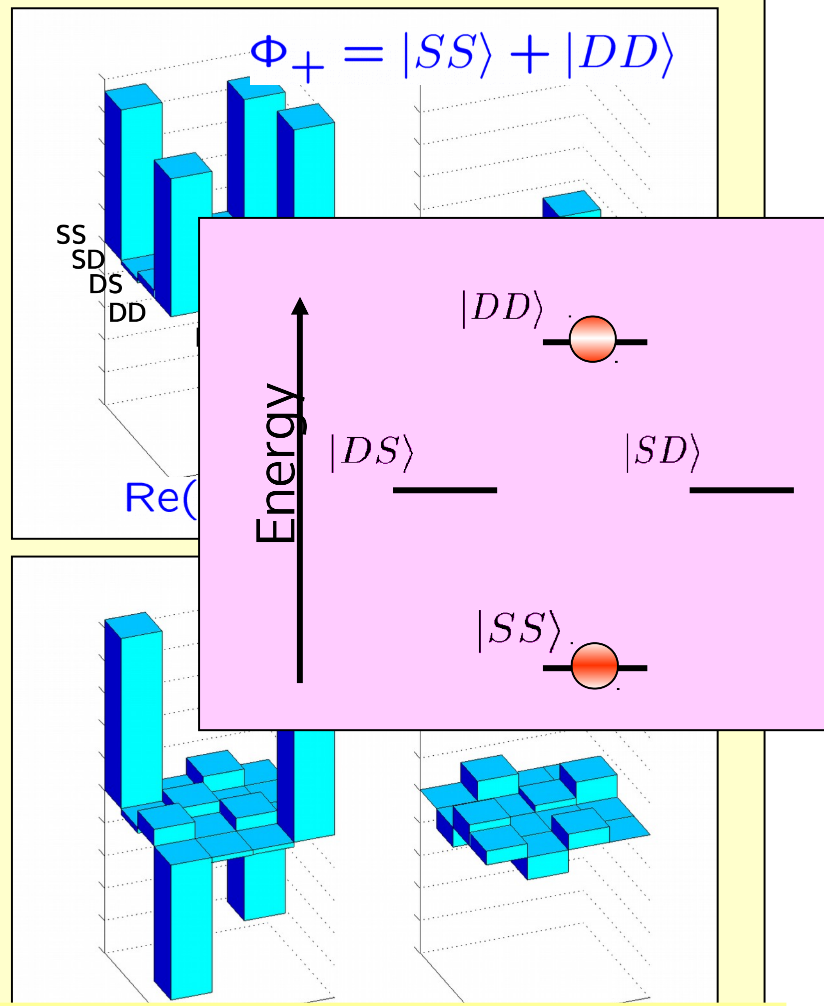
- Improved S/N ratio
  J. J. Bollinger *et al*, Phys. Rev. A **54**, 4649 (1996)
- Read out with quantum logic
  P.O.Schmidt *et al.*, Science **309**, 749 (2005)
- Spectroscopy with decoherence free subspaces
  C. F. Roos *et al.*, Nature **443**, 316 (2006)

Taking advantage of correlated noise

long lived (~ 1000 ms)



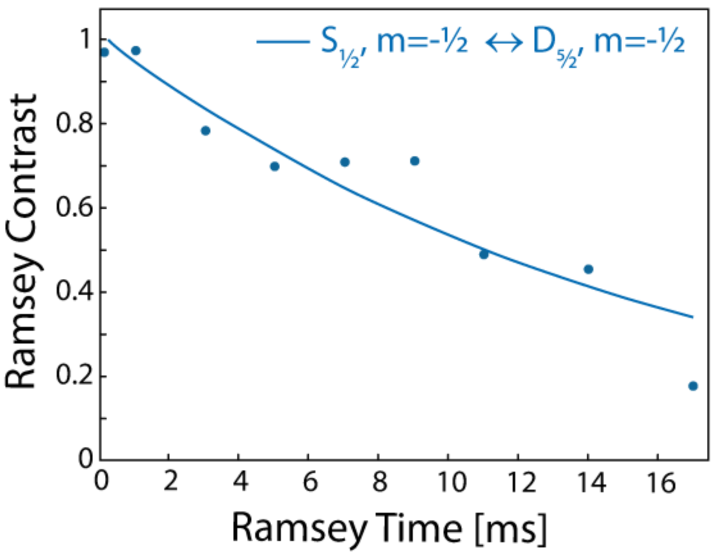
short lived (~ ms)



(*see e.g. Kielpinski et al.,Science **291**, 1013-1015 (2001)*)

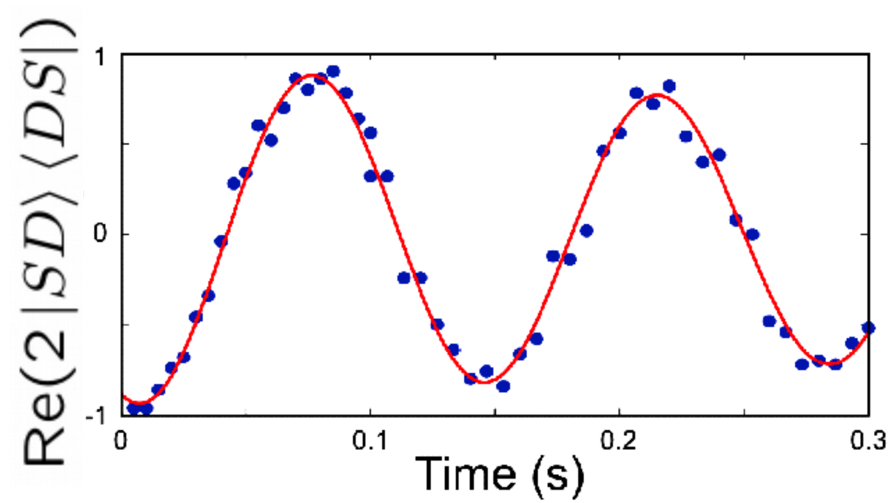
Decoherence-free subspaces

Physical Qubit
Ramsey Experiment



τ= 16 ms

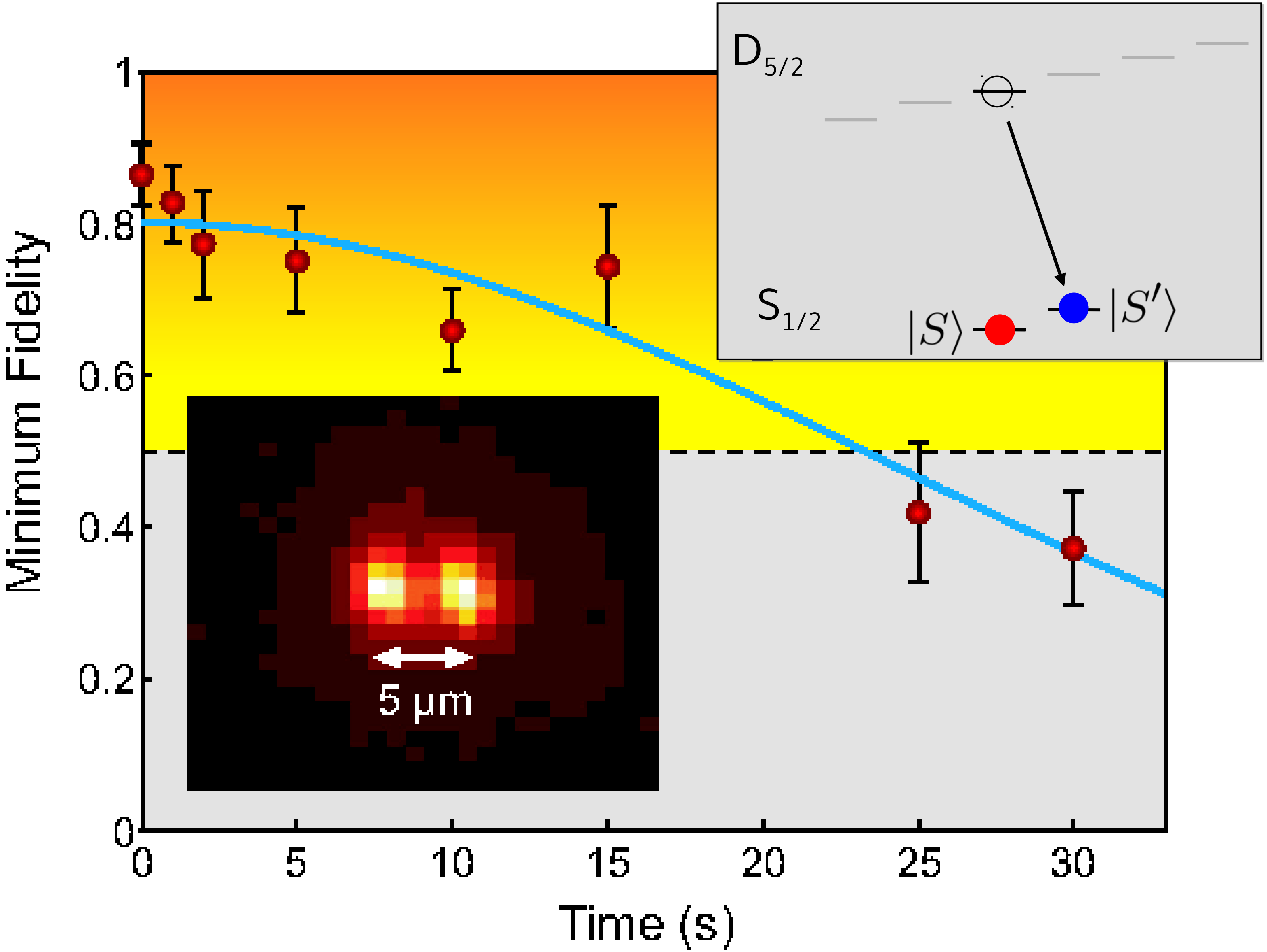
Logical Qubit
Parity Oscillations



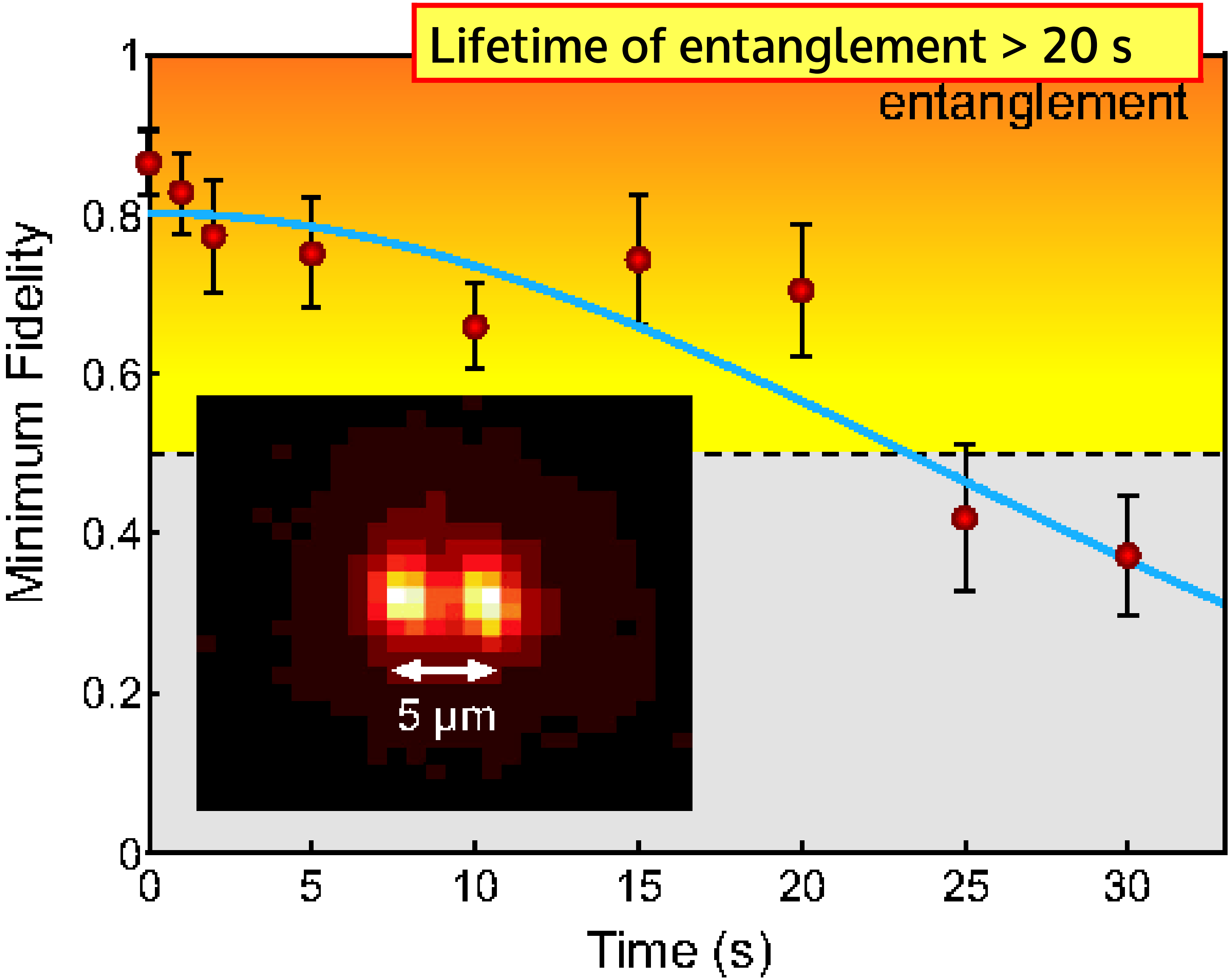
τ= 1050 ms

C.F. Roos et al., PRL 92, 220402 (2004).

Robust entanglement

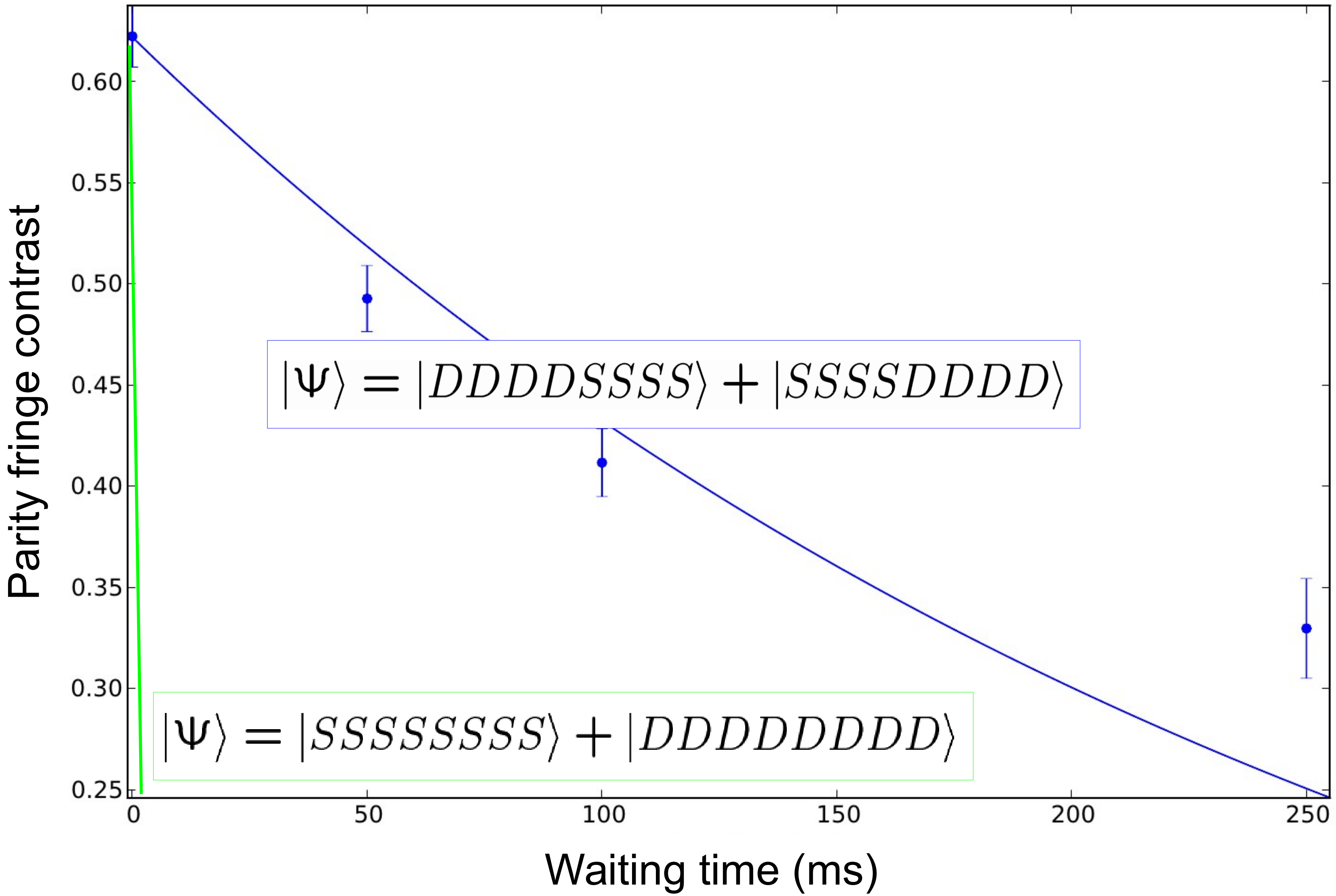


Robust entanglement

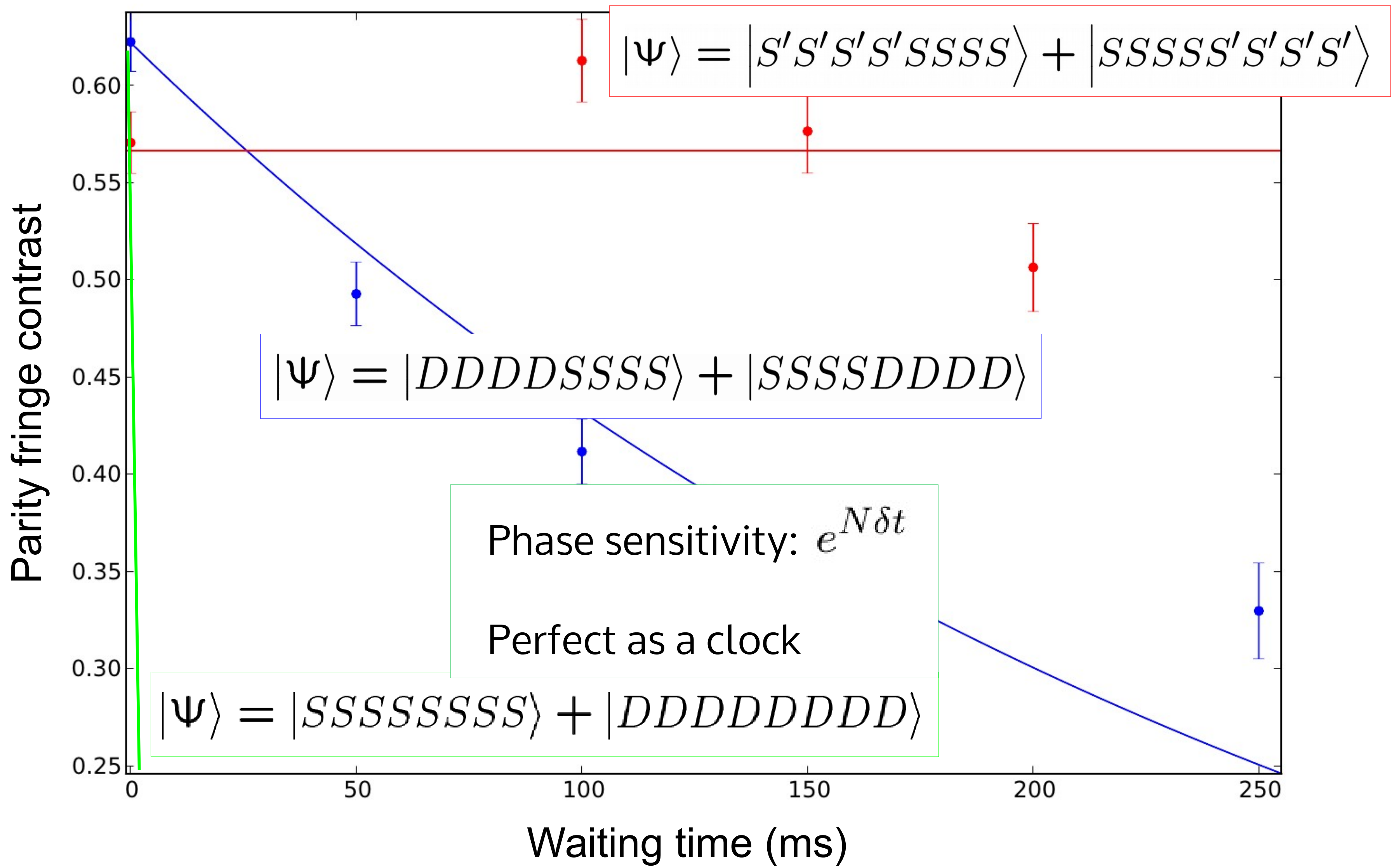


H. Häffner et al., App. Phys. B **81** 151 (2005).

Robust entanglement

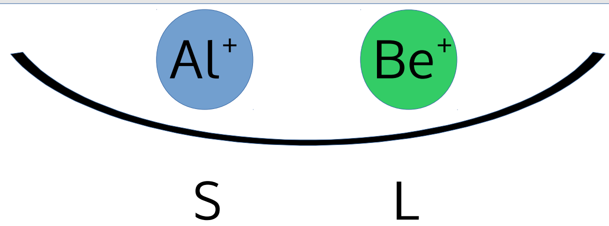


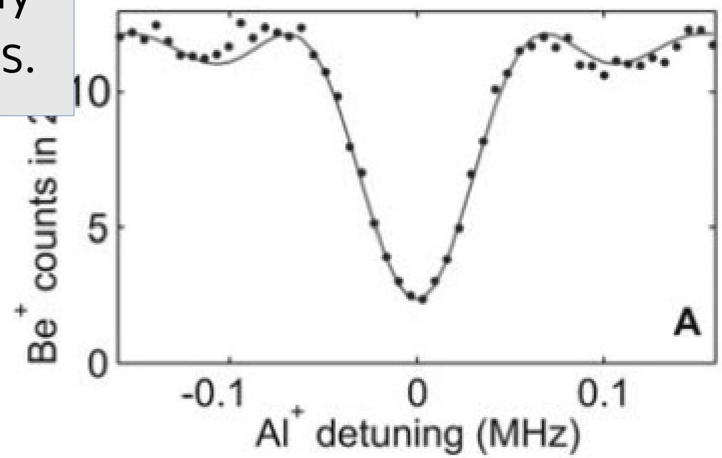
Robust entanglement

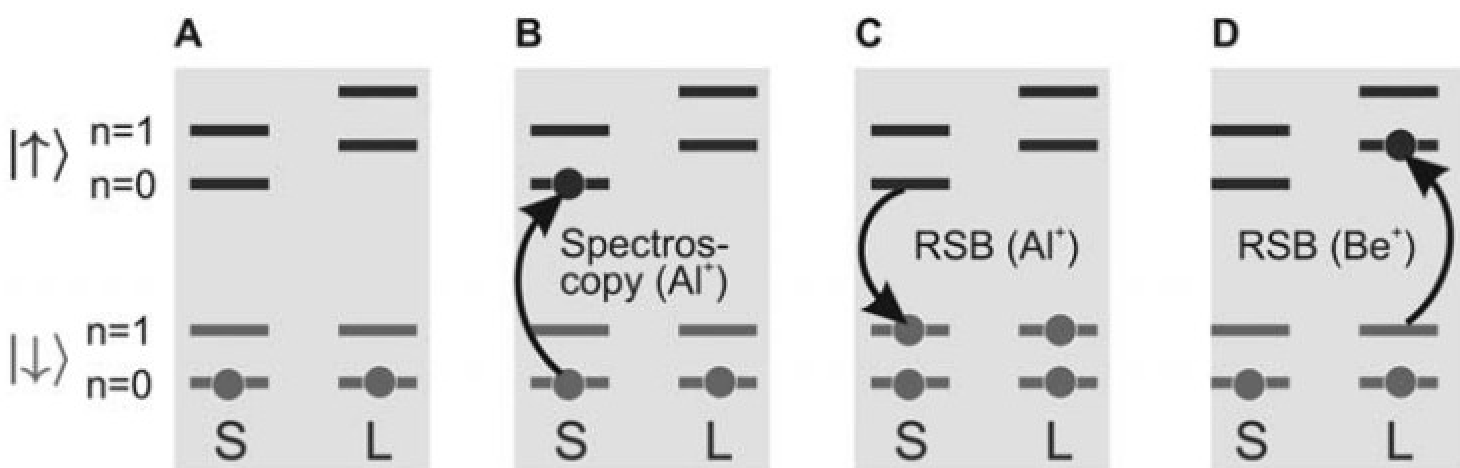


Quantum logic spectroscopy

Can do measurements on almost any ion species, including molecular ions.

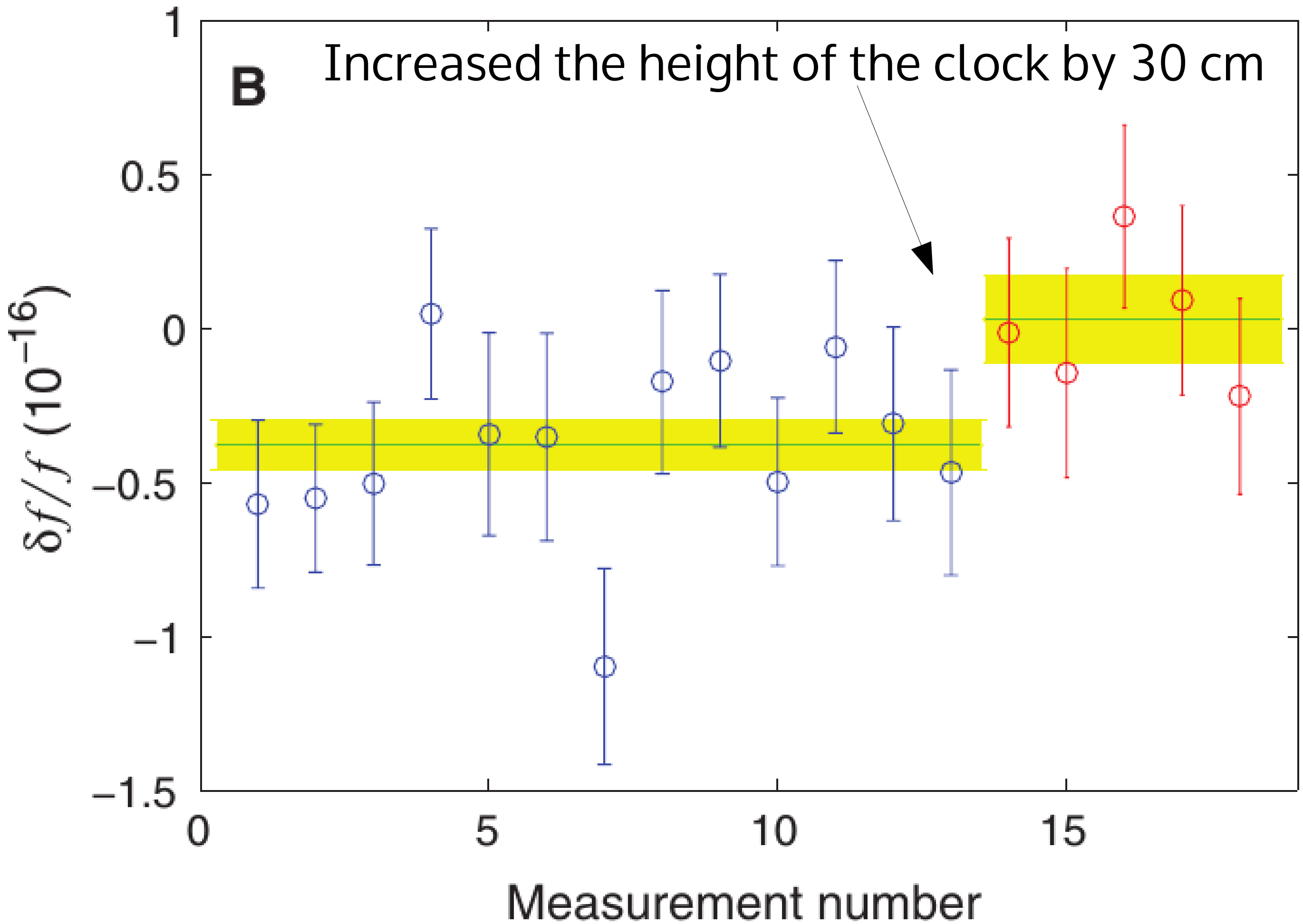






P. O. Schmidt *et al.*,, Science **309**, 749-752 (2005).

Testing general relativity



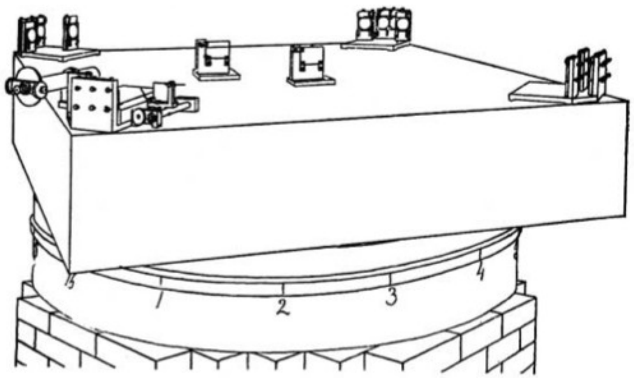
C.W. Chou *et al.*, Science **329**, 1630 (2010).

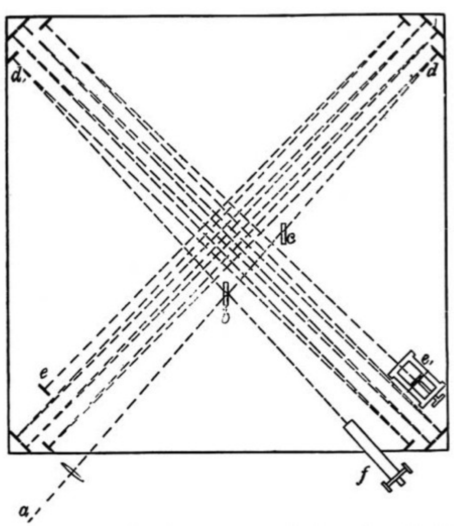
Testing relativity

Another test of relativity with tools from quantum information ….

A most famous null experiment

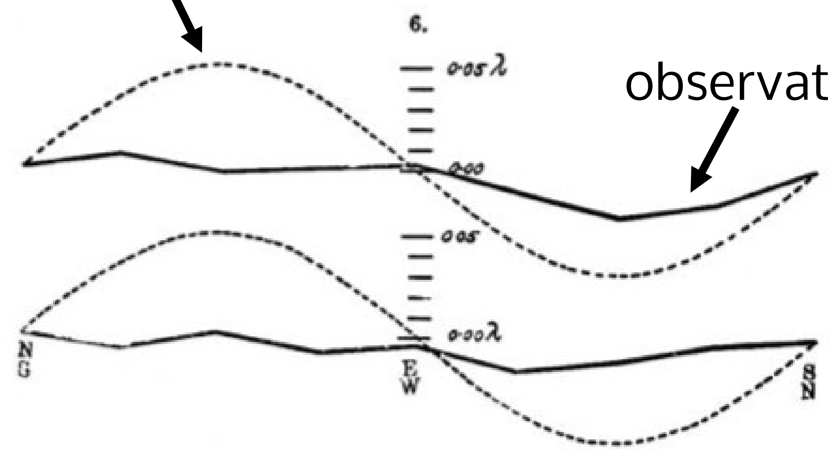
Test for “aether”.





expected fringe shift due to aether

observation



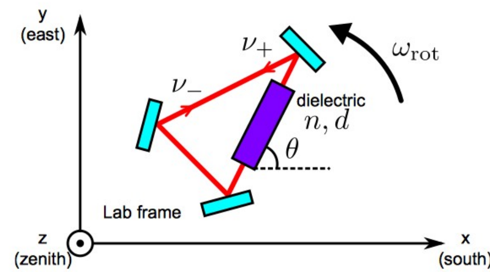
Michelson-Morley experiment
confirms Lorentz symmetry to 10^{-9}

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

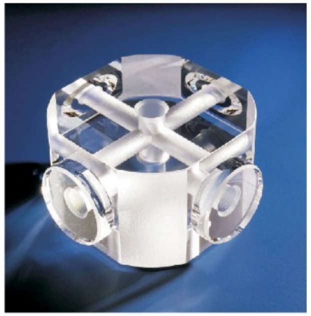
Modern tests of Lorentz symmetry

Accelerator

Optical cavities

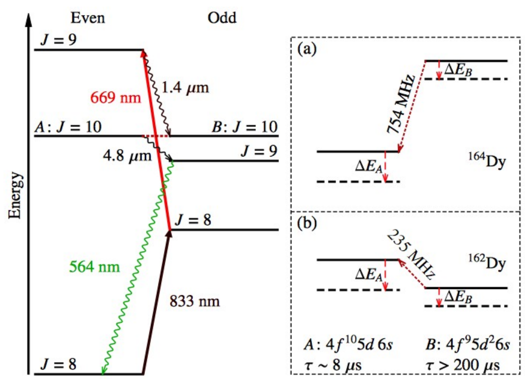


Michimura (2013)



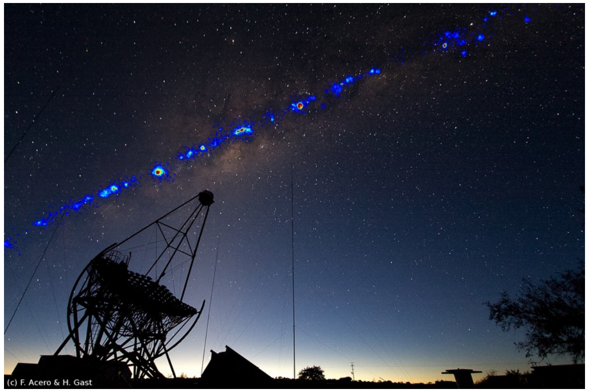
Herrmann (2009)

Spectroscopy



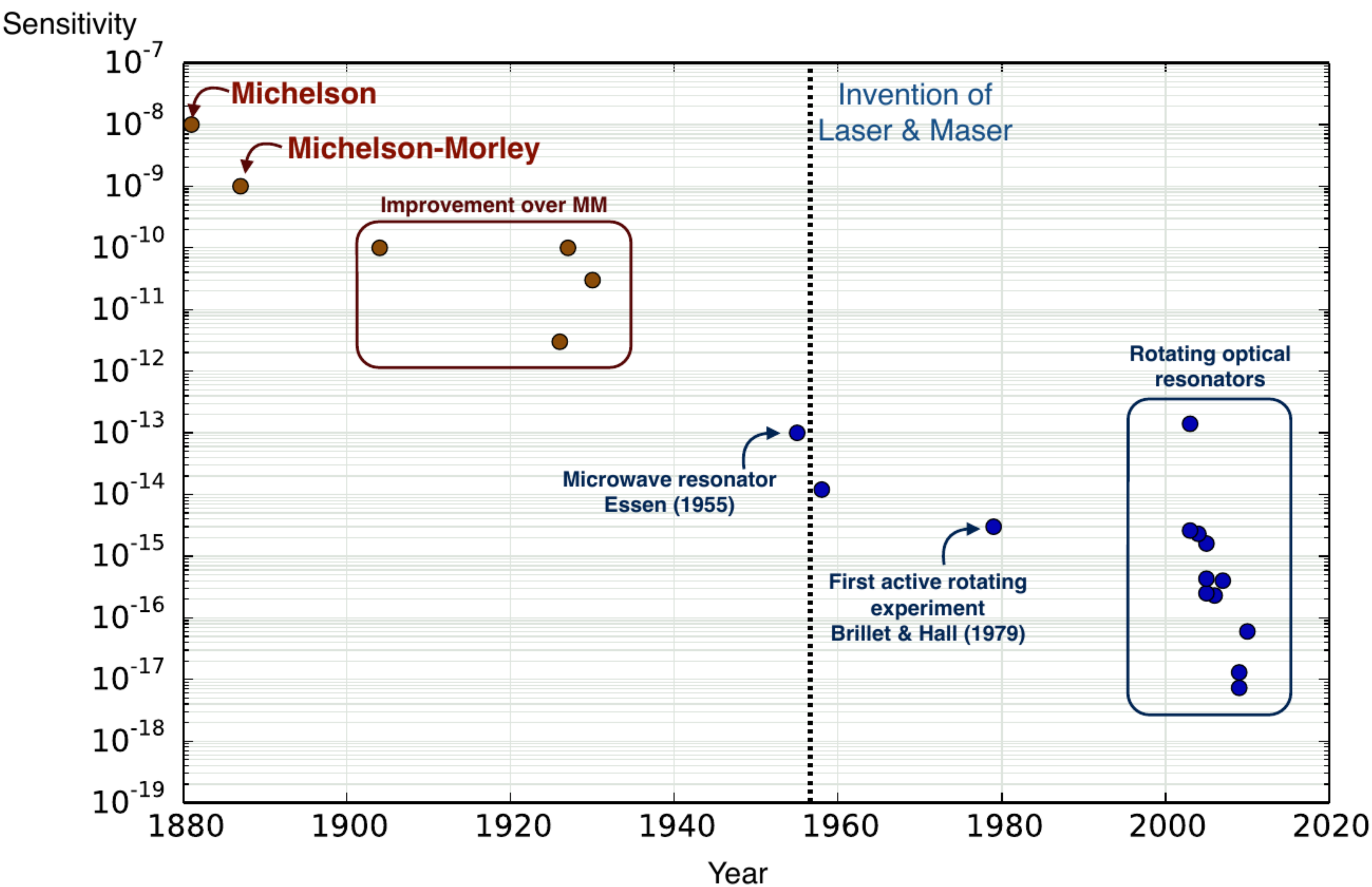
Hughes-Drever (1960/1961)
Hohensee (2013)

Astrophysics



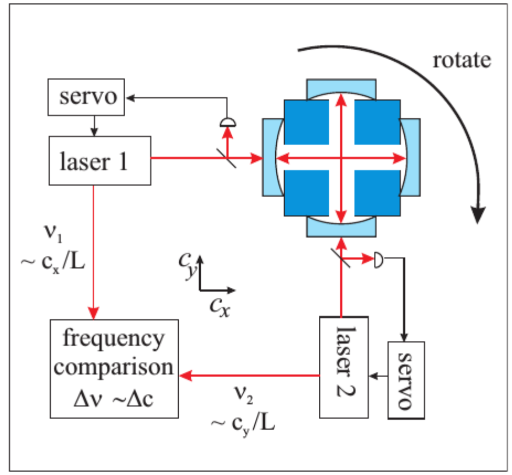
HESS telescope, Altschul (2006)

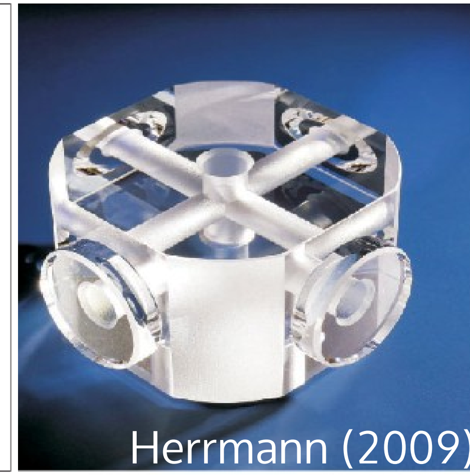
A most famous null experiment



Lorentz-violating effects?

Modern Michelson-Morley experiments

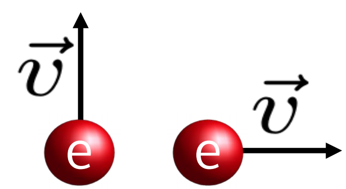




Herrmann (2009)

Electrons

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



electron

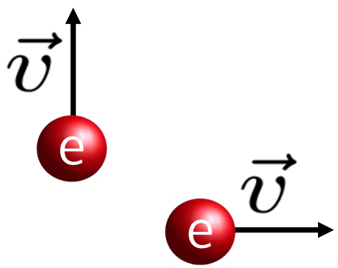
same energy?

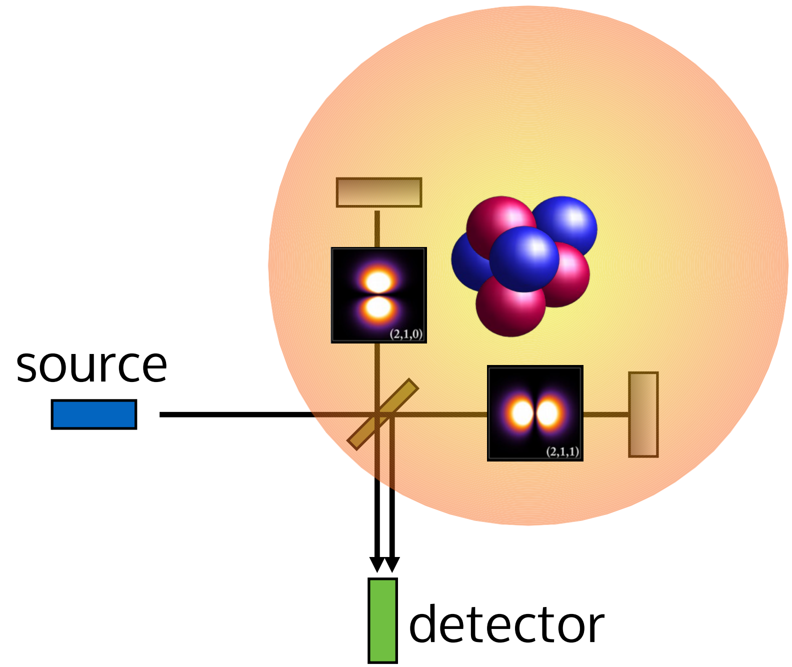
Others . . . .

- neutron, proton, ...

  ⇨ Hughes-Drever experiments

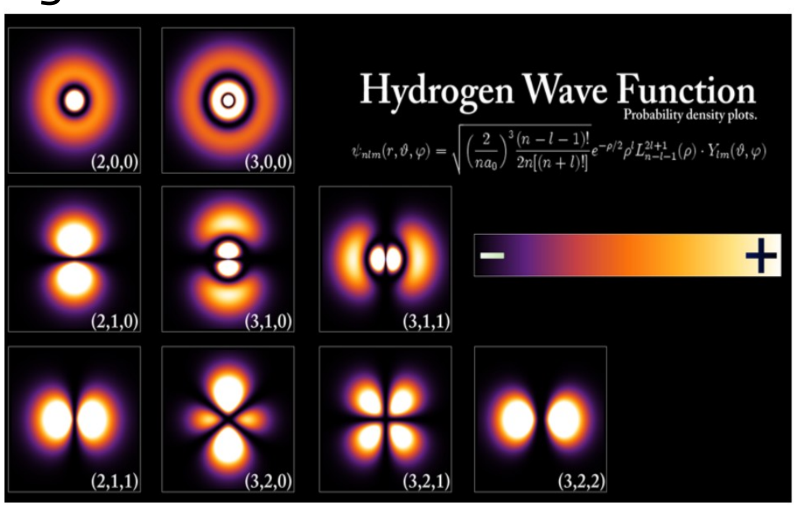
Interferometer with electrons?





Michelson interferometer

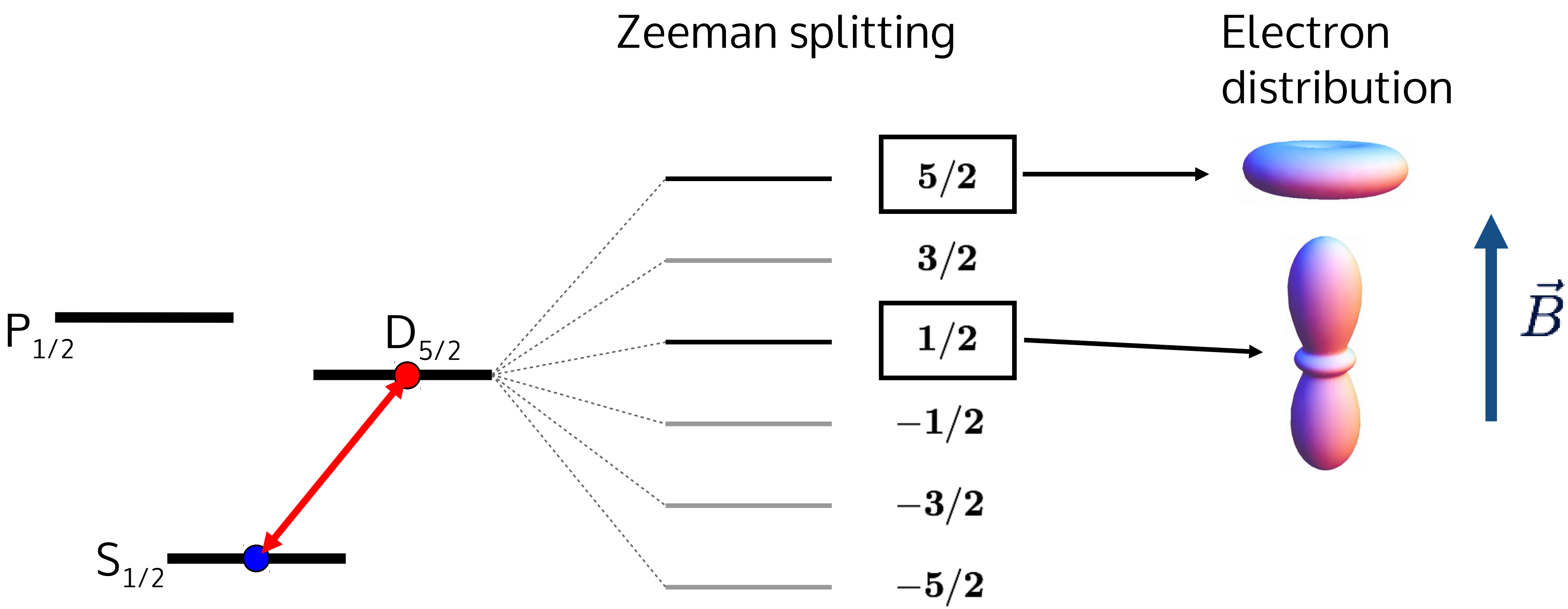
Standing waves for electrons:



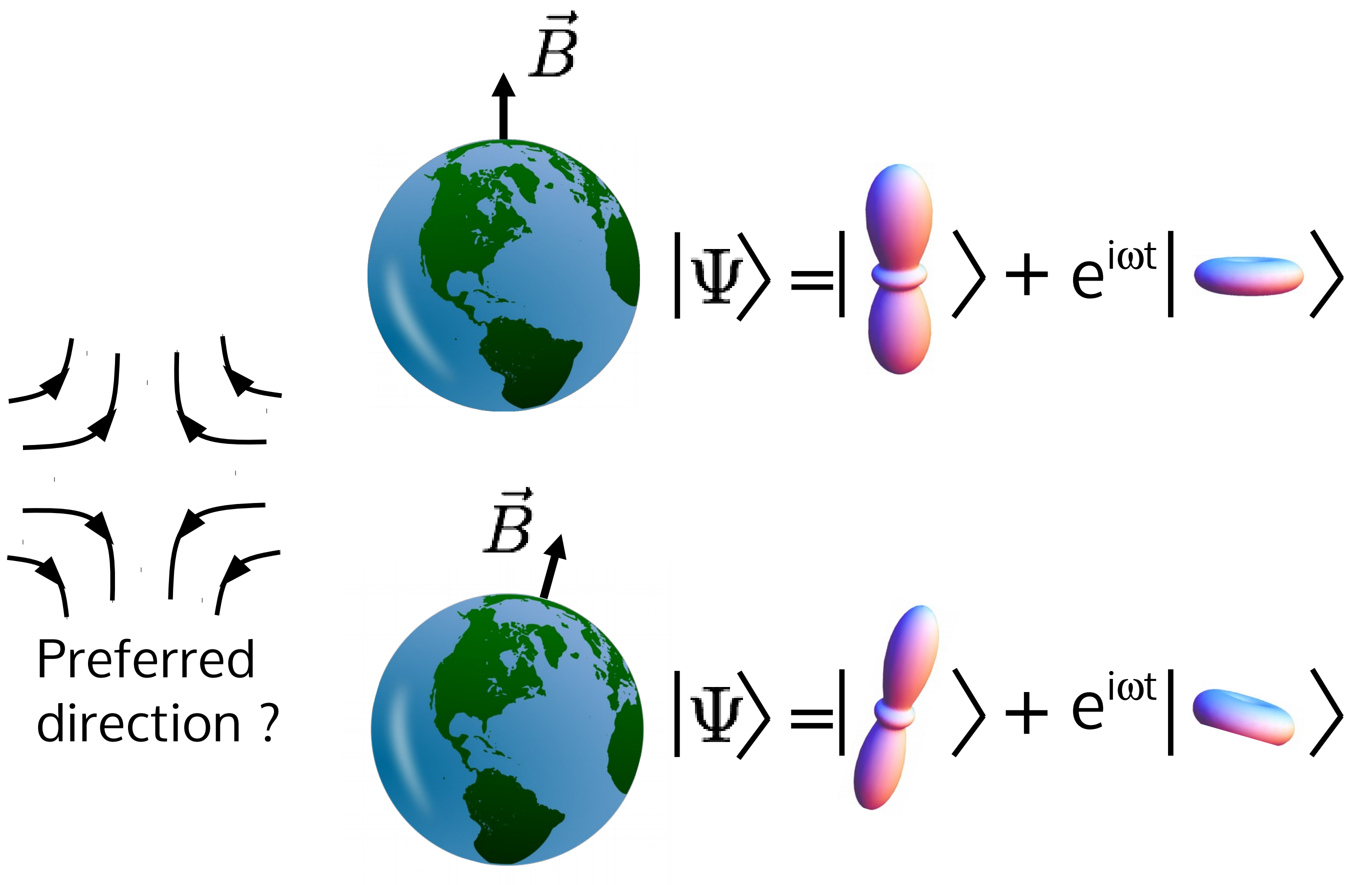
http://www.photonicquantum.info/Research/Hydrogen_Density_Plots.png

Interferometer with electrons?

Use the $D_{5/2}$-manifold of 40Ca+



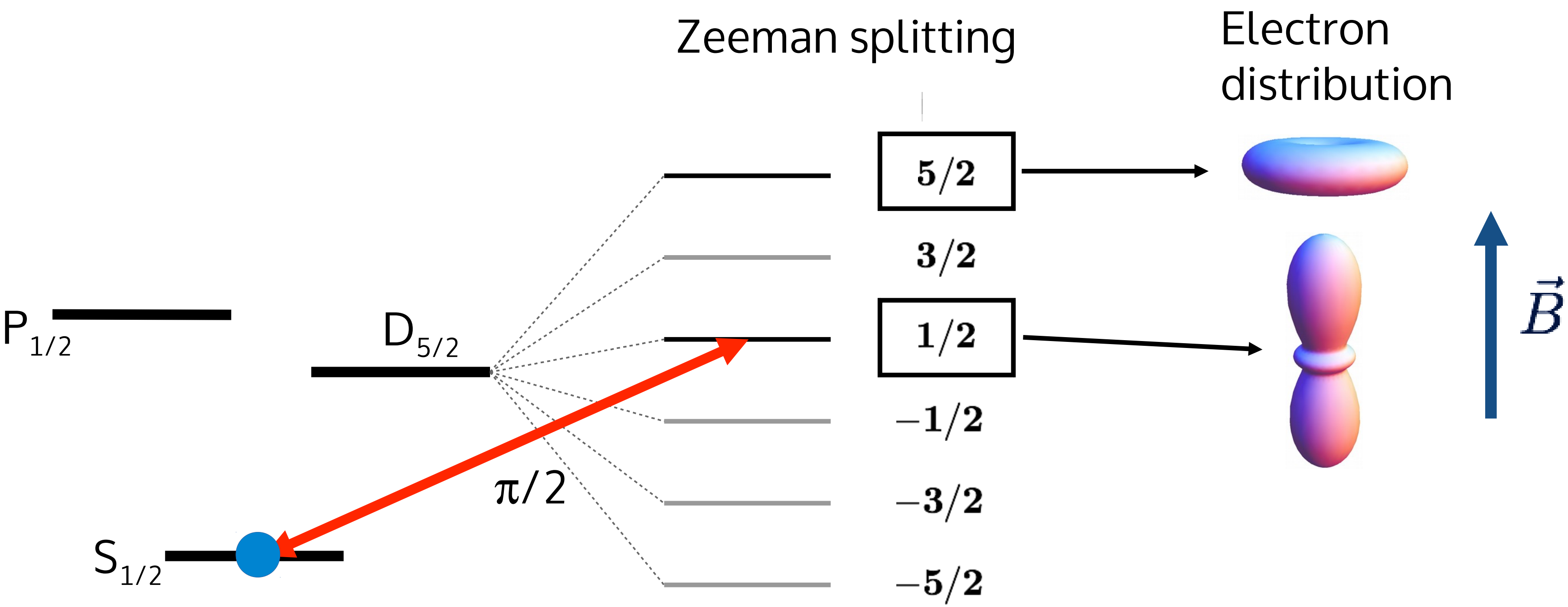
Measurement scheme



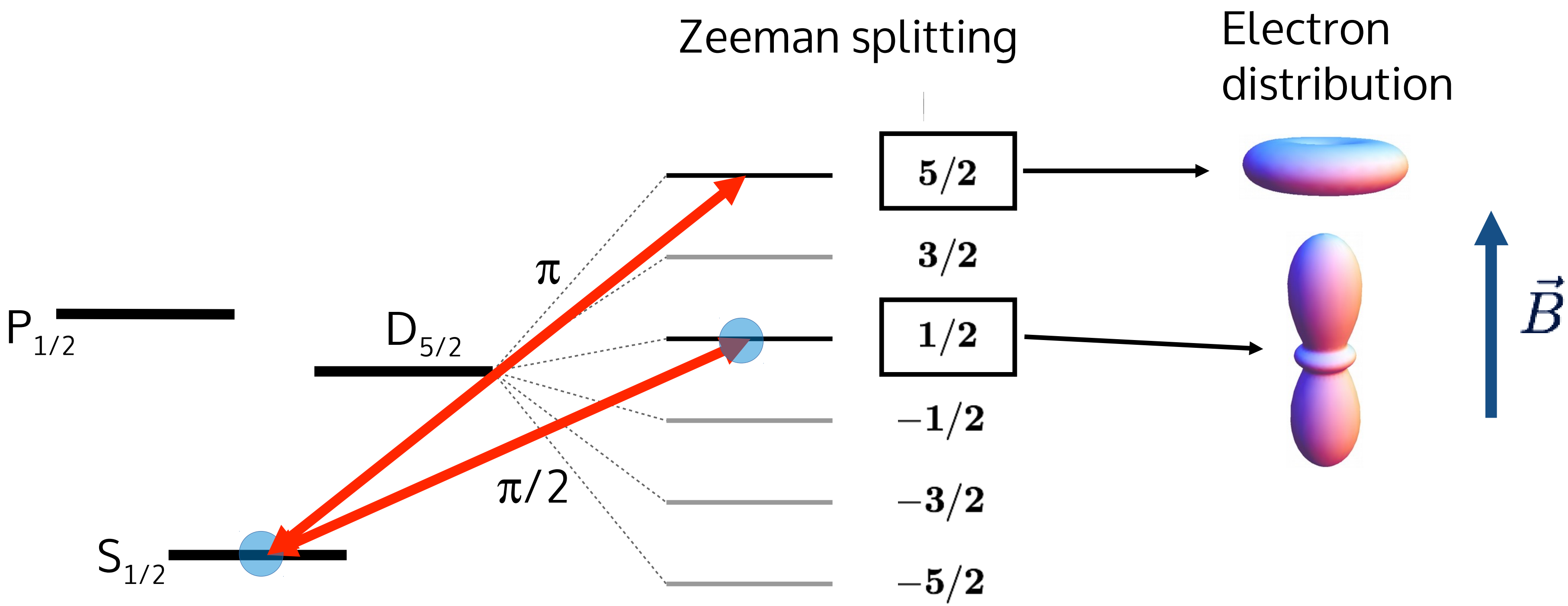
Preferred direction due to Lorentz violation ?

energy modulated with the Earth's rotation

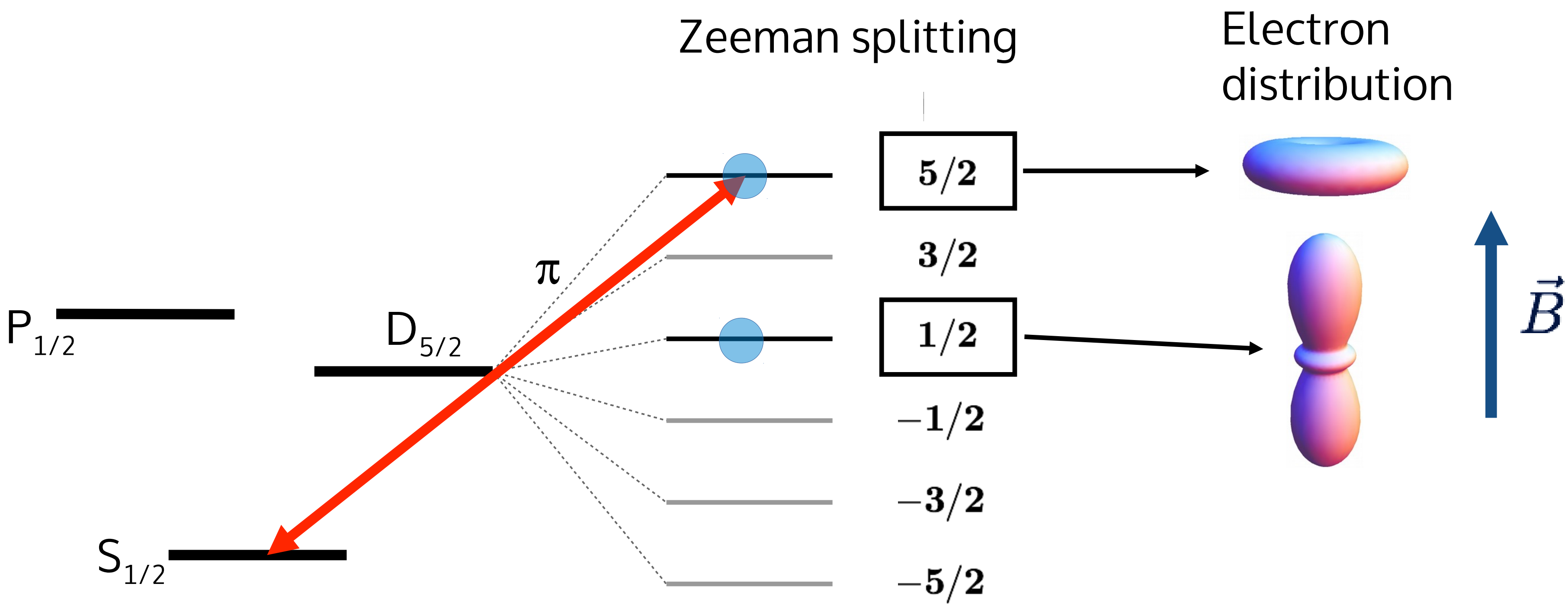
State preparation



State preparation



State preparation



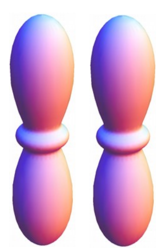
Decoherence-free subspace

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

Problem: Zeeman effect swamps phase evolution

Use two ions:

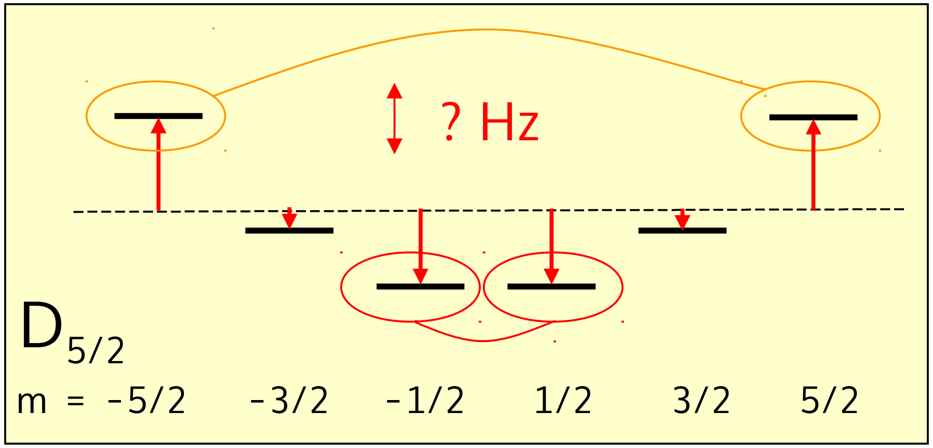
$$|\Psi\rangle = |\overbrace{-1/2,\ 1/2}^{\mu_{eff}=0}\rangle + |\overbrace{-5/2,\ 5/2}^{\mu_{eff}=0}\rangle$$

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

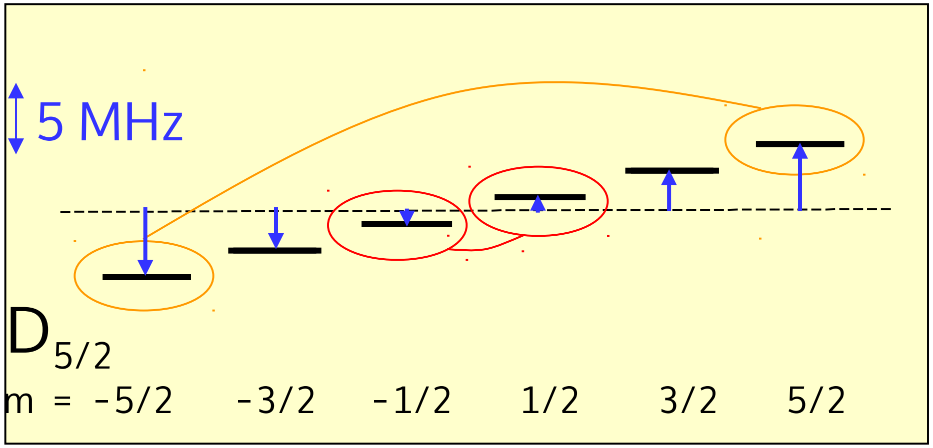
Quadrupole shift: Spectroscopy with entangled states

Prepare the two-ion Bell state $\Psi = |-5/2\rangle|5/2\rangle + |-1/2\rangle|1/2\rangle$

sensitive to quantities ~ m^2



insensitive to linear Zeeman shift



Decoherence-free subspace !

$$\Psi(t=0) \xrightarrow{\tau} \Psi(\tau) = |-5/2\rangle|5/2\rangle + e^{i\Delta\tau}|-1/2\rangle|1/2\rangle$$

Correlation measurements with two unentangled ions

Prepare the product state $$\Psi_{prod} = \tfrac{1}{2}(|S\rangle + |D\rangle) \otimes (|S\rangle + |D\rangle)$$

$$= \tfrac{1}{2}(|SS\rangle + |SD\rangle + |DS\rangle + |DD\rangle)$$

$$= \frac{1}{\sqrt{2}}\Psi_+ + \tfrac{1}{2}|S\rangle|S\rangle + \tfrac{1}{2}|D\rangle|D\rangle$$

... and let it decohere: $$\Psi_{prod} \xrightarrow{\text{time}} \rho = \frac{1}{2}\rho_{\Psi_+} + \underbrace{\frac{1}{4}\rho_{SS} + \frac{1}{4}\rho_{DD}}$$

contributes to the signal

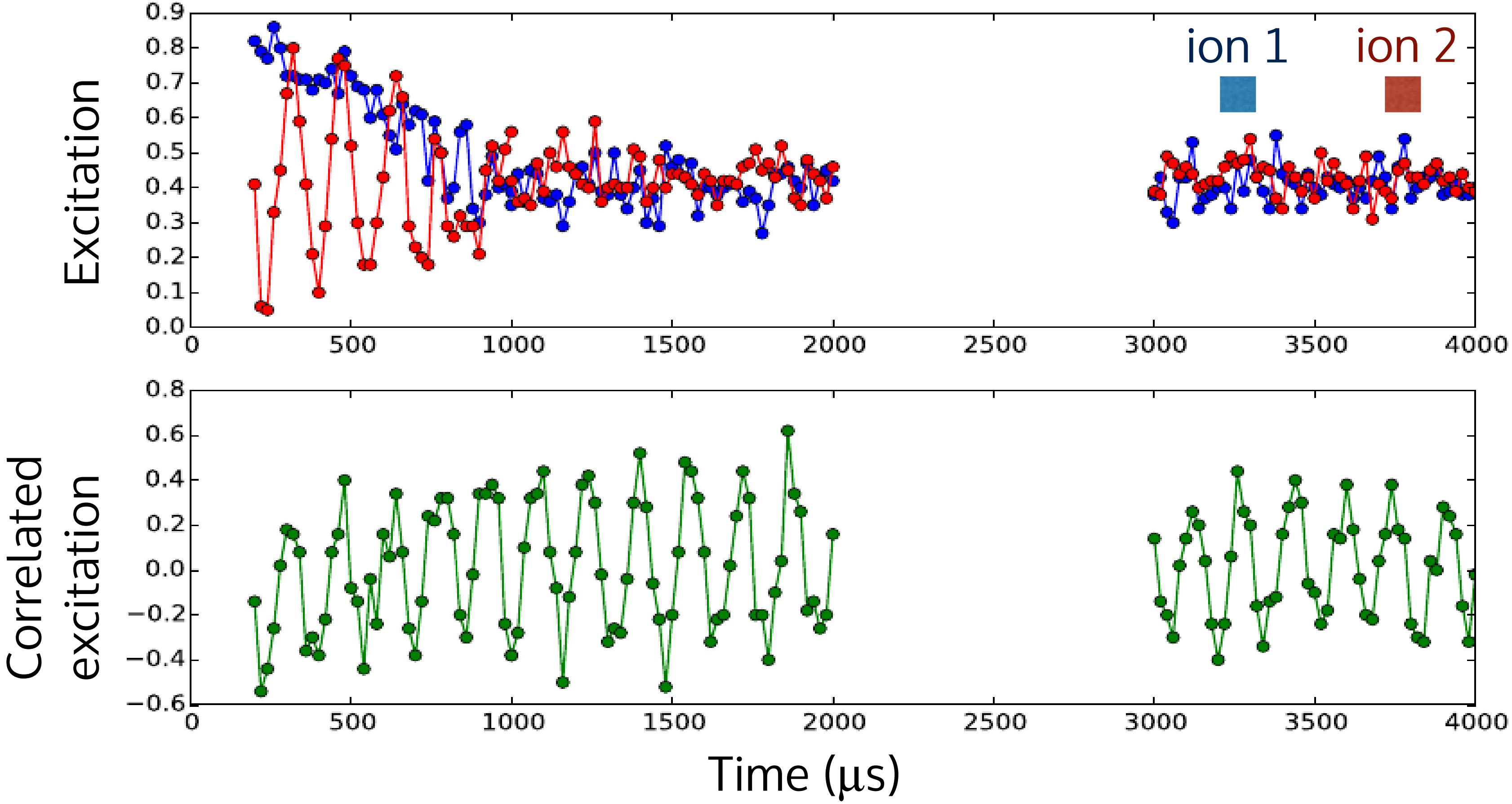
no contribution

- Parity signal contrast only 50%
- Additional quantum projection noise from ρ_{SS} and ρ_{DD} ,

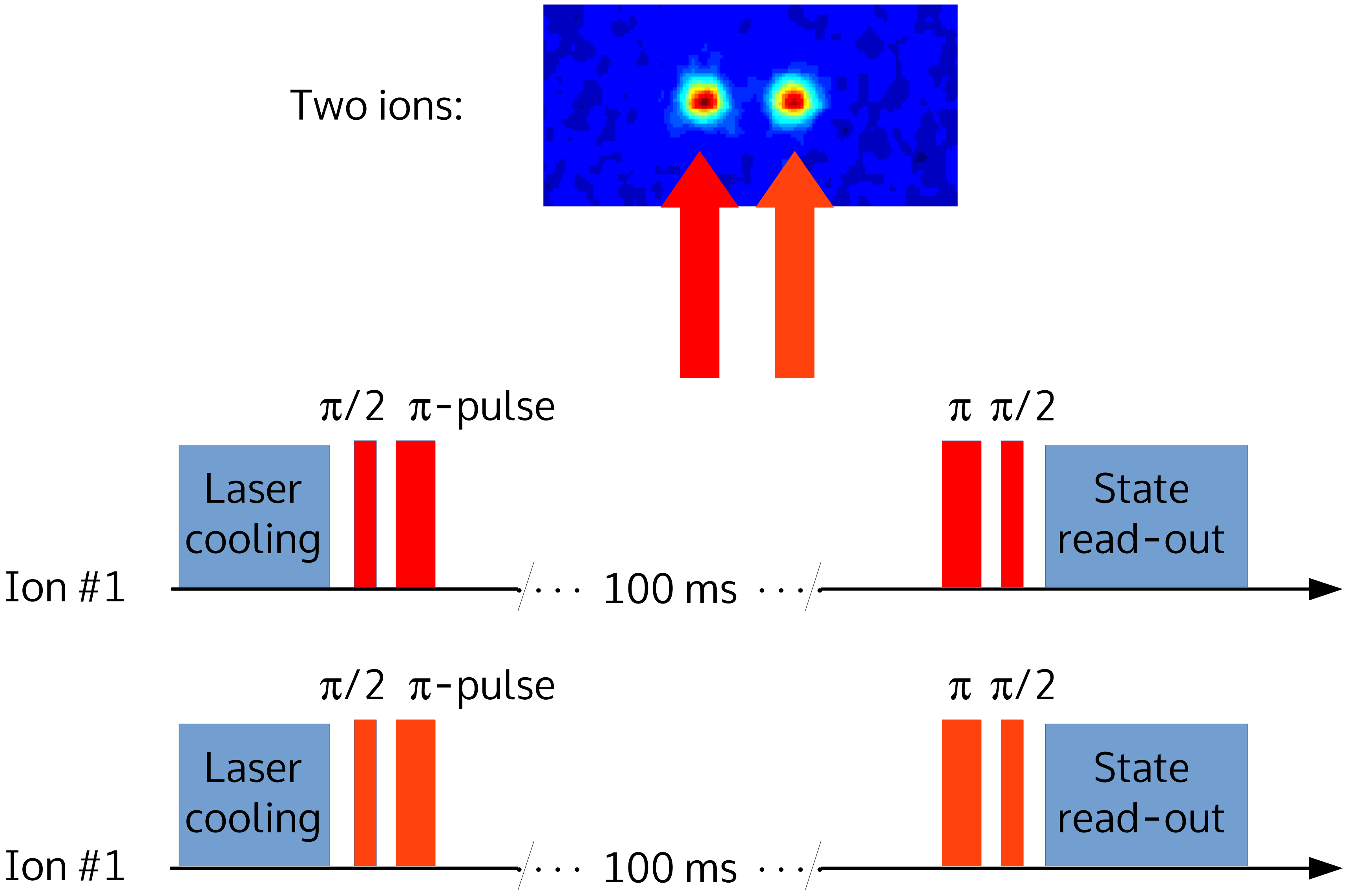
  ... but much easier to produce !

Decoherence-free subspace

Coherence time improved by 10^4
→ decoherence-free subspace

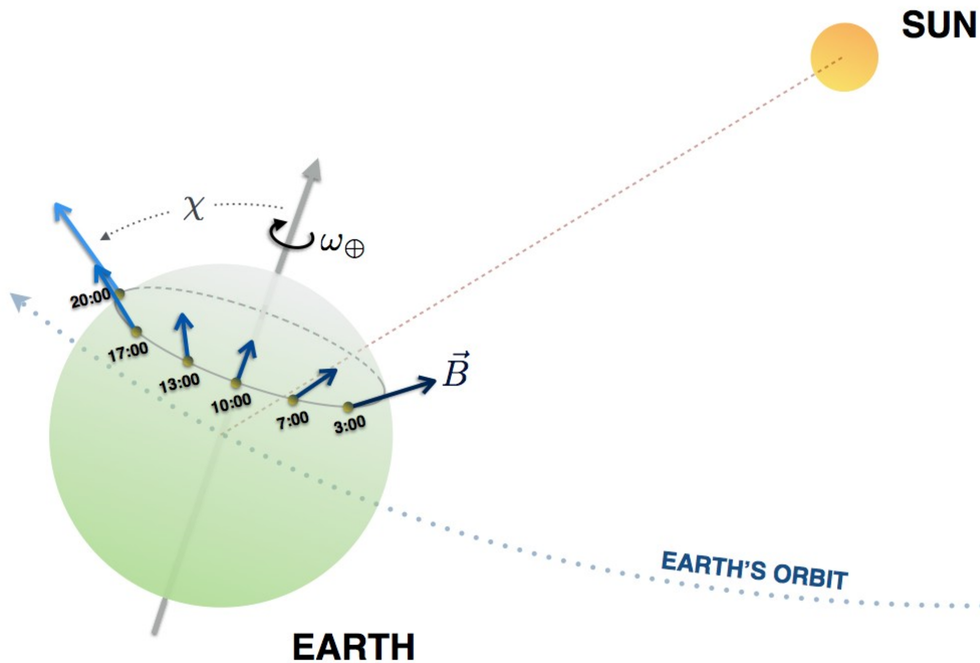


Measurement scheme



Measurement scheme

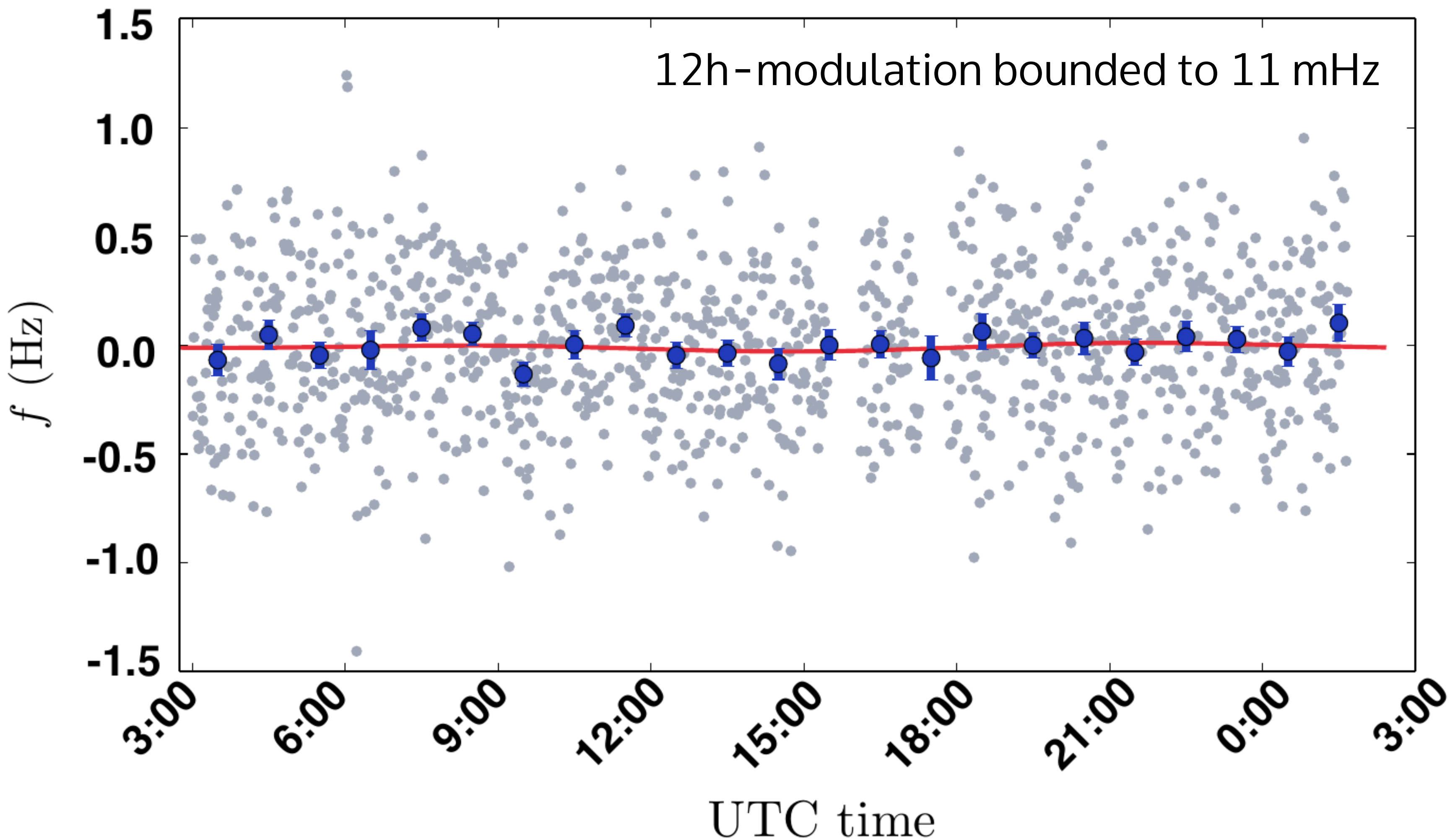
Magnetic field and wavefunction change direction.



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

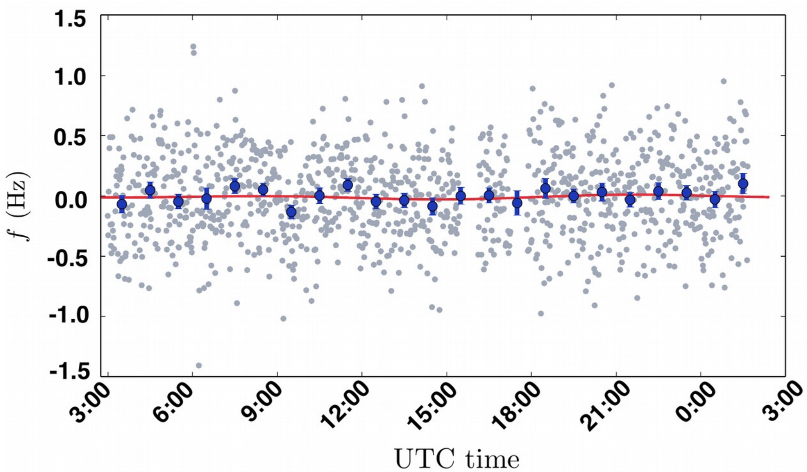
Data

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



Results

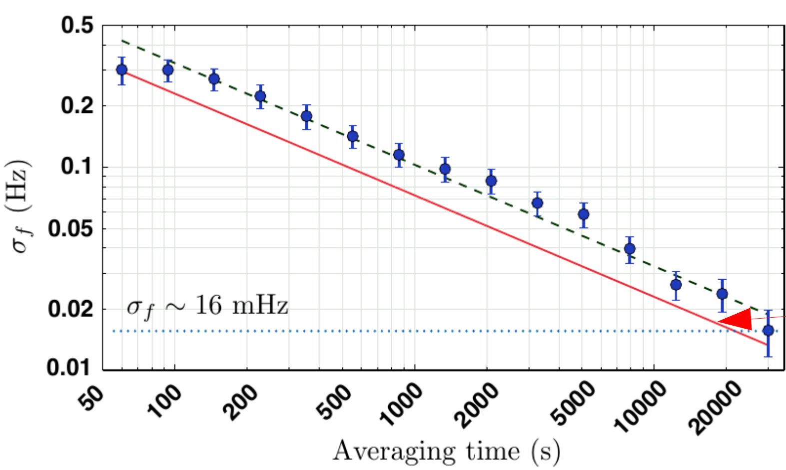
Energy variations of a pair of $^{40}Ca^{+}$ ions on April 19th 2014



12h-modulation bounded to 11 mHz

$$\frac{\Delta E}{\langle E_{\mathrm{kin}} \rangle} \approx \frac{5 \times 10^{-17}\ \mathrm{eV}}{50\ \mathrm{eV}} = 10^{-18}.$$

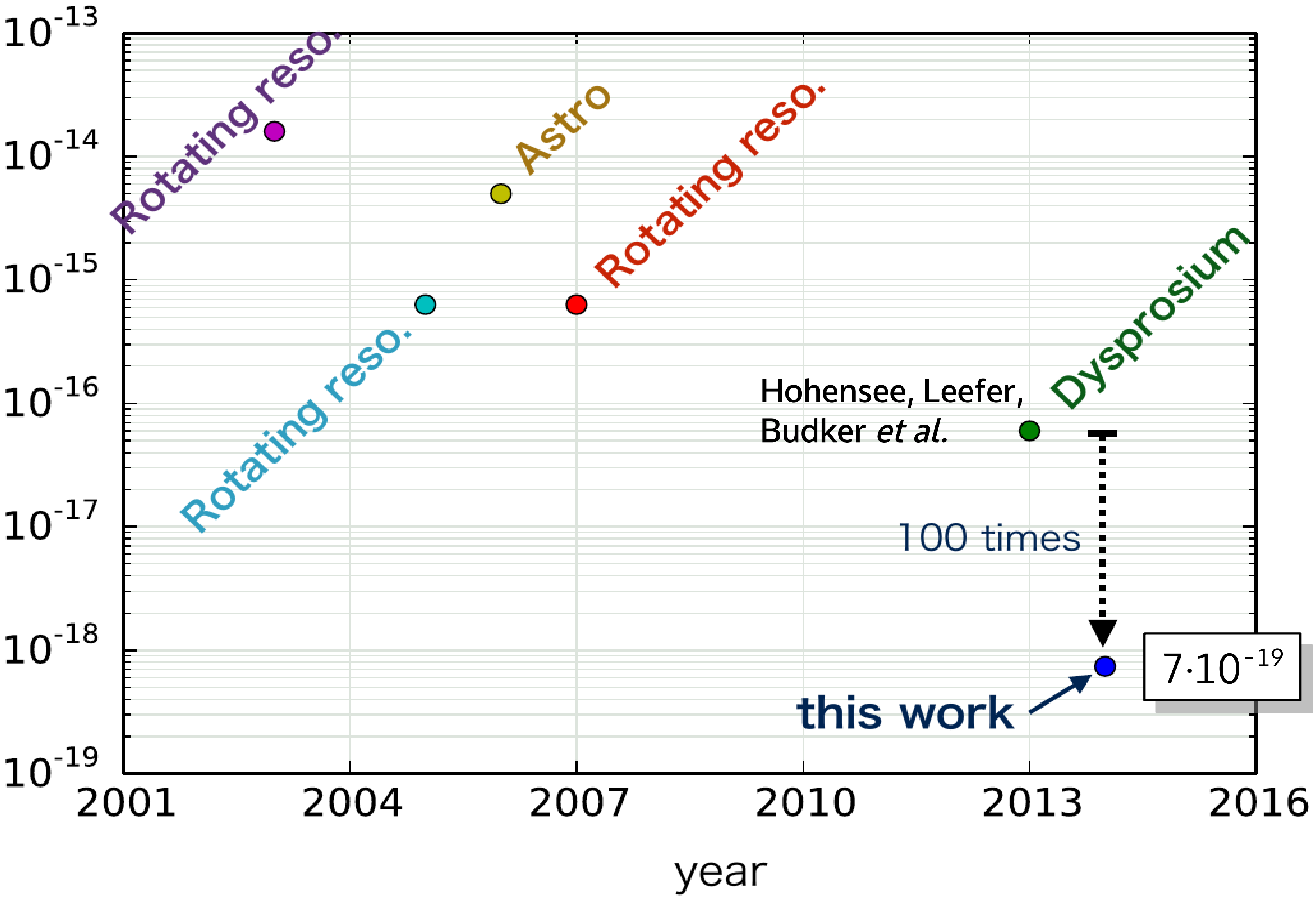
Bound as a function of averaging time



Still averaging down with $\sqrt{\tau}$,
no signs of systematic drifts.

Expected quantum projection noise.

Lorentz tests for the electron

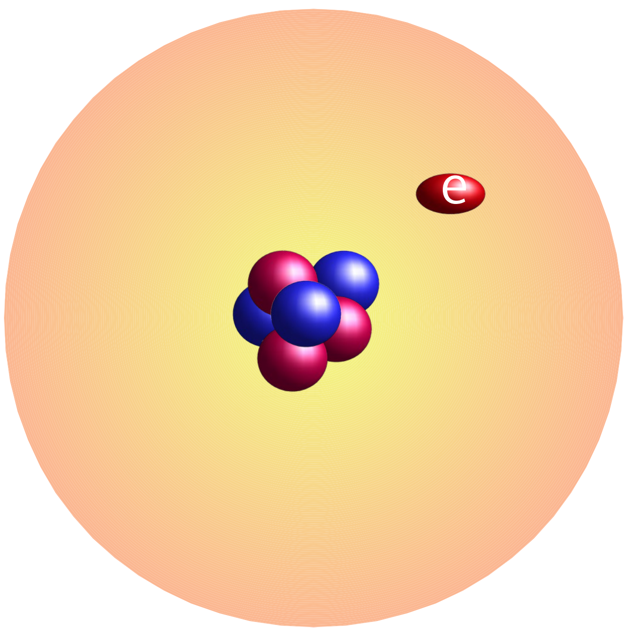


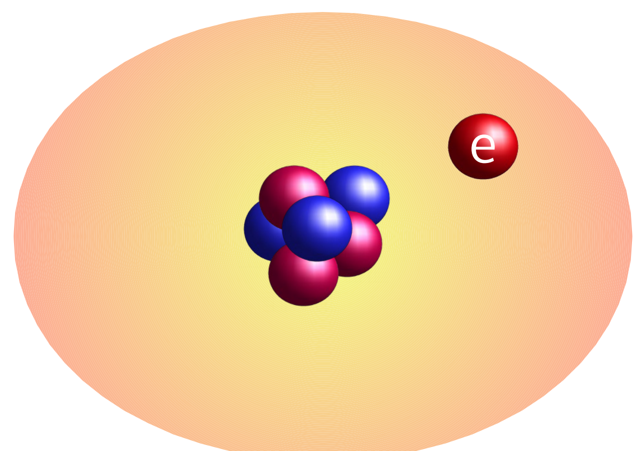
Interpretation

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

Assumption: Coulomb force is symmetric.
➡ any LV-signal is attributed to the electron

or: electron obeys Lorentz symmetry
➡ photon violates Lorentz symmetry

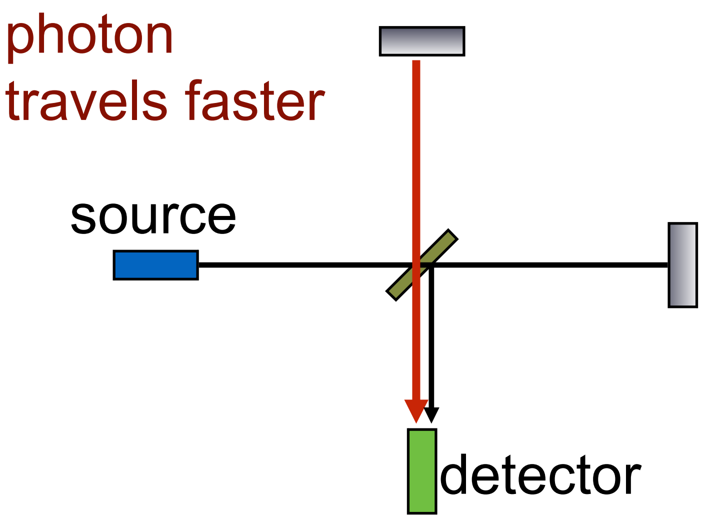


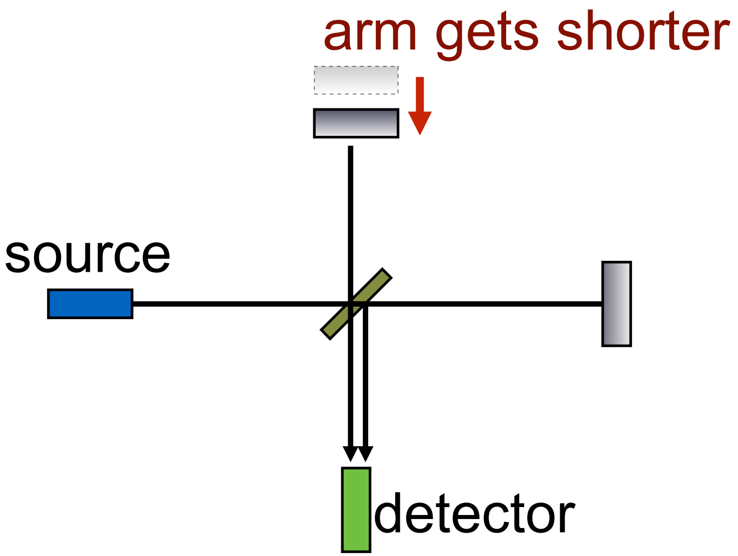


➡ We probe the difference between the electron and photon dispersion !

Interpretation of the Michelson Morley experiment

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





➡ Arm length determined by the Coulomb force and electron dispersion

Lorentz invariance tests for light

Both experiments compare
the photon and the electron dispersion relation.