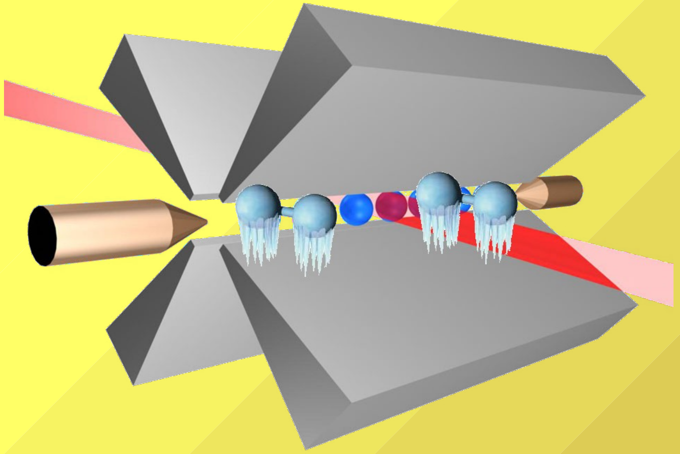
Cold Molecules for Quantum Information … and *vice versa*



Jordi Mur-Petit
Instituto de Estructura de la Materia (CSIC)

CSIC
Consejo Superior de Investigaciones Científicas

JAE CSIC 2010

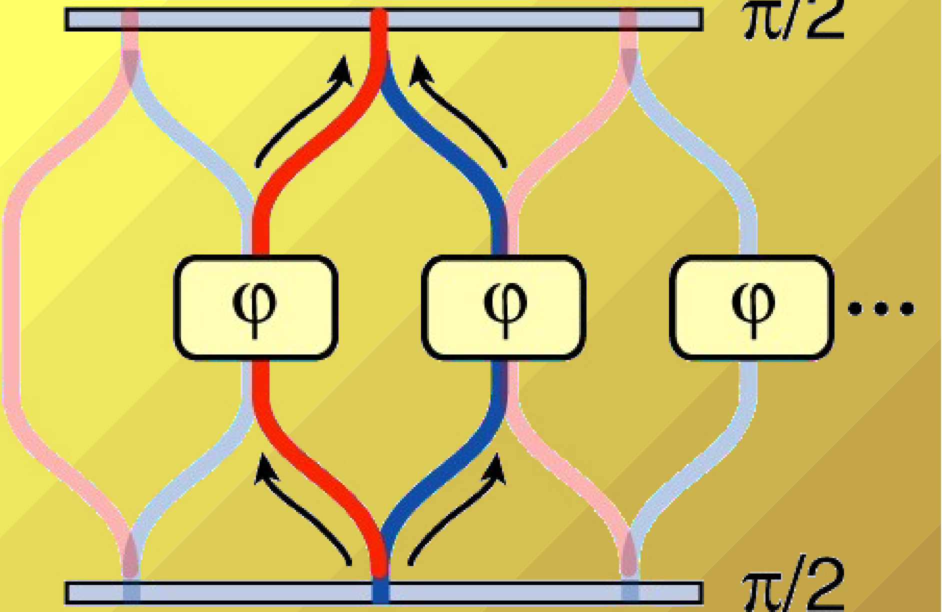
MARIE CURIE ACTIONS

Outline

- Controlled collisions — measuring scattering properties
- Trapped molecular ions
- A molecular ion qubit
- Ions and polar molecules — measuring a molecule's EDM

Outline

- **Controlled collisions — measuring scattering properties**



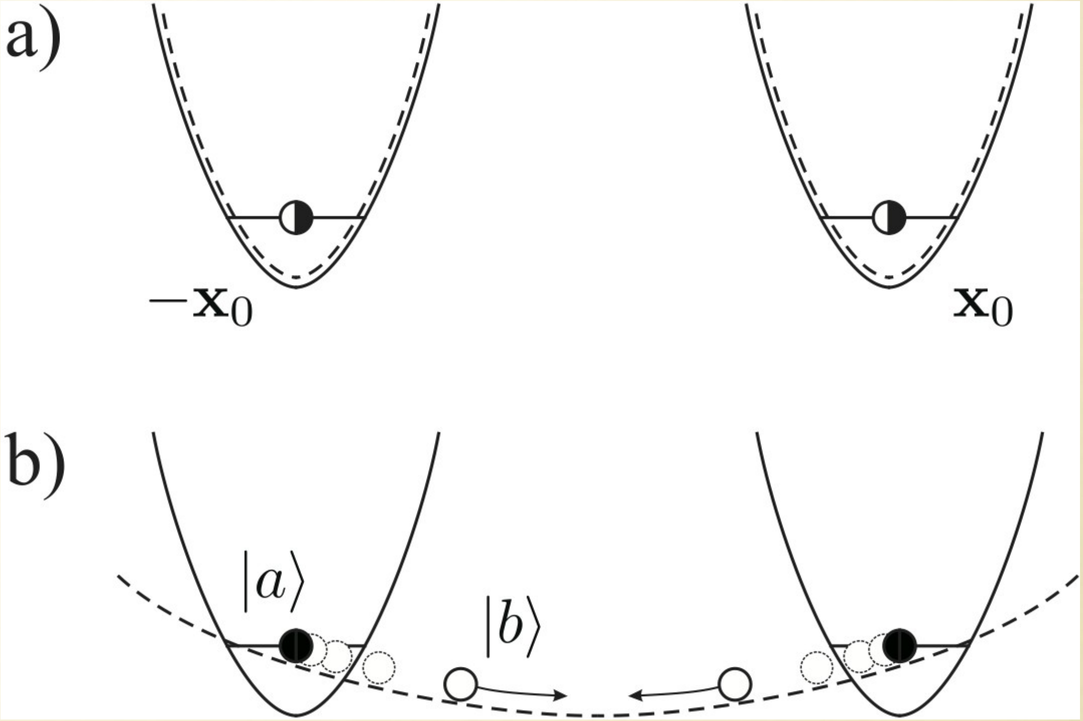
- Trapped molecular ions
- A molecular ion qubit
- Ions and polar molecules — measuring a molecule's EDM

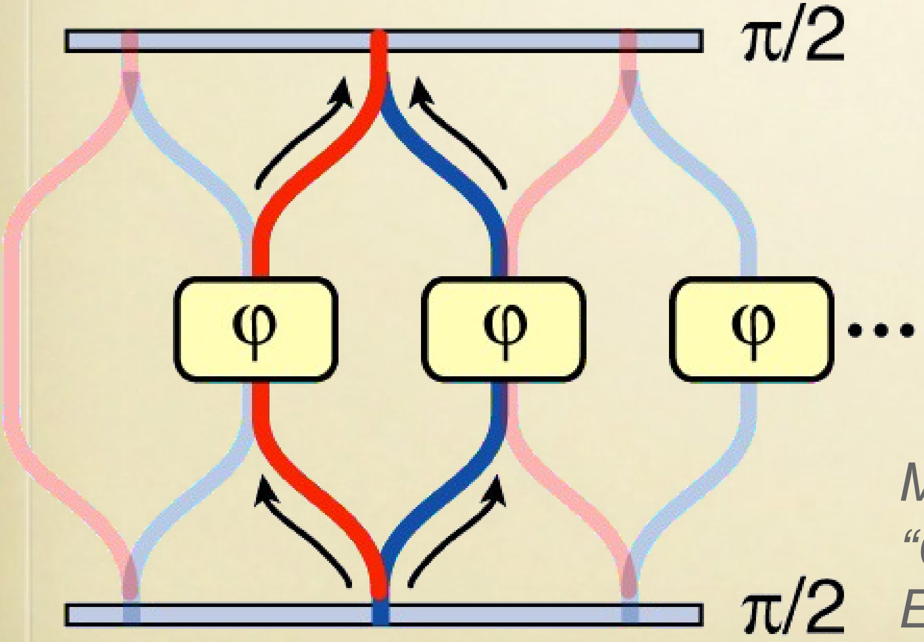
Controlling collisions

Calarco et al. (2000):

- "Release and recapture"
- Collisional phase shift accumulated
- Not sensitive to details of potential

$$\varphi \propto a_s$$





Mandel et al. [Bloch], Nature (2003)
"Controlled Collisions for Multiparticle Entanglement of Optically Trapped Atoms"

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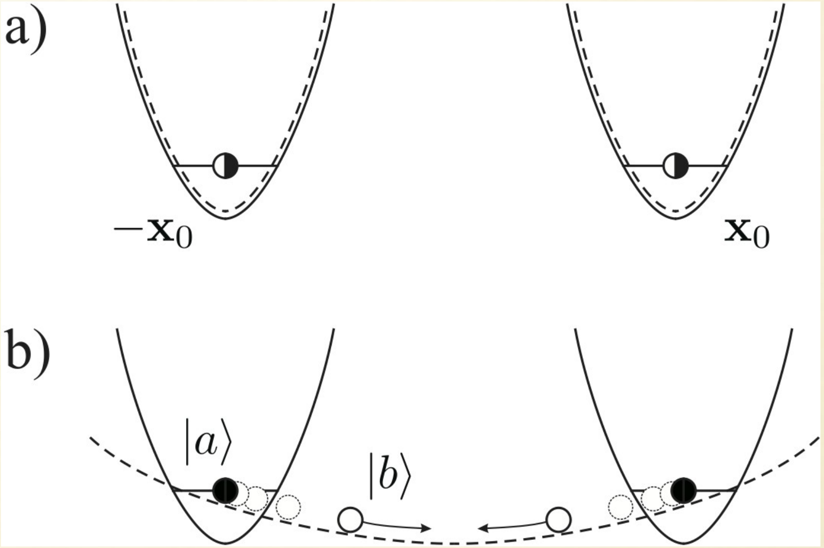
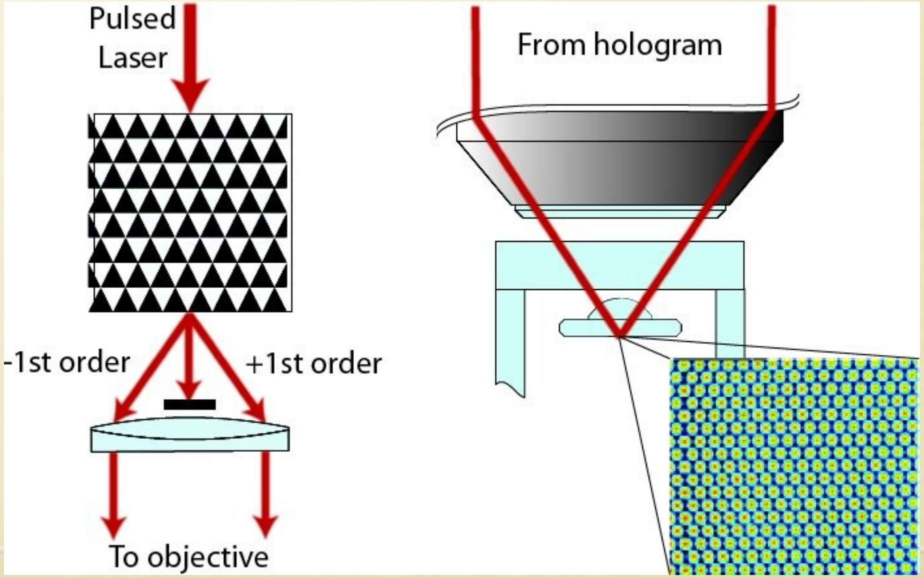


New trapping methods: holographic masks + large NA lens (Greiner, Chin...)

- Translation of lattice possible
- Two-color lattices ⟶ State-dependent



M. Greiner

Controlling collisions

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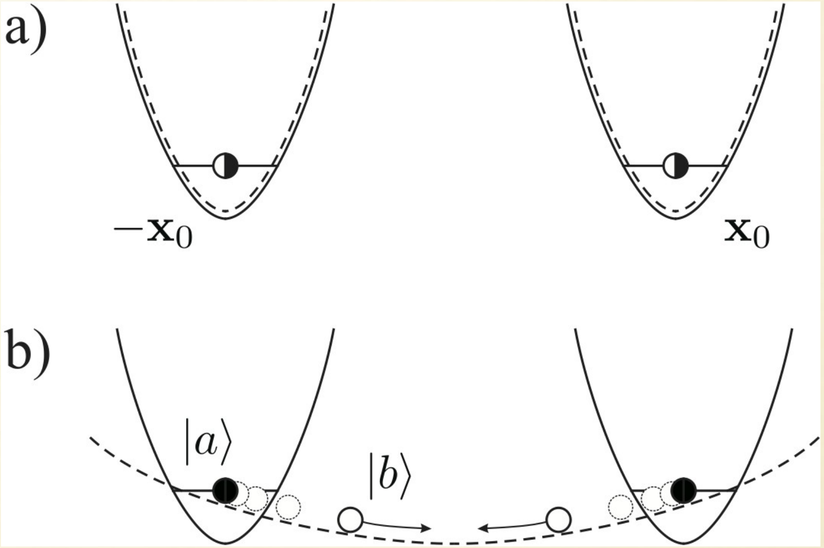
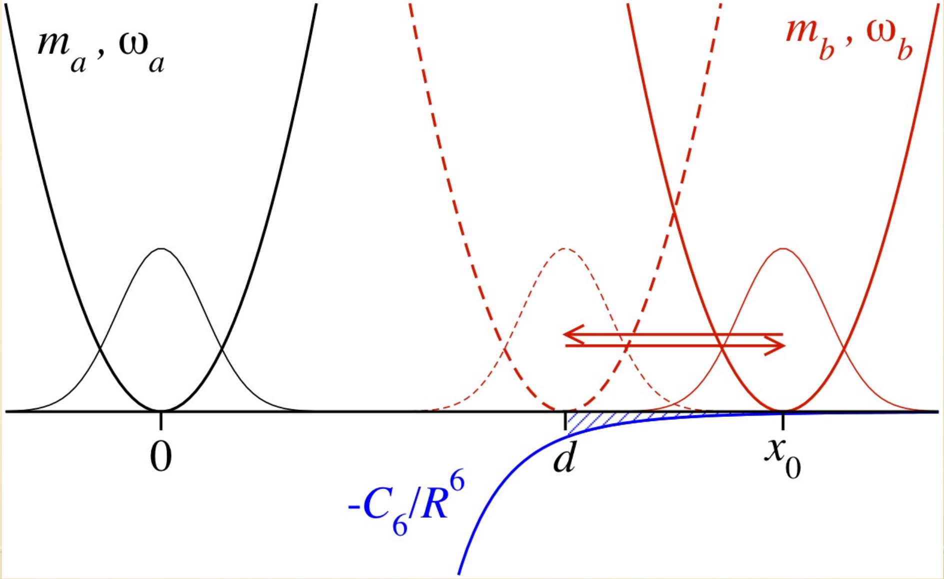


New trapping methods: holographic masks + large NA lens (Greiner, Chin...)

- Translation of lattice possible
- Two-color lattices
  - ⟶ State-dependent
  - ⟶ Multi-species



Proposal to probe long-range part of potential:

$$\varphi \propto C_6/x_0^6$$

Controlling collisions

$$\varphi(t) = \frac{1}{\hbar}\int_0^t d\tau \Delta E(\tau)$$

$$E(\tau) = \int d\mathbf{1} d\mathbf{2} V(\mathbf{1},\mathbf{2})|\Psi(\mathbf{1},\mathbf{2};\tau)|^2$$

$$\Psi(\mathbf{1},\mathbf{2};\tau) \to \Psi(\boldsymbol{R},\boldsymbol{r};\tau) = \psi_{CM}(\boldsymbol{R})\psi_{rel}(\boldsymbol{r};\tau)$$

$$V(r) = \begin{cases} \infty & r < r_{hc} \\ -C_6/r^6 & r > r_{hc} \end{cases}$$

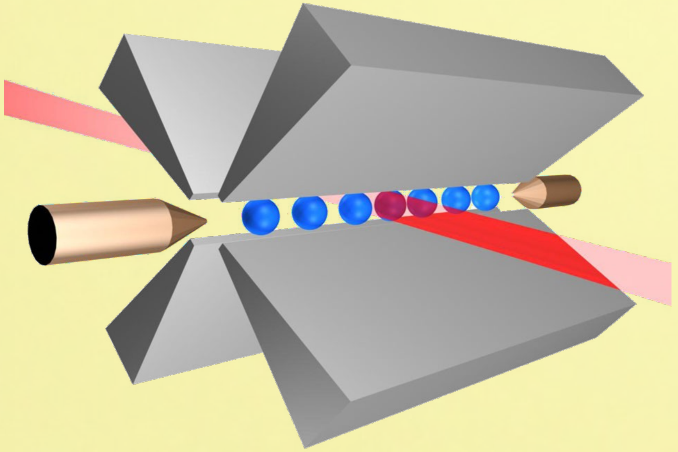
$$\psi_{rel}(r;\tau) = \begin{cases} \psi_{GF}(r;d(\tau)) & r < r_* \\ \psi_{ho}(r;d(\tau)) & r > r_* \end{cases}$$

r_{hc} fixed by C_6, a_s; r_* fixed by continuity of rel wf.

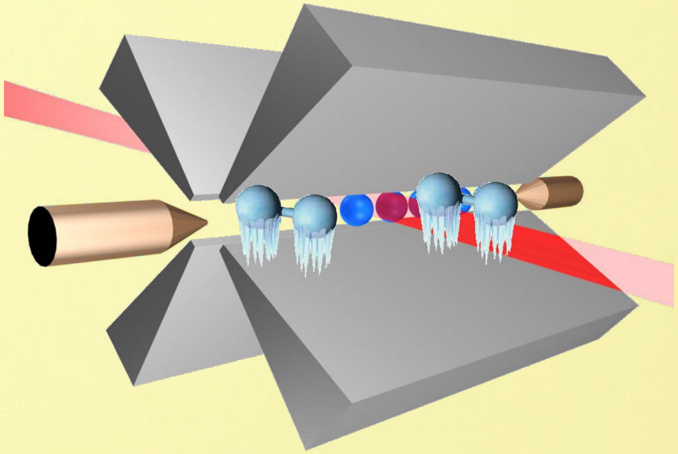
With $d \sim x_0/2$, $t \sim 1\mu s$, we only get $\varphi \sim 10^{-3}$ for Li+Cs ☹

Joining two fields

Cold molecules

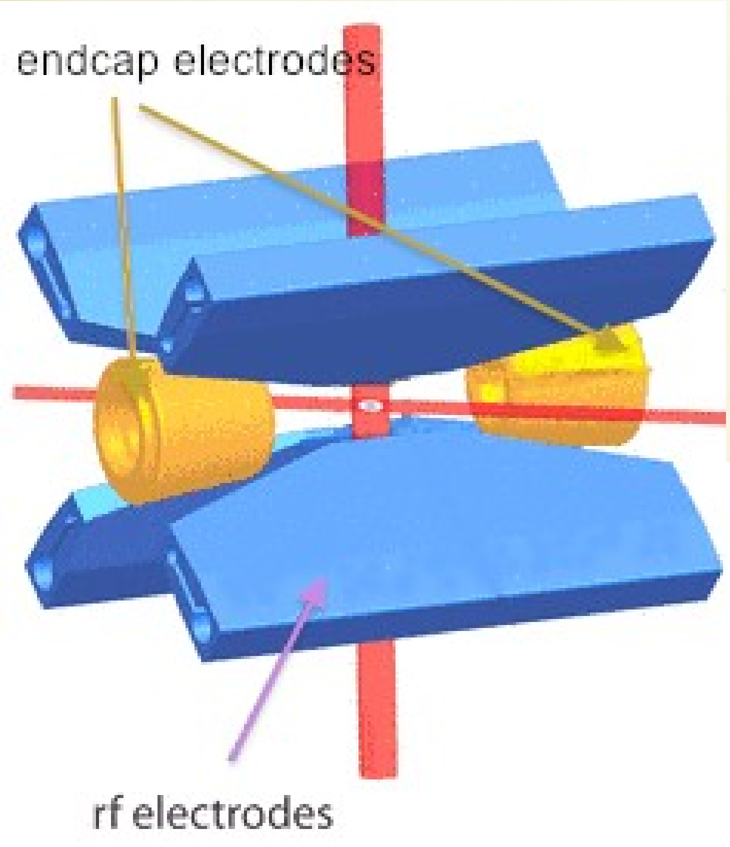


Trapped quantum ions

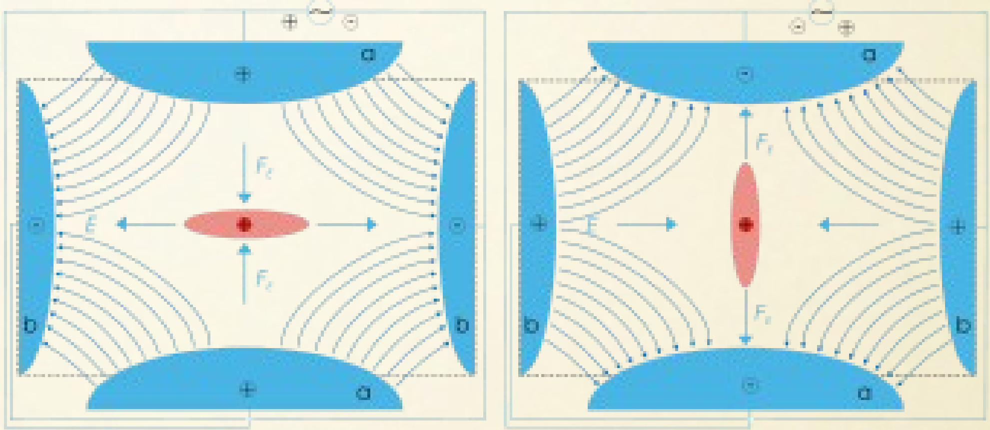


Cold molecular ions

Trapping atomic ions



Hecker-Denschlag (2011)



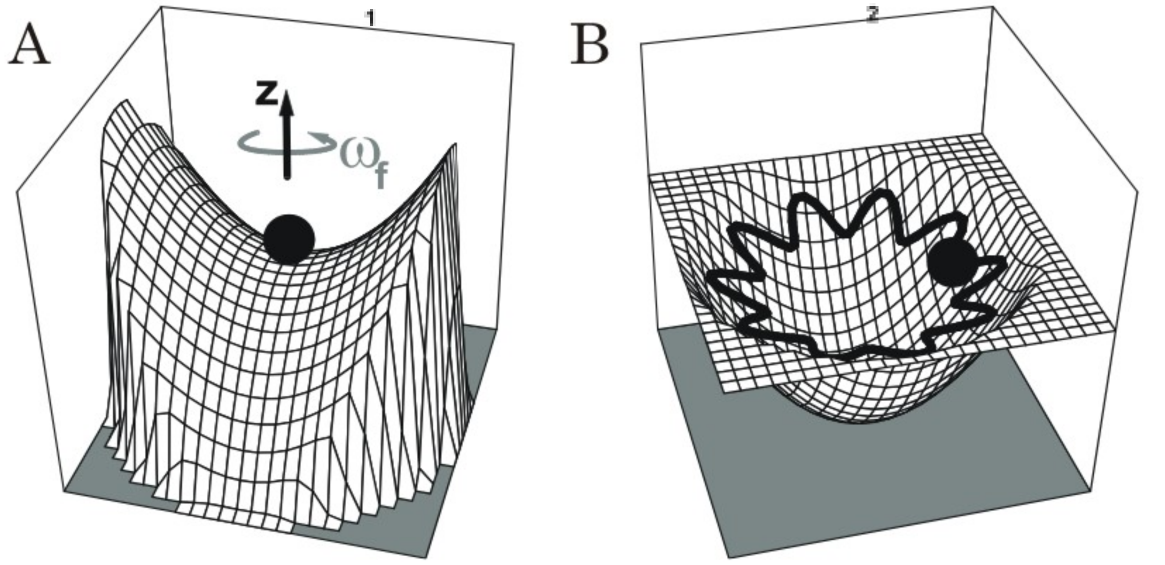
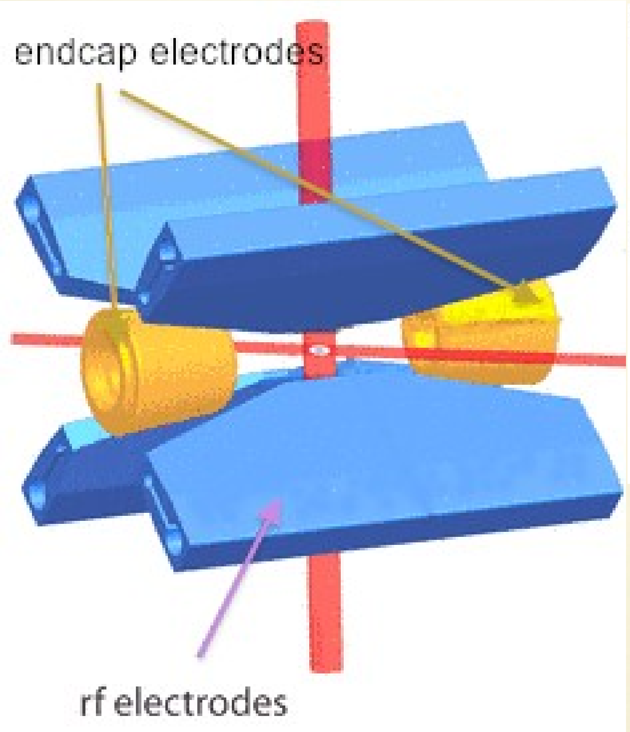


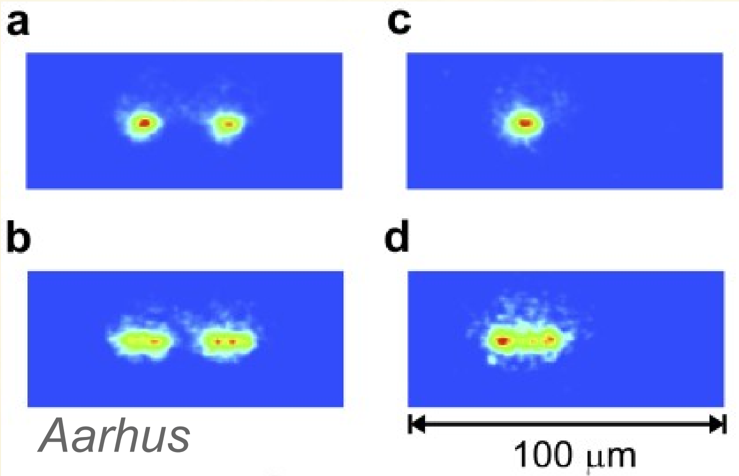
Figure 1.1: The effect of rotating the potential in part A, is a pseudopotential well which is illustrated in part B. The particle motion in the pseudopotential is indicated by the black line. The motion is a combination of a secular motion in the pseudopotential and a small amplitude micromotion at the frequency of rotation ω_f.

Molhave, MSc Thesis (2000)

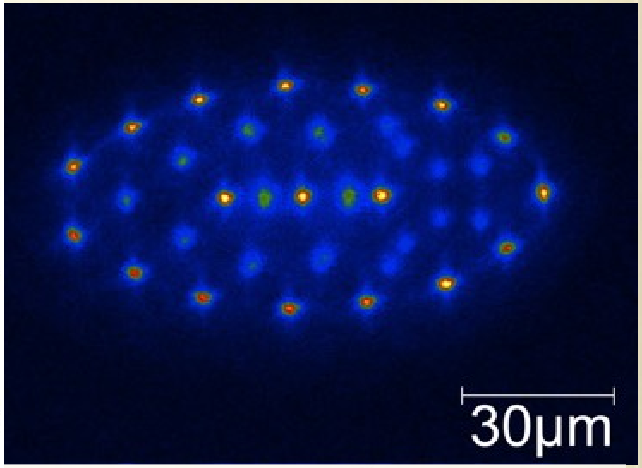
Trapping atomic ions



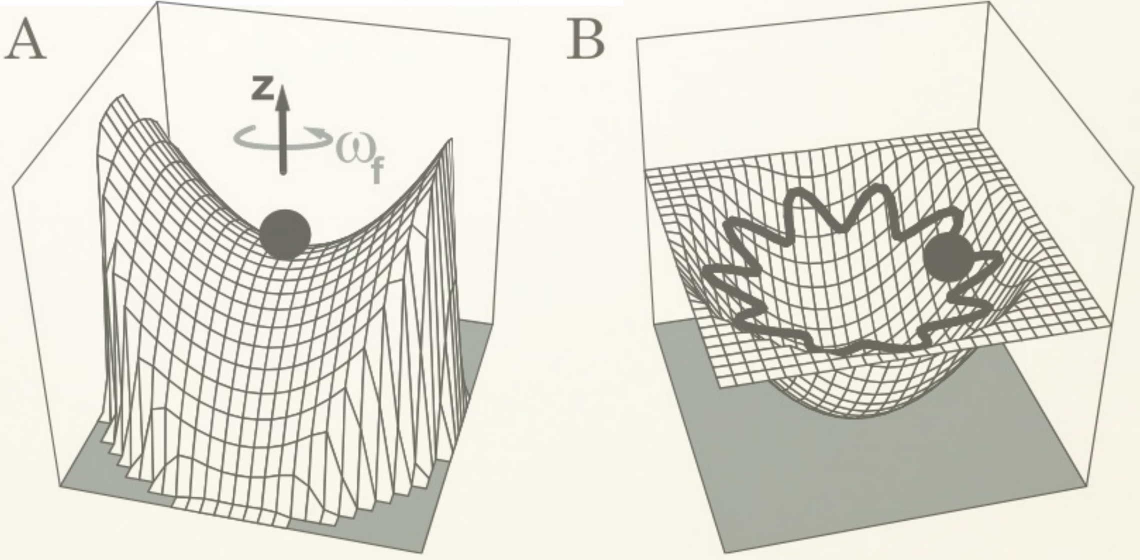
Ulm



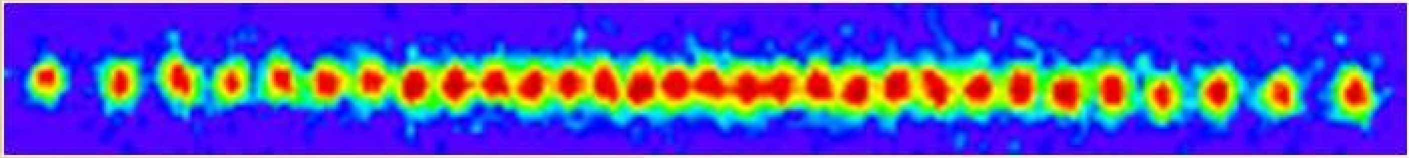
Aarhus



Basel



Innsbruck



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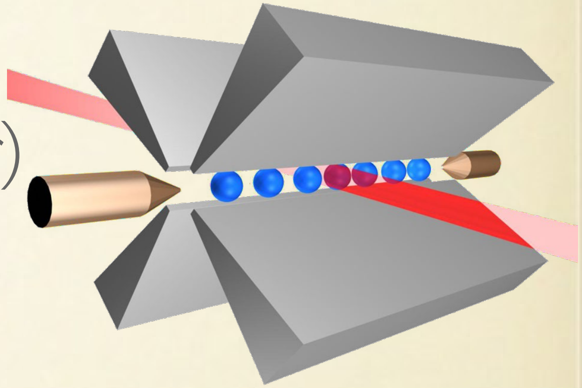
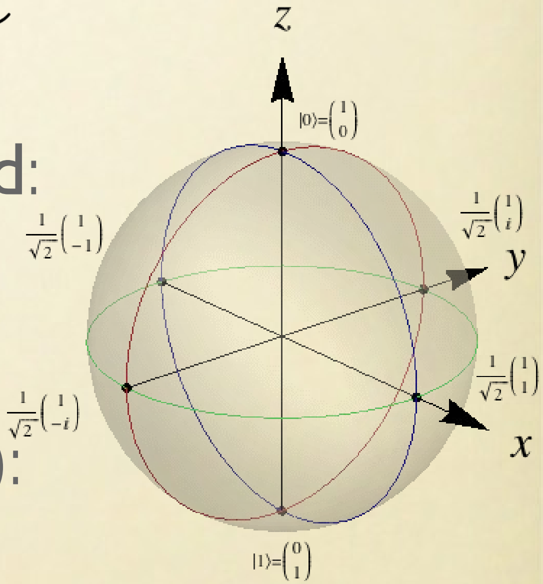
Trapped atomic ions



- *Atomic* ions trapped **in vacuum** (*P*~10^{-11} mbar)
- **Typical temperature ~ 10 mK**
- Internal state = qubit = $\alpha|0\rangle + \beta|1\rangle \quad \alpha, \beta \in \mathbb{C}$
- **Full control of single-qubit state demonstrated**:

  preparation, manipulation and measurement



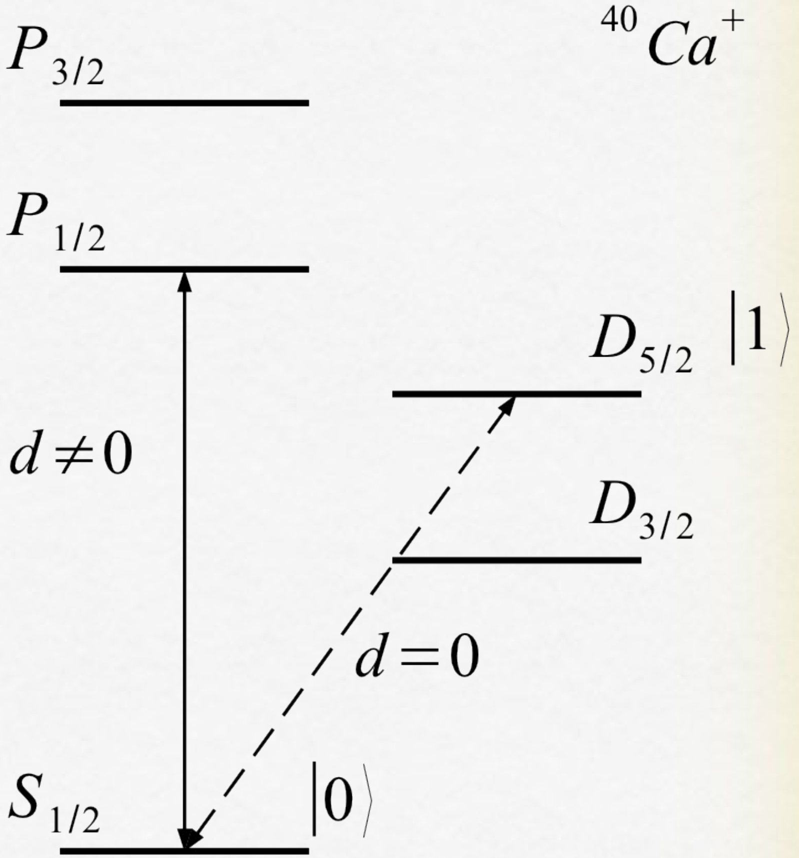
- Accurate **two-qubit operations** (>99% fidelity):

  CNOT, SWAP, factoring small numbers... **already realized**

An atomic ion as a qubit

^{40}Ca$^+$: an electronic (or optical) qubit

- Qubit: $|0\rangle = |S_{1/2}\rangle$, $|1\rangle = |D_{5/2}\rangle$
- Single-qubit operations:
  - Dipole forbidden transition: long radiative lifetime (~1 s)
  - Quadrupole transition (large intensity) or Raman coupling
- **Detection:** fluorescence



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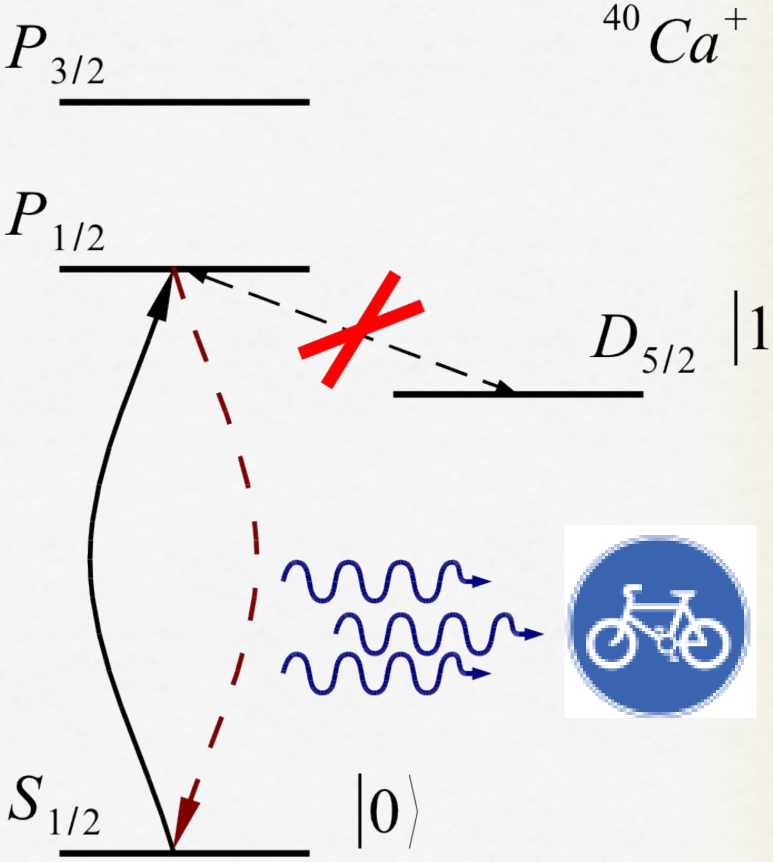
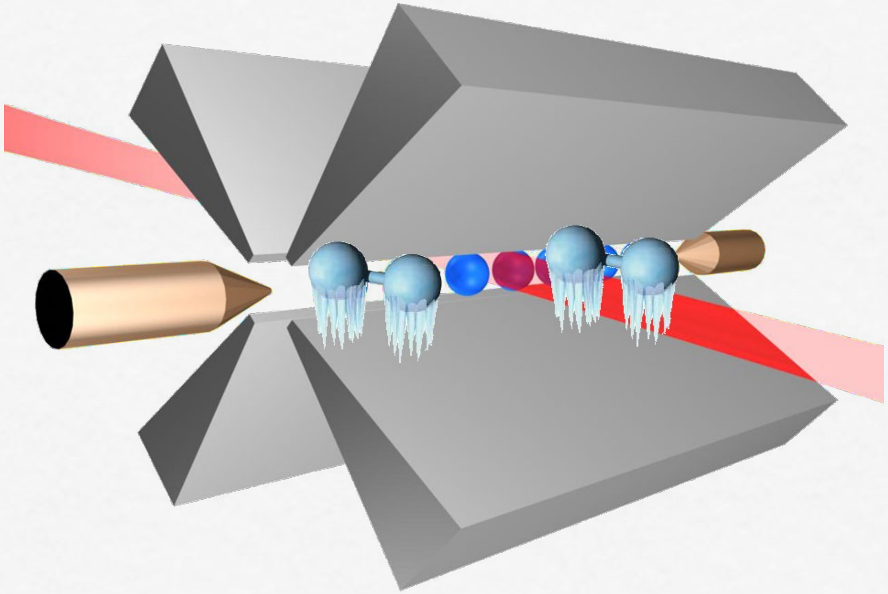
  (cycling transition)



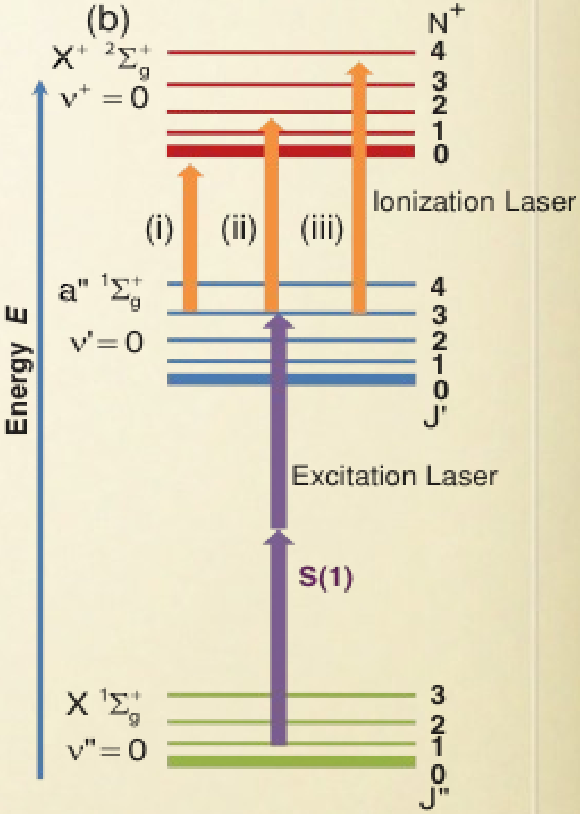
Cold *molecular* ions

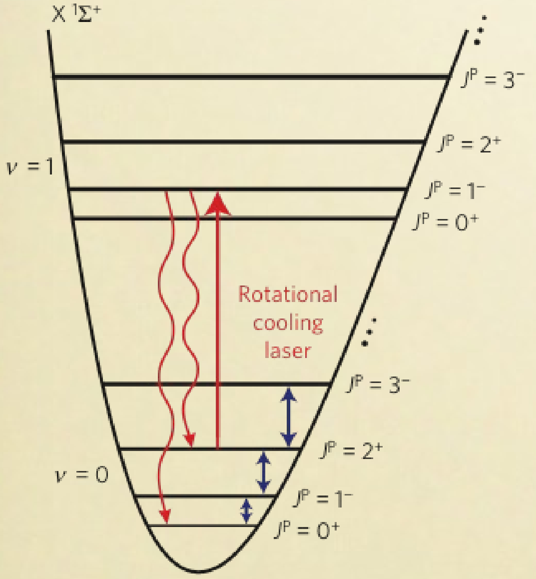


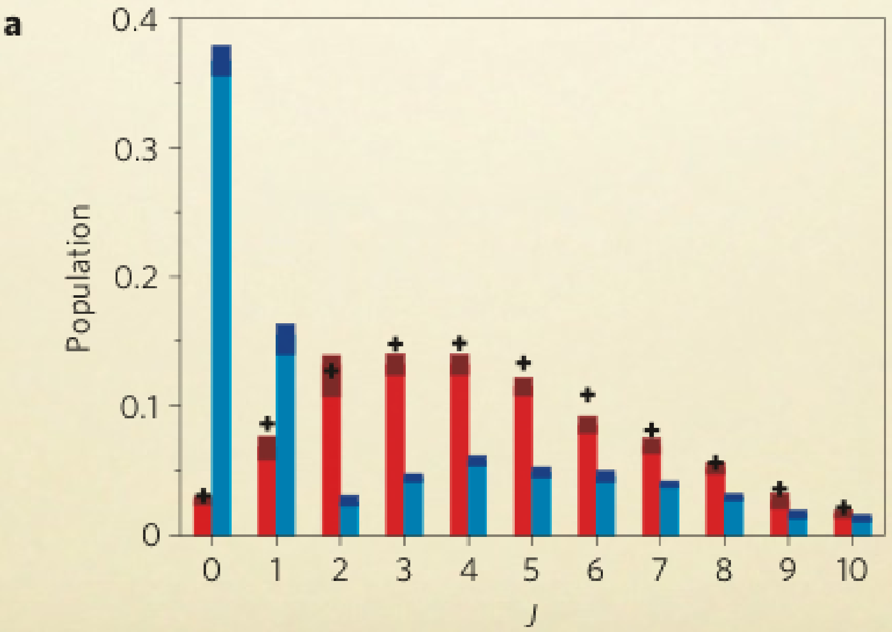
Recent experiments

Molecular ions (MgH^+, HD^+, CaH^+) have recently been cooled and prepared in well-defined rovibrational states:

- Staanum et al. [Drewsen], Nature Phys. **6**, 271 (2010)
- Schneider et al. [Schiller], ibid. **6**, 275 (2010)
- Tong, Winney & Willitsch, PRL (2010)

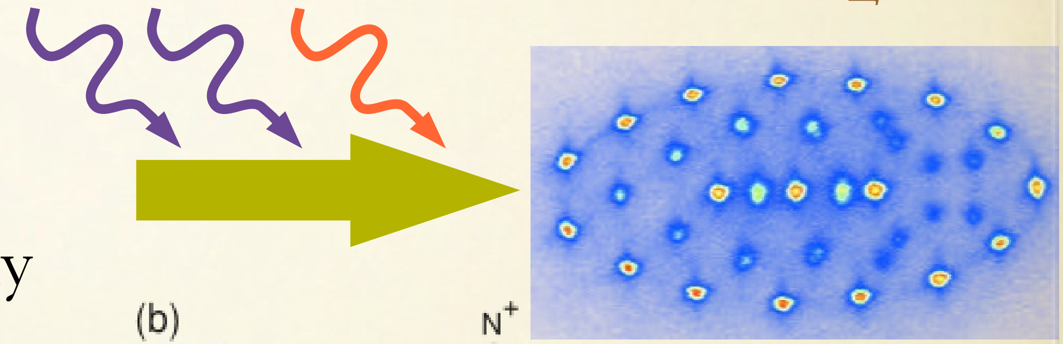


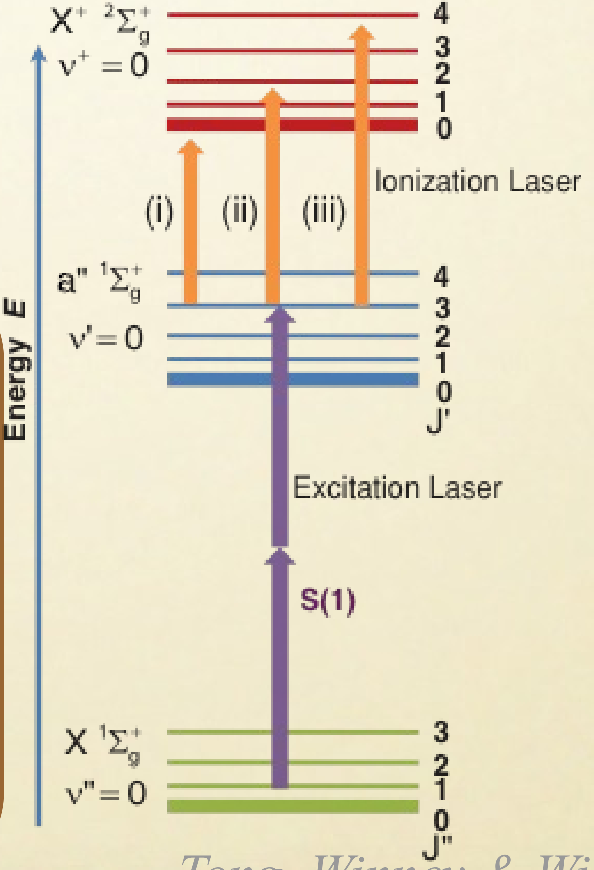




Experiment at Basel with $^{14}N_2^+$

1. N_2 selectively ionized to create N_2^+ in N^+=0,3 rotational states
2. N_2^+ trapped and sympathetically cooled with Ca^+





N_2^+ ions are prepared in ground

Electronic state	$X\ ^2\Sigma_g^+$
Vibrational state	$v = 0$
Rotational state	$N = 0$

Population > 90%

Tong, Winney & Willitsch, PRL (2010)

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1. N_2 selectively ionized to create N_2^+ in N^+=0,3 rotational states
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3. N_2^+ detected by LICT with Ar — **destructive detection!**

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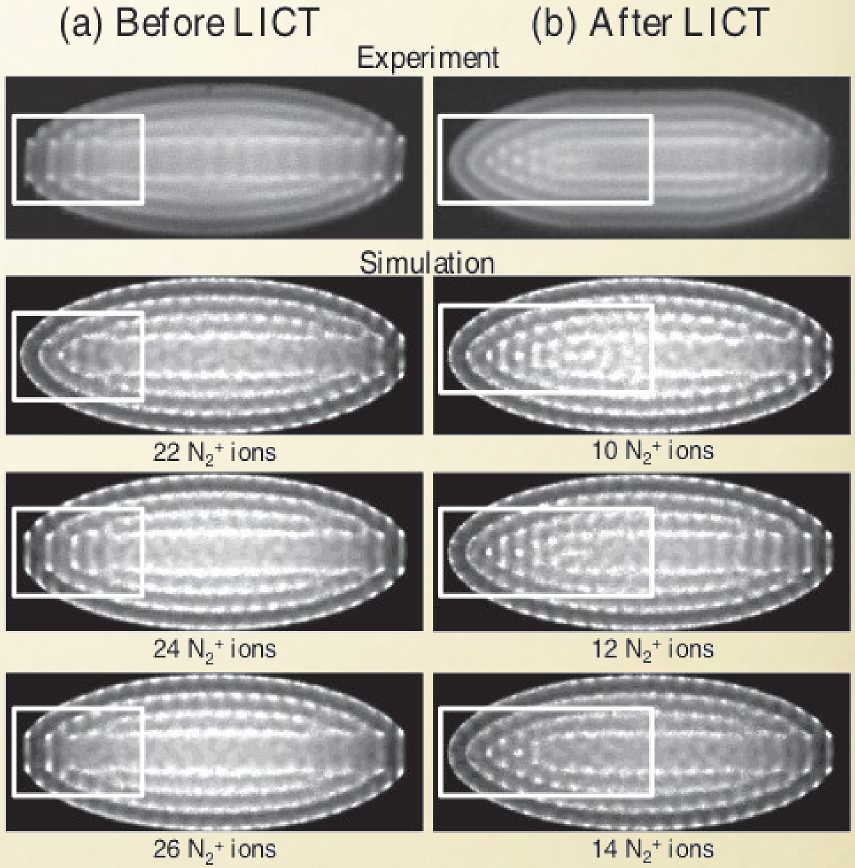
Population > 90%



Tong, Winney & Willitsch, PRL (2010)

Our goal

Measure the molecular ion state without destroying it.

Can we design a ***non-destructive*** *detection protocol?*

Recall how atomic ions are measured

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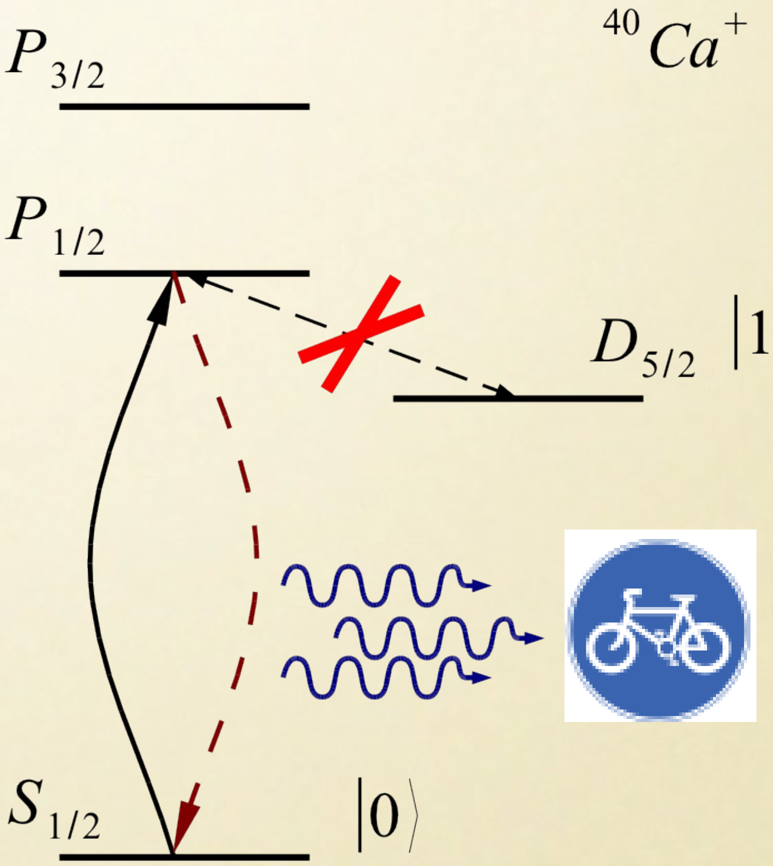
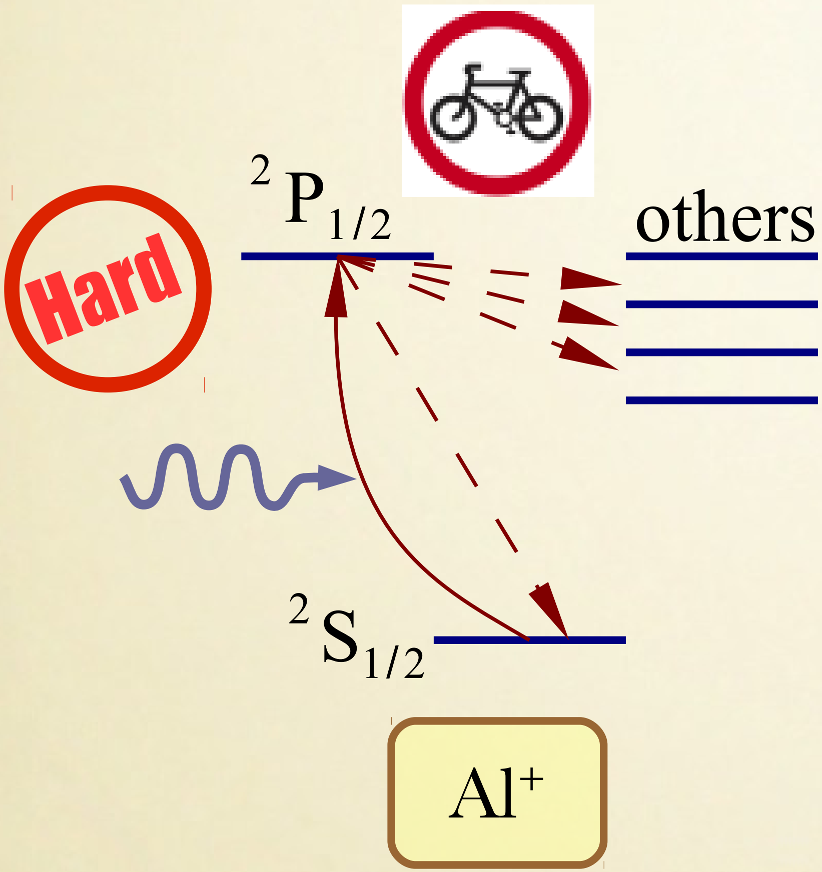
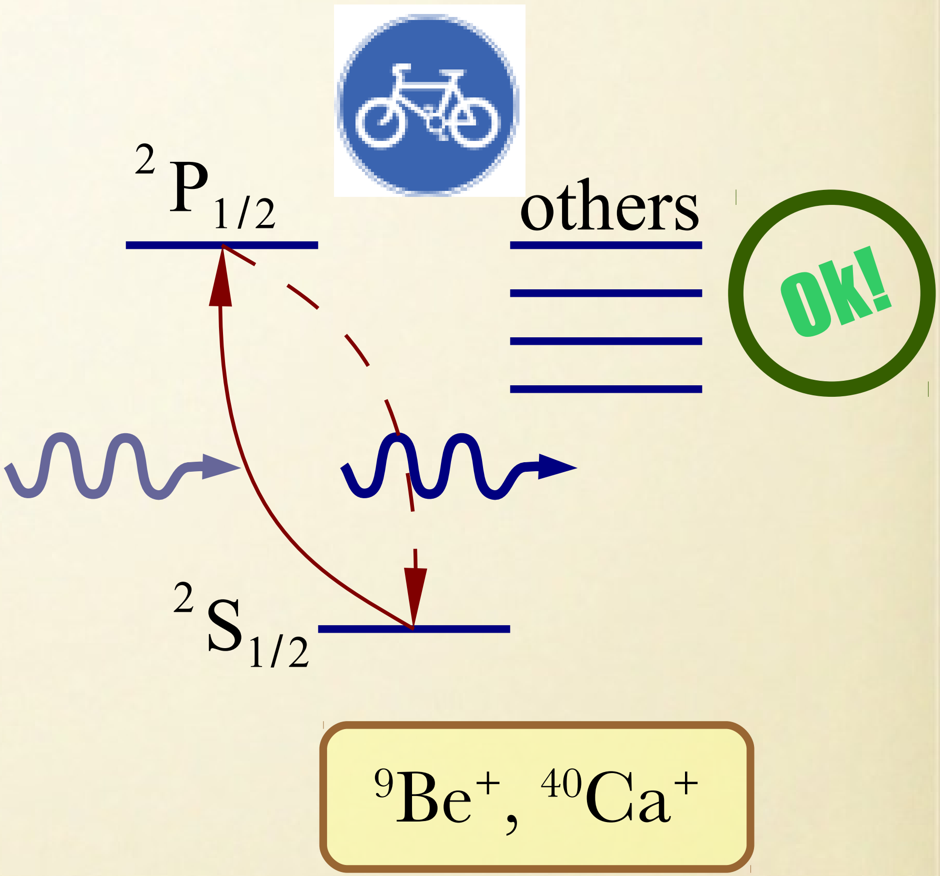


More complex ions



Al^+

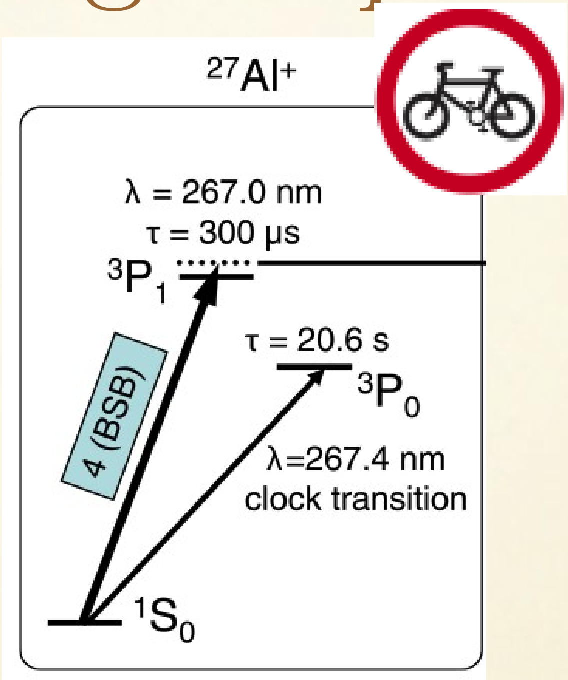


$^9\mathrm{Be}^+$, $^{40}\mathrm{Ca}^+$

Not all ions have “cycling transitions” which allow such accurate determination of the dynamics as in trapped ion QIPC experiments.

Quantum Logic Spectroscopy

How to access ${}^1S_0 \rightarrow {}^3P_{0,1}$ ${}^{27}Al^+$ transitions ?



- Good spectroscopy transitions
- But no efficient state detection!

P. O. Schmidt et al, Science **309**, 749 (2005)
T. Rosenband et al, PRL **98**, 220801 (2007)

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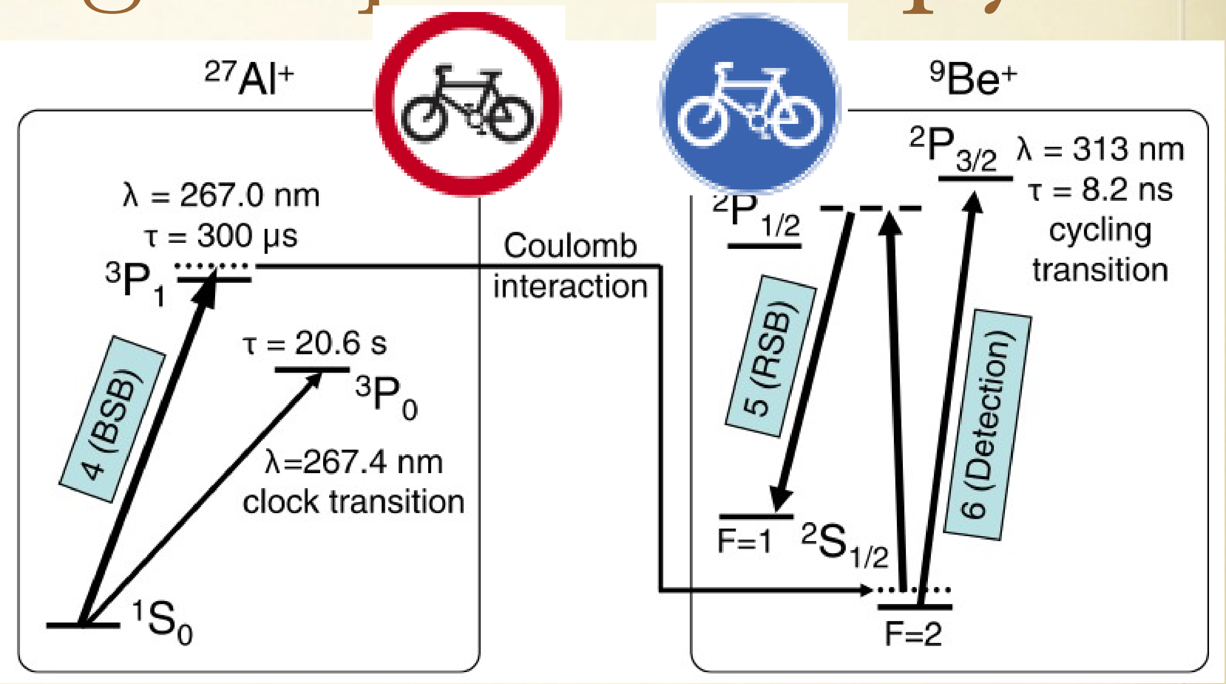
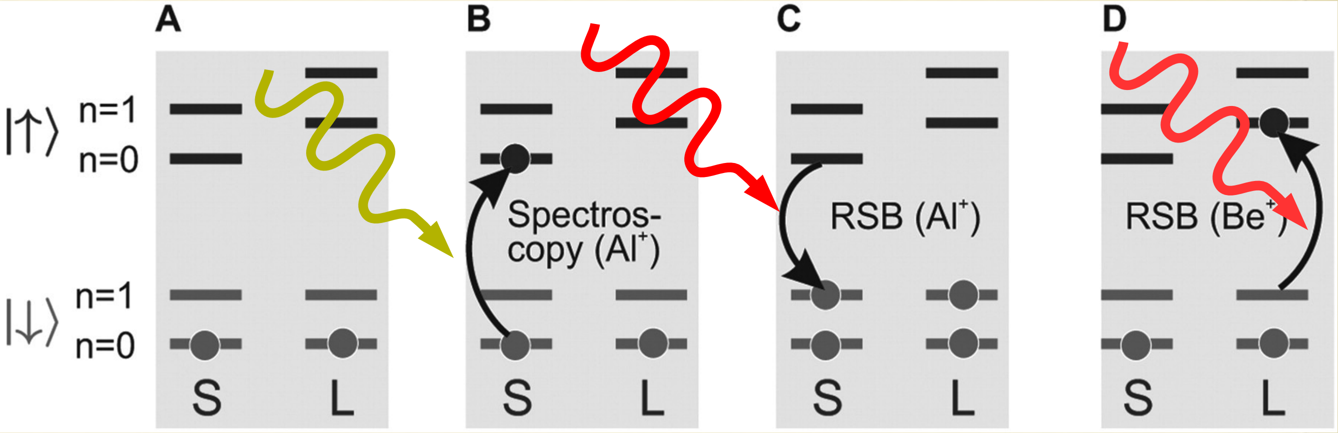


Let there Be+ !

Couple Al+ (S) and
Be+ (L) via normal modes

NB: Needs g.s. cooling of motional state



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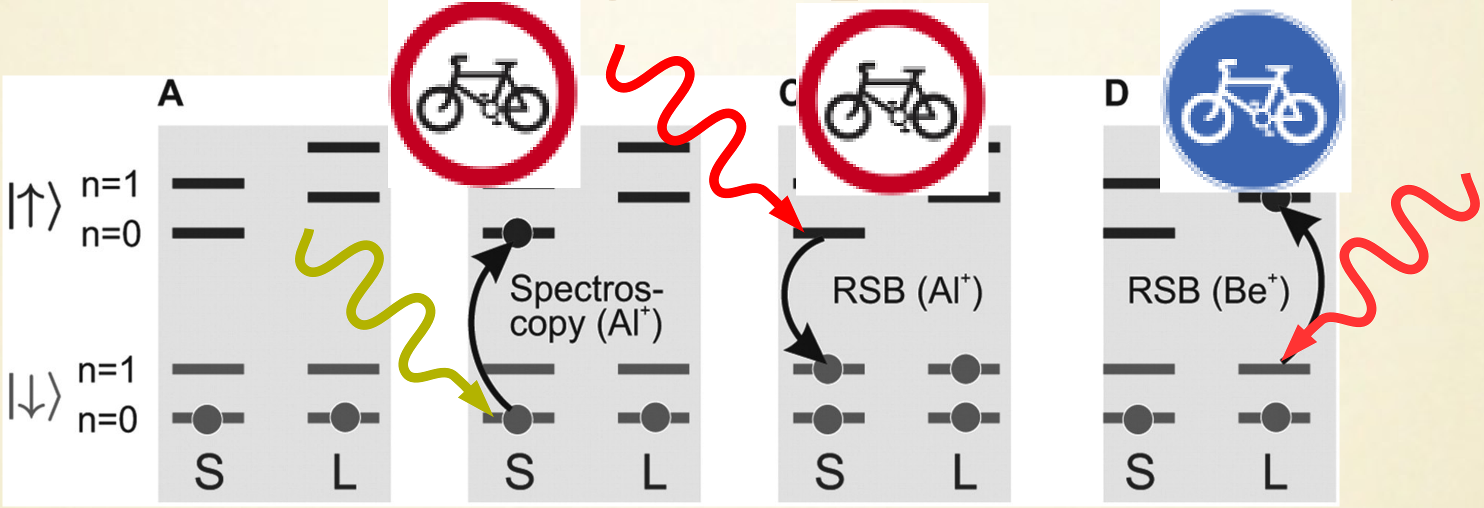


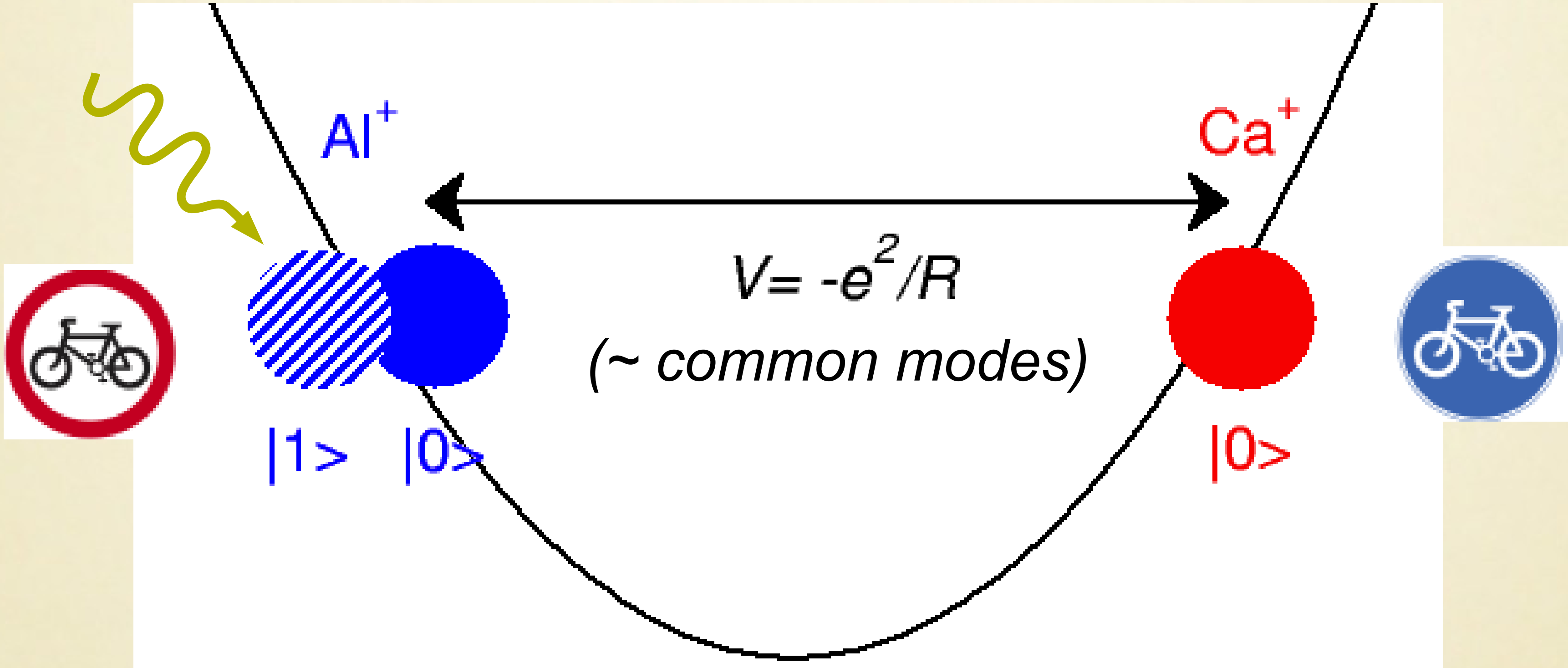
Idea: Use quantum gates to map the state of a "difficult" ion (e.g., Al^+) to a well controlled one ($^9Be^+$).

Drawbacks: Using motional states as quantum bus:

- Temperature sensitive (requires sideband cooling)
- Slow: 🕖 gate time ~ 1/trap freq *(energy must go from S to L)*
- Only works for relatively simple "difficult" ions

P. O. Schmidt et al, Science **309**, 749 (2005)
T. Rosenband et al, PRL **98**, 220801 (2007)

QLS: Physical Picture



- We apply a force (laser) on the ***first ion*** (S=Al+)
- But the ***second*** knows about it. How? **Common modes!**
- Force on 1st ion → ion moves → Coulomb force changes → 2nd ion moves too

P. O. Schmidt et al, Science **309**, 749 (2005)
T. Rosenband et al, PRL **98**, 220801 (2007)

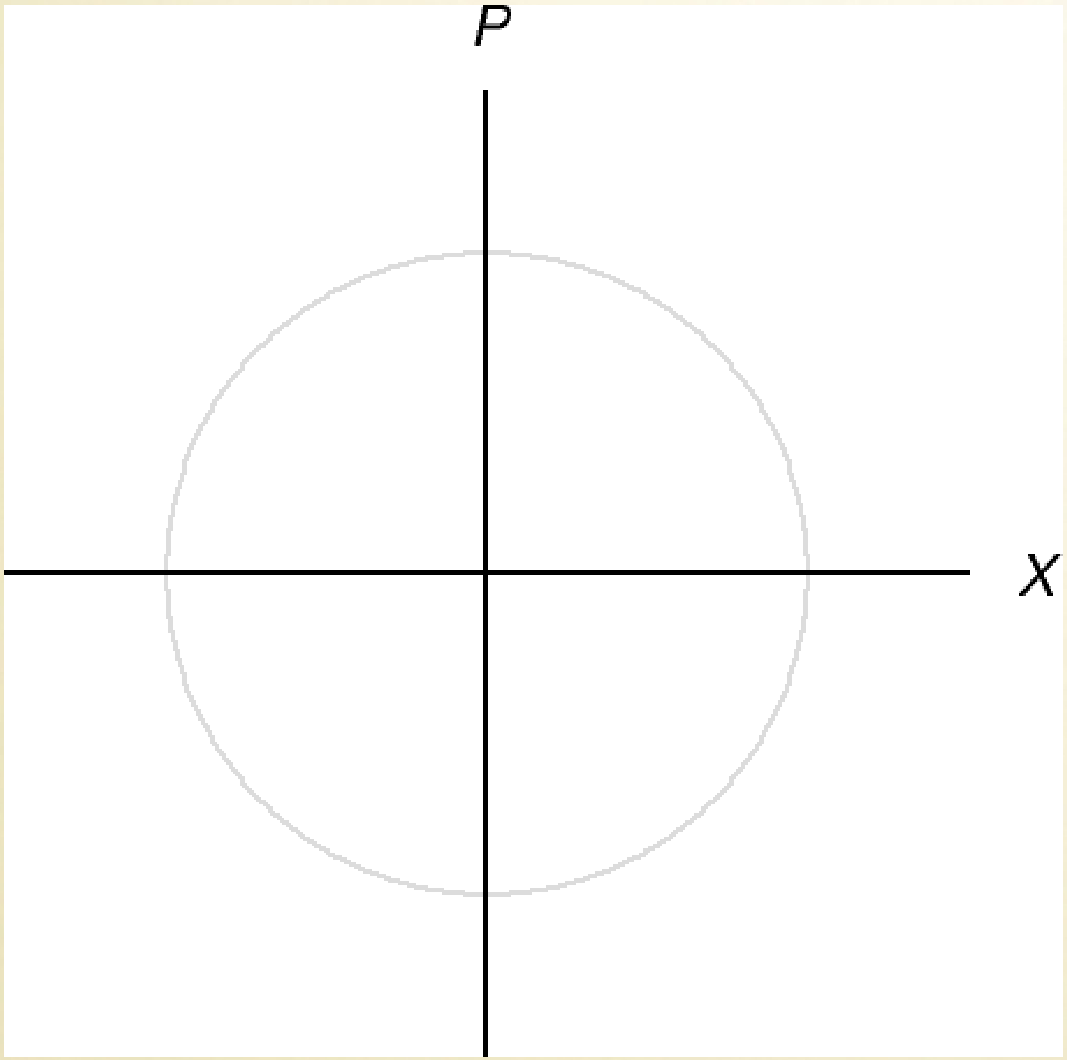
What about more complex systems such as molecular ions?

Quantum phase gates

Ingredients:

1. A harmonic oscillator
2. State-dependent forces
3. Molecular structure calculations

Two-qubit gates

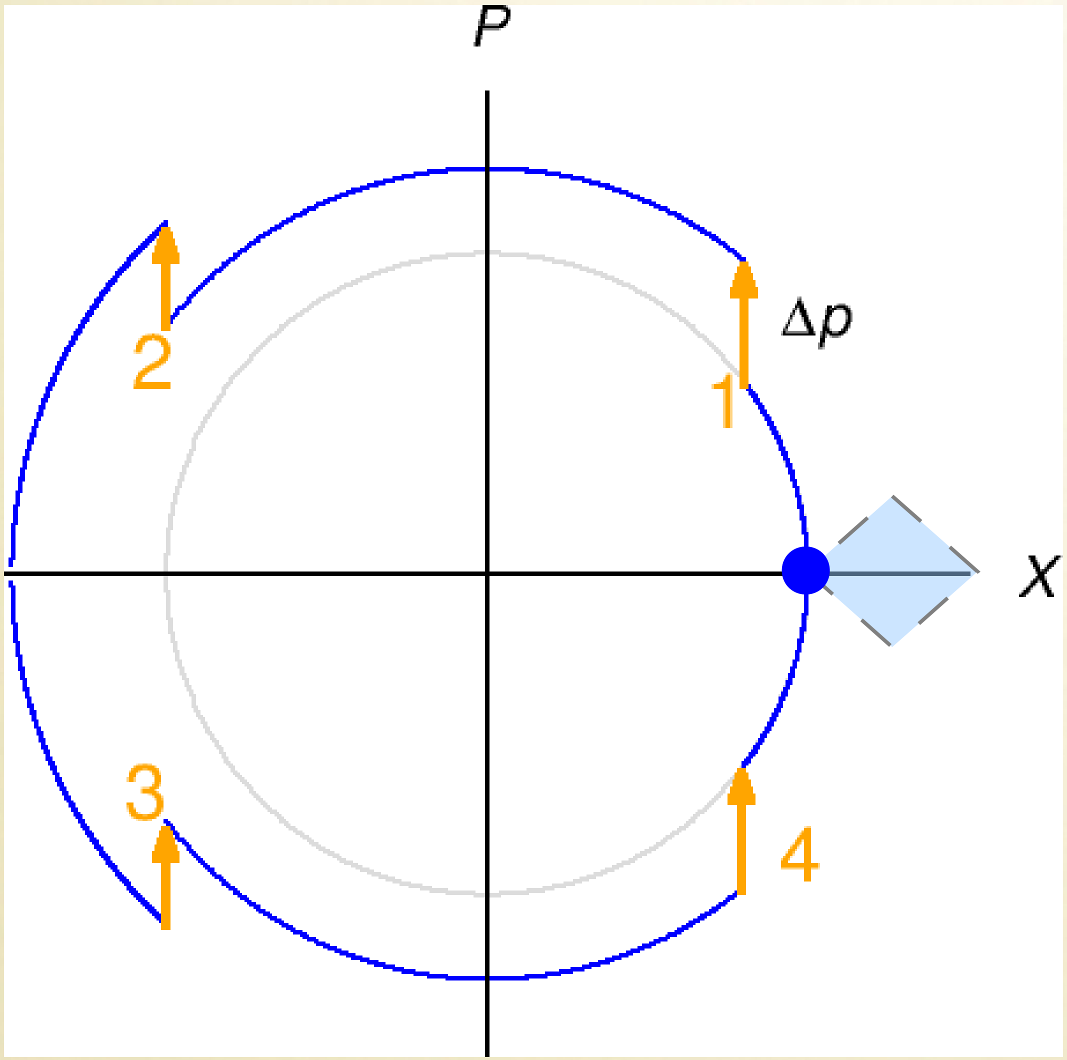


Ingredients:

- Two ions in a trap
- Coulomb interaction

Description as Normal modes
(harmonic oscillators)

A force on a harmonic oscillator



- Phase-space route is changed
- State acquires a phase
- The phase is geometric

= Area

J. Pachos, P. Zanardi, Int. J. Mod. Phys. ***B15*** *1257-1286 (2001)*
D. Leibfried et al., Nature ***422****, 413 (2003)*
J. J.García-Ripoll, P. Zoller, I. Cirac, PRL ***91****, 157901 (2003)*

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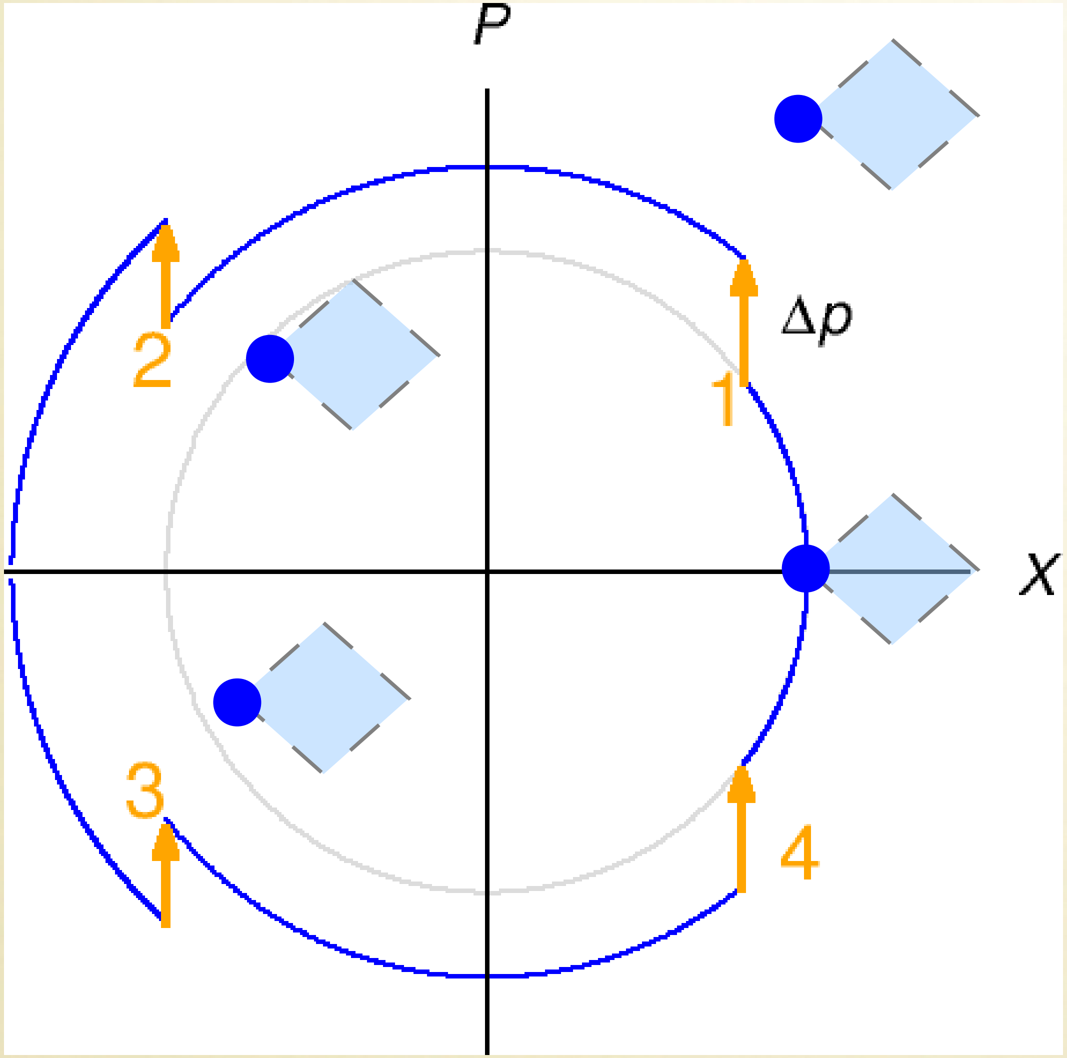
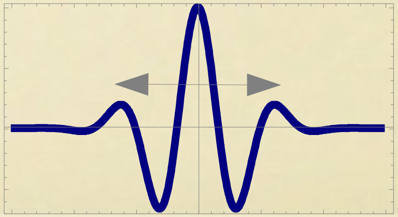


- Phase-space route is changed
- State acquires a phase
- The phase is geometric

  = Area
- Indep. initial state
- Temperature independent
- Also continuous forces



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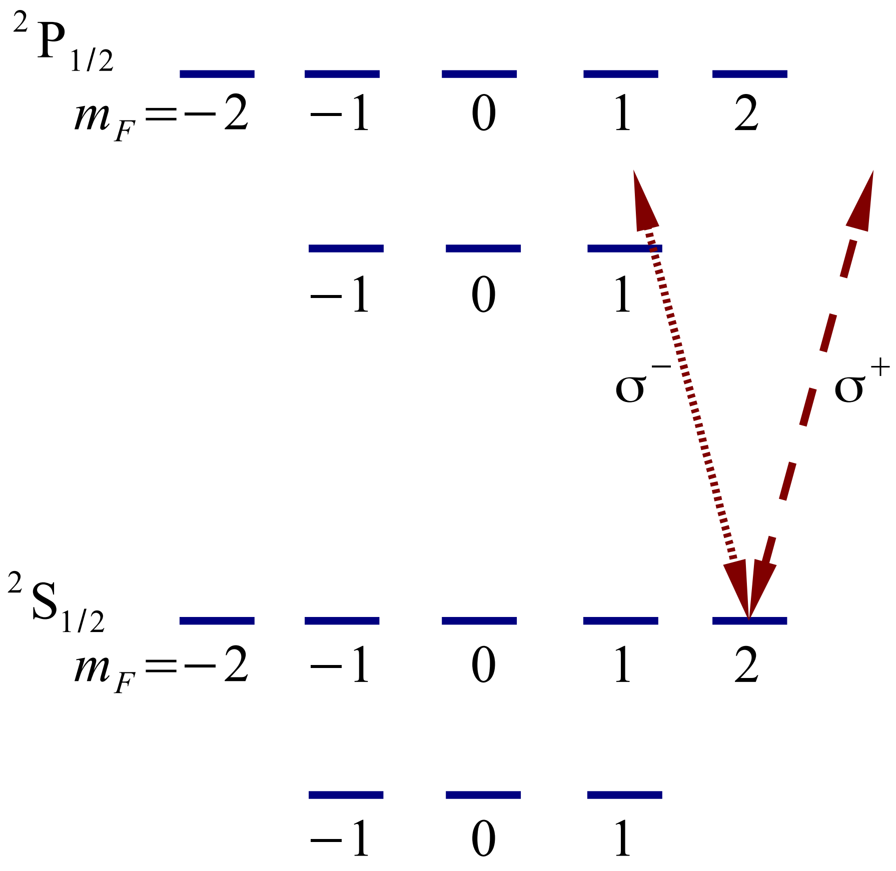
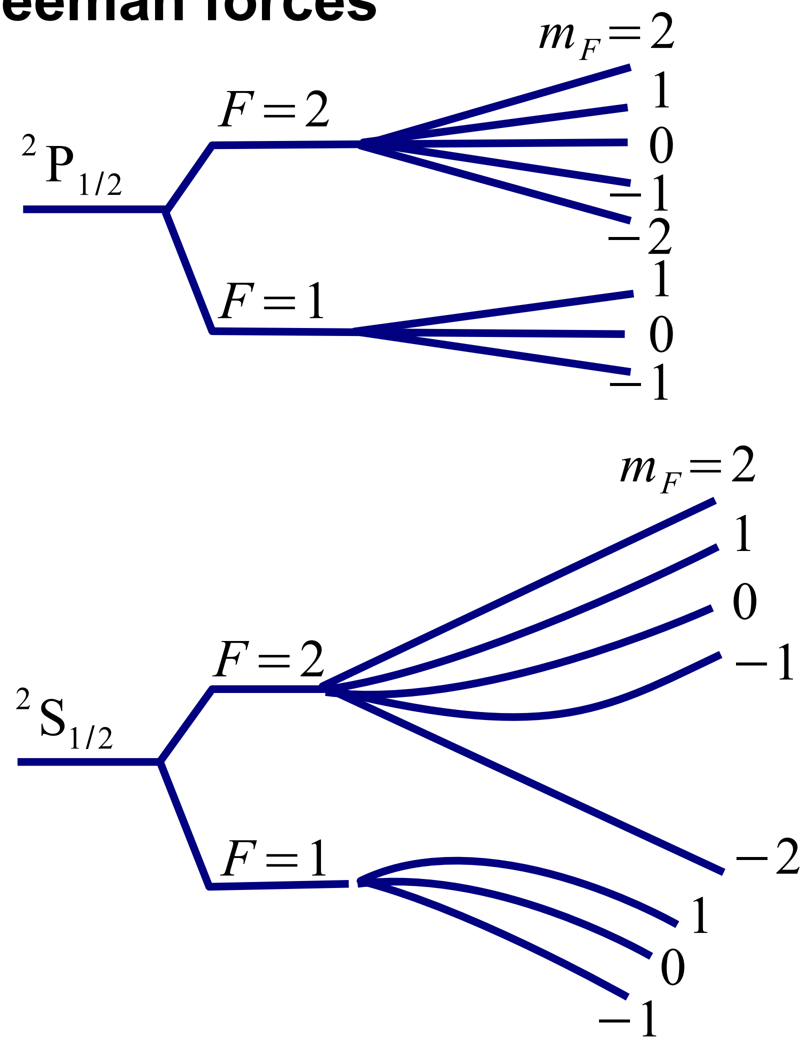
State-dependent forces

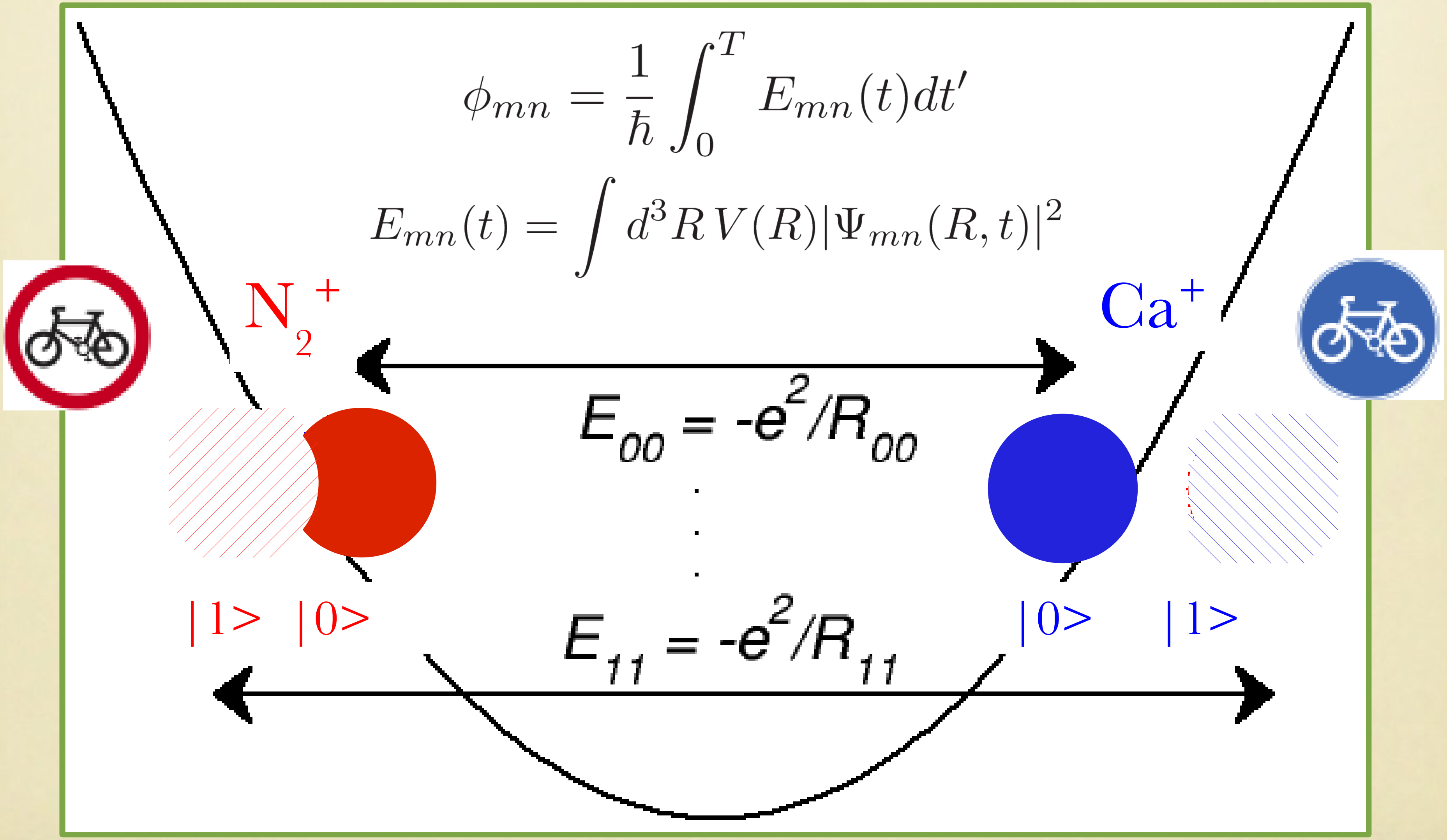
Optical (AC-Stark) forces



Zeeman forces



Physical picture: State-dep. *forces* lead to state-dep. *phases*



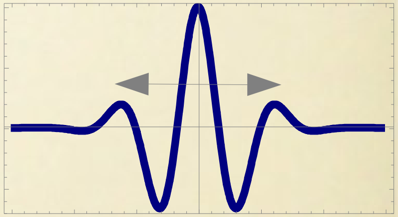
$$\phi_{mn} = \frac{1}{\hbar}\int_0^T E_{mn}(t)dt'$$

$$E_{mn}(t) = \int d^3R\,V(R)|\Psi_{mn}(R,t)|^2$$

Phase accumulated by two driven ions

$f_1(t) \propto O$

$f_2(t) \propto \sigma_2^z$



A function of the product of both forces:

$$\Phi_O = \mathrm{Im} \int_0^T \int_0^t G(|t - t'|) f_1(t) f_2(t') dt dt'$$

$$G(t) = \frac{\sin(\omega_{com} t)}{m\hbar\omega_{com}} - \frac{\sin(\omega_{str} t)}{m\hbar\omega_{str}}$$

*J. J. García-Ripoll, P. Zoller, I. Cirac, PRL **91**, 157901 (2003)*

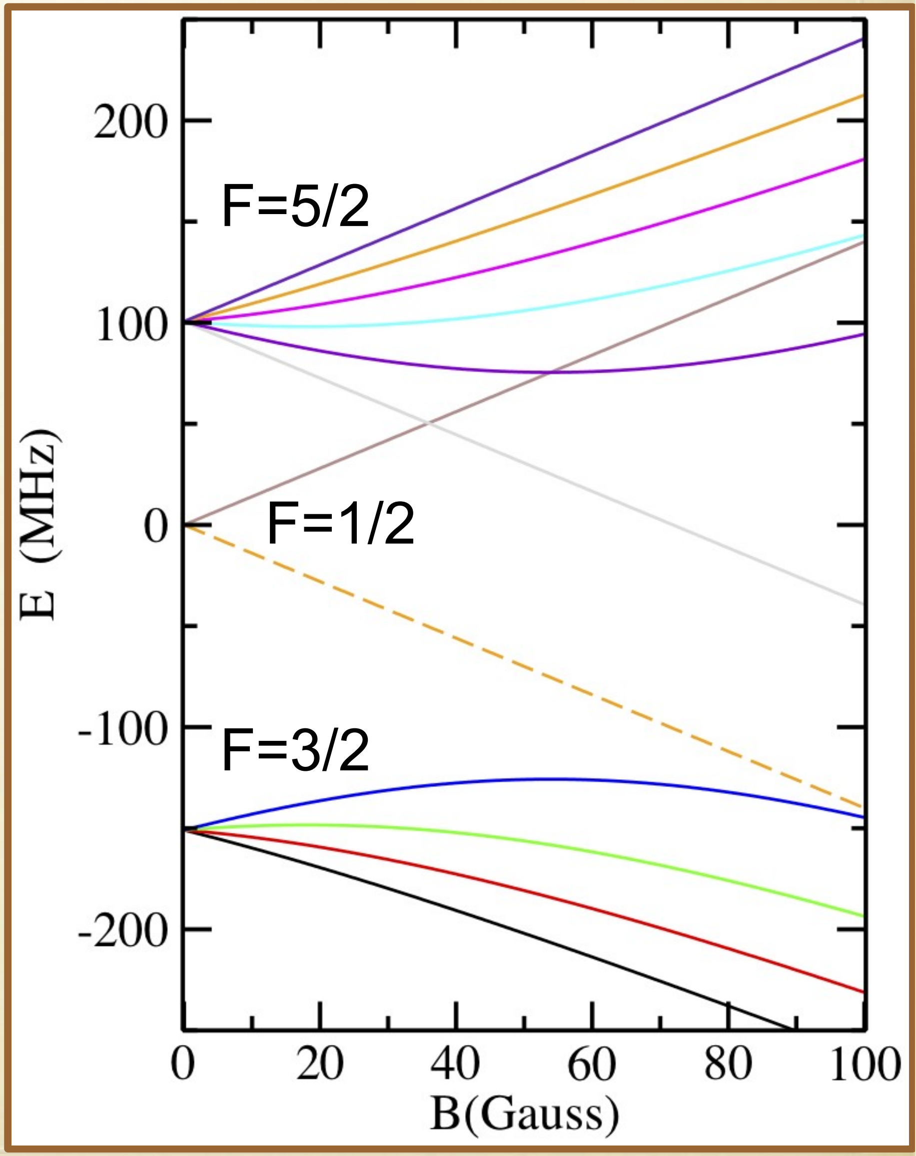
Molecular structure calculations to estimate (state-dep.) forces

We calculated the energy level structure of $^{14}N_2^+$ ($X\ ^2\Sigma_g^+$, v=0) in magnetic field:

$$H = H_{\mathsf{rot}} + H_{\mathsf{sr}} + H_{\mathsf{Z}} + H_{\mathsf{hfs}}$$

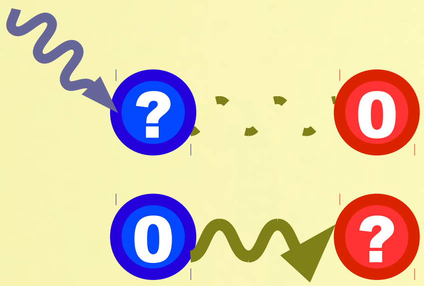
- Nuclear spin: $I_1(^{14}N)=1 \rightarrow I(^{14}N_2^+)=0, 2$
- Rotational ang. mom.: N=0, 2,...
- Hence, total spin F=1/2, 3/2, 5/2,...

Spacing ~100 MHz ~ 4.8 mK ~ T

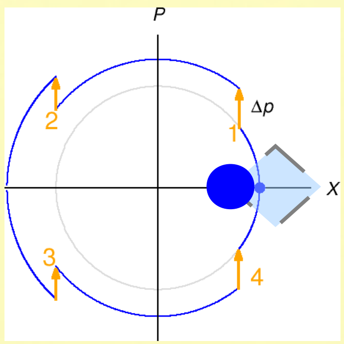


*J. Mur-Petit et al., PRA **85**, 022308 (2012)*

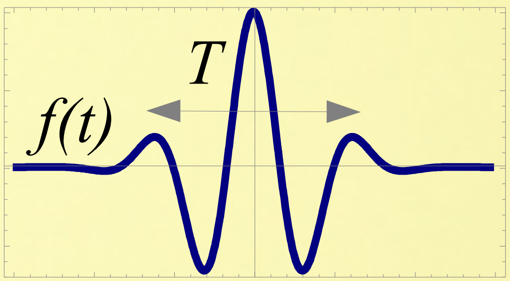
All together now!



QLS



Phase gates

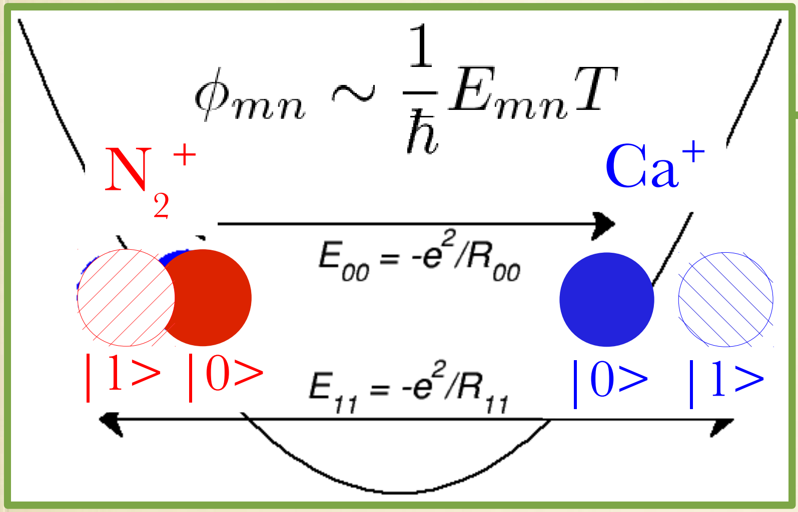


State-dep. forces (+ molec. struct.)

A new spectroscopy protocol

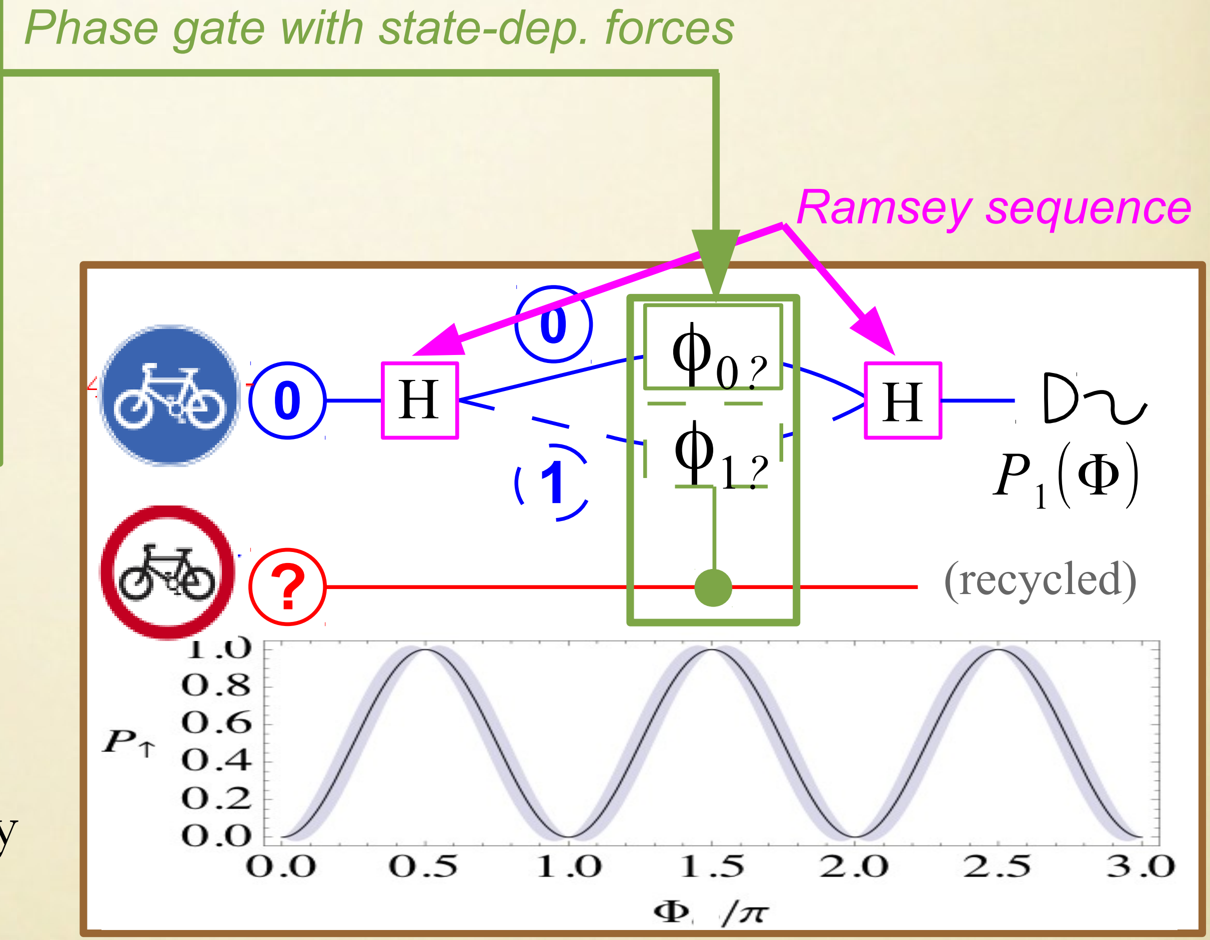
A new spectroscopy protocol

Quantum Logic Spectroscopy + State-dependent forces =
a **Non-destructive measurement protocol**



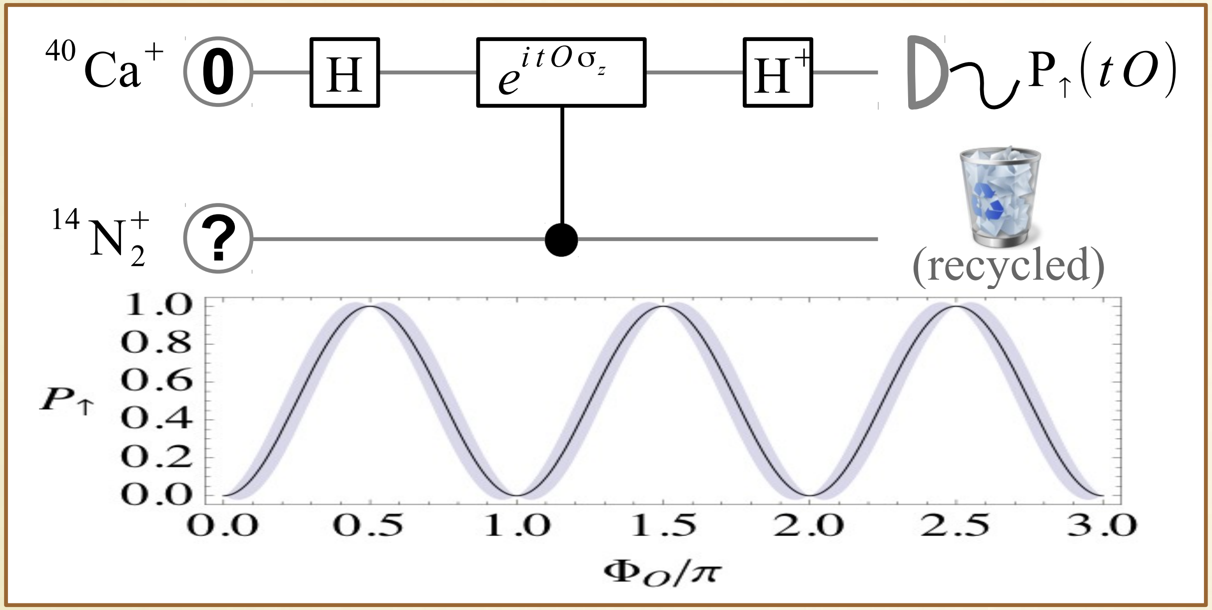
Recall: State-dependent forces lead to state-dependent phases ϕ_{mn}

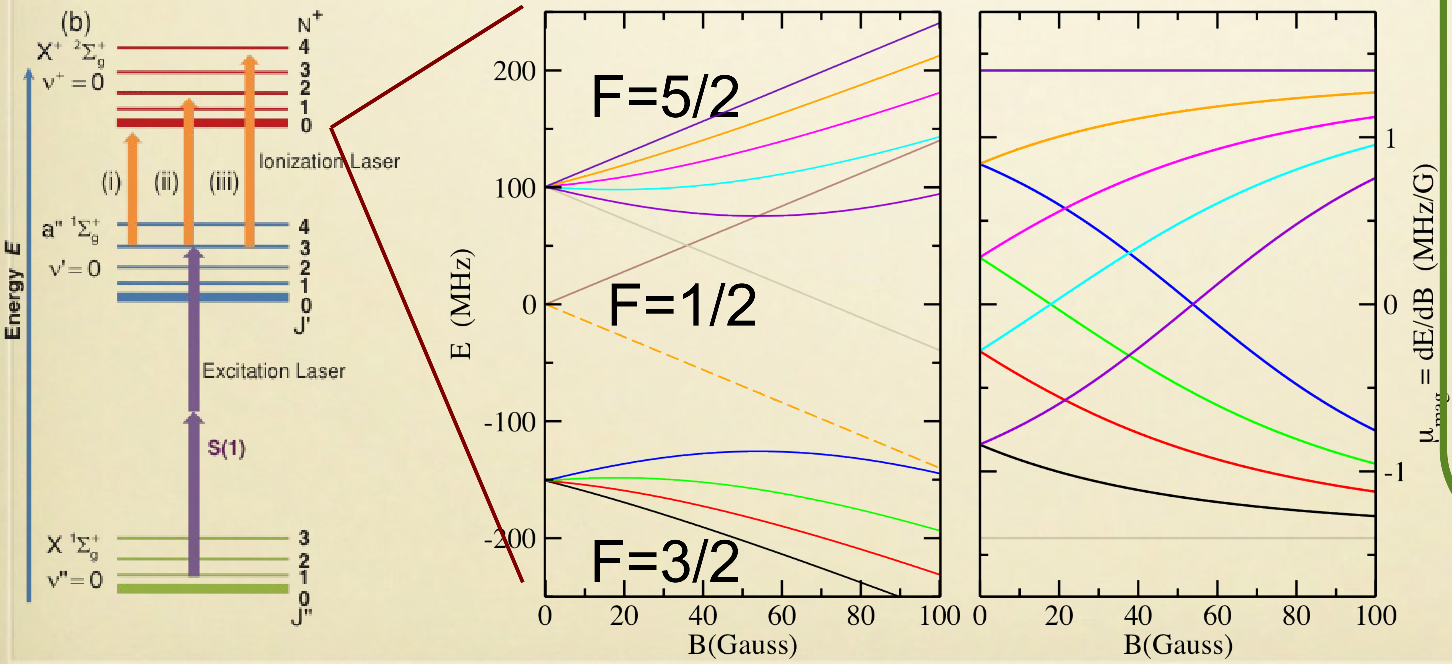
- No use of sidebands
  ⇨ **No need of cooling**
- Phase is measured, No energy transferred ⇨ **Fast** ⏲



J. Mur-Petit et al., PRA 85, 022308 (2012)

How it works – Probing Zeeman levels





1. Measure $P_\uparrow$

$O=\mu$

2. Obtain Φ_O

$\Phi_O=\Phi_O(f1,f2)$

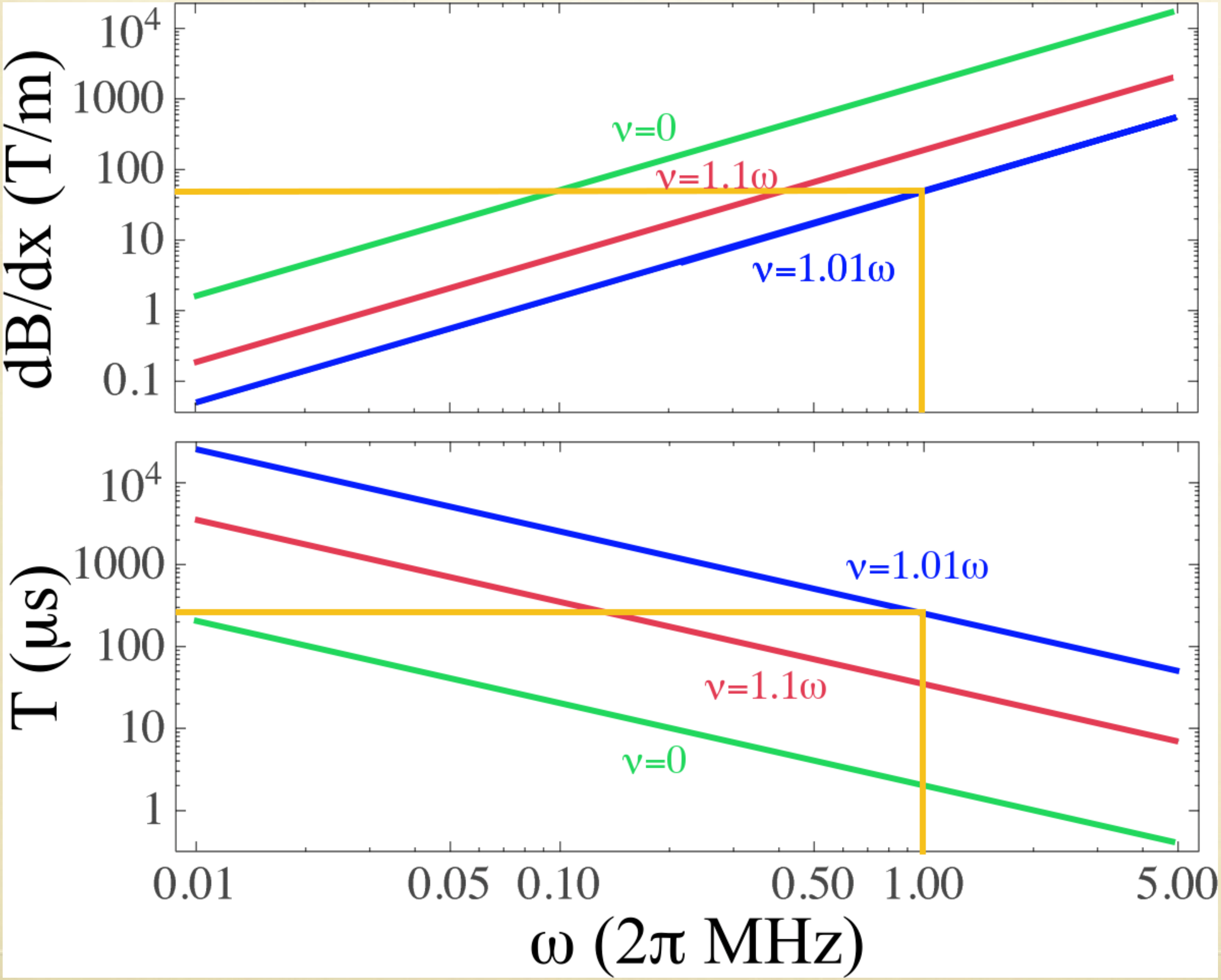
3. Deduce μ_{mag}

Structure calculations

4. Know your quantum state

[PRA **85** 022308 (2012)]

Time and field scales



$^{40}Ca^+$

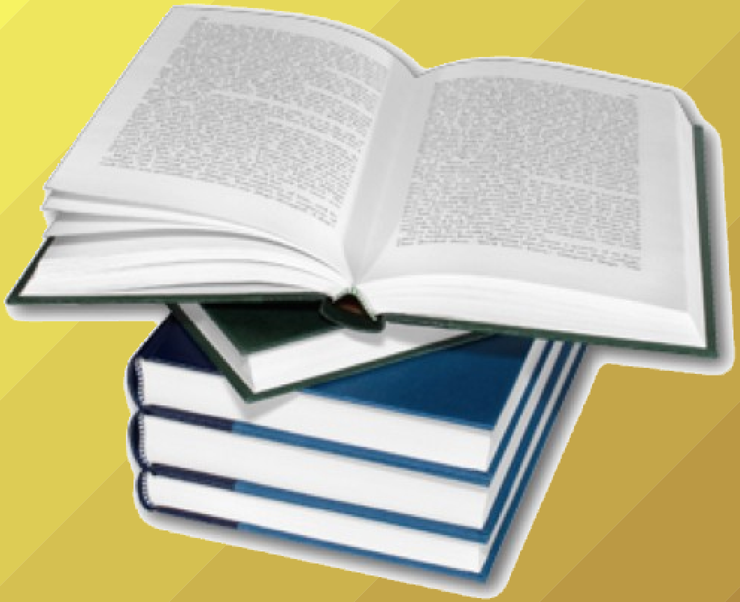
$+$

$^{14}N_2^+$

PRA **85** 022308

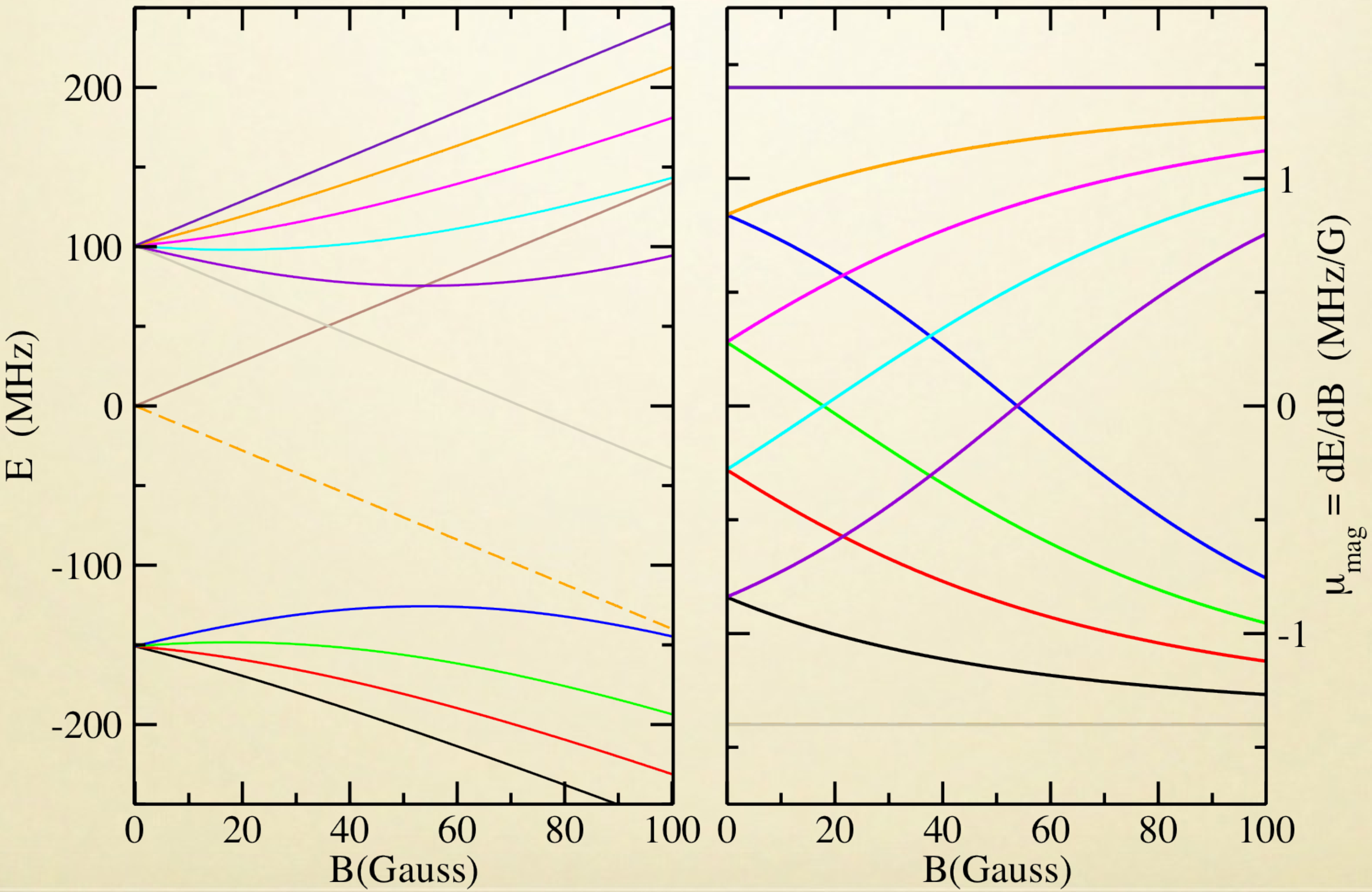
Outline

- Controlled collisions — measuring scattering properties
- Trapped molecular ions
- **A molecular ion qubit**
- Ions and polar molecules — measuring a molecule's EDM



When will a $^{14}N_2^+$ qubit decohere?

Molecular structure calculations for $^{14}N_2^+$ ($^2\Sigma_{1/2}$, v=0, J=1/2) give magnetic moments $\mu_{\mathrm{mag}} \sim \mu_B = 1.4\ \mathrm{MHz/G}$



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With magnetic field fluctuations δB~1 nT *(Häffner et al., Phys. Rep. 2008)*, dephasing becomes relevant after a time

$$|0\rangle + e^{i\phi(t)}|1\rangle$$

$$\phi(T) = \frac{\Delta\mu_{\mathsf{mag}}\delta B}{\hbar}T = 1\ \mathsf{rad}$$

$$T \sim 1\ \mathsf{ms}$$

Similar to the case of atomic ions.
Can we do better?

The case of $^{16}\mathrm{O}_2^+$

Back to our molecular hyperfine structure Hamiltonian

$$H = H_{\mathsf{rot}} + H_{\mathsf{sr}} + H_{\mathsf{Z}} + \xcancel{H_{\mathsf{hfs}}} + H_{\mathsf{so}} + H_{\Lambda-\mathsf{doubl}}$$

$^{16}\mathrm{O}_2$ has nuclear spin I=0: no hyperfine structure.

But g.s.=$^2\Pi$ (Λ=1): there are couplings to electronic rotation!

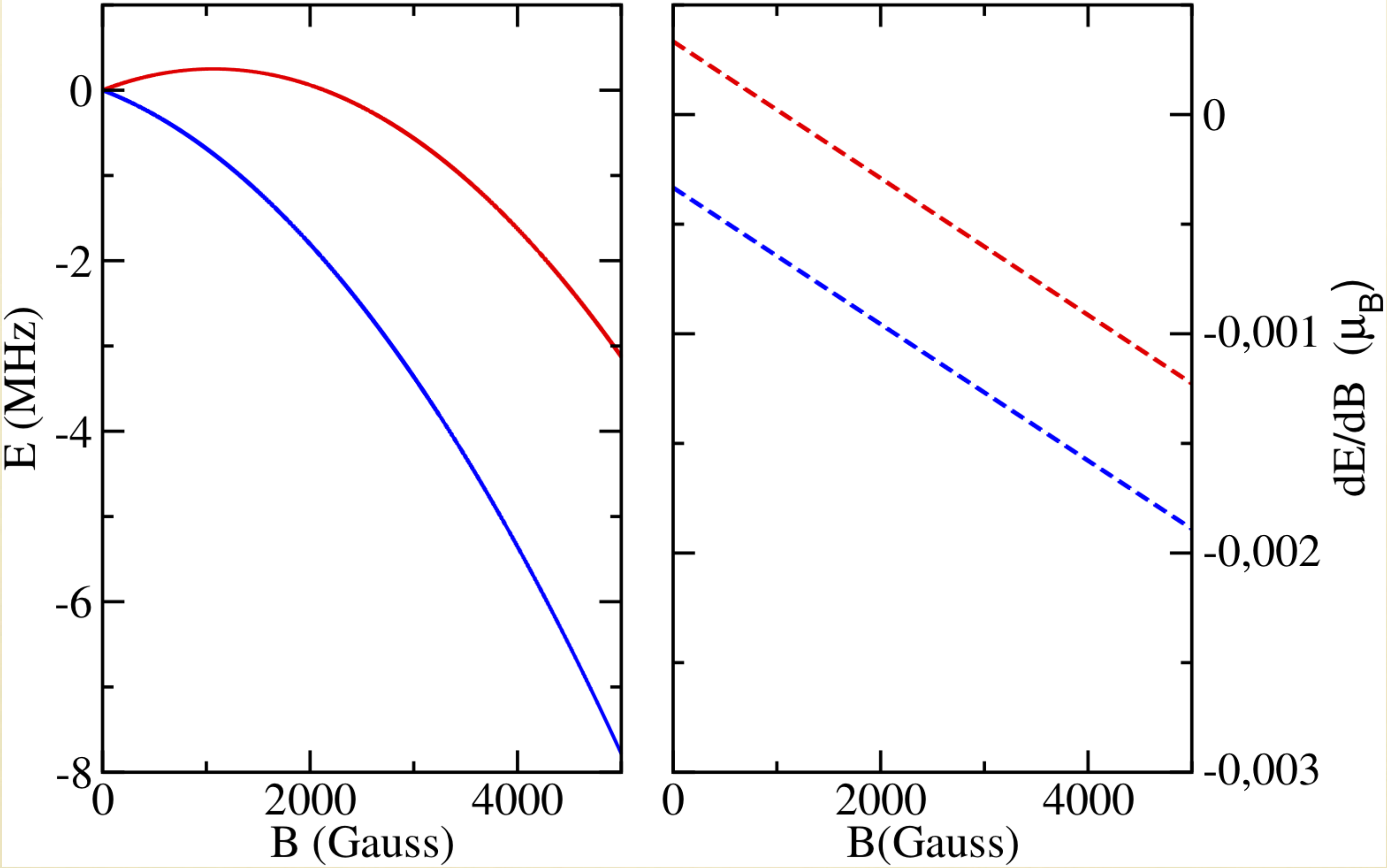
Zeeman levels of lowest rovibronic state (next one is ~12 K above):

Molecular parameters from J. A. Coxon and M. P. Haley, J. Mol. Spectrosc. 108, 119 (1984)

The case of $^{16}O_2^+$

Similar molecular structure calculations for $^{16}O_2^+$ ($^2\Pi_{1/2}$, v=0, J=1/2) give

$$\mu_{\mathsf{mag}} \sim 10^{-3}\mu_B = 1.4\ \mathsf{kHz/G}$$



J. Mur-Petit et al., "Toward a Molecular Ion Qubit" (Springer, 2013)

http://www.springer.com/physics/condensed+matter+physics/book/978-3-642-33136-7

The case of $^{16}O_2^+$

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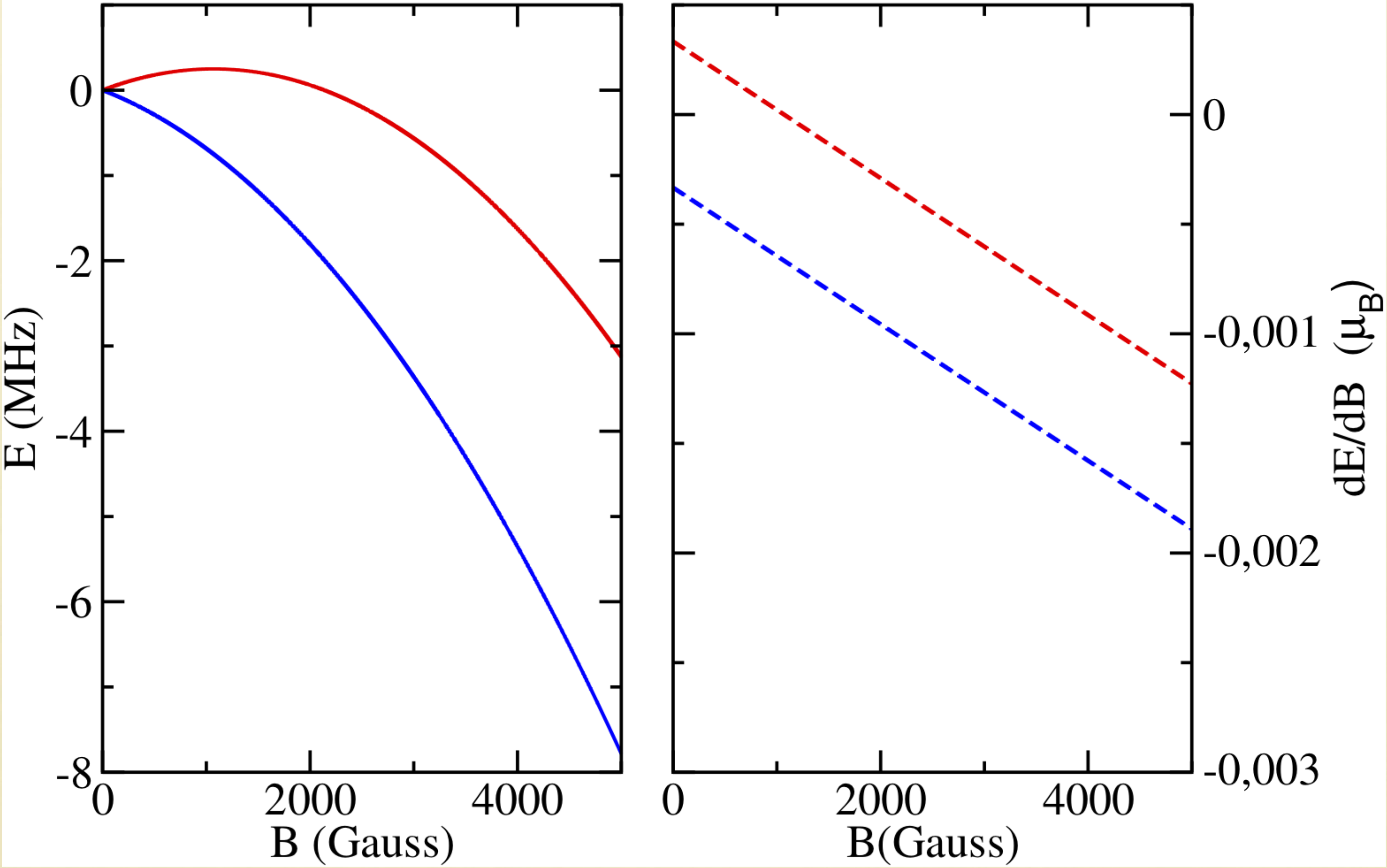
$$\mu_{\mathsf{mag}} \sim 10^{-3}\mu_B = 1.4\ \mathsf{kHz/G} \Rightarrow T \sim 1s$$



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Why this small sensitivity? Or an application to precision measurements

Zeeman Hamiltonian for ${}^{16}O_2^+$:

In a ${}^2\Pi_{|\Omega|}$ state:

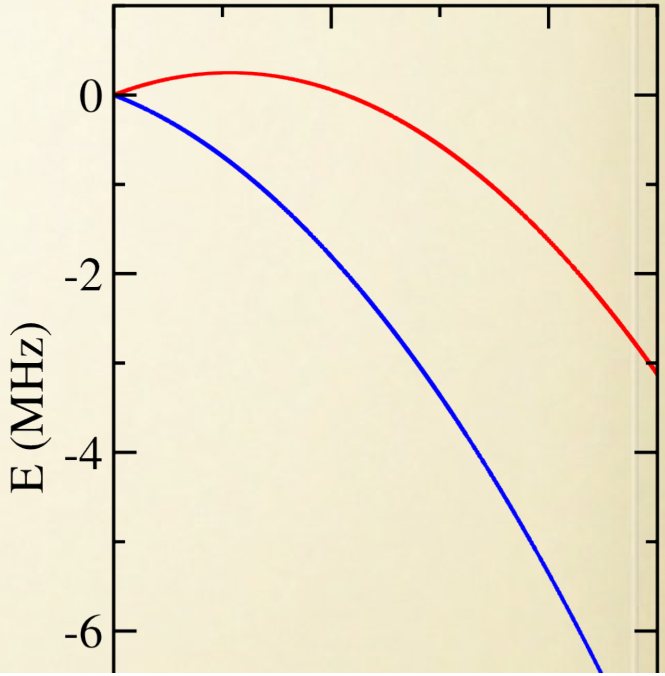
$$\langle {}^2\Pi_{|\Omega'|} J' M \pm | H_Z | {}^2\Pi_{|\Omega|} J M \pm \rangle = \mu_B B_z G(J', J, |\Omega'|, M) \times \\ \times \sum_{q=0,\pm1} \begin{pmatrix} J' & 1 & J \\ -|\Omega'| & 0 & |\Omega| \end{pmatrix} F({}^2\Pi_{|\Omega'|}, {}^2\Pi_{|\Omega|}, q) \; ;$$

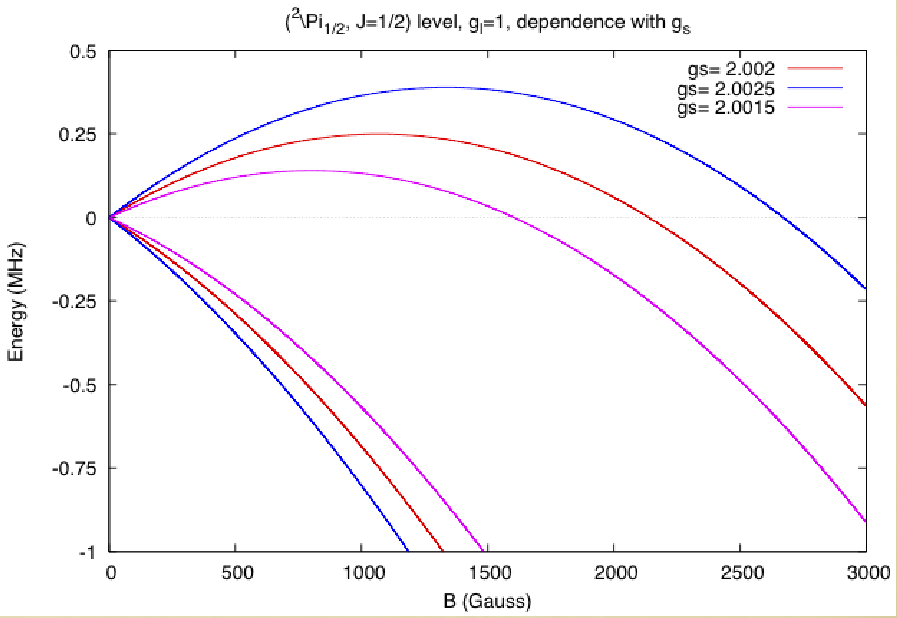
$$F({}^2\Pi_{1/2}, {}^2\Pi_{1/2}, q) = \delta_{q0} \left[g_L - \frac{g_S}{2} \right]$$

Looking for B field such that shift of

$$|X \; {}^2\Pi_{1/2}, v = 0, J = \frac{1}{2}, M = \frac{1}{2} \rangle$$

equals zero → measure g_s or g_L.





Outline

- Controlled collisions — measuring scattering properties
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- **Ions and polar molecules — measuring a molecule's EDM**

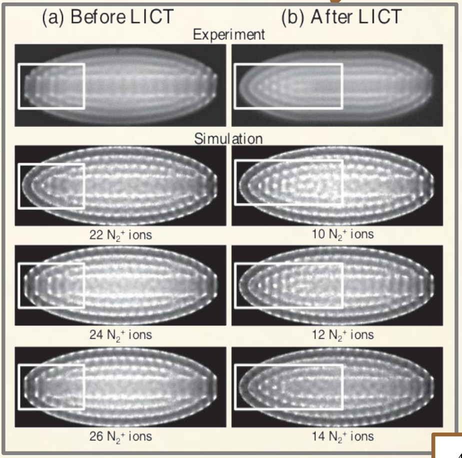
Measurement and control of polar molecules with atomic ions

(work in progress – comments welcome!)

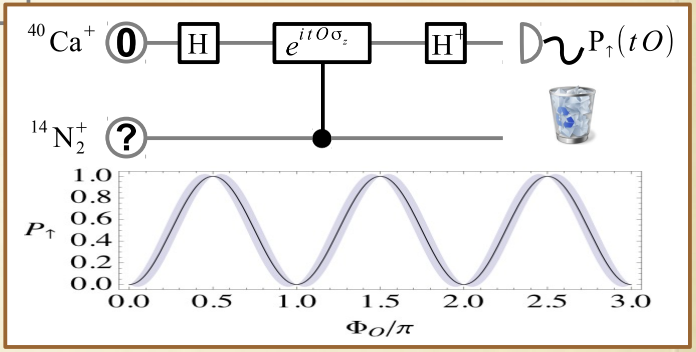
J. Mur-Petit & J. J. García-Ripoll, in preparation

Summary

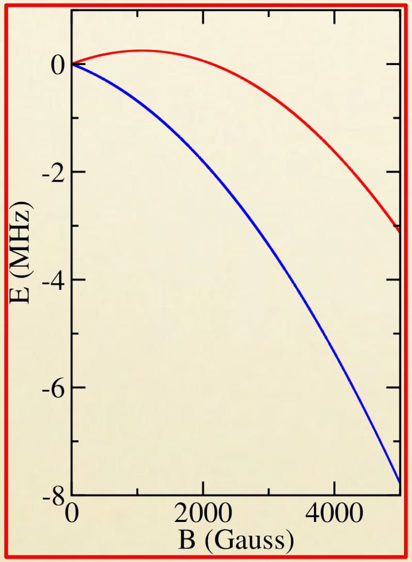
Cold molecules are good for QI



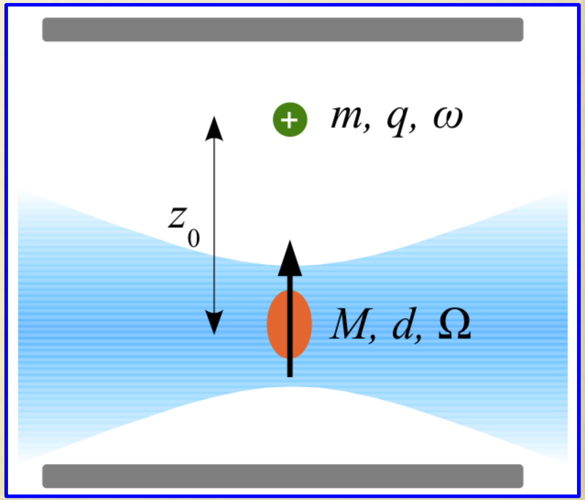
A new quantum spectroscopy protocol



A molecular-ion qubit



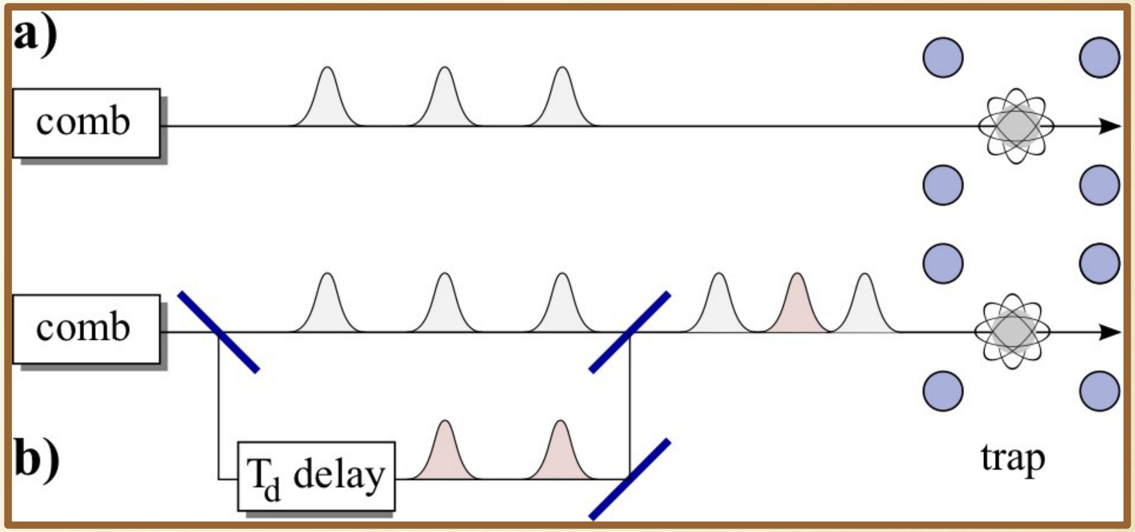
Measuring molecular EDMs



Other projects

Stabilizating a frequency comb with a trapped ion

A Cadarso, JJ Garcia-Ripoll, PO Schmidt



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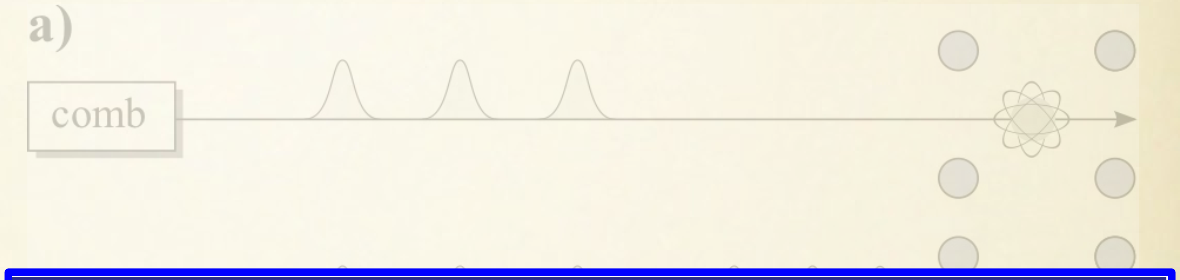
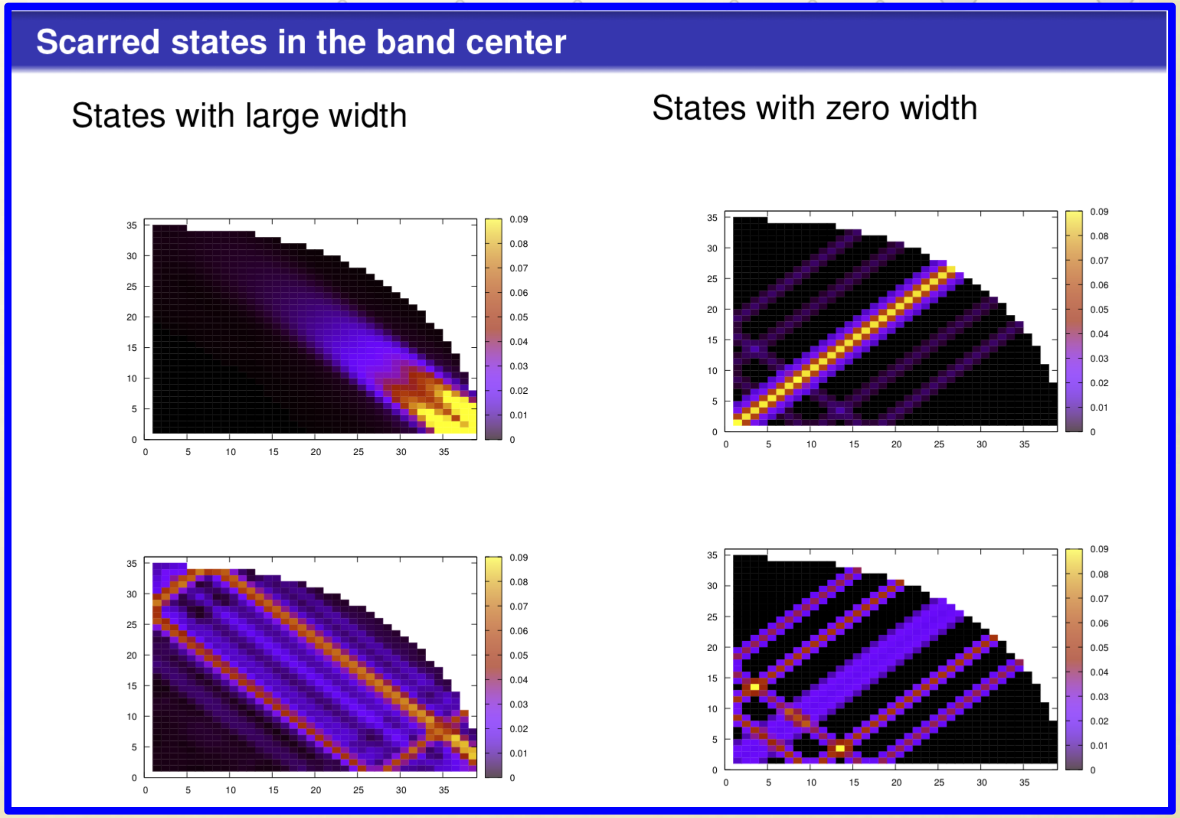
Quantum chaos in optical lattices

V Fernández, JJ Garcia-Ripoll, RA Molina




Scarred states in the band center

States with large width

States with zero width

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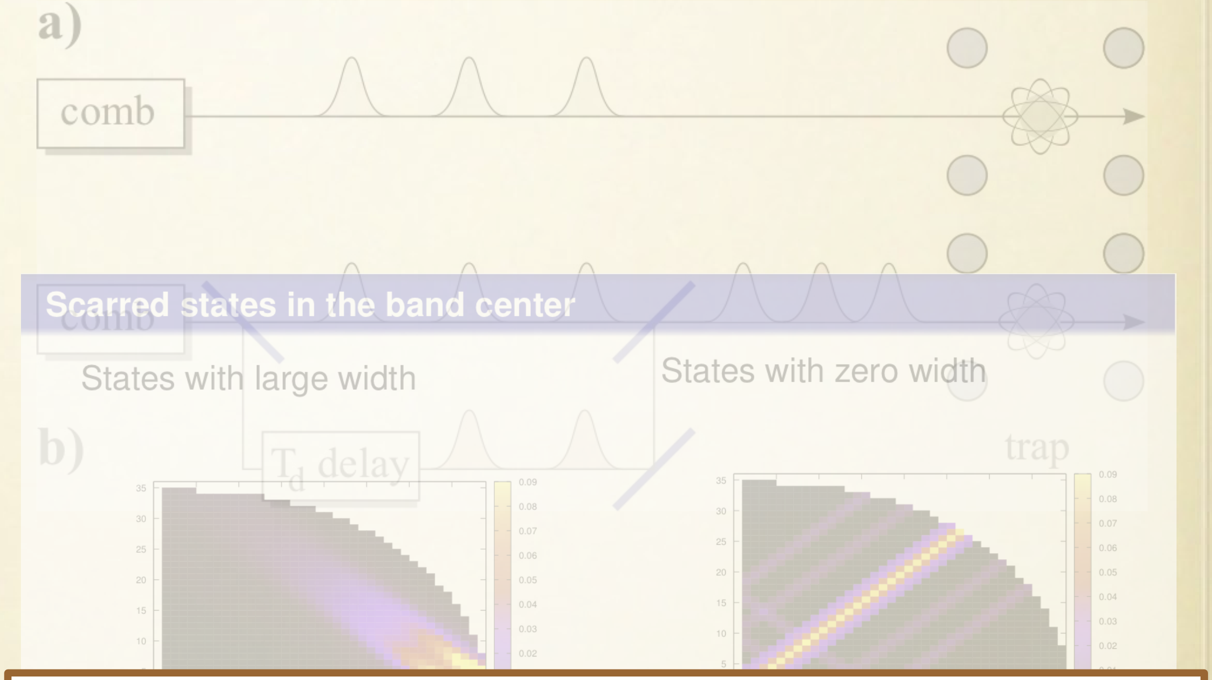
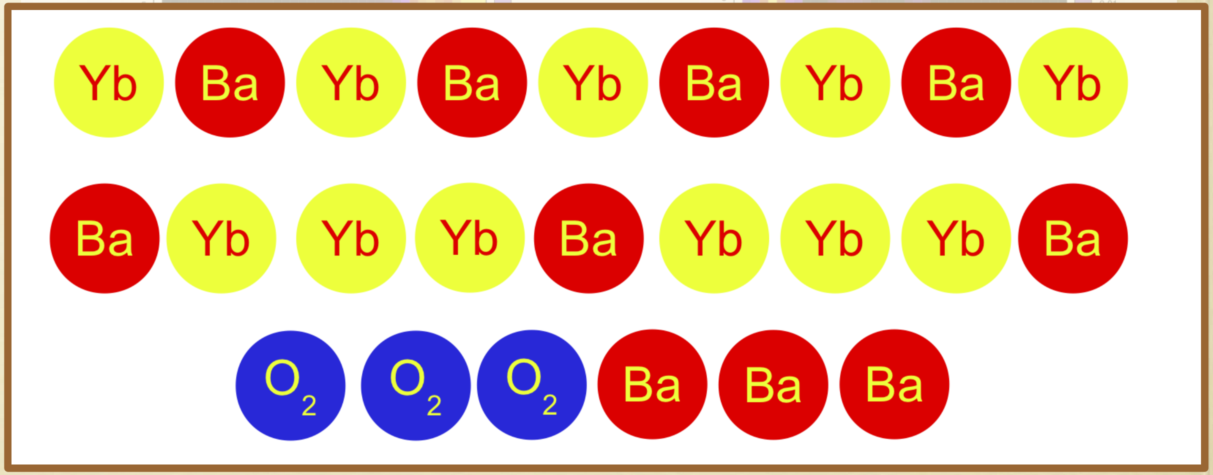
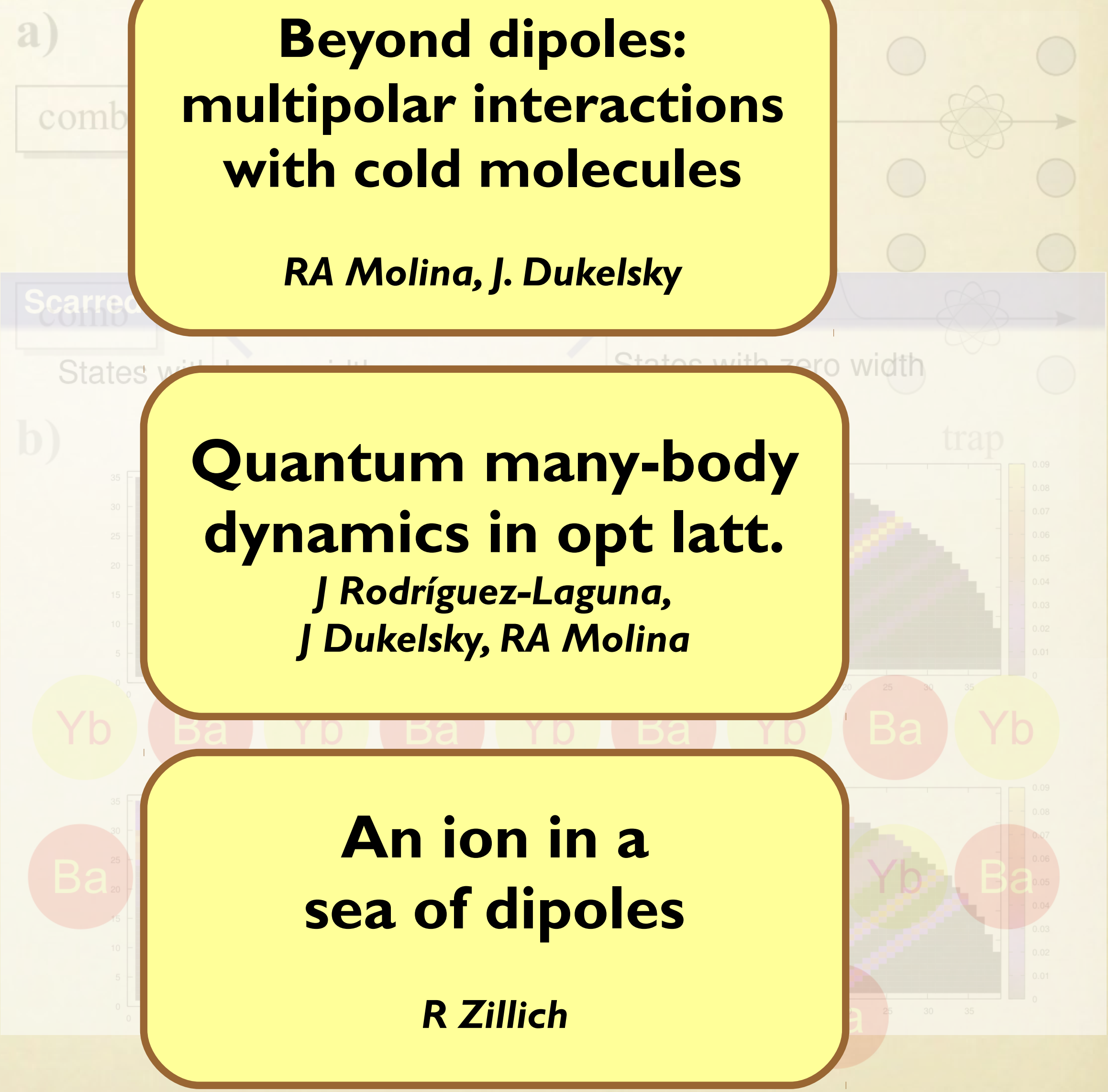
Cooling a multi-species ion crystal

JJ Garcia-Ripoll, T. Mehlstauber





Other projects



Stabilizating a frequency comb with a trapped ion

A Cadarso, JJ Garcia-Ripoll,
PO Schmidt

Beyond dipoles: multipolar interactions with cold molecules

RA Molina, J. Dukelsky

Quantum chaos in optical lattices

V Fernández, JJ Garcia-Ripoll,
RA Molina

Quantum many-body dynamics in opt latt.

J Rodríguez-Laguna,
J Dukelsky, RA Molina

Cooling a multi-species ion crystal

JJ Garcia-Ripoll, T. Mehlstauber

An ion in a sea of dipoles

R Zillich

Thank *you!* – Ackowledgements

Protocols, phase gates, etc.
Juanjo García-Ripoll (IFF)

Molecular ions
Stefan Willitsch (Basel)

Molecular structure
Jesús Pérez-Ríos, Marta Hernández,
José Campos-Martínez (IFF)
Cristina Puzzarini (Bologna)

Discussions
Robin Côté (Storrs)
Johannes Deiglmayr (ETH)
Roman Krems (UBC & ITAMP)
Silke Ospelkaus (Hannover)
All of you at KITP

Contact me at jordi.mur@csic.es

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