Atom Chip for Quantum Control

Francesco Saverio Cataliotti

QSTAR
Quantum Science and Technology in ARcetri

Atom Chip for Quantum Control

- Our Playground
- Quantum State Reconstruction
- Control of Quantum Dynamics
- Reversing Quantum Dynamics
- Quantum Zeno Dynamics
  (Control of Hilbert Space)
- Conclusions

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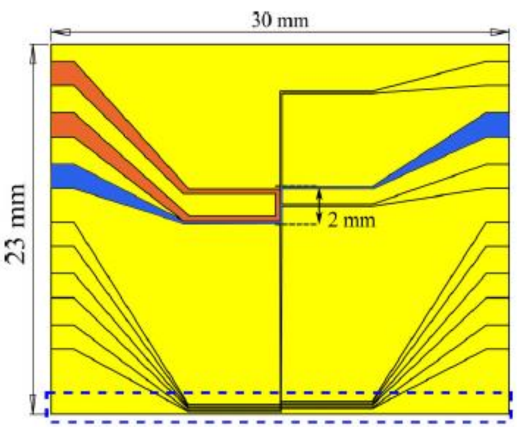
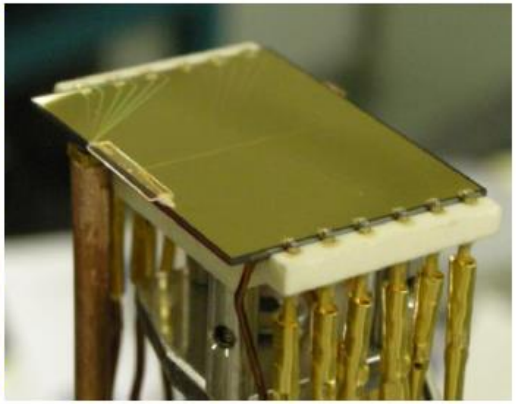
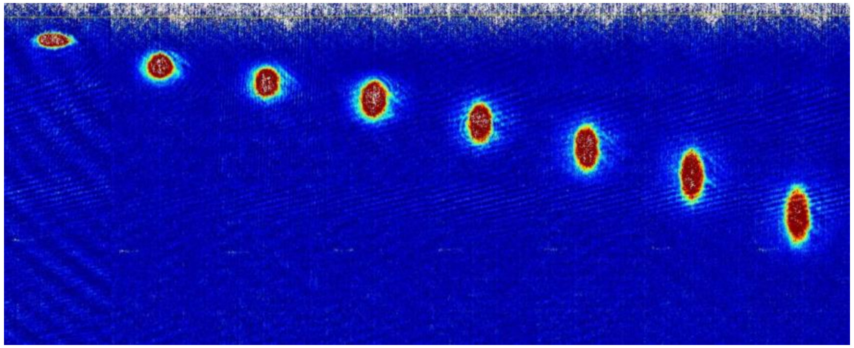
Our Playground (Expt)

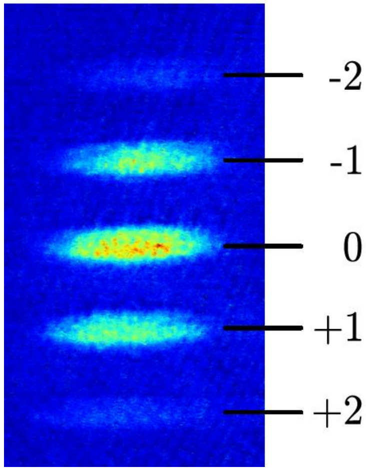




- Compact, easy-to-use and stable setup
- From zero to BEC in 8 seconds
- Integrated auxiliary conductors as RF antennae

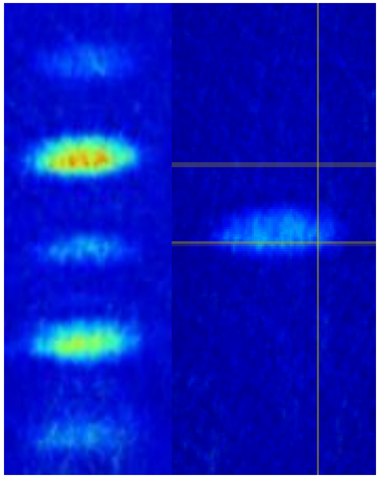


Stern-Gerlach discrimination



Hyperfine state discrimination

F=2 F=1

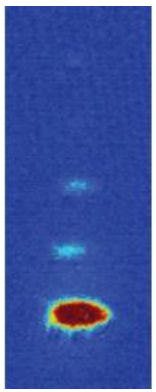


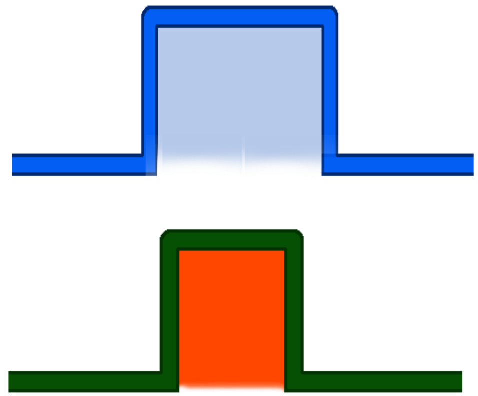
"Degenerate Quantum Gases Manipulation on Atom-chips"
I. Herrera, J. Petrovic, P.Lombardi, S. Bartalini and F.S. Cataliotti
Physica Scripta **T149**, 014002 (2012).

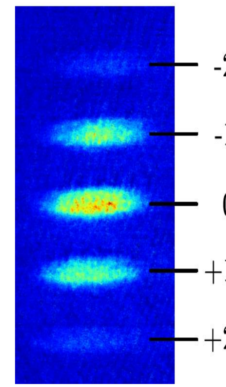
A multi-state interferometer on an atom chip
J. Petrovic, I. Herrera, P. Lombardi, F. Schaefer, F. S. Cataliotti
New Journal of Physics **15** (4), 043002 (2013)

Our Playground (Expt)

Homogeneous magnetic field







RF driving field

$|\psi_{in}> = |m_F = 2>$

$|\psi_{out}> \rightarrow \rho_{ii}$

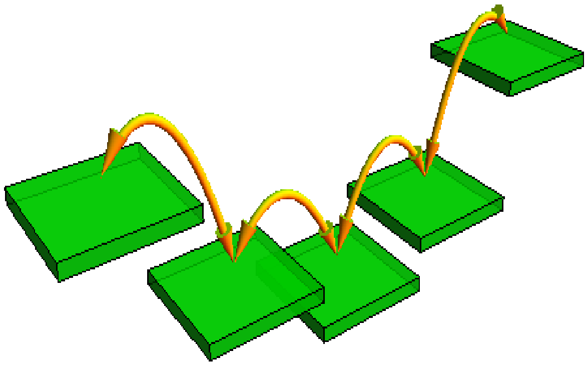
Time

Our Playground (Theo.)

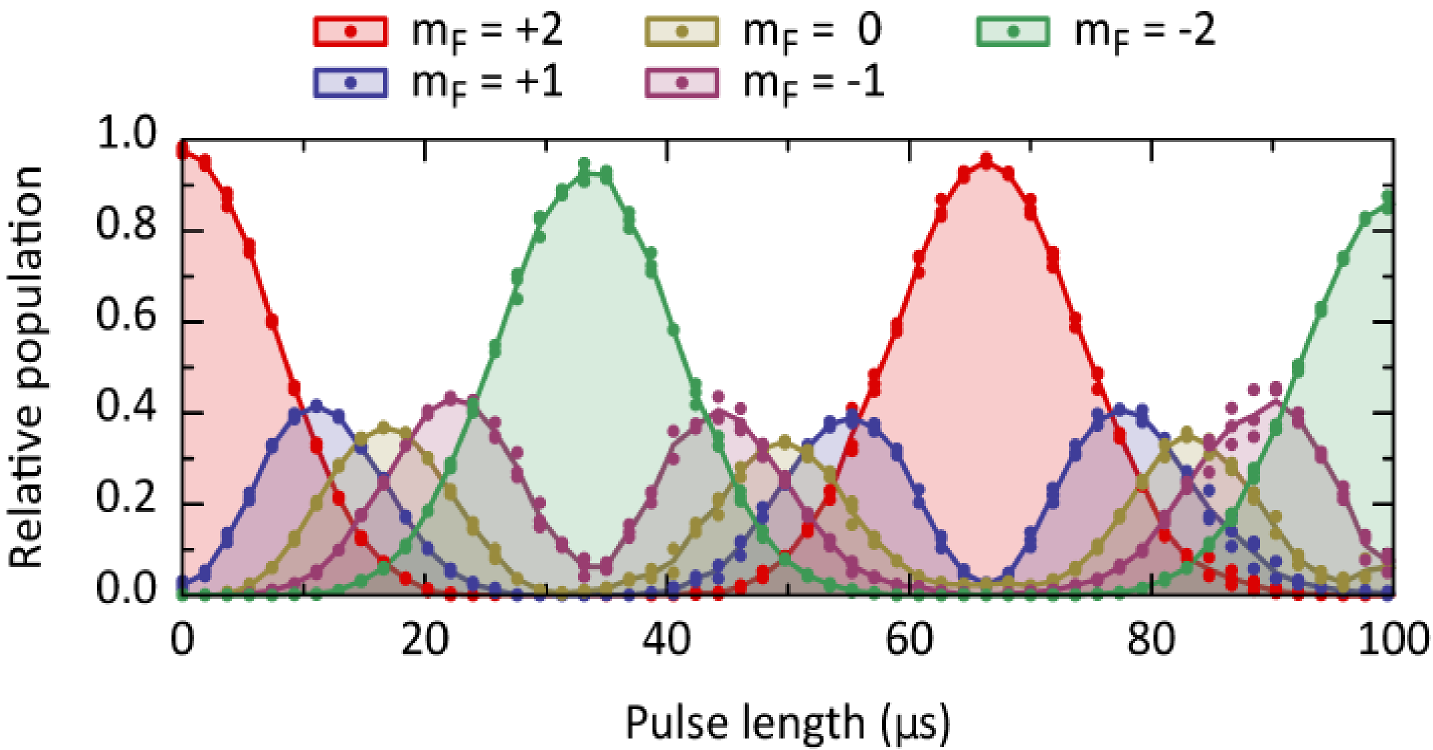
$$H_{RWA}(\alpha) = \hbar \begin{pmatrix} \omega_2(B) - 2\omega & \Omega & 0 & 0 & 0 \\ \Omega & \omega_1(B) - \omega & \sqrt{3/2}\,\Omega & 0 & 0 \\ 0 & \sqrt{3/2}\,\Omega & \omega_0(B) & \sqrt{3/2}\,\Omega & 0 \\ 0 & 0 & \sqrt{3/2}\,\Omega & \omega_{-1}(B) + \omega & \Omega \\ 0 & 0 & 0 & \Omega & \omega_{-2}(B) + 2\omega \end{pmatrix}$$

$$\alpha = \{\Omega, B, \omega\}$$

$$\omega_n(B) - n\,\omega$$



Our Signal



- RF pulse: $\Omega_{\mathrm{RF}} = 2\pi\,15\ \mathrm{kHz}$

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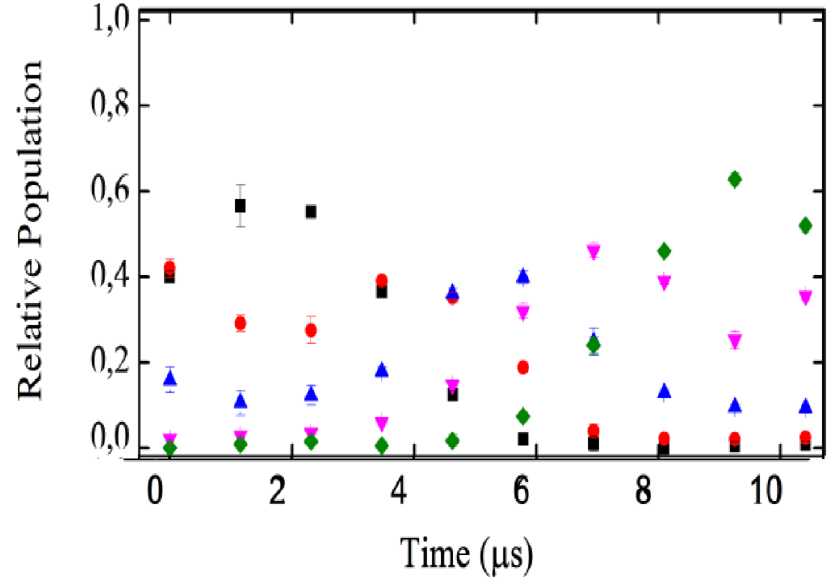
Quantum State Reconstruction

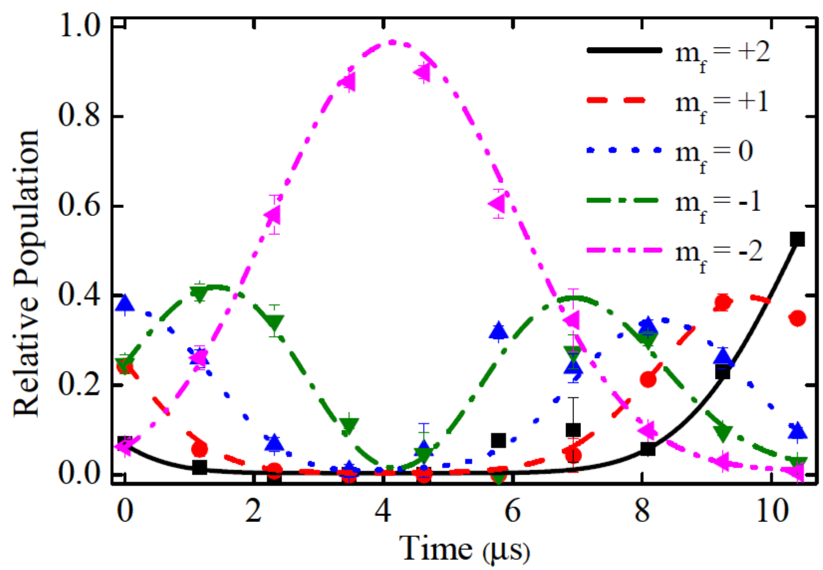
C. Lovecchio et al. arXiv:1504.01963

Evolve with a known Hamiltonian H for a time t



Start from an unknown quantum state

$|\rho_{in}\rangle$

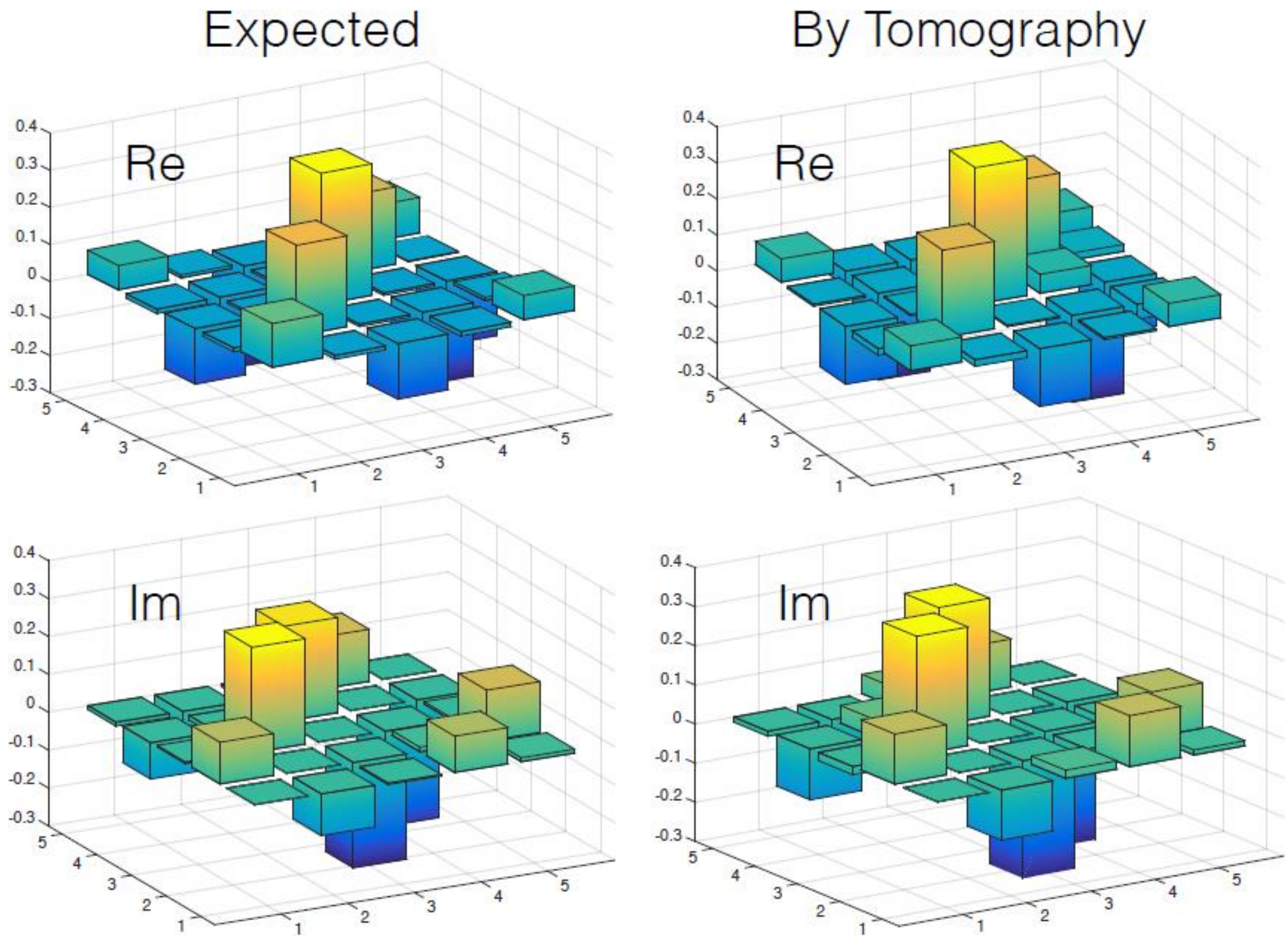


Compare with theoretical evolution optimizing the initial state to minimize error with respect to measurements

Reconstruct initial state

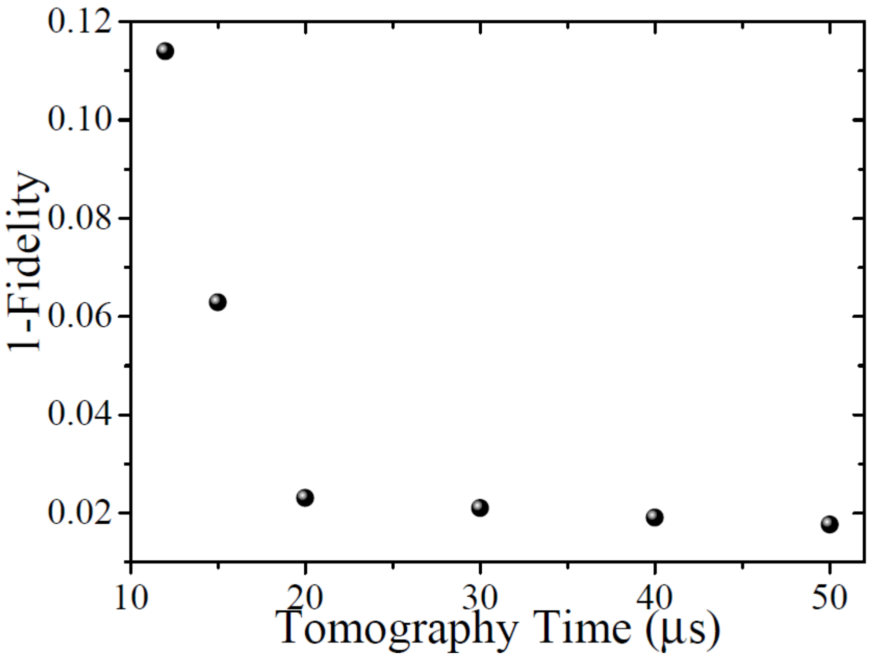
Quantum State Reconstruction

C. Lovecchio et al. arXiv:1504.01963



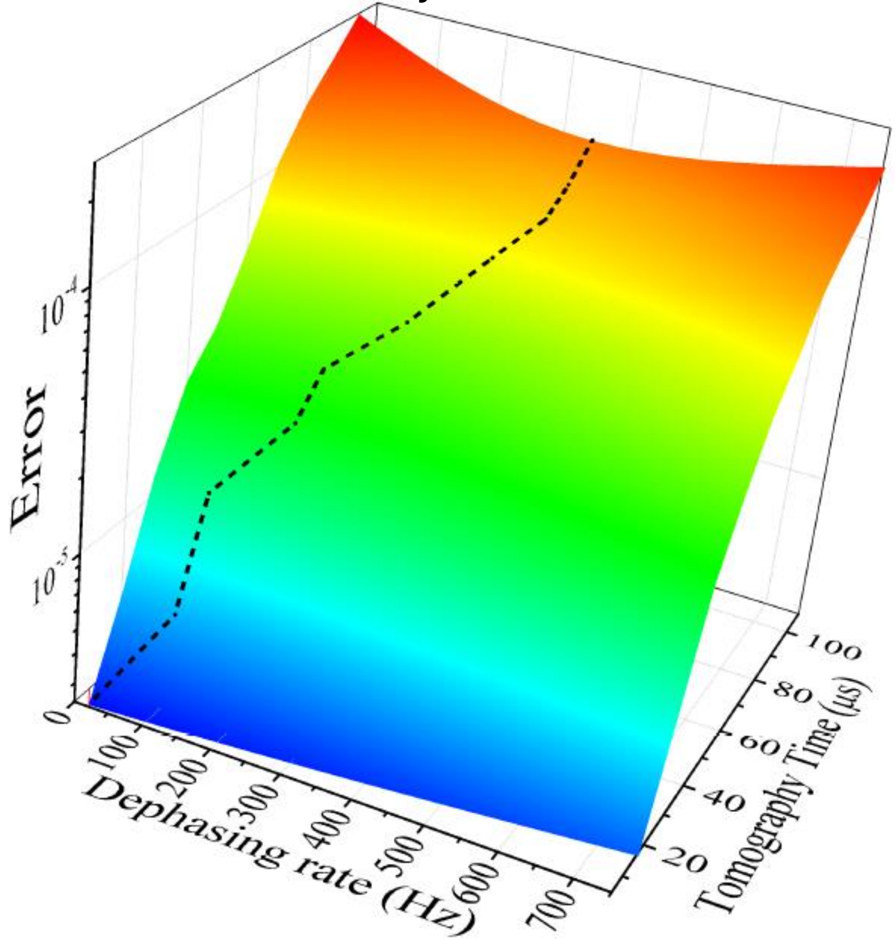
Quantum State Reconstruction

C. Lovecchio et al. arXiv:1504.01963



The fidelity of the reconstructed state quicly converges to a minimum

At longer times dephasing from external noise dominates ultimately setting the maximum attainable fidelity



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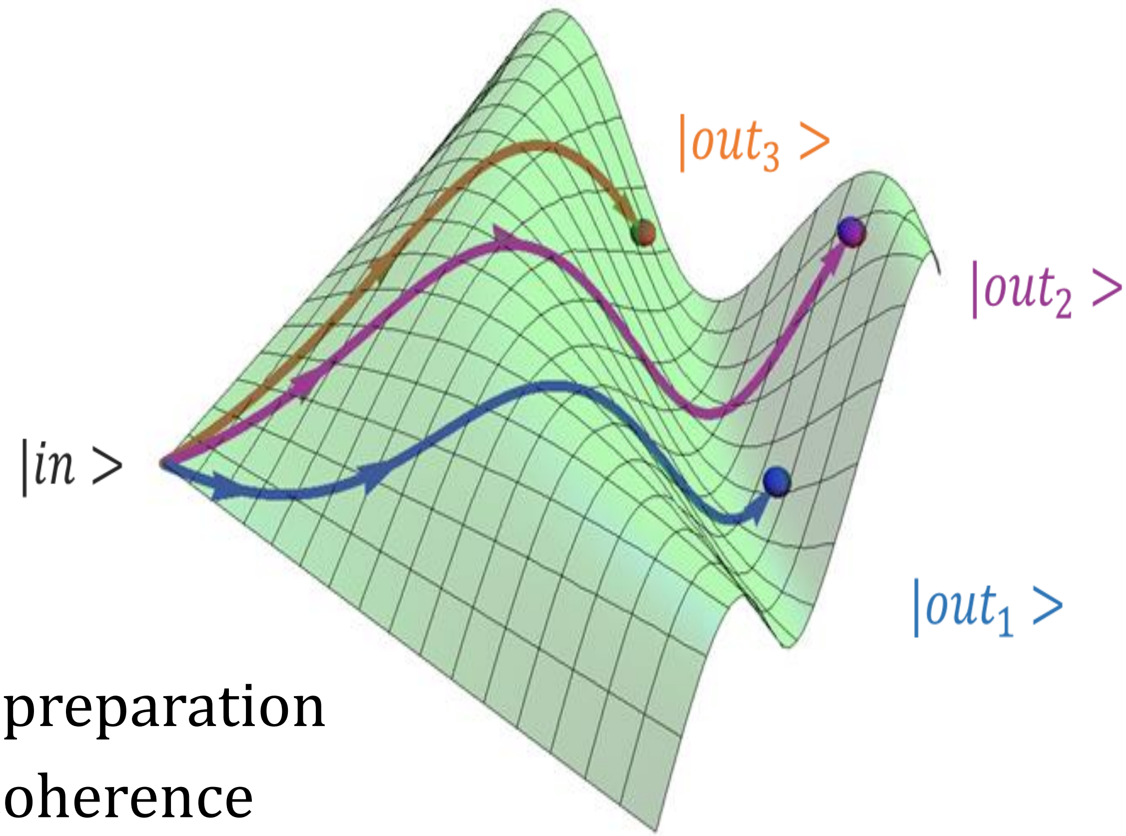
Control of Quantum Dynamics

C. Lovecchio et al. arXiv:1405.6918

- $H(t, \alpha)$
  T_0, ε_0
- $\alpha \rightarrow \alpha_i$
  $T_s \leq T_0, \varepsilon_s \leq \varepsilon_0$
- $\alpha \rightarrow \alpha(t)$



Why?

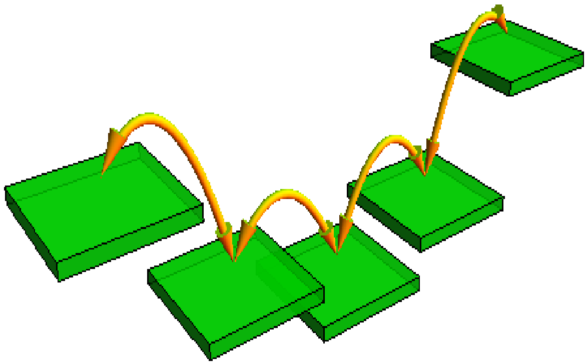
- Arbitrary state preparation
- Faster than decoherence time scale

Our Playground (Theo.)

$$H_{RWA}(\alpha) = \hbar \begin{pmatrix} \omega_2(B) - 2\omega & \Omega & 0 & 0 & 0 \\ \Omega & \omega_1(B) - \omega & \sqrt{3/2}\,\Omega & 0 & 0 \\ 0 & \sqrt{3/2}\,\Omega & \omega_0(B) & \sqrt{3/2}\,\Omega & 0 \\ 0 & 0 & \sqrt{3/2}\,\Omega & \omega_{-1}(B) + \omega & \Omega \\ 0 & 0 & 0 & \Omega & \omega_{-2}(B) + 2\omega \end{pmatrix}$$

$$\alpha = \{\Omega, B, \omega\}$$

$$\omega_n(B) - n\,\omega$$

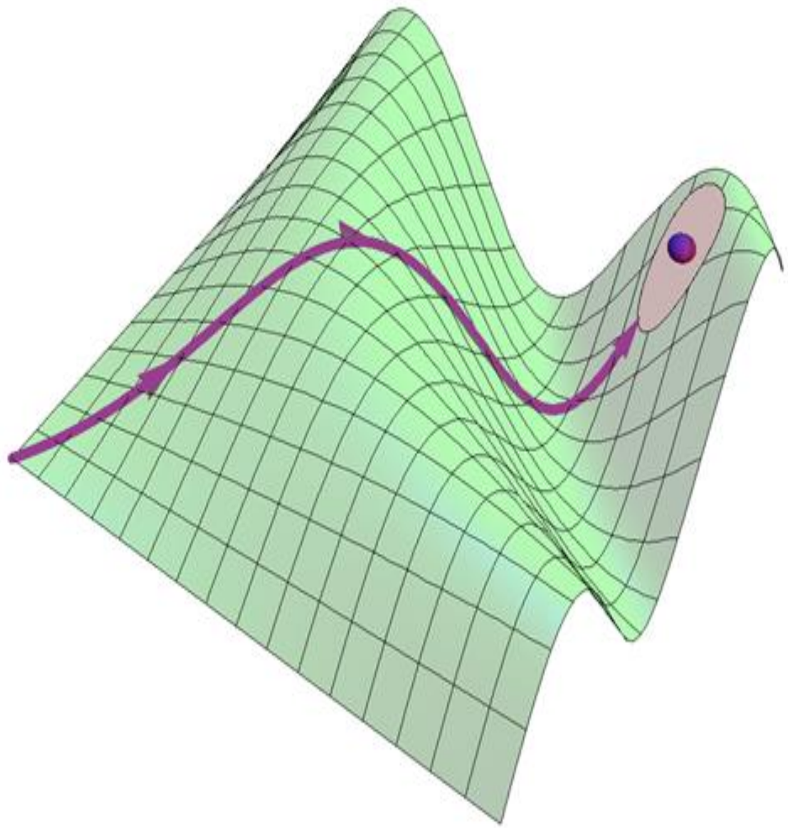


Control of Quantum Dynamics

C. Lovecchio et al. arXiv:1405.6918

CRAB optimization

- $\varepsilon = \sum_i \frac{|p_i - b_i|}{2} \rightarrow \varepsilon_{T,}\ \varepsilon_E\ (\varepsilon \in [0,1])$
- $p_i = \rho_{ii}(T)$
- b_i target state population



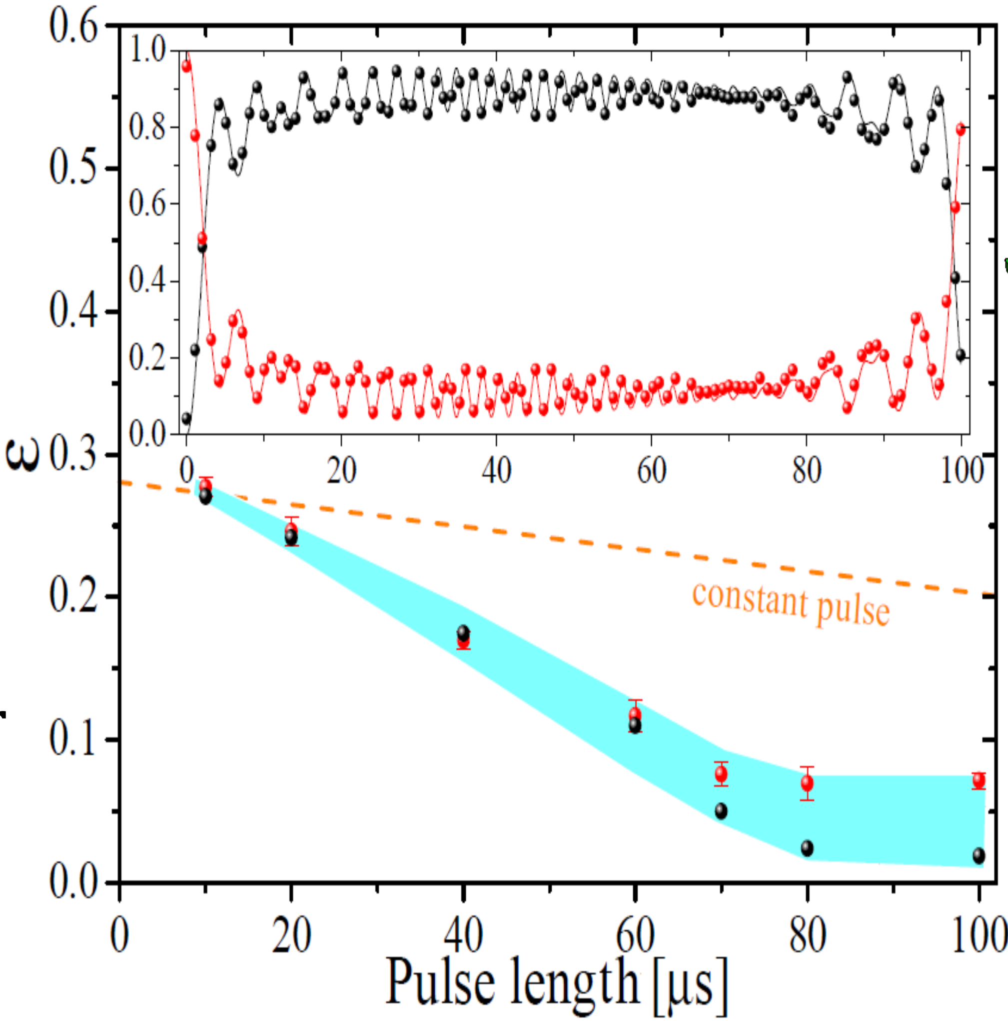
Experimental constraints

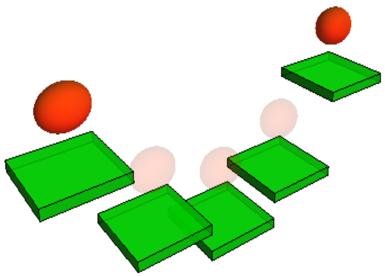
- $\omega\,(t) \in 2\pi\,[4150, 4600]$ kHz
- $B = 6.1794$ Gauss
- $\Omega = 2\,\pi\,60$ kHz
- $T = 100\ \mu s$

Control of Quantum Dynamics

C. Lovecchio et al. arXiv:1405.6918

- Target state A
- Different optimized pulse length T
- Same constraints for all pulses





Control of Quantum Dynamics

C. Lovecchio et al. arXiv:1405.6918

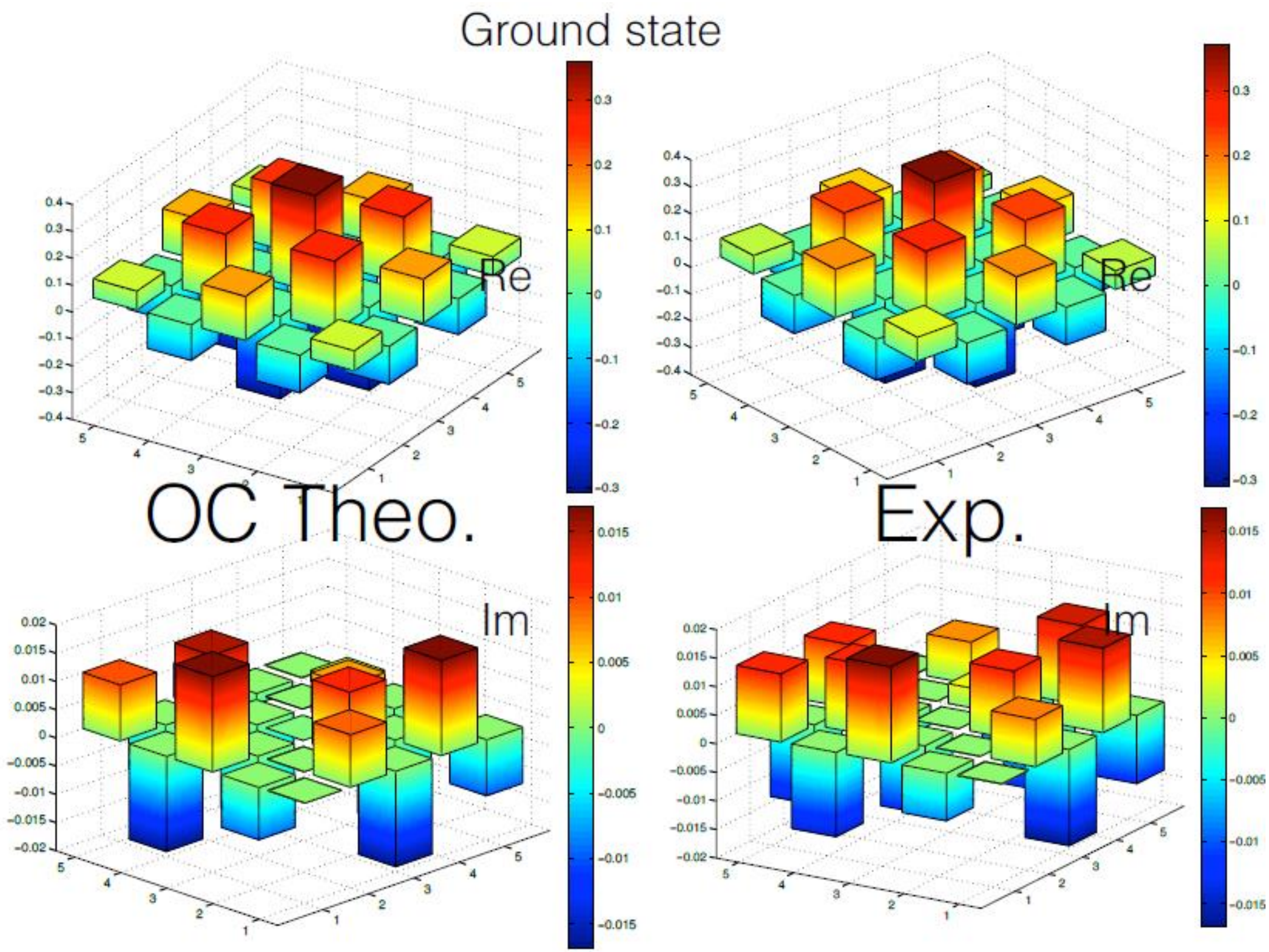
Target State	ε_T	ε_E	$\mathcal{F}$
A	0,04(3)	0,07(1)	0,71
B	0,04(2)	0,02(1)	0,67
C	0,04(3)	0,04(1)	0,11
D	0,03(2)	0,02(1)	0,71
E	0,04(2)	0,03(1)	0,02
F	0,02(1)	0,03(1)	0,45
G	0,05(4)	0,04(1)	0,15
H	0,04(3)	0,03(1)	0,07
I	0,07(3)	0,07(1)	0,15

$$\varepsilon = \sum_i \frac{|p_i - b_i|}{2}$$

$$\mathcal{F} = \mathrm{Tr}\sqrt{\rho_0^{1/2}\,\rho_G\,\rho_0^{1/2}}$$ Uhlman fidelity

Control of Quantum Dynamics

C. Lovecchio et al. arXiv:1405.6918



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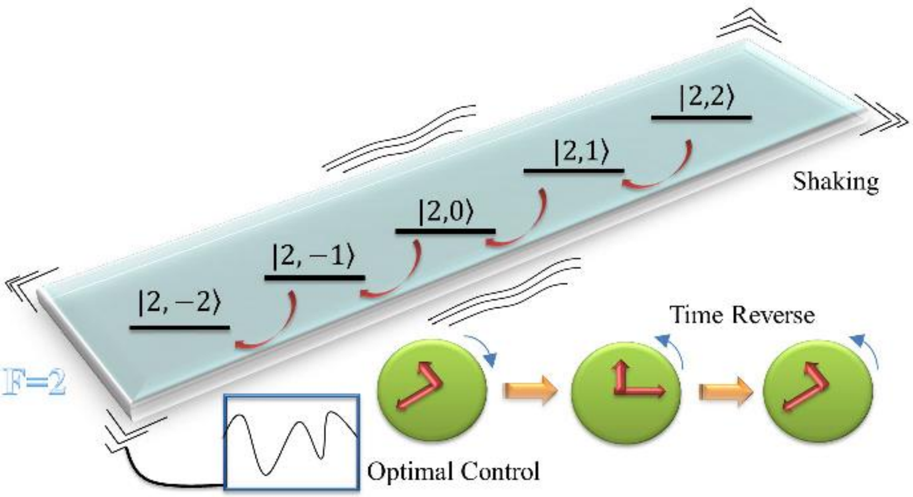
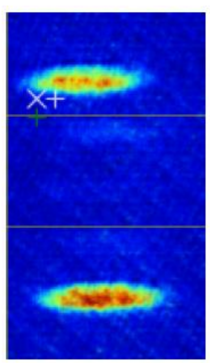
Reversing Quantum Dynamics



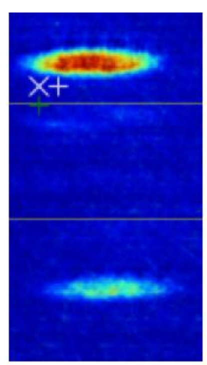
$$\frac{d}{dt}\rho(t) = -\frac{i}{\hbar}[H_0 + H_F(t), \rho(t)] + \mathcal{L}(\rho(t))$$

Starting state

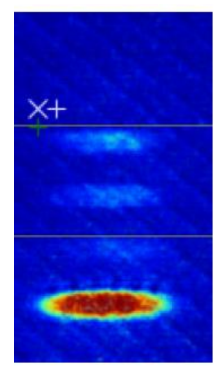
After
OC pulse



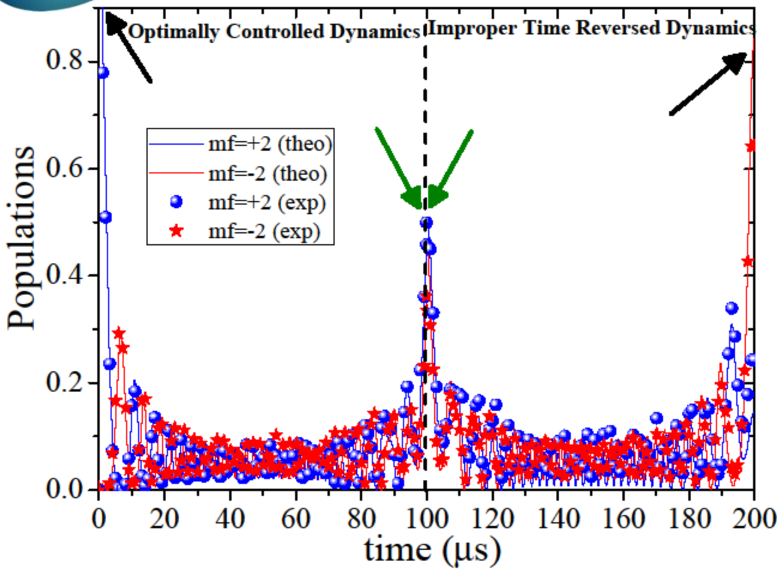
After
OC pulse – OC pulse

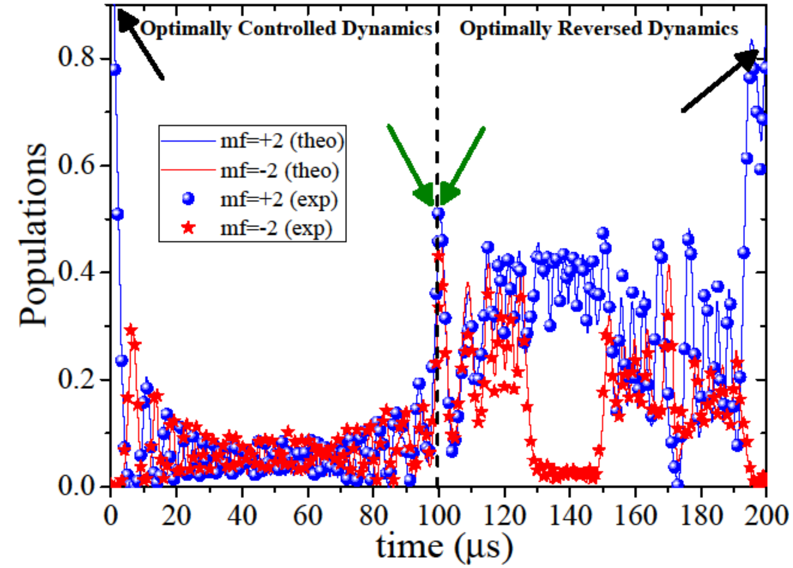


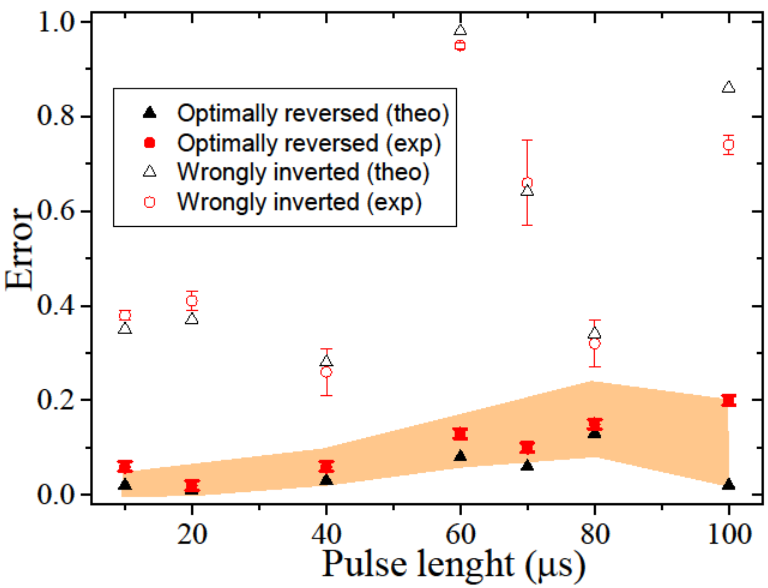
After
OC pulse + OR pulse

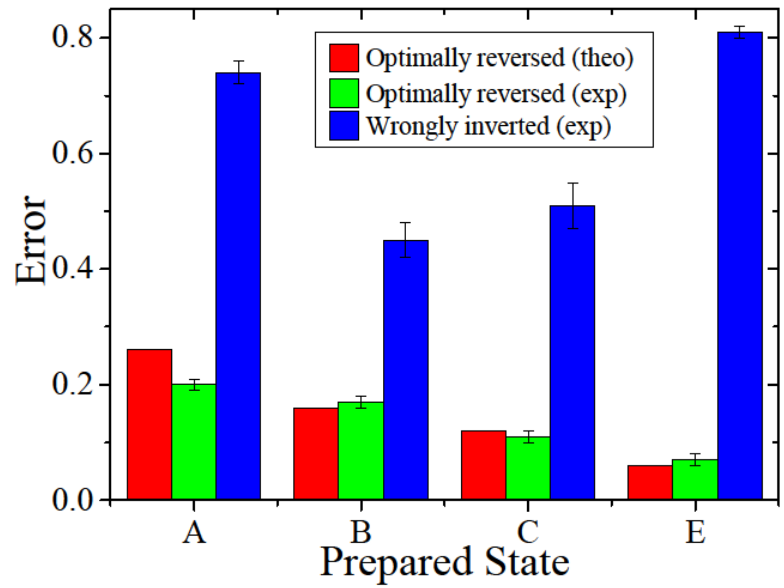


Reversing Quantum Dynamics









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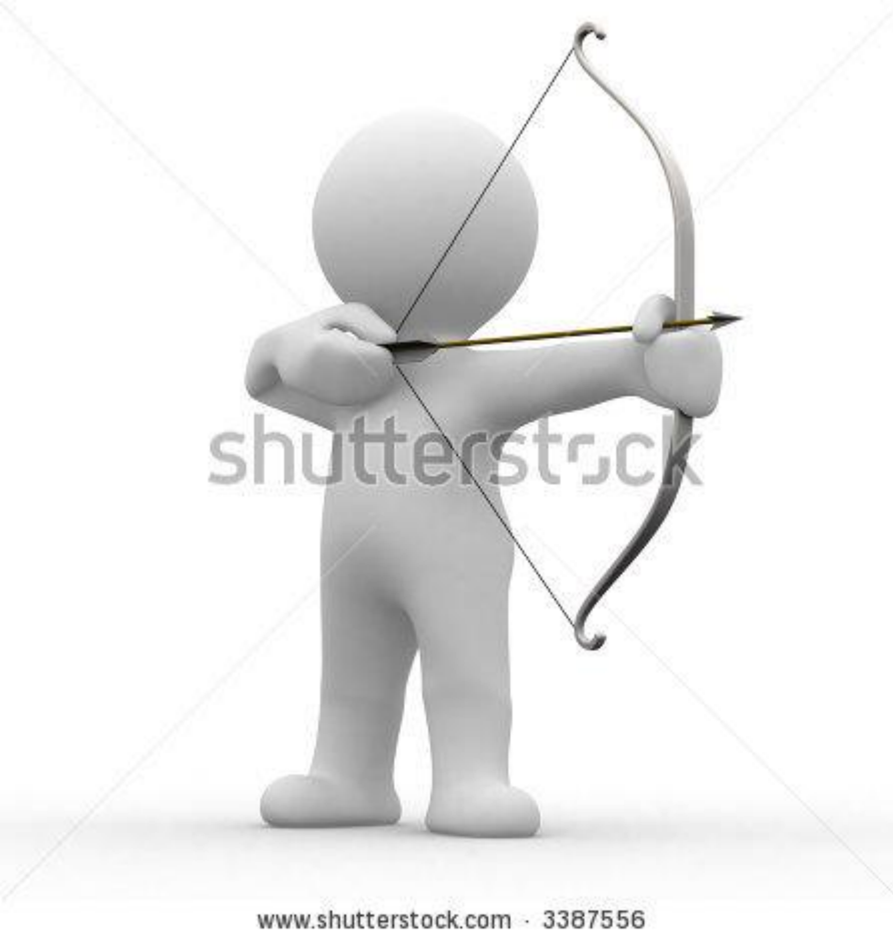
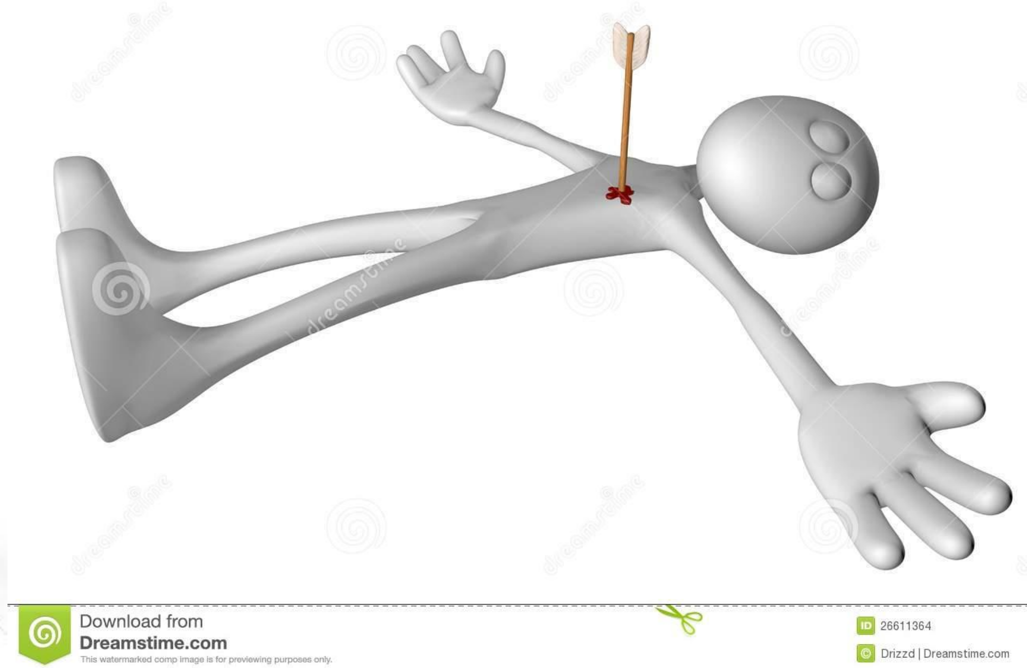
Quantum Zeno effect

- Zeno of Elea (V century BC): *A flying arrow is always at rest when observed*
- J. Von Neumann (1932): *A quantum state can be steered in any other one by a specific sequence of measurements*
- Misra and Sudarshan (1977): *Frequent observation of a given quantum state prevents its evolution*
- Facchi and Pascazio (2002): *Quantum backaction can be used to restrict dynamics within a reduced Hilbert space*

Classical Zeno effect Expt.



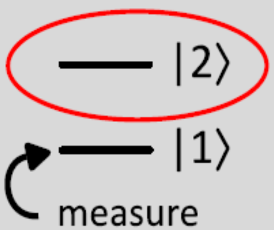


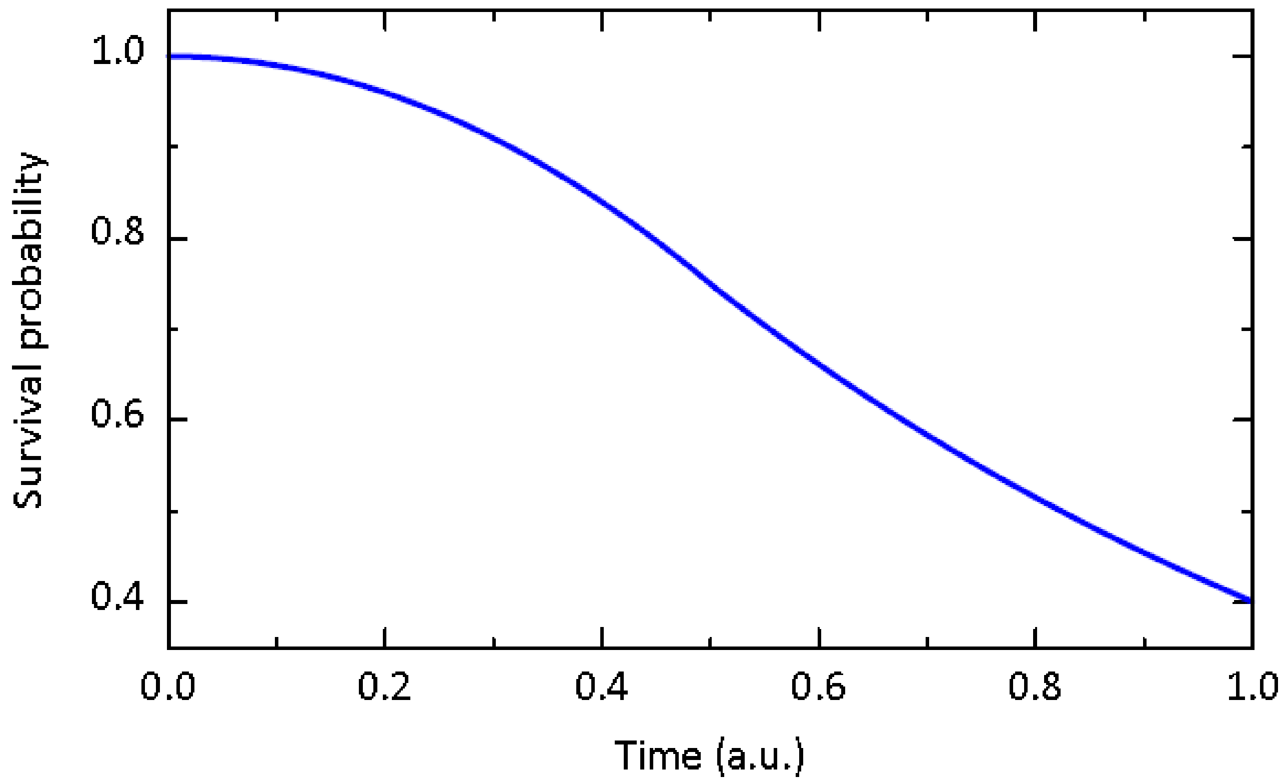
EPIC FAIL

Quantum Zeno effect

Current situation

- Two-level system





Quantum Zeno effect

Current situation

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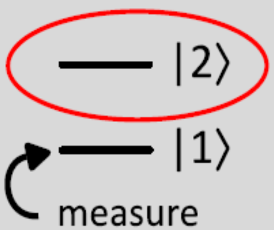

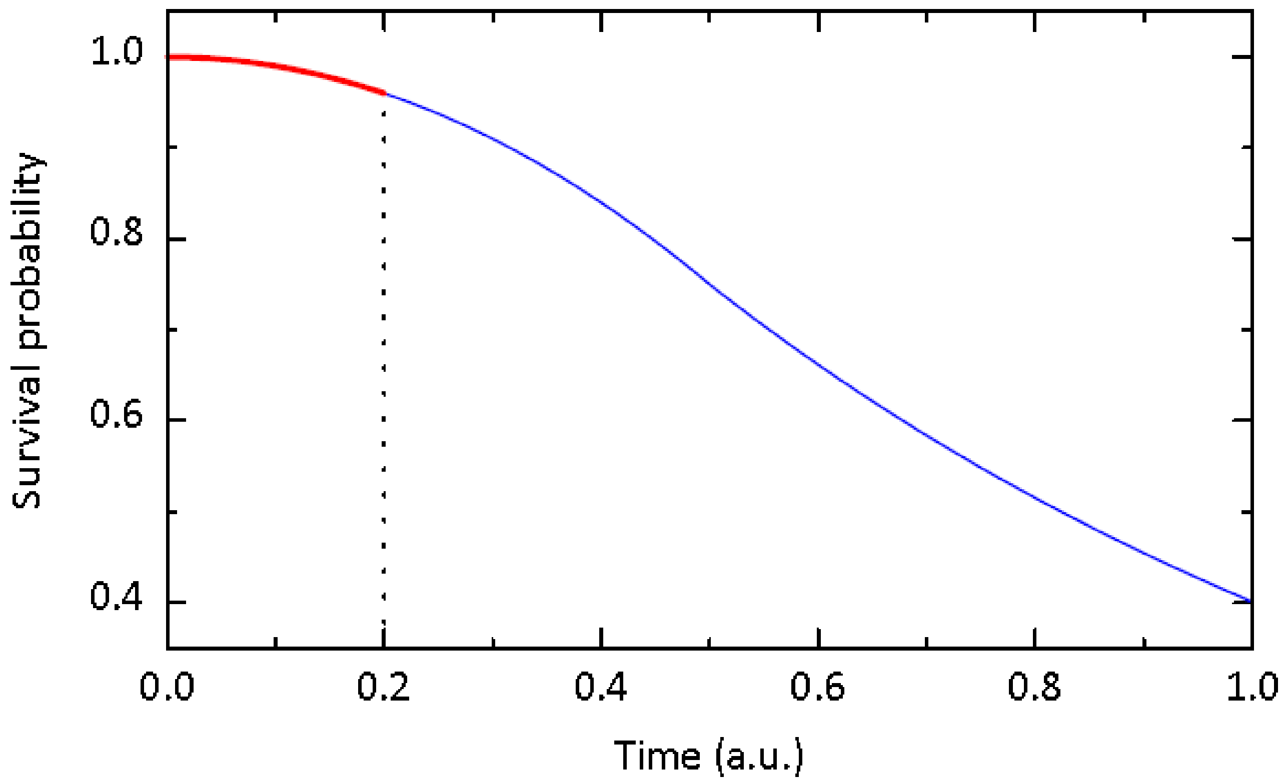

Quantum Zeno effect

Current situation

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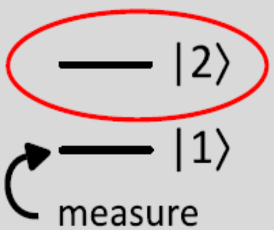

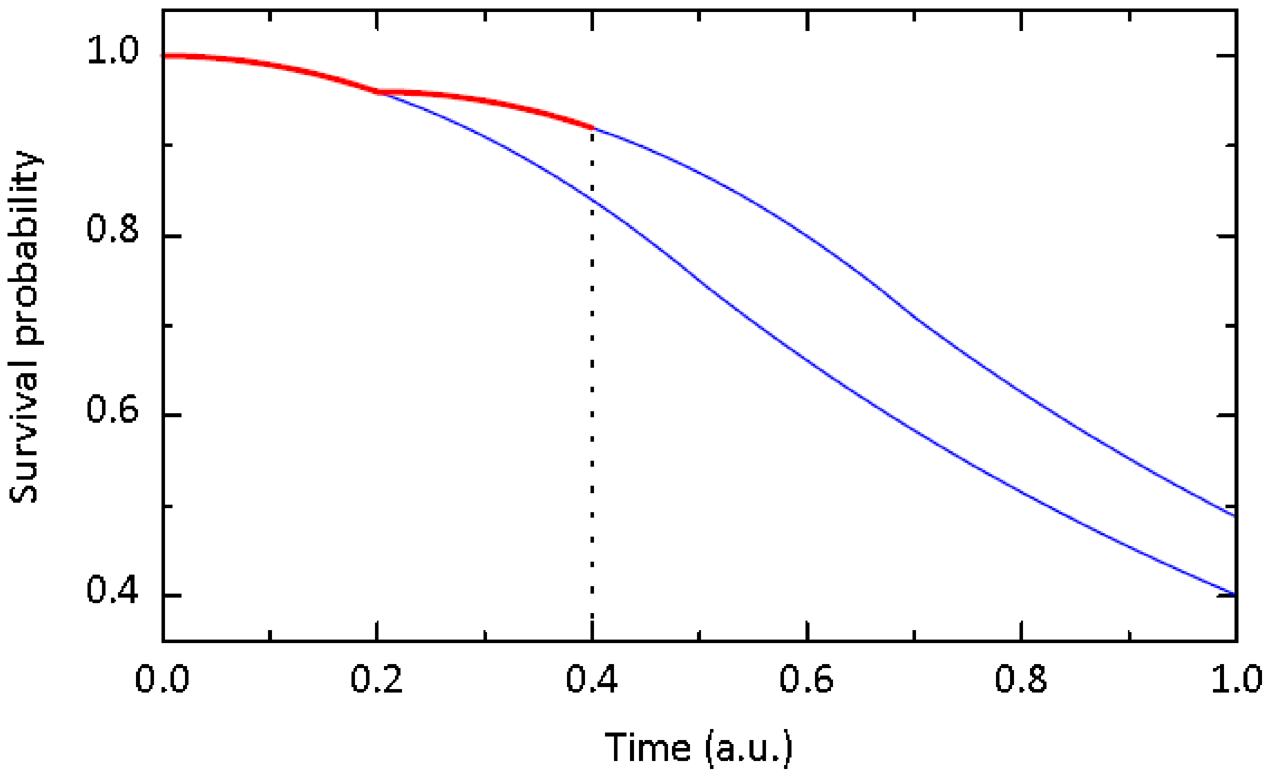

Quantum Zeno effect

Current situation

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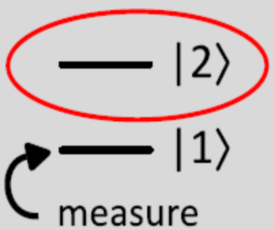
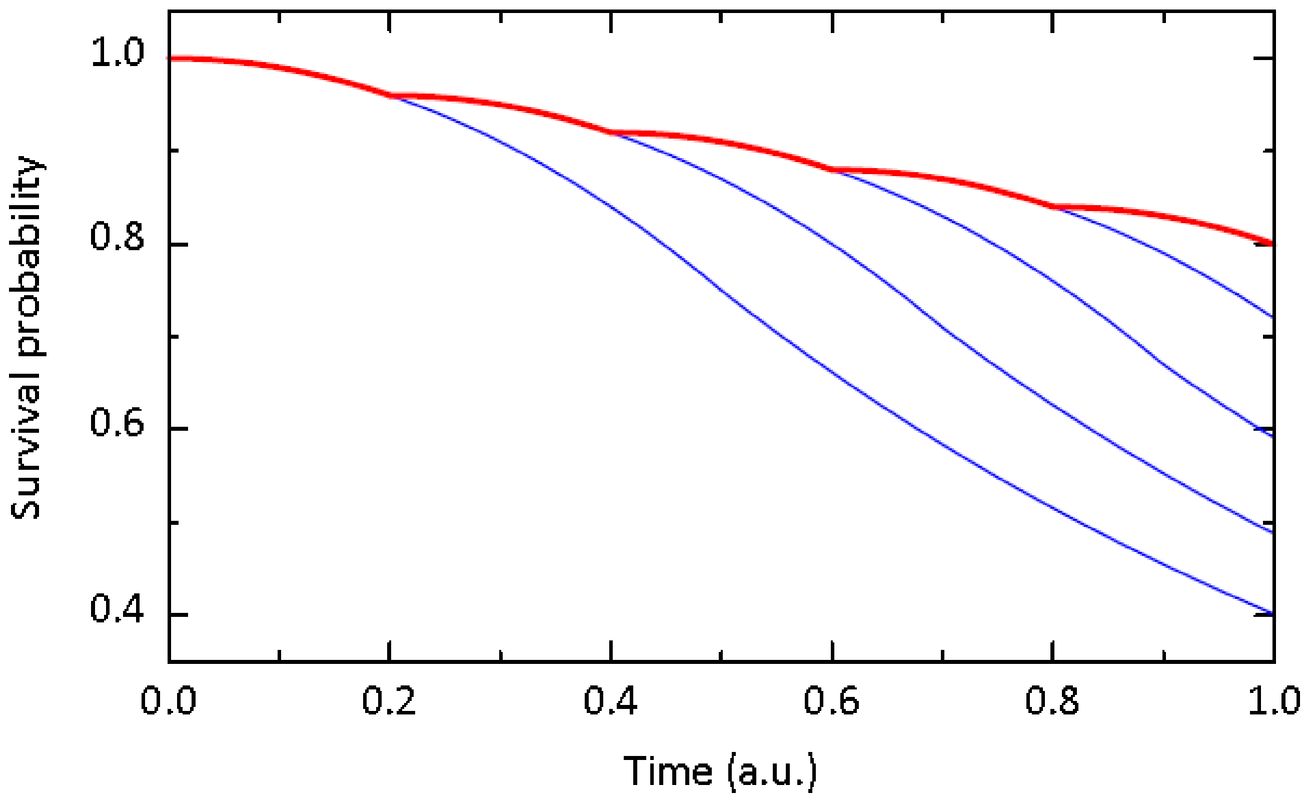




Quantum Zeno effect

Many experiments on many different physical systems already demonstrated the QZE.

1990 Itano, Heinzen, Bollinger, Wineland (→ 5000 Be^+)

1997 Nagels, Hermans, Chapovsky (→ nuclear spin isomers)

2000 Balzer, Huelsmann, Neuhauser, Toschek (→ single Yb^+)

2001 Fischer, Gutierrez-Medina, Raizen (→ cold Na atoms)

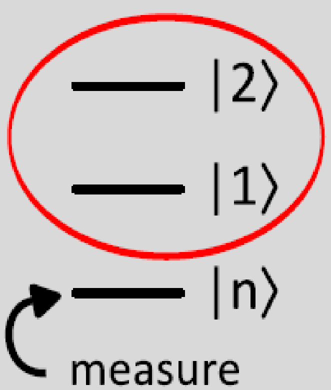
2006 Streed, Mun, Boyd, Campbell, Medley, Ketterle, Pritchard (→ BEC of Rb atoms)

2008 Bernu, Sayrin, Kuhr, Dotsenko, Brune, Raimond, Haroche (→ Photons in cavity)

Quantum Zeno dynamics

Our experiment

- Multi-level system



A measurement projects into subspaces

- Multi-dimensional Hilbert space: $\mathcal{H}$
- Time evolution: $U(t) = \exp(-i\, H\, t)$
- Projection operator: P with $[P, H] \neq 0$
- Subspace: $\mathcal{H}_P$ with $P\mathcal{H} = \mathcal{H}_P$

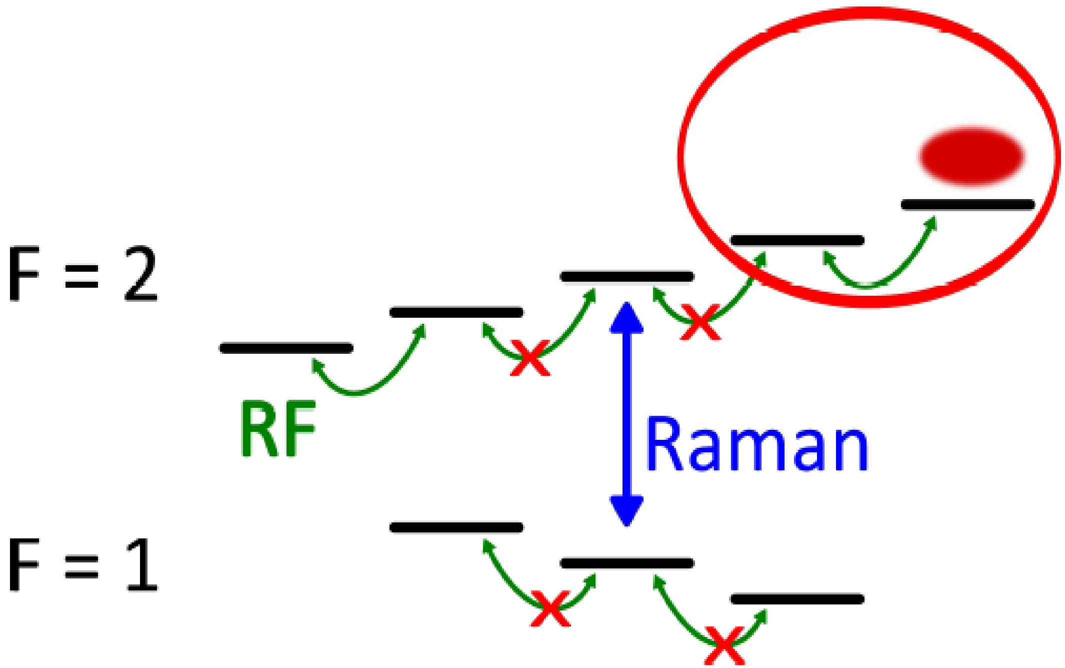
Zeno time evolution

- After N projections: $V_N(t) = \big(P\, U(t/N)\, P\big)^N$
- Limiting time evolution:
  $V_Z(t) = \lim_{N\to\infty} V_N(t) = P \exp(-i\, PHP\, t)$
- Evolution $V_Z(t)$ is unitary in $\mathcal{H}_P$.

Facchi and Pascazio, PRL 89, 080401 (2002).

Quantum Zeno Dynamics

F. Schaefer et al Nat. Comm. 5:3194 (2014)



The system is projected into a subspace of the original Hilbert space. Quantum Dynamics within the subspace is preserved!

$$PH_{F=2}P = \begin{pmatrix} 0 & \frac{\sqrt{4}}{2}\Omega & 0 & 0 & 0 \\ \frac{\sqrt{4}}{2}\Omega & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{\sqrt{4}}{2}\Omega \\ 0 & 0 & 0 & \frac{\sqrt{4}}{2}\Omega & 0 \end{pmatrix}$$

Quantum Zeno Dynamics

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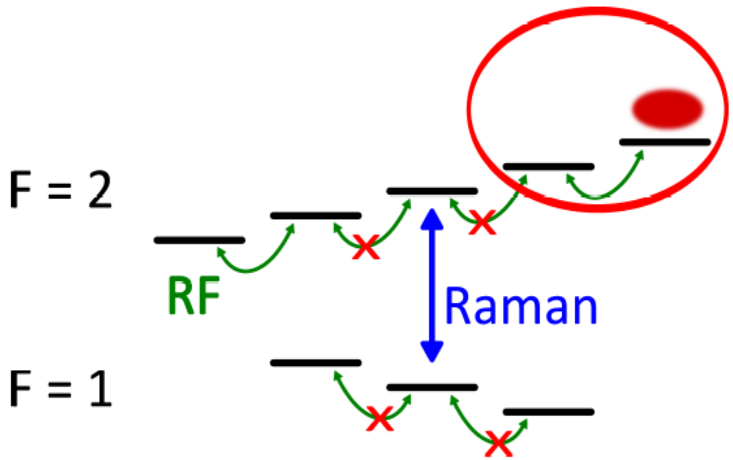
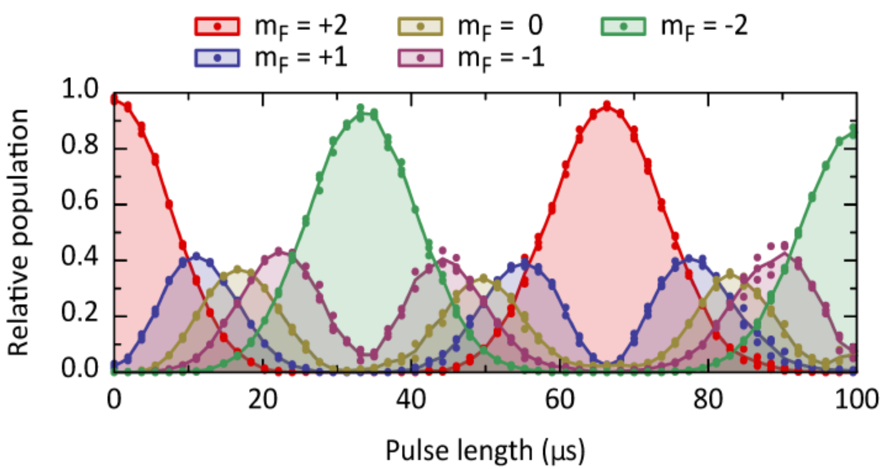
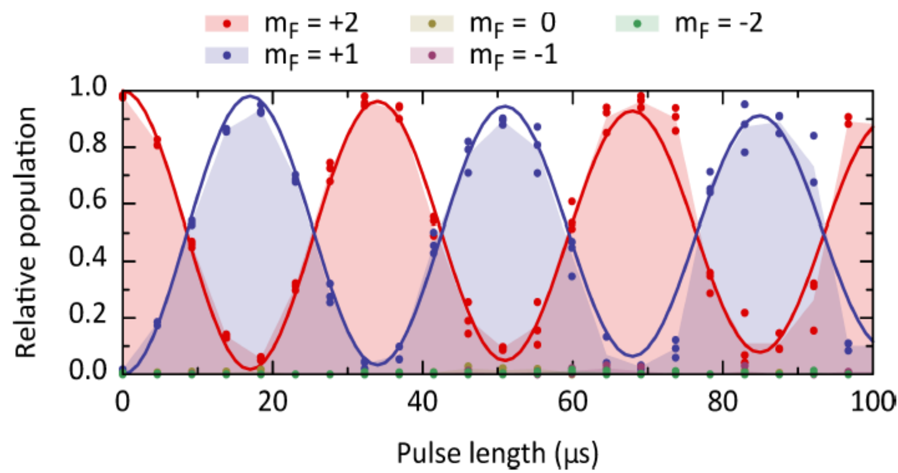


Subspace dynamics:

$$PH_{F=2}P = \begin{pmatrix} 0 & \frac{\sqrt{4}}{2}\Omega & 0 & 0 & 0 \\ \frac{\sqrt{4}}{2}\Omega & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{\sqrt{4}}{2}\Omega \\ 0 & 0 & 0 & \frac{\sqrt{4}}{2}\Omega & 0 \end{pmatrix}$$



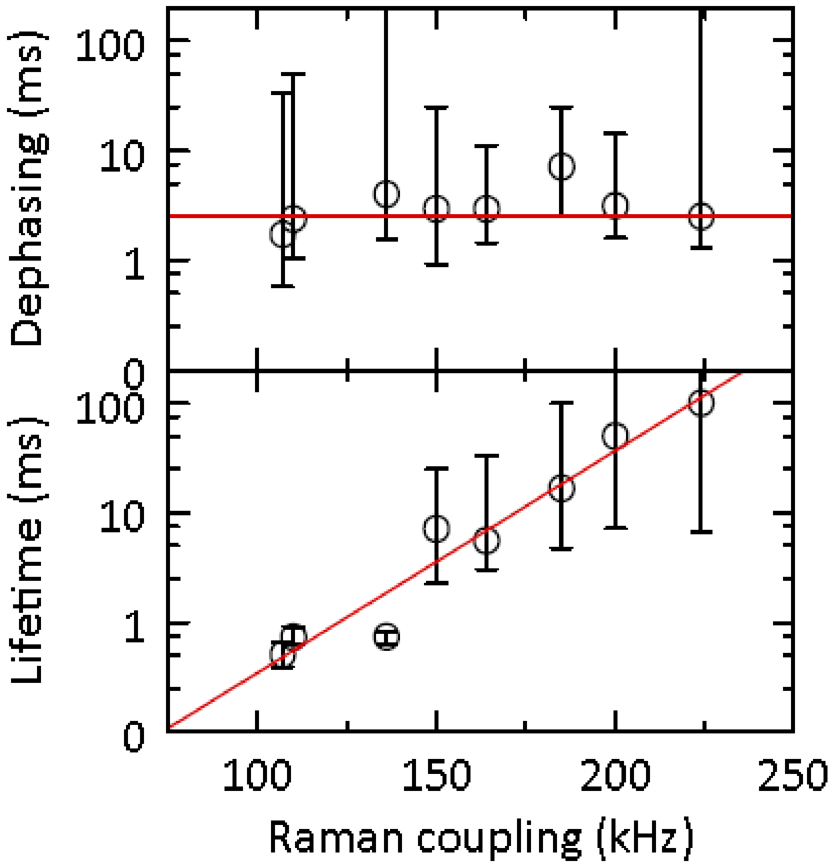
- RF pulse: $\Omega_{RF} = 2\pi\, 15$ kHz
- Raman beams: off



- $\Omega_{RF} = 2\pi\, 15$ kHz, $\Omega_{Raman} = 2\pi\, 200$ kHz
- $t_{lifetime} = 50$ ms, $t_{deph} = 3.1$ ms

Quantum Zeno Dynamics

F. Schaefer et al Nat. Comm. 5:3194 (2014)



- Observe a strong transition from free to Zeno dynamics
- Lifetime increases by factor ≈ 100
- Dephasing time approx. constant

Quantum Zeno Dynamics

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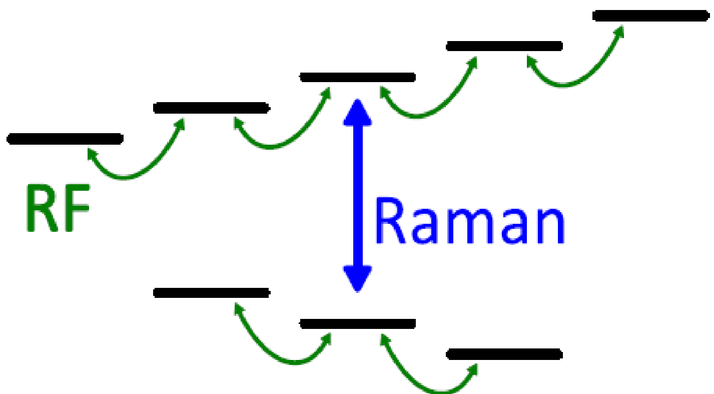
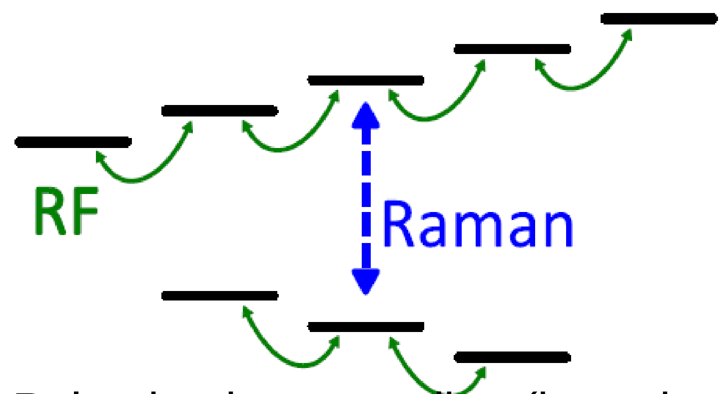
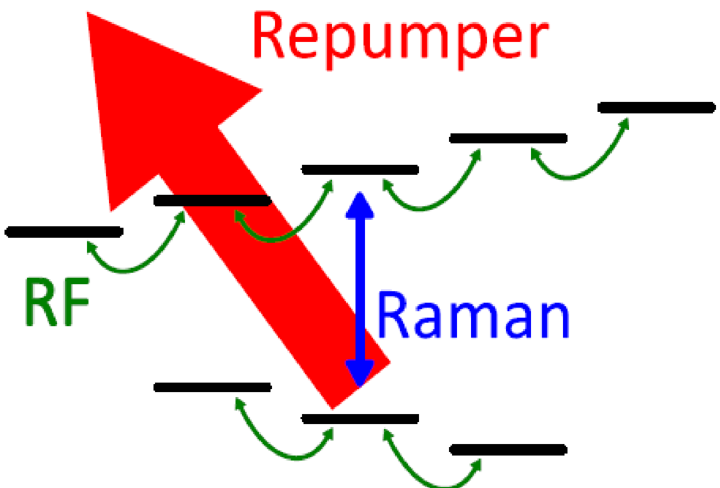


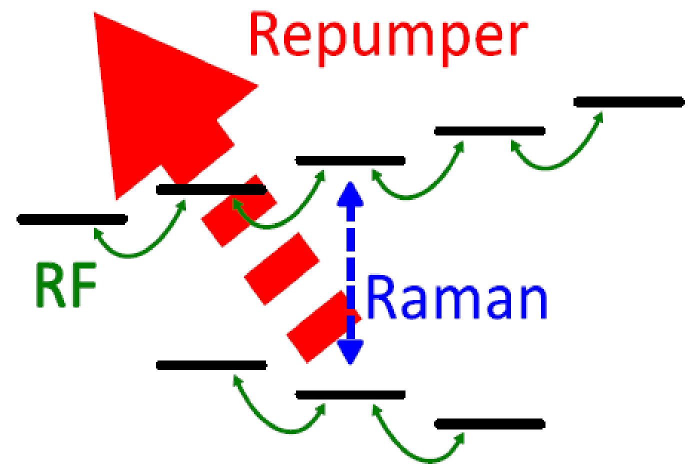
CW unitary coupling



Pulsed unitary coupling (bang-bang)



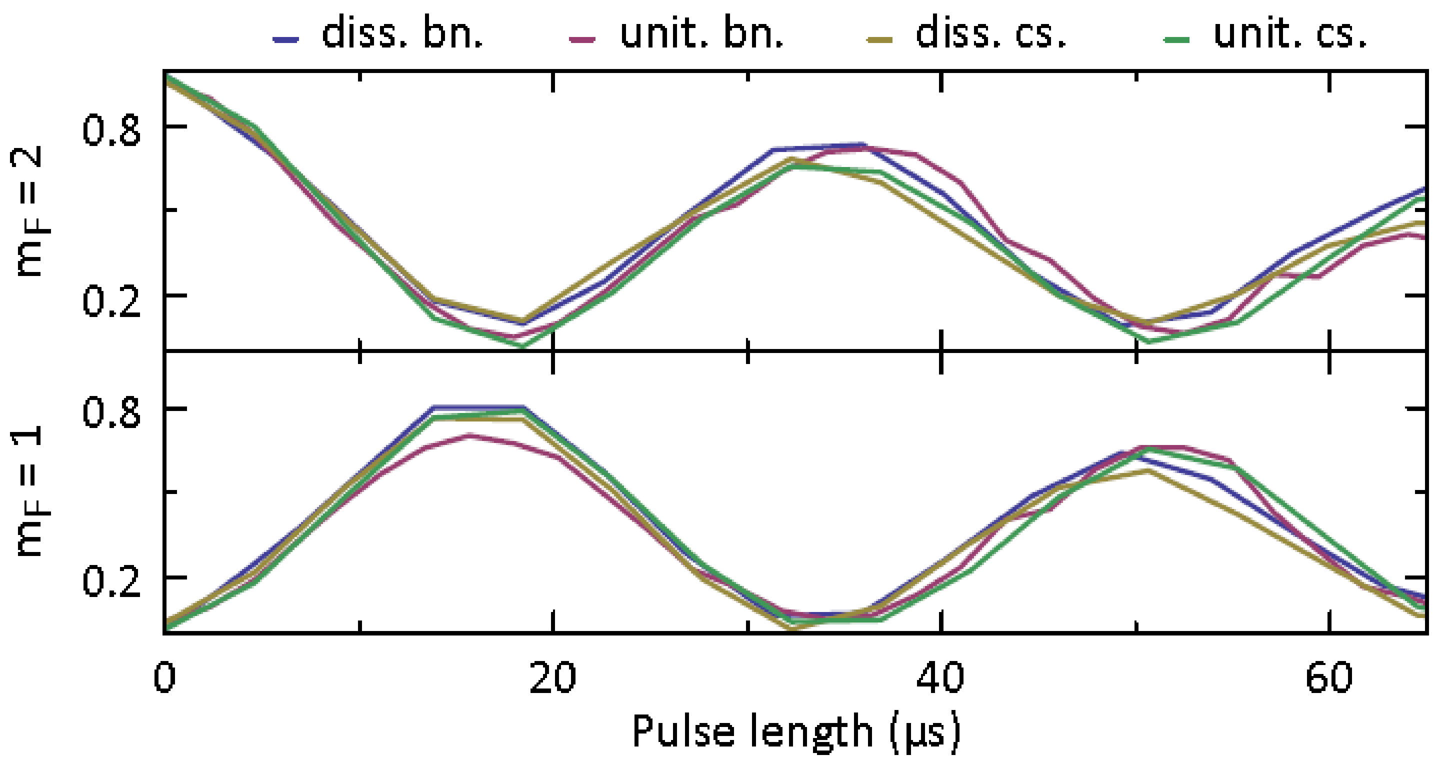
CW dissipative coupling



Pulsed dissipative coupling (measurement)

Quantum Zeno Dynamics

F. Schaefer et al Nat. Comm. 5:3194 (2014)



- Experiment: the observed dynamics is comparable
- Theory: all cases should reduce to subspace projections

Conclusion (I part)

- Very good knowledge of quantum dynamics allows full reconstruction of an unknown quantum state

- Optimal control strategy allow to reach any point of the Hilbert space of interest.

- The error in the states preparation depends on the time length of the optimized evolution.

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Conclusion (II part)

- Frequent observations with negative results can confine the dynamics to a subspace of the complete Hilbert space.
- The lifetime in the subspace depends strongly on the rate of observation.
- The coherence in the subspace decays only slowly.
- Resulting dynamics of different "measurement" schemes are observed to be similar.
- We created a dynamically protected Qubit.

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Proving Coherence

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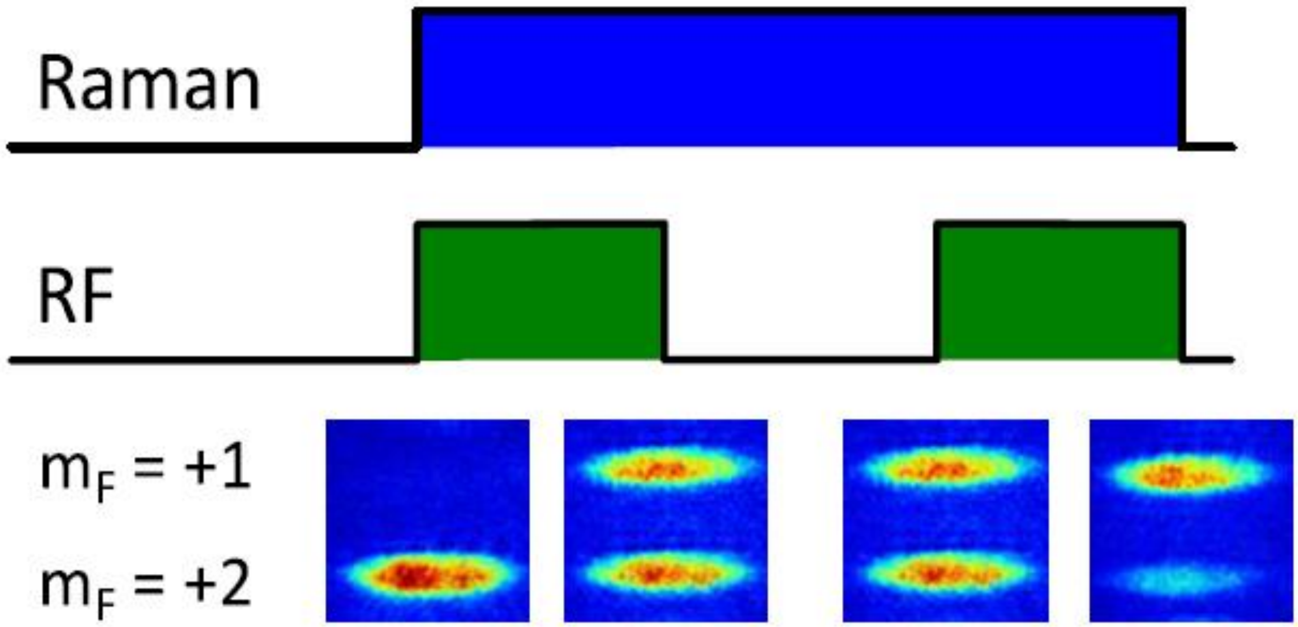

- Vary delay time between the two RF pulses
- Coherence ⇔ Population oscillation between both states

Proving Coherence

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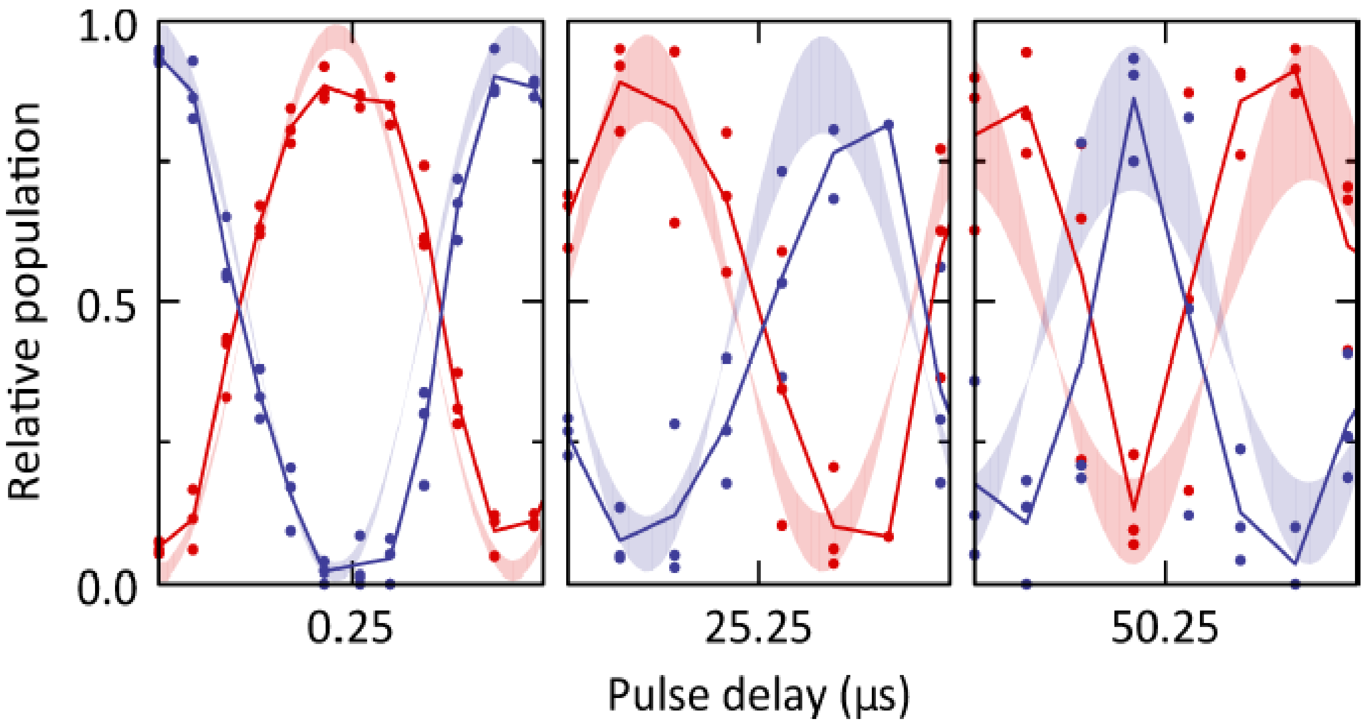

- $\Omega_{\mathrm{RF}} = 2\pi\, 15$ kHz, $\Omega_{\mathrm{Raman}} = 2\pi\, 140$ kHz
- Coherence decays very slowly ($t_{\mathrm{deph}} \approx 3$ ms)