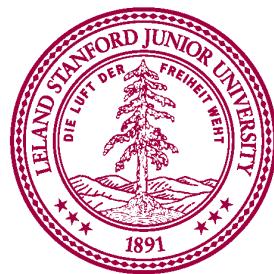


Spin echo in semiconductors using ultrafast optical pulses

Kai-Mei Fu
LABS^{hp}

Susan Clark
Qiang Zhang
Thaddeus Ladd
Yoshihisa Yamamoto

Colin Stanley
 University
of Glasgow



Stanford University

Research Organization of Information and Systems
国立情報学研究所
National Institute of Informatics

National Institute of Informatics

Why semiconductor quantum computer?

- Previous Knowledge
- Small
- Optical Control
- Fast
- Scalable

But there's the problem of decoherence, qubits interact with the environment

- T_2^* and T_2 are much shorter than the measured T_1 time due to interactions with the environment
- Looking for ways to extend the T_2^* and T_2 times

Why optical?

Speed: more manipulations before decoherence

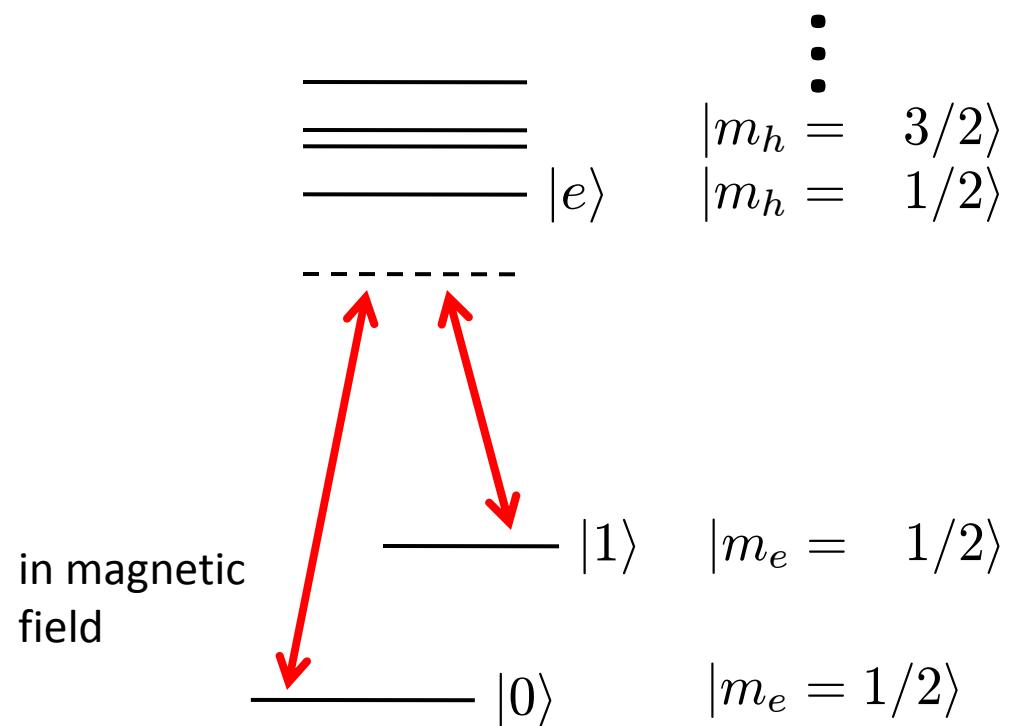
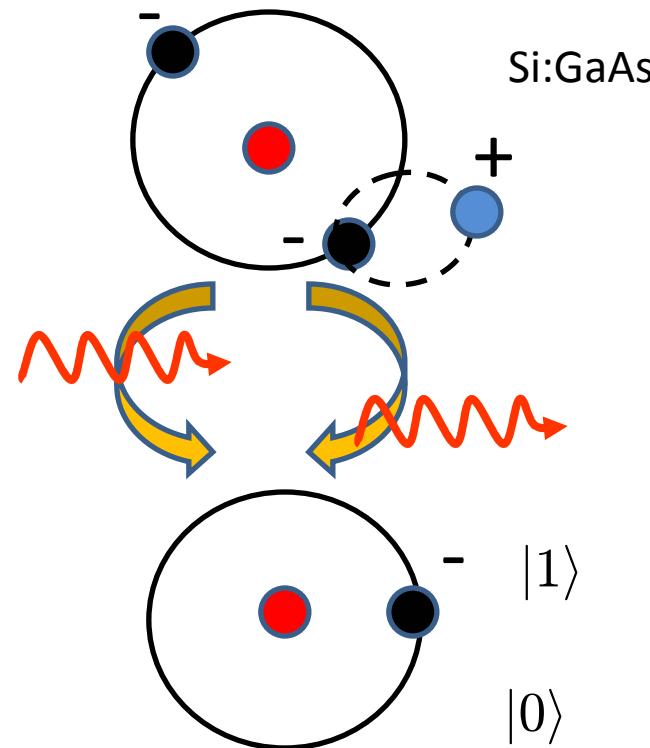
Why optical spin echo?

- Measure T2, evaluate system with fast pulses
- First step toward dynamic decoupling, extending coherence times
- Goal for simplest system

Optical Spin Echo Outline

- Donor bound electron system
- Optical pulses to manipulate solid-state spins
 - Rabi oscillations (1 pulse experiment)
 - Ramsey fringes (2 pulse experiment)
- Optical pulses to extend coherence
 - Small angle spin echo (3 pulse experiment)
 - Dynamic decoupling (many pulse)

Donor bound electron system: best of atomic and semiconductor systems



details:

$5 \times 10^{13} / \text{cm}^3$ doping

observing $\sim 10,000\text{-}100,000$ donors

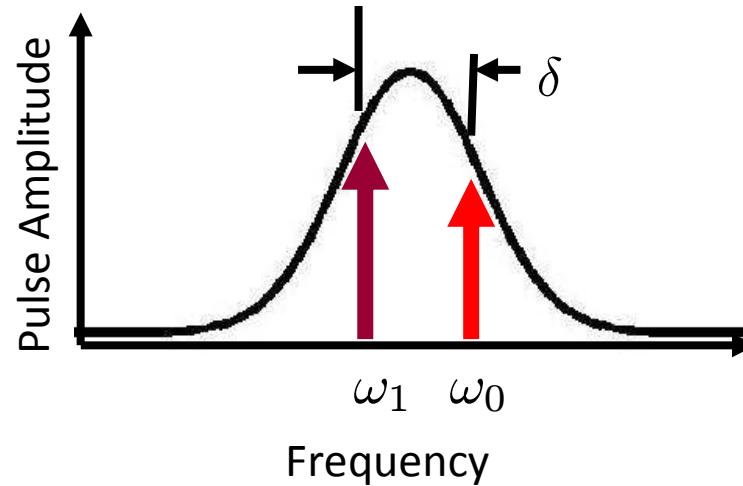
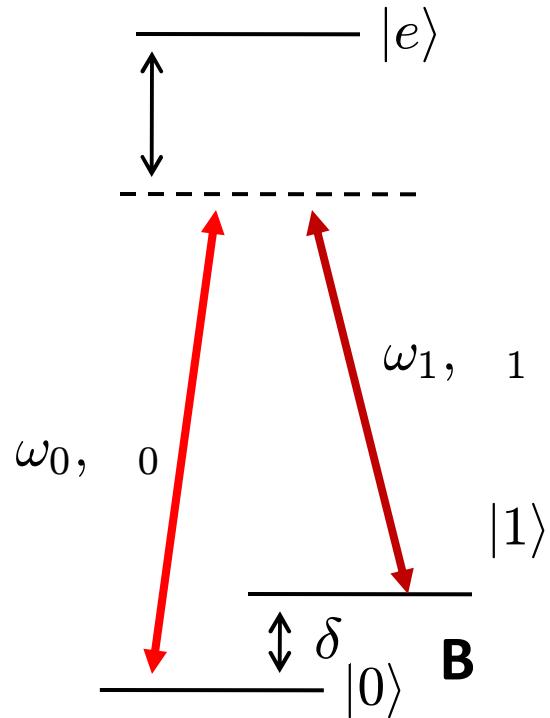
linewidth $\sim 100 \text{ MHz -} 1 \text{ GHz}$

Atomic positives:
Homogenous

Solid state positives:
Easy to fabricate
small
Fast timescales

Karasyuk, et al. PRB **49** 16381 (1994)

Ultrafast Pulses to rotate spins



Gupta, et al. *Science* **292** 2458 (2001).

rotation angle $\int \Omega_{\text{eff}} dt$ is proportional to pulse energy

et al. *PRB*, **74** 125306 (2006).

Omou, et al. *PRB*, **74** 205415 (2006).

rotation axis depends on phase differences between frequency pairs

Berezhiani, et al. *PRL* **99** 040501 (2007).

Fu, Clark, et al. *Nat. Phys.* **4** 780 (2008).

Can get to any point on Bloch sphere using combination of

optical rotation and precession in B field

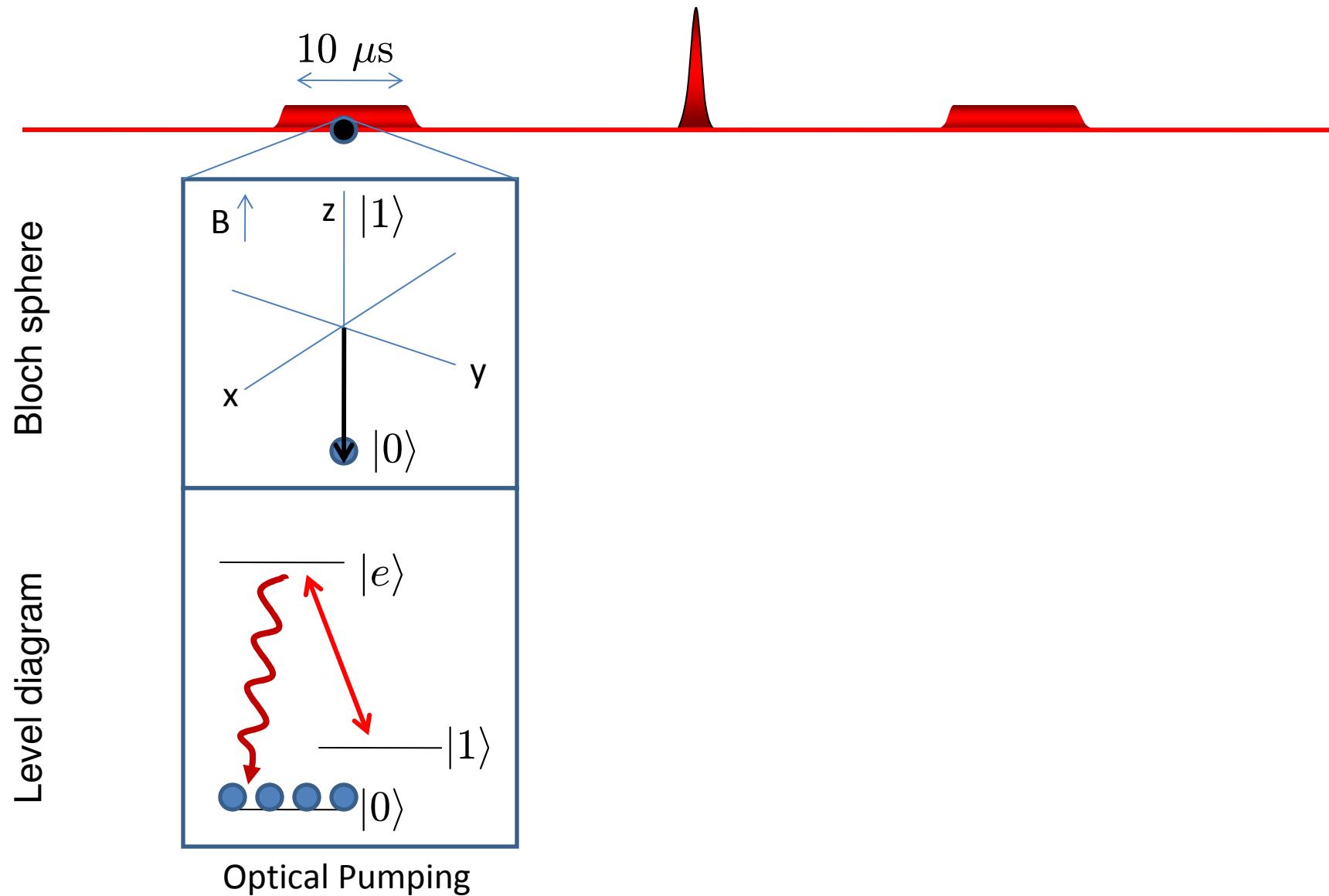
Greilich, et al. *Nature Phys.* **5** 262 (2009).

Phelps, et al. *PRL* **102** 237402 (2009).

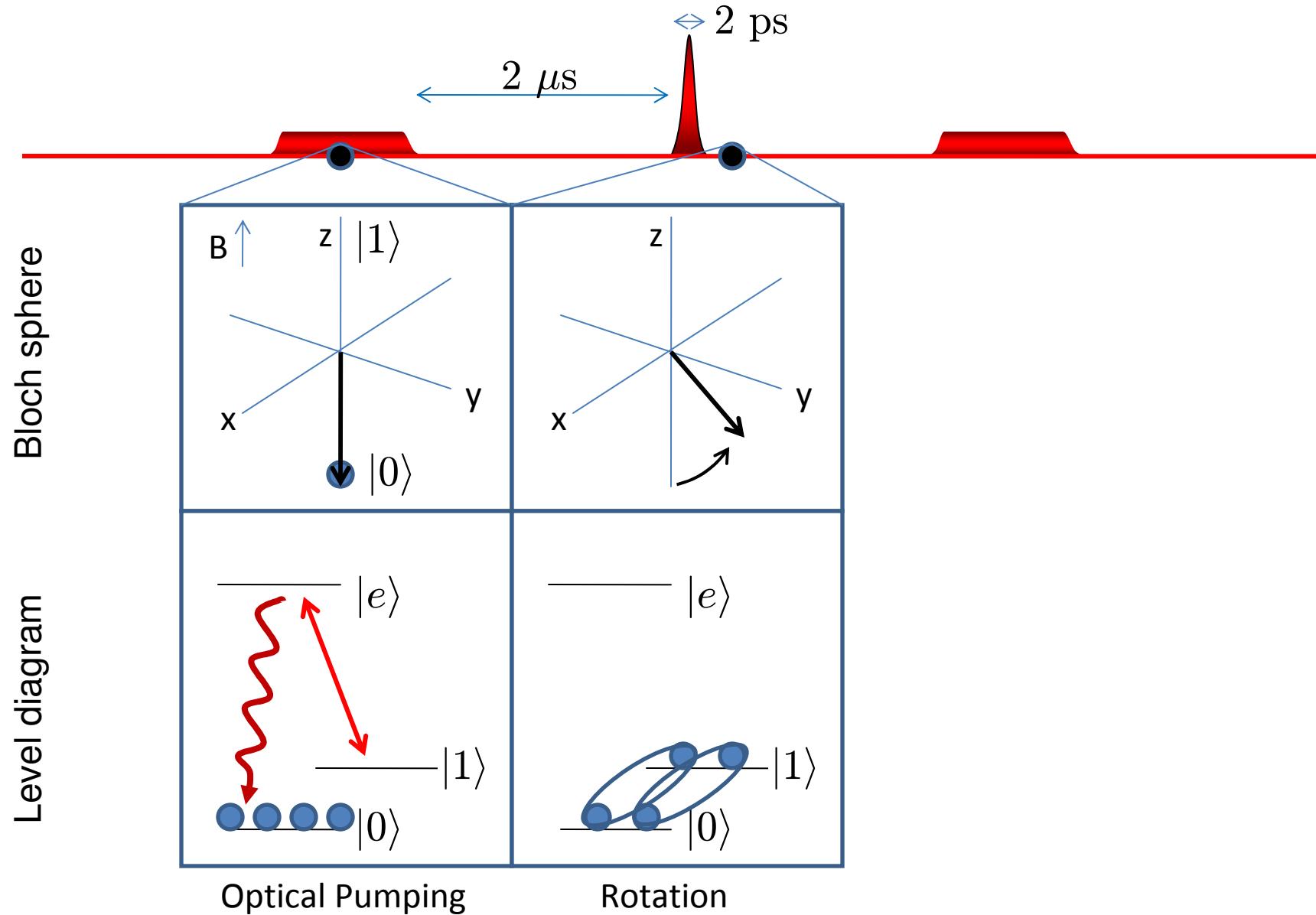
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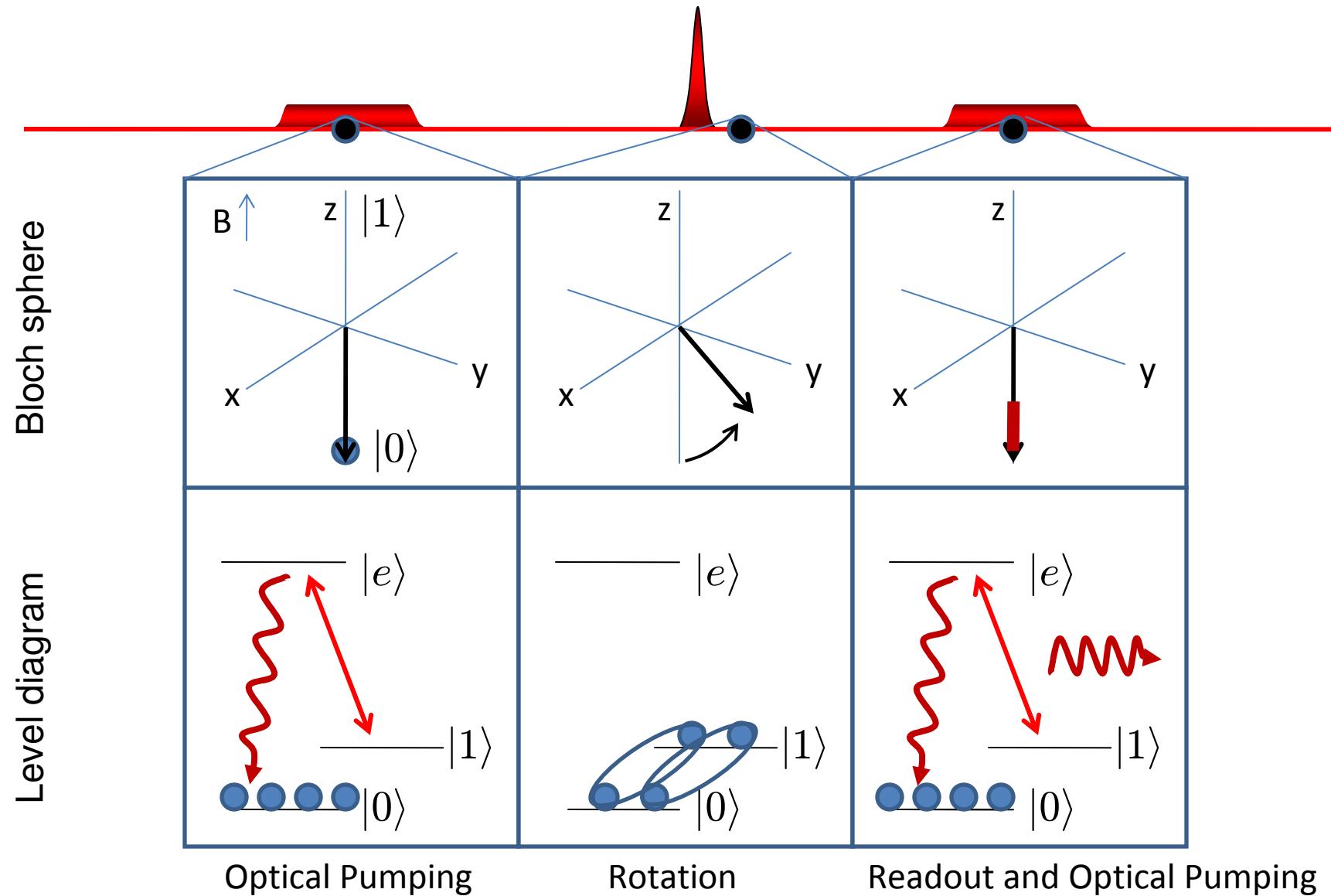
Rabi oscillation experiment (1 pulse)



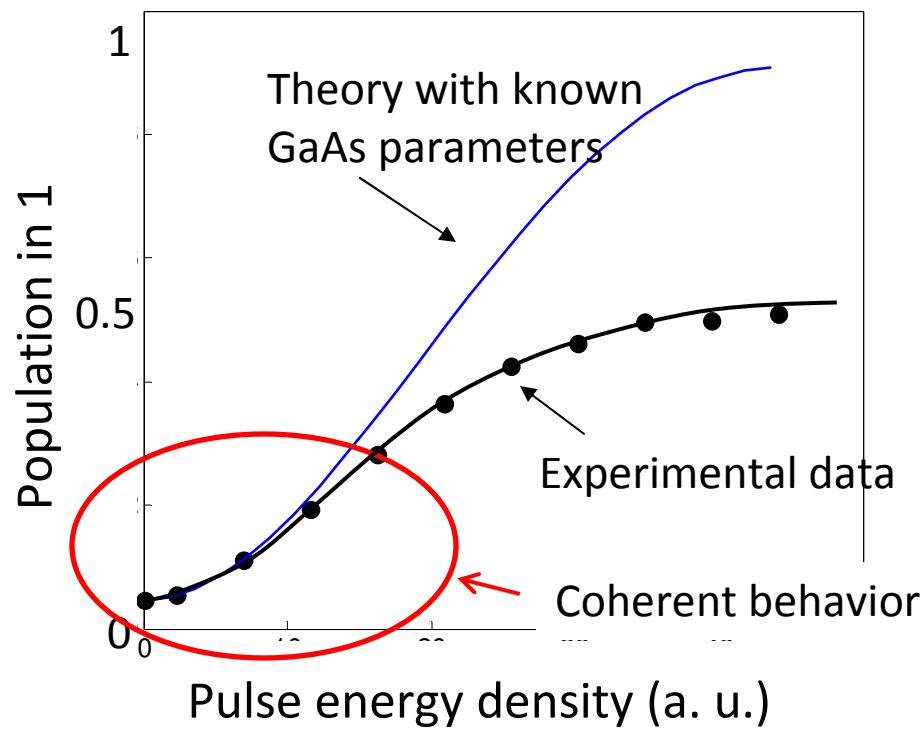
Rabi oscillation experiment (1 pulse)



Rabi oscillation experiment (1 pulse)

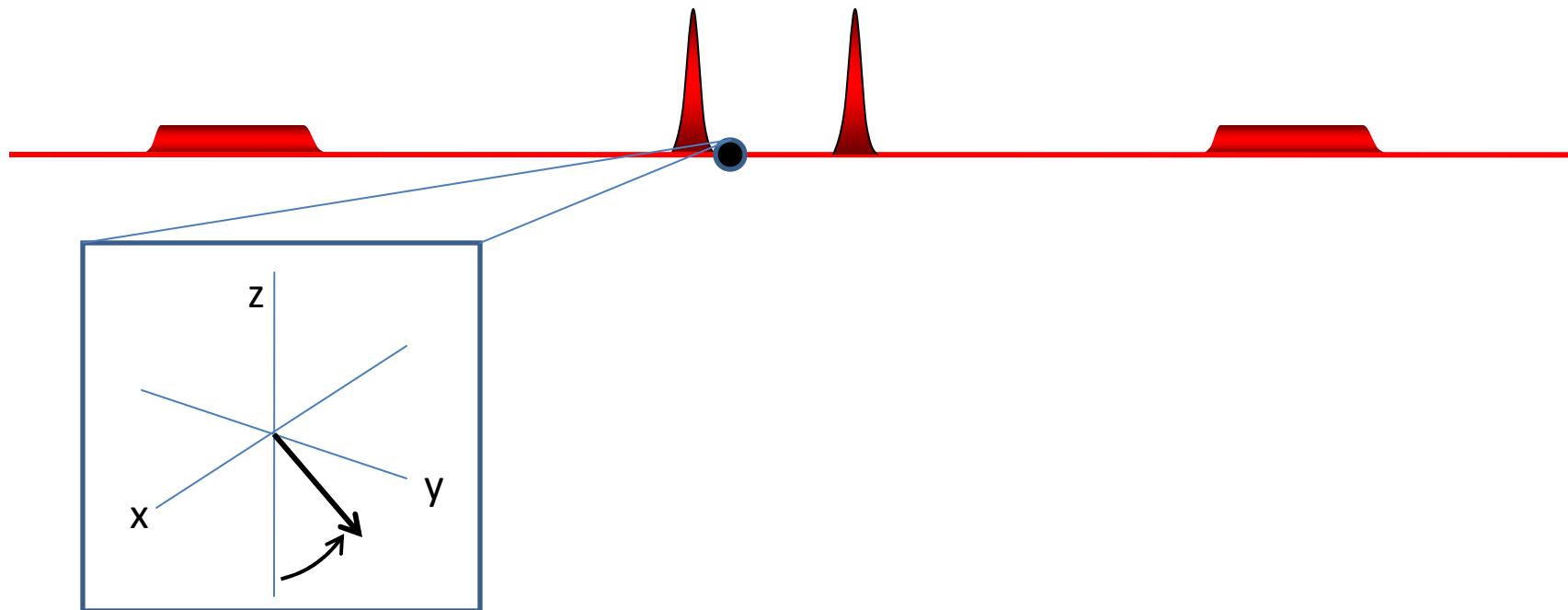


Rabi oscillations (1 pulse)

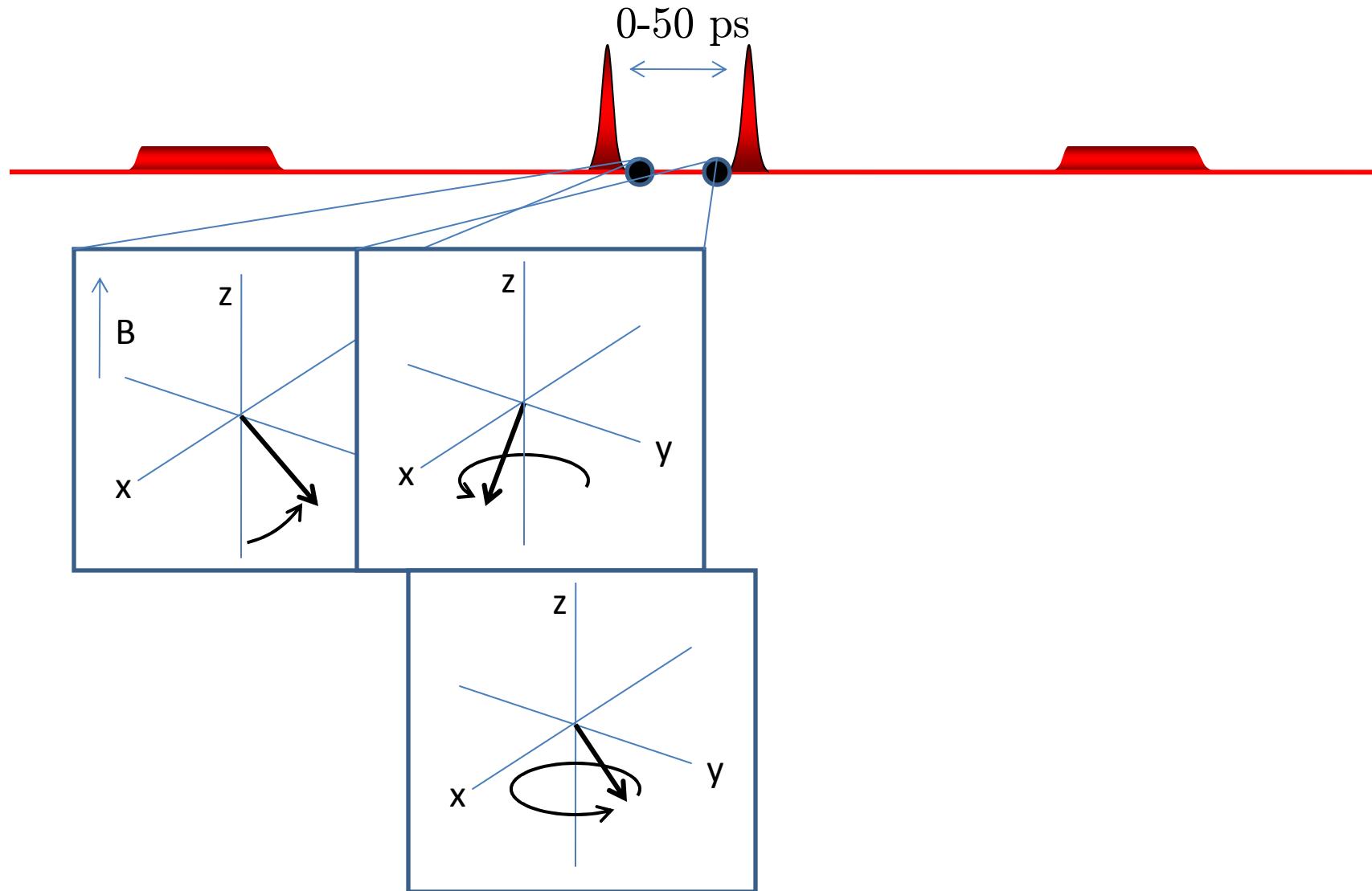


Can fit with a power dependent decoherence – possibly due to free excitons

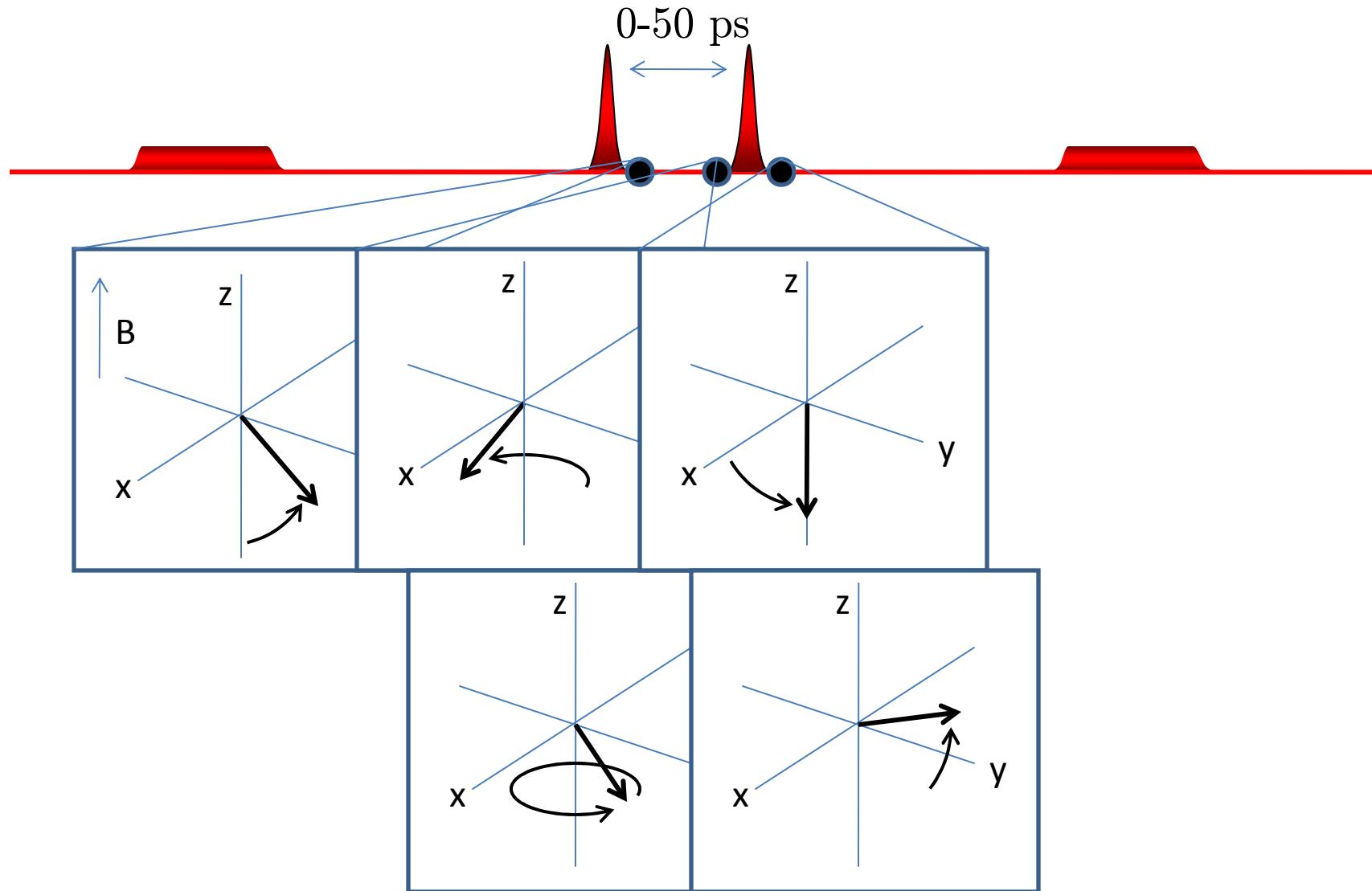
Ramsey Fringes (2 pulse)



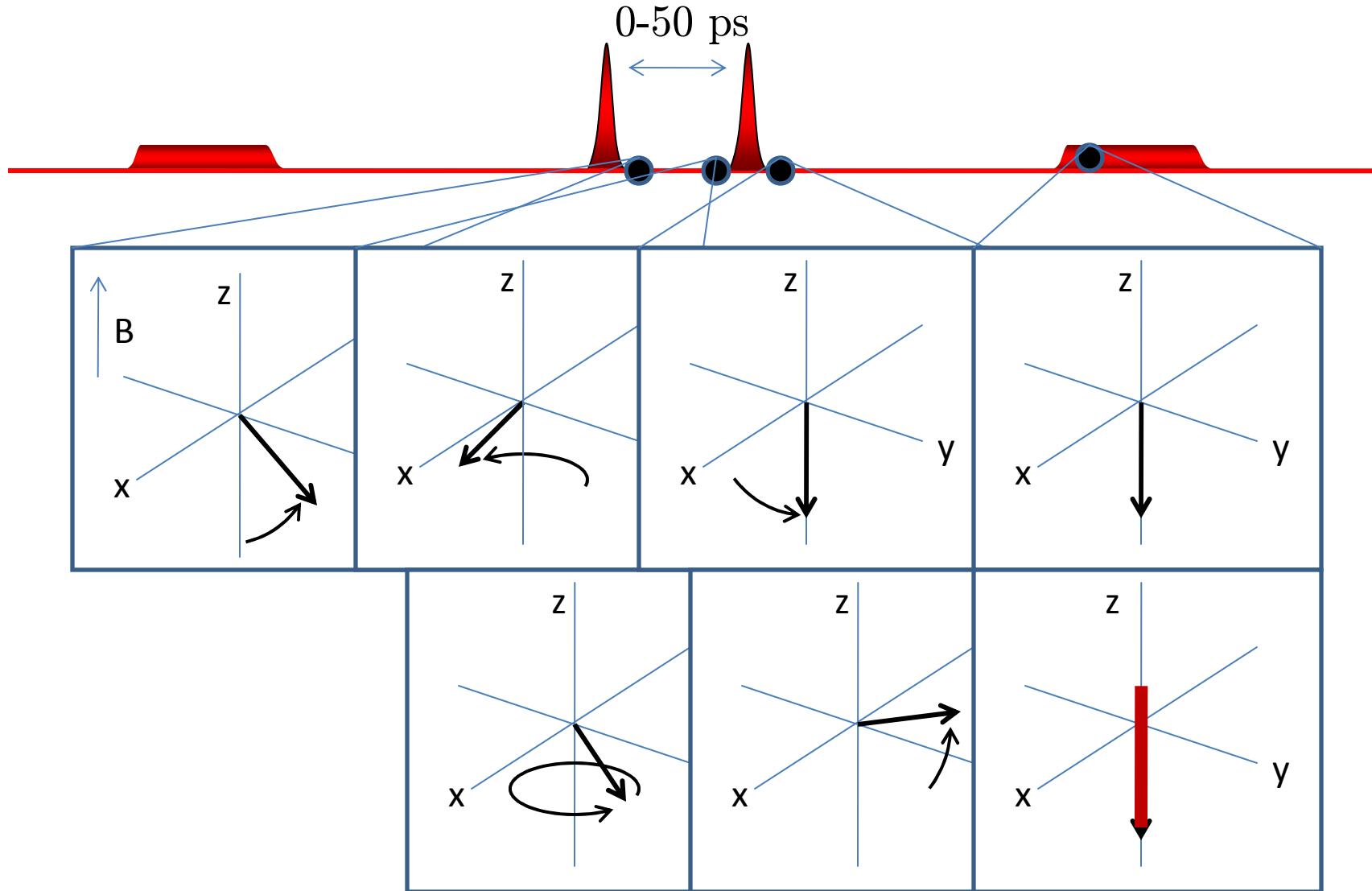
Ramsey Fringes (2 pulse)



Ramsey Fringes (2 pulse)



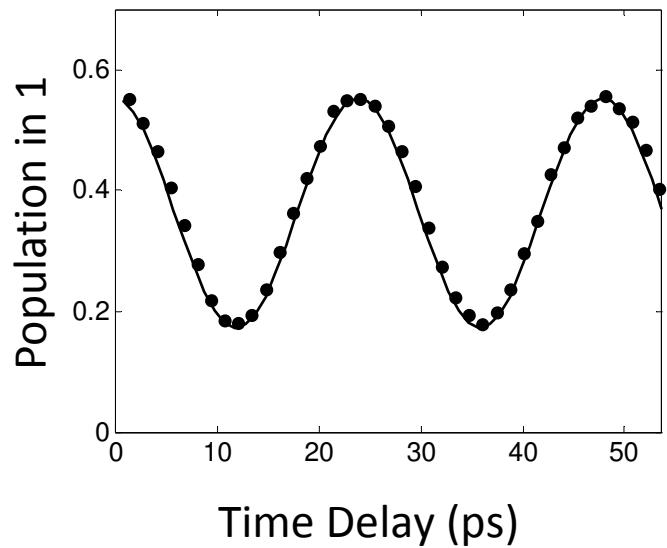
Ramsey Fringes (2 pulse)



Ramsey Fringes (2 pulse)

Fit using additional decoherence that depends on pump power

Population in state 1 vs. time delay



- Shows that we are coherently rotating spins
- Limited to low power (small rotation angle) pulses

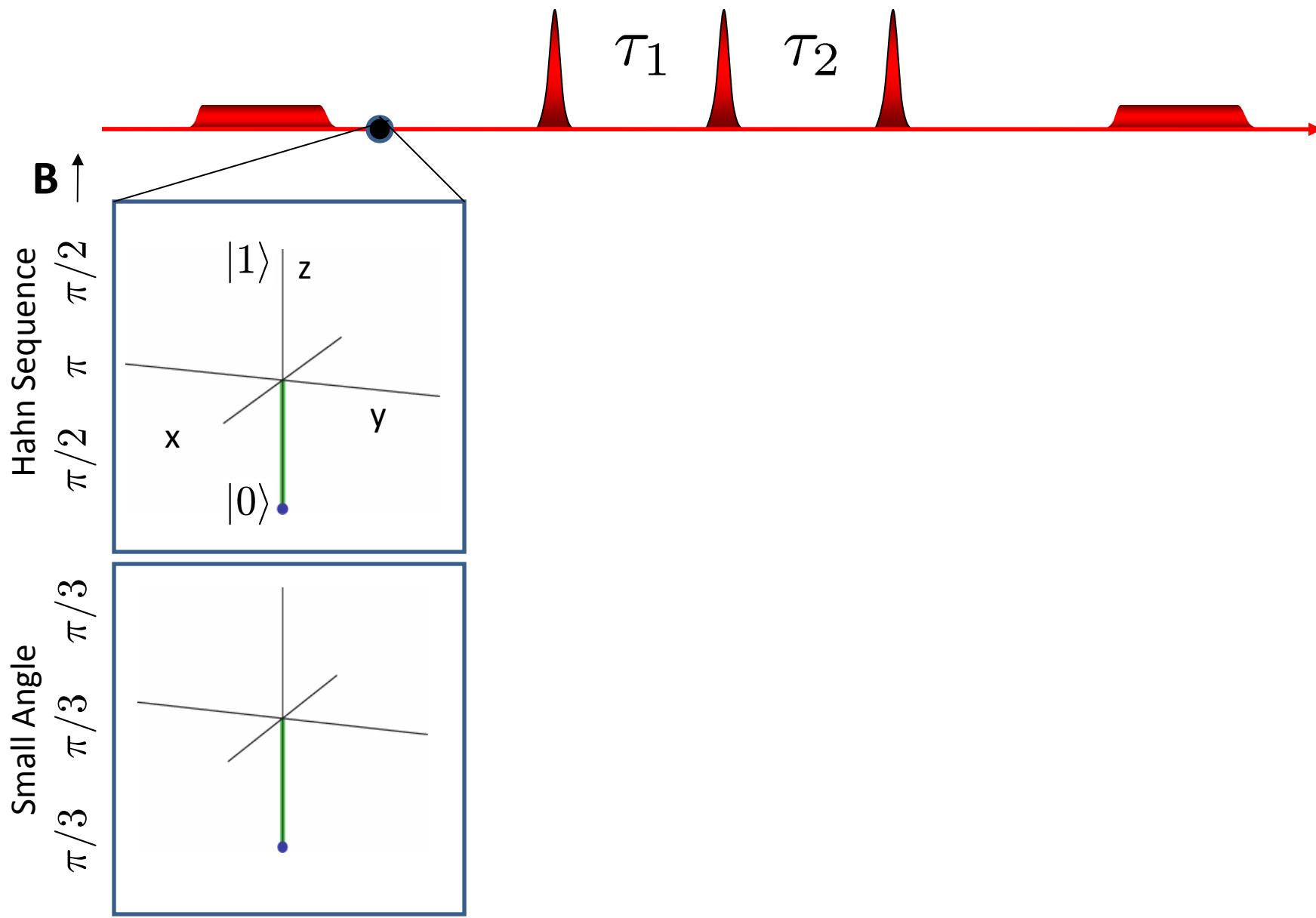
$$\begin{aligned}\pi/3 \text{ rotation} &\sim 0.91 \text{ Fidelity} \\ \pi/3 + \pi/3 &\sim 0.73 \text{ Fidelity}\end{aligned}$$

K.-M. Fu, S. Clark et al. *Nat. Phys.* **4** 780 (2008).

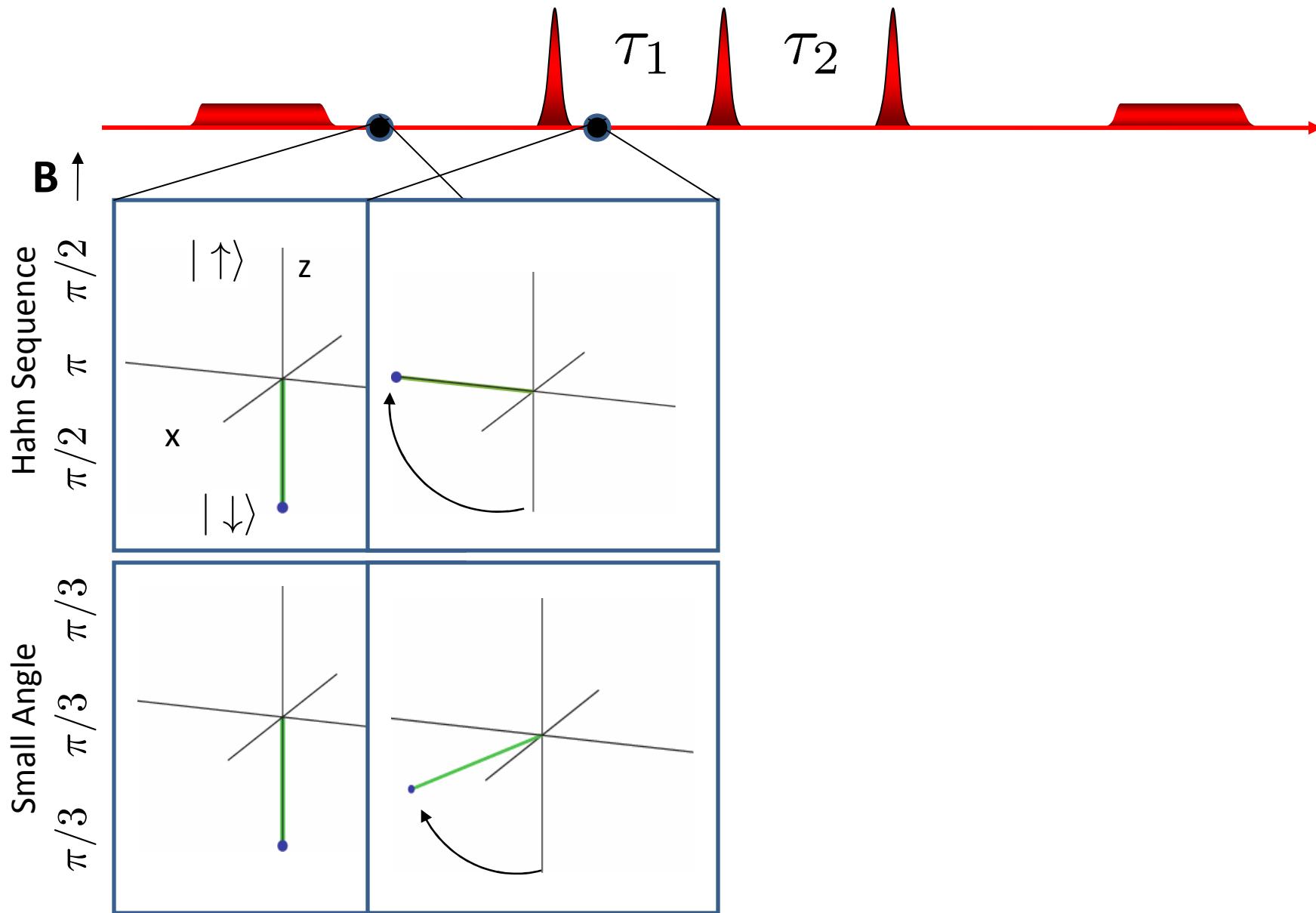
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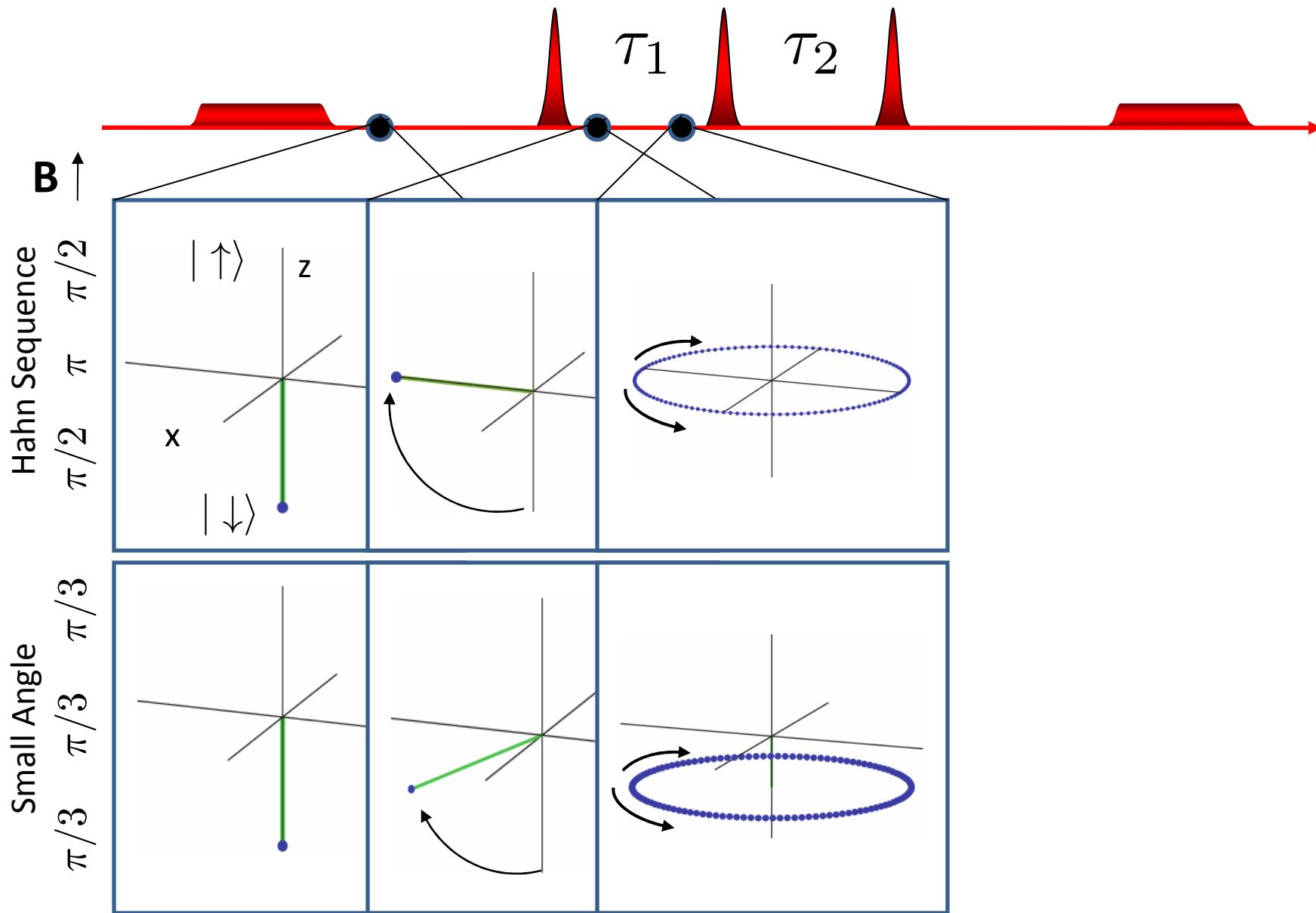
How (small angle) spin echo works



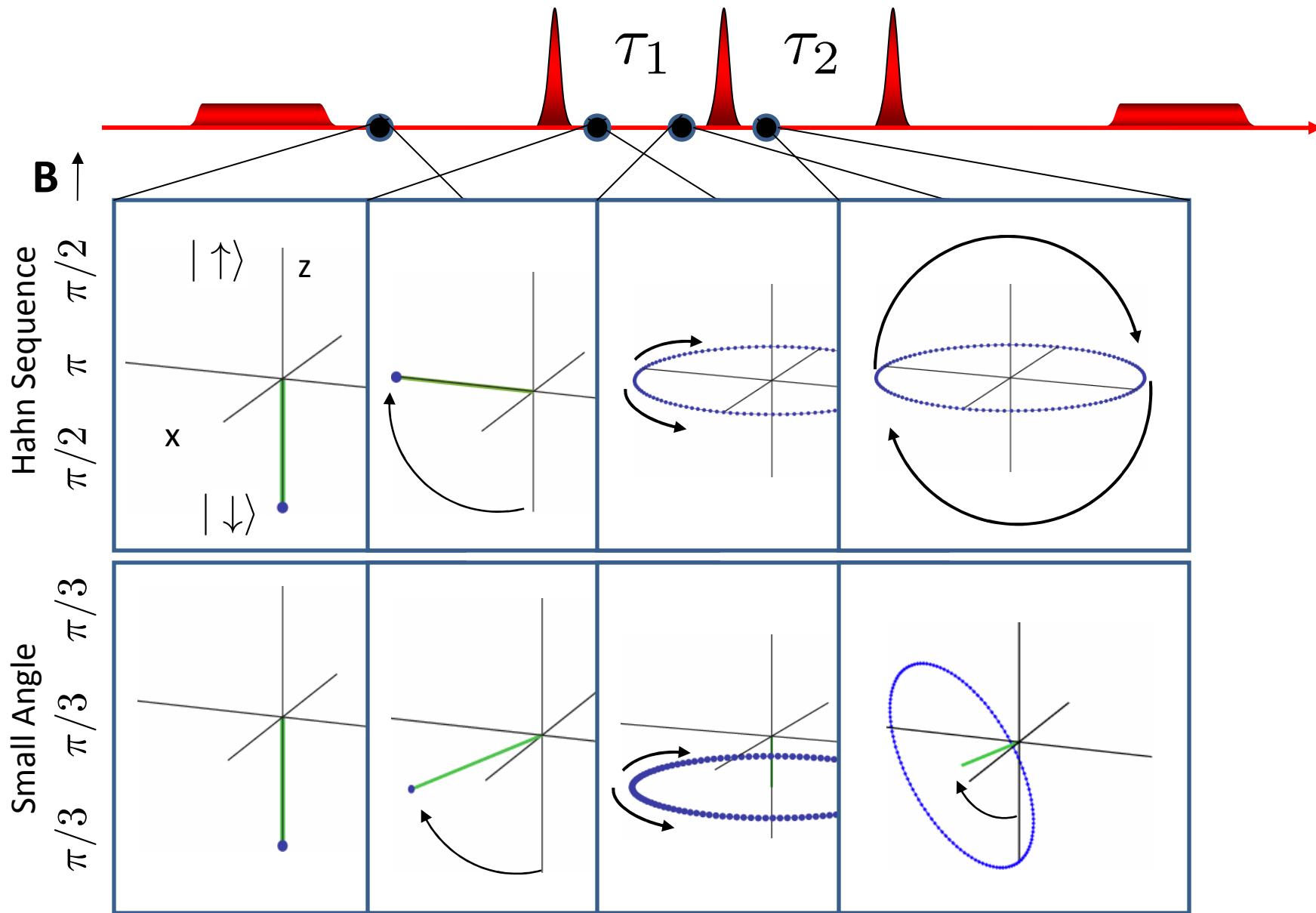
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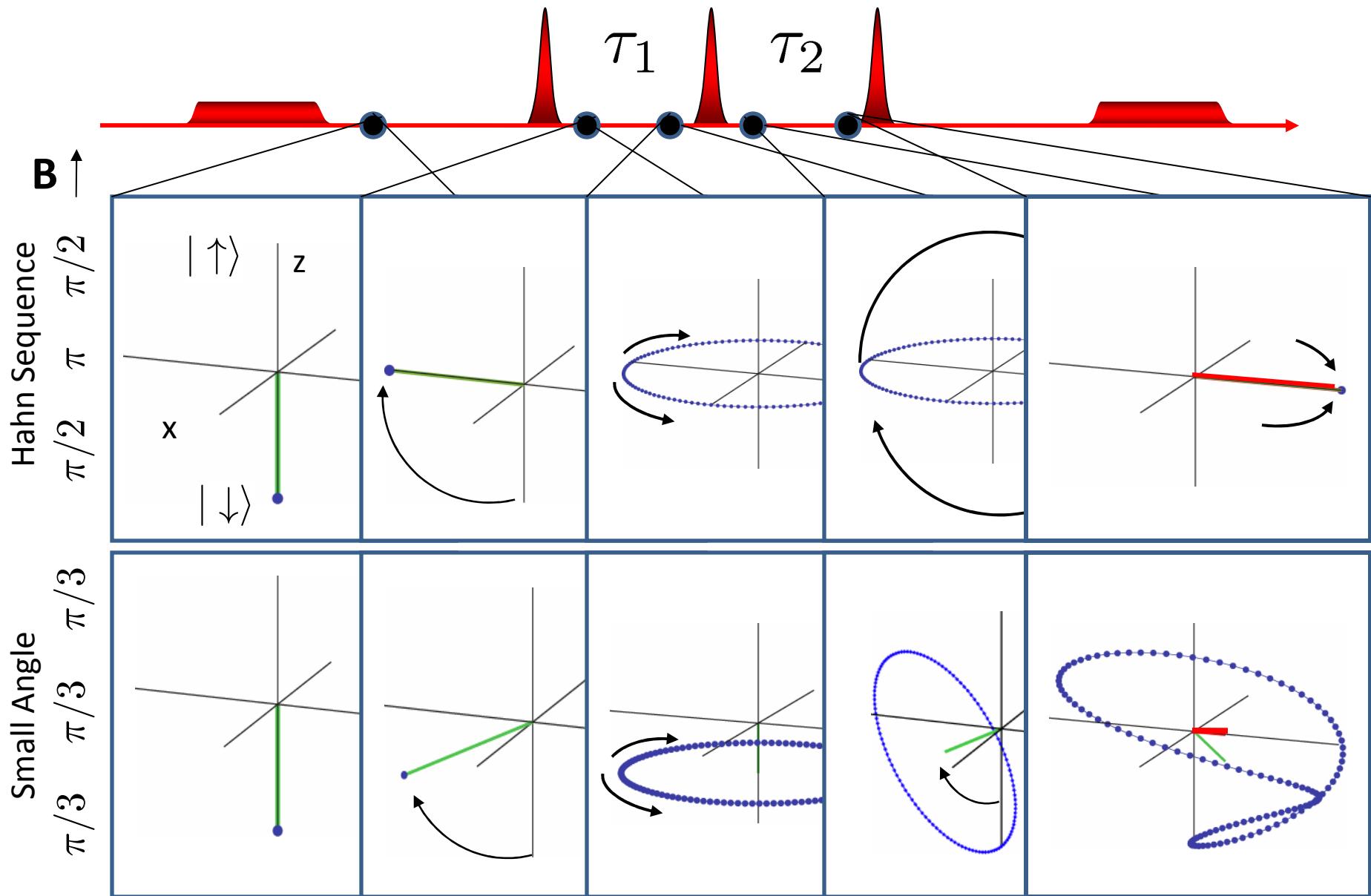
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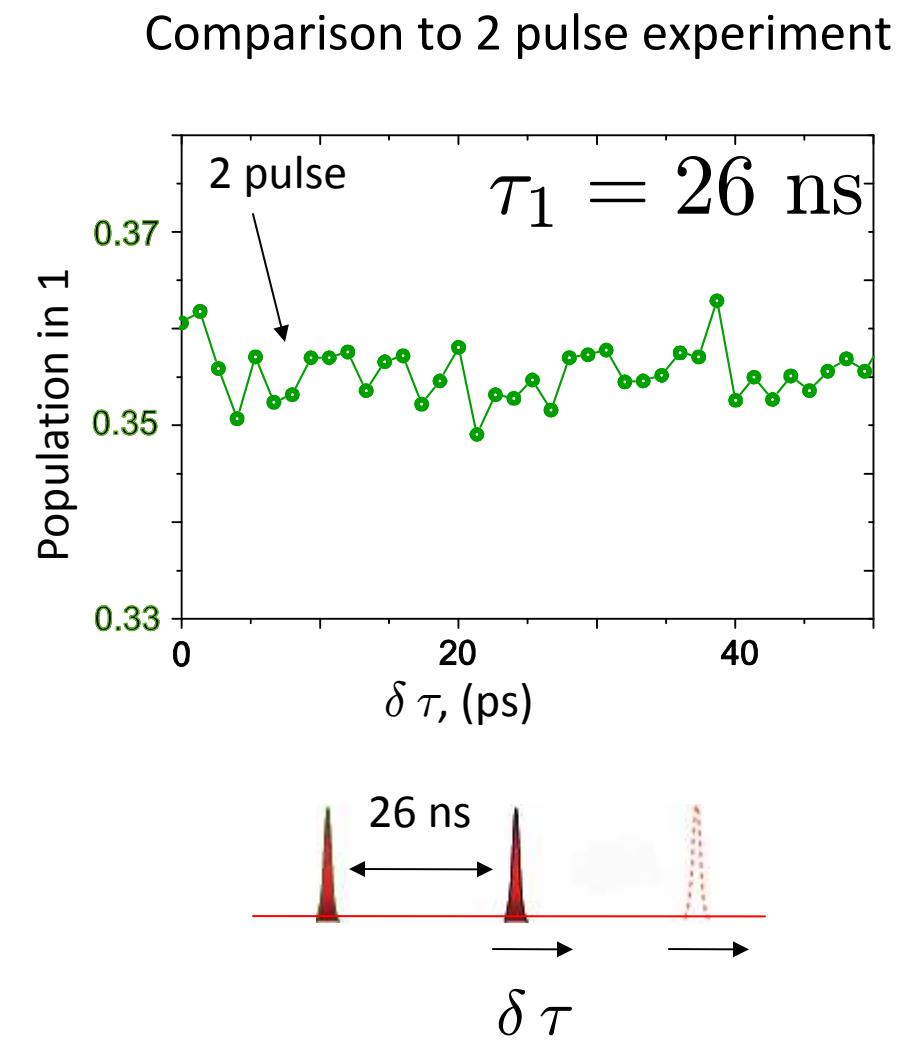
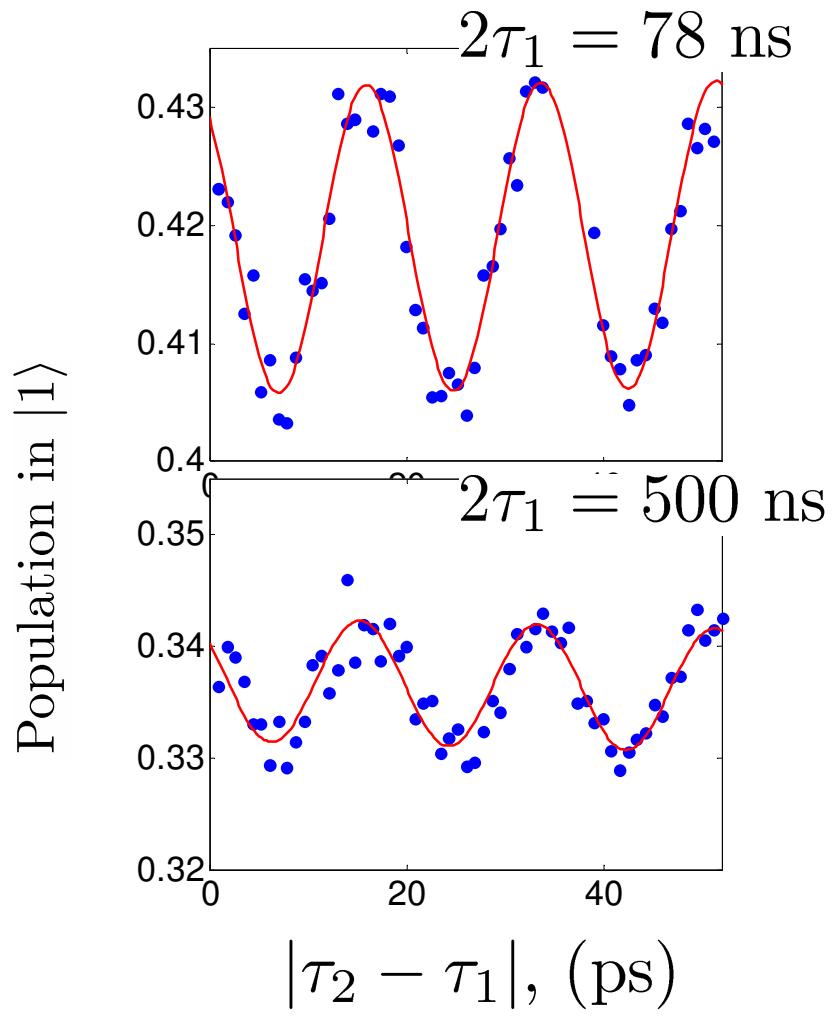
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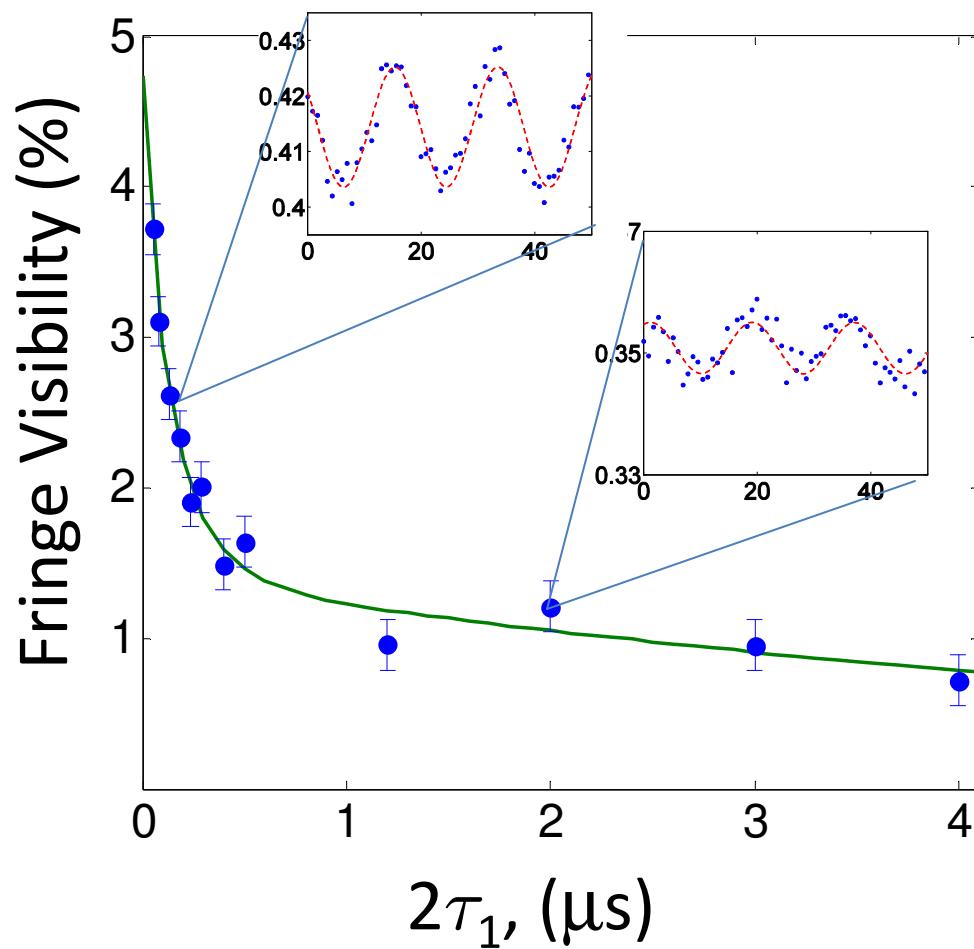


We see expected fringes



Clark, et al. *PRL* **102** 247601 (2009)

Decay of fringe visibility



Clark, et al. *PRL* **102** 247601 (2009)

Model with two sources
of decoherence

1. Intrinsic T_2 , ($6 \mu s$) likely nuclear spin diffusion, supported by theory*
2. Pulse induced excitations (phonons, excited impurity states) cause decoherence proportional to their population (~ 200 ns)

T_2 similar to previous measurements using spin locking in quantum dots
Greilich, et al. *Science* **313** 341 (2006)

*Paget *PRB* **25** 4444 (1982)
de Sousa and Das Sarma *PRB* **67** 033301 (2003)
Yao, Liu, and Sham *PRB* **74** 195301 (2006)

Dynamic Decoupling (many pulses)

- Apply pi pulses faster than fluctuations that cause decoherence
- continually refocus spins
- can extend decoherence time

We need:

- system with full pi pulses (F:ZnSe?) or cascaded pulses
- dynamic decoupling scheme using small angle pulses

L. Viola and S. Lloyd. *PRA* **58** 2733 (1998)
Witzel and Das Sarma *PRL* **98** 077601 (2007)
Yao, Liu, and Sham *PRL* **98** 077602 (2007)
Uhrig *PRL* **98** 100504 (2007)

Conclusion

- Successful implementation of optical spin echo in a semiconductor system
- Ultrafast pulses are fast, but have additional decoherence.
- Donor system still promising



susan.clark@gmail.com
Stanford University

