Title: Learning from experiments on coherent control

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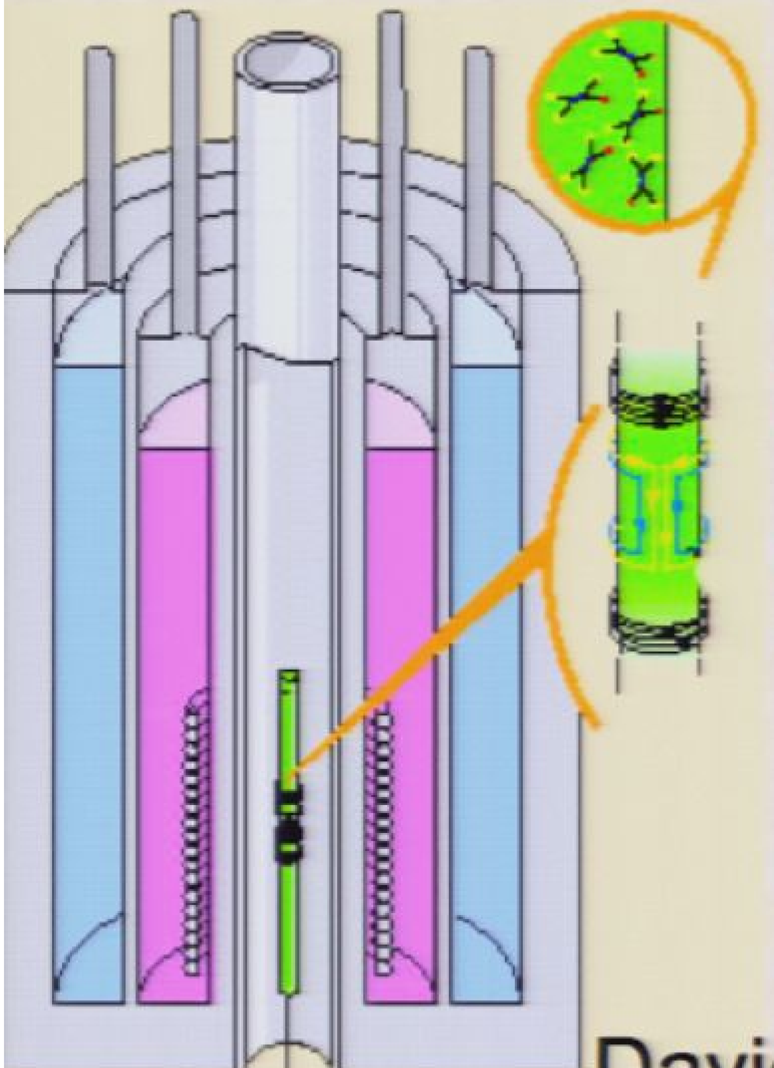
URL: http://pirsa.org/08080039

Abstract: I will discuss a few case studies of coherent control experiments and how we use quantum esstimation to motivate improved experiments. Examples from NMR with physical and logical quits, electron/nuclear spin systems and persistent current flux qubits



Learning from experiments on coherent control

David G. Cory
Nuclear Science & Engineering
Massachusetts Institute of Technology

We work to develop experimental measures that would inform discussions of fault tolerance.

- how quickly do 2-body terms fall off with distance?
- do they fall below a threshold?
- how important are n-body terms?
- what are the correlation (time/space) functions of noise?

I will not discuss these today.

Bread and Butter of lab is finding means of bending coherent dynamics to our desires.

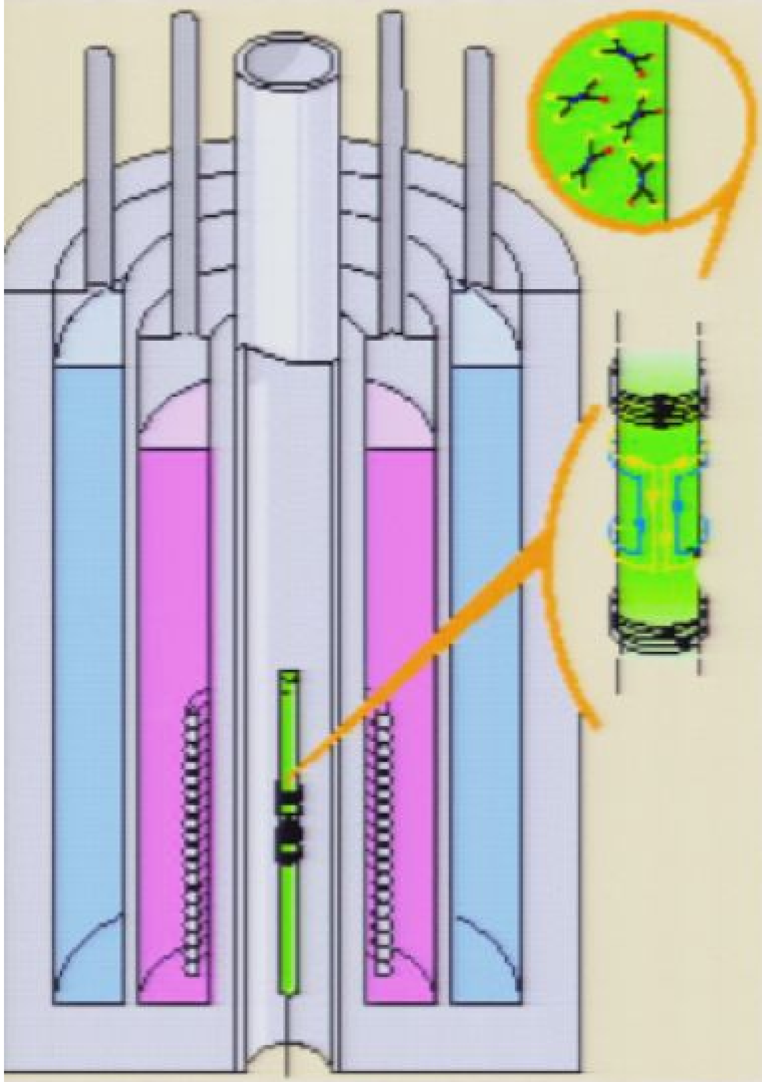
- to accomplish this we carryout a few measurements
- try to understand them in terms of a physically relevant model
- use this to motivate the next experiment

Today I will work through a few case studies with you

- liquid state NMR, physical qubits (nuclear spins)

- logical qubits

- superconducting, persistent current flux qubits



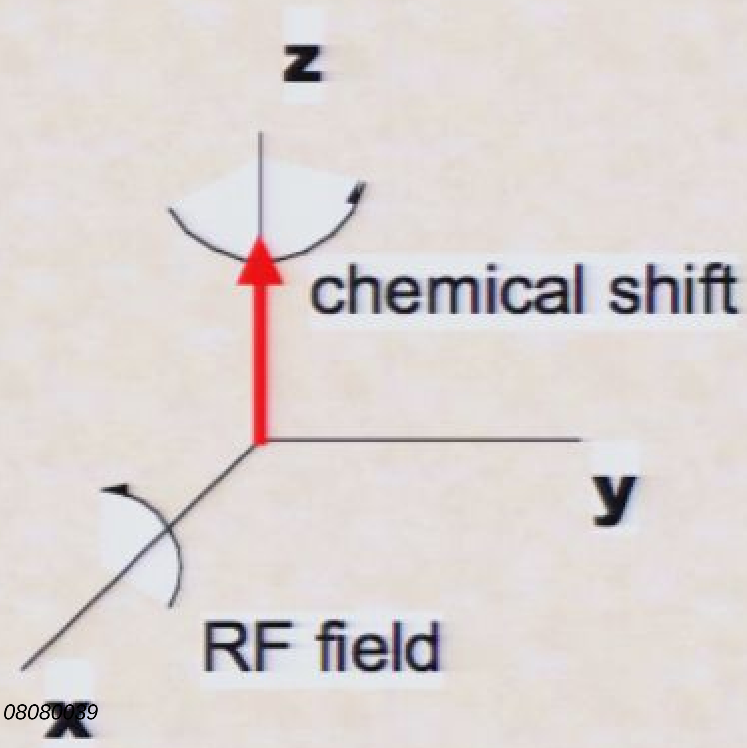
Dr. Timothy Havel
Professor Seth Lloyd
Professor Raymond Laflamme (UW)
Dr. Sekhar Ramanathan
Professor Joseph Emerson (UW)
Dr. Nicolas Boulant
Dr. Paola Cappellaro
Dr. Yaakov Weinstein
Dr. Michael Henry
Dr. Jonathan Hodges
Dr. Jamie Yang
Dr. Jonas Bylander
Dr. Will Oliver

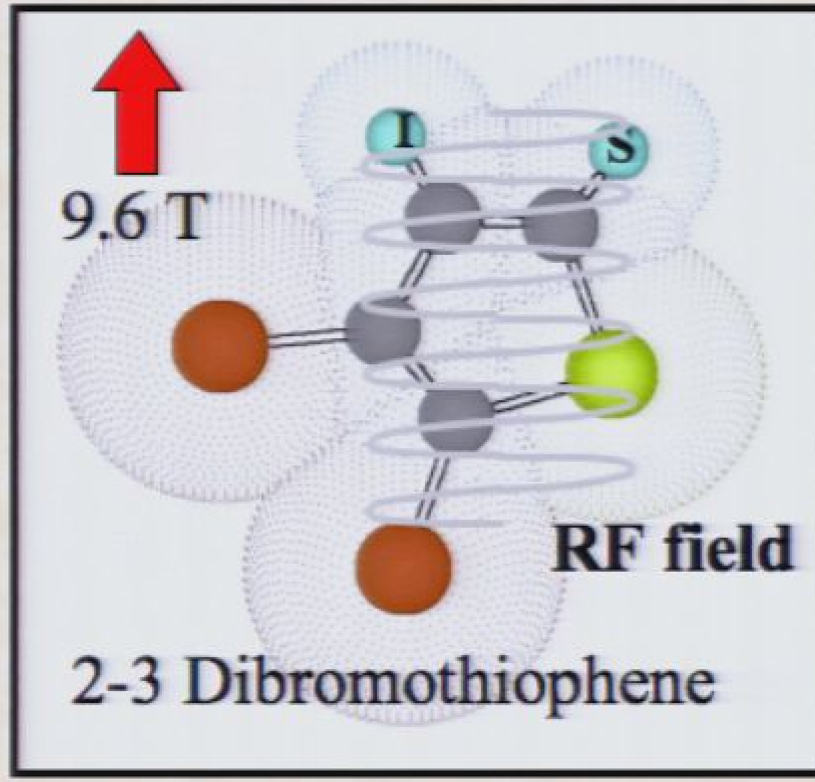
Control through time-dependent spin Hamiltonian

$$H_{int} = \underbrace{\omega_I I_z + \omega_S S_z}_{\text{interaction with B field}} + \underbrace{2\pi J_{IS} I_z S_z}_{\text{spin-spin coupling}}$$

interaction with B field

spin-spin coupling





$$H_{ext} = \underbrace{\omega_{RF}(t)\, I_x}_{\text{I spin with RF field}} + \underbrace{\omega_{RF'}(t)\, S_x}_{\text{S spin with RF field}}$$

I spin with RF field

S spin with RF field

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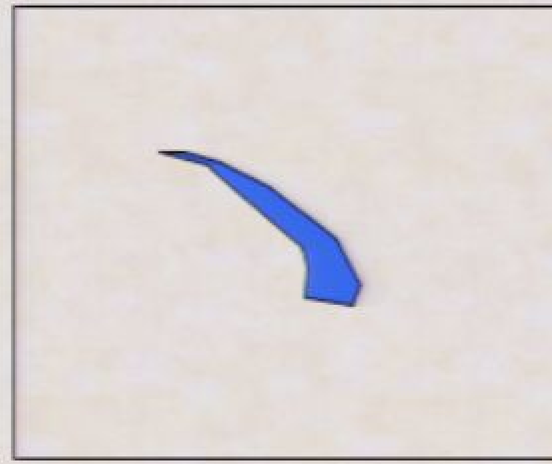
RF



static field

Model

- chemical shifts
- coupling constants
- range of fields (correlations, distributions)
- other spins in the system
- model of RF transmitter (non-linearity, transients)
- relaxation times
- correlation times

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Superoperator - Liouvillian Space

Robust Method for Estimating the Lindblad Operators of a Dissipative Quantum Process from Measurements of the Density Operator at Multiple Time Points. N. Boulant, T. F. Havel, M. A. Pravia and D. G. Cory, *Physical Review A*, 2003, **67**, 042322-1-12.

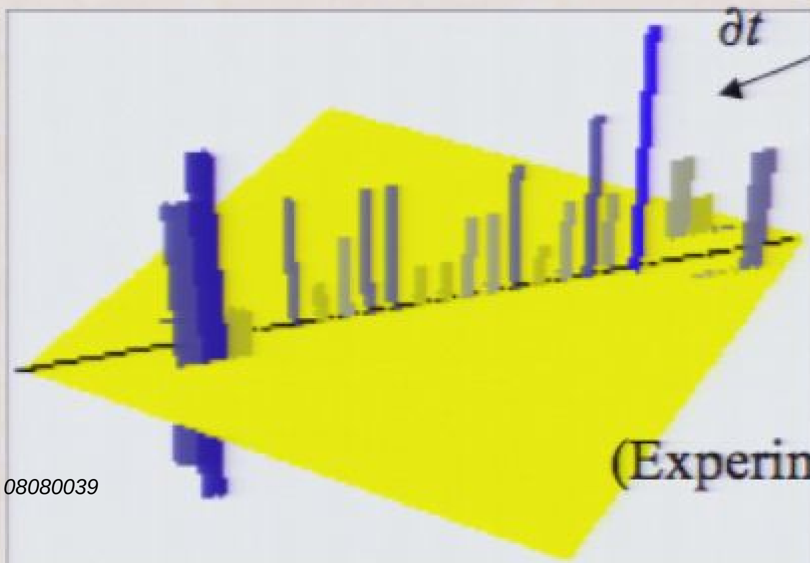
- Superoperator - a compact representation of the complete system evolution, including coherent, incoherent, and decoherent parts.

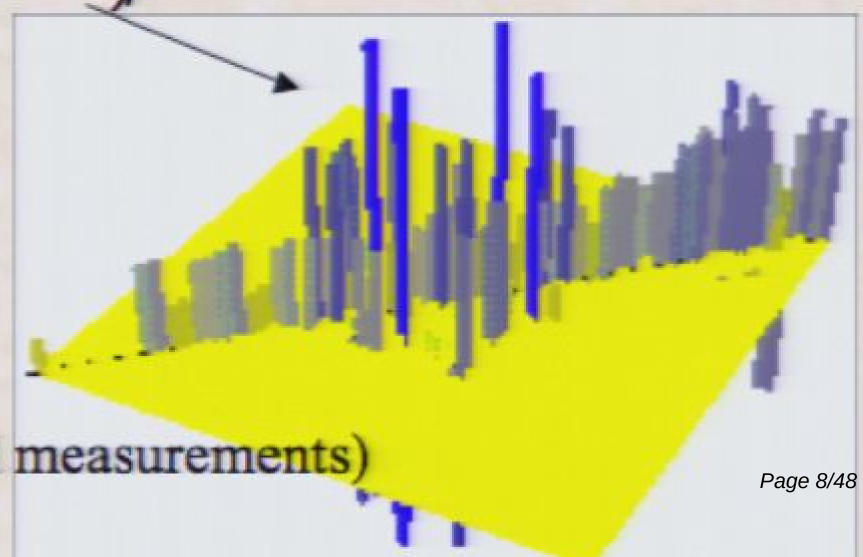
A closed quantum system evolves via the Liouville-von Neumann equation:

$$\frac{\partial \rho}{\partial t} = -i[H, \rho]$$

An open quantum system evolves via the Master Equation:

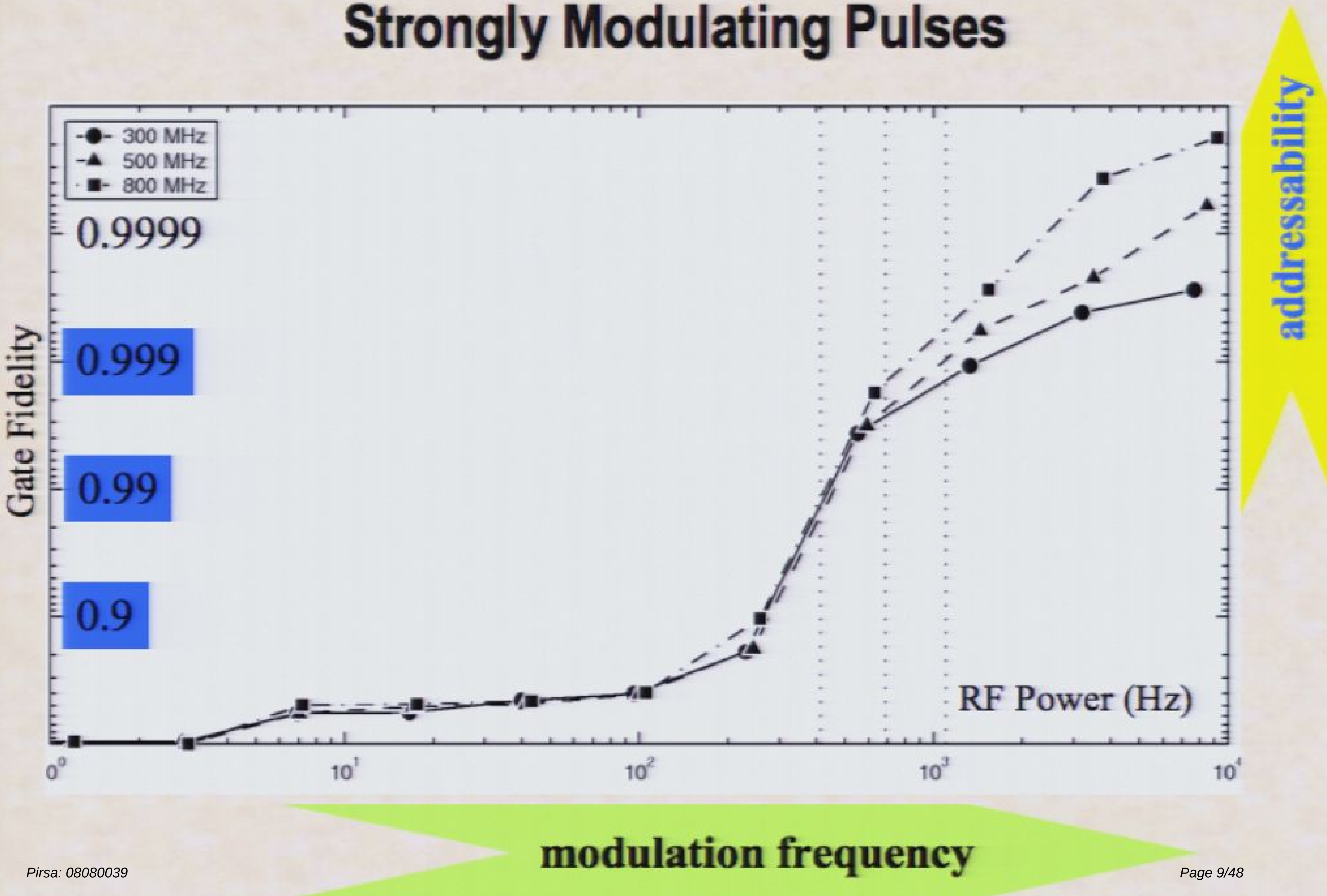
$$\frac{\partial \hat{\rho}}{\partial t} = \left(-i\tilde{H} - \tilde{\Gamma}\right)\hat{\rho}$$





(Experimental measurements)

Strongly Modulating Pulses



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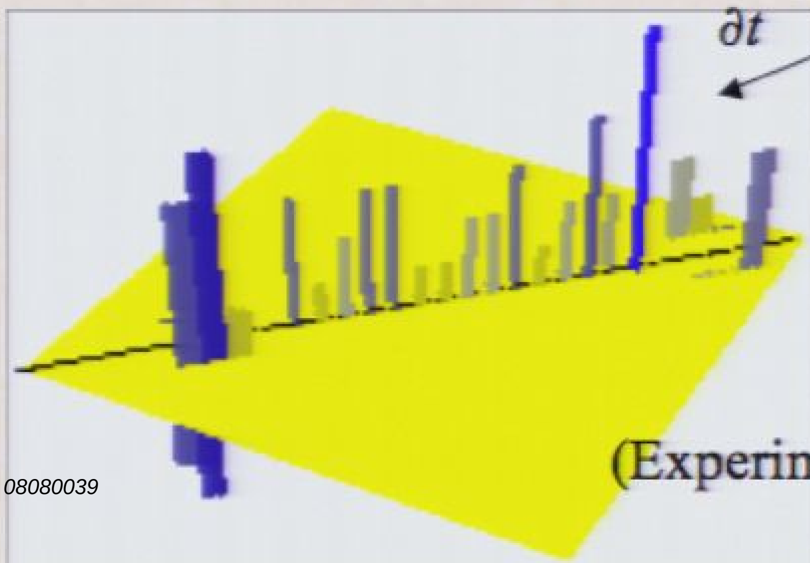

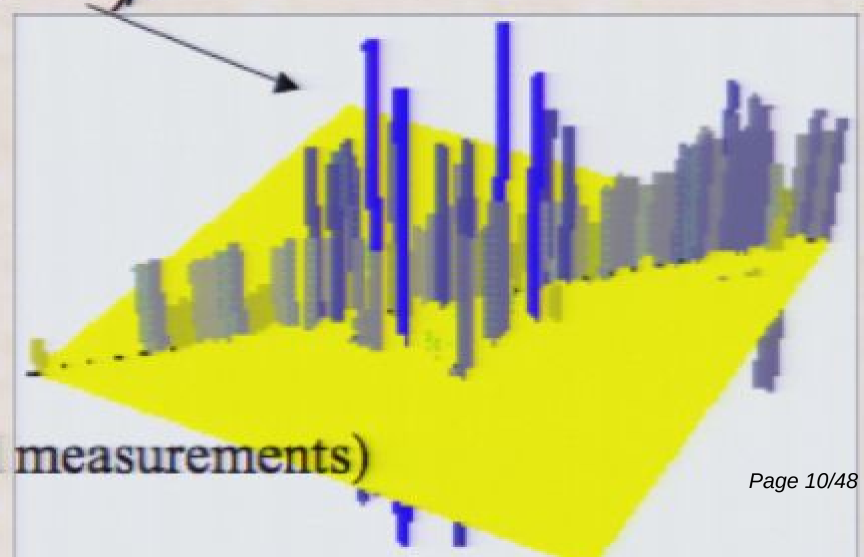

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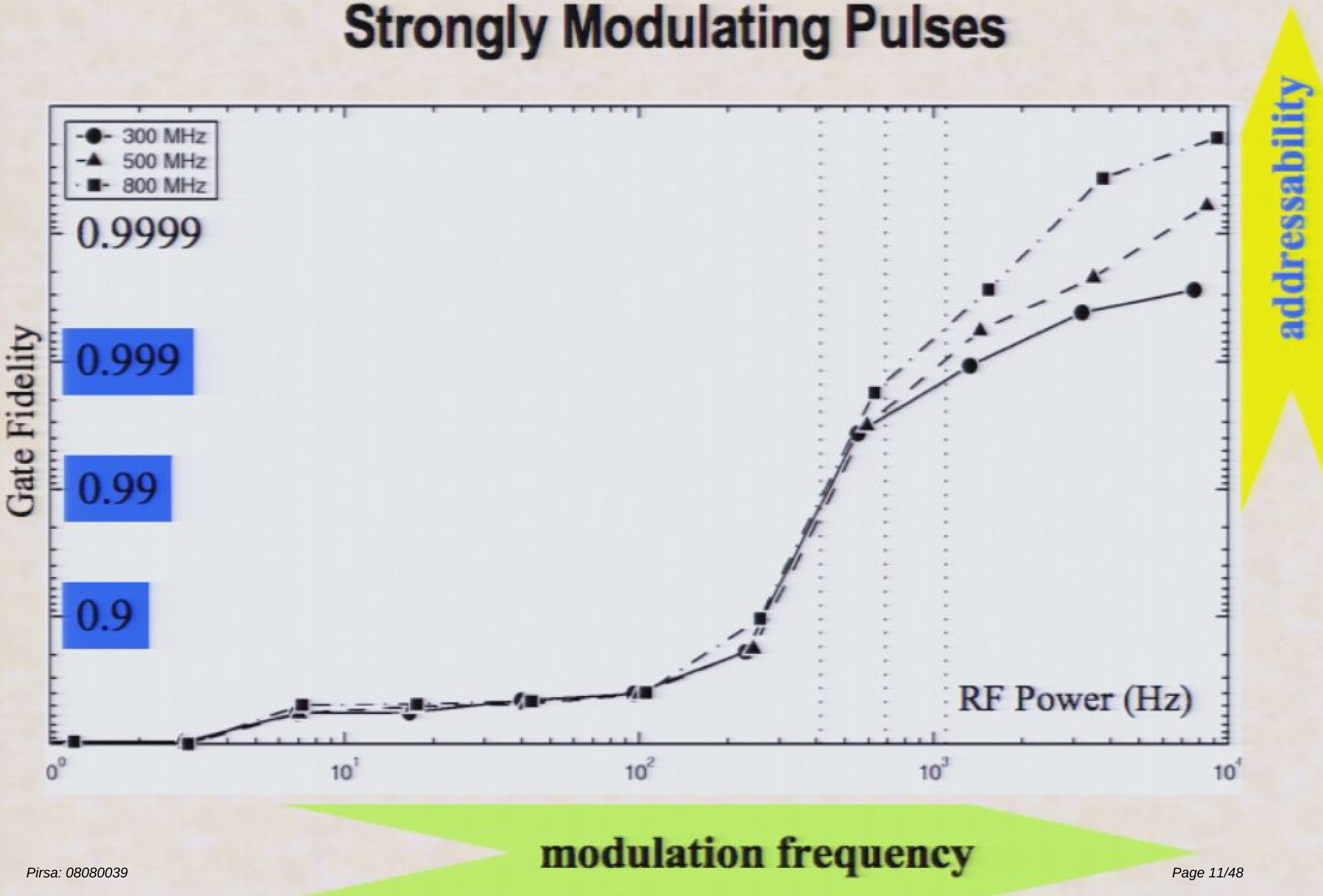
Strongly Modulating Pulses



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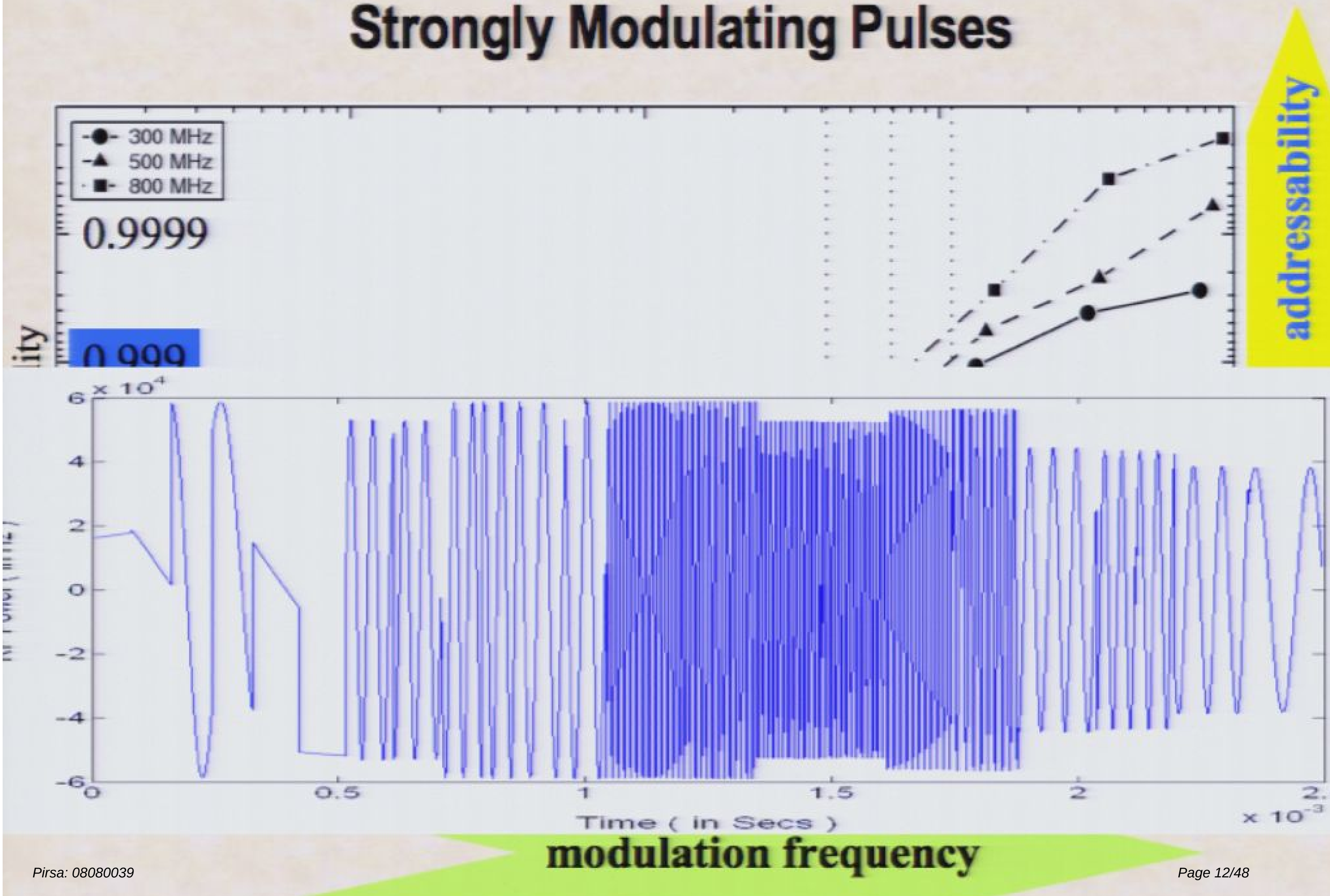

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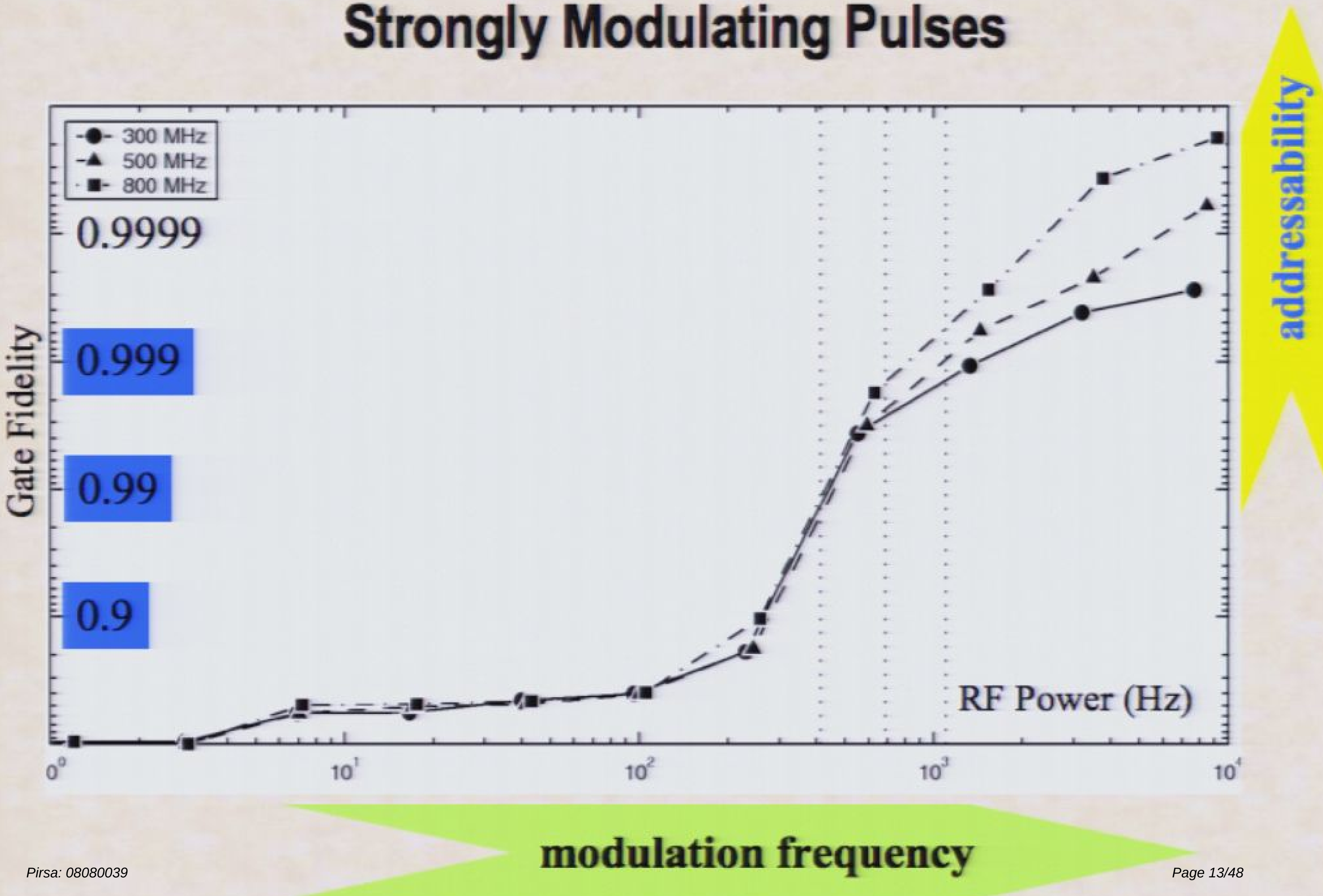

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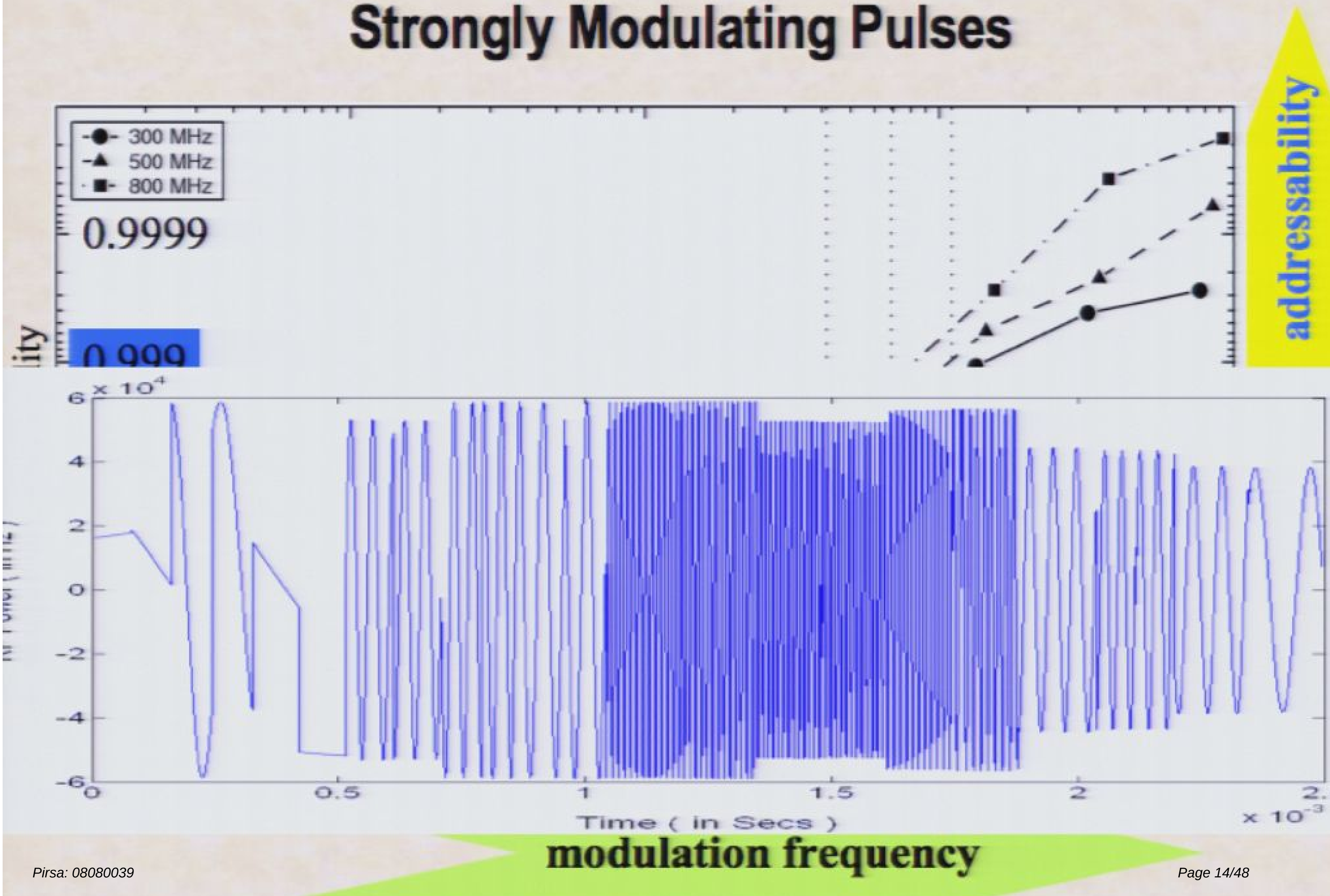
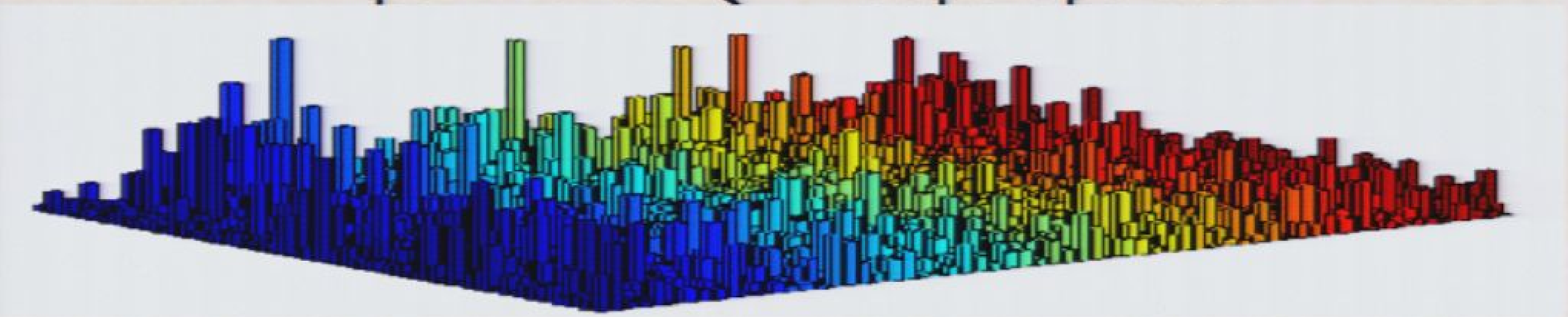


QFT Superoperator

Theoretical QFT Superoperator

Experimental QFT Superoperator



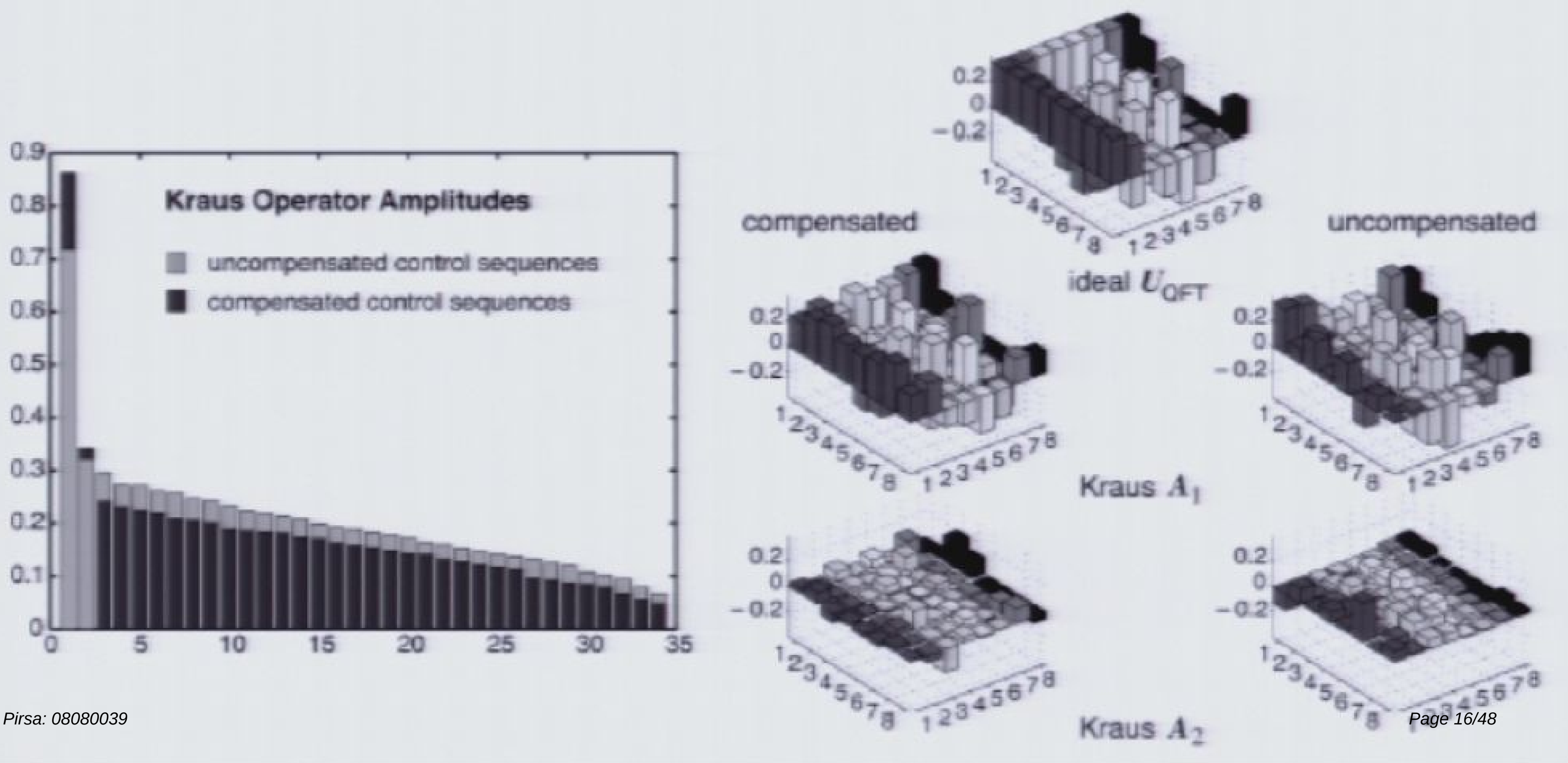
Quantum Process Tomography of the Quantum Fourier Transform, Y. Weinstein, T. Havel, J. Emerson, N. Boulant, M. Saraceno, S. Lloyd and D. G. Cory, *Journal of Chemical Physics*, 2004, **121**, 6117

Quantum Fourier Transform

A comparison of two different control schemes,

the "compensated" data set removes

most of the errors from RF inhomogenieties.



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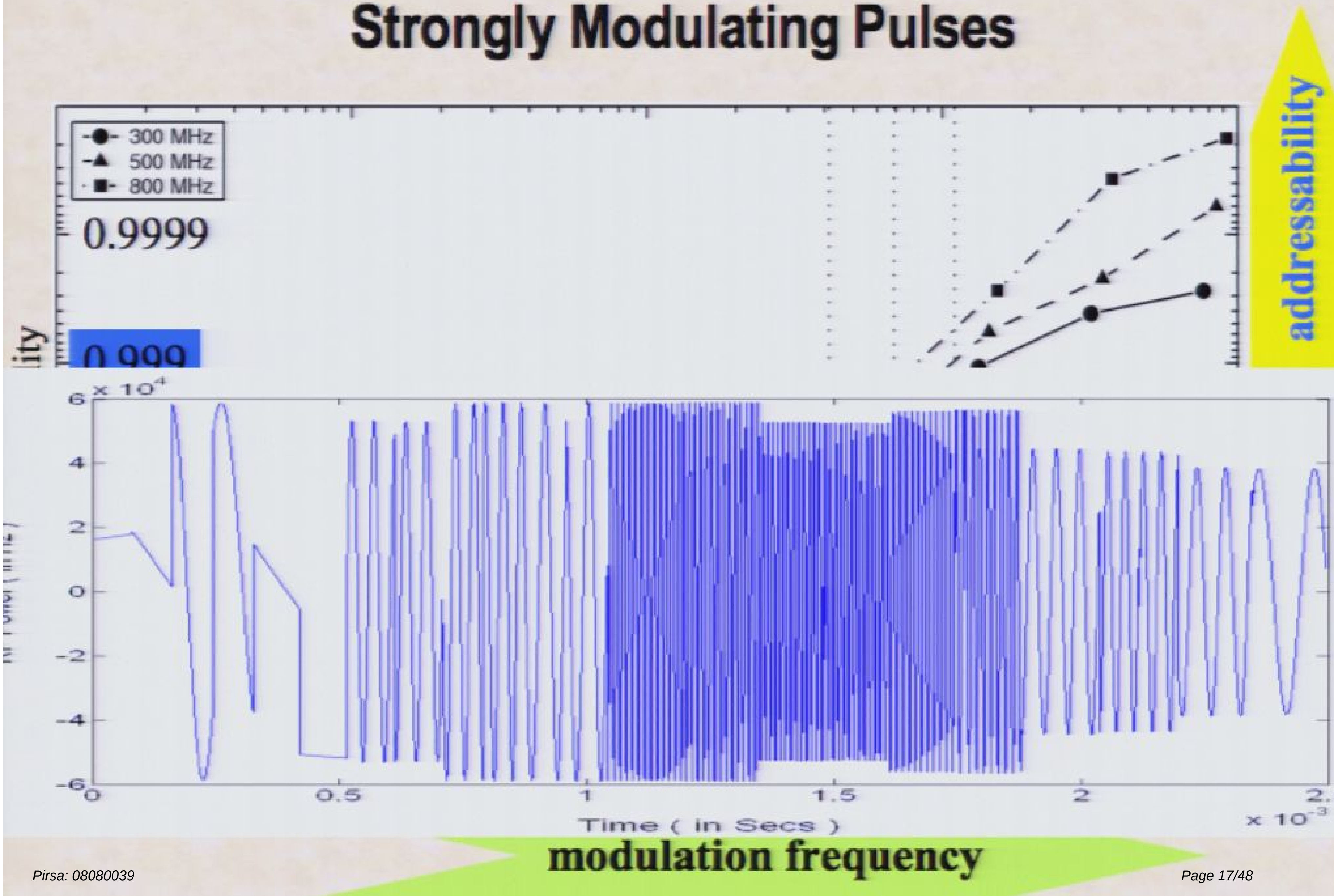

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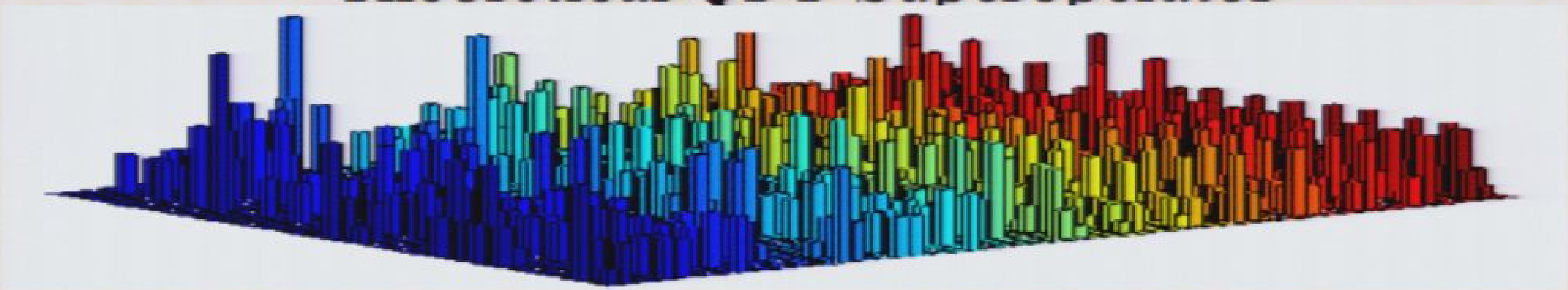

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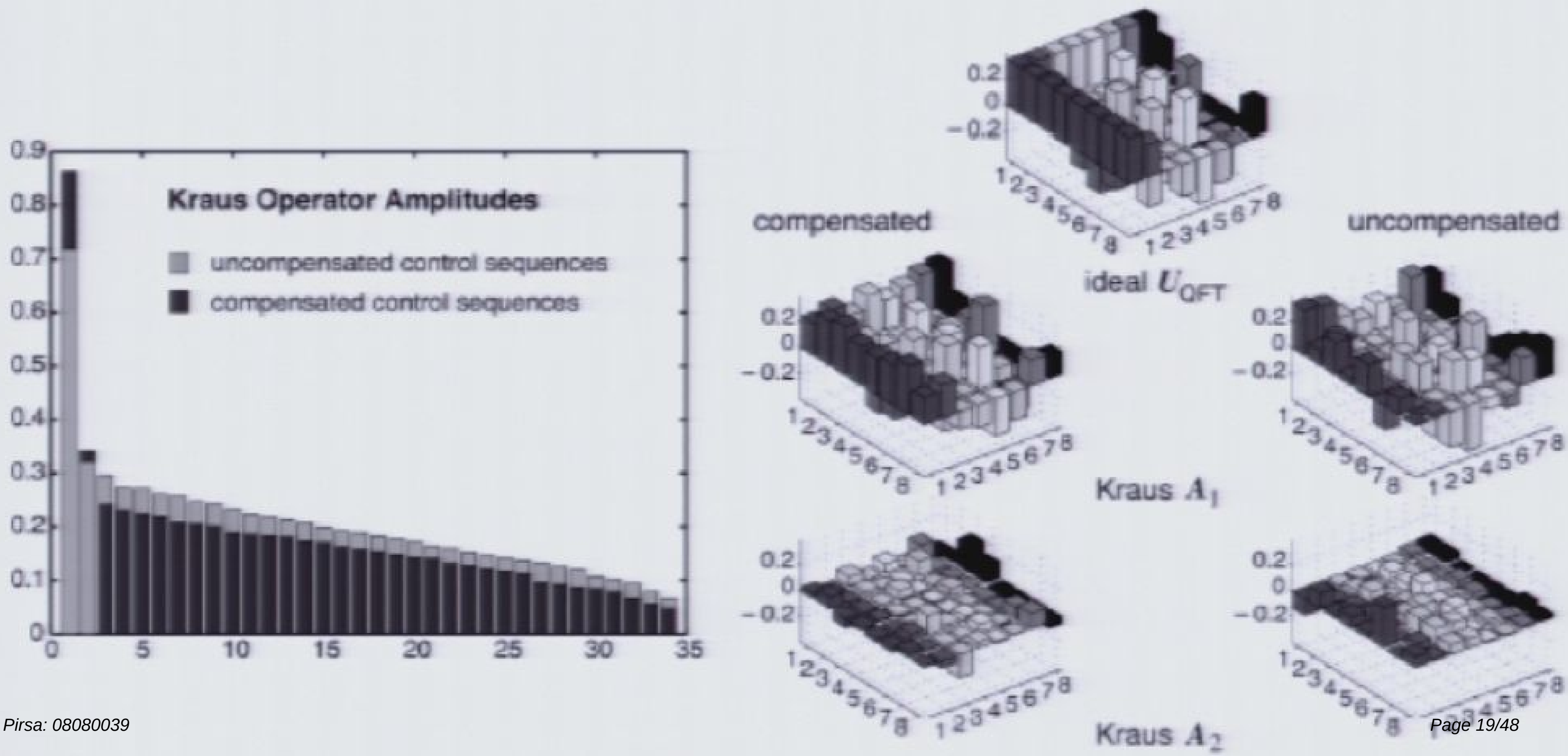
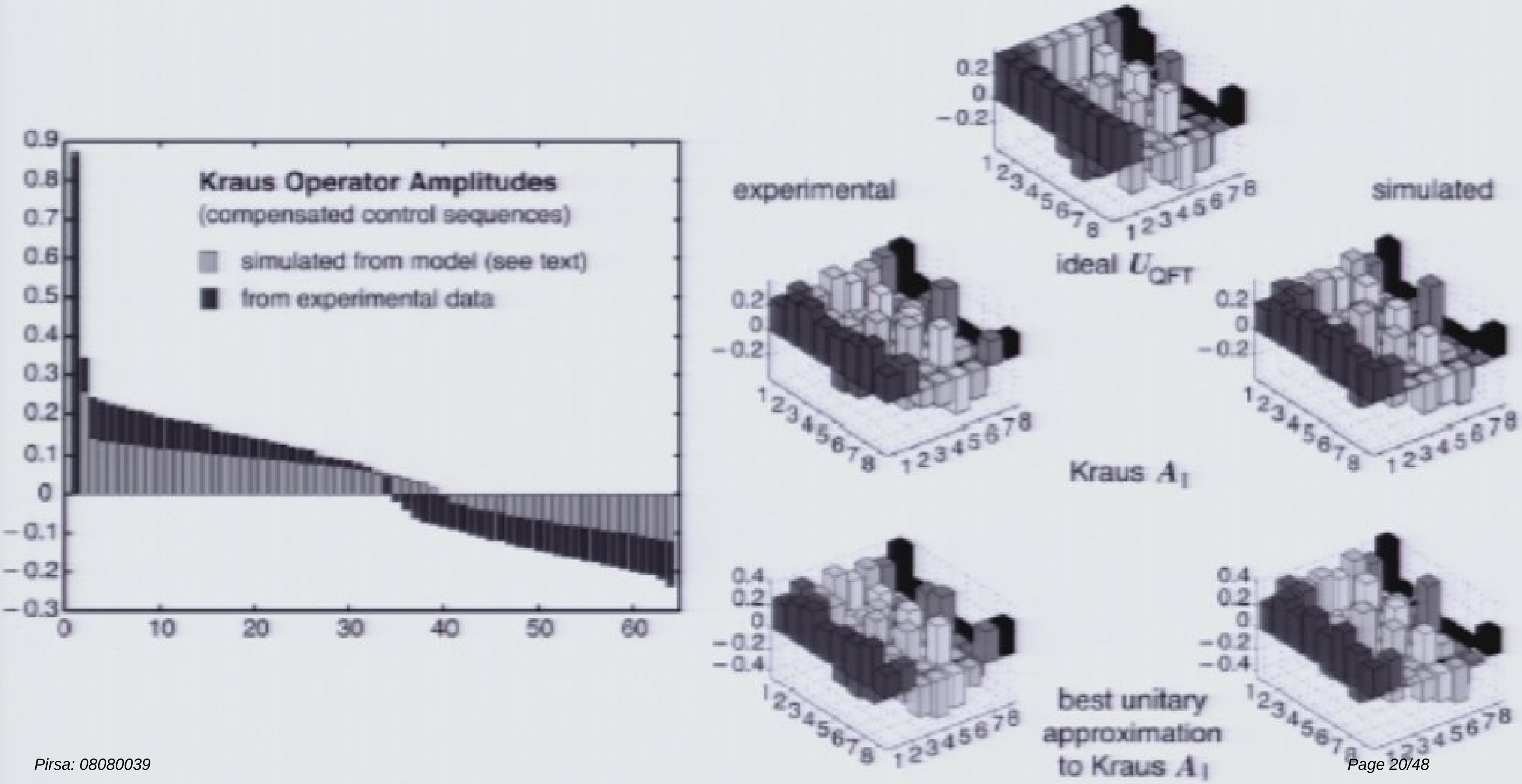
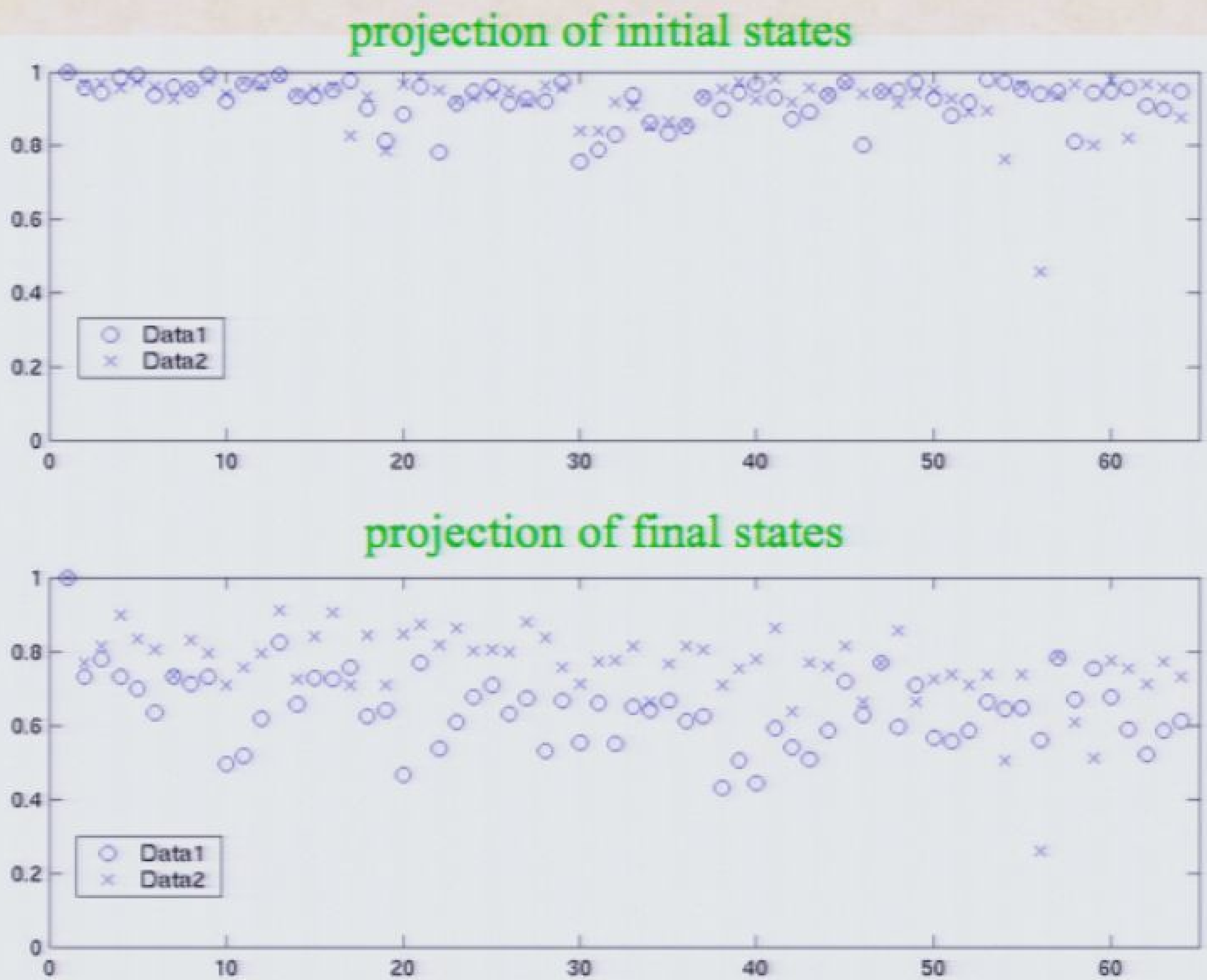


Quantum Fourier Transform

A test of our system model



Experimental Improvement



QFT gate fidelity, F = .64 QFT average Projection, <P> = .82

Quantum Fourier Transform

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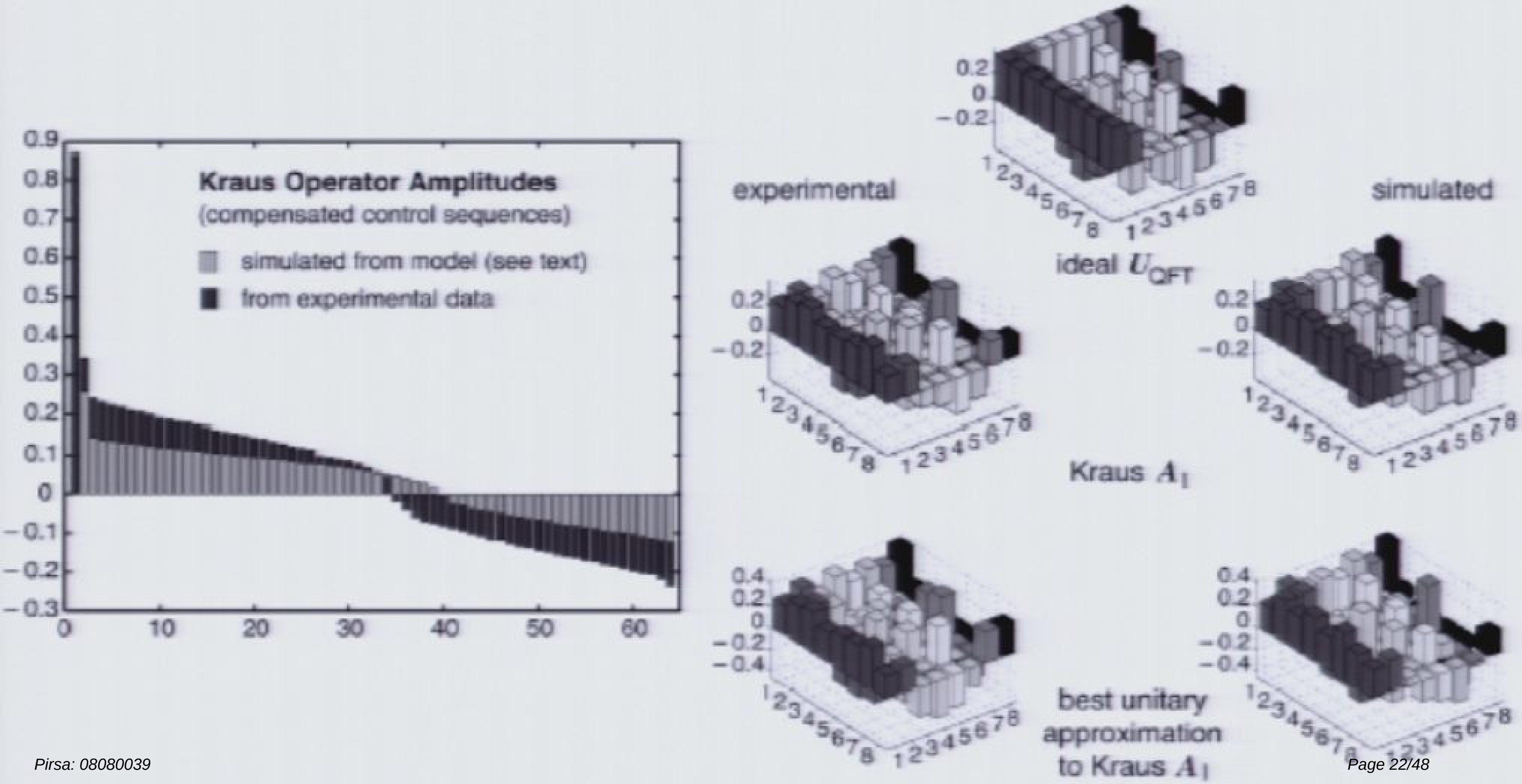
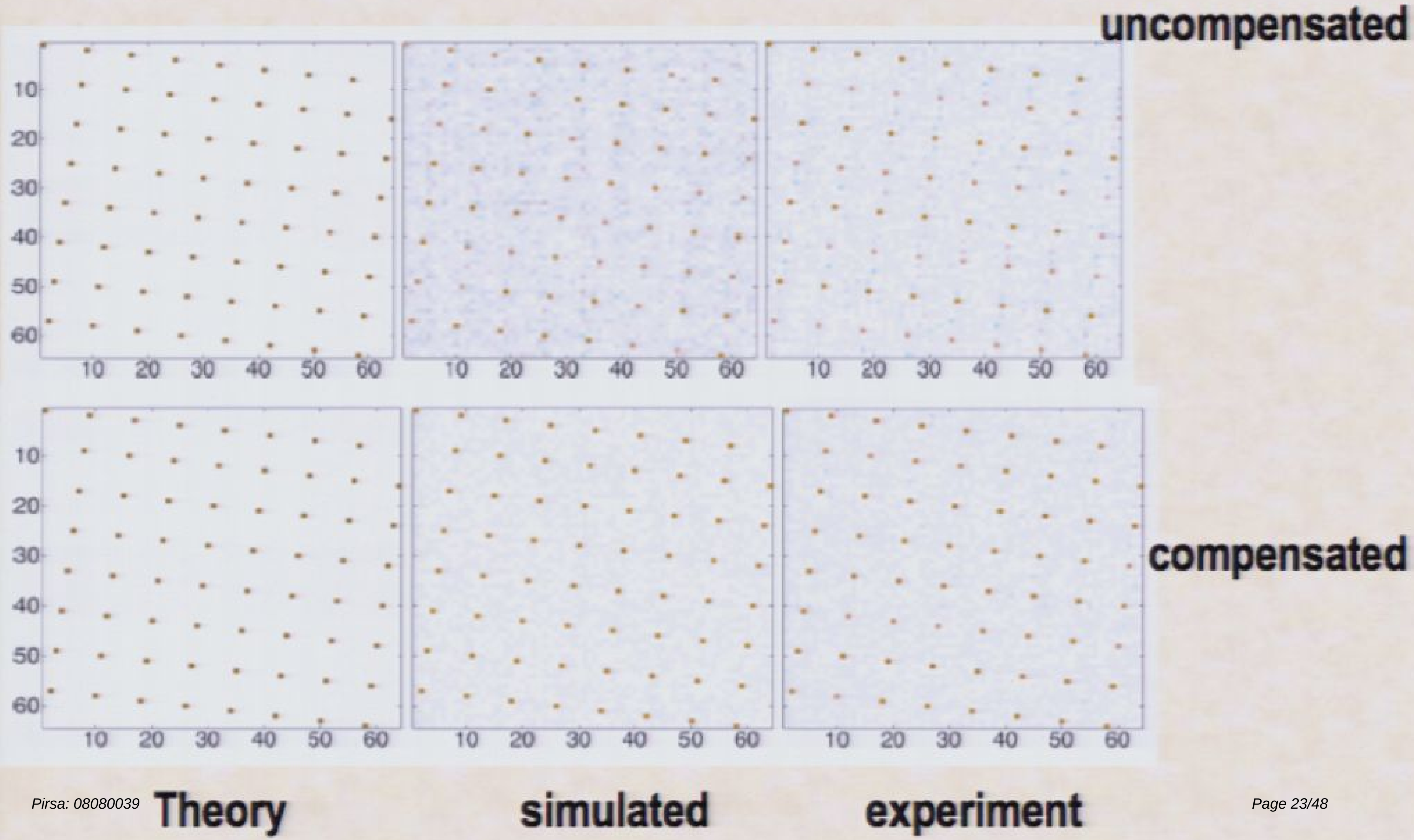
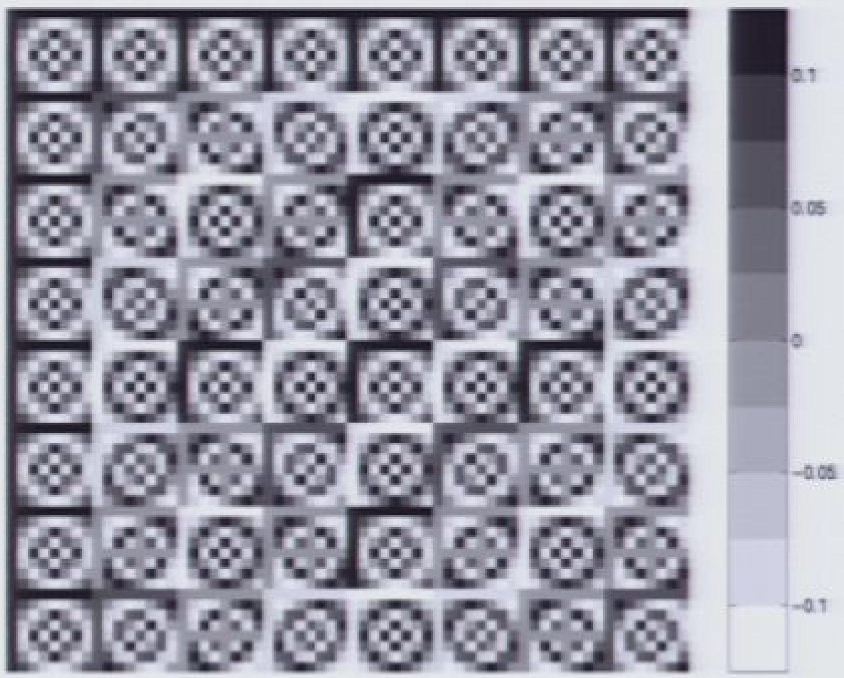


Quantum Fourier Transform

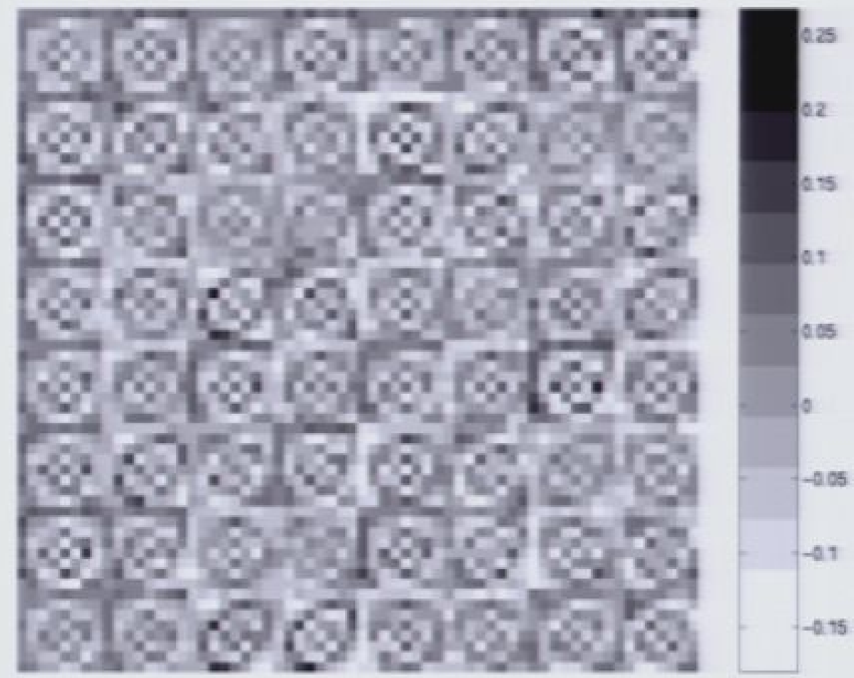
The Quantum Fourier transform is a permutation matrix in phase space.



QFT Superoperator



Ideal QFT Superoperator



Experimental QFT Superoperator

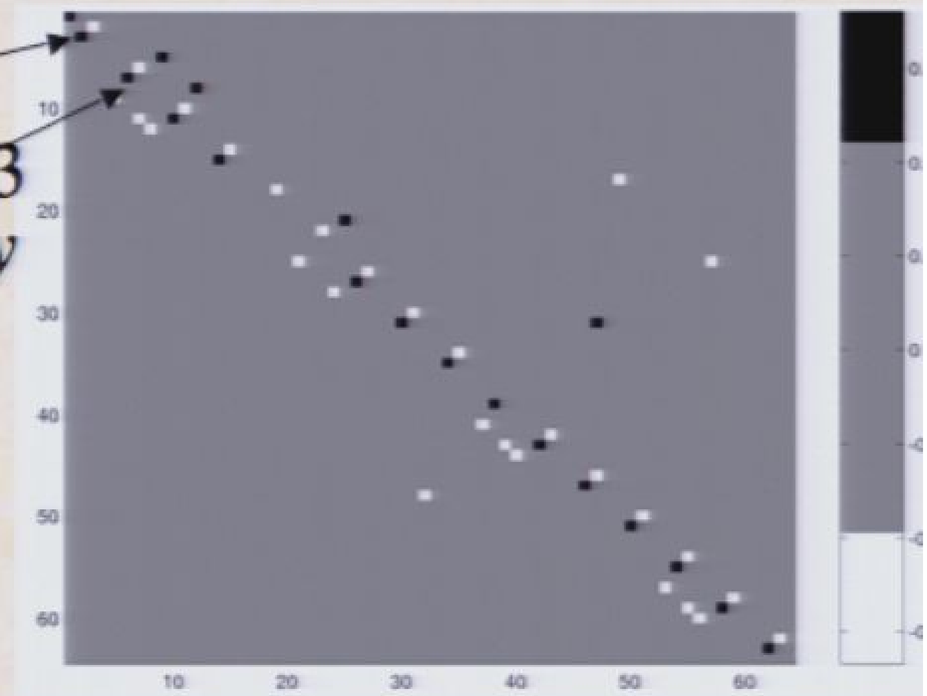
Basis is Zeeman.

Product Operator Basis

$$\sigma_x^3 \Rightarrow \sigma_y^3$$

Largest error: σ_z^3

$$\sigma_x^2\sigma_x^3 \Rightarrow \sigma_x^2\sigma_y^3$$



2nd largest error: σ_z^2

$$\sigma_x^2 \Rightarrow \sigma_y^2 \quad \sigma_x^2\sigma_x^3 \Rightarrow \sigma_y^2\sigma_x^3$$

Errors show up clearly when the theoretical action of the QFT is removed and the remainder in transformed to the product operator basis.

Superoperatror Eigenvalues

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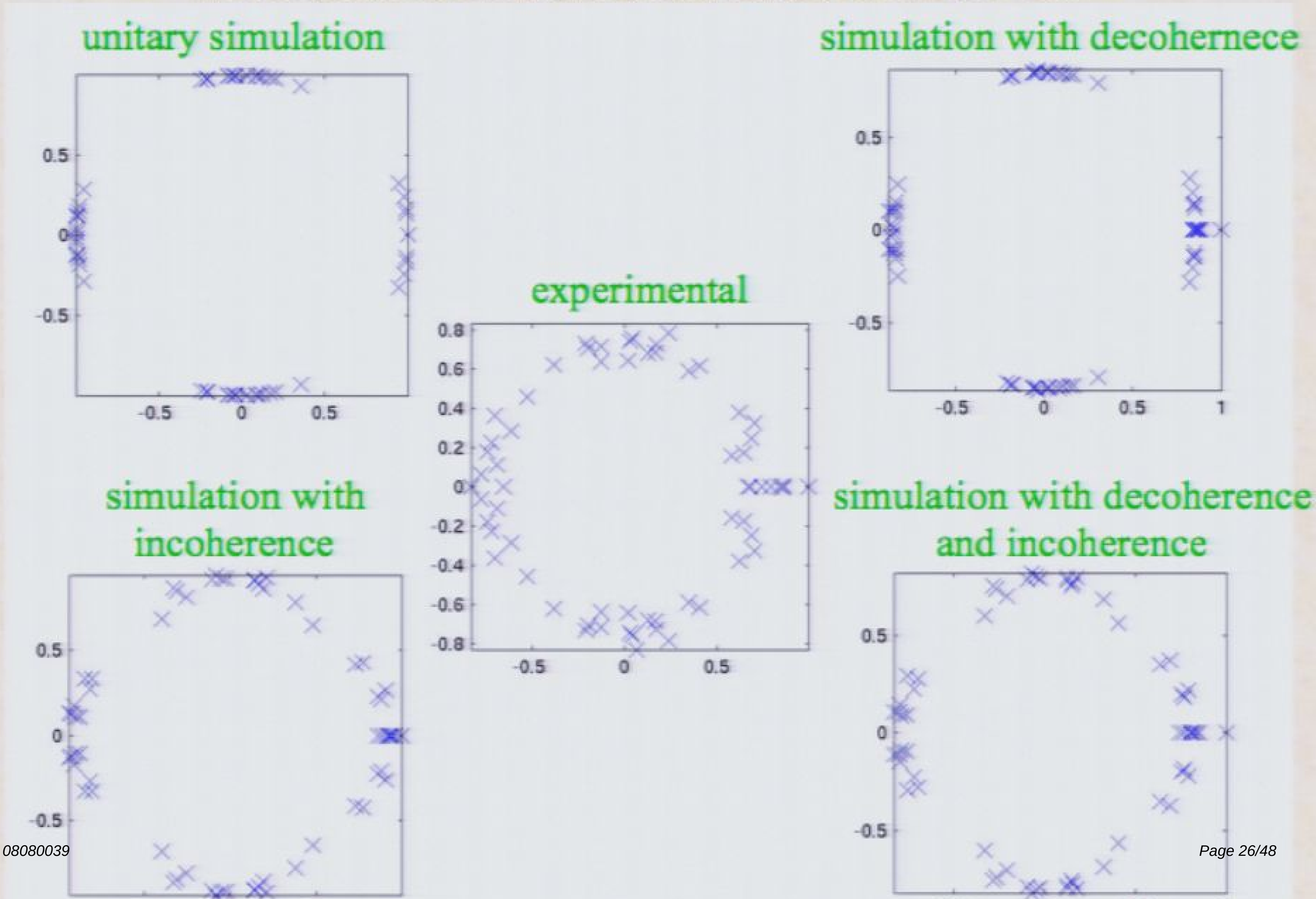


Quantum Process Tomography of a 3-Qubit Fourier Transform

What we learned:

Gate fidelity with theoretical superoperator of 0.64

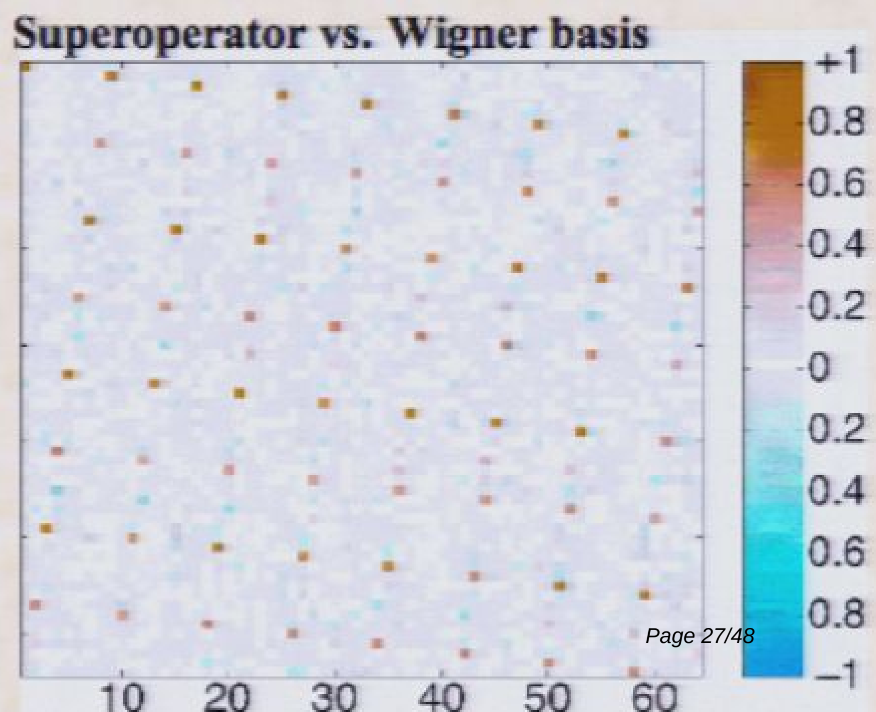
Correlation with superoperator simulated from full system model 0.79

Lack of complete positivity of experimental due primarily to systematic variation of operations over the ensemble

Complete positivity could however be restored with only small changes to the superoperator (correlation 0.97 before & after)

Correlation with simulation could be increased to 0.97 by single qubit rotations

System model is very good, but could be still better. Know the statics, now we need to add transients.



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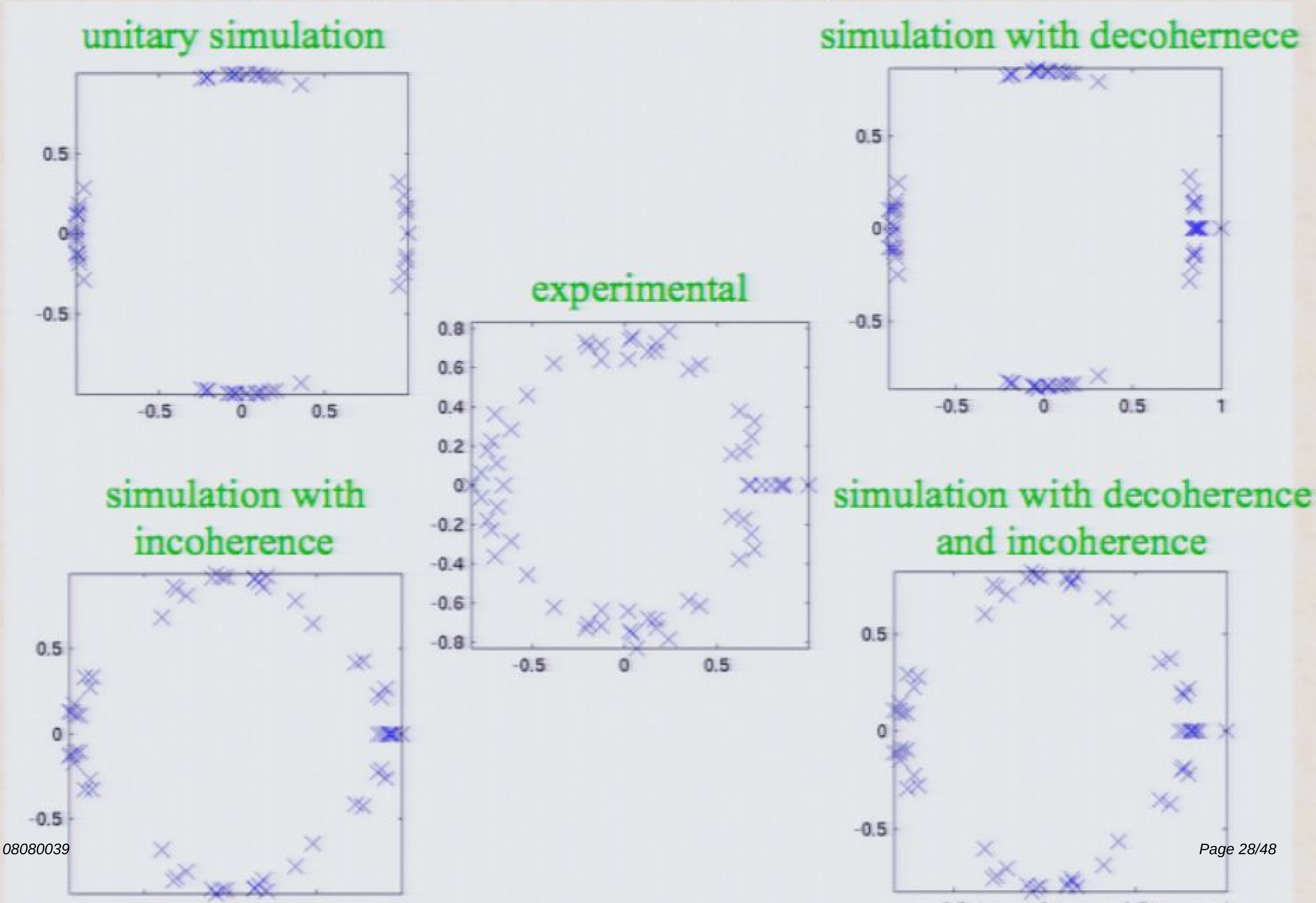

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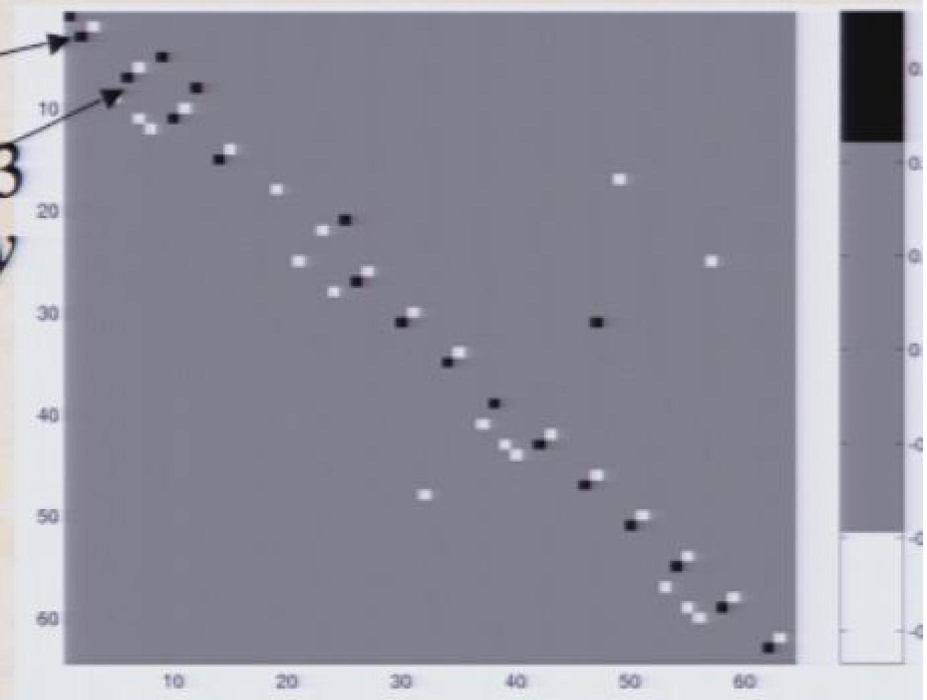

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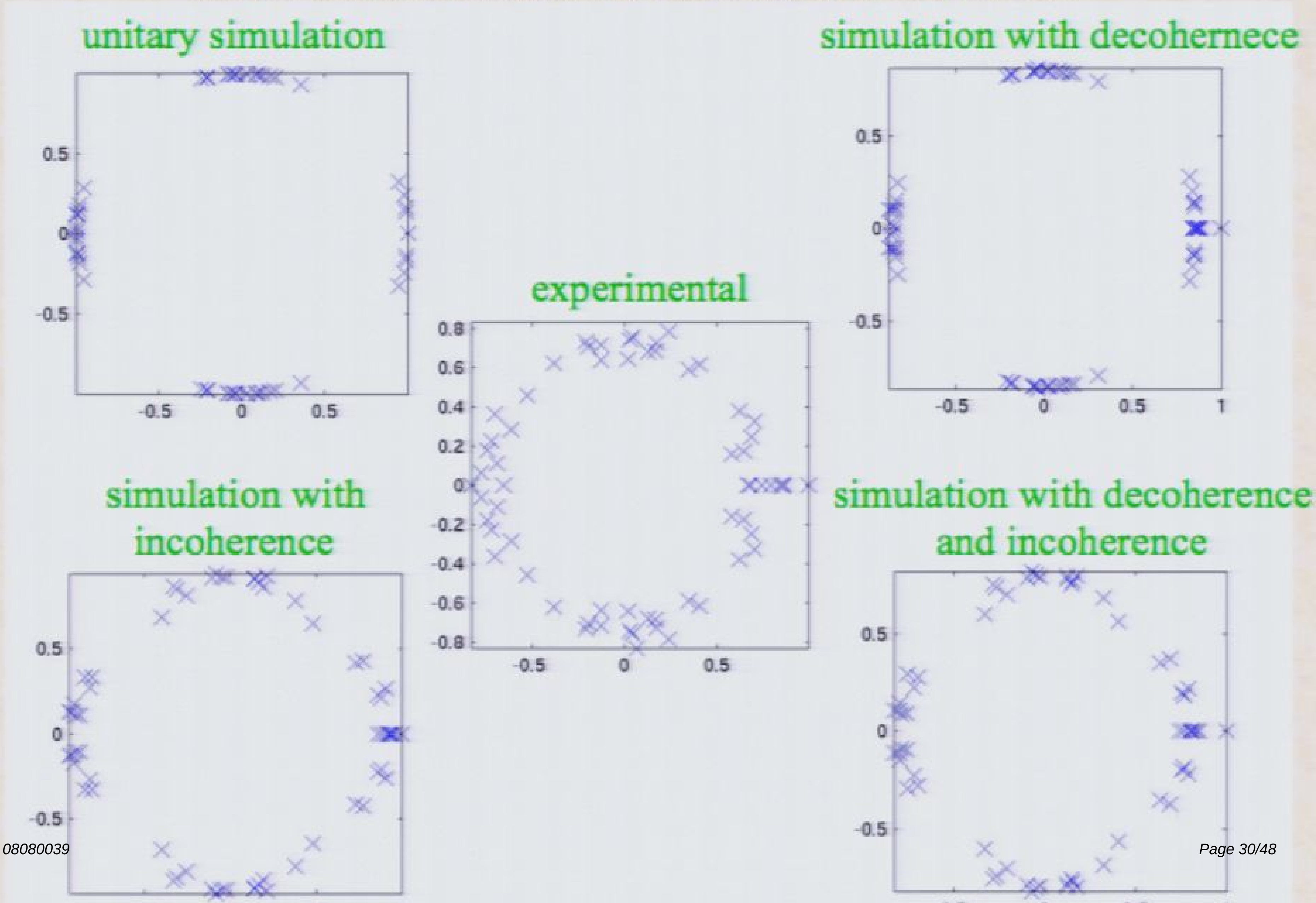

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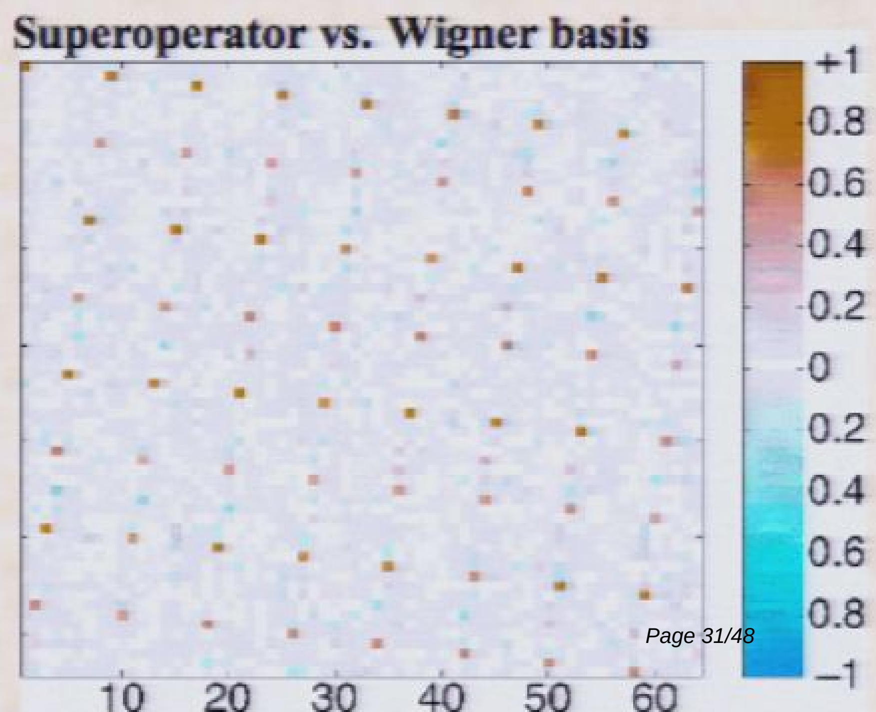

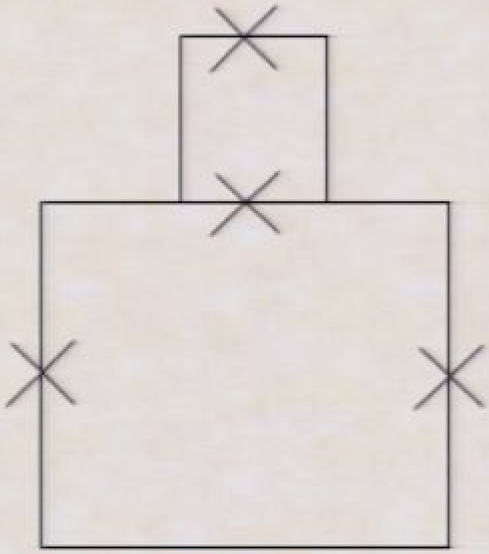

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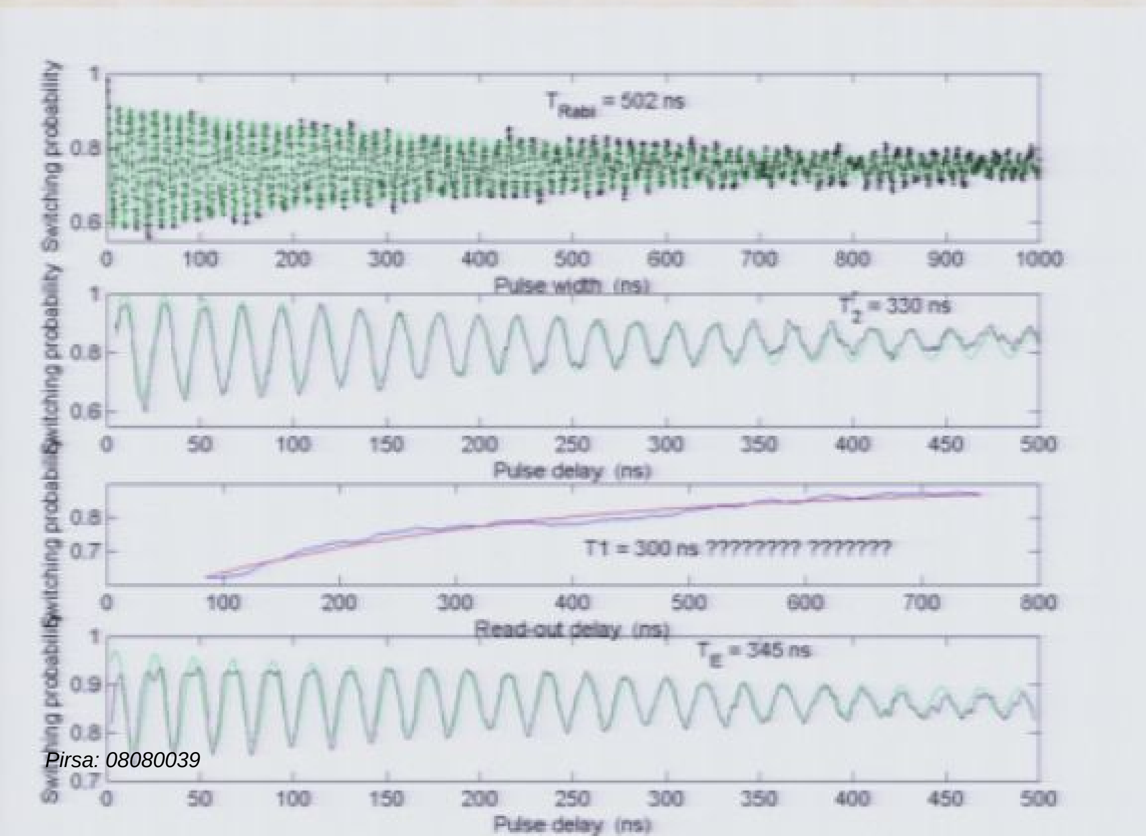
$$H_{\mu w}(t) = \omega_A(t) Cos[\omega_T t + \phi](\sigma_z + \varepsilon\sigma_x)$$



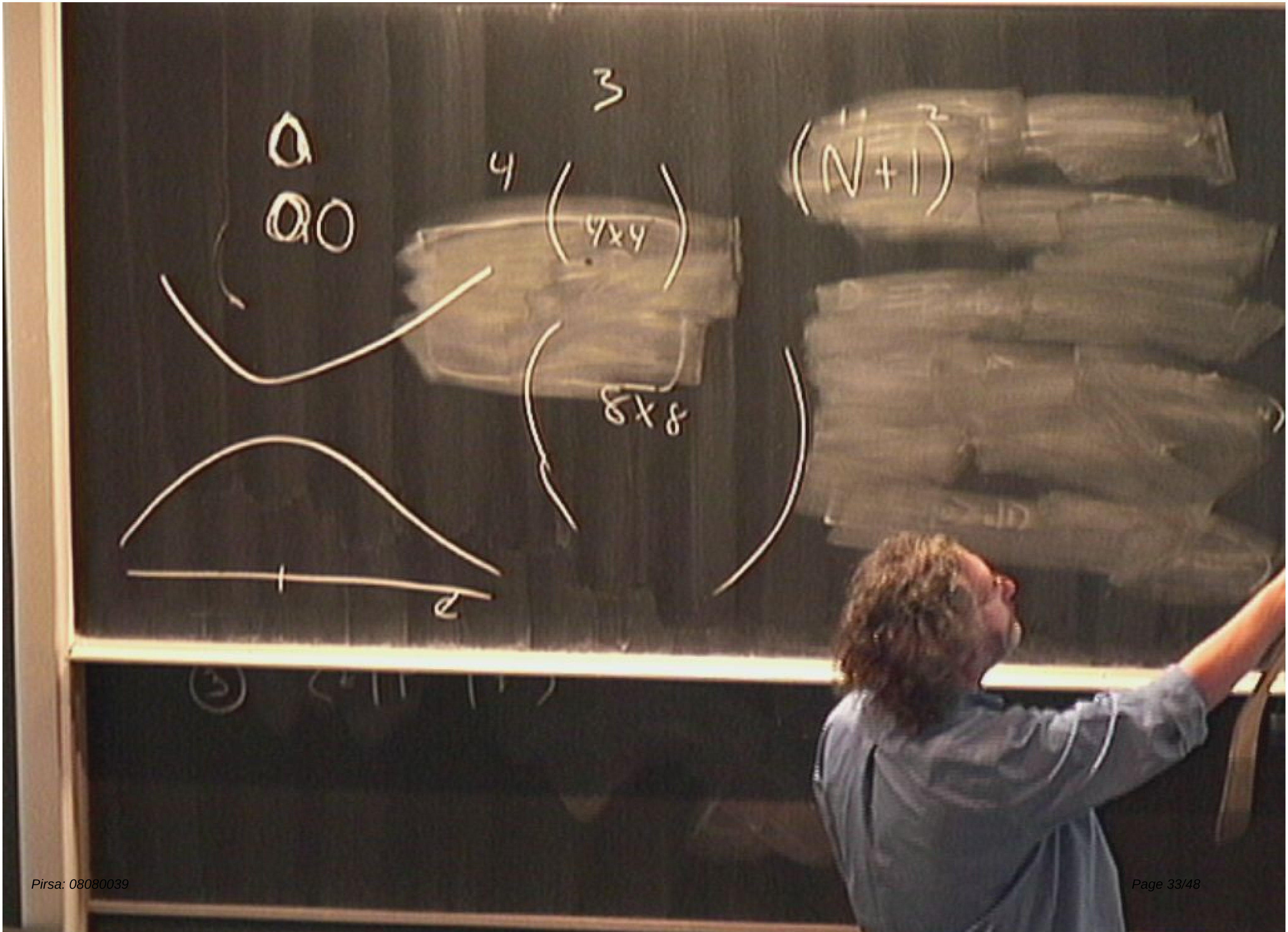
At anti-crossing

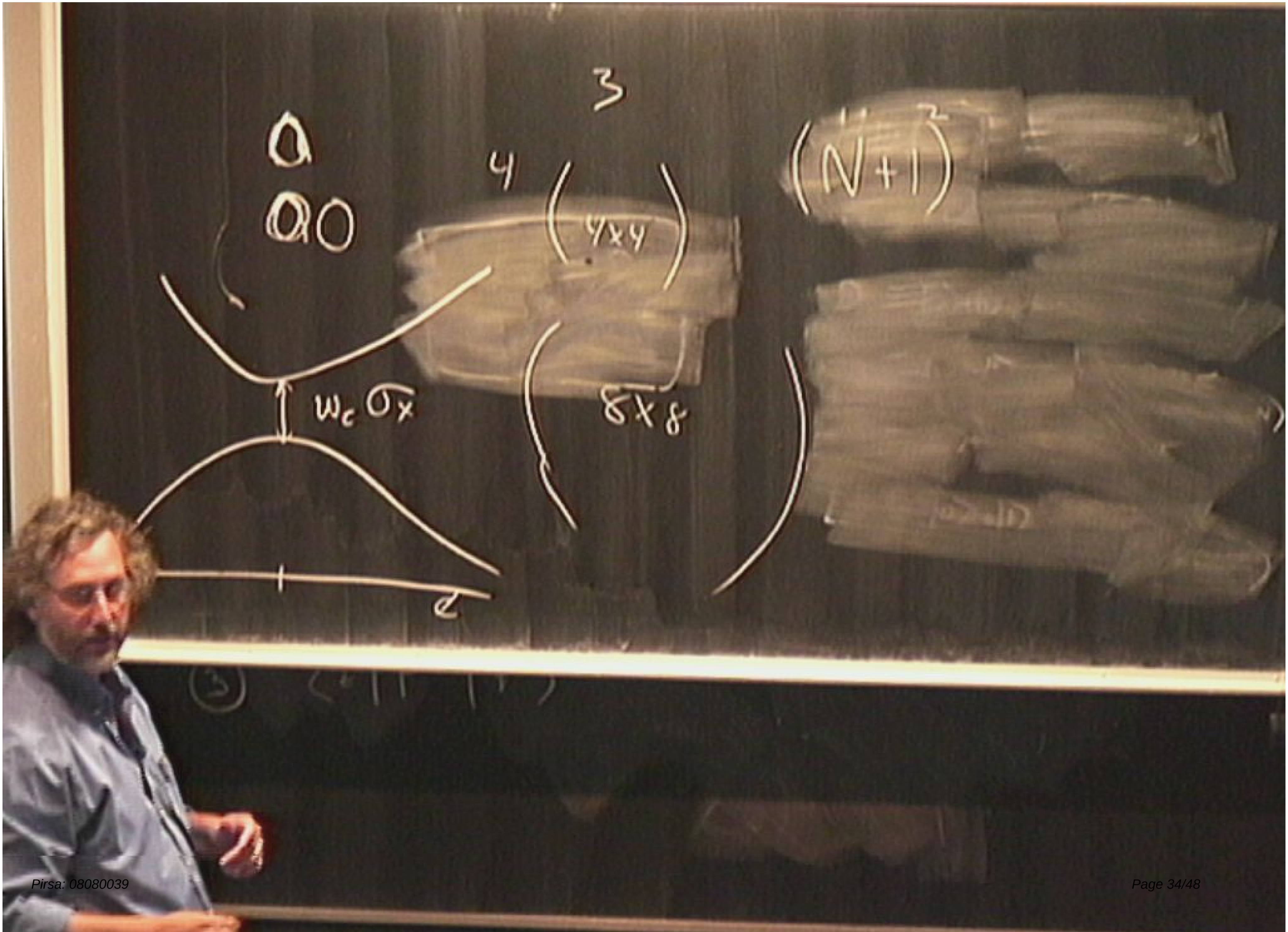
T_1 = 300 ns

T_2^* = 330 ns

T_{echo} = 345 ns

T_{Rabi} = 500 ns


3
4
4x4
8x8
(N+1)


3
4
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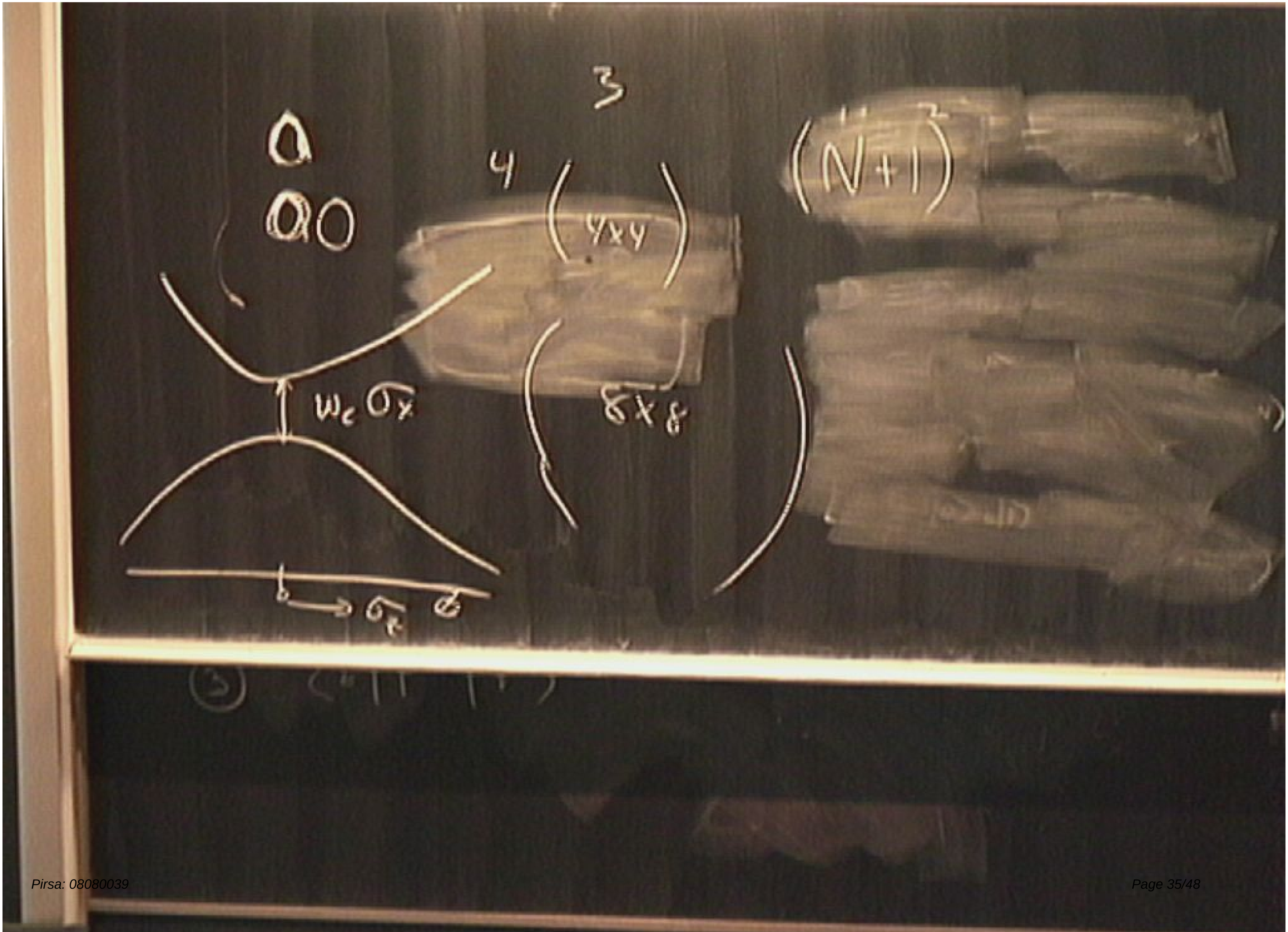
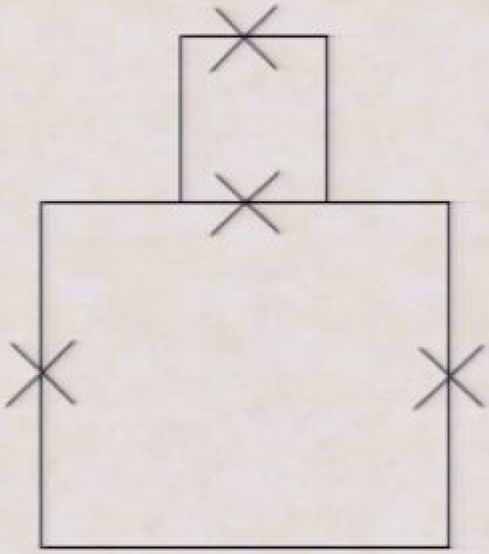
ω_c σ_x


3
4
4x4
8x8
(N+1)
$\omega_c \sigma_x$
σ_z



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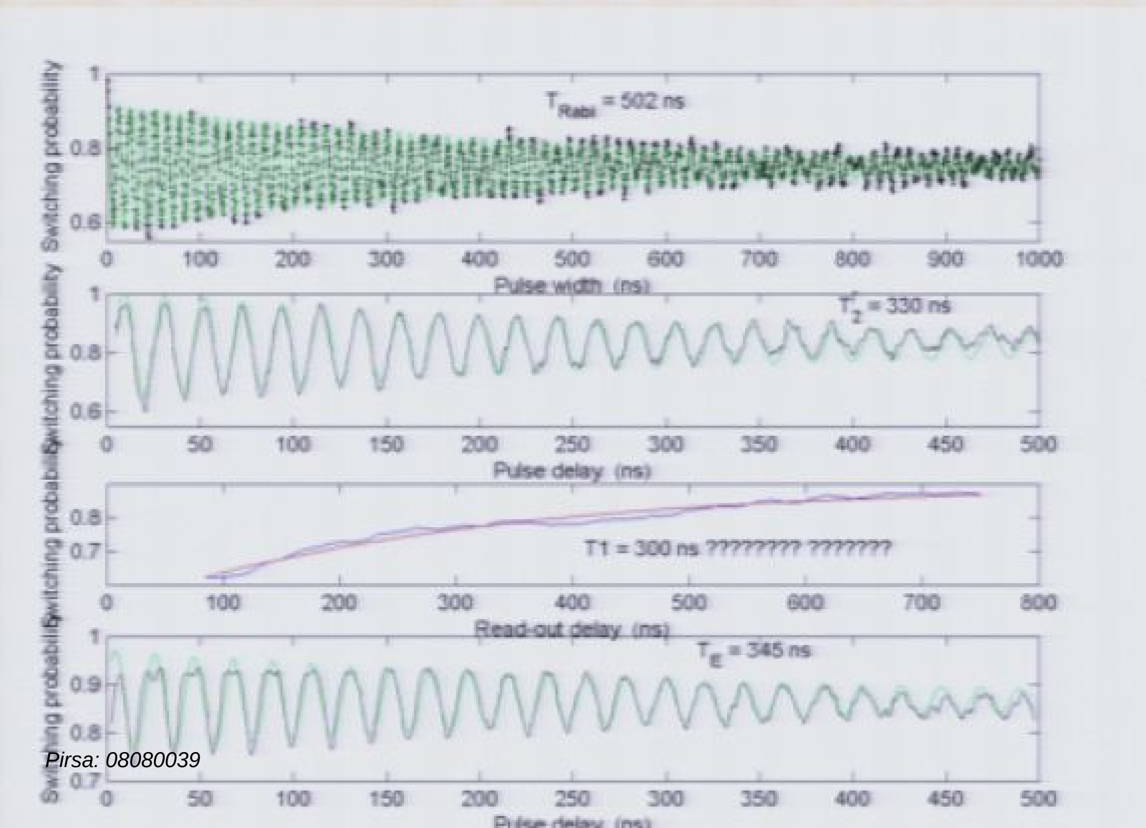

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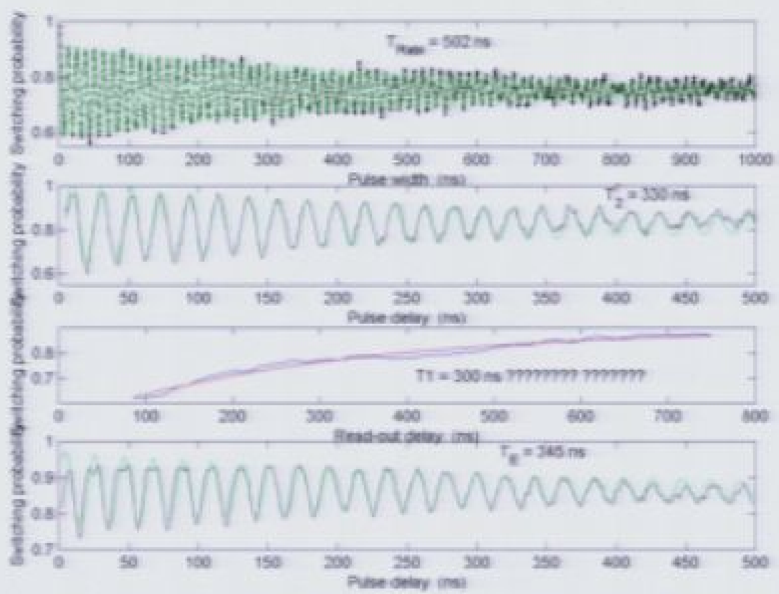
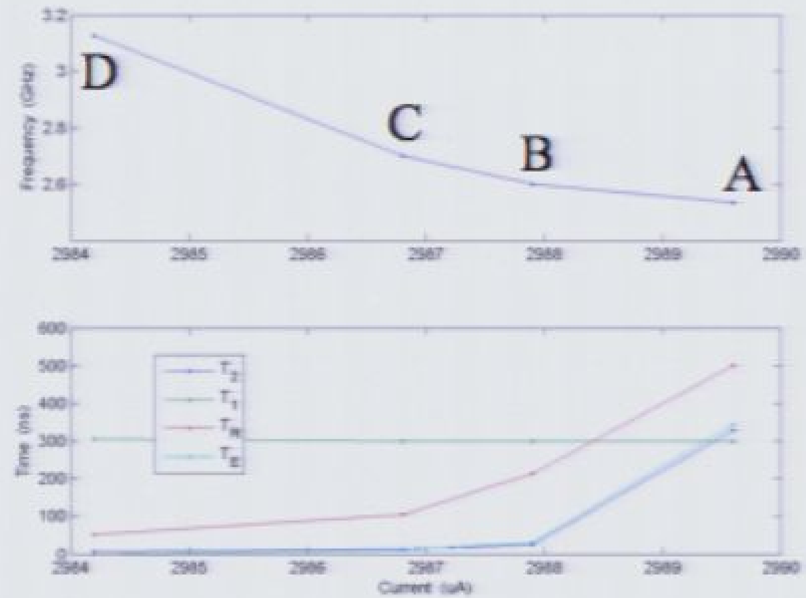
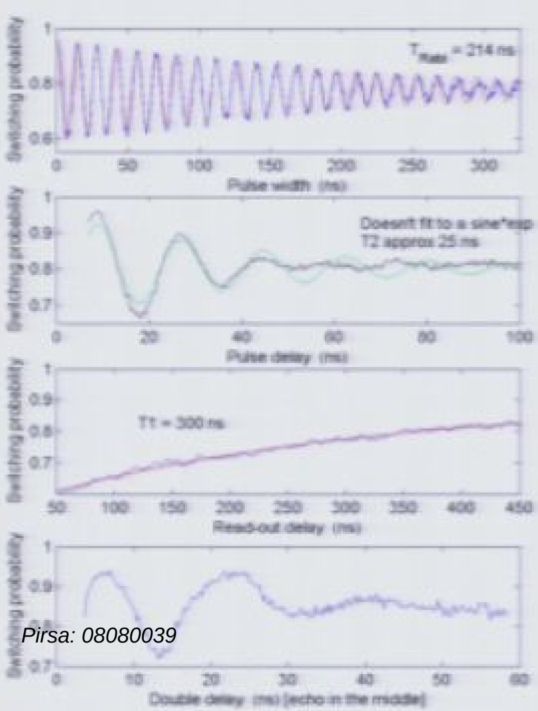
Coherence dies fast when off degeneracy

A

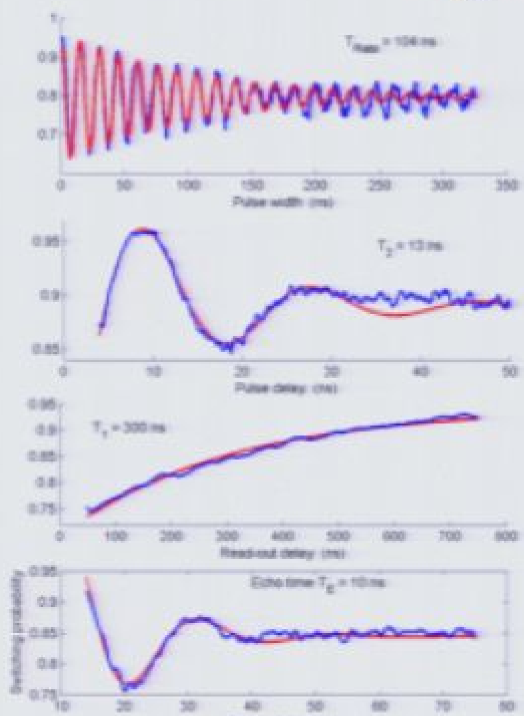




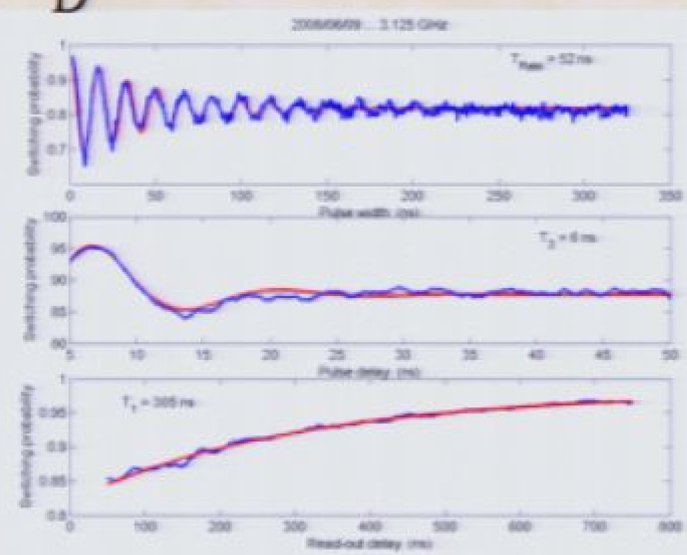
B



C



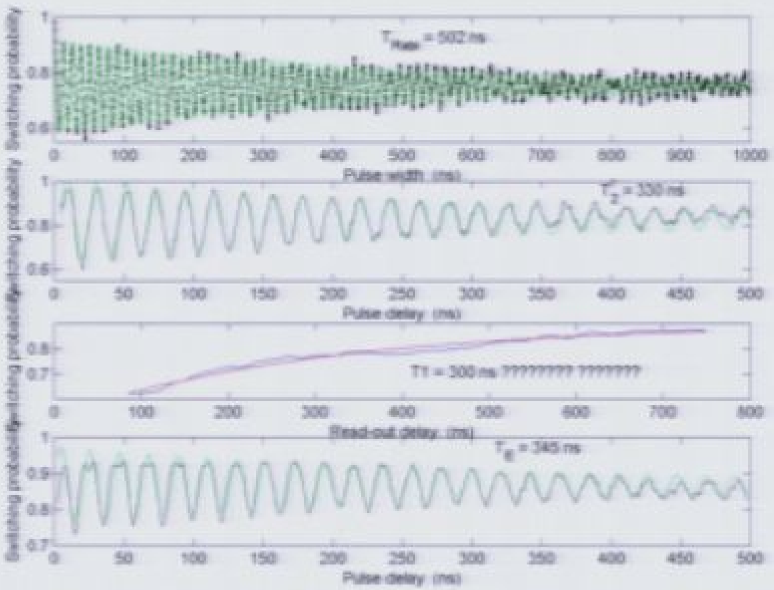
D

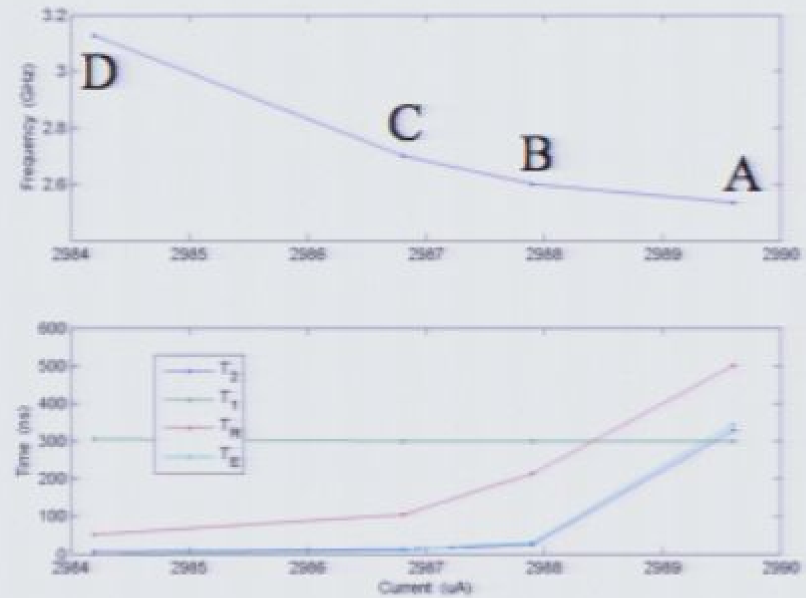


(No echo observed)

Coherence dies fast when off degeneracy

A





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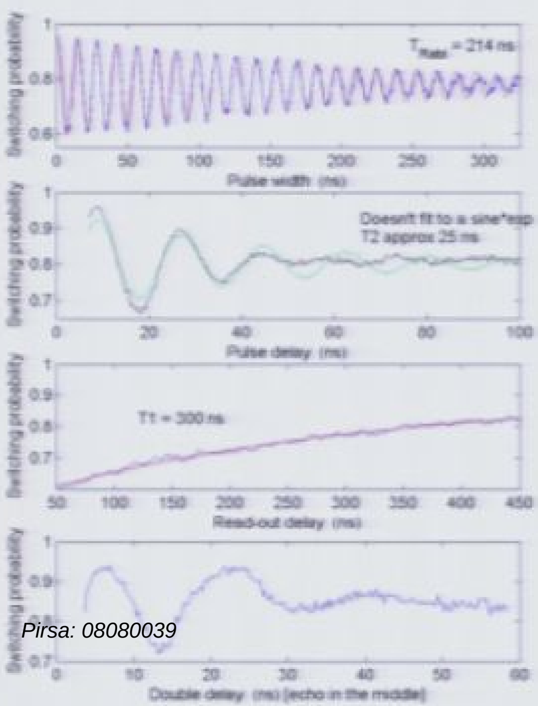

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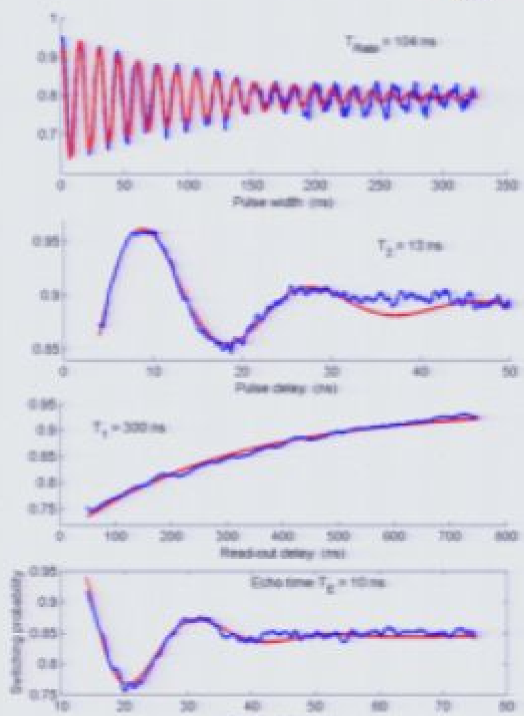
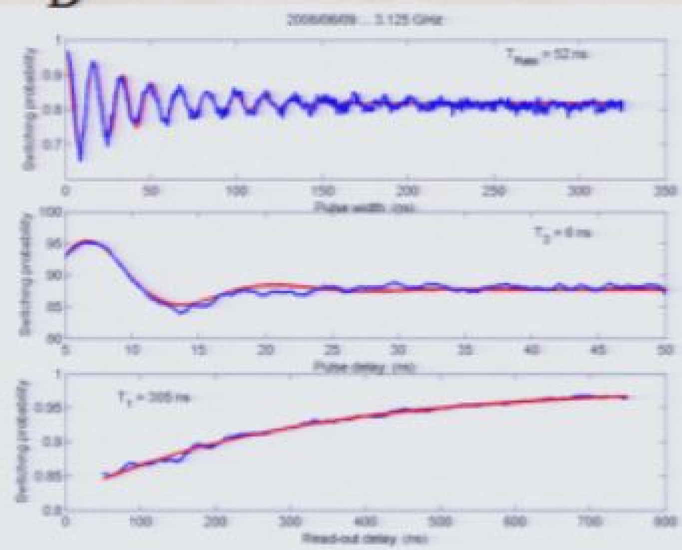


D



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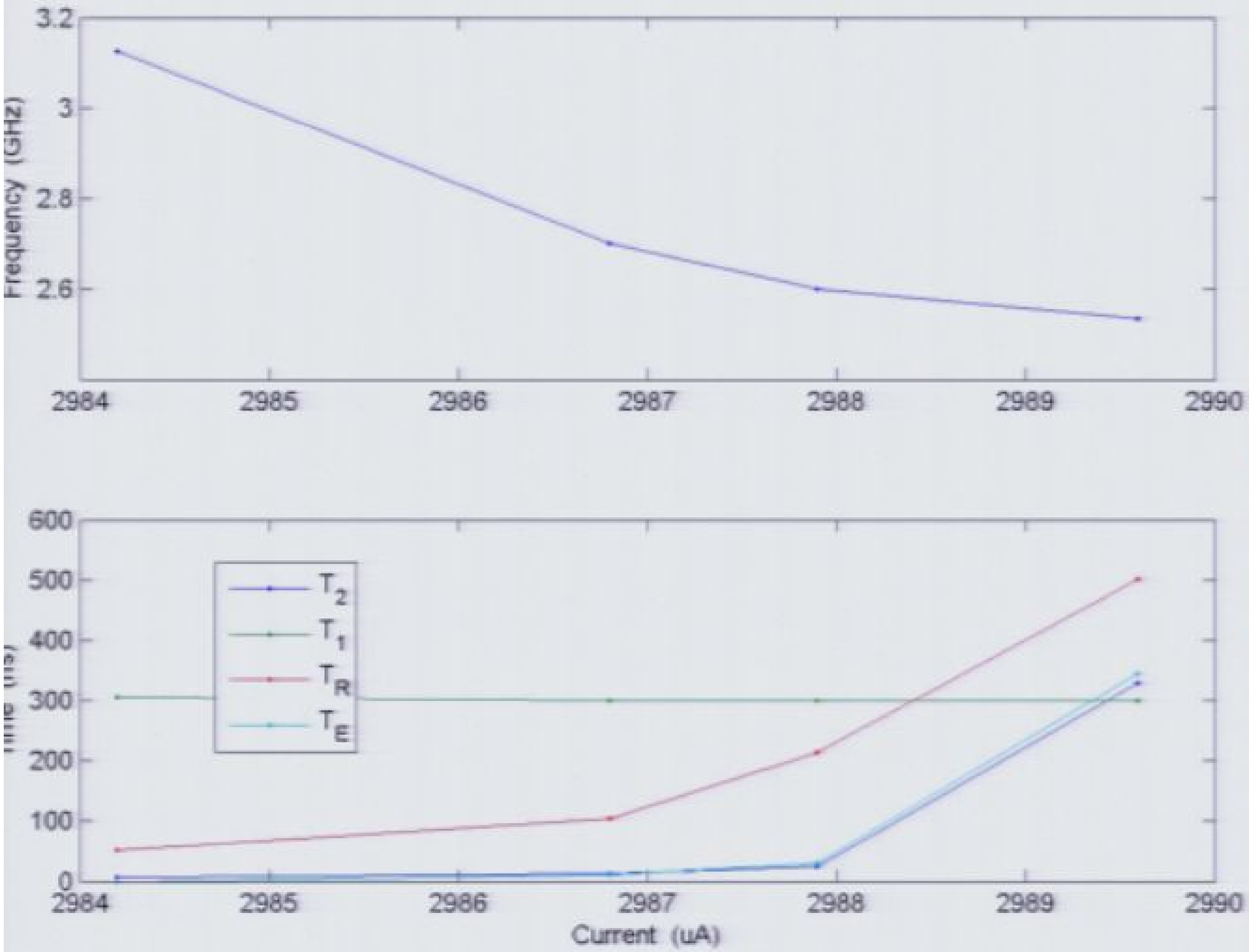


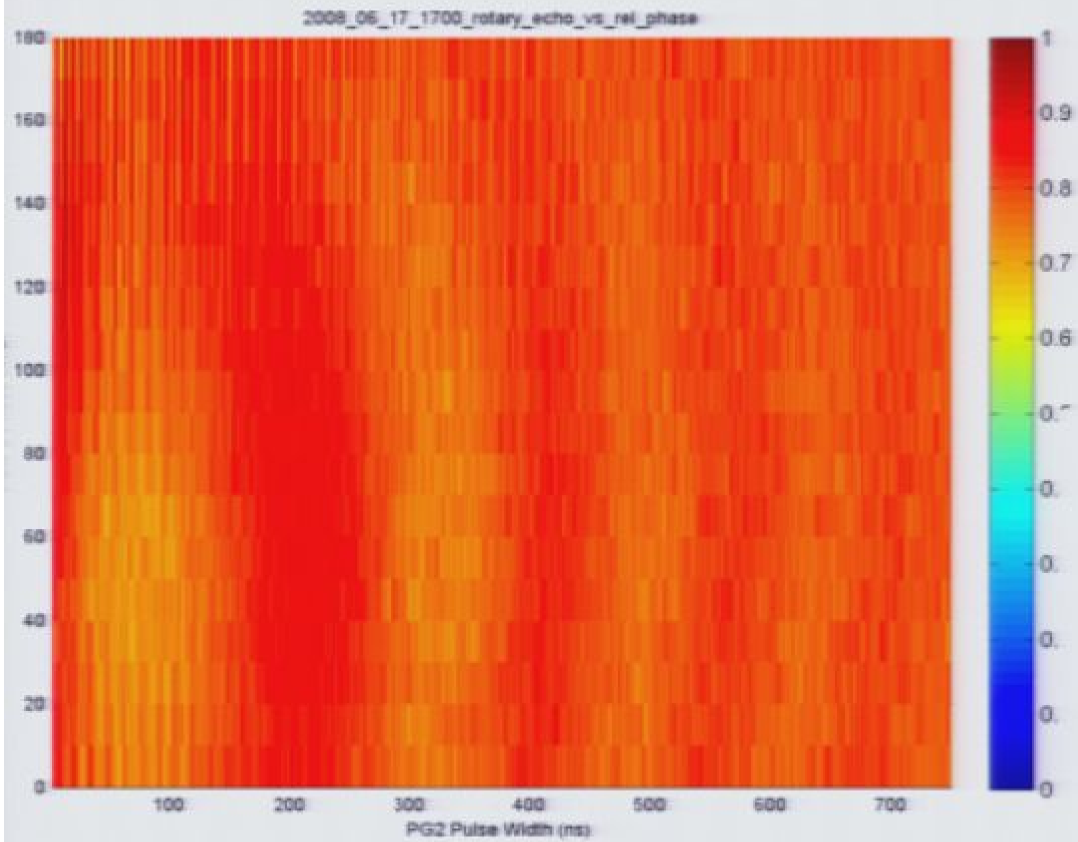
T_1 is constant
-high frequency noise isotropic

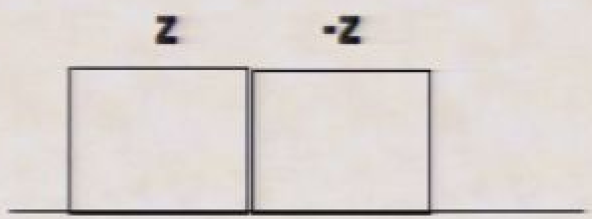
$T_2^* \sim T_{echo}$
-noise along the quantization axis is not entirely static

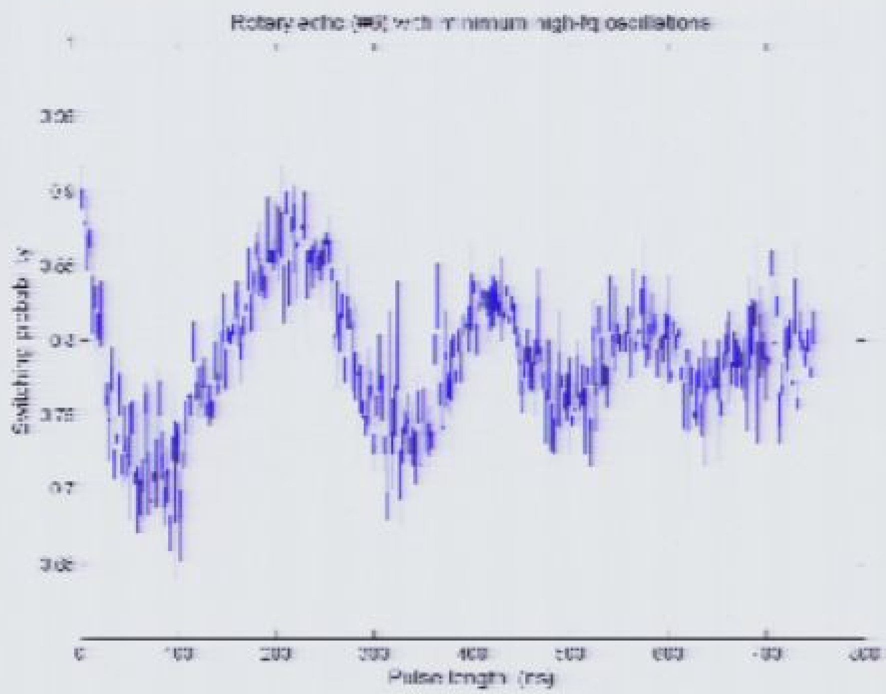
$T_{Rabi} > T_2^*$
-can refocus noise with modulation perpendicular to quantization axis

Rotary echo

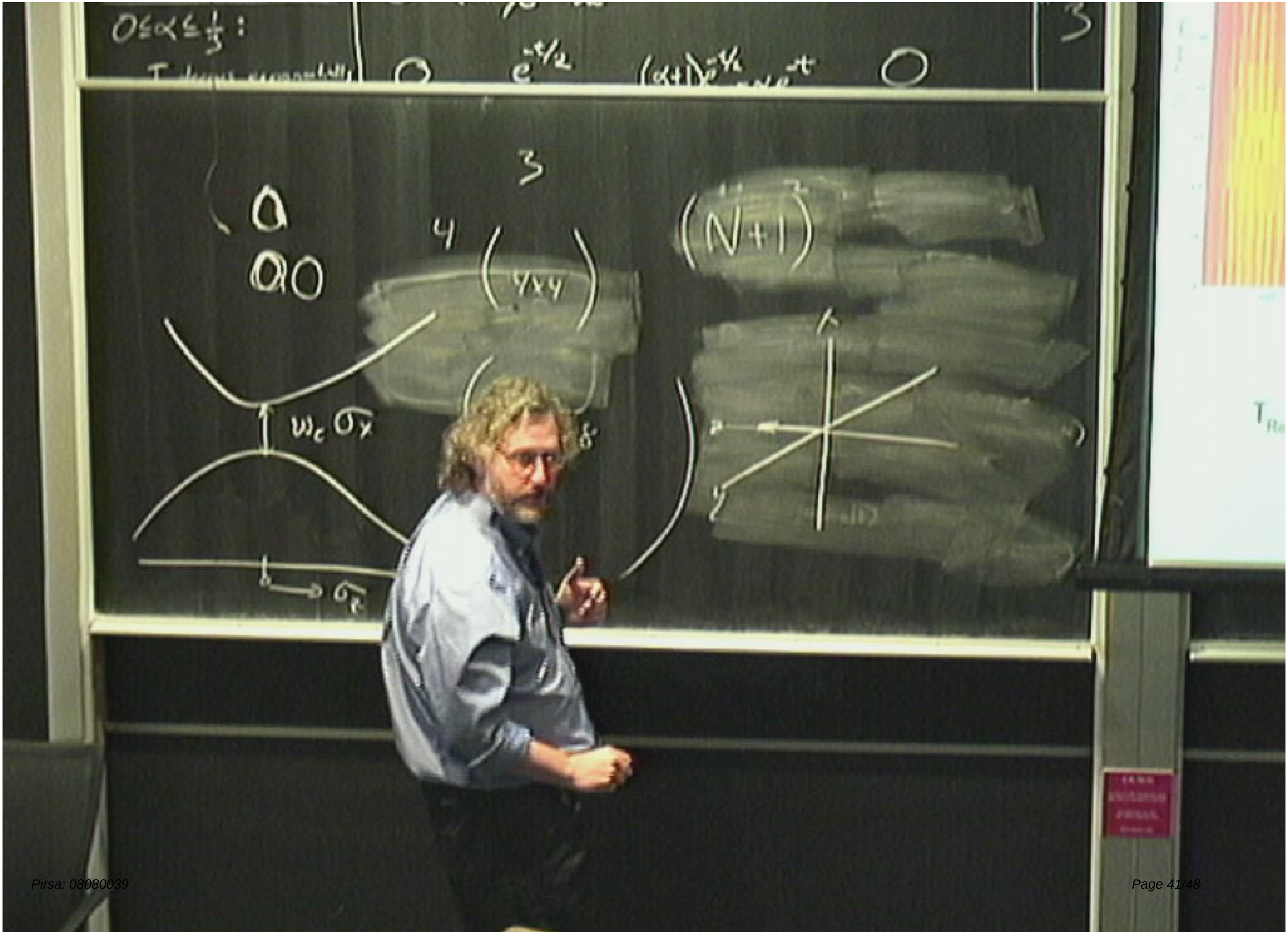
What limits T_{Rabi}?

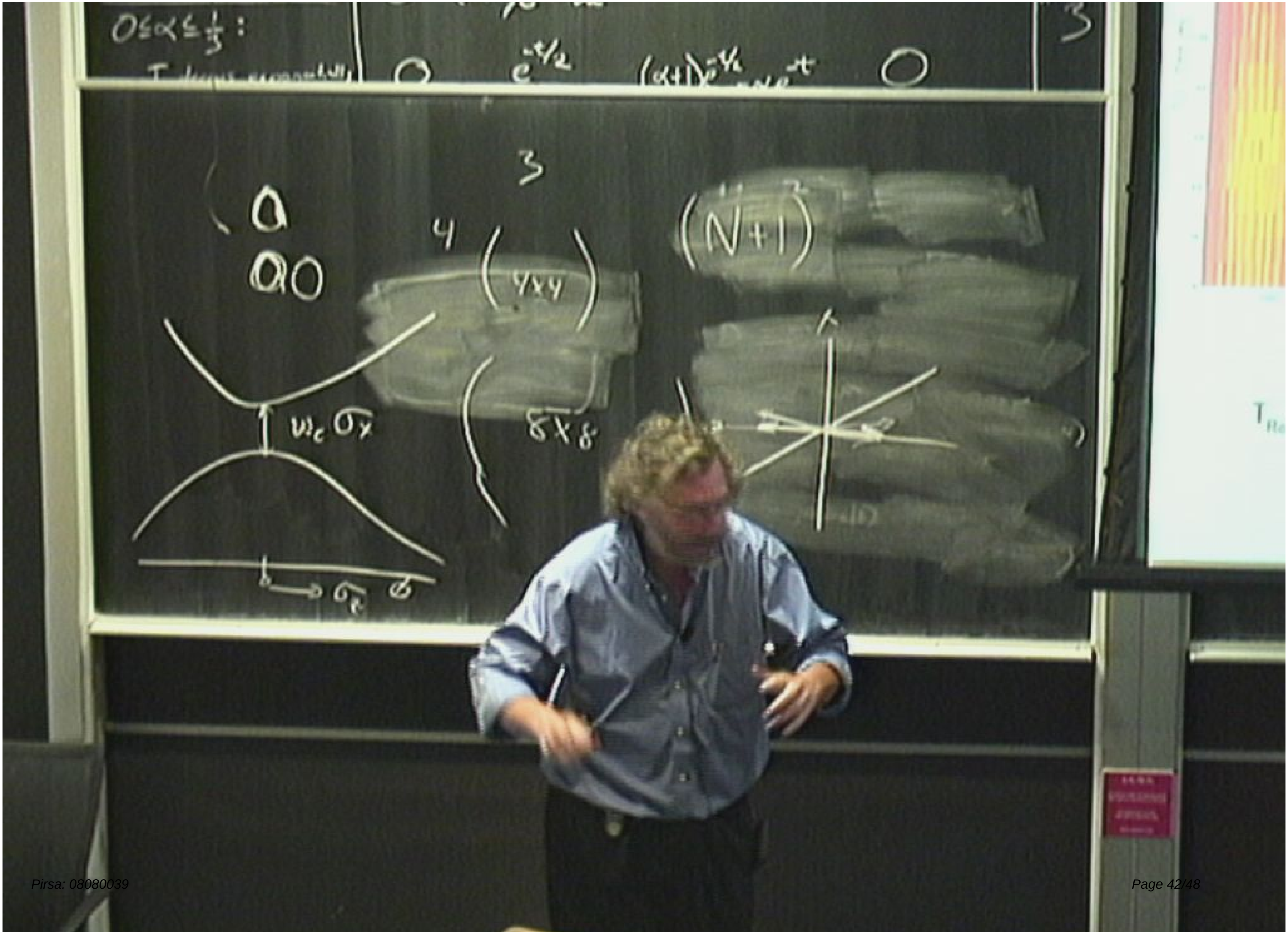






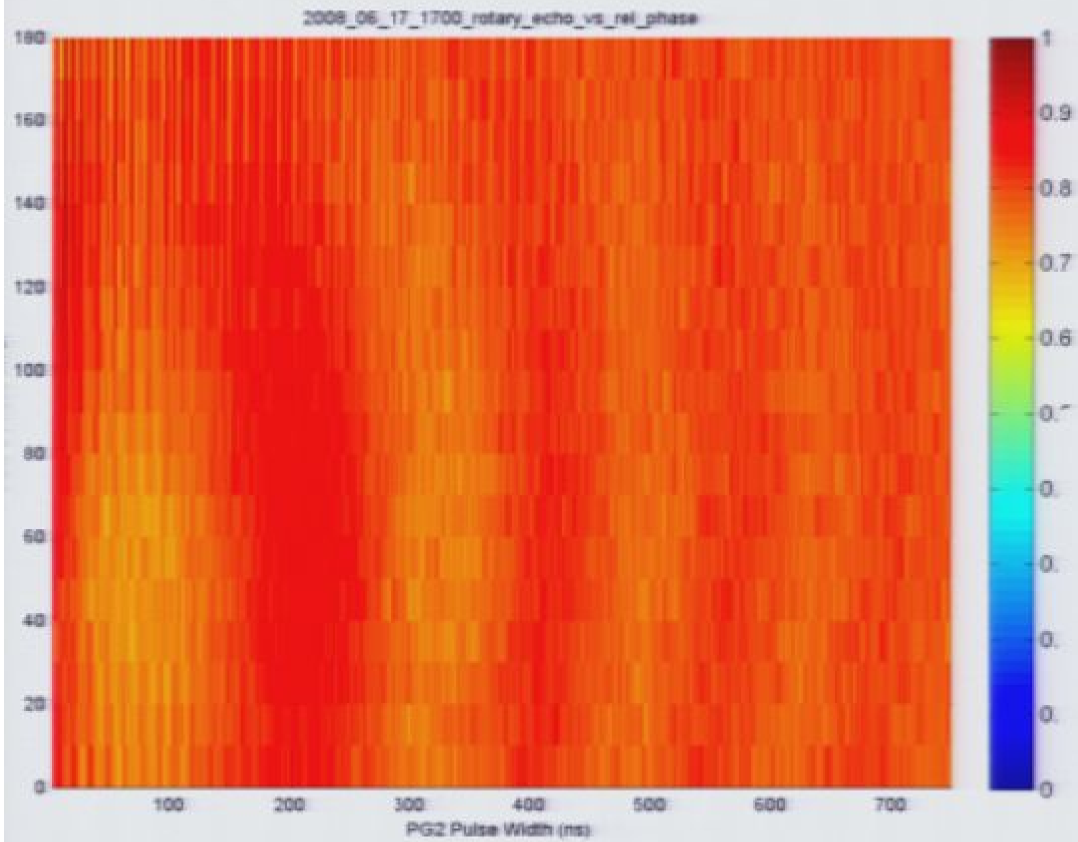
$T_{Rotary} > T_{Rabi}$ - noise in drive field

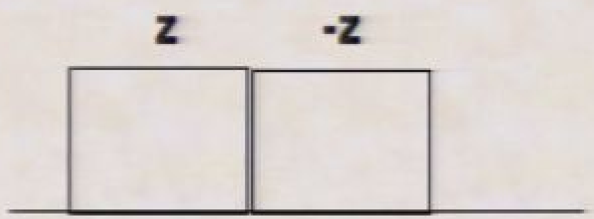


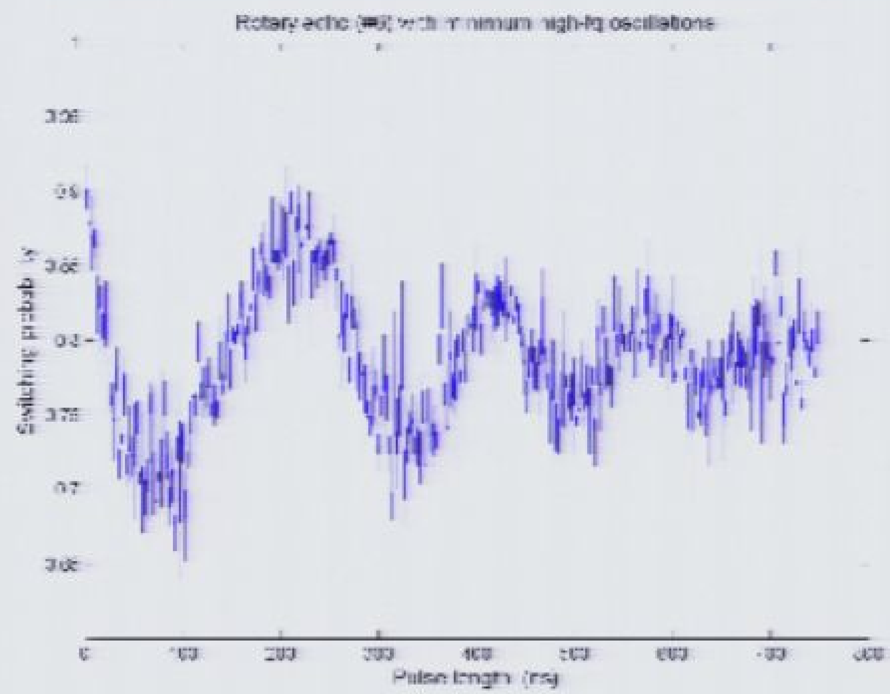

3
4
4x4
8x8
(N+1)

Rotary echo

What limits T_{Rabi}?

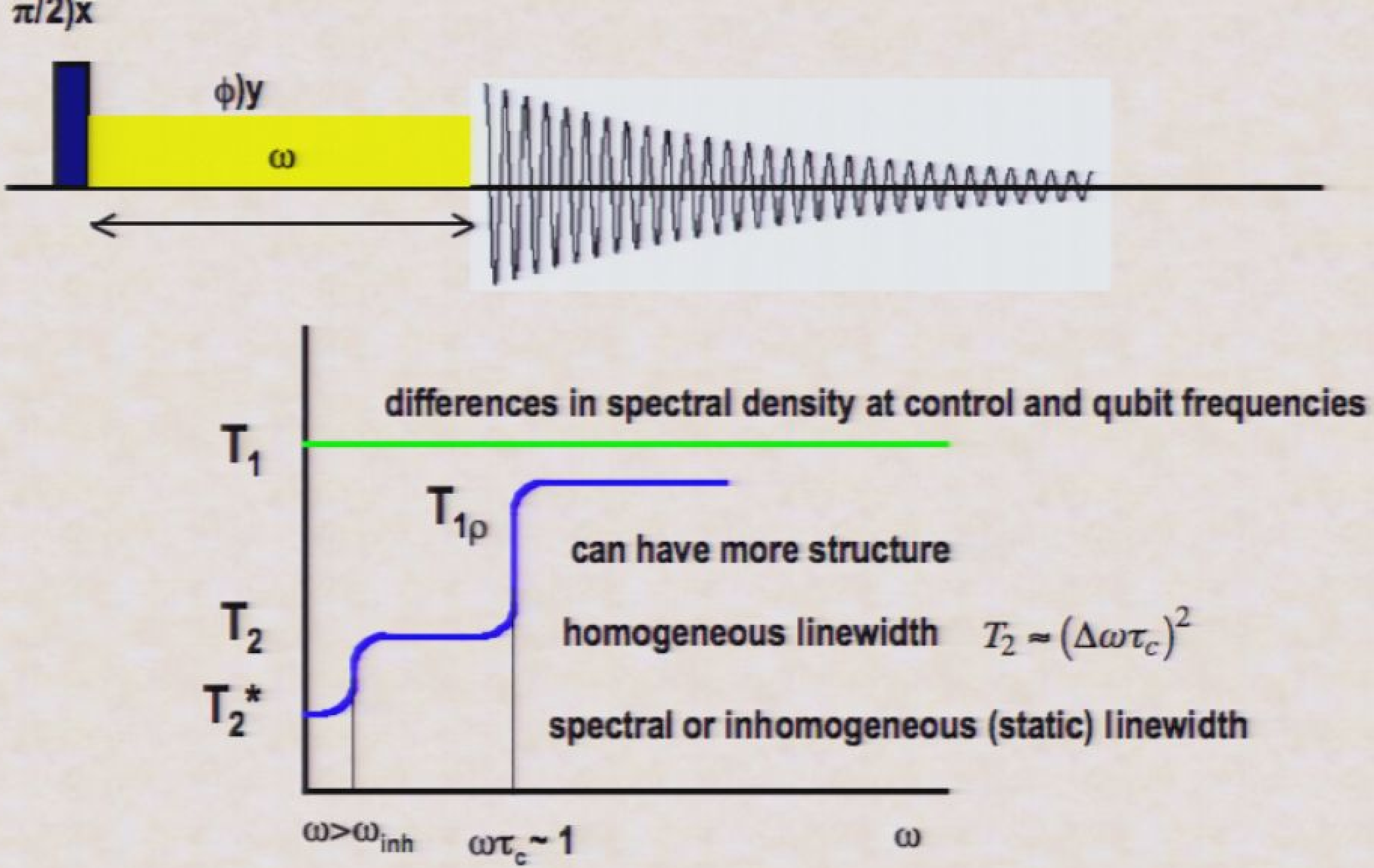




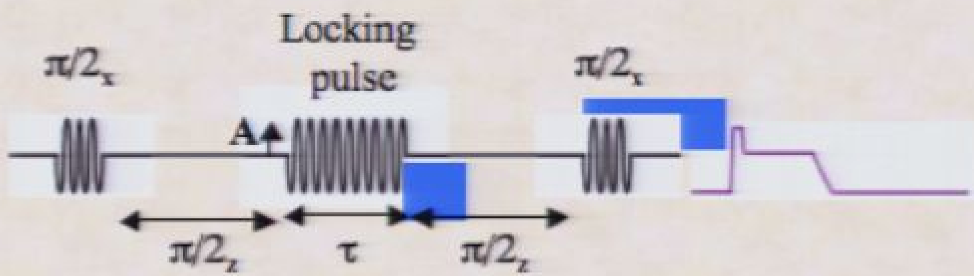


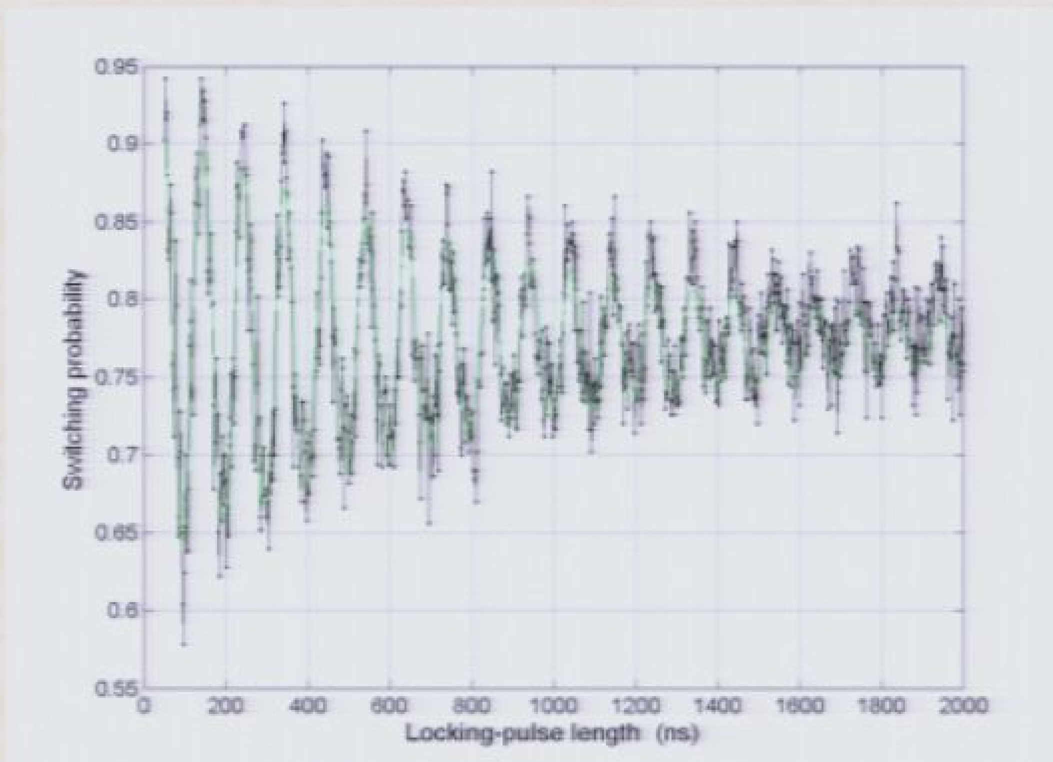
$T_{Rotary} > T_{Rabi}$ - noise in drive field

Spin locking

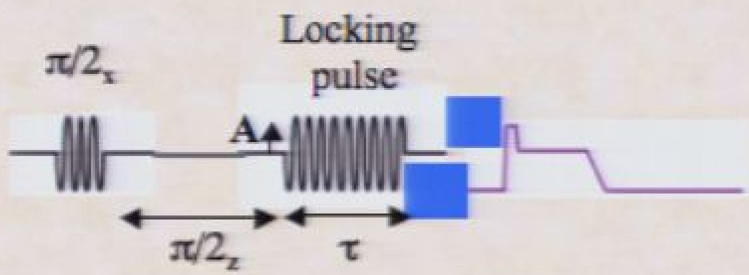


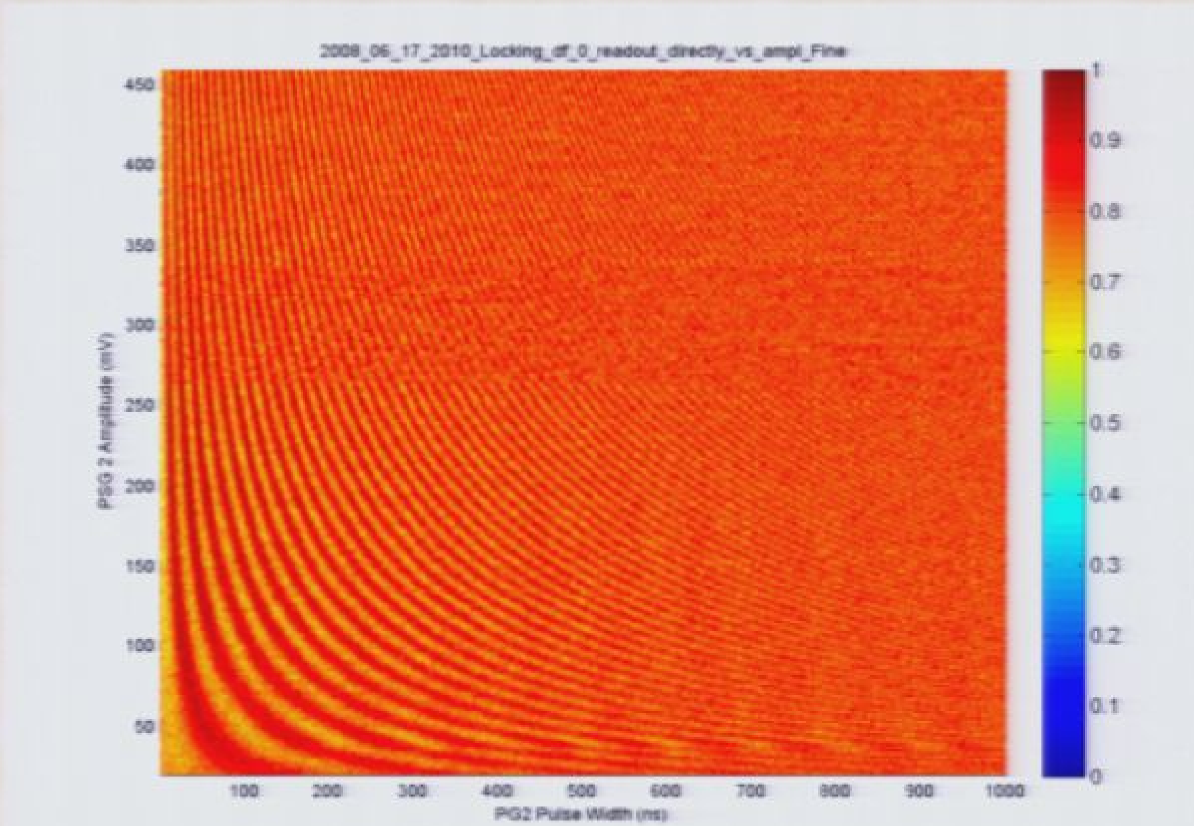
Spin locking

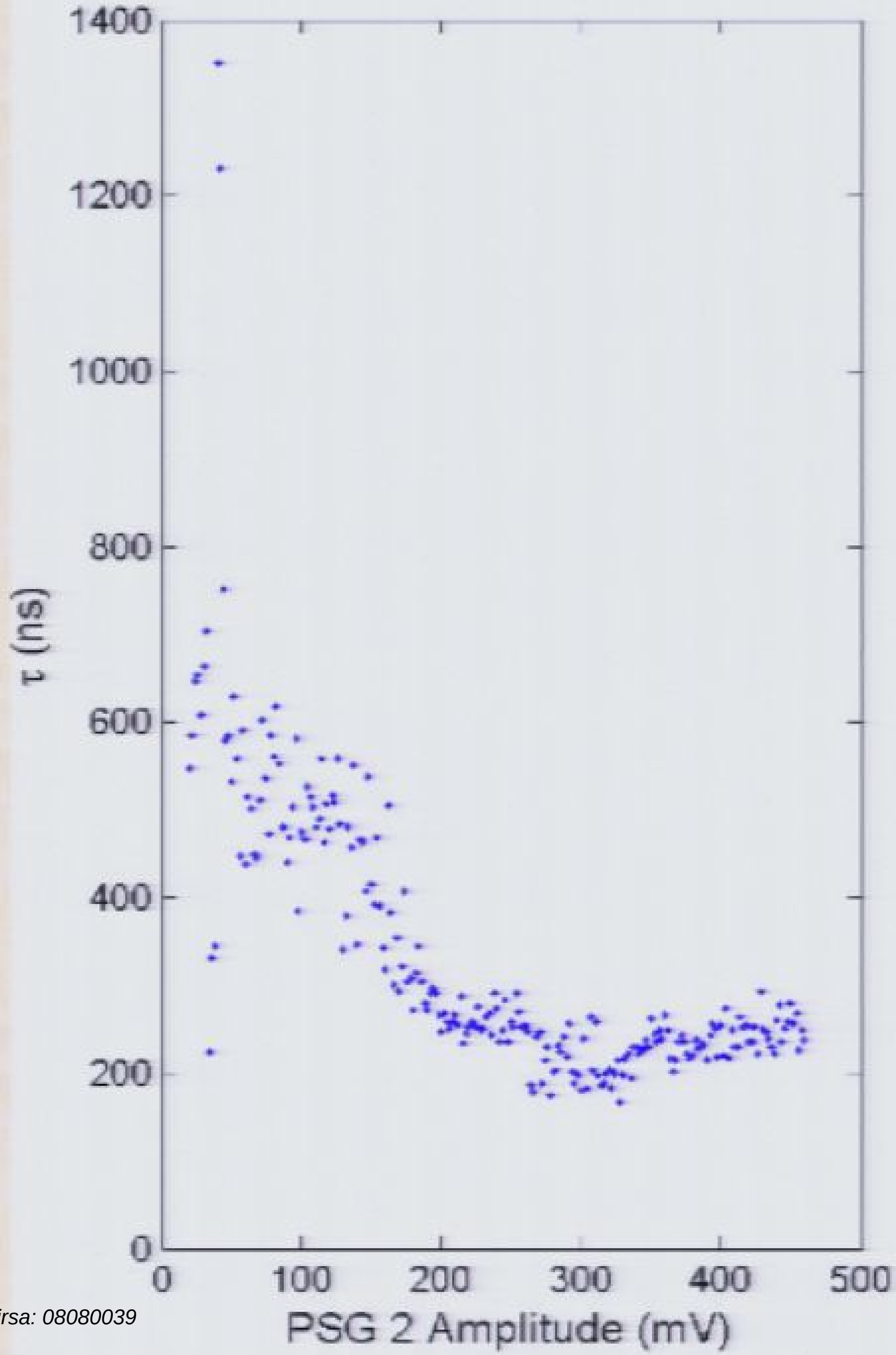




Spin locking







Here we plot the time constants of the $T_{2\rho}$

The overall decay is probably the same physics as was seen in the rotary echo

What is happening at lower frequencies where we measure values up to > 4 T_1 ?

Bloch picture

define quantization axis

rotate into tilted reference frame

move into interaction frame of the transmitter frequency

suppress high frequency, transverse field

$$\frac{d\Phi_x}{dt} = \omega_A(Cos\theta - \varepsilon Sin\theta)\big(Cos(\phi)\Phi_y - Sin(\phi)\Phi_z\big) - \frac{\Phi_x}{T_1}$$

$$\frac{d\Phi_y}{dt} = -\big(\Delta\omega + \omega_A(Sin\theta + \varepsilon Cos\theta)Cos(\omega_T t + \phi)\big)\Phi_z - \omega_A(Cos\theta - \varepsilon Sin\theta)Cos(\phi)\Phi_x - \frac{\Phi_y}{T_2}$$

$$\frac{d\Phi_z}{dt} = \big(\Delta\omega + \omega_A(Sin\theta + \varepsilon Cos\theta)Cos(\omega_T t + \phi)\big)\Phi_y + \omega_A(Cos\theta - \varepsilon Sin\theta)Sin(\phi)\Phi_x - \frac{\Phi_z}{T_2}$$

$$\theta = \tan^{-1}\left(\frac{\omega_{bias}}{\omega_0 + \varepsilon\omega_{bias}}\right)$$

$$\Delta\omega = \sqrt{(\omega_0 + \varepsilon\omega_{bias})^2 + \omega_{bias}{}^2} - \omega_T$$