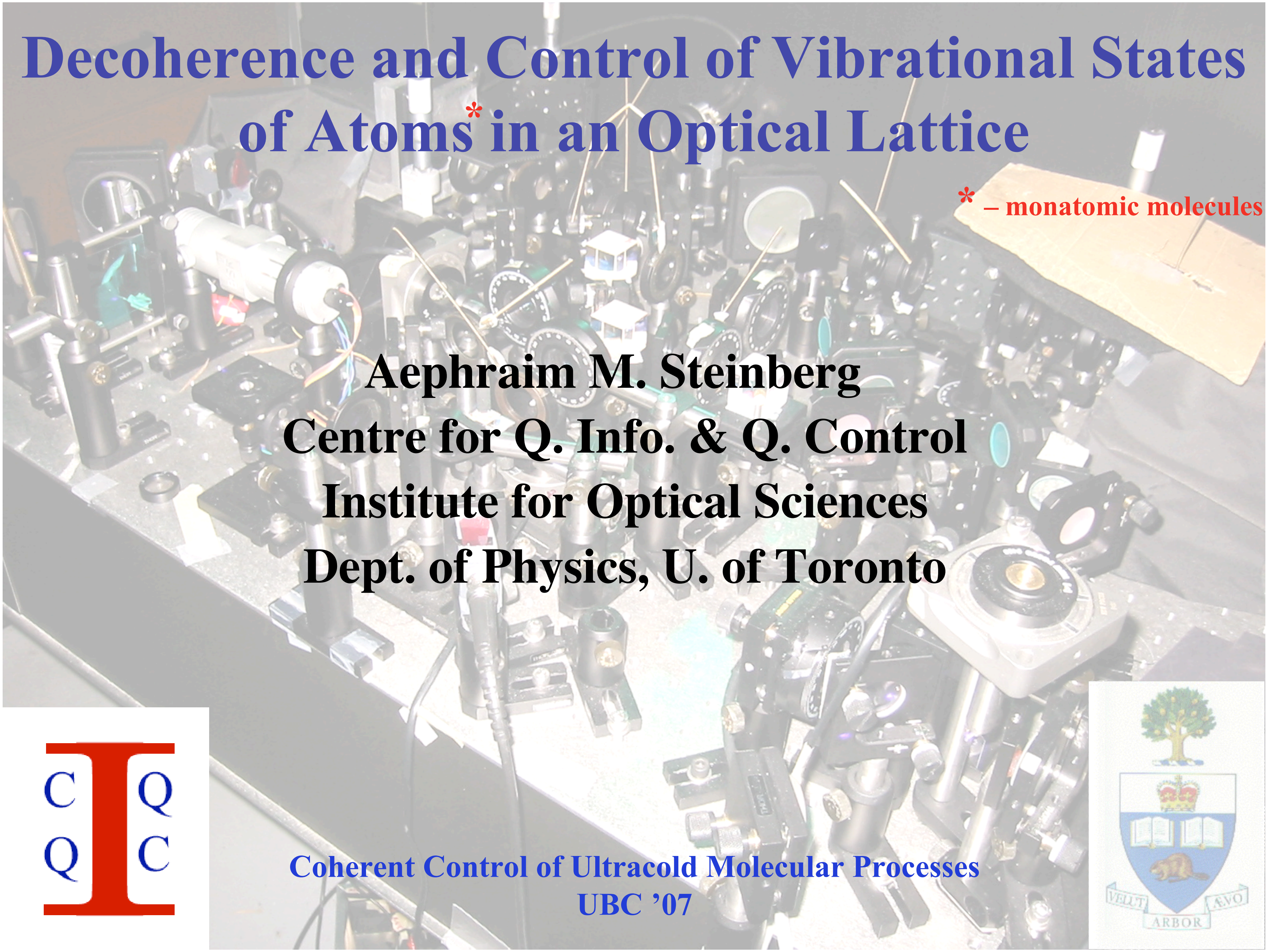

Decoherence and Control of Vibrational States of Atoms* in an Optical Lattice

* – monatomic molecules

Aephraim M. Steinberg
Centre for Q. Info. & Q. Control
Institute for Optical Sciences
Dept. of Physics, U. of Toronto

Coherent Control of Ultracold Molecular Processes
UBC '07

DRAMATIS PERSONÆ

Toronto quantum optics & cold atoms group:

Postdocs: An-Ning Zhang(→ IQIS) Morgan Mitchell (→ ICFO)

(HIRING!) Matt Partlow(→Energetiq) Marcelo Martinelli (→ USP)

Optics: Rob Adamson Kevin Resch(→Wien →UQ→IQC)

Lynden(Krister) Shalm Jeff Lundeen (→Oxford)

Xingxing Xing

Atoms: Jalani Fox (→Imperial) Stefan Myrskog (→BEC→ ECE)

(SEARCHING!) Mirco Siercke (→ ...?) Ana Jofre(→NIST →UNC)

Samansa Maneshi Chris Ellenor

Rockson Chang **Chao Zhuang** **Xiaoxian Liu**

UG's: Ardavan Darabi, **Nan Yang**, Max Touzel, Michael Sitwell, Eugen Friesen

Some helpful theorists:

Pete Turner, Michael Spanner, H. Wiseman, J. Bergou, M. Mohseni, J. Sipe, Daniel James, Paul Brumer, ...

PHOTONICS RESEARCH ONTARIO
DARPA
25 years cifar Canadian Institute for Advanced Research
NSERC CRSNG
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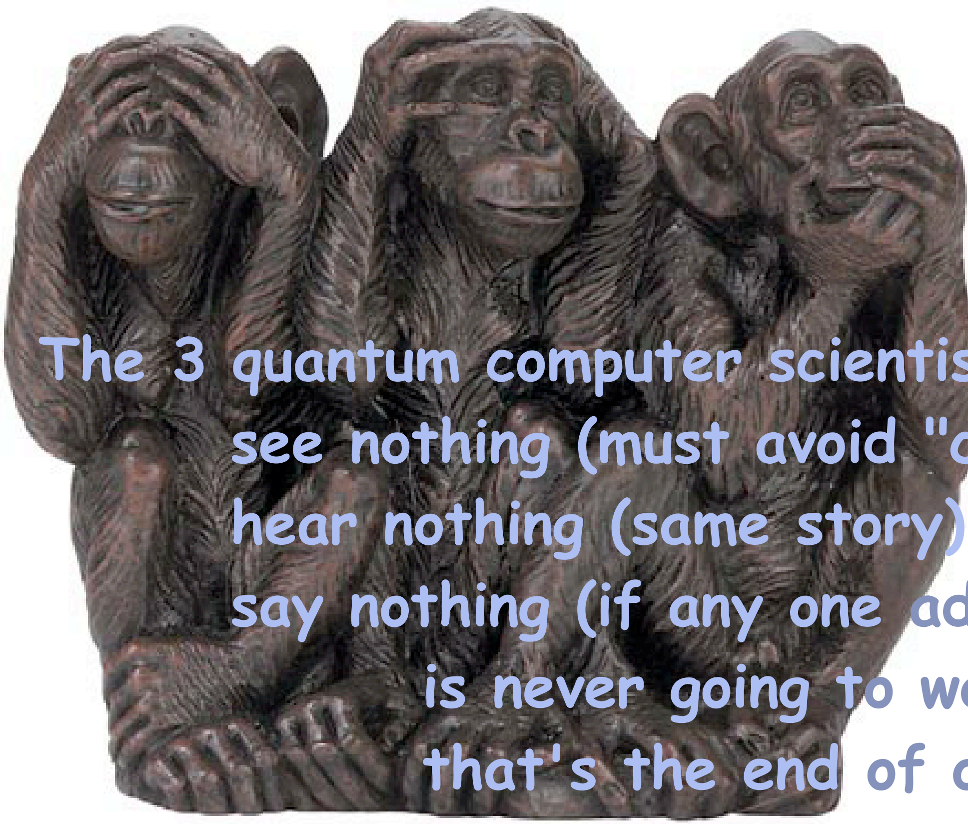
Quantum Computer Scientists



The 3 quantum computer scientists:

see nothing (must avoid "collapse"!)

hear nothing (same story)

say nothing (if any one admits this thing is never going to work, that's the end of our funding!)

OUTLINE

(generic physics talk of the 2nd type)

Something we were trying to do

Preparing & tomographing quantum states in lattices

Something we didn't anticipate [complicated plots]

Pulse echo and a "fidelity freeze"

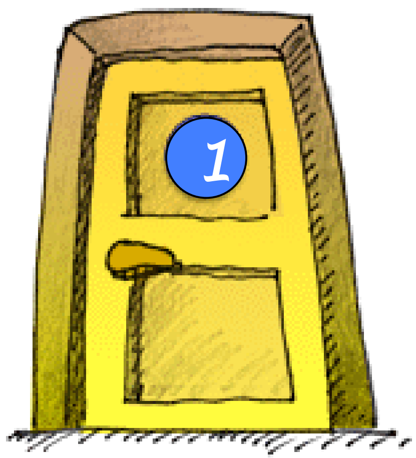
Pretty pictures in case I've already lost you

Probing decoherence with 2D pump-probe spectro.

A completely different topic just to keep you on your toes (or because I'm indecisive)

1-vs-2 coherent control of vibrational excitations

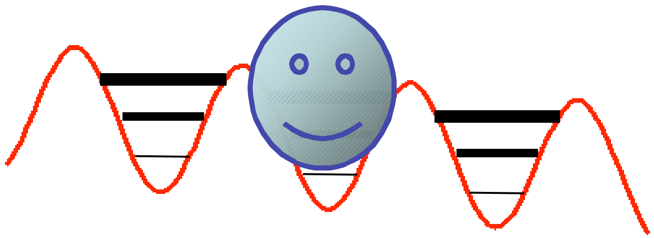
Summary



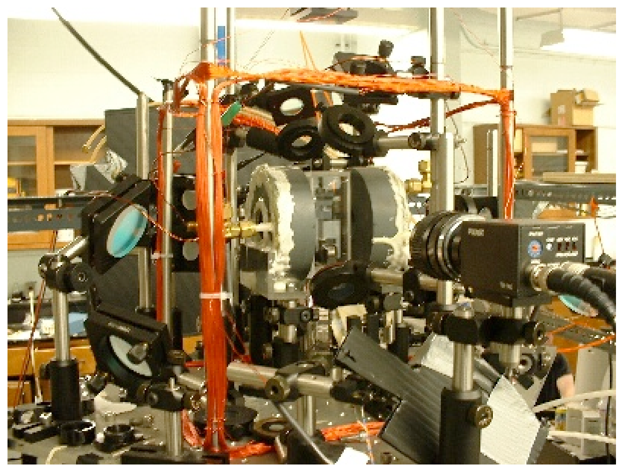
Quantum CAT scans

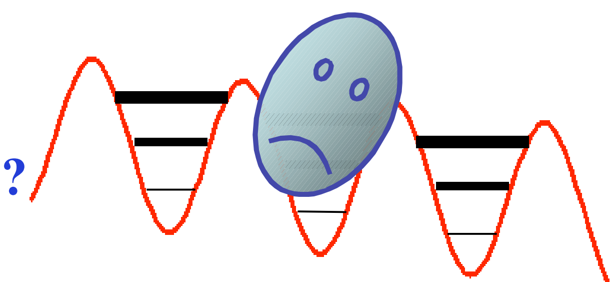
Tomography & control in Lattices

[Myrkog *et al.*, PRA 72, 013615 (05)
Kanem *et al.*, J. Opt. B7, S705 (05)]



Rb atom trapped in one of the quantum levels of a periodic potential formed by standing light field (30GHz detuning, c. 20 E_R in depth)





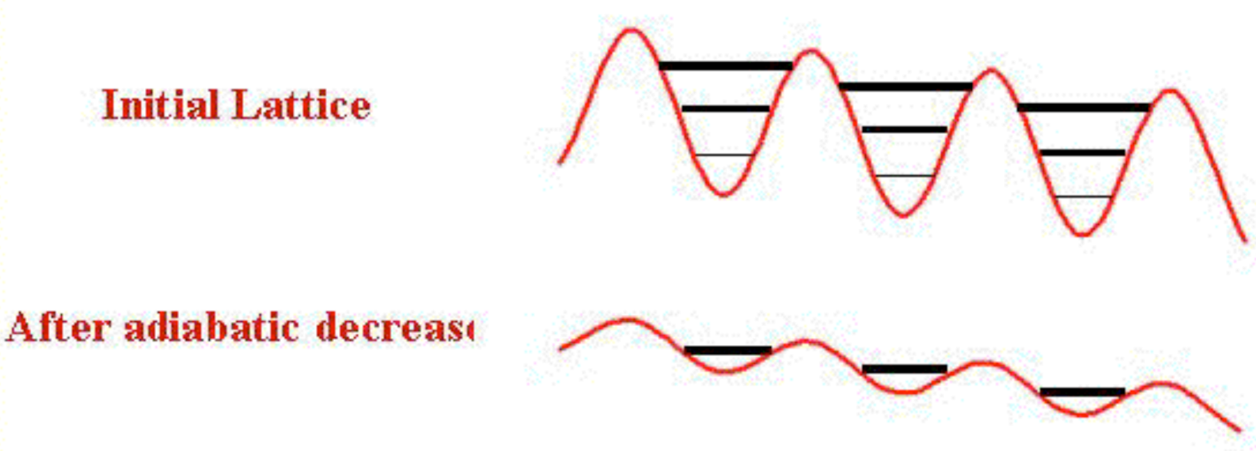
Goals:
How to fully characterize time-evolution due to lattice?
How to correct for "errors" (preserve coherence,...)?
How to convince the NSA that this is important for building quantum computers?

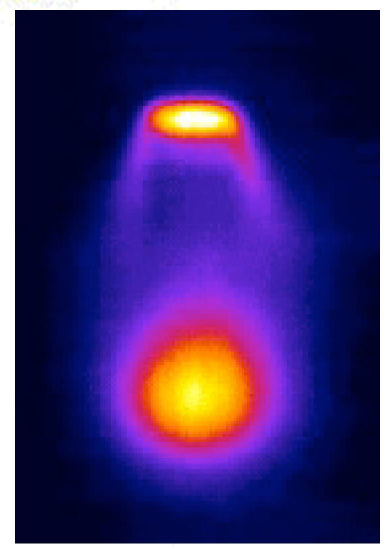
The workhorse: measuring state populations

Adiabatically lower the depth of the wells in the presence of gravity. Highest states become classically unbound and are lost. Measure ground state occupation.

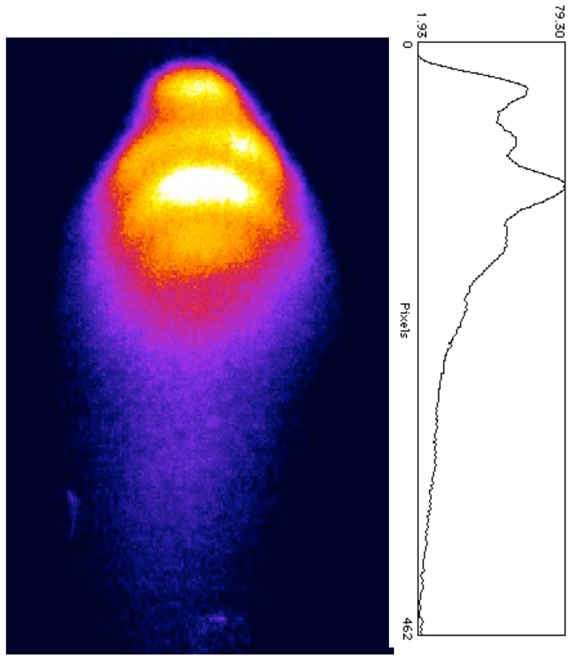
Two Methods : - Ramp down and hold. Observe population as a function of depth.

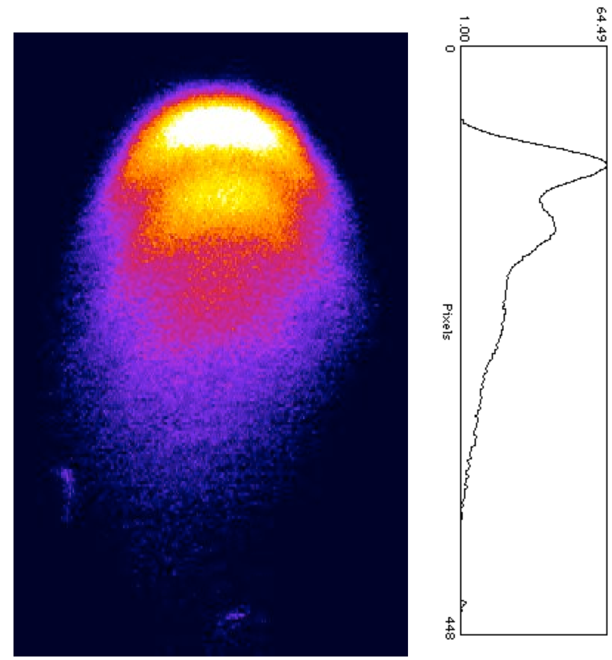
OR - Ramp down very slowly and observe different states leave at distinct times.





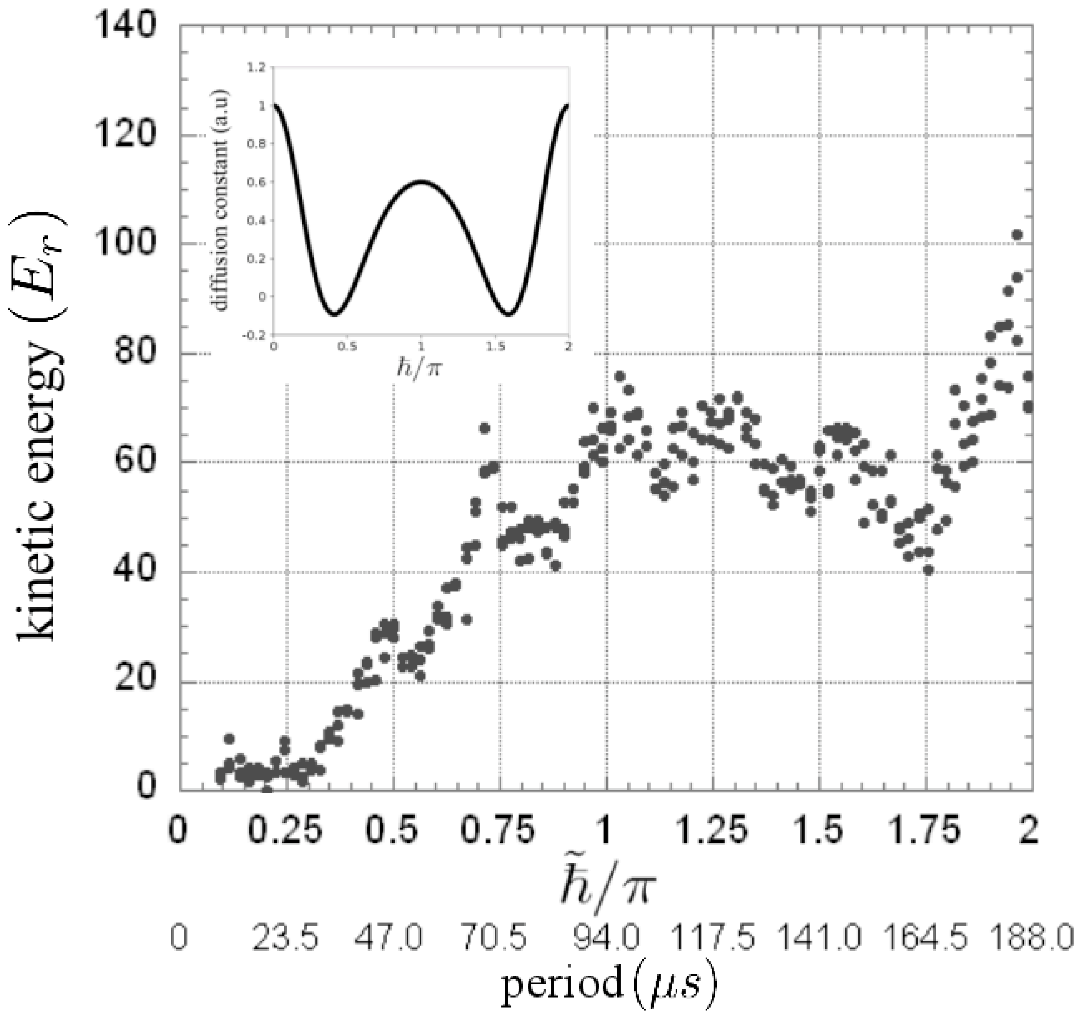
Time-resolved quantum states





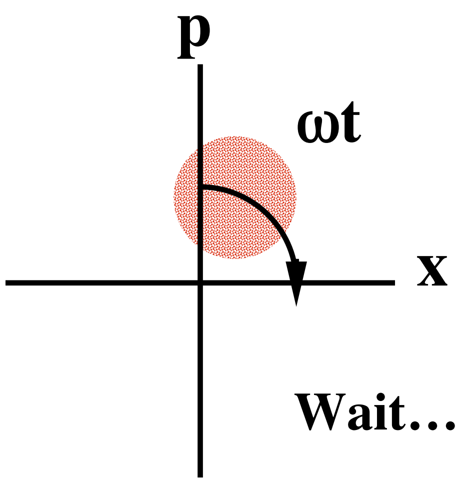
Aside: an unrelated interesting result

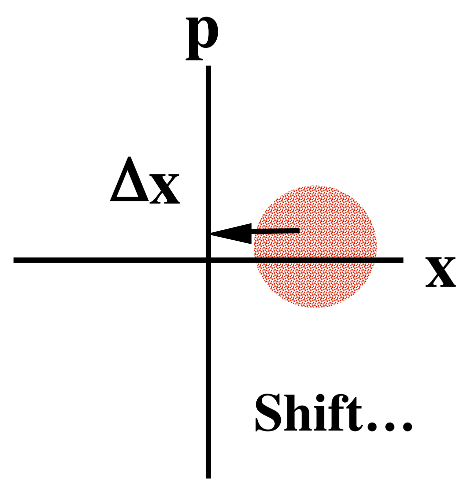
Fractional wavepacket revivals in a delta-kicked rotor experiment (fractional quantum resonances)

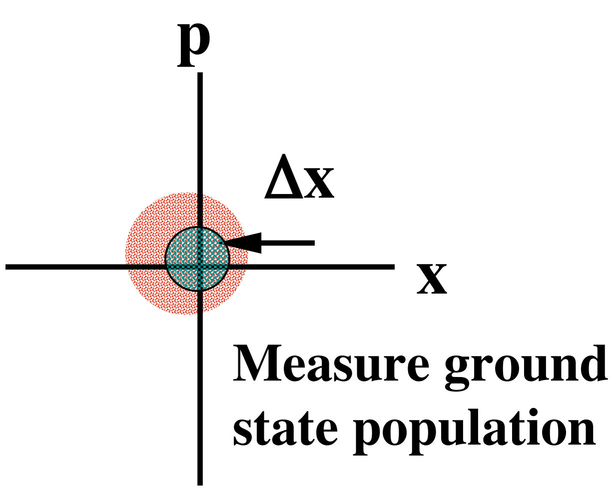


Kanem *et al.*, PRL 98, 083004 (07)

Quantum state reconstruction







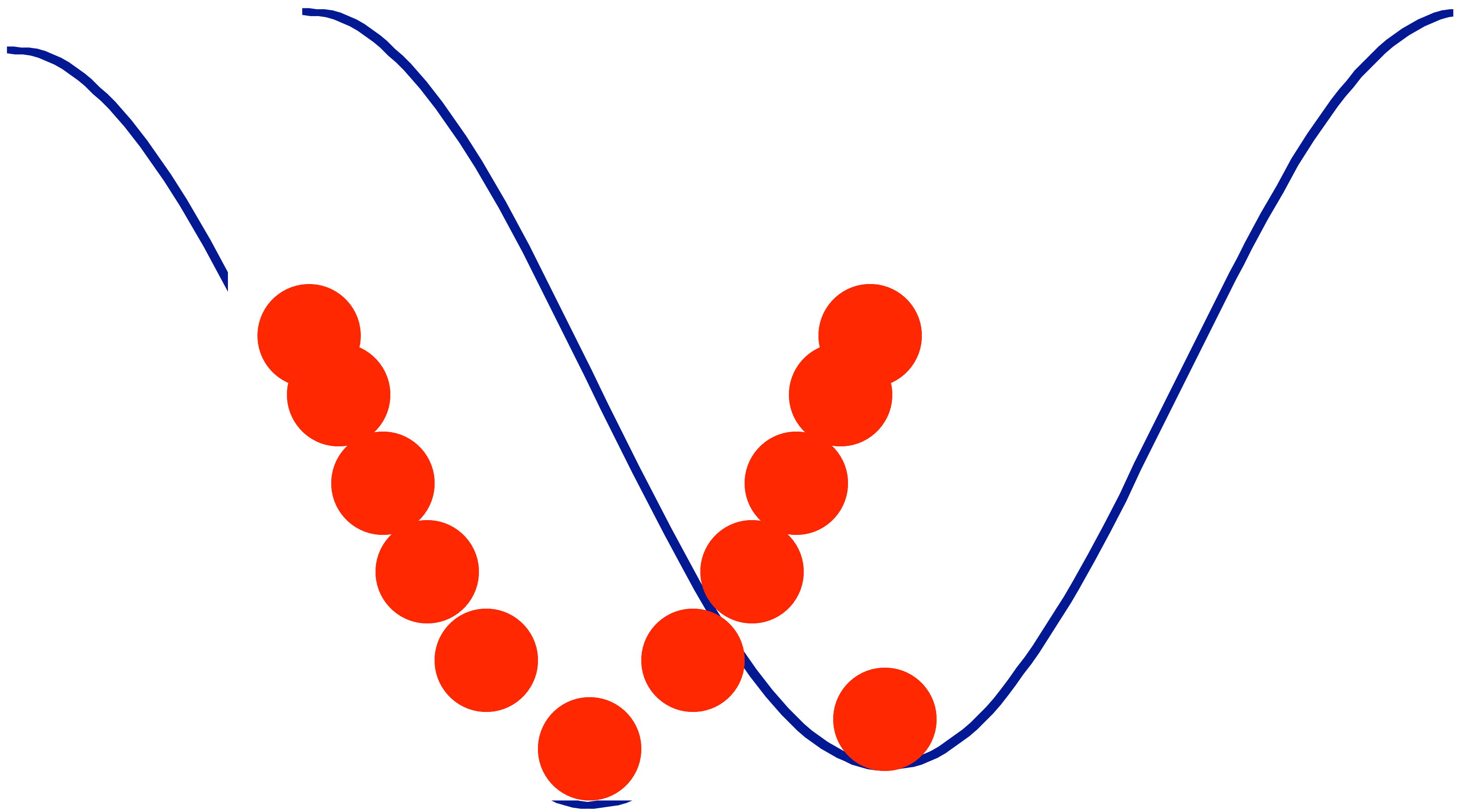
$$Q(0,0) = \frac{1}{\pi} P_g$$

$$W(0,0) = \frac{1}{\pi} \Sigma \, (-1)^n \, P_n$$

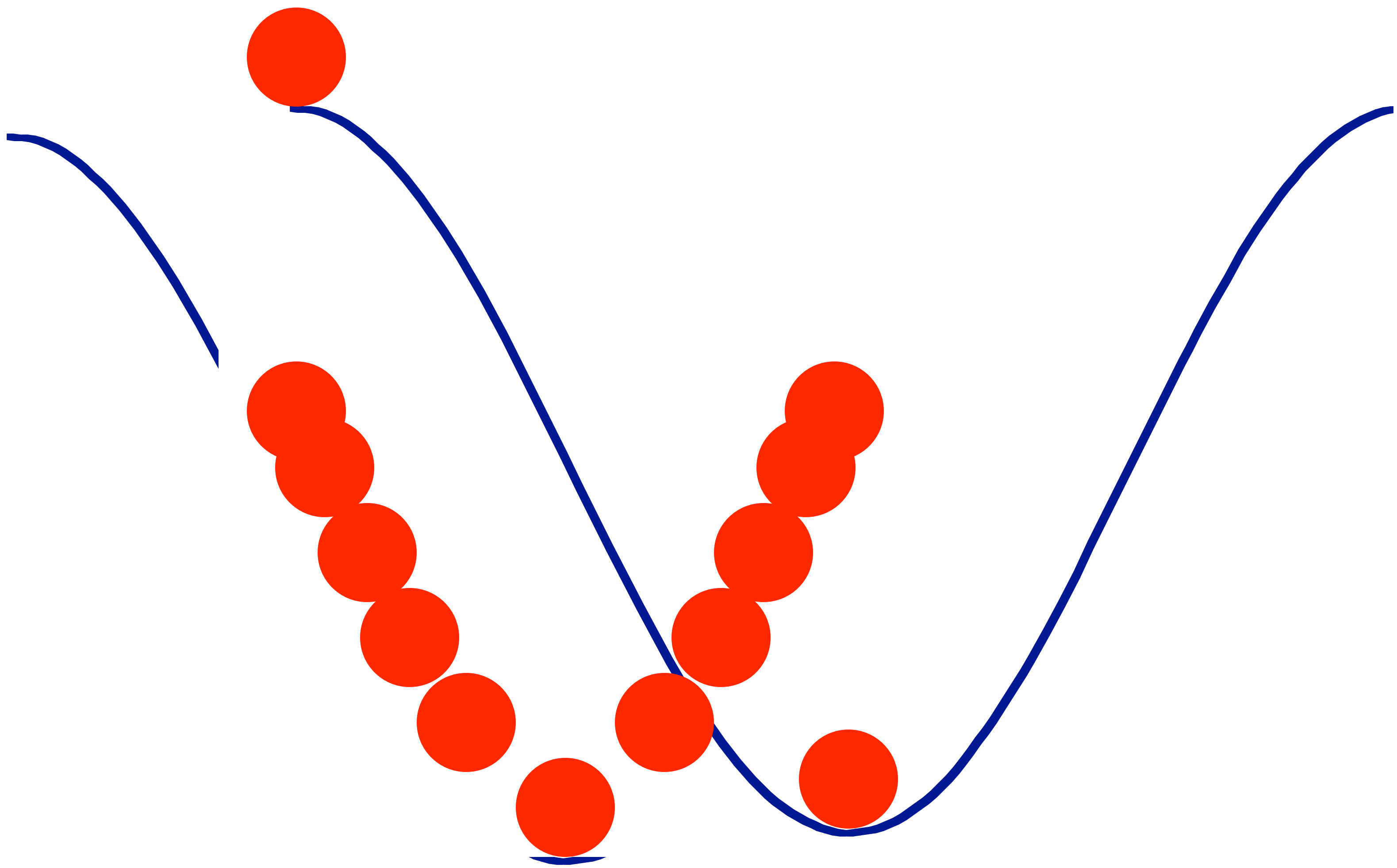
(former for HO only; latter requires only symmetry)

Cf. Poyatos,Walser,Cirac,Zoller,Blatt, PRA 53, 1966 ('96)
& Liebfried,Meekhof,King,Monroe,Itano,Wineland, PRL77, 4281 ('96)

Recapturing atoms after setting them into oscillation...

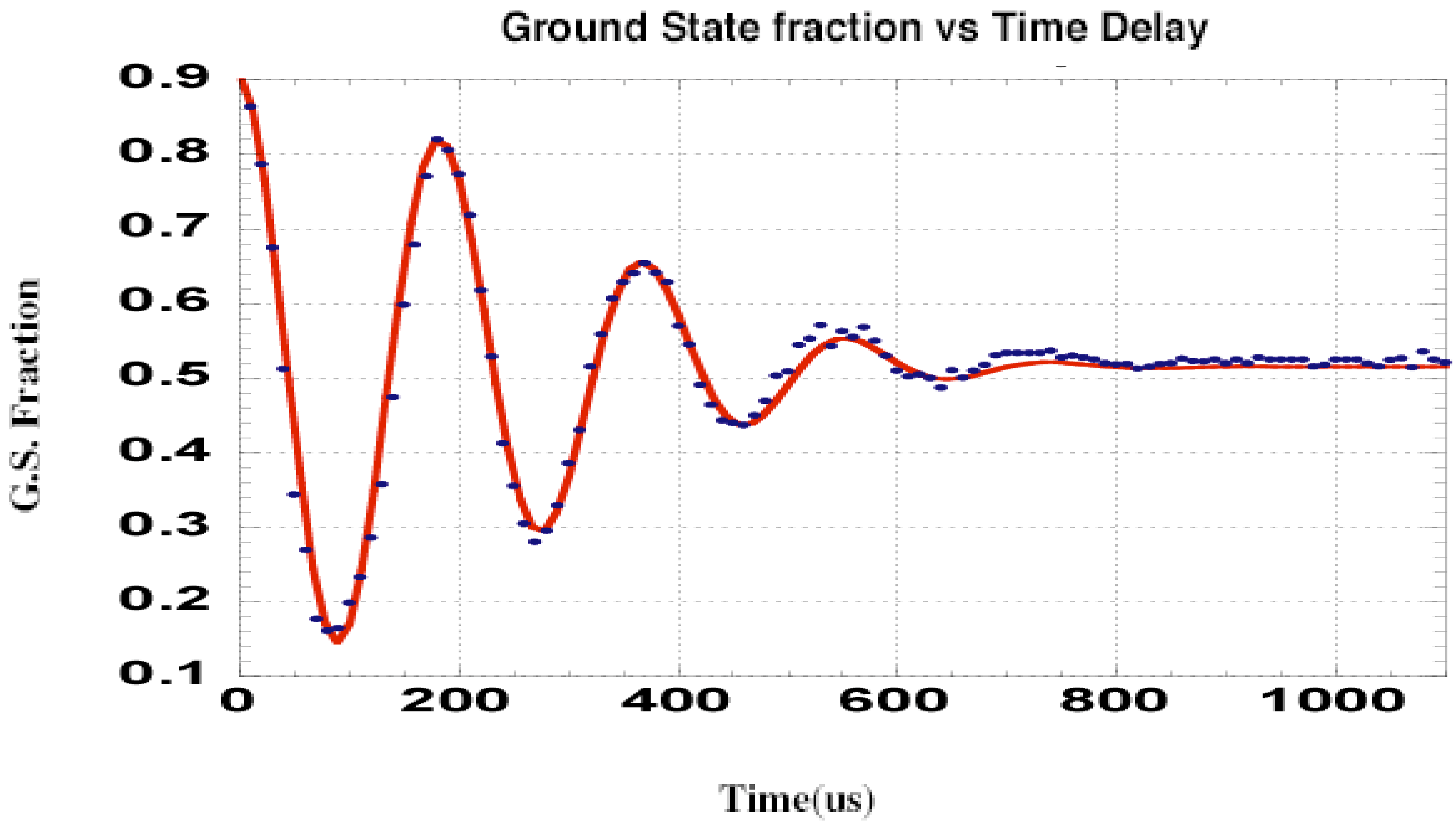


...or failing to recapture them if you're too impatient

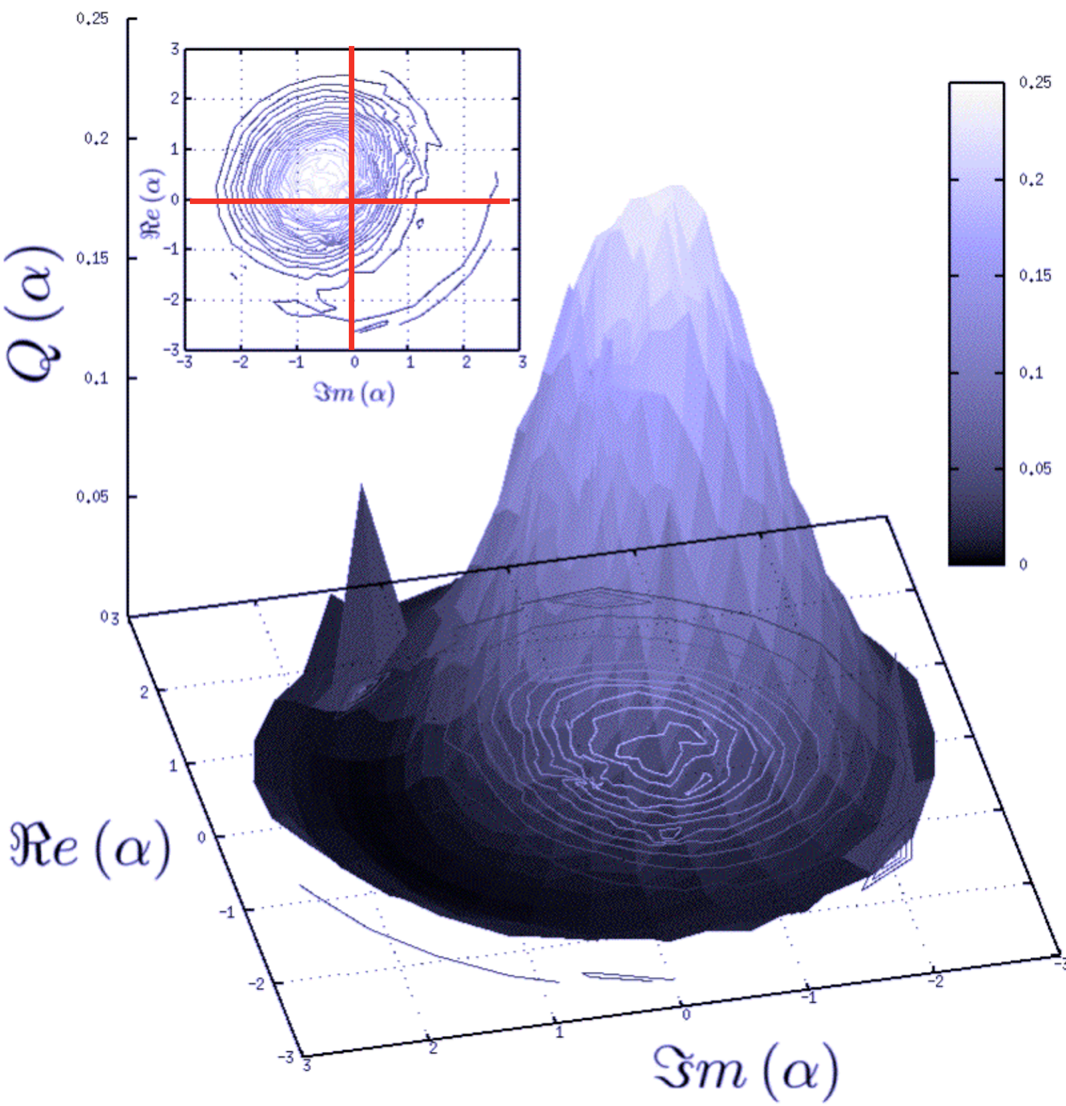


Oscillations in lattice wells

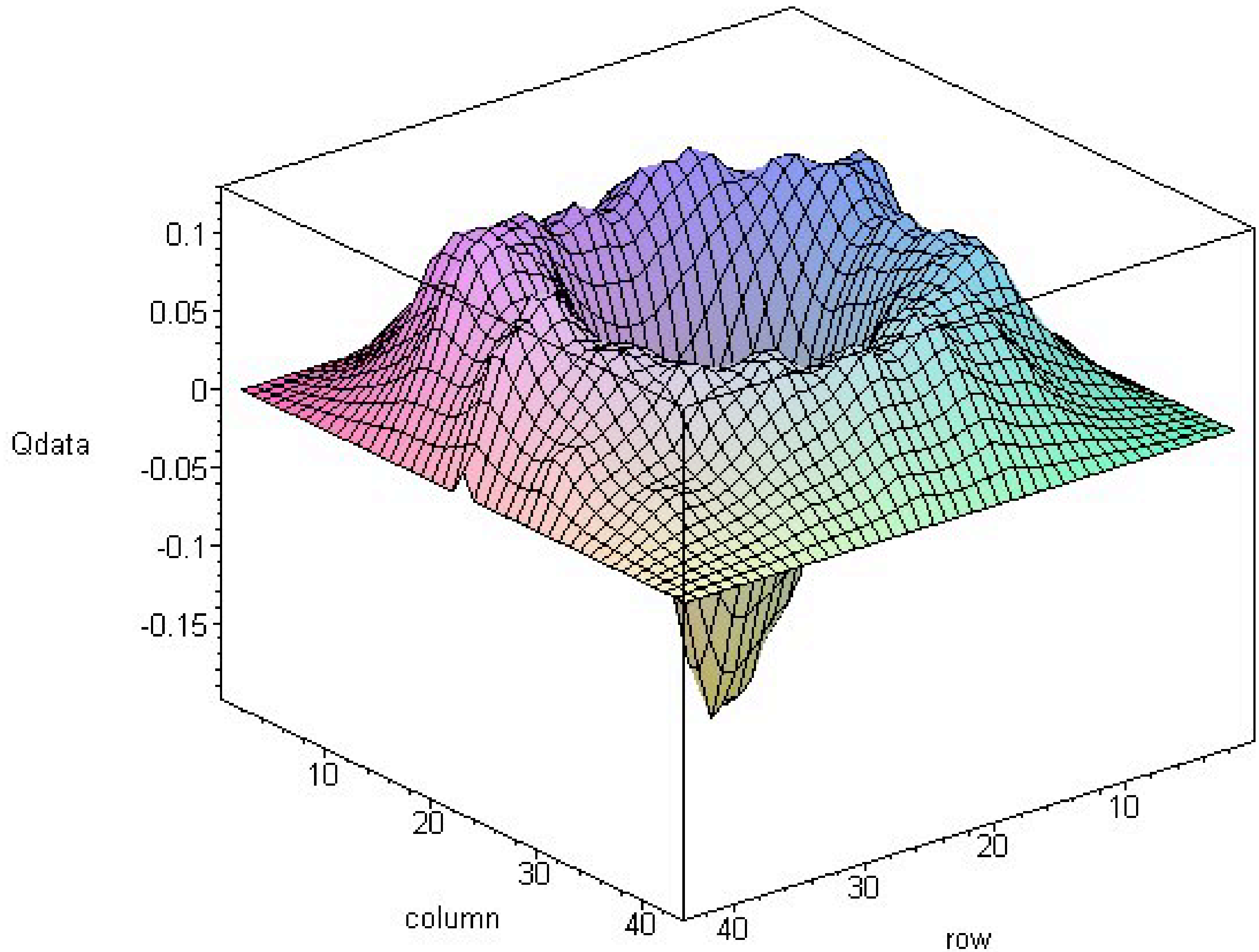
(Direct probe of centre-of-mass oscillations in 1μm wells;
can be thought of as Ramsey fringes or Raman pump-probe exp't.)



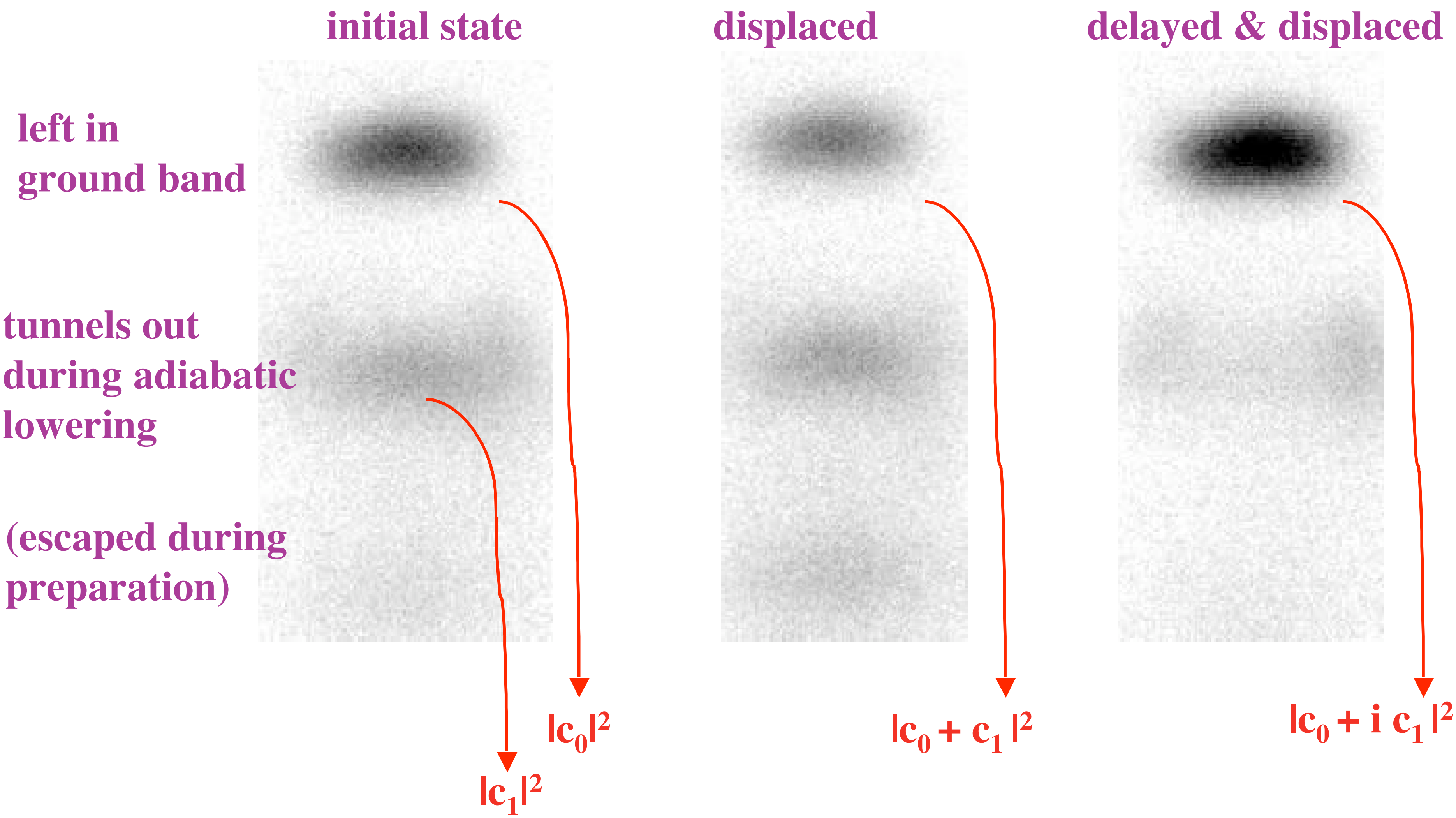
Husimi distribution of coherent state



Data:"W-like" $[P_g-P_e](x,p)$ for a mostly-excited incoherent mixture



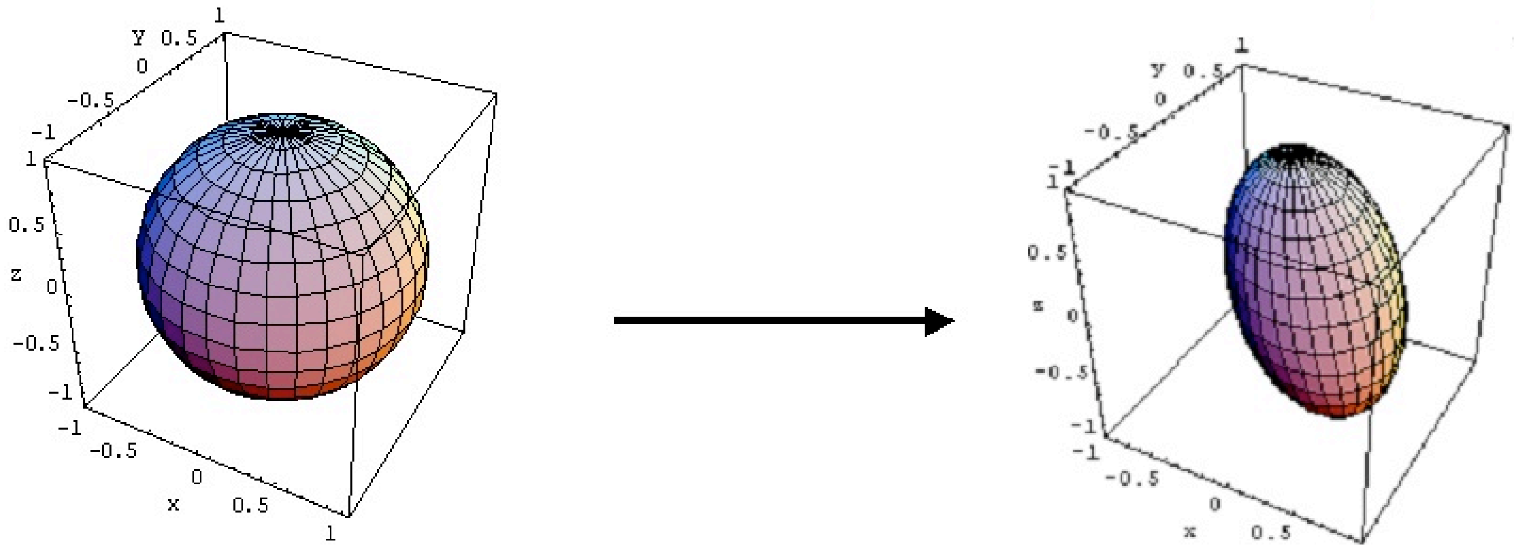
Atomic state measurement
(for a 2-state lattice, with $c_0|0\rangle + c_1|1\rangle$)



Extracting a superoperator:

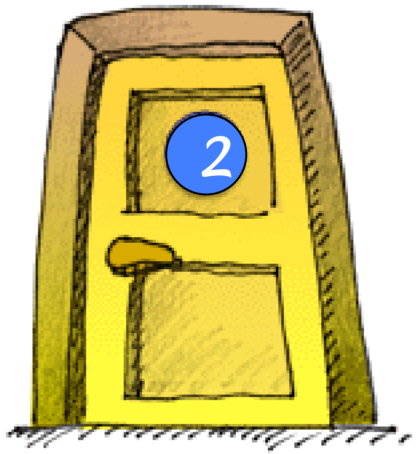
prepare a complete set of input states and measure each output

Operation:
Sitting in the lattice
for 1 period.



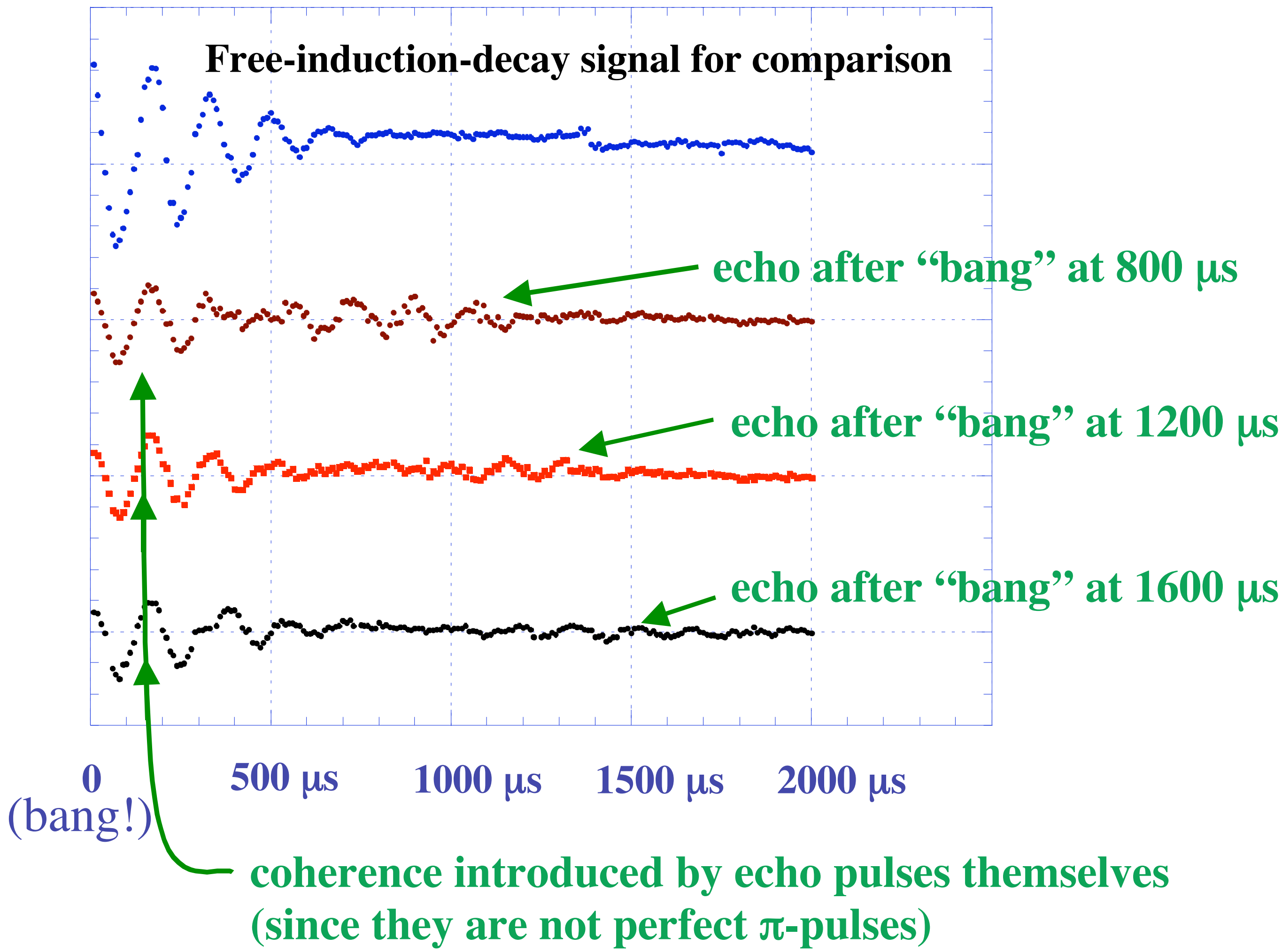
Likely sources of decoherence/dephasing:

- **Real photon scattering (100 ms; shouldn't be relevant in 150 μs period)**
- **Inter-well tunneling (10s of ms; would love to see it)**
- **Beam inhomogeneities (expected several ms, but are probably wrong)**
- **Parametric heating (unlikely; no change in diagonals)**
- **Other**



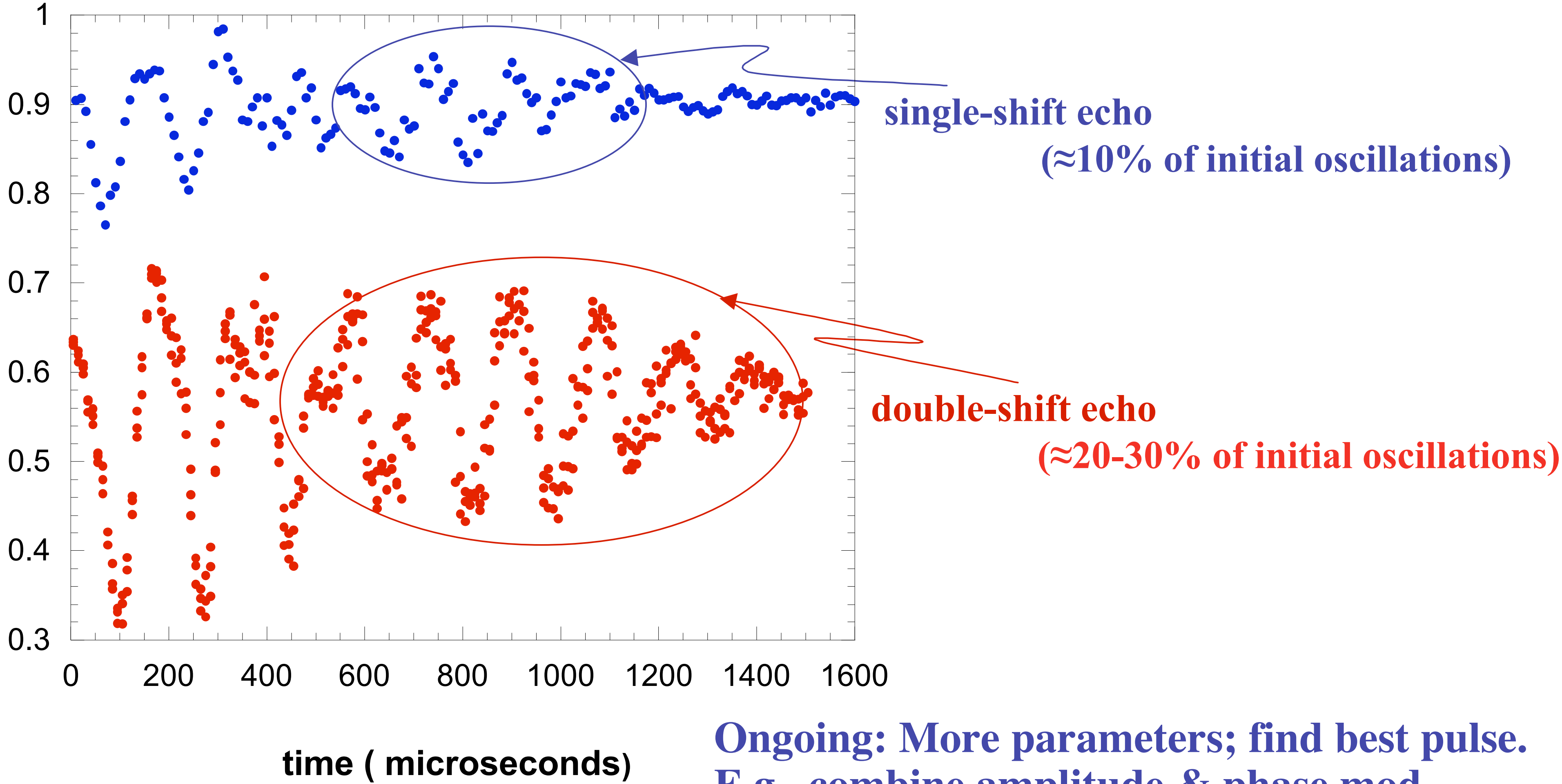
Atom echoes

Towards bang-bang error-correction: pulse echo indicates T2 ≈ 1 ms...



Echo from compound pulse

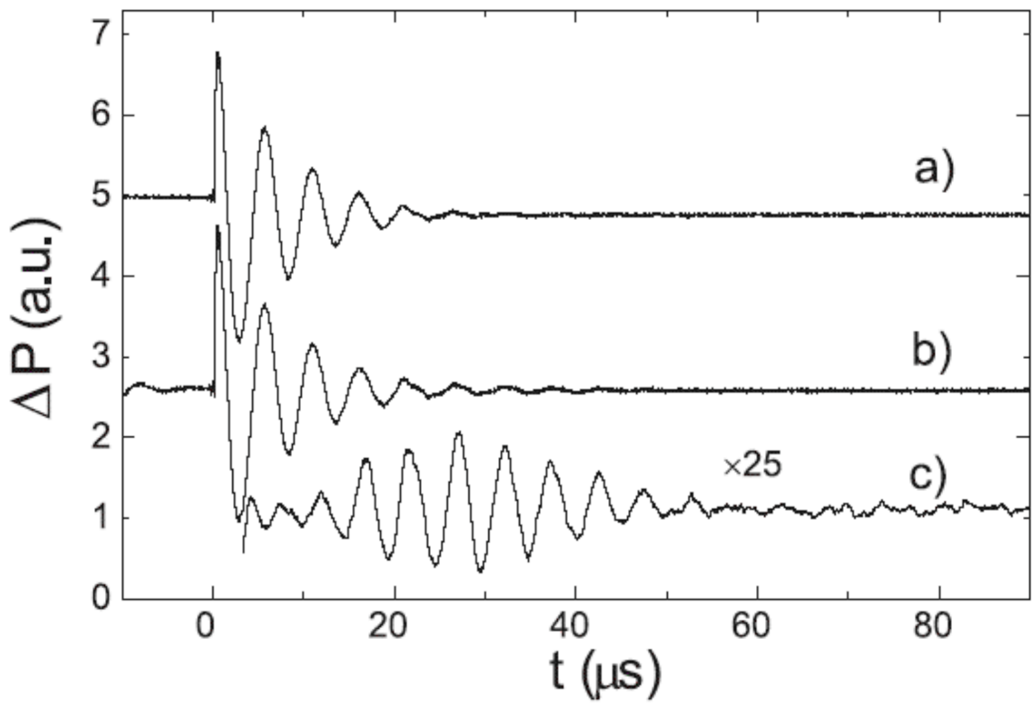
Pulse 900 us after state preparation,
and track oscillations



Ongoing: More parameters; find best pulse.
E.g., combine amplitude & phase mod.

Also: optimize # of pulses.

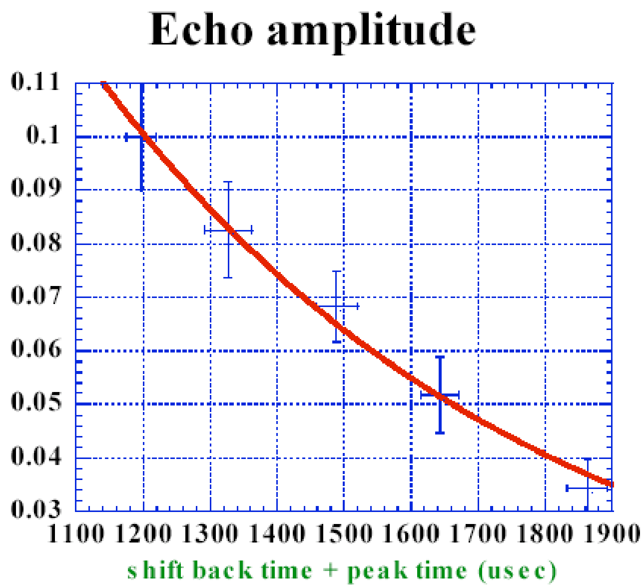
Cf. Hannover experiment



Far smaller echo, but far better signal-to-noise ("classical" measurement of <X>)
Much shorter coherence time, but roughly same number of periods
– dominated by anharmonicity, irrelevant in our case.

Buchkremer, Dumke, Levsen, Birkl, and Ertmer, PRL **85**, 3121 (2000).

Why does our echo decay?



Present best guess = finite bath memory time:

So far, our atoms are free to move in the directions transverse to our lattice. In 1 ms, they move far enough to see the oscillation frequency change by about 10%... which is about 1 kHz, and hence enough to dephase them.

Why does our echo decay?

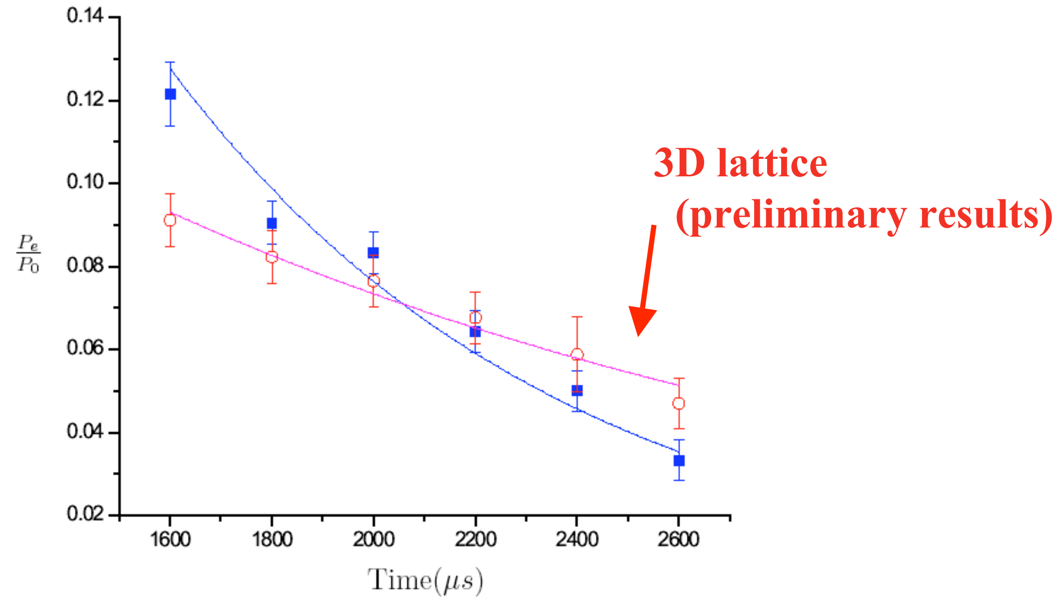
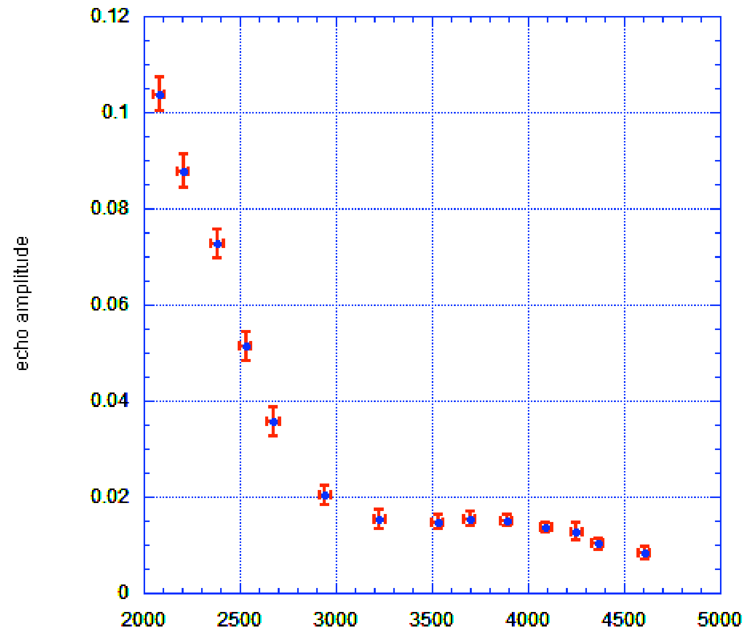


Figure 6.7: Comparison of echo amplitude decay in 1D and 3D lattice.

Present best guess = finite bath memory time:

So far, our atoms are free to move in the directions transverse to our lattice. In 1 ms, they move far enough to see the oscillation frequency change by about 10%... which is about 1 kHz, and hence enough to dephase them.

Why does our echo decay?



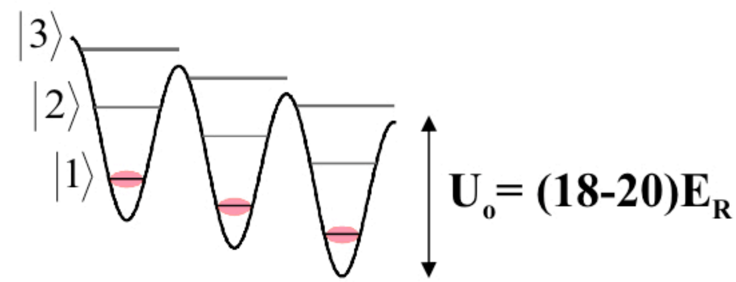
Except for one minor disturbing feature:

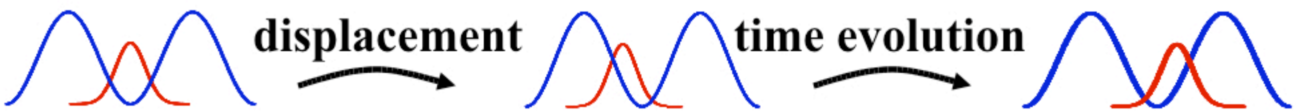
These data were first taken *without* the 3D lattice, and we don't have the slightest idea what that plateau means. (Work with Daniel James to relate it to autocorrelation properties of our noise, but so far no understanding of why it's as it is.)

Designing excitation pulses...

Pulses are consisted of time-dependent translations of the lattic
(Combination of displacements and time delays)

atoms are prepared in the lowest state
(incoherent filling of the first band)

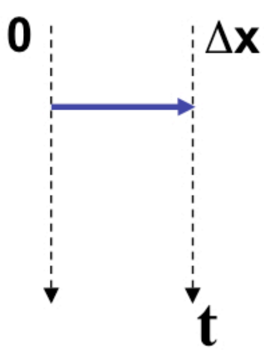




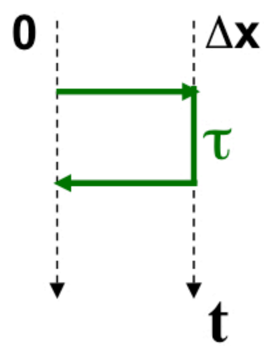
$|1\rangle$ $\qquad a|1\rangle + b|2\rangle + c|3\rangle + \ldots$ $\qquad e^{-i\omega_1 t} a|1\rangle + e^{-i\omega_2 t} b|2\rangle + e^{-i\omega_3 t} c|3\rangle + \ldots$

3 pulses :

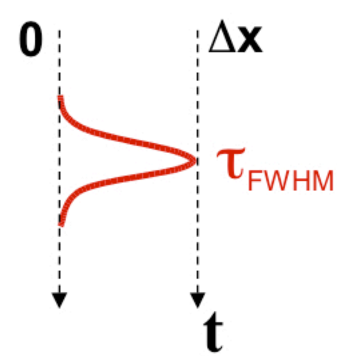
Single-step pulse



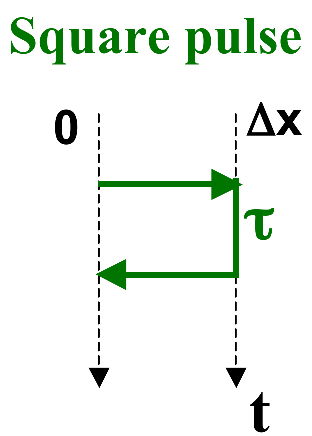
Square pulse

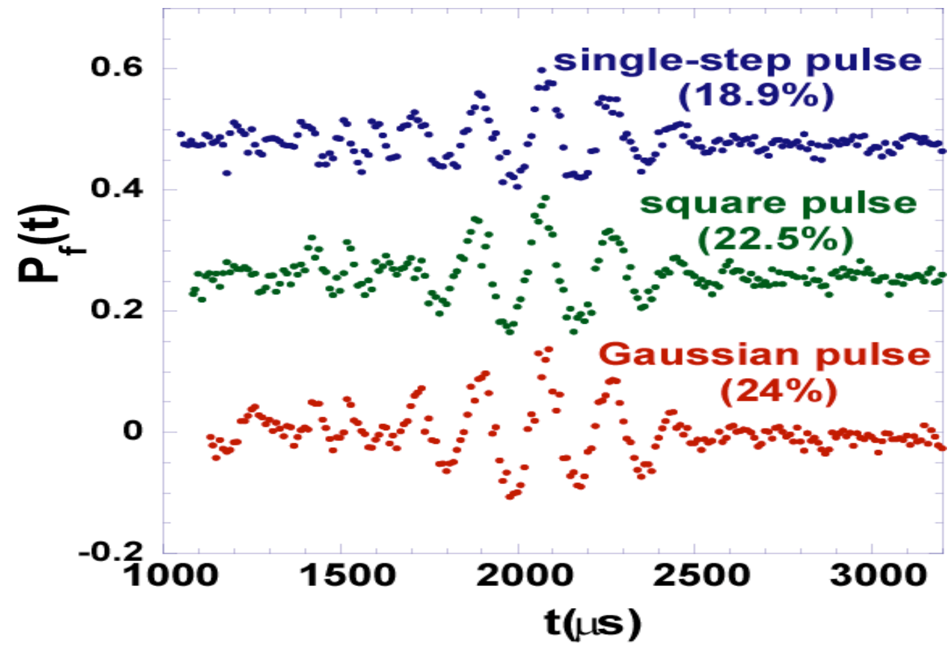


Gaussian pulse

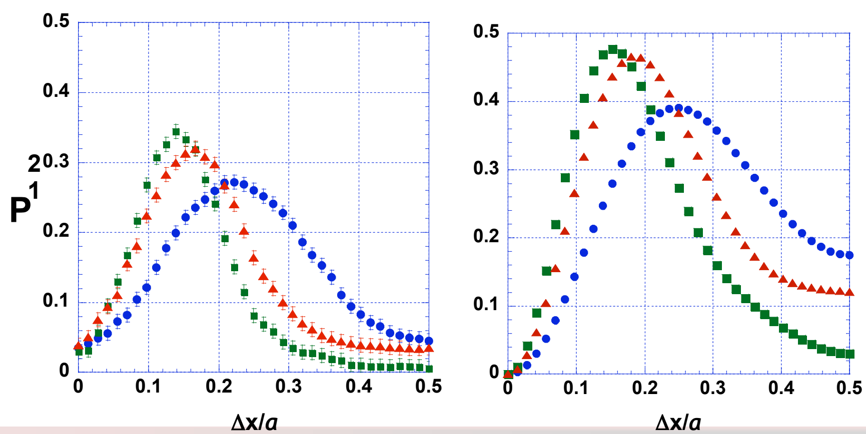


Improved echo pulses





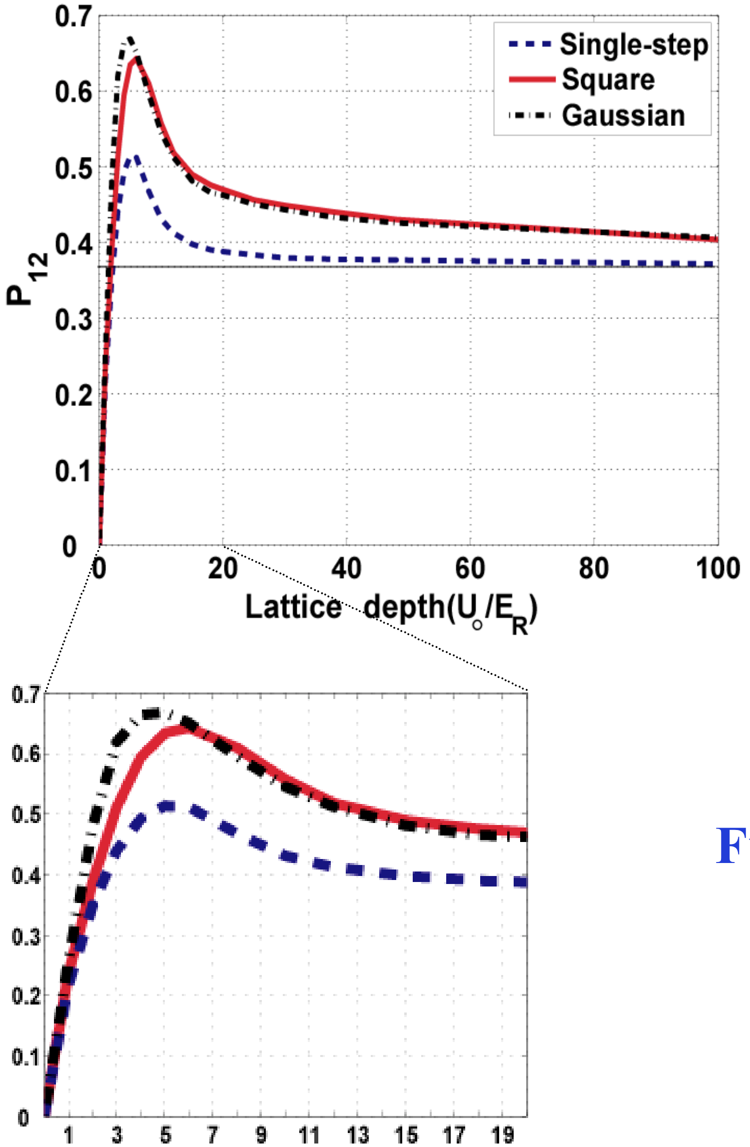
Coupling eff. of 3 pulse shapes versus shift
– **Theory & Experiment (you guess which is which)**



Loss from lattice	
Single-step	~71%
Square	~70%
Gaussian	~55%

S. Maneshi *et al.*, quant-ph/0706.3072

Going off the shallow end

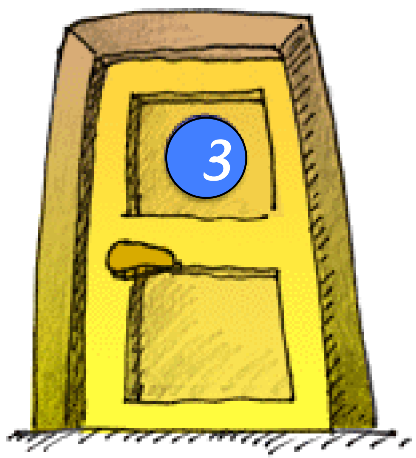


***The optimal coupling into |1>
is 1/e in a harmonic oscillator,
but rises to 67% (gaussian pulse)
in a shallow lattice.***

In our vertical configuration, we can't go that far – have reached about 35% (square pulse).

Further thoughts on excitation pulses:

- **adiabatic rapid passage**
- **AM + PM (later in this talk)**
- **optimal control (GRAPE, etc)**
- **(very shallow) horizontal lattice**



Our thinking shows one-dimensionality

2D Fourier Transform Spectroscopy

2D spectroscopy is a technique to quantitatively distinguish multiple time scales: e.g., the homogeneous and inhomogeneous time scales, and the correlation time.

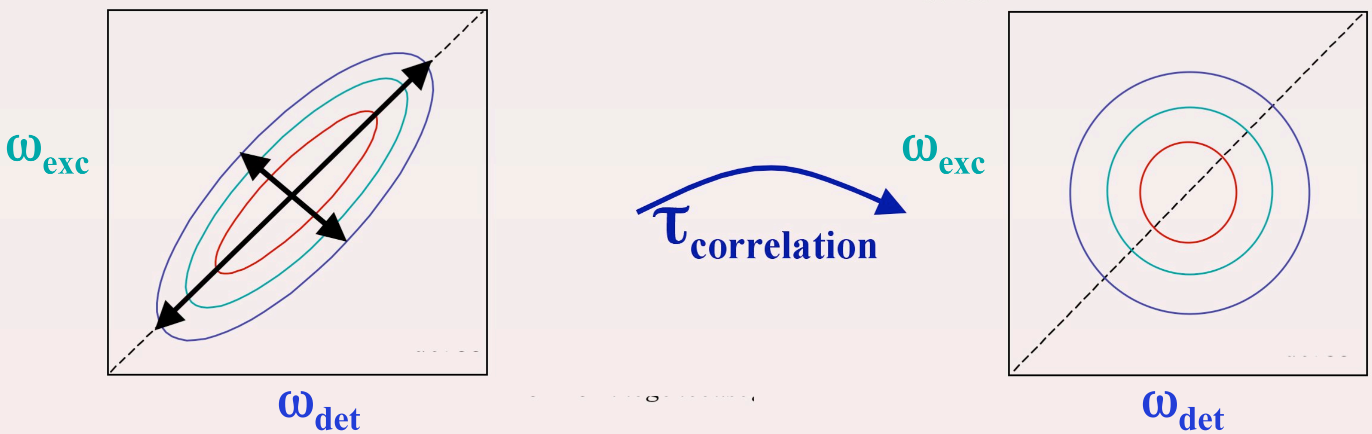
Method:	apply ω_{exc} $\longrightarrow$ detect ω_{det}

shape of the 2D spectrum

inhomogeneous

$\Gamma_{\text{inhomogeneous}} >> \Gamma_{\text{homogeneous}}$

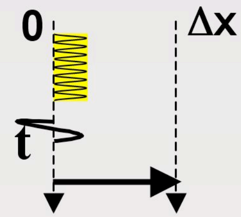
homogeneous

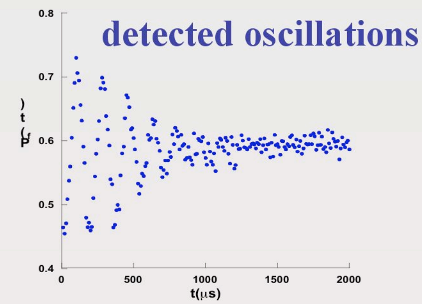


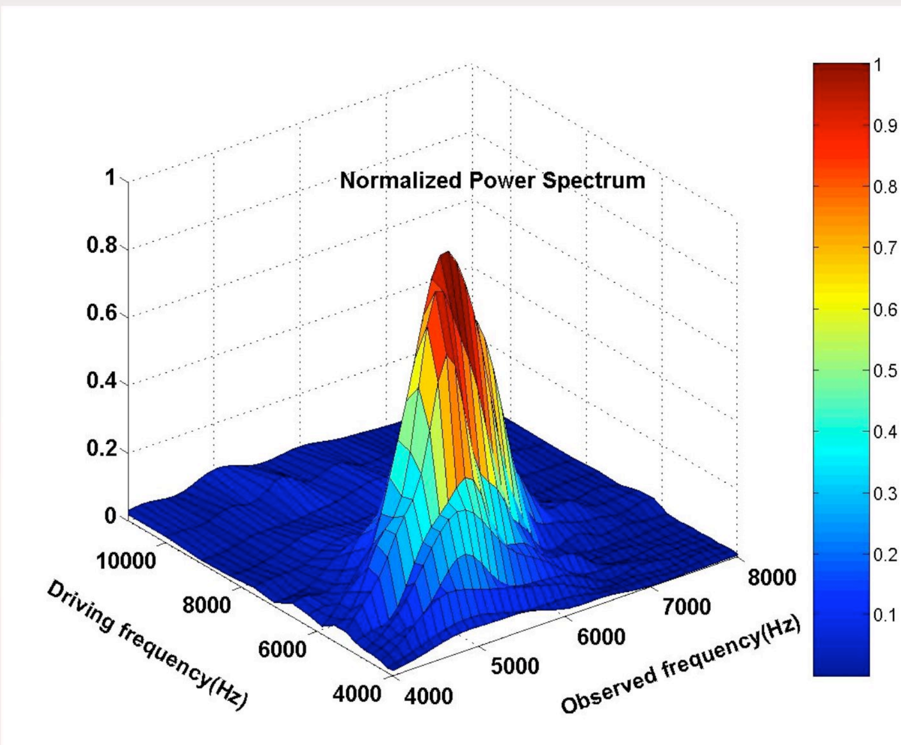
2D Spectrum of Modulation (in progress)

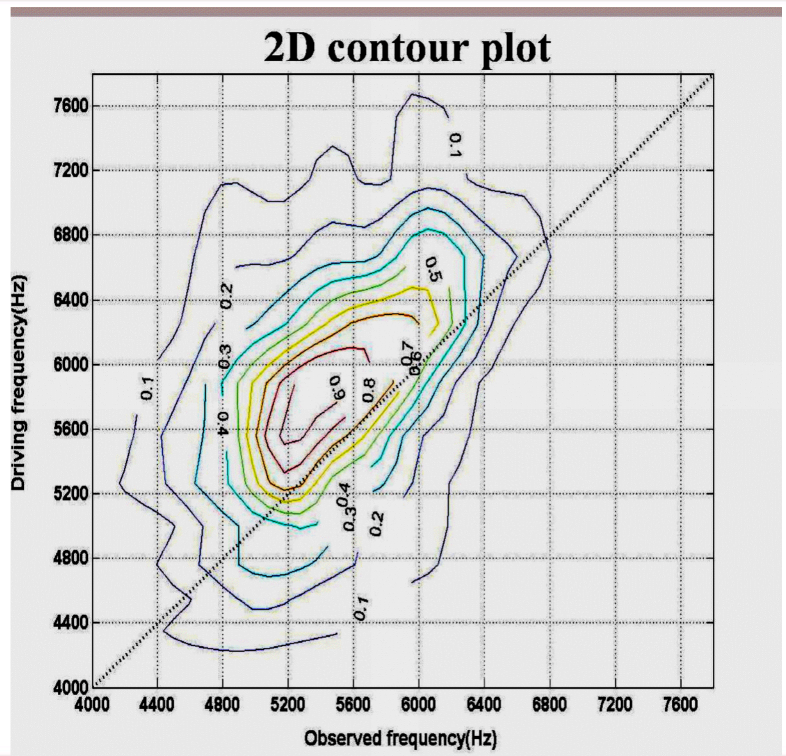
shaking the lattice at different frequencies by phase modulating one lattice beam

- **modulation periods:**
- **modulating for 8 cycles**
- **amplitude of modulation:**
- **detected oscillations are Fourier transformed and the 2D spectrum is obtained.**



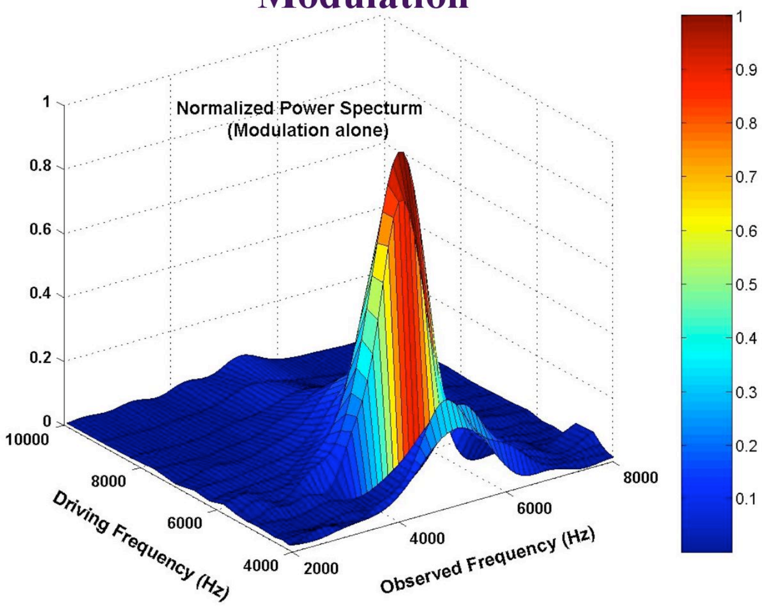




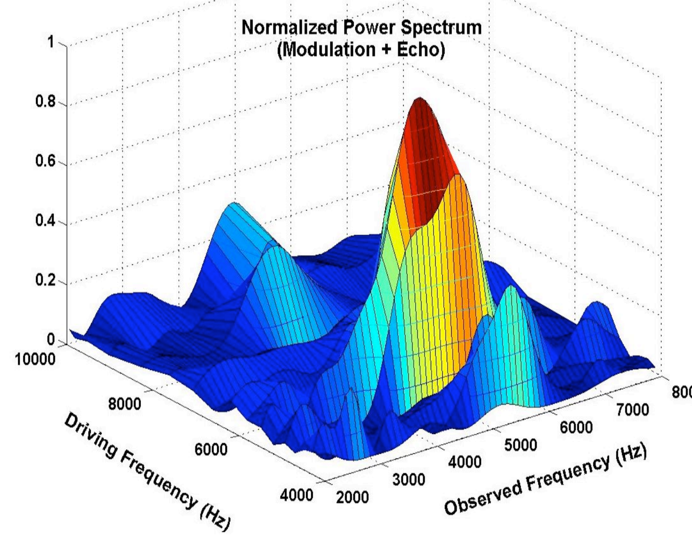


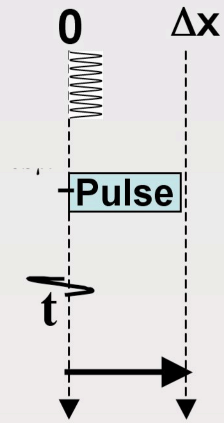
Preliminary data on 2D Spectroscopy of Echo (in progress)

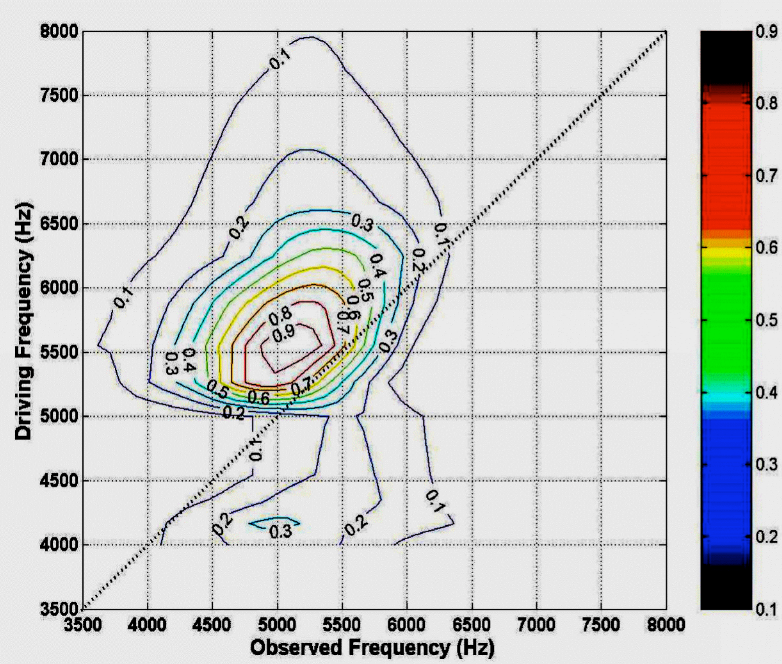
Modulation

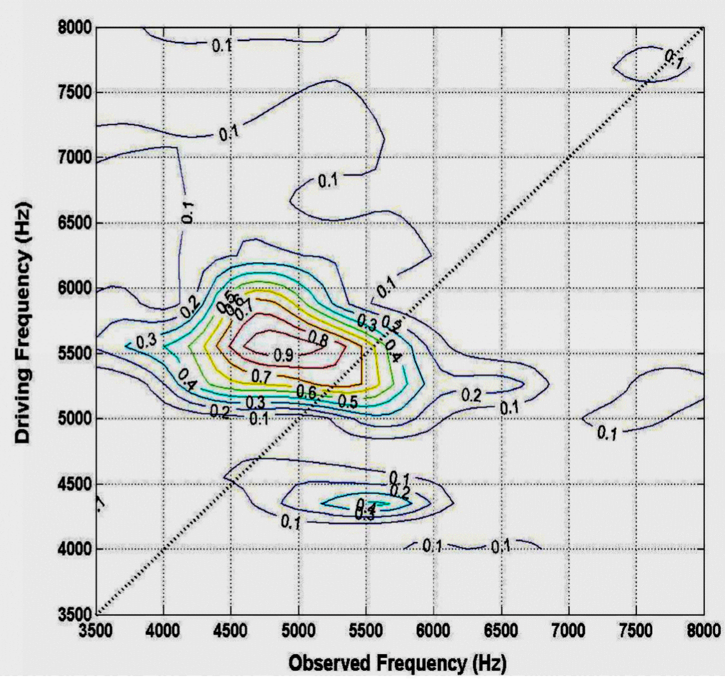


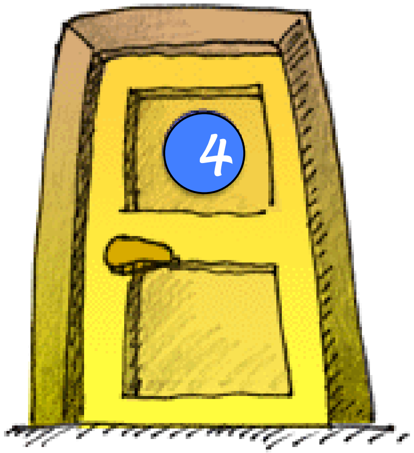
Modulation + Echo square pulse





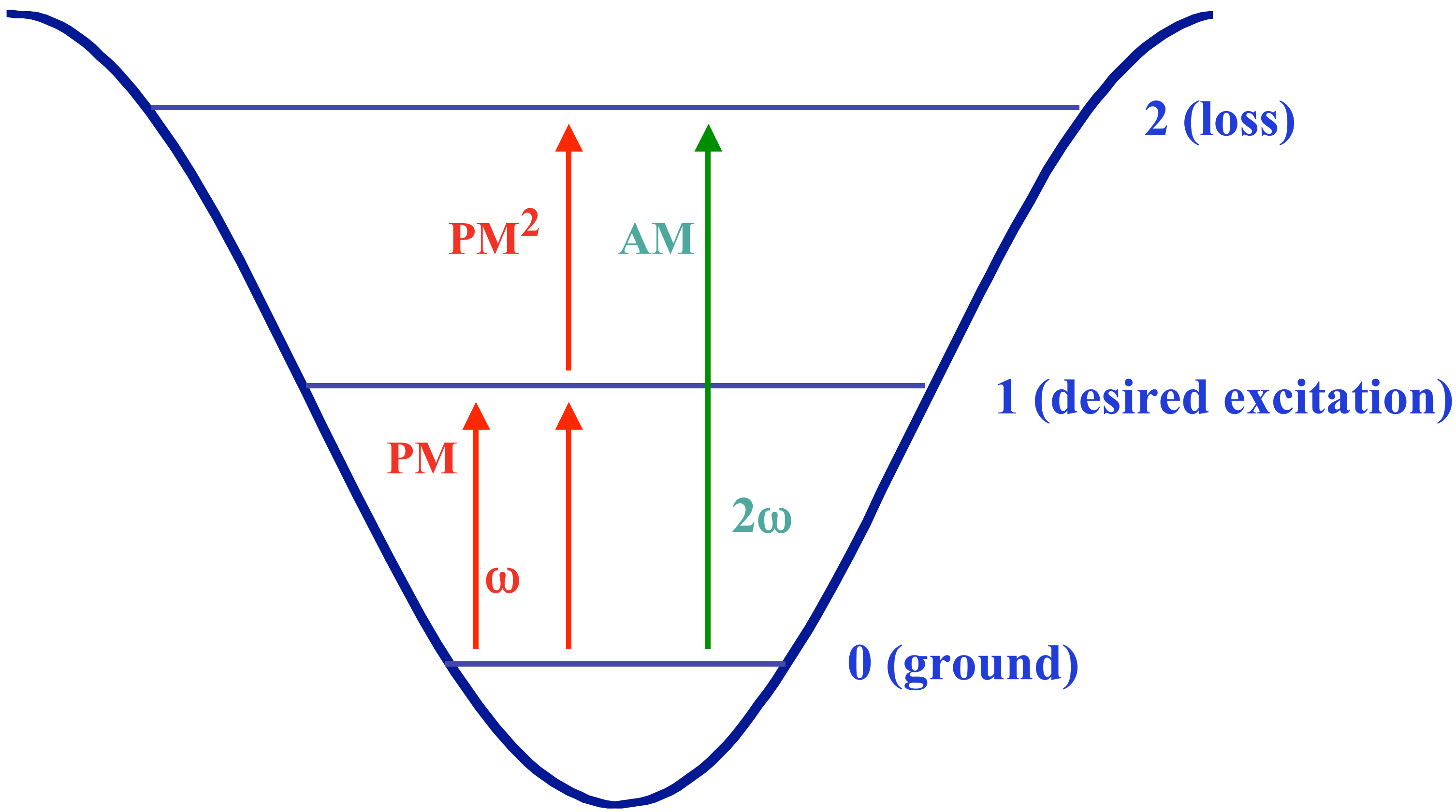






And finally, towards coherent control

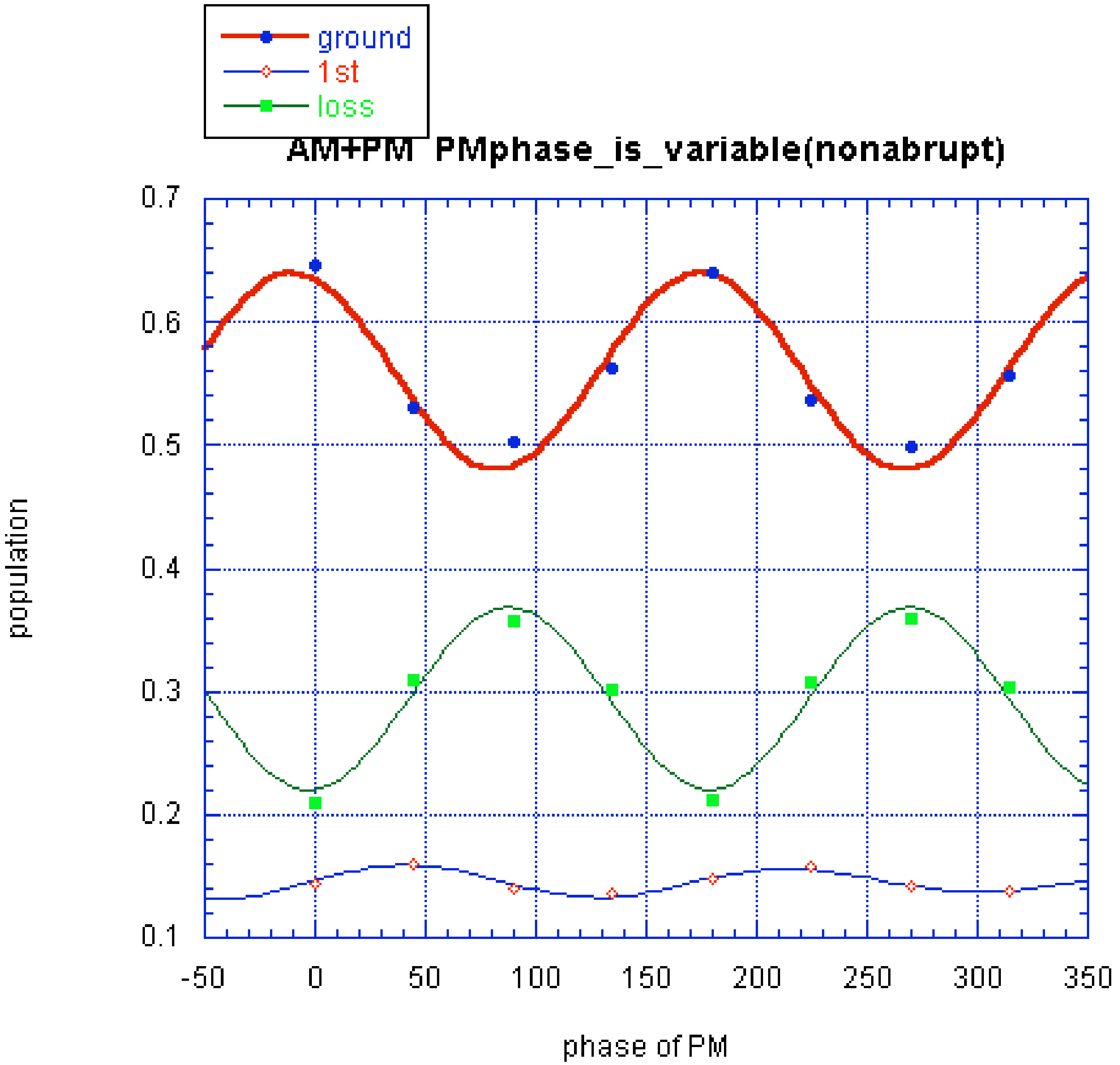
One scheme for reducing leakage?



May expect loss ∝ cos (ϕ_{AM} - 2ϕ_{PM} - *some phase*)

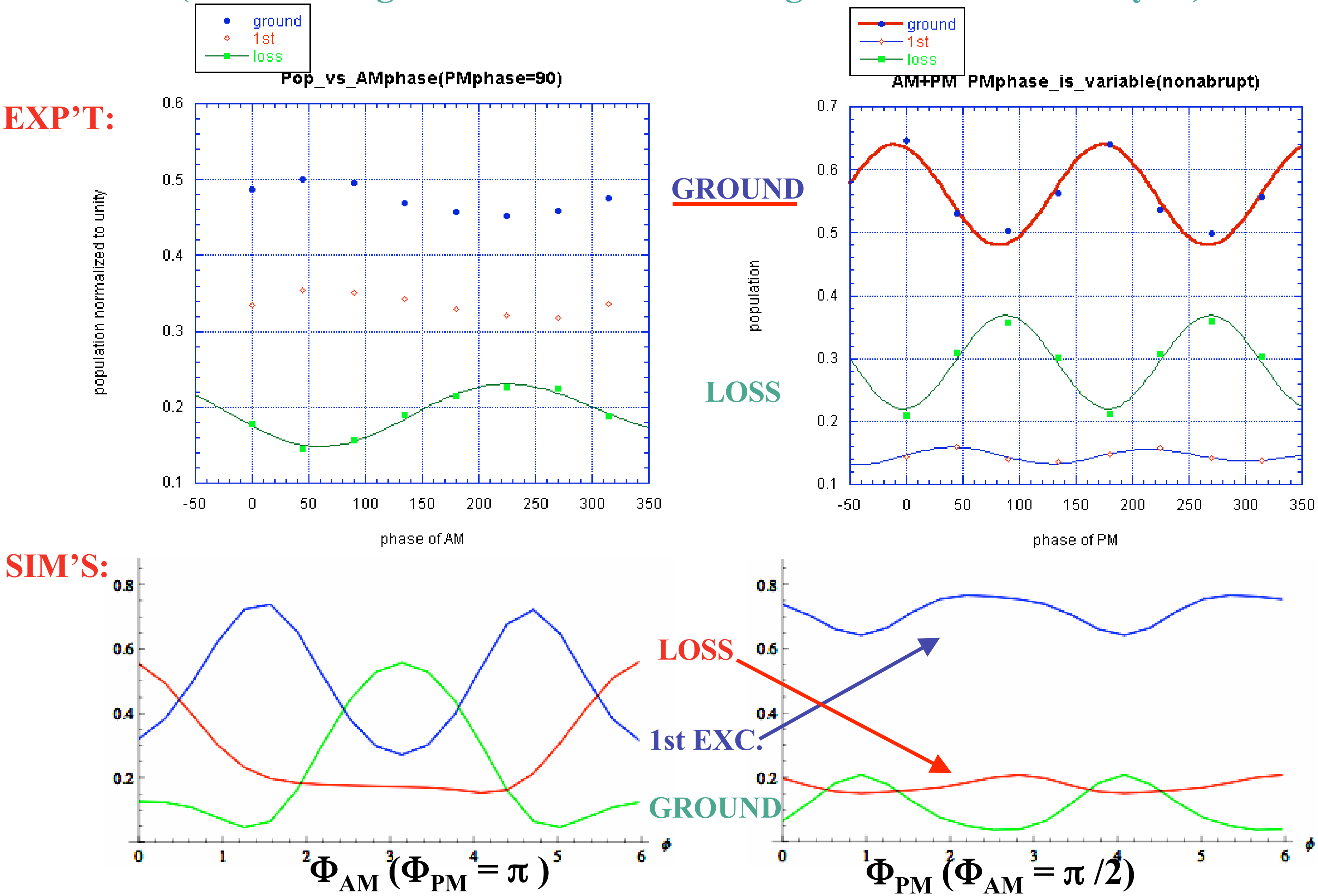
Classical explanation as "sideband engineering," or something more?

Preliminary evidence for 1+2 coherent control

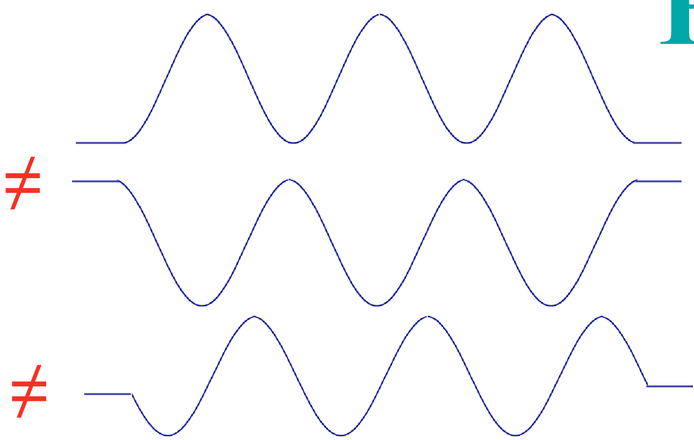


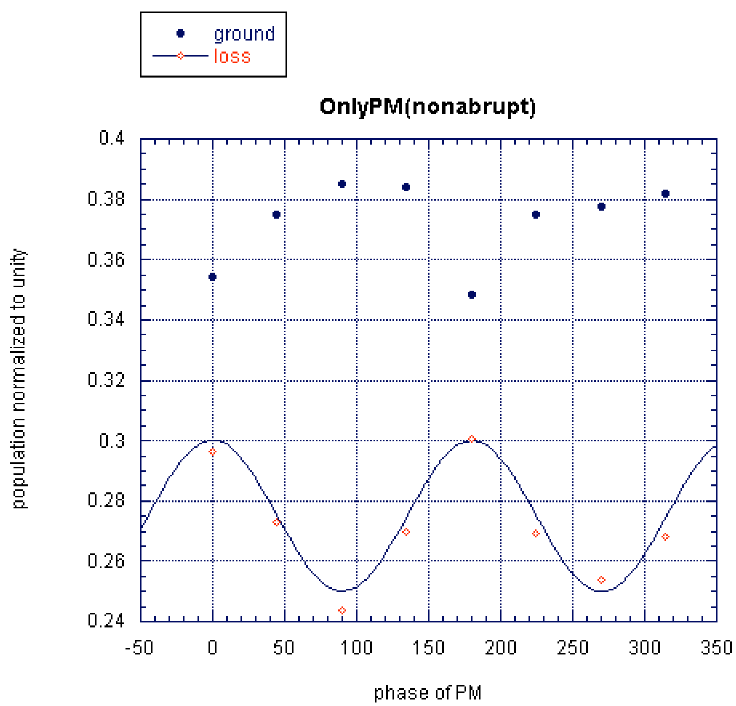
More preliminary data

(recent enough that we haven't even agreed on conventions yet!)

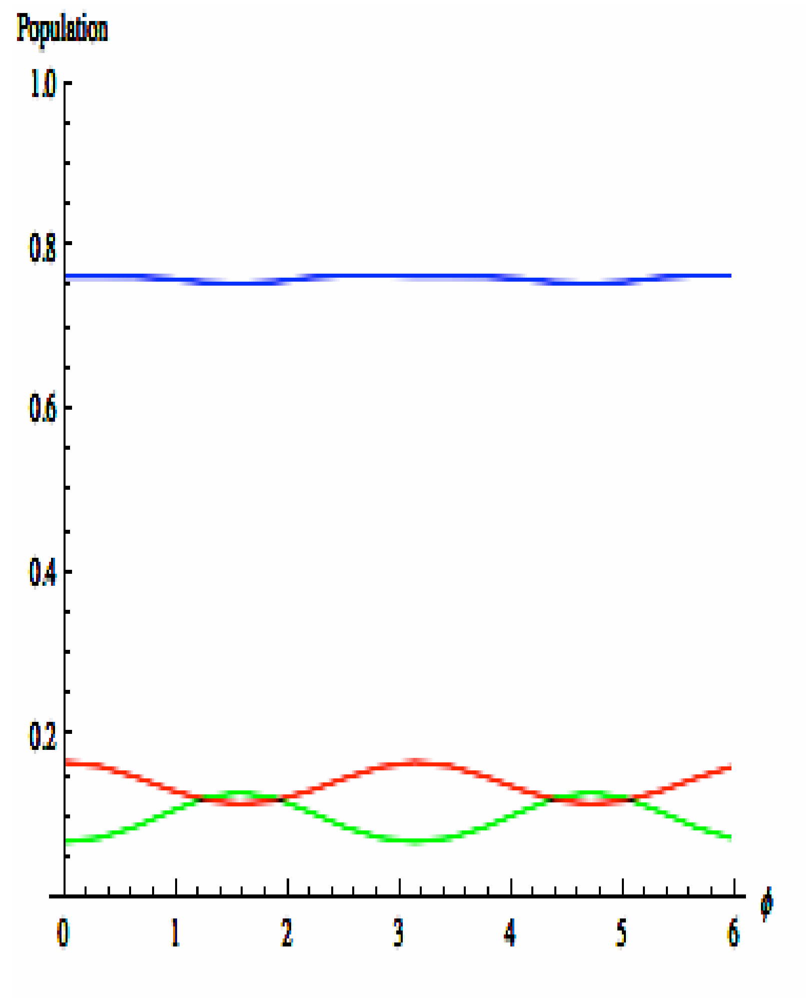


Spurious phase-dependence of PM alone



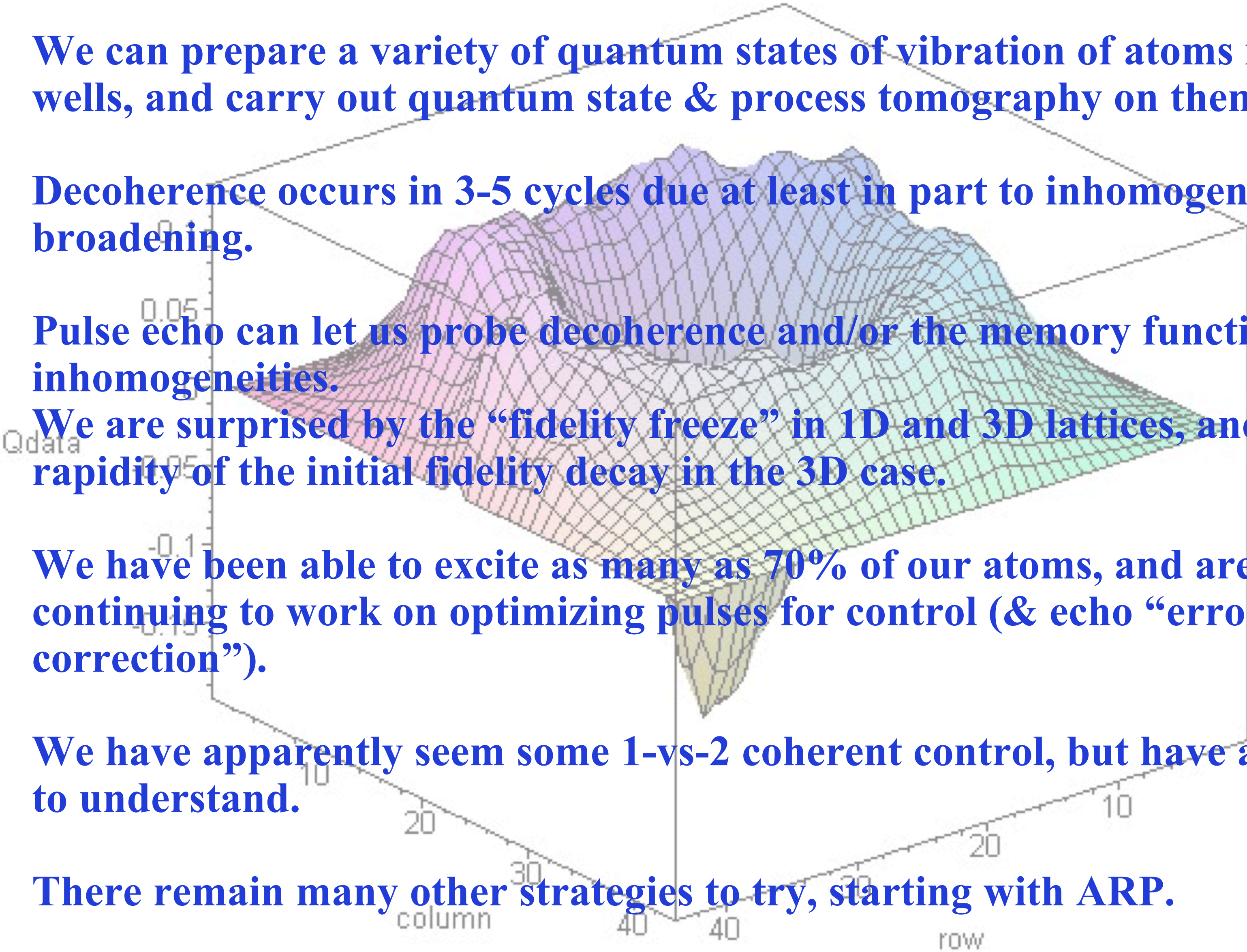


Experiment



Theory

Summary



1 We can prepare a variety of quantum states of vibration of atoms in lattice wells, and carry out quantum state & process tomography on them.

2 Decoherence occurs in 3-5 cycles due at least in part to inhomogeneous broadening.

3 Pulse echo can let us probe decoherence and/or the memory function of the inhomogeneities.
We are surprised by the "fidelity freeze" in 1D and 3D lattices, and by the rapidity of the initial fidelity decay in the 3D case.

4 We have been able to excite as many as 70% of our atoms, and are continuing to work on optimizing pulses for control (& echo "error correction").

5 We have apparently seem some 1-vs-2 coherent control, but have a lot more to understand.

6 There remain many other strategies to try, starting with ARP.