Quantum Coherence, Control, & Distinguishability in Experiments with Atoms and Photons

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DRAMATIS PERSONÆ

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QC

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

Lynden(Krister) Shalm Jeff Lundeen (→Oxford)

Xingxing Xing

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

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

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Some helpful theorists:

Pete Turner, Michael Spanner, Howard Wiseman, János Bergou, Masoud Mohseni, John Sipe, Paul Brumer

PHOTONICS RESEARCH ONTARIO

DARPA

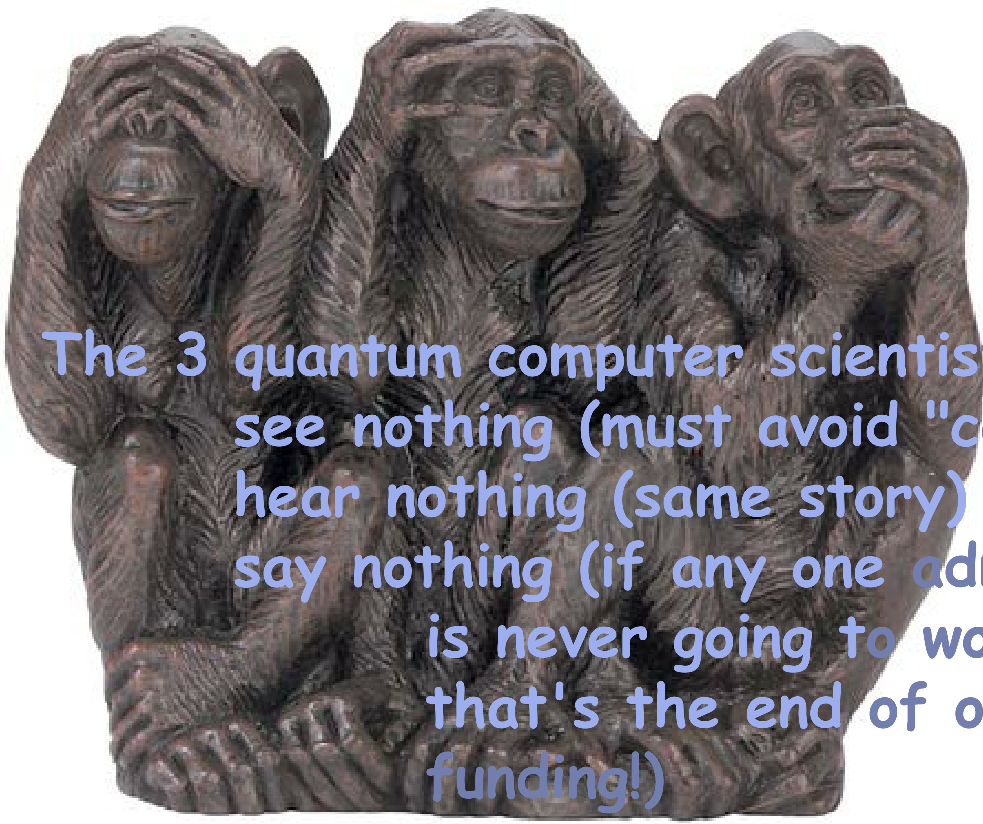
25 years cifar
Canadian Institute for Advanced Research

NSERC CRSNG

ICIP CIPI

Canada Foundation for Innovation

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

- Postselective generation of N-photon entangled states

Something we didn't anticipate [complicated plots]

- Subtleties of *measuring* multi-photon states

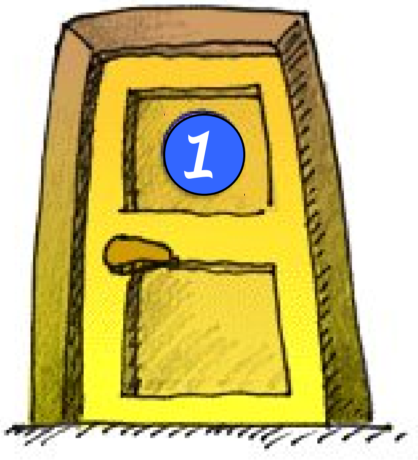
Pretty pictures in case I've already lost you

- Triphoton tomography on the Poincaré sphere

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

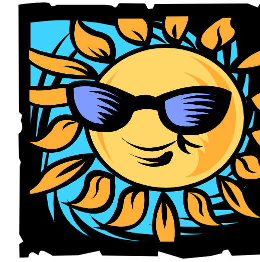
- Pulse echoes in an optical lattice
- Towards quasimomentum-independent coupling

Summary



Building up entanglement photon by photon by using post-selective nonlinearity

Highly number-entangled states ("3003" experiment).

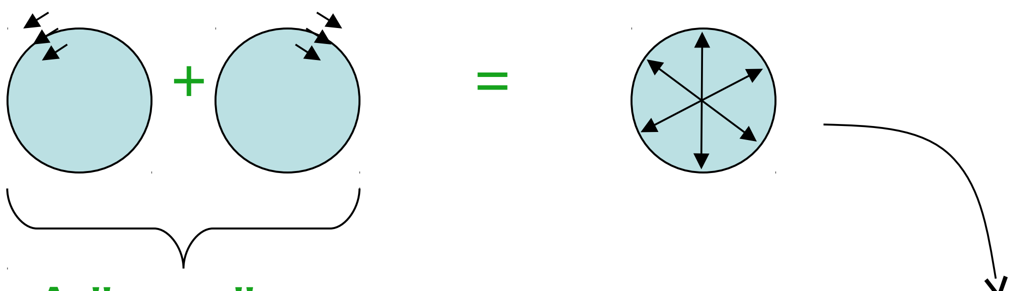


M.W. Mitchell *et al.*, Nature **429**, 161 (2004)

States such as |n,0> + |0,n> ("noon" states) have been proposed for high-resolution interferometry – related to "spin-squeezed" states.

Important factorisation:

$$\left(a^{\dagger 3} + b^{\dagger 3}\right) = \left(a^{\dagger} + b^{\dagger}\right)\left(a^{\dagger} + e^{2\pi i/3} b^{\dagger}\right)\left(a^{\dagger} + e^{-2\pi i/3} b^{\dagger}\right)$$

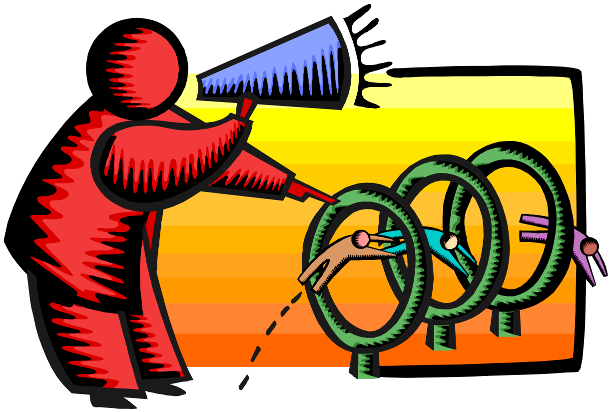


A "noon" state

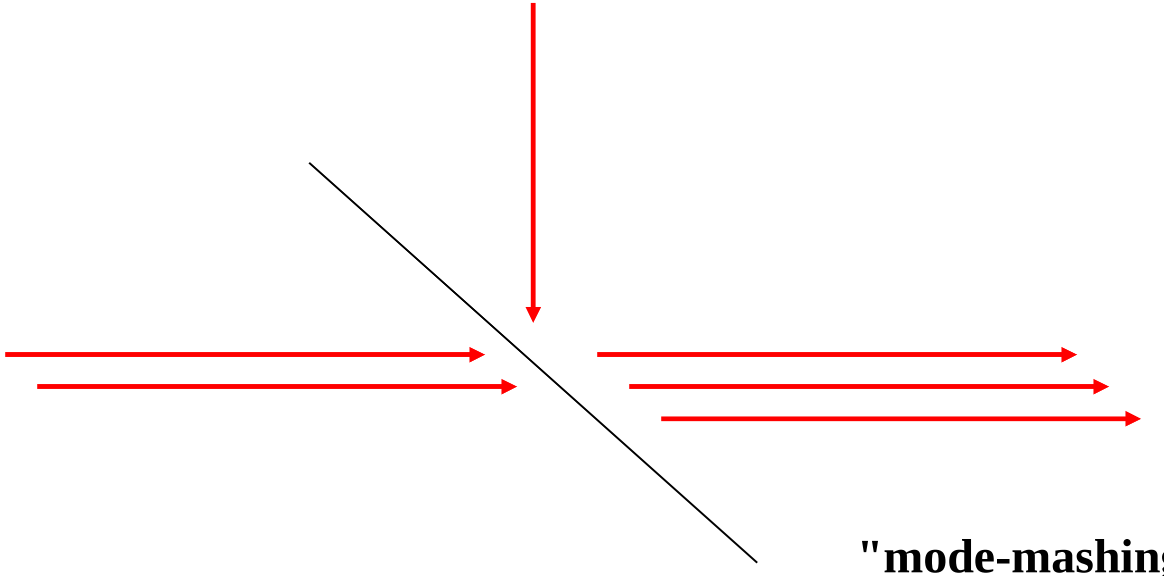
A really odd beast: one 0^{o} photon, one 120^{o} photon, and one 240^{o} photon... but of course, you can't tell them apart, let alone combine them into one mode!

Theory: H. Lee *et al.*, Phys. Rev. A 65, 030101 (2002); J. Fiurásek, Phys. Rev. A 65, 053818 (2002)

Making 3 photons jump through hoops



How to combine three non-orthogonal photons into one spatial mode?



"mode-mashing"

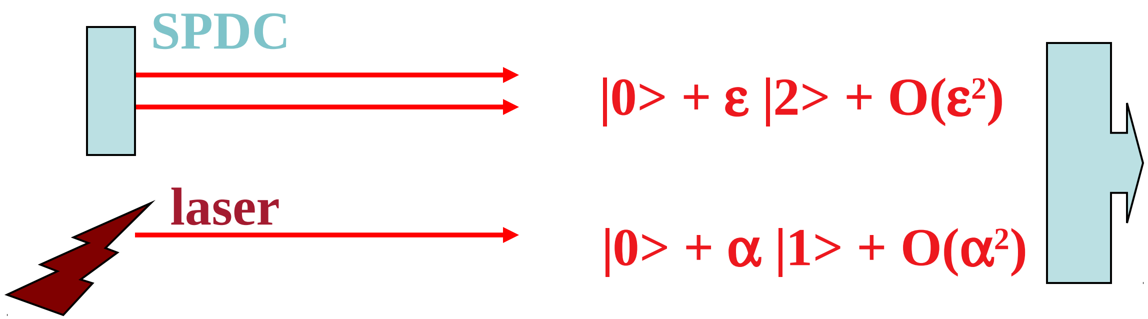
Yes, it's that easy! If you see three photons out one port, then they all went out that port.

Post-selective nonlinearity

Making 3 photons in the first place

Okay, we don't even have single-photon sources*.

But we can produce *pairs* of photons in down-conversion, and very *weak* coherent states from a laser, such that *if* we detect three photons, we can be pretty sure we got only one from the laser and only two from the down-conversion...



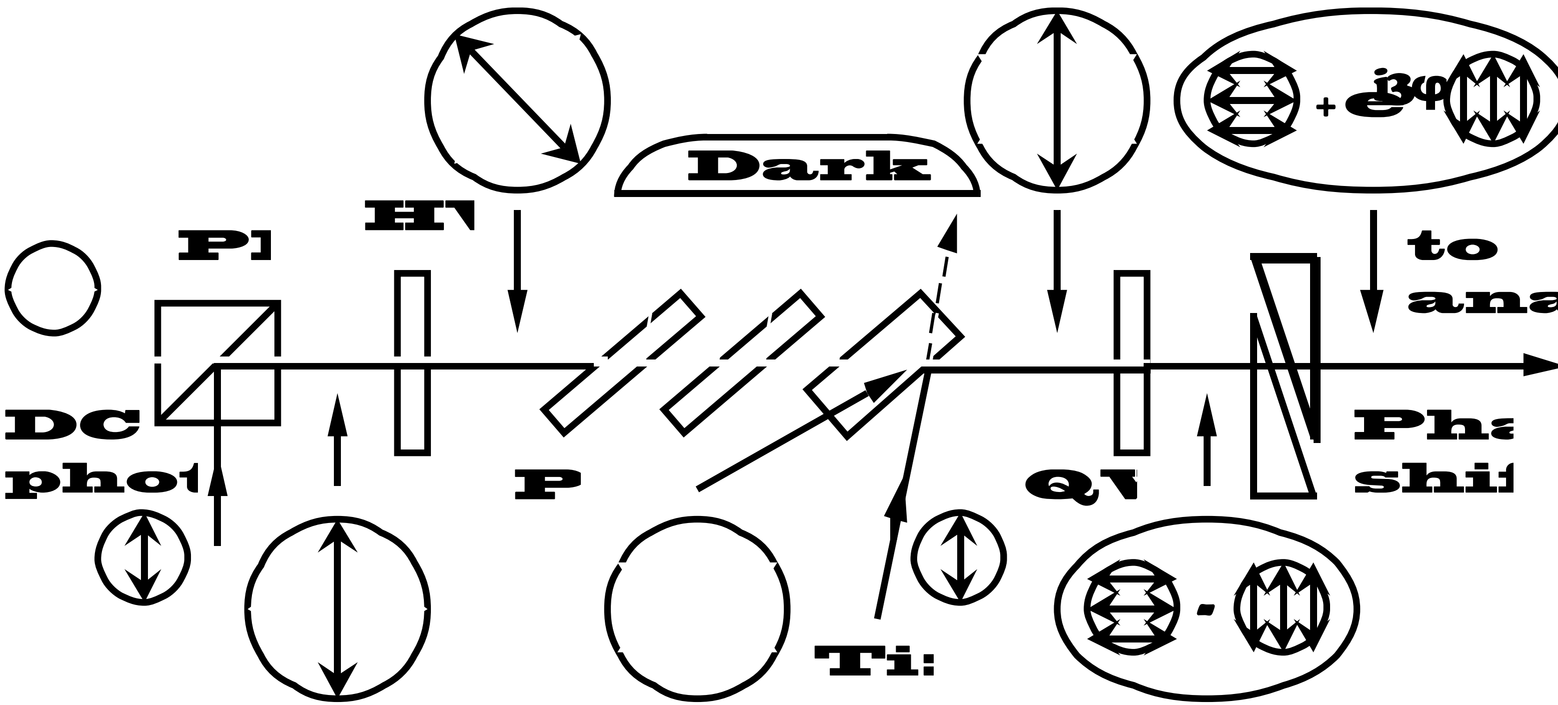
$|0\rangle + \varepsilon\, |2\rangle + O(\varepsilon^2)$

$|0\rangle + \alpha\, |1\rangle + O(\alpha^2)$

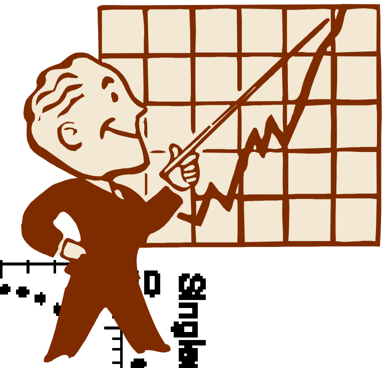
$\varepsilon\alpha\, |3\rangle + O(\alpha^3) + O(\varepsilon^2)$
$+$ terms with <3 photons

*But we're working on it (collab. with Rich Mirin's quantum-dot group at NIST; also next-generation experiment using triggered down-conversion)

The basic optical scheme



It works!

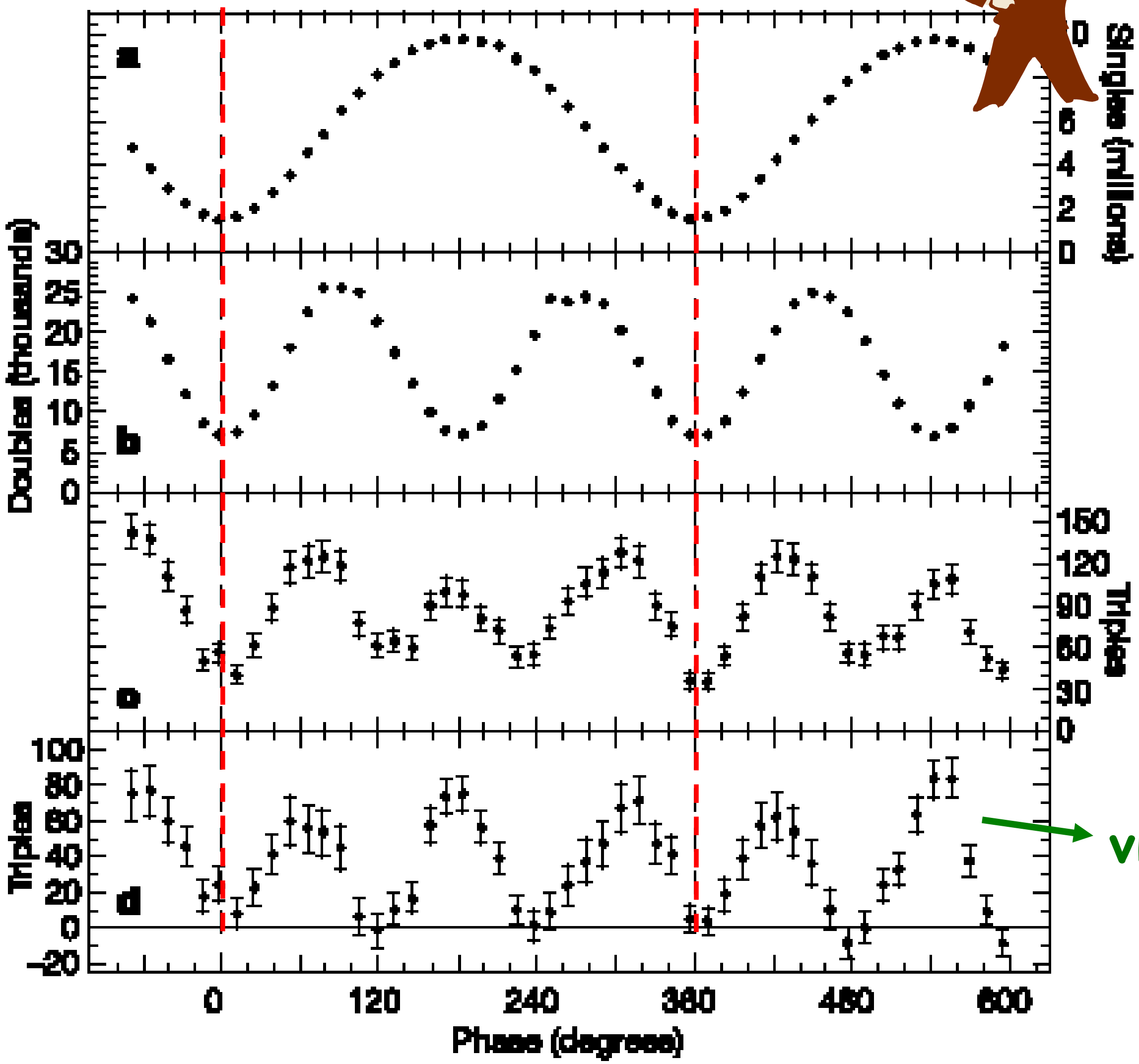


Singles:

Coincidences:

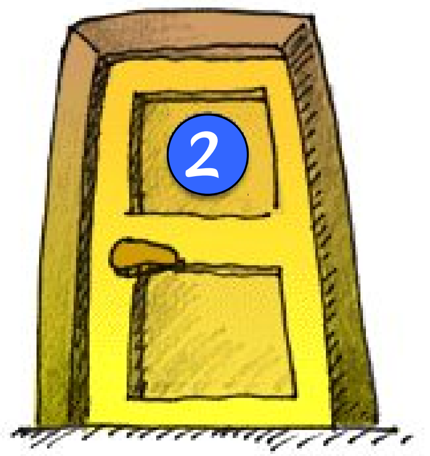
Triple coincidences:

Triples (bg subtracted):



vis > 100% !

M.W. Mitchell, J.S. Lundeen, and A.M. Steinberg, Nature 429, 161 (2004)



Complete characterisation
when you have incomplete information

Fundamentally Indistinguishable vs. Experimentally Indistinguishable

But what if when we combine our photons, there is some residual distinguishing information: some (fs) time difference, some small spectral difference, some chirp, ...?

This will clearly degrade the state – but how do we characterize this if all we can measure is polarisation?

Quantum State Tomography

Indistinguishable Photon Hilbert Space

$$\{|2_H,0_V\rangle,|1_H,1_V\rangle,|0_H,2_V\rangle\}$$

$$\{|HH\rangle,|HV\rangle+|VH\rangle,|VV\rangle\}$$

?

Distinguishable Photon Hilbert Space

$$\{|H_1H_2\rangle,|V_1H_2\rangle,|H_1V_2\rangle,|V_1V_2\rangle\}$$

Yu. I. Bogdanov, et al
Phys. Rev. Lett. 93, 230503 (2004)

If we're not sure whether or not the particles are distinguishable, do we work in 3-dimensional or 4-dimensional Hilbert space?

If the latter, can we make all the necessary measurements, given that we don't know how to tell the particles apart ?

The Partial Density Matrix

The answer: there are only 10 linearly independent parameters which are invariant under permutations of the particles. One example:

$$\begin{pmatrix} \begin{pmatrix} \rho_{HH,HH} & \rho_{HV+VH,HH} & \rho_{VV,HH} \\ \rho_{HH,HV+VH} & \rho_{HV+VH,HV+VH} & \rho_{VV,HV+VH} \\ \rho_{HH,VV} & \rho_{HV+VH,VV} & \rho_{VV,VV} \end{pmatrix} & \begin{matrix} \text{Inaccessible} \\ \text{information} \end{matrix} \\ \begin{matrix} \text{Inaccessible} \\ \text{information} \end{matrix} & \left(\rho_{HV-VH,HV-VH}\right) \end{pmatrix}$$

The sections of the density matrix labelled “inaccessible” correspond to information about the ordering of photons with respect to inaccessible degrees of freedom.

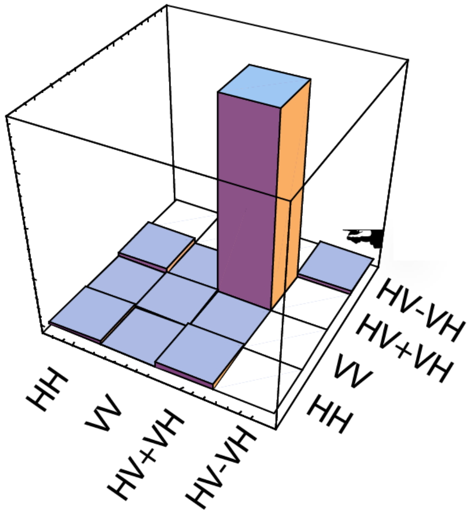
For n photons, the # of parameters scales as n^3, rather than 4^n
Note: for 3 photons, there are 4 extra parameters – one more than just the 3 pairwise HOM visibilities.

Experimental Results

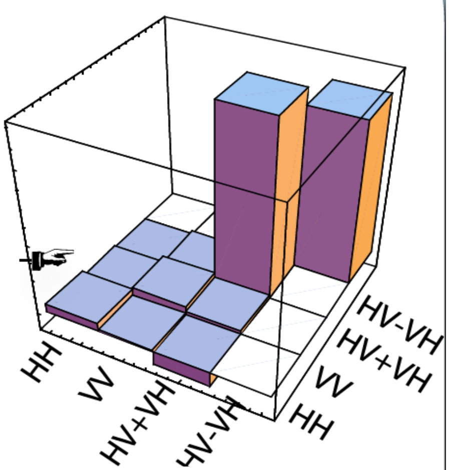
R.B.A. Adamson, L.K. Shalm, M.W. Mitchell, AMS, PRL 98, 043601 (2007)

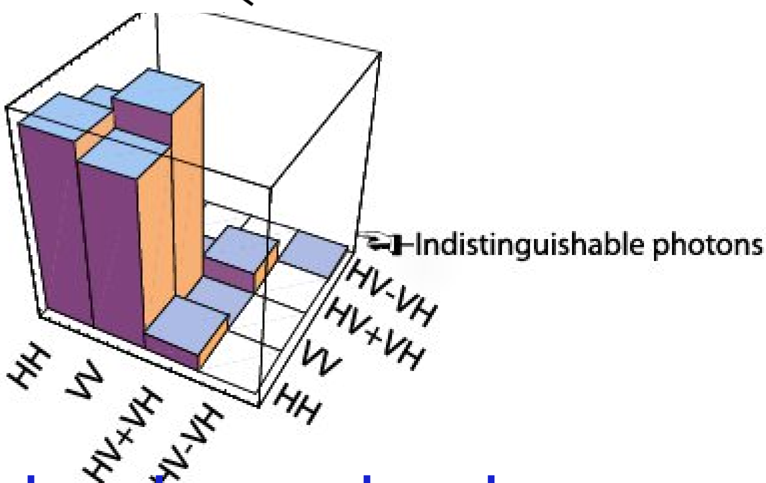
No Distinguishing Info

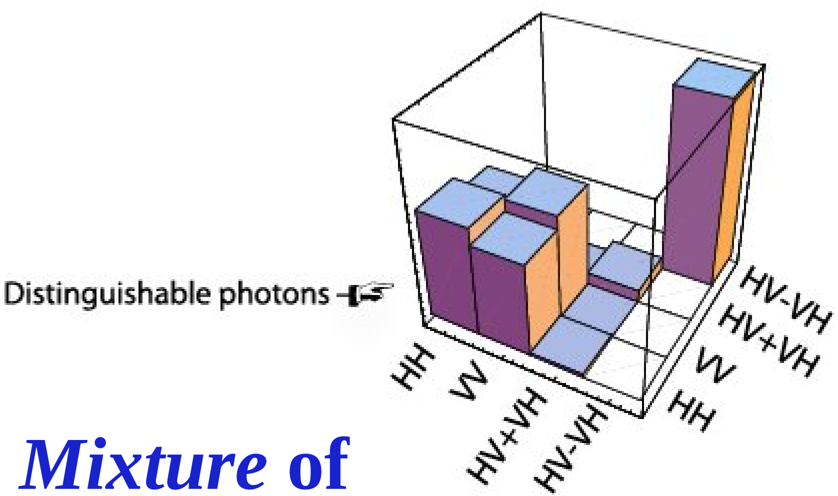
Distinguishing Info



When distinguishing information is introduced the HV-VH component increases without affecting the state in the symmetric space





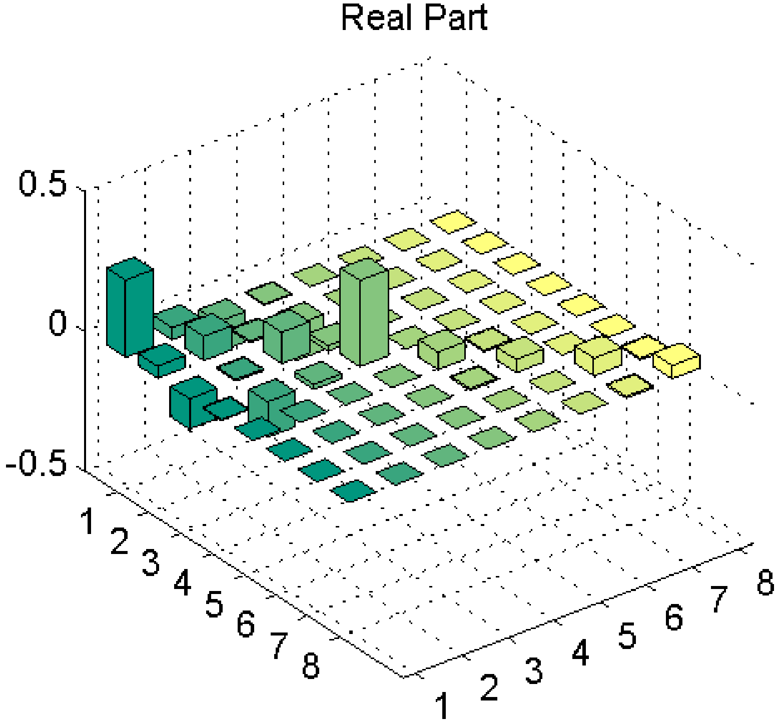


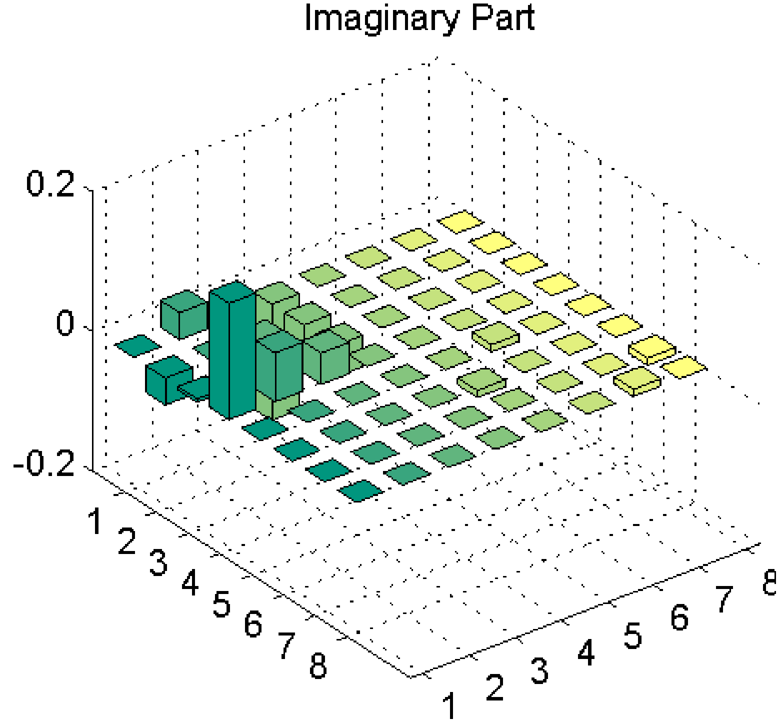
$|H\rangle|H\rangle + |V\rangle|V\rangle$

***Mixture* of**
$|45\rangle|-45\rangle$ **and** $|-45\rangle|45\rangle$

Hot off the presses (well, actually, not on them yet):

Density matrix of the triphoton

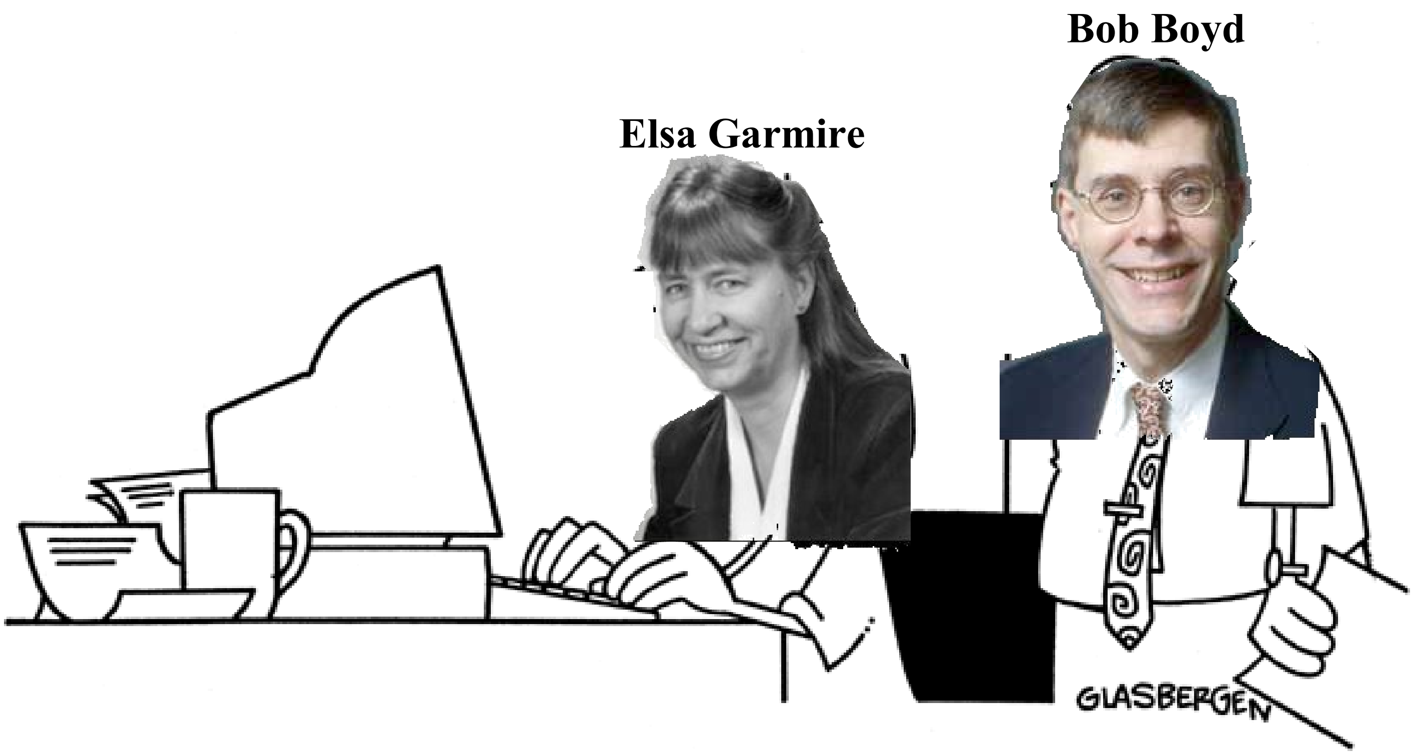




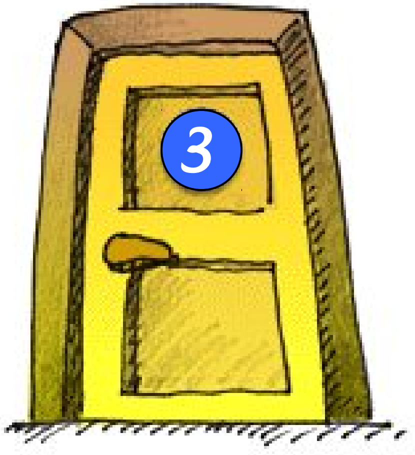
(80% of population in symmetric subspace)

Extension to n-particle systems: R.B.A. Adamson, P.S. Turner, M.W. Mitchell, AMS, quant-ph/0612081

Words of Wisdom from Alice (almost) and Bob



"We don't need to worry about information security or message encryption. Most of our communications are impossible to understand in the first place."



A better description than density matrices?

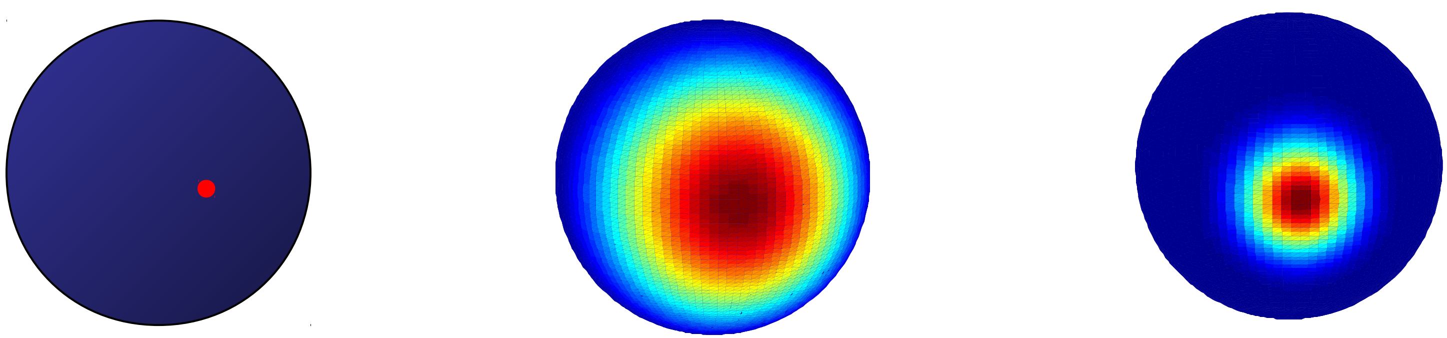
Wigner distributions on the Poincaré sphere ?

(Consider a purely symmetric state: N photons act like a single spin-N/2)

Any pure state of a spin-1/2 (or a photon) can be represented as a point on the surface of the sphere – it is parametrized by a single amplitude and a single relative phase.

This is the same as the description of a classical spin, or the polarisation (Stokes parameters) of a classical light field.

Of course, only one basis yields a definite result, so a better description would be some "uncertainty blob" about that classical point... for spin-1/2, this uncertainty covers a hemisphere, while for higher spin it shrinks.

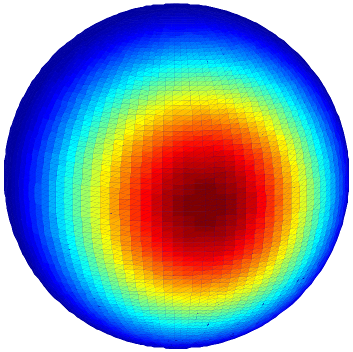


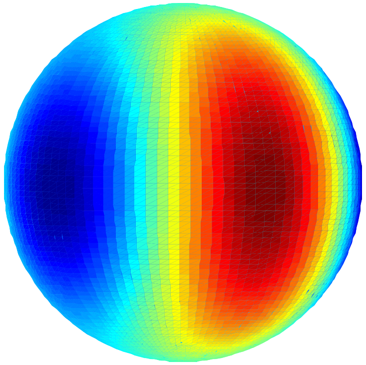
Wigner distributions on the Poincaré sphere

[Following recipe of Dowling, Agarwal, & Schleich, PRA 49, 4101 (1993).]
{and cf. R.L. Stratonovich, JETP 31, 1012 (1956), I'm told}

Can such quasi-probability distributions over the "classical" polarisation states provide more helpful descriptions of the "state of the triphoton" than density matrices?

"Coherent state" = N identically polarized photons





"Spin-squeezed state" trades off uncertainty in H/V projection for more precision in phase angle.

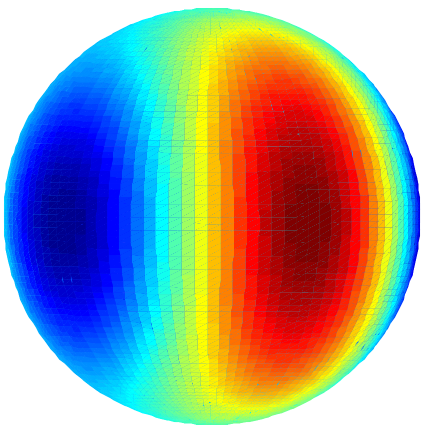
Please to note: *there is nothing* inside *the sphere!*

Pure & mixed states are simply different *distributions* on the surface, as with W(x,p).

Beyond 1 or 2 photons...

A 1-photon pure state may be represented by a *point* on the surface of the Poincaré sphere, because there are only 2 real parameters.

squeezed state



2 photons:

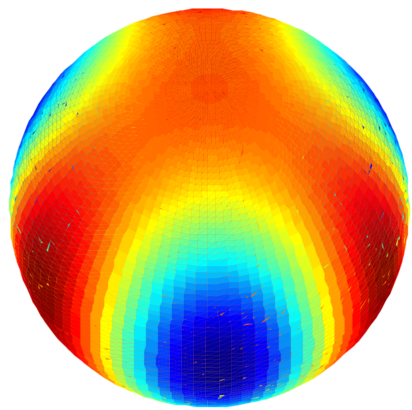
4 param's:

Euler angles

+ squeezing (eccentricity)

+ orientation

3-noon



3 photons:

6 parameters:

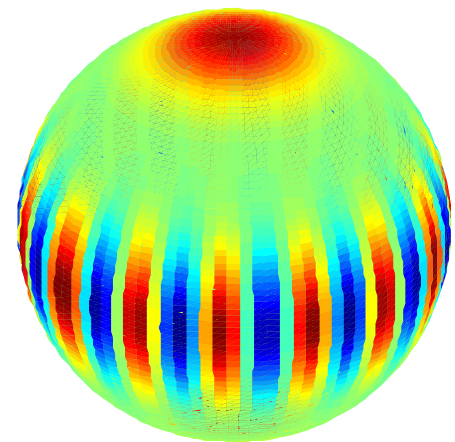
Euler angles

+ squeezing (eccentricity)

+ orientation

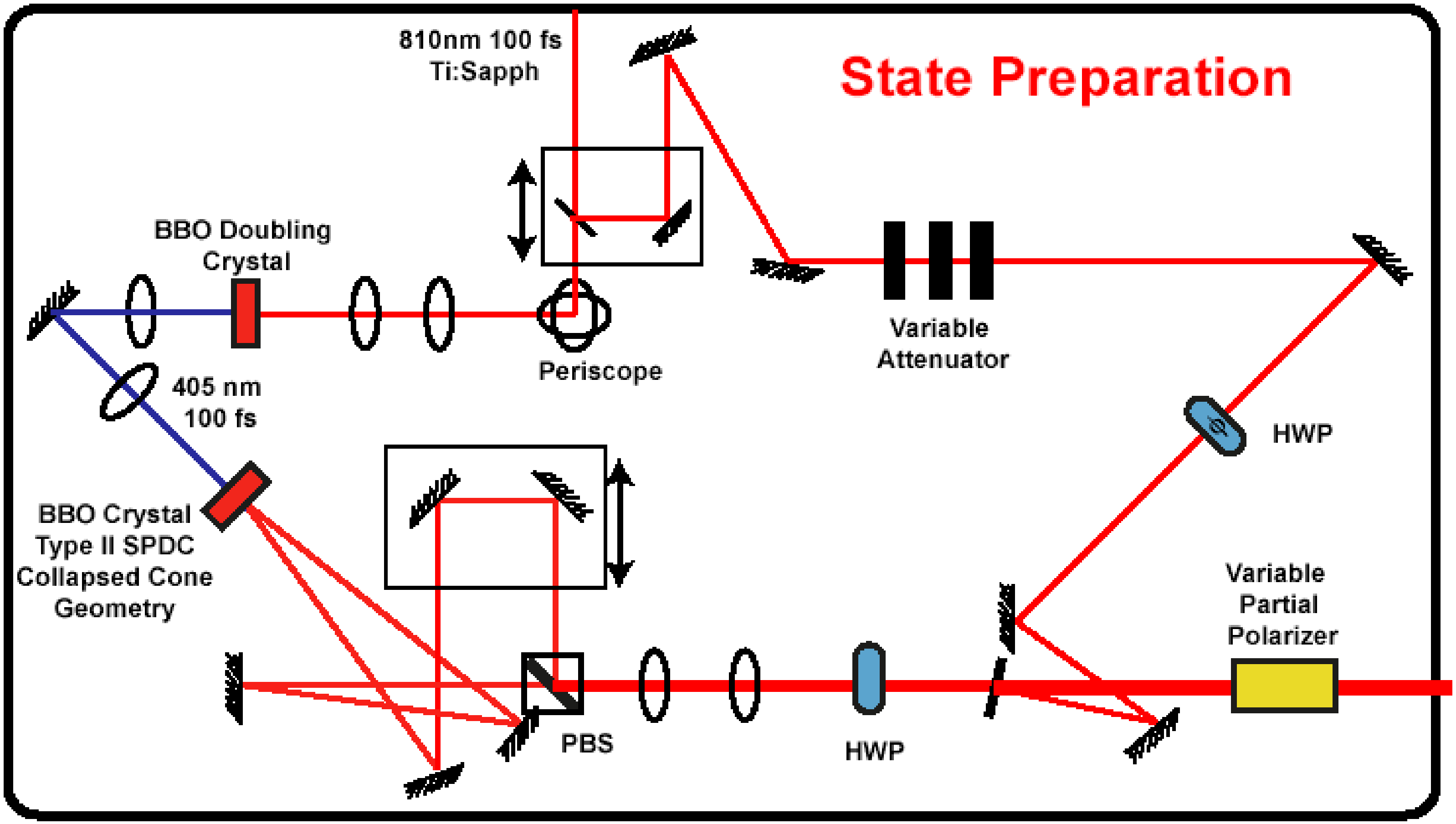
+ more complicated stuff

15-noon

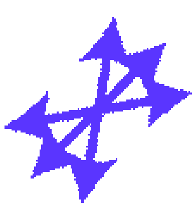


QuickTime™ and a
YUV420 codec decomp
are needed to see this pi

Making more triphoton states...



E.g.,

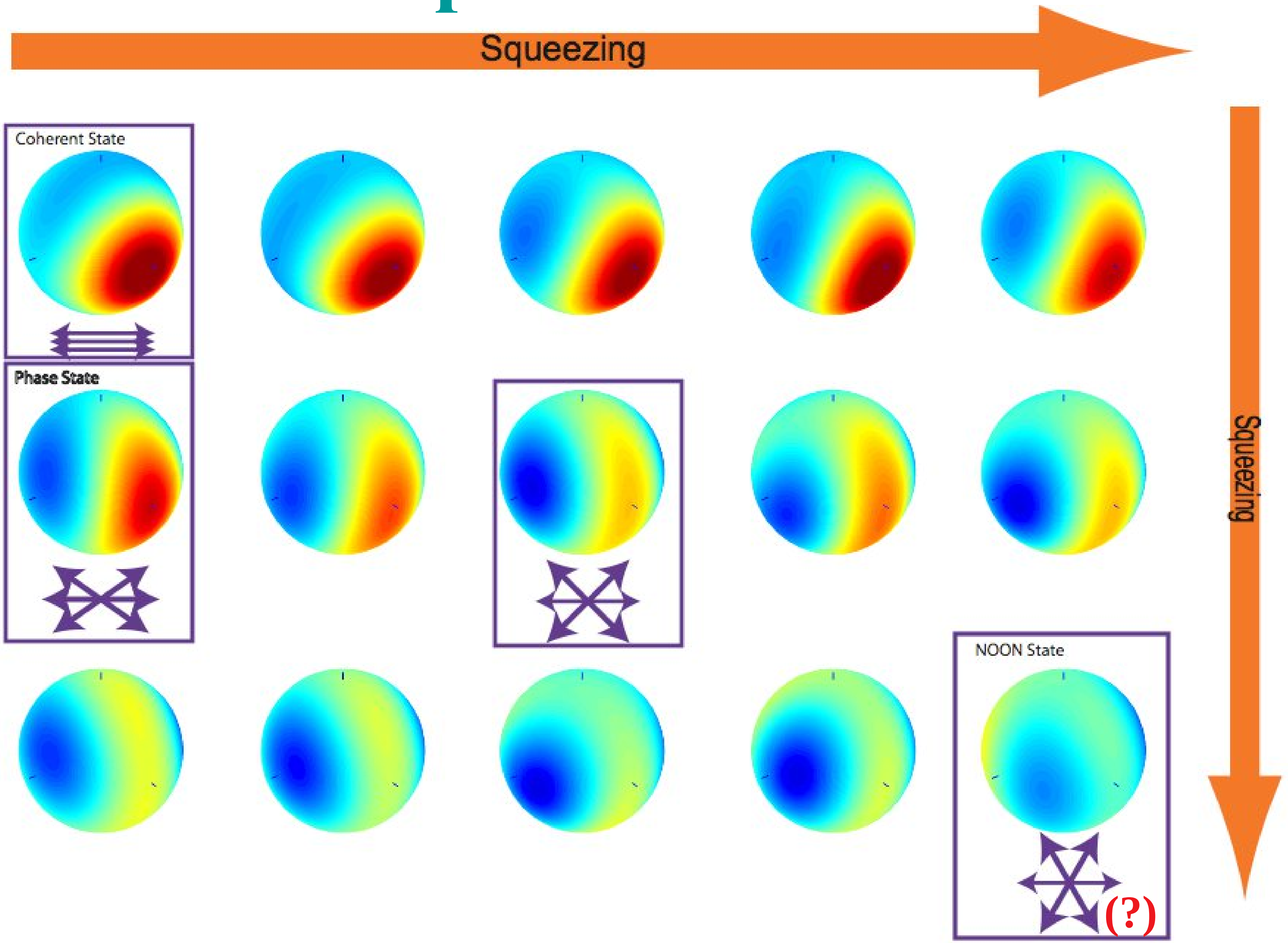


$HV(H+V) \quad = (R + iL)\,(L + iR)\,(R+iL+L+iR)$

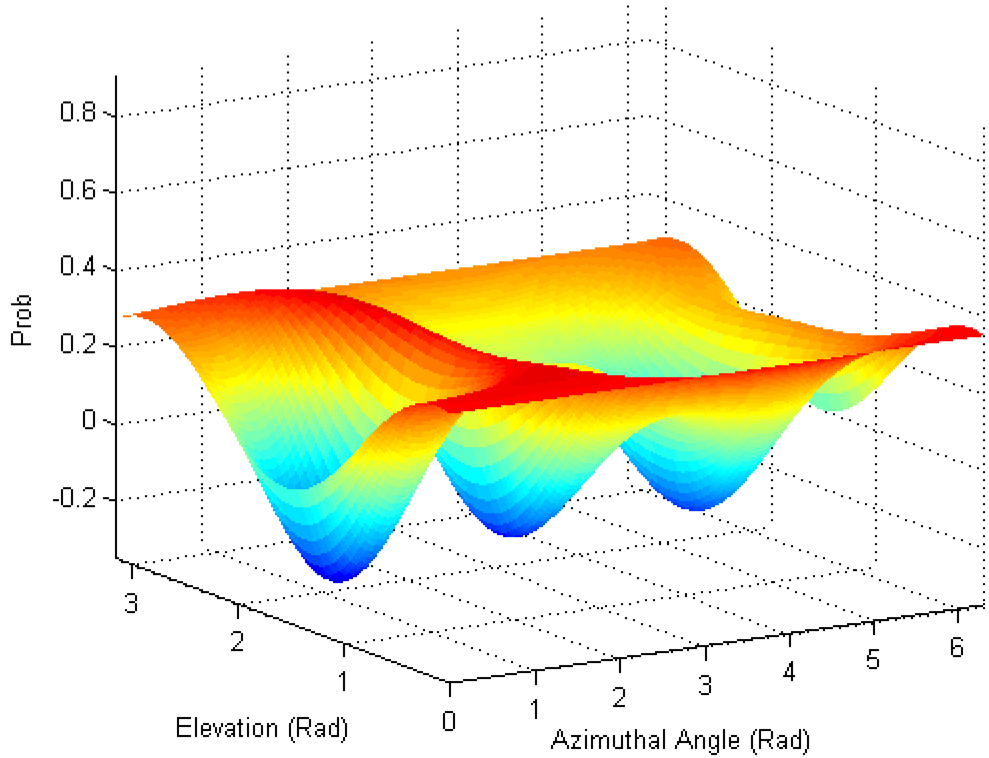
$\propto R^2+L^2\,(R+L) = \qquad R^3 + R^2L + RL^2 + L^3$

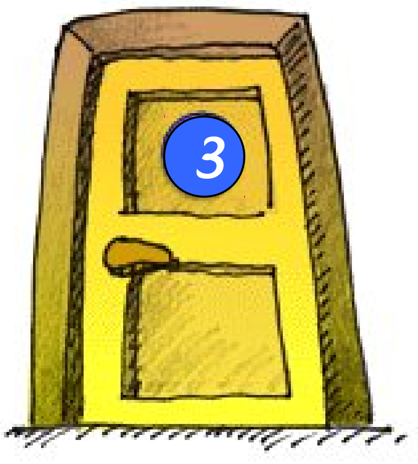
In HV basis, $H^2V + HV^2$ looks “number-squeezed”; in RL basis, phase-squeezed.

The Triphoton on the rack



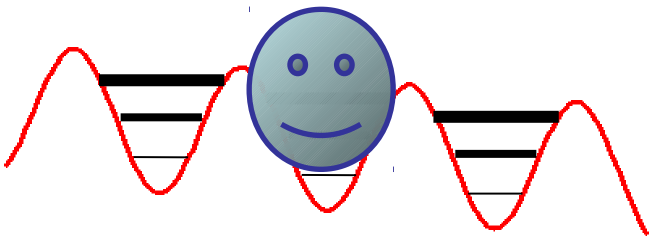
Another perspective on the problem





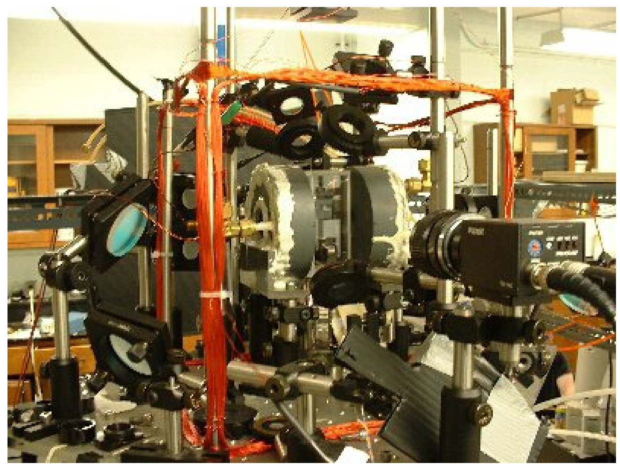
Quantum CAT scans

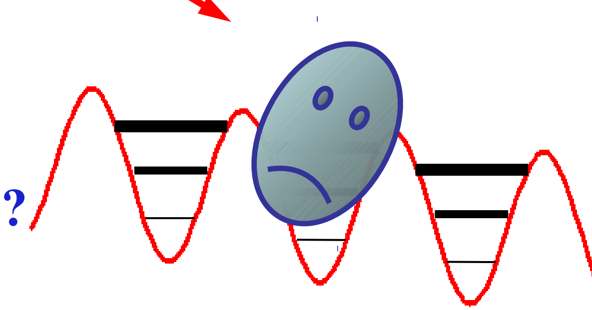
Tomography & control in Lattices



[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)





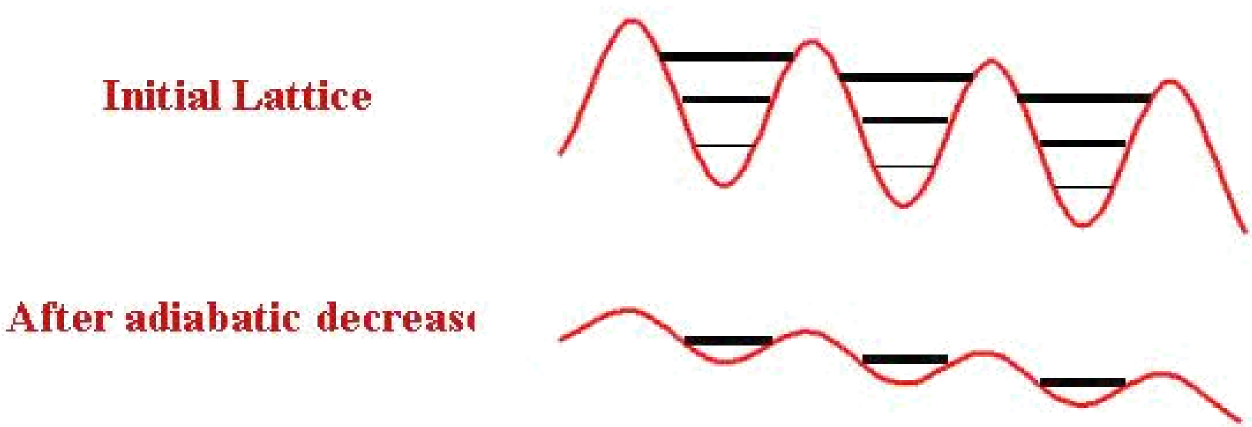
Goals:
How to fully characterize time-evolution due to lattice?
How to correct for "errors" (preserve coherence,...)?
How to convince the NSA that this is important for building quantum computers?

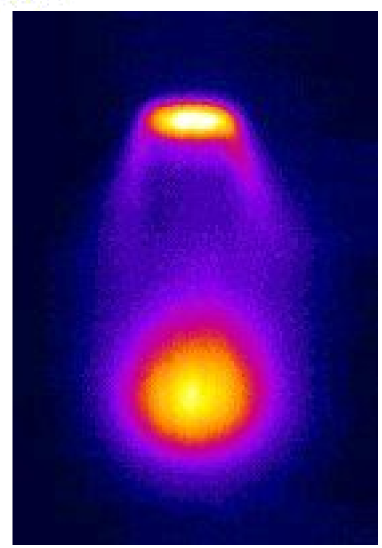
The workhorse: measuring state populations

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

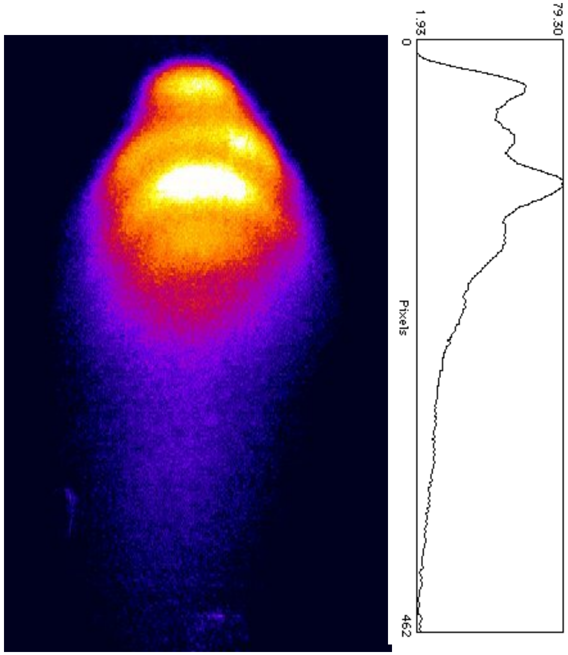
Two Methods : - Ramp down and hold. Observe population as a function of depth.

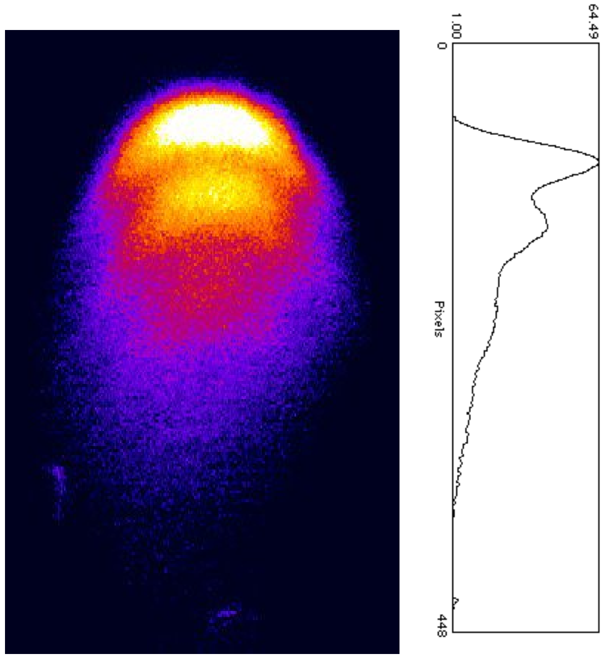
OR - Ramp down very slowly and observe different states leave at distinct times.





Time-resolved quantum states



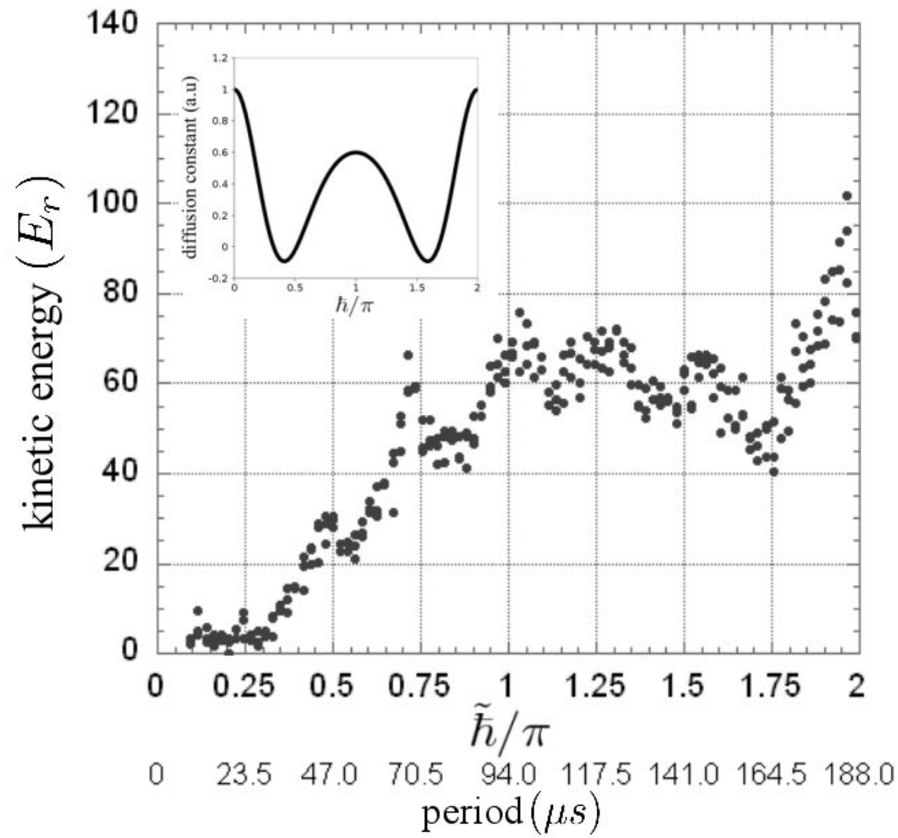


Some fun results

Negative Wigner function for inverted population (70% of atoms in vibrationally excited state of lattice well)

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

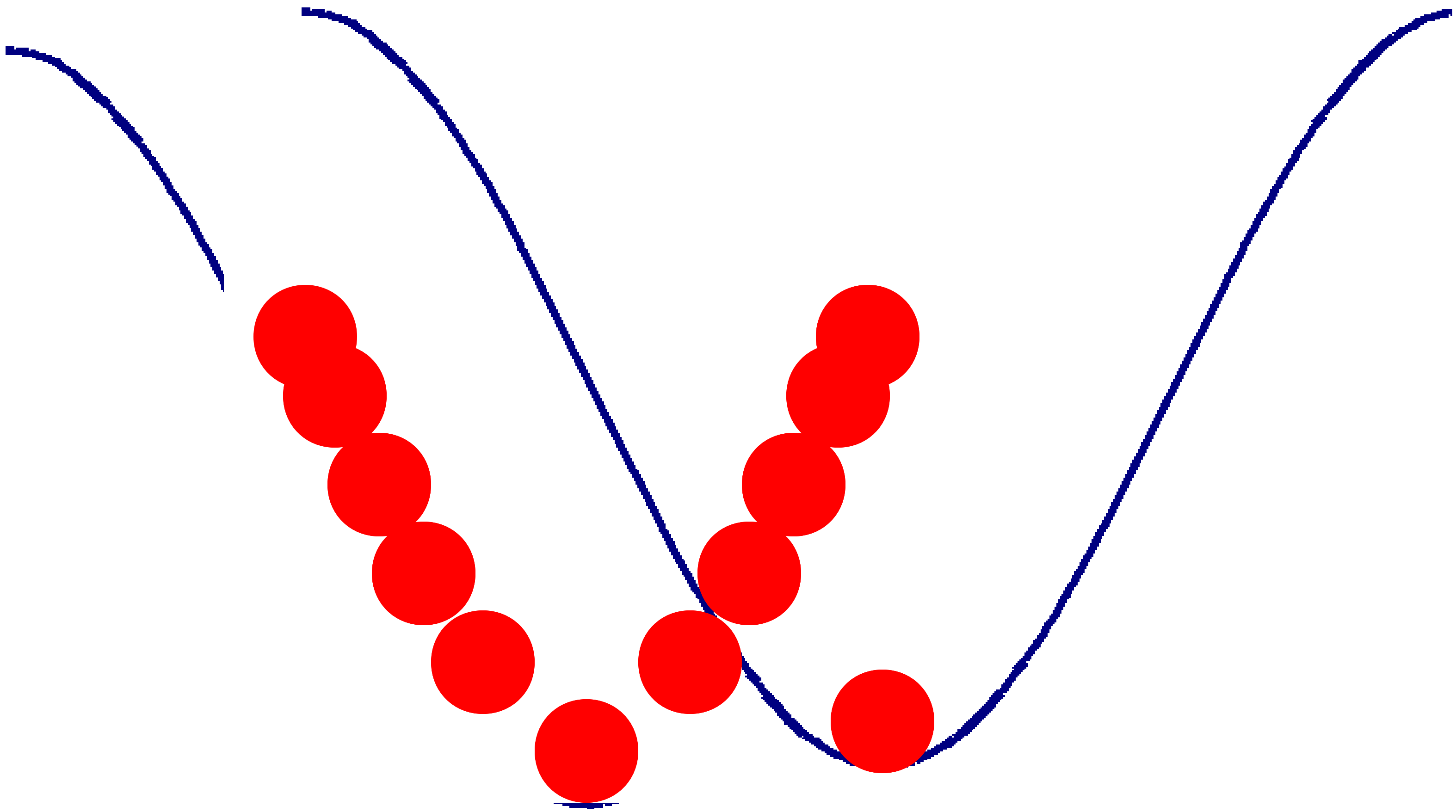
Fractional wavepacket revivals in a delta-kicked rotor experiment (fractional quantum resonances)



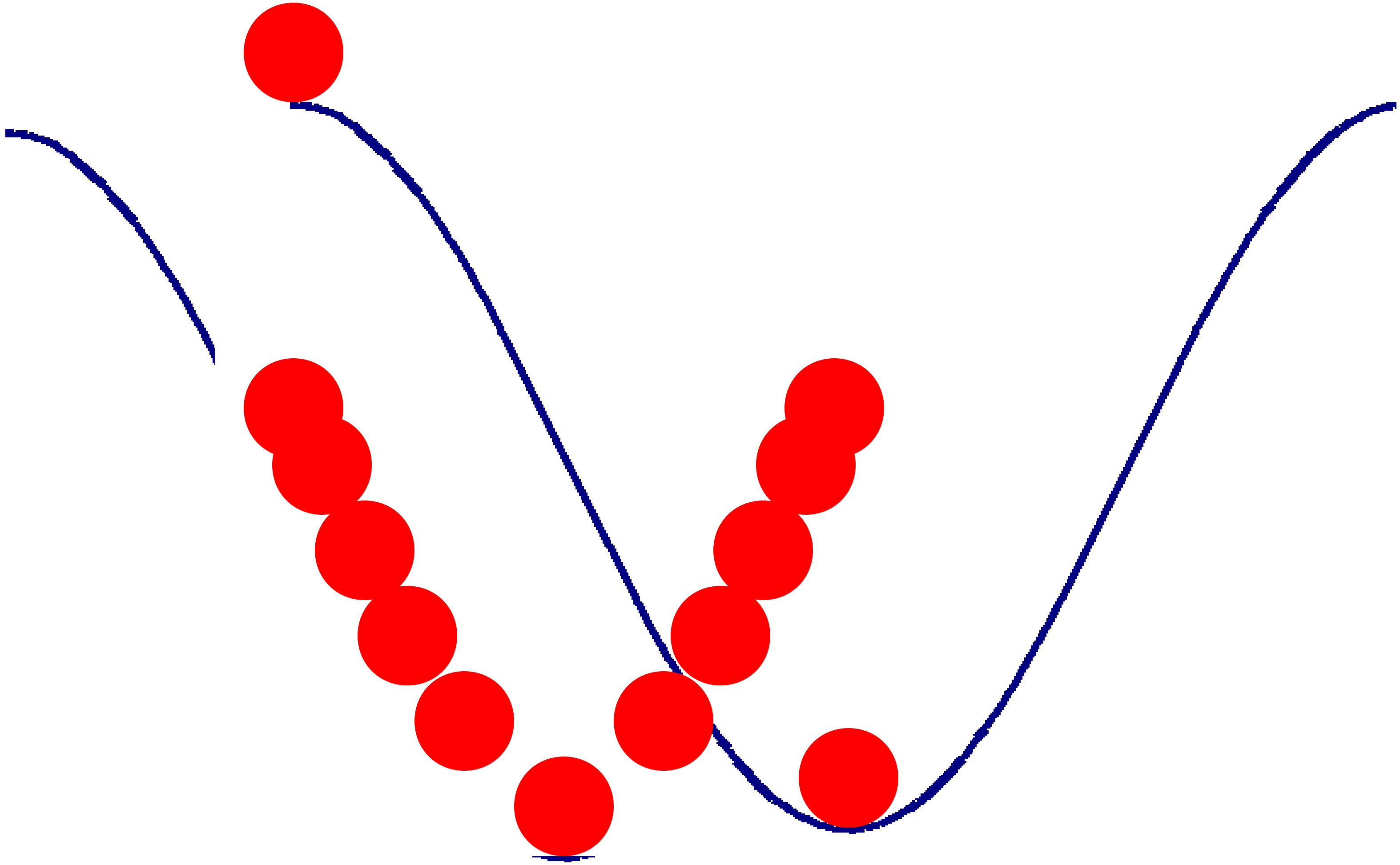
Kanem *et al.*, J. Opt. B7, S705 (05)

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

Recapturing atoms after setting them into oscillation...

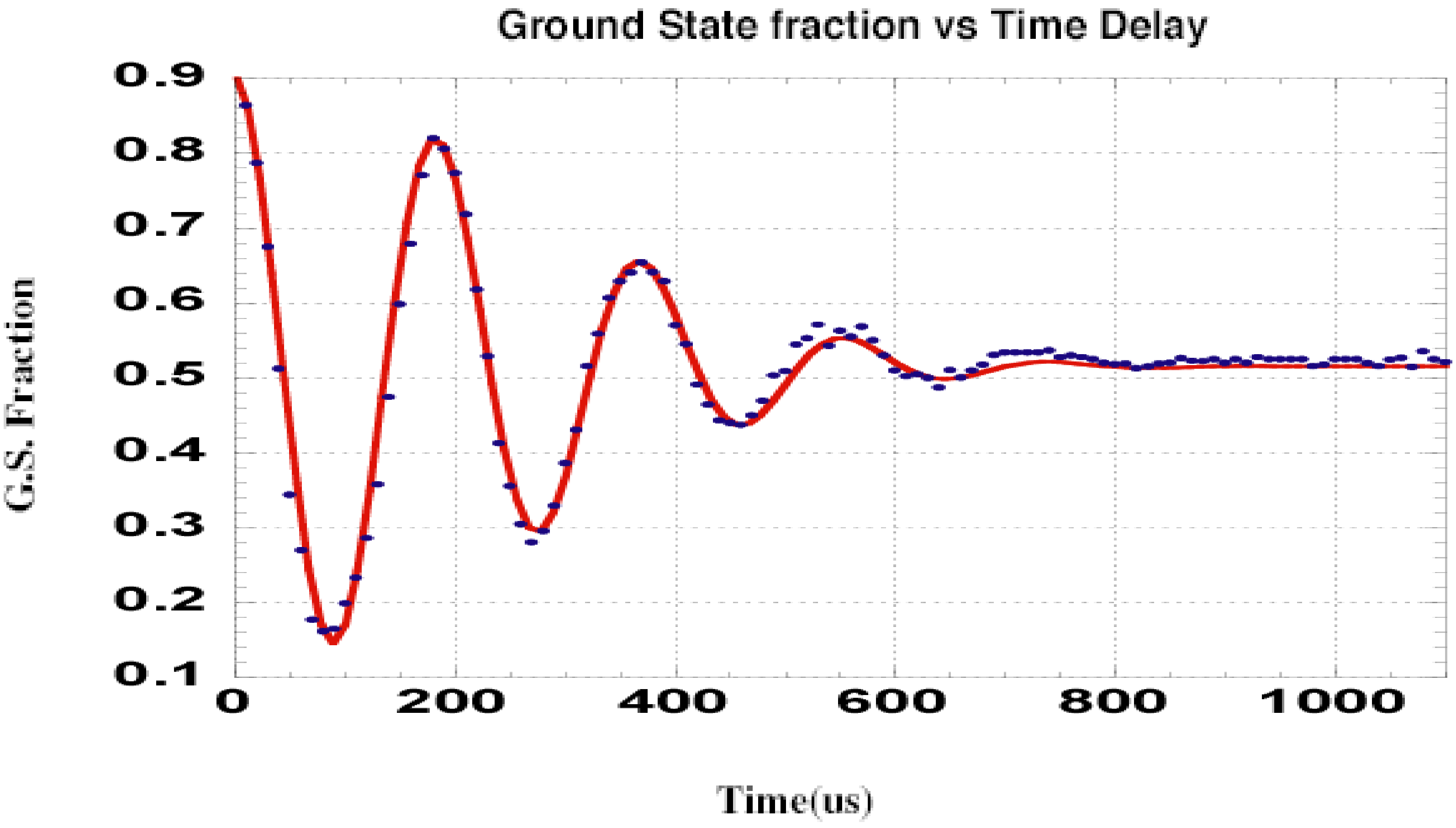


...or failing to recapture them if you're too impatient

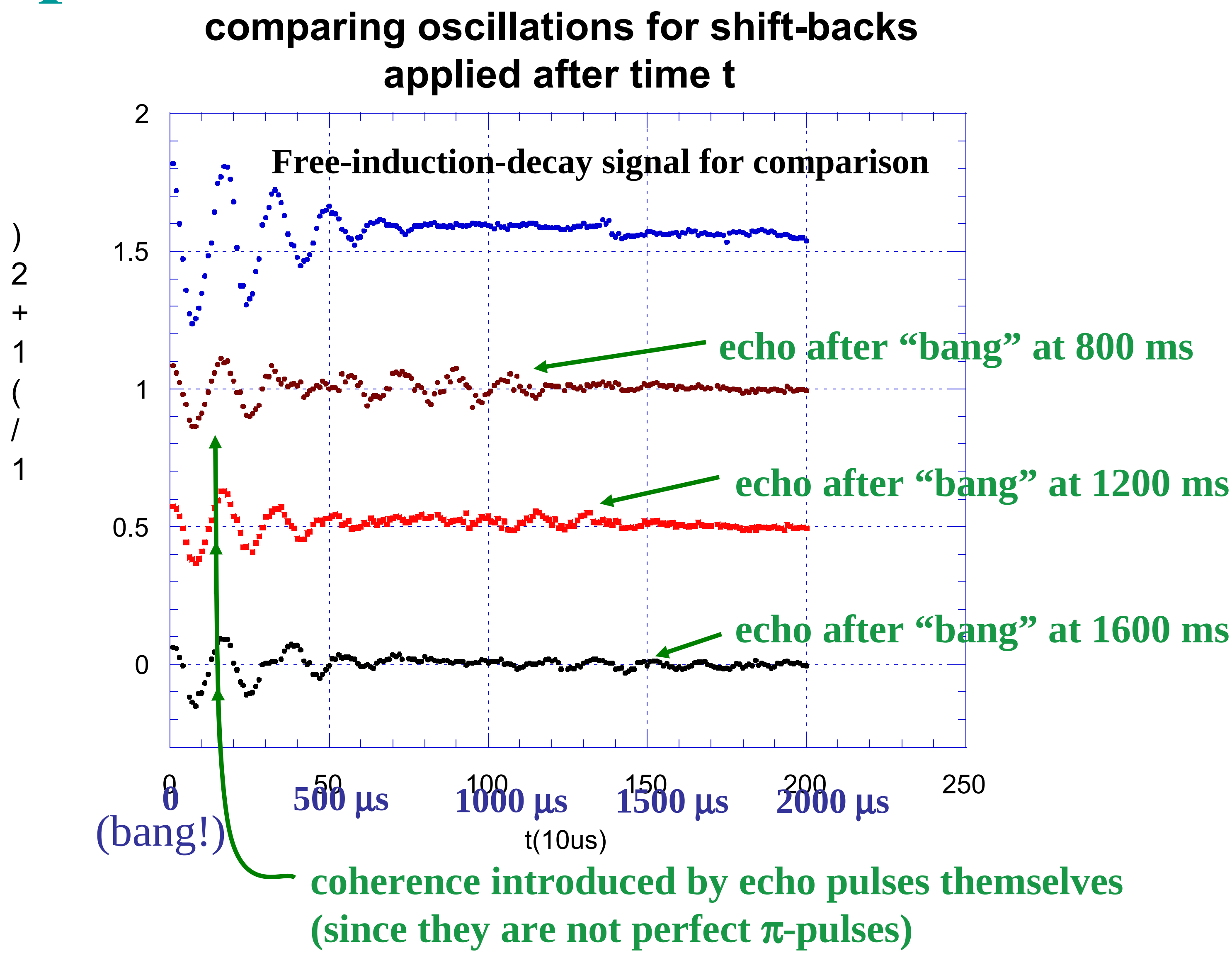


Oscillations in lattice wells

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

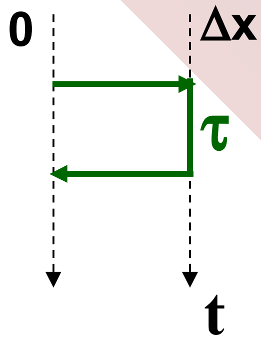


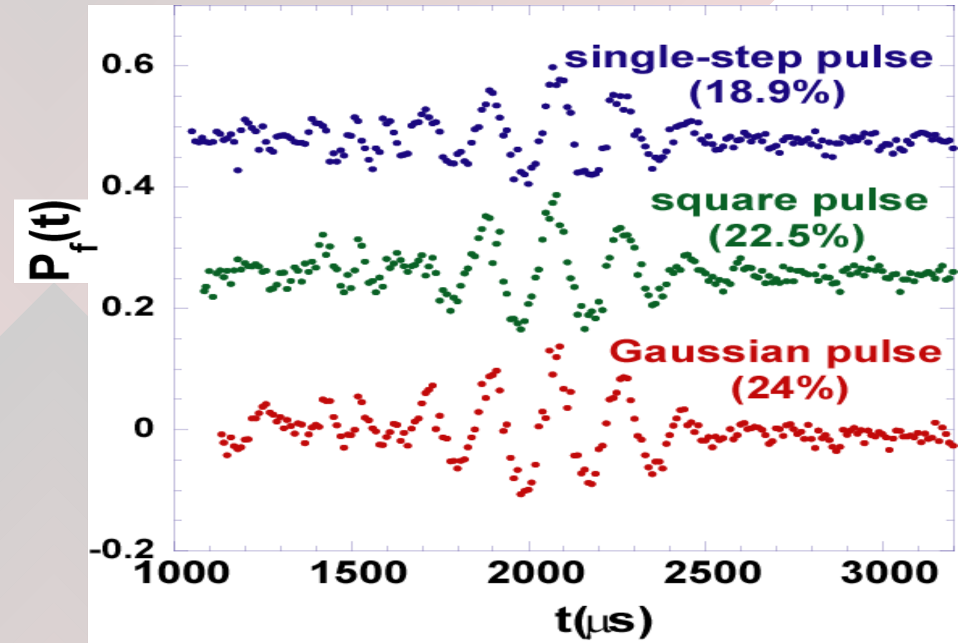
Towards bang-bang error-correction: pulse echo indicates T2 ≈ 1 ms...



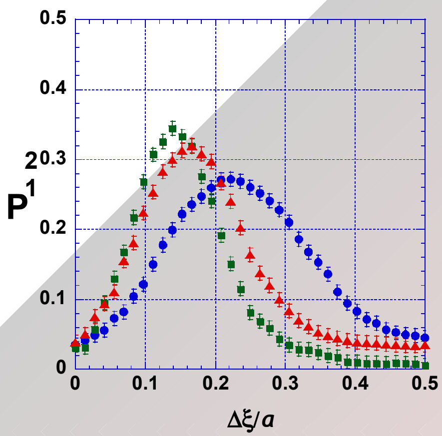
Improved echo pulses

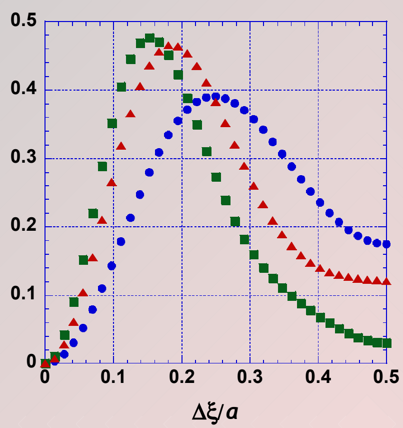
Square pulse





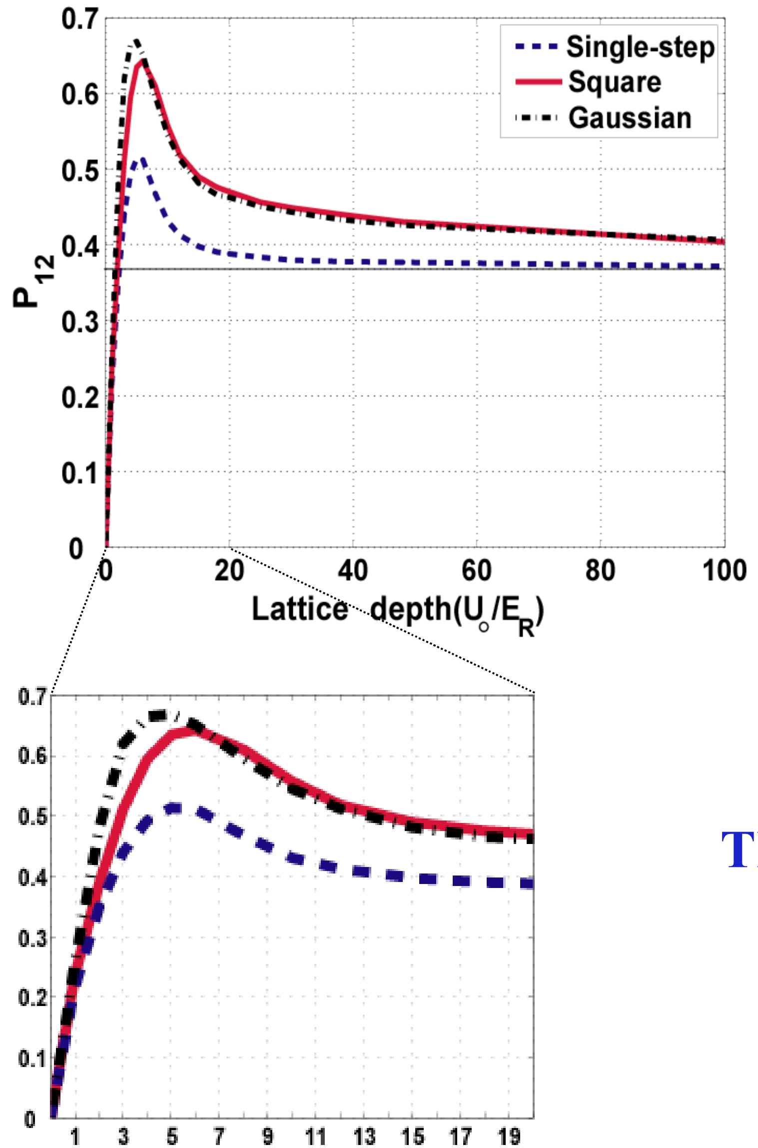
Coupling eff. of 3 pulse shapes versus shift
– Theory & Experiment (you guess which is which)





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

Going off the shallow end



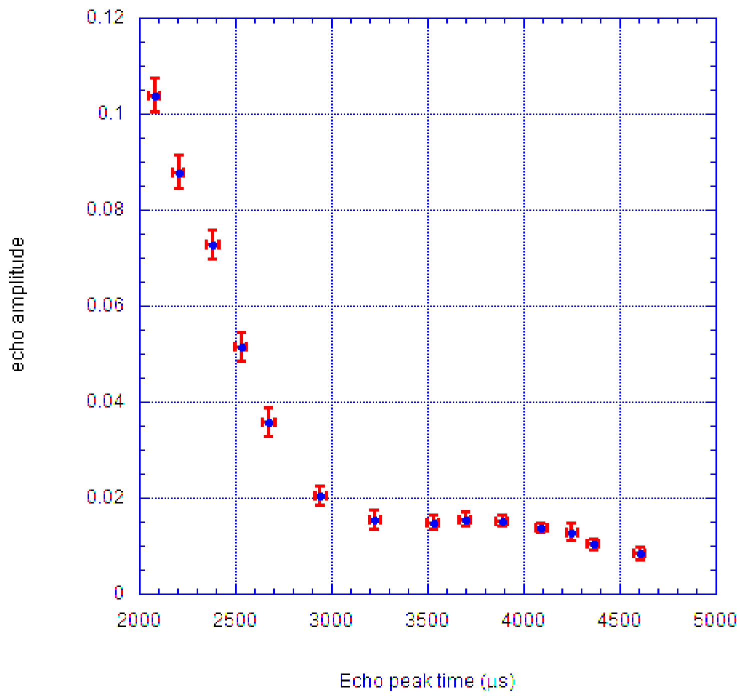
The optimal coupling into |1>
is 1/e in a harmonic oscillator,
but rises to 67% (gaussian pulse)
in a shallow lattice.

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

The future:

- **adiabatic rapid passage**
- **AM + FM (sideband engineering?)**
- **optimal control (GRAPE, etc)**
- **horizontal lattice**

Why does our echo decay?



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minary results)

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Except for one minor disturbing feature:

These data were 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.)

The moral of the story

1 **Multi-photon entangled states may be built “from the ground up” – no need for high-frequency parent photons.**

2 **A modified sort of tomography is possible on “practically indistinguishable” particles; there remain interesting questions about the characterisation of the distinguishability of >2 particles.**

3 **A more *anschaulich* description of multi-photon states may be had on the Poincaré sphere.**

4 **There are interesting issues involved in controlling the quantum states of atoms in lattices, broadened by quasimomentum (inter-well tunneling) and by spatial inhomogeneities.**

5 **Pulse echoes should allow us to study (and control?) spatial coherence in the optical lattice. So far, we don’t really understand what’s going on.**