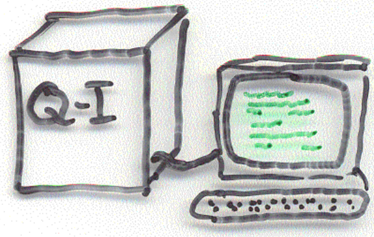
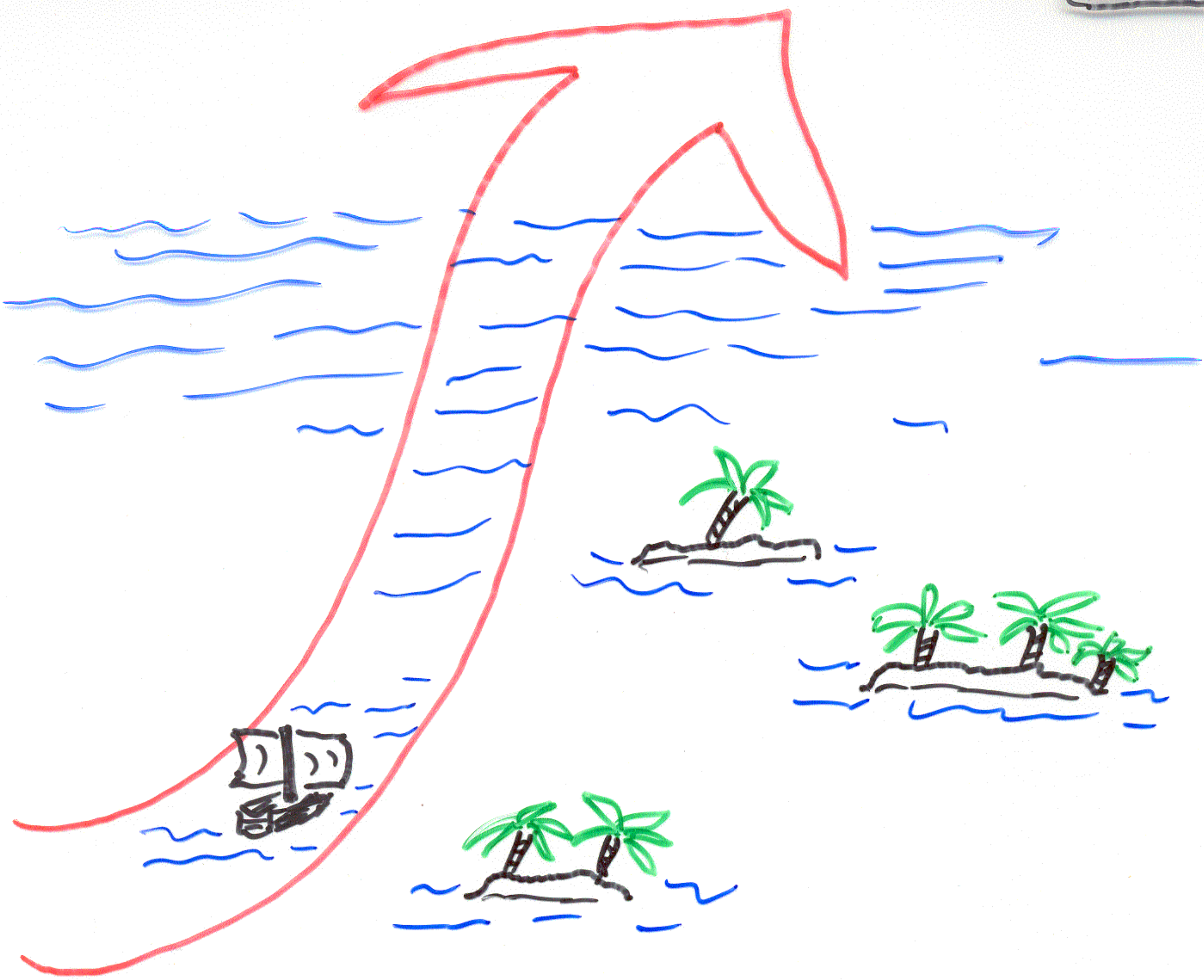
Quantum Computing

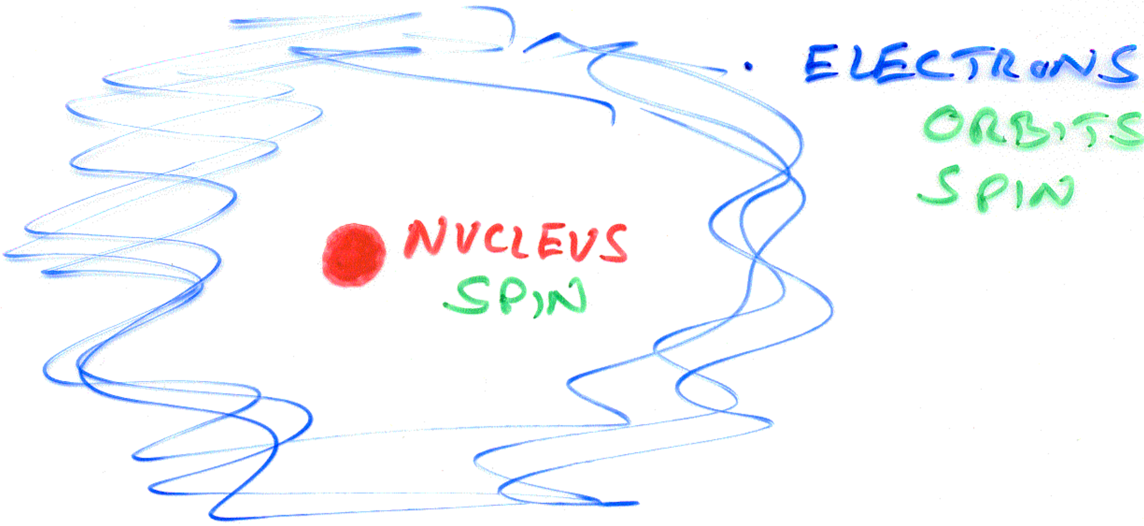
with Ions and Atoms





1. Brief reminder of atomic proposals
2. Experimental status and difficulties
3. What's on the islands?

ATOMS AND IONS



- MANY DISCRETE LEVELS
  - HYPERFINE LEVELS // LONG LIFETIMES
  - METASTABLE STATES // LONG LIFETIMES
  - OPTICAL TRANSITIONS // SHORT LIFETIMES
- EFFECTIVE MANIPULATION
  - OPTICAL
  - MAGNETIC
  - RF
- SPATIAL LOCALIZATION
  - COOLING & TRAPPING

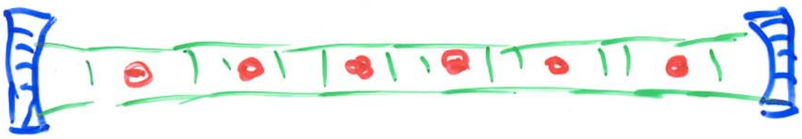
CIRAC & ZOLLER PROPOSALS

(ATOM-ATOM COMMUNICATION)

- TRAPPED IONS

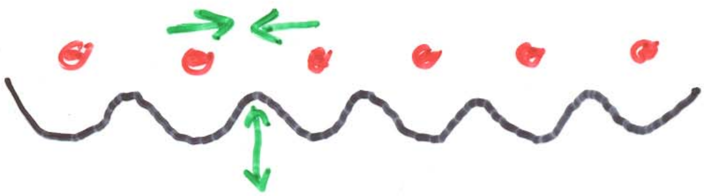
COLLECTIVE VIBRATION

- ATOMS AND IONS IN CAVITIES



QUANTIZED FIELD MODE

- ATOMS IN MICROTRAPS / LATTICES



CONTROLLED COLLISION

CLOSE (g-g)

DISTANT (r-r)

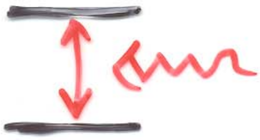
– WELL-ESTABLISHED EXPERIMENTS

– TWO-BIT GATES

– EXPERIMENTAL STATUS AND OUTLOOK OF "THE QUANTUM COMPUTER PROJECT"

ATOMIC CLOCKS

F=5

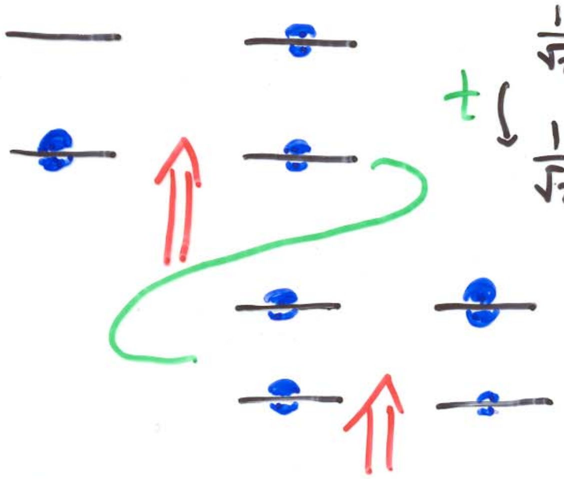


9 192 631 770 Hz

F=4

Cs

ARE ALREADY QUANTUM COMPUTERS:



$\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$

t

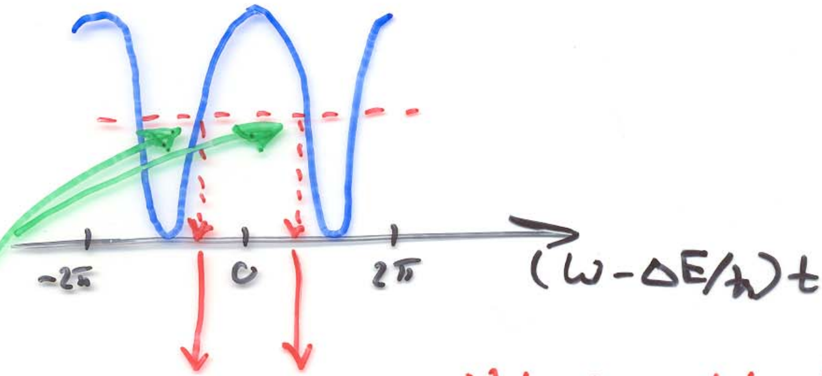
$\frac{1}{\sqrt{2}}(|0\rangle \underline{e^{-iE_0 t/\hbar}} + |1\rangle \underline{e^{-iE_1 t/\hbar}})$

MEASURE

$\underbrace{(\omega - \frac{\Delta E}{\hbar})t}_{\text{ACCUMULATED PHASE DIFFERENCE}}$

RAMSEY SPECTROSCOPY

ENTANGLEMENT AND MULTI-BIT GATES IN CLOCKS ?



ω_-, ω_+ : $N_1(\omega_-) = N_1(\omega_+) \simeq \frac{N}{2}$

$\omega = \frac{1}{2}(\omega_- + \omega_+)$

COUNTING STATISTICS

$N_1 \simeq \frac{N}{2} \pm \frac{\sqrt{N}}{2}$ BINOMIAL

SETS CURRENT LIMIT OF THE ATOMIC CLOCK !

— HARD TO INCREASE t (FREE FALL)

— NOT GOOD TO INCREASE N ($\Delta\omega$ - SHIFTS)

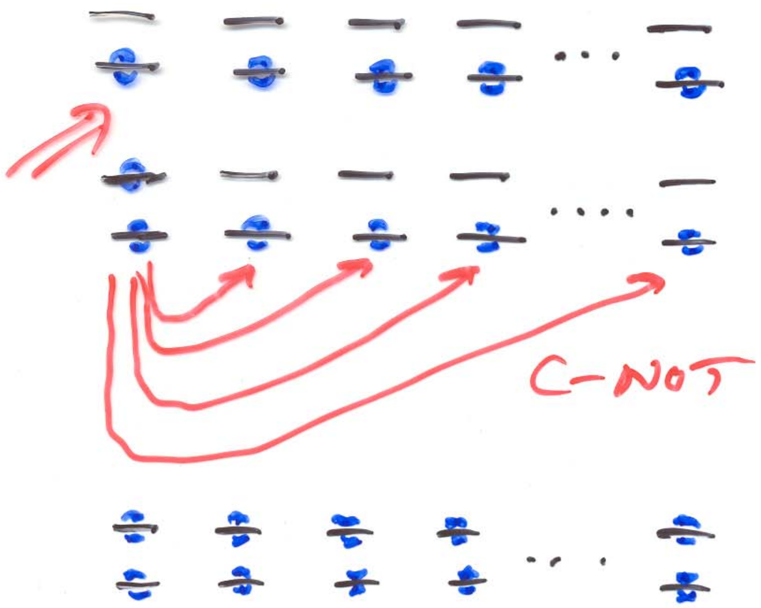
! CORRELATE THE ATOMS

→ SUB-BINOMIAL STATISTICS

A MODEST TASK FOR ALL ATOMIC QUANTUM COMPUTERS

ATOMIC CLOCKS

"NOW WITH C-NOT'S"



$$[|0\rangle]^N$$

$$\downarrow$$

$$\frac{1}{\sqrt{2}}(|0\rangle+|1\rangle)[|0\rangle]^{N-1}$$

$$\downarrow$$

$$\frac{1}{\sqrt{2}}(|0\rangle^N+|1\rangle^N)$$

NOT

$$\cancel{\left[\frac{1}{\sqrt{2}}(|0\rangle+|1\rangle)\right]^N}$$

$$\frac{1}{\sqrt{2}}\left(|0\rangle^N \underline{e^{-iNE_0t/\hbar}} + |1\rangle^N \underline{e^{-iNE_1t/\hbar}}\right)$$

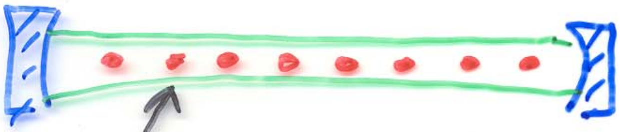
FREQUENCY $N\cdot\frac{\Delta E}{\hbar}$

$\Rightarrow$ IMPROVED RESOLUTION

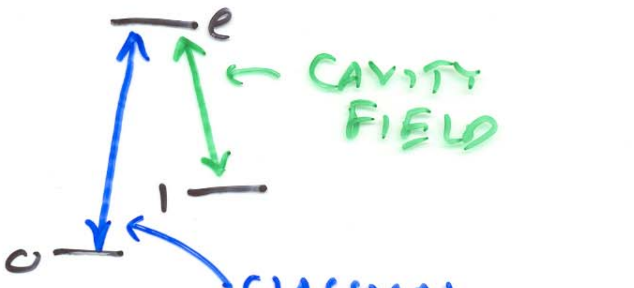
4 IONS: WINELAND

CASE STUDY:

CAVITY QED



— INDIVIDUAL ACCESS



$$g\,\Omega(t)\,a^{\dagger}\,(|1\rangle\langle 0|)_i + \text{H.c.}$$

— HIGH FIDELITY: NO ATOMIC DECAY $g \gg \Gamma$

NO CAVITY DECAY $g \gg \kappa$

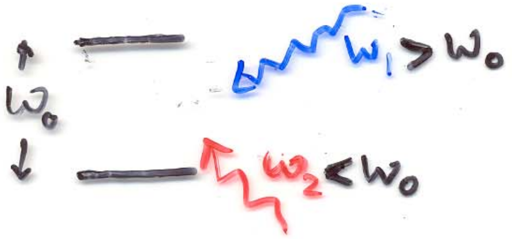
$\rightarrow$ GOOD CAVITY $\dfrac{g^2}{\kappa\Gamma} \gg 1$

CAN WE USE THE SAME COUPLING

- WITHOUT INDIVIDUAL ACCESS
- IN A BAD CAVITY $\dfrac{g^2}{\kappa\Gamma} \ll 1$

TO IMPROVE THE ATOMIC CLOCK?

THE TRICK OF TWO COLOURS

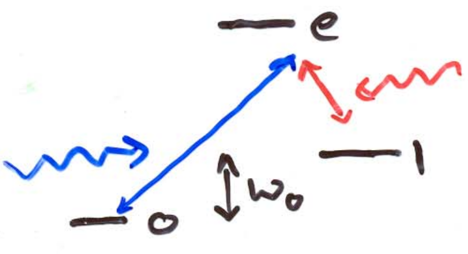


$\omega_1 + \omega_2 = 2\omega_0$

→ PAIR TRANSITION $|00\rangle \leftrightarrow |11\rangle$

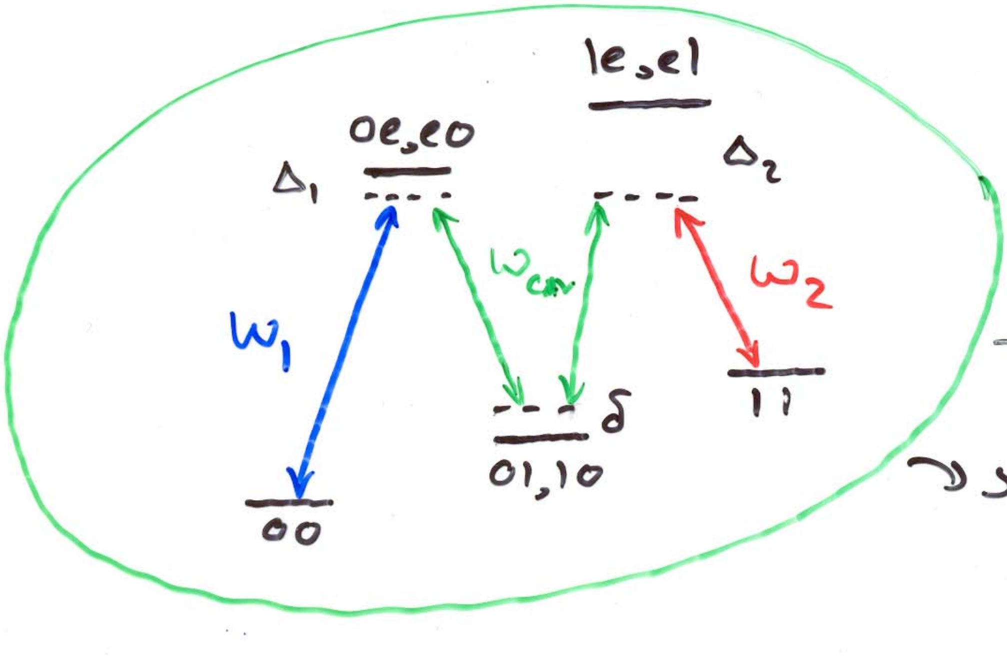
$H_{eff} \propto S_{+_1} S_{+_2} \to S_+^2$

REQUIRES INTERACTION BETWEEN ATOMS!



$\omega_1 - \omega_2 = 2\,\omega_0$

→ TWO-ATOM RAMAN



→ MANY ATOMS

→ SUM OVER ALL PAIRS

$S_\pm : |0\rangle \rightleftarrows |1\rangle$

$$H_{eff}^{ideal} = \frac{\Omega_1 g_1 g_0 \Omega_2}{4\Delta_1\Delta_2\delta}\left(S_+^2 + S_-^2\right)$$

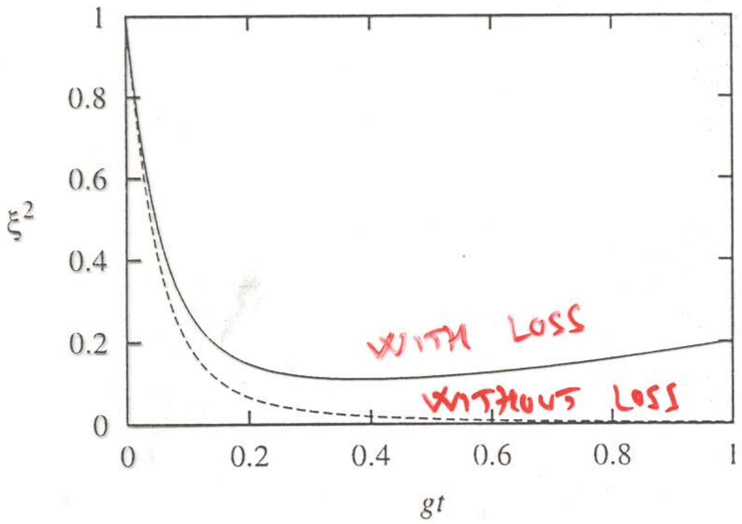
$$+ \frac{\Omega_1^2\, g_0^2}{4\Delta_1^2\,\delta} S_+ S_- + \frac{\Omega_2^2\, g_1^2}{4\Delta_2^2\,\delta} S_- S_+$$

DISSIPATION (κ AND Γ)

HEISENBERG PICTURE
COUPLED EQS. FOR S_+^2, S_+S_- etc

$$\frac{d}{dt}\langle J_+J_+\rangle = -\frac{\Gamma}{\Delta_1^2+\frac{\Gamma^2}{4}}\frac{|\Omega_1|^2}{4}\langle J_+J_+\rangle - \frac{\Gamma}{\Delta_2^2+\frac{\Gamma^2}{4}}\frac{|\Omega_2|^2}{4}\langle J_+J_+\rangle$$
$$-\frac{2iN}{\delta^2+\frac{\kappa'^2}{4}}\Bigg[\frac{|\Omega_1|^2|g_b|^2}{4(\Delta_1^2+\frac{\Gamma^2}{4})^2}\left(\Delta_1^2+\frac{\Gamma^2}{4}\right)\left(\delta+i\frac{\kappa'}{2}\right)\langle J_+J_+\rangle + \frac{|\Omega_2|^2|g_a|^2}{4(\Delta_2^2+\frac{\Gamma^2}{4})^2}\left(\Delta_2+i\frac{\Gamma}{2}\right)^2\left(\delta-i\frac{\kappa'}{2}\right)\langle J_+J_+\rangle$$
$$+\frac{\Omega_1\Omega_2^* g_a g_b^*}{4(\Delta_2^2+\frac{\Gamma^2}{4})(\Delta_1^2+\frac{\Gamma^2}{4})}\Bigg(\left(\Delta_1+i\frac{\Gamma}{2}\right)\left(\Delta_2-i\frac{\Gamma}{2}\right)\left(\delta+i\frac{\kappa'}{2}\right)\langle J_-J_+\rangle$$
$$+\left(\Delta_1+i\frac{\Gamma}{2}\right)\left(\Delta_2+i\frac{\Gamma}{2}\right)\left(\delta-i\frac{\kappa'}{2}\right)\langle J_+J_-\rangle\Bigg)\Bigg],$$

NUMERICAL SOLUTION



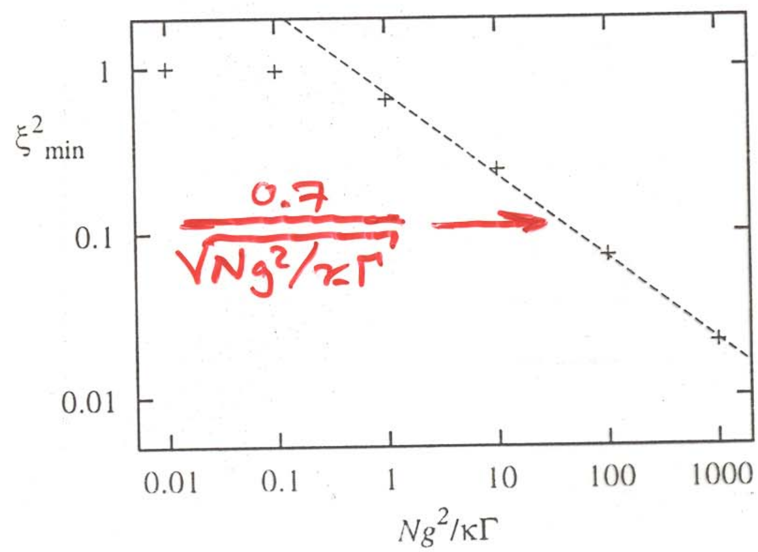
$$\xi^2 = \frac{N\,\Delta S_x^2}{\langle S_z\rangle^2}$$

$g^2/\kappa\Gamma = 10^{-4}$

$N = 10^6$

$N g^2/\kappa\Gamma = 10^2$

SIMPLE SCALING OF OPTIMUM



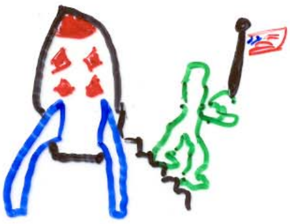
A. SORENSEN, KM
QUANT-PH/0202073
PRA <u>66</u> 022314 (2002)

WHY DOES SPIN SQUEEZING WORK IN A BAD CAVITY WITH

$$\frac{g^2}{\kappa\Gamma} = 10^{-4} \quad ?$$

① BECAUSE SPIN SQUEEZING IS FAST
(Kitagawa & Ueda)
$\rightarrow \quad \tau \sim 1/N$!

② BECAUSE SPIN SQUEEZING ...



"... IS A SMALL STEP FOR AN ATOM,

BUT A LARGE STEP FOR THE SAMPLE."

(ΔS_x REDUCED BY FACTOR 100
BUT INDIVIDUAL ATOMIC
DENSITY MATRICES ALMOST UNCHANGED)

IF FEW ATOMS DECAY THE STATE
IS STILL SPIN SQUEEZED !

WE ONLY NEED $N \dfrac{g^2}{\kappa\Gamma} \gg 1$!

RISQ - COMPUTING

REDUCED INSTRUCTION SET

QUANTUM COMPUTING

QUANT-PH/0004014
J. MOD. OPT. 47, 2515 (2000)

SEE ALSO QUANT-PH/0207011

THE PHYSICAL QUANTUM COMPUTER SOLVES ITS OWN SCHRÖDINGER EQUATION

→ GENERIC HAMILTONIANS

- NEAREST NEIGHBOUR SPIN-INTERACTION
  ISING, HEISENBERG

- HUBBARD / BOSE-HUBBARD MANY-BODY
  HAMILTONIAN, SUPERCONDUCTIVITY

NATURAL MODELLING

- ONLY FEW "GATES", GLOBAL ACCESS
- ONLY FINITE PRECISION NEEDED
- ADJUSTABLE PARAMETERS + NOISE

CONCLUSION

ATOMIC CLOCKS ARE QUANTUM COMPUTERS, AND THEY WILL IMPROVE WITH "QUANTUM GATES".

QUANTUM COMPUTERS ARE MANY-BODY SYSTEMS WITH CONTROLLED INTERACTIONS (FEYNMAN), AND ATOMIC QUANTUM COMPUTERS ALREADY SOLVE GENERAL QUANTUM MANY-BODY PROBLEMS....

... MORE IS TO COME!

("FIND THE PHYSICS OF THE MATHEMATICS")

QUANTUM COMPUTING WILL CERTAINLY LET US DO SOMETHING WE COULD NOT DO IN ANY OTHER WAY!!!