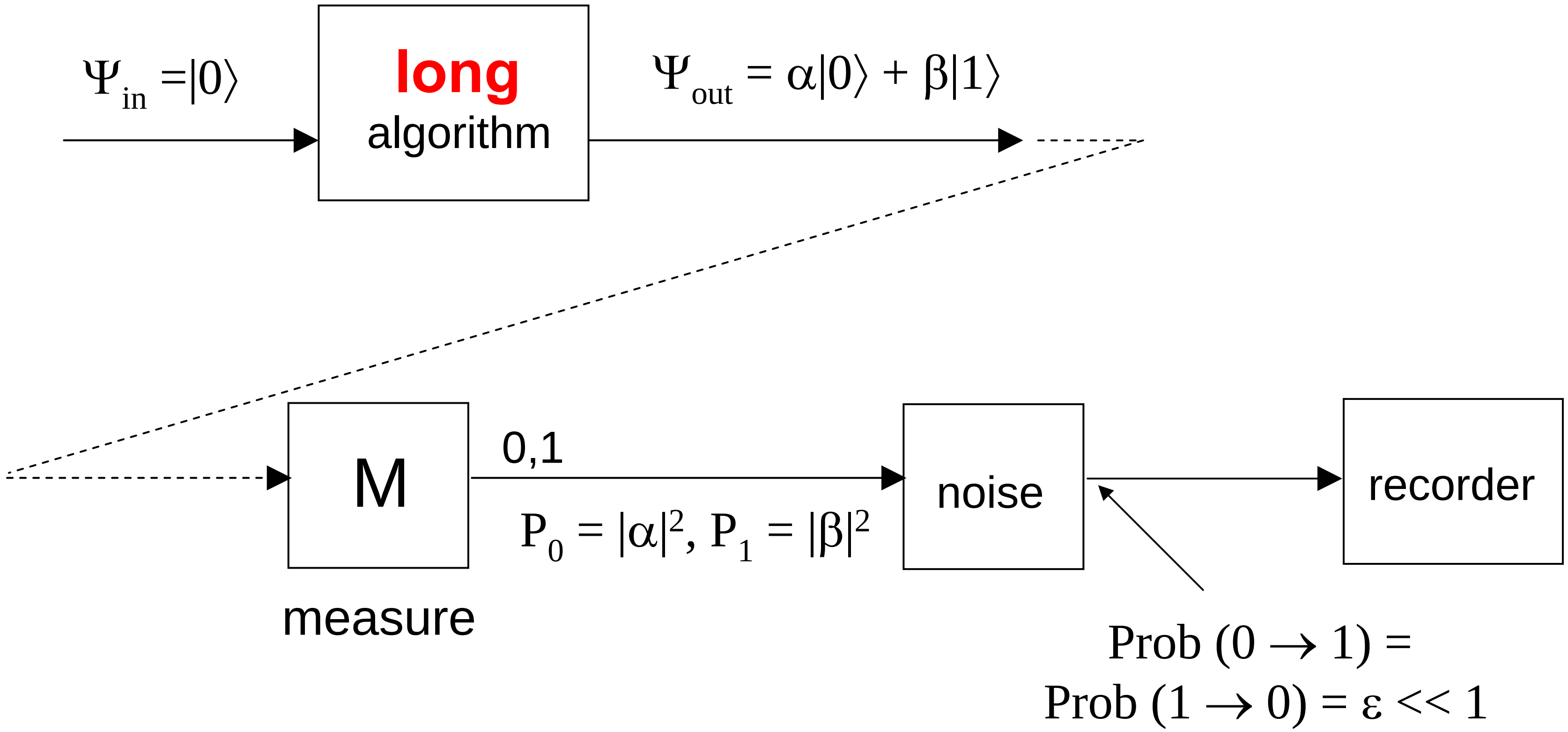
Implications of quantum information for measurement and standards

Quantum metrology, some examples:

- enhanced quantum state measurement efficiency
- standards:
  - improved interferometry
    - e.g., spectroscopy and atomic clocks
  - quantum information mapping

Enhanced quantum state detection with Quantum Information Processing



Make copies of Ψ_{out} and measure all copies ?

Universal (unitary) cloning machine:

$$U_{clone}|\Psi_{out}\rangle|0\rangle = |\Psi_{out}\rangle|\Psi_{out}\rangle$$

$$U_{clone}|\Phi_{out}\rangle|0\rangle = |\Phi_{out}\rangle|\Phi_{out}\rangle$$

inner products:

$$\langle 0|\langle\Phi_{out}|\underbrace{(U_{clone})^{\dagger}\, U_{clone}}|\Psi_{out}\rangle|0\rangle$$

$$= \langle 0|\langle\Phi_{out}|\Psi_{out}\rangle|0\rangle = \langle\Phi_{out}|\Psi_{out}\rangle$$

$$\langle\Phi_{out}|\langle\Phi_{out}|\Psi_{out}\rangle|\Psi_{out}\rangle = \langle\Phi_{out}|\Psi_{out}\rangle^{2}$$

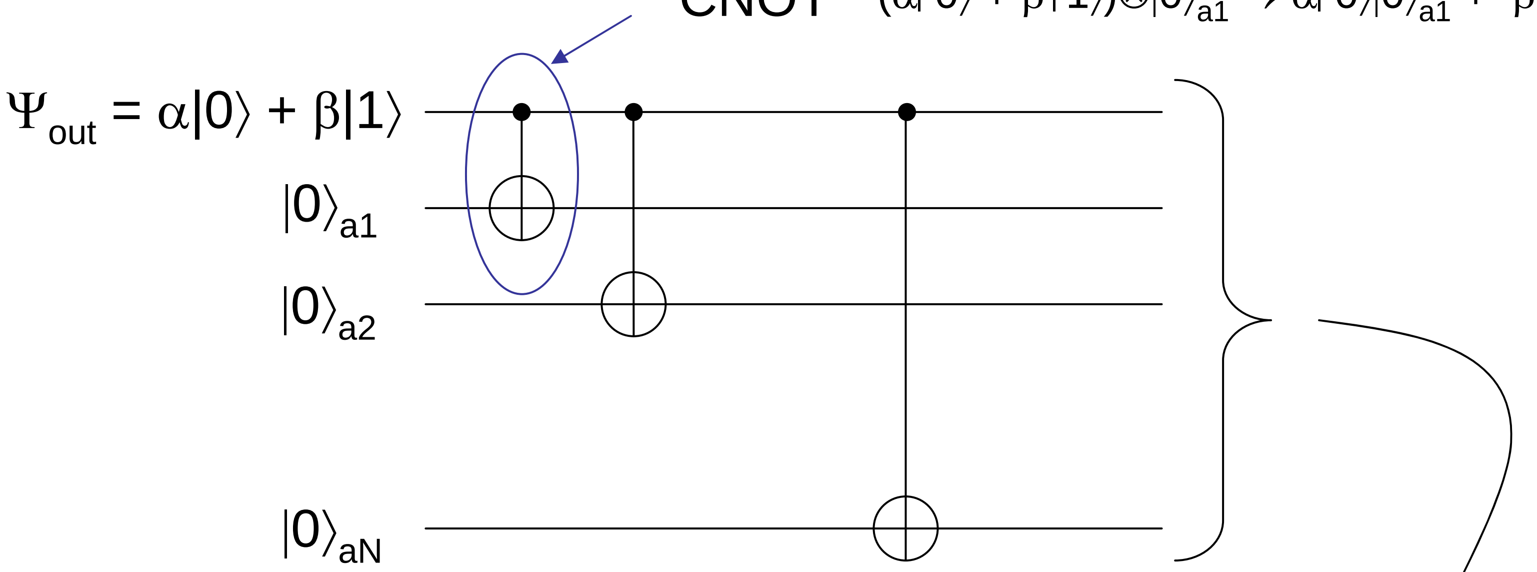
$$\neq \langle\Phi_{out}|\Psi_{out}\rangle$$

“no cloning” theorem:

W. K. Wootters and W. H. Zurek, *Nature*, ‘82

Use controlled-nots: (David DiVincenzo, ’01)

CNOT $(\alpha|0\rangle + \beta|1\rangle)\otimes|0\rangle_{a1} \rightarrow \alpha|0\rangle|0\rangle_{a1} + \beta|1\rangle|1\rangle_{a1}$

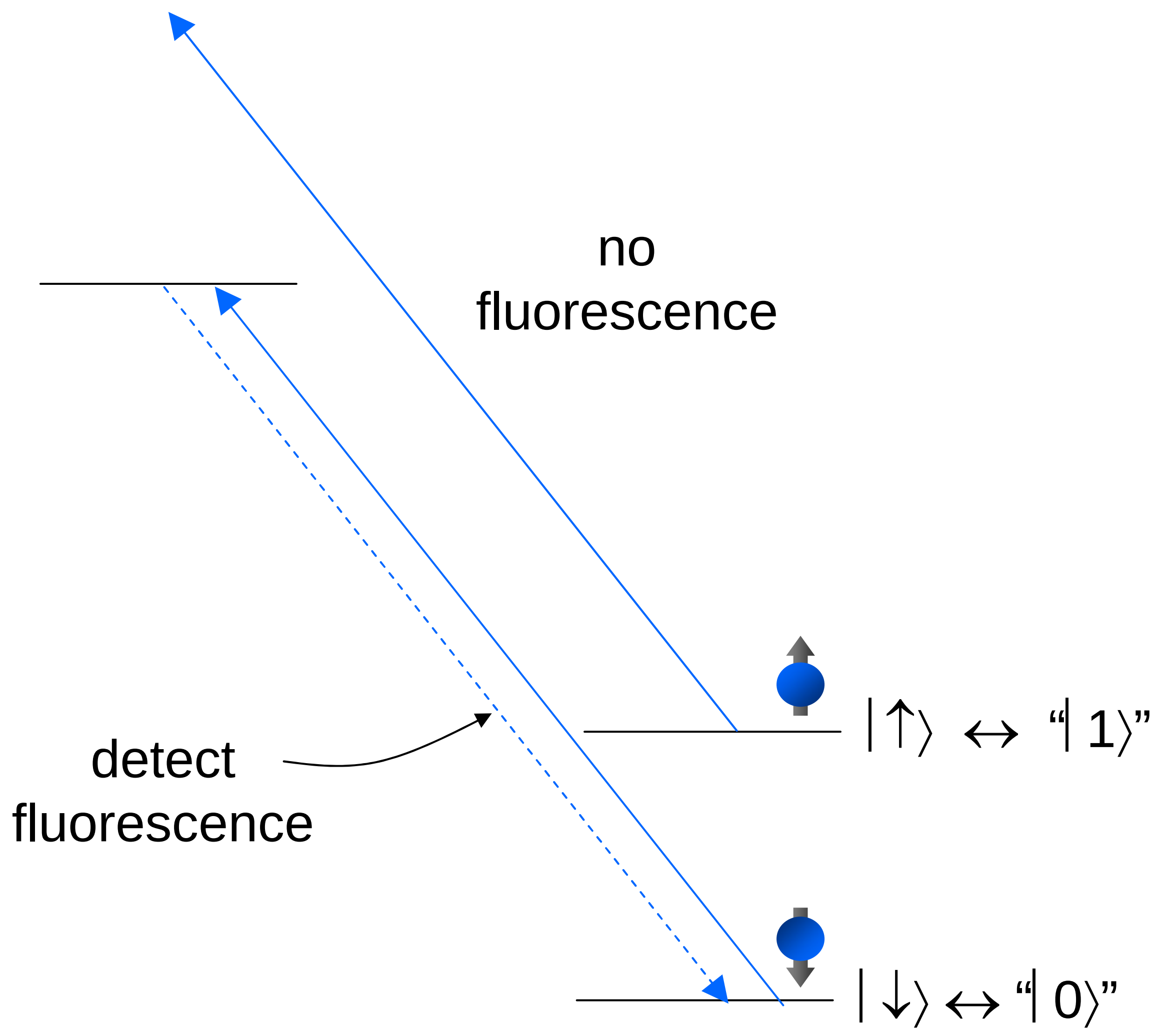


$$\Psi_{out} = (\alpha|0\rangle + \beta|1\rangle)\otimes|0\rangle_{a1}\otimes|0\rangle_{a2} \cdots \otimes|0\rangle_{aN}$$

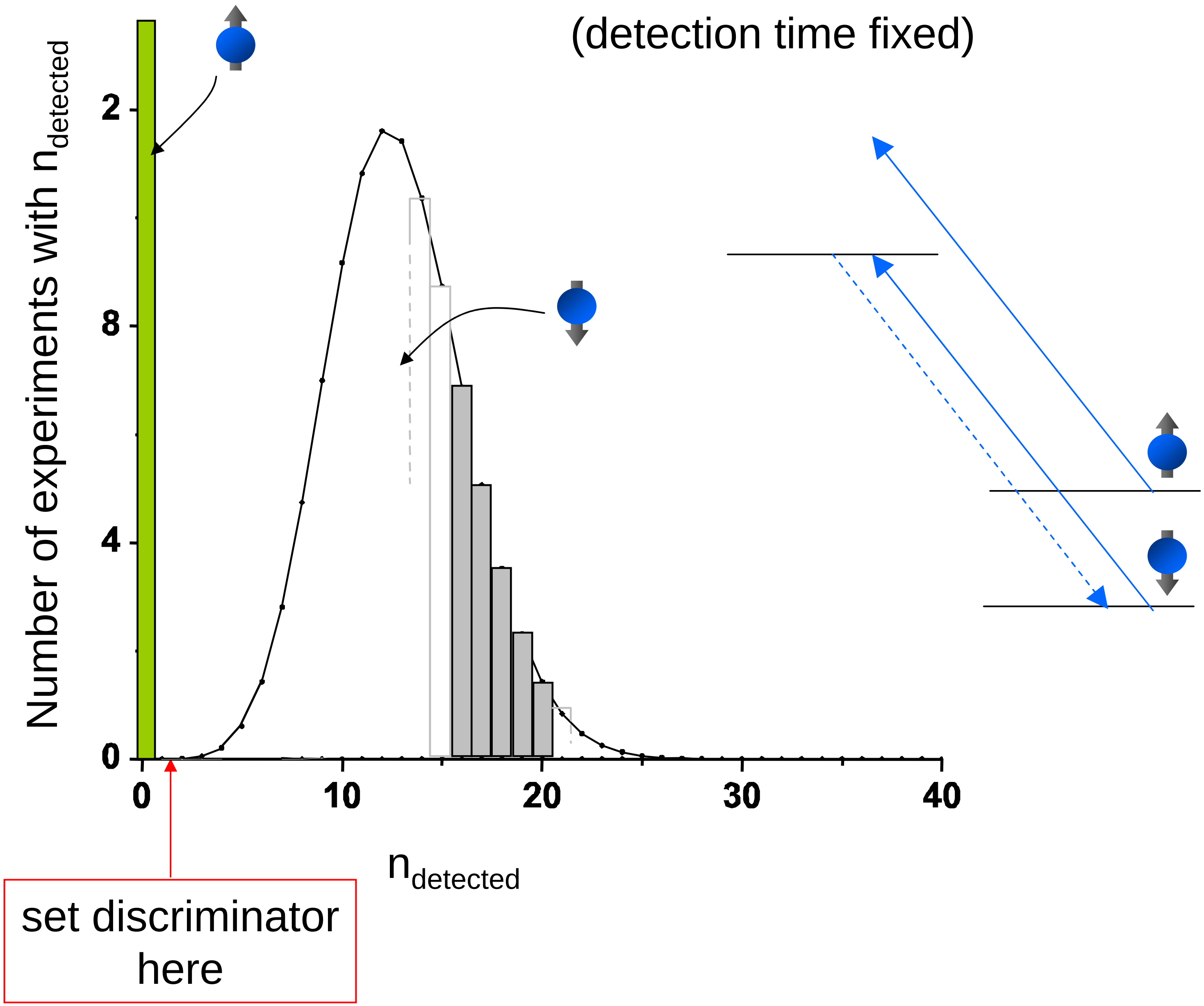
$$\rightarrow \alpha|0\rangle|0\rangle_{a1}|0\rangle_{a2} \cdots |0\rangle_{aN} + \beta|1\rangle|1\rangle_{a1}|1\rangle_{a2} \cdots |1\rangle_{aN}$$

e.g., measure all bits, take a majority vote

example: state detection with atomic qubits:

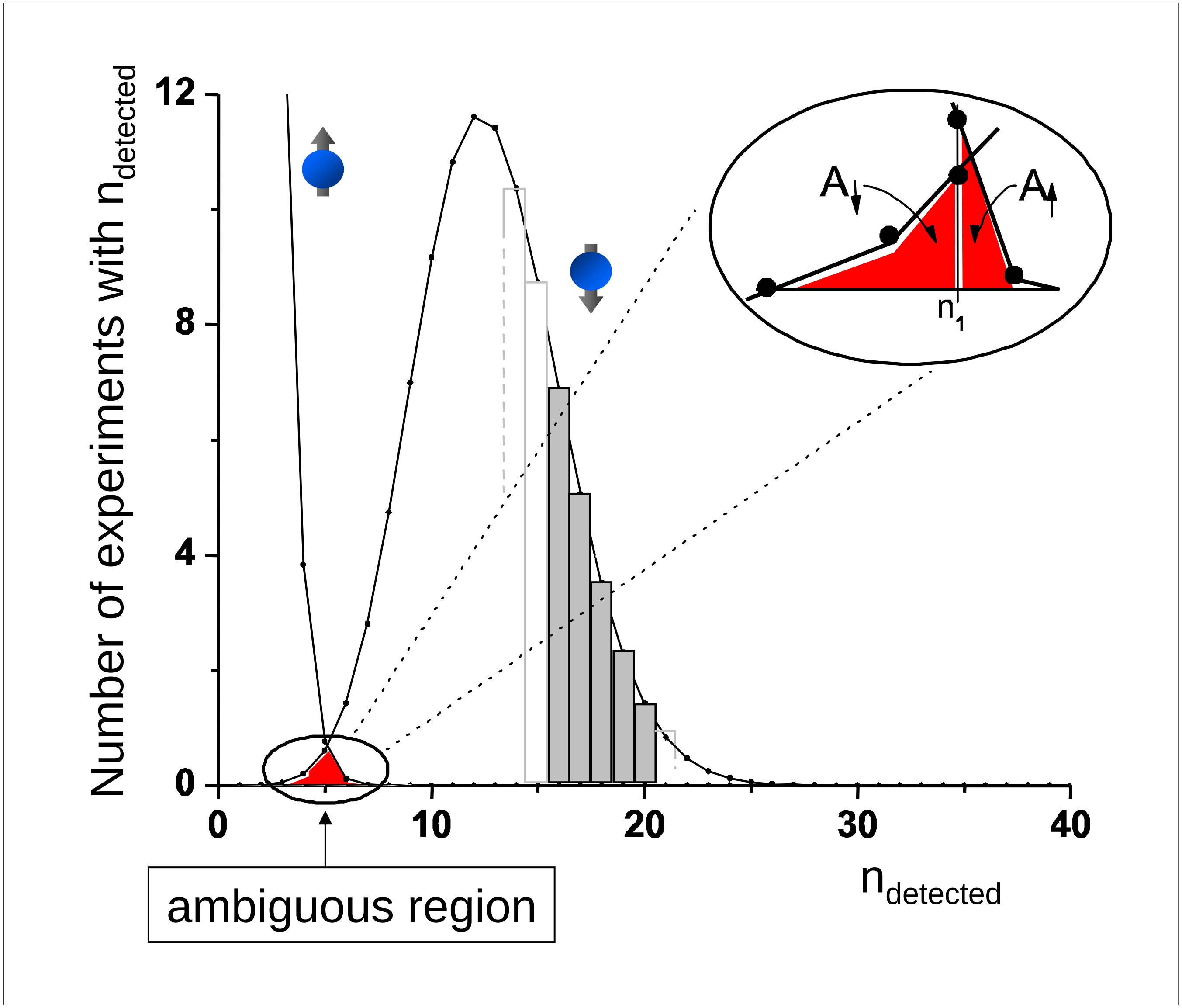


Ideal case,
(detection time fixed)

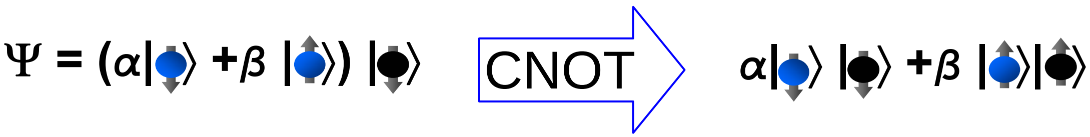


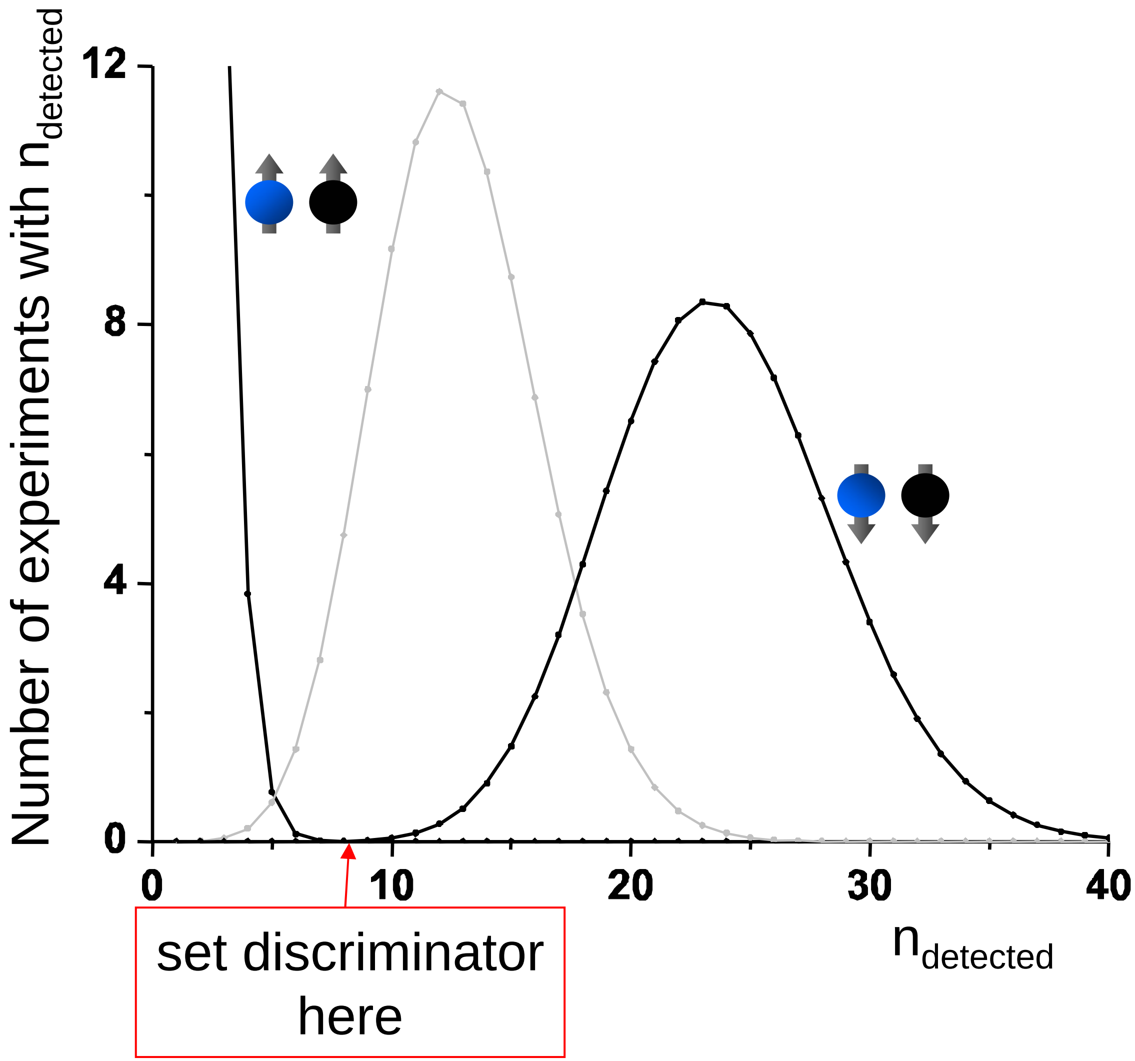
non-ideal case (added background noise)

$$\langle \dot{n}_{background} \rangle = 0.125 \langle \dot{n}_{\downarrow} \rangle$$



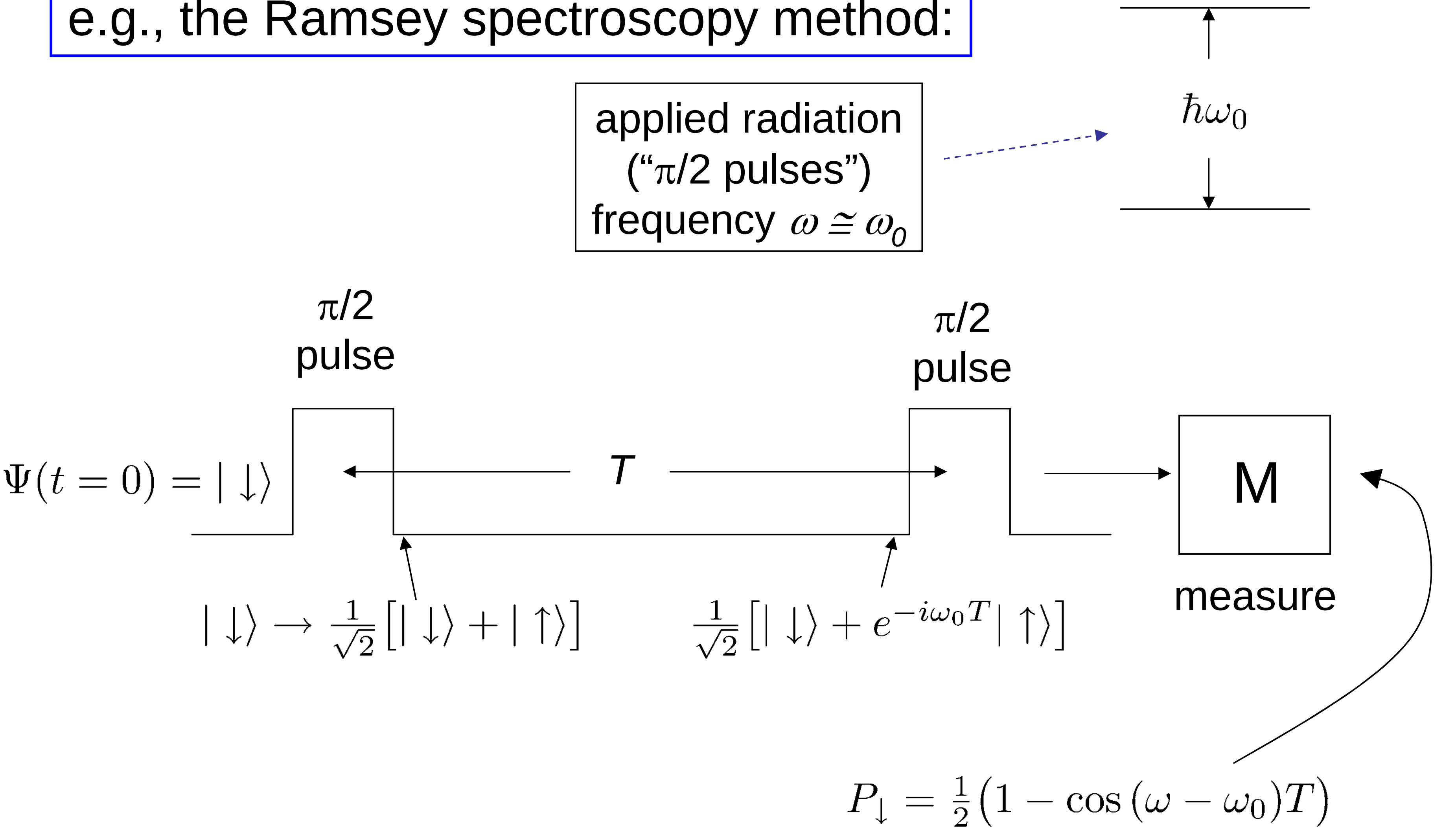
Amplification with one ancilla bit





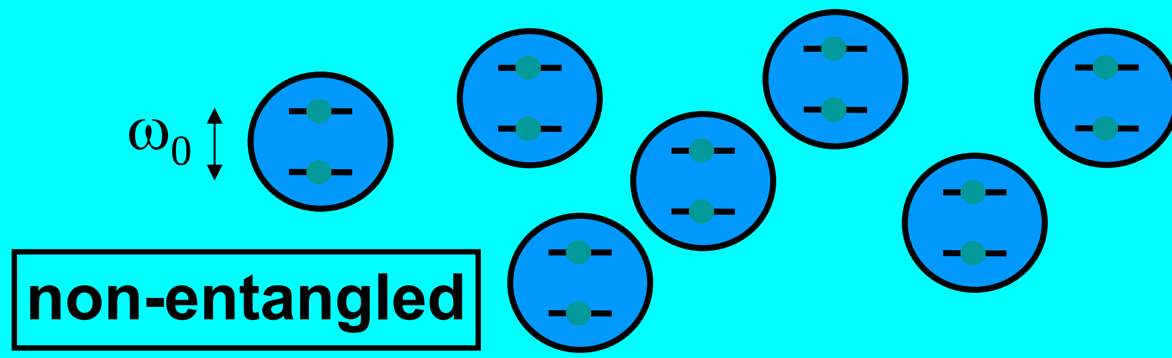
detect both
bits simultaneously
(experimental demonstration:
Tobias Schaetz *et al.*)

Quantum interferometry
e.g., the Ramsey spectroscopy method:



Entangled atom spectroscopy

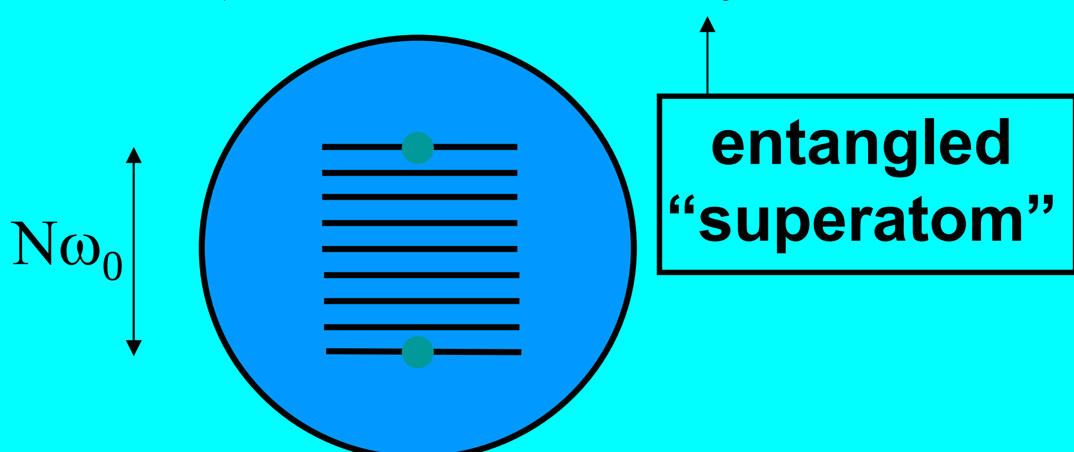
$$\Psi=(|\downarrow\rangle + e^{-i\omega_0 t}|\uparrow\rangle)\cdot(|\downarrow\rangle + e^{-i\omega_0 t}|\uparrow\rangle)\cdots(|\downarrow\rangle + e^{-i\omega_0 t}|\uparrow\rangle)/2^{N/2}$$



standard quantum limit:

$$\Delta\omega = \frac{1}{\sqrt{NT}}$$

$$\Psi = (|\downarrow\downarrow\downarrow\cdots\downarrow\rangle + \exp(-i\mathbf{N}\omega_0 t)\,|\uparrow\uparrow\uparrow\cdots\uparrow\rangle)/2^{1/2}$$



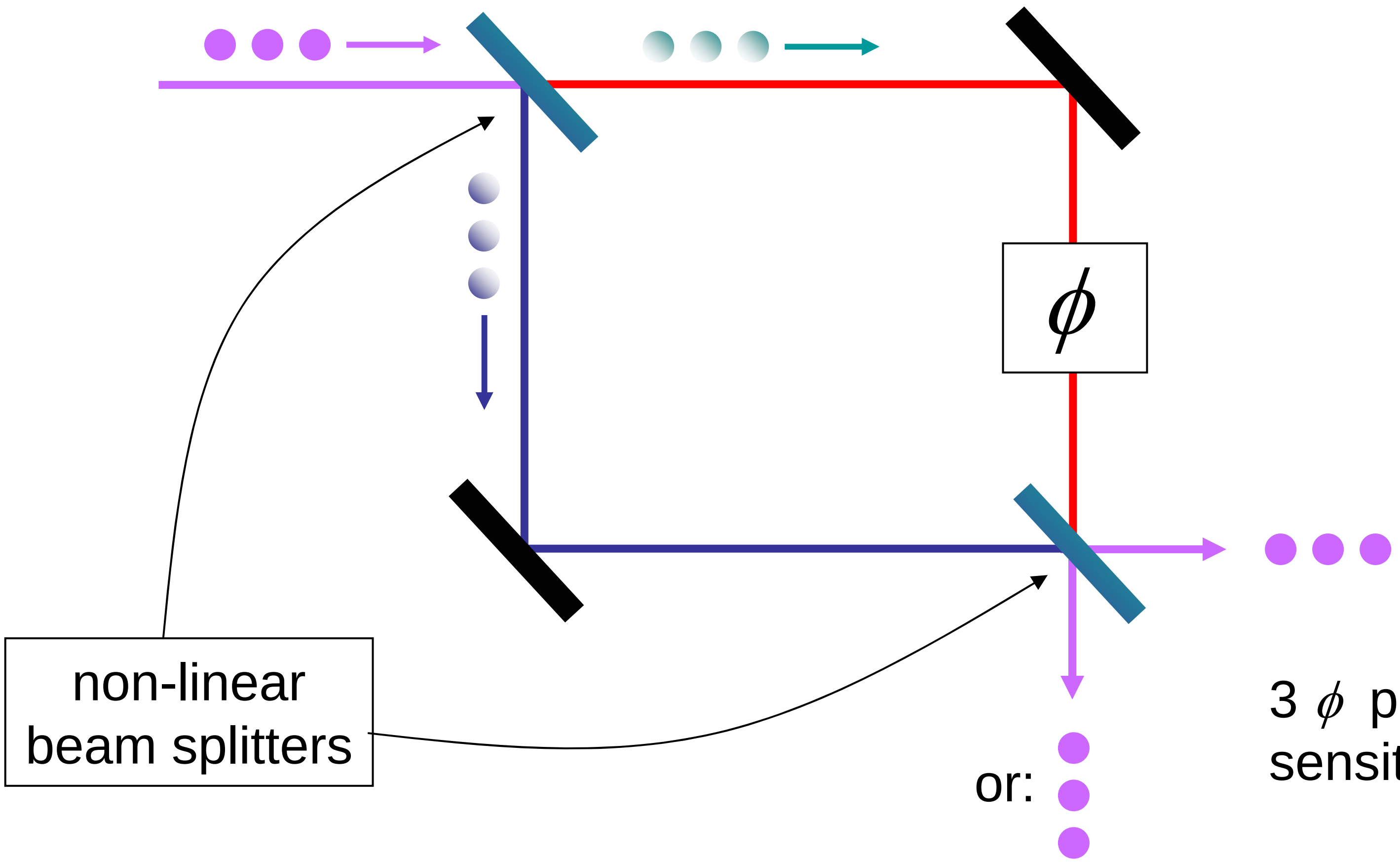
Heisenberg limited:

$$\Delta\omega = \frac{1}{N\sqrt{T}}$$

(John Bollinger *et al*., PRA '96)

Particle (e.g., photons, atoms) interferometers?

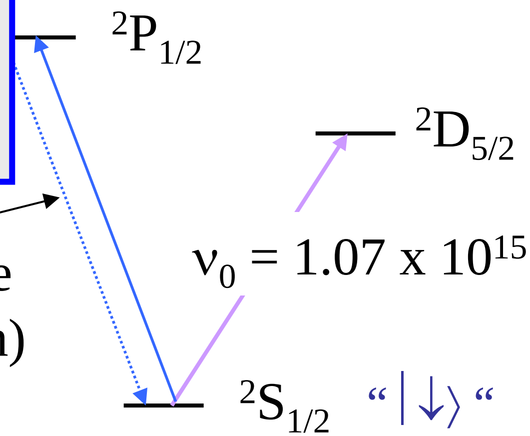
analog to the Ramsey experiment:

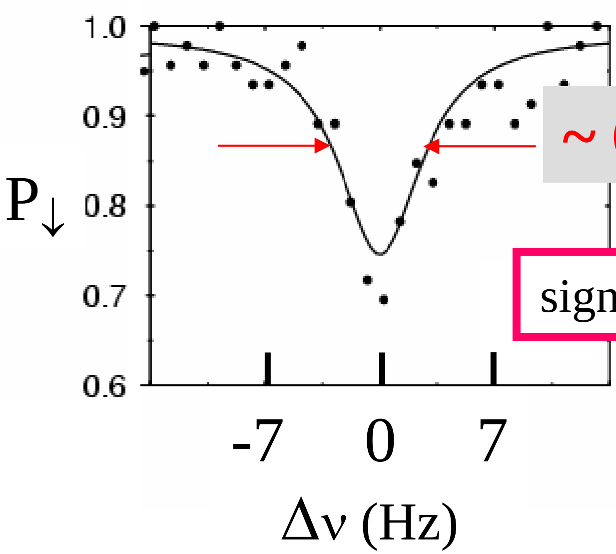


single $^{199}Hg^{+}$-ion optical frequency standard (Jim Bergquist *et al.*)

entry level:
inaccuracy < 1 part in 10^{15}

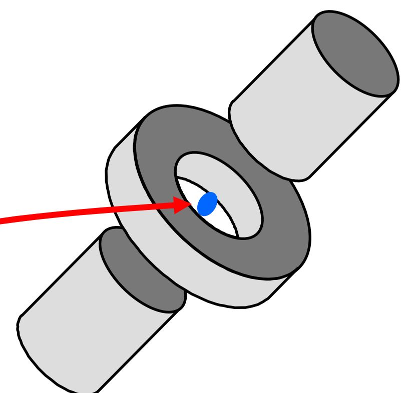
Observe fluorescence (λ = 194 nm)





~ 6.5 Hz, Q = 1.6×10^{14}

signal is lifetime limited



$^{2}D_{5/2}$ state has quadrupole moment.
Measure ν_0 along three B-field directions (Wayne Itano)

quadrupole shift

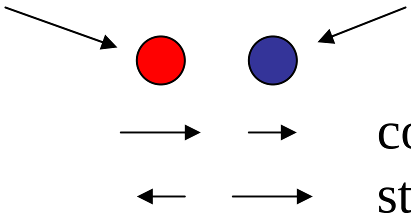
Quantum information mapping:

example application: cooling and detection of clock ions
with quantum-information processing

Basic idea (2 trapped ions):

"Logic" ion
(e.g., $^{9}Be^{+}$)

"Clock" ion



common mode "a"
stretch mode "b"

- Cool and detect Clock ion with Logic ion
  - increases clock ion possibilities
  - sympathetic (laser) cooling during clock transition

Sequence:

1. Cool and pump to ground states:
   $\psi_{\text{initial}} = |\downarrow\rangle_L|\downarrow\rangle_C|0\rangle_a|0\rangle_b = |\downarrow\rangle_L|\downarrow\rangle_C|0\rangle_M$

2. Drive clock transition: $\psi \rightarrow \psi' = |\downarrow\rangle_L\,(\,\alpha|\downarrow\rangle_C + \beta|\uparrow\rangle_C)\,|0\rangle_M$

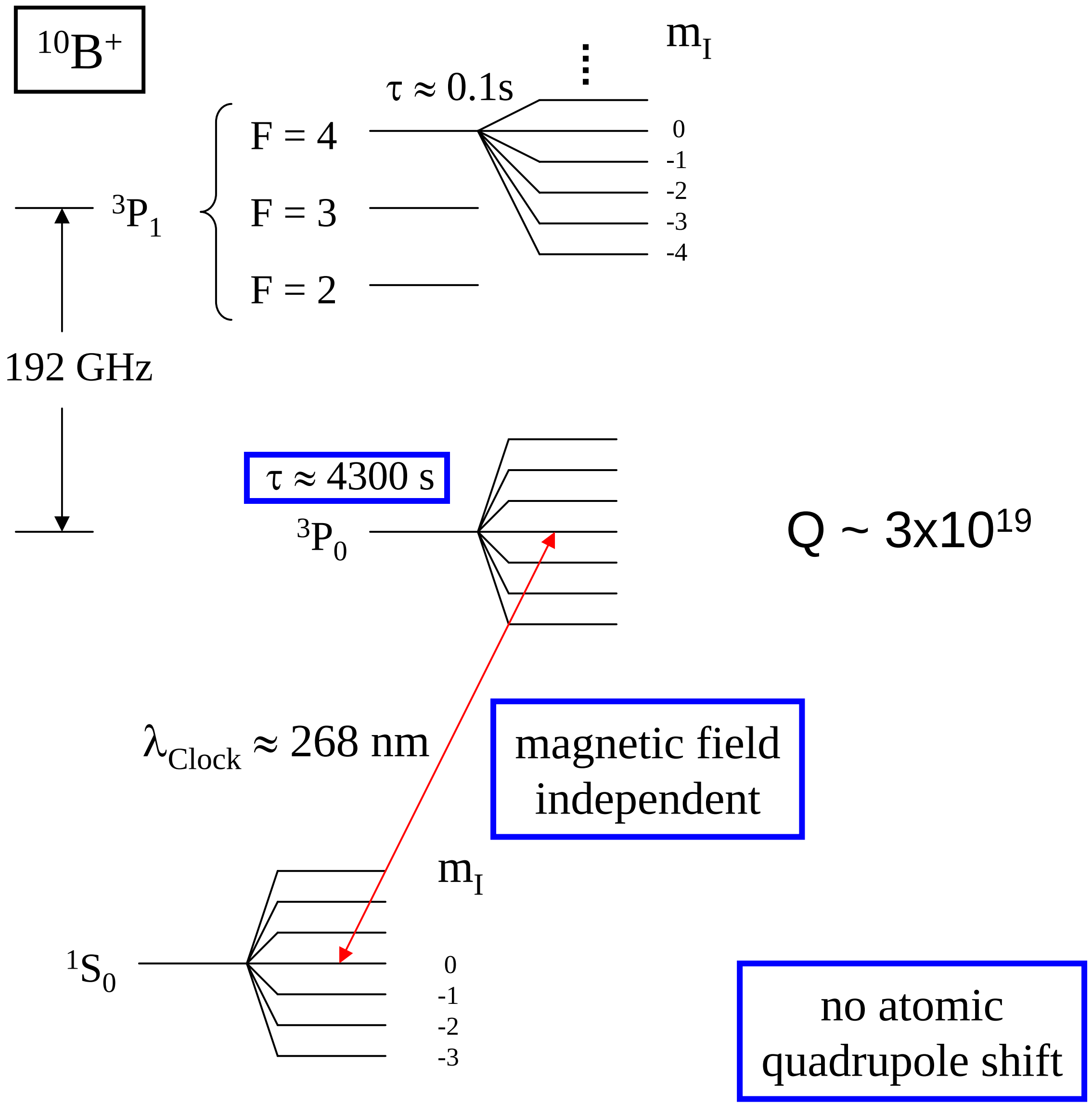
3. Map clock state to motional mode, then map motional state to logic ion
   $\psi' \rightarrow |\downarrow\rangle_L|\uparrow\rangle_C(\alpha|1\rangle_M + \beta|0\rangle_M) \rightarrow (\alpha|\uparrow\rangle_L + \beta|\downarrow\rangle_L)\,|\uparrow\rangle_C|0\rangle_M$

4. Measure logic ion (cycling transition): $P_\uparrow = |\alpha|^2$, $P_\downarrow = |\beta|^2$

5. Reset to ψ_{initial} & repeat

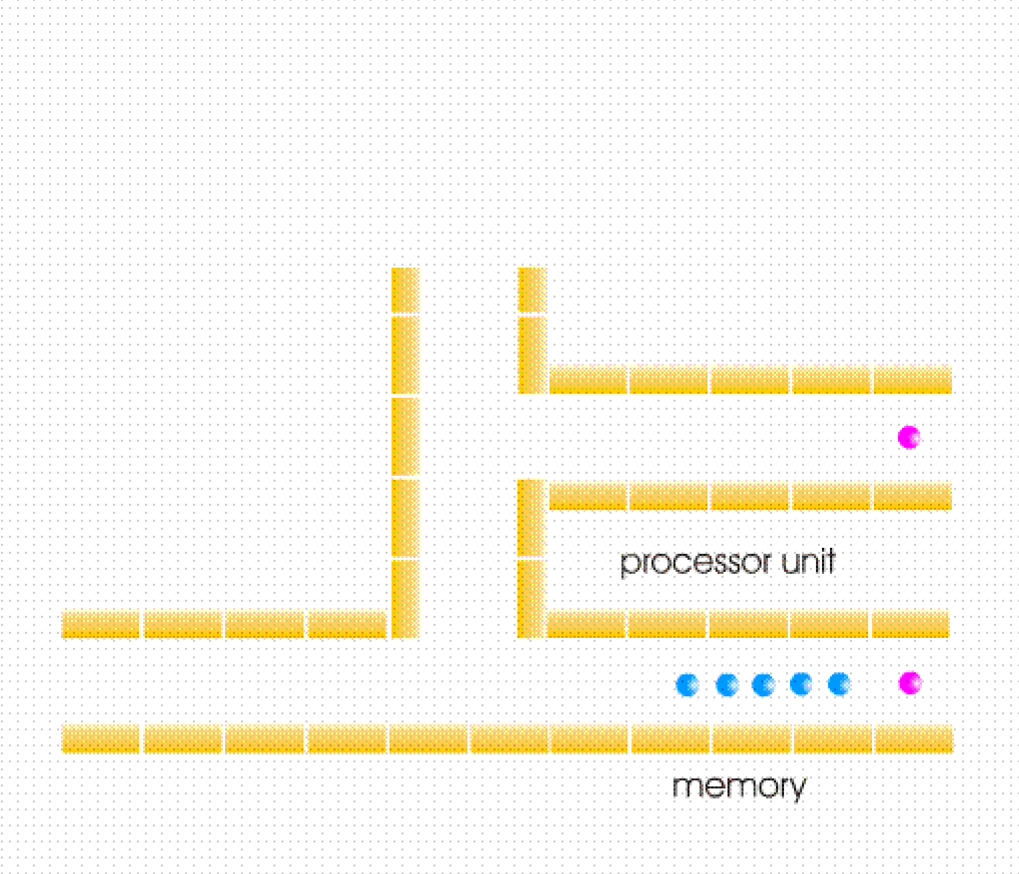
mapping & detection can be done fast (~ 1 ms)

The “dream”



10B+
mI
τ ≈ 0.1s
F = 4
F = 3
F = 2
3P1
0
-1
-2
-3
-4
192 GHz
τ ≈ 4300 s
3P0
Q ~ 3x10^19
λClock ≈ 268 nm
magnetic field independent
mI
1S0
0
-1
-2
-3
no atomic quadrupole shift

scale up? multiplexed ion traps



interconnected multi-zone structure

- subtraps decoupled

move ions with electrode potentials

processor ions sympathetically cooled

- only a few normal modes to cool
- weak cooling in memory zone

individual optical addressing during gates not required

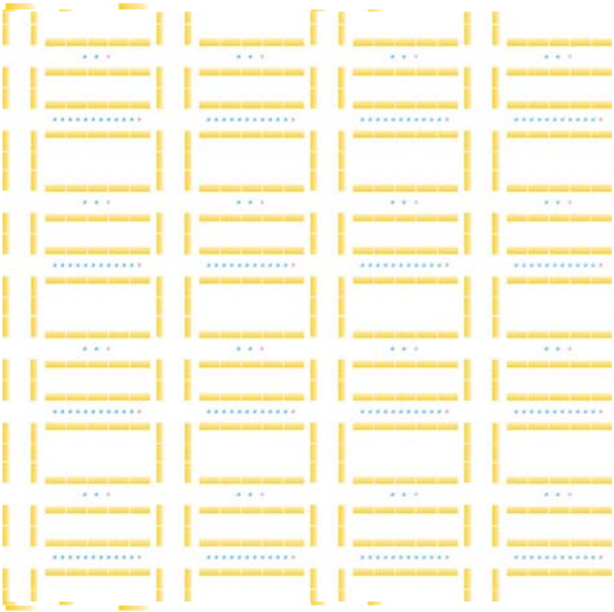
- gates in tight trap $\Rightarrow$ fast

readout for error correction in (shielded) subtrap

- no decoherence from fluorescence

D. J. W. *et al.*, J. Res. Nat. Inst. Stand. Technol. **103**, 259 (1998).
D. Kielpinski, C. Monroe, and D. J. Wineland, Nature **417**, 709 (2002).
Other proposals: DeVoe, Phys. Rev. A **58**, 910 (1998); Cirac & Zoller, Nature **404**, 579 (2000); L.-M. Duan, et. al., quant-ph/0401020 (2004)

Modularity

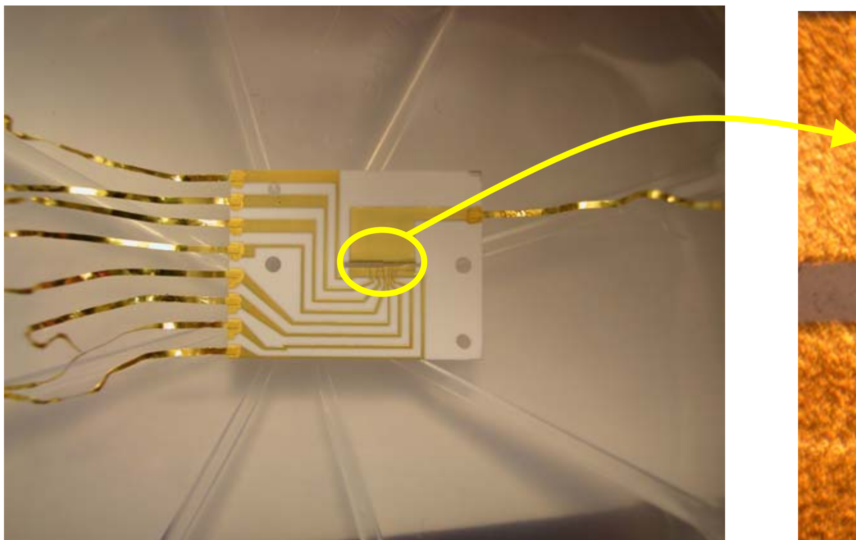


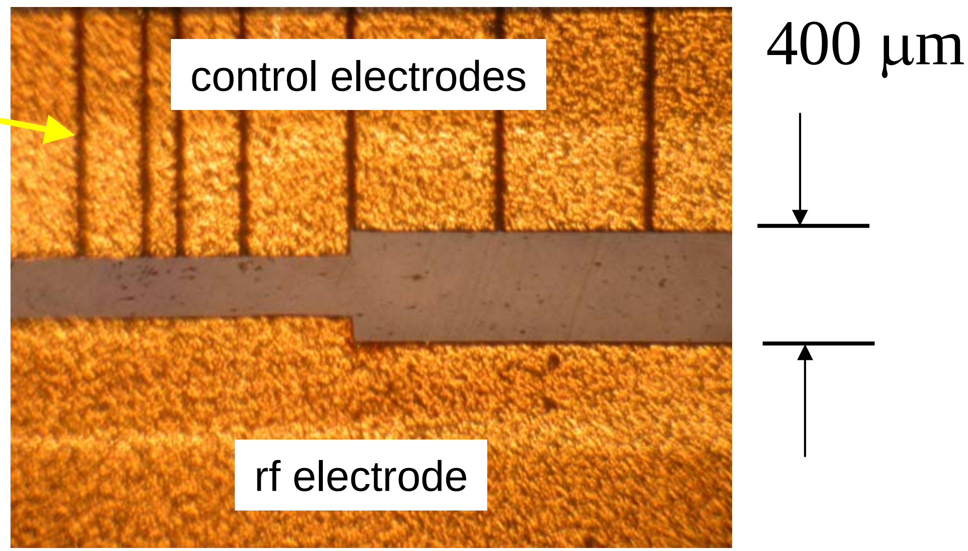
array N→4N:
- no additional motional modes
- mode frequencies same

"only" have to demonstrate basic module

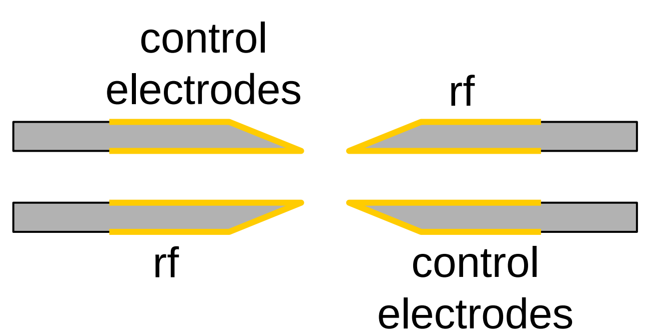
(6-zone) alumina/gold trap (NIST)

(Murray Barrett *et al*.)





view along axis:



What we need to do …

I. **incorporate all building blocks**

more complicated algorithms & metrology, quantum error correction, …

II. **reach operation fidelity of > 99.9%**

reduce sources of technical errors (beam intensity fluctuations,…)

III. **build larger (and more reliable) trap arrays**

new trap fabrication: lithography, chemical machining, MEMS, ?

IV. **“scale” electronics and optics**

integrated electronics and optics (multiplexers, DACs, MEMS mirrors, …)

NIST ions, March, '04

From left to right:

Joe Britton, Jim Bergquist, John Chiaverini, Windell Oskay, Marie Jensen, John Bollinger, Vladi Gerginov, Taro Hasegawa, Carol Tanner, Wayne Itano, Jim Beall, Dave Wineland, Didi Leibfried, Chris Langer, Tobias Schaetz, John Jost, Roee Ozeri, Till Rosenband, Piet Schmidt, Brad Blakestad