Quantum measurement – a paradigm for multiscale science

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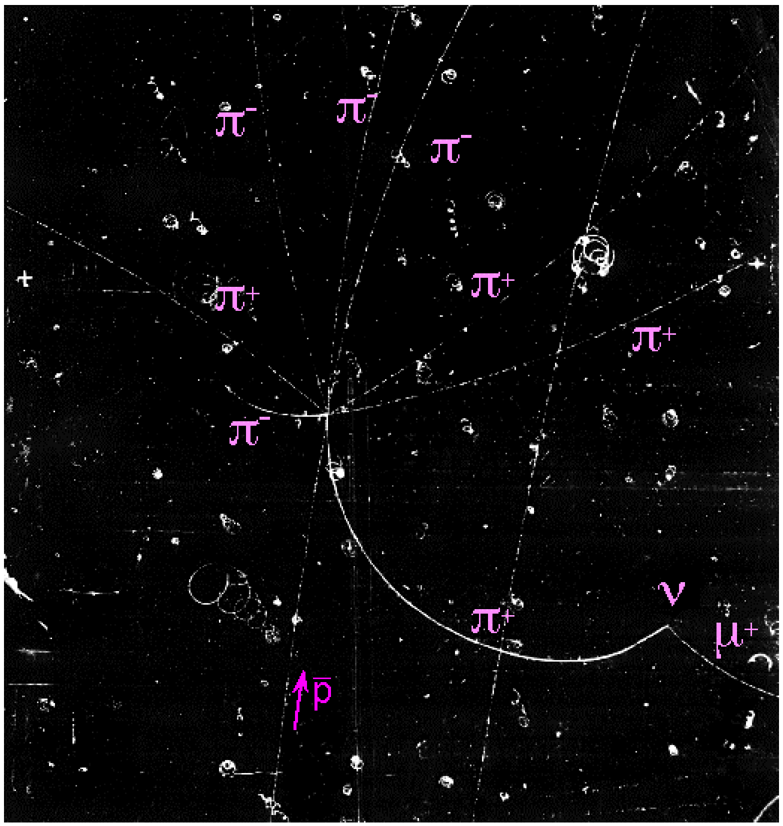
Outline:

- the quantum—classical transition
- quantum measurement "theory"
- quantum feedback control
- adaptive quantum measurements

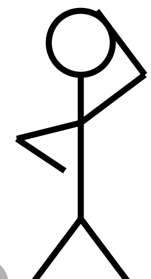
A frontier in the middle?

microscopic
(elementary particle physics)

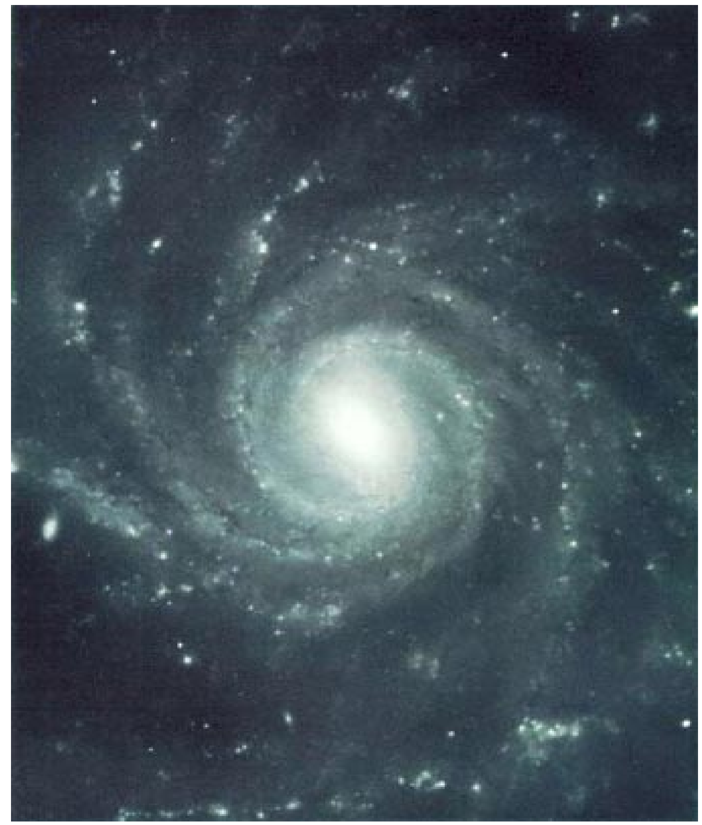


Quantum physics

quantum—classical interface



macroscopic
(galactic dynamics)



Classical physics

Quantum vs. classical phenomenology

microscopic
(individual atoms, electrons, …)

macroscopic
(cells, rocks, airplanes, …)

1q. Some measurable attributes are *complementary*

$$\Delta x \, \Delta p \geq \hbar/2$$

"Heisenberg uncertainty principle"

1c. All measurable attributes are *compatible*

the safe is ten feet above my head **and** falling at 50 mph

2q. Uncertainty can be *intrinsic*

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|x_1\rangle + |x_2\rangle\right)$$

2c. Uncertainty is ignorance

will the safe hit me if I don't move?

3q. Et cetera …

3c. Et cetera …

Quantum measurement theory

def: a strange piece of orthodoxy whose unenviable job is to predict what happens when we perform experiments on microphysical systems with macroscopic equipment (how do particles move dials?).

"Jumping over" the interface apparently induces/requires:

- irreducible randomness
- projection into orthogonal "alternatives"

⊠ x_1 + ⊠ x_2 ♦ ⊠ x_1 *or* ⊠ x_2

conj: quantum measurement is a Rosetta Stone for the quantum—classical transition.

Multiscale perspective:

- *Show that measurement rules can be derived by model reduction*
- *Show that the canonical rules are approximate by extreme testing*

Quantum measurement theory?

• we know that quantum theory can be used to predict the statistics of measurement outcomes, with exquisite accuracy

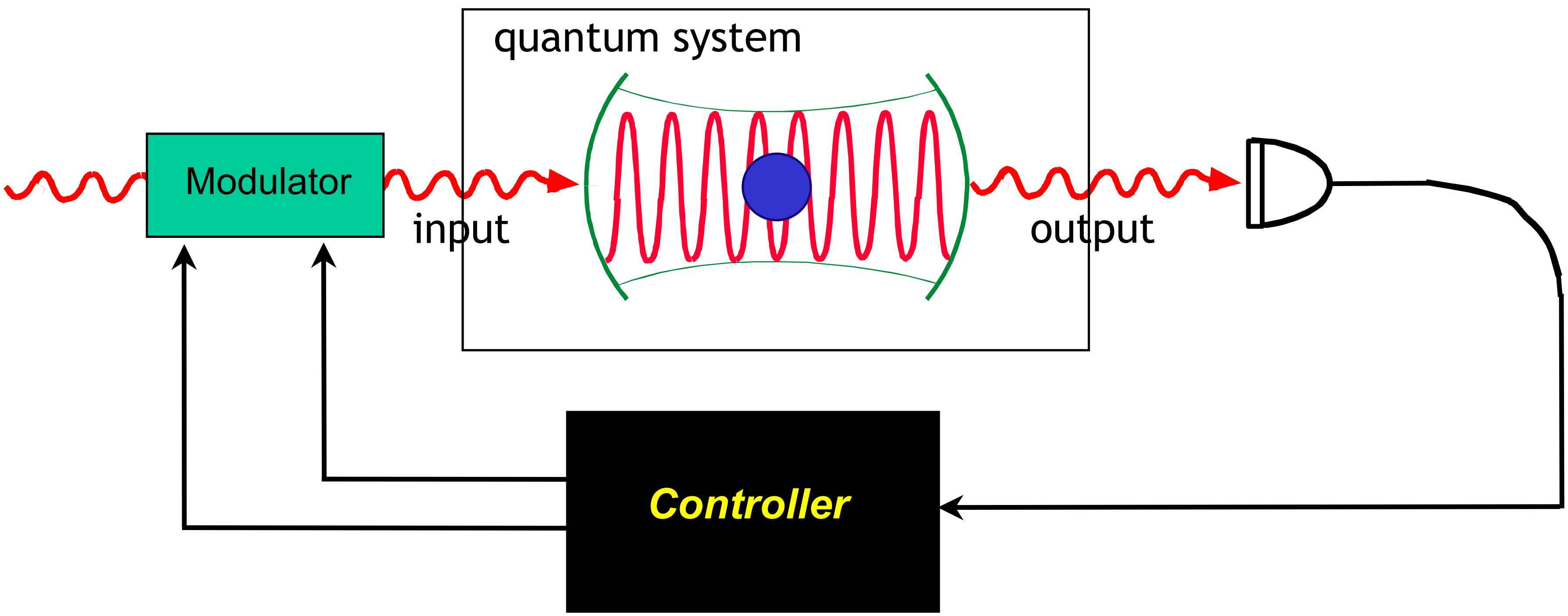
• we're not so sure that we really know how to predict the post-measurement state of a system, given a particular outcome

conditional evolution

can't measure the state of a single quantum system!

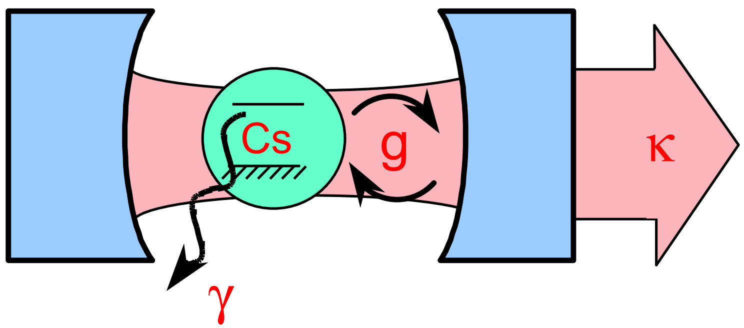
Feedback control tests conditional evolution

<u>input—output</u> perspective on conditional evolution of
continuously-observed quantum systems



- design controller to be sensitive to conditional dynamics
- closed-loop input—output behavior verifies model

Cavity quantum electrodynamics



Critical photon number

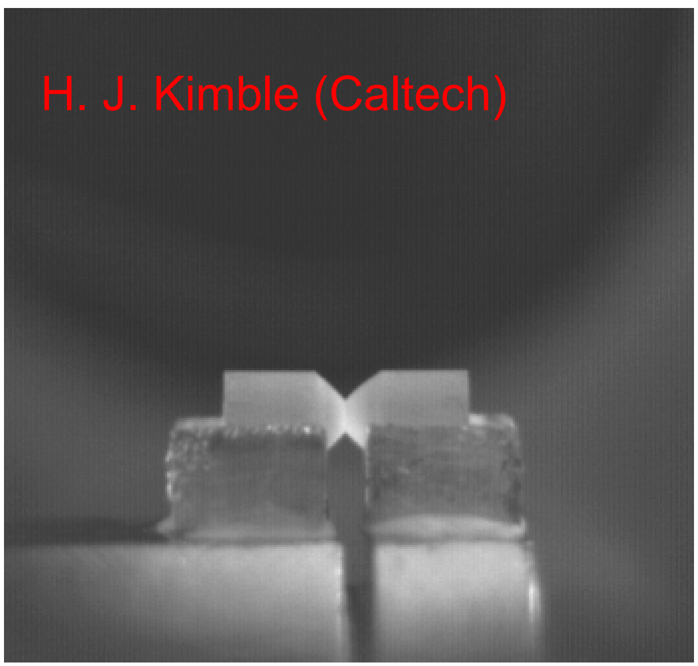
$$m_0 \approx \frac{\gamma^2}{2g^2} < 1$$

Nonlinear optics with *one photon* per mode

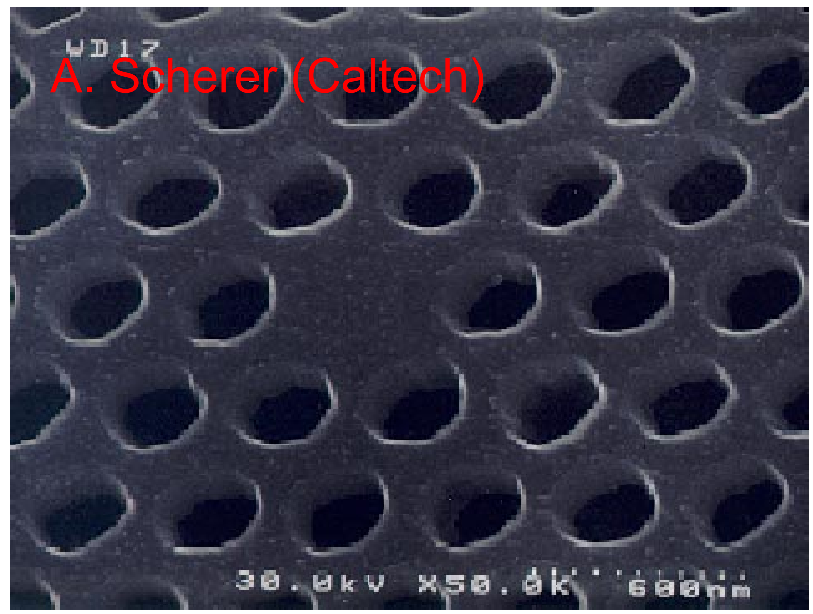
Critical atom number

$$N_0 \approx \frac{2\gamma\kappa}{g^2} < 1$$

Single-atom switching of optical cavity response

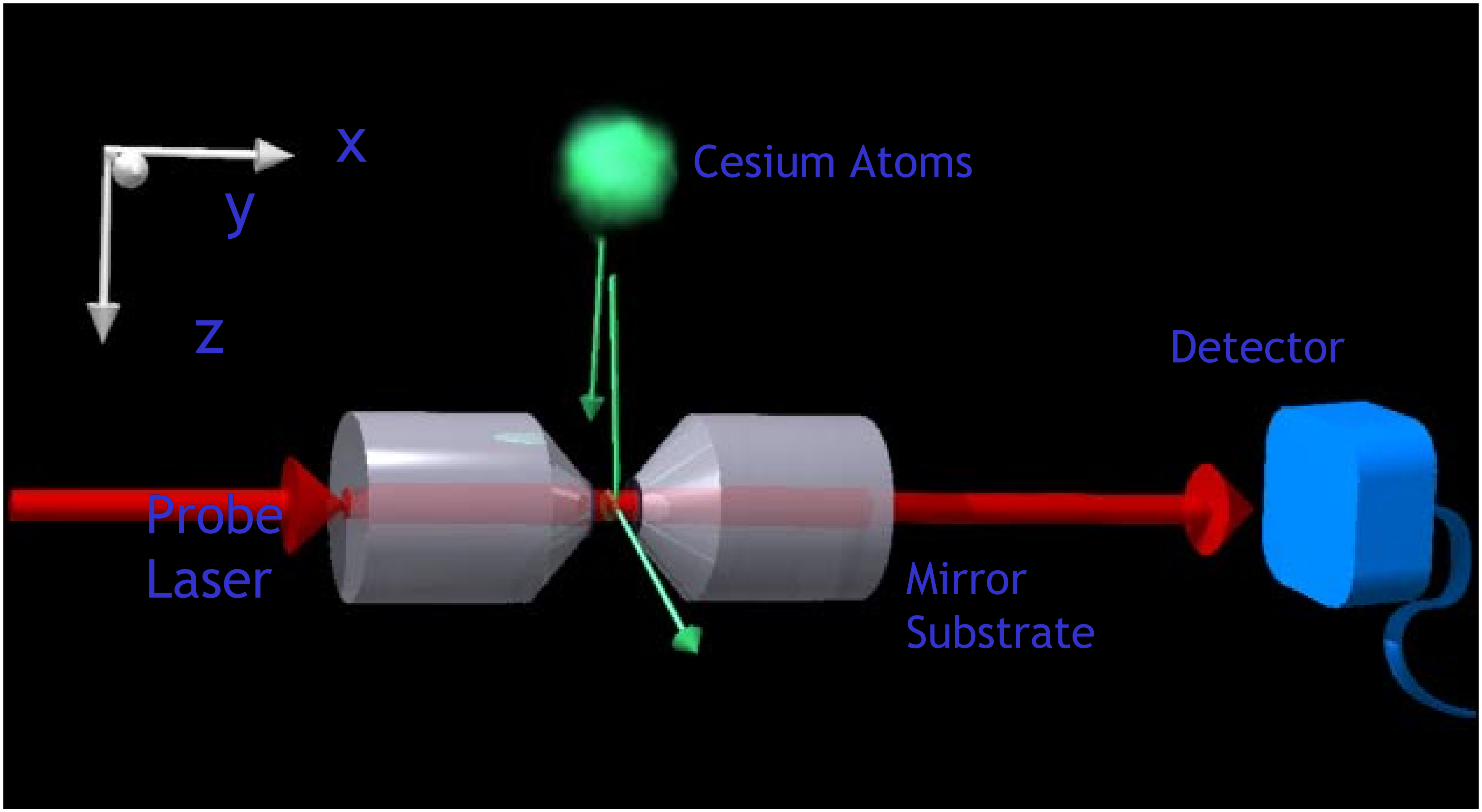


$m_0 \approx 10^{-4}$ $N_0 \approx 10^{-3}$



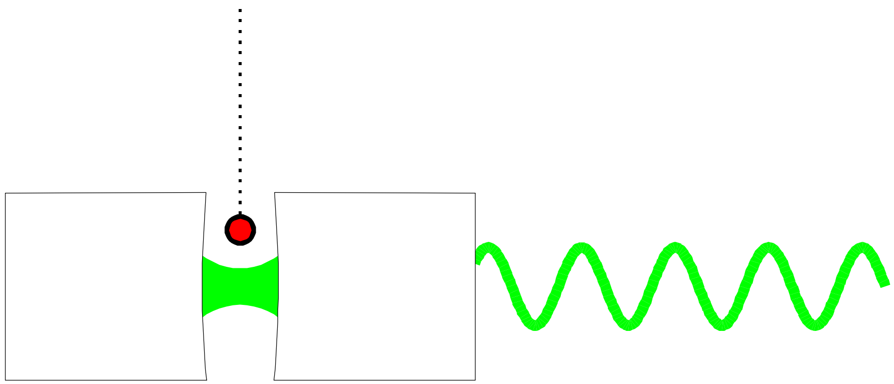
m_0 ? 10^{-8} N_0 ? 10^{-2}

Cavity QED with cold atoms

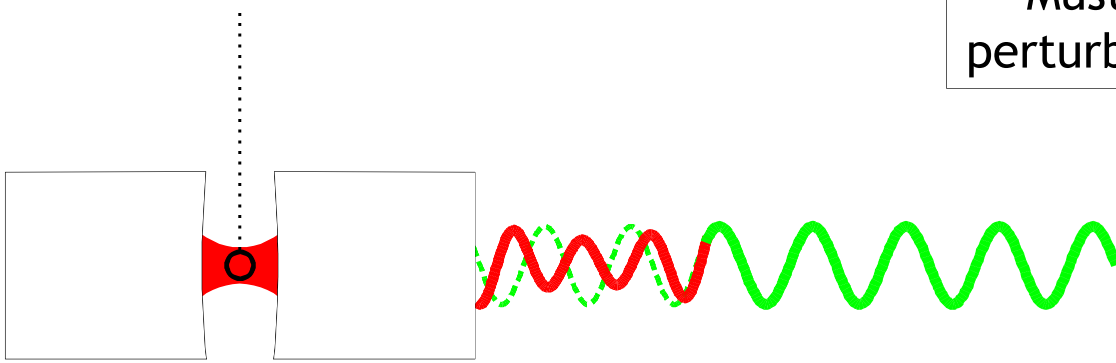


C. J. Hood

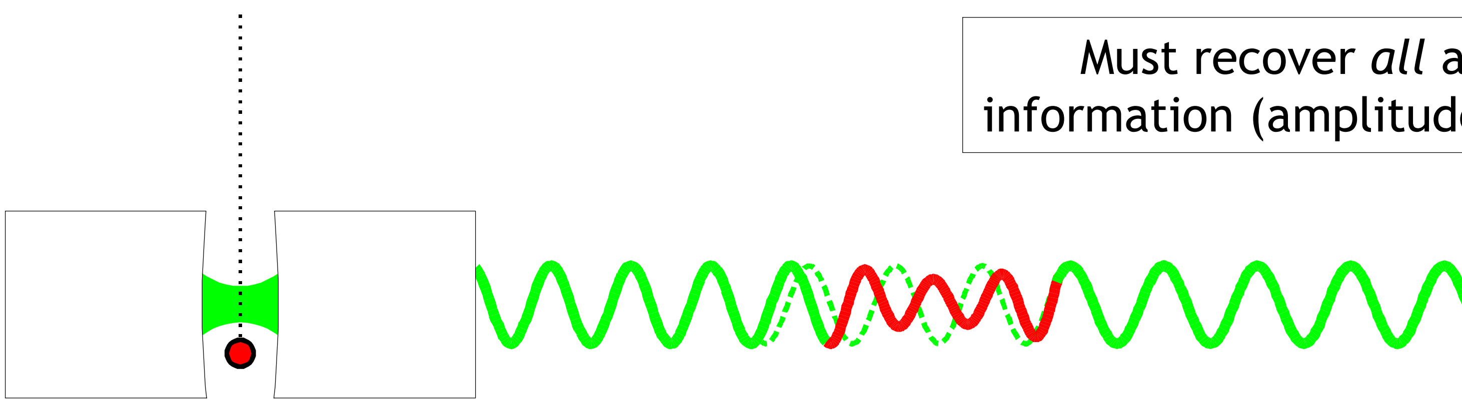
Full observation of single-atom dynamics



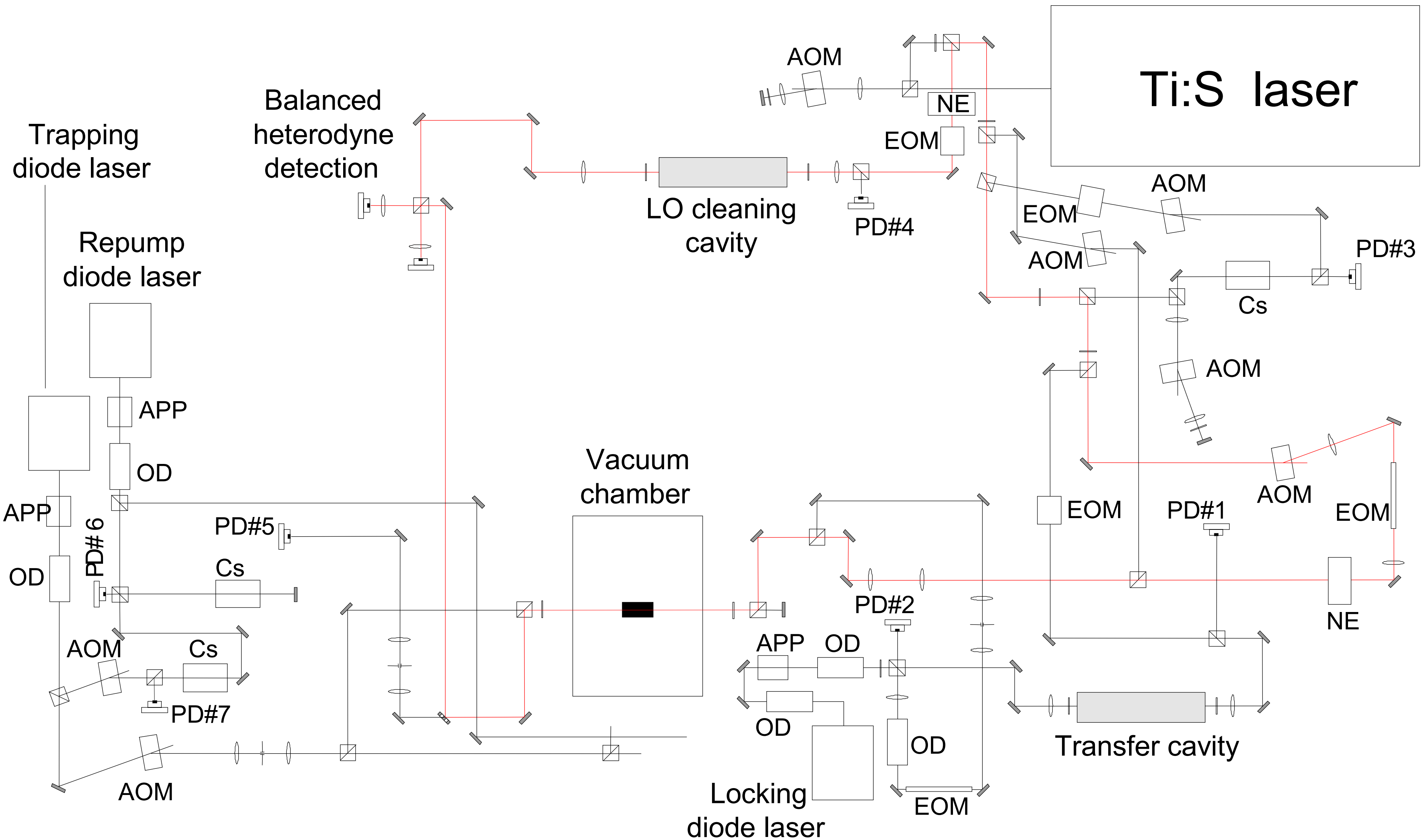
Must realize minimum possible
perturbation per information gained



Must recover *all* available
information (amplitude and phase)

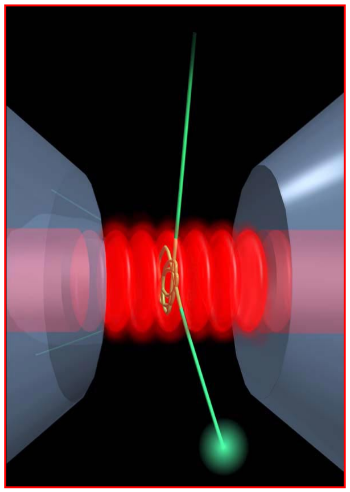


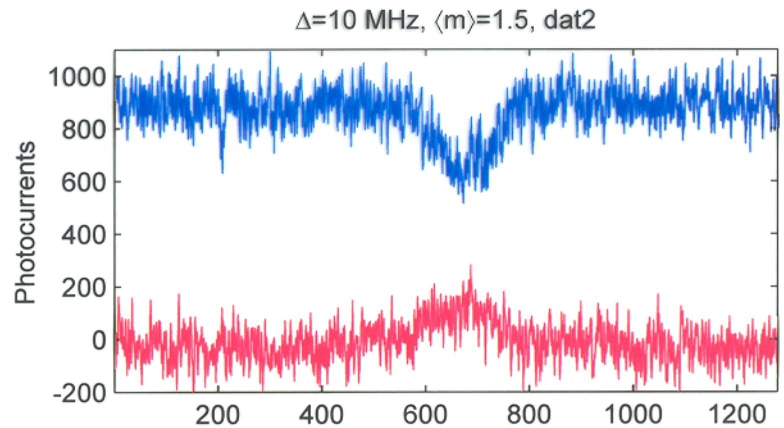
Cavity QED with cold atoms (really)

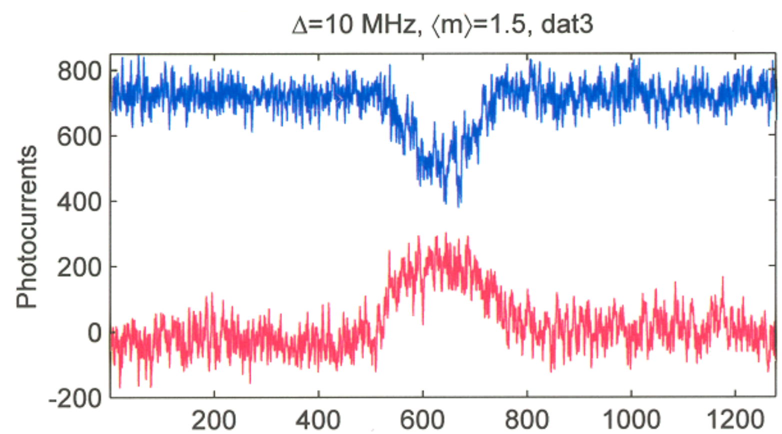


Single-atom spatial trajectories

(with J. Ye and H. J. Kimble)

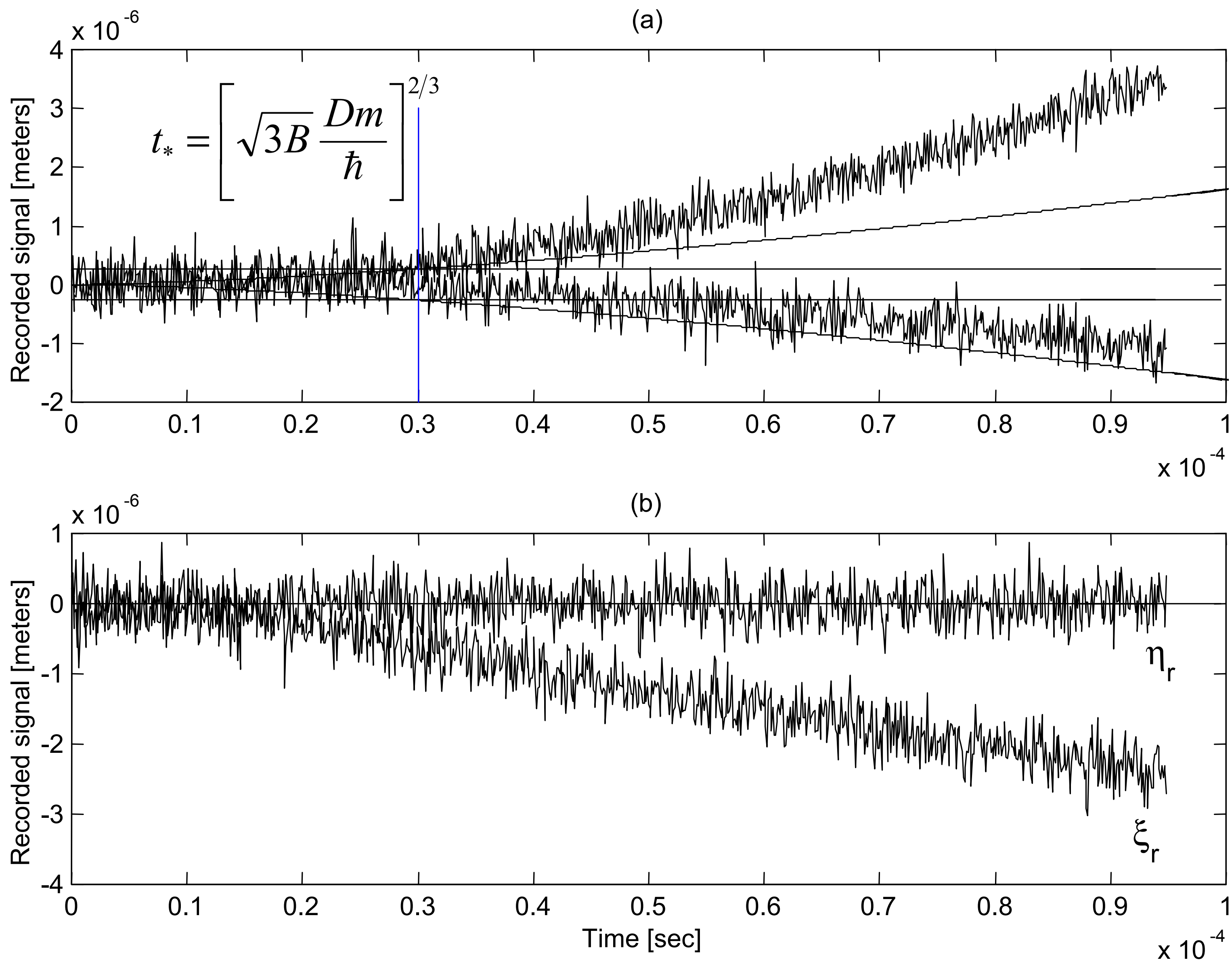






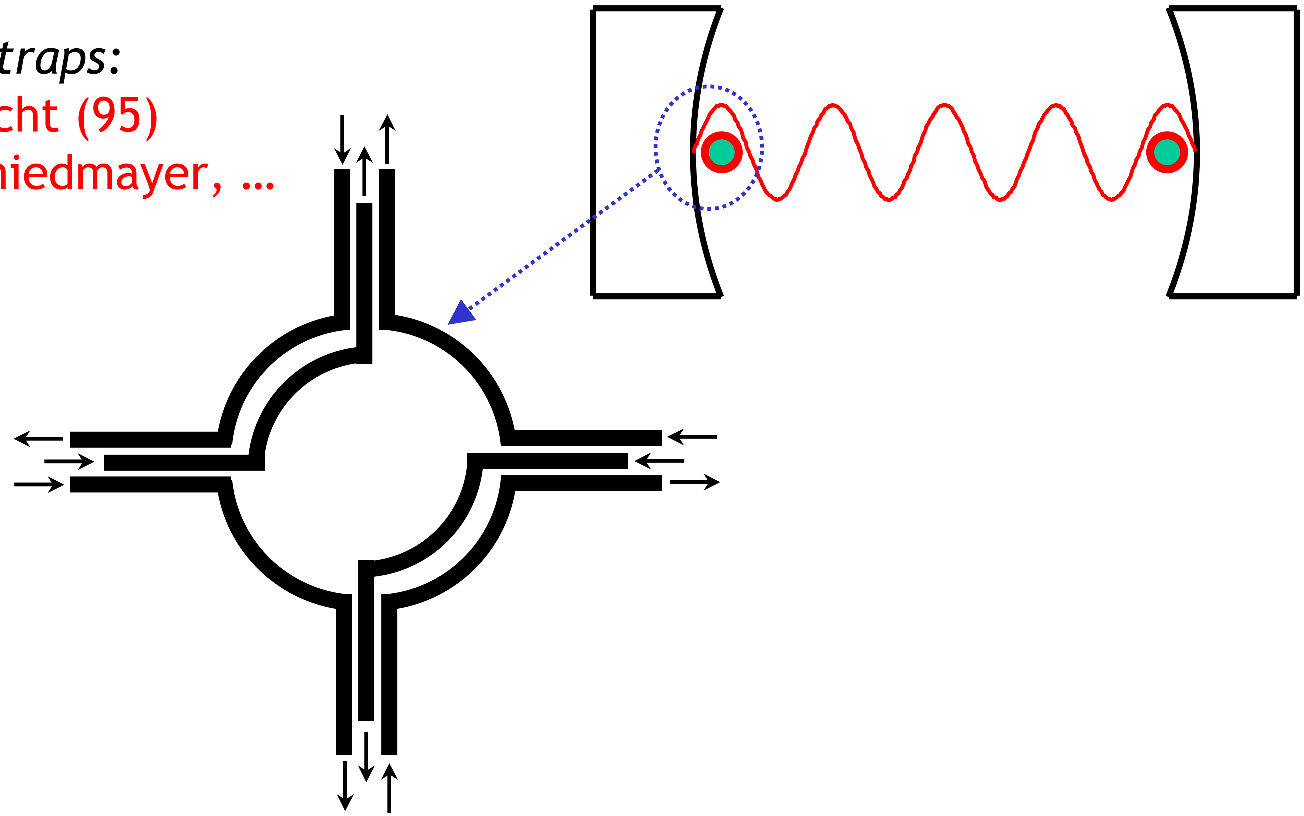
- quantum-limited sensitivity, we believe
- but how to prove it?

Proving you're at the SQL (simulated!)

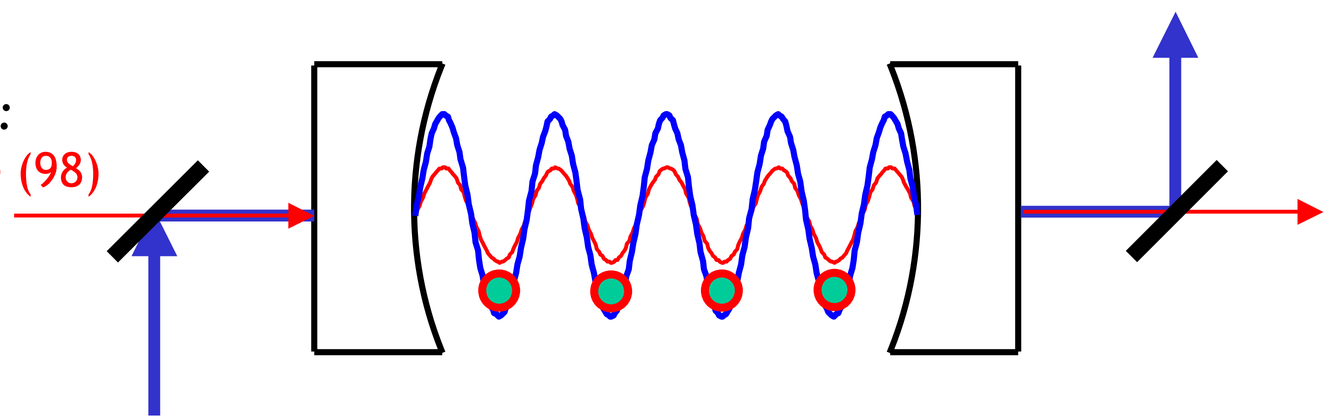


Intracavity atom traps

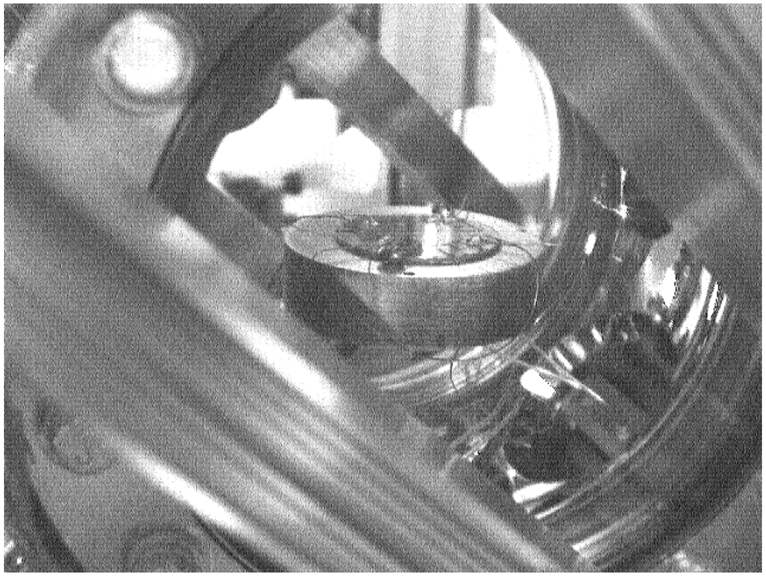
Planar magnetic microtraps:
Weinstein and Libbrecht (95)
Haensch, Hinds, Schmiedmayer, …

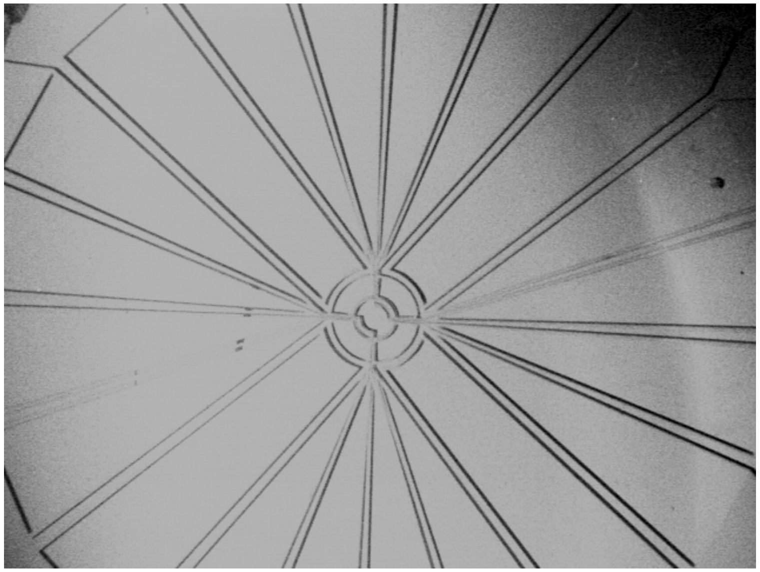


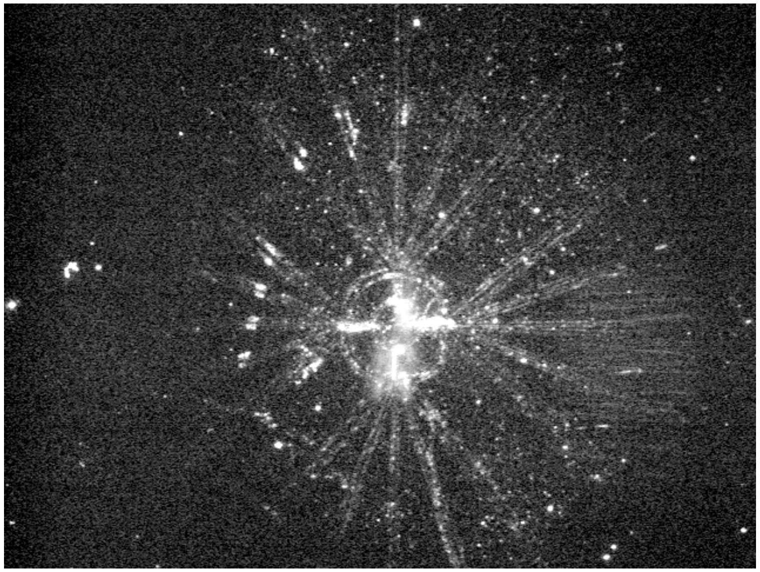
Intracavity optical lattice:
Vernooy, Ye, and Kimble (98)
Jessen, Deutch, …



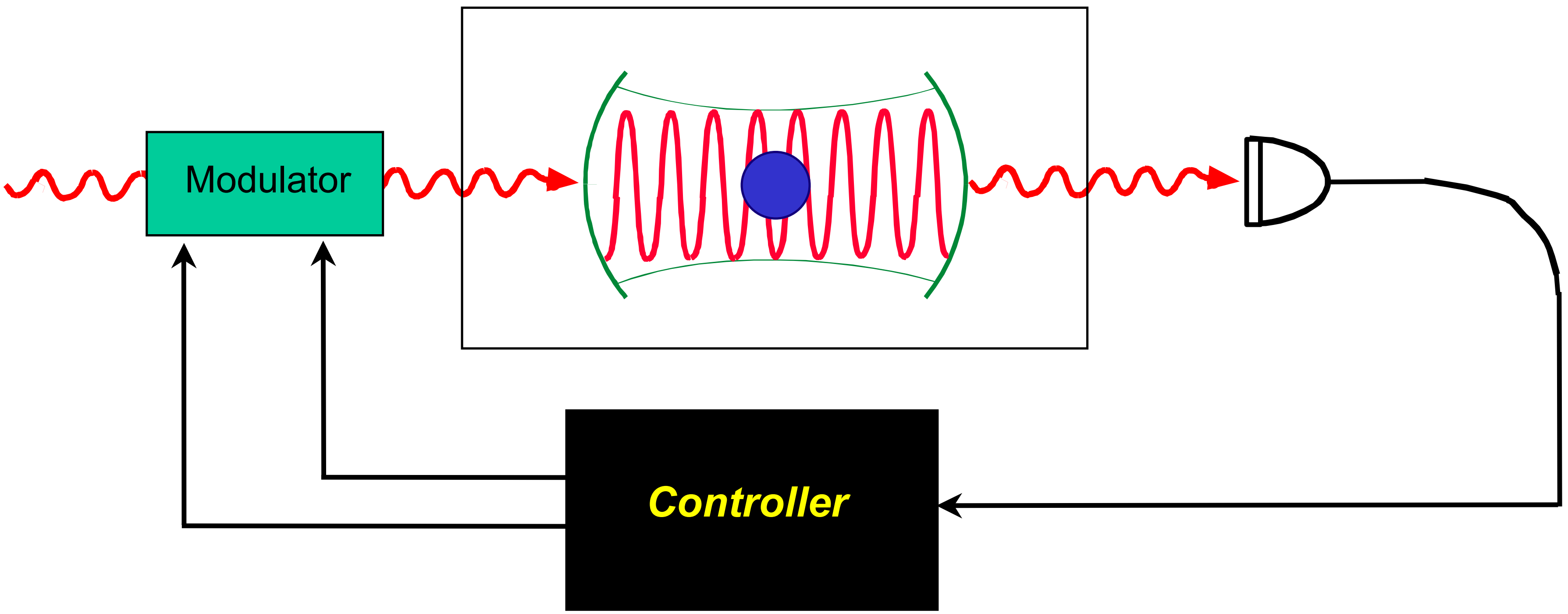
Micromagnetic traps

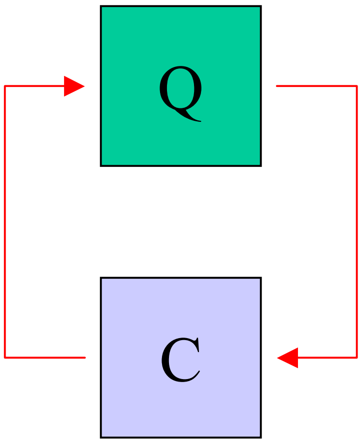






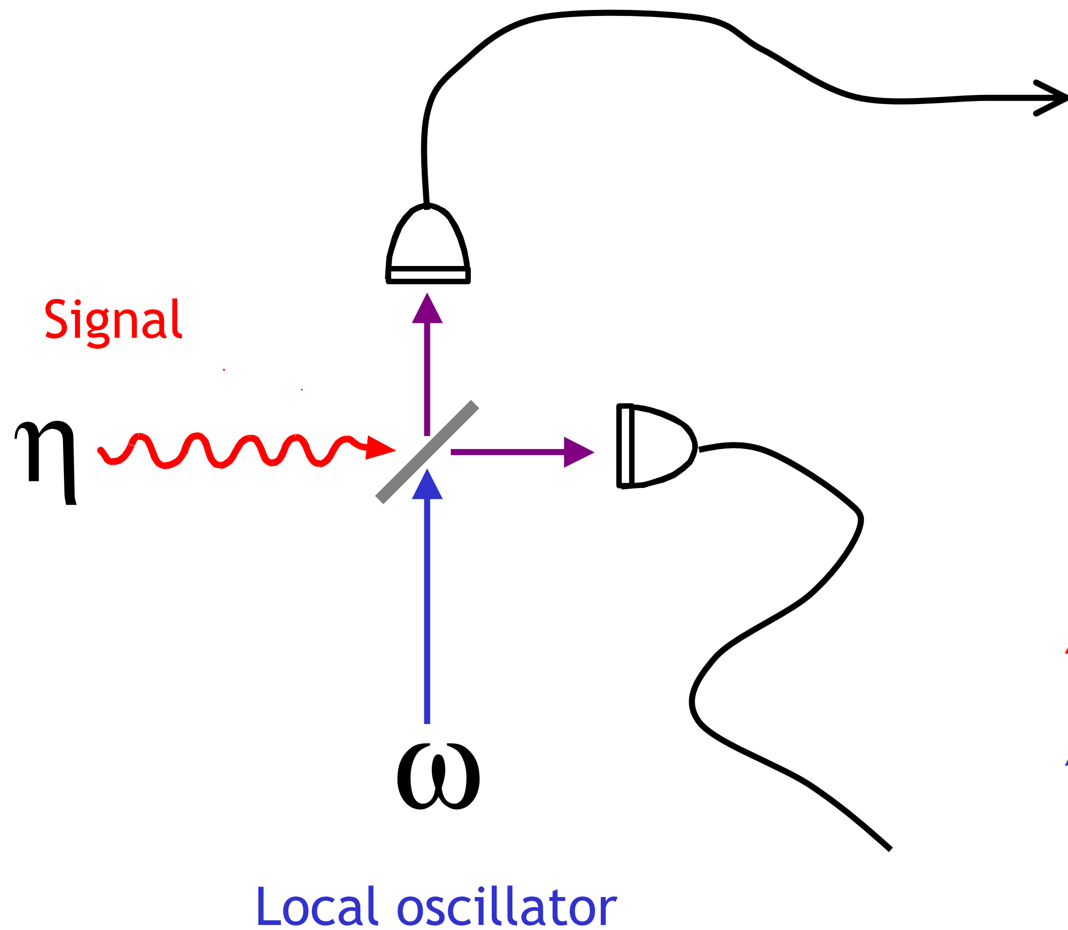
Quantum feedback control

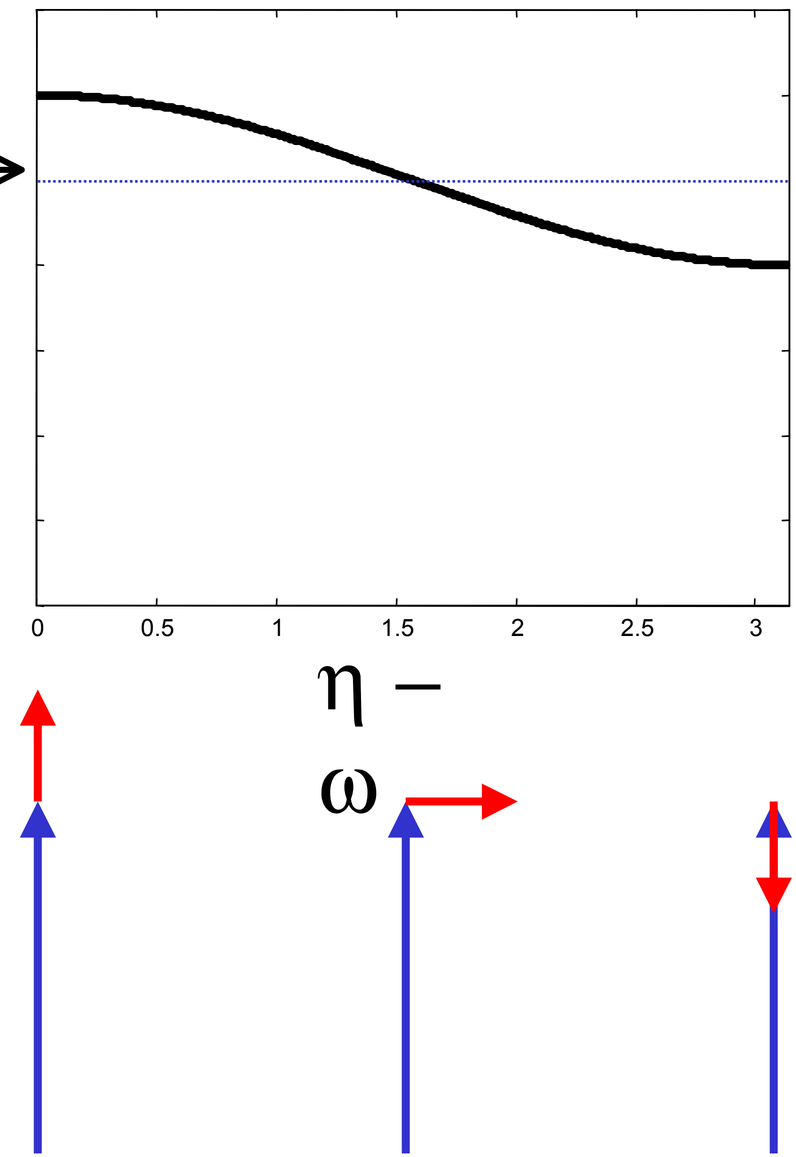




- Reaching through the quantum—classical—quantum interface
- Feedback provides a tool for managing uncertainty
- Stabilization against noise, quantum noise
- Closed—loop measurement and system identification

Optical homodyne measurement

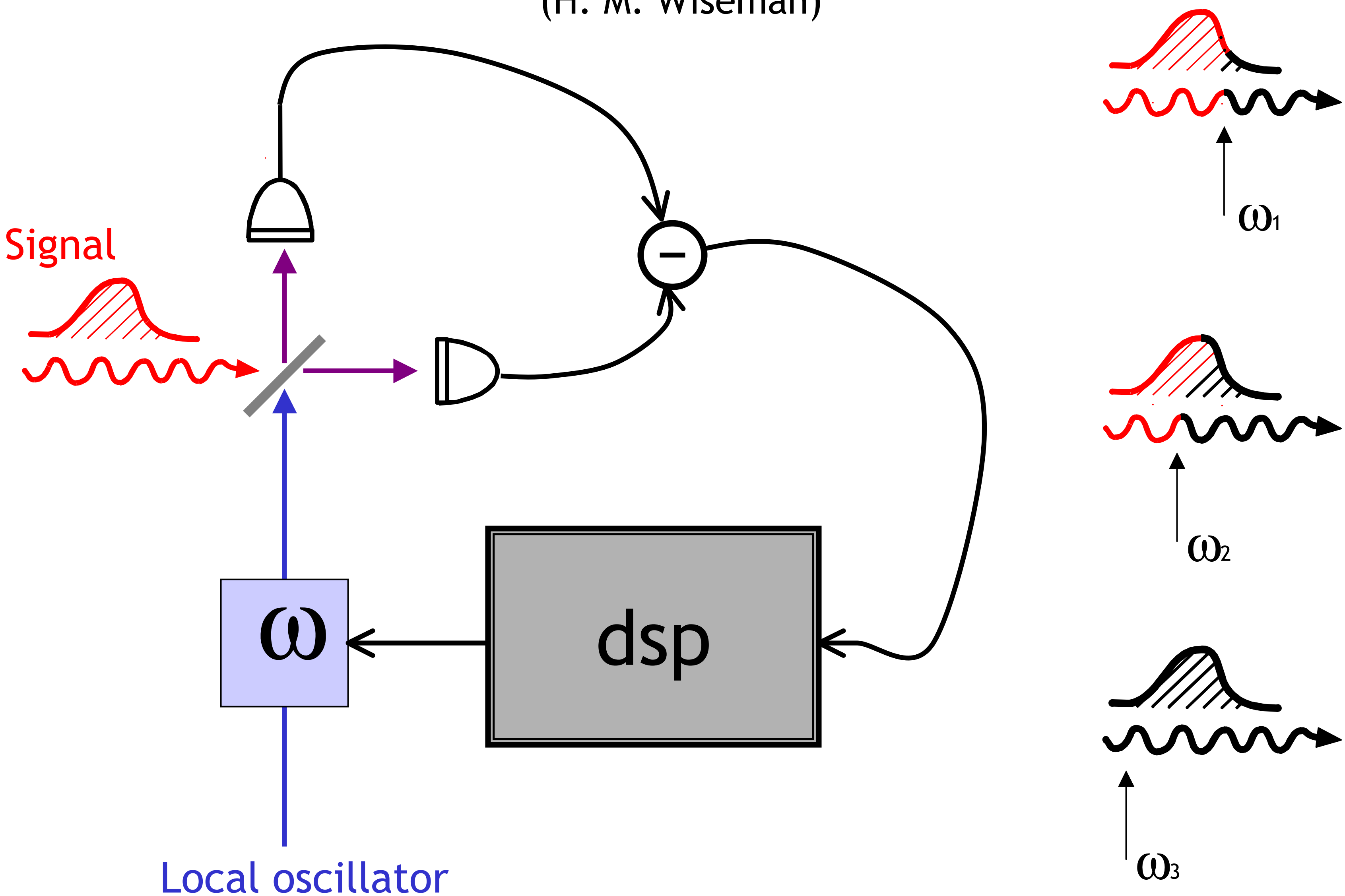




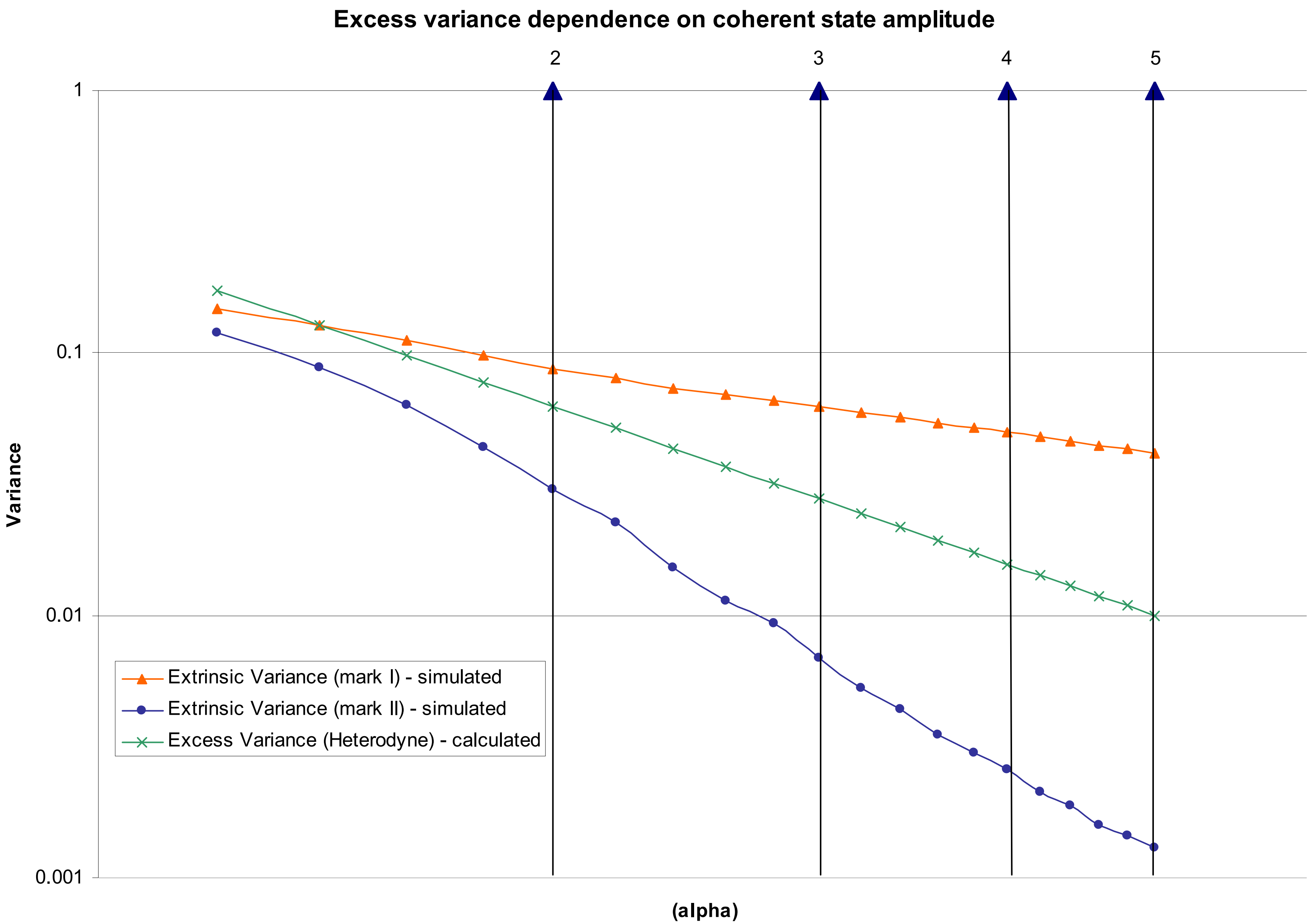
approximates canonical phase measurement,
given prior knowledge of mean phase

Adaptive homodyne measurement

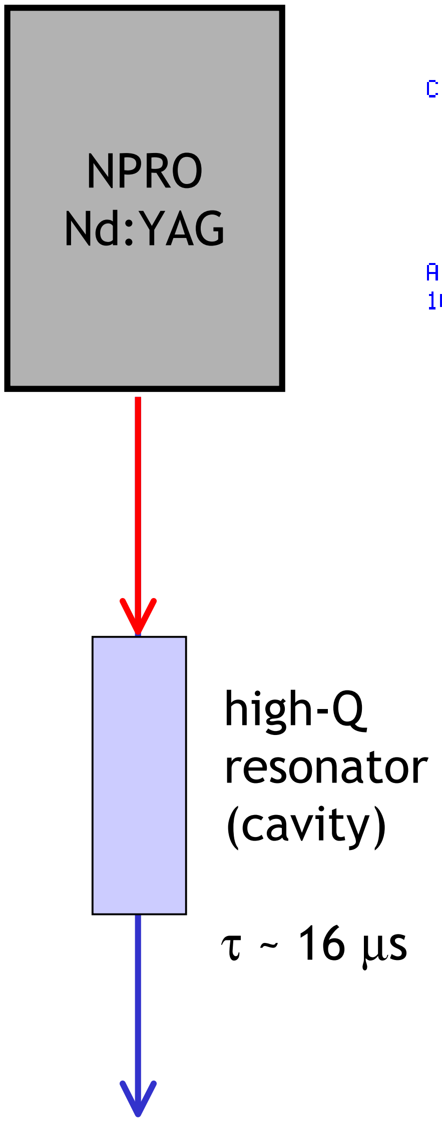
(H. M. Wiseman)

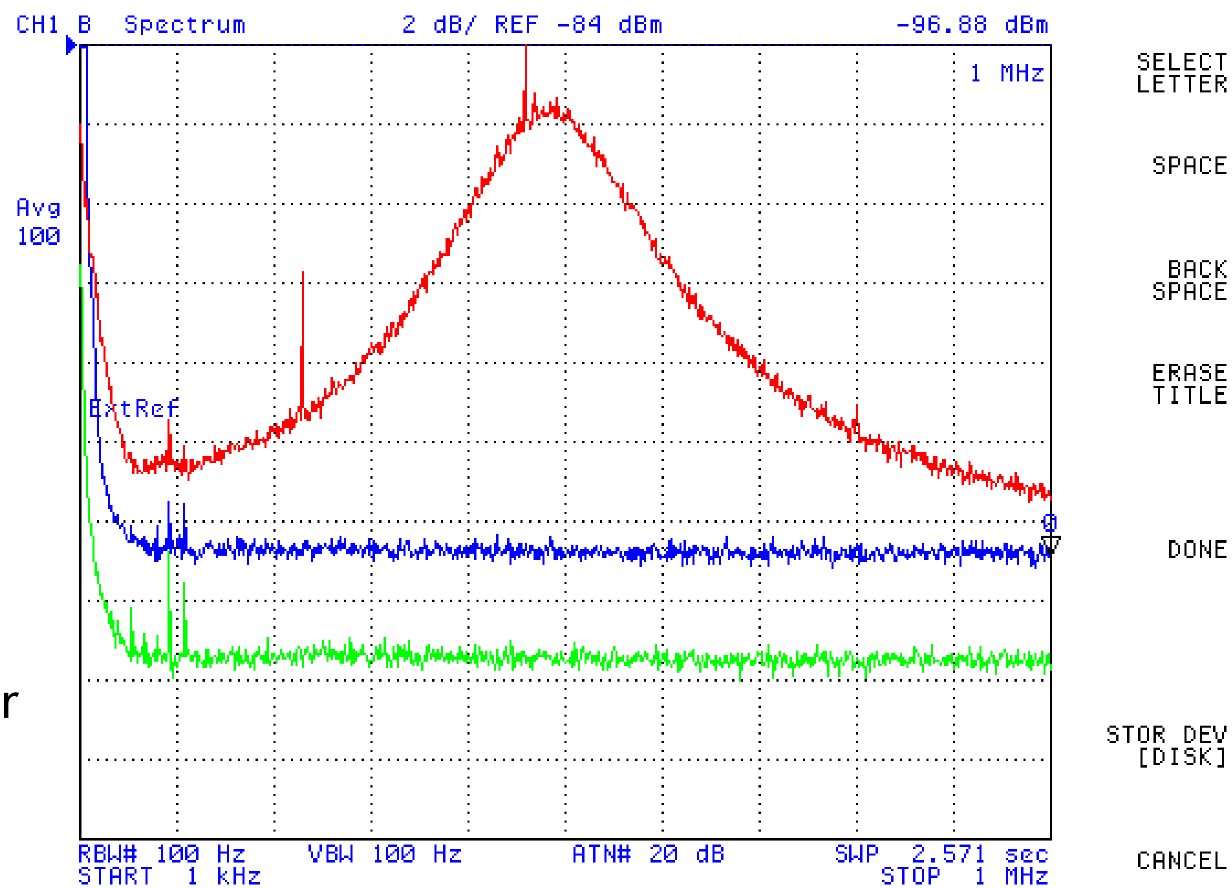


Quantitative analysis of algorithms

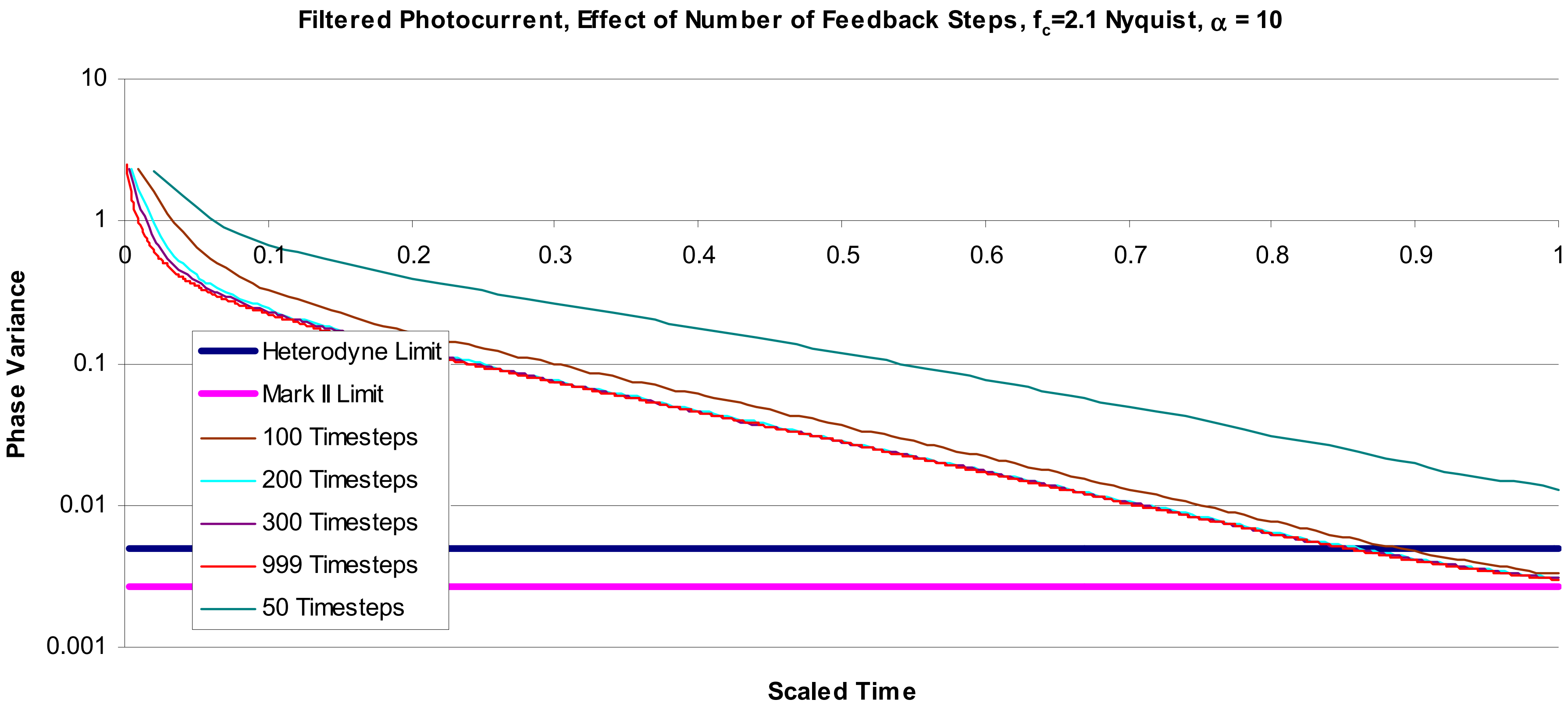


Technical challenges – laser noise

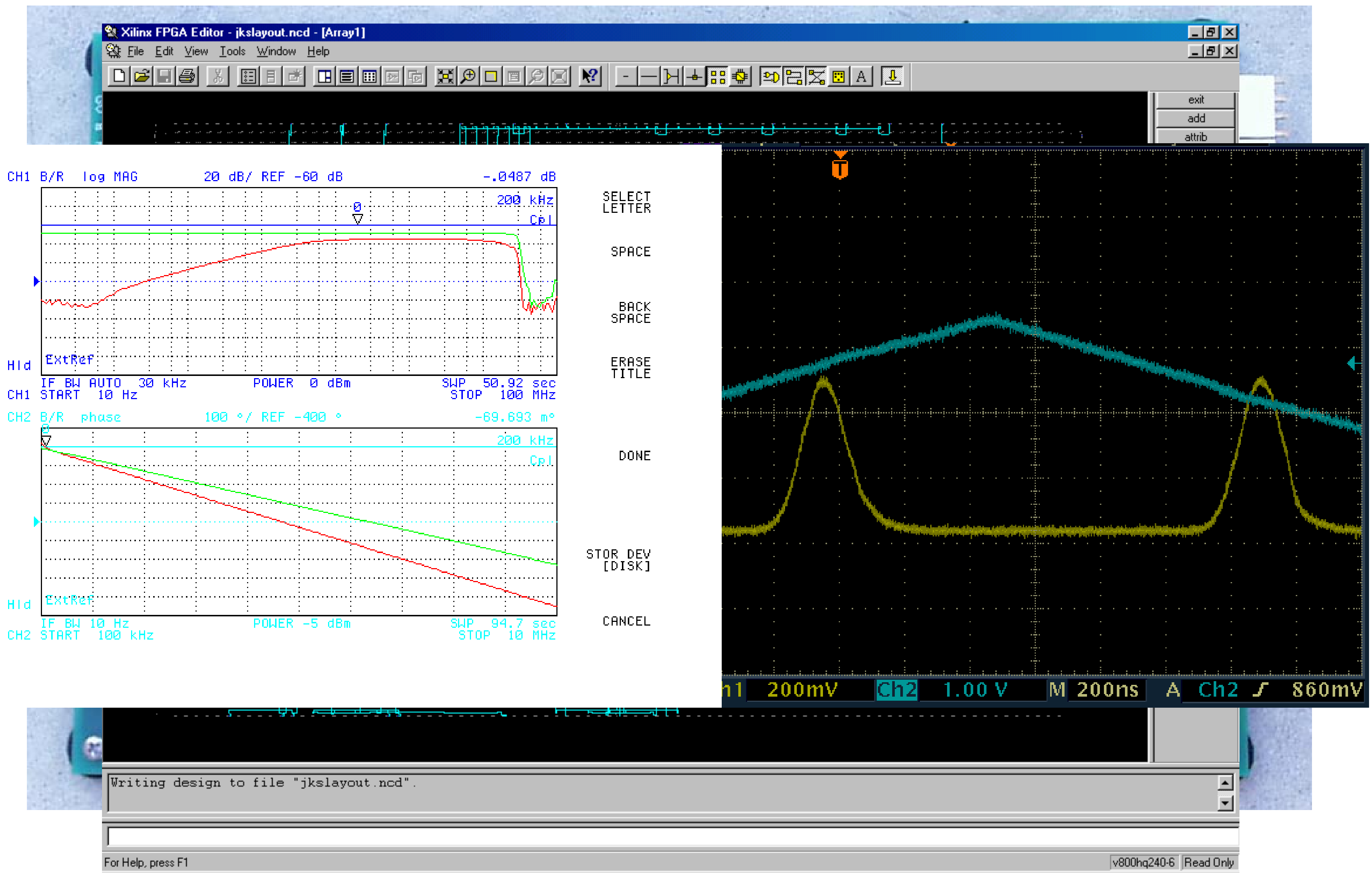




Technical challenges – loop delay



Field-Programmable Gate Arrays



Closing the loop