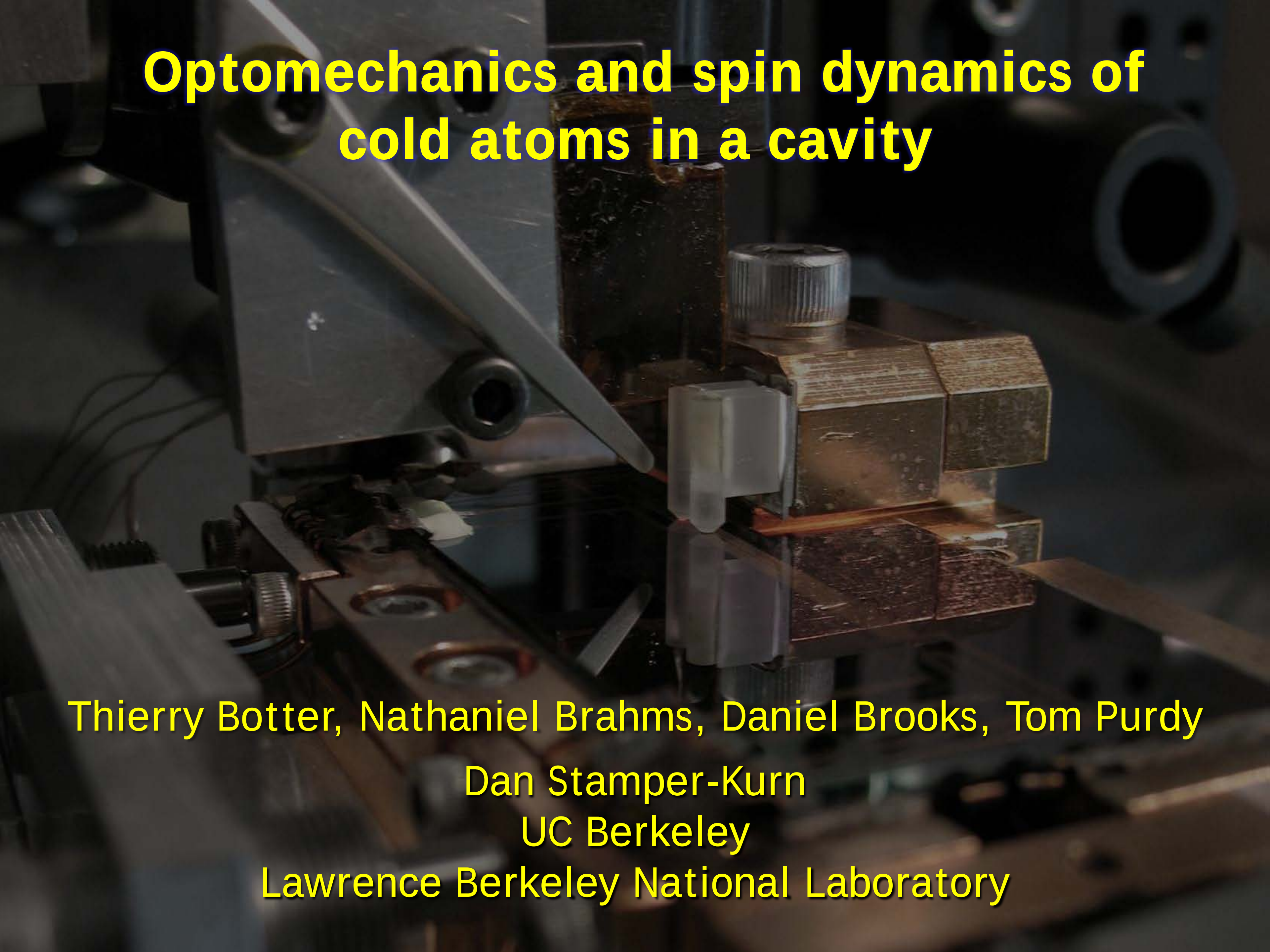

Optomechanics and spin dynamics of cold atoms in a cavity

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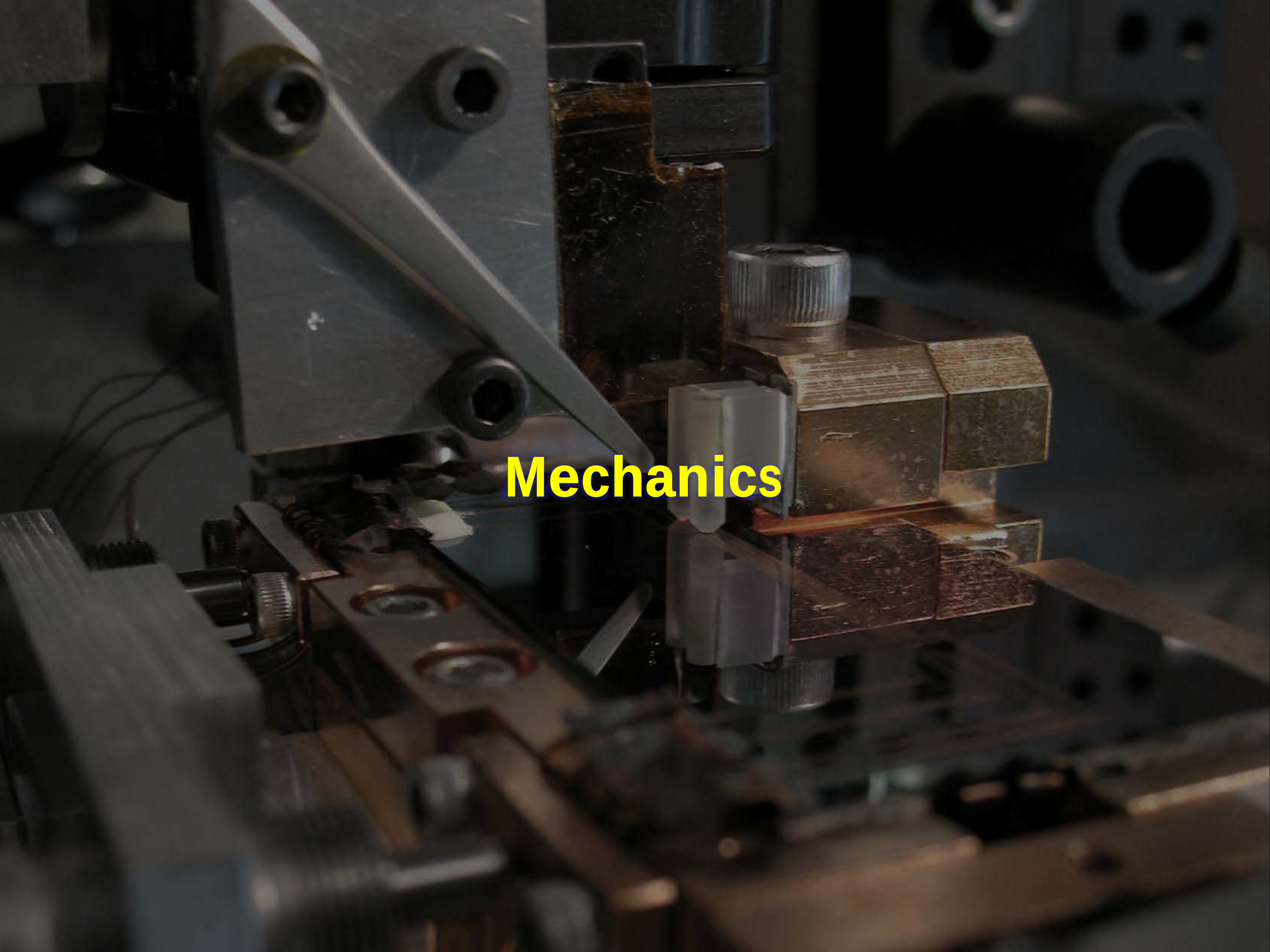
Dan Stamper-Kurn
UC Berkeley
Lawrence Berkeley National Laboratory

- Ultracold atomic gas
  - collective variables: motion, spin
  - long-coherence, state preparation
- High-finesse, small-volume cavity
  - enhanced dispersive sensitivity
  - controlled, strong measurement back-action

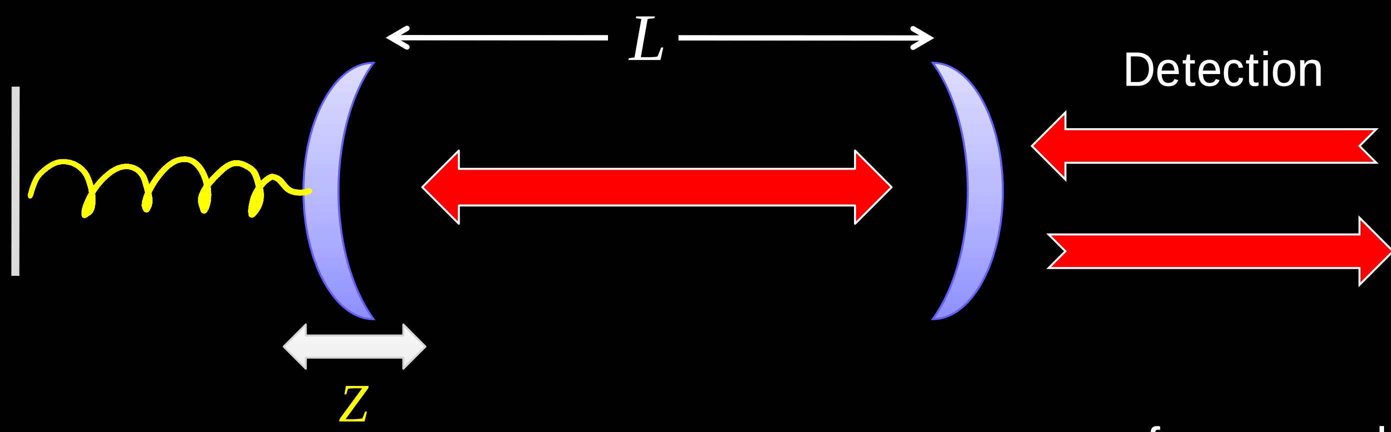
- microscopy of quantum systems
- quantum metrology
- “hybrid” quantum systems of atoms and light

Why “beyond standard optical lattice” folks might care

- Optical probes of optical lattice systems
- Many-body physics in a Hamiltonian with backaction
- Many-body physics in a system under constant measurement
- Cavity-mediated interactions b/w mechanical elements, atomic spins, both: ≠ super-exchange
- Motion ⇔ spin
- Potential for using solid-state optomechanical systems as quantum simulators


Mechanics

One paradigm for cavity optomechanics



$$\phi = \frac{Z\,f}{\hbar\kappa}$$

force per photon:

$$f = \frac{hc}{\lambda L}$$

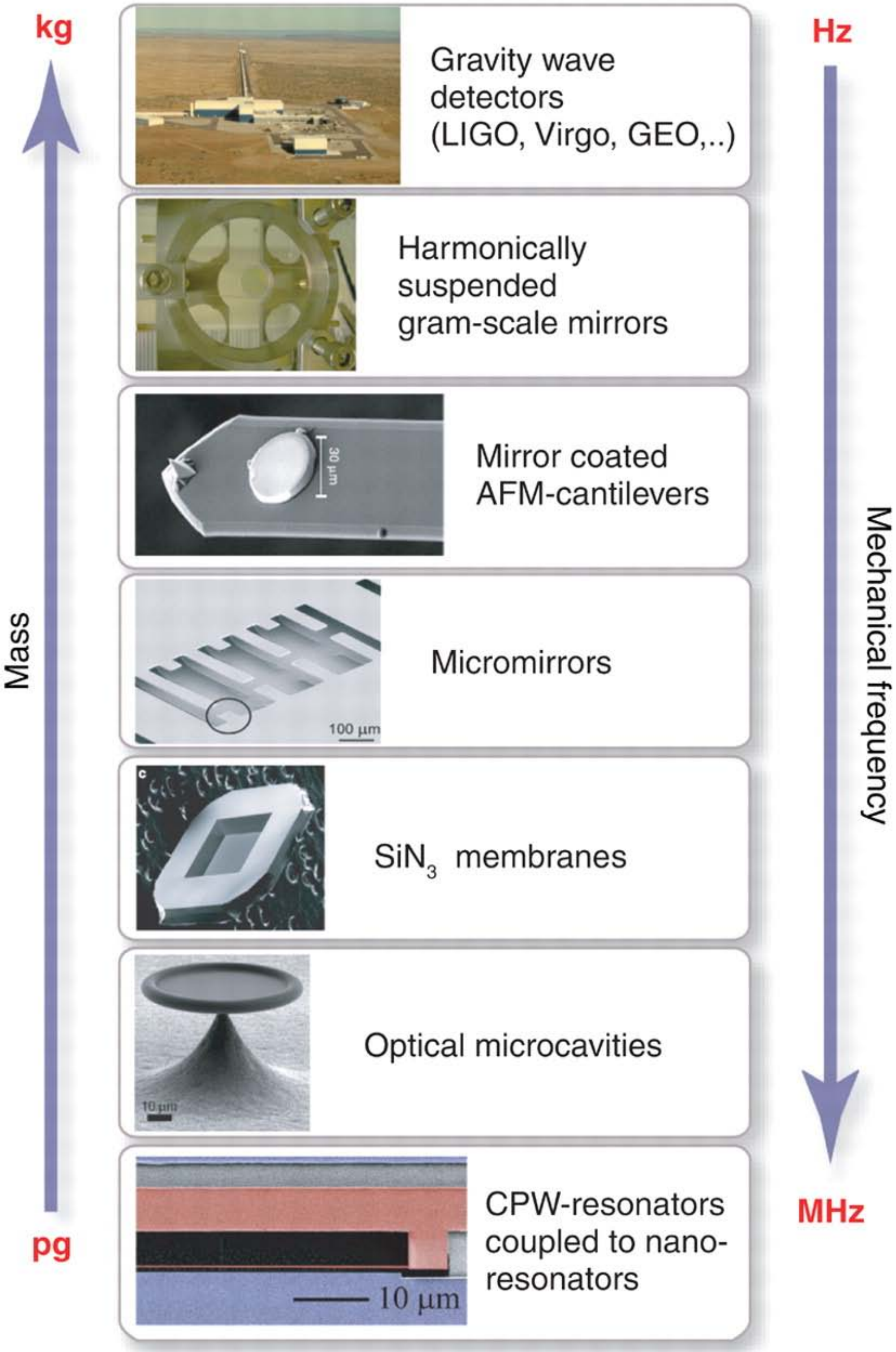
$$H = H_{osc} + H_{cav} + H_{in/out} - Z\,f\,n$$

Cavity frequency shift due to oscillator displacement

(sensitivity to oscillator motion)

Optical force on oscillator

(optical back-action on oscillator)



Common goals:

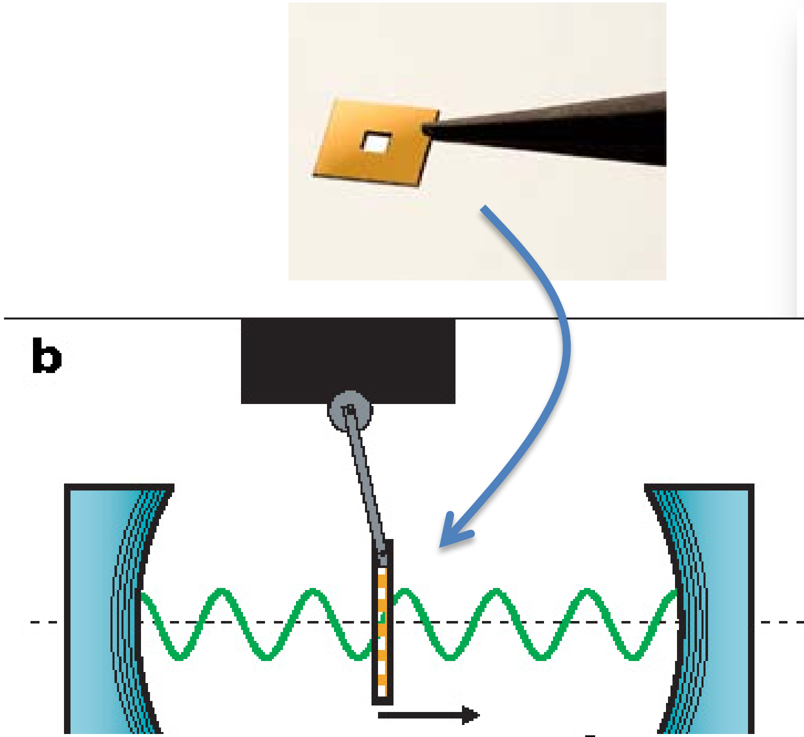
- Dominance of quantum fluctuations over thermal fluctuations
  - cooling mechanical oscillator to ground state
  - reaching quantum limits for sensitivity
- Study and use quantum effects
  - quantifying measurement backaction
  - squeezed light (pondermotive squeezing)
  - entanglement of macroscopic object with light

Common means:

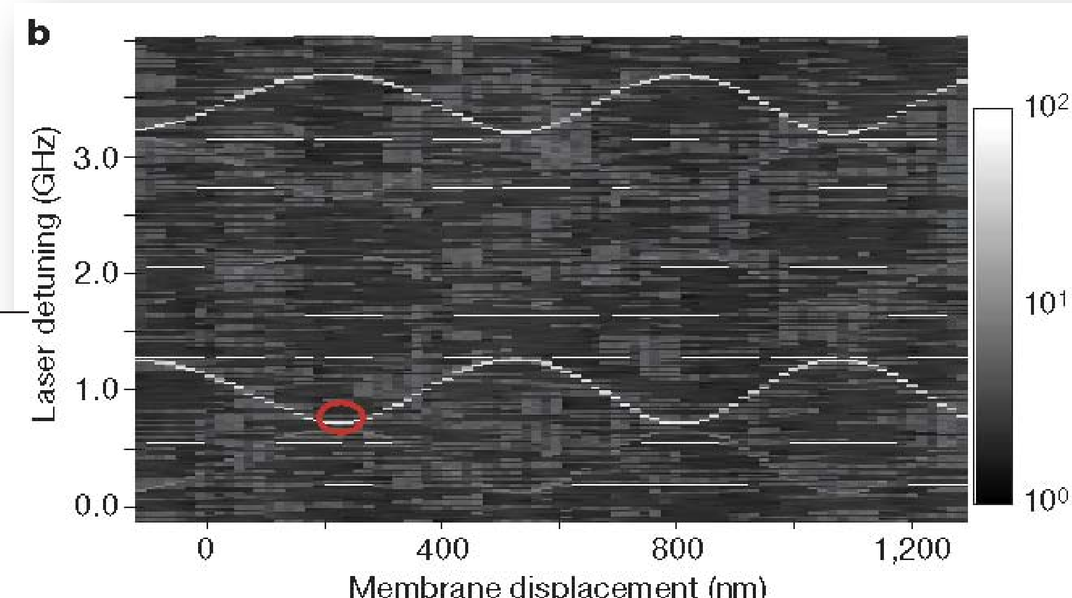
- Better isolation from environment
- Colder starting points
- Stronger optomechanical coupling

Kippenberg and Vahala, Science **321**, 1172 (2008)

Experimental Cavity Optomechanics:
e.g. mechanical oscillator = membrane



$$\varphi = 2kZ_0$$



Harris group (Yale), Nature **452**, 72 (2008)

$$H_{om} = E(2\varphi)\hat{n} - F\sin(2\varphi)\hat{Z}_{CoM}\hat{n} - Fk\cos(2\varphi)\hat{Z}^2_{CoM}\hat{n} + \ldots$$

linear coupling:
optical spring, bistability,
ponderomotive squeezing...

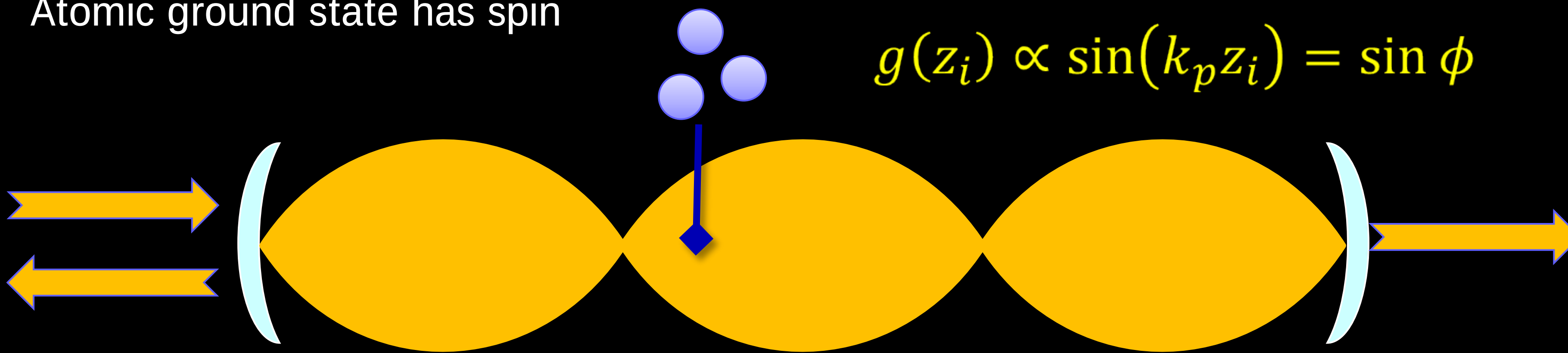
quadratic coupling:
phonon QND,...

Many atom cavity QED

Atomic ground state has spin

light-atom coupling(s)

$$g(z_i) \propto \sin(k_p z_i) = \sin\phi$$



Dispersive regime (detuning Δ_{ca} is large):

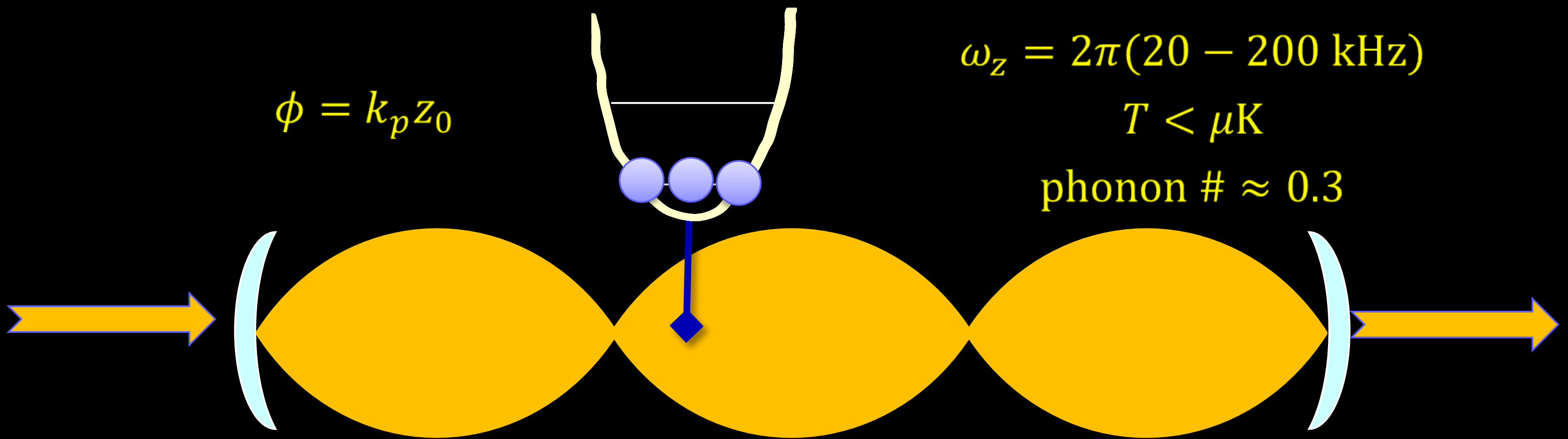
Cavity frequency shift per atom:

$$\frac{g_s^2(z_i)}{\Delta_{ca}}\left(1 + \varepsilon\hat{k}\cdot\vec{s_i}\right)$$

Coupling to collective position variables
(atoms = membrane)

Coupling to collective spin variables
(circular birefringence, magneto-optics)

Tunable cavity optomechanics with cold atoms



$$H_{om} = \sum_{atoms} \frac{\hbar g^2(\hat{z}_i)}{\Delta_{ca}} \hat{n} \simeq \hbar\Delta_N^0 \hat{n} - F \sin(2\phi)\, \hat{Z}_{CoM} \hat{n} - F\, k_p \cos(2\,\phi) \left[\hat{Z}_{CoM}^2 + \hat{\sigma}^2\right] \hat{n}$$

- Tunability of optomechanical coupling (strength, type)
- Immediately in the quantum regime (ultracold)
- Dominated by quantum radiation pressure fluctuations (thermally isolated)
- Connected directly to basic theory (quantum optics, atomic physics)

Granular regime of optomechanics

define dimensionless granularity parameter:

$$\varepsilon = \frac{Z_{SQL}}{\delta Z = \hbar\kappa / F}$$

$$\frac{\text{zero-point position spread}}{\text{measurement uncertainty from single photon}}$$

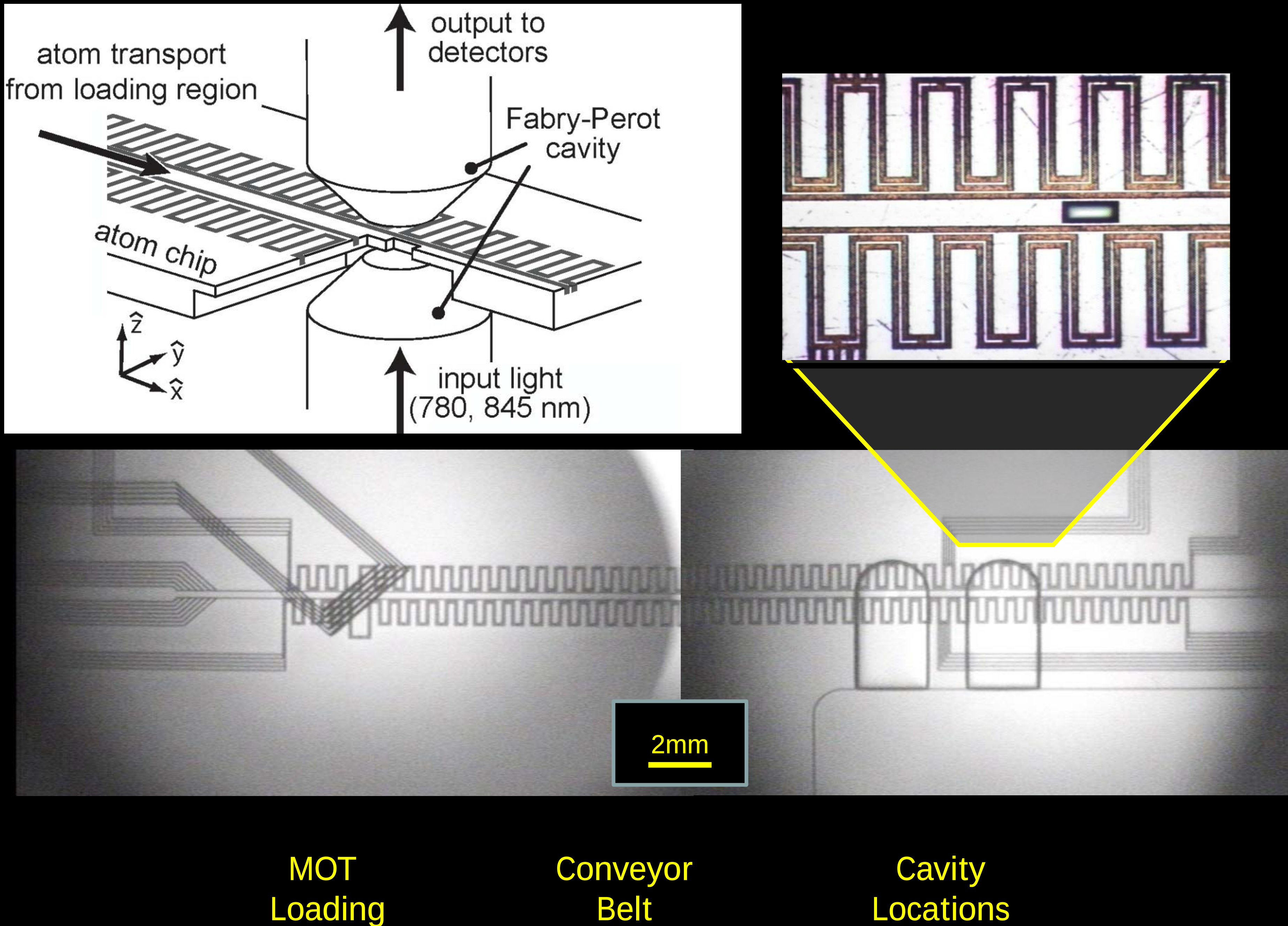
Does a single photon measure the cantilever to better than the SQL?

$$\varepsilon = \frac{F \times \frac{1}{\kappa}}{\hbar / Z_{SQL}}$$

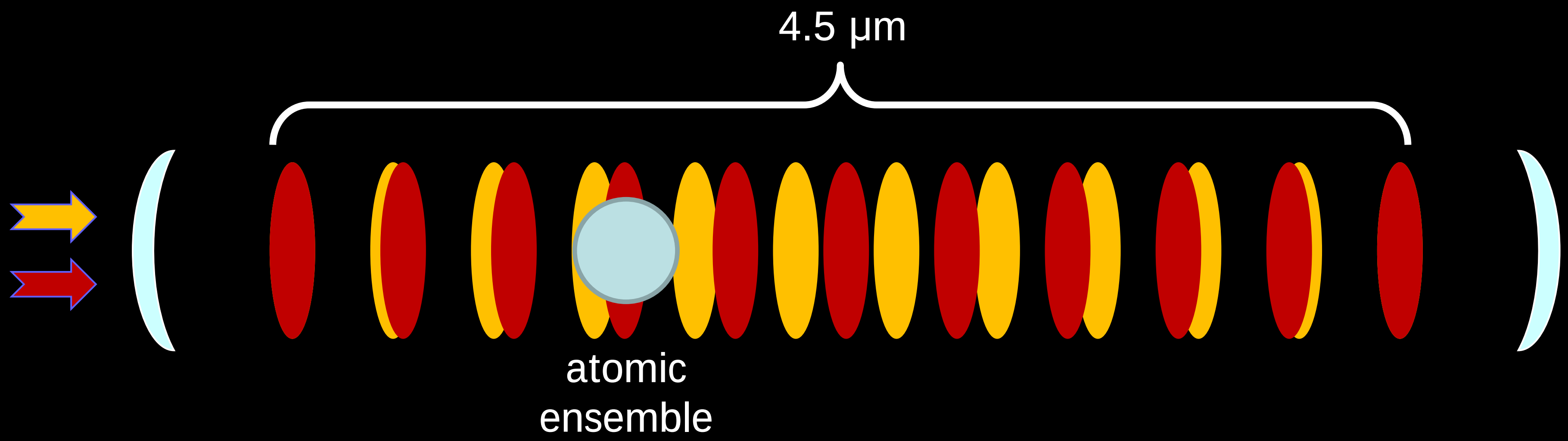
$$\frac{\text{(single-photon force) x (residence time of photon)}}{\text{zero-point momentum spread}}$$

Does a single photon's kick significantly perturb the cantilever?

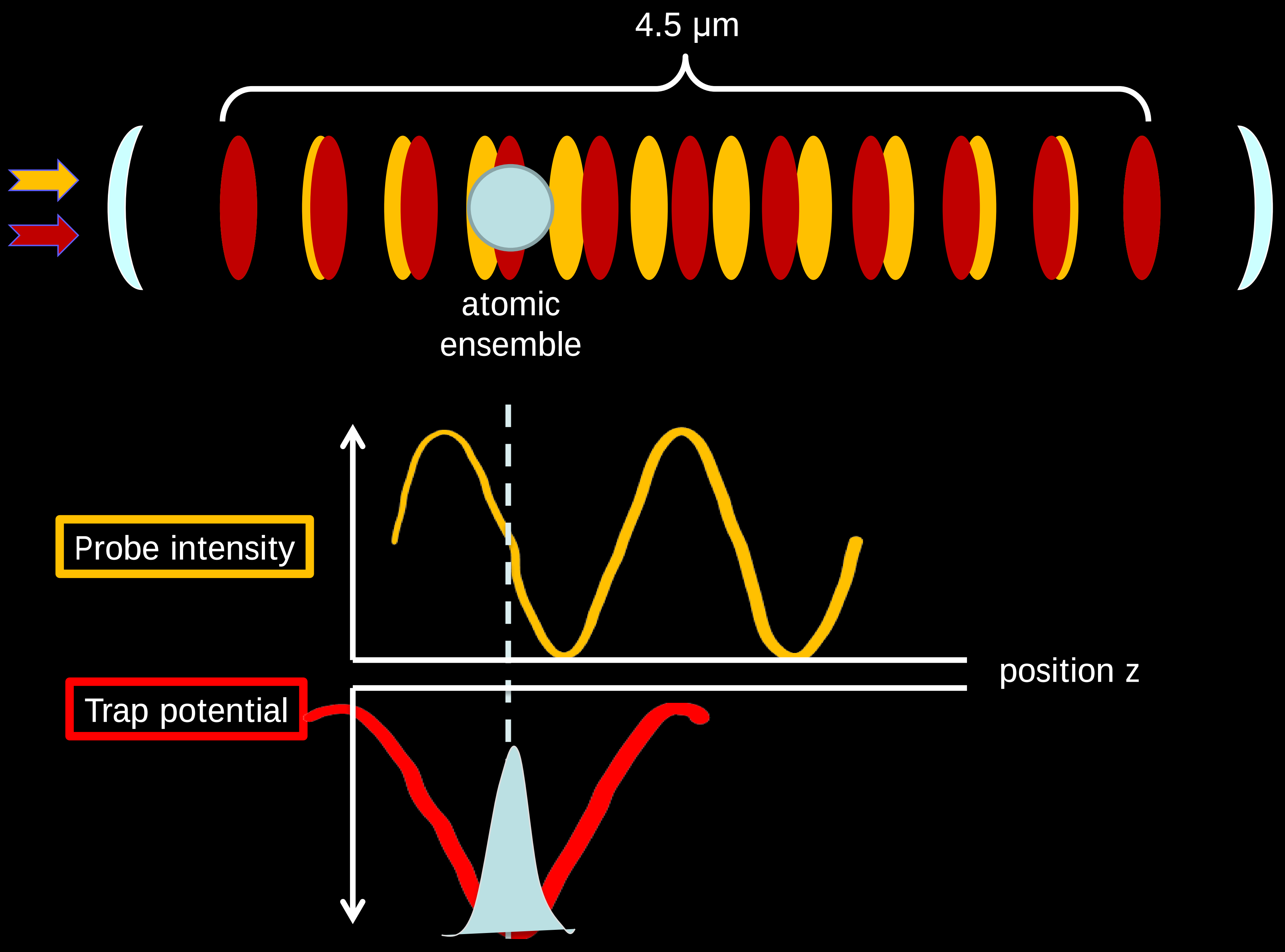
- Cantilever-based optomechanics: $\varepsilon = 10^{-7} - 10^{-5}$
- Atoms-based optomechanics: $\varepsilon = 0.01 - 10$

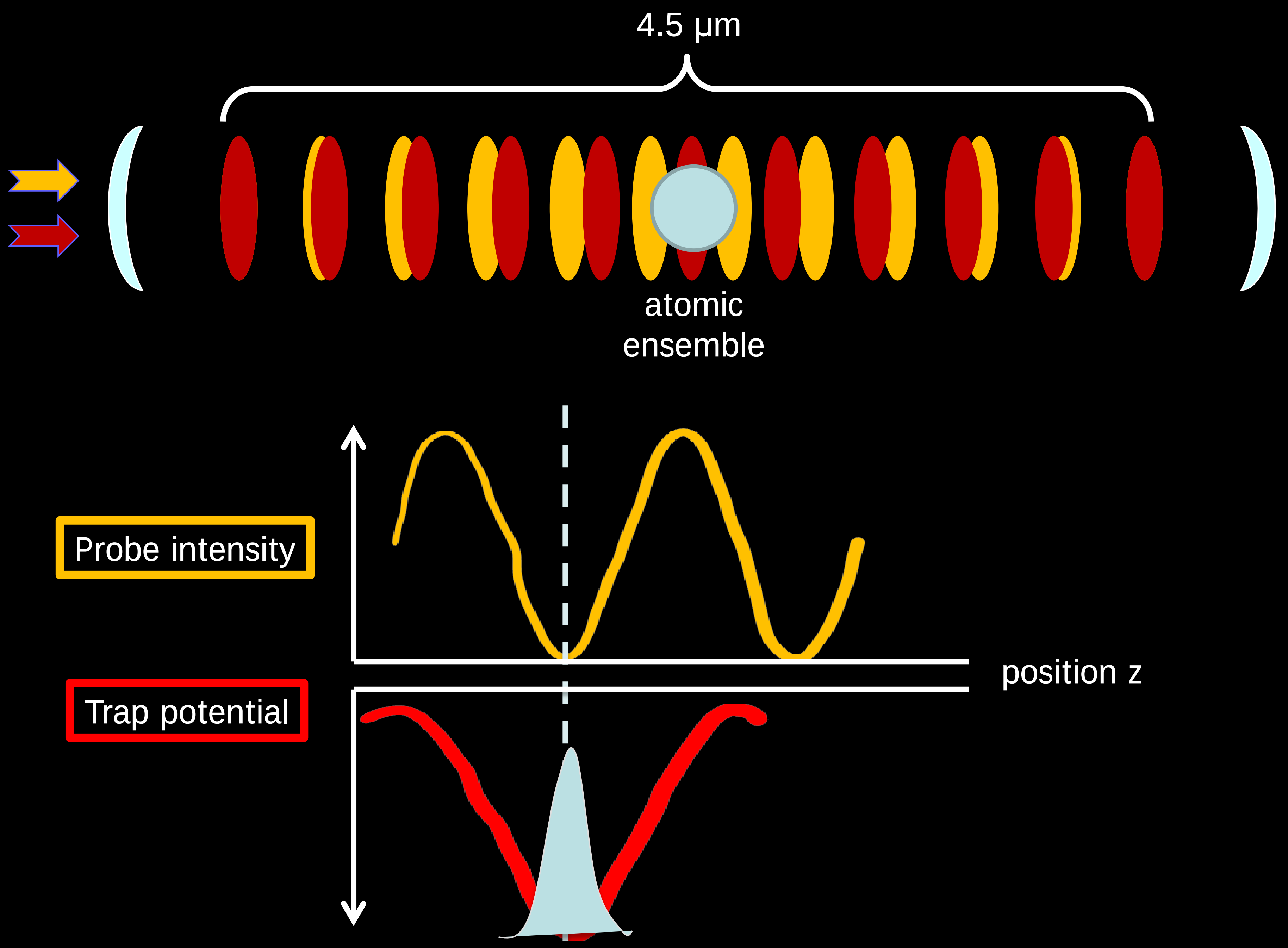


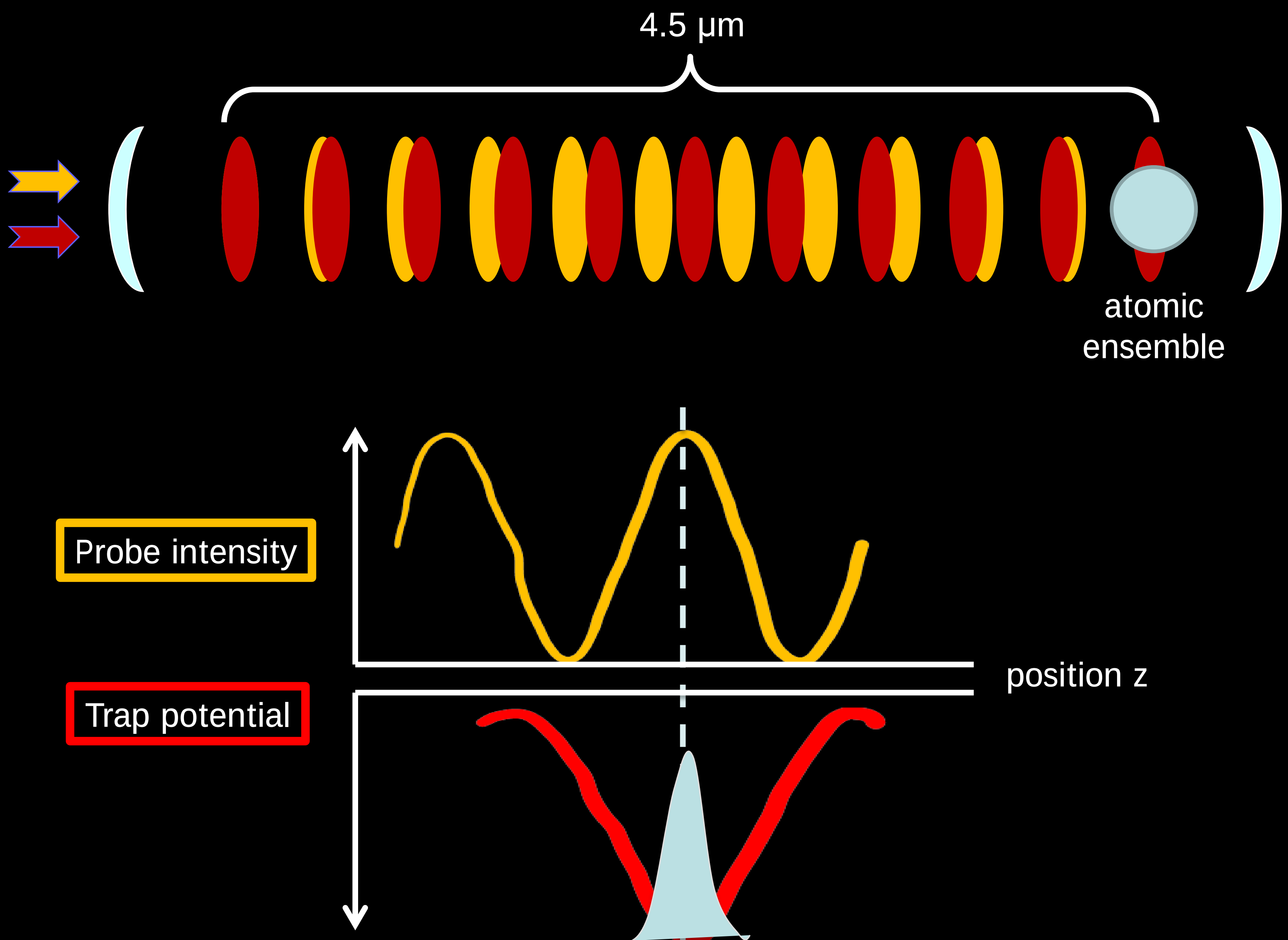
output to detectors
atom transport from loading region
Fabry-Perot cavity
atom chip
input light (780, 845 nm)
ẑ
ŷ
x̂
2mm
MOT Loading
Conveyor Belt
Cavity Locations



- pre-position with magnetic trap
- load into 845 nm optical trap
- probe with 780 nm light
  (either red [attractive] or blue [repulsive] detuned)

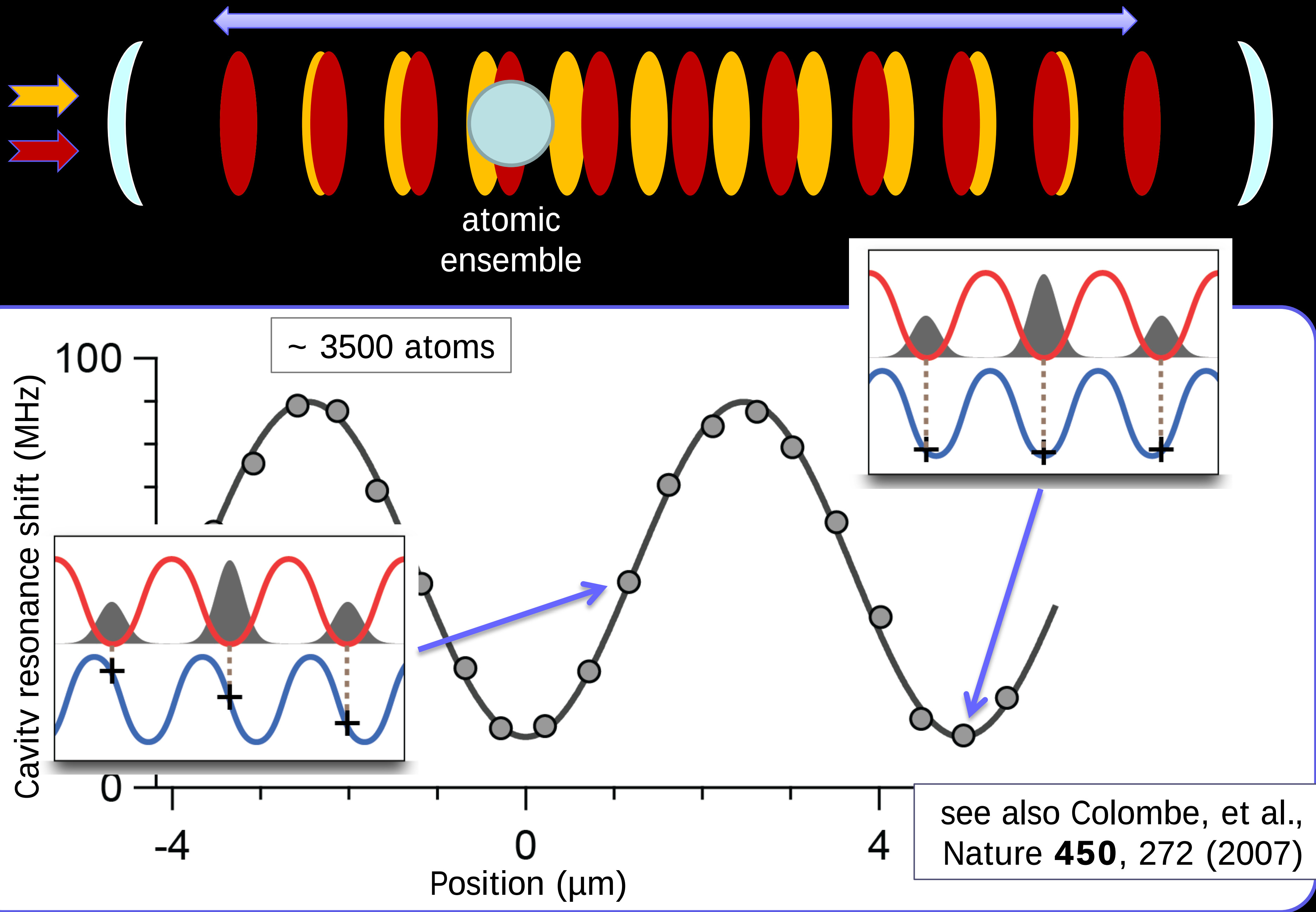

4.5 µm
atomic ensemble
Probe intensity
position z
Trap potential


4.5 μm
atomic ensemble
Probe intensity
position z
Trap potential

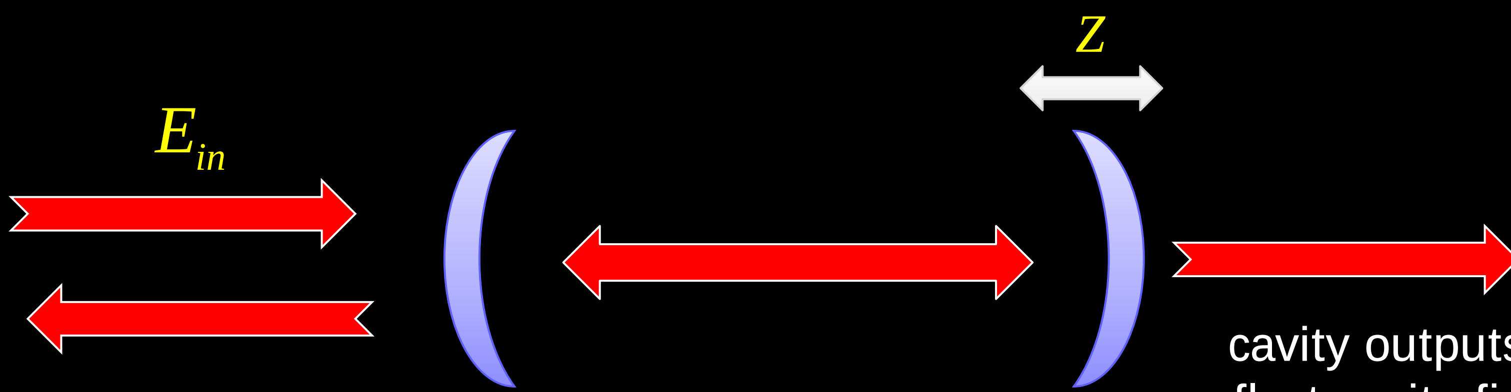


4.5 µm
atomic ensemble
Probe intensity
position z
Trap potential

Sub-wavelength positioning within the cavity mode



Motion detection in opto-mechanics

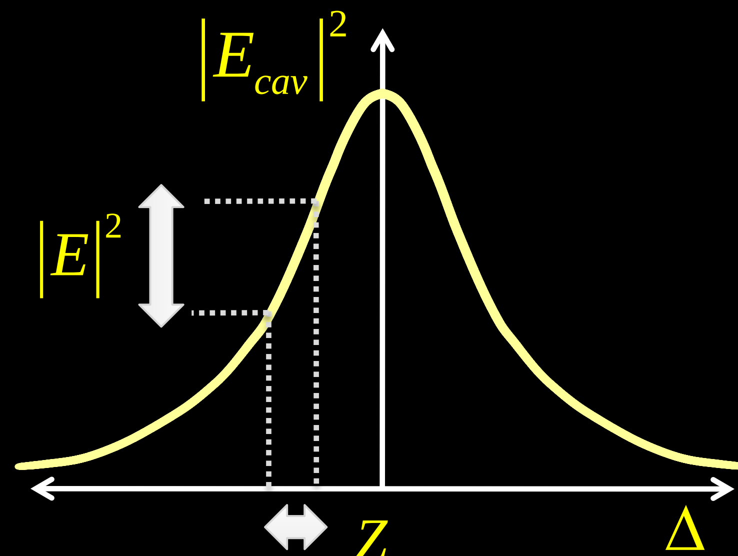


cavity outputs
reflect cavity field

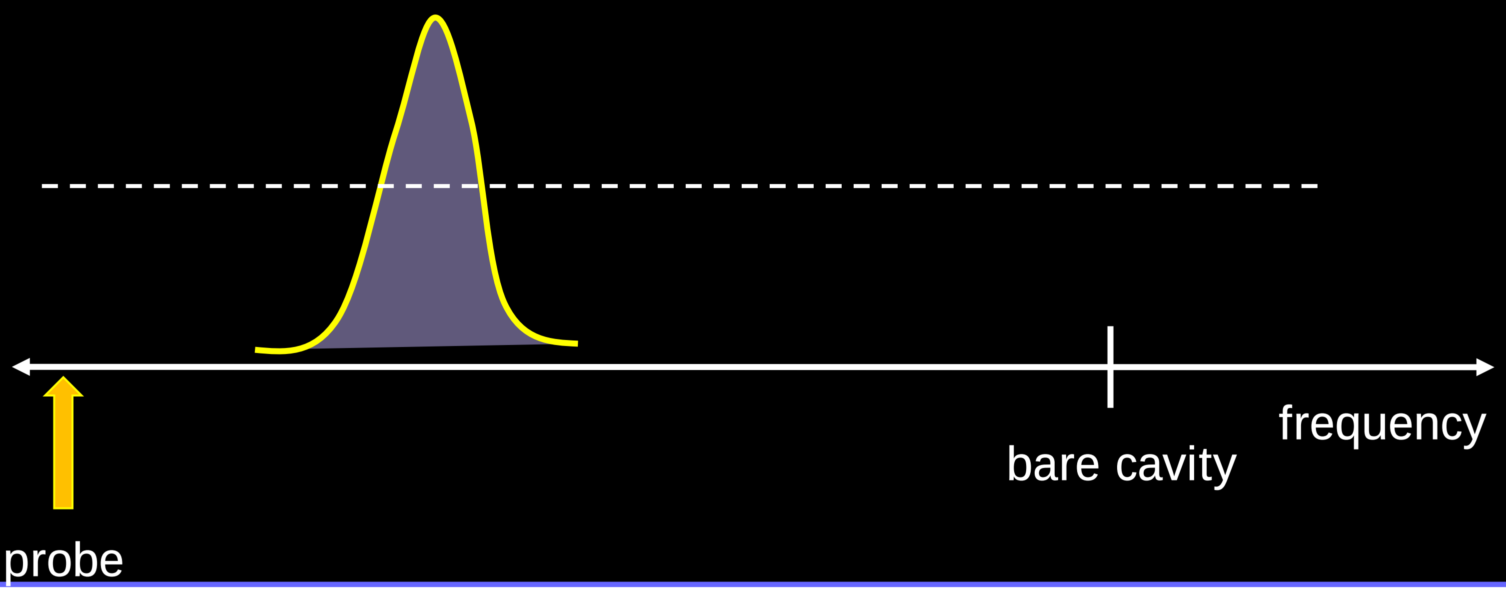
$$E_{cav} = \frac{\eta}{\kappa - i\Delta(Z)}$$

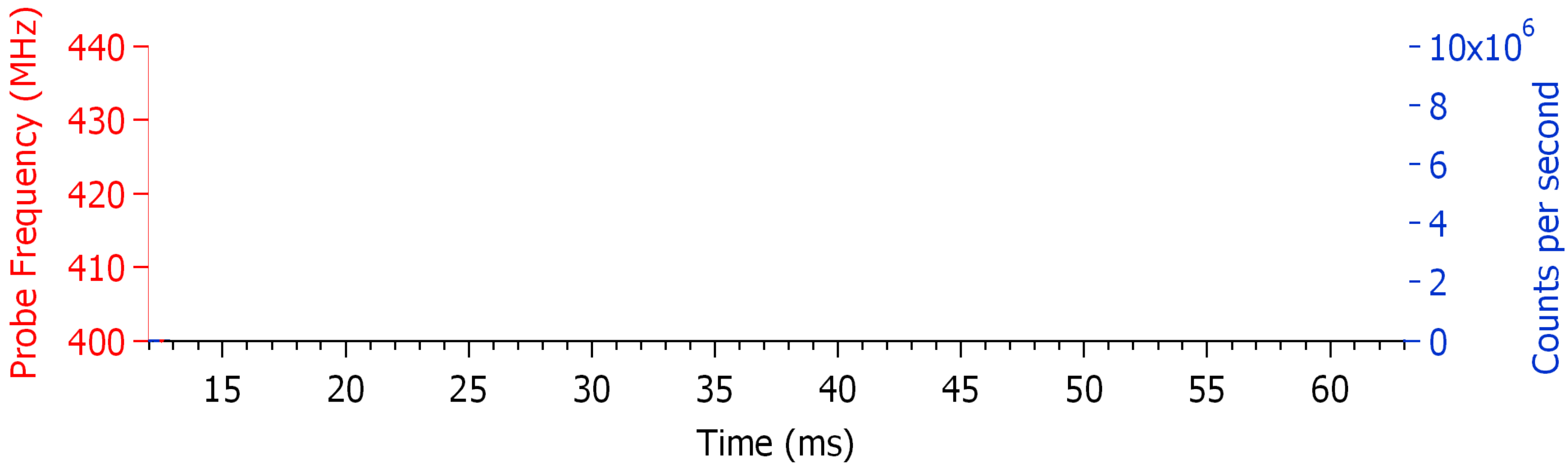
How to measure?

1. Optimal: Measure field quadrature
2. Sub-optimal: Measure intensity (transmission, fluorescence)

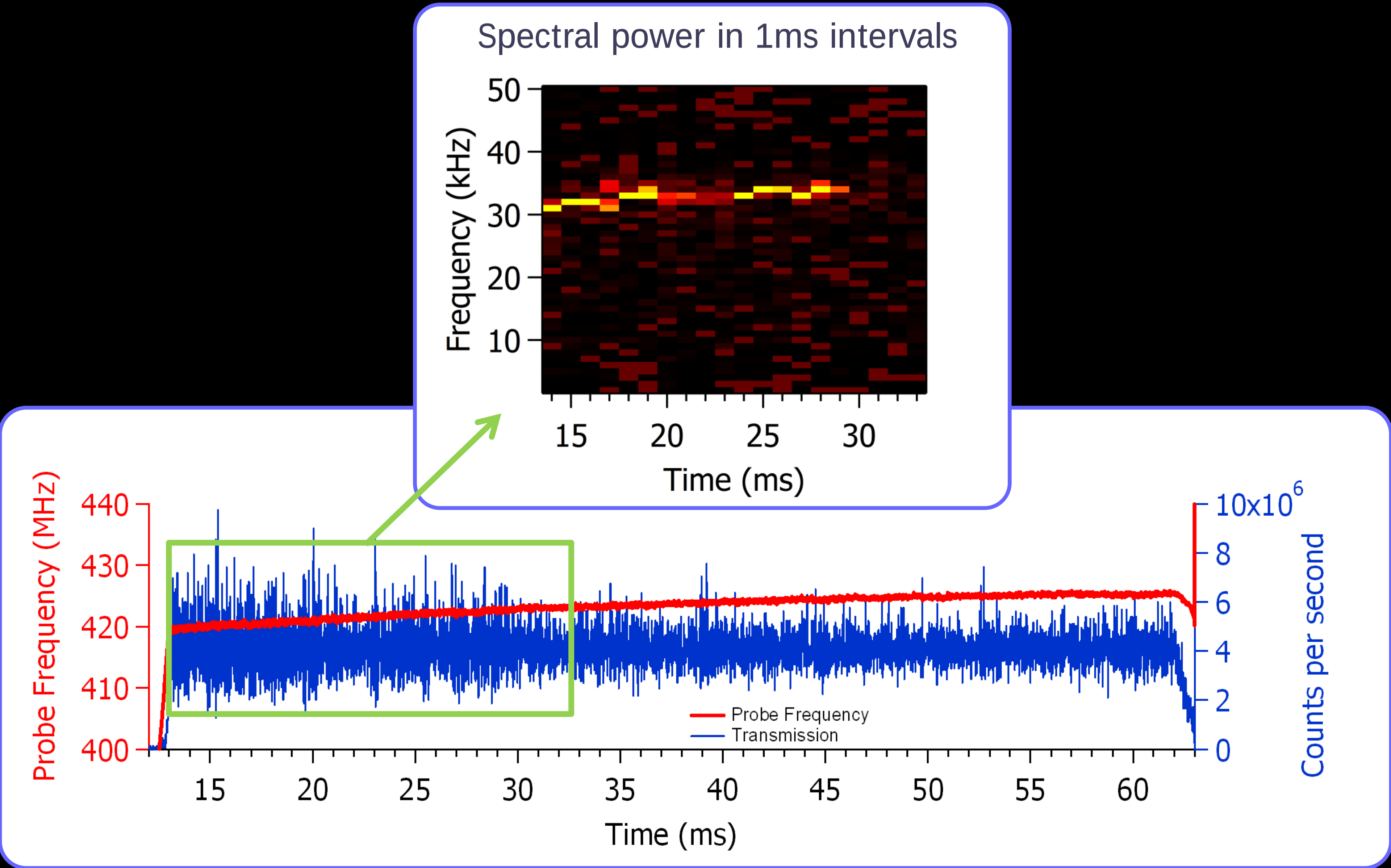


Direct observation of collective atomic motion: probe side-lock





Direct observation of collective atomic motion: probe side-lock



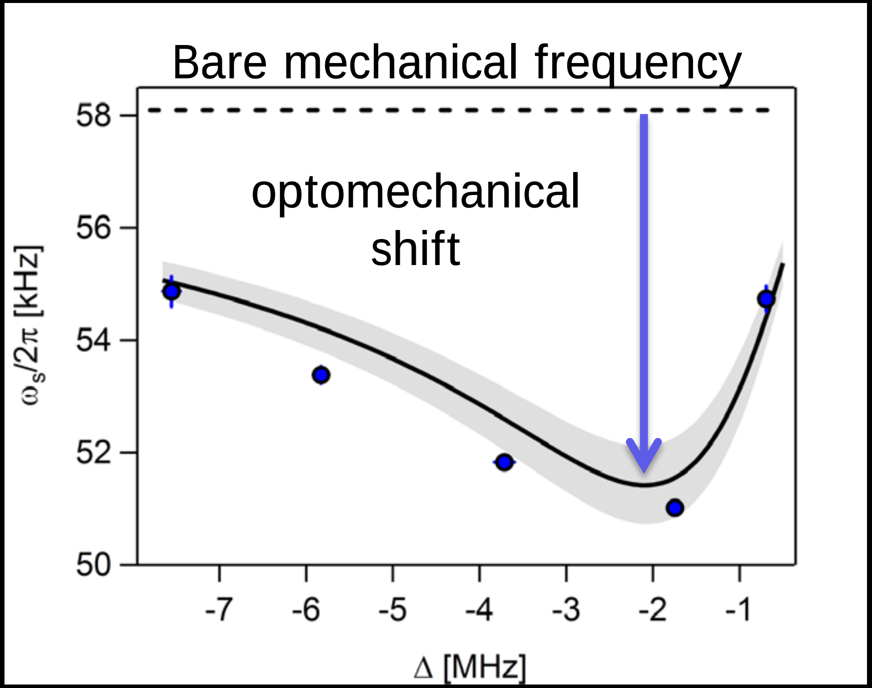
Detection is influential

Consider:

- Dynamical optomechanical frequency shift: the “optical spring”

force on collective variable:

$$F_Z = Fn(Z) - M\omega_z^2 Z$$

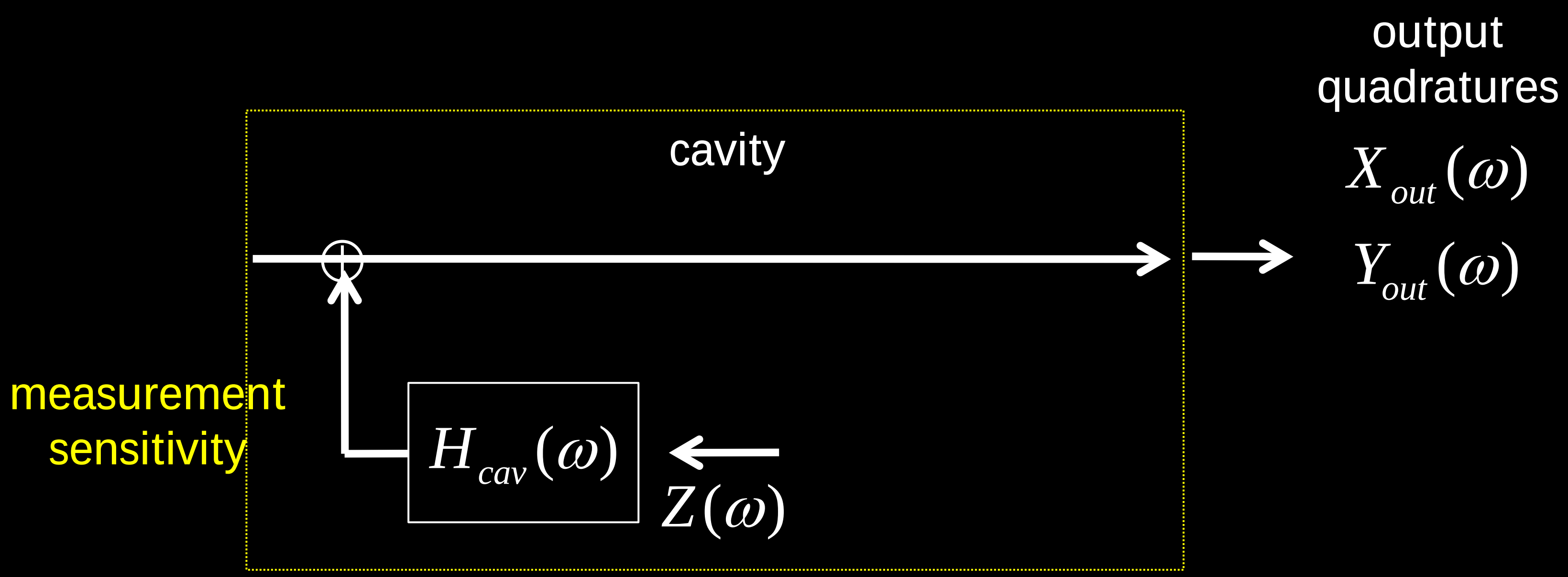


Purdy et al., PRL **105**, 133602 (2010)

- Q: Why is cantilever moving?
  A: Radiation pressure fluctuations

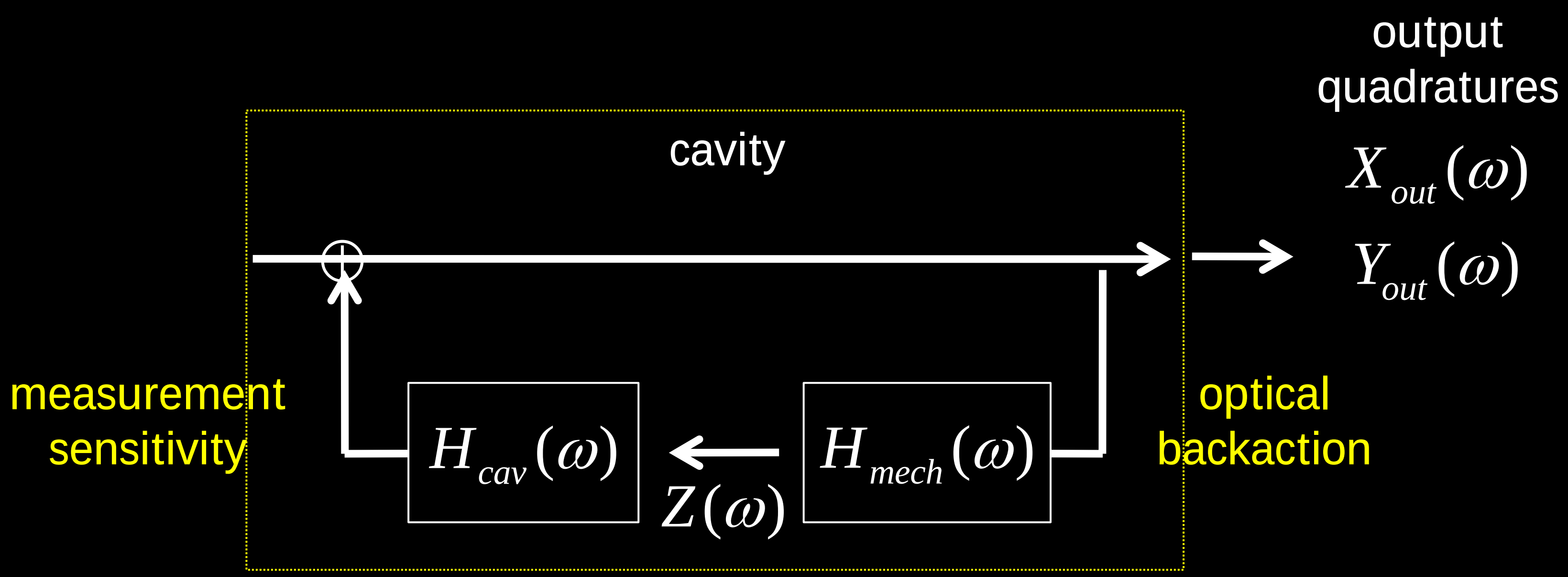
Measurement and feedback in cavity optomechanics

- Measurement scenario



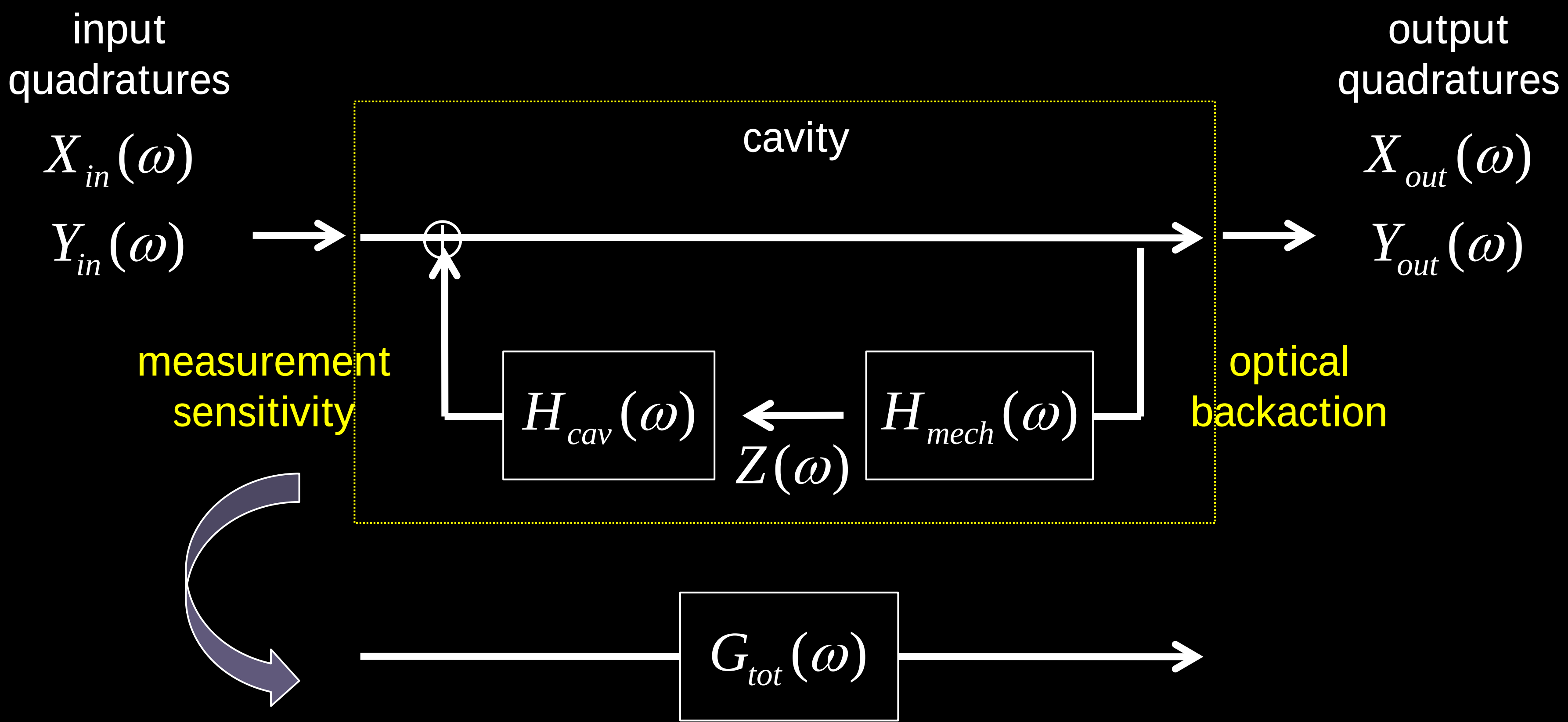
Measurement and feedback in cavity optomechanics

- Coherent backaction scenario
  - optomechanical frequency shift
  - cavity nonlinearity and bistability



Measurement and feedback in cavity optomechanics

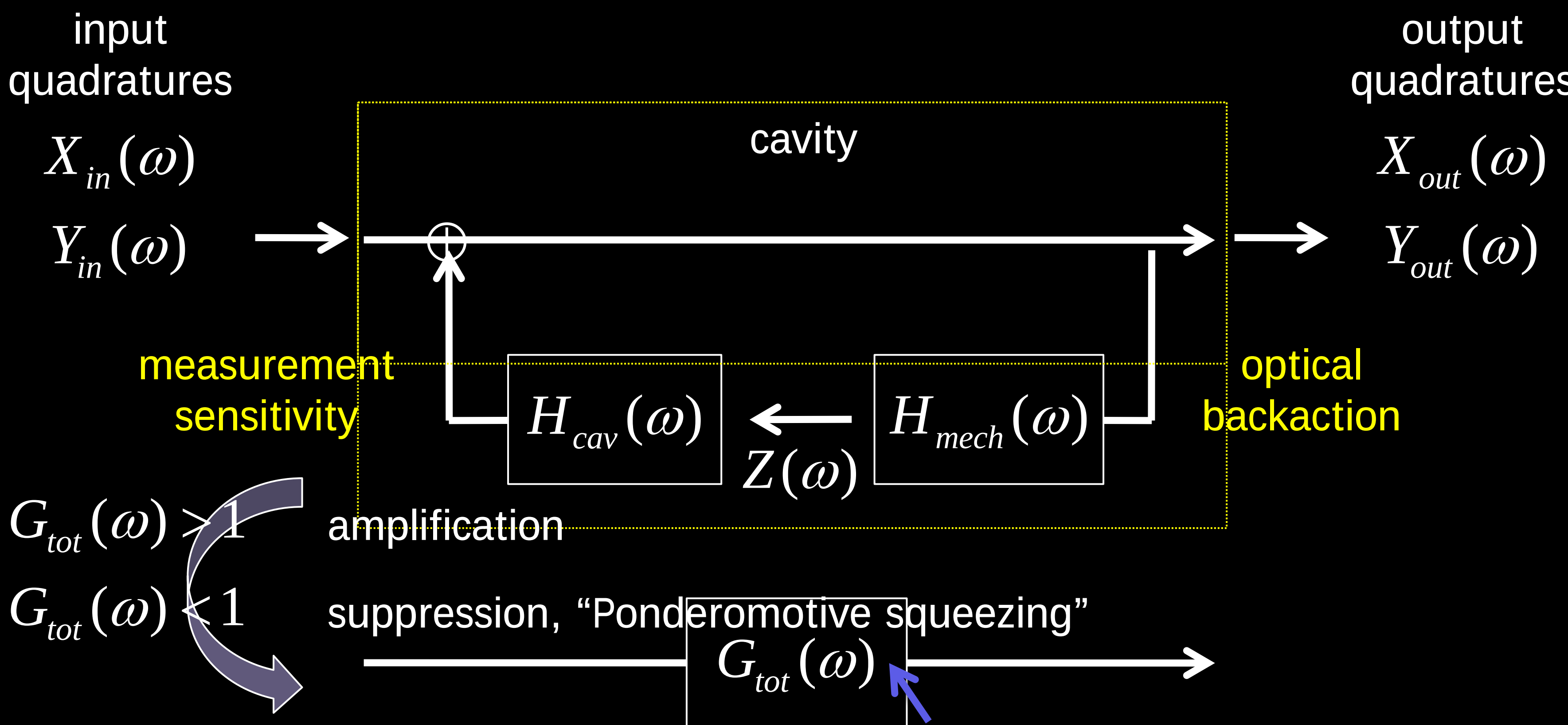
- Optomechanical amplification/squeezing of light



Optomechanical gain spectrum

Measurement and feedback in cavity optomechanics

- Optomechanical amplification/squeezing of light

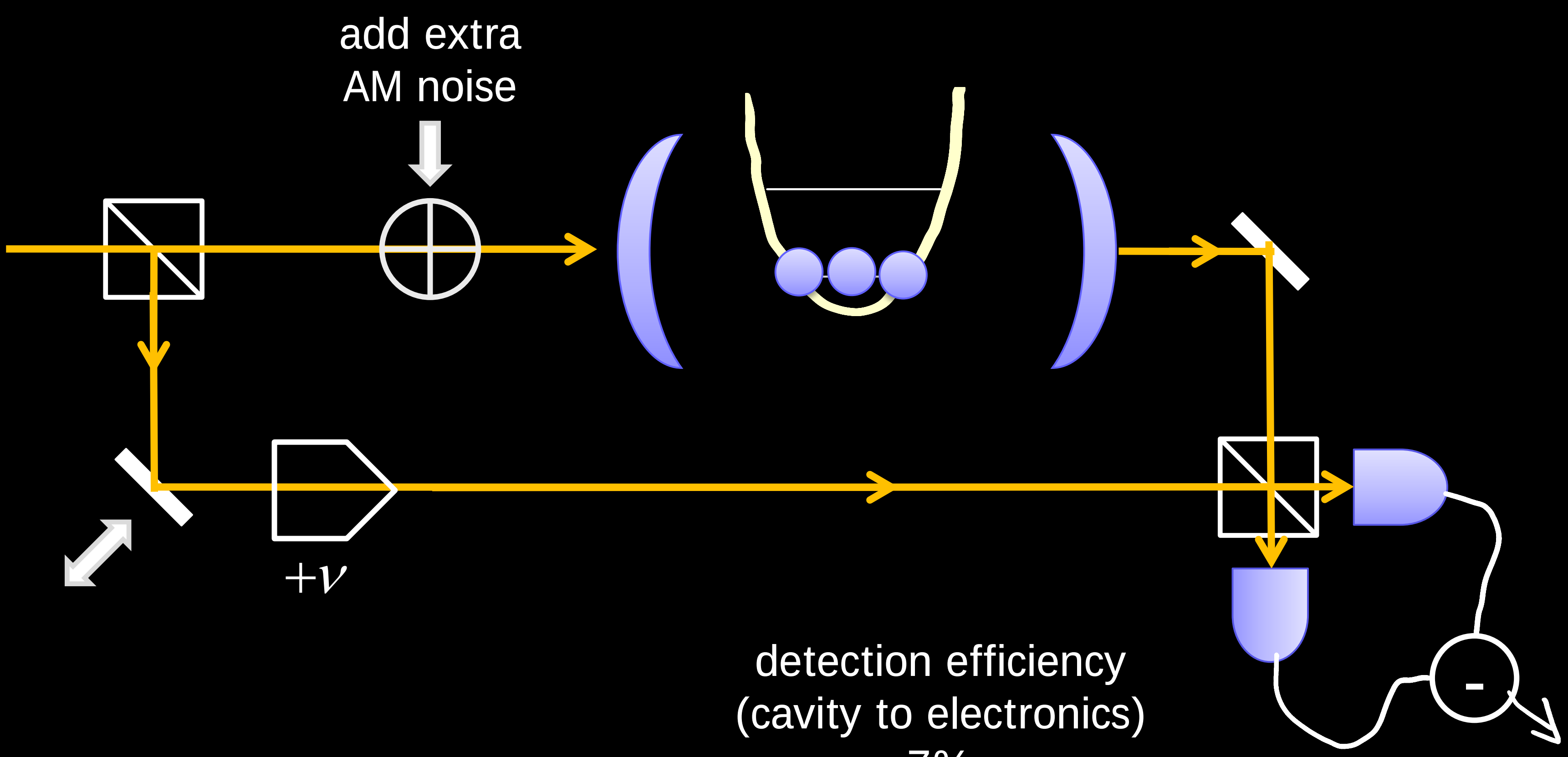


Key component in future of LIGO: from detector to observatory

see Kimble et al., PRD **62**, 022002 (2002).

Measurements of optomechanical gain spectrum

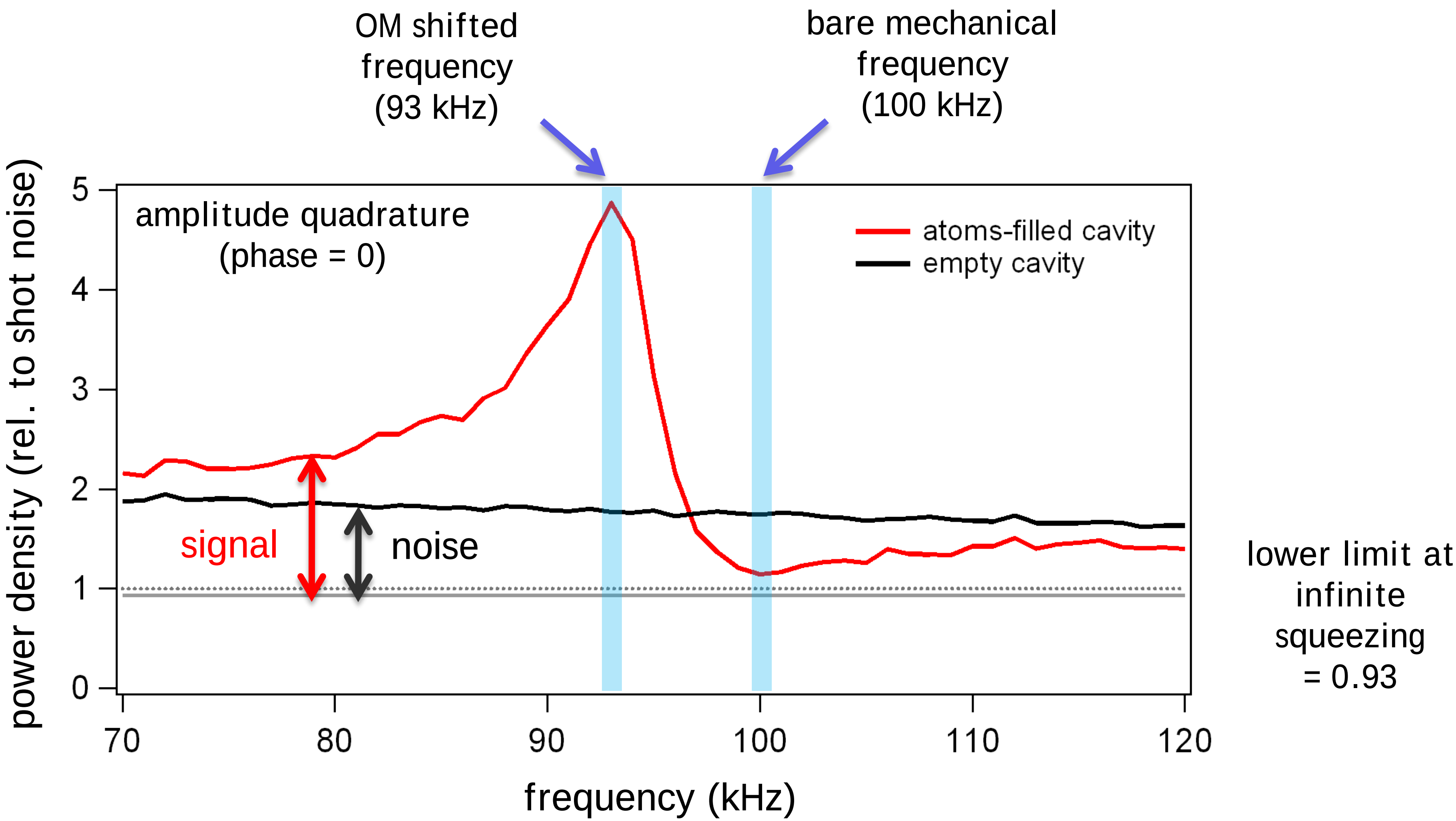
see Marino et al., PRL **104**, 073601 (2010); Verlot et al.,ibid, 133602.



detection efficiency
(cavity to electronics)
7%

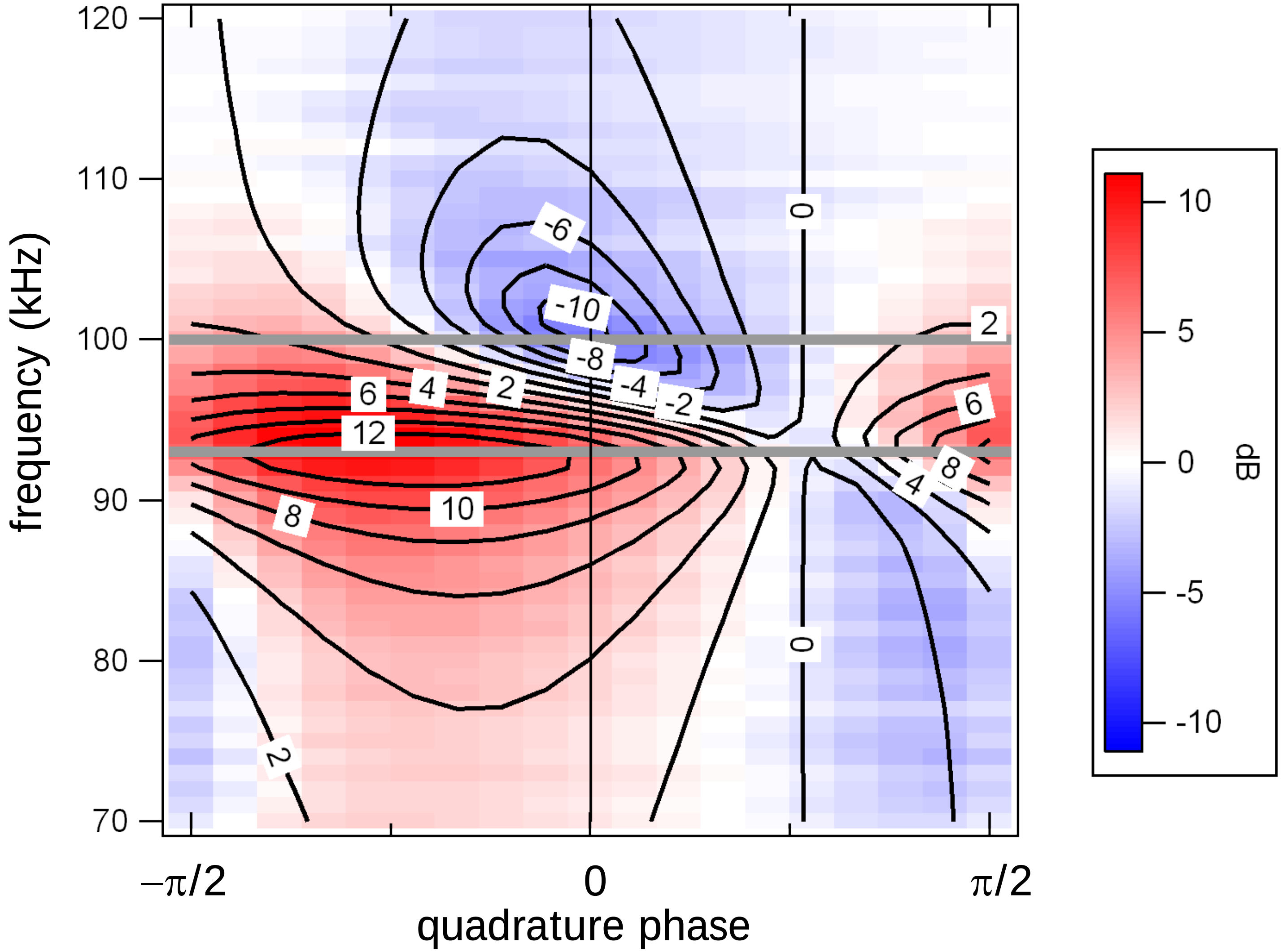
Spectral record of noise-driven atomic motion

- added noise ~ 10x shot noise



Measurements of optomechanical gain spectrum

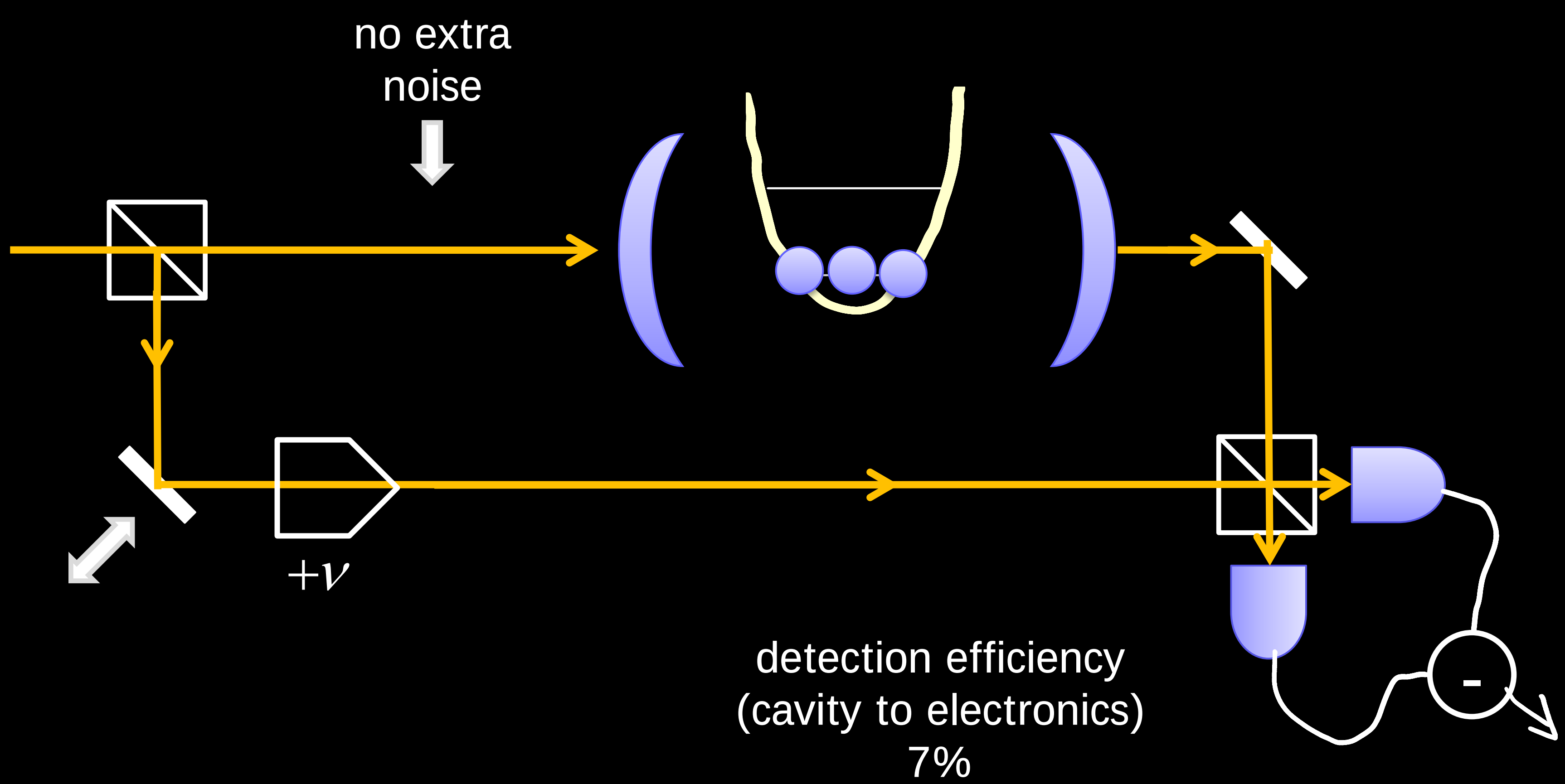
- adjusted for detector efficiency



settings:
Δ_{ca} = -2 GHz
5000 atoms
<n> = 2

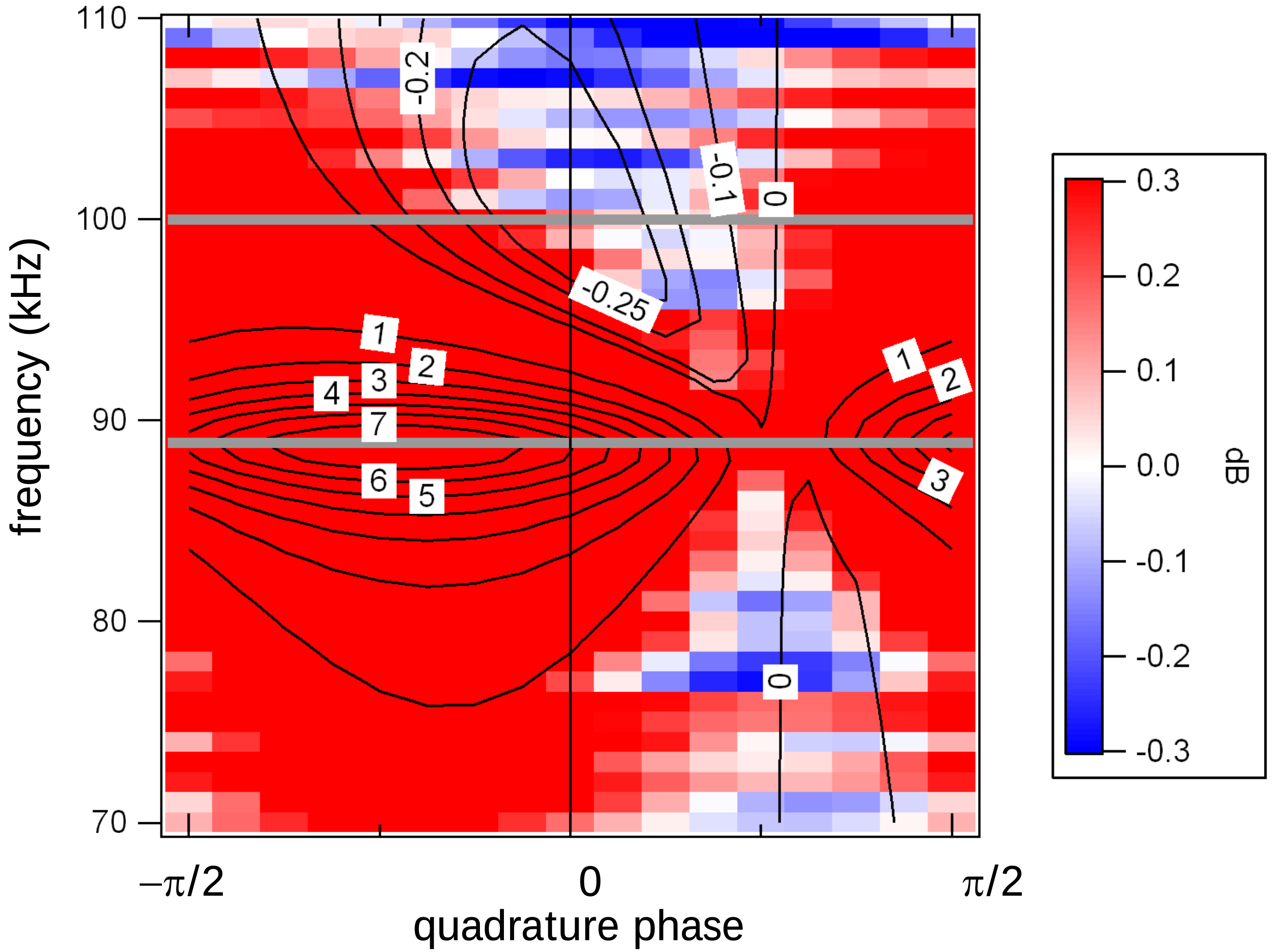
- Theory: semiclassical Langevin equations, one free parameter
  Fabre et al., PRA **49**, 1337 (1994); Mancini and Tombesi, ibid., 4055.

Ponderomotive squeezing?

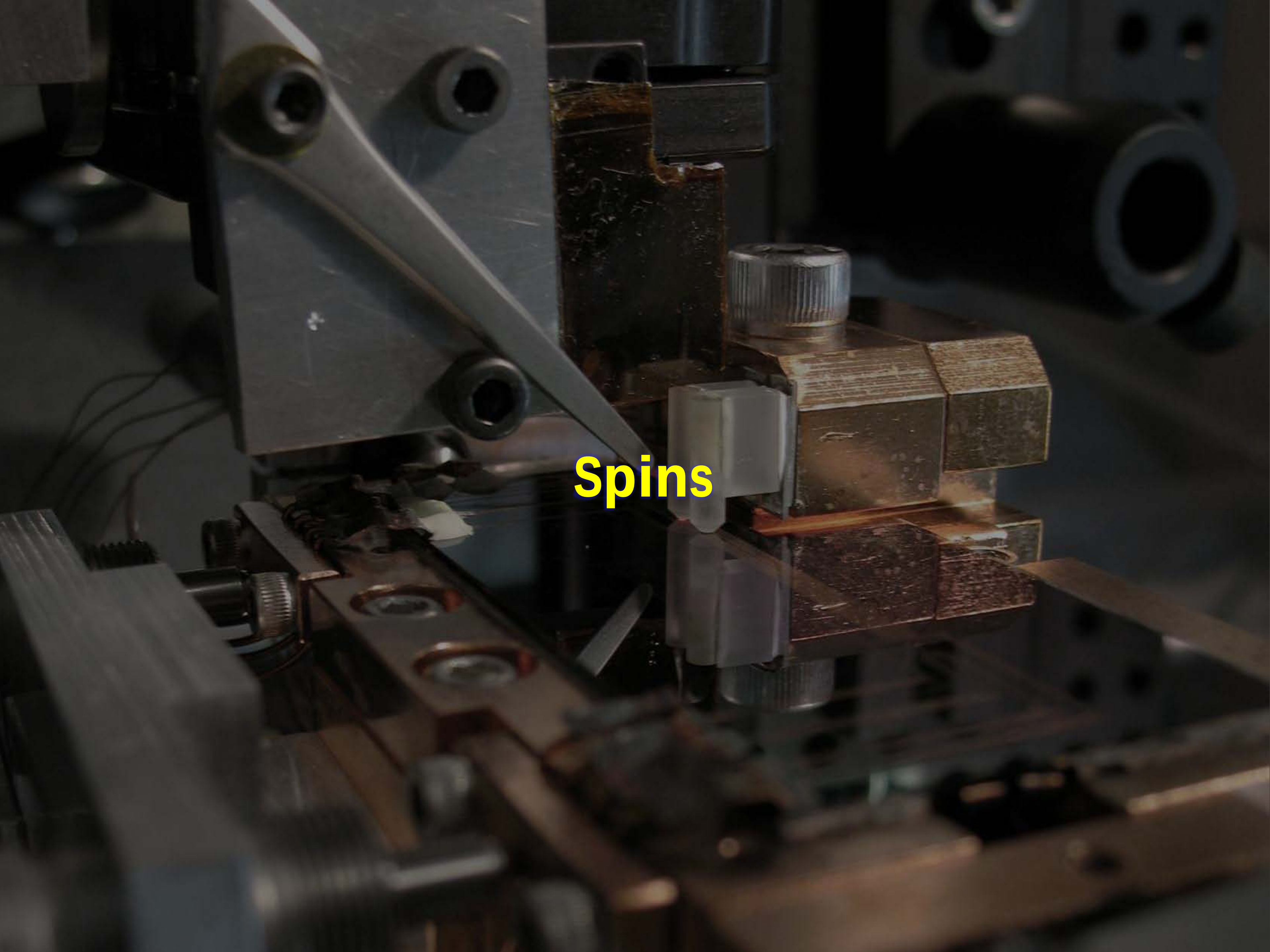


Ponderomotive squeezing? (not clear yet)

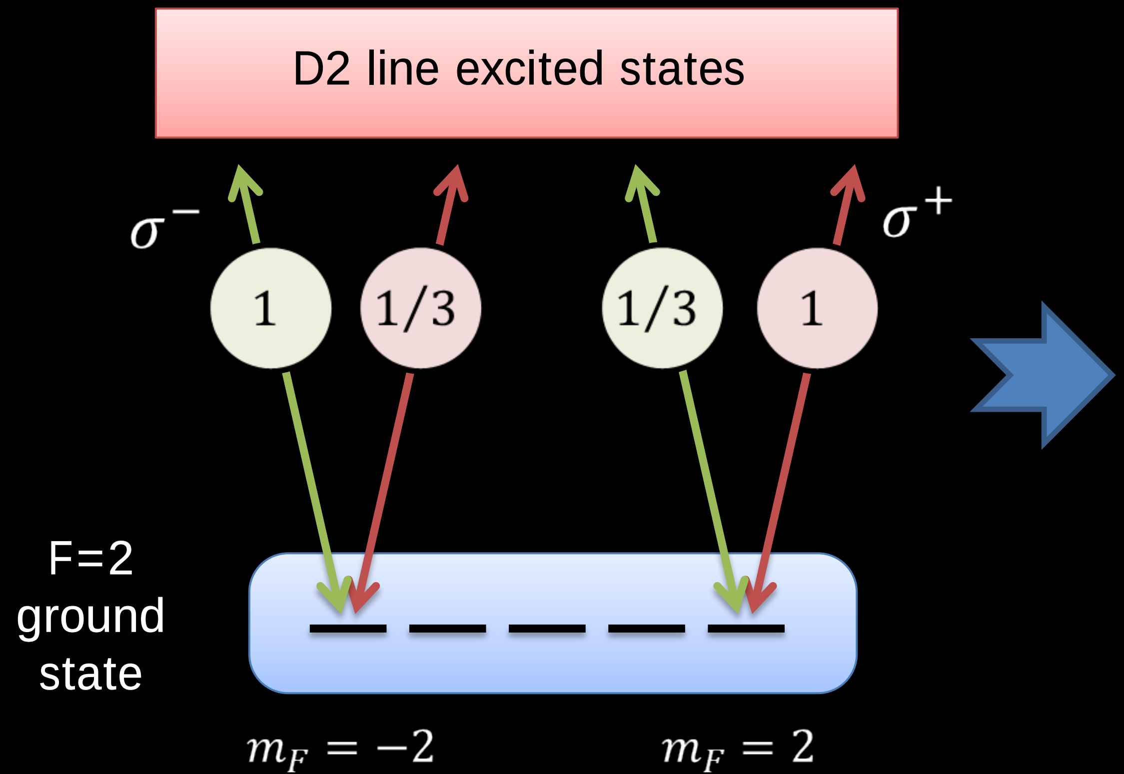
- NOT adjusted for detector efficiency (max reduction to 0.93 = - 0.3 dB)



settings:
Δ_{ca} = -2 GHz
3700 atoms
<n> = 2.5


Spins

Cavity optical detection of spin ensembles

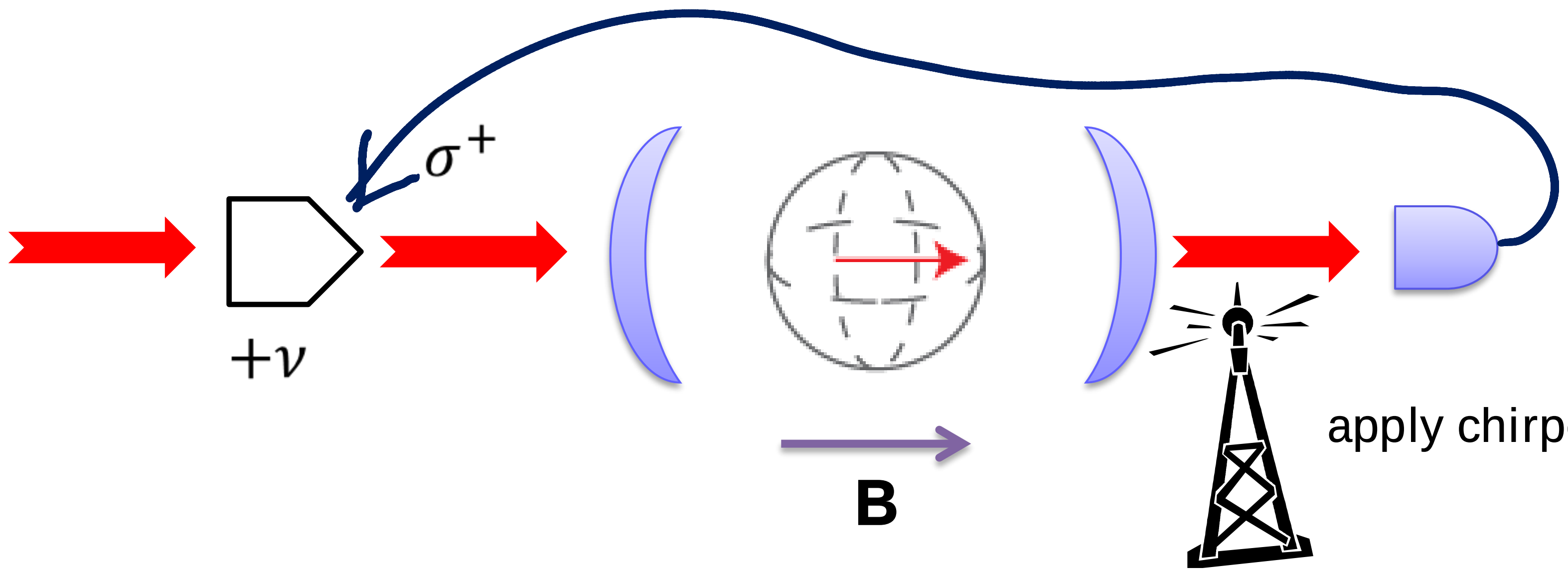


Circular birefringence:

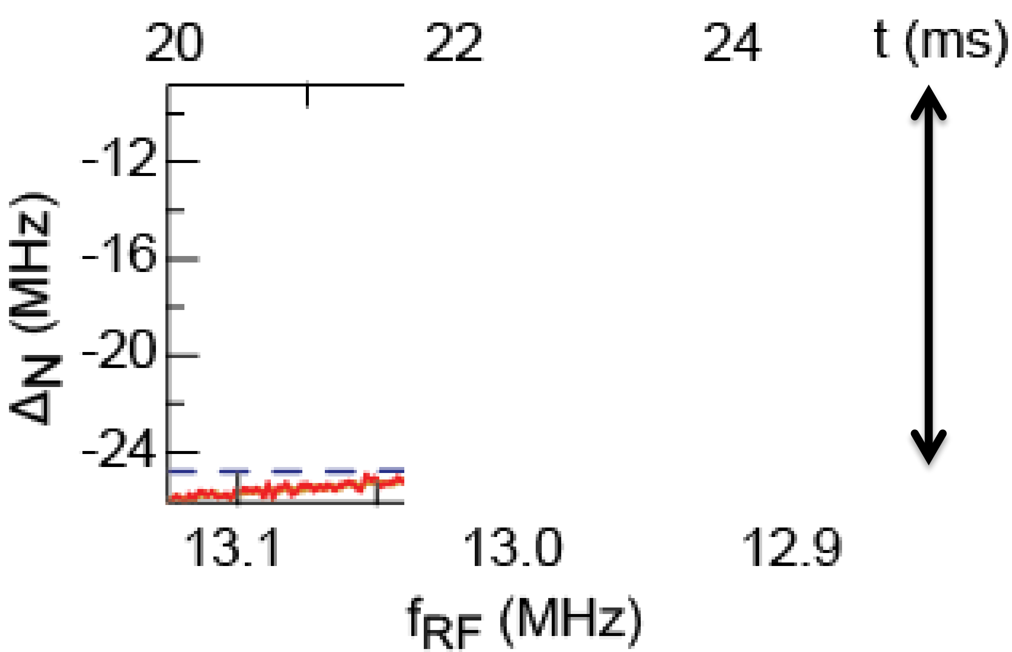
Cavity resonance frequency depends linearly on projection of collective spin (measurement)

Polarized cavity photons produce effective magnetic field along cavity axis (back action)

Cavity optical detection of spin ensembles



apply chirped rf field

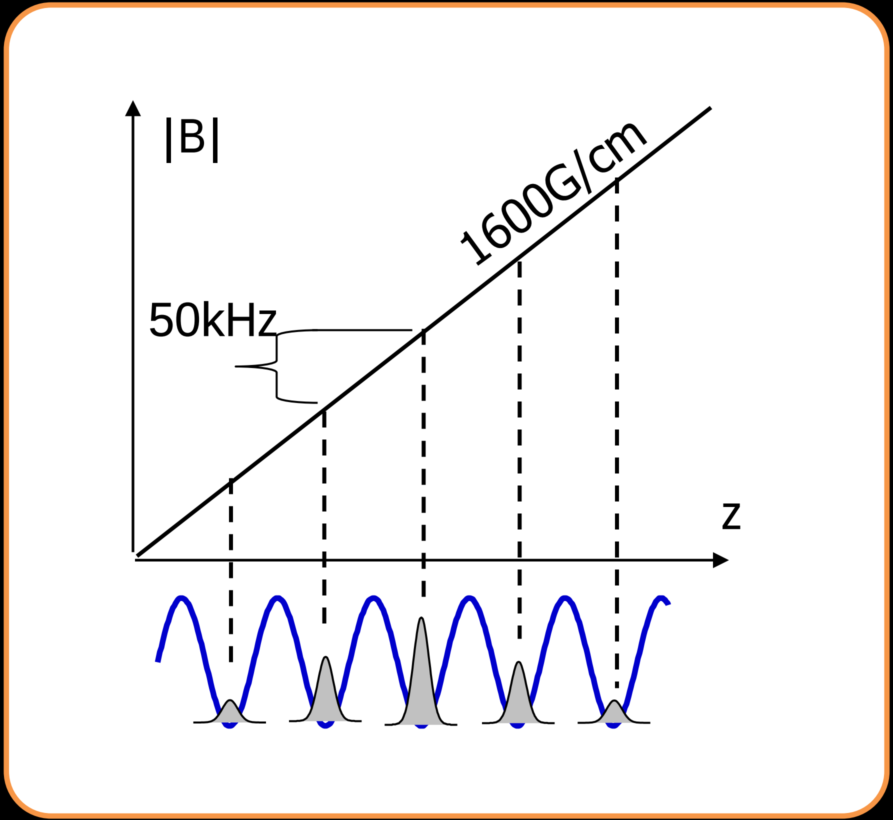


Freq. shift varies factor of 3 when spins are inverted.

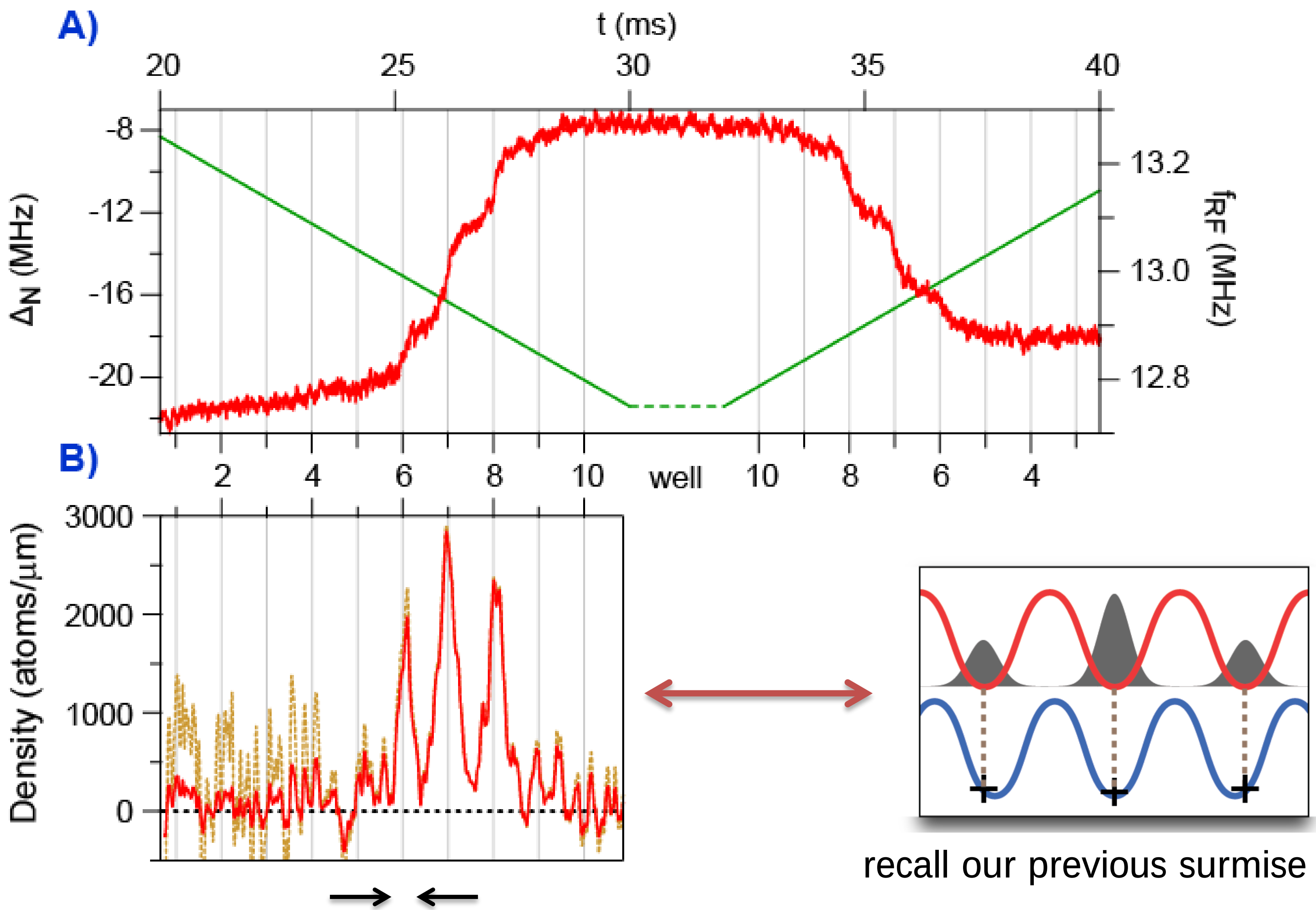
Step height measures magnetization

Magnetic resonance imaging of atoms in a 1D lattice

- Apply strong magnetic field to distinguish RF resonance at each lattice site
- Sweep frequency of applied RF drive
- Monitor cavity resonance frequency (using side lock)

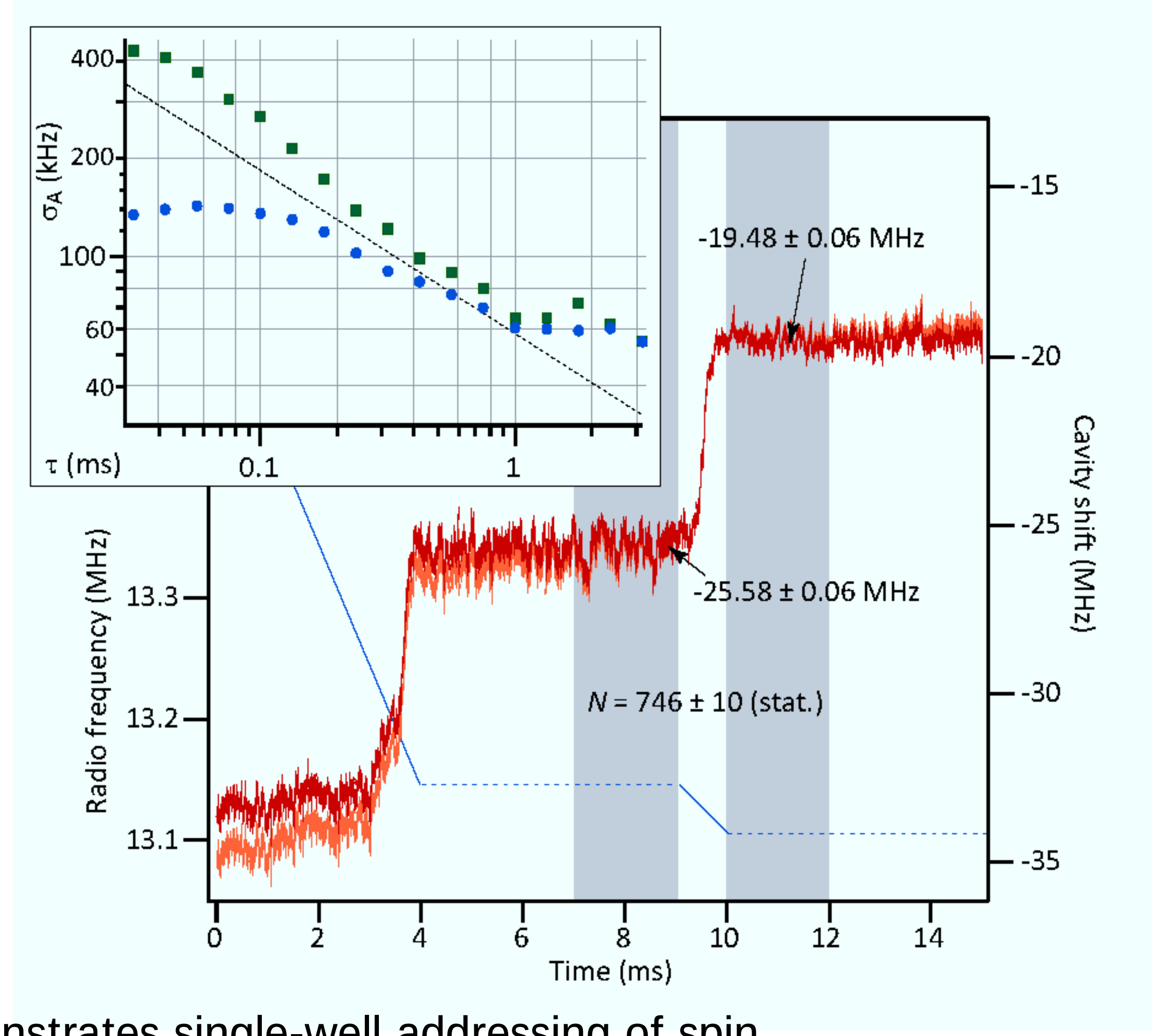


Single shot MRI of atoms in a 425-nm-spacing optical lattice



recall our previous surmise

Dynamic range and precision for a single well



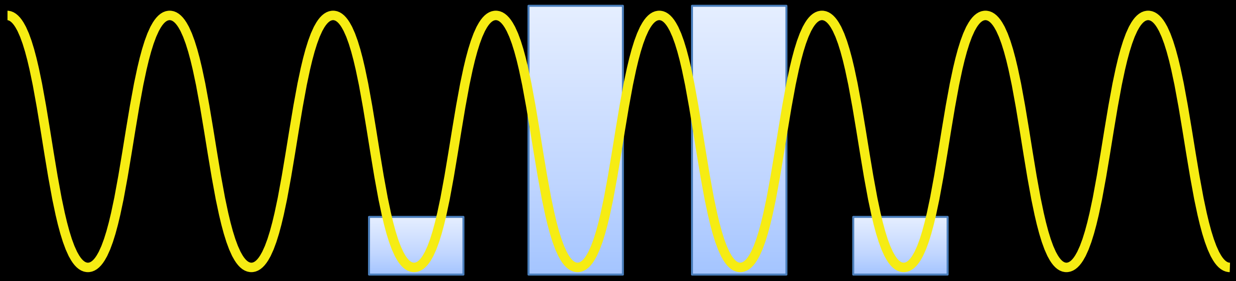
Statistical uncertainty below the Poisson limit

Also demonstrates single-well addressing of spin

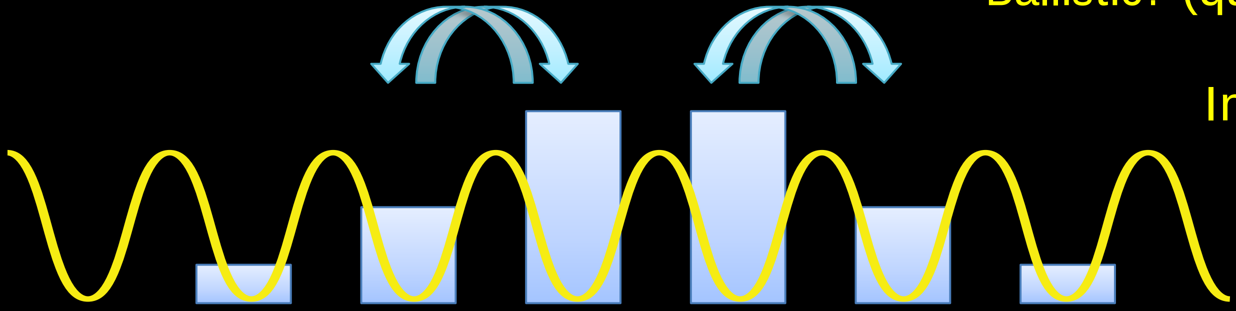
“Optical cavity-aided magnetic resonance imaging of atoms in an optical lattice,” submitted

app: microscopy of quantum transport in an optical lattice

1. Deposit atoms localized in a few wells of the optical lattice



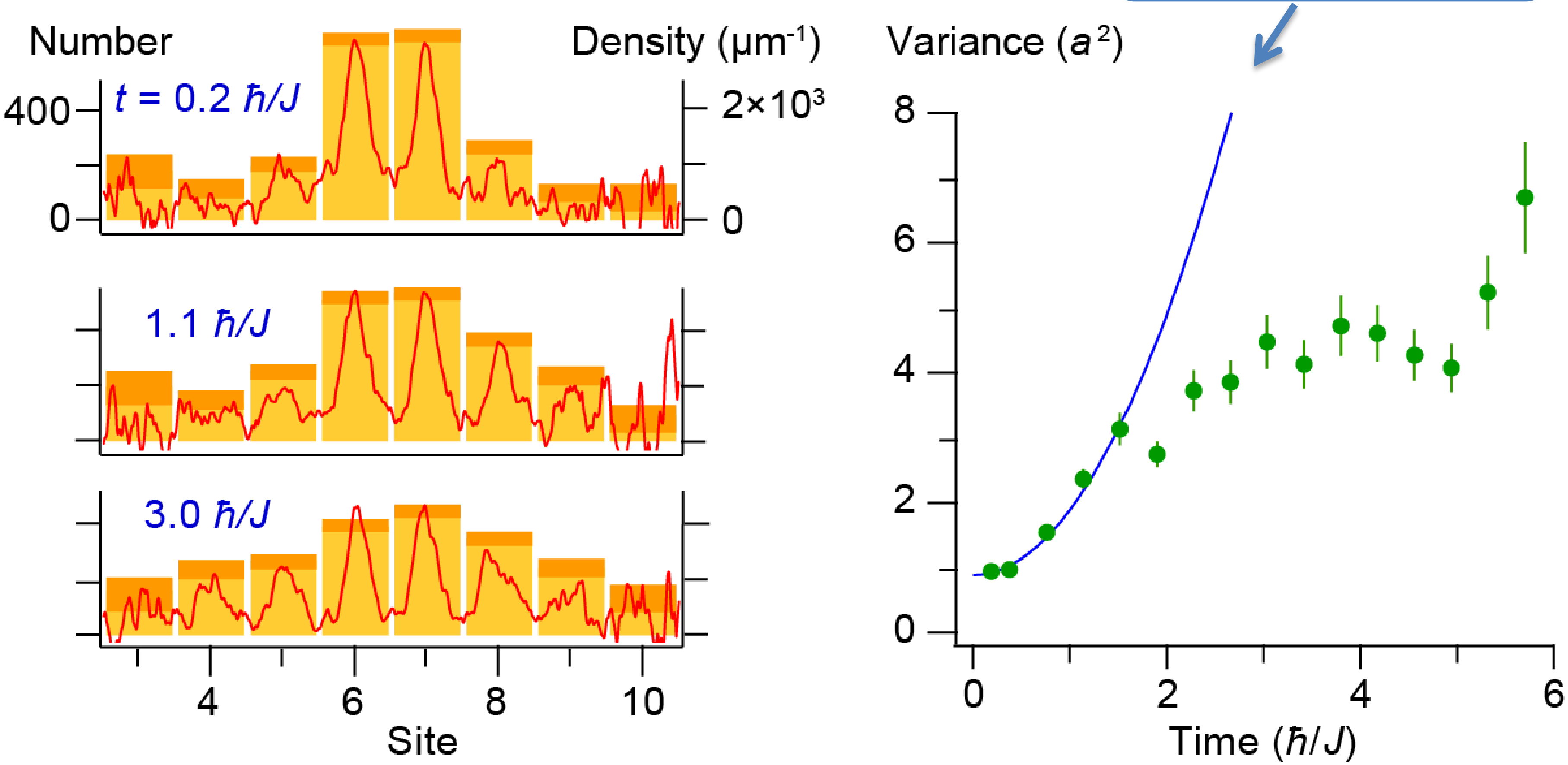
2. Lower lattice depth + tune to resonance to allow tunneling



Ballistic? (quantum random walk)
Diffusive?
Interactions?

3. Raise lattice depth + take MRI

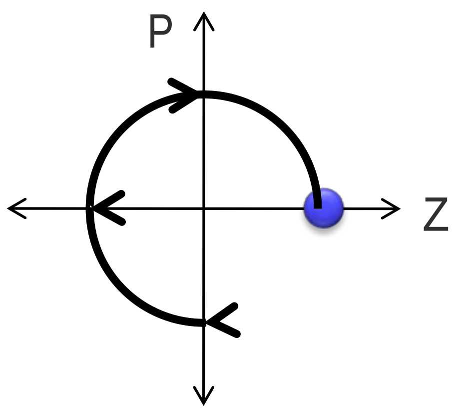
Blue curve: No free parameters, ballistic quantum transport



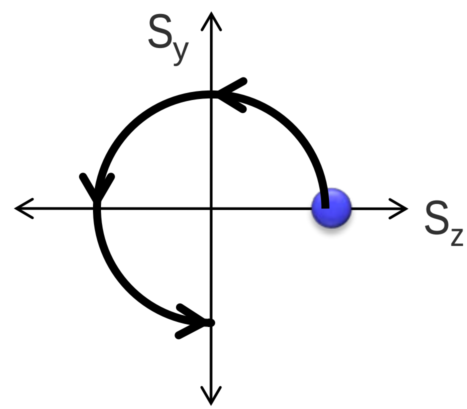
Theory help from Hazzard and Rey (JILA)

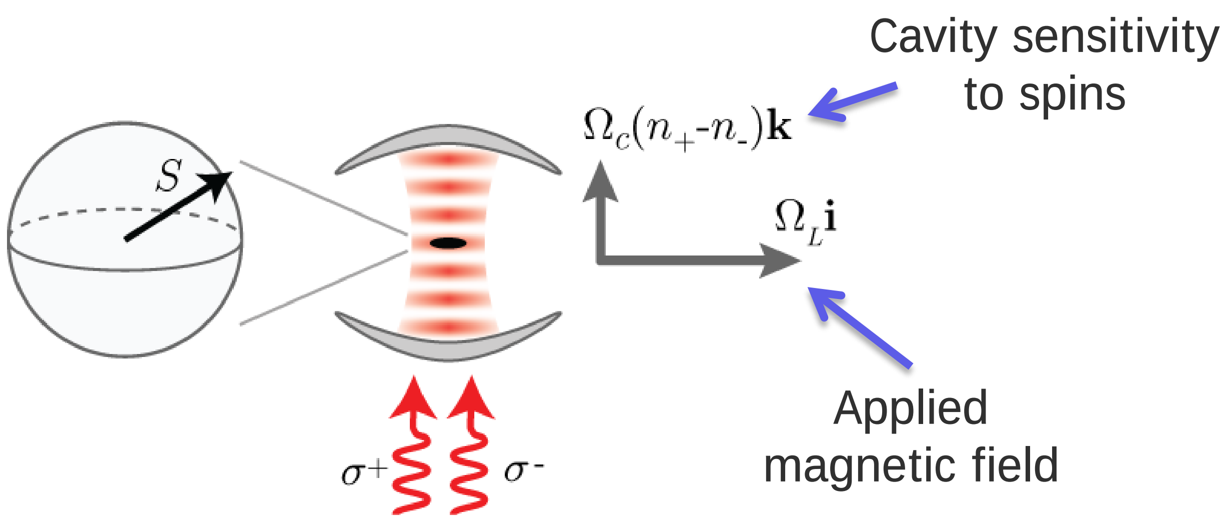
Cavity spin optodynamics
spins = "cantilever"

<u>cantilever:</u>



<u>Larmor precession:</u>

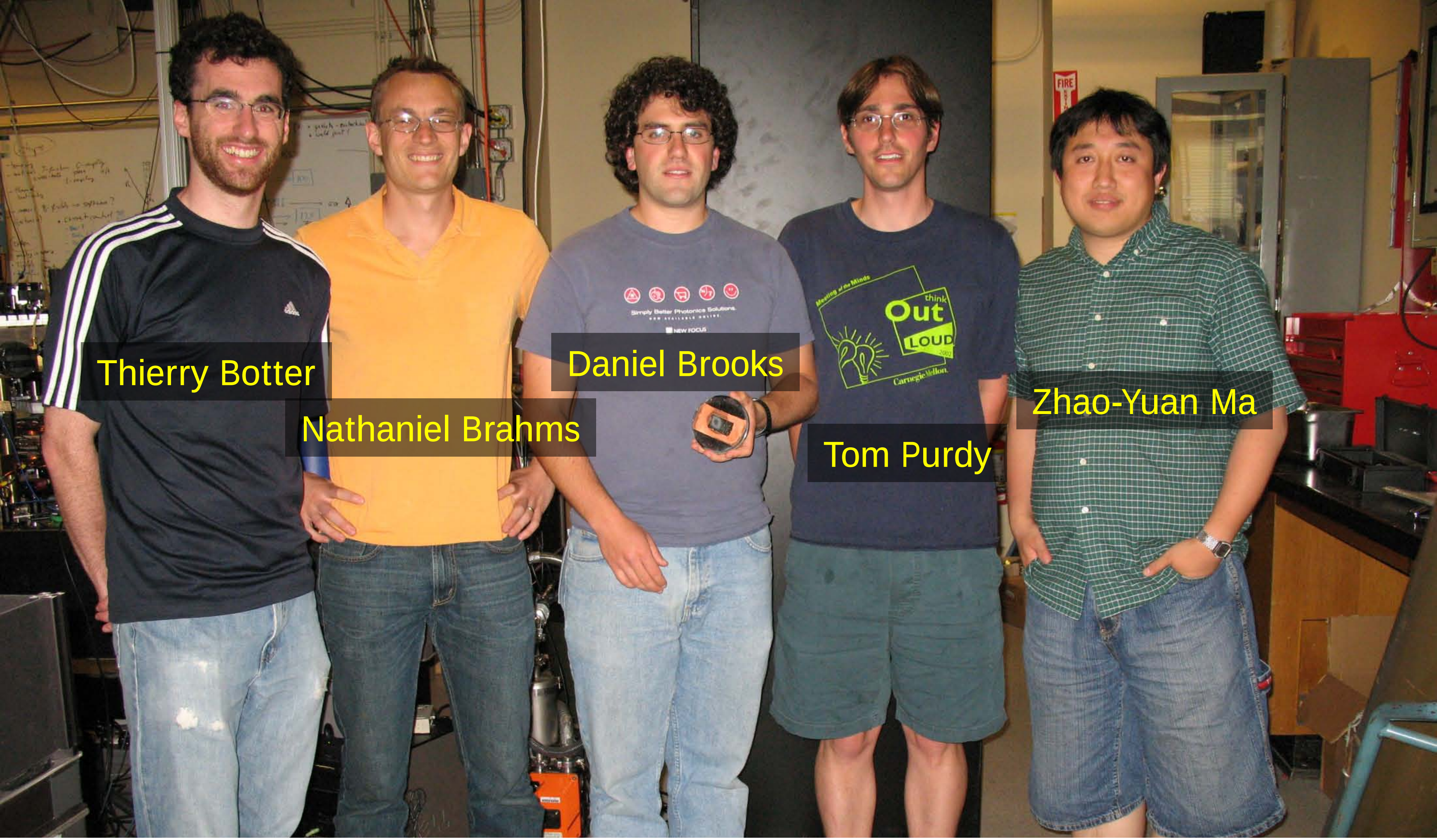




Cavity spin optodynamics
spins = “cantilever”

cavity optomechanics		cavity spin optodynamics
optomechanical bistability	→	cavity-spin bistability
optomechanical frequency shift	→	Larmor precession shifts
cavity-induced cooling / amplification	→	coherent amplification and damping of spin
ponderomotive squeezing	→	spin optodynamical squeezing

N. Brahms and DMS-K, PRA **82**, 041804(R) (2010)



Supported generously by:
US National Science Foundation
US Air Force Office of Scientific Research