

Condensed-matter physics with ultracold atoms and molecules: assessment and perspective

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a humble assessment of >15 years of studying CM physics with ultracold atoms

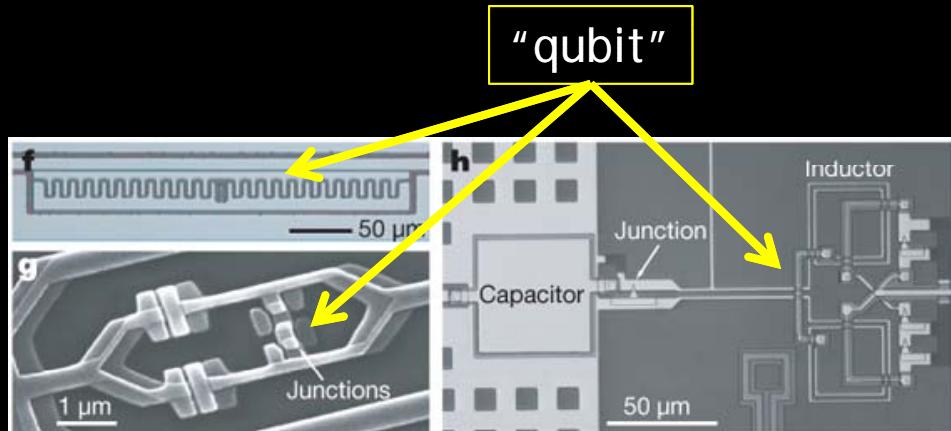
- Are we pushing the boundaries of what is possible?
 - ◆ Creating model systems and controlling quantum matter
 - cavity optomechanics
- Are we discovering?
 - ◆ Creating/discovering novel materials;
addressing the “quantum many-body physics problem”
 - resonant Fermi gases
 - ◆ Novel many-body quantum physics far from equilibrium
 - quantum quenches
- Are we producing technological and economic benefit?
 - ◆ Ultracold-atom magnetometers

structural matters

- Growth and saturation?
- Funding for an interdisciplinary field
- Training for an interdisciplinary field

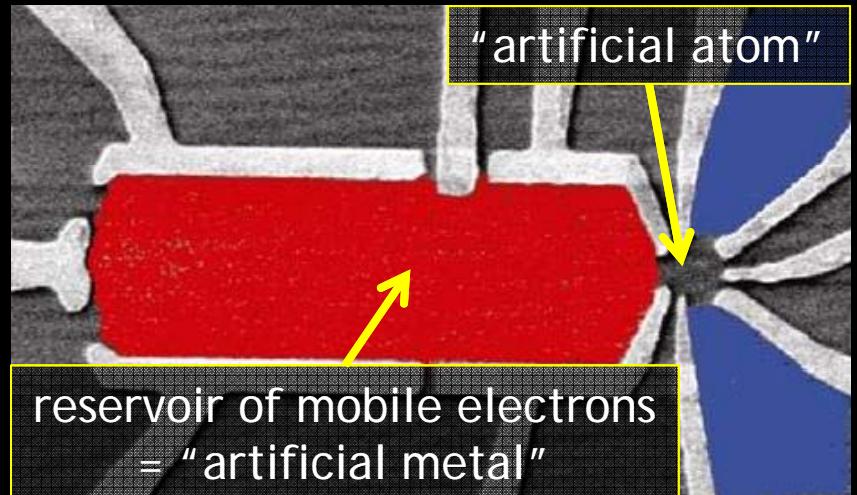
Physicists are control freaks

Superconducting electronics



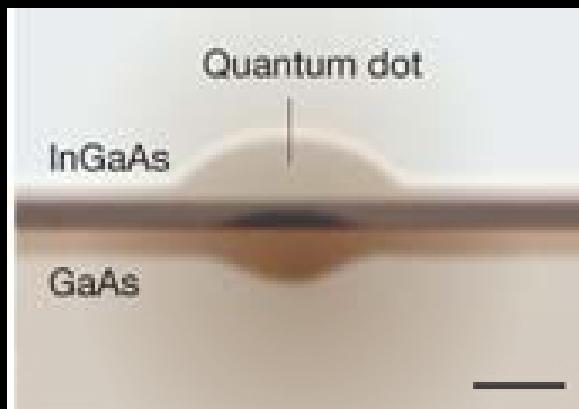
Schoelkopf, Mooij, Martinis

Mesoscopic electronics



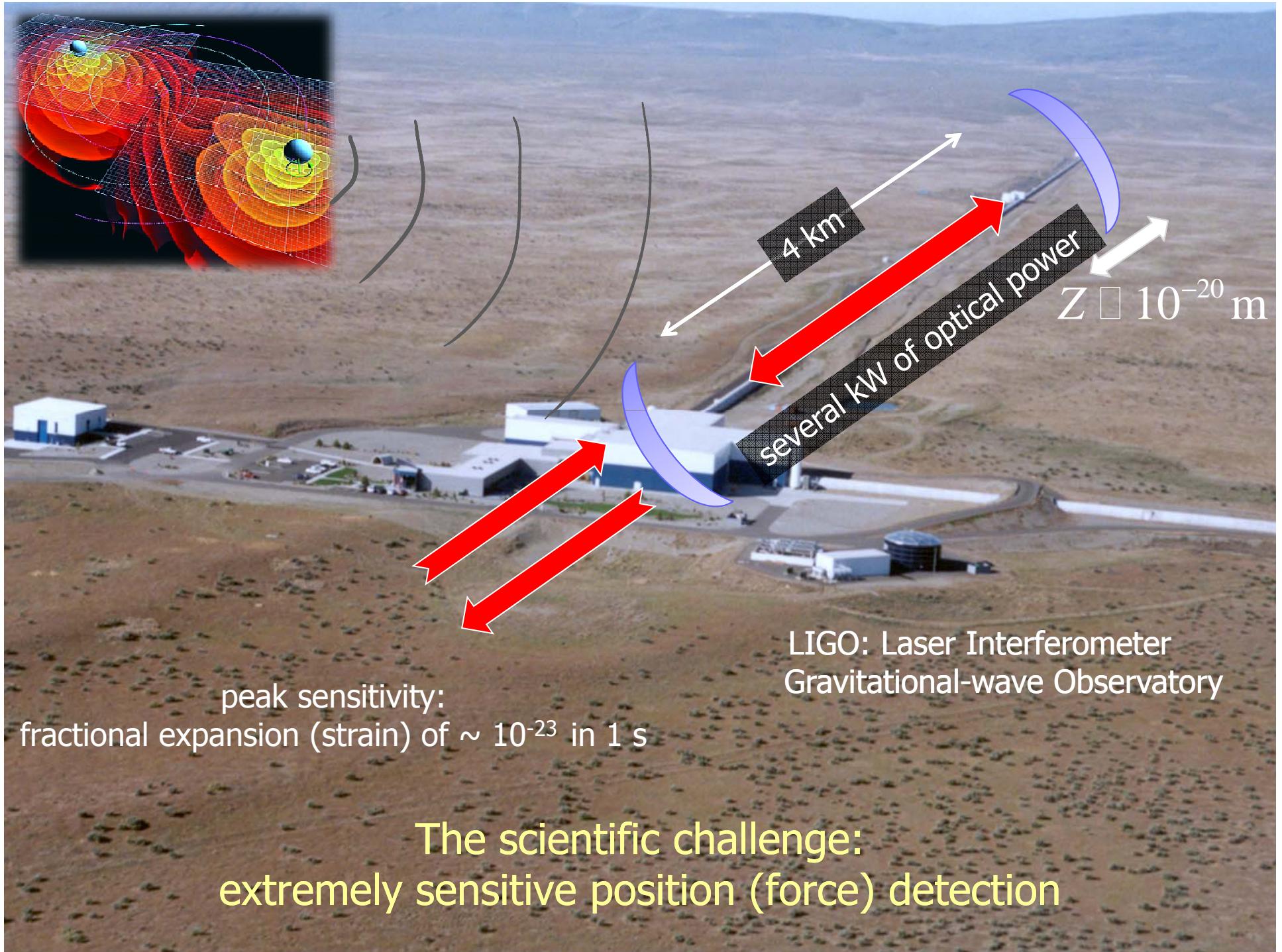
Goldhaber-Gordon

Quantum dots

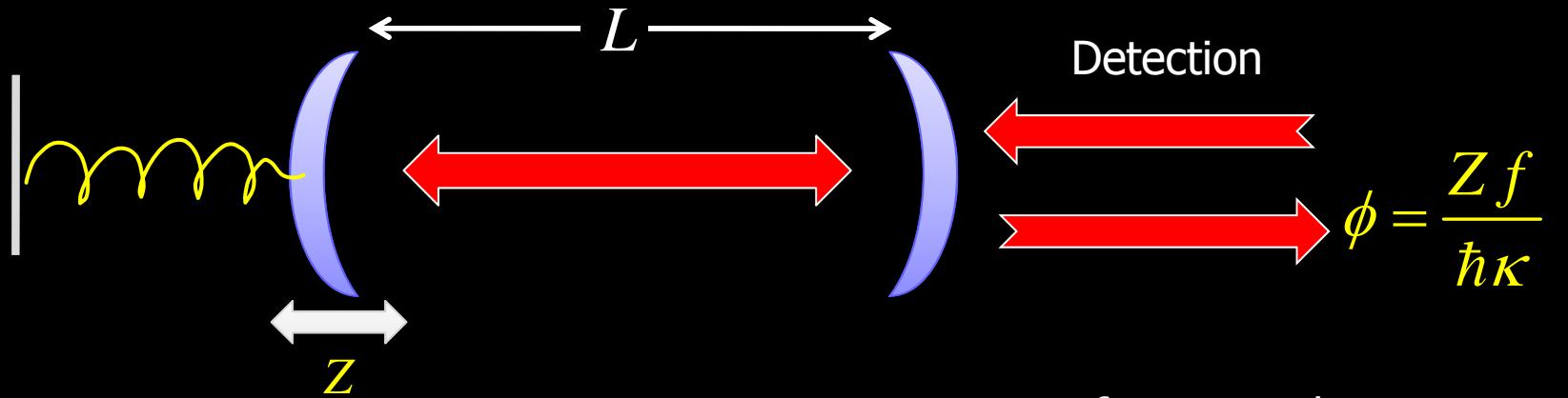


Awschalom

- Exhibit/study/test physical principles most directly
- Frontiers are good place to make discoveries



One paradigm for cavity opto-mechanics



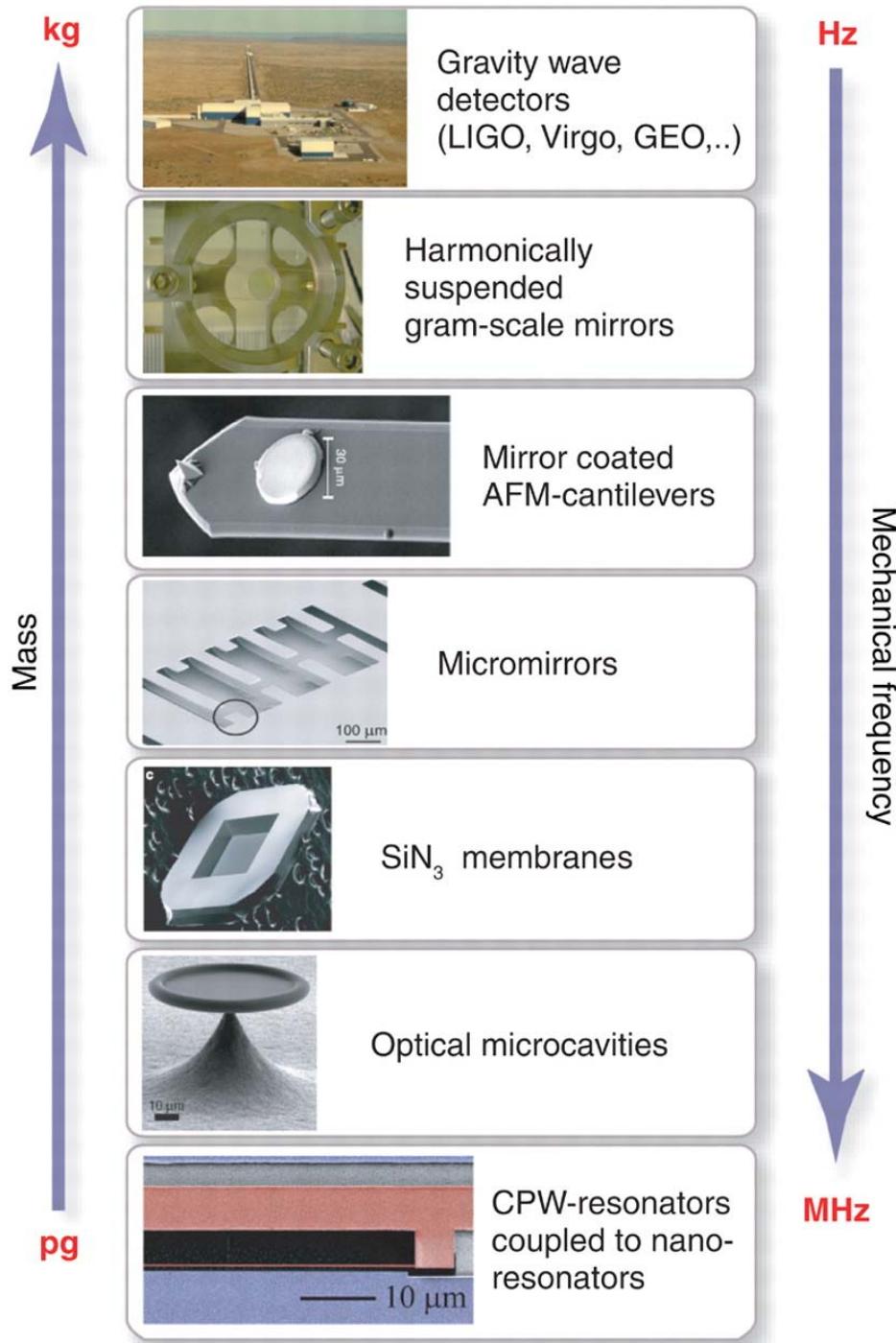
$$H = H_{osc} + H_{cav} + H_{in/out} - \boxed{Zfn}$$

force per photon:

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

Cavity frequency shift due to oscillator displacement
(sensitivity to oscillator motion)

Optical force on oscillator
(measurement back-action on oscillator)



Common goals:

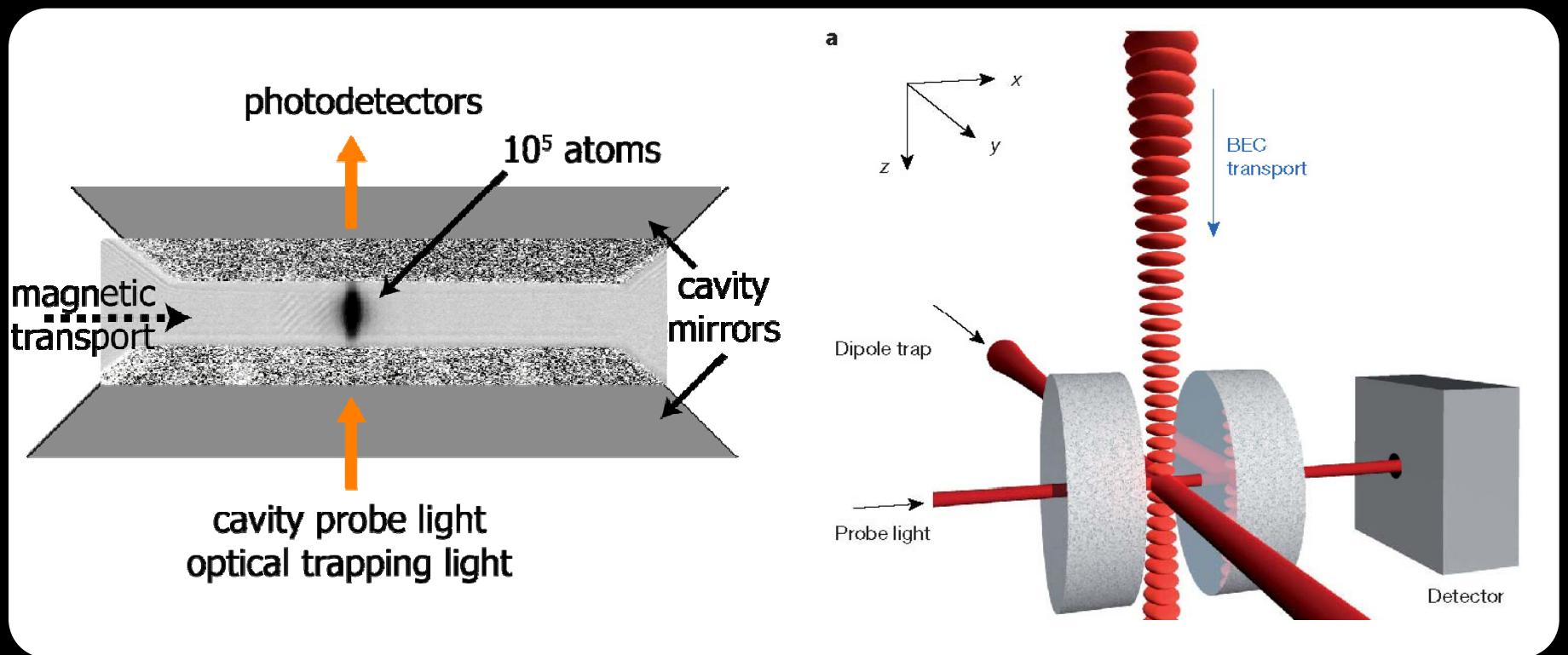
- Dominance of quantum fluctuations over thermal fluctuations
 - ◆ cooling mechanical oscillator to ground state
 - ◆ reaching quantum limits for sensitivity
- Study and use quantum effects
 - ◆ quantifying measurement backaction
 - ◆ squeezed light (ponderomotive squeezing)
 - ◆ entanglement of macroscopic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

Common means:

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

Kippenberg and Vahala,
Science 321, 1172 (2008)

Cavity optomechanics with ultracold atoms

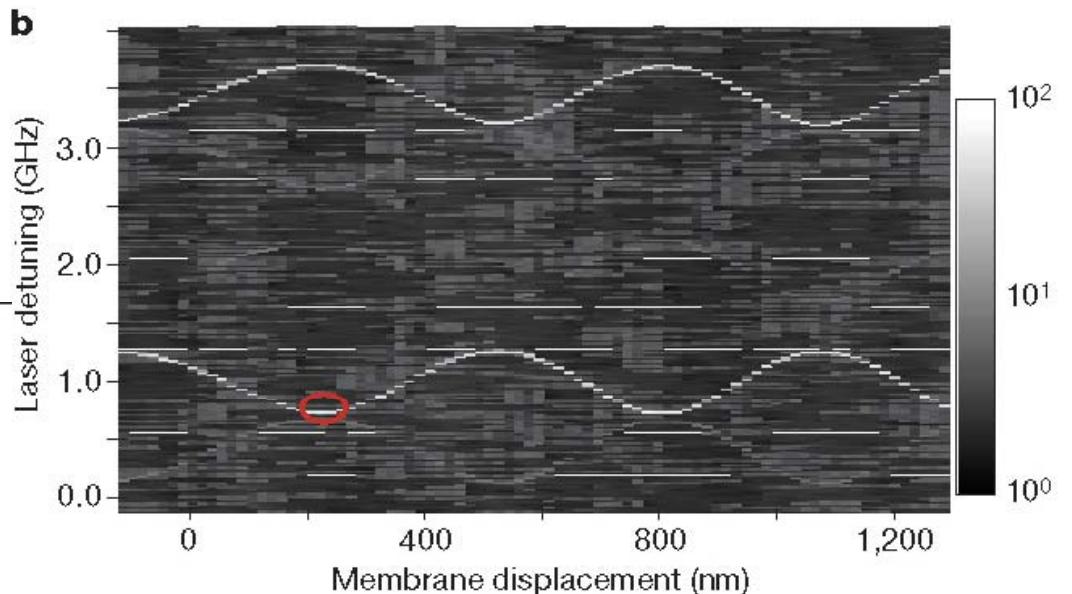
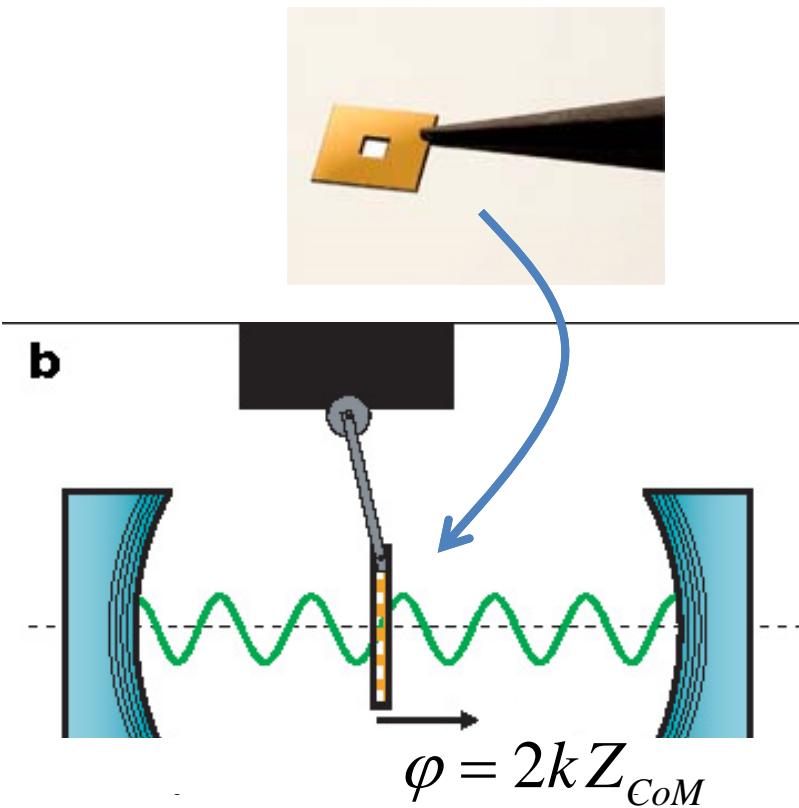


Berkeley

Esslinger, Zürich

Optomechanics with SiN membranes

Harris, Yale; now others too

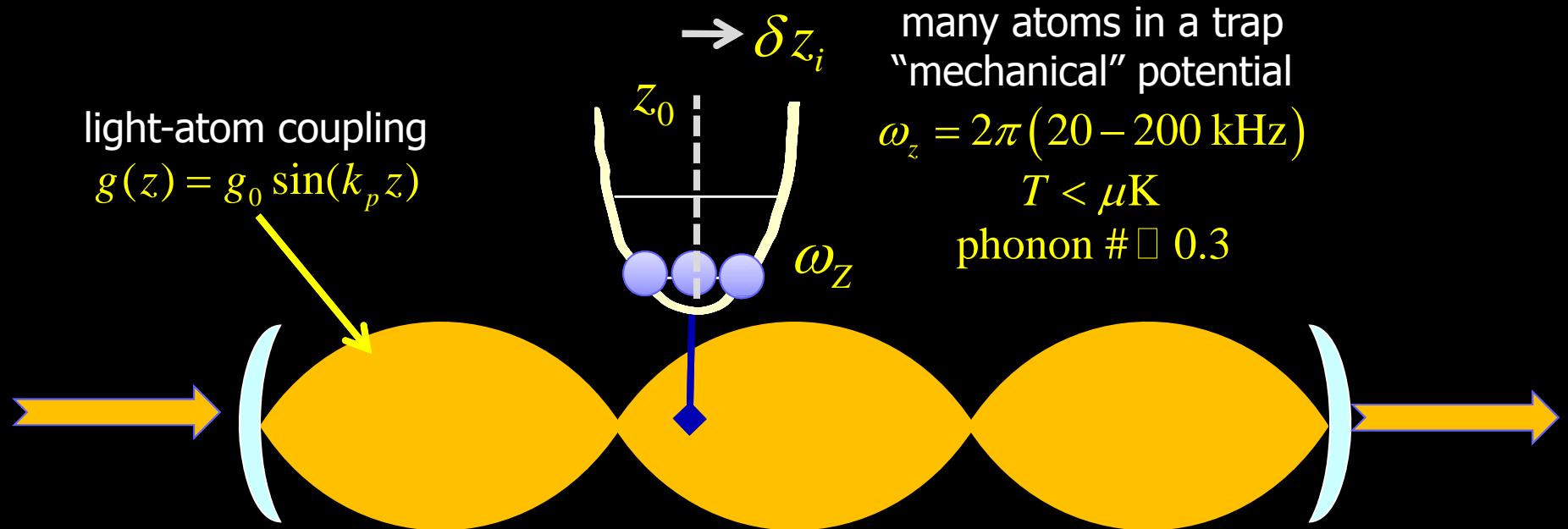


Nature 452, 72 (2008)

$$H_{om} = E(2\varphi)n - f \sin(2\varphi)Z_{CoM}n - f k \cos(2\varphi)Z_{CoM}^2n + \dots$$

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

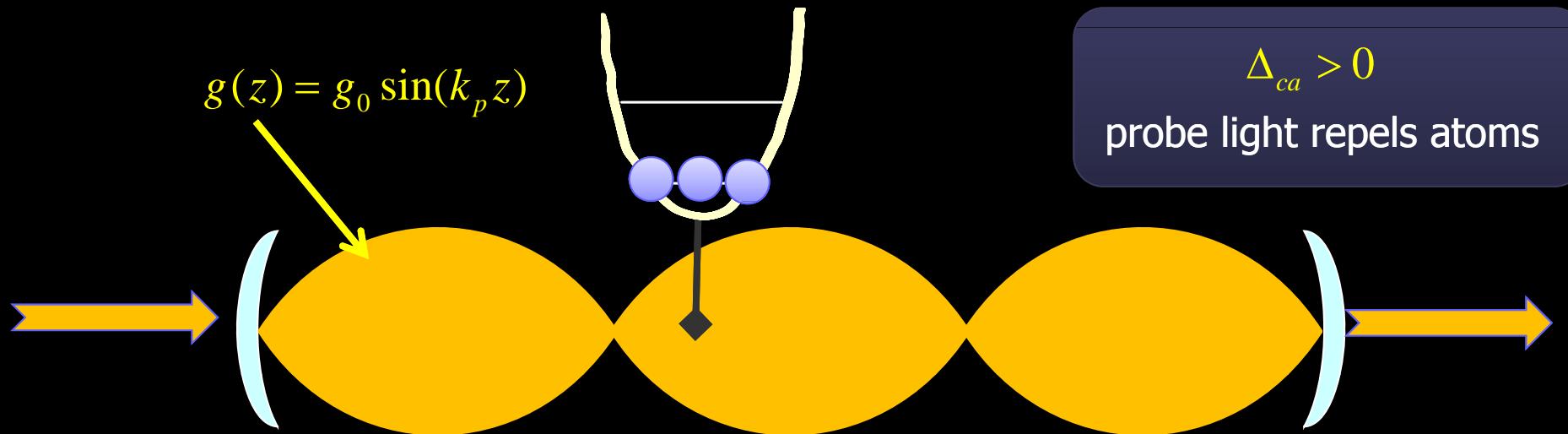
quadratic coupling:
phonon QND,...



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

- 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)

Measuring radiation pressure forces



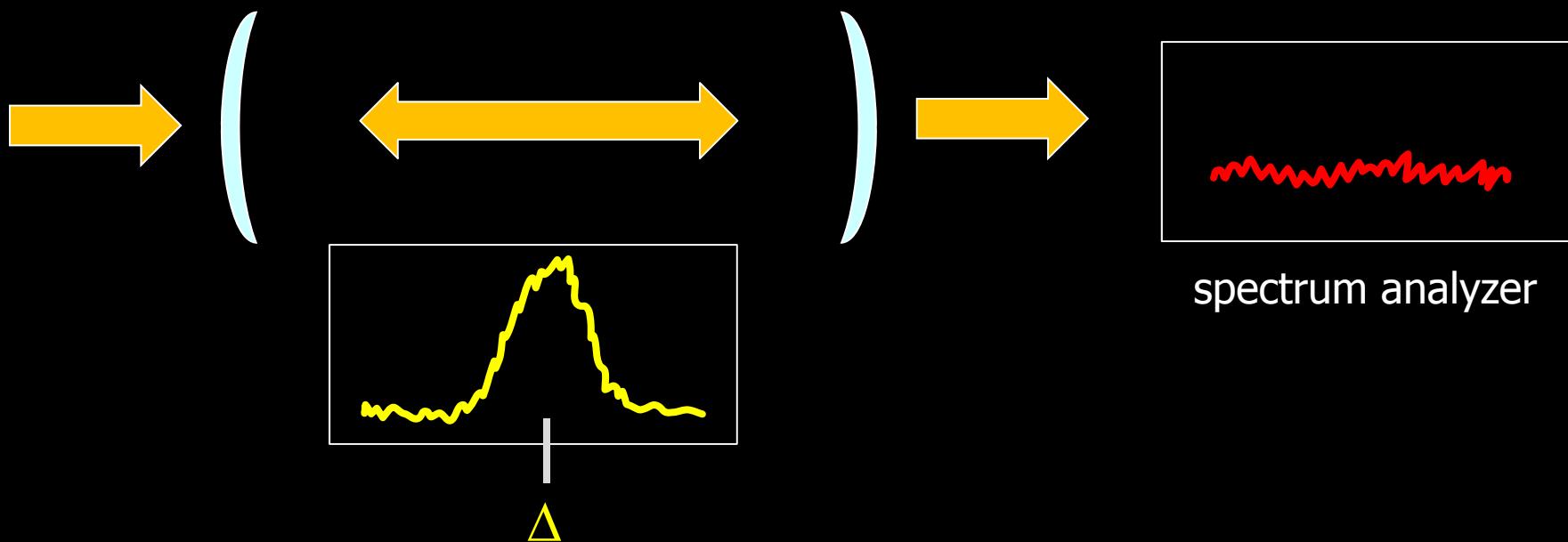
- “Coherent” effect: Optical forces in the cavity will displace the trapped atoms
 - ◆ Probing the cavity shifts the cavity resonance \Rightarrow nonlinear cavity optics [PRL 99, 213601 (2007)]
- “Incoherent” effect: Quantum force fluctuations \Rightarrow momentum diffusion
 - ◆ Atoms act as intracavity sensor of photon number fluctuations
 - ◆ momentum diffusion = quantum backaction of position measurement [Nature Physics 4, 561 (2008)]

Quantum optics: intracavity photon shot noise spectrum

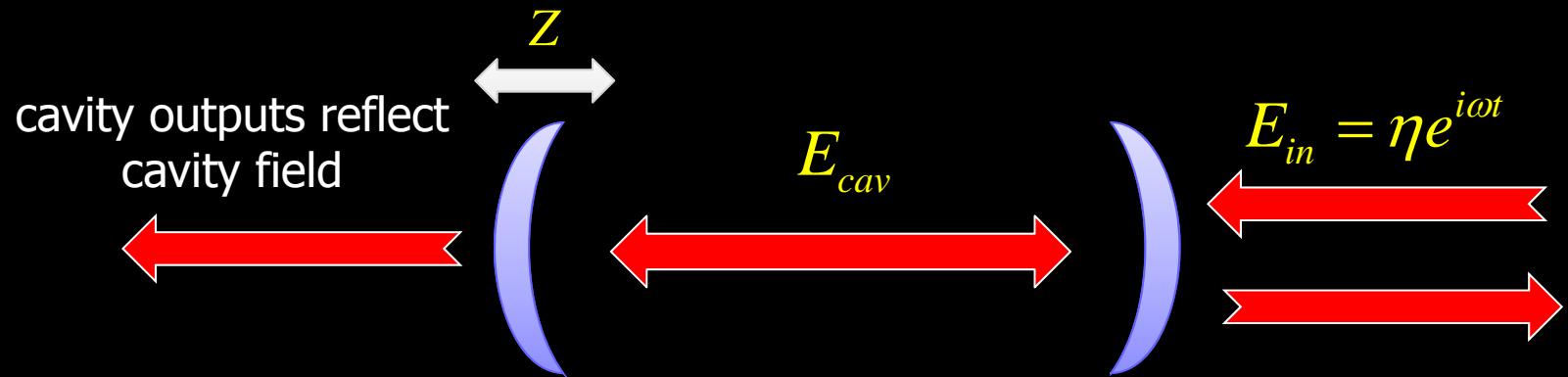
- For a coherently driven cavity:

$$S_{nn}(\omega) \propto \frac{2\bar{n}}{\kappa} \frac{1}{1 + (\Delta - \omega)^2 / \kappa^2}$$

Spectral power density of photon number fluctuations (inter alia, force fluctuations)



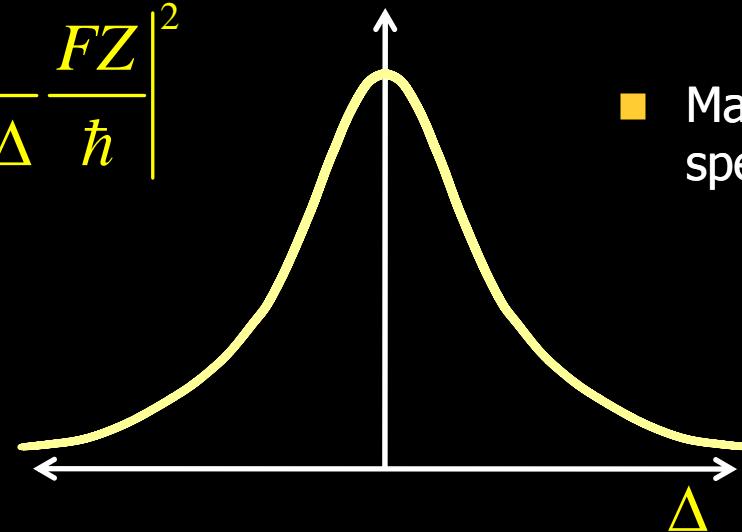
Quantum measurement: backaction of position measurement



$$E_{cav} \square E_{cav}(Z=0) \left[1 + \frac{i}{\kappa - i\Delta} \frac{FZ}{\hbar} \right] \quad \Delta = \omega - \omega_0 + \frac{FZ}{\hbar}$$

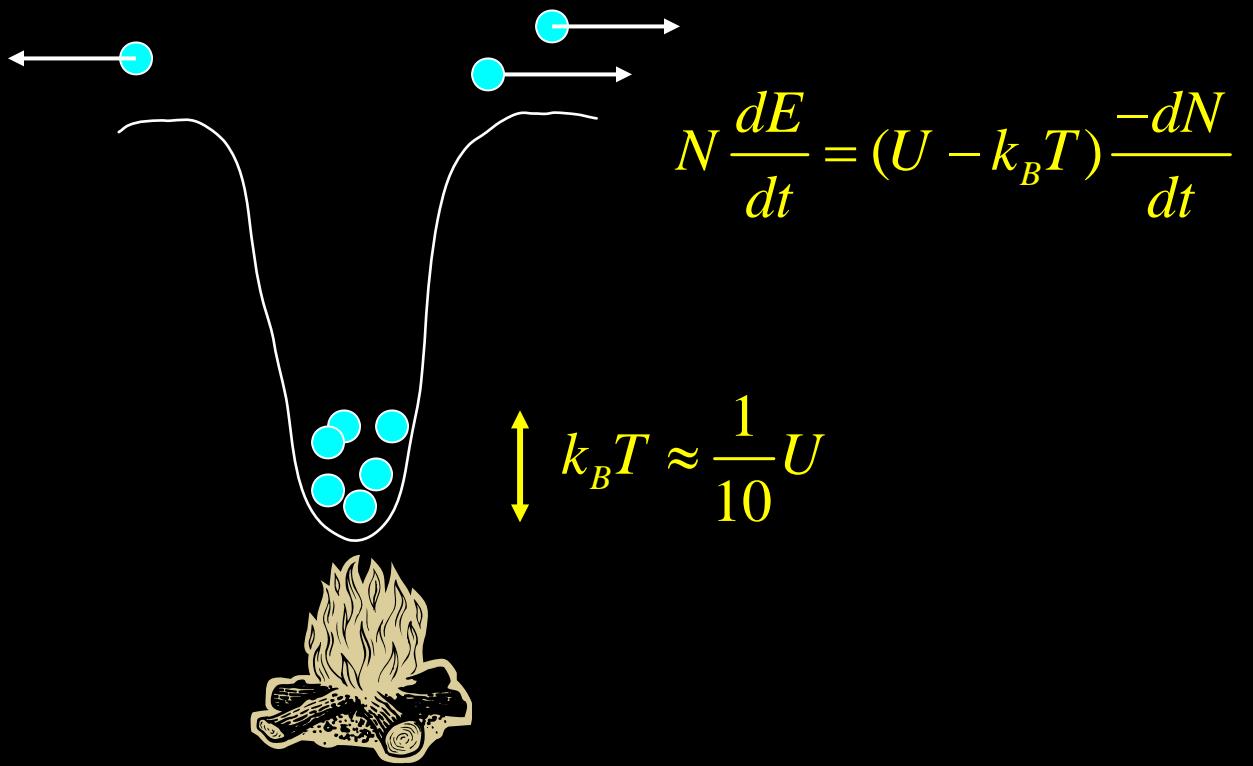
Information per photon:

$$\left| \frac{i}{\kappa - i\Delta} \frac{FZ}{\hbar} \right|^2$$



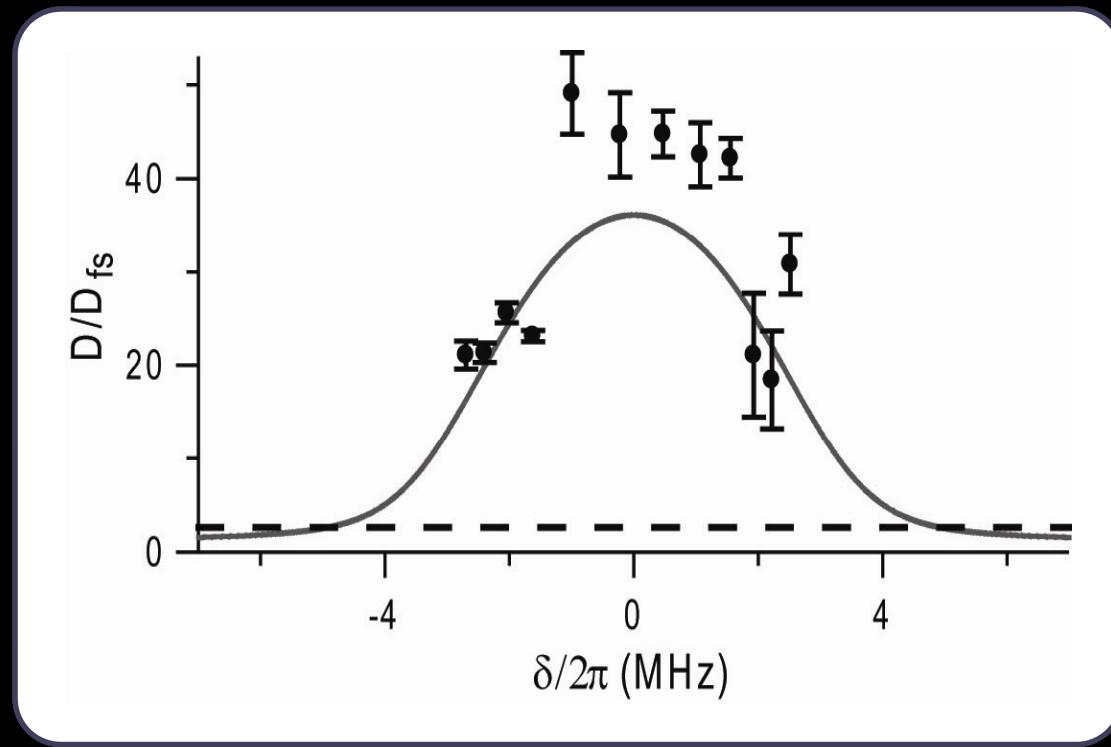
- Matches force fluctuation spectrum (as it must)

Cavity-induced heating: measured by atom loss



Cavity-induced heating: measured by atom loss

Heating rate per cavity photon compared to free space value



What this means:

- Quantum fluctuations of radiation pressure dominate over other heating sources
- Quantum metrology: back-action heating of macroscopic object at level prescribed by quantum measurement limits

Granular regime of optomechanics

define dimensionless granularity parameter:

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

zero-point position spread

measurement uncertainty from single photon

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

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

(single-photon force) x (residence time of photon)

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: $\varepsilon = 0.01 - 10$

a humble assessment of >15 years of studying CM physics with ultracold atoms

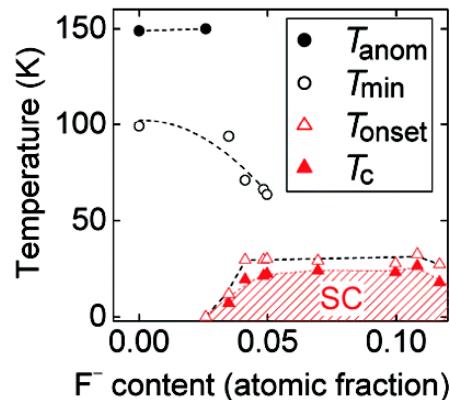
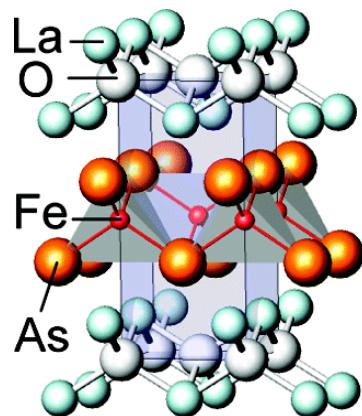
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structural matters

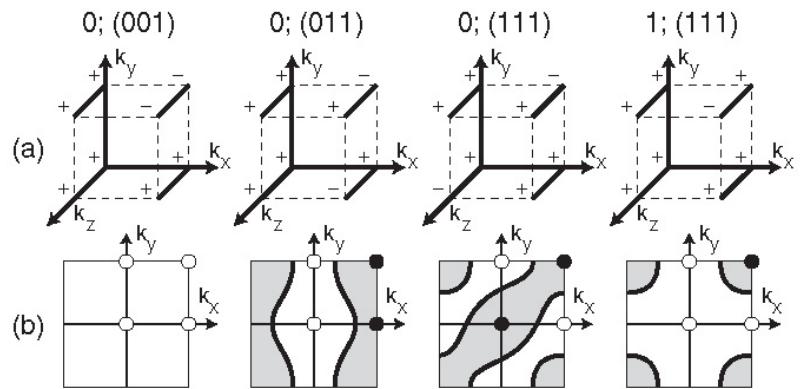
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What does discovering look like?

Iron-based SC: "experimental discovery"



Topological insulators: "theoretical discovery"



Parent compounds identified 2006 - 2008
Flurry of synthesis + reports
Focused experimental probing +
theoretical development

From 2D QSH effect to 3D concept 2007
Suggestions lead to ARPES observations
in Bi materials
Topological superconductors,
classifications, suggested applications

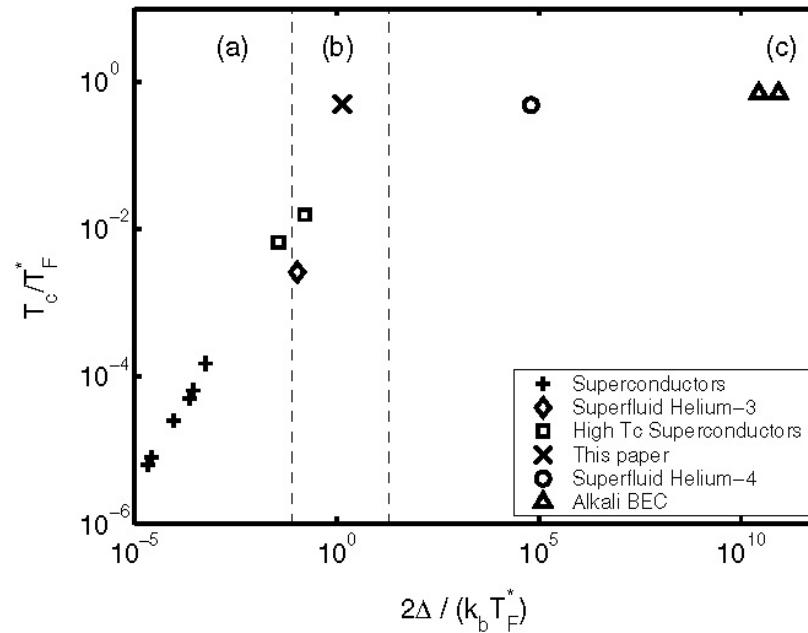
Resonance Superfluidity in a Quantum Degenerate Fermi Gas

M. Holland,¹ S. J. J. M. F. Kokkelmans,¹ M. L. Chiofalo,² and R. Walser¹

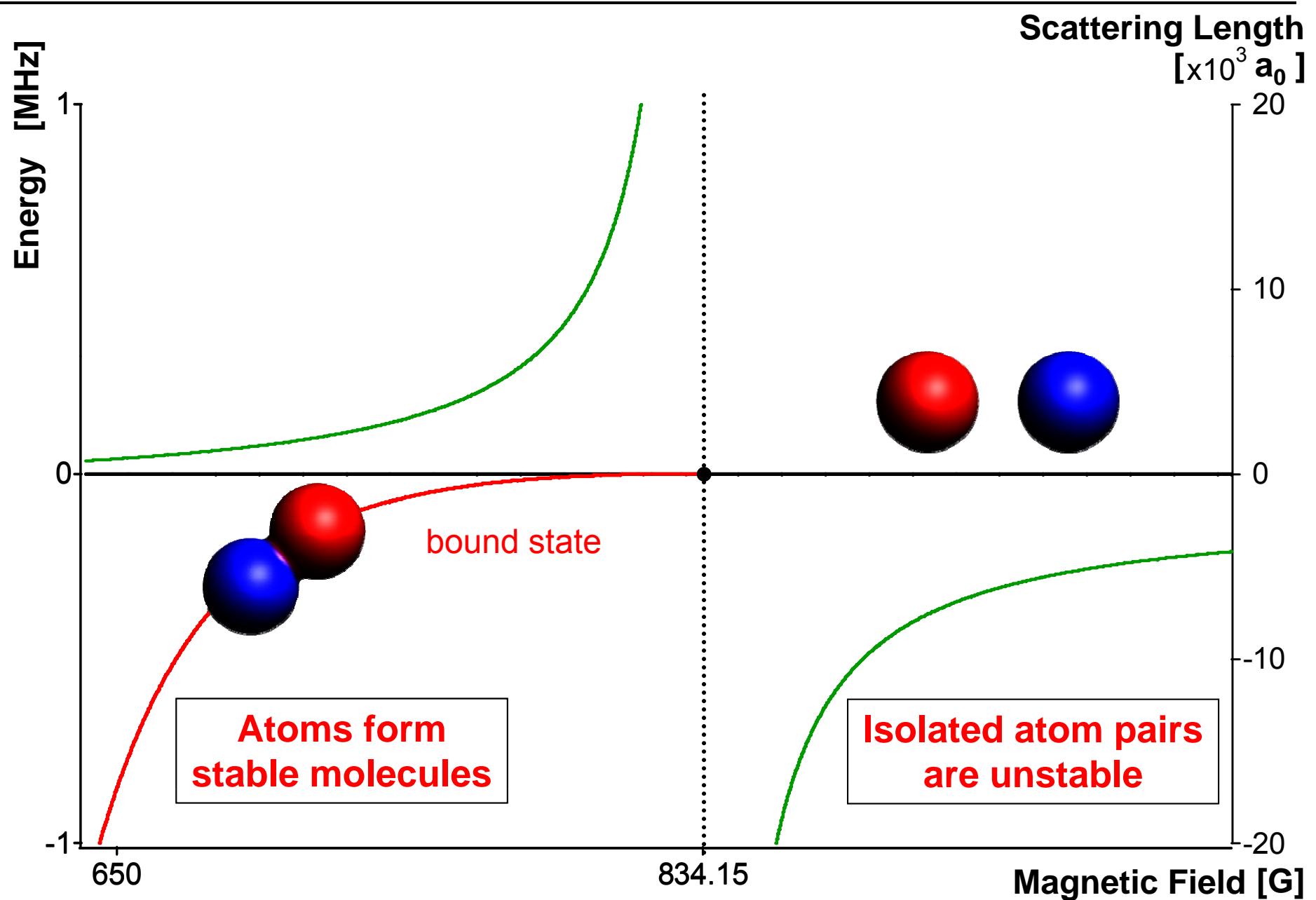
¹*JILA, University of Colorado and National Institute of Standards and Technology,
Boulder, Colorado 80309-0440*

²*INFM and Scuola Normale Superiore, Piazza dei Cavalieri 7, I-56126 Pisa, Italy*

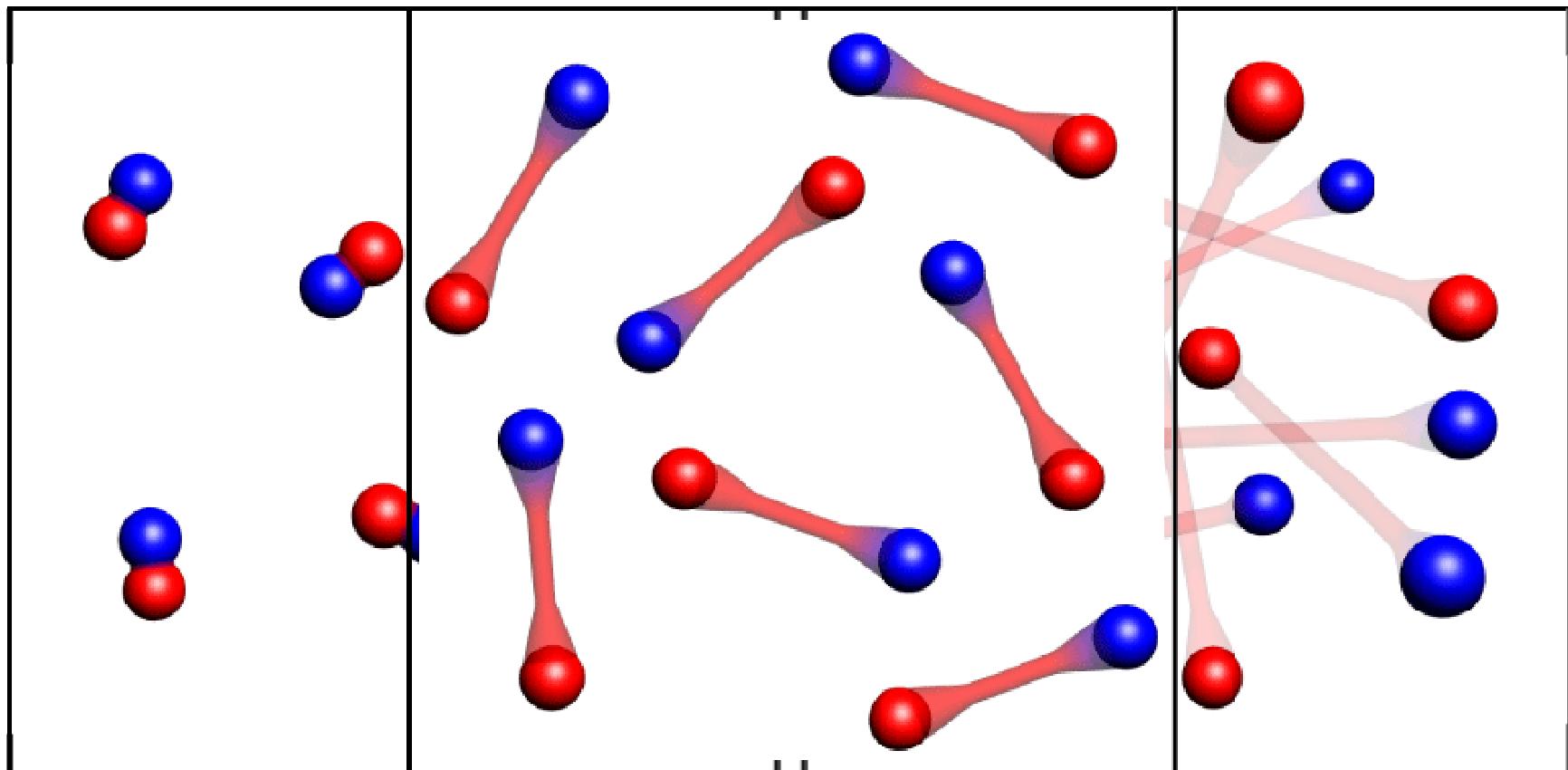
(Received 22 March 2001; published 31 August 2001)



Feshbach Resonances



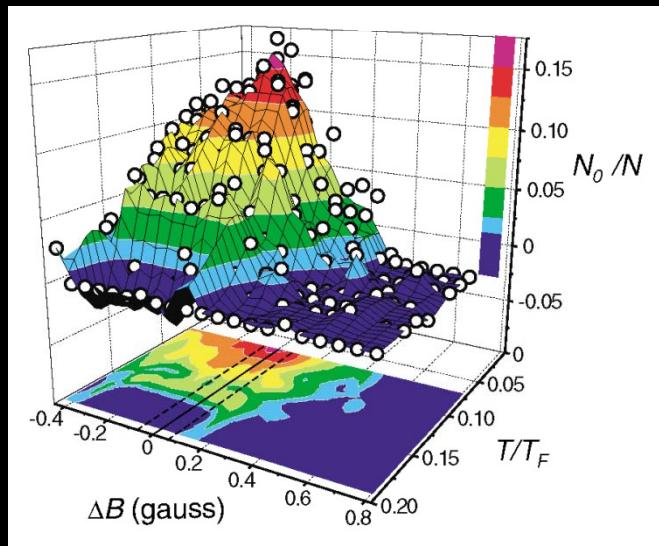
The BEC-BCS Crossover



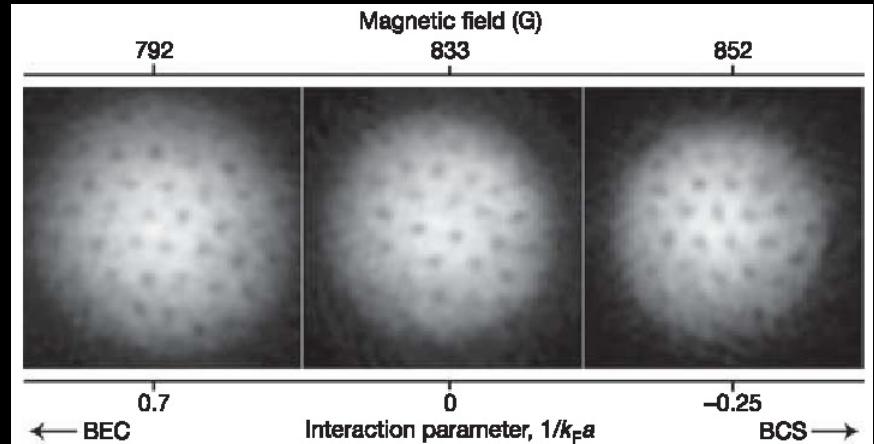
BEC of Molecules **Crossover** Superfluid BCS state

Thanks to Martin Zwierlein for slides

Experimental realization



Jin



Zwierlein, Ketterle

- Studied using techniques benchmarked from prior BEC research:
 - ◆ Hydrodynamics of expanding gas (Thomas et al.)
 - ◆ Collective excitations (Grimm, Salomon)
 - ◆ Vortices and critical velocity (Ketterle)
 - ◆ Photoassociation (Hulet)
- ... and newly developed/refined techniques
 - ◆ RF spectroscopy (Grimm, Jin, Ketterle)
 - ◆ Noise correlations (Jin)

Shina Tan's relations

Universal thermodynamics...

- Many properties of the interacting Fermi gas are determined by high-momentum portion of the 2-body wave-function

$$P(k) = C/k^4 \quad C = \text{"Contact"}$$

such as...

- Local density of pairs (related to photoassociation rate)
- Sum of kinetic and interaction energy
- Change in total energy due to small adiabatic change in scattering length
- Virial relation between total energy and potential energy in harmonic trap
- Relation between pressure and total energy
- Inelastic two-body loss rate (again relates to density of pairs)
- Clock shift in RF transitions

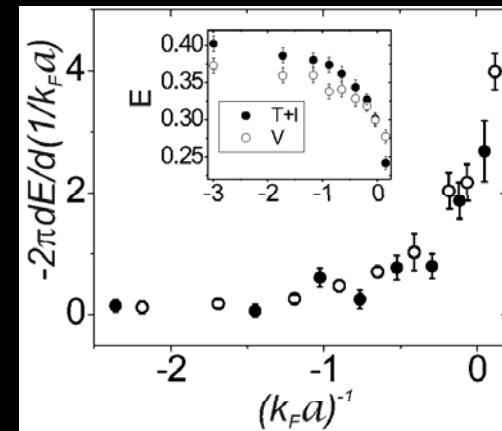
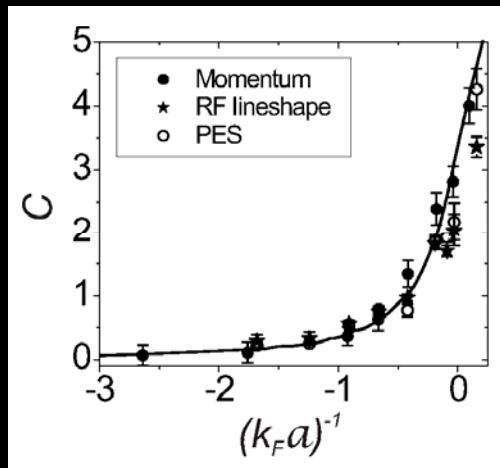
Shina Tan's relations: experimental verification

“Verification of universal relations in a strongly interacting Fermi gas,”

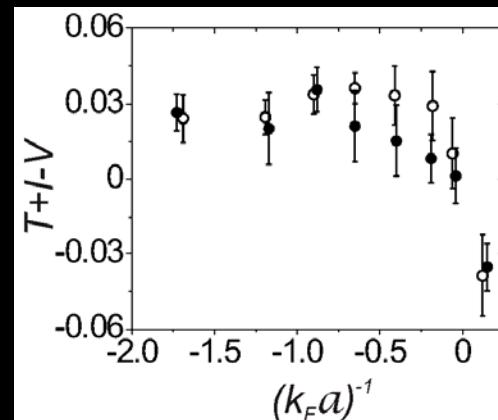
Stewart et al (Jin group), preprint arXiv:1002.1987

- Change in total energy due to small adiabatic change in scattering length

measure the contact, then test...

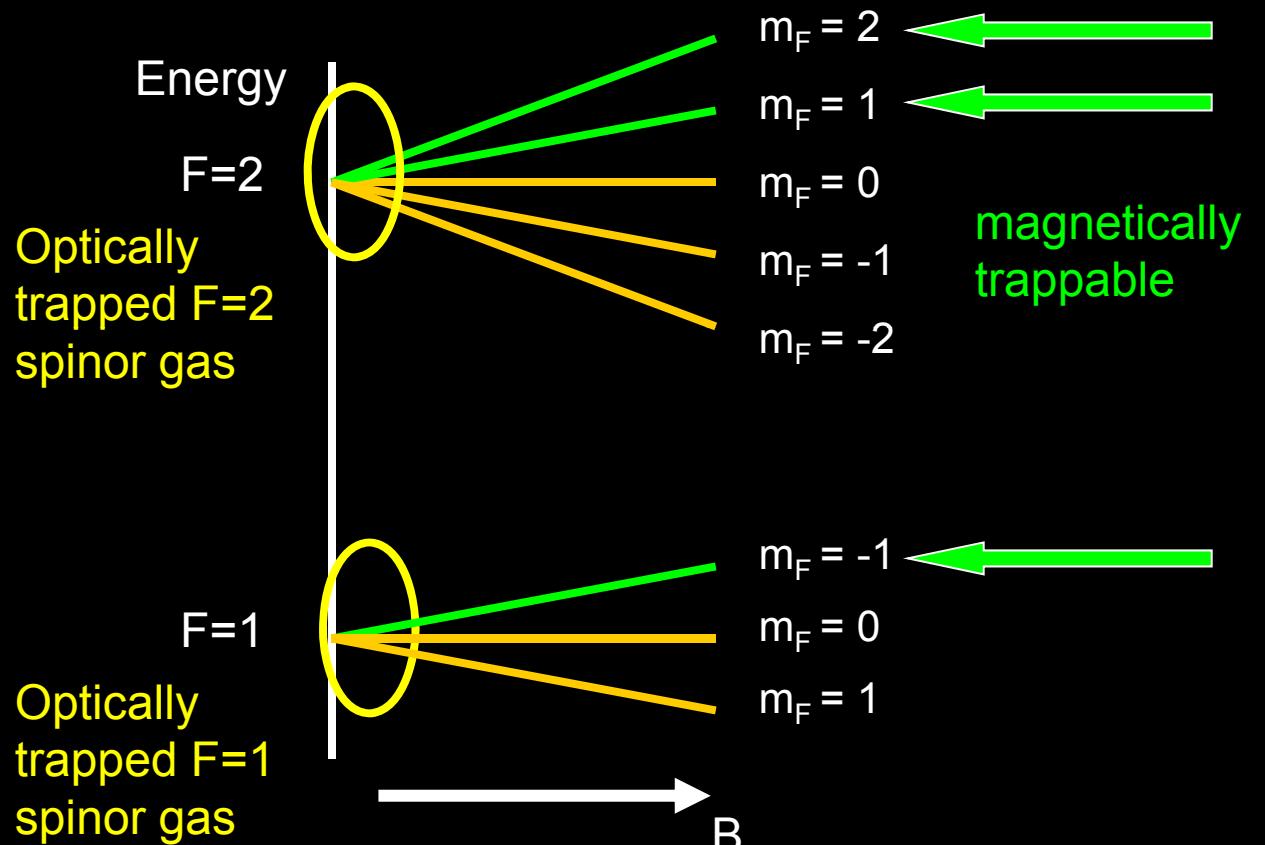
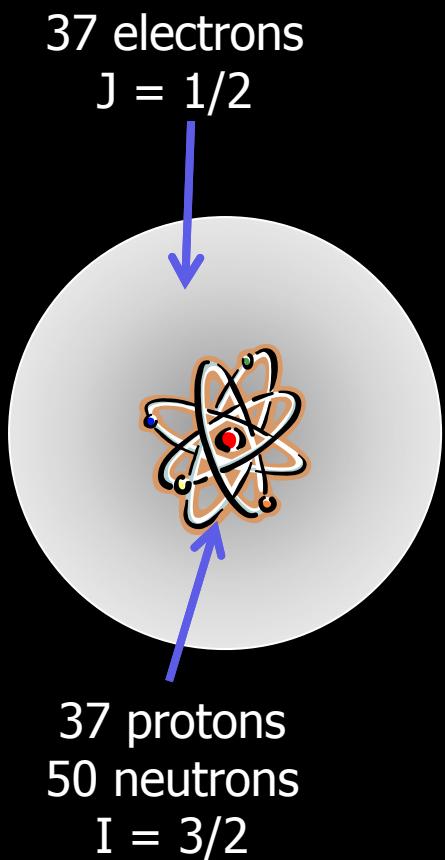


- Virial relation between total energy and potential energy in harmonic trap



see also Hu et al. (Vale group), preprint arXiv:1001.3200

New material: spinor Bose gas



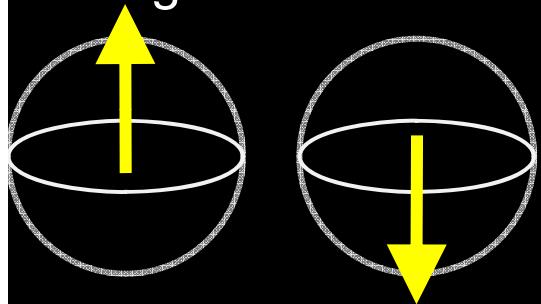
$$\vec{F} = \vec{I} + \vec{J}$$

Phases and symmetries

$$E = -|c_2|n\langle \vec{F} \rangle^2 + q\langle F_z^2 \rangle$$

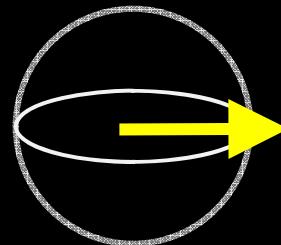
ferromagnetic states

longitudinal axis



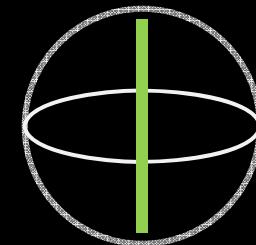
$Z_2 \times U(1)$

transverse plane



$SO(2) \times U(1)$

unmagnetized state



$U(1)$

← 0

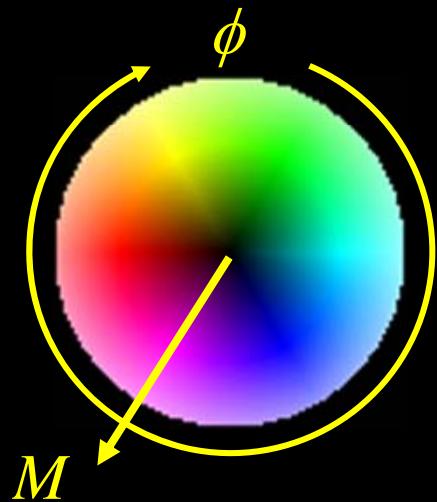
← BEC →

$$q_0 = 2|c_2|n$$

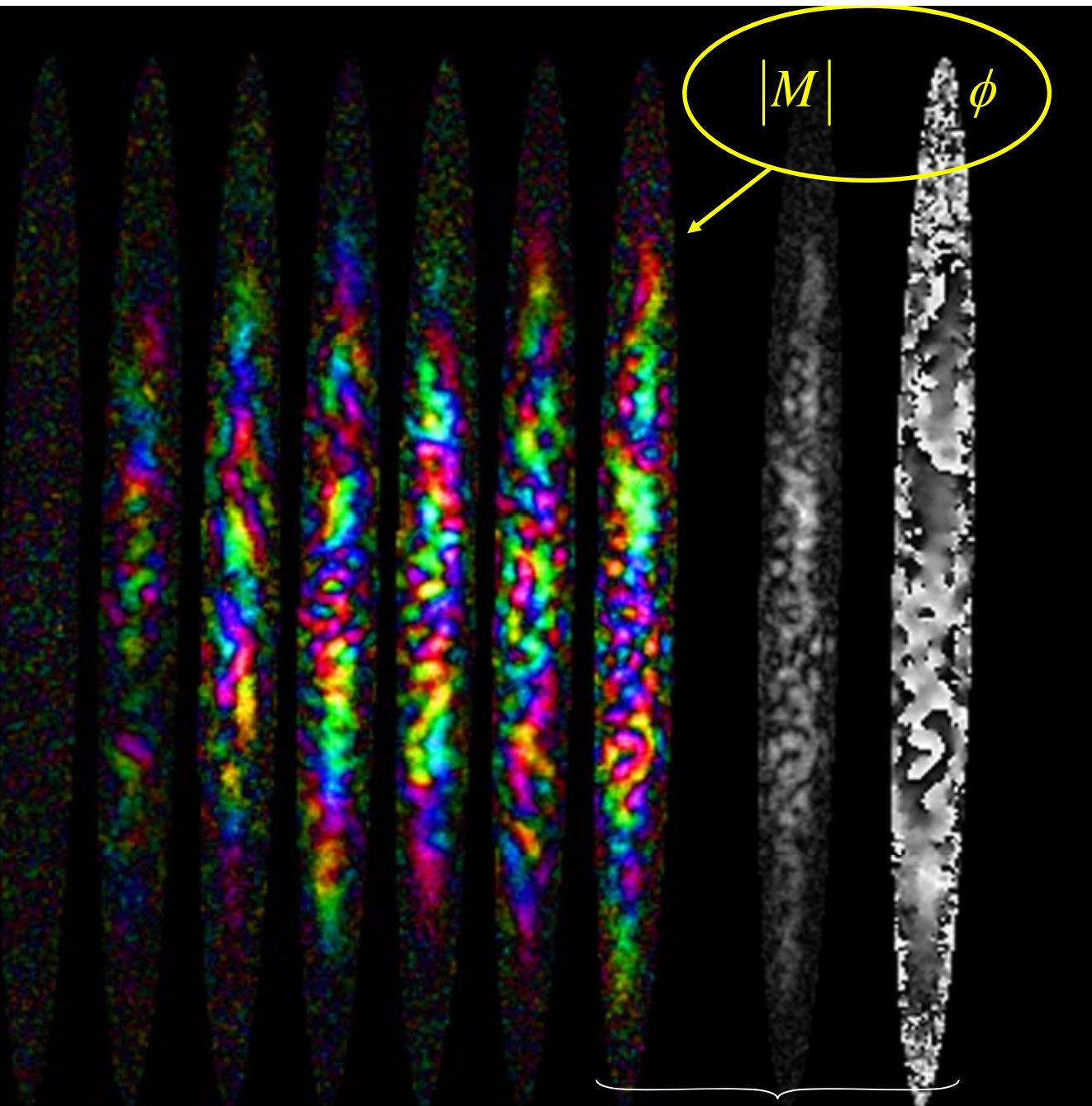
Quantum quench:
Non-equilibrium (quantum) dynamics at a (quantum) phase transition

Spontaneous ferromagnetism

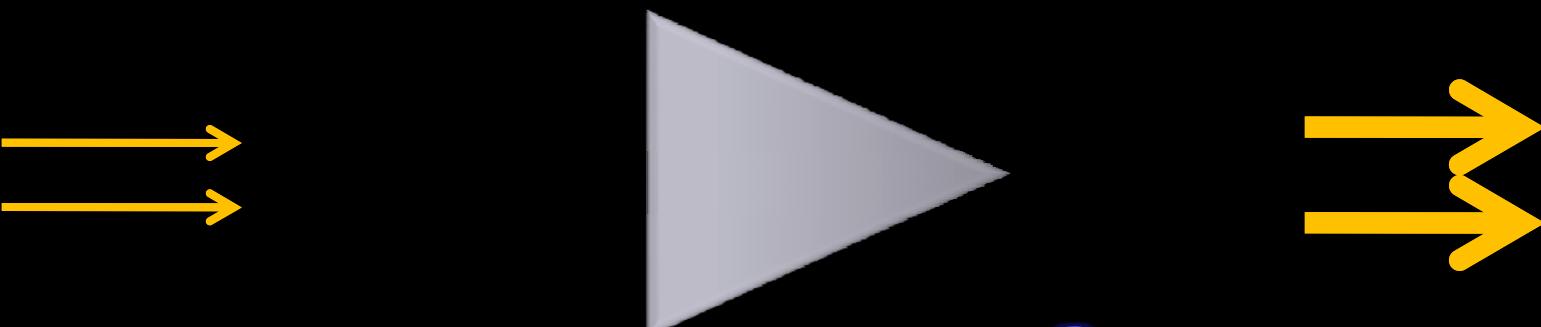
- inhomogeneously broken symmetry
- ferromagnetic domains, large and small
- unmagnetized domain walls marking rapid reorientation

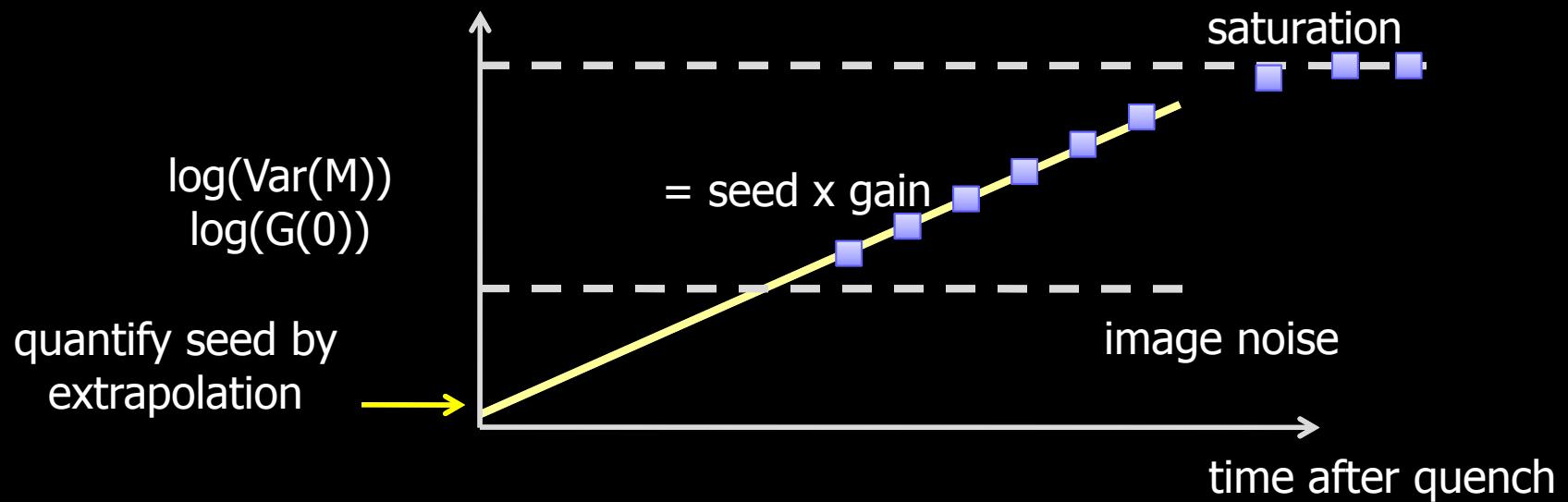


$T_{\text{hold}} = 30 \quad 60 \quad 90 \quad 120 \quad 150 \quad 180 \quad \underbrace{\quad \quad \quad \quad \quad \quad}_{210 \text{ ms}}$



Quantum (?) spin fluctuations and quantum (?) spin amplifiers


$$\left(\text{quantum spin fluctuations} \right) \times \left(\text{gain of quantum-limited parametric amplifier} \right) \stackrel{?}{=} \left(\text{fluctuation (variance) of macroscopic spin texture} \right)$$



Quantum quench theory: Lamacraft, PRL 98, 160404 (2007);
expt: PRA 79, 043631 (2009)

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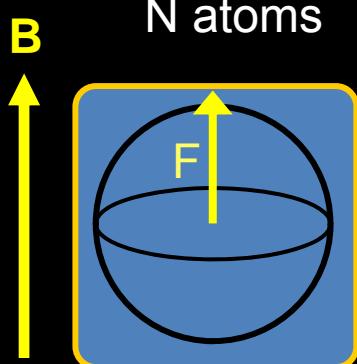
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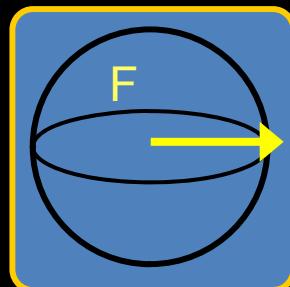
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Spinor gas magnetometry

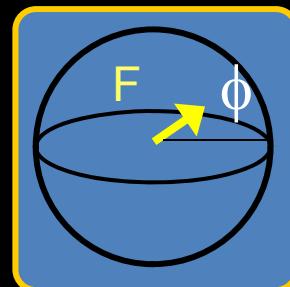
N atoms



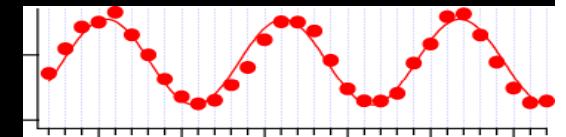
$t = 0$



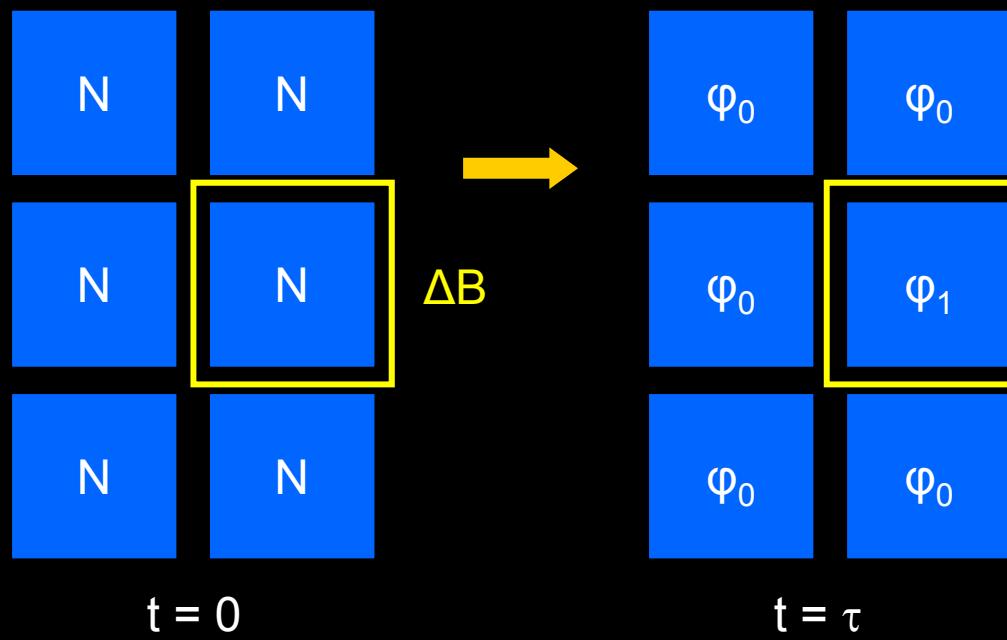
$t = \tau$



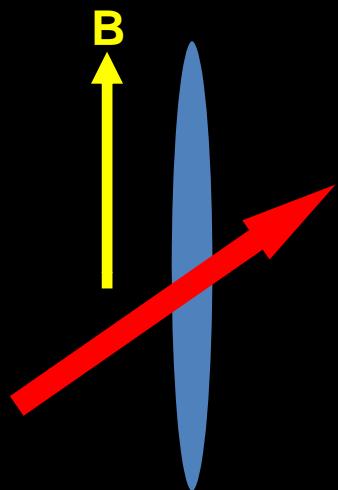
Probe:



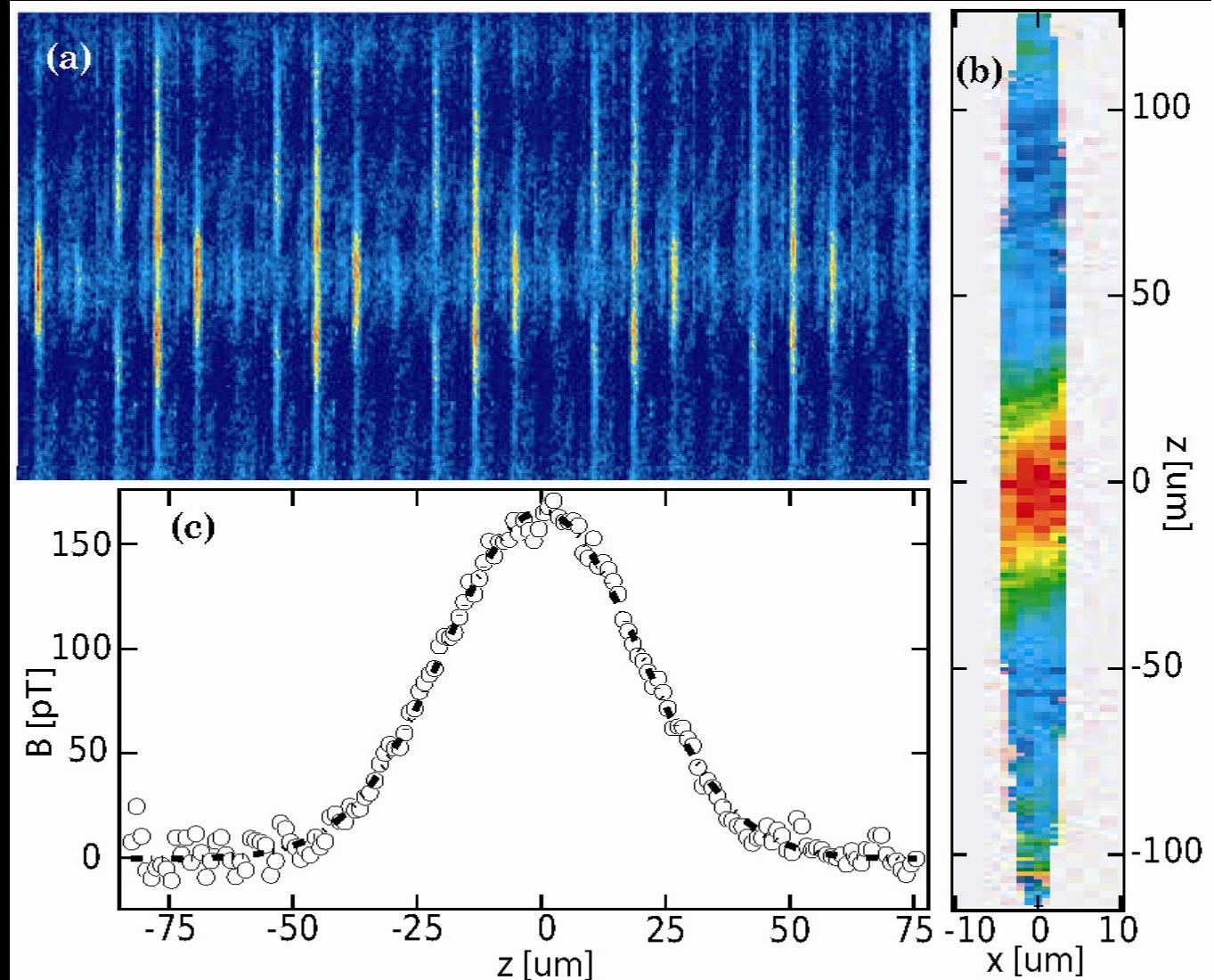
Budker and Romalis, Nature Phys. 3, 227 (2007)



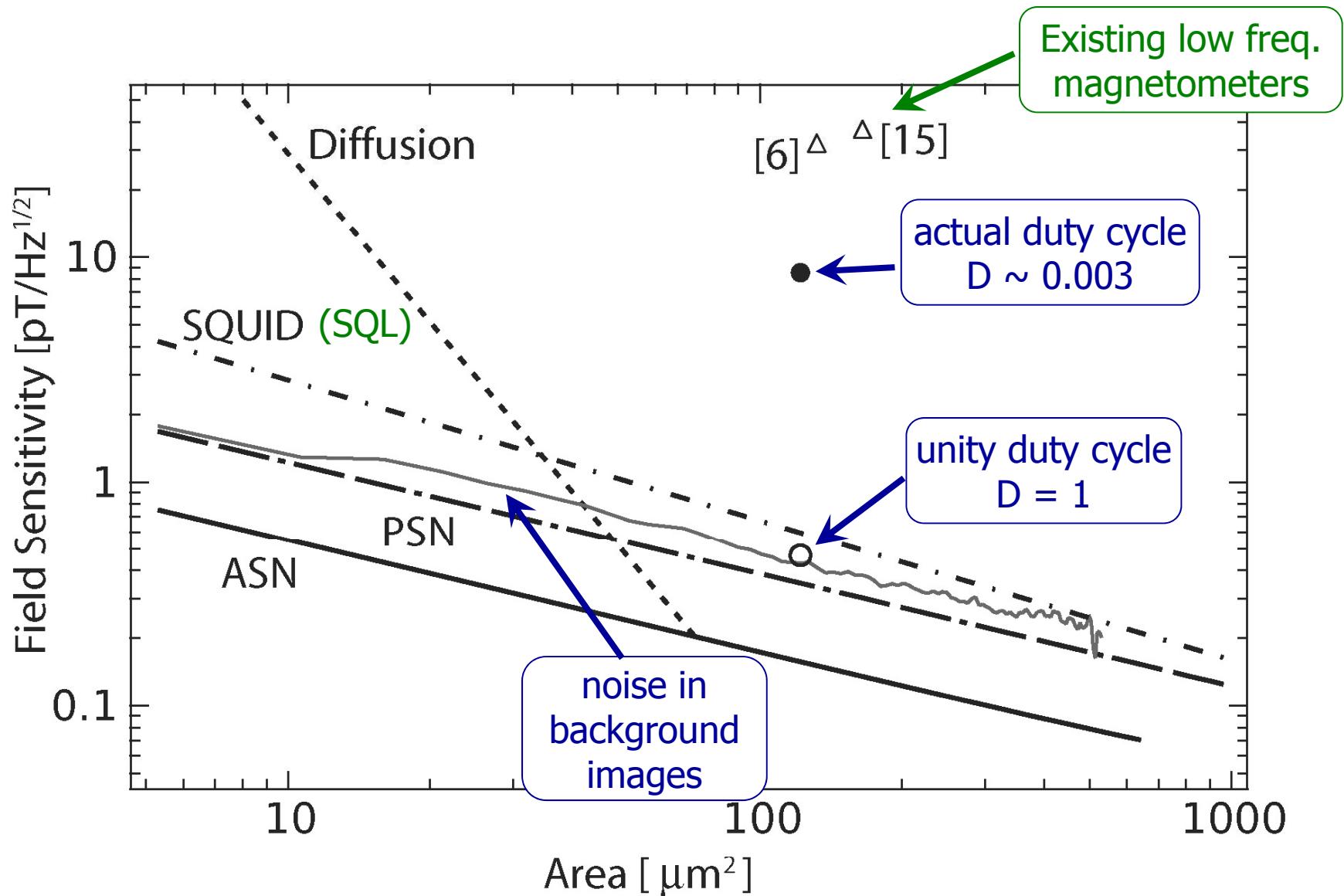
“Field” measurements



AC Stark shift =
“Fictitious” magnetic
field



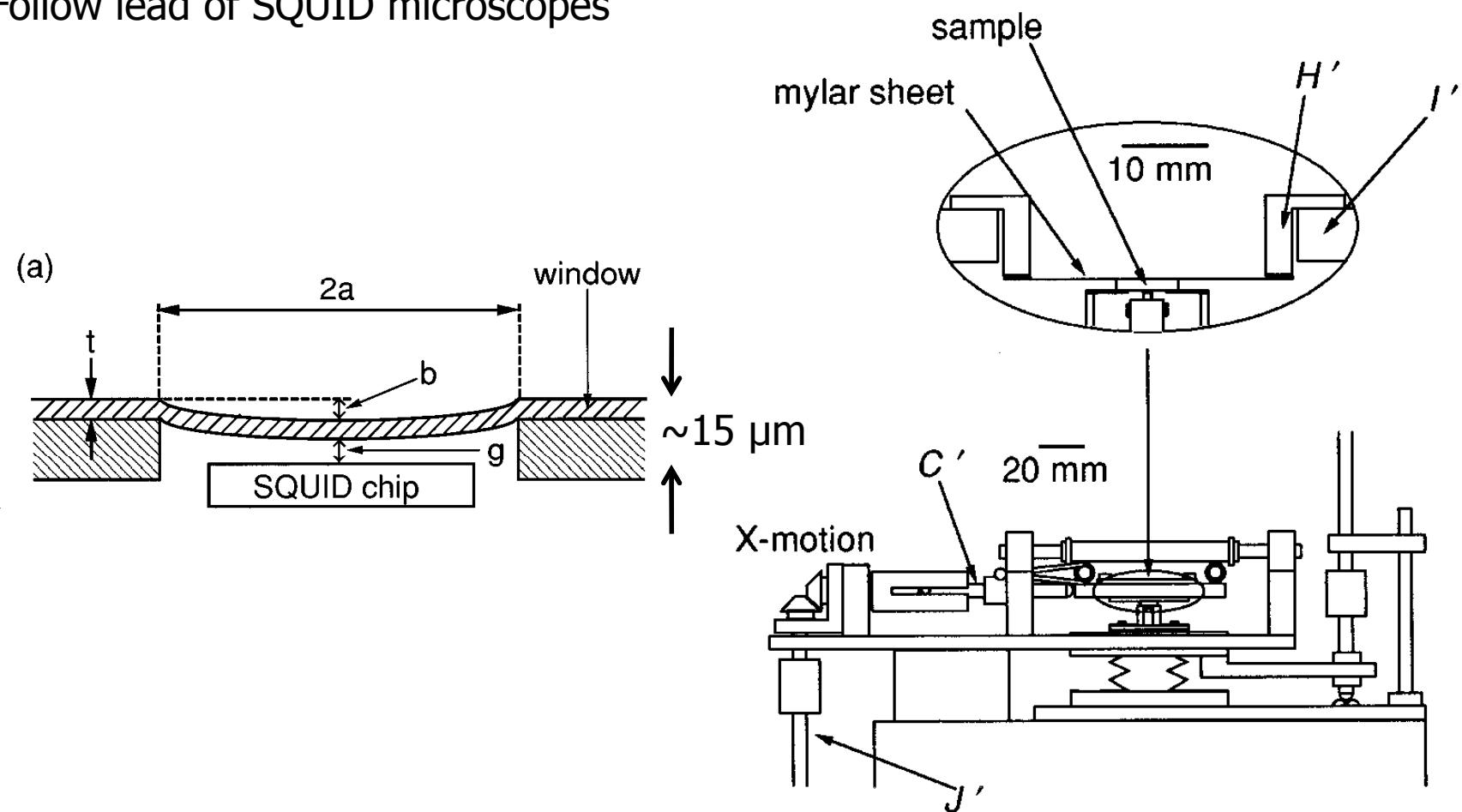
Comparing atoms & SQUIDs

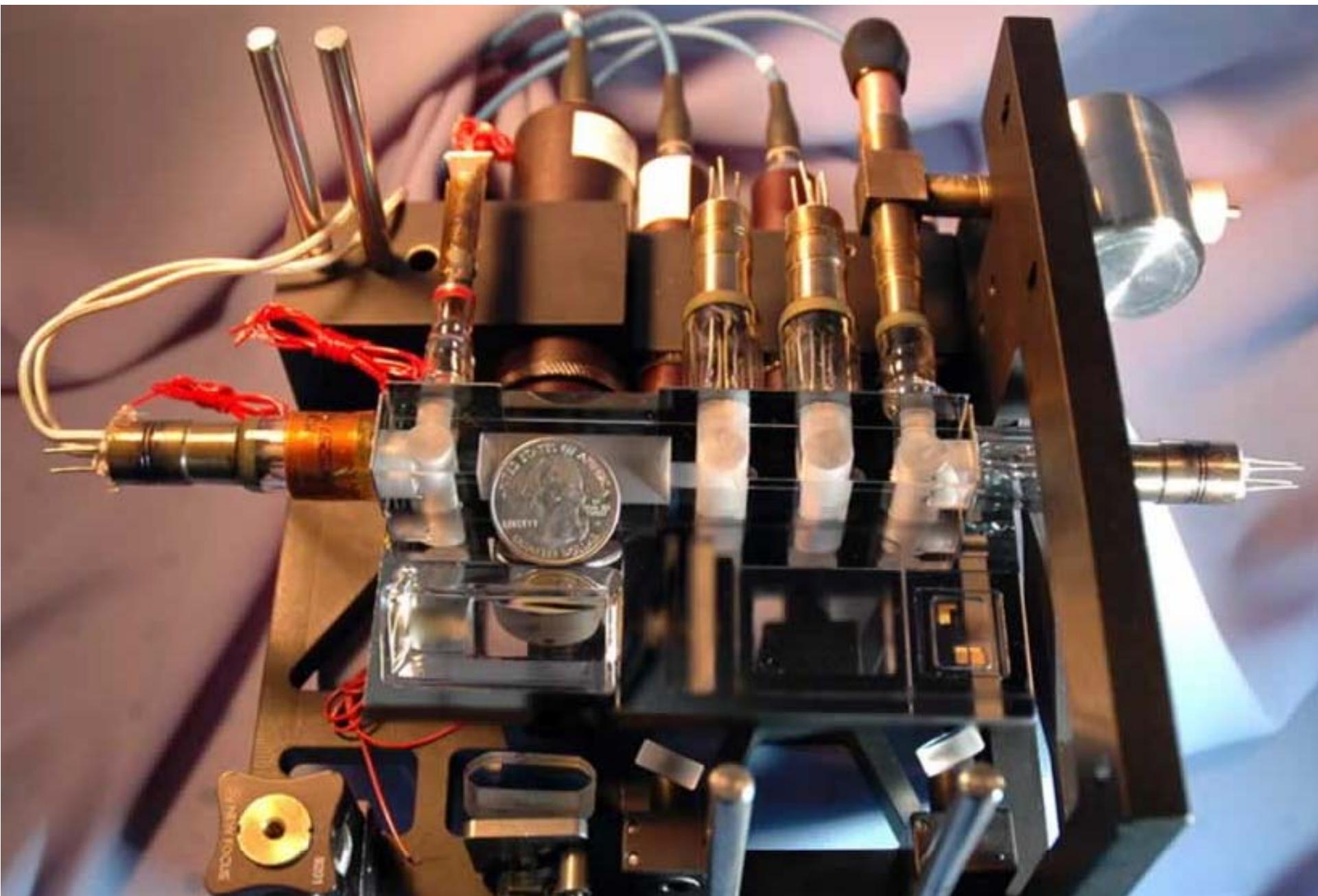


"High resolution magnetometry with a spinor BEC," PRL **98**, 200801 (2007)

(Im)practicalities

Follow lead of SQUID microscopes





by courtesy of Dana Anderson, JILA [Proprietary]; new company = ColdQuanta
kudos to DARPA gBECi program for visionary support

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Growth / Saturation?

Too many people? Too few?

Examples of several ~recent hires

Bose-Hubbard model
Chin, Chicago; DeMarco,
Illinois; Porto, Spielman, MD

spinor Bose gases
Fertig, GA; S-K

cold plasmas
Killian, Rice

superfluid hydrodynamics
Anderson, AZ; Engels; WSU

resonant Fermi gases
Zwierlein, MIT; O'Hara, PSU

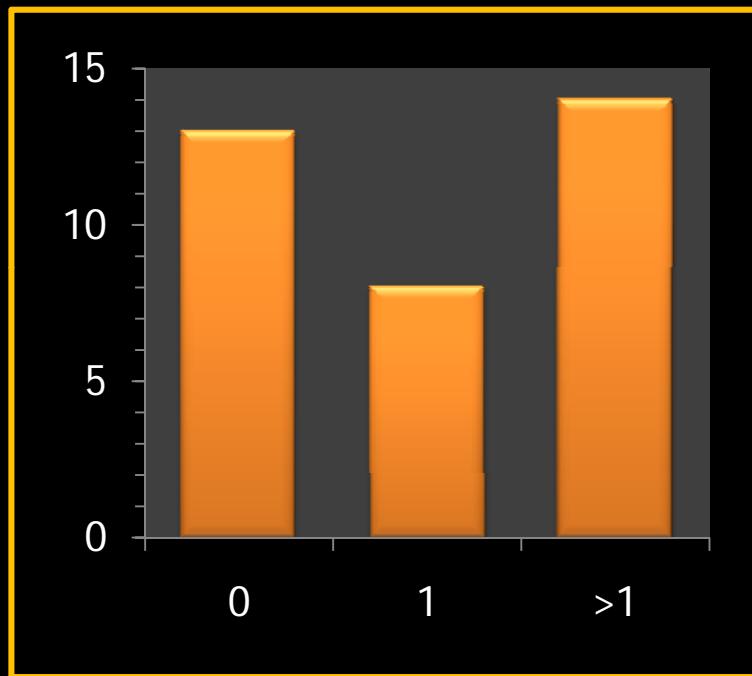
quantum (atom) optics
Vuletic, MIT; Thompson, JILA;
Mabuchi, Stanford; Steck,
Oregon; S-K

interferometry
Mueller, UCB; Sackett, UVA; S-K

cold molecules
Ye, Lewandowski, JILA;
Hudson, UCLA; Odom,
NW; Abraham, OK

Growth / Saturation?

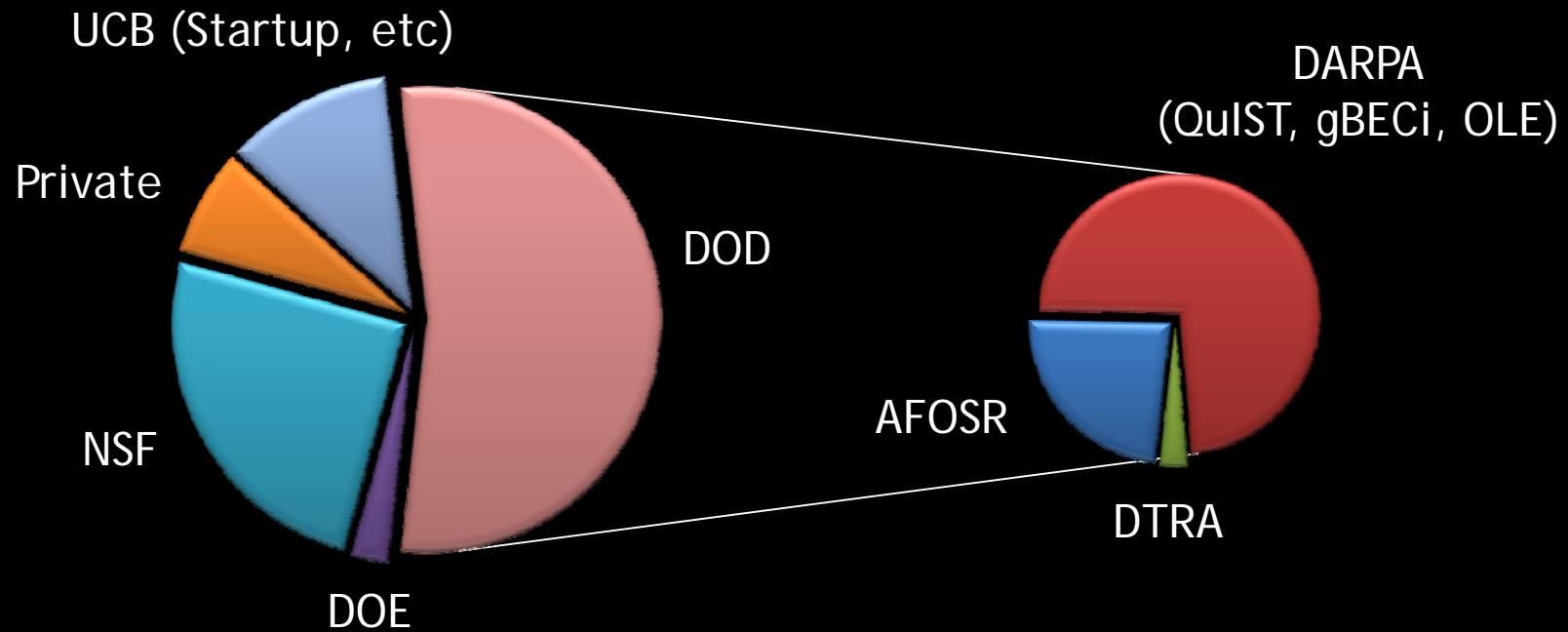
experimental faculty researching cold atoms/ions
at "top" ~36 Physics graduate schools



- One example: University of California (10 campuses, 13k faculty) has four

Funding picture from PI's perspective

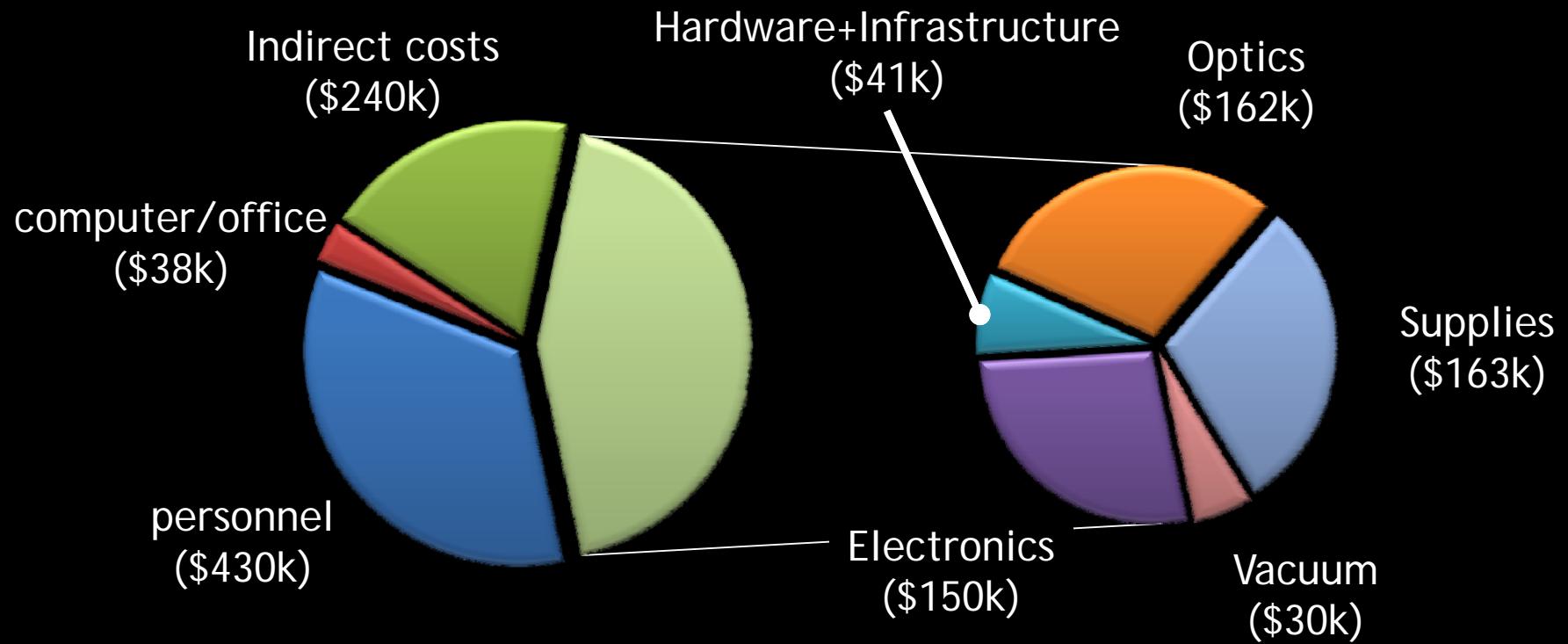
- Example: my group's funding over 9 years at Berkeley: \$9M total



- Barriers exist between disciplines (e.g. NSF), but this hasn't been clear barrier to success of field
- DOD long-term vision for AMO science is crucial
- Caveat: discrepancies bewteen "large" / "elite" programs and others

Funding picture from PI's perspective

- Breakdown of a single year's expenditures
 - ◆ \$1250k, supporting 4 experiments, some in development



- Single grant rarely enough to cover cost of an experiment
- Starting up new experiments is very expensive - done either with startup or DARPA

Thoughts about training

- Scant coursework for graduate students entering the field
 - ◆ Example: Course offerings before 2008 @ UC Berkeley:
 - AMO courses: 1 undergraduate + occasional engineering laser course
 - CM courses: 2 undergraduate, 3 graduate
 - ◆ Where do AMO students learn the CM needed for their research + visa versa?
- Few texts
 - ◆ situation is improving (see upcoming volume by Levin, Fetter and S-K)
- Crossover of personnel between fields limited almost entirely to theorists
 - ◆ see Debbie Jin for famous exception