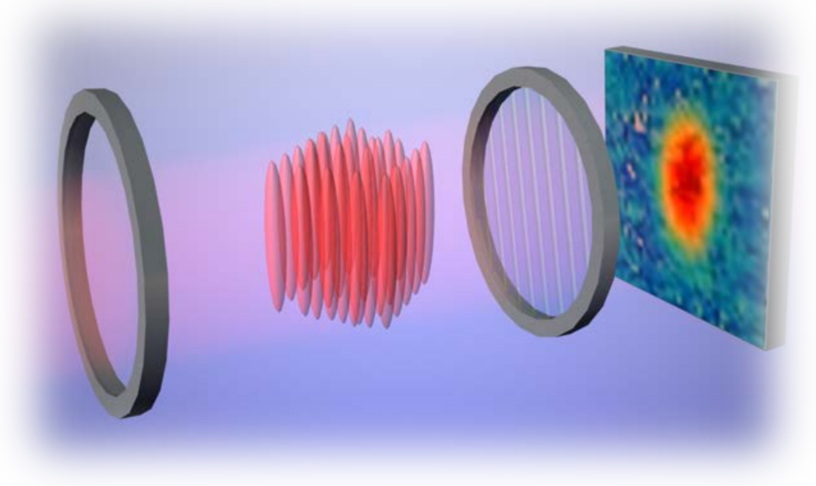


The Excitement of the MURIs

Dr. Peter Reynolds
Senior Research Scientist
Physical Sciences
Army Research Office

Some MURIs I have known

- **Atom Optics**
- *Optical Clocks/Frequency Combs*
- Laser cooling of solids (e.g., semiconductors)
- Quantum Computing/Quantum Information
    - Quantum Memories, Interfaces, Repeaters…
- Quantum Imaging
- Optical Lattices
- Atomtronics
- *Ultra-cold Molecules*

Outline

- Case study: Atom Optics MURI
    - Basic Research as Foundation to MURIs
    - MURI Research
    - Follow-on programs
    - Transition to Industry
- Some recent and current MURIs

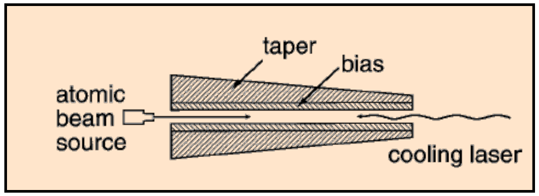
Case study: Atom Optics MURI

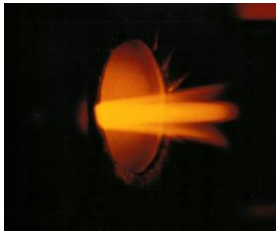
Basic research pre-history—Key elements

- 1980s to early 1990s: Laser cooling and trapping of atoms
  - Used largely for improving spectroscopy / fundamental measurements. (e.g., Parity Non-conservation)
  - Potential role in time and frequency recognized by ONR and NIST
- ~1990: Atom interferometry
  - Largely based on atomic beams, then later incorporated laser cooling
  - 1991: First atom interferometry using nanofabricated mechanical grating
- 1993: Atom guiding
  - JILA experiments, first with hollow optical fibers, later with magnetic guides
- 1995: First demonstration of Bose-Einstein condensation
- 1995: Atom analog of optical laser
  - BEC and more generally “ultracold” became a focal point for AMO physics
- 1997: Atom guiding and interferometry on “atom chips”
- ~2000: Fermi degeneracy and later superfluidity

A History of Basic Research in Cold Atoms

W.D. Phillips, Rev. Mod. Phys. 70, 721 (1998)



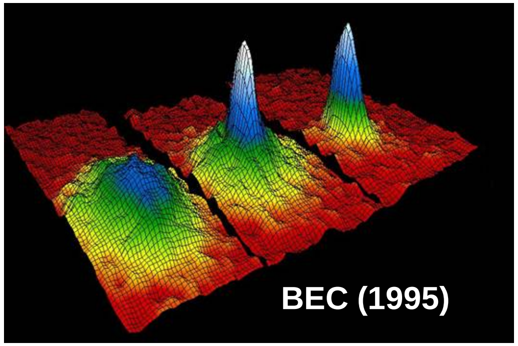


Courtesy: Paul Lett, NIST

Zeeman cooling (1982)

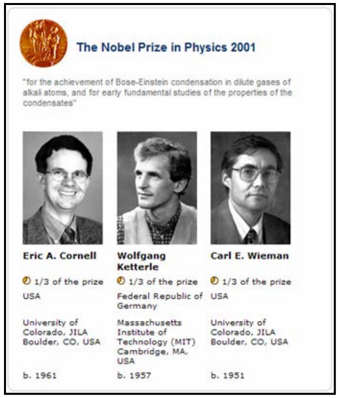
MOT w/ vapor cell (1990)

T ~ 1 μK



Science 269, 198 (2005)

T ~ 170 nK

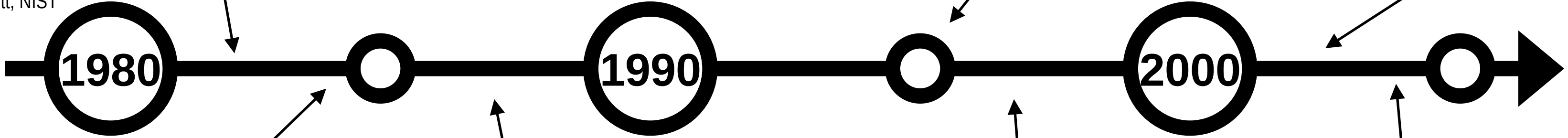


The Nobel Prize in Physics 2001

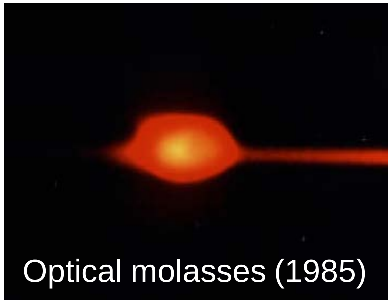
"for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates"

Eric A. Cornell	**Wolfgang Ketterle**	**Carl E. Wieman**
◔ 1/3 of the prize	◔ 1/3 of the prize	◔ 1/3 of the prize
USA	Federal Republic of Germany	USA
University of Colorado, JILA Boulder, CO, USA	Massachusetts Institute of Technology (MIT) Cambridge, MA, USA	University of Colorado, JILA Boulder, CO, USA
b. 1961	b. 1957	b. 1951

Nobelprize.org



T ~ 240 μK

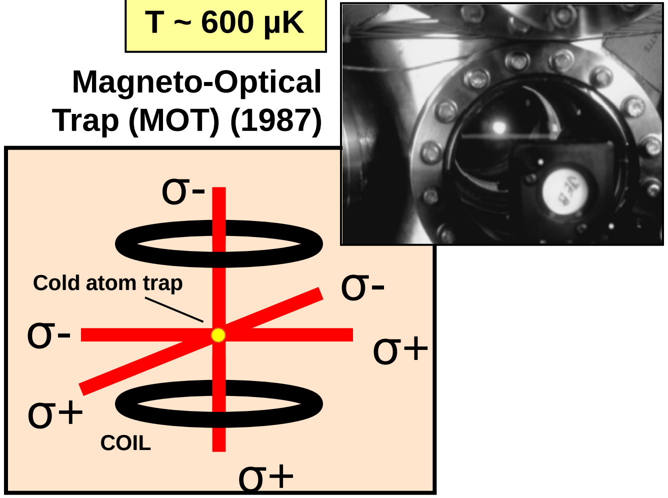


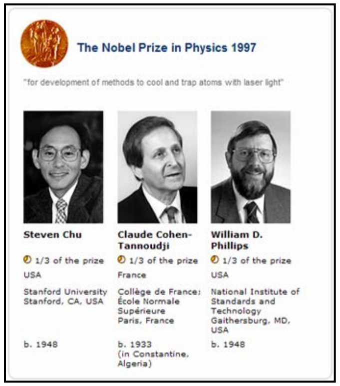
Rev. Mod. Phys. 70, 685 (1998)

T ~ 600 μK

Magneto-Optical Trap (MOT) (1987)

Rev. Mod. Phys. 70, 685 (1998)





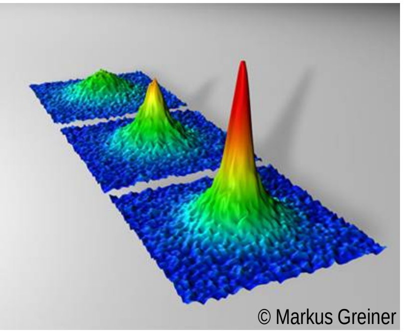
The Nobel Prize in Physics 1997

"for development of methods to cool and trap atoms with laser light"

Steven Chu	**Claude Cohen-Tannoudji**	**William D. Phillips**
◔ 1/3 of the prize	◔ 1/3 of the prize	◔ 1/3 of the prize
USA	France	USA
Stanford University Stanford, CA, USA	Collège de France; École Normale Supérieure Paris, France	National Institute of Standards and Technology Gaithersburg, MD, USA
b. 1948	b. 1933 (in Constantine, Algeria)	b. 1948

Nobelprize.org

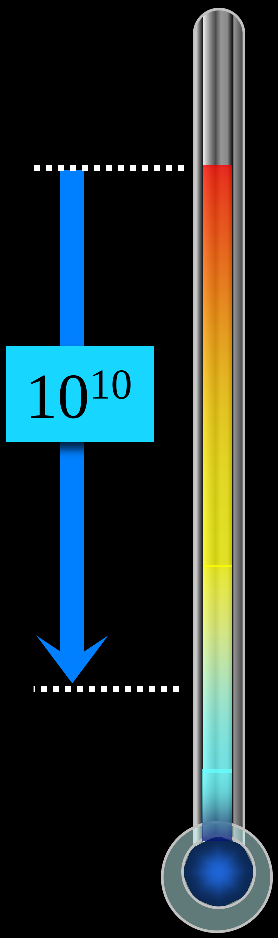
Fermionic Condensate (2004)



© Markus Greiner

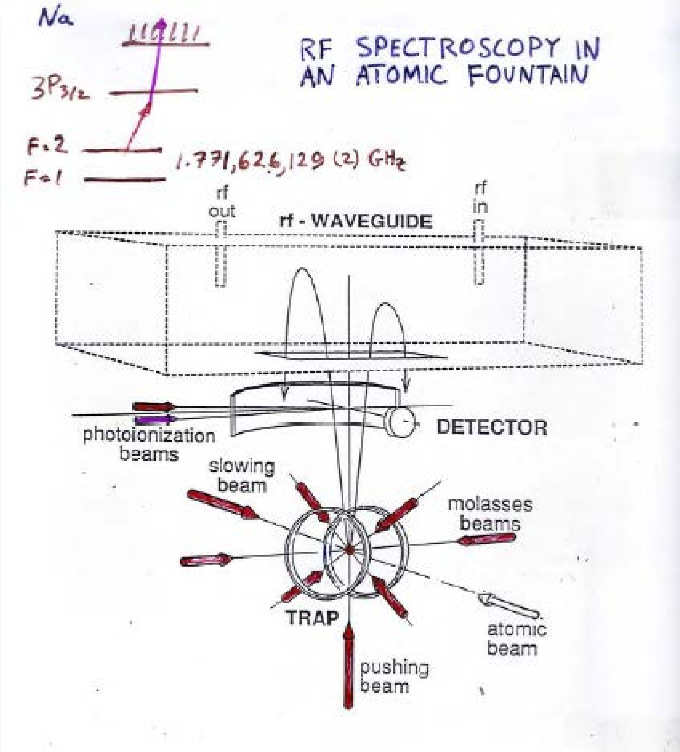
Phys. Rev. Lett. 92, 040403 (2004) – used by permission

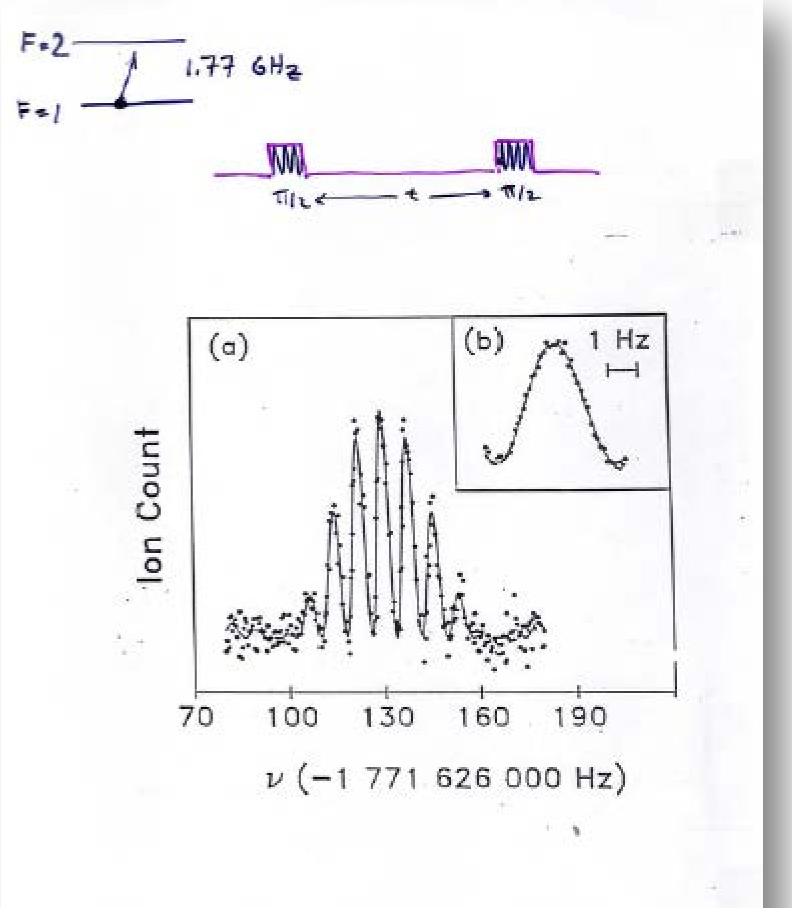
The Wavelength of an Atom (^{87}Rb)



T (K)	λ (nm)	v (m/s)	t (s)
300	.02	300	.03
	(Smaller than the atom itself)		
1	0.3	20	0.2
	(The size of a small molecule)		
10^{-3}	9	0.5	6
	(The size of a medium molecule)		
10^{-6}	300	2 cm/s	2 min
	(Approaching the wavelength of light)		
10^{-9}	9000	0.5 mm/s	1.5 hr
	(MEMS size)		

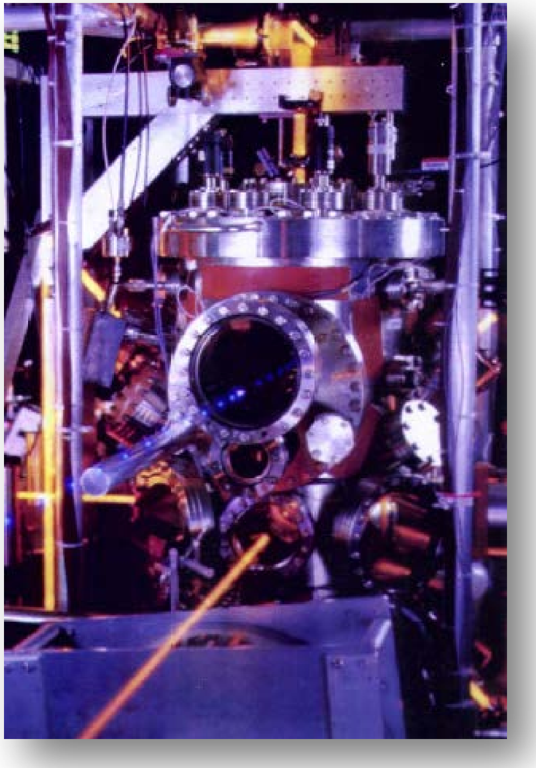
1989 Atomic Fountain RF Spectroscopy

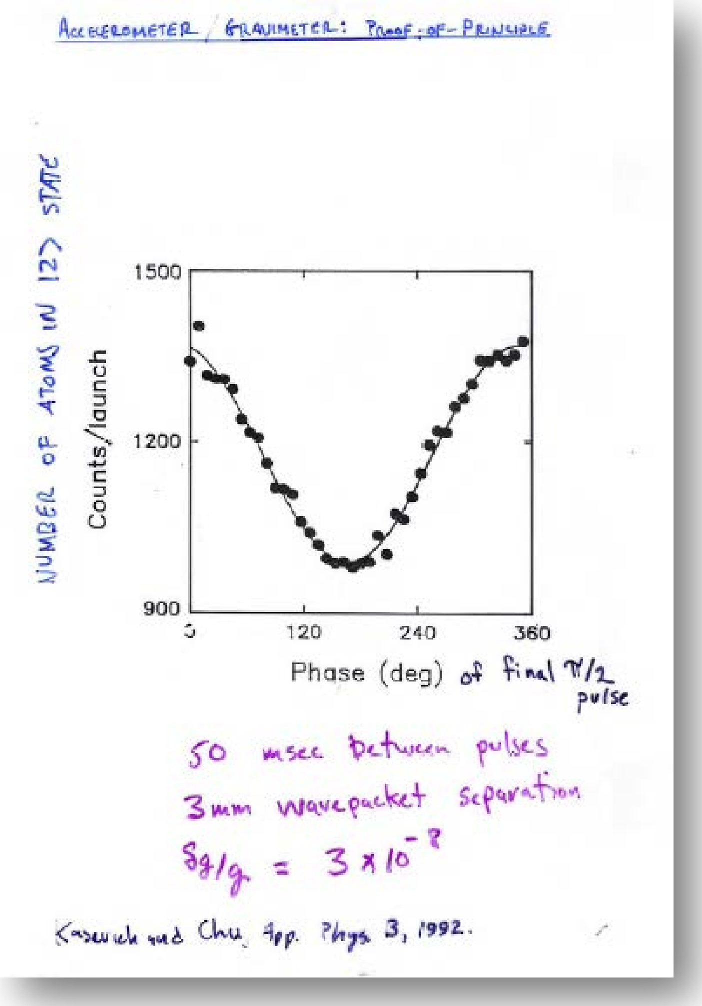




Kasevich, Riis, DeVoe, Chu, PRL 63, 612, 1989

1991 Light-Pulse Atom Interferometer





ACCELEROMETER / GRAVIMETER: PROOF-OF-PRINCIPLE

50 msec between pulses

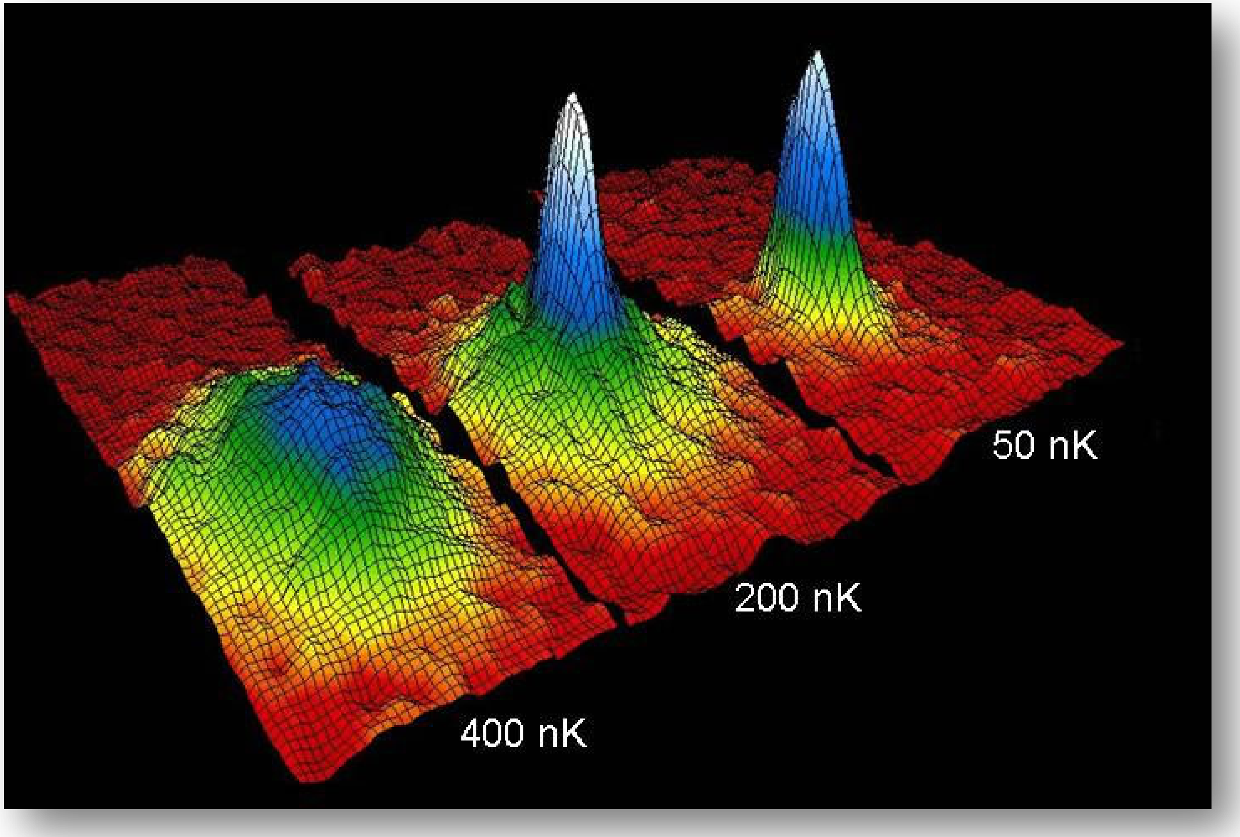
3mm wavepacket separation

$\delta g/g = 3 \times 10^{-8}$

Kasevich and Chu, App. Phys. B, 1992.

1995 Bose-Einstein Condensation

- Thermal cloud
  - Maxwell-Boltzman distribution of energies



- BEC
  - All atoms share same quantum wavefunction
  - Quantum mechanical coherence

What is a BEC?

The BEC:

A source of mutually
coherent *atoms*

BEC

Atom Optics

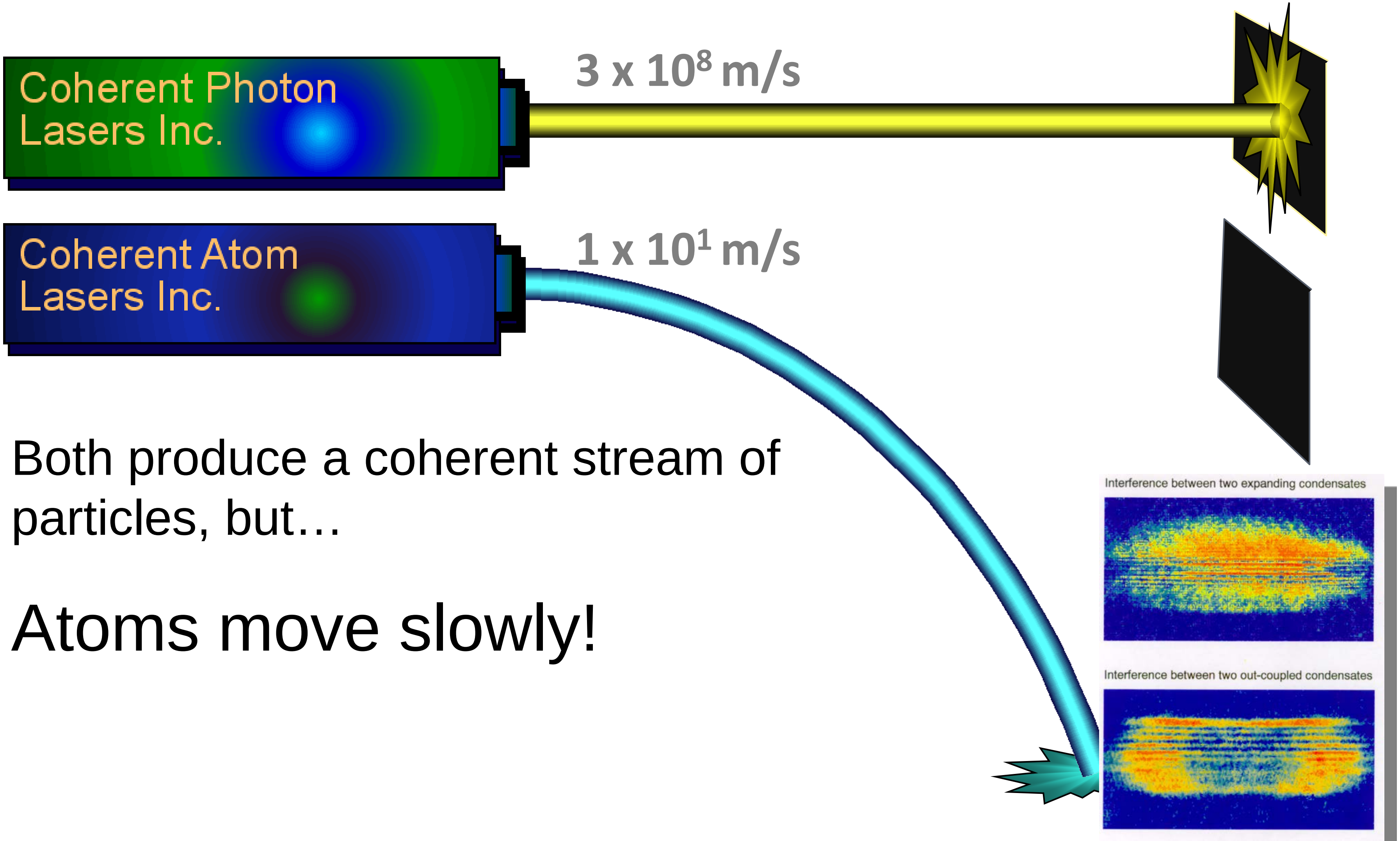
The Laser:

A source of mutually
coherent *photons*

Laser

Photon Optics

Photonic versus atomic laser



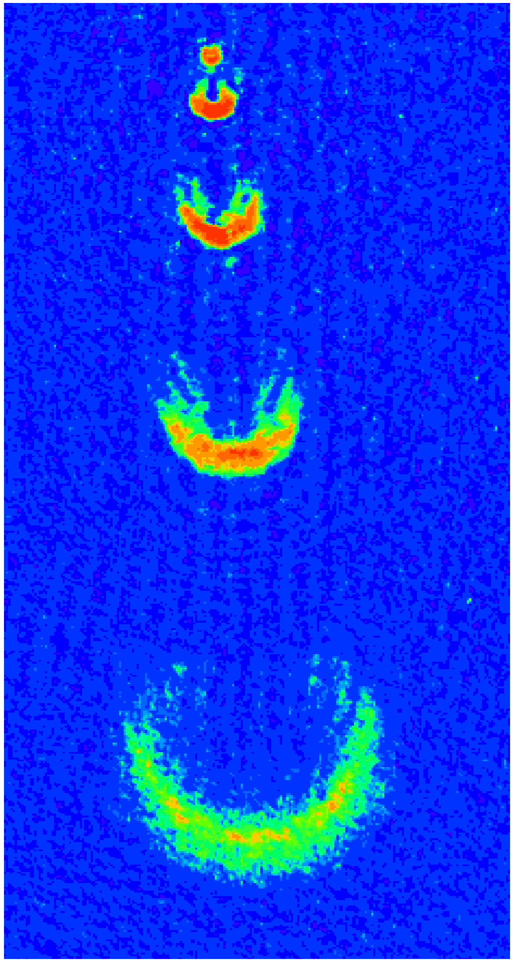
Interference between two expanding condensates

Interference between two out-coupled condensates

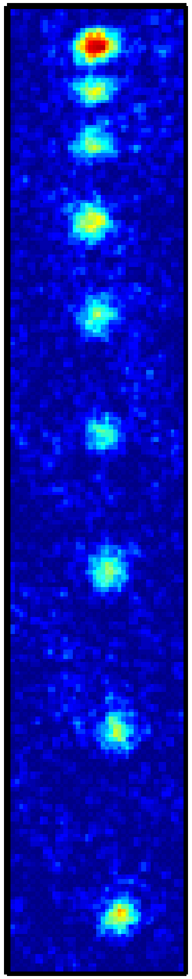
Both produce a coherent stream of particles, but…

Atoms move slowly!

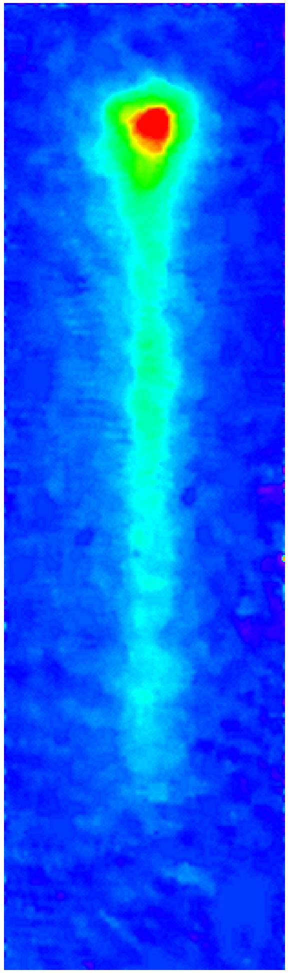
Atom Laser Gallery



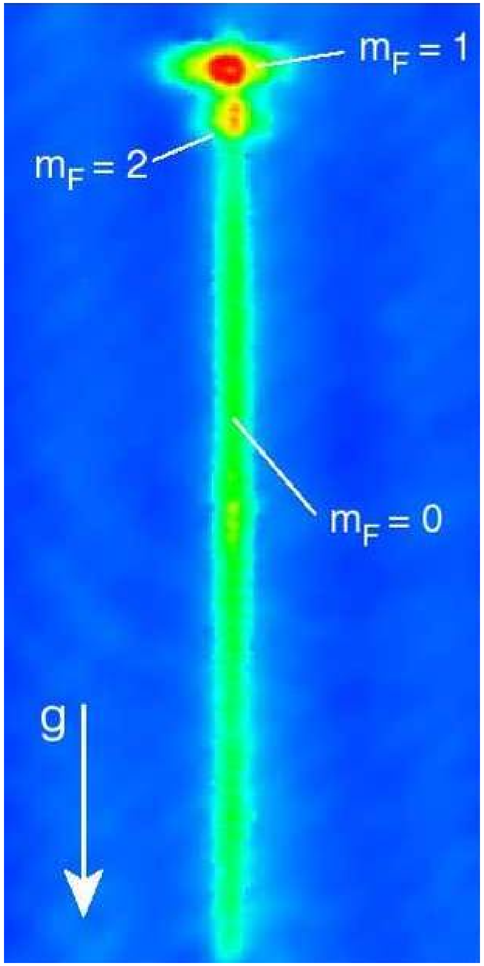
MIT



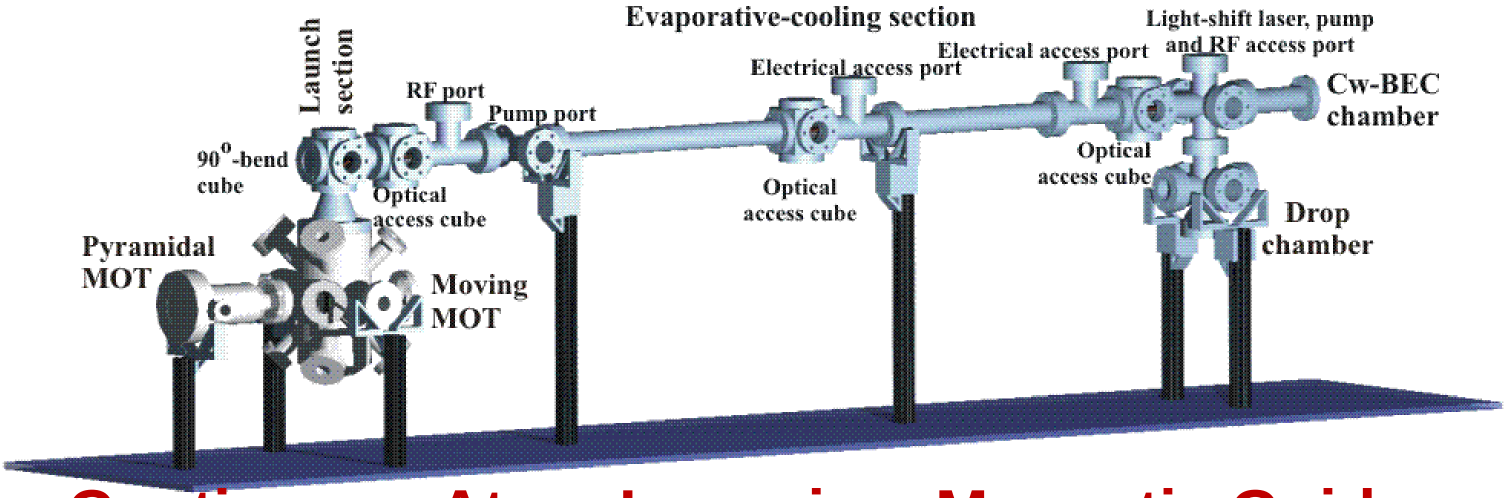
Yale



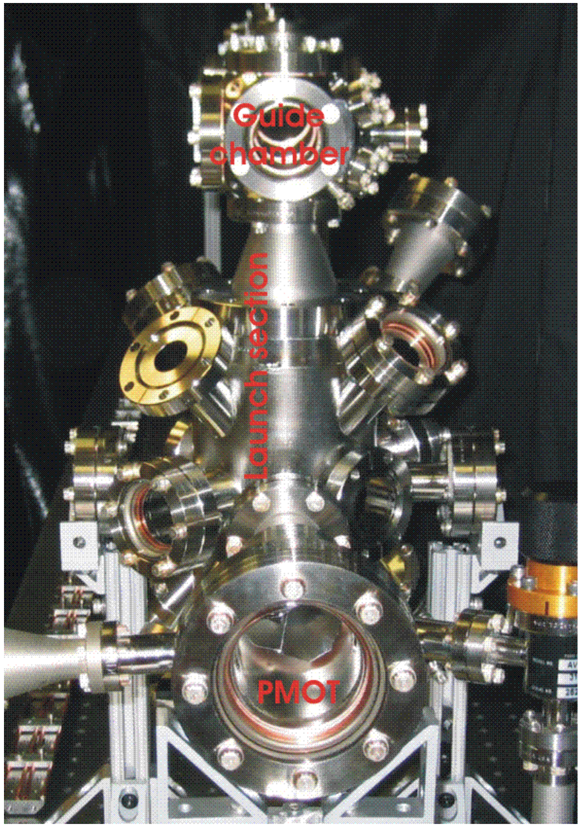
NIST

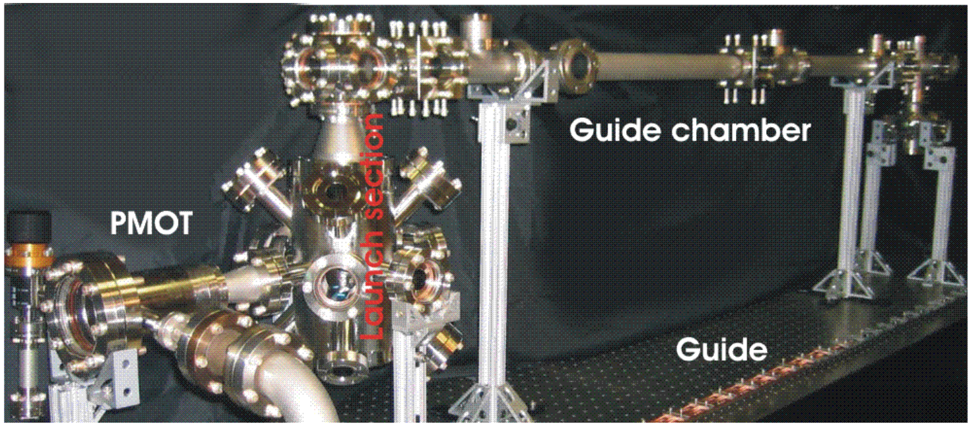


Munich



Continuous Atom Laser in a Magnetic Guide

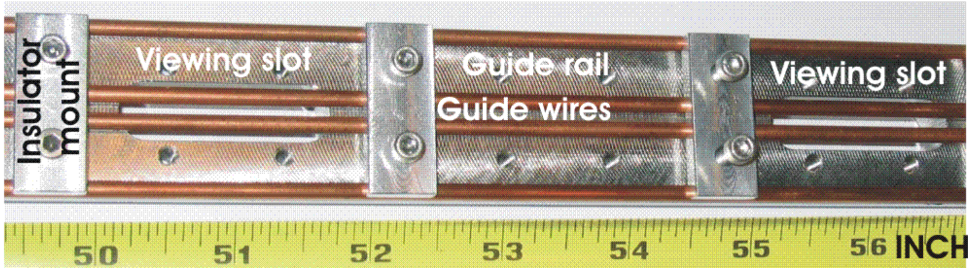




Main chamber side view

Main chamber front view

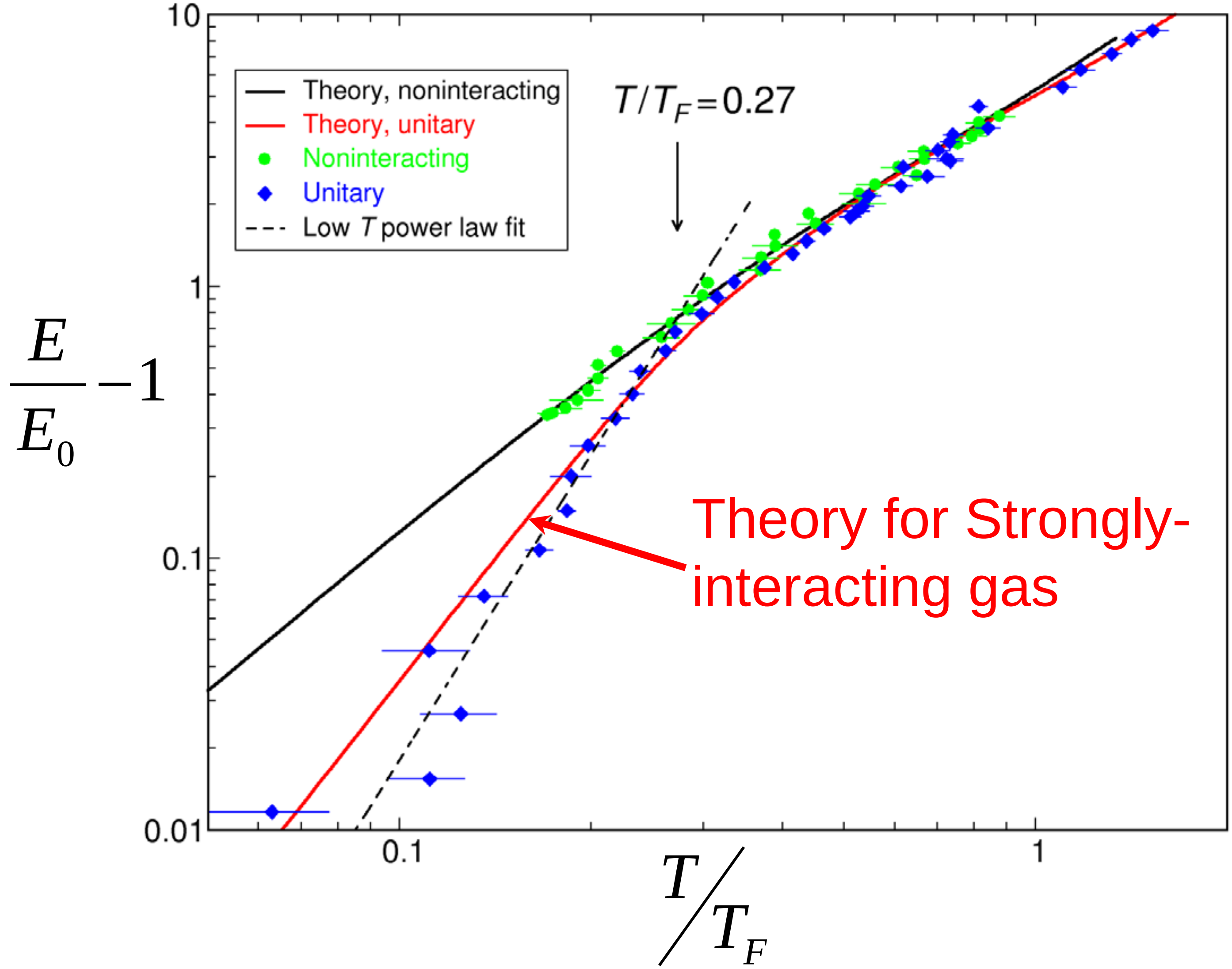
Guide detail



Cooling Fermions

- More difficult to reach degeneracy
- Final step towards BEC requires evaporative cooling
- Need interactions for constant re-equilibration
- Fermions “see” each other less as T is reduced
- Quantum degeneracy has potential for even more exotic behavior than with Bosons
- Pairing (e.g., Cooper pairs) possible
- Novel superfluids
- Insights into ordinary and high Tc superconductivity

Cooling Fermions: Superfluid Transition

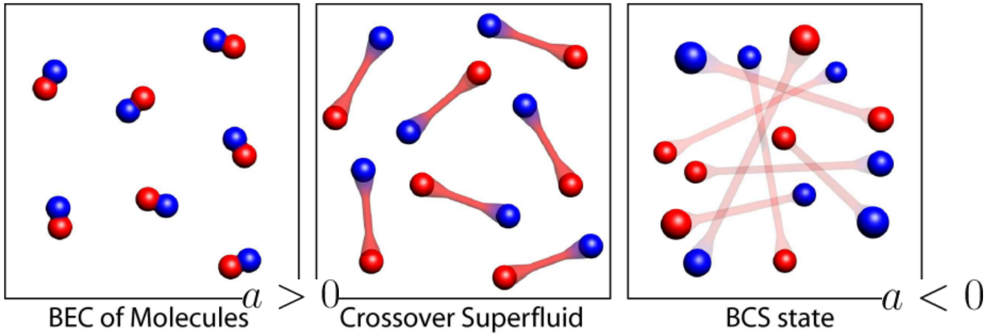


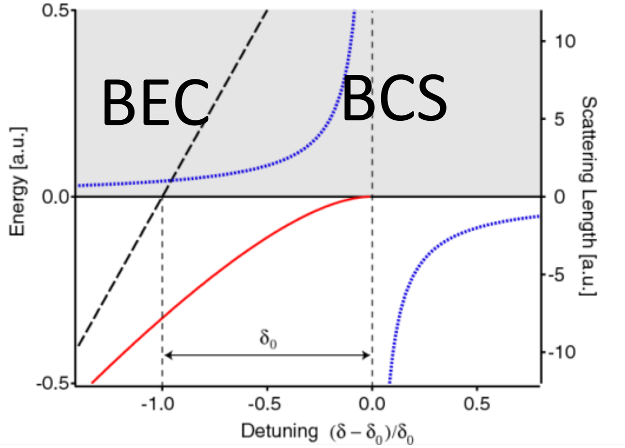
Theory for Strongly-interacting gas

Feshbach Resonance Control of Interactions

BEC to BCS crossover

- Superfluid of Fermion pairs



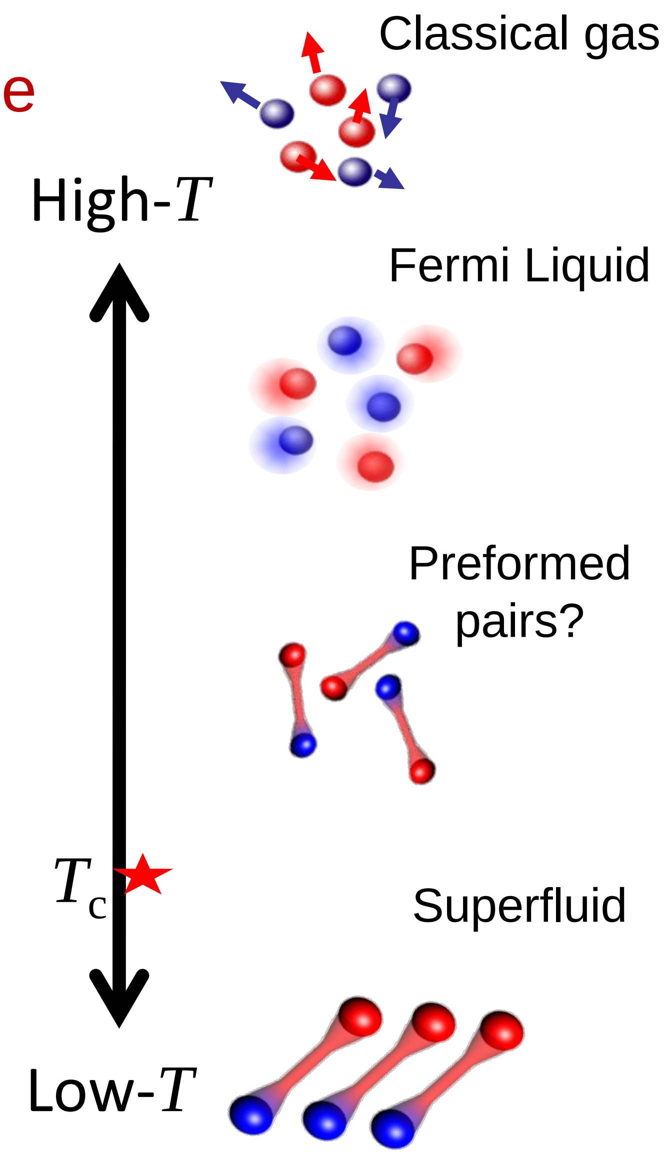


- Molecules on BEC side (2-body bound state)
- Cooper pairs on BCS side (Many-body physics)

Control of interactions
Thermodynamics of Unitary Fermi Gas

Spin ½ - Fermi gas at Feshbach resonance
(strong coupling regime)

- *Normal state:*
  - Is it a Fermi liquid?
  - Are there preformed pairs (a pseudogap regime)?
- *Superfluid properties*:
  - Transition temperature
  - Critical entropy
  - Energy of the superfluid
  - …



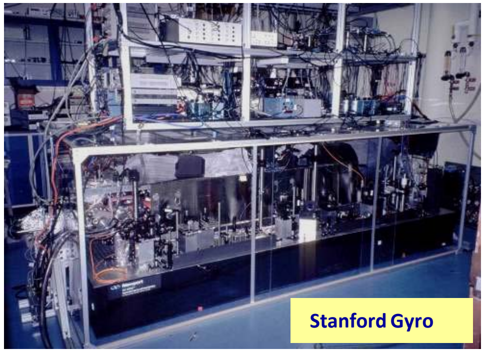
1998: Ultracold Atom Optics MURI

Do for atom optics what lasers, waveguides… did for light

- Develop general-purpose cold-atom techniques amenable to a wide variety of applications
  - Waveguides, beamsplitters, traps, taps, couplers, manipulators, detectors
  - Cold atom and BEC sources, EIT cells
- Use atom interferometry for sensing
- Bring cold atom S&T to broader research community
  - Make BEC economical and routine
  - Simplify and evolve laser cooling and trapping technology towards “standardization”

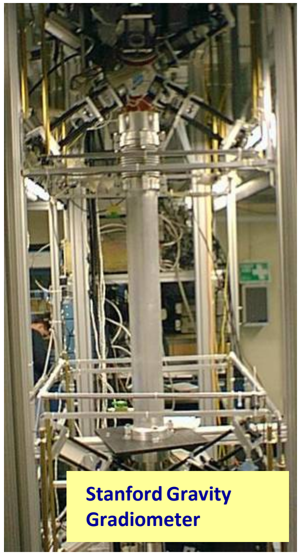
The Virtues of Cold Atoms

Translation and Rotation



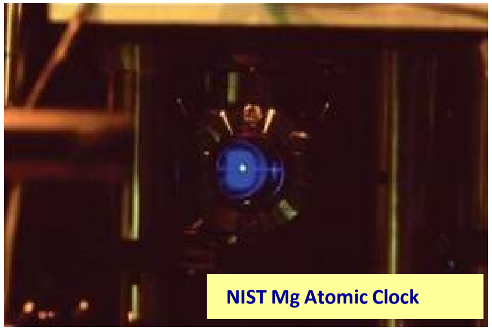
Rotational Sensitivity: 4×10^{-8} (rad/s)/Hz$^{1/2}$

Gravity Sensing



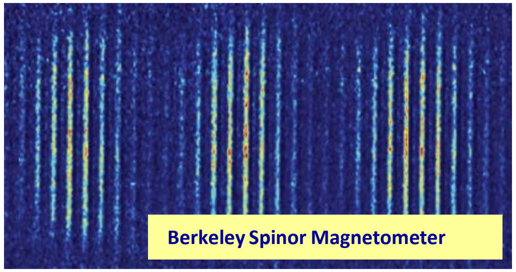
Differential Acceleration Sensitivity: 4×10^{-9} g/Hz$^{1/2}$

Time



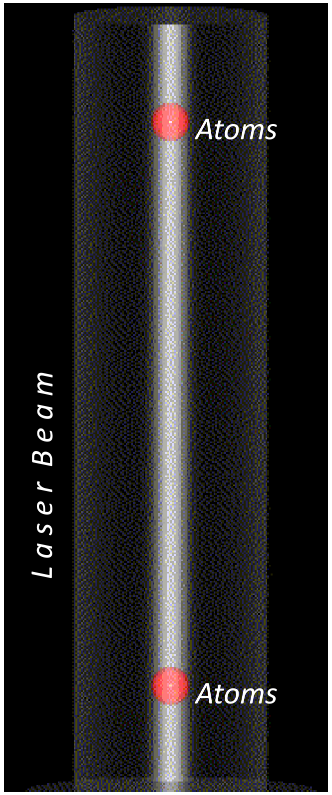
Accurate to 1 s per billion years

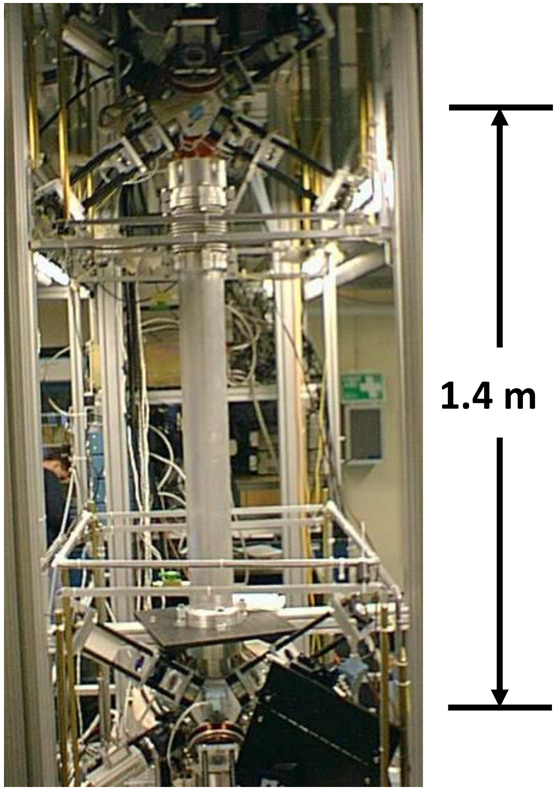
Magnetic Field Sensing



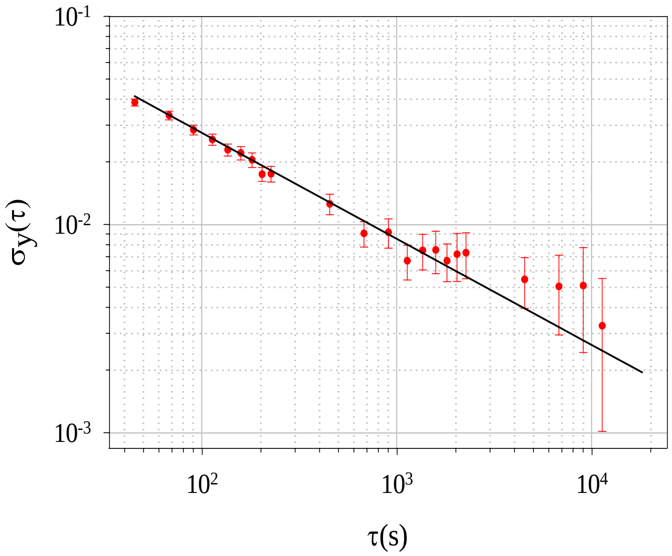
Magnetic Field Sensitivity: 8.3 pT/Hz$^{1/2}$

1998 Stanford/Yale laboratory gravity gradiometer





Distinguish gravity induced accelerations from those due to platform motion with differential acceleration measurements.

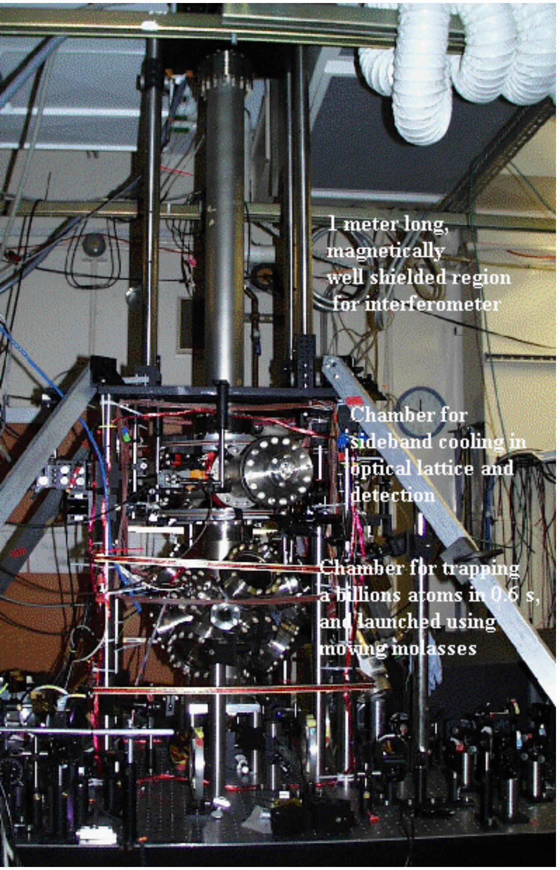


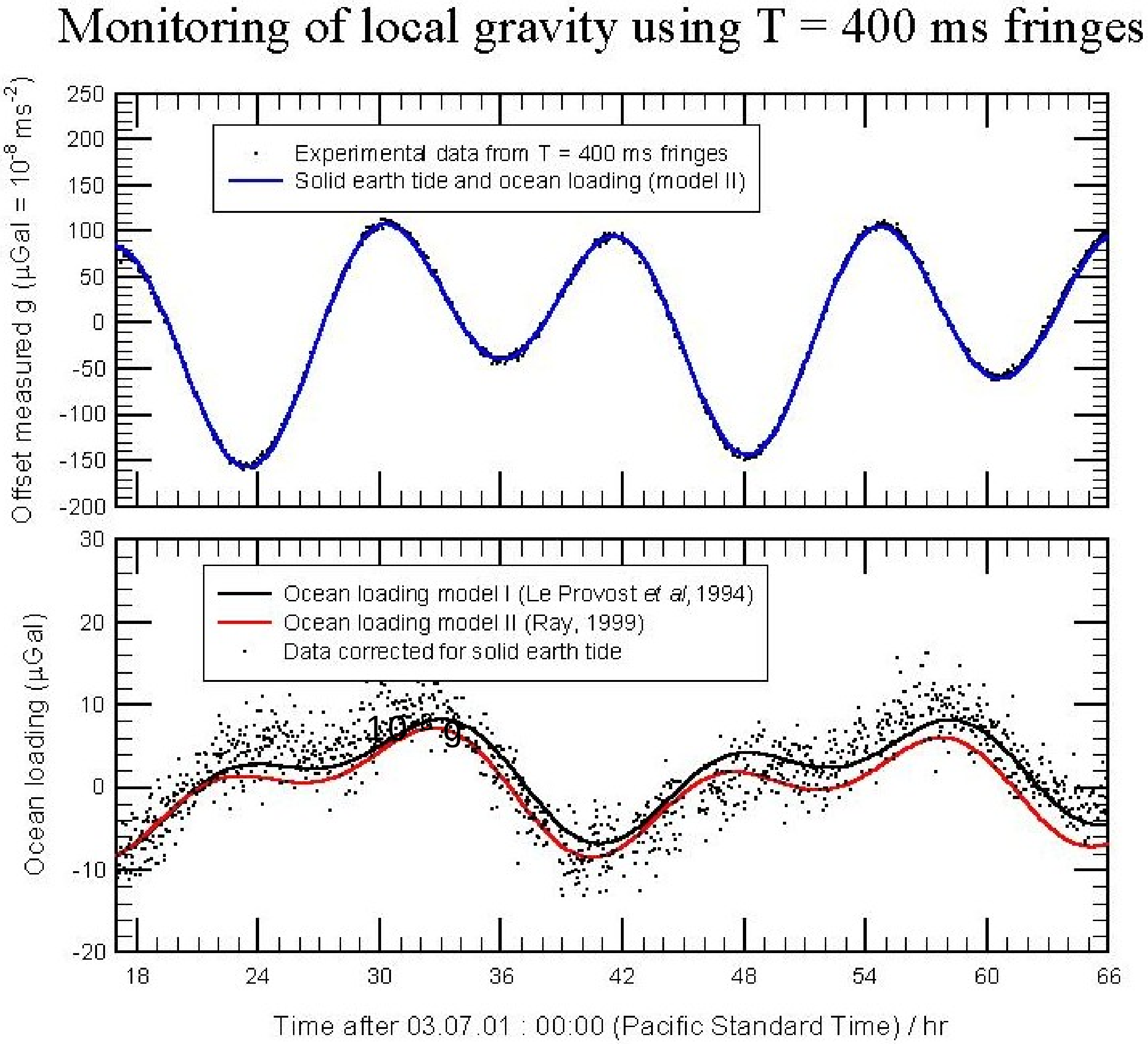
Demonstrated diffential acceleration sensitivity:

$4x10^{-9}$ g/Hz$^{1/2}$

($2.8x10^{-9}$ g/Hz$^{1/2}$ per accelerometer)

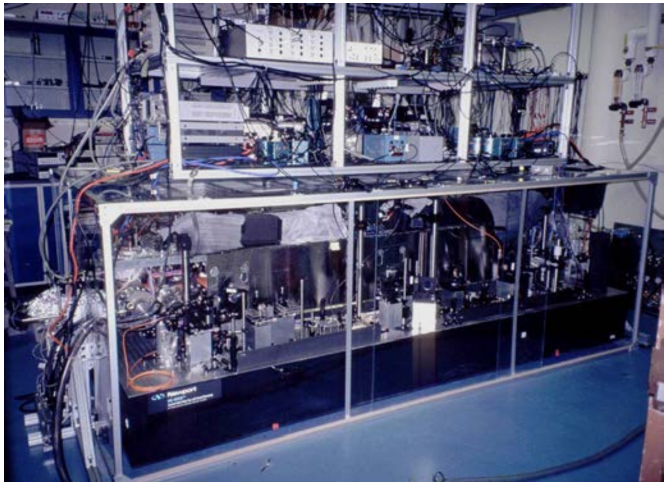
2000 Stanford laboratory gravimeter





Courtesy of S. Chu, Stanford

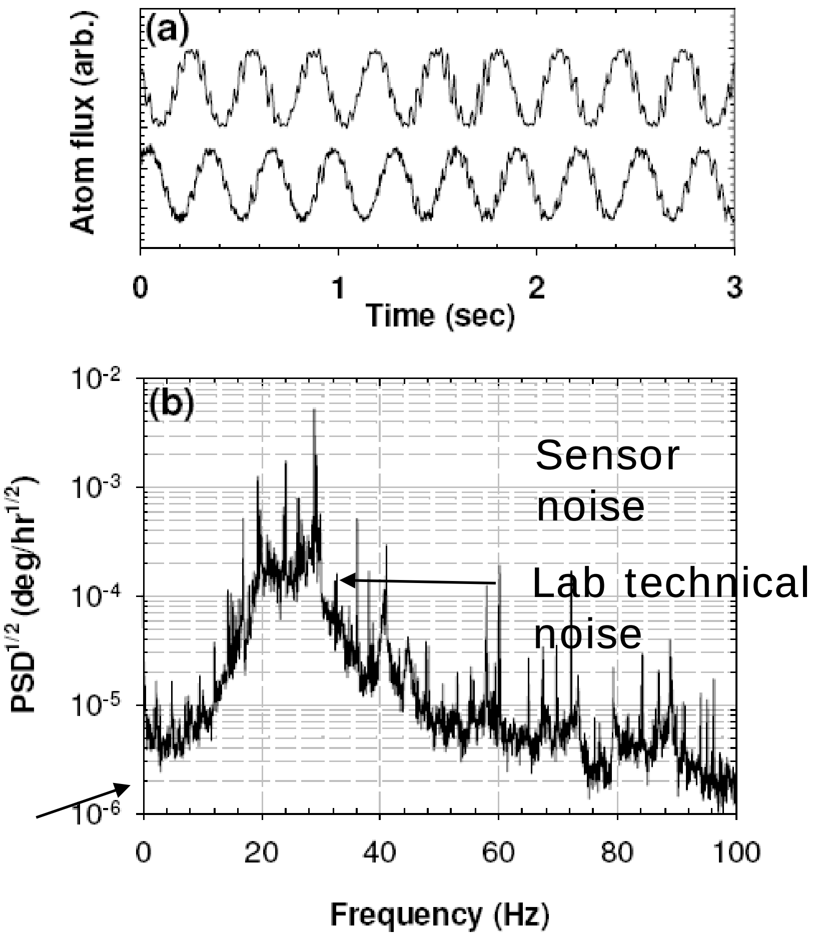
1997-2003 Gyroscope



AI gyroscope

Noise:	3 μdeg/hr$^{1/2}$
Bias stability:	< 60 μdeg/hr
Scale factor:	< 5 ppm

Gyroscope interference fringes:



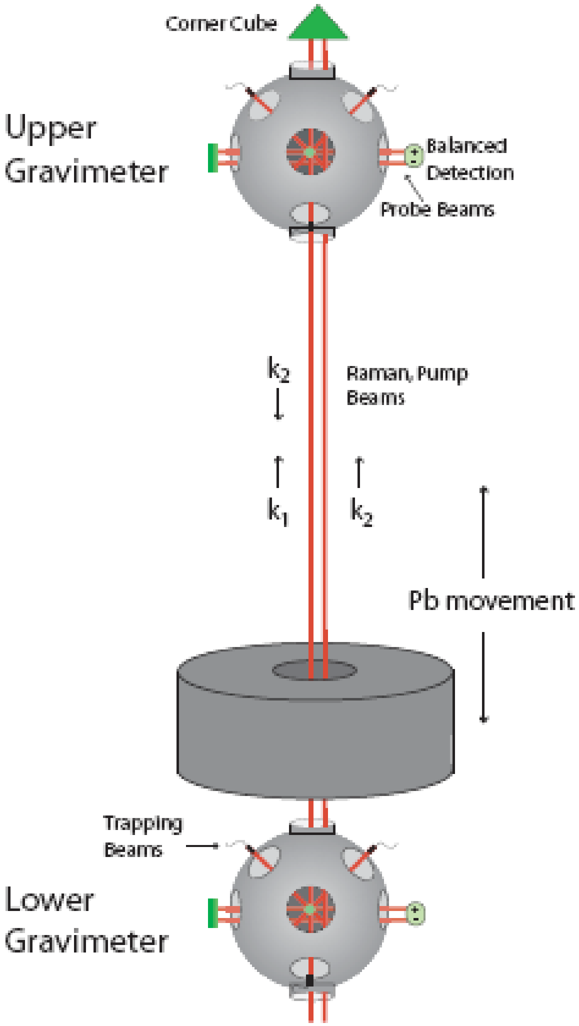
Sensor noise

Lab technical noise

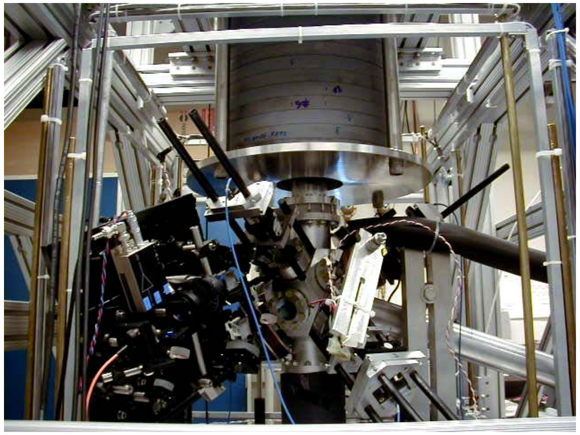
Atom shot noise

Gustavson, et al., PRL, 1997,
Durfee, et al., PRL, 2006

2003 Measurement of Newton’s Constant

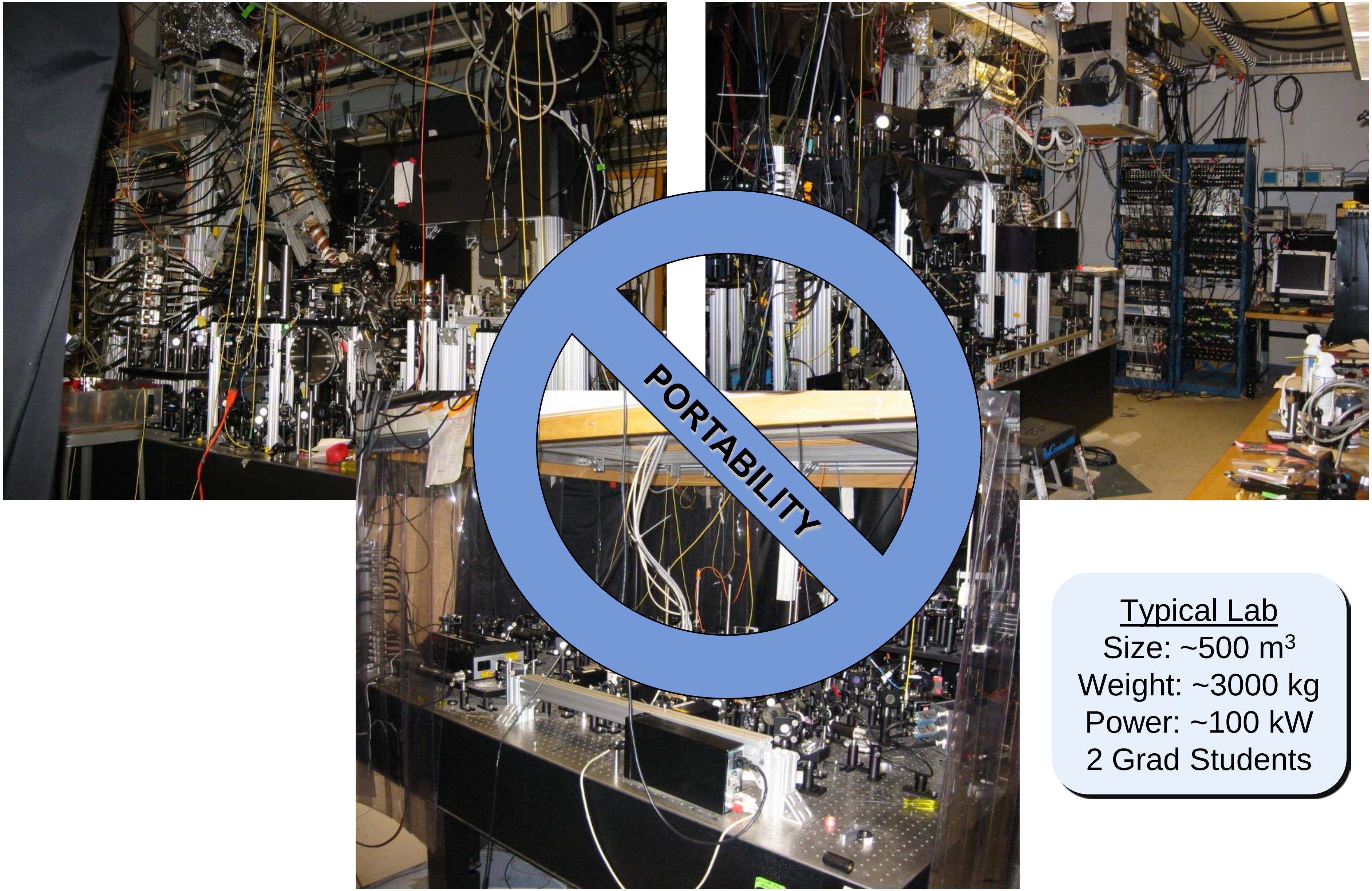


Pb mass translated vertically along gradient measurement axis.



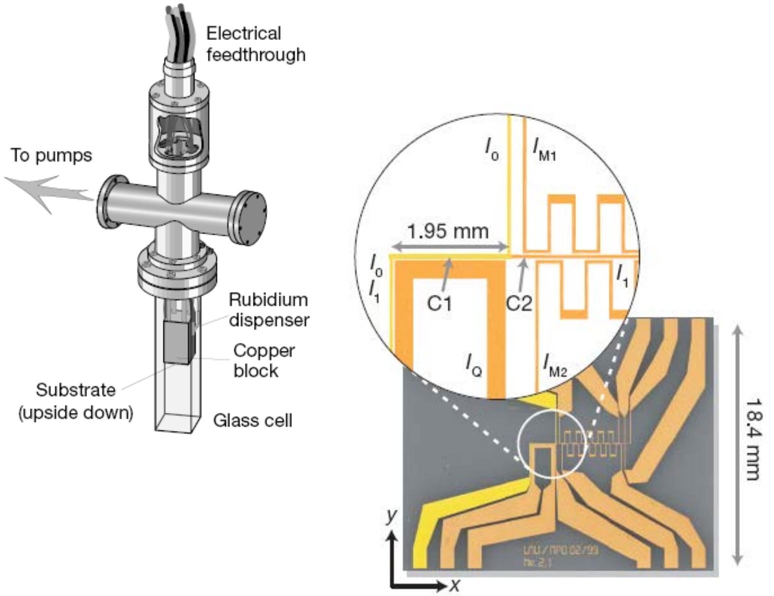
Characterization of source mass geometry and atom trajectories (with respect to source mass) allows for determination of Newton’s constant G.
Use gravity gradiometer to reject spurious technical vibrations.

The Vices of Cold Atoms



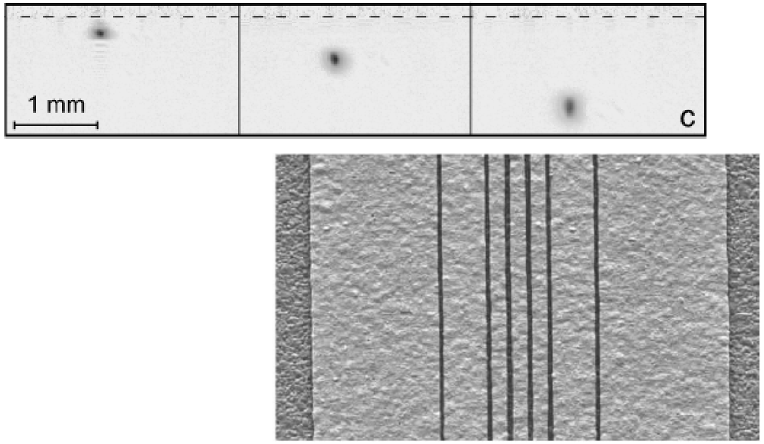
Typical Lab
Size: ~500 m^3
Weight: ~3000 kg
Power: ~100 kW
2 Grad Students

One Solution: Atom Chips



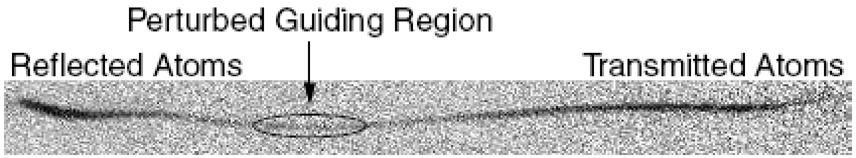
W. Hänsel *et al*., Nature **413**, 498 (2001)

(Hansch Group)



H. Ott *et al*., Phys. Rev. Lett. **87**, 230401 (2001)

(Zimmerman Group)

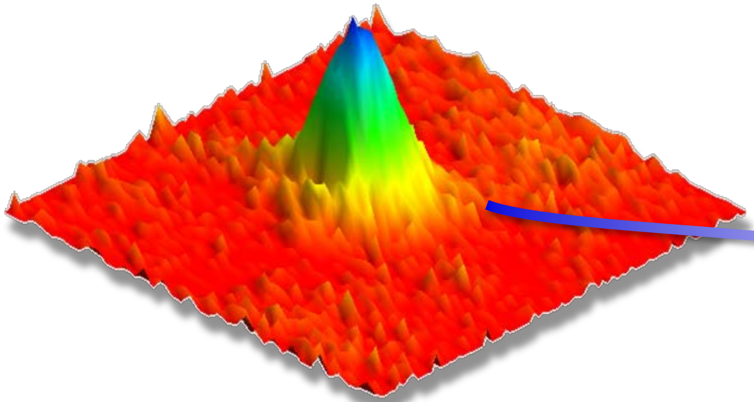


A.E. Leanhardt *et al*., Phys. Rev. Lett. **89**, 040401 (2002)

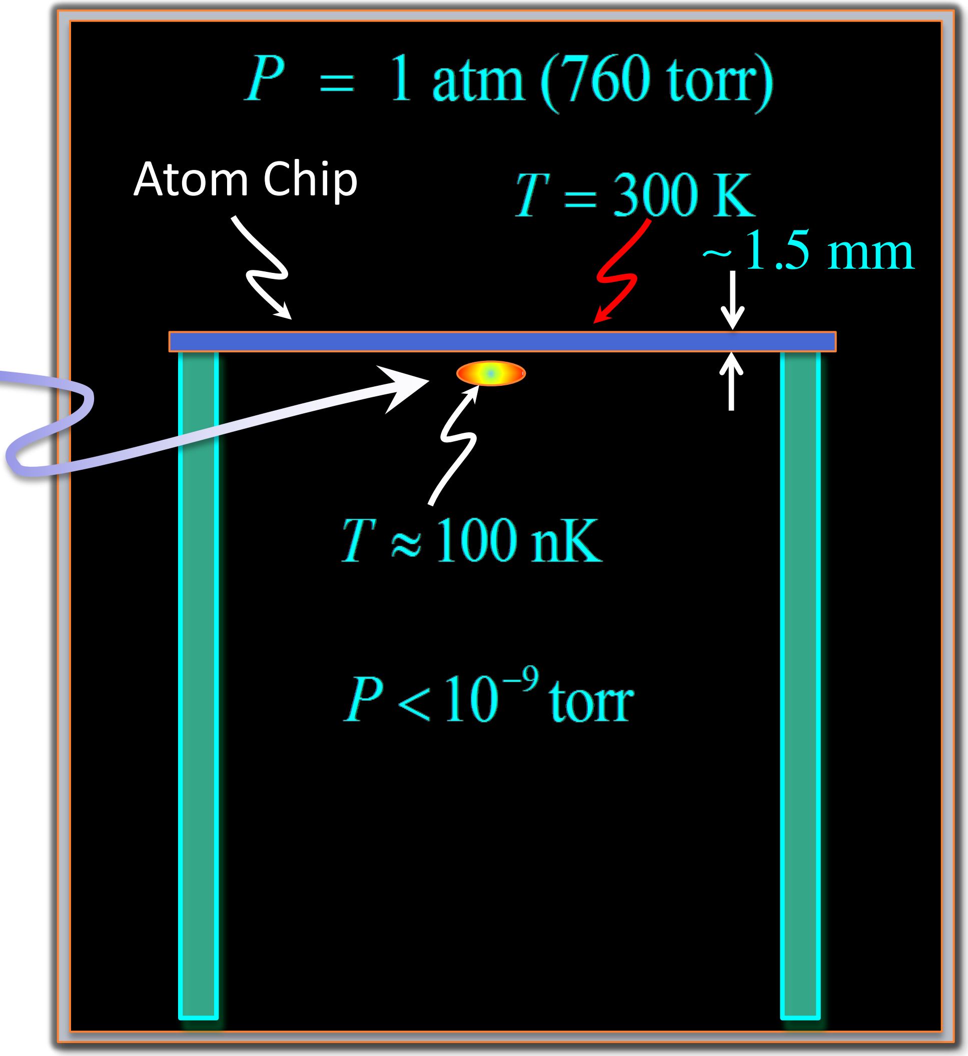
(Ketterle Group)

Atoms: Ultracold & Ultraclose

Ultracold:



A macroscopic ensemble of atoms occupying a single quantum state.



From MURI onward: 2004 -

- Success of S&T under MURI led to DARPA Precision Inertial Navigation and Sensing (PINS) program
  - emphasis on *enabling technology for inertial sensing based on ultracold atoms.*

- ~2007 DARPA PINS split into:
  - PINS with more engineering focus on inertial sensing
  - gBECi (guided BEC interferometry) with a more basic focus

- Additional investments from SP-24, NGA, and others

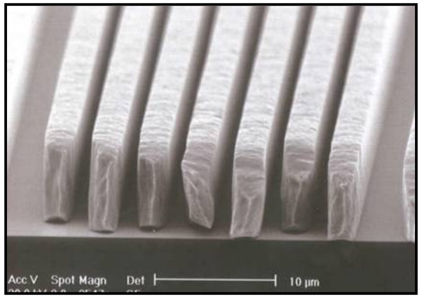
- Spin-off companies: AOSense and ColdQuanta

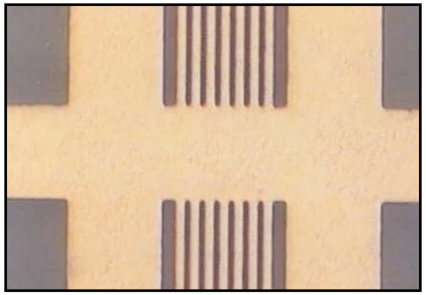
Multi-scale Atom Chips

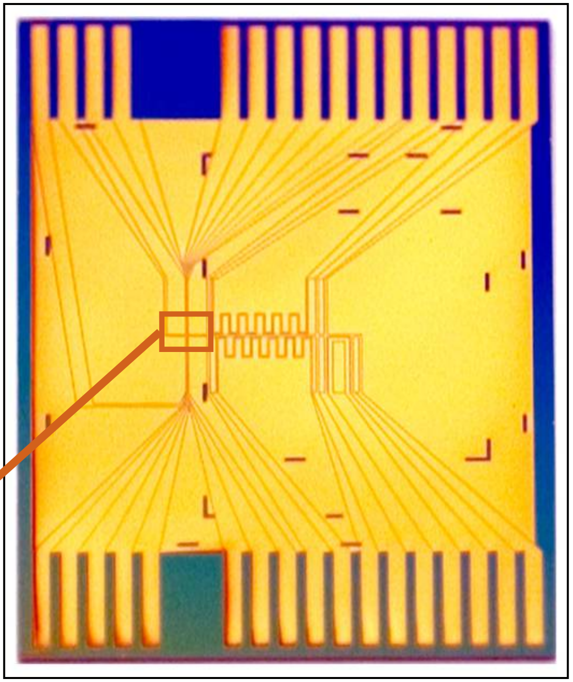
- Integrated high-current large scale features with low-current small-scale features on the same chip
- Features of metal deposition: ~ 8-10mm tall; ~ 2mm line/space
- Current chips utilize high-vacuum through-chip via arrays for electrical connections, and curved waveguides for controlled, closed loop atom motion

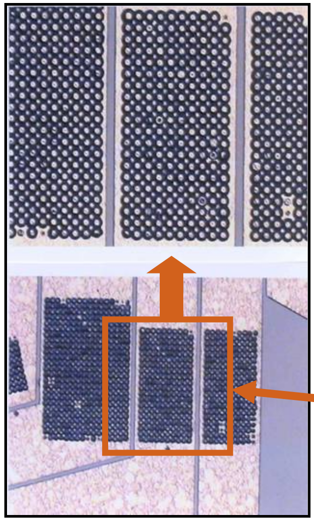
Detailed views of beamsplitter structure segment for single layer atom chip.

- (far right) Top view
- (right) SEM of side view detail

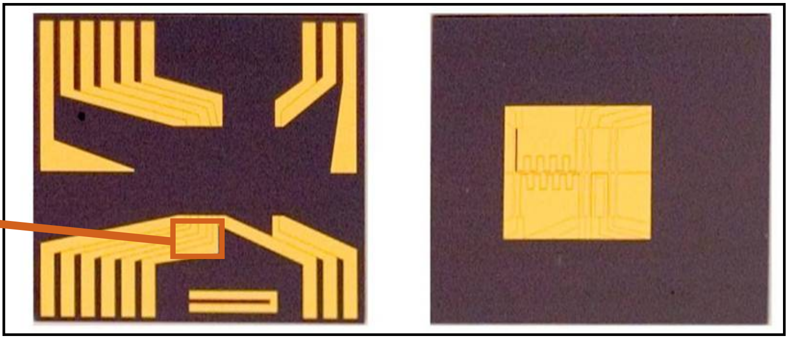




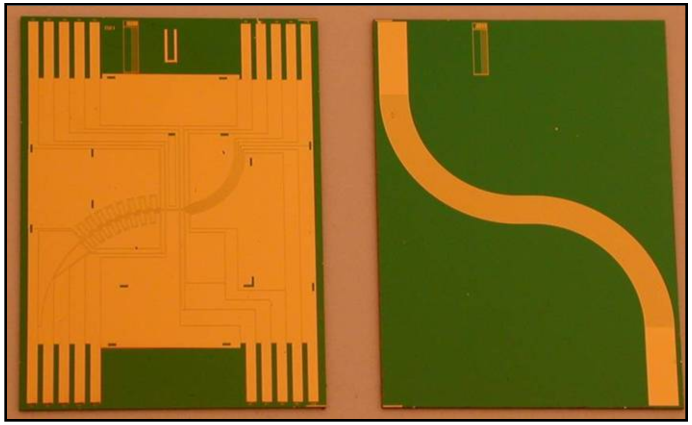




- (below) Front and back view of Via Chip
- (left) Detailed view of ultra-high vacuum-compatible via arrays used for each high current electrical feedthrough on Via Chip

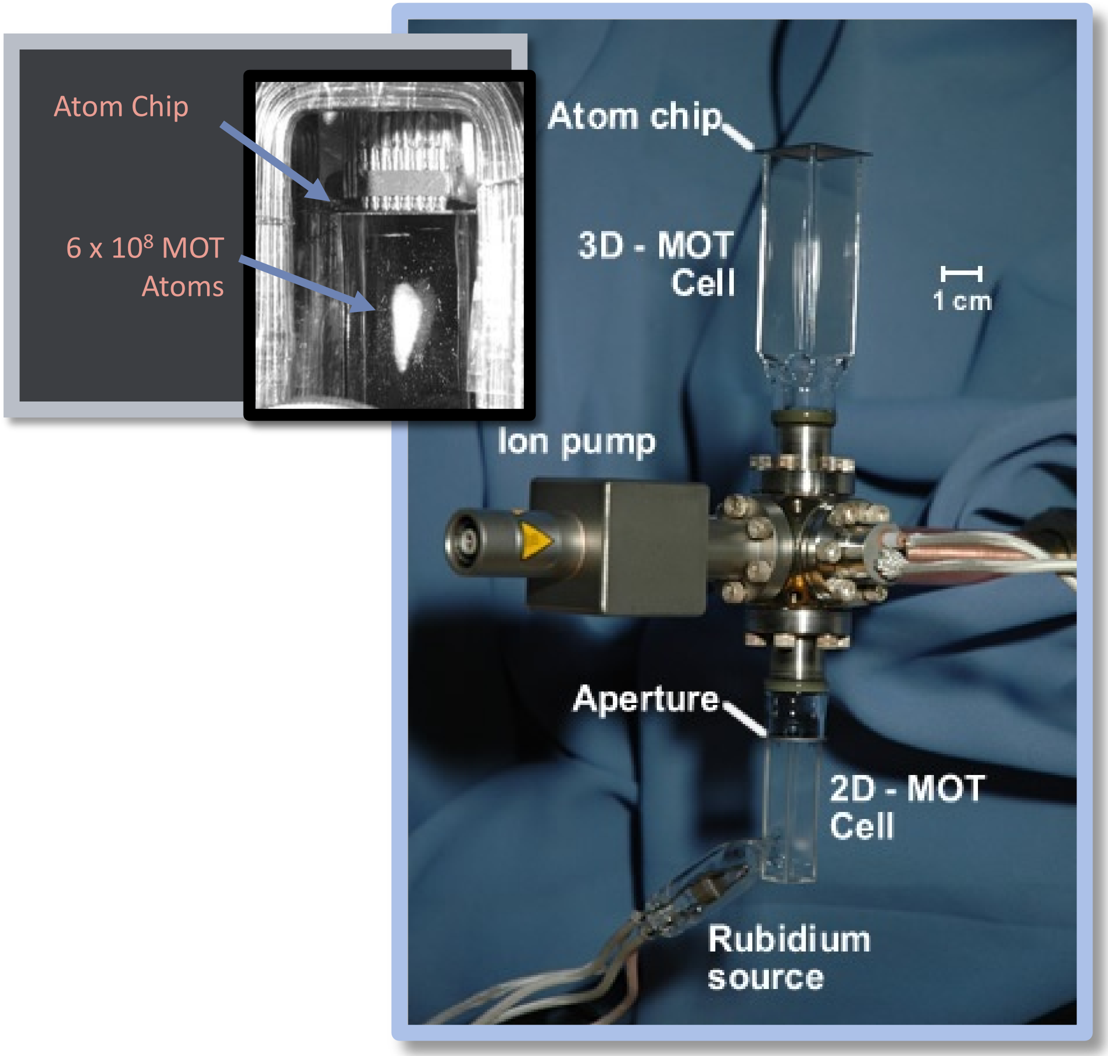


- (left) Fabricated one-layer atom chip on Si
- (right) Curved atom waveguide chip

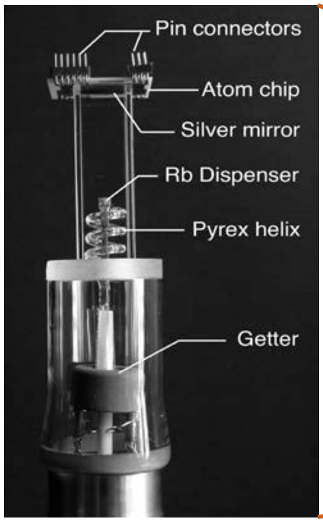


Double-MOT Atom Chip Cell

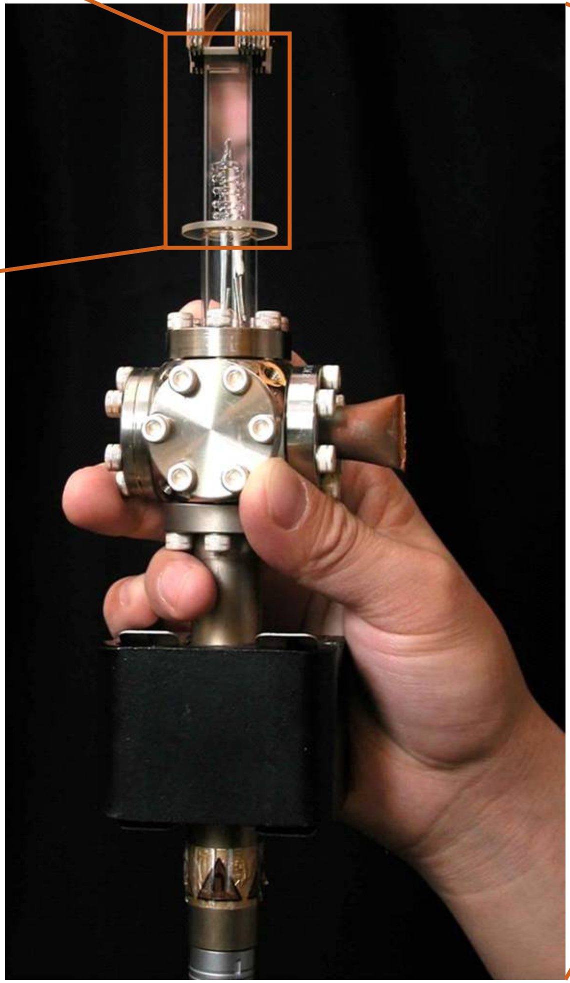
Actual Cell

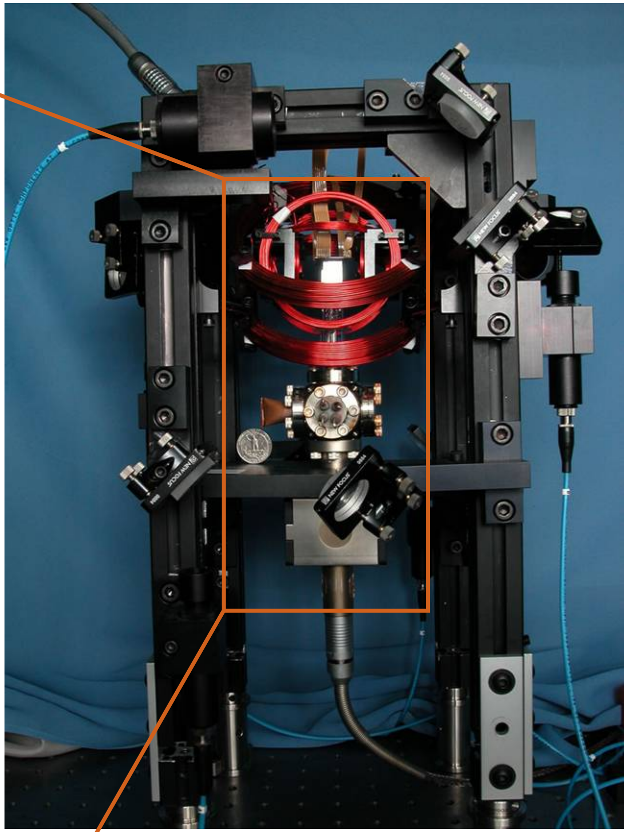


Vacuum Cell Construction
Hand-held Atom Chip Cell and the "Hat"



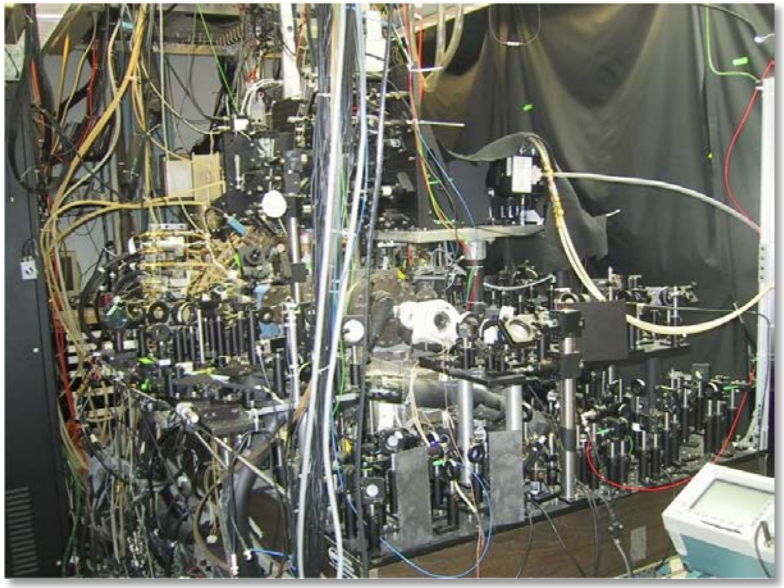
- Complete self-contained UHV atom chip vacuum cell
- Atom chip produces a Magneto-Optical Trap or a Bose-Einstein Condensate
- Inserts into "Hat" assembly
  - Carries bias & MOT magnetic field coils
  - Fiber coupled cooling & imaging beams
  - Enormously simplifies alignment
  - Typically achieve MOT in 2-3 hours after pinch-off vs days with conventional setup





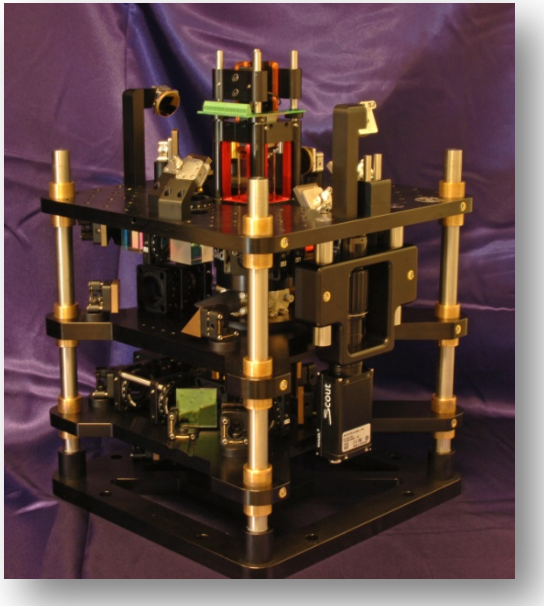
From Room Scale to Chip Scale

That was then…

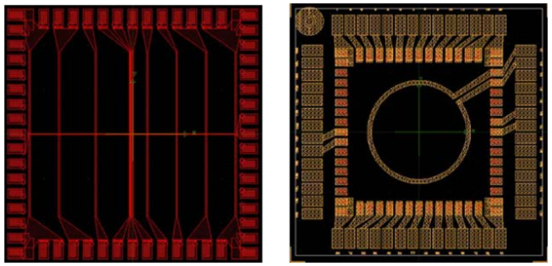


Ketterle BEC System on a 8’x4’ table

…this is now

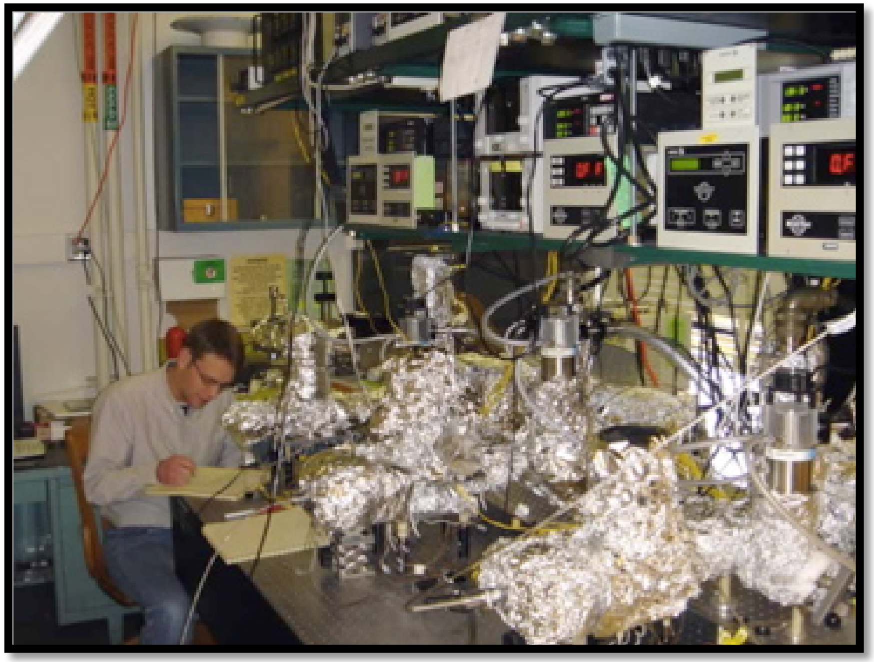


Compact Atom Chip System
about 50 x 30 x 30 cm



Atom chip technology has enabled miniaturization of ultracold atom systems from 7 ft to 12” systems

Ultracold Receiver

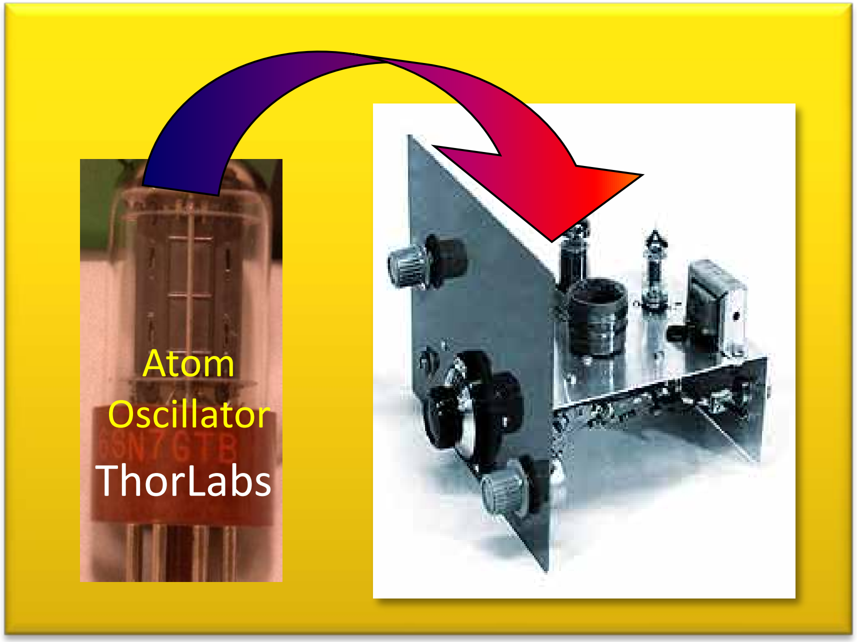


Custom atom chip component

Into a

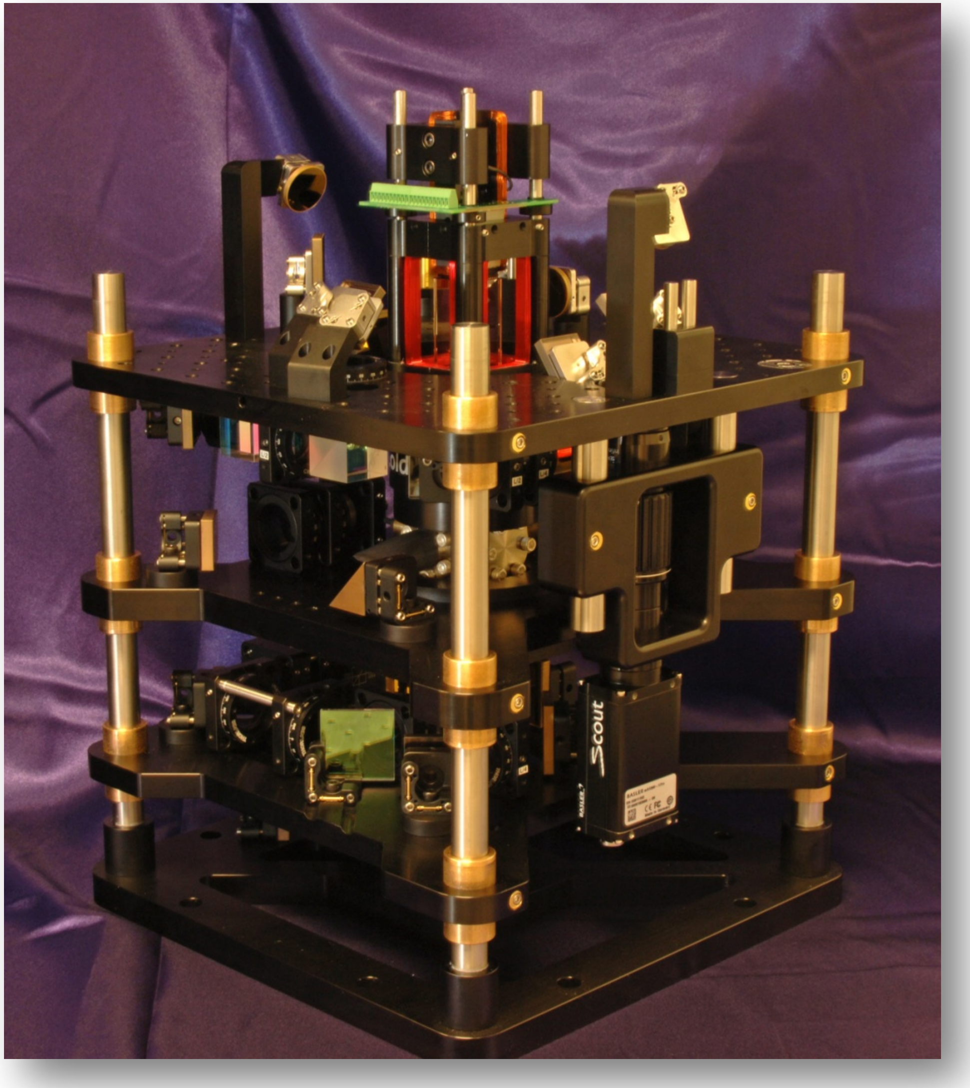
Standardized atom chip receiver

Atom chip cell “mass” production



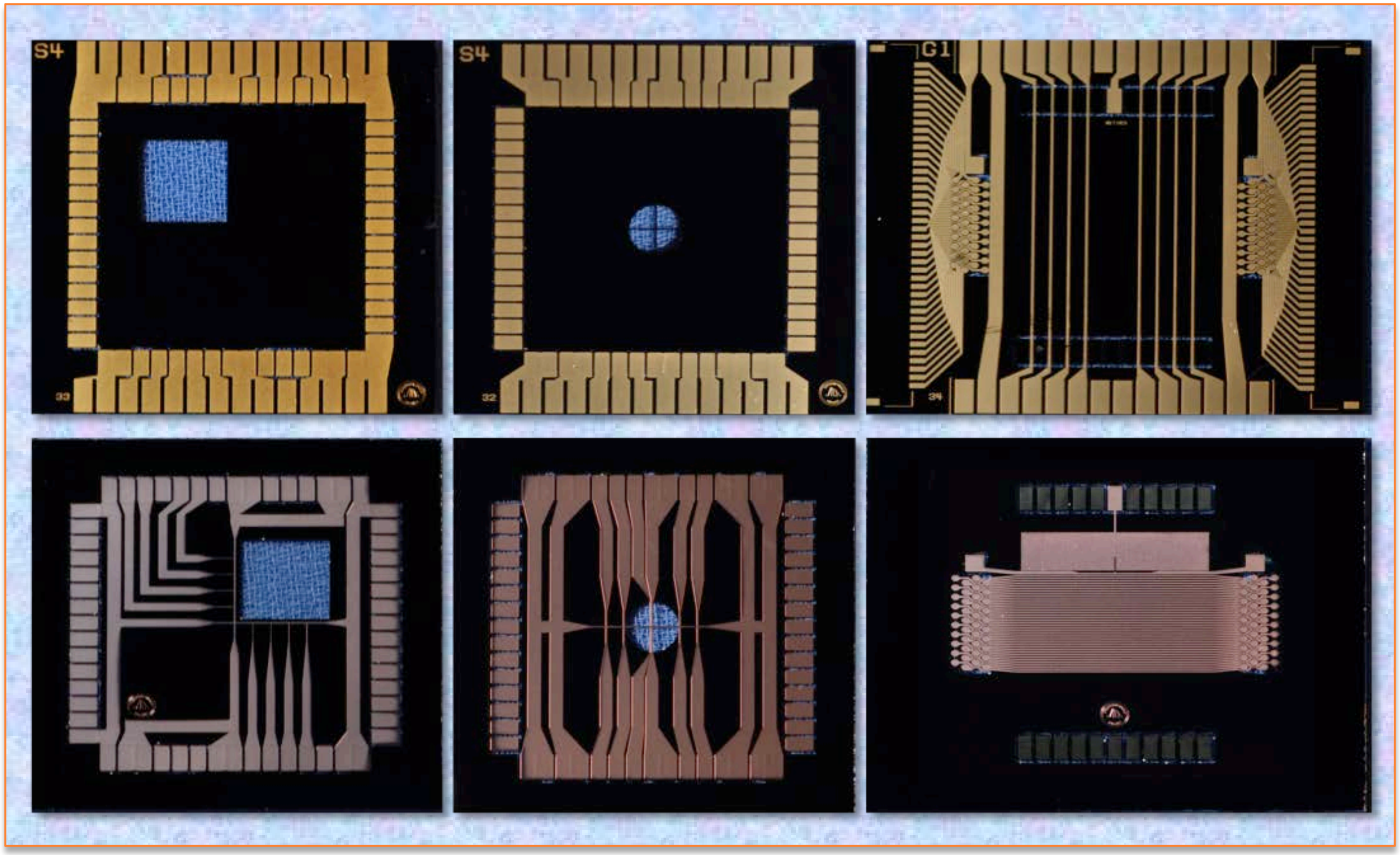
Atom Chip “Receiver”…

- Rapidly remove and replace an atom chip cell
- Still provides flexible access to the atom chip



Versatility of Atom Chip Approach

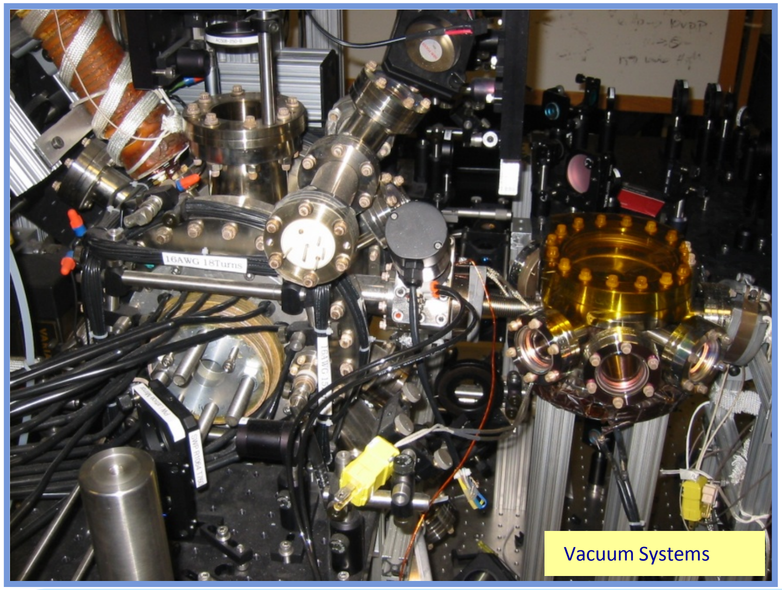
- The ultracold atom source remains constant, while *functionality is* determined by chip design.
- Below are chips for three different BEC systems (chips are ~23 mm x 23 mm).

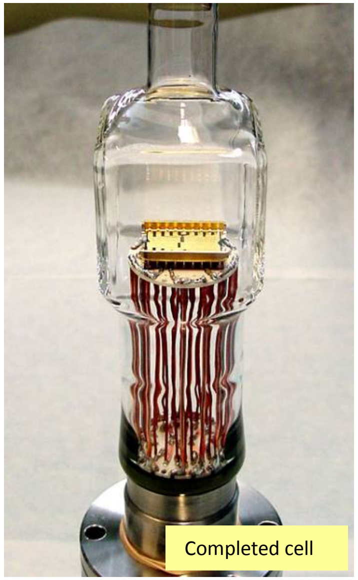


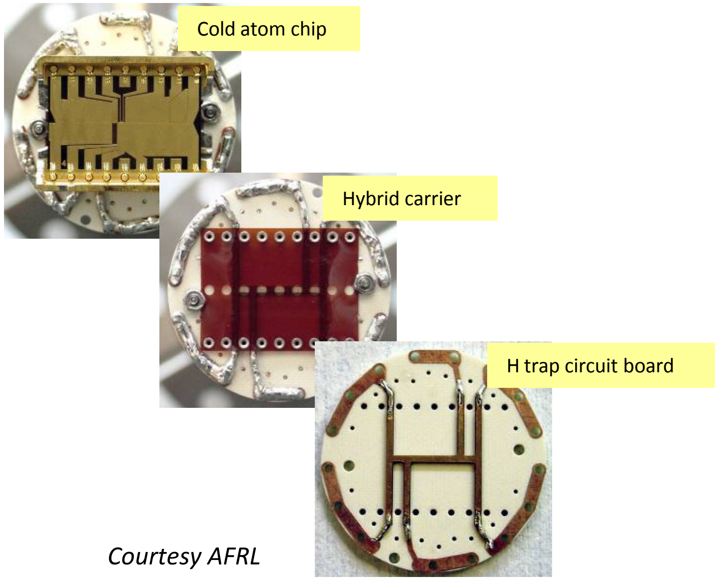
Ambient

Vacuum

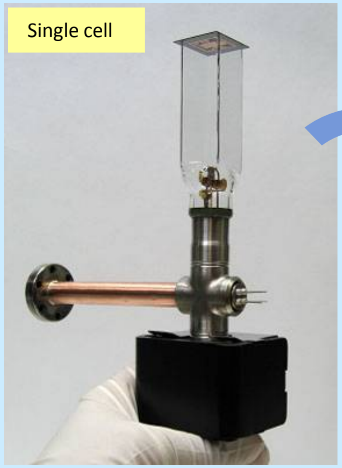
Portable Vacuum Systems



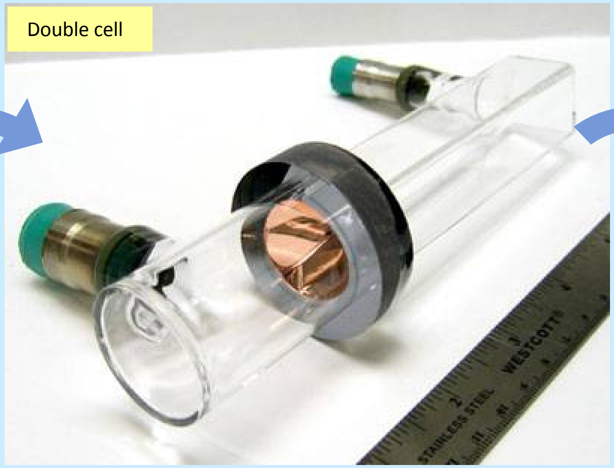




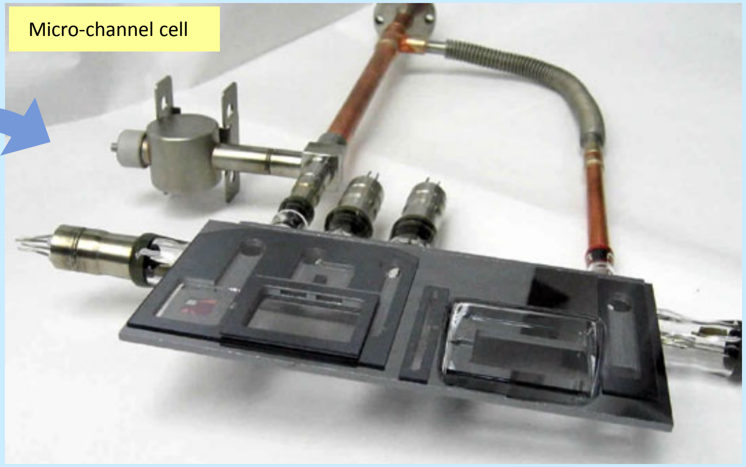
Courtesy AFRL



Single cell design: Achieved an unprecedented level of integration.



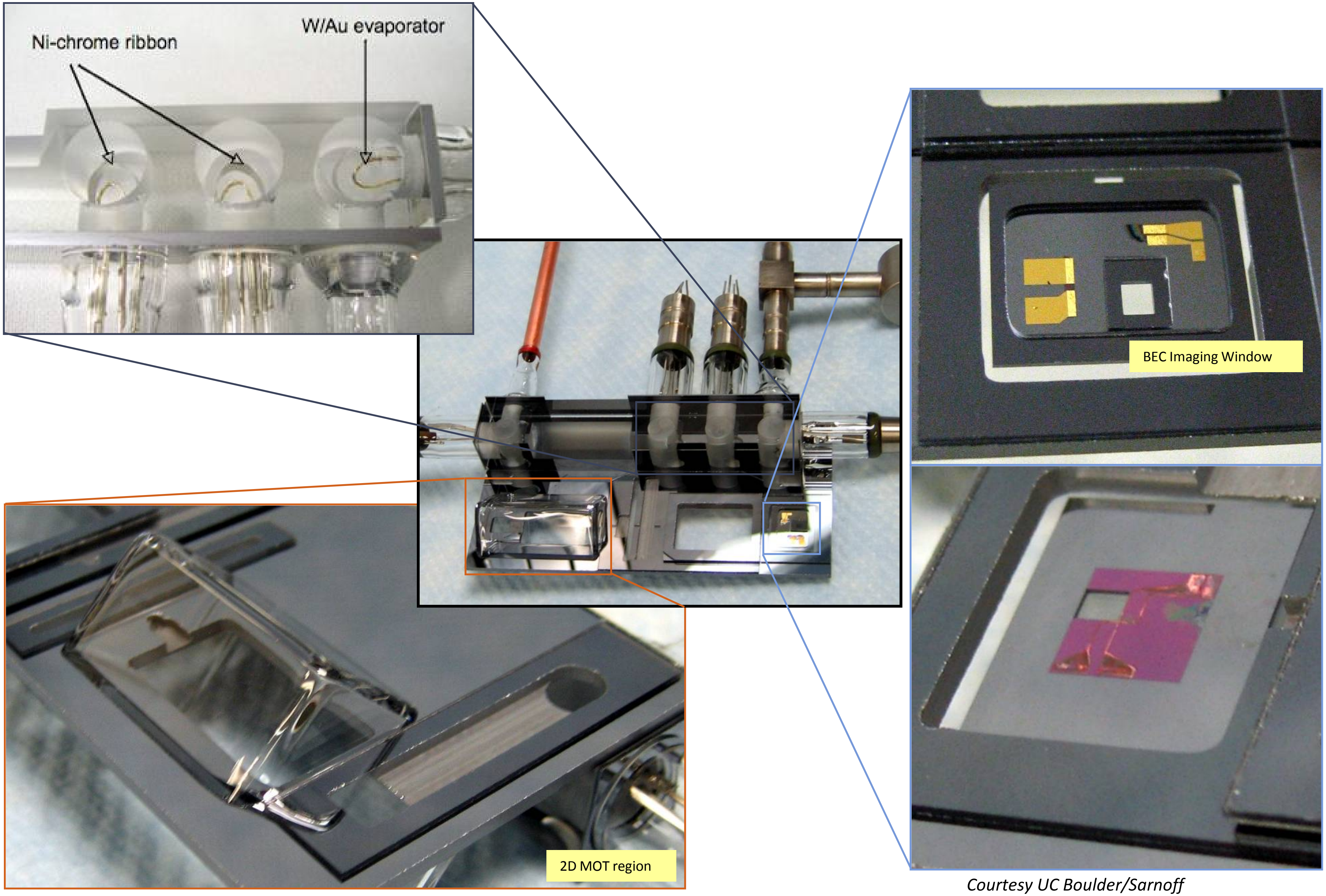
Double cell design: Additional differential pumping to reduce background pressure and increase source brightness.



Micro-channel design: Improved differential pumping and additional optical isolation to reduce light scattering and increase duty cycle.

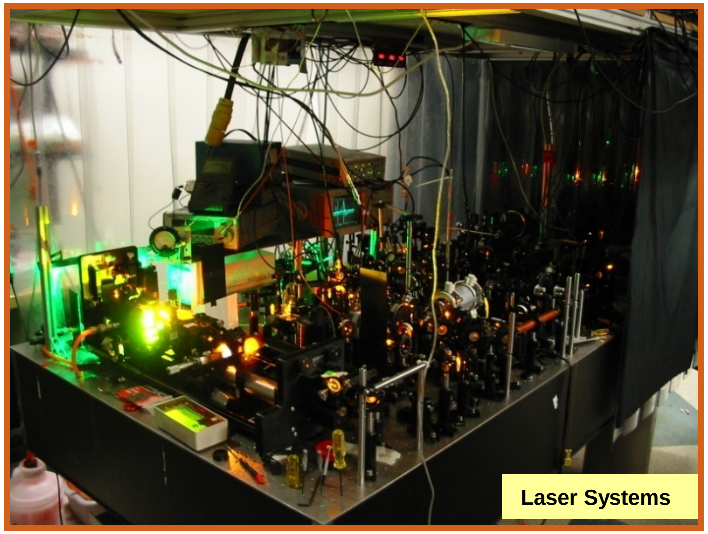
Courtesy UC Boulder/Sarnoff

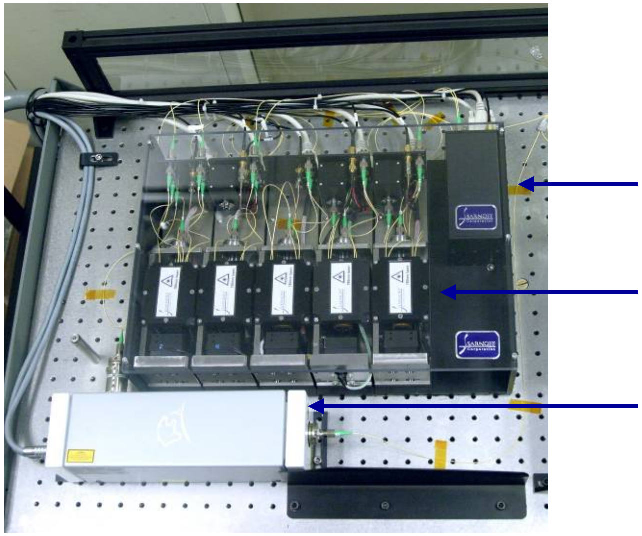
Micro-Channel Cell Details



Courtesy UC Boulder/Sarnoff

Portable Laser Systems



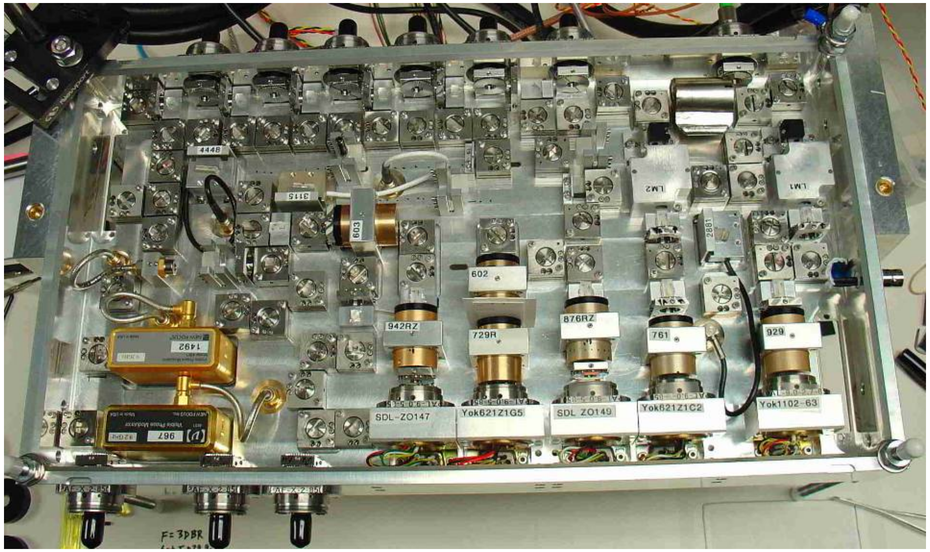

Saturated Absorption Spectroscopy

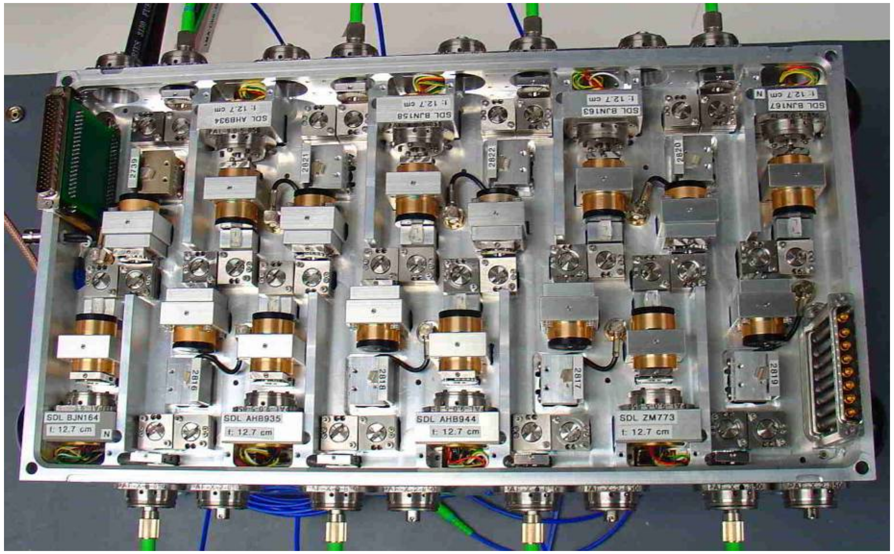
DFB Laser Modules

Tapered Amplifier

Courtesy UC Boulder/Sarnoff/Vescent

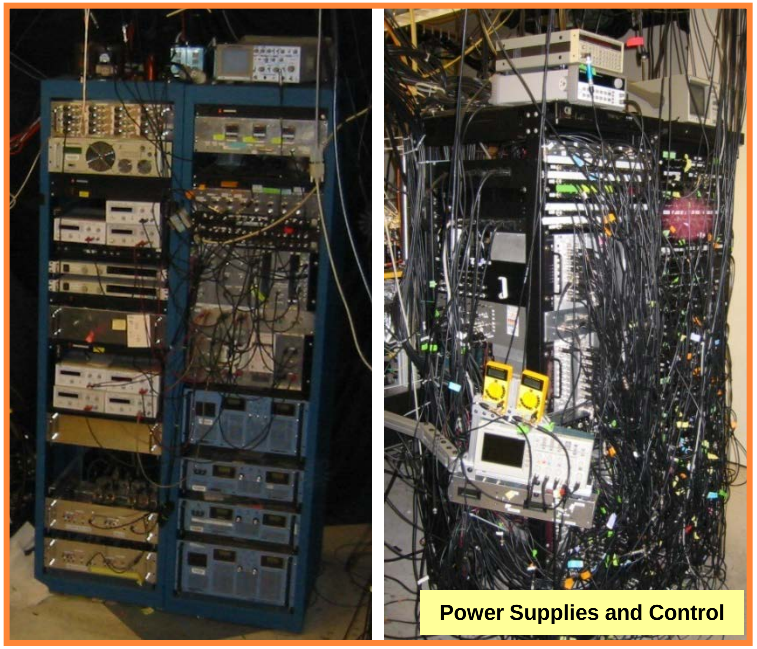
Rb MOT Laser System


Master Laser


Laser Amplifier

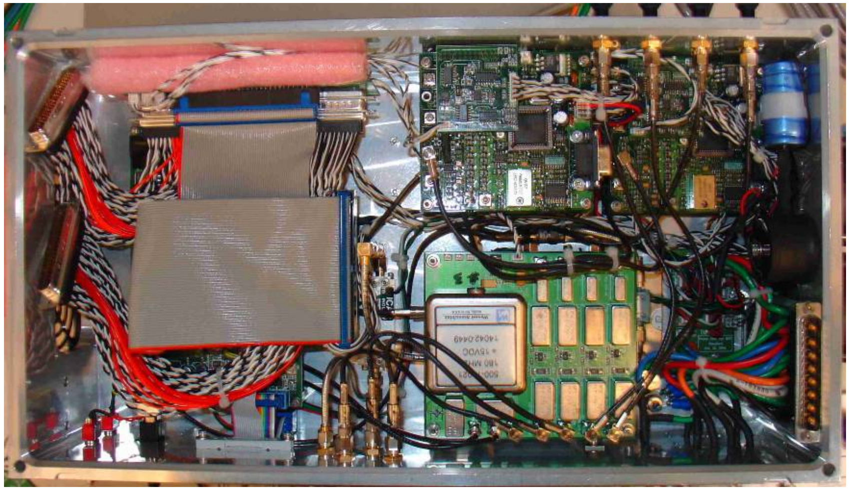
Courtesy Stanford/AOSense

Portable Power and Control Systems

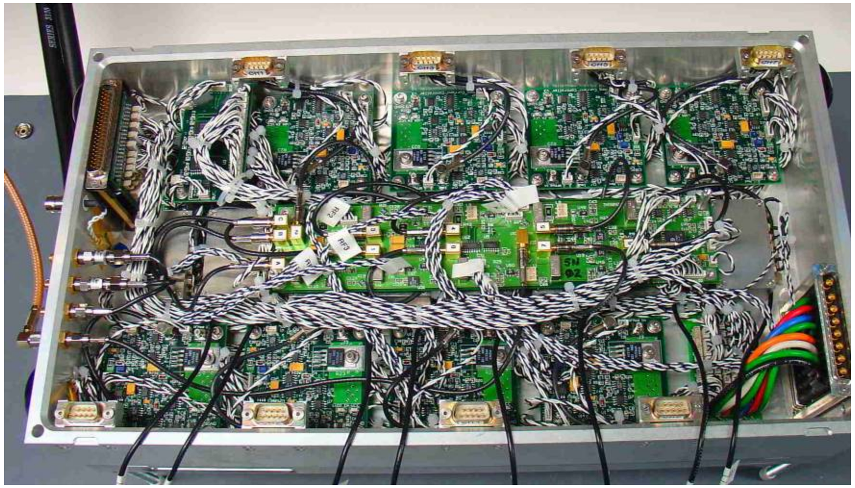


Laser Controller

Courtesy UC Boulder/Sarnoff/Vescent



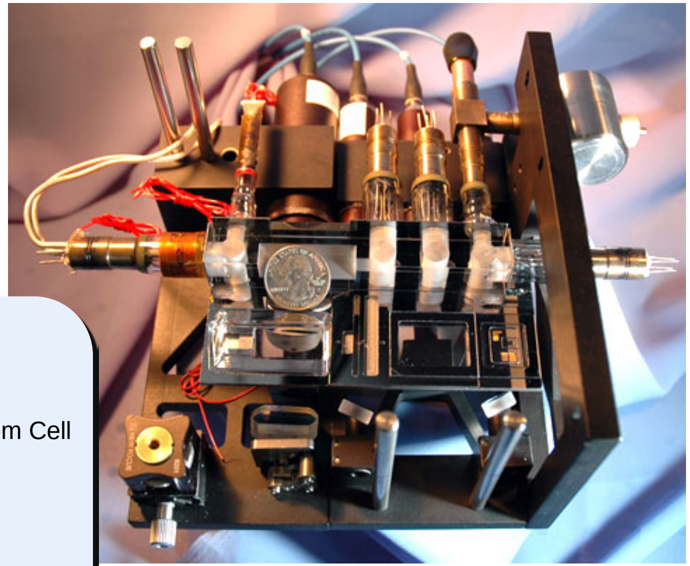
Digital Signal Processor



RF Amplifiers

Courtesy Stanford/AOSense

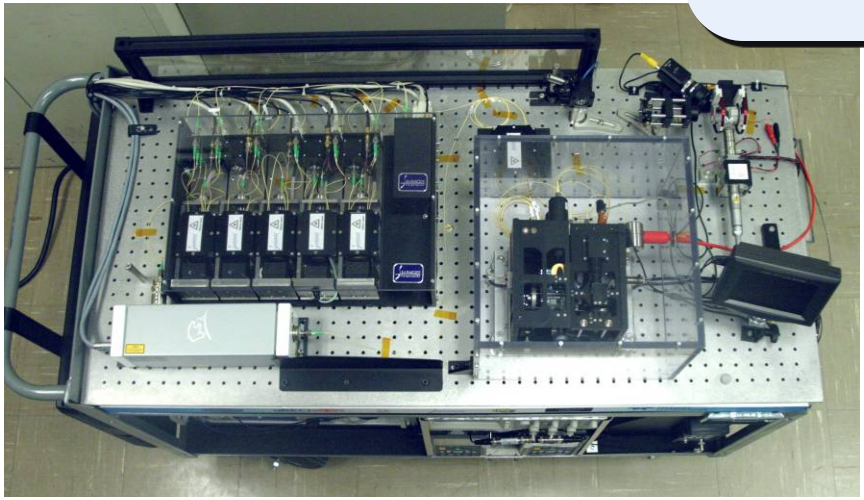
1st Generation Portable Cold Atom System



Portable MOT Demonstration

- Integrated Cold Atom Cell
- 5 Laser System
- Control Electronics
- Instrumentation
- UPS

Battery Powered
Operational while in motion

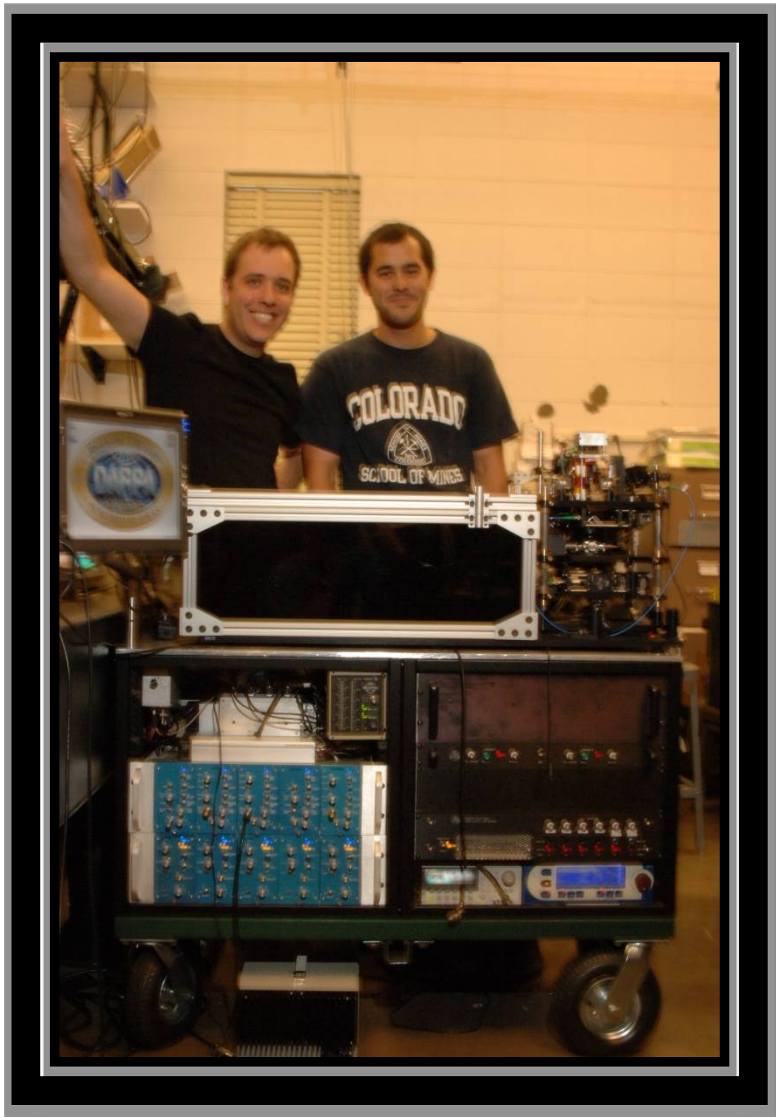


Courtesy UC Boulder/Sarnoff/Vescent

World’s Smallest BEC System

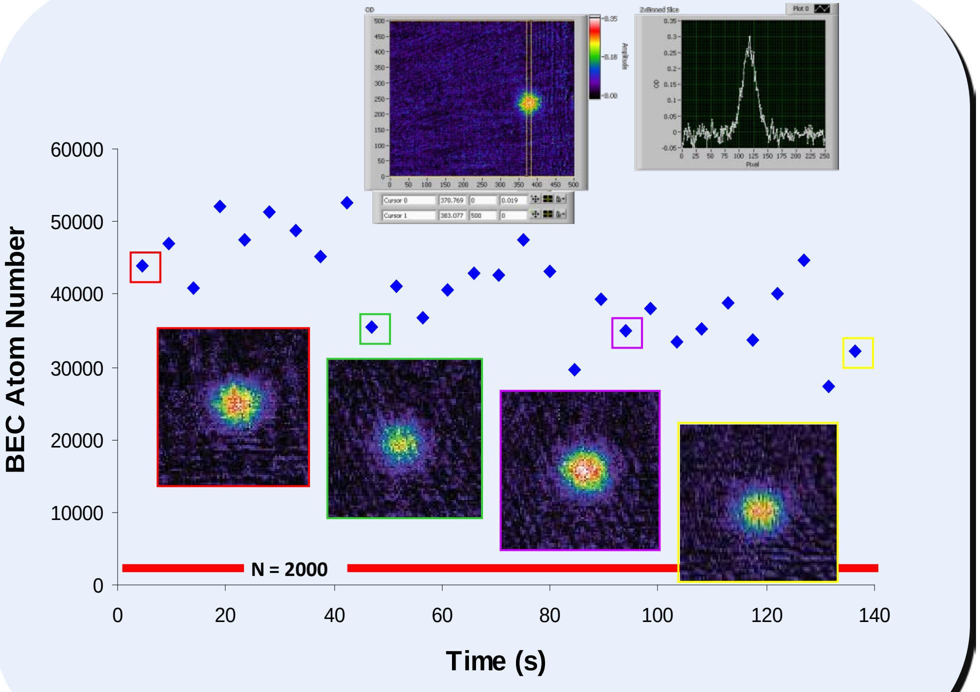
FIRST BEC PUBLIC DEMO: APS MARCH MEETING 2010

- $< 0.4\ m^3$;
- 187 kg (400 lbs);
- 500 Watts
- BECs in less than 3 s
- First on-road BEC



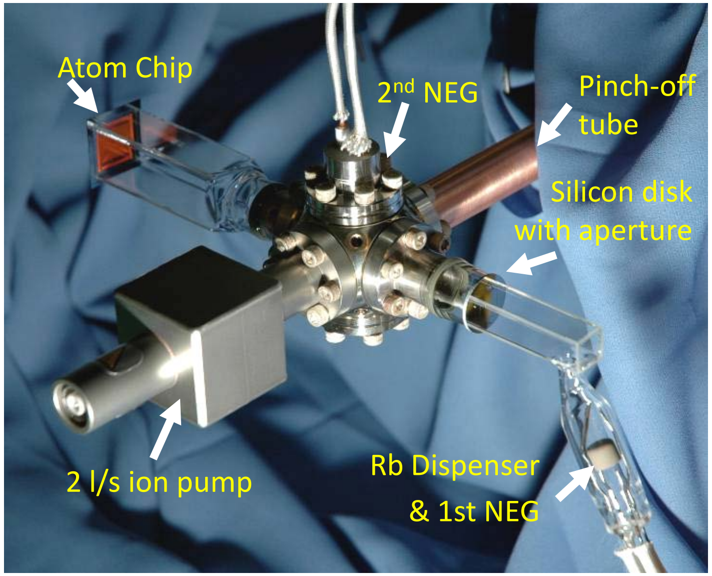
Rapid BEC Production

Quasi-Continuous BEC

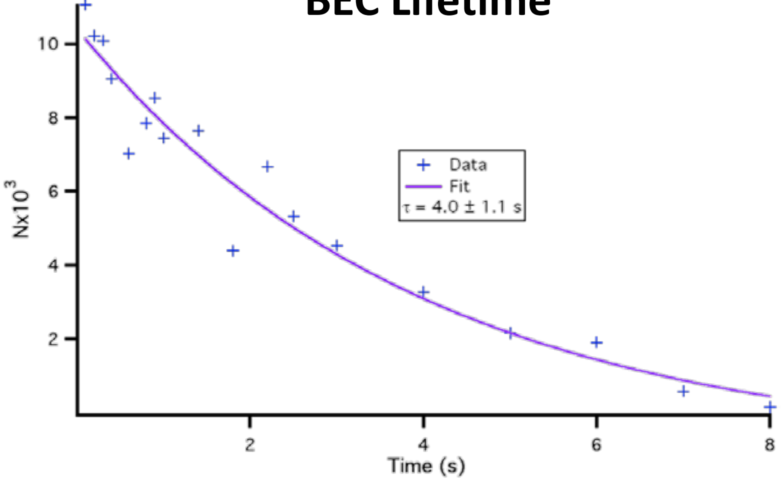


40,000 BEC atoms produced every 4.7 s

Portable Apparatus

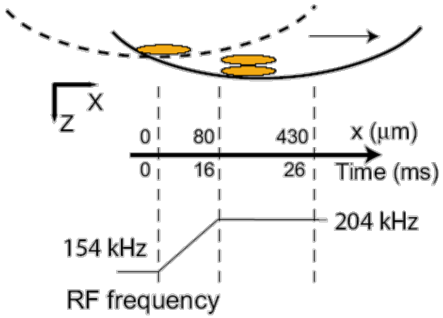


BEC Lifetime

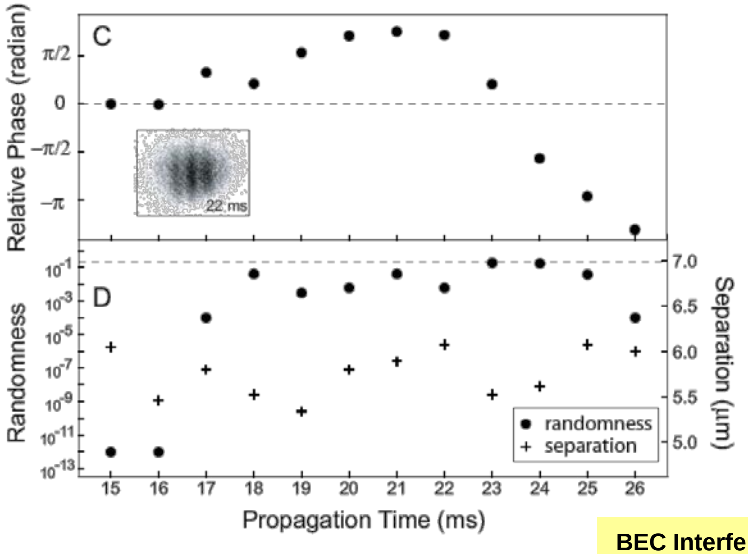


Atom-chip BEC lifetimes of 4 s

Rotationally-Sensitive Chip-Based Interferometry

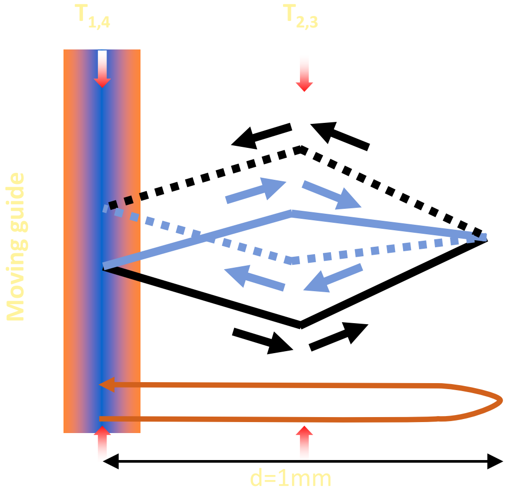


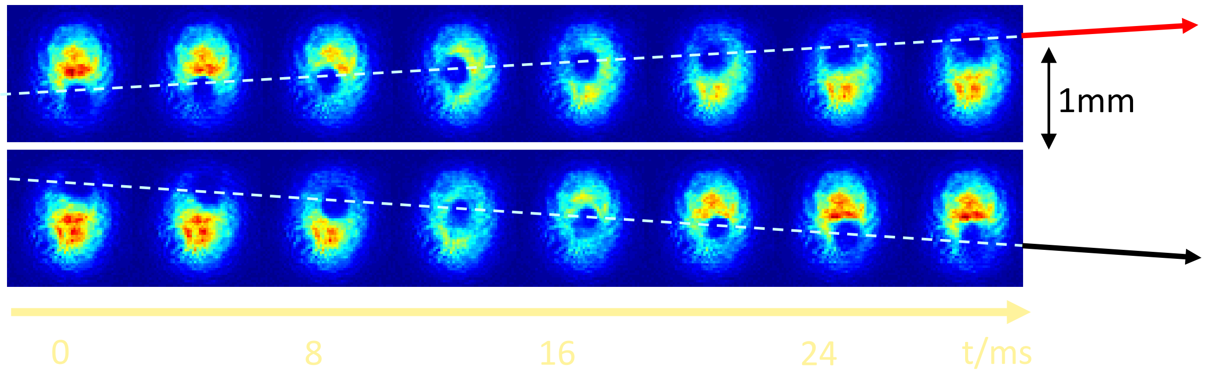
$$S_\Omega = 7.9\times10^{-5}\,\frac{rad}{\Omega_e}$$



BEC Interferometer

Courtesy of MIT



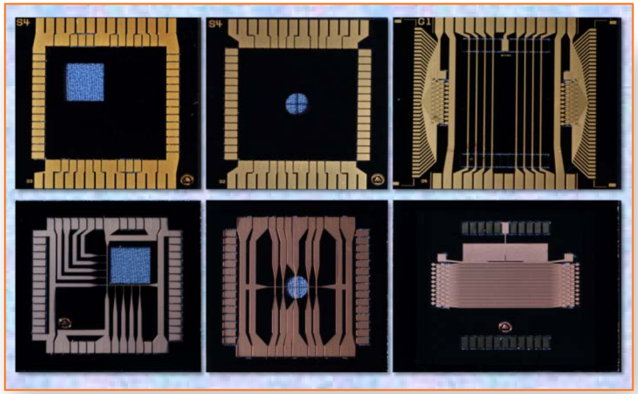


$$S_\Omega = 0.04\,\frac{rad}{\Omega_e}$$

Cold atom interferometer

Courtesy of Harvard

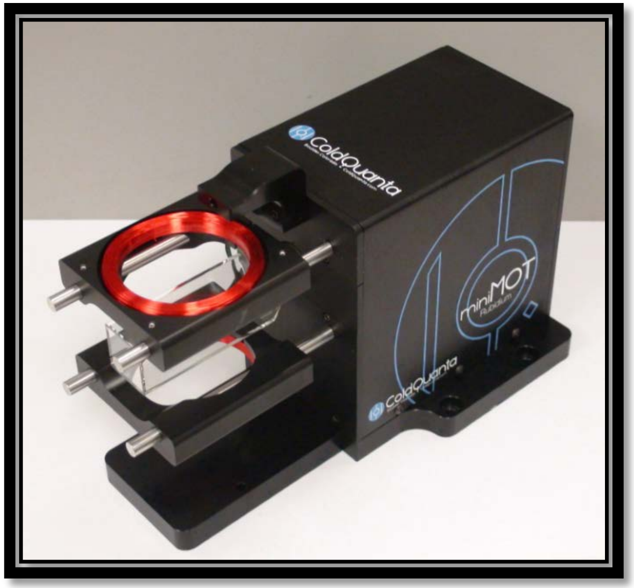
Commercialization of Cold & Ultracold Instruments



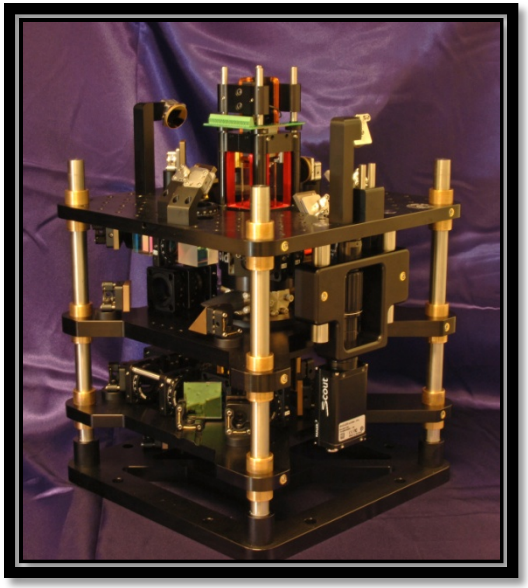
Custom atom chips

ColdQuanta, Incorporated

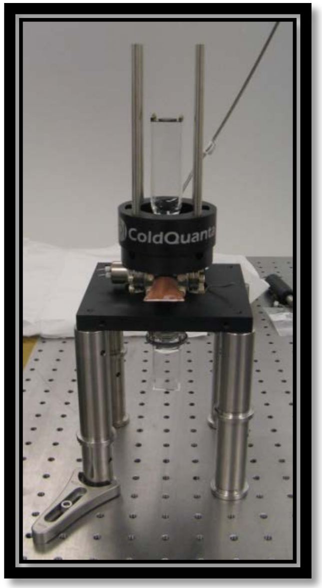
- Founded in 2007
  Rainer Kunz, Jakob Reichel,
  Ted Hänsch, & D. Z. Anderson



miniMOT™ & miniMOT kit



BEC Physics Station



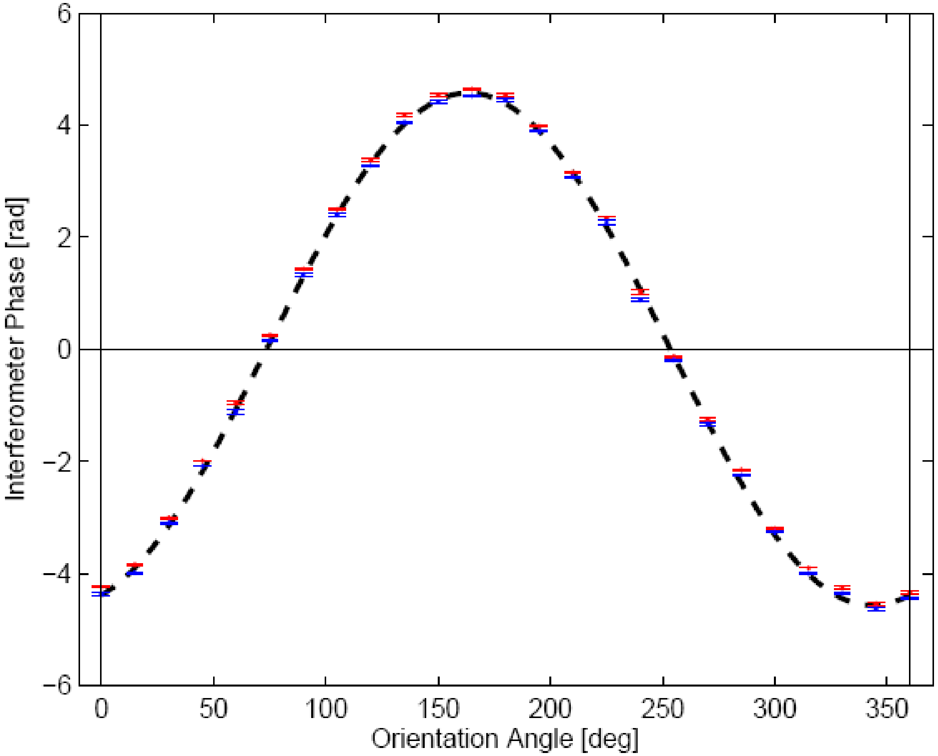
RuBECi

Another Route: *Free Space* Interferometry

2007 Hybrid Sensor/Gyroscope Mode

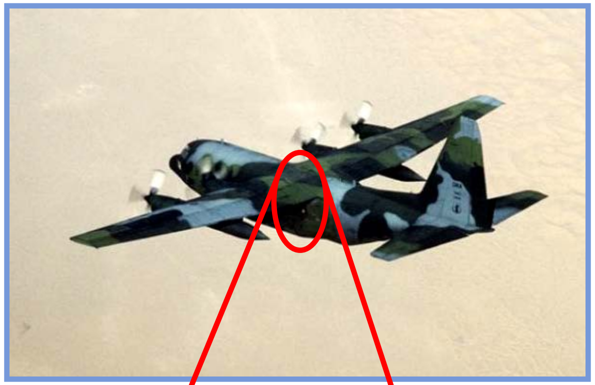
- Inferred ARW: ~ 100 μdeg/hr$^{1/2}$
- 10 deg/s max input
- <100 ppm absolute accuracy

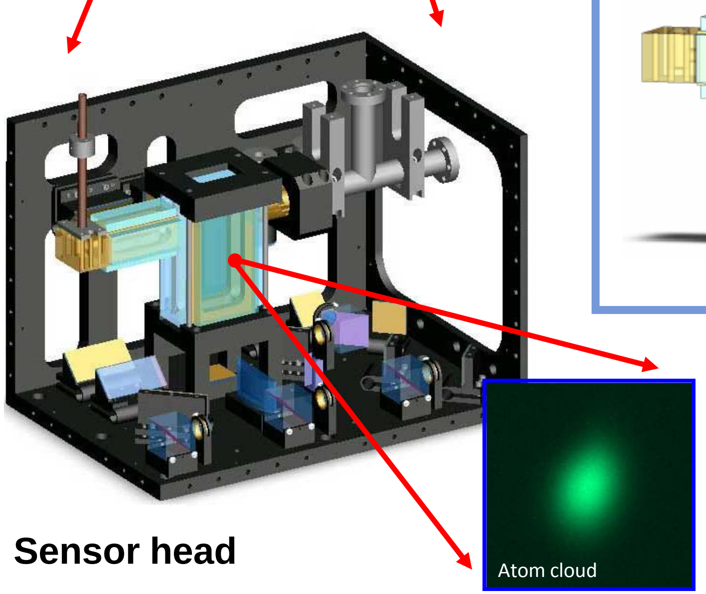
Measured gyroscope output vs.orientation:



Atom Interferometer-based Inertial Navigation (DARPA)

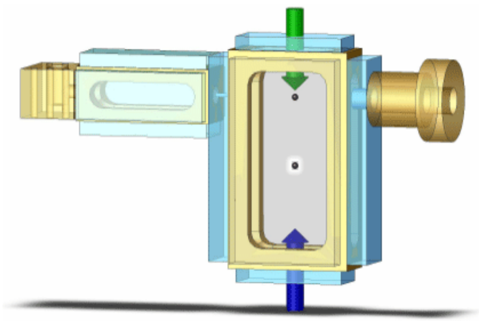
- Demonstrated performance of single-sensor designs
  - Accelerometer: <10ng bias
  - Gyro: <5 μdeg/hr bias
  - Gradiometer: <10 E/Hz$^{1/2}$
- Phase 3 Goal: 5 meter/hour gravity-compensated inertial navigation system demonstration



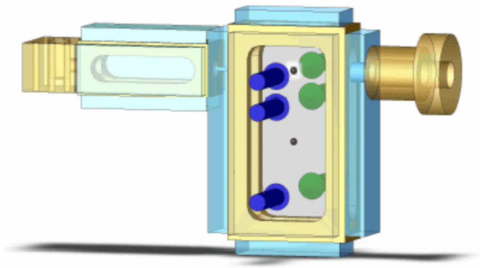


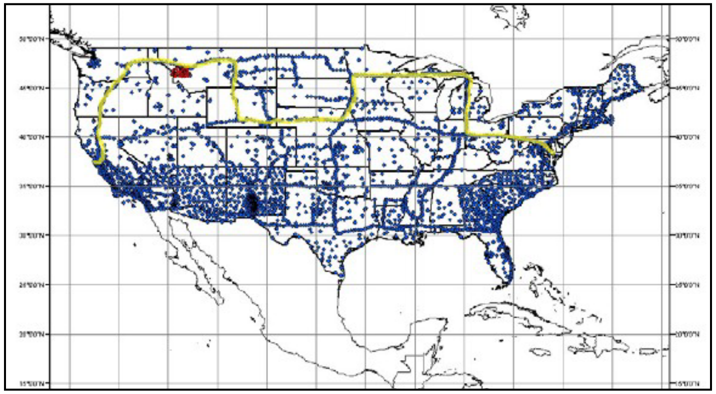
Sensor head

Gravimeter mode



Accelerometer/gyroscope mode

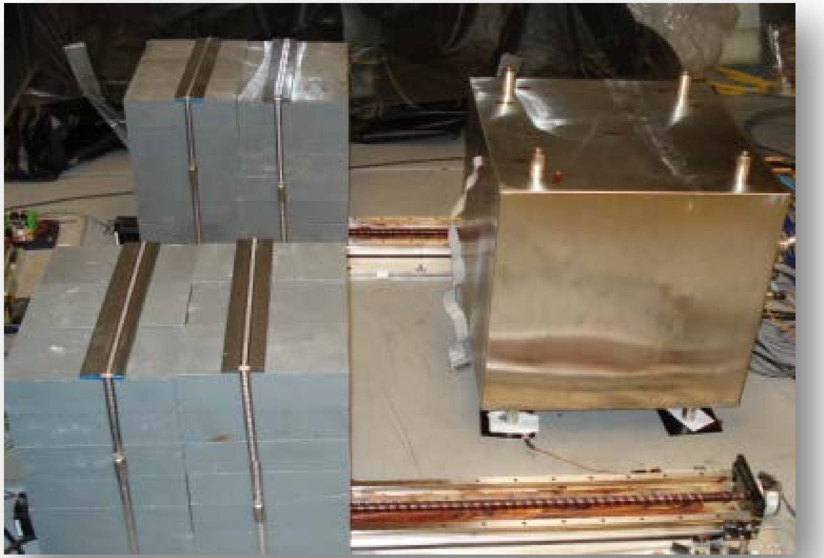


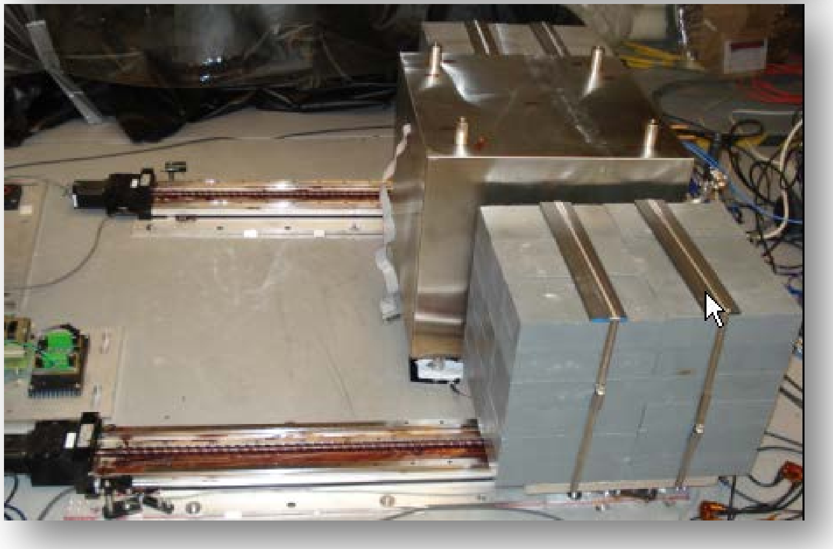


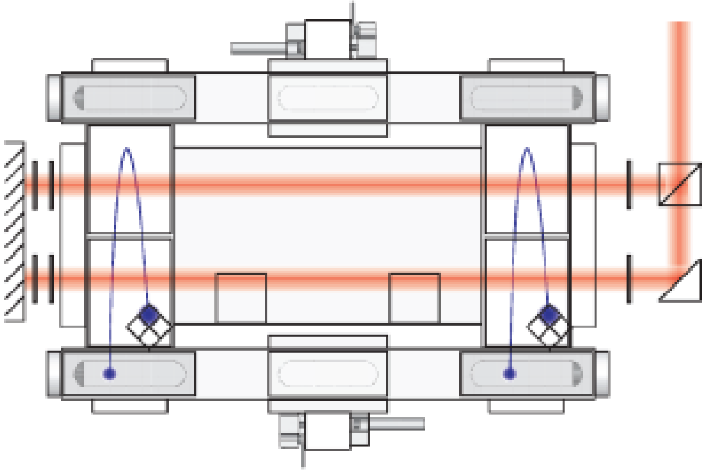
Cross-country Navigation Test Route

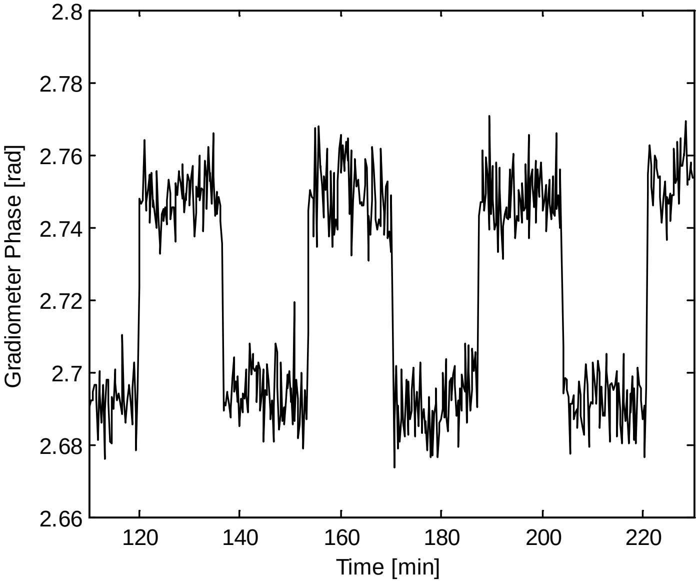
Navigation Test Vehicle

2007 Hybrid Sensor/Gravity gradient mode (SP-24)

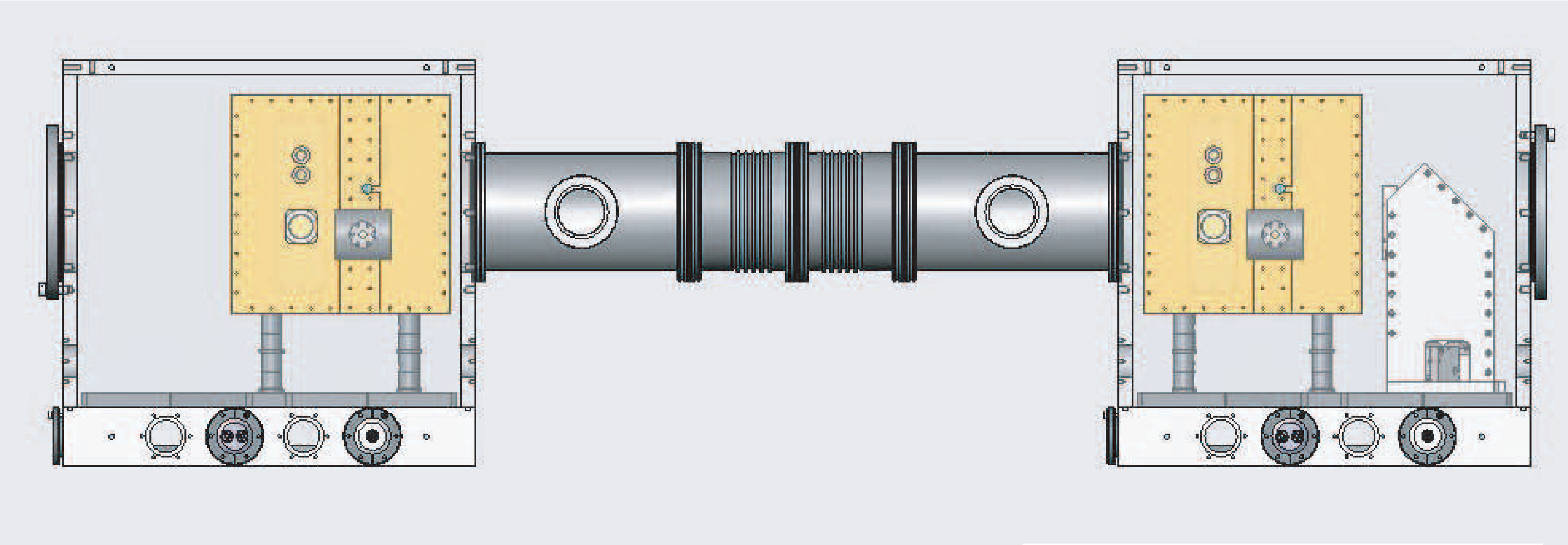


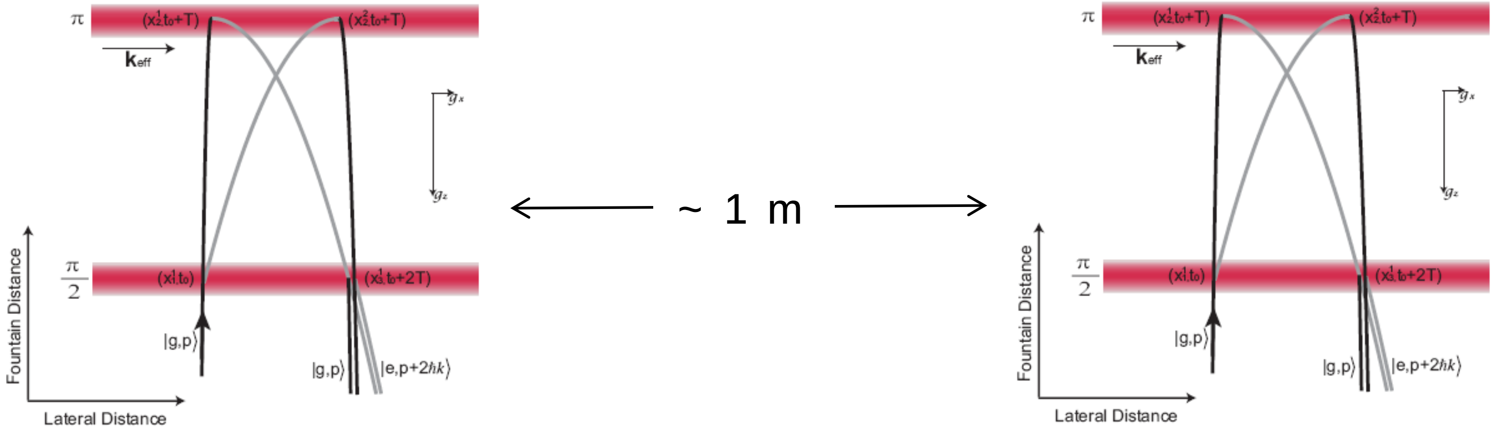






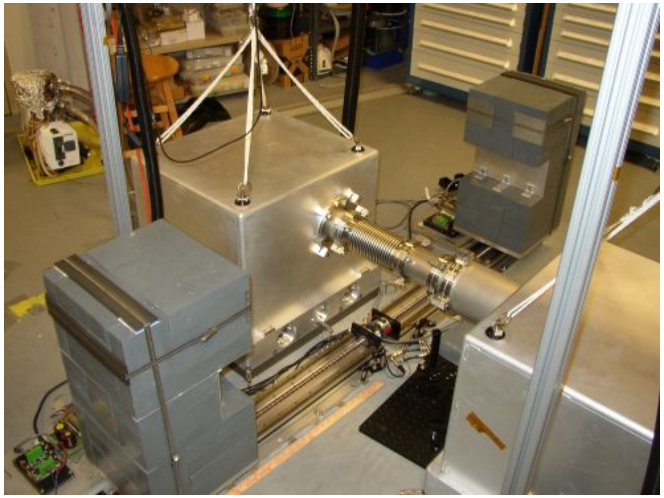
2007 Gravity Gradiometer (NGA)

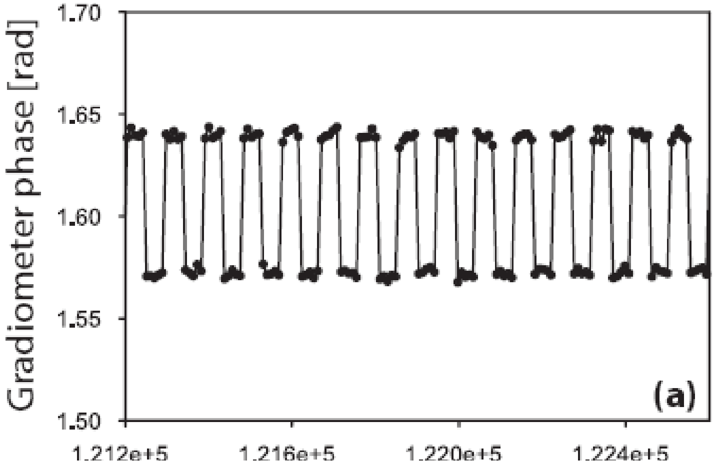


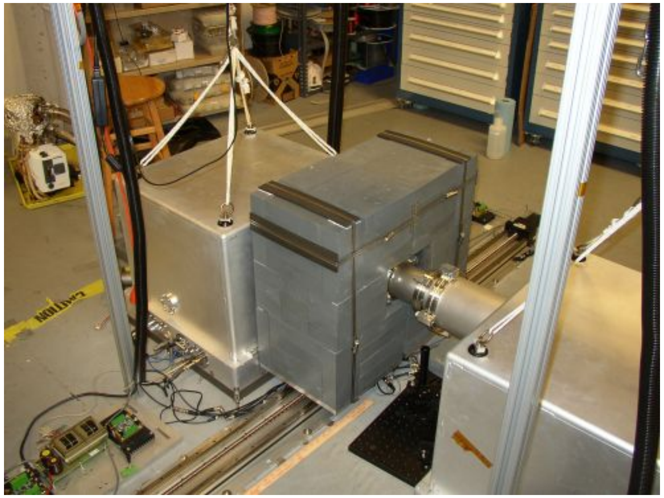


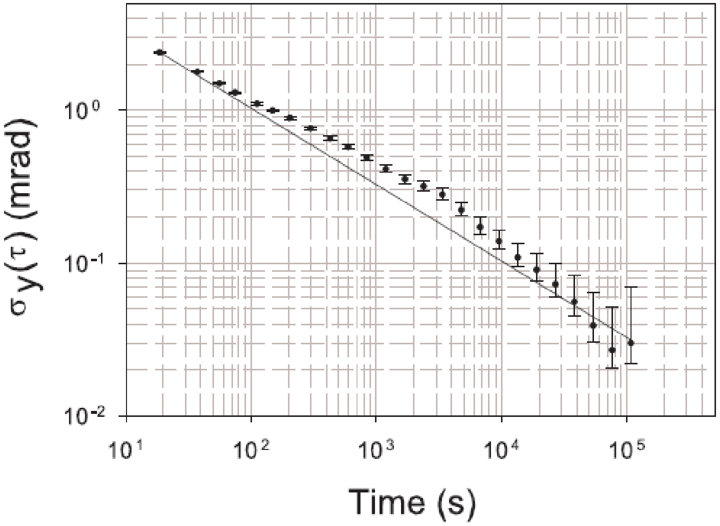
Applications in precision navigation and geodesy

2007 Gravity Gradiometer (NGA)









Demonstrated accelerometer resolution: ~10^{-11} g.

2007 Truck-based Gravity Gradient Survey (NGA)

ESIII loading platform survey site

AOSense, Inc.

- Formed in 2004 to develop cold-atom navigation sensors
- Core capability is design, fabrication and testing of sensors based on cold-atom technologies
- 20k sq. ft. R&D space, located in Sunnyvale, CA

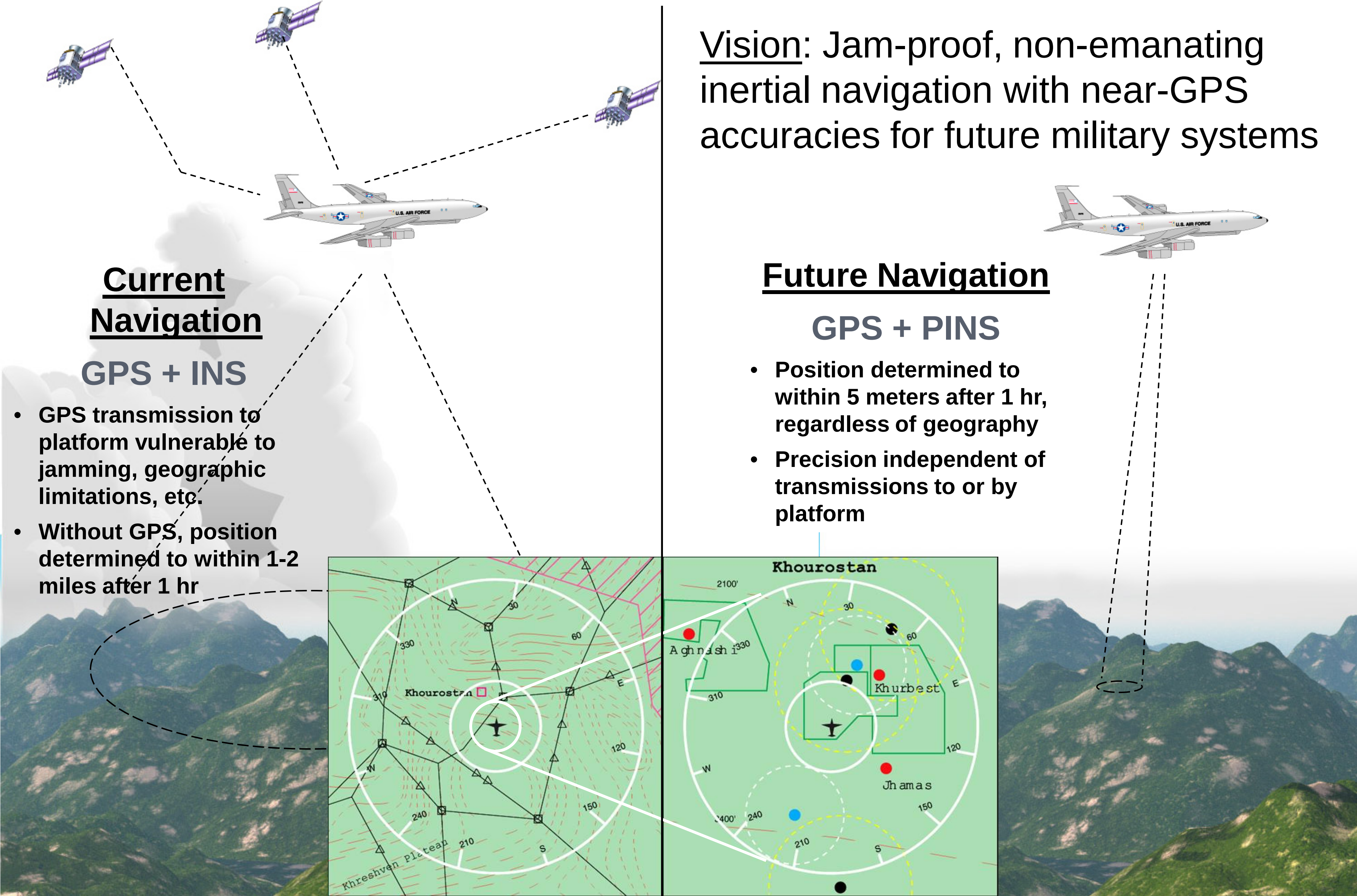
Commercial Cold Atom Gravimeter

- Noise < 1 $\mu g/Hz^{1/2}$
- Shipped 11/22/10
- First commercial atom optics sensor

AOSense

byoung@aosense.com

Atomic and Molecular Physics leads to DoD Application



Vision: Jam-proof, non-emanating inertial navigation with near-GPS accuracies for future military systems

Current Navigation

GPS + INS

- GPS transmission to platform vulnerable to jamming, geographic limitations, etc.
- Without GPS, position determined to within 1-2 miles after 1 hr

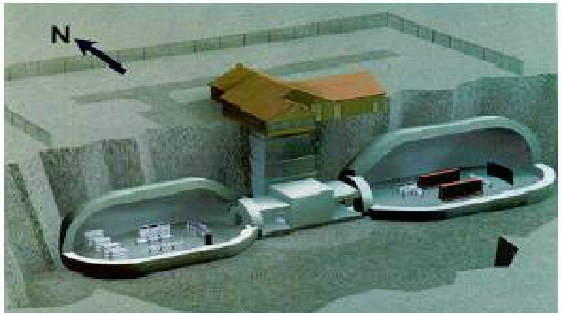
Future Navigation

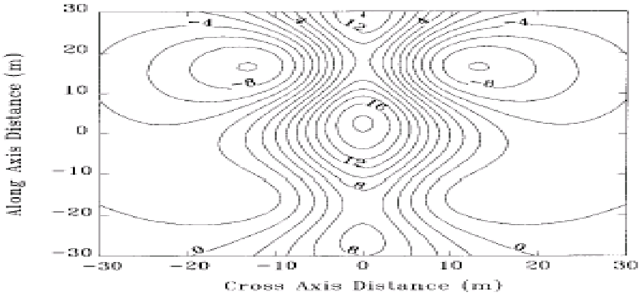
GPS + PINS

- Position determined to within 5 meters after 1 hr, regardless of geography
- Precision independent of transmissions to or by platform

Atomic and Molecular Physics leads to DoD Application

- Standoff detection of underground structures: a long-standing Army need
- Conventional gravity gradiometers can detect geological formations
- Atom Interferometery gravity gradiometer
  - x10 sensitivity improvement (0.1 E/(Hz)$^{1/2}$)
  - Excellent long-term stability
  - Intrinsic immunity to vibrations
  - Sensitivity to detect 5 meter diameter tunnels by aircraft 500 feet above ground
  - . . . or a 50 ton tank at 100 meters (5 mph)
- Possible further improvement of ~10^8

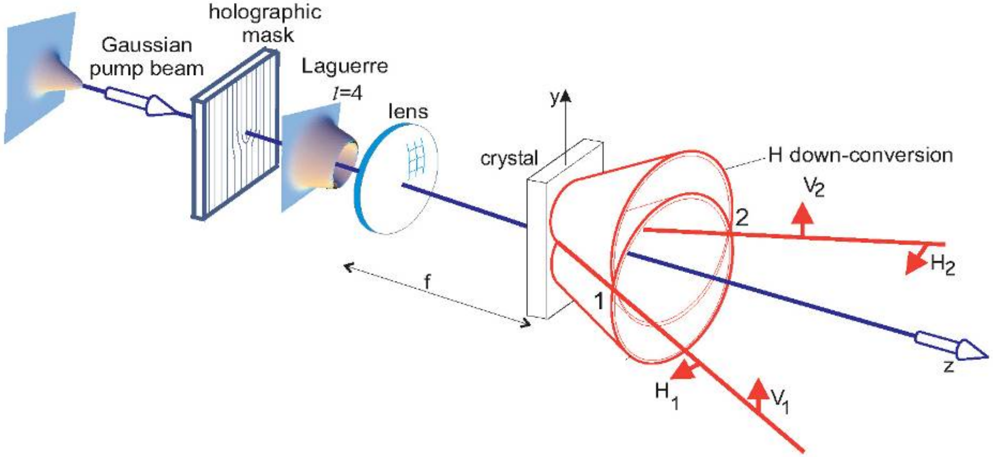




Some recent and current MURIs

- Quantum Imaging
- Optical Lattices
- Atomtronics
- Quantum Information Sciences

Quantum Imaging MURI



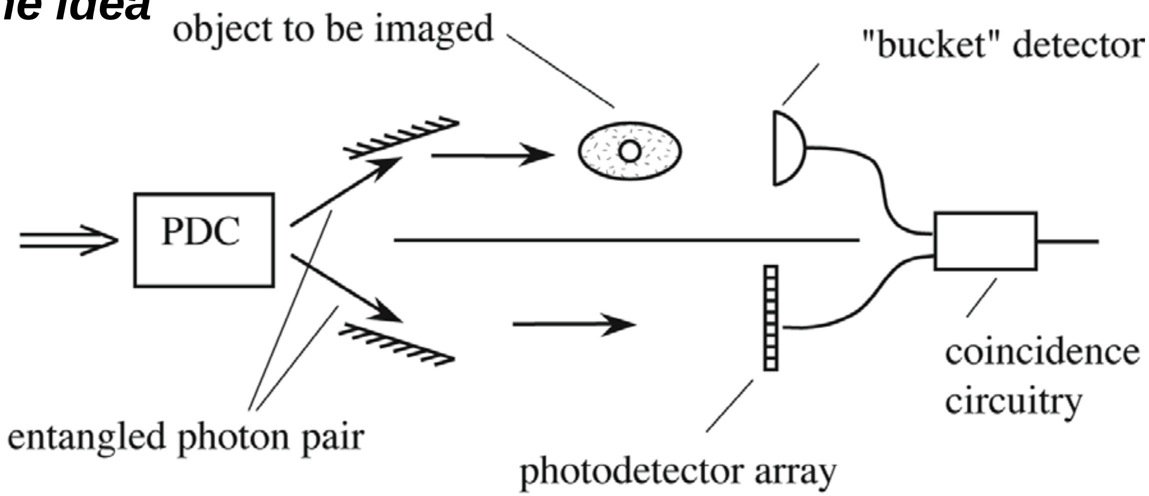
Motivations and Research Goals

- Can images be formed with higher resolution, greater sensitivity, or by interaction-free measurement through use of quantum states of light?
- For example, can one “beat” the Rayleigh limit?
- Can one use “ghost imaging” for detection and surveillance?

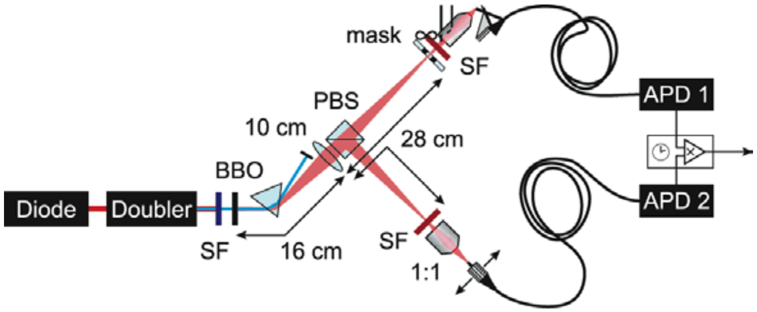
Coincidence (Ghost) Imaging

- Image is formed by photons that have never interacted with the object
- Obvious applicability to surveillance and remote sensing
- Utilizes entangled photons, correlated beams, or intensity fluctuations
- Can enable imaging through obscurants; or in different spectral bands than sensor

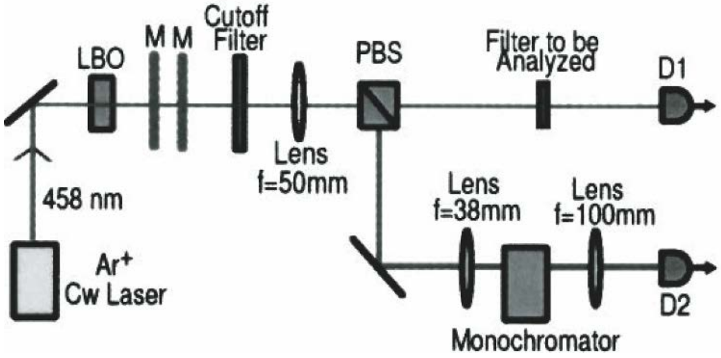
The idea



Entangled light source



Ghost spectroscopy setup

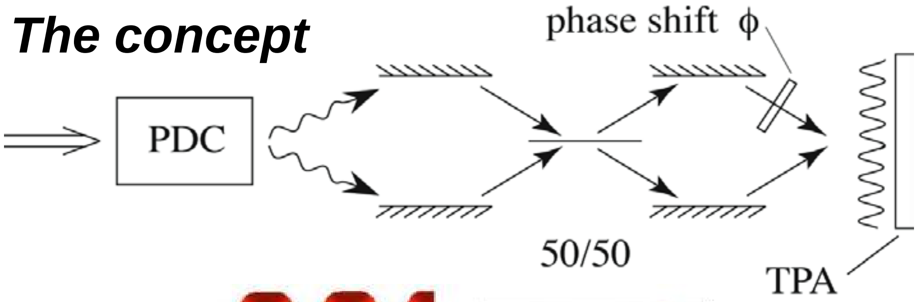


Quantum Lithography

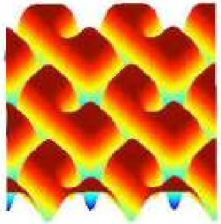
Objectives

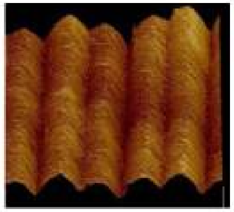
- Perform photolithography with sub-Rayleigh resolution
- Develop related methods for obtaining sub-Rayleigh resolution in microscopy and other imaging

The concept



Simulation of arbitrary pattern





AFM of lab fringes

Approach

- Create entangled photons by down conversion; Construct OPA source
- Combine interferometrically
- Observe non-classical fringe spacing
- Develop sensitive multiphoton lithographic materials

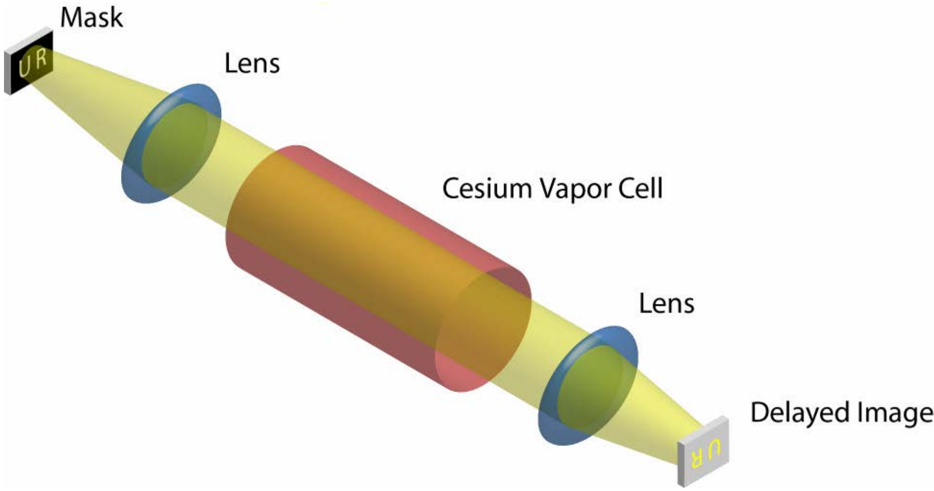
Accomplishments

- Performed study of use of OPA as an intense source of entangled photons
- Established PMMA as suitable recording material; identified more sensitive alternatives
- Demonstrated ability to write $\lambda/6$ features
- Developed protocol for writing non-sinusoidal features

High-Dimensional Entanglement and Imaging

Objectives

- Measure & characterize high-D entanglement
- Demonstrate high-D cryptosystem
- Demonstrate high-D spin violation of Bell's inequalities (e.g., spin 20 to 50)
- Single photon transverse coherence
- Low noise, coherence-preserving buffer for quantum images



Approach

- Measure & characterize time-energy and transverse entanglement
- Use Fourier transform pairs for quantum particles to generate secret key with security
- Use transverse entangled photons and analogs with spin to violate Bell inequality with continuous variables
- Use steep dispersion in double resonance system for delaying images

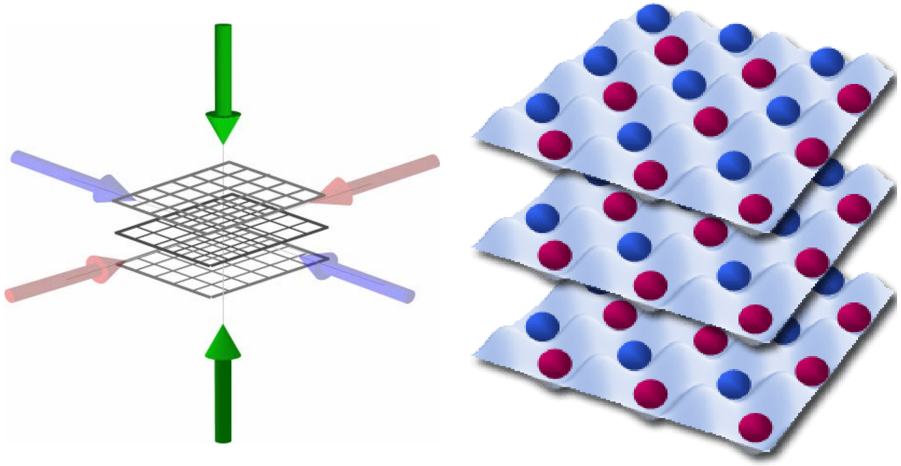
Accomplishments

- Measured over 6000 states in a single pair of entangled photons
- Demonstrated 10 bit/pair high-D cryptosystem
- Theory and simulation of transverse entanglement and spin
- Demonstrated single photon transverse coherence
- Demonstrated excellent fidelity single photon or classical image buffering in a vapor

Optical Lattices MURI

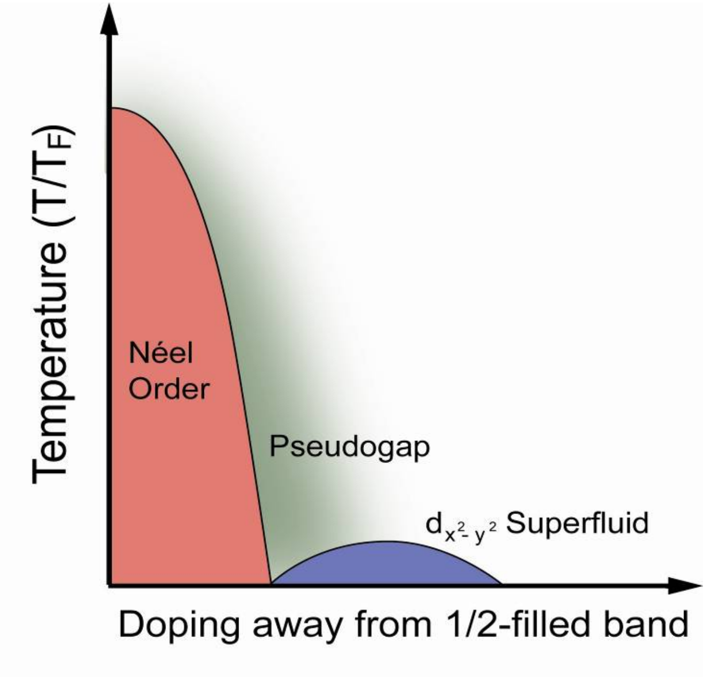
Objectives:

- Ability to design matter
- Quantum simulation of systems that can’t be treated by computer
- “Parallel” sensing with squeezing



- New functional materials
- Room temperatures superconductors
- New classes of devices

Hubbard Model
Anti-ferromagnetism and superconductivity

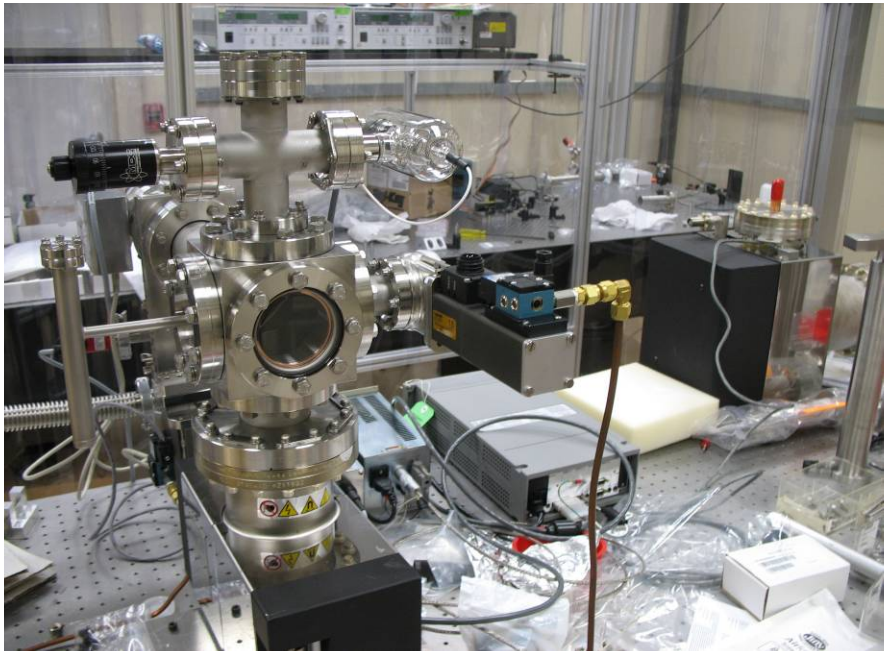


Phase diagram of the high-T_c superconducting cuprates.

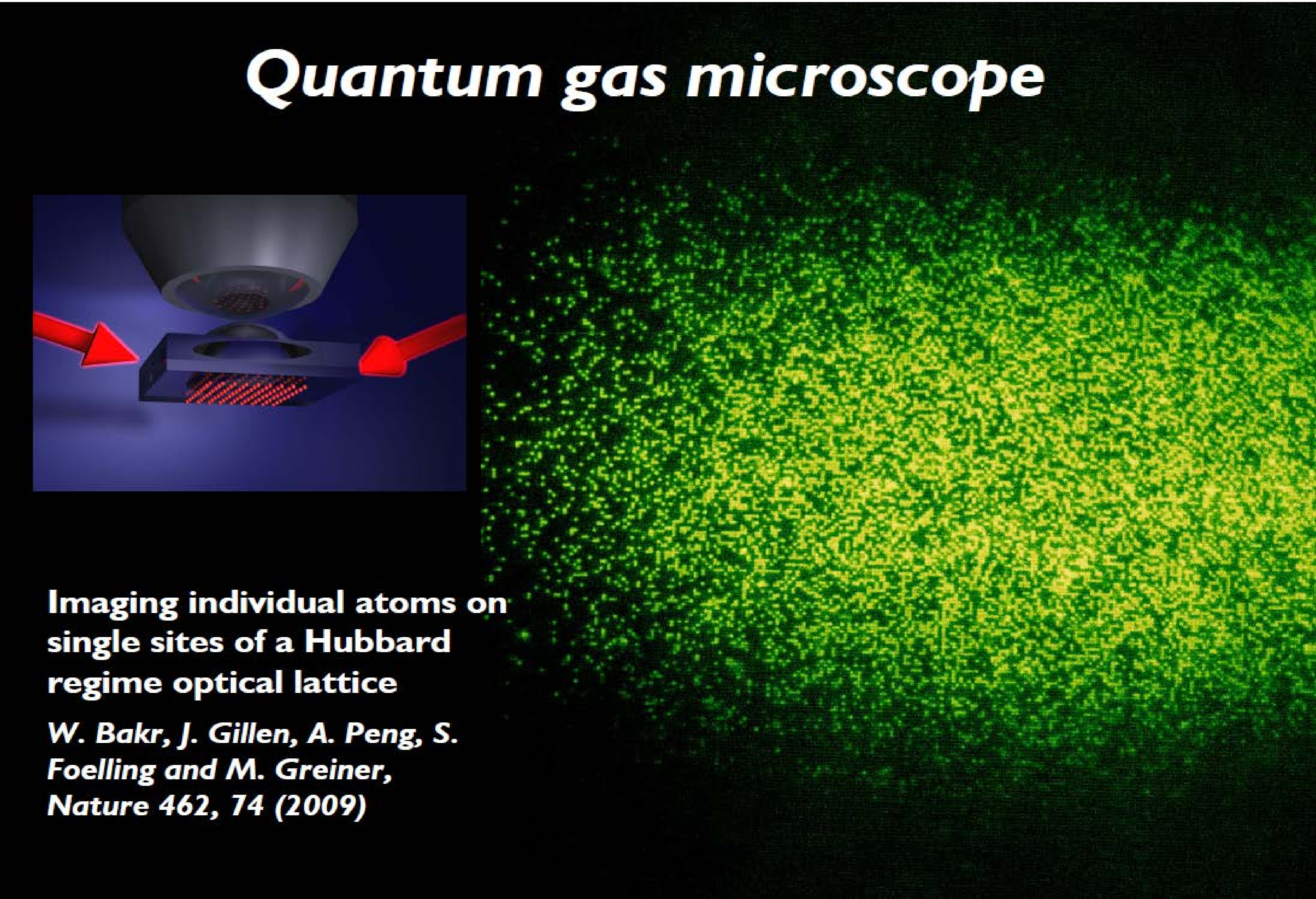
Whether or not the Hubbard model exhibits a similar phase diagram is an open question.

Accomplishments

- Bose Hubbard studied: Mott insulator transition studied and matched to theory
- 1D Fermi lattice studied / crossover to 3D
- New ways to cool/remove entropy to reach AFM state in *3D* lattice with harmonic confinement



Direct Imaging



Quantum gas microscope

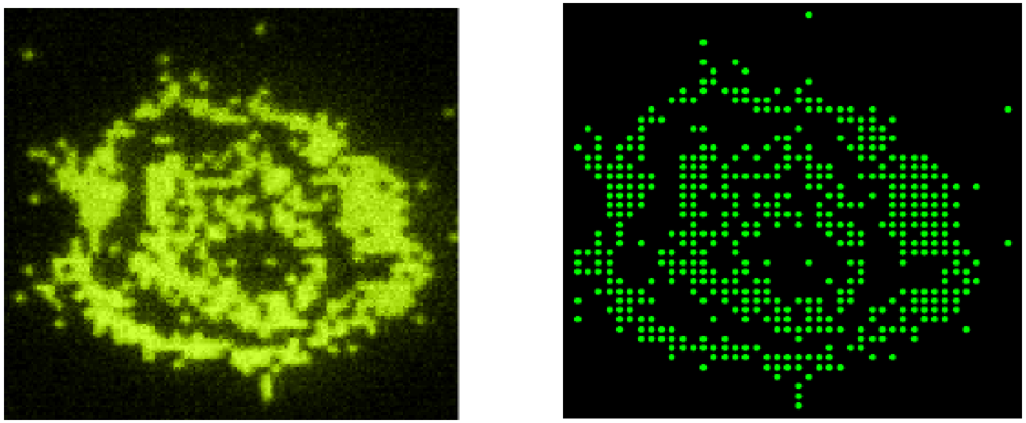
Imaging individual atoms on single sites of a Hubbard regime optical lattice

W. Bakr, J. Gillen, A. Peng, S. Foelling and M. Greiner, Nature 462, 74 (2009)

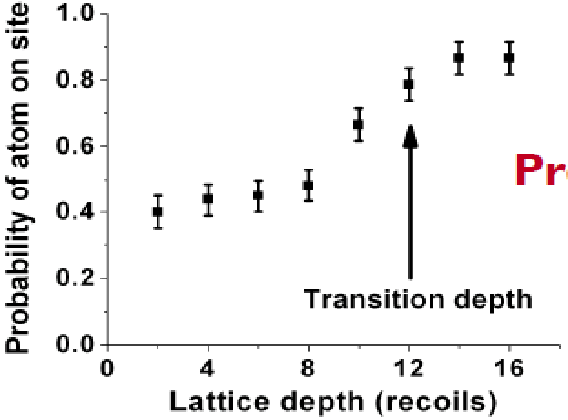
Direct Detection of Mott Insulating Phase

Harvard, Greiner

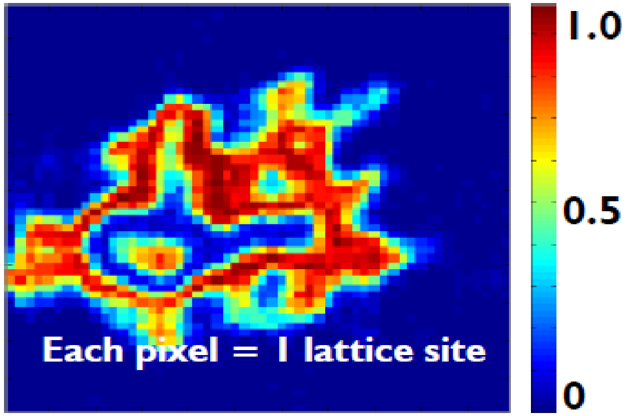
- Directly detect Mott insulator phases with 1, 2, 3, 4 atoms per lattice site
- High fidelity imaging with defect densities as low as 5%



4 shells: Mott insulator with 4 – 3 – 2 – 1 atoms/site



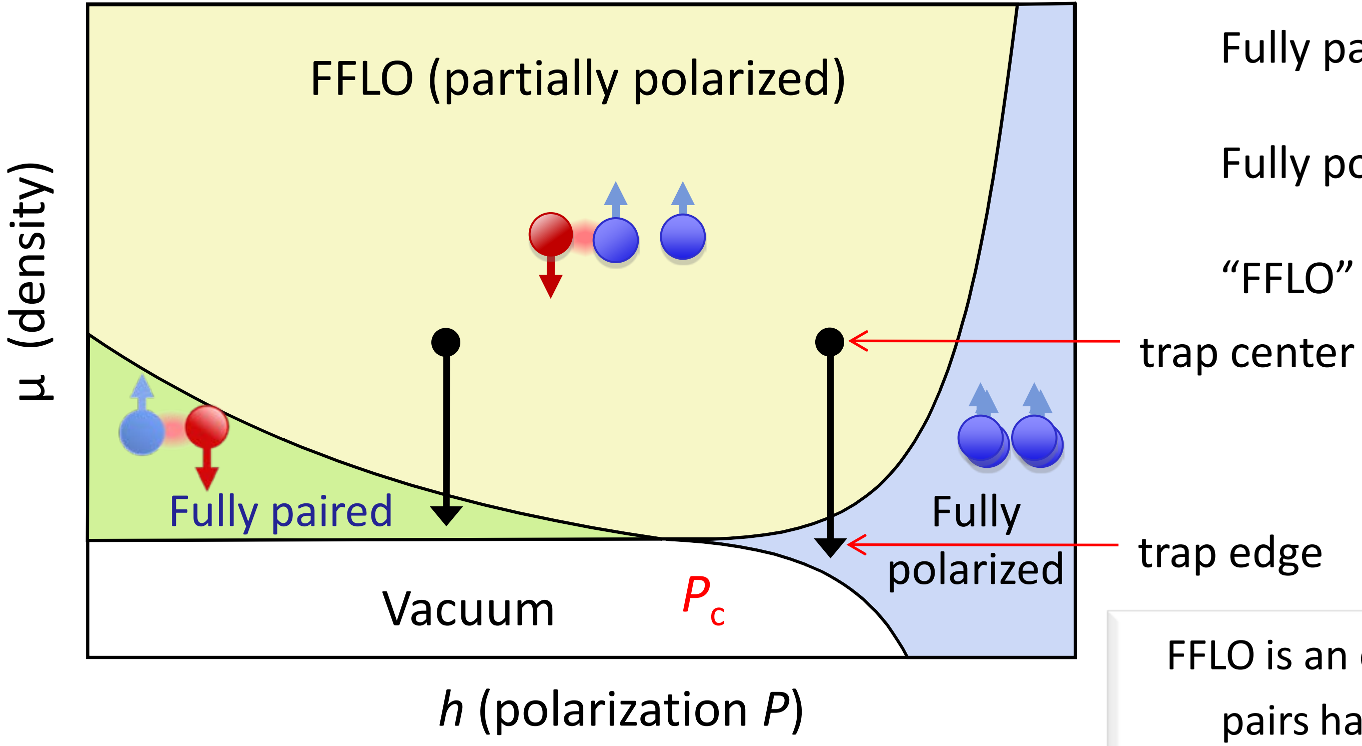
Preliminary



Single atoms on sites fitted, then averaged over 100 runs

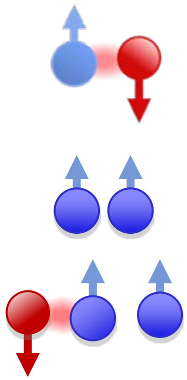
Spin Imbalanced 1D Fermi Gas

Rice, Hulet



3 distinct phases:

- Fully paired
- Fully polarized
- "FFLO"



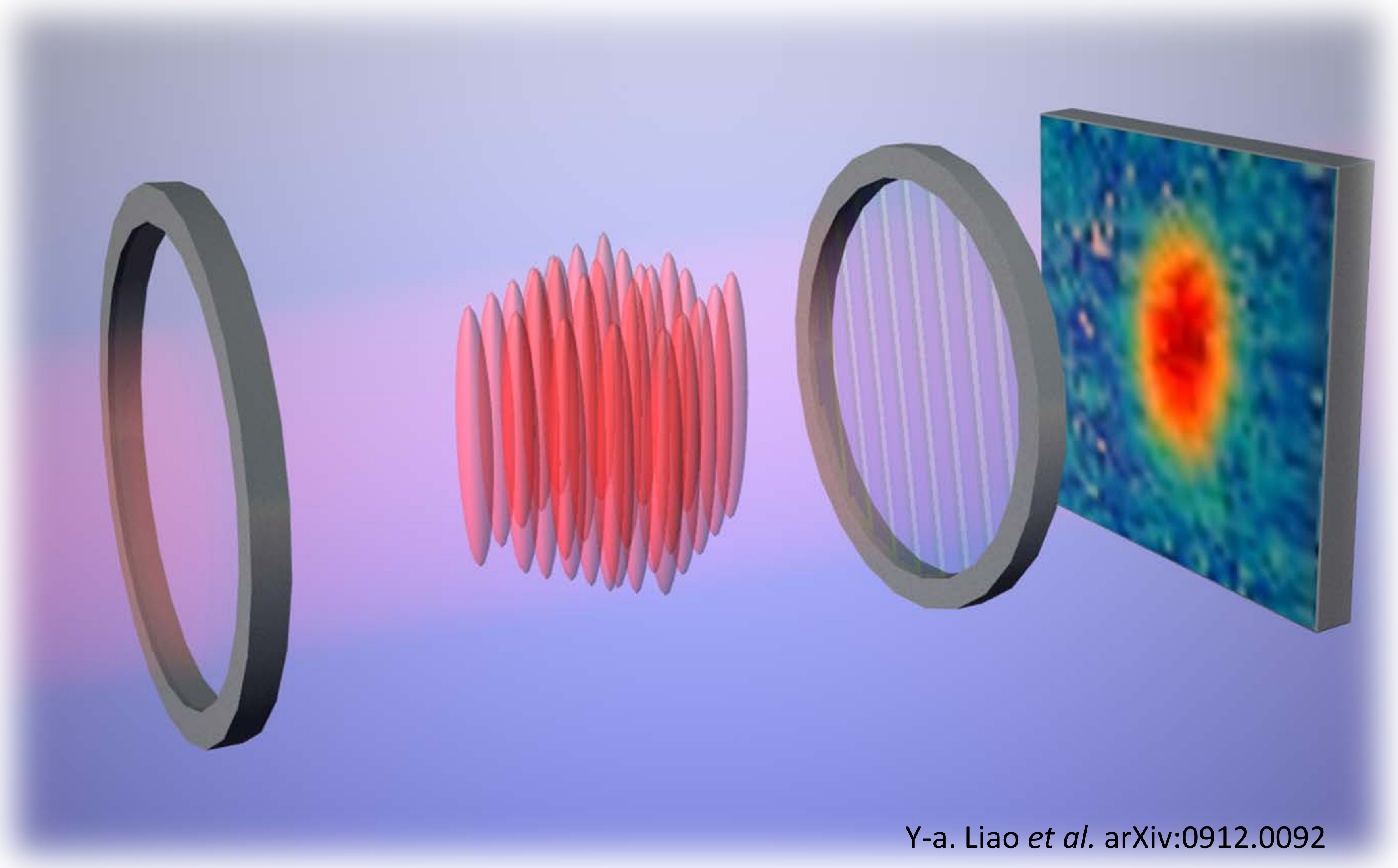
FFLO is an exotic superfluid whose pairs have finite momentum
→ Breaks translational symmetry

Coexisting magnetic and superconducting order found in heavy Fermion compounds — but smoking gun for FFLO not previously observed

Orso, PRL (2007); Hu *et al.*, PRL (2007)

1D-3D crossover

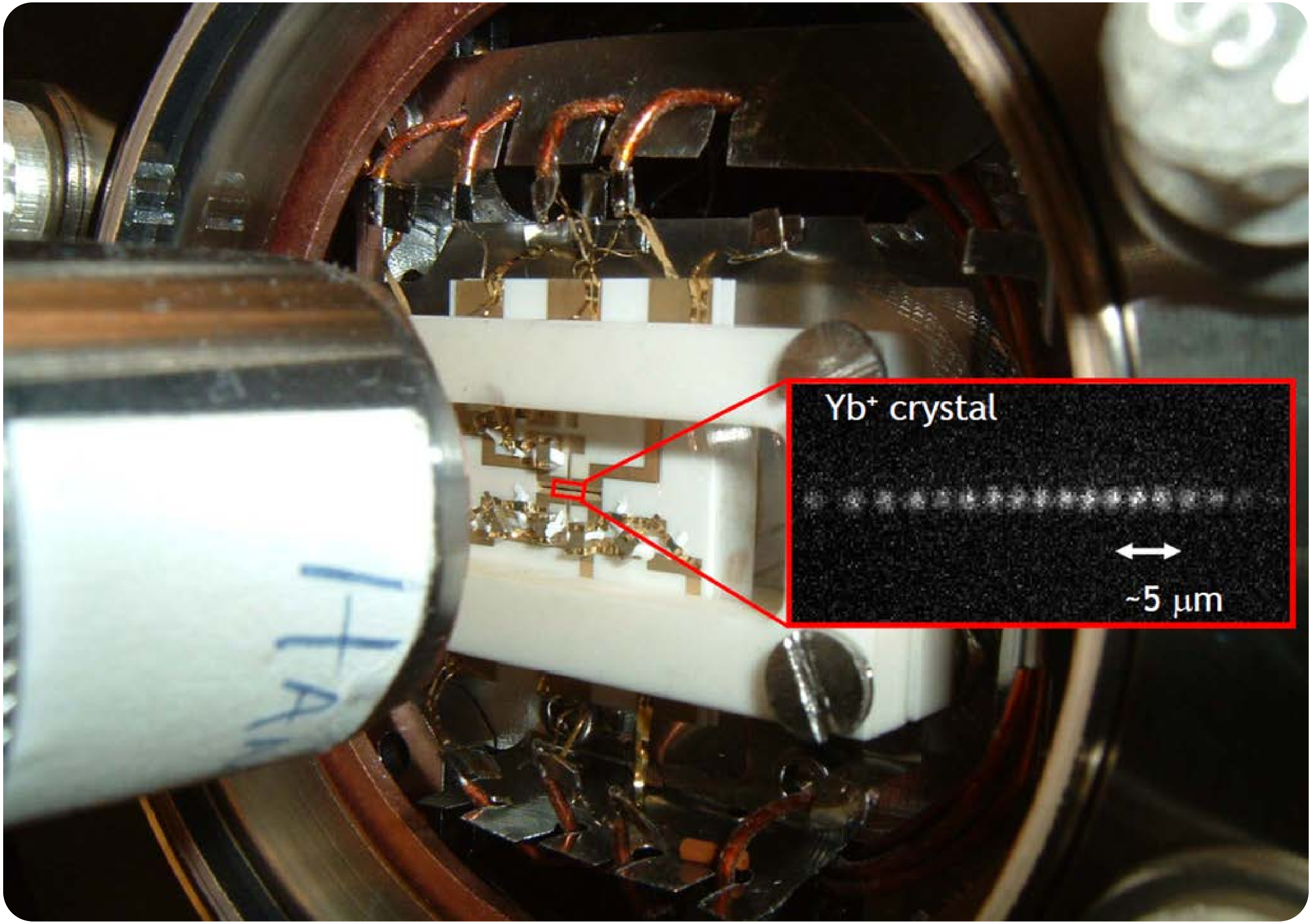
Rice, Hulet



Y-a. Liao *et al.* arXiv:0912.0092

Simulation of 1D Quantum Magnetism with Trapped Ions

Maryland, Monroe

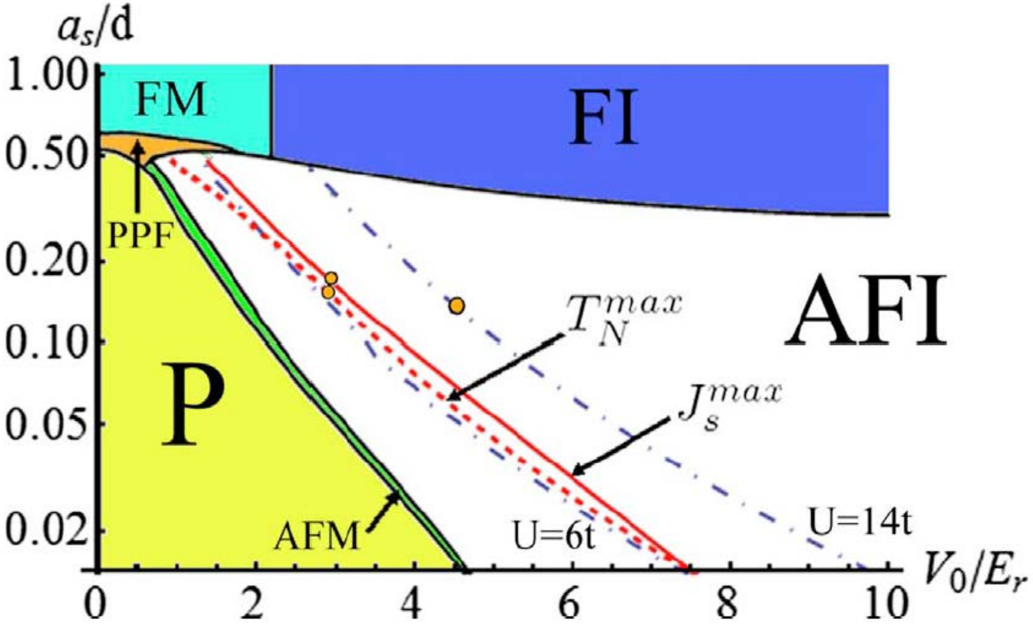


Magnetic ordering of atoms in optical lattices

Multi-species lattices lead to complex ordering/phase diagrams

Groups and platforms:

- *JQI/NIST/UMD (Porto) Yb-Rb mixture*
- *UC Berkeley (Stamper-Kurn) Li-Rb mixture*
- *Univ. of Chicago (Chin) 2-comp. Cs and 2-comp. Li*



Atomtronics MURI

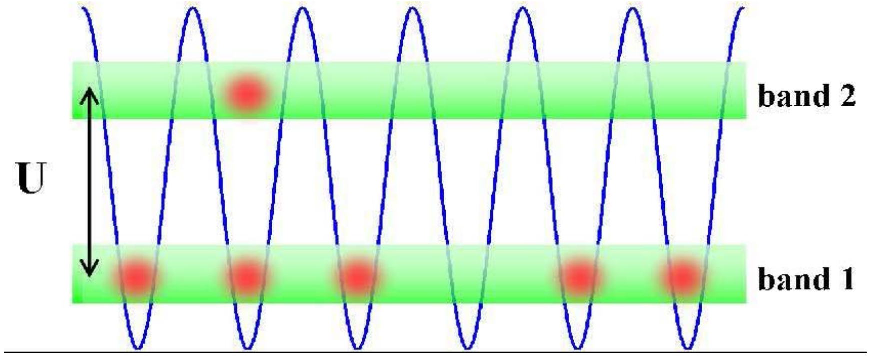
Devices & circuits *based on ultracold atoms* instead of electrons

Novelty: considerably more degrees of freedom to exploit

- What do all the additional degrees of freedom enable?
  - ❖ Internal state structure
  - ❖ Spin symmetry including mixtures
  - ❖ Variable mass, including mixtures
  - ❖ Variable charge, including mixtures
  - ❖ Spin (e.g. spintronics), including multiple spin states

- Not just analogs of electronic devices but something possibly quite new!

Band structure: conductor



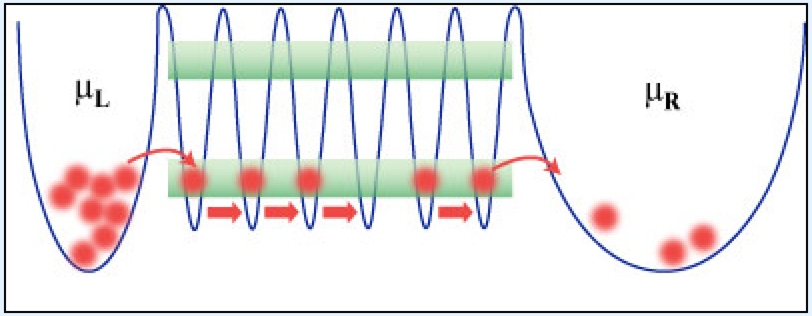
Band gap results from

- On-site interaction U (Bosons)
- Pauli principle (Fermions)

Strange new physics of wires:

1D allows controllable Fermionization of Bosons

Atomtronic battery



Atomtronics "Battery"

Credit: Brian Seaman

Reservoirs on left and right control chemical potentials

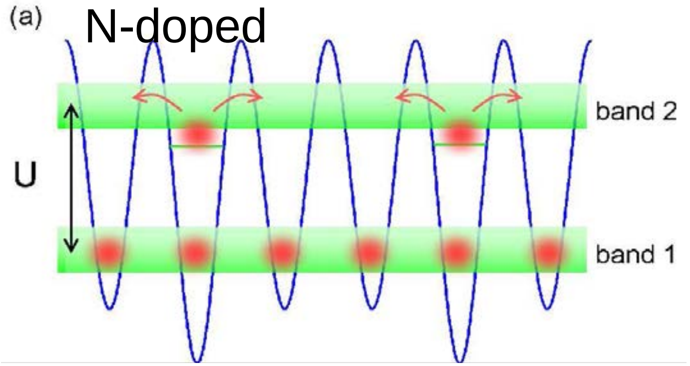
$V \equiv \mu_L - \mu_R$

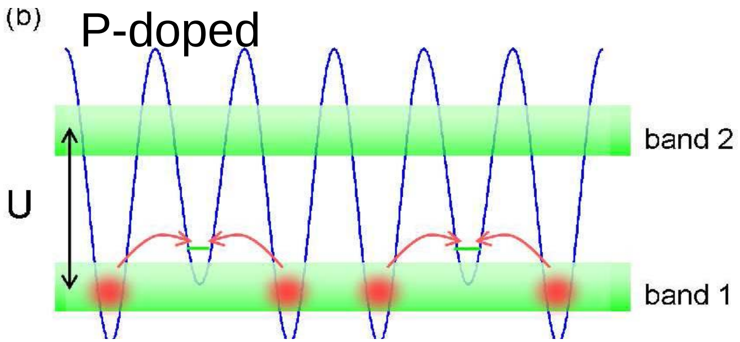
One clear impact of spin statistics:

- Supercurrents for Bosons—dissipationless “resistance” in I-V curve
- Metallic behavior for Fermions
- Further differences arise in both diodes and transistors

“Semiconductors”: doped lattices

- Replacing atoms in certain wells seems obvious… but
  - ❖ more difficult to load
  - ❖ not the true analog
- Locally modifying lattice potential is the analogy
- Defects are deeper or shallower levels; at low density act as acceptors or donors





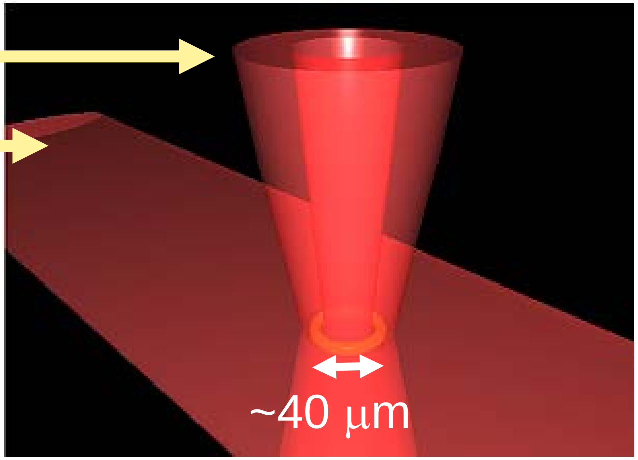
“SQUIDs”: BEC in optical toroidal trap

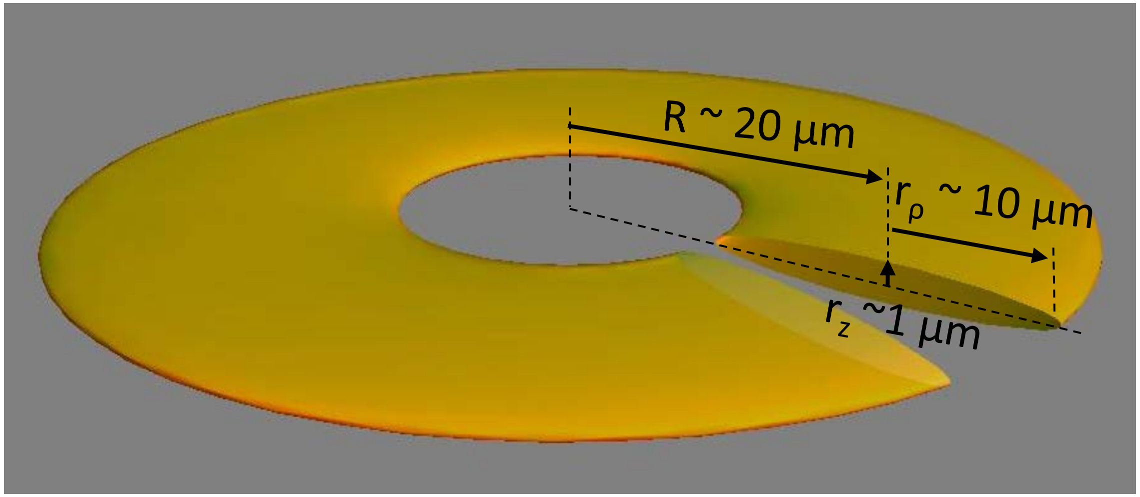
Inducing Circulation with OAM Beams

LG_{01} ‘Ring’ beam

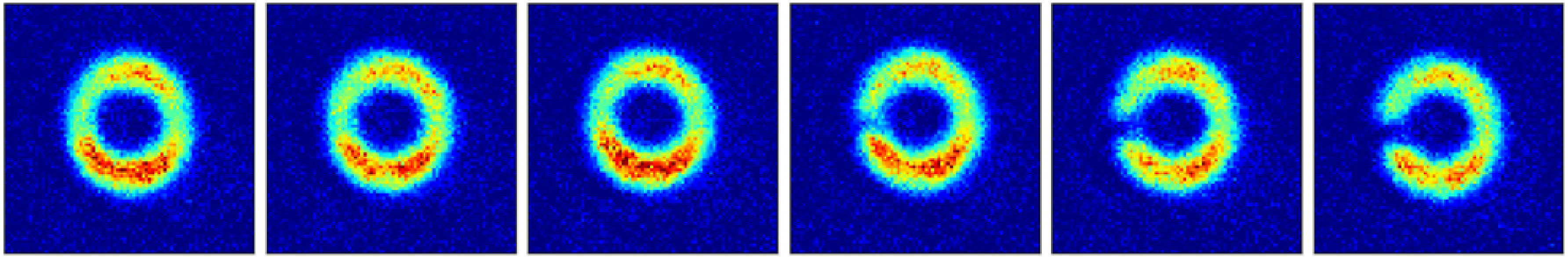
‘Sheet’ beam

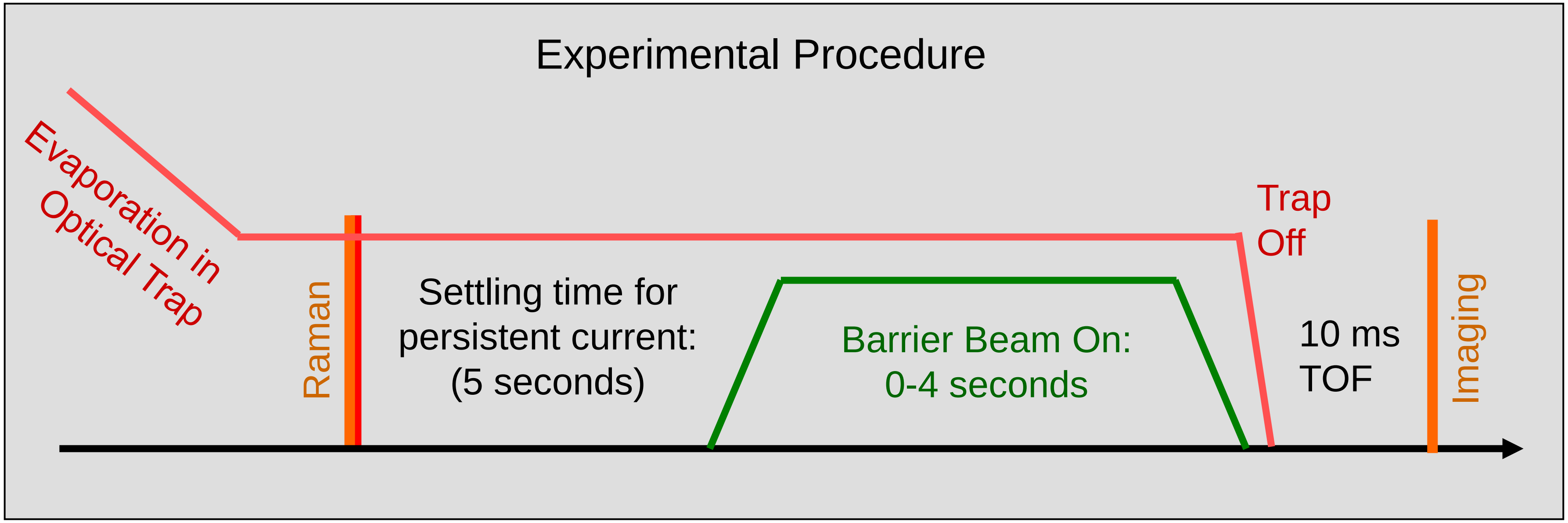
T < 40nK





Breaking the Flow With a Barrier





Experimental Procedure

Evaporation in Optical Trap

Raman

Settling time for
persistent current:
(5 seconds)

Barrier Beam On:
0-4 seconds

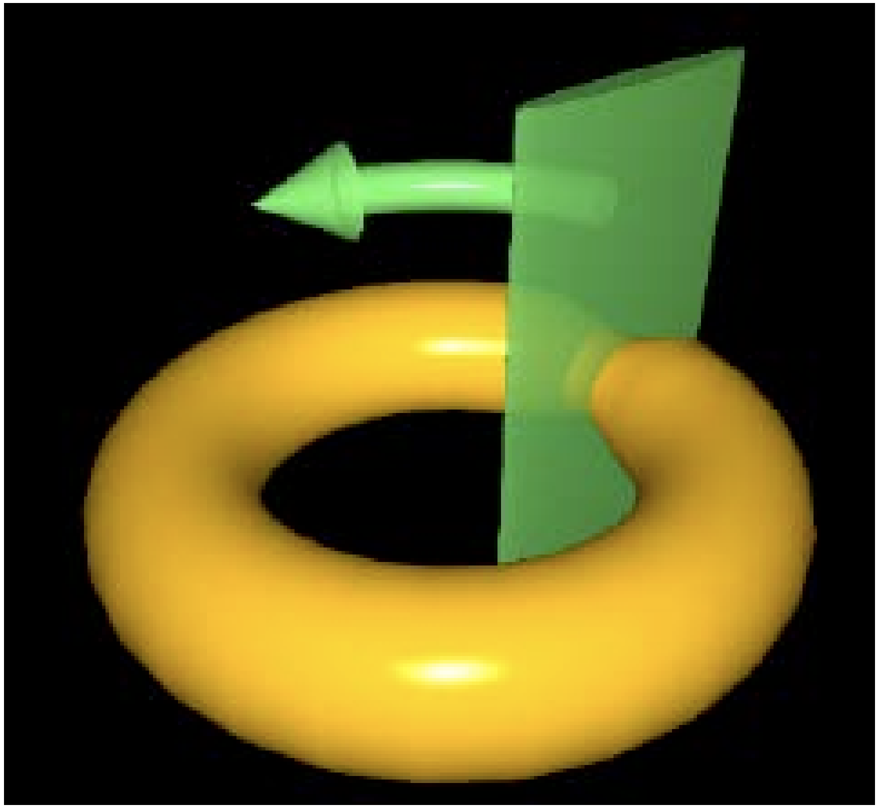
Trap
Off

10 ms
TOF

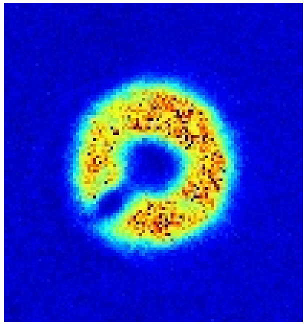
Imaging

Superfluid Atom Circuits

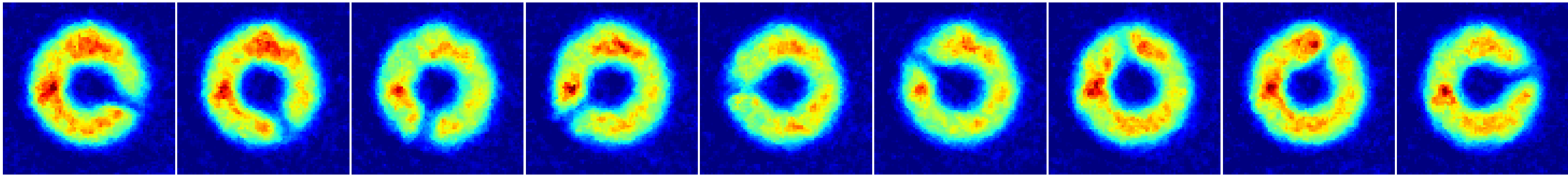
- Superconducting Josephson junction analog
- Changing the rotation velocity is like changing the applied field to a SQUID.
- What happens if you stir slower than one quantum?
- How fast can you stir?



Rotating the Barrier



Barrier can be controlled dynamically using a 2-axis AOD deflector



Rotational Quanta:

$v_0 = 0.13$ mm/s

$\Omega_0 = 0.9$ Hz

Sound Speed:

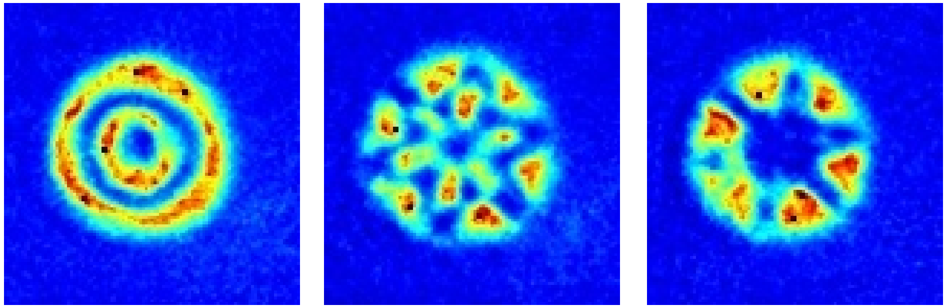
$c = 3\text{-}5$ mm/s

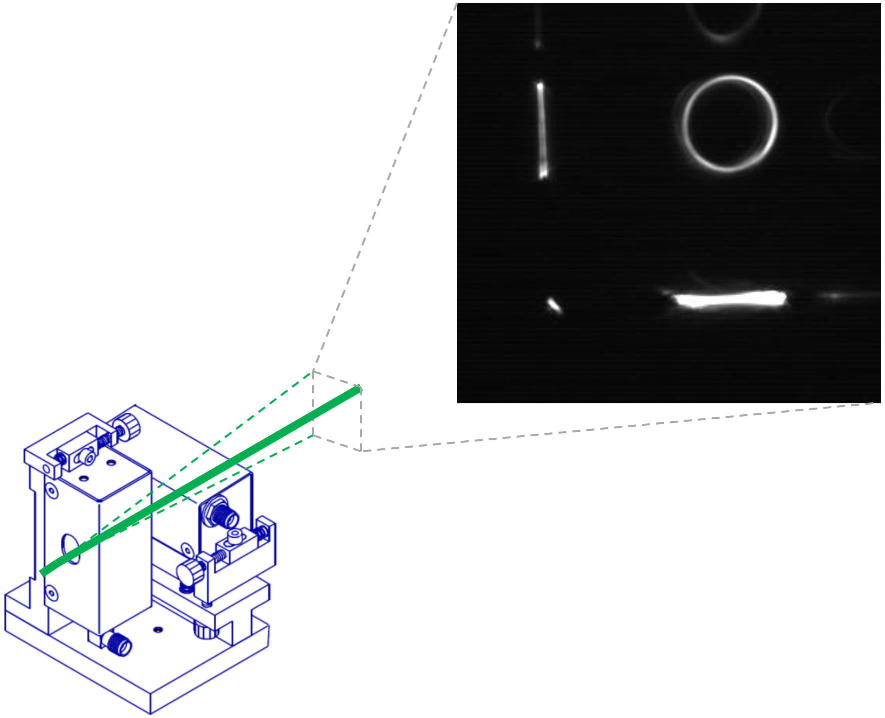
$\Omega_s = 20\text{-}35$ Hz

$\tau_s = 50$ ms

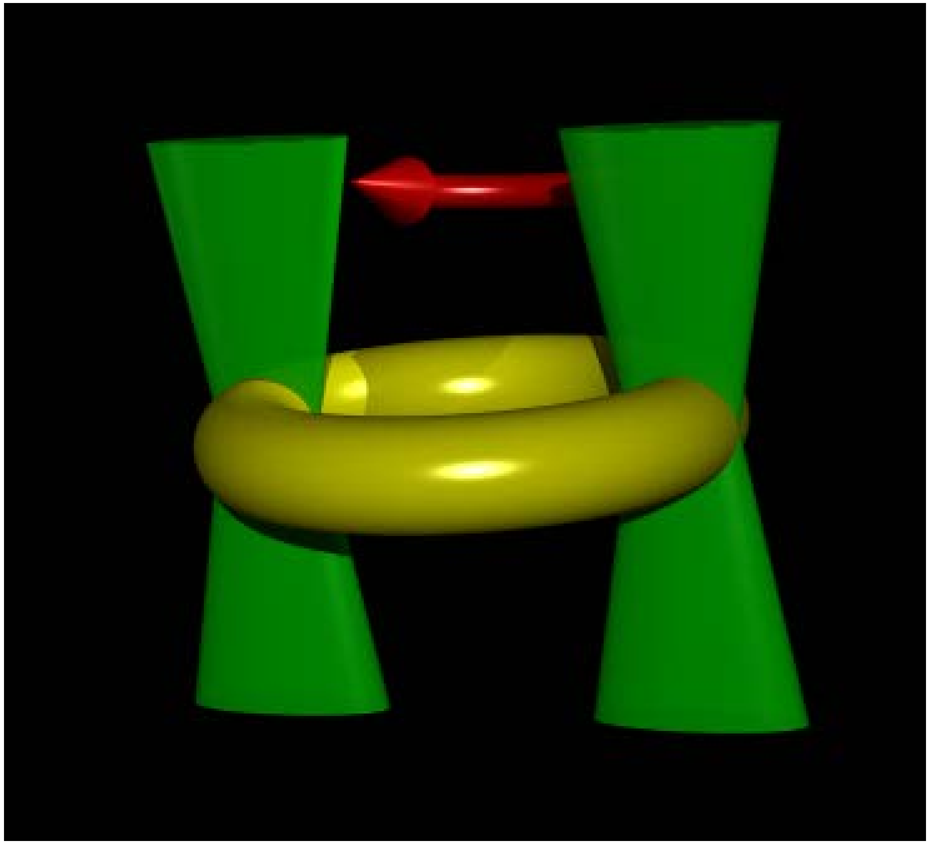
Dynamically vary trap geometry-

`Etched' potentials:

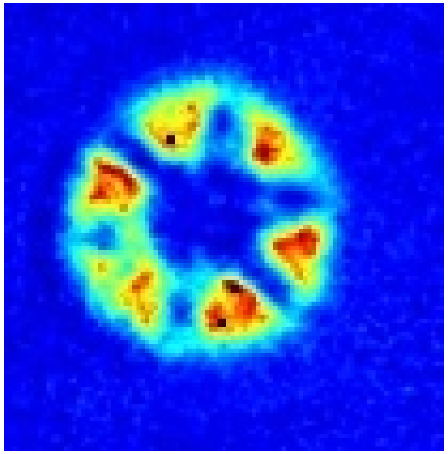




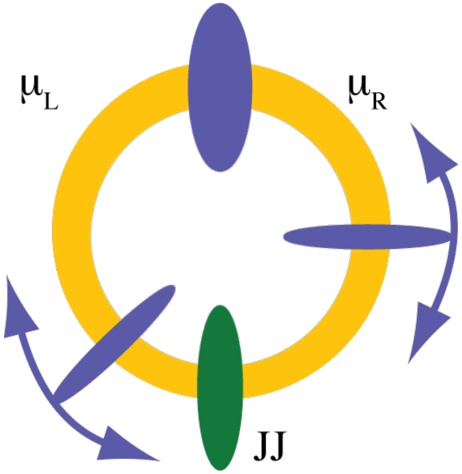
Double Barrier



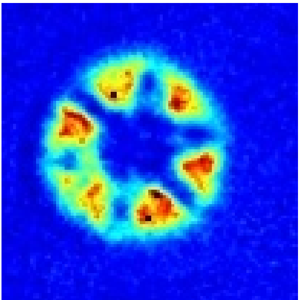
- Movable double-barrier: analogous to biased DC SQUID
- Could it also be used to detect changes in acceleration across the ring, i.e as a Gradiometer
- What about a ring lattice i.e a Josephson Junction Array?

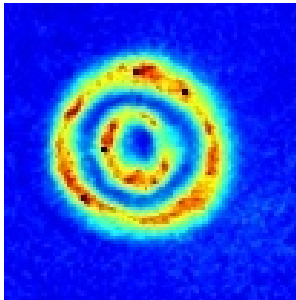


Circuit elements



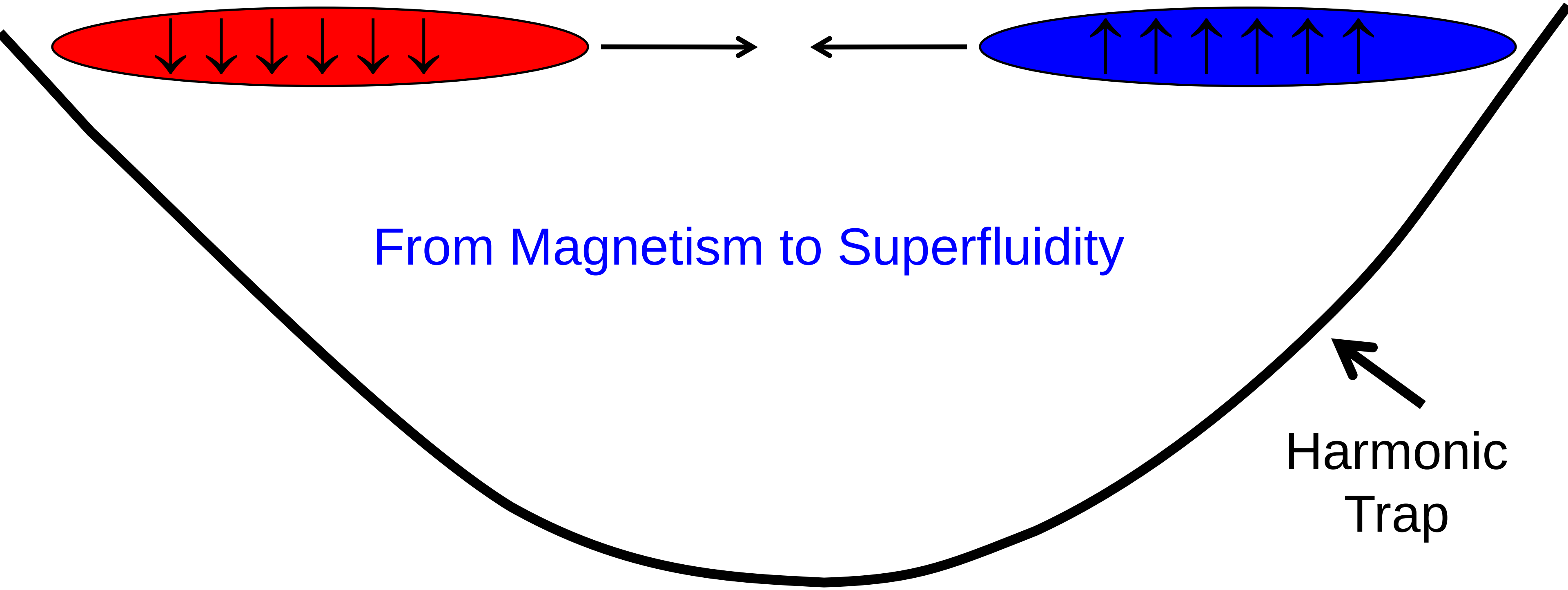
- 3-terminal functionality?
- Batteries-Ability to create "reservoir" of chemical potential
    - Study the effects of static and dynamic periodic potentials applied to the ring
- How could other elements be created: *i.e.*, capacitors, inductors, resistors
- Coupling rings together





Controlling Spin Dynamics

A ↓ Fermi gas collides with a ↑ cloud
with resonant interactions



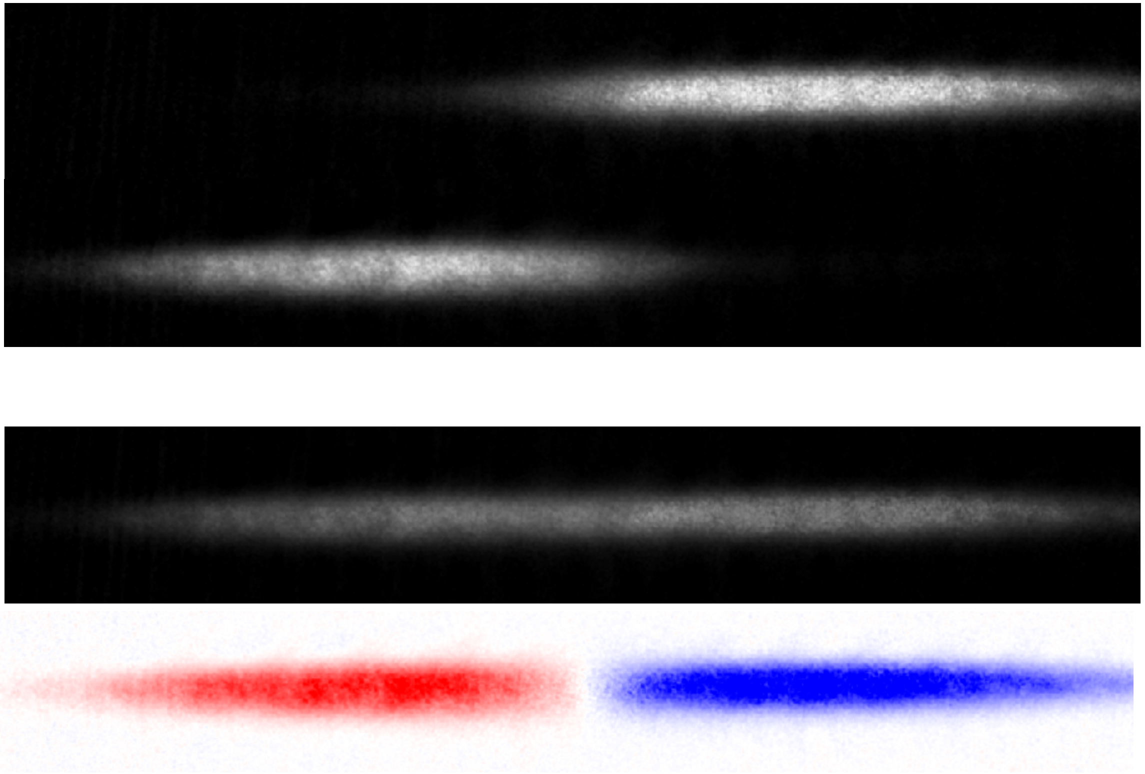
From Magnetism to Superfluidity

A. Sommer, M. Ku, G. Roati, MWZ, Nature **472**, 201 (2011)

Little Fermi Collider

Preparation: Mix, cool, kick, and rush to resonance

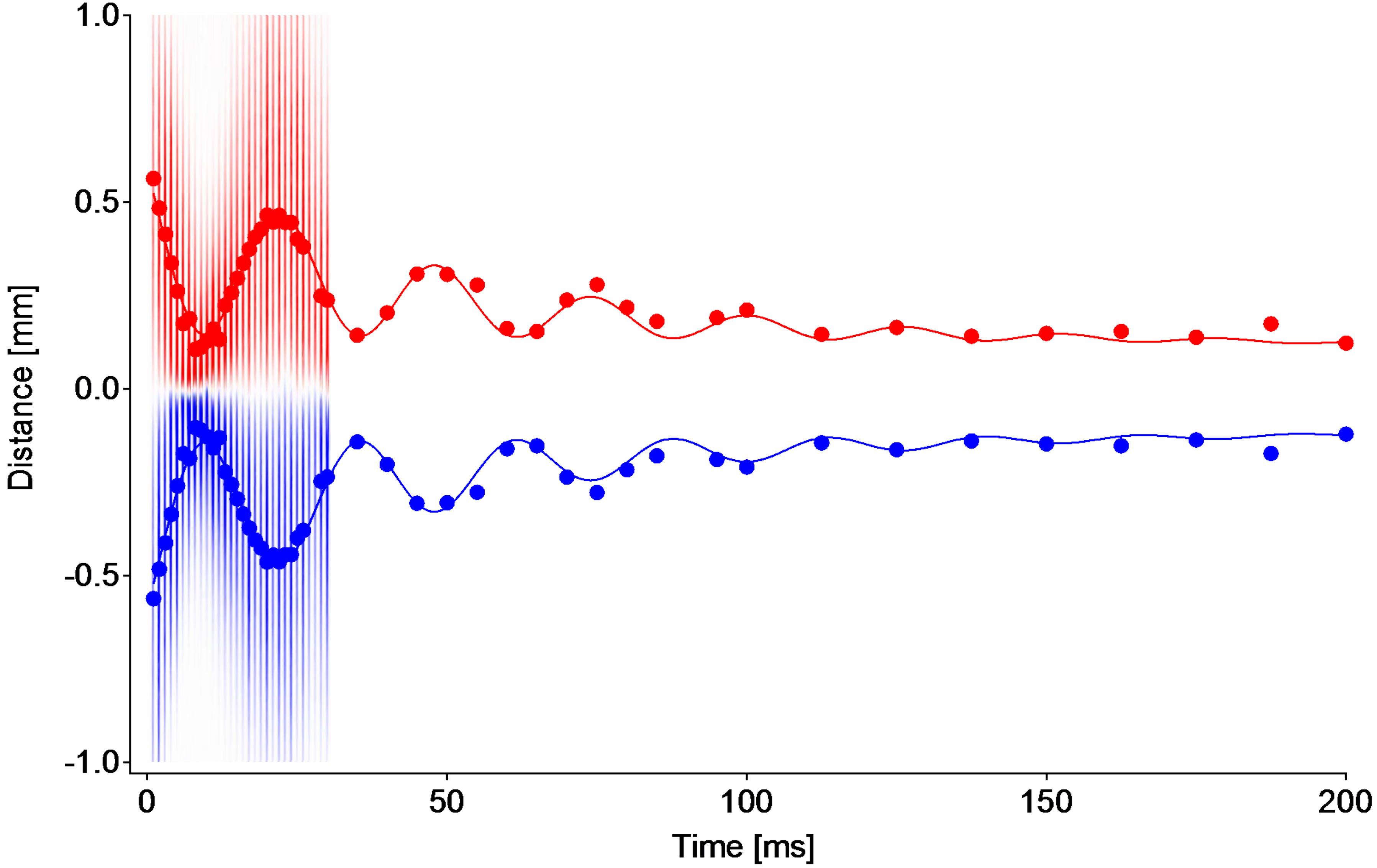
Rapid (10 μs) probing of spin up and down



Total OD

Difference

Completely Impenetrable at Resonance

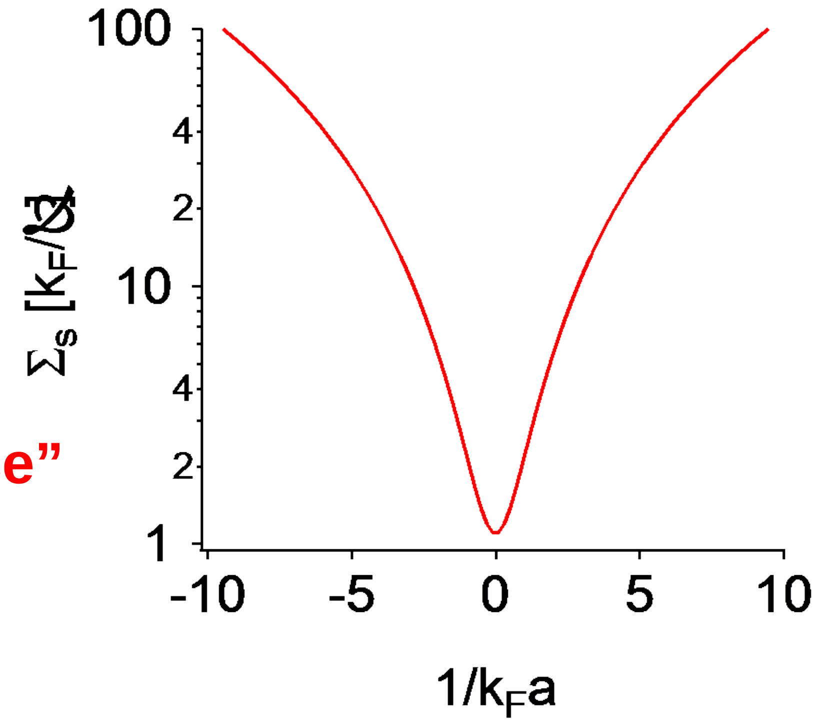


Tunable Spin Conductivity

- Spin conductivity in cold Fermi gases is tunable over a wide range

$$\Sigma_{spin} = \frac{n}{m}\frac{1}{\Gamma_{SD}} = \frac{1}{m\sigma v}$$

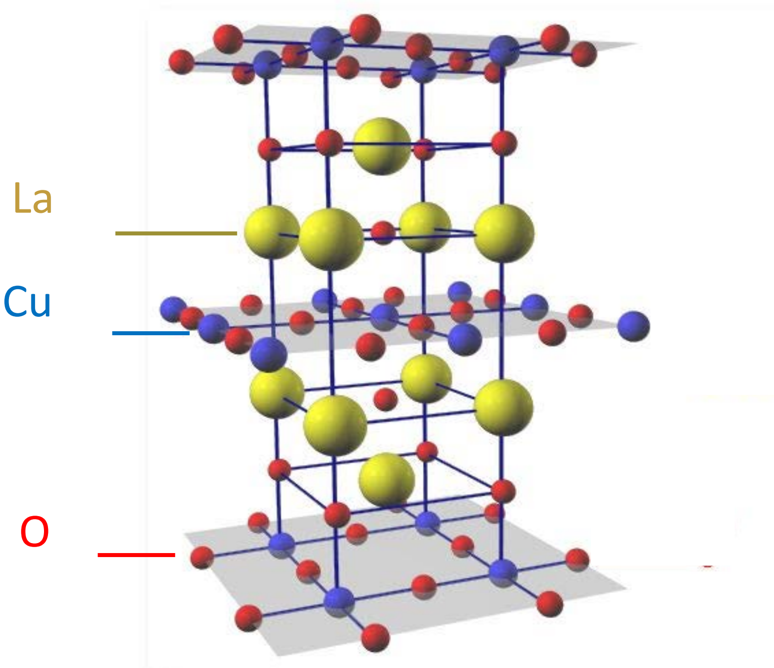
$$\Sigma_{spin} \underset{T\sim T_F}{\approx} \frac{k_F}{\hbar}\frac{1+ck_F^2a^2}{a^2}$$



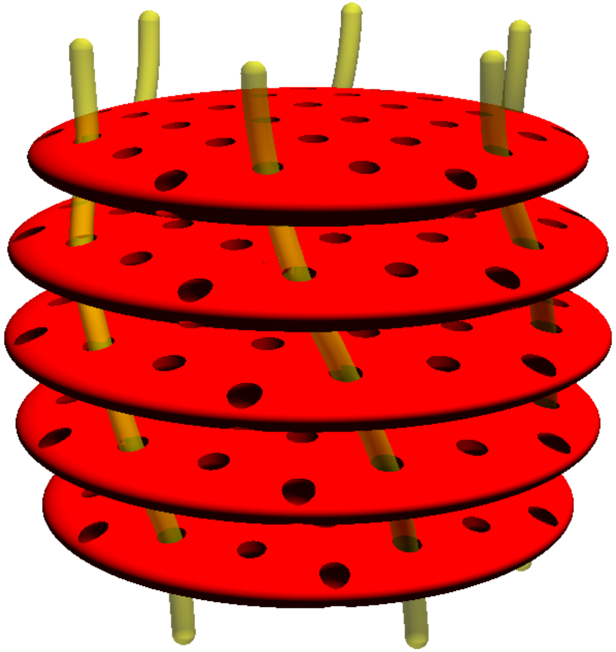
“Giant Magneto Spin Resistance”

Layered Superfluids for Atomtronic Devices

Inspiration: layered superconductors



High-T_c Superconductor with stacks of CuO planes



Stacks of 2D fermionic superfluids

Features of high T_c superconductors (e.g. cuprates, organics)

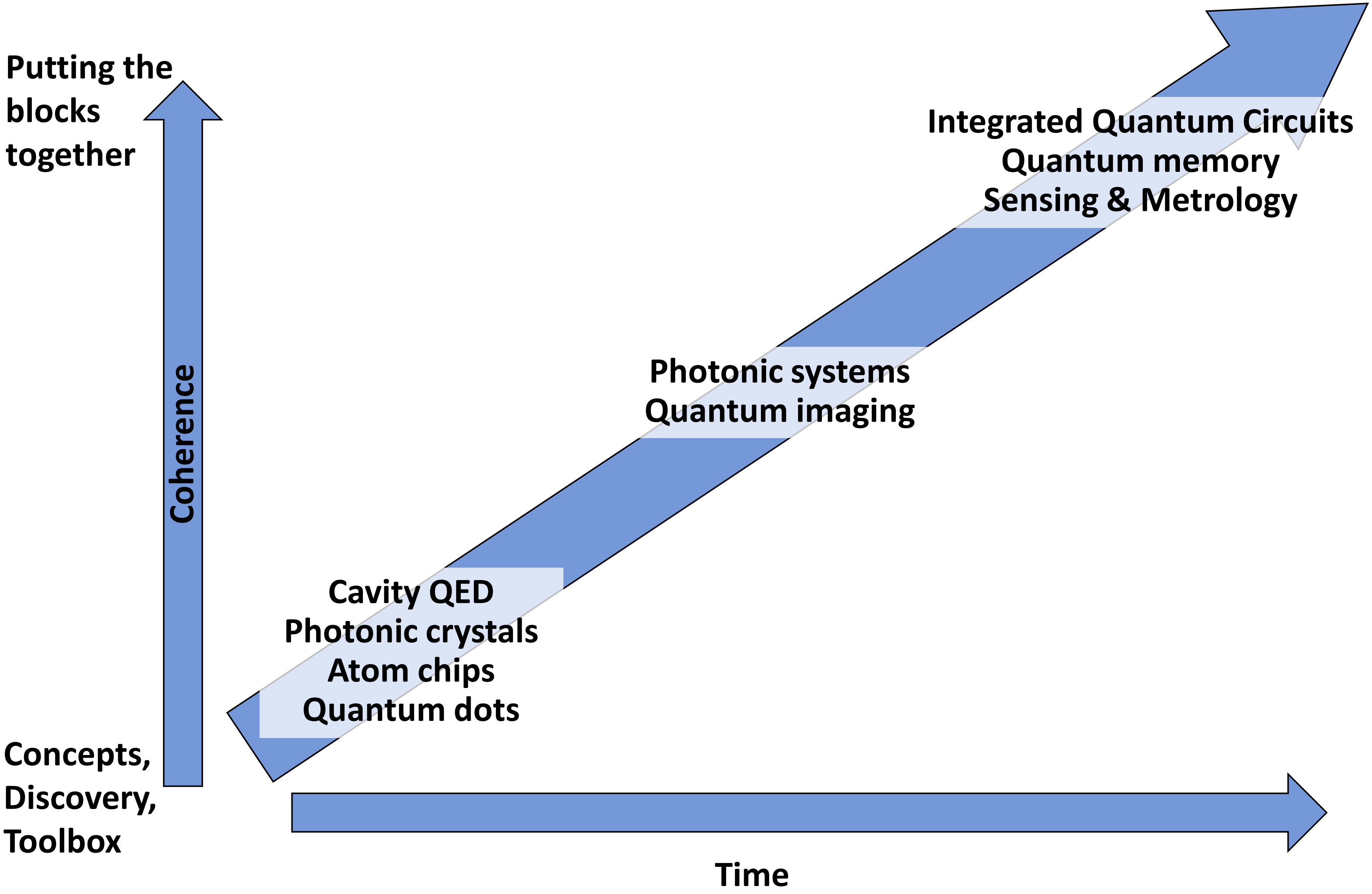
- 2D planes with strong correlations
- Interlayer coupling plays important role in enhancing T_c

Model: Anderson’s interlayer pair tunneling model (1992)

Quantum Information MURIs

- Exploiting quantum mechanics for useful functionality
- Better than classical capabilities
  - Quantum Computing
    - Quantum systems for qubits
    - Quantum algorithms
    - Quantum memories
    - Quantum repeaters
    - Quantum teleportation
    - Interchange of quantum information
  - Quantum Metrology
  - Quantum Sensing
  - Quantum Communication/Quantum Encryption
  - Quantum Imaging

Quantum Information Science
A Decade of QIS MURIs



Putting the
blocks
together

Coherence

Concepts,
Discovery,
Toolbox

Cavity QED
Photonic crystals
Atom chips
Quantum dots

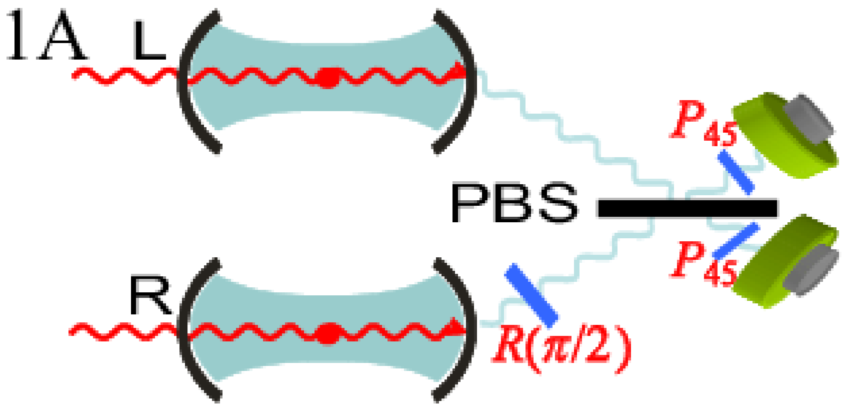
Photonic systems
Quantum imaging

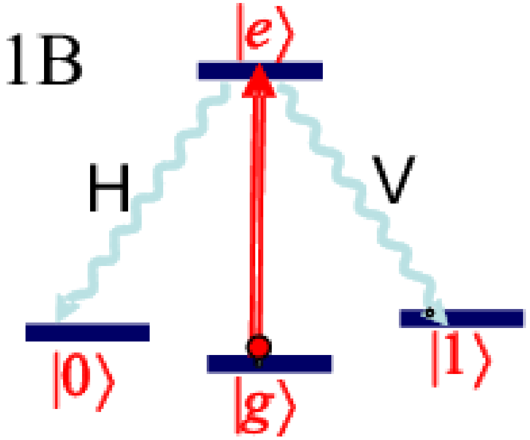
Integrated Quantum Circuits
Quantum memory
Sensing & Metrology

Time

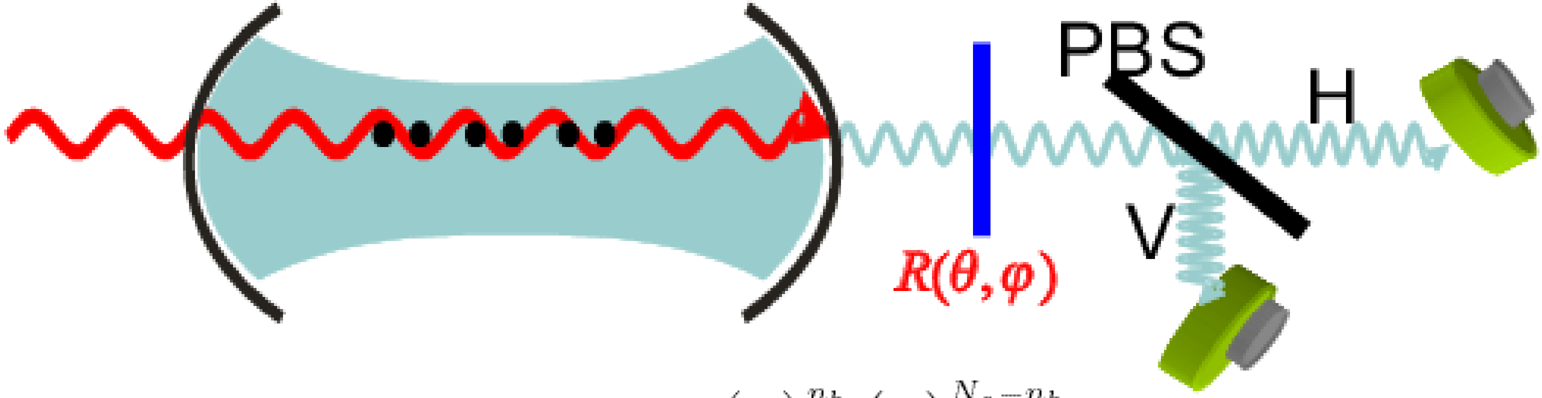
Efficient engineering of multi-atom entanglement

Entanglement generation between atoms in different cavities (L, R)



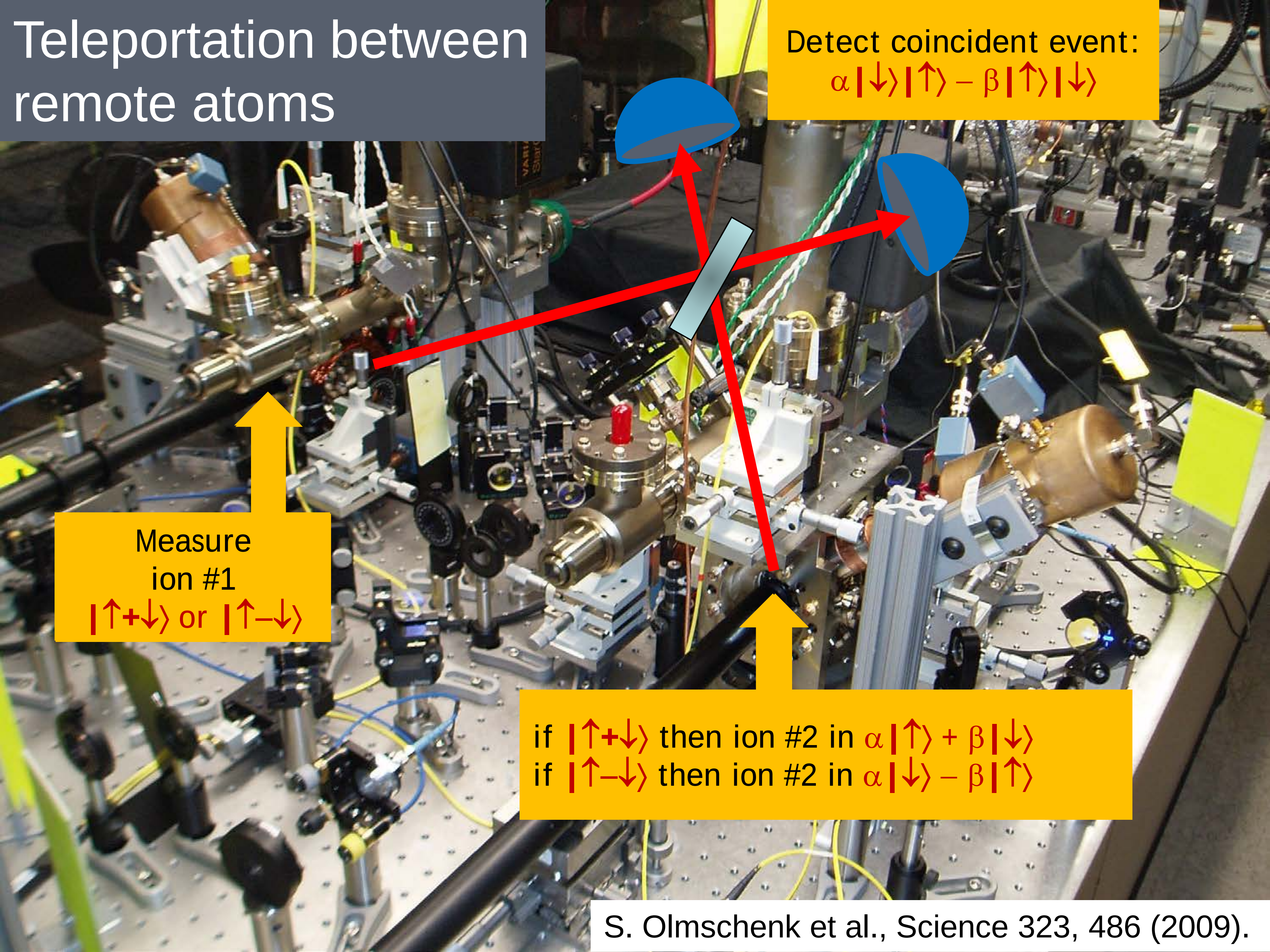


Entanglement generation between multiple atoms in the same cavity –
Arbitrary superpositions of symmetric Dicke states



$$|N_a, n_h\rangle = c\left(n_h\right)\left(s_0^\dagger\right)^{n_h}\left(s_1^\dagger\right)^{N_a-n_h}|G\rangle$$

Teleportation between remote atoms



Detect coincident event: $\alpha|\downarrow\rangle|\uparrow\rangle - \beta|\uparrow\rangle|\downarrow\rangle$

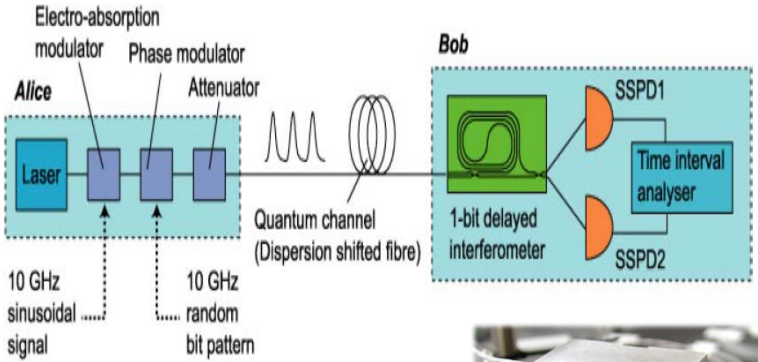
Measure ion #1
$|\uparrow+\downarrow\rangle$ or $|\uparrow-\downarrow\rangle$

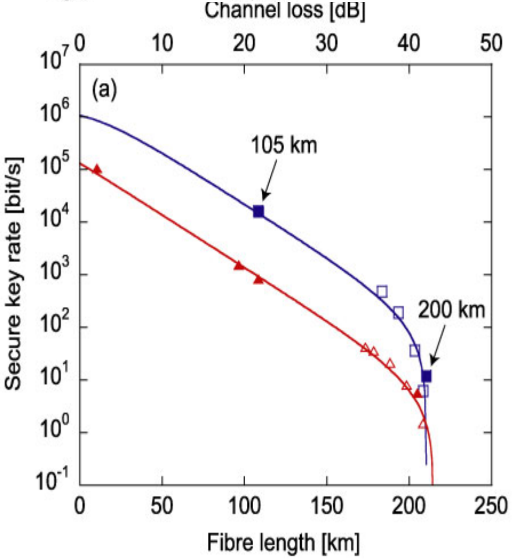
if $|\uparrow+\downarrow\rangle$ then ion #2 in $\alpha|\uparrow\rangle + \beta|\downarrow\rangle$
if $|\uparrow-\downarrow\rangle$ then ion #2 in $\alpha|\downarrow\rangle - \beta|\uparrow\rangle$

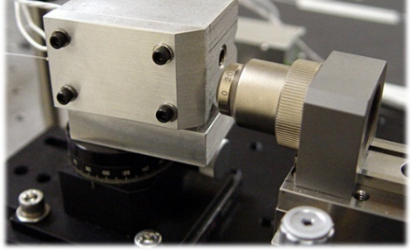
S. Olmschenk et al., Science 323, 486 (2009).

Photonic Quantum Information Processing

Yoshi Yamamoto, Marty Fejer (Stanford, Sae Woo Nam (NIST)

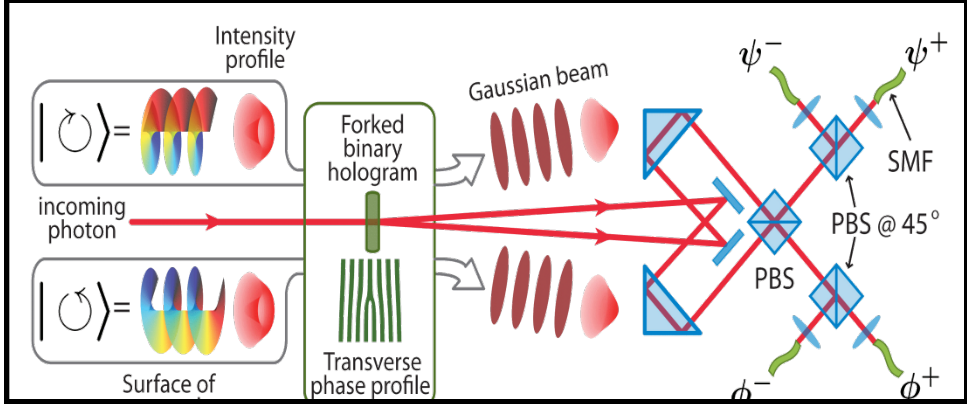


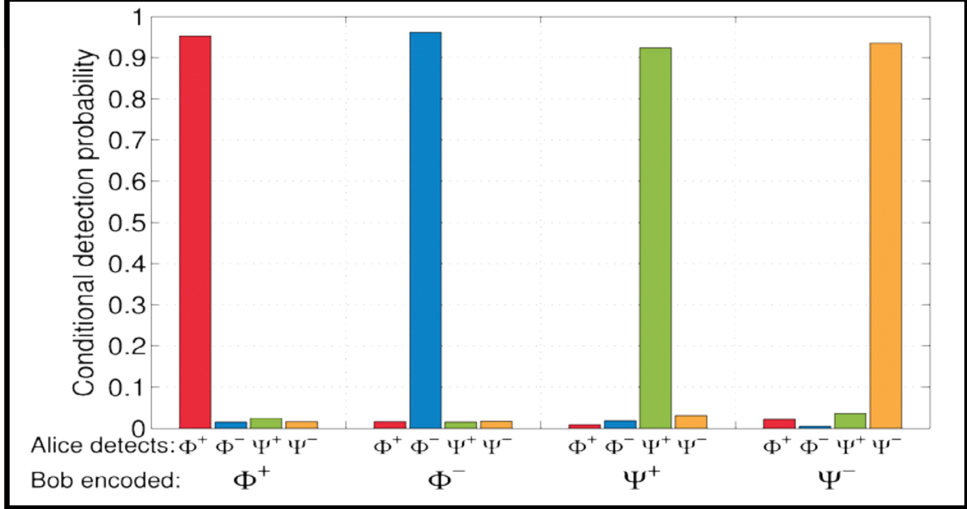




- QKD experiments in fiber
- Secure key rate ~17Kbit/s over 105Km, ~12bit/s over 200Km (error rate <4.1%)

Paul Kwiat (UIUC)

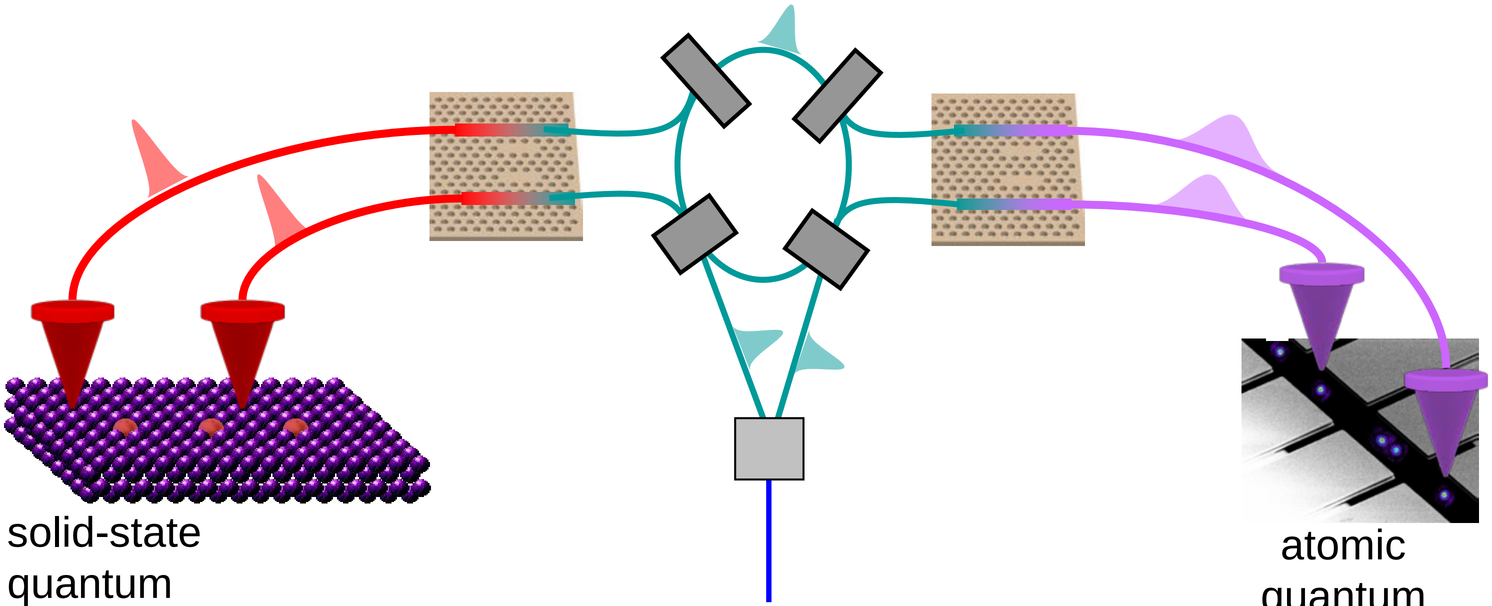




- Hyper-entanglement Enabled Full Bell-State Analysis

- Average success probability: 94%

Integrated Photonic Quantum Circuitry

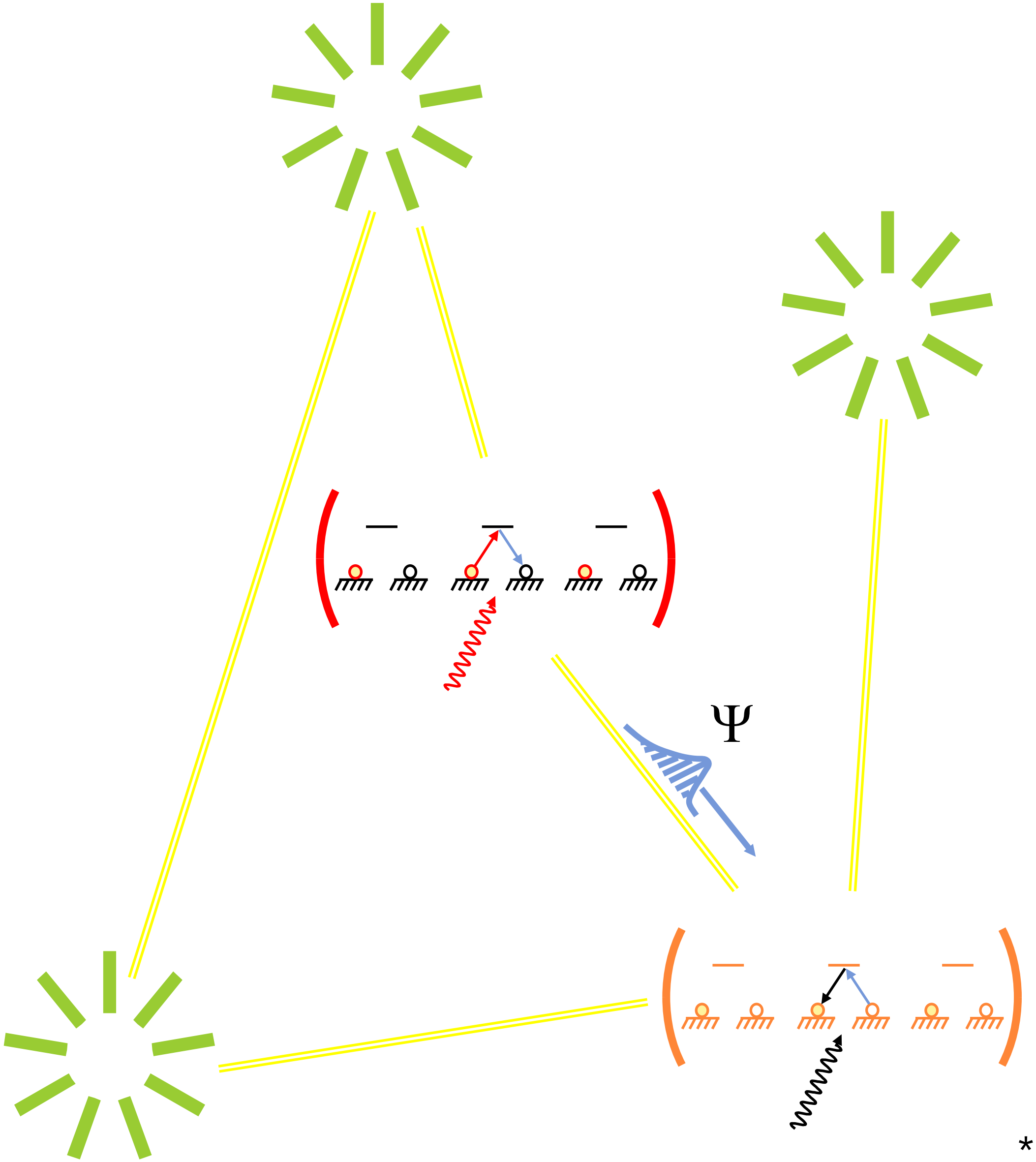


solid-state
quantum
processor

integrated optics:
- photonic bandgap materials
- fiber and MEMS switchyards
- downconverted entangled photons

atomic
quantum
memory

Tools for Quantum Networks



simple quantum state transfer can convert local entanglement* into distributed entanglement

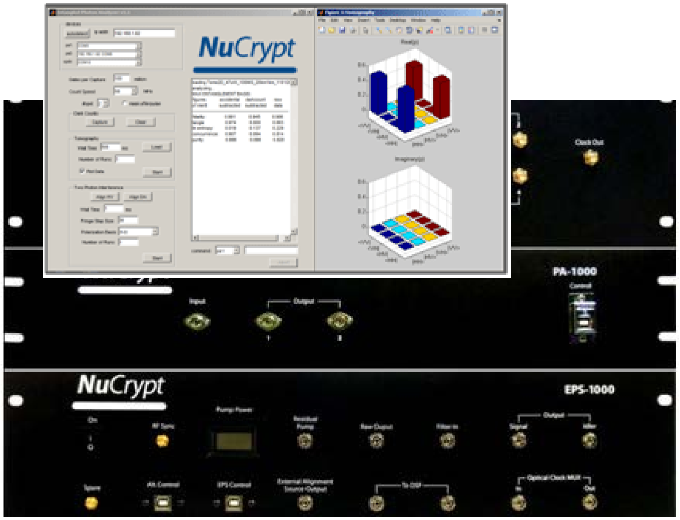
entanglement purification schemes have been invented that require limited local storage and processing

distributed entanglement* enables quantum repeater architectures based on state teleportation

quantum repeaters enable long-distance quantum networking; fault-tolerance analyses have been made

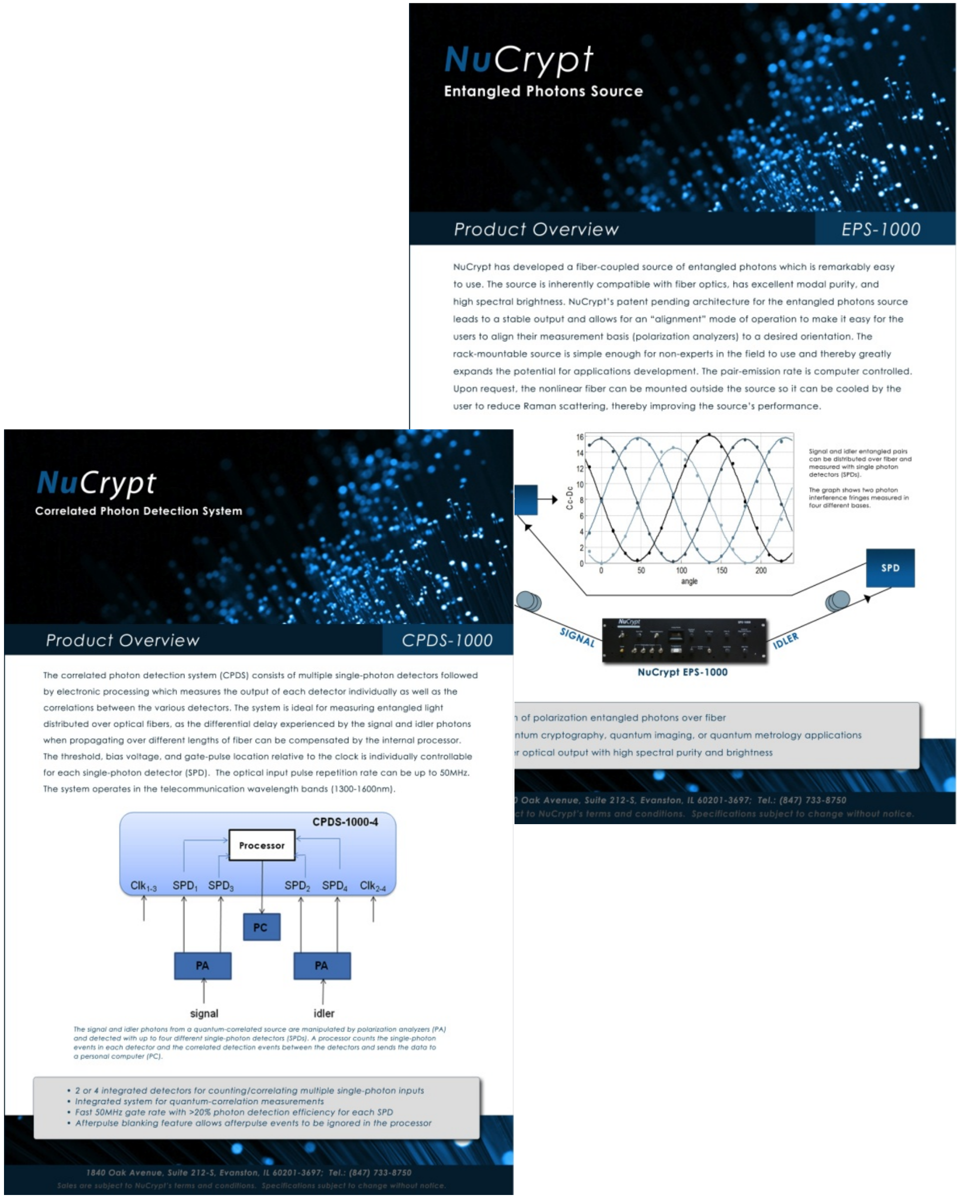
*produced by quantum logic or measurements

Commercialization



From MURIs to STTRs to commercial products for quantum communication in fiber

- Single photon sources
- Single photon detectors
- Tomography



NuCrypt
Entangled Photons Source

Product Overview EPS-1000

NuCrypt has developed a fiber-coupled source of entangled photons which is remarkably easy to use. The source is inherently compatible with fiber optics, has excellent modal purity, and high spectral brightness. NuCrypt's patent pending architecture for the entangled photons source leads to a stable output and allows for an “alignment” mode of operation to make it easy for the users to align their measurement basis (polarization analyzers) to a desired orientation. The rack-mountable source is simple enough for non-experts in the field to use and thereby greatly expands the potential for applications development. The pair-emission rate is computer controlled. Upon request, the nonlinear fiber can be mounted outside the source so it can be cooled by the user to reduce Raman scattering, thereby improving the source's performance.

Signal and idler entangled pairs can be distributed over fiber and measured with single photon detectors (SPDs).

The graph shows two photon interference fringes measured in four different bases.

NuCrypt EPS-1000

n of polarization entangled photons over fiber
ntum cryptography, quantum imaging, or quantum metrology applications
r optical output with high spectral purity and brightness

0 Oak Avenue, Suite 212-S, Evanston, IL 60201-3697; Tel.: (847) 733-8750
ct to NuCrypt's terms and conditions. Specifications subject to change without notice.

NuCrypt
Correlated Photon Detection System

Product Overview CPDS-1000

The correlated photon detection system (CPDS) consists of multiple single-photon detectors followed by electronic processing which measures the output of each detector individually as well as the correlations between the various detectors. The system is ideal for measuring entangled light distributed over optical fibers, as the differential delay experienced by the signal and idler photons when propagating over different lengths of fiber can be compensated by the internal processor. The threshold, bias voltage, and gate-pulse location relative to the clock is individually controllable for each single-photon detector (SPD). The optical input pulse repetition rate can be up to 50MHz. The system operates in the telecommunication wavelength bands (1300-1600nm).

The signal and idler photons from a quantum-correlated source are manipulated by polarization analyzers (PA) and detected with up to four different single-photon detectors (SPDs). A processor counts the single-photon events in each detector and the correlated detection events between the detectors and sends the data to a personal computer (PC).

- *2 or 4 integrated detectors for counting/correlating multiple single-photon inputs*
- *Integrated system for quantum-correlation measurements*
- *Fast 50MHz gate rate with >20% photon detection efficiency for each SPD*
- *Afterpulse blanking feature allows afterpulse events to be ignored in the processor*

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