OPTICAL
LATTICE EMULATOR

OLE

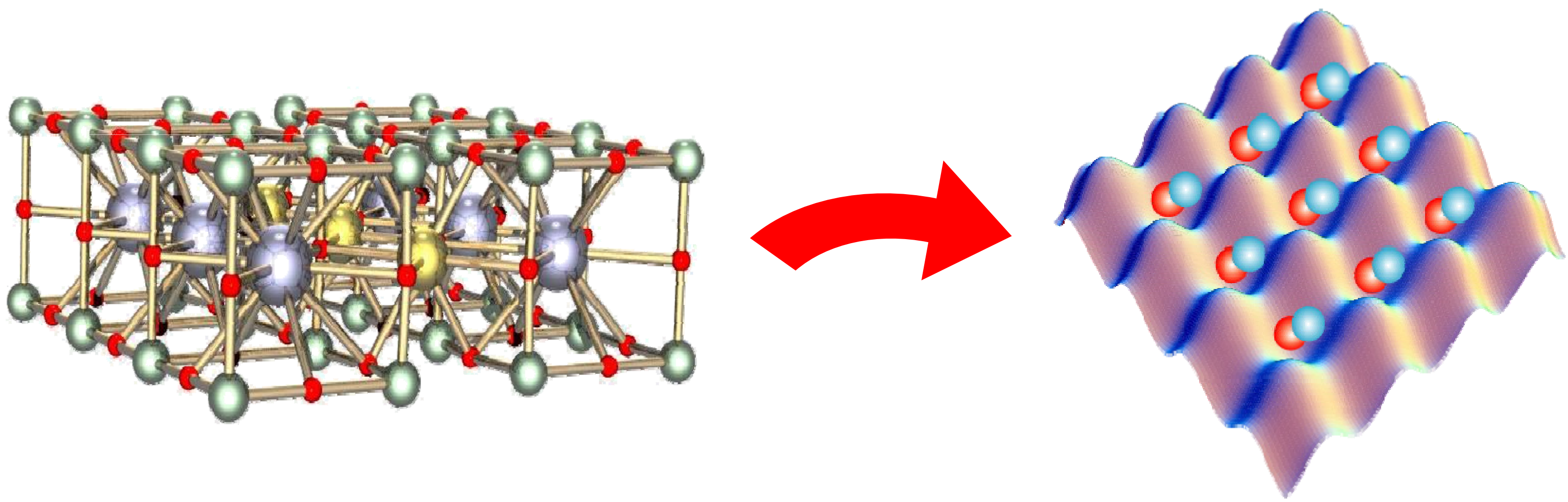
What is an Optical Lattice Emulator?
and
Why is it useful?

July 2008

Jay Lowell

How does the OLE Tool Work?

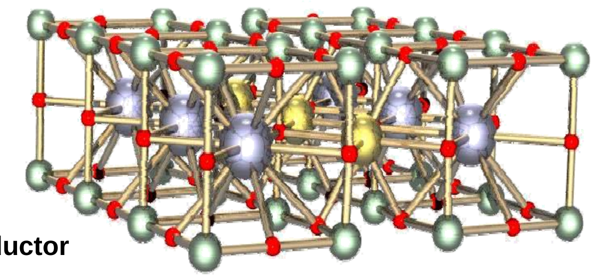
- OLE is an atom-based analog computer designed to emulate strongly-correlated condensed matter systems.



- Underlying principle: “Solve” an intractable physical system using a more flexible physical system governed by the same dynamics.

Why is this seemingly complicated approach needed?

- **Simulation of strongly correlated many-body systems of tremendous technical interest are computationally intractable.**

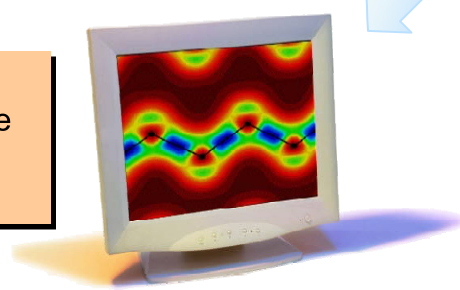


YBCO superconductor

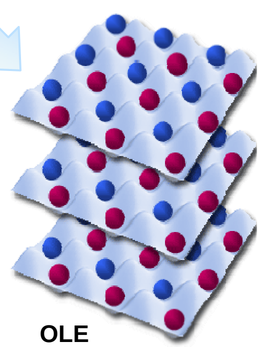
Intractable lattice-based many-body Hamiltonians

$$H = -t\sum_{\langle i,j\rangle}\left(a_i^{\dagger}a_j + a_j^{\dagger}a_i\right) - \mu\sum_i n_i + V\sum_{\langle i,j\rangle} n_i n_j + \frac{U}{2}\sum_i n_i\left(n_i - 1\right) + \cdots$$

- Computation time, t ~ c^N
- Scaling **dependent** on size
- System max size ~ **4 x 4** lattice sites



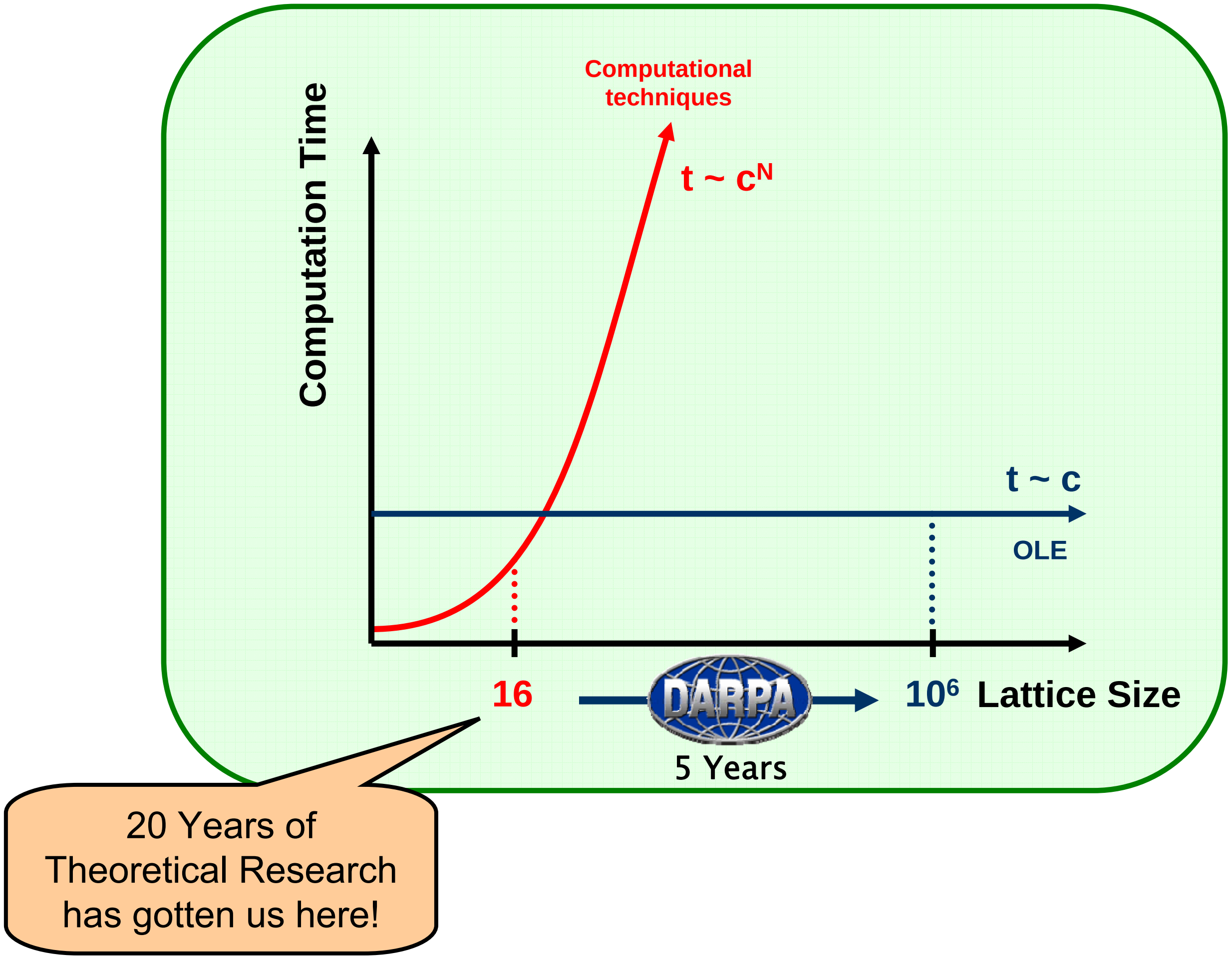
Traditional computational techniques



OLE

- Computation time, t ~ **const**
- Scaling **independent** of size
- System max size ~ **10^6** lattice sites

OLE vs. Computational Techniques

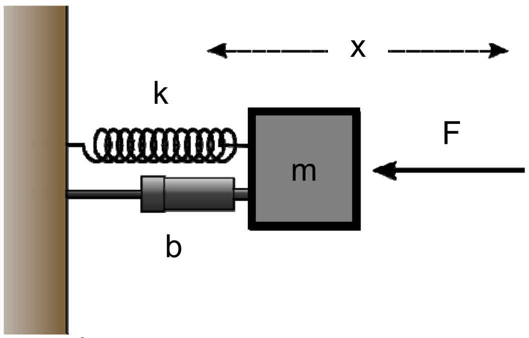


OLE will make strongly-correlated systems tractable.

Equivalence of Physical Systems

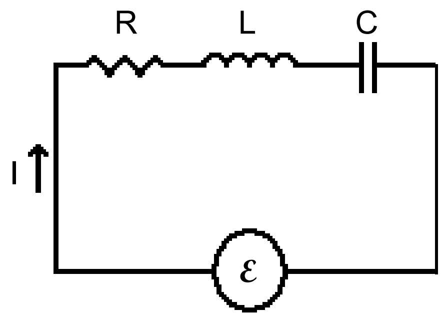
Distinct physical systems governed by the same equations behave identically.

Equivalence of physical systems
Example: Mechanical & Electrical Oscillators



$$m\frac{d^2x}{dt^2}+b\frac{dx}{dt}+kx=F\cos(\omega t)$$

Driven damped oscillator



$$L\frac{d^2q}{dt^2}+R\frac{dq}{dt}+\frac{1}{C}q=\mathcal{E}\cos(\omega t)$$

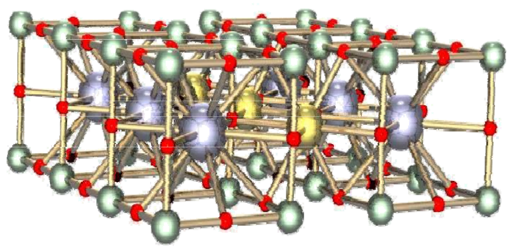
RLC Circuit

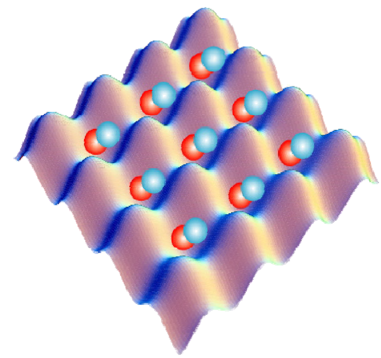
ANALOGOUS MECHANICAL & ELECTRICAL QUANTITIES

Mechanical		Electrical	
x	Displacement	q	Charge
$\dot{x}$ (v)	Velocity	$\dot{q}$ (I)	Current
m	Mass	L	Inductance
b	Friction	R	Resistance
1/k	Mechanical Compliance	C	Capacitance
F	Amplitude of impressed force	$\mathcal{E}$	Amplitude of impressed emf

Distinct physical systems governed by the same equations behave identically.

Equivalence of physical systems
Example: Condensed Matter & Atomic Systems





$$H_{YBCO} = -t_e \sum_{<i,j>,\sigma} (c_{i,\sigma}^{\dagger} c_{j,\sigma} + h.c.) + U_C \sum_{i=1} n_{i\uparrow} n_{i\downarrow}$$

YBCO Superconductor

$$H_{FH} = -t_a \sum_{<i,j>,\sigma} (c_{i,\sigma}^{\dagger} c_{j,\sigma} + h.c.) + U_s \sum_{i=1} n_{i\uparrow} n_{i\downarrow}$$

Optical Lattice

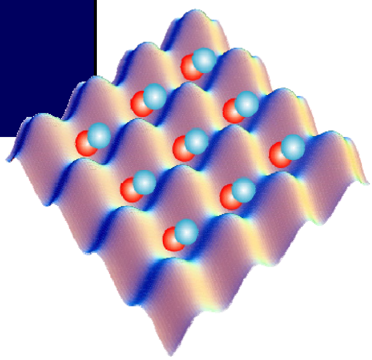
ANALOGOUS CONDENSED MATTER AND OPTICAL LATTICE QUANTITIES

	Condensed Matter		Atom-Optical
Carriers	Electron/Holes		Fermionic atoms
$e^- e^-$	Coulomb charge coupling	s	S-wave scattering length
m_e	Electron mass	m_a	Atomic mass
U_c	Coulomb Interaction	U_s	S-wave Interaction
t_e	Electronic tunneling energy	t_a	Atomic tunneling energy
Lattice	Atomic ions		Optical standing waves
a, b, c	Lattice Constants	$(\lambda_x, \lambda_y, \lambda_z)/2$	Optical wavelength
V_{ion}	Binding energy	V_{lat}	Lattice depth

Distinct physical systems governed by the same equations behave identically.

Optical Lattices

- The “crystal” that the atoms reside in is formed by pairs of counterpropagating, detuned laser beams that form an optical standing wave potential.



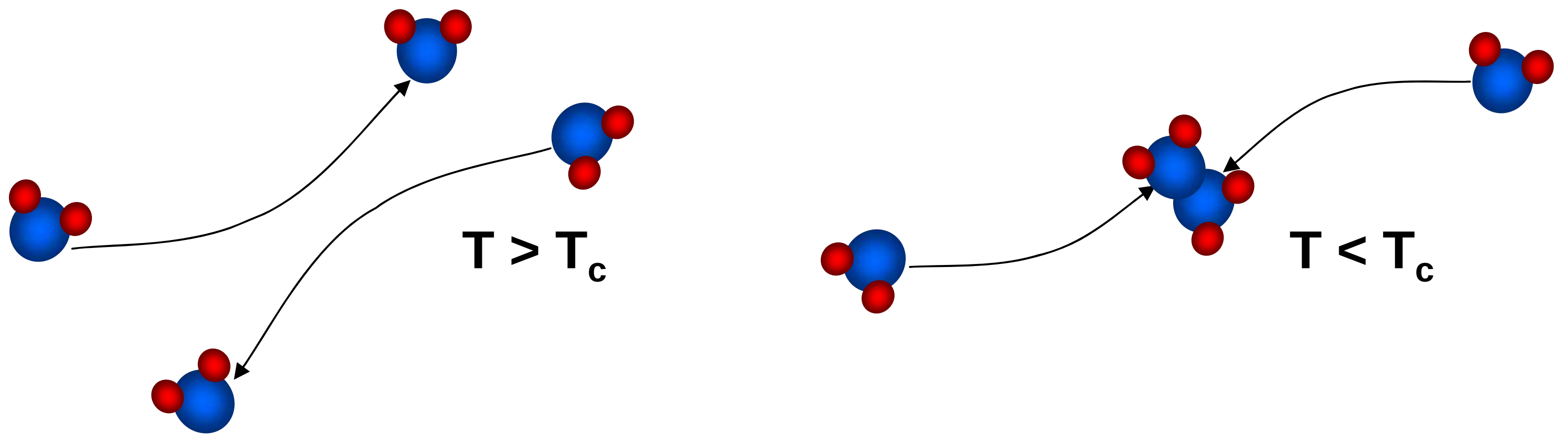
What material behavior will the OLE tool emulate?

- By engineering a Hamiltonian describing the relevant features of an intractable condensed matter system, OLE will determine the conditions under which each quantum phase can exist.

"Phase diagrams" are maps for optimizing materials.

Example: Gas-to-Liquid phase transition

- A gas will condense to a liquid when the molecular binding energy becomes (roughly) equivalent to the thermal energy.



Fast moving H_20 molecules rebound upon collision.

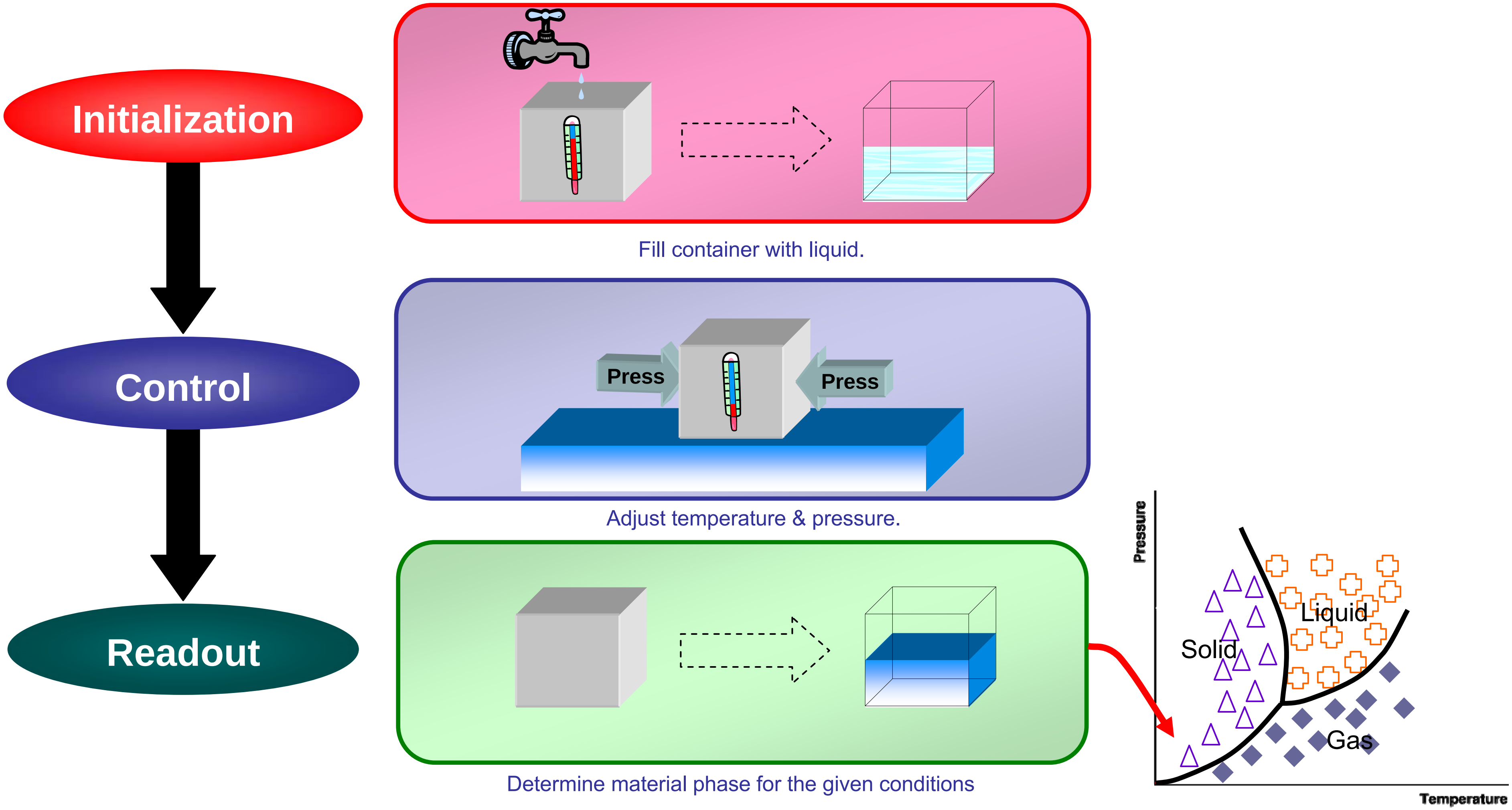
Slow moving H_20 molecules “stick”, condensing to a liquid.

$$\text{Energy} = \sum_{i}^{N} \frac{p_i^2}{2m} + \varepsilon \sum_{i,j}^{N} \left(\left(\frac{r_0}{r_{ij}} \right)^{12} - \left(\frac{r_0}{r_{ij}} \right)^{6} \right)$$

Thermal energy   van der Waal Interaction

Gas-Liquid transition driven by competition between kinetic and potential energies.

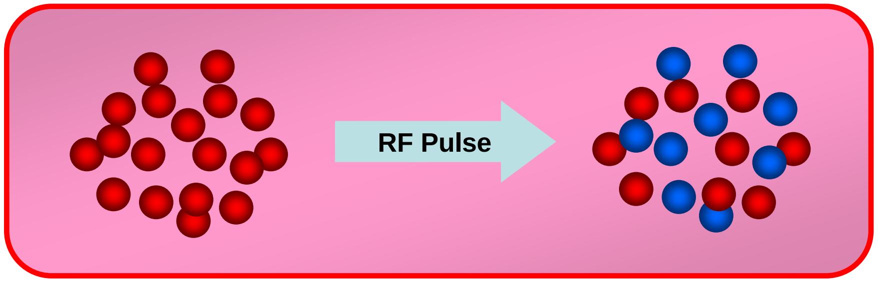
Mapping a classical phase diagram



Phase diagrams measure the boundaries between different states of matter.

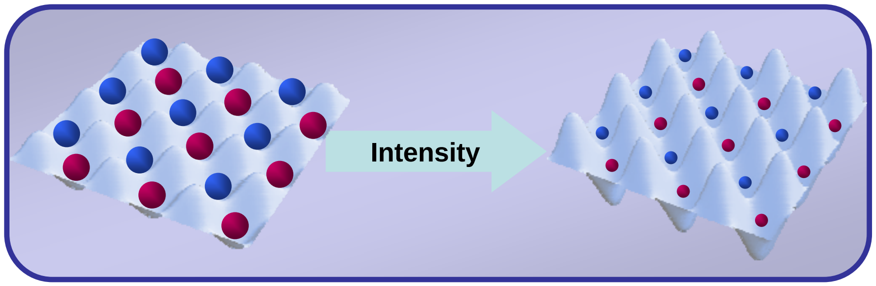
Mapping a quantum phase diagram

Initialization



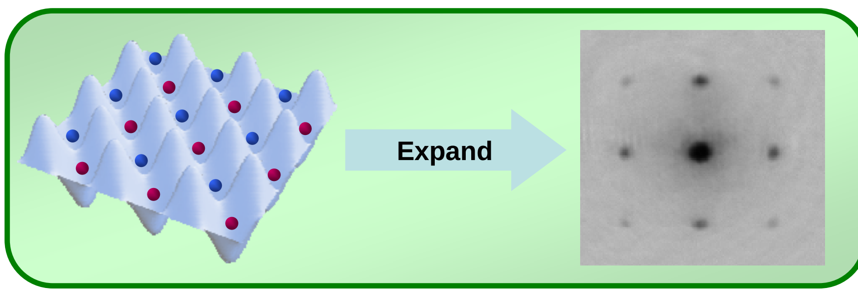
Produce atomic samples with requisite populations & temperature.

Control

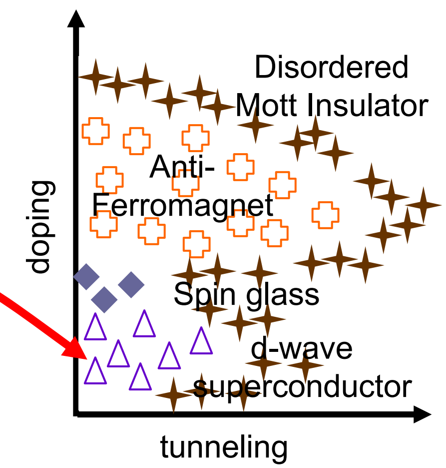


Load atoms into lattice and vary system parameters.

Readout



Determine material phase for the given conditions



The OLE tool will produce a phase diagram for an emulated material.

OLE

OPTICAL LATTICE EMULATOR

Example: Conductor-to-Insulator Transition

DARPA DSO

BRIDGING THE GAP DARPA 1958 2008 50 YEARS POWERED BY IDEAS

Example: Conductor-to-Insulator Phase Transition

Quantum Mechanical Description: Bose-Hubbard Hamiltonian

$$H_{BH} = \boxed{-t} \sum_{<i,j>} \boxed{(a_i^\dagger a_j + h.c.)} + \boxed{\frac{U_0}{2} \sum_i n_i (n_i - 1)}$$

Tunneling (kinetic) energy

On-site (Potential) energy

Tunneling Strength

$$t = - < \psi(x - x_i) \,|\, -\frac{\hbar^2 \nabla^2}{2m} + V_{lat}(x) \,|\, \psi(x - x_j) >$$

Kinetic Energy

Barrier Height

Quantum Bookkeeping

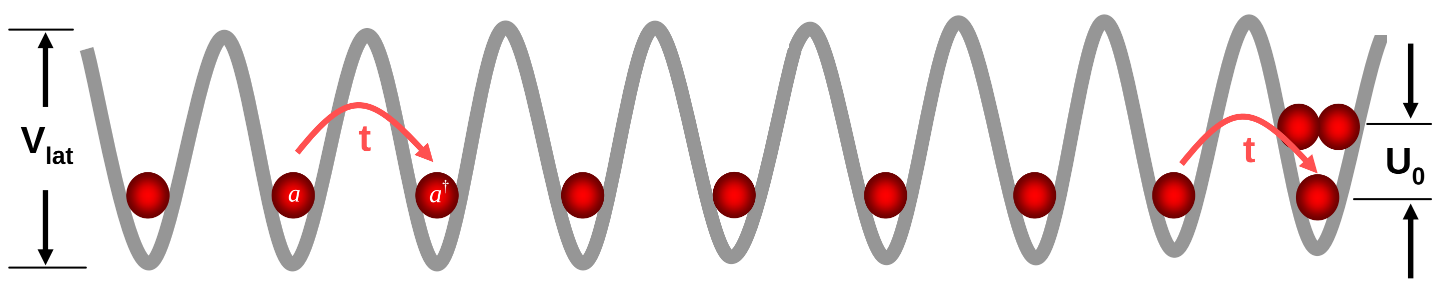
$$\left(a_i^\dagger a_j \right)$$

Create a particle at site i ($a_i^\dagger$) & annihilate a particle at j (a_j).

On-Site Repulsion

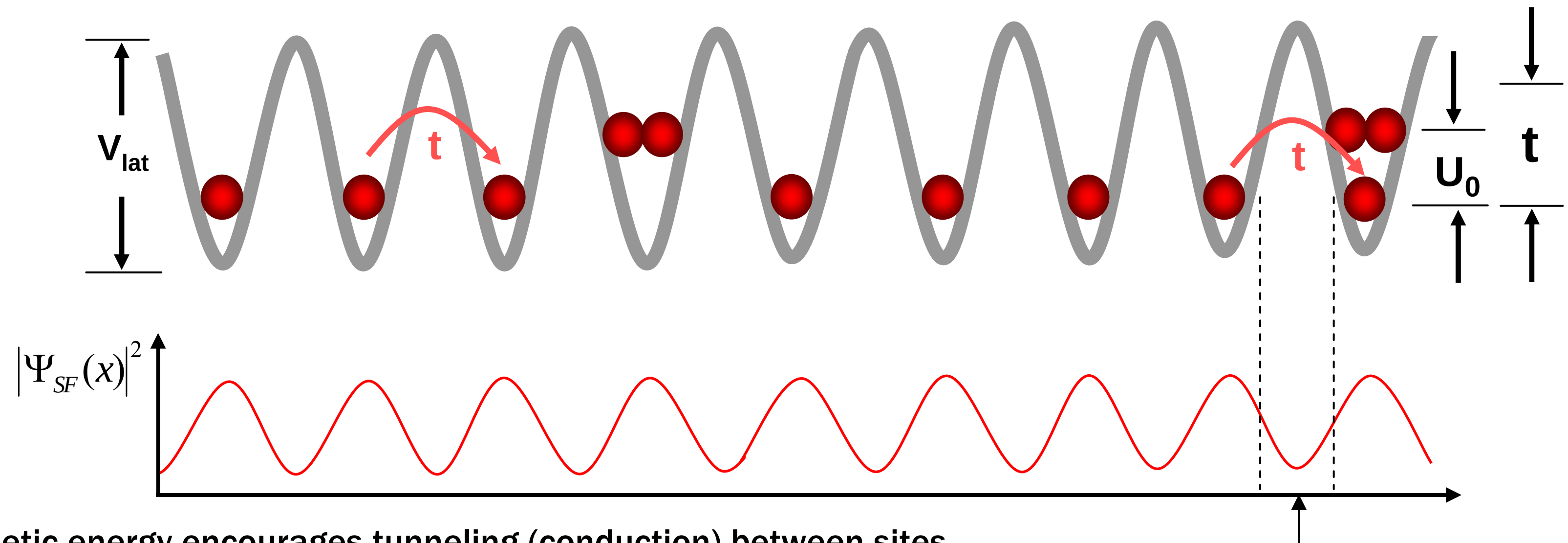
$$U_0 = \frac{4\pi\hbar^2 s}{m} |\psi(x)|^4$$

s – s-wave scattering length
$|\psi(x)|^4$ - Overlap between particles
n_i - # of particles at site i



Example: Conductor-to-Insulator Phase Transition

Weak Lattice (Conducting) Regime



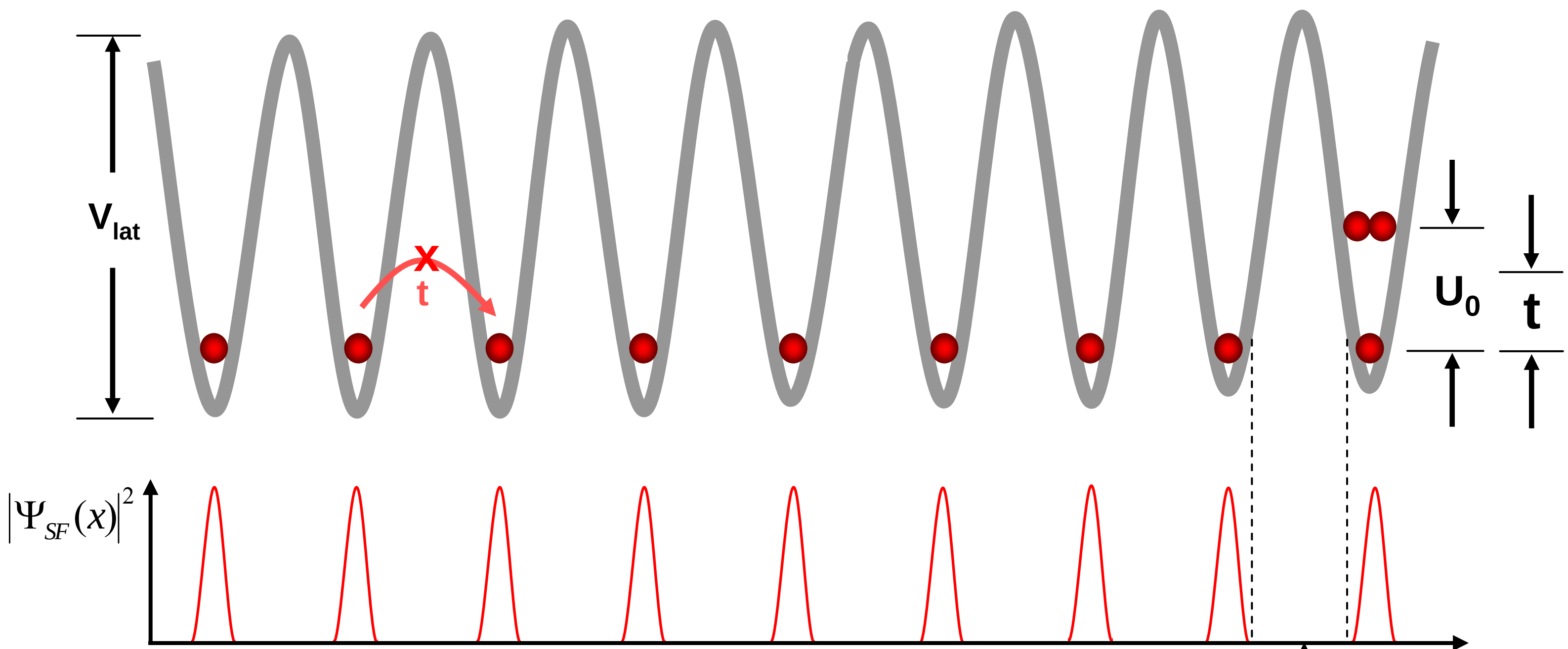
Tunneling Strength > On site interaction

$$-t\sum_{<i,j>}(a_i^{\dagger}a_j + h.c.) > \frac{U_0}{2}\sum_i n_i(n_i - 1)$$

- Kinetic energy encourages tunneling (conduction) between sites.
  - Tunneling reflected in probability "tail" within classically forbidden region.
  - Tunneling strength (t) dependent on barrier height (V_{lat}).
- On-site repulsive interactions between atoms inhibit tunneling to occupied sites.
  - Strength proportional to two-body scattering length between atoms.
- Phase information carried by tunneling atoms
  - Quantum state wavefunction with single phase (delocalized superfluid).

Example: Conductor-to-Insulator Phase Transition

Strong Lattice (Insulating) Regime



- On-site repulsive interactions between atoms prevents tunneling between occupied sites.
  - Atoms completely localized to individual sites with fixed particle number.
  - Wavefunction “tail” is zero between sites.
- No phase relation between lattice sites.
  - Quantum state represented as a product of local (Fock) states with no phase relation (Mott Insulator state).

Tunneling Strength < On site interaction

$$-t\sum_{<i,j>}(a_i^{\dagger}a_j + h.c.) < \frac{U_0}{2}\sum_i n_i(n_i - 1)$$

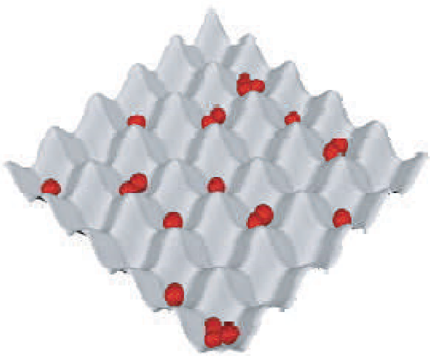
Conductor-Insulator transition driven by competition between kinetic and potential energies.

Example: Conductor-to-Insulator Phase Transition

Two distinct phases of matter based on the competition between tunneling and interactions.

- **Tunneling (conducting) regime**

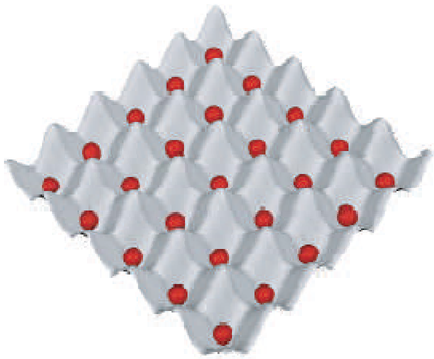
$$-t\sum_{<i,j>}(a_i^\dagger a_j + h.c.) > \frac{U_0}{2}\sum_i n_i(n_i - 1)$$



• Particles free to tunnel between sites.
• Poissonian distribution of particles
• Coherence over entire lattice

- **Insulating regime**

$$\frac{U_0}{2}\sum_i n_i(n_i - 1) > -t\sum_{<i,j>}(a_i^\dagger a_j + h.c.)$$



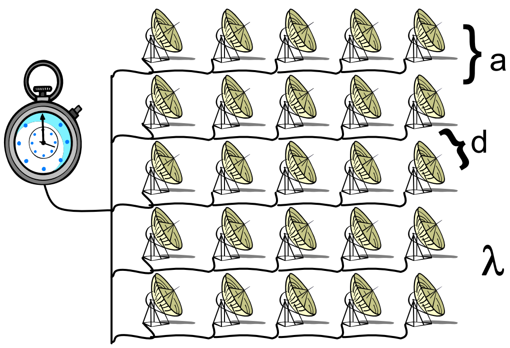
• Particles confined to individual sites.
• Fixed number of particles per site.
• No phase relation between sites

Example: Conductor-to-Insulator Phase Transition

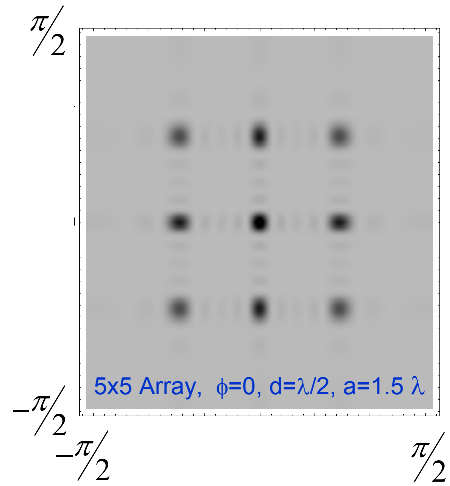
How is the phase transition from conductor to insulator detected?

- In the conducting (coherent) state the atoms behave like a phased array of antennas.

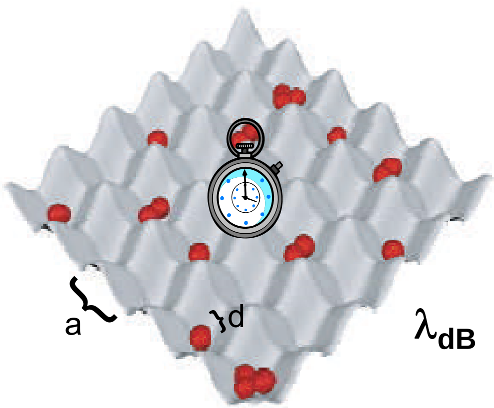
Common oscillator
•Global phase



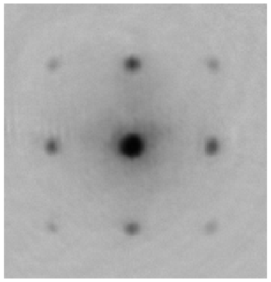
Far-field



Superfluid state
•Global phase



Ballistic Expansion of
Atom wavefunctions



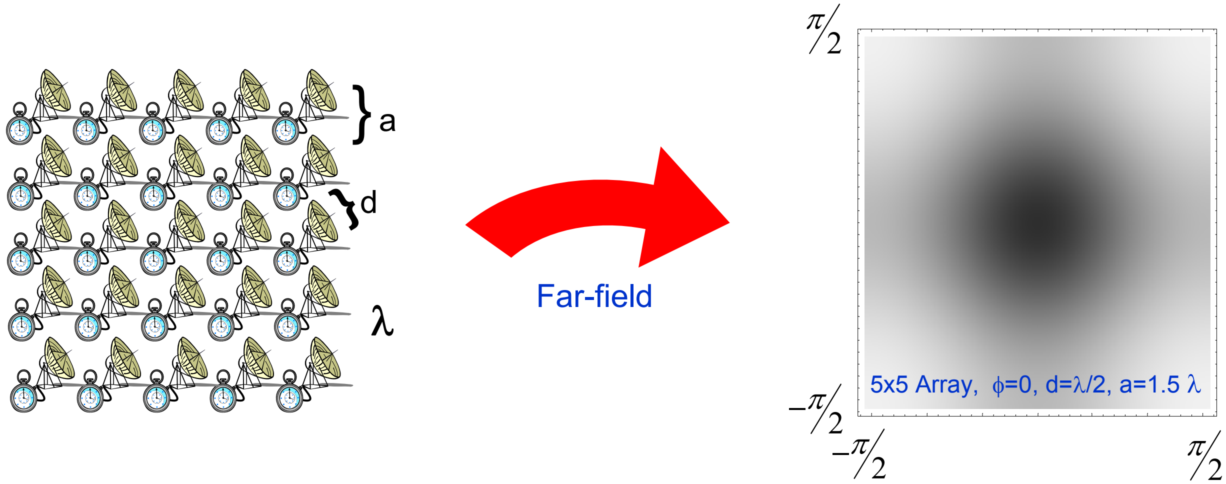
The superfluid state exhibits to sharp interference in time-of-flight expansion.

Example: Conductor-to-Insulator Phase Transition

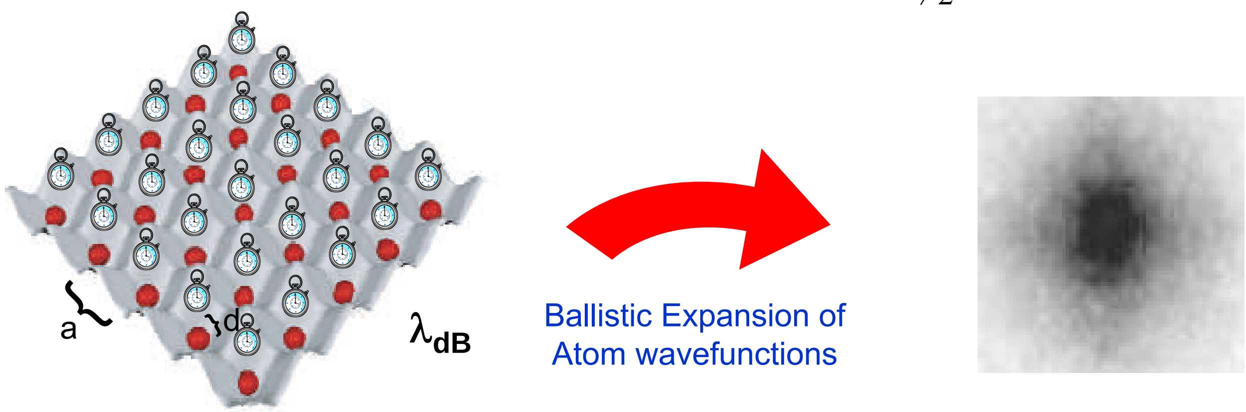
How is the phase transition from conductor to insulator detected?

- In the insulator (incoherent) state the atoms behave like an array of random antennas.

Local oscillator
- No global phase
- No interference

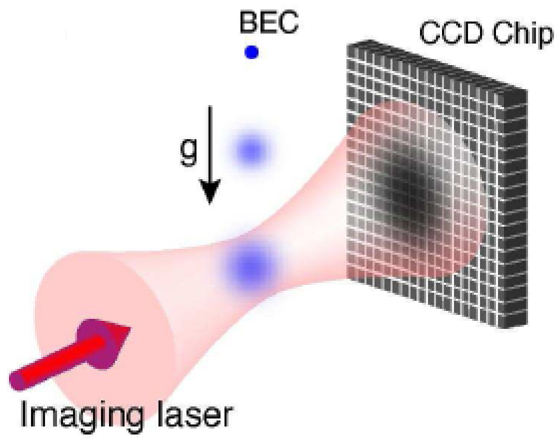


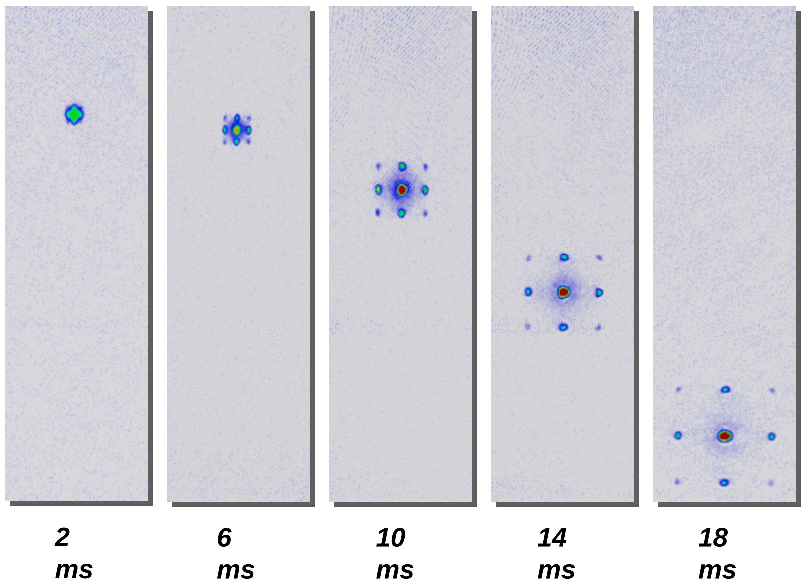
Insulating state
- No atom coherence
- No atom interference
- *Number squeezing!*

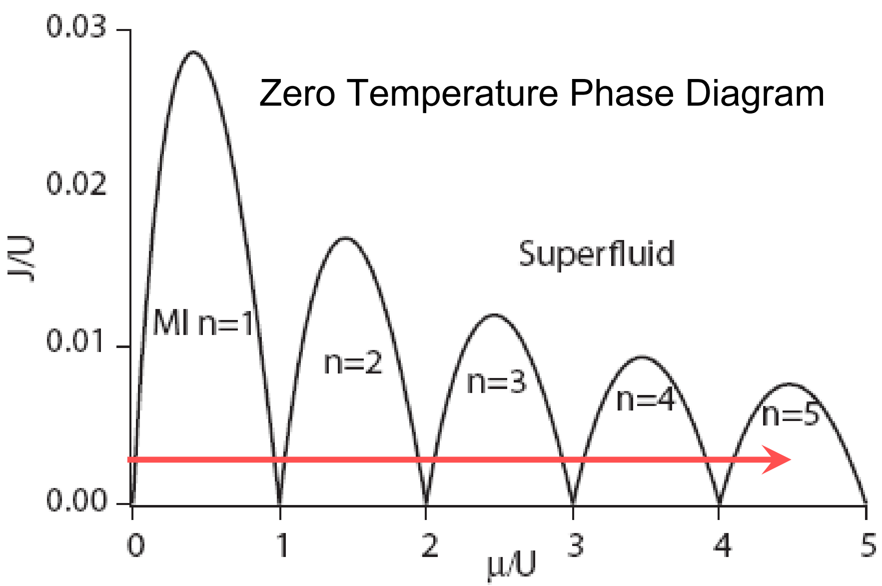


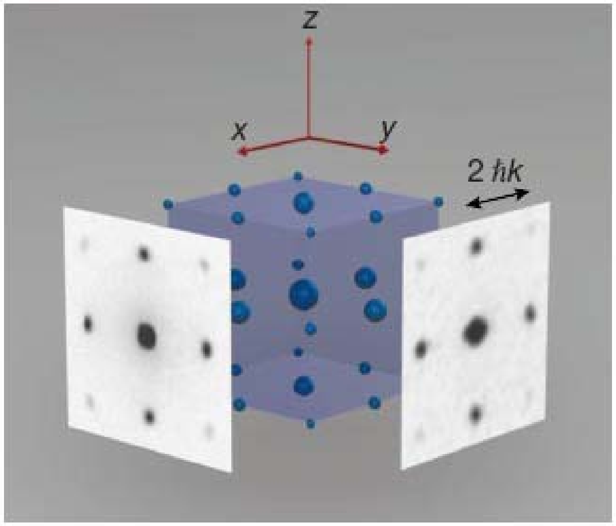
In the insulating (Mott) state random phases at each site wash out the interference pattern.

Mott Insulator Transition Experiment and Phase Diagram





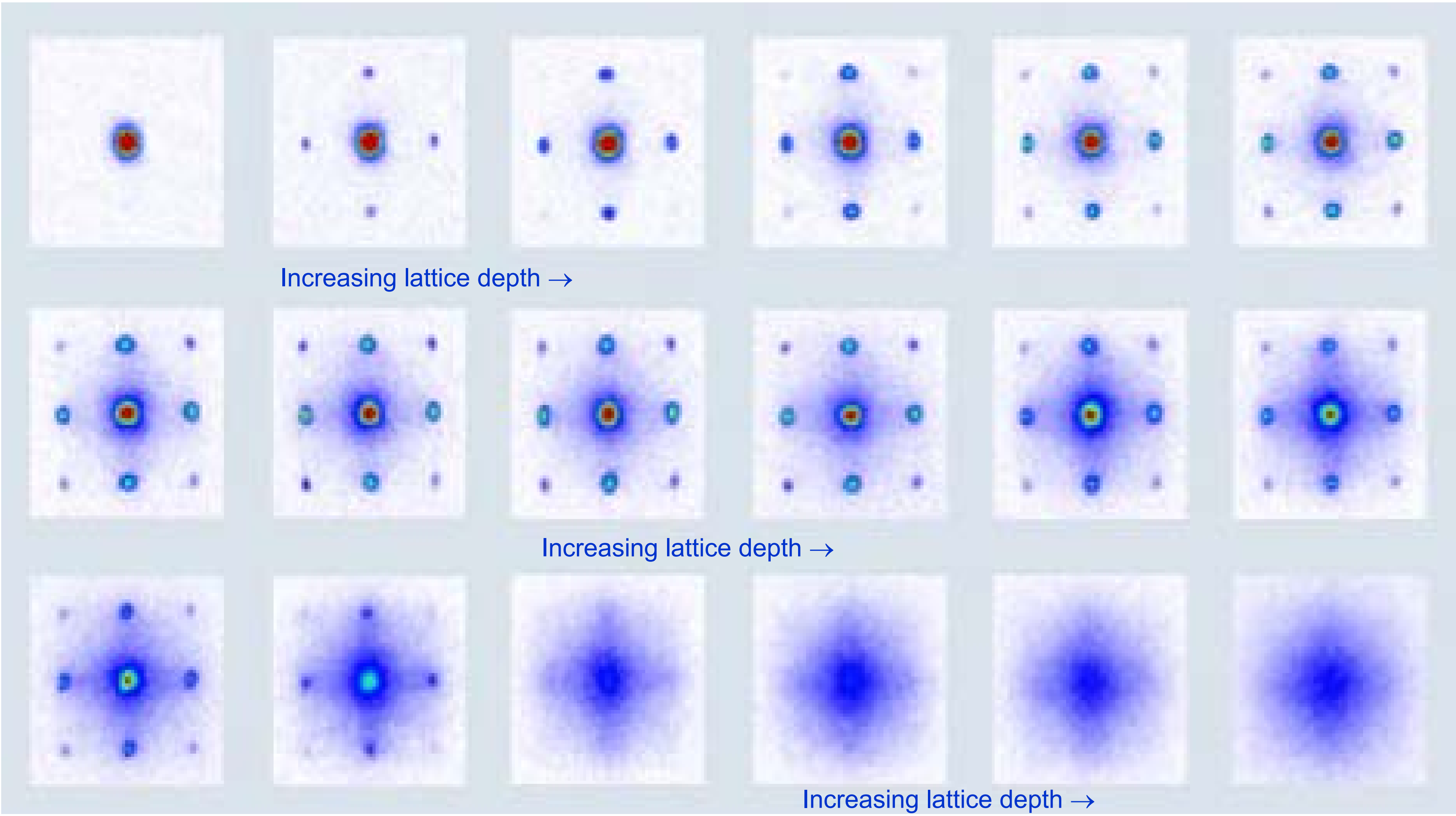




Mott Insulator Transition

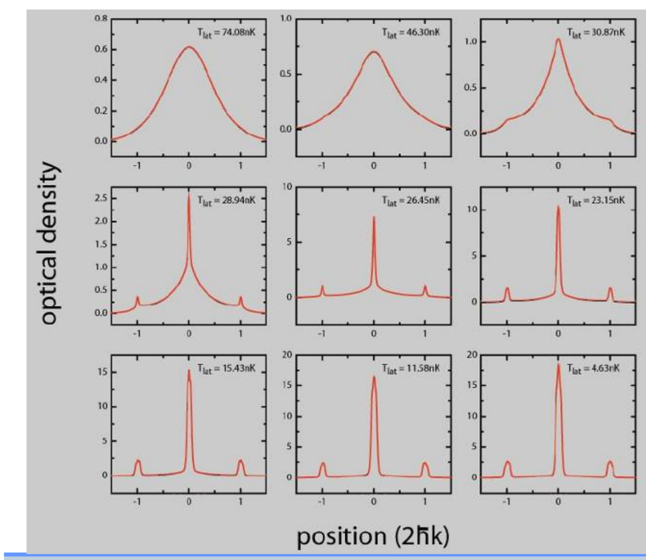
Experimental Data
M. Greiner *et al.* Nature **415**, 39-44 (2002)

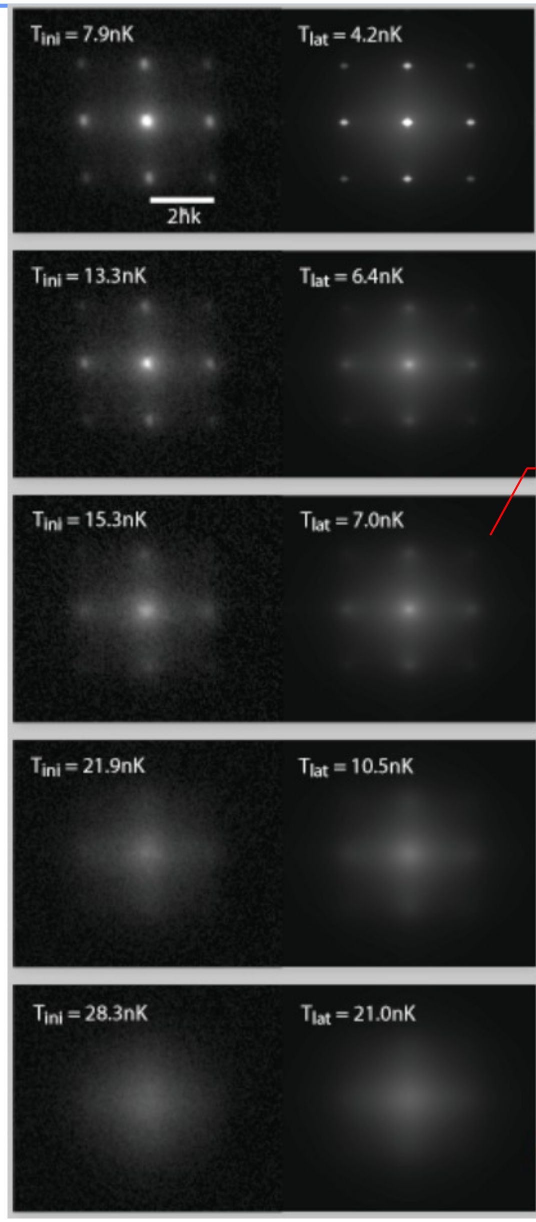
Demonstration provides confidence in measuring material phases using atoms in optical lattice

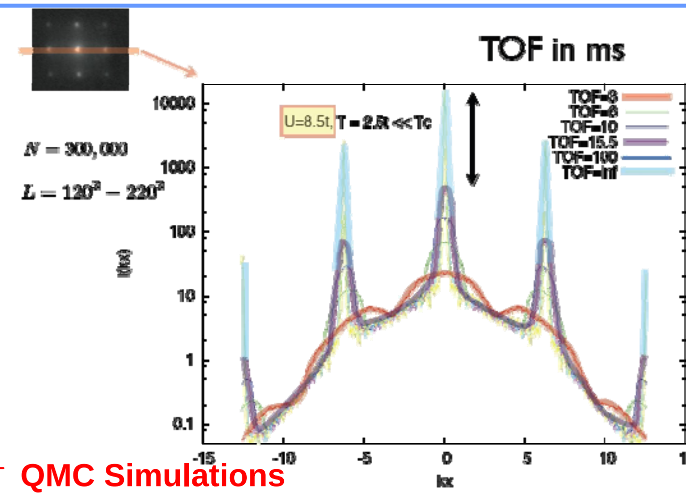


OLE program result: Revisit Mott-Insulator experiment

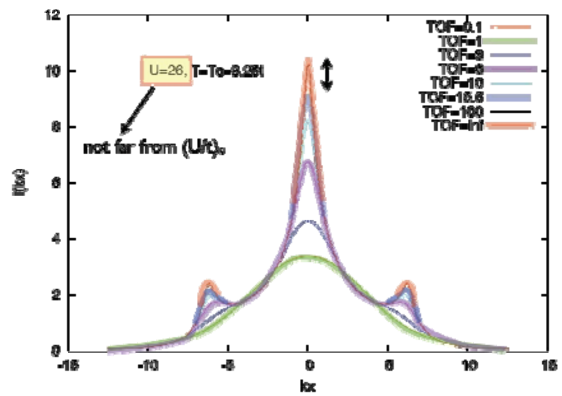
- Using experimental conditions as inputs, OLE team has done a first principles Quantum Monte Carlo Simulations of entire range of Mott-Insulator experiment with no fitting parameters thus validating experimental approach







QMC Simulations



- In simulation of detection method, found a significant theoretical result indicating that the time of flight over which the atoms were dropped affected the visibility of the momentum space interference

OLE

OPTICAL
LATTICE EMULATOR

Phase I

DARPA DSO

BRIDGING THE GAP
1958 DARPA 2008
50 YEARS
POWERED BY IDEAS

Program Direction

Phase I – Validation of OLE concept on benchmark Hamiltonians

Milestones:

- Validate optical lattice emulation approach by producing phase diagram of computationally realizable system
- Theory and experiment must agree better than 90%
- Emulation must be completed in under 12 hours

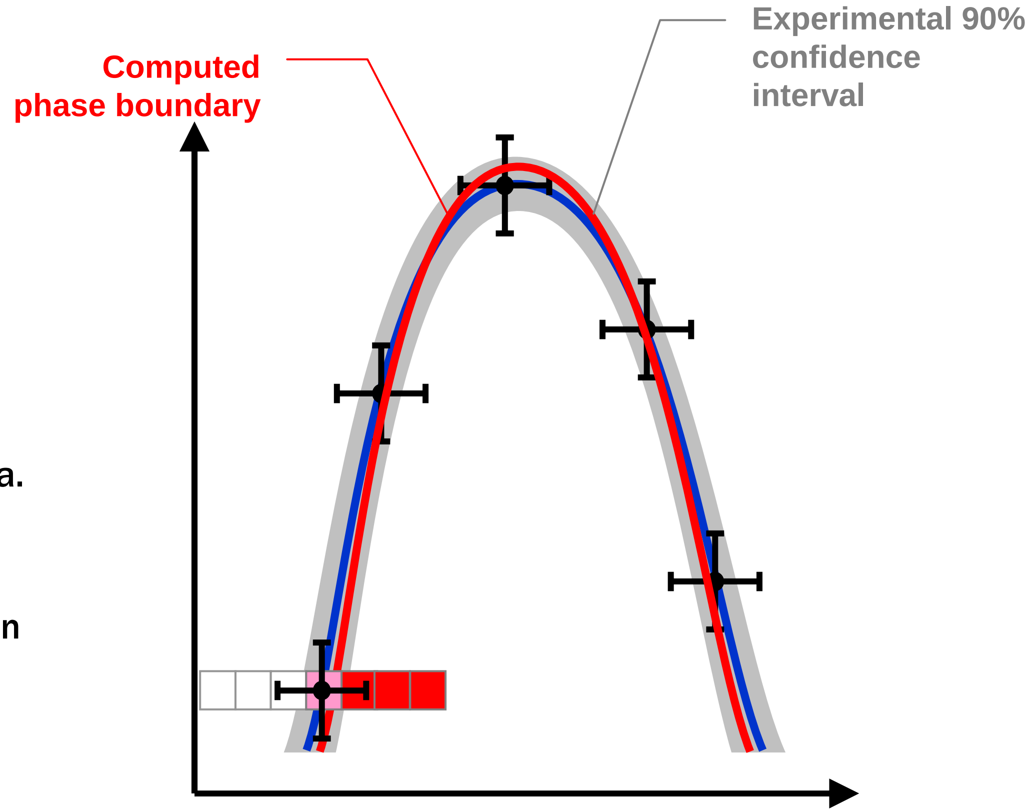
Program Direction

Phase I – Validation of OLE concept on benchmark Hamiltonians

Milestones:

- Validate optical lattice emulation approach by producing phase diagram of computationally realizable system
- Theory and experiment must agree better than 90%
- Emulation must be completed in under 12 hours

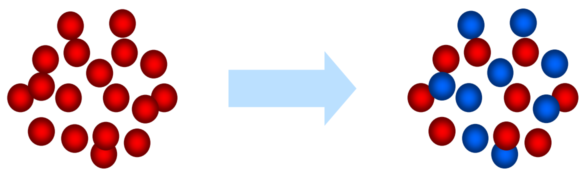
- Mapping phase diagram to 90% confidence level:
  1. Search for phase transition.
  2. Locate the transition point.
  3. Locate other transition points in parameter space.
  4. Fit a curve to the experimental data.
  5. Establish the 90% confidence interval.
  6. Verify that the theoretical prediction lies within this interval.



OLE in the context of computing

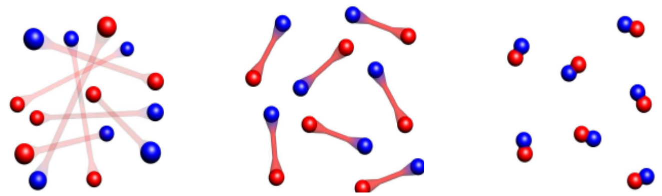
Tasks: Develop suite of robust experimental controls for…

Initialization



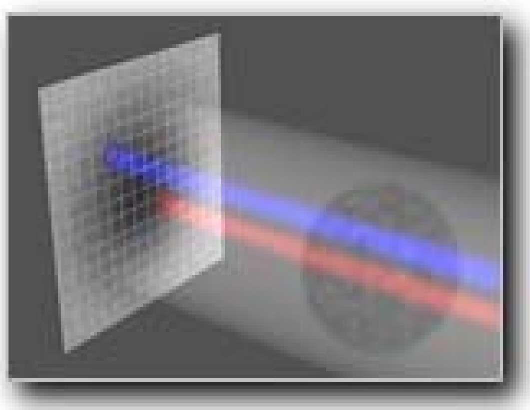
- Temperature & loading techniques, etc…

Control



- Interaction & tunneling manipulation, etc…

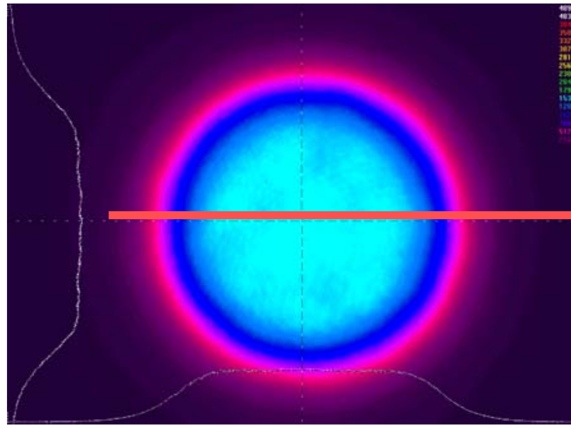
Readout

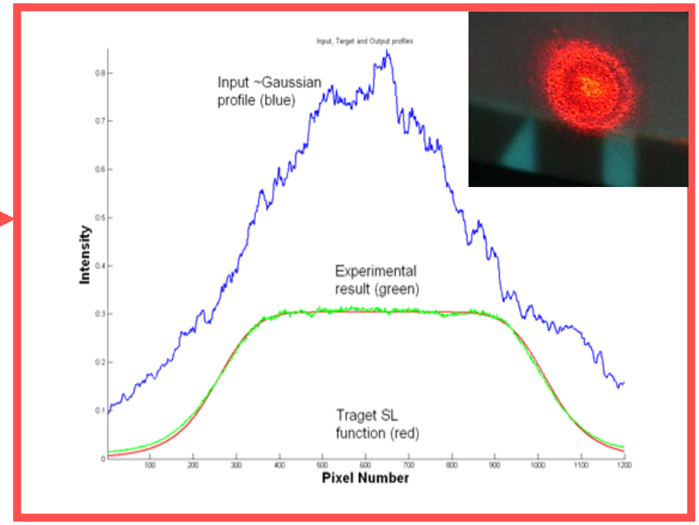


- Measurement techniques, etc…

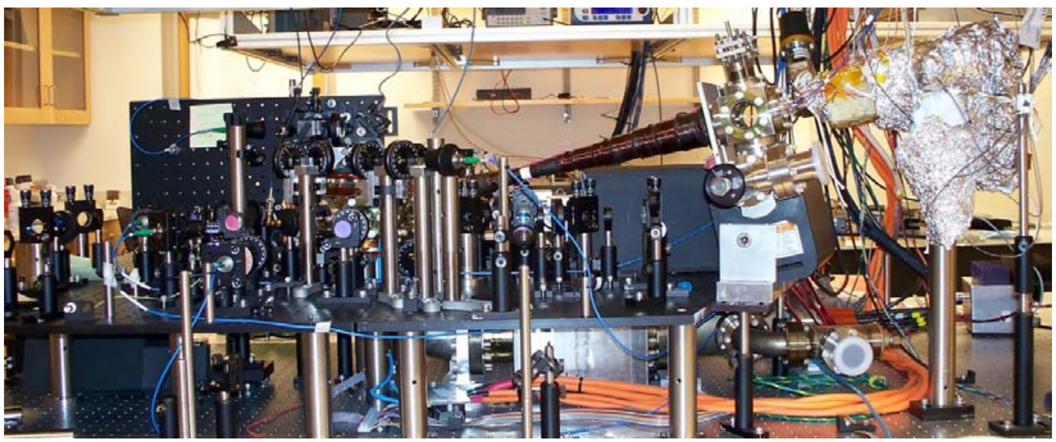
Current Progress

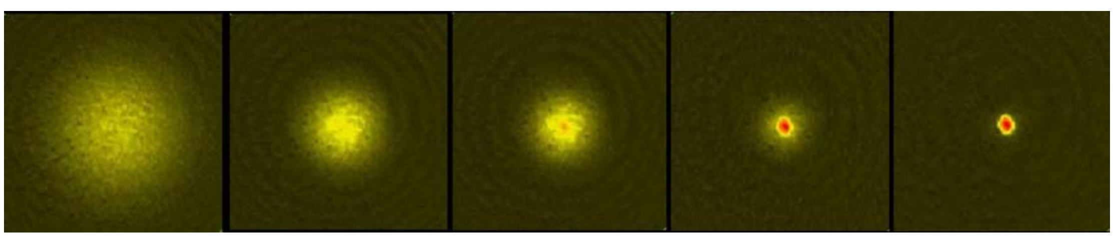
Initialization





Flat-top beam profiles for uniform lattices
RMS error from flat: 0.5% over center 30%



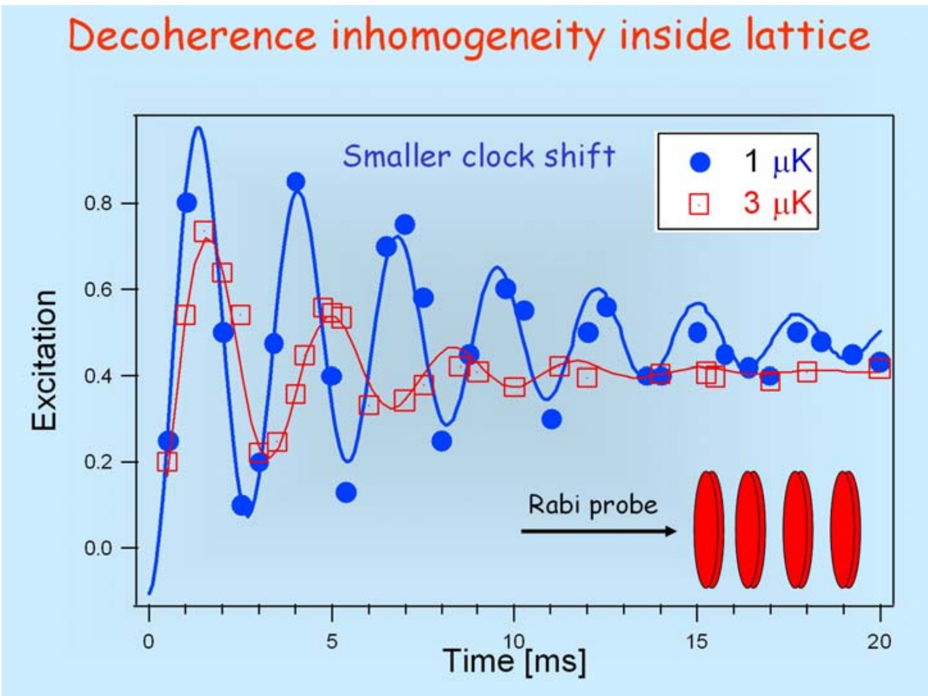


7 sec production of Cs BEC via novel magnetic tipping technique

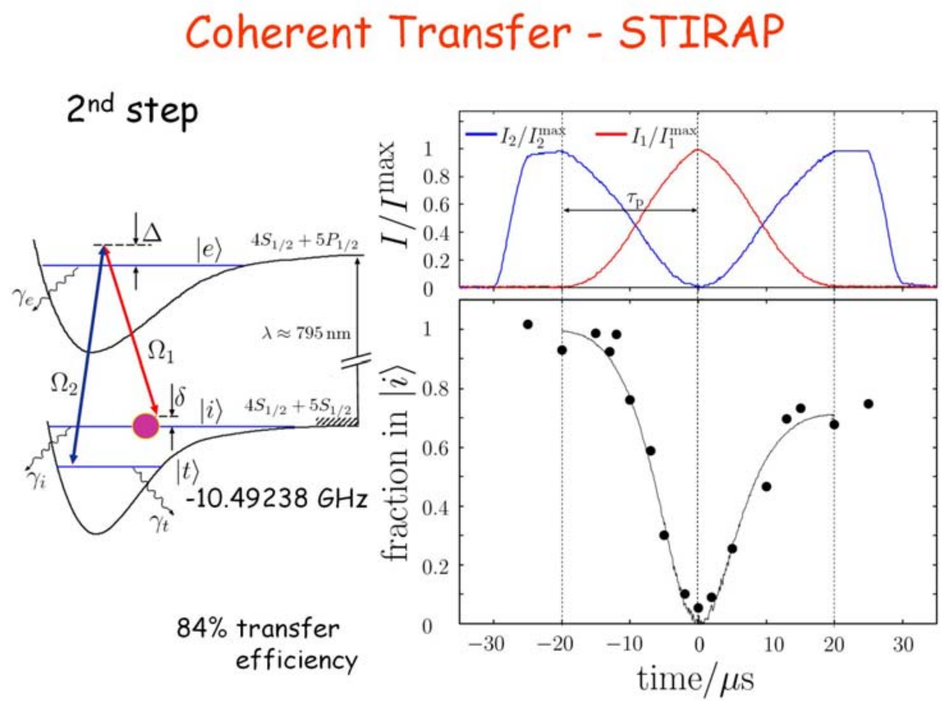
Solid-state Na laser source (589 nm)

Current Progress

Control



Control of temperature in Sr lattice reduces atomic decoherence, giving observable error signal

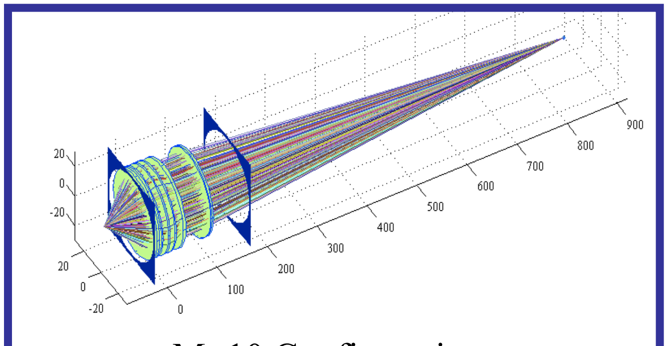


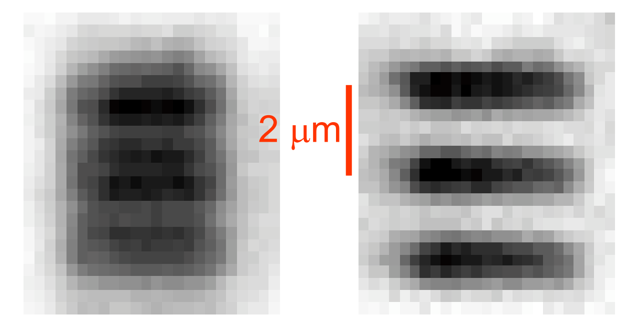
Production of bound heteronuclear molecules in ground state provides large dipole moment to control extent of lattice interactions (beyond on-site) for OLE

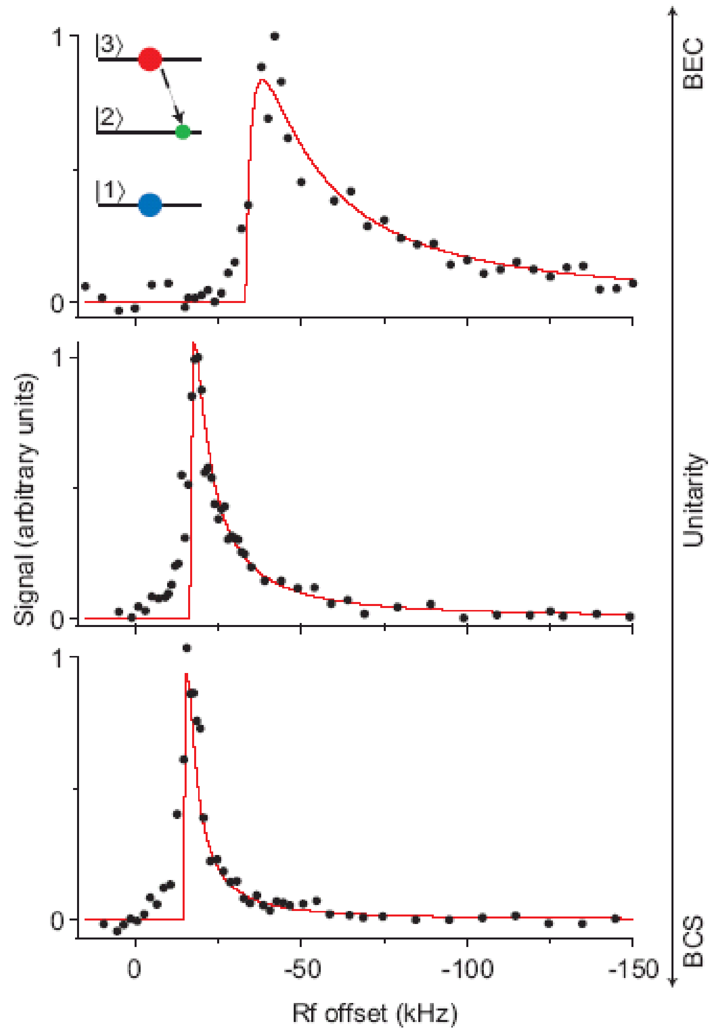
Current Progress

OPTICAL LATTICE EMULATOR OLE

Readout







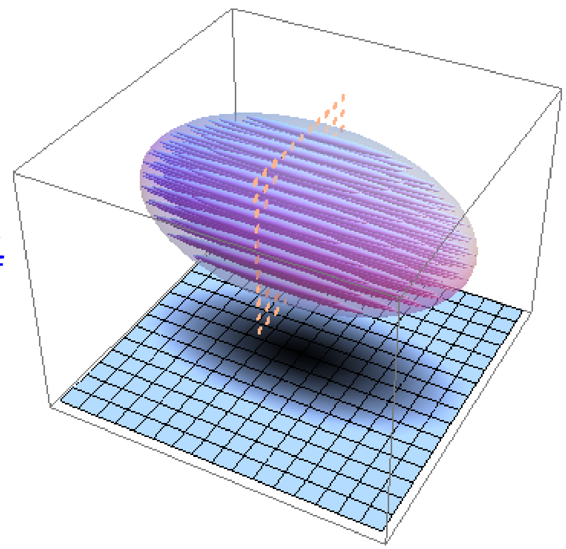
Development of high resolution imaging for lattice tomography

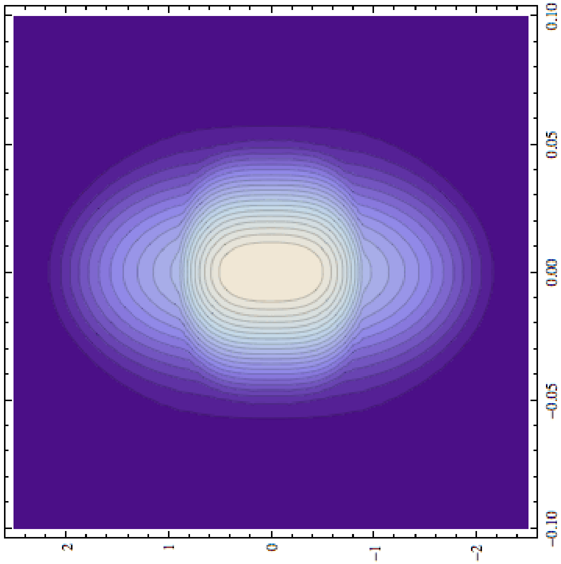
Radio frequency spectroscopy to detect fermion pairing

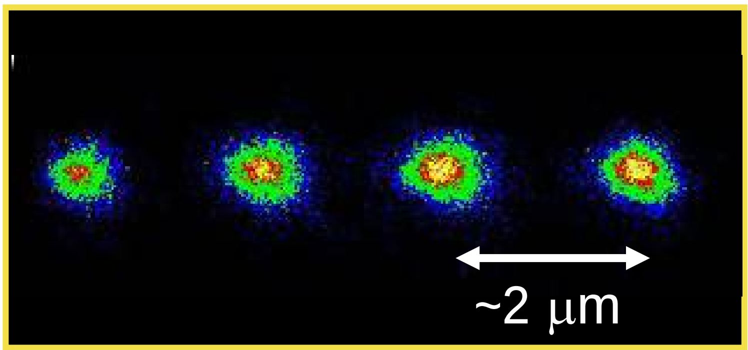
Current Progress

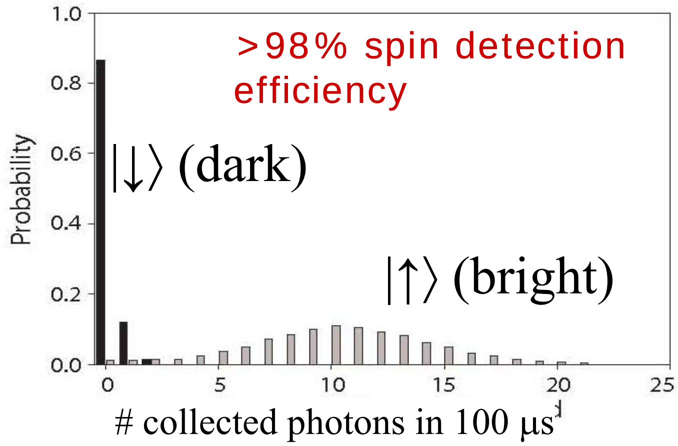
Readout

Detailed theoretical treatment of how imaging a collection of 1D lattice tubes can produce information about average internal population distribution within each tube



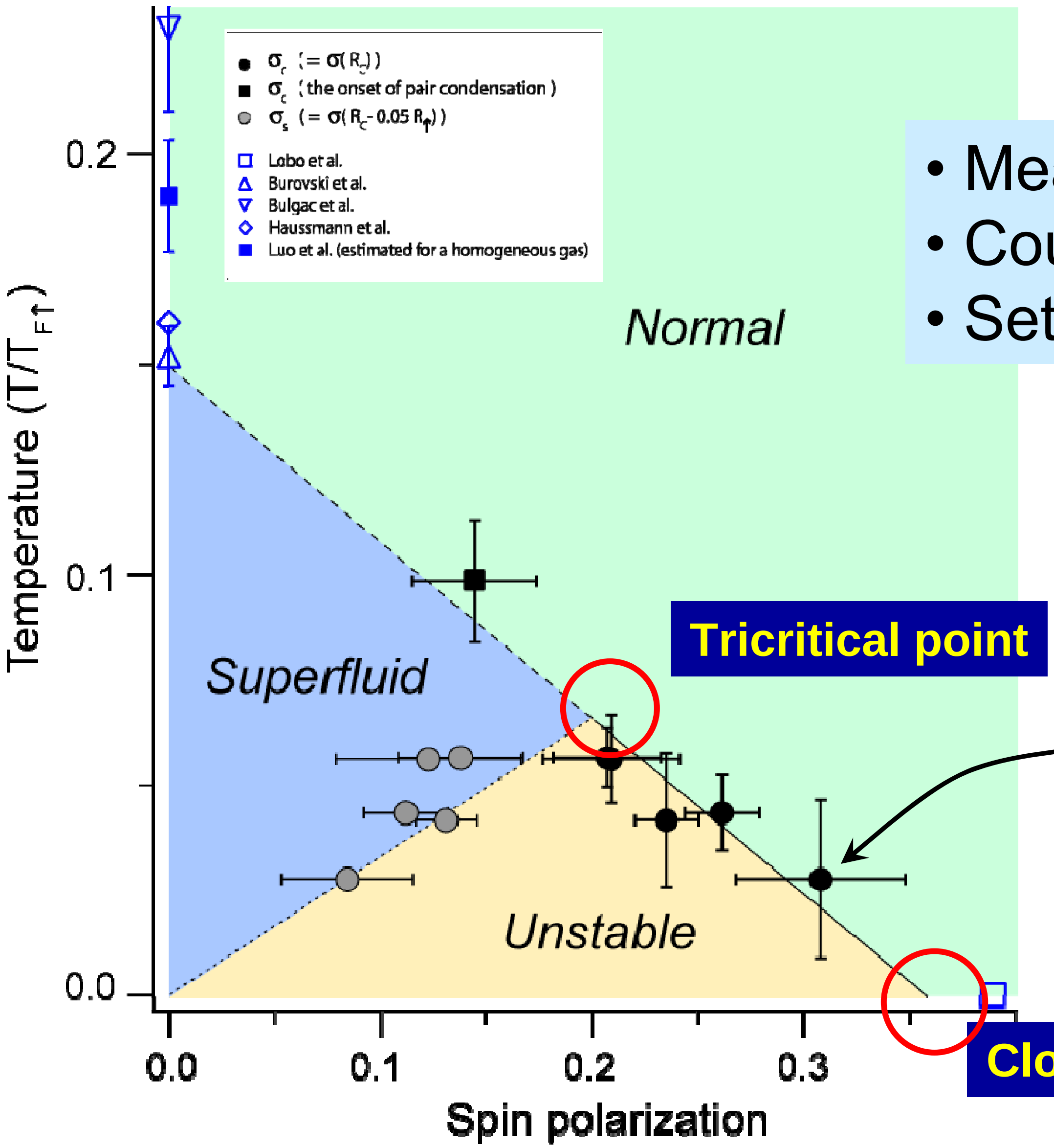




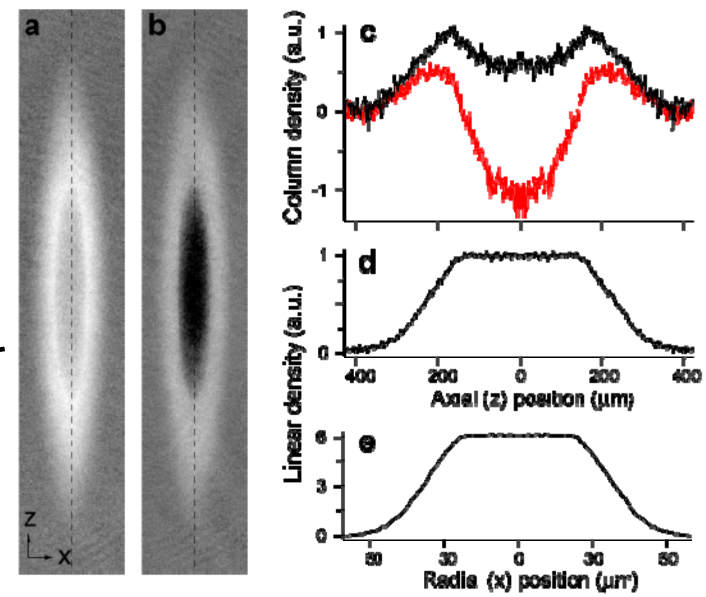


Development of high-fidelity spin detection scheme for fast state characterizations

Putting techniques together to produce a phase diagram for a 2 component polarized Fermi gas

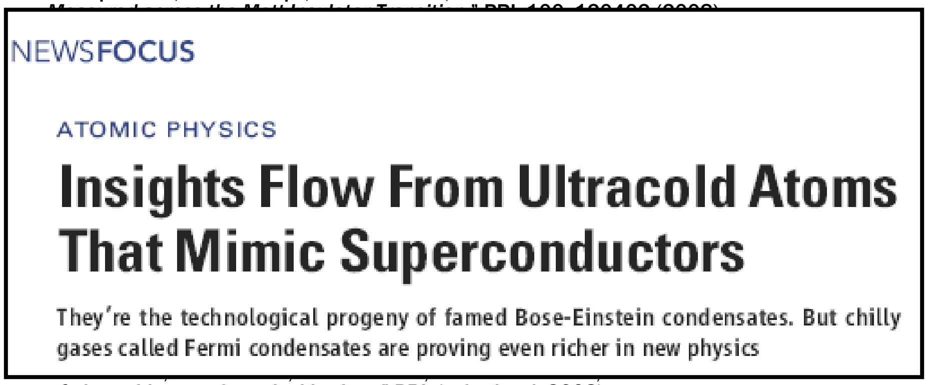


- Measured 2D phase diagram
- Could not be calculated
- Settled theoretical controversy



OLE Publications in 10 months

1. I. B. Spielman, W. D. Phillips, and J. V. Porto, "*Condensate Fraction in a 2D Bose Gas*


NEWSFOCUS

ATOMIC PHYSICS

Insights Flow From Ultracold Atoms That Mimic Superconductors

They're the technological progeny of famed Bose-Einstein condensates. But chilly gases called Fermi condensates are proving even richer in new physics

of ultracold atoms in optical lattices," PRL (submitted, 2008)

7. J. K. Freericks and A. V. Joura, "*N*
strongly correlated materials ac
(Springer, Berlin, 2008)

8. Wei Zhang, G.-D. Lin, L.-M. Duan
the Significance of Dressed Mole

9. G.-D. Lin, Wei Zhang, and L.-M. D
optical lattice," arXiv/0802.070

10. A. D. Ludlow et al., "*Evaluation o*
with a Ca clock," Science 319, 1

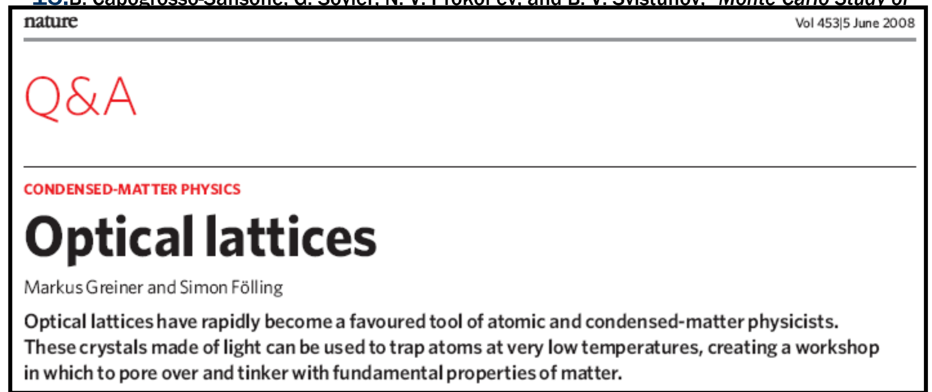
11. J. Ye, H. J. Kimble, and H. Katori
state-insensitive light traps," Sci

12. Erhai Zhao, W. Vincent Liu. "*Fiel*
arXiv:0804.4461.

13. C.J.M Mathy and David A. Huse,
cubic optical lattice" arXiv:0805

14. K. Van Houcke, E. Kozik, N. Prok
arXiv:0802.2923

15. B. Capogrosso-Sansone, G. Soyler, N. V. Prokof'ev, and B. V. Svistunov, "*Monte Carlo Study of*


nature Vol 453|5 June 2008

Q&A

CONDENSED-MATTER PHYSICS

Optical lattices

Markus Greiner and Simon Fölling

Optical lattices have rapidly become a favoured tool of atomic and condensed-matter physicists. These crystals made of light can be used to trap atoms at very low temperatures, creating a workshop in which to pore over and tinker with fundamental properties of matter.

20. Emmanuel Mimoun, Luigi de Sario, Jean-Jacques Zondy, Jean Dalibard, Fabrice Gerbier, "*An*
r-unit efficiency", (submitted to Optics Letters)

er, David A. Huse. "*Quasi-one-dimensional*
9, 250403 (2007).

conversion and laser source based on such
cques Zondy, Jean Dalibard, Fabrice Gerbier

. Zoller, M. Lukin, and H.P. Büchler, "*Repulsive*
457 (2008). (submitted to prl)

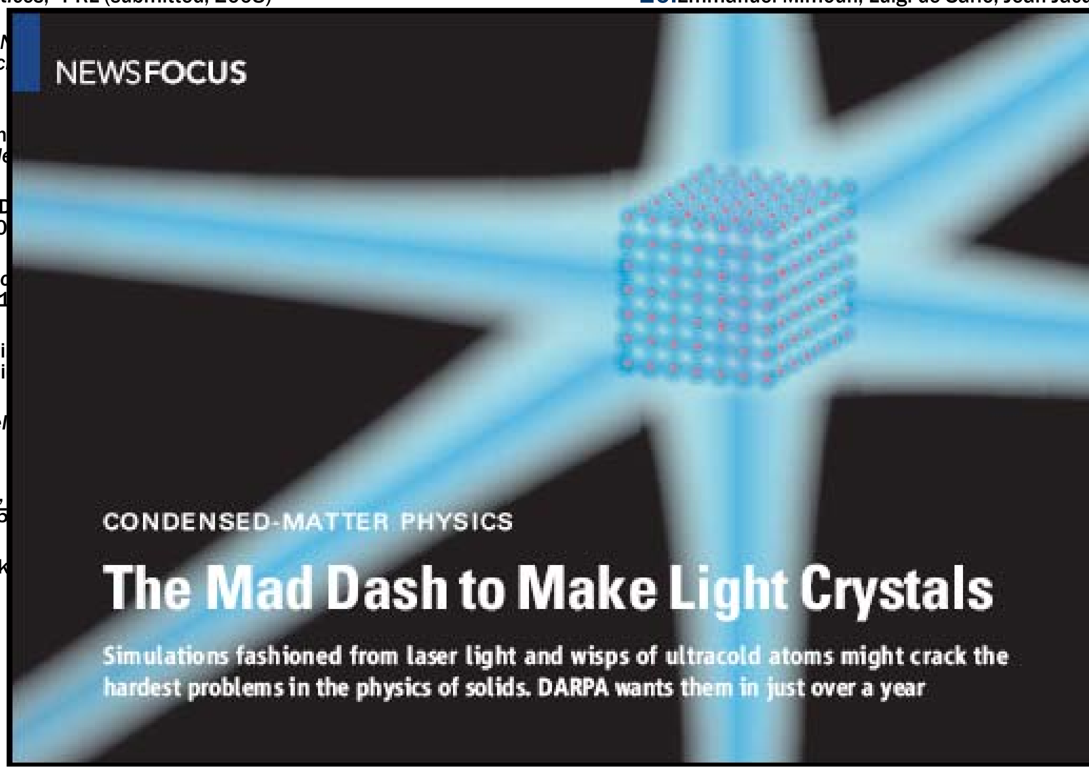
er, M. Moreno-Cardoner, S. Foelling, I. Bloch,
an optical superlattice" arXiv:0804.3372

olini "*Collective excitations in one-dimensional*
Xiv:0805.4743

of correlations and entanglement after a
model" J. Stat. Mech. (2008) P05018

Matthias Troyer, "*Temperature changes when*
Xiv:0801.1887

woeck, T. Giamarchi, "*The quasi-periodic Bose-*
ional cold atomic gases" arXiv:0802.3774


NEWSFOCUS

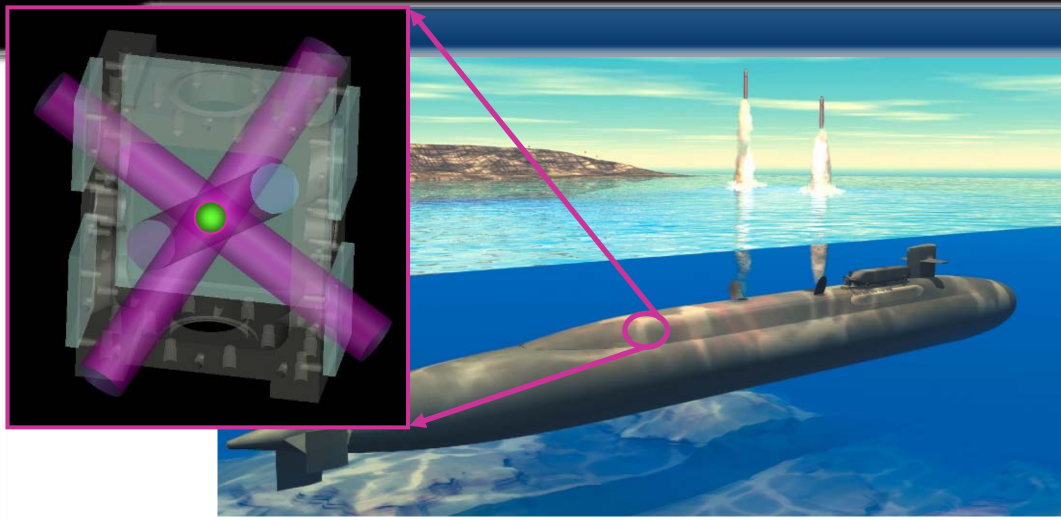
CONDENSED-MATTER PHYSICS

The Mad Dash to Make Light Crystals

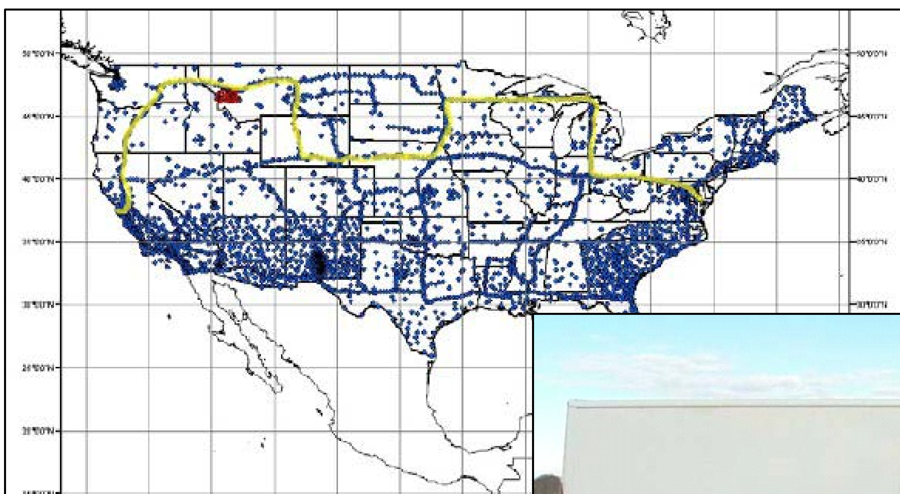
Simulations fashioned from laser light and wisps of ultracold atoms might crack the hardest problems in the physics of solids. DARPA wants them in just over a year

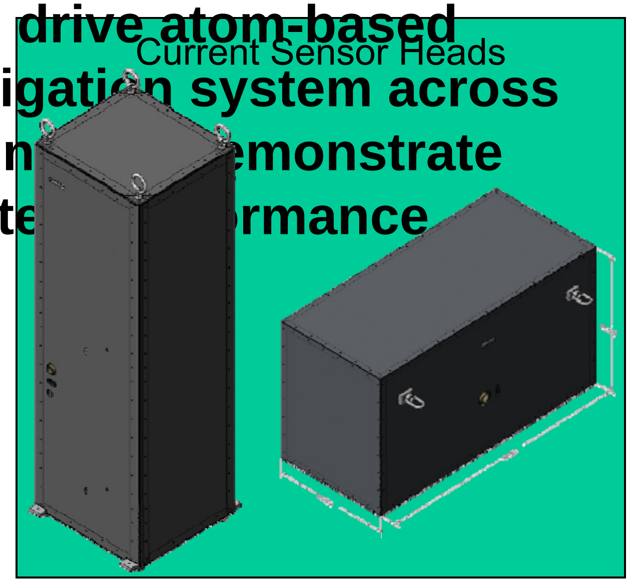
OLE Vision

Precision Inertial Navigation Systems: Ultra-cold Atom-based Inertial Measurements



- Ultracold atom navigation relies on precise measurements of forces acting on atom cloud
  - Platform motion decoupled from acceleration, rotation measurements
  - System measures gravity to compensate for local variations in gravity vector
- <u>Available regardless of geography, jamming, etc.</u>
- **Will drive atom-based navigati n system across coun emonstrate syste rmance**



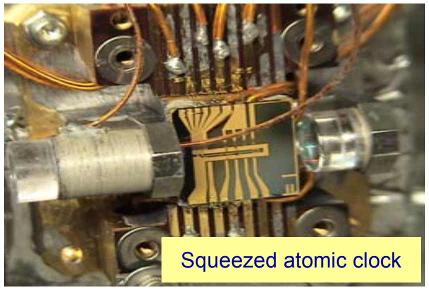


Guided BEC Interferometry

Build upon recent advances in atomic physics for producing and manipulating ultra-cold atoms (Bose-Einstein Condensate (BEC) coherent "atom-laser" sources)

- **Construct compact BEC system**
- **Develop coherent, BEC-based atom chip sensors**

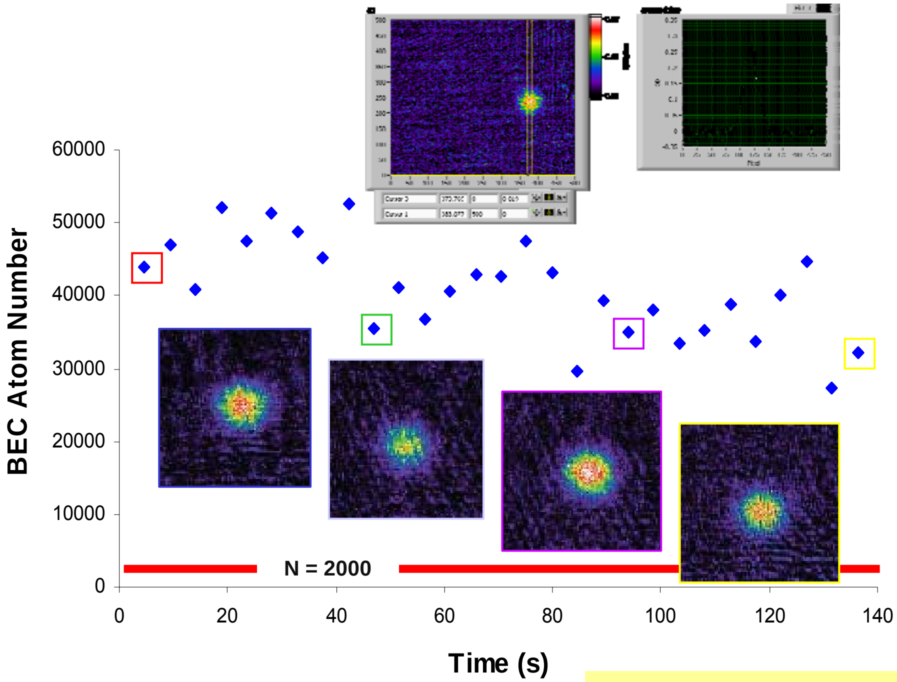
Atom-Chip Sensors



Squeezed atomic clock

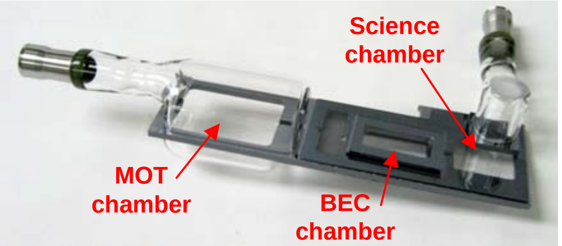
Magnetometer

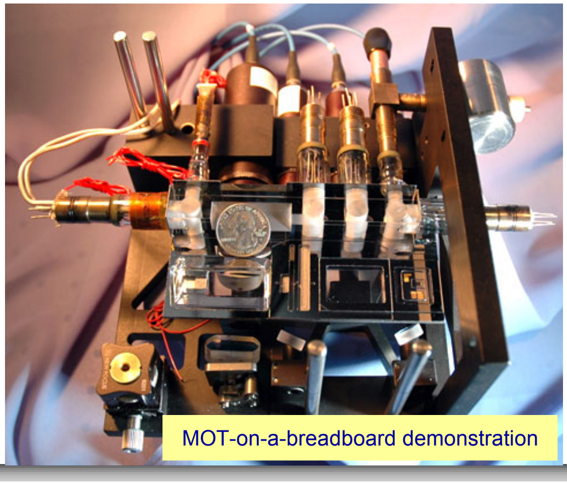
Quasi-Continuous Sources



40,000 BEC atoms produced every 4.7 s

Portable Systems

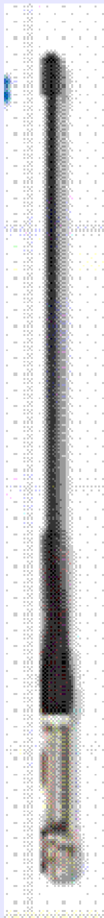




MOT-on-a-breadboard demonstration

Negative Index Materials

Current Focus: NIM Antenna



~3 fold size reduction with no reduction in radiated power

SOA: Antenex Model DG420TN

Frequency 420-450 MHz
Unity Gain
Length 0.158m
ka = 1.41
Input Power 100 W
Input Current 1.0 A

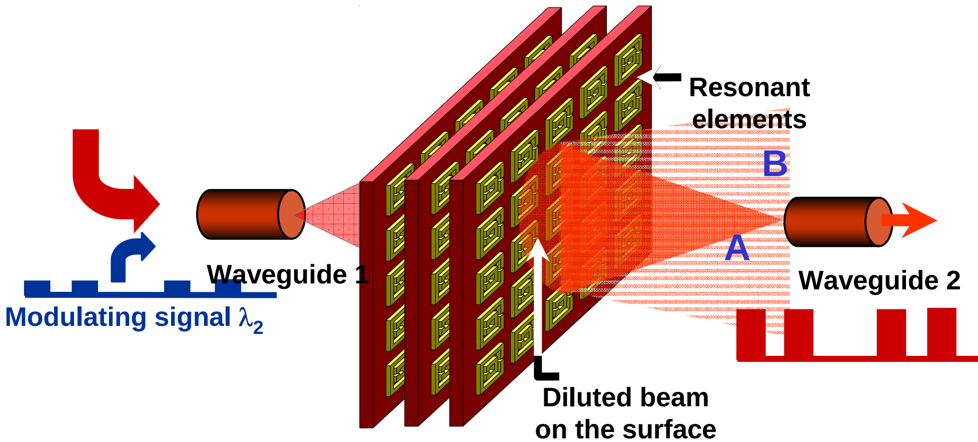
Radiated Power = 0.90 x 100 W =90 W

NIM Antenna

Frequency 430 MHz
Unity Gain
Height = 0.050 m
ka = 0.45
Input Power 100 W
Input Current 1.0 A

Radiated Power = 0.91x100 W =91 W

Next Step: Demonstrate NIM at IR wavelengths

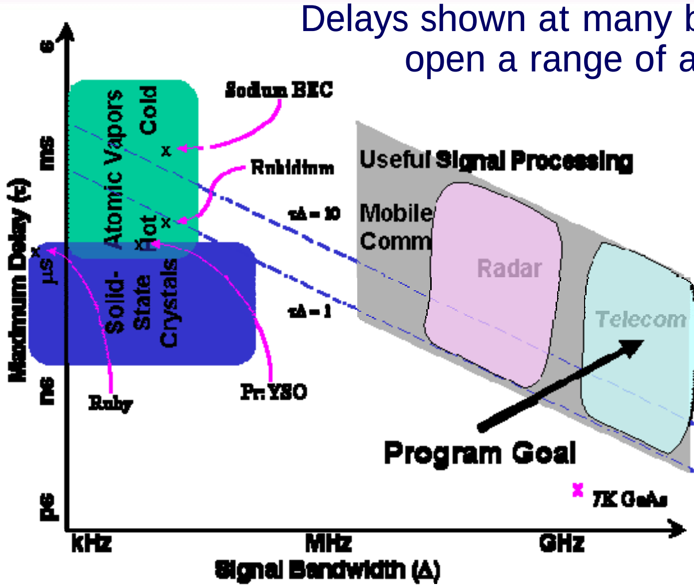


- A NIM modulator that can be very compact and engineered to work at a specific wavelength (microwave to infrared to visible).
- The modulator can operate in several modes; as a dynamic superlens, as a shutter, or as an interferometric device, at > 100 GHz

Developing technologies for slowing, storing, and manipulating light (Slow light $n_{group} << C$)

- All optical signal processing
- Photon generation for quantum information applications

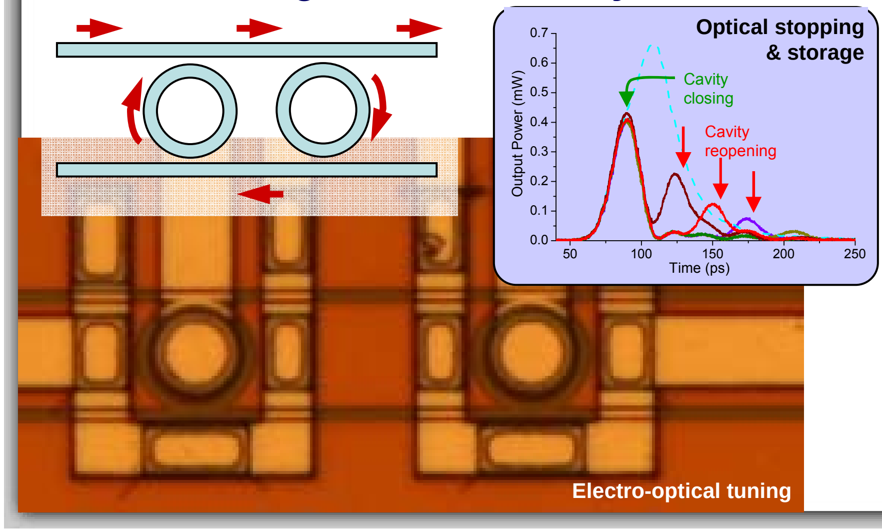
Delays shown at many bandwidths open a range of applications



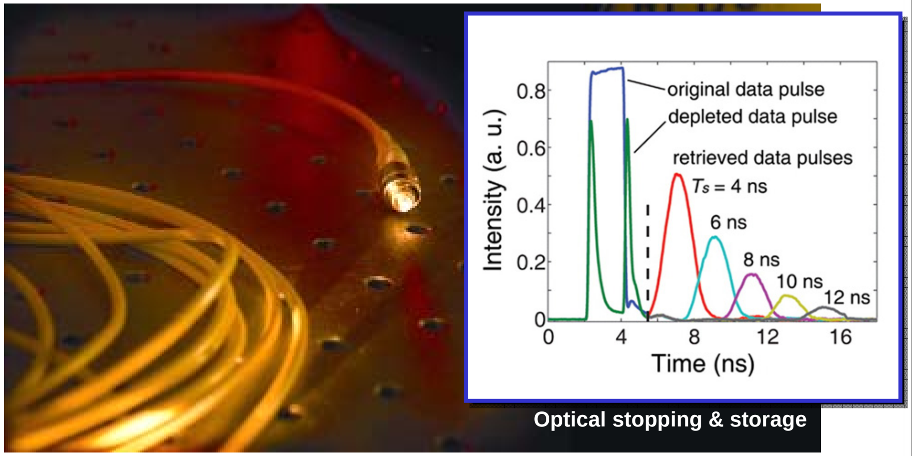
Demonstrated

- **All optical stopping and storing of light in room temperature optical fibers & ring resonators.**
- **Electro-optical cavity tuning of ring resonators.**

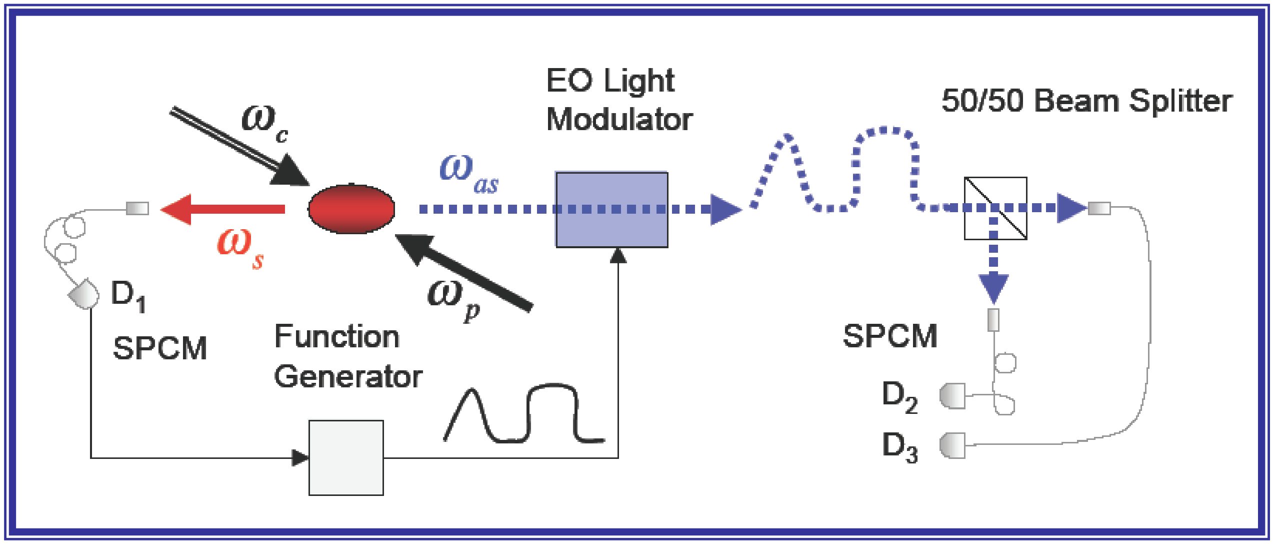
Stopping and storage in a ring resonator cavity



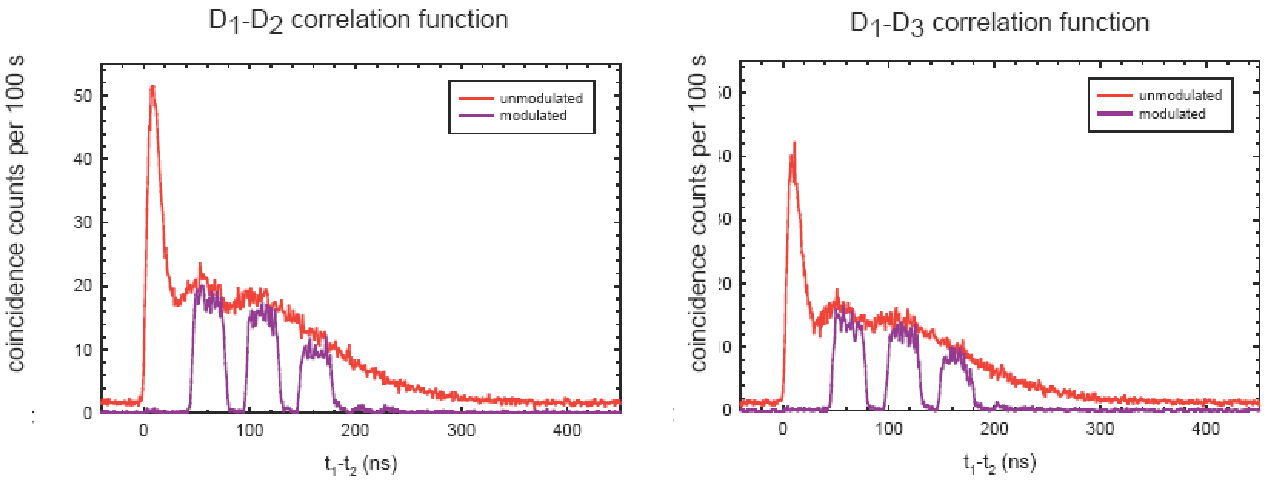
Stopping and storage in room temperature optical fiber



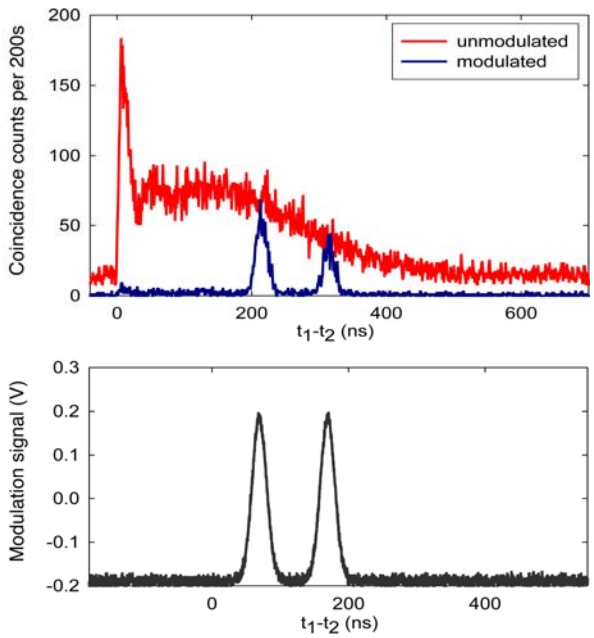
Conditional modulation of biphoton waveforms



Modulation with three square pulses

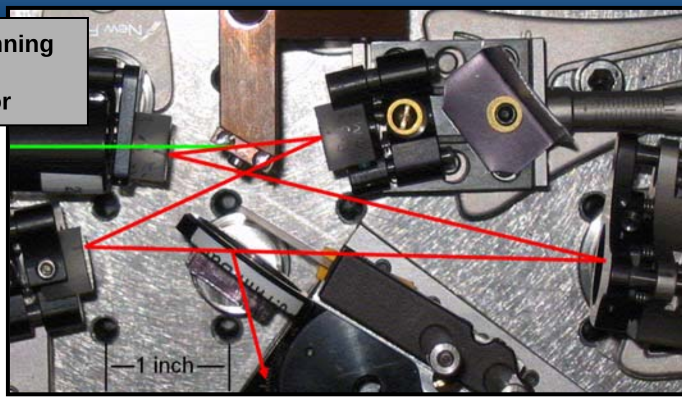


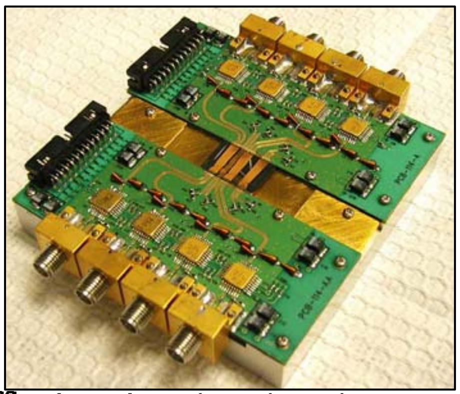
Modulation with two Gaussian pulses



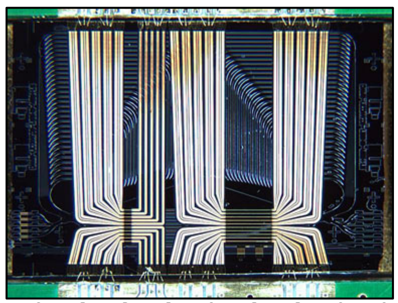
Optical Arbitrary Waveform Generation (OAWG)

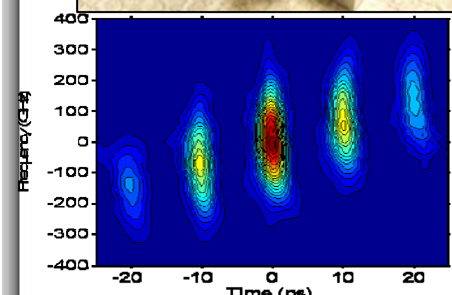
1 GHz octave-spanning carrier-envelope stabilized oscillator

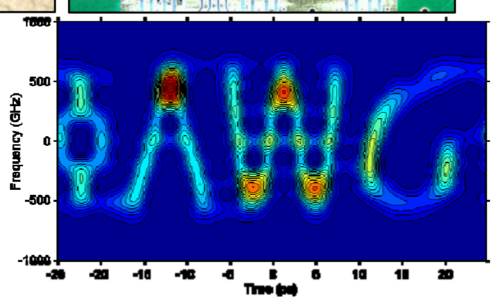




10-channel x 10 GHz InP waveform encoder







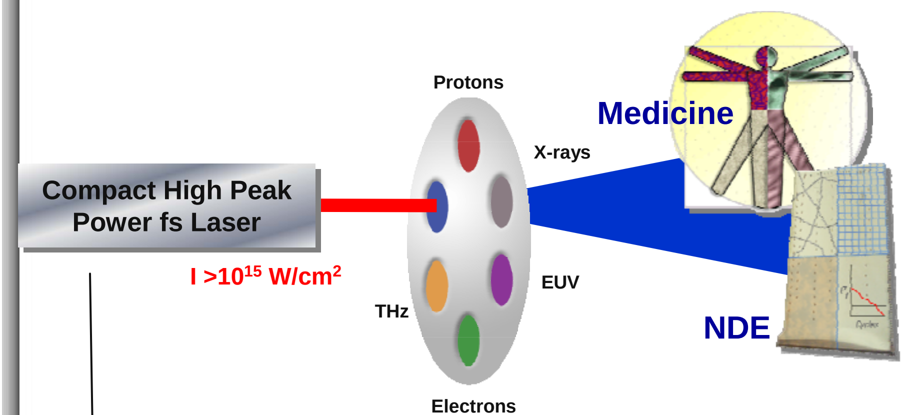
Pulse with incrementing frequencies (left) and an 'OAWG' pulse (right) generated using a silica-based OAWG

- **Goal**
  - To develop technologies capable of producing arbitrary optical waveforms with capabilities comparable to modern day electronic arbitrary waveform generators
- **Technical Challenges**
  - Compact, stable, high-bandwidth optical oscillators based on carrier-envelope-phase-stabilized, mode-locked femtosecond lasers
  - Scalable, ultra compact, high-performance optical encoder/decoders
    - High-speed electronic drivers
    - Minimize phase errors and crosstalk
  - Precision OAWG measurements
- **Key Accomplishments**
  - Functioning 1GHz frequency comb clock
  - RF packaging of the 1st InP OAWG optical chip (10 channels @ 10 GHz spacing)
  - Operational silica-based OAWG
  - Demonstrated digital matched filter
- **Impact**
  - Applications include high performance RADAR, > 1 TB/s optical communications, synthetic aperture LADAR, …

Hyperspectral Radiography Sources

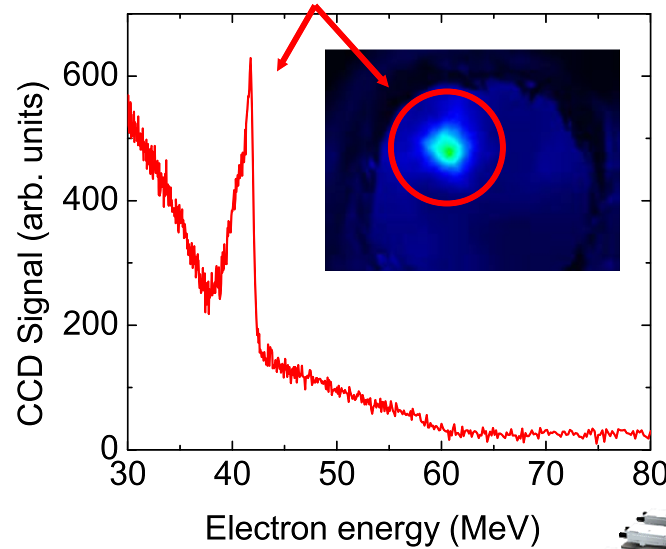
- **Produce radiation and particle beams for imaging, tomography, therapy, and nonlinear spectroscopy using a single, laser-driven source**
- **Two areas where this will have immediate impact: non-destructive material evaluation (NDE) and medicine (imaging and therapeutics)**

Bring high-quality radiation sources to the experiments, rather than experiments to the radiation sources; bring near-national facility capability to the table-top.

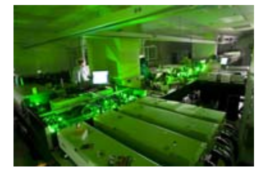


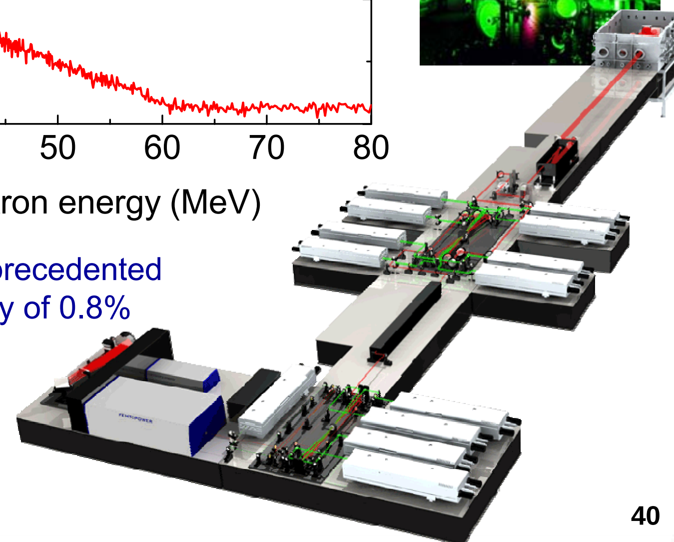
Produce particle beams and optical radiation with short (~1 s) reconfiguration times that are **tunable**, **monochromatic** and with high **brightness** and **coherence**.

Laser accelerated multi-MeV energy stable electron beam



Laser has unprecedented energy stability of 0.8% rms @ 8hrs





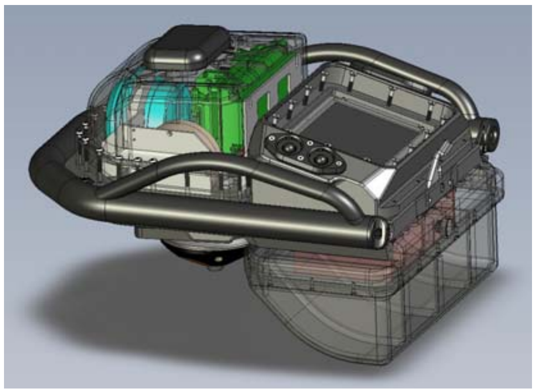
Powerswim

Results to Date

- **Sustained speeds 50% greater than with fins during ½ mile swims**
- **Achieved speeds up to 2kt with OFD's**
- **Preliminary results: >50% improvement in metabolic efficiency**

Specification	***Current SOA - Fins***	***Oscillating Foils - Objective***
Max Sustainable Speed	**1 kt**	**2.5 kt**
Propulsive Efficiency	**15%**	**5X**
Caloric Efficiency	**2.5%**	**5X**
Weight	**3 lb**	**Same as fins**
Packed Volume	**960 in3**	**Same as fins**

Tactical Underwater Navigation System



- **Bringing diver navigation out of the 18th Century…**
  - **Integrates inertial sensors, moving map display, Doppler sonar**
  - **Low size, weight and power; robust packaging**
  - **Diver location algorithms robust to varied speed, swimmer heading…**
  - **GPS-denied CEP of >100 m after an hour swim – Verified in open water tests October 2007**
  - **Sonar-based hydrographic survey for amphibious reconnaissance**