Quantum-gas physics in orbit

prospects for microgravity Bose-Einstein condensates aboard ISS with NASA CAL (Cold Atom Laboratory)

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University of Virginia colloquium

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GUIDING QUESTIONS

- Can experiments on ultracold atoms shed light on fundamental physics issues?
- Can we use ultracold atoms to do something "useful"?
- How close to absolute zero can we get?

Colloquium on advanced cooling techniques


Portland, Maine has a 'snow dump' so tall that it's posing a hazard to aircraft

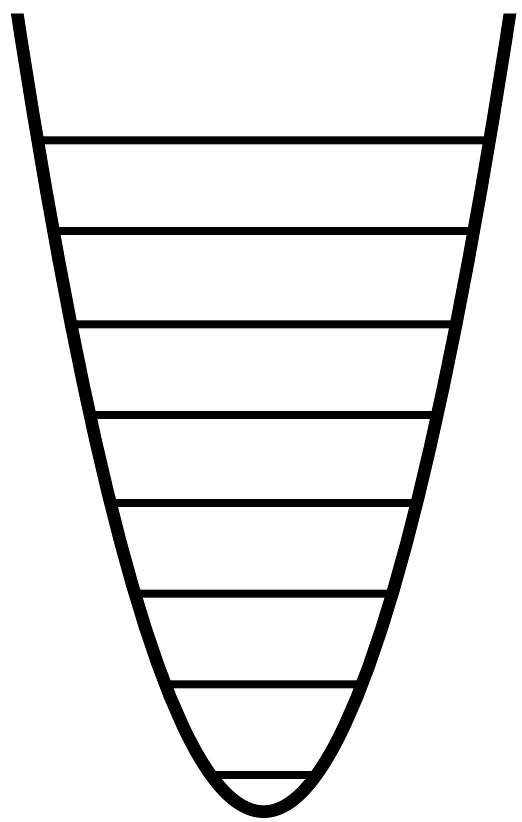
Outline

- Bose-Einstein condensation refresher
- NASA CAL
- Tailored bubbles of quantum gas aboard CAL
- Tailored lattices for terrestrial BEC

Outline

- **Bose-Einstein condensation refresher**
- NASA CAL
- Tailored bubbles of quantum gas aboard CAL
- Tailored lattices for terrestrial BEC

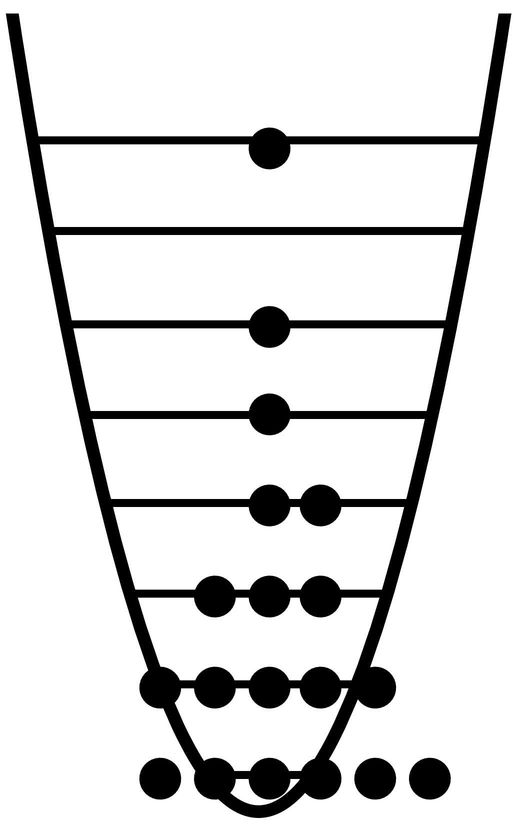
BEC



- Given some local minimum in potential energy, how does a cloud of **N** atoms in equilibrium at temperature **T** (*of order the energy-level spacing but not zero*) distribute among the energy levels?

- Maxwell-Boltzmann statistics (distinguishable)
- Fermi-Dirac statistics
- Bose-Einstein statistics

BEC



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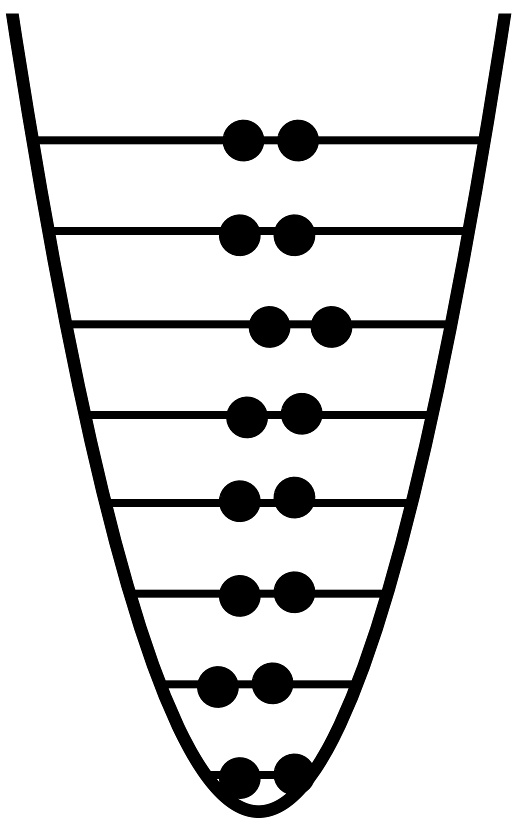

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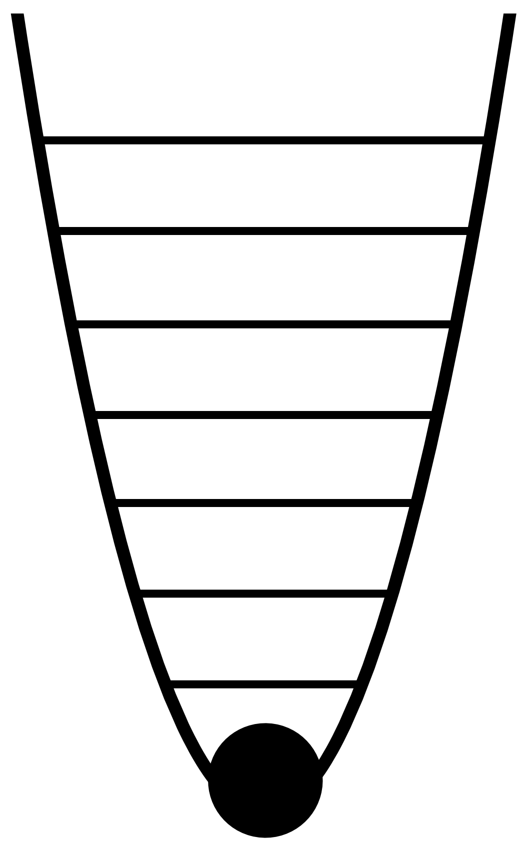
BEC



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- *Startling pileup in the lowest-energy state at nonzero **T**!*

20 (or 90) years of BEC

Quantentheorie des einatomigen idealen Gases.

Zweite Abhandlung.

Von A. Einstein.

Ich behaupte, daß in diesem Falle eine mit der Gesamtdichte stets wachsende Zahl von Molekülen in den 1. Quantenzustand (Zustand ohne kinetische Energie) übergeht, während die übrigen Moleküle sich gemäß dem Parameterwert $\lambda = 1$ verteilen. Die Behauptung geht also dahin, daß etwas Ähnliches eintritt wie beim isothermen Komprimieren eines Dampfes über das Sättigungsvolumen. Es tritt eine Scheidung ein; ein Teil »kondensiert«, der Rest bleibt ein »gesättigtes ideales Gas« ($A = 0$ $\lambda = 1$).

"I maintain that, in this case, a number of molecules steadily growing with increasing density goes over in the first quantum state (which has zero kinetic energy) while the remaining molecules separate themselves … *A separation is effected; one part 'condenses', the rest remains a saturated ideal gas.*"

20 years of BEC

Quantenthe … en Gases.

Ich behaupte, d … ts wach-
sende Zahl von Mol … netische
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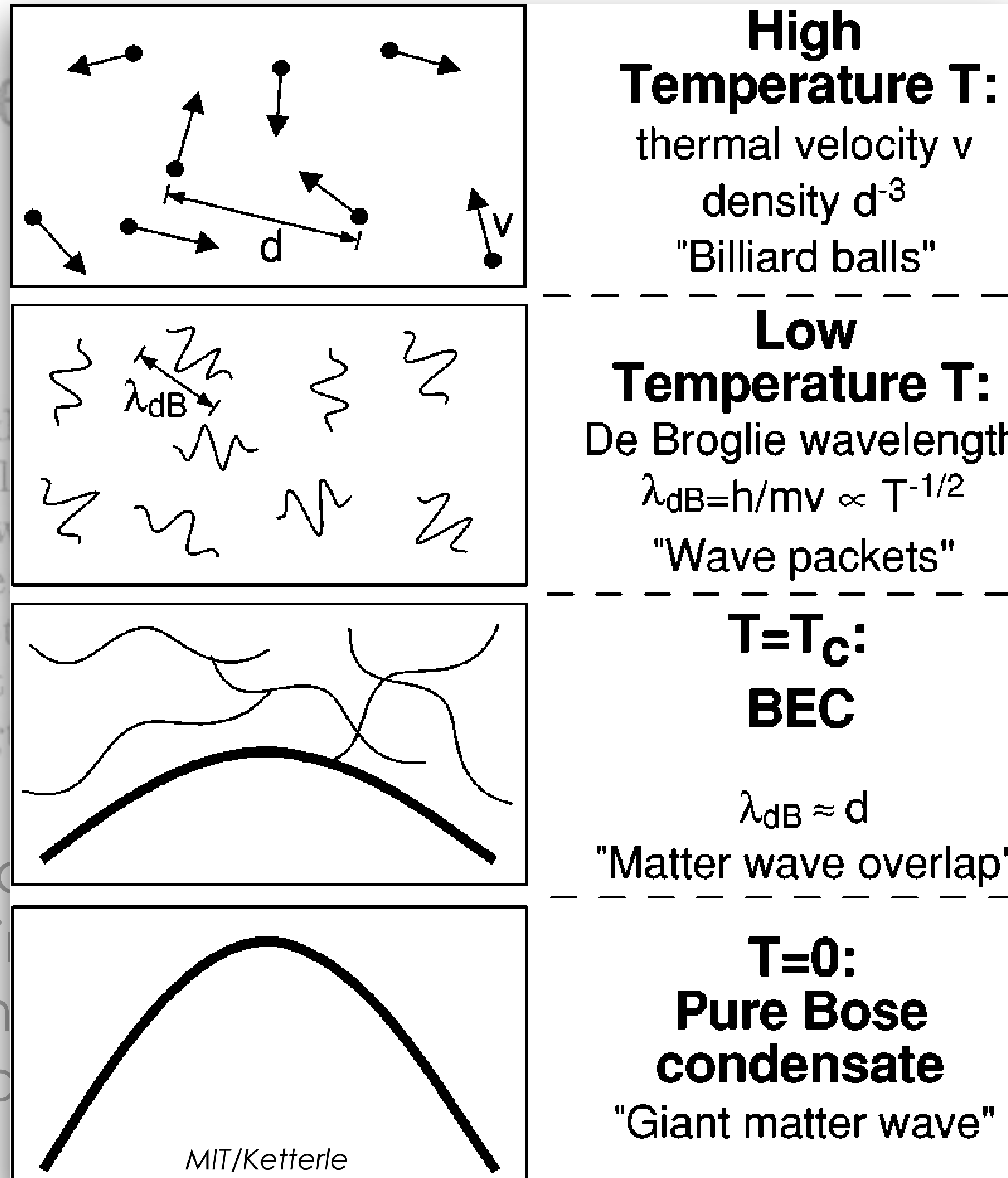

"I maintain th … s steadily
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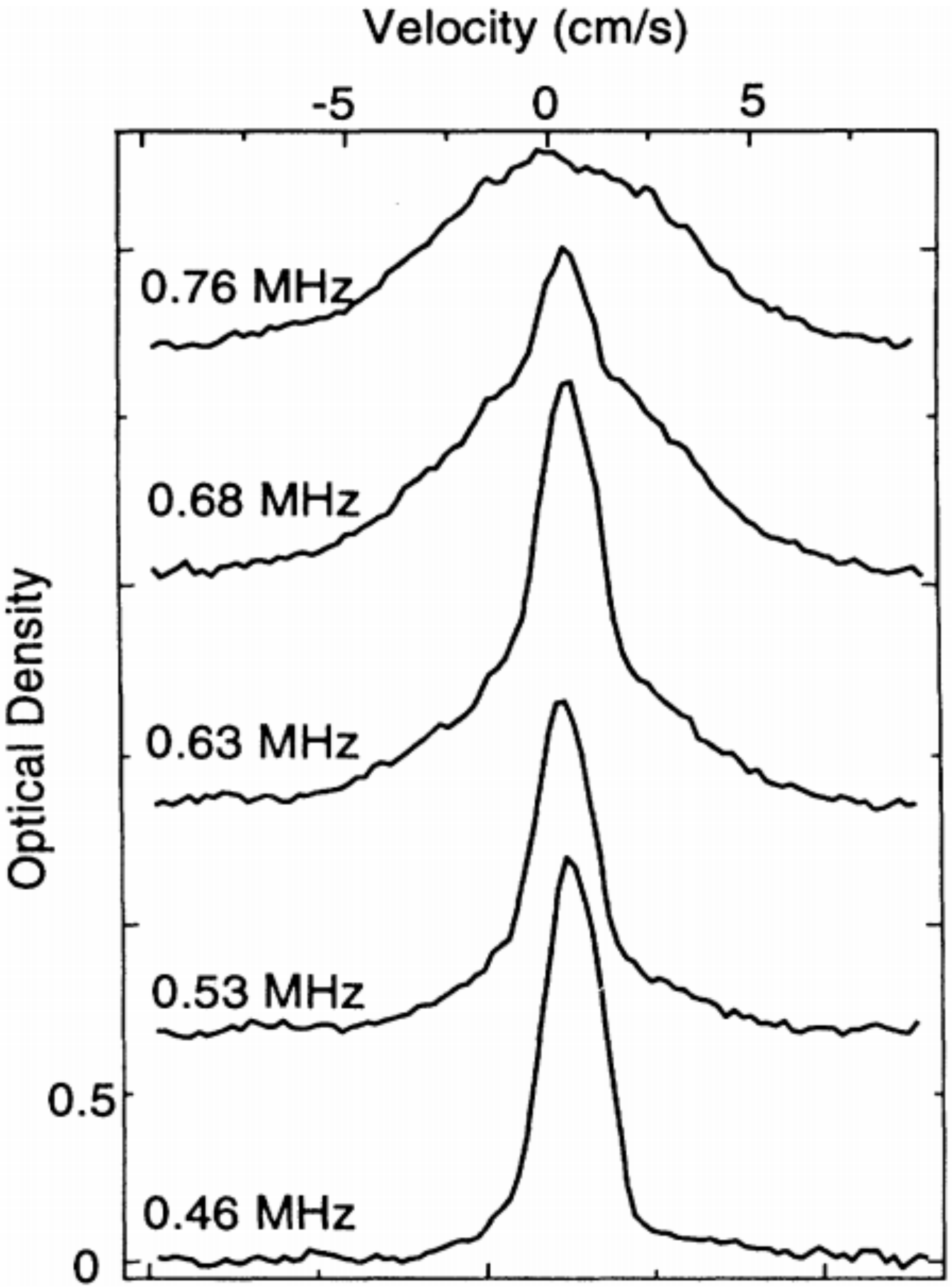
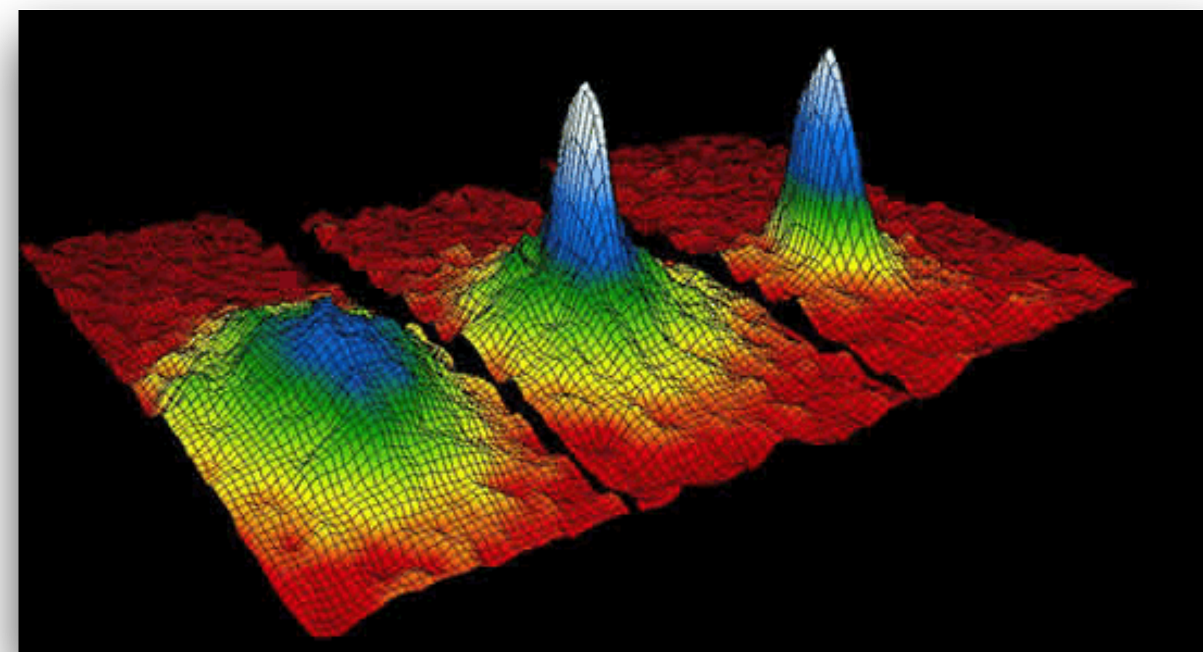
20 years of BEC

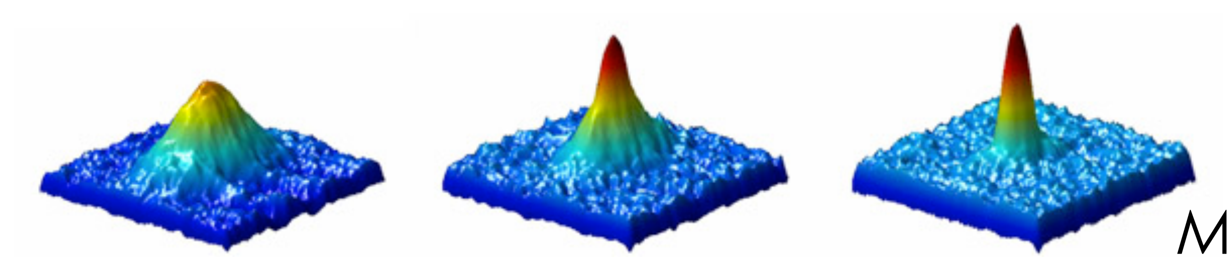


MIT 1995 sodium; also 1998 hydrogen

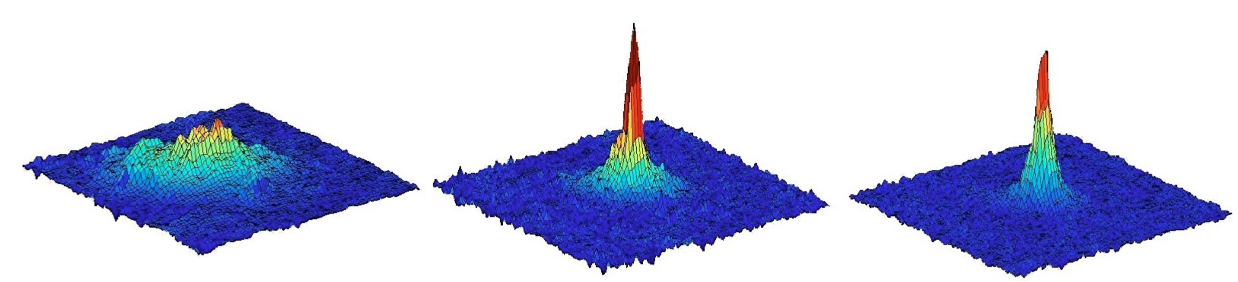


JILA 1995

(Other early BEC: Rice 1995, Texas 1997, Rowland 1997, Stanford 1997, Konstanz 1997, MPQ 1998, NIST 1998…)



MPQ



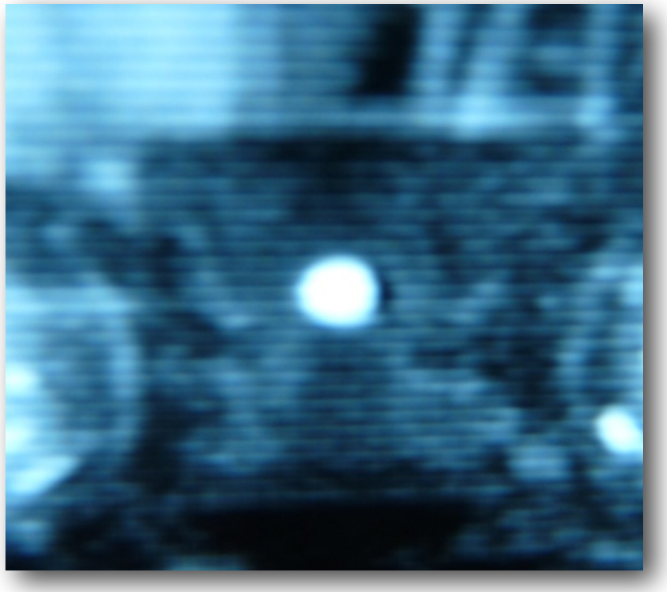
JPL 2005

Early growth of a field

- ~30 ultracold labs in 2001, ~150 today?
- 1999: first degenerate Fermi gas (DFG)
- 1998-2002: early development of BECs in periodic potentials ("optical lattices")
- 2002: observation of Mott-insulator/superfluid transition of a BEC in an optical lattice
- ultracold molecules at various stages…

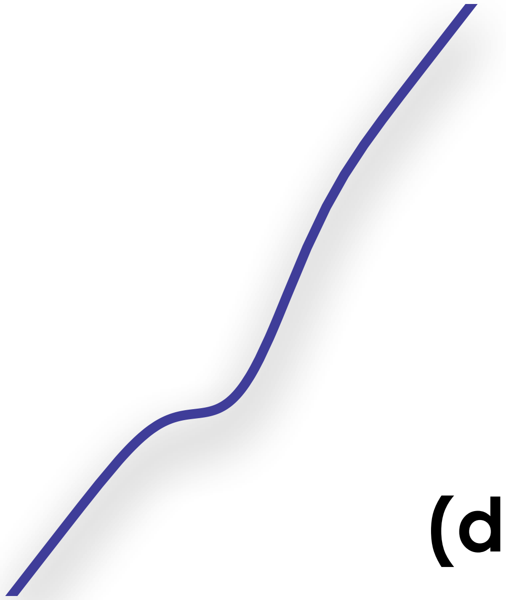
Making BECs & terrestrial limitations

- ➢ Source: alkali (among many more now) vapors or beams
- ➢ Laser cooling to roughly sub-mK temps
- ➢ Transfer to conservative trap: optical or magnetic
- ➢ Evaporative cooling to nK regime
- ➢ Lower T… weaker trap? Collision rate limits equilibration (as does background vacuum pressure)



➢ **m g / k (Rb) = 0.1 mK / mm**

➢➢➢



(dumping)

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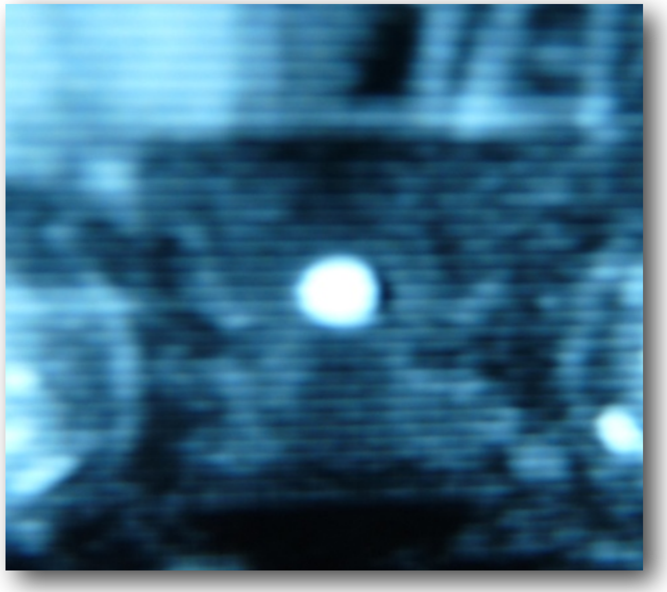

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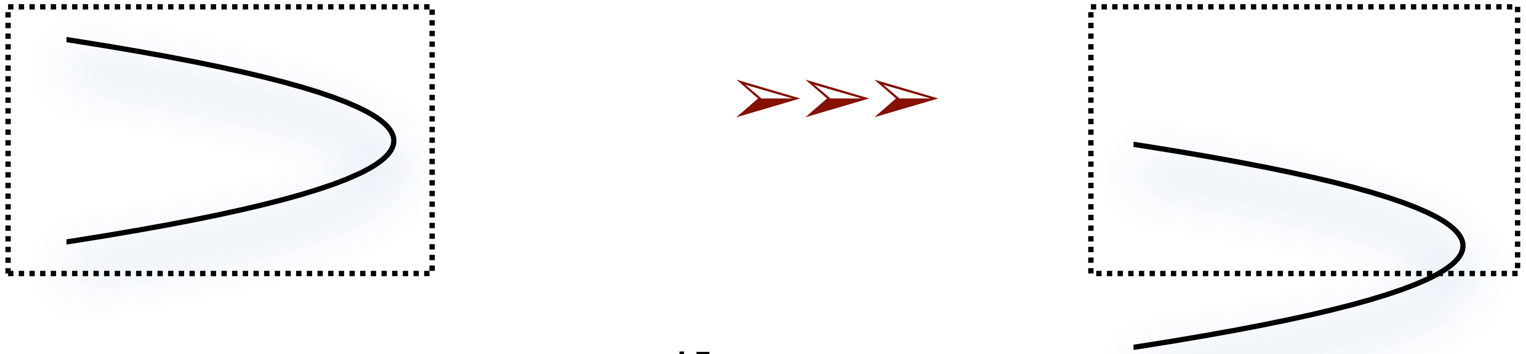

(trap sag)

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BEC physics in microgravity

- **NASA CAL**: BEC machine in (extended, orbital) microgravity.

What does freefall give us?

- Very *long* interrogation times of released clouds (opportunity for attempts at pK temperatures)
- Very *weak* traps without sag or dumping
- Symmetry: no more *mgz* preferential direction!

Bates

CAL mission architecture

Human Exploration and Operations Mission Directorate:
Space Life and Physical Sciences Division:
Physical Science Research Program
NRA: *Research Opportunities in Fundamental Physics*

Science Definition Sept 2012 → Development 2012-2016 → Delivery Sept 2016 → Launch Dec 2016 → Mission Operations Jan 2017-2020

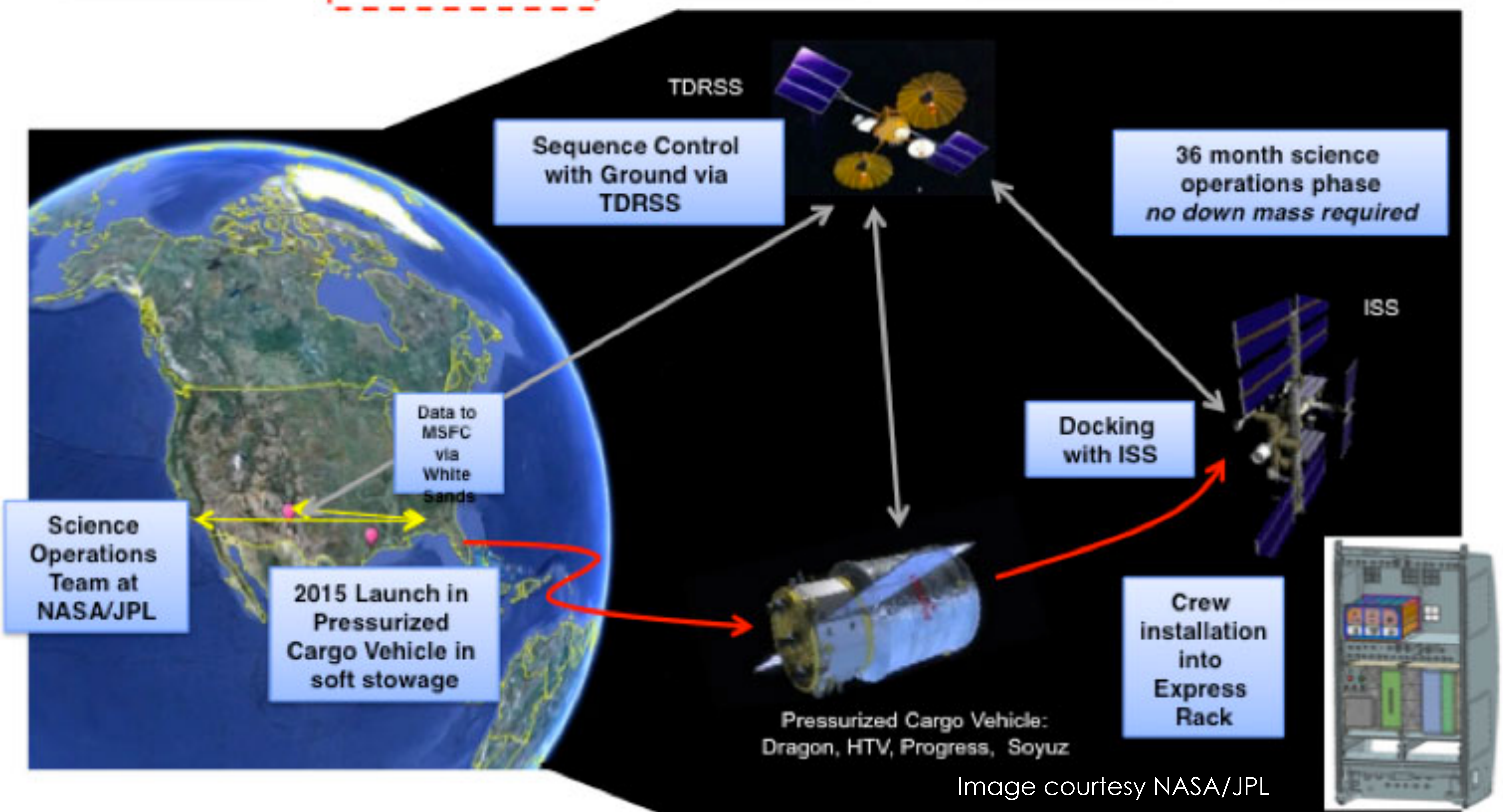
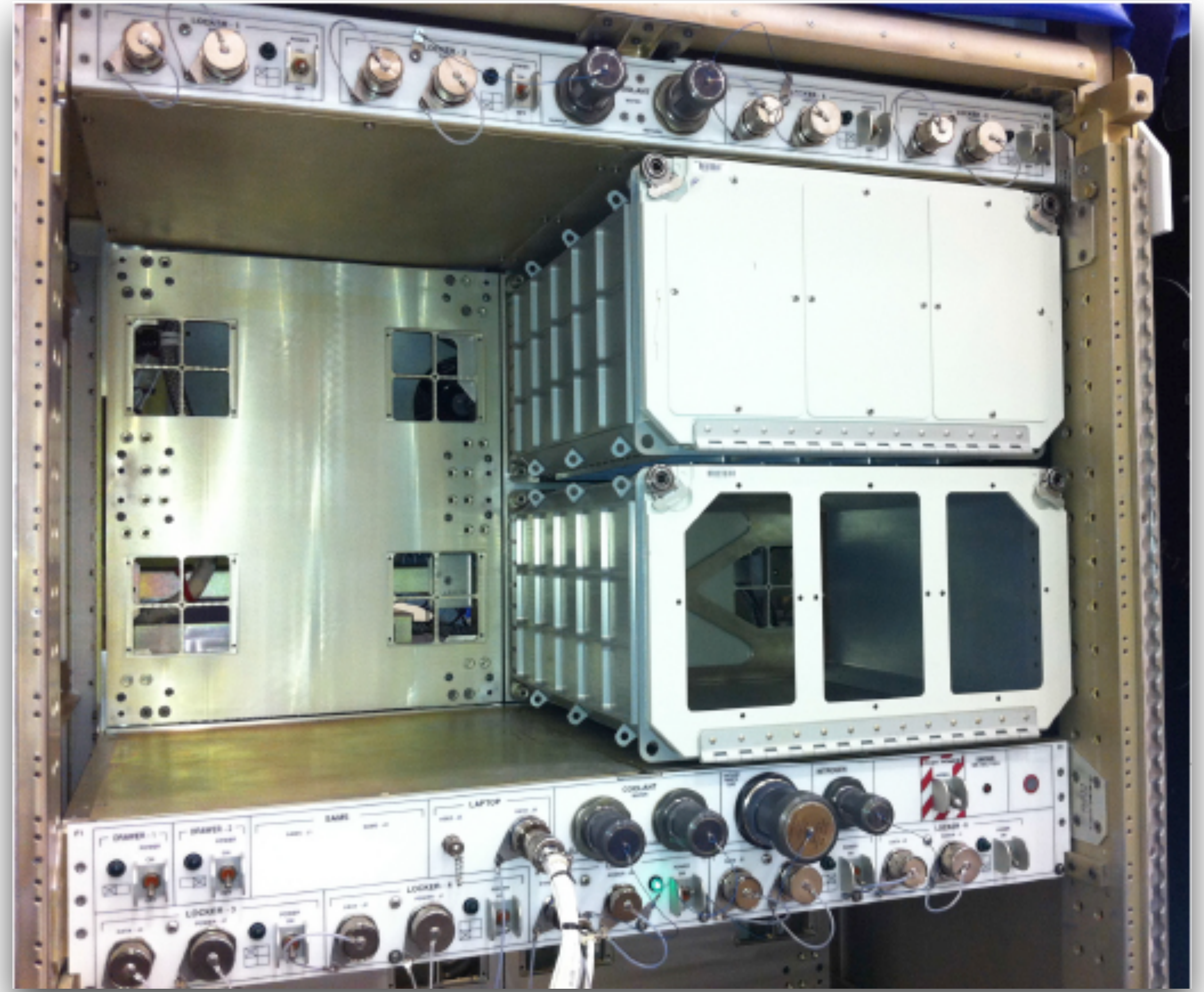


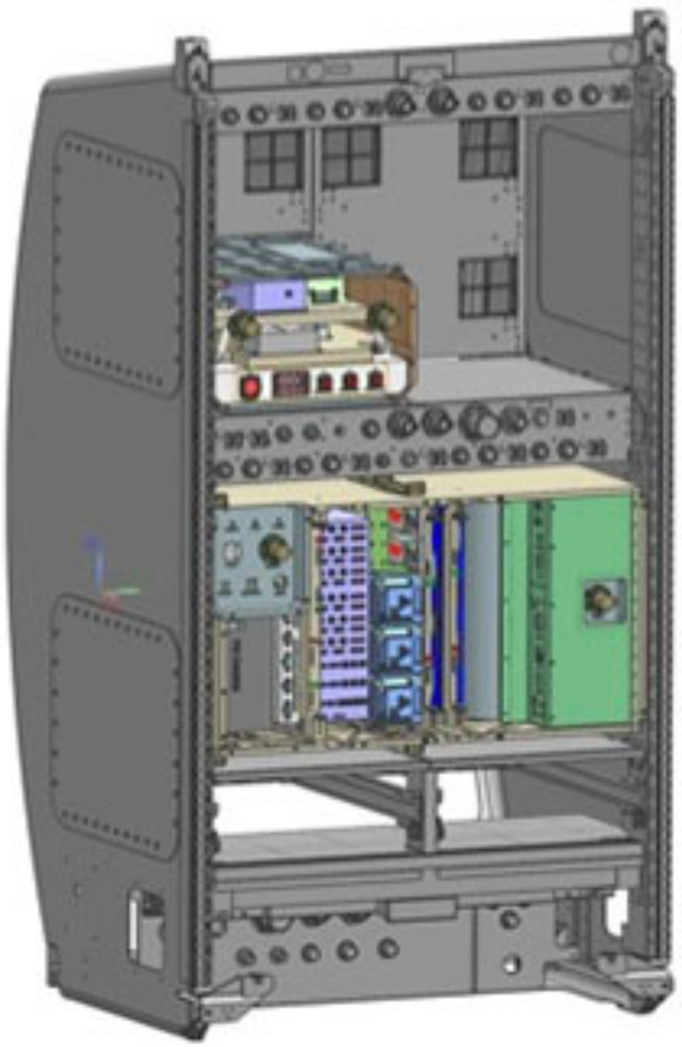
Image courtesy NASA/JPL

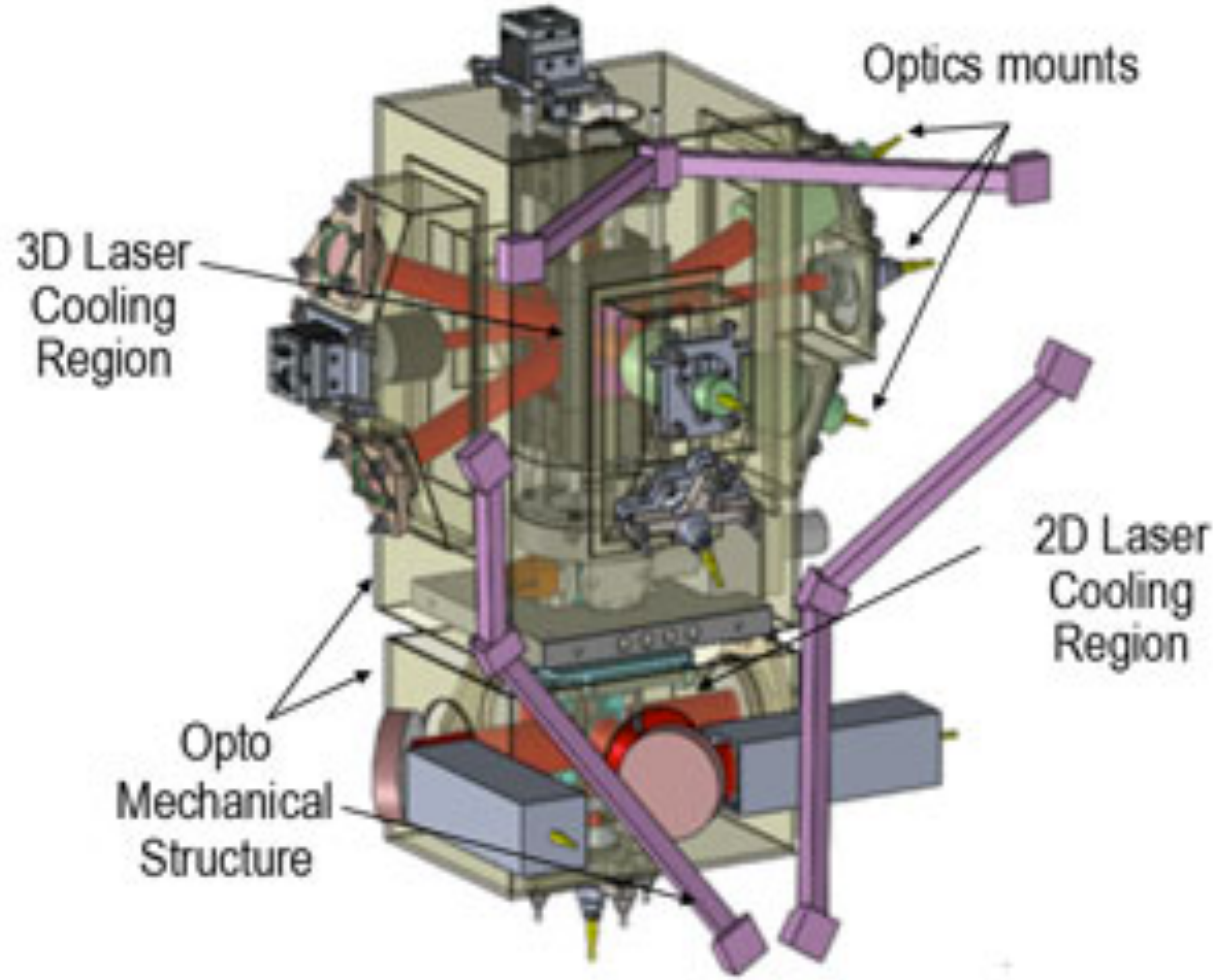
Pressurized cargo vehicle aboard Dragon

EXPRESS rack



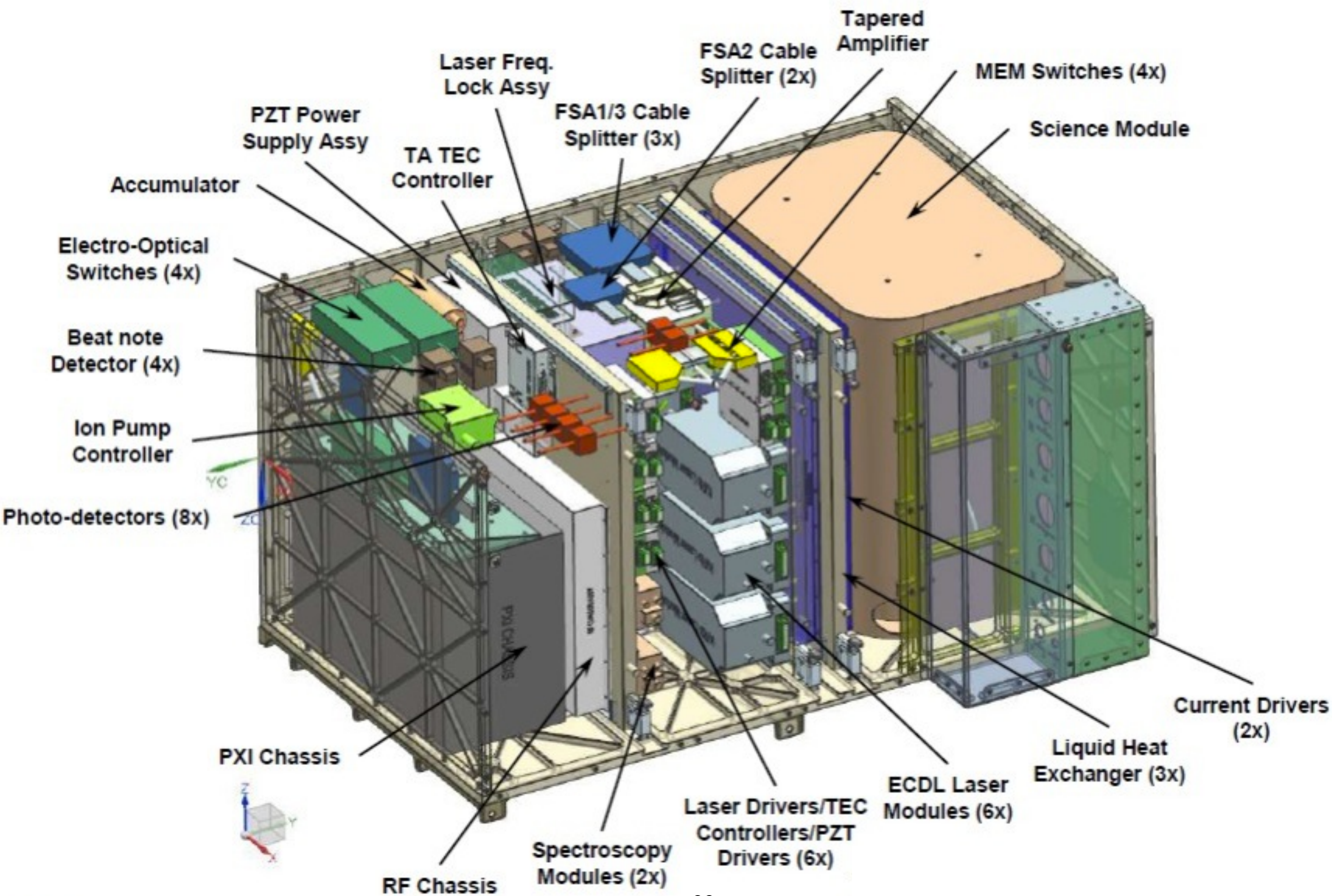
CAL in rack / Science Module





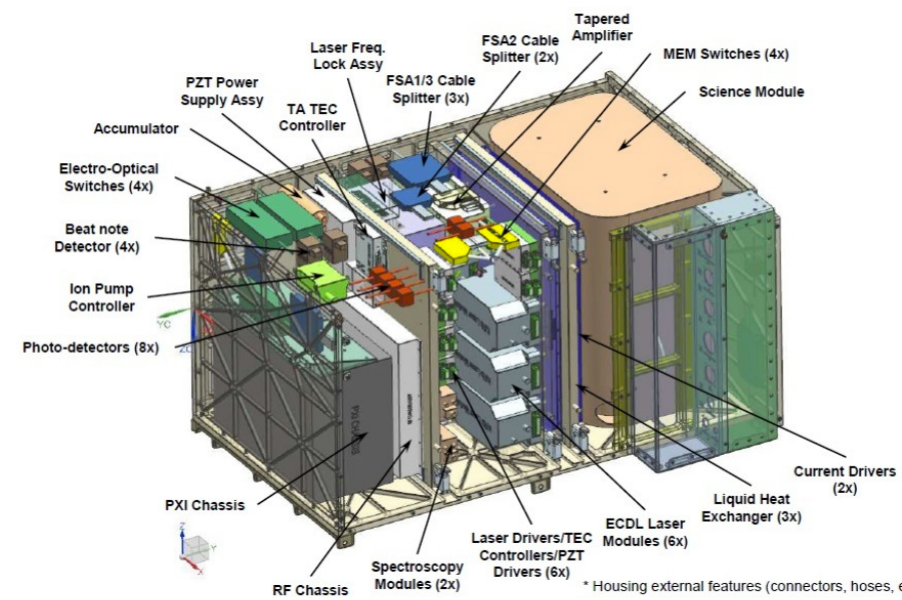
Science Module
(magnetic shield not shown)

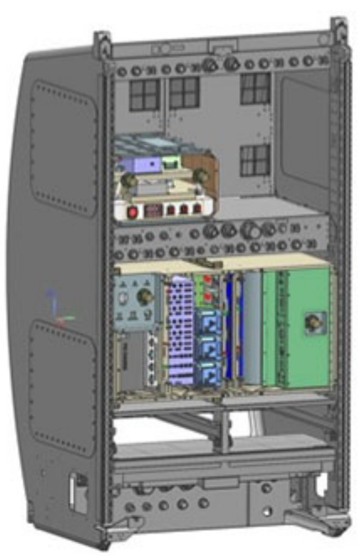
CAL in rack / Science Module

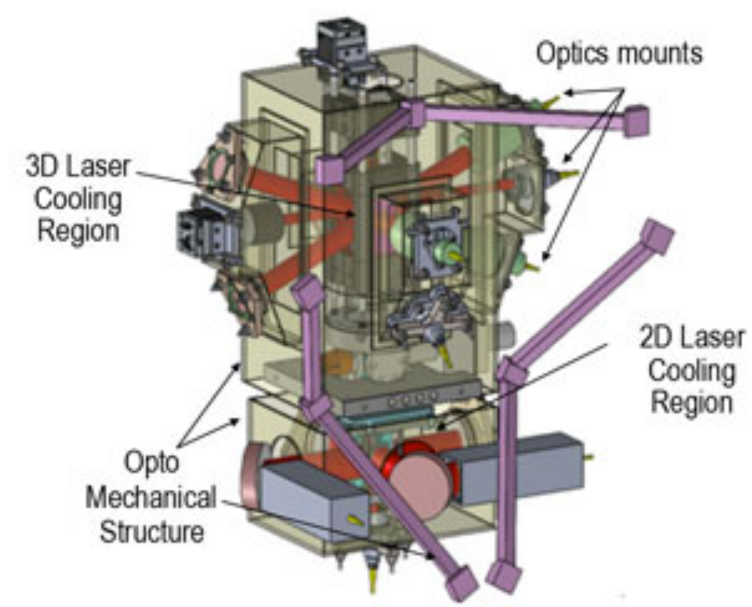


BEC as user facility?

- ➢ Single-mode fiber coupling
- ➢ Polarization control
- ➢ Optical alignment in general
- ➢ Laser or atomic source replacement?







Science Module
(magnetic shield not shown)

Turn-key BEC system?

Employment | Contact

ColdQuanta

Cold Atom & Ultracold Atom Products Company Atomic Physics Resources

Ultracold Atoms & BEC

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PRODUCTS

- Optical Lattice & Atom Chips
- **Ultracold Atoms & BEC**
- Cold Atoms Magneto-Optical Trap (MOT)
- Custom Vacuum Products
- AR Coated Glass Cells
- BEC and Ultracold Atom Electronics

New: Portable Ultracold Atom Lab

Roll your BEC or ultracold atom system to your desired location in your premises. The system consists of an ultra-high vacuum cell, complete physics package and all the required electronics, lasers, optics, and imaging equipment to create and image Bose-Einstein condensate and forms of ultracold atoms

NASA CAL science projects

- "Coherent magnon optics"
- "Atom interferometry with quantum gases in microgravity"
- "Zero-g Studies of few-body and many-body physics"
- "Microgravity dynamics of bubble-geometry BEC"
- "High-precision microwave spectroscopy of long-lived circular-state Rydberg atoms in microgravity"
- "Consortium for Ultracold Atoms in Space"
- "Development of Atom Interferometry Experiments for ISS CAL"

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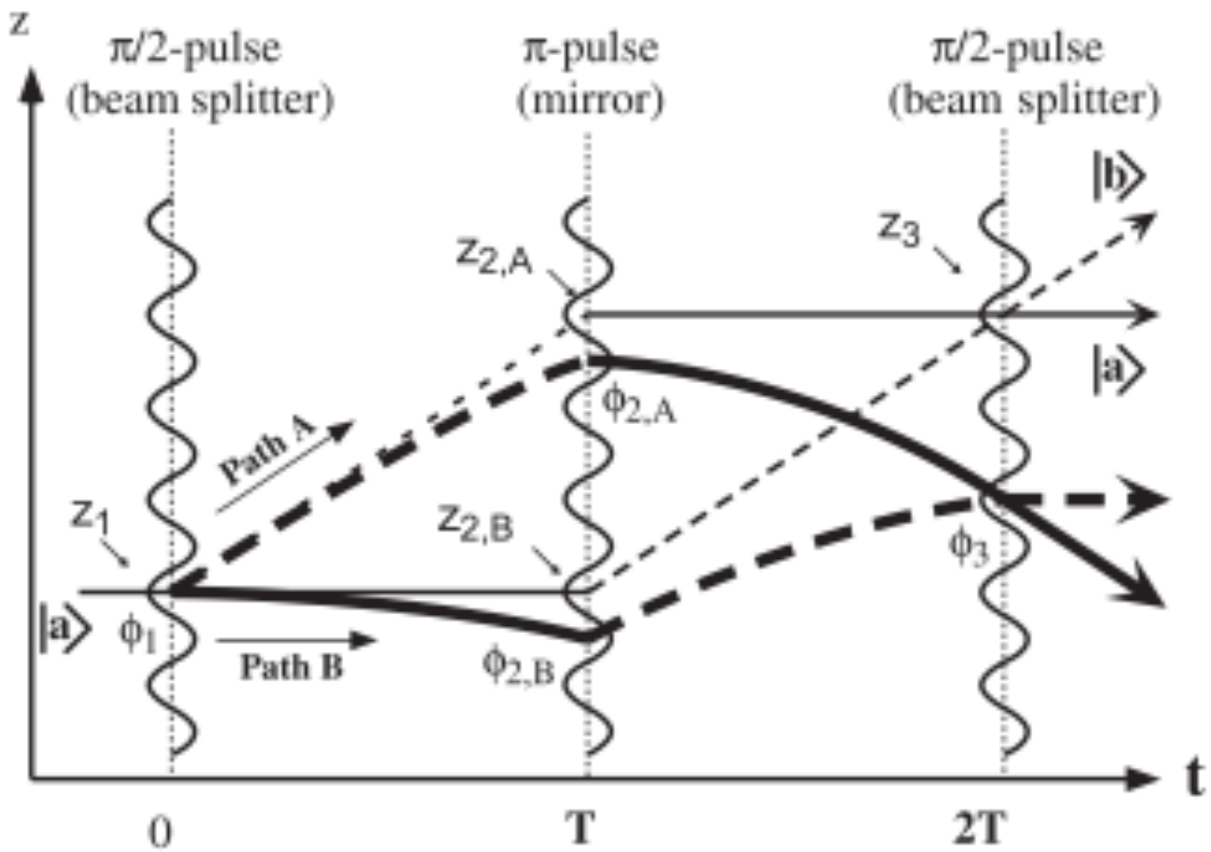
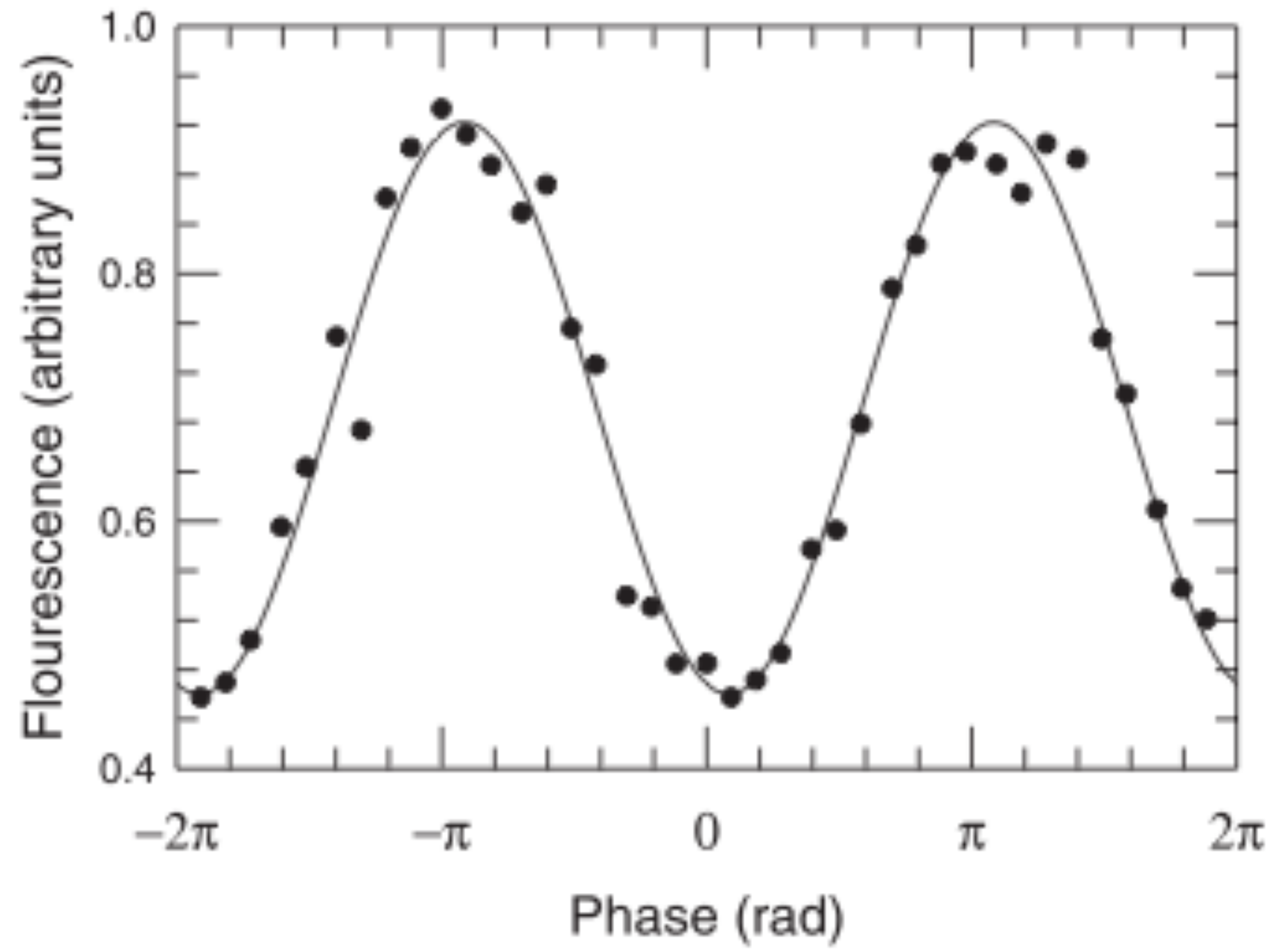
Jet Propulsion Laboratory
California Institute of Technology

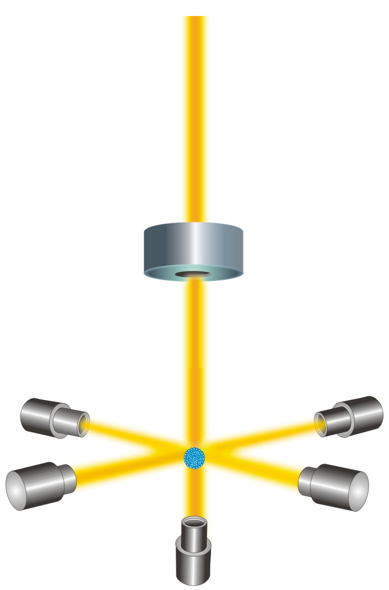
Bates

Atom interferometry



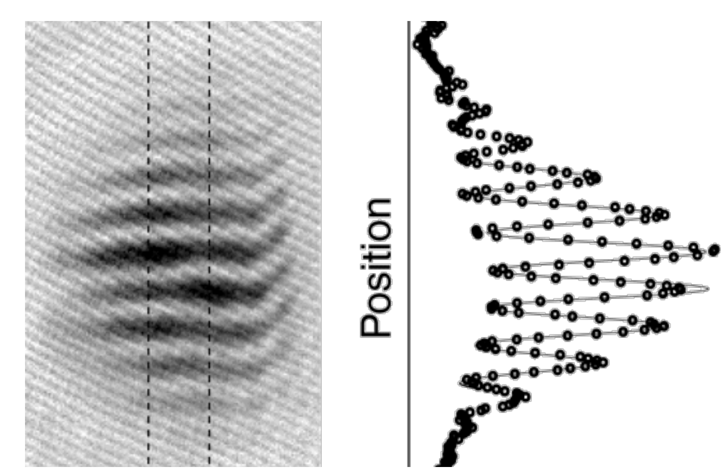
Kasevich 2008





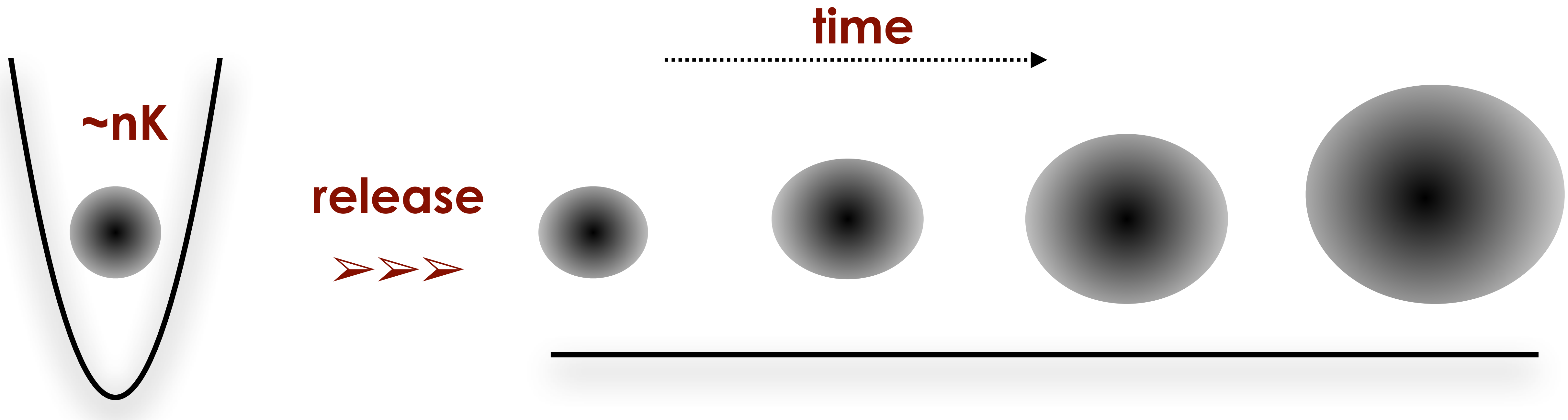
NIST

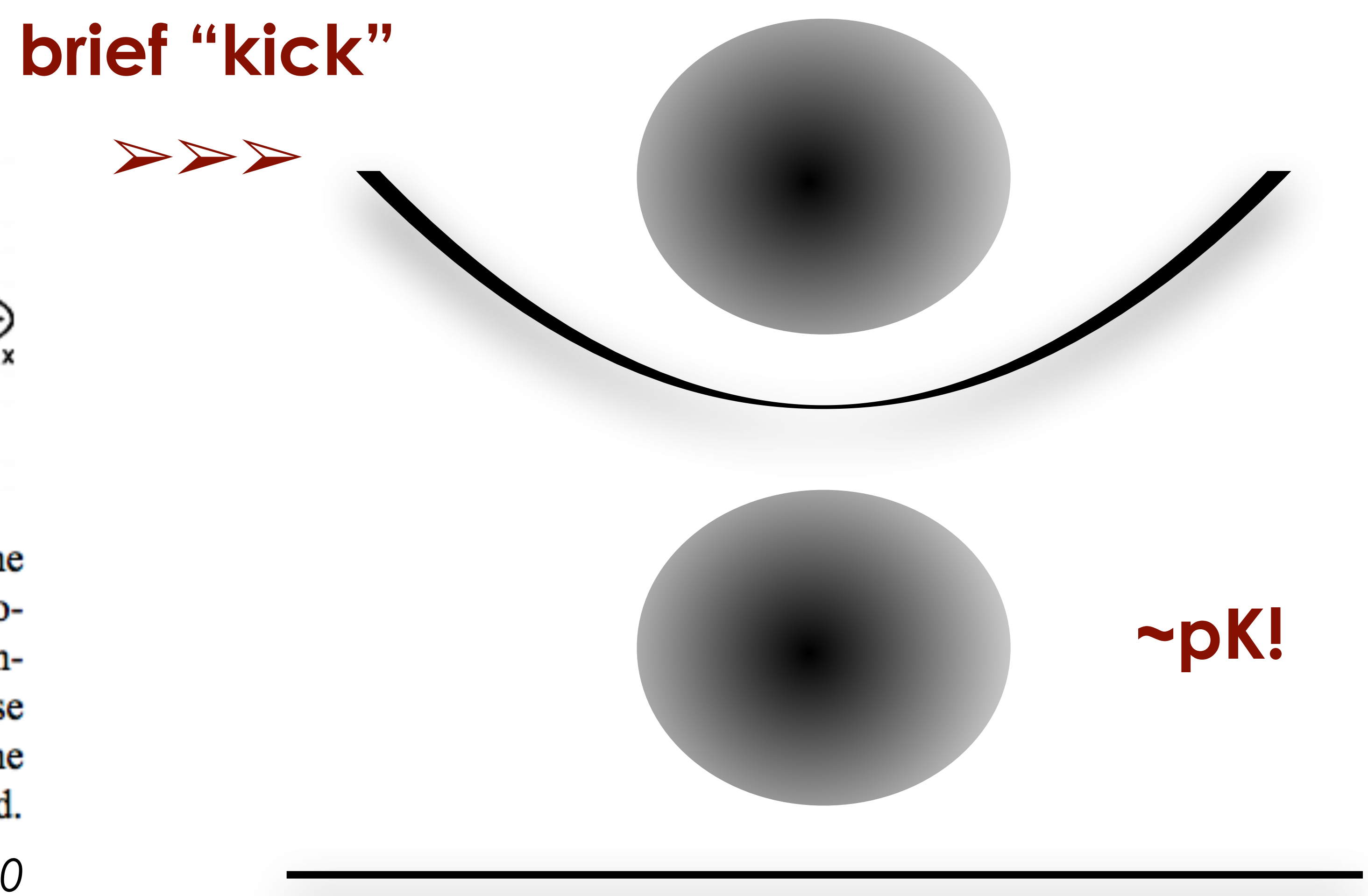
- ➢ NIST F1 time standard (Cs fountain)
- ➢ Evolution time limited by gravity
- ➢ Can do interferometry with BECs…



MIT

Delta-kicked cooling





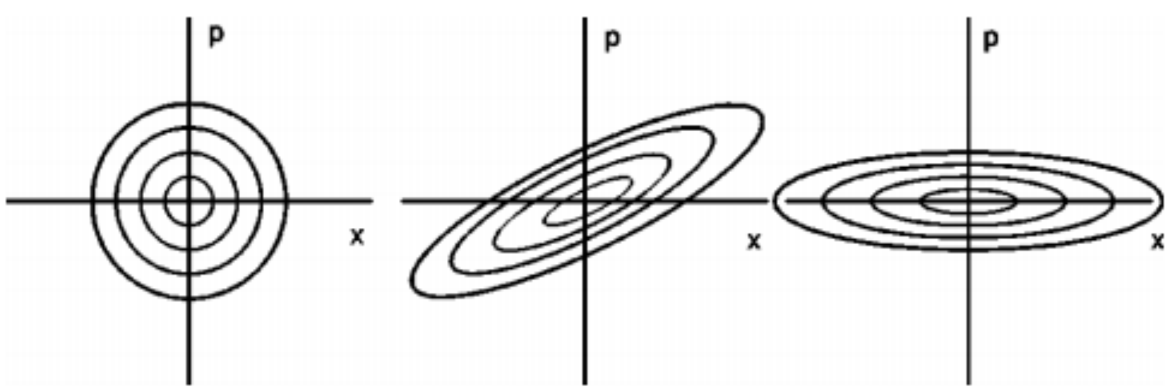


FIG. 1. Phase-space diagrams. (a) Upon release from a trap, the atoms have independent Gaussian distributions in position and momentum. (b) After a period of free expansion, position and momentum are partially correlated, leading to a tilted ellipse in phase space. (c) Application of a pulsed harmonic potential rotates the distribution onto the x axis, lowering the temperature of the cloud.

Myrskog 2000

Outline

- ➢ Bose-Einstein condensation
- ➢ NASA CAL
- ➢ **Tailored bubbles of quantum gas aboard CAL**
- ➢ Tailored lattices for terrestrial BEC

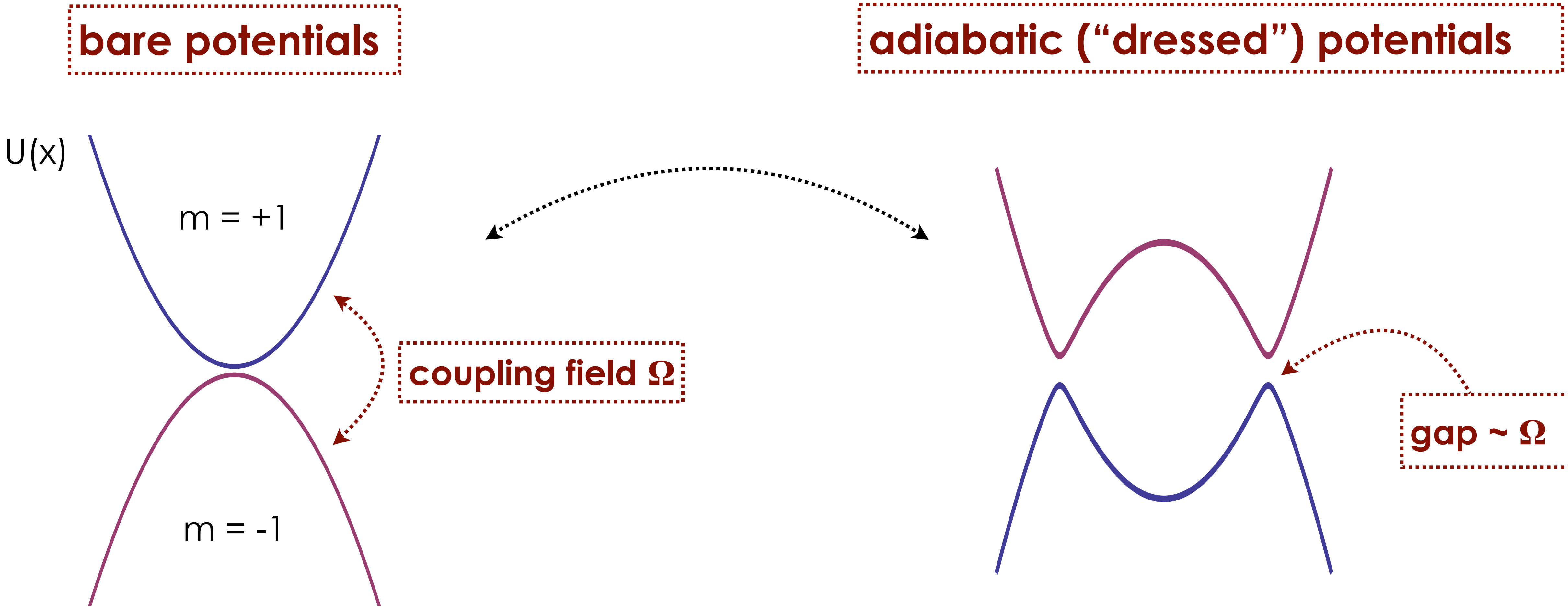
New BEC geometries

➢ History of the field has been an exploration of **geometry**, **dimensionality** and **topology**. 1D condensates, 2D condensates (BKT physics), toroidal condensates, box condensates, double-wells.

➢ Proposal: a **bubble-geometry** BEC system: i.e. local minimum of a potential at nonzero radial position (spherical or elliptical)

➢ Features: boundary-free system, new kinds of collective excitations, possibly interesting vortex behavior, expansion dynamics, 1D/2D crossover, neat dynamical engineering of potentials…

Technique



➢ Take levels with **opposite potential curvature** and apply some external coupling Ω (perhaps rf or microwave for ground-state Zeeman sublevels)

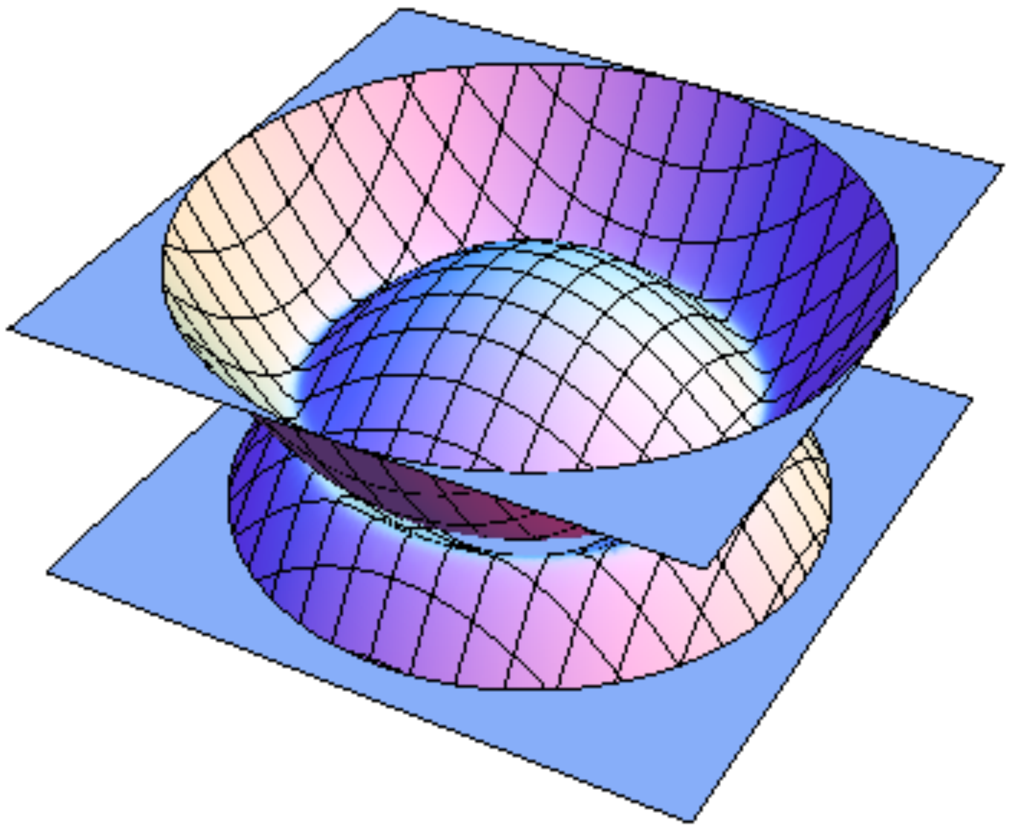
➢ Lower adiabatic potential used for evaporative cooling: upper one less used

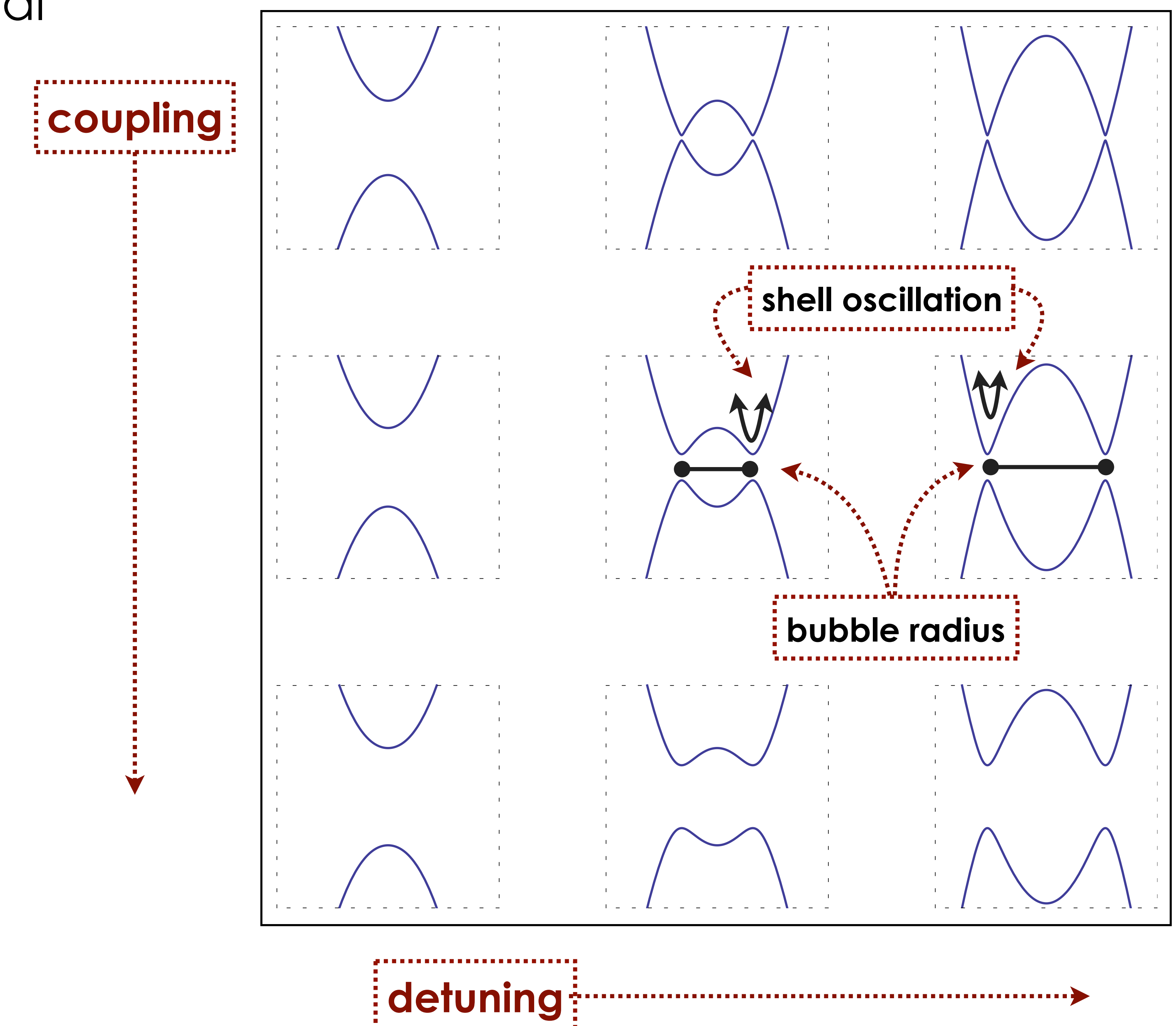
➢ theory straightforward…move to rotating frame w/ RWA, get the coupled/dressed/adiabatic potentials with LZ gap ~ Ω

➢ spatially-dependent spin superposition

Radiofrequency dressing

➢ Slice through 3D bubble potential





➢ Dressed **gap** increases with coupling, suppressing nonadiabatic losses

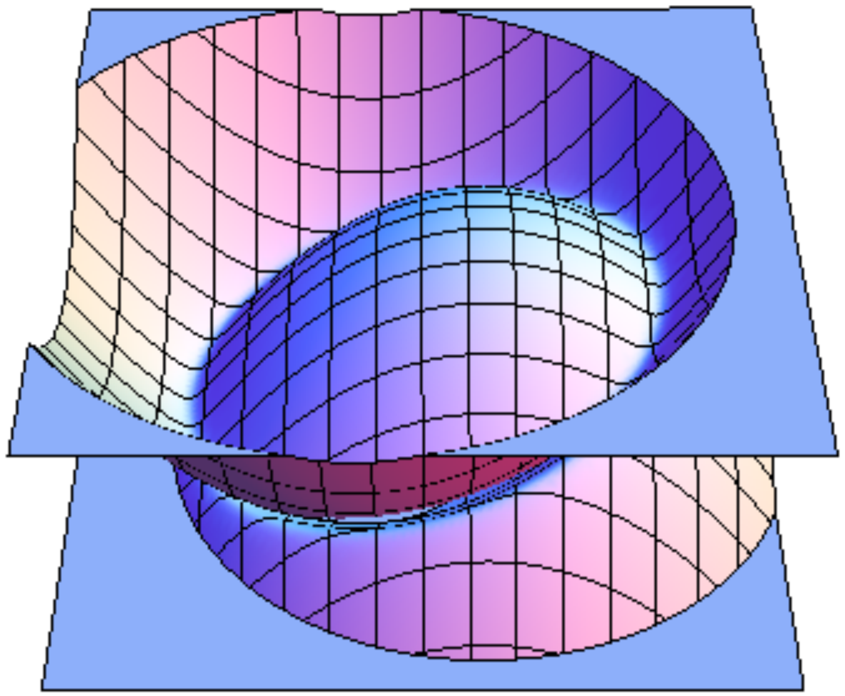
➢ Bubble **radius** increases with detuning

➢ Shell trap-**frequency** (controlling 1D vs 2D bubble) decreases with coupling

Bates

Why not terrestrial bubbles?

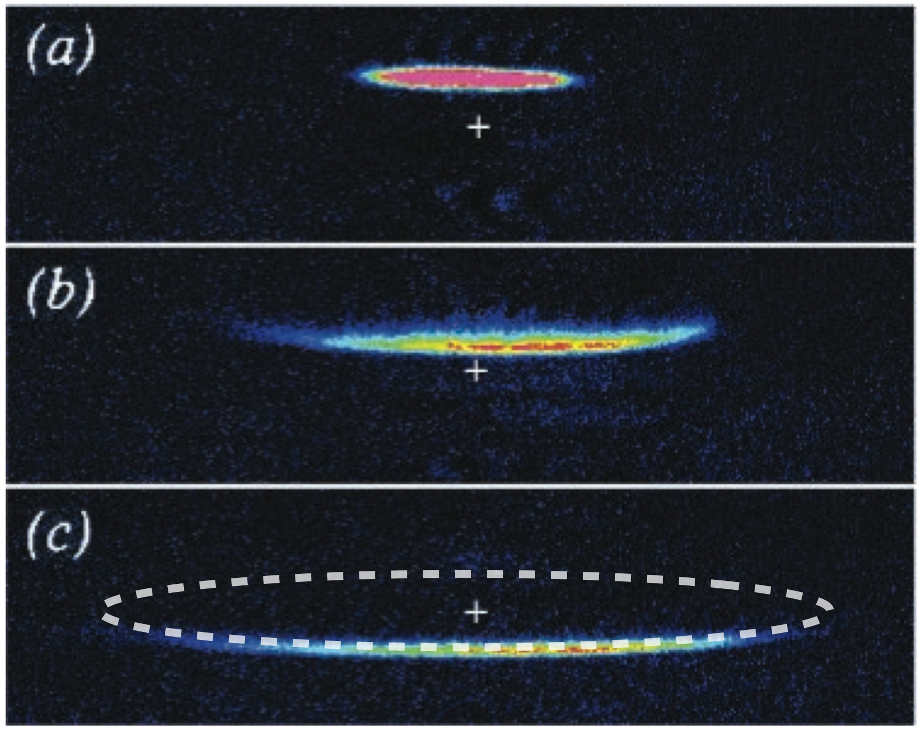
➢ “2D” slice with tilt: depending on bubble radius, BEC won’t live on shell



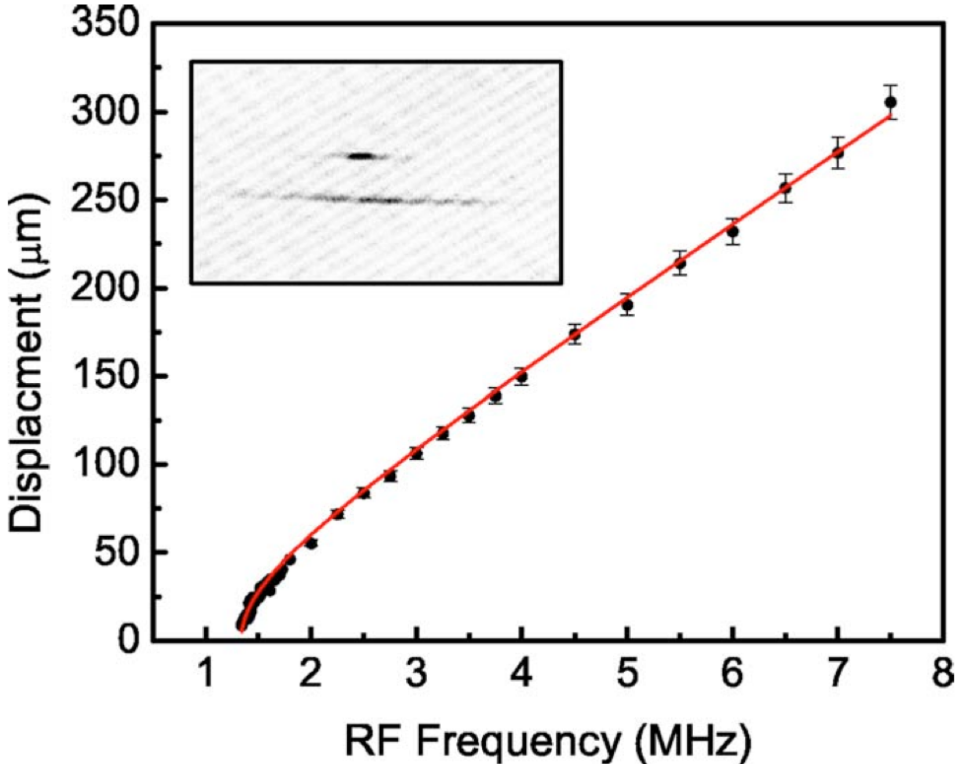
➢ Can maybe play with *very* strong traps, also light-shift gradient compensation: tough!

➢ Significant work done by **Perrin** group (Paris), **Demarco** (UIUC) creating 2D condensate held by gravity at bottom of a bubble potential. Also **Foot** (Oxford) similar work in a TAAP

➢ In this case folks deliberately use gravity: we are seeking to complete this shell/bubble!



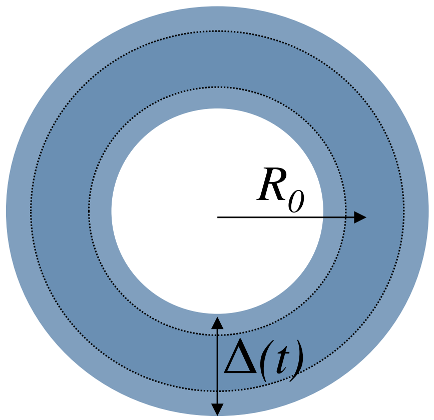
Colombe….Perrin, Europhys. Lett. ***67*** *593 (2004)*

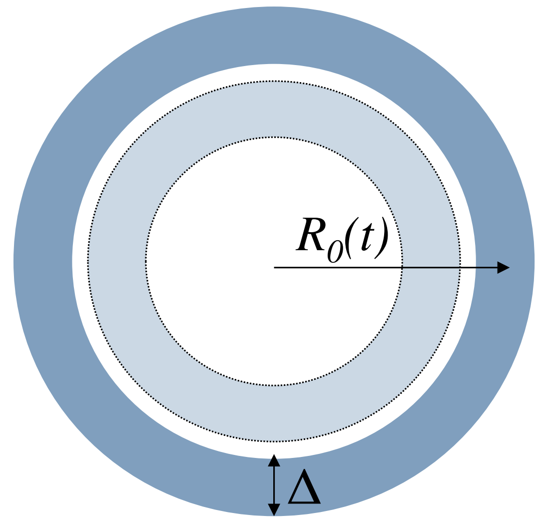


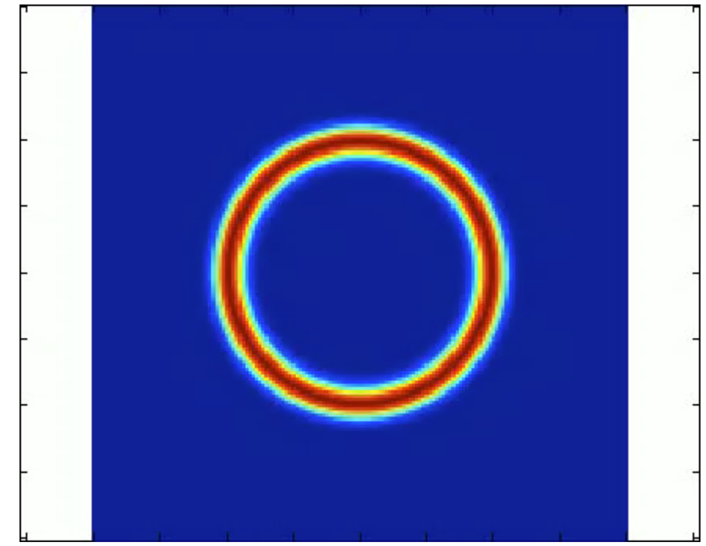
White….DeMarco, PRA ***74*** *023616 (2006)*

Bates

Possible observations



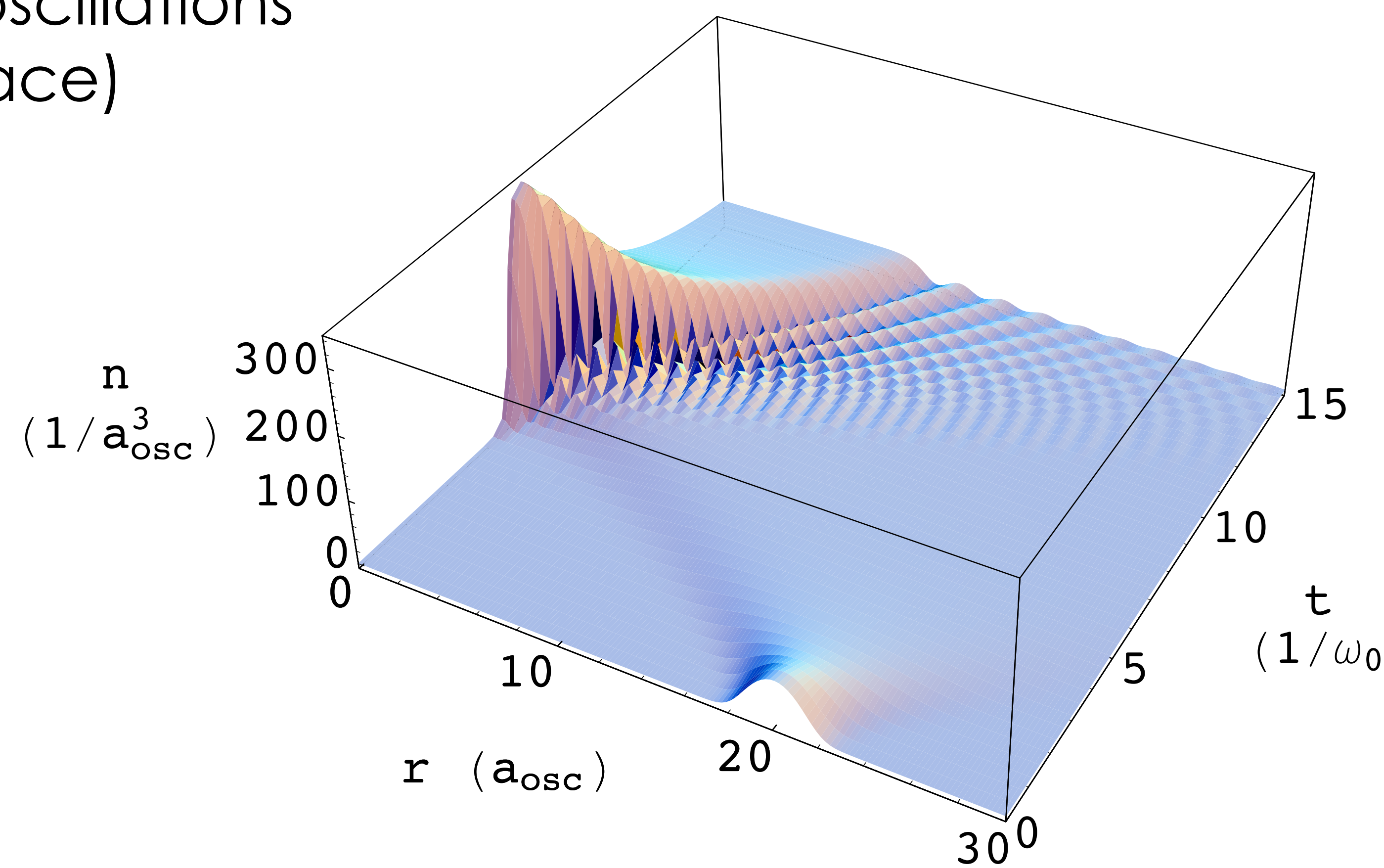




Lannert et al. unpublished

- ➢ "Accordion" mode, "balloon" mode oscillations (match up w/ theory over parameter space)
- ➢ "Collapse" of shell in time-of-flight
- ➢ 2D-3D crossover (thick/thin shell)?
- ➢ Vortex dynamics on curved surface and on unbounded simply-connected surface (possibly more interesting on ellipsoidal shell- nonconstant curvature)

(vortices are repelled from regions of positive curvature and attracted to regions of negative curvature, independent of direction of circulation)



Lannert….Vishveshwara, PRA **75**, 013611 (2007)

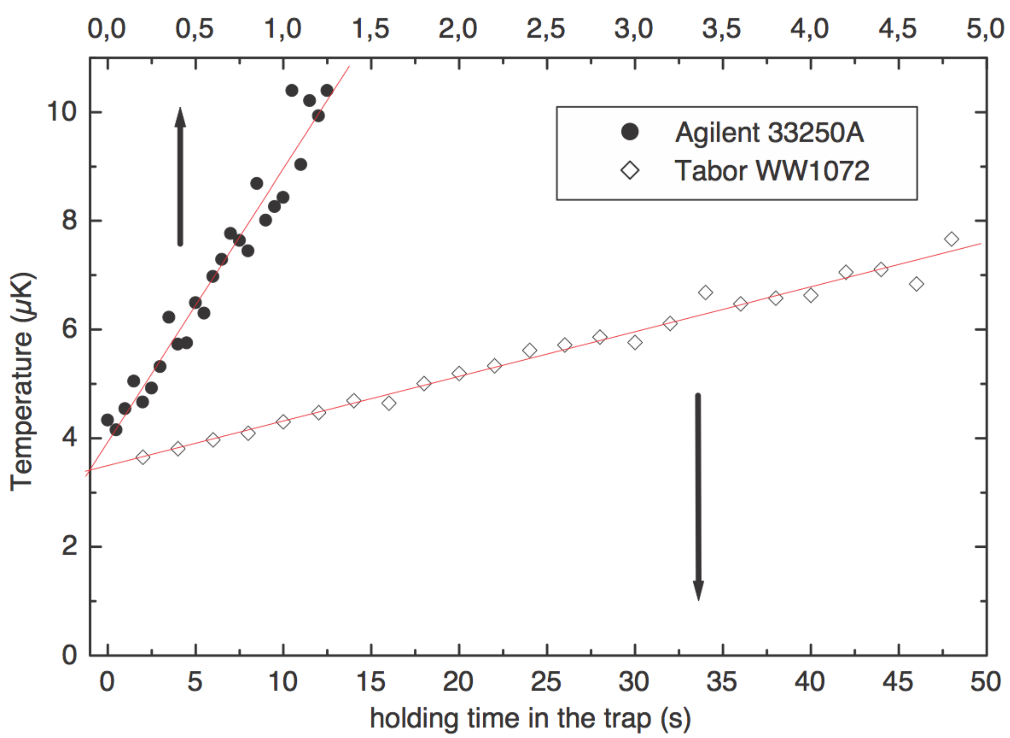
Challenges!

➢ Aspect ratio & geometry

Spherical likely impossible, but 2:1, 3:1… shouldn't affect physics too much as long as initial condensate isn't effective 1D (although worth exploring anyway)

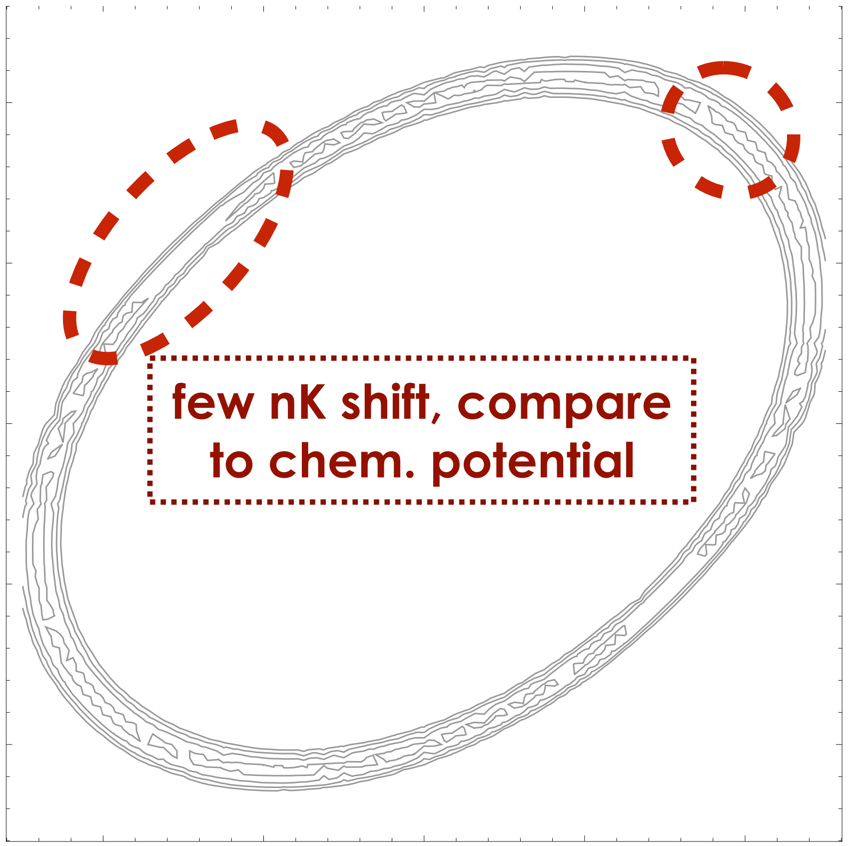
➢ Heating?

Dressing needs to be very low-noise: phase-coherent sweeping, very stable trap…



Morizot….Perrin, Europhys. Lett. ***47*** *209 (2008)*

➢ Uniformity?



Cause: wandering of angle of trap bias field…

➢ Adiabaticity?

Rabi frequency of rf coupling needs to be 10s of kHz otherwise system will just decay to lowest adiabatic potential (Landau-Zener problem, or Born-Oppenheimer failure)

Next steps

ColdQuanta, Inc

➢ Bates & JPL: building Bates-local mockup of CAL-chip BEC machine, study dressing process on machines as close to flight hardware as possible

➢ Focus on: adiabaticity, trap uniformity, heating and frequency stability, LZ losses, diagnostics & imaging, BEC thermometry, Ω calibration…

➢ Theory work- excitations, dimensionality, trap shape and confinement, vortices, uniformity and chemical potential issues

➢ Development of dressed-state intuition with primary Bates BEC machine.

➢ Direct tests of current terrestrial sagged-bubble ideas and theory

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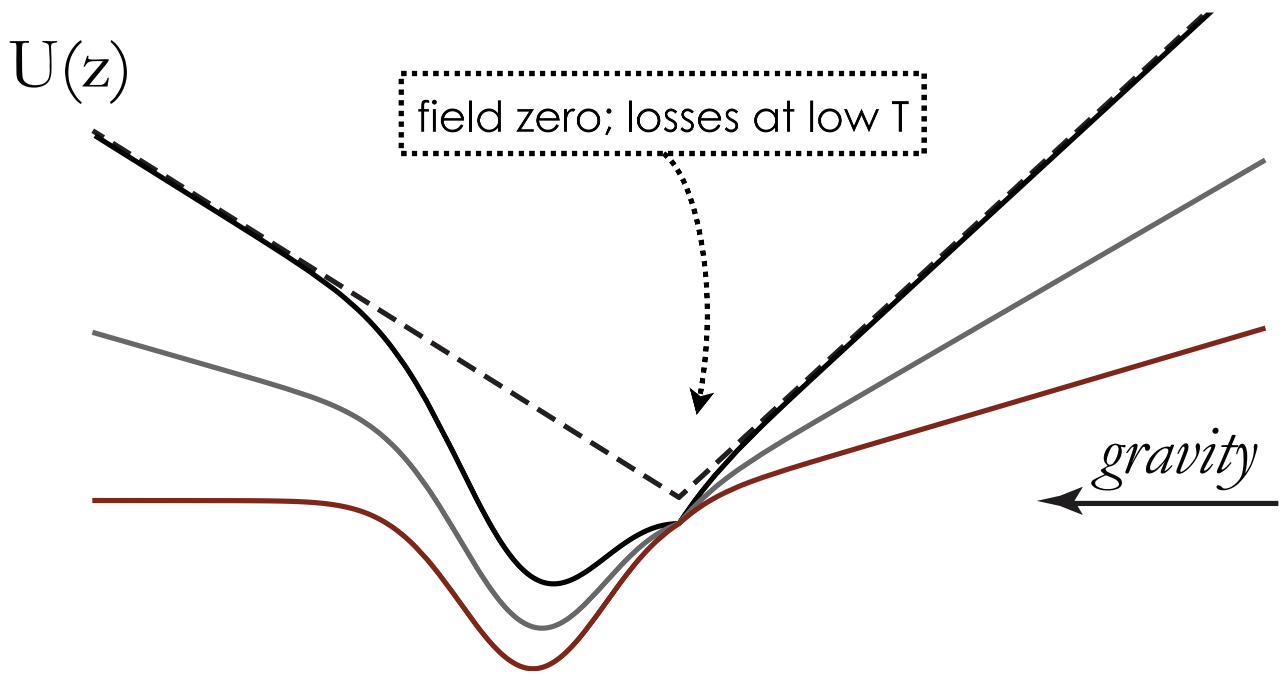
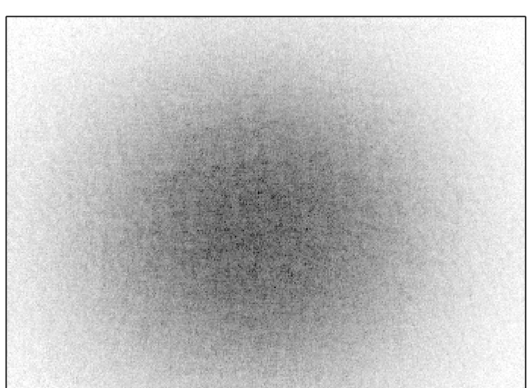
BEC research at Bates

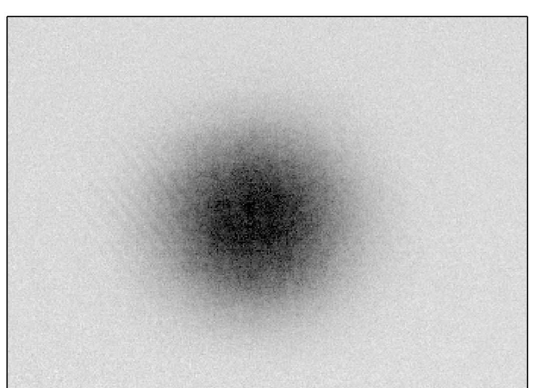
➢ Solid-state analogues with BECs loaded into nonstandard optical lattices

➢ BEC machine: hybrid magnetic/optical trap: exploit trap volume & ease of magnetic trap and stable/spinor nature of optical trap

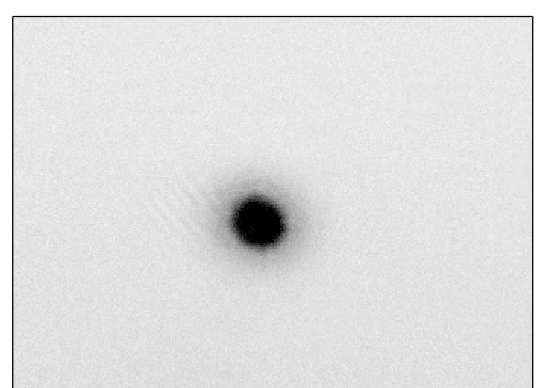




T ≈1800 nK, N ≈ 3×10^6

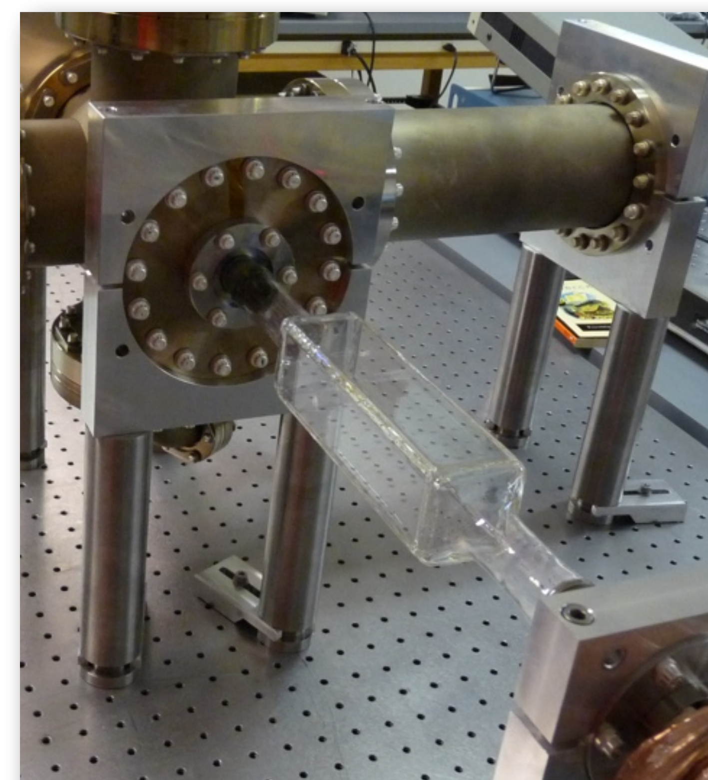


T ≈ 400 nK, N ≈ 1×10^6



T < 100 nK, N **BEC** ≈ 2×10^5

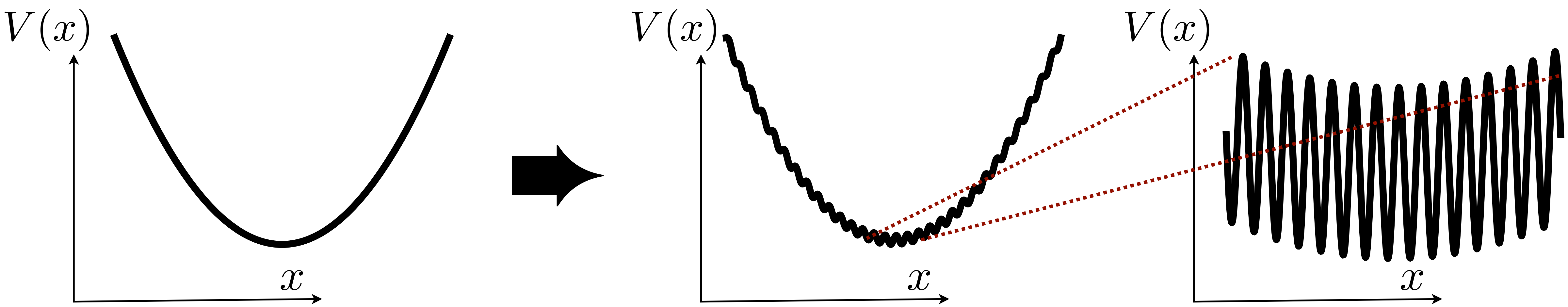
Zeeman slower



UHV cell (pre-envelopment)

Using a BEC to simulate solid-state physics

- Now what to do?   Take the BEC and raise up a periodic potential!



ANALOGOUS to electrons moving in the crystal lattice of a solid

- NEED BEC: these sine potentials are weak, also want ground state
- can perform *quantum simulation* of particles in a crystal lattice

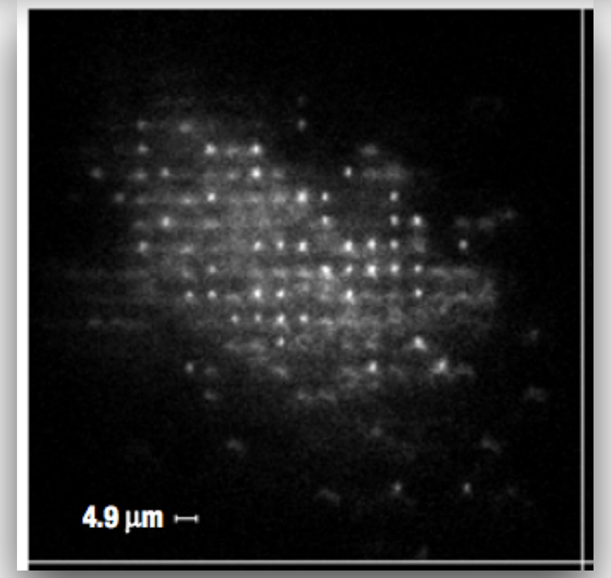
Optical lattice menagerie

- Solid-state simulation, arrays of neutral-atom qubits, dimensionality…

Quantum phase transition from a superfluid to a Mott insulator in a gas of ultracold atoms

Observation of a One-Dimensional Tonks-Girardeau Gas

Imaging single atoms in a three-dimensional array



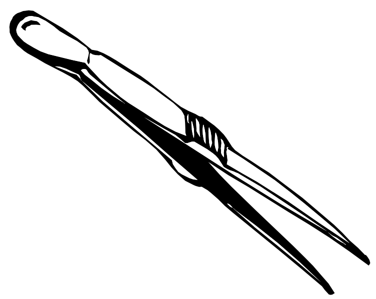
Controlled exchange interaction between pairs of neutral atoms in an optical lattice

Single-spin addressing in an atomic Mott insulator

Time-Resolved Observation and Control of Superexchange Interactions with Ultracold Atoms in Optical Lattices

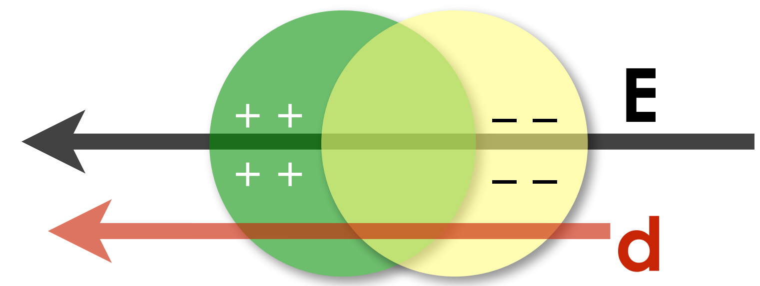
Realization of the Hofstadter Hamiltonian with Ultracold Atoms in Optical Lattices

LIGHT FORCES



= laser light

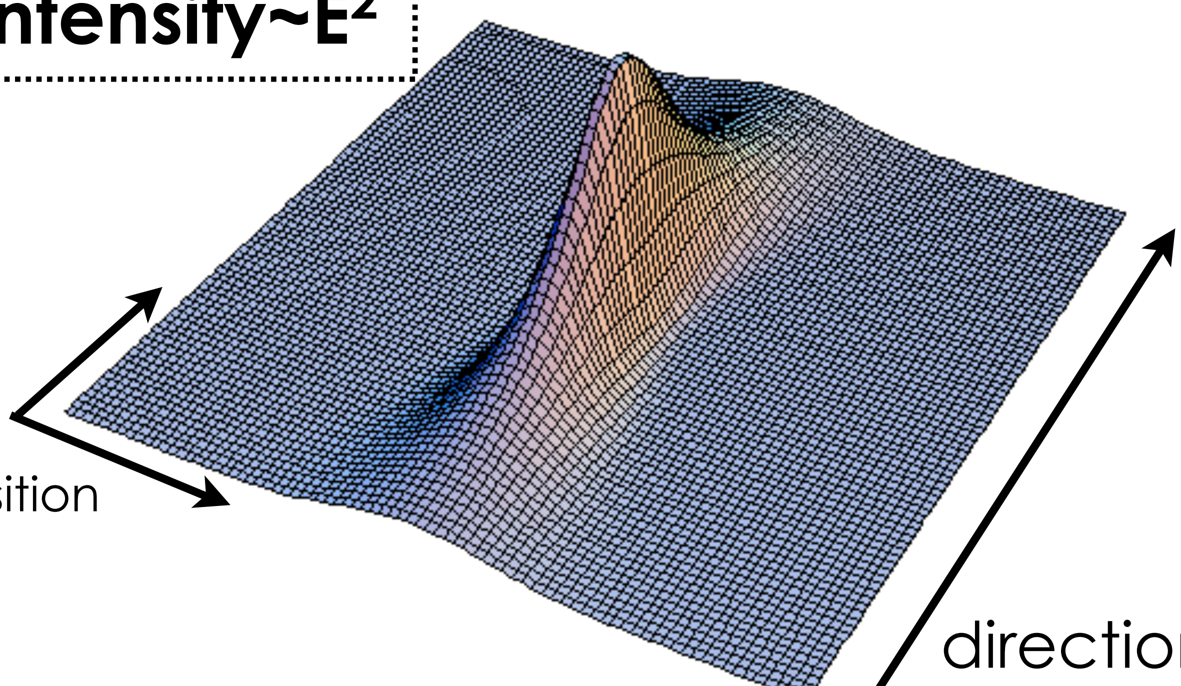
focused laser beams ,
RED or BLUE of resonance
($\alpha < 0$, $\alpha > 0$)



$$\mathbf{d} = \alpha \mathbf{E}$$ atomic polarizability: $\alpha(\lambda)$

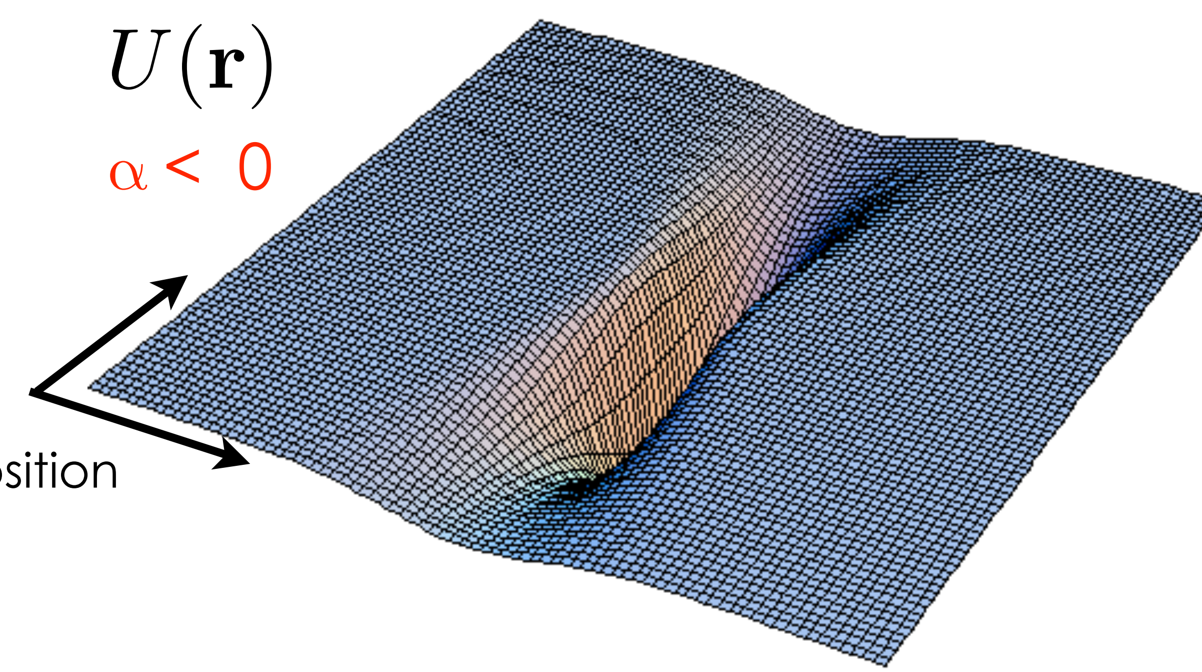
$$U(\mathbf{r}) = -\langle \mathbf{d} \cdot \mathbf{E} \rangle \propto -\alpha |\mathbf{E}(\mathbf{r})|^2$$

intensity~E^2

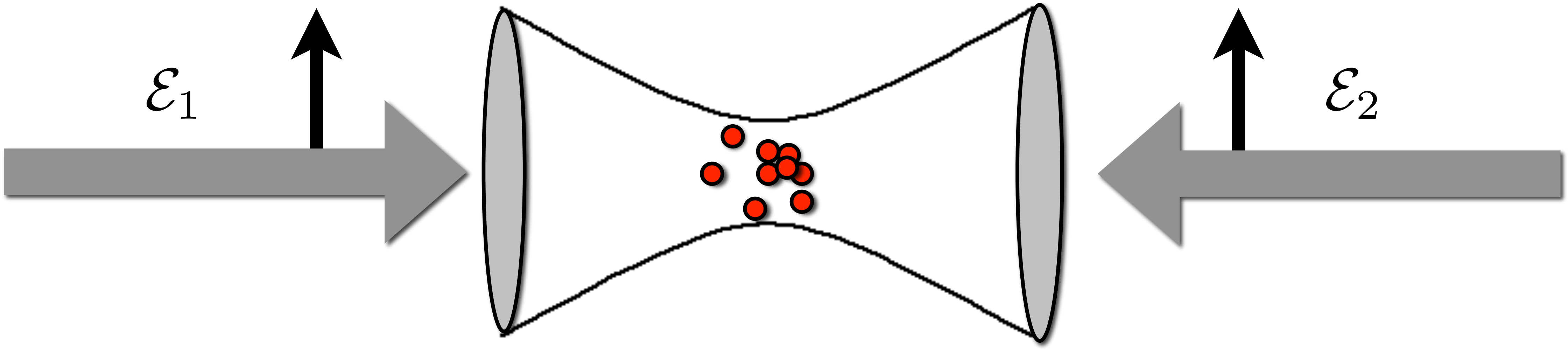


$U(\mathbf{r})$

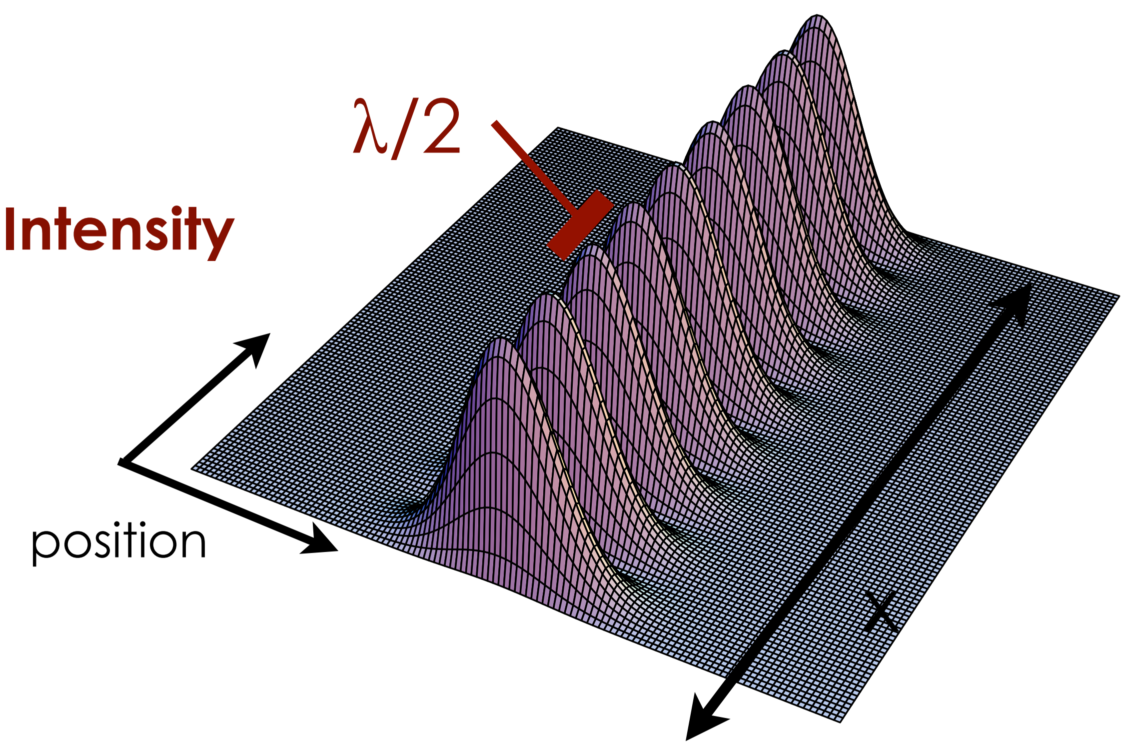
$\alpha < 0$

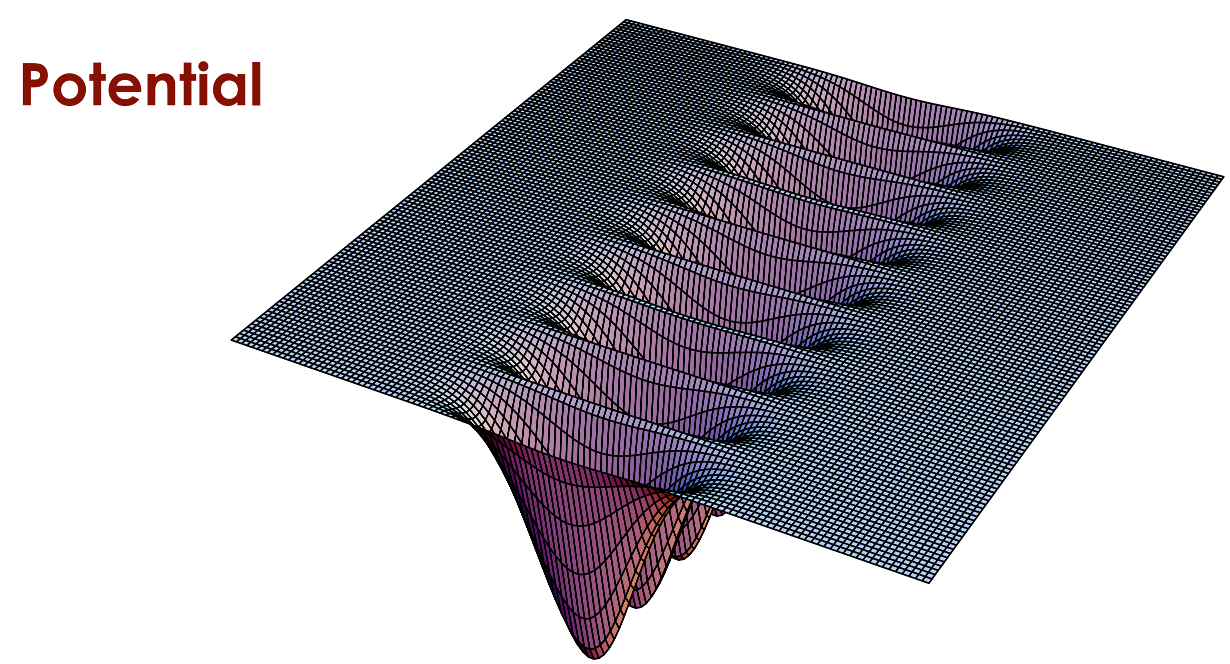


OPTICAL LATTICES



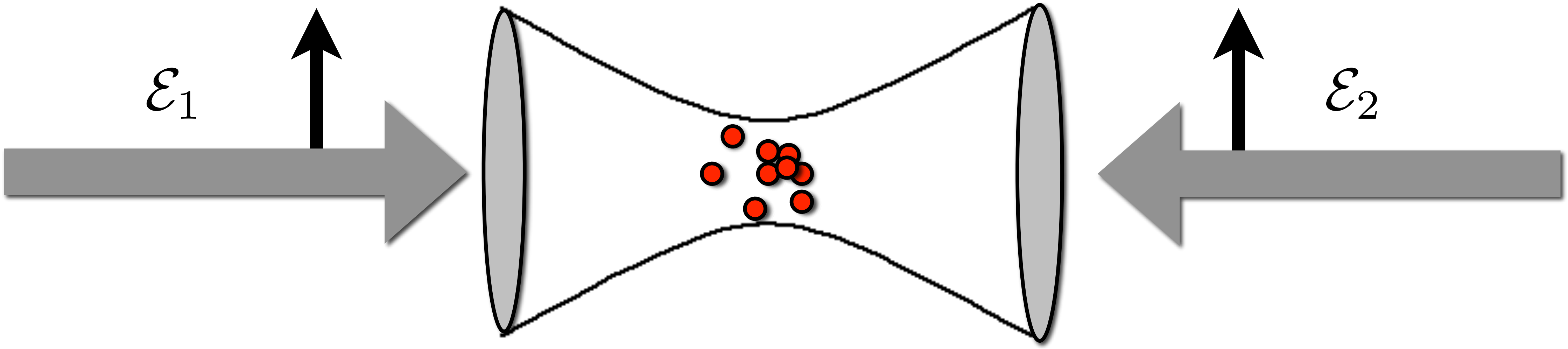
$$\mathcal{I}(x) \sim (\mathcal{E}_1 + \mathcal{E}_2)\cdot(\mathcal{E}_1^* + \mathcal{E}_2^*) = \mathcal{I}_1 + \mathcal{I}_2 + 2\sqrt{\mathcal{I}_1\mathcal{I}_2}\,\boxed{\cos(\frac{2\pi x}{\lambda/2})}$$





Any intensity pattern yields a potential energy surface

OPTICAL LATTICES



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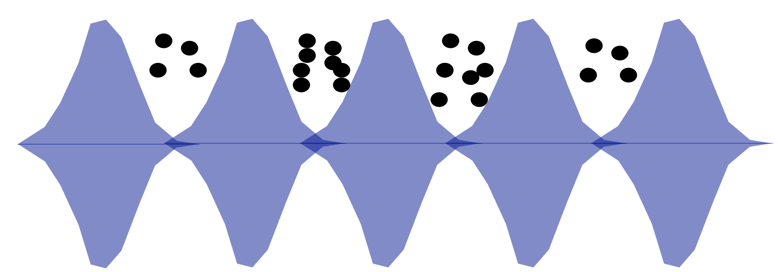
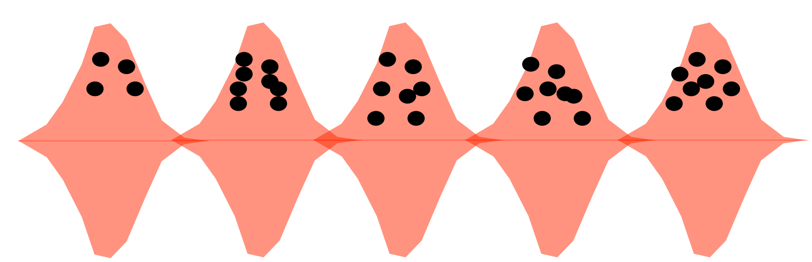
blue-detuned:

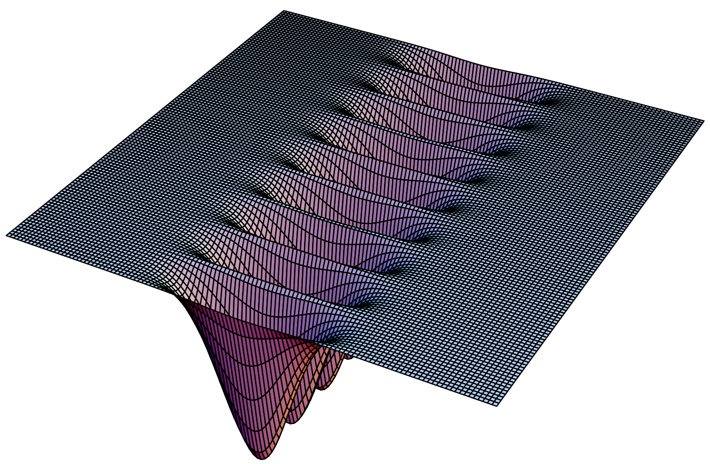


red-detuned:



Any intensity pattern yields a potential energy surface

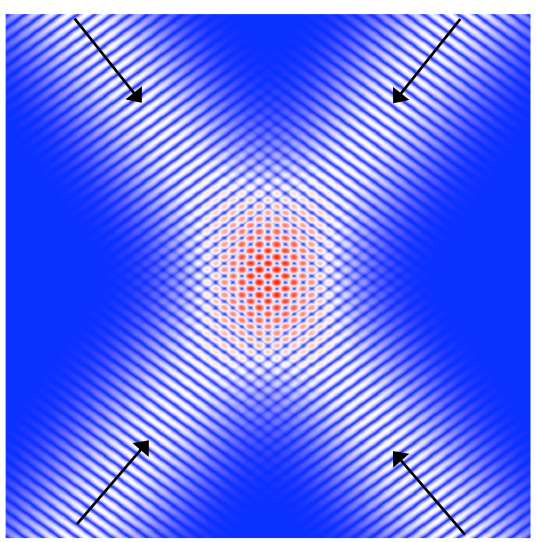
OPTICAL LATTICES



1D

2 beams: pile of wells

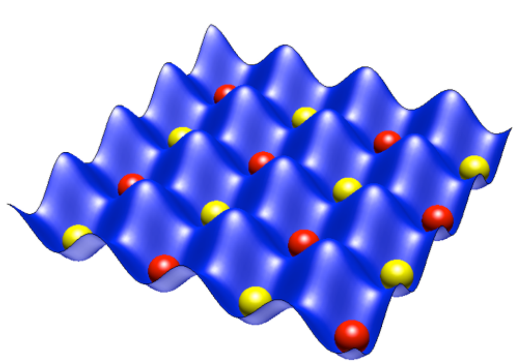
atoms form quasi-2D traps



2D

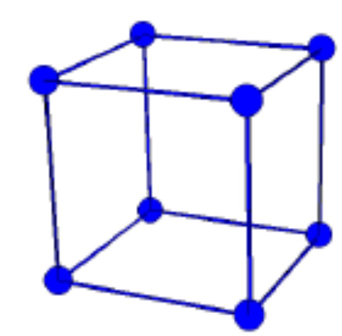
4 beams: bundle of long, skinny wells

atoms form quasi-1D systems

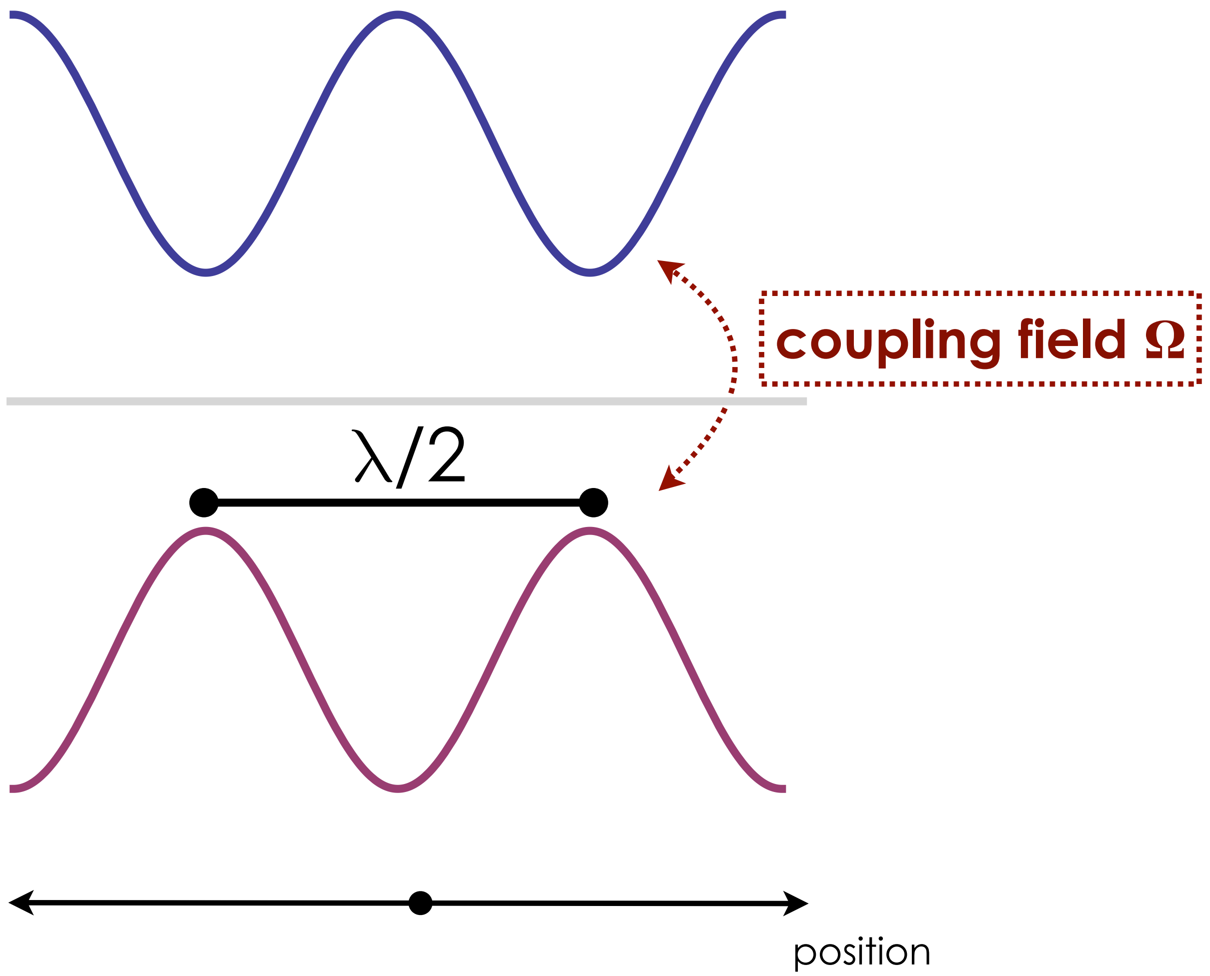


3D

6 beams: complete 3D lattice: simple cubic "optical crystal" (minima every half-wavelength)



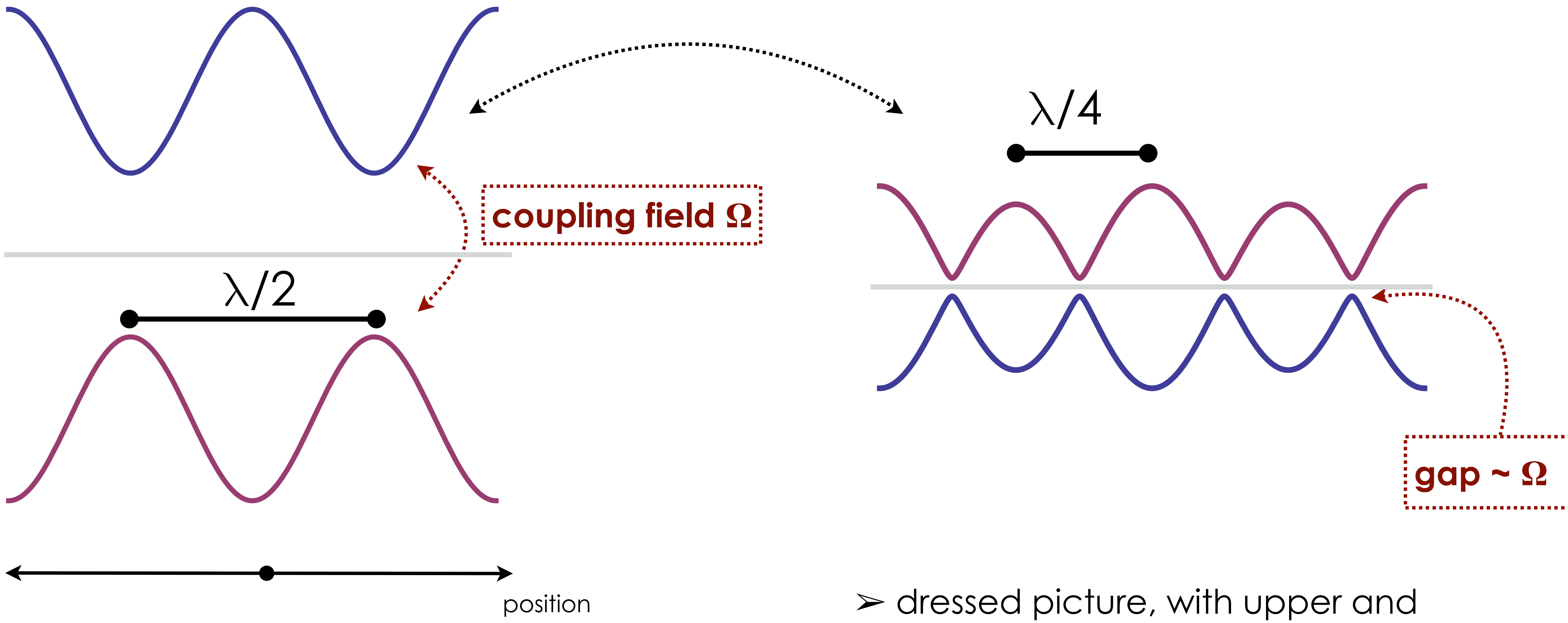
Radiofrequency dressing



➢ (Very) spin-dependent 1D optical lattice for ^{87}Rb

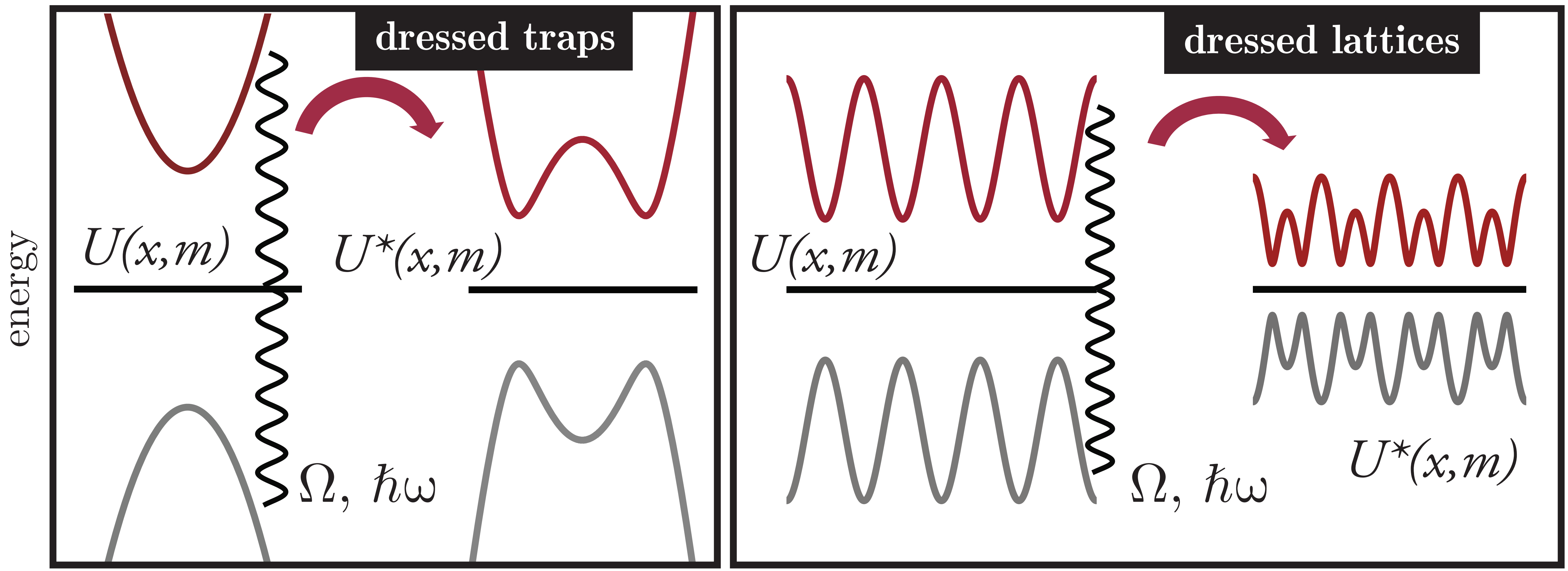
➢ Circularly-polarized lattice beams at 790.06 nm (tune-out wavelength) between D1 and D2

Radiofrequency dressing



- ➢ (Very) spin-dependent 1D optical lattice for ^{87}Rb
- ➢ Circularly-polarized lattice beams at 790.06 nm (tune-out wavelength) between D1 and D2
- ➢ dressed picture, with upper and lower adiabatic potentials
- ➢ which "bare" (lab-basis) spin state you're in depends on where you are...
- ➢ real-time alteration of lattice properties (periodicity, tunnelling, interaction, etc.)

Radiofrequency dressing



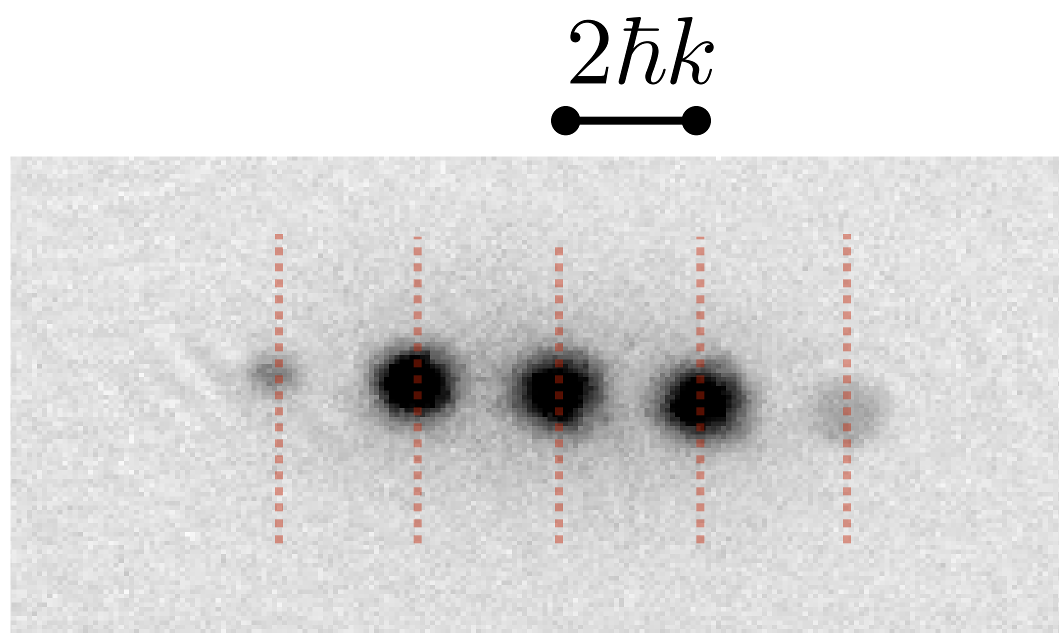
"bare" optical potential for m = -1

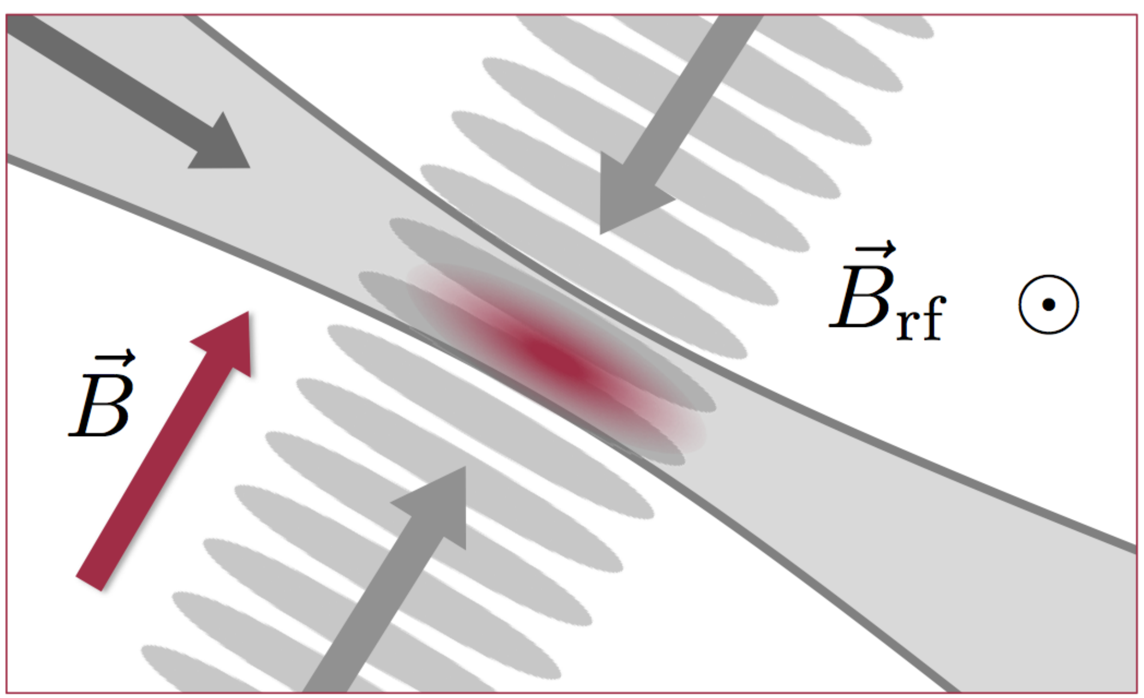
$$\mathcal{H}(\mathbf{r}) = \begin{pmatrix} U(x,-1)-\delta & \Omega/2 & 0 \\ \Omega/2 & U(x,0) & \Omega/2 \\ 0 & \Omega/2 & U(x,+1)+\delta+\delta' \end{pmatrix}$$

coupling

1D **momentum**-space data

➢ **bare lattice**
(orders spaced at twice lattice photon momentum)

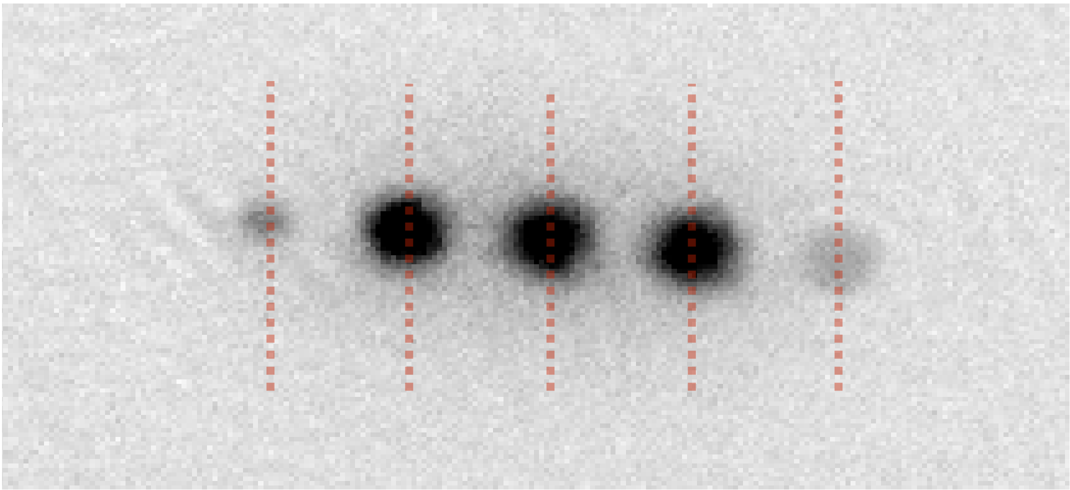




➢ *ramp up lattice, turn on rf off-resonance, ramp B-field over few ms to dress the system*

1D momentum-space data

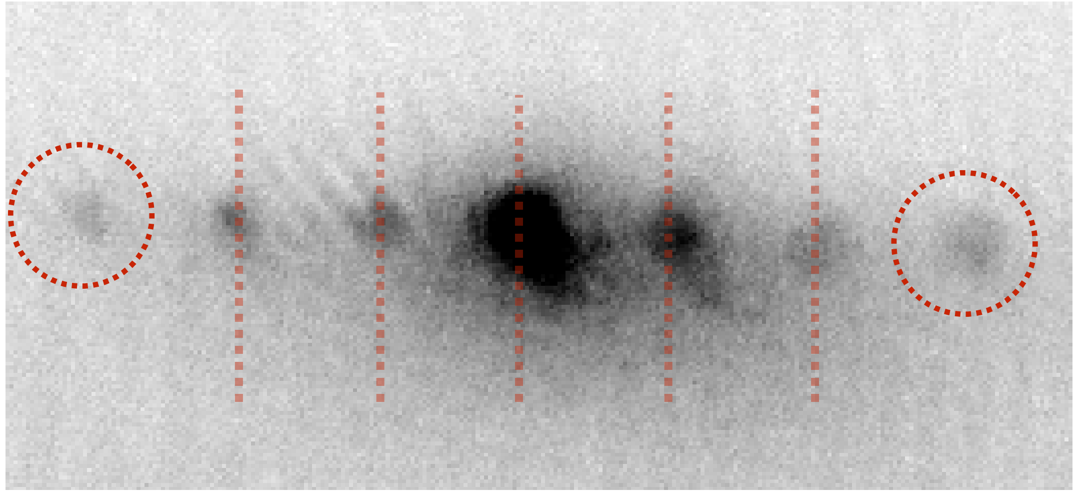
$2\hbar k$



➢ **bare lattice**
(orders spaced at twice lattice photon momentum)

components predicted from simple Bloch theory

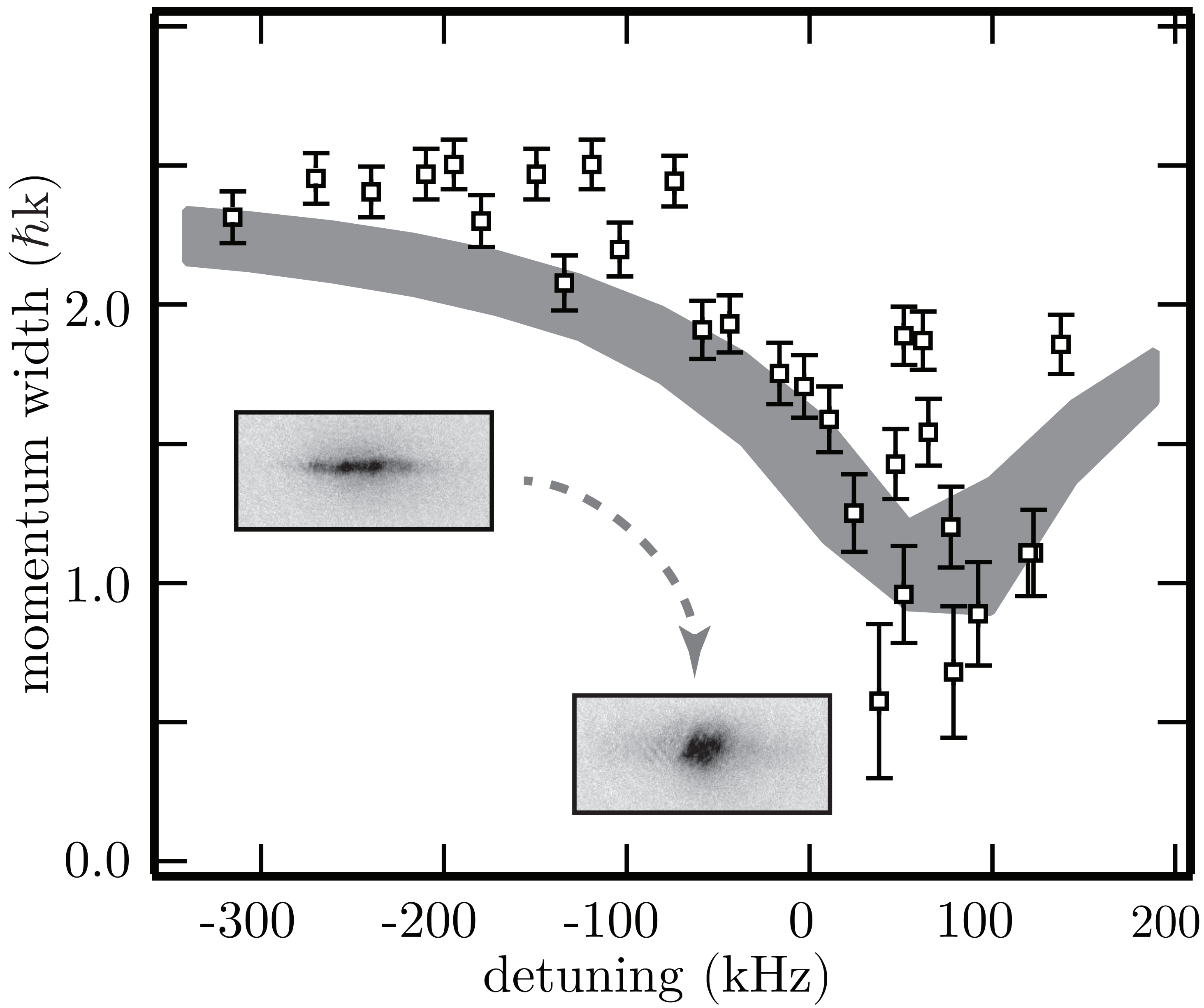
$2\hbar k$



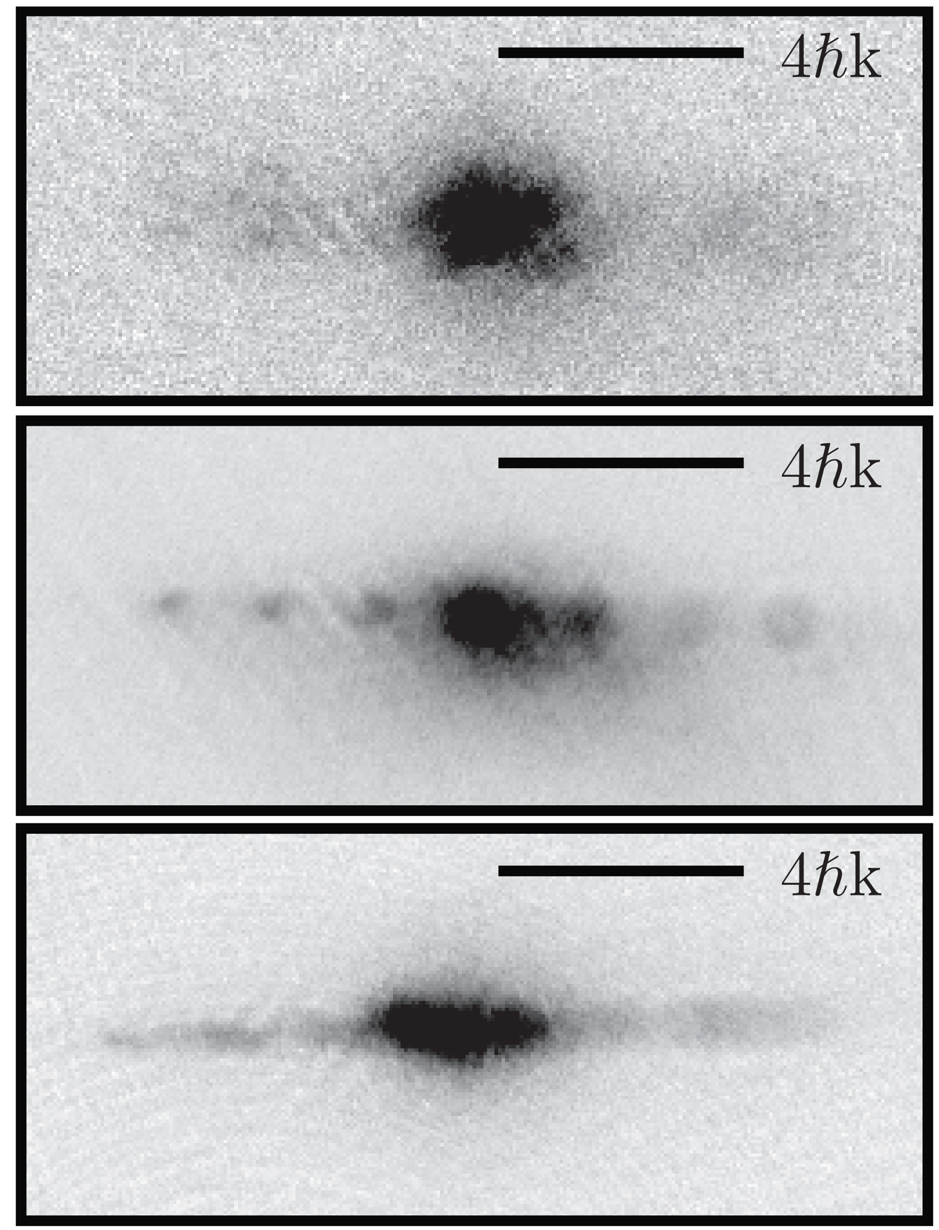
➢ **dressed** near (not at) the $\lambda/4$ "sweet spot"

note +/- 4, 6, note "long tail"

Momentum-space distortion signature



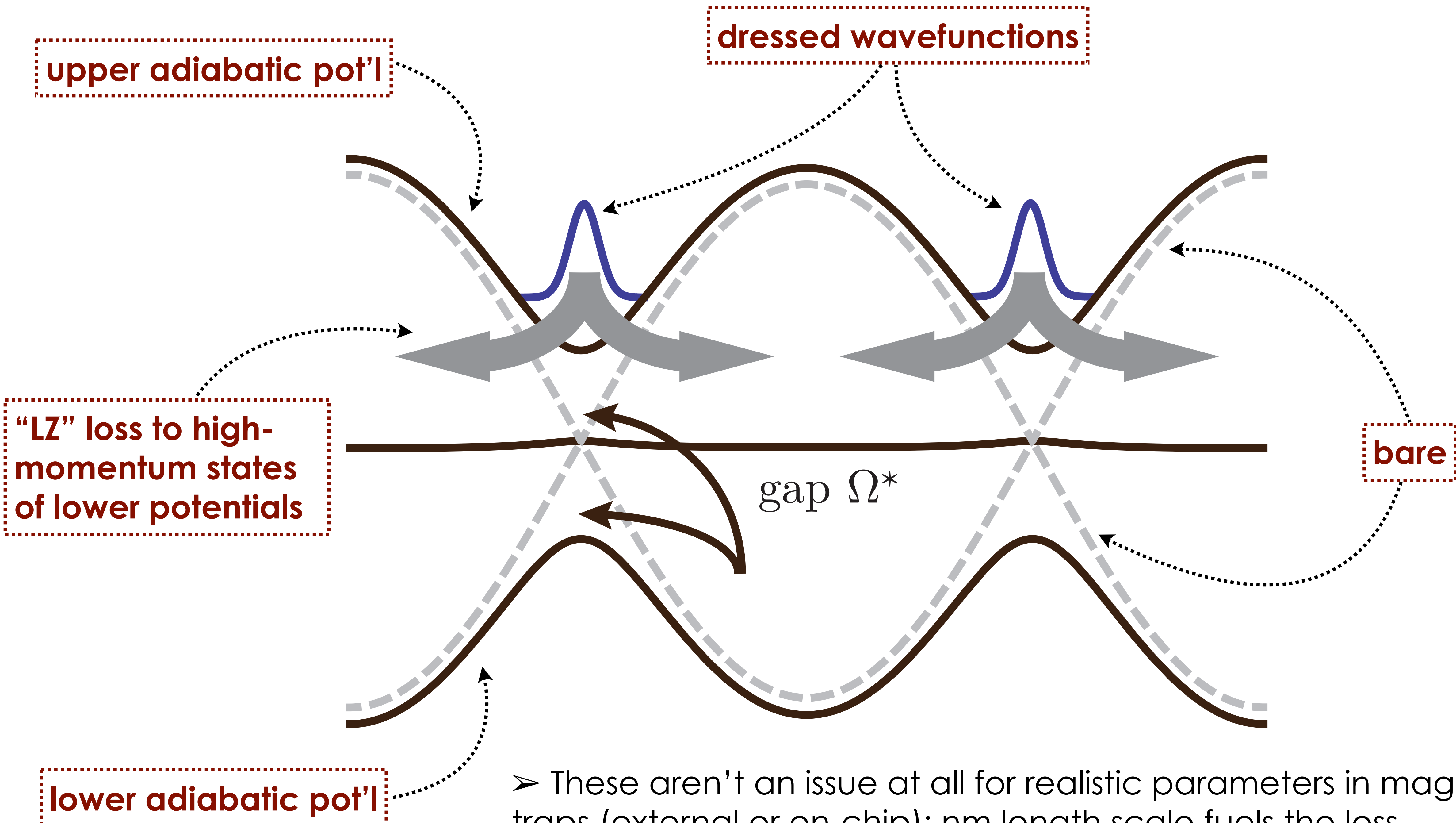
typical data "near" sweet spot



variance from residual COM motion in trap.

➢ **Moan, Ansari, Guo, Lundblad: Phys. Rev. A (2014)** ***"Observations of $\lambda/4$ structure in a low-loss radio-frequency-dressed optical lattice"***

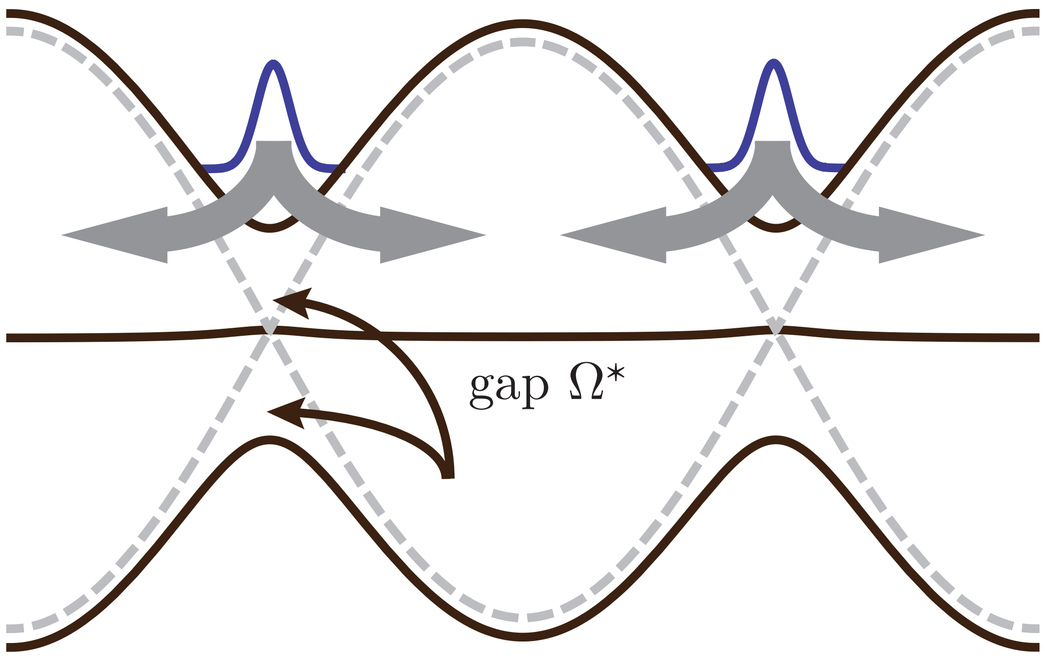
Nonadiabatic losses

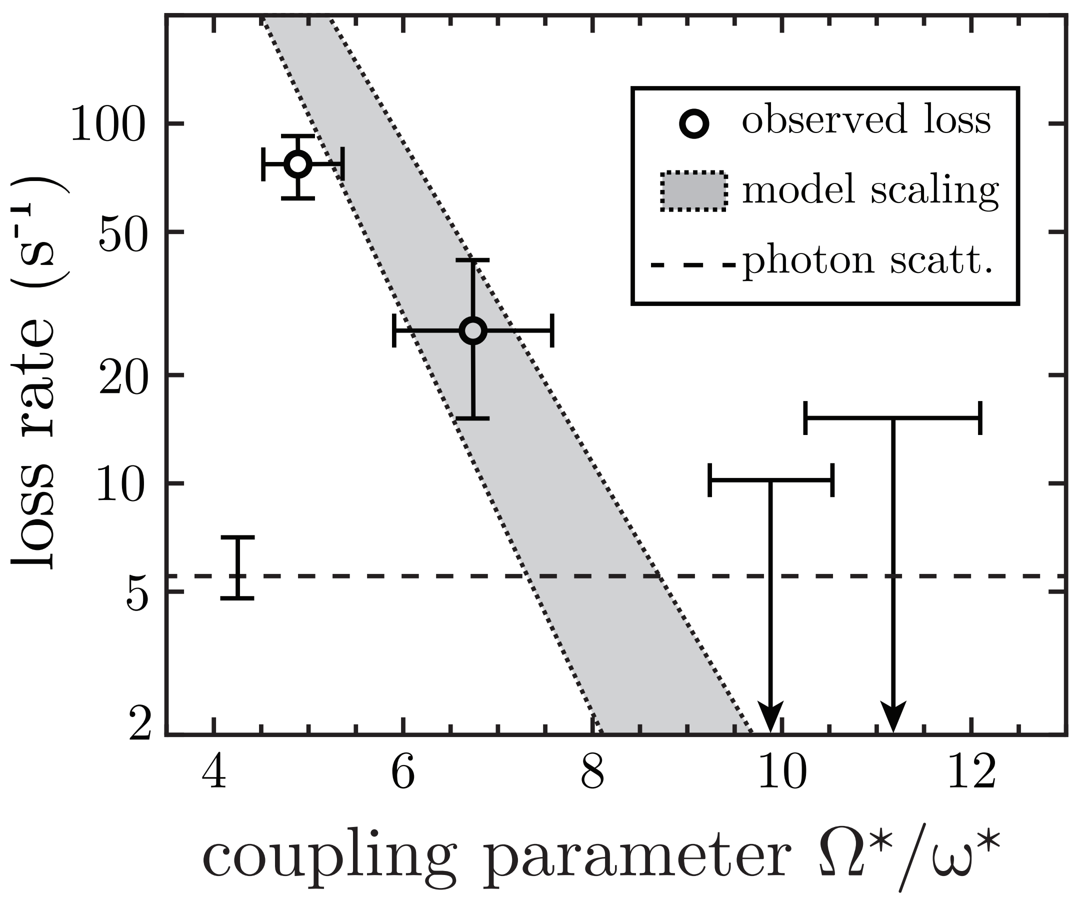


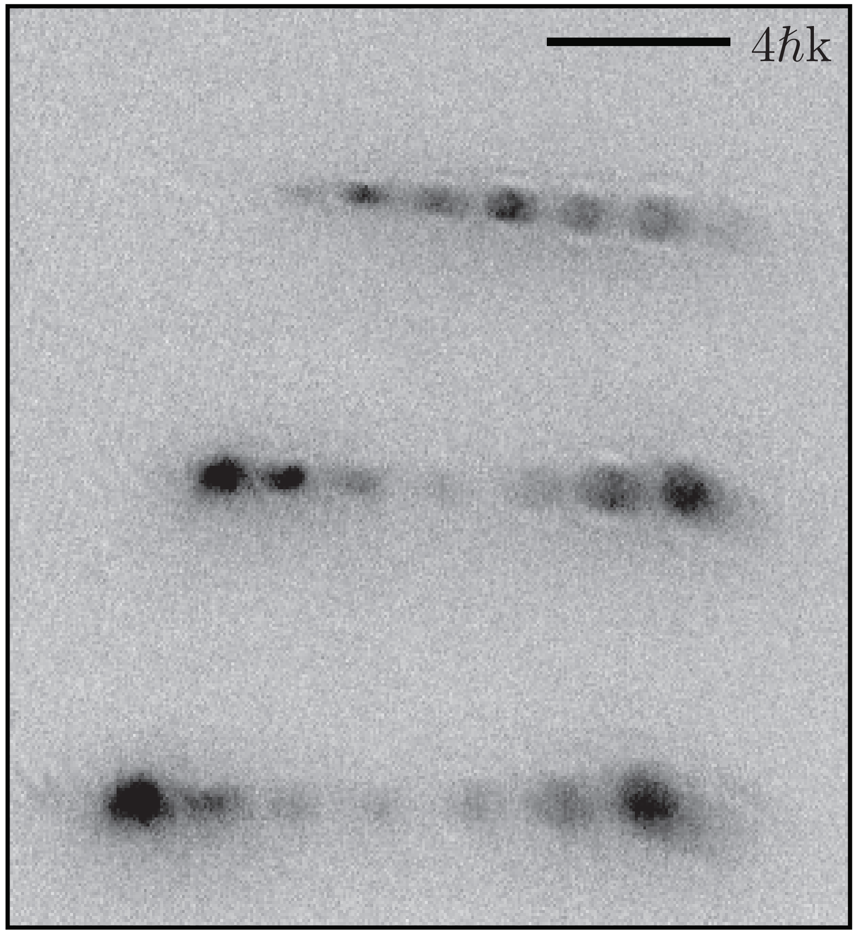
➢ These aren't an issue at all for realistic parameters in magnetic traps (external or on-chip); nm length scale fuels the loss.

➢ Limiting factor in proof-of-principle 2D-lattice work at NIST in 2007

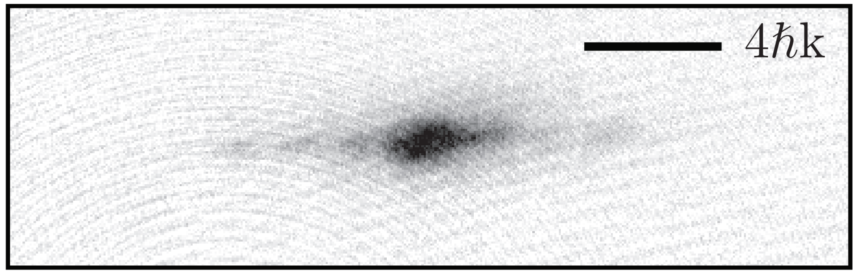
Nonadiabatic losses



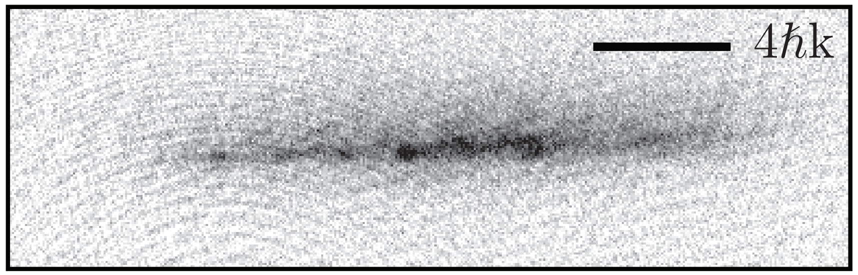




lossy, SG



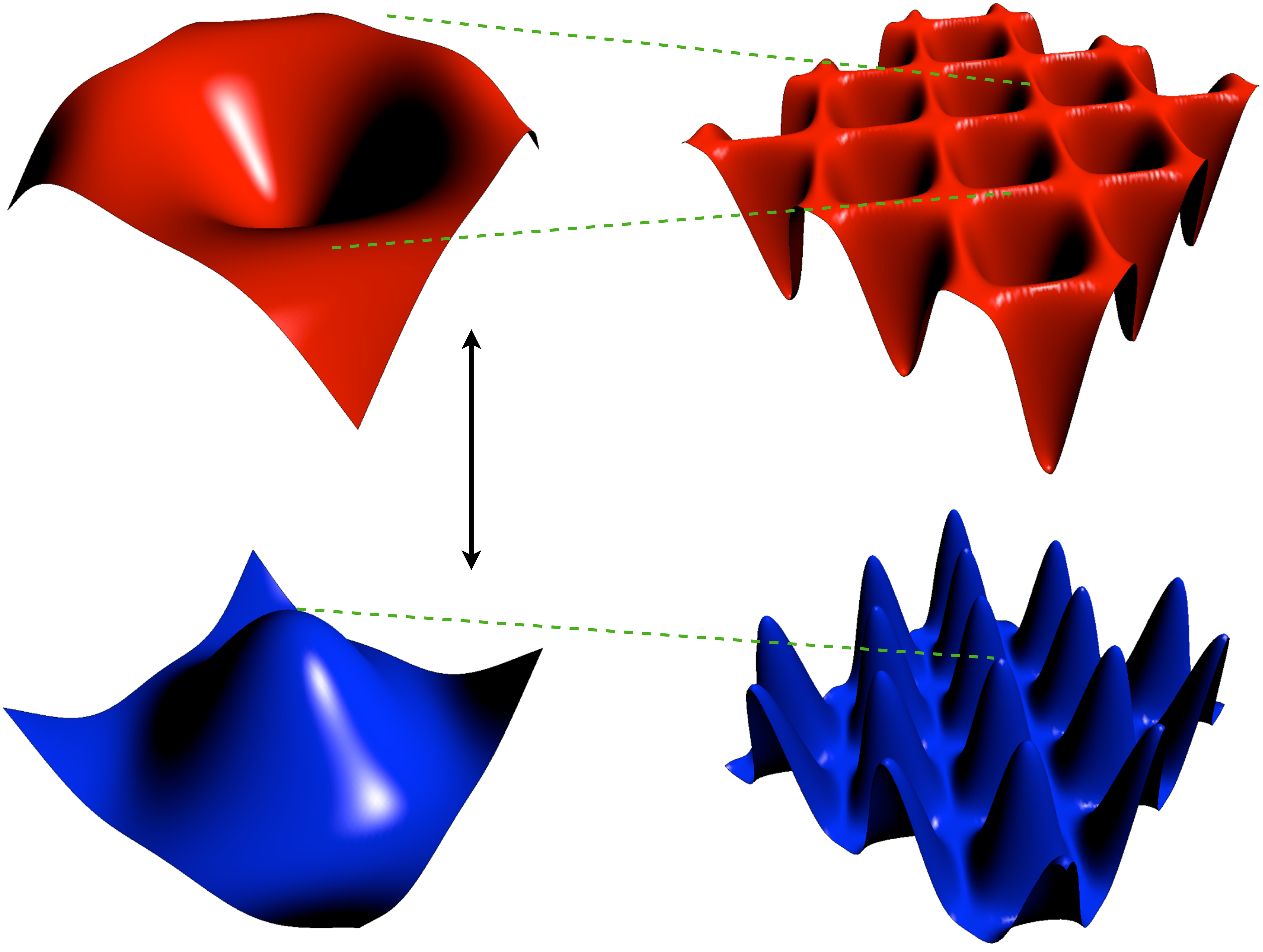
stable



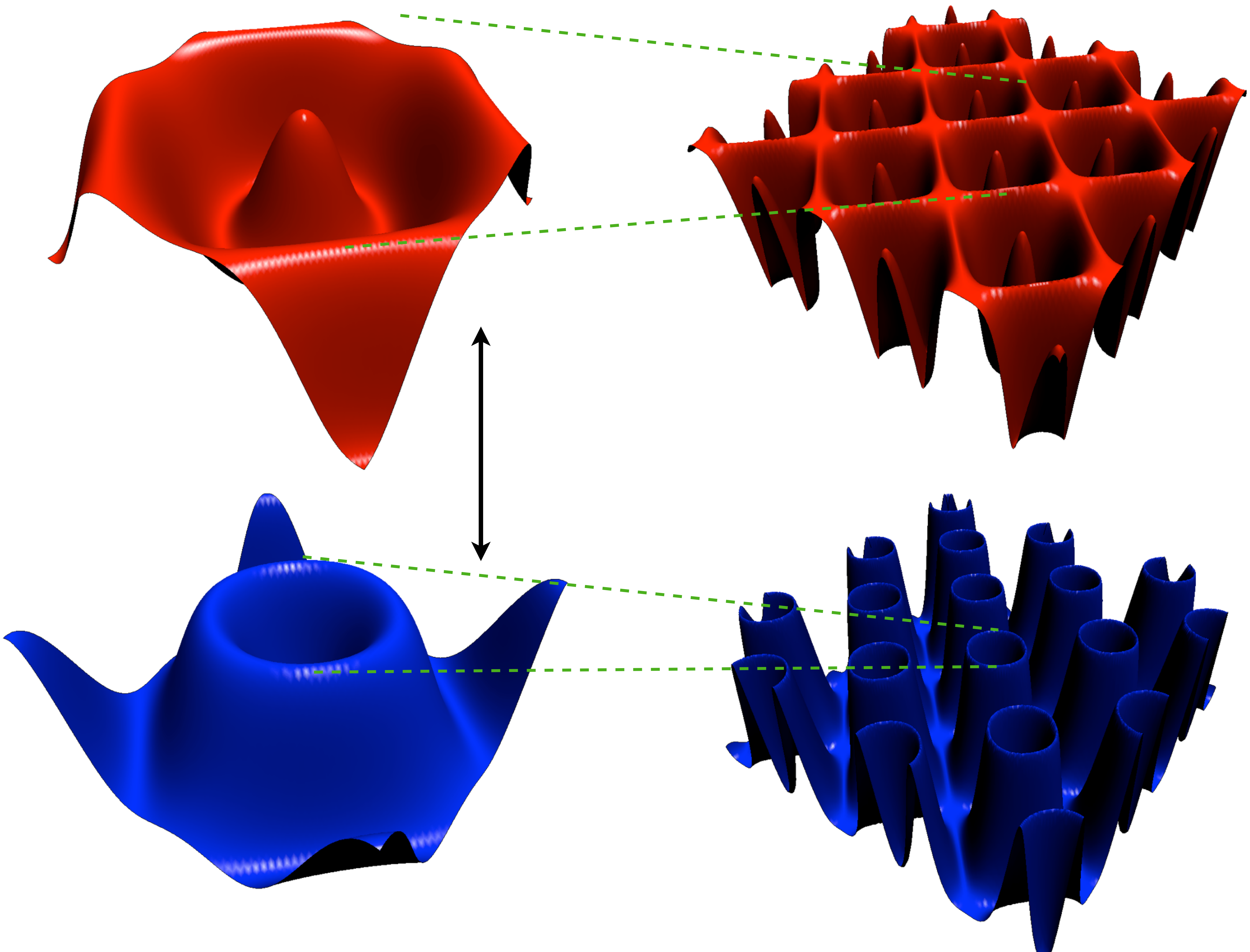
lossy

Bates

Next…2D?



Next…2D?



Takeaways

- ➢ **Quantum gases: almost twenty years of insights into quantum mechanics (single-particle and many-body), statistical physics & thermodynamics, precision measurements…**

  - ➢ **NASA CAL: BEC machine in (extended, orbital) microgravity.**

  - ➢ **Can tailor geometries for BEC with a diverse toolbox**

  - ➢ **Can tailor geometries for BEC with optical-lattice interference and rf-dressing techniques.**

  - ➢ **Can do BEC physics at an undergraduate institution!**

Acknowledgments

- ➢ NASA CAL collaborators

- ➢ Courtney Lannert (UMass / Smith College)

- ➢ David Aveline (Jet Propulsion Laboratory)

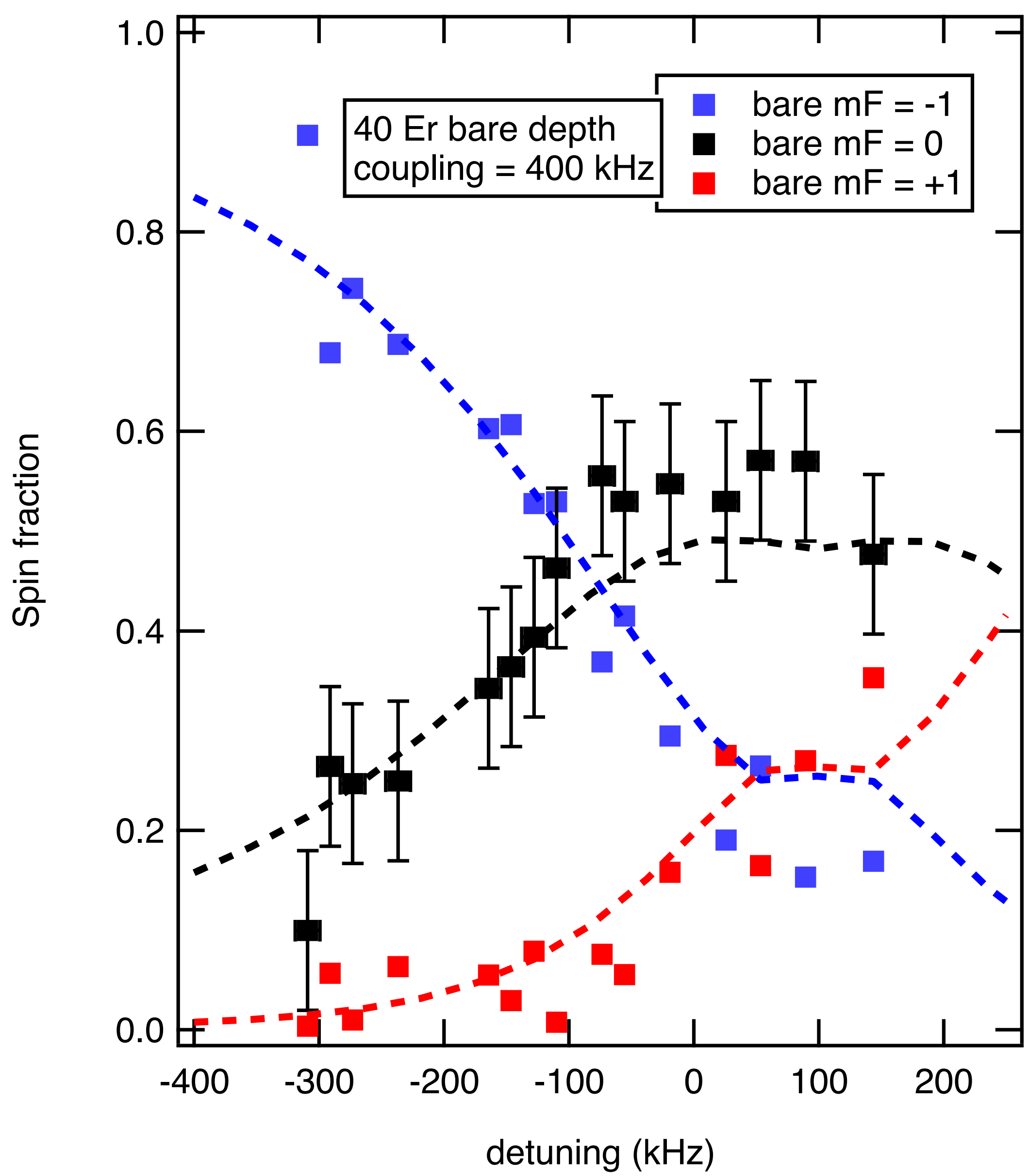
- ➢ Bates group:
  - ➢ Ben Lovitz ‘15
    Spencer Goossens ‘15
    Tiago Correia ‘17
  - ➢ New postdoc Tom Jarvis
  - ➢ Recent work: Chris Guo (Stanford Mech. Eng.), Eddie Moan (UVA physics), Saad Ansari (physics TBA)

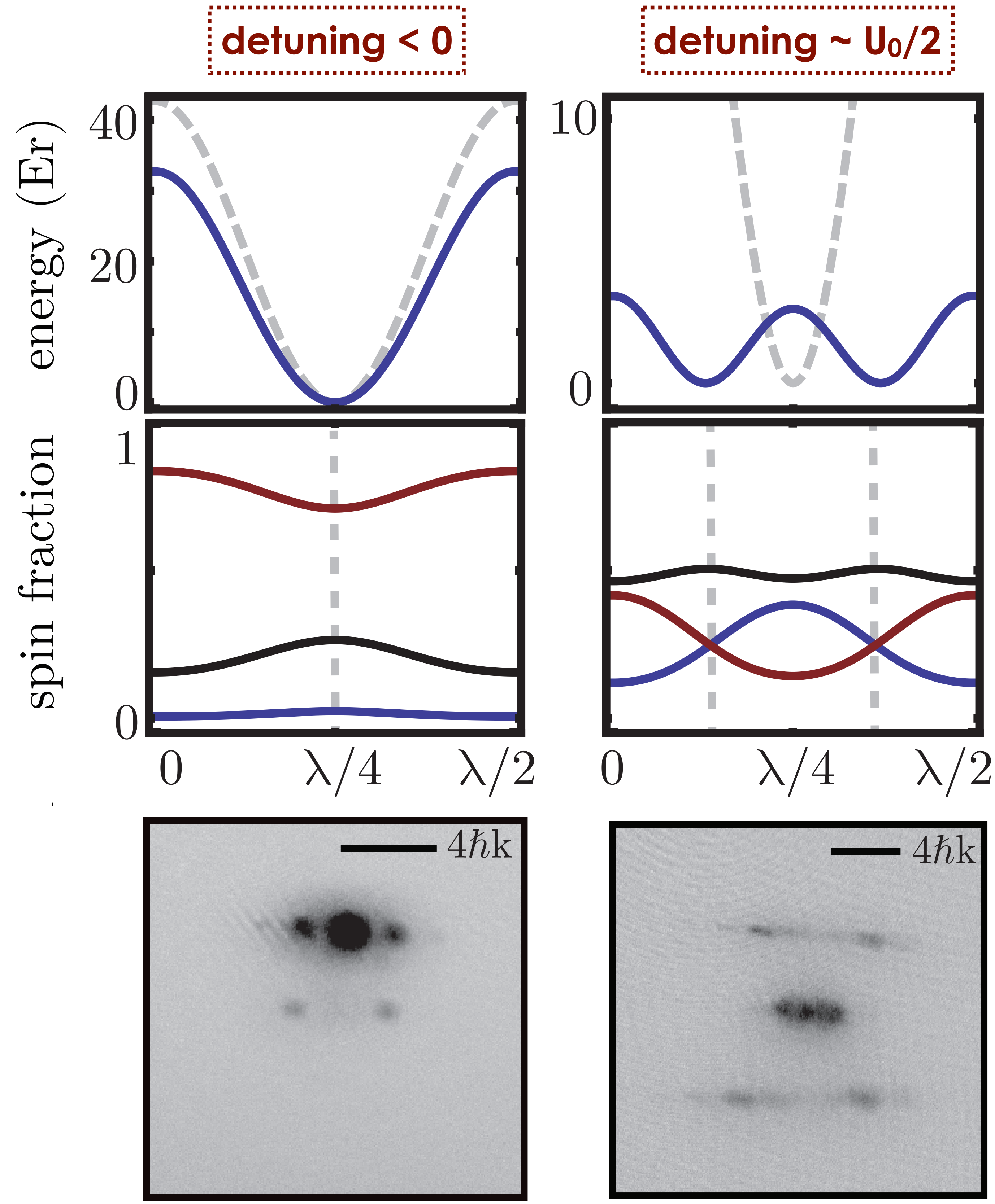
$: NASA CAL: JPL RSA No. 1502172 also: AFOSR , NSF MRI

Bates

Stern-Gerlach analysis

➢ Apply B-gradient during time-of-flight expansion to separate out lab-basis spin components





Effects of coupling strength