Probing and Controlling Ultracold Quantum Matter under Extreme Conditions

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$ DARPA (OLE)

erc synergy

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Outline

Introduction

Single Atom Imaging

Three Applications

SF-Mott Insulator Transition/Thermometry/
Quantum Fluctuations

Controlling Single Spins

'Higgs'-Amplitude Mode in 2D

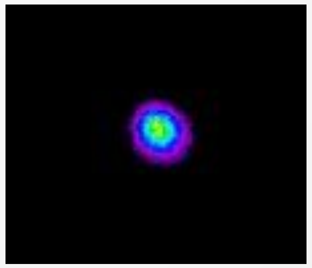
Artificial Gauge Fields - Extreme Magnetic Fields

Quantum Matter at Negative Absolute Temperature

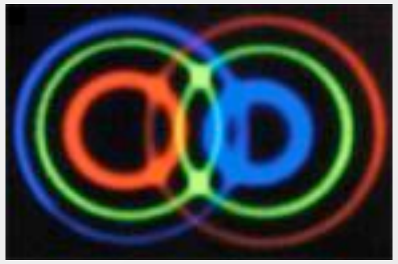
Outlook

The Challenge of Many-Body Quantum Systems

Control of single particles



Single Atoms and Ions



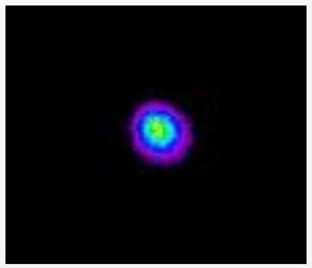
Photons

D. Wineland

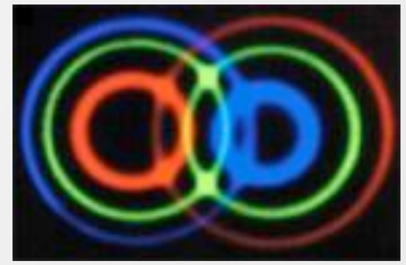
S. Haroche

The Challenge of Many-Body Quantum Systems

Control of single particles



Single Atoms and Ions



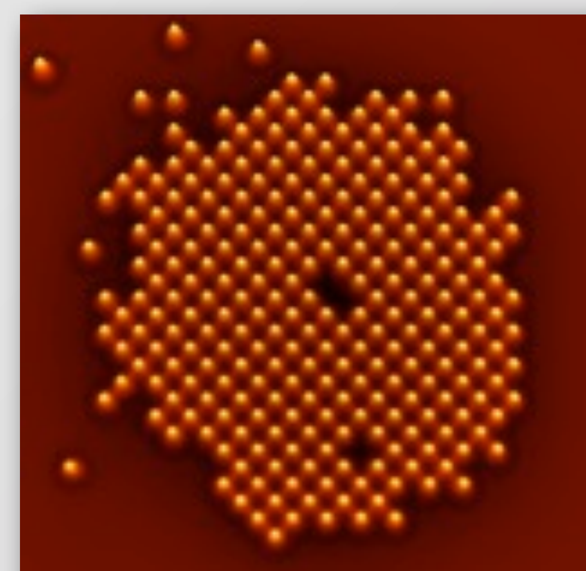
Photons

D. Wineland S. Haroche

Challenge: ... towards ultimate control of many-body quantum systems

R. P. Feynman's Vision

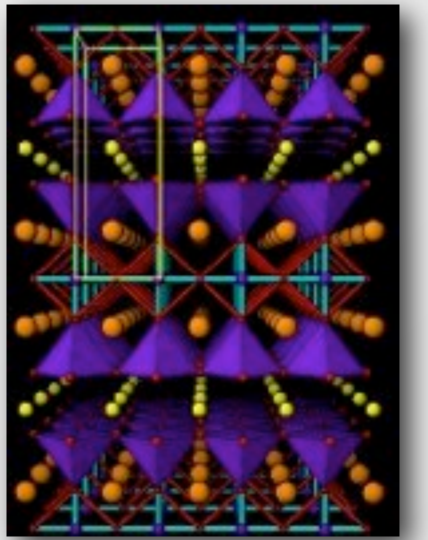
A Quantum Simulator to study the dynamics of another quantum system.

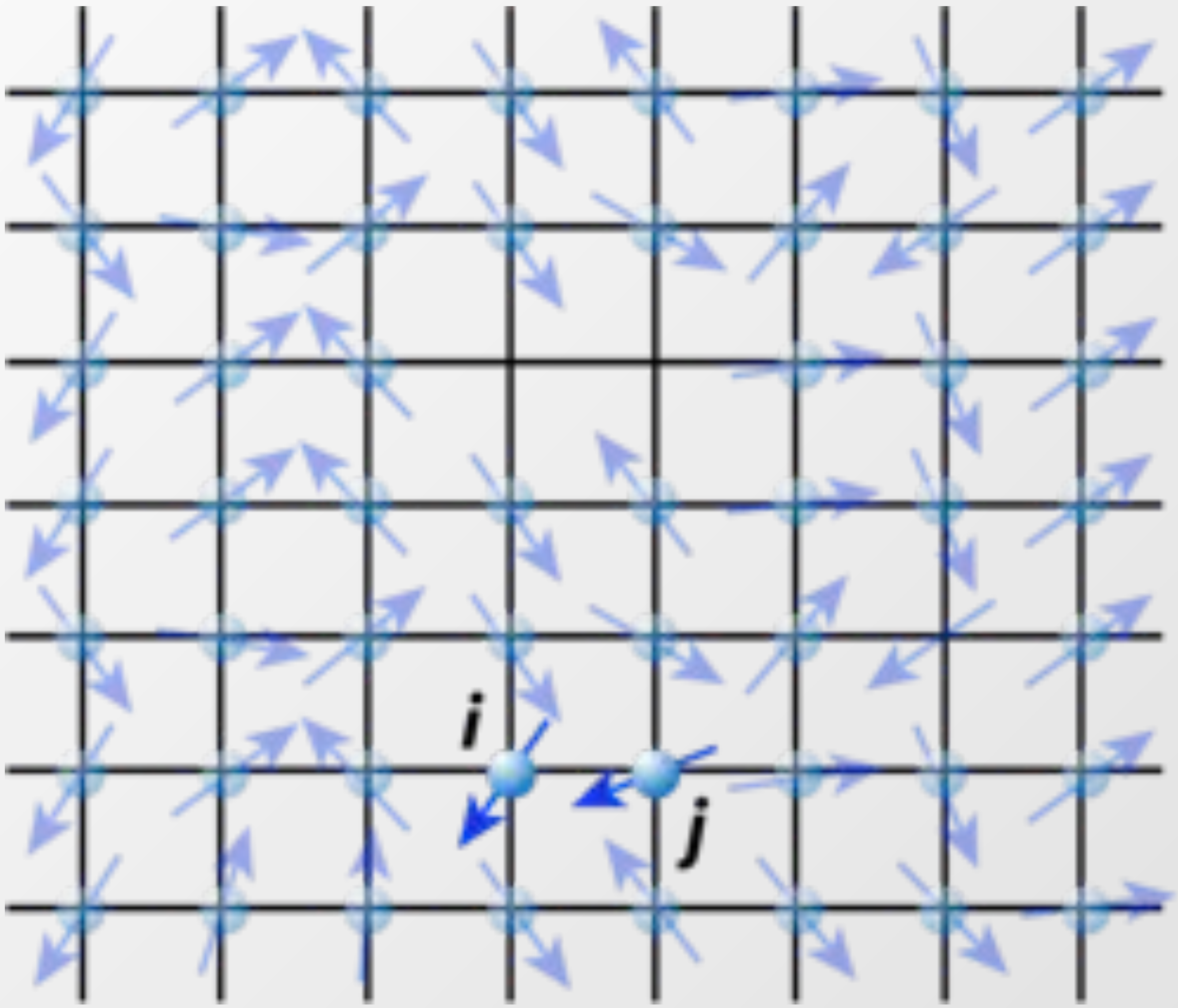


Crystal of Atoms Bound by Light

Strongly Correlated Electronic Systems

$$H = -J \sum_{\langle i,j \rangle,\sigma} \hat{c}^{\dagger}_{i,\sigma}\hat{c}_{j,\sigma} + U\sum_{i}\hat{n}_{i,\uparrow}\hat{n}_{i,\downarrow} + V_0 \sum_{i,\sigma} R_i^2 \hat{n}_{i,\sigma}$$





In strongly correlated electron system spin-spin interactions exist.

$$-J_{ex}\vec{S}_i \cdot \vec{S}_j$$

Underlying many solid state & material science problems:
Magnets, High-Tc Superconductors, Spintronics ....

Starting Point – Ultracold Quantum Gases

Parameters:

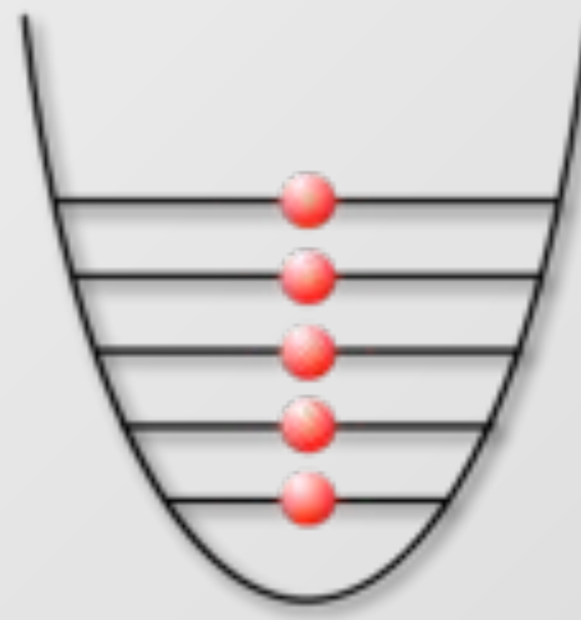
Densities: 10^{15} cm^{-3}

Temperatures: Nano Kelvin

Atom Numbers 10^{6}

Ground States at T=0

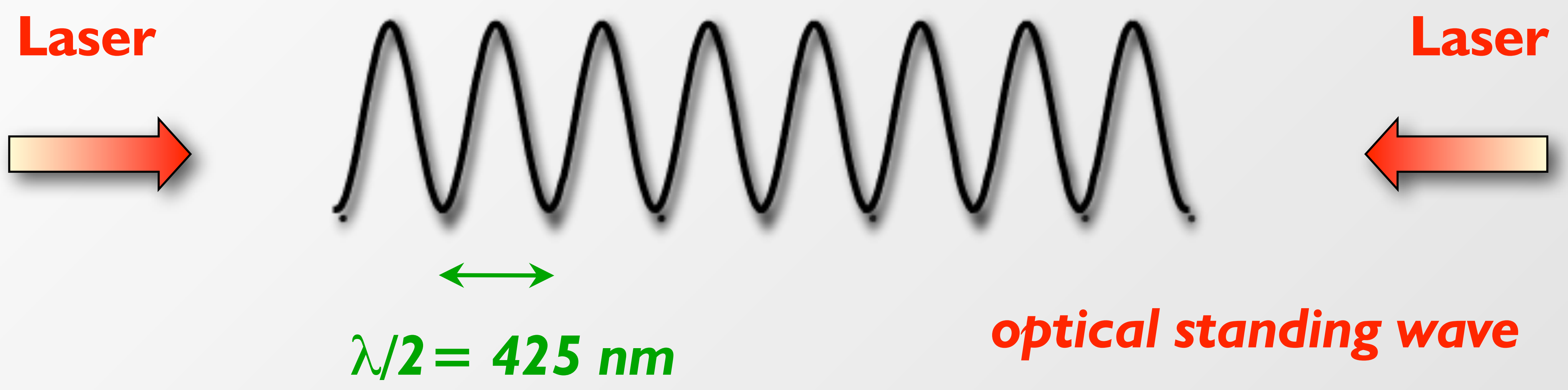
Bose-Einstein Condensates e.g. ^{87}Rb

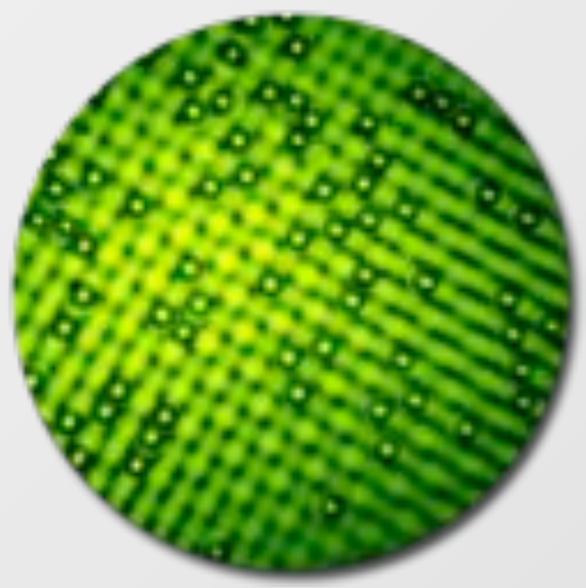


Degenerate Fermi Gases e.g. ^{40}K

Centennial Nobel Prize in Physics for BEC
E. Cornell, C. Wieman & W. Ketterle

Optical Lattice Potential – Perfect Artificial Crystals

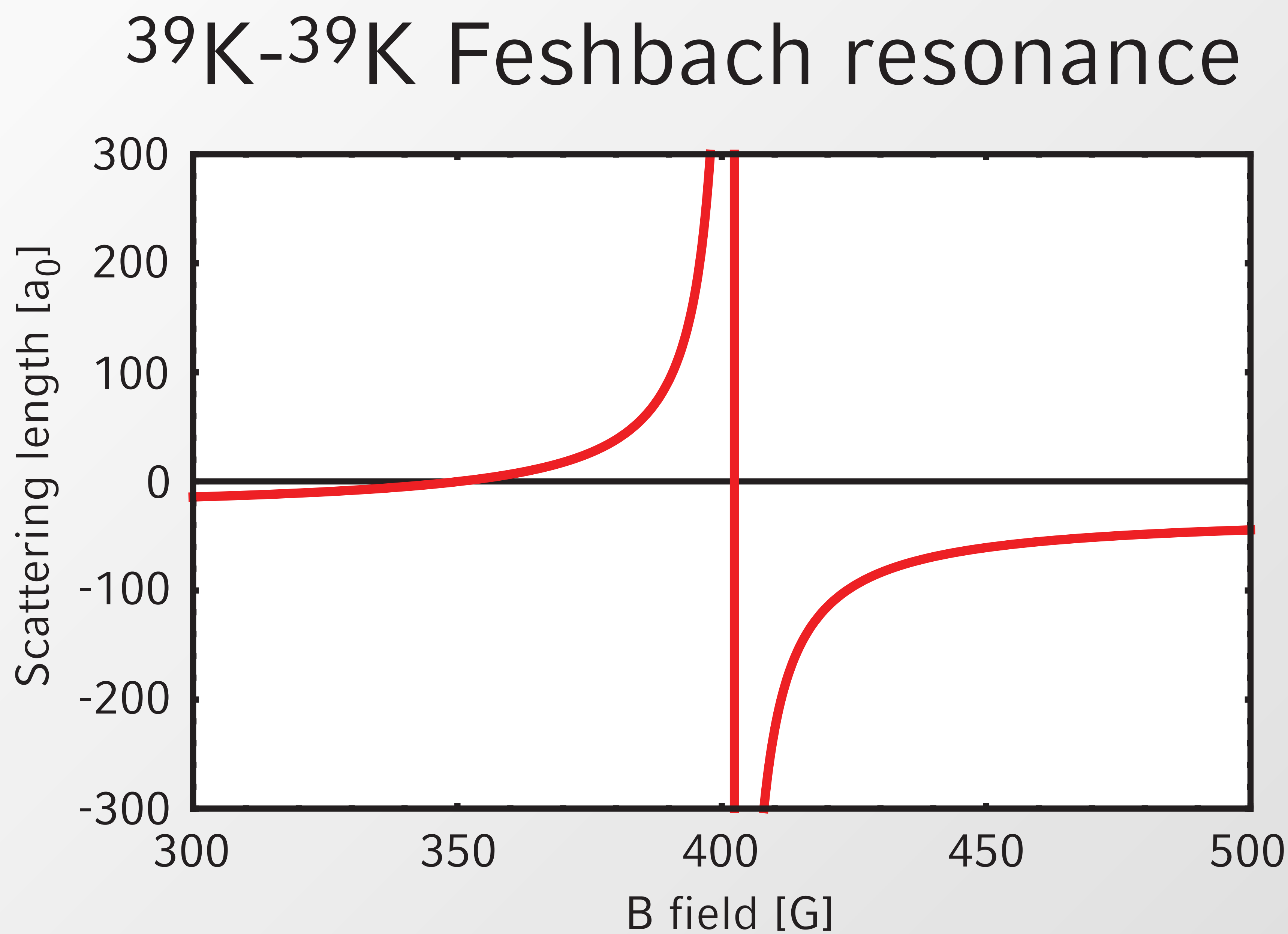




Perfect model systems for a fundamental understanding of quantum many-body systems

Periodic intensity pattern creates 1D,2D or 3D light crystals for atoms (Here shown for small polystyrol particles).

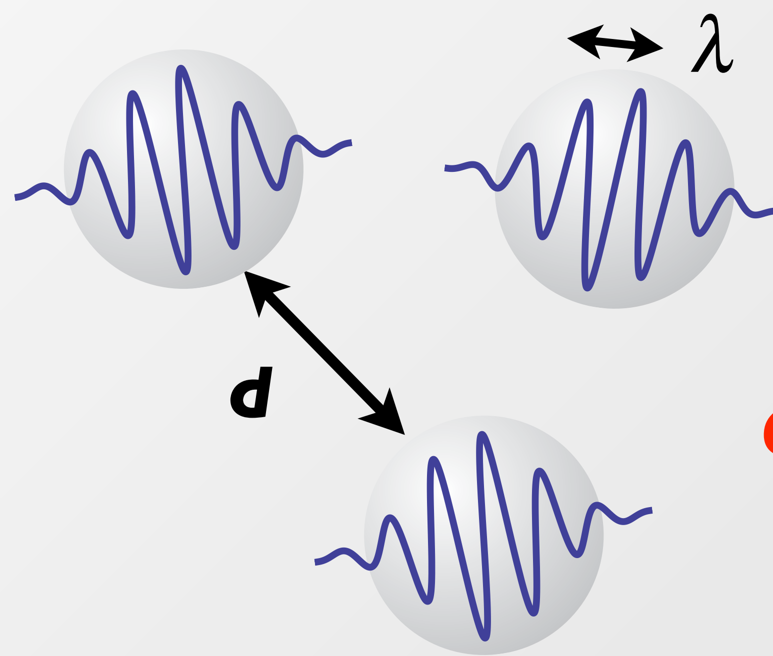
Tuning Interactions



Feshbach resonance allow us to control interactions!

Quantum Regime

$$\lambda/d \gtrsim 1$$



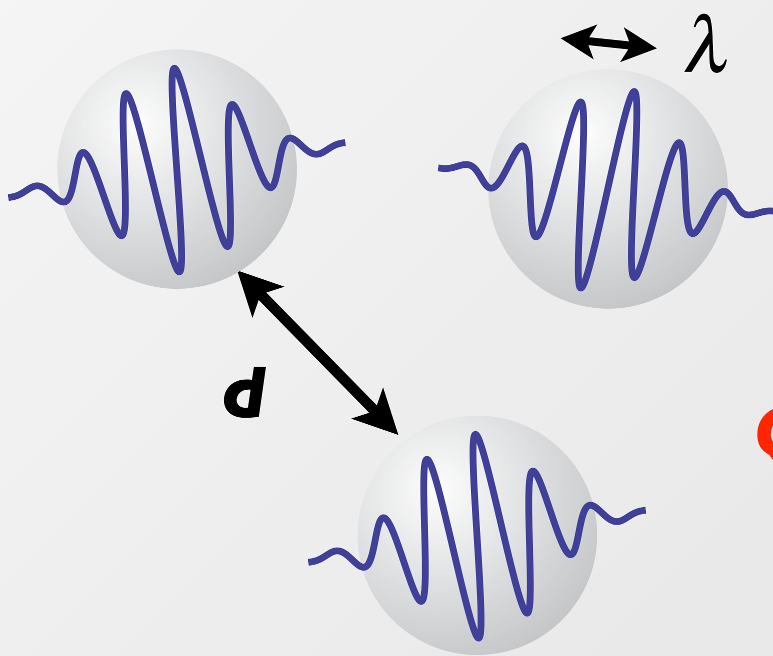
de Broglie Wavepackets

Universality of Quantum Mechanics!

From Artificial Quantum Matter to Real Materials

Quantum Regime

$\lambda/d \gtrsim 1$

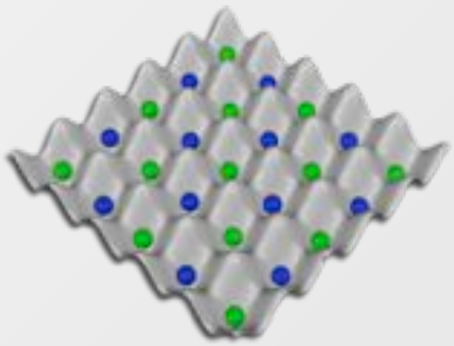


de Broglie Wavepackets

Universality of Quantum Mechanics!

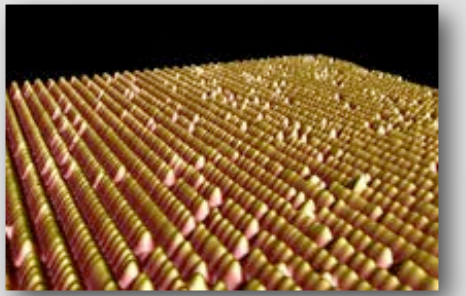
Ultracold Quantum Matter

- **Densities:** **$10^{14}/cm^3$**
  (100000 times thinner than air)
- **Temperatures:** **few nK**
  (100 million times lower than outer space)



Real Materials

- **Densities:** **10^{24}-$10^{25}/cm^3$**
- **Temperatures:** **mK – several hundred K**



(Neuchatel)

Same λ/d !

Bose-Hubbard Hamiltonian

Expanding the field operator in the Wannier basis of localized wave functions on each lattice site, yields :

$$\hat{\psi}(\boldsymbol{x}) = \sum_i \hat{a}_i w(\boldsymbol{x} - \boldsymbol{x}_i)$$

Bose-Hubbard Hamiltonian

$$H = -J \sum_{\langle i,j \rangle} \hat{a}_i^\dagger \hat{a}_j + \sum_i \varepsilon_i \hat{n}_i + \frac{1}{2} U \sum_i \hat{n}_i (\hat{n}_i - 1)$$

Tunnelmatrix element/Hopping element

$$J = -\int d^3x\, w(\boldsymbol{x} - \boldsymbol{x}_i) \left(-\frac{\hbar^2}{2m} \nabla^2 + V_{lat}(\boldsymbol{x}) \right) w(\boldsymbol{x} - \boldsymbol{x}_j)$$

Onsite interaction matrix element

$$U = \frac{4\pi \hbar^2 a}{m} \int d^3x \, |w(\boldsymbol{x})|^4$$

M.P.A. Fisher et al., PRB 40, 546 (1989); D. Jaksch et al., PRL 81, 3108 (1998)

Mott Insulators now at: Munich, Mainz, NIST, ETHZ, Texas, Innsbruck, MIT, Chicago, Florence,...
see also work on JJ arrays H. Mooij et al., E. Cornell,...

From Weak to Strong Interactions

$$\gamma = \frac{\text{Interaction Energy}}{\text{Kinetic Energy}} >> 1$$

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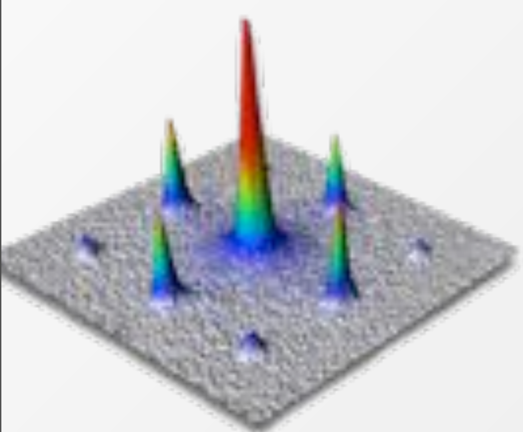
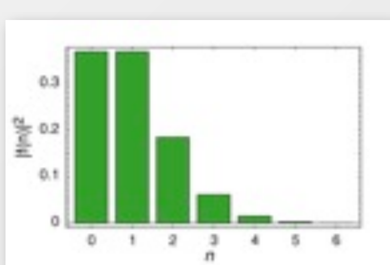
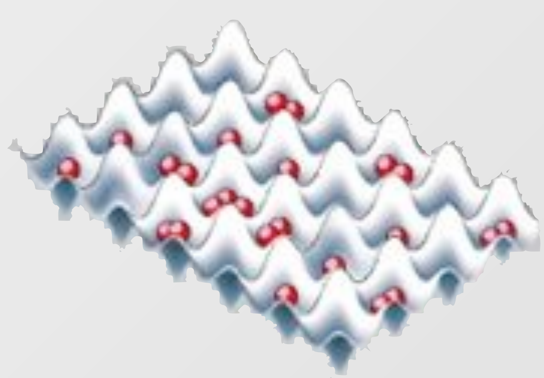


Weak Interactions





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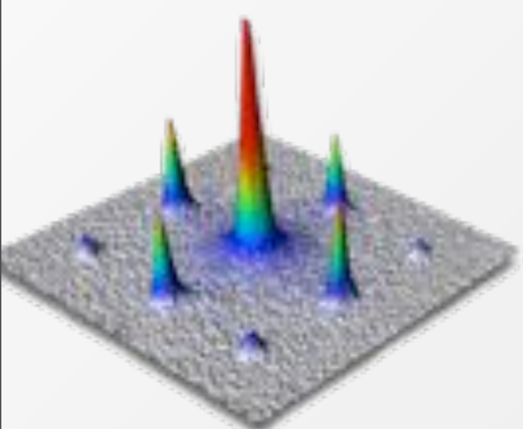
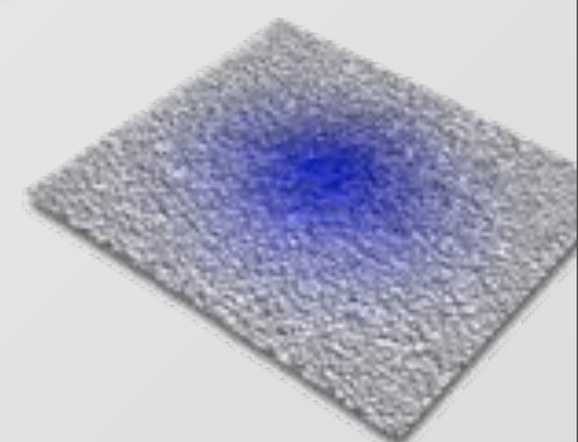
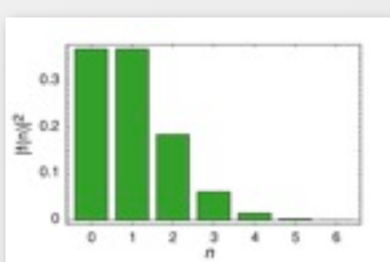
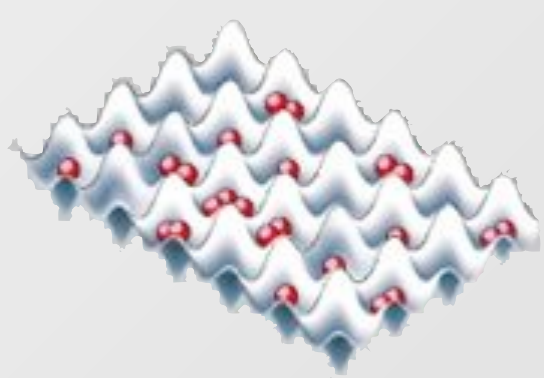


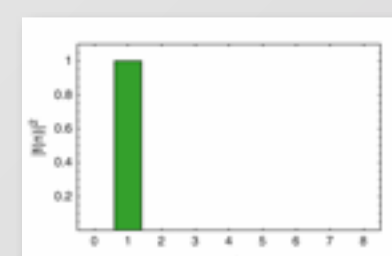


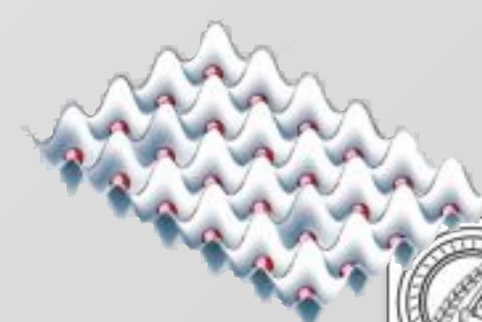
Weak Interactions

Strong Interactions



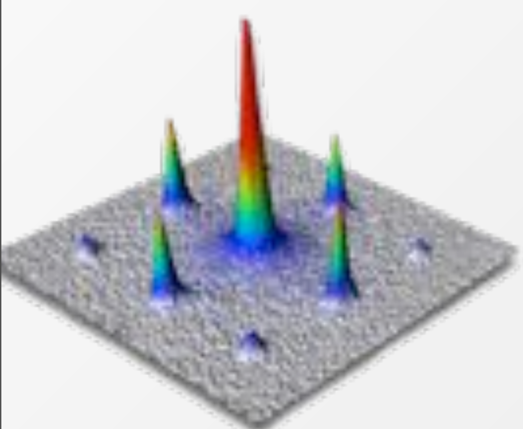


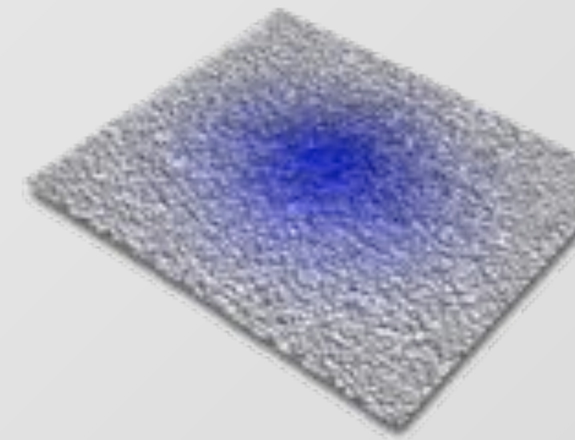




From Weak to Strong Interactions

$$\gamma = \frac{\text{Interaction Energy}}{\text{Kinetic Energy}} >> 1$$



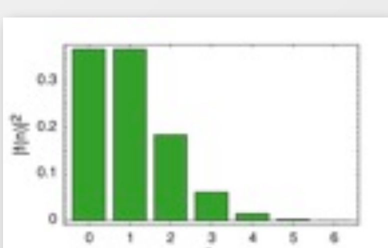


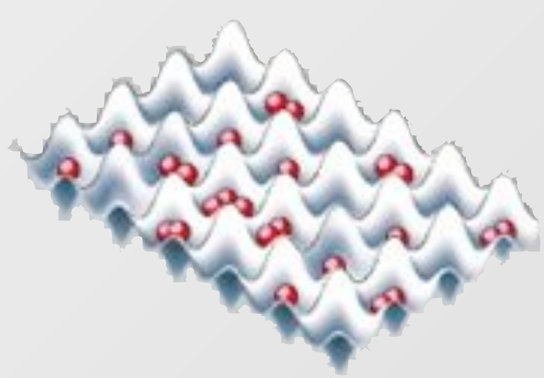
Quantum Phase Transition

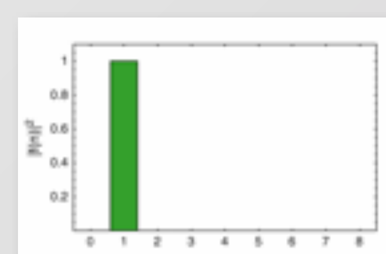
See S. Sachdev & B. Keimer Phys. Today 2011

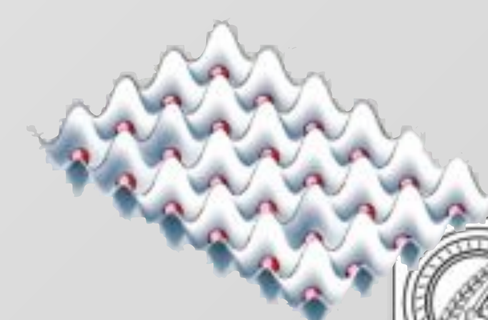
Weak Interactions

Strong Interactions

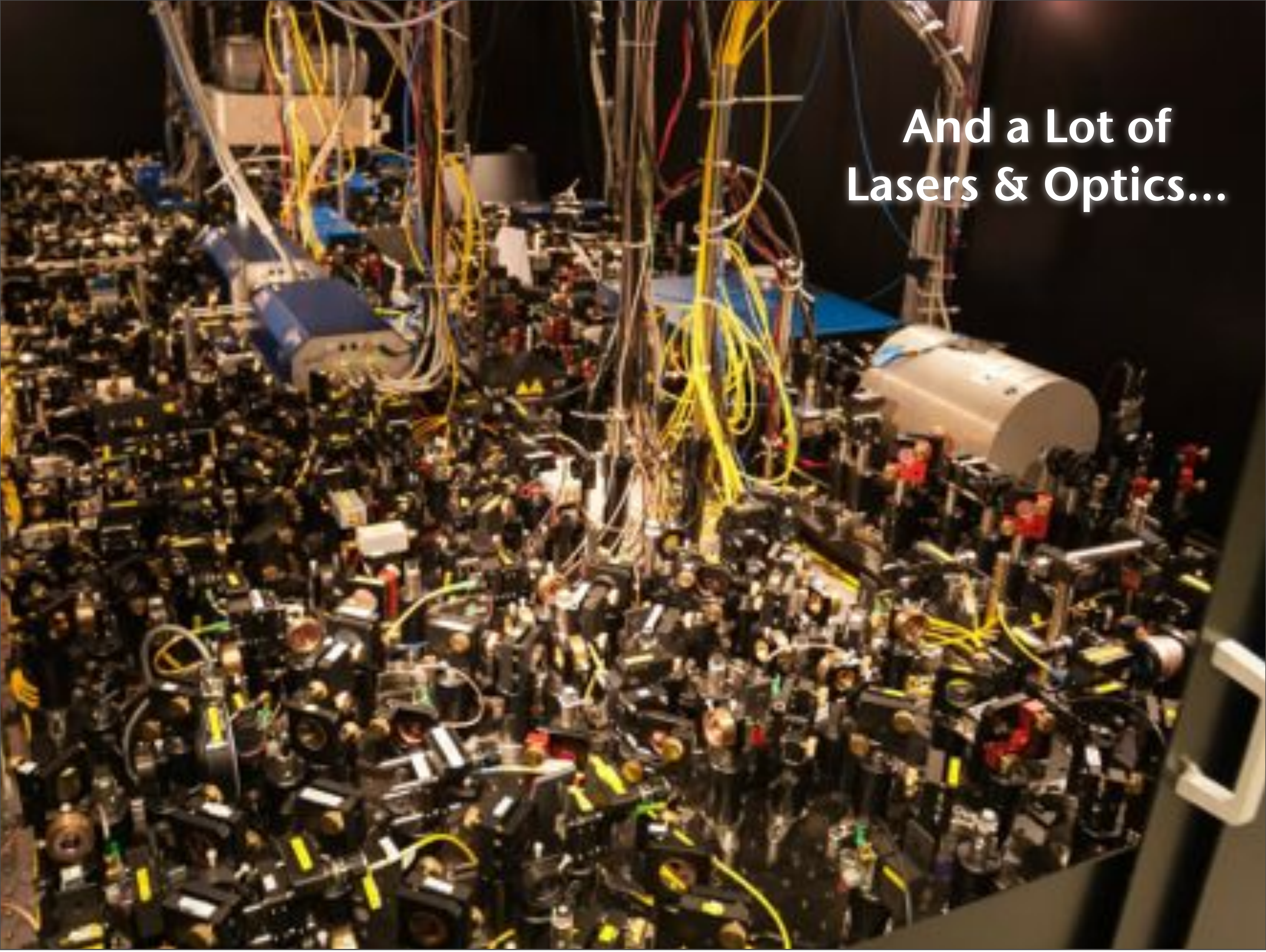








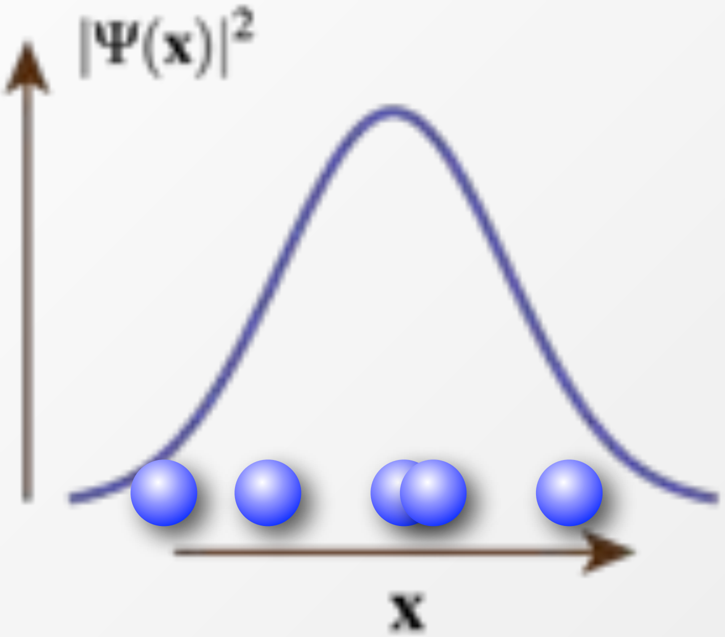
And a Lot of Lasers & Optics...



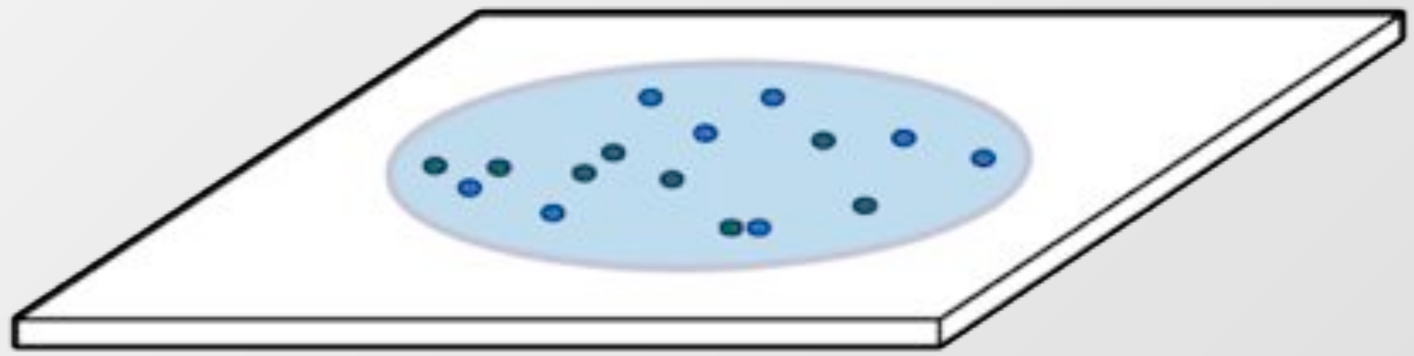
Single Atom Detection in a Lattice

Sherson et al. Nature 467, 68 (2010),
see also Bakr et al. Nature (2009) & Bakr et al. Science (2010)

Measuring a Quantum System



Single Particle



Correlated 2D Quantum Liquid

$\Psi(\mathbf{x})$ wave function

$|\Psi(\mathbf{x})|^2$ probability distribution

$$\Psi(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3, \ldots, \mathbf{x}_N)$$

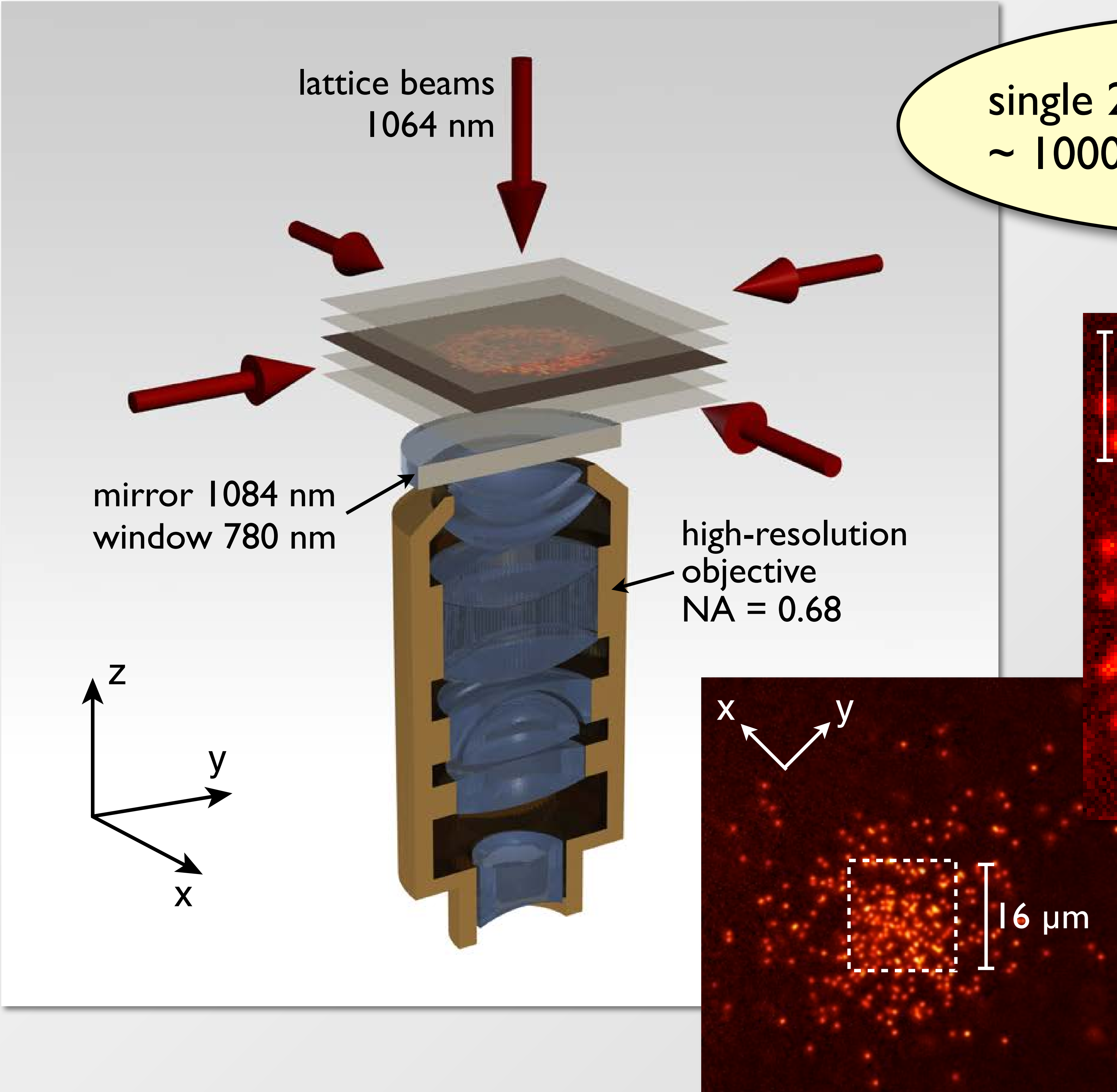
$$|\Psi(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3, \ldots, \mathbf{x}_N)|^2$$

averaging over single-particle measurements, we obtain $|\Psi(\mathbf{x})|^2$

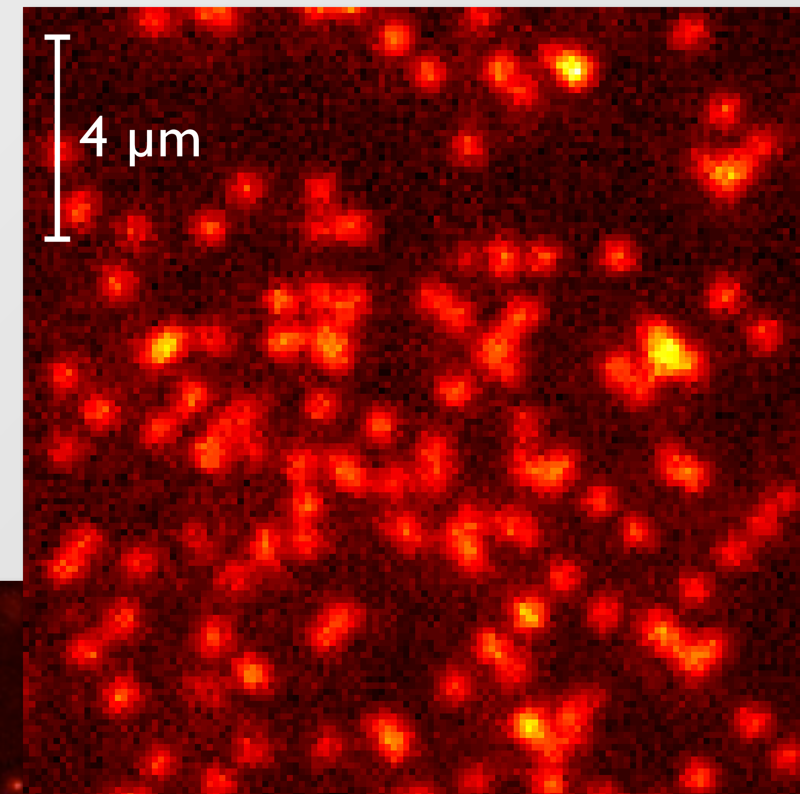
For many-body system: need access to single snapshots of the many-particle system!

Enables Measurement of Non-local Correlations

Experimental Setup



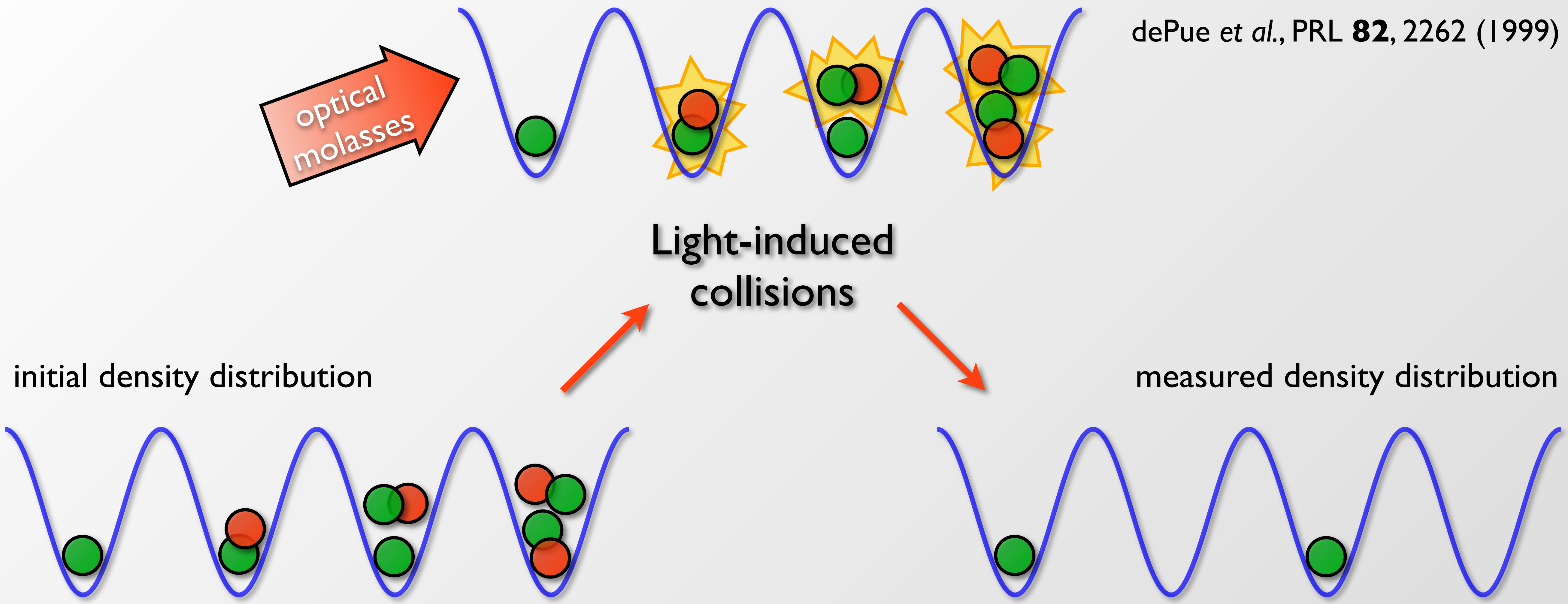
single 2D degenerate gas
~ 1000 ^{87}Rb atoms (bosons)



resolution of the
imaging system:
~700 nm

Parity projection

dePue *et al.*, PRL **82**, 2262 (1999)



measured occupation: $n_{\text{det}} = \text{mod}_2 n$

measured variance: $\sigma^2_{\text{det}} = \langle n^2_{\text{det}} \rangle - \langle n_{\text{det}} \rangle^2$

parity projection $\Rightarrow$ $\langle n^2_{\text{det}} \rangle = \langle n_{\text{det}} \rangle$

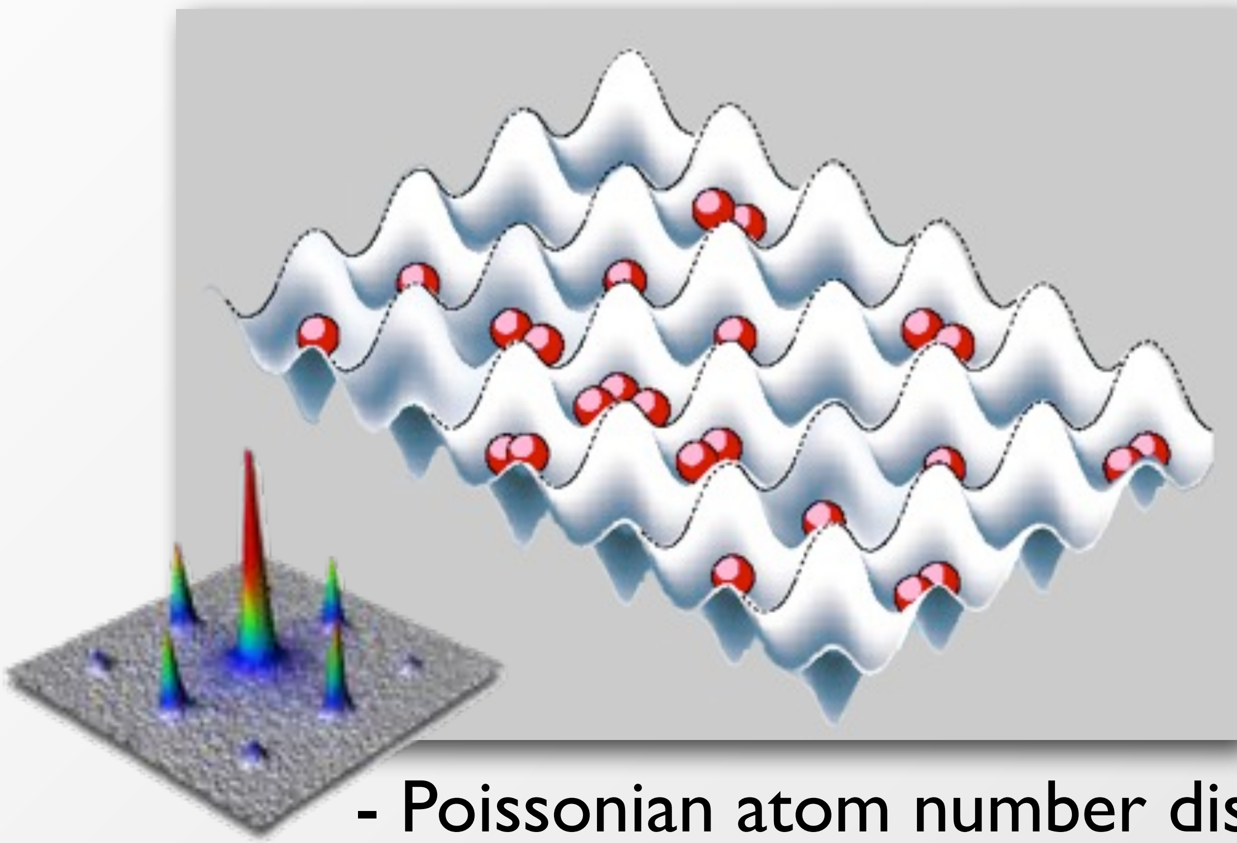
see also E. Kapit & E. Mueller, Phys. Rev. A **82**, 013644 (2010)

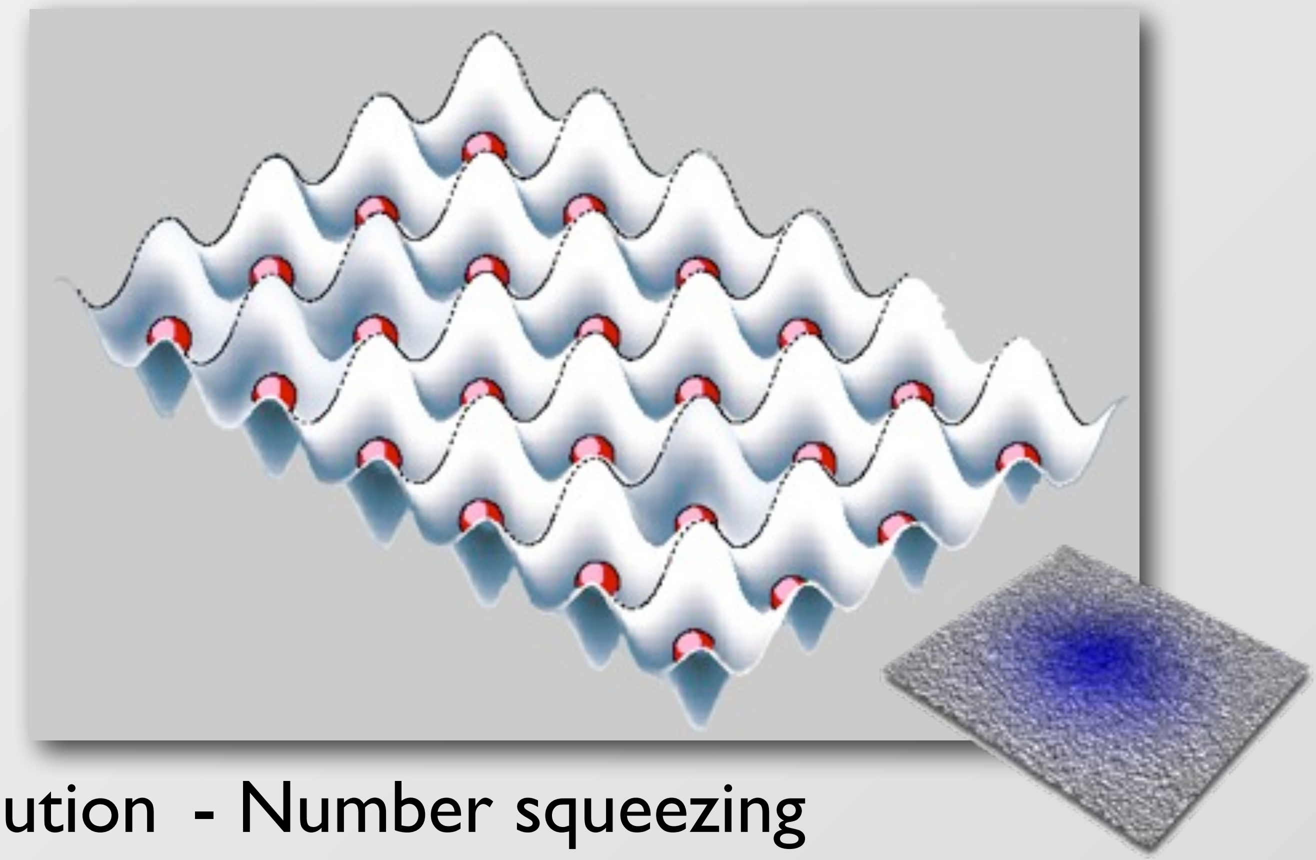
In-Situ Imaging of a Mott Insulator

J. Sherson et al. Nature **467**, 68 (2010),
see also S. Fölling et al. Phys. Rev. Lett (2006), G.K. Campbell et al. Science (2006)
N. Gemelke et al. Nature (2009), W. Bakr et al. Science (2010)

Mott Insulators

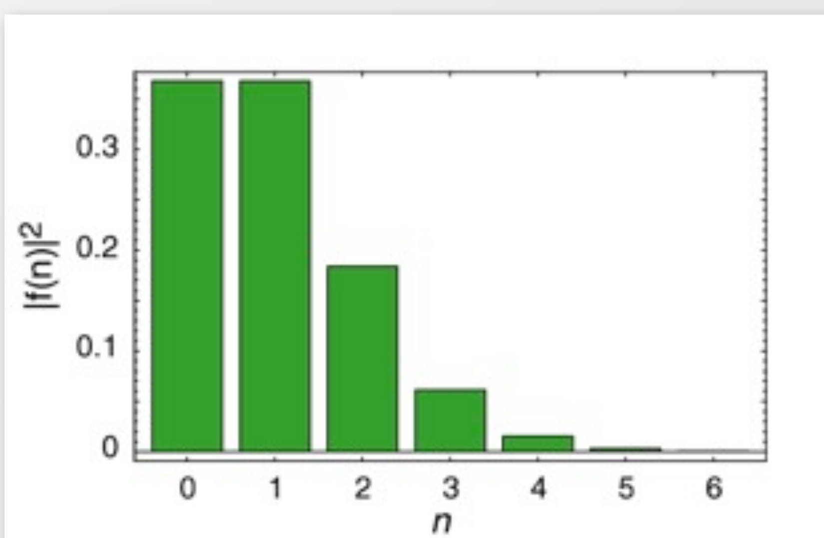
Superfluid | **Mott-Insulator**

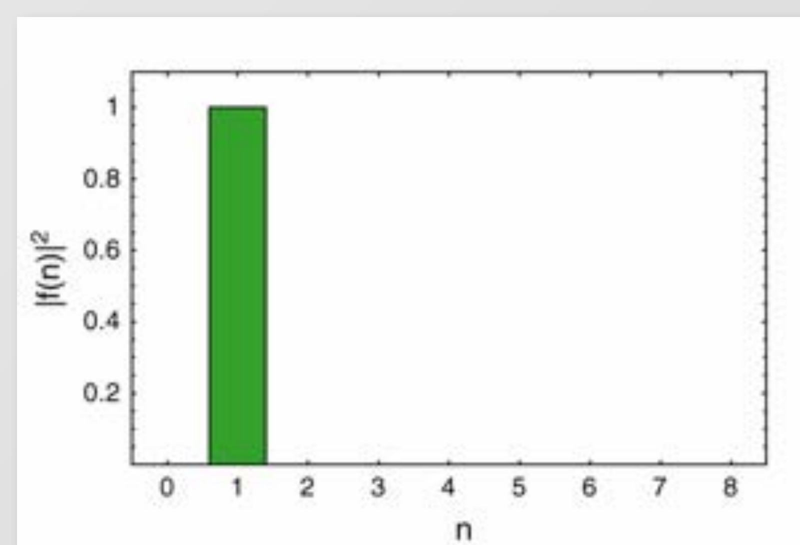




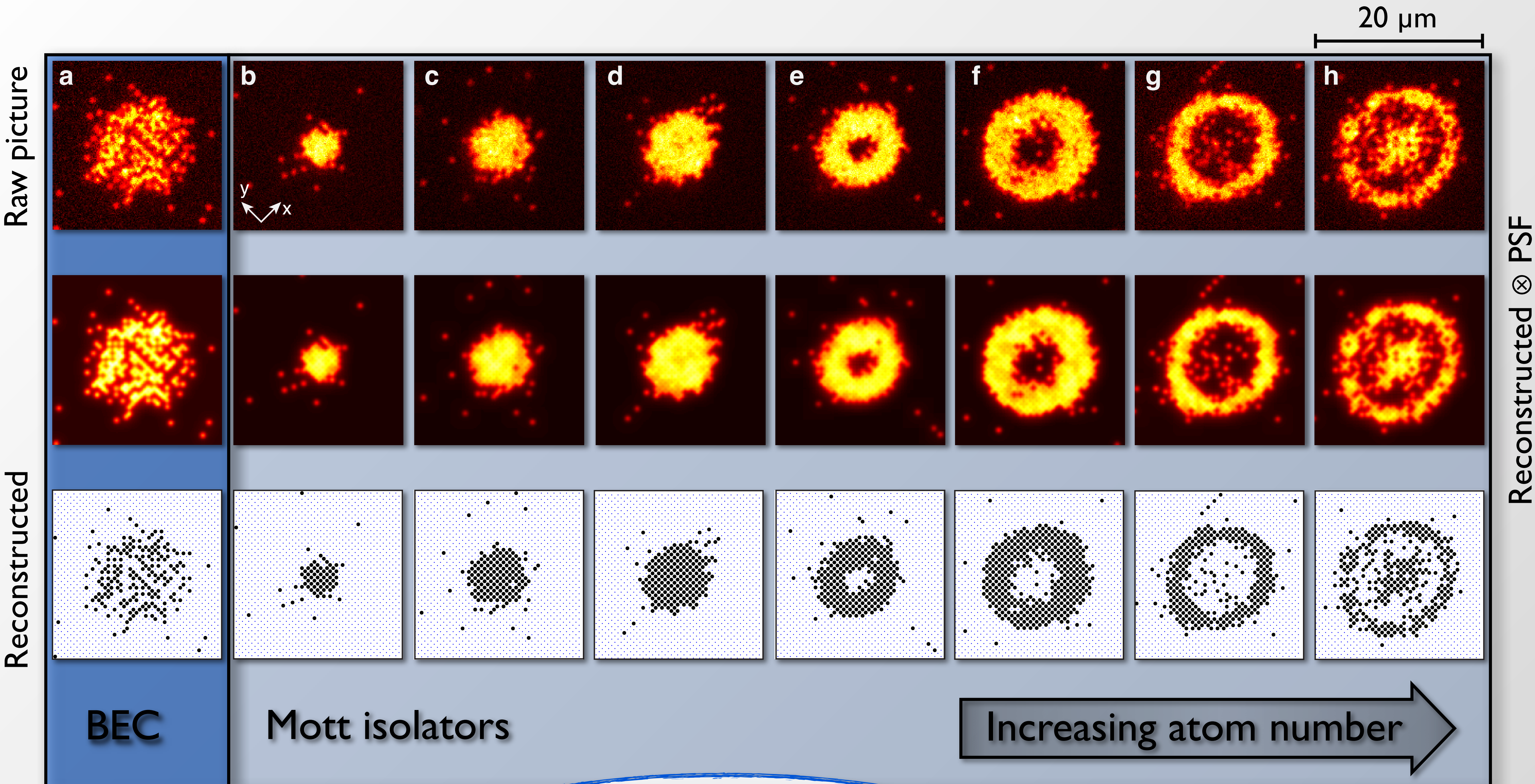
- Poissonian atom number distribution
- Long range phase coherence

- Number squeezing
- No phase coherence





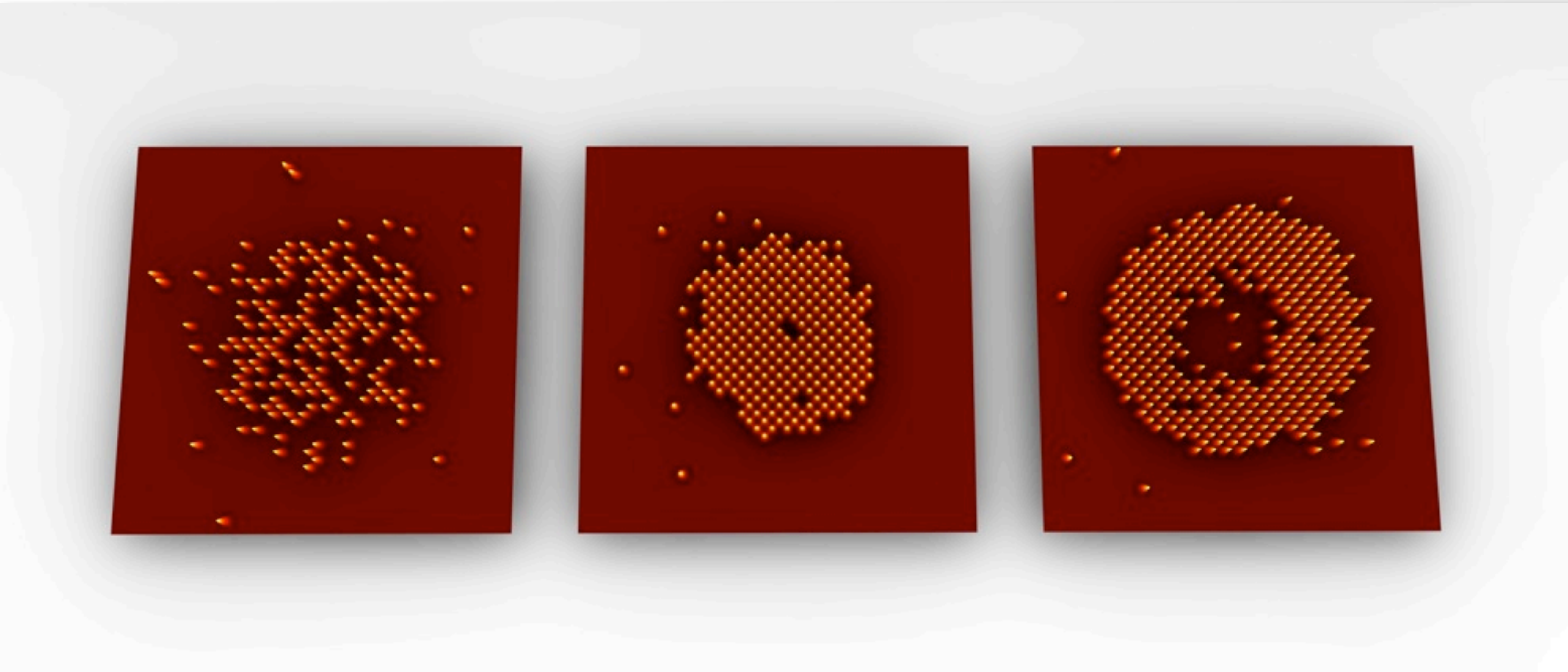
In-situ observation of a Mott insulator



for the Mott insulators: U/J ~ 300 (critical U/J ~ 16)

⇒ only thermal fluctuations

Snapshot of an Atomic Density Distribution

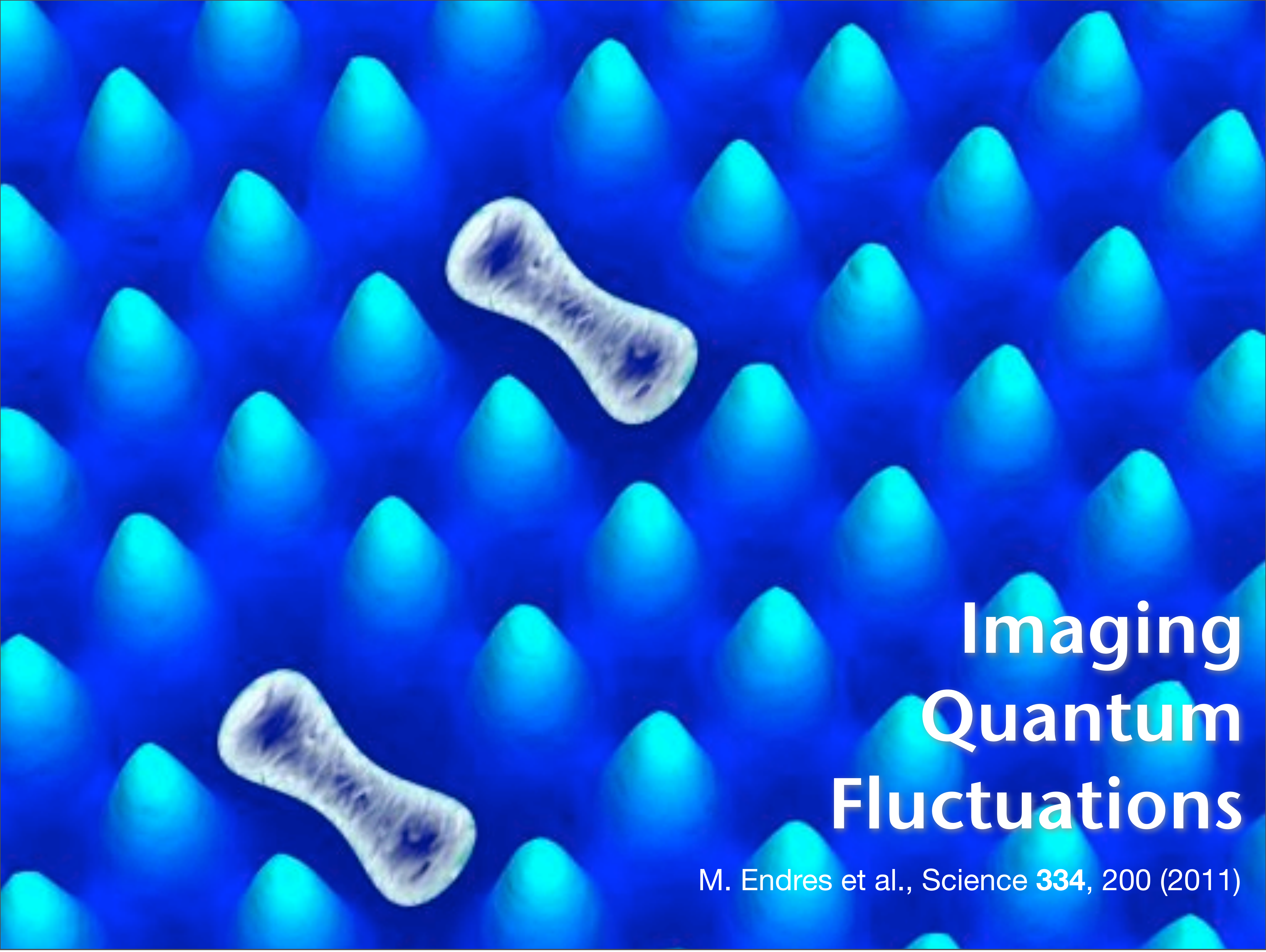


BEC

n=1
Mott Insulator

n=1 & n=2
Mott Insulator

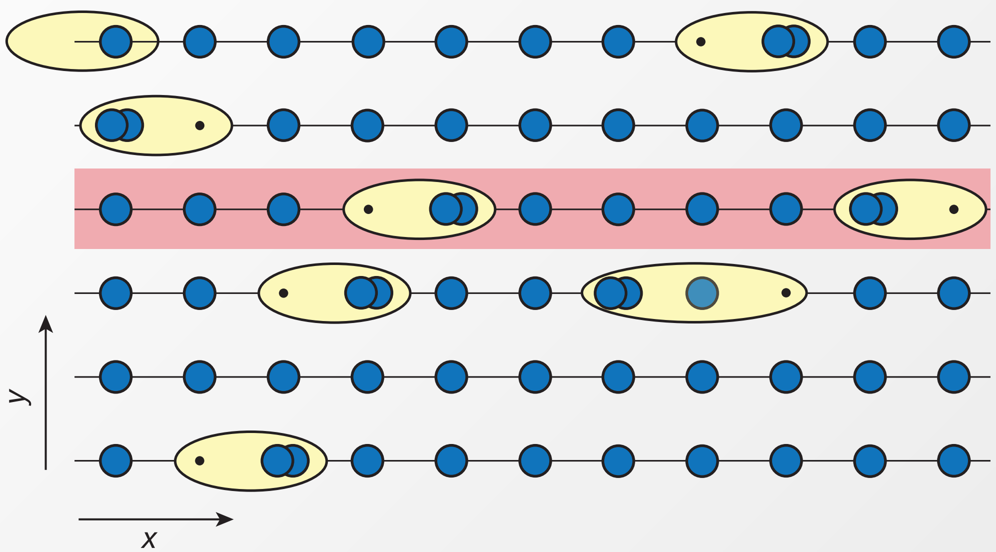
J. Sherson *et al.* Nature **467**, 68 (2010)

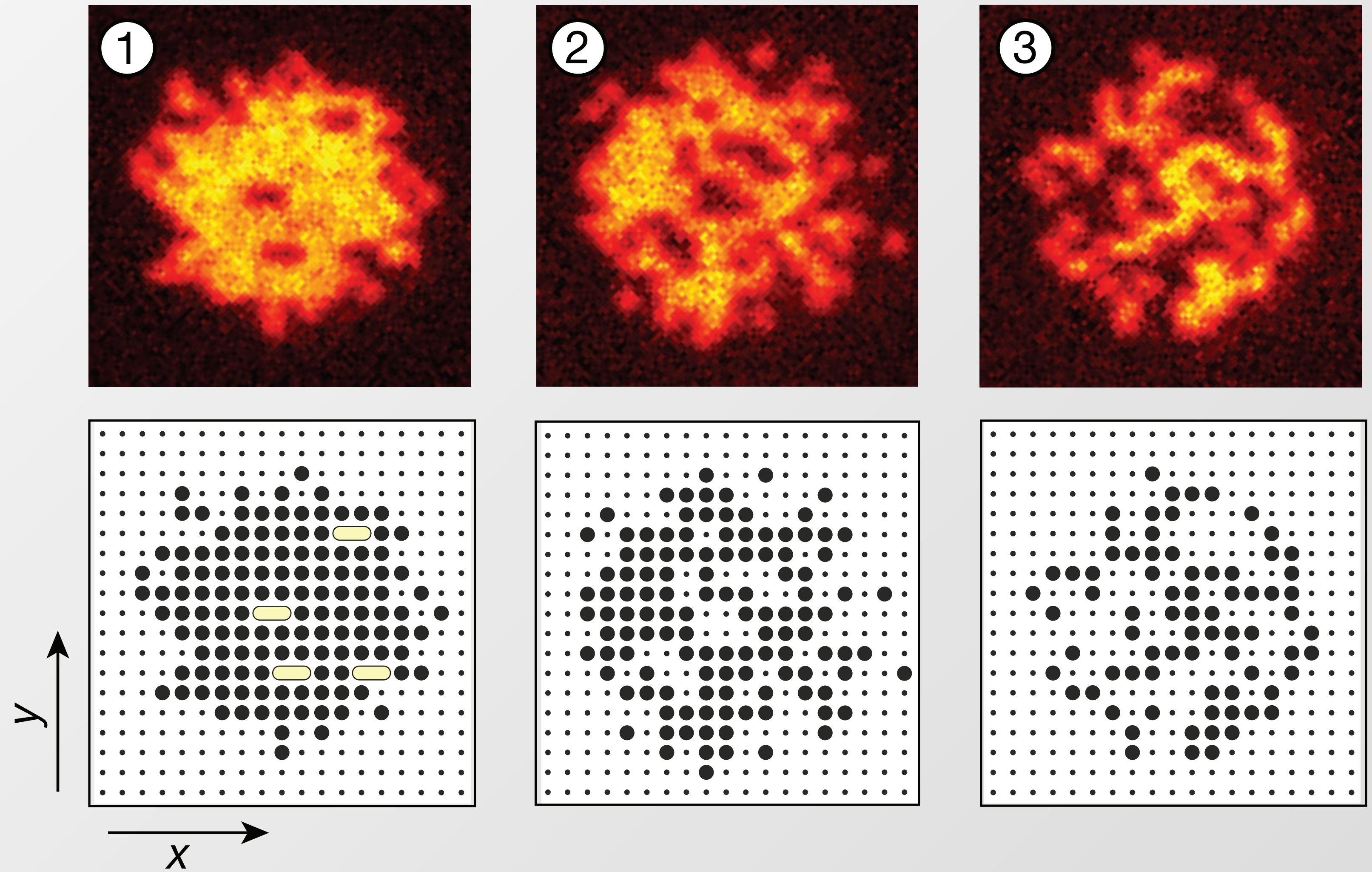


Imaging Quantum Fluctuations

M. Endres et al., Science **334**, 200 (2011)

Quantum Correlated Particle Hole Correlations





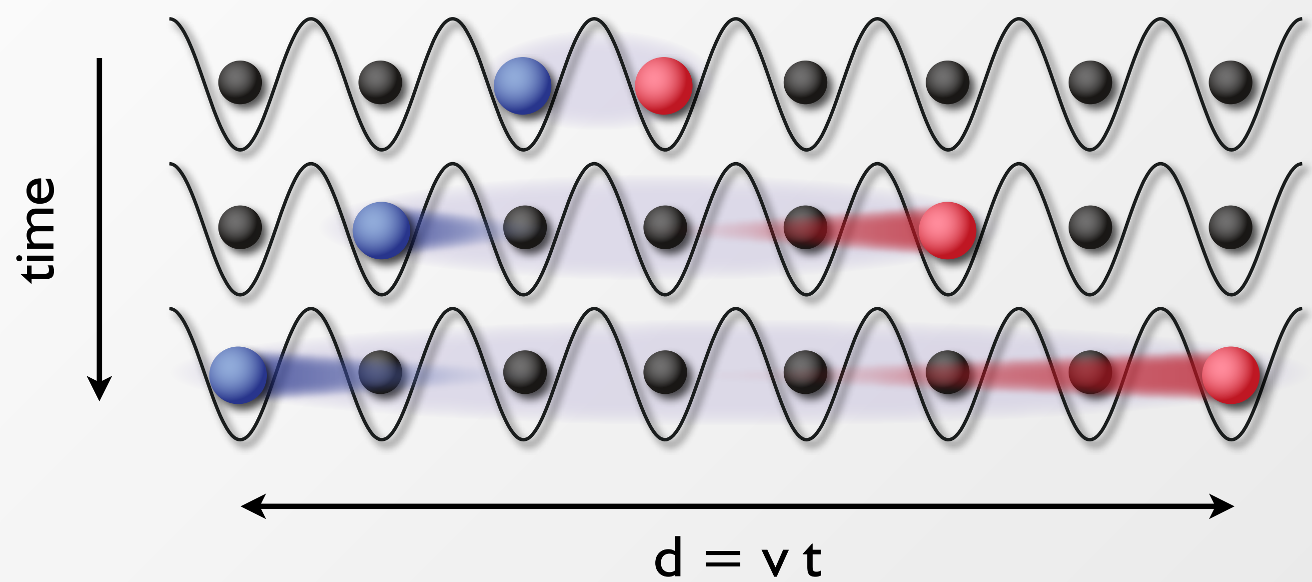
$J/U=0.06$ $J/U=0.11$ $J/U=0.3$

$$C(d) = \langle \hat{s}_k \hat{s}_{k+d} \rangle - \langle \hat{s}_k \rangle \langle \hat{s}_{k+d} \rangle$$

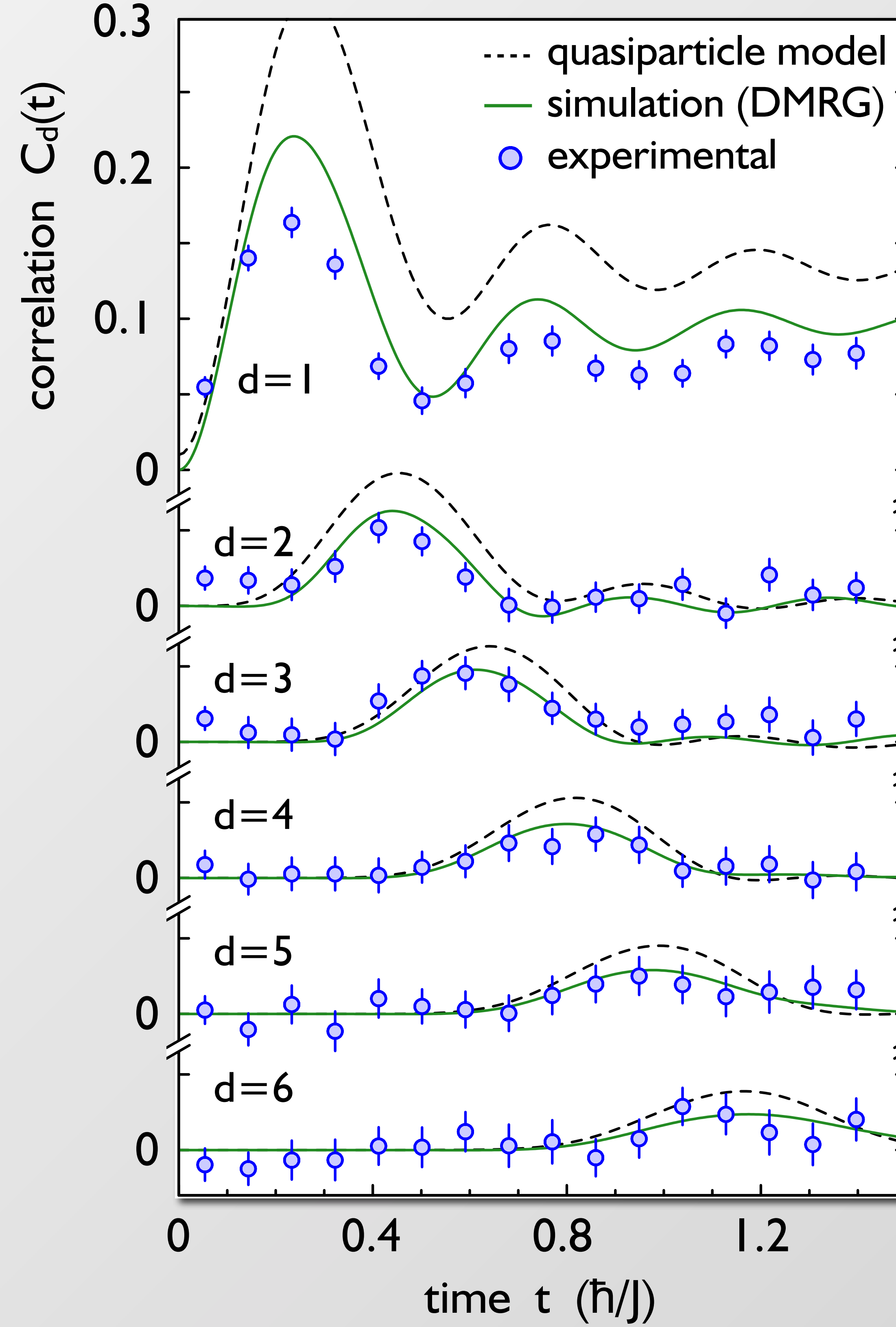
Two point correlator

Light-cone spreading of correlations

- Quasiparticle dynamics



E. Lieb & D.W. Robinson (1972)
Bravyi, Hastings and Verstraete (2006)
Calabrese and Cardy (2006)
Eisert and Osborne (2006)
Nachtergaele, Ogata and Sims (2006)
... ***and many others since then***

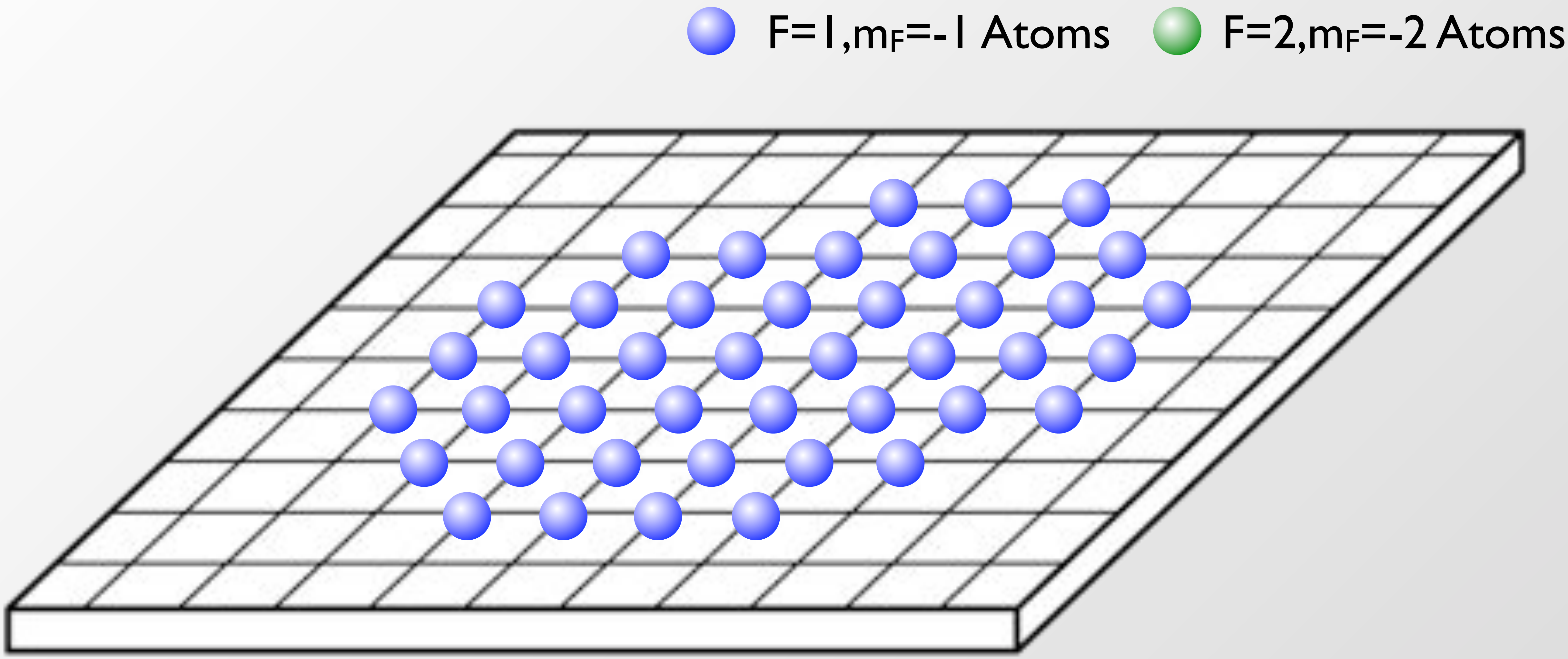


M. Cheneau et al. Nature (2012)

Single Site Addressing

Ch. Weitenberg et al., Nature 471, 319-324 (2011)

Coherent Addressing of Atoms

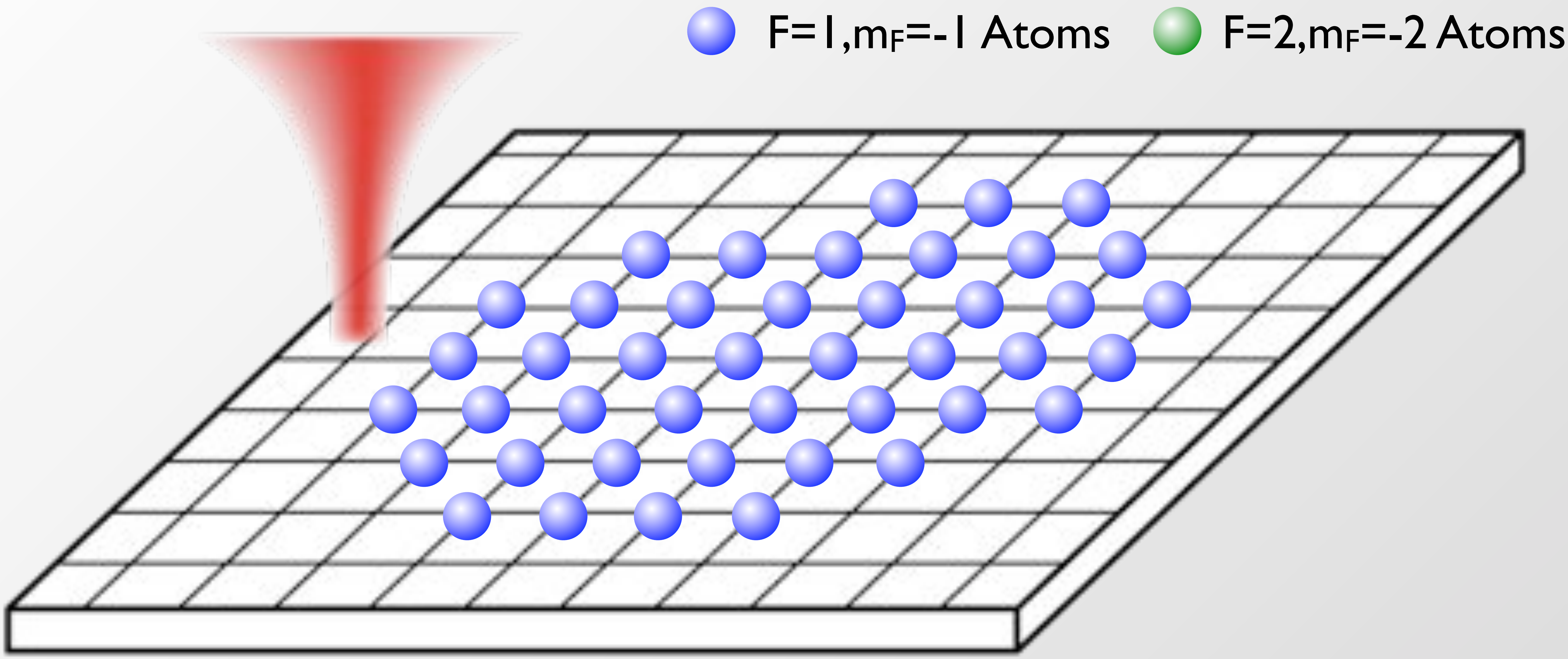


Differential light shift allows to coherently address single atoms!

Landau-Zener Microwave sweep to coherently convert atoms between spin-states.

D.S. Weiss et al., PRA (2004),
Zhang *et al.*, PRA (2006)

Coherent Addressing of Atoms



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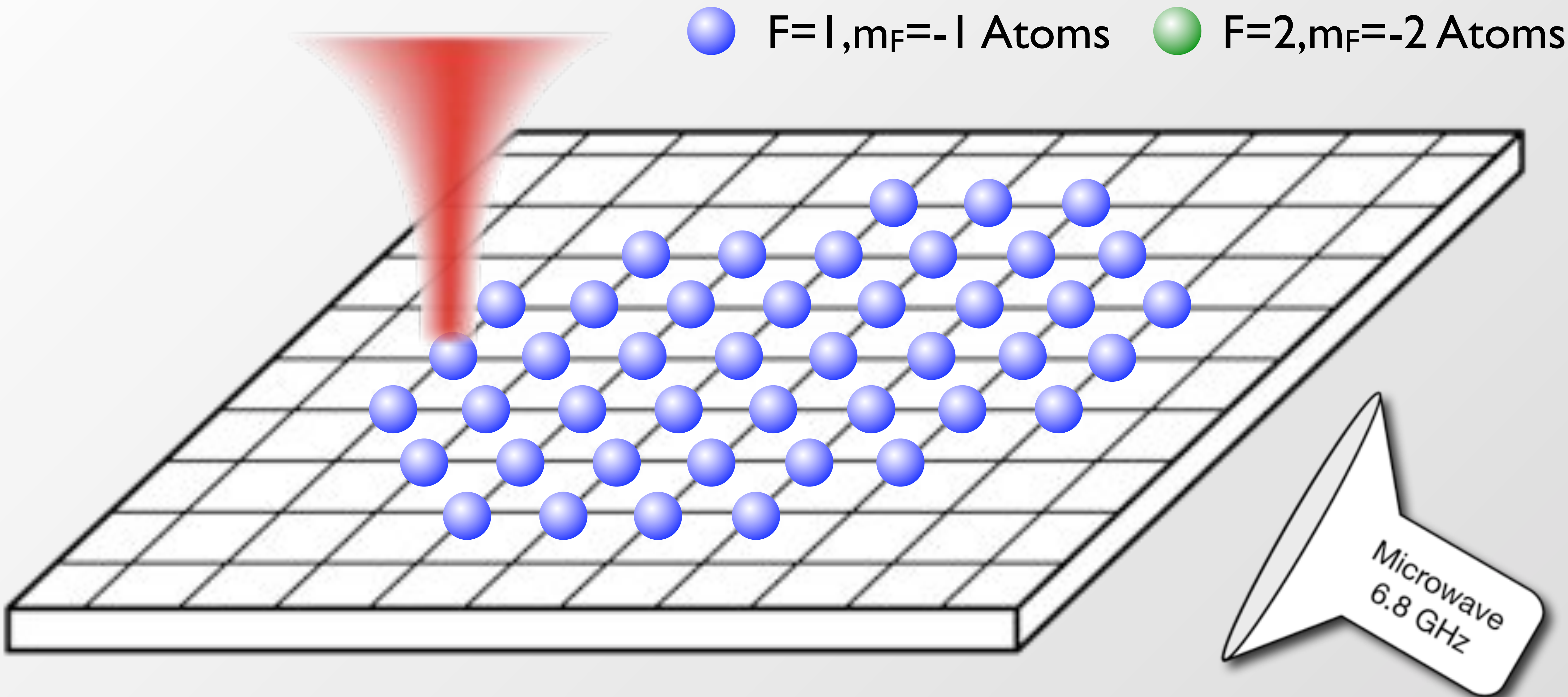

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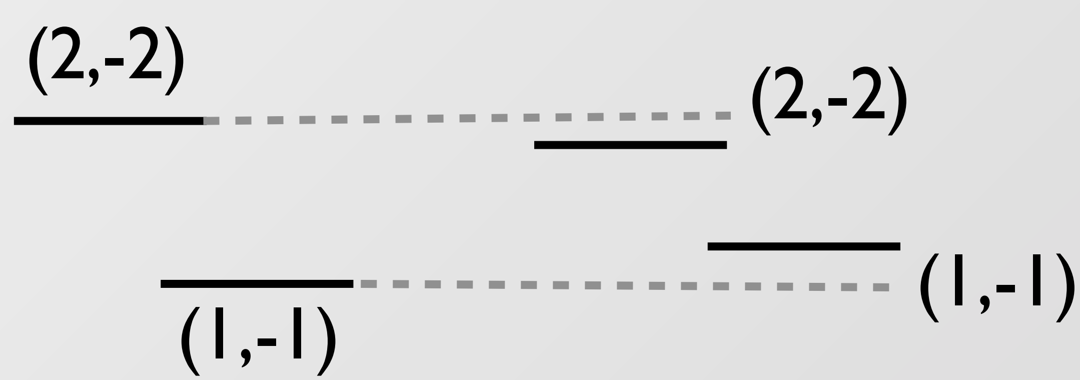

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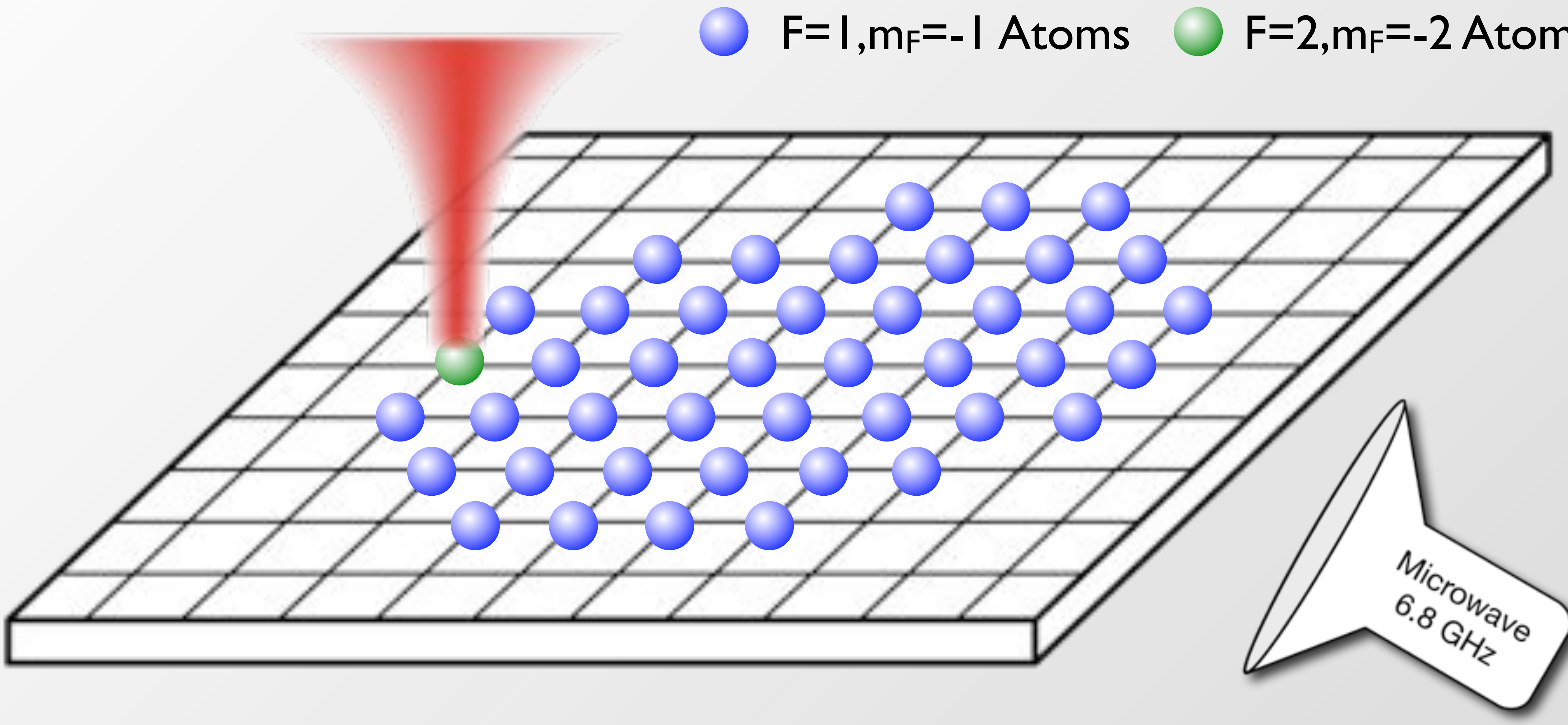

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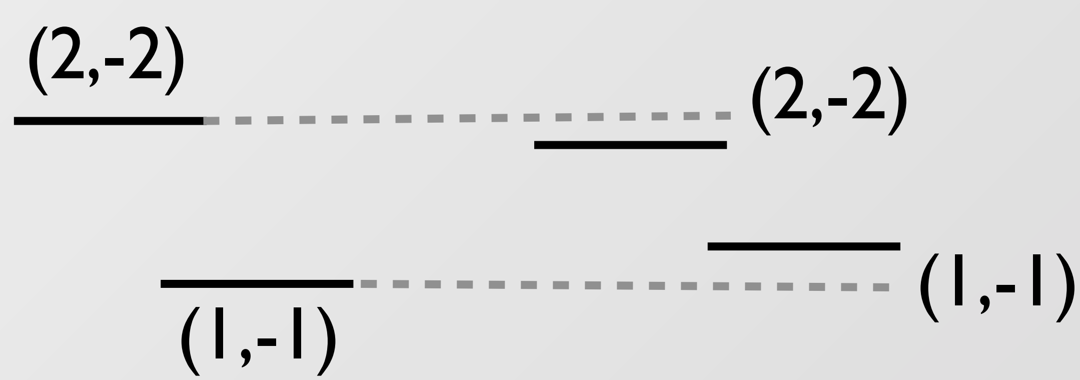
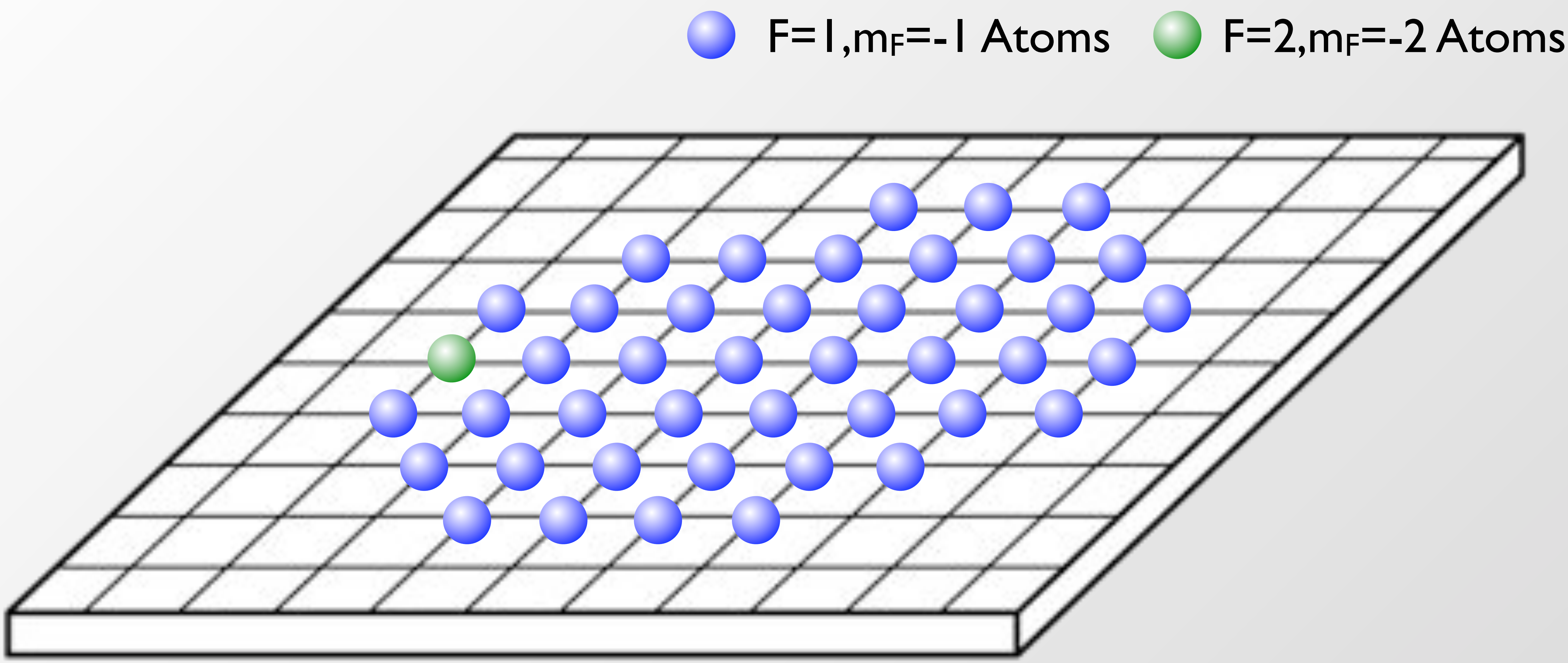
Landau-Zener Microwave sweep to coherently convert atoms between spin-states.



D.S.Weiss et al., PRA (2004),
Zhang *et al.*, PRA (2006)

Coherent Addressing of Atoms



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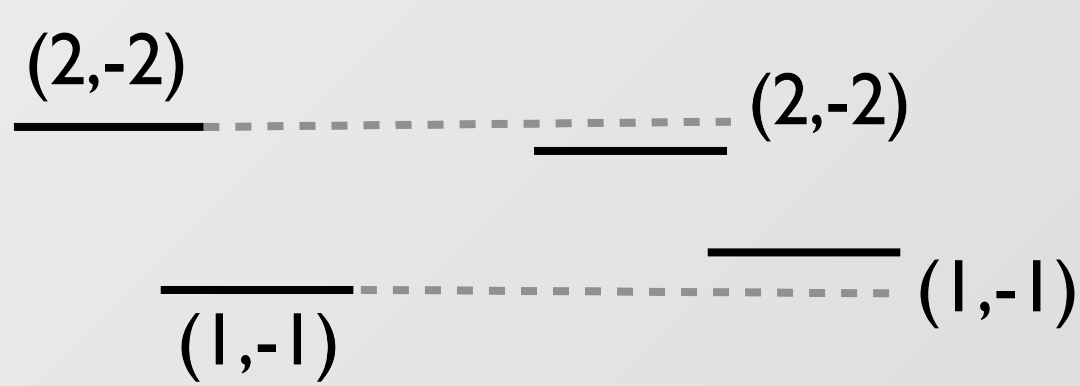

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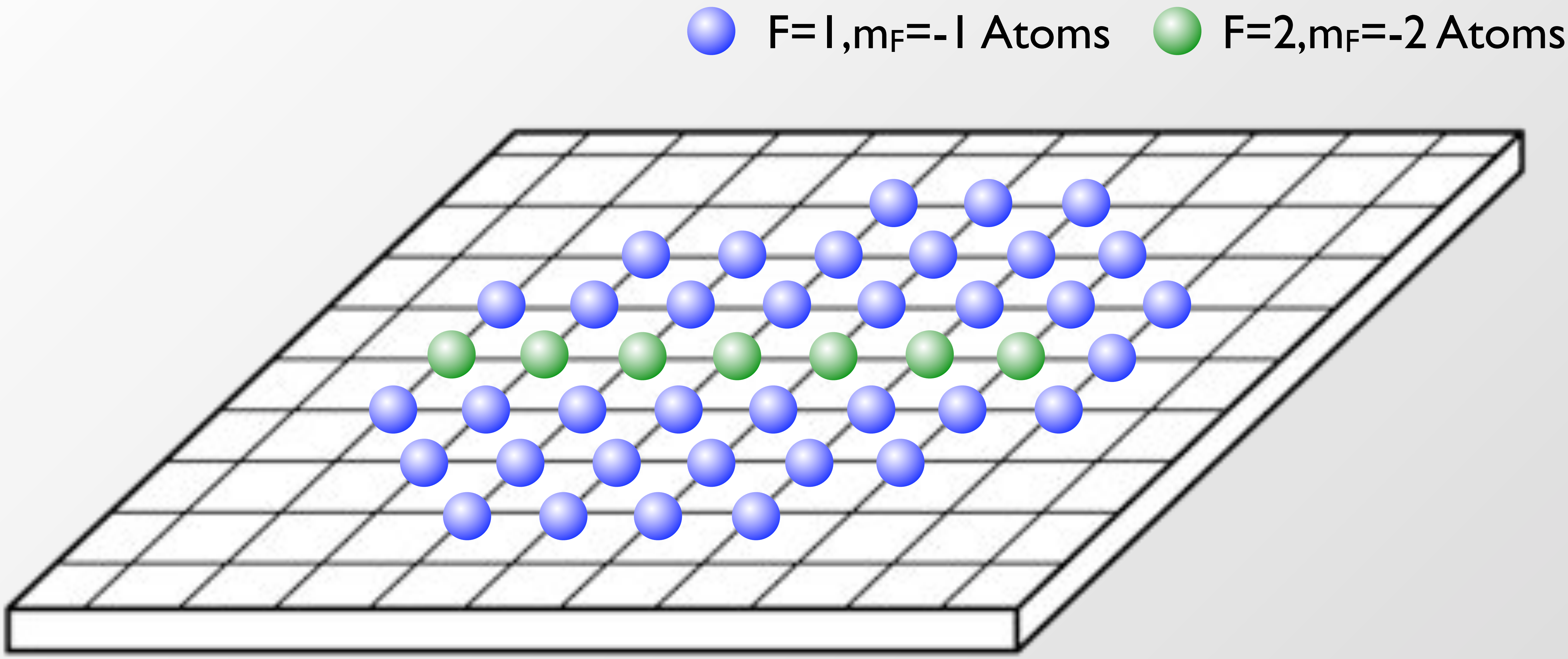

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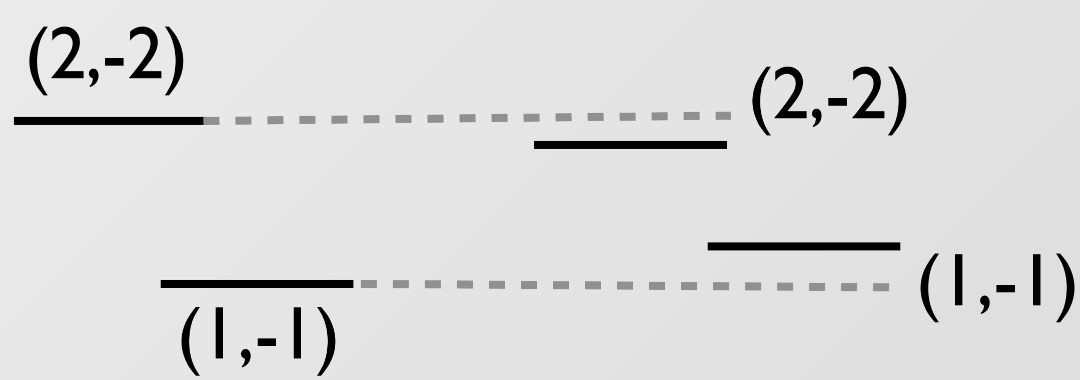
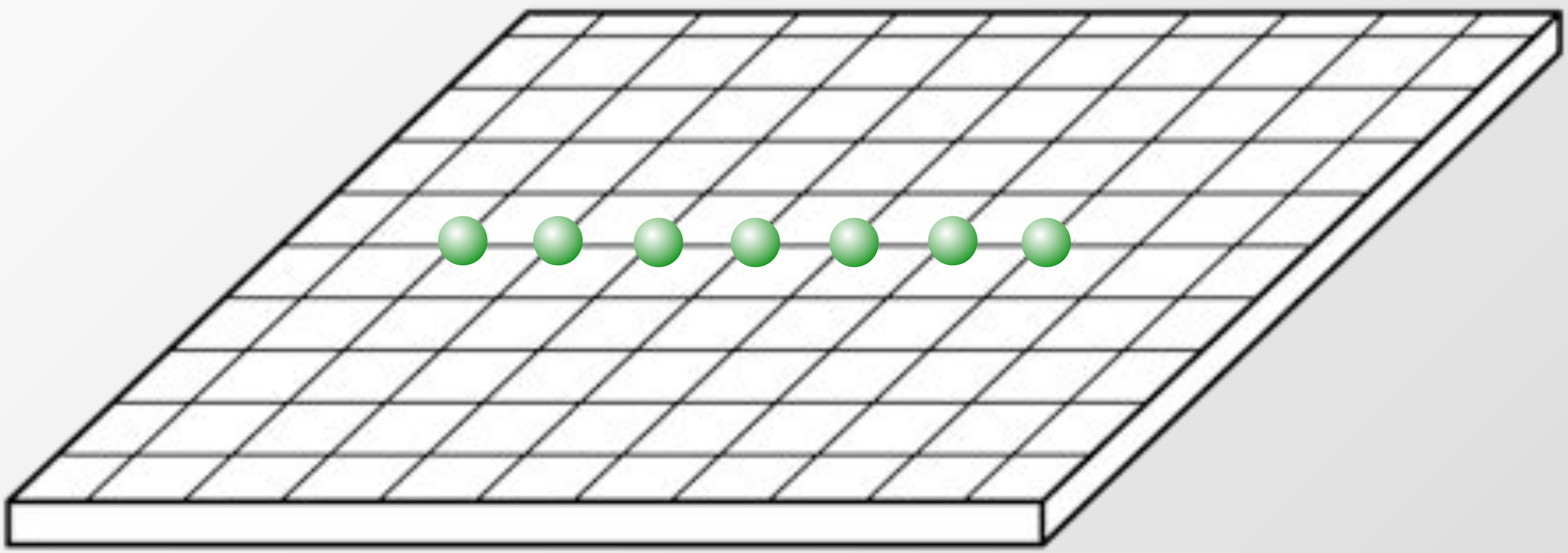


D.S.Weiss et al., PRA (2004),
Zhang *et al.*, PRA (2006)

Coherent Addressing of Atoms

$F=1, m_F=-1$ Atoms $F=2, m_F=-2$ Atoms



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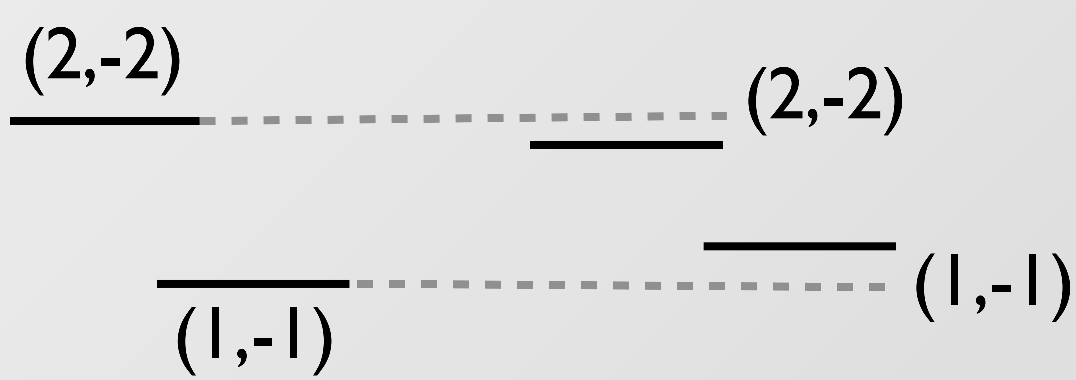
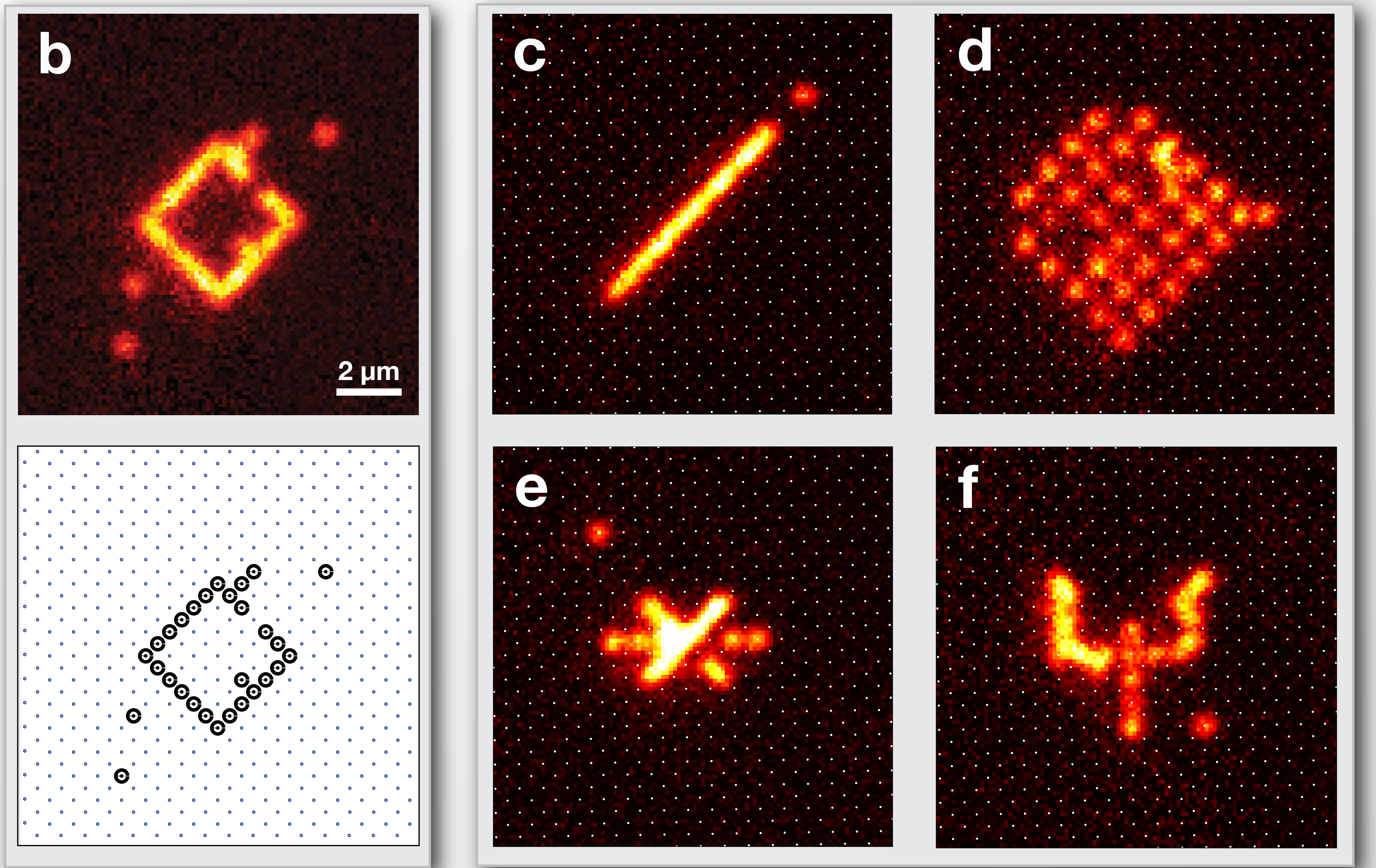


D.S. Weiss et al., PRA (2004),
Zhang *et al.*, PRA (2006)

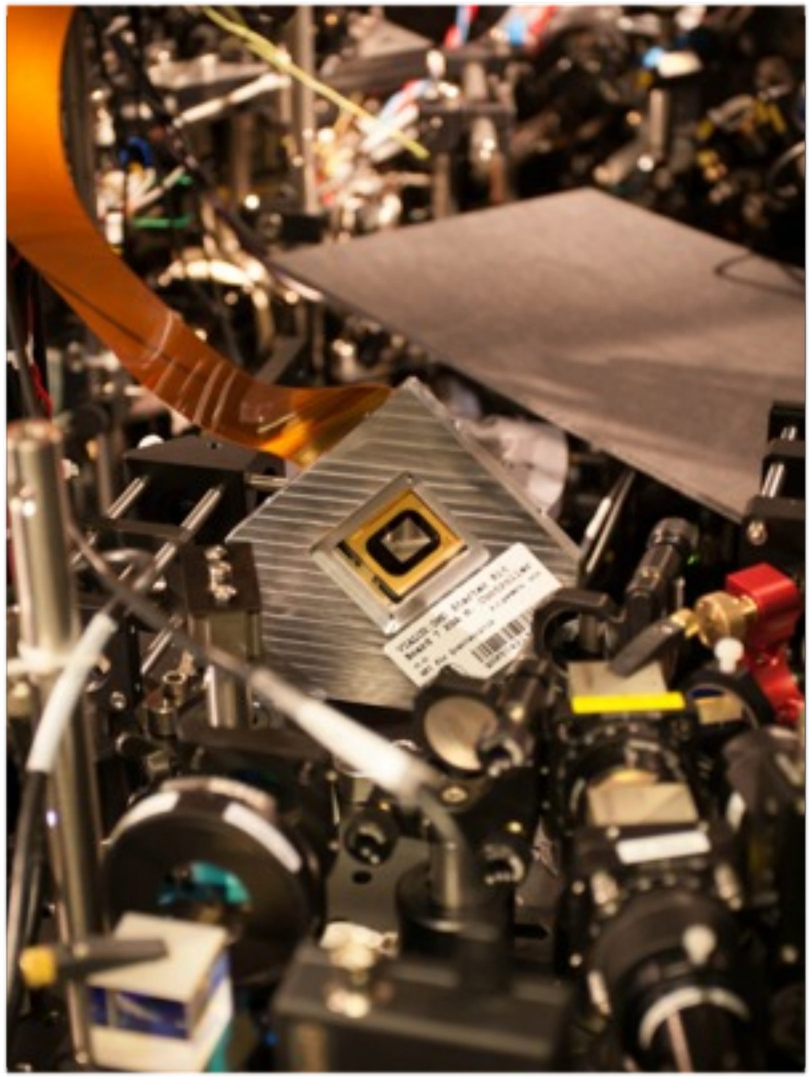
Coherent Spin Flips - Positive Imaging



Subwavelength spatial resolution: 50 nm

Ch. Weitenberg et al., Nature **471**, 319-324 (2011)

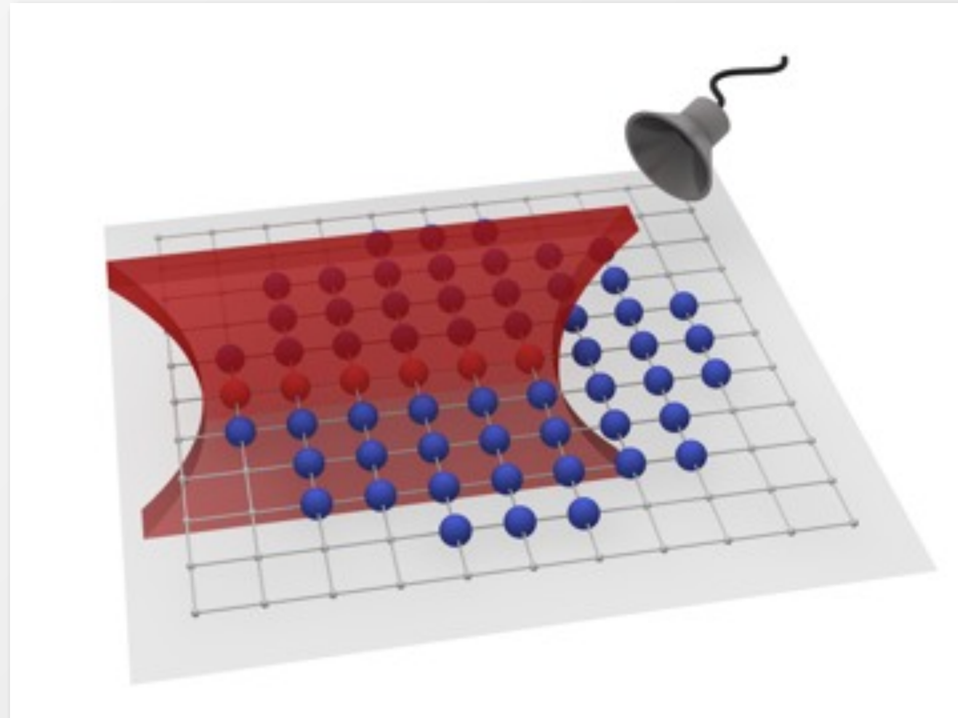
Arbitrary Light Patterns

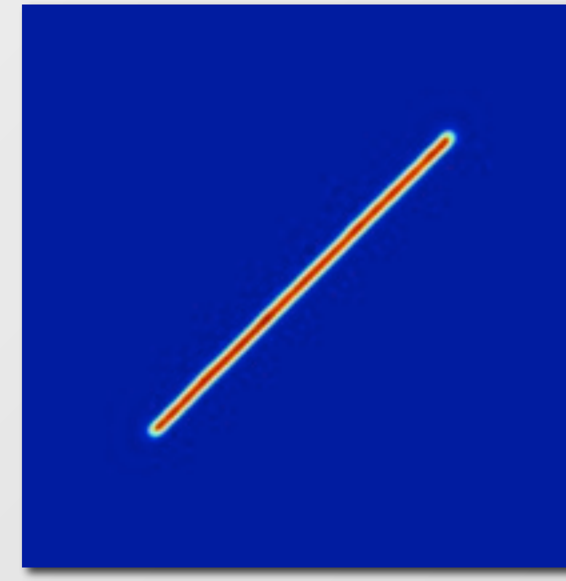


Digital Mirror Device
(DMD)

Arbitrary Light Patterns

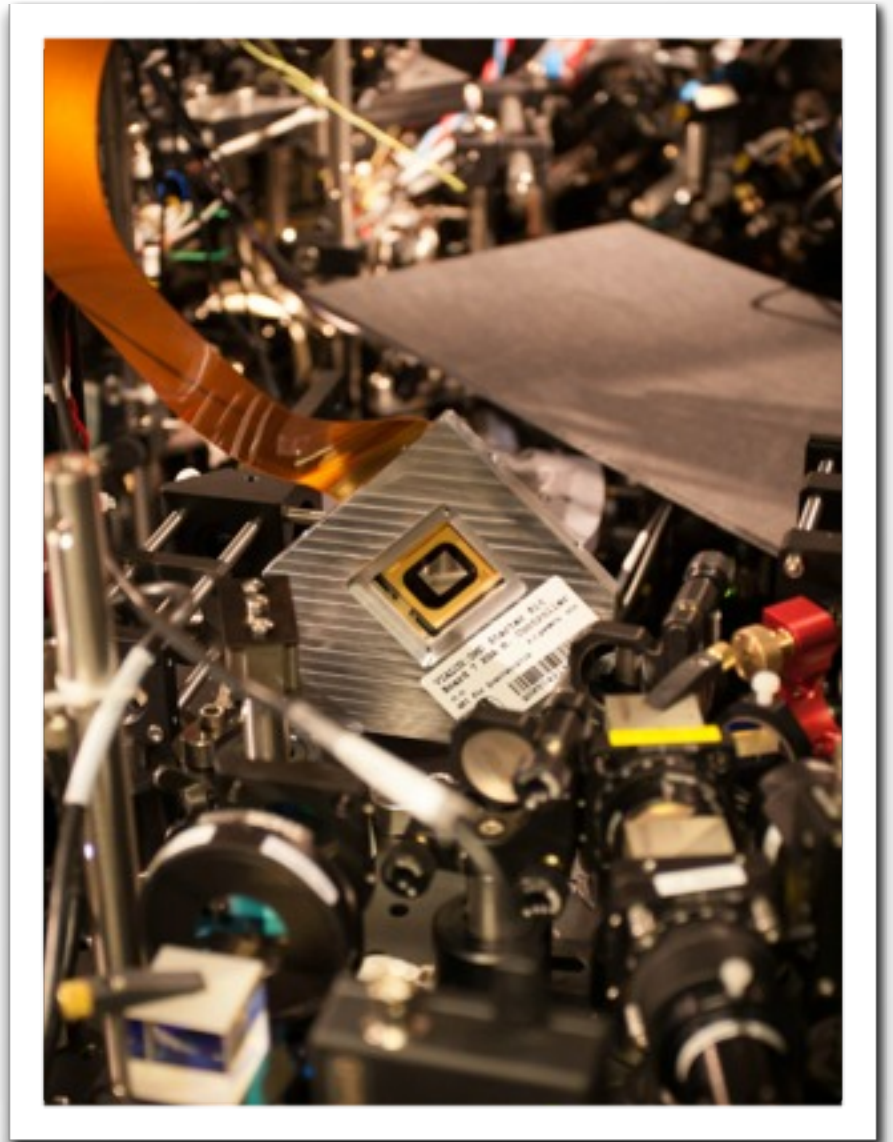
Digital Mirror Device
(DMD)



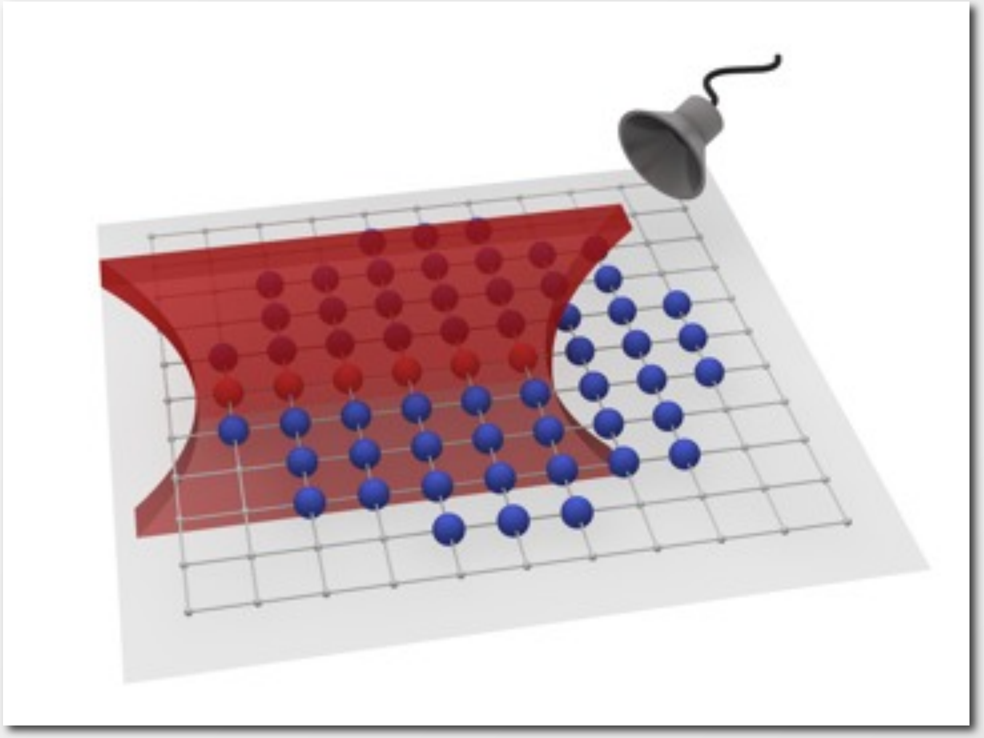


Measured Light Pattern

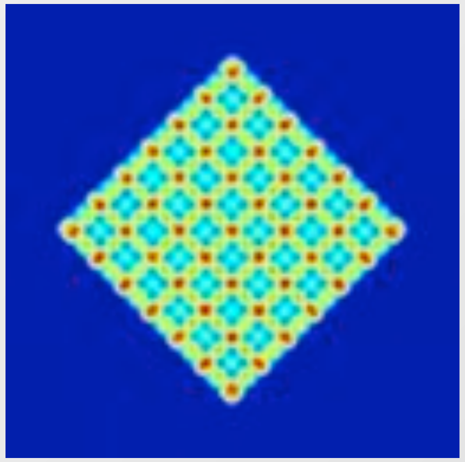
Arbitrary Light Patterns



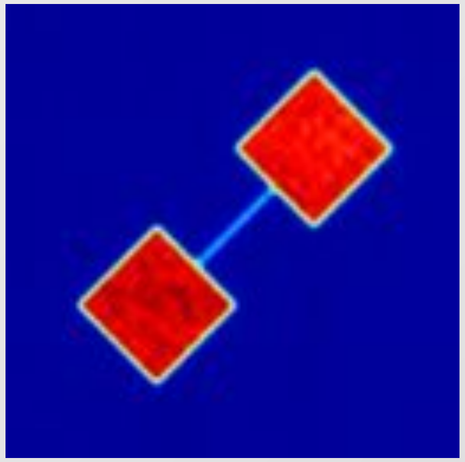
Digital Mirror Device (DMD)



Measured Light Pattern



Exotic Lattices

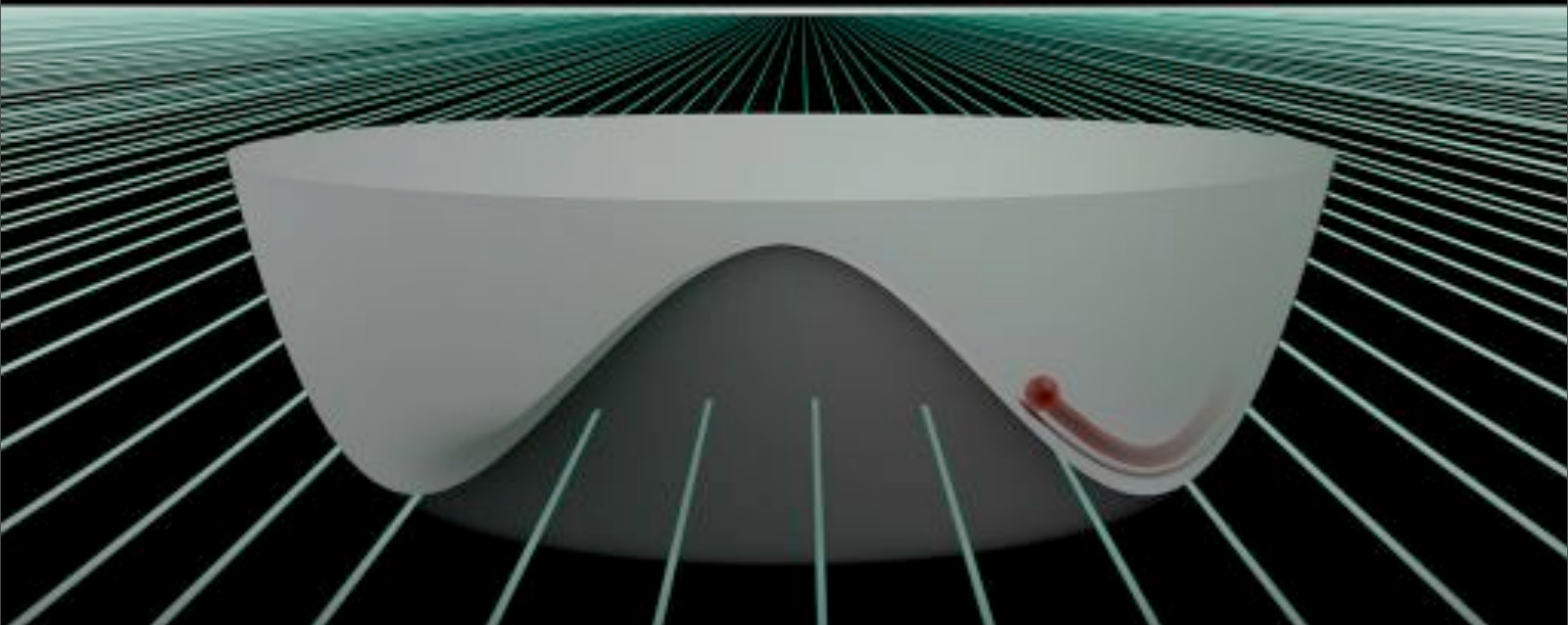


Quantum Wires

Box Potentials

Almost Arbitrary Light Patterns Possible!

Single Spin Impurity Dynamics, Domain Walls, Quantum Wires, Novel Exotic Lattice Geometries, ...



‘Higgs’ Amplitude Mode in Flatland

M. Endres, T. Fukuhara, M. Cheneau, P. Schauss, D. Pekkar, E. Demler, S. Kuhr & I.B.

M. Endres et al. Nature (2012)
Chubukov & Sachdev, PRB 1993; Sachdev, PRB 1999; Zwerger, PRL 2004; Altman, Blatter, Huber, PRB 2007, PRL 2008; U. Bissbort et al. Phys. Rev. Lett. (2011); D. Podolsky, A. Auerbach, D. Arovas, PRB 2011

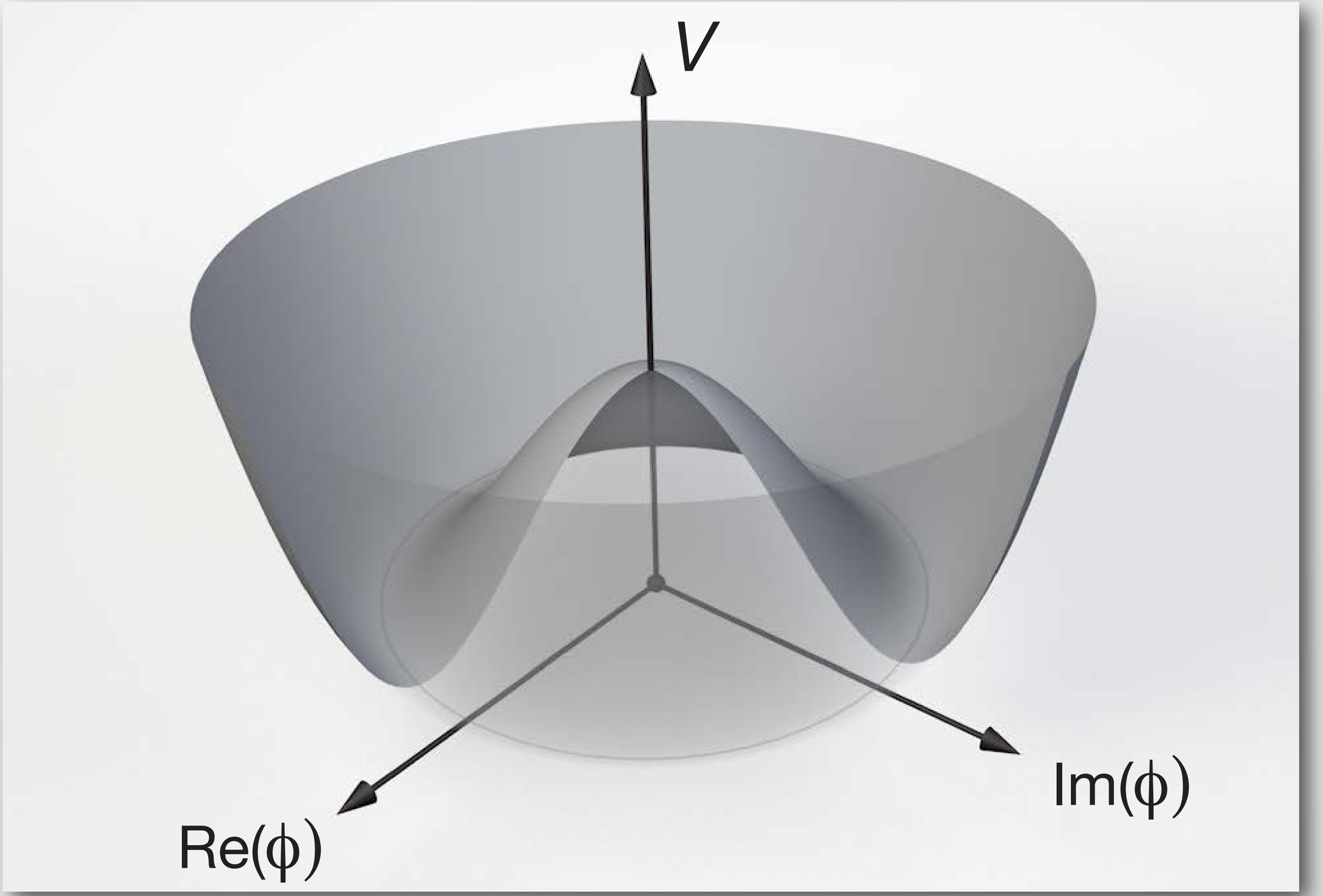
Spotaneous Symmetry Breaking

$$L = \partial_\mu \phi^* \partial^\mu \phi - m^2 \phi^* \phi - \frac{1}{2}\lambda(\phi^*\phi)^2$$

Relativistic Quantum Field-Theory of complex field ϕ with mass m.

$$L = \partial_\mu \phi^* \partial^\mu \phi + m^2 \phi^* \phi - \frac{1}{2}\lambda(\phi^*\phi)^2$$

Imagine negative mass term.



$$L = \partial_\mu \phi^* \partial^\mu \phi - V(\phi)$$

$$\phi(x) \rightarrow \phi(x) e^{i\theta}$$

Lagrangian is U(1) symmetric

Spontaneous Symmetry Breaking - Modes

$$V(\phi) = -\frac{1}{2}\lambda v^2 \phi^* \phi + \frac{1}{2}\lambda(\phi^*\phi)^2 \qquad v^2 = -2m^2/\lambda$$

Minimum of Mexican Hat at: $|\phi|^2 = \frac{v^2}{2}$

Pick one vacuum state! Expand field around: $\phi = \frac{1}{\sqrt{2}}(v + \varphi_1 + i\varphi_2)$

$$L = \frac{1}{2}\left[(\partial_\mu \varphi_1)^2 + (\partial_\mu \varphi_2)^2\right] - \frac{1}{2}\lambda v^2 \varphi_1^2 + \ldots$$

φ_1, φ_2 real scalar fields

Spontaneous Symmetry Breaking - Modes

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Massless Nambu-Goldstone mode

φ_1, φ_2 real scalar fields

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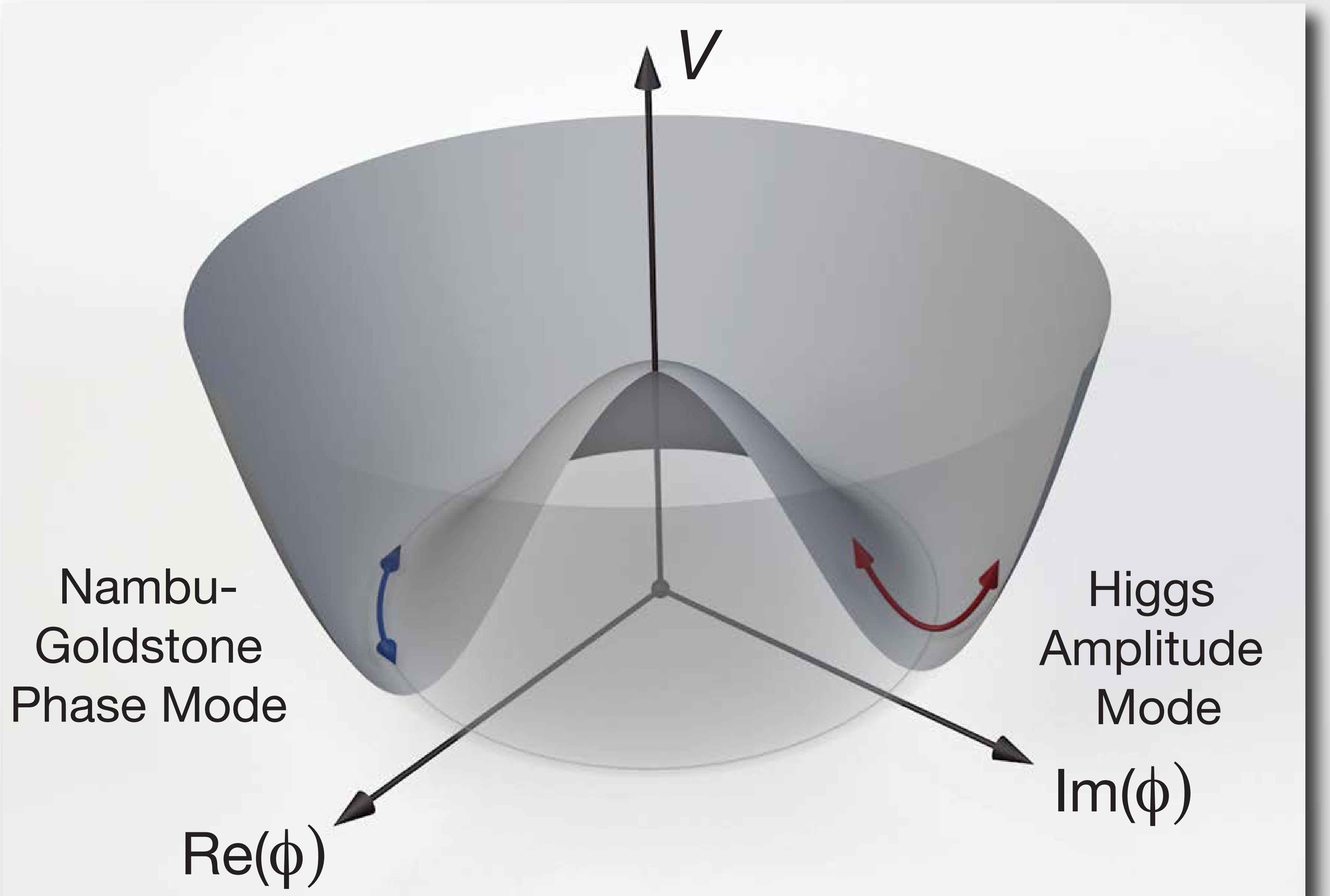
Massless Nambu-Goldstone mode

Massive Higgs mode

φ_1, φ_2 real scalar fields

Spontaneous Symmetry Breaking - Modes



Excitations in radial direction are gapped due to 'Higgs mass'!

Anderson-Higgs Mechanism

$\theta \rightarrow \theta(x)$ Extend to local U(1) gauge symmetry.

$A_\mu \rightarrow A_\mu(x) - \frac{1}{e}\partial_\mu \theta(x)$ introduces vector potential

$D_\mu \phi = \partial_\mu \phi + ieA_\mu \phi$ minimal coupling

$$L = D_\mu \phi^* D^\mu \phi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - V(\phi)$$

Breaking symmetry leads to:

$$L = \frac{1}{2}(\partial \varphi_1)^2 + \frac{1}{2}(\partial_\mu \varphi_2 + e v A_\mu)^2 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2}\lambda v^2 \varphi_1^2 + \ldots$$

Photons have become massive (m^2=ev)! ⇒ Meissner effect Anderson 1963

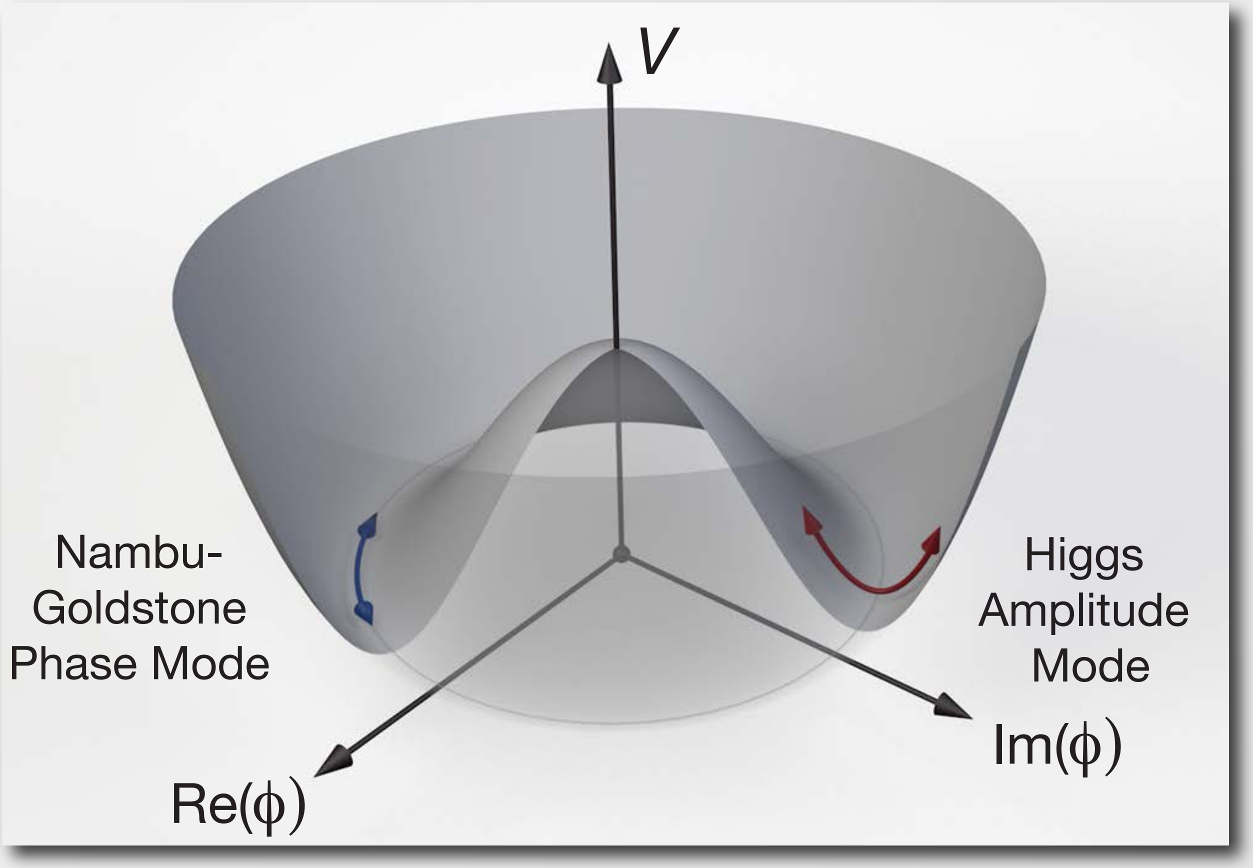
Similiar for non-Abelian gauge theory U(1)xSU(2) ⇒ W,Z bosons acquire mass

Englert, Brout, Higgs, Guralnik, Hagen, Kibble, Weinberg ~1964

Anderson-Higgs Mode in CM Physics

Close to a quantum critical point, effectively relativistic field theory!
see e.g.: Subir Sachdev, Quantum Phase Transitions

Here: SF-MI transition for *n*=1, O(2) field theory in 2+1 dimension



Fundamental question in 2D:
is mode observable or overdamped?

Chubukov & Sachdev, PRB 1993
Sachdev, PRB 1999; Zwerger, PRL 2004;
Altman, Blatter, Huber, PRB 2007, PRL 2008;
Menotti & Trivedi, PRB 2008; Podolsky, Auerbach, Arovas, PRB 2011; Pollet & Prokof'ev PRL 2012; Sachdev & Podolsky, PRB 2012; ...

Other systems: Quantum spin systems O(3) in 3+1 dimensions
Ch. Rüegg et al. Physical Review Letters (2008)

in superconductors coupled to CDW:
C. Varma & P. Littlewood PRL, PRB (1981,1982)

Dynamics in the Superfluid Phase

Far from the Mott lobe, SF described by Gross-Pitaevskii action:

$$S = \int d^3 r dt \left(-i\psi^* \partial_t \psi - \frac{1}{2m^*} |\nabla \psi|^2 + \mu |\psi|^2 - g|\psi|^4 \right)$$

Galilean invariant. Predicts massless Goldstone mode, but n

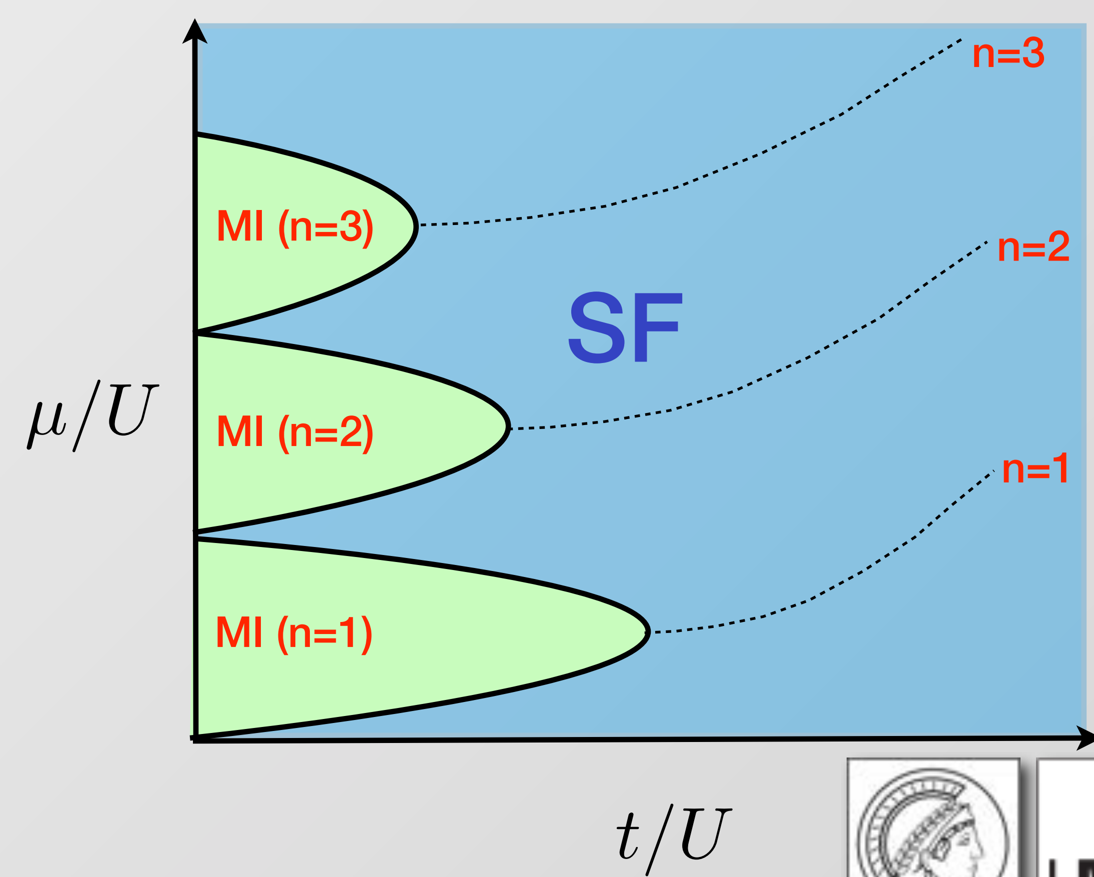
GPE: Phase and amplitude mode are c.c. variables! Therefore only one mode!

Close to QCP: Phase and ampltiude of order parameter commute: two

Near the Mott lobe at integer filling, particle-hole symmetry leads to relativistic dynamics:

$$S = \int d^3 r\, dt \left(|\partial_t \psi|^2 - c^2 |\nabla \psi|^2 + r|\psi|^2 - u|\psi|^4 \right)$$

*Lorentz invariant. Predicts Goldstone mode **and** Higgs mode.*



Courtesey: Danny Podolsky (Technion)

Relativistic vs Gross-Pitaevskii Dynamics

From Euler-Lagrange equation, we obtain:

Lorentz invariant action

$$\ddot{\varphi}_1 = c_s^2 \nabla^2 \varphi_1 - \Delta_0^2 \varphi_1$$
$$\ddot{\varphi}_2 = c_s^2 \nabla^2 \varphi_2$$

$$\omega_1(k) = \sqrt{\Delta_0^2 + c_s^2 k_1^2}$$ Relativistic Mode — Amplitude!

$$\omega_2(k) = c_s k$$ Sound Mode — Density!

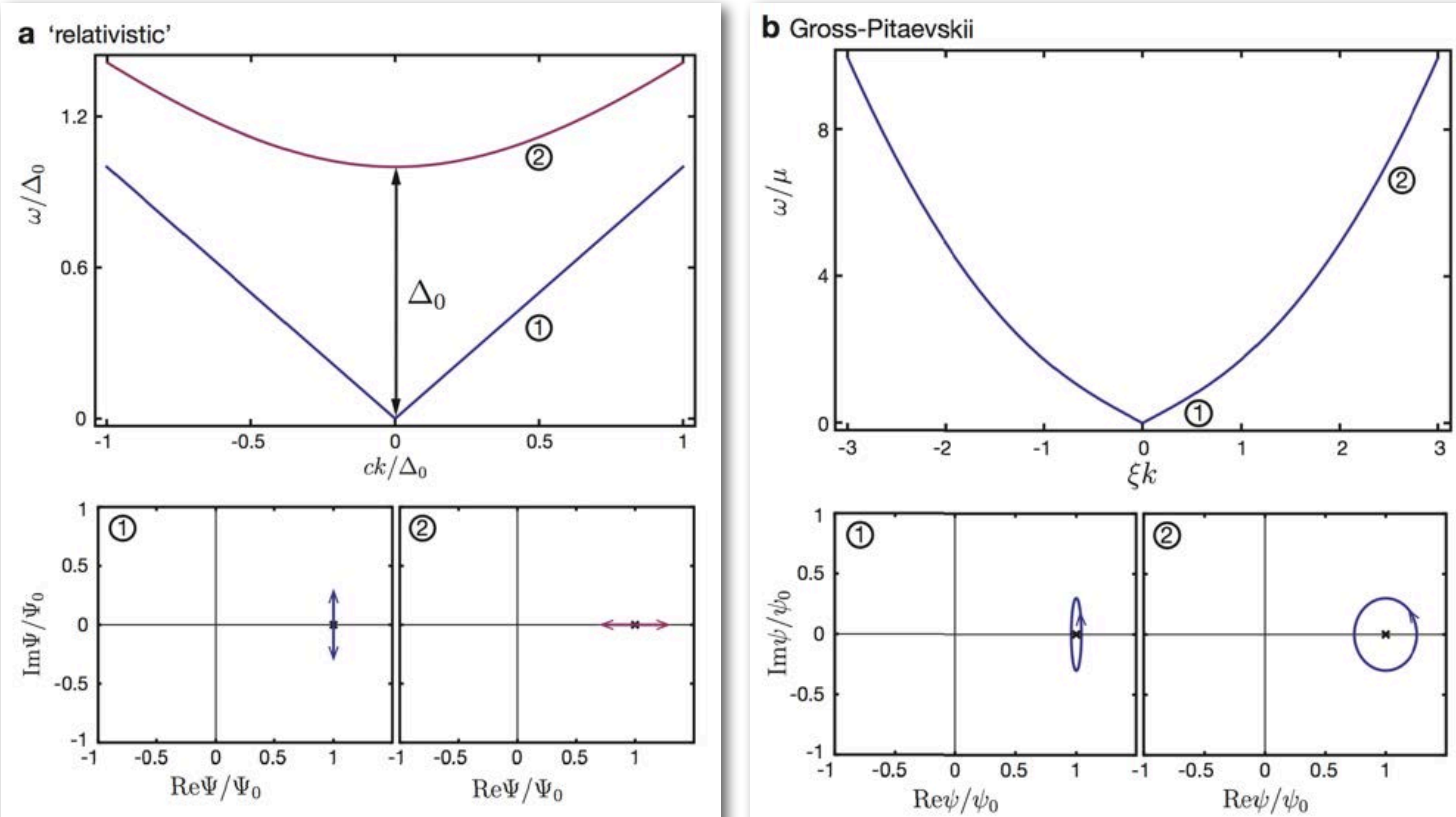
Galilean invariant action

$$-\dot{\varphi}_1 = \frac{\hbar^2}{2m} \nabla^2 \varphi_2$$
$$\dot{\varphi}_2 = \frac{\hbar^2}{2m} \nabla^2 \varphi_1 - 2\mu \varphi_1$$

$$\omega(\tilde{k}) = \sqrt{\mu^2 \tilde{k}^2 (\tilde{k}^2 + 2)}$$ Bogoliubov Mode

Amplitude-Density Coupled!

Relativistic vs Gross-Pitaevskii Dynamics



'Relativistic'
Lorentz Invariant

'Classical
Galilean Invariant

Broken Symmetry and Collective Modes

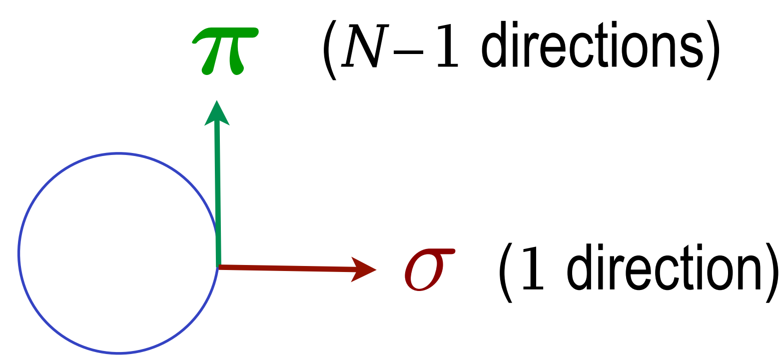
Courtesey: Danny Podolsky (Technion)

Broken Symmetry and Collective Modes

Two ways to parameterize deviations from the ordered state :

I) Cartesian : $\phi = (\sqrt{N} + \sigma, \boldsymbol{\pi})$

$$\mathcal{L}_0 = \frac{1}{2g}\left[(\partial_\mu \sigma)^2 - m^2\sigma^2 + (\partial_\mu \boldsymbol{\pi})^2\right]$$



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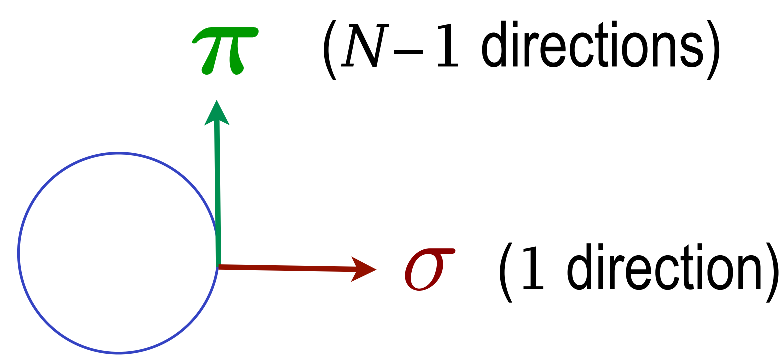
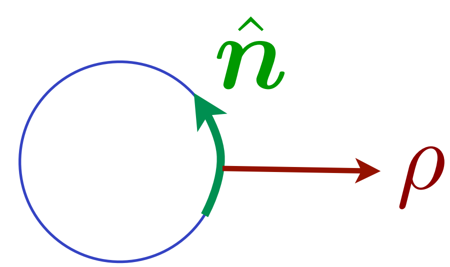
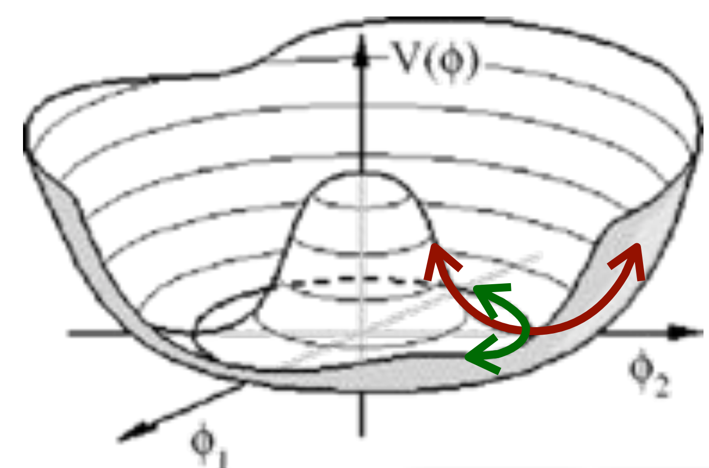


2) Polar : $\phi = \sqrt{N}\,(1+\rho)^{1/2}\,\hat{\boldsymbol{n}}$





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Broken Symmetry and Collective Modes

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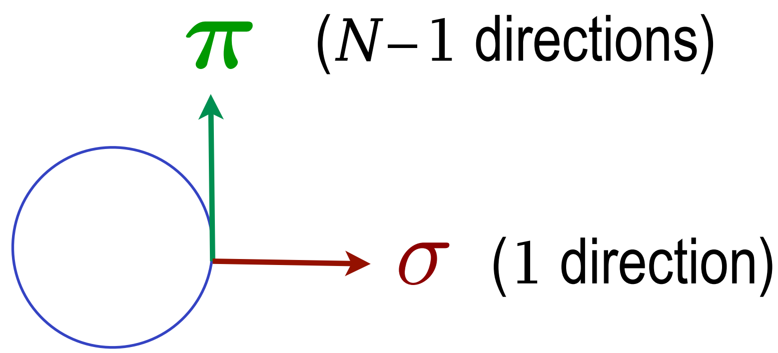
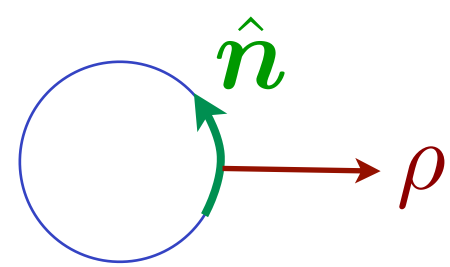


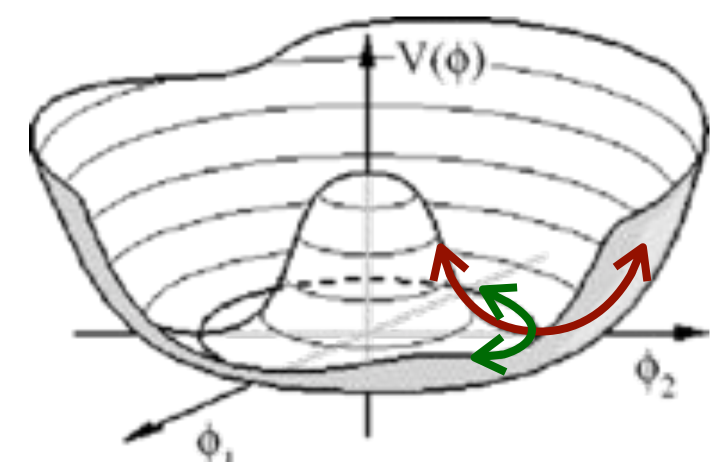
$$\mathcal{L}_0 = \frac{1}{2g}\left[(\partial_\mu \sigma)^2 - m^2\sigma^2 + (\partial_\mu \boldsymbol{\pi})^2\right]$$

$$\mathcal{L}_1 = \frac{m^2}{2g}\left[\frac{1}{\sqrt{N}}\,\sigma\boldsymbol{\pi}^2 + \frac{1}{\sqrt{N}}\,\sigma^3 + \frac{1}{4N}\,\sigma^4 + \frac{2}{N}\,\sigma^2\boldsymbol{\pi}^2 + \frac{1}{4N}(\boldsymbol{\pi}^2)^2\right]$$

2) Polar : $\phi = \sqrt{N}\,(1+\rho)^{1/2}\,\hat{\boldsymbol{n}}$



$$\mathcal{L} = \frac{1}{2g}\left[N(1+\rho)(\partial_\mu \hat{\boldsymbol{n}})^2 + \frac{(\partial_\mu \rho)^2}{4(N+\rho)} + \frac{m^2\rho^2}{4N}\right]$$

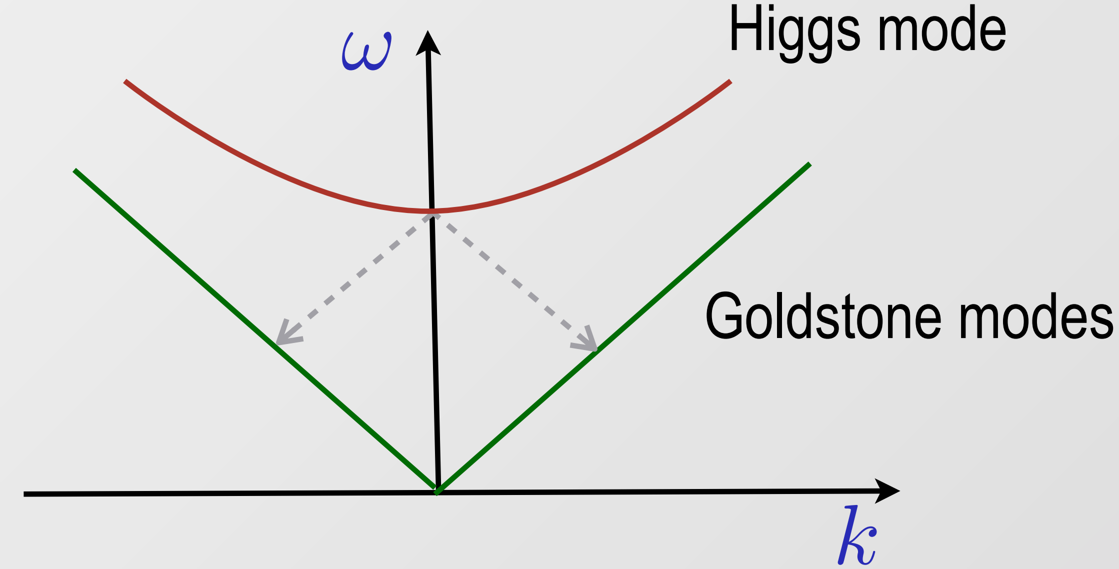


Courtesey: Danny Podolsky (Technion)

Lifetime of Higgs Excitation

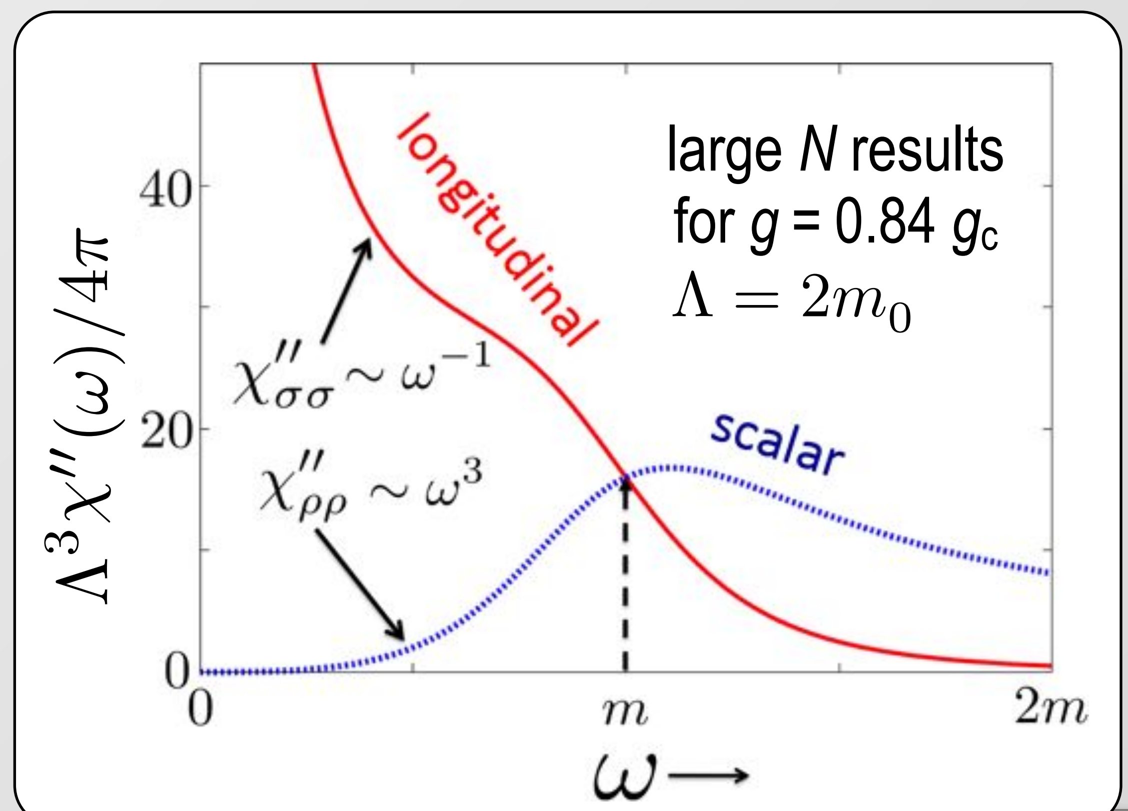
It can decay into a pair of Goldstone bosons :

$$\mathcal{L}_{\rm int} \propto \begin{cases} \sigma \boldsymbol{\pi}^2 & \text{(Cartesian)} \\ \rho\,(\partial_\mu \hat{\boldsymbol{n}})^2 & \text{(polar)} \end{cases}$$



Cartesian and polar calculations correspond to *different correlation functions.*

Depends on the type of experiment performed.



Courtesey: Danny Podolsky (Technion)

Higgs Response Function

The longitudinal response function is measured by an experiment where the probe couples directly to the order parameter field:

$$S_{\rm probe} = \int d^d x \int dt \, \boldsymbol{h}(\boldsymbol{x}, t) \cdot \boldsymbol{\phi}(\boldsymbol{x}, t)$$

Example : neutron scattering in an antiferromagnet.

Courtesey: Danny Podolsky (Technion)

Higgs Response Function

The longitudinal response function is measured by an experiment where the probe couples directly to the order parameter field:

$$S_{\mathrm{probe}} = \int d^d x \int dt \, \boldsymbol{h}(\boldsymbol{x}, t) \cdot \boldsymbol{\phi}(\boldsymbol{x}, t)$$

Example : neutron scattering in an antiferromagnet.

The scalar response function is measured by an experiment where the probe couples directly to the magnitude of the order parameter field:

$$S_{\mathrm{probe}} = \int d^d x \int dt \, u(\boldsymbol{x}, t) \left| \boldsymbol{\phi}(\boldsymbol{x}, t) \right|^2$$

$$|\phi|^2 = N(1 + \rho)$$

Examples : lattice modulation spectroscopy

Courtesey: Danny Podolsky (Technion)

Exciting the Amplitude Mode

V

Modulate coupling strength close to Quantum Phase Transition!

$$j = j + \delta j \sin(\omega t)$$

$$j = J/U$$

ϕ

Amplitude Modulation of Lattice

Bragg spectroscopy: couples mainly to phonons

Exp.: Ch. Schori et al. Phys. Rev. Lett. (2004) (ETHZ), Theory: C. Kollath et al., Phys. Rev. Lett (2006)
U. Bissbort et al. Phys. Rev. Lett. (2011) (Frankfurt, Hamburg)

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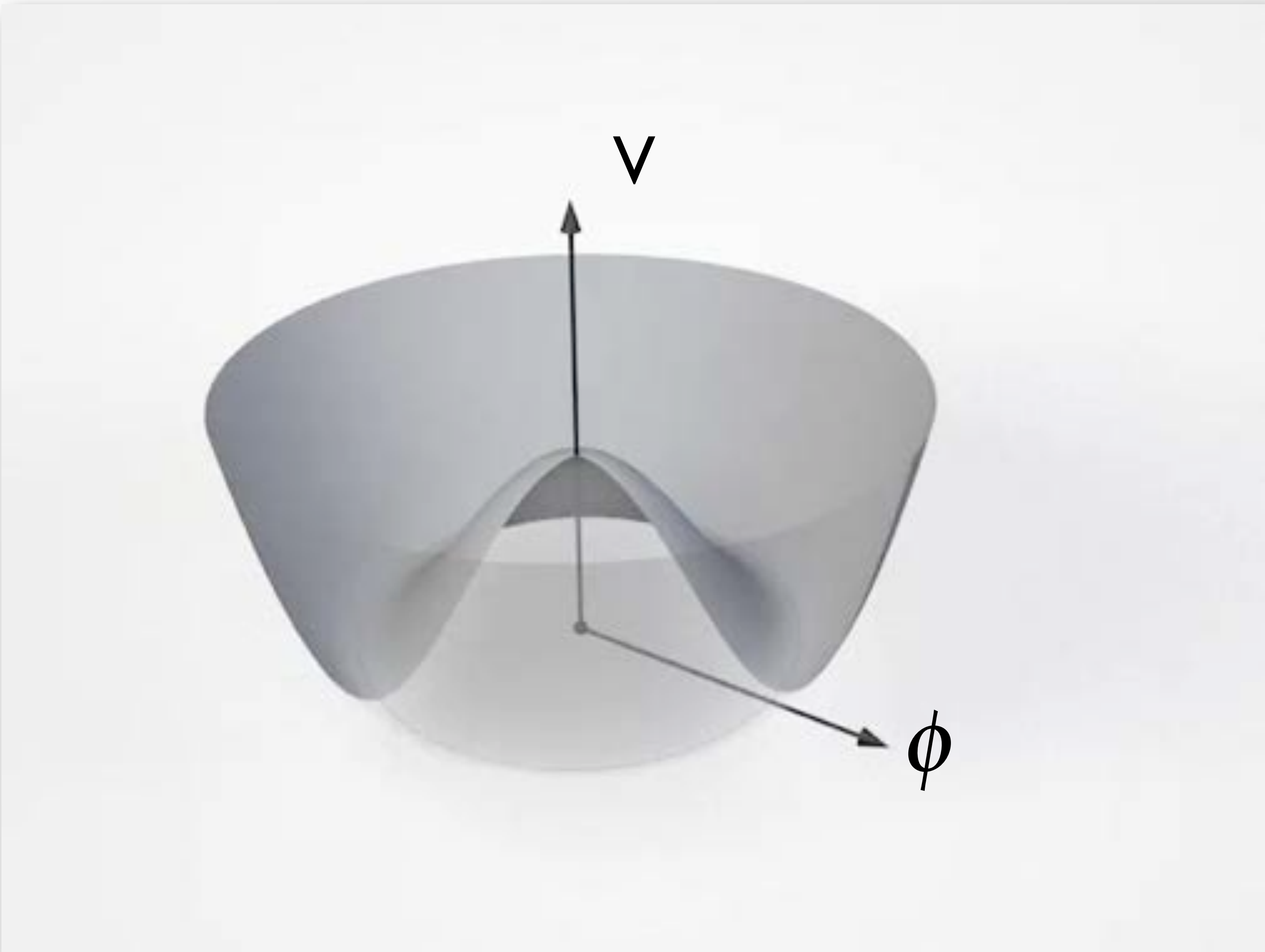

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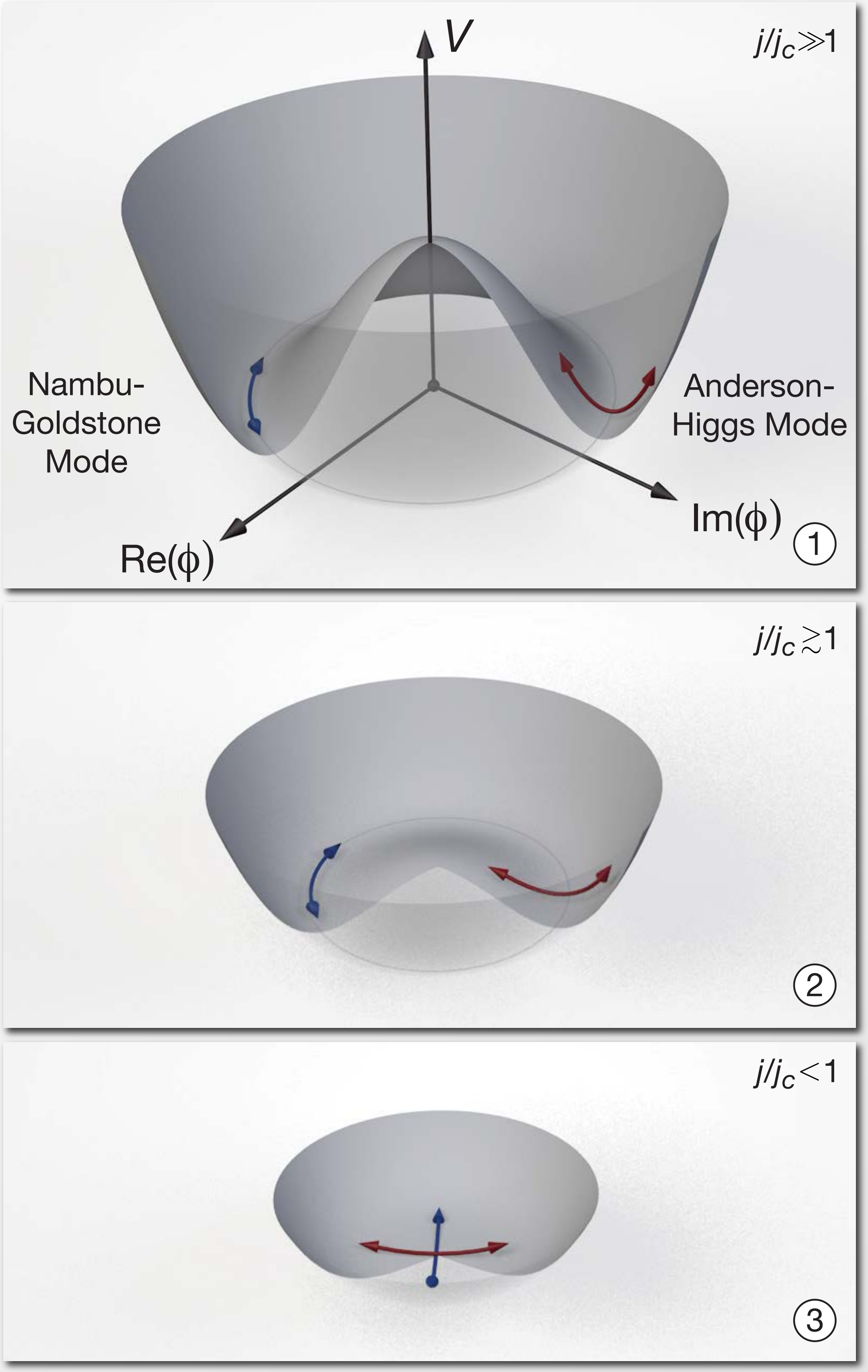
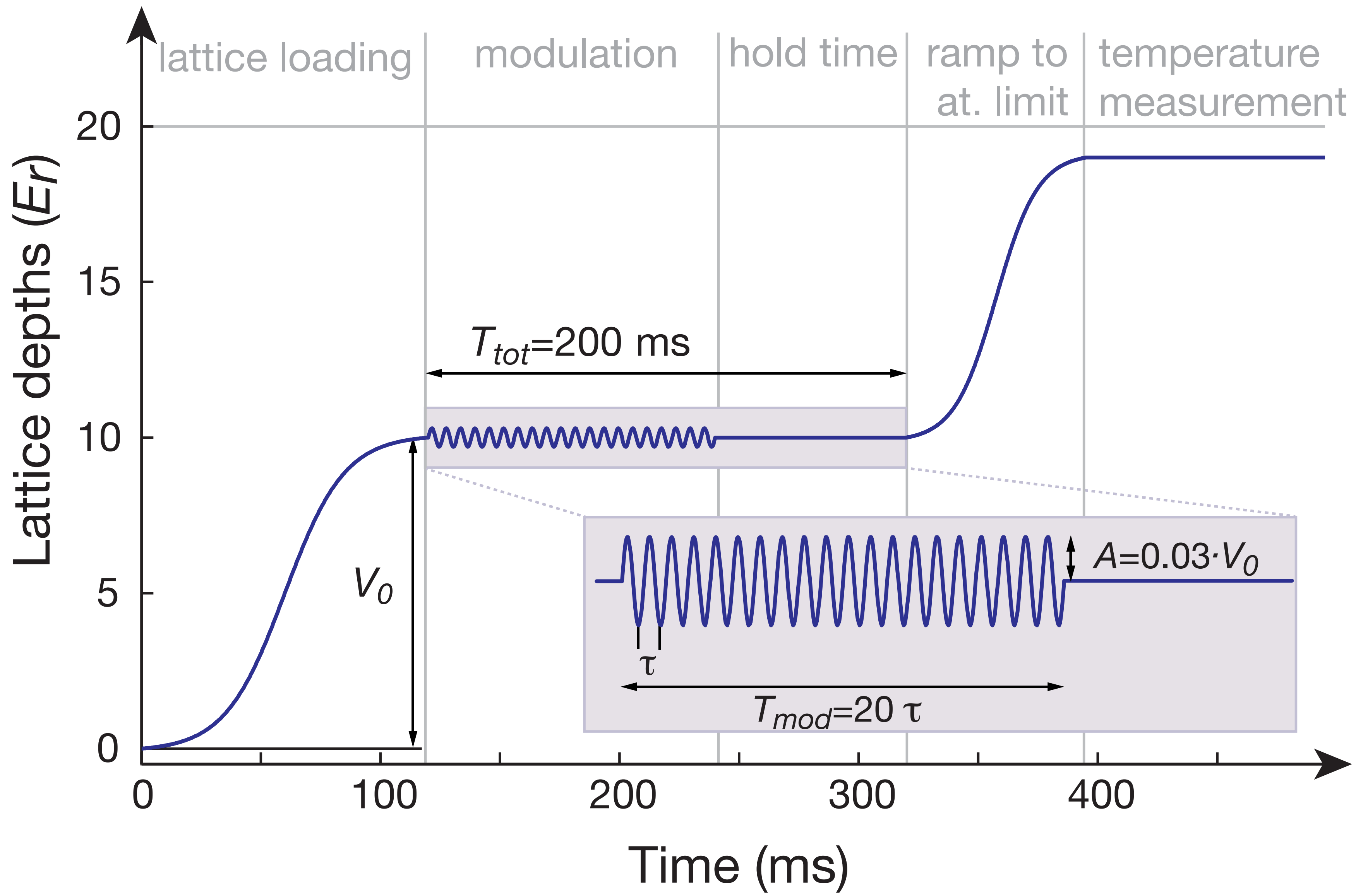
U. Bissbort et al. Phys. Rev. Lett. (2011) (Frankfurt, Hamburg)

Evolution Across Critical Point



Higgs mode softens towards critical point!

Exciting the Amplitude Mode



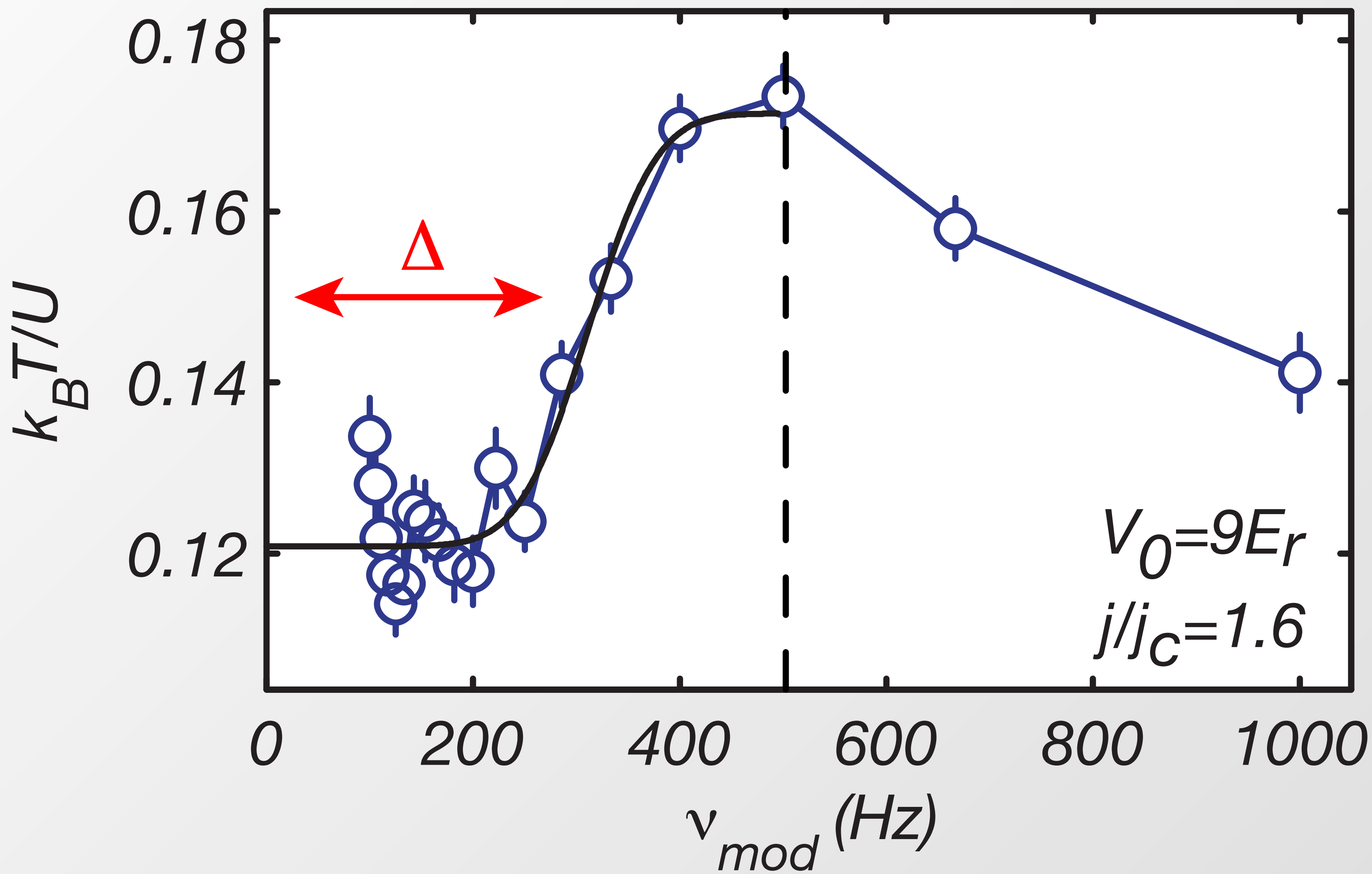
Absorbed energy

$$E = 2\pi(\delta J)^2 S(\omega)\omega T_{\mathrm{mod}}$$

Very low modulation amplitude!

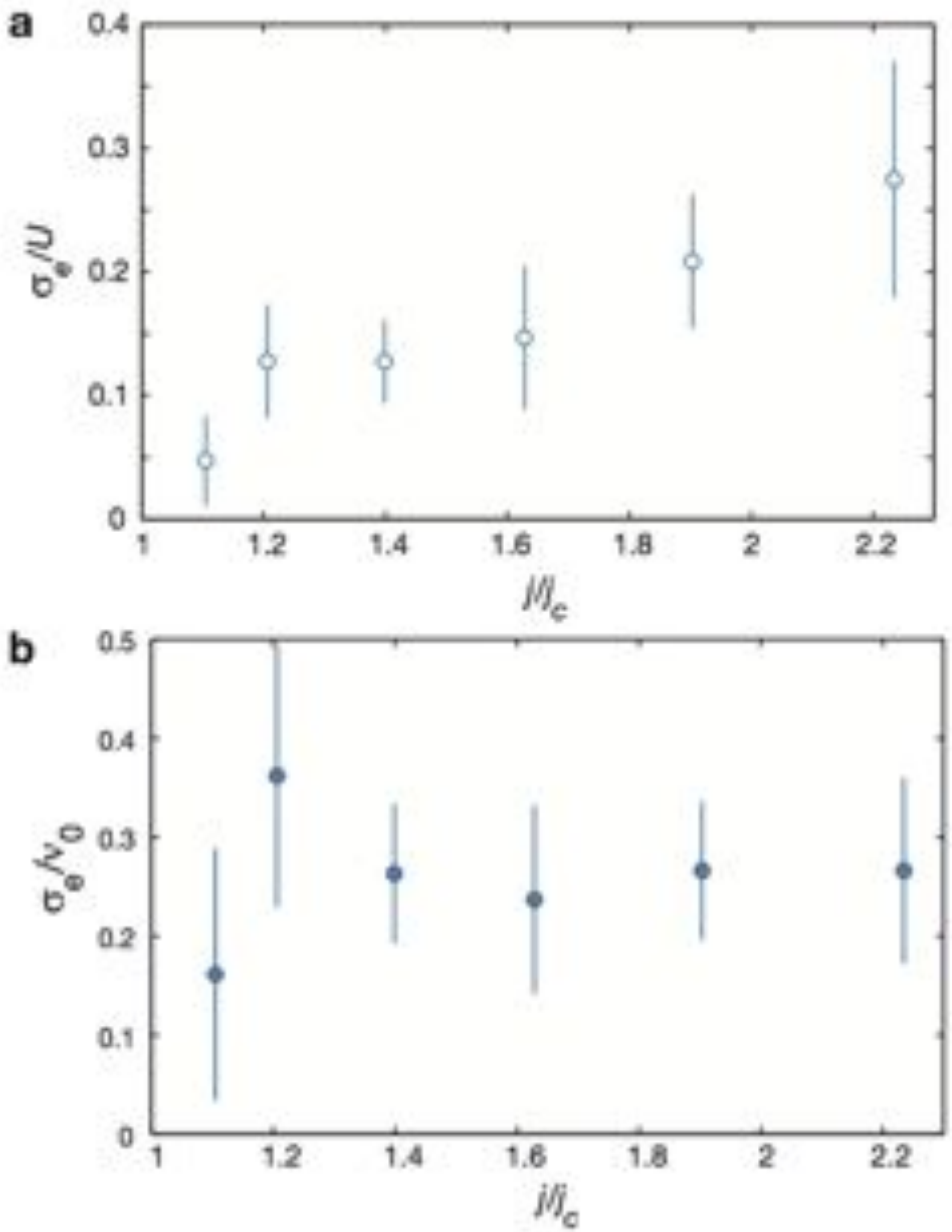
Very sensitive temperature measurement!

Single Spectrum



Use fit with error function to find minimum excitation frequency!
(also avoids inhomogeneous trap effects)

Width vs Resonance Frequency

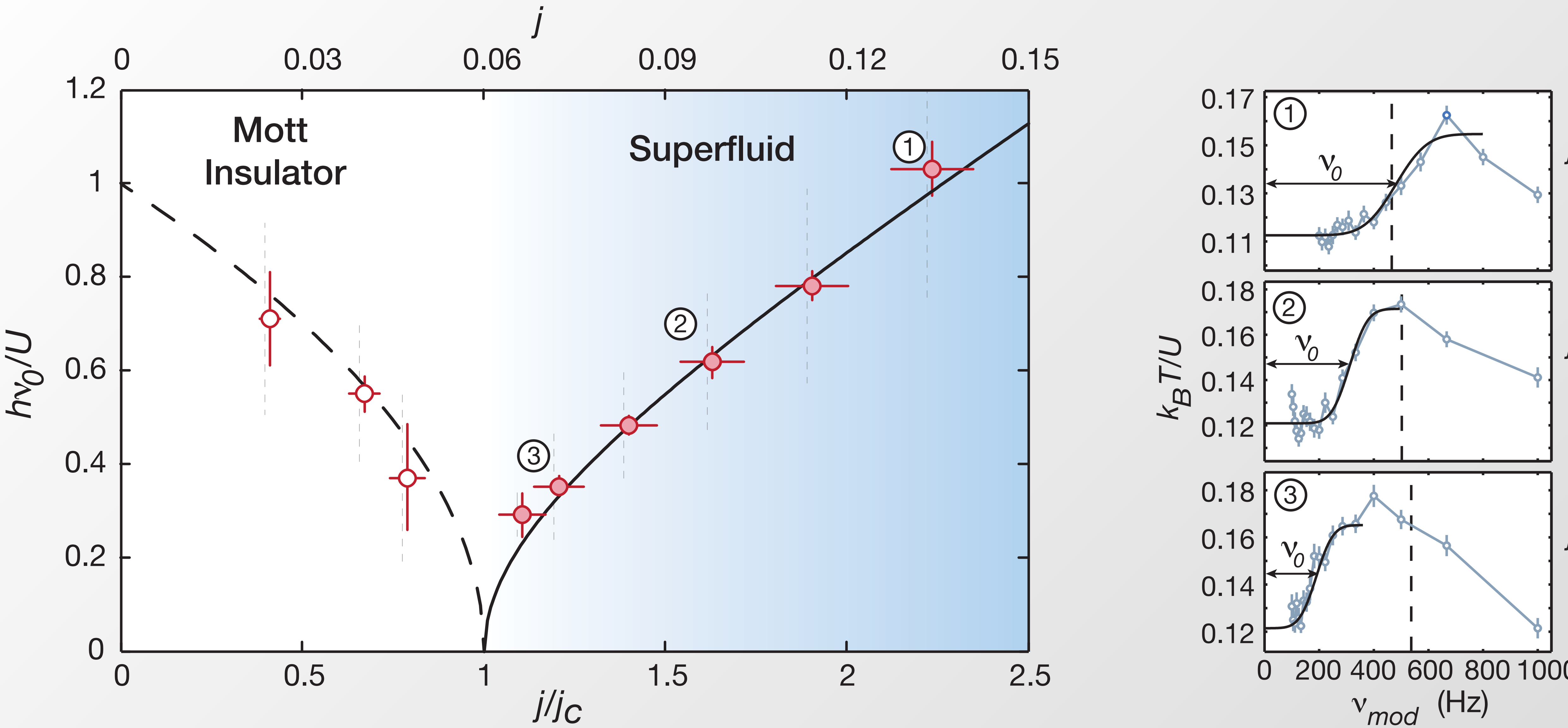


Width of model 'error' function

Ratio width vs resonance frequency

Mode remains well defined upon approaching the critical point!

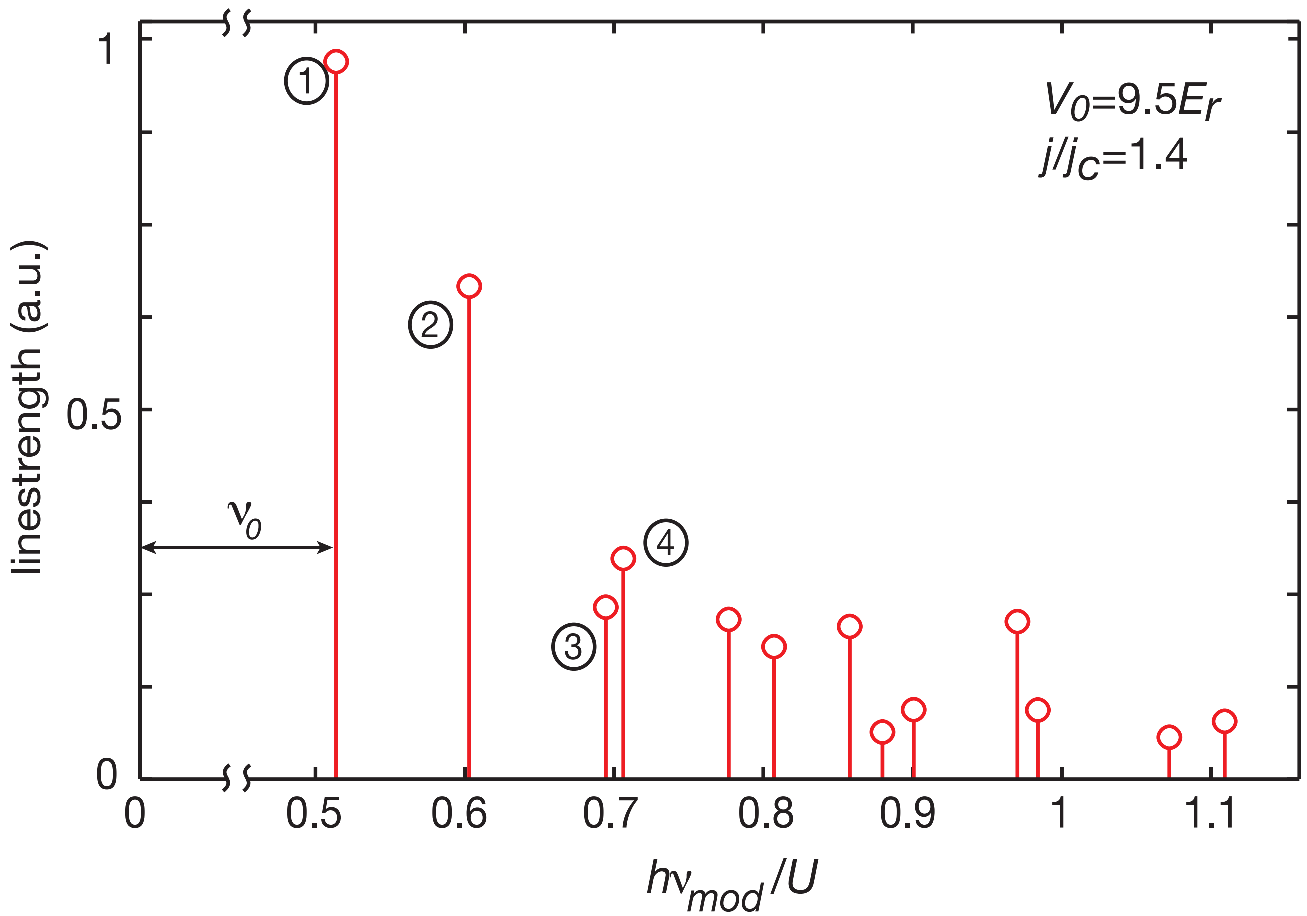
Measuring Across the QCP



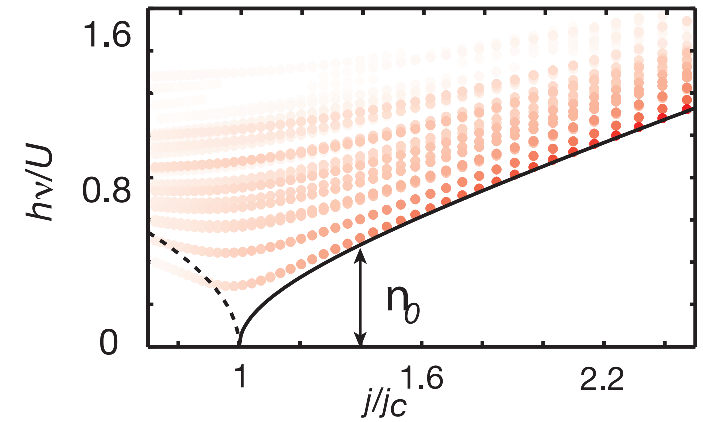
Anderson-Higgs mode softens towards critical point and turns into opening gap of Mott Insulator!

Theory in SF (S. Huber et al. PRB 2007) $\Delta_m = \sqrt{3\sqrt{2}-4}\sqrt{(j/j_c)^2-1}$

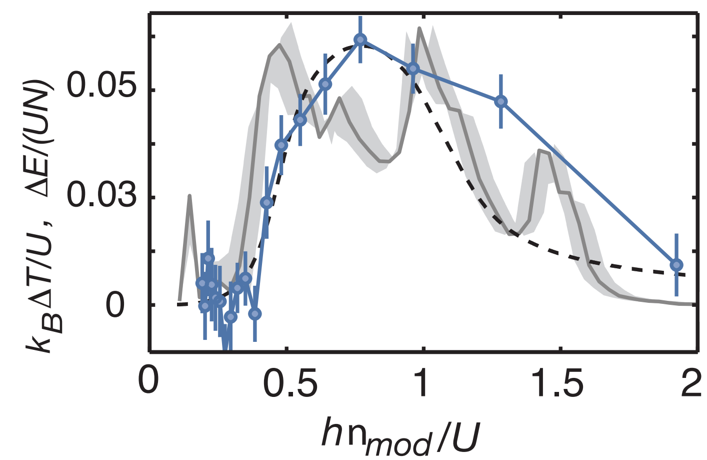
Higgs drum



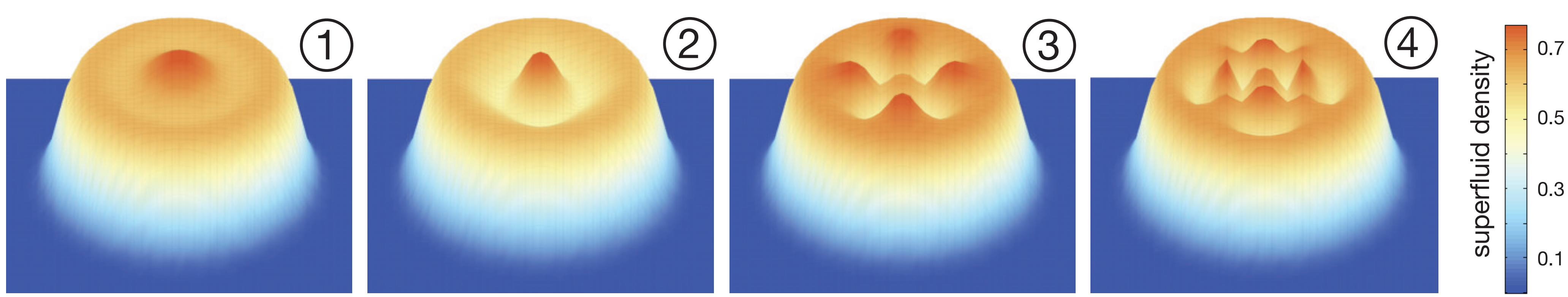
linestrength (a.u.)
1
0.5
0
0
0.5
0.6
0.7
0.8
0.9
1
1.1
$h\nu_{mod}/U$
V_0=9.5E_r
j/j_c=1.4
ν_0
①
②
③
④



1.6
0.8
0
$h\nu/U$
1
1.6
2.2
j/j_c
ν_0



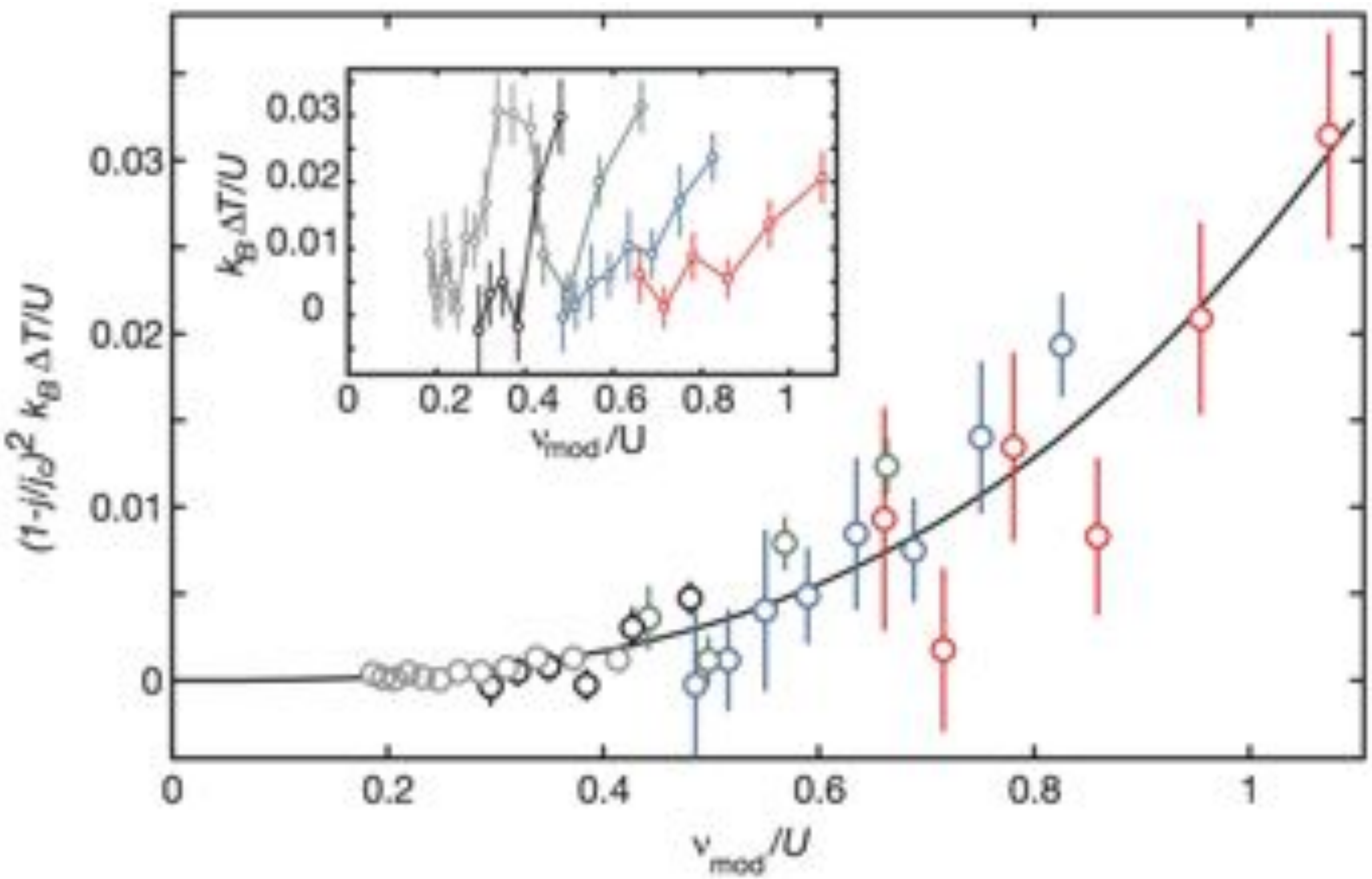
$k_B\Delta T/U$, $\Delta E/(UN)$
0.05
0.03
0
0
0.5
1
1.5
2
$h\nu_{mod}/U$



①
②
③
④
superfluid density
0.7
0.5
0.3
0.1

Scaling of Low Frequency Response

$$F\left(\nu, \frac{j}{j_c}\right)_u = A\Delta^{3-2/\nu_c}\Phi\left(\frac{\nu}{\Delta}\right) \Rightarrow F\left(\nu, \frac{j}{j_c}\right)_u = A\left(1-\frac{j}{j_c}\right)^{-2}\nu^3$$



Fit Function

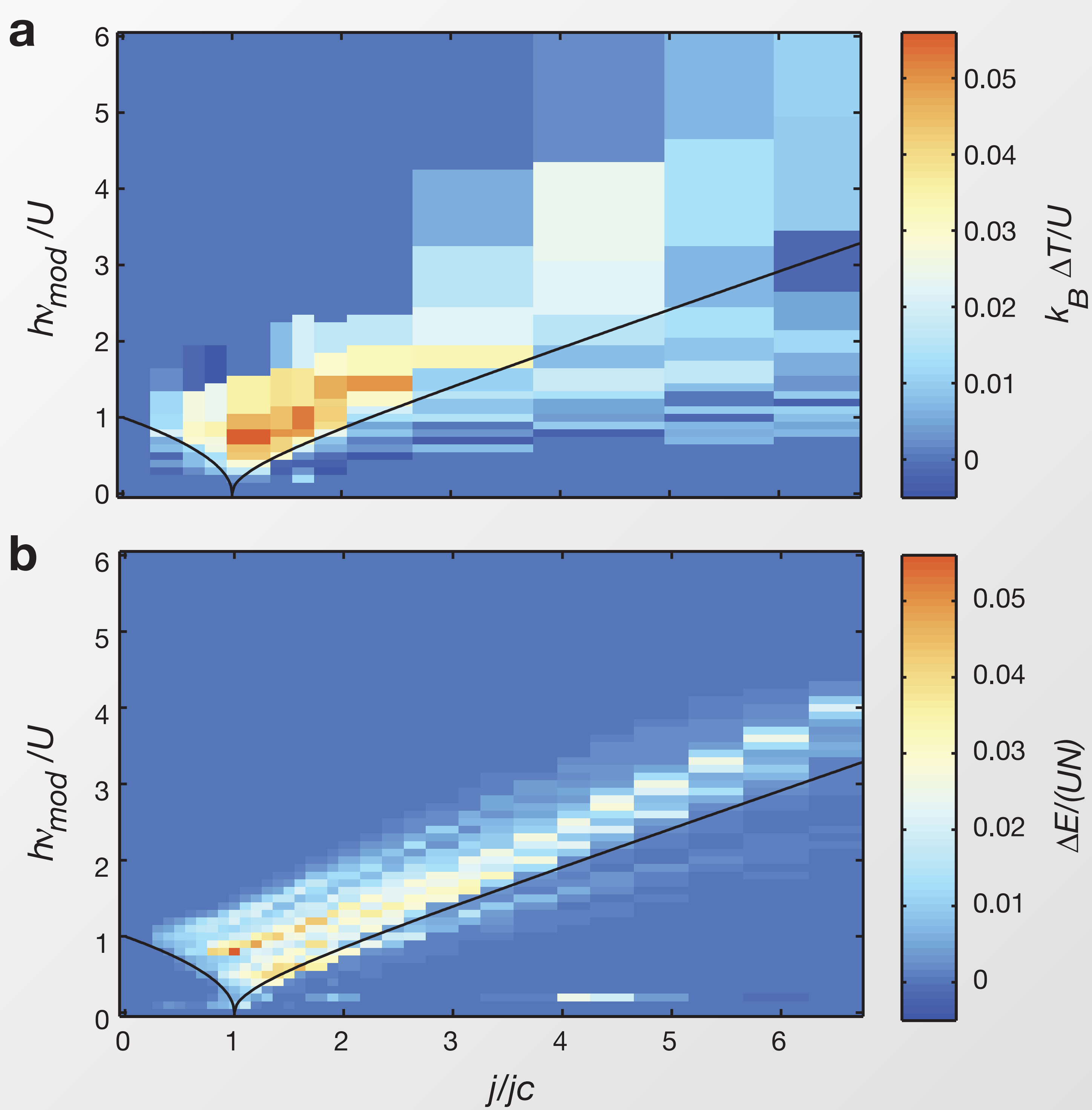
$$a\nu^b$$

we obtain

$$b = 2.9(5)$$

S. Sachdev. *Quantum Phase Transitions*. Cambridge University Press, Cambridge, (2011)
D. Podolsky, A. Auerbach, and D. P. Arovas. Phys. Rev. B **84**, 174522 (2011)
D. Podolsky and S. Sachdev, Phys. Rev. B **86**, 054508 (2012)

Full Spectral Response

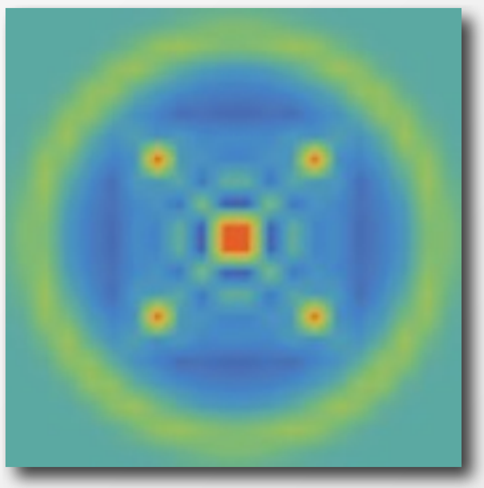


Open theory question: what is the fate of Higgs mode towards weaker interactions?

Outlook

✓ Selectively excite Higgs eigenmodes (larger system, spatial modulation)

✓ Probe Quantum Critical behaviour via Dynamical critical scaling



Higgs drum, spatial eigenmodes!

✓ Fate of mode at weaker interactions (towards GPE)

✓ Ratio of 'Higgs' mass to Mott gap

✓ Well defined mode down to critical point?

✓ Anderson-Higgs Mechanism via Coupling to (Dynamical) Gauge Field

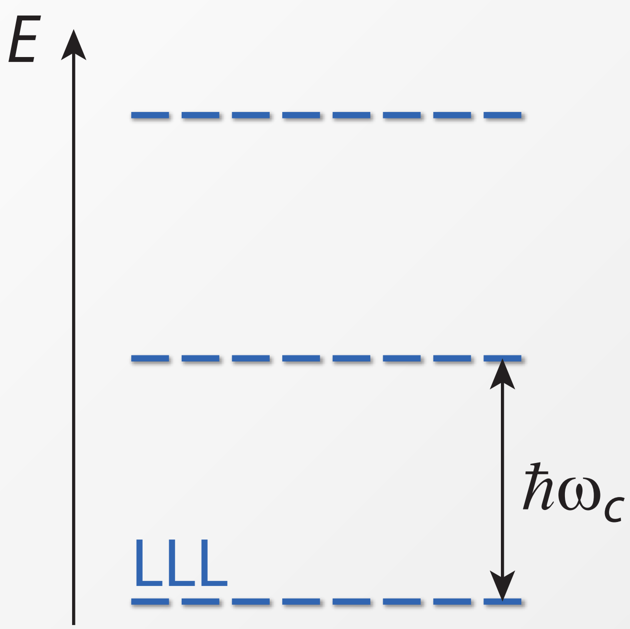
Generation of Large Effective Magnetic Fields

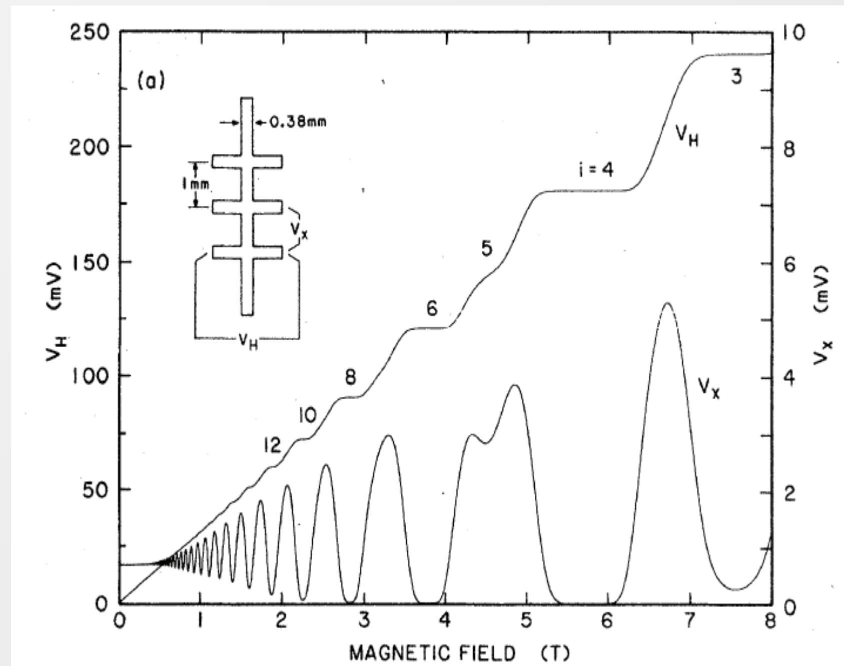
M. Aidelsburger, M. Atala, S. Nascimbène, Yu-Ao Chen & I. Bloch

M. Aidelsburger et al. PRL 107, 255301 (2011)
D. Jaksch & P. Zoller NJP (2003), F. Gerbier & J. Dalibard NJP (2010)

Quantum Hall Effect in 2D Electron Gases

Integer Quantum Hall Effect

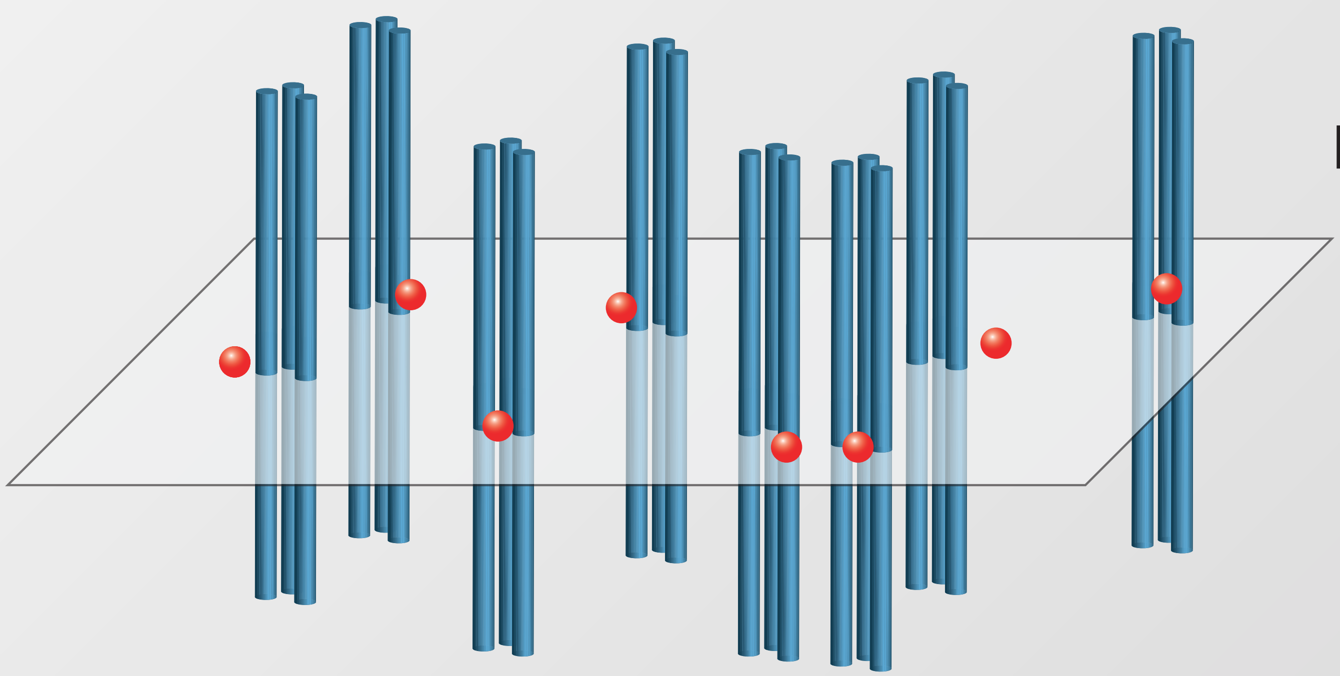




$$\sigma_{xy} = \nu e^2/h$$

ν Integer

Fractional Quantum Hall Effect



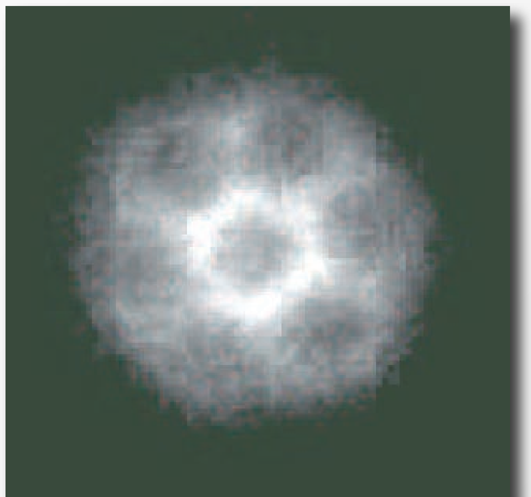
Laughlin state at $\nu = 1/3$

flux quantum ϕ_0=h/ec

electron

State of the Art

1) Rotation

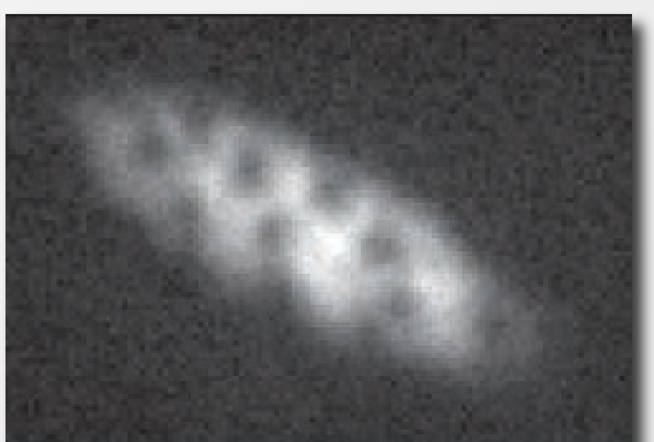


In rapidly rotating gases, ***Coriolis force*** is equivalent to ***Lorentz force***.

$$\mathbf{F}_{\mathrm{L}} = q\,\mathbf{v} \times \mathbf{B} \Longleftrightarrow \mathbf{F}_{\mathrm{C}} = 2m\,\mathbf{v} \times \Omega_{\mathrm{rot}}$$

K. Madison *et al.*, PRL (2000)
J.R. Abo-Shaeer *et al.* Science (2001)

2) Raman Induced Gauge Fields



Spatially dependent optical couplings lead to a **Berry phase** analoguous to the **Aharonov-Bohm phase**

Y. Lin *et al.*, Nature (2009)

State of the Art

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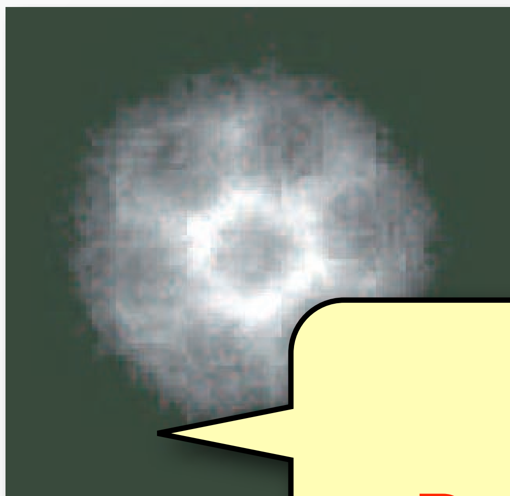


In rapidly rotating gases, ***Coriolis force*** is equivalent to ***Lorentz force***.

$\mathbf{v} \times \Omega_{\text{rot}}$

t al., PRL (2000)

. Science (2001)

Problem in both cases: small B-fields (large ν>1000 for now), heating...

2) Raman

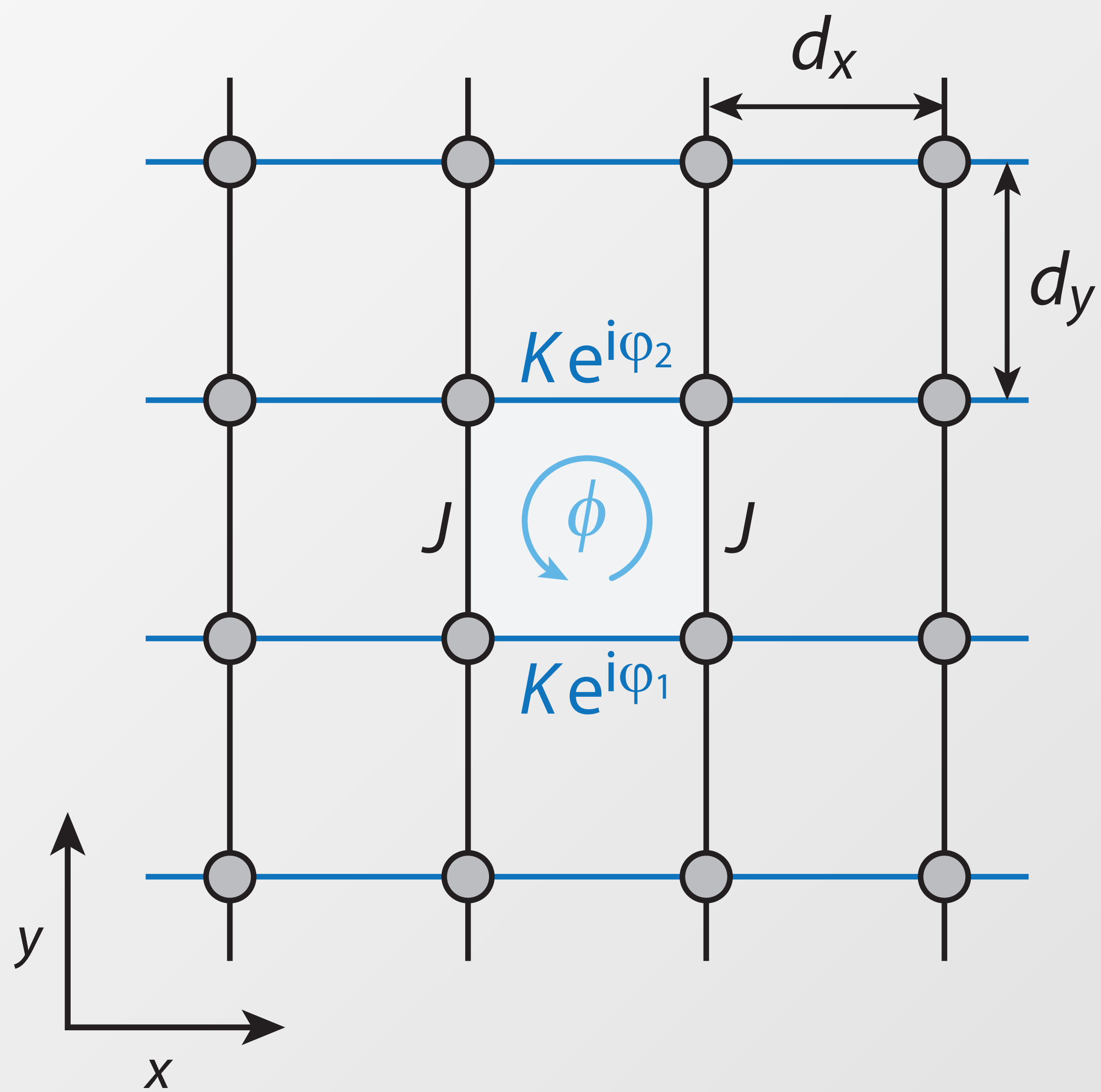
Spatially dependent optical couplings lead to a **Berry phase** analoguous to the **Aharonov-Bohm phase**

Y. Lin *et al.*, Nature (2009)

Artificial B-Fields with Ultracold Atoms

Controlling atom tunneling along *x* with Raman lasers leads to effective tunnel coupling with spatially-dependent Peierls phase $\varphi(\mathbf{R})$

$$\hat{H} = -\sum_{\mathbf{R}} \left(K e^{i\varphi(\mathbf{R})}\, \hat{a}^\dagger_{\mathbf{R}} \hat{a}_{\mathbf{R}+\mathbf{d}_x} + J\, \hat{a}^\dagger_{\mathbf{R}} \hat{a}_{\mathbf{R}+\mathbf{d}_y} \right) + \text{h.c.}$$



Magnetic flux through a plaquette:

$$\phi = \int_{\blacksquare} B\, \mathrm{d}S = \varphi_1 - \varphi_2$$

D. Jaksch & P. Zoller, New J. Phys. (2003)
F. Gerbier & J. Dalibard, New J. Phys. (2010)
E. Mueller, Phys. Rev. A (2004)
L.-K. Lim et al. Phys. Rev. A (2010)
A. Kolovsky, Europhys. Lett. (2011)

see also: lattice shaking
E. Arimondo, Phys. Rev. . Lett (2007)
K. Sengstock, Science (2011)

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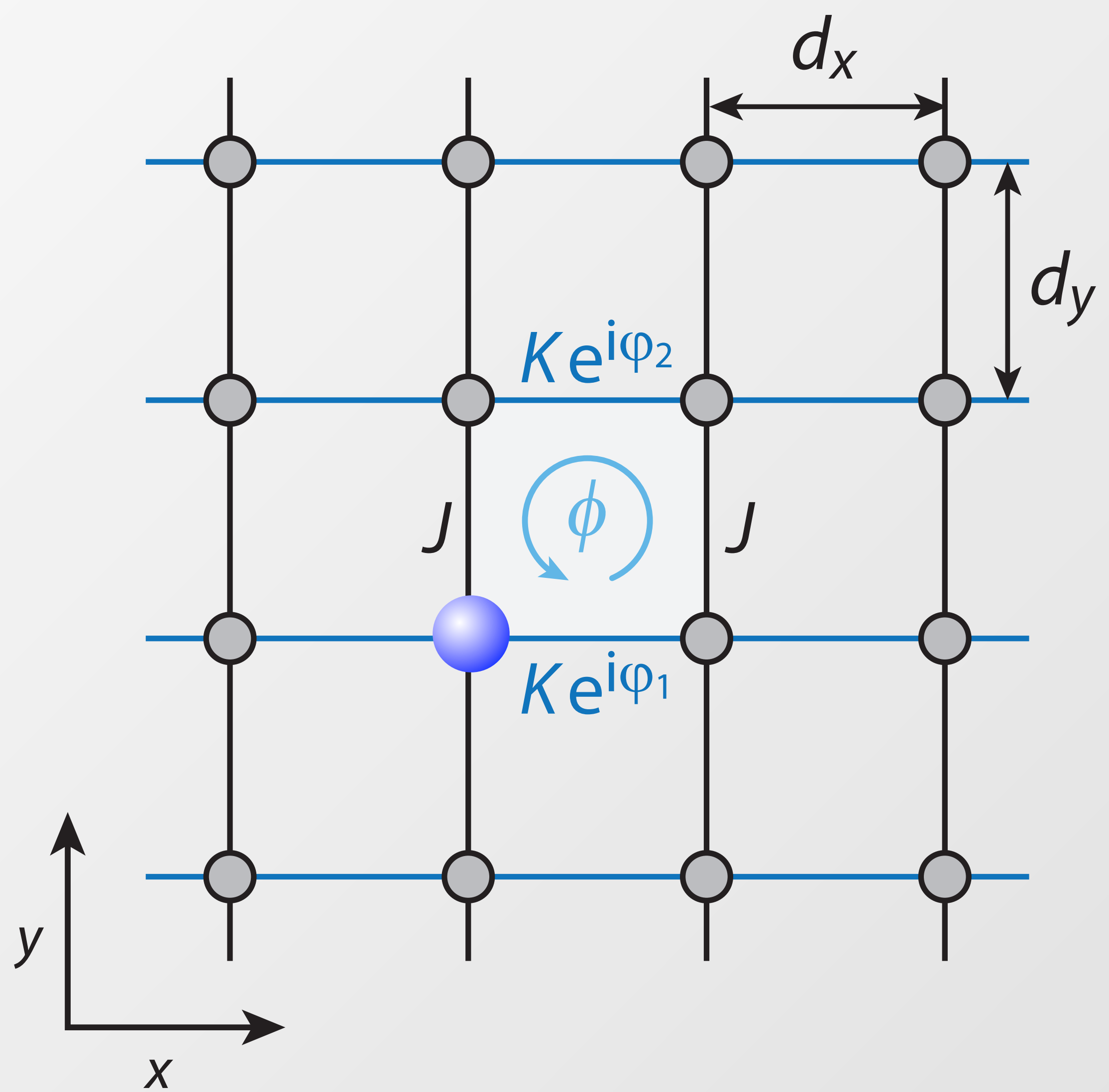

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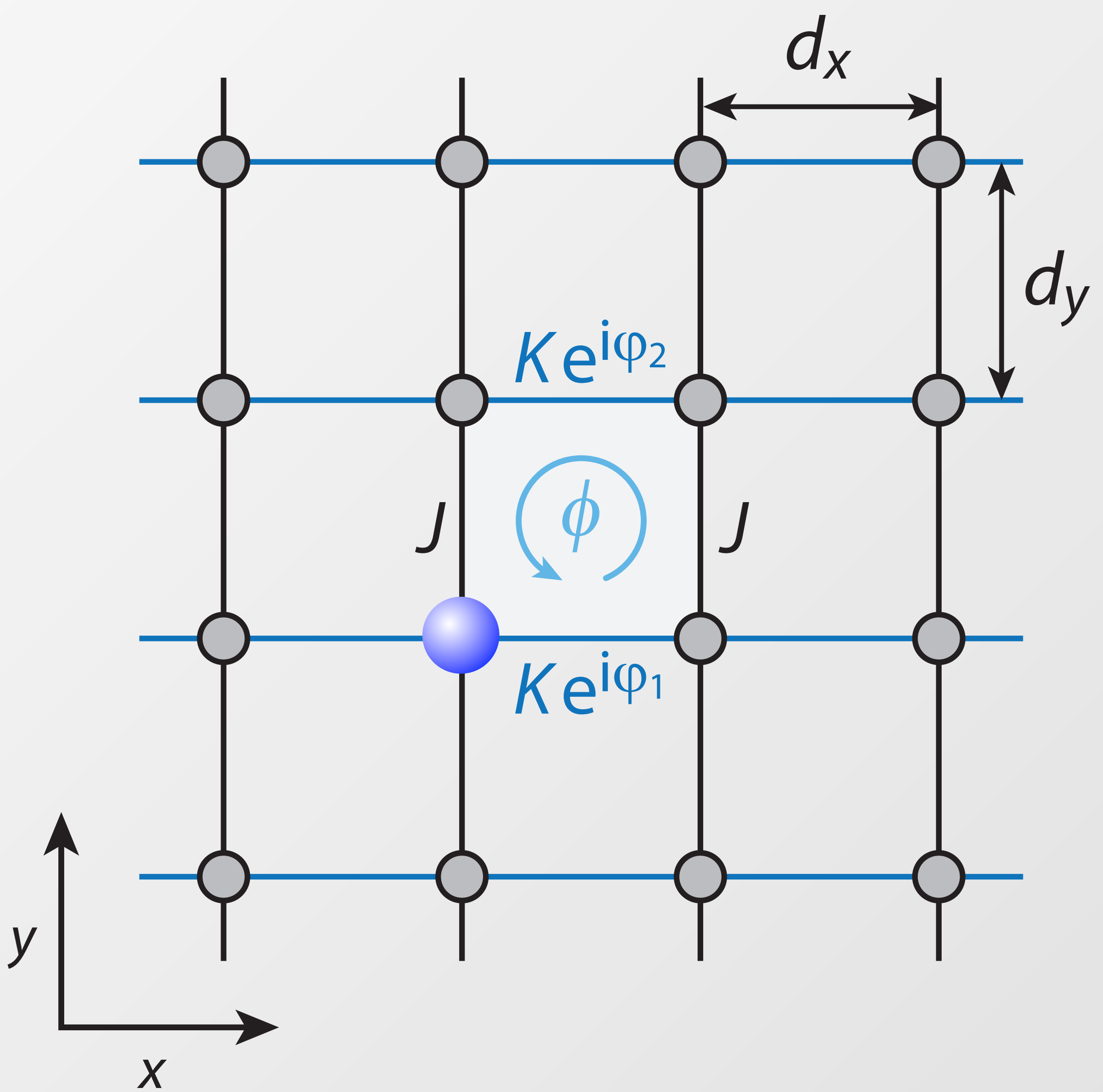

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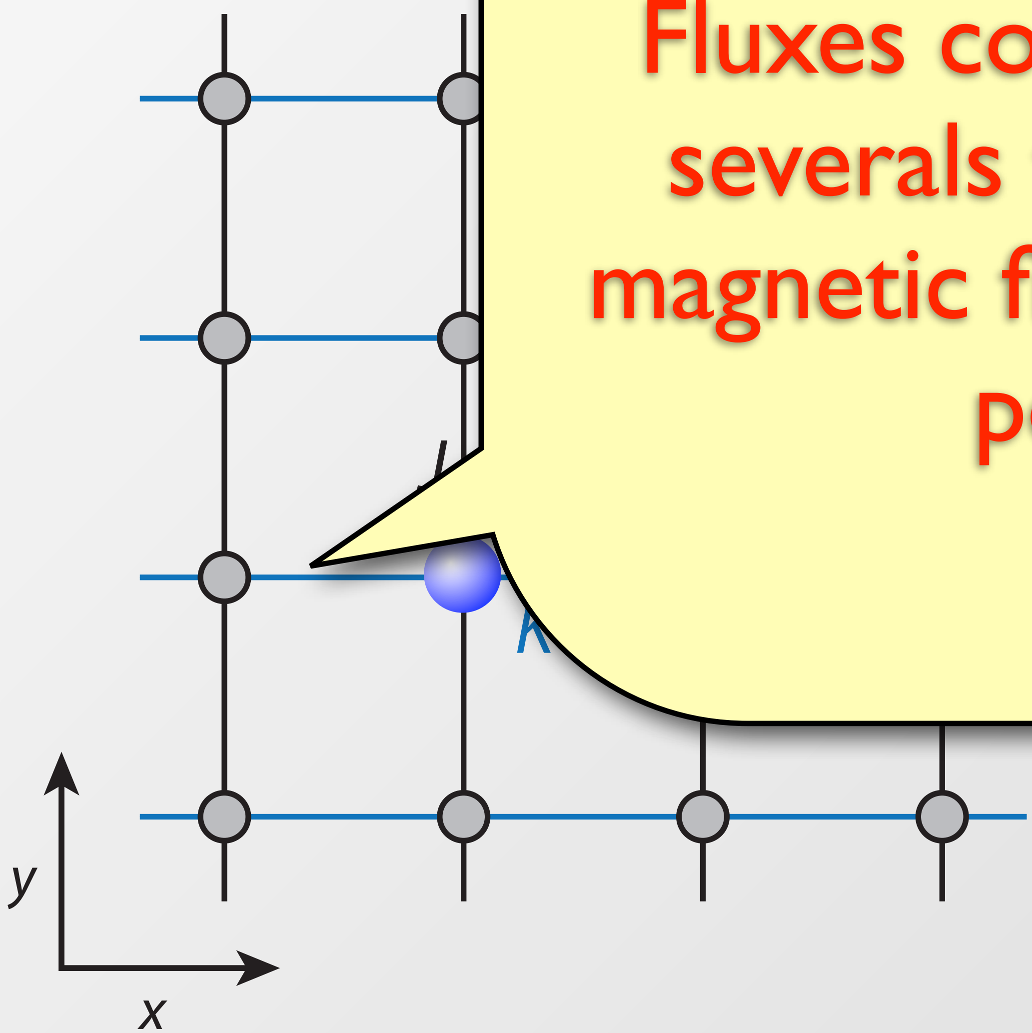


Fluxes corresponding to severals thousand Tesla magnetic field strength are possible!

...ough a plaquette:

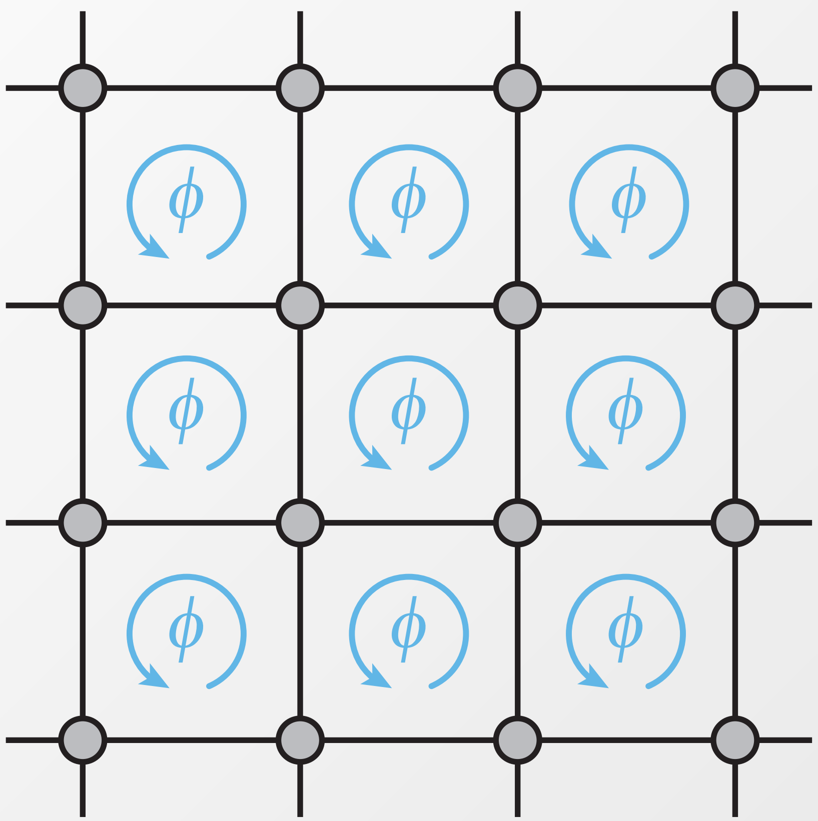
$$\ldots dS = \varphi_1 - \varphi_2$$

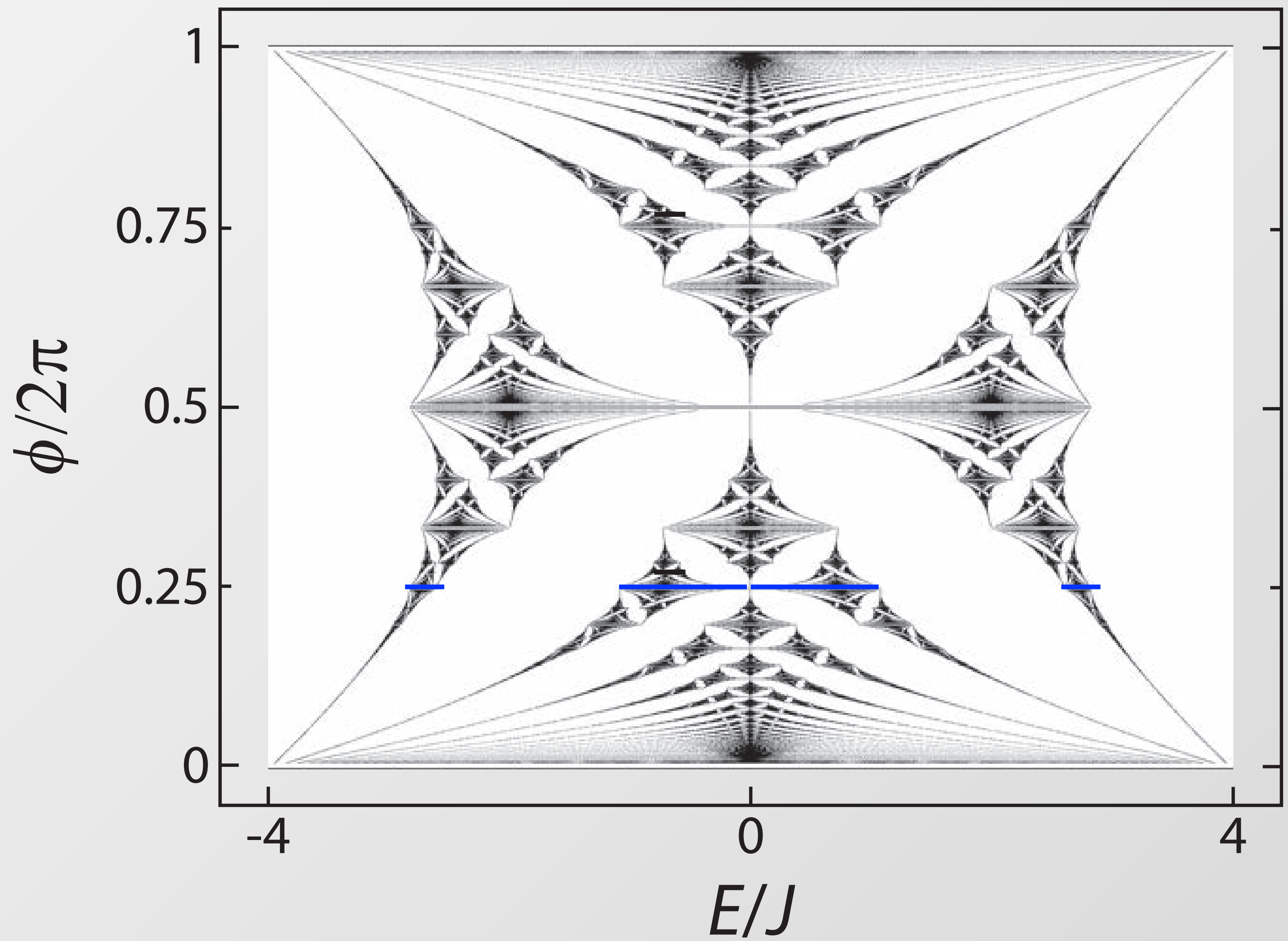
...ksch & P. Zoller, New J. Phys. (2003)
...rbier & J. Dalibard, New J. Phys. (2010)
E. Mueller, Phys. Rev. A (2004)
L.-K. Lim et al. Phys. Rev. A (2010)
A. Kolovsky, Europhys. Lett. (2011)

see also: lattice shaking
E. Arimondo, Phys. Rev. . Lett (2007)
K. Sengstock, Science (2011)

Harper Hamiltonian and Hofstadter Butterfly

Harper Hamiltonian: J=K and ϕ uniform.



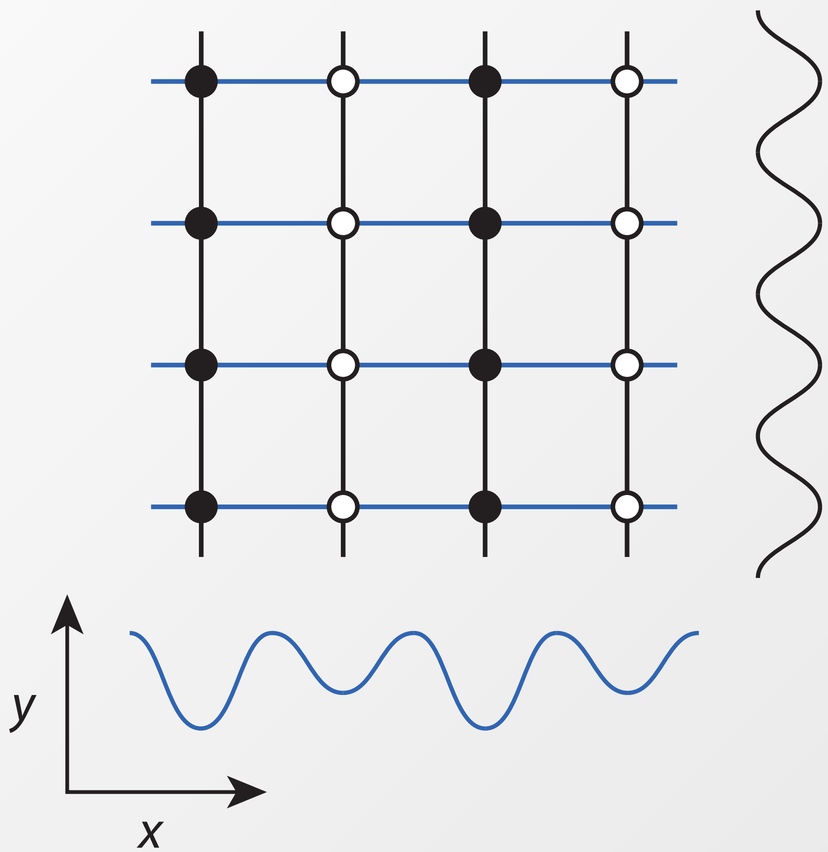


The lowest band is topologically equivalent to the lowest Landau level.

D.R. Hofstadter, Phys. Rev. B **14**, 2239 (1976)
see alo Y. Avron, D. Osadchy, R. Seiler, Physics Today 38, 2003

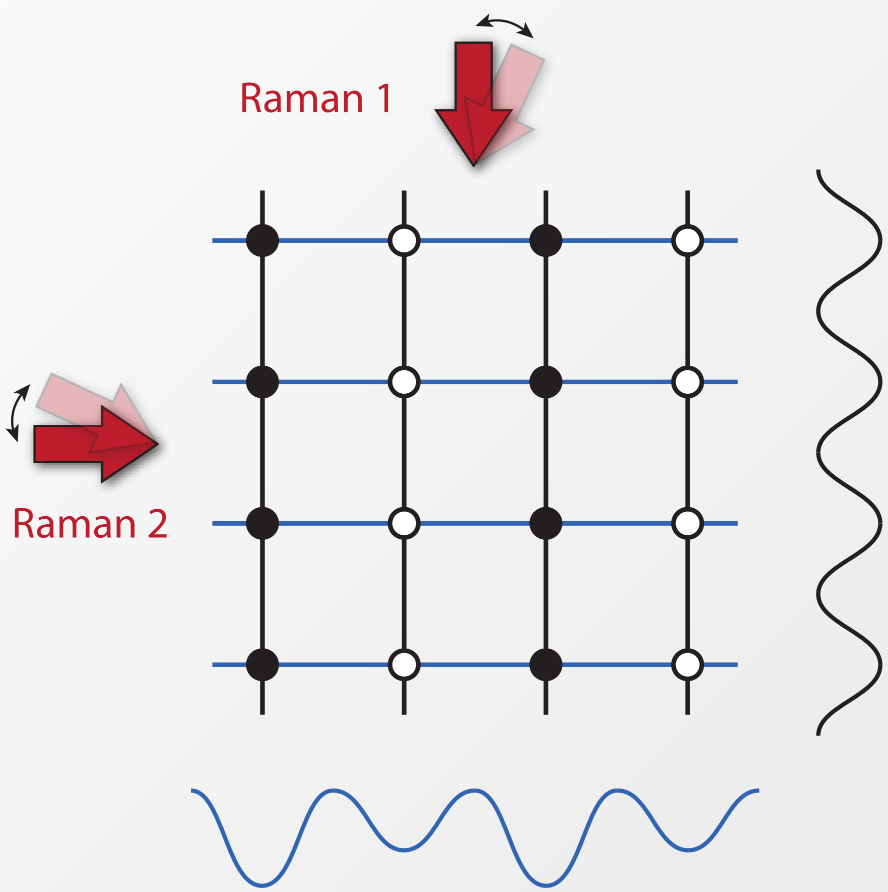
Staggered Flux Lattice

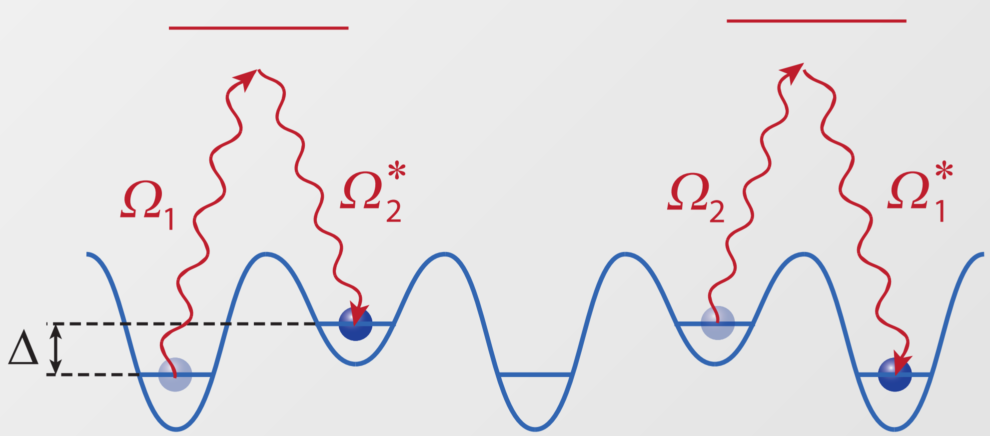
2D lattices - tunneling inhibited along the x-direction



Staggered Flux Lattice

Tunneling is restored with Raman beams

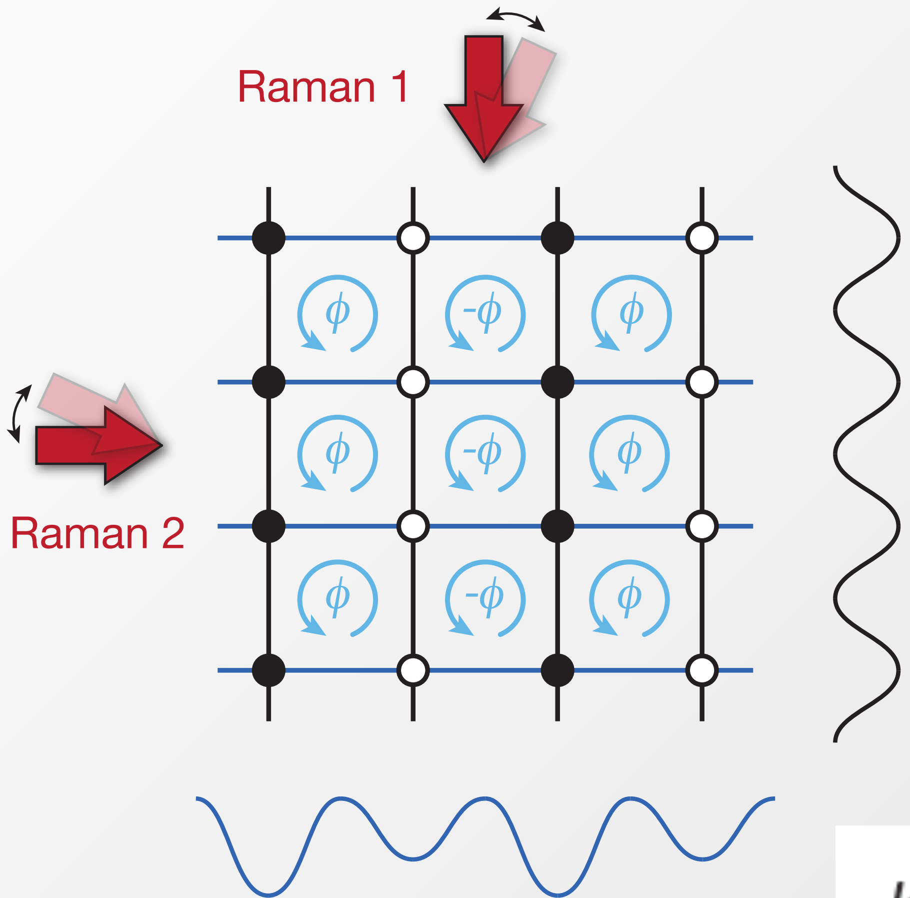


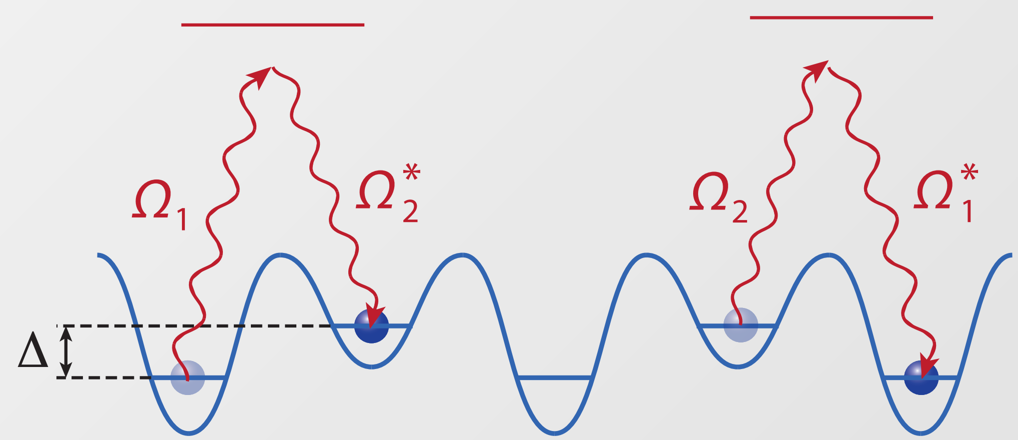


$$\delta\mathbf{k} = \mathbf{k}_1 - \mathbf{k}_2$$

Staggered Flux Lattice

Staggered flux with zero mean



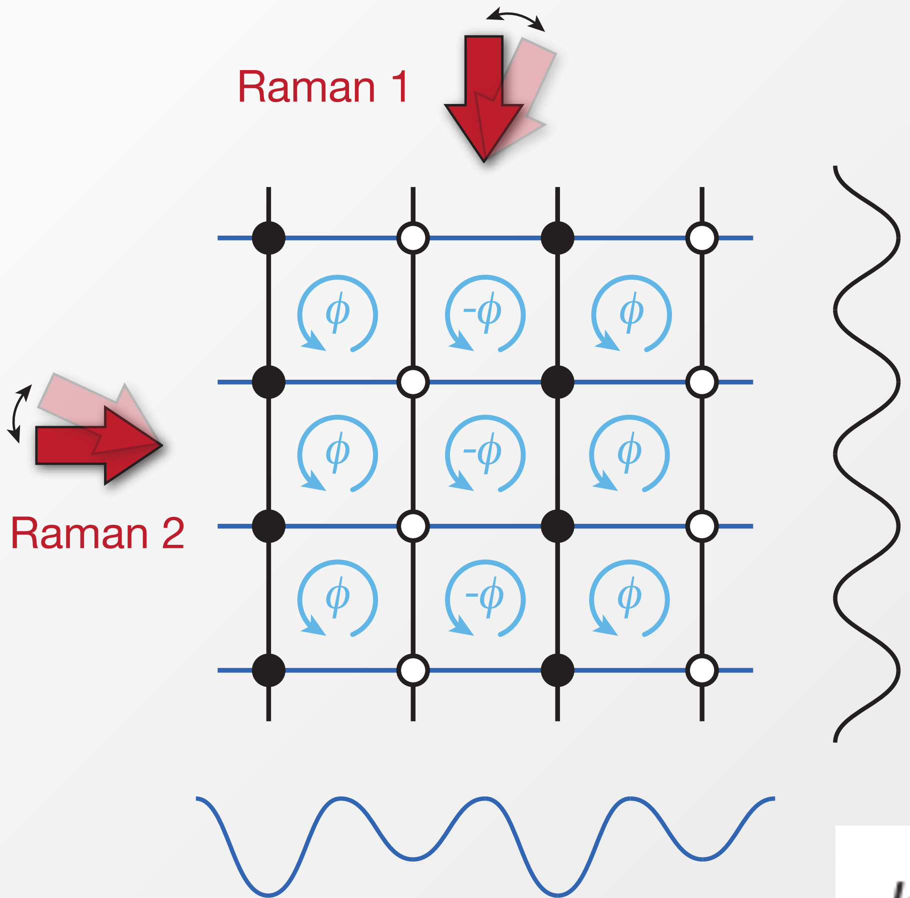


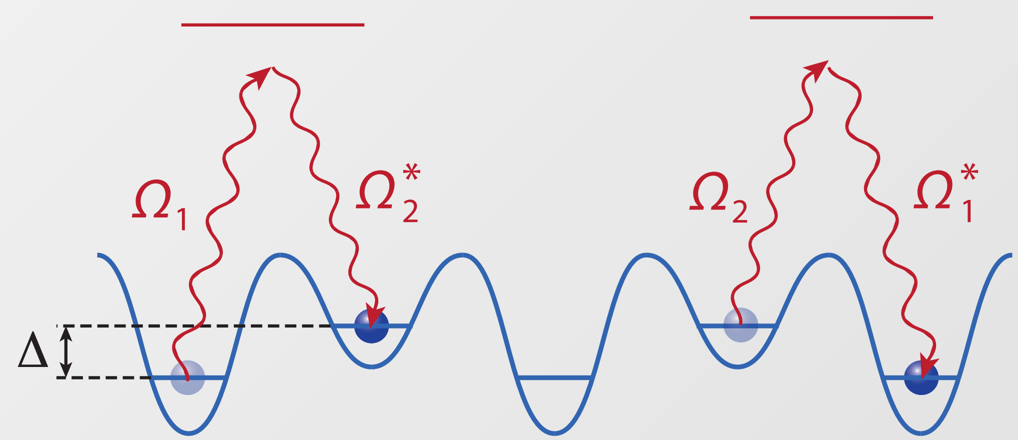
$$\delta \boldsymbol{k} = \boldsymbol{k}_1 - \boldsymbol{k}_2$$

$$K_{|\bullet\rangle \to |\circ\rangle}(\mathbf{R}) = K\, e^{i\delta\mathbf{k}\cdot\mathbf{R}}, \quad K_{|\circ\rangle \to |\bullet\rangle}(\mathbf{R}') = K\, e^{-i\delta\mathbf{k}\cdot\mathbf{R}'}$$

Staggered Flux Lattice

Staggered flux with zero mean





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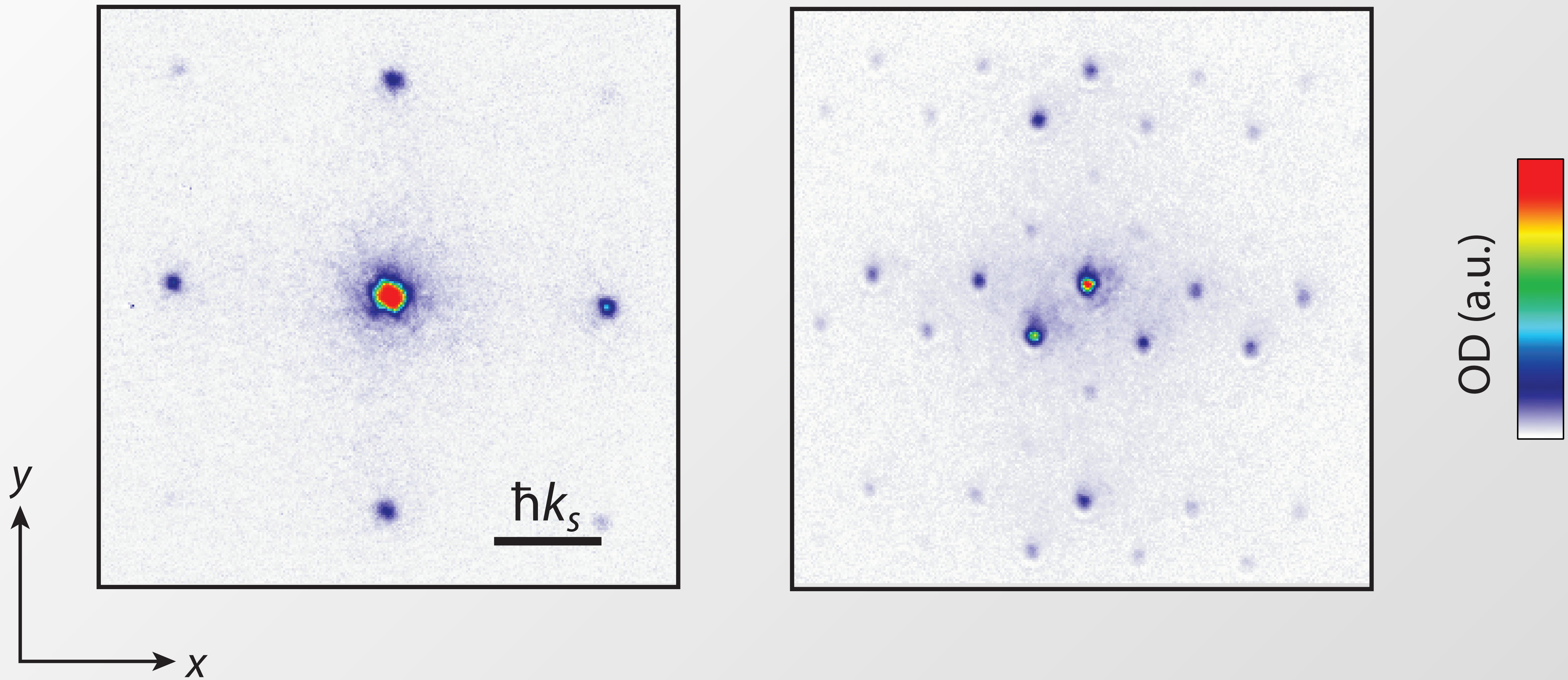
From the geometry of the Raman lasers (angle 90°, wavelength $\lambda = 4d_x = 1534$ nm), we obtain:

$$\phi = \frac{\pi}{2}$$

Momentum Distribution (J=K)

Reference: cubic lattice
(no Raman drive)

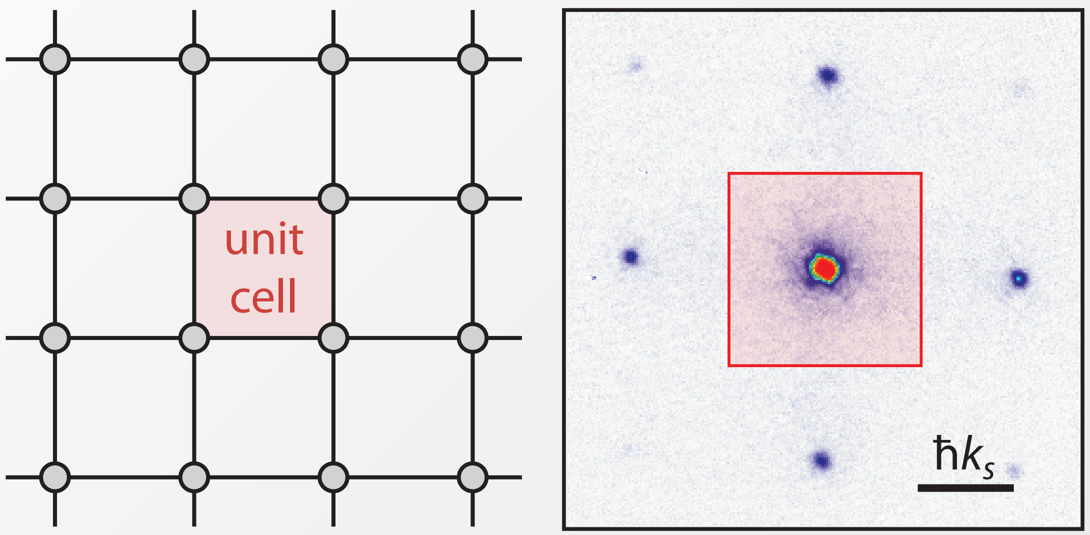
J/K=1.0(1)

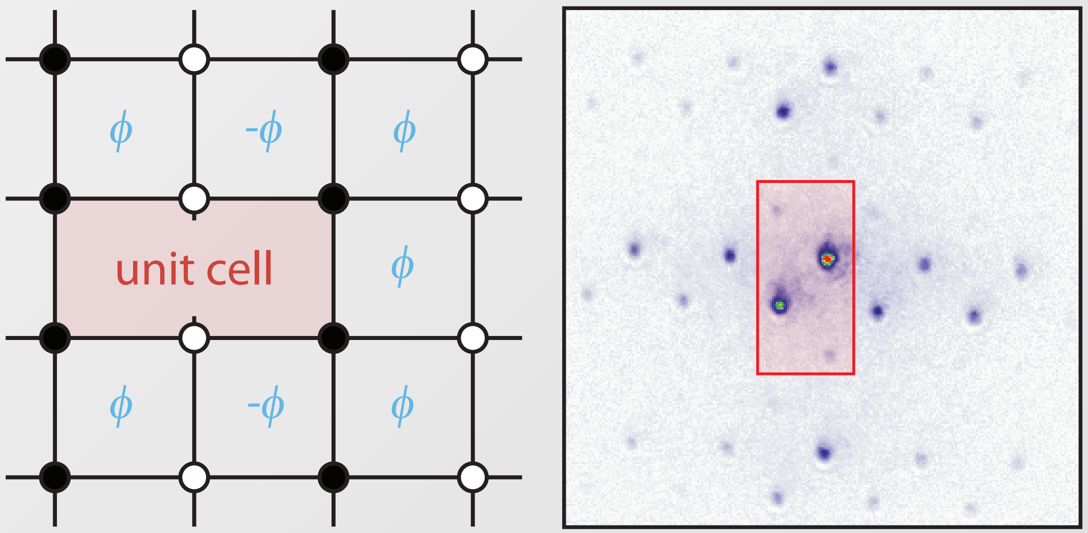


Due to the frustration introduced by the phase factors in $K(\boldsymbol{R})$, the condensation occurs at non-zero momenta.

Band Structure

Magnetic unit cell and Brillouin zone.





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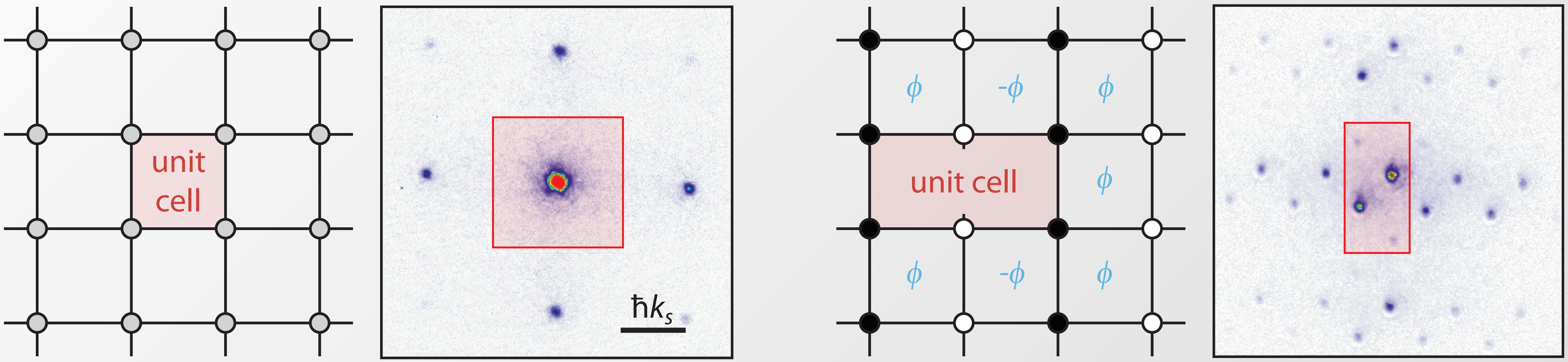

Single-particle spectrum in the tight-binding approximation.
From the magnetic translation symmetries:

$$\psi_{|k_x,k_y\rangle}(\mathbf{R} = m\,\mathbf{d_x} + n\,\mathbf{d_y}) = \mathrm{e}^{i(m\cdot k_x d_x + n\cdot k_y d_y)} \times \begin{cases} \psi_e & m \text{ even} \\ \psi_o \ \mathrm{e}^{i\frac{\pi}{2}(m+n)} & m \text{odd} \end{cases} ,$$

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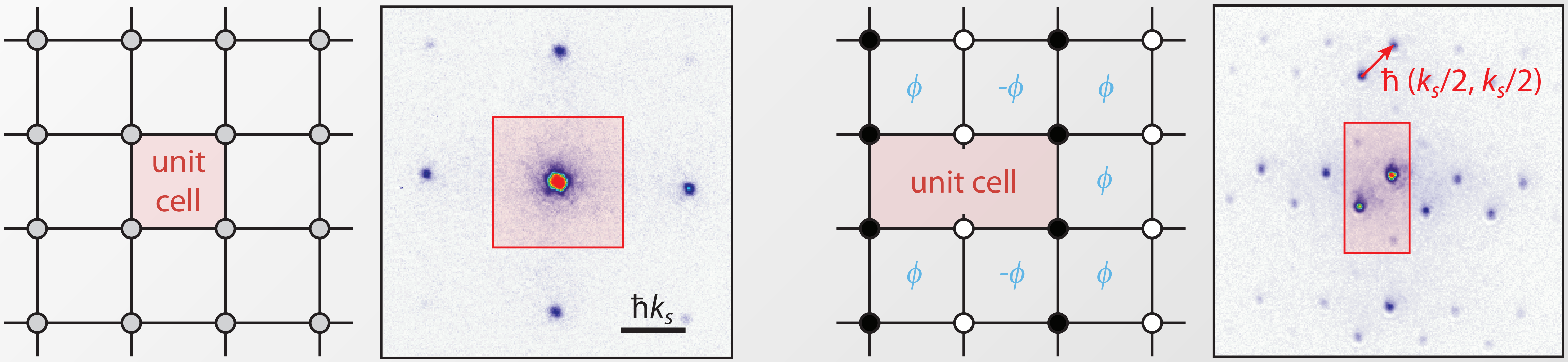

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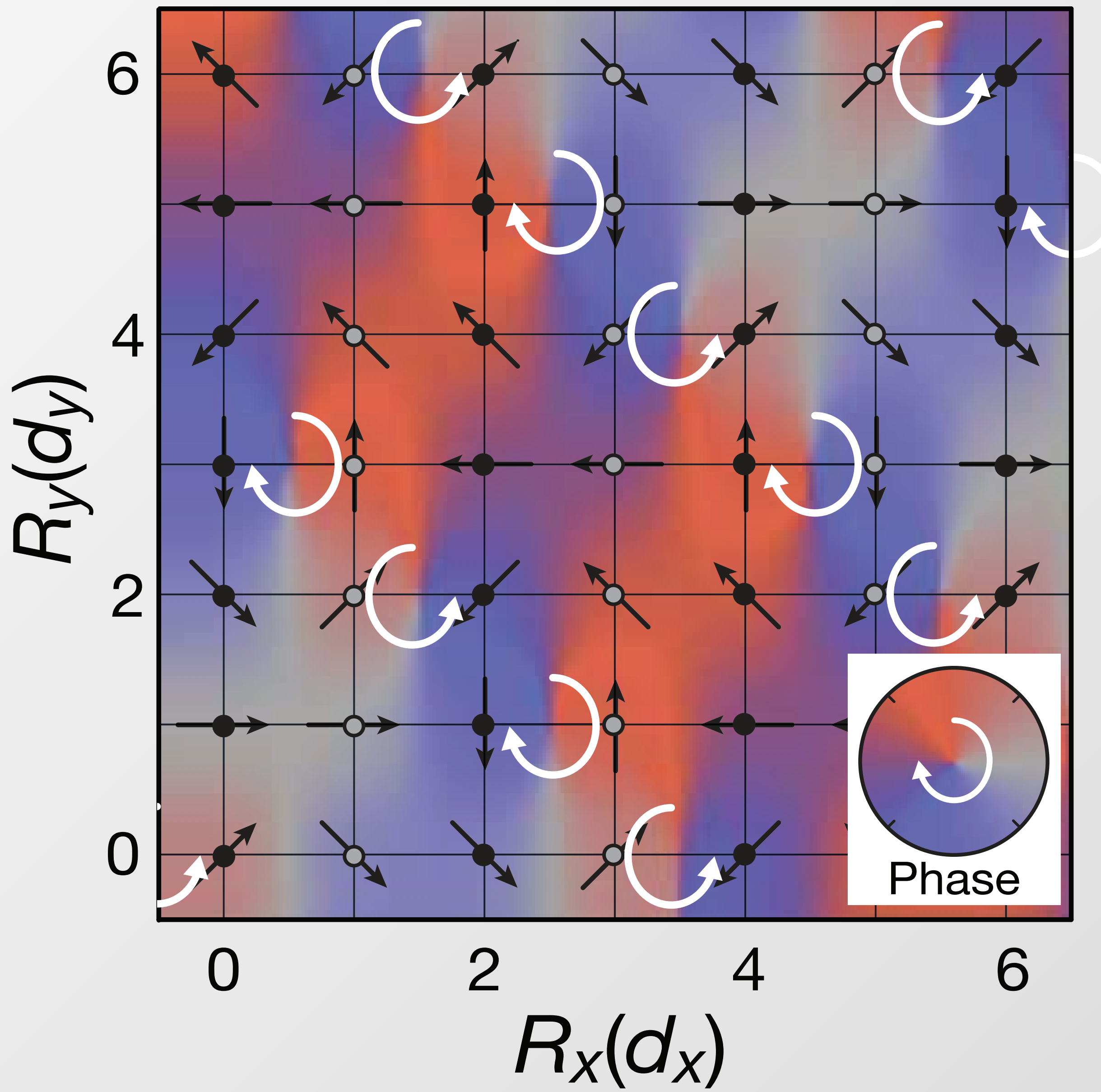
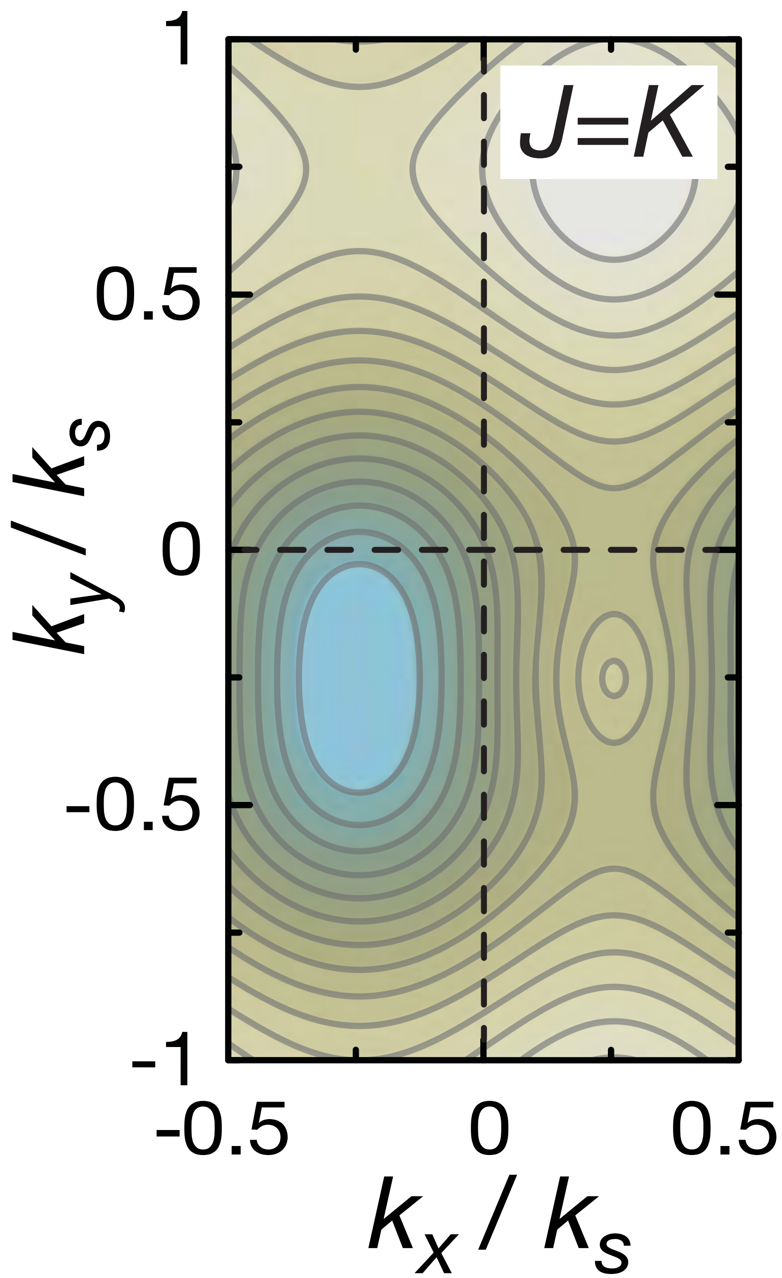
An eigenstate $|k_x, k_y\rangle$ has two momentum components

Local manifestation of magnetic field: vortices

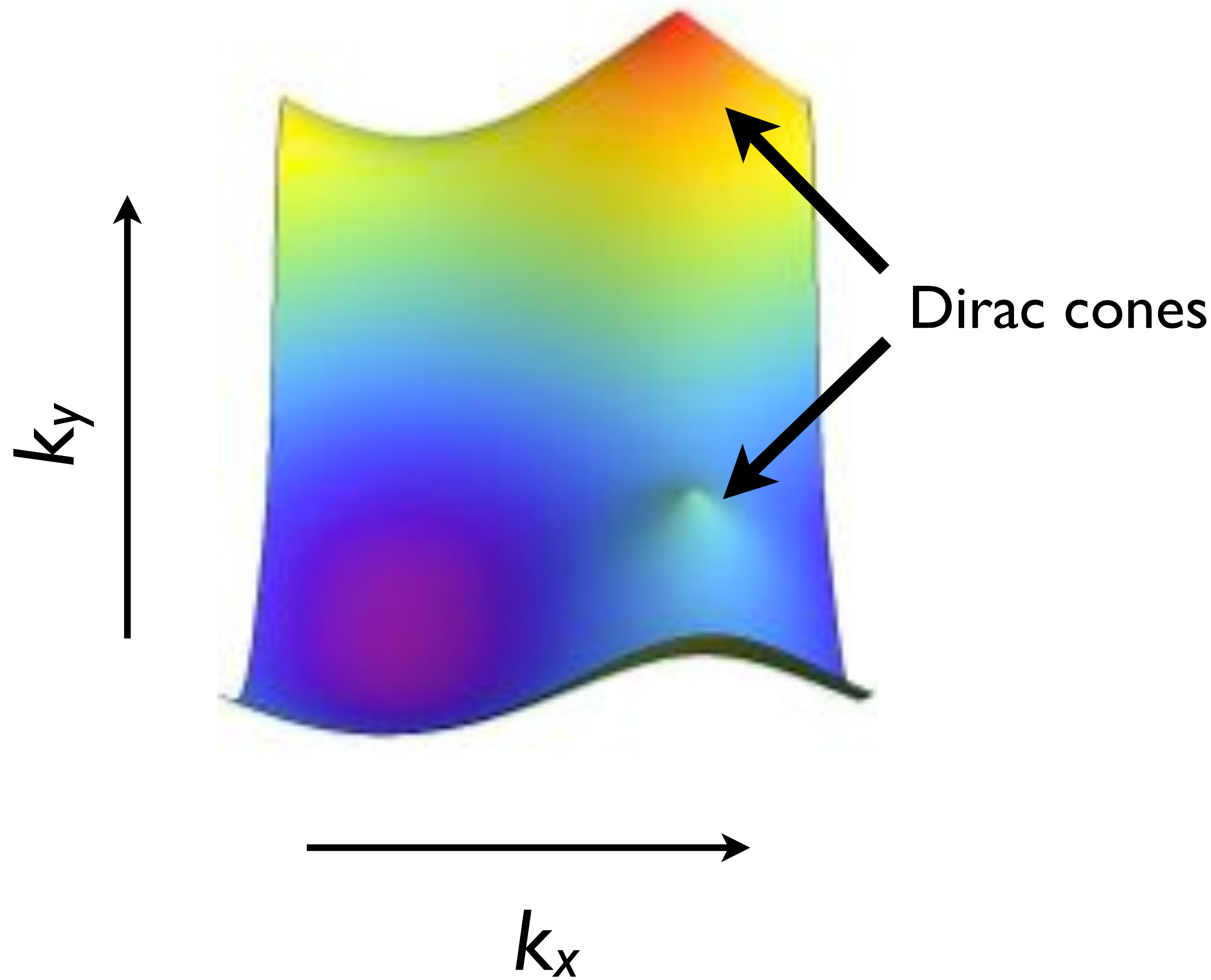
We consider again J=K.



Dispersion Relation



Magnetic Brillouin Zone

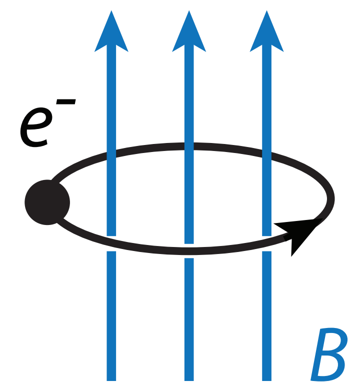


see hexagonal lattices: L. Tarruell et al. Nature (2012)

Probing the Quantum Motion in the Magnetic Field

Classical:

Charged particle in magnetic field



Probing the Quantum Motion in the Magnetic Field

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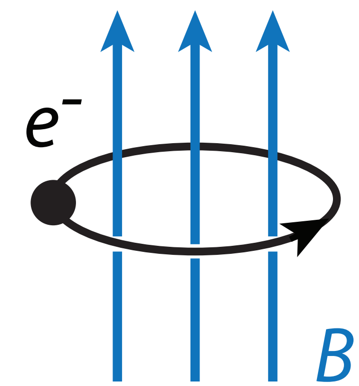
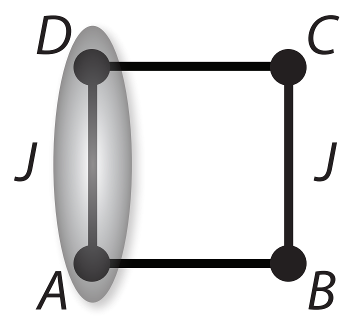


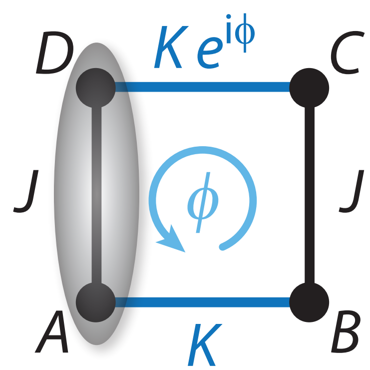
Quantum Analogue:

Initial State:
Single Atom in the ground state of a tilted plaquette.



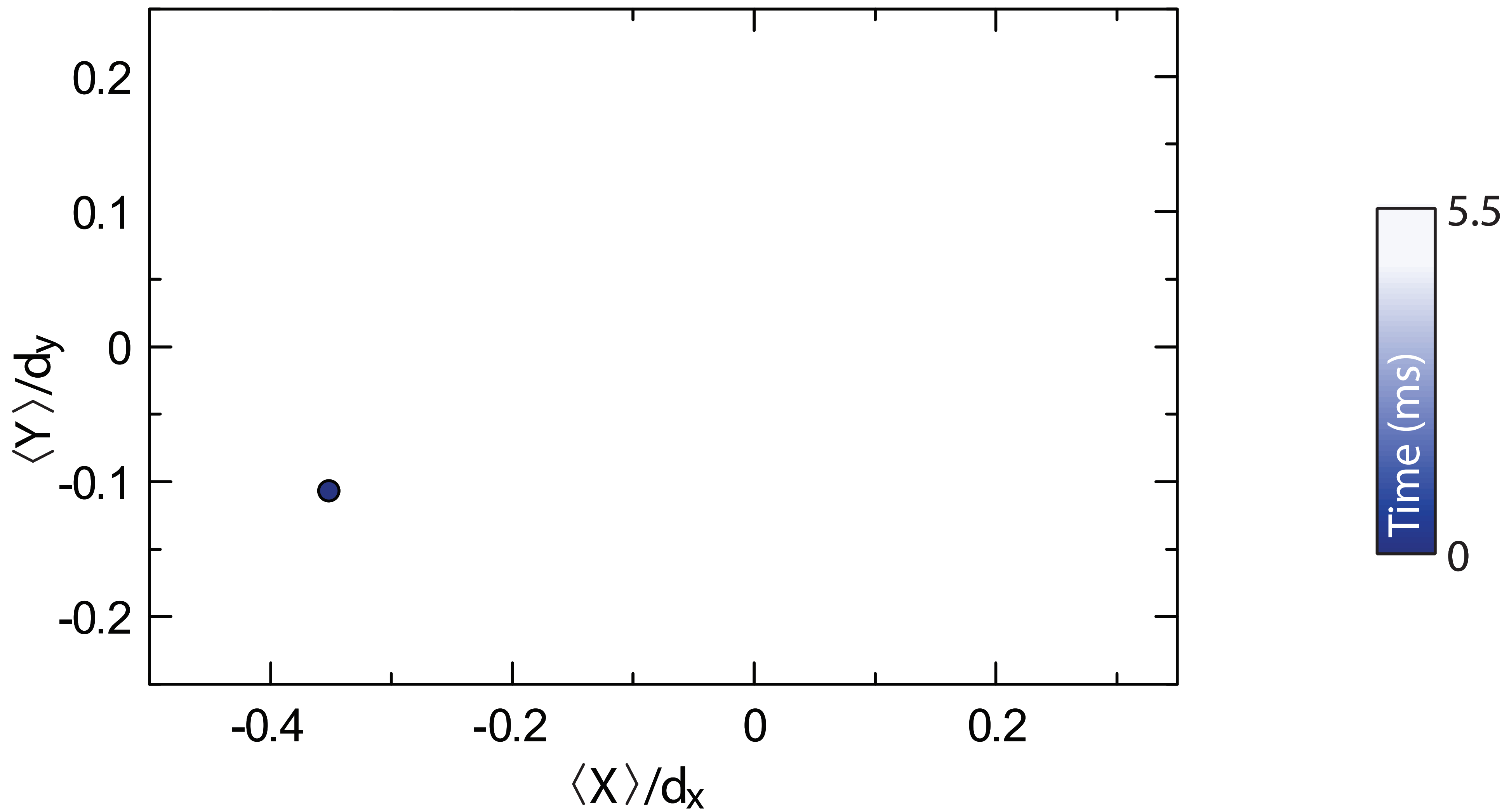
$$|\psi_0\rangle = \frac{|A\rangle + |D\rangle}{\sqrt{2}}$$

Switch on Raman coupling to induce tunneling



Lattice 'Cyclotron' Orbits

We plot the mean atom position during the evolution.



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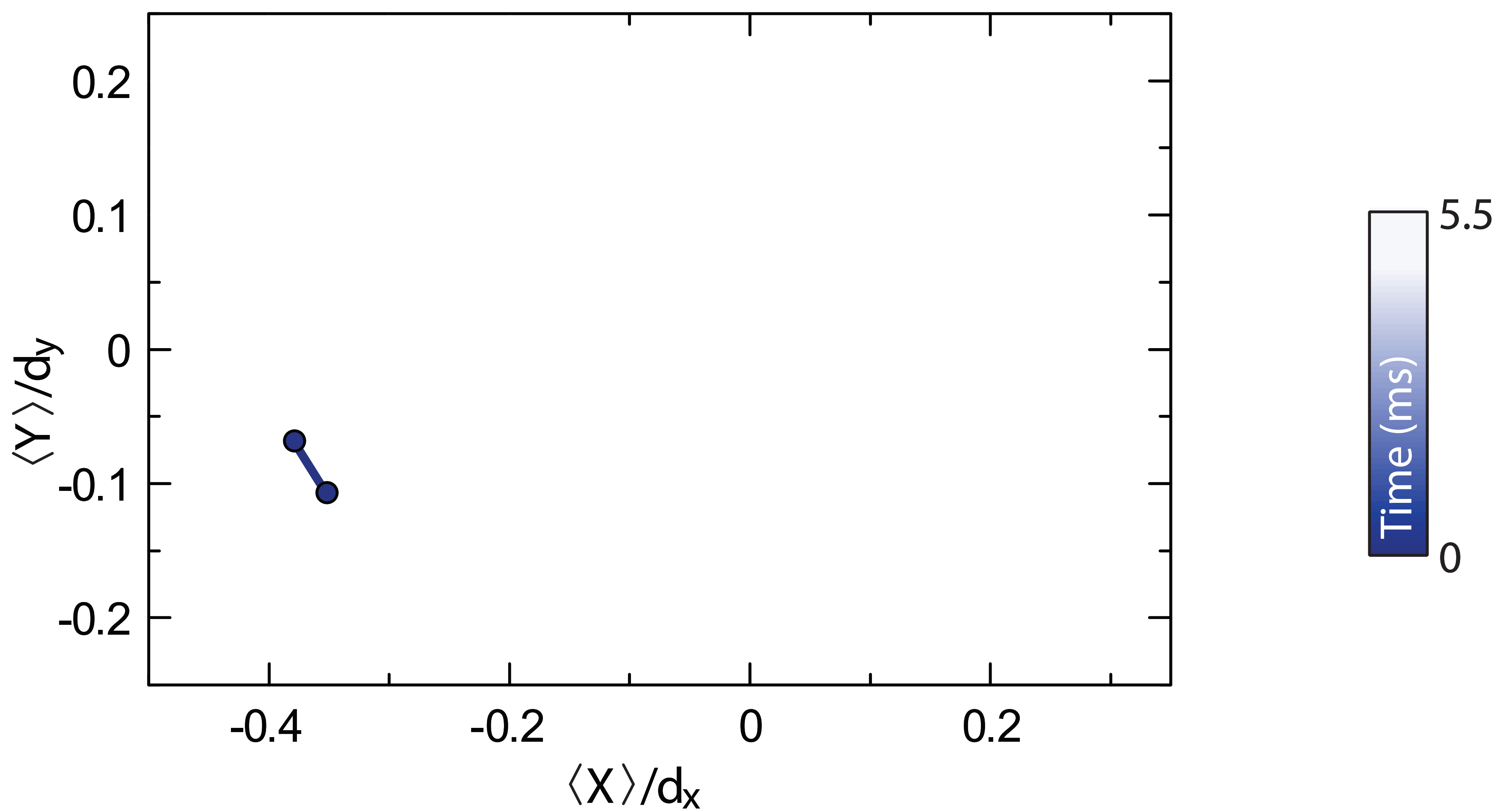

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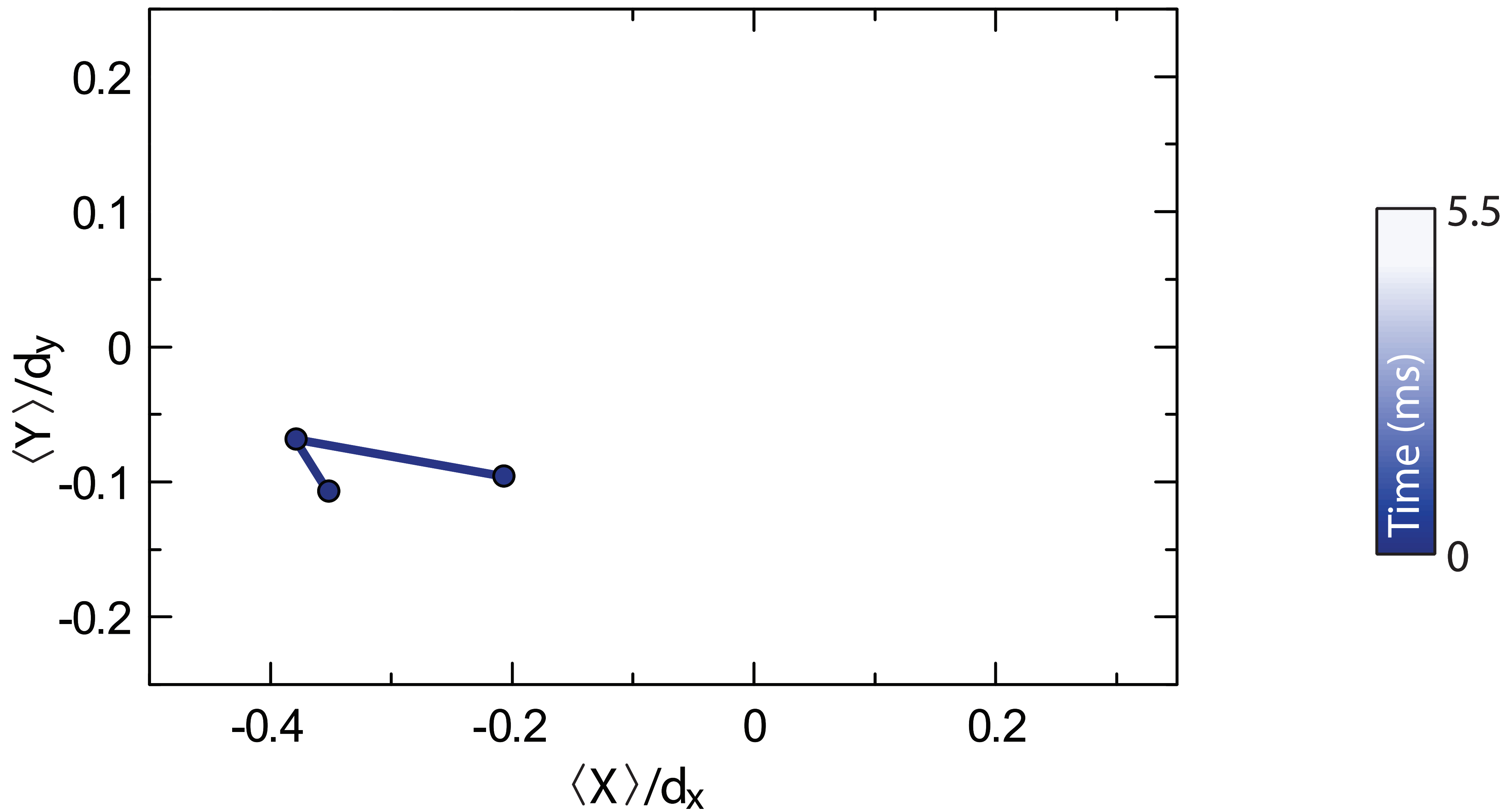

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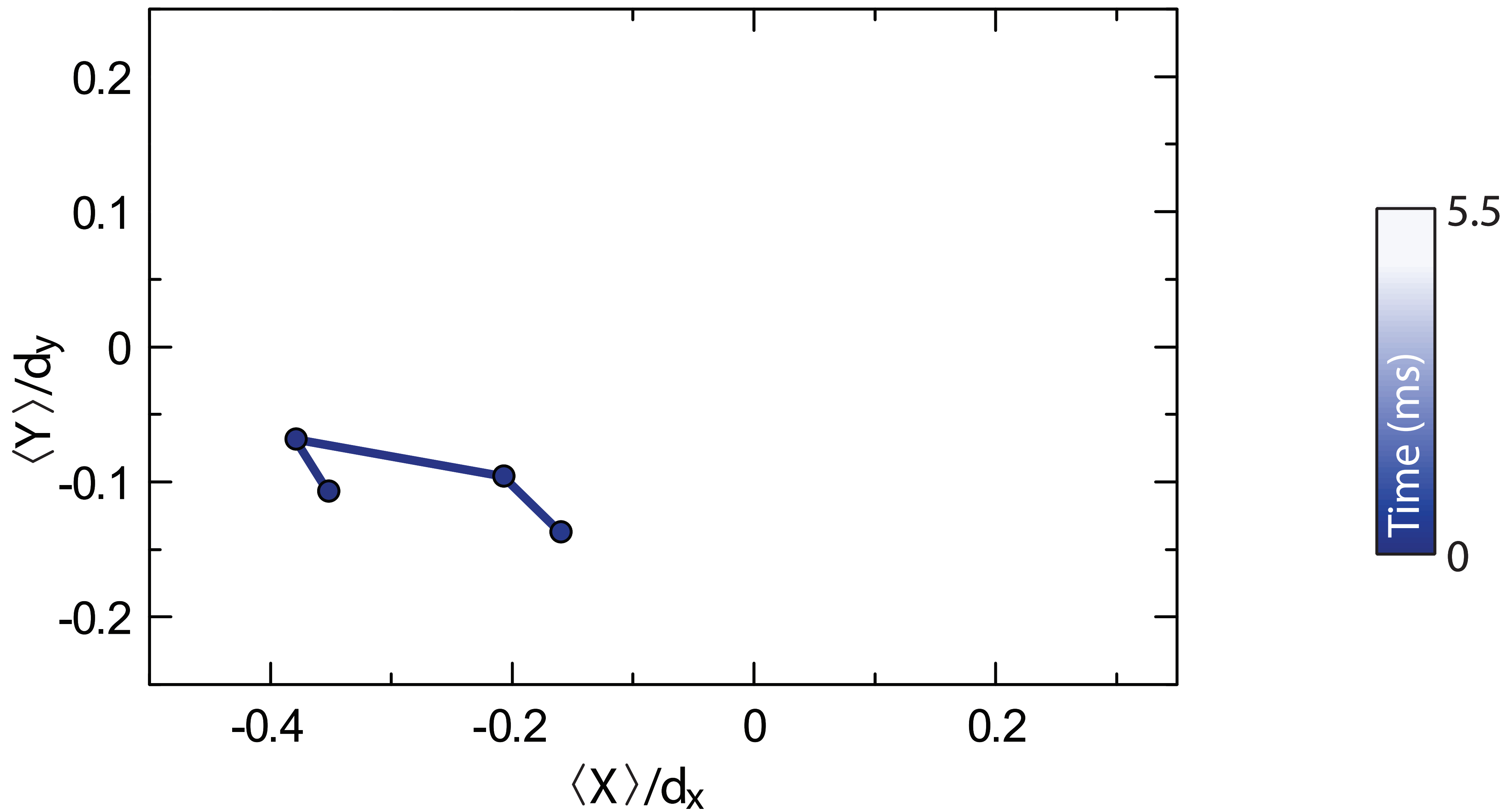

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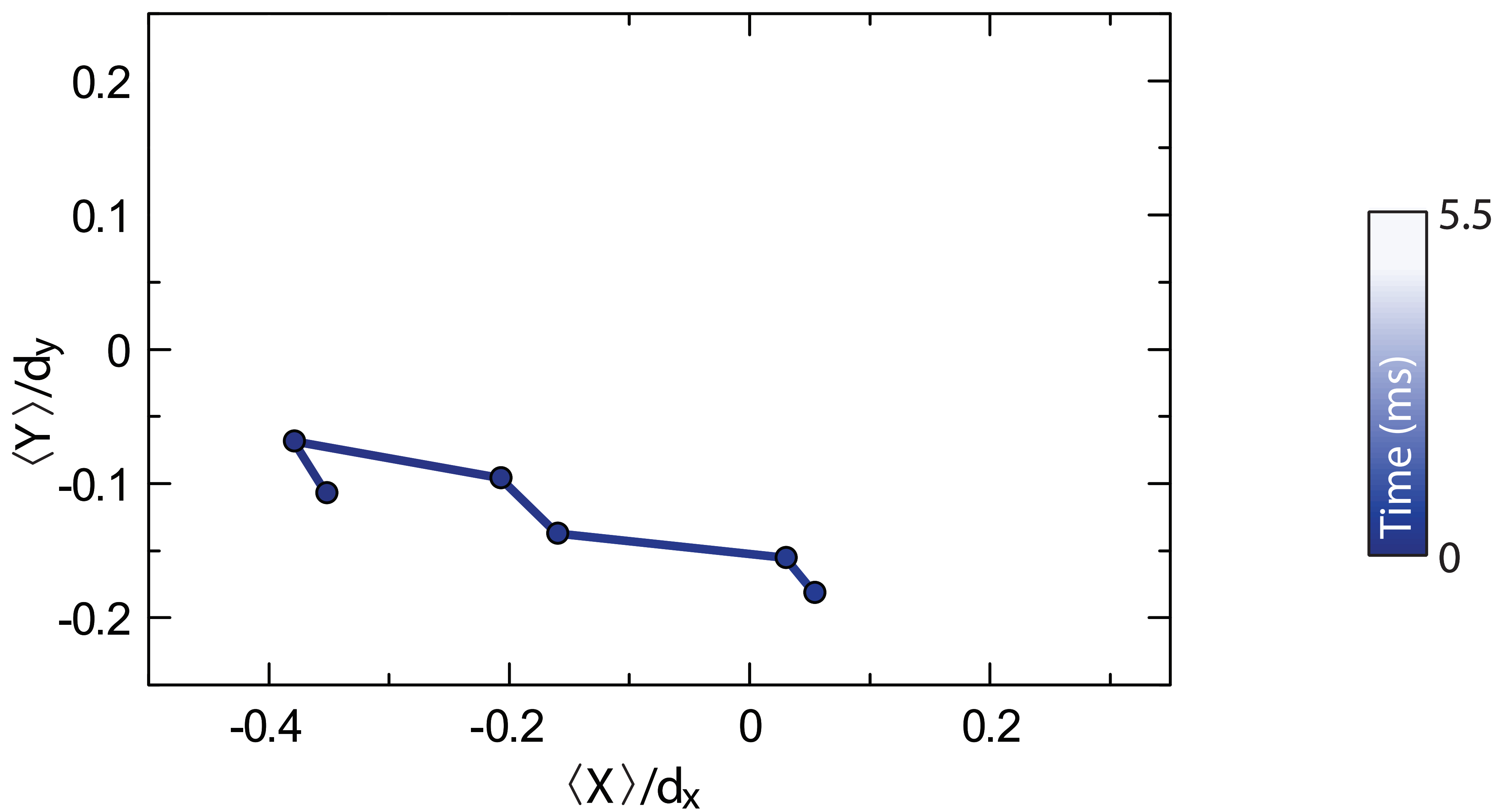

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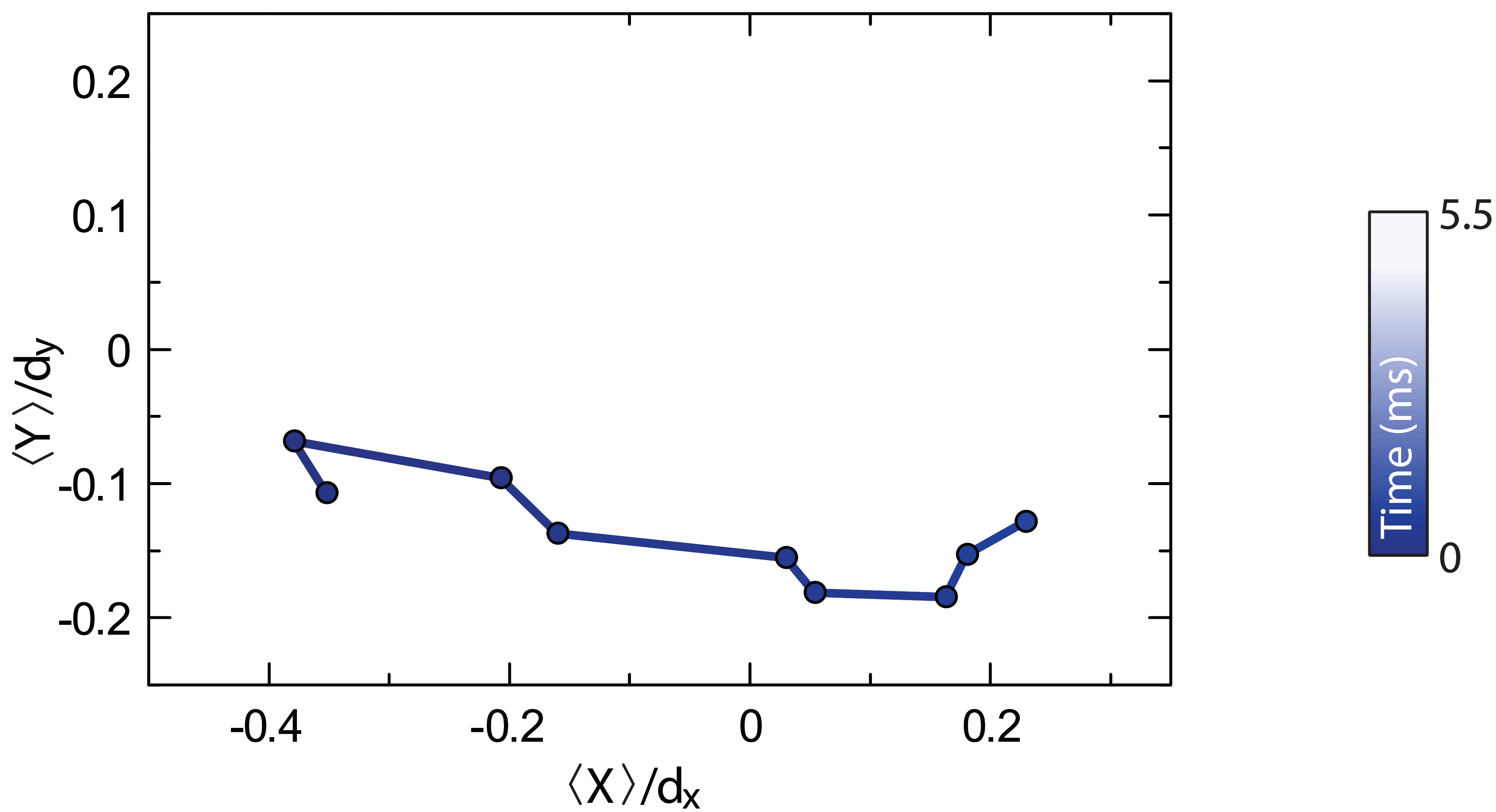

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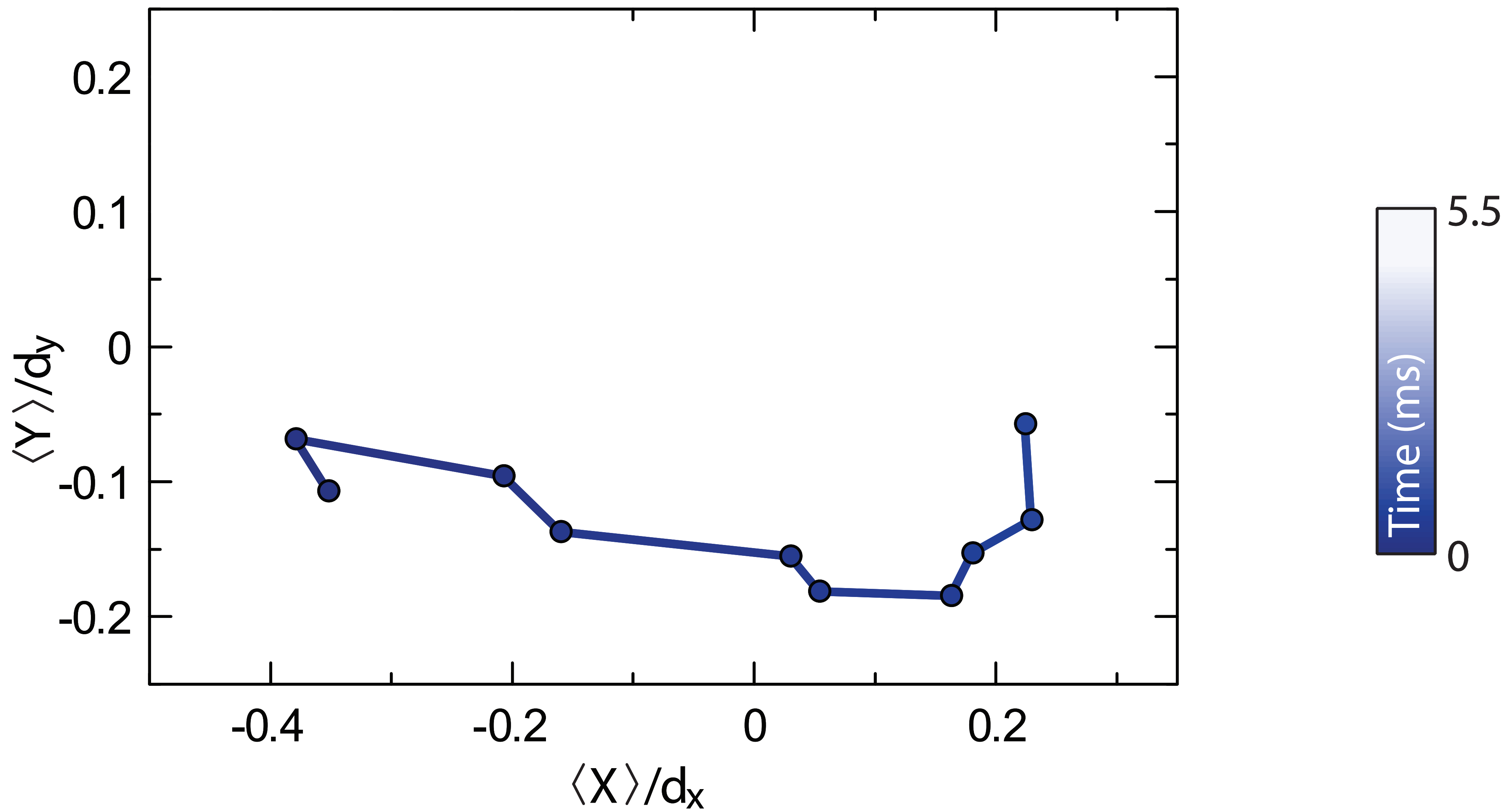

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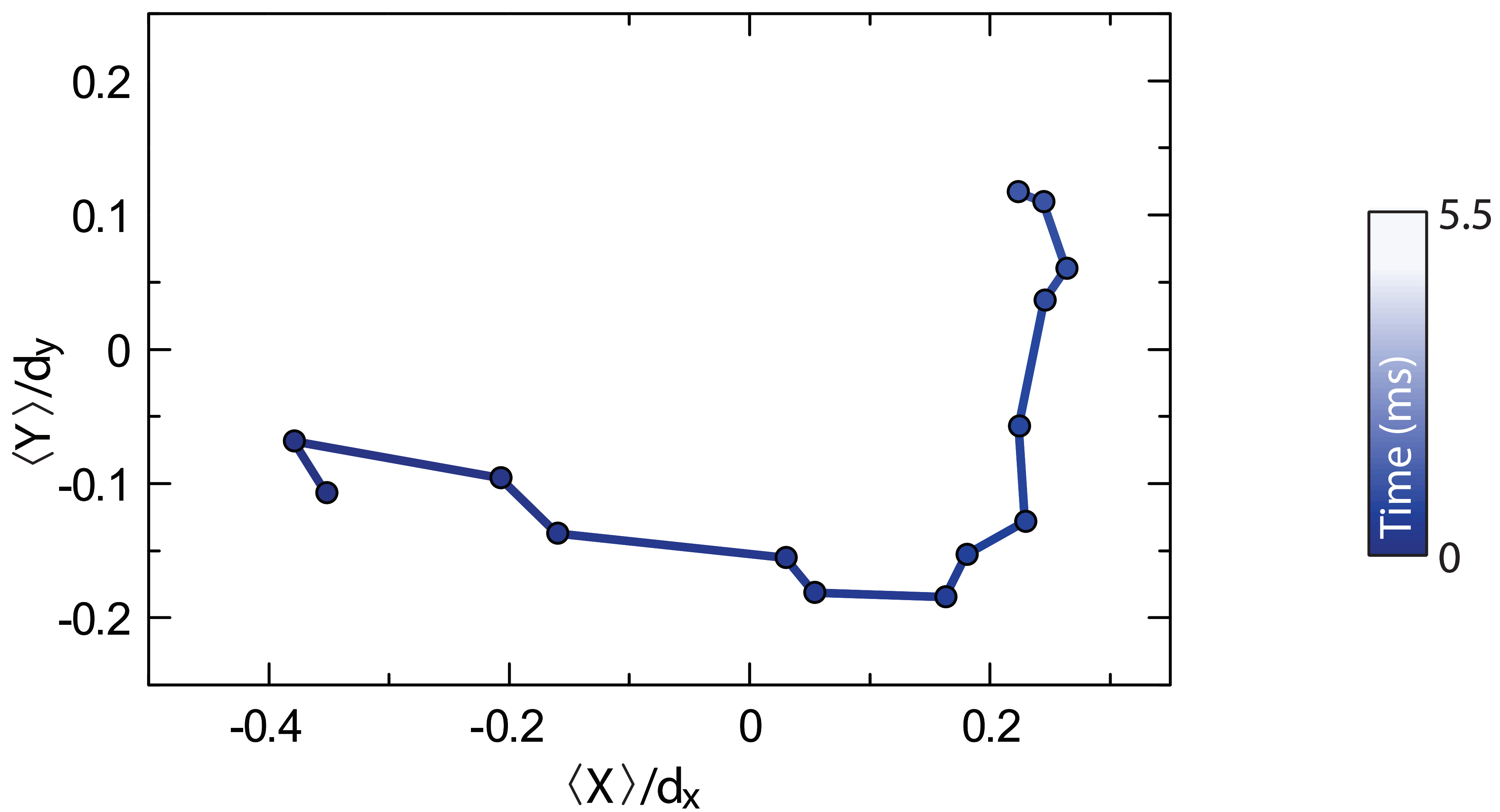

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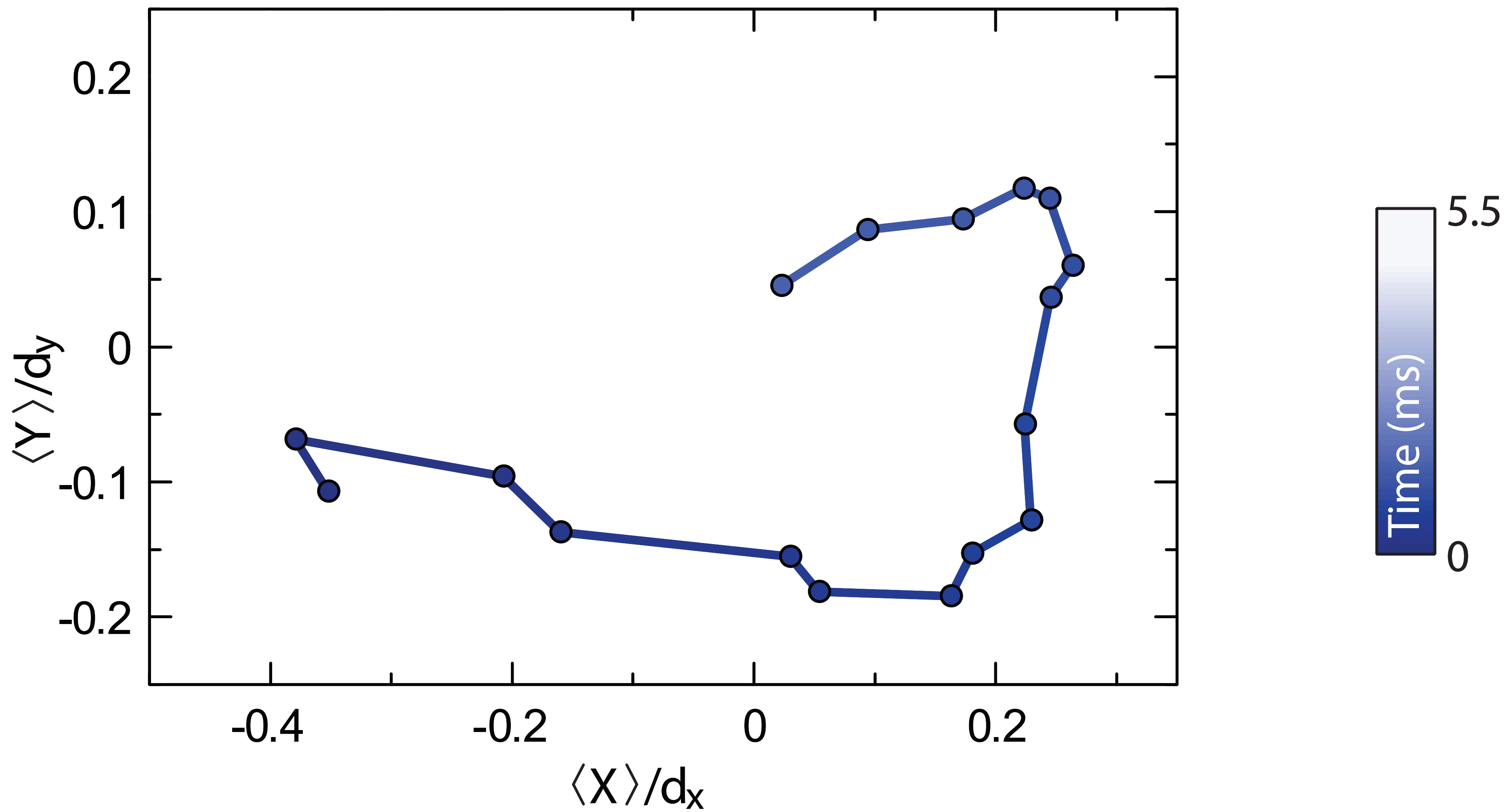

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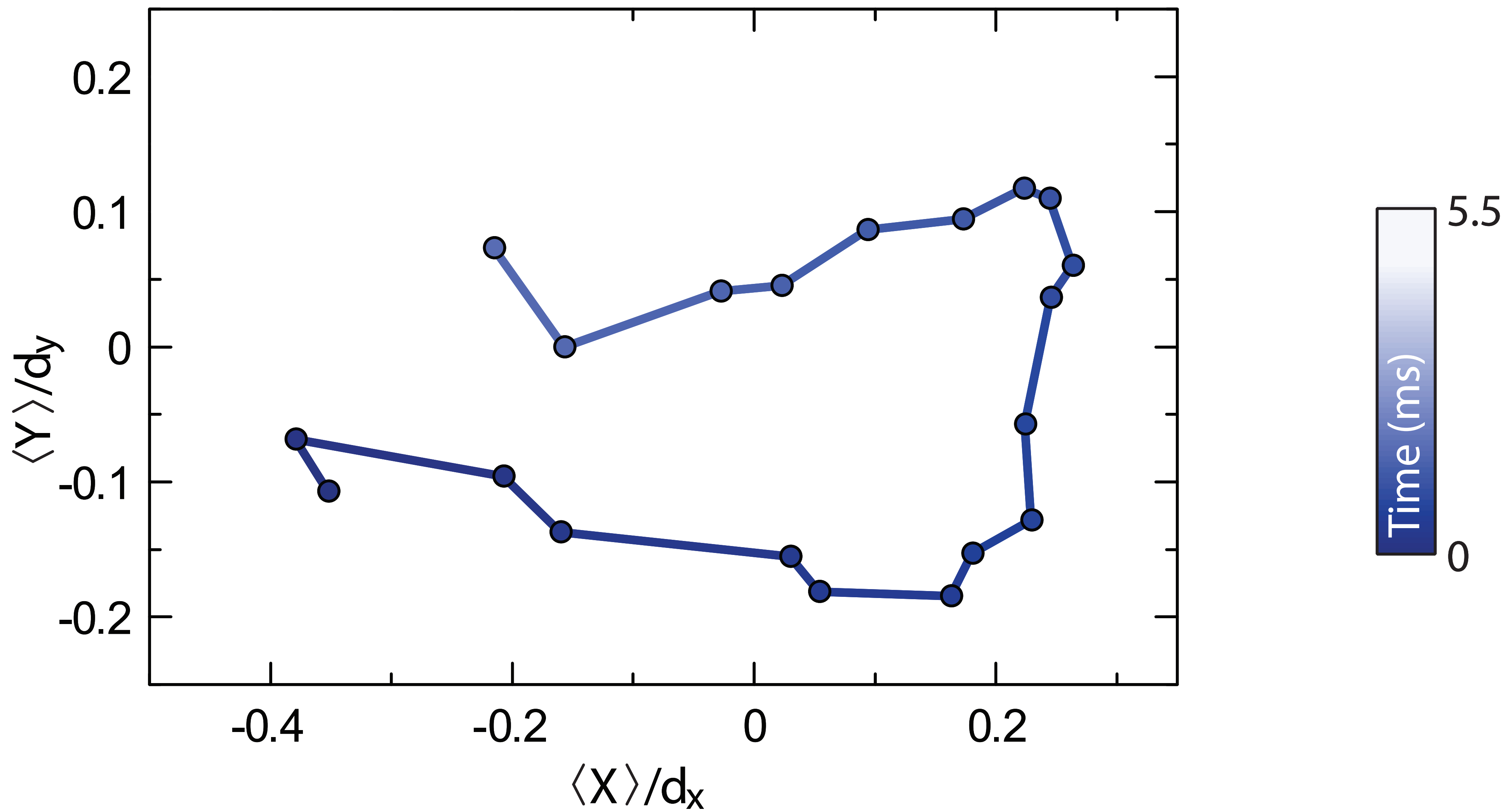

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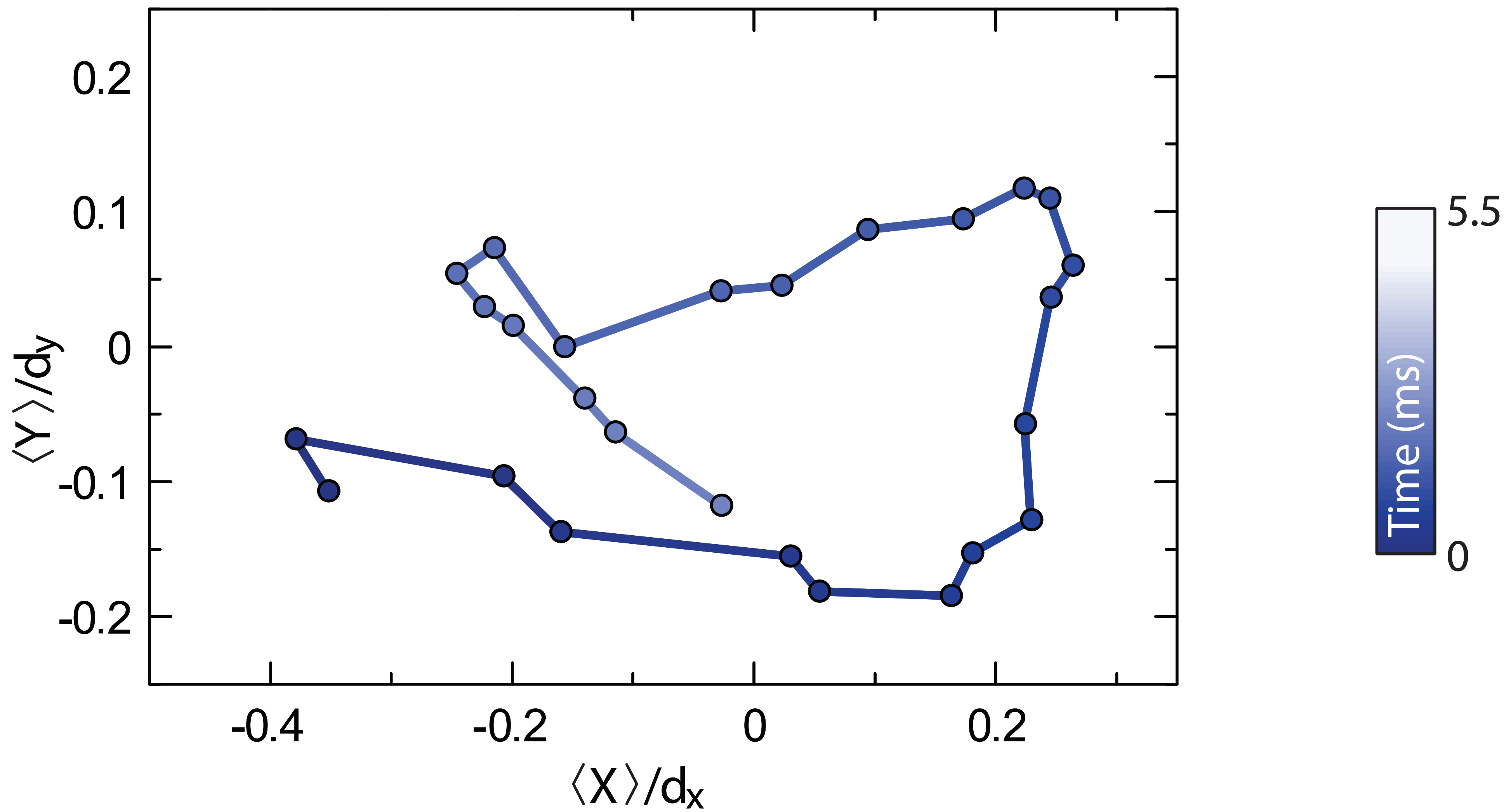

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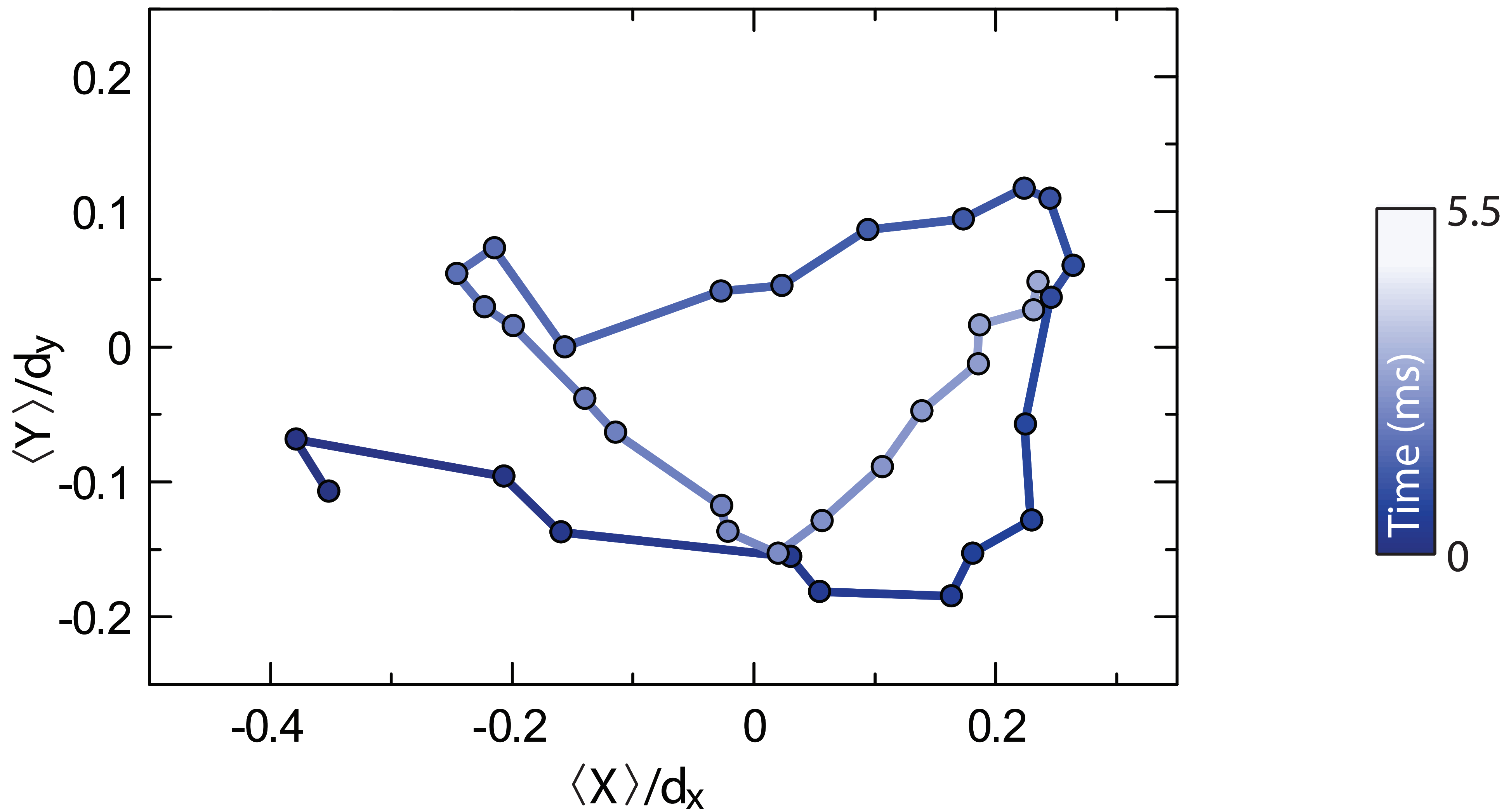

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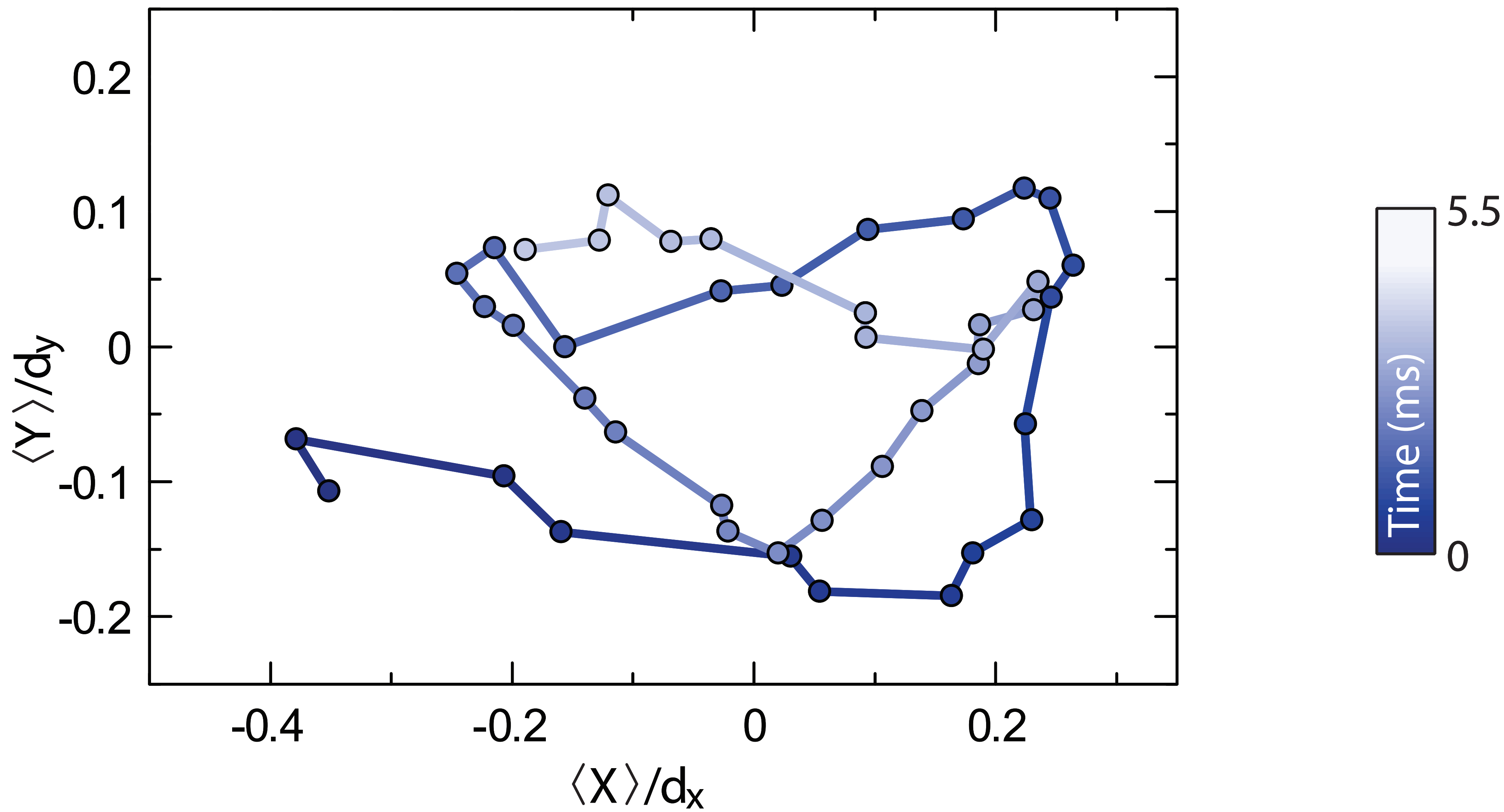

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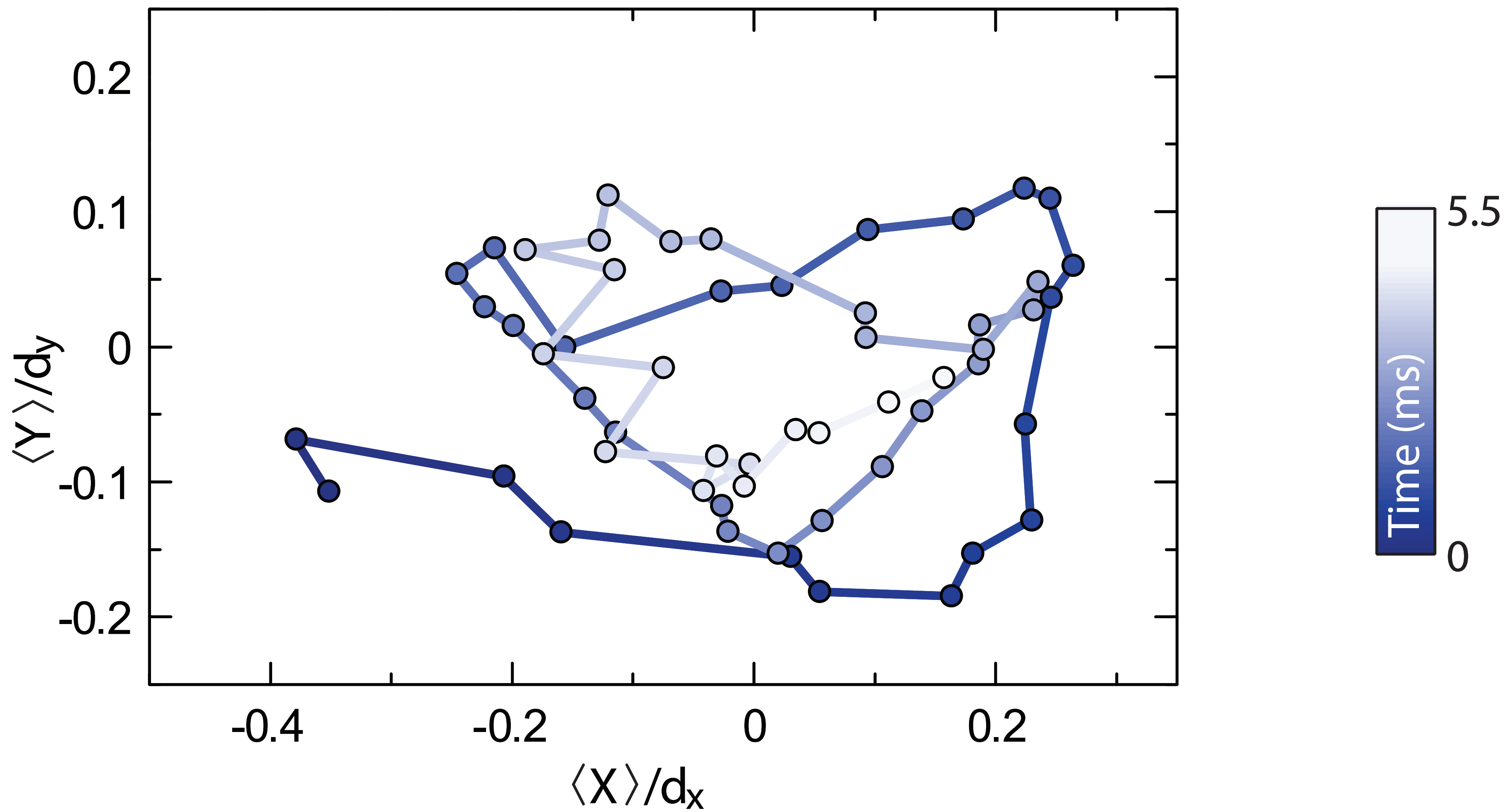

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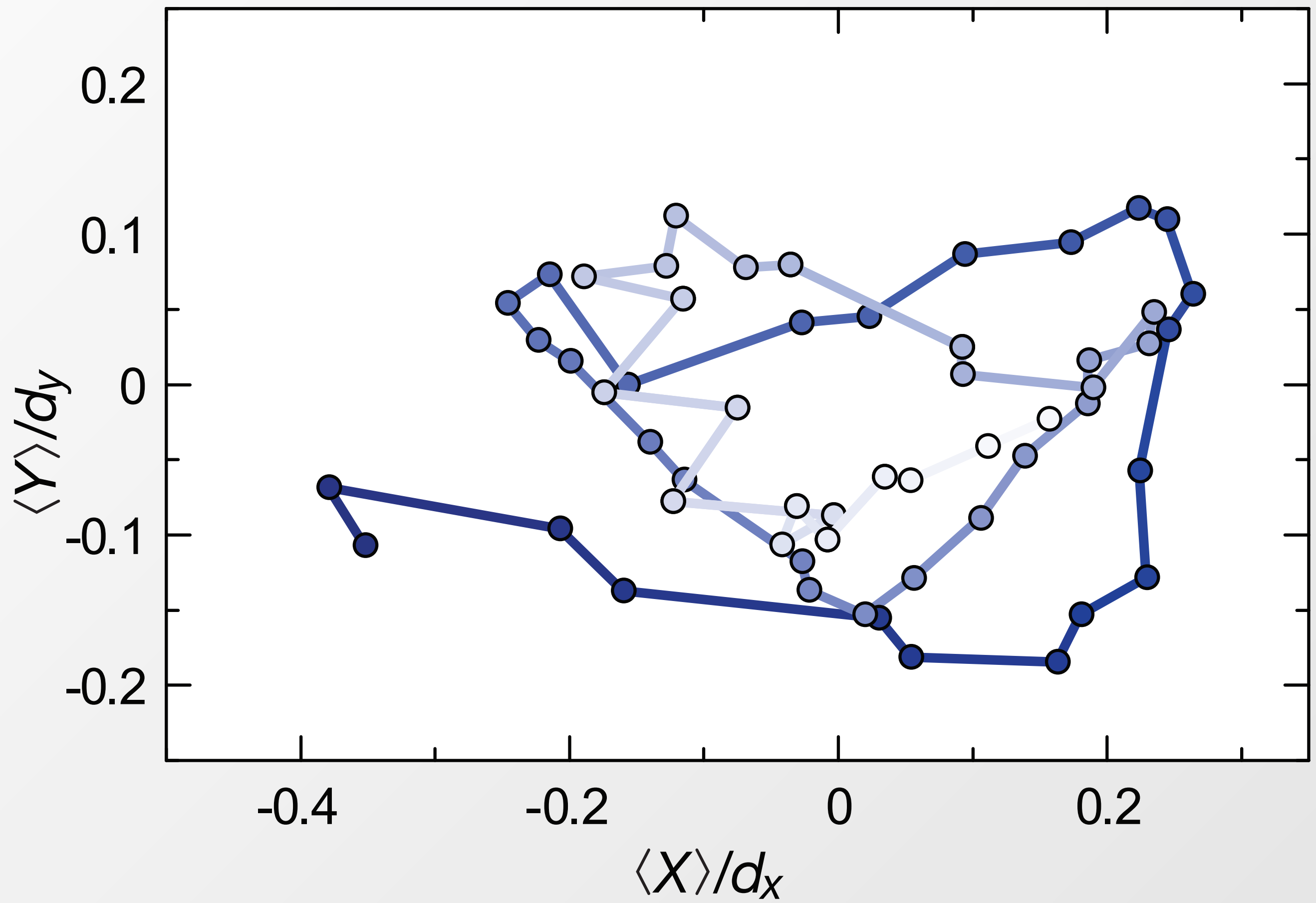
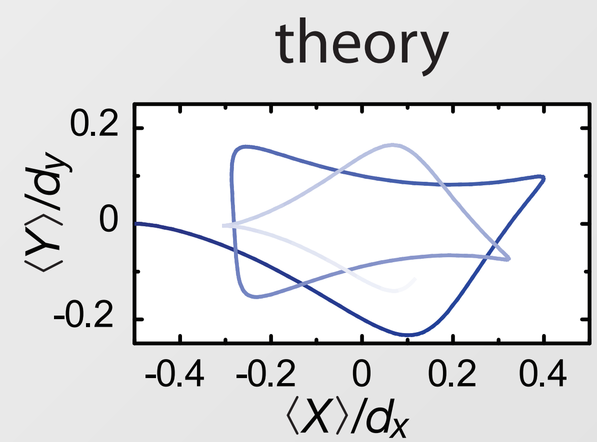
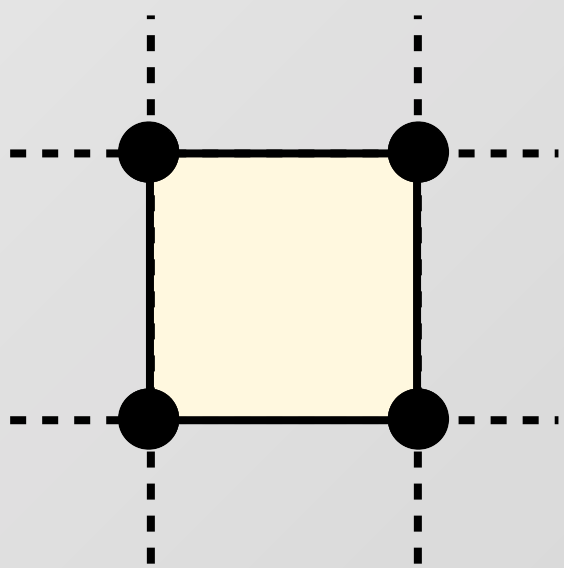




Quantum cyclotron orbit allows us to measure the applied flux!



$$\phi = 0.73(5)\frac{\pi}{2}$$

Deviation from π/2 due to geometric reasons.

'Cyclotron' Orbits

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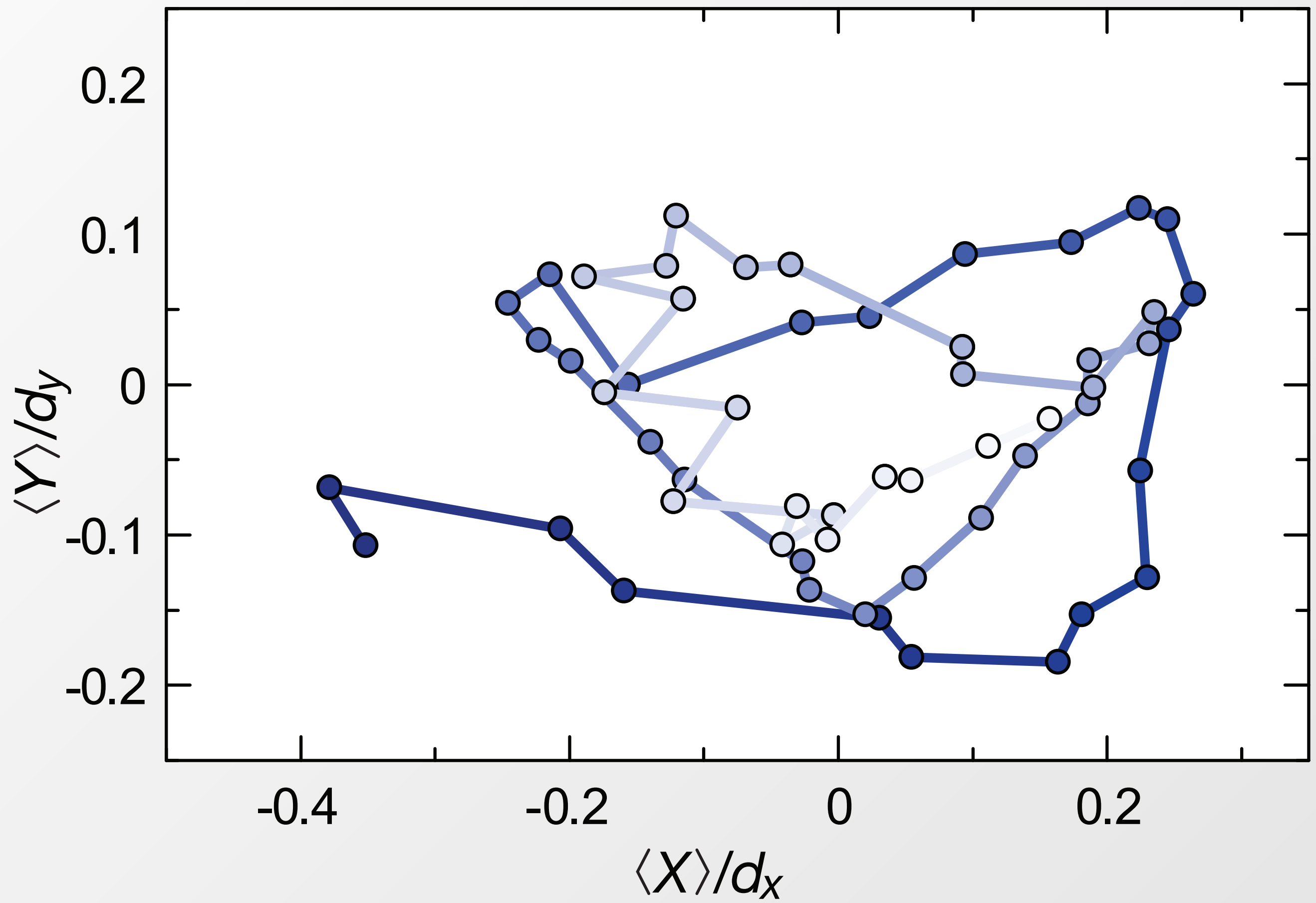
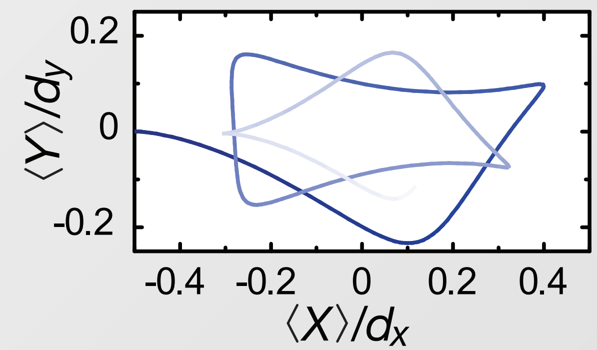


theory



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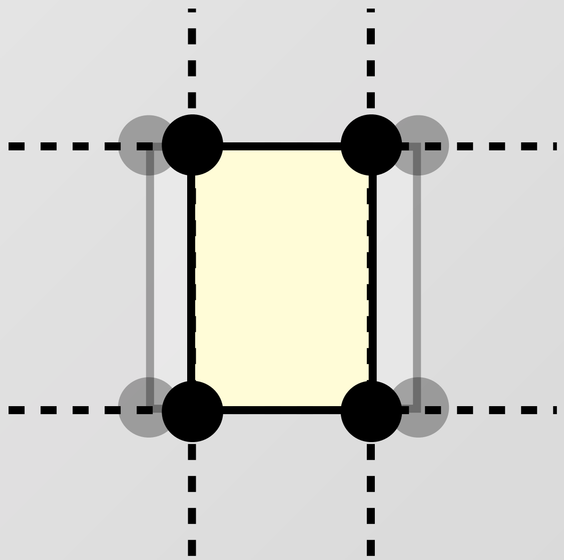

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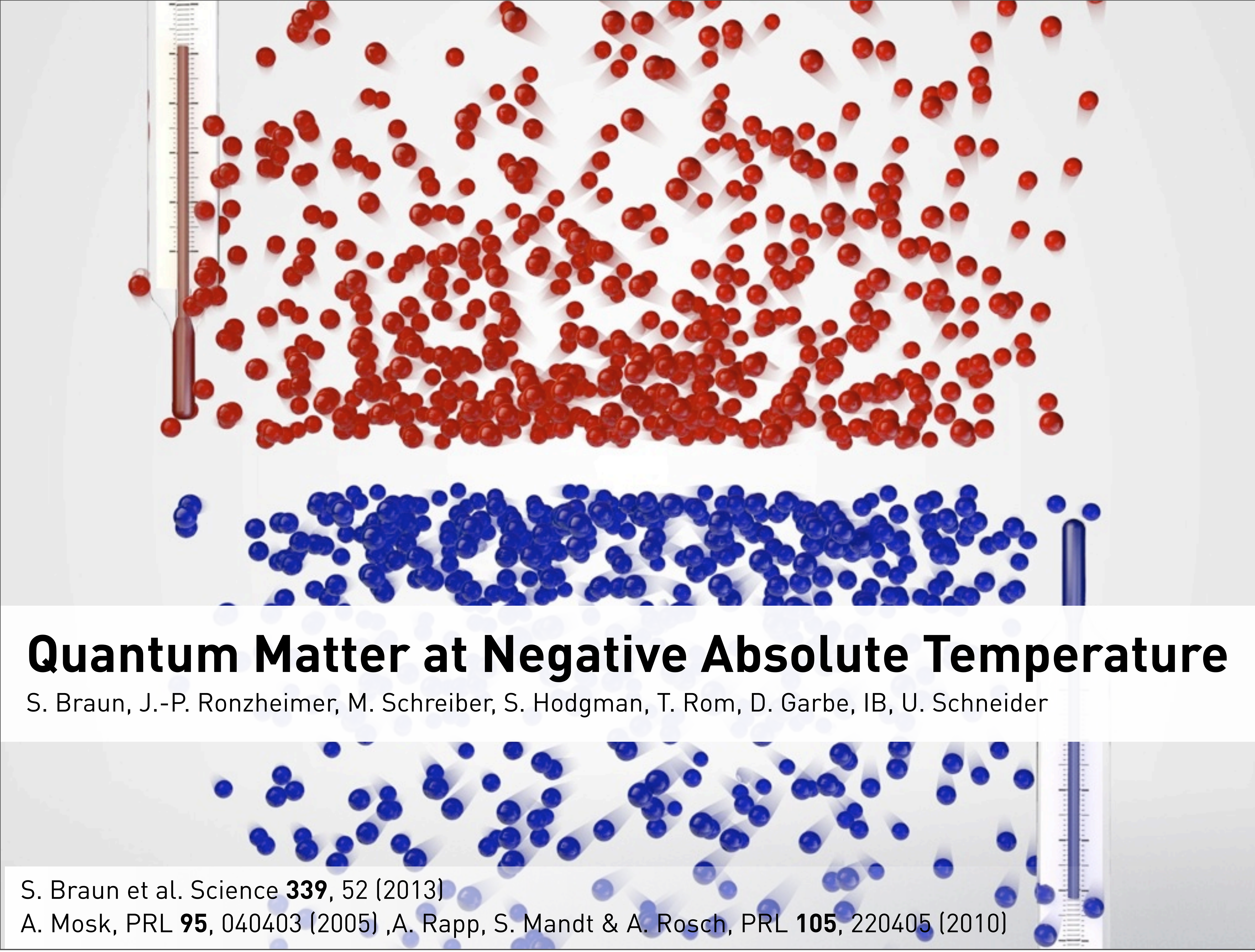

Quantum Matter at Negative Absolute Temperature

S. Braun, J.-P. Ronzheimer, M. Schreiber, S. Hodgman, T. Rom, D. Garbe, IB, U. Schneider

S. Braun et al. Science **339**, 52 (2013)

A. Mosk, PRL **95**, 040403 (2005) ,A. Rapp, S. Mandt & A. Rosch, PRL **105**, 220405 (2010)

Thermodynamic Definition of Temperature

$$\frac{1}{T} = \left(\frac{\partial S}{\partial E}\right)_V$$

Positive Temperature

Entropy increases with Energy

Negative Temperature

Entropy decreases with Energy

Thermodynamic Definition of Temperature

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Entropy increases with Energy

Negative Temperature

Entropy decreases with Energy

Thermodynamic theorems apply in negative as well as positive temperature regime!

Thermodynamic Definition of Temperature

$$\frac{1}{T} = \left(\frac{\partial S}{\partial E}\right.$$

mperature

with Energy

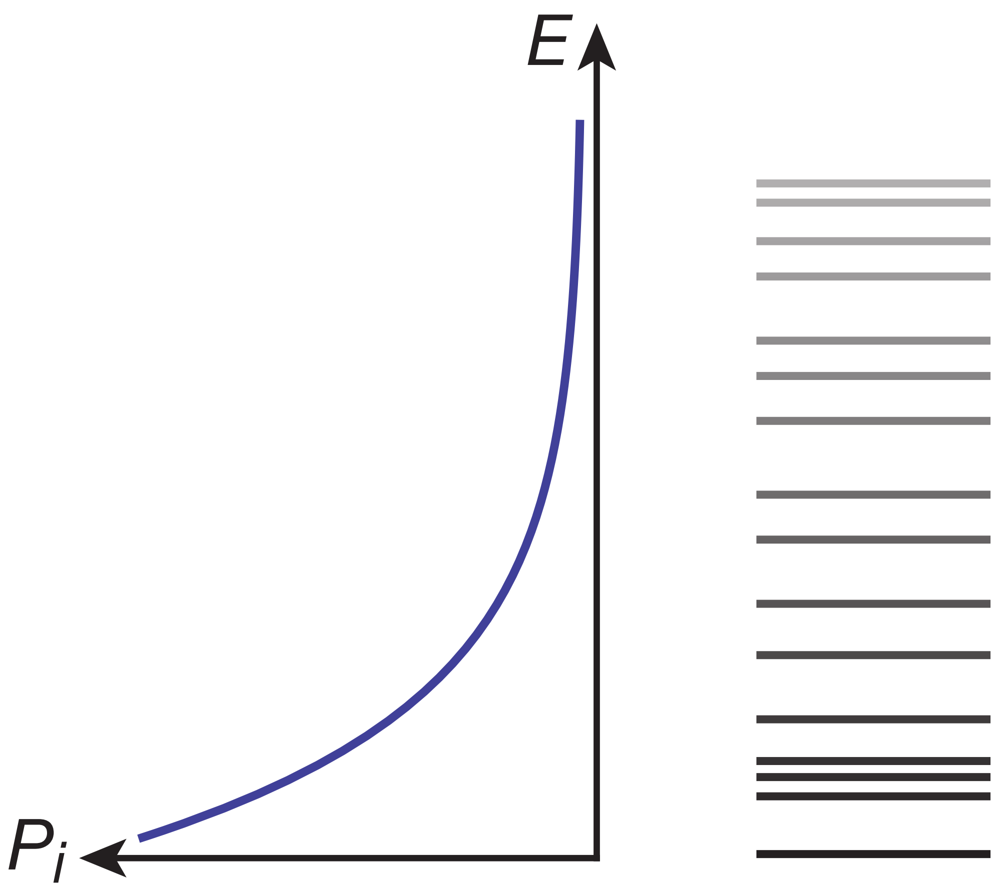
Warning:
Temperature does not measure energy content!!!

erature

es with Energy

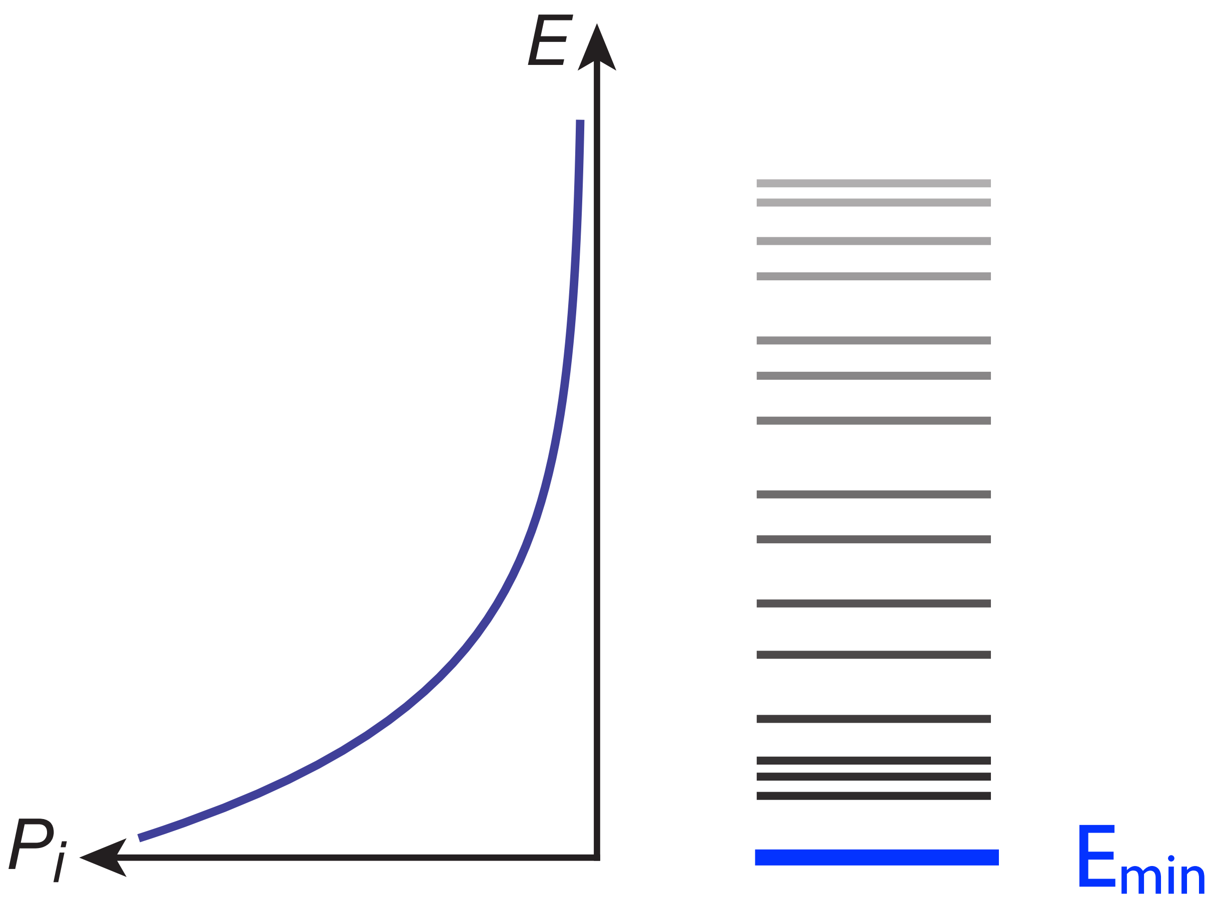
Thermodynamic theorems apply in negative as well as positive temperature regime!

Requirements



$$P_i \propto e^{-\frac{E_i}{k_B T}}$$

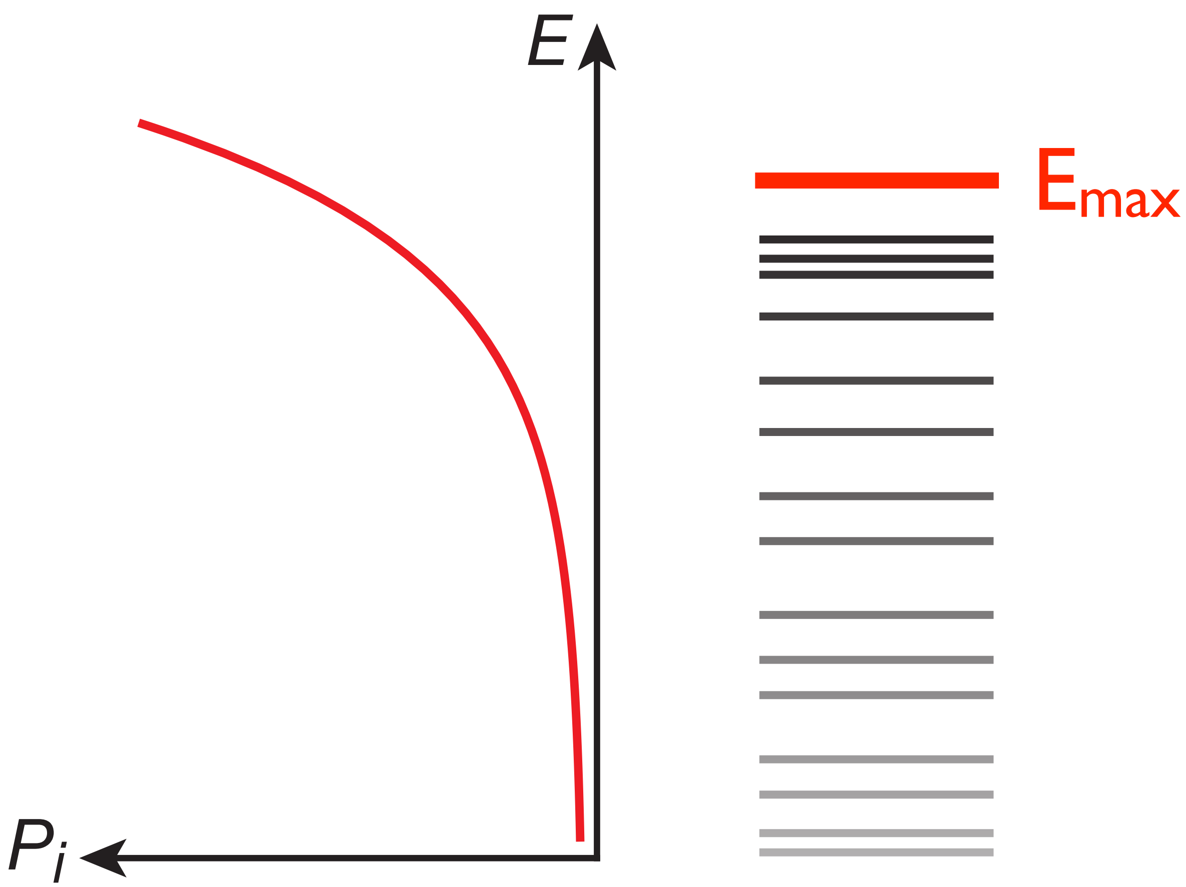
Requirements



$$P_i \propto e^{-\frac{E_i}{k_B T}}$$

For positive temperatures, we require lower energy bound E_{min}!

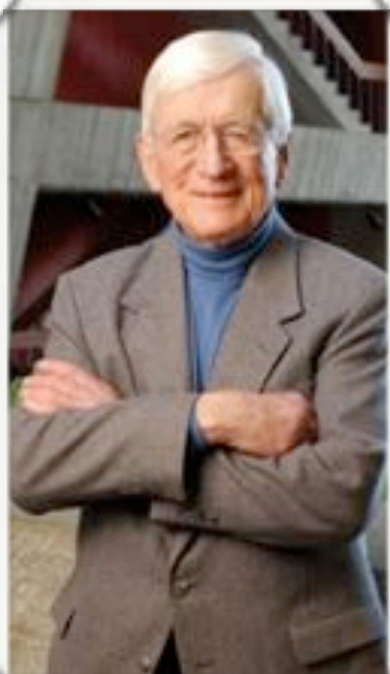
Requirements



$$P_i \propto e^{-\frac{E_i}{k_B(-T)}}$$

For negative temperatures, we require upper energy bound E_{max}!

Requirements



Norman Ramsey
(1915-2011)

PHYSICAL REVIEW VOLUME 103, NUMBER 1 JULY 1, 1956

Thermodynamics and Statistical Mechanics at Negative Absolute Temperatures

Norman F. Ramsey*
Harvard University, Cambridge, Massachusetts, and Clarendon Laboratory, Oxford, England
(Received March 26, 1956)

As discussed in Sec. III below, the conditions for the existence of a system at negative temperatures are so restrictive that they are rarely met in practice except with some mutually interacting nuclear spin systems.

E.M. Purcell & R.V. Pound, Phys. Rev. **81**, 279 (1951)
N. Ramsey, Phys. Rev. **103**, 20 (1956)
M.J. Klein, Phys. Rev. **104**, 589 (1956)
P. Hakonen & O.V. Lounasmaa, Science, **265**, 1821(1994)

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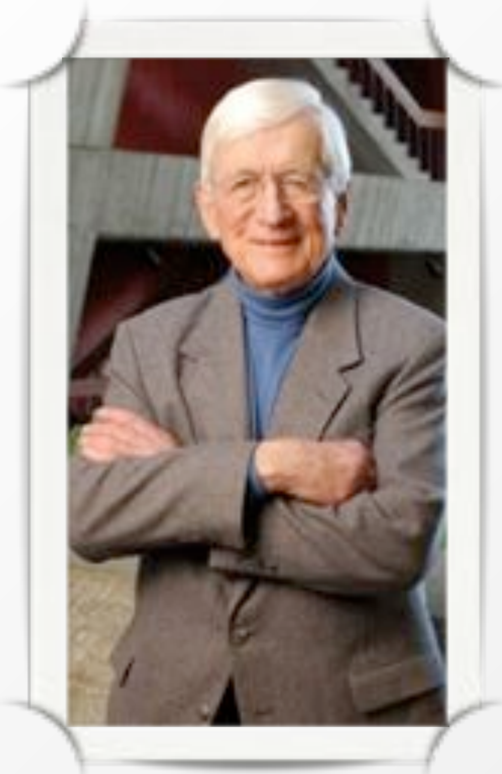

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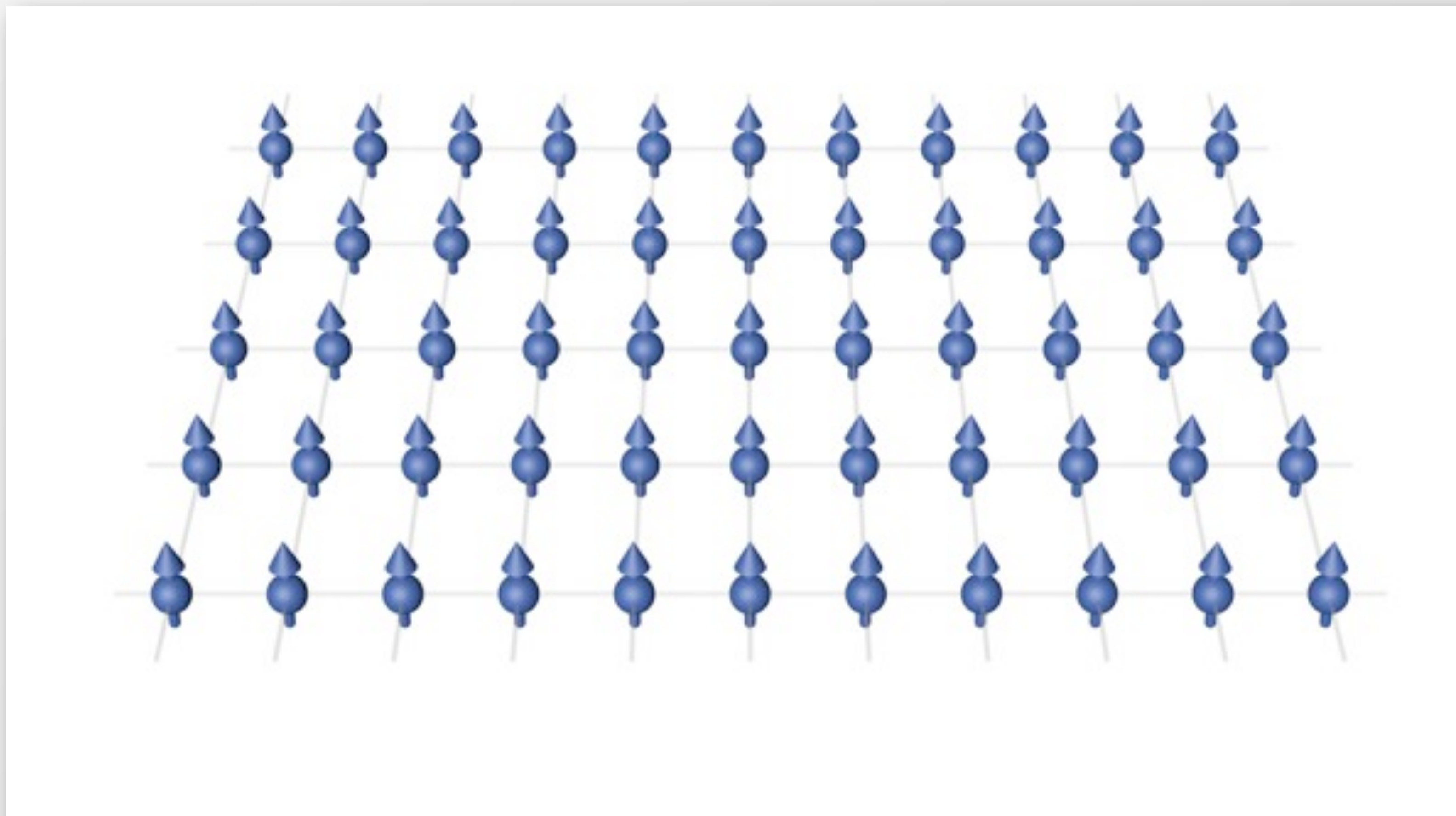

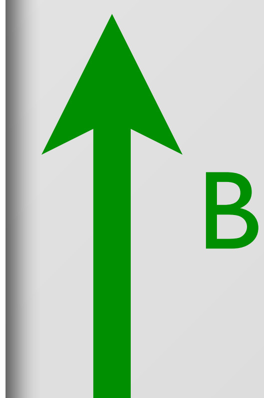

Lowest Energy State E_{min}

E.M. Purcell & R.V. Pound, Phys. Rev. **81**, 279 (1951)
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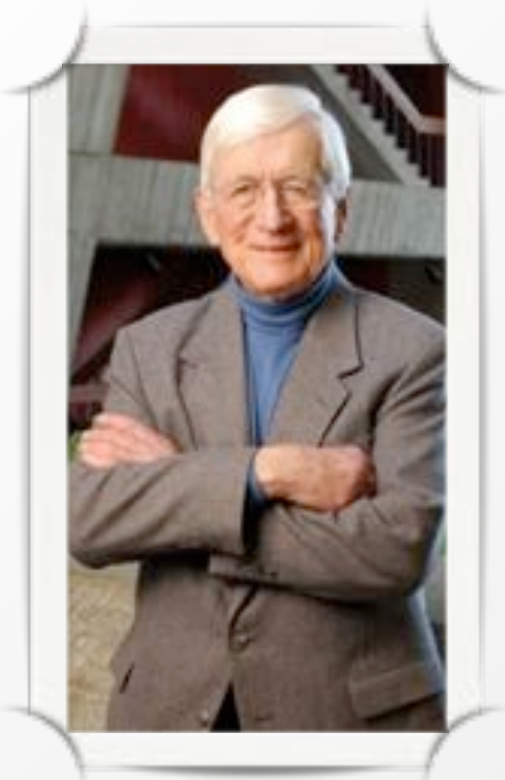

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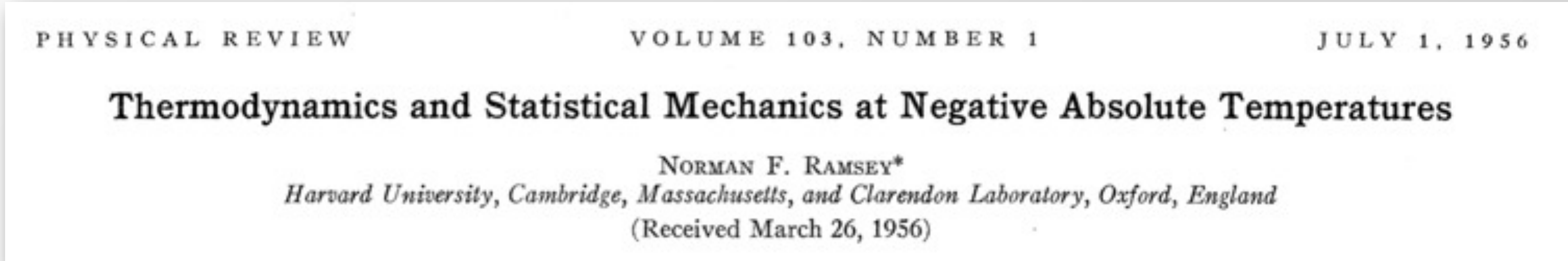

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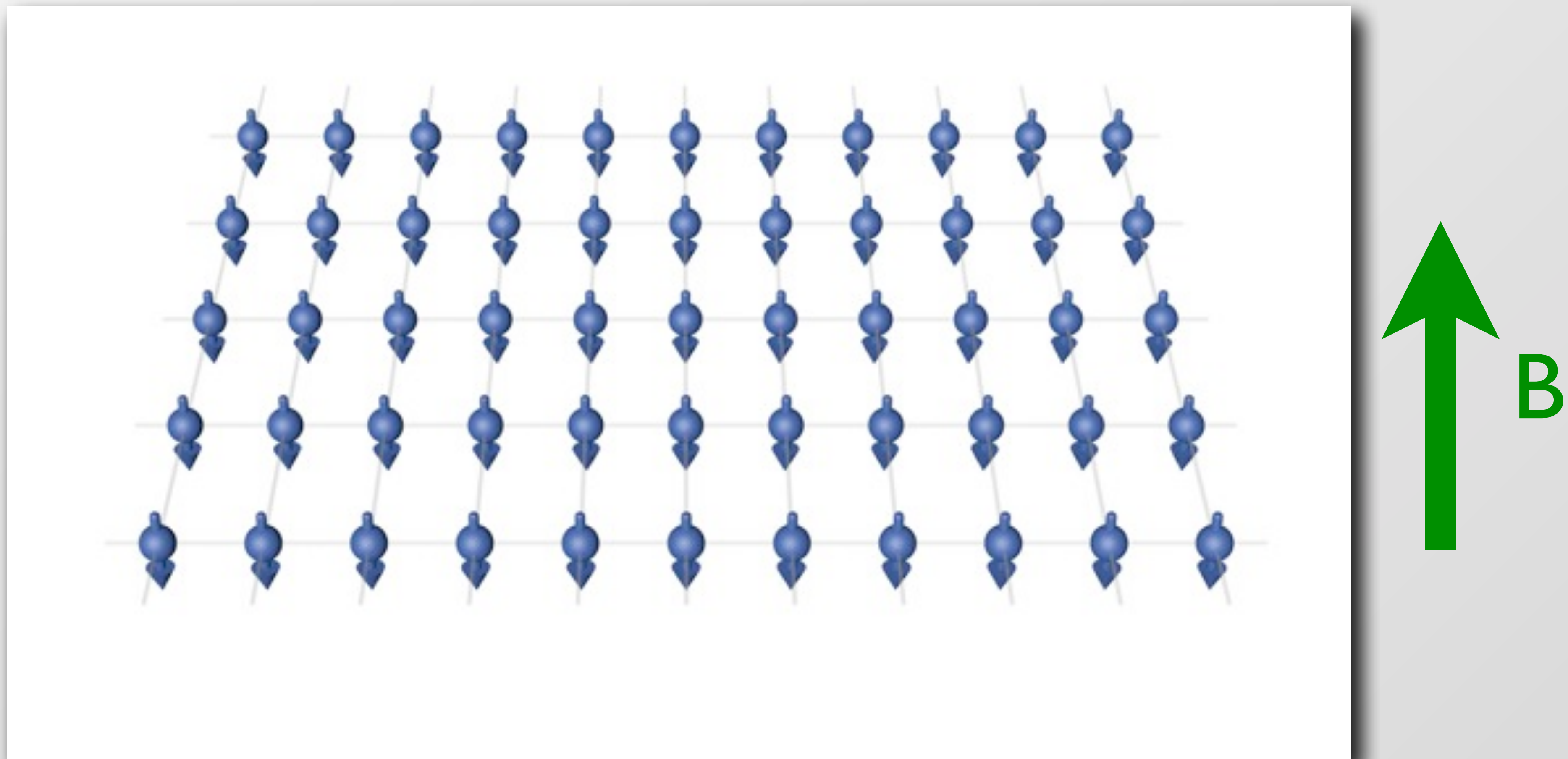

Highest Energy State E_{max}

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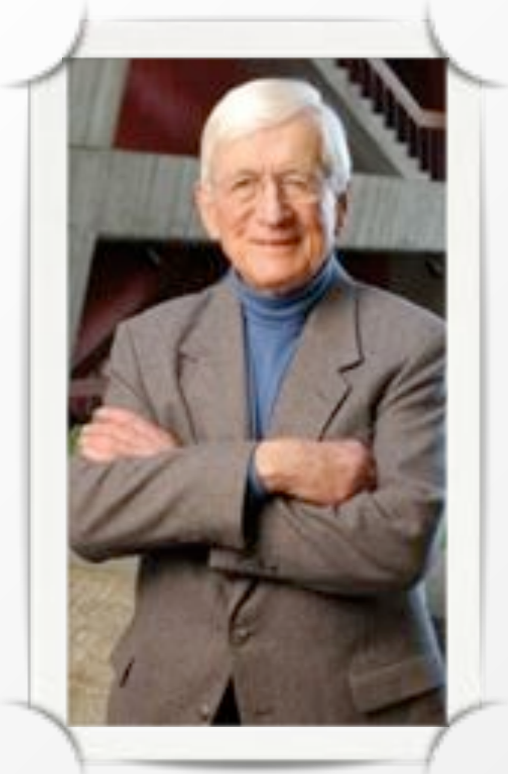

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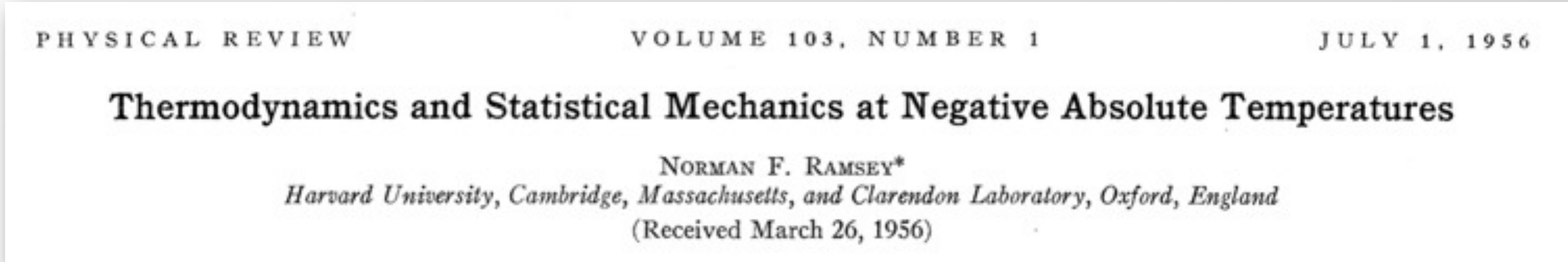

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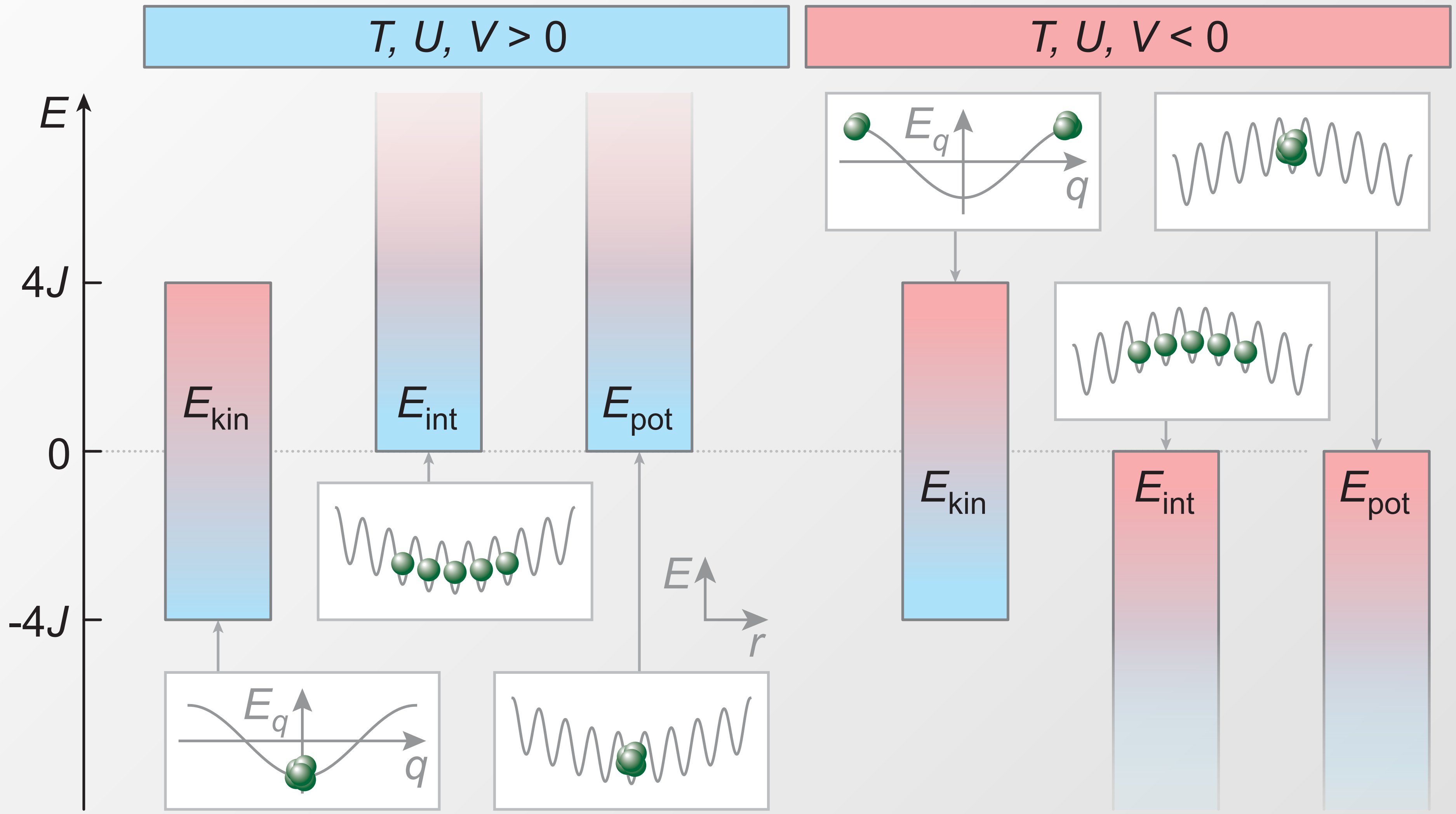
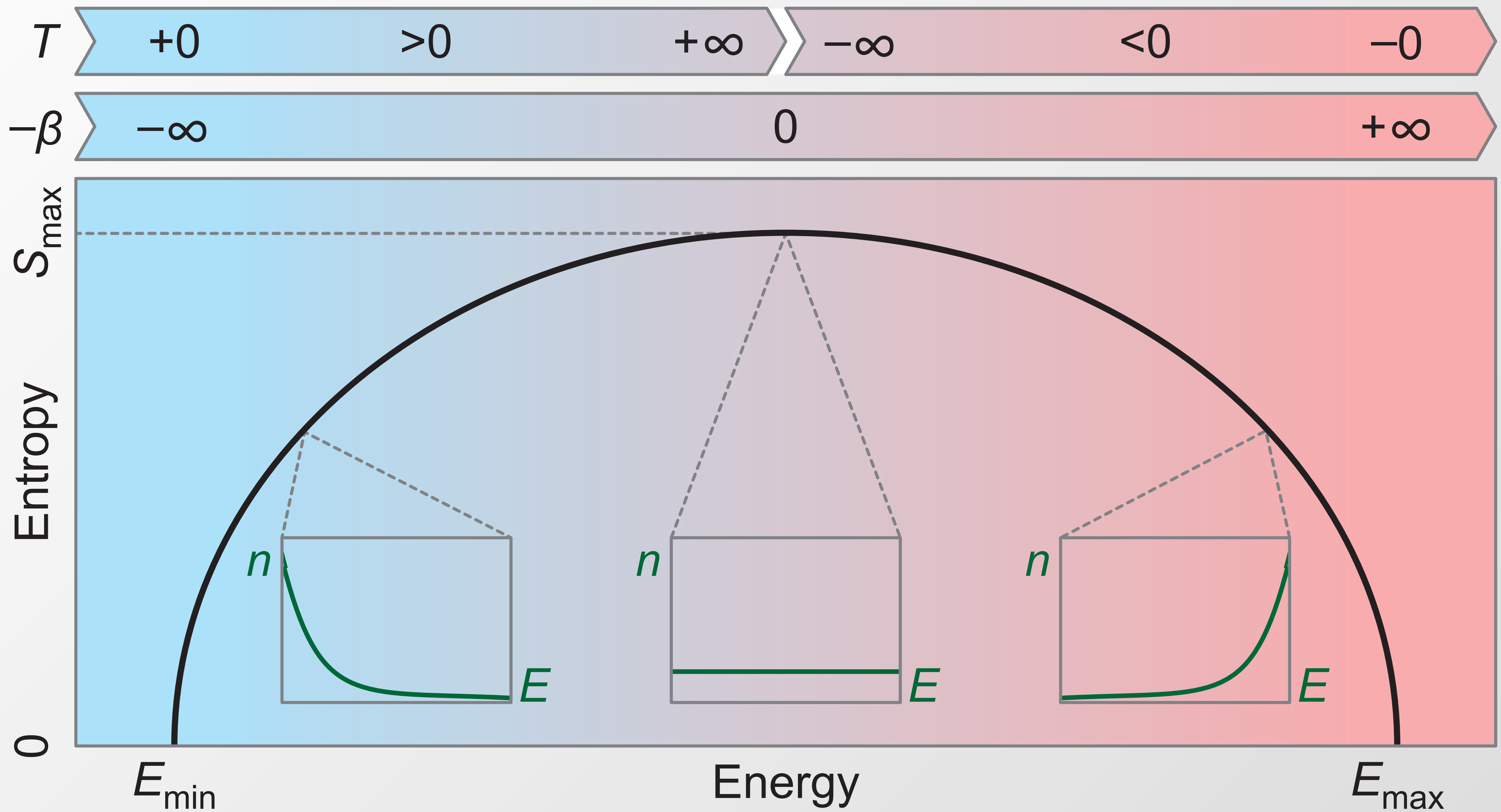
Energy Bounds of the BH Model

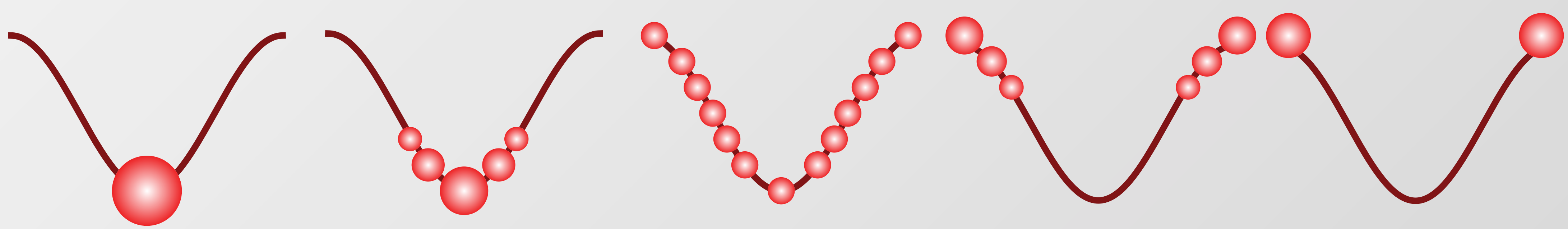


$$\hat{H} = -J \sum_{\langle i,j \rangle} \hat{a}_i^\dagger \hat{a}_j + \frac{U}{2} \sum_i \hat{n}_i \left(\hat{n}_i - 1\right) + V \sum_i \mathbf{R}_i^2 \hat{n}_i$$

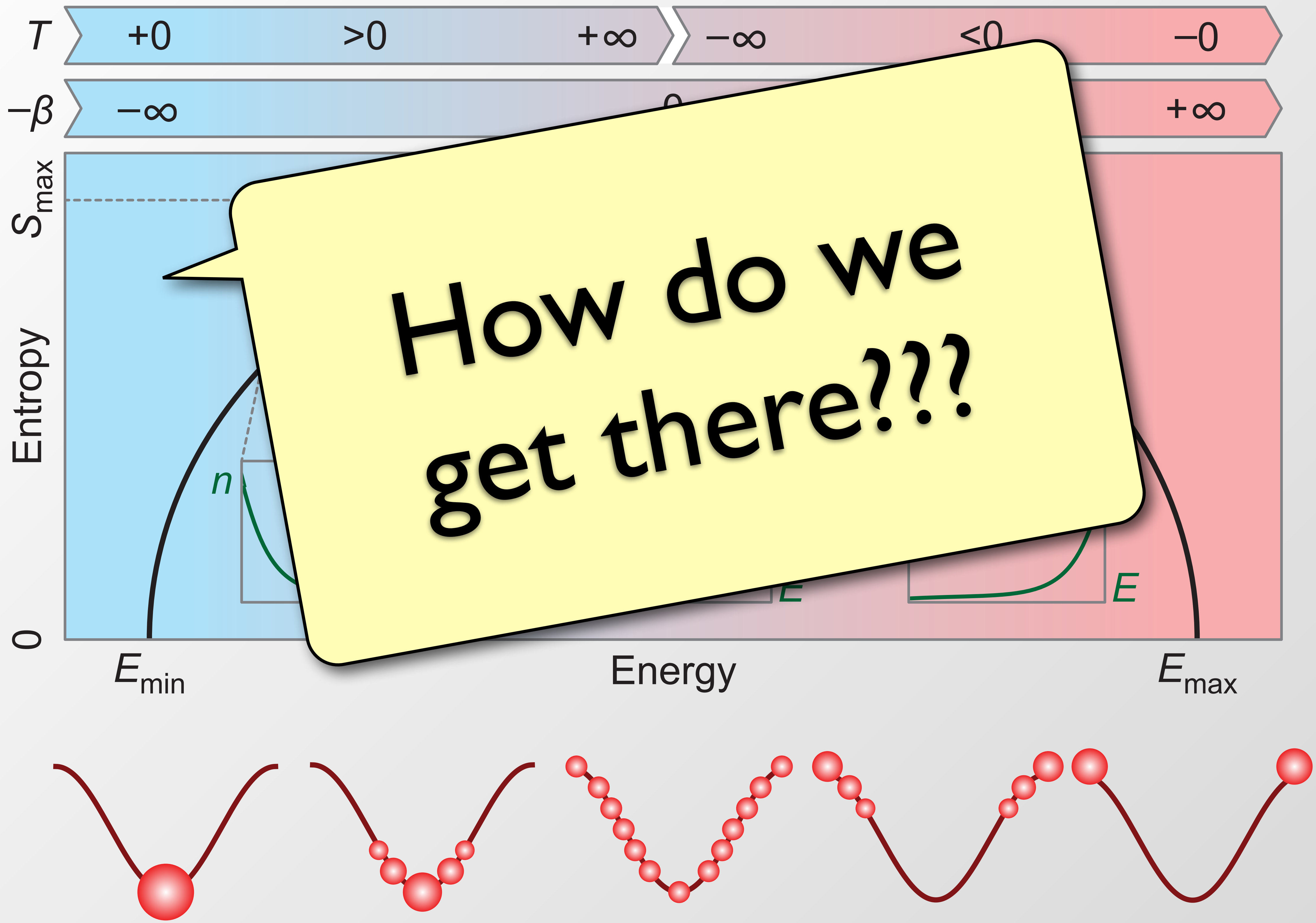
U,V < 0 required for upper energy bound!

Entropy vs Energy



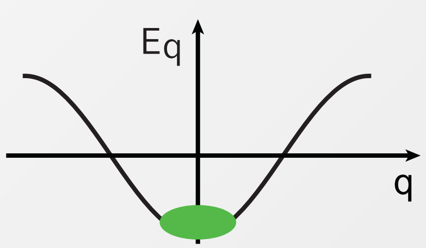


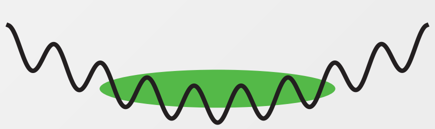
Entropy vs Energy



Experimental Sequence

Superfluid





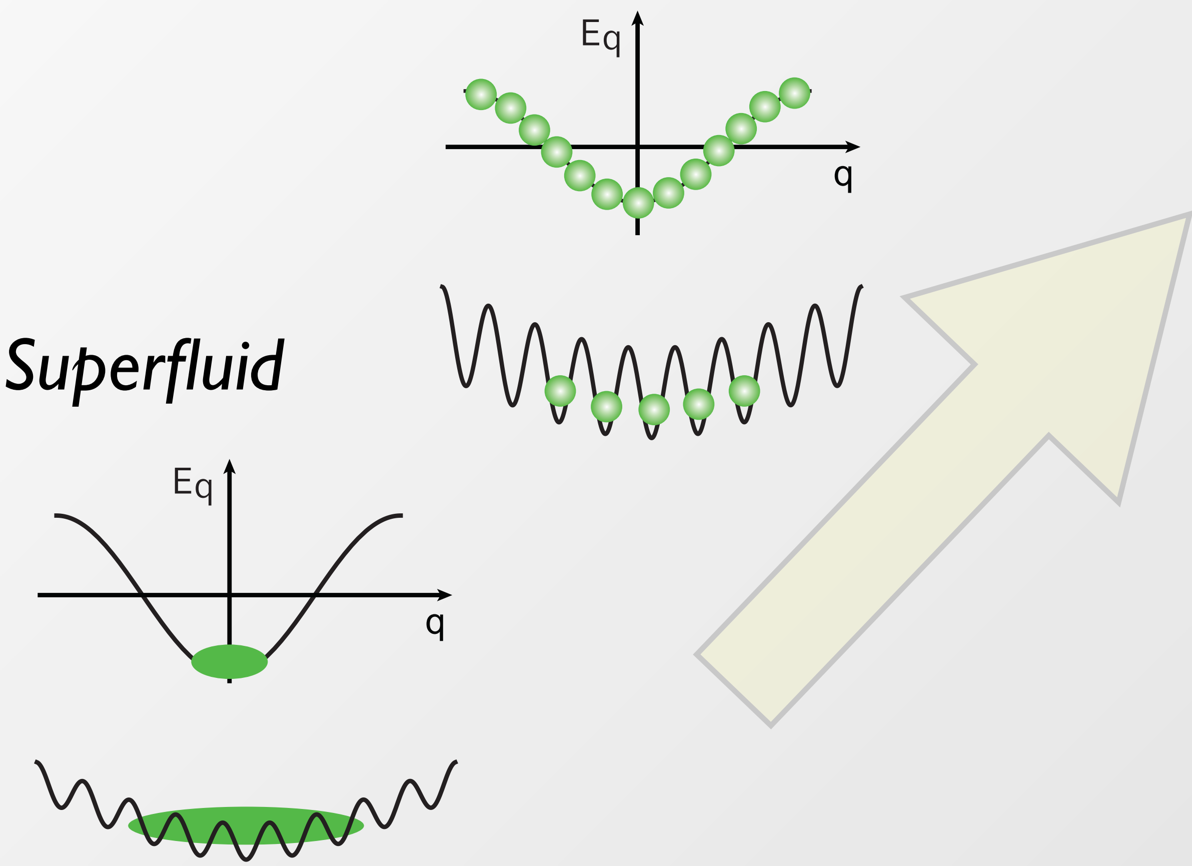
T,U,V >0

Sequence: A. Rapp, S. Mandt & A. Rosch, PRL (2010)

Experimental Sequence

Mott Insulator

Superfluid



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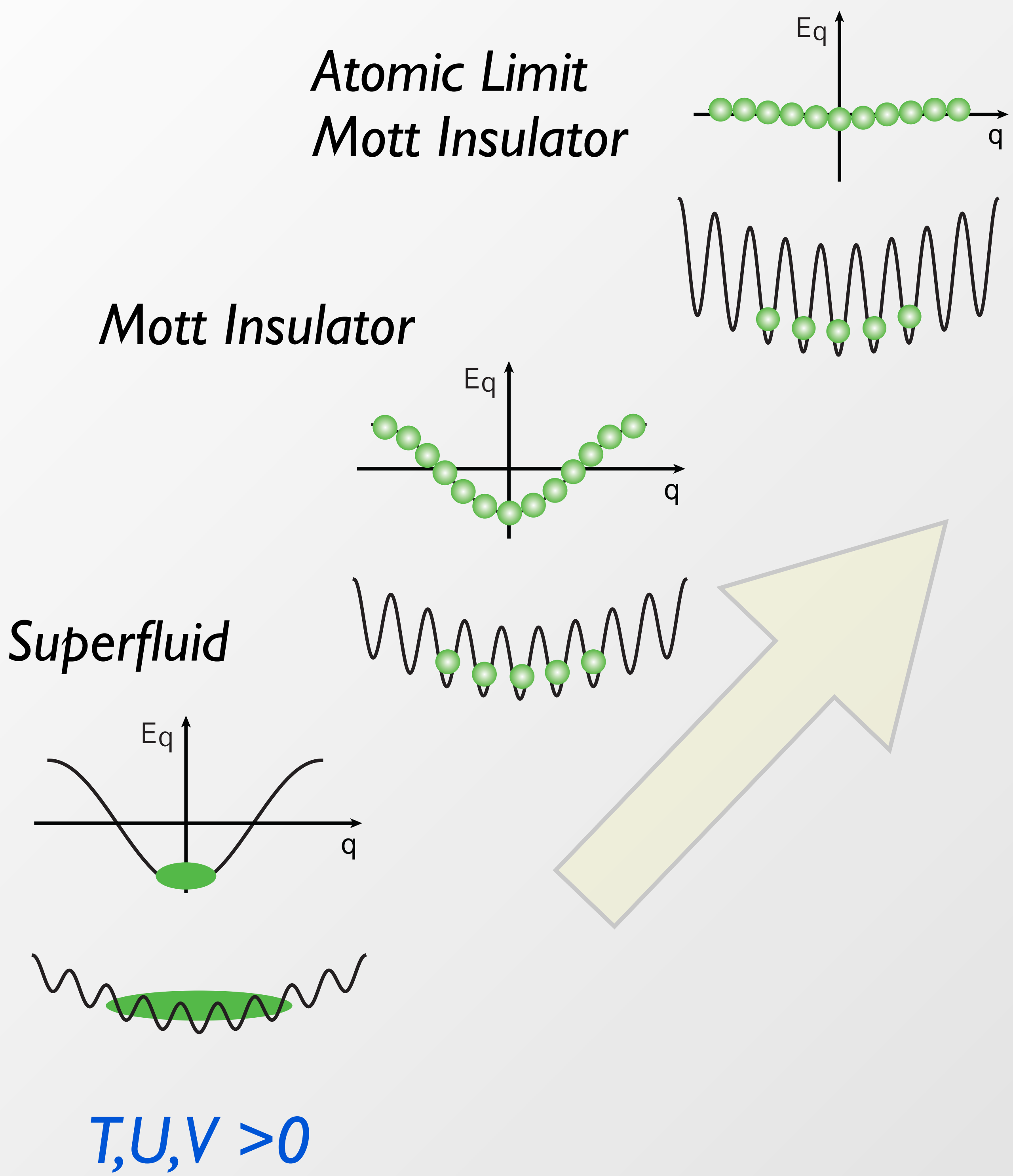
Experimental Sequence



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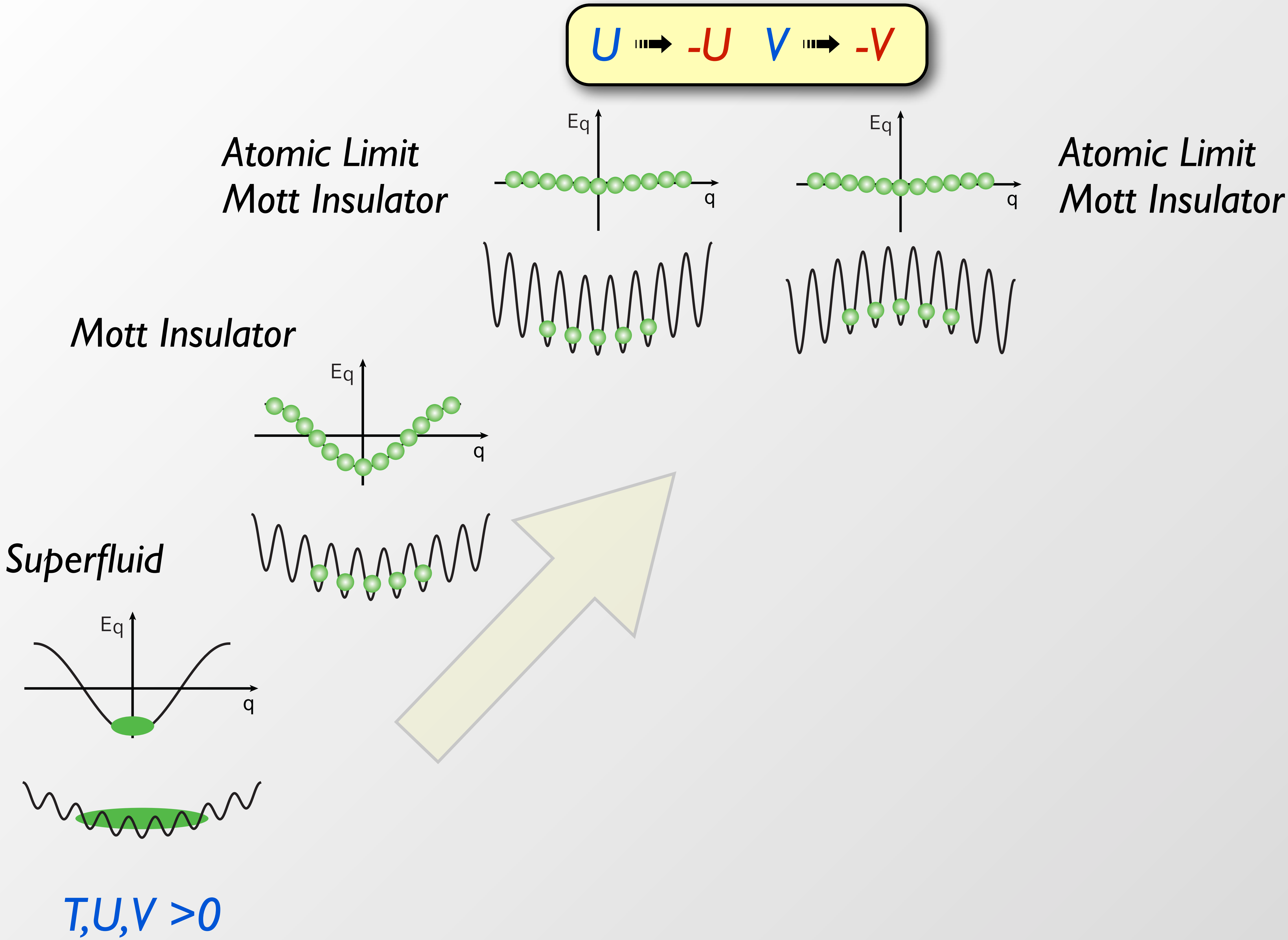

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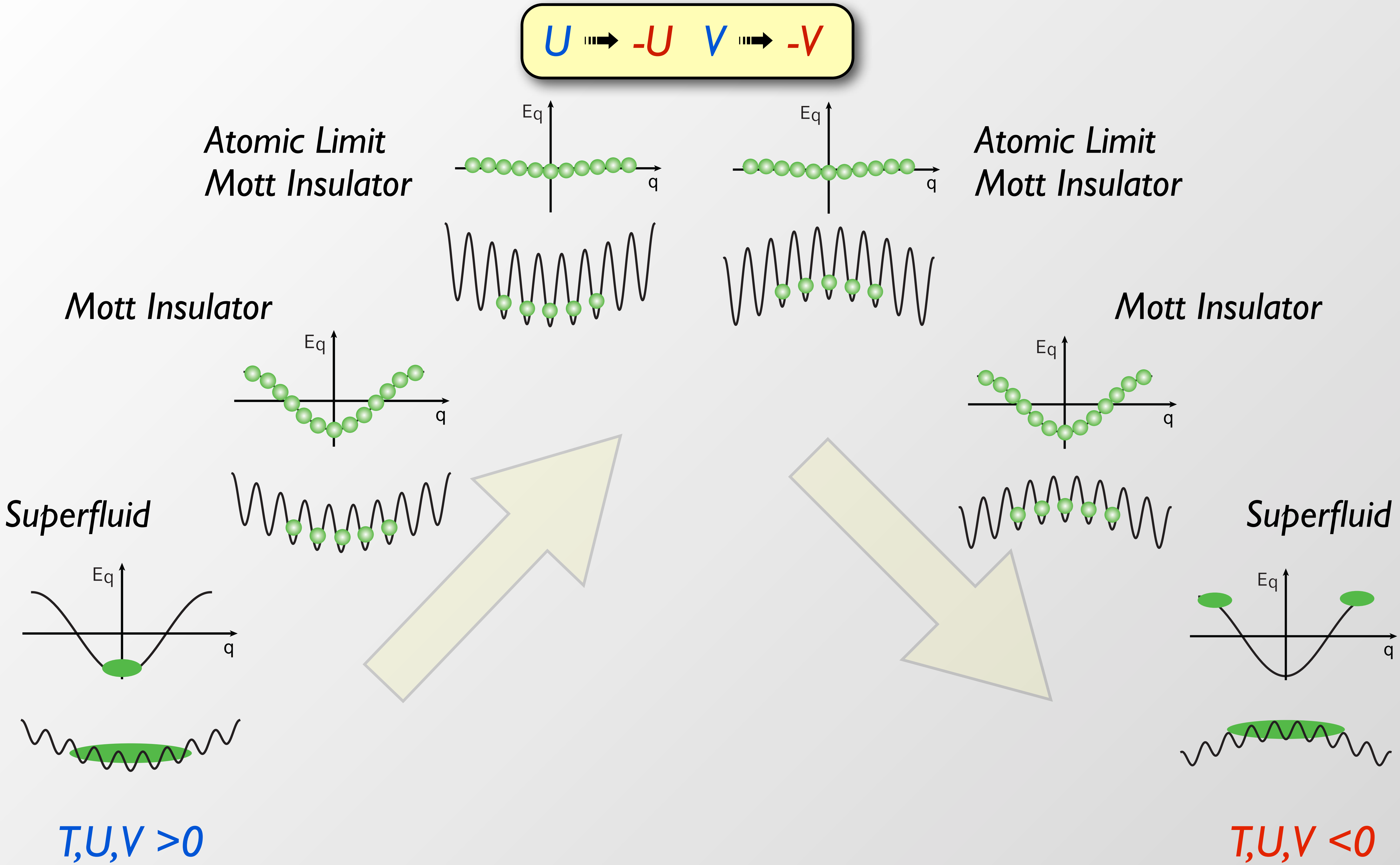

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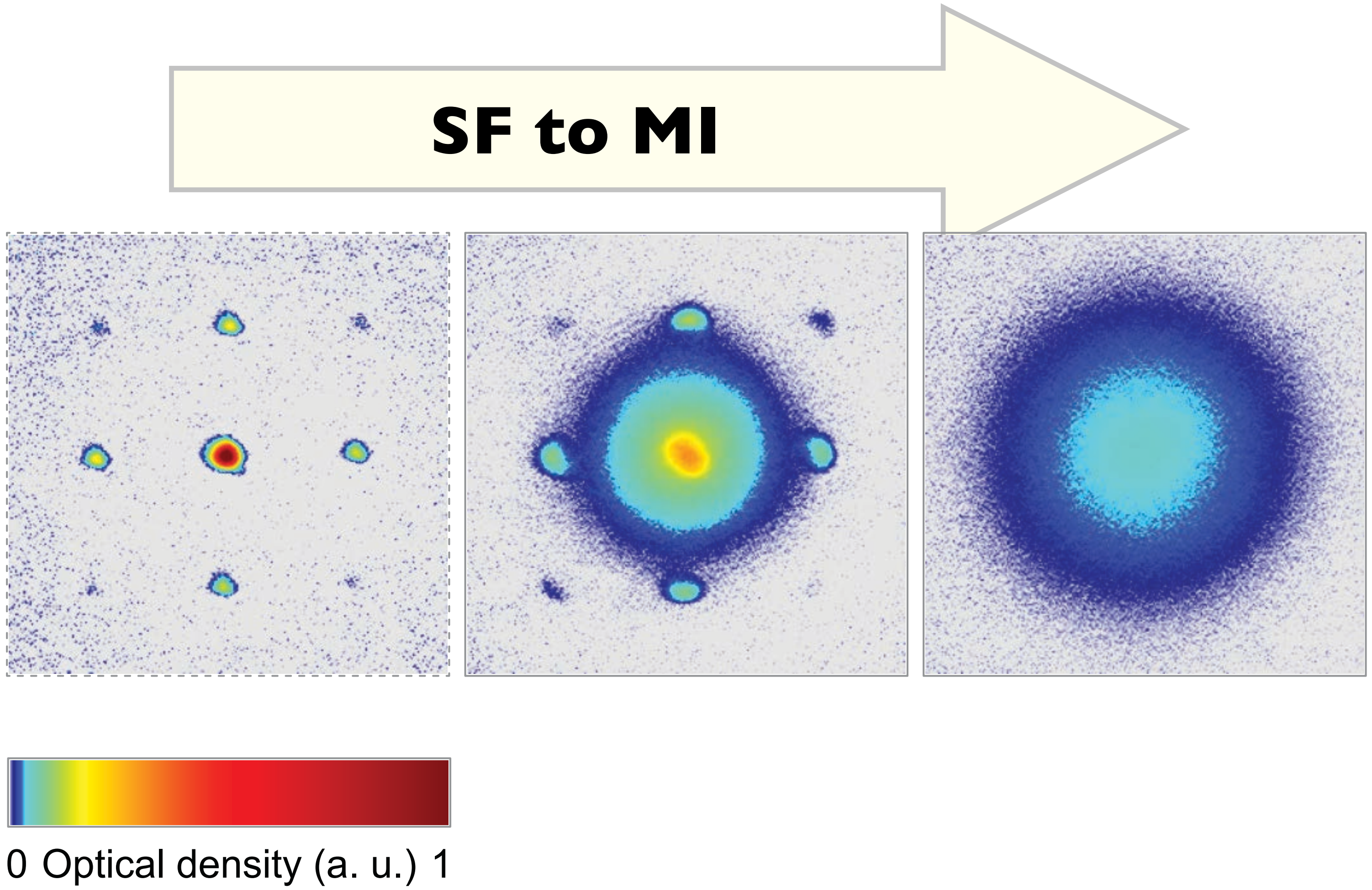
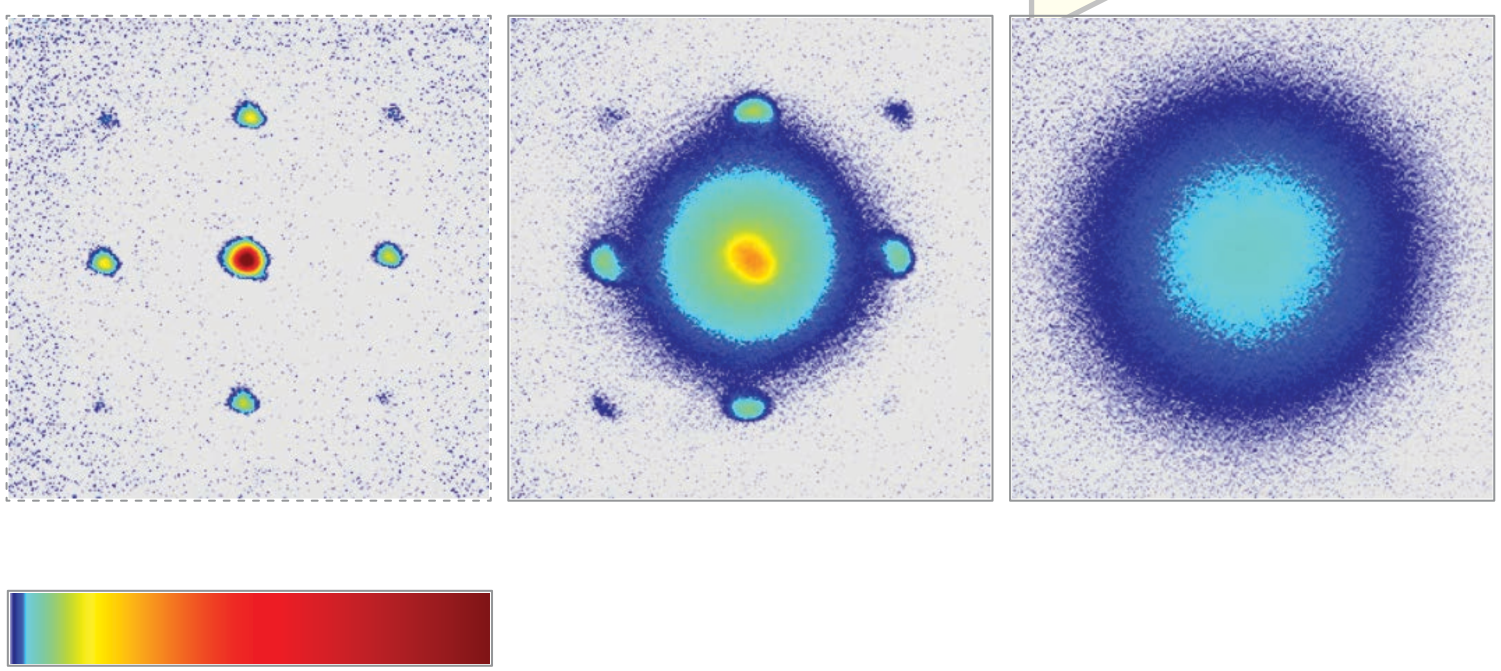
Experimental Results

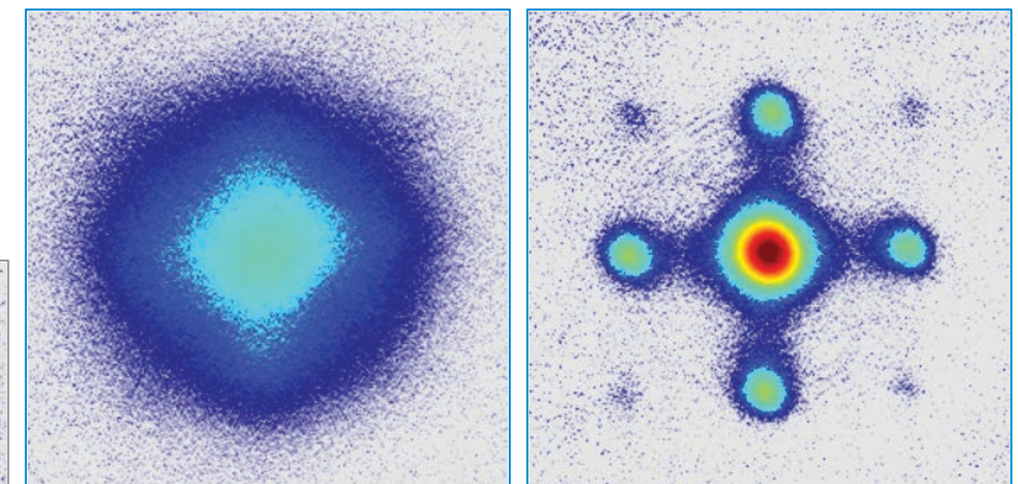


Experimental Results

SF to MI



Positive Temperature w/o switching



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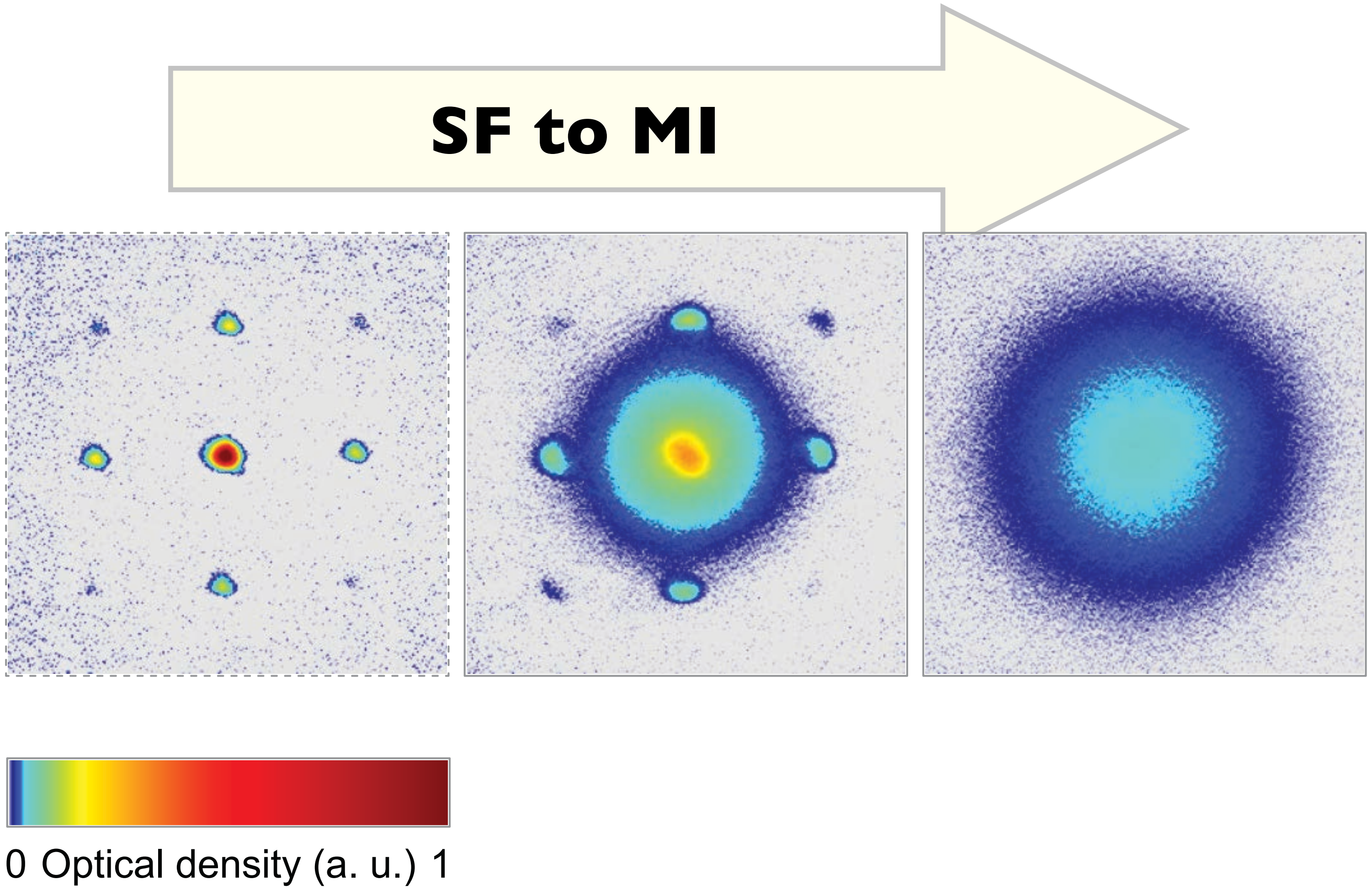

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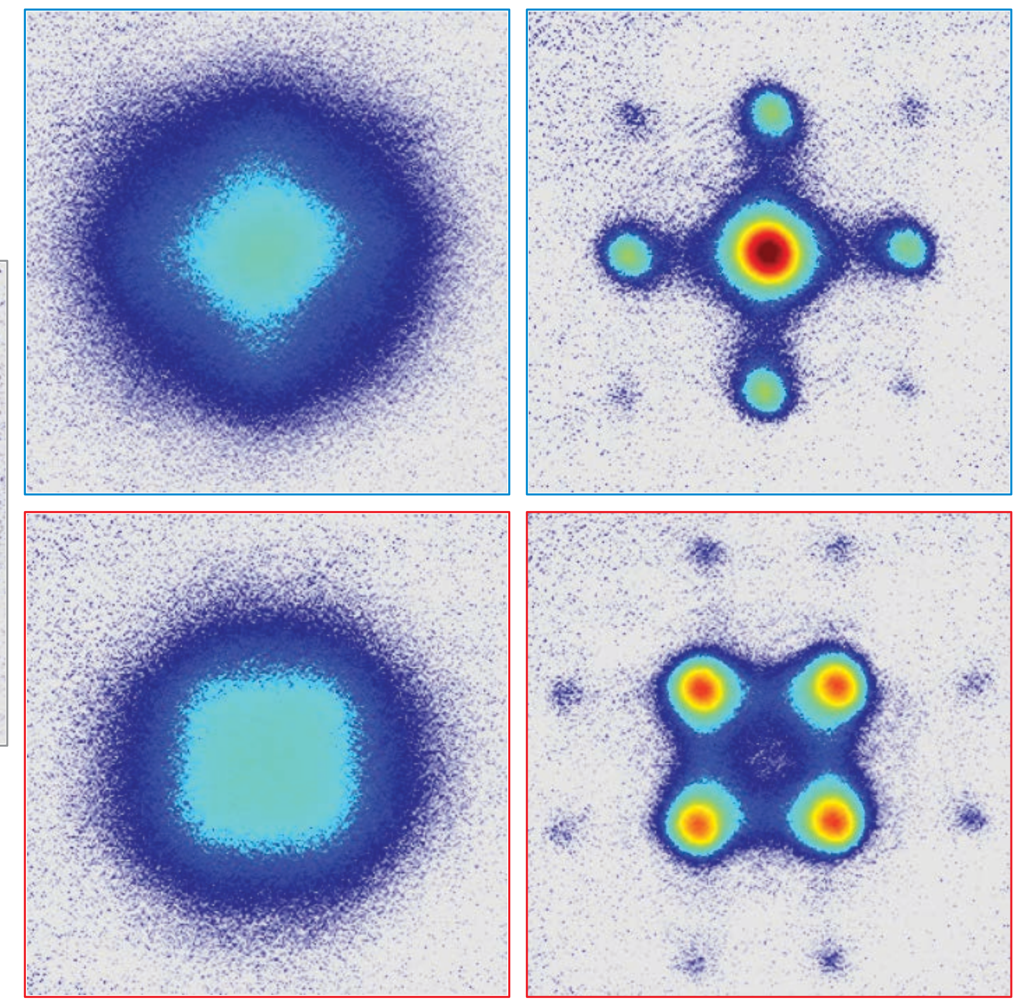
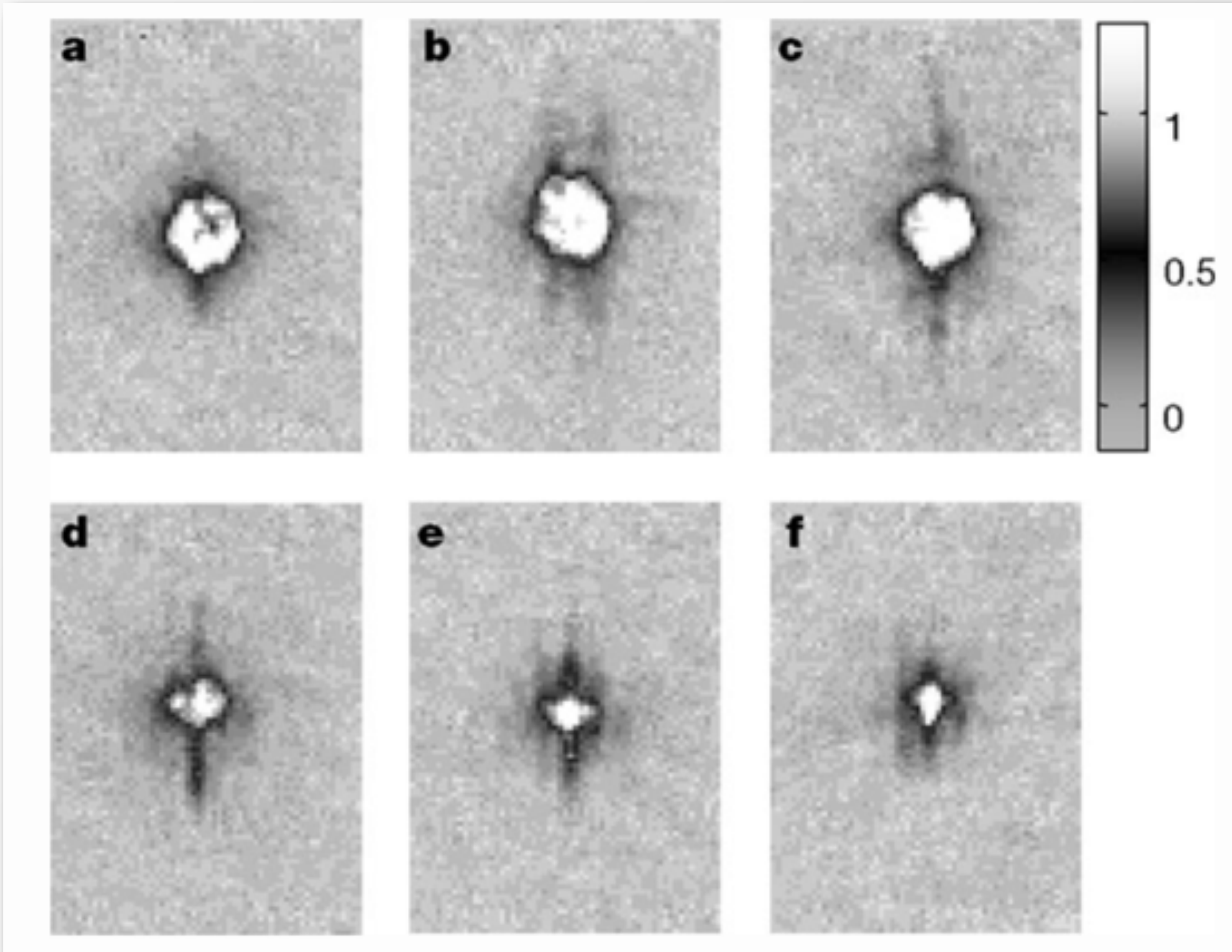


Negative Temperature w switching

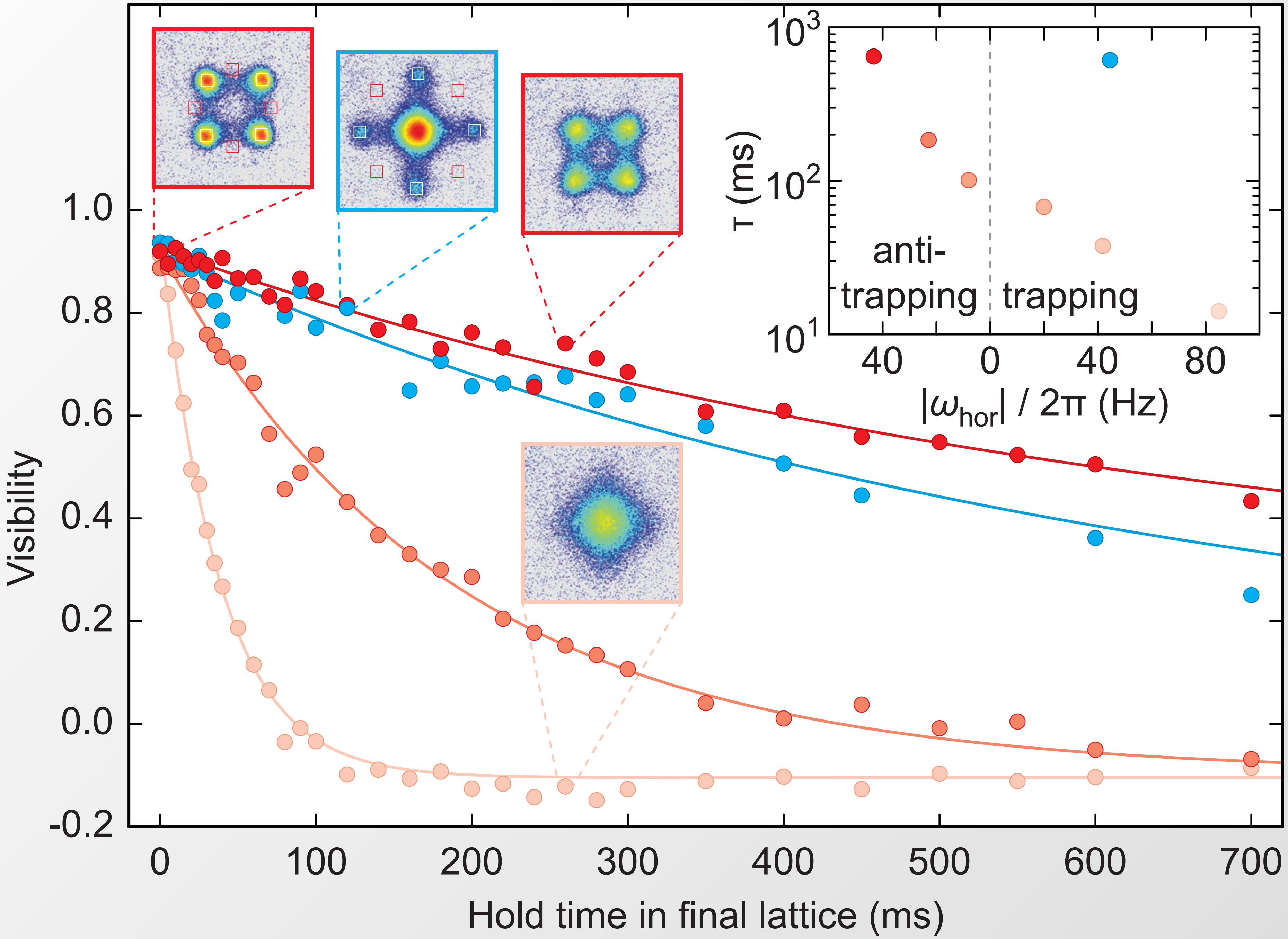
Collapse of Condensate

For attractive interactions (a<0), condensate collapses!



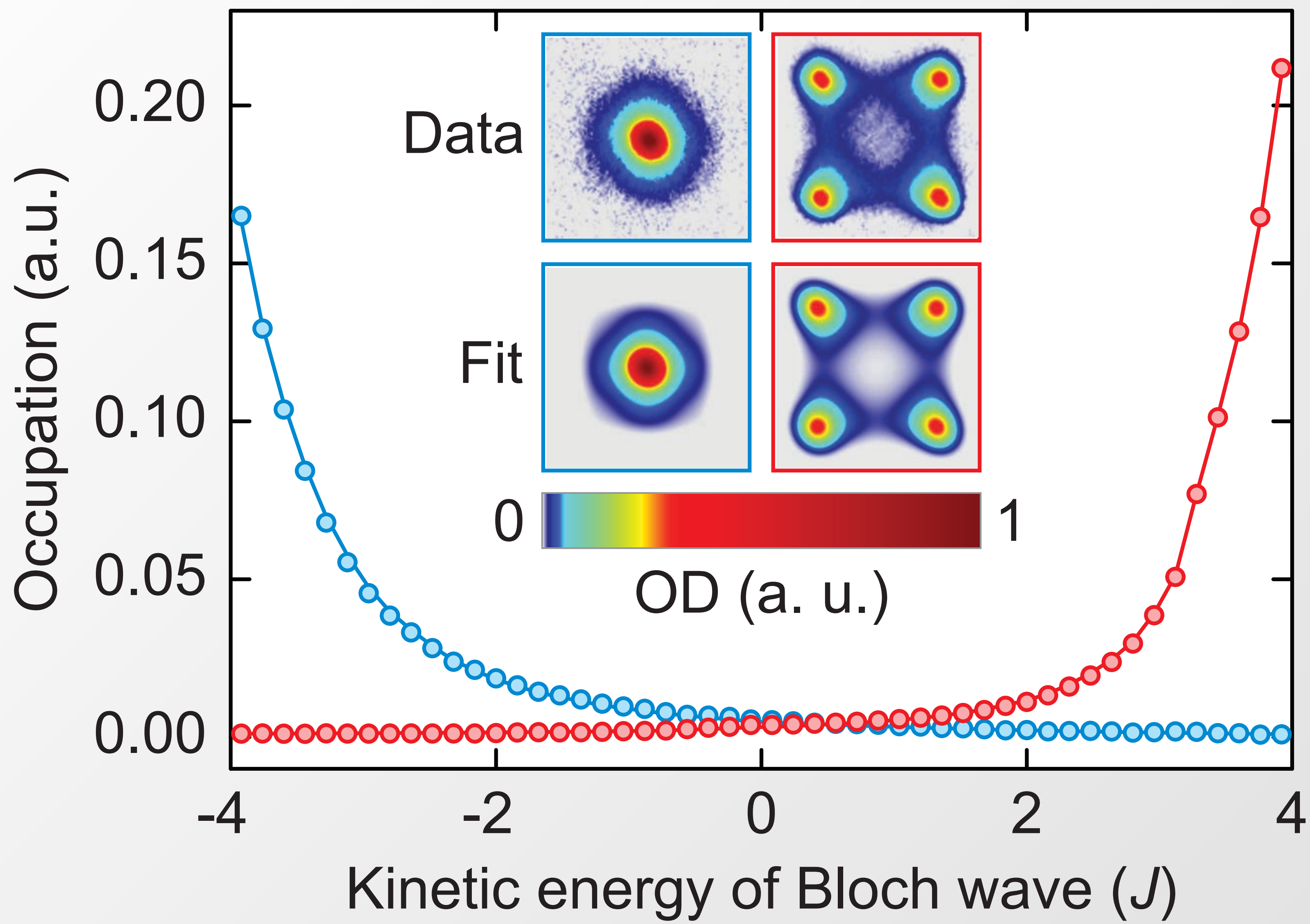
E.A. Donley et al. *Nature* **412,** 295-299 (2001)
J. M. Gerton et al. *Nature* 408, 692 (2000)

Stability



Negative Temperature State as Stable as Positive Temperature State!

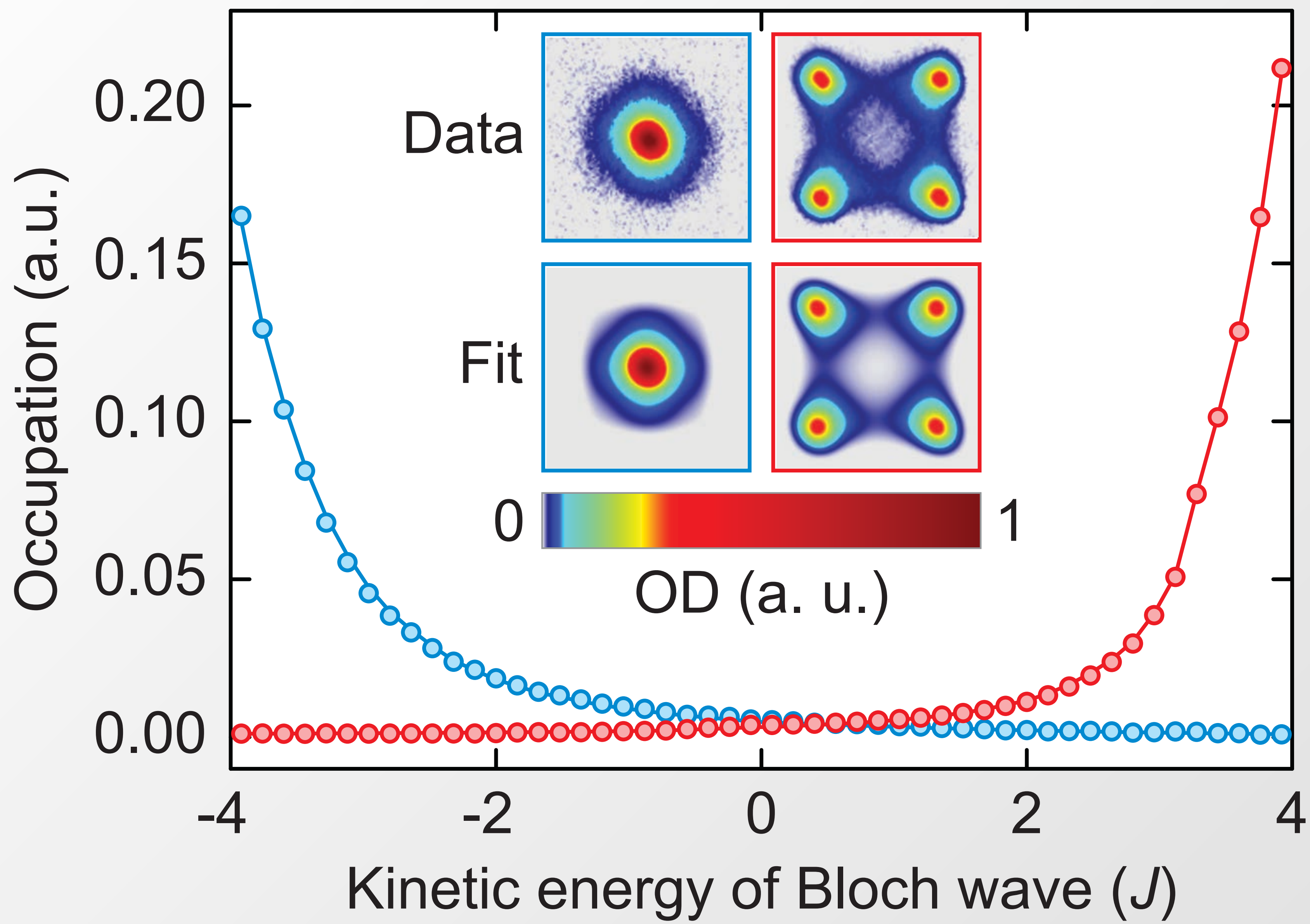
Occupation of Energy States



$$n(q_x, q_y) = \frac{1}{e^{(E_{kin}(q_x, q_y) - \mu)/k_B T} - 1}$$

$$E_{kin}(q_x, q_y) = -2J\,[\cos(q_x d) + \cos(q_y d)]$$

Occupation of Energy States



T=-2.2J/k$_B$

$$n(q_x, q_y) = \frac{1}{e^{(E_{kin}(q_x,q_y)-\mu)/k_B T} - 1}$$

$$E_{kin}(q_x, q_y) = -2J\left[\cos(q_x d) + \cos(q_y d)\right]$$

Implications

Gases with **negative temperature** possess **negative pressure**!

$$\left.\frac{\partial S}{\partial V}\right|_E \geq 0 \qquad \text{and} \qquad dE = TdS - PdV$$

$$\Rightarrow \quad \left.\frac{\partial S}{\partial V}\right|_E = \frac{P}{T} \geq 0$$

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Carnot engines **above unit efficieny!**

$$\eta = \frac{W}{Q_1} = 1 - \frac{T_2}{T_1}$$

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Some statements for the second law of thermodynamics become invalid!

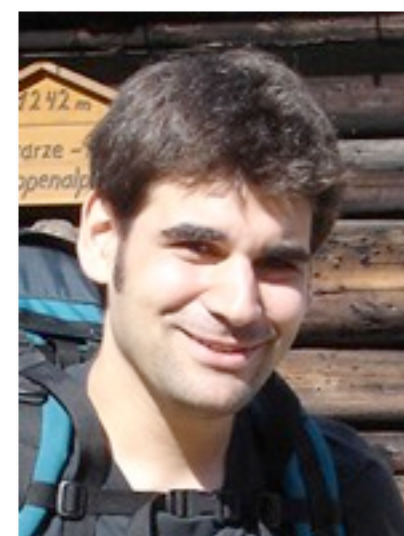
Negative Temperature Team

Simon Braun

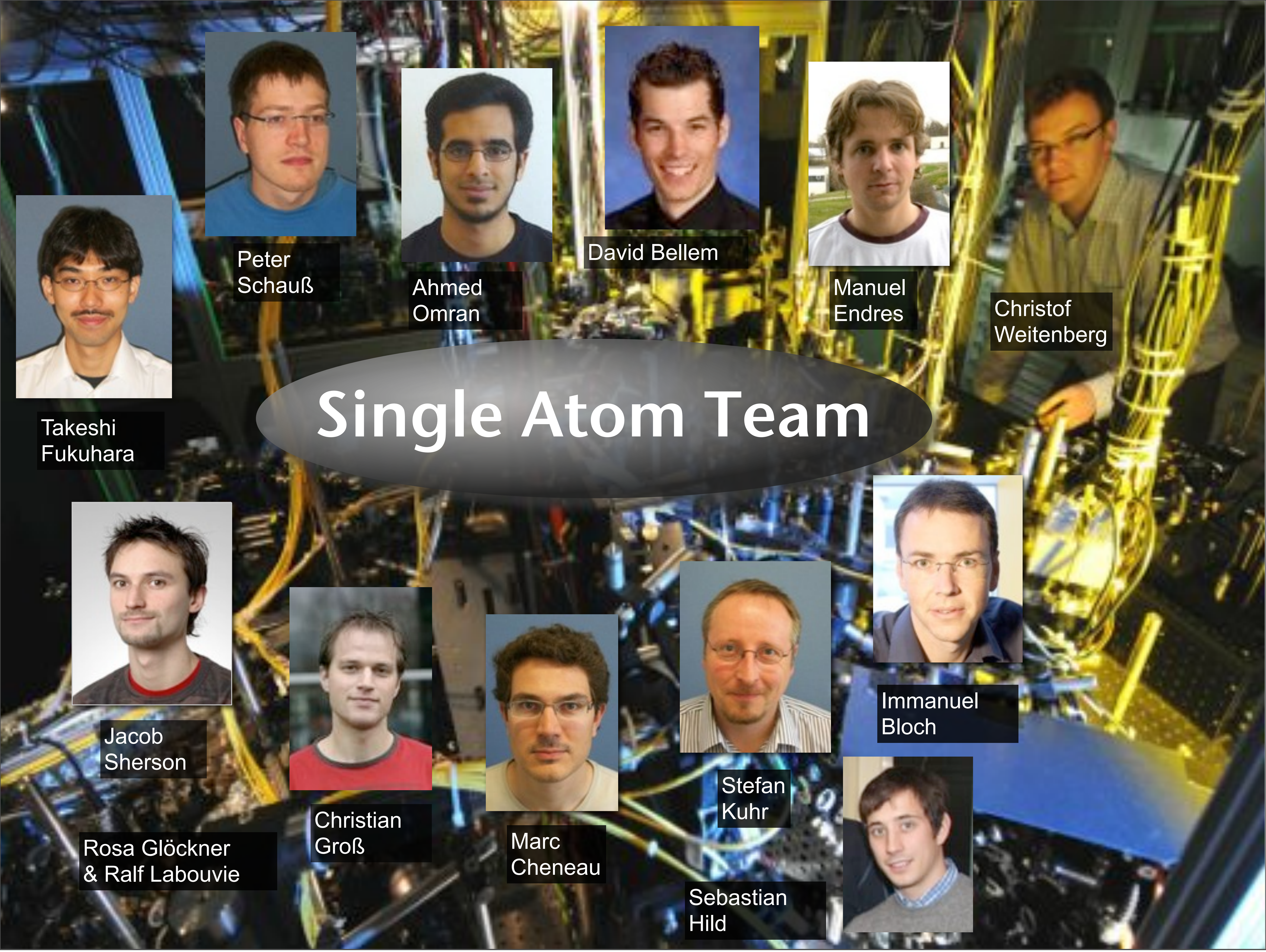
Sean Hodgman

Philipp Ronzheimer

Michael Schreiber



Ulrich Schneider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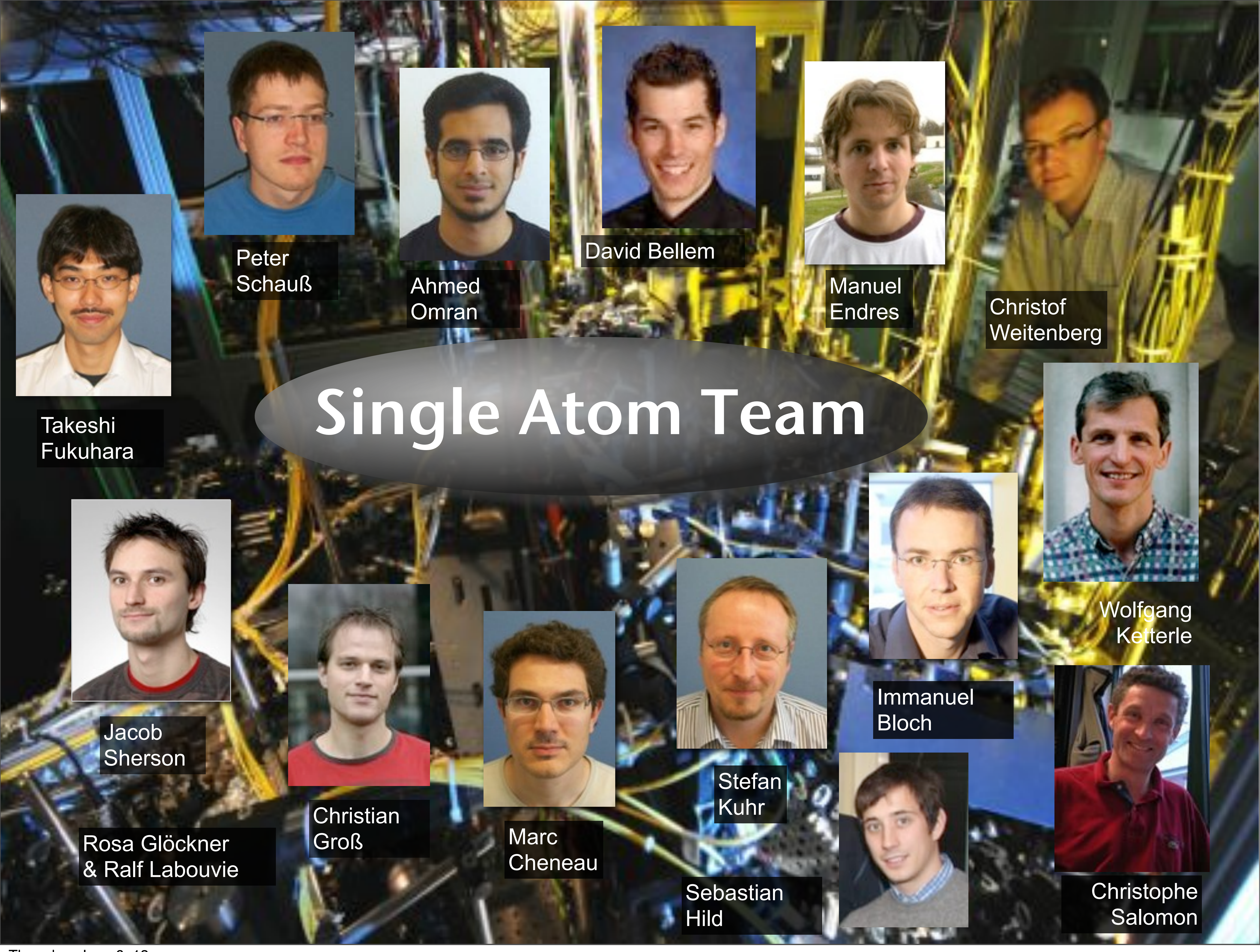
Christof Weitenberg
Takeshi Fukuhara
Jacob Sherson
Christian Groß
Marc Cheneau
Stefan Kuhr
Immanuel Bloch
Sebastian Hild
Rosa Glöckner & Ralf Labouvie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Thank you for your attention!

www.quantum-munich.de