Title: Solitons and Spin-Charge Correlations in Strongly Interacting Fermi Gases

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Abstract: Ultracold atomic Fermi gases near Feshbach resonances or in optical lattices realize paradigmatic, strongly interacting forms of fermionic matter. Topological excitations and spin-charge correlations can be directly imaged in real time. In resonant fermionic superfluids, we observe the cascade of solitonic excitations following a pi phase imprint. A planar soliton decays, via the snake instability, into vortex rings and long-lived solitonic vortices.

For fermions in optical lattices, realizing the Fermi-Hubbard model, we detect charge and antiferromagnetic spin correlations with single-site resolution. At low fillings, the Pauli and correlation hole is directly revealed. In the Mott insulating state, we observe strong doublon-hole correlations, which should play an important role for transport.

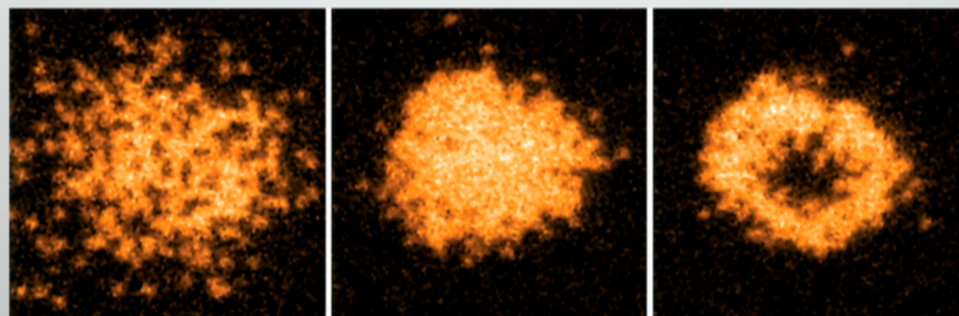
Perimeter Institute, 8/22/2016

Solitons and spin-charge correlations in strongly interacting Fermi gases

Martin Zwierlein

Massachusetts Institute of Technology

Center for Ultracold Atoms

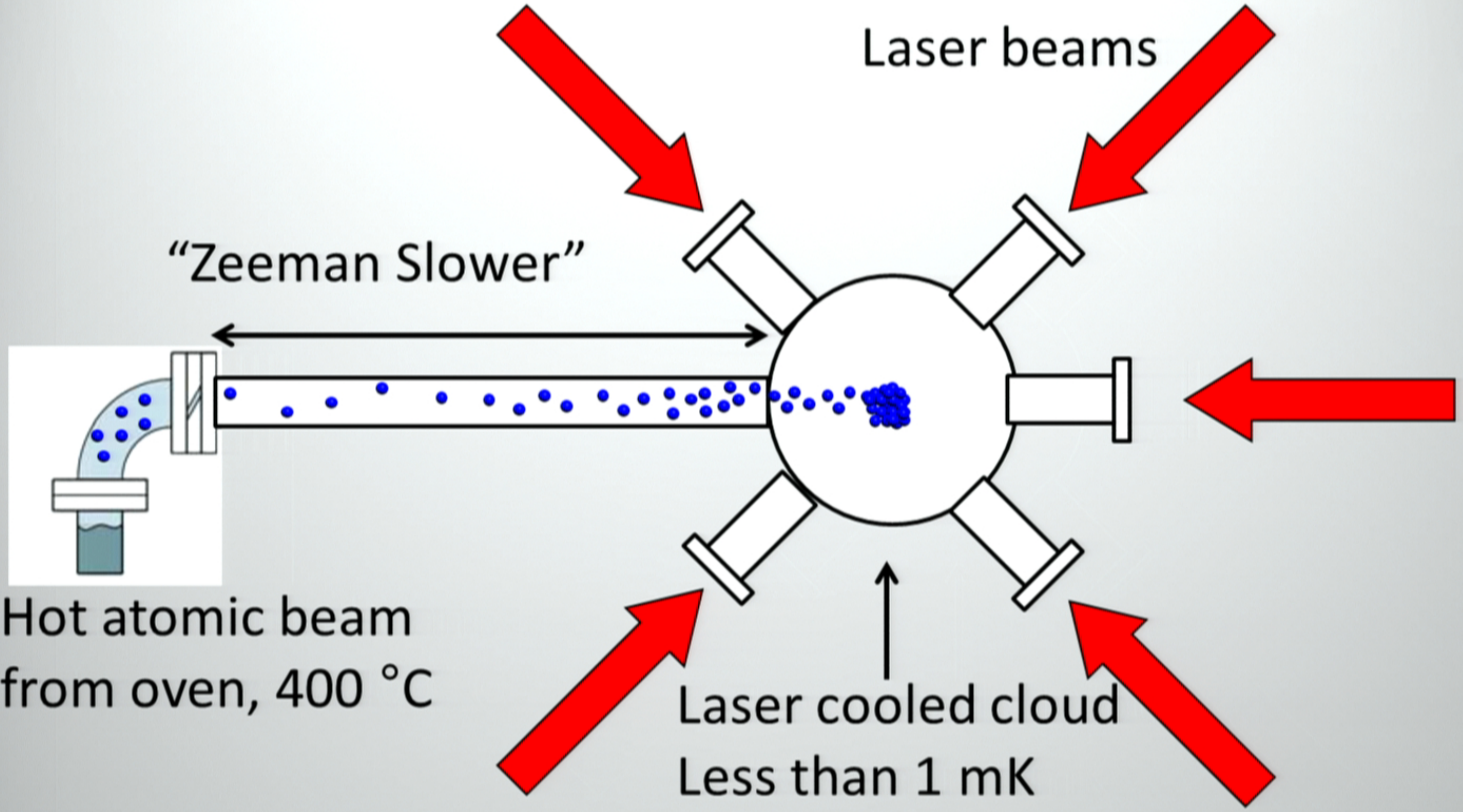


The cooling methods

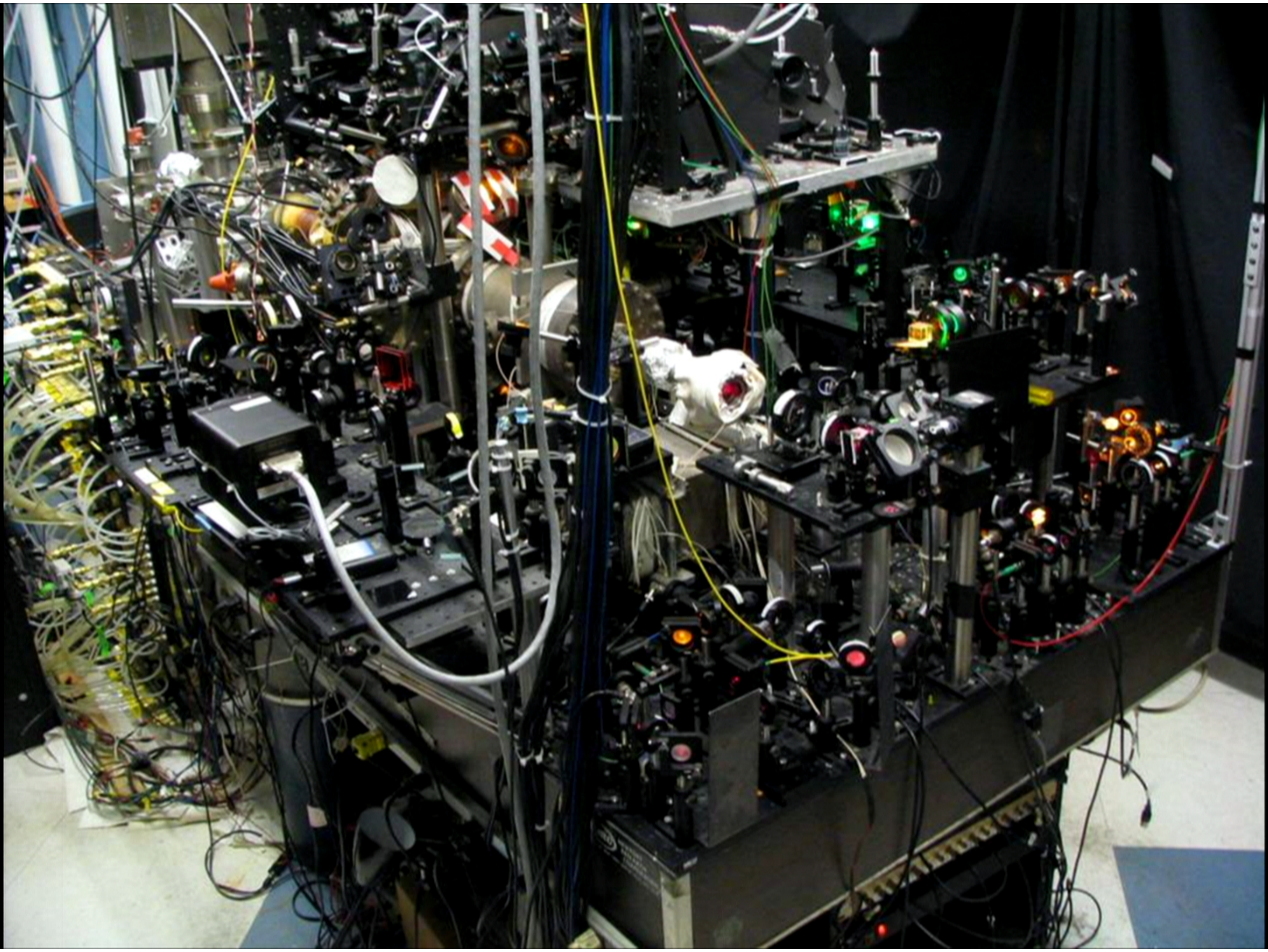
- Laser Cooling → ~ 1 mK

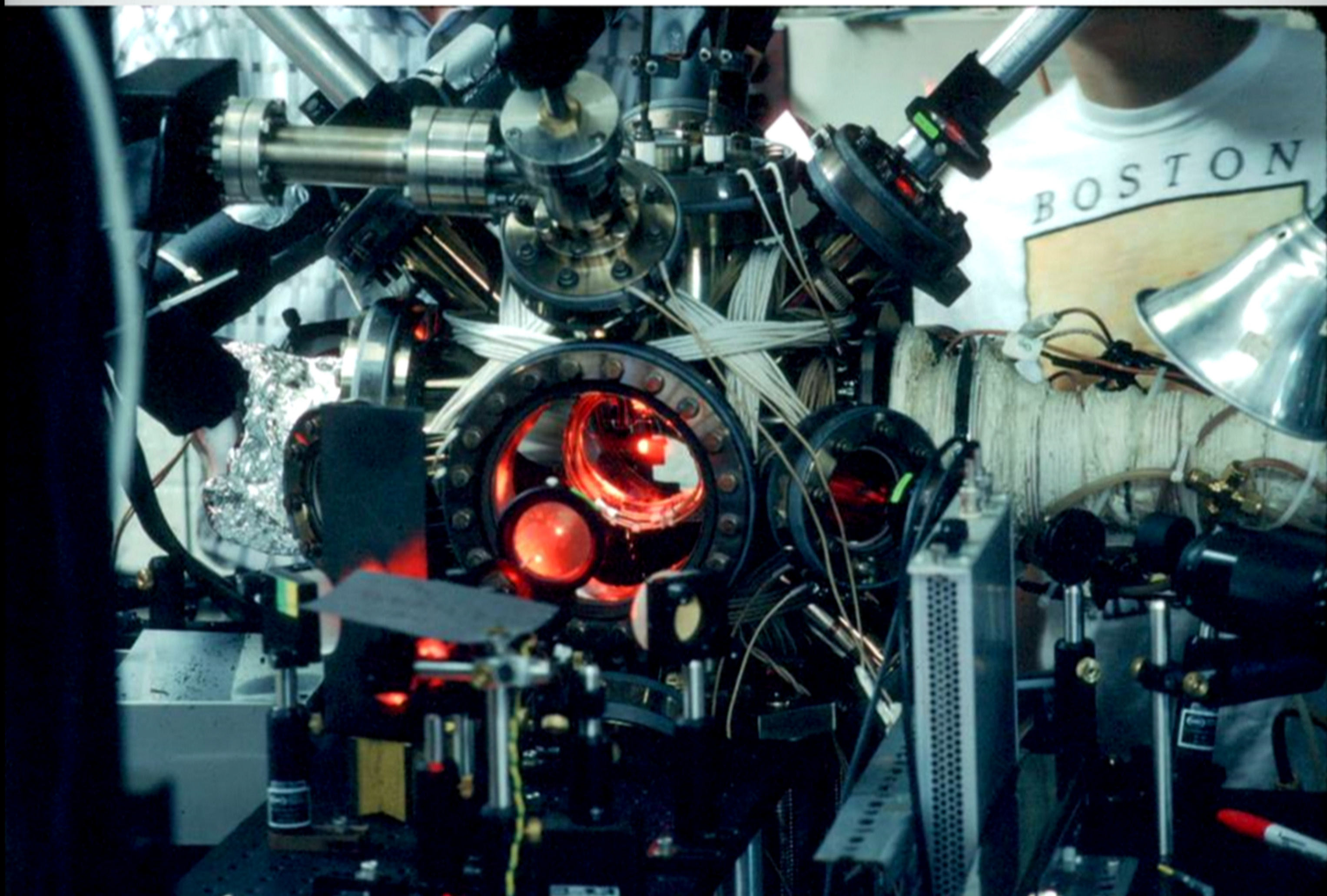
- Evaporative Cooling → ~ 10 nK

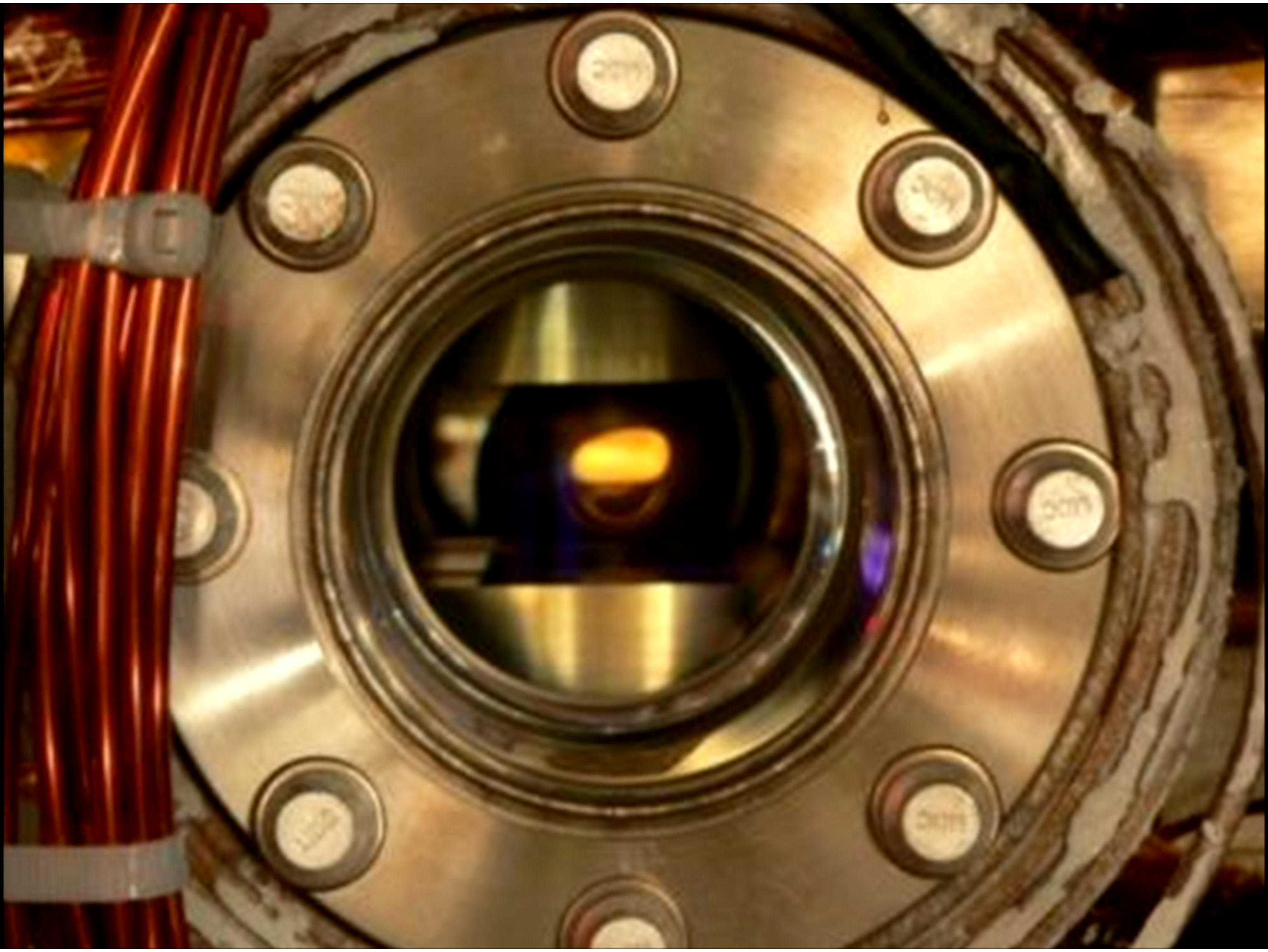
Laser Cooling



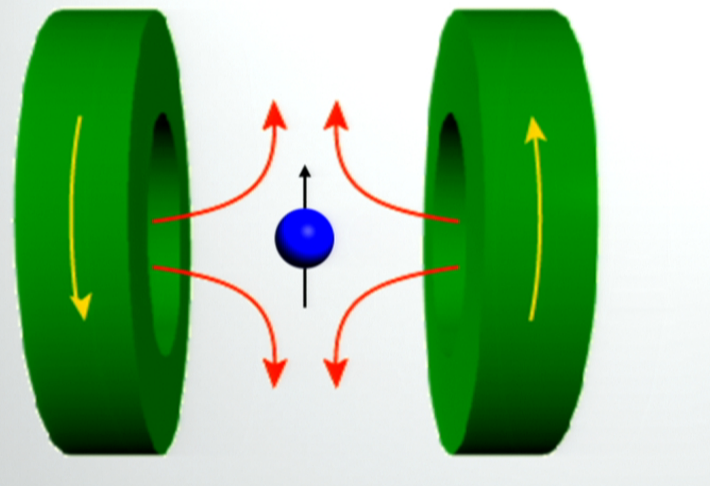
Chu, Cohen-Tannoudji, Phillips, Pritchard, Ashkin, Lethokov, Hänsch, Schawlow, Wineland ...

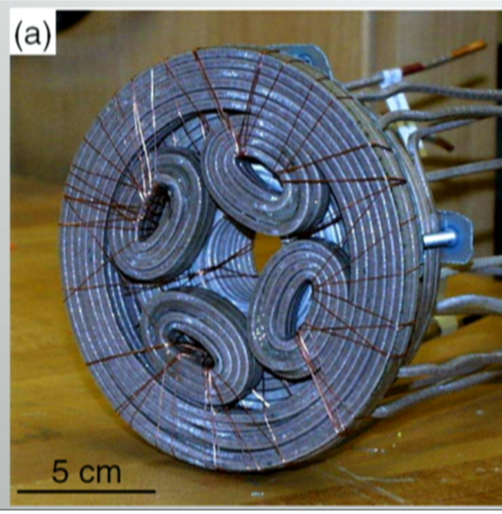



BOSTON



Magnetic traps for neutral atoms





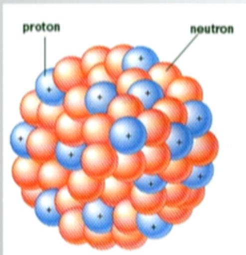
In this ideal thermist:
Evaporative Cooling

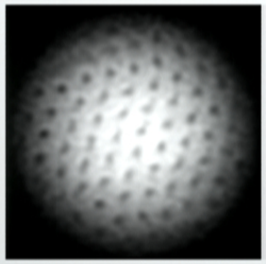
Strongly Interacting Fermi Systems

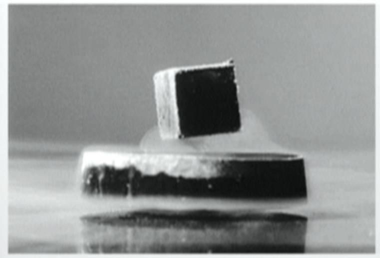
A good place to search for exotic physics

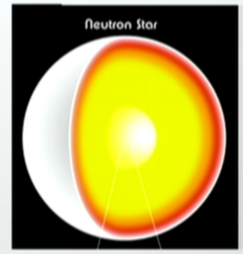
Length scales

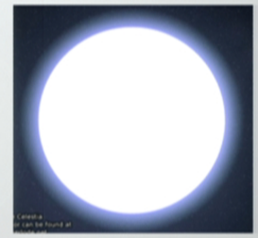
10^{-15} m	1 mm	1 m	10^{4} m	10^{7} m









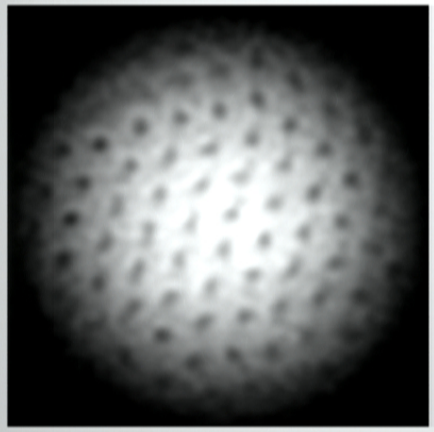


Nuclei	Ultracold Gases	High-T_c Superconductors	Neutron Star	White dwarf

- **A wealth of unusual quantum phases**
- **Many open qualitative questions**
  (e.g. Pseudo-gap phase in High-Tc materials)
- **Highly challenging theoretically**
  ("Fermion Sign Problem")

Ultracold Atomic Fermi Gases

Ideal test-bed for Many-Body physics



Interactions

Geometry

Spin Composition etc…

Realize idealized models of many-body physics

Benchmarking the many-body problem

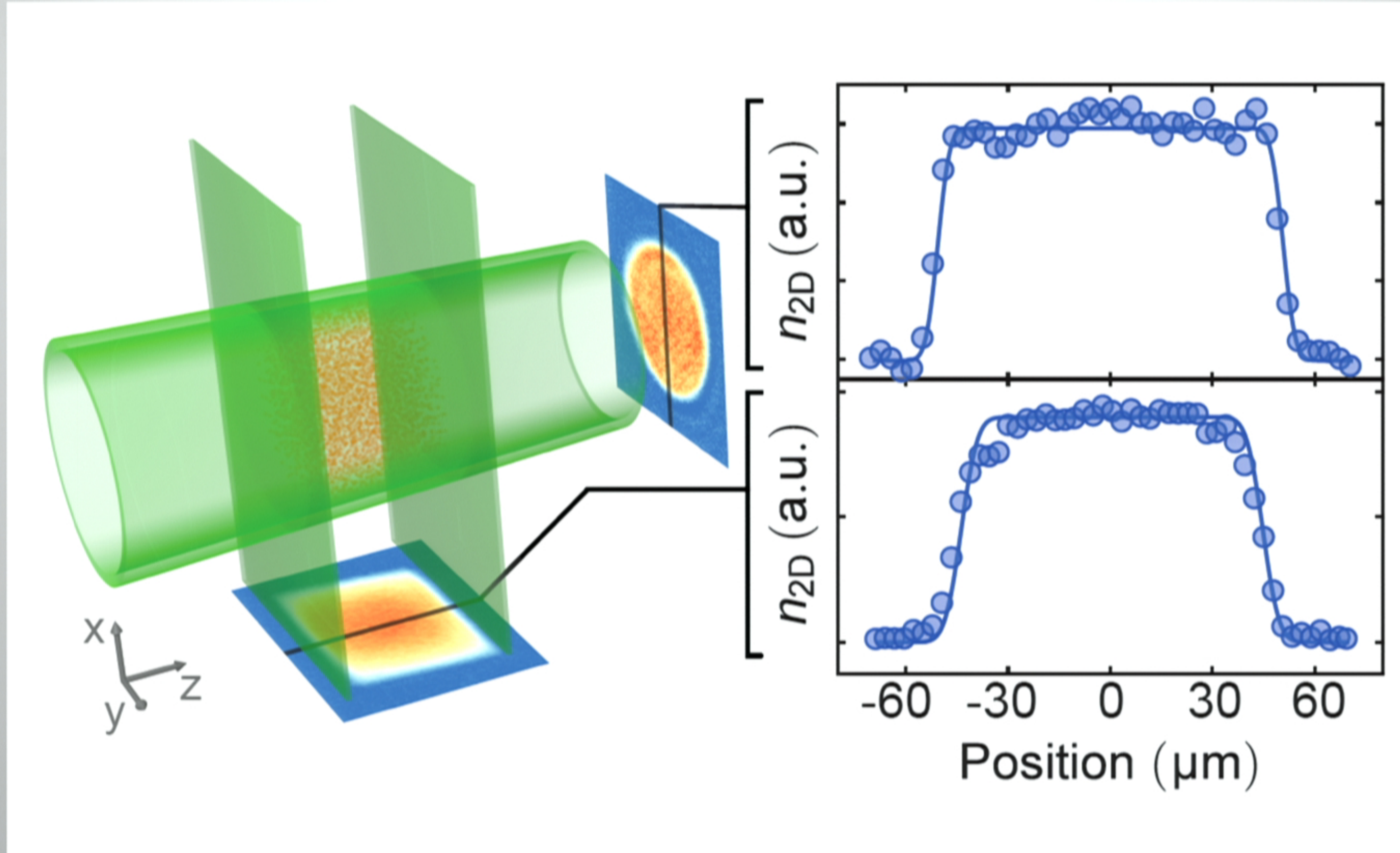
→ ***Unitary Fermi Gas, Fermi-Hubbard Model…***

Create entirely new systems

→ ***Dipolar Fermi gases***

→ ***Topological Superfluids?***

Fermions in a Box



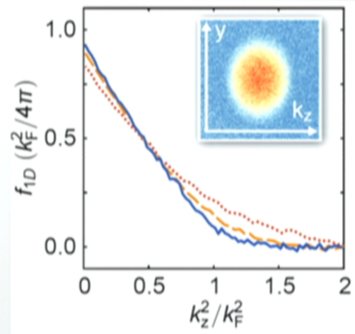
Z. Yan, P. Patel, B. Mukherjee, Z. Hadzibabic, T. Yefsah, J. Struck, MWZ, soon on arXiv

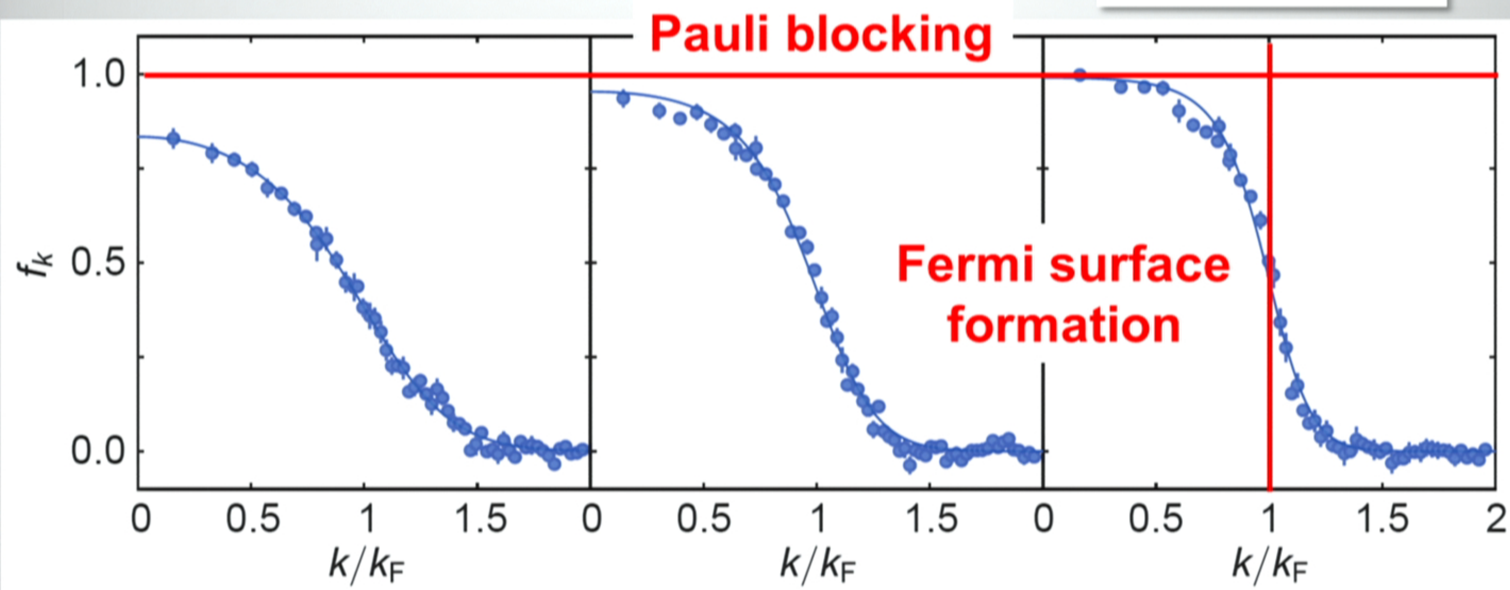
Measuring the Fermi-Dirac distribution

Expansion into harmonic potential along z

$\triangleq$ "Infinite" free time of flight $\quad k_z = \frac{m\omega_z}{\hbar} z$

e.g. Shvarchuck et al., PRL 89, 270404 (2002)





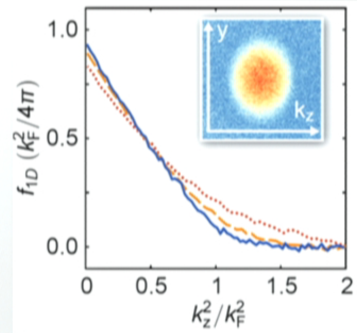
Alternative method: Drake et al., PRA 2012, selectively probe the central portion of an inhomogeneous gas.

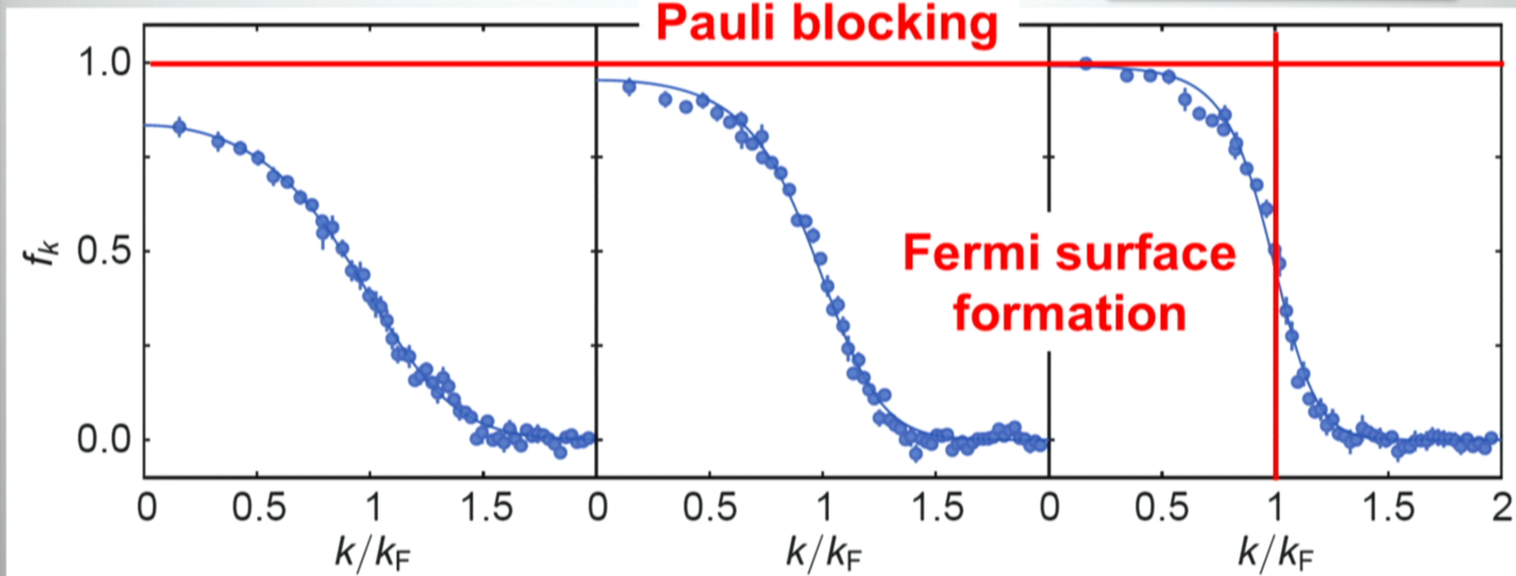
Z. Yan, P. Patel, B. Mukherjee, Z. Hadzibabic, T. Yefsah, J. Struck, MWZ, soon on arXiv

Measuring the Fermi-Dirac distribution

$$f_k = \frac{1}{e^{\beta(\varepsilon_k - \mu)} + 1}$$

90th anniversary





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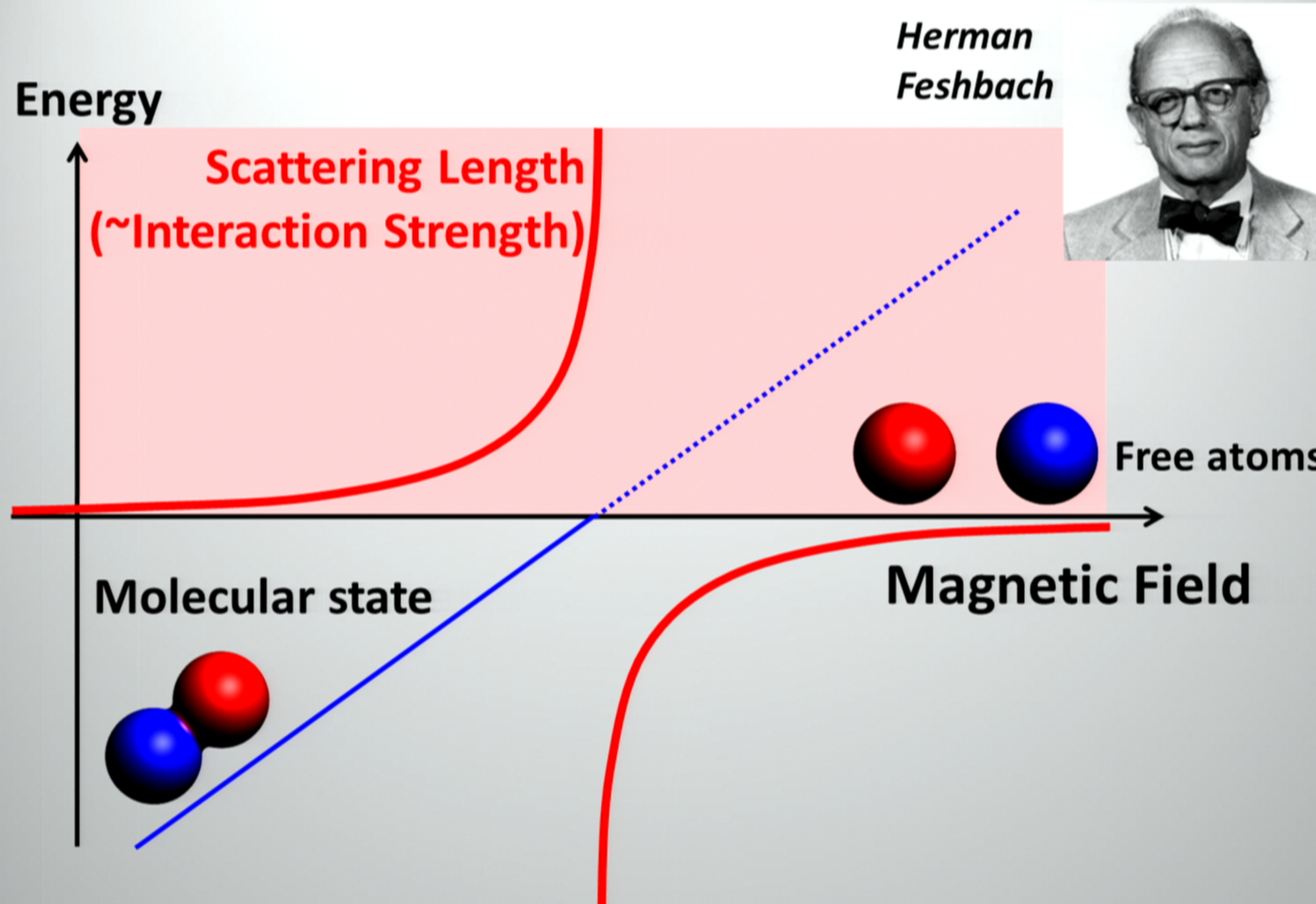
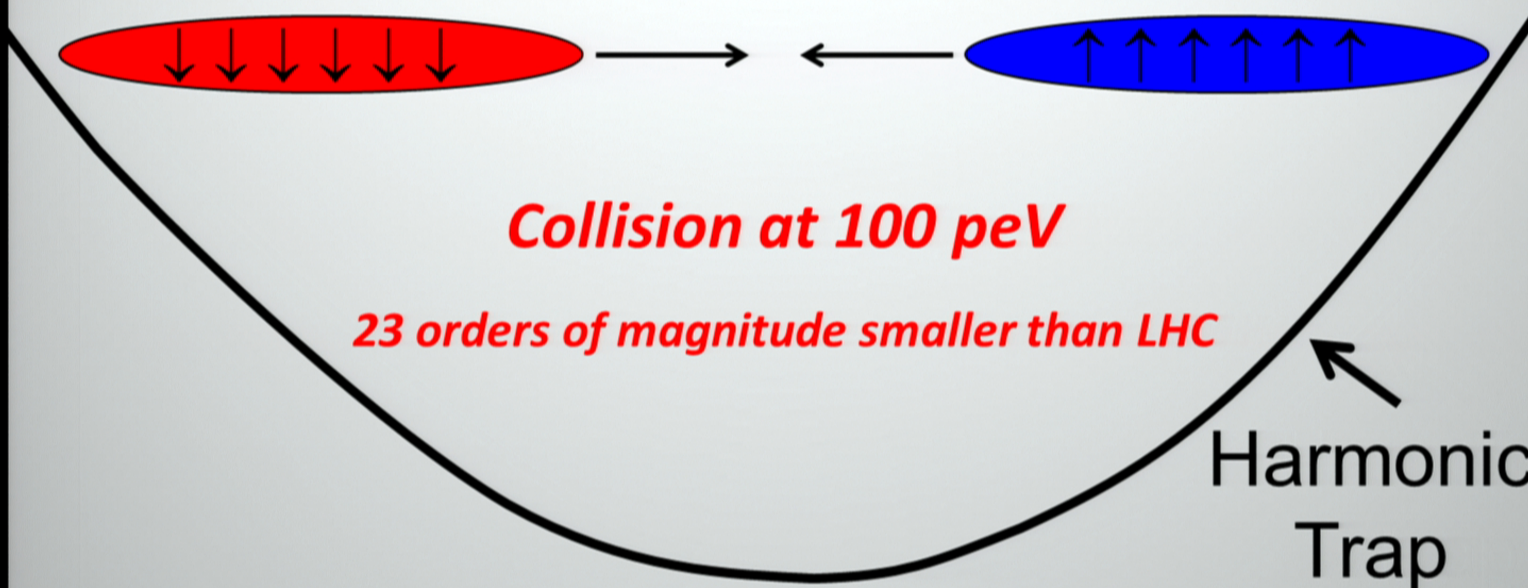
Strong interactions via Feshbach resonances



Little Fermi Collider (LFC)

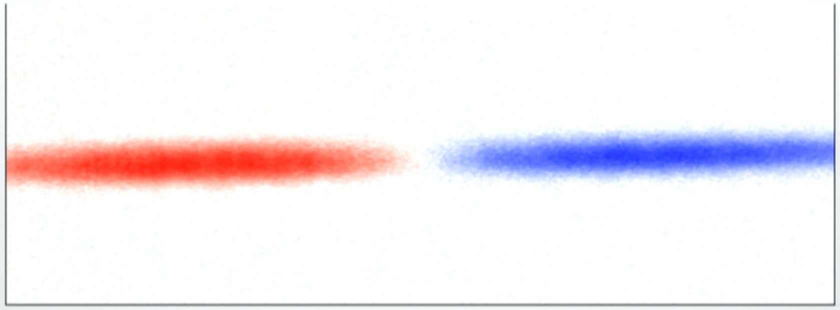
A ↓ Fermi gas collides with a ↑ cloud with resonant interactions



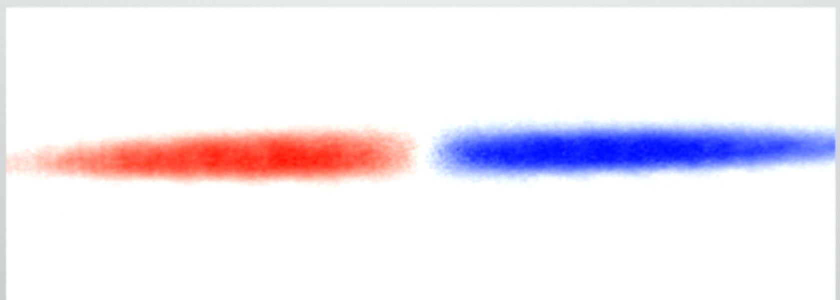
A.T. Sommer, M.J.H. Ku, G. Roati, M.W. Zwierlein, Nature 472, 201 (2011)

Little Fermi Collider (LFC)

Without Interactions



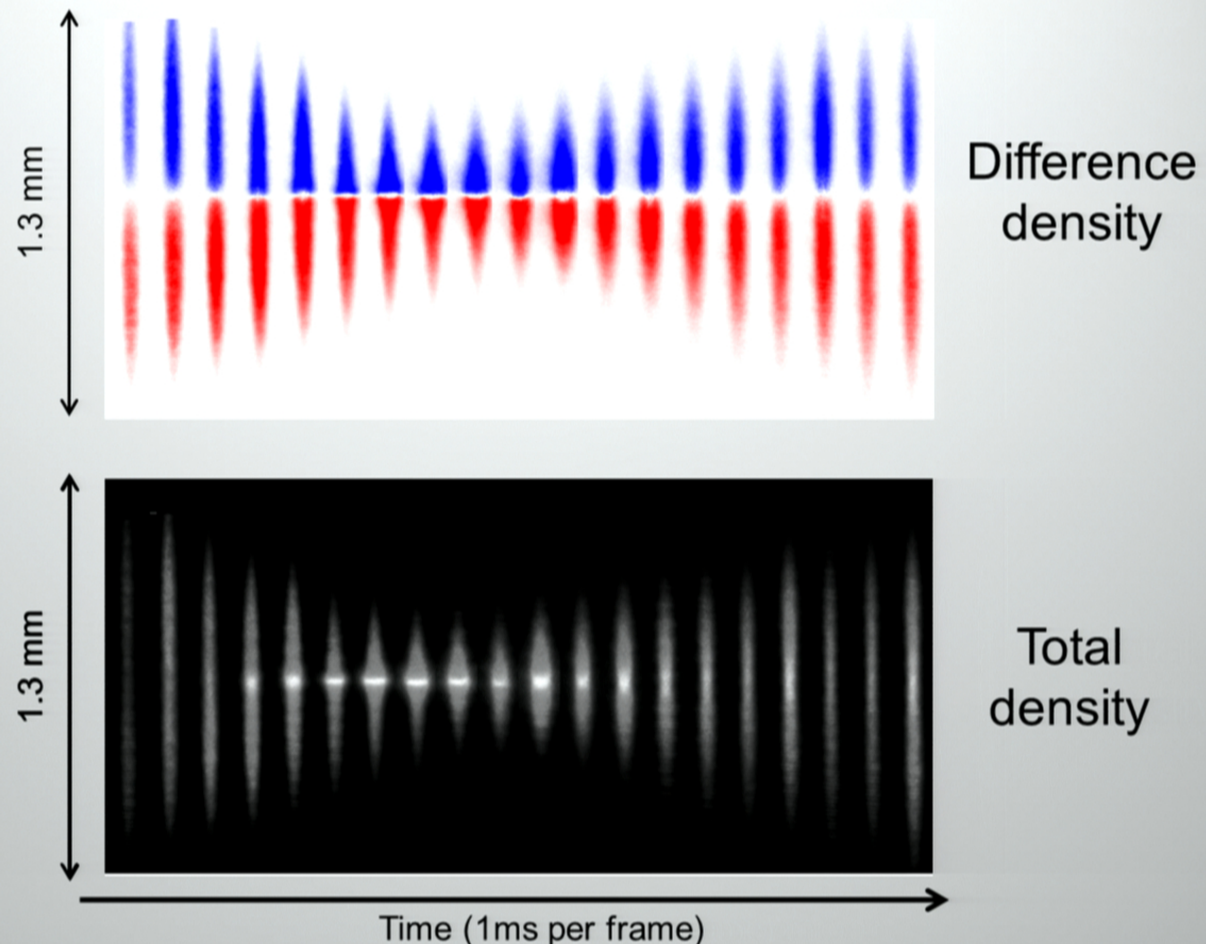
Resonant Interactions



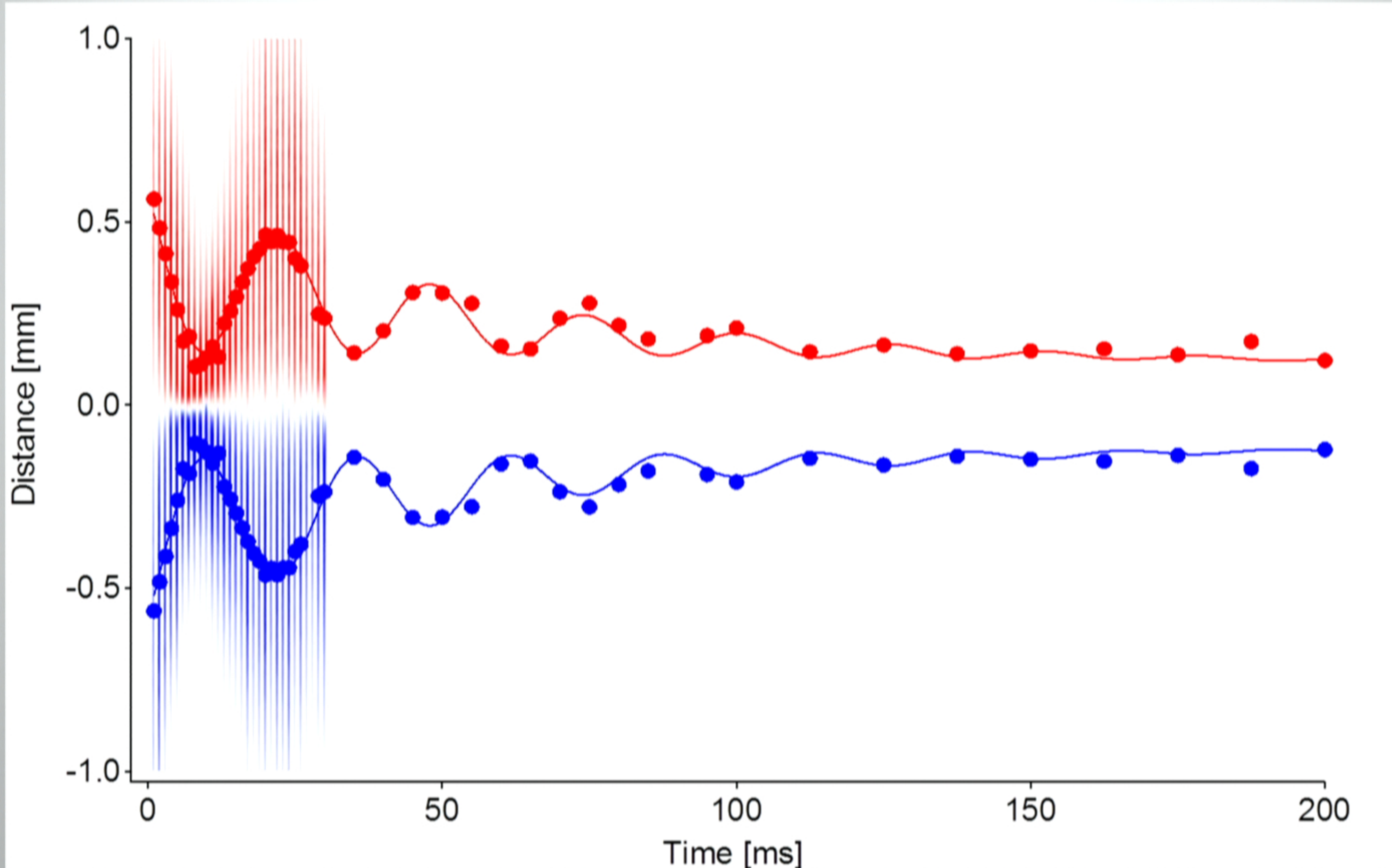
A.T. Sommer, M.J.H. Ku, G. Roati, M.W. Zwierlein, Nature 472, 201 (2011)

The bouncing gas

First collision

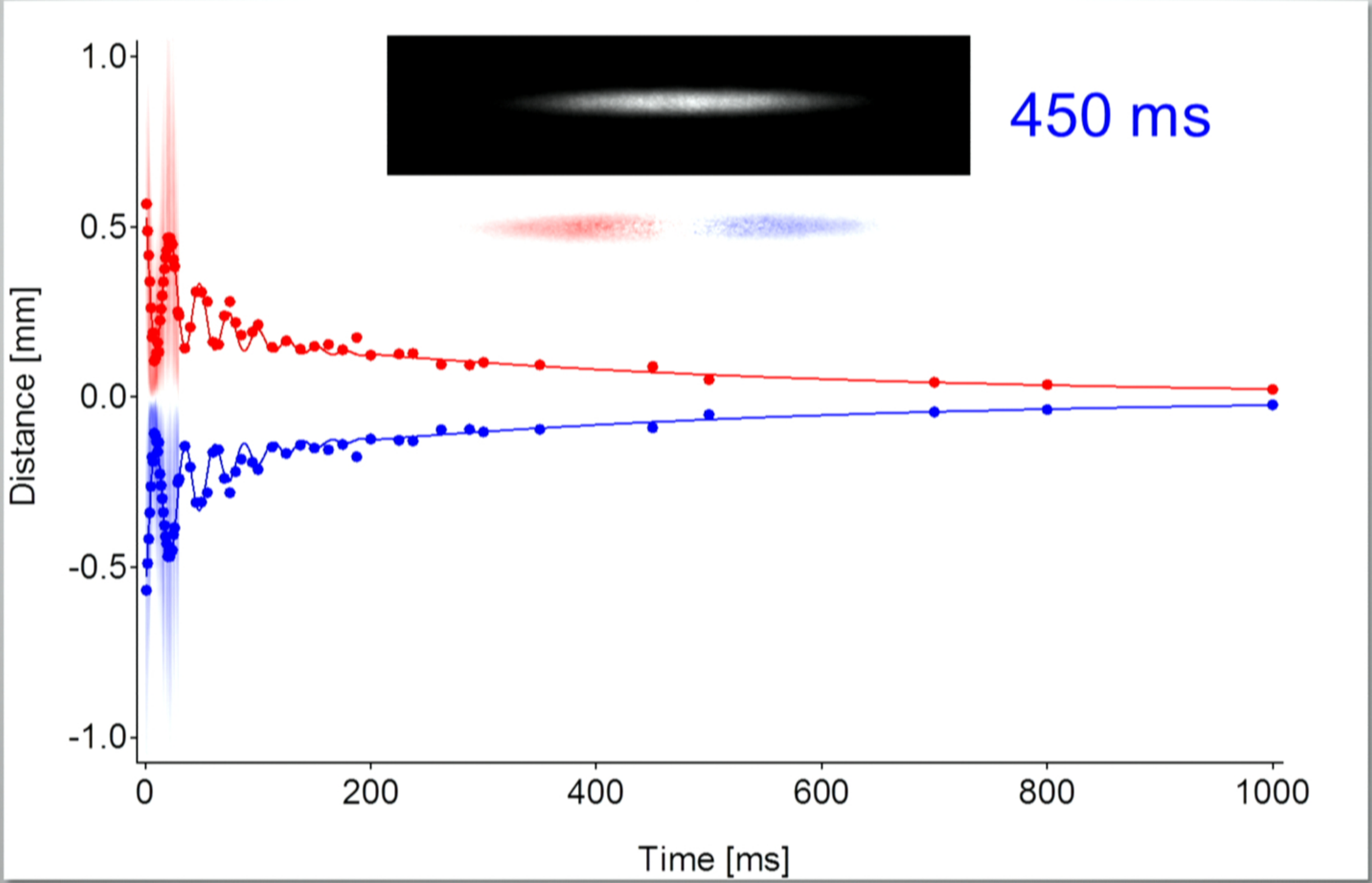


Later times



A.T. Sommer, M.J.H. Ku, G. Roati, M.W. Zwierlein, Nature 472, 201 (2011)

Much later times



A.T. Sommer, M.J.H. Ku, G. Roati, M.W. Zwierlein, Nature 472, 201 (2011)

Quantum limit of spin diffusion

Mean free path ~ Interparticle spacing d

Diffusion constant:

$$D \sim \text{mean free path} \times \text{average velocity}$$

$$\cancel{d} \times \frac{\hbar}{m\cancel{d}}$$

$$D \sim \frac{\hbar}{m} = \frac{\text{Planck's constant}}{\text{Particle mass}} = \frac{(0.1\text{ mm})^2}{1\text{s}}$$

→ Quantum Limit of Diffusion

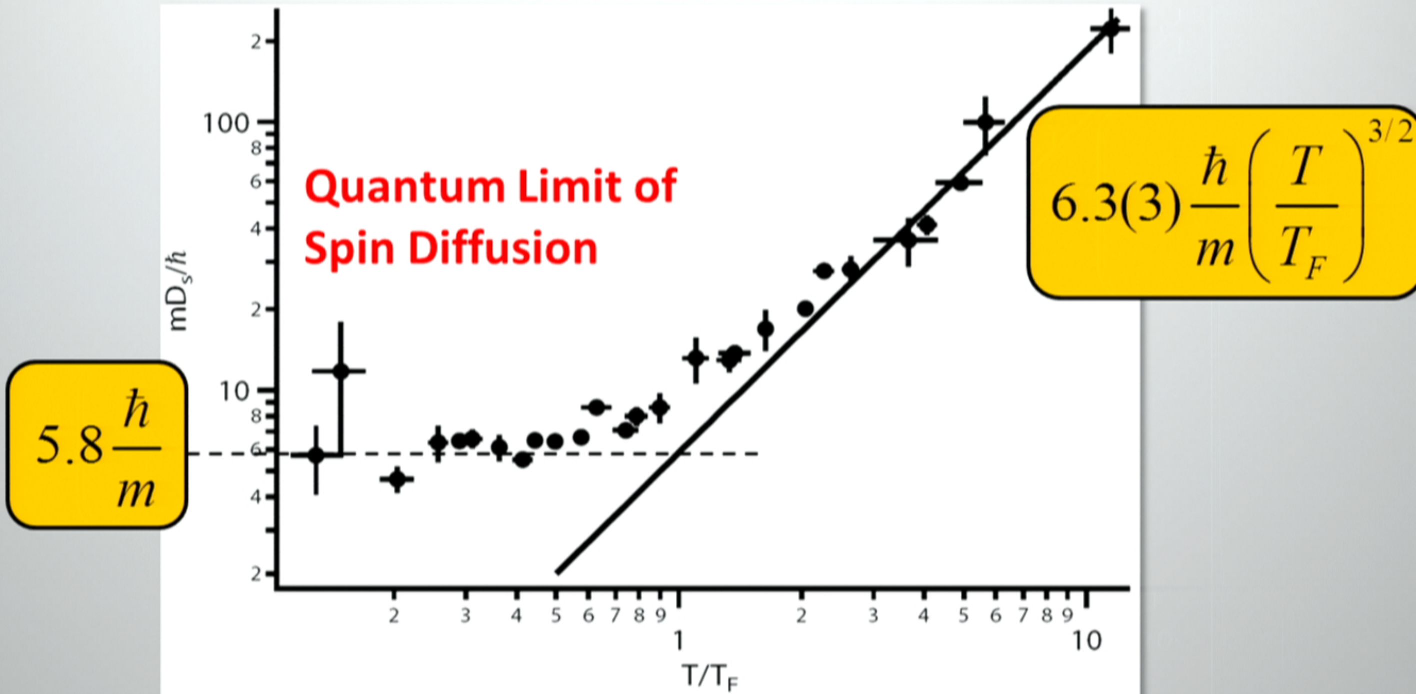
In a hot relativistic fluid (e.g. Quark-Gluon Plasma): $D \sim \frac{\hbar c^2}{T}$

$$mc^2 \to T$$

Spin Diffusion vs Temperature

Spin current = -D · Spin density gradient

Universal high-T behavior:

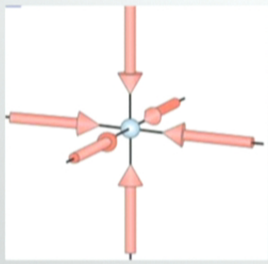


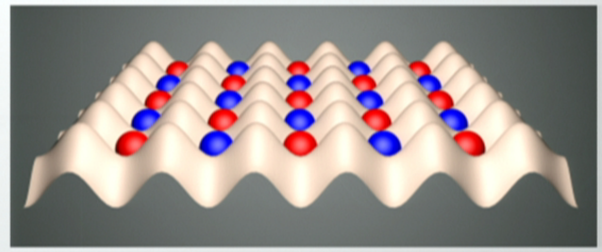
A.T. Sommer, M.J.H. Ku, G. Roati, M.W. Zwierlein, Nature 472, 201 (2011)

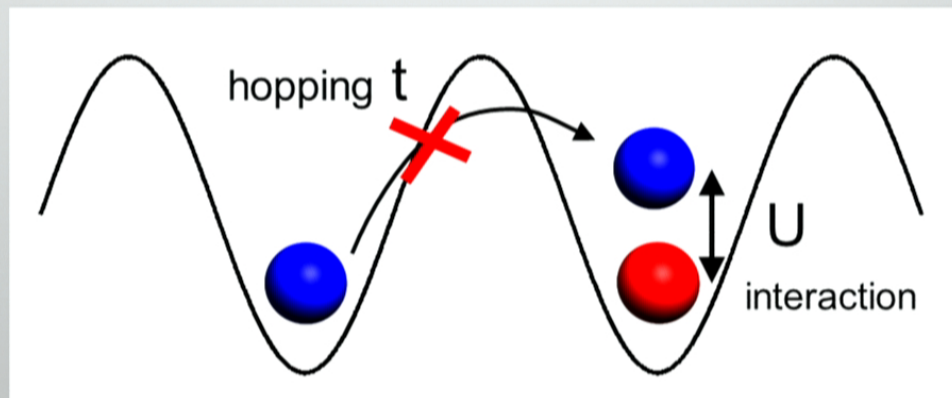
Other types of interaction

Confine atoms in optical lattices

Quench kinetic energy
Promote the role of interactions

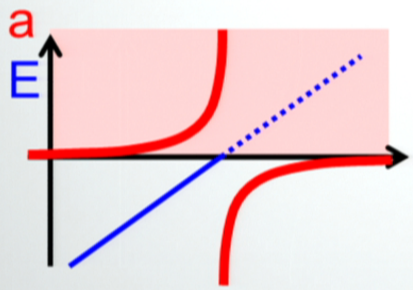


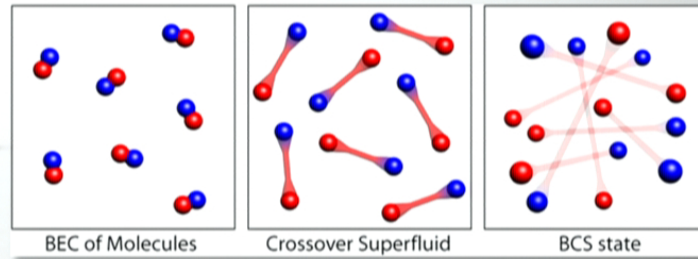




Creating strongly interacting Fermi Gases

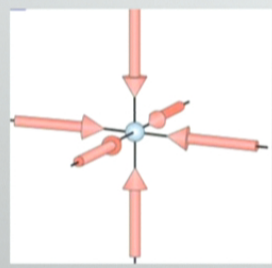
Feshbach Resonances → e.g. BEC-BCS Crossover

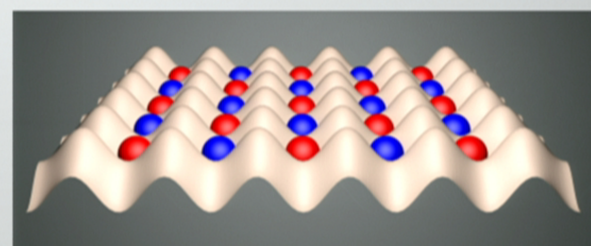




Quantum Gases → Quantum Fluids

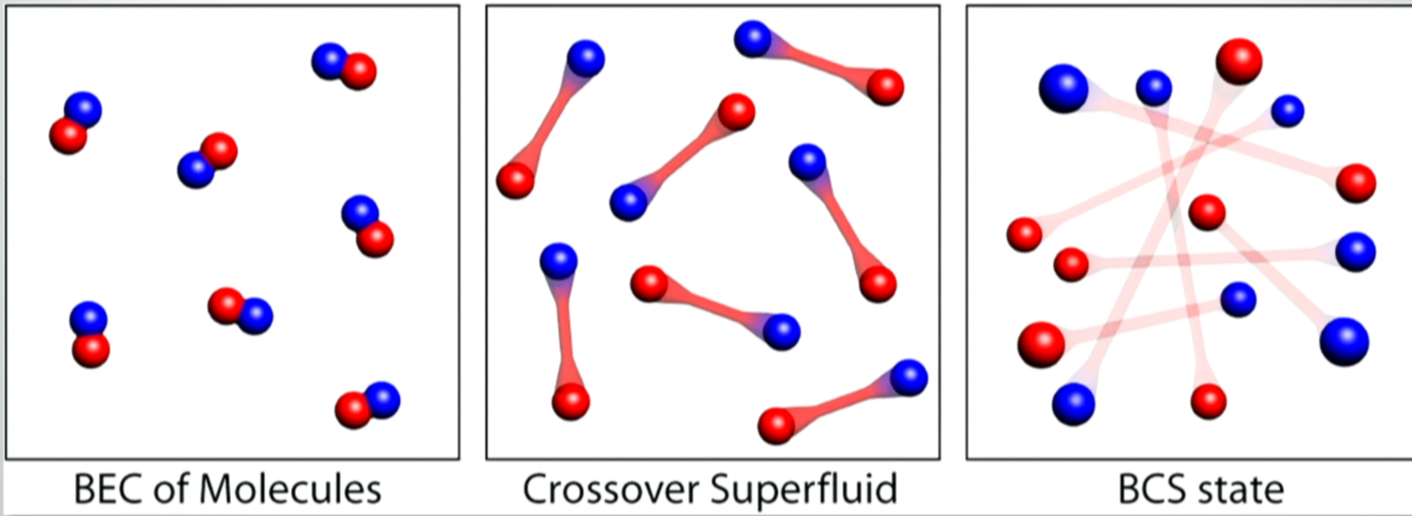
Optical Lattices → e.g. Fermi-Hubbard model





Quantum Gases → Quantum Solids

From BEC to BCS

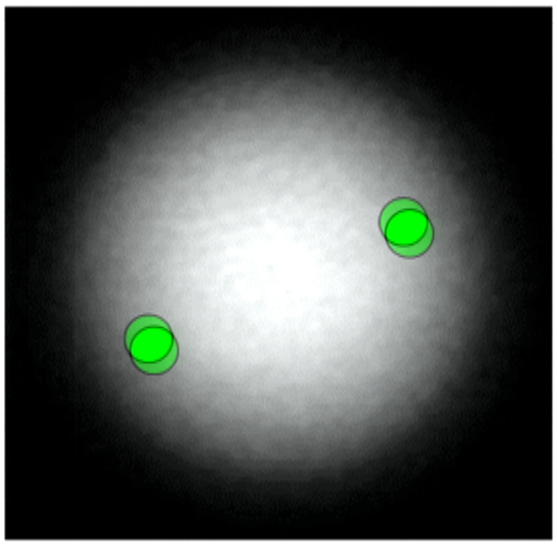


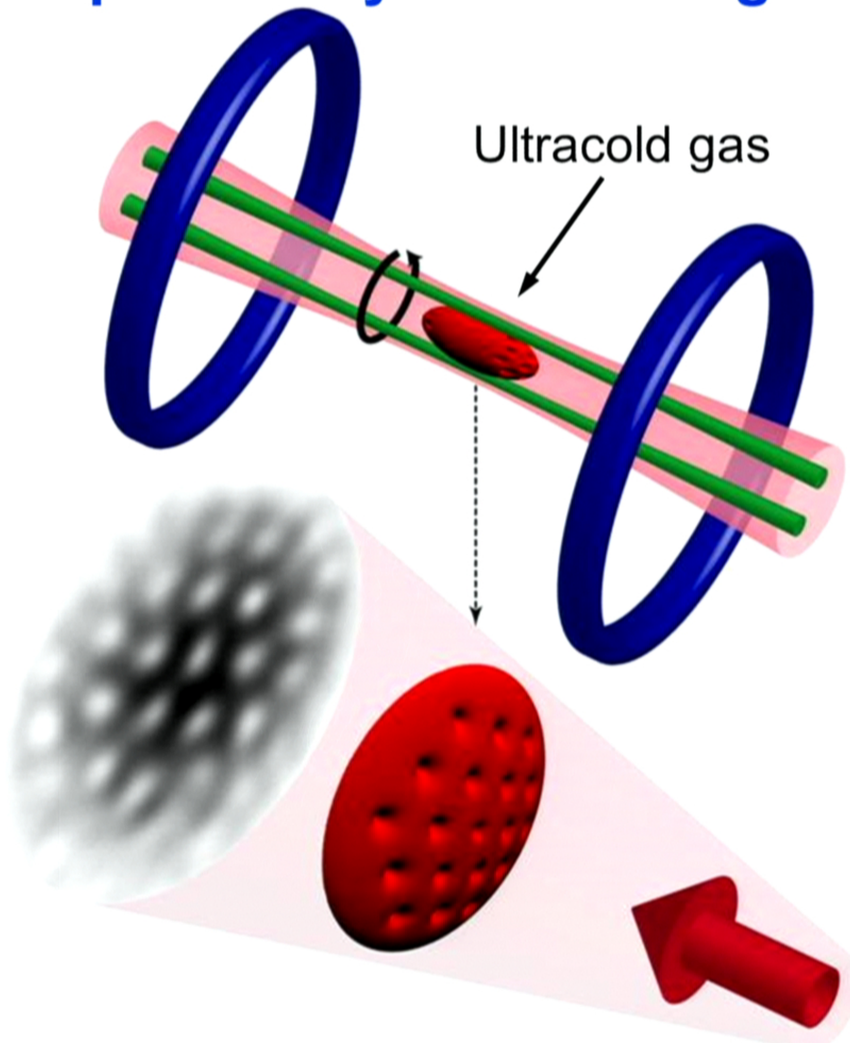
$\gg 1$ $\quad$ 1 $\quad$ 0 $\quad$ -1 $\quad$ $\ll -1$

$$(k_F a)^{-1} = \frac{\text{Interparticle Distance}}{\text{Scattering Length}}$$

Weakly Interacting Bosons
→ Strongly Interacting Bosons
→ Strongly Interacting Fermions
→ Weakly Interacting Fermions

Demonstration of superfluidity in a Fermi gas





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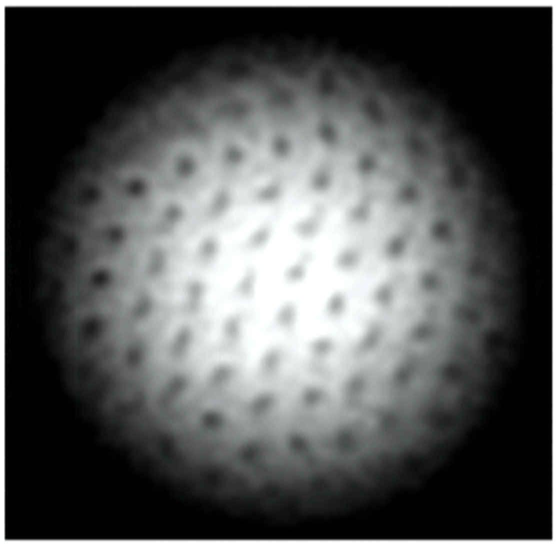
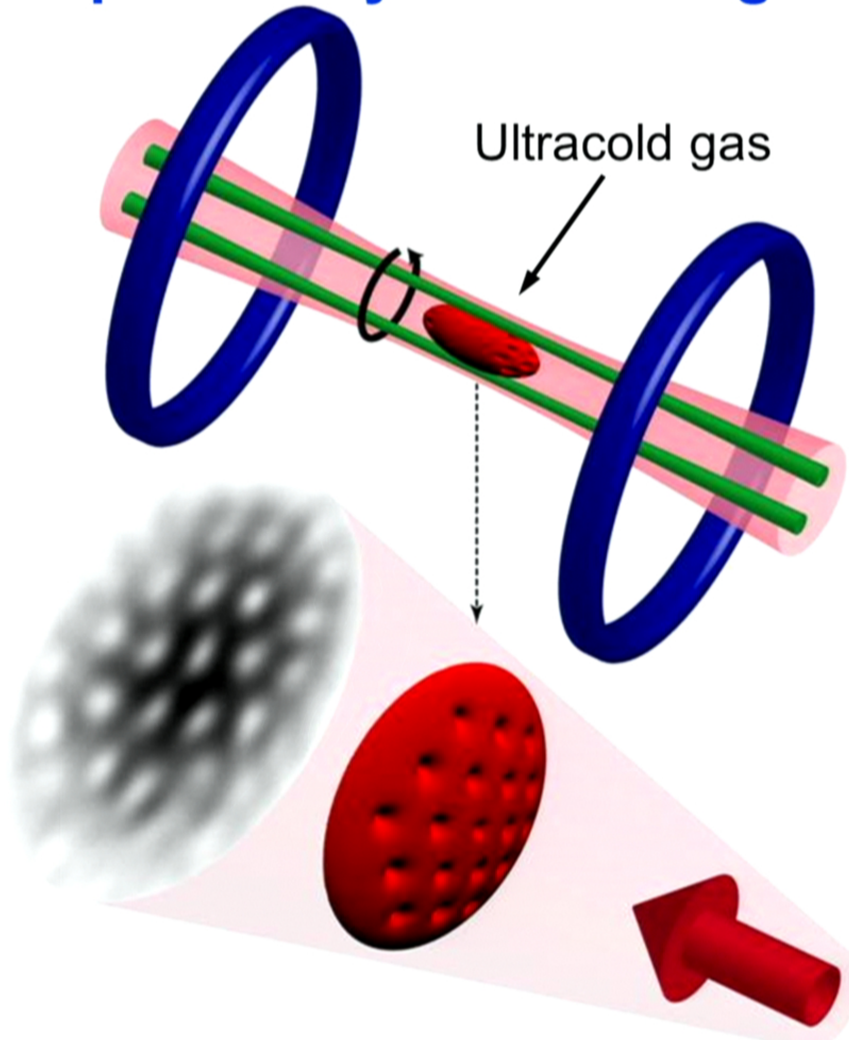
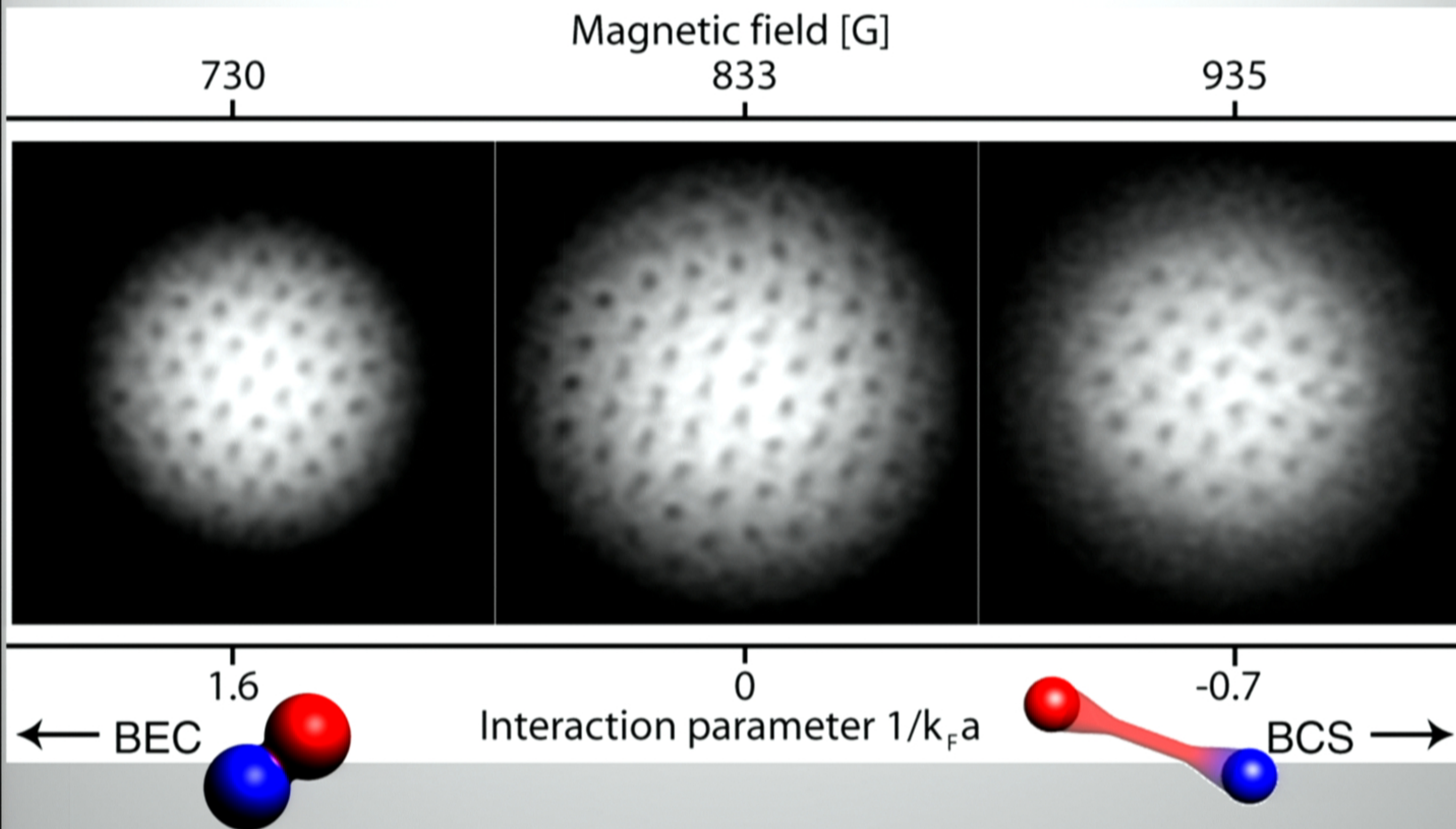




Vortex lattices in the BEC-BCS crossover



M.W. Zwierlein, J.R. Abo-Shaeer, A. Schirotzek, C.H. Schunck, W. Ketterle, Nature 435, 1047-1051 (2005)

Measuring the Equation of State

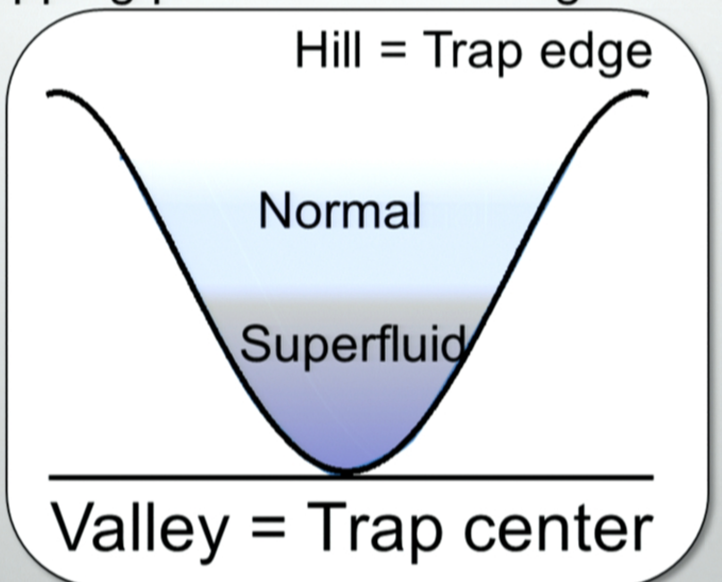
When climbing a mountain, the air gets thinner...

Equation of state → density as a function of height

The inverse works as well!

Density as a function of height → equation of state

Atoms in our trapping potential ≙ air in gravitational potential



Homogeneous EoS:

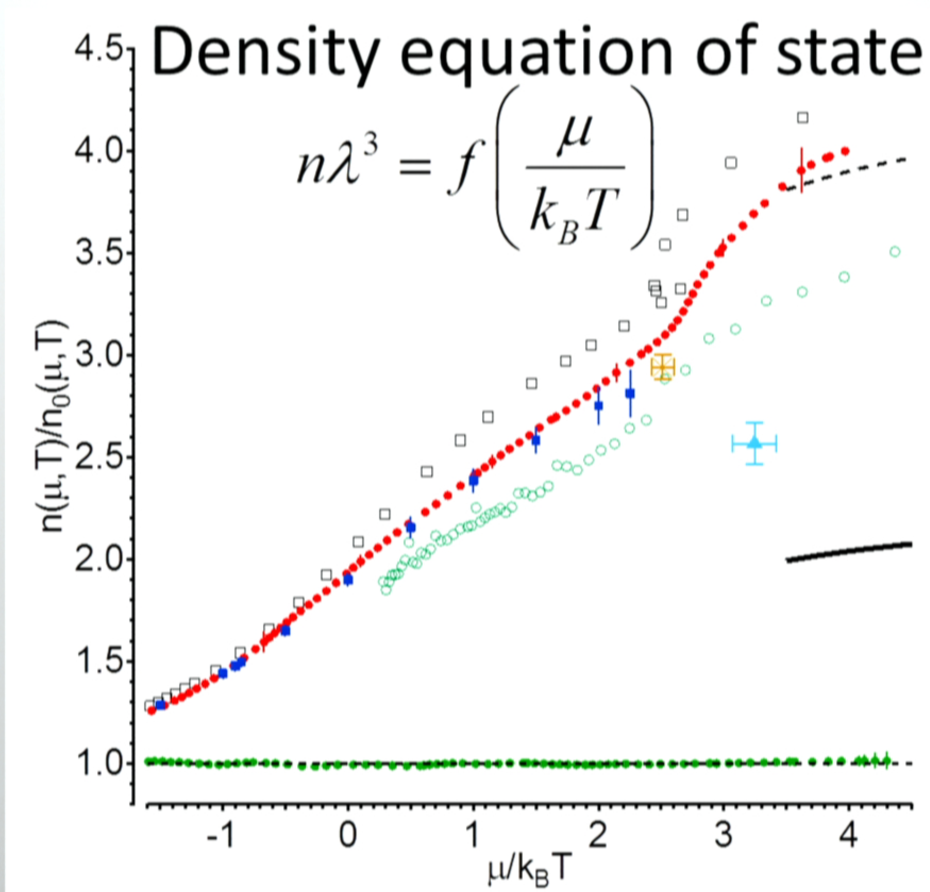
3D Fermions: ENS, Tokyo, MIT, LENS

2D Bosons: ENS, JILA, Chicago, Cambridge

2D Fermions: Heidelberg, Swinburne, Bonn

Fermi-Hubbard: Zürich, Rice, Bonn

Equation of State of a Strongly Interacting Fermi Gas



Unitary Gas (Expt.)

Meanfield

Non-Interacting Gas

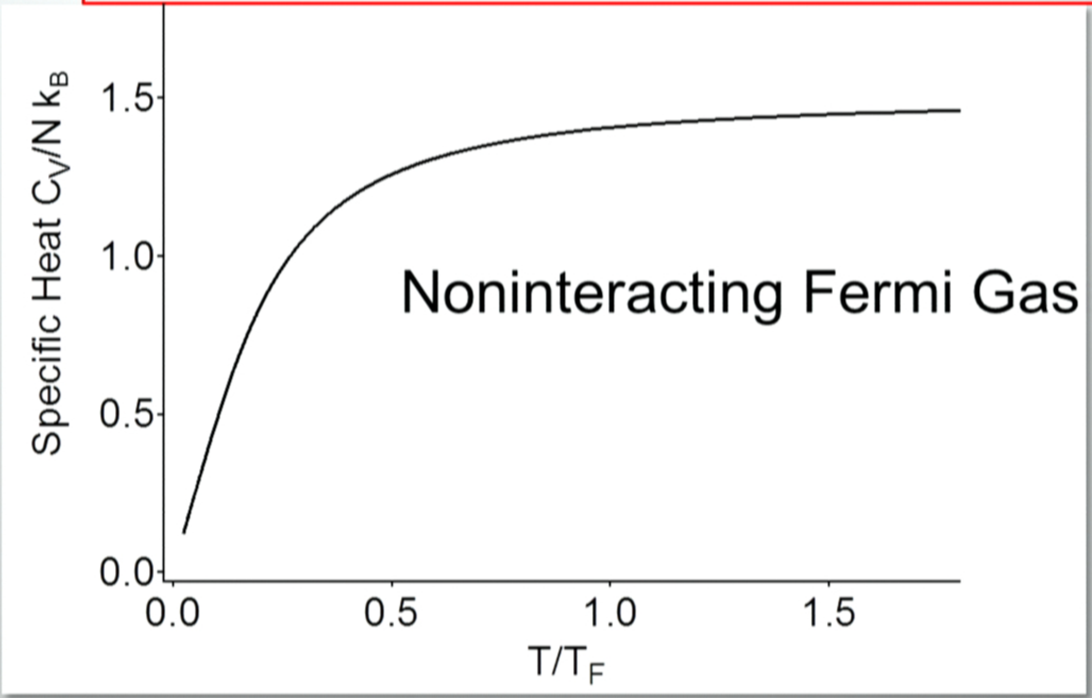
Mark Ku, Ariel Sommer, Lawrence Cheuk, MWZ, Science **335**, 563-567 (2012)
K. Van Houcke, F. Werner, E. Kozik, N. Prokofev, B. Svistunov,
M. Ku, A. Sommer, L. Cheuk, A. Schirotzek, MWZ, Nature Physics **8**, 366 (2012)

Heat capacity

For a resonant gas:

$$P = \frac{2}{3}\frac{E}{V}$$

$$\frac{C_V}{Nk_B} = \frac{\mathrm{d}\left(E/Nk_B\right)}{\mathrm{d}T}\bigg|_{N,V} = \frac{\mathrm{d}\left(P/nE_F\right)}{\mathrm{d}(T/T_F)} = \frac{3}{2}\frac{T_F}{T}\left(\frac{P}{P_0} - \frac{\kappa_0}{\kappa}\right)$$



Mark J. H. Ku, Ariel T. Sommer, Lawrence W. Cheuk, Martin W. Zwierlein
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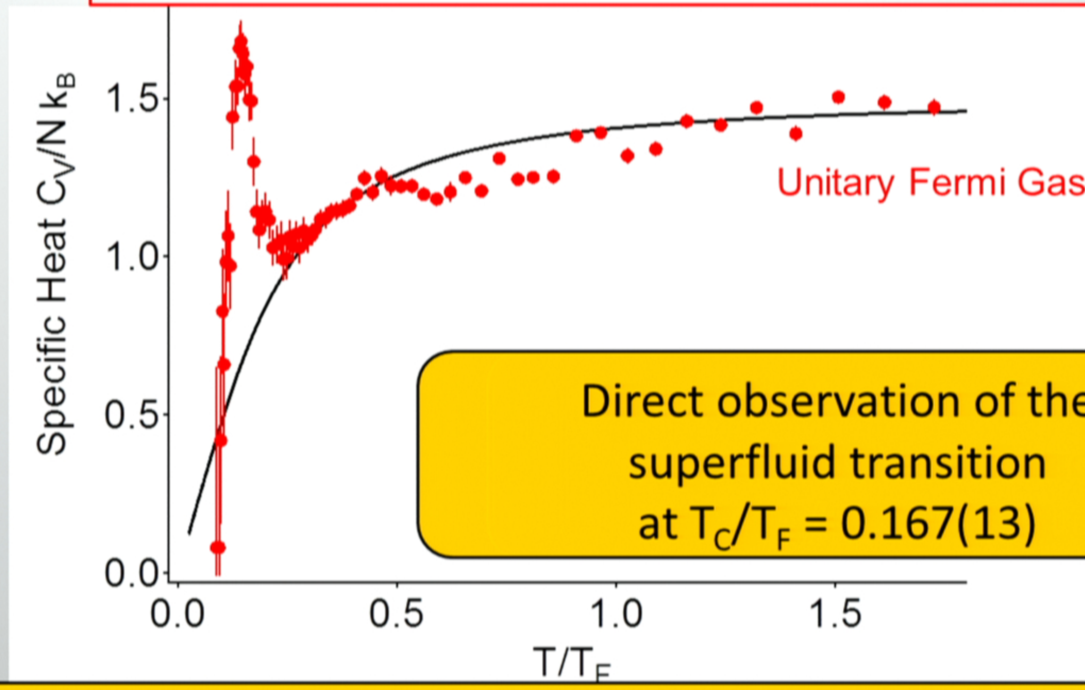


Direct observation of the superfluid transition at $T_C/T_F = 0.167(13)$

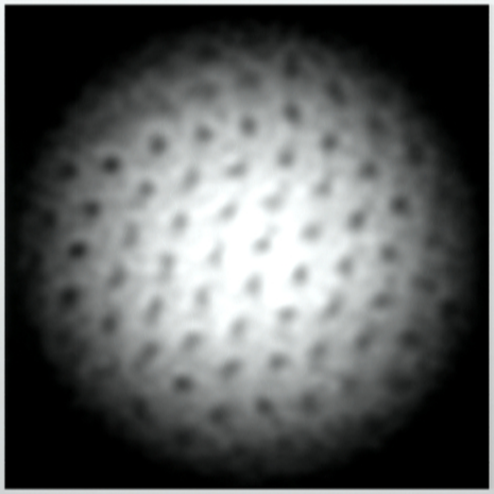
Scaled to the density of electrons in a solid, superfluidity would occur far above room temperature

How about excitations?

Vast body of work: Collective excitations, first sound, second sound, pair breaking excitations (PA, RF, PES), polarons (Innsbruck, Duke/NCSU, Rice, JILA, ENS, Swinburne, Heidelberg, MIT,...)

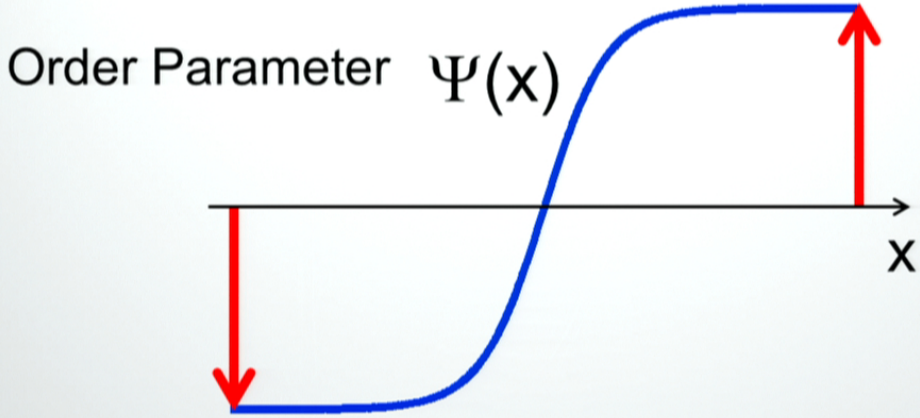
Regarding the superfluid wavefunction:

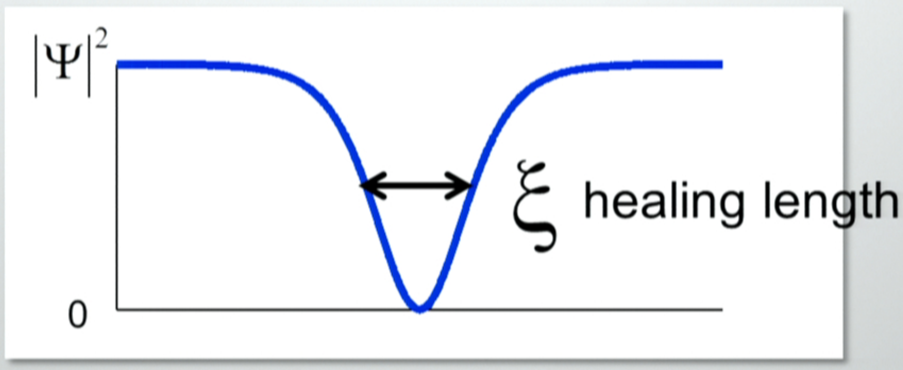
We know we have matter waves...



But we do not know the wave equation

Solitary Waves as Microscopic Probe





A localized, highly non-linear excitation

An excellent probe for the medium in which it propagates

Ex: Fiber optics, BEC, Dirac Fields, Holographic Theories

Dark Solitons in a Fermionic Superfluid

Limit of small gap: Andreev equation

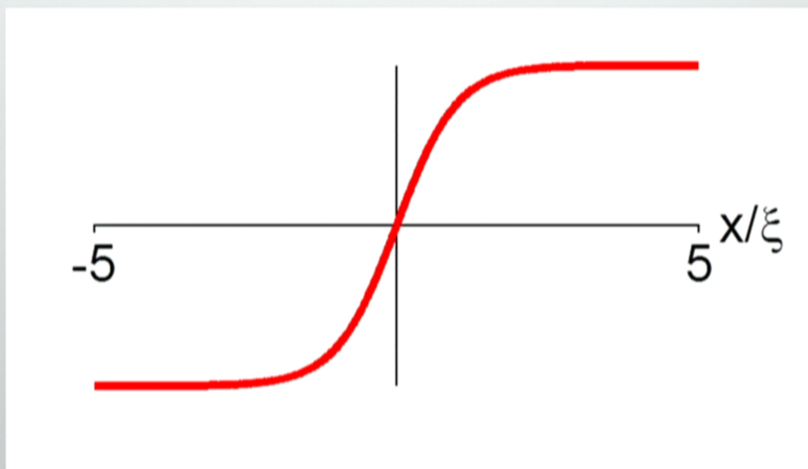
$$\left(-i\hbar v_F \frac{\partial}{\partial z}\sigma_z + \Delta(z)\sigma_x\right)\begin{pmatrix} u_n \\ v_n \end{pmatrix} = E_n \begin{pmatrix} u_n \\ v_n \end{pmatrix}$$

Dirac equation with spatially varying mass

Solitons with fermion number ½, Jackiw, Rebbi 1976

= continuum version of Su-Schrieffer-Heeger model 1979/80

$$\Delta = \Delta_0 \tanh\left(\frac{z}{\xi}\right)$$



Recent solution for finite velocity soliton: V. Galitski, D.K. Efimkin, PRA **91**, 023616 (2015)

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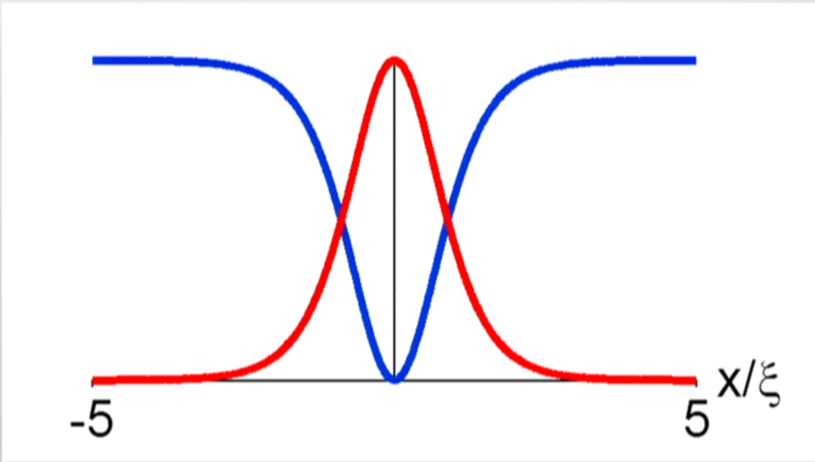
Dirac equation with spatially varying mass

Solitons with fermion number ½, Jackiw, Rebbi 1976

= continuum version of Su-Schrieffer-Heeger model 1979/80

$$|\Delta|^2 = \Delta_0^2 \tanh^2\left(\frac{z}{\xi}\right)$$



Andreev Bound State

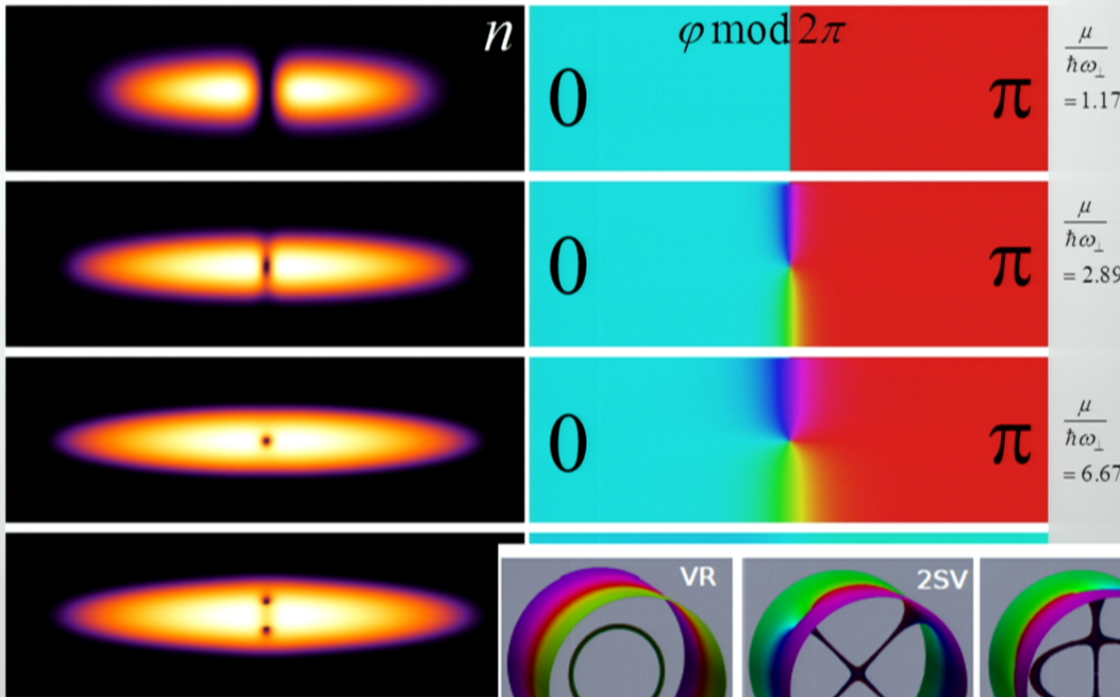
Recent solution for finite velocity soliton: V. Galitski, D.K. Efimkin, PRA **91**, 023616 (2015)

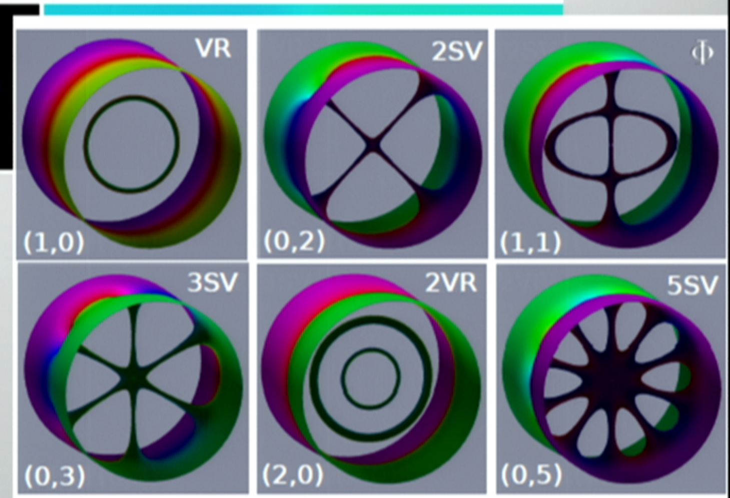
Generalization in 3D: Solitary Waves

Soliton

Solitonic Vortex

Vortex Ring





After
Brand, Reinhardt
PRA 65, 043612 (2002)

All examples of

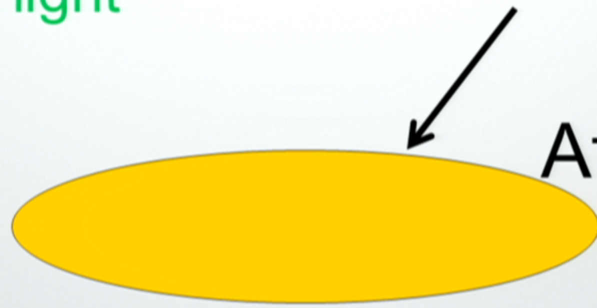
Chladni Solitons

Mateo, Brand, PRL 113, 255302 (2014)

Making Solitons by phase imprinting

Pulse
off-resonant light

superfluid



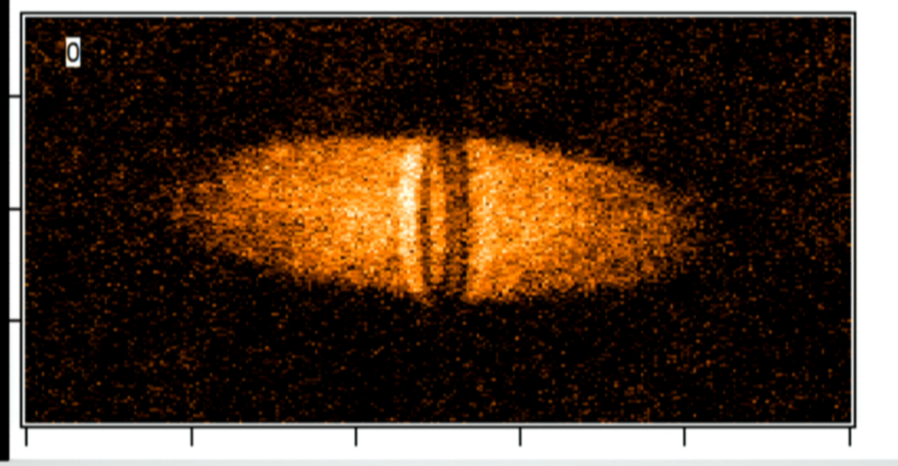
After the pulse:

$$\Delta\varphi = \frac{2Ut}{\hbar}$$

Needs to be fast enough: $t < \frac{\hbar}{\mu} \sim 100\,\mu s$

Solitons in BECs by phase imprinting: Hannover, Hamburg, NIST,...

Cascade of Solitary Waves in a Unitary Fermi Gas

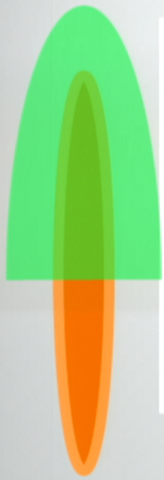


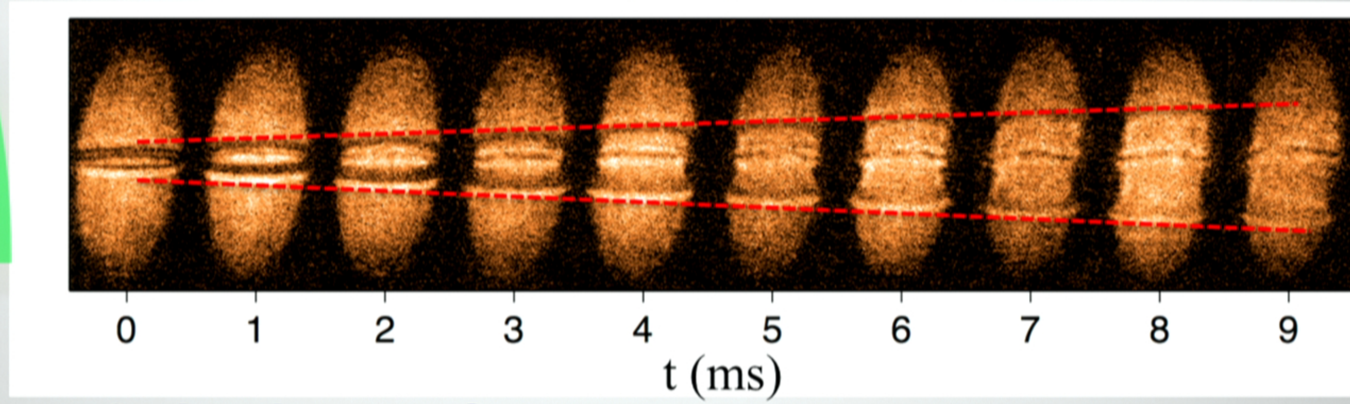
Planar soliton →
vortex ring →
vortex / anti-vortex pair →
solitonic vortex

Mark J.H. Ku, Biswaroop Mukherjee, Tarik Yefsah, Martin W. Zwierlein
PRL **116**, 045304 (2016)

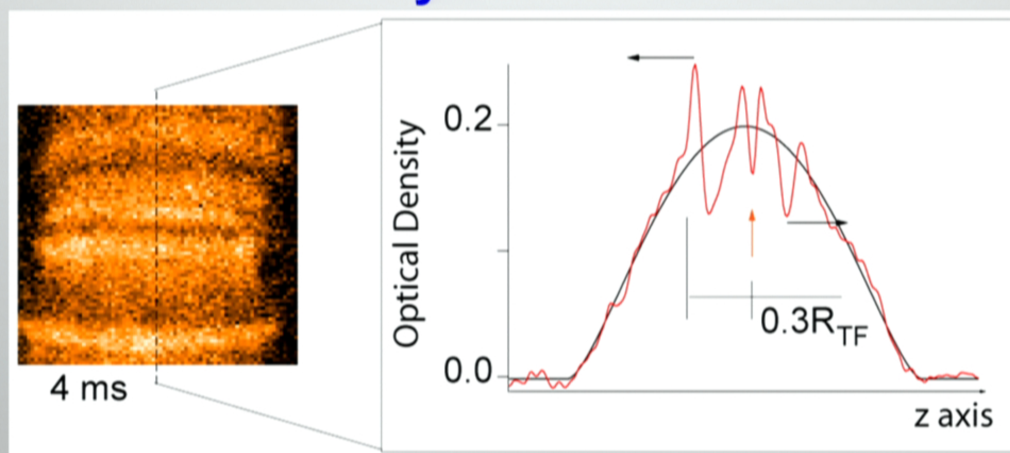
Instability Cascade of Solitary Waves in Unitary Fermi Gas

Early time dynamics after imprint (central slice)



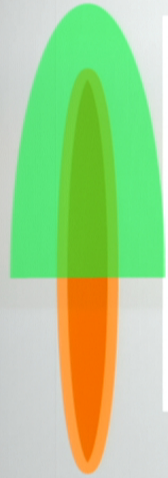


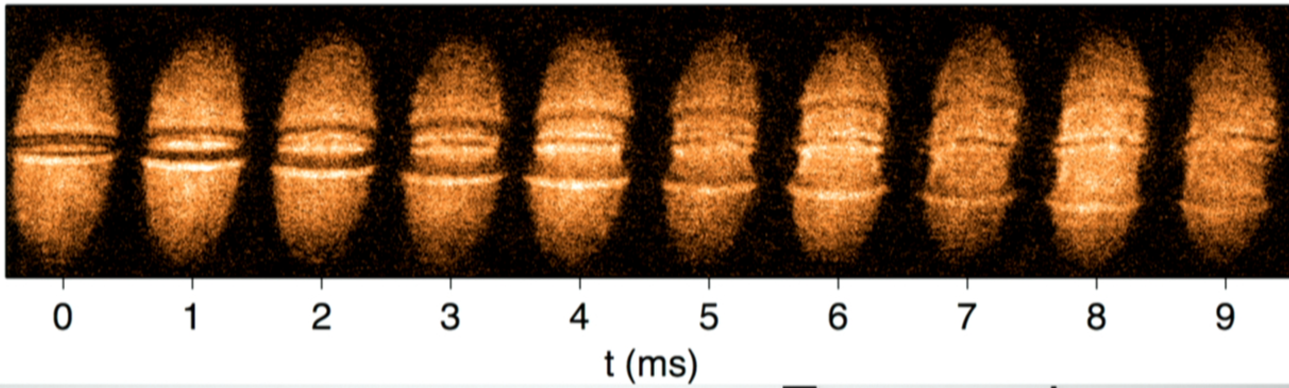
2 shock wave fronts +
1 slow solitary wave



Instability Cascade of Solitary Waves in Unitary Fermi Gas

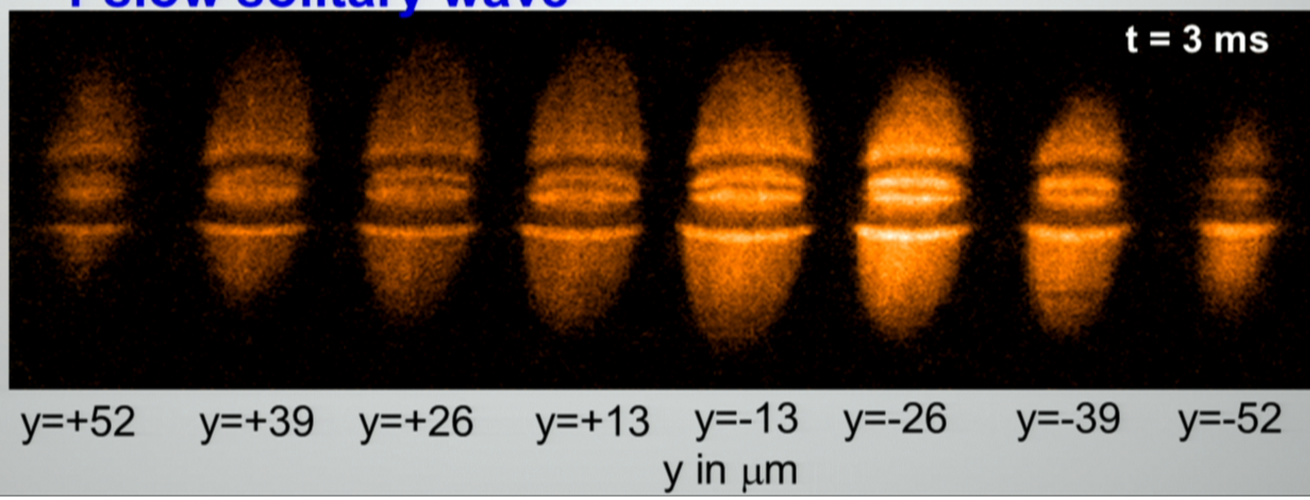
Early time dynamics after imprint (central slice)





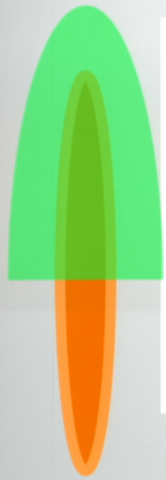
2 shock wave fronts +
1 slow solitary wave

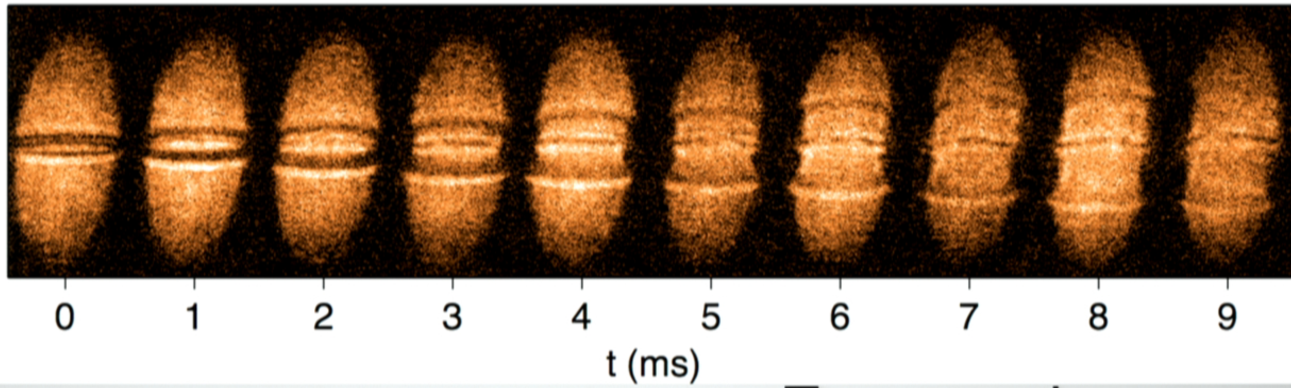
Tomography:



Instability Cascade of Solitary Waves in Unitary Fermi Gas

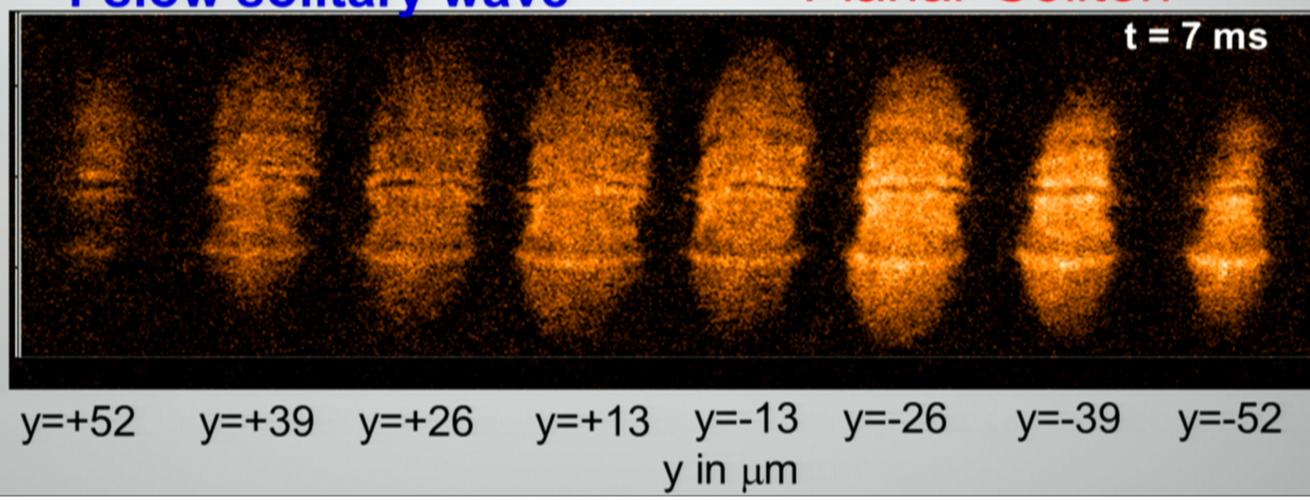
Early time dynamics after imprint (central slice)





2 shock wave fronts +
1 slow solitary wave

Tomography:
Planar Soliton



Instability Cascade of Solitary Waves in Unitary Fermi Gas

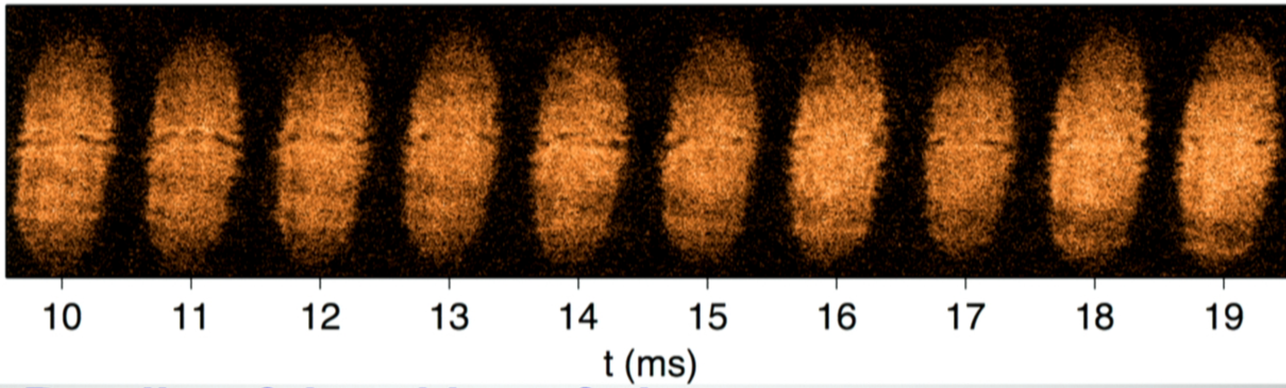
t (ms)

Planar Soliton + two shock fronts (a)

Snake instability (b)

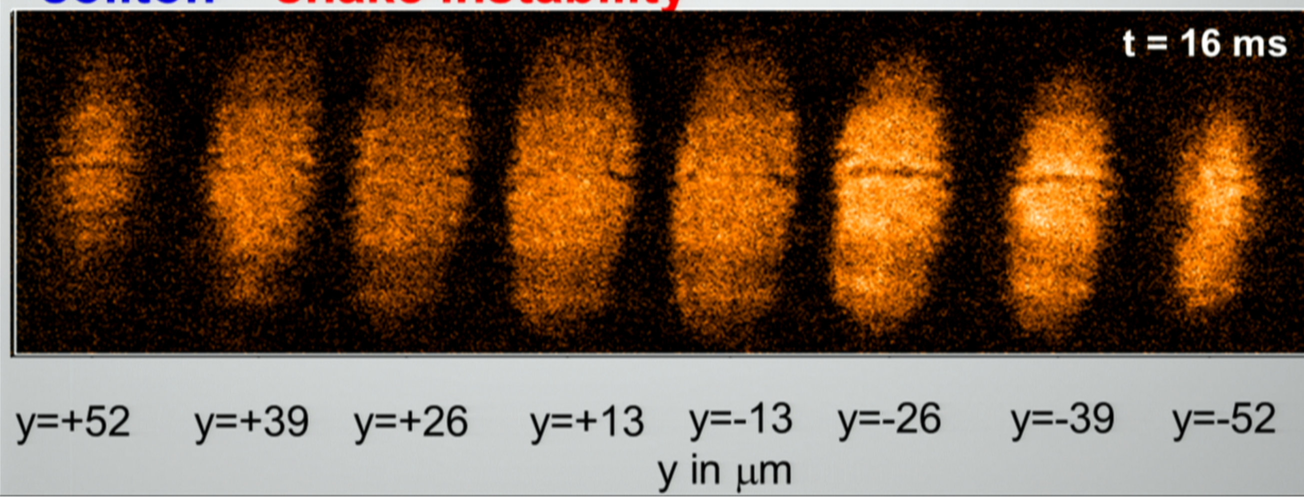
10 50 100 500 1000

Early time dynamics after imprint (central slice)

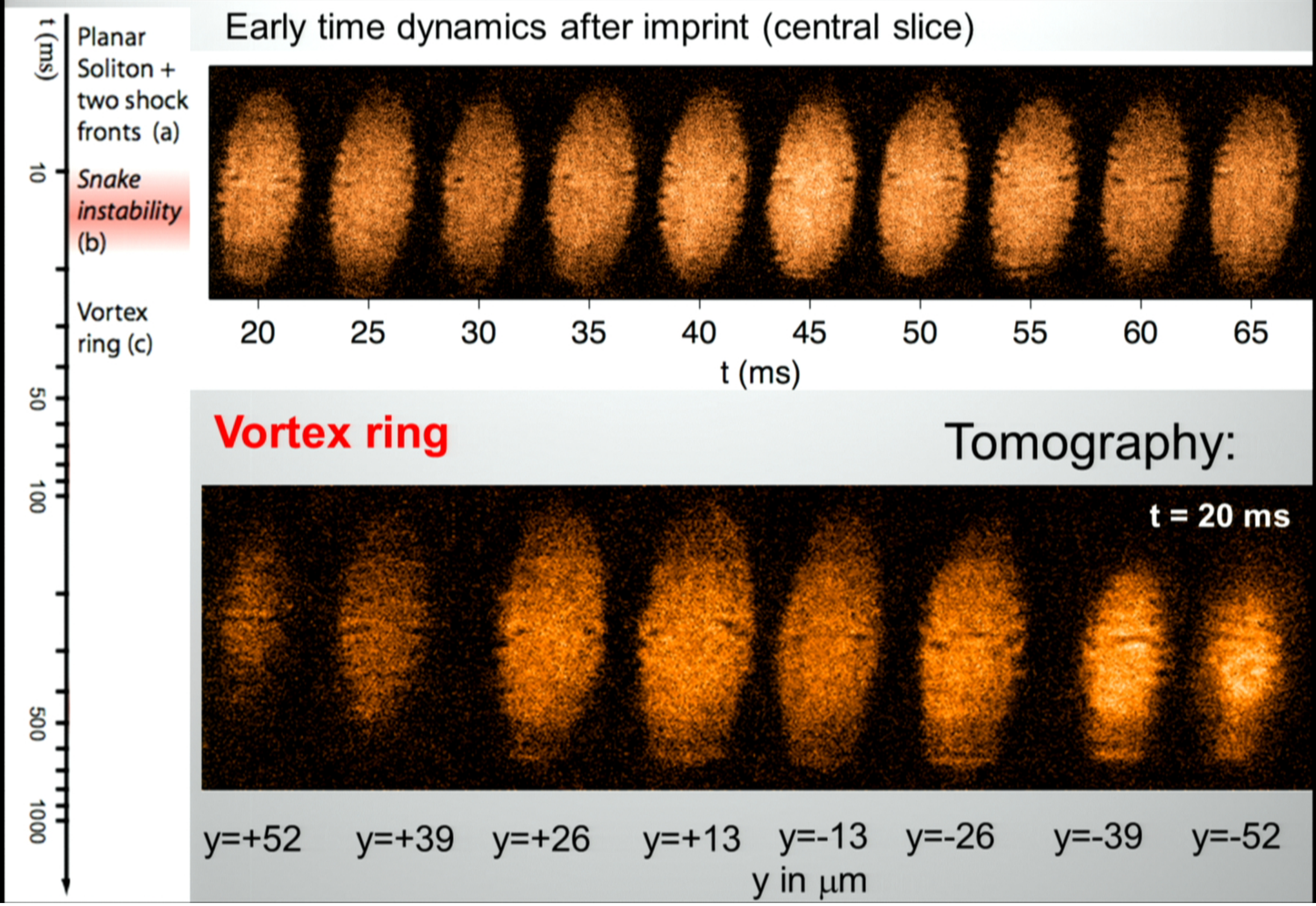


Bending & breaking of planar soliton – snake instability

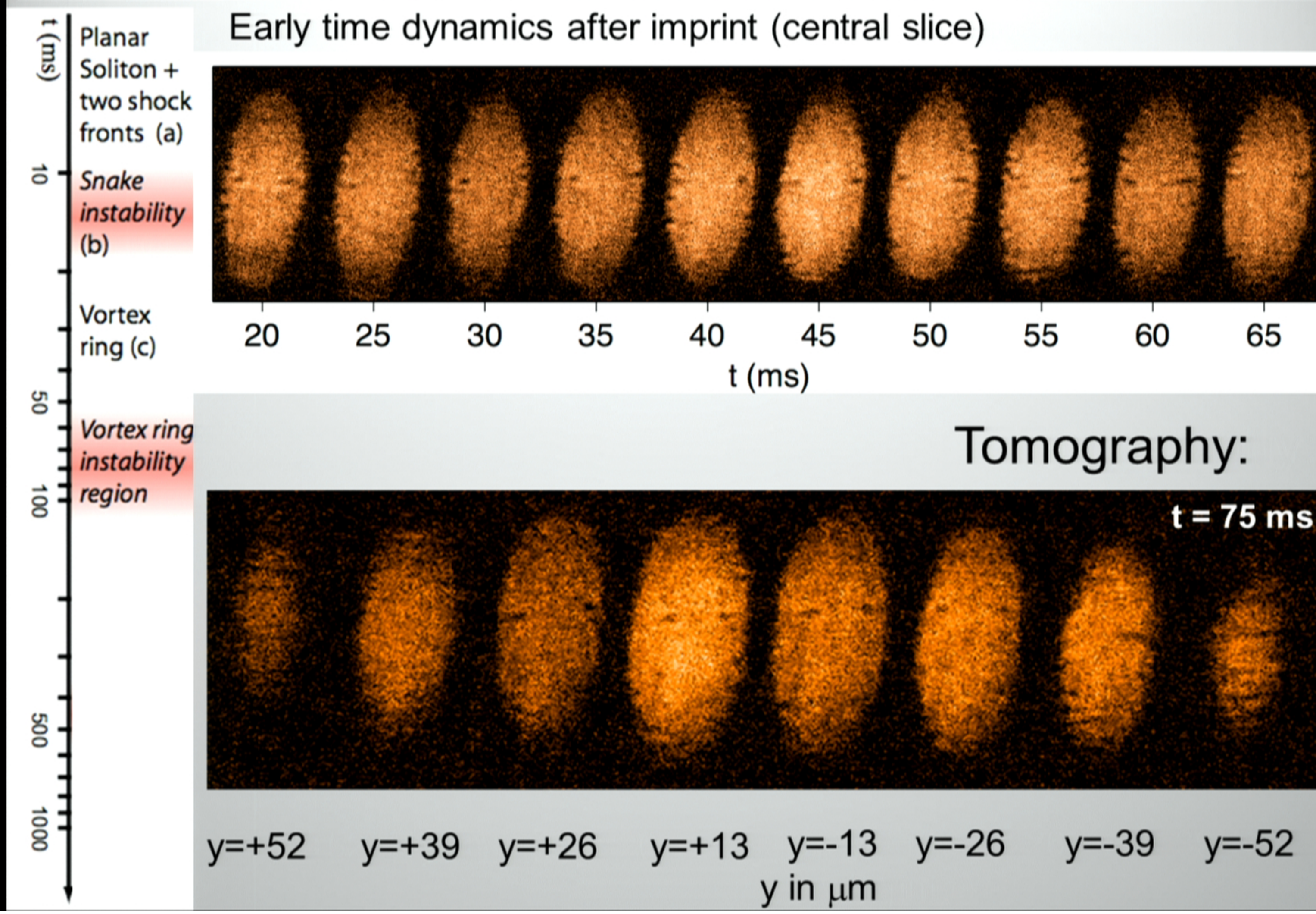
Tomography:



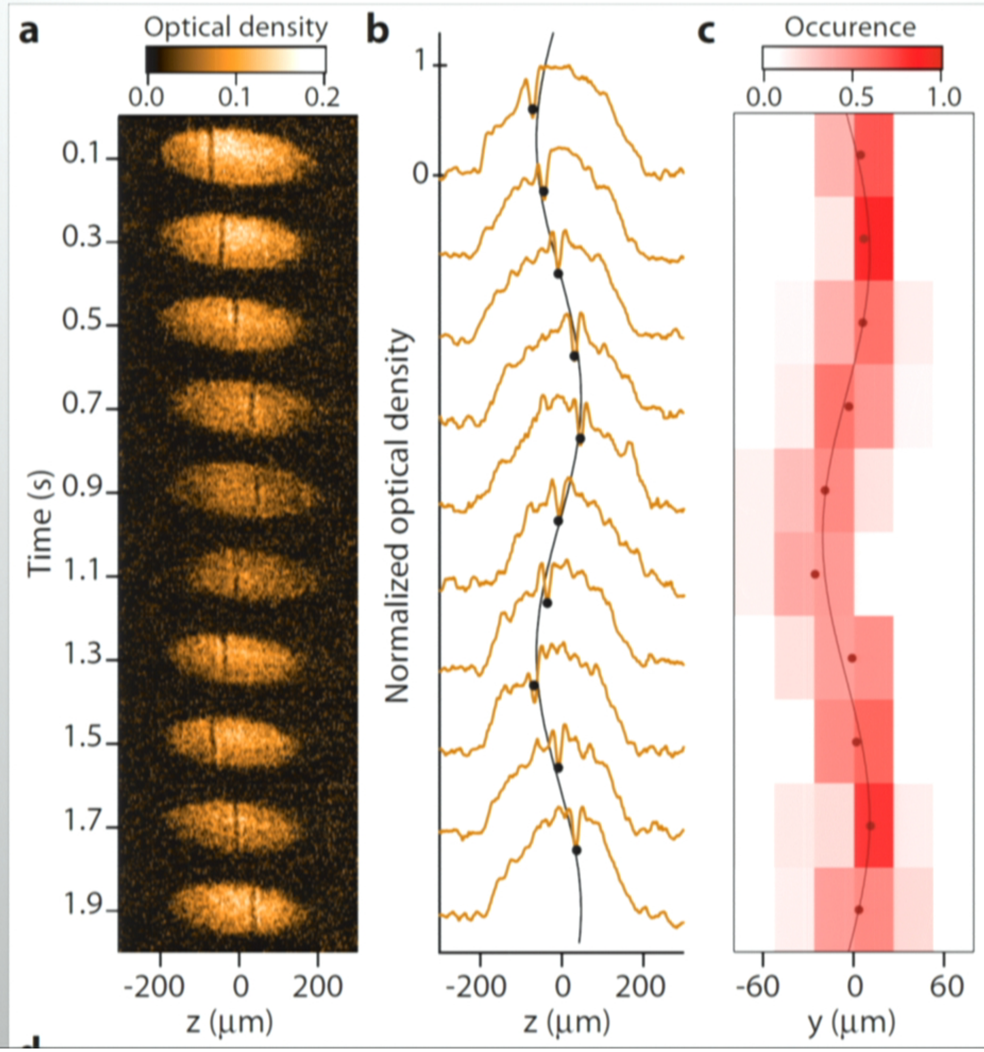
Instability Cascade of Solitary Waves in Unitary Fermi Gas



Instability Cascade of Solitary Waves in Unitary Fermi Gas

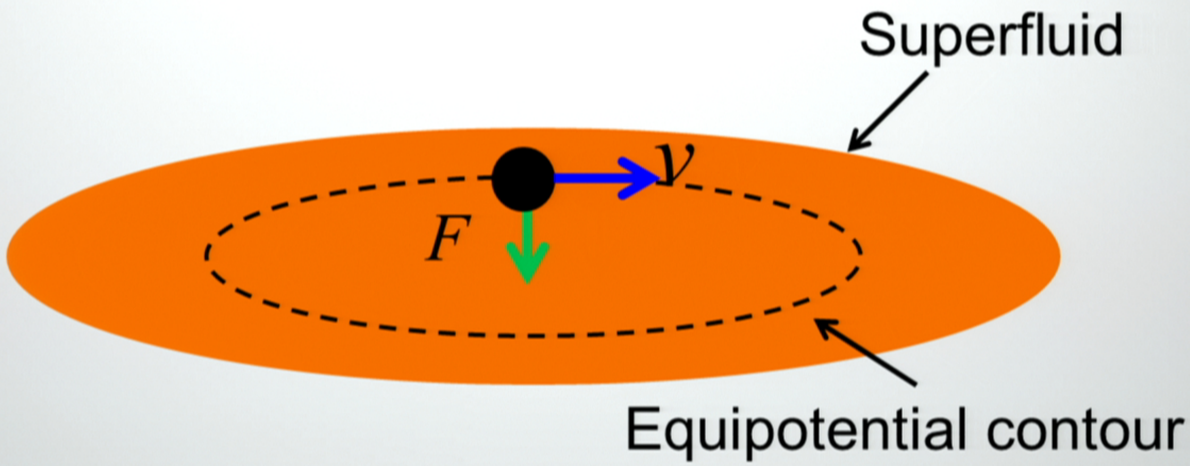


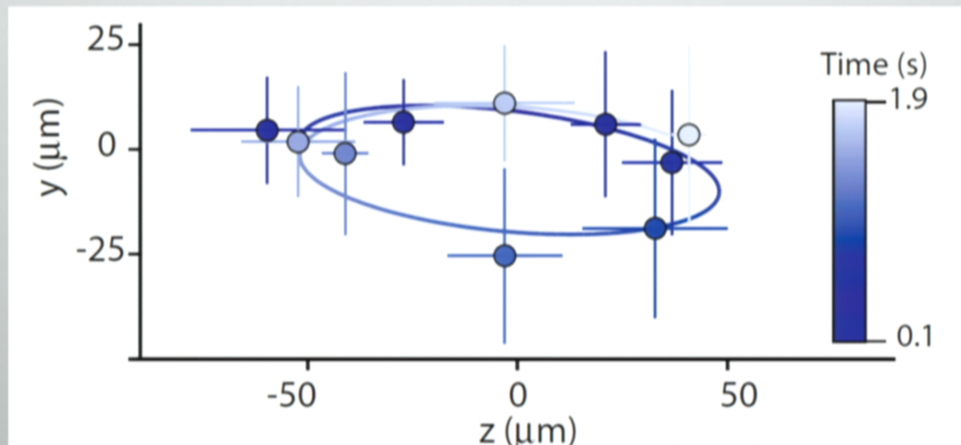
Direct observation of vortex precession



Direct observation of vortex precession

Magnus Force $h\bar{n}_S\vec{v}_V \times \hat{\Omega} = -\nabla E_V$ External Force on vortex





Compressibility controls Vortex Period

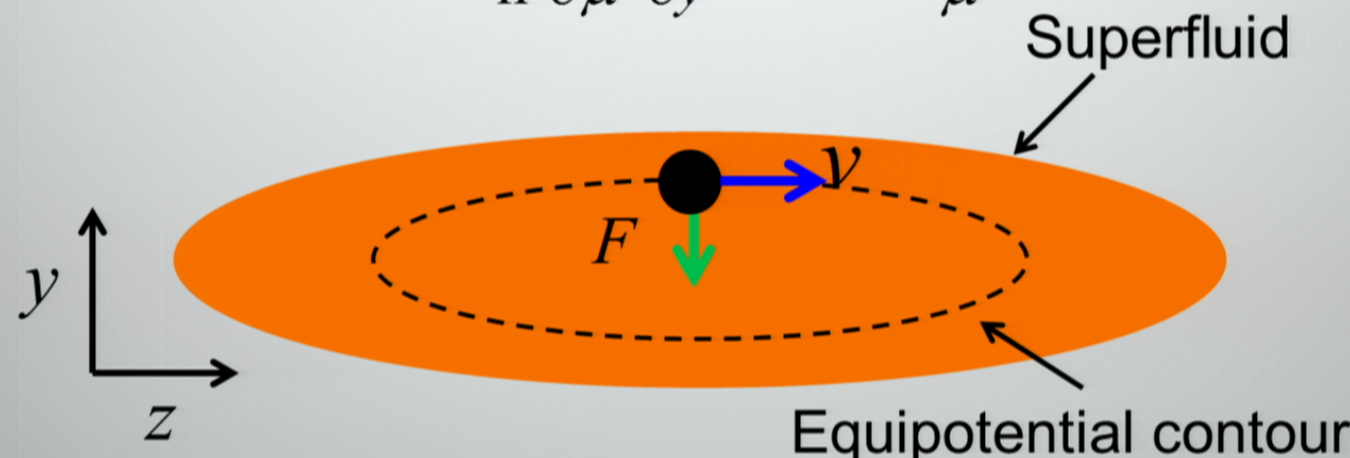
Magnus Force $h\bar{n}_S \vec{v}_V \times \hat{\Omega} = -\nabla E_V$ External Force on vortex

$\hat{\Omega}$ Circulation direction

$$E_V = \frac{\pi \hbar^2 L}{m_B} \bar{\mathrm{n}}(\mathrm{y}_V, \mathrm{z}_V)$$

$$F \sim -\nabla \bar{\mathrm{n}} \sim -\frac{\partial \bar{\mathrm{n}}}{\partial \mu} \nabla V$$

$$v_z \sim -\frac{1}{\bar{\mathrm{n}}} \frac{\partial \bar{\mathrm{n}}}{\partial \mu} \frac{\partial V}{\partial y} \sim -\alpha \frac{\hbar \omega_\perp \omega_z}{\mu} y \qquad \alpha = \frac{\mu}{\bar{n}} \frac{\partial \bar{n}}{\partial \mu}$$



Vortex Period in the BEC-BCS Crossover

Magnus Force $h\bar{n}_S \vec{v}_V \times \hat{\Omega} = -\nabla E_V$ External Force on vortex

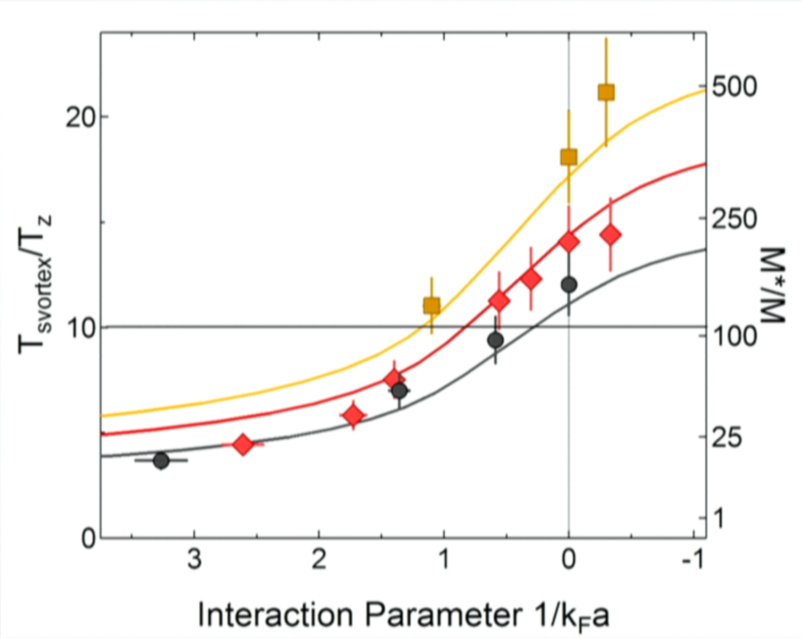
$$E_V = \frac{\pi\hbar^2 L}{m_B}\bar{\mathrm{n}}(\mathrm{y}_V, \mathrm{z}_V)$$

$$\frac{T_V}{T_z} = 4\frac{\mu(\mathrm{r}_V)}{\hbar\omega_\perp}\frac{1}{\alpha L}$$

$$\alpha = \frac{\mu}{\bar{n}}\frac{\partial\bar{n}}{\partial\mu} = \frac{3}{2}\ (\mathrm{BEC}) = 2\ (\mathrm{Unitarity})$$

Data from:
T. Yefsah, A. Sommer, M. J.-H. Ku, L. Cheuk, W. Ji, W. Bakr, MWZ, Nature **499**, 426–430 (2013)

Theory from:
Mark J.-H. Ku, W. Ji, B. Mukherjee, E. Guardado-Sanchez, L. W. Cheuk, T. Yefsah, MWZ, arXiv:1402.7052 PRL, to appear

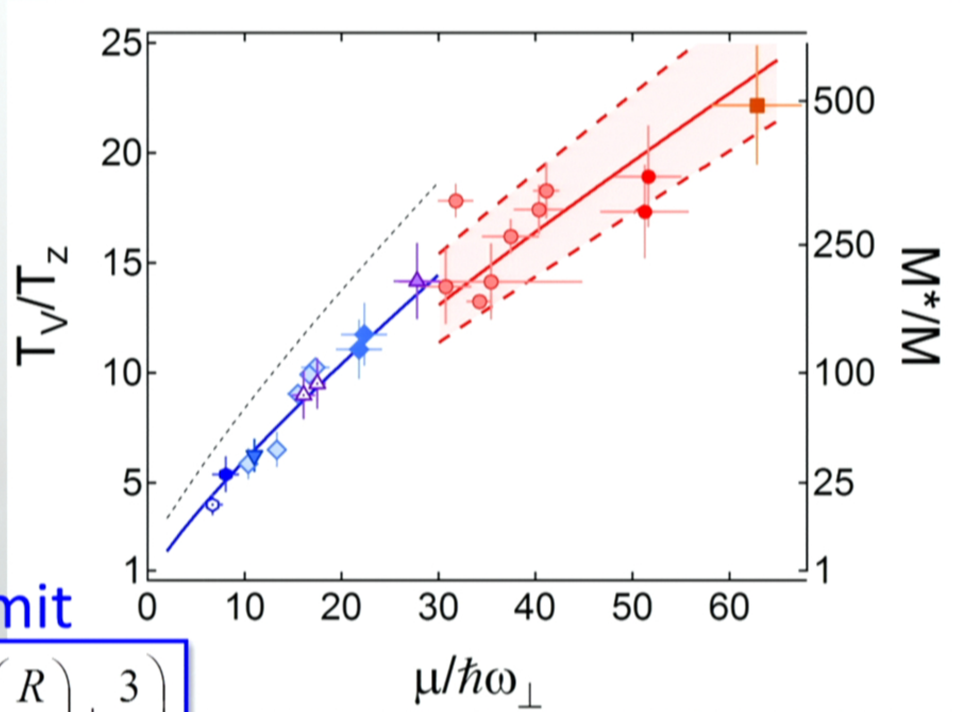


$N = 3 \times 10^5$

$L = \log(R/\xi)$

Vortex Period in the BEC-BCS Crossover

BEC limit



Resonance

$$\frac{8}{3}\frac{\mu}{\hbar\omega_\perp}\left(\ln\left(\frac{R}{\xi}\right)+\frac{3}{4}\right)$$

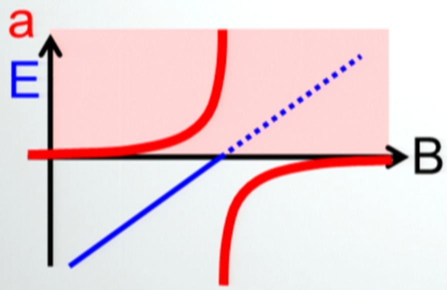
Lundh, Ao, PRA 2000
Fetter, Kim, JLTP 2001

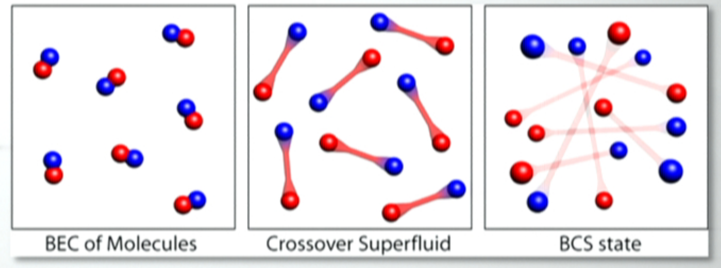
$$\frac{R}{\xi}=\frac{4\mu}{\hbar\omega_\perp}$$

MJHK, W. Ji, B. Mukherjee, E. Guardado-Sanchez, L.W. Cheuk, T. Yefsah, M. W. Zwierlein, arXiv:1402.7052 (2014), PRL, to appear

Creating strongly interacting Fermi Gases

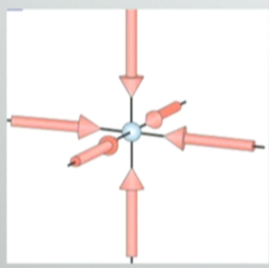
Feshbach Resonances → e.g. BEC-BCS Crossover

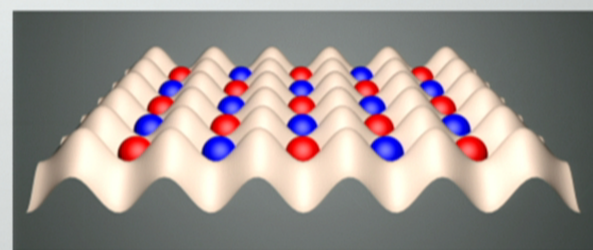




Quantum Gases → Quantum Fluids

Optical Lattices → e.g. Fermi-Hubbard model

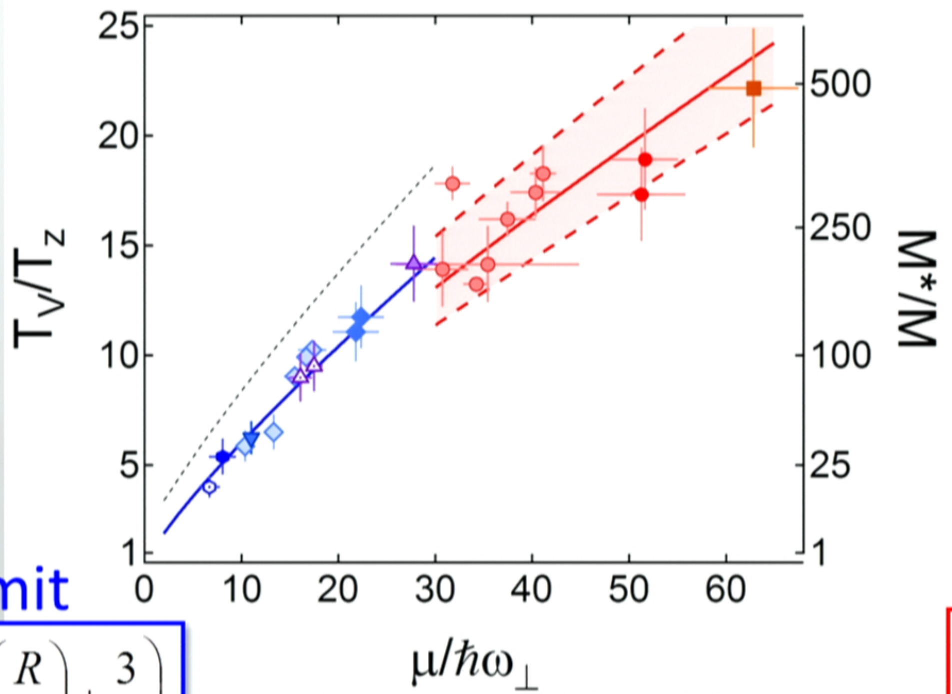




Quantum Gases → Quantum Solids

Vortex Period in the BEC-BCS Crossover

BEC limit



Resonance

$$\frac{8}{3}\frac{\mu}{\hbar\omega_\perp}\left(\ln\left(\frac{R}{\xi}\right)+\frac{3}{4}\right)$$

$$2\frac{\mu}{\hbar\omega_\perp}\ln\left(\frac{R}{\xi}\right)$$

Lundh, Ao, PRA 2000
Fetter, Kim, JLTP 2001

$$\frac{R}{\xi}=\frac{4\mu}{\hbar\omega_\perp}$$

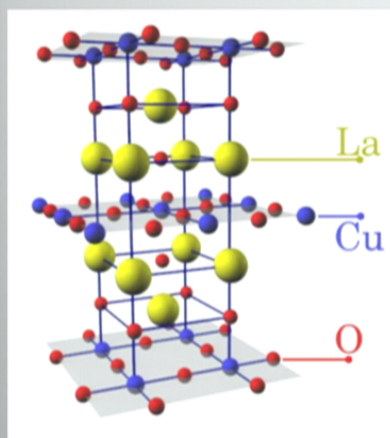
$$\frac{R}{\xi}=0.5\ldots2\times\frac{2}{\sqrt{0.37}}\frac{\mu}{\hbar\omega_\perp}$$

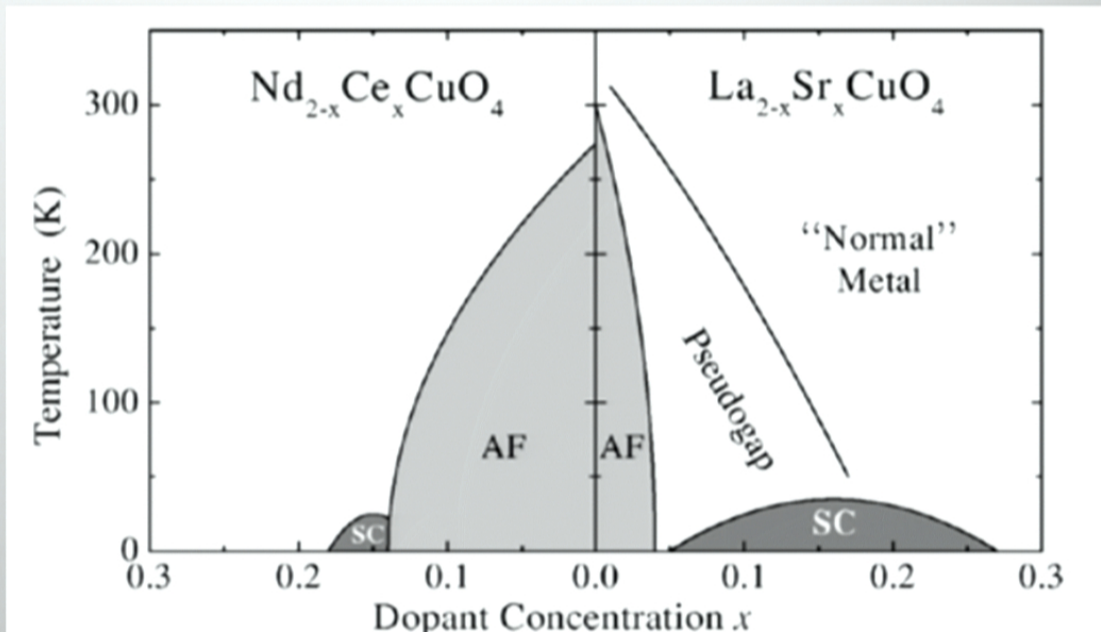
MJHK, W. Ji, B. Mukherjee, E. Guardado-Sanchez, L.W. Cheuk, T. Yefsah, M. W. Zwierlein, arXiv:1402.7052 (2014), PRL, to appear

Fermi-Hubbard Model

$$H = -t \sum_{\langle i,j \rangle,\sigma} c_{i\sigma}^{\dagger} c_{j\sigma} + U \sum_{i} \hat{n}_{i\uparrow} \hat{n}_{i\downarrow}$$

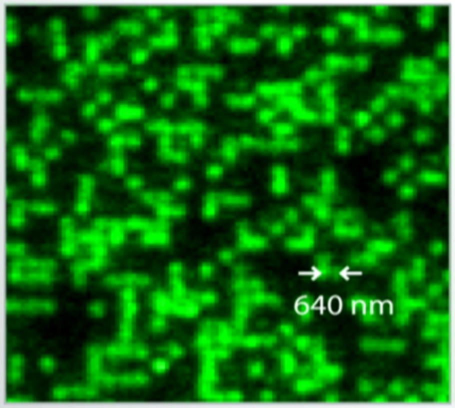
Introduced to describe strongly correlated electrons
Believed to contain essential features of
High-Temperature Superconductors



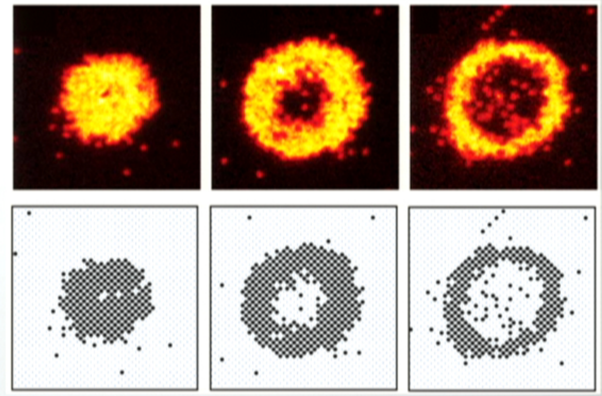


Damascelli et al., RMP 2003

Quantum Gas Microscopy



Bosons
^{87}Rb



Bakr *et al.*, Nature 462, 74-77 (2009)

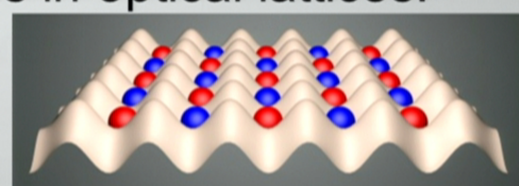
Sherson *et al.*, Nature 467, 68-71 (2010)

Also, recently: ^{174}Yb bosons, Miranda et al., PRA 91, 063414 (2015)
Yamamoto et al., NJP 18, 023016 (2016)

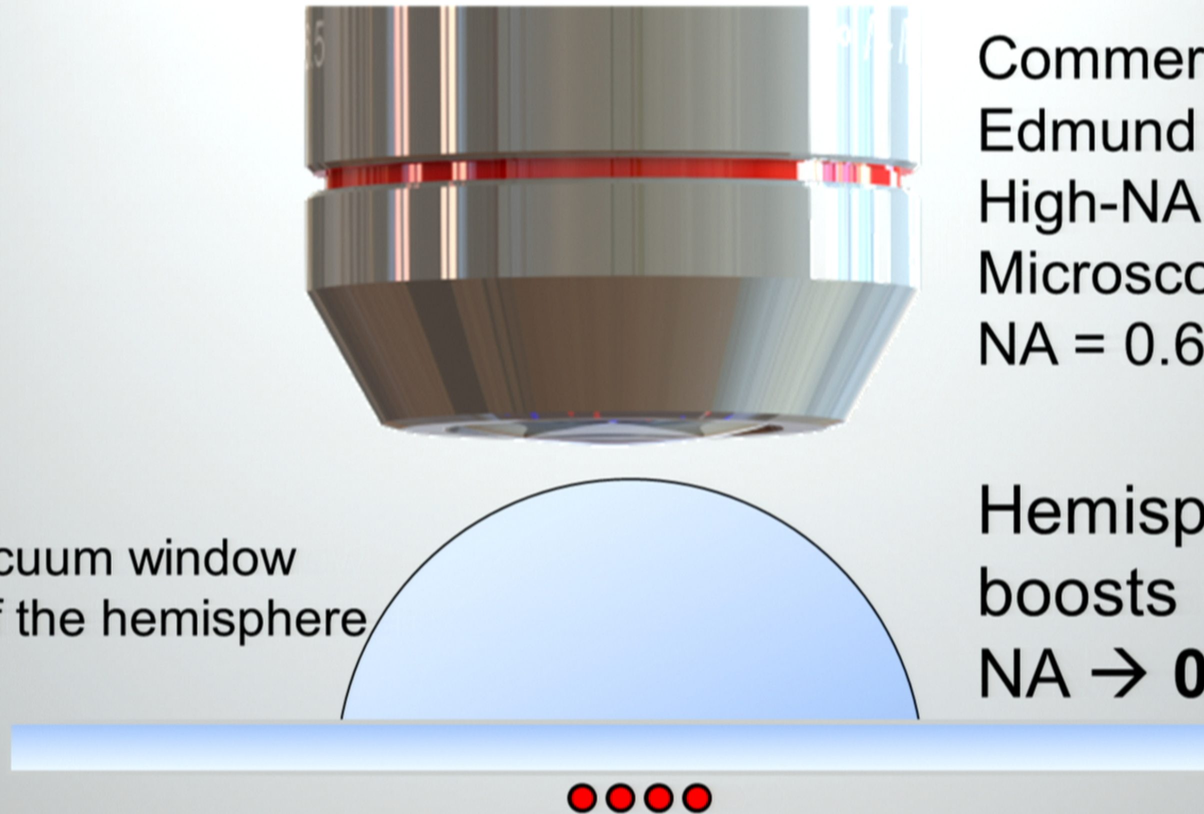
Great Prospect for Fermi Gas Microscopes:

Single-site resolution imaging of fermions in optical lattices:

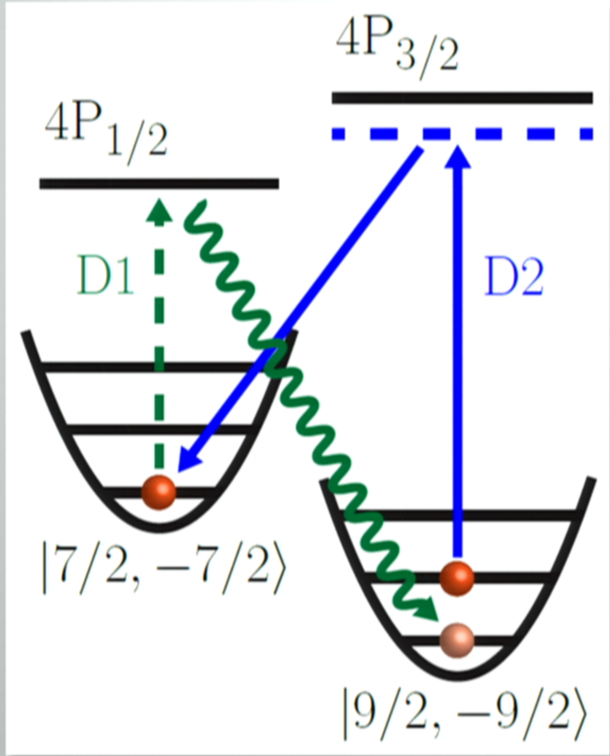
→ Clean, tunable, controllable systems
→ Directly measure magnetic order
→ Higher-order real-space correlations
→ Single site addressing, Quantum Gates, Implant Impurities…

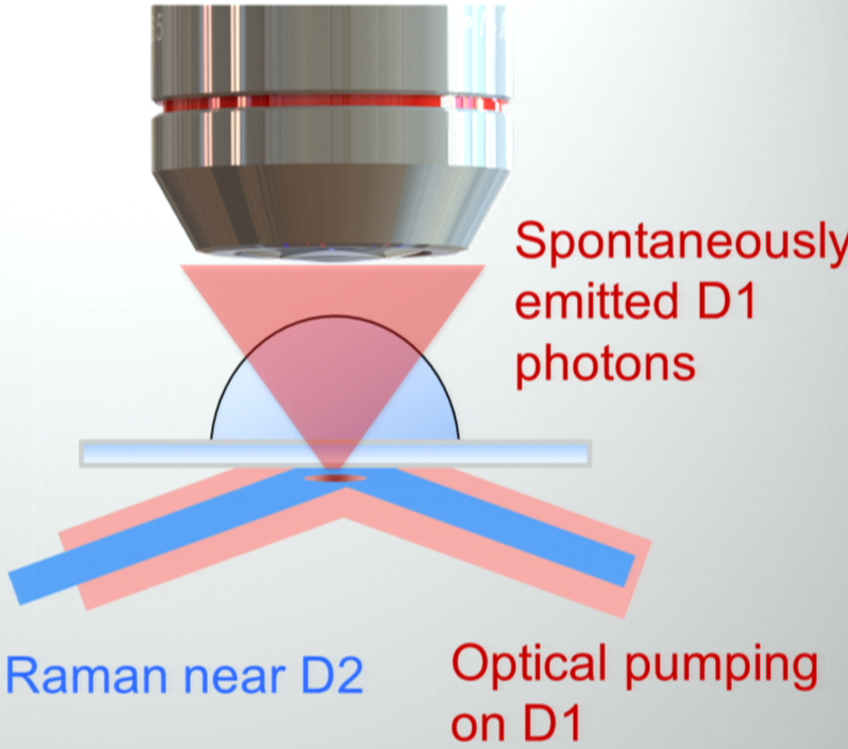


Obtaining single-site resolution



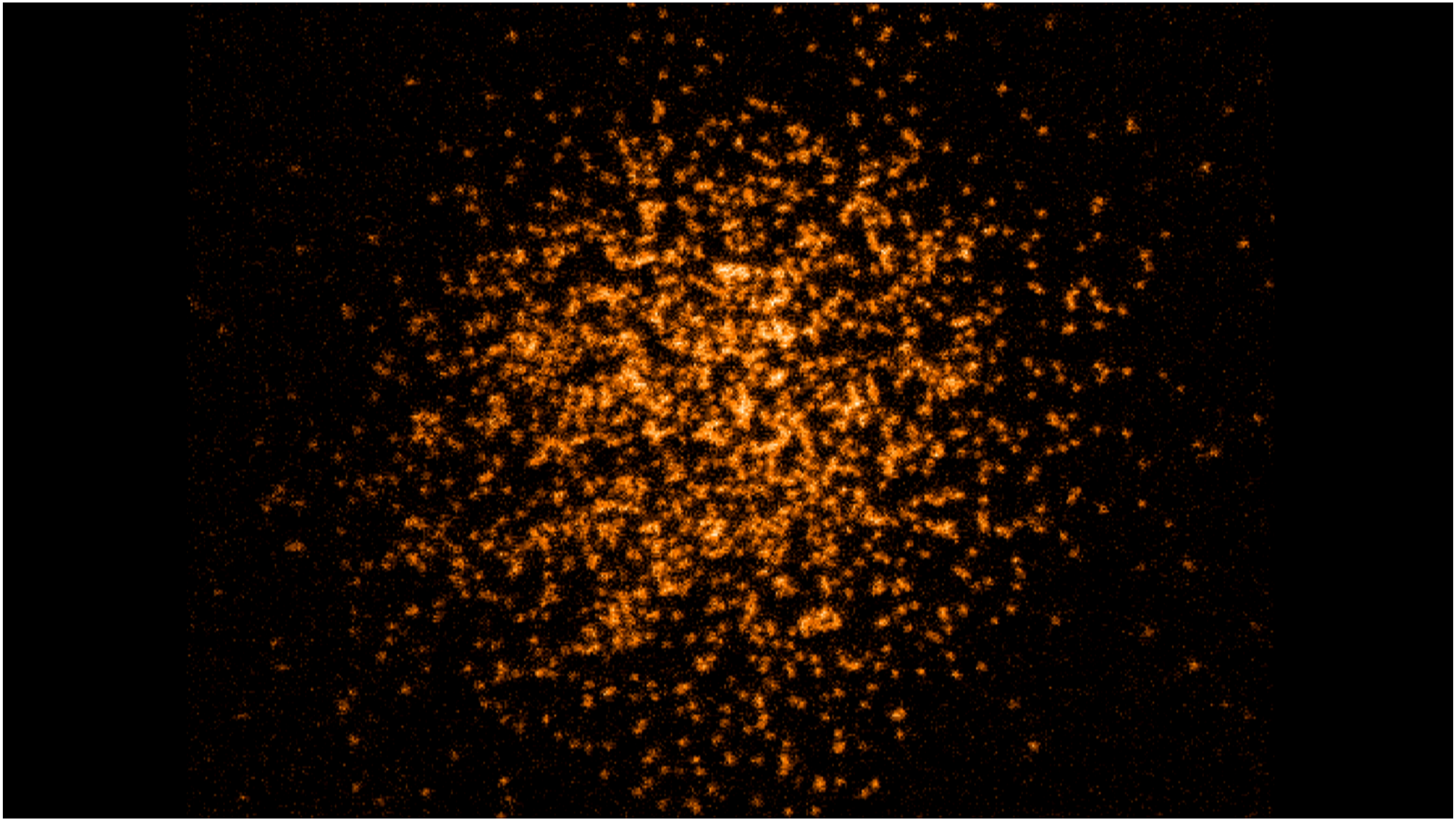
Raman Sideband Cooling



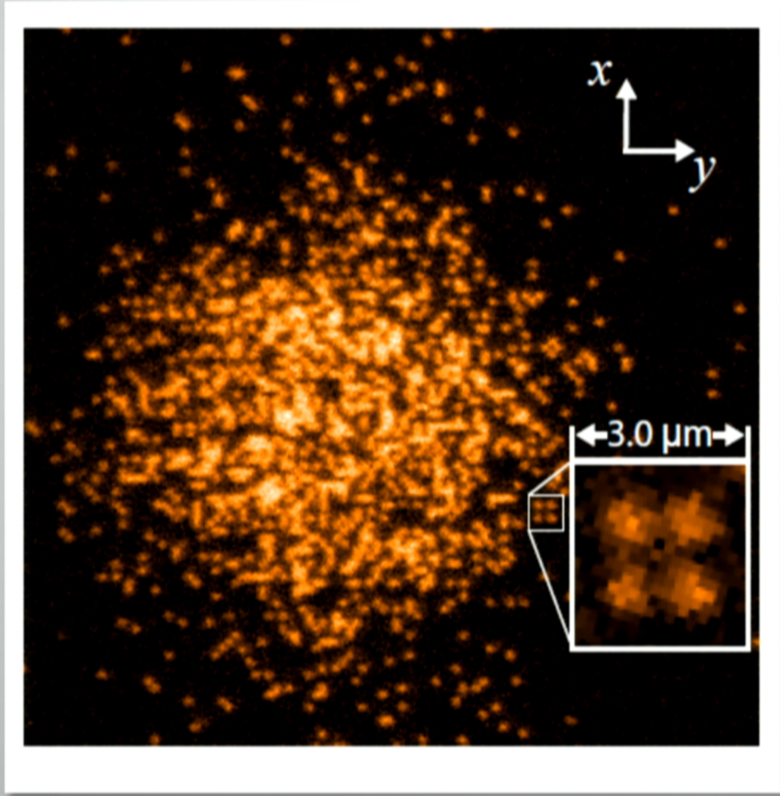


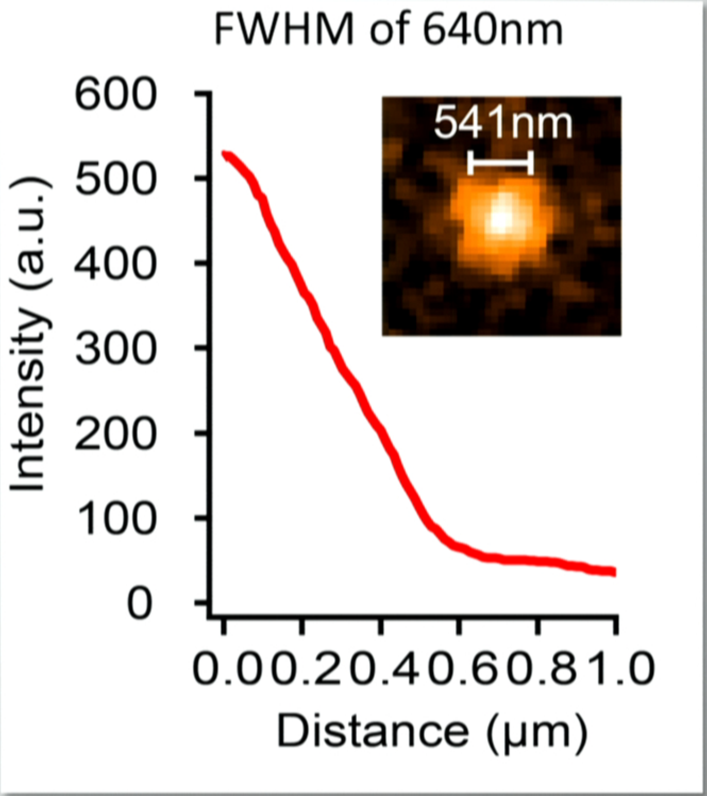
Imaging is spin-insensitive, and parity-projecting

For ions: Wineland, Dehmelt, … for atoms: Jessen (2D), Chu&Vuletic, Weiss (3D), …



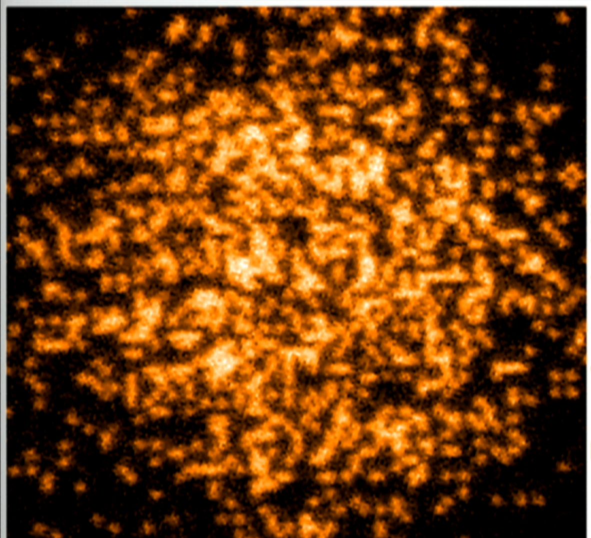
Single-site resolution imaging for ^{40}K

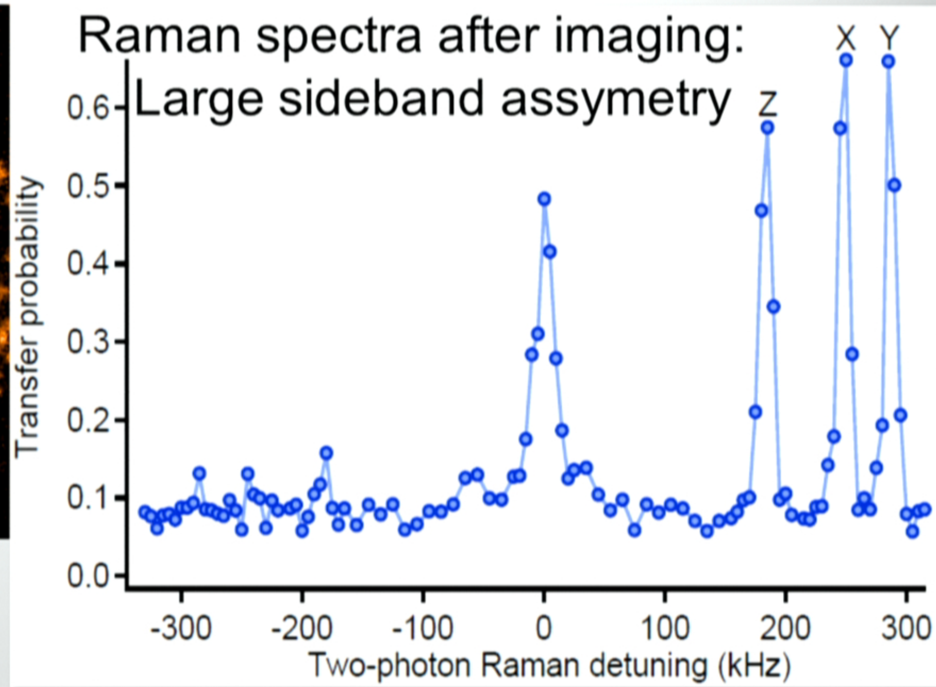




L. Cheuk, M. Nichols, M. Okan, T. Gersdorf, V. Ramasesh, W. Bakr, T. Lompe, MWZ
PRL **114**, 193001 (2015)

Keeping atoms cold



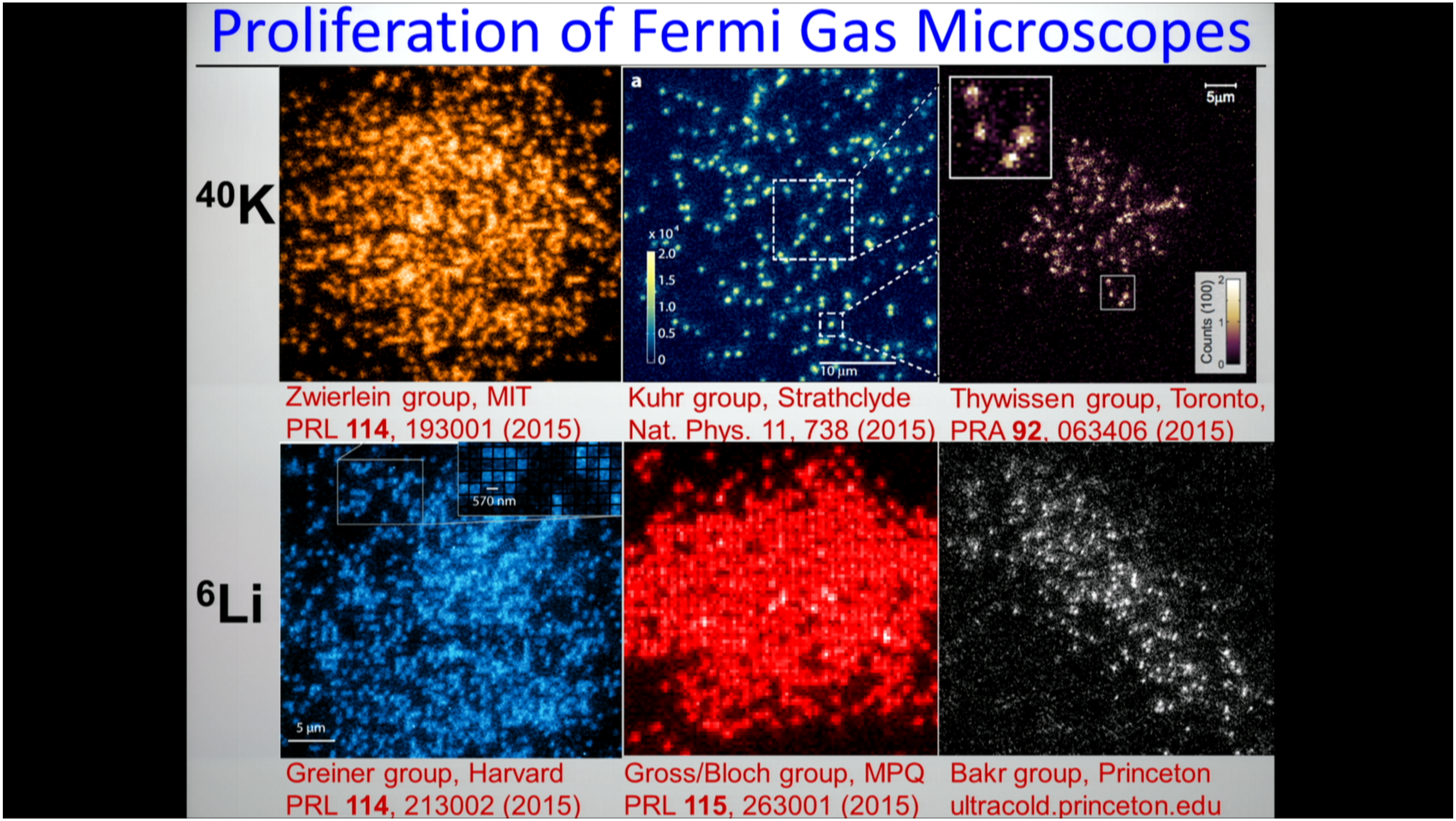


Occupation numbers: n_x=0.08, n_y=0.08, n_z=0.14

After 2 seconds of imaging:

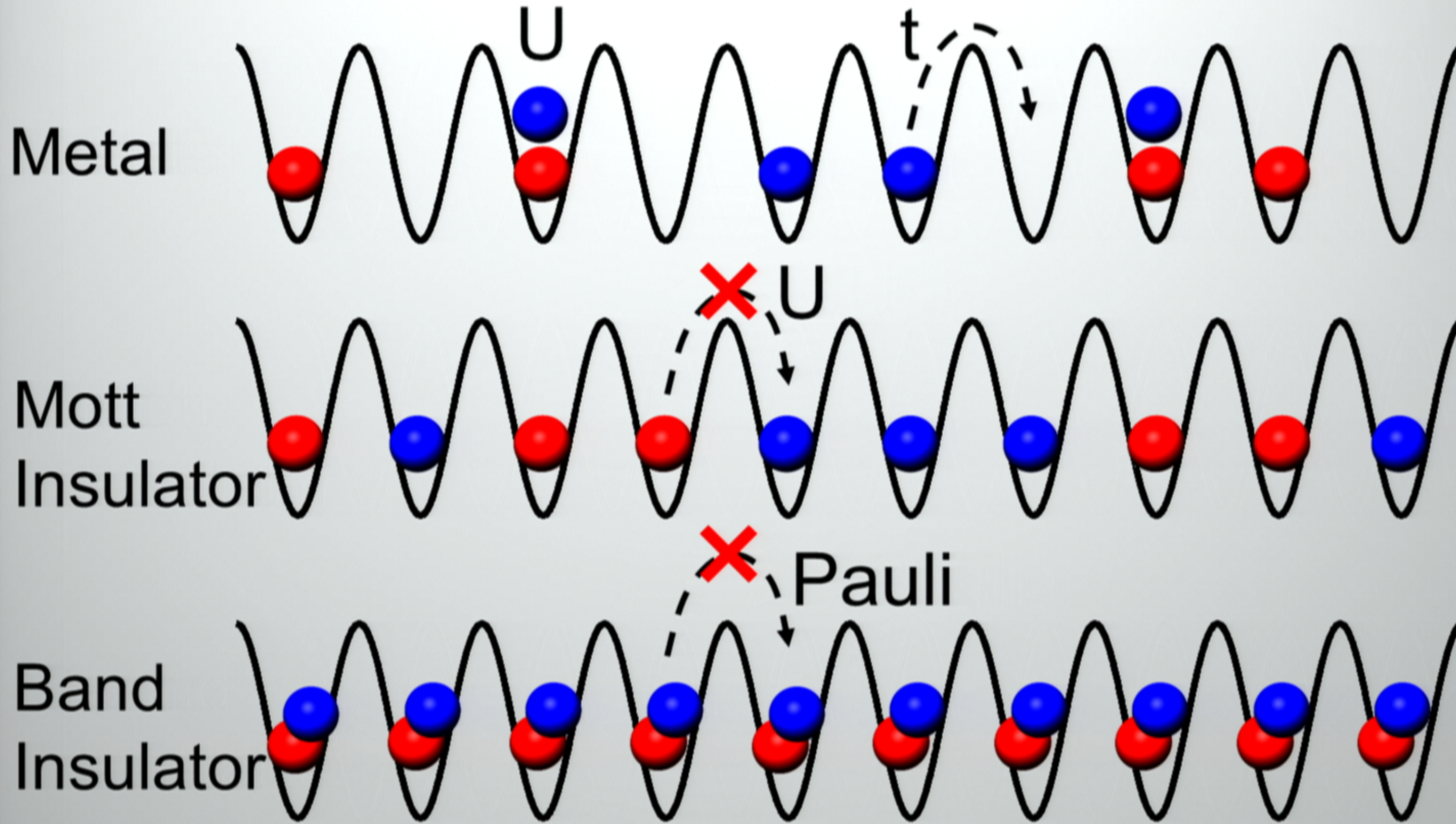
3D Ground State Population 72%

L. Cheuk, M. Nichols, M. Okan, T. Gersdorf, V. Ramasesh, W. Bakr, T. Lompe, MWZ
PRL **114**, 193001 (2015)


Proliferation of Fermi Gas Microscopes
40K
6Li
a
x 10^4
2.0
1.5
1.0
0.5
0
10 μm
5μm
Counts (100)
570 nm
5 μm
Zwierlein group, MIT
PRL 114, 193001 (2015)
Kuhr group, Strathclyde
Nat. Phys. 11, 738 (2015)
Thywissen group, Toronto,
PRA 92, 063406 (2015)
Greiner group, Harvard
PRL 114, 213002 (2015)
Gross/Bloch group, MPQ
PRL 115, 263001 (2015)
Bakr group, Princeton
ultracold.princeton.edu

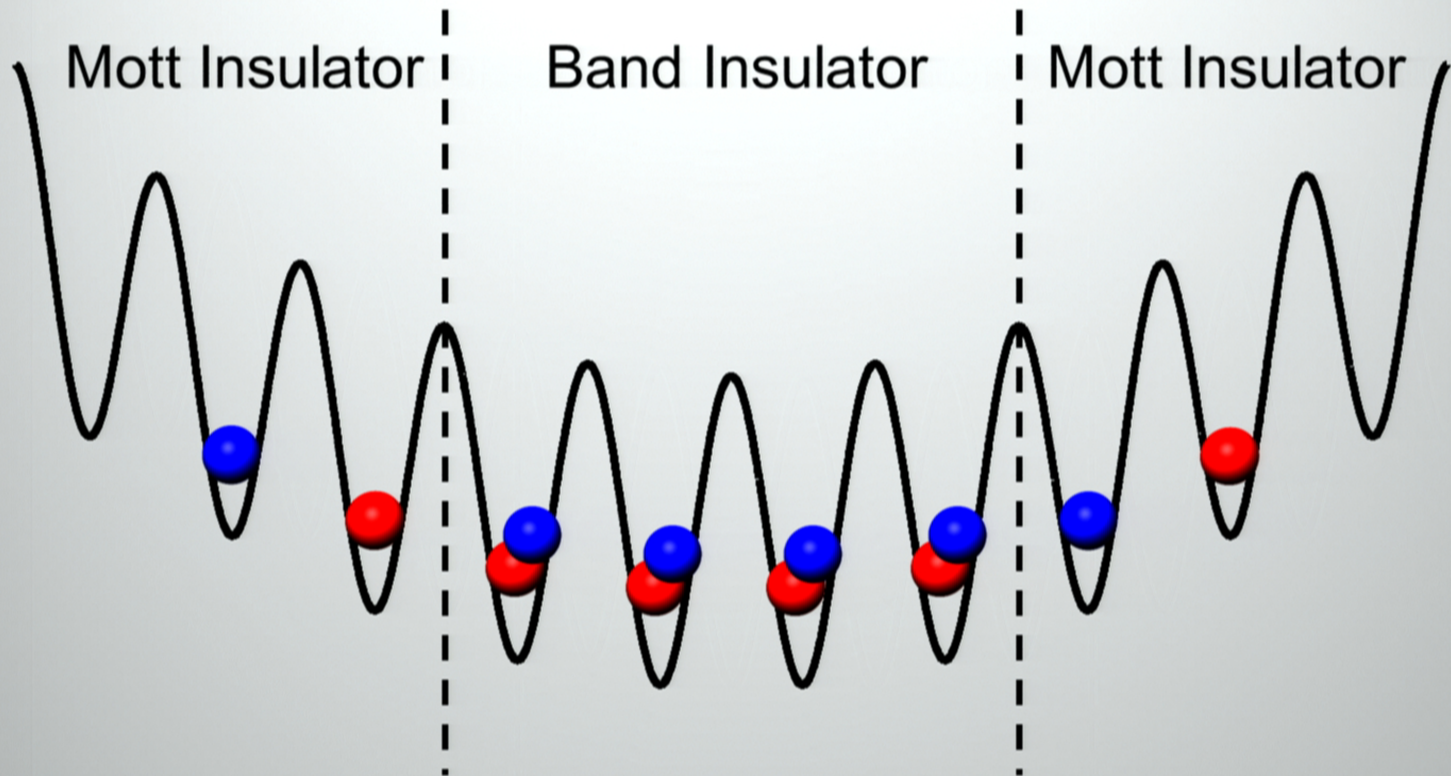
Fermi-Hubbard Model

Fermions hopping (t) and repelling (U) in a lattice



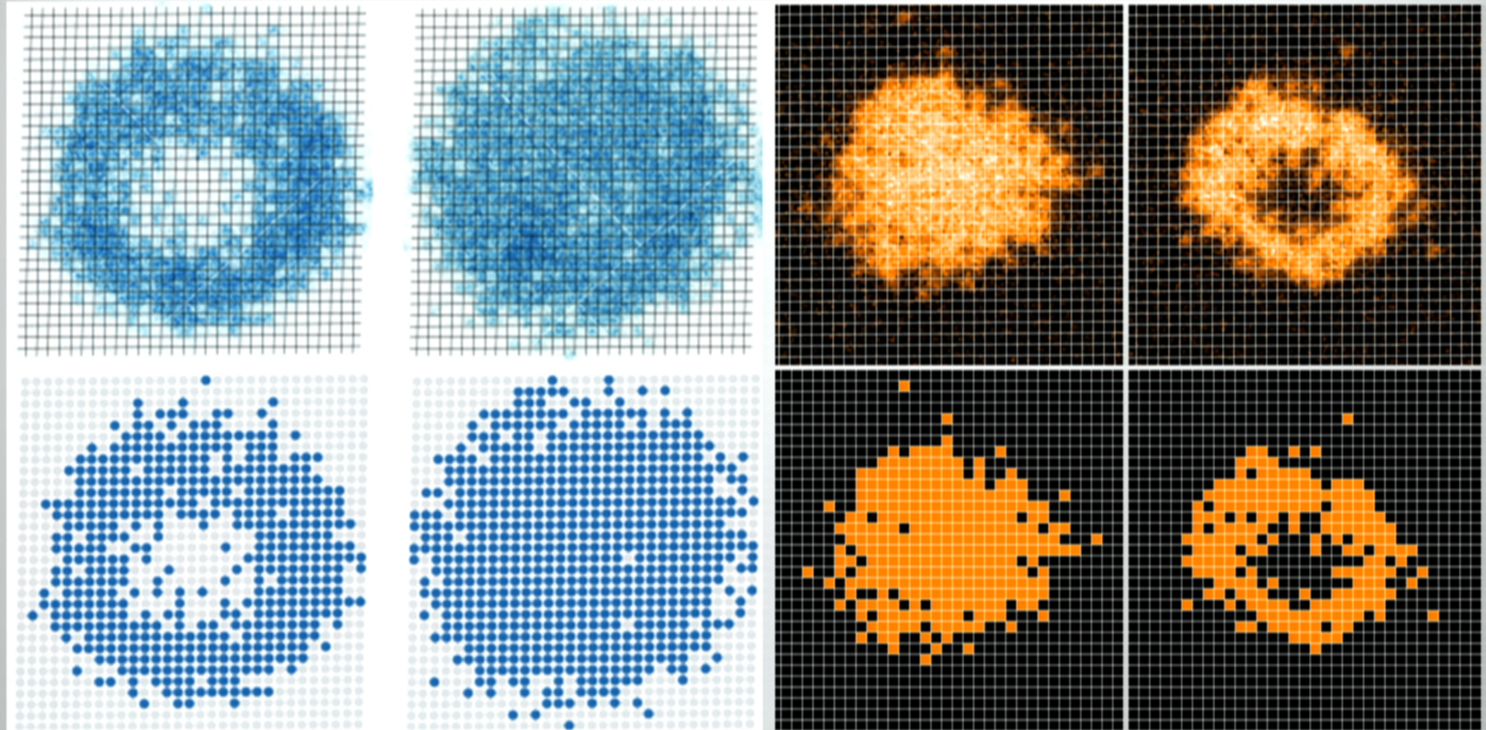
Fermi-Hubbard Model in a Trap

Fermions hopping (t) and repelling (U) in a lattice



At finite temperature: metallic states in between and outside

Fermionic Mott Insulators of ^{6}Li and ^{40}K



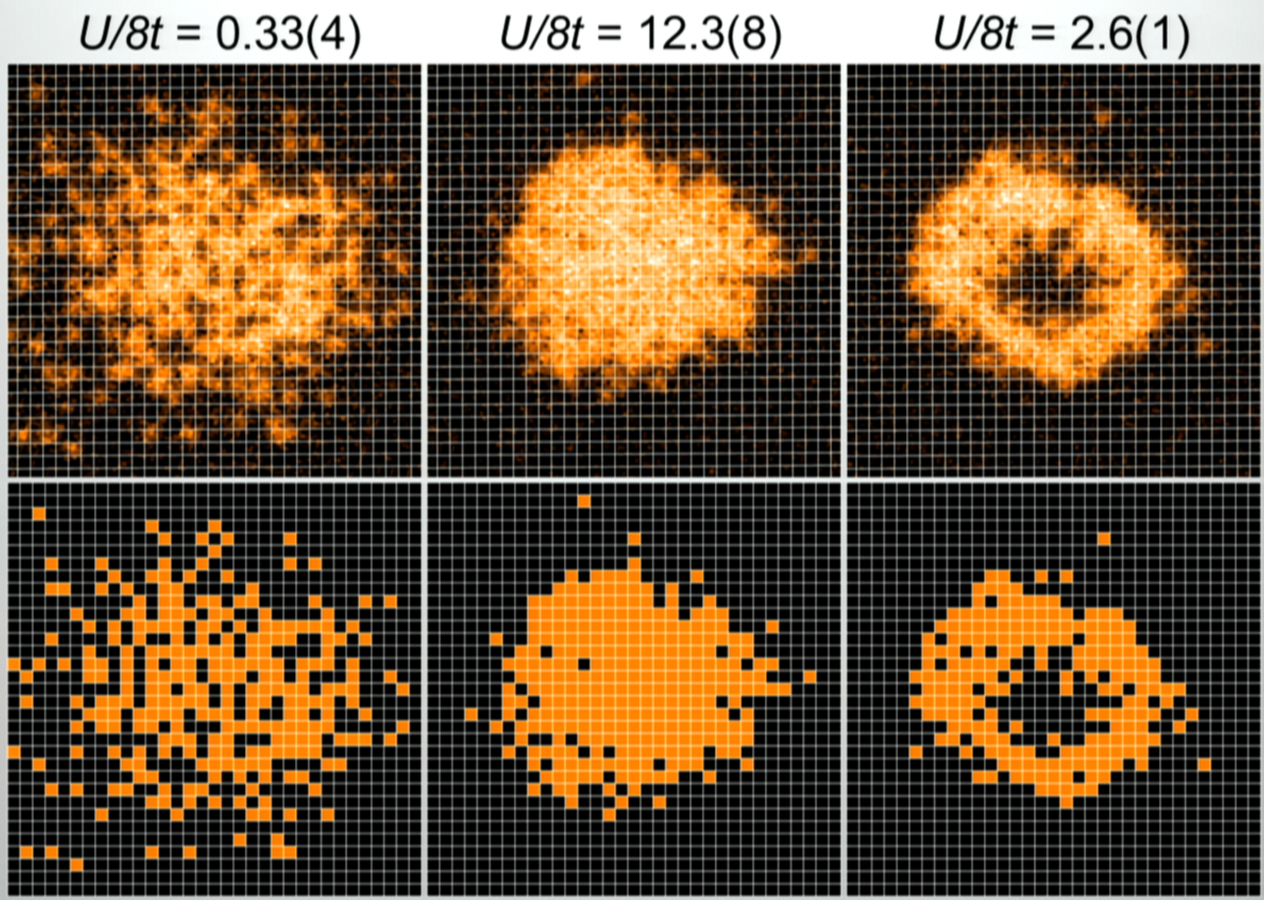
^{6}Li

D. Greif et al, Science **351** 953-957 (2016)

^{40}K

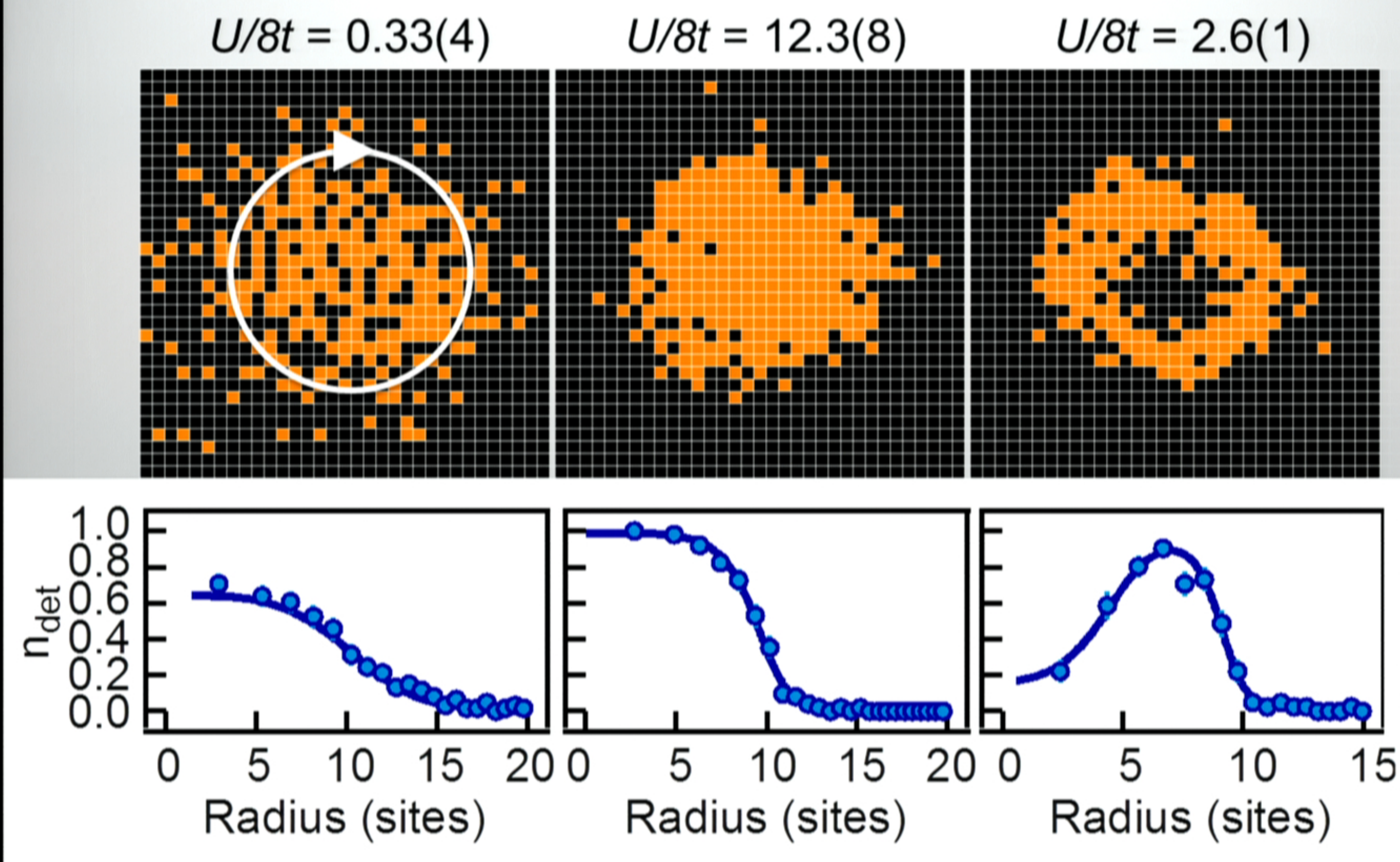
L.W. Cheuk, M.A. Nichols, K. Lawrence, M. Okan, H. Zhang, MWZ, PRL **116**, 235301 (2016)

States of the Fermi-Hubbard Model



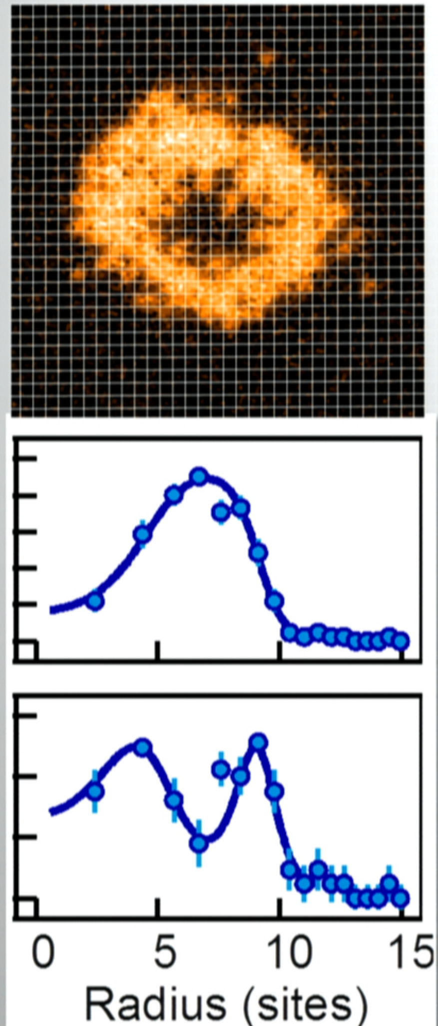
Cheuk, Nichols, Lawrence, Okan, Zhang, MWZ, PRL 116, 235301 (2016)
Single-Site Imaging of Mott Insulators in ^{6}Li: Greif et al., Science 351, 953 (2016)

Density Profiles



Cheuk, Nichols, Lawrence, Okan, Zhang, MWZ, PRL 116, 235301 (2016)
Single-Site Imaging of Mott Insulators in ^{6}Li: Greif et al., Science 351, 953 (2016)

The Local Moment



Parity imaging detects

singly occupied sites

Corresponds *for fermions* to operator

$$\hat{m}^2_{z,i} = (\hat{n}_{\uparrow,i} - \hat{n}_{\downarrow,i})^2$$

Local Moment:

$$m^2_{z,i} = \left\langle (\hat{n}_{\uparrow,i} - \hat{n}_{\downarrow,i})^2 \right\rangle$$

Variance:

$$\Delta m^4_{z,i} = m^2_{z,i}(1 - m^2_{z,i})$$

Variance is not giving new information

Local Moments in Fermi-Hubbard

$$H = -t \sum_{<i,j>,\sigma} c^{\dagger}_{\sigma,i} c_{\sigma,j} + U \sum_{i} \hat{n}_{\uparrow,i} \hat{n}_{\downarrow,i} - \mu \sum_{i} \left(\hat{n}_{\uparrow,i} + \hat{n}_{\downarrow,i} \right)$$

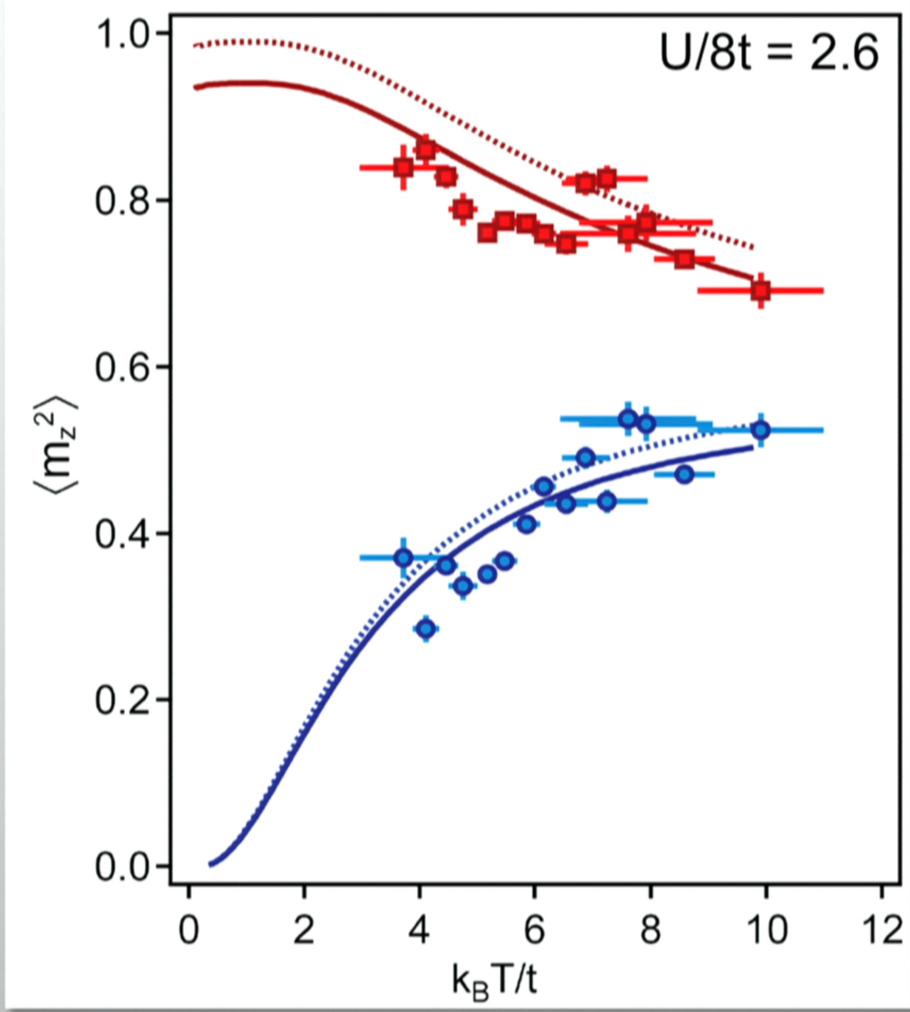
For fermions: $\hat{n}_{\uparrow}\hat{n}_{\downarrow} = -\frac{1}{2}\underbrace{(\hat{n}_{\uparrow} - \hat{n}_{\downarrow})^2}_{\hat{m}^2_{z,i}} + \frac{1}{2}(\hat{n}_{\uparrow} + \hat{n}_{\downarrow})$

$$H = -t \sum_{<i,j>,\sigma} c^{\dagger}_{\sigma,i} c_{\sigma,j} - \frac{U}{2} \sum_{i} \hat{m}^2_{z,i} - \mu' \left(\hat{n}_{\uparrow} + \hat{n}_{\downarrow} \right)$$

$\mu' = \mu - \frac{U}{2}$

- Interactions promote the formation of local moments
- Images directly yield potential energy

Formation of Local Moments



Red:
Half-Filling
$n = 1$

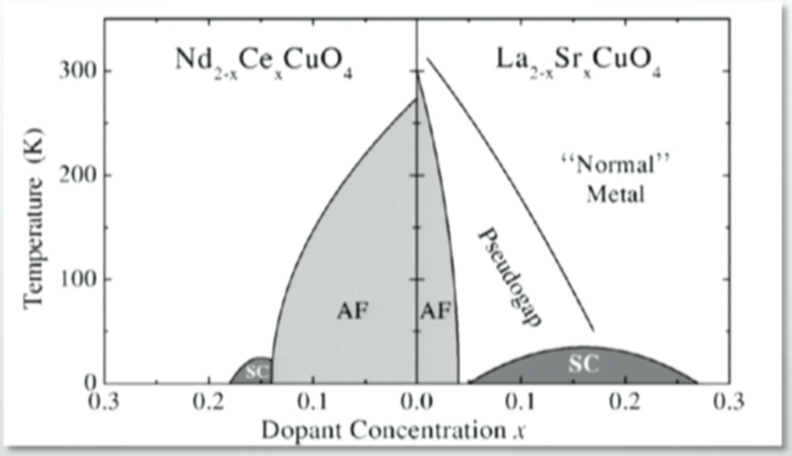
→ Forming a Mott Insulator

Blue:
$\mu / U = -0.25$

→ Metallic region

$n \to 0$ as $T \to 0$

Spin and Charge Correlations



- At half-filling: expect AF spin correlations
- But: Superconductivity needs doping
  → away from half filling
- Here: Charge correlations should dominate

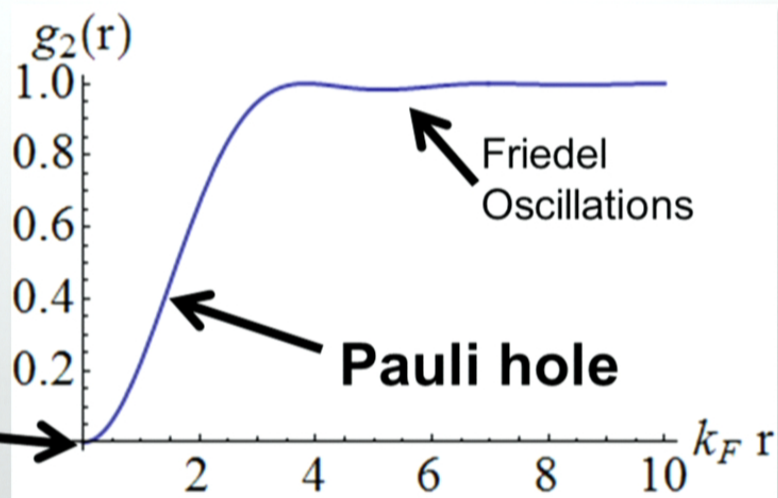
→ Need to look at both spin and charge correlations

Density Correlations in Fermi Gases

$$g_2(r) = \frac{\langle n(r)n(0)\rangle}{\langle n(r)\rangle\langle n(0)\rangle}$$

g_2 function: Knowing a fermion is at ***r***=0, what is the probability to find another one at ***r***?

Fermion anti-bunching



Pauli hole extends about one interparticle spacing

No direct experimental observation of spatial hole

Signature of anti-bunching in TOF:
T. Rom et al., Nature 2006, Jeltes et al., Nature 2007
Reduction of density fluctuations:
Sanner et al., PRL 2010, Mueller et al., PRL 2010

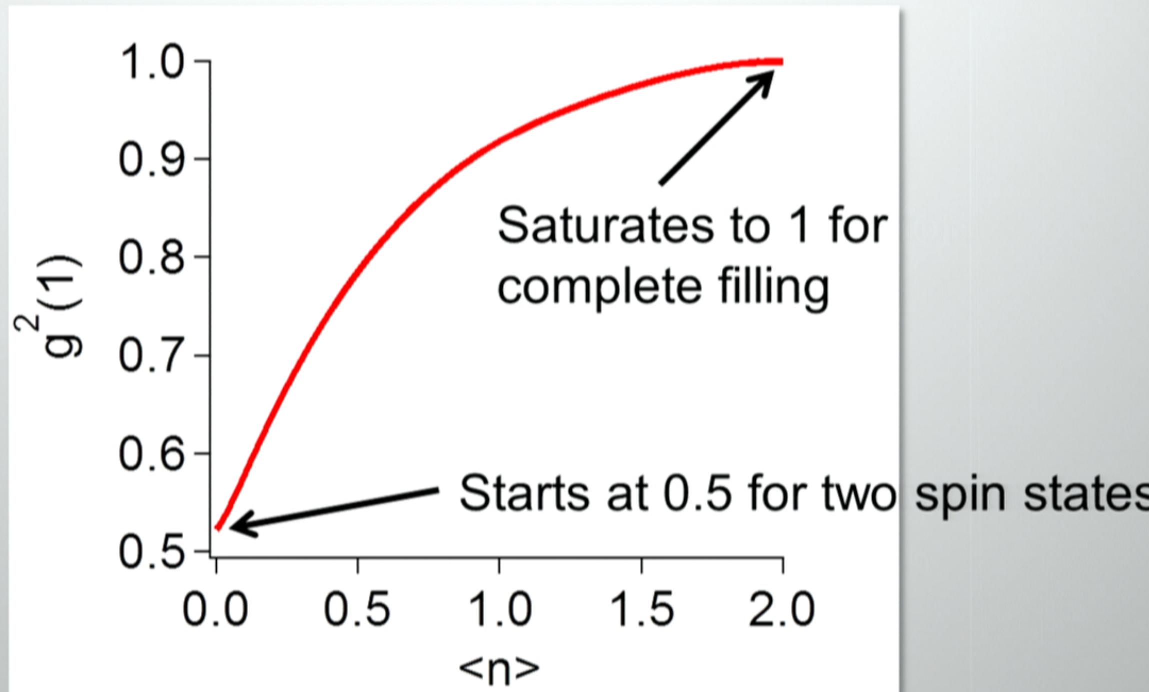
Density Correlations in a Lattice Gas

$$g_2(i) = \frac{\langle \hat{n}_i \hat{n}_0 \rangle}{\langle \hat{n}_i \rangle^2}$$

g_2 always reduced below one

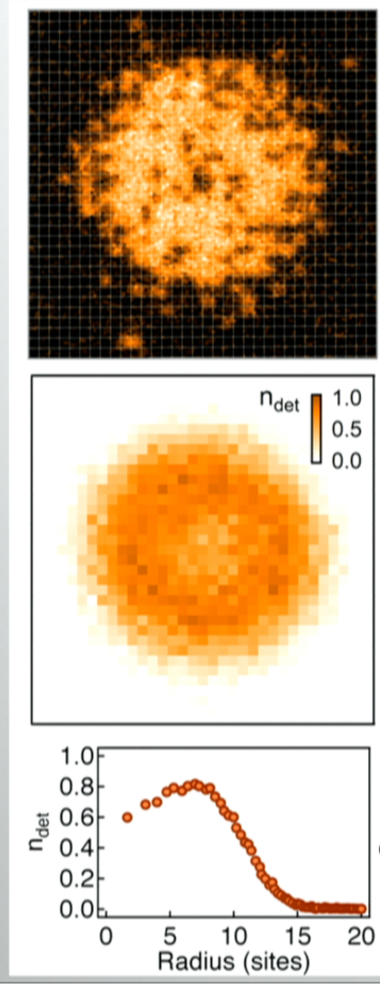
Low filling: lattice spacing << interparticle distance

→ One site away one is deep inside the Pauli hole

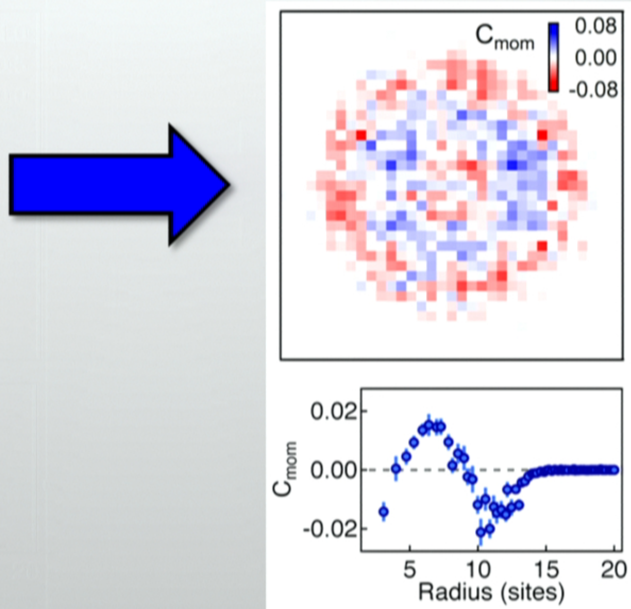


Measuring Spin and Charge Correlations

$m_z{}^2$

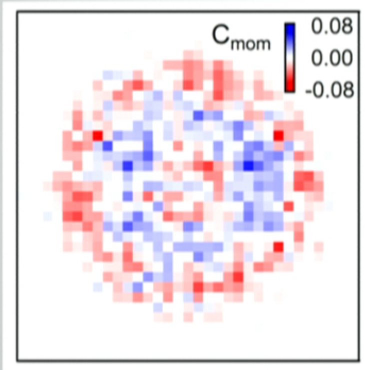


$\langle m_z{}^2 \rangle$



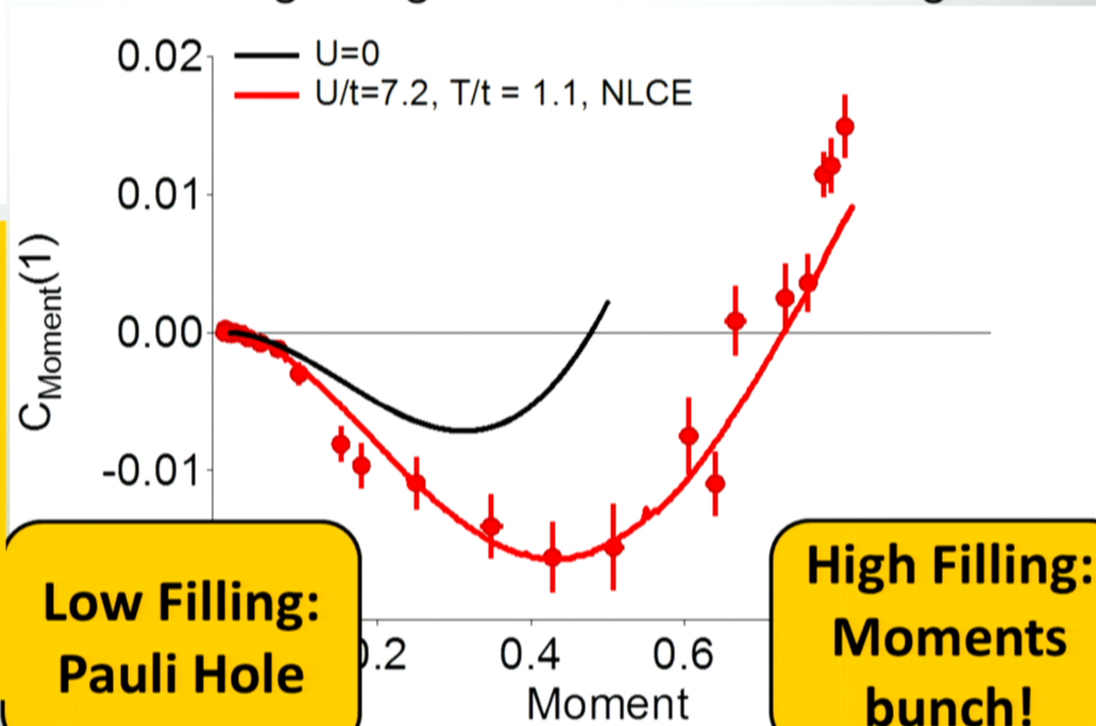
$\langle m_{z,i}^2 m_{z,j}^2 \rangle_c$

Moment Correlator: Seeing the Pauli Hole



$$C_{moment}(\mathrm{i},\mathrm{j}) = \langle m_{z,i}{}^2 m_{z,\mathrm{j}}{}^2 \rangle - \langle m_{z,i}{}^2 \rangle \langle m_{z,\mathrm{j}}{}^2 \rangle$$

Changes sign as a function of filling



Excellent agreement (no fit) with

New NLCE data
Marcos Rigol and
Ehsan Khatami

New DQMC data
Thereza Paiva
Nandini Trivedi

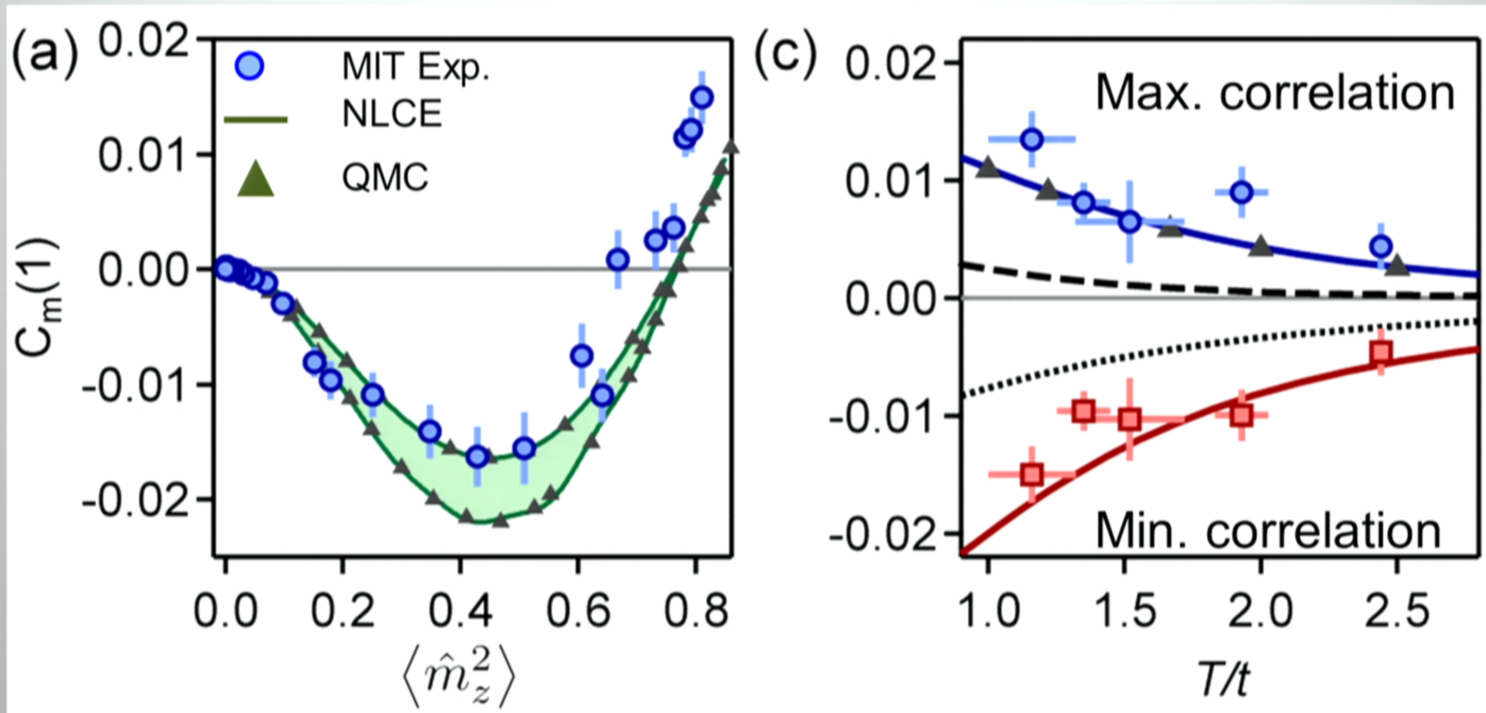
Low Filling: Pauli Hole

High Filling: Moments bunch!

Cheuk, Nichols, Lawrence, Okan, Zhang, Khatami, Trivedi, Paiva, Rigol, Zwierlein, arXiv: 1606.04089 (2016)

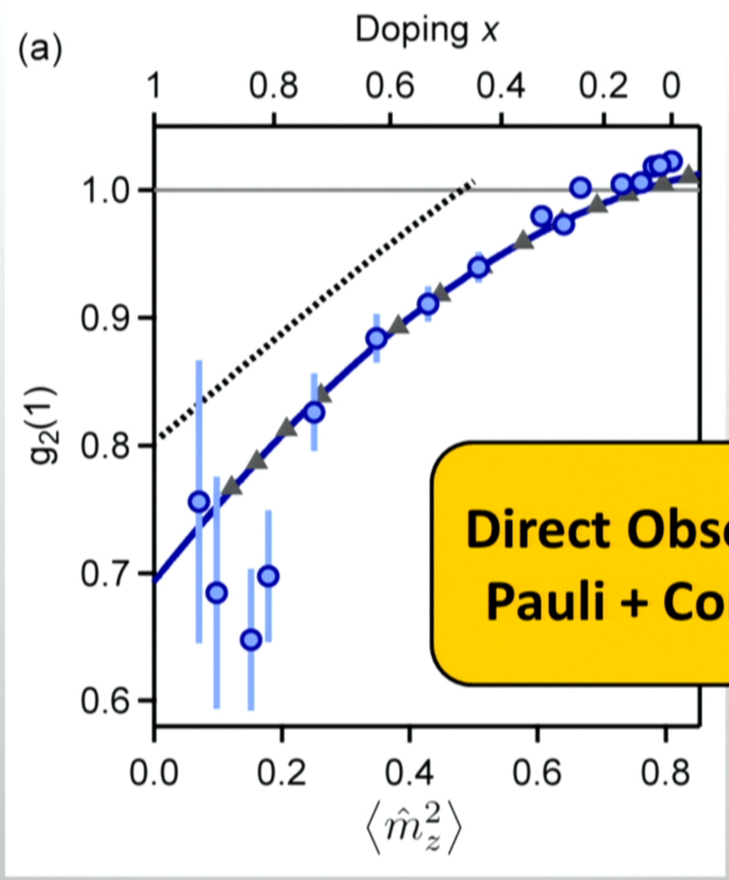
Moment Correlations

$$C_{moment}(\mathrm{i},\mathrm{j}) = \langle m_{z,i}{}^2 m_{z,\mathrm{j}}{}^2 \rangle - \langle m_{z,i}{}^2 \rangle \langle m_{z,\mathrm{j}}{}^2 \rangle$$



Pair correlation function

$$g_2(r) = \langle \hat{m}_z^2(r)\hat{m}_z^2(0)\rangle / \langle \hat{m}_z^2\rangle^2$$

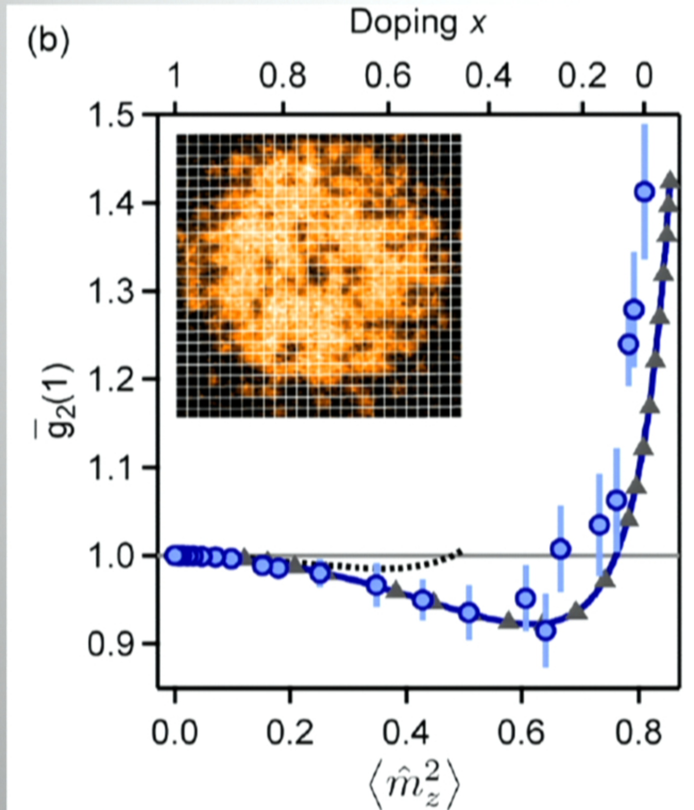


Direct Observation of the Pauli + Correlation Hole

Pair correlation function for "Anti-Moments"

$$< m_{z,i}^2 m_{z,j}^2 > = < (1 - m_{z,i}^2)(1 - m_{z,j}^2) > + \text{disconnected avgs.}$$

Moment correlations = Correlations of "Anti-moments", holes and doubles



Doublon-Hole Bunching

Expected upon singlet formation: Every singlet can fluctuate into a doublon-hole pair

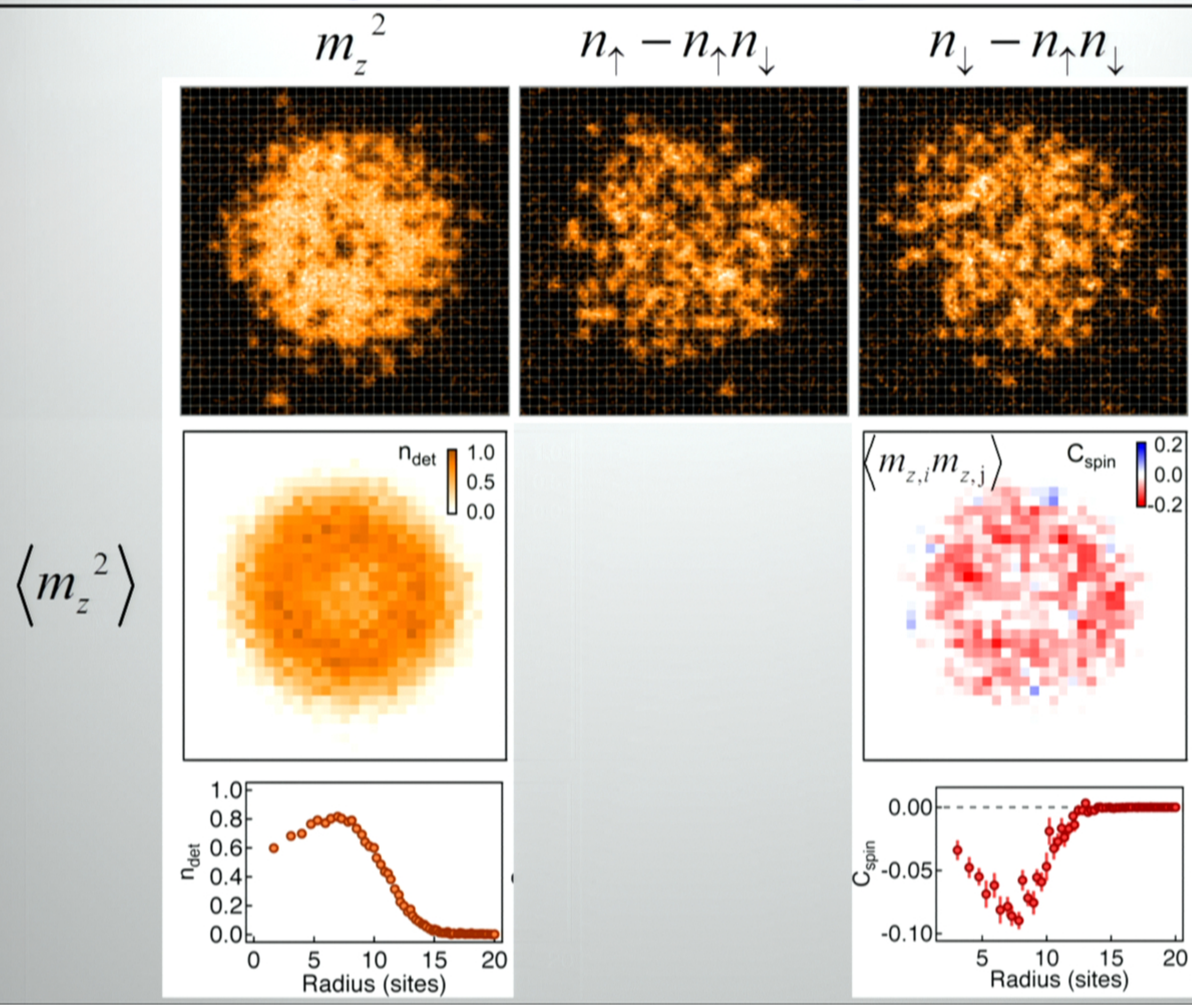
$$|\uparrow\rangle_i |\downarrow\rangle_{i+1} - |\downarrow\rangle_i |\uparrow\rangle_{i+1}$$

$$|\uparrow\downarrow\rangle_i |0\rangle_{i+1} + |0\rangle_i |\uparrow\downarrow\rangle_{i+1}$$

(see ground-state of double-well for finite U)

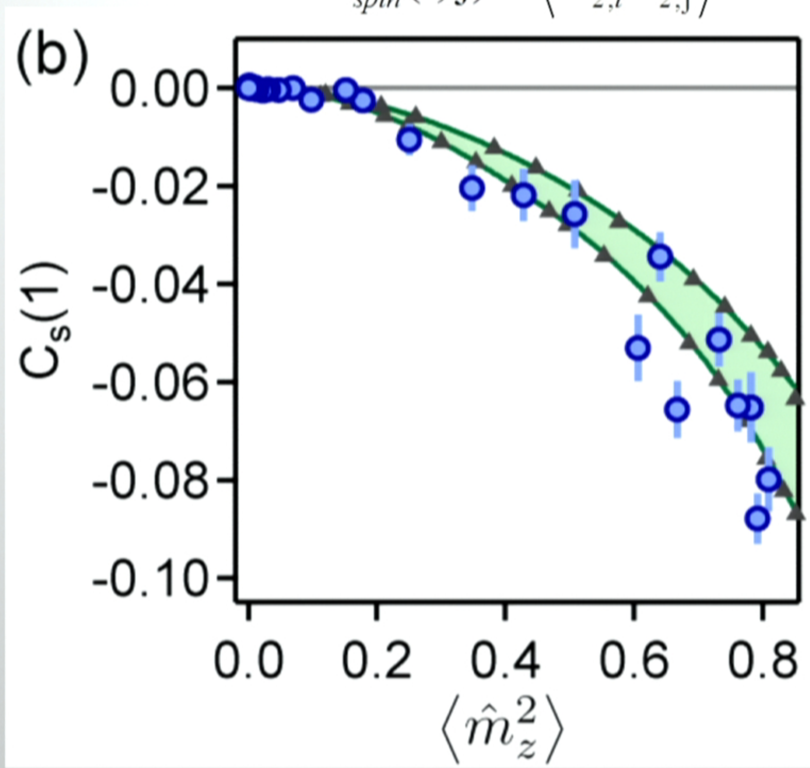
Particle-Hole fluctuations in bosons: Kuhr/Bloch group, Endres et al., Science 334, 200 (2011)

Measuring Spin and Charge Correlations



Spin Correlations

$$C_{spin}(\mathrm{i},\mathrm{j}) = \langle m_{z,i} m_{z,\mathrm{j}} \rangle$$



Cheuk, Nichols, Lawrence, Okan, Zhang, Khatami, Trivedi, Paiva, Rigol, Zwierlein, arXiv: 1606.04089 (2016)

Harvard: Parsons et al., arXiv:1605.02704 (2016) in 2D ^{6}Li

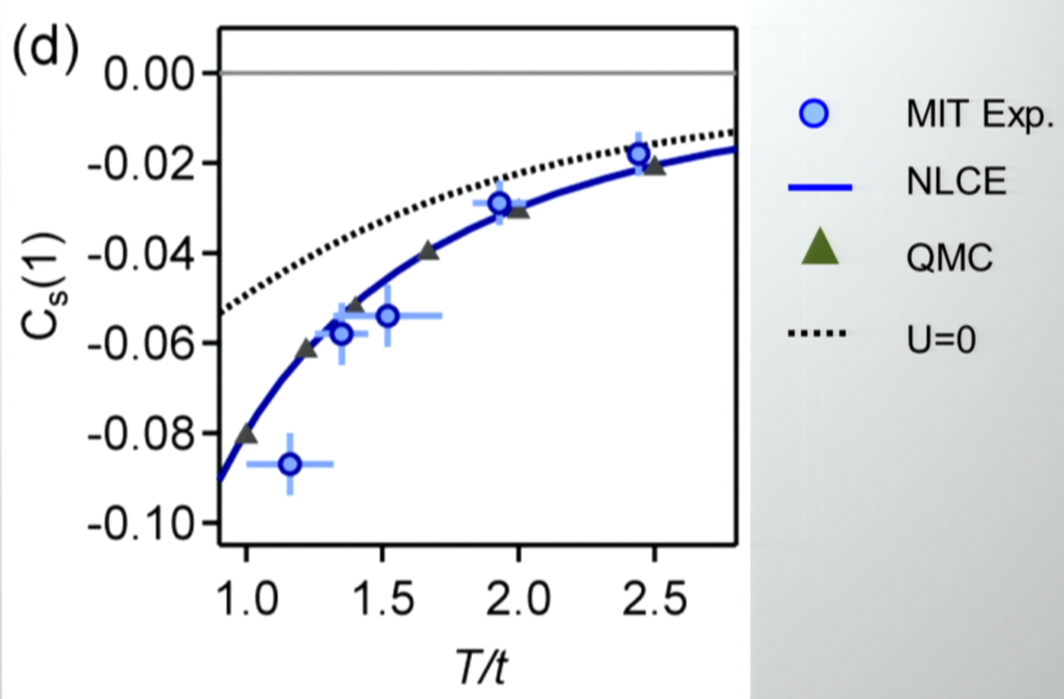
MPQ: Boll et al., arXiv:1605.05661 (2016) in 1D ^{6}Li

Bonn: Drewes et al., arXiv:1607.00392 (2016) in 2D ^{40}K

Spin Correlations

$$C_{spin}(\mathrm{i},\mathrm{j}) = \left\langle m_{z,i} m_{z,\mathrm{j}} \right\rangle = \left\langle (n_\uparrow - n_\downarrow)(n_\uparrow - n_\downarrow) \right\rangle = 2\left\langle n_\uparrow n_\uparrow \right\rangle - 2\left\langle n_\uparrow n_\downarrow \right\rangle$$

at half-filling

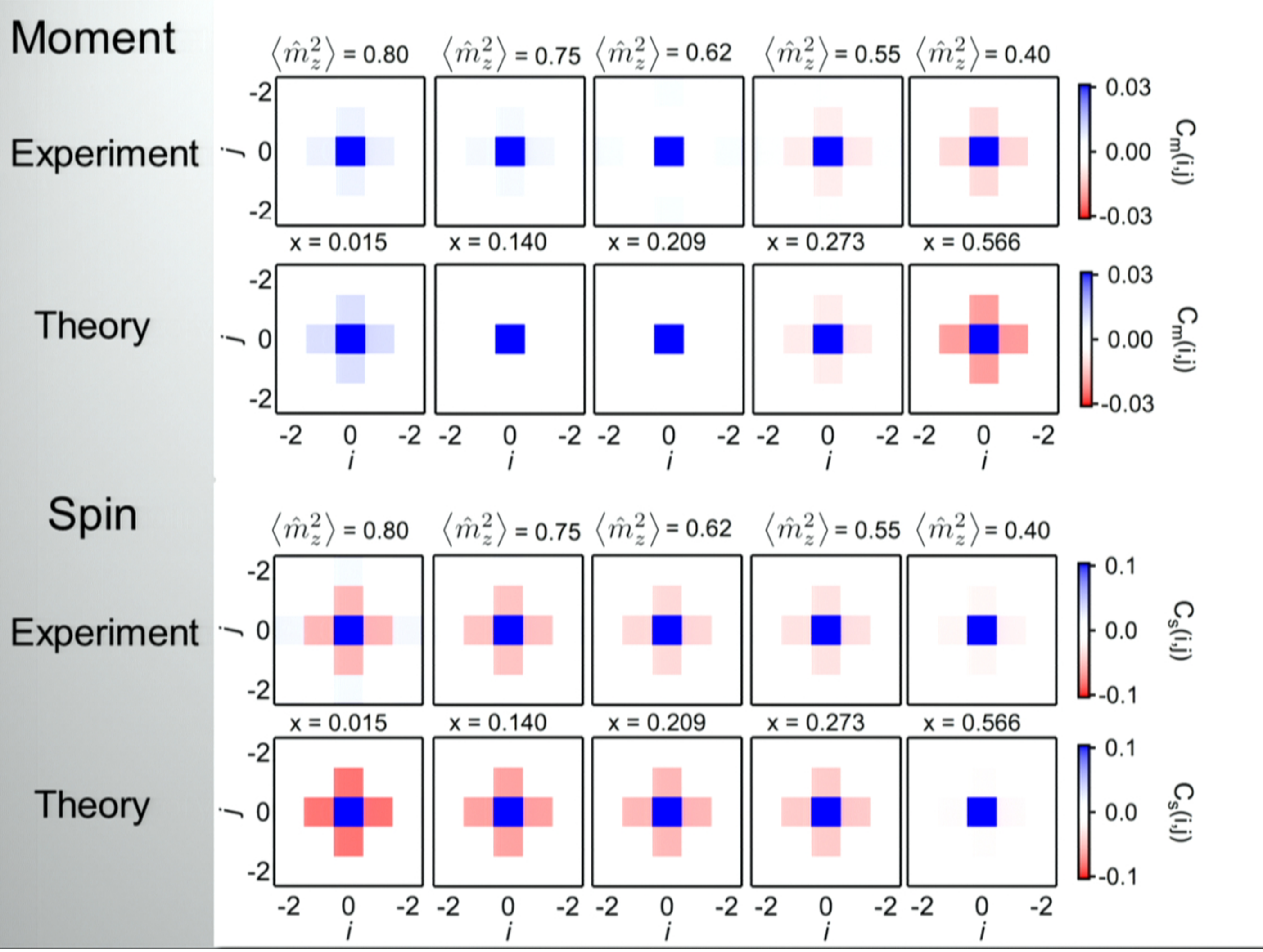


Cheuk, Nichols, Lawrence, Okan, Zhang, Khatami, Trivedi, Paiva, Rigol, Zwierlein, arXiv: 1606.04089 (2016)

See also: Parsons et al., arXiv:1605.02704 (2016) in 2D ^{6}Li

Boll et al., arXiv:1605.05661 (2016) in 1D ^{6}Li

Spin and Charge Correlations beyond n.n.

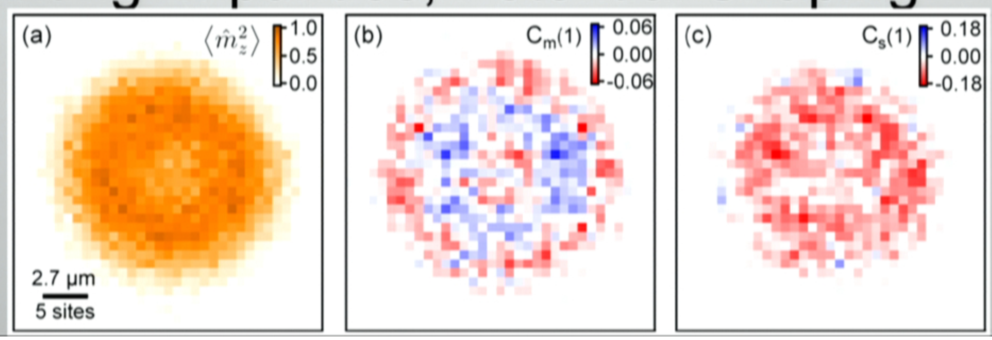


Conclusions and Outlook

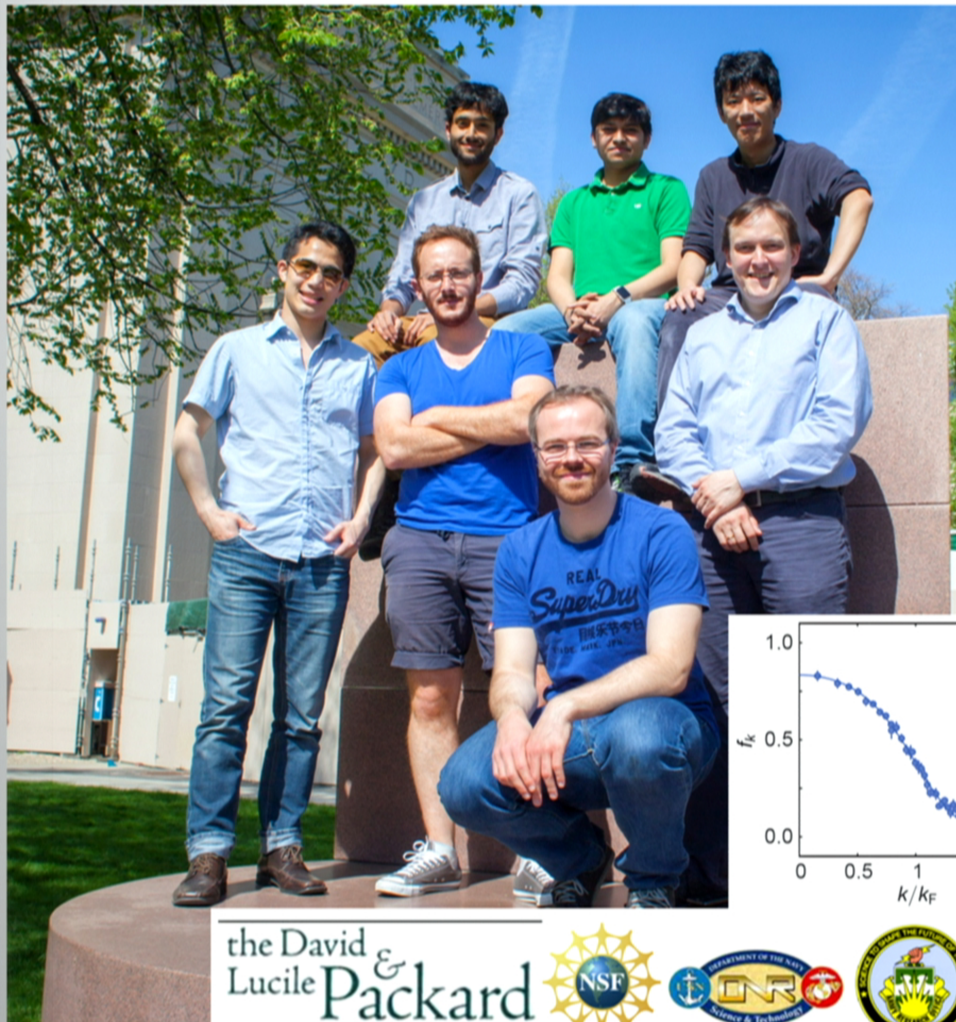
- Observed Fermionic Mott Insulators, Band Insulators, metals with single-site resolution
- In-situ observation of
  - Fermion anti-bunching and Pauli+Correlation hole
  - Doublon-Hole Bunching
  - Antiferromagnetic correlations

Outlook:

- Lower Temperatures
- Repulsive vs Attractive Hubbard Model
- Implanting Impurities, Potential Shaping…



Fermions in a Box



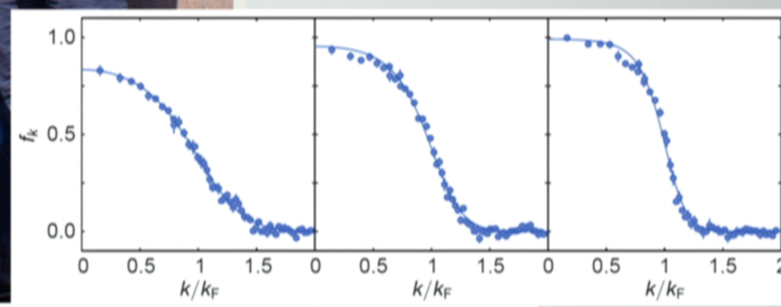
BEC 1

Fermions in a box

Biswaroop Mukherjee
Parth Patel
Zhenjie Yan
Dr. Julian Struck

Visiting Professor:
Zoran Hadzibabic

Tarik Yefsah (→ ENS)



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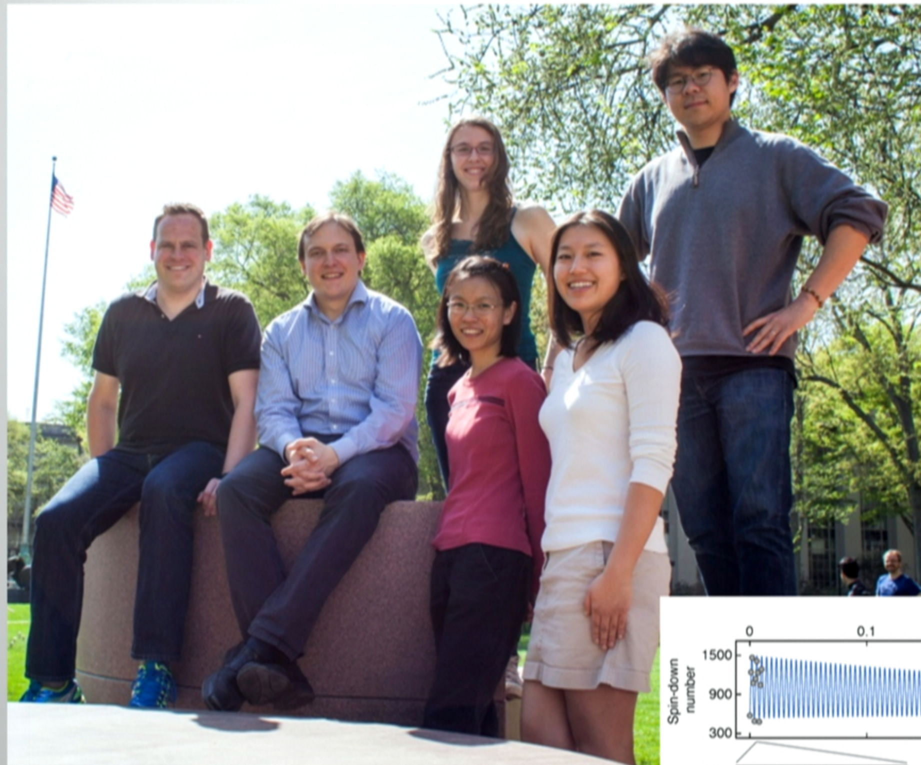
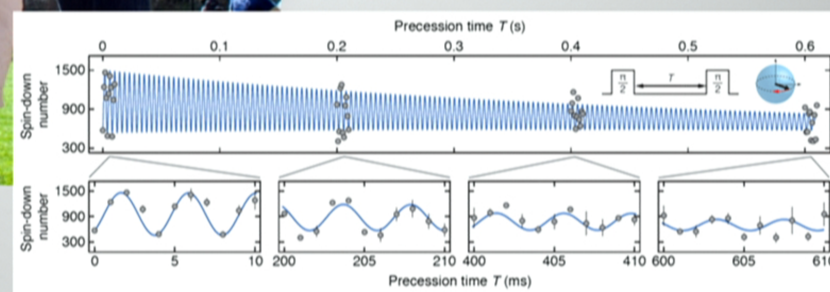
NaK Molecules



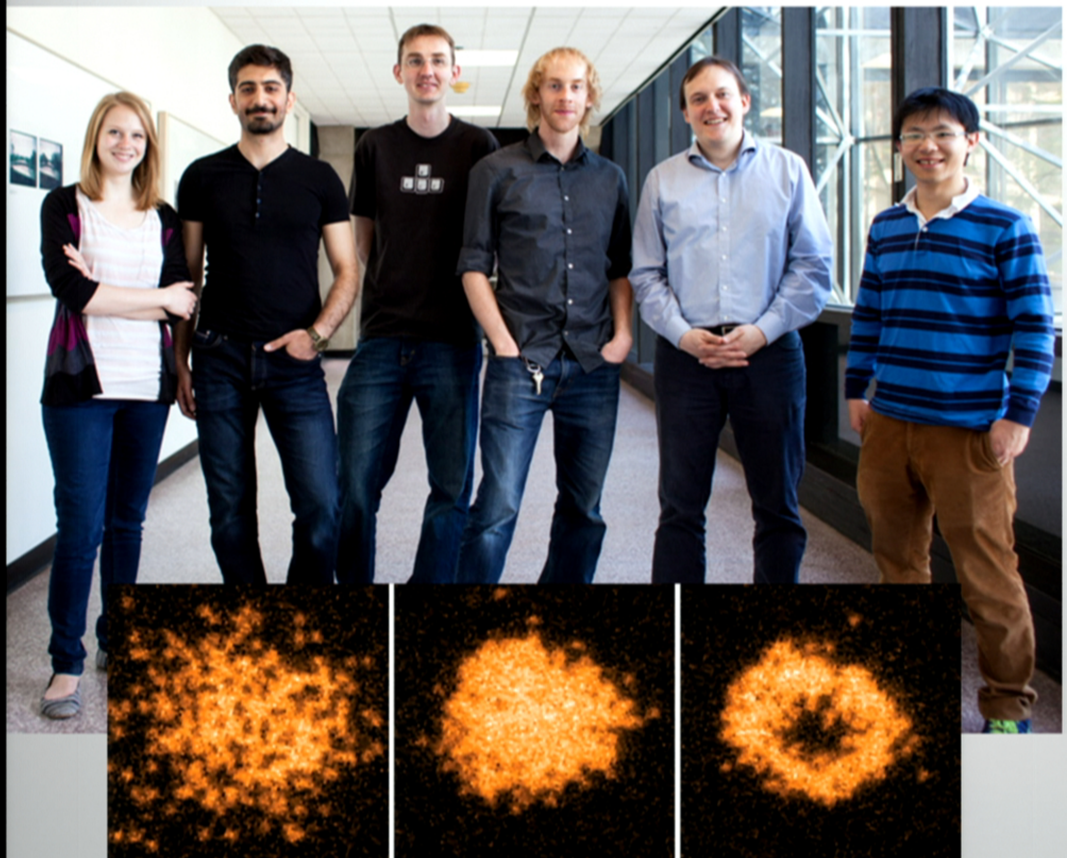
Fermi 1

NaK Dipolar Molecules

Jeewoo Peter Park (PhD 2016)
Zoe Yan
Yiqi Ni
Dr. Huanqian Loh
Dr. Sebastian Will
(→ Columbia U.)



Fermi-Hubbard Model under the Microscope



Fermi 2

Lawrence Cheuk
Melih Okan
Matthew Nichols
Katherine Lawrence
Dr. Hao Zhang

Former members:
Waseem Bakr
(Princeton U.)
Thomas Lompe
(Hamburg)

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