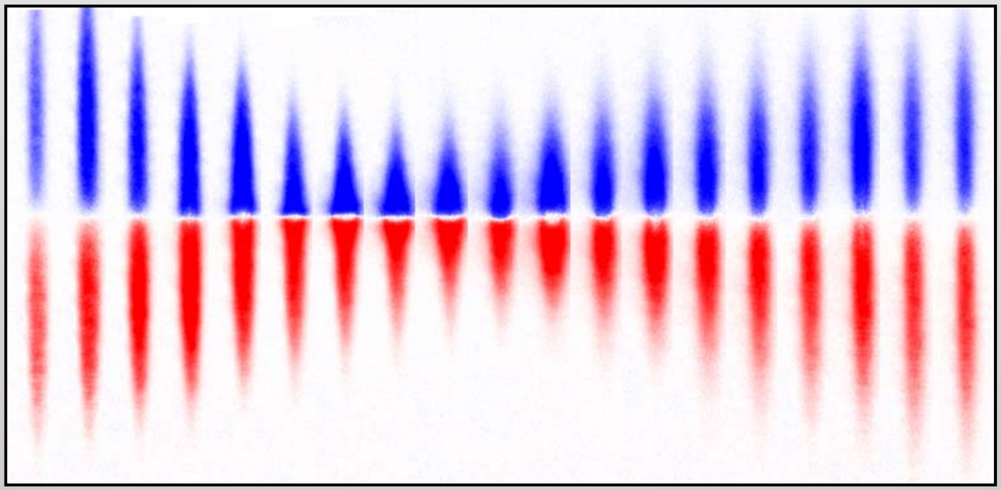
Physics Colloquium, University of Toronto, 2/7/2013

A Little Big Bang:
Strong Interactions in Ultracold Fermi Gases

Martin Zwierlein



Massachusetts Institute of Technology

Center for Ultracold Atoms

How cold is ultracold?

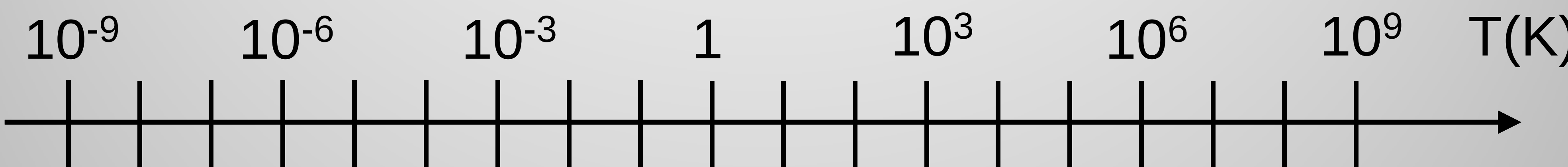
Atoms move at:

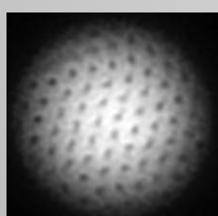
~ 1 mm/s

~ 100 m/s

~ 10^6 m/s

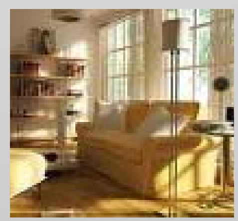
Paris in 10 seconds



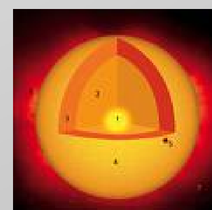


Ultracold atom experiments

Outer space



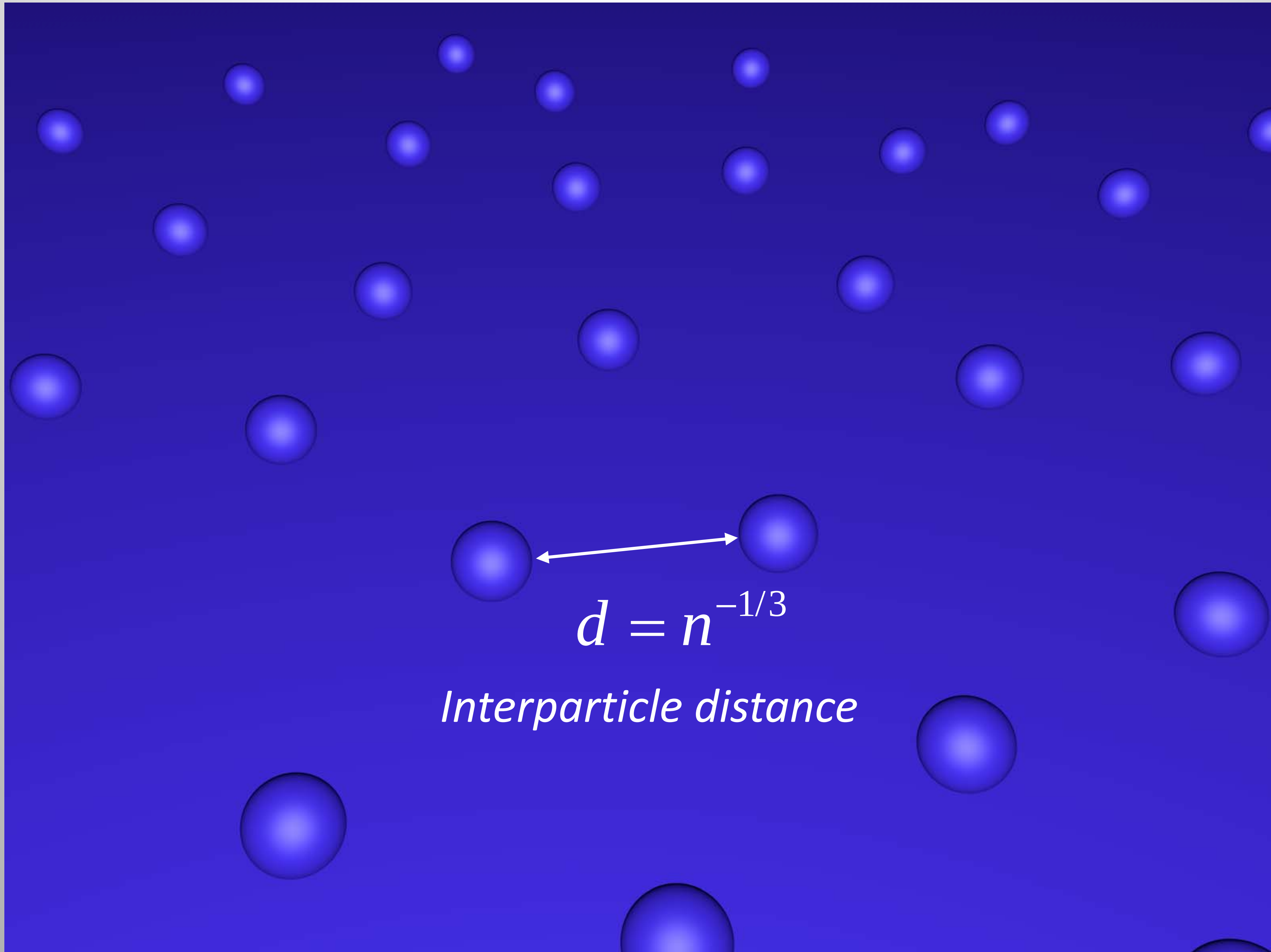
Your living room



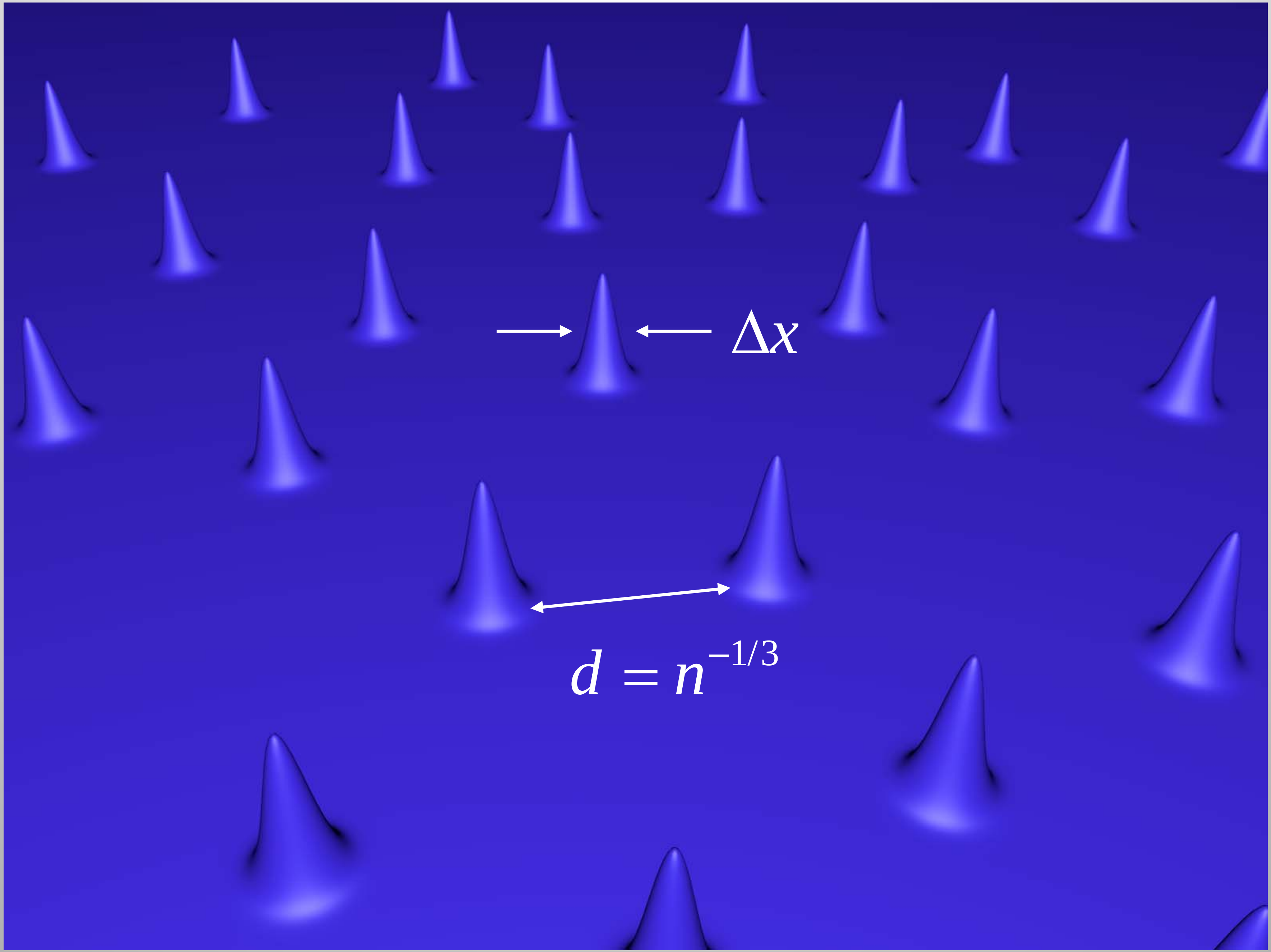
Center of the sun

Supernova explosion

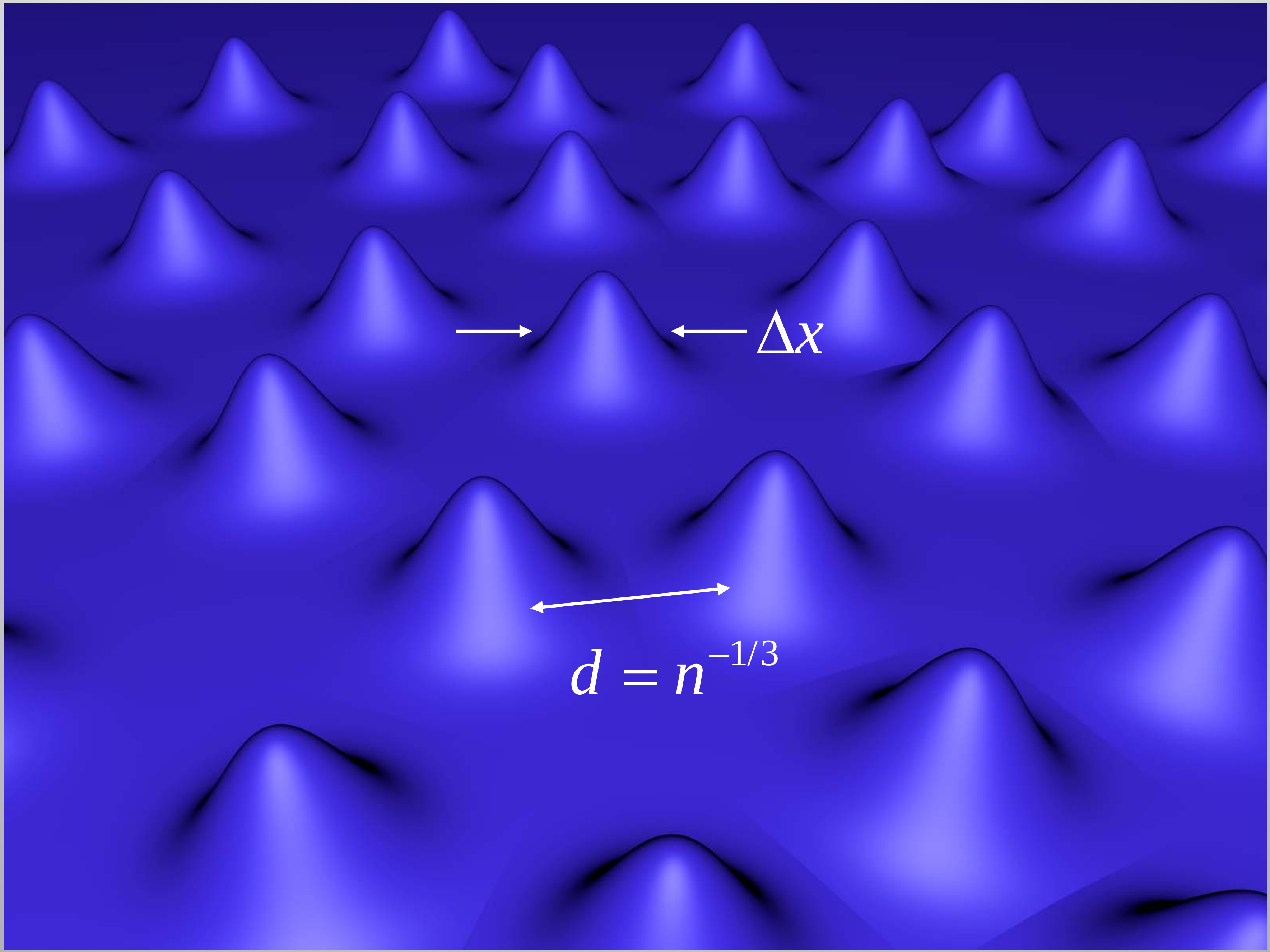
Particles...



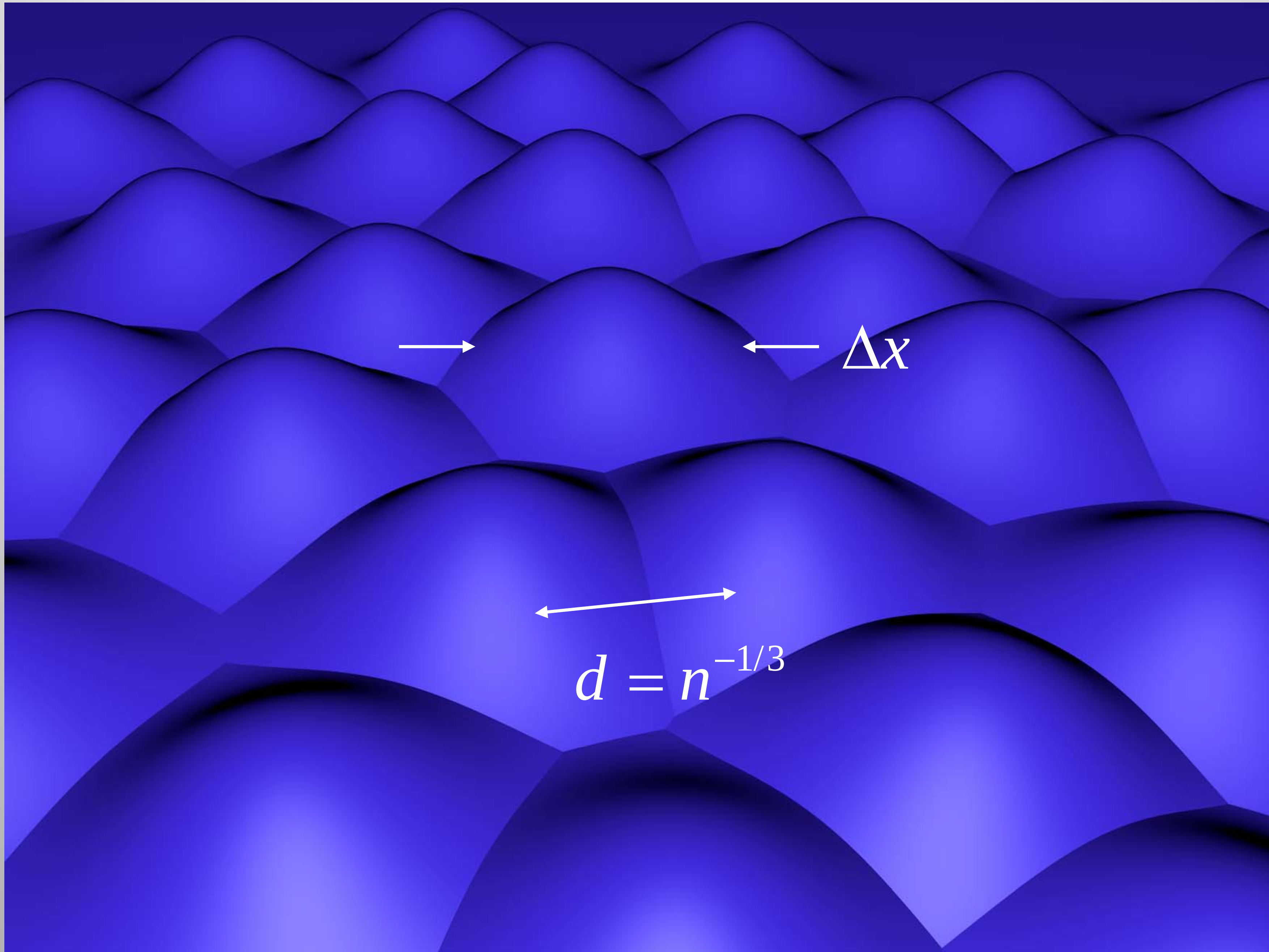
...behave as waves



When does wave mechanics matter?



When does wave mechanics matter?



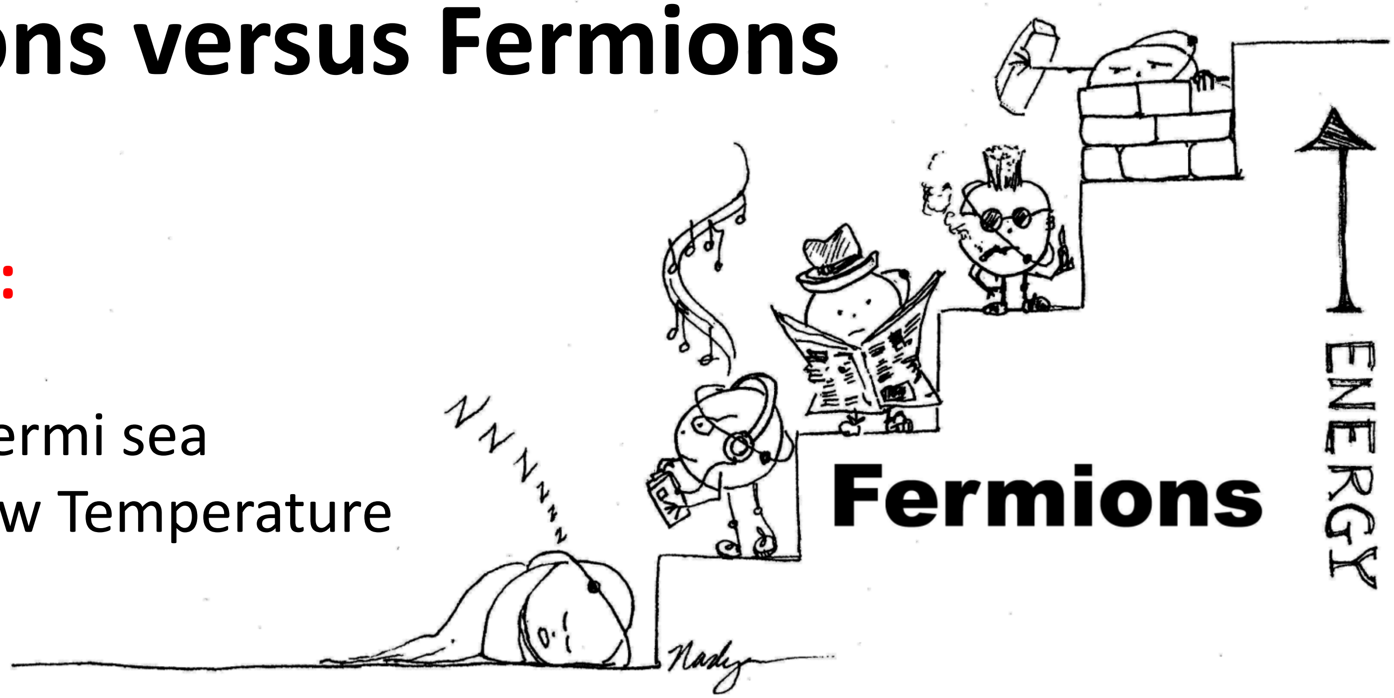
Bosons versus Fermions

Fermions (unsociable):

Half-Integer Spin

Pauli blocking → Form Fermi sea

No phase transition at low Temperature



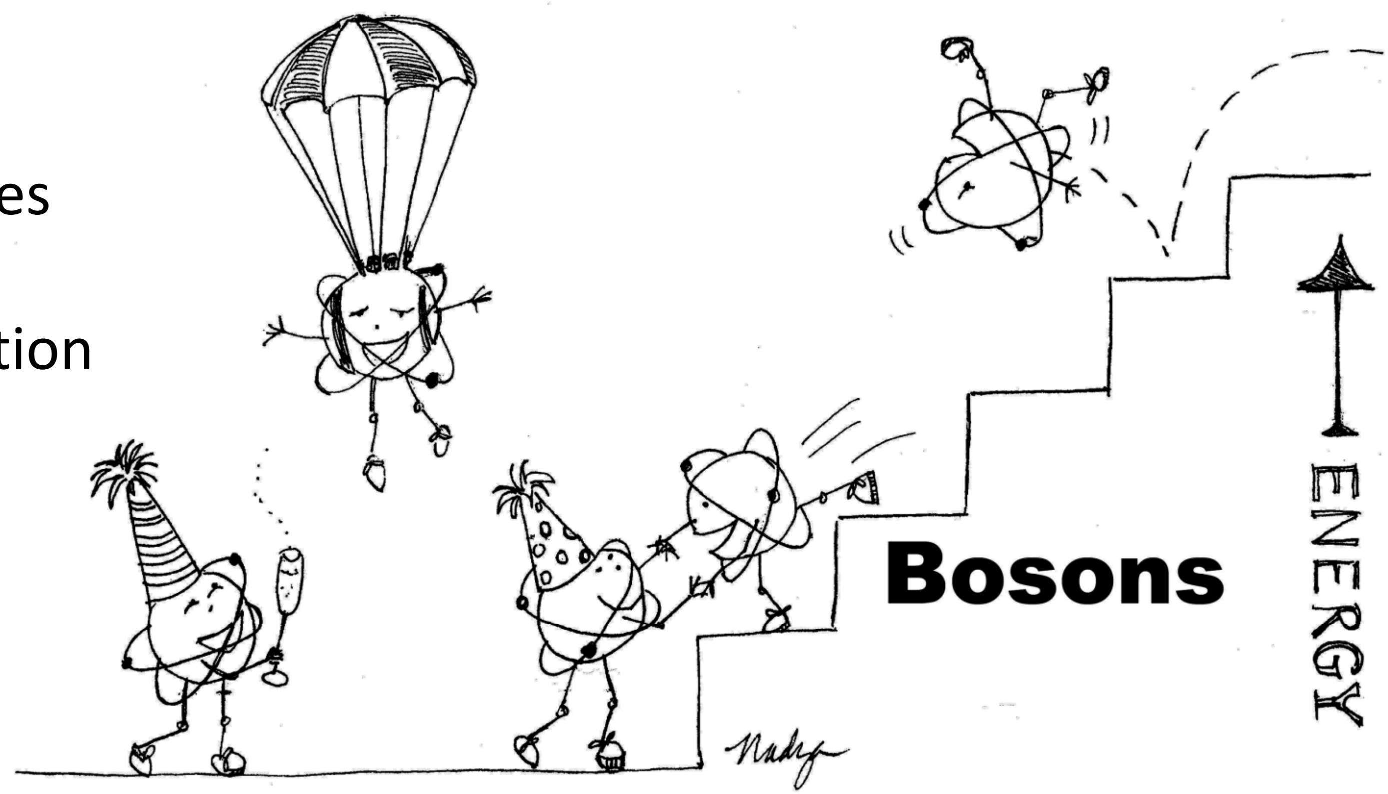
Bosons (sociable):

Integer Spin

Can share quantum states

At low temperatures:

Bose-Einstein condensation



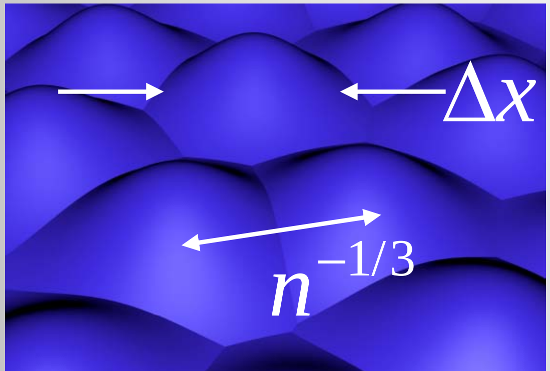
Bosons


N bosons sharing one and the same macroscopic matter wave
(Artist’s conception)

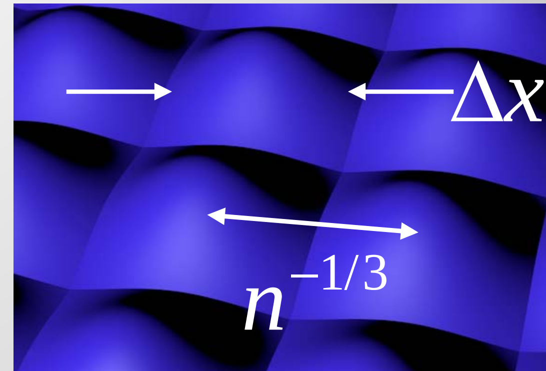
Fermions

Condition for quantum degeneracy

Position uncertainty ~ Interparticle spacing

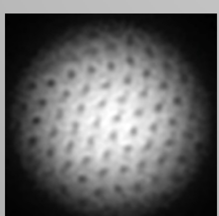


$$\Delta x = \frac{\hbar}{\Delta p} \approx n^{-1/3}$$

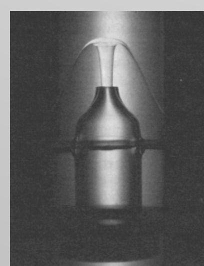


$$k_B T_{\mathrm{Degeneracy}} \approx \frac{\hbar^2}{m} n^{2/3} \approx E_F$$ **Fermi energy**

10^{-6} 10^{-3} 1 10^{3} 10^{6} 10^{9} 10^{12} T_{Deg}(K)



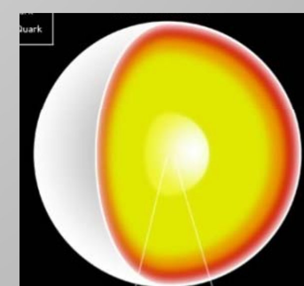
Ultracold atomic gases



Liquid Helium

Metals

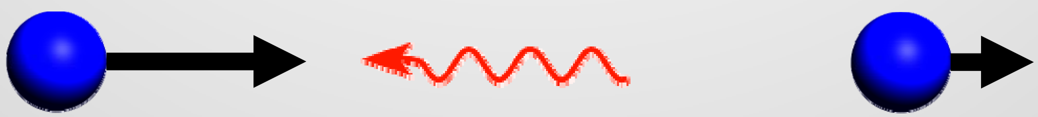
White dwarf



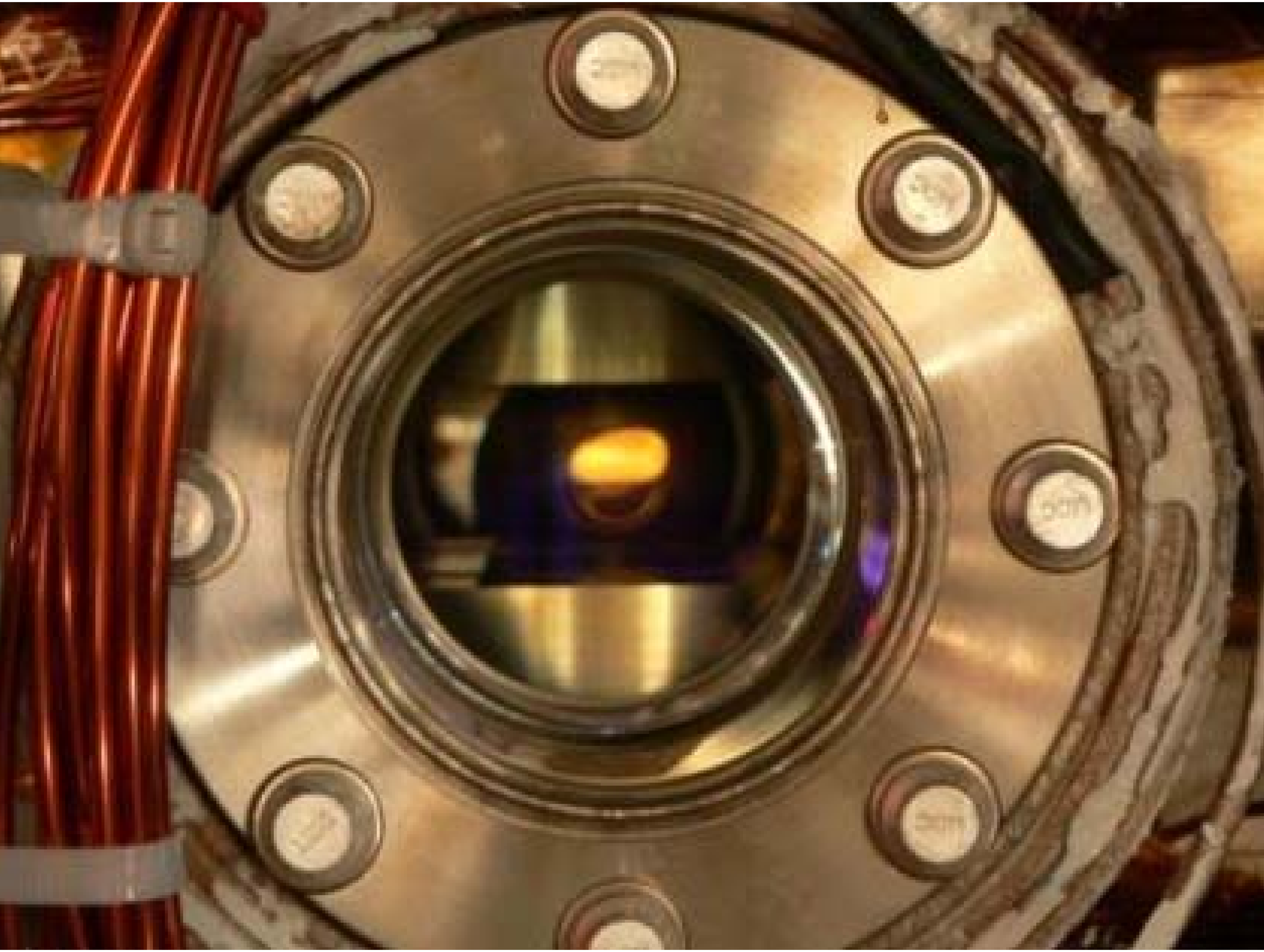
Neutron star

The cooling methods

- Laser Cooling → ~ 1 mK

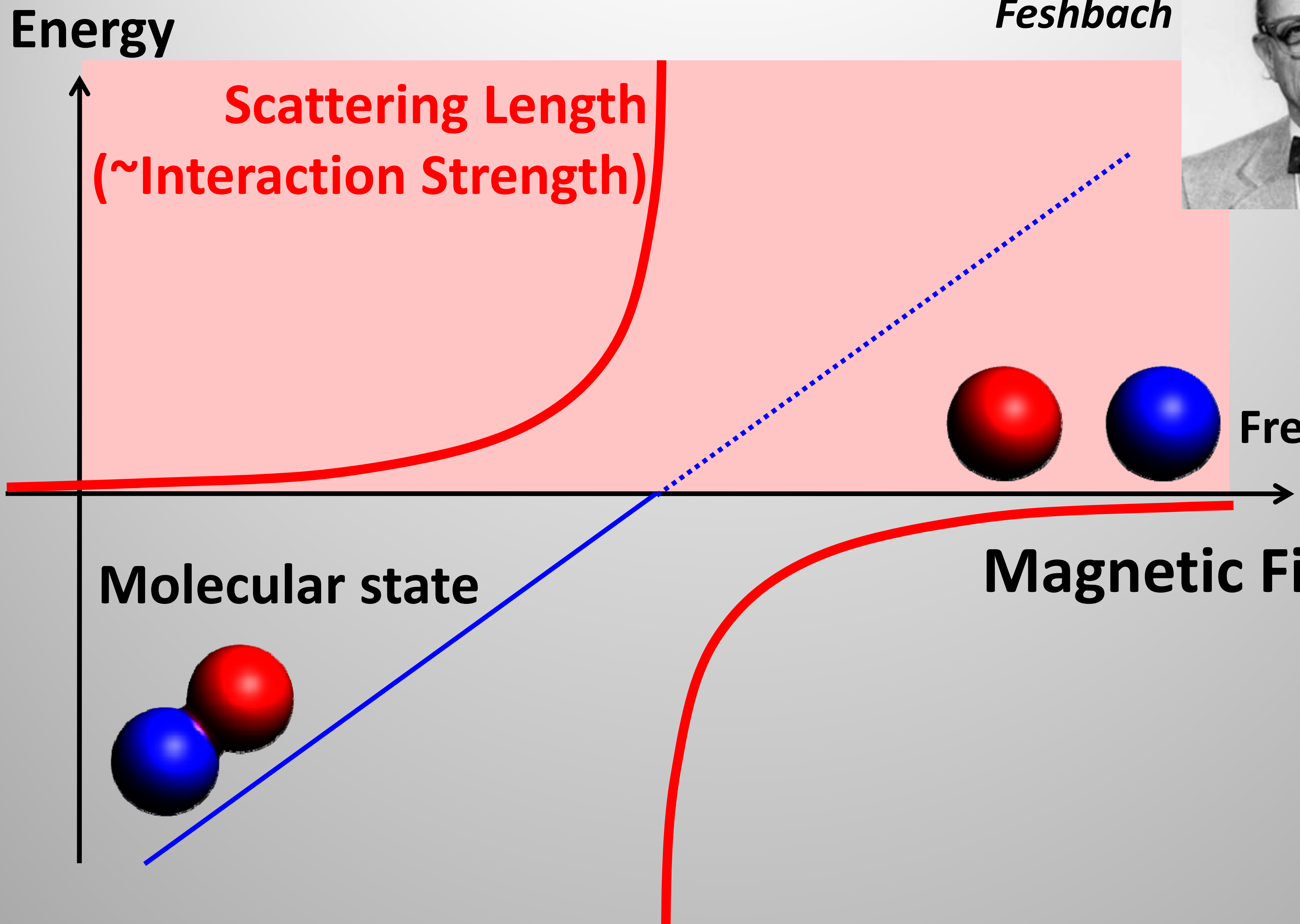


- Evaporative Cooling → ~ 10 nK



Feshbach resonances: Tuning the interactions

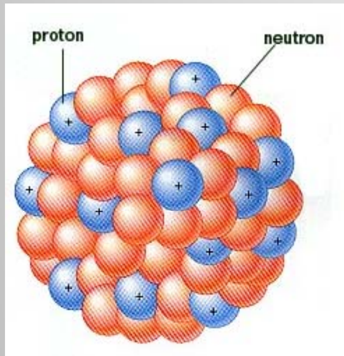
Herman Feshbach



Many-Body Quantum Mechanics

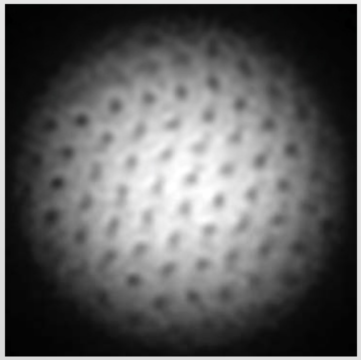
Length scales →

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



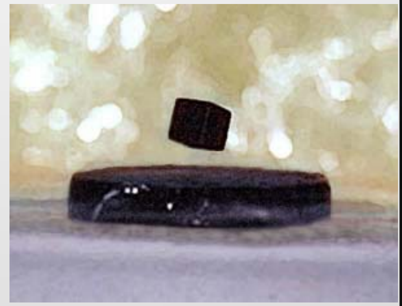
Nuclei

Small



Ultracold Atomic Gases

(Relatively) easily accessible + widely tunable



High-T_c Superconductors

Superfluid Helium

Extremely difficult

White dwarf

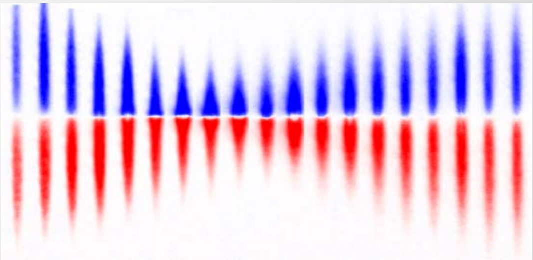
Far

Interactions, Geometry, Composition etc.

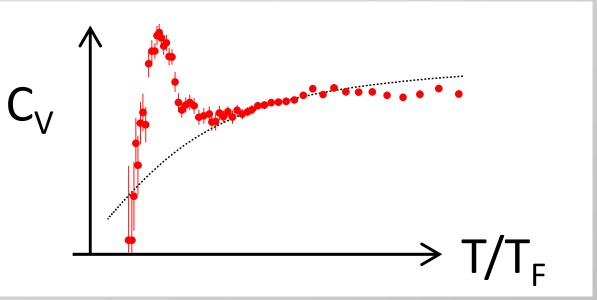
→ **Feynman's "quantum simulator"**

Many-Body Physics with Ultracold Fermi Gases

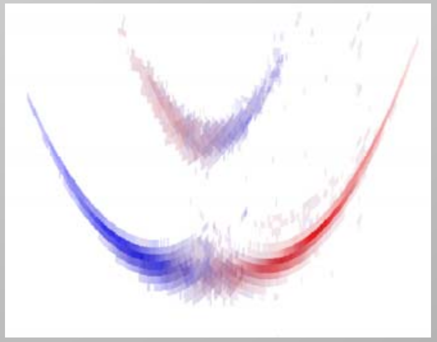
- Real-time dynamics → Spin Transport



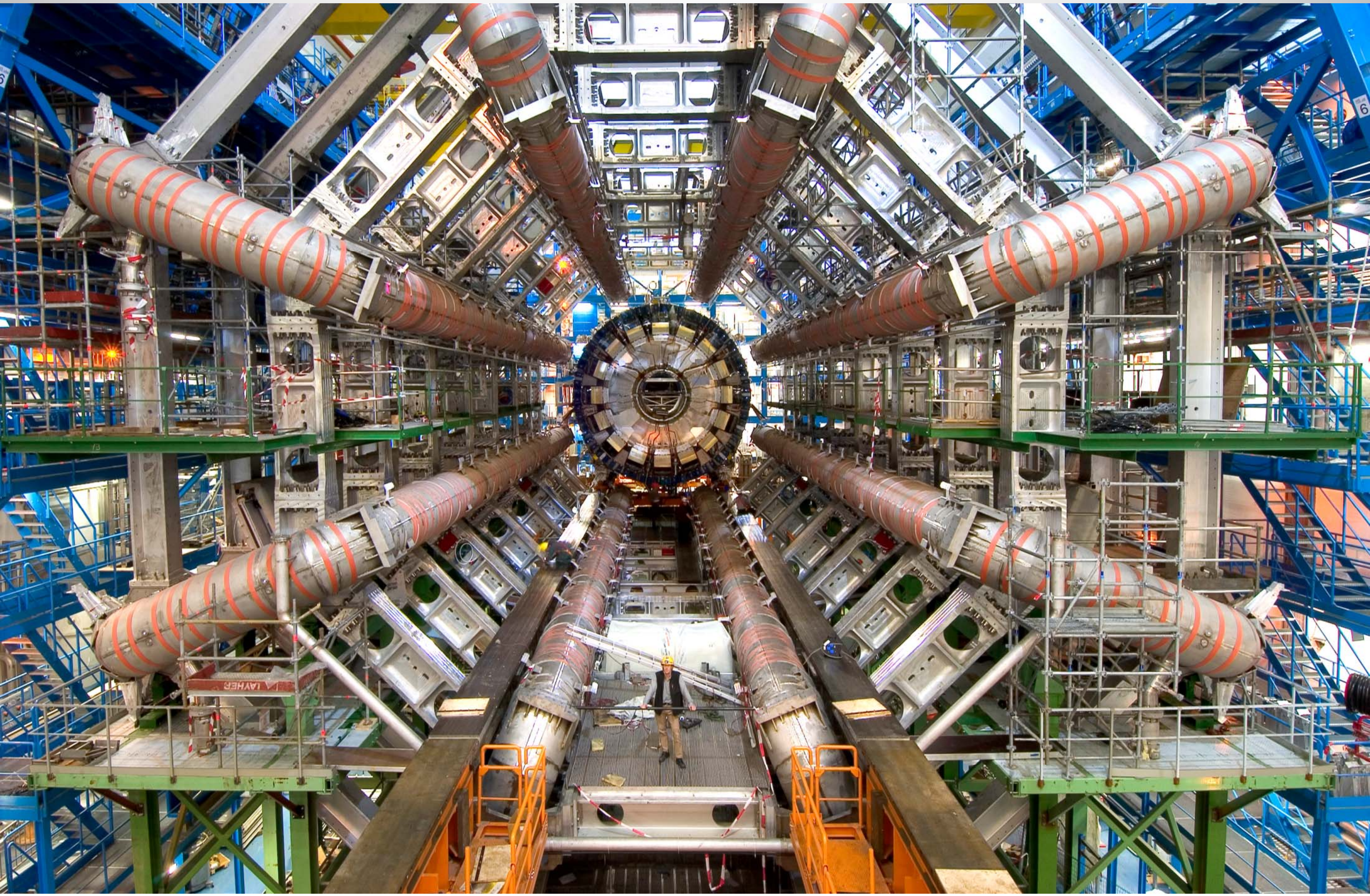
- Thermodynamics → Superfluid Transition

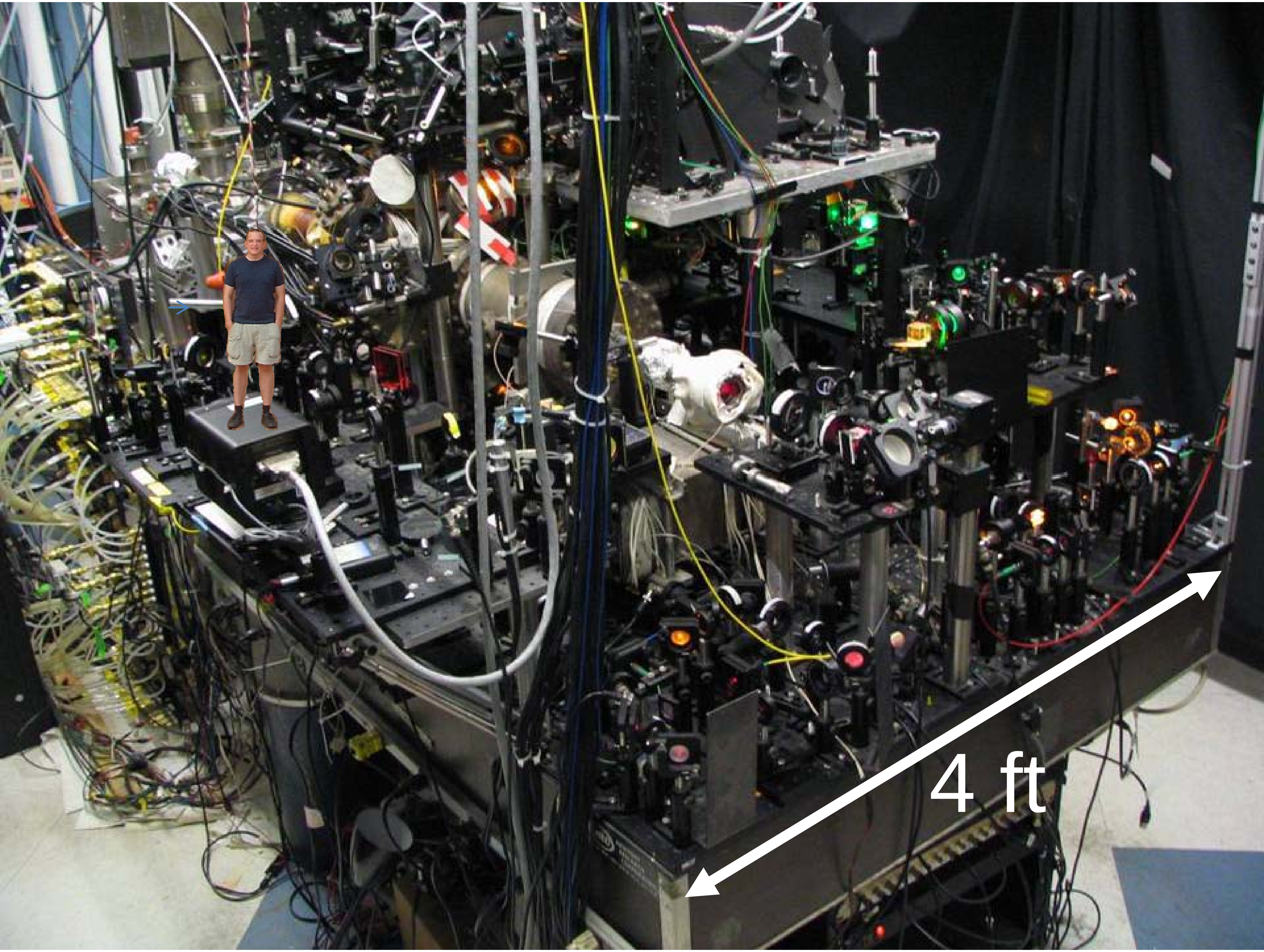


- Novel Fermi Systems → Spin-Orbit Coupled Gas



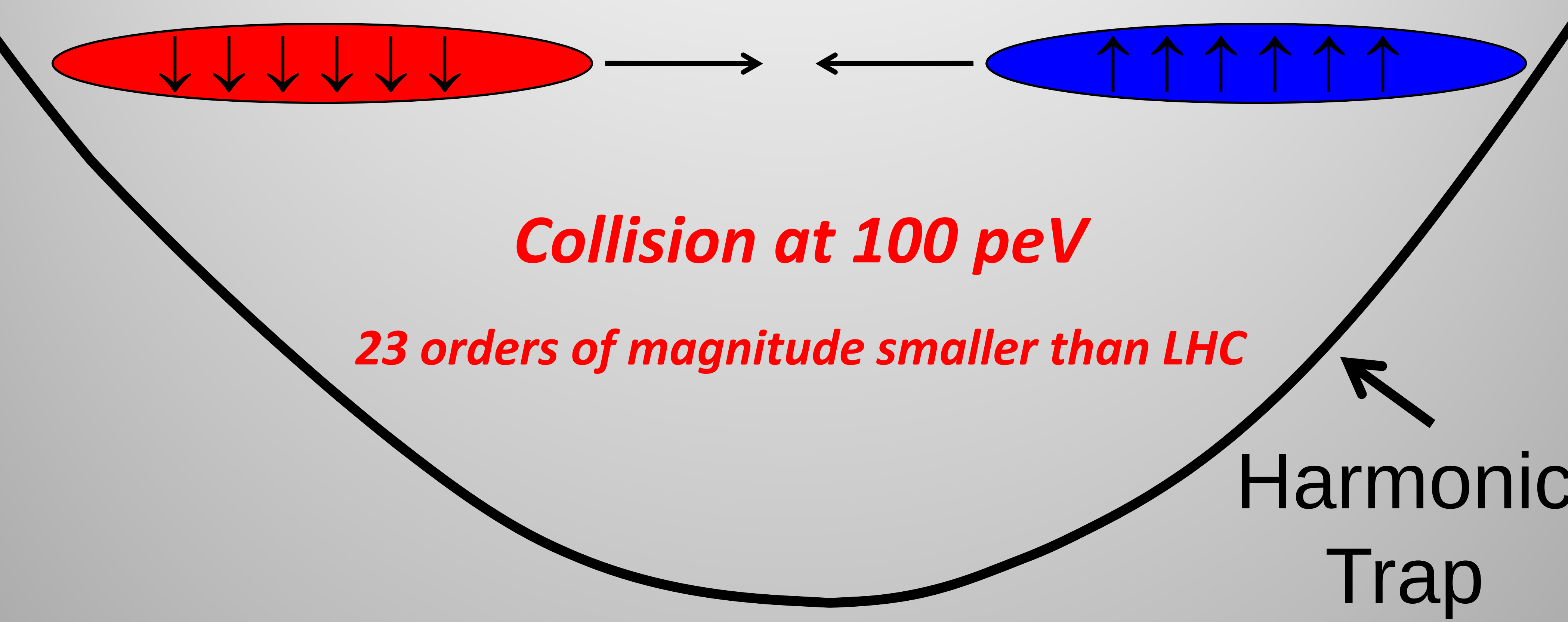
Large Hadron Collider (LHC)




4 ft

Little Fermi Collider (LFC)

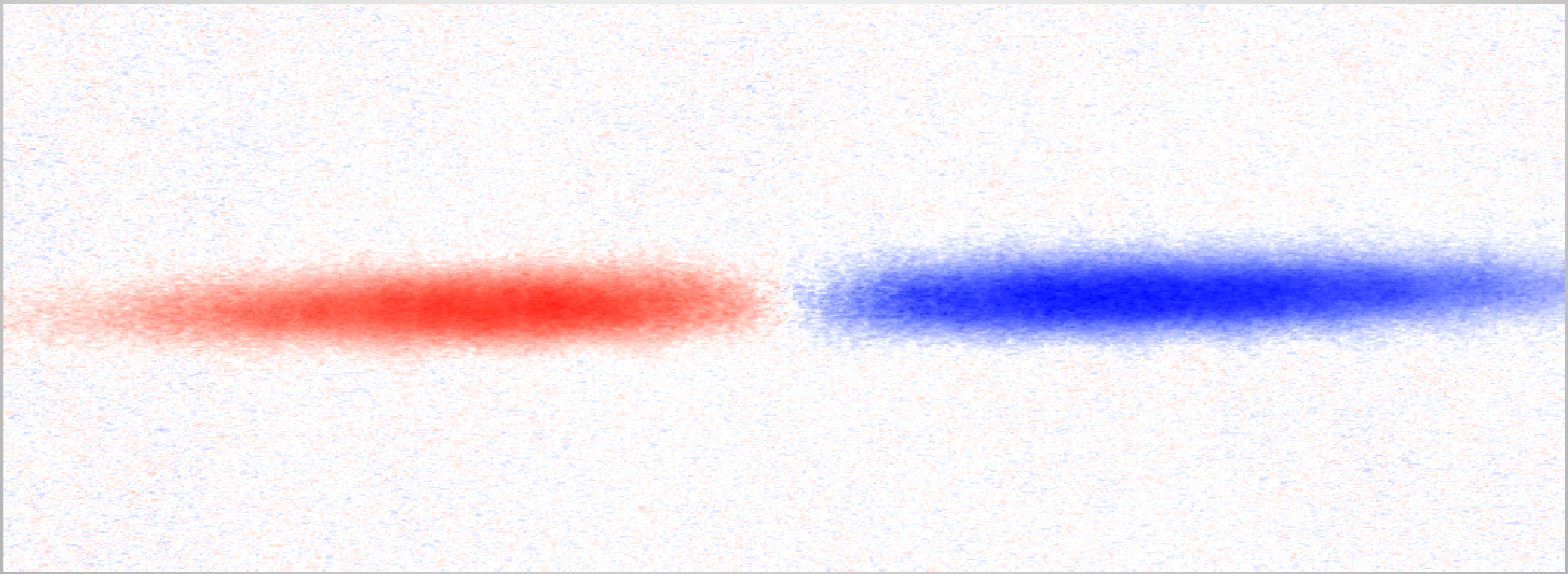
A ↓ Fermi gas collides with a ↑ cloud with resonant interactions



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

Little Fermi Collider (LFC)

Without Interactions



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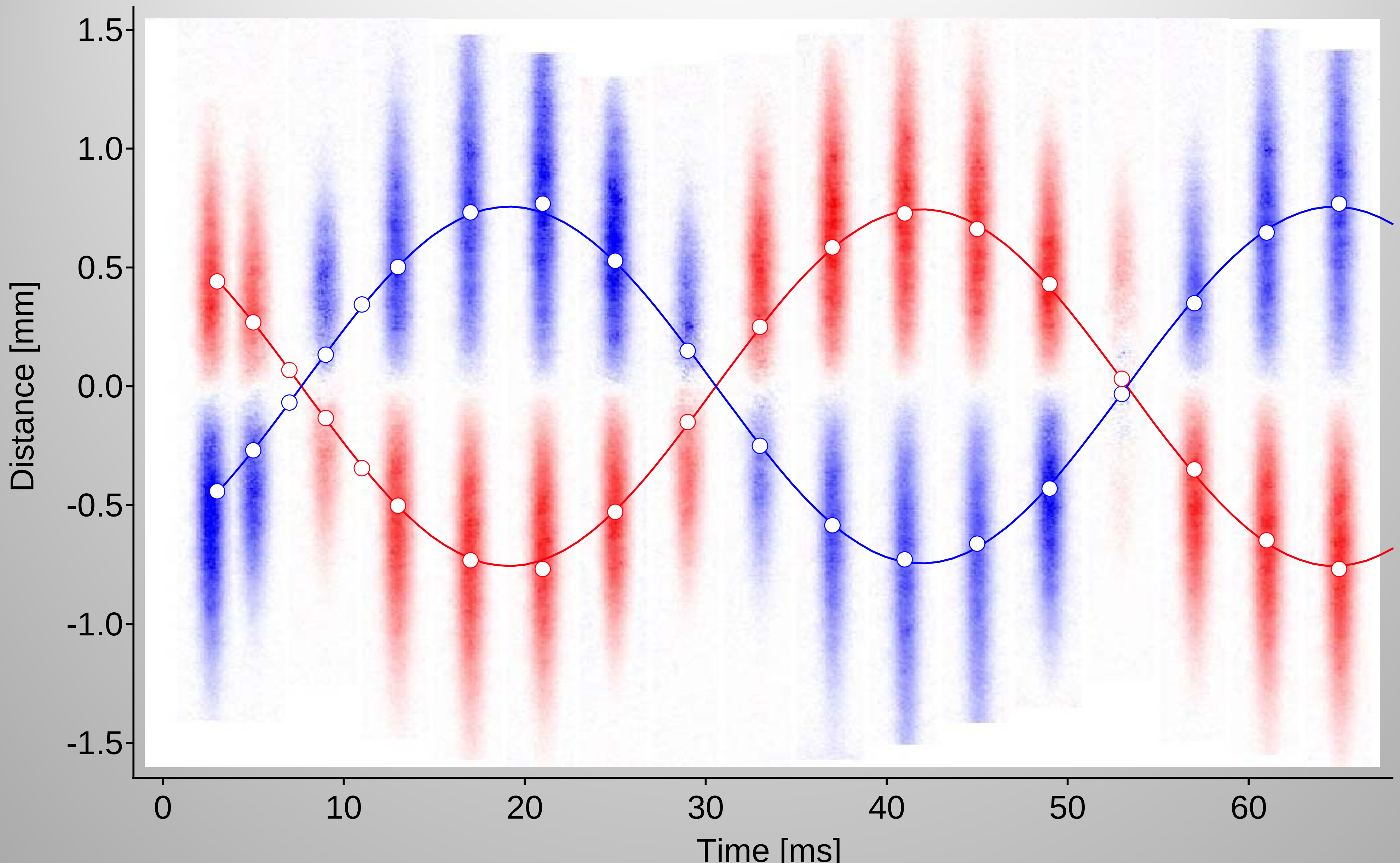
Little Fermi Collider (LFC)

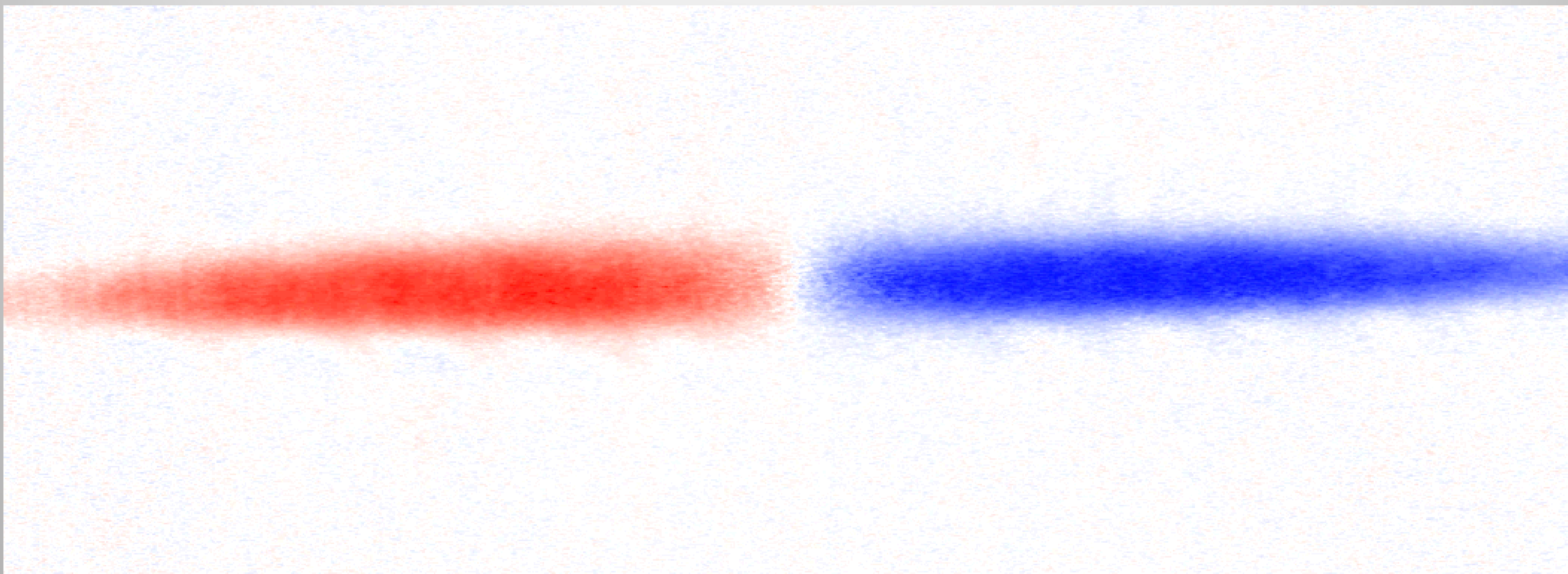
Without Interactions



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

Little Fermi Collider (LFC)

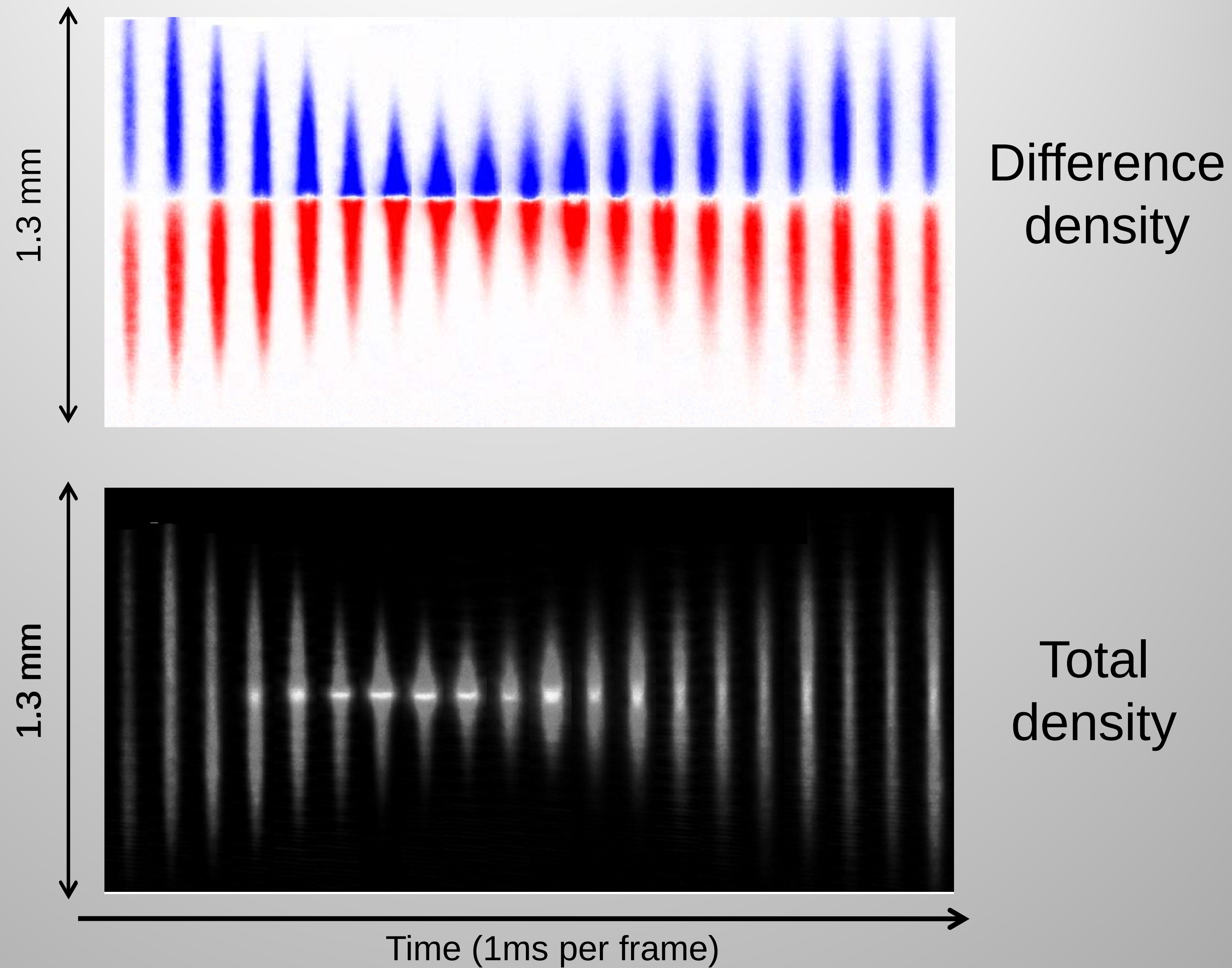
With resonant interactions



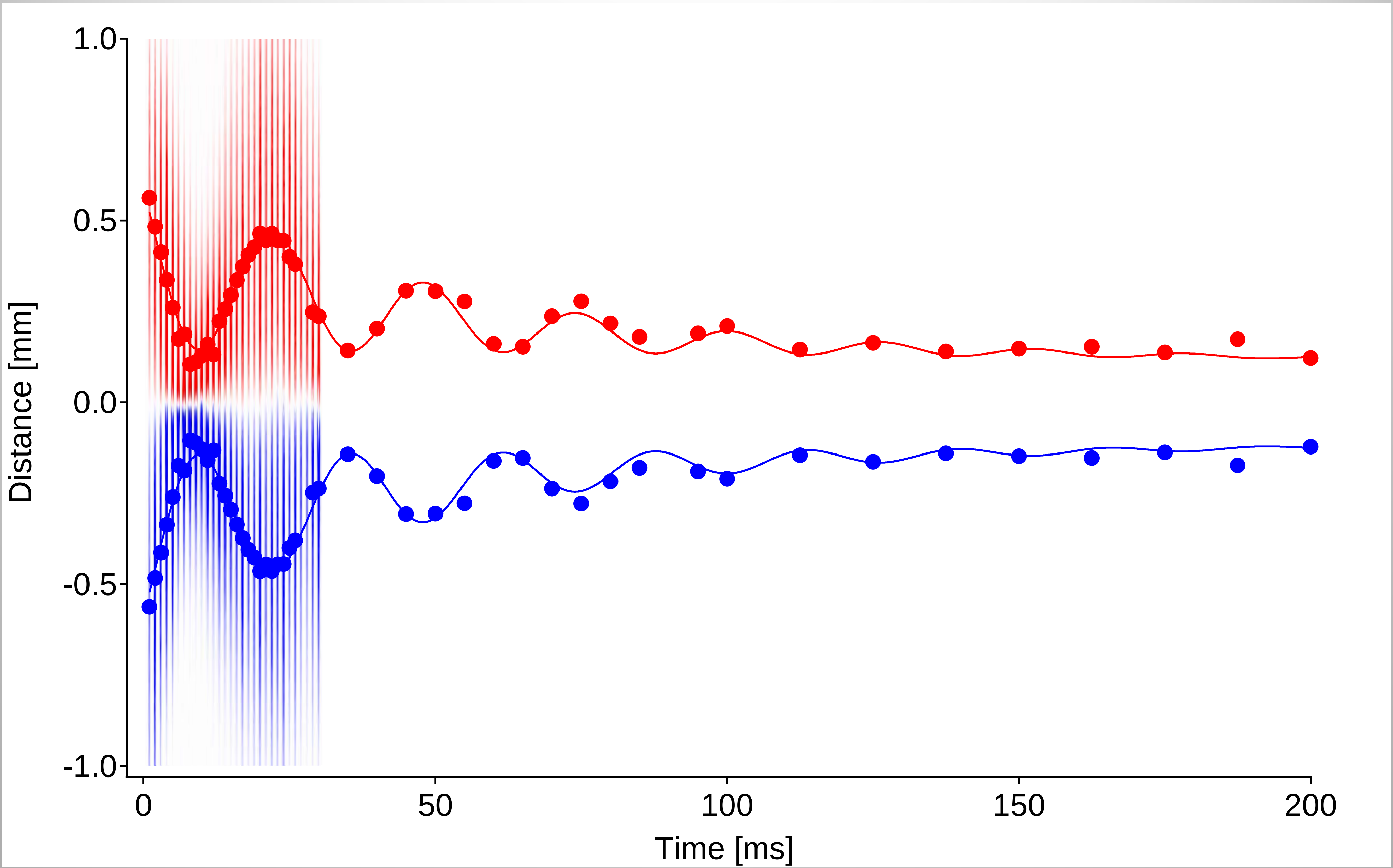
A.T. Sommer, M.J.H. Ku, G. Roati, M.W. Zwierlein, Nature 472, 201 (2011)

The bouncing gas

First collision

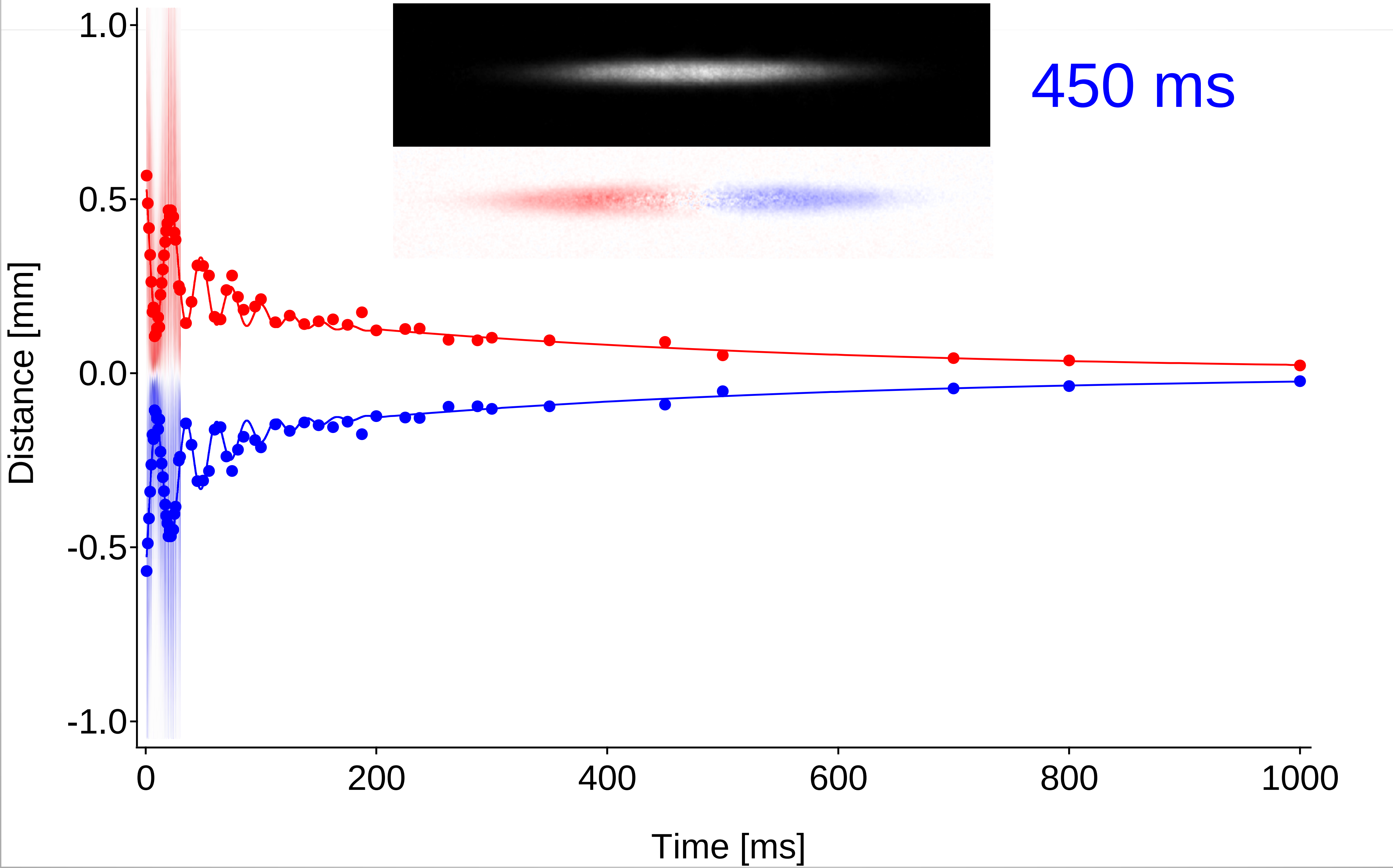


Later times



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:

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

$$d \times \frac{\hbar}{md}$$

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

→ Quantum Limit of Diffusion

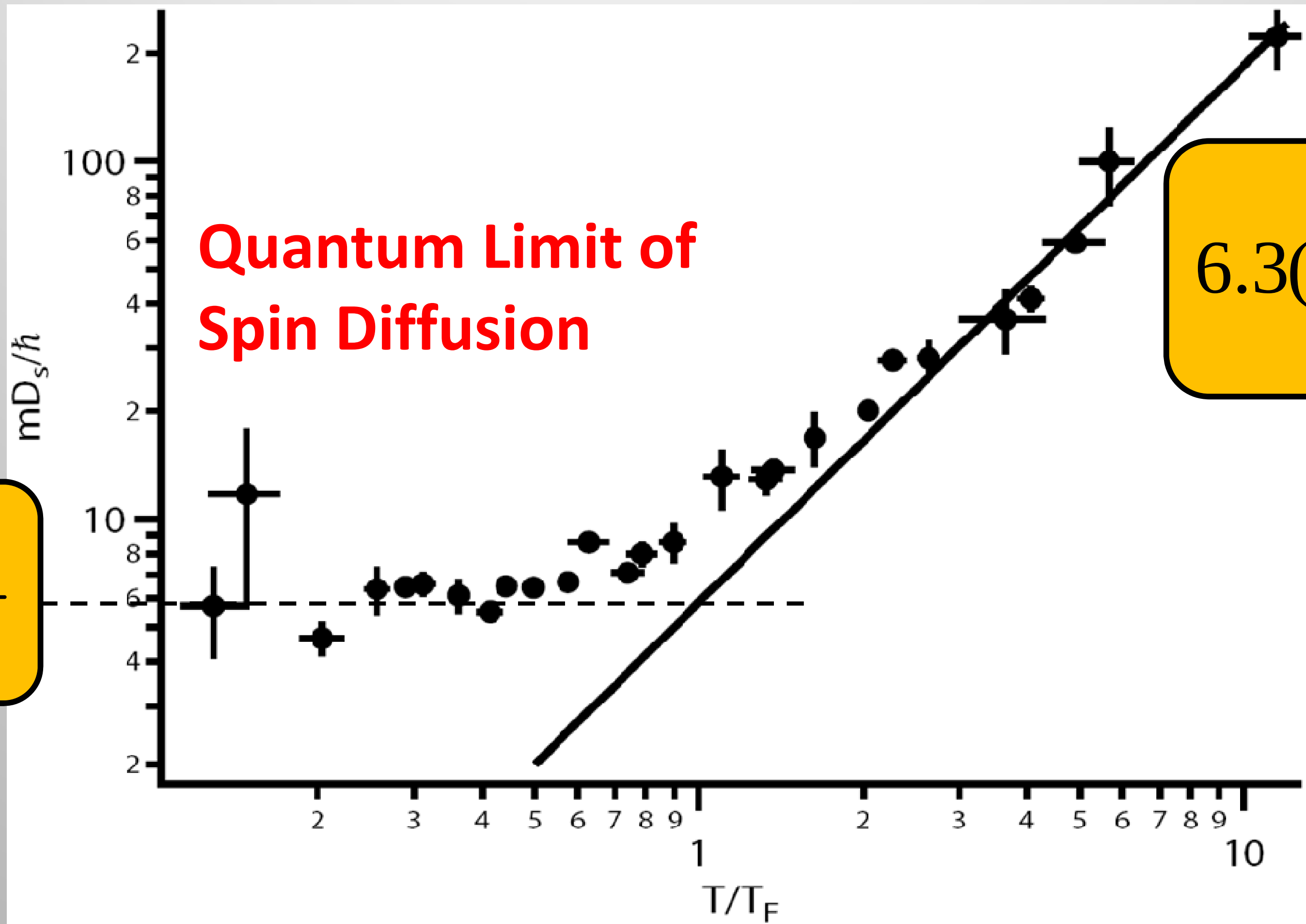
In a hot relativistic fluid (e.g. Quark-Gluon Plasma): $D \sim \frac{\hbar c^2}{T}$

$$mc^2 \rightarrow T$$

Spin Diffusion vs Temperature

Spin current = -D · Spin density gradient

Universal high-T behavior:



$$5.8\frac{\hbar}{m}$$

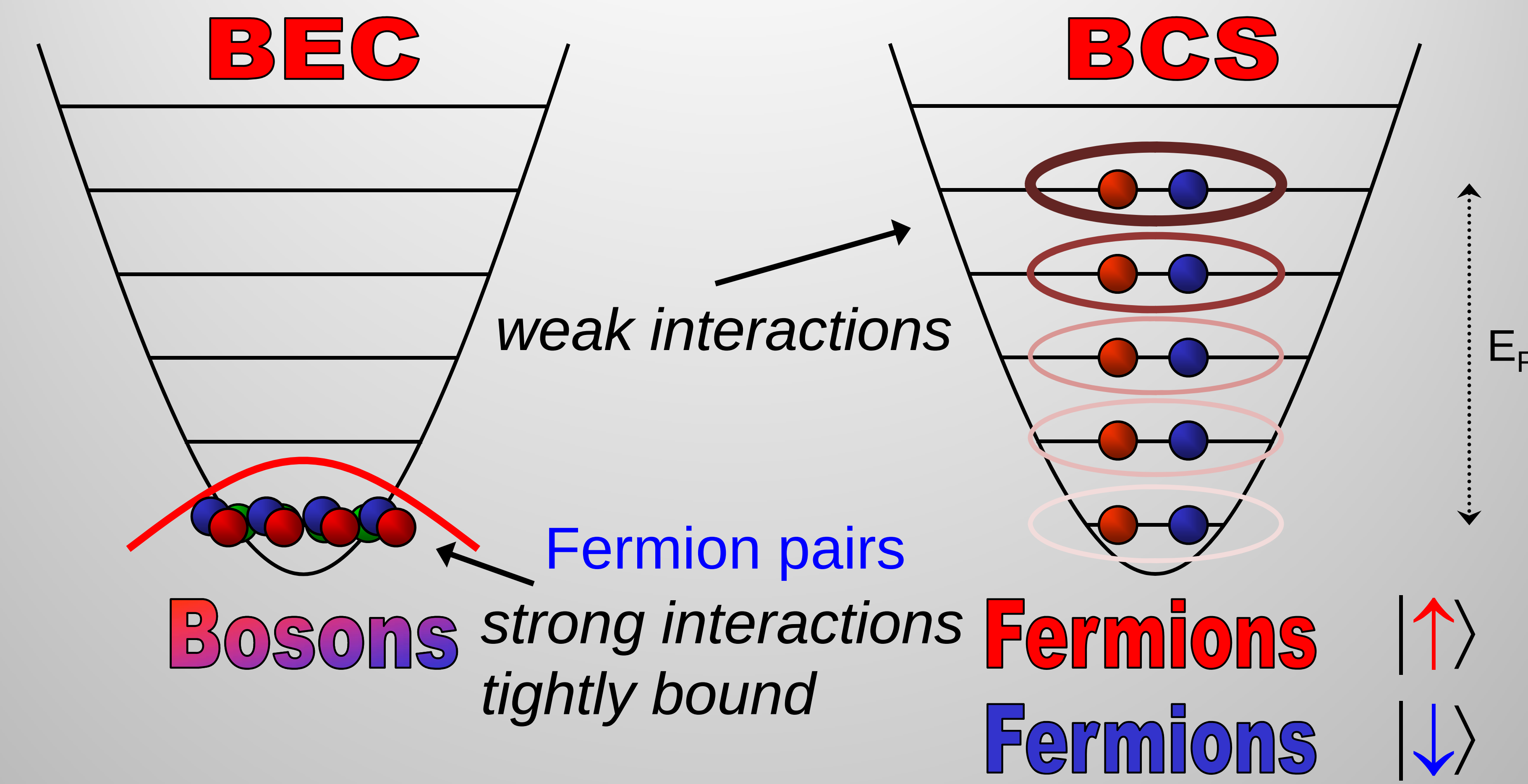
$$6.3(3)\frac{\hbar}{m}\left(\frac{T}{T_F}\right)^{3/2}$$

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

High-Temperature Superfluidity

in an Ultracold Fermi Gas

Bosons vs Fermions



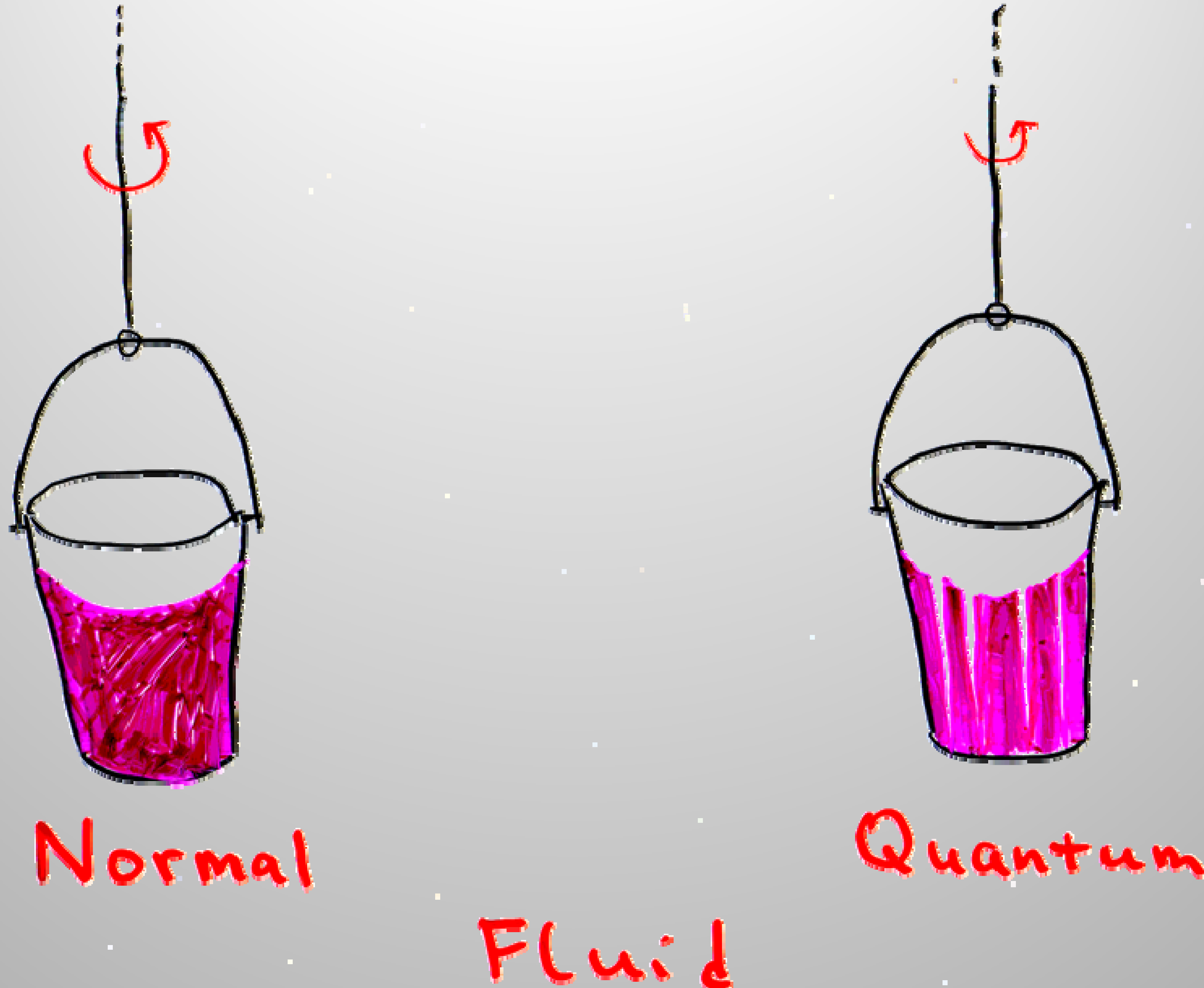
e.g.: $e^- + p$, ^{1}H, ^{23}Na, $^{6}Li_2$, $^{6}Li + ^{6}Li$

$$T_C \approx T_F$$

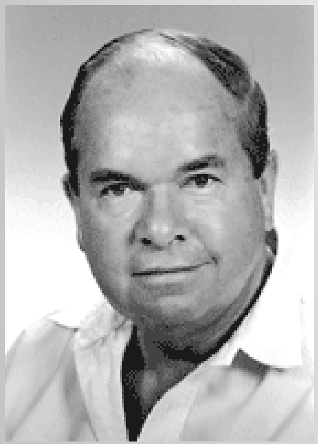
e.g.: e^-, ^{3}He, ^{6}Li, ^{40}K

$$T_C \approx T_F e^{-\pi/2k_F|a|}$$

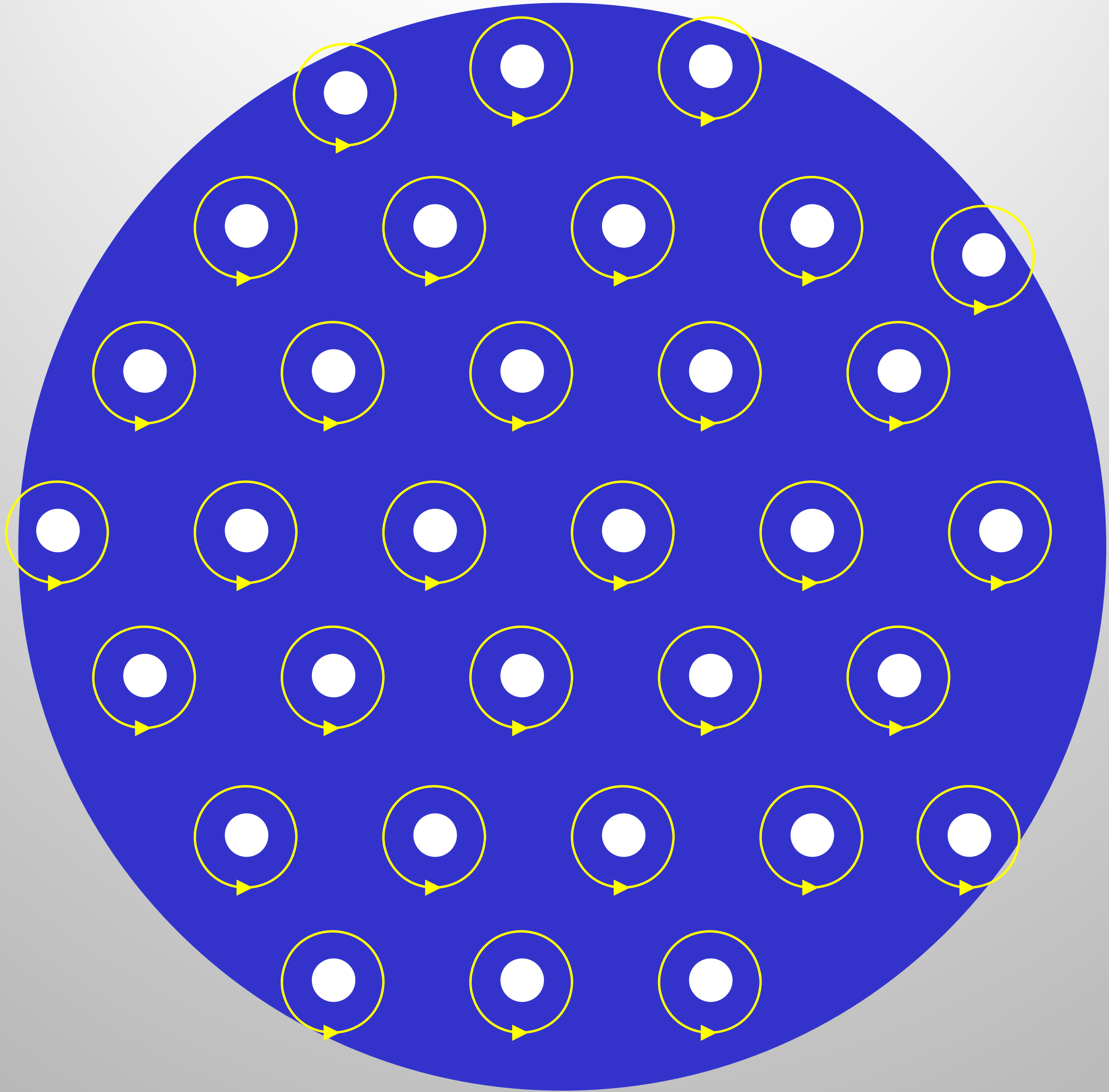
Rotating Fluids



Looking into the bucket



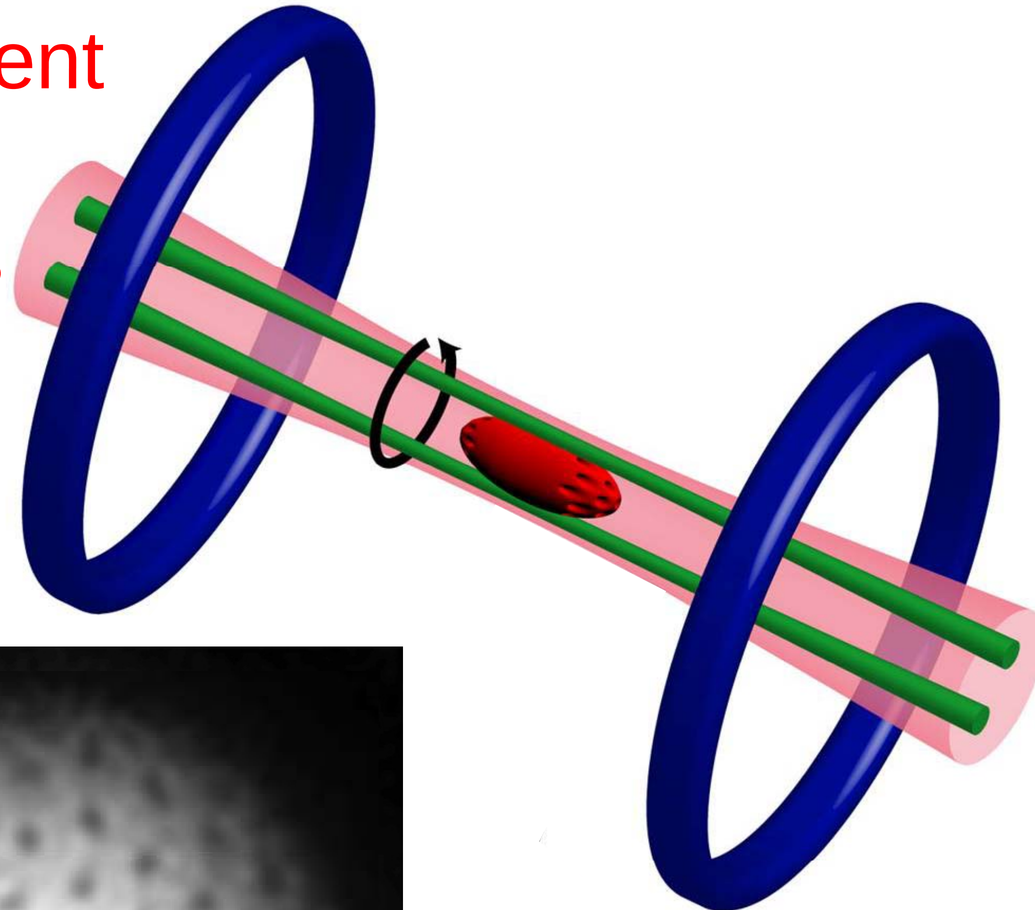
Aleksei A. Abrikosov

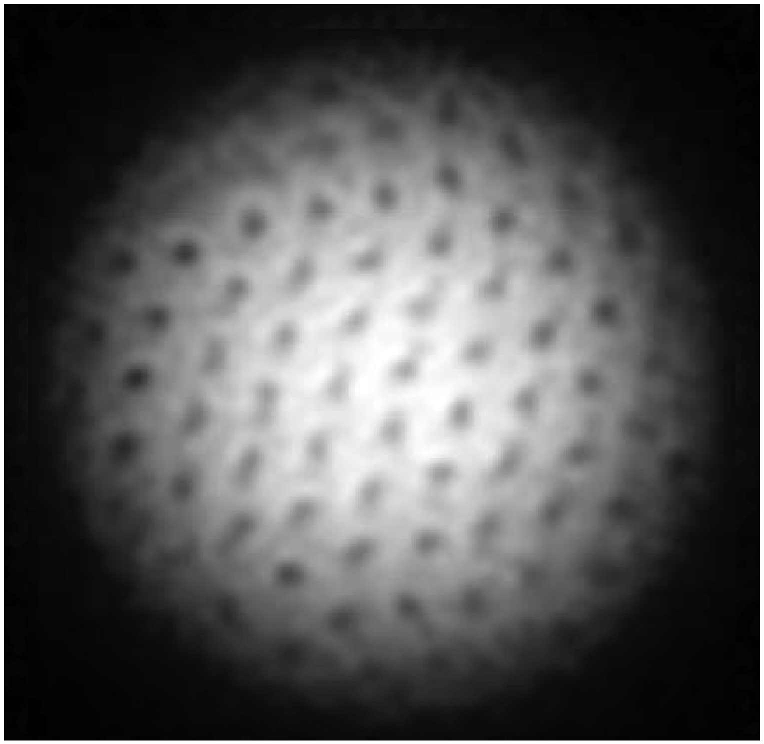


Abrikosov lattice (triangular lattice)

Spinning a strongly interacting Fermi gas

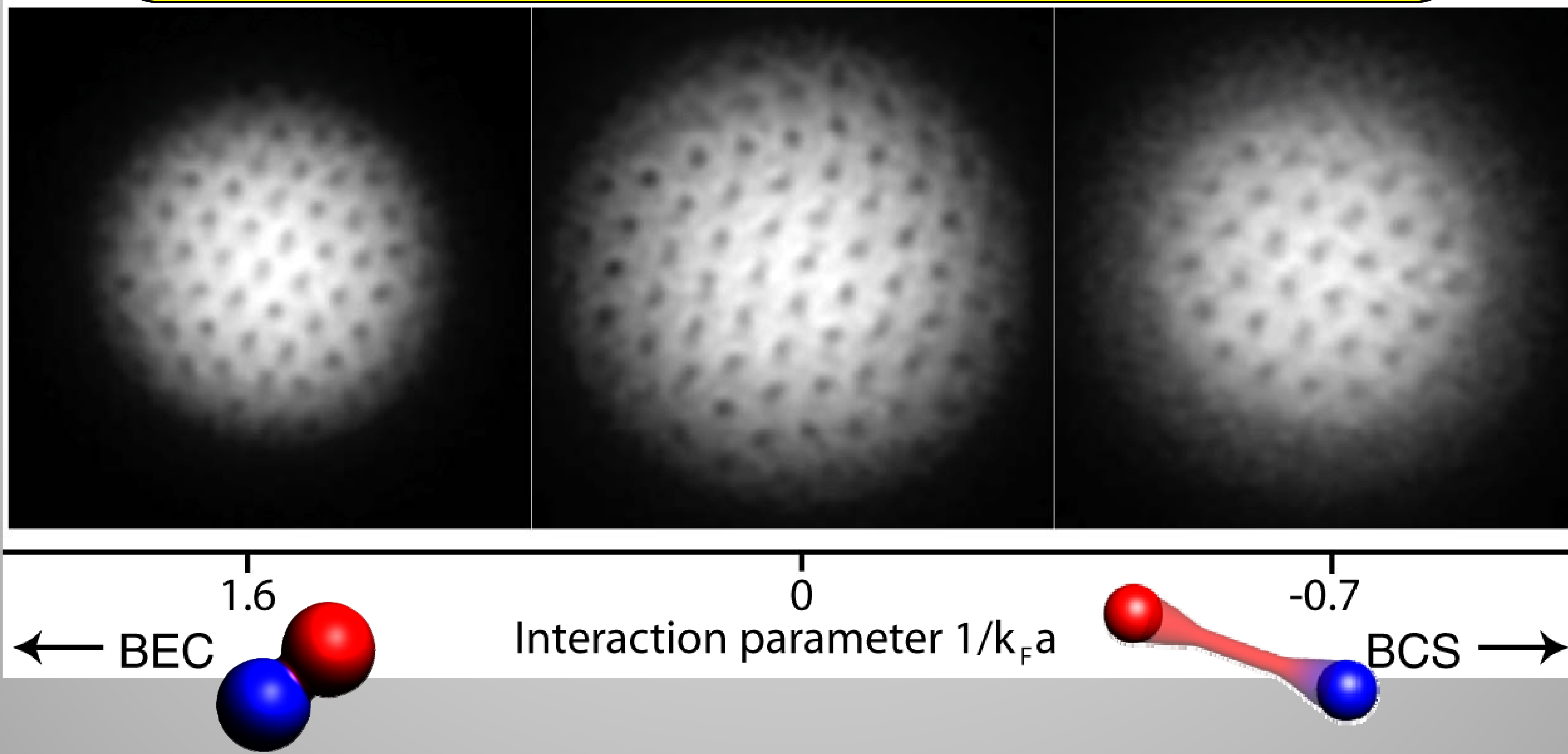
The rotating bucket experiment with a strongly interacting Fermi gas, a million times thinner than air



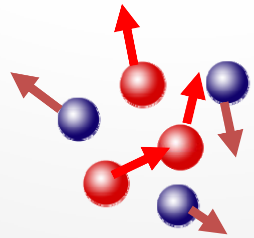


Vortex lattices in the BEC-BCS crossover

Establishes *superfluidity* and *phase coherence*
in gases of fermionic atom pairs

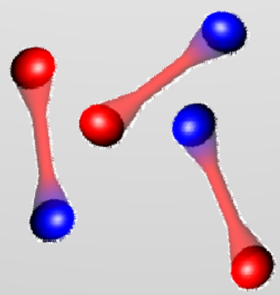


M.W. Zwierlein, J.R. Abo-Shaeer, A. Schirotzek, C.H. Schunck, W. Ketterle,
Nature 435, 1047-1051 (2005)



Classical gas Equation of State (EoS):

$$P = nk_B T$$

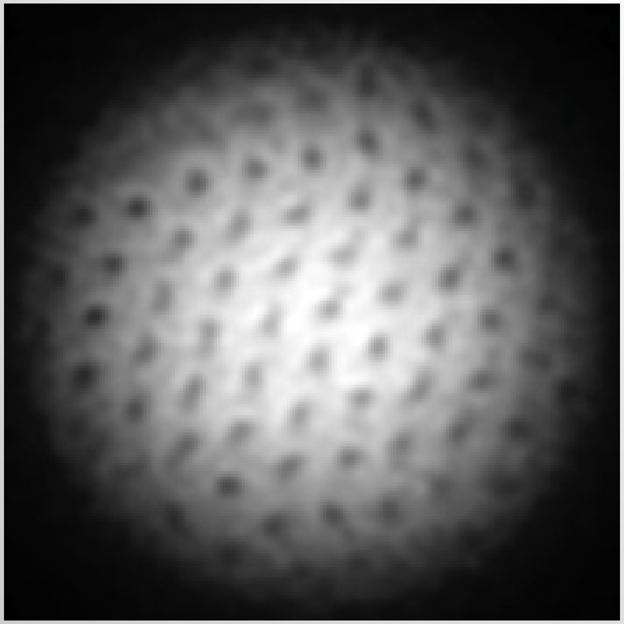


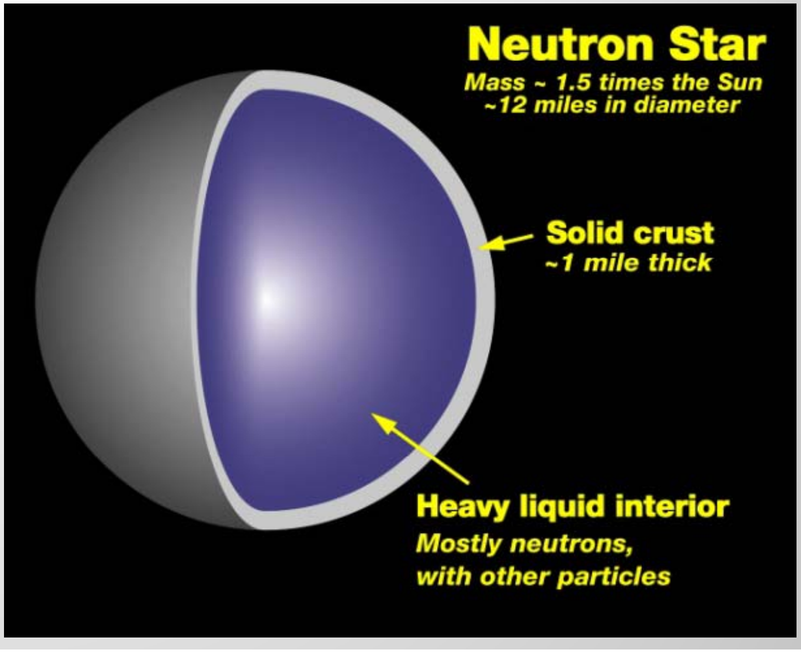
What is the EoS of a strongly interacting Fermi gas?

$$P(n,T)$$

Many expts: Thomas, Jin, Salomon, Grimm, Ketterle, Hulet, Mukaiyama, Vale

Relation to equation of state of a neutron star





Property	Atoms	Neutrons
Spin	Pseudospin ½	Spin ½
Interparticle distance $n^{-1/3}$	1 μm	1 fm
Density	10^{13} cm^{-3}	10^{38} cm^{-3}
Fermi Energy	1 μK = 10^{-10} eV	10^{12} K = 150 MeV
Scattering length a	freely tunable	-19 fm

Both systems lie in universal regime: $a \gg n^{-1/3}$

small print: neglecting effective range

Measuring the Equation of State

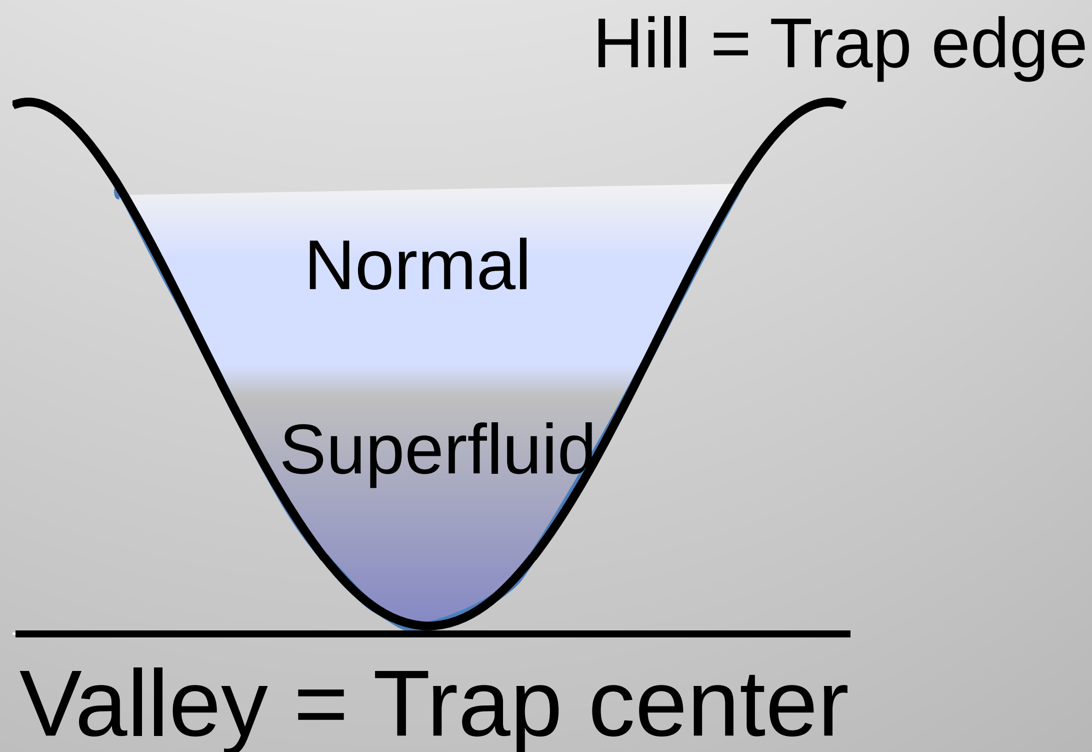
When climbing a mountain, the air gets thinner...

Equation of state → density as a function of height

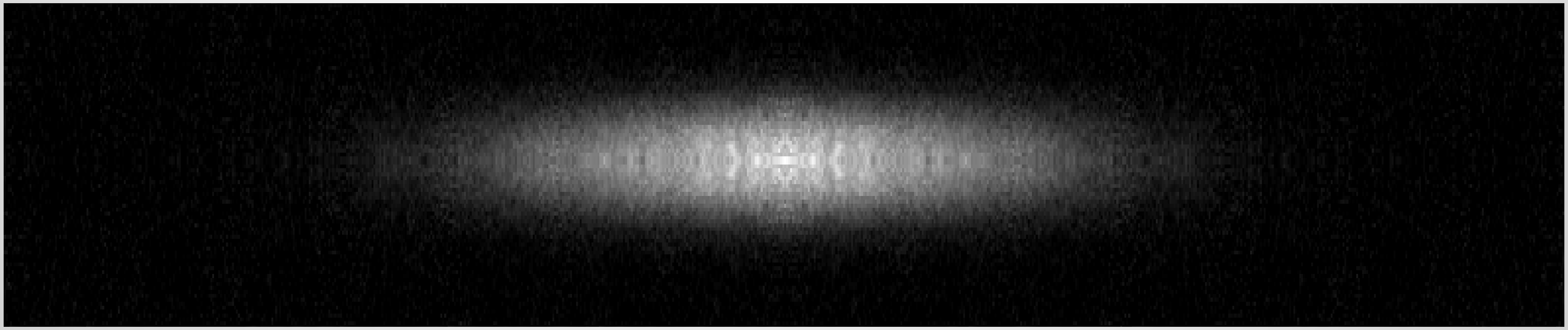
The inverse works as well!

Density as a function of height → equation of state

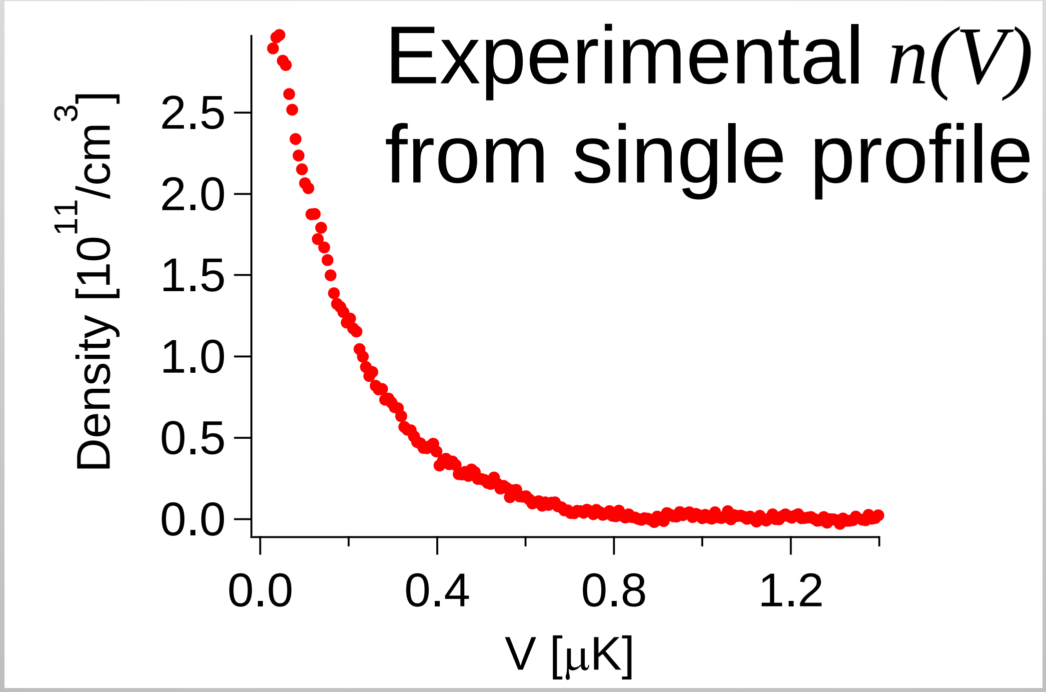
Atoms in our trapping potential air in gravitational potential



Equation of State: Measuring density



Exploiting cylindrical symmetry and careful characterization of trapping potential:



Equation of State: Measuring pressure

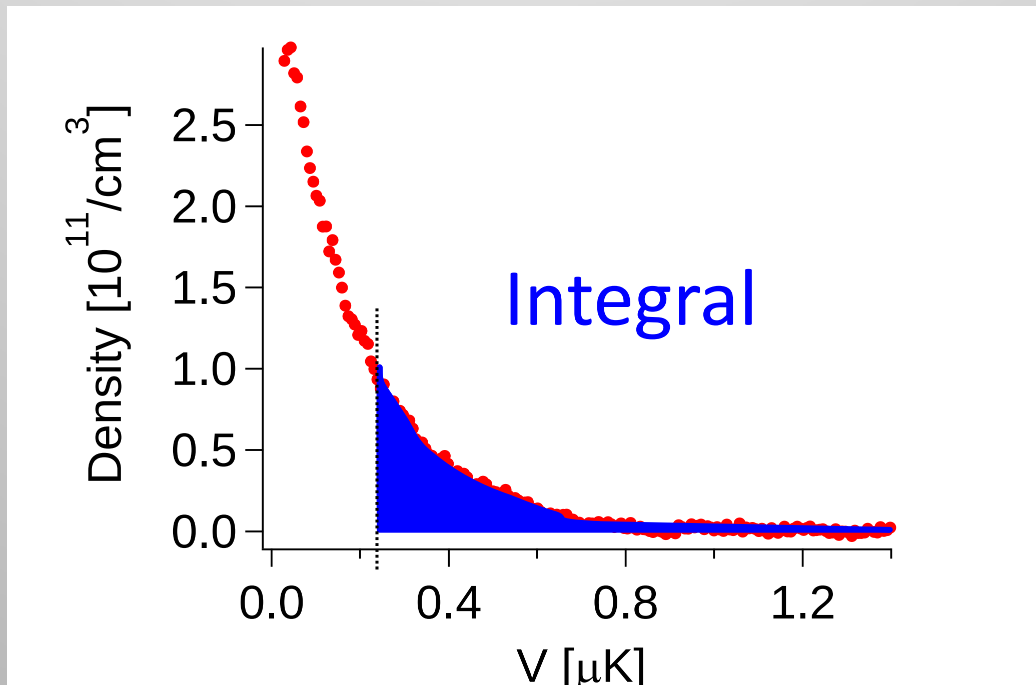
Pressure = weight / unit area of air above you

For atom trappers: replace m g h → V

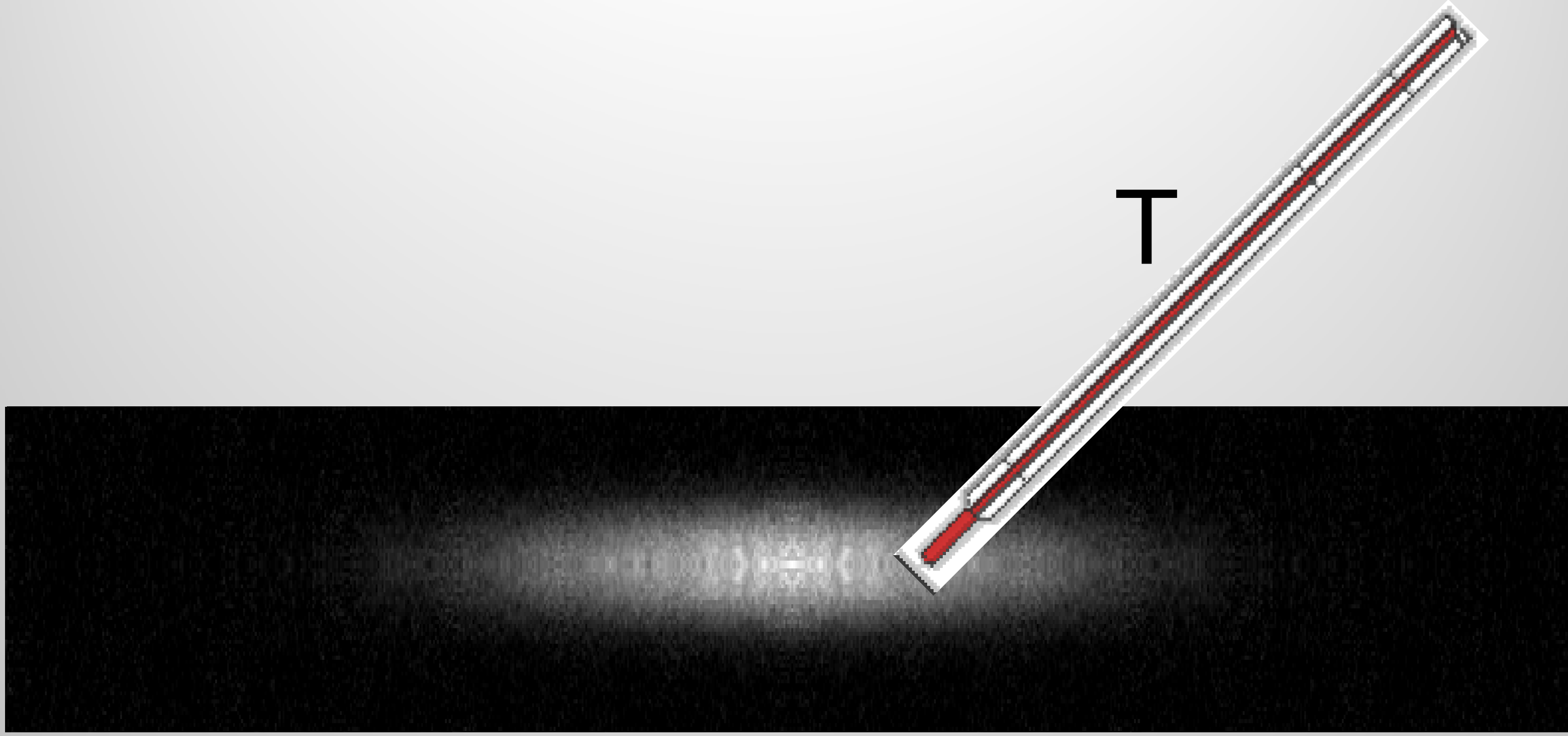
Pressure = integrated density over potential

Local pressure

$$P = \int_{V}^{\infty} \mathrm{d}V' \; n(V')$$



How to get T?

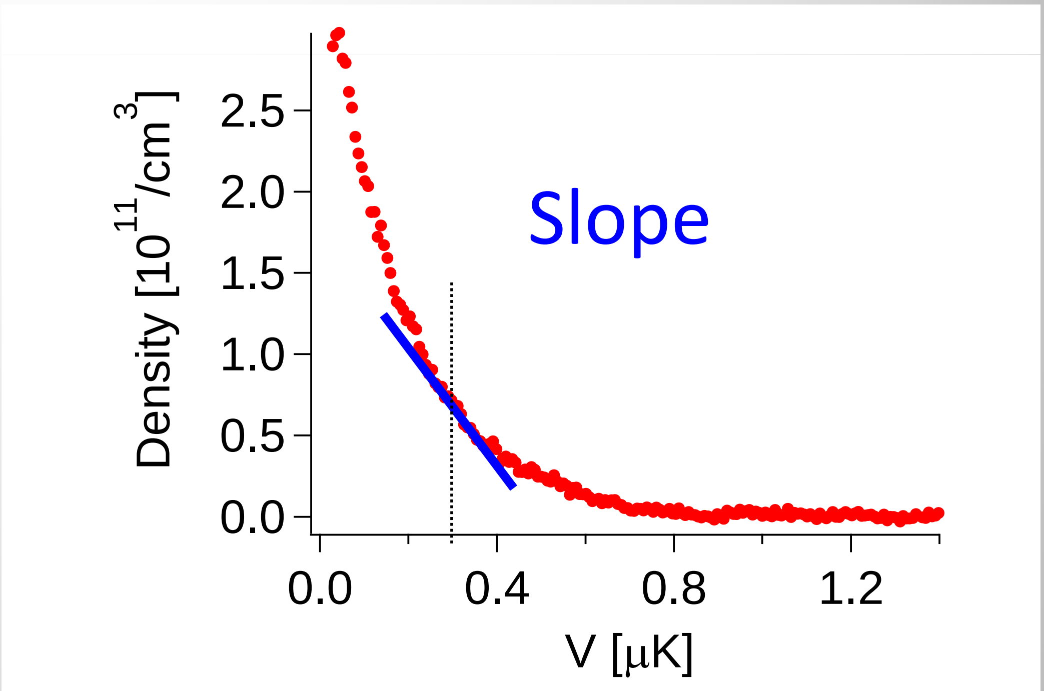


...Not impossible, but it's very difficult, so...

Don't! Instead:

Local compressibility

$$\kappa = -\frac{1}{n^2}\frac{\mathrm{d}n}{\mathrm{d}V}$$



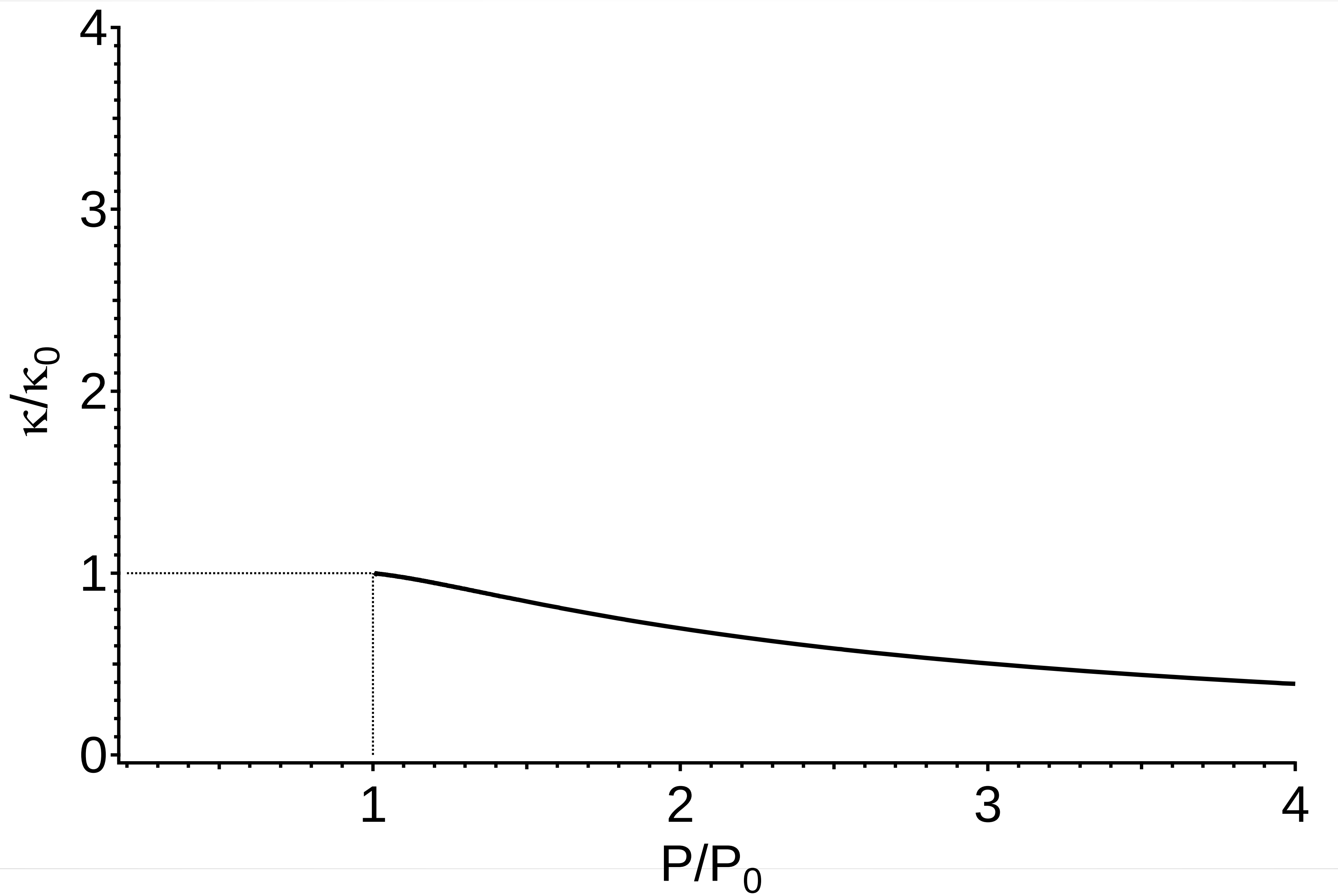
Compressibility Equation of State

$$\kappa(n, P)$$

All other thermodynamic quantities follow!

Mark J. H. Ku, Ariel T. Sommer, Lawrence W. Cheuk, Martin W. Zwierlein
Science **335**, 563-567 (2012)

Compressibility Equation of State



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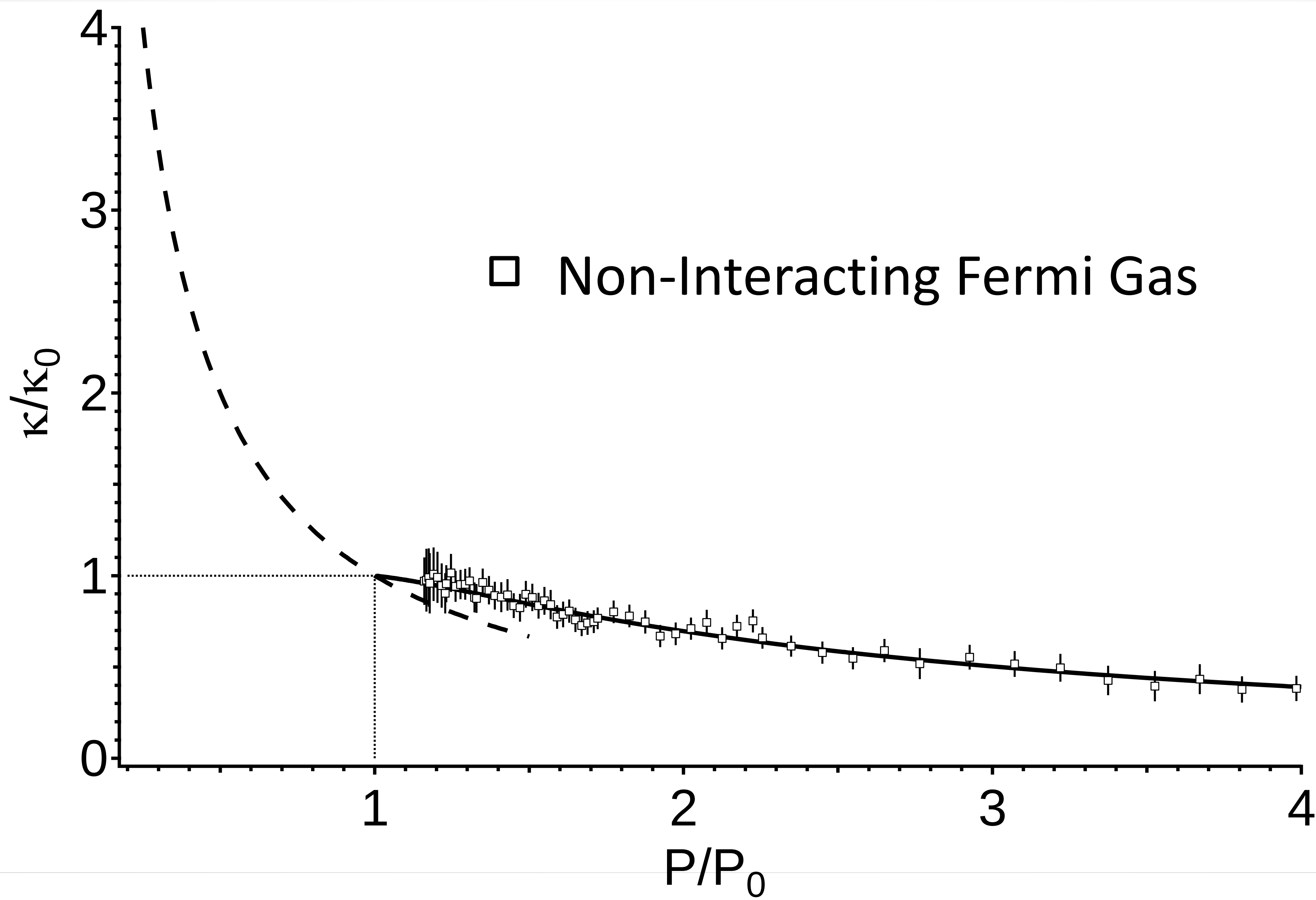

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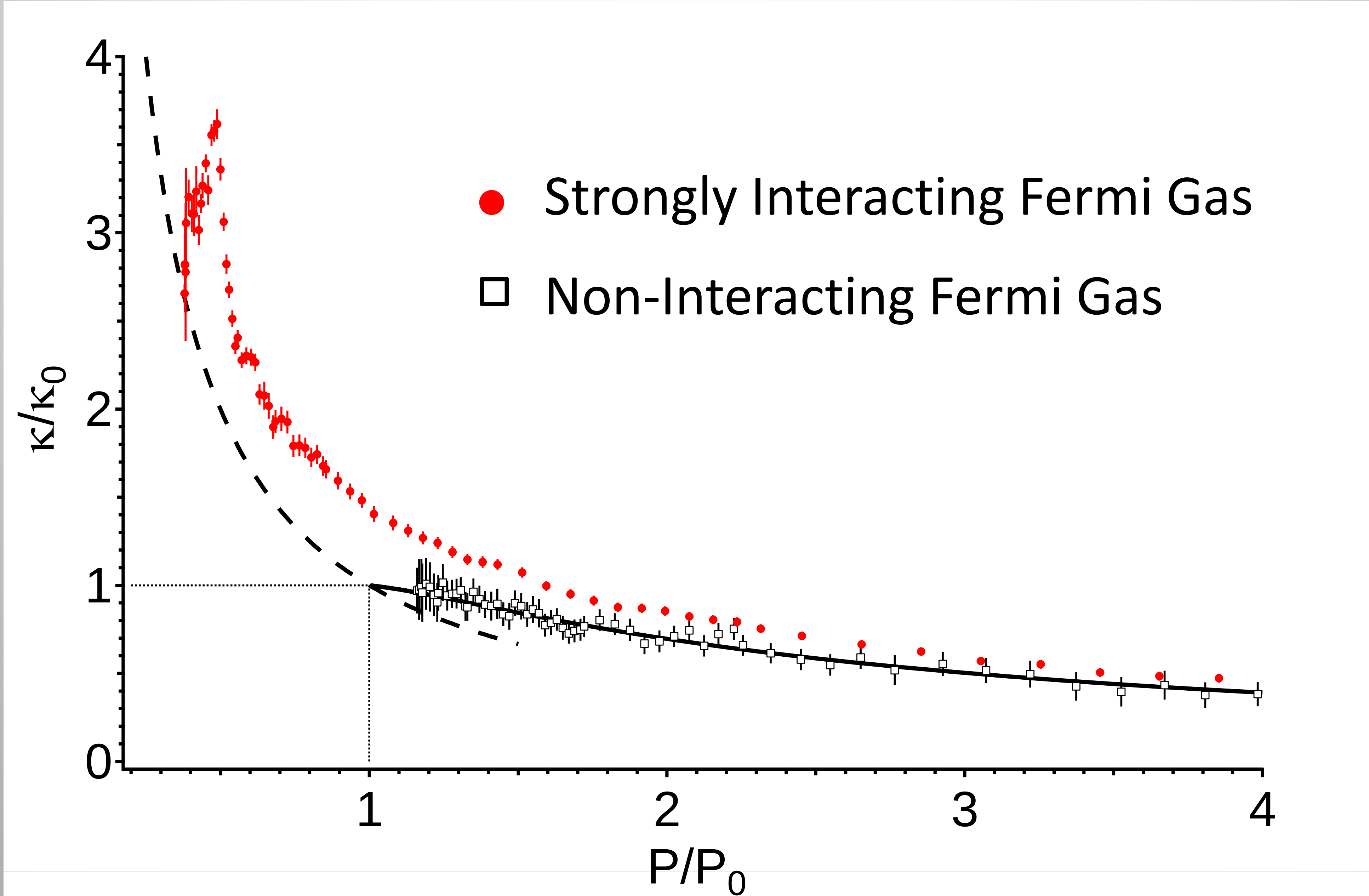

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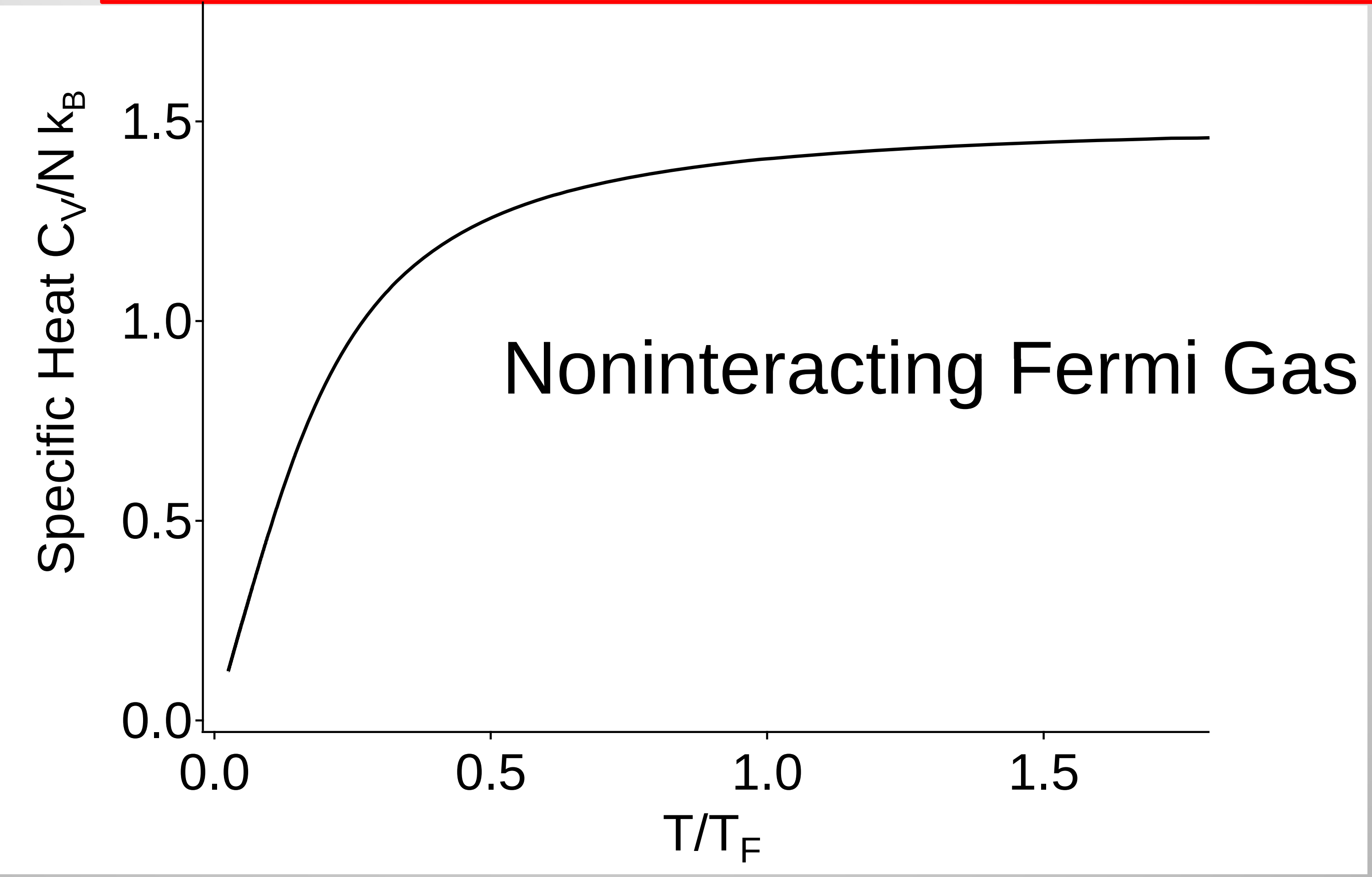
Heat capacity

For a resonant gas:

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

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



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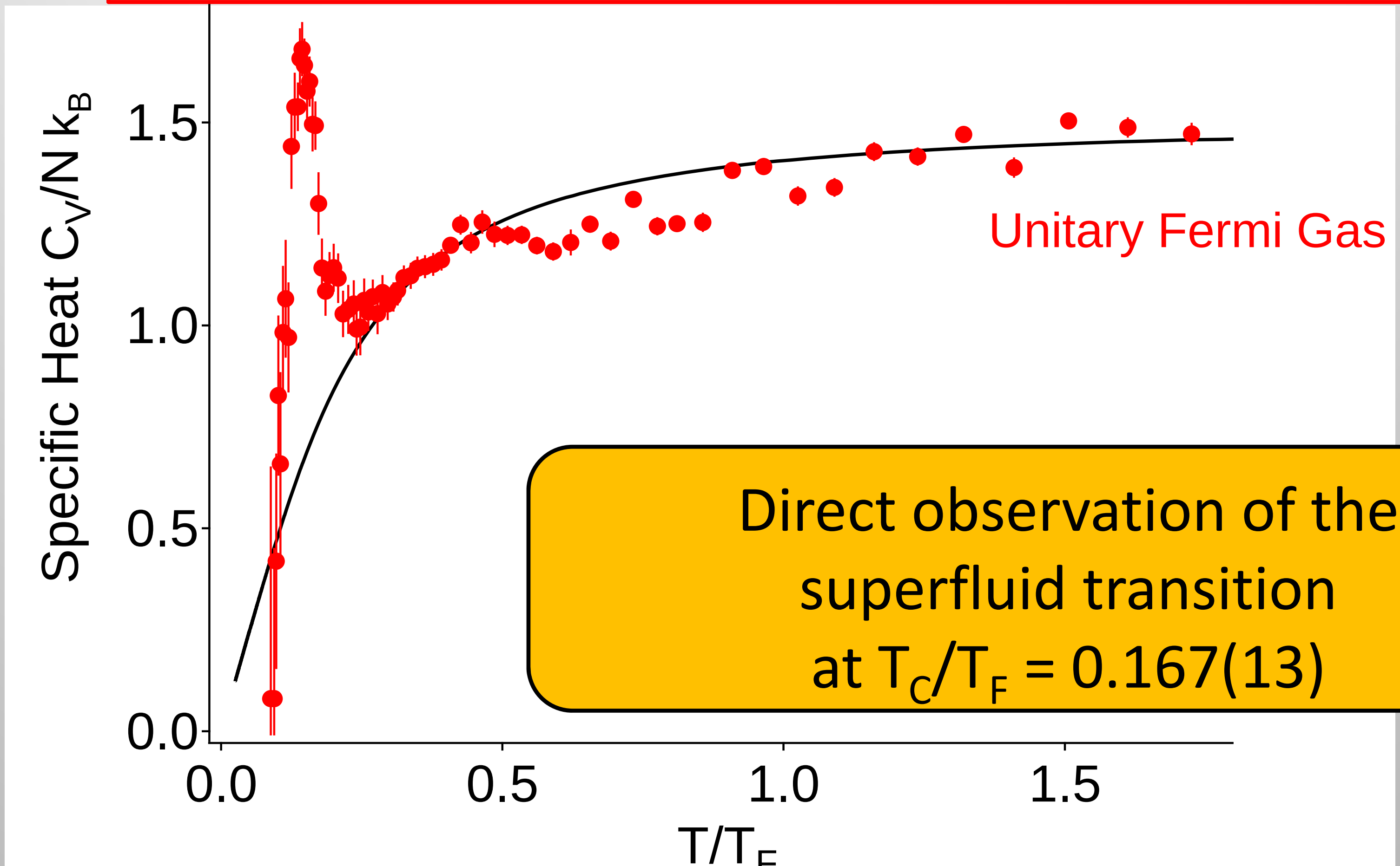
For a resonant gas:

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

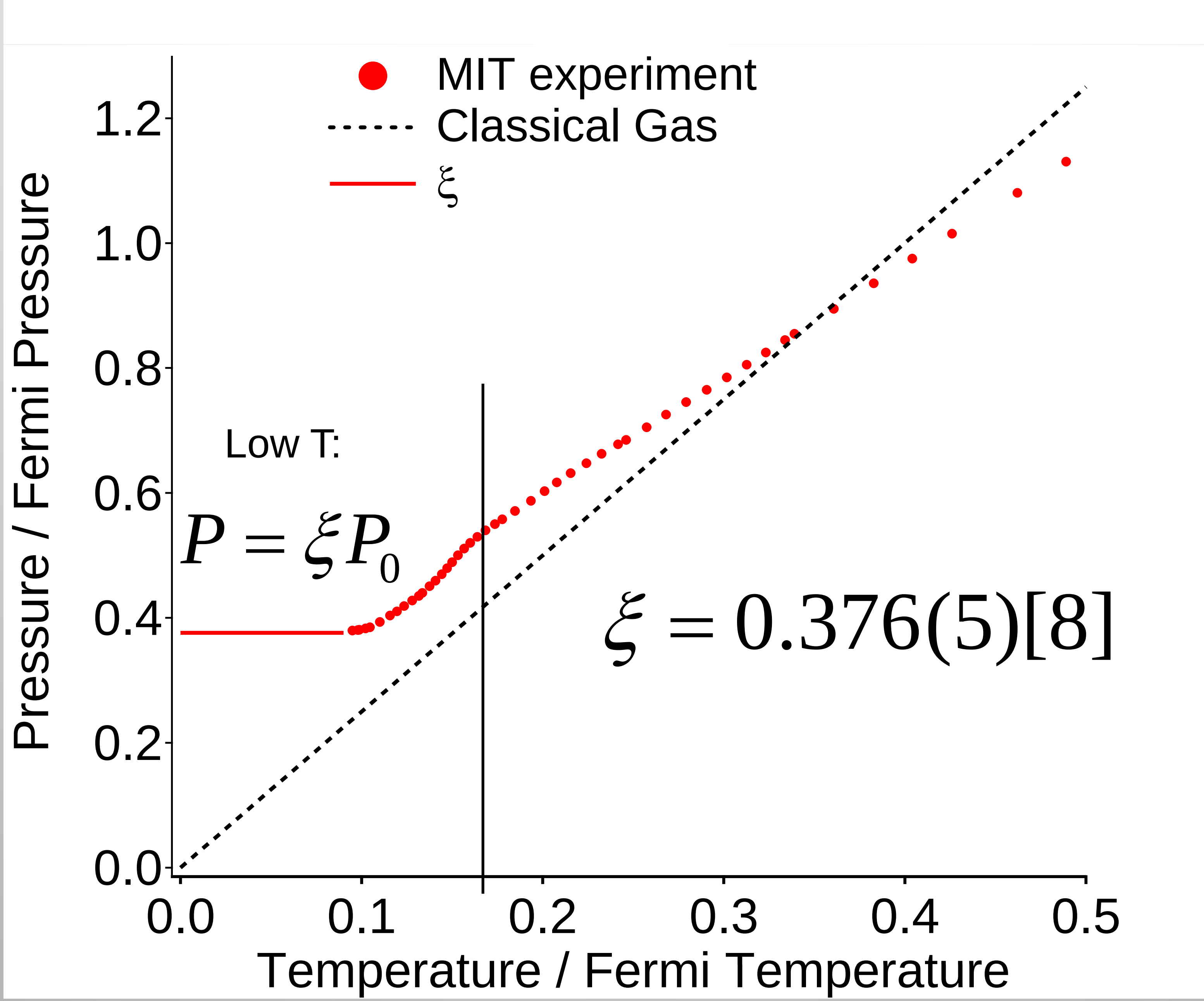
$$\frac{C_V}{Nk_B} = \left.\frac{d(E/Nk_B)}{dT}\right|_{N,V} = \frac{d(P/nE_F)}{d(T/T_F)} = \frac{3}{2}\frac{T_F}{T}\left(\frac{P}{P_0} - \frac{\kappa_0}{\kappa}\right)$$



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

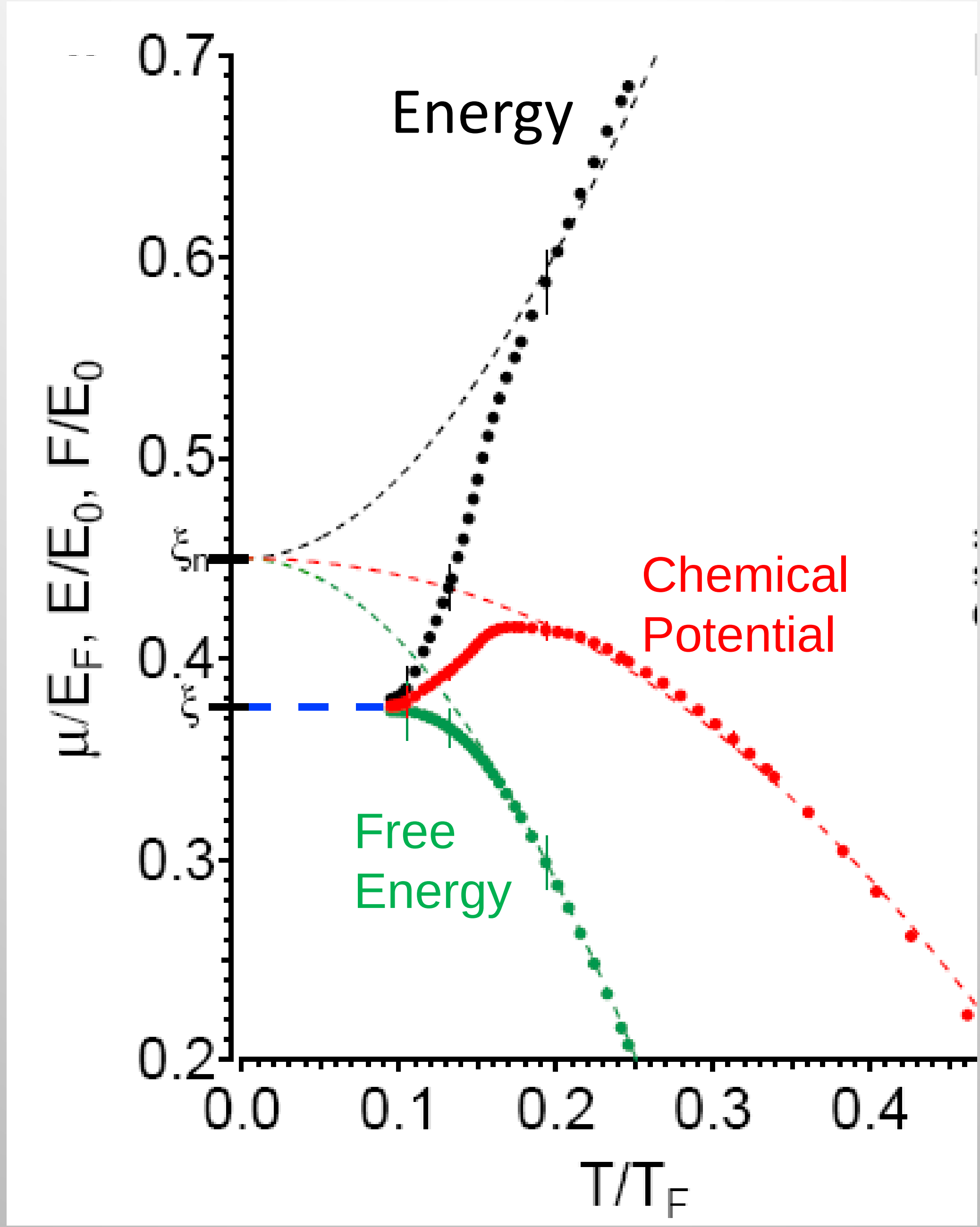
Scaled to the density of electrons in a solid, superfluidity would occur far above room temperature

Pressure versus Temperature



Mark J. H. Ku, Ariel T. Sommer, Lawrence W. Cheuk, Martin W. Zwierlein
Science **335**, 563-567 (2012)

Energy, Chemical Potential, Free Energy



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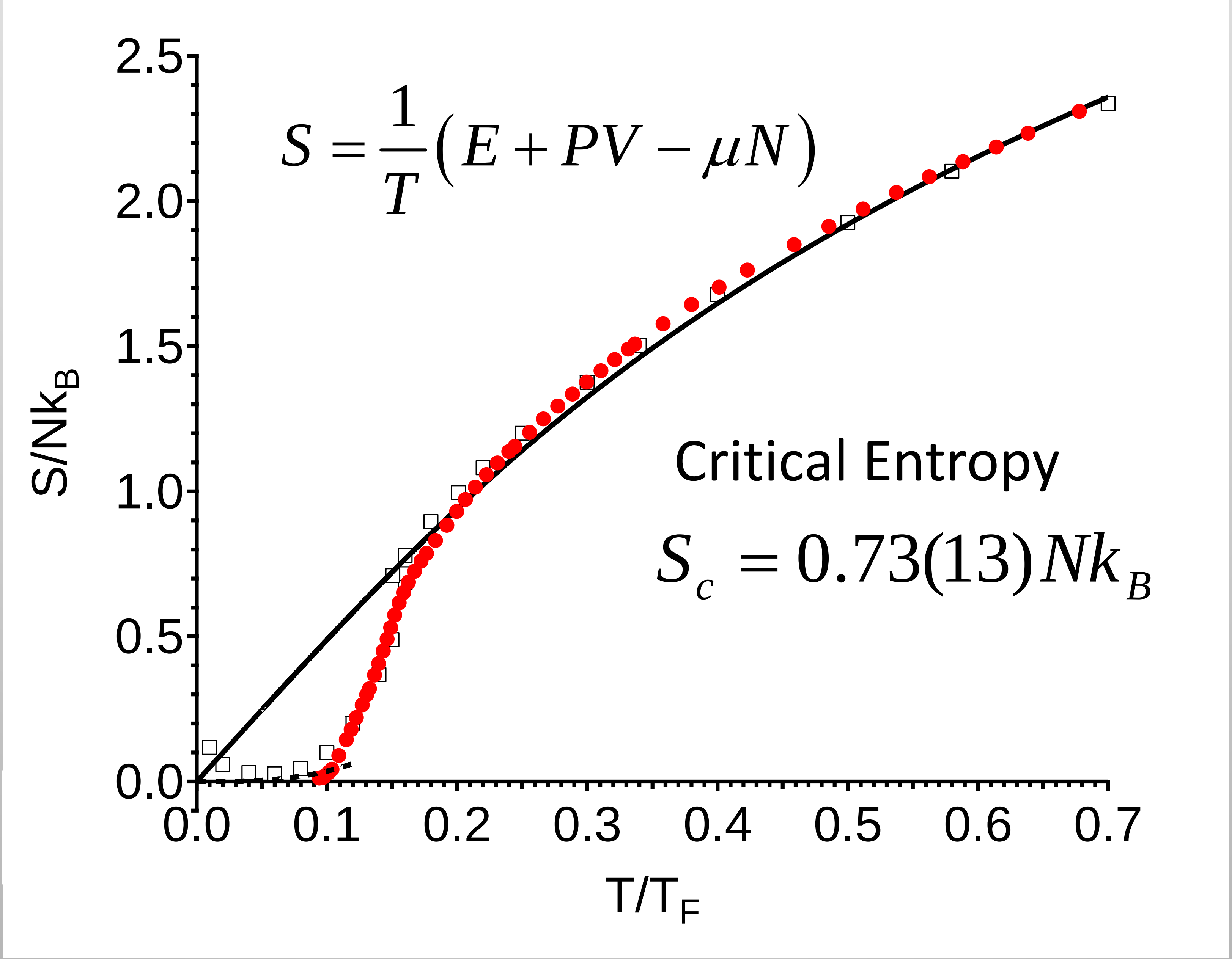
Science **335**, 563-567 (2012)

Entropy



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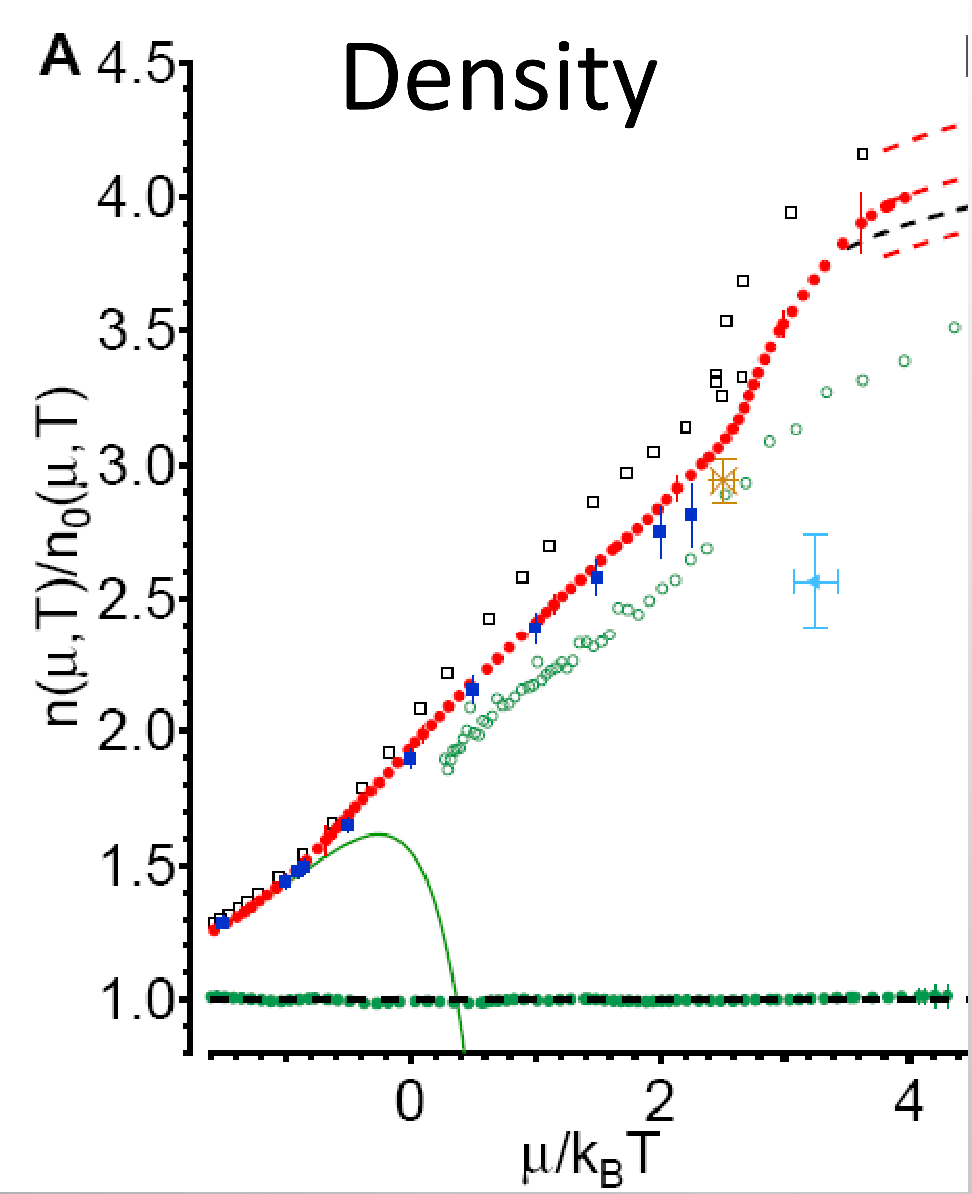
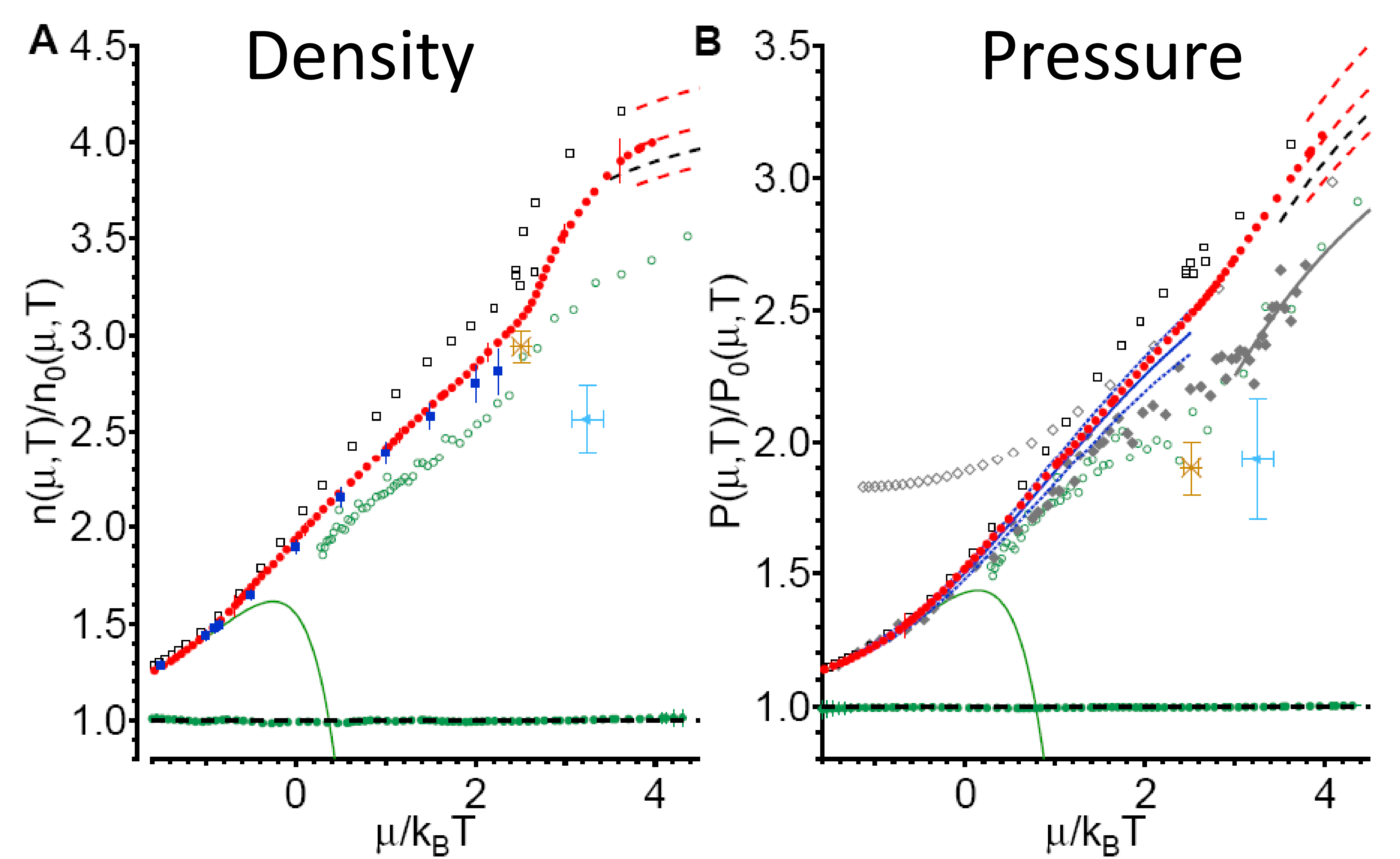
Science **335**, 563-567 (2012)

Realization of a Feynman Quantum Simulation



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)

Realization of a Feynman Quantum Simulation



Mark Ku, Ariel Sommer, Lawrence Cheuk, MWZ, Science **335**, 563-567 (2012)
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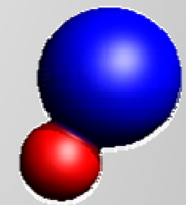
M. Ku, A. Sommer, L. Cheuk, A. Schirotzek, MWZ, Nature Physics **8**, 366 (2012)

Novel Fermi Systems

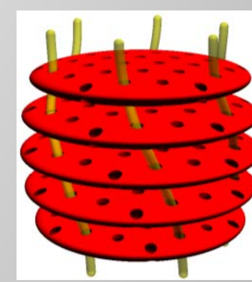
- Towards Stable Dipolar Fermionic Molecules

Cheng-Hsun Wu, Jee Woo Park, Peyman Ahmadi, Sebastian Will, MWZ
Phys. Rev. Lett. **109**, 085301 (2012)

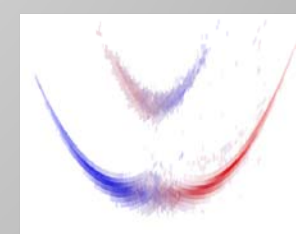


- Lower-Dimensional Fermi Gases

Ariel Sommer, Lawrence Cheuk, Mark Ku, Waseem Bakr, MWZ
Phys. Rev. Lett. **108**, 045302 (2012) Viewpoint in Physics, Jan ‘12



- Spin-Orbit coupled Fermi gases



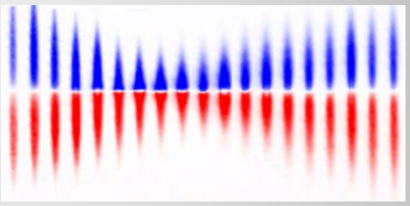
Lawrence Cheuk, Ariel Sommer, Zoran Hadzibabic, Tarik Yefsah, Waseem Bakr, MWZ,
Phys. Rev. Lett. **109**, 095302 (2012) Viewpoint in Physics, Aug‘12

Beyond isotropic s-wave interactions

→ Towards Topological Phases of Matter

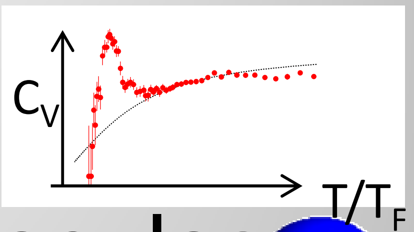
Conclusion

- Universal Spin Transport



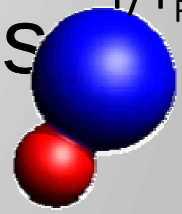
Ariel Sommer, Mark Ku, Giacomo Rota, MWZ
Nature 472, 201 (2011)

- Universal Thermodynamics



Mark Ku, Ariel Sommer, Lawrence Cheuk, MWZ
Science 335, 563-567 (2012)

- Towards Stable Dipolar Fermionic Molecules



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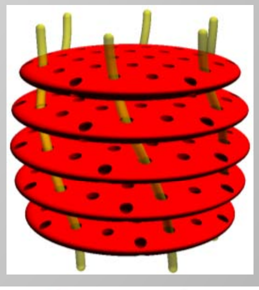

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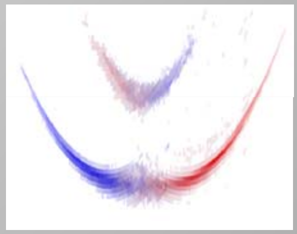
- Spin-Orbit coupled Fermi gases



Lawrence Cheuk, Ariel Sommer, Zoran Hadzibabic, Tarik Yefsah,
Waseem Bakr, MWZ, PRL **109**, 095302 (2012) Viewpoint Aug'12

→ Towards Understanding and Control of Strongly Interacting Fermi System

Fermions and Bosons

BEC I

Fermi Gases in 3D and 2D
Synthetic Gauge Fields

Ariel T. Sommer
Mark J.H. Ku
Lawrence W. Cheuk
Wenjie Ji
Dr. Tarik Yefsah
Dr. Waseem Bakr

Fermi I

LiNaK Mixtures
Dipolar Fermions

Cheng-Hsun Wu
Jee Woo Park
Jenny Schloss
Dr. Sebastian Will

Fermi II

Fermi Gas Microscope

Thomas Gersdorf
Lawrence Cheuk
Melih Okan
Matthew Nichols
Vinay Ramasesh
Dr. Waseem Bakr

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I. Santiago, M.S. 2012 (→ Oxford U.)
Dr. P. Ahmadi, Postdoc (→ Nufern)
C. Clausen (Visiting student, 2008)
Visitors:
Dr. Giacomo Roati, LENS, Florence (2010)
Dr. Zoran Hadzibabic, Cambridge, UK

Past UROPs:
Sara Campbell (→ JILA/U. Colorado)
Caroline Figgatt (→ JQI/U.Maryland)
Pangus Ho (MIT '11)
Kevin Fischer (MIT '12)
Jacob Sharpe (MIT '12)
David Reens (MIT '12)
Jordan Goldstein (MIT'14)

Thanks to: