70 YEAR QUEST ENDS IN SUCCESS

BOSE-EINSTEIN CONDENSATION

2001 NOBEL PRIZE IN PHYSICS

8.044, LECTURE 33, SPRING 2004

BOSE-EINSTEIN CONDENSATION IS A QUANUM MECHANICAL EFFECT

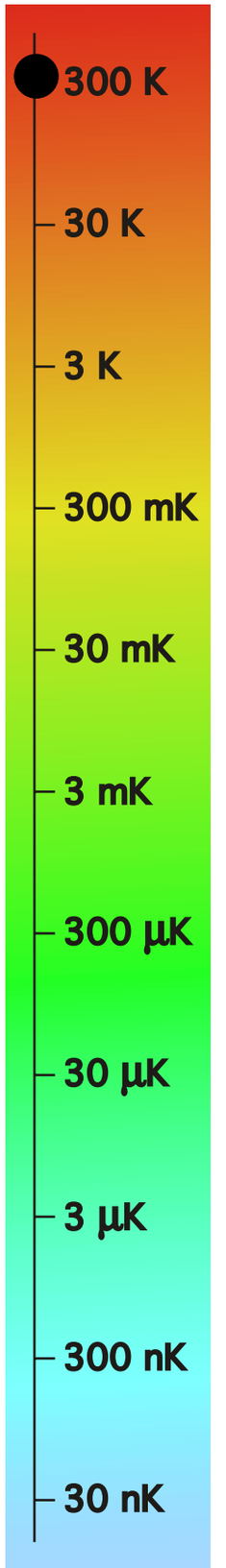


Image removed due to copyright reasons.

Figure 36 from Wright, Orville. *How We Invented the Airplane, An Illustrated History*. New York, NY: Dover, 1988. ISBN: 0486256626.

WITHOUT QUANTUM MECHANICS

Image removed due to copyright reasons.

Image removed due to copyright reasons.

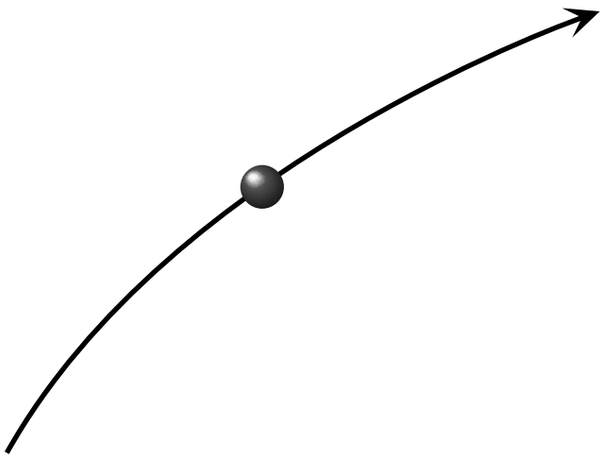
WE COULD NOT BREATHE

ALL MATTER WOULD COLLAPSE

Image removed due to copyright reasons.

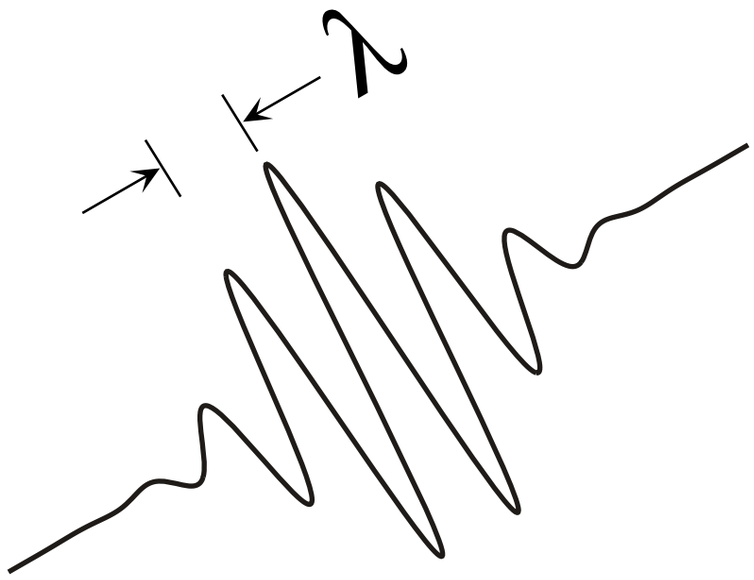
THE SUN WOULD NOT SHINE

CLASSICAL MODEL

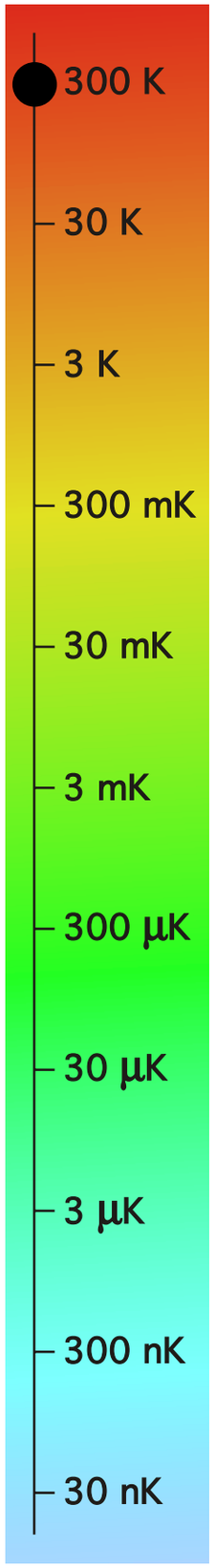


POINT-LIKE
PARTICLES
FOLLOWING
TRAJECTORIES

QUANTUM REALITY



WAVES
PROPAGATING
THROUGH
SPACE



$$\lambda \propto \frac{1}{m \times V}$$

FOR ATOMS MOVING AT THERMAL VELOCITY AT ROOM TEMPERATURE (300K), $\lambda <$ THEIR PHYSICAL SIZE.

FOR THE ELECTRONS MOVING AROUND THE NUCLEI IN THOSE ATOMS, $\lambda \approx 1$ ANGSTROM.

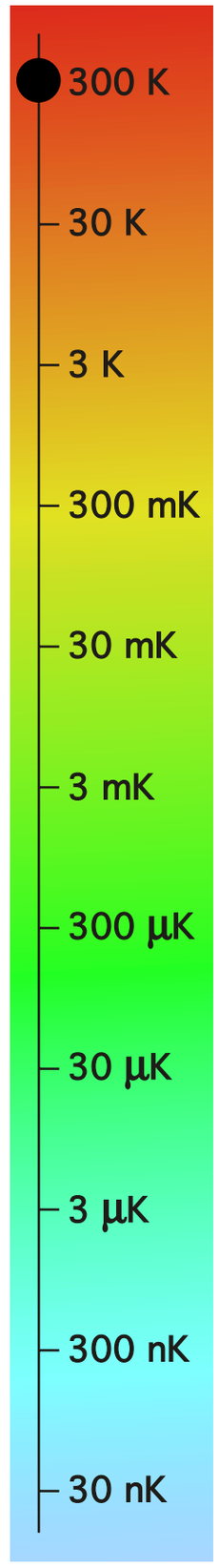


Image removed due to copyright reasons.

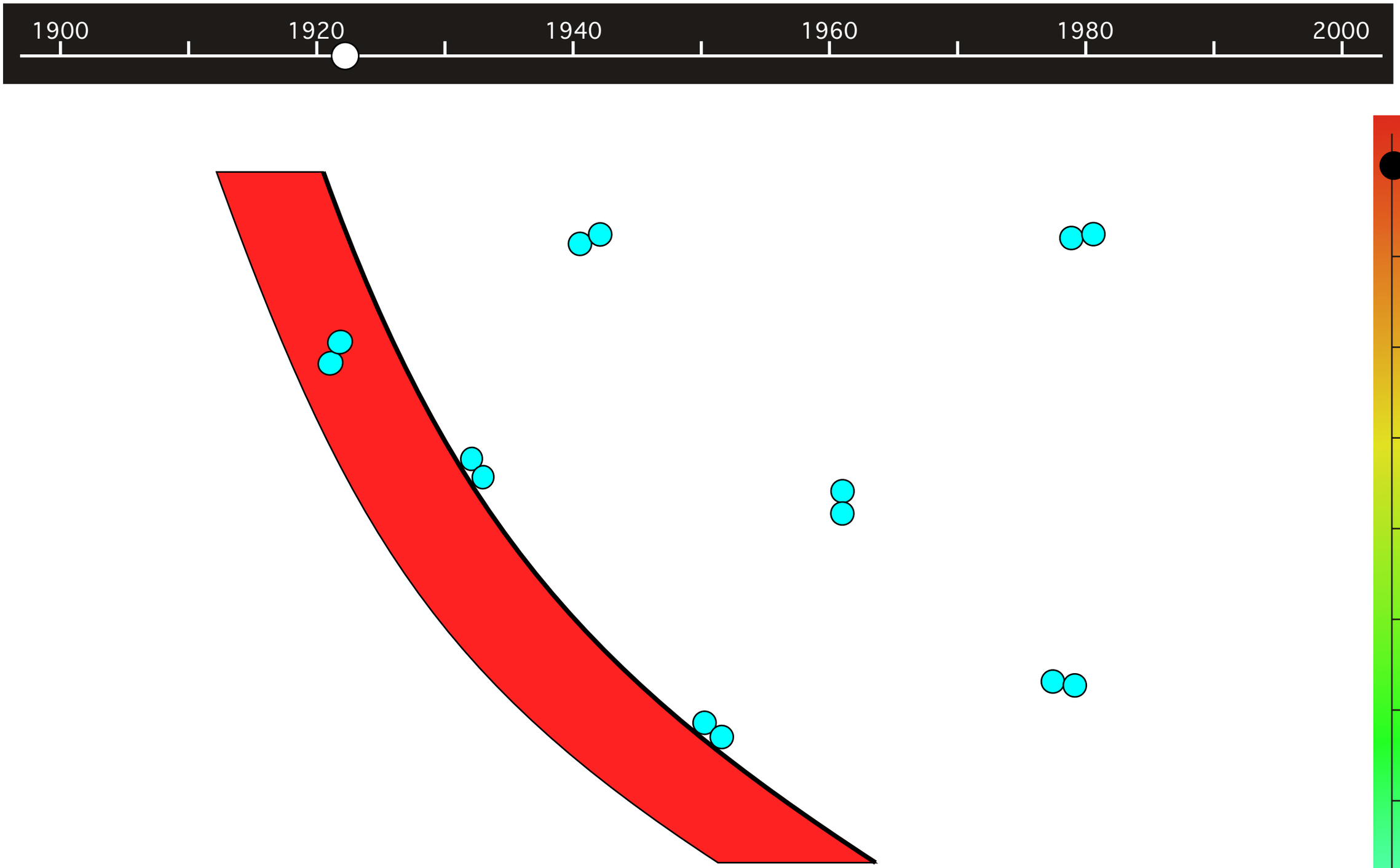
Figure 5-5 from LinkLeighton, Robert B. *LinkPrinciples of modern physics*. New York, NY: McGraw-Hill, 1959.

THE WAVE NATURE OF THE ELECTRONS STABILIZES THEM AGAINST LOSING ENERGY AND FALLING INTO THE NUCLEUS.

Image removed due to copyright reasons.

Figure 3.3 from Kippenhahan, Rudolf. *100 Billion Suns: The Birth, Life, and Death of the Stars.* Princeton, NJ: Princeton University Press, Reprint edition, April 19, 1993, ISBN: 0691087814.

THE WAVE NATURE OF PROTONS ALLOWS THEM TO GET CLOSE ENOUGH DURING COLLISIONS IN THE SUN TO INITIATE FUSION.



QM ALLOWS MOLECULES TO HAVE A STATISTICAL CHANCE OF ADSORBING ON A SURFACE INSTEAD OF REMAINING IN THE BULK GAS

IN 1924 AND 1925 SATYENDRA BOSE AND ALBERT EINSTEIN INVESTIGATED THE INFLUENCE OF QM ON THE COLLECTIVE BEHAVIOR OF PARTICLES.

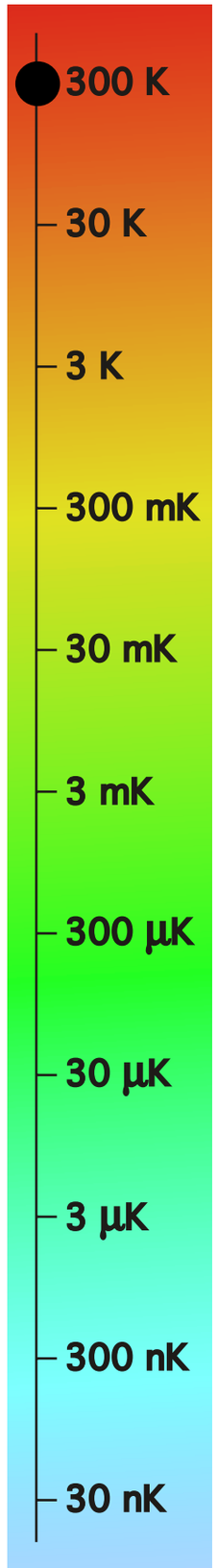
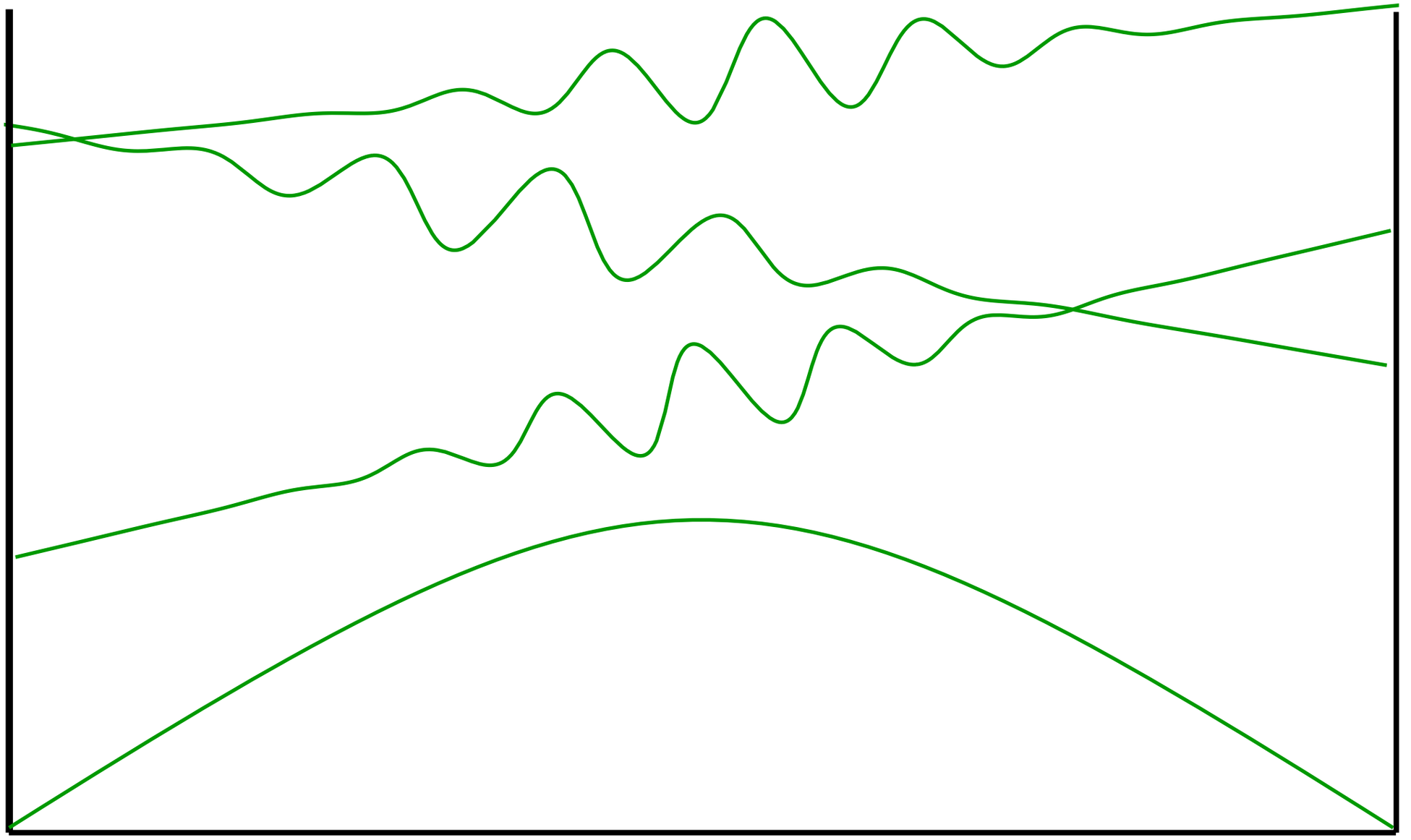


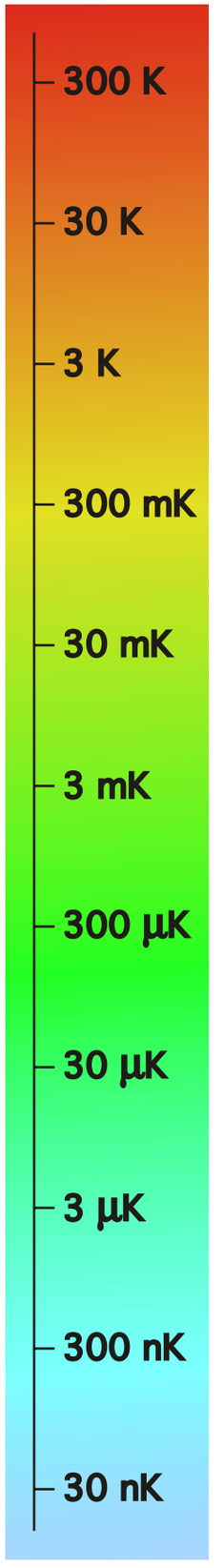
Image of Satyendra Bose

Image of Albert Einstein

Image of the Nobel prize medal

1921
"for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect"





WHEN THE WAVELENGTH BECOMES COMPARABLE TO THE SEPARATION, A PHASE TRANSITION OCCURS. SOME OF THE ATOMS LOSE THEIR IDENTITY AND BECOME PART OF A SINGLE WAVE SPANNING THE CONTAINER.

HALF THE ATOMS IN THE WORLD FOLLOW THE RULES OF BOSE AND EINSTEIN AND ARE CALLED "BOSONS". THE OTHER HALF FOLLOW RULES SET OUT BY ENRICO FERMI AND PAUL DIRAC AND ARE CALLED "FERMIONS".

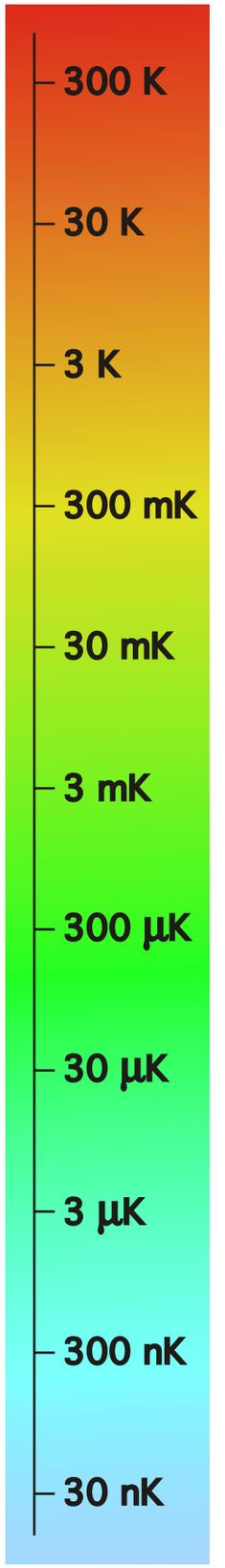


Image of Enrico Fermi

Image of Paul Dirac

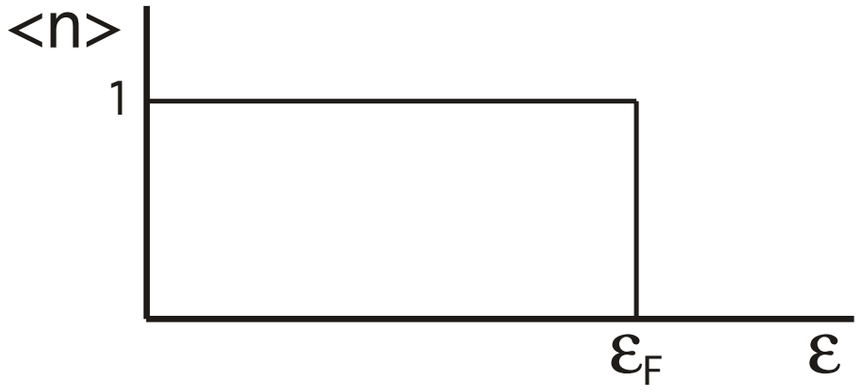
Image of the Nobel prize medal

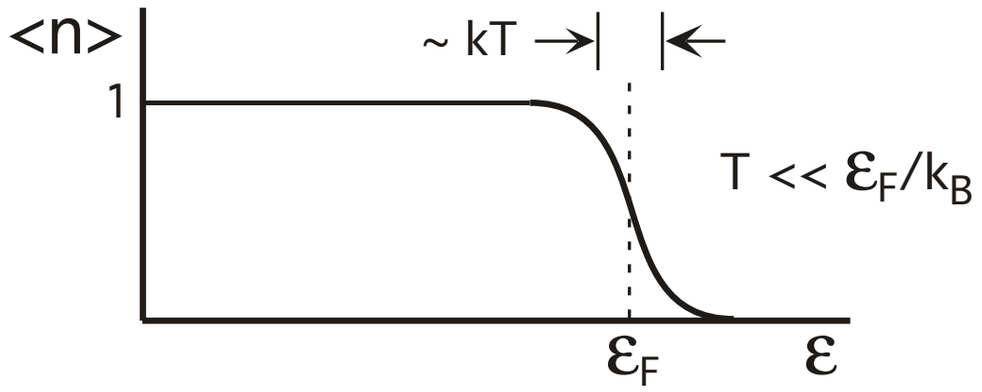
Image of the Nobel prize medal

T = 0

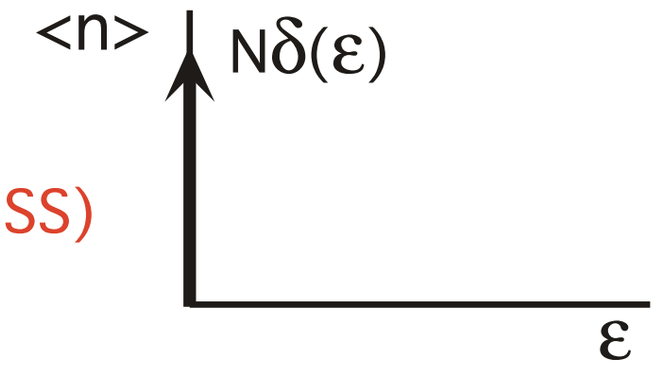
FINITE T

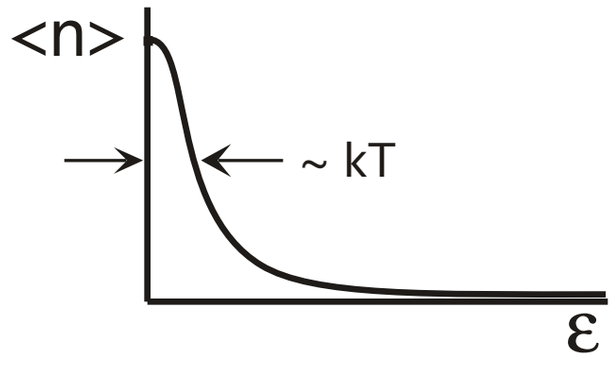
FERMI



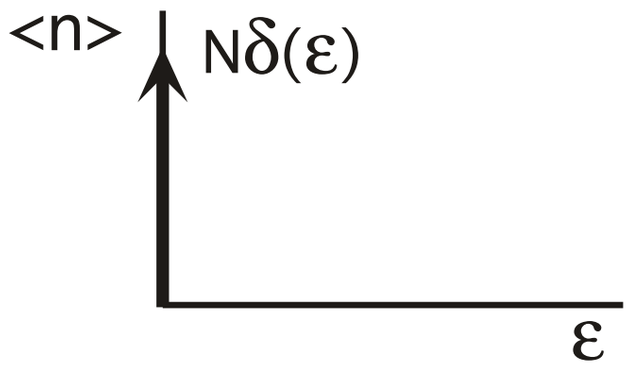


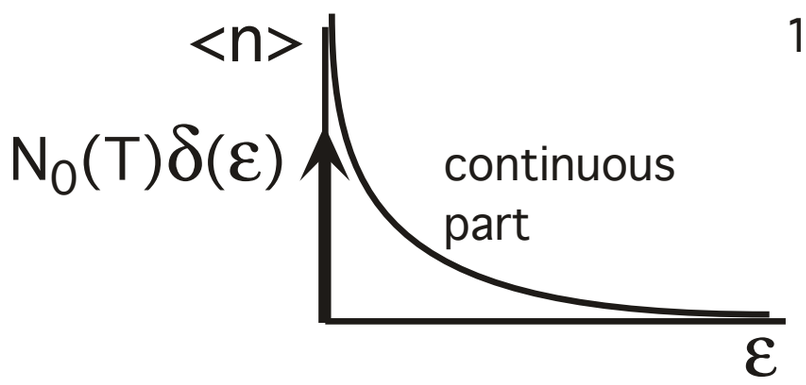
BOSE
(GOOD GUESS)

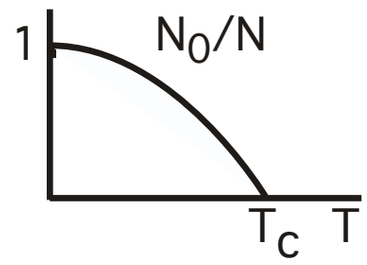


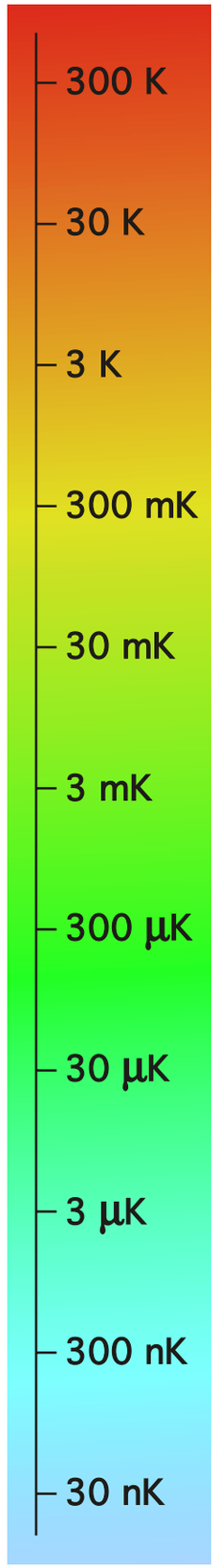


BOSE
(ACTUAL)









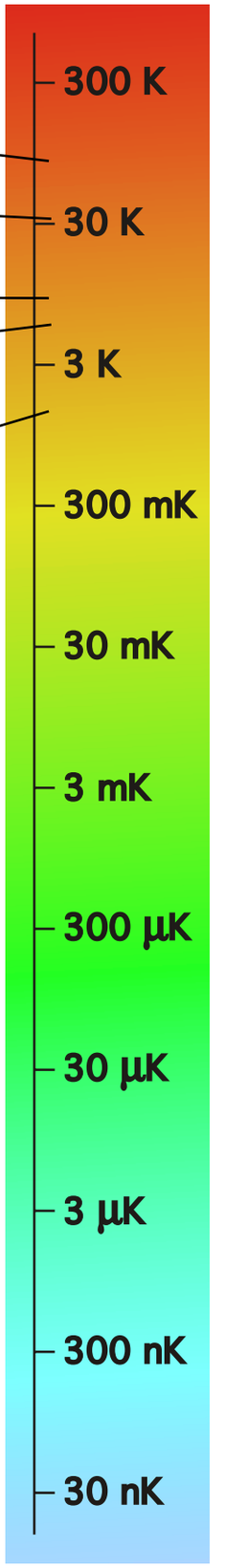
O_2 LIQUEFIES AT 90K

O_2 FREEZES AT 50K

H_2 LIQUEFIES AT 20K

H_2 FREEZES AT 14K

He LIQUEFIES AT 4K



REAL ATOMS OR MOLECULES DO INTERACT WITH EACH OTHER AND UNDERGO LIQUEFICATION AND FREEZING DUE TO THESE INTERACTIONS.

SUPERCONDUCTIVITY WAS DISCOVERED BY KAMERLINGH ONNES IN 1911.

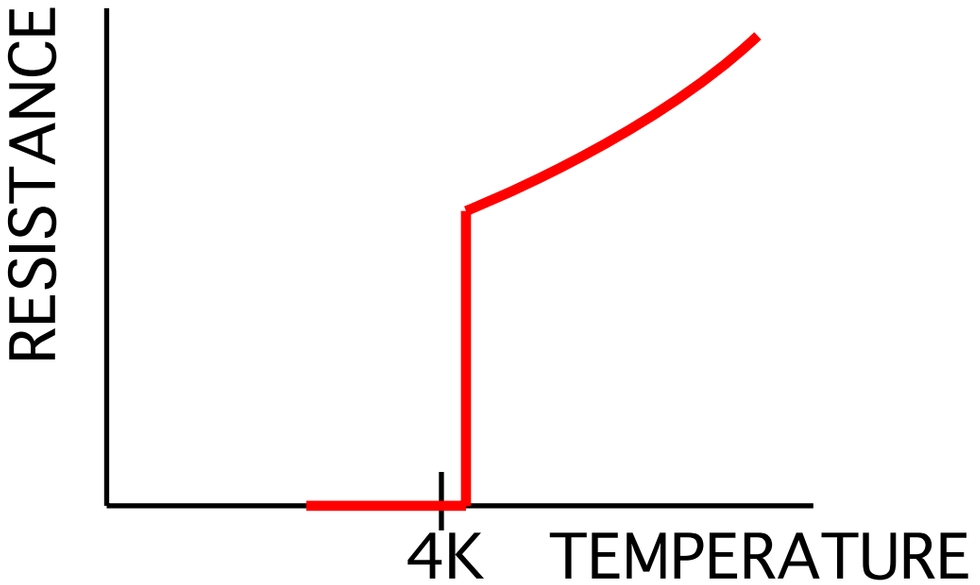


Image of Kamerlingh Onnes

Image of the Nobel prize medal

1913
"for his investigations on the properties of matter at low temperatures which led, inter alia, to the production of liquid helium"

The Nobel Prize in Physics 1972

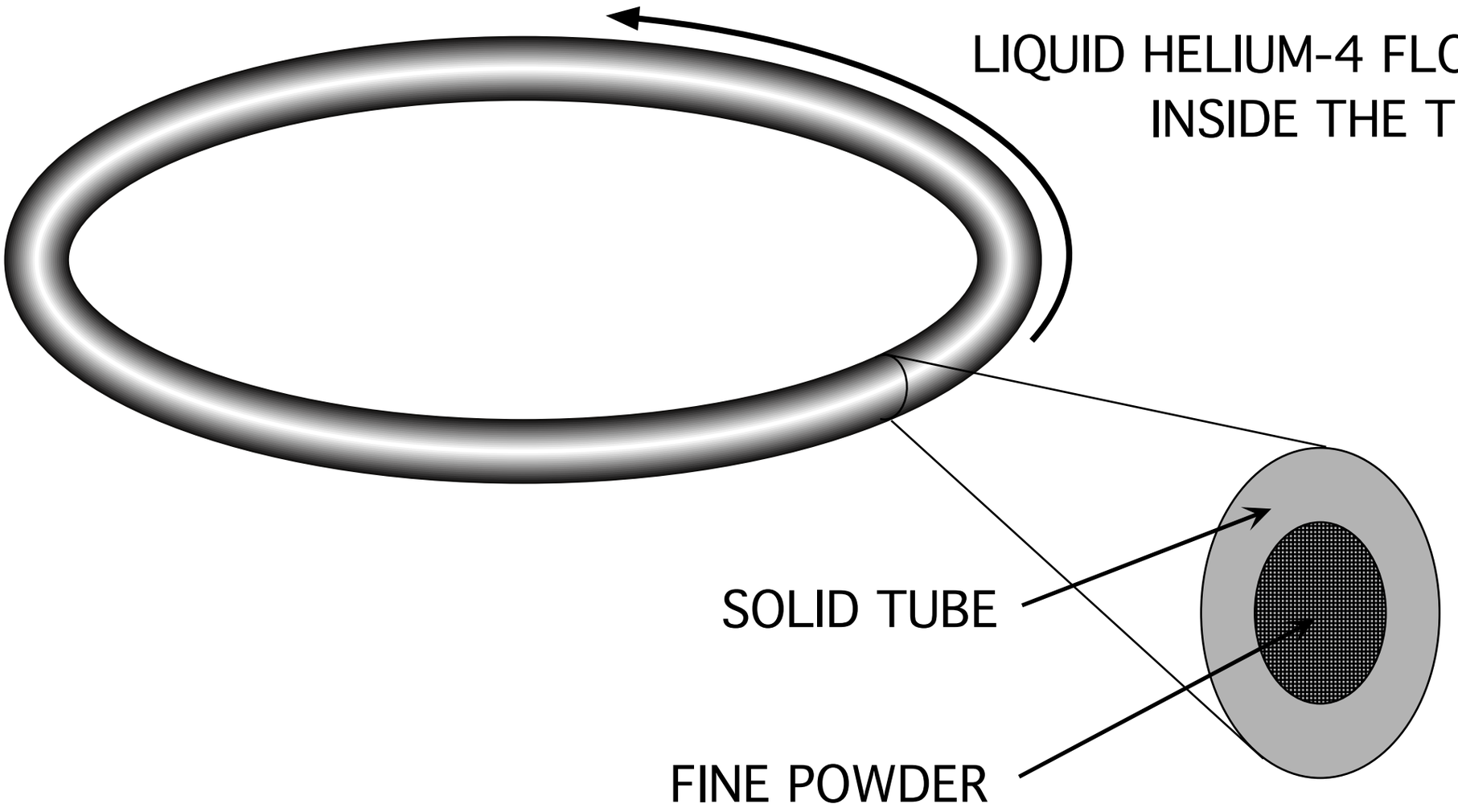
Image of the Nobel prize medal

"for their jointly developed theory of superconductivity, usually called the BCS-theory"

Image of John Bardeen

Image of Leon Neil Cooper

Image of John Robert Schrieffer



SUPERFLUIDITY WAS DISCOVERED IN HELIUM-4 IN THE 1930s AT A TEMPERATURE OF 2 KELVIN.

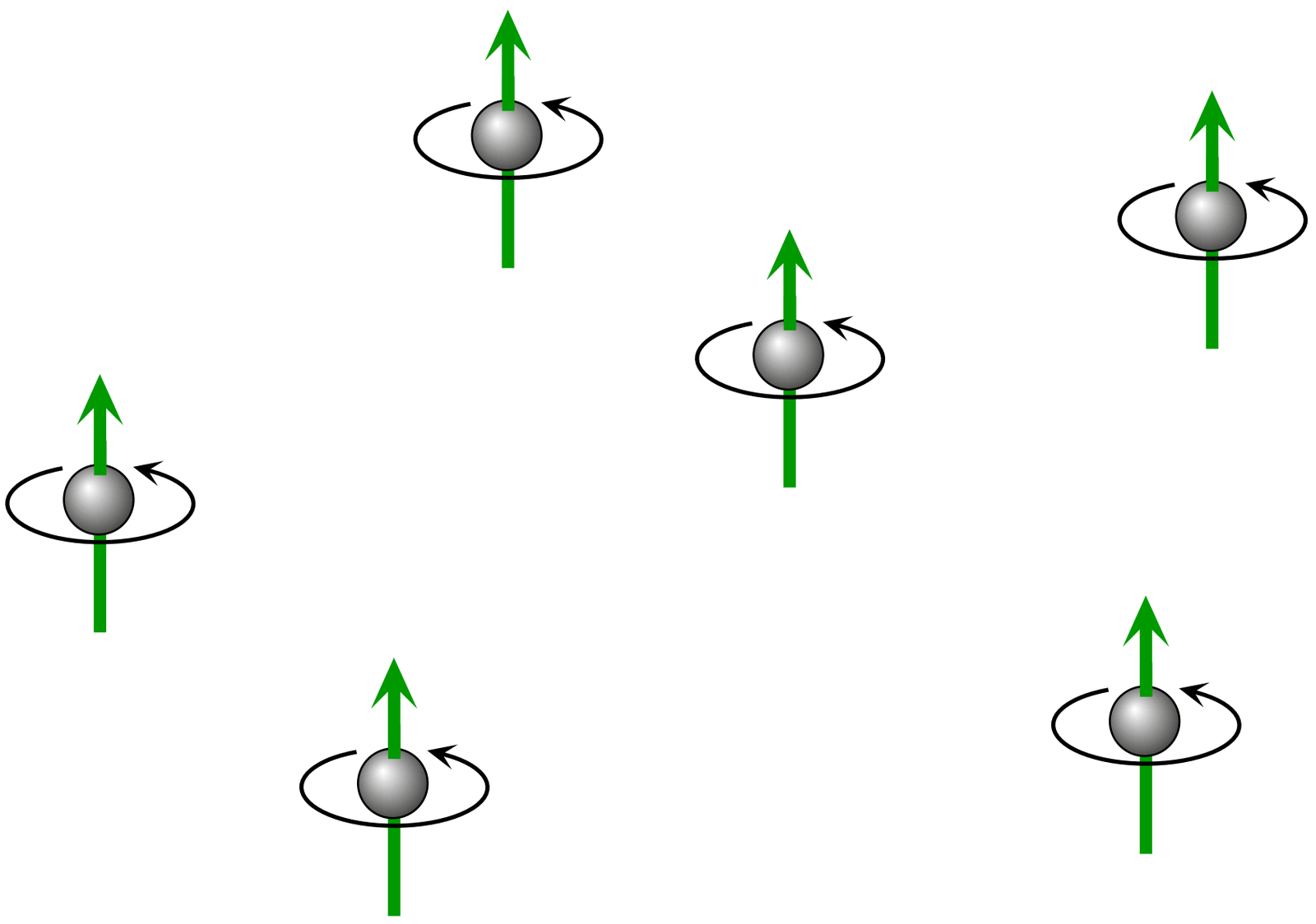
The Nobel Prize in Physics 1996

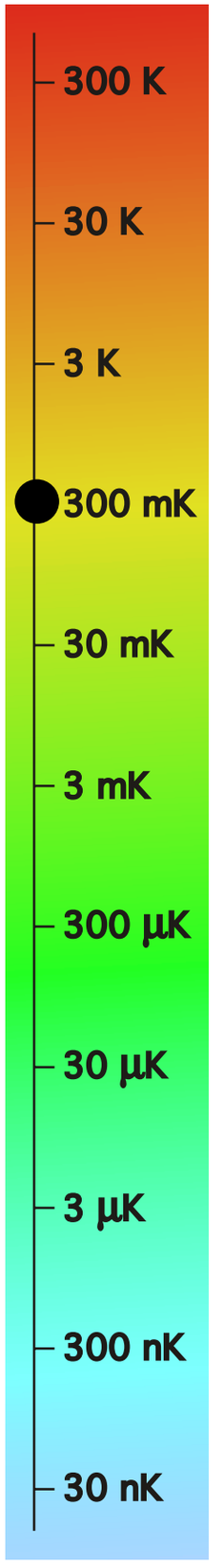
Image of the Nobel prize medal

"for their discovery of superfluidity in helium-3"

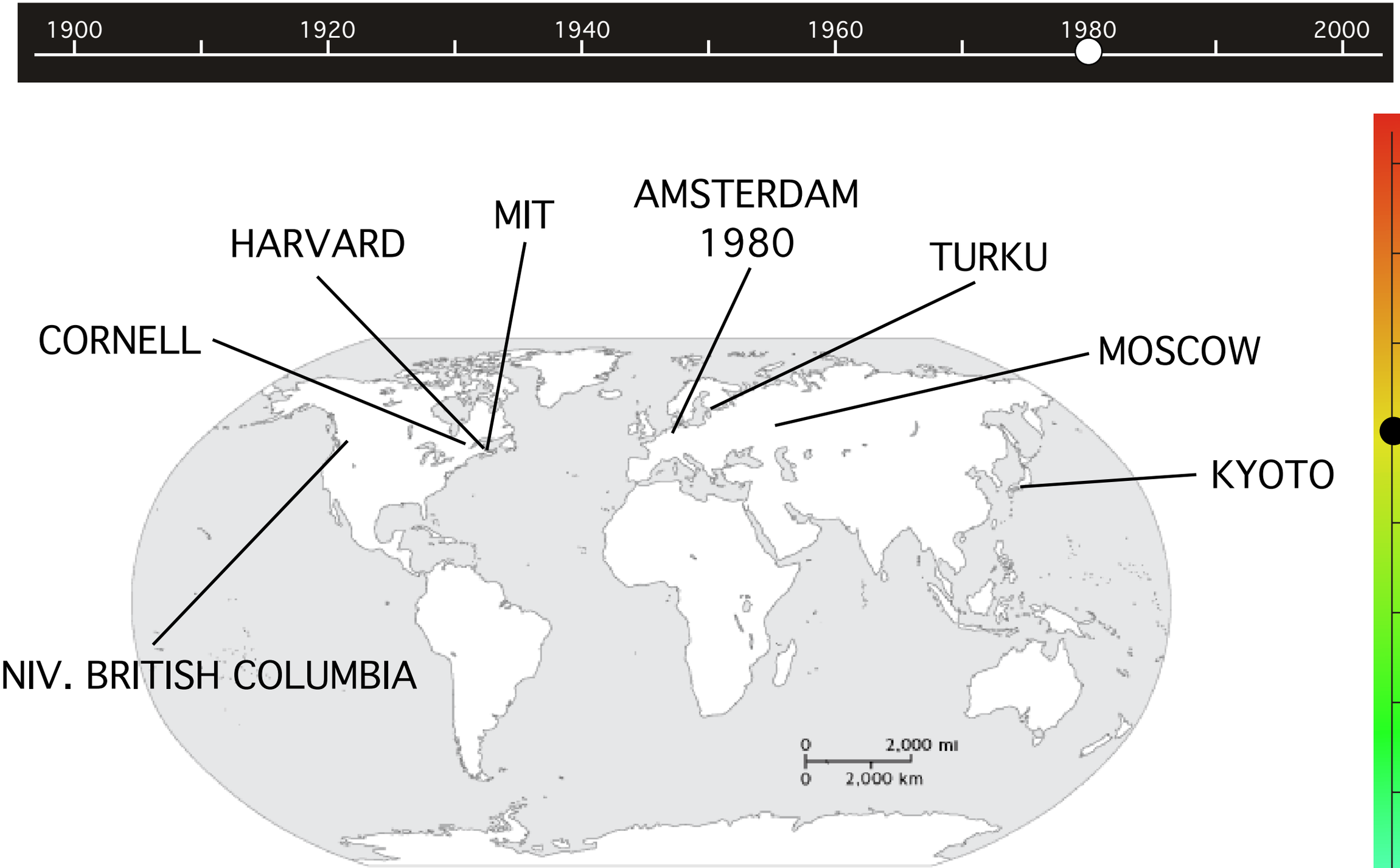
Image of the Nobel Prize winners David M. Lee, Douglas D. Osheroff, and Robert C. Richardson.

SUPERFLUIDITY WAS DISCOVERED IN HELIUM-3 IN 1972 AT A TEMPERATURE OF 2 MILLIKELVIN.

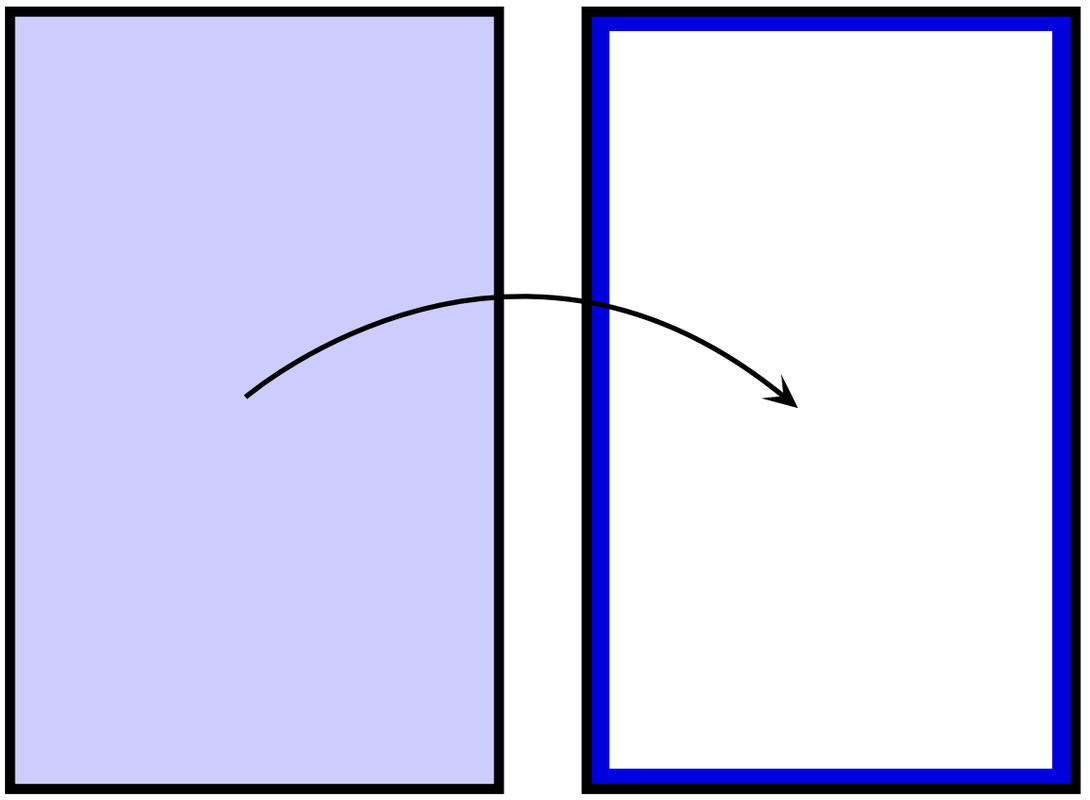




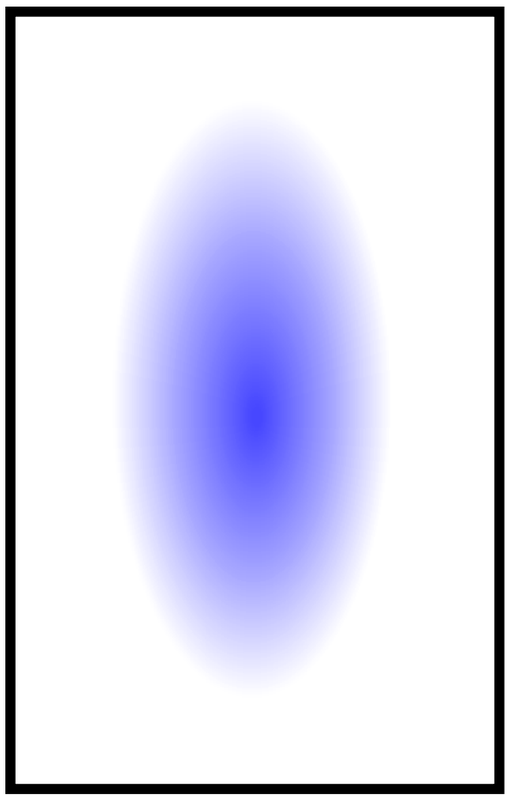
ATOMIC HYDROGEN WILL REMAIN A GAS DOWN TO ABSOLUTE ZERO IF ITS MAGNETIC MOMENTS ARE ALIGNED BY A MAGNETIC FIELD.



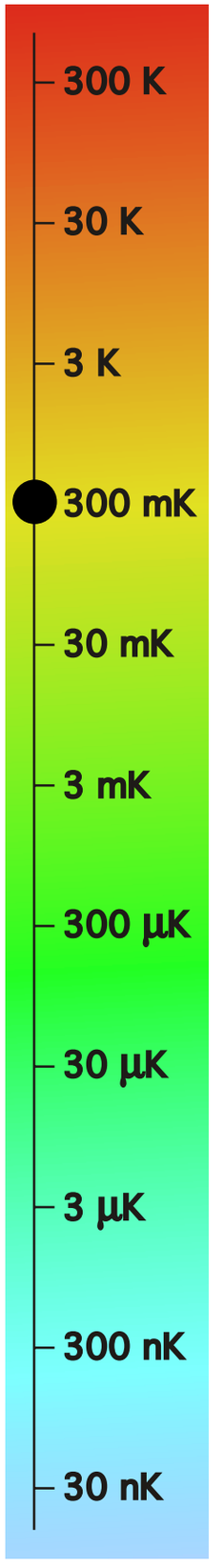
GROUPS WORKING ON SPIN-POLARIZED ATOMIC HYDROGEN



CONFINEMENT BY WALLS



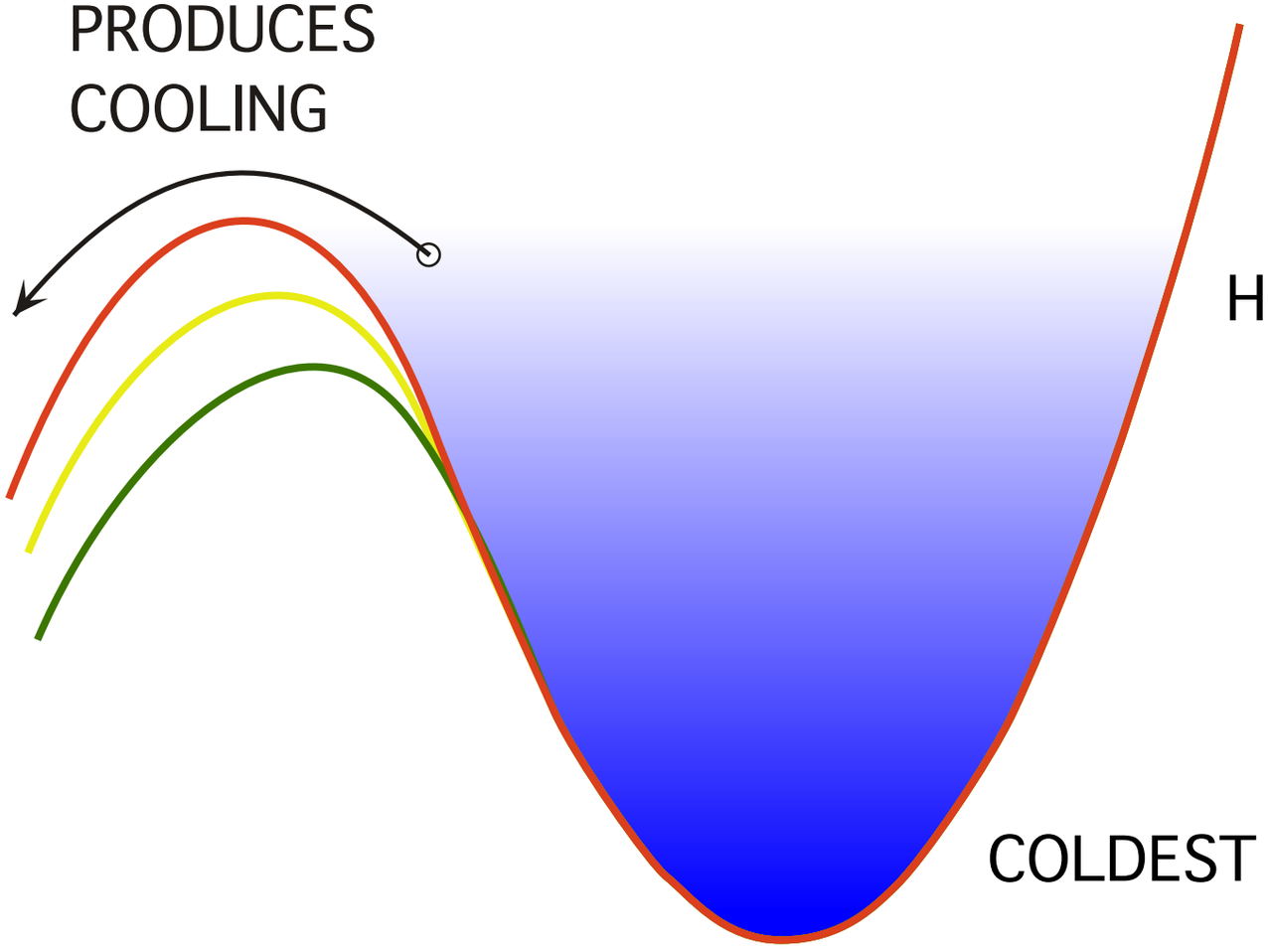
TRAPPING BY A
MAGNETIC FIELD



WALLS CAUSE THE MOMENTS TO FLIP; THEN THE ATOMS RECOMBINE INTO MOLECULES AND FREEZE OUT.

A MAGNETIC TRAP KEEPS THE ATOMS OFF THE WALLS.

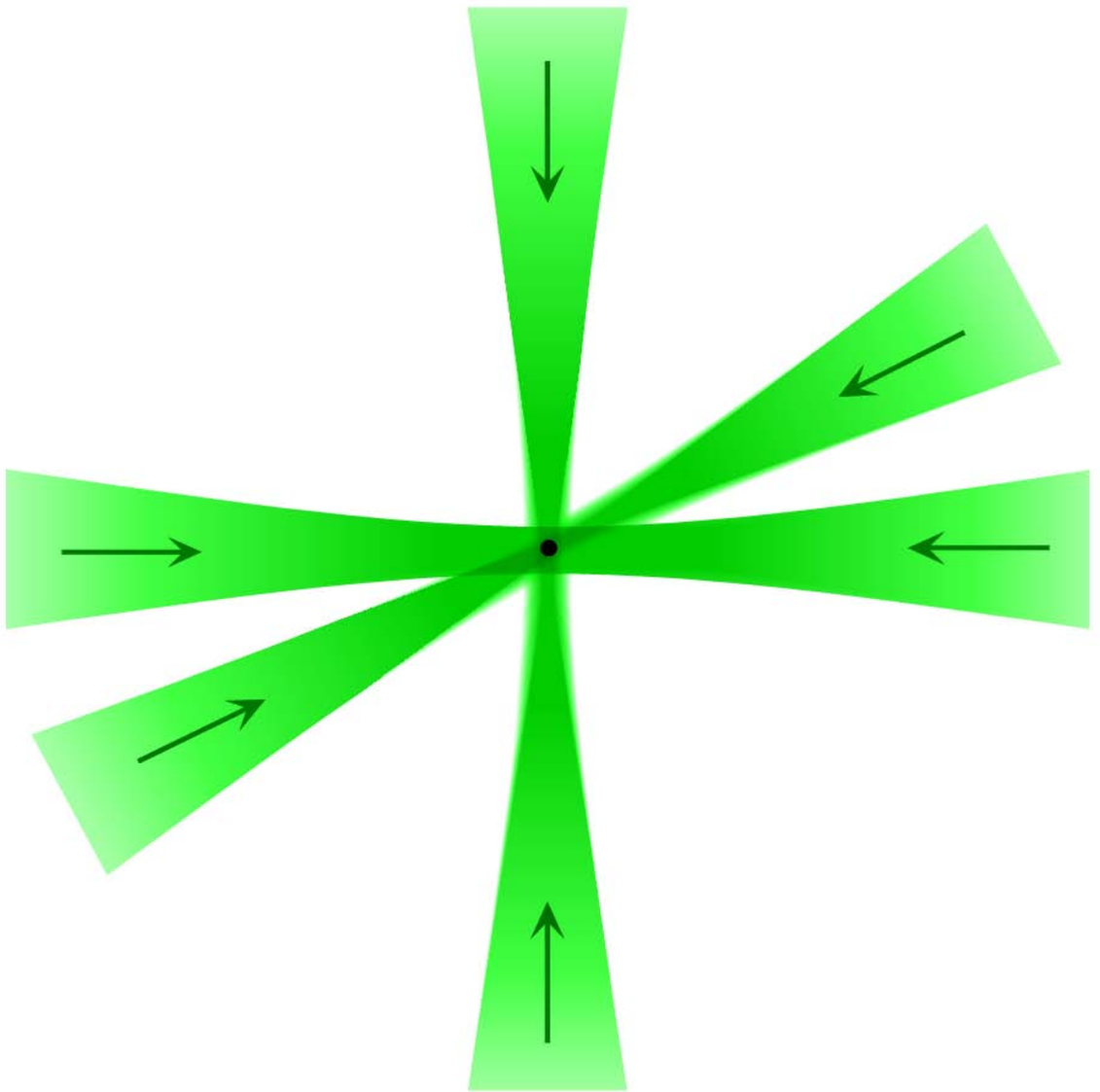
EVAPORATION
PRODUCES
COOLING

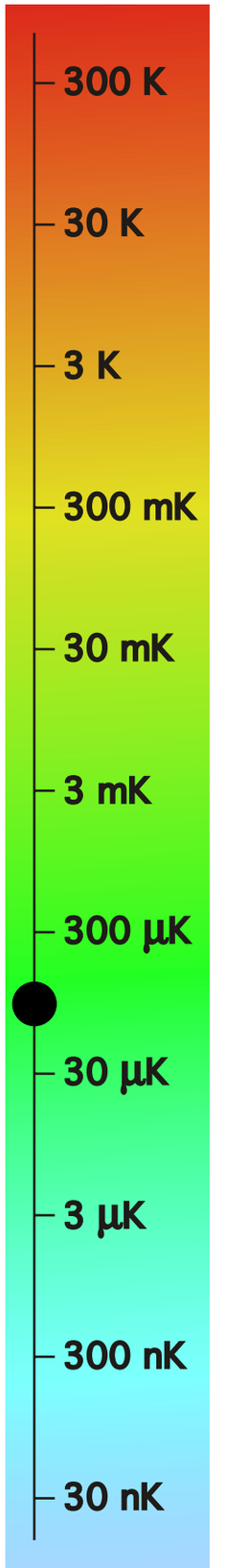


HOTTEST ATOMS

COLDEST ATOMS

IN 1986 HARALD HESS, A POSTDOCTORAL FELLOW IN MIT'S HYDROGEN GROUP, PROPOSES MAGNETIC TRAPPING AND EVAPORATIVE COOLING.





BEGINNING IN THE 1980s, METHODS WERE DEVELOPED TO COOL ATOMS INTO THE MICROKELVIN REGION OF TEMPERATURES USING LASERS.

The Nobel Prize in Physics 1997

Image of the Nobel prize medal

"for development of methods to cool and trap atoms with laser light"

Image of Steven Chu

Image of Claude Cohen-Tannoudji

Image of William Phillips

LASER COOLING WORKS BEST WITH CERTAIN ATOMS SUCH AS LITHIUM (Li), SODIUM (Na), and RUBIDIUM (Rb).

BUT LASER COOLING ALONE CAN NOT GET THESE ATOMS COLD ENOUGH TO ACHIEVE BEC.

FOR THE FINAL STAGE OF COOLING ONE MUST TURN TO EVAPORATIVE COOLING.

THEN THE RACE BEGAN: LOWER THE TEMPERATURE WHILE INCREASING THE DENSITY.

ERIC CORNELL & CARL WIEMAN
JILA (NIST AND UNIV. OF COLORADO)

Rb

Image removed due to copyright reasons.

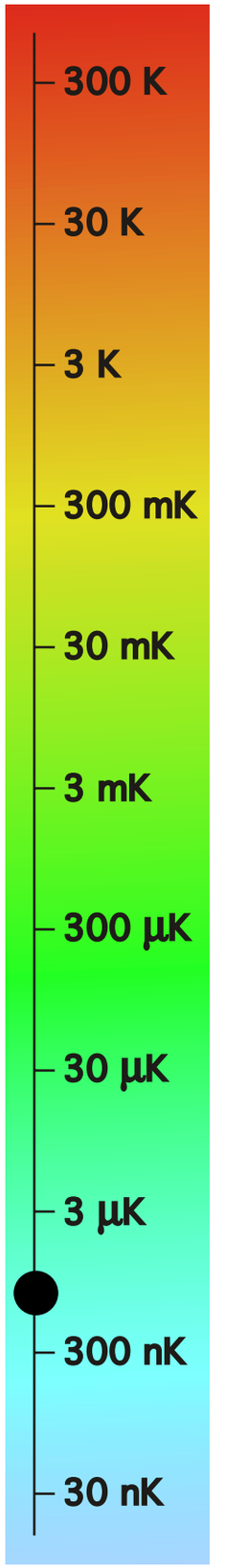


Image removed due to copyright reasons.

RANDALL HULET
RICE UNIVERSITY

Li

WOLFGANG KETTERLE
MIT

Na

Image removed due to copyright reasons.

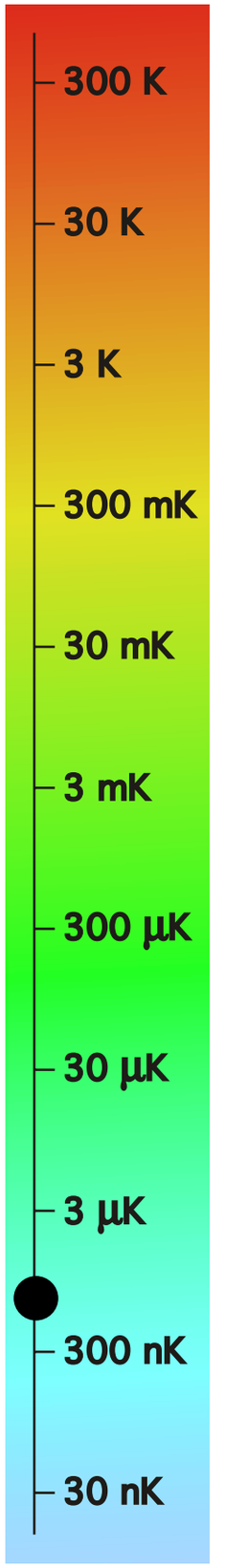
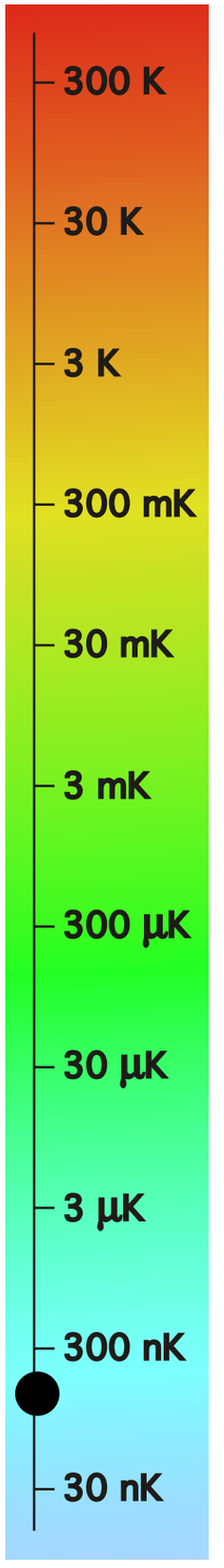


Image of Dan Kleppner, Tom Greytak, Wolfgang Ketterle, and Dave Pritchard.

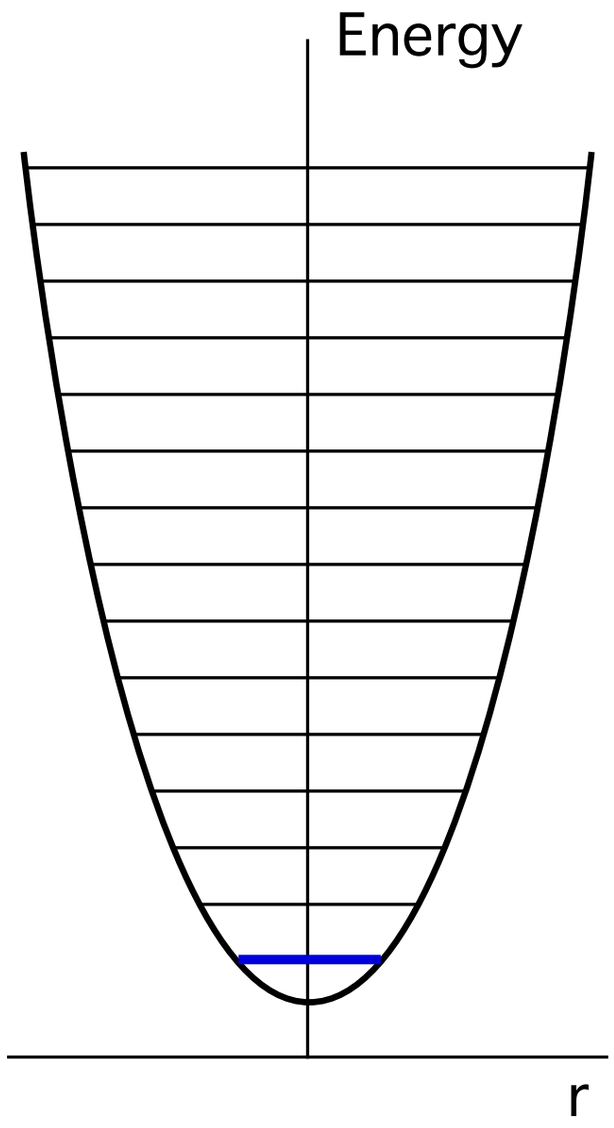
WOLFGANG KETTERLE DAVE PRITCHARD

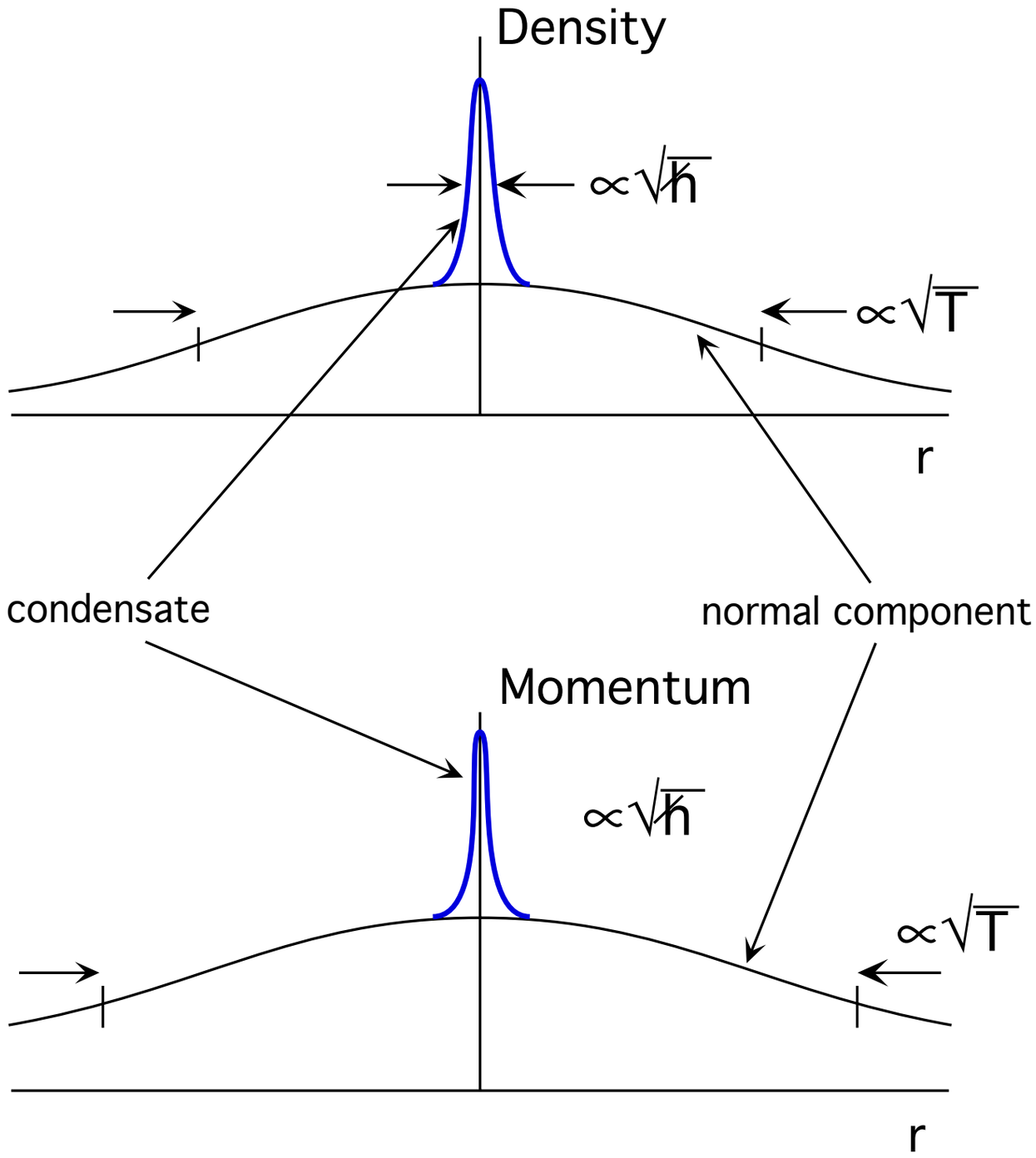
DAN KLEPPNER TOM GREYTAK

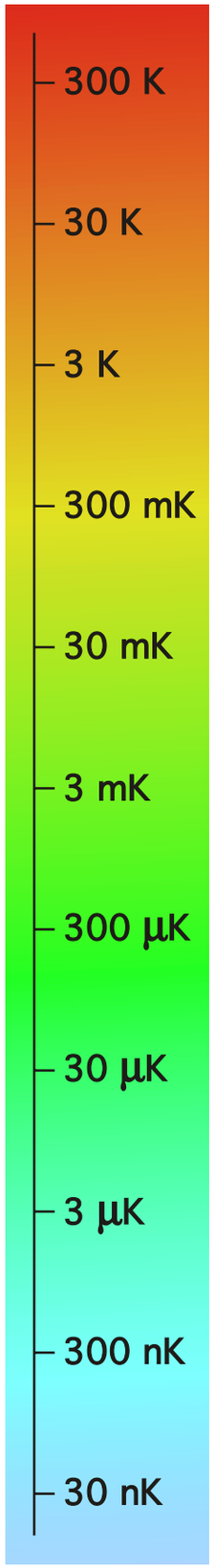


A graphical timeline of the race for BEC

Bose-Einstein Condensation in a Parabolic Trap

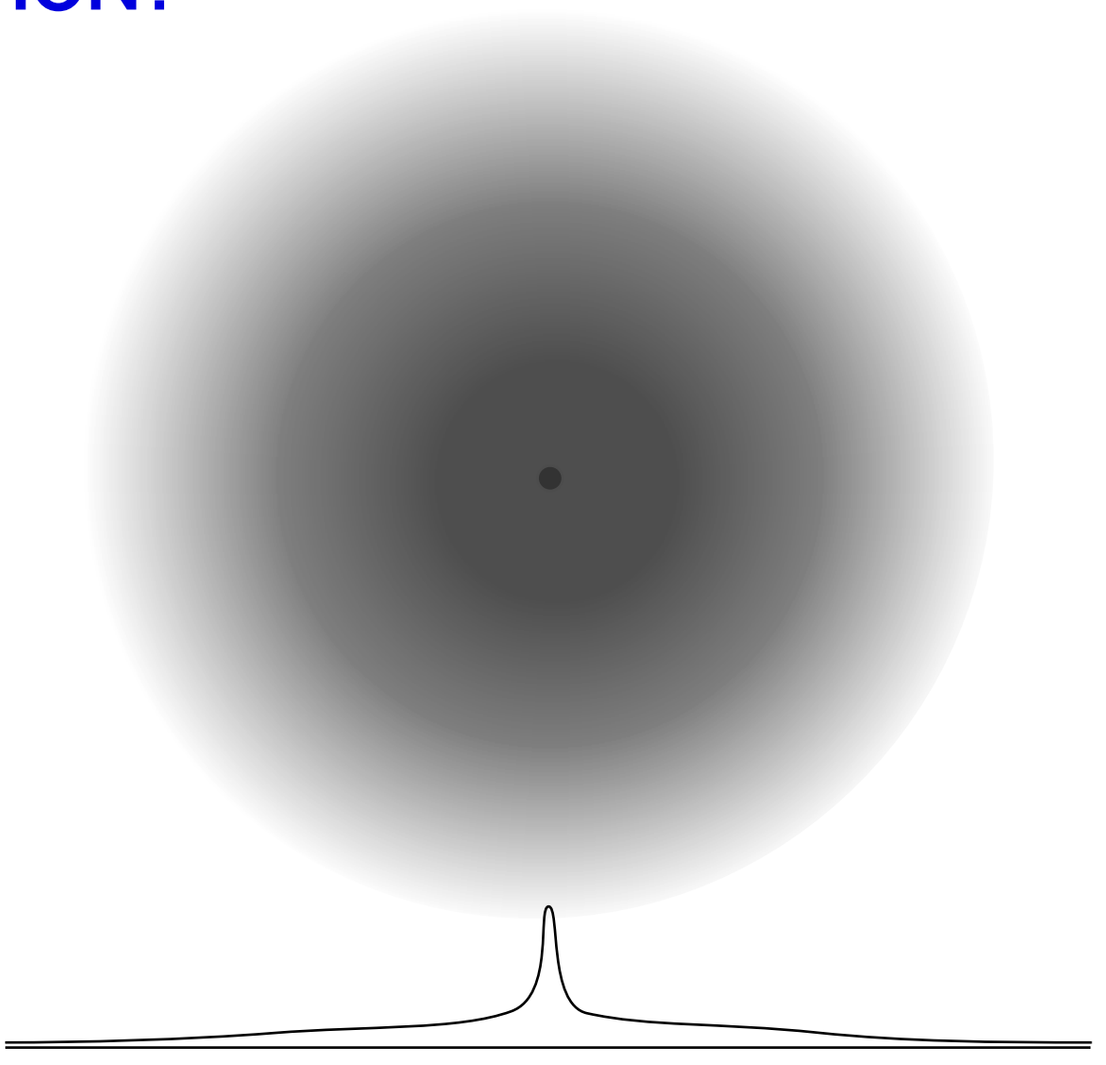






HOW DID THEY KNOW THEY HAD BOSE-EINSTEIN CONDENSATION?

IN THE TRAP, ATOMS IN THE CONDENSATE ARE ALMOST AT REST, THE REMAINDER HAVE THERMAL SPEEDS.



WHEN THE TRAP IS TURNED OFF THE THERMAL ATOMS SPEED AWAY, BUT THE CONDENSATE ATOMS REMAIN NEAR THE ORIGIN.

Cover of Science, 14 July 1995, Vol 269.

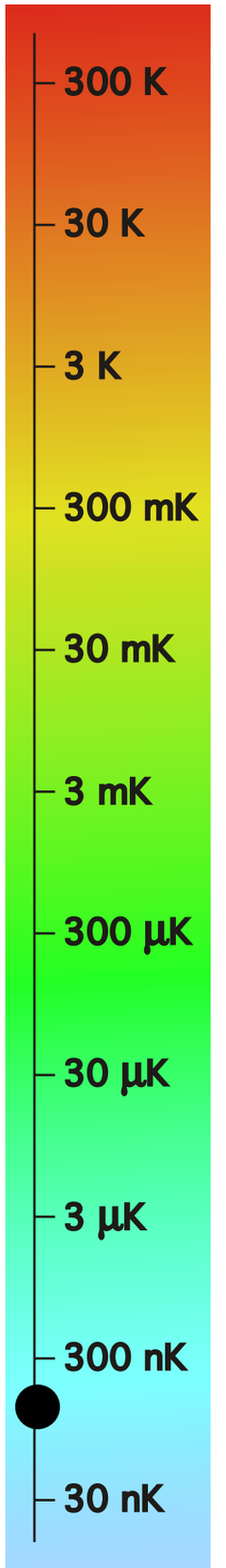


Image of Carl Wieman, Michael Mattews, Michael Anderson, Jason Ensher, and Eric Cornell.

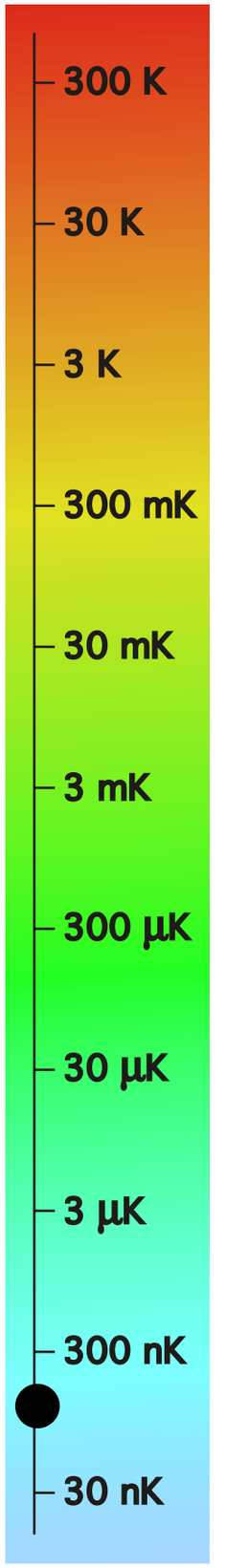
CARL WIEMAN

MICHAEL ANDERSON

ERIC CORNELL

MICHAEL MATTHEWS

JASON ENSHER



A graphical timeline of the race for BEC

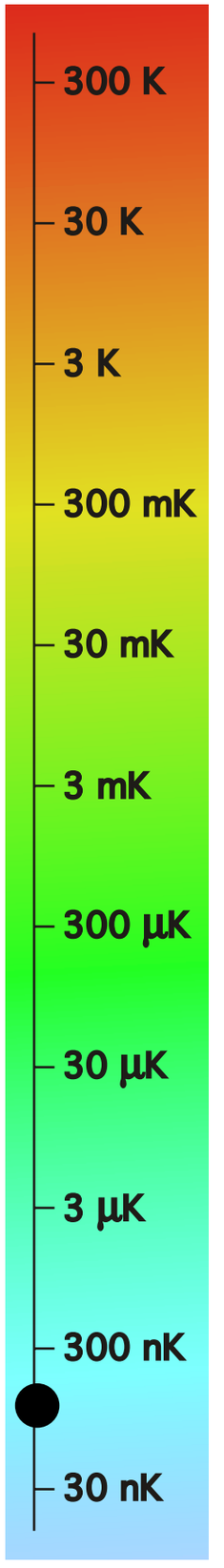


Image removed due to copyright reasons.

SUCCESSIVE REAL SPACE IMAGES OF A SODIUM CONDENSATE FORMING IN A KETTERLE TRAP

The Nobel Prize in Physics 2001

Image of the Nobel prize medal

"for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates"

Image of Eric A. Cornell, Carl F. Wieman, and Wolfgang Ketterle.

Image removed due to copyright reasons.

WOLFGANG KETTERLE & RANDALL HULET IN STOCKHOLM

Image removed due to copyright reasons.

INTERFERENCE OF MATTER WAVES

Image removed due to copyright reasons.