Rubber, Quarks and high-temperature superconductivity: Physics at Strong Coupling

Exotic insulating states of matter

January 14-16th, 2010

The Johns Hopkins University

The workshop will focus on experimental and theoretical developments in the areas of:

- Topological insulators and the stability of their edge and surface states
- Bose insulating states and the 2D superconductor-insulator quantum phase transition
- Mott insulators and underdoped high temperature superconductors
- Other unconventional insulating and related states of matter

Fpr further information, please visit:
http://icamconferences.org/jhu2010/
or contact the organizers:

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ICAM-I2CAM
Institute for Complex Adaptive Matter

Confirmed Speakers:

Boris Altshuler (Columbia)
Y. Ando (Osaka)
Leon Balents (UC Santa Barbara)
Andrei Bernevig (Princeton)
Anton Burkov (Waterloo)
Moses Chan (Penn State)
Yu Lin Chen (Stanford)
S. Das Sarma (UMD-College Park)
Brian de Marco (UIUC)
Matthew Fisher (Caltech)
Michael Fuhrer (UMD-College Park)
Liang Fu (Harvard)
Allen Goldman (Univ. of Minn.)
Zahid Hasan (Princeton)
Charlie Kane (Univ. of Pennsylvania)
Frank Kruger (UIUC)
Gene Mele (Univ. of Pennsylvania)
Joel Moore (UC Berkeley)
Phuan Ong (Princeton)
Joe Orenstein (UC Berkeley)
Iuliana Radu (Katholieke Universiteit)
Gil Refeal (Caltech)
Benjamin Sacepe (Univ. Geneva)
Subir Sachdev (Harvard)
G. Sambdamurthy (SUNY-Buffalo)
Ian Spielman (NIST)
Tudor Stanescu (Univ. of W. Virginia)
Zlatko Tesanovic (Johns Hopkins)
John Traquada (Brookhaven)
Jean-Marc Triscone (Univ. Geneva)
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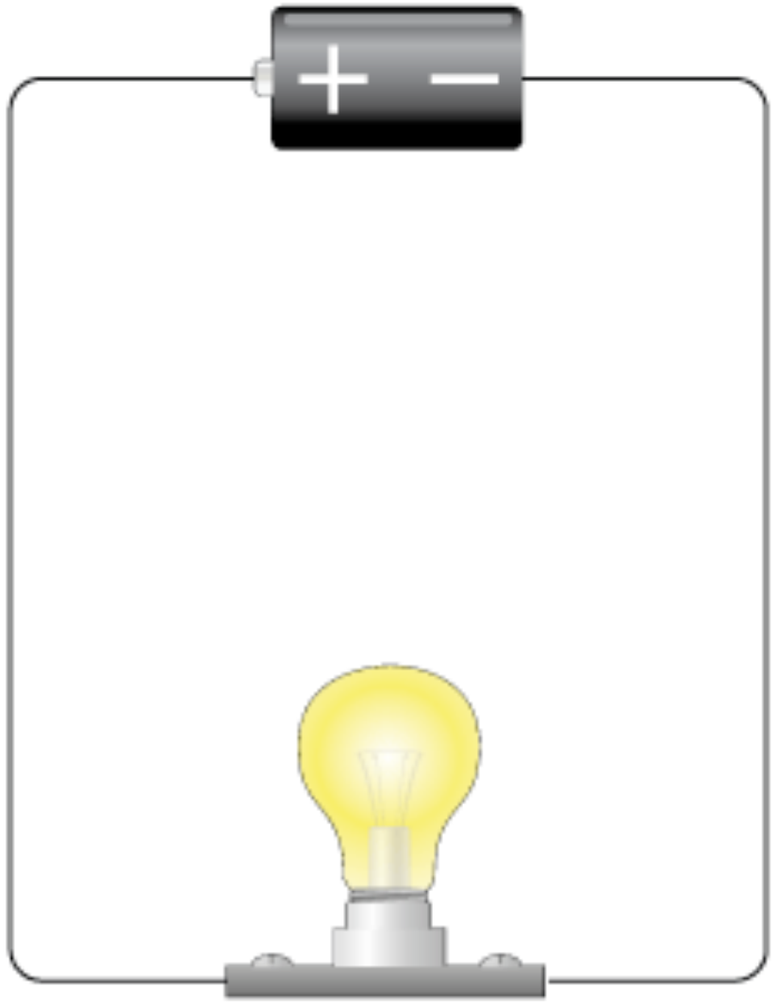
What is an insulator?



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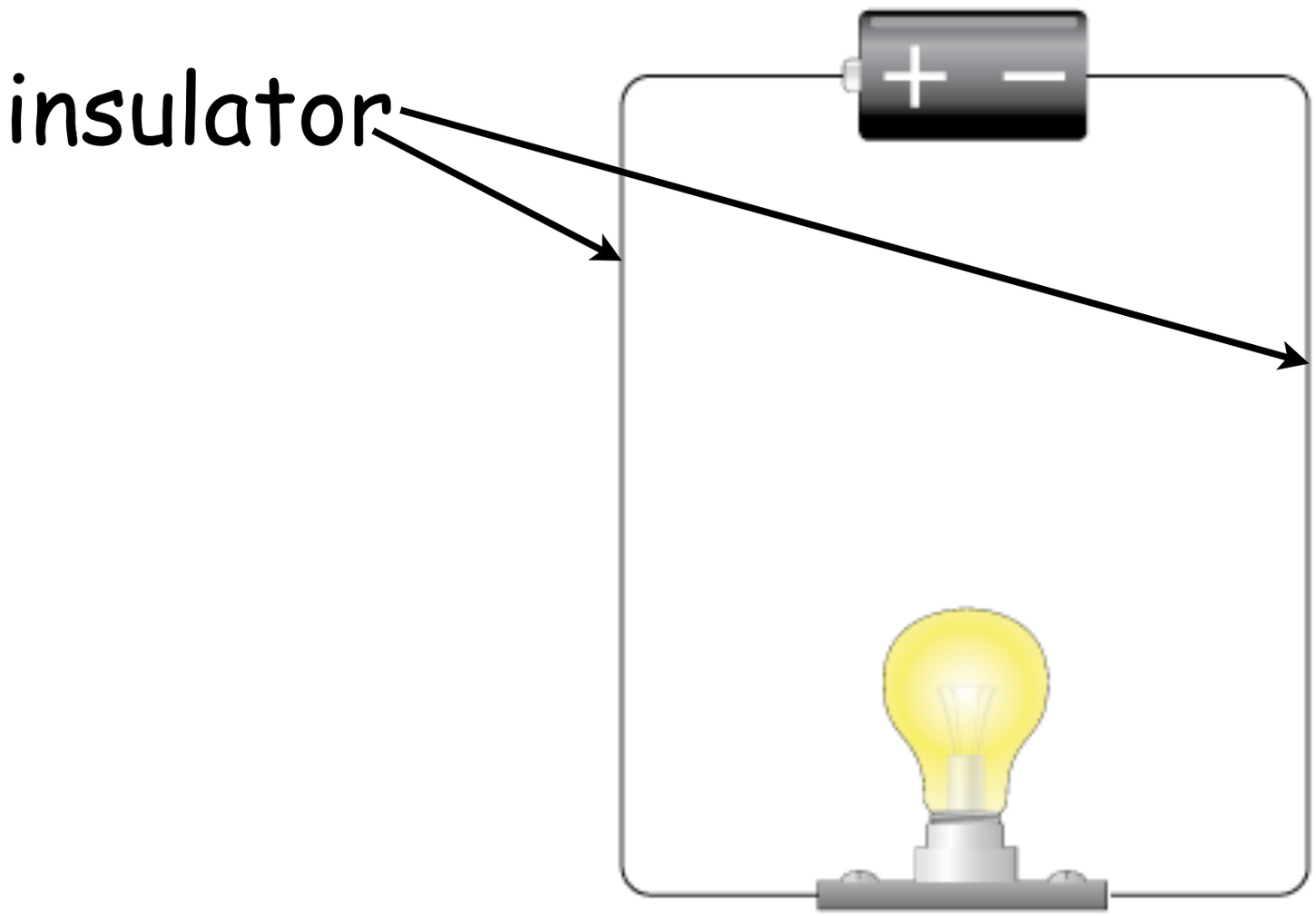

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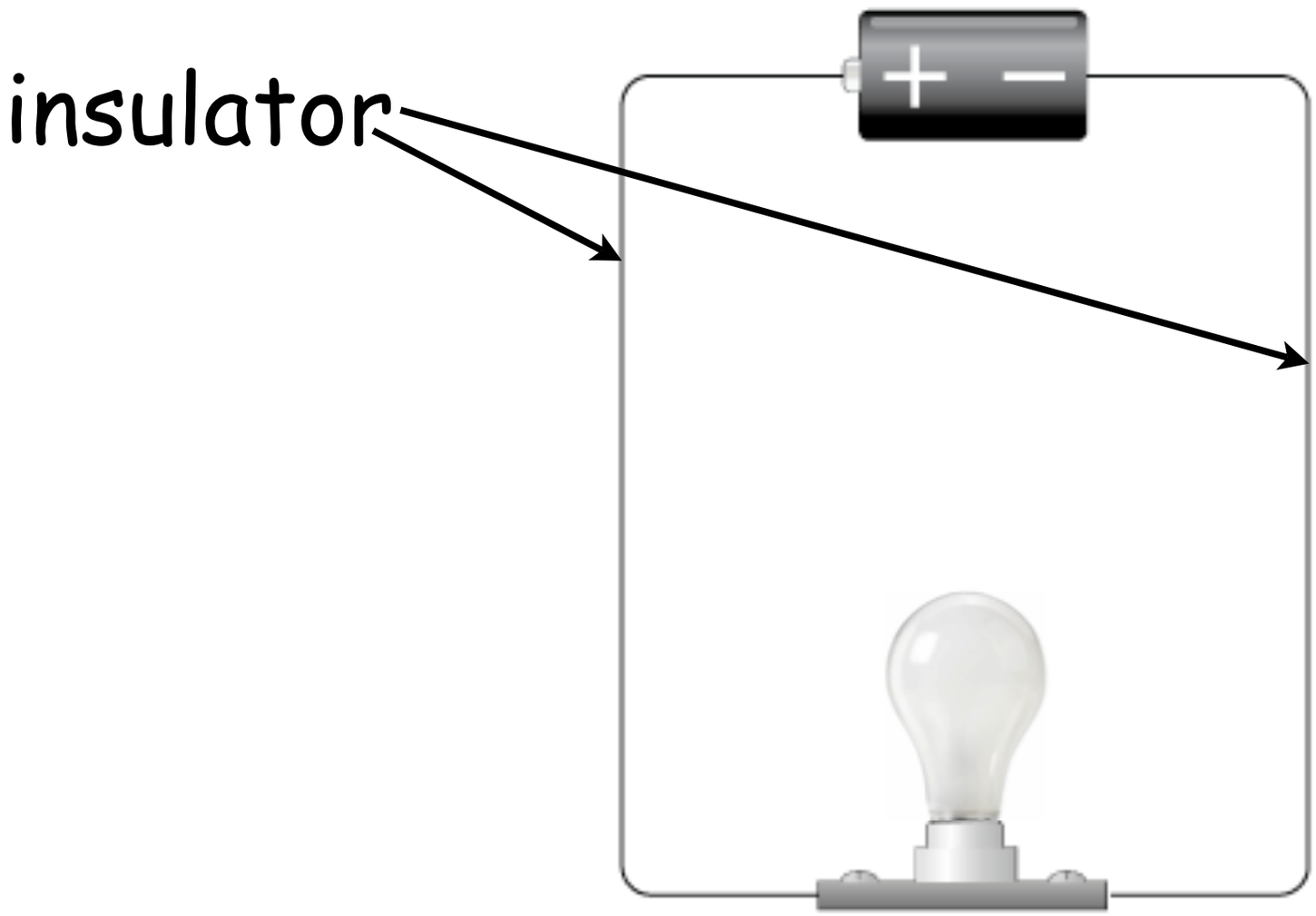

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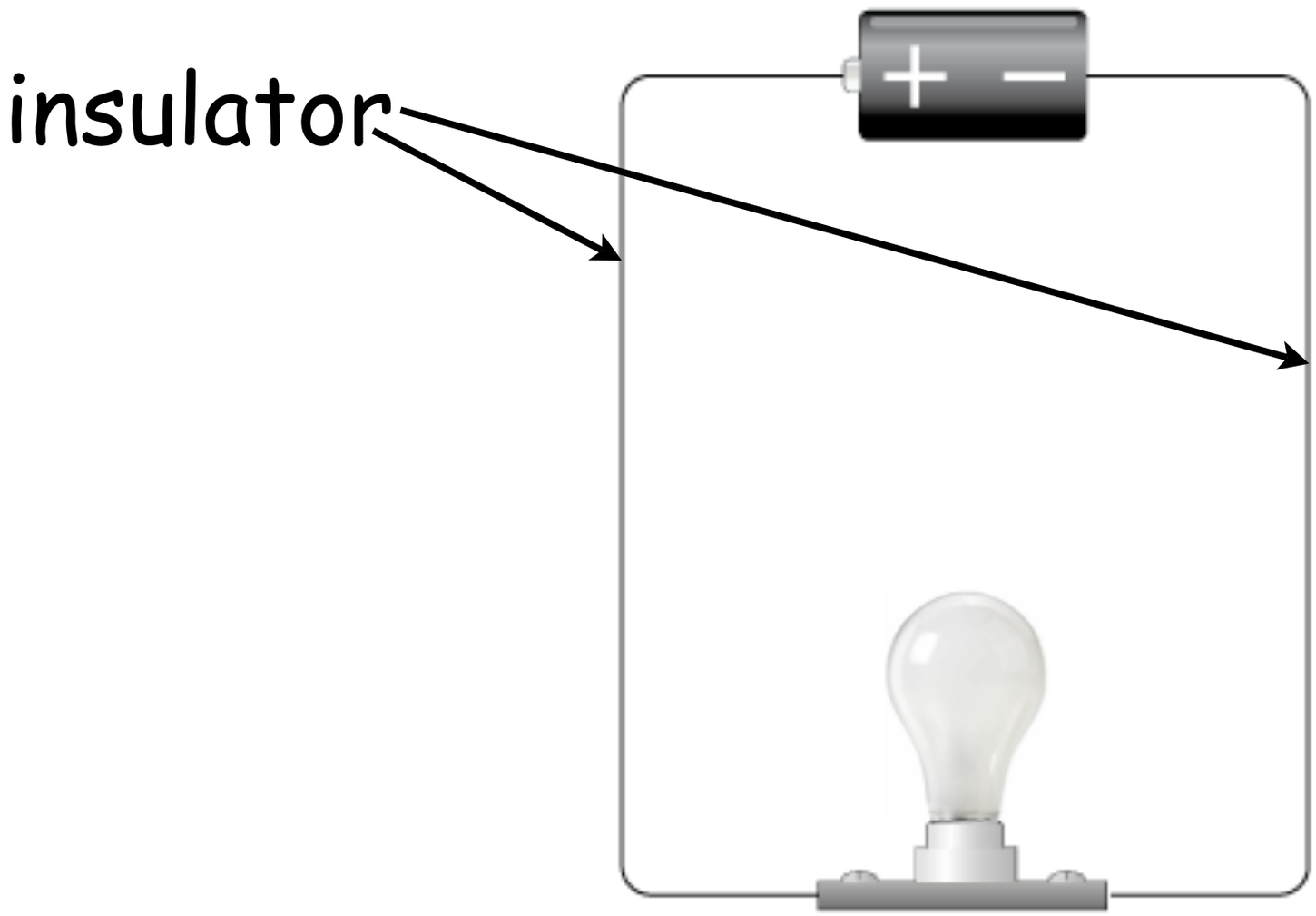
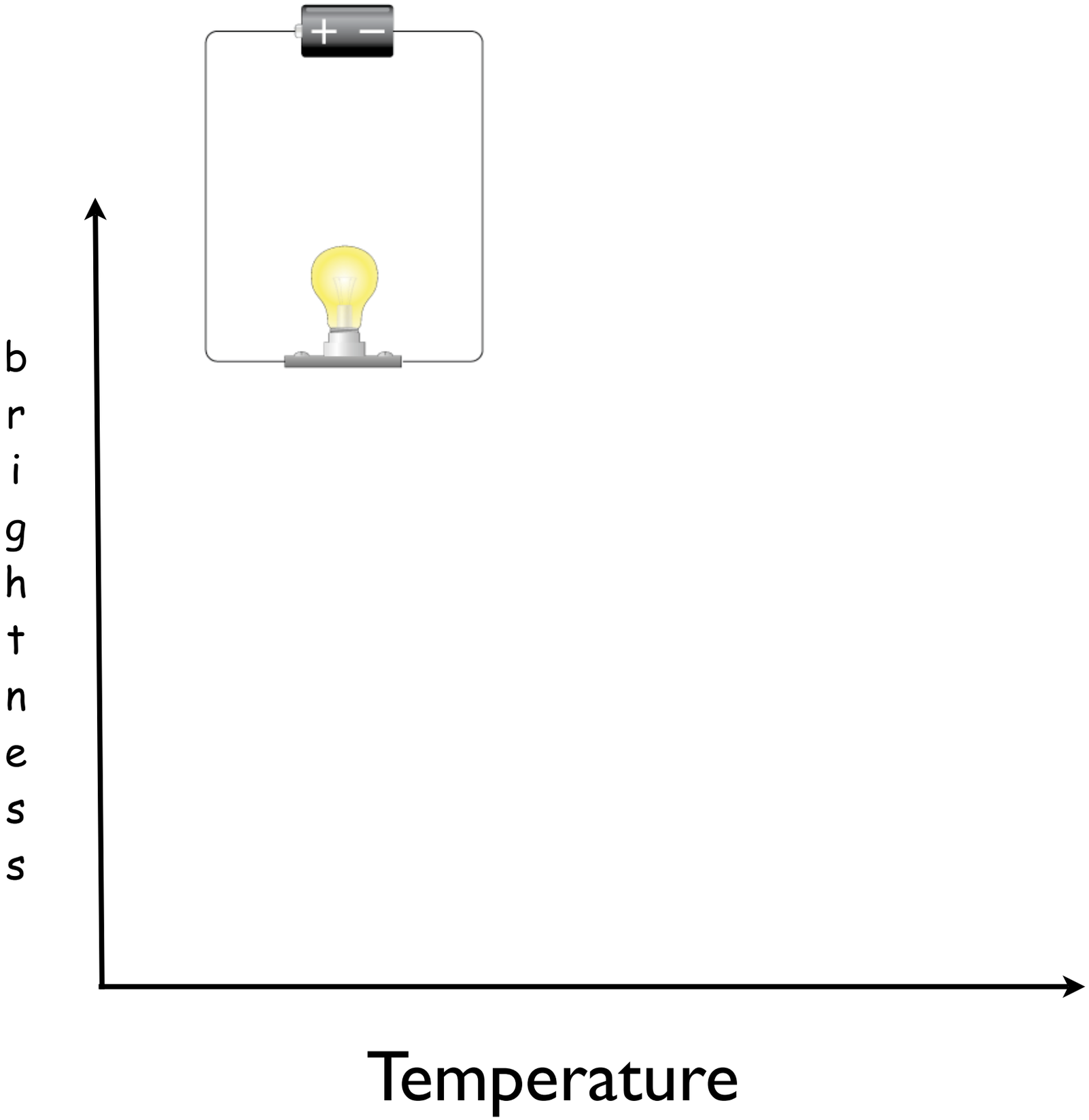
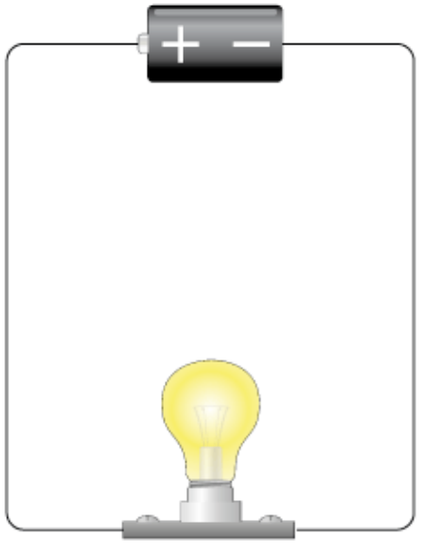


no current flows in an insulator


+ −
brightness
Temperature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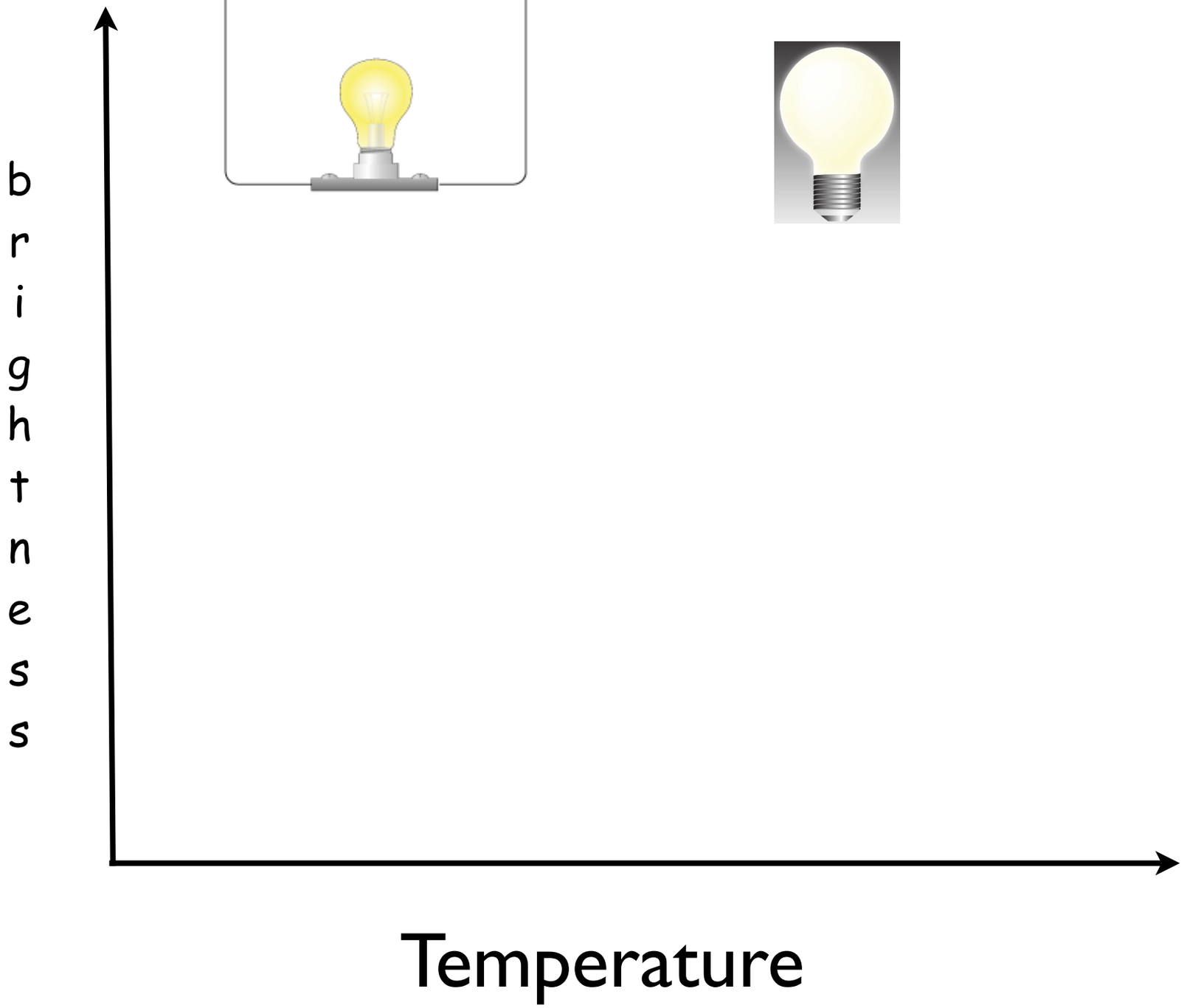
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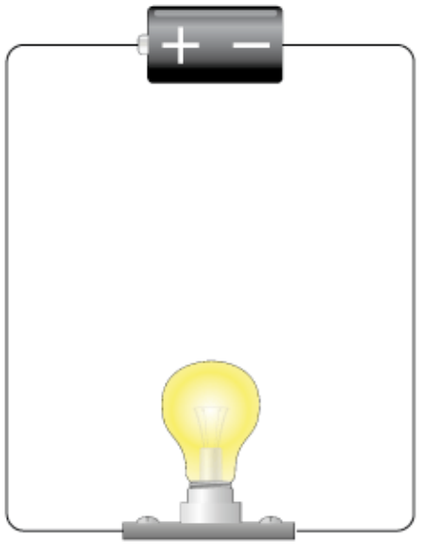
Temperature


+
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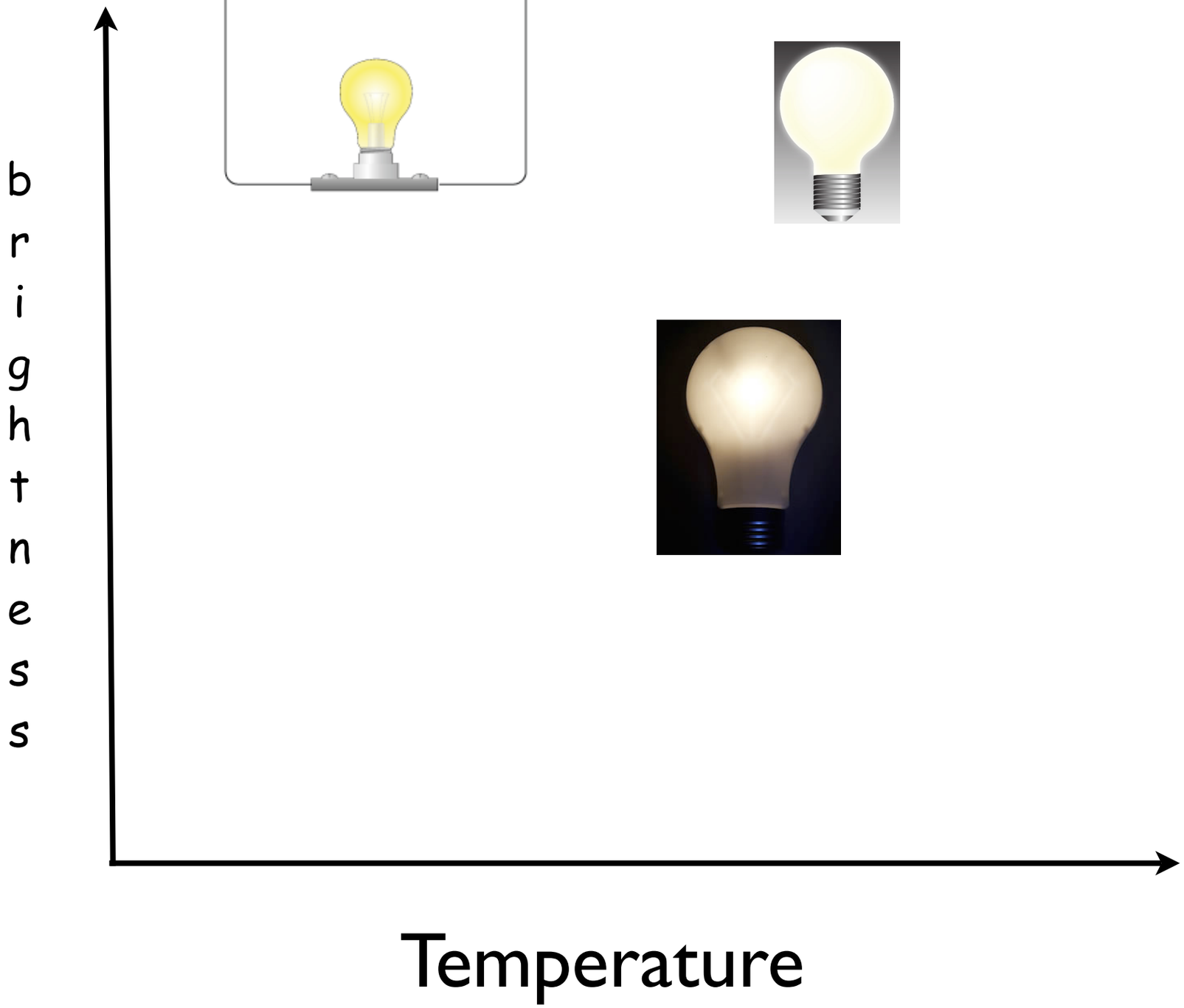
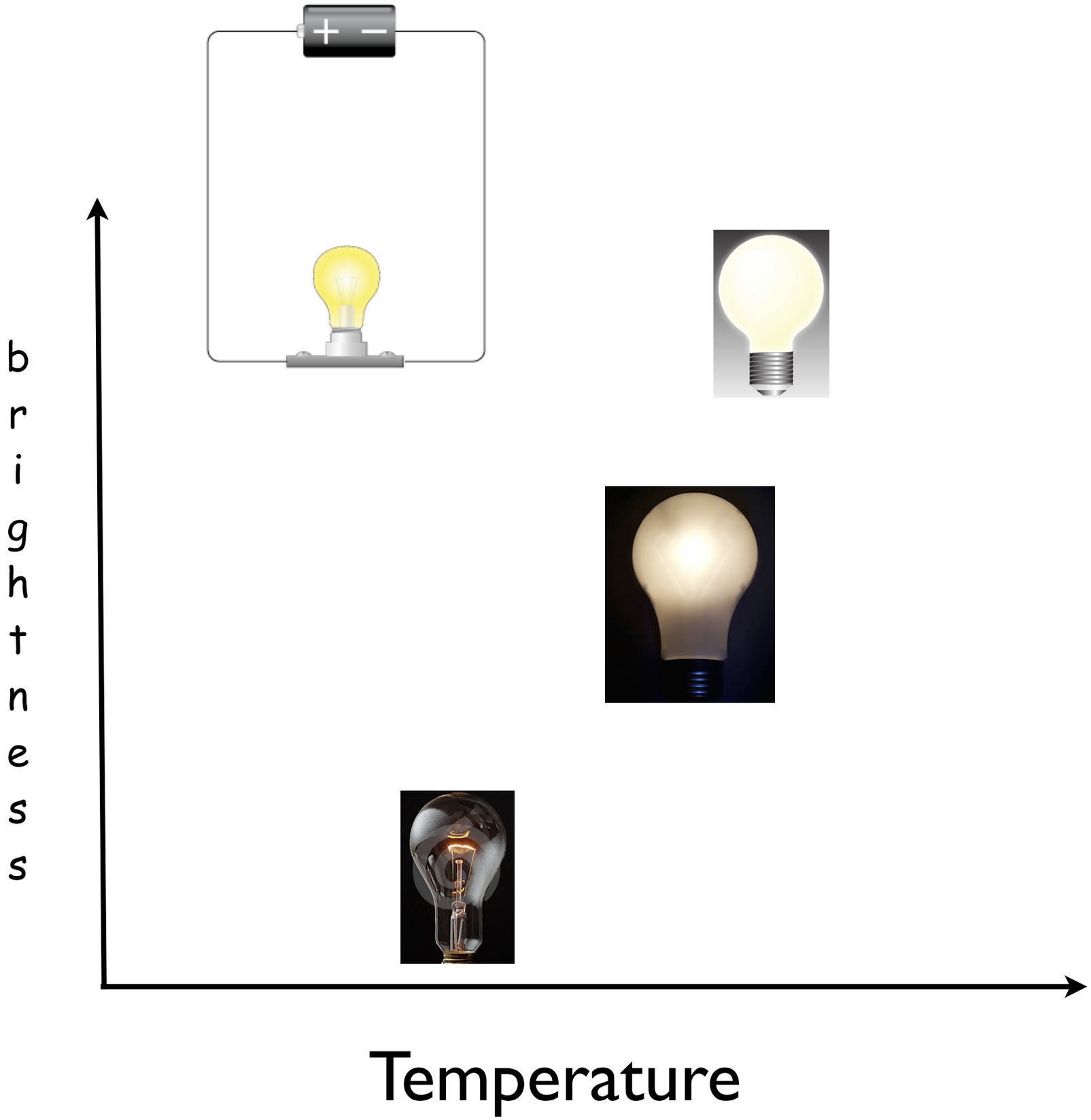

brightness
Temperature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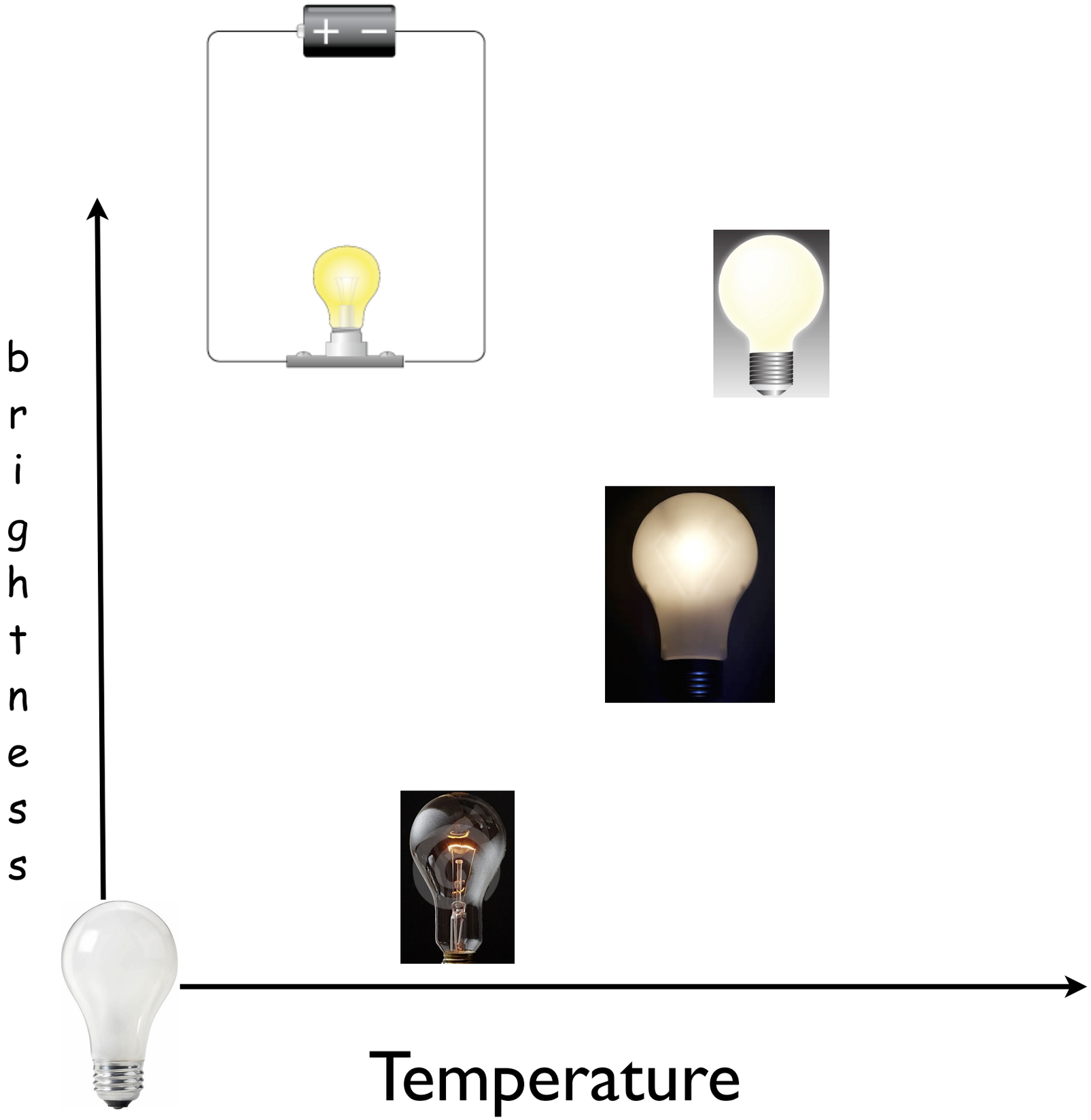
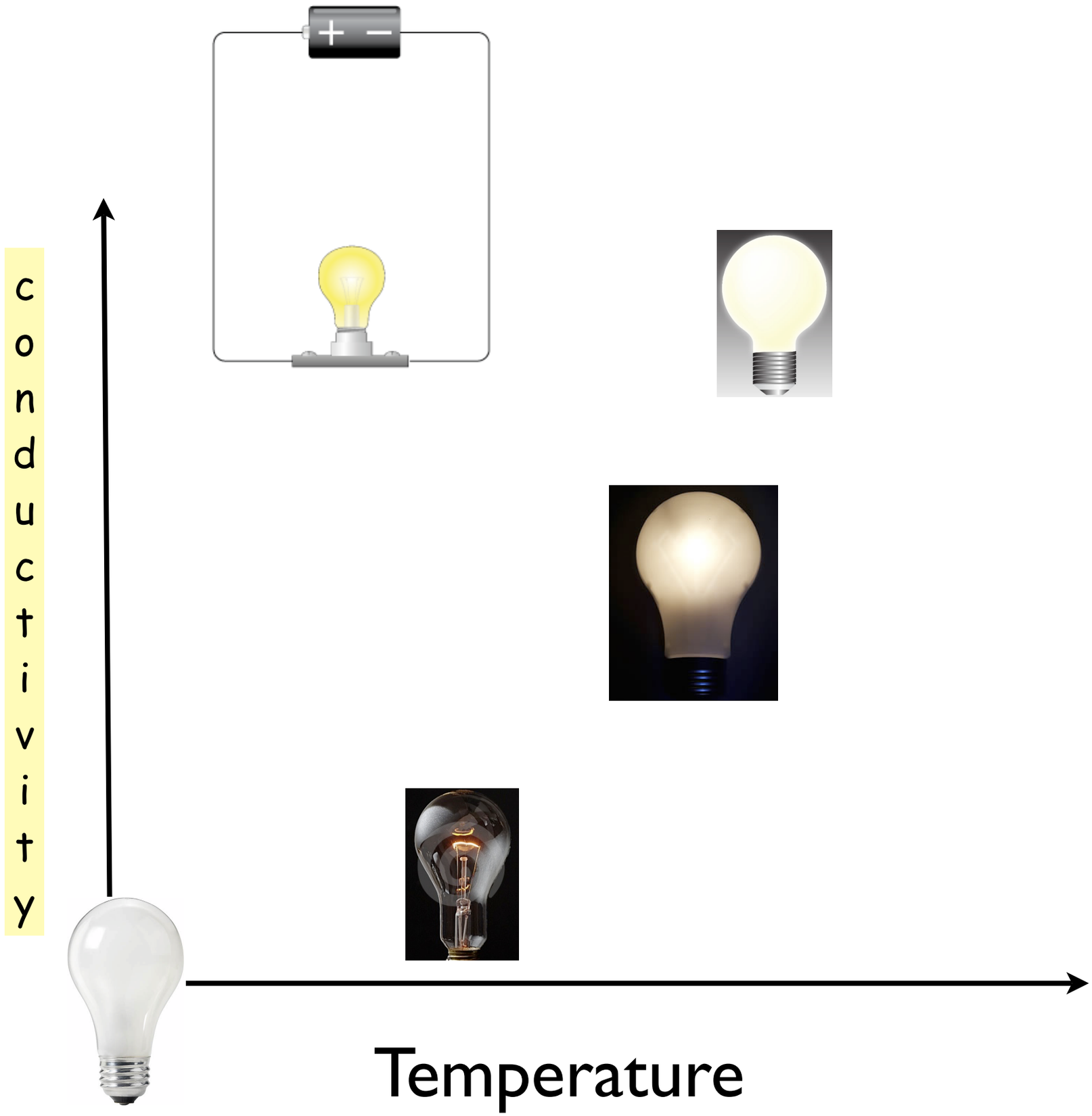
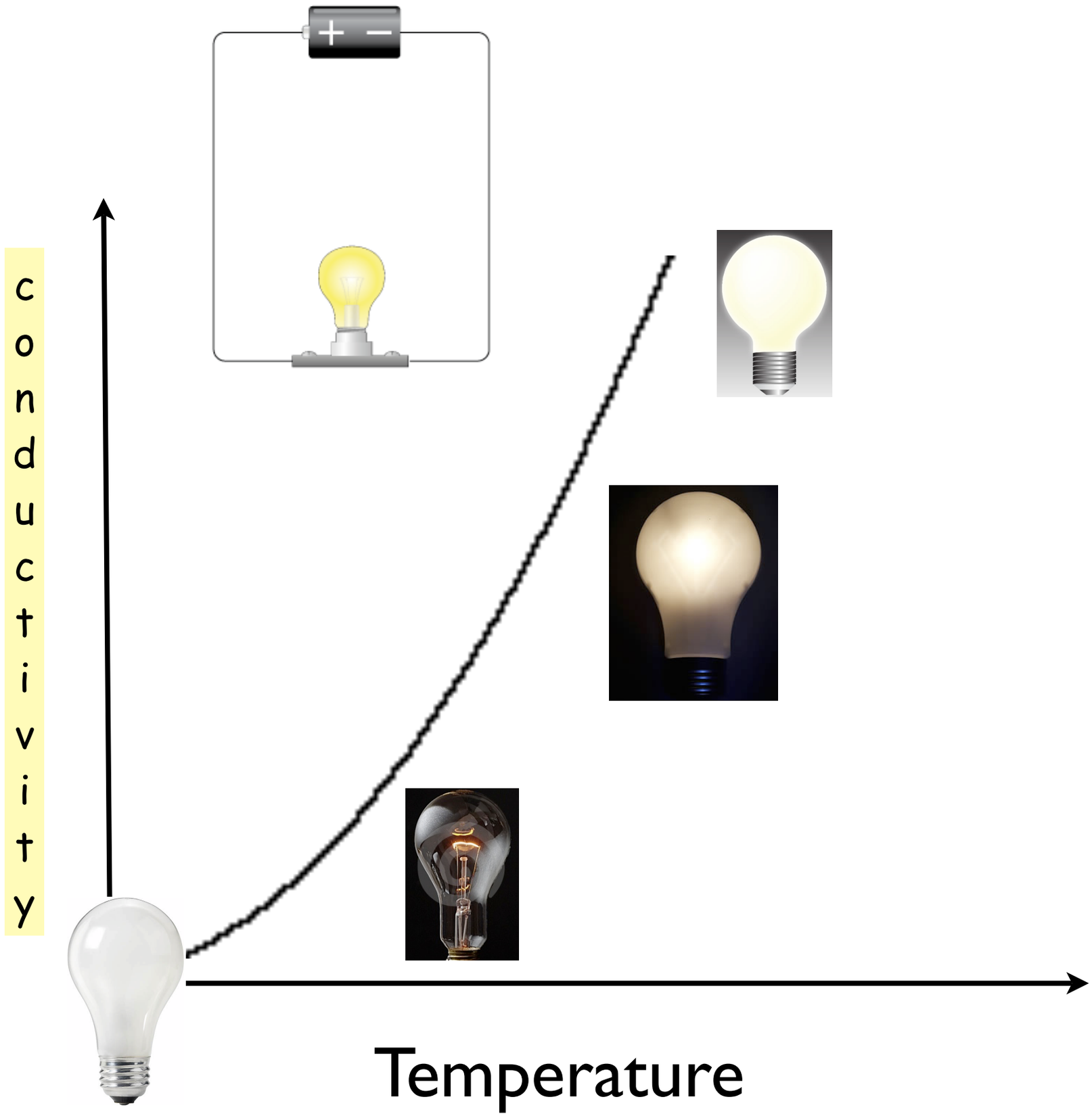
brightness
Temperature


+ −
brightness
Temperature


conductivity
Temperature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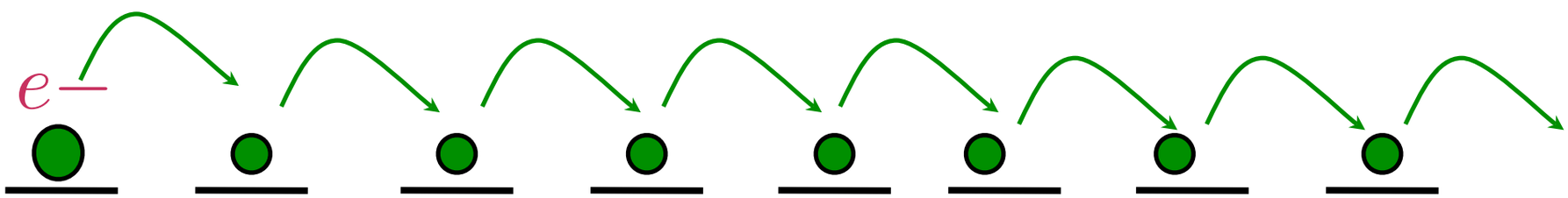
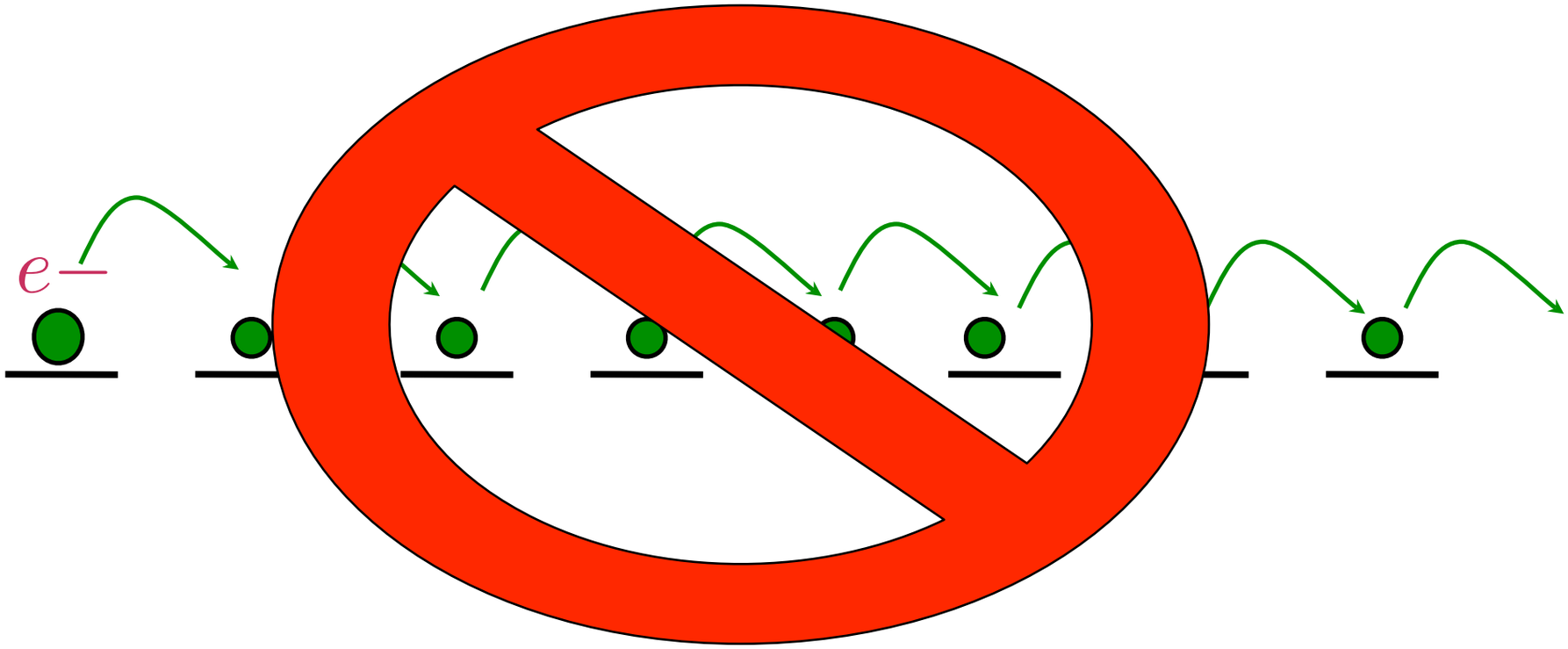
conductivity
Temperature


e^-


e^-

Why?

Why?

internal structure of electrons

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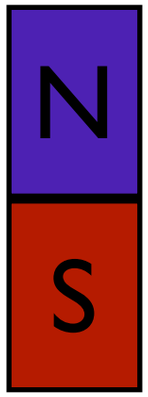
internal structure of electrons



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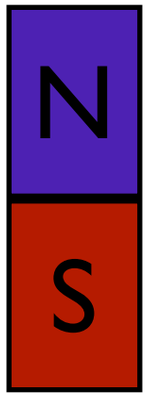
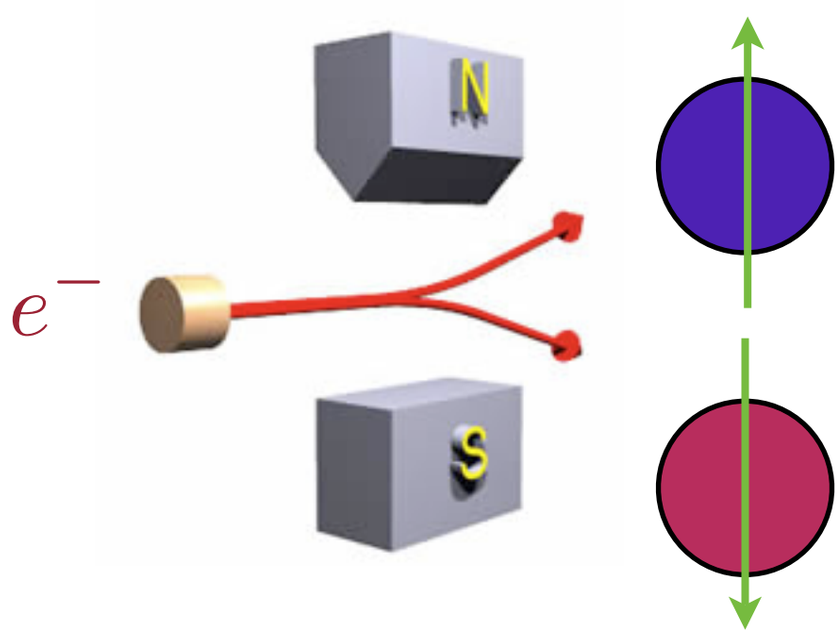
internal structure of electrons

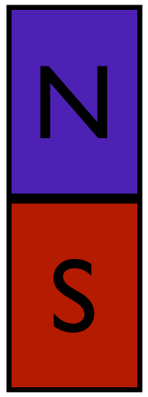


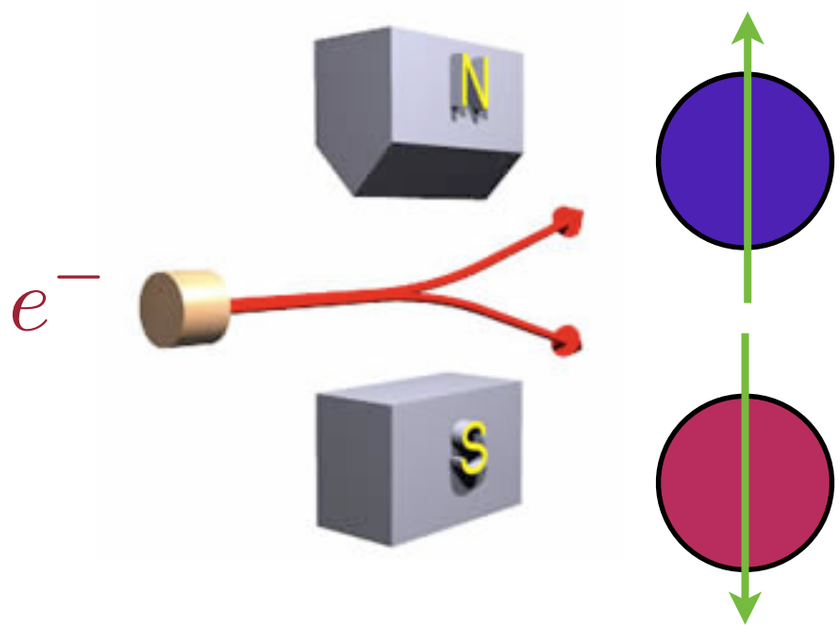


spin

Why?

internal structure of electrons



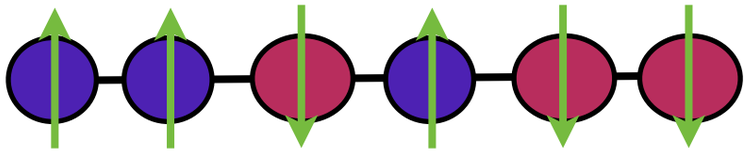


spin

1943 Nobel Prize: O. Stern and W. Gerlach

electron spin=acrobatics

electron spin=acrobatics



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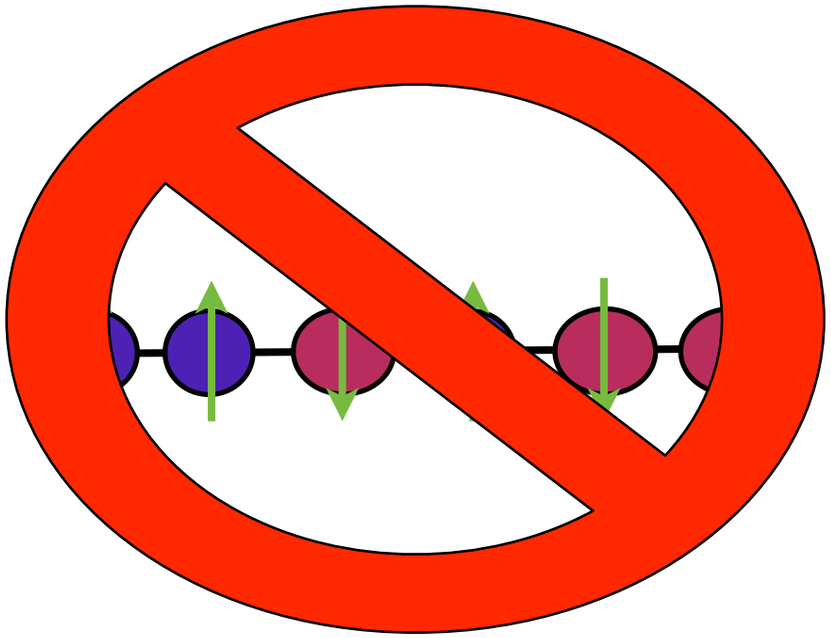

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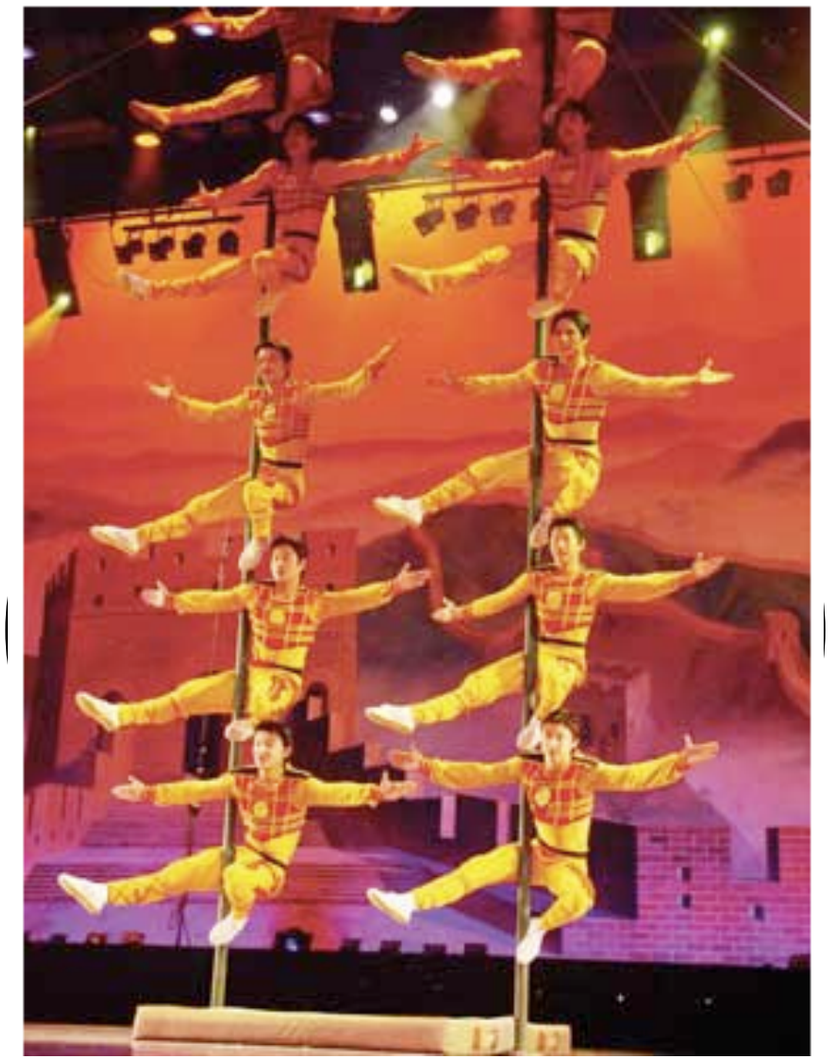

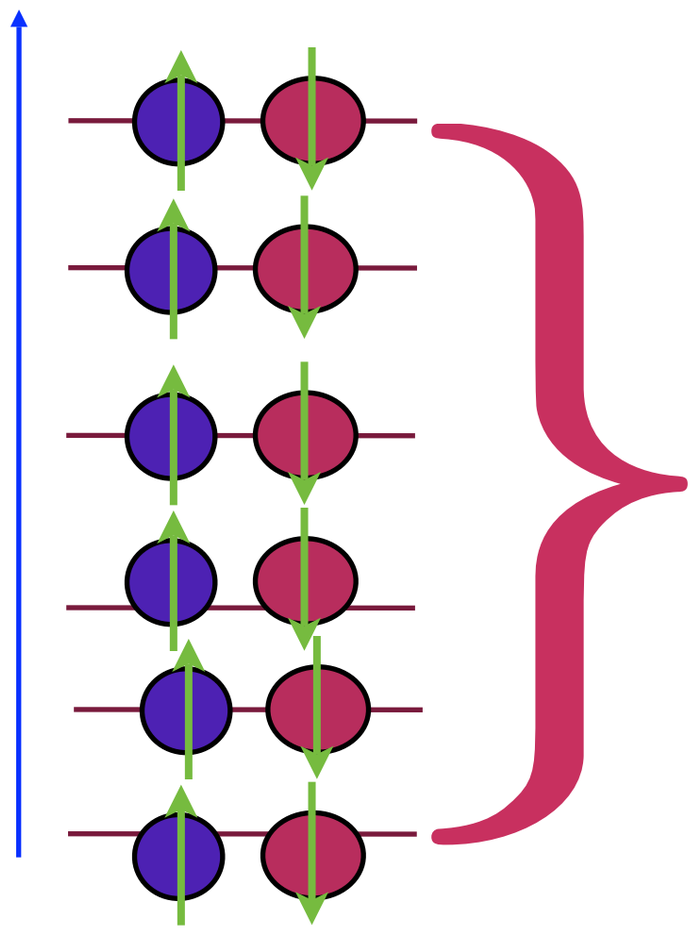

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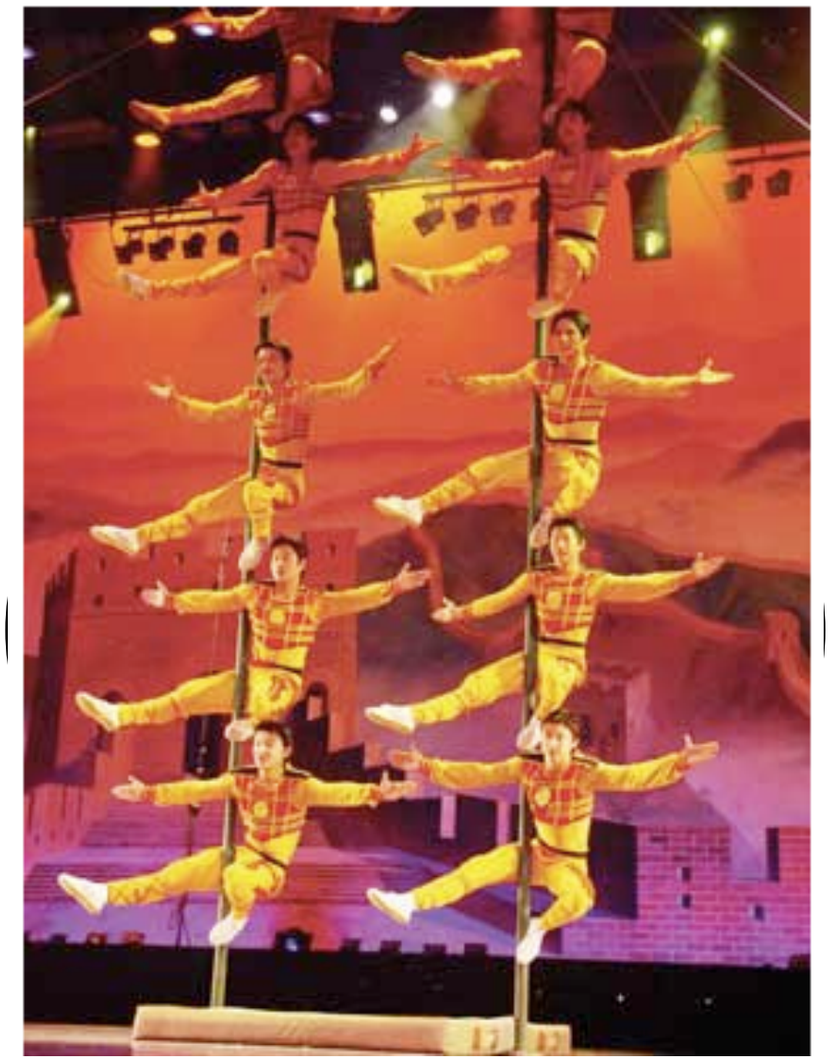
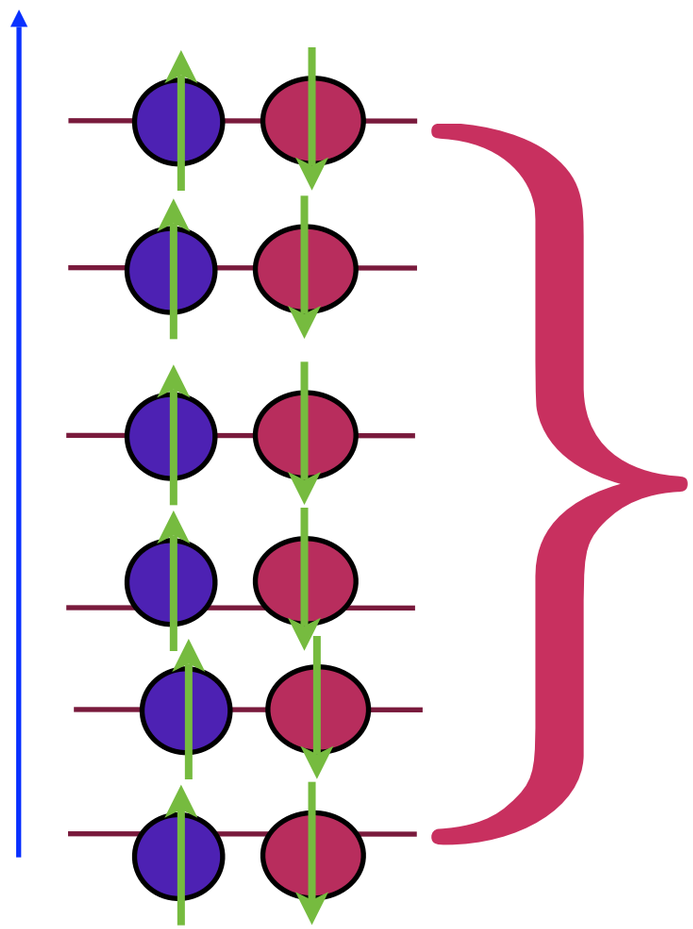
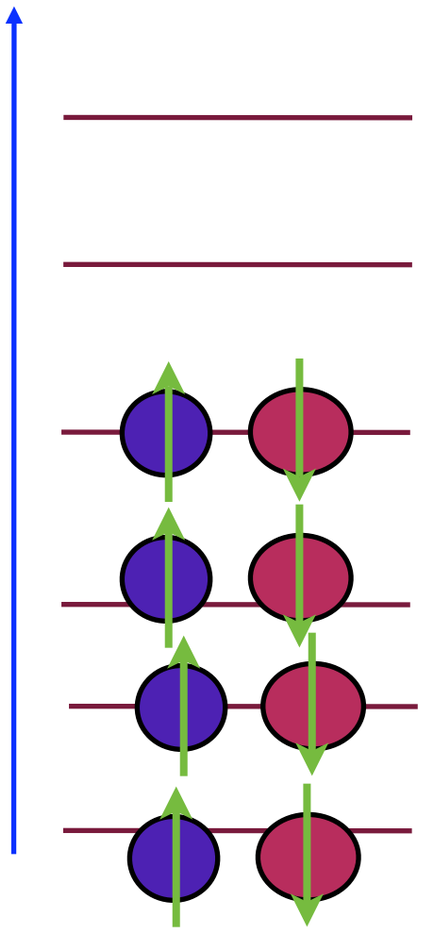


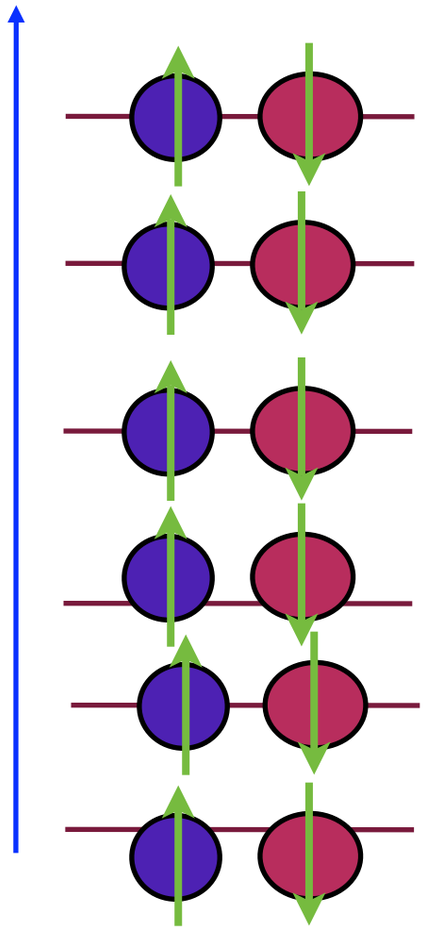


NO EMPTY STATES

INSULATOR

simple lesson





EMPTY STATES=
METAL

ALL STATES FILLED=
BAND INSULATOR

band theory of metals

acrobatics= chemistry

metals

1 H Hydrogen 1.00794																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
11 Na Sodium 22.989770	12 Mg Magnesium 24.3050											13 Al Aluminum 26.981538	14 Si Silicon 28.0855	15 P Phosphorus 30.973761	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955910	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938049	26 Fe Iron 55.845	27 Co Cobalt 58.933200	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.61	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.29
55 Cs Cesium 132.90545	56 Ba Barium 137.327	57 La Lanthanum 138.9055	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.078	79 Au Gold 196.96655	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98038	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium (226)	89 Ac Actinium (227)	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (262)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 (269)	111 (272)	112 (277)	113	114				

58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92534	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
90 Th Thorium 232.0381	91 Pa Protactinium 231.03588	92 U Uranium 238.0289	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

acrobatics= chemistry

metals

1 H Hydrogen 1.00794																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
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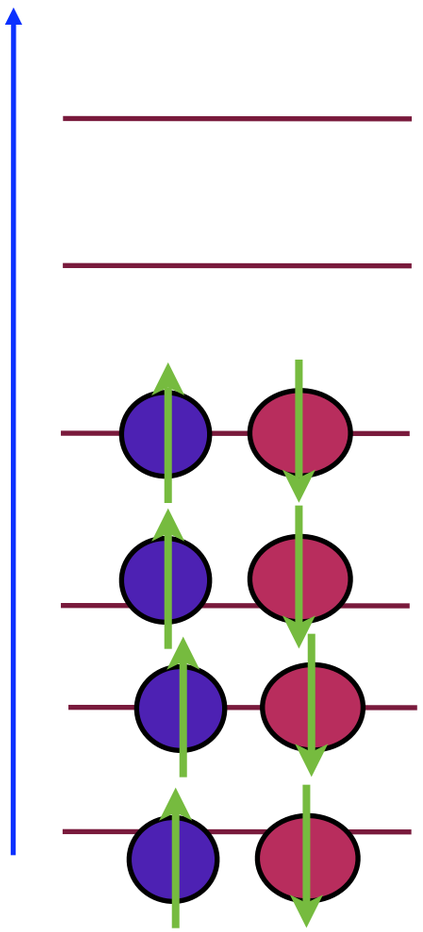

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37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.29
55 Cs Cesium 132.90545	56 Ba Barium 137.327	57 La Lanthanum 138.9055	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.078	79 Au Gold 196.96655	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98038	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium (226)	89 Ac Actinium (227)	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (262)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 (269)	111 (272)	112 (277)	113	114				

58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92534	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
90 Th Thorium 232.0381	91 Pa Protactinium 231.03588	92 U Uranium 238.0289	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

conductivity=

conductivity=

conductivity=

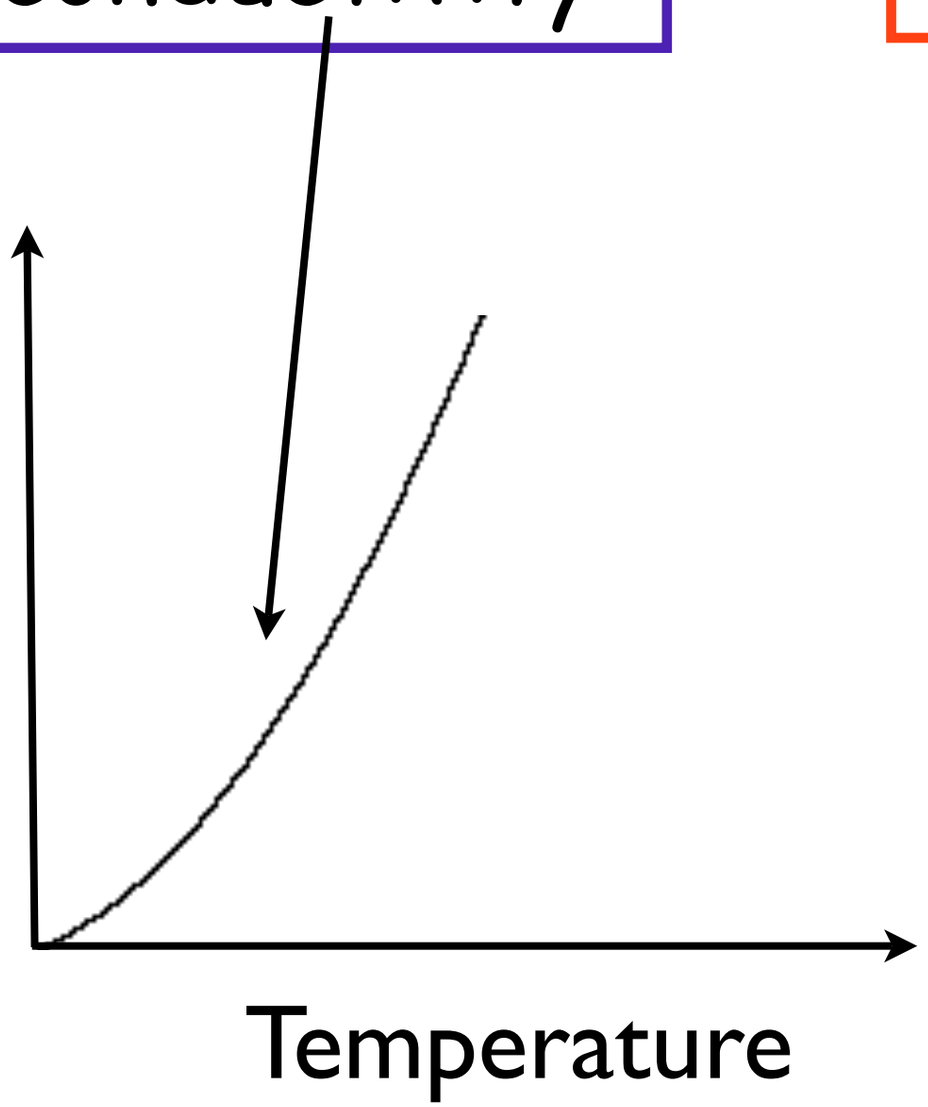
conductivity=

1/resistivity

conductivity=

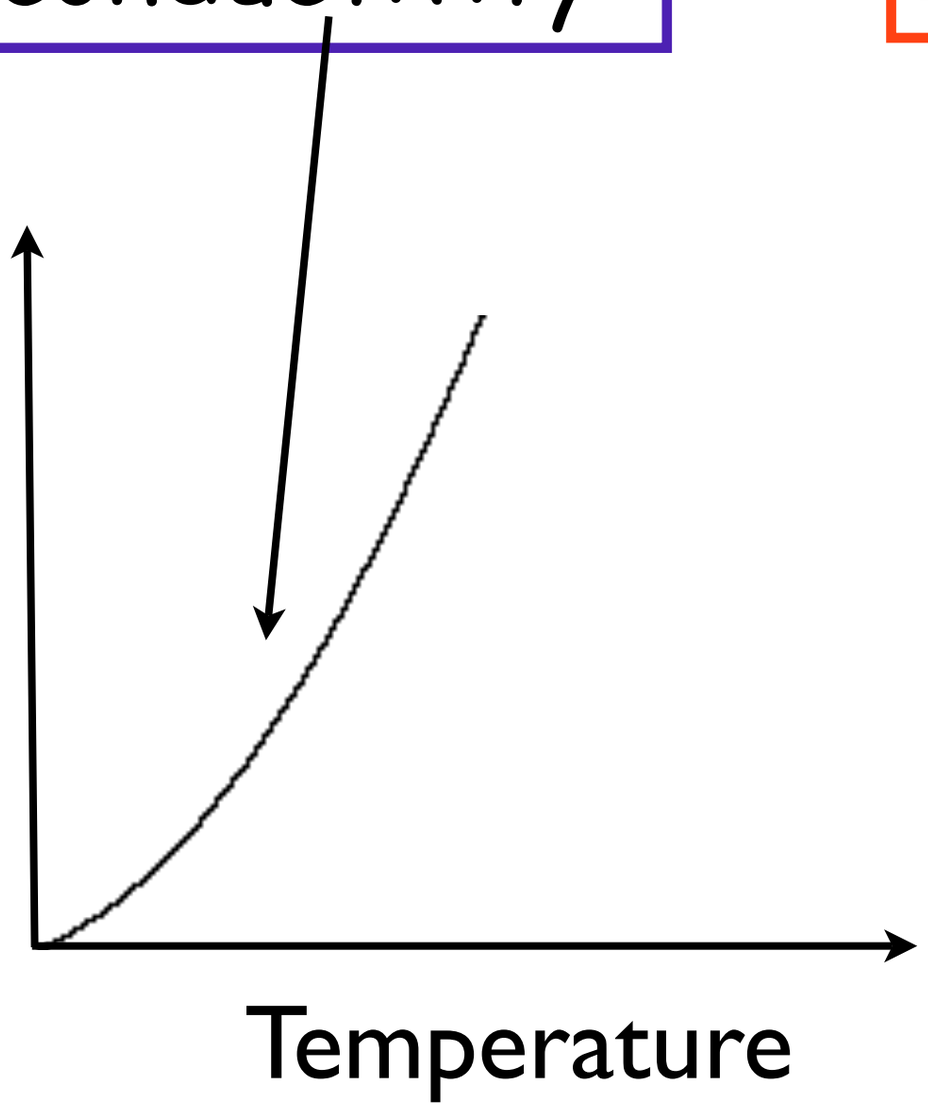
conductivity=

1/resistivity

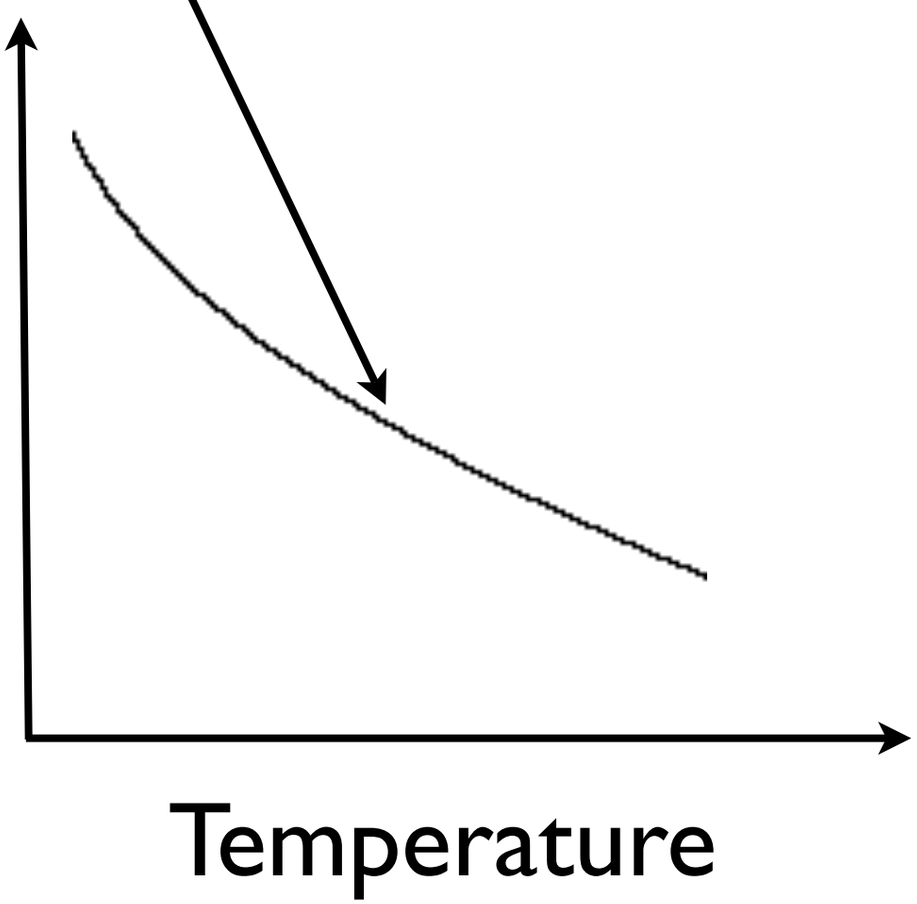


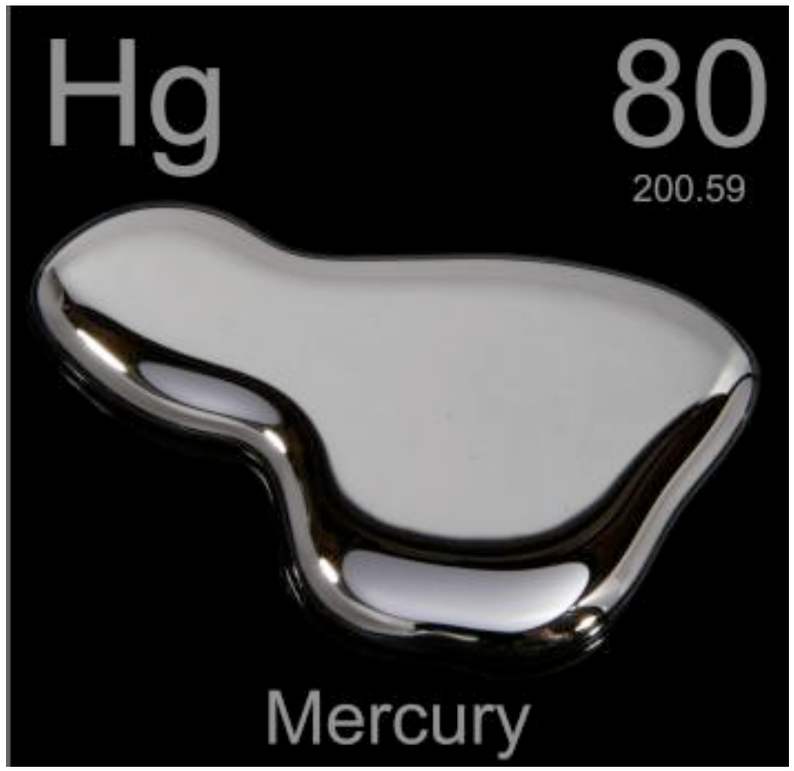
conductivity=

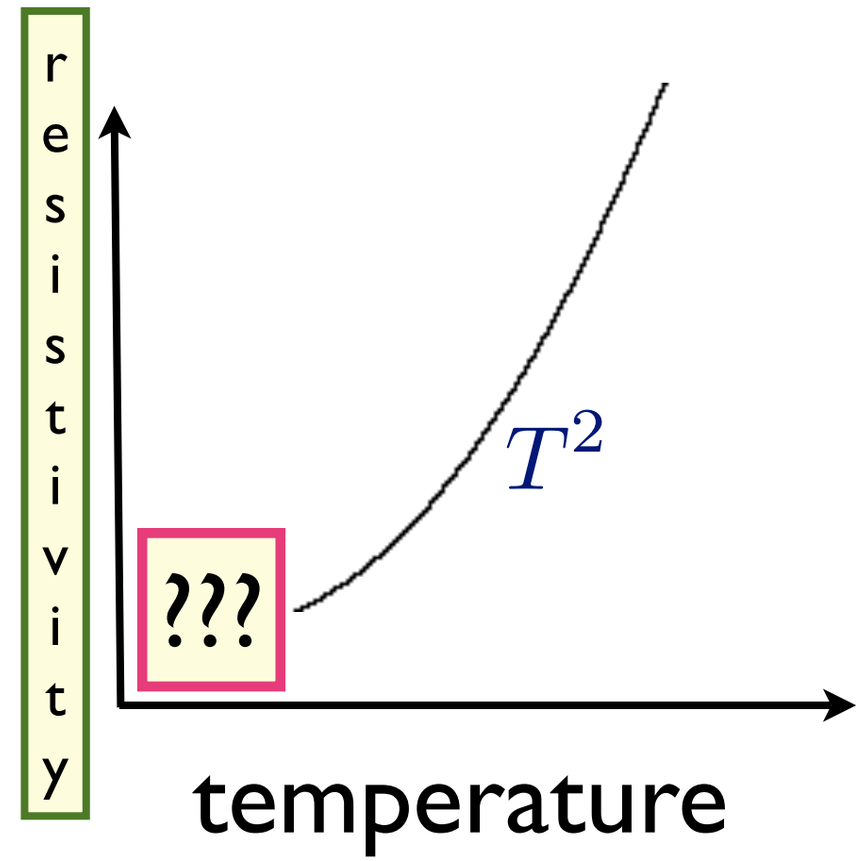
conductivity=

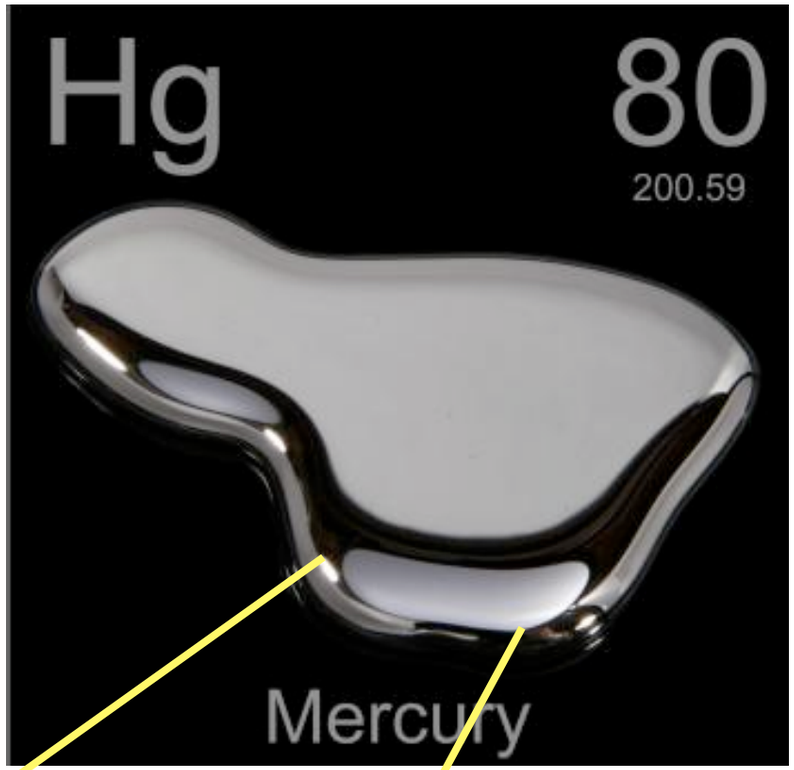


1/resistivity




Hg
80
200.59
Mercury


resistivity
???
T^2
temperature


Hg
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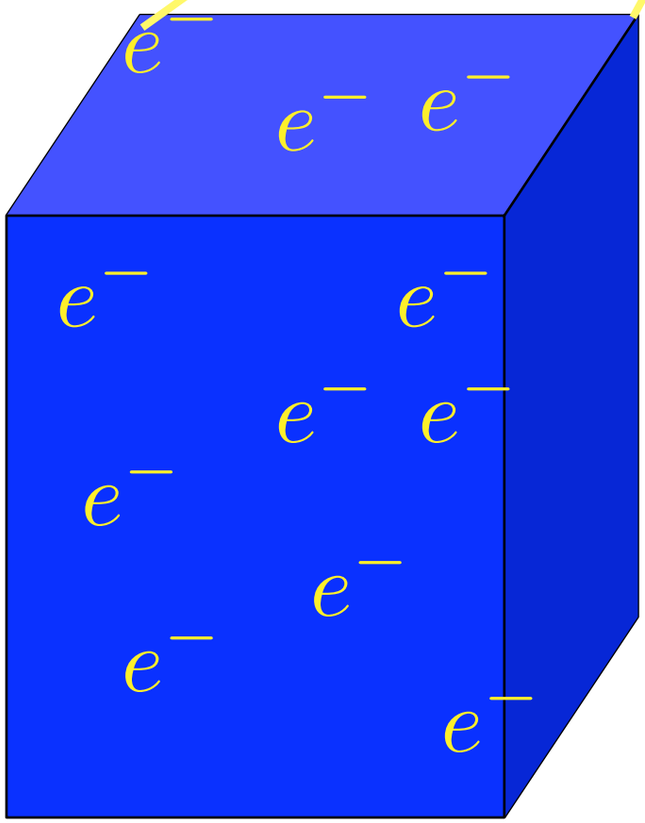
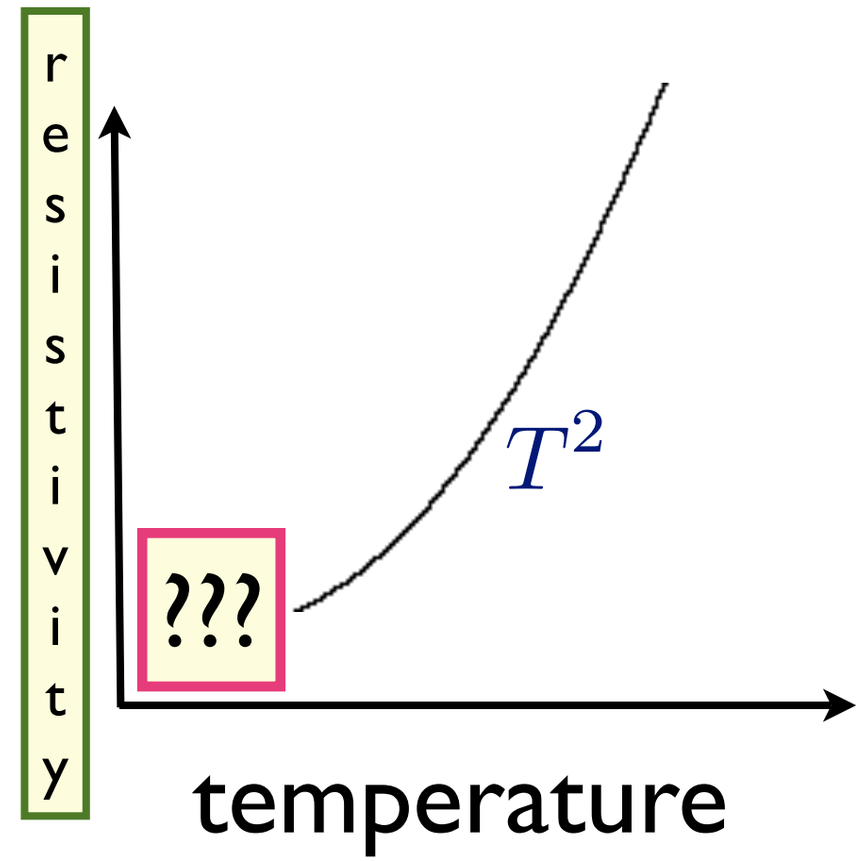
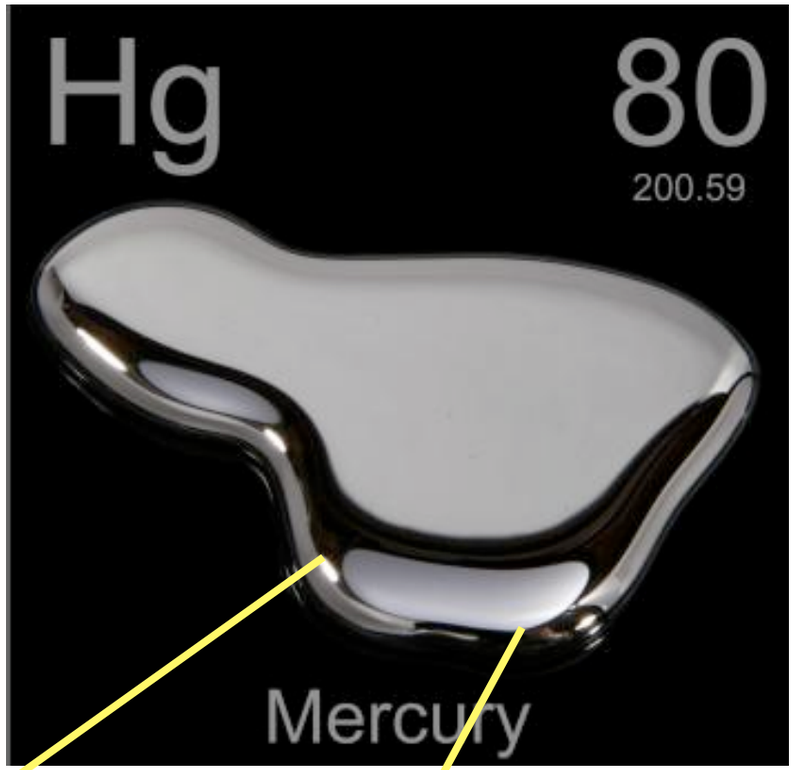
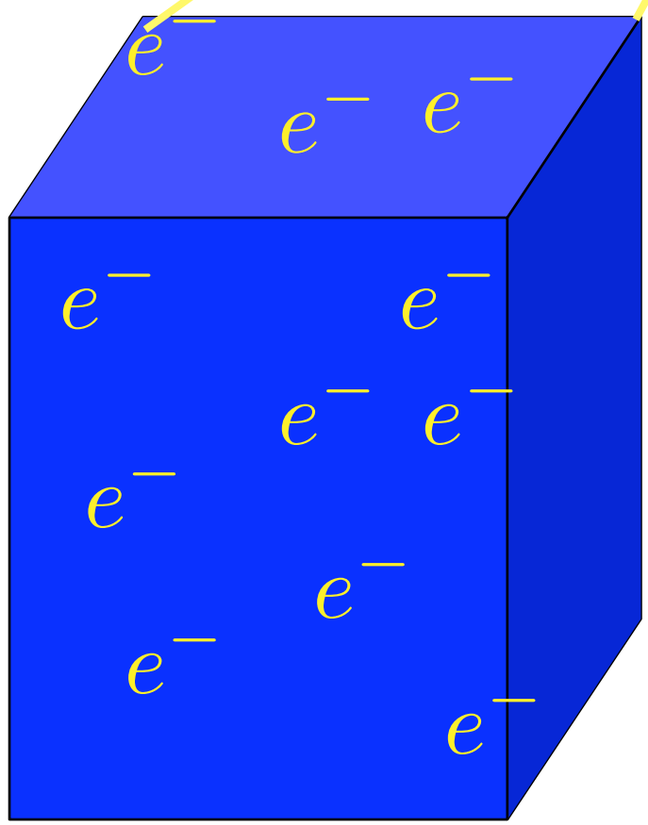
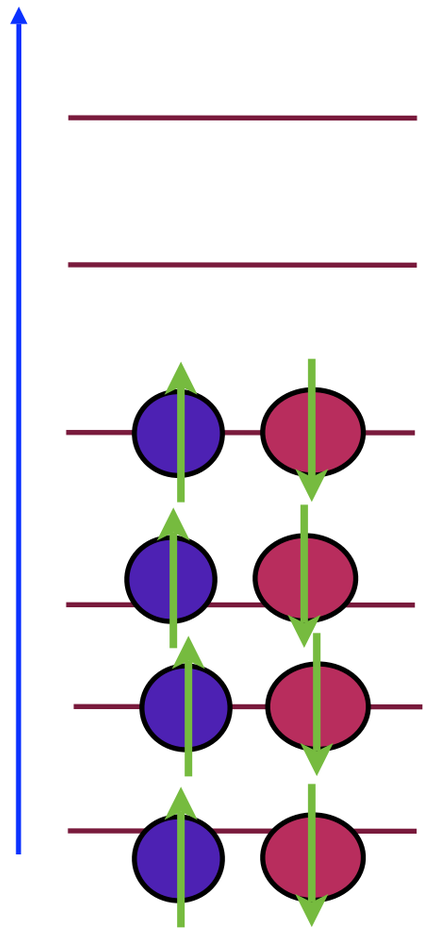
200.59
Mercury

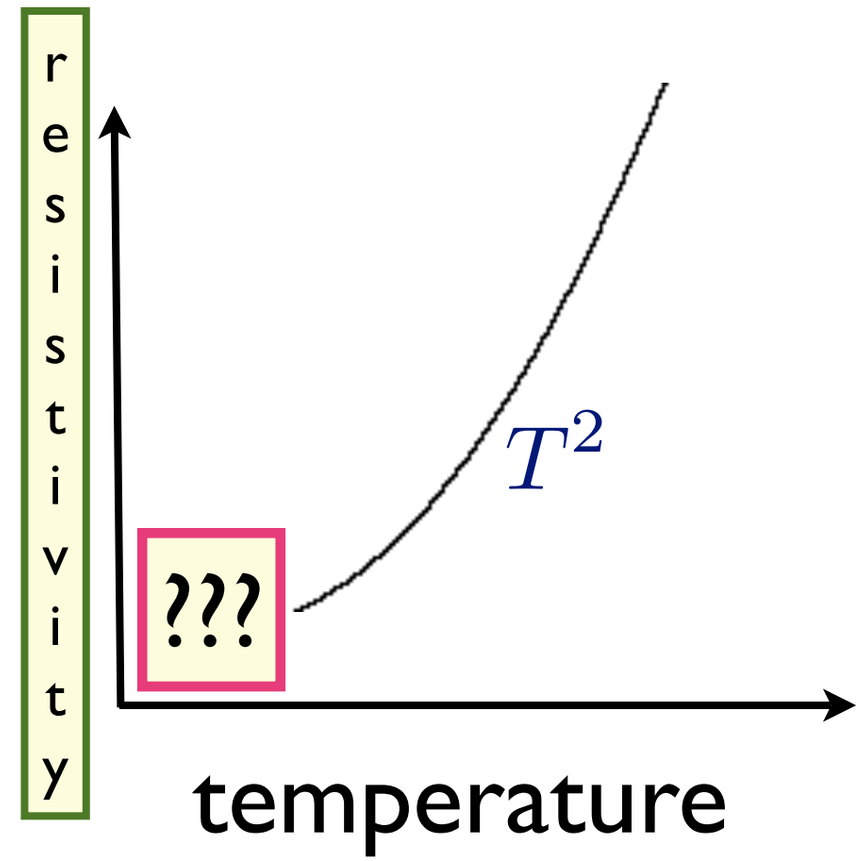

e^-


resistivity
???
T^2
temperature









EMPTY STATES= METAL

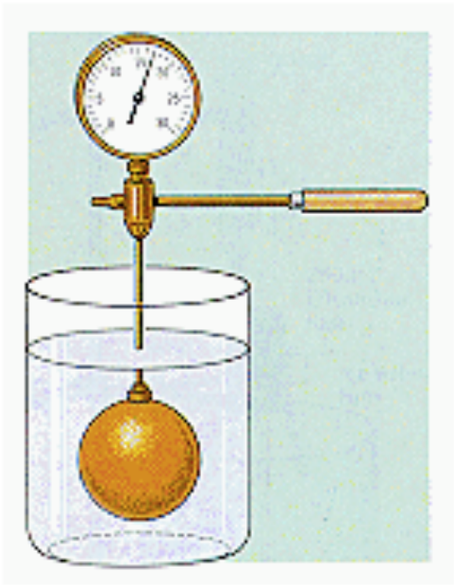
What is low temperature?

What is low temperature?

Amontons's Law

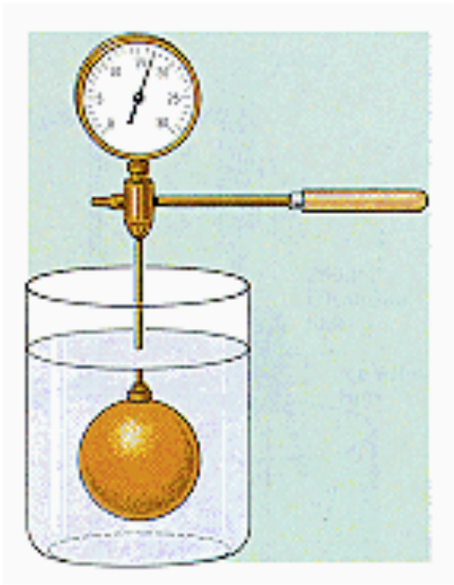
What is low temperature?

Amontons's Law



What is low temperature?

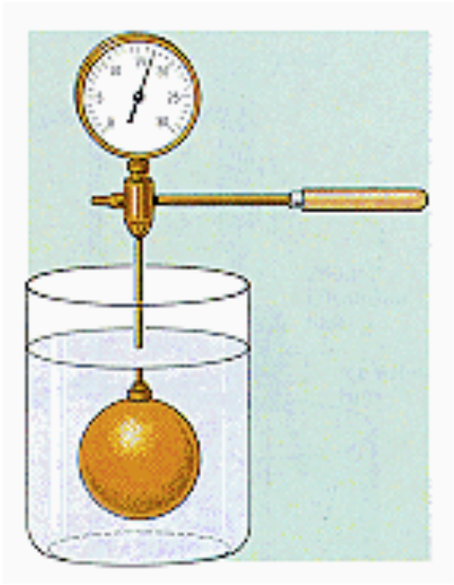
Amontons's Law



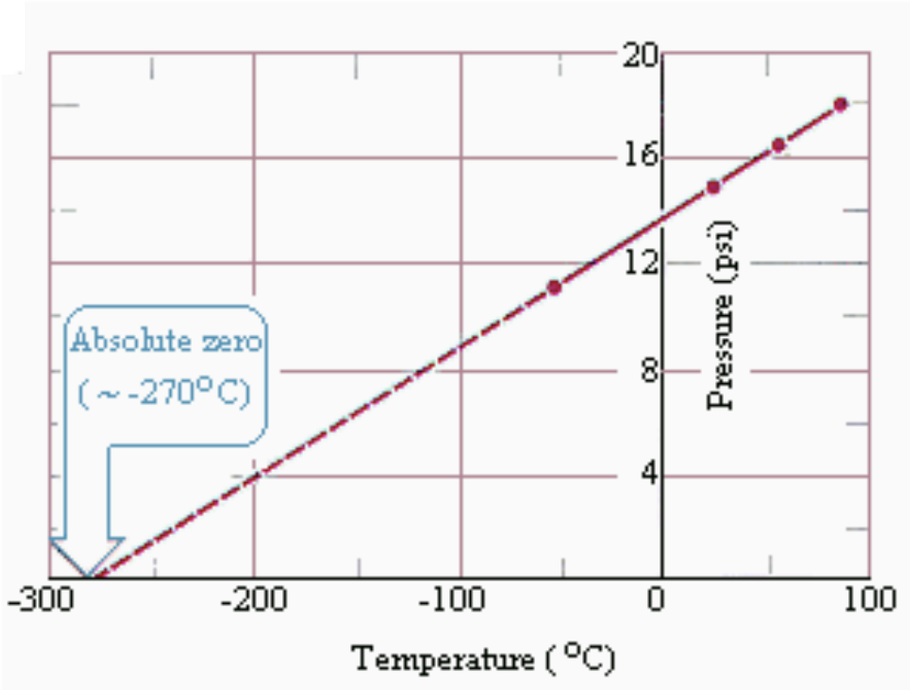
$$P \propto T$$

What is low temperature?

Amontons's Law

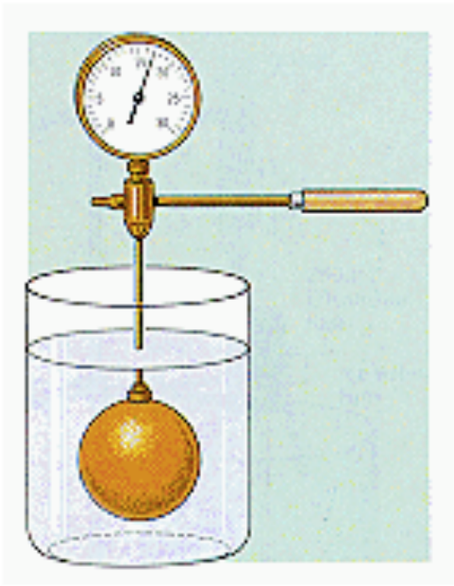


$$P \propto T$$

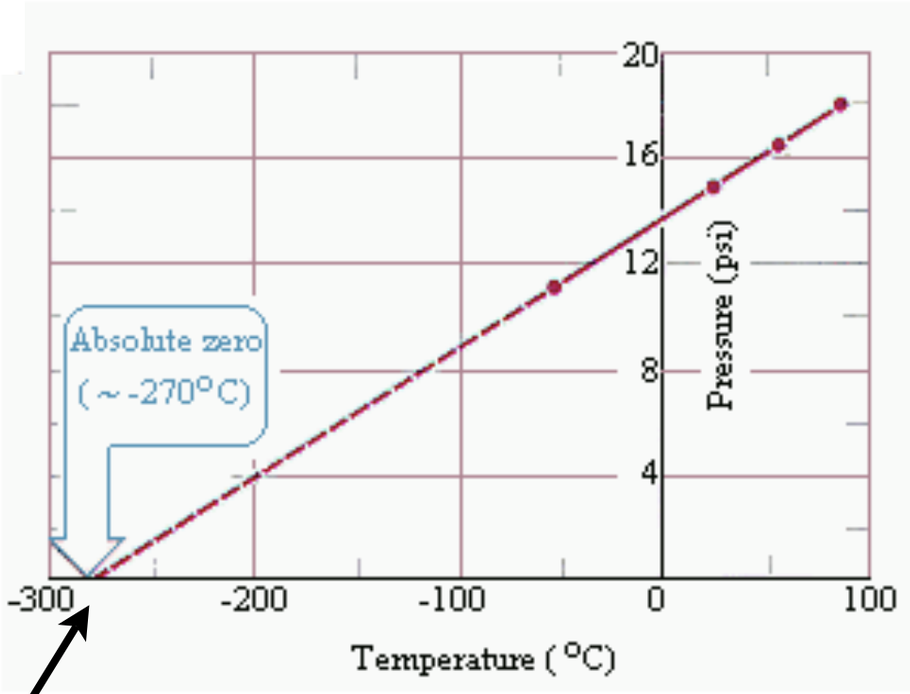


What is low temperature?

Amontons's Law



$$P \propto T$$



0 K

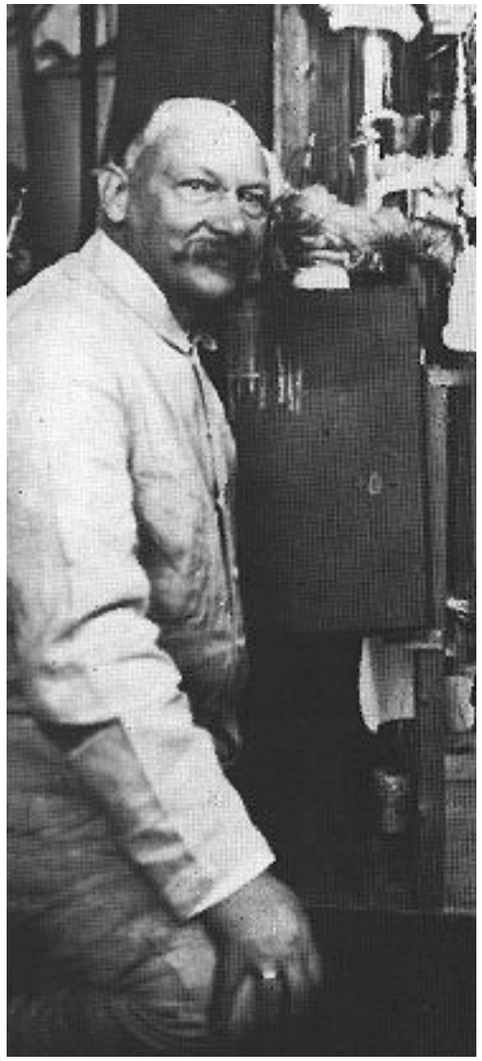
298 K (room temperature)

Kelvin Temperature Scale

Race to zero

'Minds are like parachutes they only function when they are open'- James Dewar, Scottish physicist 1842 –1923

liquified hydrogen, 1898 (20.52K)



H. K. Onnes

Race to zero

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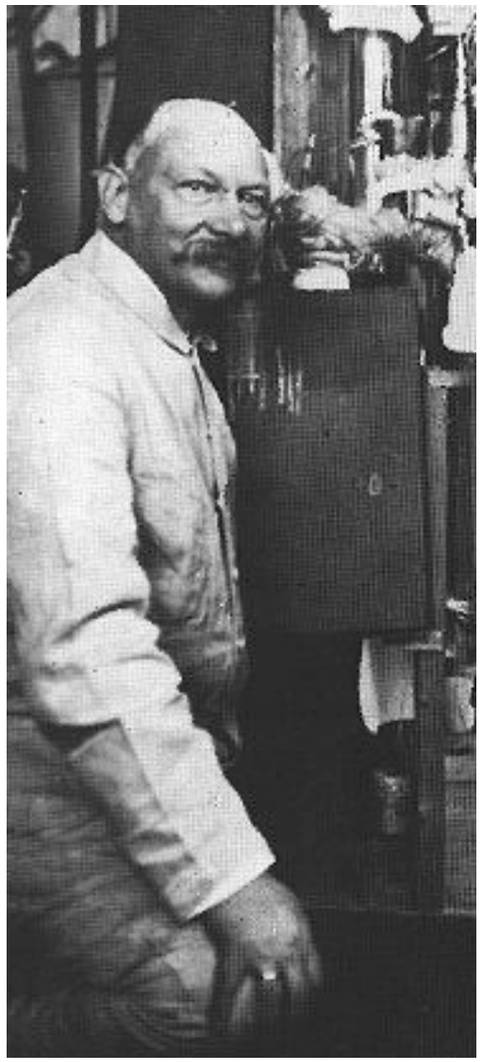
Race to zero



H. K. Onnes

1898: building lab

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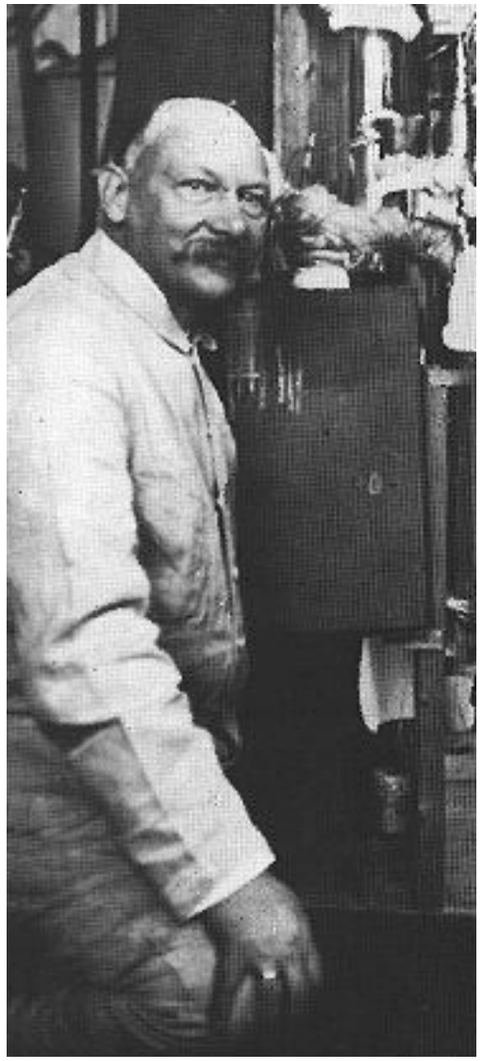
Race to zero



H. K. Onnes

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1908: liquified Helium (0.9K)

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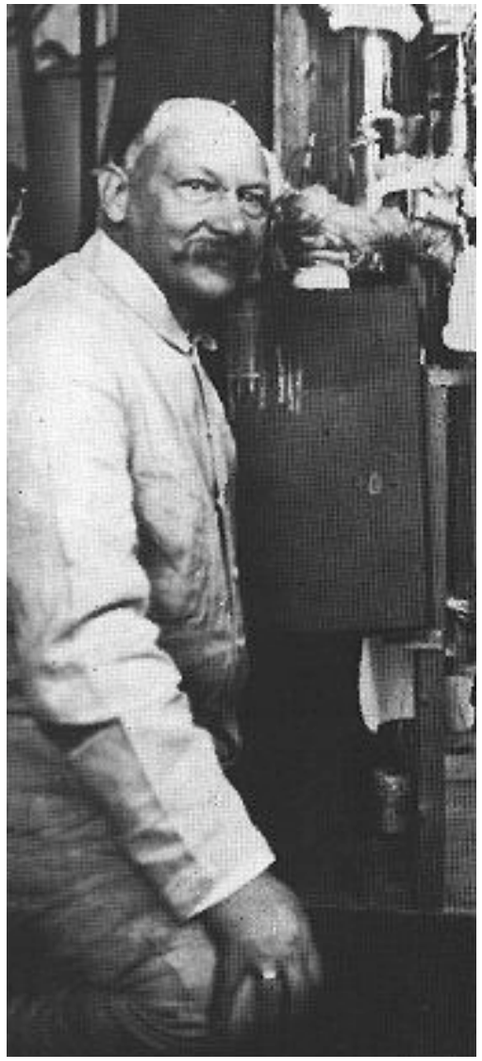

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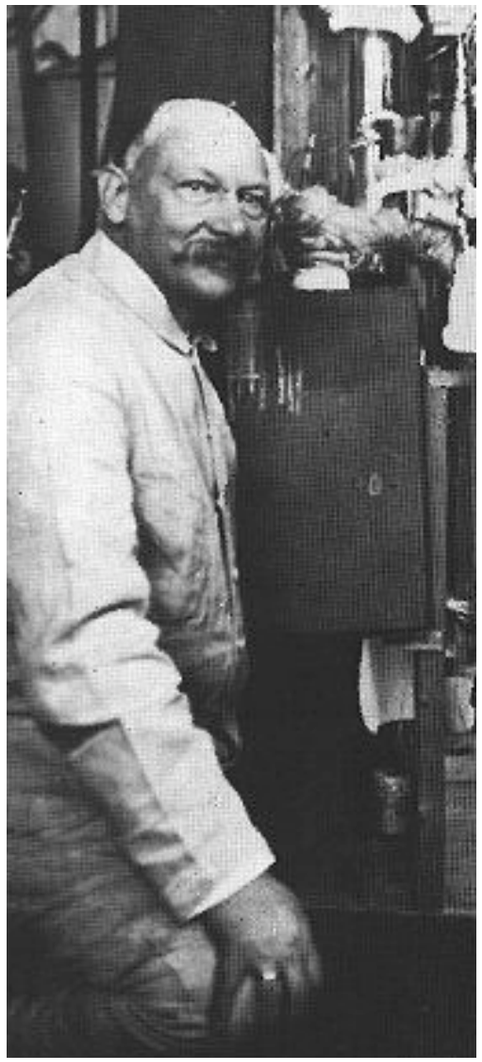

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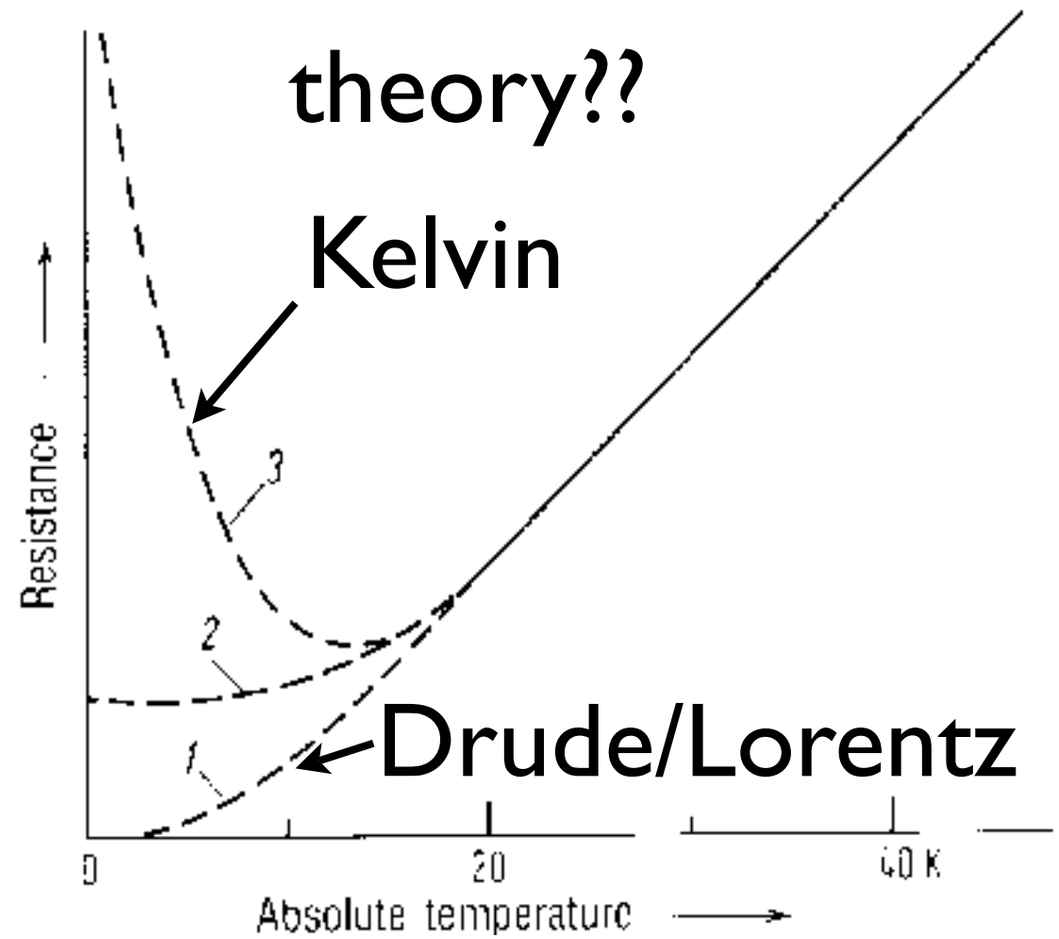
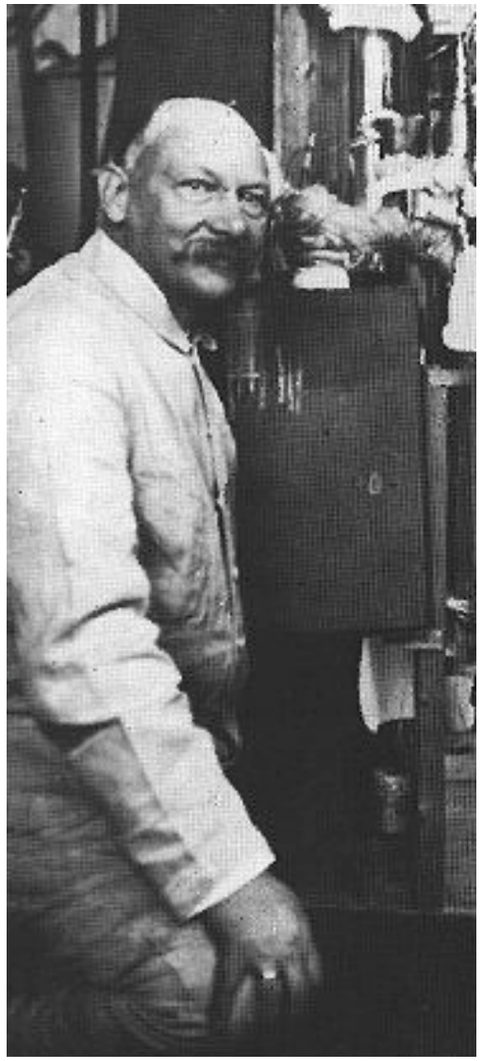


Race to zero



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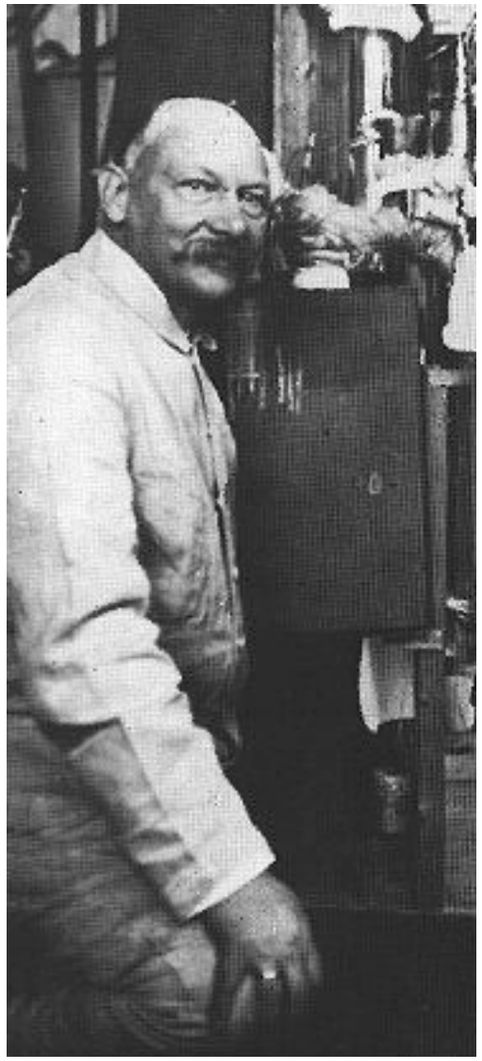

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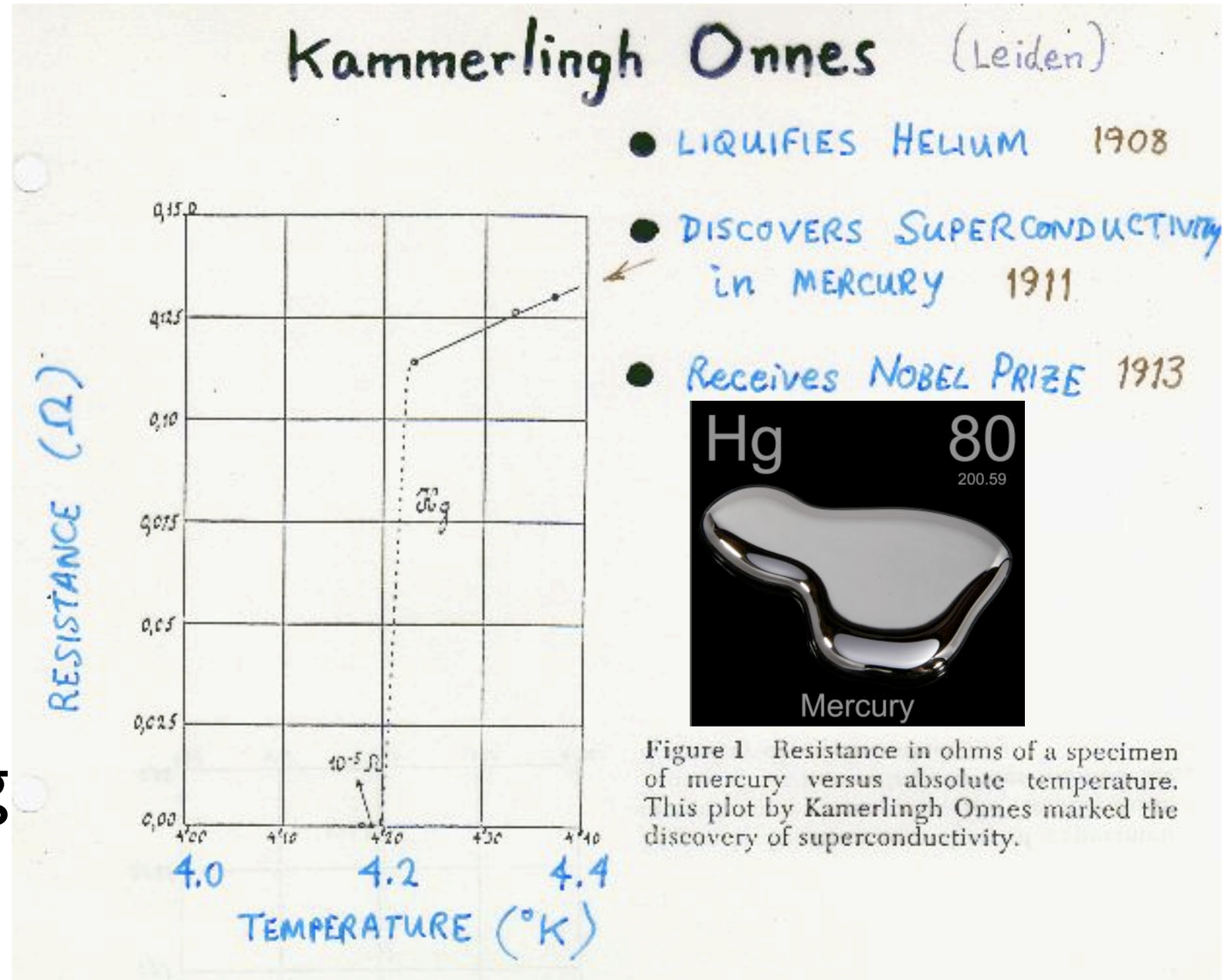
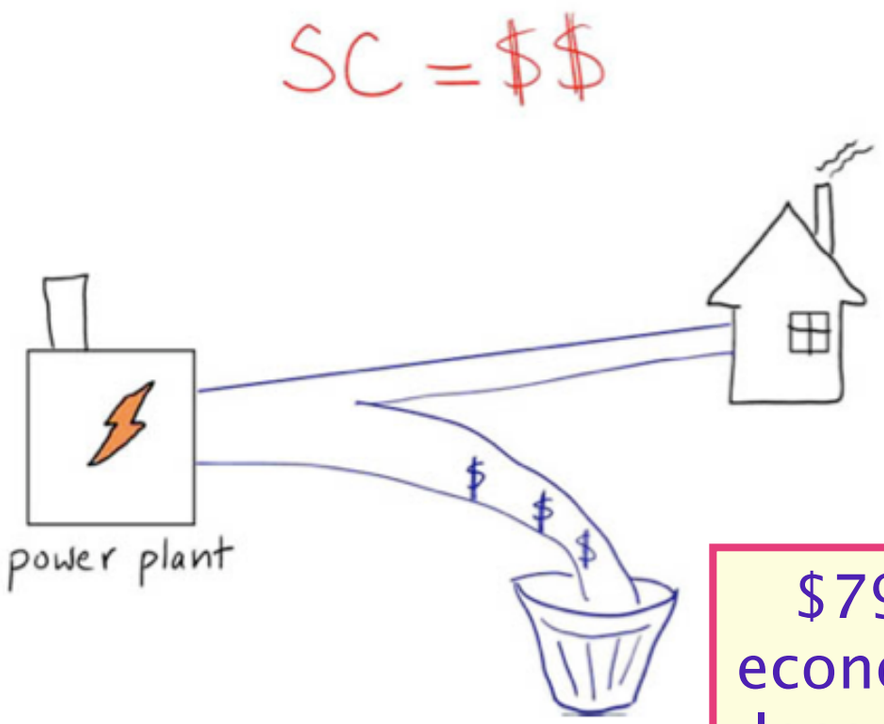


Figure 1 Resistance in ohms of a specimen of mercury versus absolute temperature. This plot by Kamerlingh Onnes marked the discovery of superconductivity.

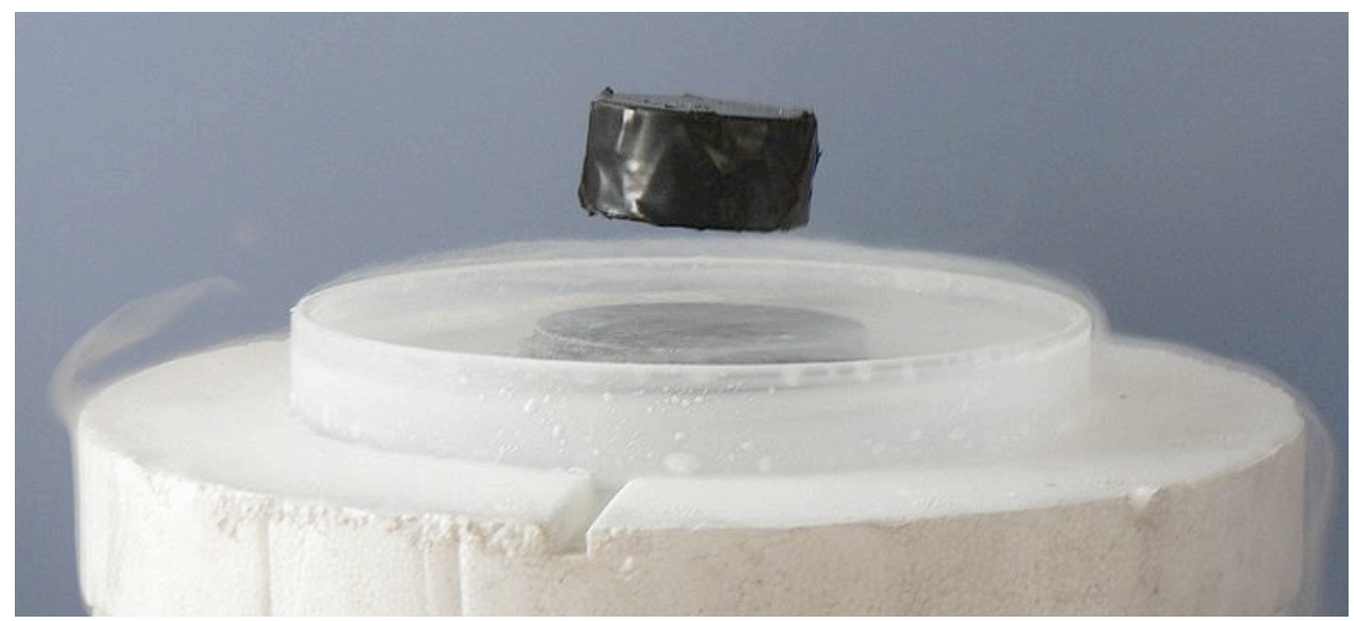
superconductivity

zero resistance:
conduction
without loss

repulsion
of magnetic fields



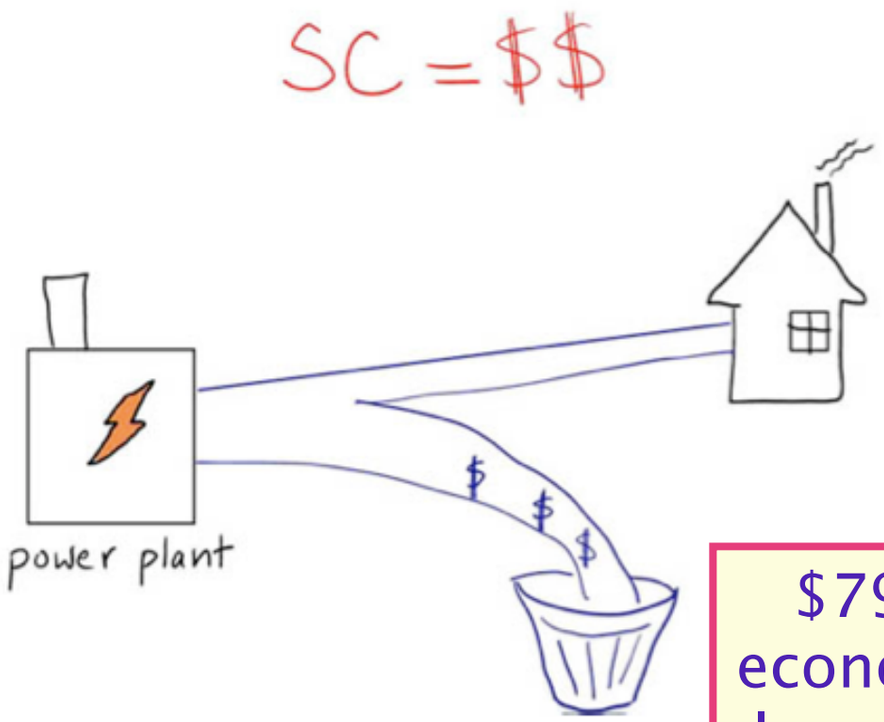
$79 B
economic
loss (US)



why?

superconductivity

zero resistance:
conduction
without loss

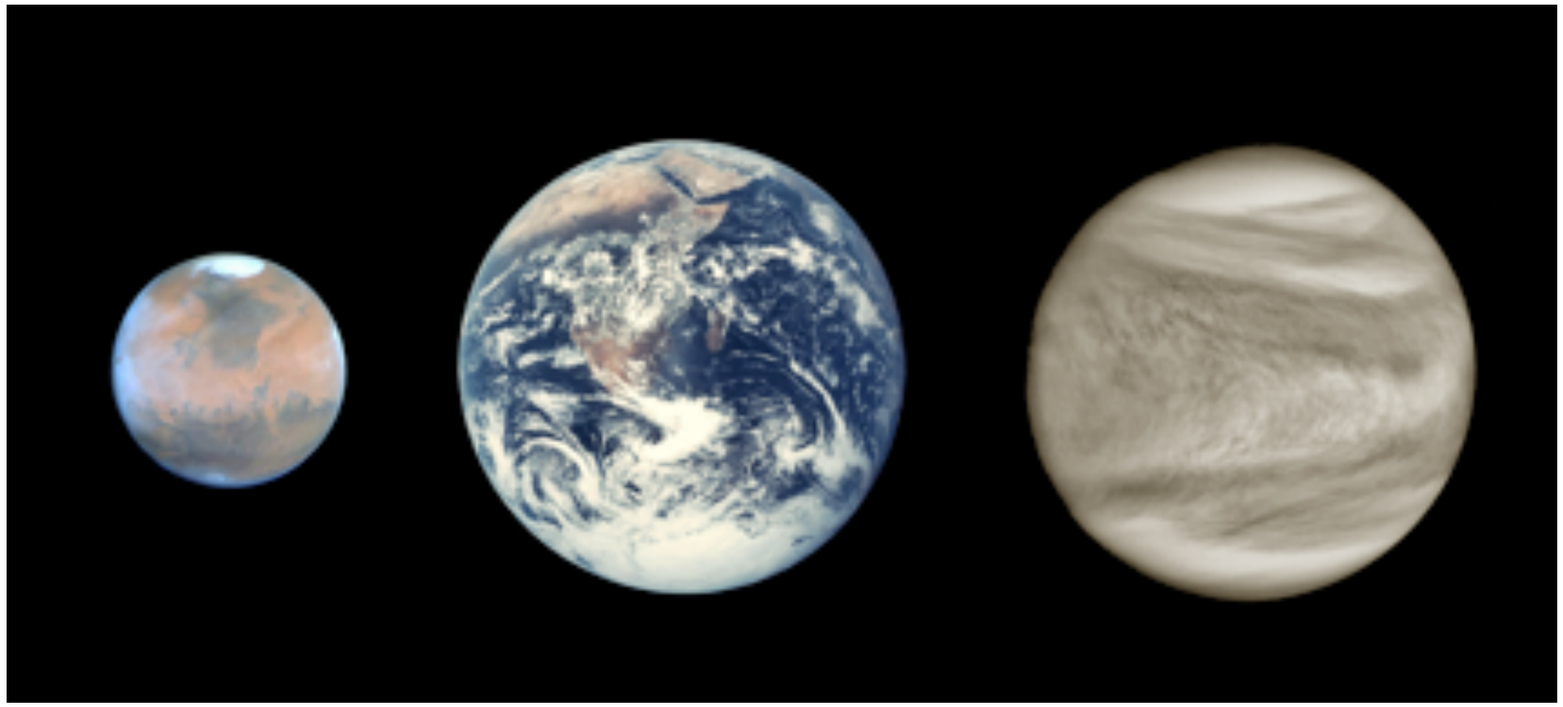


$79 B
economic
loss (US)

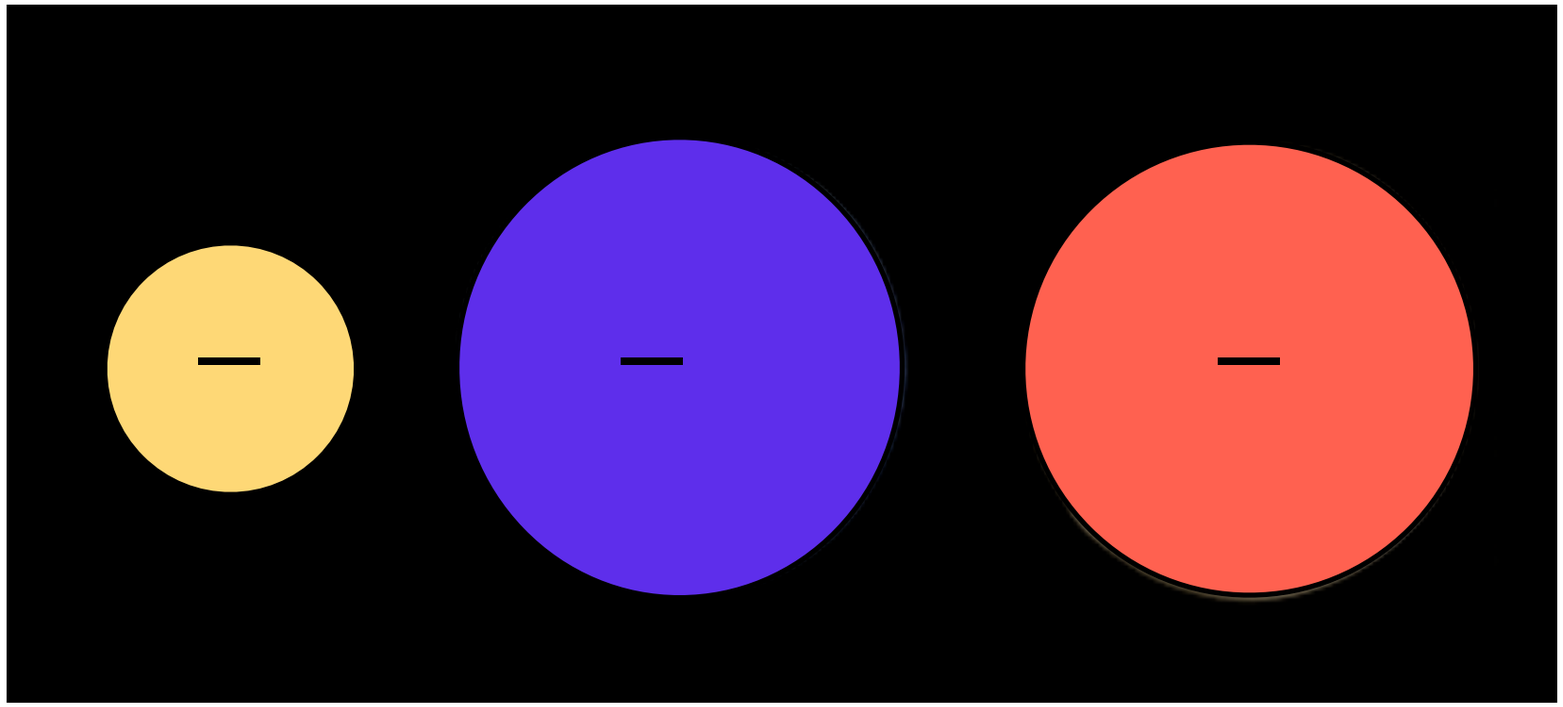
repulsion
of magnetic fields

why?

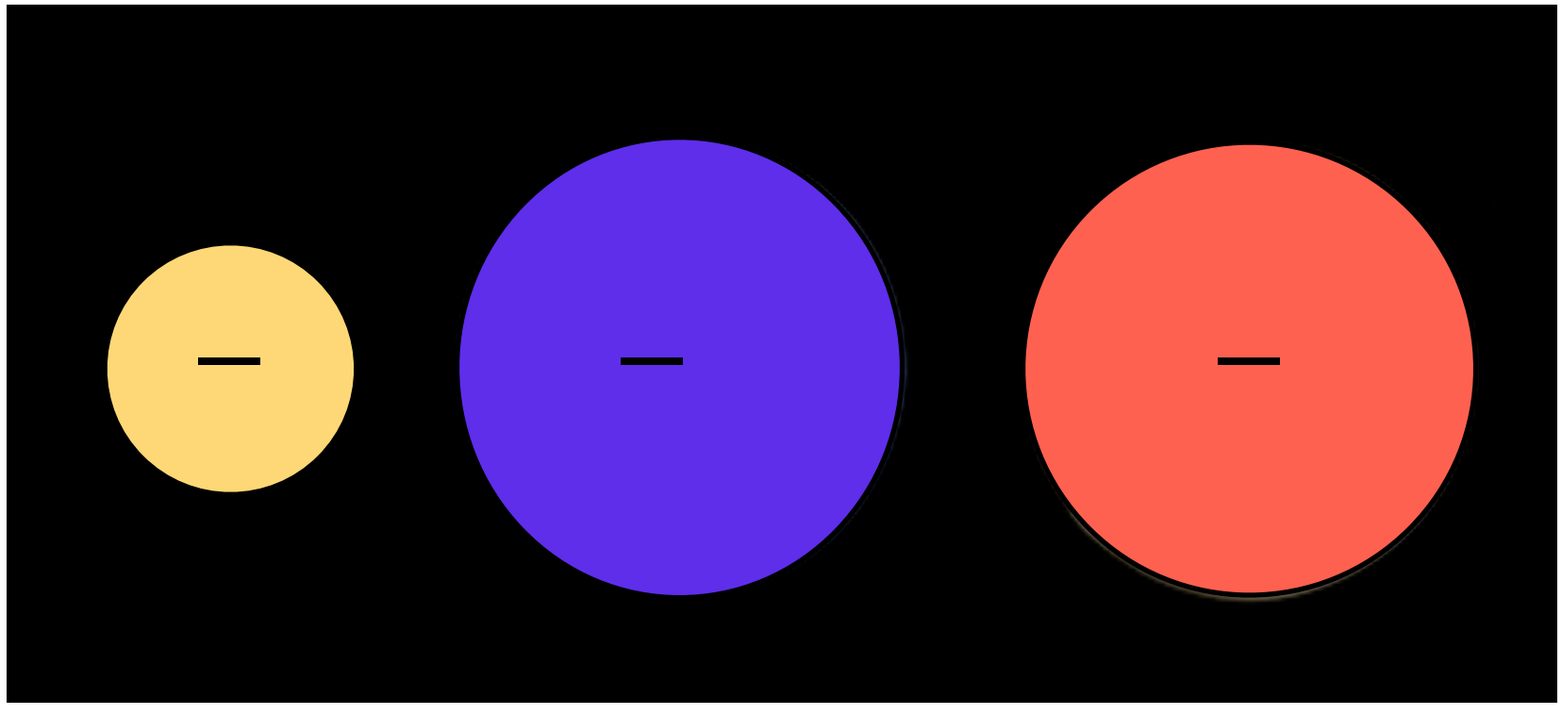
Coulomb's Law

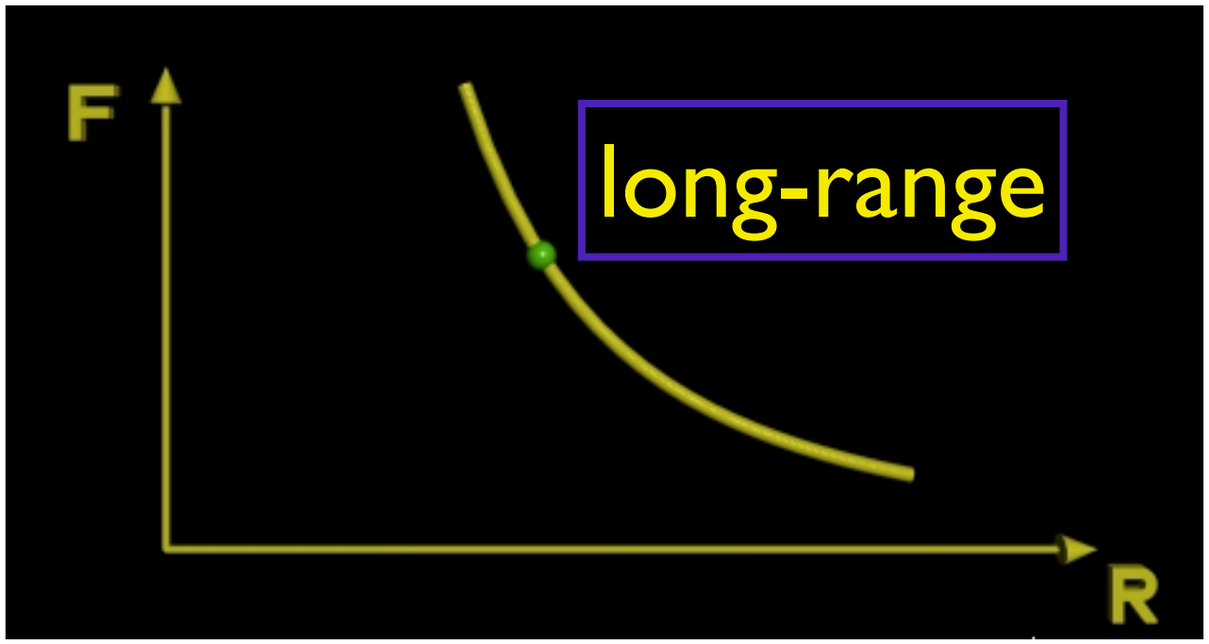


Coulomb's Law

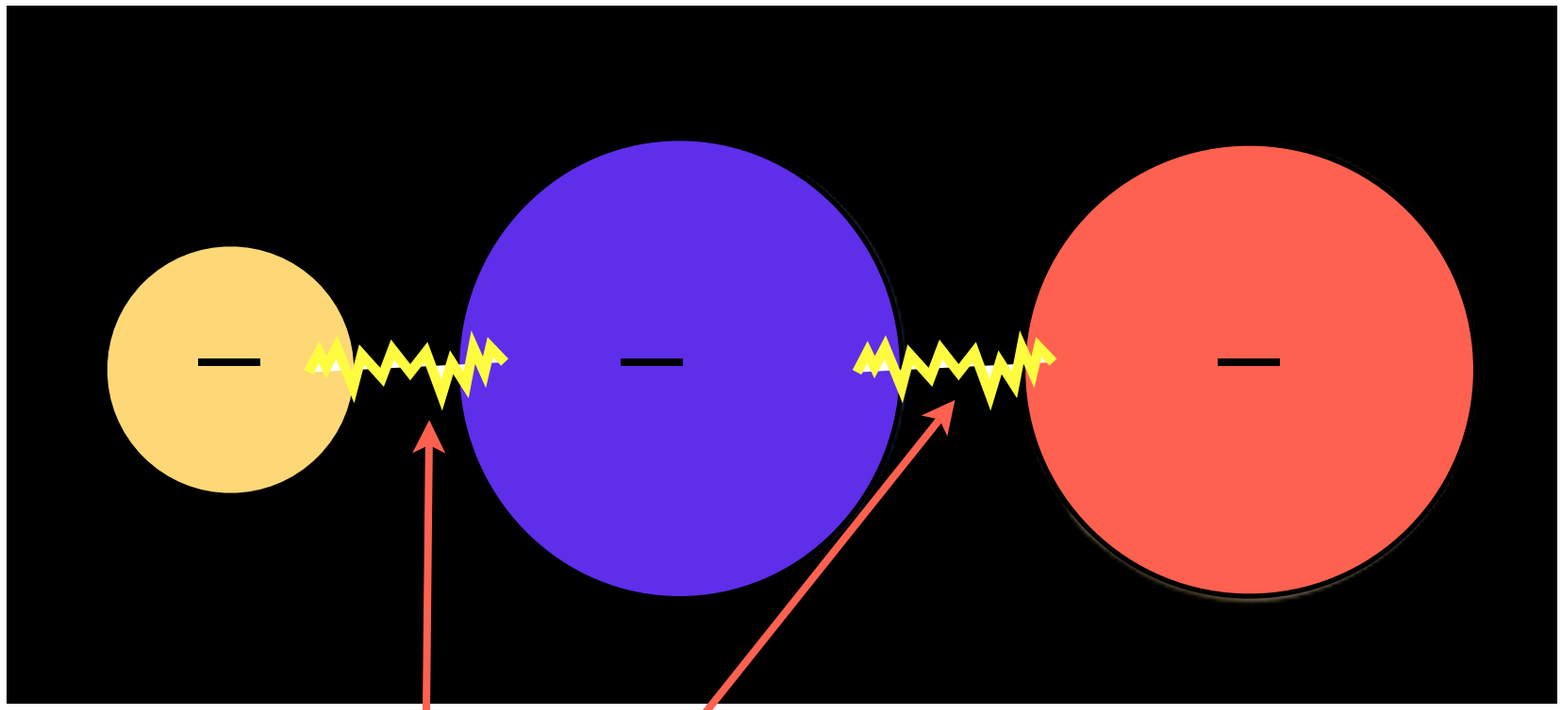


Coulomb's Law

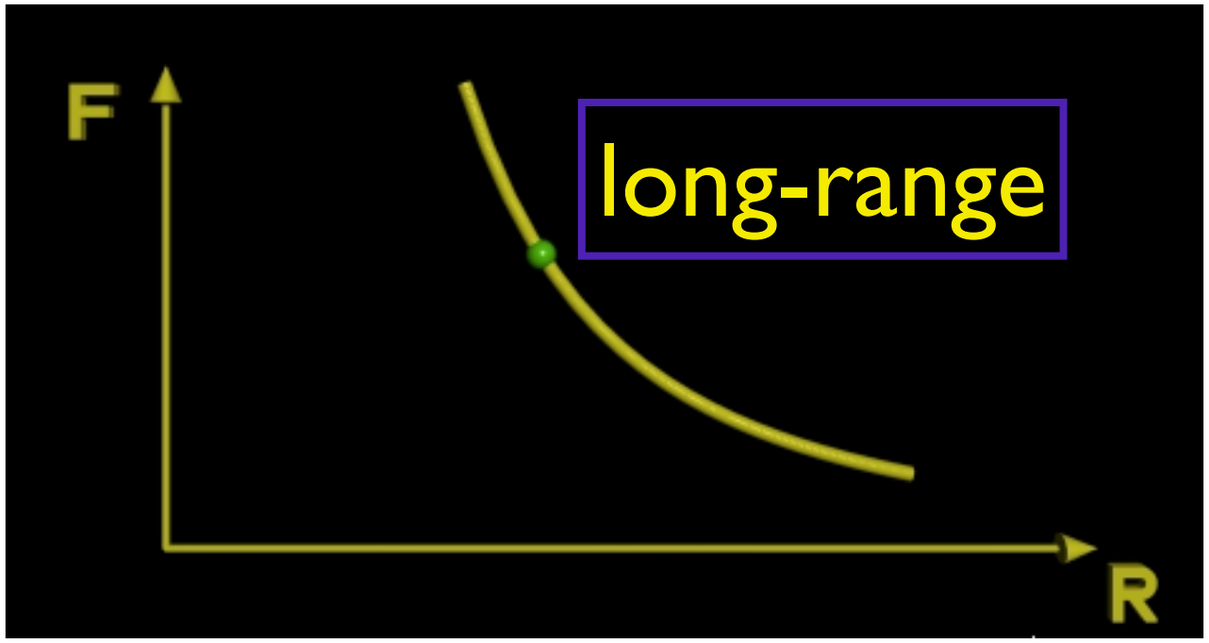


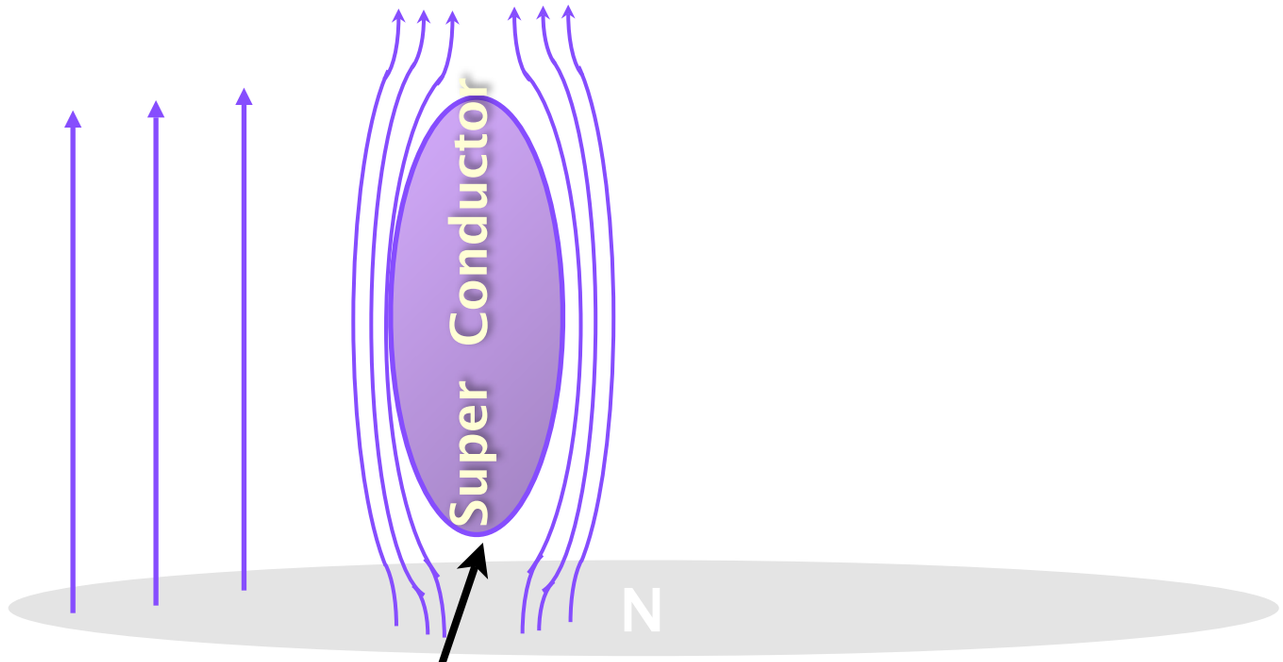


Coulomb's Law



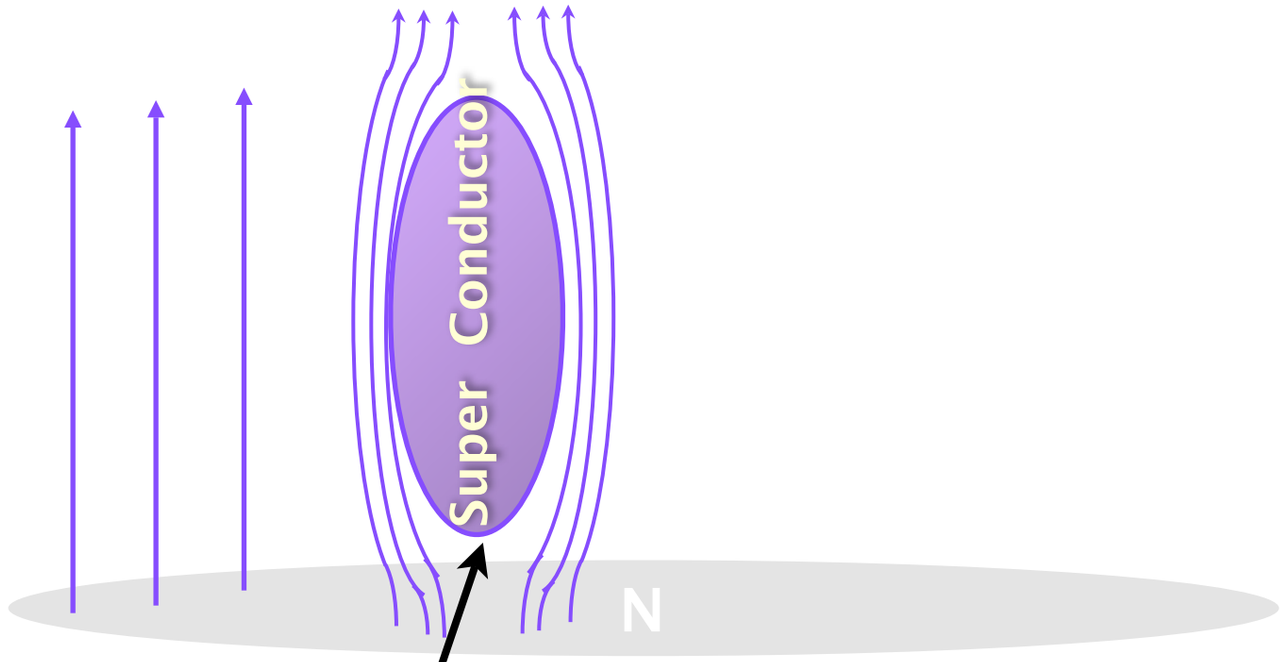
massless
particle: photon





magnet

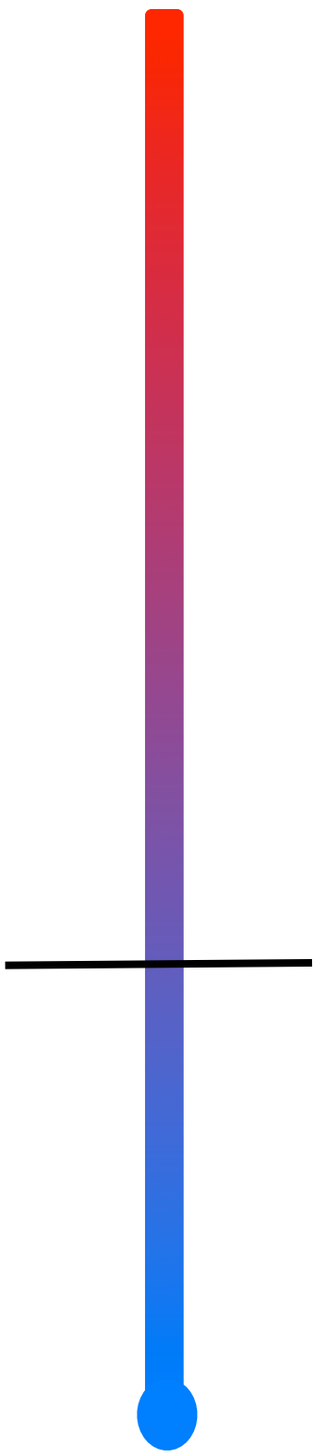
magnetic field
is short-ranged

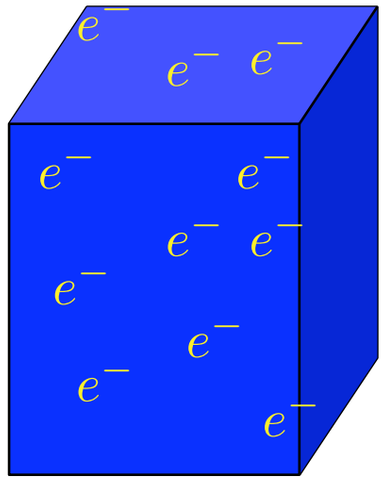


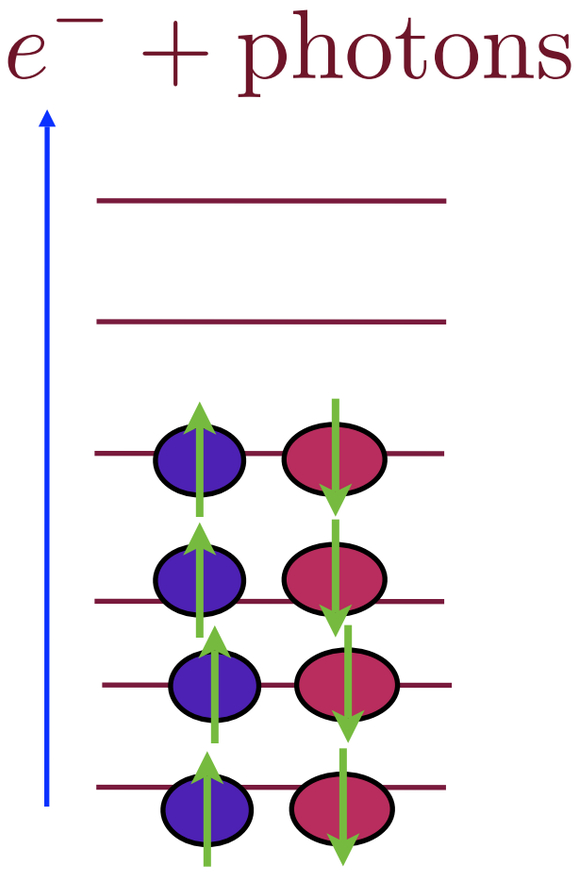
magnet

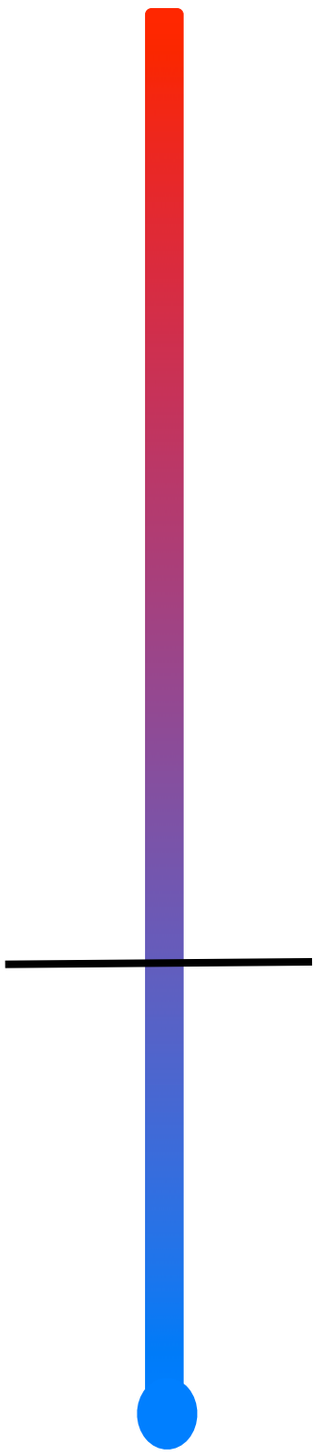
magnetic field
is short-ranged

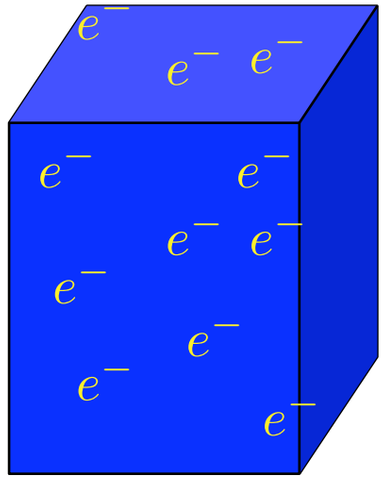
photon is massive
in a
superconductor



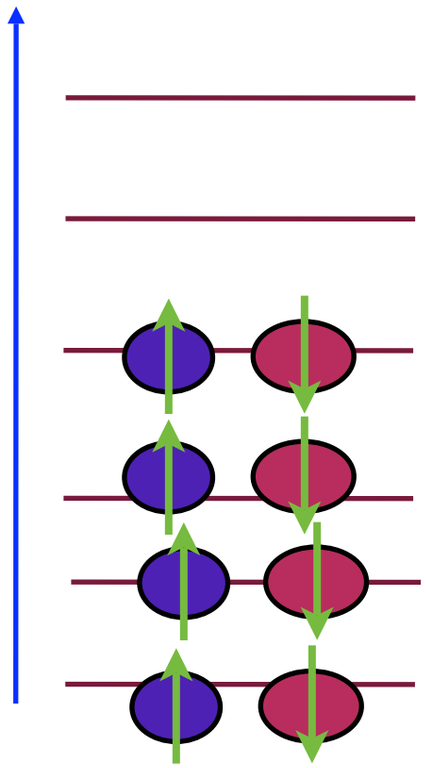

e^-


e^- + photons

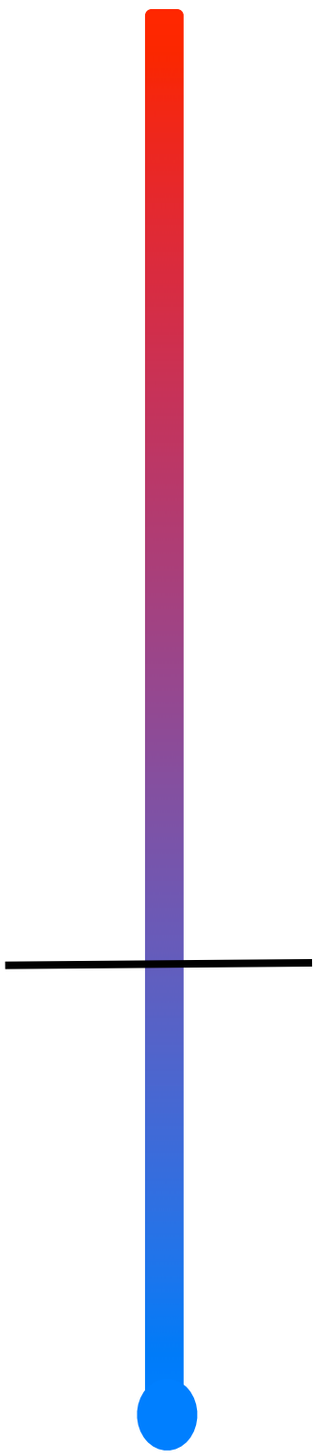


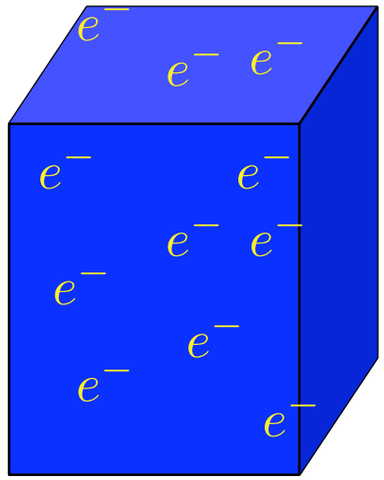


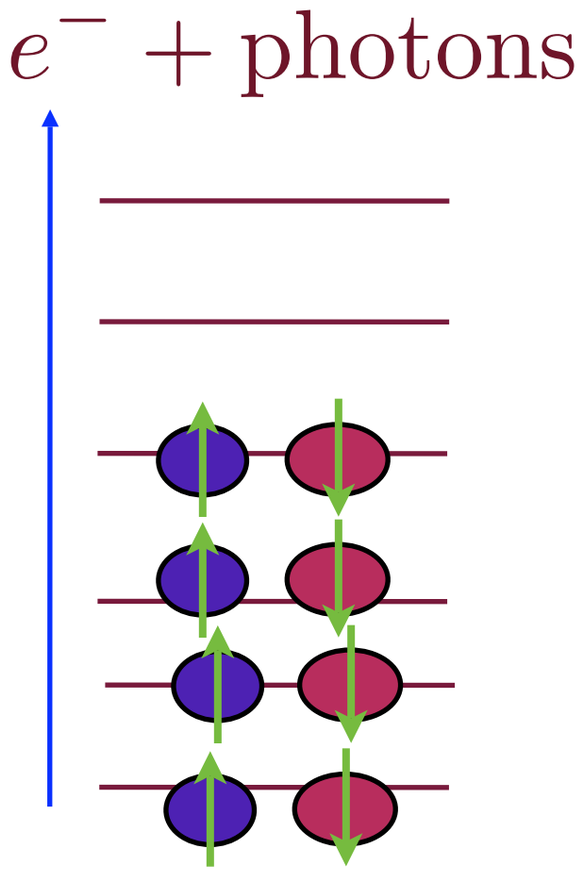
$e^- +$ photons

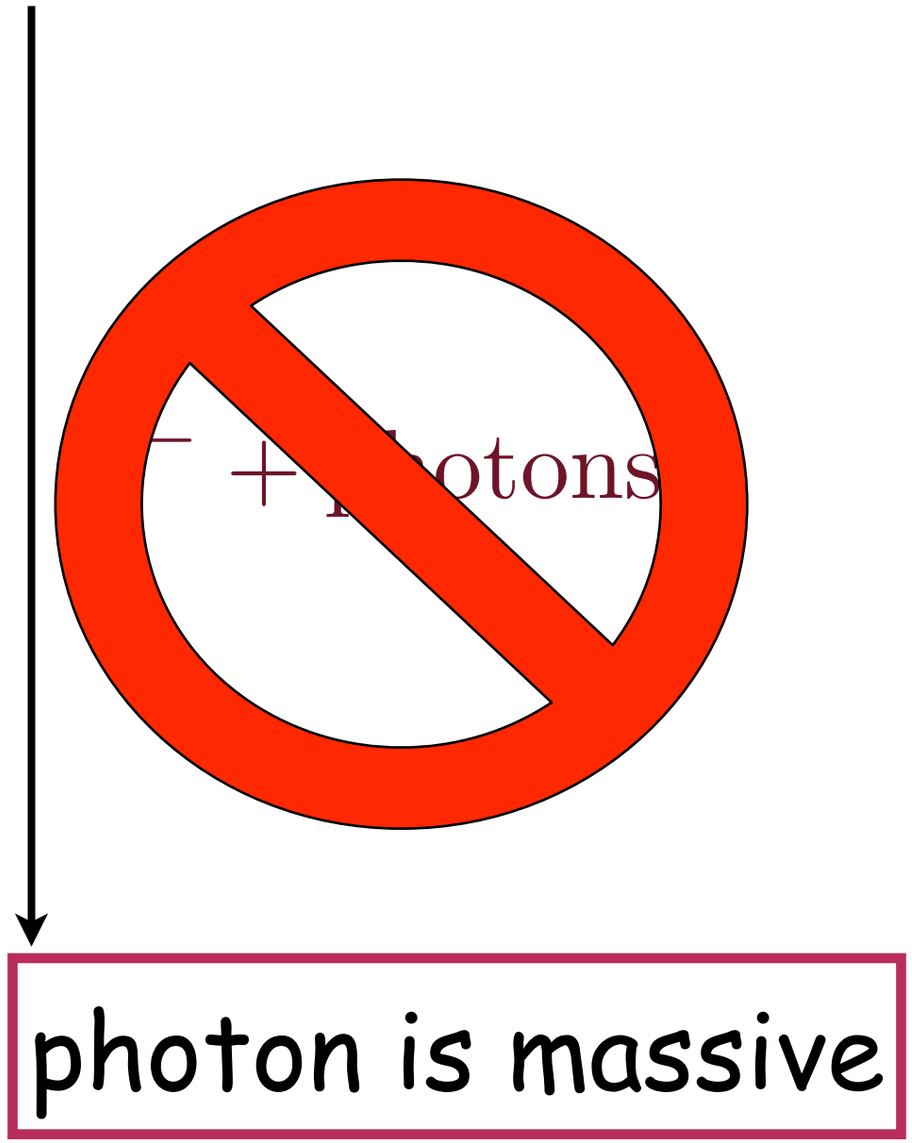


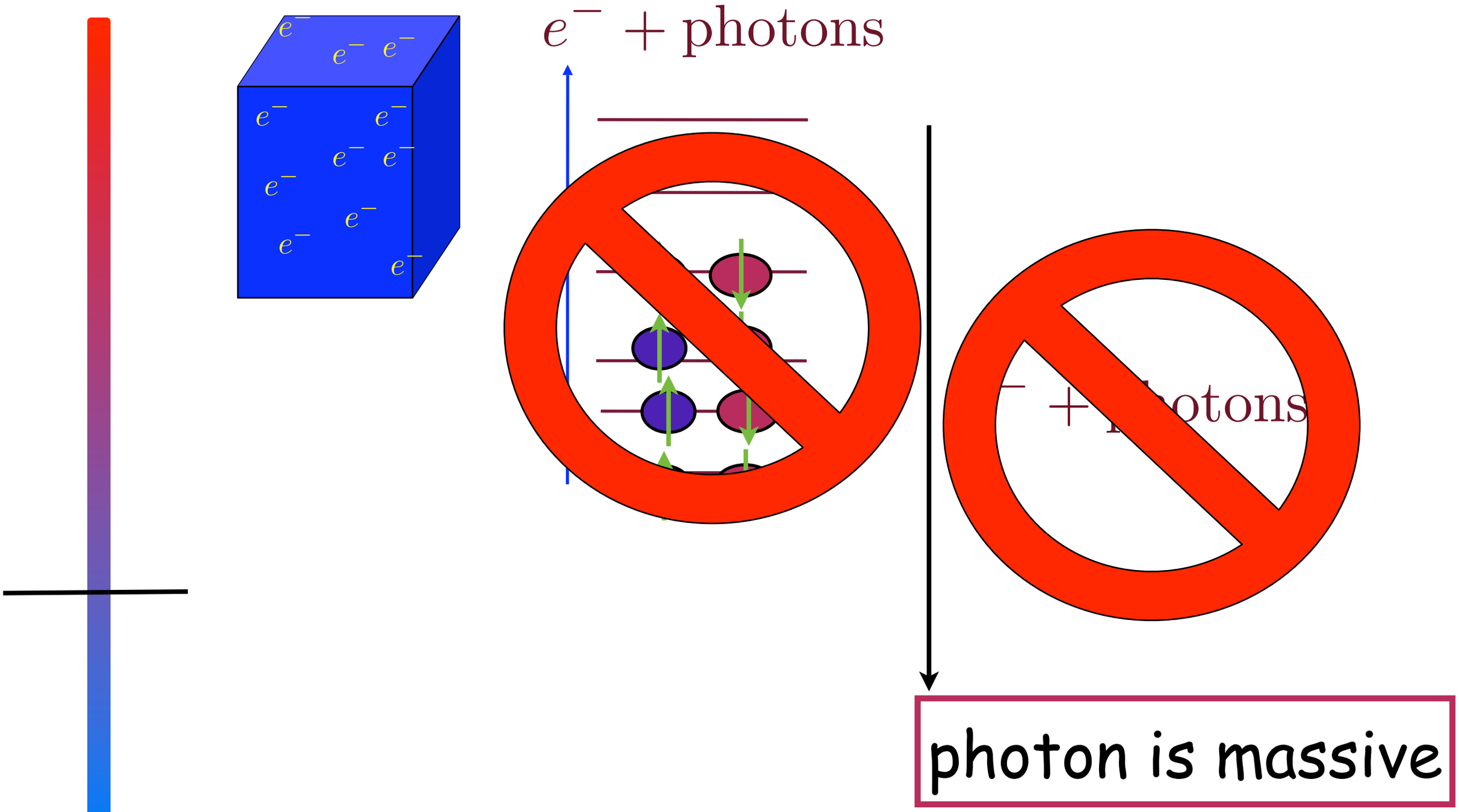
photon is massive

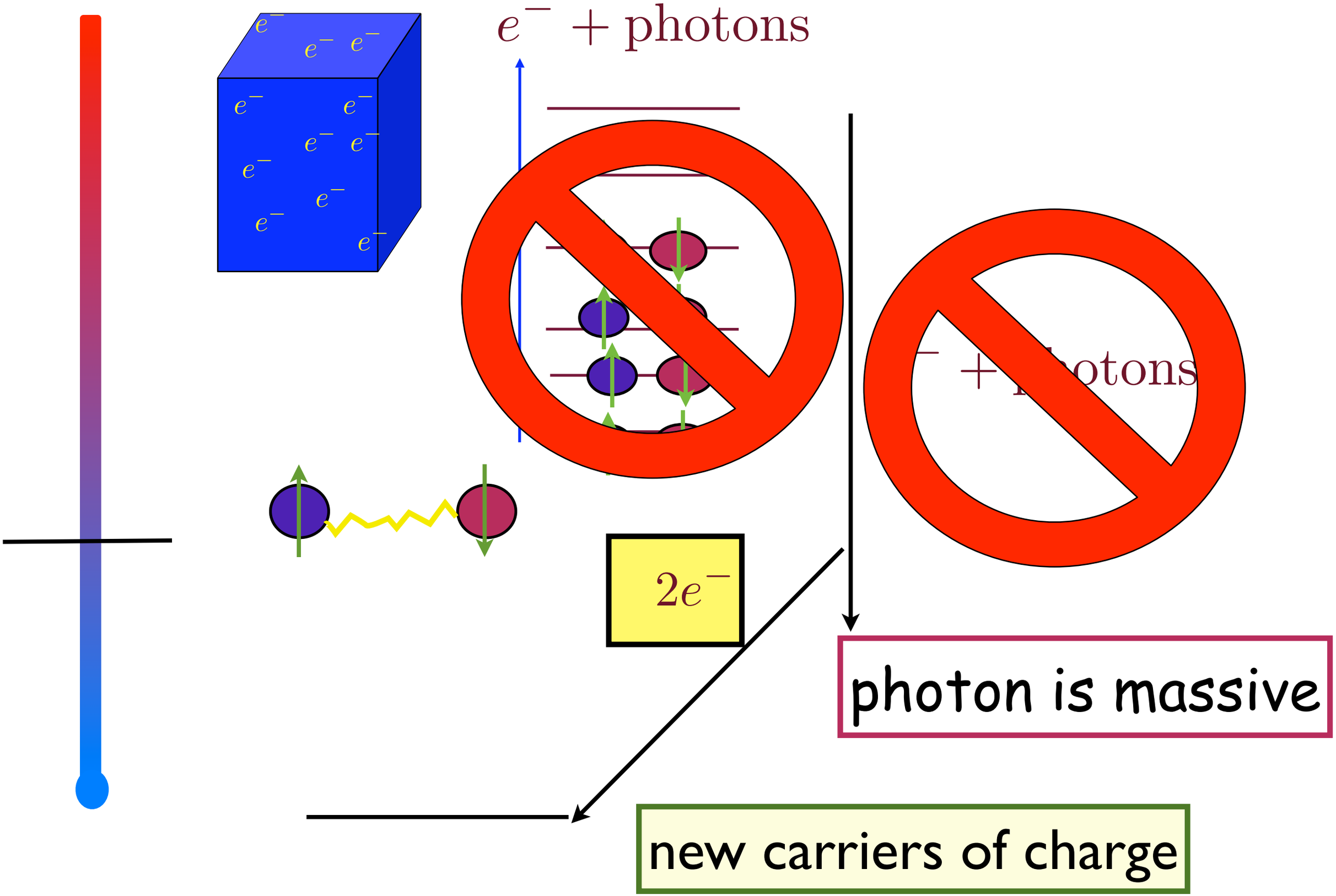


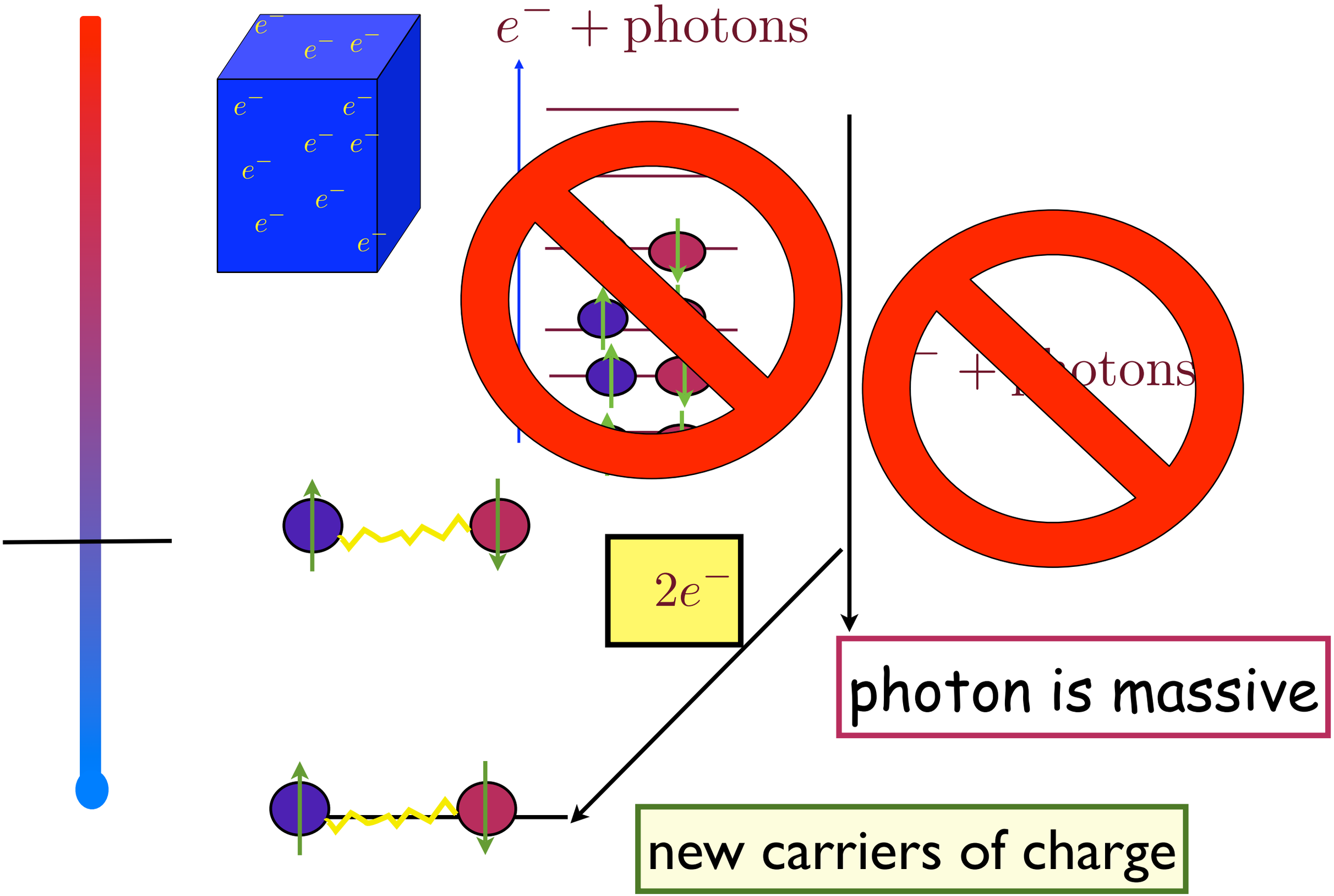

e^-

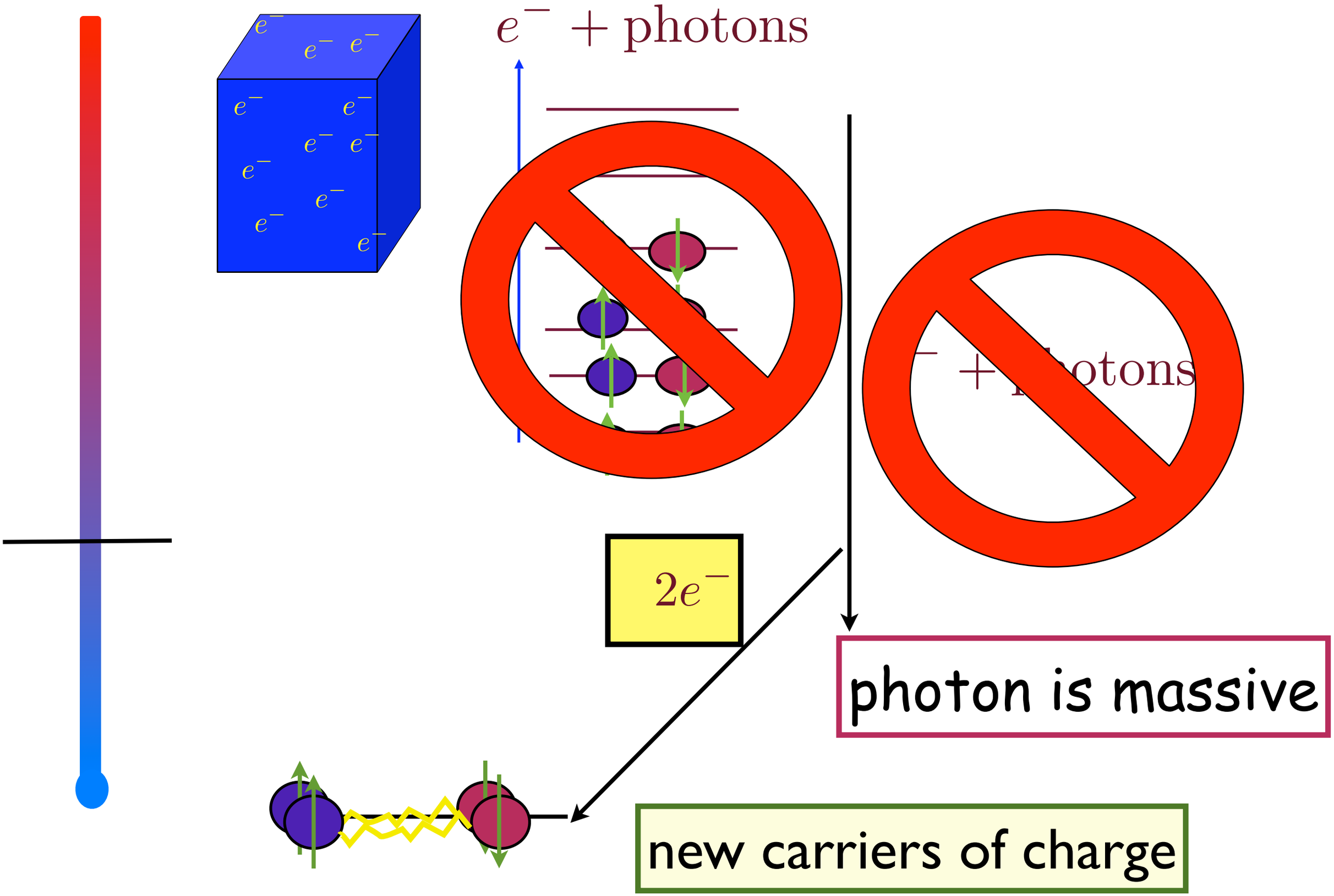

$e^- +$ photons

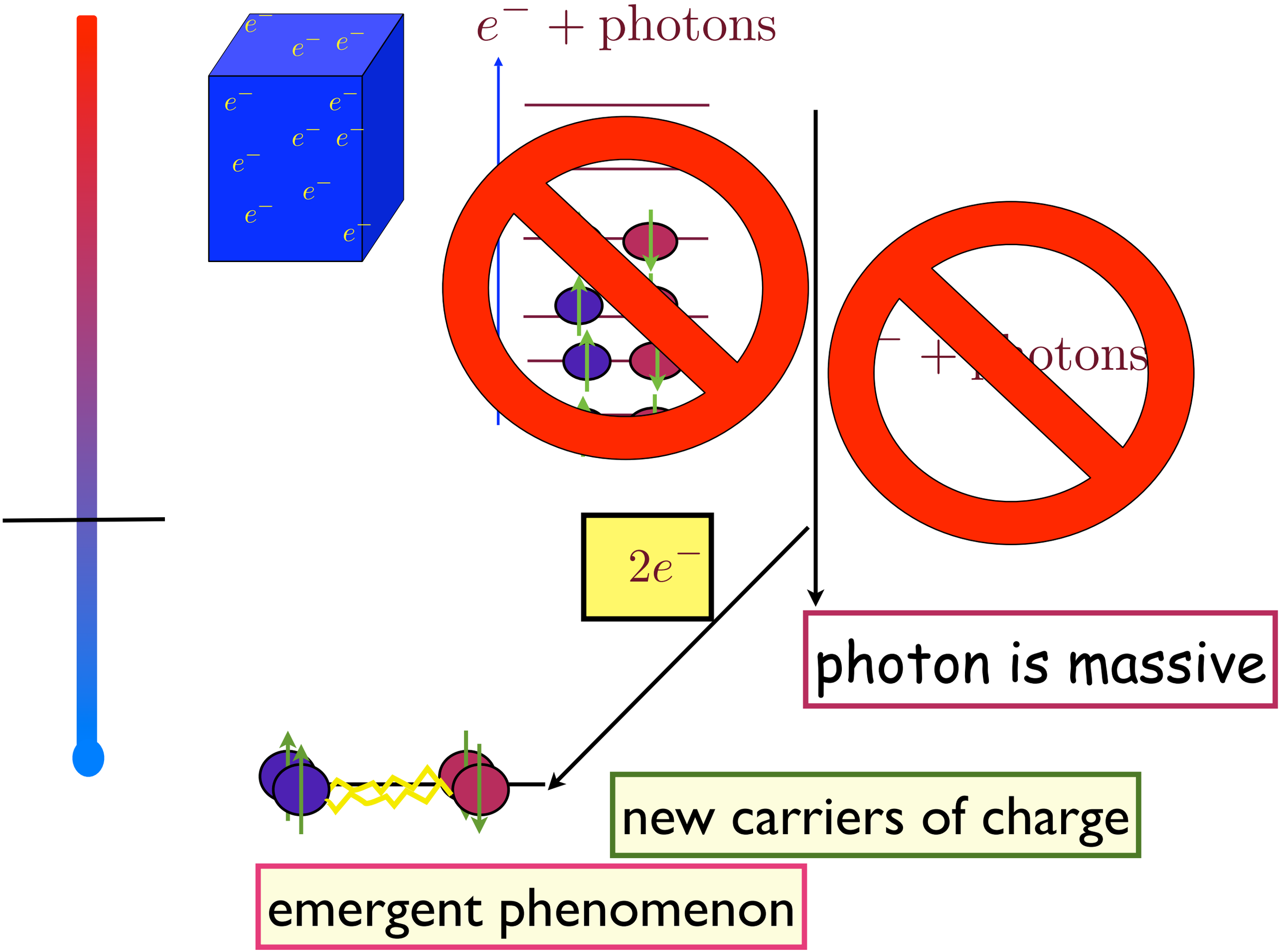

photon is massive

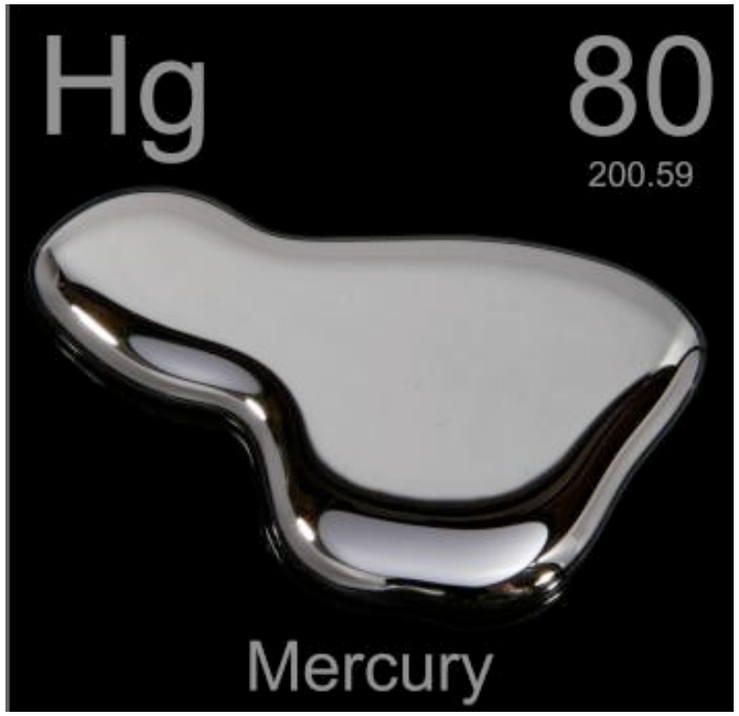

e^- + photons
e^- + photons
photon is massive

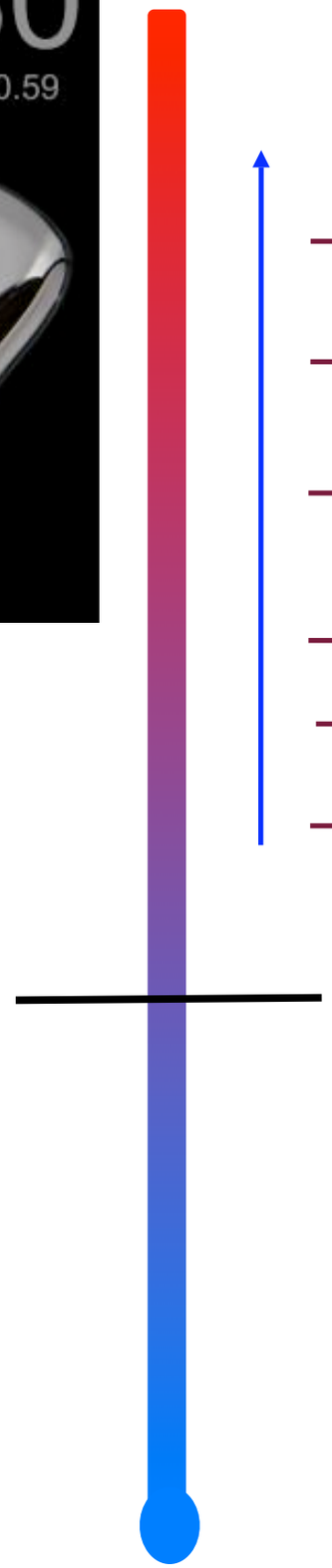

$e^- + \text{photons}$
e^-
$2e^-$
photon is massive
new carriers of charge

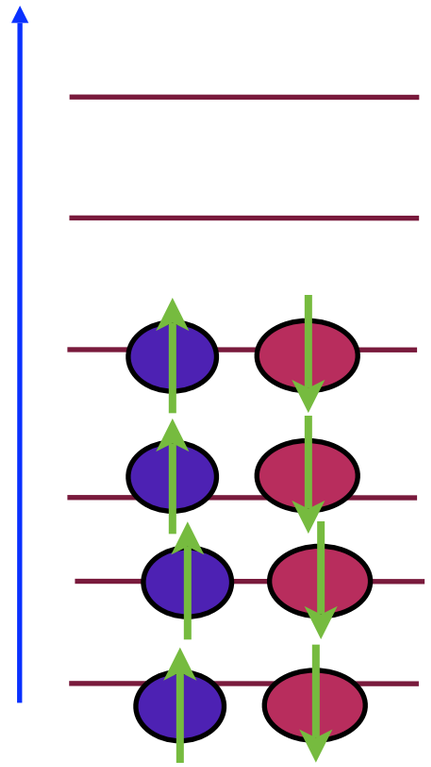

$e^- + \text{photons}$
e^-
$2e^-$
photon is massive
new carriers of charge


$e^- + \text{photons}$
$2e^-$
photon is massive
new carriers of charge

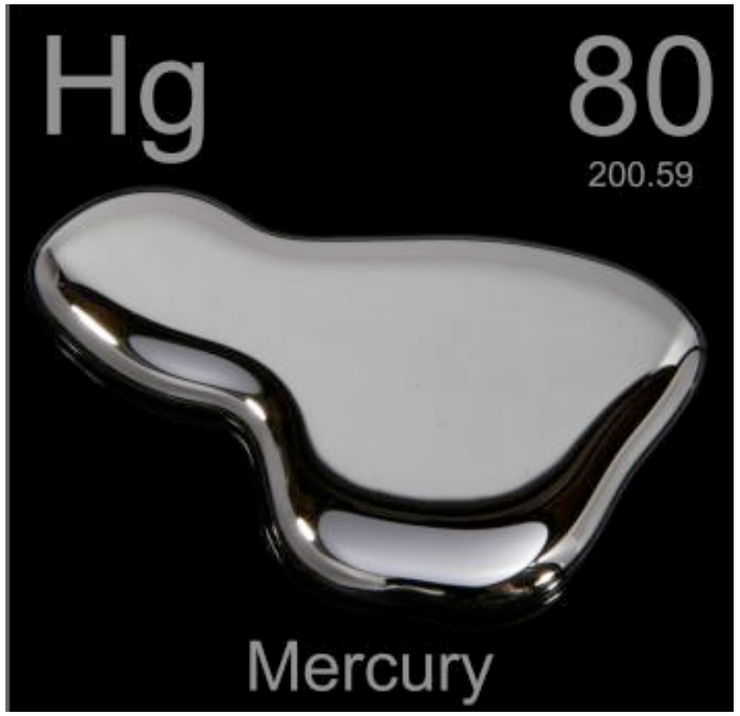

$e^- + \text{photons}$
$2e^-$
photon is massive
new carriers of charge
emergent phenomenon

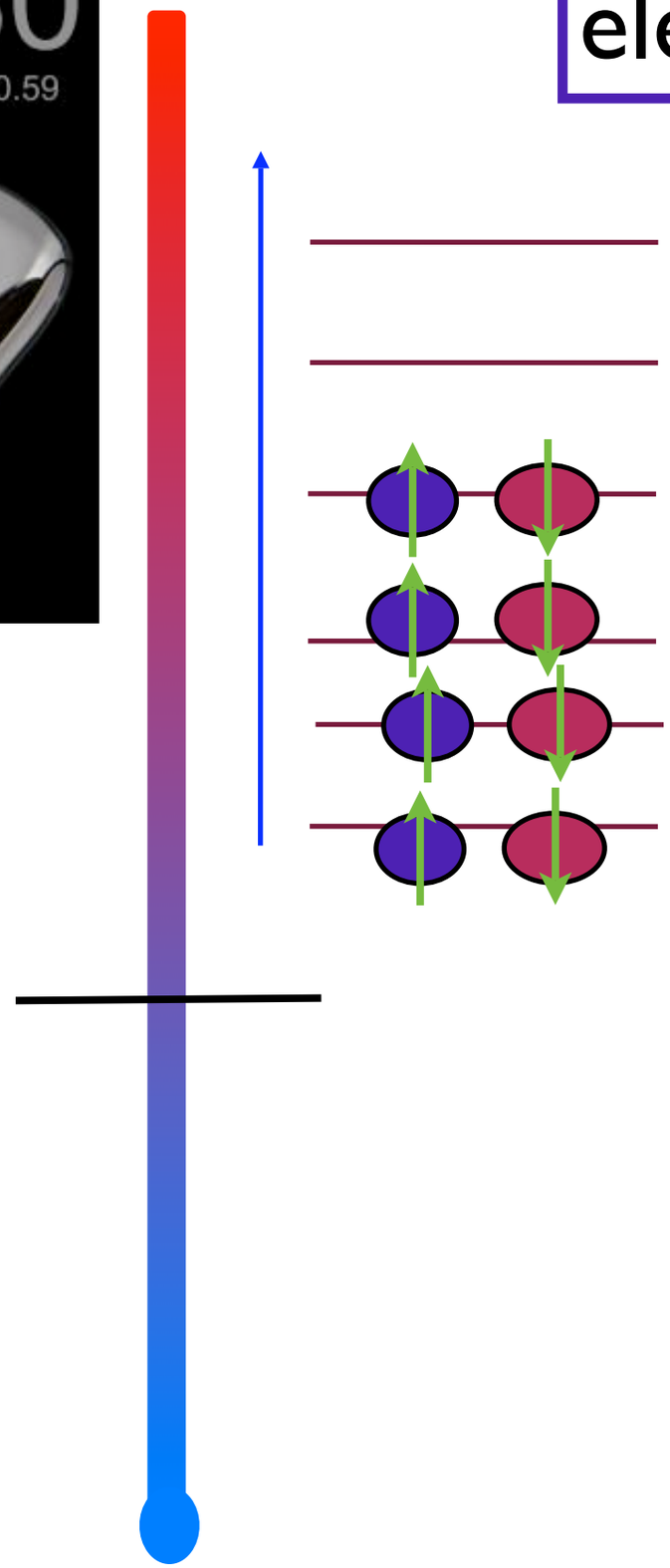




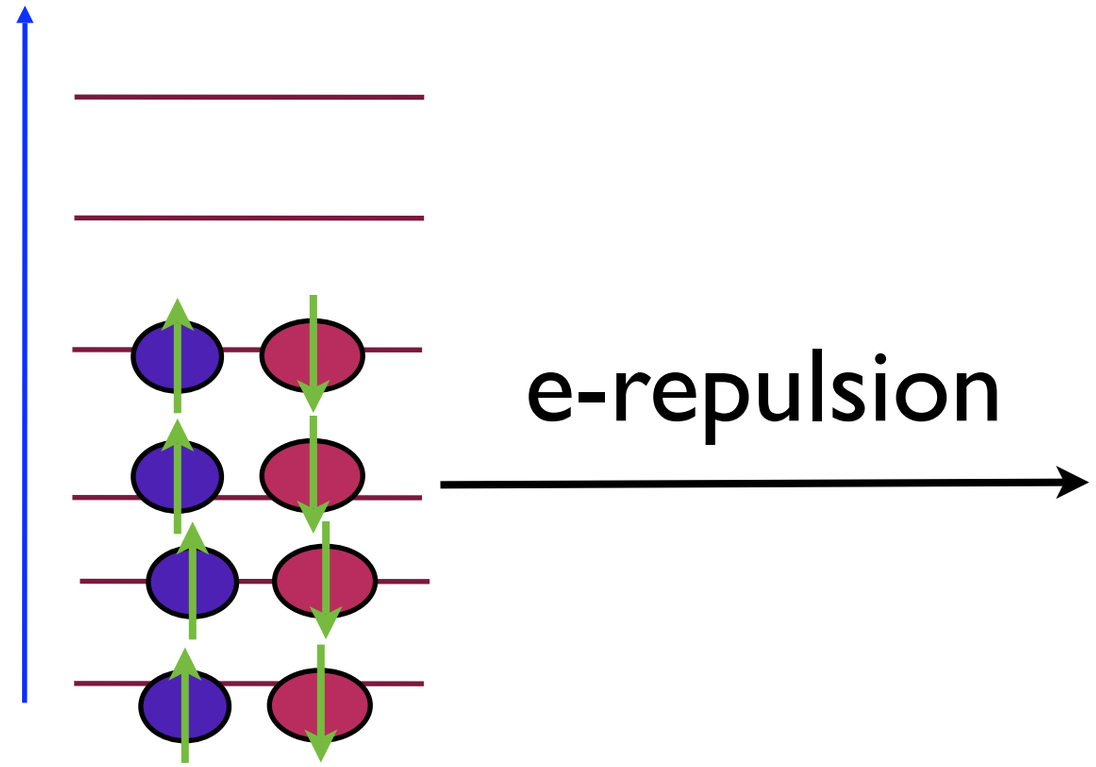


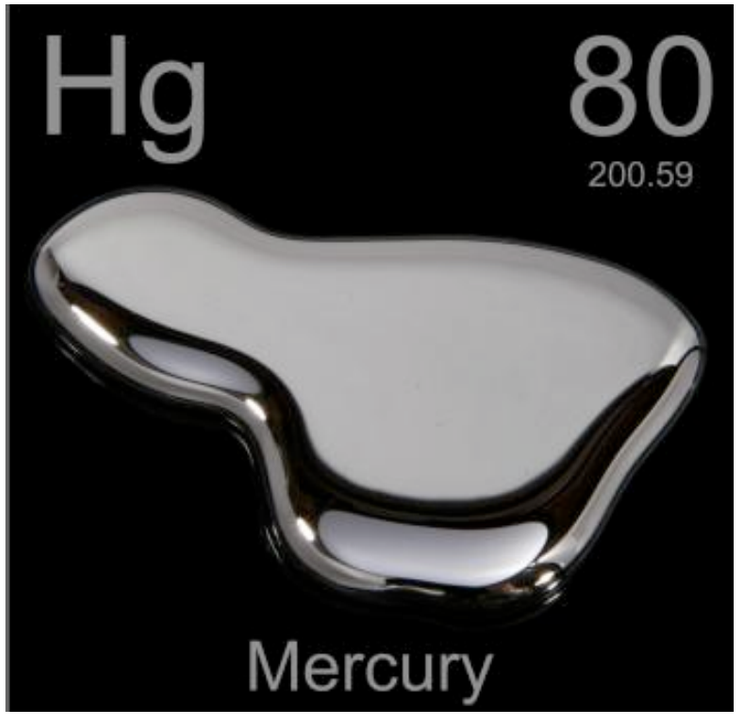
electrons are free

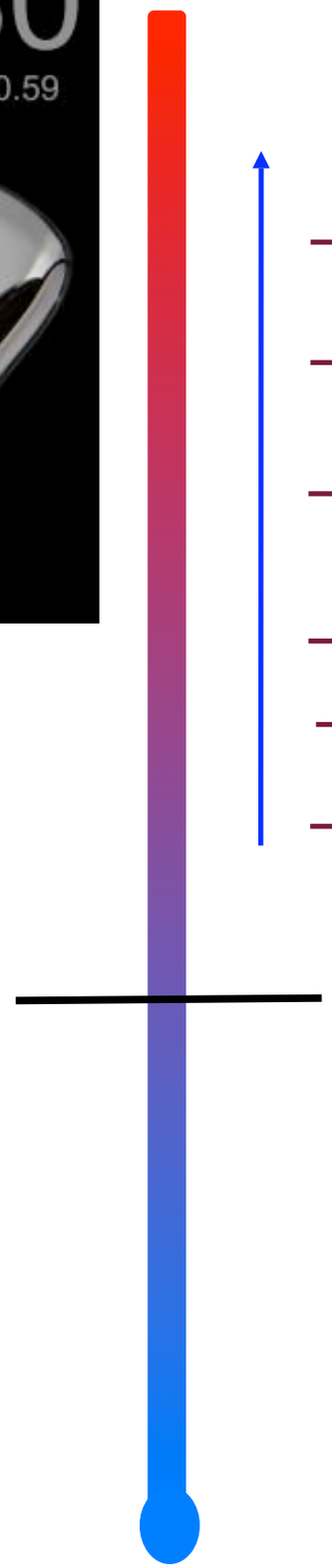




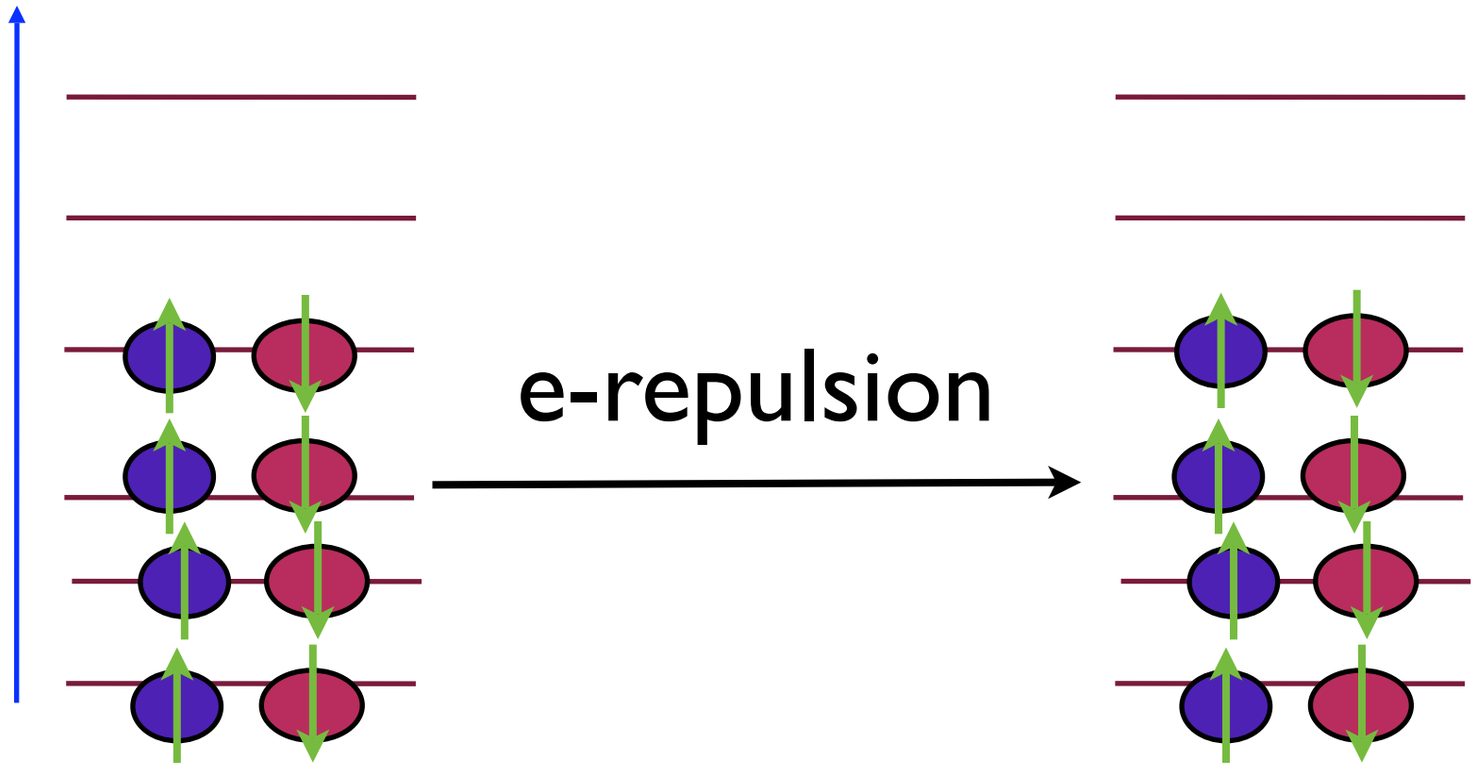
electrons are free

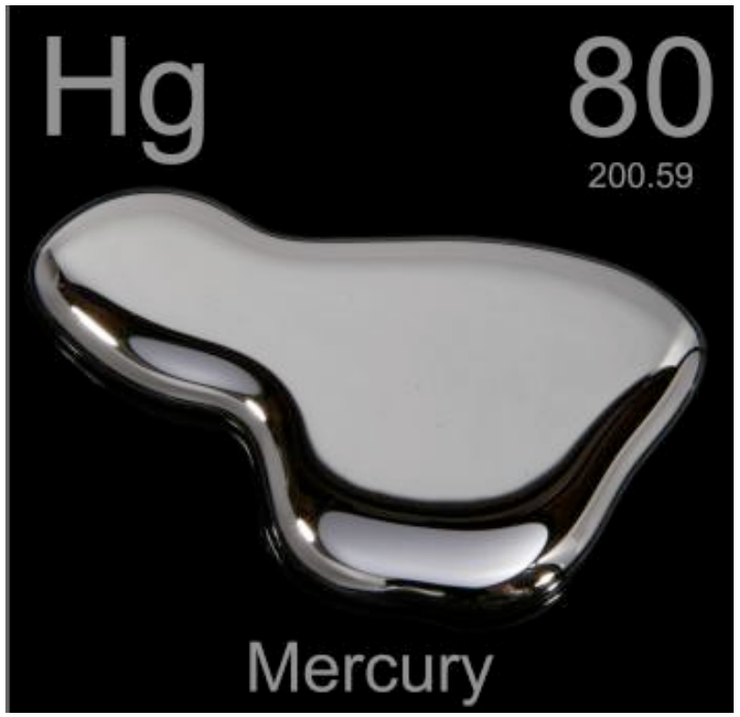


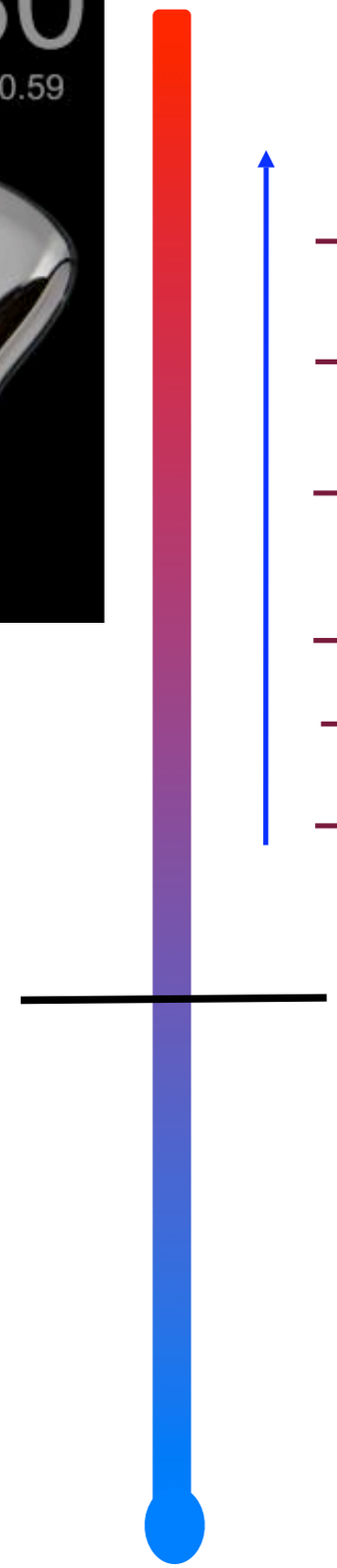




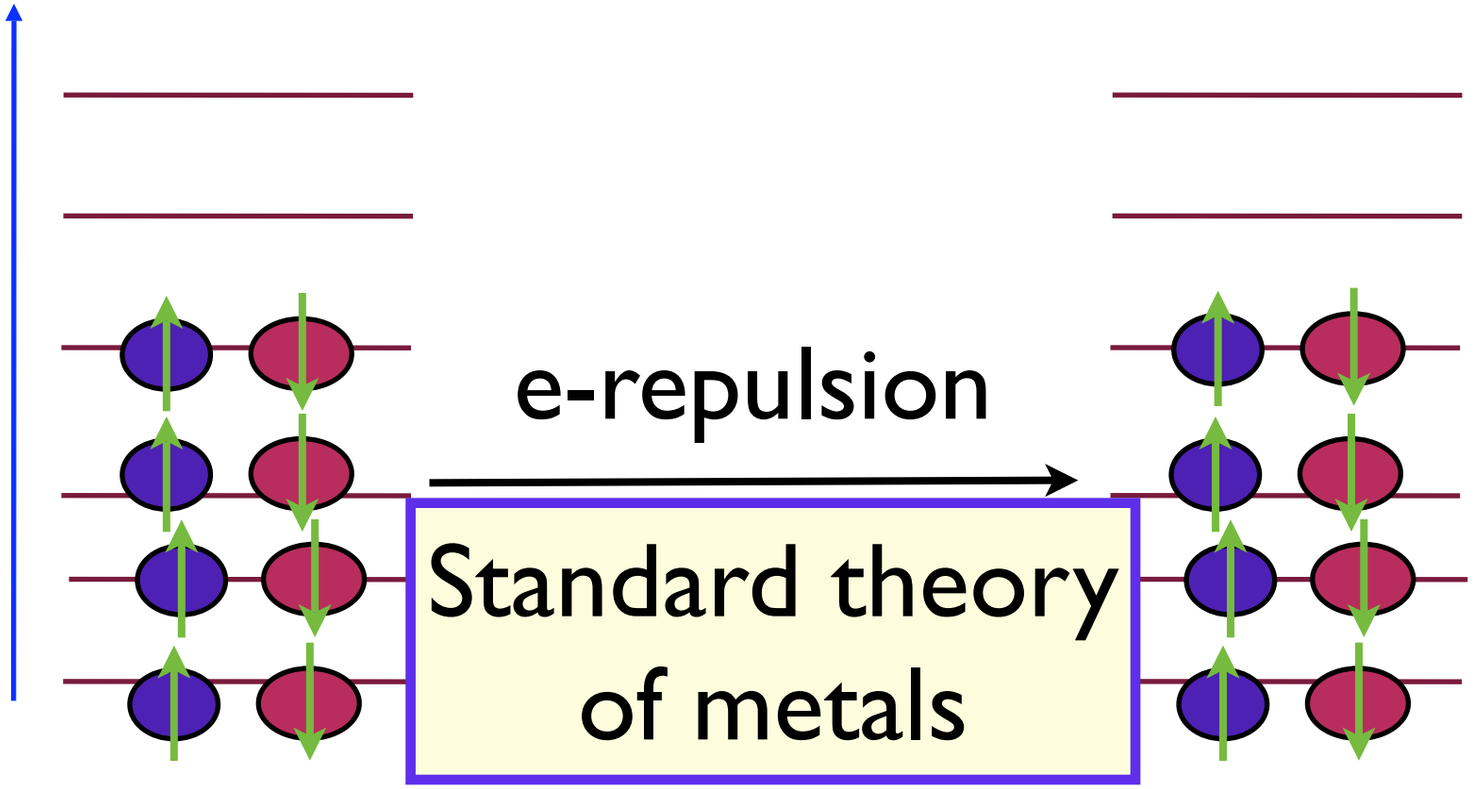
electrons are free

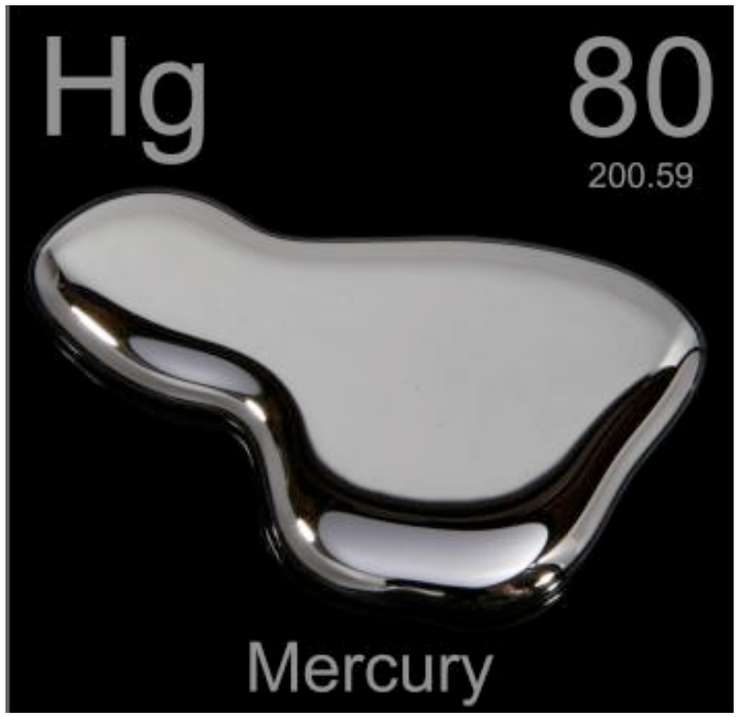


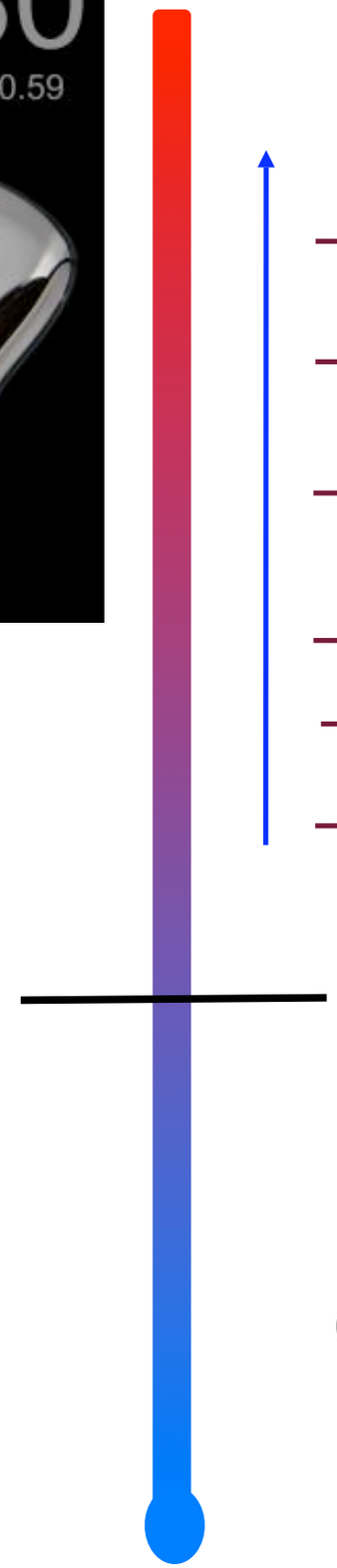




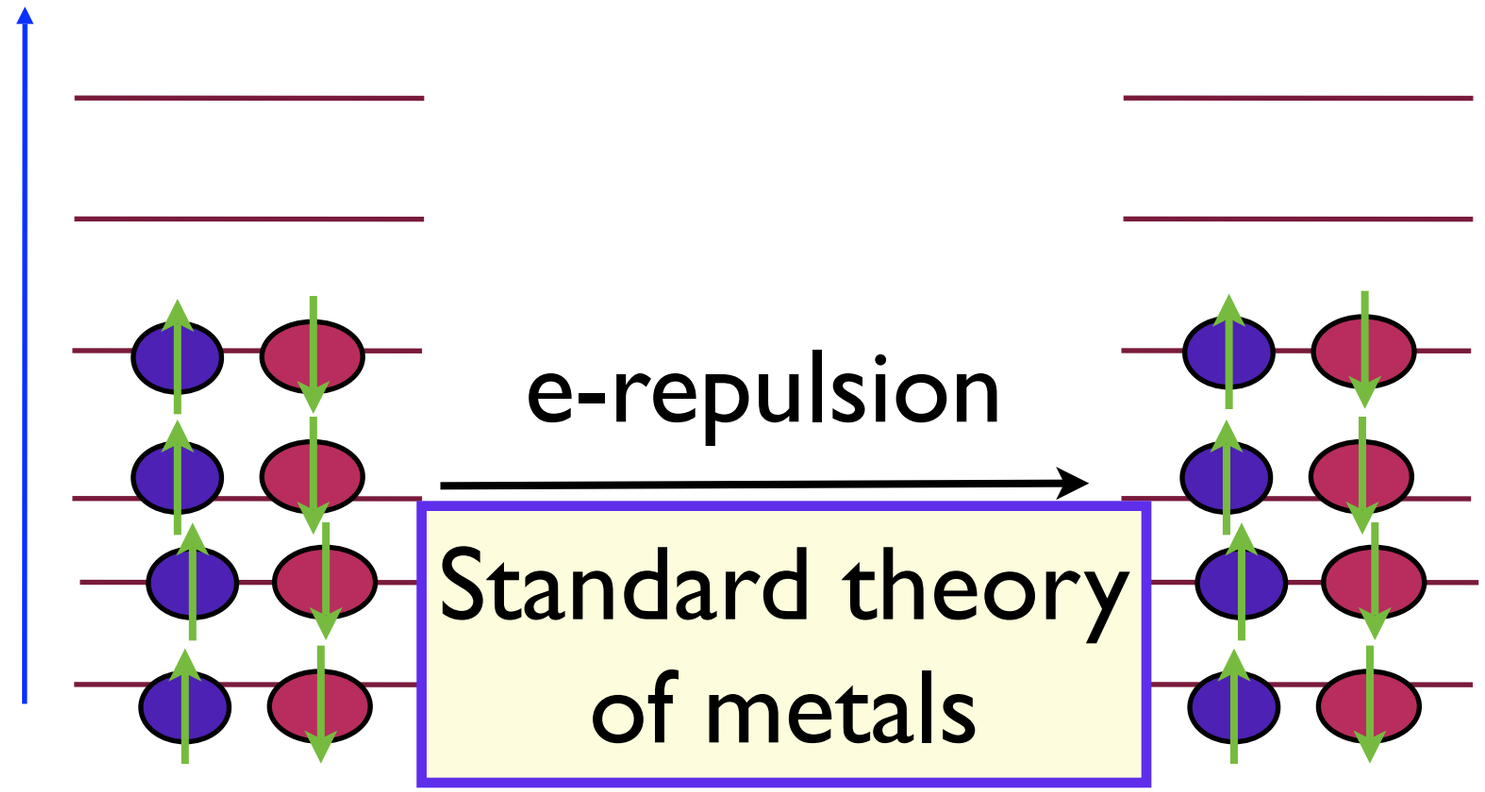
electrons are free

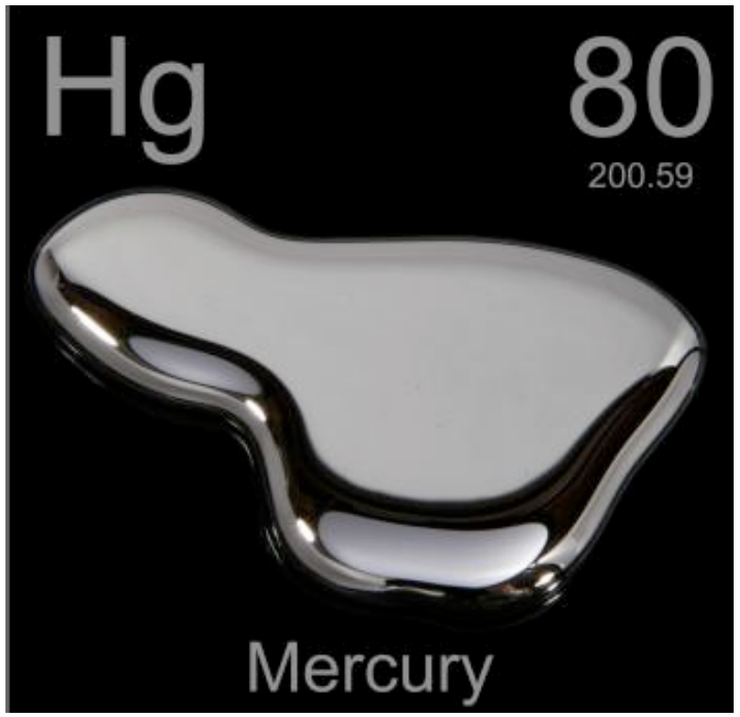




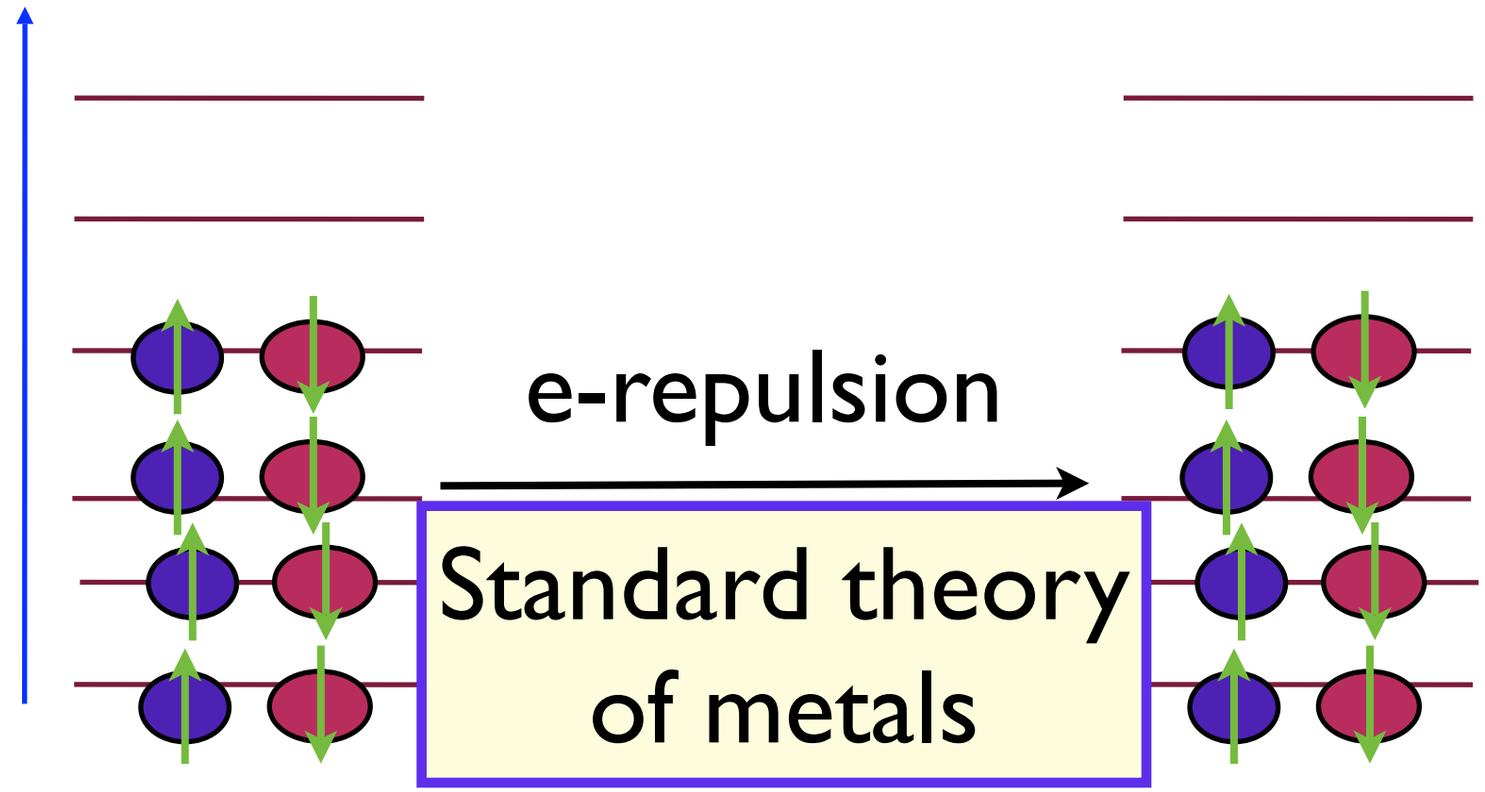


electrons are free

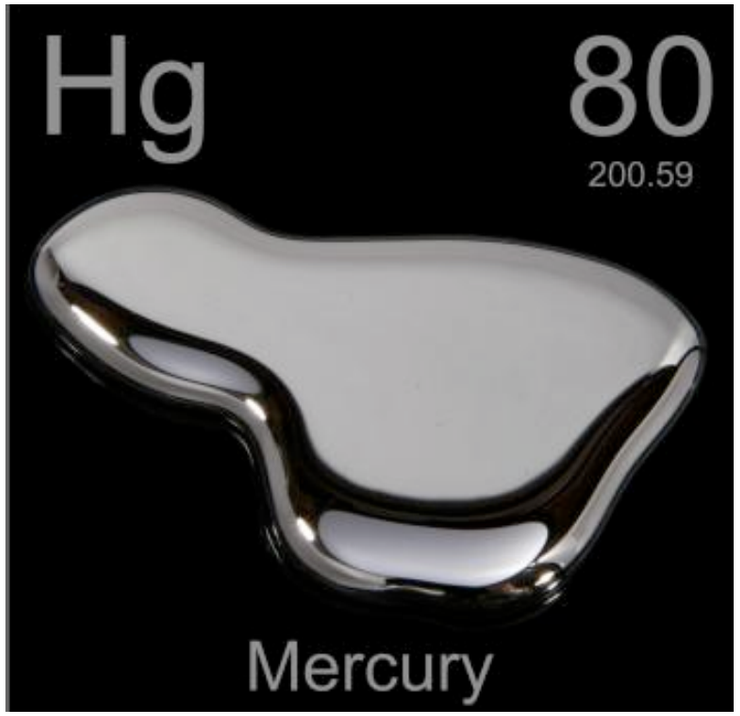




electrons are free

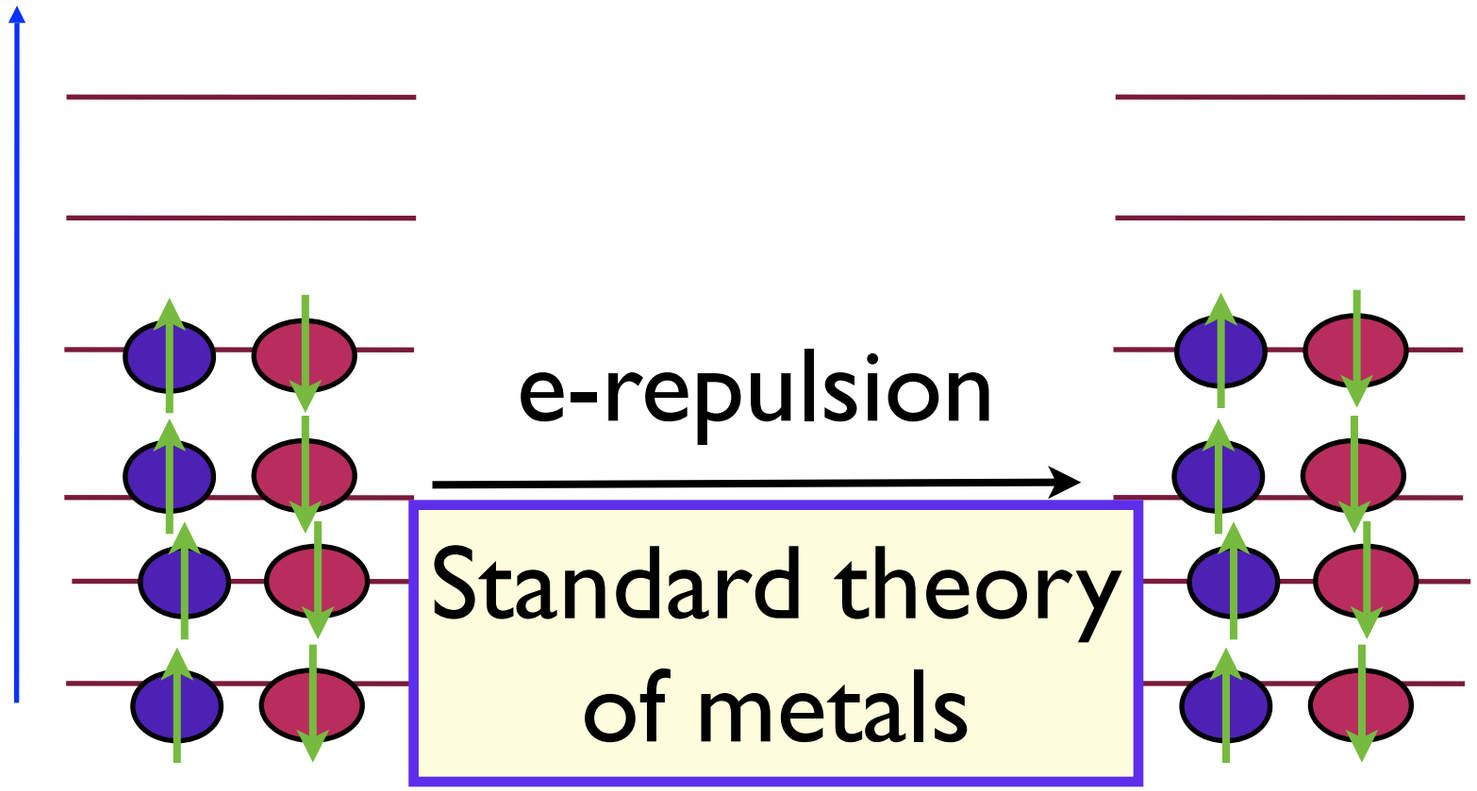


1. massive photon
2. zero resistance
3. energy to pull electrons apart (gap)



BCS theory: 1957
Nobel: 1972

electrons are free



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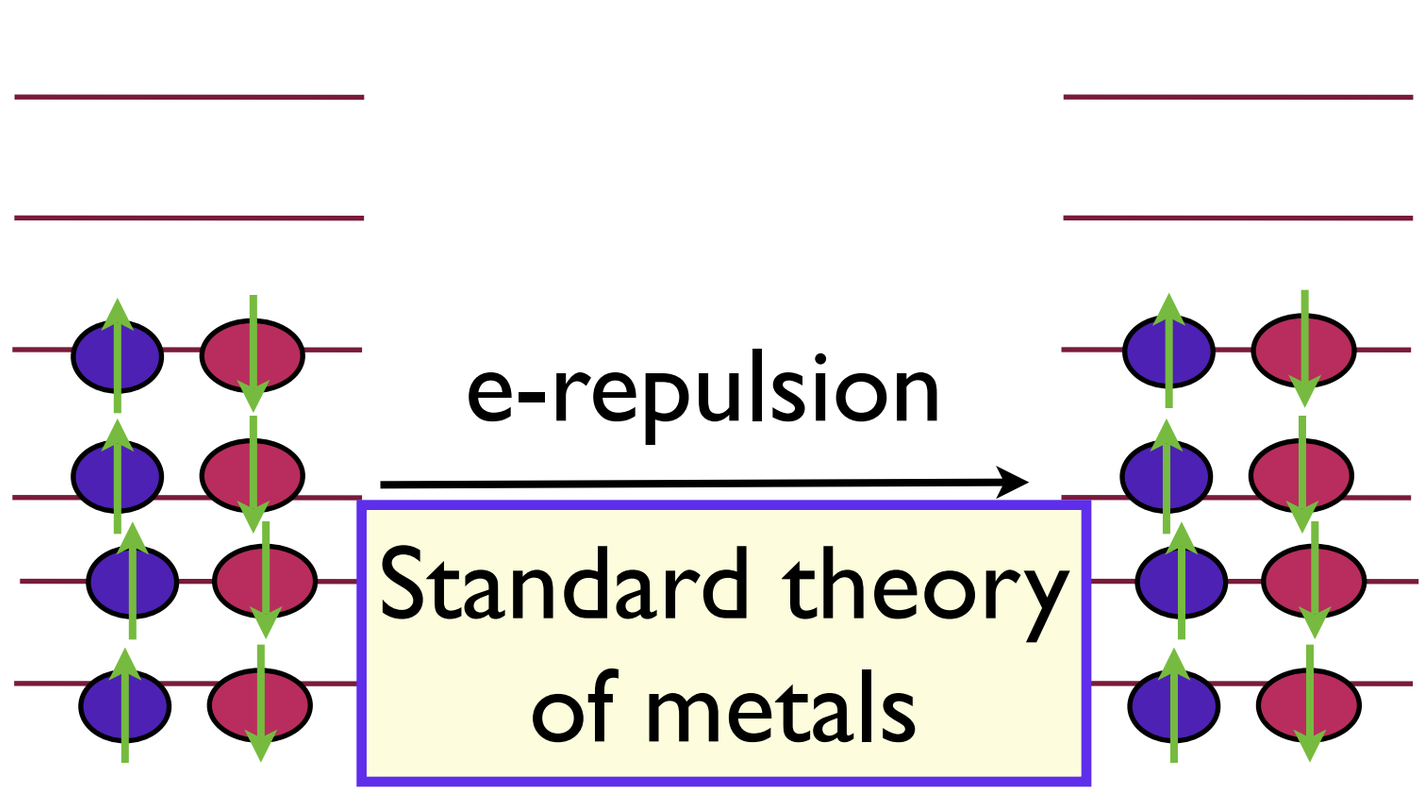

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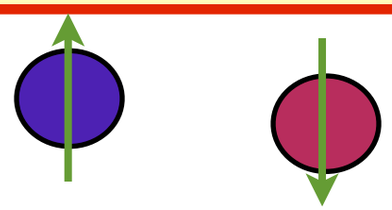
Key to BCS

they knew what to look for: weakly interacting objects

Key to BCS

free electrons

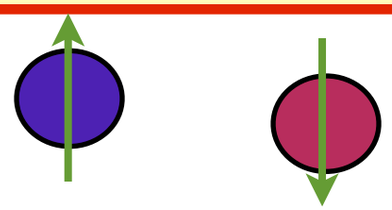


high T

they knew what to look for: weakly interacting objects

Key to BCS

free electrons



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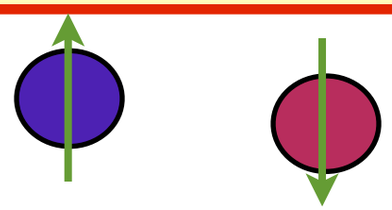
L. D. Landau
Nobel:1962

Key to BCS

free electrons



high T

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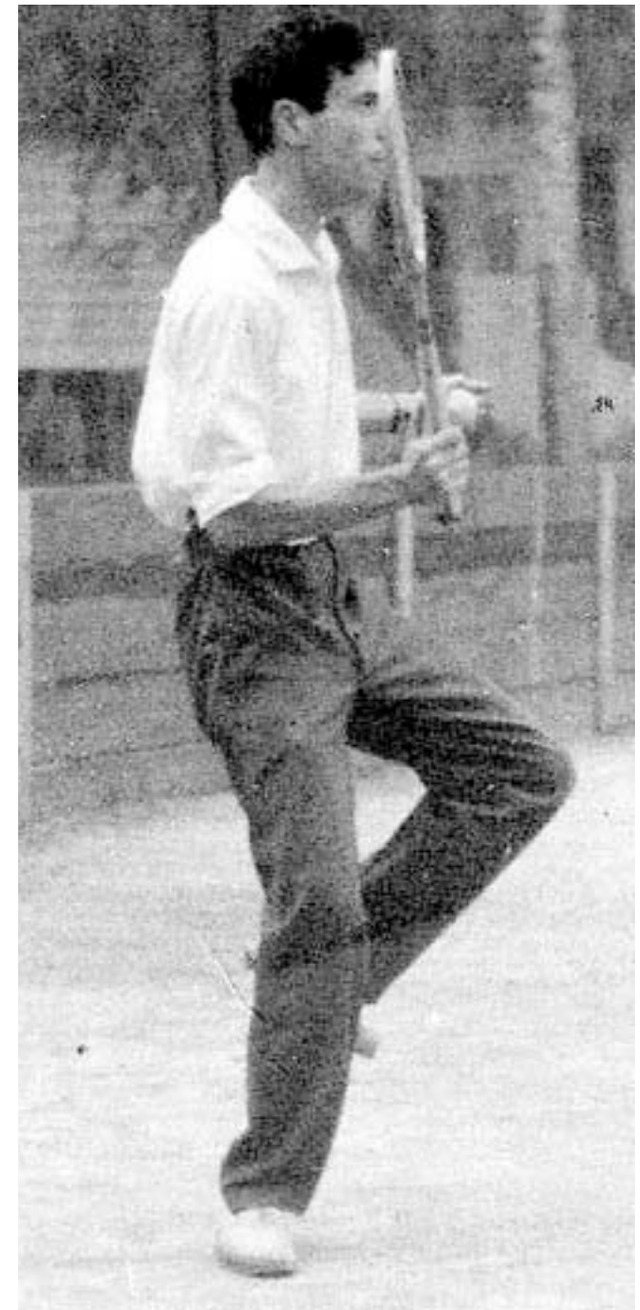
low T



L. D. Landau
Nobel:1962

New Superconductors

New Superconductors

Unusually
Good Metal

Matthias Rules for Superconductivity

Matthias, Bernd T.

Scanned at the American
Institute of Physics

Matthias Rules for Superconductivity

1.) symmetric lattices

2.) avoid oxygen

3.) avoid magnetism

4.) avoid insulators

Matthias Rules for Superconductivity

1.) symmetric lattices

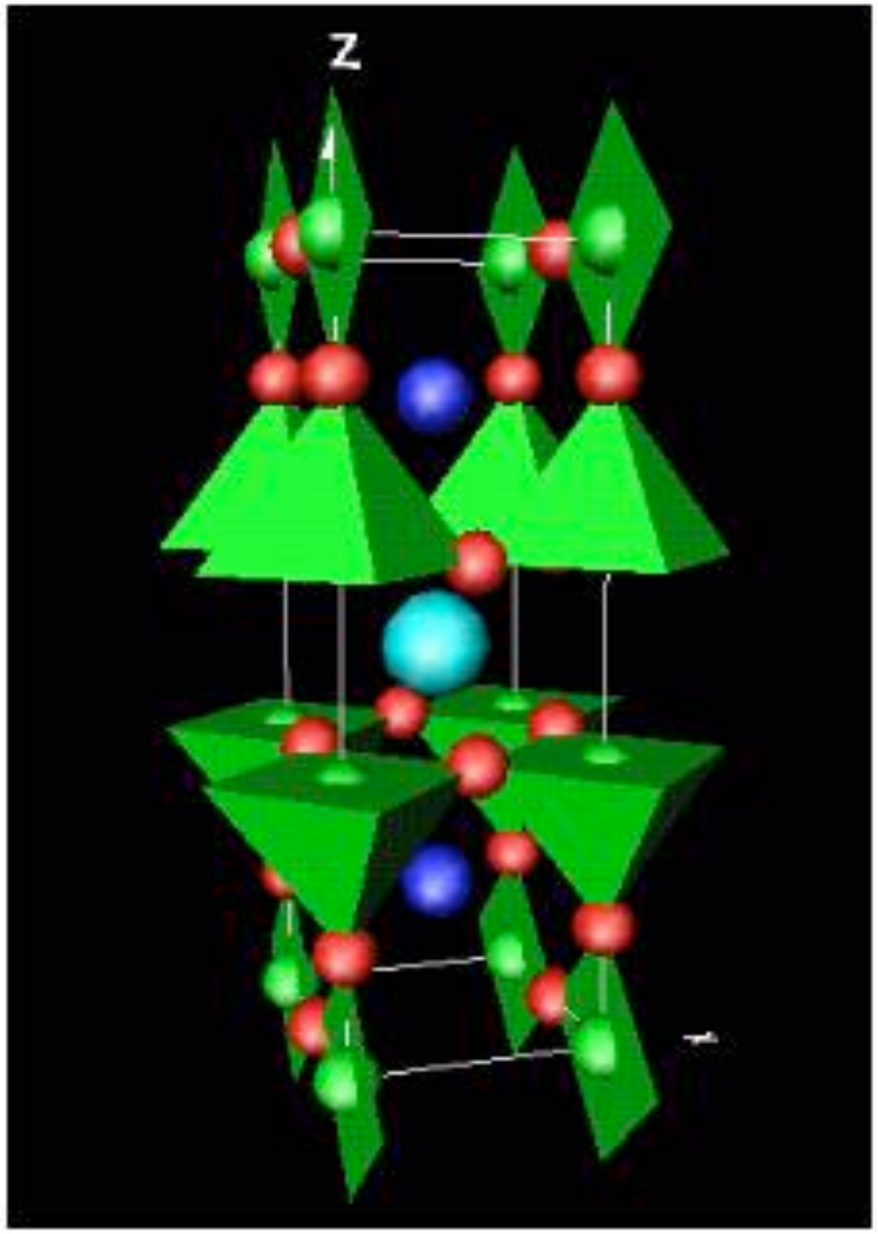
2.) avoid oxygen

3.) avoid magnetism

4.) avoid insulators

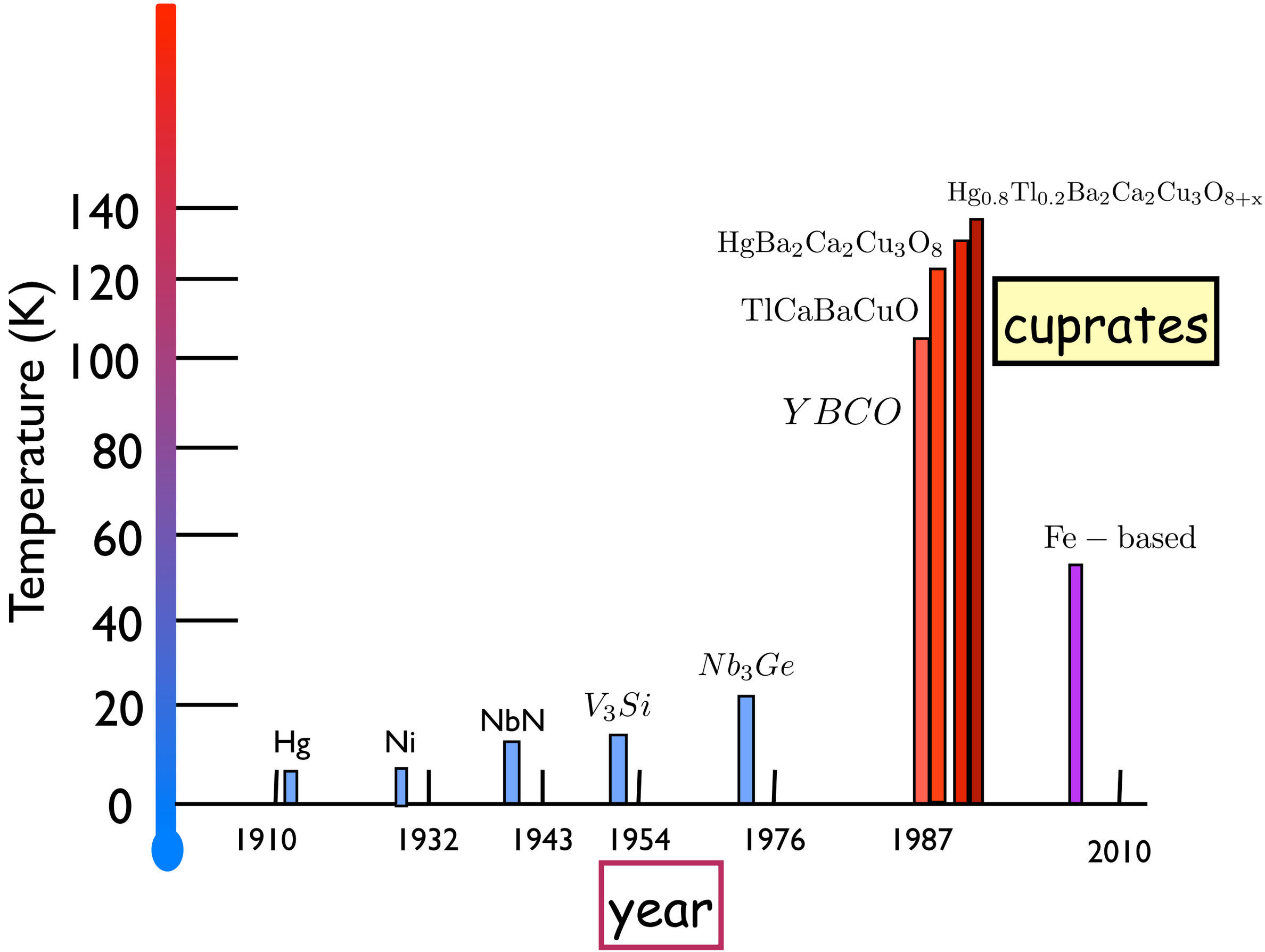
5.) don't talk to theorists!!

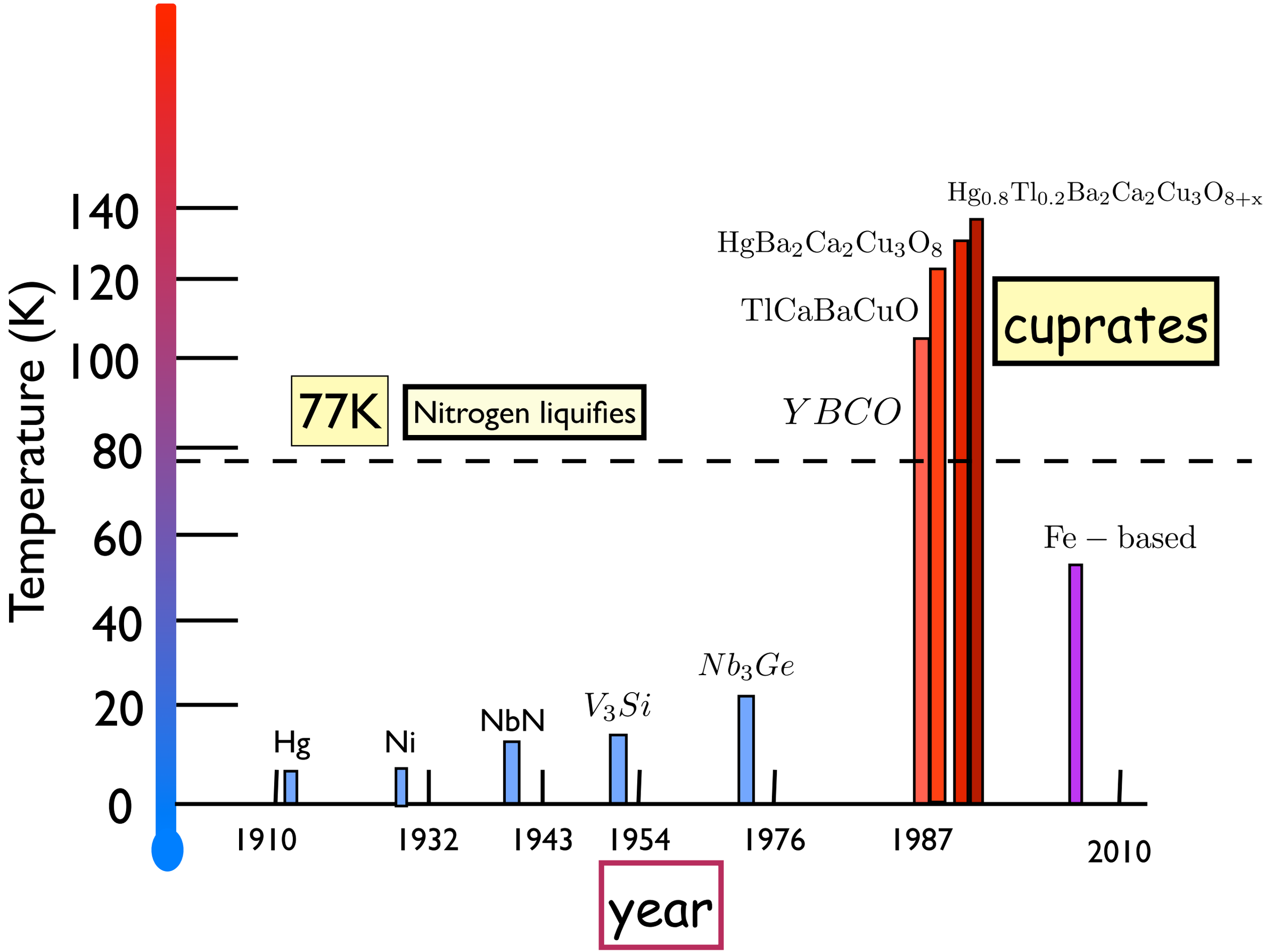
orthorhombic
not cubic



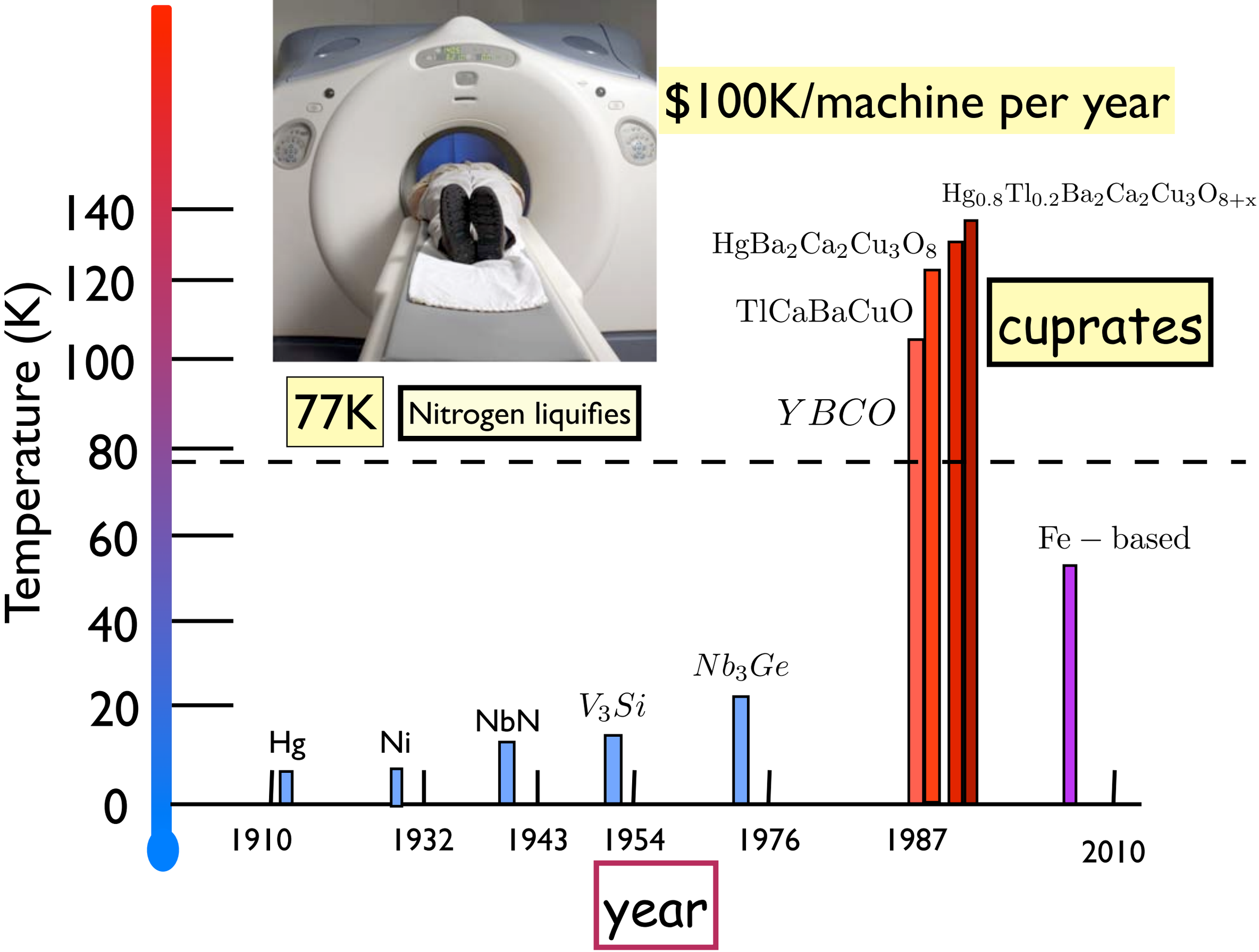
$YBa_2Cu_3O_7$
Cuprate Superconductors

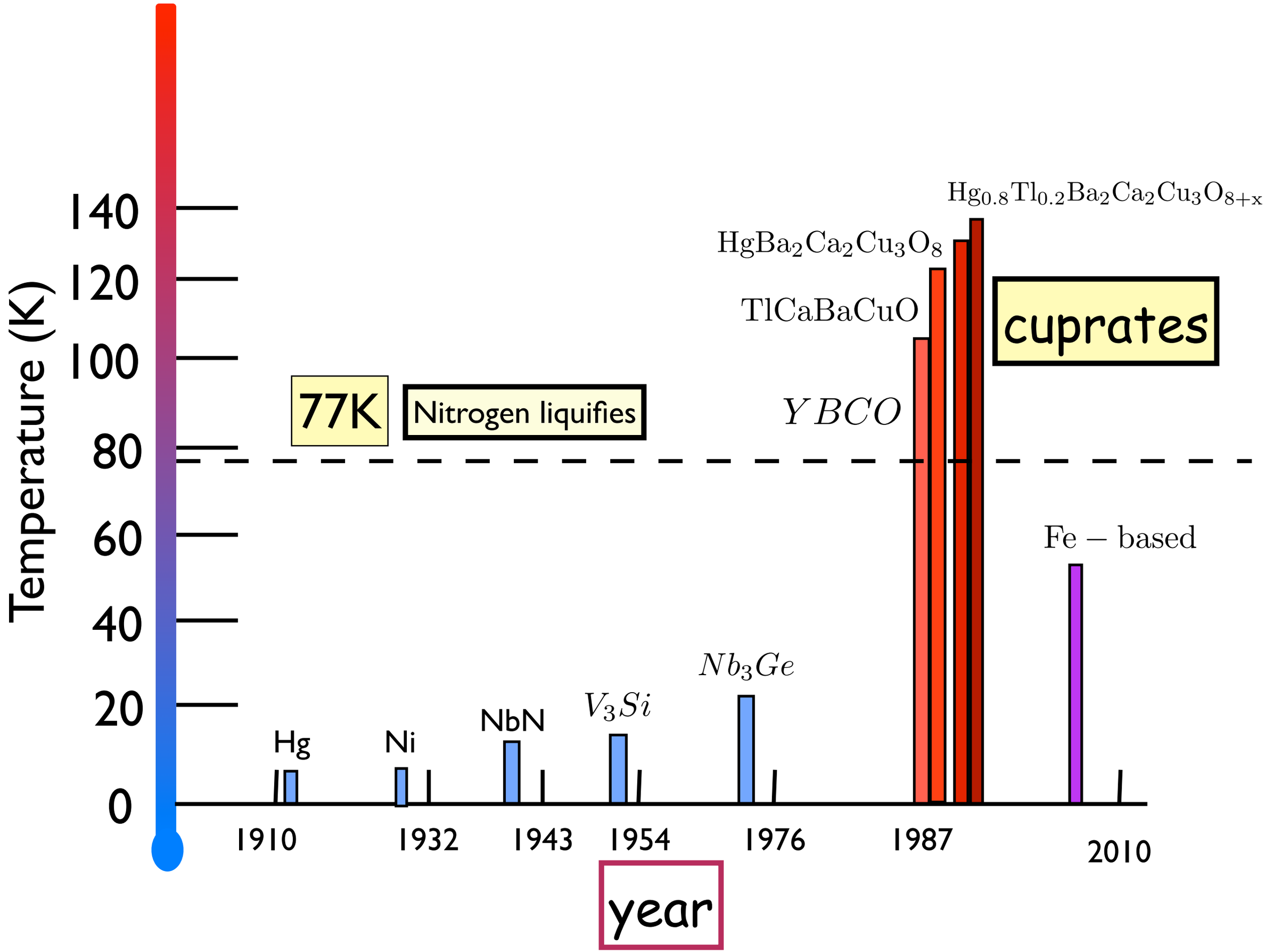
ceramics


Temperature (K)
140
120
100
80
60
40
20
0
Hg
Ni
NbN
V_3Si
Nb_3Ge
$HgBa_2Ca_2Cu_3O_8$
TlCaBaCuO
$YBCO$
$Hg_{0.8}Tl_{0.2}Ba_2Ca_2Cu_3O_{8+x}$
cuprates
Fe − based
1910
1932
1943
1954
1976
1987
2010
year


Temperature (K)
140
120
100
80
60
40
20
0
77K
Nitrogen liquifies
Hg
Ni
NbN
V_3Si
Nb_3Ge
$YBCO$
$TlCaBaCuO$
$HgBa_2Ca_2Cu_3O_8$
$Hg_{0.8}Tl_{0.2}Ba_2Ca_2Cu_3O_{8+x}$
cuprates
$Fe-based$
1910
1932
1943
1954
1976
1987
2010
year

$100K/machine per year

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1910
1932
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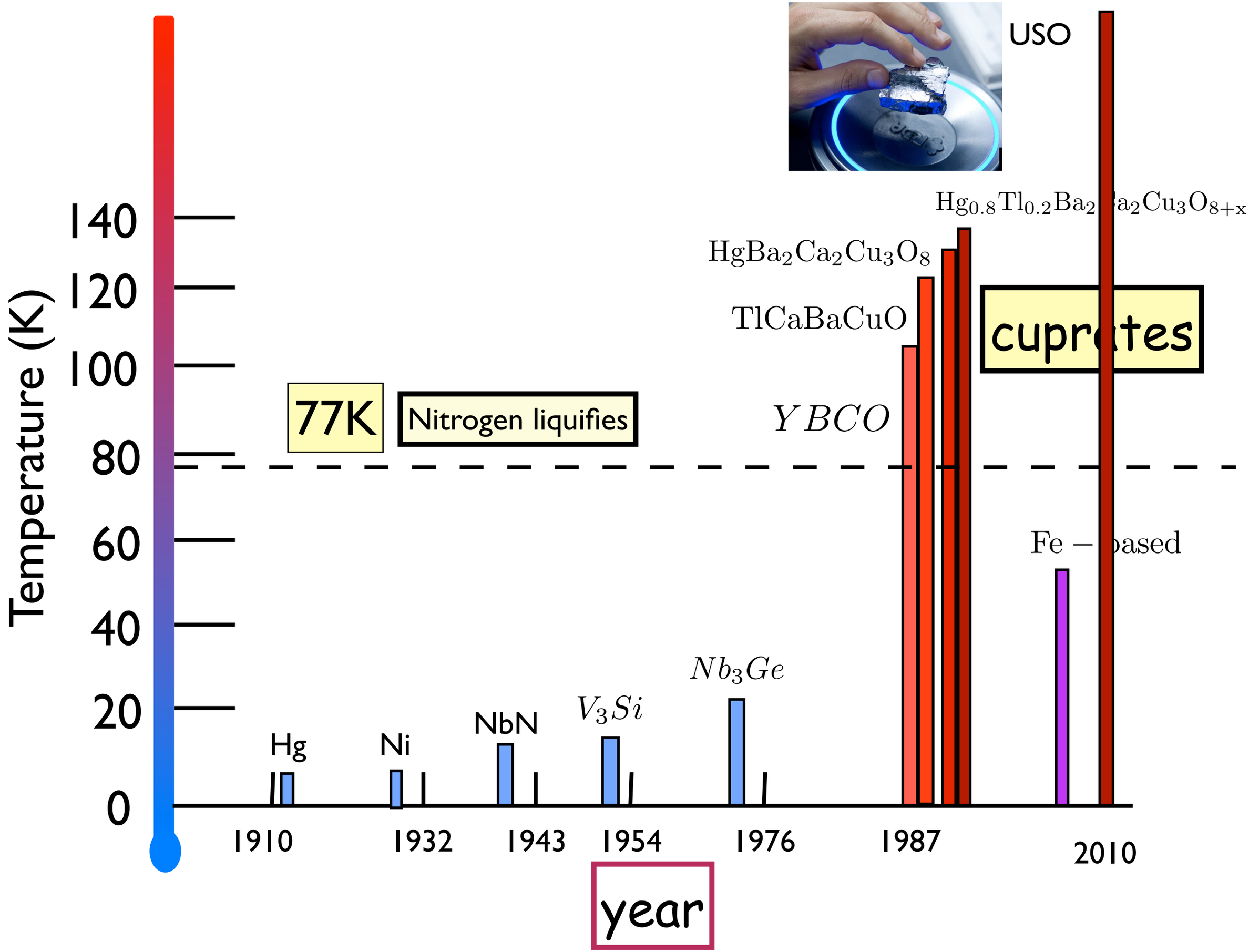
1976
1987
2010
year


USO
$Hg_{0.8}Tl_{0.2}Ba_2$ $a_2Cu_3O_{8+x}$
$HgBa_2Ca_2Cu_3O_8$
TlCaBaCuO
cuprates
$YBCO$
77K
Nitrogen liquifies
Fe − based
Nb_3Ge
V_3Si
NbN
Hg
Ni
Temperature (K)
140
120
100
80
60
40
20
0
1910
1932
1943
1954
1976
1987
2010
year

What is left of Matthias' Rules?

1.) cubic structures

2.) avoid oxygen

3.) avoid magnetism

4.) avoid insulators

What is left of Matthias' Rules?

2.) avoid oxygen

3.) avoid magnetism

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What is left of Matthias' Rules?

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What is left of Matthias' Rules?

4.) avoid insulators

What is left of Matthias' Rules?

New Problem: Mottness

Sir Neville Mott
Nobel Prize, 1977

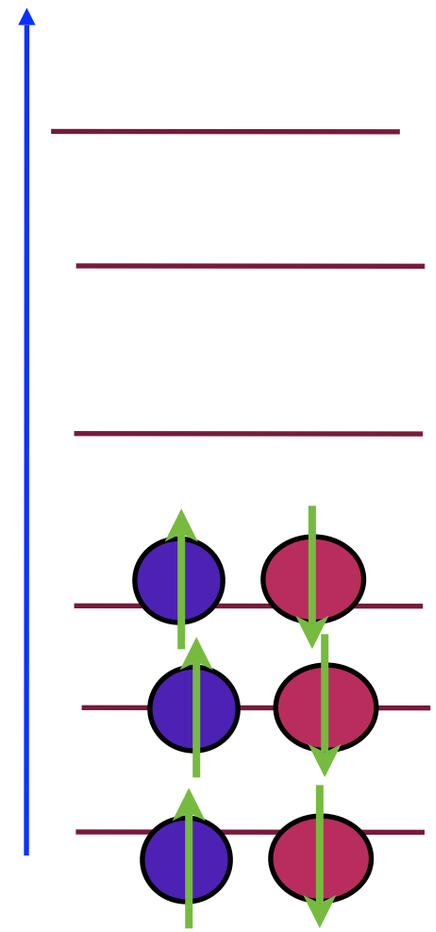
Mott
Insulators

What is a Mott Insulator?

NiO insulates
?

What is a Mott Insulator?

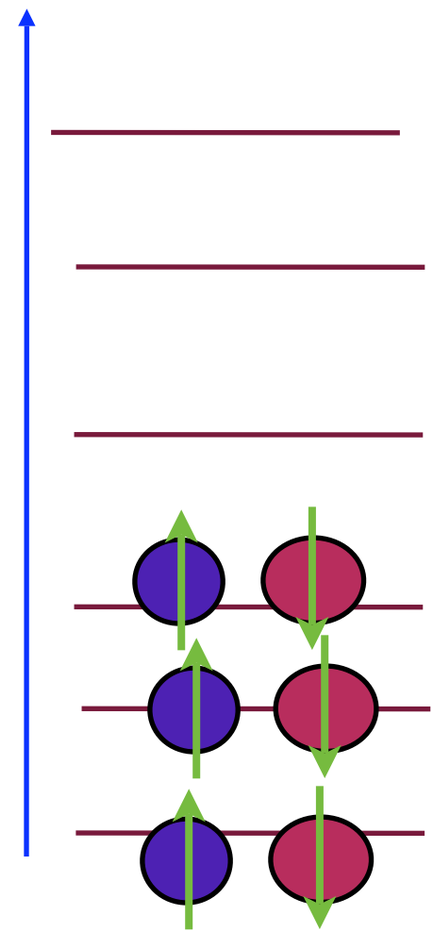
NiO insulates
?



EMPTY STATES=
METAL

What is a Mott Insulator?

NiO insulates
?

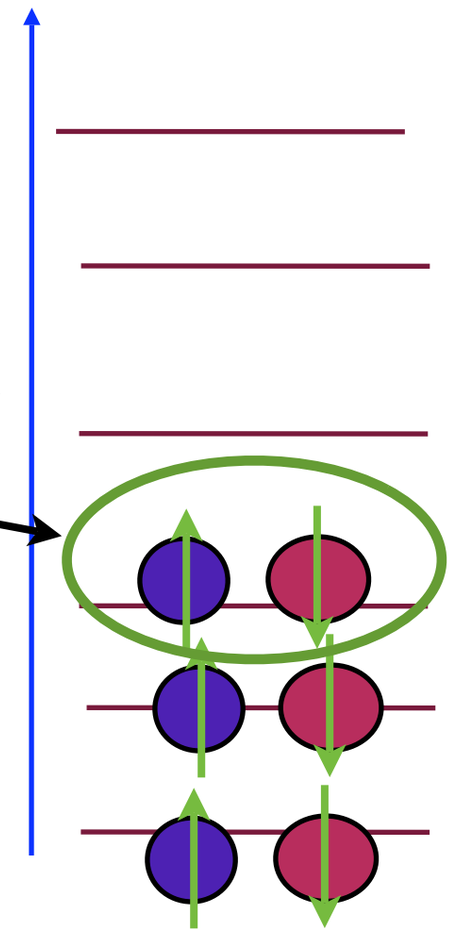


EMPTY STATES=
METAL

band theory fails!

What is a Mott Insulator?

NiO insulates
?
perhaps this
costs energy

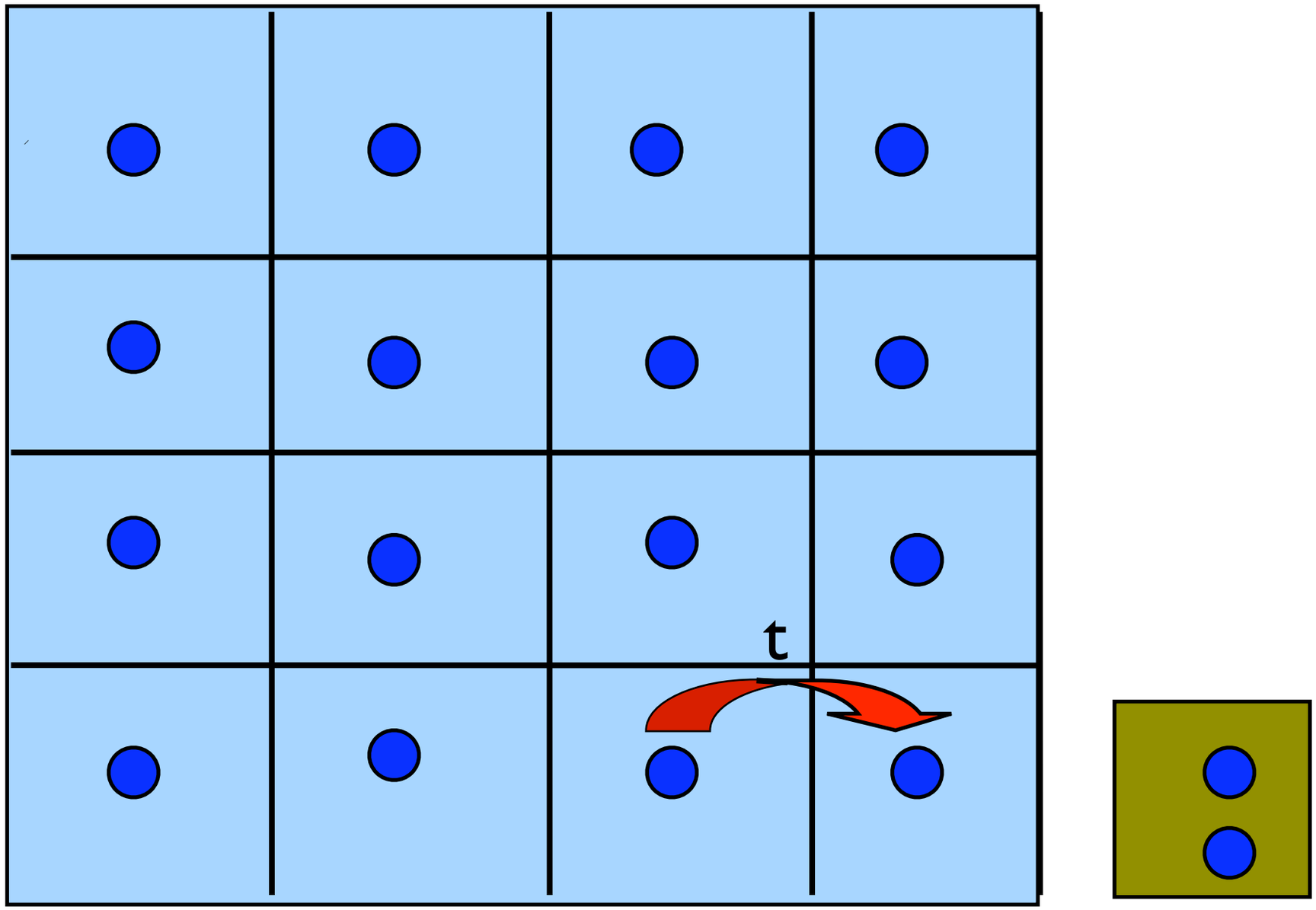


EMPTY STATES=
METAL

band theory fails!

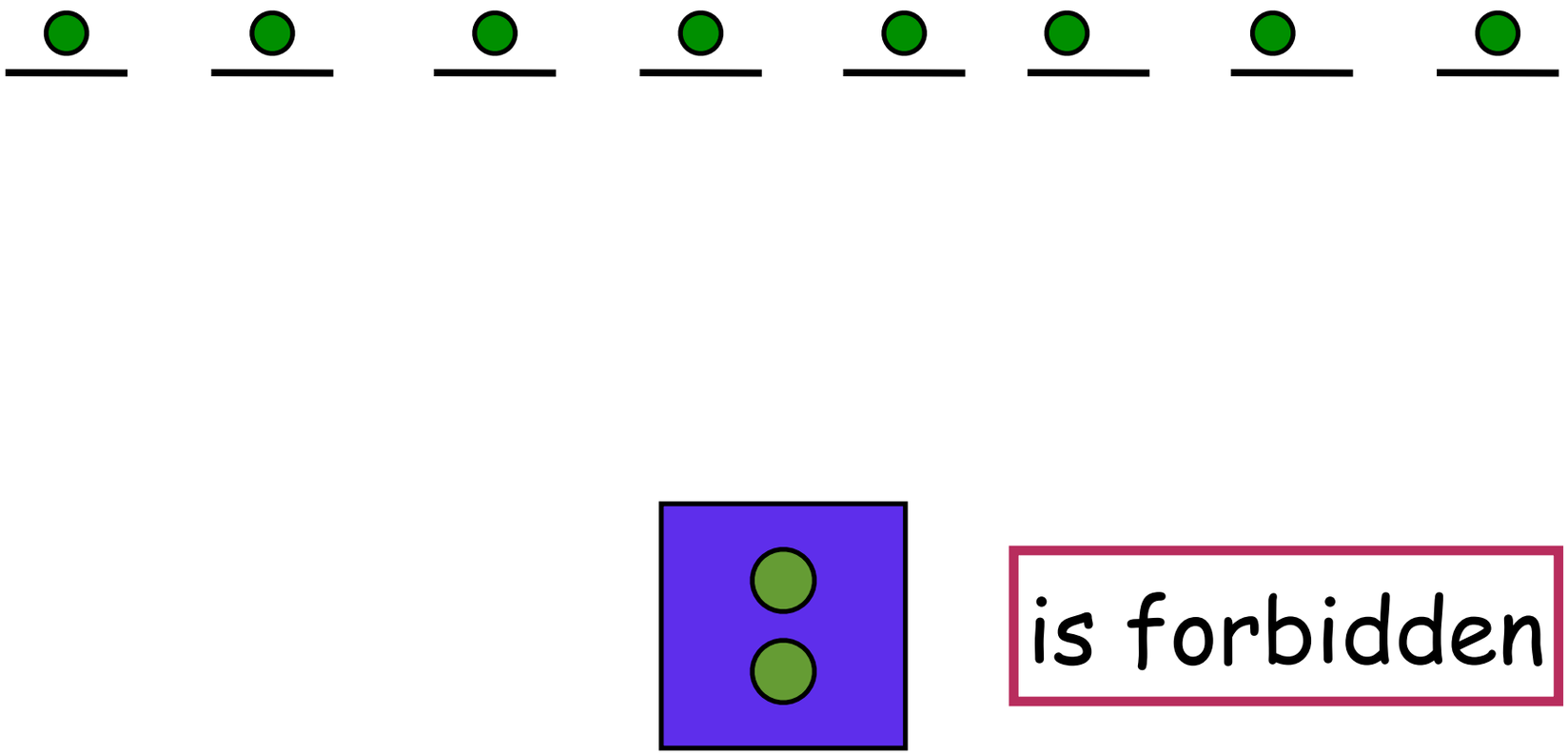
Mott Problem: NiO (Band theory failure)

Collonade (N rooms N occupants)

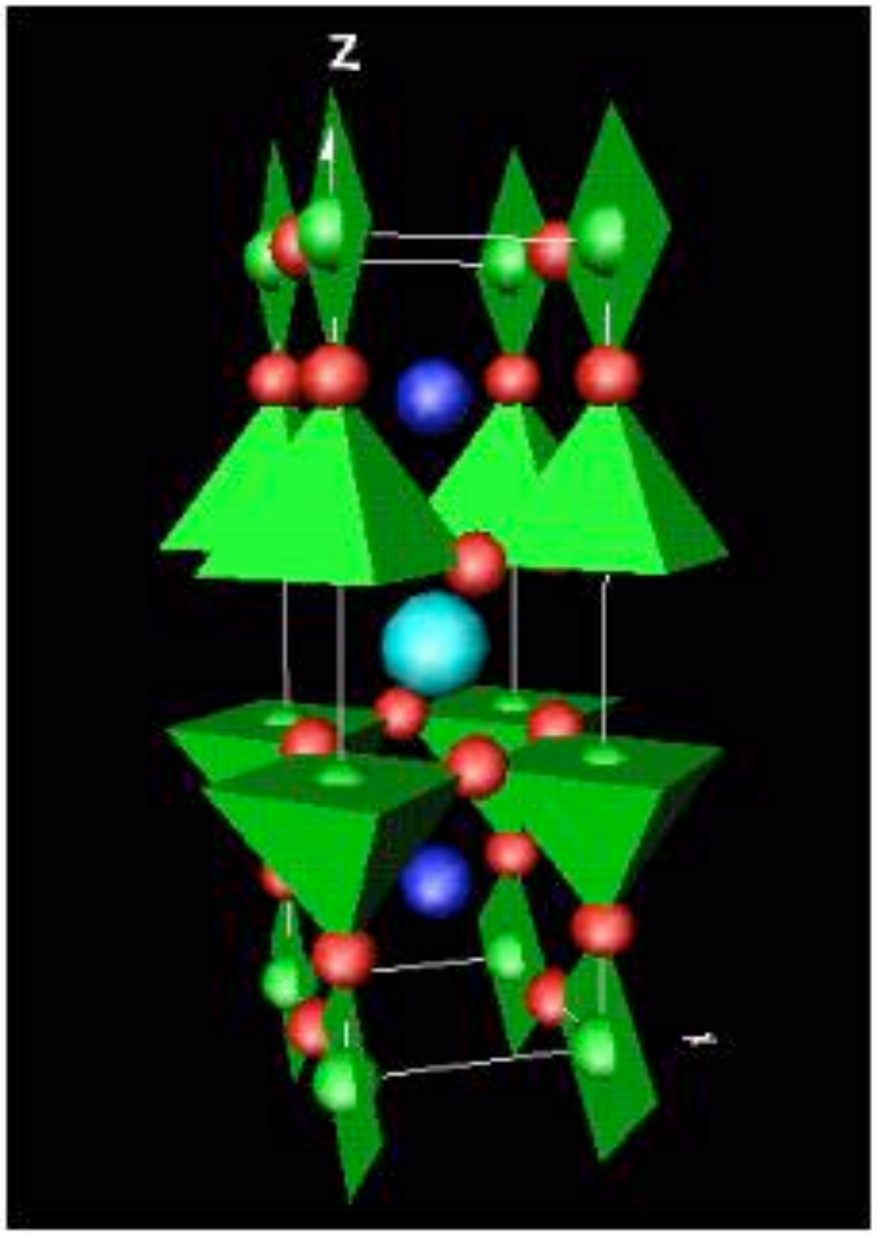


$U \gg t$

classical picture

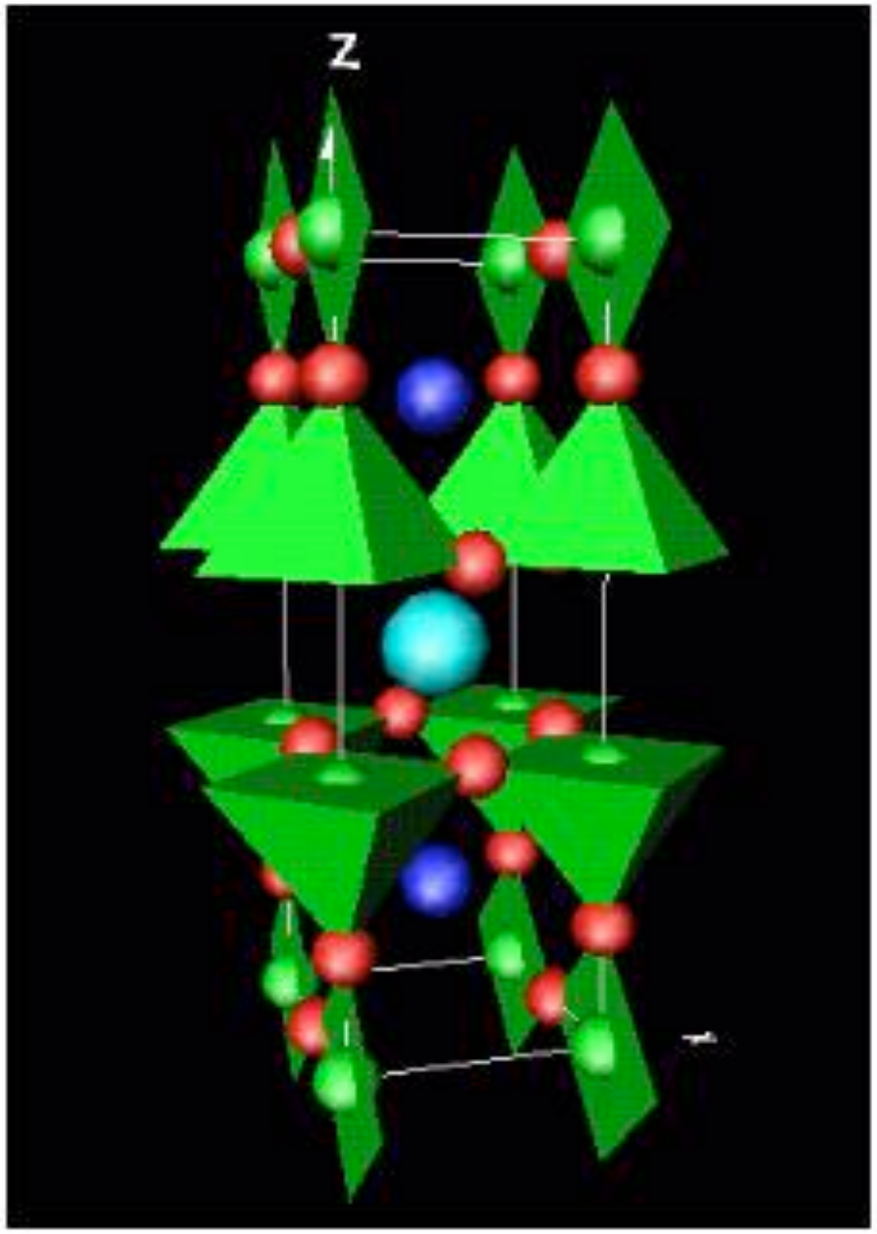


Are the cuprates in the Mott regime?



$YBa_2Cu_3O_7$

Cuprate Superconductors



$$U/t = 10 \gg 1$$

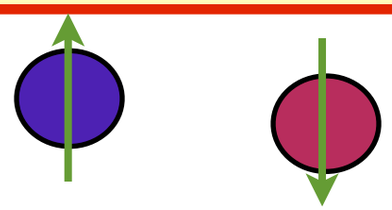
interactions dominate:
Strong Coupling Physics

$Y\,Ba_2Cu_3O_7$
Cuprate Superconductors

Yes

What is left of BCS?

free electrons



high T

they knew what to look for: weakly interacting objects

attraction $\longrightarrow 2e^-$

low T

L. D. Landau
Nobel:1962

What is left of BCS?

they knew what to look for: weakly interacting objects

low T

attraction $\longrightarrow 2e^-$

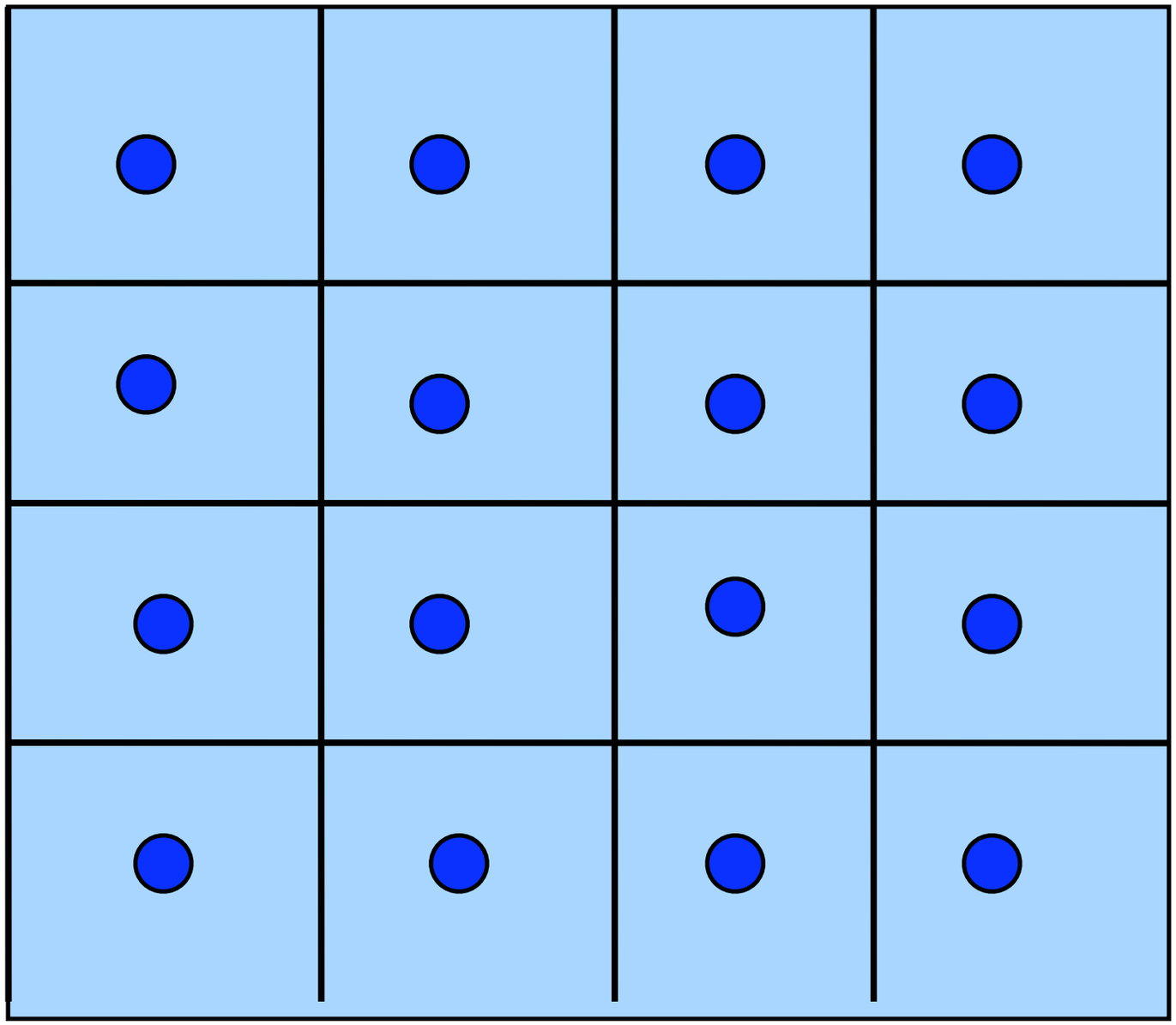
What is left of BCS?

they knew what to look for: weakly interacting objects

pairing idea:
but what to pair up?

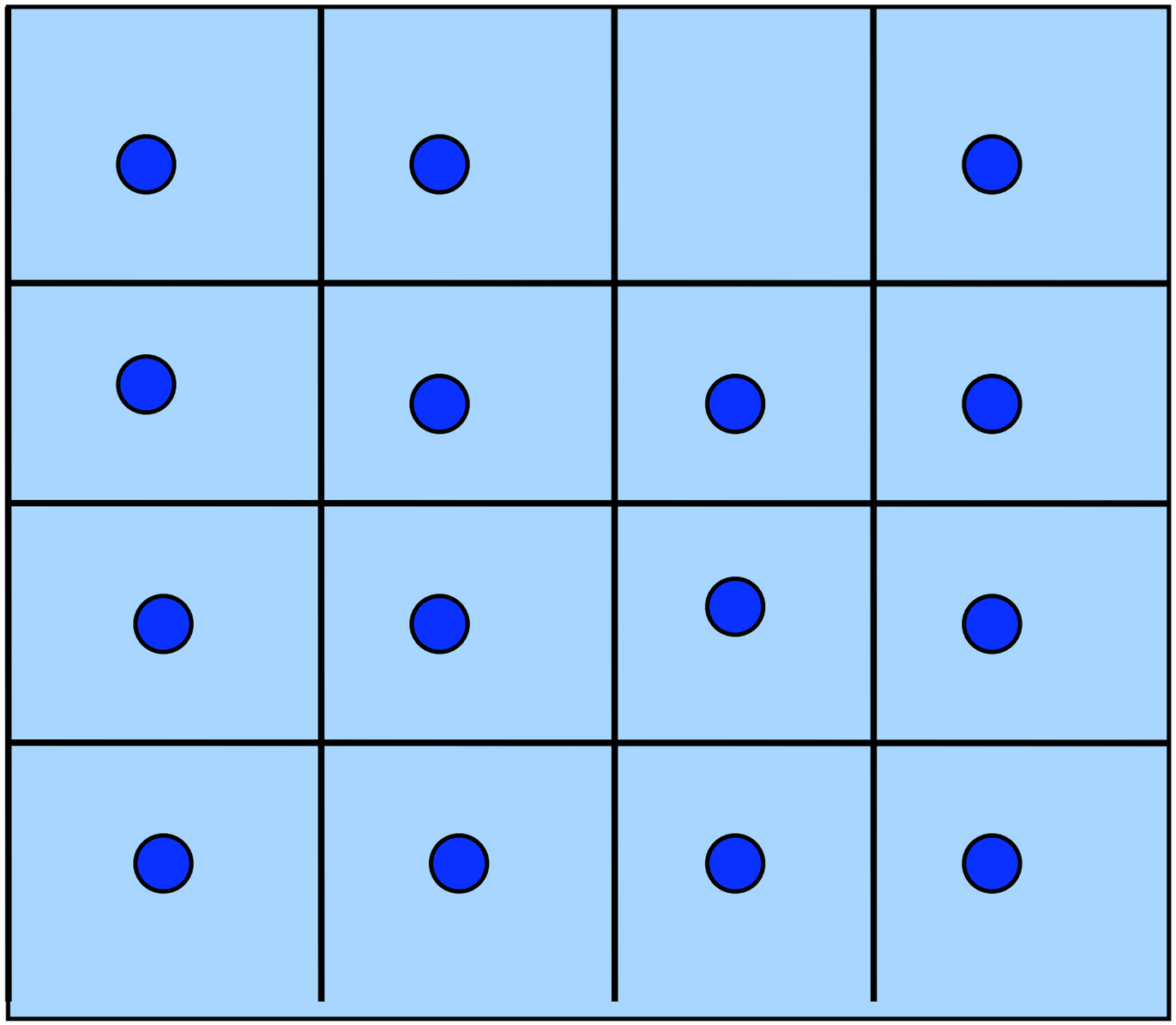
Doping a Mott insulator

x= fraction of empty rooms (holes)



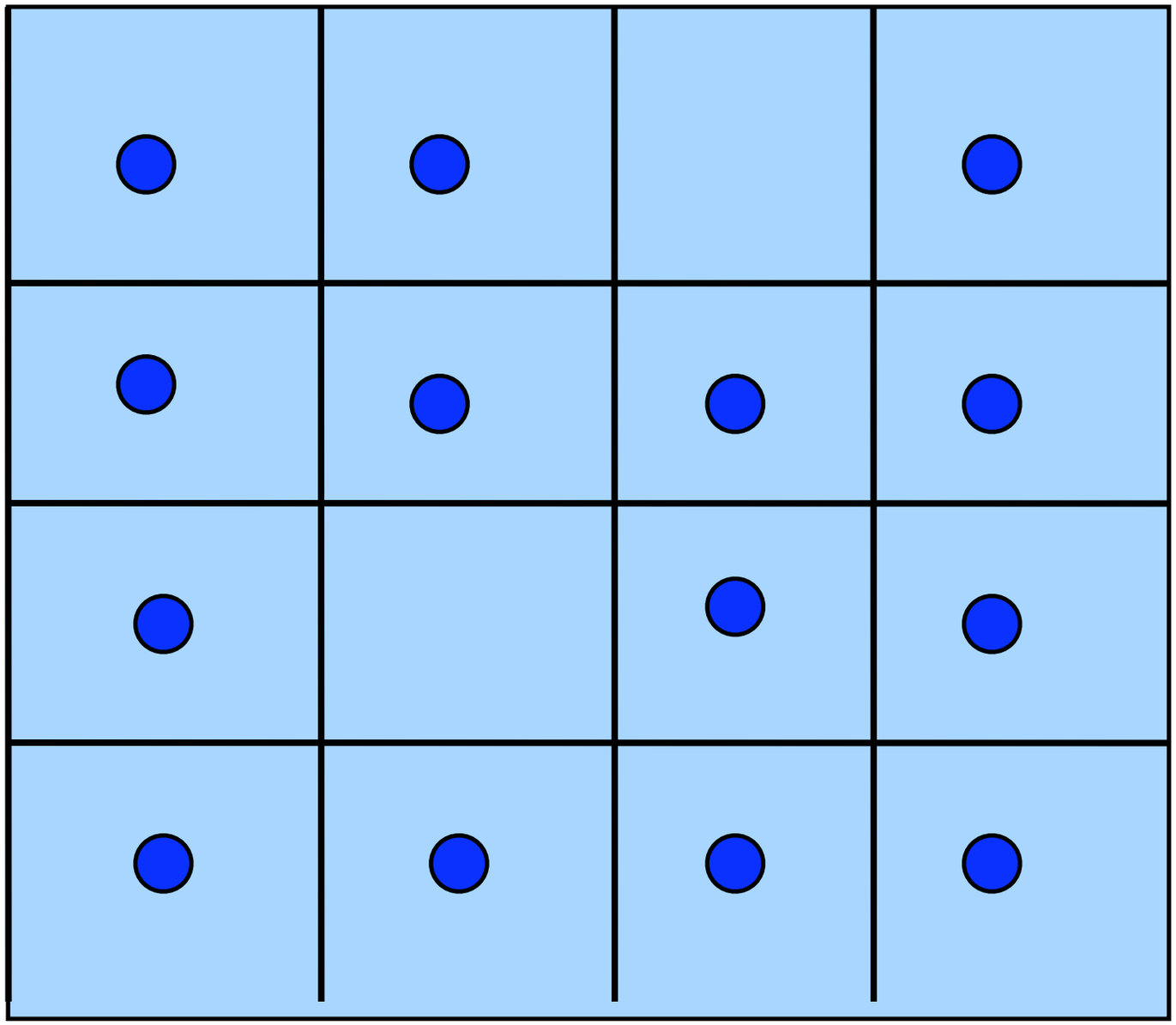
Doping a Mott insulator

x= fraction of empty rooms (holes)



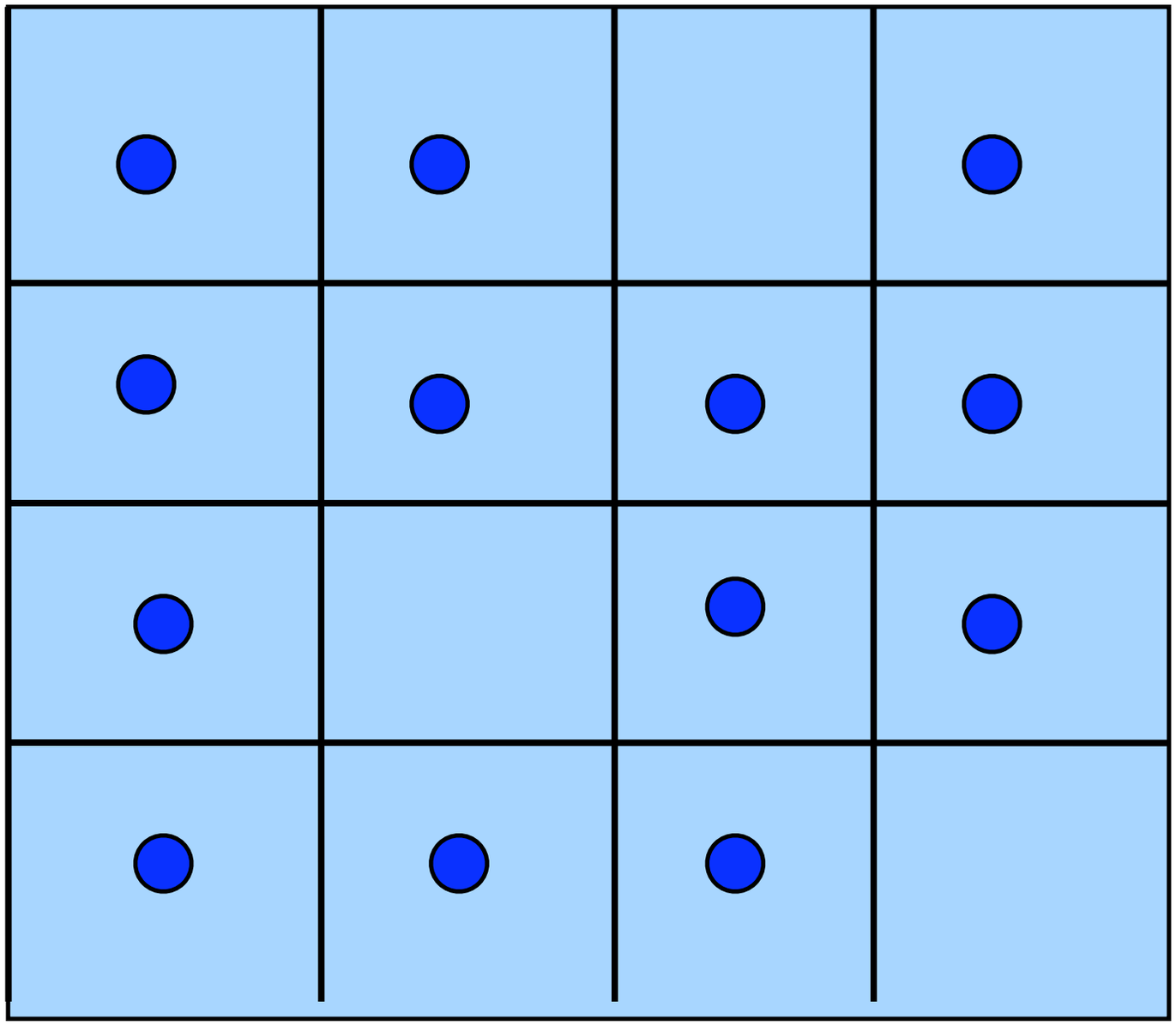
Doping a Mott insulator

x= fraction of empty rooms (holes)



Doping a Mott insulator

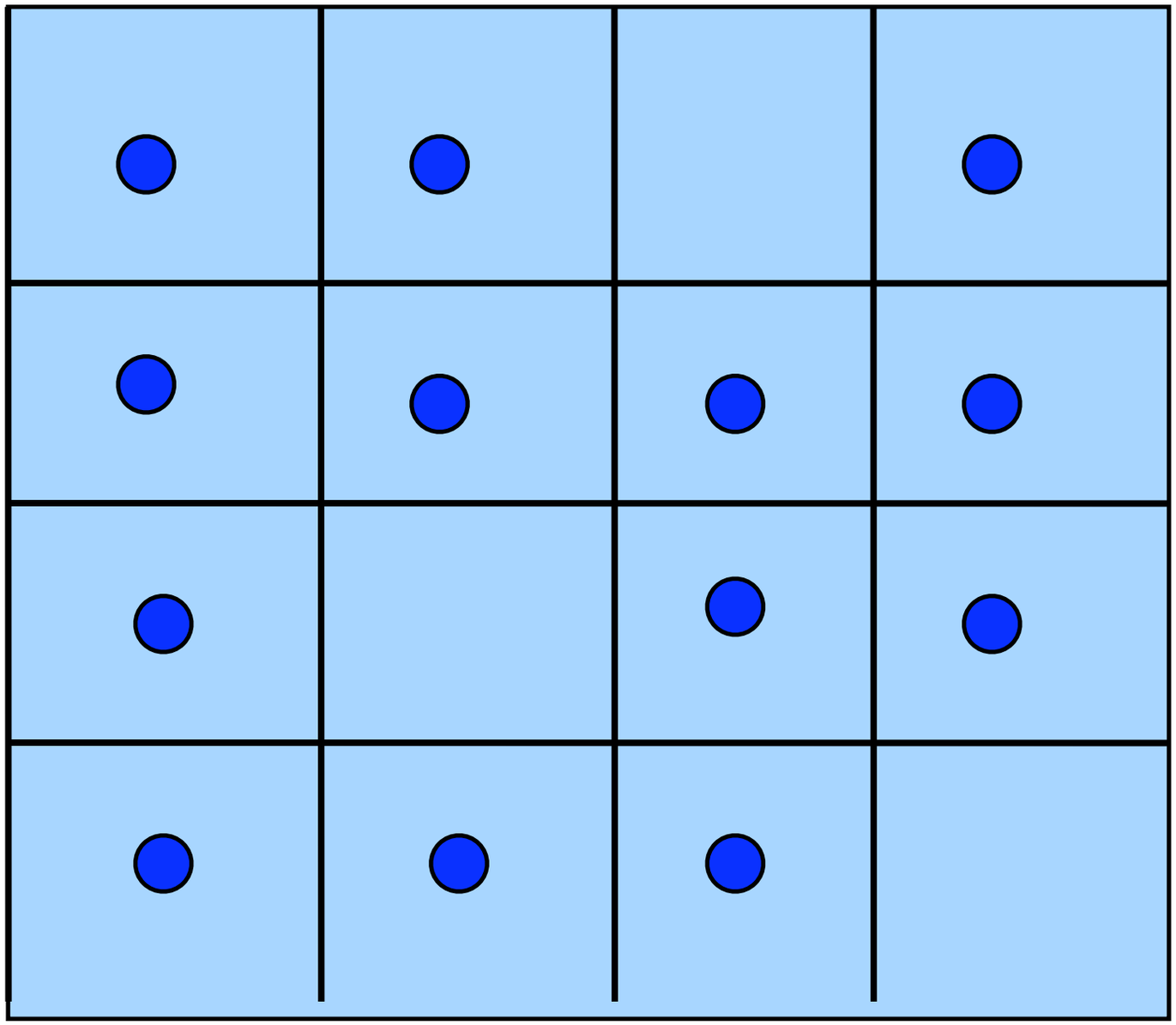
x= fraction of empty rooms (holes)

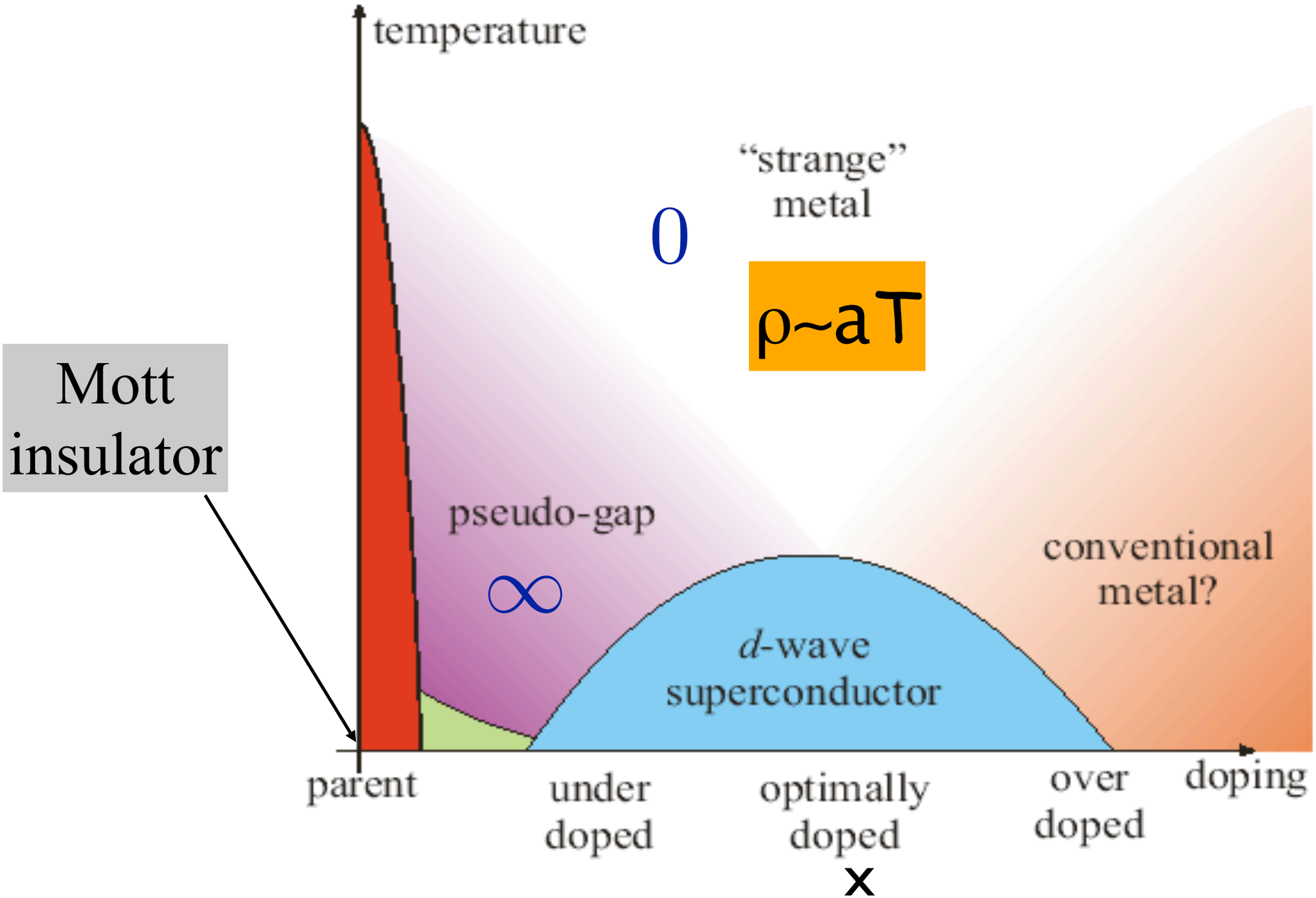


Doping a Mott insulator

x= fraction of empty rooms (holes)

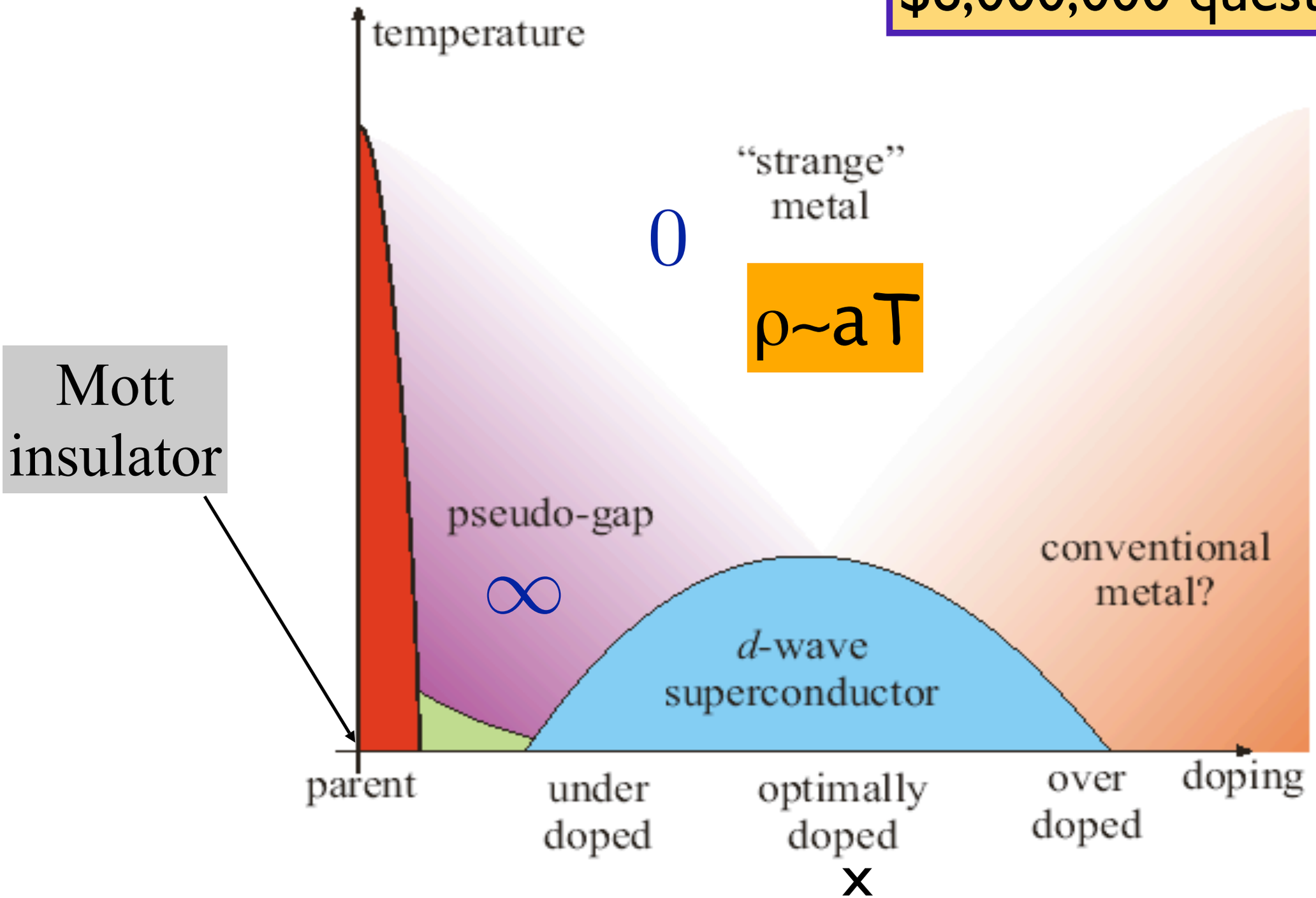
X=3/16




temperature
Mott insulator
"strange" metal
0
ρ~aT
pseudo-gap
∞
conventional metal?
d-wave superconductor
parent
under doped
optimally doped
over doped
doping
x

How does the standard theory of metals breakdown?

$6,000,000 question?



Cuprates: The Perfect Storm

collective failure

collective failure

New Concept

collective failure

"I'm not into this detail stuff. I'm more concepty."

New Concept

strong coupling:bound states not in high-energy theory

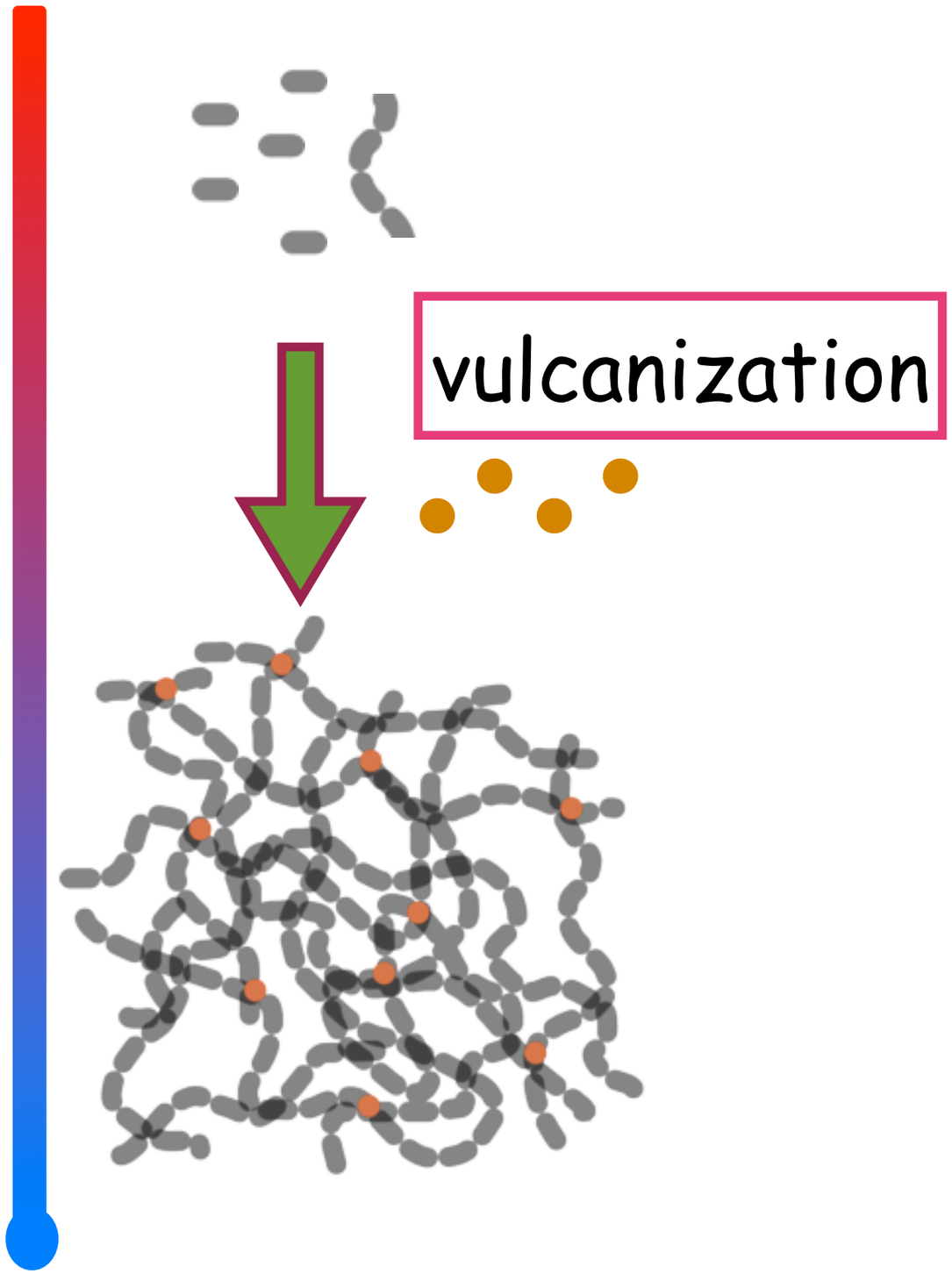
strong coupling:bound states not in high-energy theory

strong coupling:bound states not in high-energy theory

how?

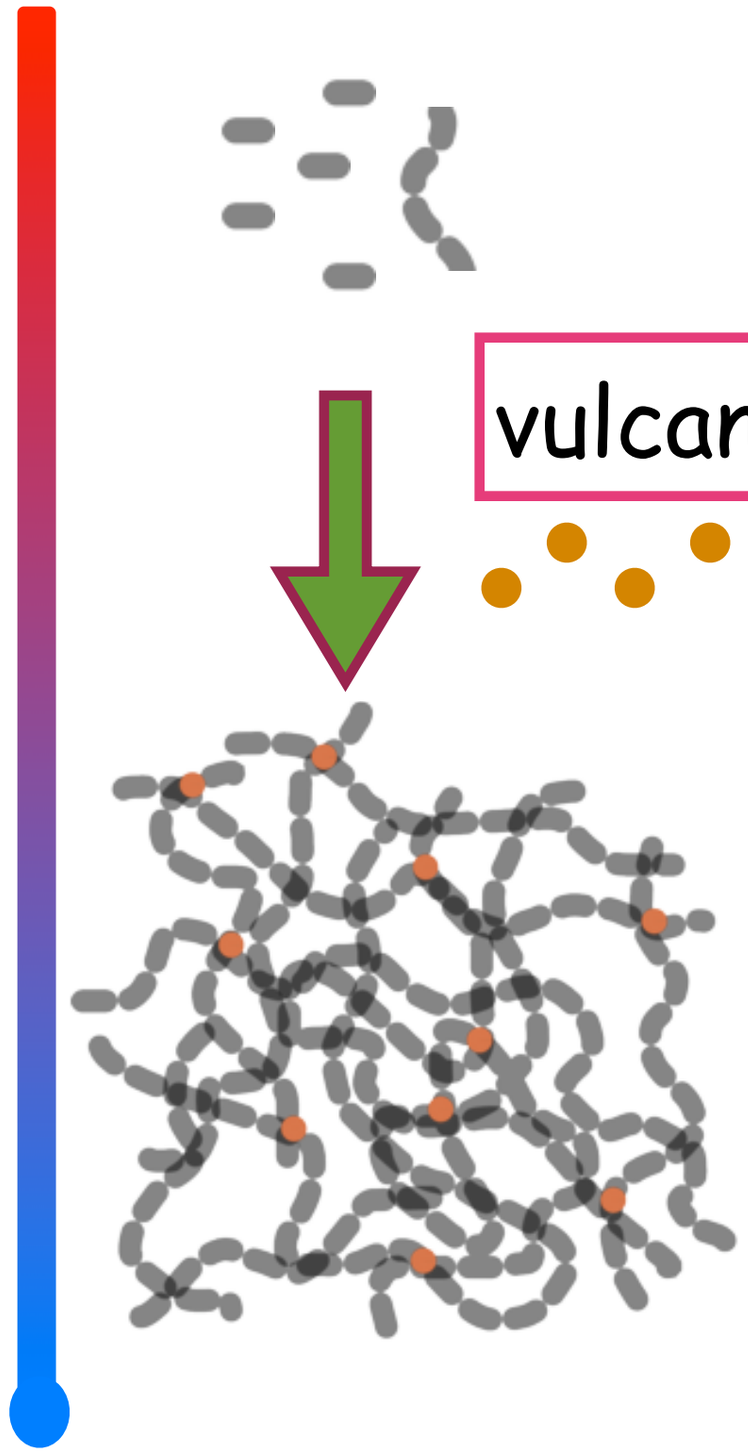
strong coupling:bound states not in high-energy theory

how?



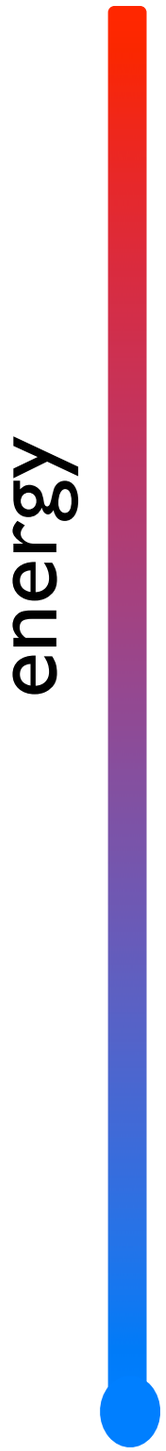
strong coupling:bound states not in high-energy theory

how?

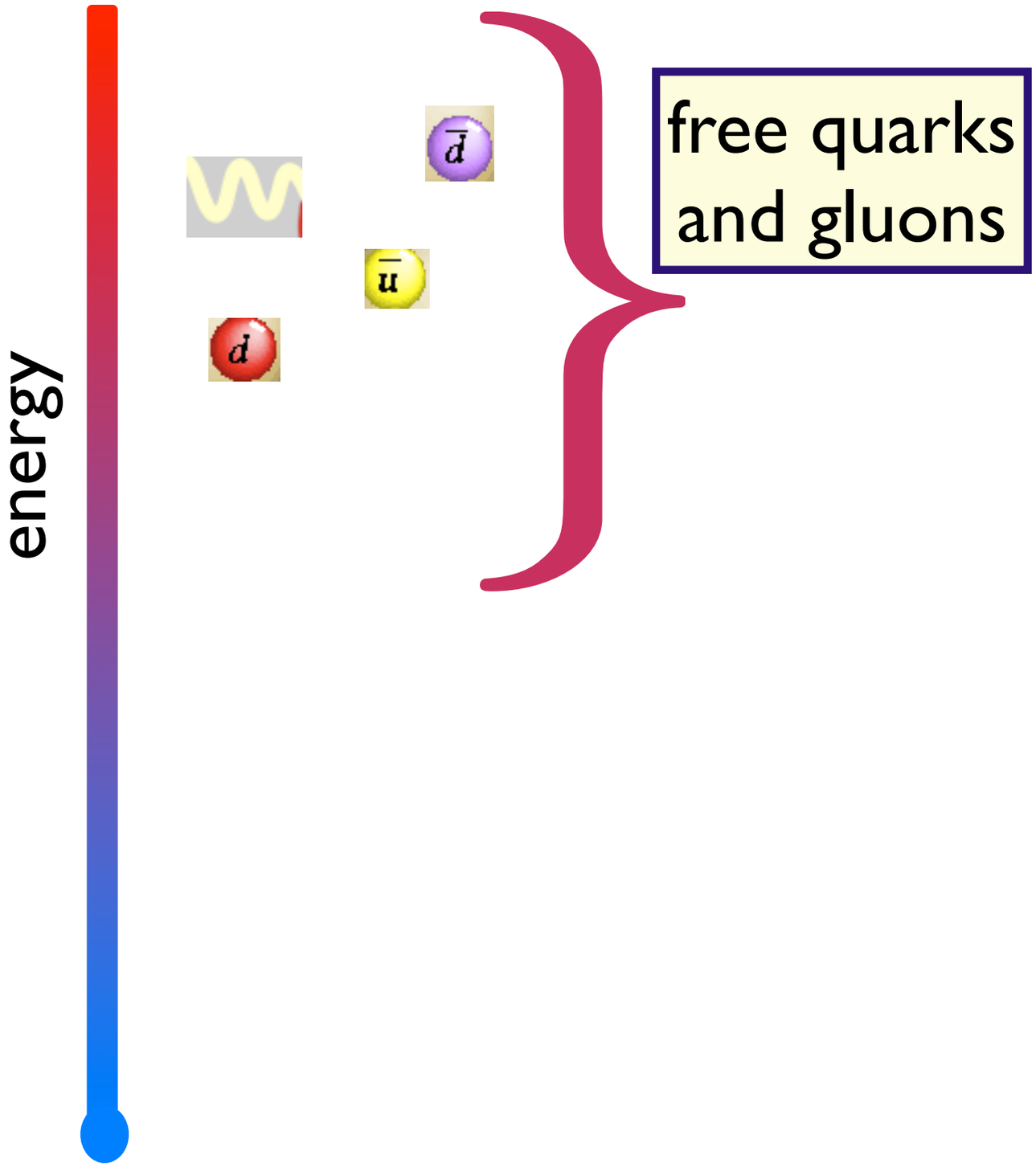


emergent
low-energy physics

Quantum Chromodynamics: Protons, neutrons, pions (hadrons)

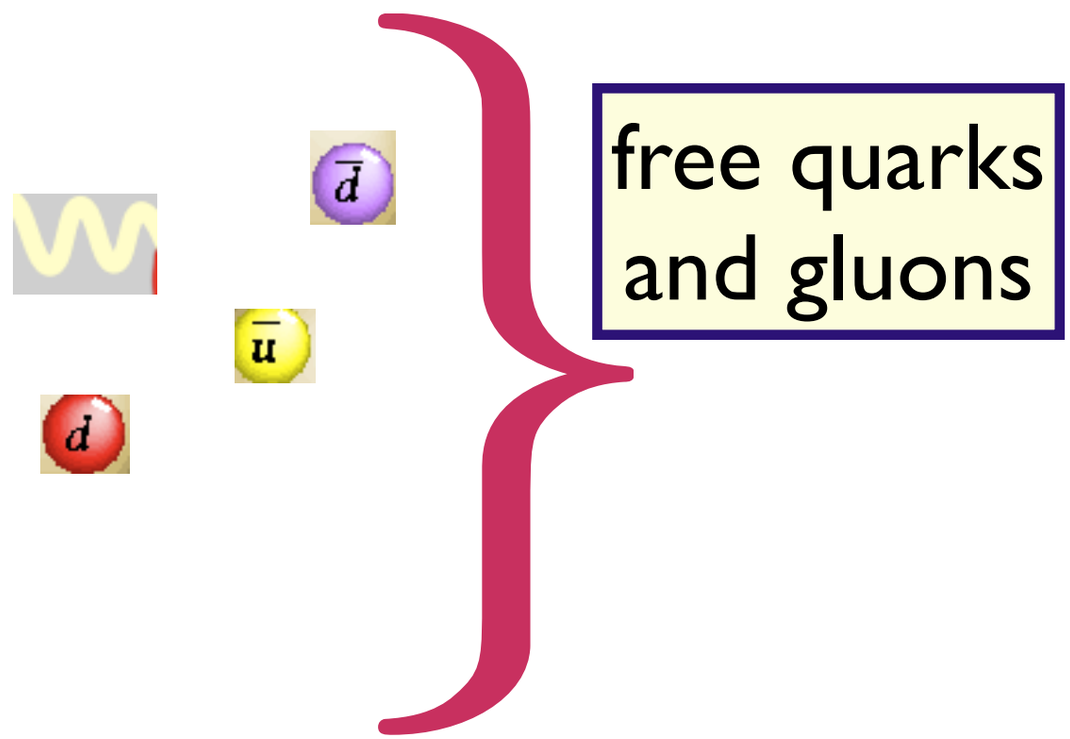


Quantum Chromodynamics: Protons, neutrons, pions (hadrons)

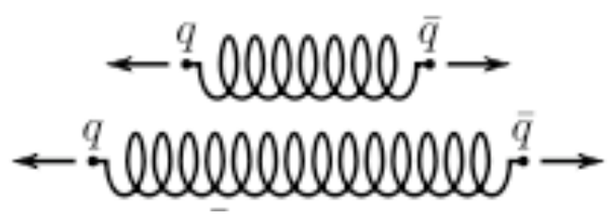


Quantum Chromodynamics: Protons, neutrons, pions (hadrons)

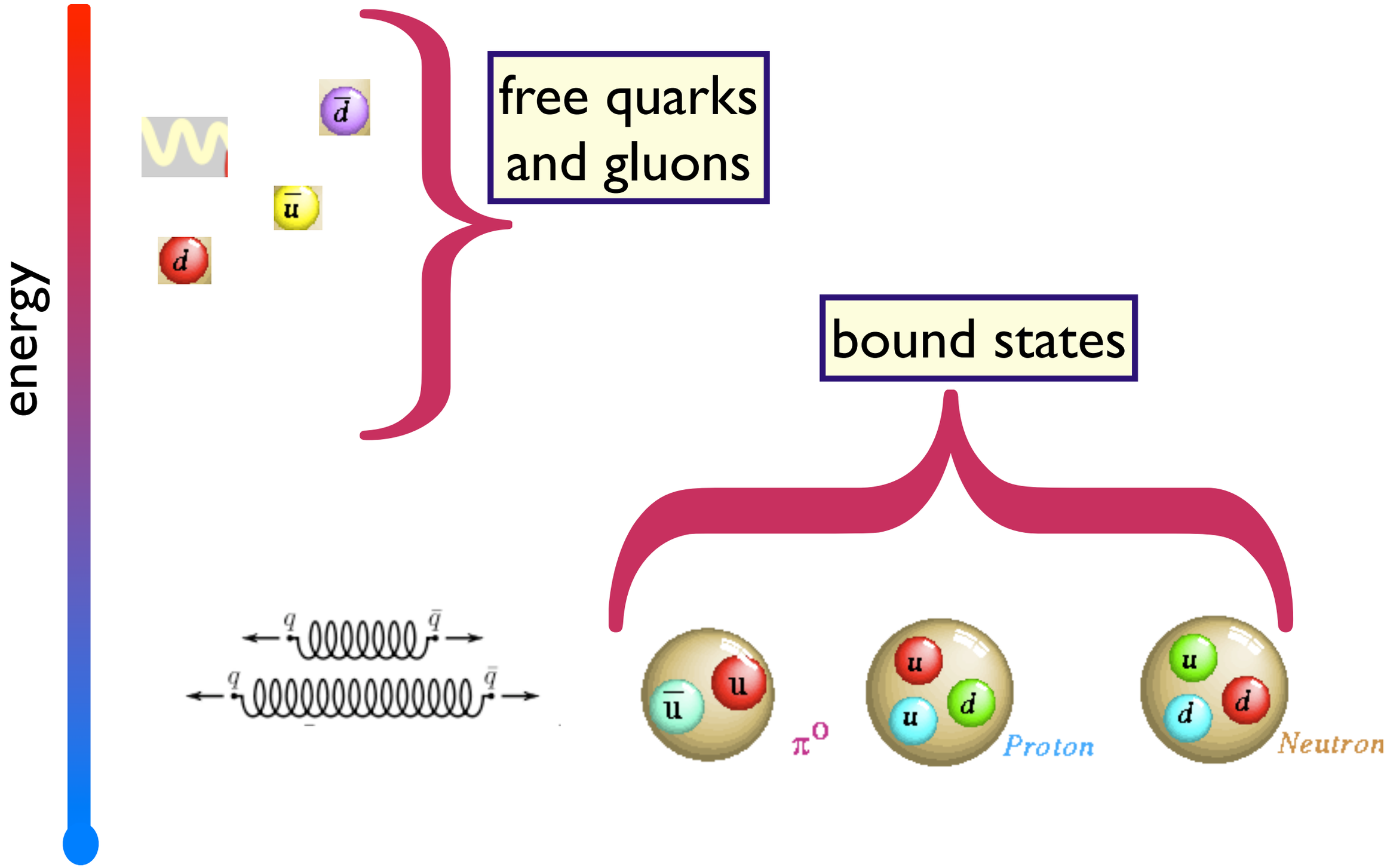
energy

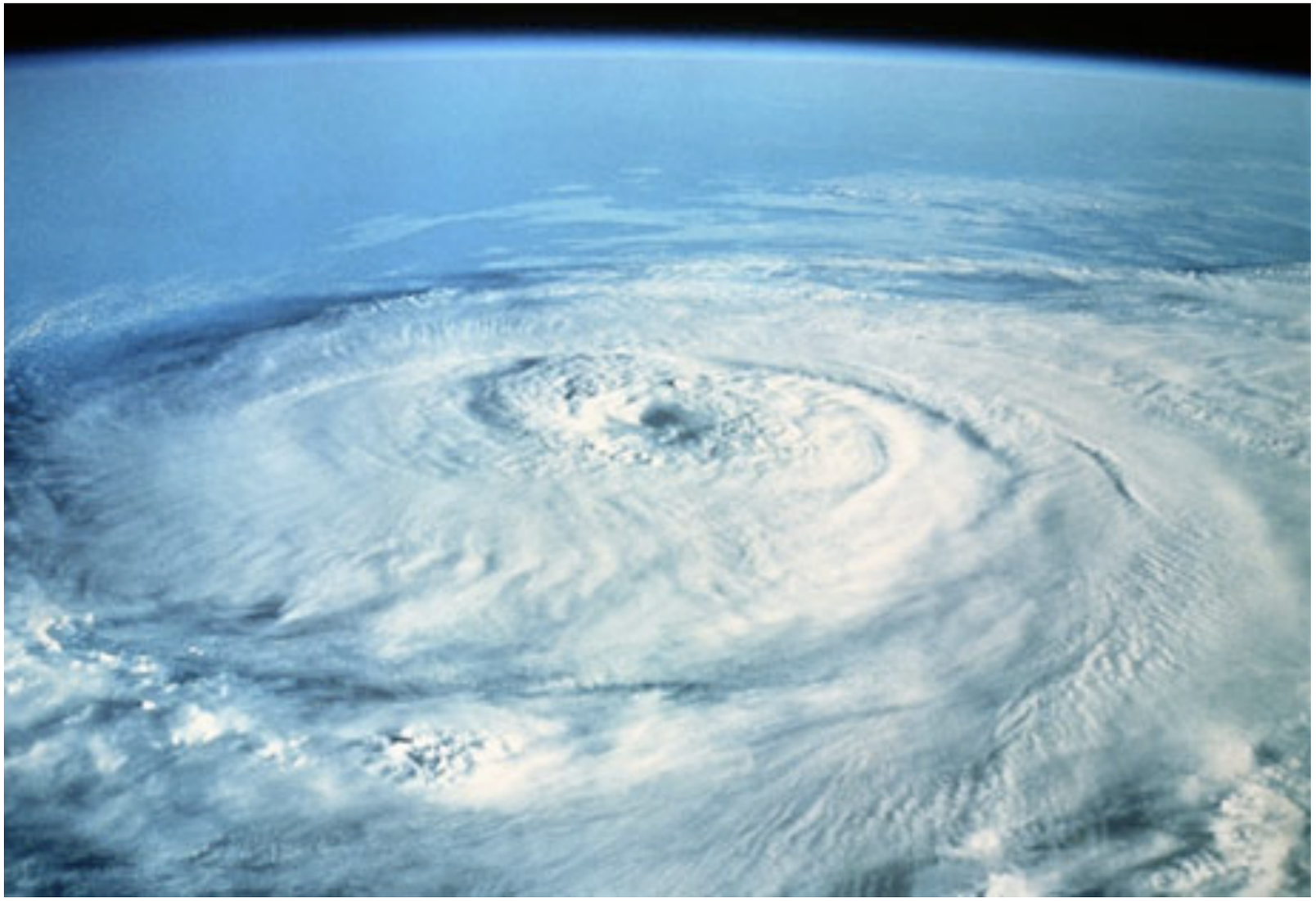


free quarks and gluons



Quantum Chromodynamics: Protons, neutrons, pions (hadrons)





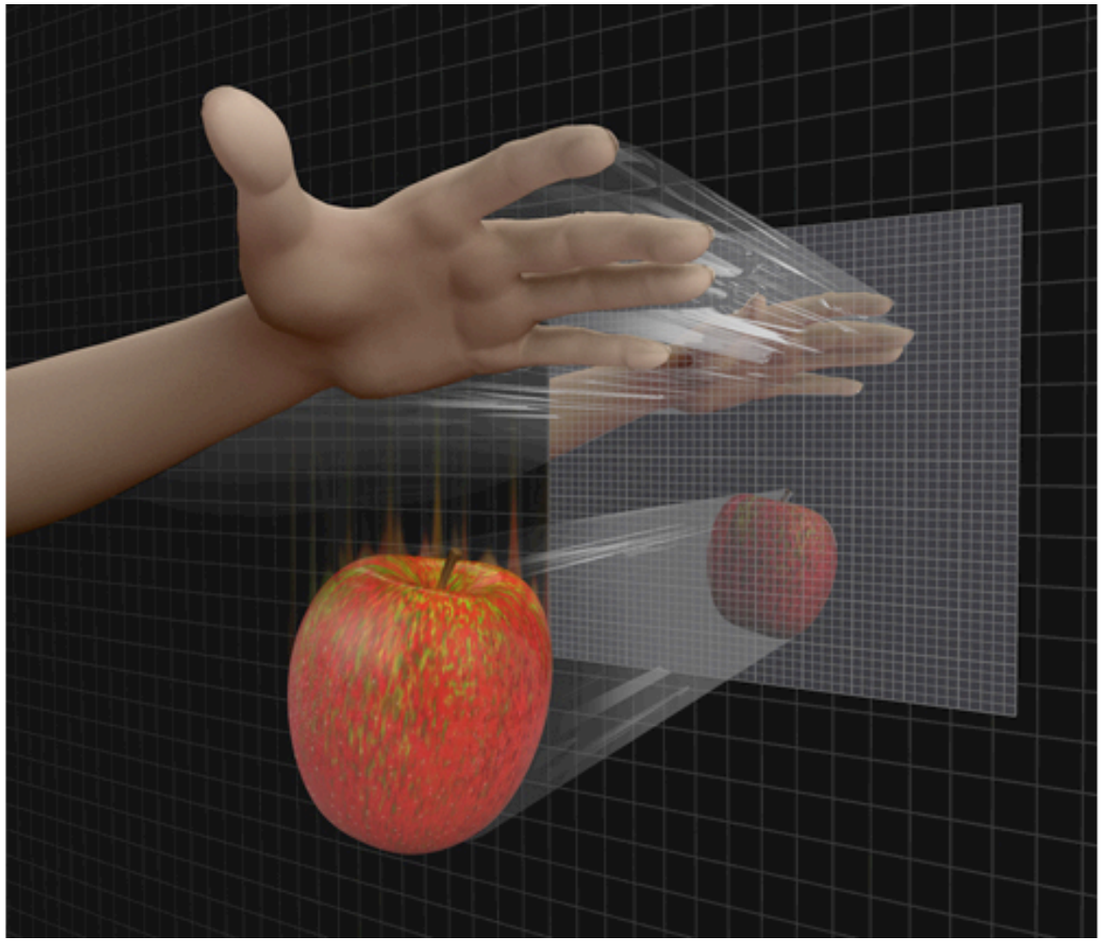
weakly interacting

what are the new bound states?

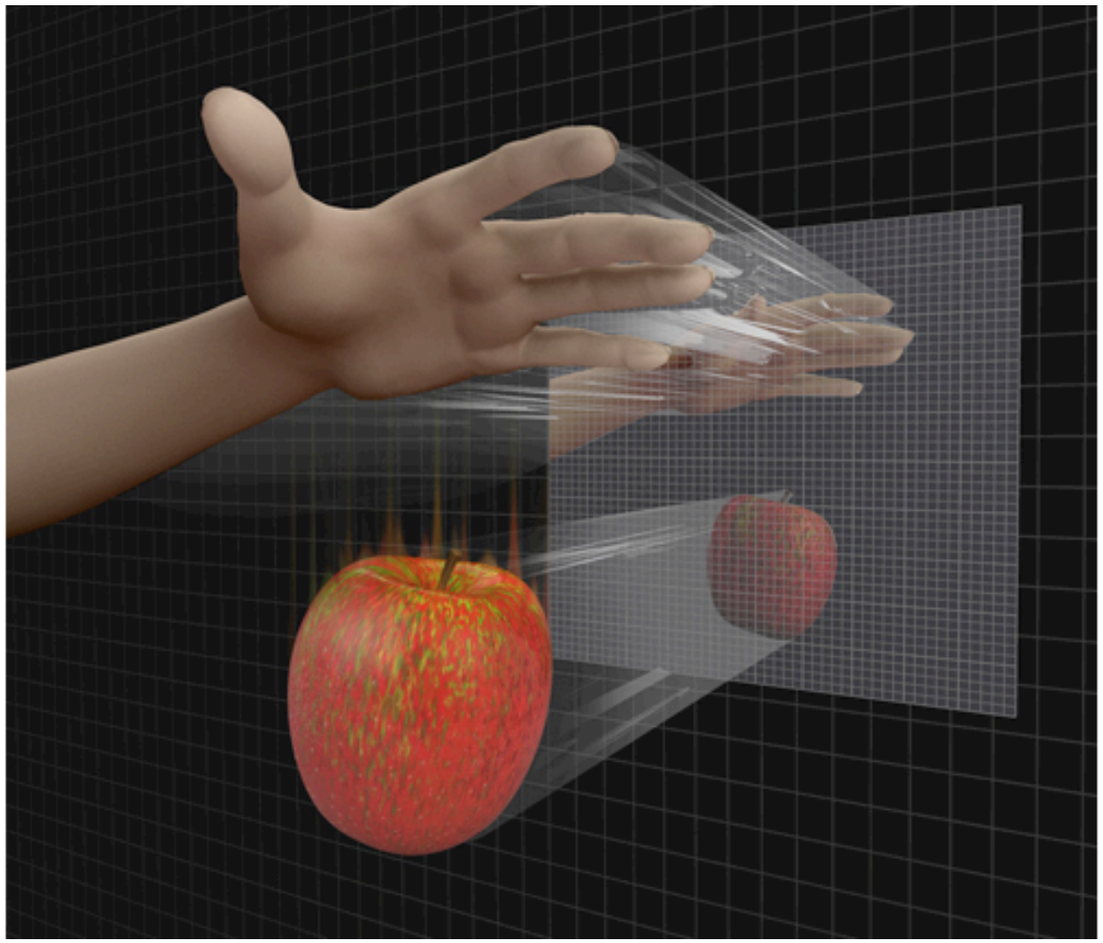
Is string theory the answer?

No?

holography

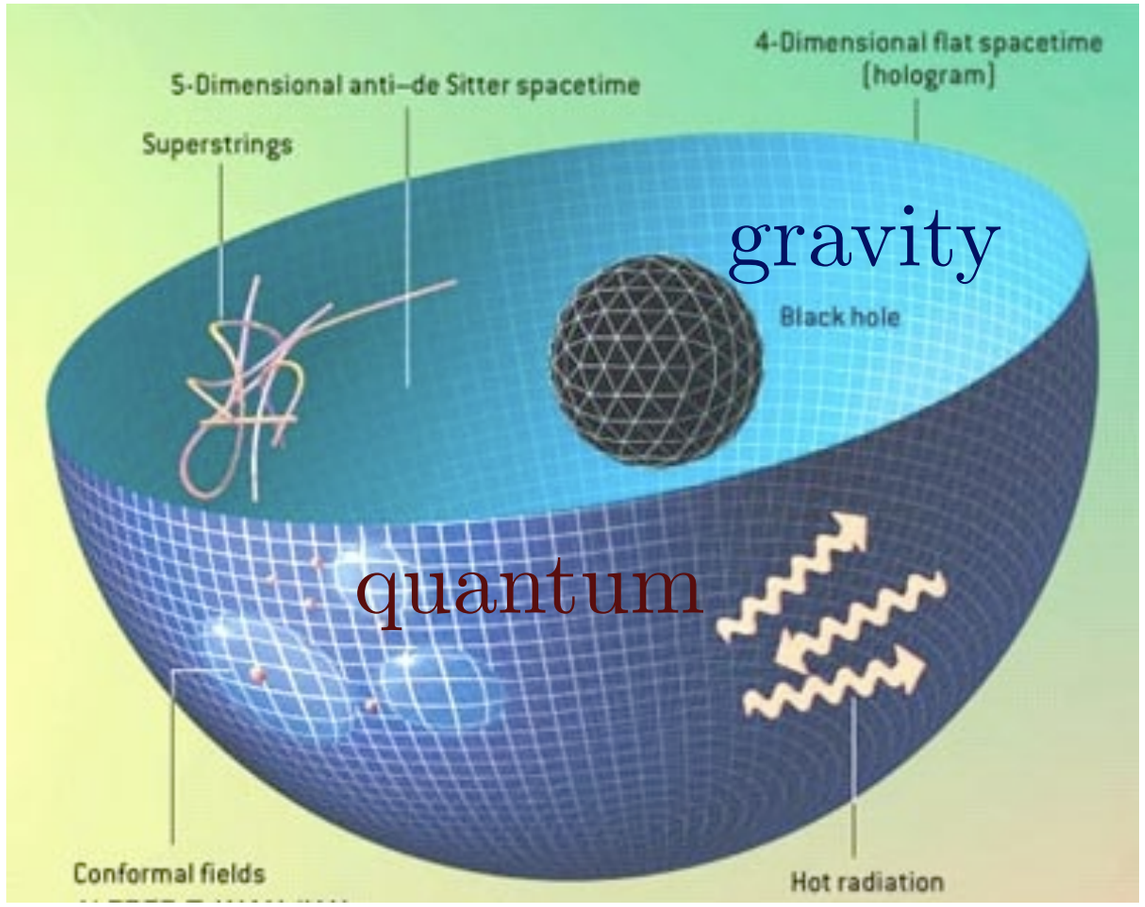


holography



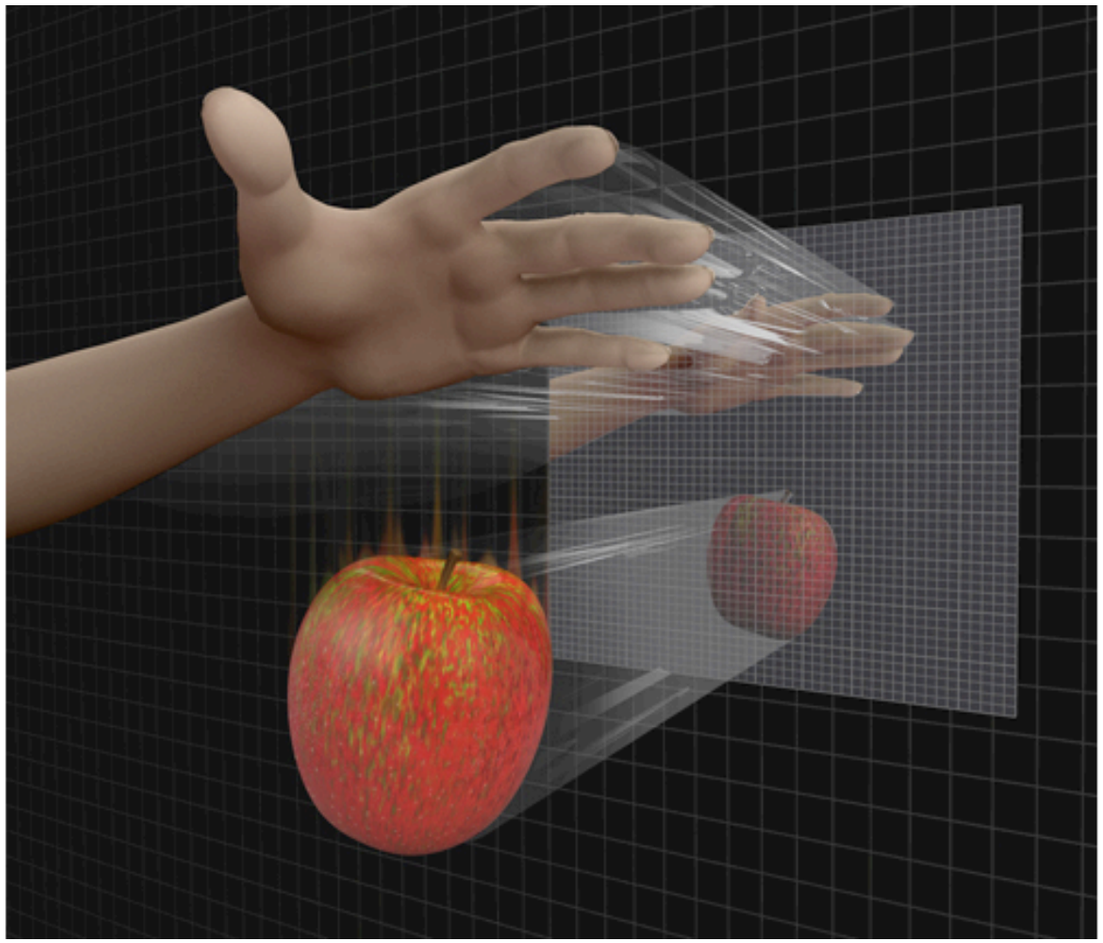
quantum holography

quantum $\Longleftrightarrow$ gravity

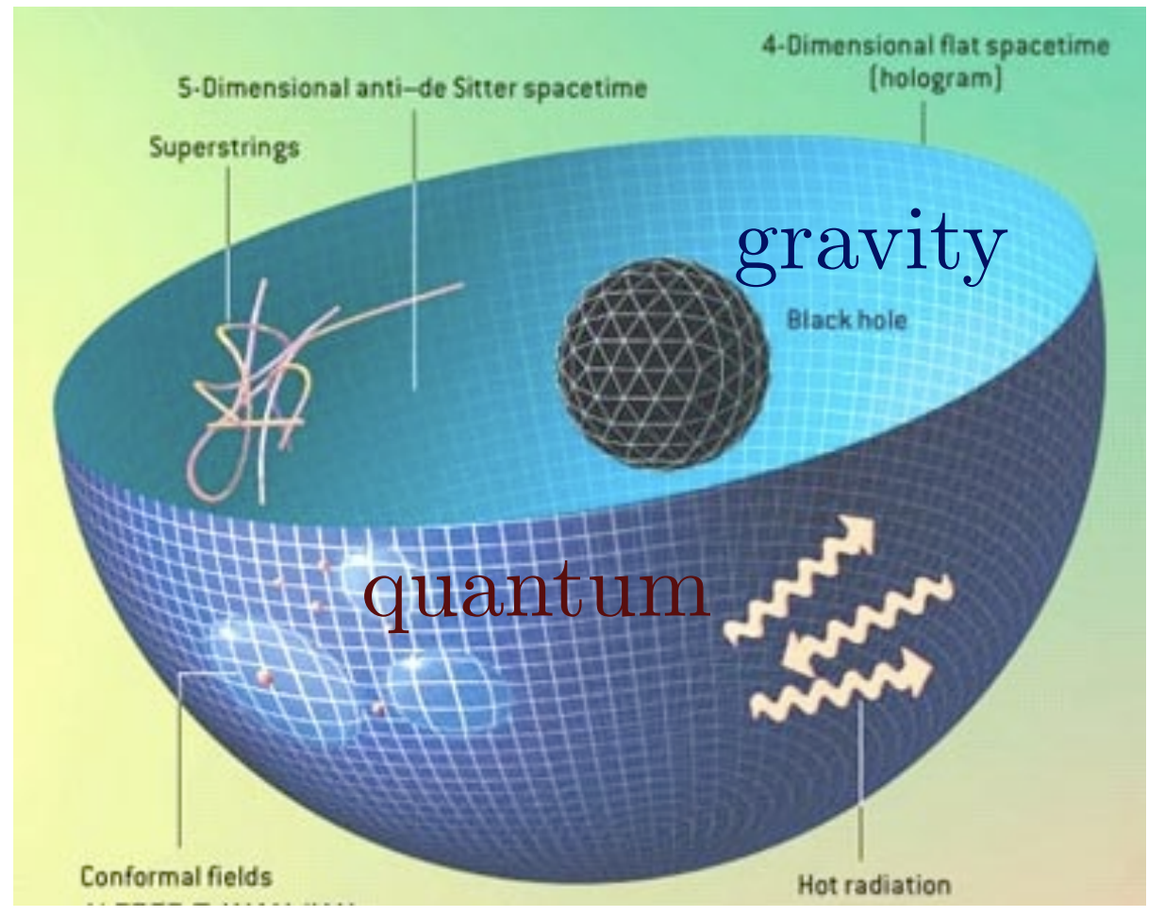


quantum holography

holography

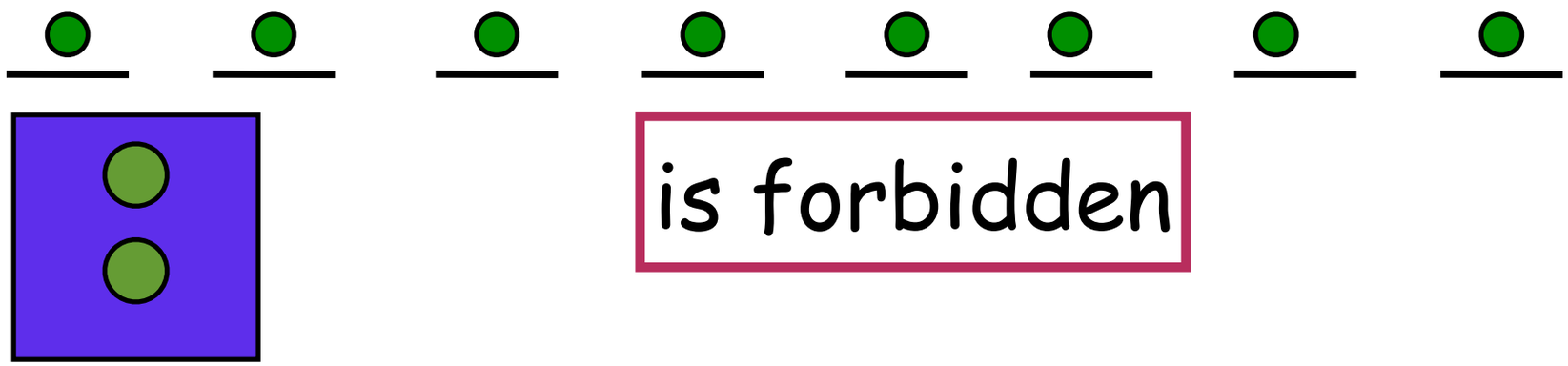


quantum $\Longleftrightarrow$ gravity

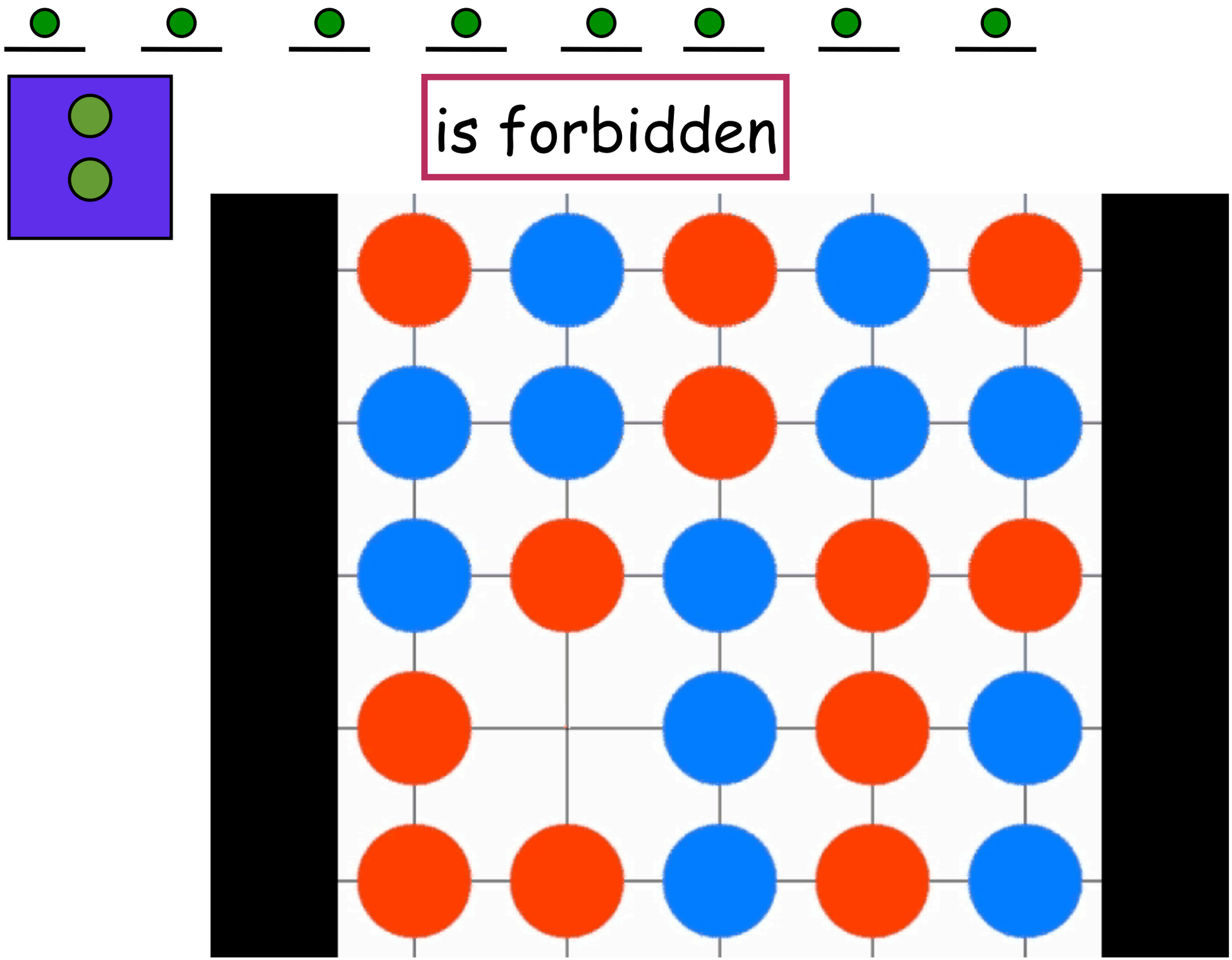


$$\rho \propto T$$

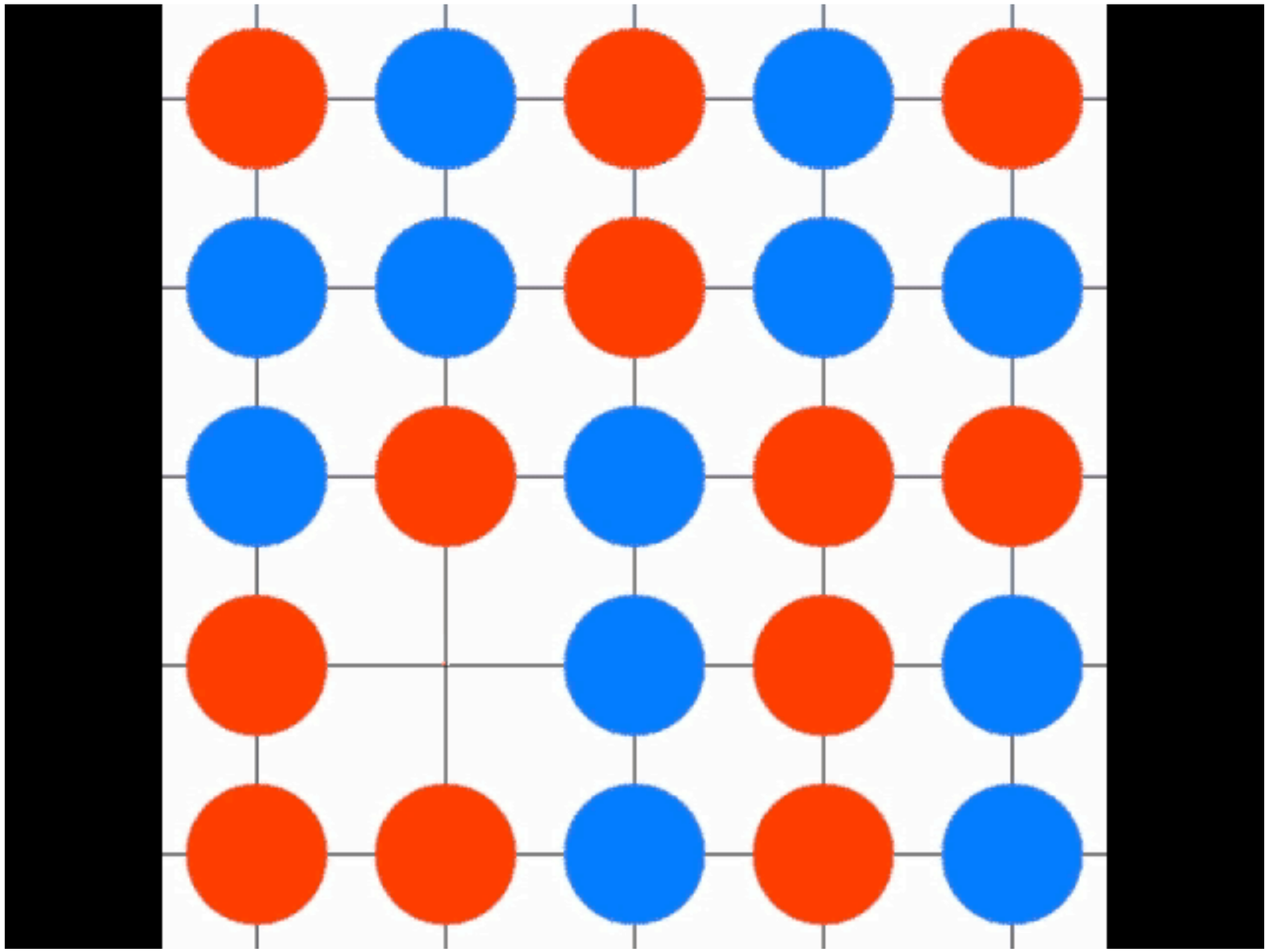
classical vs quantum Mottness



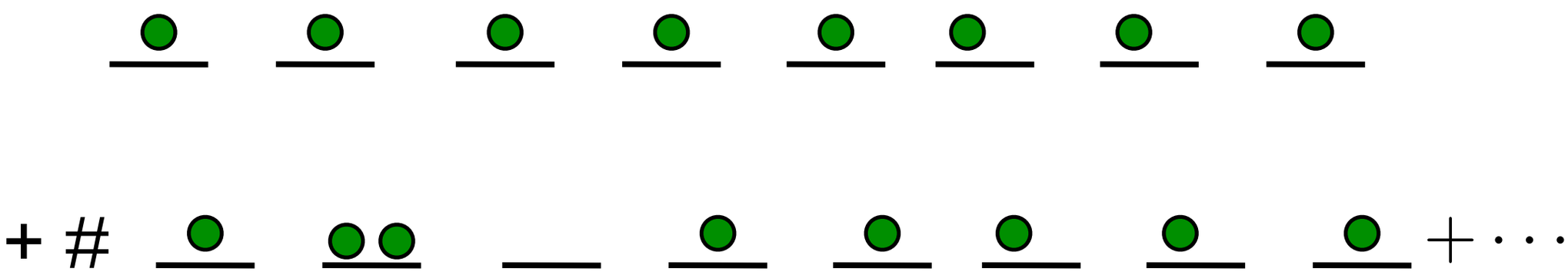
classical vs quantum Mottness



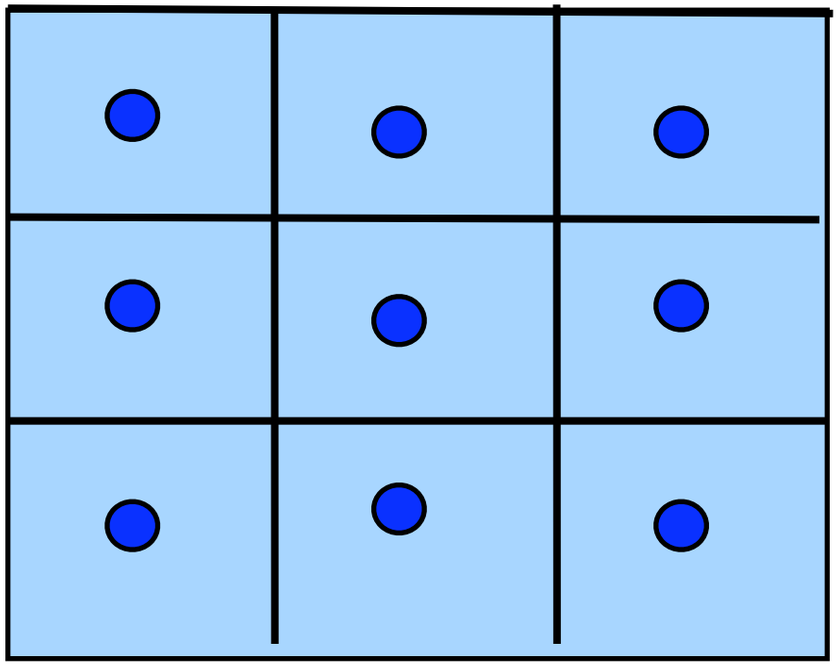
classical vs quantum Mottness



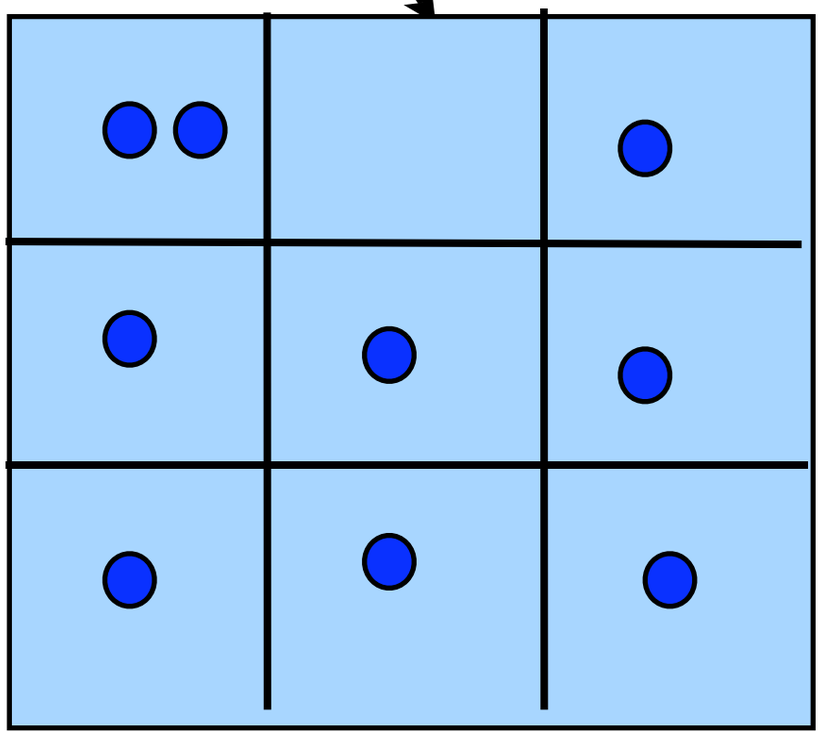
Why does a Mott insulator insulate?



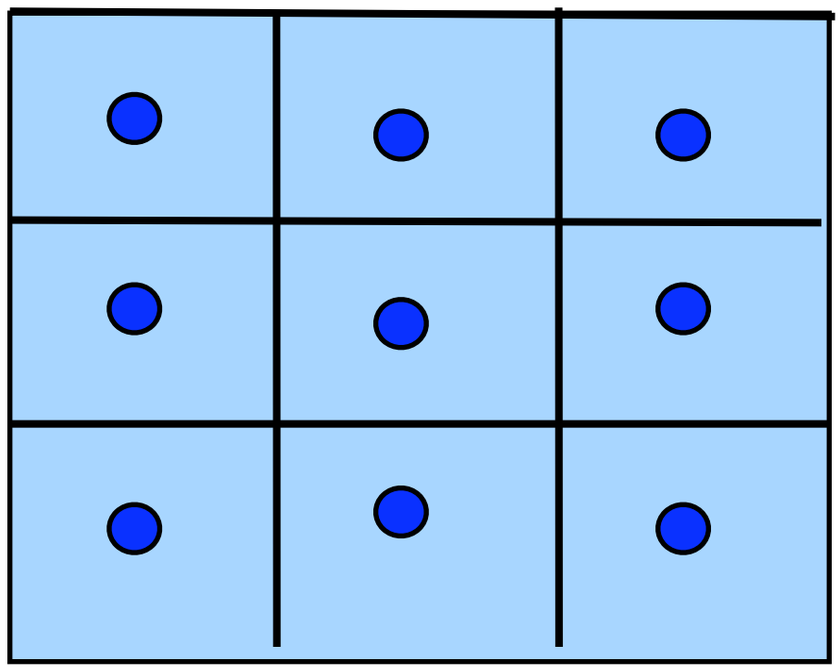
is the empty site mobile??



+ #



is the empty site mobile??



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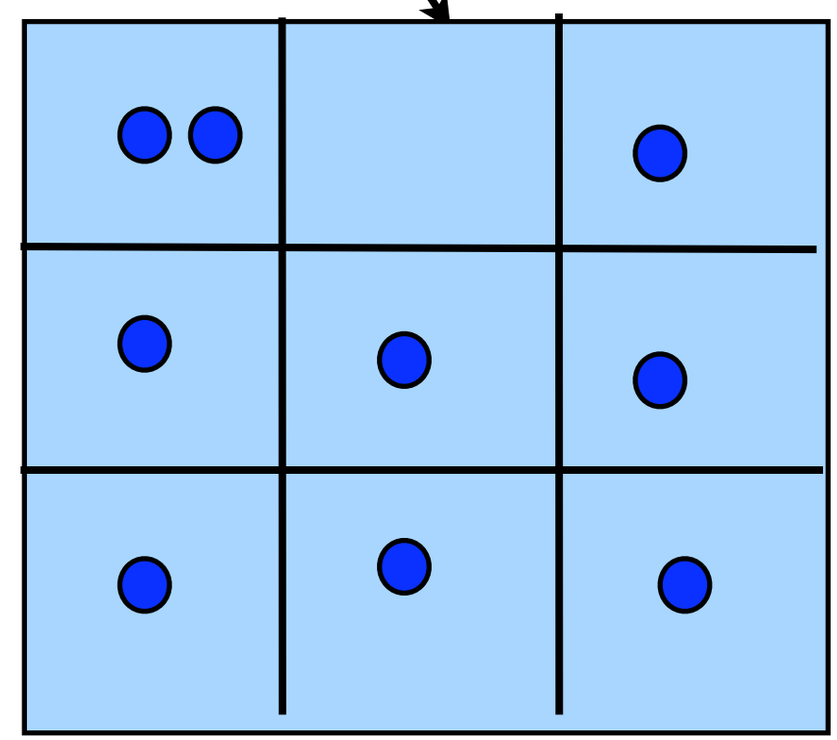
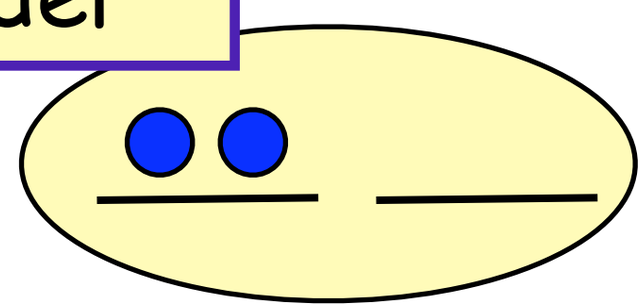
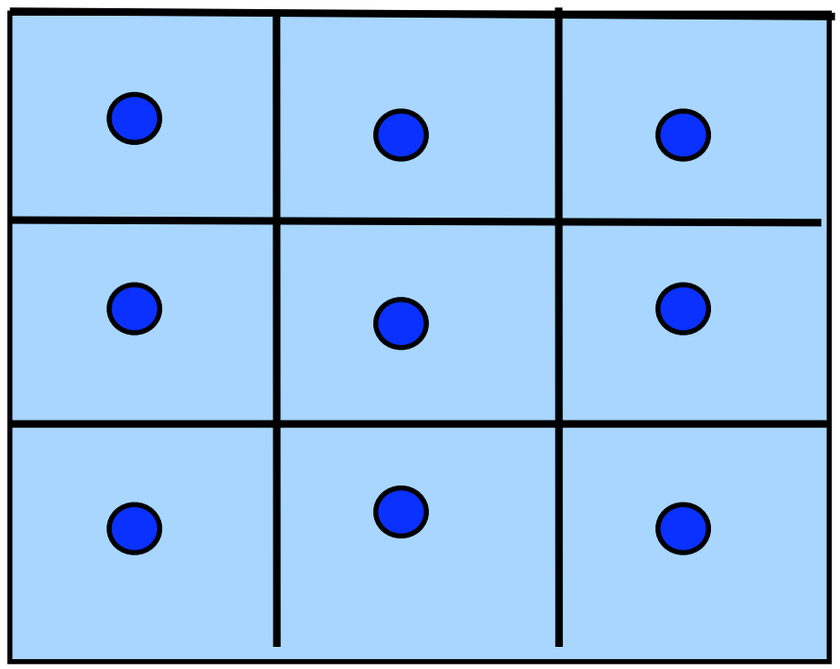


if yes, then 1.)
Mott insulator is a metal,
2.) no magnetic order

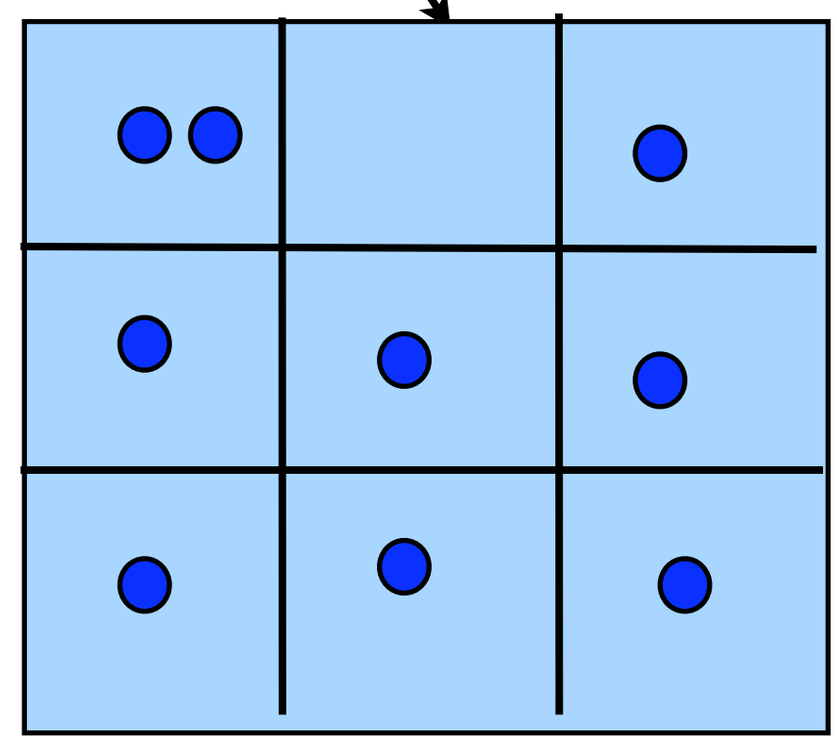


New bound state

is the empty site mobile??



+ #



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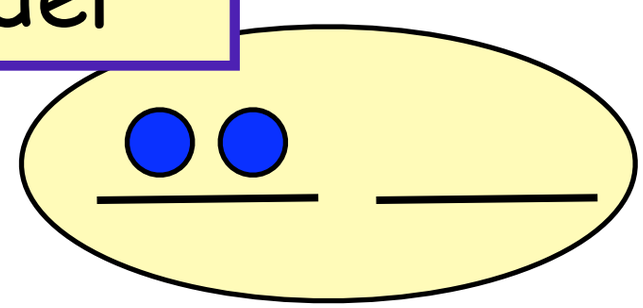
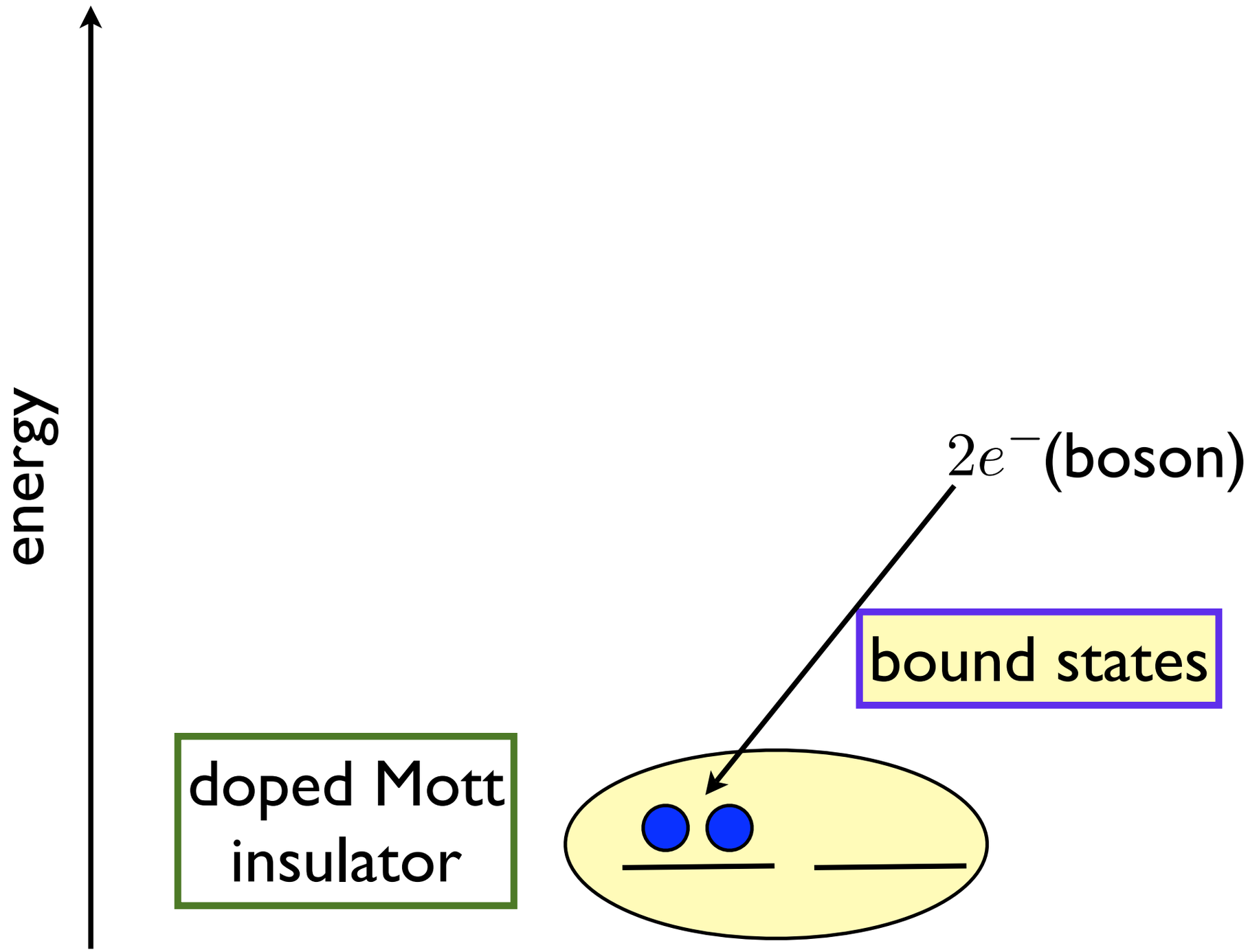
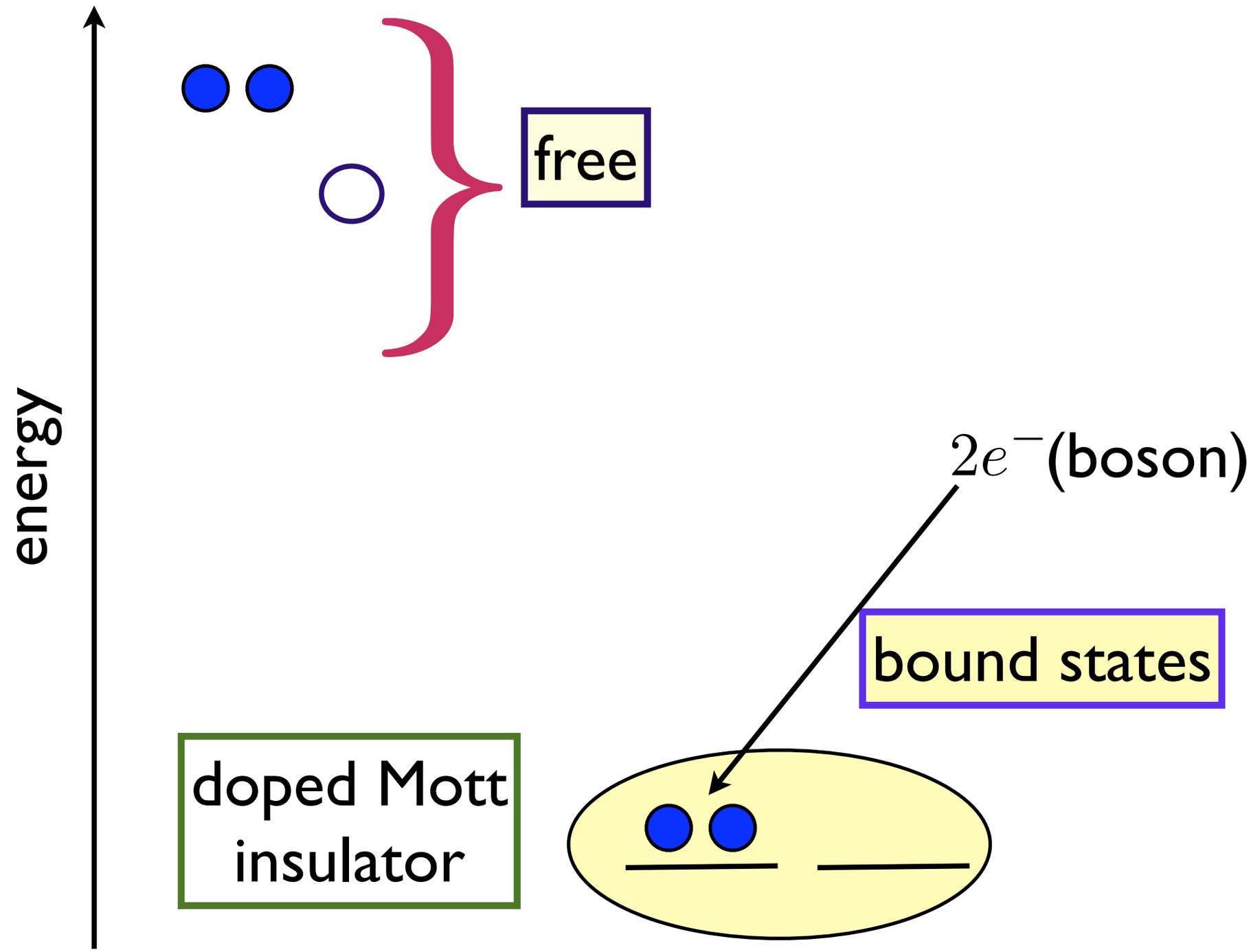
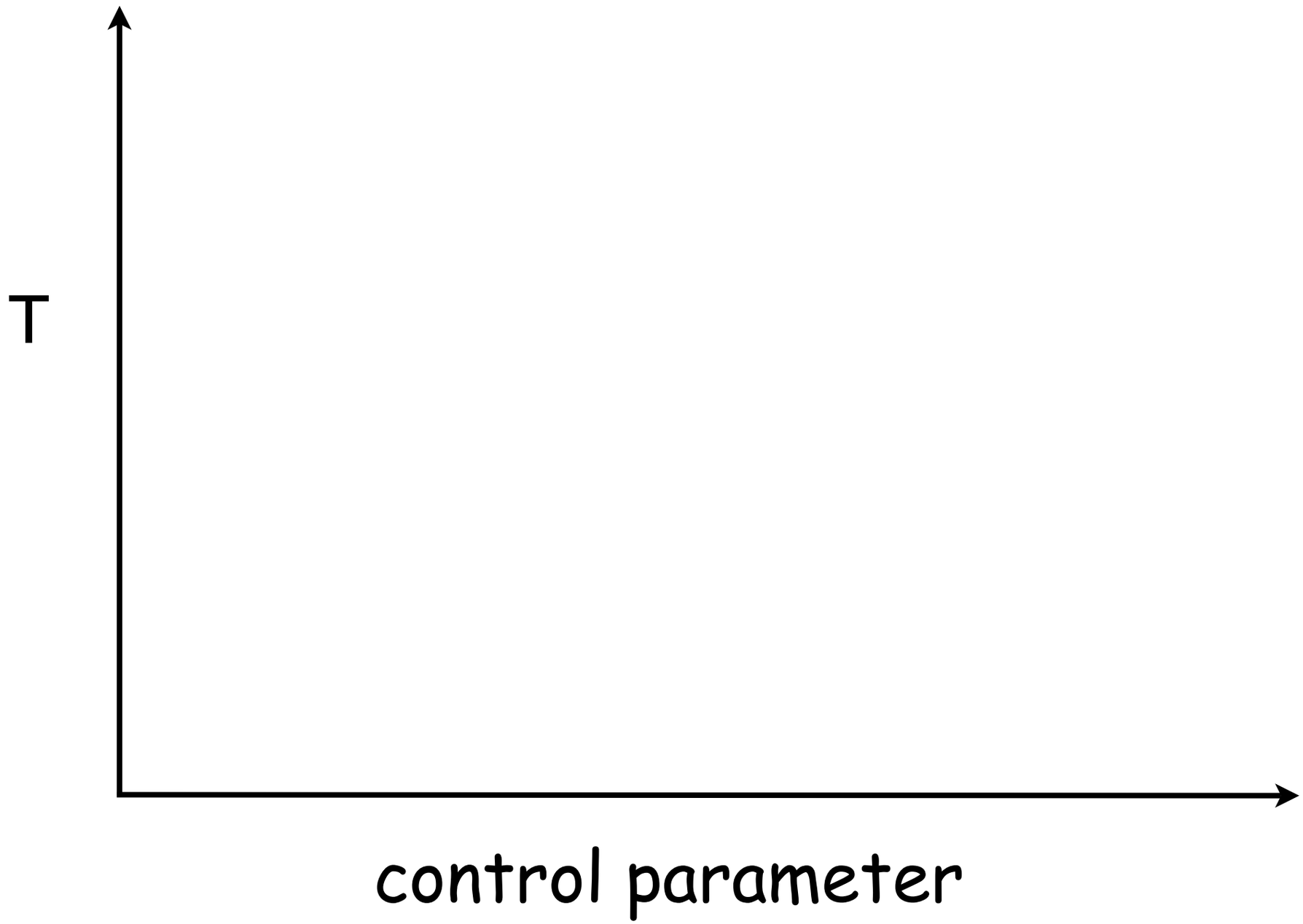


New bound state

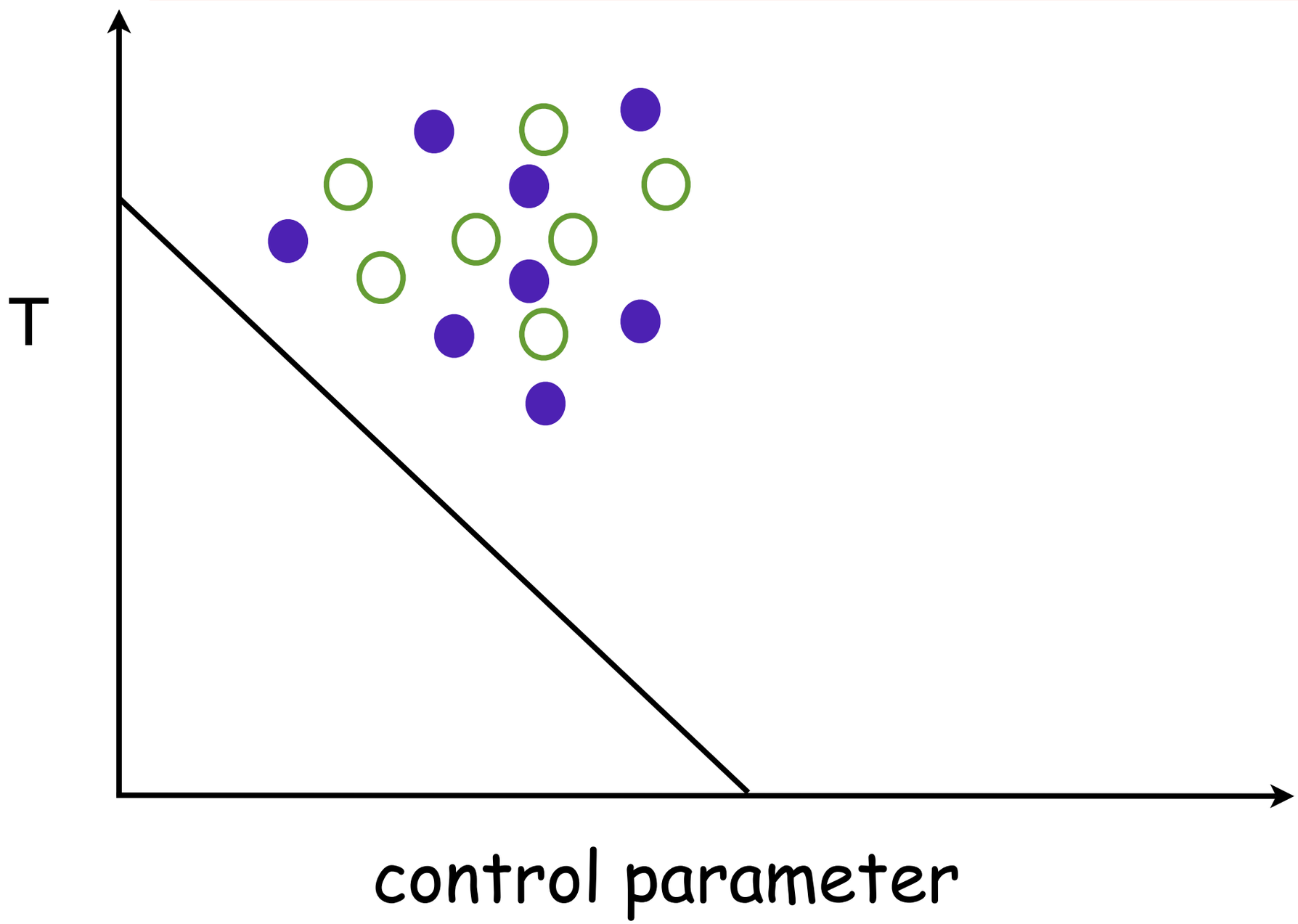

energy
$2e^-$(boson)
bound states
doped Mott insulator


energy
free
$2e^-$(boson)
bound states
doped Mott insulator

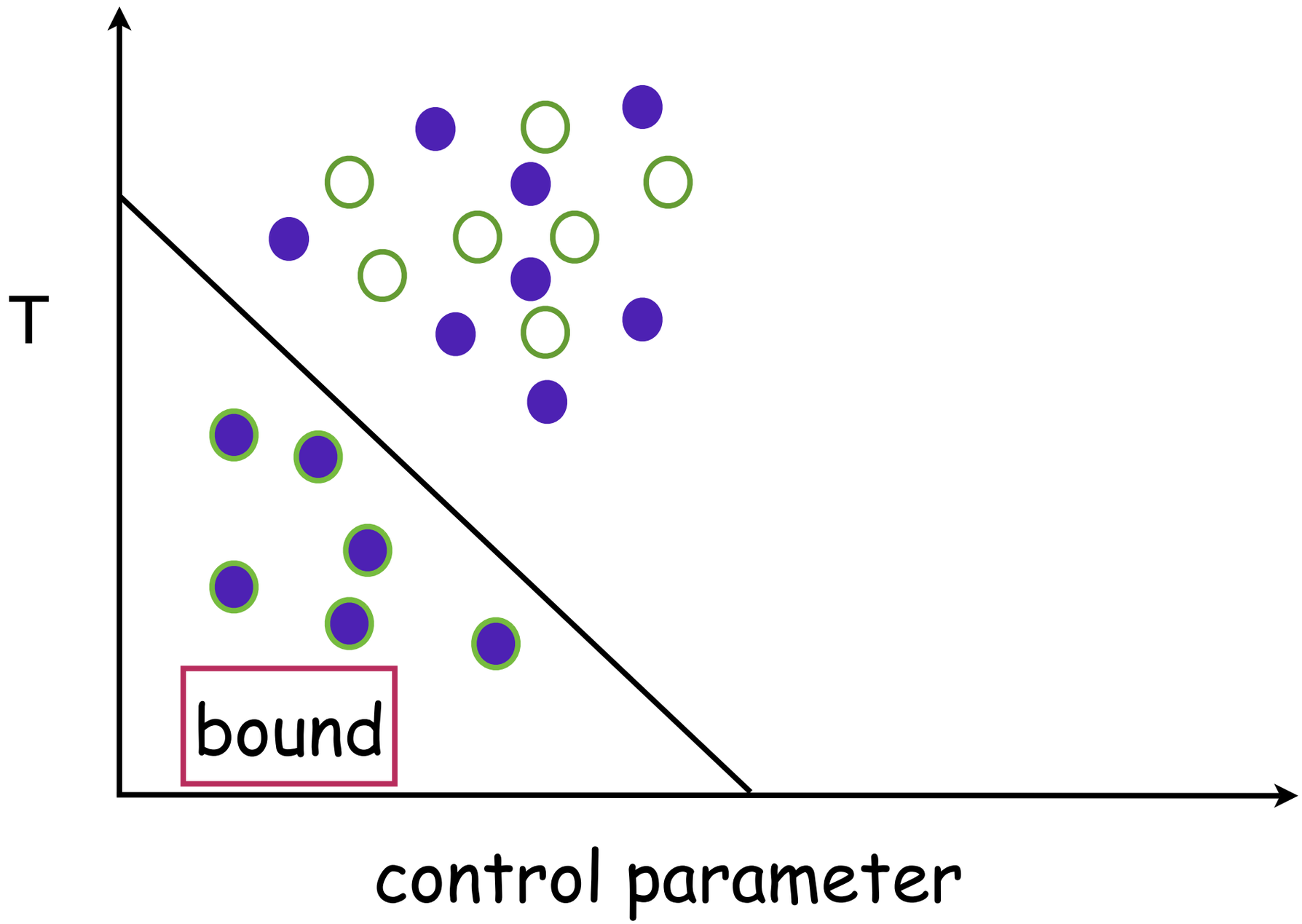
new model of doped Mott insulator

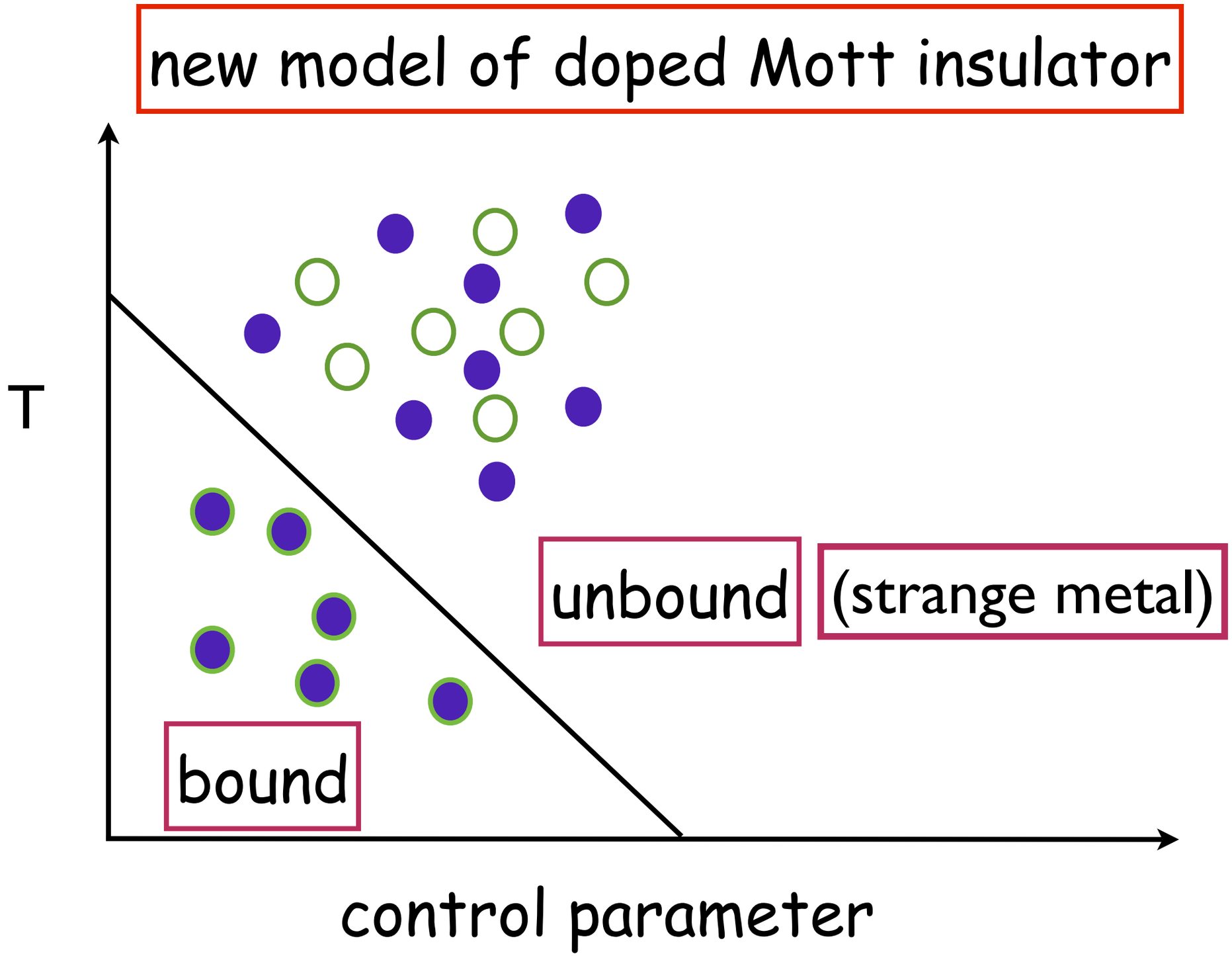


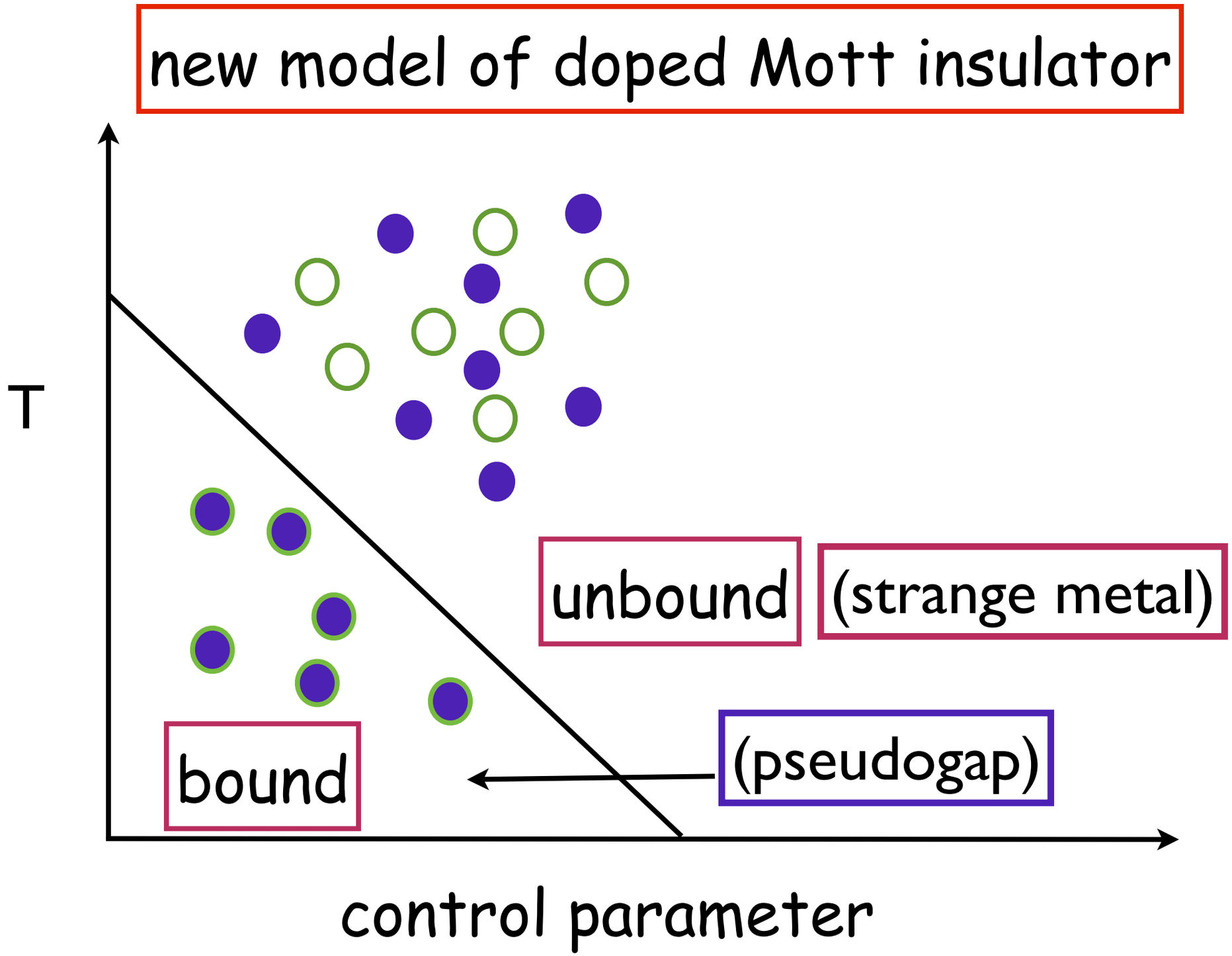
new model of doped Mott insulator

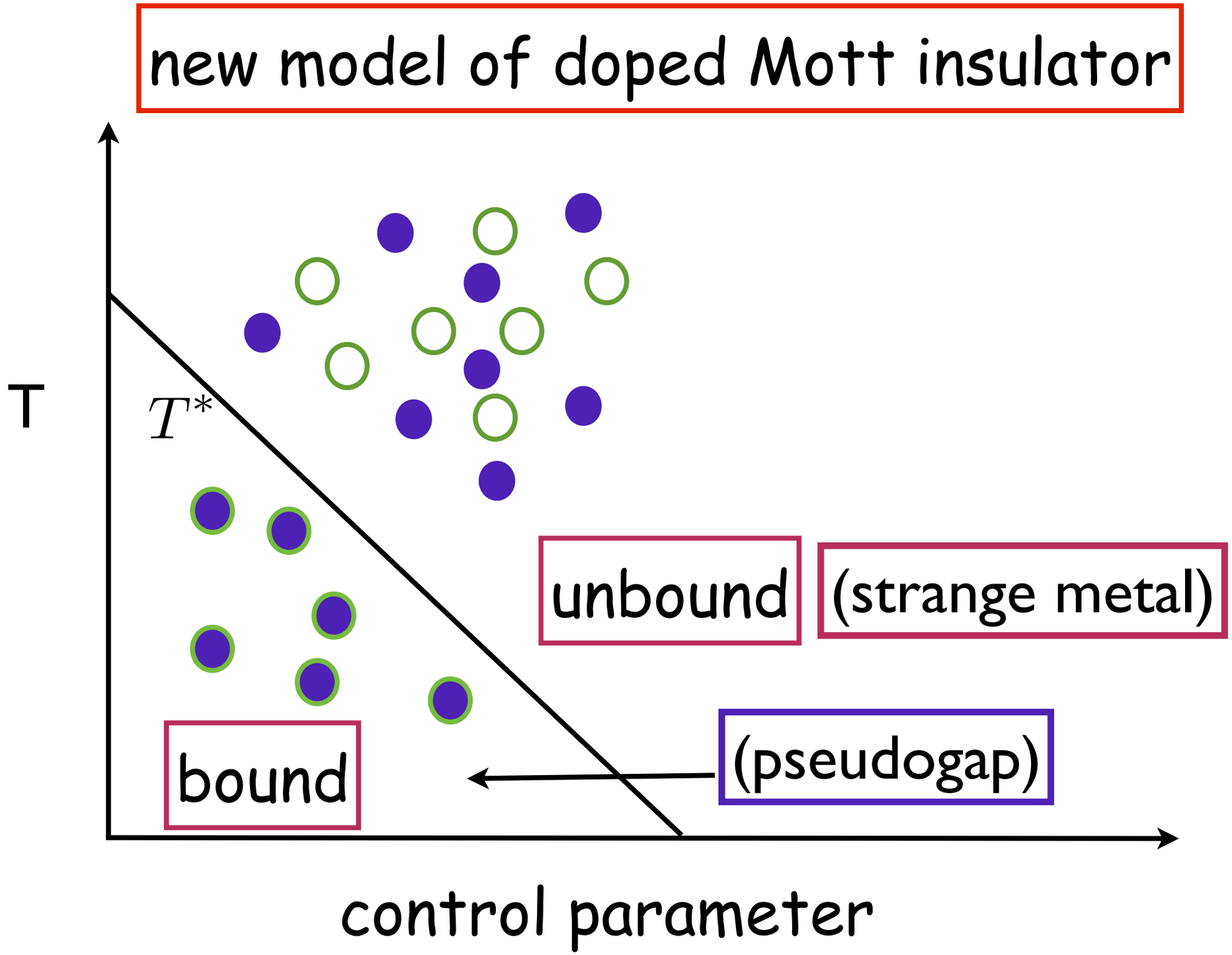


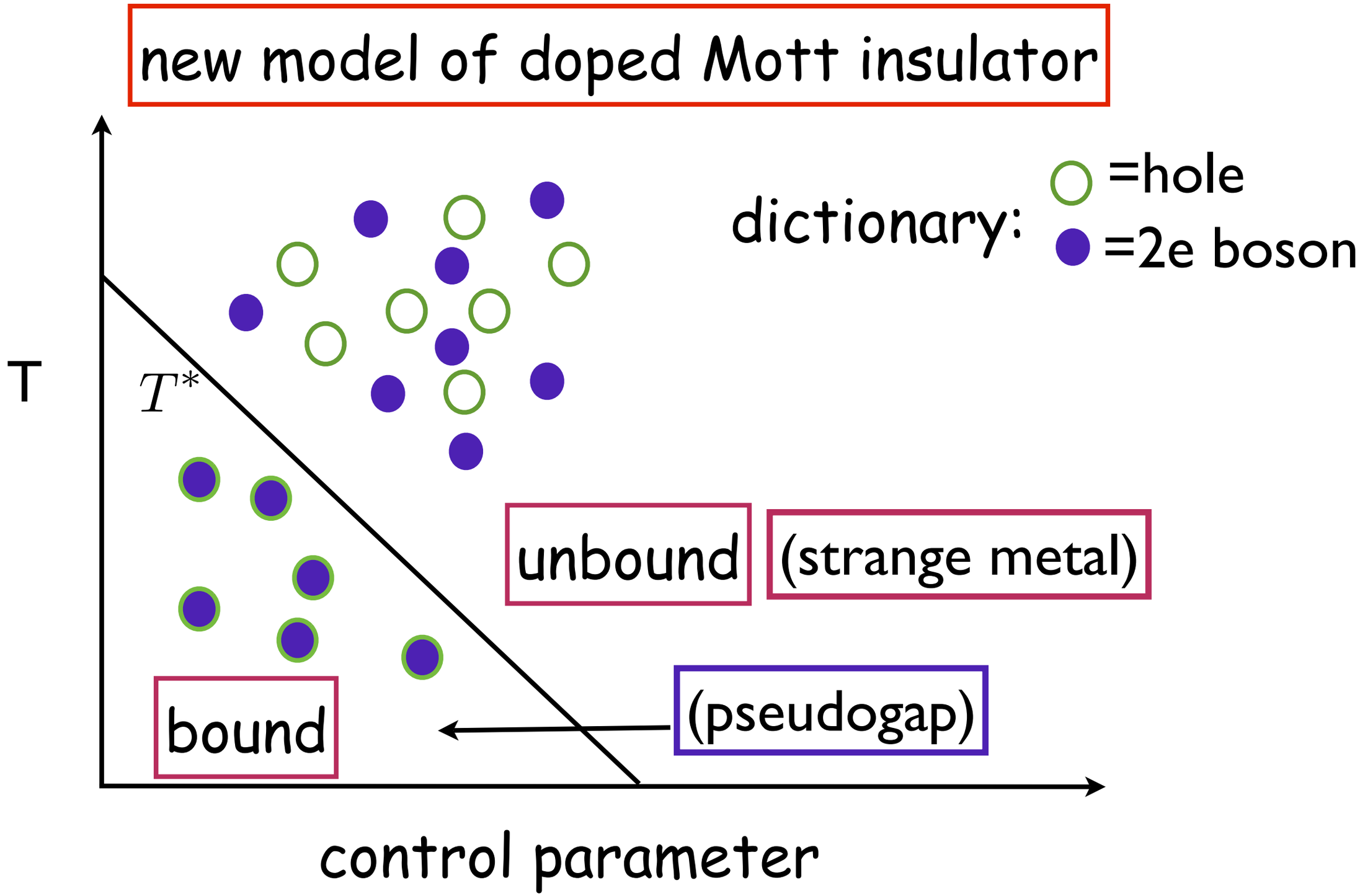
new model of doped Mott insulator

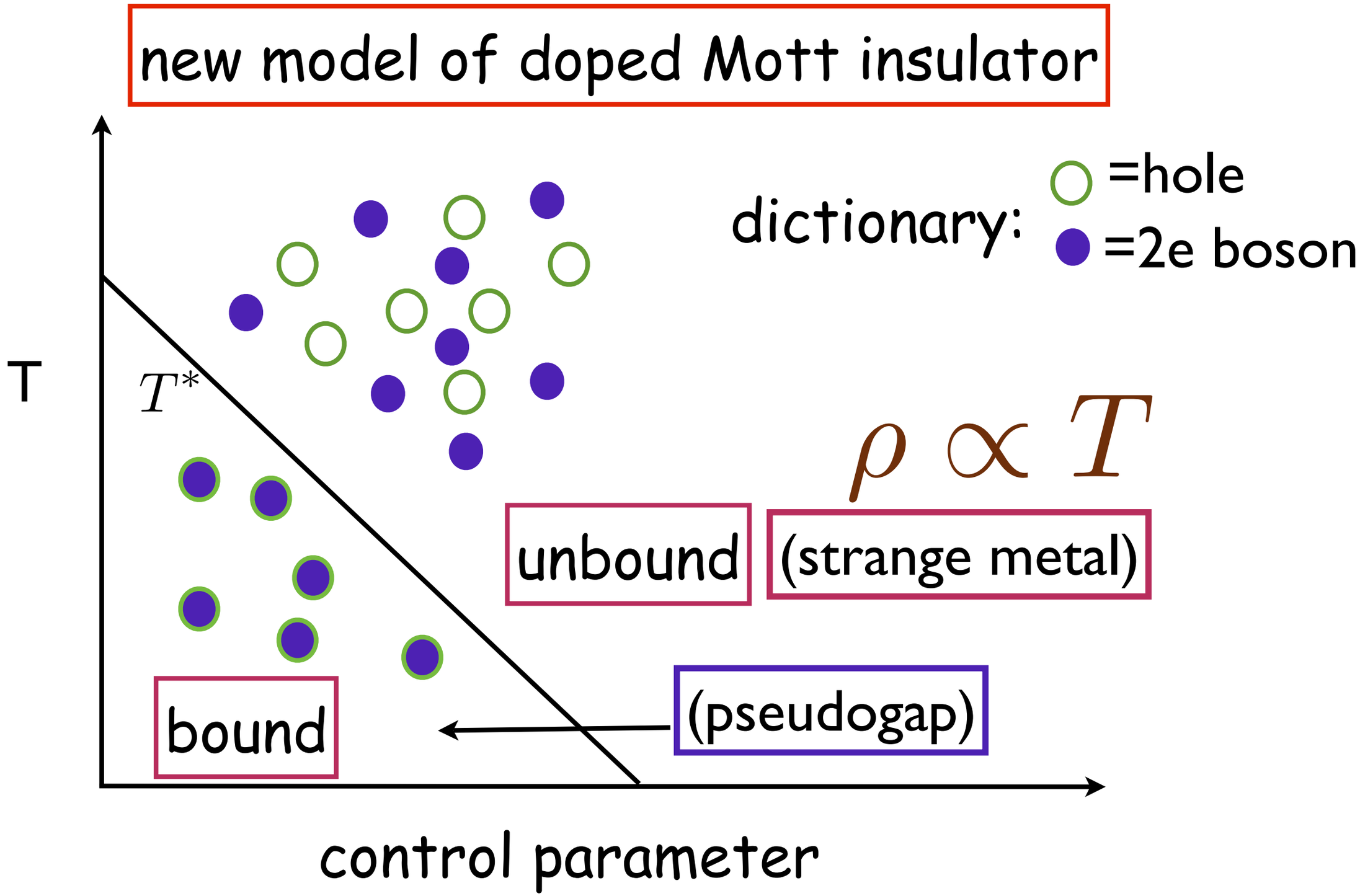



new model of doped Mott insulator
T
unbound
(strange metal)
bound
control parameter

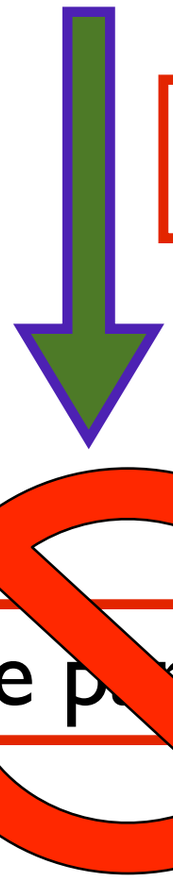

new model of doped Mott insulator
T
unbound
(strange metal)
bound
(pseudogap)
control parameter


new model of doped Mott insulator
T
T^*
unbound
(strange metal)
bound
(pseudogap)
control parameter


new model of doped Mott insulator
dictionary:
=hole
=2e boson
T
T^*
unbound
(strange metal)
bound
(pseudogap)
control parameter


new model of doped Mott insulator
dictionary:
=hole
=2e boson
T
T^*
$\rho \propto T$
unbound
(strange metal)
bound
(pseudogap)
control parameter

Mottness: Strong Coupling



low-energy reduction

composite or bound states not in UV theory

Pseudogap=confinement

Key Experimental Prediction:

More particle addition states at low temperature than at high (T*)

superconductivity?

superconductivity?

Thanks to: T.-P. Choy, R. Leigh, NSF

Superconductivity

POWERING THE FUTURE

PROGRESS AND PROMISE

1986

- First HTS discovery: lanthanum-barium-copper-oxide by Bednorz and Müller

1987

- Yttrium-barium-copper-oxide HTS T_c = 93K

1988

- Bismuth-strontium-calcium-oxide HTS T_c = 110K
- First HTS thin film

1989

- First BSCCO/silver HTS wire
- Thallium-barium-calcium-copper-oxide HTS T_c = 125K

1990

- Initial HTS coils built
- 10-meter lengths of BSCCO/silver wire manufactured
- First HTS motor demonstrated (dc)

1991

- DC HTS motor output reaches 0.03 horsepower

1992

- 1-meter HTS cable conductor demonstrated
- World Record, 2,000 ampere HTS current leads developed

1993

- World's first synchronous motor using HTS coils - 2 hp output
- World Record, 2.5 tesla HTS coil demonstrated
- 100-meter lengths of BSCCO/silver wire manufactured

1994

- 1-kilometer BSCCO/silver wire carries over 20 kA/cm²
- 5-hp synchronous motor with rotating HTS field coils cooled to 77K
- Lab-scale TBCCO wire samples surpass 200 kA/cm²
- 1,100 ampere, 1-meter cable demonstrated

1995

- 2 tesla, refrigerator cooled magnet demonstrated
- World record, 3.0 tesla coil demonstrated
- 2,300 ampere, 1-meter cable demonstrated
- Produced flexible coated YBCO/IBAD-PLD tape conducting 200 A/cm-width at 1 million A/cm²

1996

- 250-horsepower HTS motor demonstrated and exceeds design goals by 60%
- 2.4 kV HTS current controller demonstrated and exceeds design goals by 37%
- 50-meter underground HTS power cable built

1997

- World record, 4 tesla HTS coil at 4.2K
- Demonstrated a 1 MVA single-phase HTS transformer
- 100 A/cm-width demonstrated with e-beam deposited YBCO on RABITS
- First continuously processed YBCO meter tapes (IBAD-PLD) produced in U.S.

1998

- Achieved J_c = 1.6 MA/cm² (BaF_2 method) & J_c = 3.0 MA/cm² in YBCO/RABITS-PLD tape
- 50 meter HTS cable successfully tested at 115 kV. At 69 kV, carried 3,000 A dc capable of carrying 2,000 A ac (warm dielectric)
- U.S. HTS wire production reached 350 km
- Achieved J_c over 1 million A/cm² by MOCVD technique

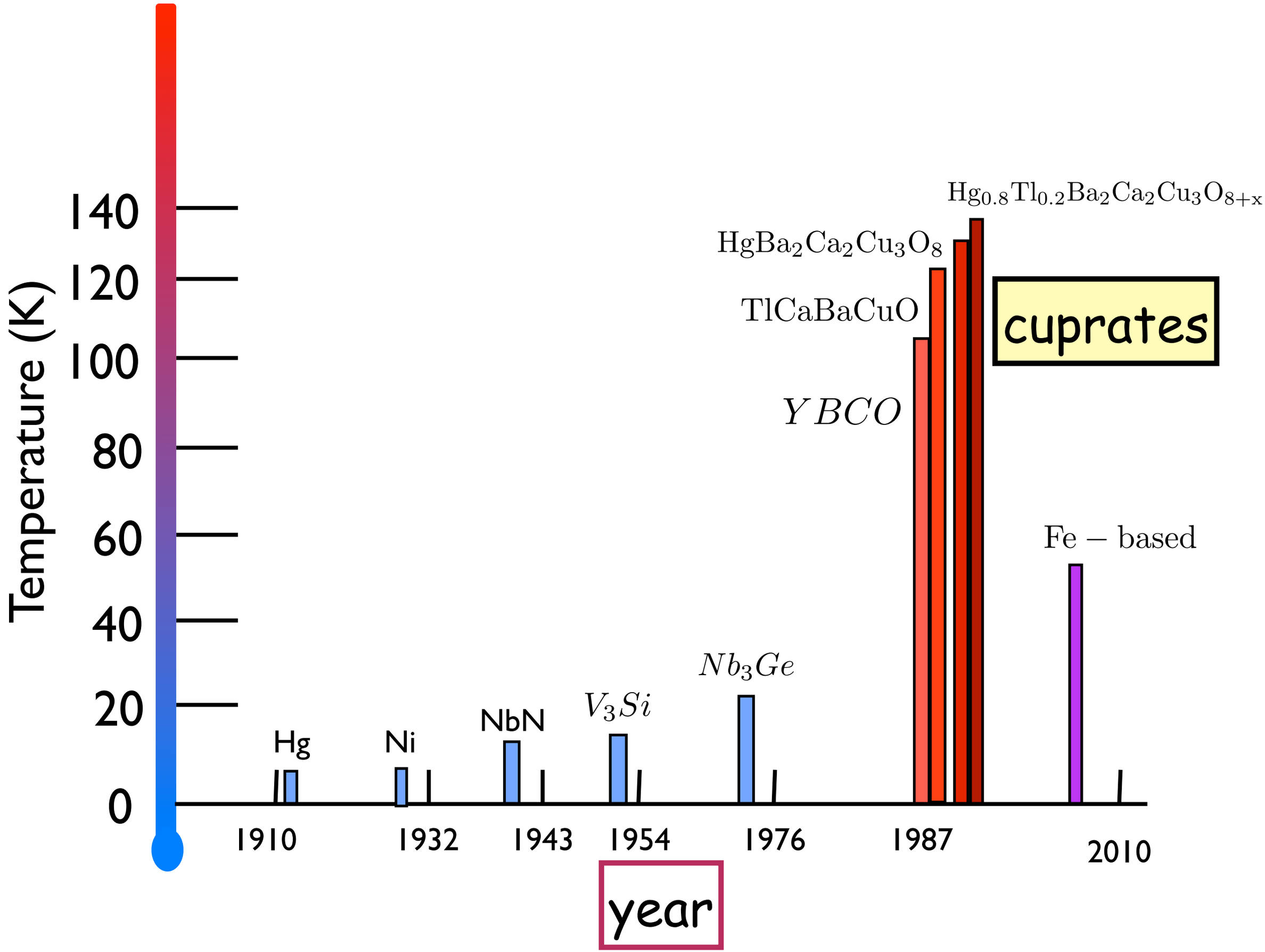
1999

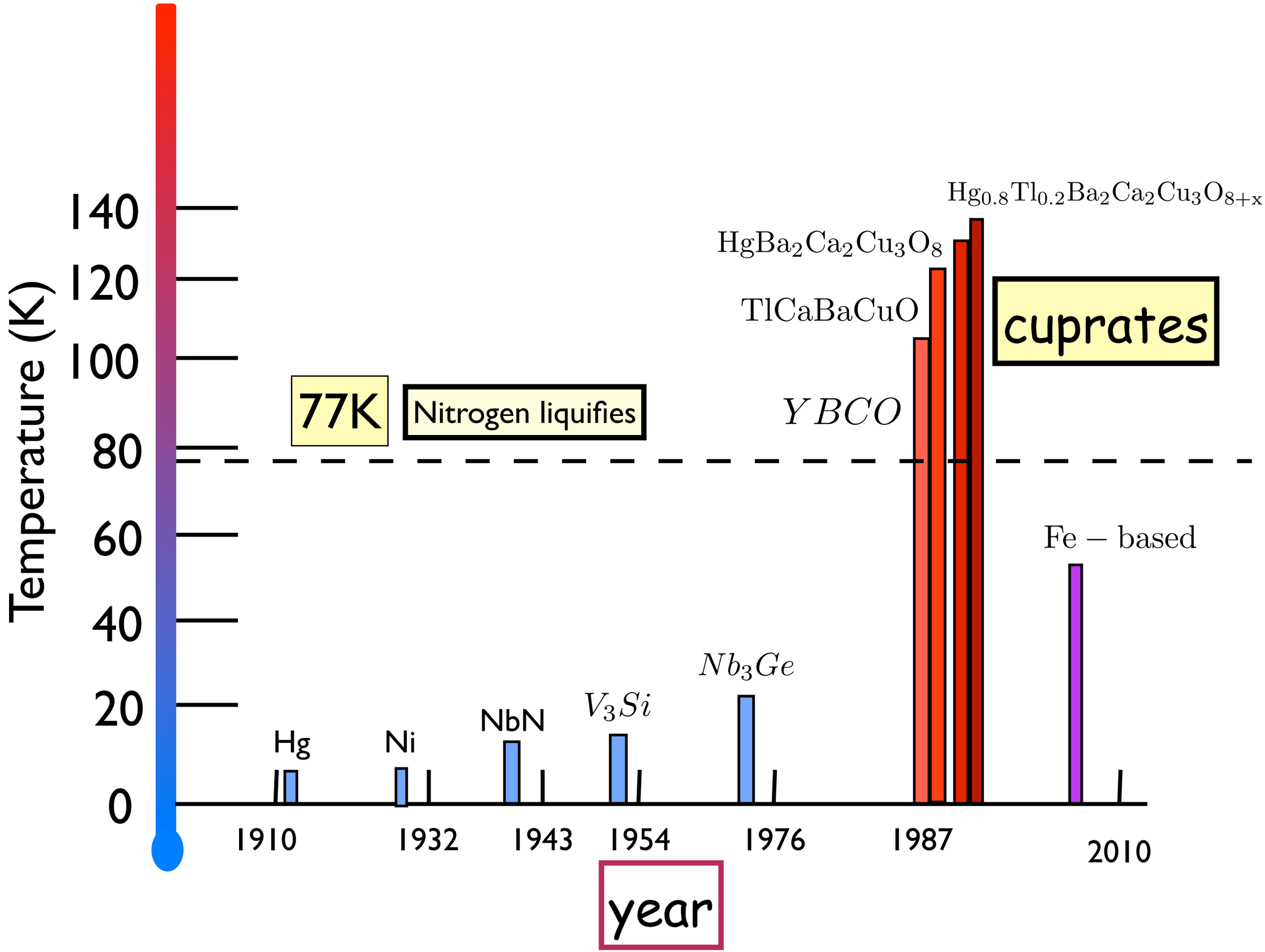
- World's first industrial test of a (3-phase, 12.5 kV, 1,250 A) HTS power cable (cold-dielectric)
- 15 kV HTS current controller tested at utility substation. Carried 9,000 A during fault condition
- World Record, engineering current density of 42,000 A/cm² in YBCO/IBAD-PLD tape
- Produced meter long YBCO tape (IBAD-PLD) carrying 122 A/cm-width
- Industry achieved J_c = 1.9 MA/cm² with MOD (non-vacuum) YBCO film on RABITS

2000

- Achieved J_c > 1 million A/cm² (I_c > 200 A/cm-width) with flexible tapes containing low-cost IBAD MgO and PLD YBCO films
- Developed ISD process for rapid deposition of textured templates
- Designed & tested 3 kW flywheel electricity system using HTS bearings & scalable to a 100 kW/10 kWh system
- Built & tested 1,000 hp HTS motor. Completed design for 5,000 hp HTS motor

U.S. DEPARTMENT OF ENERGY


Temperature (K)
140
120
100
80
60
40
20
0
Hg
Ni
NbN
V_3Si
Nb_3Ge
$HgBa_2Ca_2Cu_3O_8$
TlCaBaCuO
$YBCO$
$Hg_{0.8}Tl_{0.2}Ba_2Ca_2Cu_3O_{8+x}$
cuprates
Fe − based
1910
1932
1943
1954
1976
1987
2010
year


Temperature (K)
140
120
100
80
60
40
20
0
77K
Nitrogen liquifies
Hg
Ni
NbN
V_3Si
Nb_3Ge
$YBCO$
$TlCaBaCuO$
$HgBa_2Ca_2Cu_3O_8$
$Hg_{0.8}Tl_{0.2}Ba_2Ca_2Cu_3O_{8+x}$
cuprates
$Fe-based$
1910
1932
1943
1954
1976
1987
2010
year


Temperature (K)
140
120
100
80
60
40
20
0
1910
1932
1943
1954
1976
1987
2010
year
d_3O_{8+x}
S
d