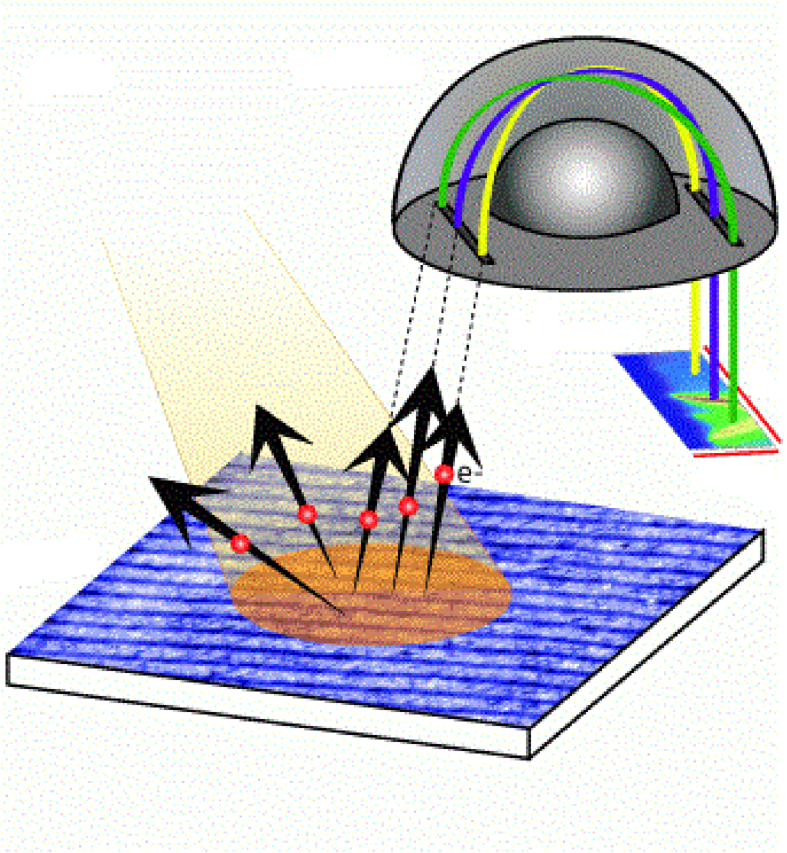
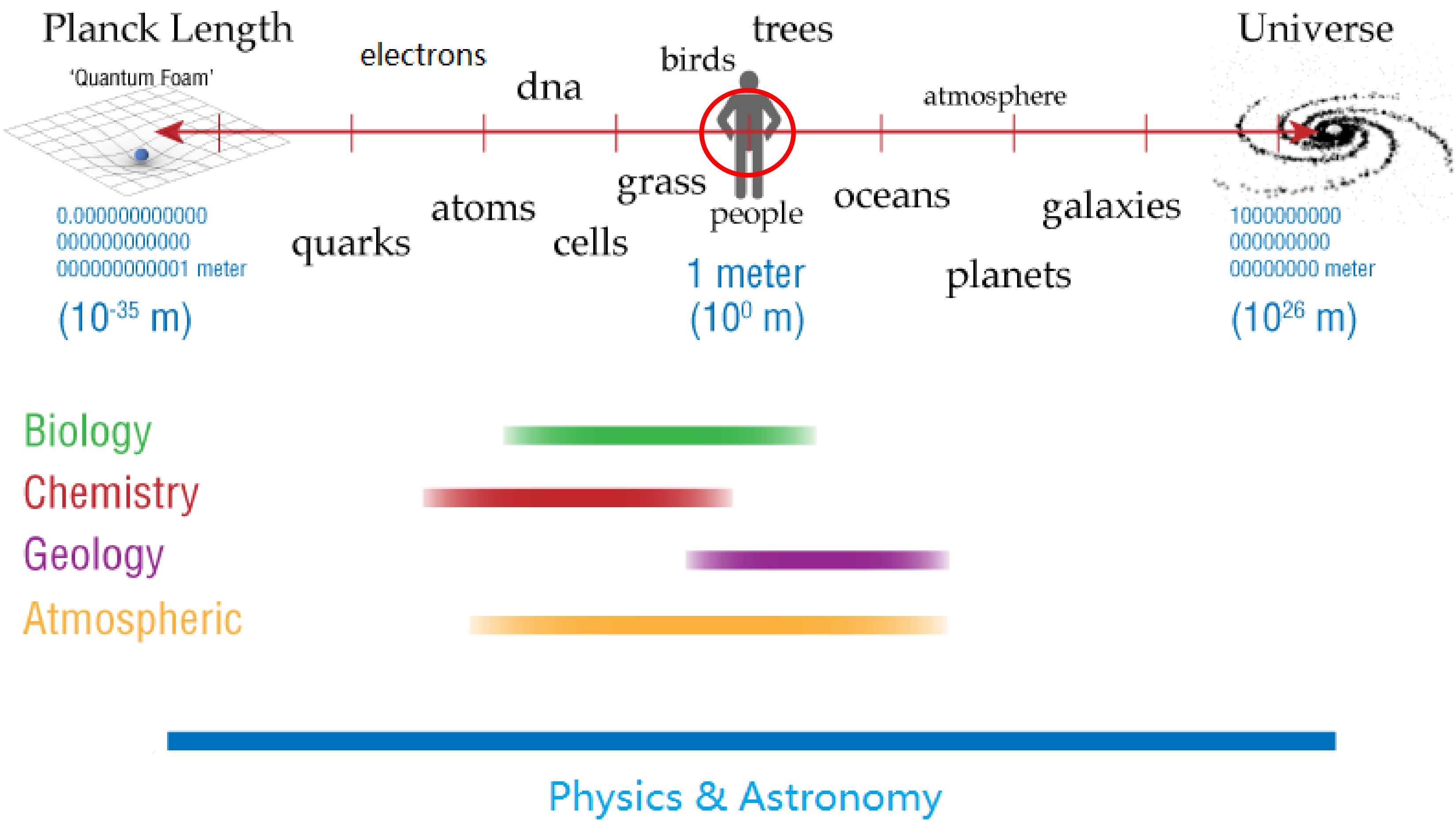
Unveiling Electronic States in Quantum Materials --- ARPES



Junfeng He

University of Science and
Technology of China

The scale of things



Planck Length

'Quantum Foam'

0.000000000000
000000000000
000000000001 meter

$(10^{-35}$ m$)$

electrons

quarks

atoms

dna

cells

grass

birds

trees

people

1 meter

$(10^{0}$ m$)$

atmosphere

oceans

planets

galaxies

Universe

1000000000
000000000
00000000 meter

$(10^{26}$ m$)$

Biology

Chemistry

Geology

Atmospheric

Physics & Astronomy

The stone age – mastering all things stone and bone

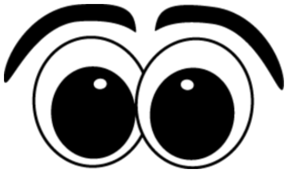
3.3 Million Years

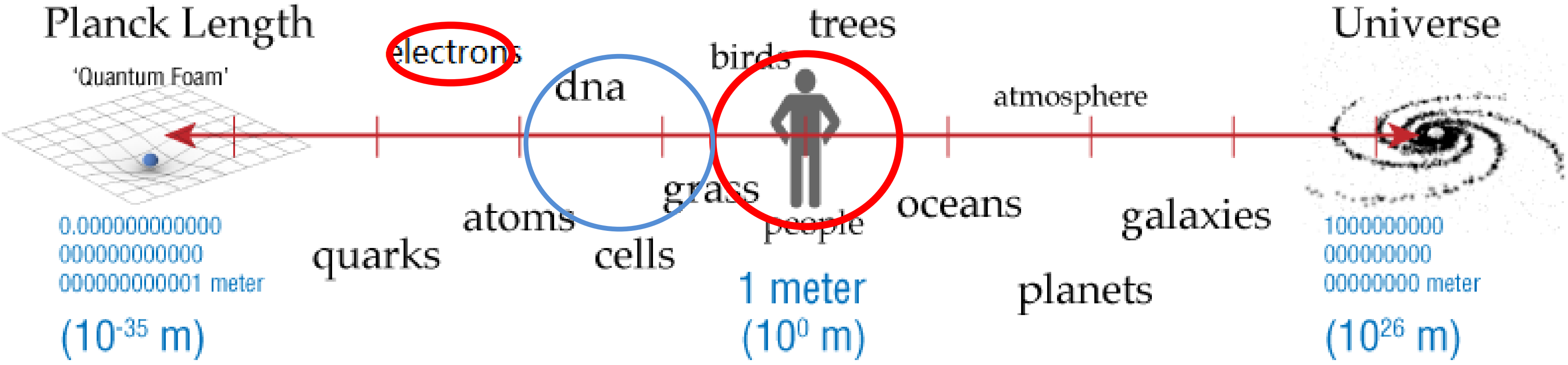
The metals age – mastering all things metal

5000 Years

Expanding the horizon with new tools

Exploring the nature by



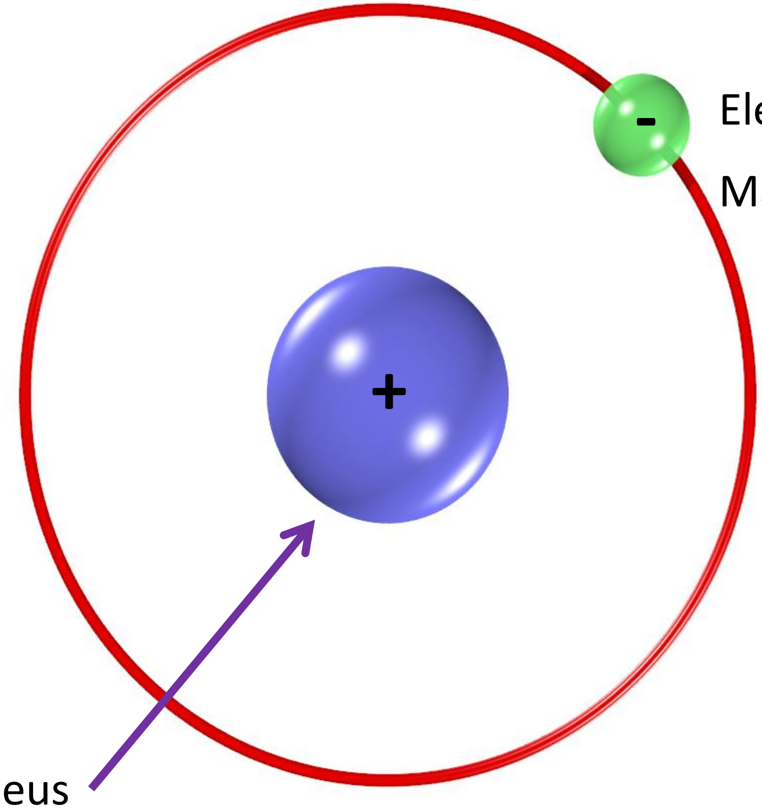


~1600

Electrons in quantum materials

Cartoon Physics

The atom



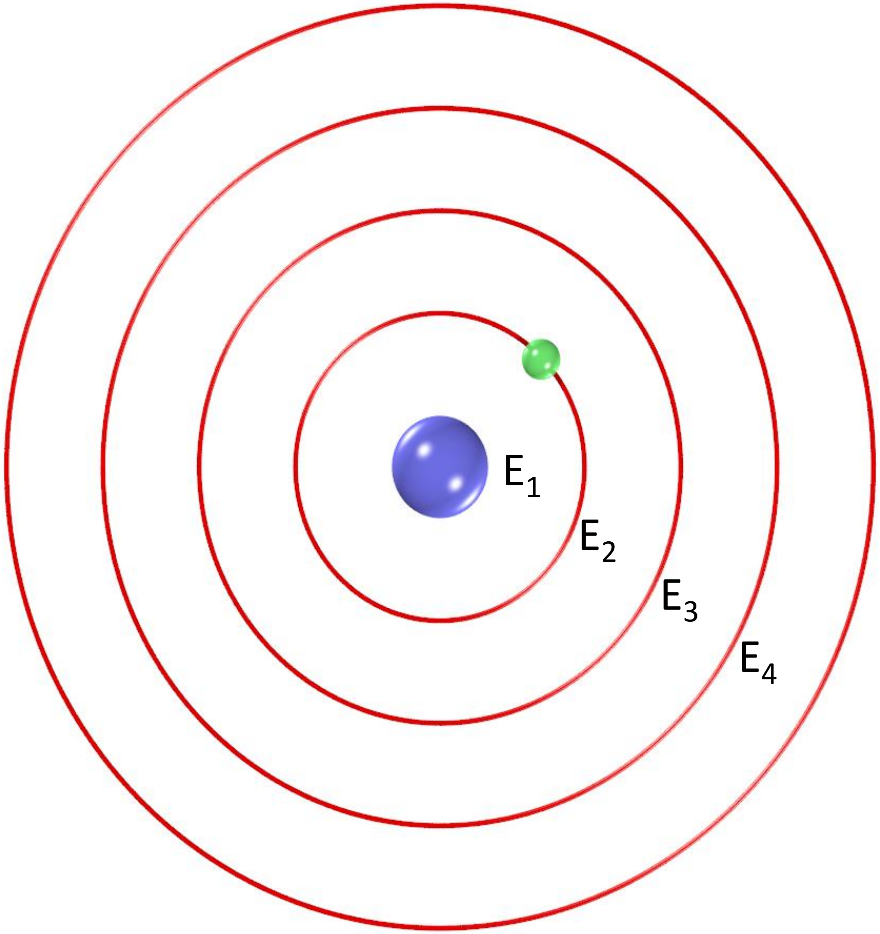
Electron

Mass of electron = 9.1×10^{-31} kg

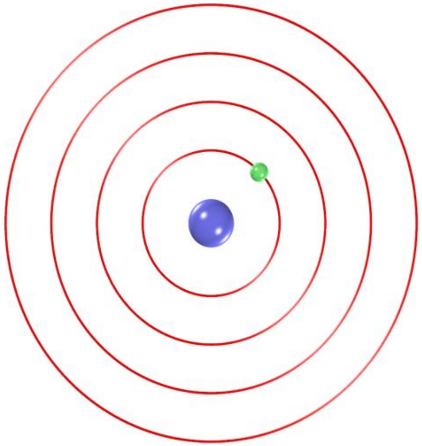
Nucleus

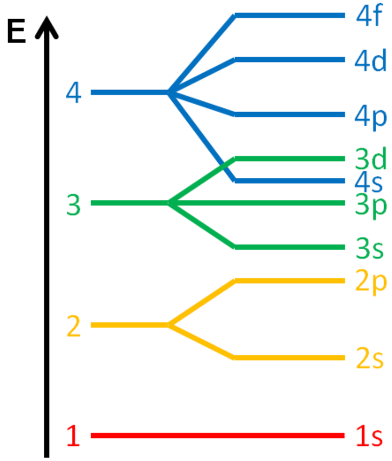
Mass of proton = 1.67×10^{-27} kg
Mass of neutron = 1.67×10^{-27} kg

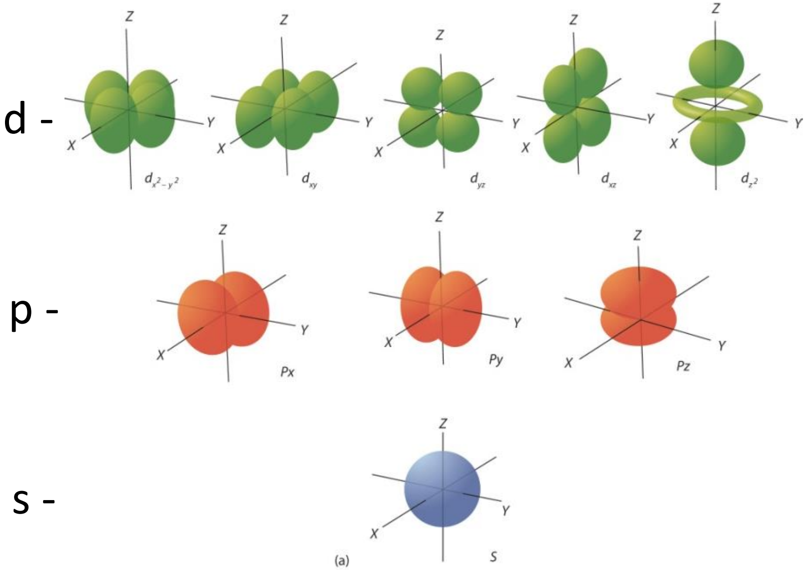
Electron energy levels



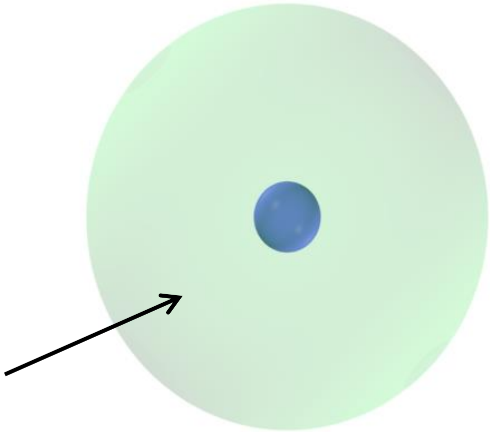
Electron orbitals



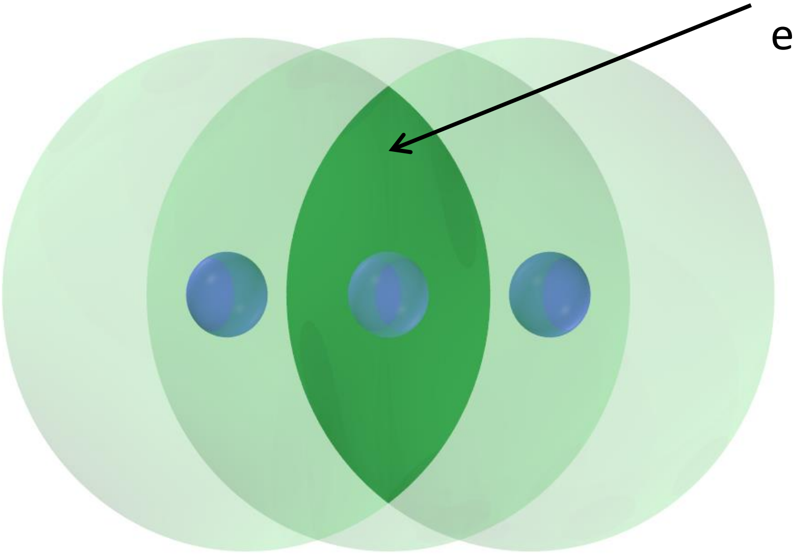




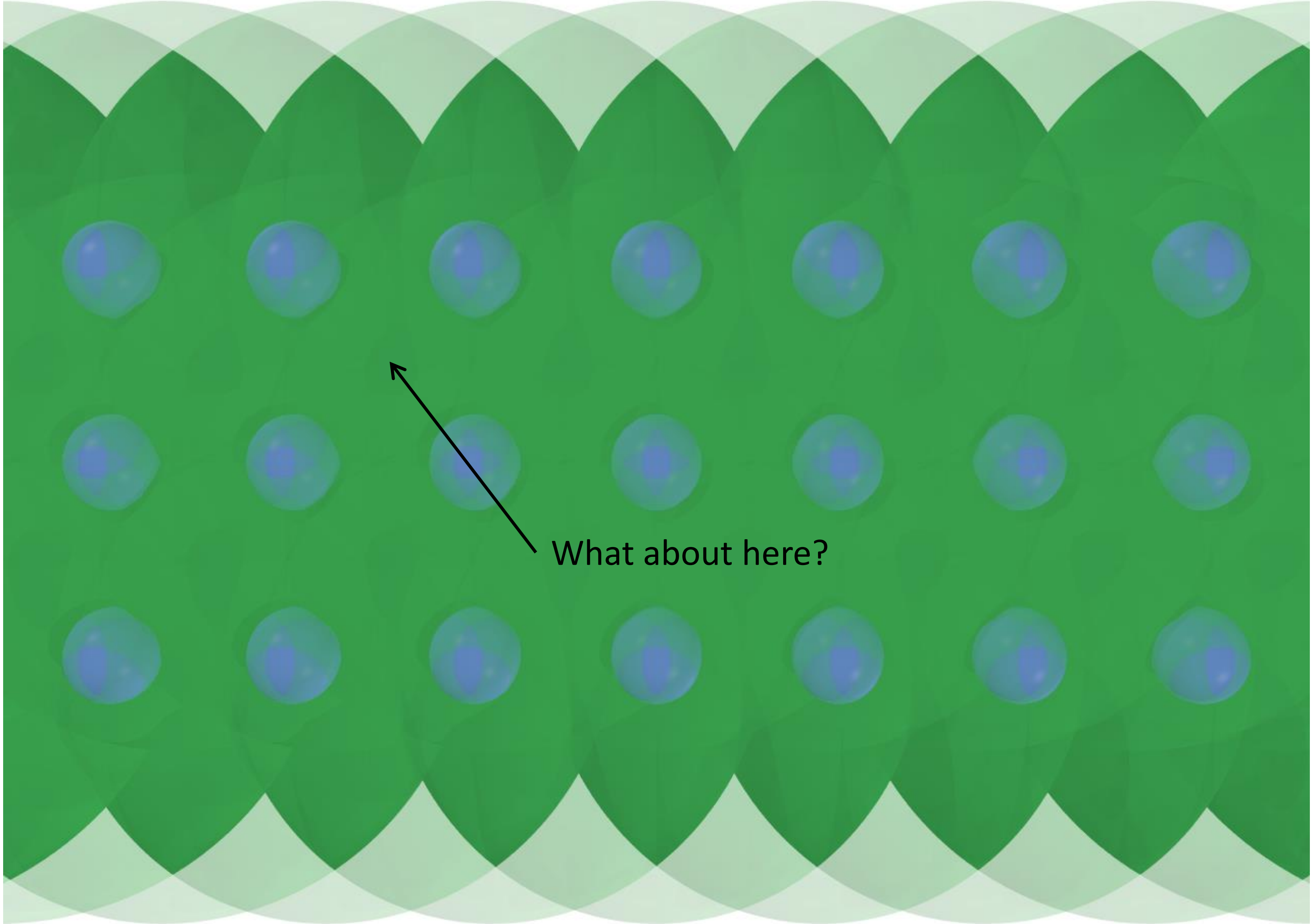
Chain of atoms



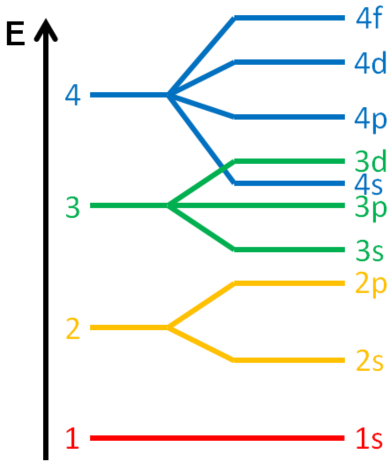
Electron "cloud"

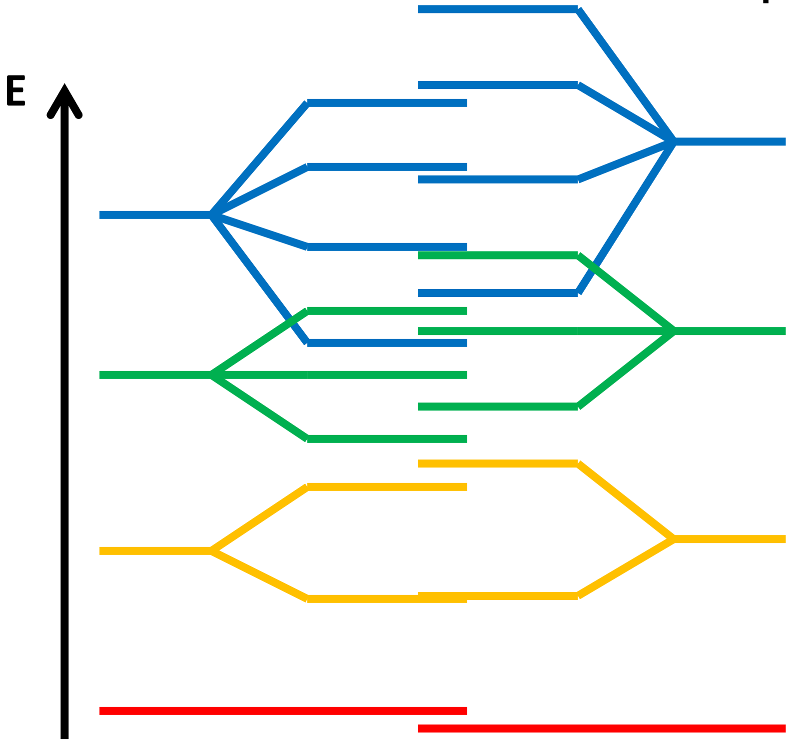


Which atom does an electron here belong to?

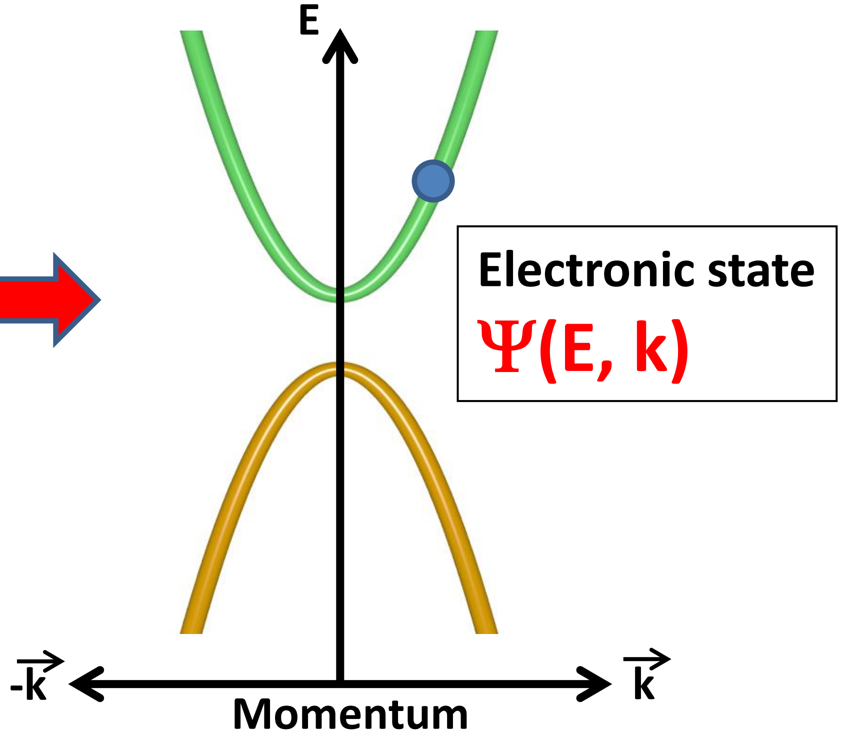

What about here?

Energy bands





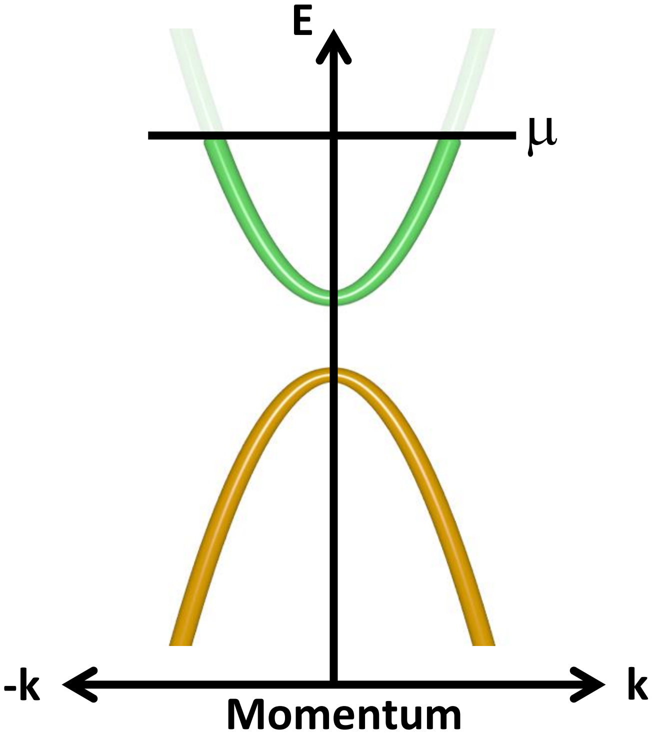
Road map of electrons



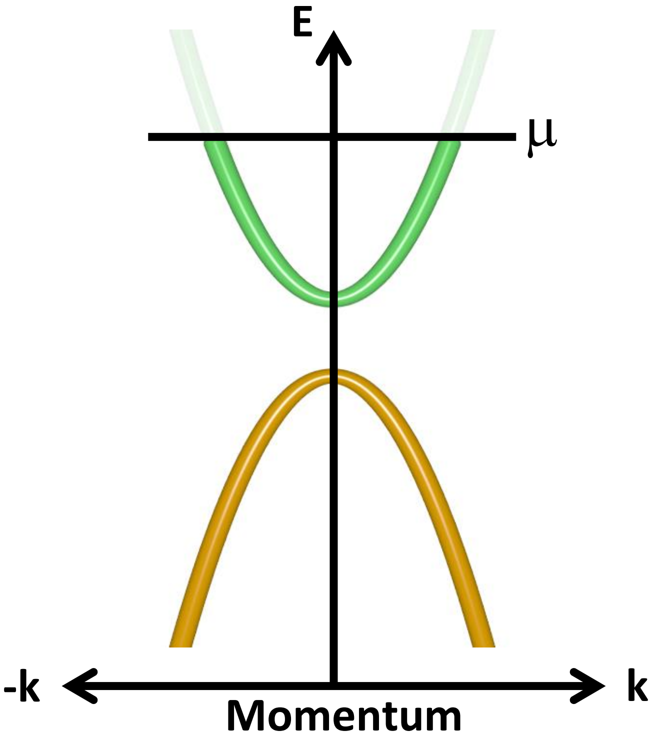
Electronic state

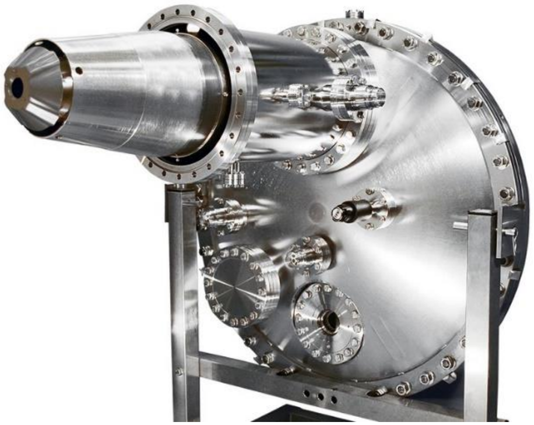
$\Psi(E, k)$

Chemical potential– μ

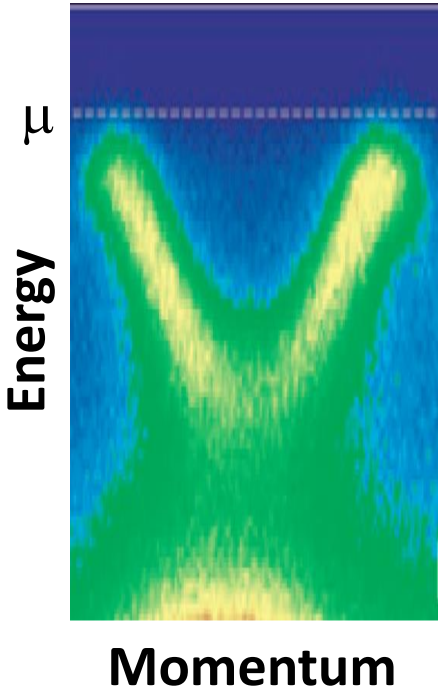


Can we really see the electron energy bands ?



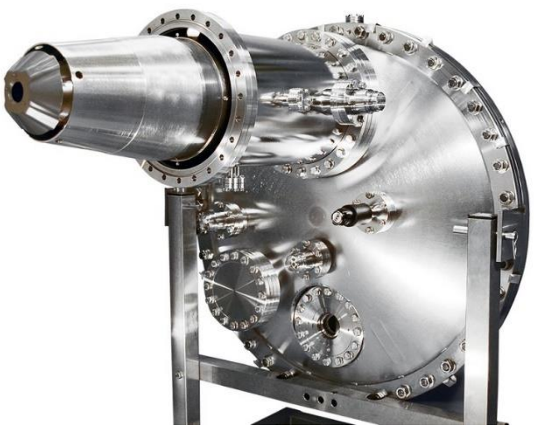


Angle-Resolved Photoemission Spectroscopy

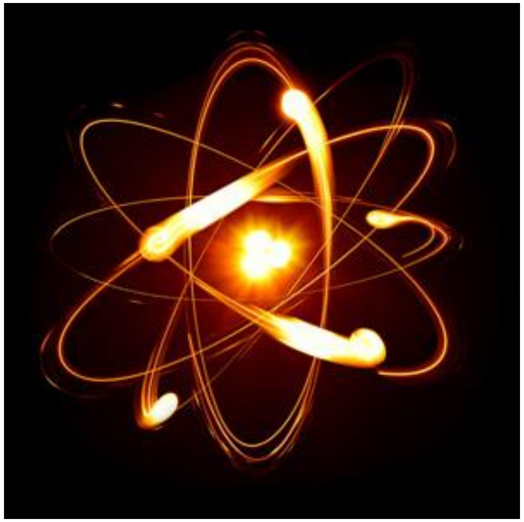


Part I

Angle-Resolved Photoemission Spectroscopy

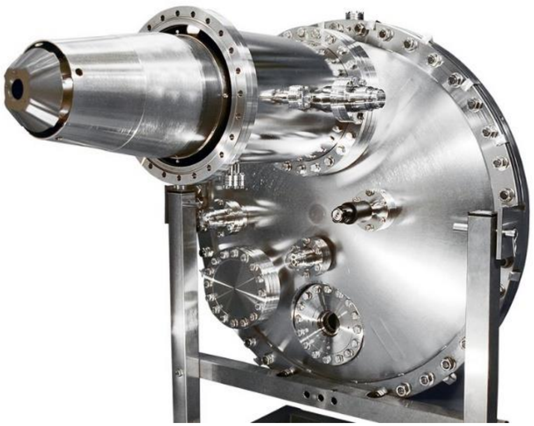


Example:
Understanding quantum phenomena from ***electron energy band***



Part I

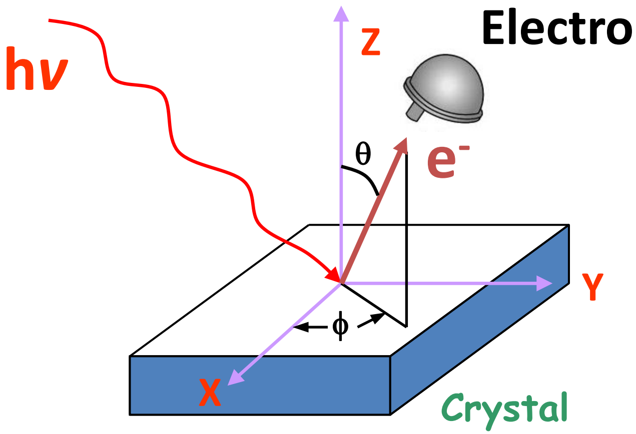
Angle-Resolved Photoemission Spectroscopy



Example:

Understanding quantum phenomena from ***electron energy band***

Angle-Resolved Photoemission Spectroscopy (*ARPES*)



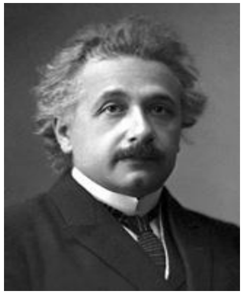
Photoemitted electrons

Kinetic Energy: E_{kin}
Momentum: K

Energy Conservation: $E_B = h\nu - E_{kin} - \Phi$
Momentum Conservation: $K_{||} = k_{||} + G_{||}$

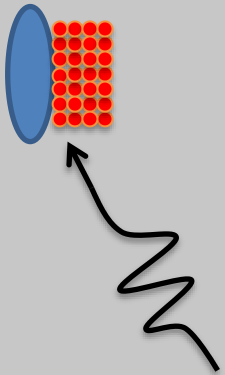
Electronic state in solid:

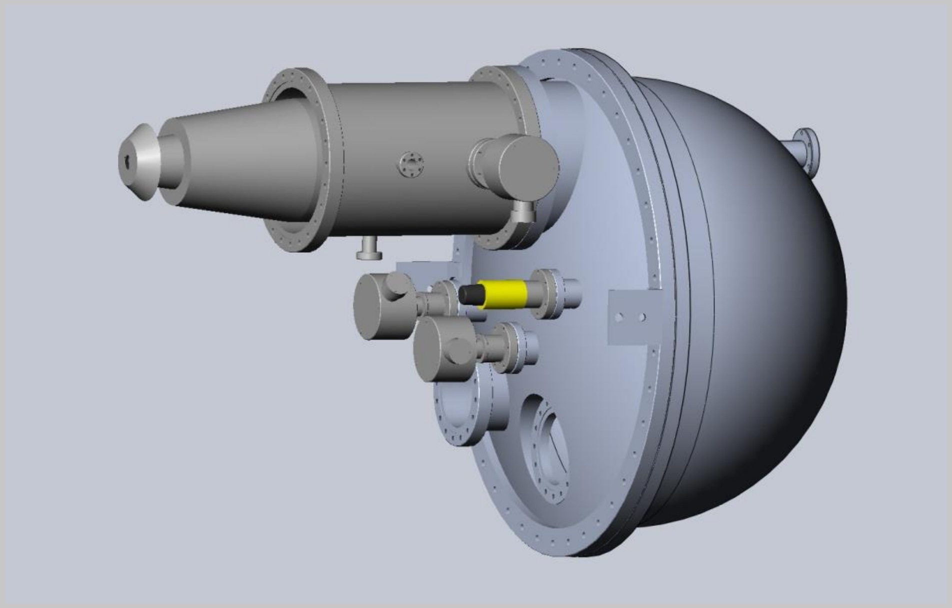
$$\Psi(E_B, k_{||})$$

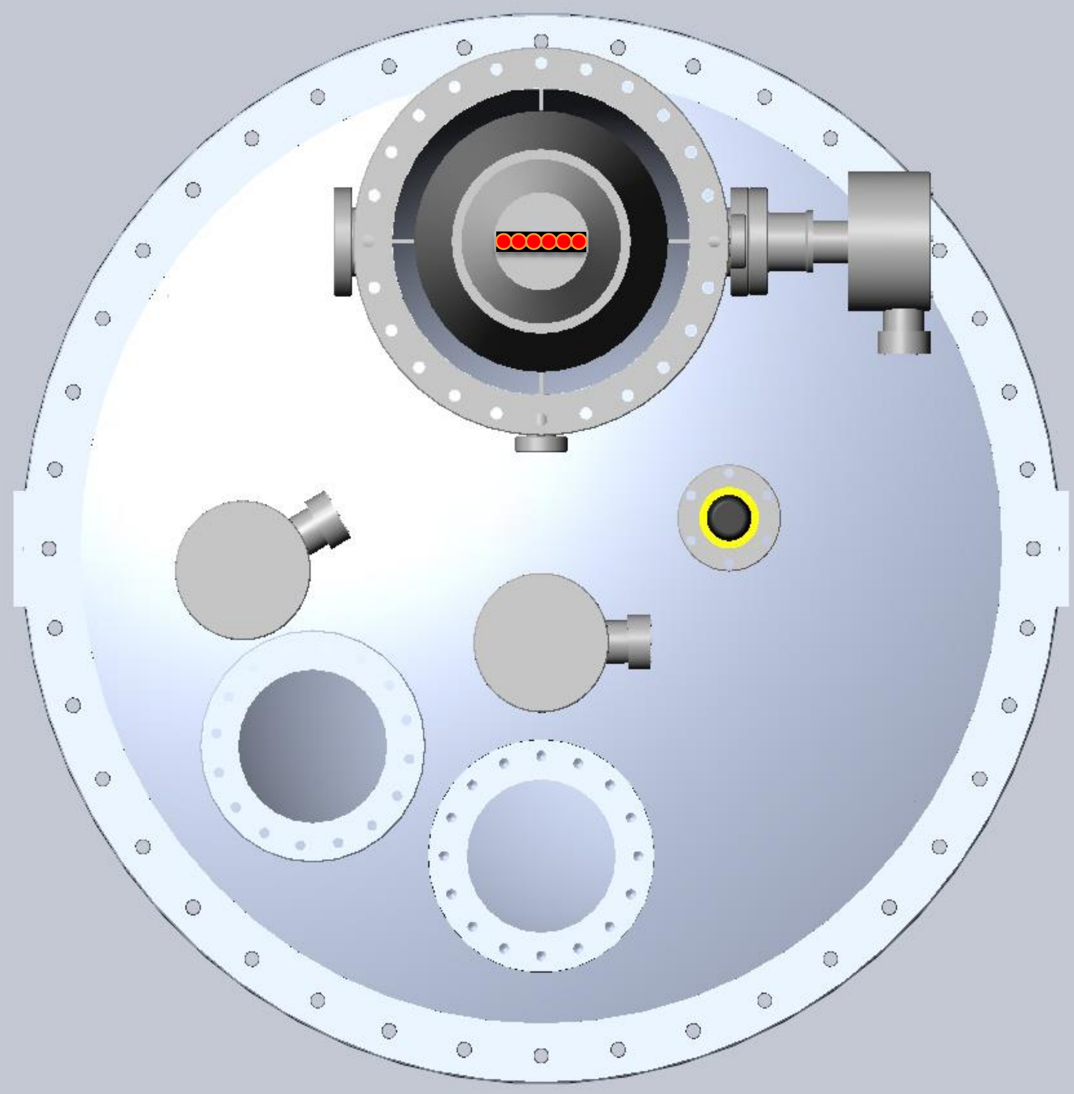


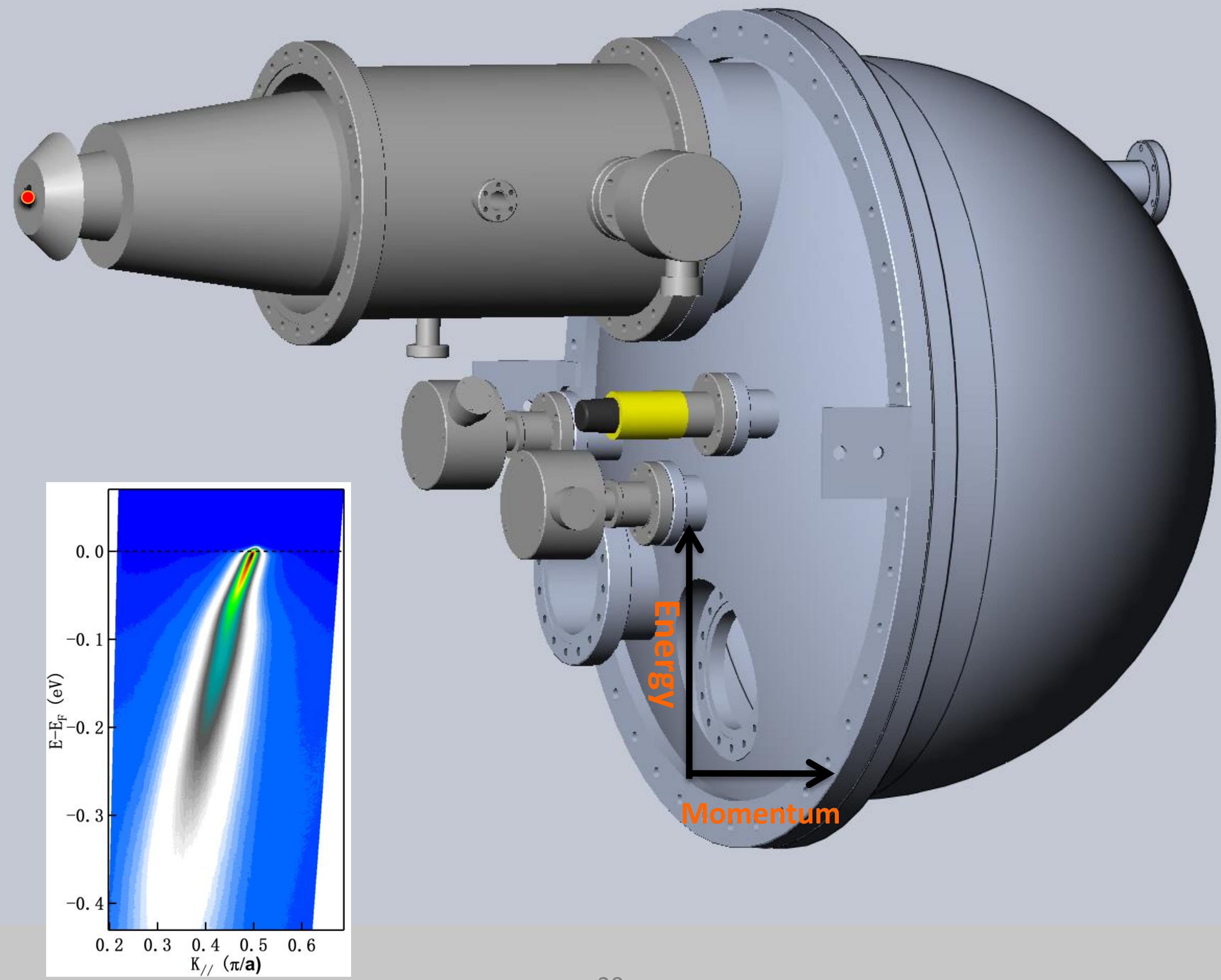
The Nobel Prize
in Physics 1921

The law of The Photoelectric Effect



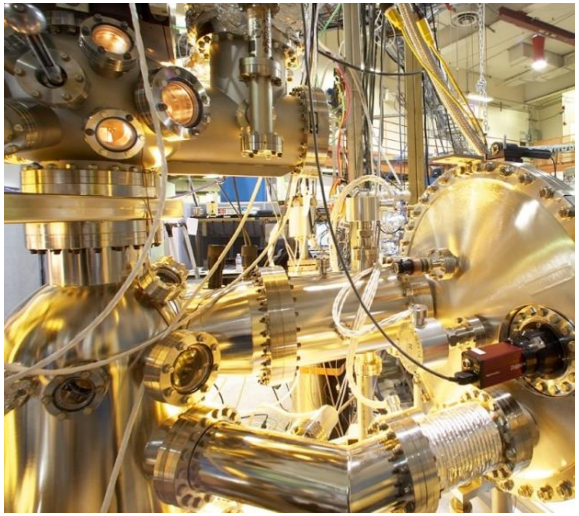




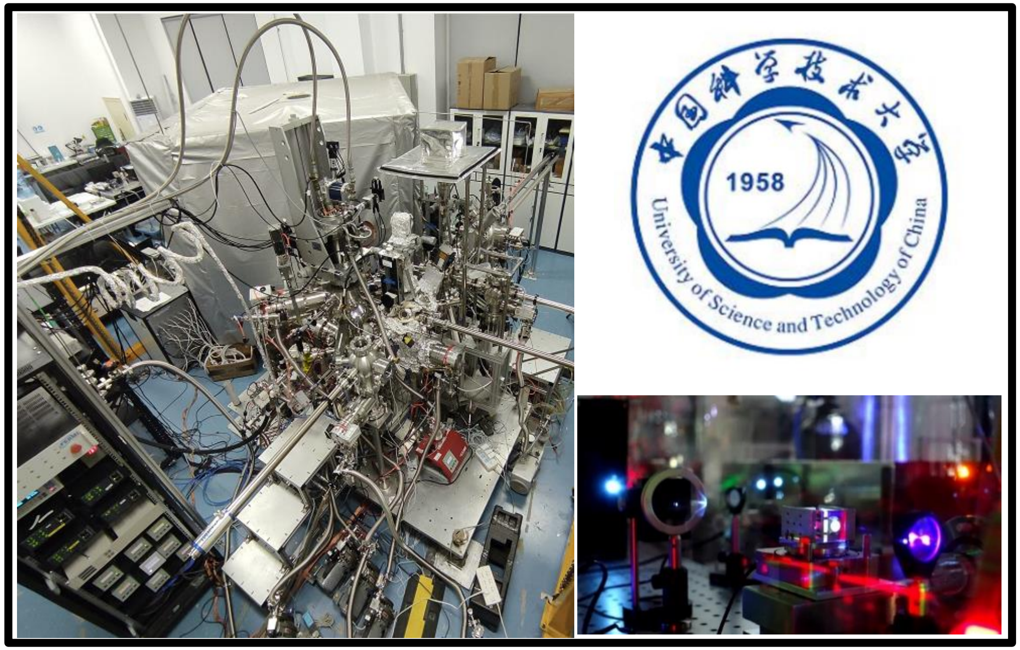

Energy
Momentum
0. 0
−0. 1
−0. 2
−0. 3
−0. 4
E−E_F (eV)
0. 2
0. 3
0. 4
0. 5
0. 6
$K_{//}$ (π/a)

State-of-the-art ARPES systems

Synchrotron ARPES

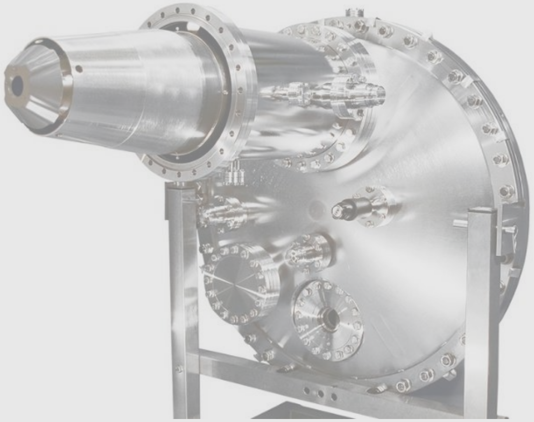


Laser ARPES



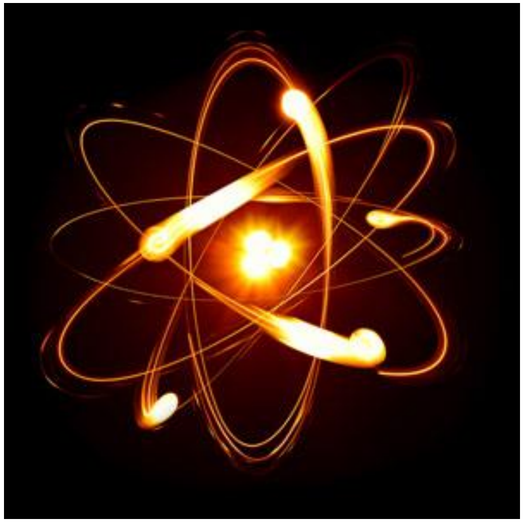
Part I

Angle-Resolved Photoemission Spectroscopy



Example:

Understanding quantum phenomena from ***electron energy band***



Example: extreme magnetoresistance

Magnetoresistance — **Resistance** increases under magnetic filed

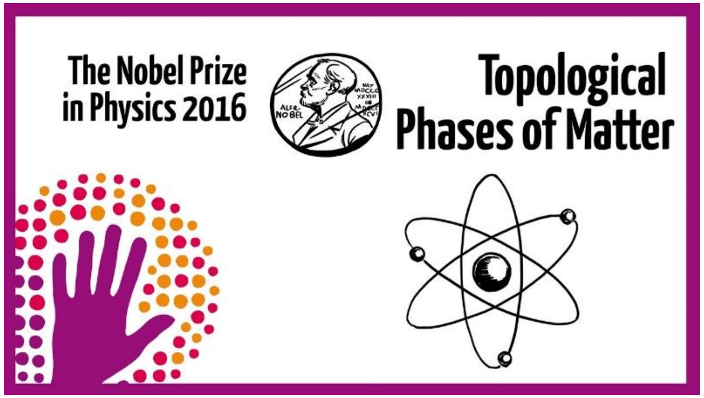
Giant magnetoresistance

x 750,000 =

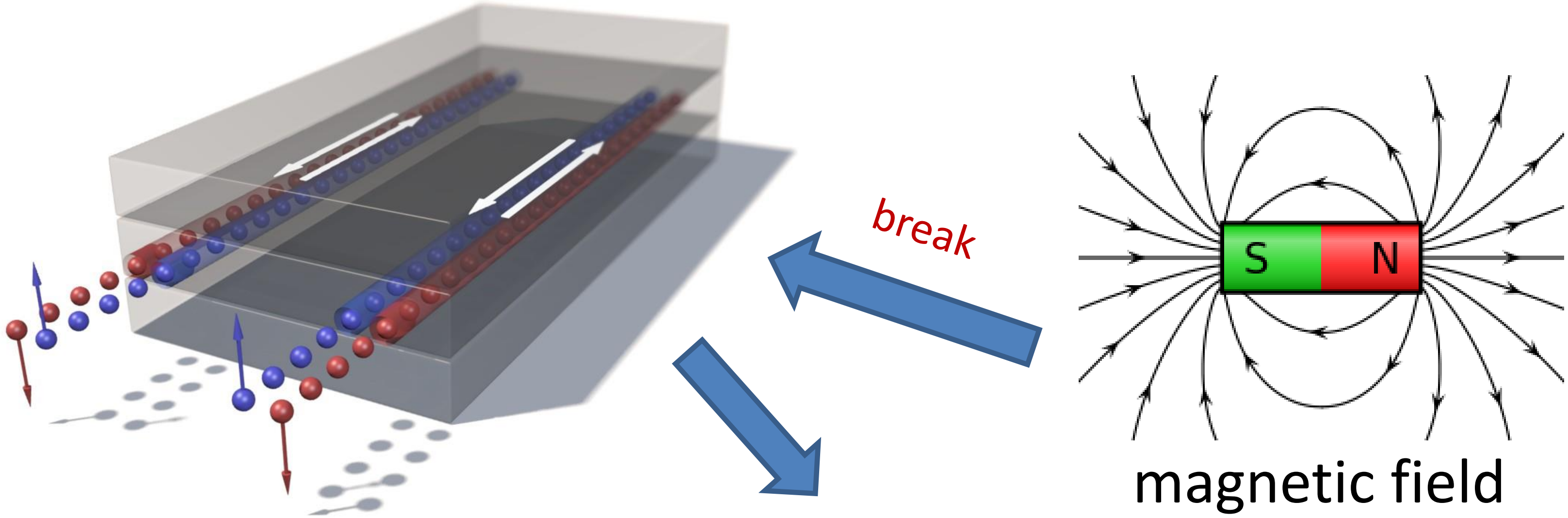
Extreme magnetoresistance

Origin? → **Better materials**

Origin of extreme magnetoresistance --- breaking topological protection ?



Topological Protection



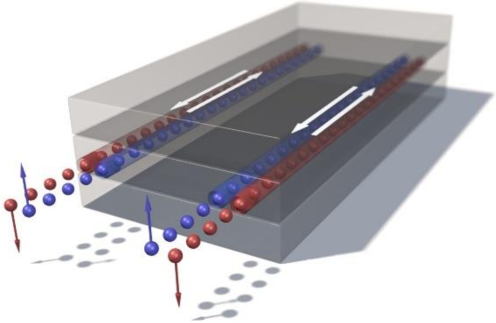
break

magnetic field

Low resistance

Resistance increases

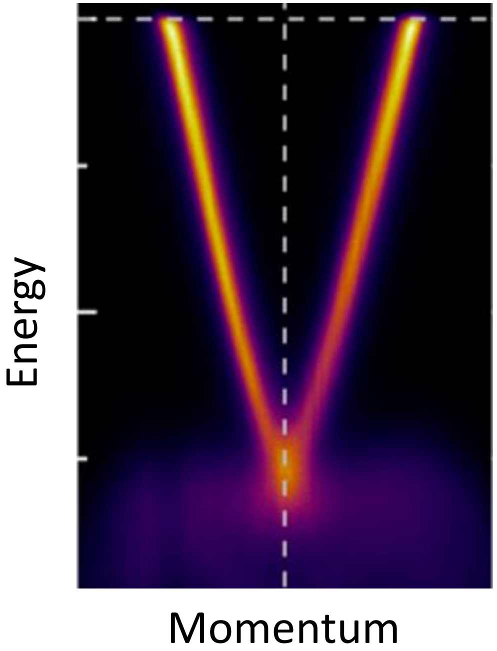
How to experimentally measure It?



Topological Protection

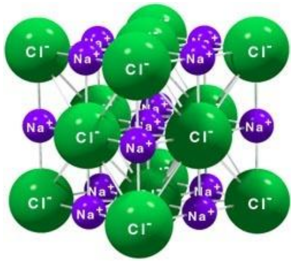
Topologically non-trivial electronic states

Linear Band

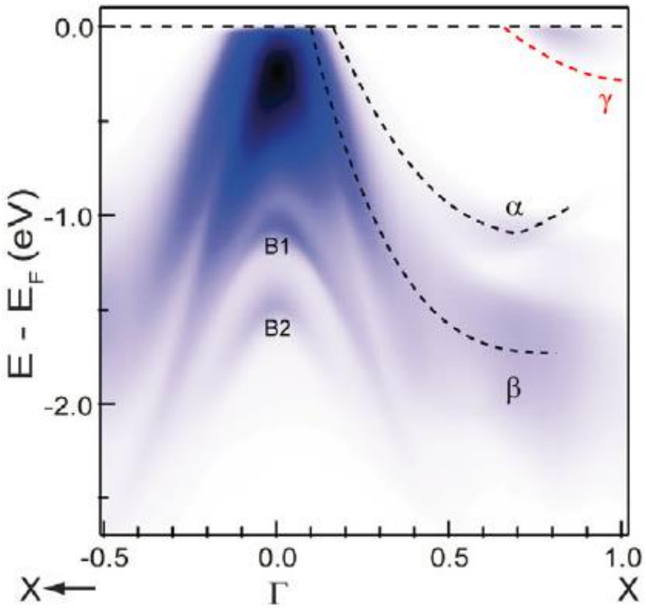


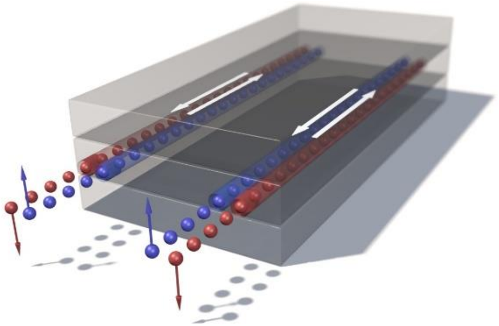
Experiment --- breaking topological protection ?

YSb



Extreme magnetoresistance





Topological Protection

NO

NO

Topologically non-trivial electronic states

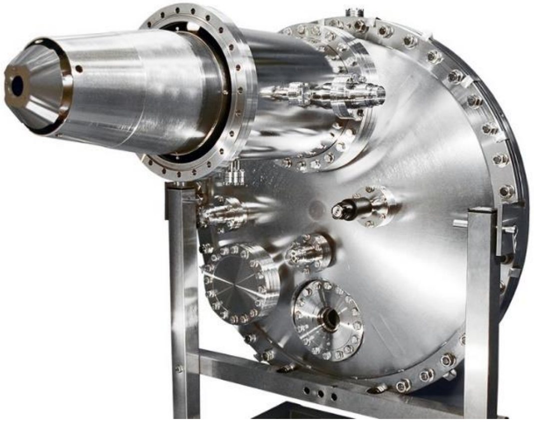
Junfeng He *et al.*,
Physical Review Letters 117, 267201 (2016)

Summary

- Breaking of the topological protection is NOT a must for extreme magnetoresistance.

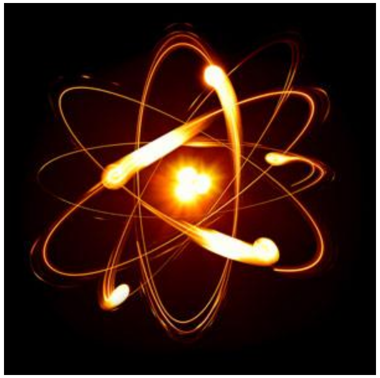
- Materials with extreme magnetoresistance do not have to be topological materials.

Summary of part I



Angle-Resolved Photoemission Spectroscopy

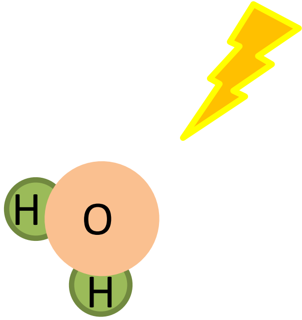
- Yes, we see the electron energy band using the new tool!
- We understand an interesting quantum phenomenon from electron energy band.



Part II

Let’s consider more complicated systems

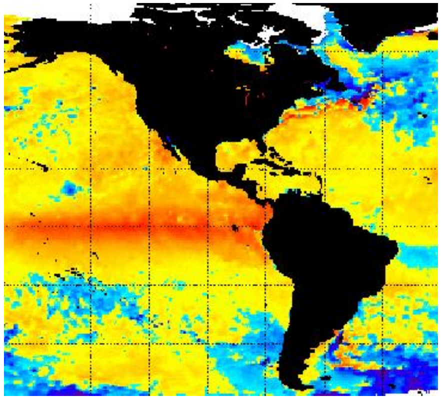
“More is different”

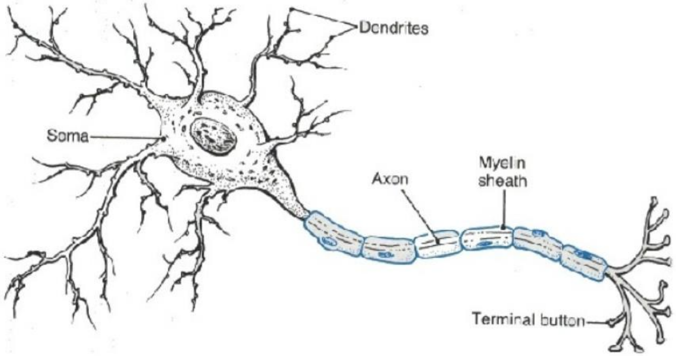


Water molecule

x 10^{46}

El Niño





Neuron

x 10^{11}

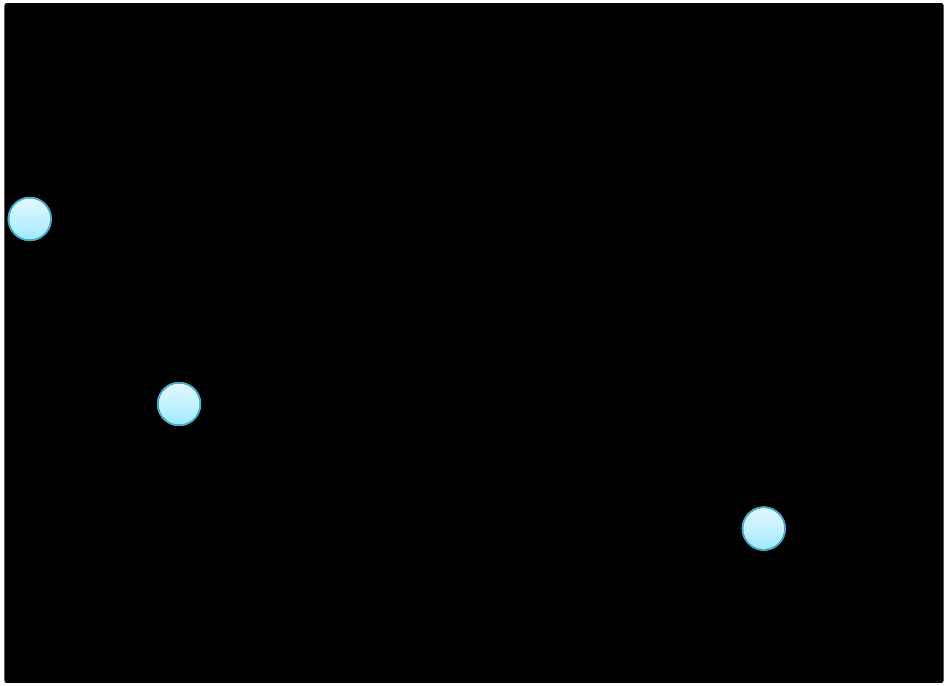
Brain activity

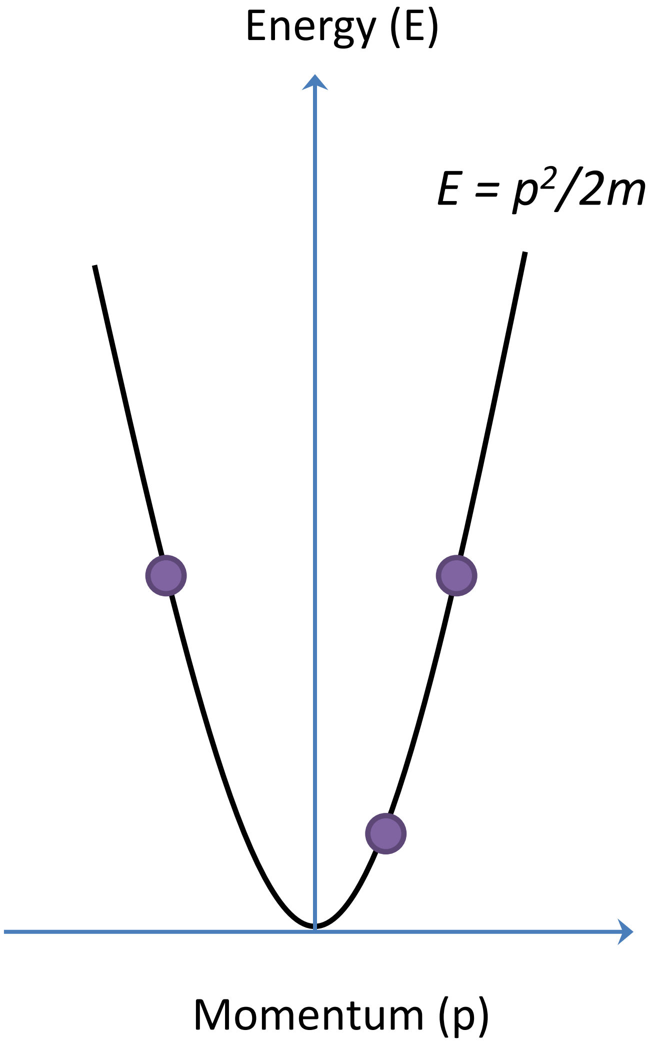
Ant

x 10^{8}

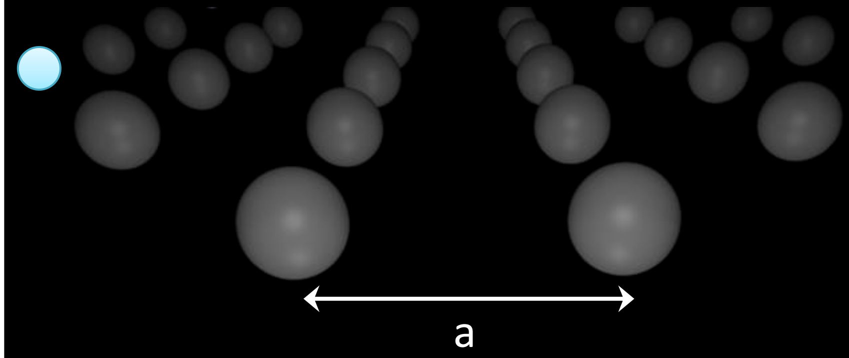
Ant colony

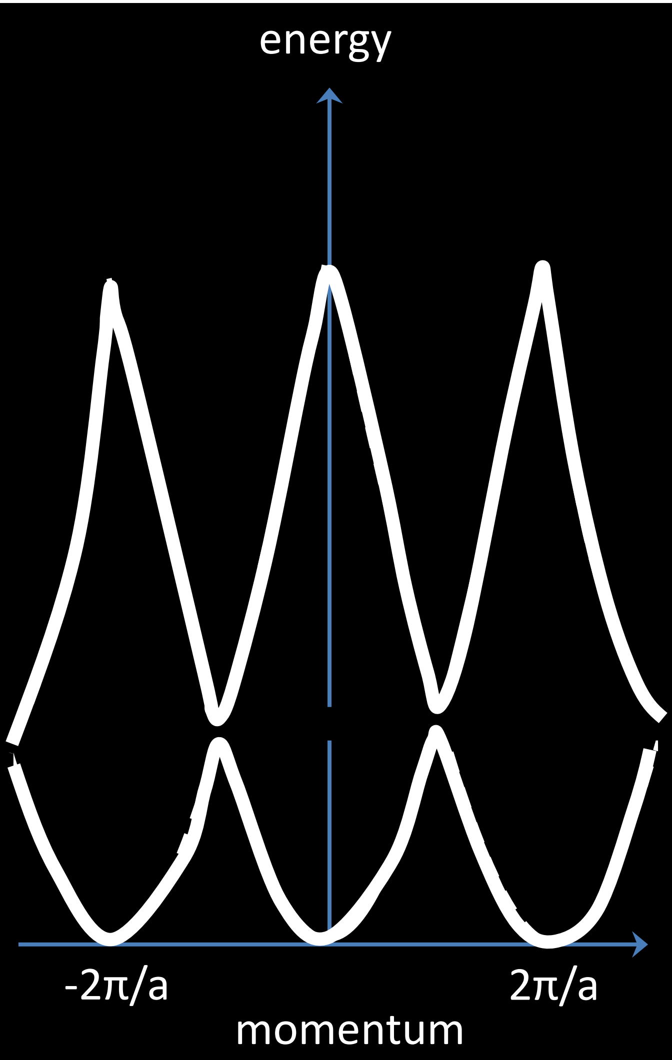
Electron energy band





Electrons in periodic lattice

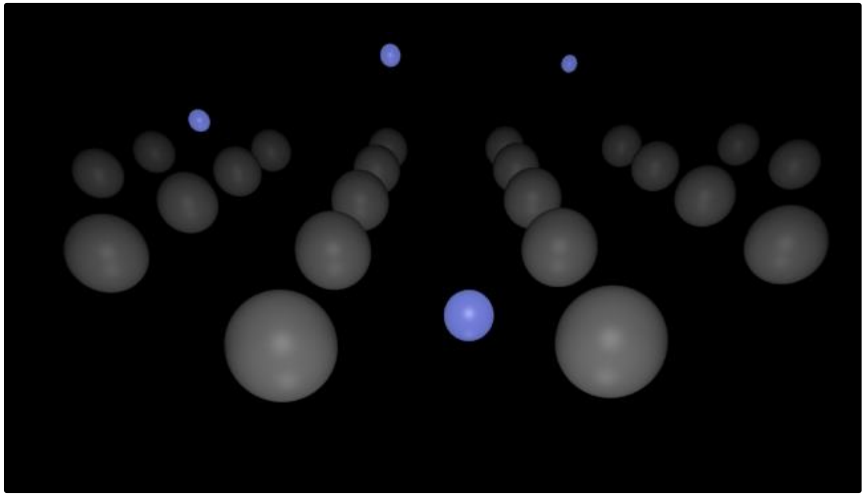


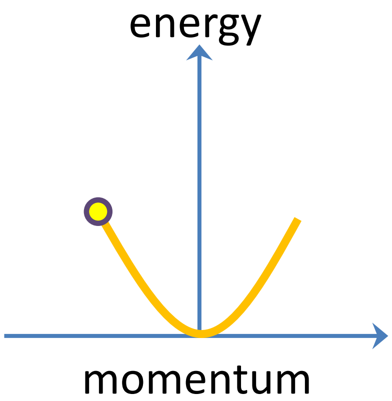


Interactions

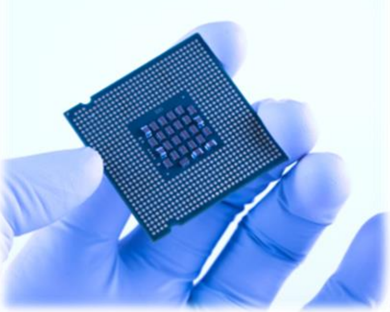
Non-interacting Fermi gas

$$E = E_0 + \sum_{\vec{k},\sigma} \epsilon_\sigma(\vec{k})\delta n_\sigma(\vec{k})$$



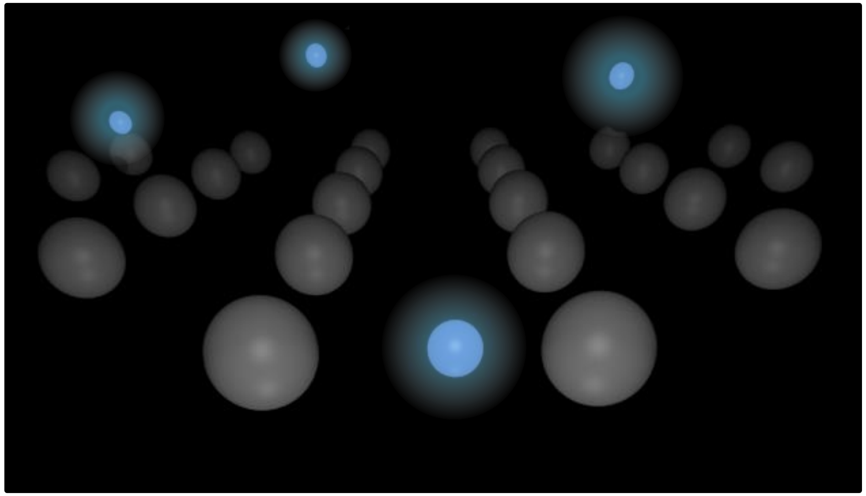


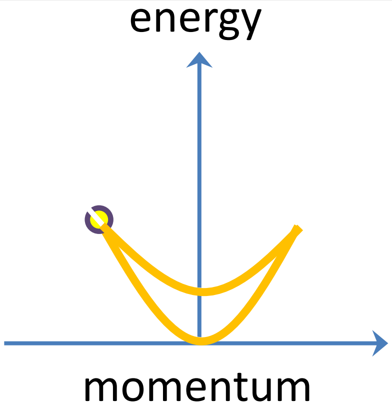
doped silicon



Weakly-interacting Fermi liquid

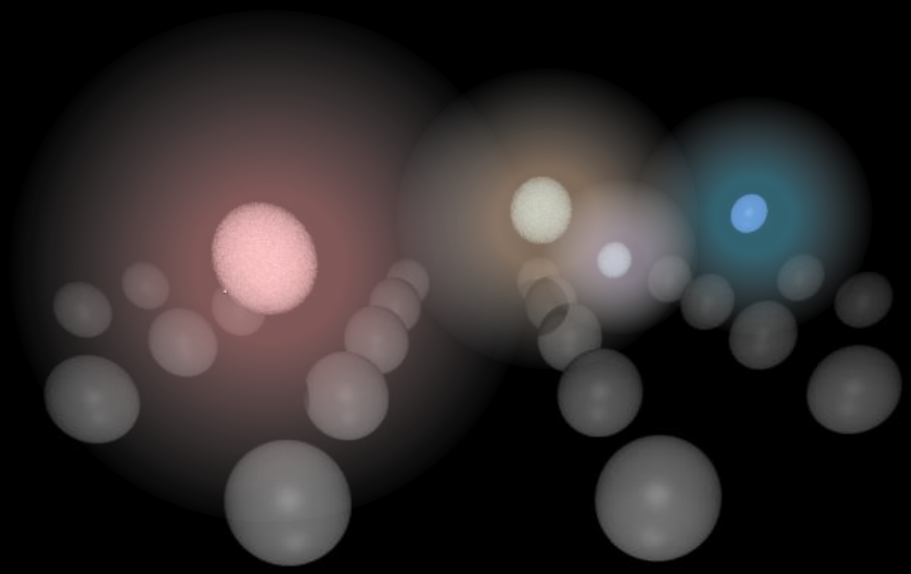
$$+ \frac{1}{2\Omega}\sum_{\vec{k},\vec{k}'}\sum_{\sigma,\sigma'} f_{\sigma\sigma'}(\vec{k},\vec{k}')\delta n_\sigma(\vec{k})\delta n_{\sigma'}(\vec{k}')$$

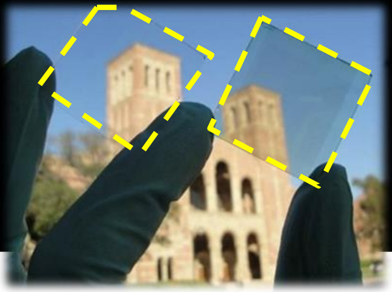




^{3}He

Strong electron-electron interactions

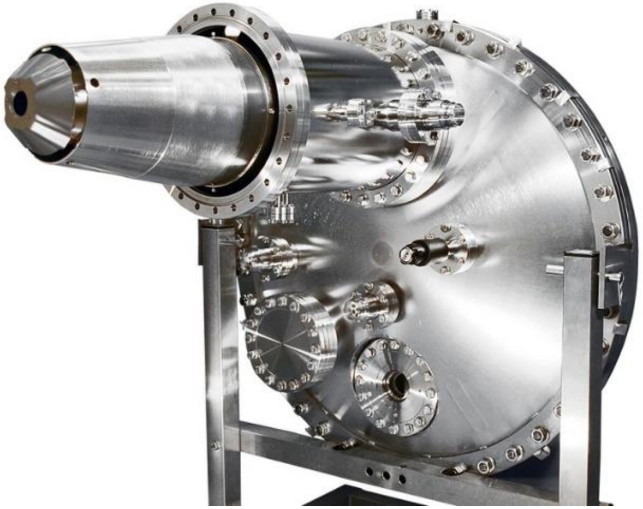




Smart window

Y. Gao et al., Energy Environ. Sci. 5, 6104 (2012)

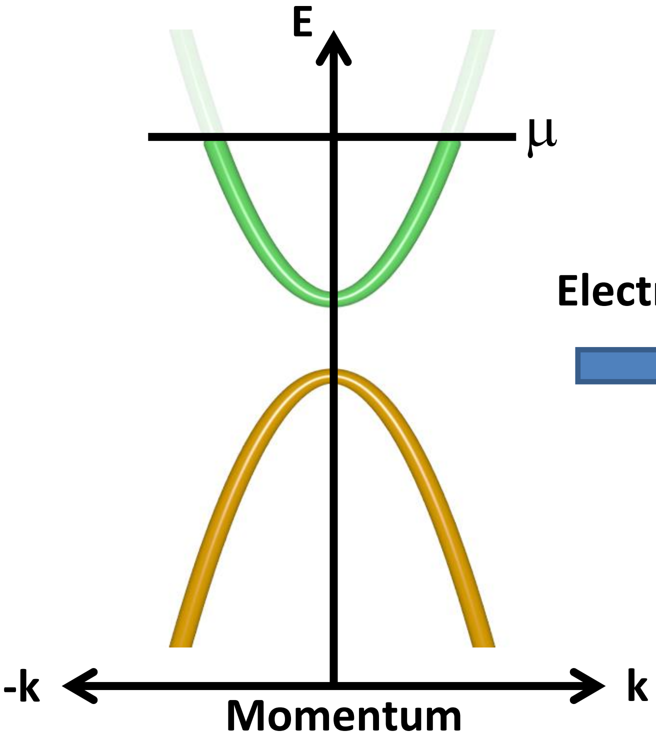
Discovering and understanding quantum phenomena in strongly correlated systems



Angle-Resolved Photoemission Spectroscopy

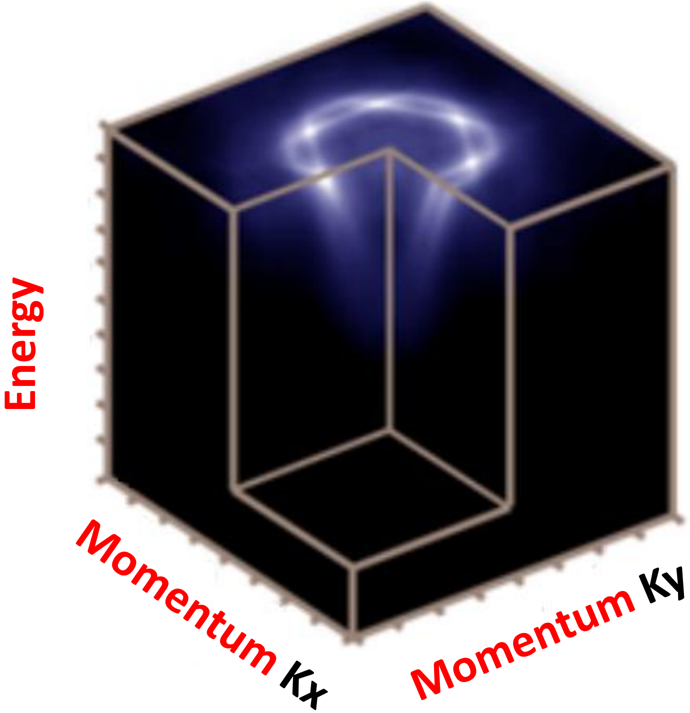
Electron bands in 3D

2D

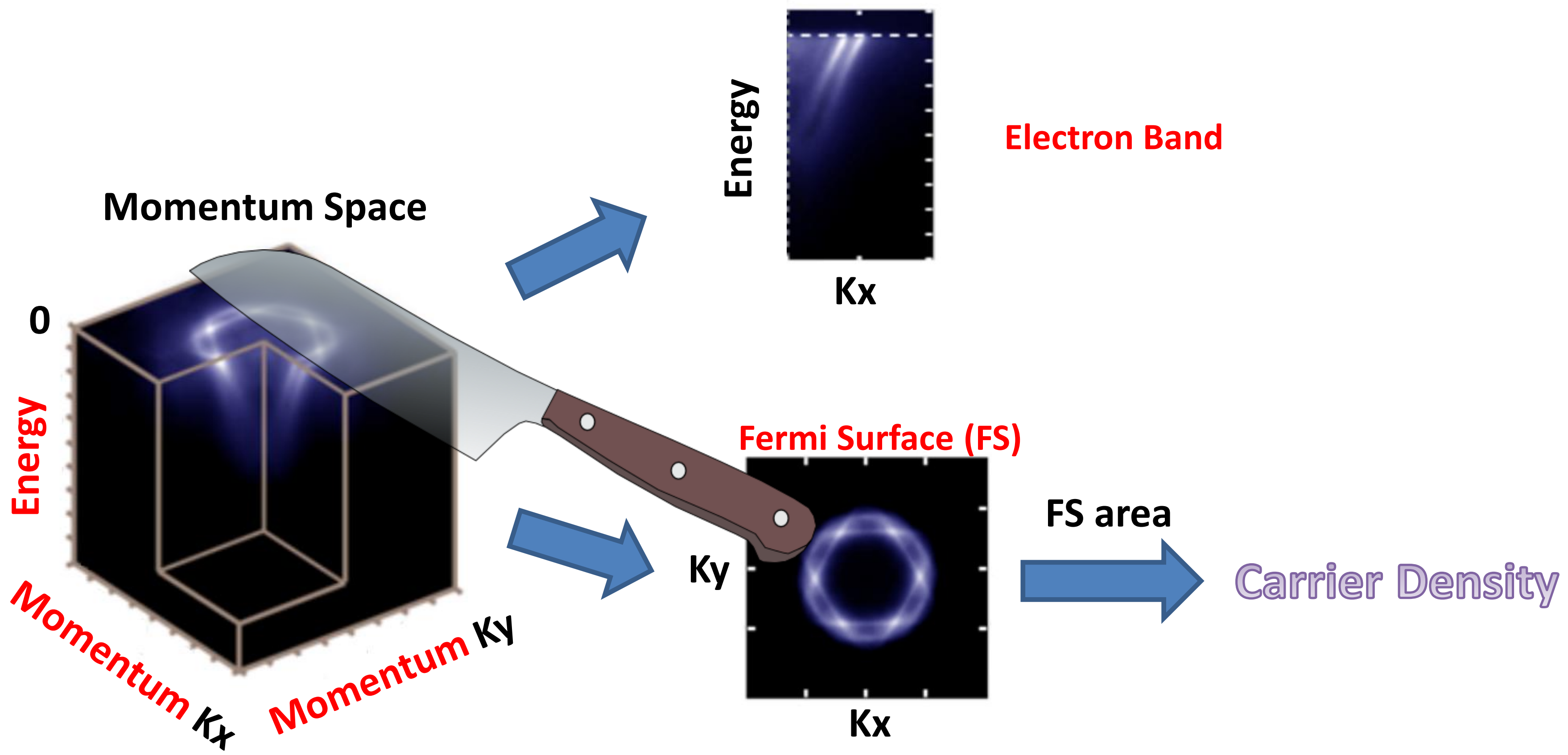


Electrons moving in a plane

3D



How to read the 3D “Map”?



Momentum Space

Electron Band

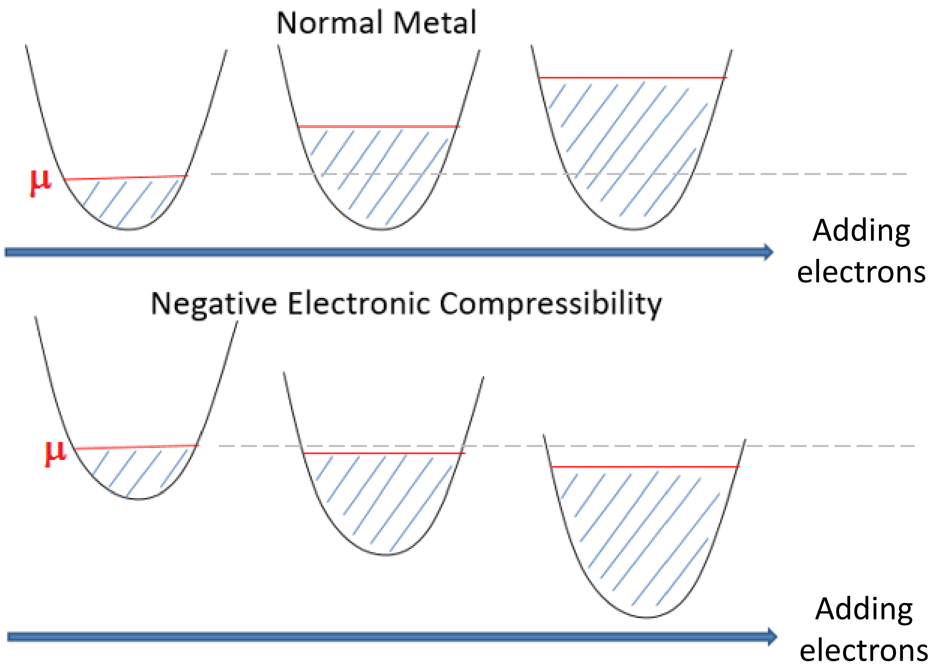
Fermi Surface (FS)

FS area

Carrier Density

Example: first observation of negative electronic compressibility in a correlated bulk material

Electronic Version

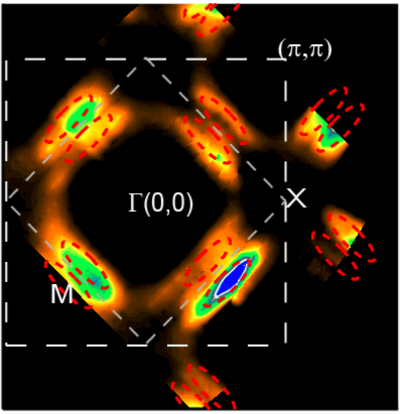


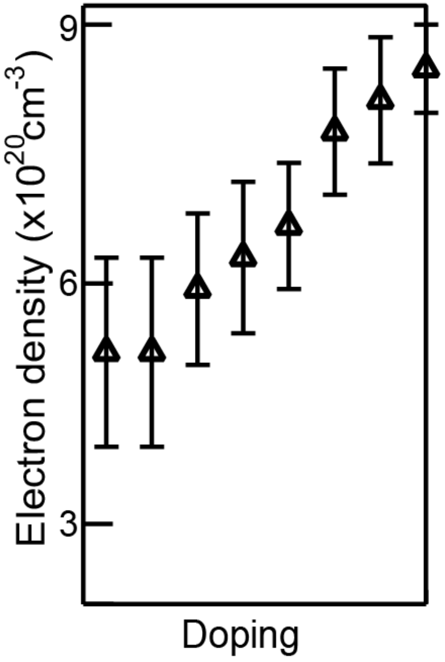
Electronic Compressibility: $\chi_e = (\frac{1}{n^2})(\frac{\partial n}{\partial \mu})$, (n is the carrier density and μ is the chemical potential)

Example: negative electronic compressibility

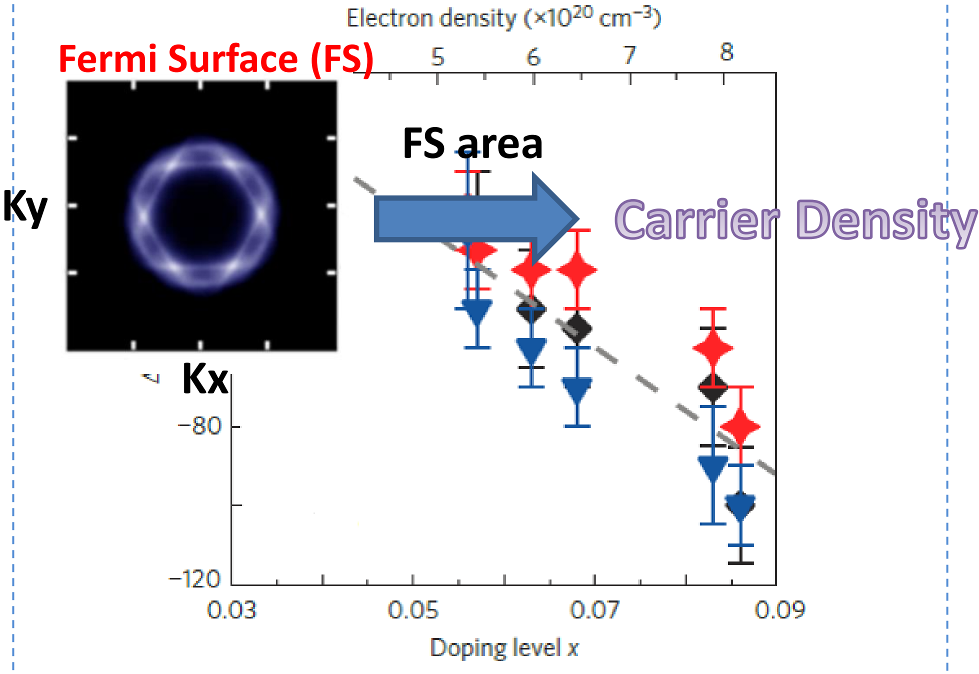
Electron-doped iridate: $(Sr_{1-x}La_x)_3Ir_2O_7$ $\Delta\mu/\Delta n<0$?

Carrier Density n





Chemical Potential μ

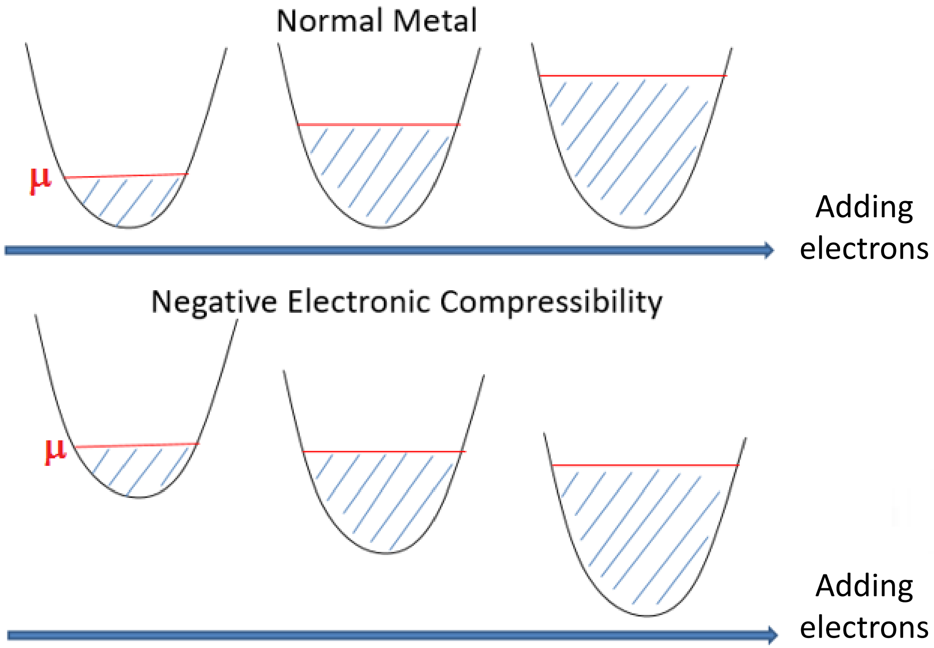


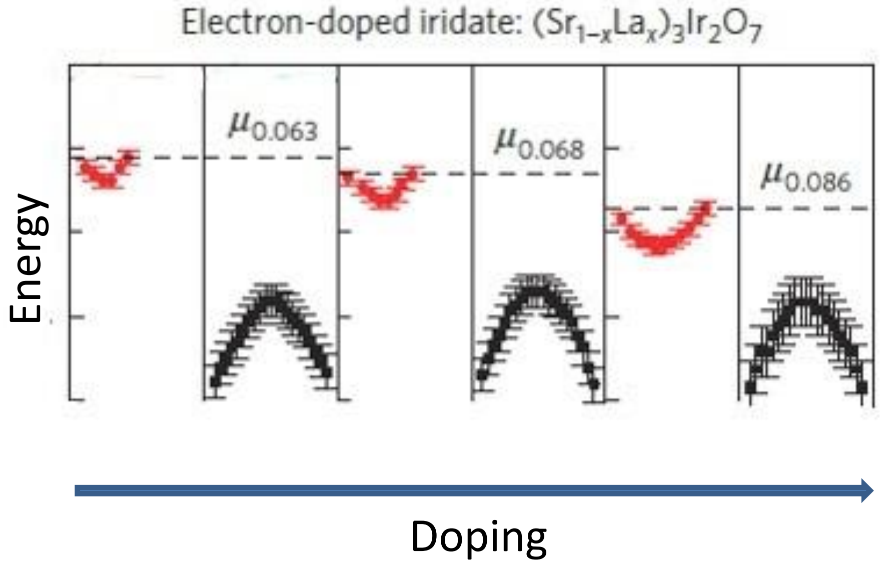
$\Delta\mu/\Delta n<0$

Junfeng He *et al.*, Nature Materials 14, 577-582 (2015)

Junfeng He *et al.*, Scientific Reports 5, 8533 (2015)

What's the origin?





❑ Observed the first example of correlation induced negative electronic compressibility (NEC) in bulk materials

❑ Due to the reduced correlation gap

Junfeng He *et al.*,
Nature Materials 14, 577-582 (2015)

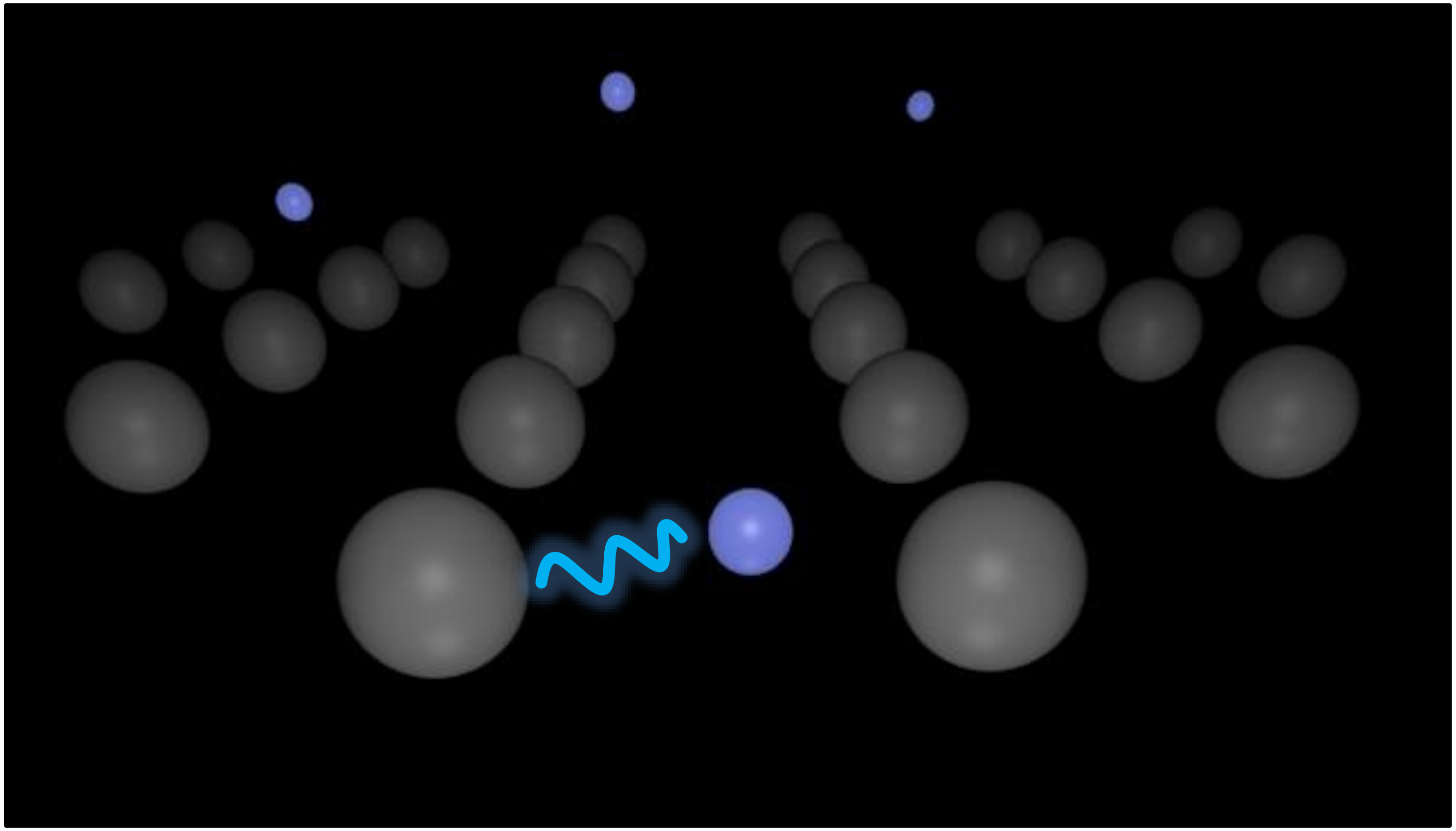
Summary of Part II

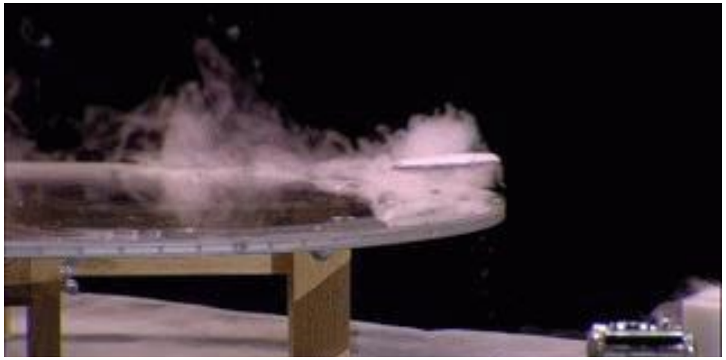
- We observed a new quantum phenomenon
- We figured out that this phenomenon is induced by strong correlation

Part III

Lattice at play

Electron-phonon interactions

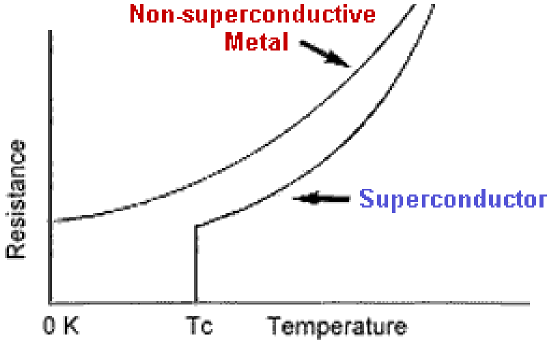




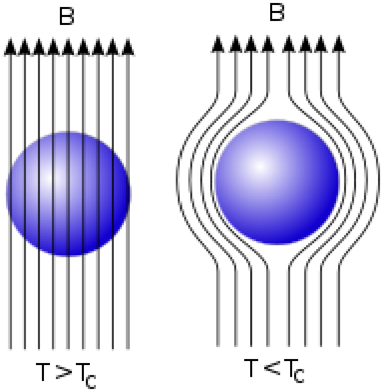
superconductivity

Superconductivity

zero electrical resistance



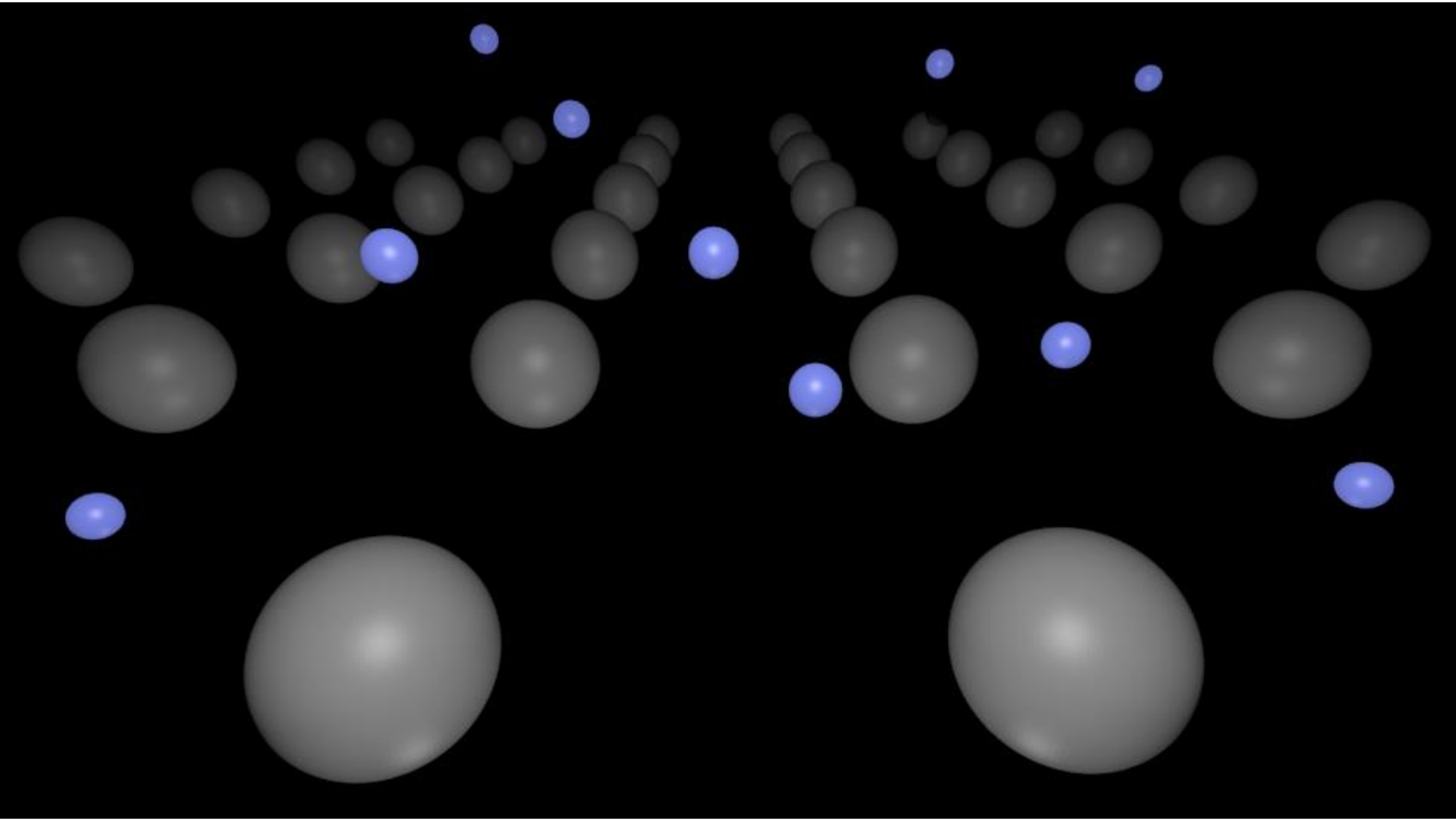
expulsion of magnetic field



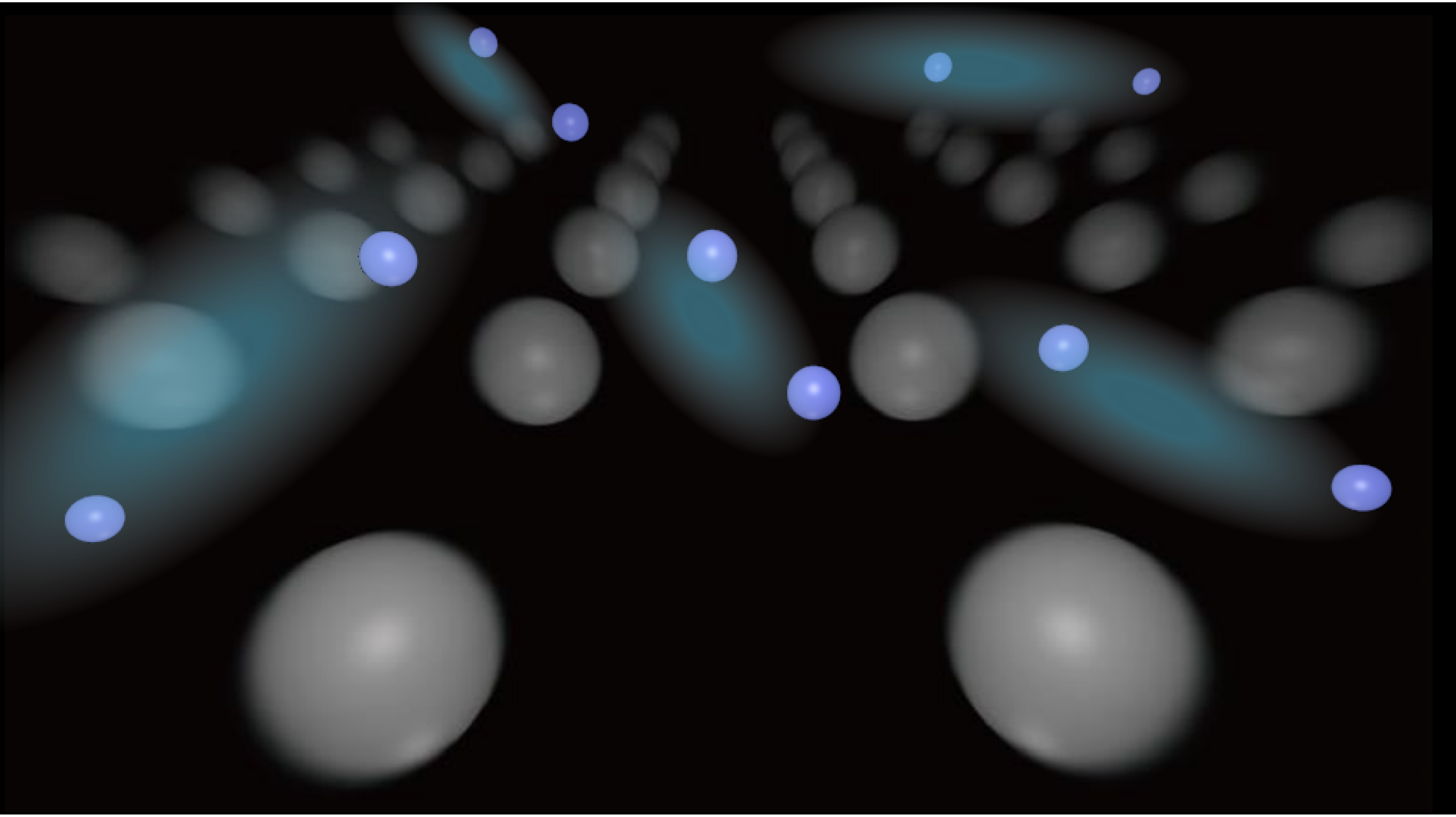
Electric power transmission

High-speed rail

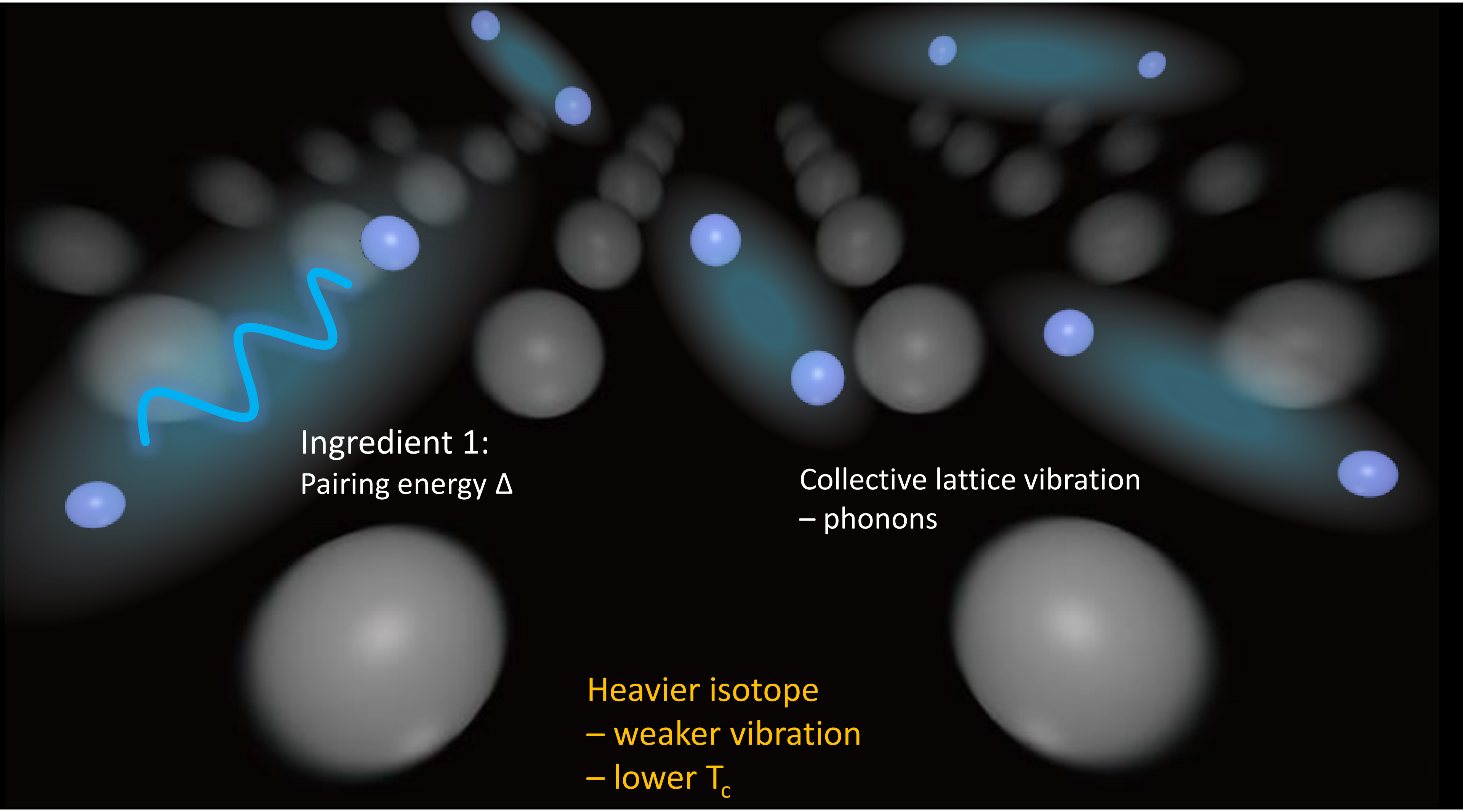
Phonon mediated superconductivity



Phonon mediated superconductivity



Phonon mediated superconductivity

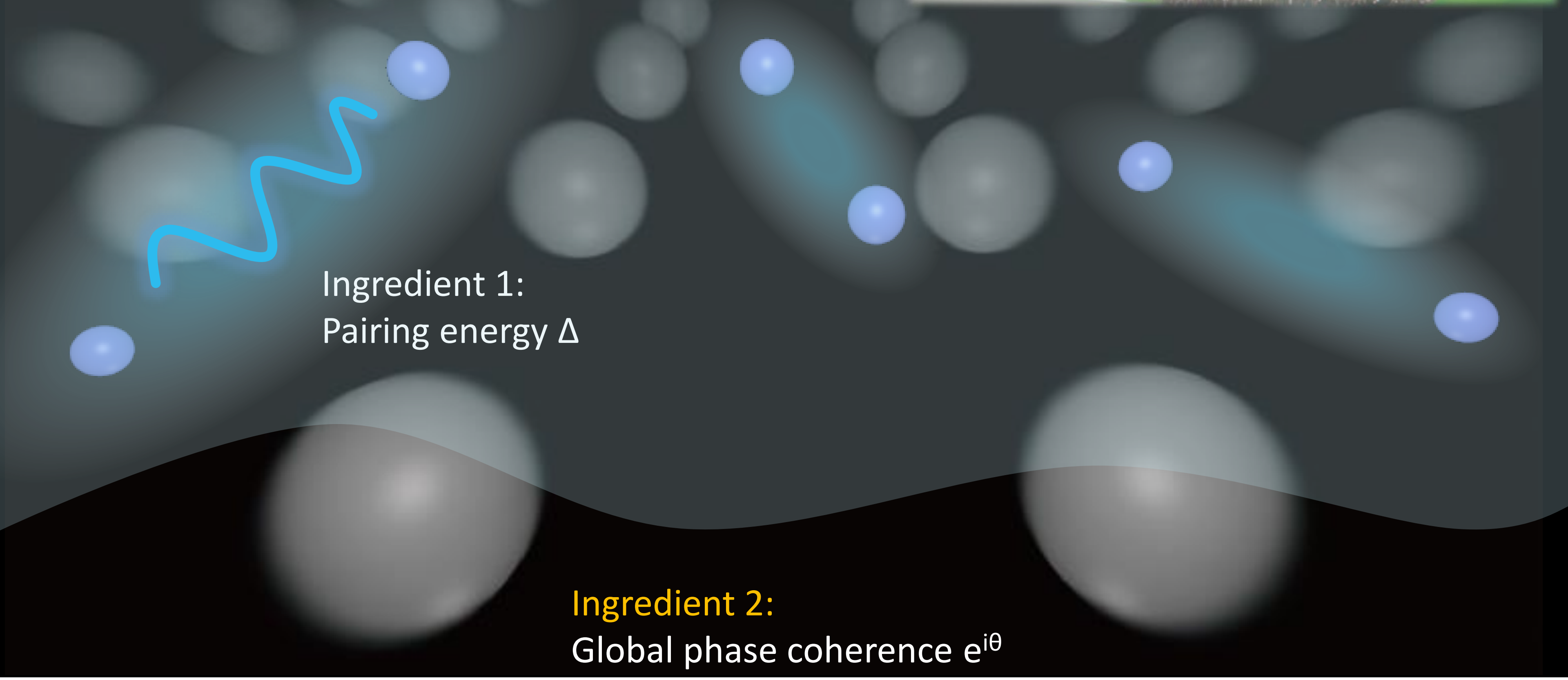


Ingredient 1:
Pairing energy Δ

Collective lattice vibration
– phonons

Heavier isotope
– weaker vibration
– lower T_c

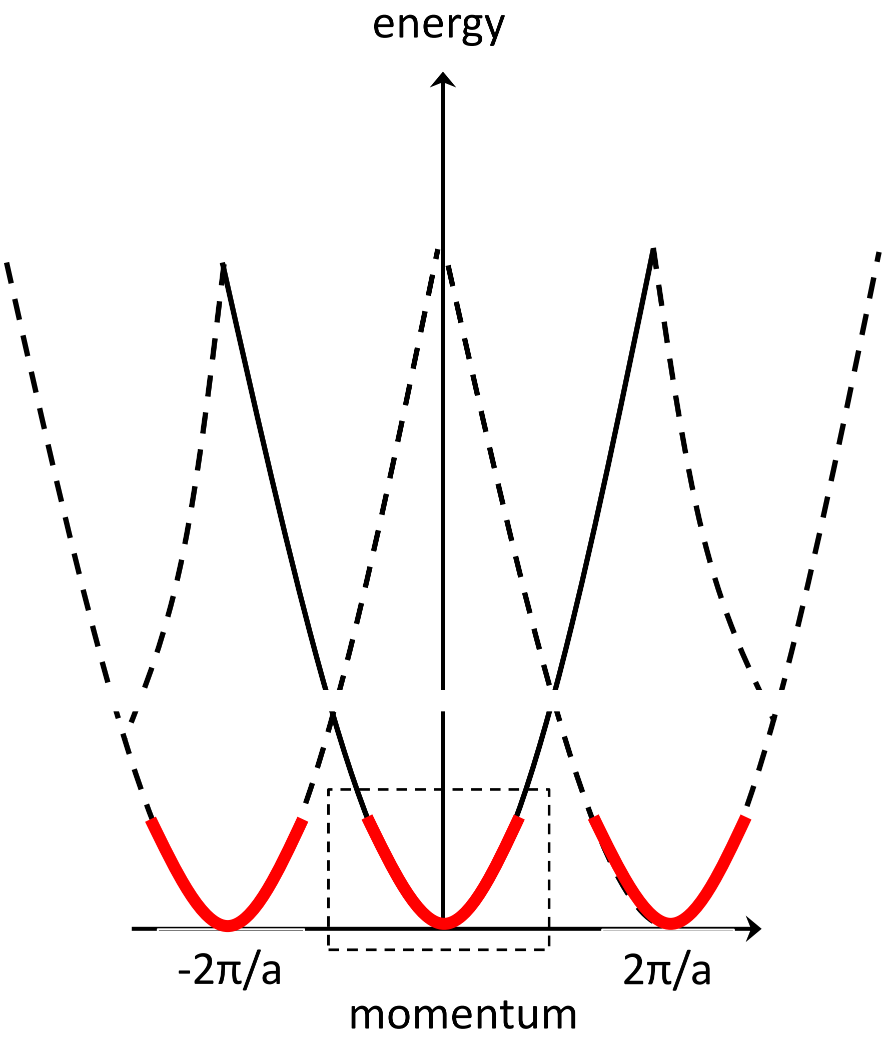
Phonon mediated superconductivity



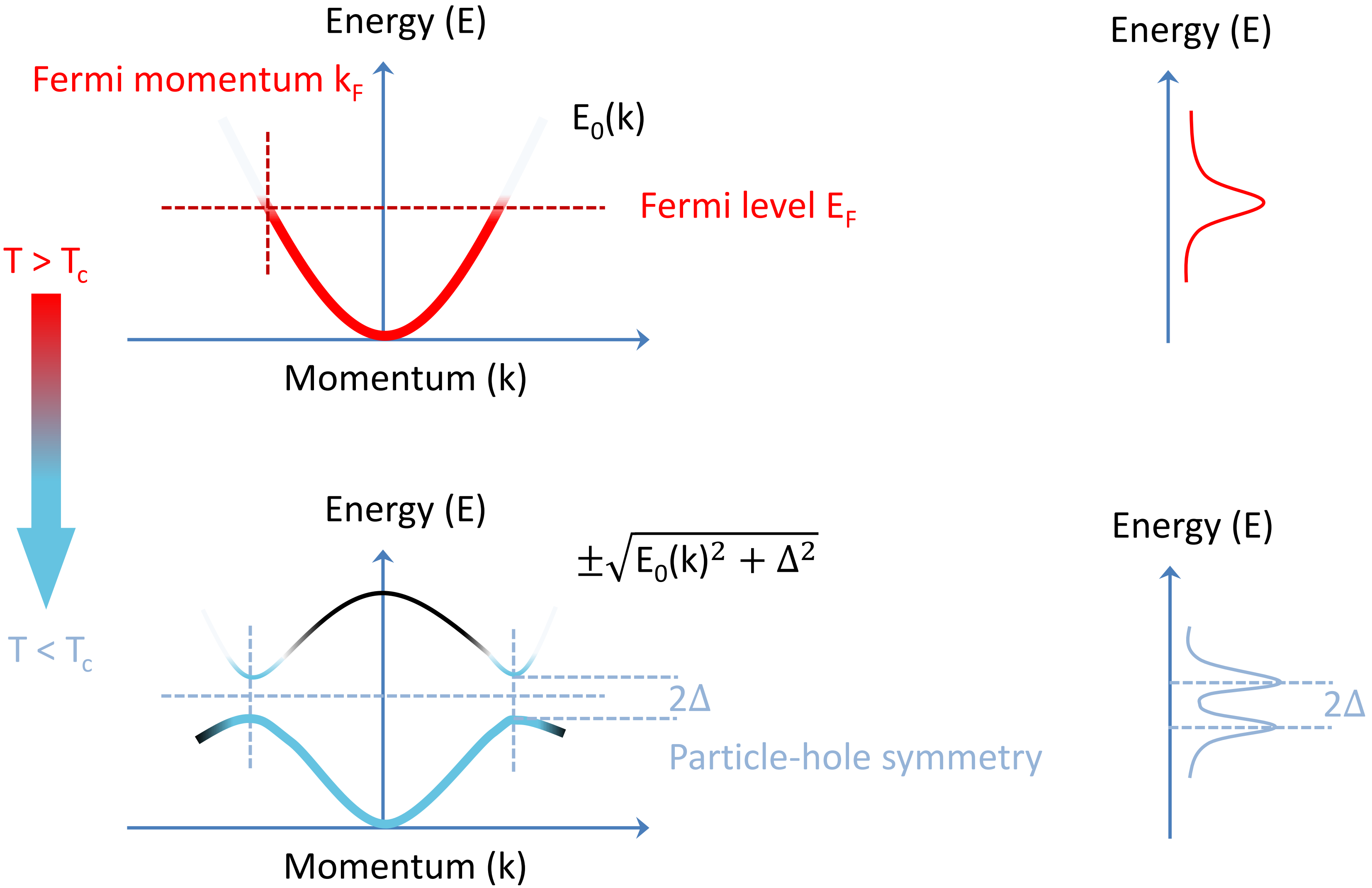
Ingredient 1:
Pairing energy Δ

Ingredient 2:
Global phase coherence $e^{i\theta}$

Superconductivity in energy-momentum space



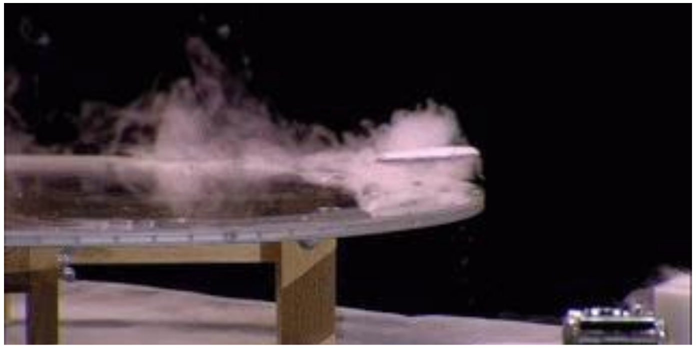
Superconductivity in energy-momentum space



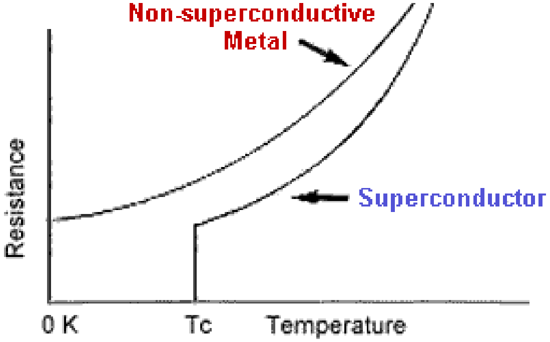
Is this the end of the story?

High Tc superconductivity

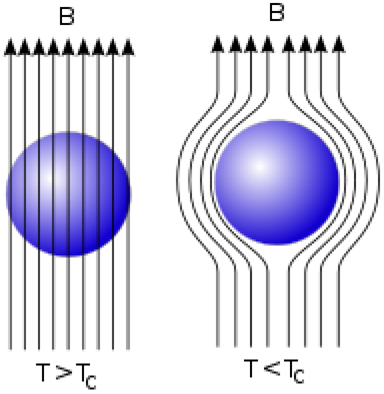
superconductor



zero electrical resistance



expulsion of magnetic field



Superconducting transition Temperature (Tc) is too low

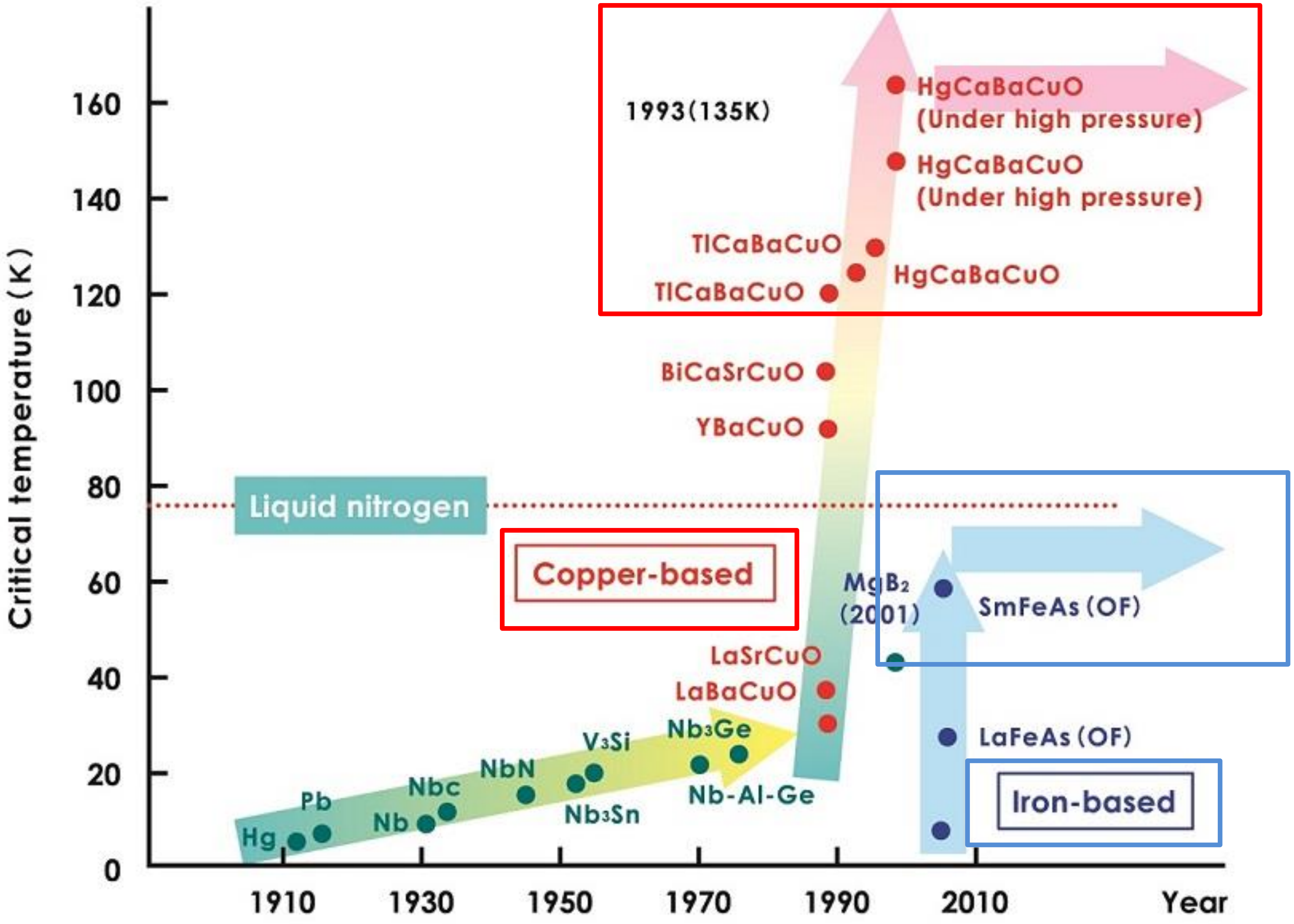
High Tc superconductors?

Electric power transmission

High-speed rail

Superconducting transition temperature (Tc) VS time

Two events in the past century

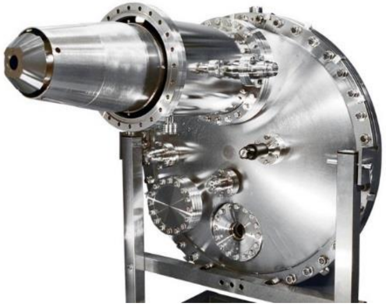


What’s the origin?

- Electron-electron interaction?
- Electron-boson coupling (e.g. electron-phonon coupling)?

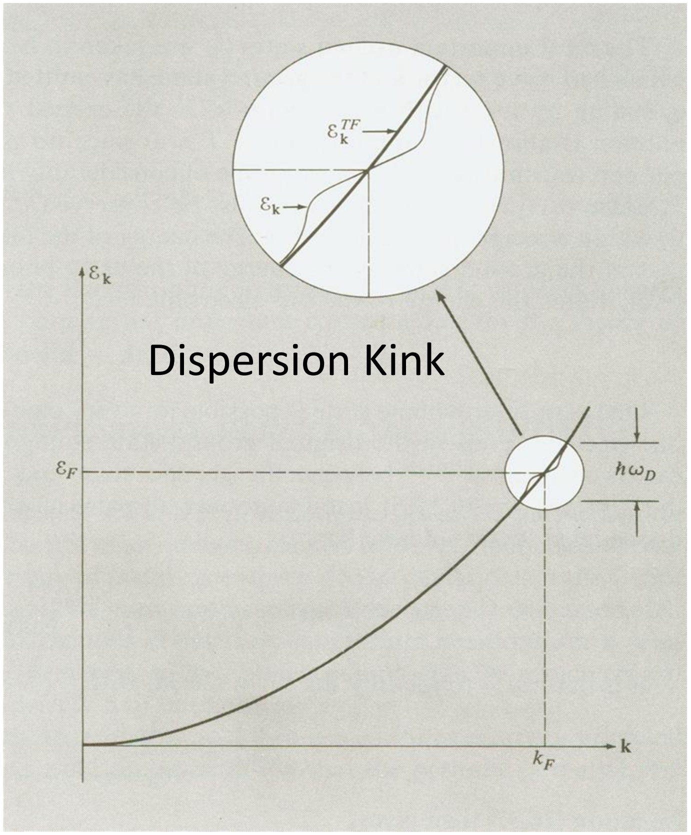
What’s the origin?

- Electron-electron interaction? ✓
- **Electron-boson coupling (e.g. electron-phonon coupling)?**



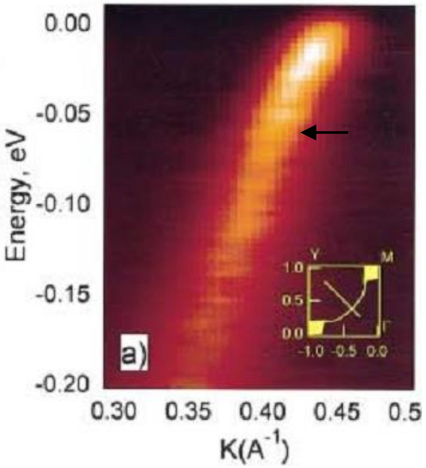
Observation of electron-boson coupling and a long-standing puzzle

Electron-Boson Coupling



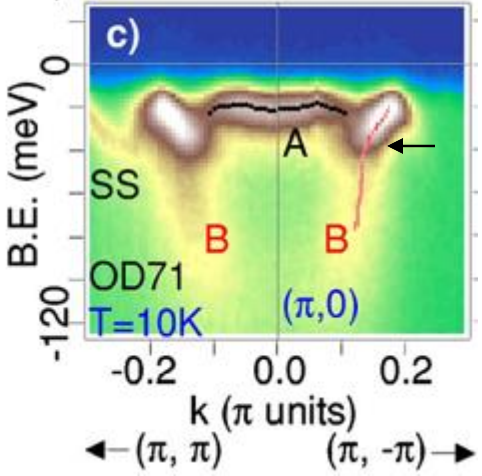
Ashcroft-Mermin, Solid State Physics

~70meV nodal kink



Phys. Rev. Lett. 85, 2581 (2000)
Nature (London) 423, 398 (2003) etc.

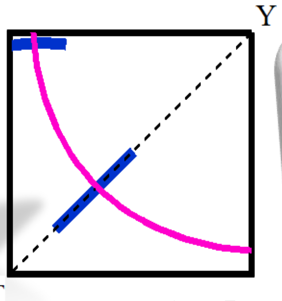
~40meV antinodal kink



Phys. Rev. B 68, 174520 (2003)

The different energy scales lead to a long-standing puzzle about their relationship

A kink near nodal direction



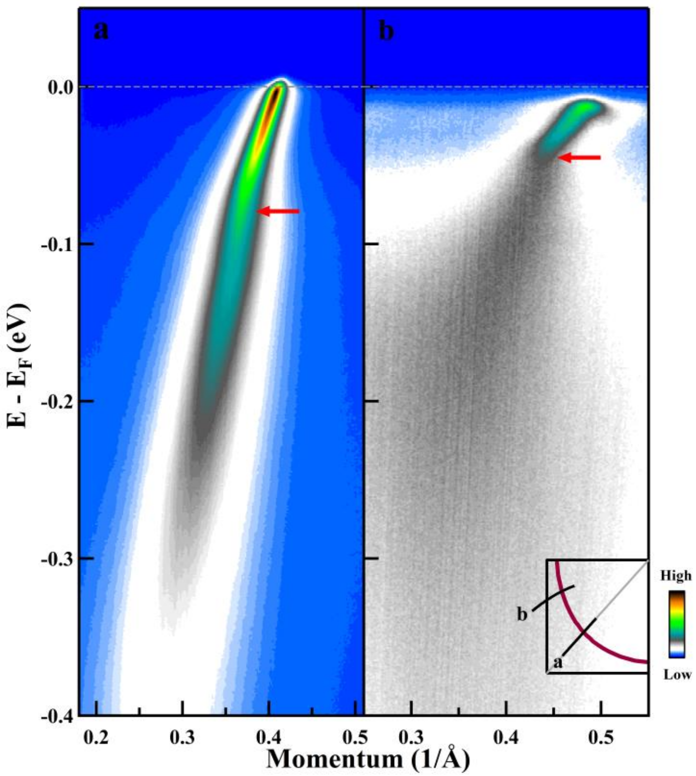
A kink near antinodal direction

What happens in between

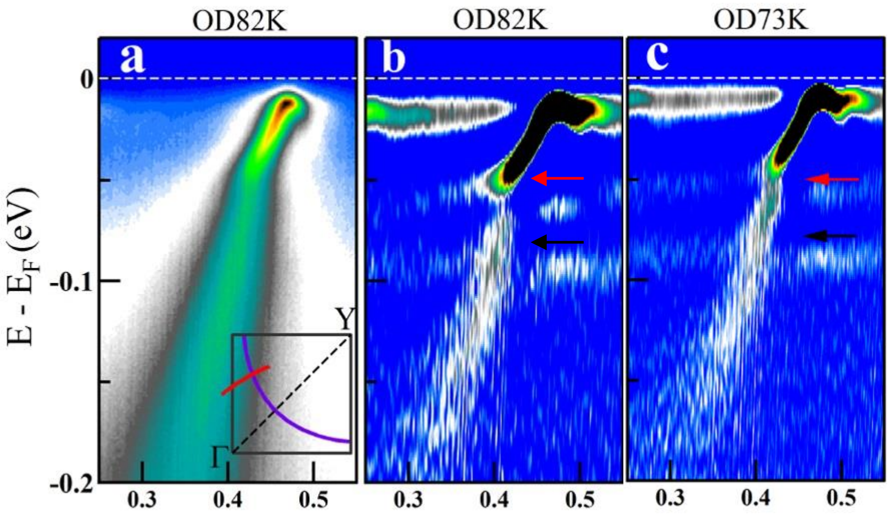
Do they belong to the same mode?

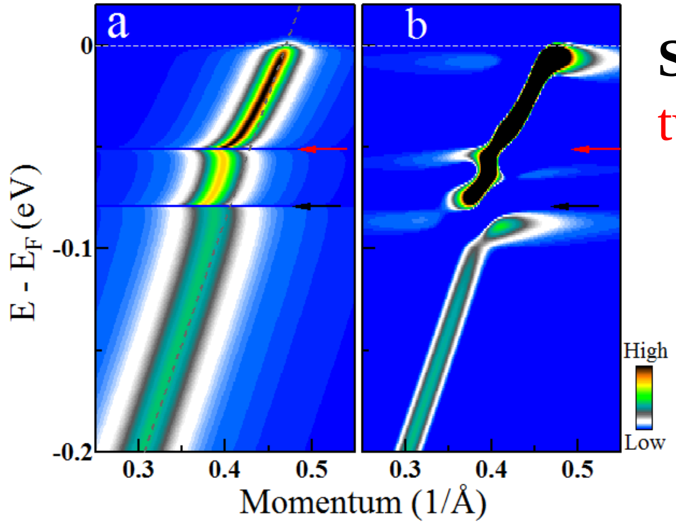
Resolving a long-standing puzzle in high temperature superconductors

Laser ARPES



~70meV & ~40meV





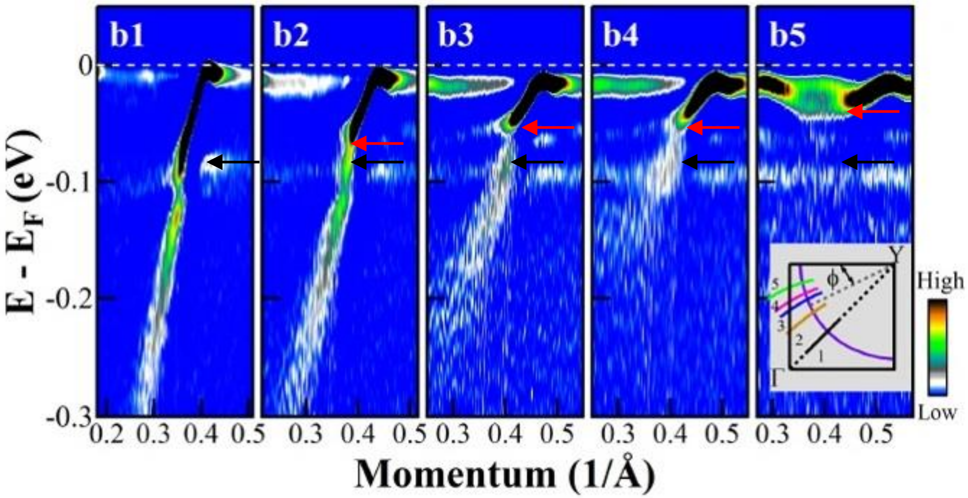
Simulation:

two modes

Coexistence of Two Energy Scales

Junfeng He *et al.*, Physical Review Letters 111, 107005 (2013)

Momentum dependence of the two energy scales



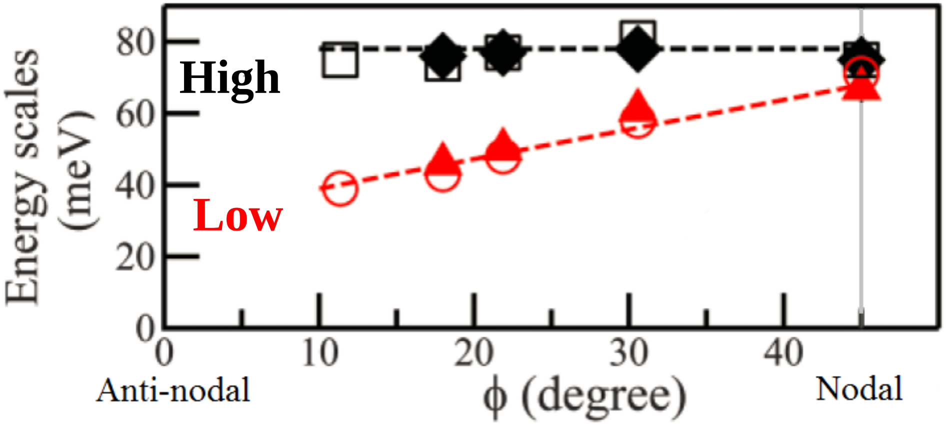
A kink near nodal direction

A kink near antinodal direction

What happens in between?

Do they belong to the same mode?

NO

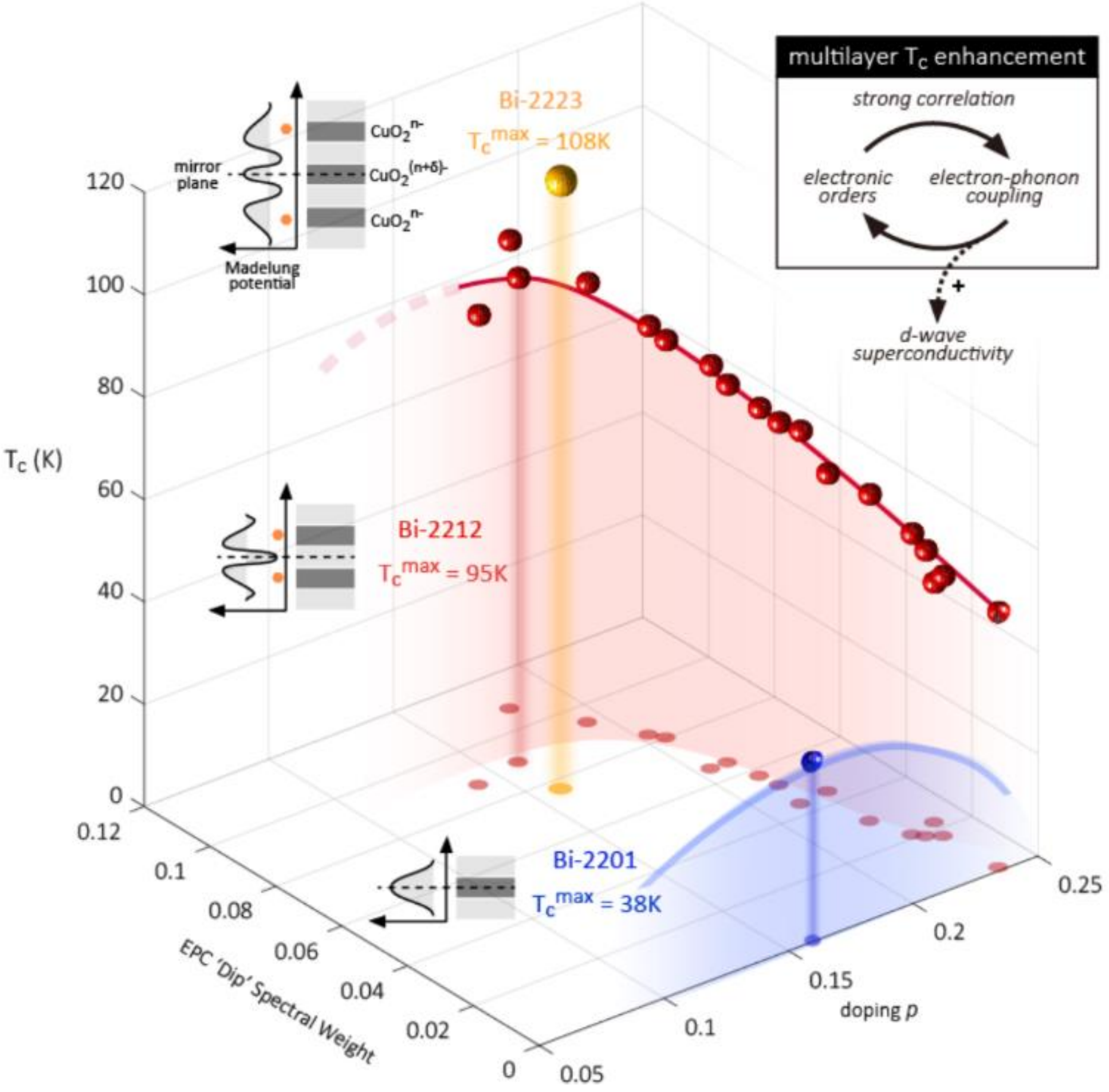


- Two energy scales **coexist** from nodal region to anti-nodal region

- **High** energy mode stays at ~70meV, **Low** energy mode decreases from ~70meV to ~40meV

Junfeng He *et al.*, Physical Review Letters 111, 107005 (2013)

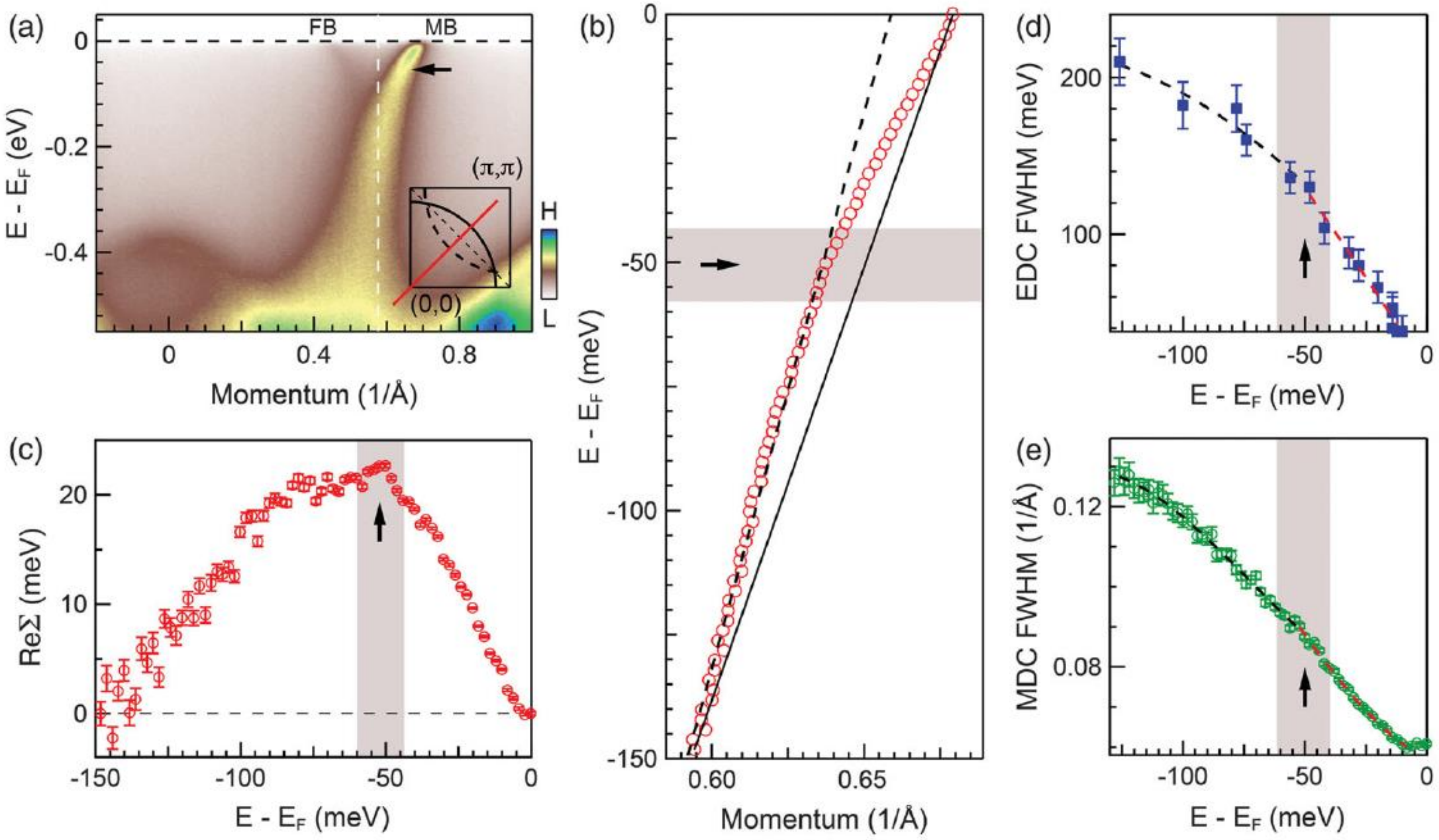
Electron-electron correlation, electron-phonon coupling and superconductivity



Y. He..J.-F. He *et al.*, Science 362, 62 (2018).

Electron-boson coupling in a similar system

Electron-doped Sr_2IrO_4

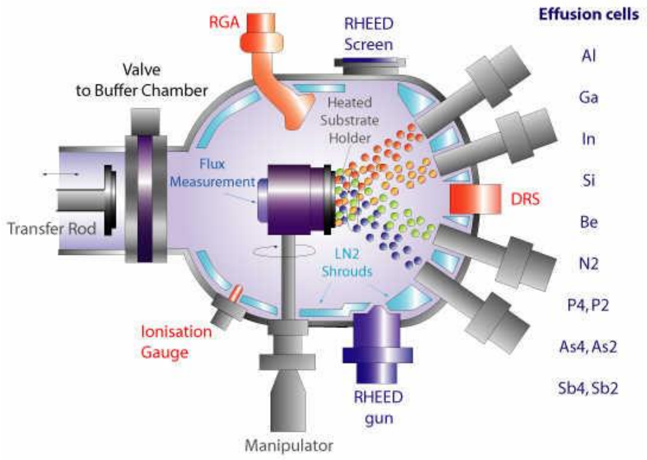


Y. Hu *et al.*, J.-F. He*, Physical Review Letters 123, 216402 (2019).

Part IV

Manipulating electronic states in quantum materials

Thin Film



MBE

Bulk Crystal

Floating zone

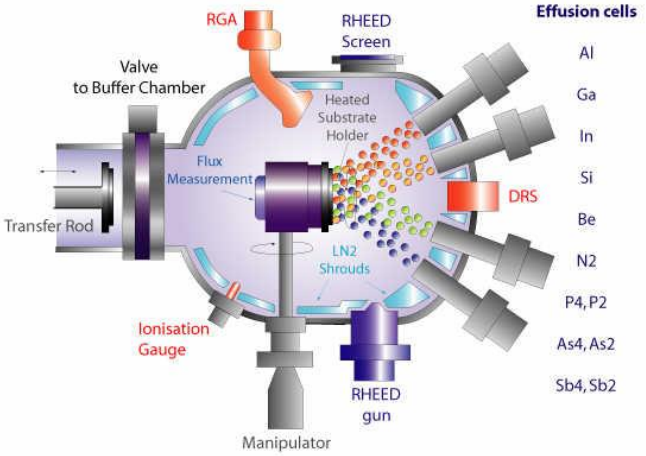
Single-layer FeSe film grown on $SrTiO_3$ (STO)

Single-layer FeSe

$SrTiO_3$ Substrate

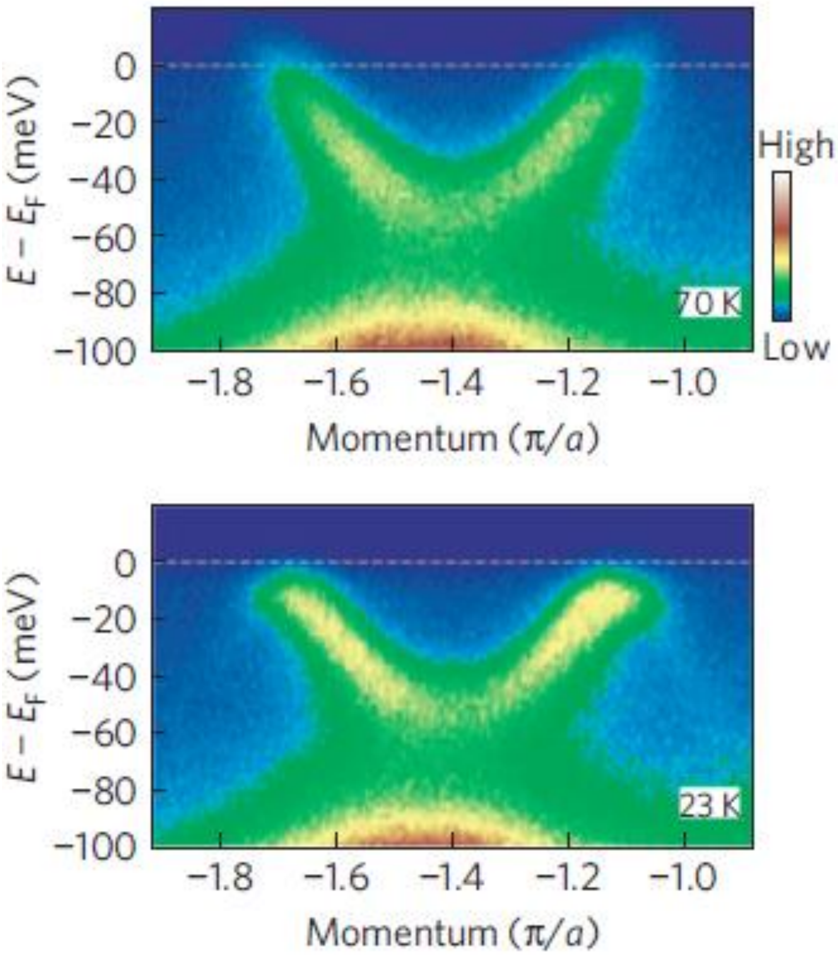
Is it superconducting?

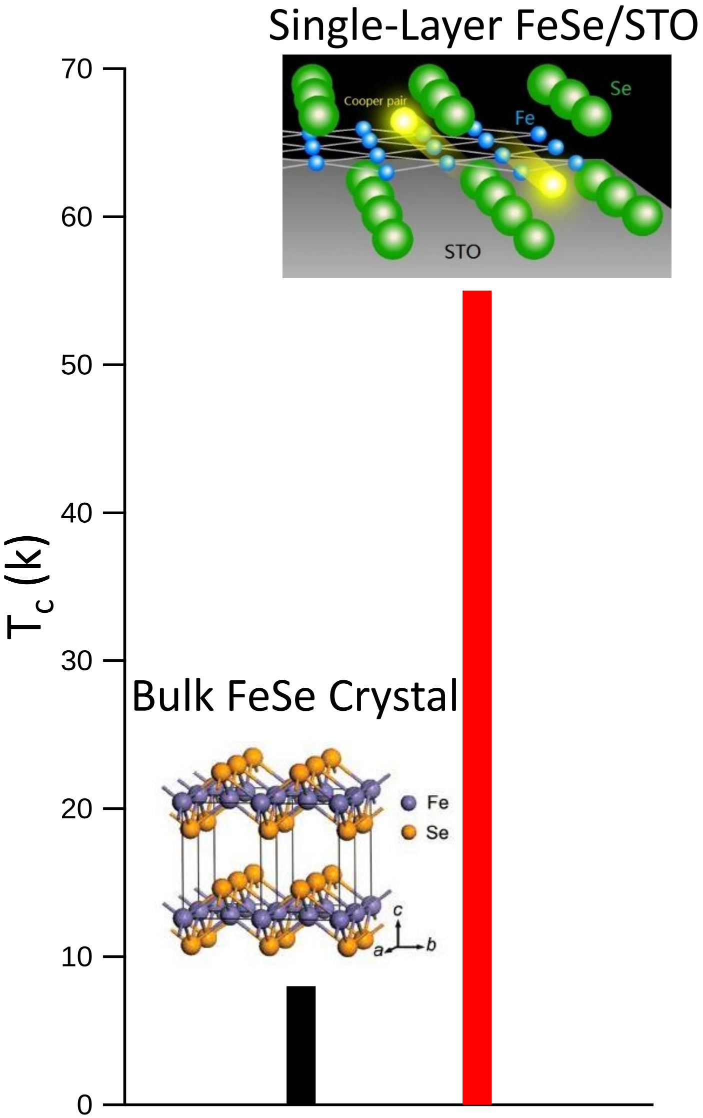
Molecular Beam Epitaxy (MBE)



Q. Wang & Q.-K. Xue et al.,
Chin. Phys. Lett. 29, 037402 (2012)

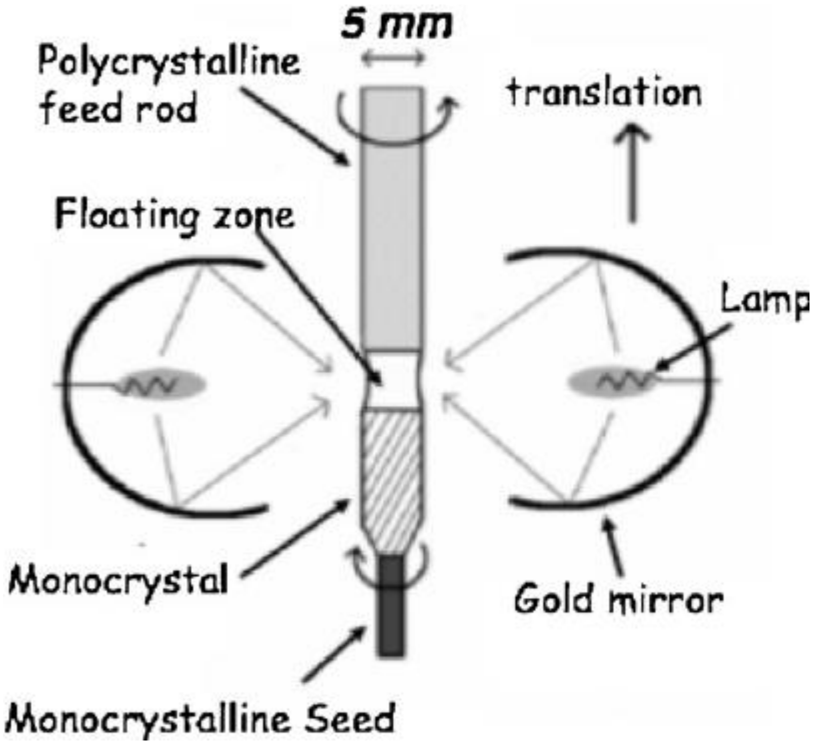
Enhance superconducting transition temperature





Junfeng He*, et al, Nature Communications (2012), Nature Materials (2013), PNAS (2014), Nature Communications (2014)

Floating zone: single crystal growth



Key for successful growth: keep the melting zone in a good shape

Too small -- break

Too big -- drop

- Hard to find out the optimal growth parameters
- Continuous monitoring of the growth (2~4 weeks)
- Heavily depends on the experience

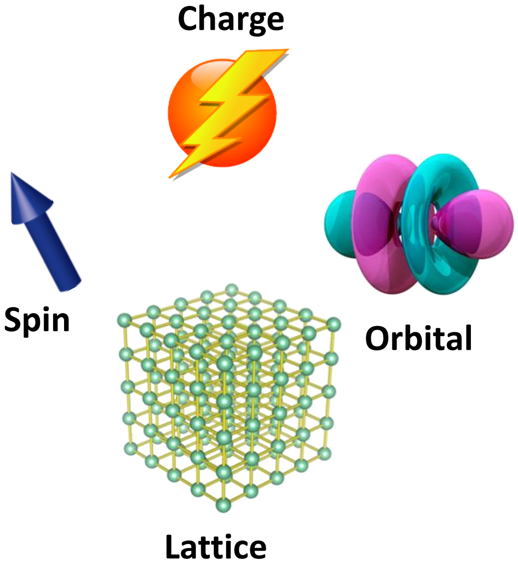
Let the machine do the job!

Outlook

More is different

Manipulating the many-body effects in quantum materials

Interplay of Multiple Physics Components



Extreme Properties

- Superconductivity
- Extreme magnetoresistance
- Negative electronic compressibility
- Metal-insulator transition
- Low dimensional materials
- … …

Functional Materials

- superconducting magnet
- Memory devices
- Low power IC
- selector device
- Displays
- … …

State-of-Art Experimental Tools
ARPES
X-ray scattering
etc.

+

Advanced Material Growth
MBE
Floating zone growth
etc.

→

Mastering Quantum Materials

Thank you!