Title: Rob Moore: Stanford Institute for Materials and Energy Sciences

Date: Apr 04, 2018 07:00 PM

URL: http://pirsa.org/18040002

Abstract: <p>From the Stone Age to the Silicon Age, nothing has had a more profound influence on the world than our understanding of the materials around us. The Industrial Revolution of the 19th century and the Information Revolution of the 20th were fueled by humankindâ€™s ability to understand, harness, and control materials.

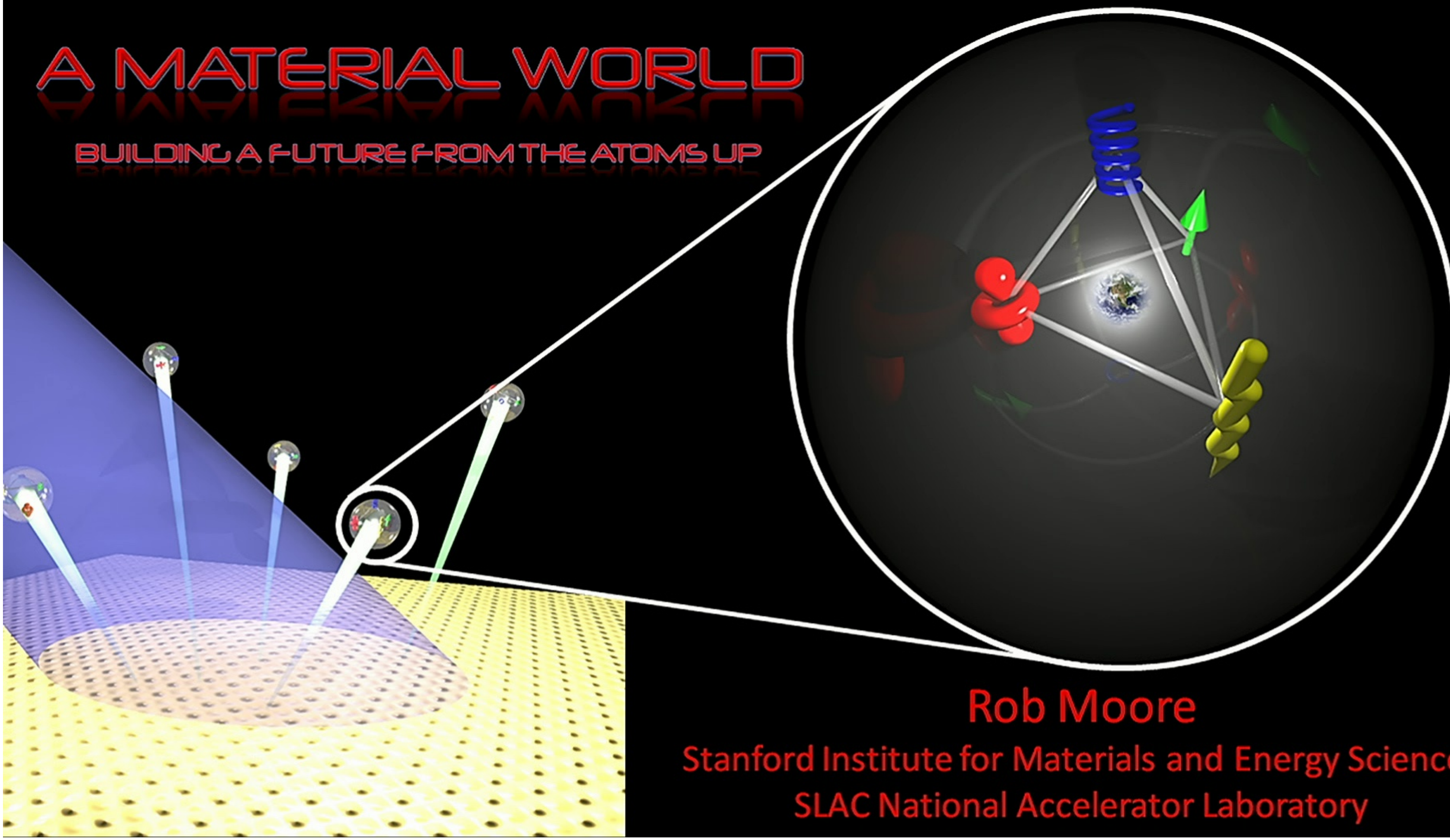
Our ongoing quest to find and develop new kinds of materials, in hopes of tackling some of societyâ€™s most challenging energy problems, requires us to learn how to build materials from the atom up. Doing so means combining state-of-the-art technologies (such as growing thin-film materials) with cutting-edge techniques for probing the electron structure. Relatively recent advances in these fields have given researchers unprecedented understanding and insight into creating new materials with exotic and useful properties.

In his public lecture at Perimeter Institute, Rob Moore will explore how the next great â€œageâ€• of humankind may well be forged in this new quantum world of materials.</p>

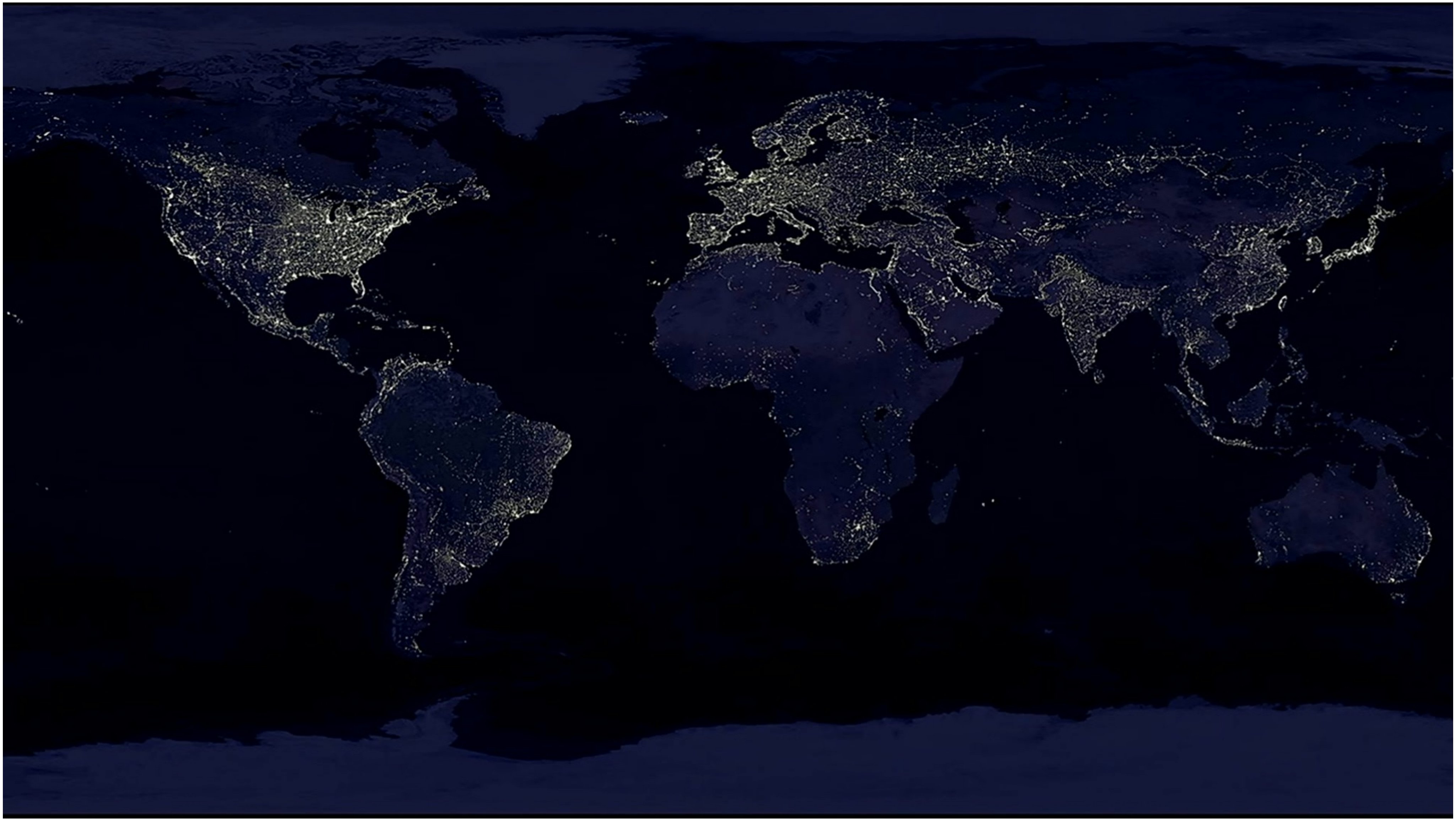
PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

A MATERIAL WORLD

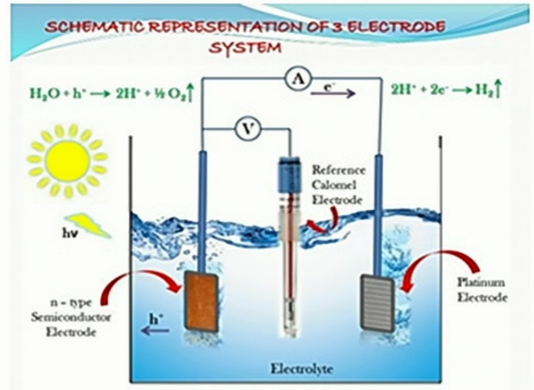
BUILDING A FUTURE FROM THE ATOMS UP

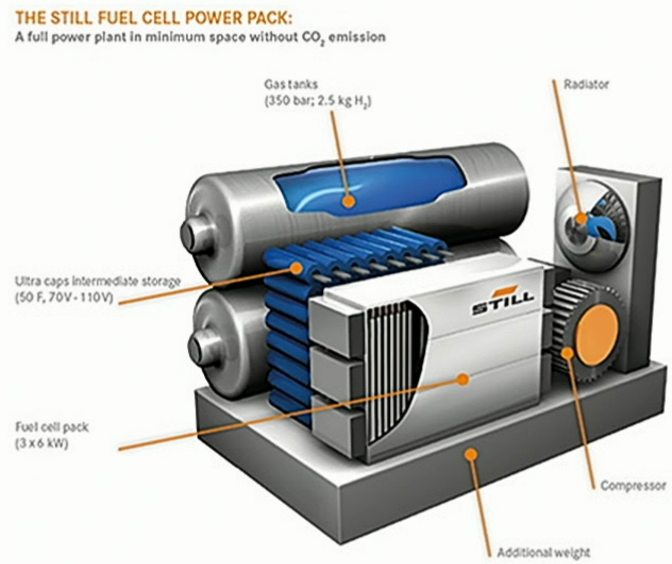


Rob Moore
Stanford Institute for Materials and Energy Sciences
SLAC National Accelerator Laboratory

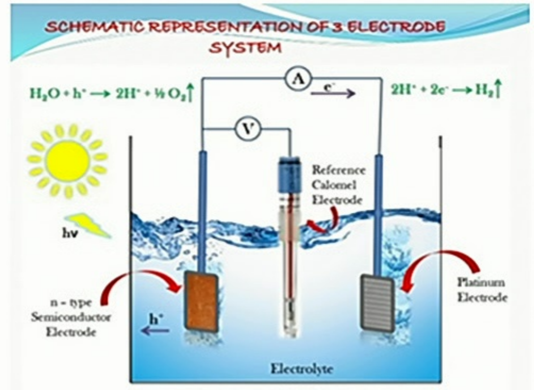


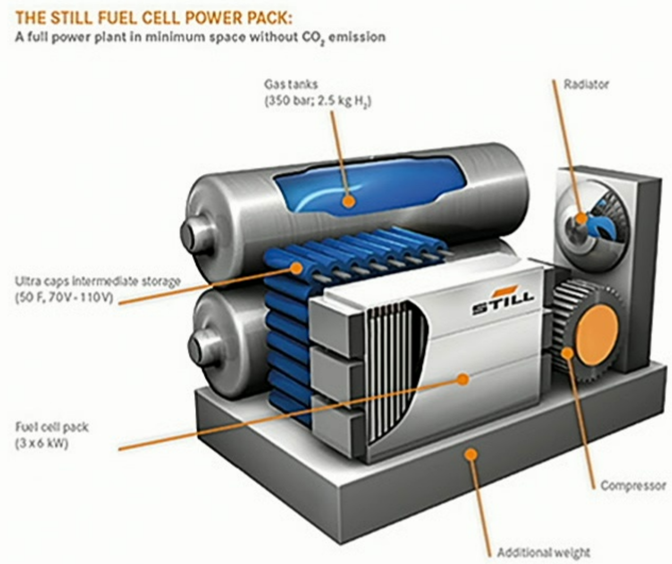

Panasonic
9V
SANYO
CR123A
2CR5
CR-P2
Energizer


SCHEMATIC REPRESENTATION OF 3 ELECTRODE SYSTEM
$H_2O + h^+ \rightarrow 2H^+ + ½O_2\uparrow$
$2H^+ + 2e^- \rightarrow H_2\uparrow$
A
V
e^-
Reference Calomel Electrode
hv
h^+
n - type Semiconductor Electrode
Platinum Electrode
Electrolyte


THE STILL FUEL CELL POWER PACK:
A full power plant in minimum space without CO_2 emission
Gas tanks (350 bar; 2.5 kg H_2)
Radiator
Ultra caps intermediate storage (50 F, 70V - 110V)
STILL
Fuel cell pack (3 x 6 kW)
Compressor
Additional weight


Panasonic
Super Heavy Duty
9V
SANYO
CR123A
2CR5
CR-P2
Energizer
Energizer


SCHEMATIC REPRESENTATION OF 3 ELECTRODE SYSTEM
$H_2O + h^+ \rightarrow 2H^+ + ½O_2$↑
$2H^+ + 2e^- \rightarrow H_2$↑
A
V
e^-
hν
Reference Calomel Electrode
n - type Semiconductor Electrode
h^+
Platinum Electrode
Electrolyte

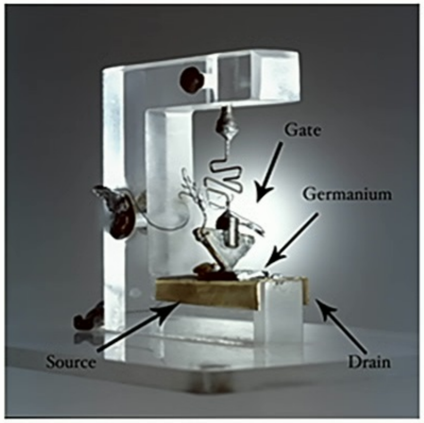

THE STILL FUEL CELL POWER PACK:
A full power plant in minimum space without CO_2 emission
Gas tanks
(350 bar; 2.5 kg H_2)
Radiator
Ultra caps intermediate storage
(50 F, 70V - 110V)
Fuel cell pack
(3 x 6 kW)
Compressor
Additional weight
STILL


SCHEMATIC REPRESENTATION OF 3 ELECTRODE SYSTEM
Reference Calomel Electrode
n - type Semiconductor Electrode
Electrolyte
GLOBAL INFORMATION GRID
in minimum space without CO_2 emission
Gas tanks (350 bar; 2.5 kg H_2)
Radiator
Compressor
Additional weight

The Metals Age – Mastering All things Metal

5000 Years

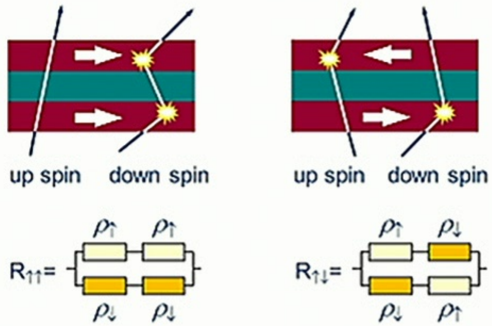
The Semiconductor Age – Mastering All things Kinda Metal



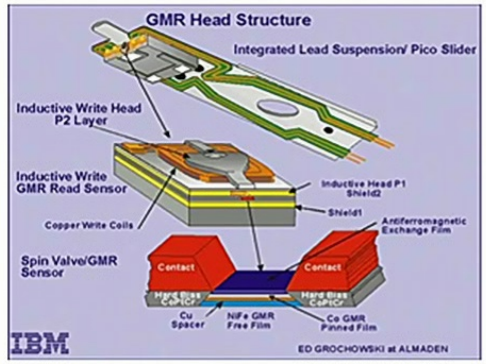
60 Years

Today's Material Cycle – Giant Magneto Resistance

1988



1997



2006

10 Years

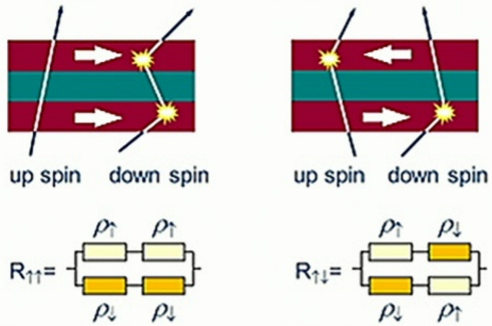
10 Years

10 Years

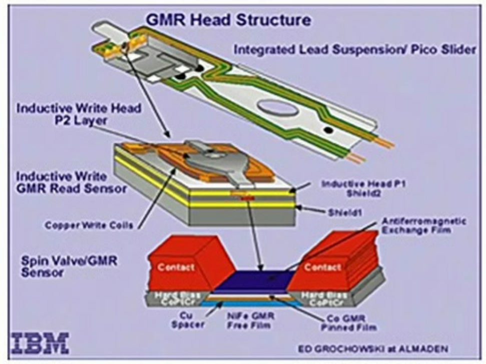
1980s

Today's Material Cycle – Giant Magneto Resistance

1988



1997



2006

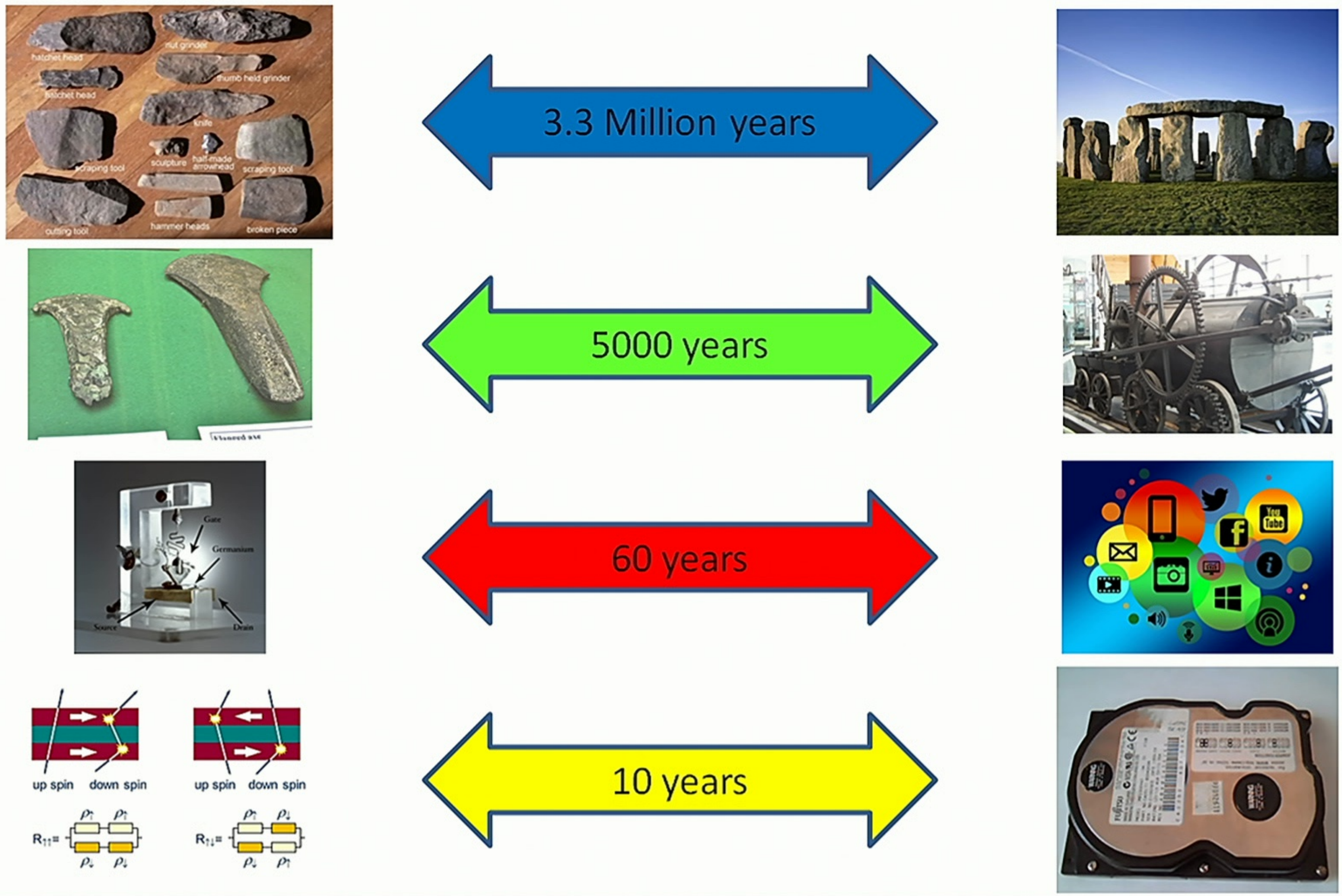
10 Years

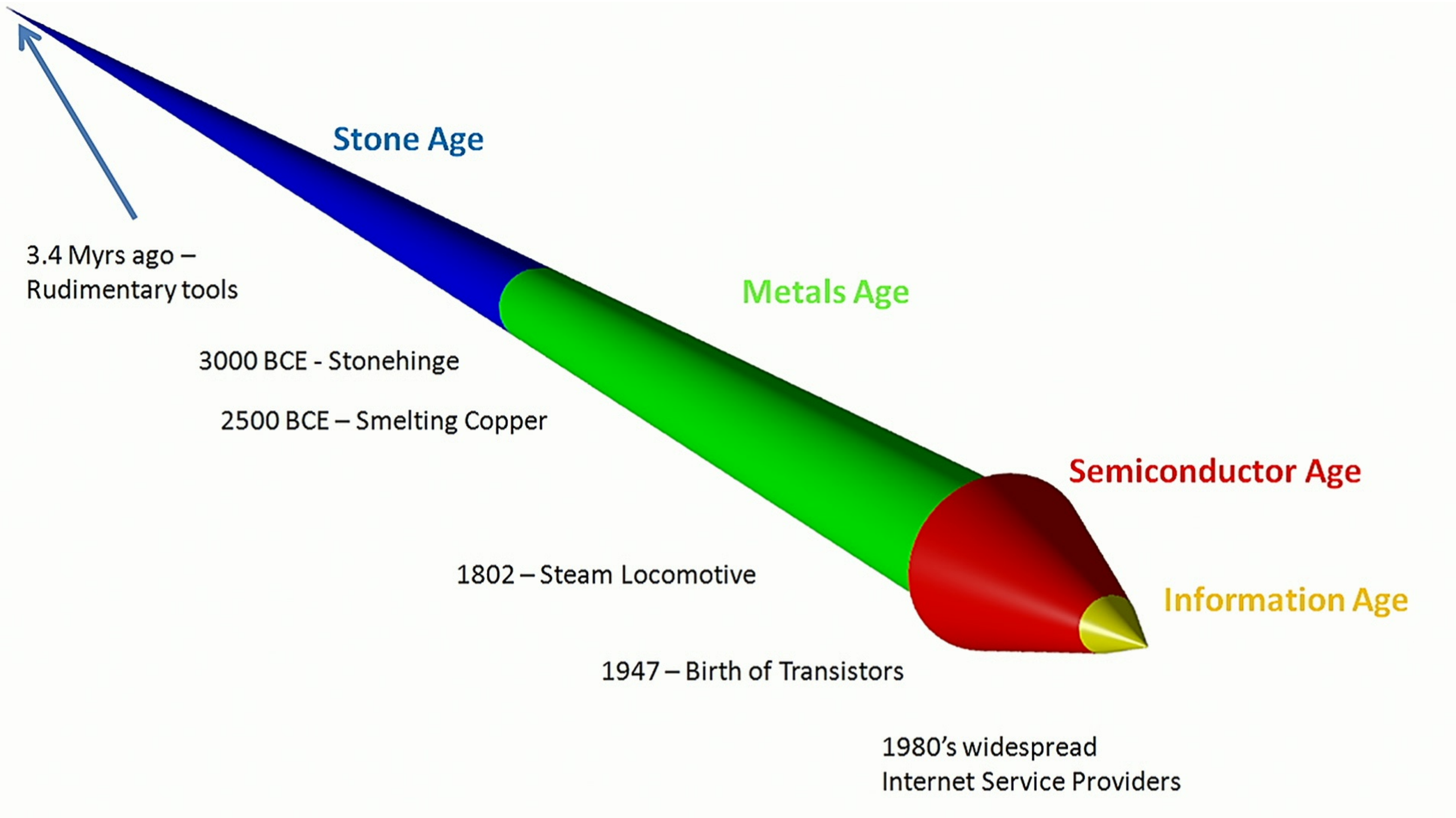
10 Years

10 Years

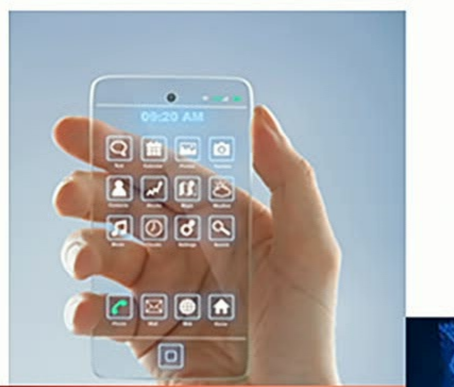
1980s

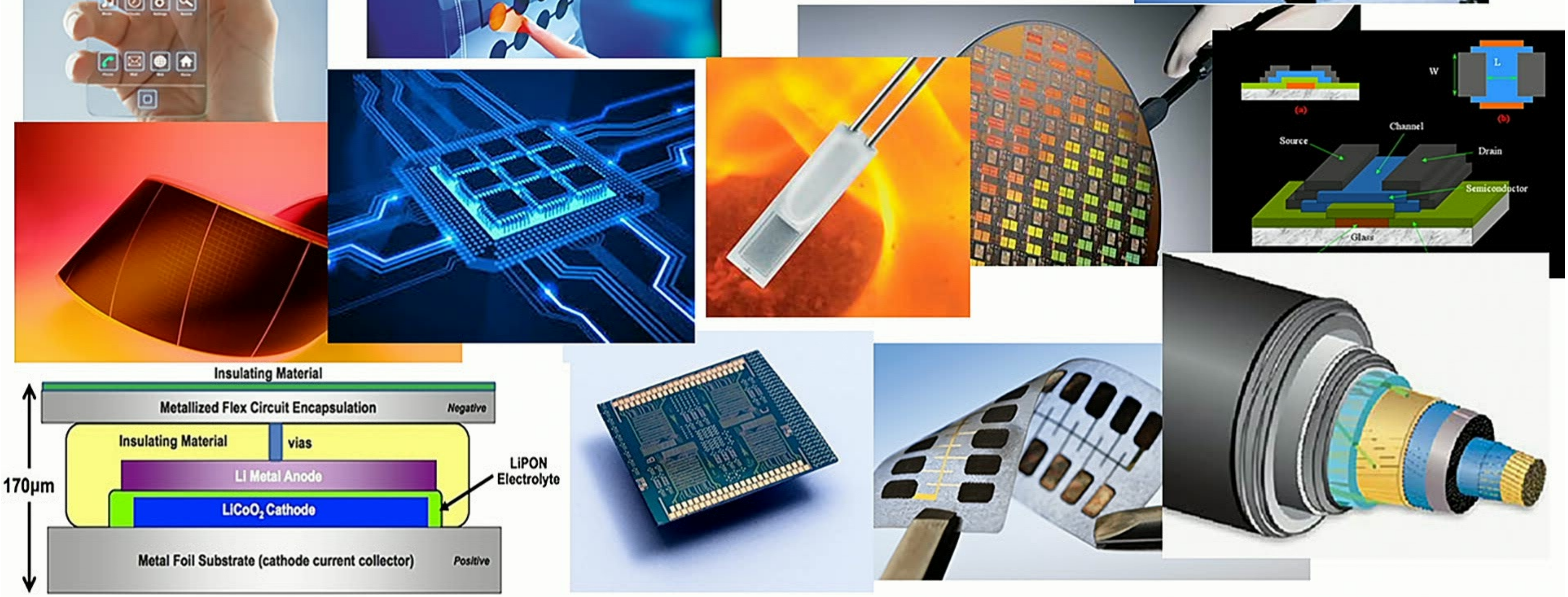
x 750,000 =


hatchet head
nut grinder
thumb held grinder
hatchet head
knife
scraping tool
sculpture
half-made arrowhead
scraping tool
cutting tool
hammer heads
broken piece
3.3 Million years
5000 years
Gate
Germanium
Source
Drain
60 years
up spin
down spin
up spin
down spin
10 years

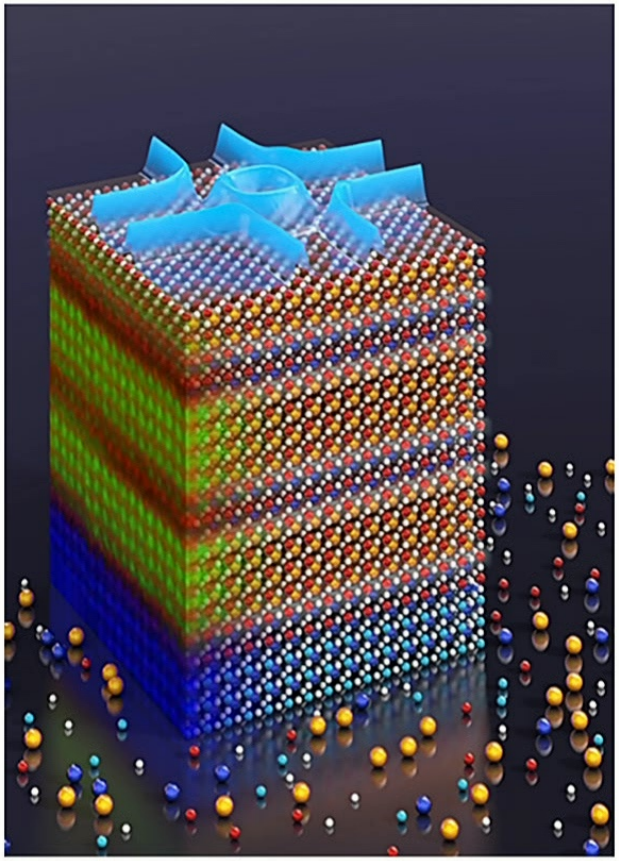

Stone Age
3.4 Myrs ago –
Rudimentary tools
Metals Age
3000 BCE - Stonehinge
2500 BCE – Smelting Copper
Semiconductor Age
Information Age
1802 – Steam Locomotive
1947 – Birth of Transistors
1980's widespread
Internet Service Providers

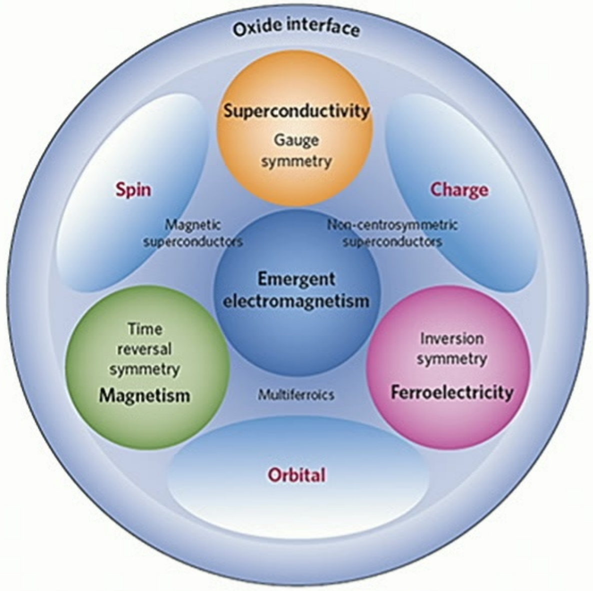
State of the Art



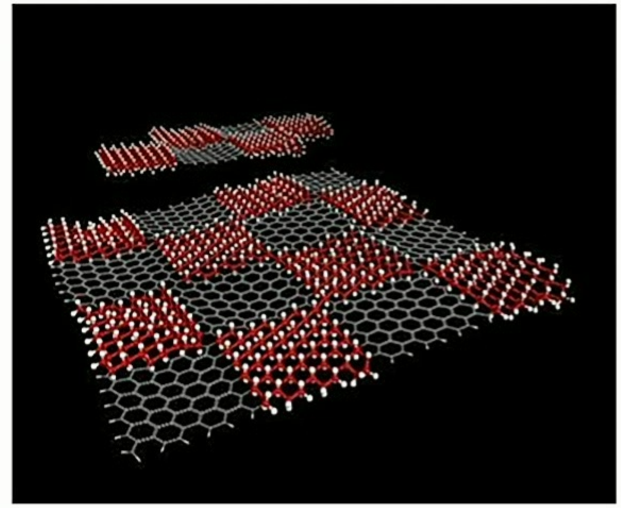


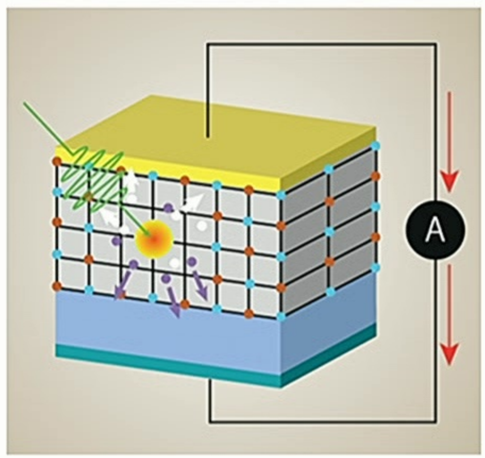
The Next Age........



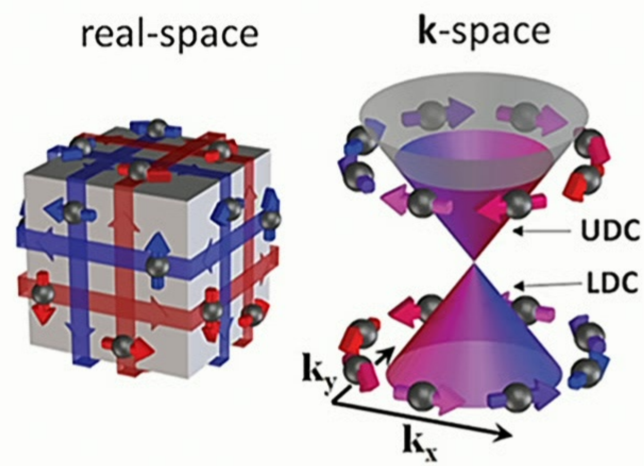


Oxide interface
Superconductivity
Gauge symmetry
Spin
Charge
Magnetic superconductors
Non-centrosymmetric superconductors
Emergent electromagnetism
Time reversal symmetry
Magnetism
Multiferroics
Inversion symmetry
Ferroelectricity
Orbital



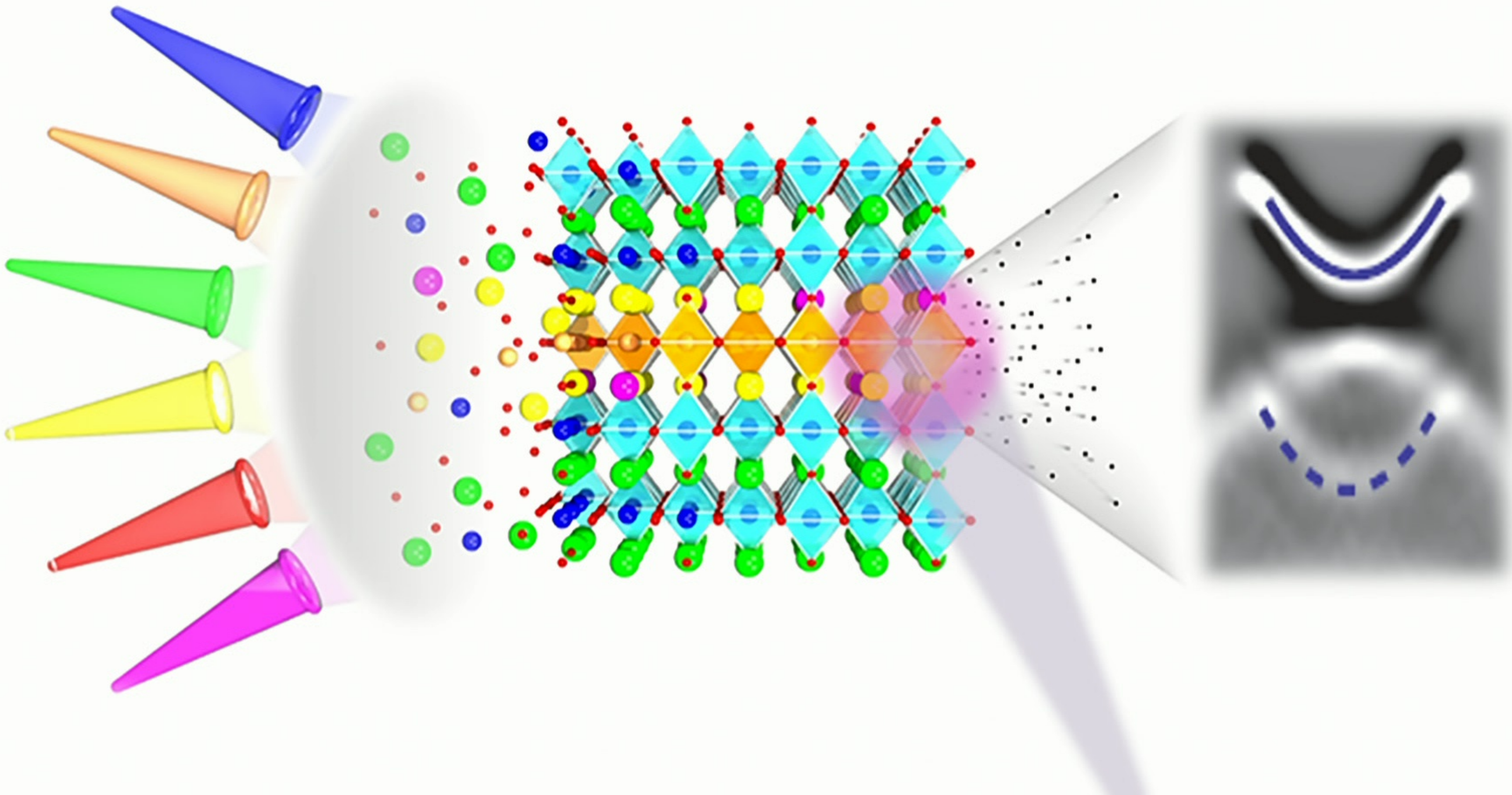


A

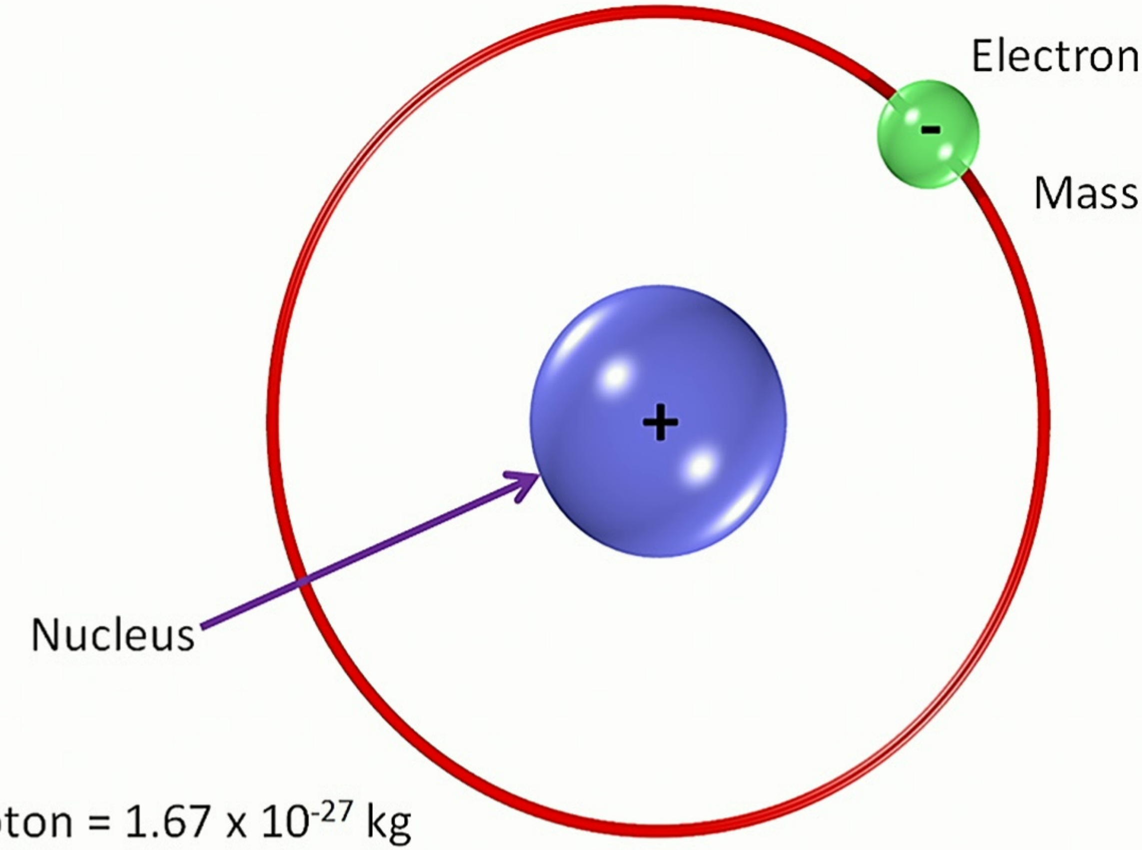


real-space
k-space
UDC
LDC
k_y
k_x

What We Do.......................



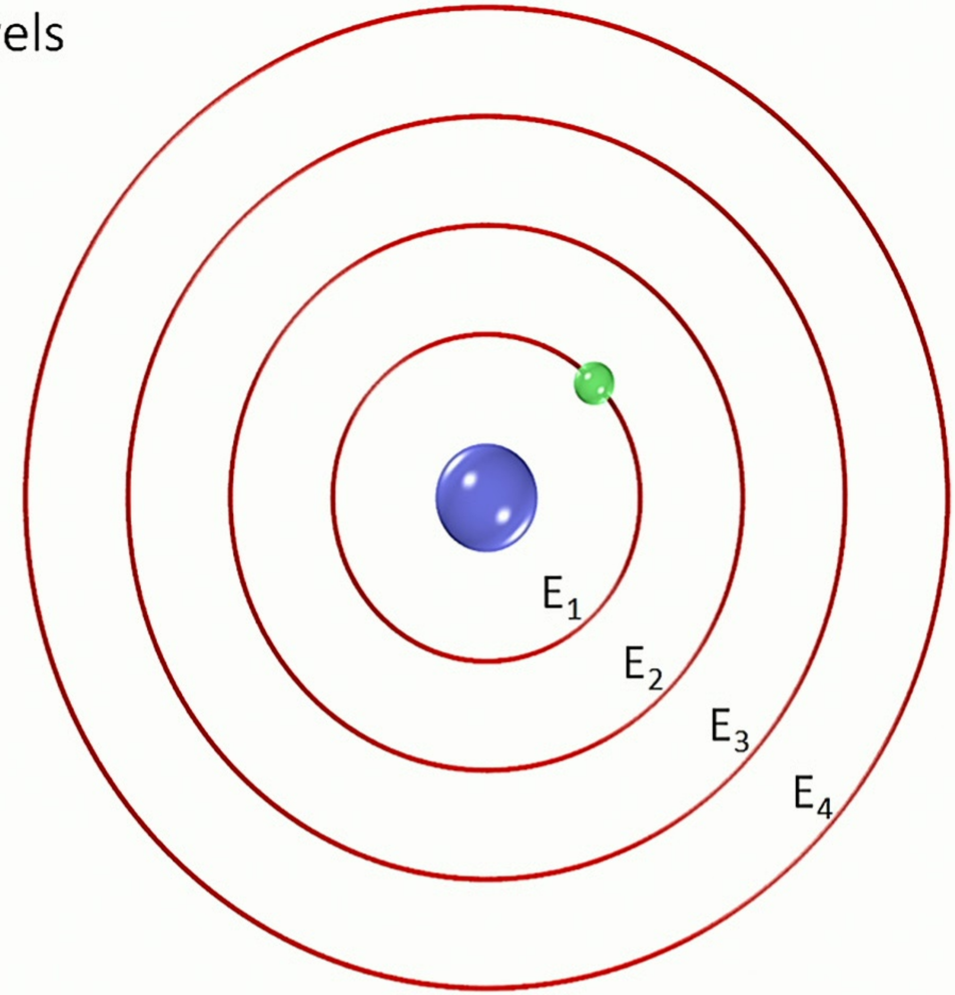
The Atom



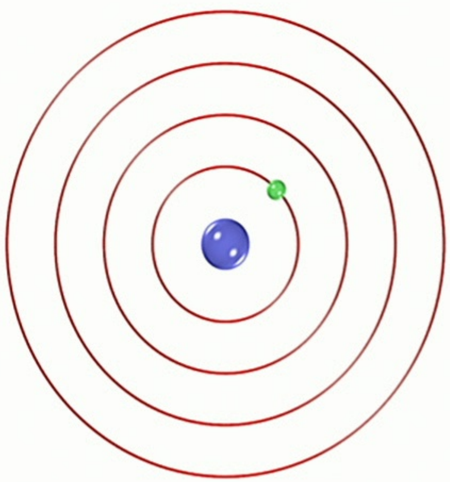
Mass of electron = 9.1×10^{-31} kg

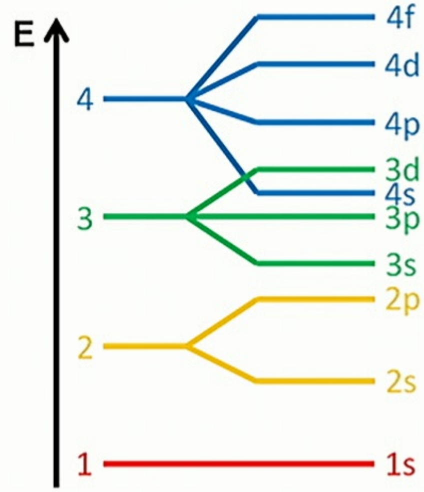
Mass of proton = 1.67×10^{-27} kg
Mass of neutron = 1.67×10^{-27} kg

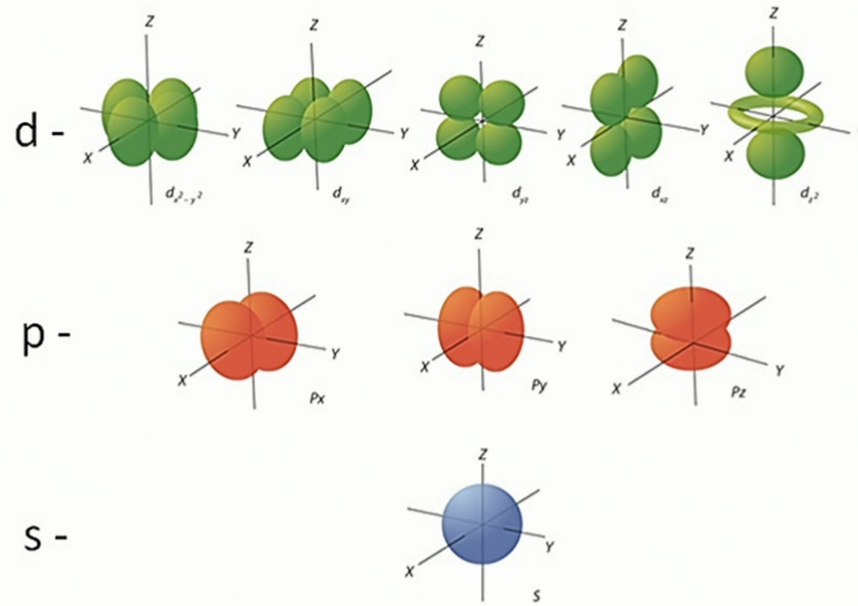
Electron Energy Levels



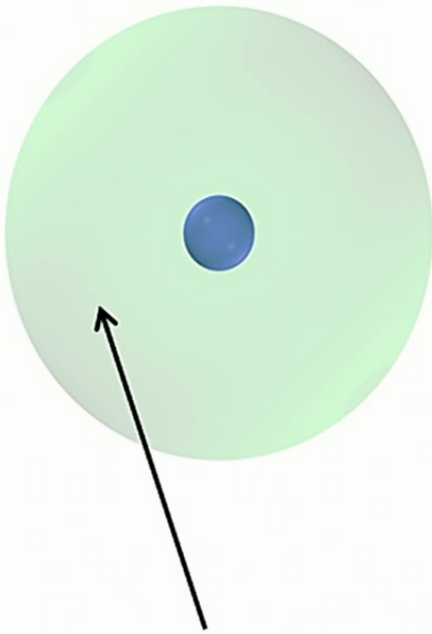
Electron Orbitals

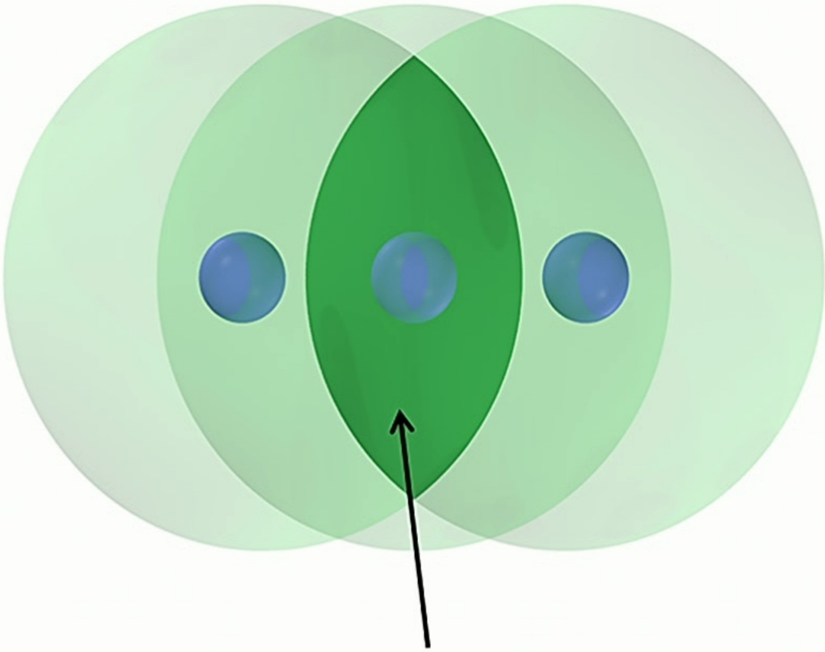


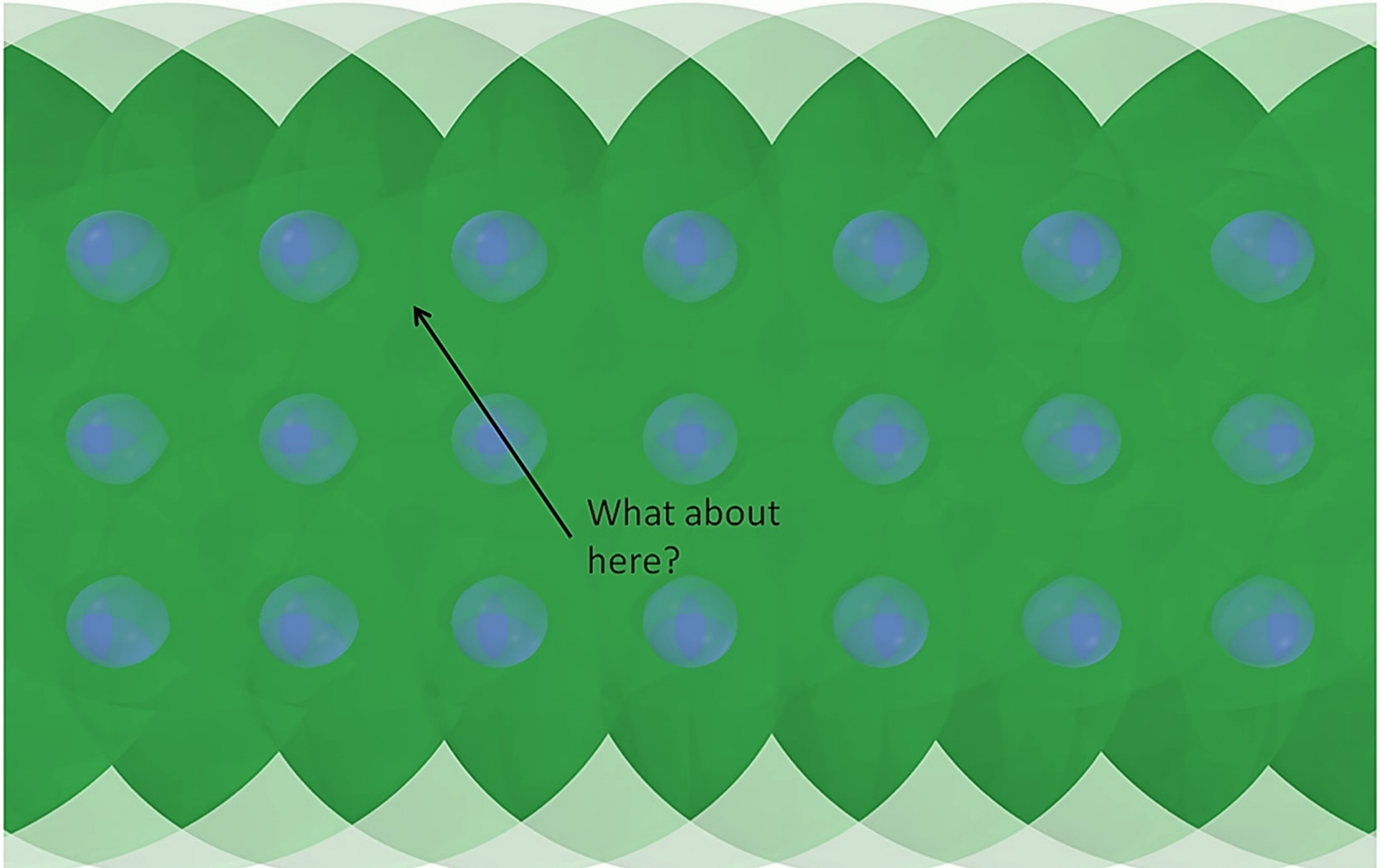




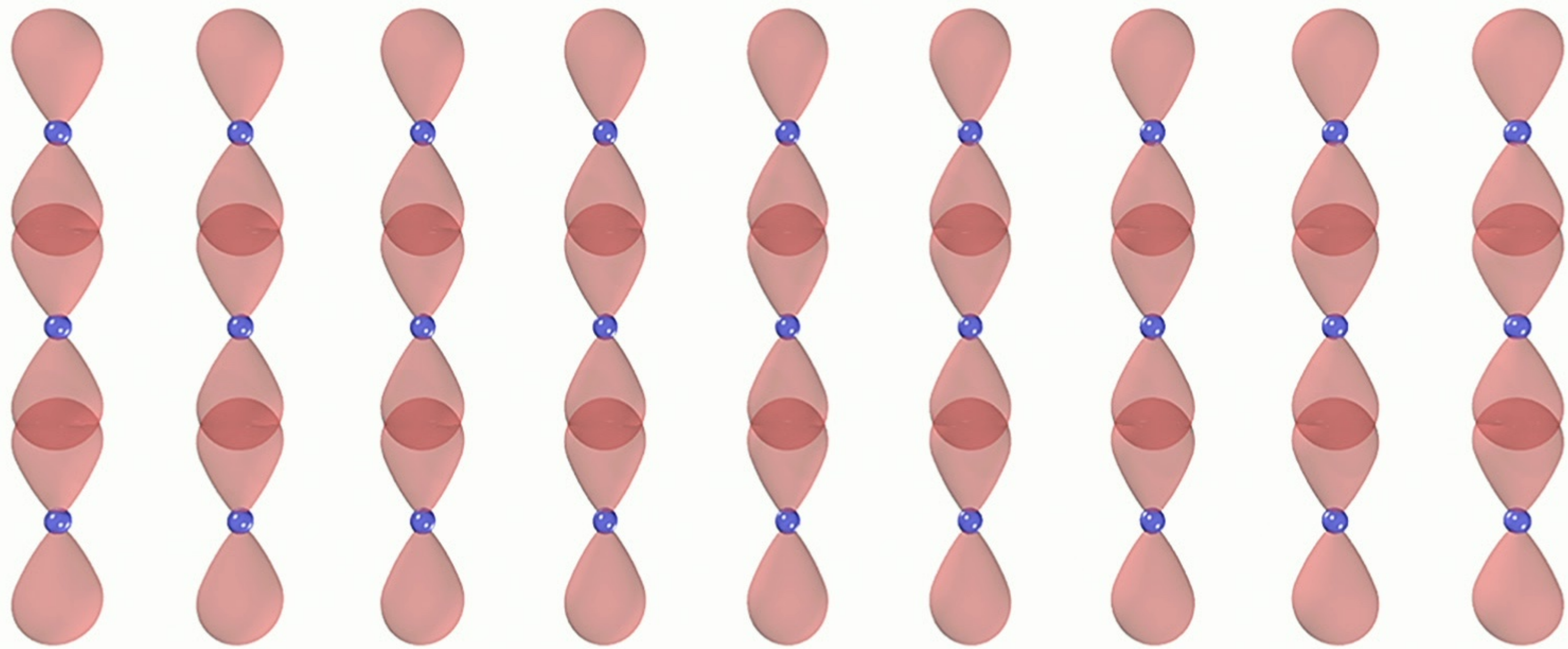
Chain of Atoms



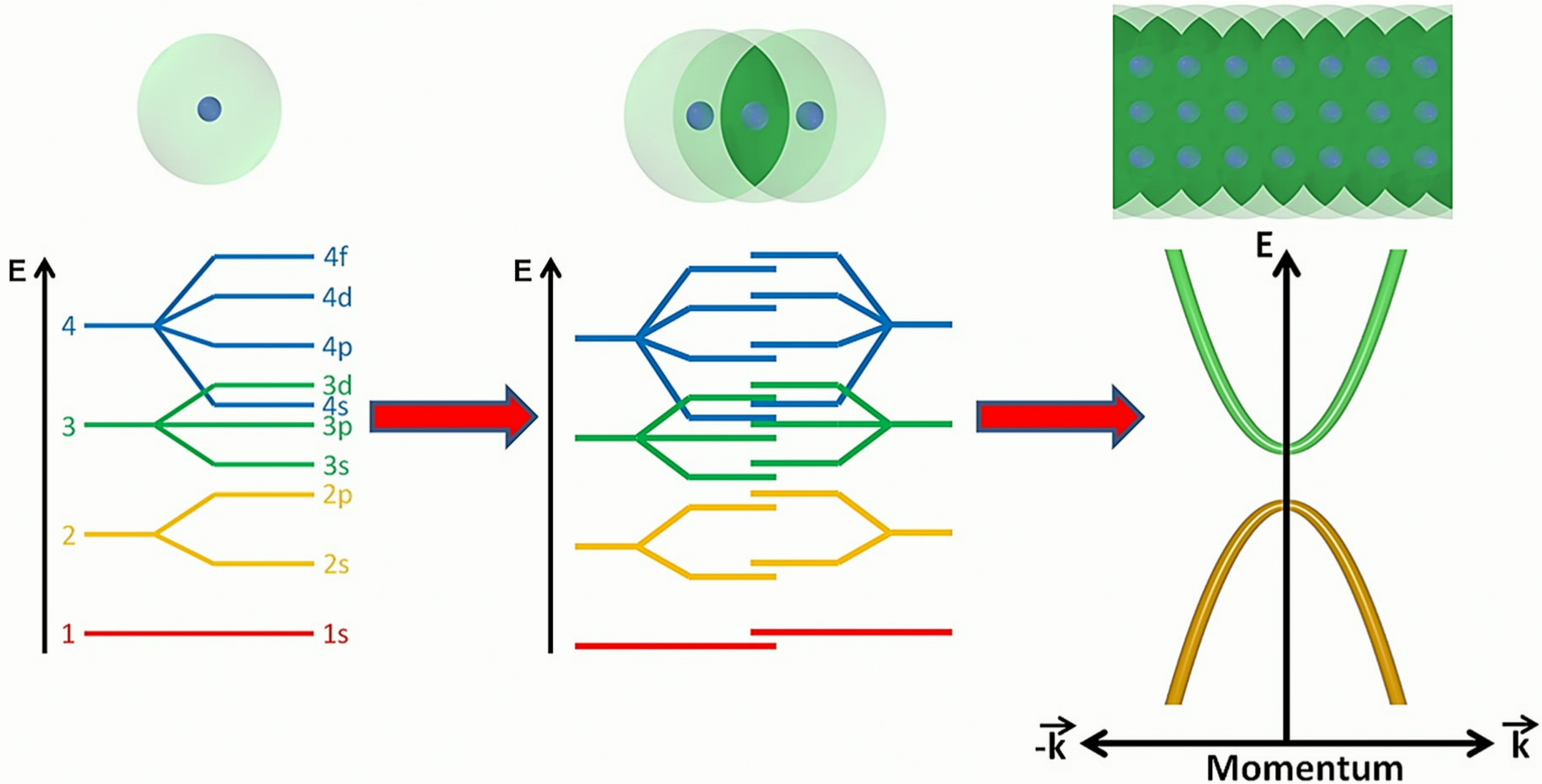



What about
here?

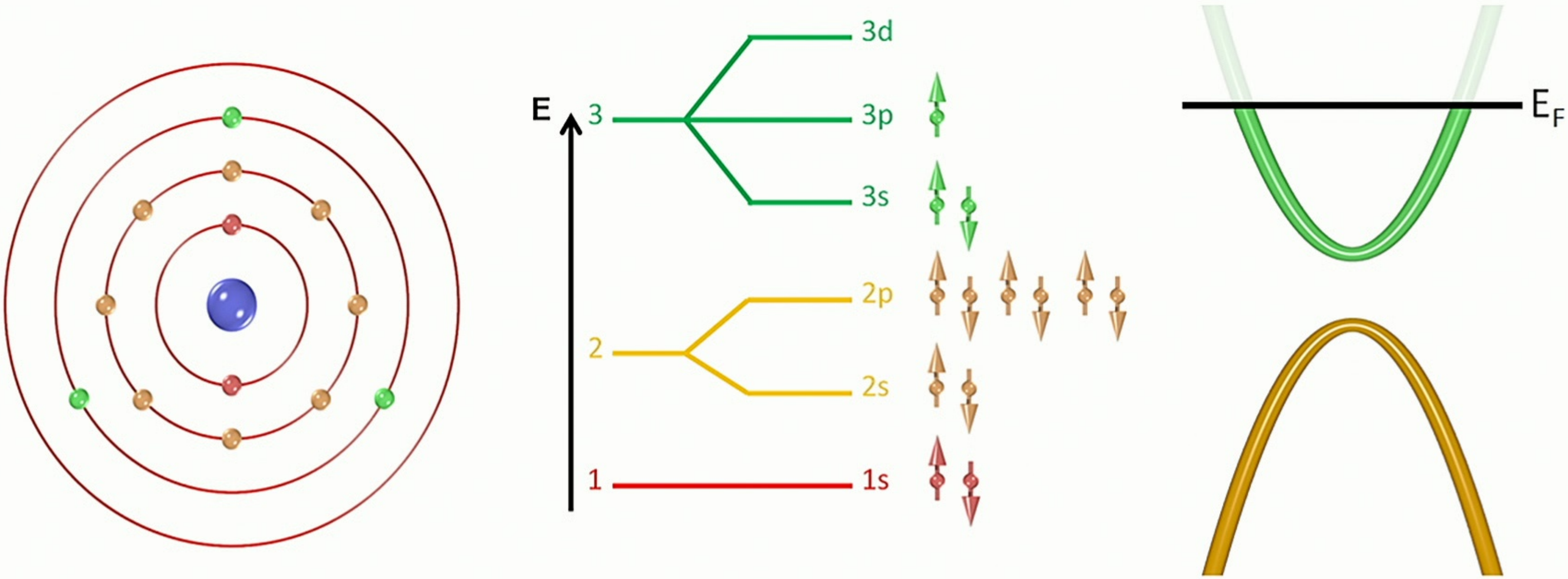
Orbital Overlap



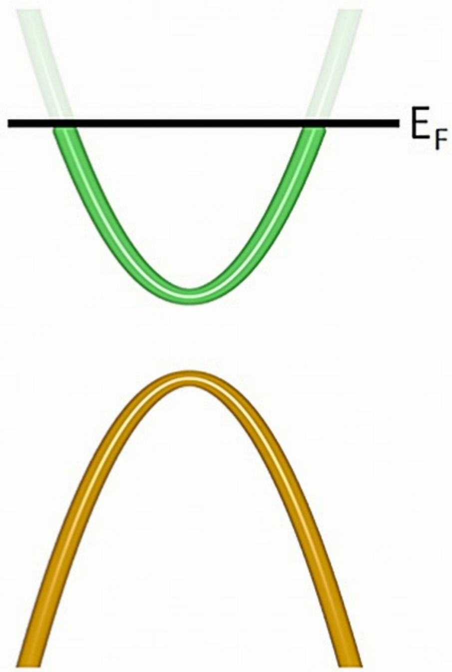
Energy Bands

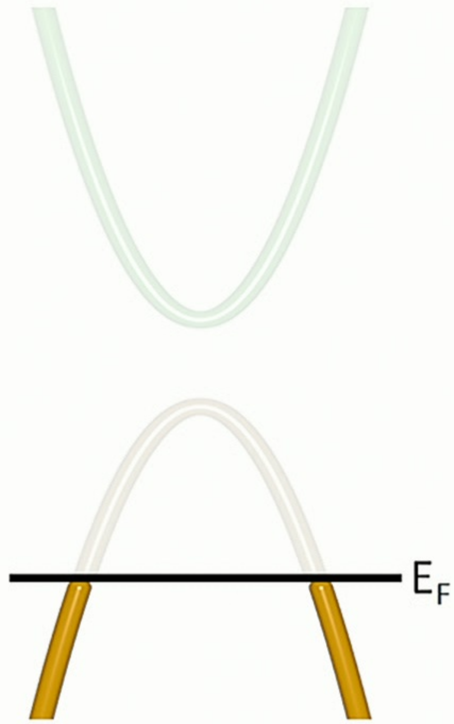


Fermi Energy – E_F

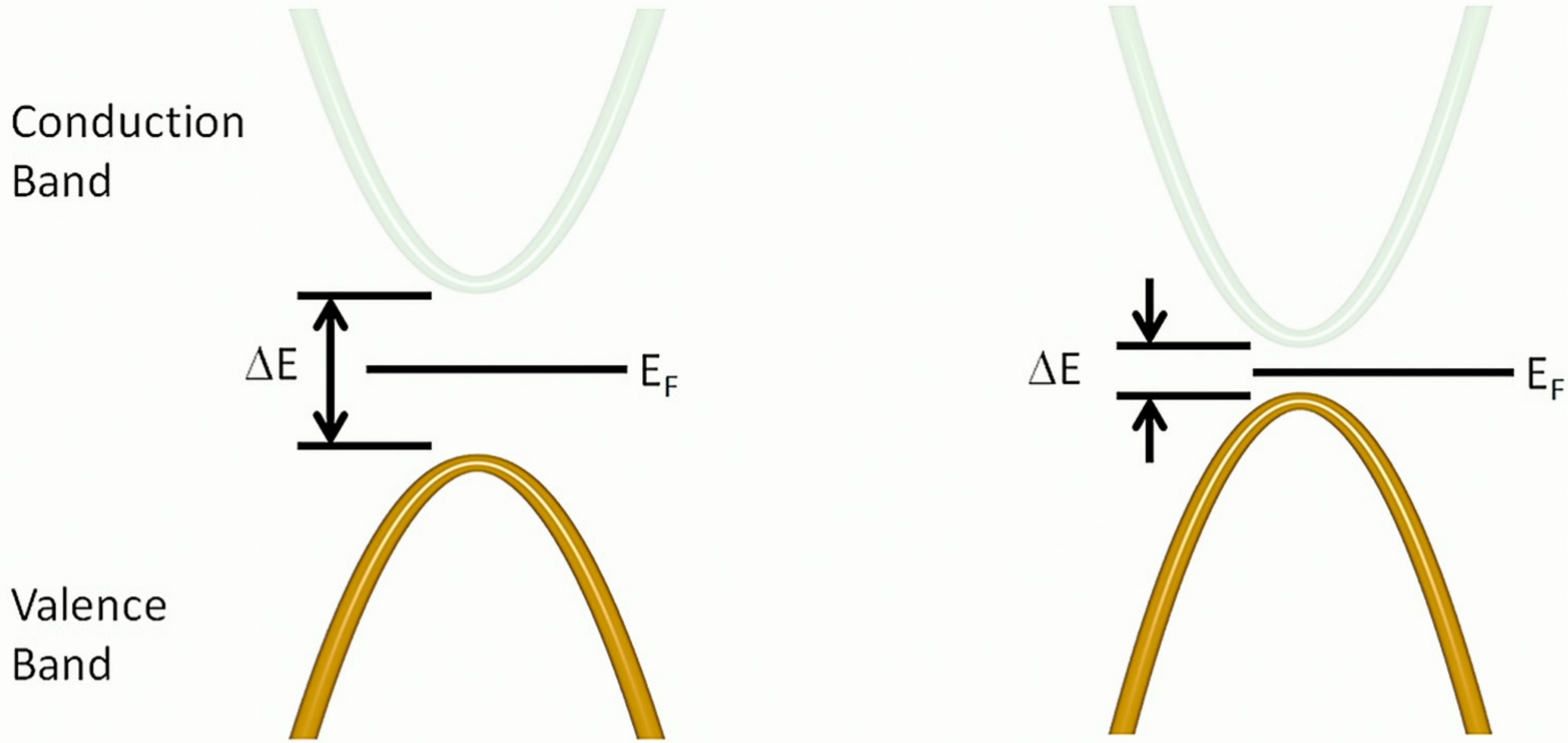


Metals





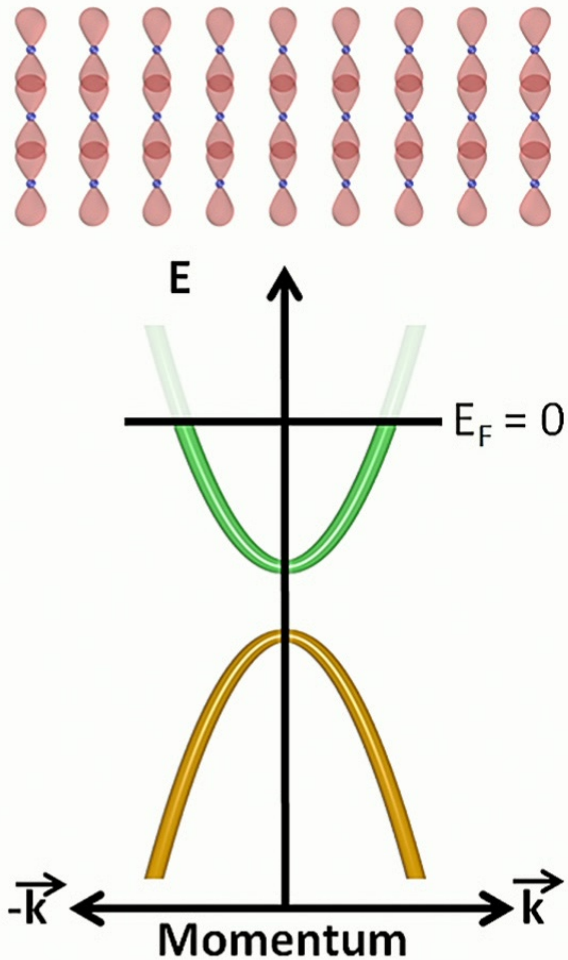
Band Gap

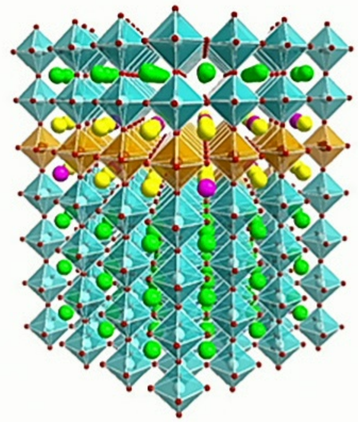


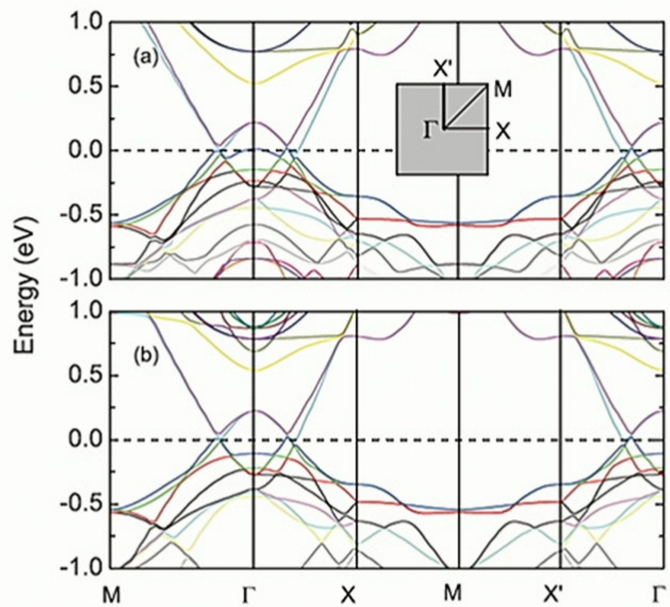
Large Gap = Insulator

Small Gap = Semiconductor

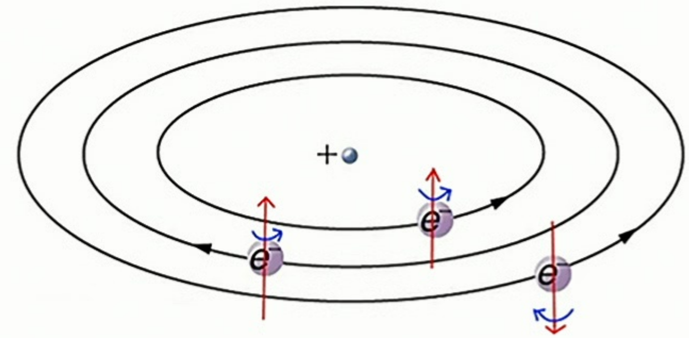
From Models to Materials

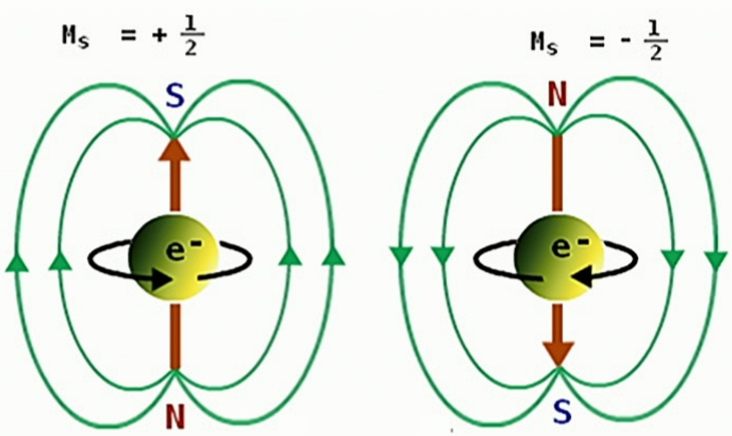


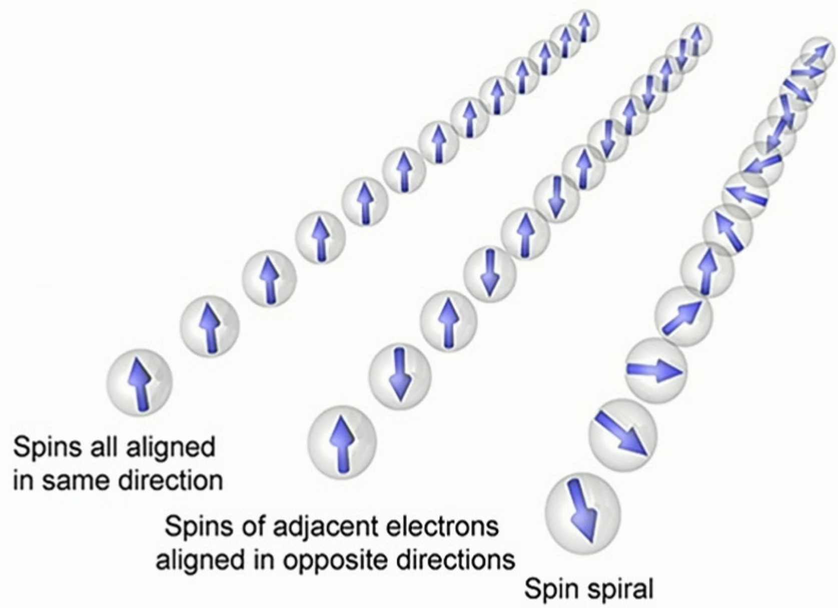




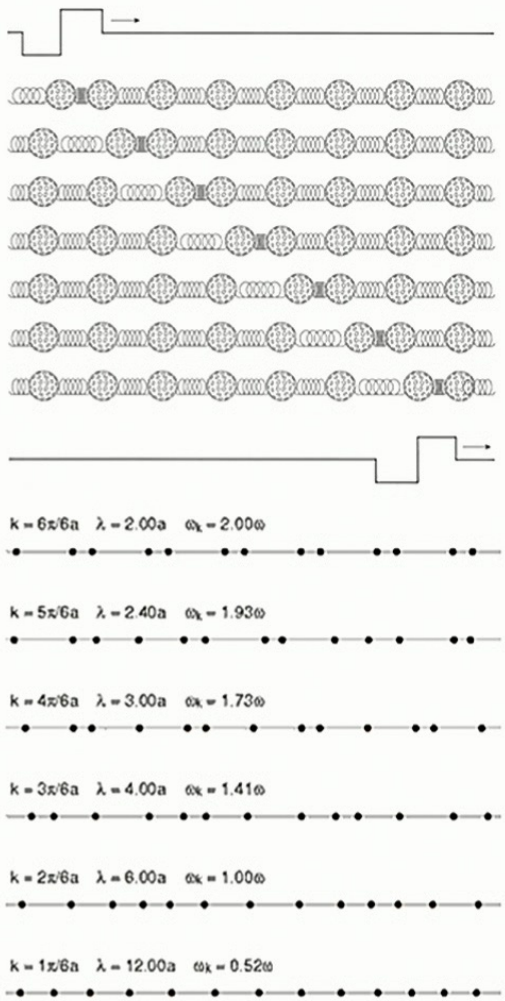
Electron Spin







Phonons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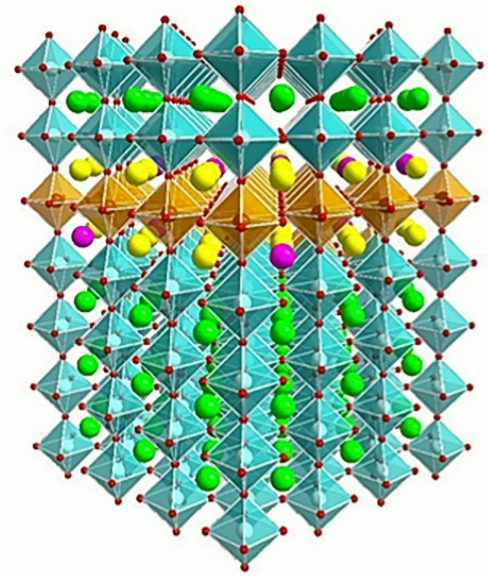
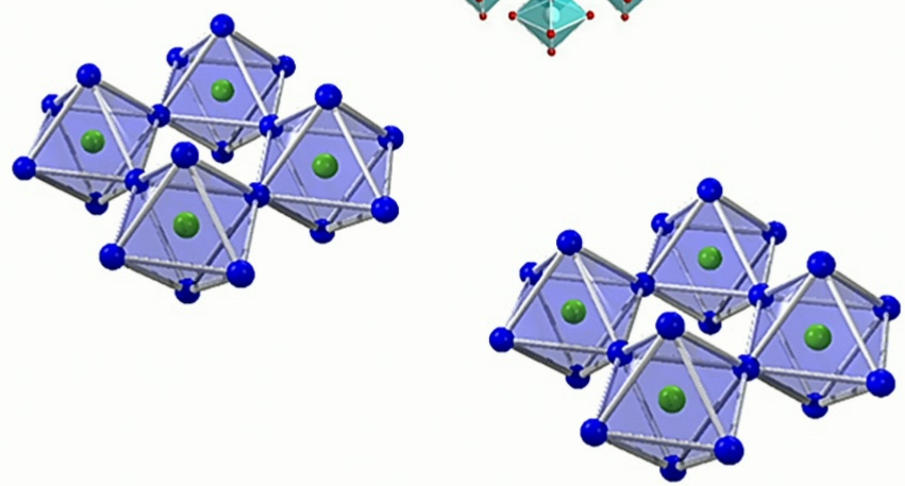
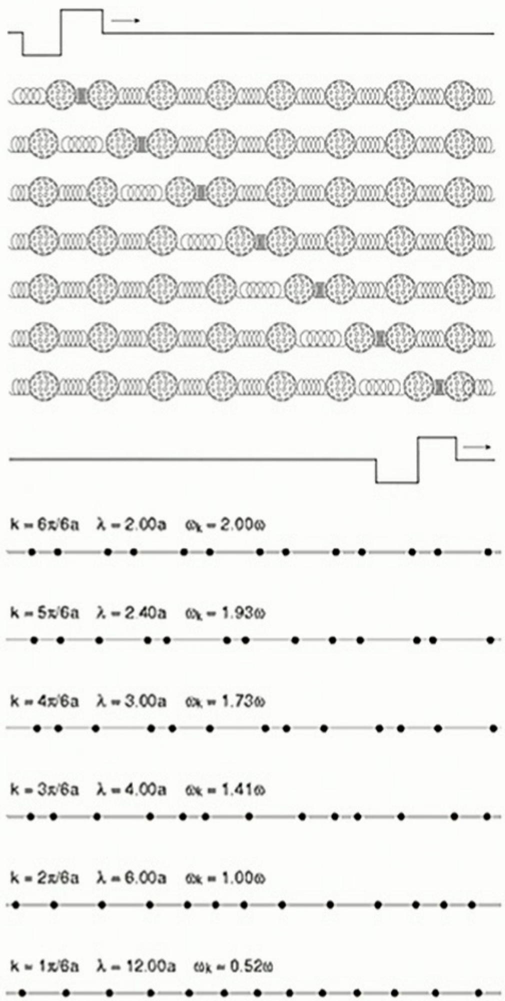
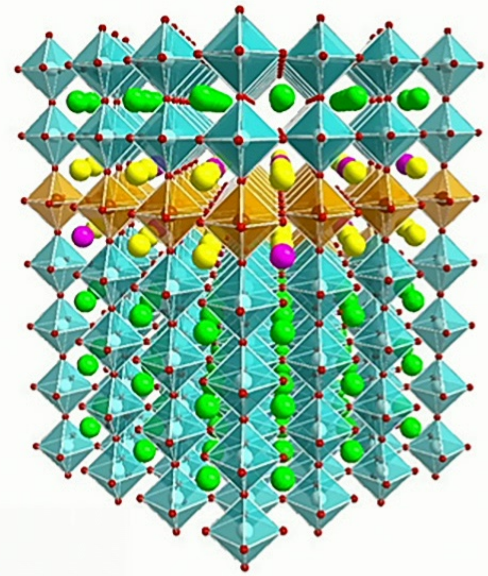
k = 5π/6a λ = 2.40a ω_k = 1.93ω
k = 4π/6a λ = 3.00a ω_k = 1.73ω
k = 3π/6a λ = 4.00a ω_k = 1.41ω
k = 2π/6a λ = 6.00a ω_k = 1.00ω
k = 1π/6a λ = 12.00a ω_k = 0.52ω

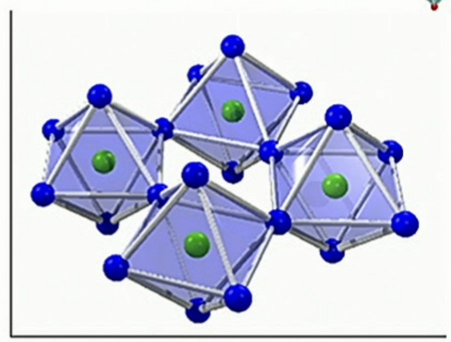


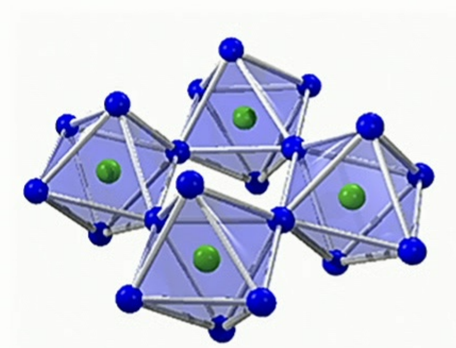


Phonons

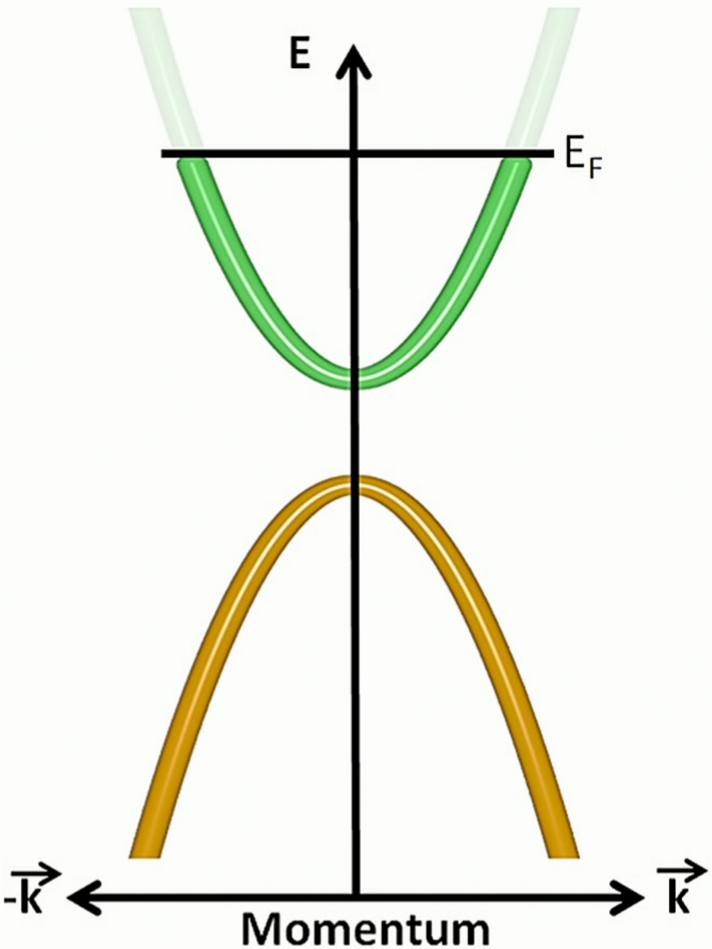

k = 6π/6a λ = 2.00a ω_k = 2.00ω
k = 5π/6a λ = 2.40a ω_k = 1.93ω
k = 4π/6a λ = 3.00a ω_k = 1.73ω
k = 3π/6a λ = 4.00a ω_k = 1.41ω
k = 2π/6a λ = 6.00a ω_k = 1.00ω
k = 1π/6a λ = 12.00a ω_k = 0.52ω

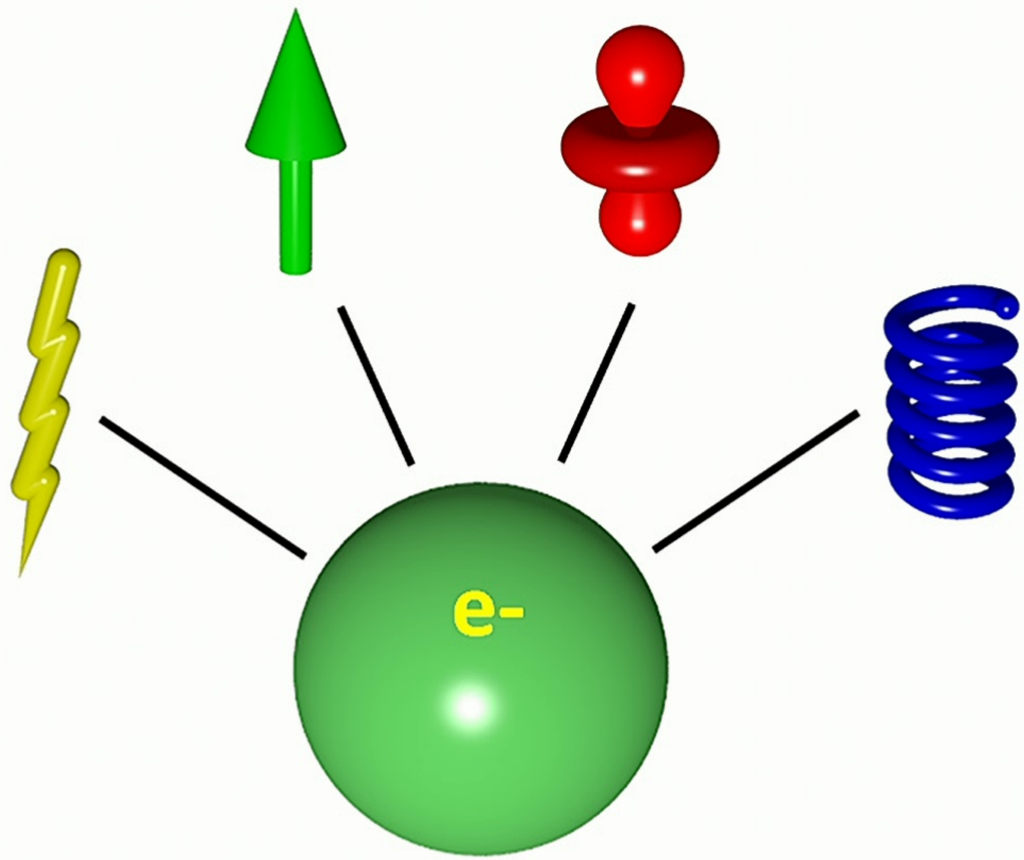


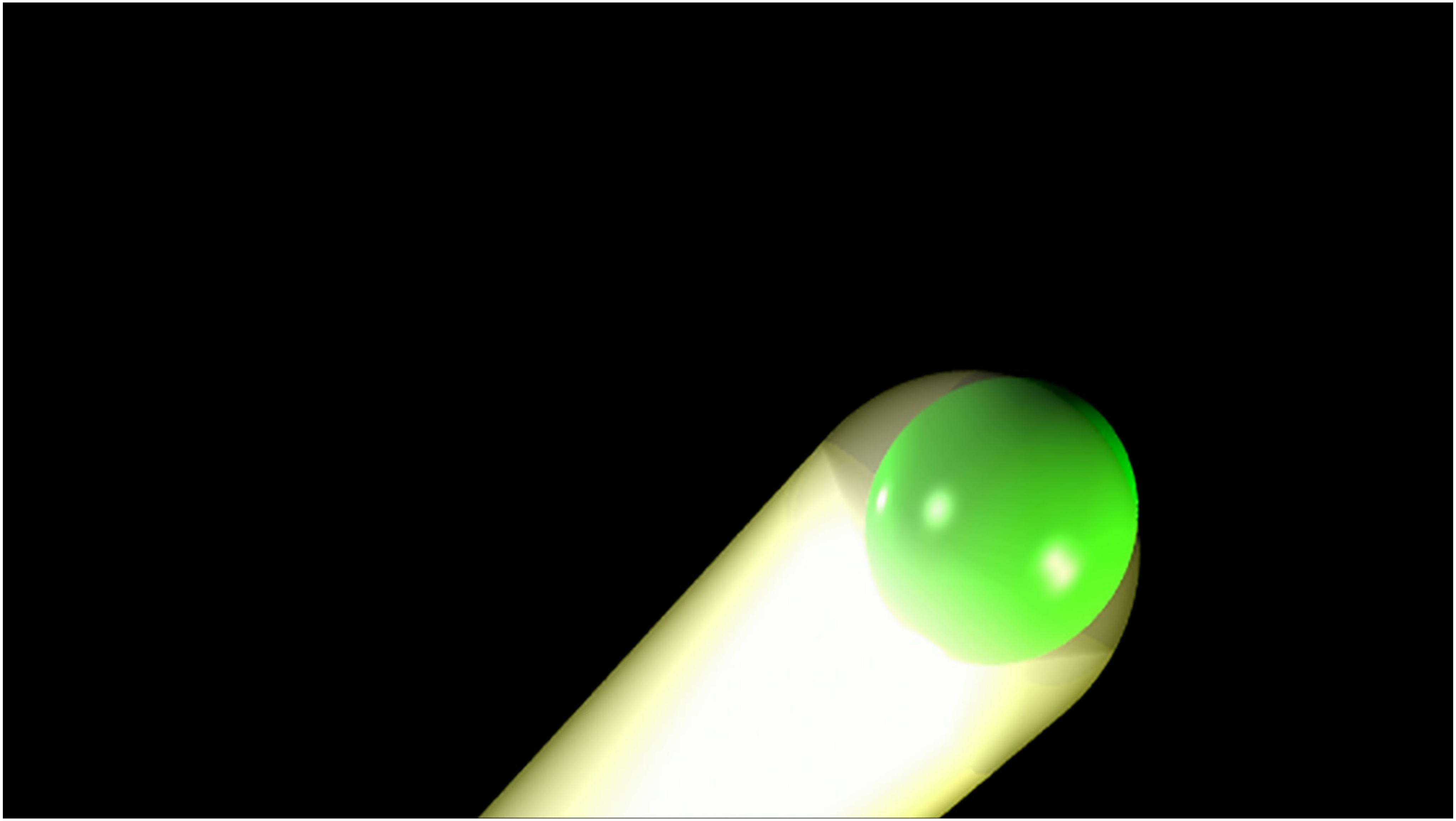


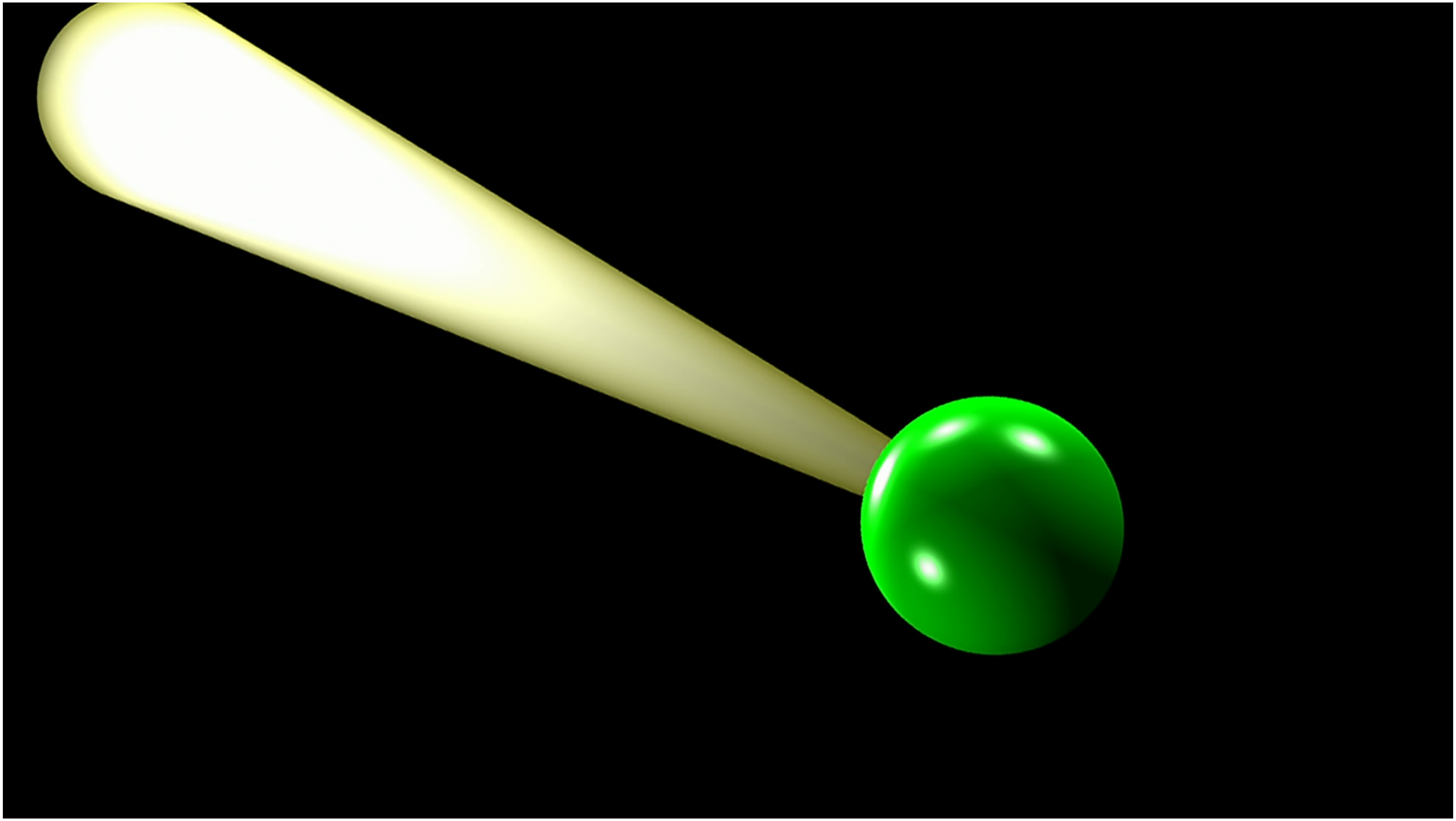


The Types of Players



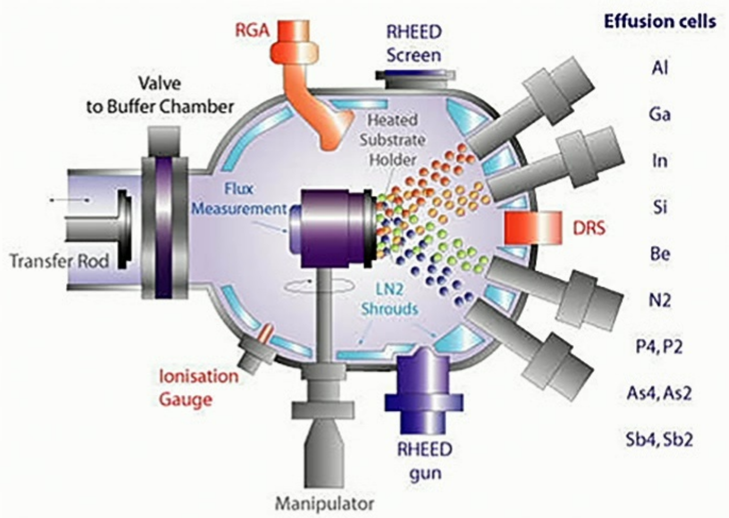


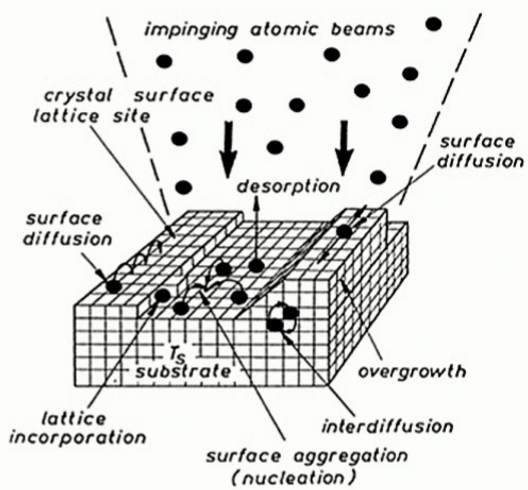


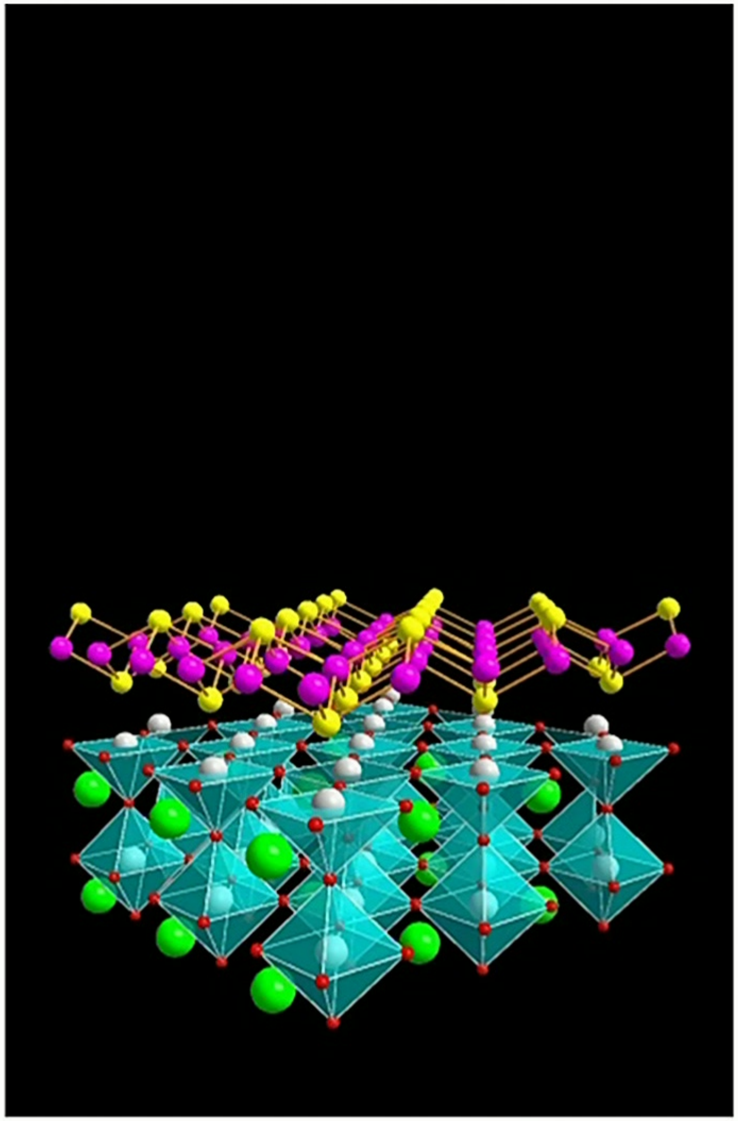


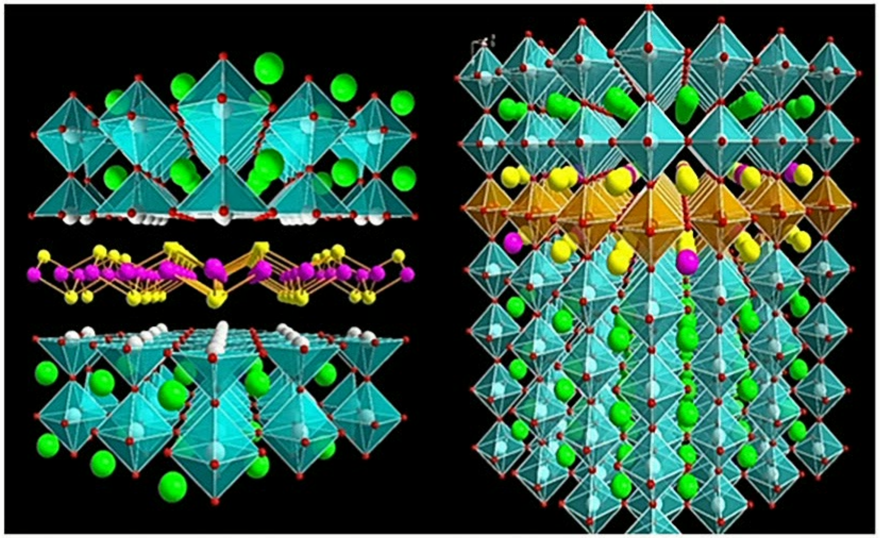
Now that we know the players, what is the game?

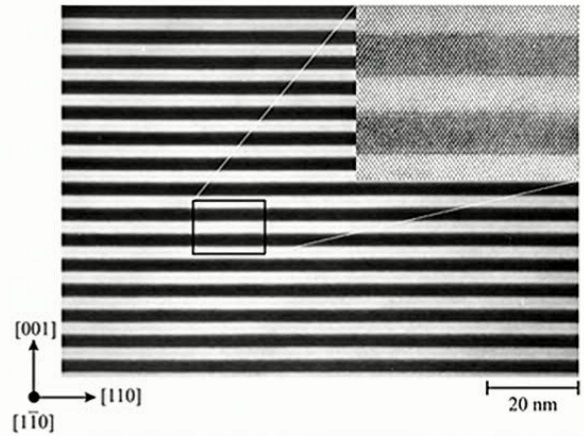
Molecular Beam Epitaxy (MBE)

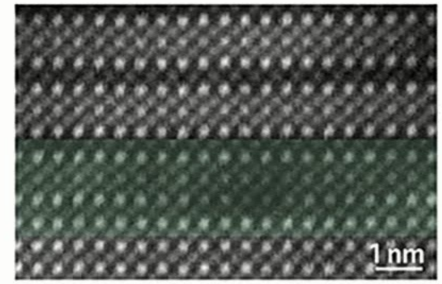

RGA
RHEED Screen
Effusion cells
Al
Ga
In
Si
Be
N2
P4, P2
As4, As2
Sb4, Sb2
Valve to Buffer Chamber
Heated Substrate Holder
Flux Measurement
Transfer Rod
DRS
LN2 Shrouds
Ionisation Gauge
RHEED gun
Manipulator

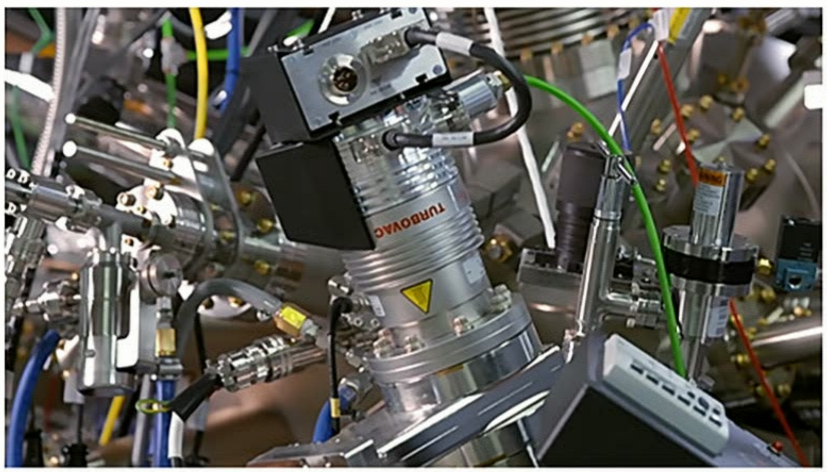

impinging atomic beams
crystal surface lattice site
surface diffusion
desorption
surface diffusion
T_S substrate
overgrowth
lattice incorporation
interdiffusion
surface aggregation (nucleation)

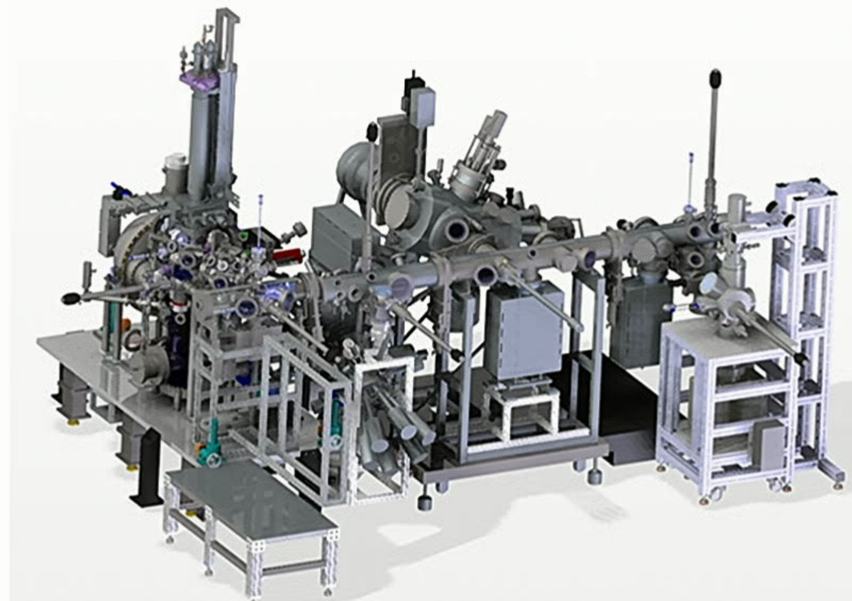


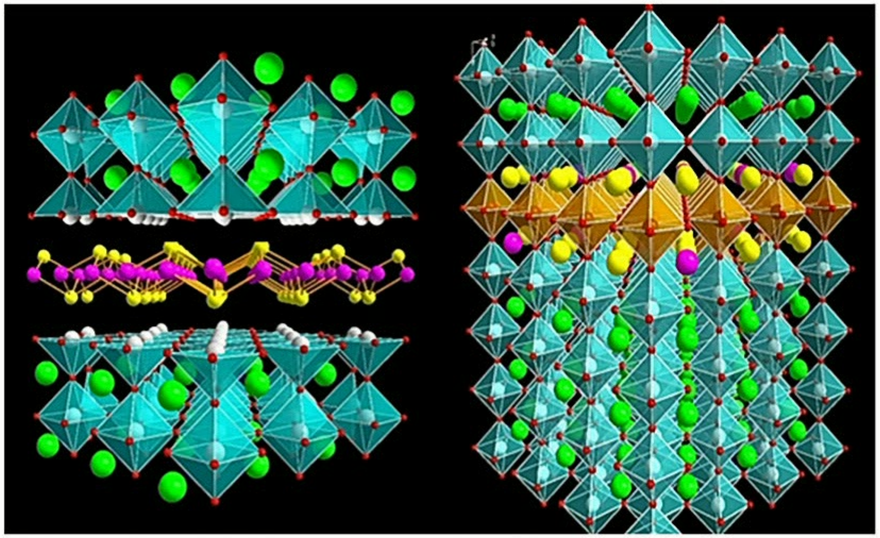


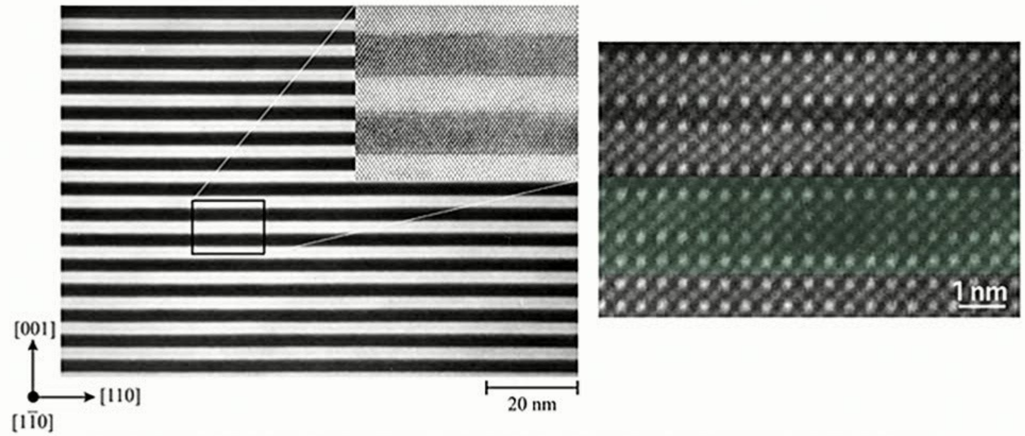

[001]
[110]
[1$\bar{1}$0]
20 nm

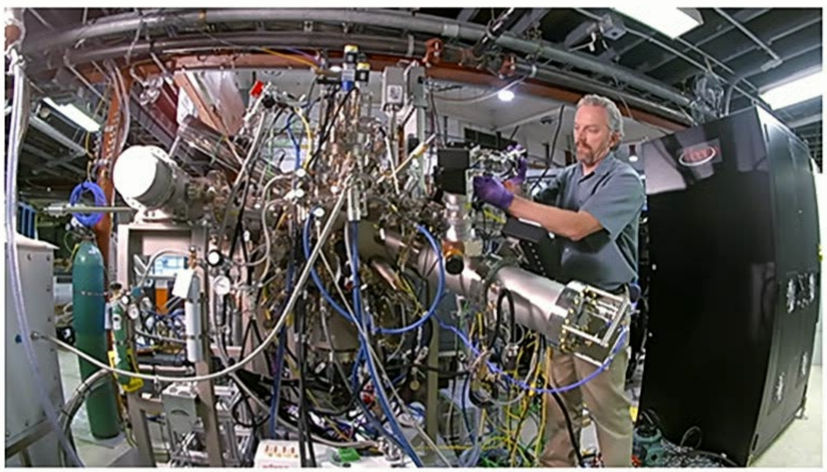

1 nm

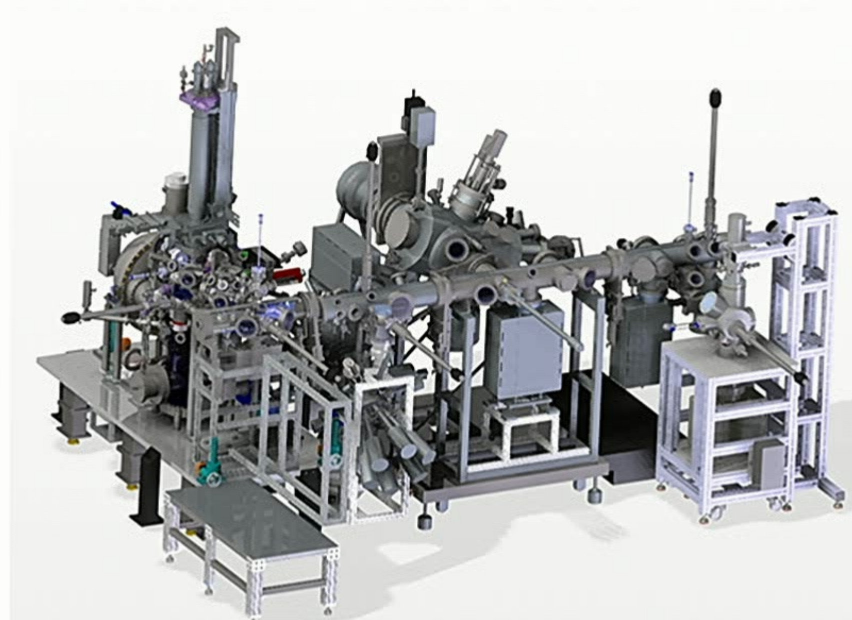

TURBOVAC

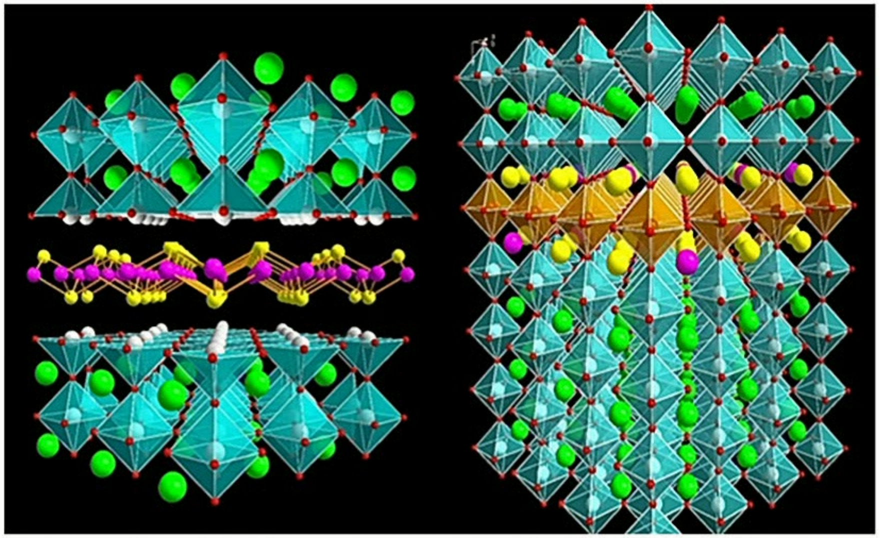


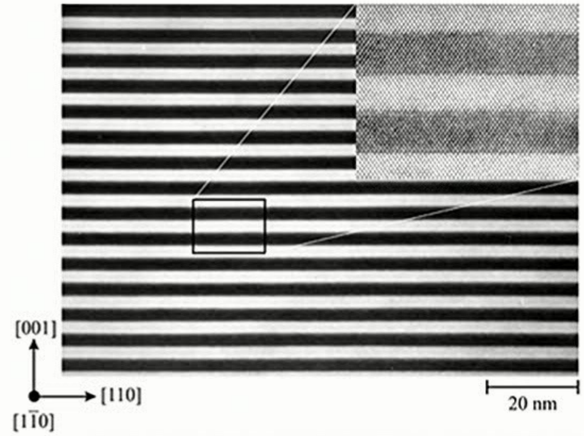



[001]
[110]
[1$\bar{1}$0]
20 nm
1 nm





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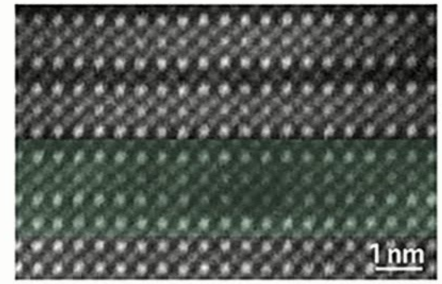
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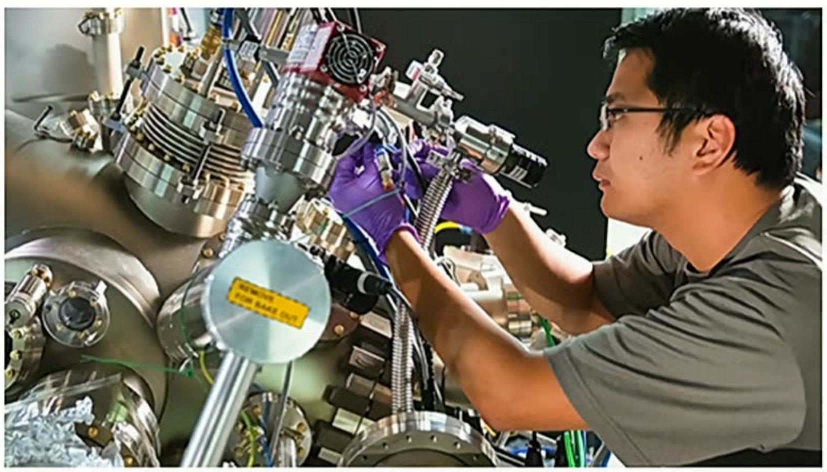
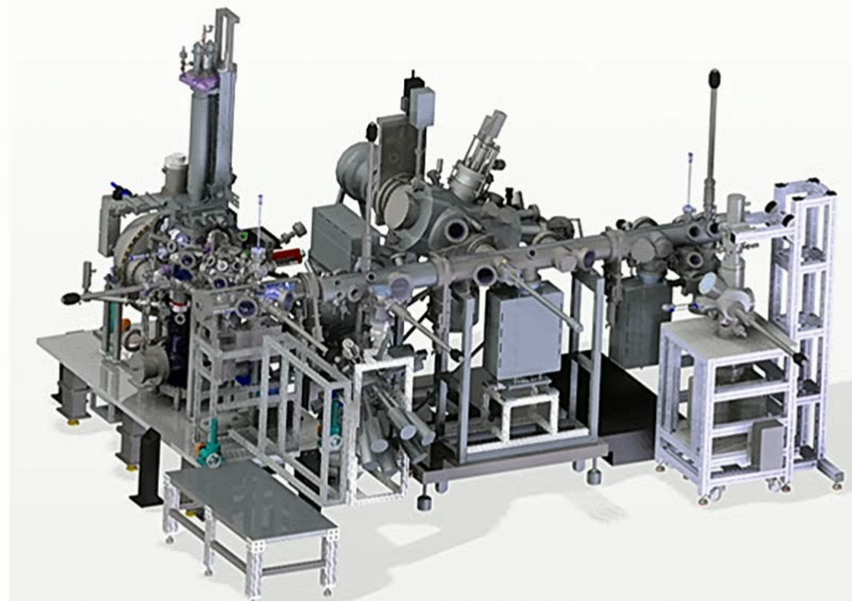
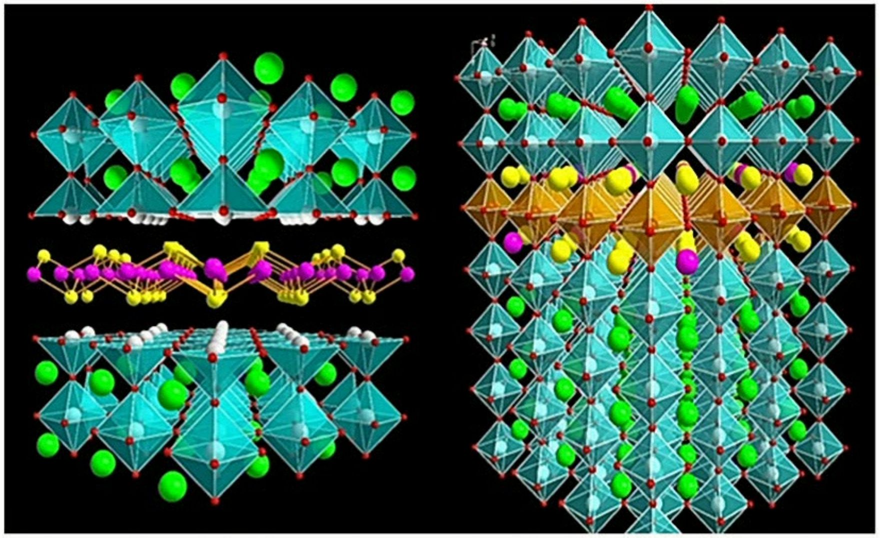
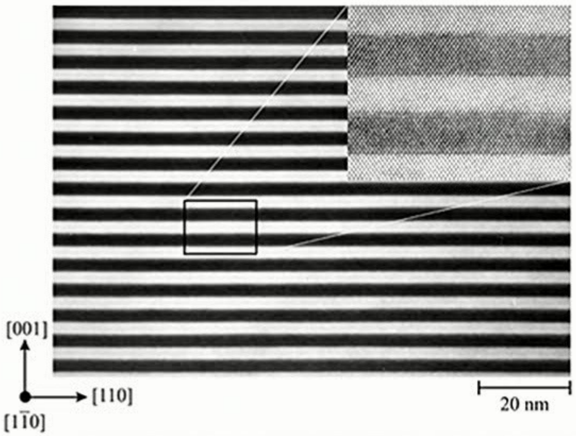
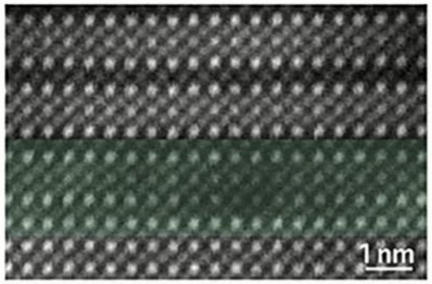




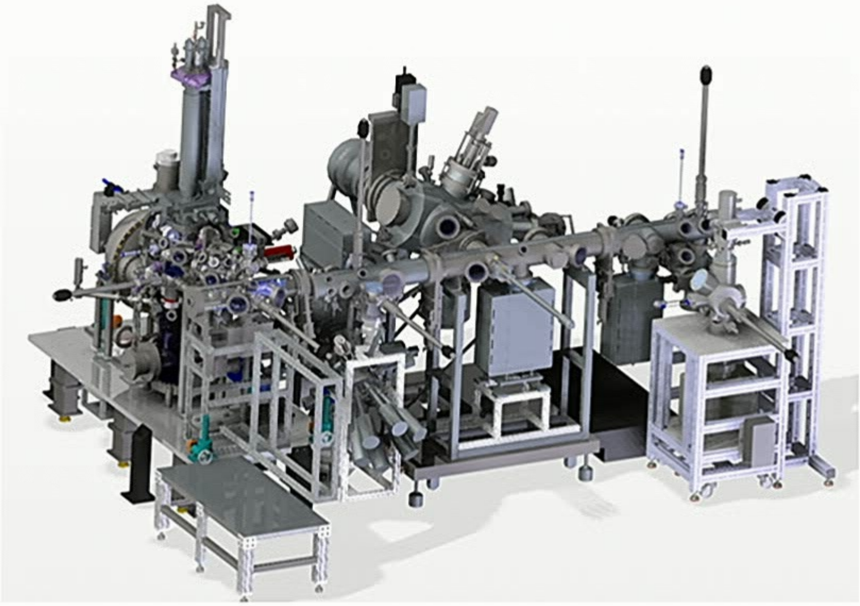




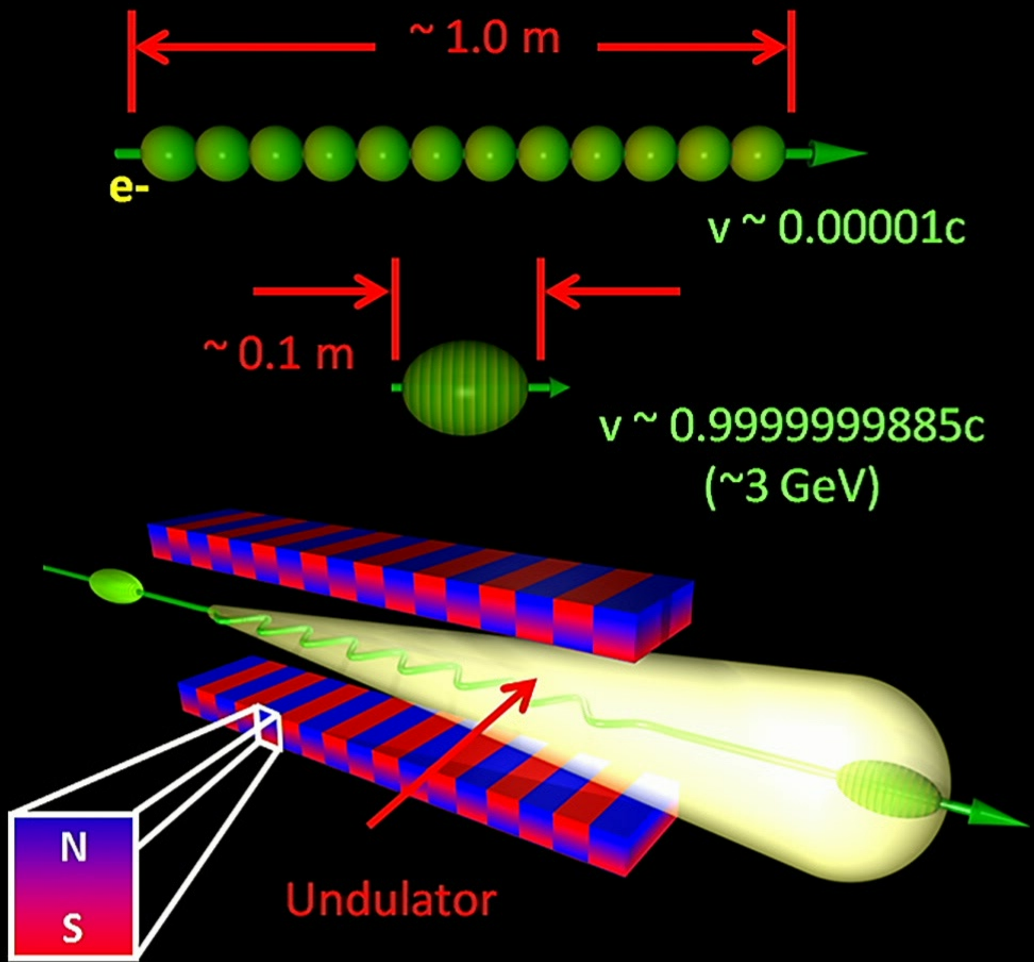
[001]
[110]
[1$\bar{1}$0]
20 nm



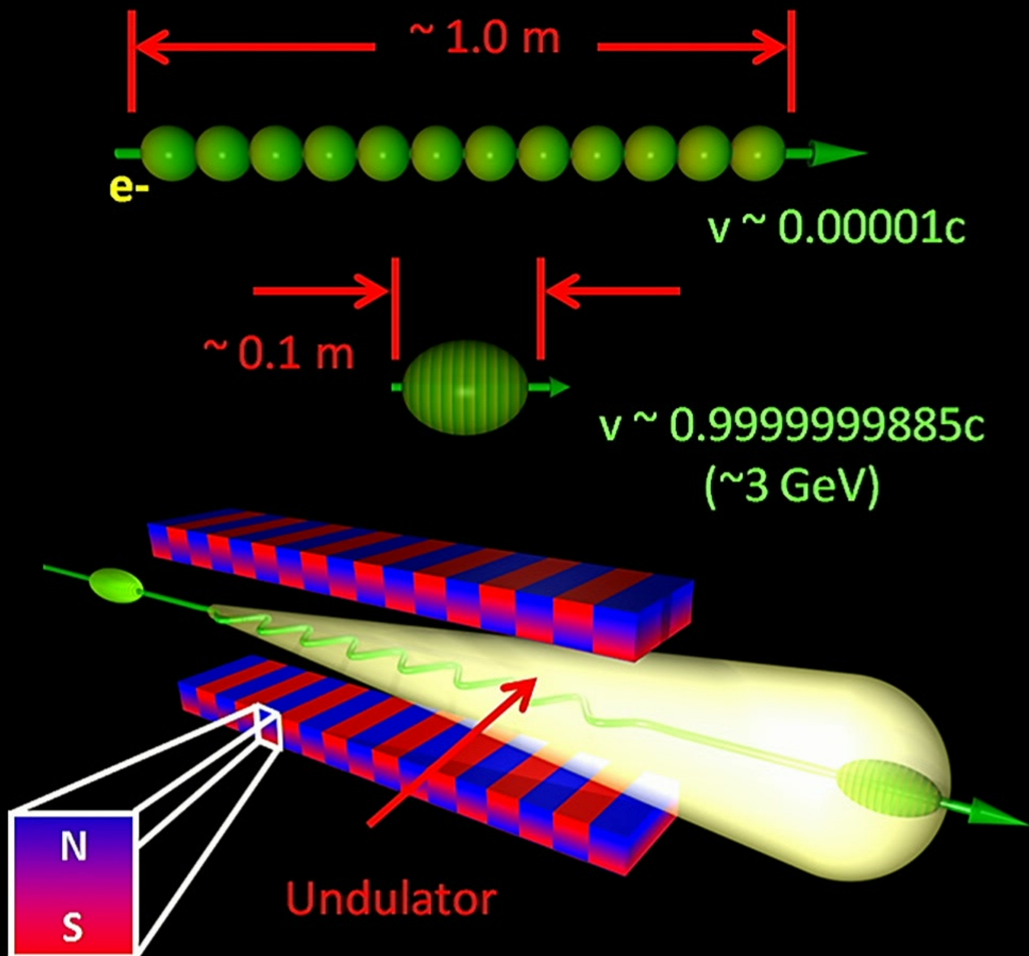
1 nm

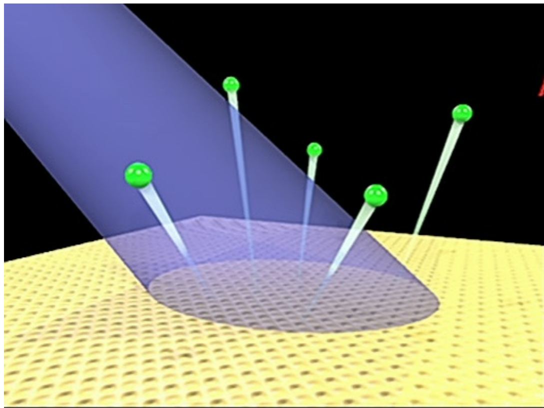


Synchrotron Radiation

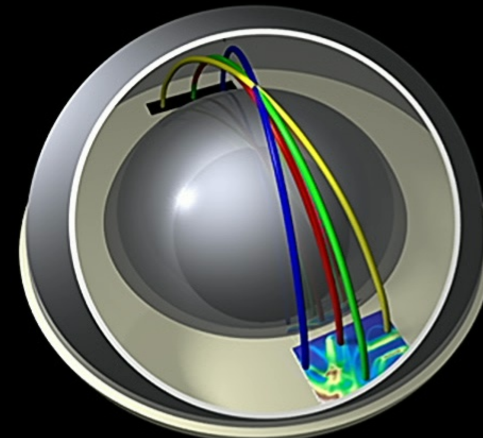


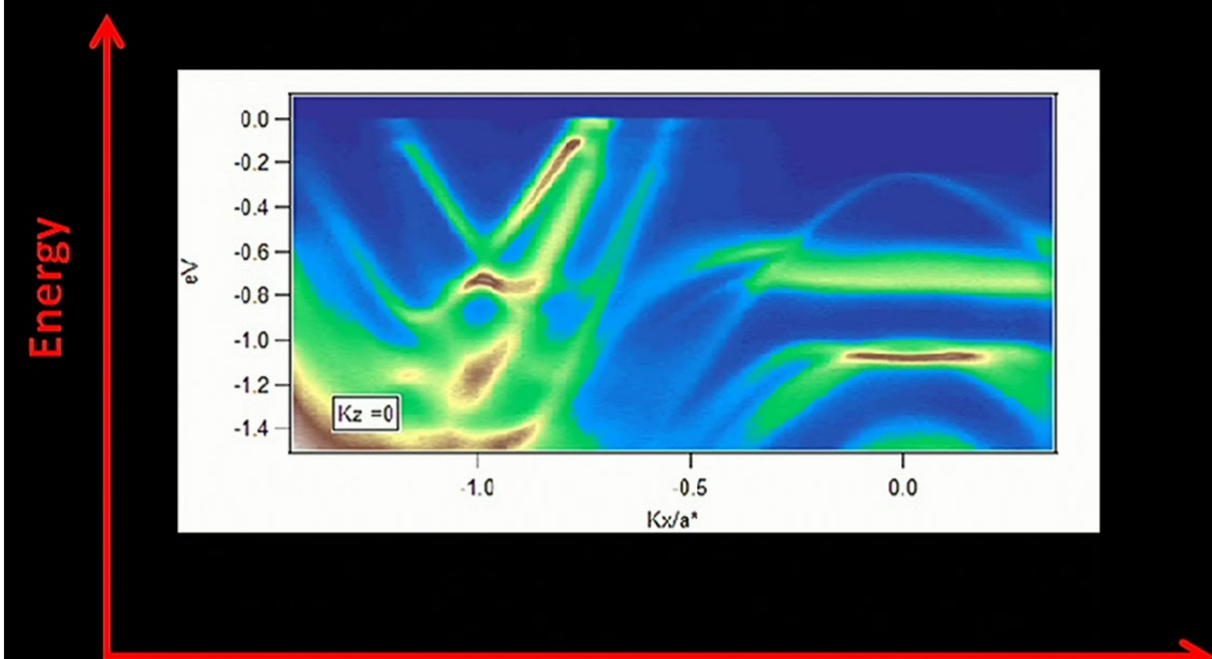
Synchrotron Radiation

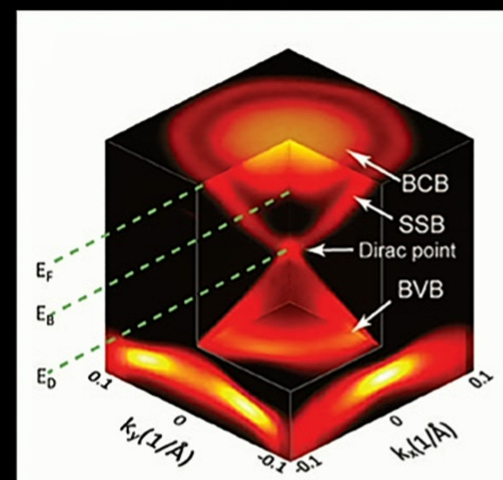


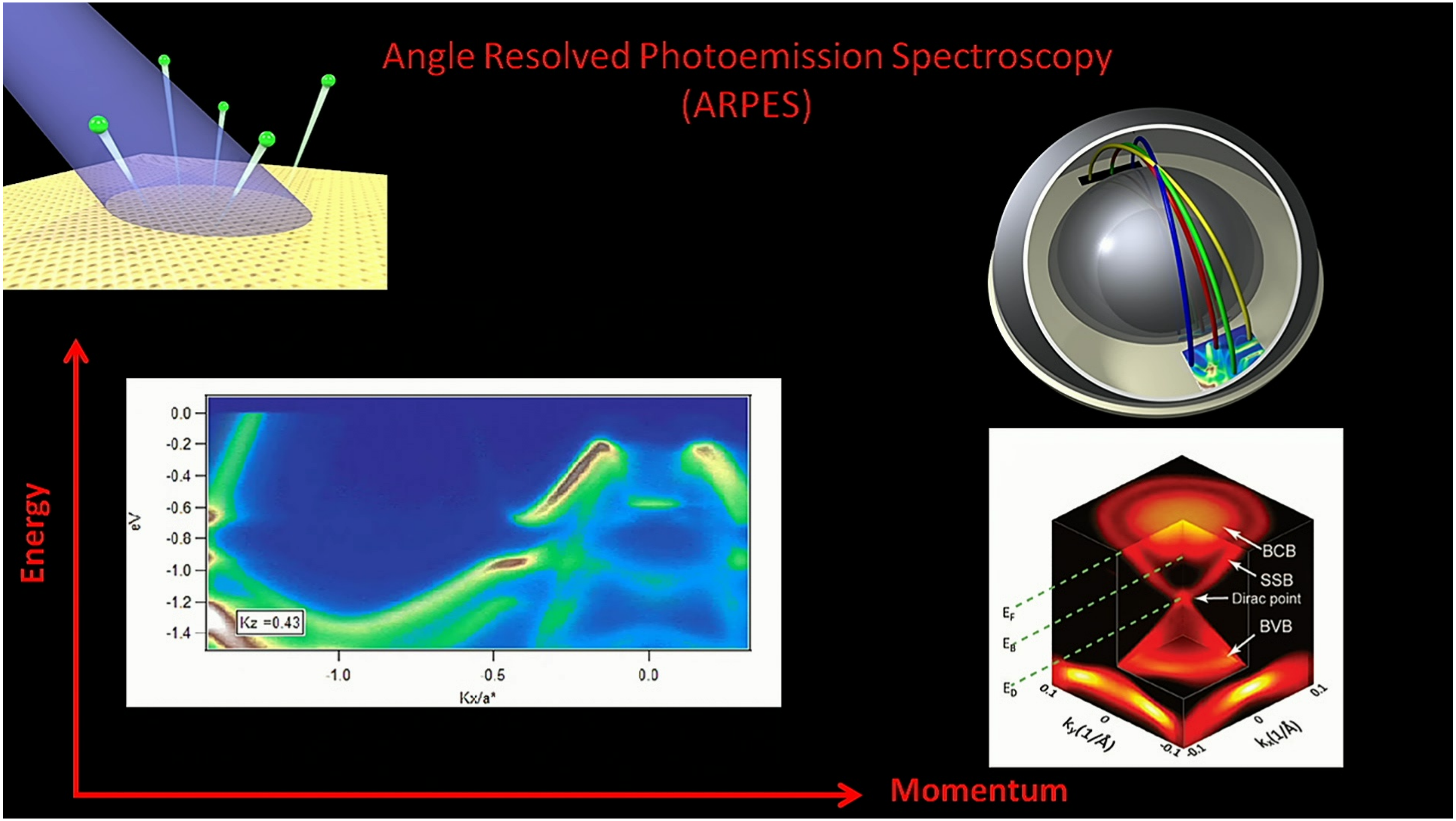


Angle Resolved Photoemission Spectroscopy (ARPES)

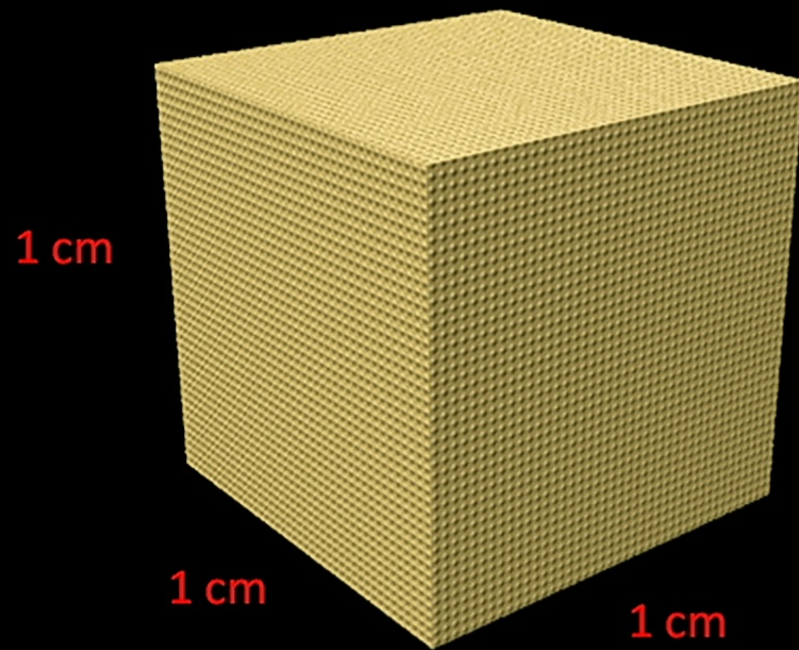




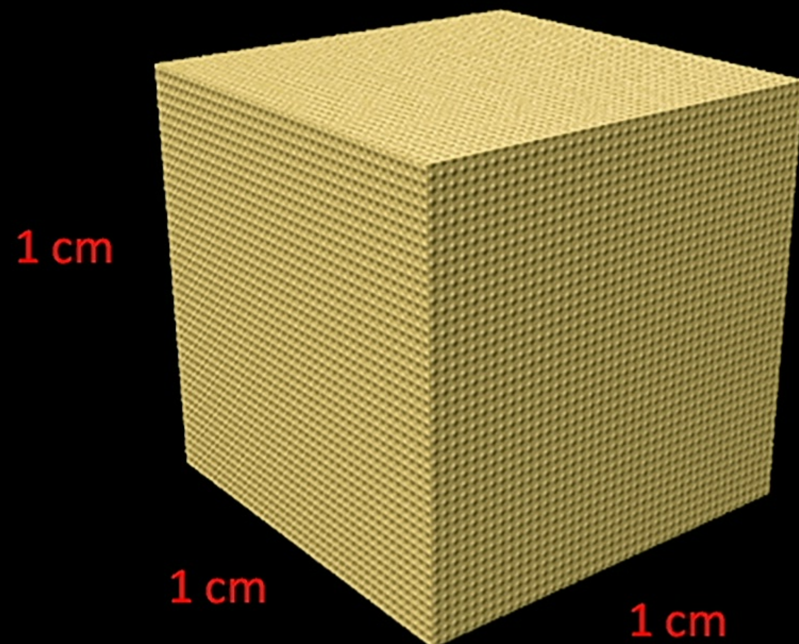



Angle Resolved Photoemission Spectroscopy
(ARPES)
Energy
Momentum
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
eV
Kz =0.43
-1.0
-0.5
0.0
Kx/a*
BCB
SSB
Dirac point
BVB
E_F
E_B
E_D
0.1
0
-0.1
-0.1
0
0.1
k_y(1/Å)
k_x(1/Å)

Many-body Physics

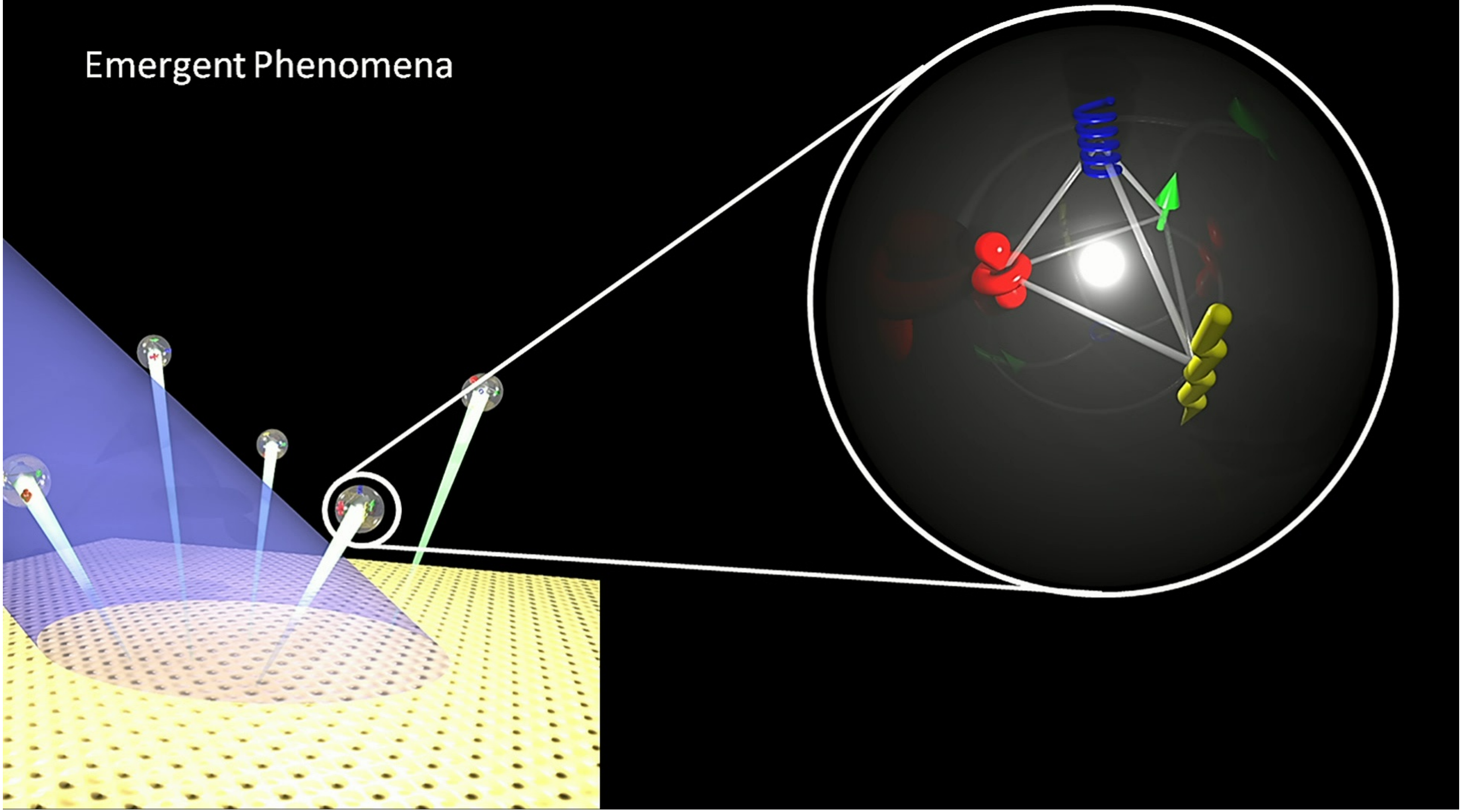


Many-body Physics

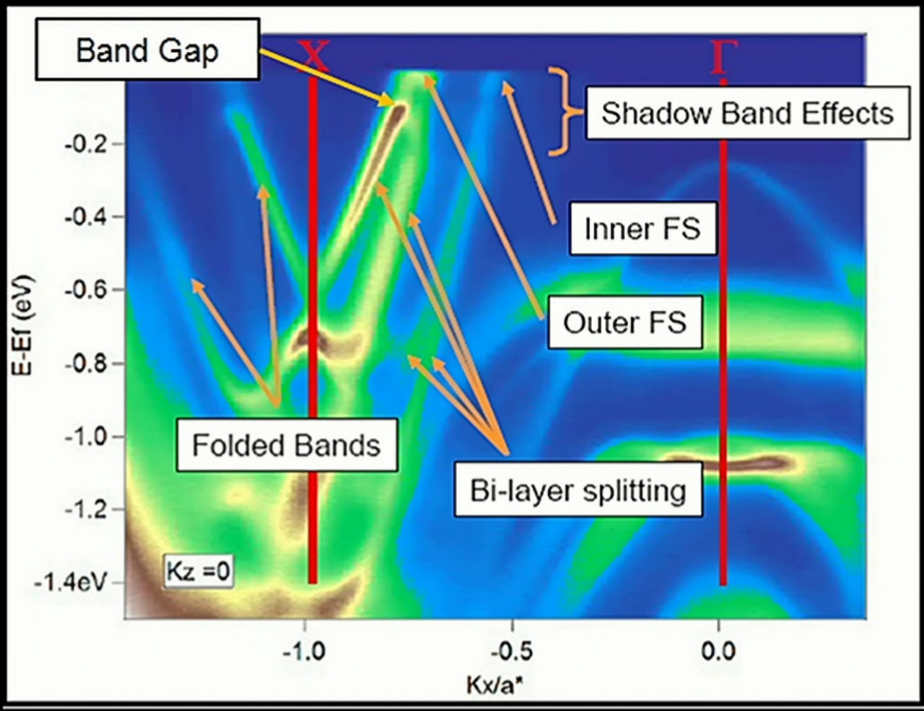


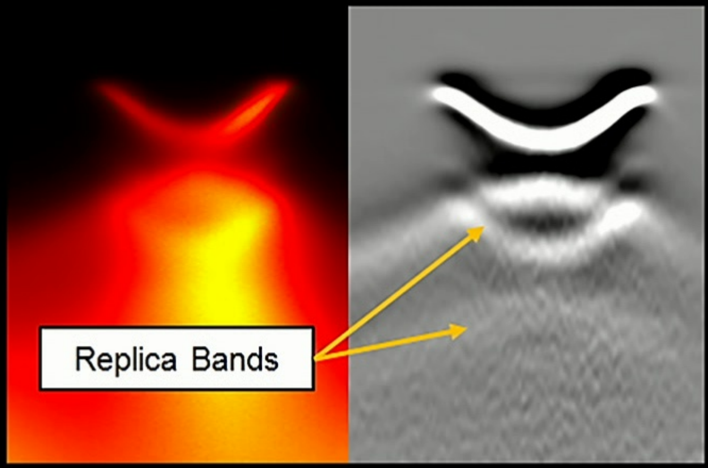
Number of atoms: ~50,000,000,000,000,000,000,000

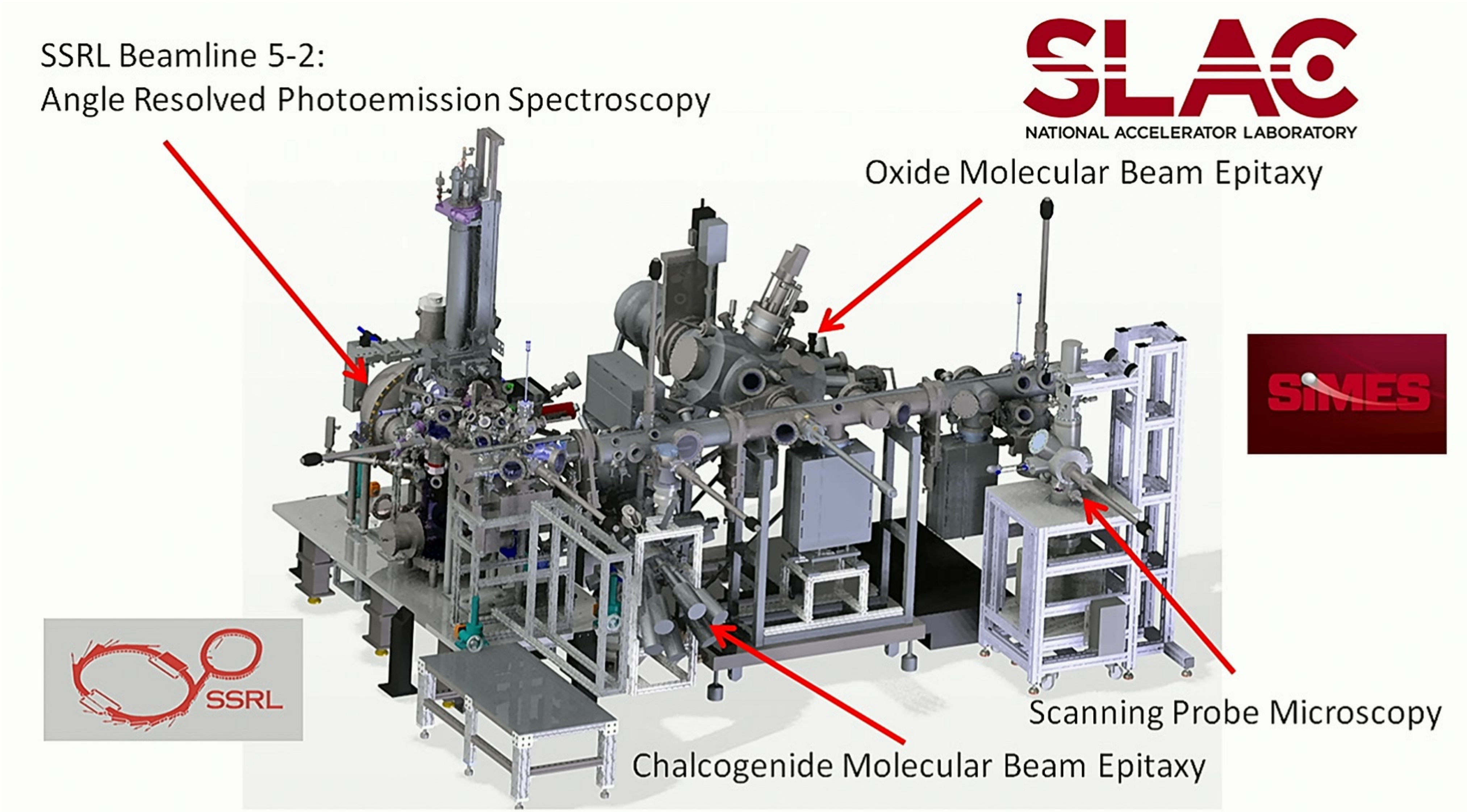
Emergent Phenomena



Emergent Phenomena

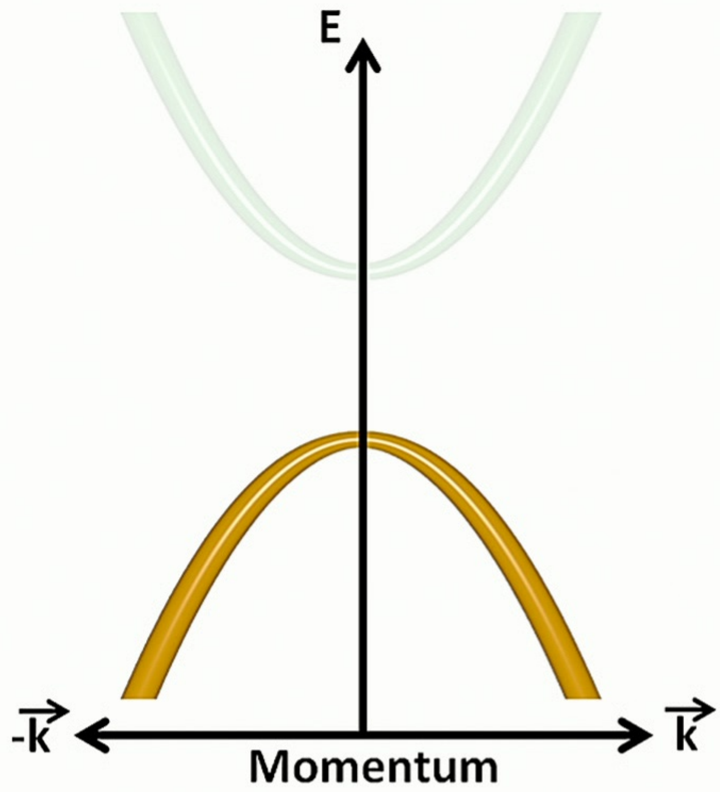




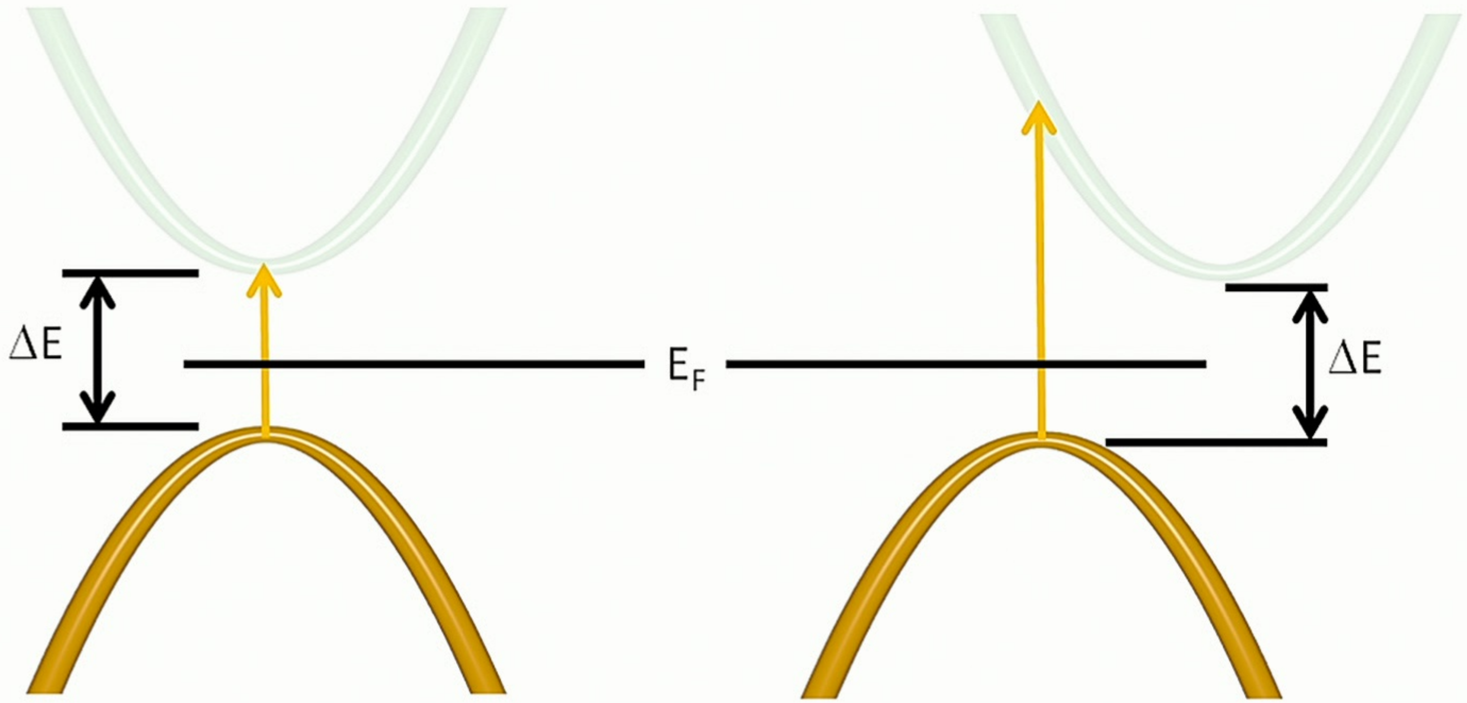

SSRL Beamline 5-2:
Angle Resolved Photoemission Spectroscopy
SLAC
NATIONAL ACCELERATOR LABORATORY
Oxide Molecular Beam Epitaxy
SIMES
SSRL
Scanning Probe Microscopy
Chalcogenide Molecular Beam Epitaxy

A straight shot

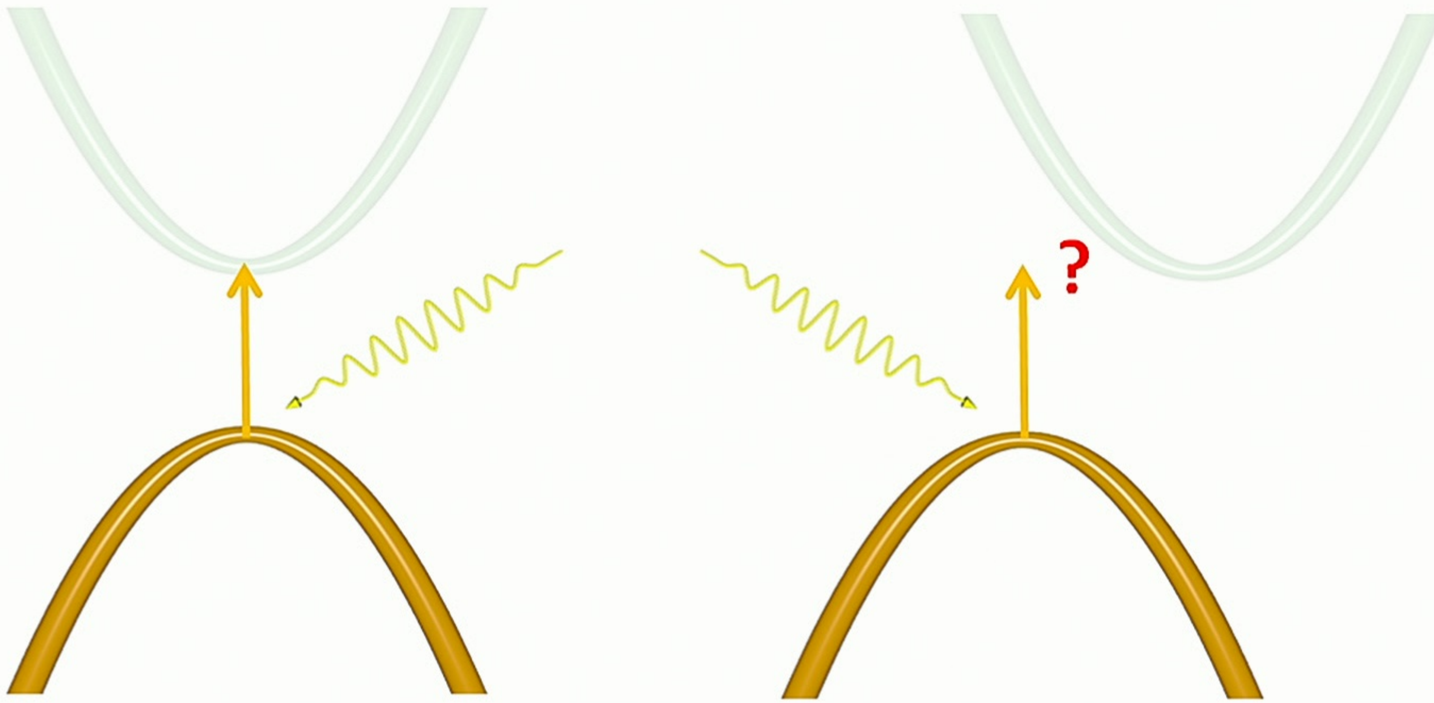
Short Term Memory Test:



Direct vs Indirect Band Gap



How to Bridge the Gap: Electron-Phonon Coupling



One way to think about it.............

We start with $H' = H_{eP} + H_{eL}$

where for a crystal $H_{eL} = \sum_{\substack{\{\mathbf{R}+\tau_{\mathbf{R},j,\alpha_j}+\eta_{\mathbf{R},j,\alpha_j}\}, \\ \{\mathbf{R}'+\tau_{\mathbf{R}',j,\alpha_{j'}}\}}} V\left(\{\mathbf{r} - \mathbf{R} + \tau_{\mathbf{R},j,\alpha_j} + \eta_{\mathbf{R},j,\alpha_j}\}\right) - V\left(\{\mathbf{r} - \mathbf{R}' + \tau_{\mathbf{R}',j',\alpha_{j'}}\}\right)$

with small displacements $\left\langle \vec{R}', j', \alpha_{j'} \middle| H_{eL} \middle| \vec{R}, j, \alpha_j \right\rangle = \frac{\partial V}{\partial d} \hat{d} \bullet \left(\eta_{\vec{R},j,\alpha_j} - \eta_{\vec{R}',j',\alpha_{j'}}\right)$

where $\mathbf{d} \equiv \mathbf{R} + \tau_j + \eta_{\mathbf{R},j,\alpha_j} - \mathbf{R}' - \tau_{j'} - \eta_{\mathbf{R}',j',\alpha_{j'}}$

expand in phonon eigen vectors $\eta_{\mathbf{R},j,\alpha_j} = \sum_{\lambda,\mathbf{q}} \left(\frac{\eta}{2NM_j \omega_{\lambda,\mathbf{q}}} \right)^{1/2} \left[\hat{\mathbf{e}}_{\lambda\mathbf{q}} e^{i\mathbf{q}\bullet(\mathbf{R}+\tau_j)} A(\lambda,\mathbf{q}) + \hat{\mathbf{e}}^*_{\lambda\mathbf{q}} e^{-i\mathbf{q}\bullet(\mathbf{R}+\tau_j)} A'(\lambda,\mathbf{q}) \right]$

A and A' are operators with $\left\langle n_{\lambda\mathbf{q}} - 1 \middle| A(\lambda,\mathbf{q}) \middle| n_{\lambda\mathbf{q}} \right\rangle = \sqrt{n_{\lambda\mathbf{q}}}$ $\quad \left\langle n_{\lambda\mathbf{q}} + 1 \middle| A^*(\lambda,\mathbf{q}) \middle| n_{\lambda\mathbf{q}} \right\rangle = \sqrt{n_{\lambda\mathbf{q}} + 1}$

and phonon occupation $n_{\lambda,\mathbf{q}} = \left(e^{\frac{\eta\omega_{\lambda,\mathbf{q}}}{kT}} - 1 \right)^{-1}$

in other words $H' = 42$

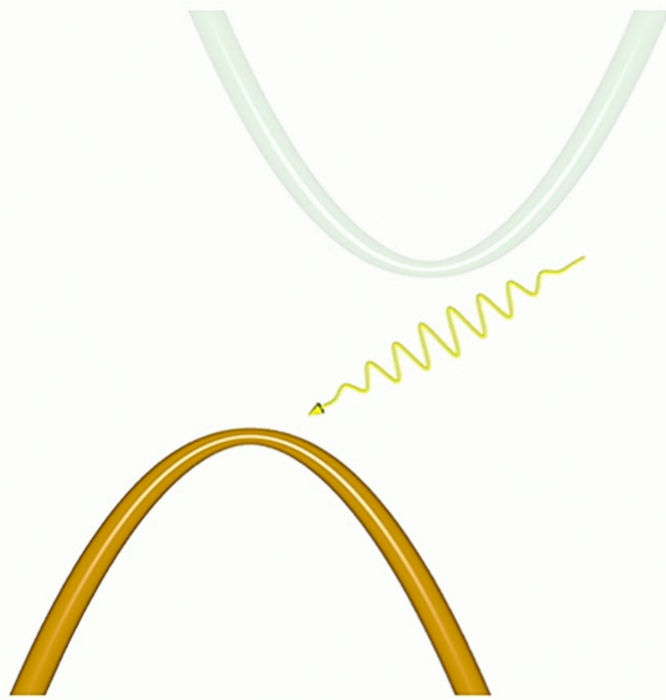

GOLDEN STATE
WARRIORS

Physics of the Alley-oop…….

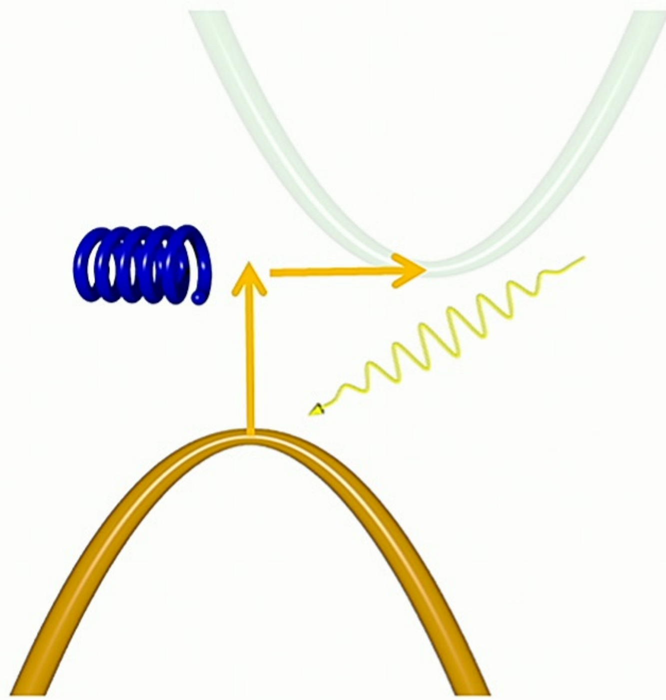
Physics of the Alley-oop…….

Physics of the Alley-oop…….

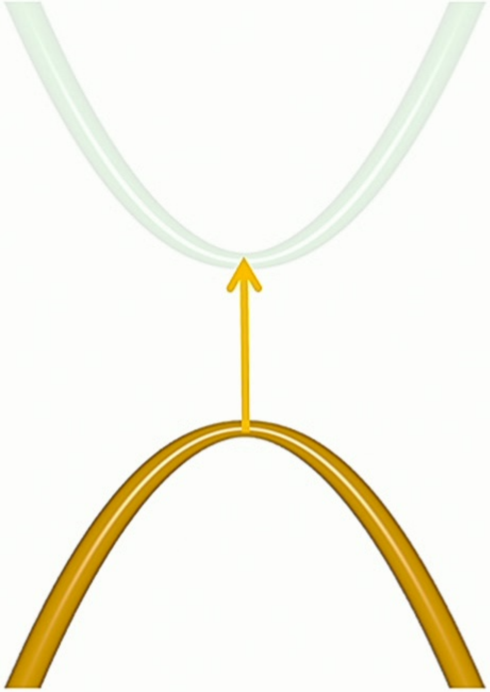
Electron-Phonon Coupling



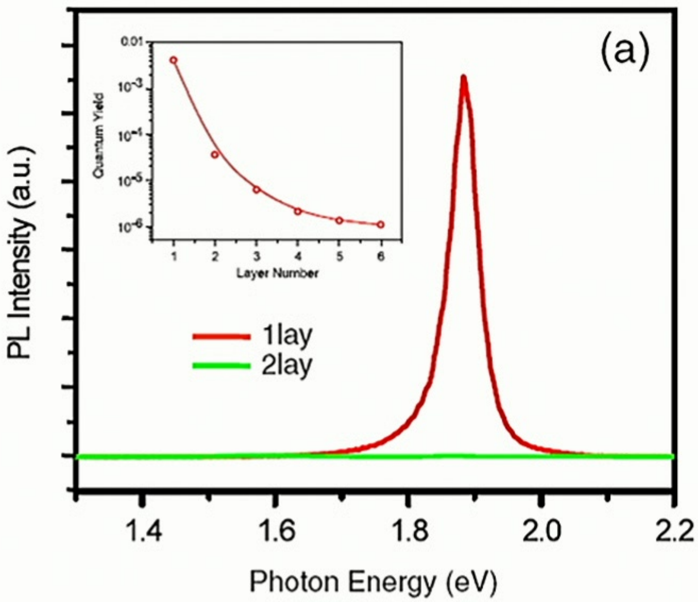
Electron-Phonon Coupling

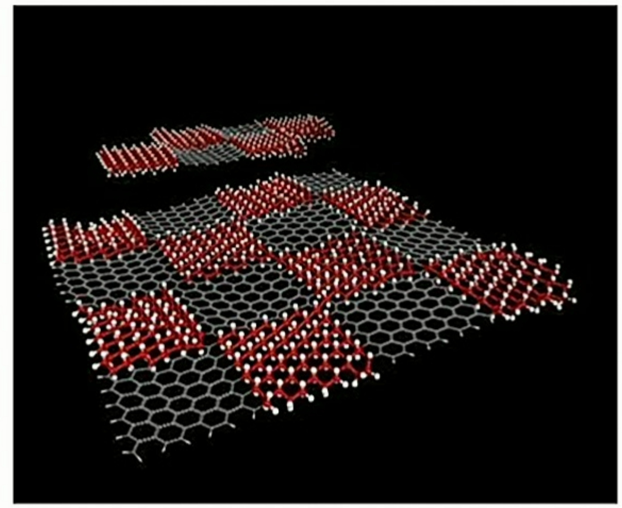


The Straight Shot



Transition Metal Dichalcogenides

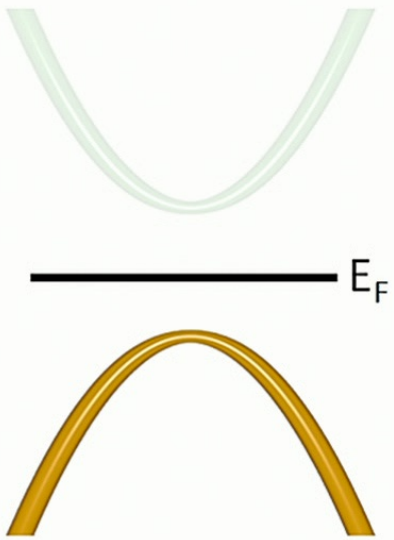


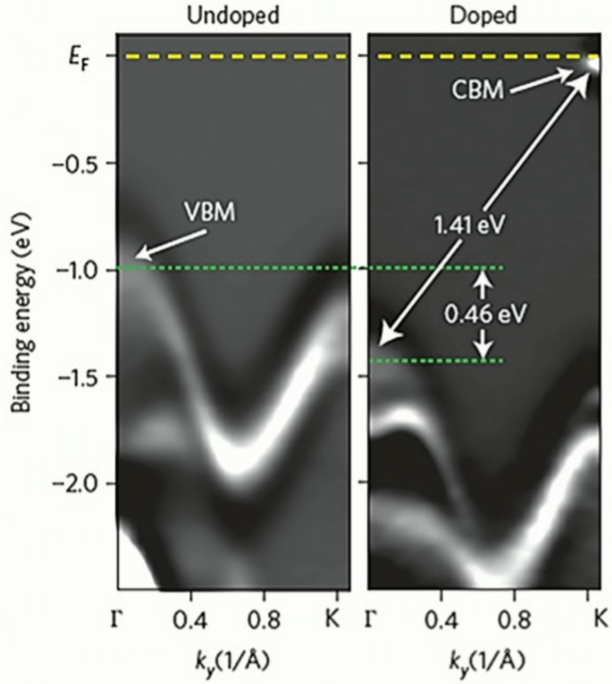


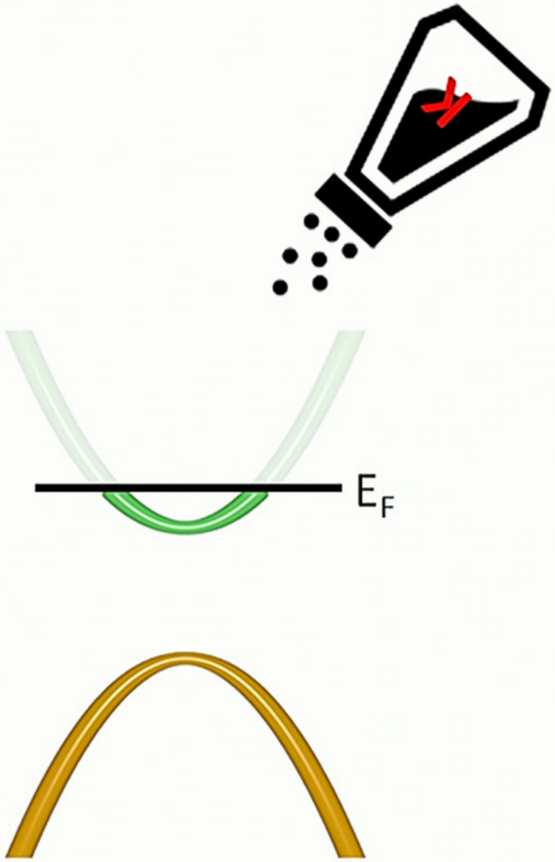
• MX_2 has non-linear response to light at wavelengths used in optical communications, but only when one layer is present
• Theory suggests this is due to an indirect to direct bandgap transition in the electronic structure

Doping Electrons – Moving E_F

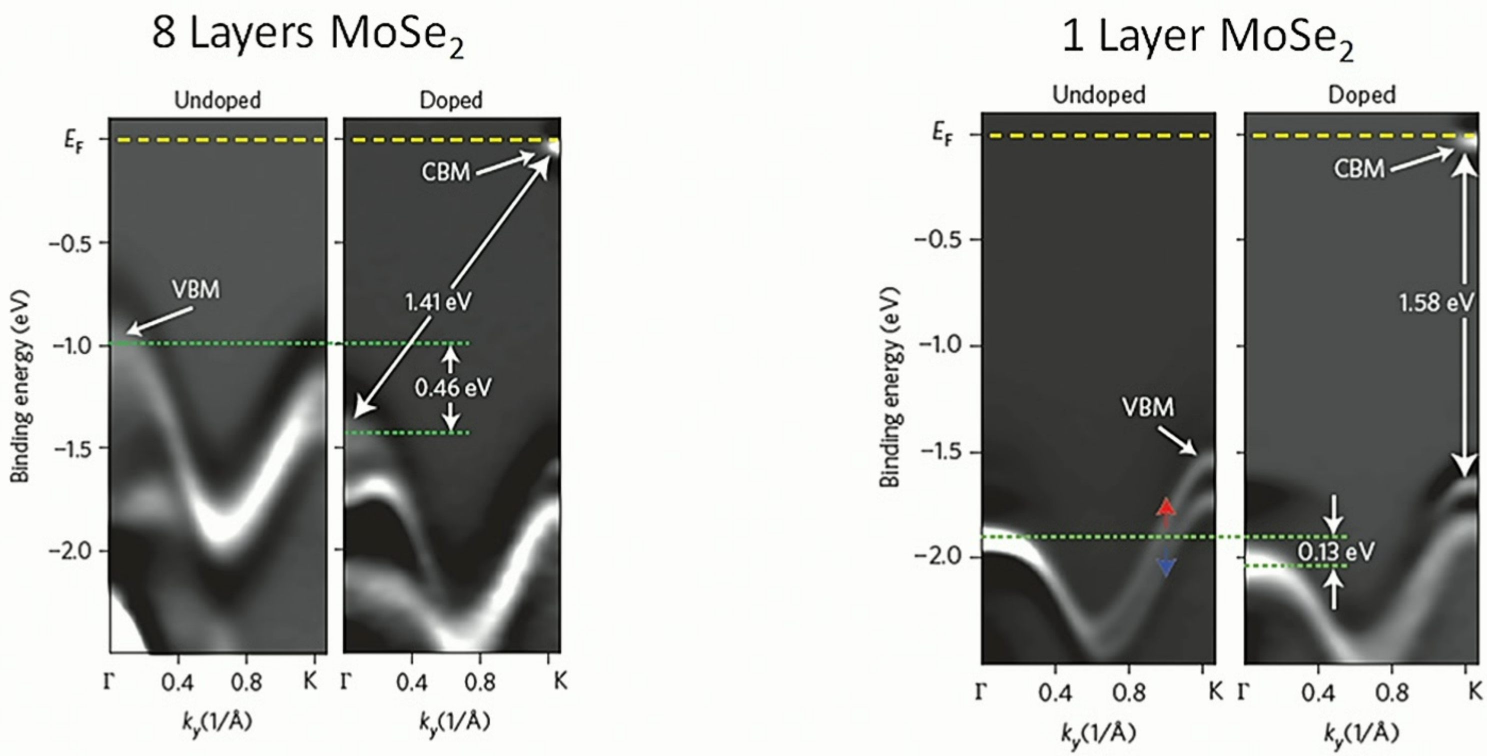
8 Layers $MoSe_2$





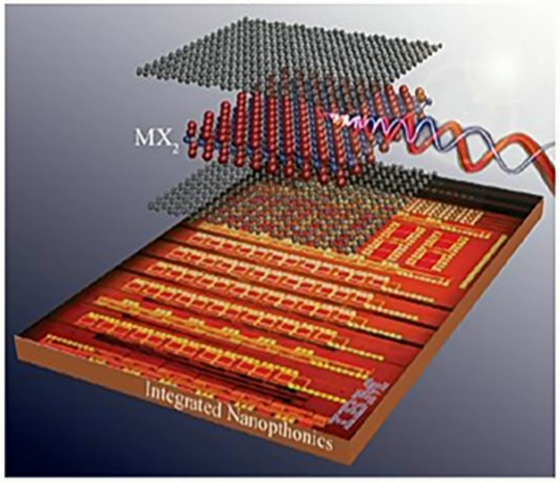


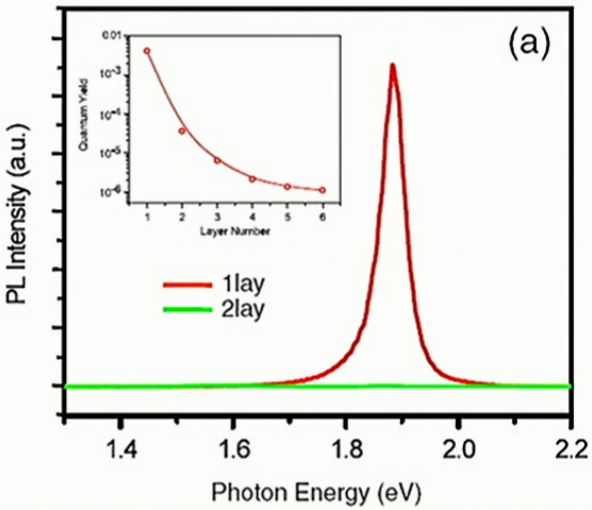
Single Layer Direct Bandgap Transition

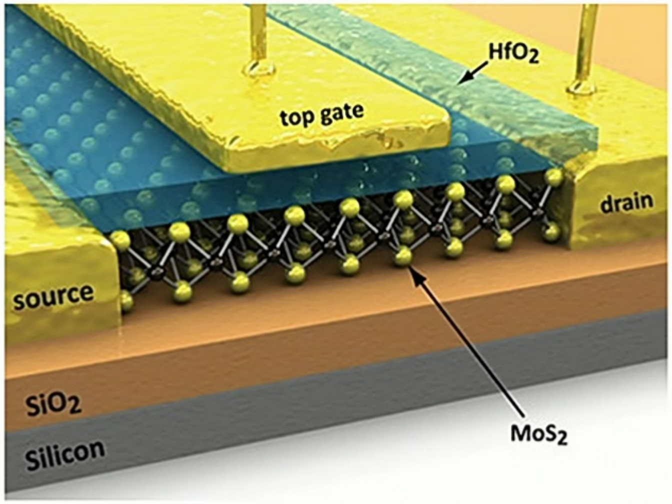


- By adding potassium, we can add electrons to the system and shift the bands down in energy
- Direct observation of the direct-indirect band gap crossover
- Doping also revealed a tunable direct bandgap!!

Expanding Bandwidth and Efficiency in Optoelectronics

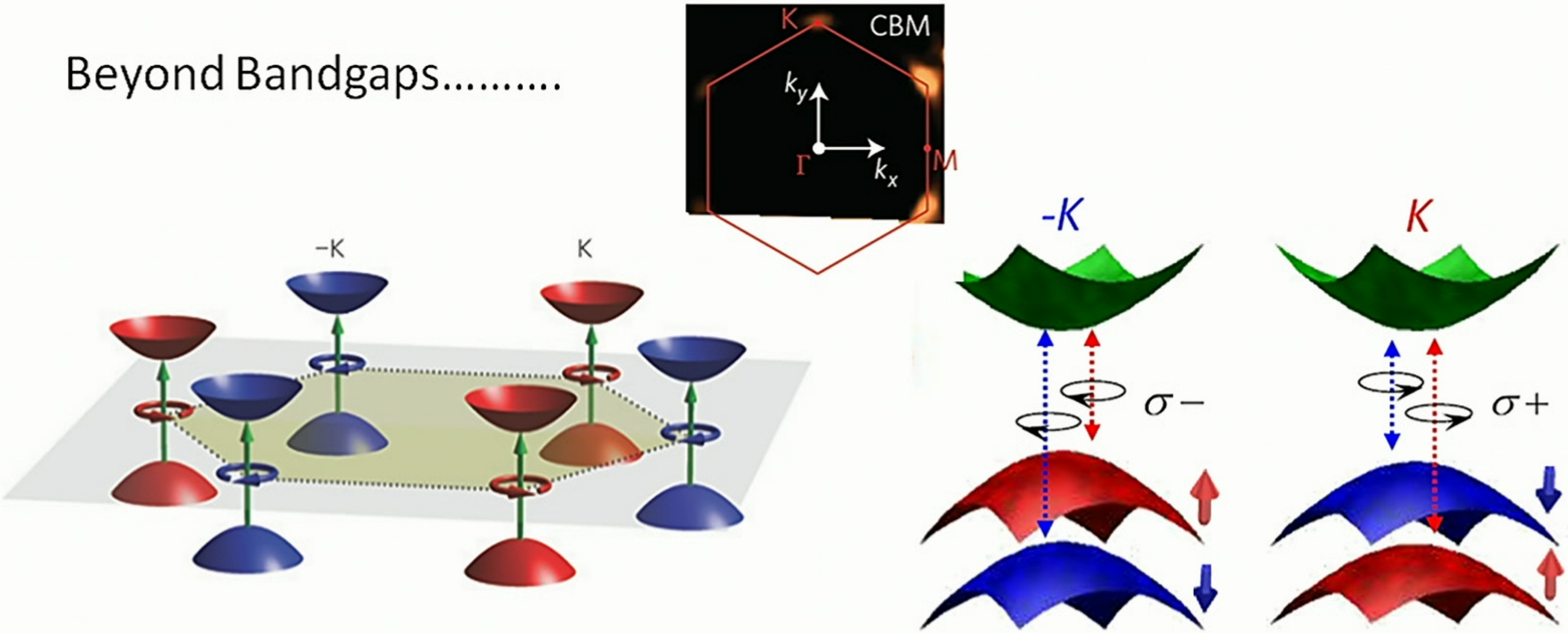






- A direct bandgap semiconductor one layer thick has great potential for optoelectronic applications
- Improving efficiency on the quantum level
- Theory suggested MoS_2 and $MoSe_2$ could be just such a system

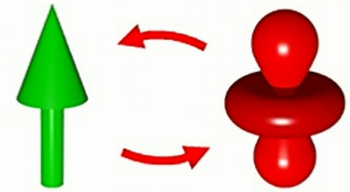
Beyond Bandgaps……….

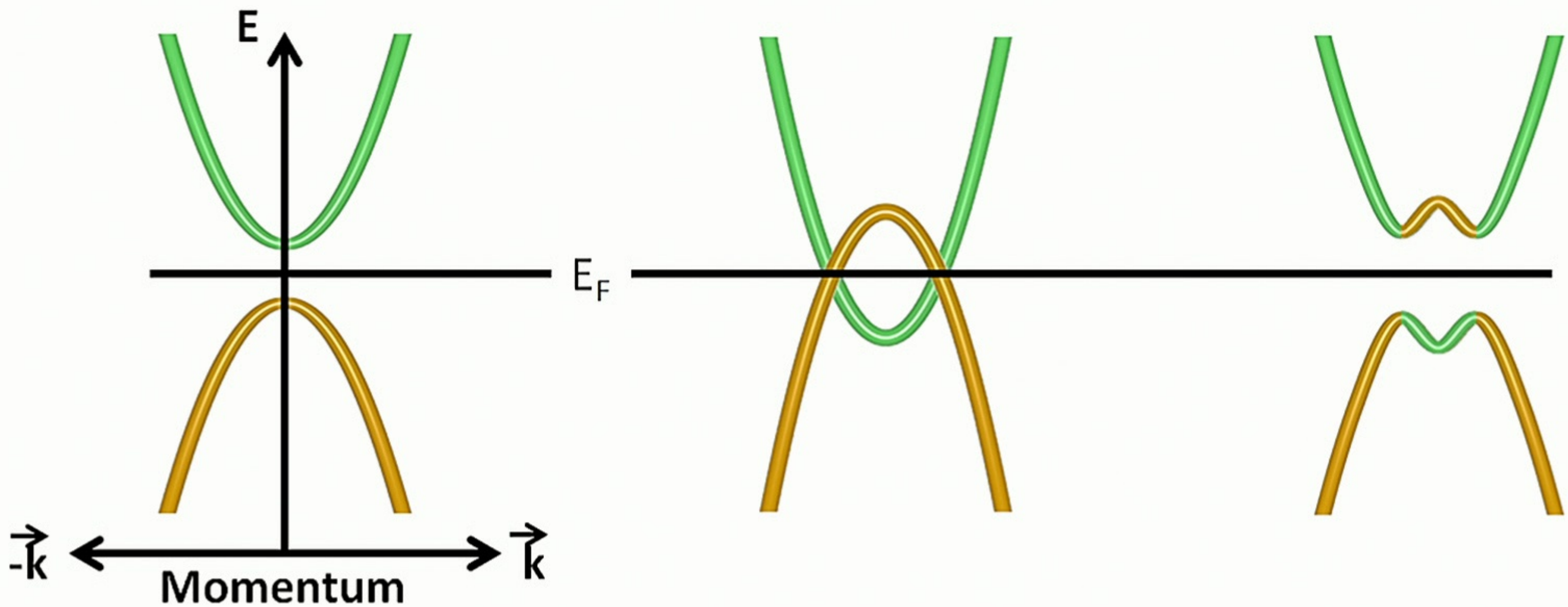


- Lack of spatial inversion symmetry creates contrast in bandstructure
- Opens possibility to couple to different electronic states
- “Valleytronics” and “Spintronics” offers new routes for information storage
- Only possible with direct bandgap

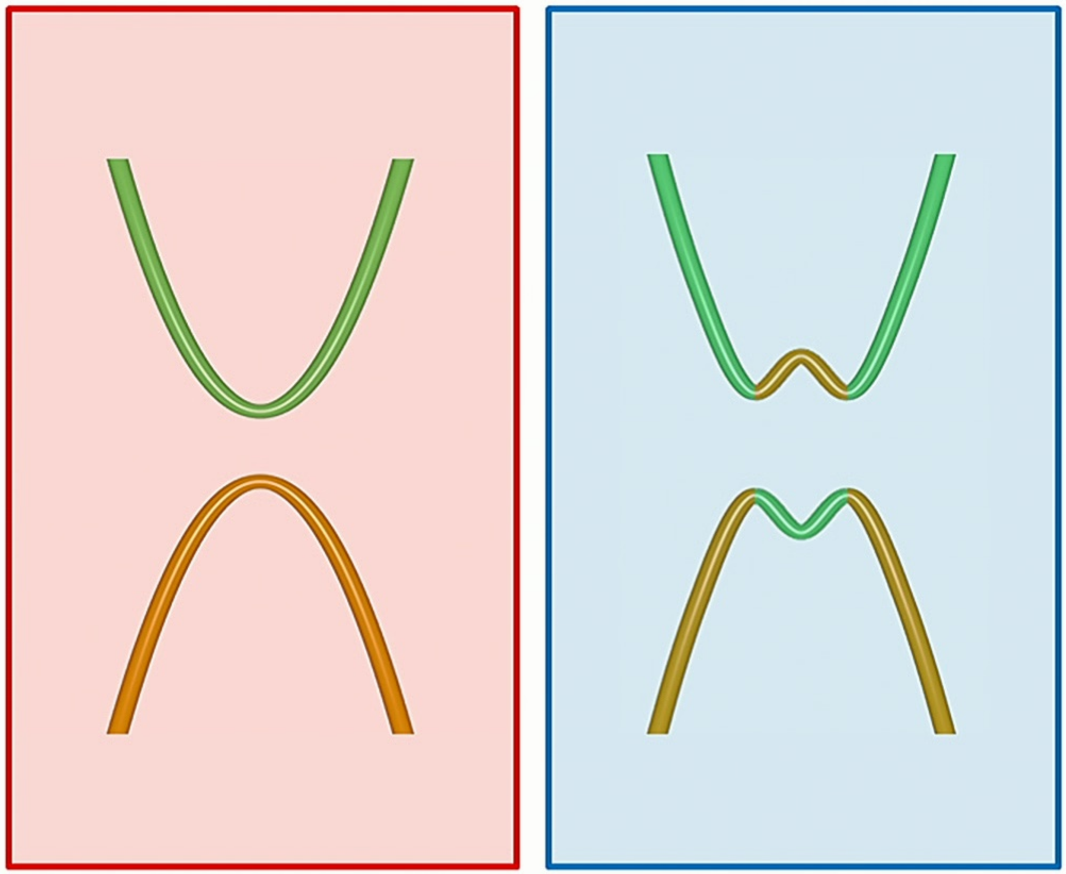
Just Ignore the Mess

The Coupling of Electron Spin and Orbit

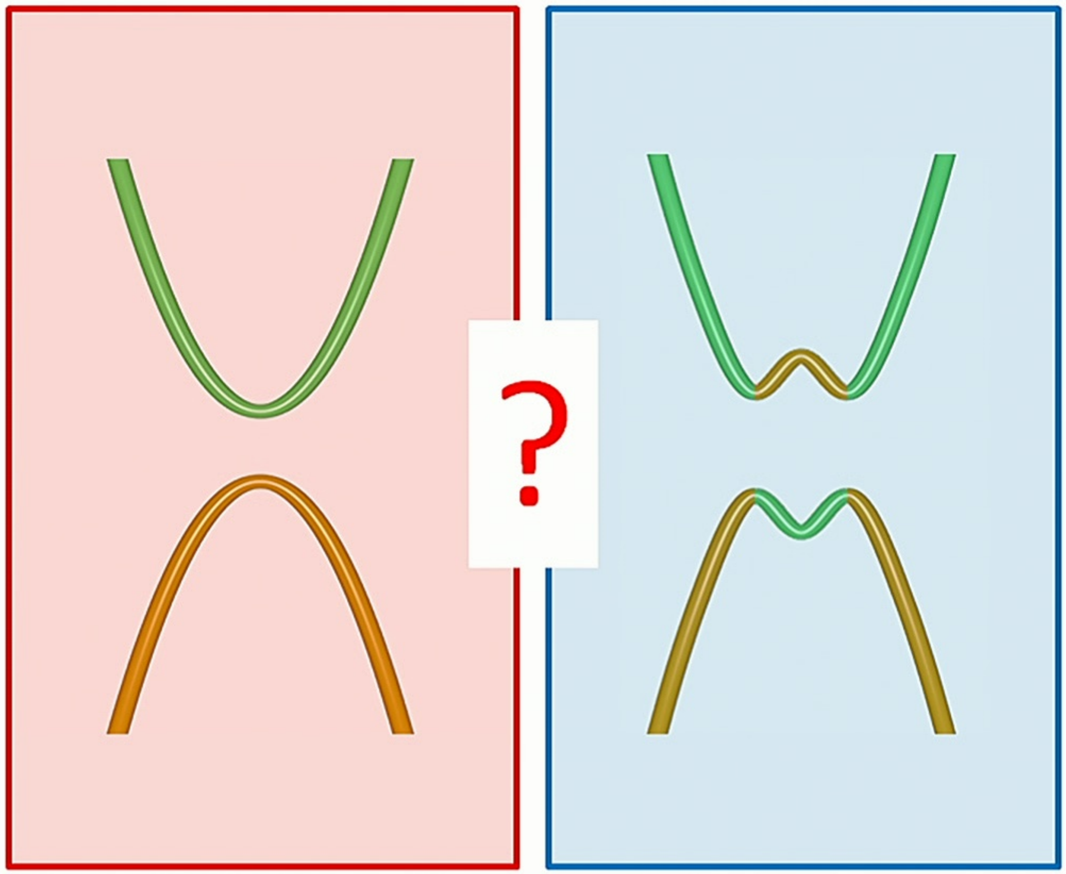




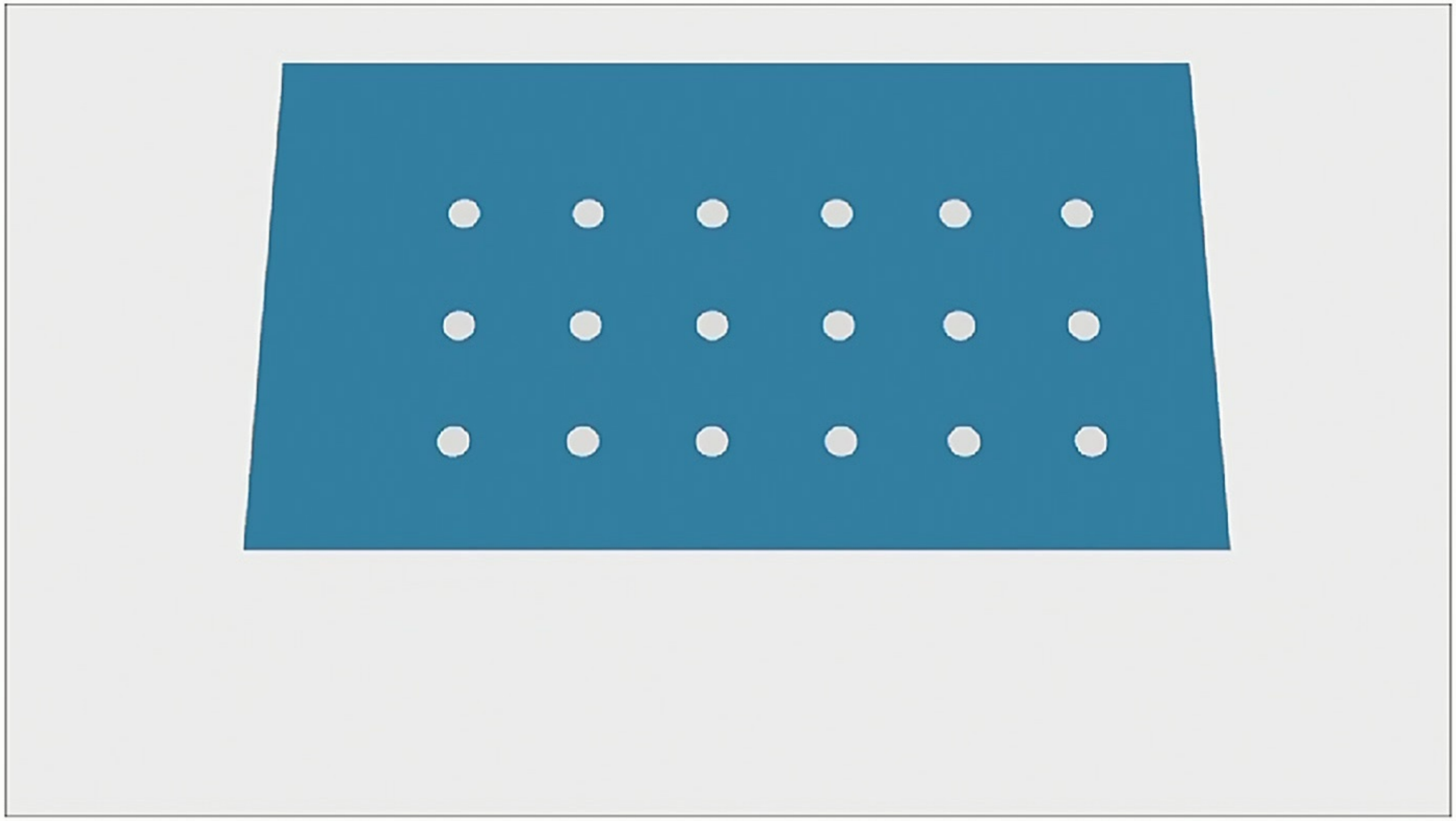
Interface of Materials with Different Spin-Orbit Coupling



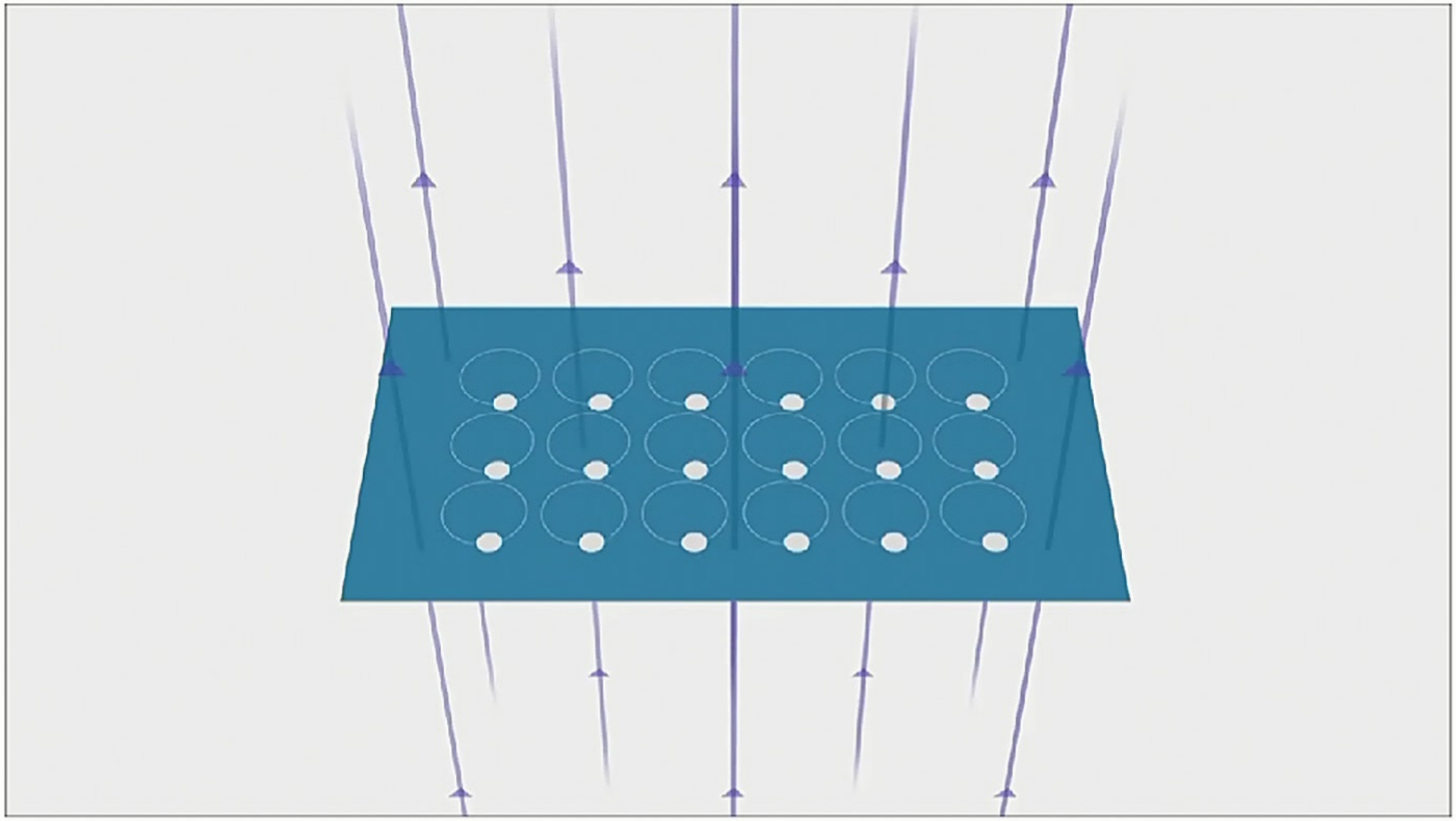
Interface of Materials with Different Spin-Orbit Coupling



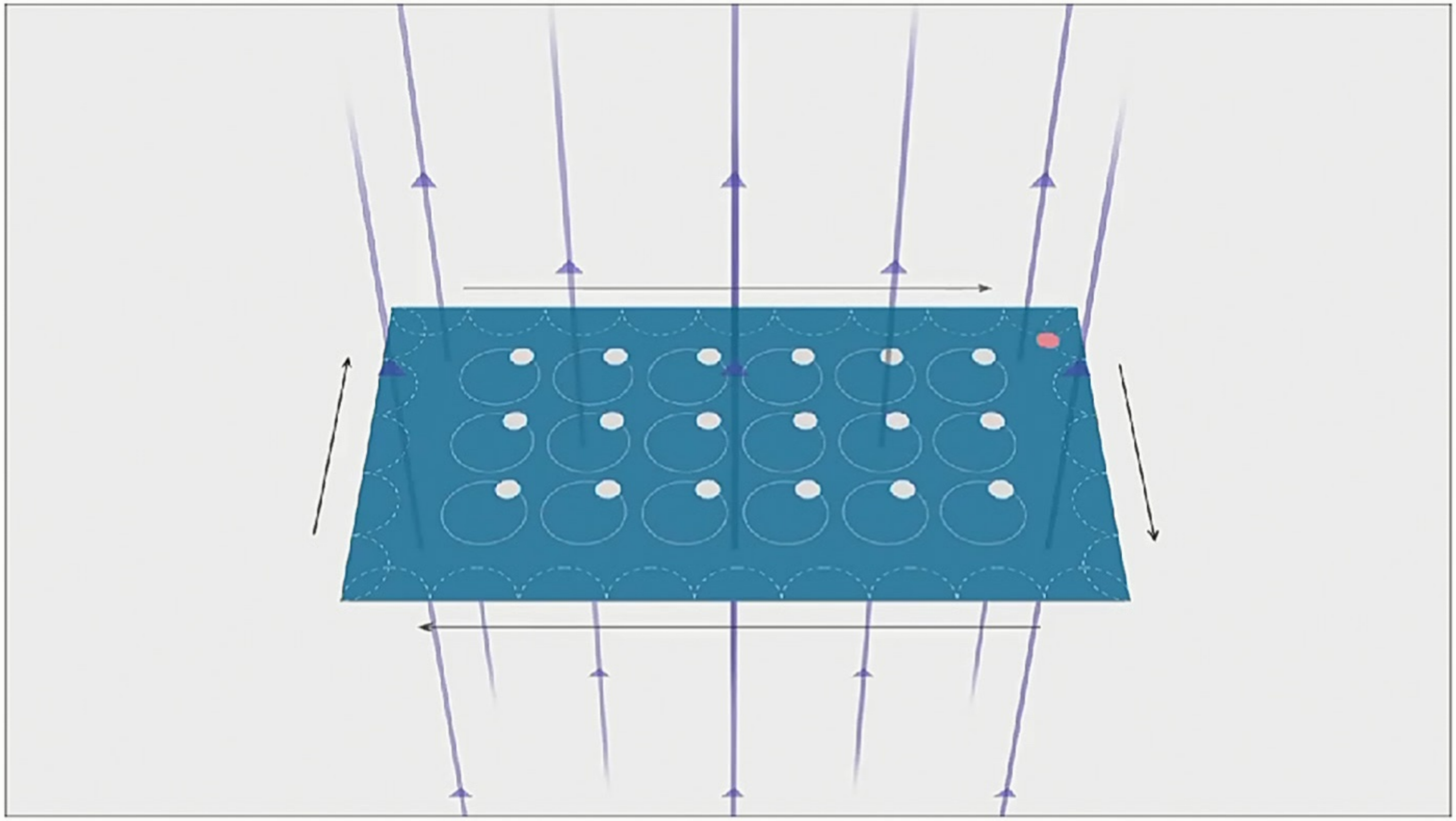
Edge Conduction and Topology



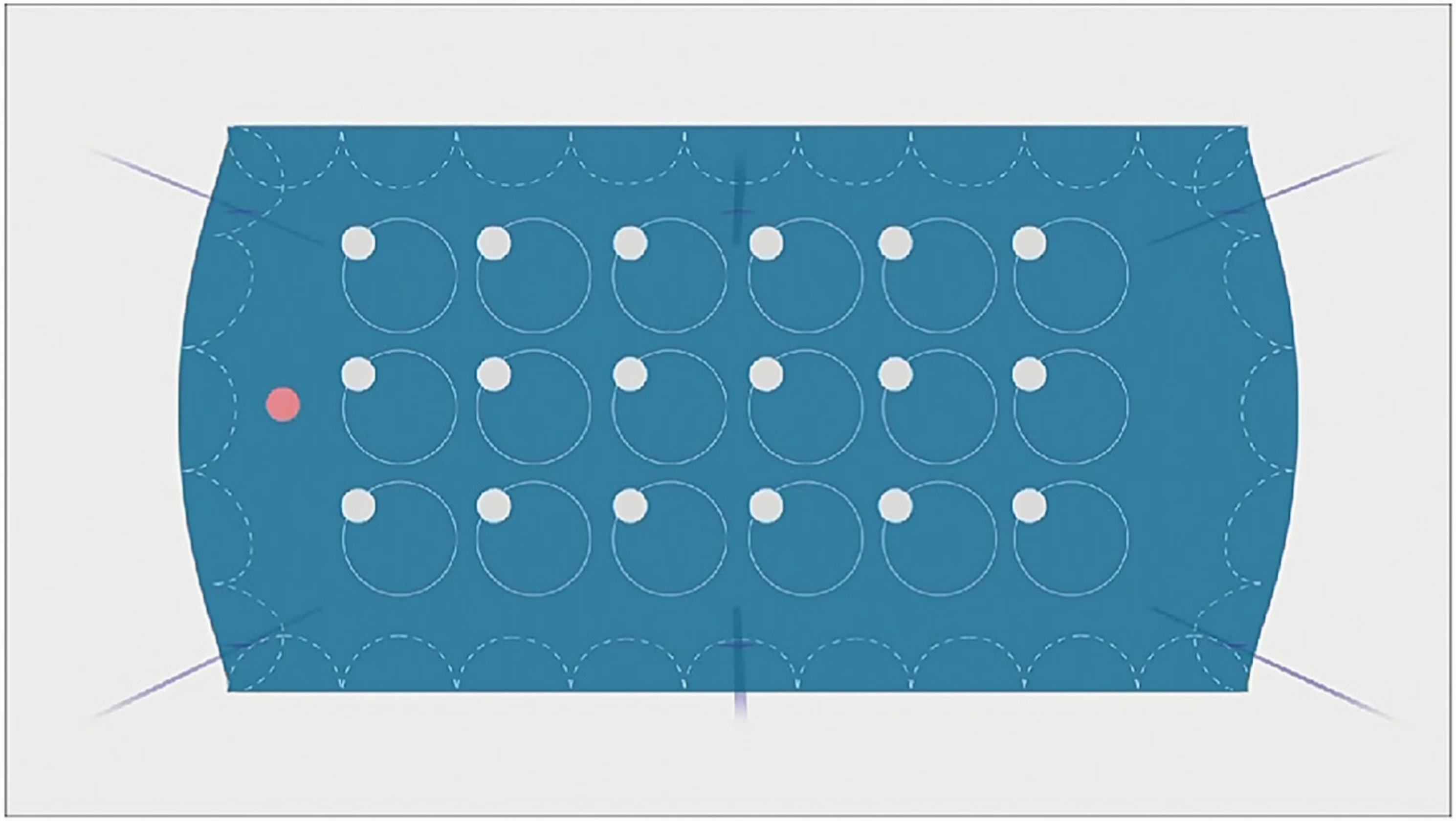
Edge Conduction and Topology



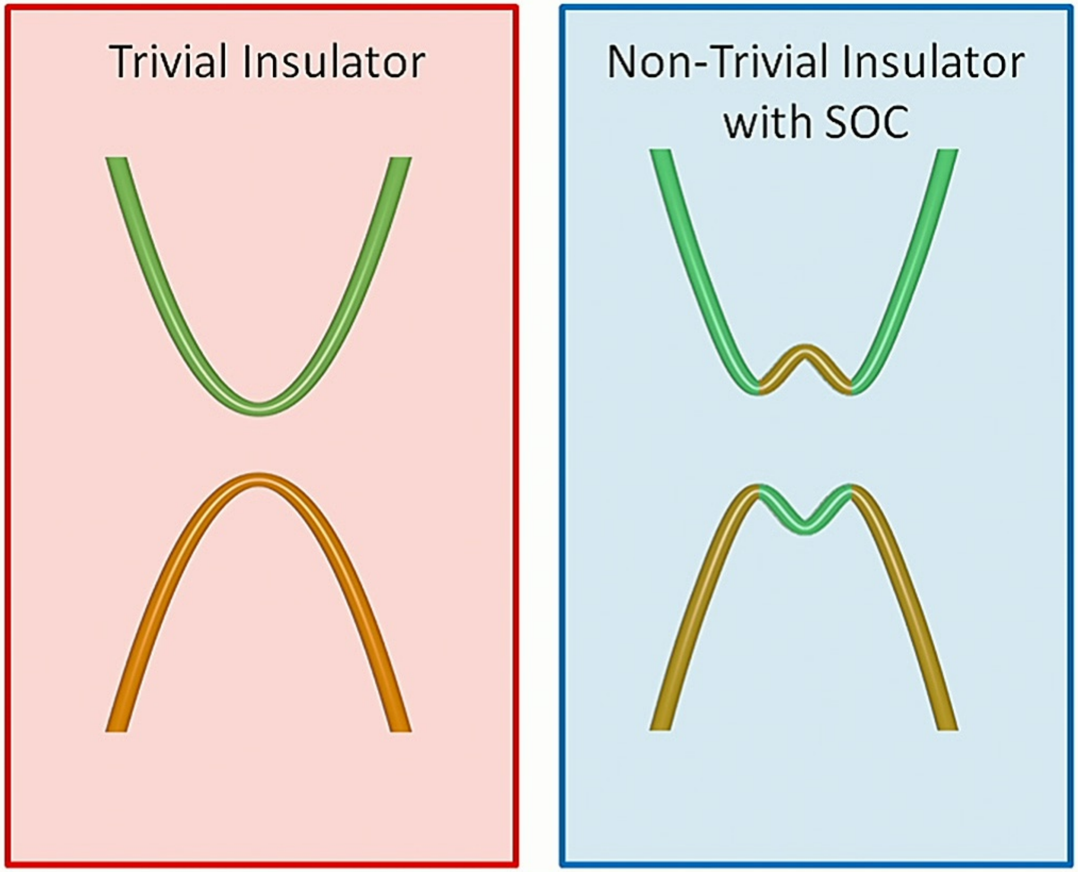
Edge Conduction and Topology



Edge Conduction and Topology



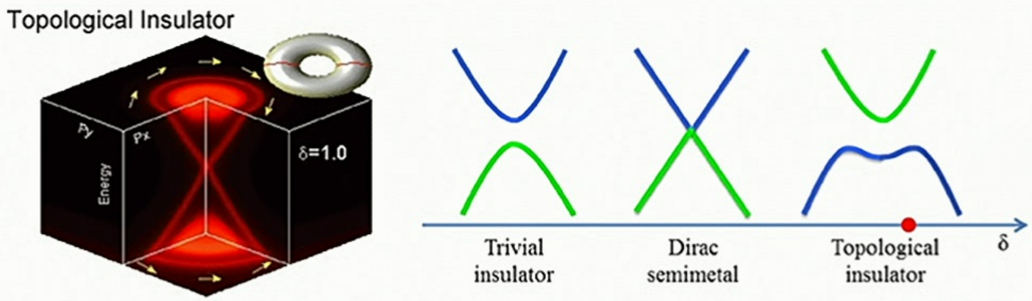
Interface of Materials with Different Spin-Orbit Coupling

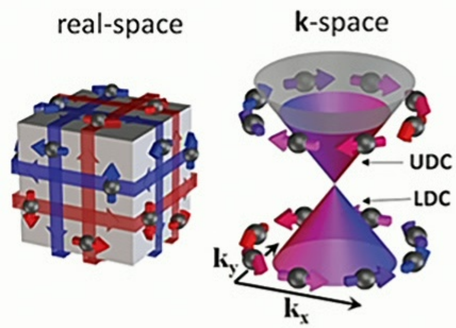


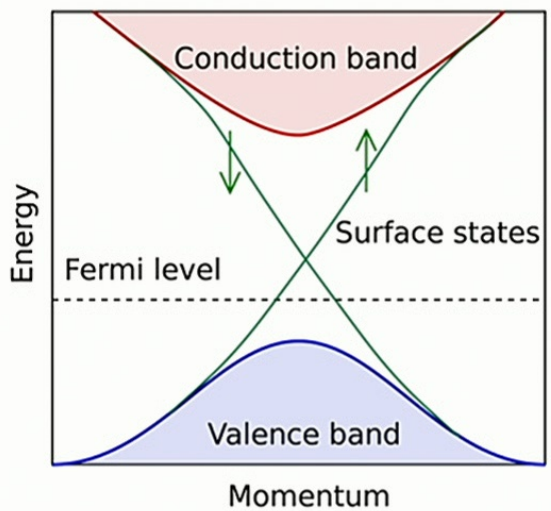
Topological Protection

- Proposed Bridge to connect Hong Kong and China's mainland
- Connecting Left-handed and Right-handed traffic

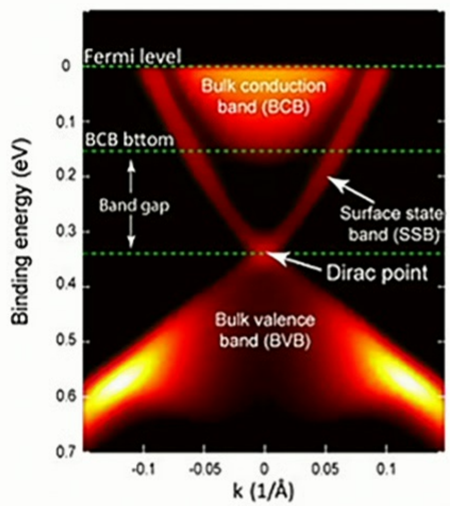
Topological Insulators



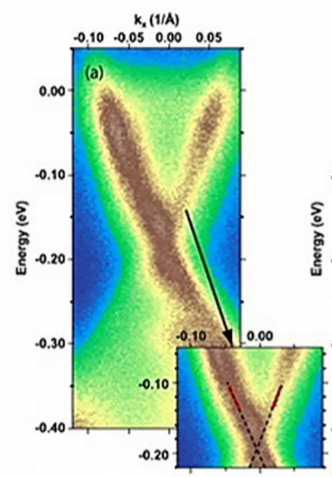


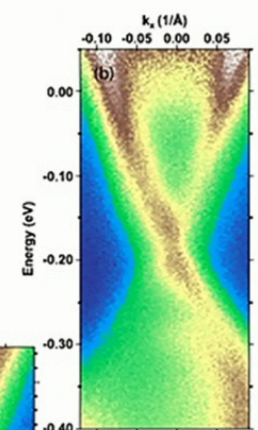


Bulk Bi_2Se_3

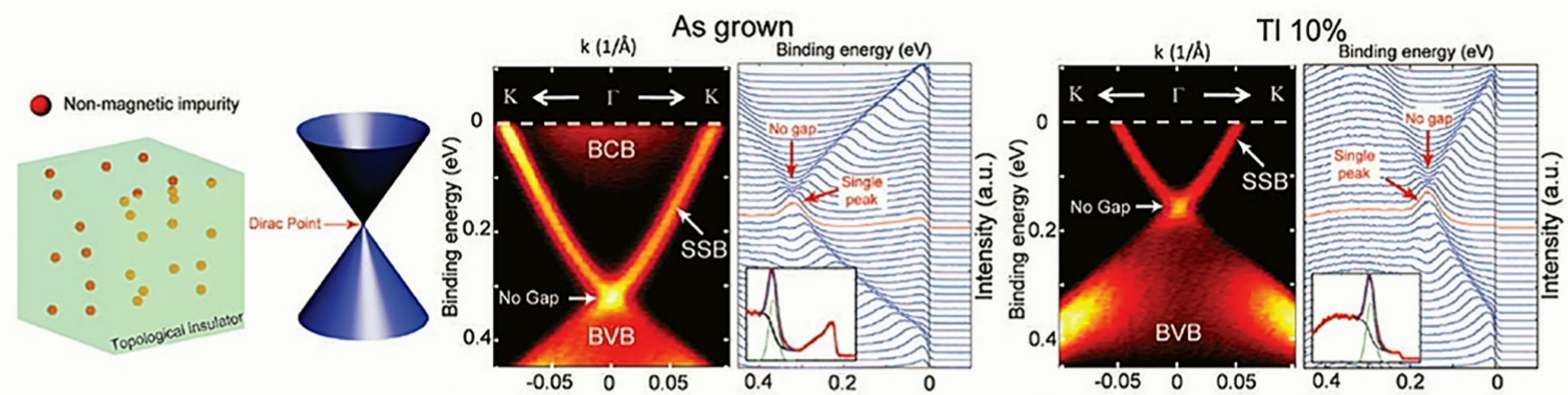


Thin Film Bi_2Se_3

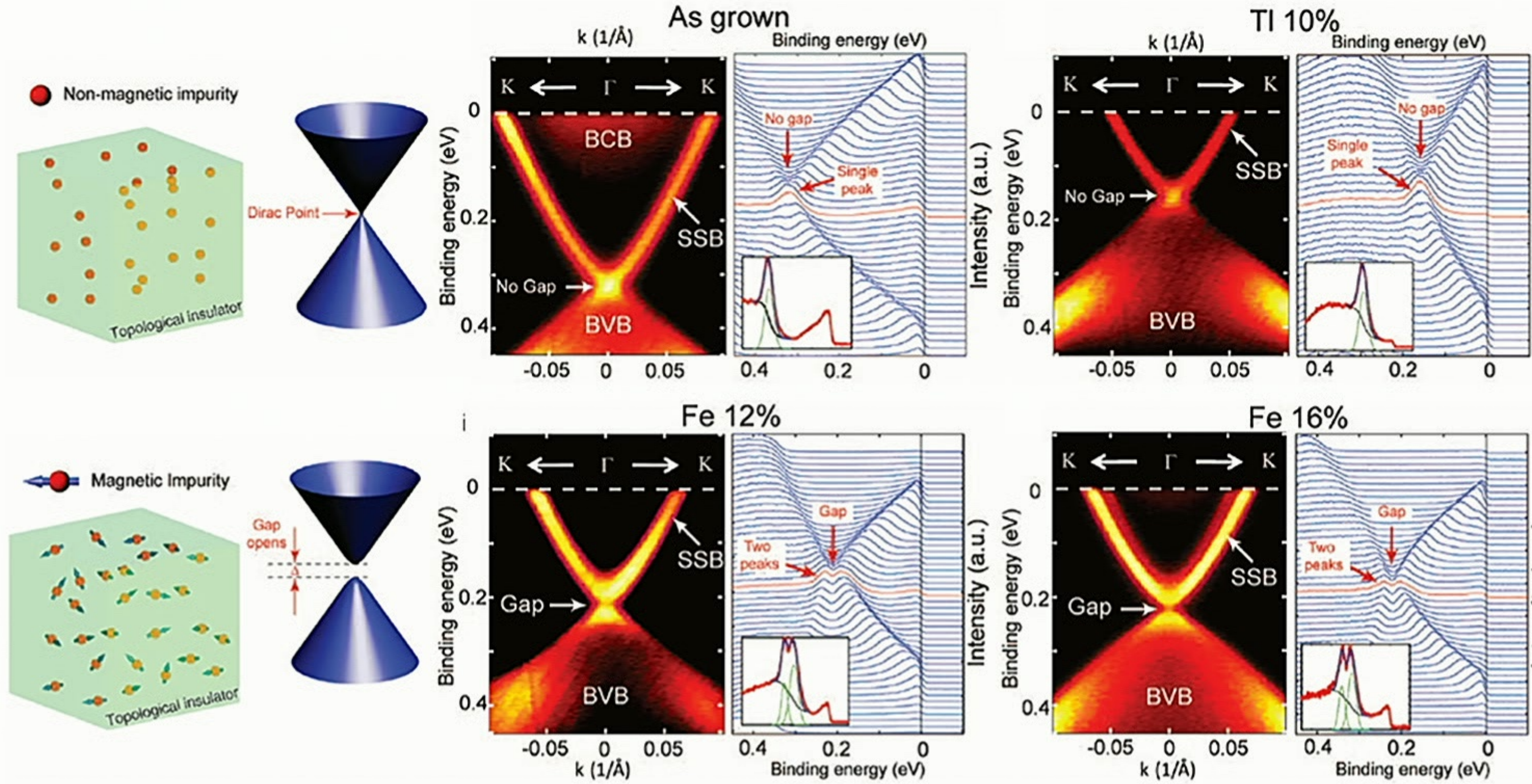




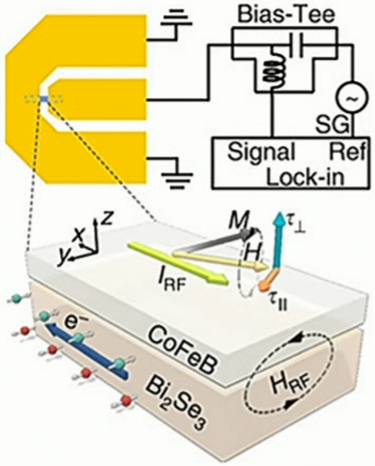
Mom was Right – Some Dirt You Just Can't Ignore

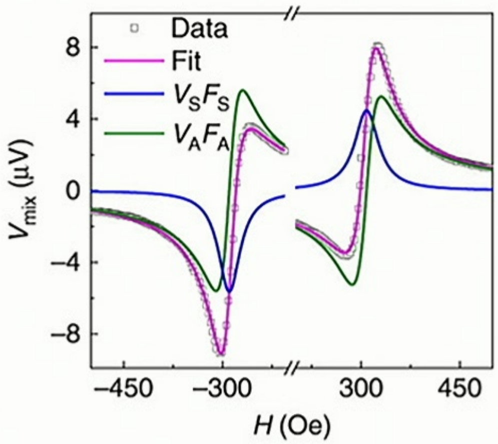


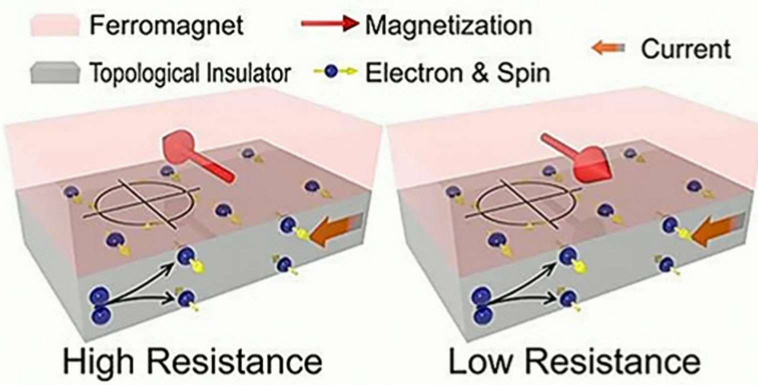
Mom was Right – Some Dirt You Just Can't Ignore



Controlling Spin

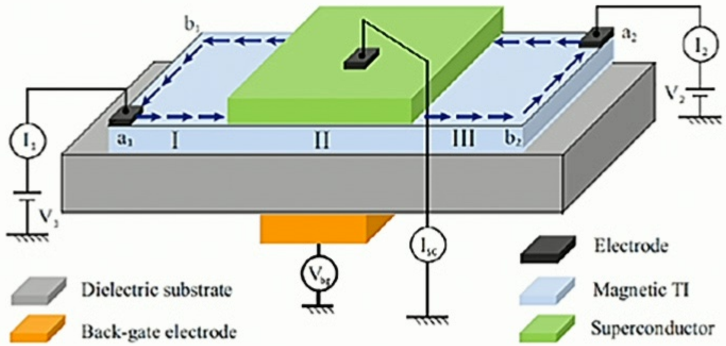


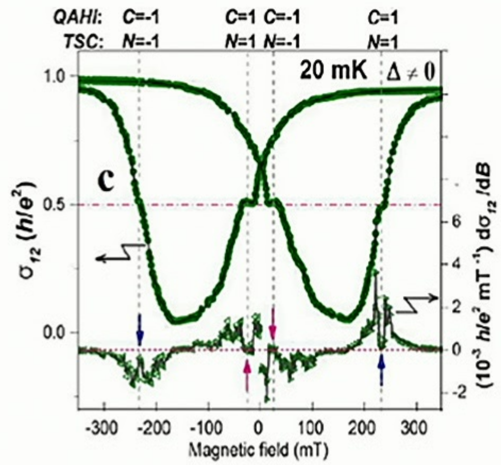




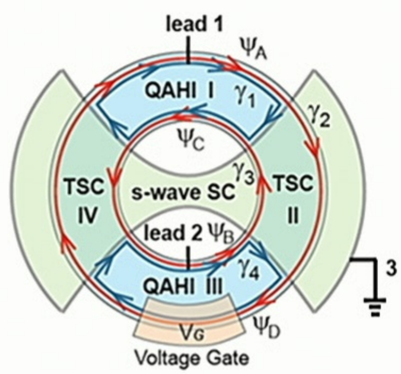
- Controlling spins across material interface
  - Spin valves
  - Magnetoresistive memory
  - Spintronics
- Improved efficiency by conducting spins without dissipative energy loss

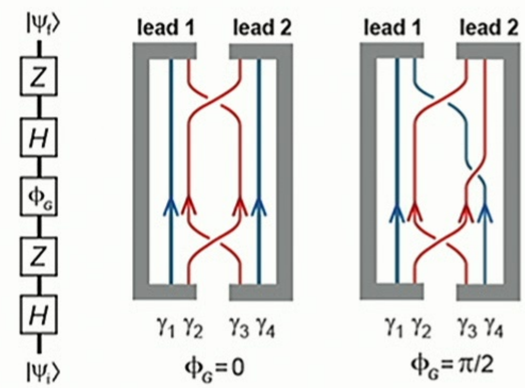
Topological Protection and Quantum Computing





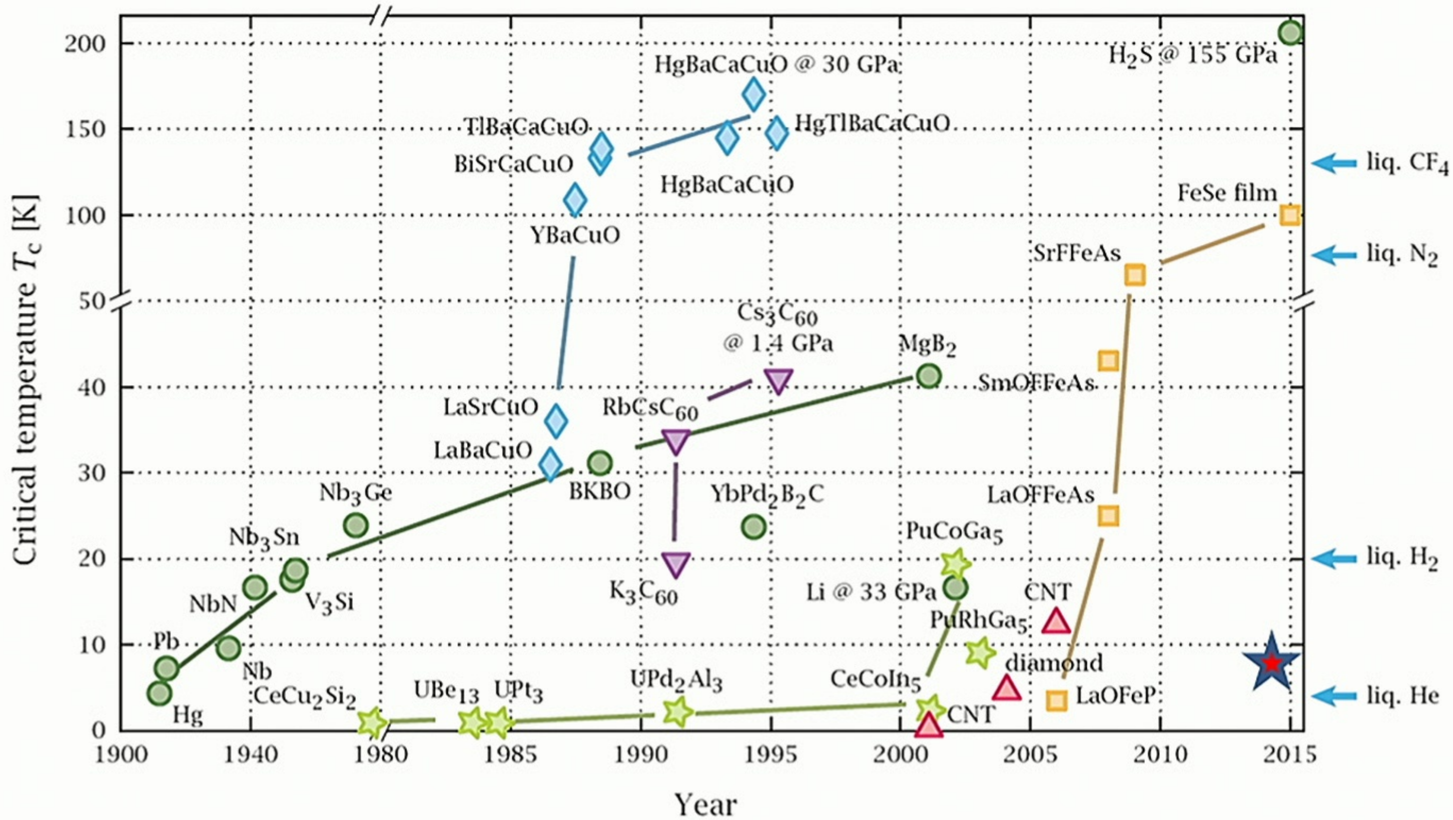
- Discovery of Majorana Fermions
  - Particles that are their own Antiparticle
  - Building block of Qubits
- Robust entangled states requiring less error correction



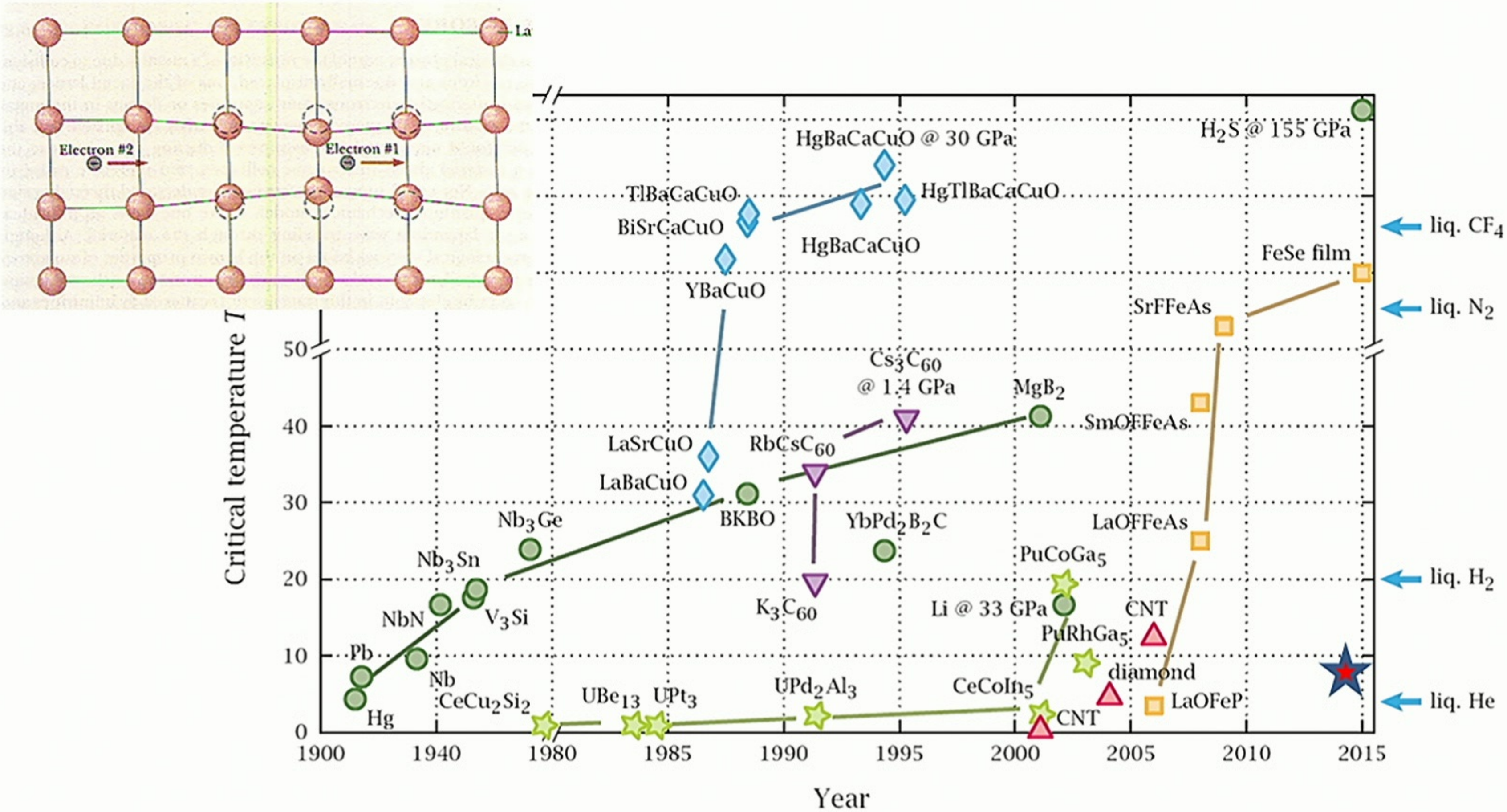


Resistance is futile

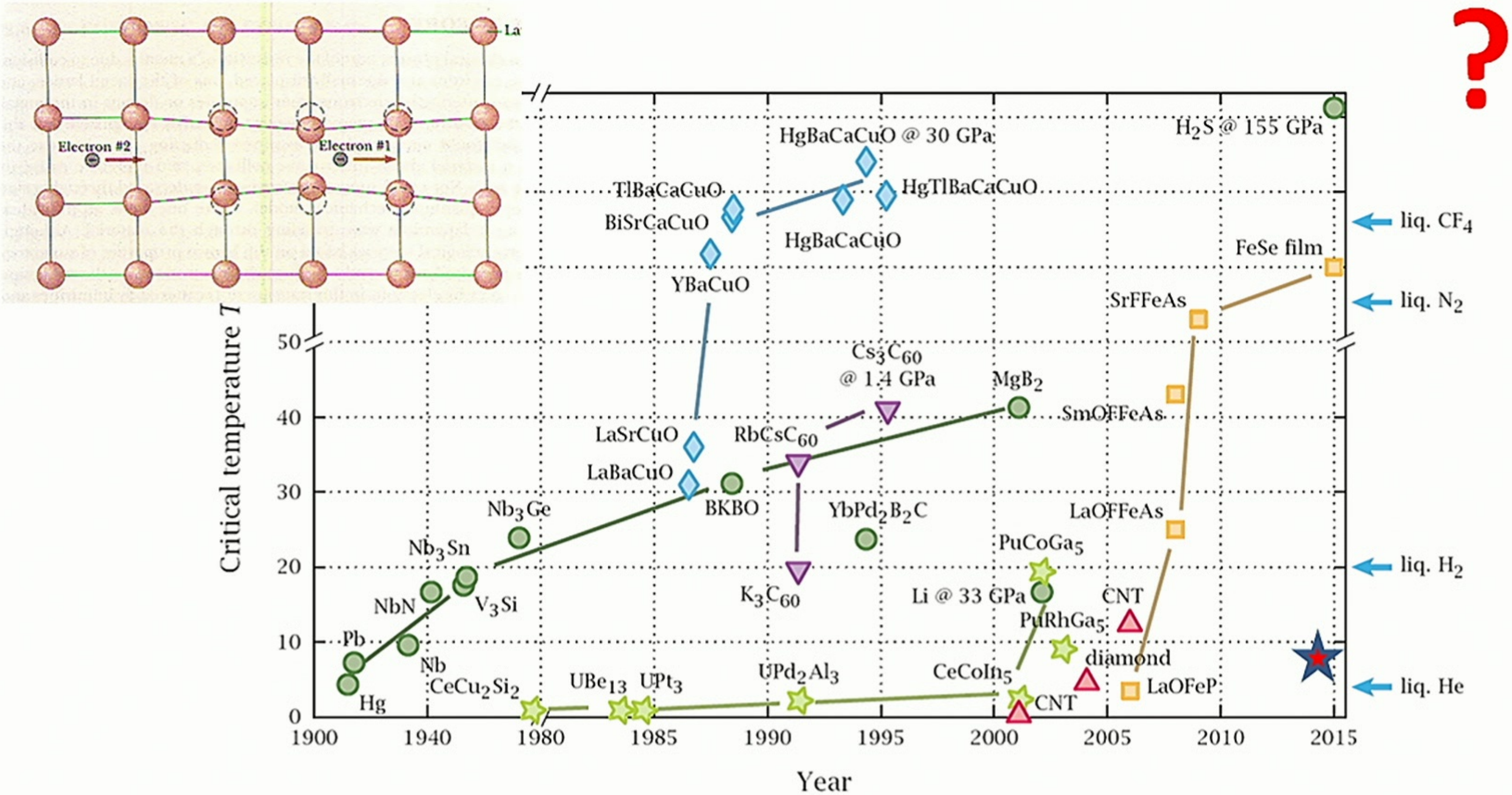
Superconductivity – Electrical Current without Resistance



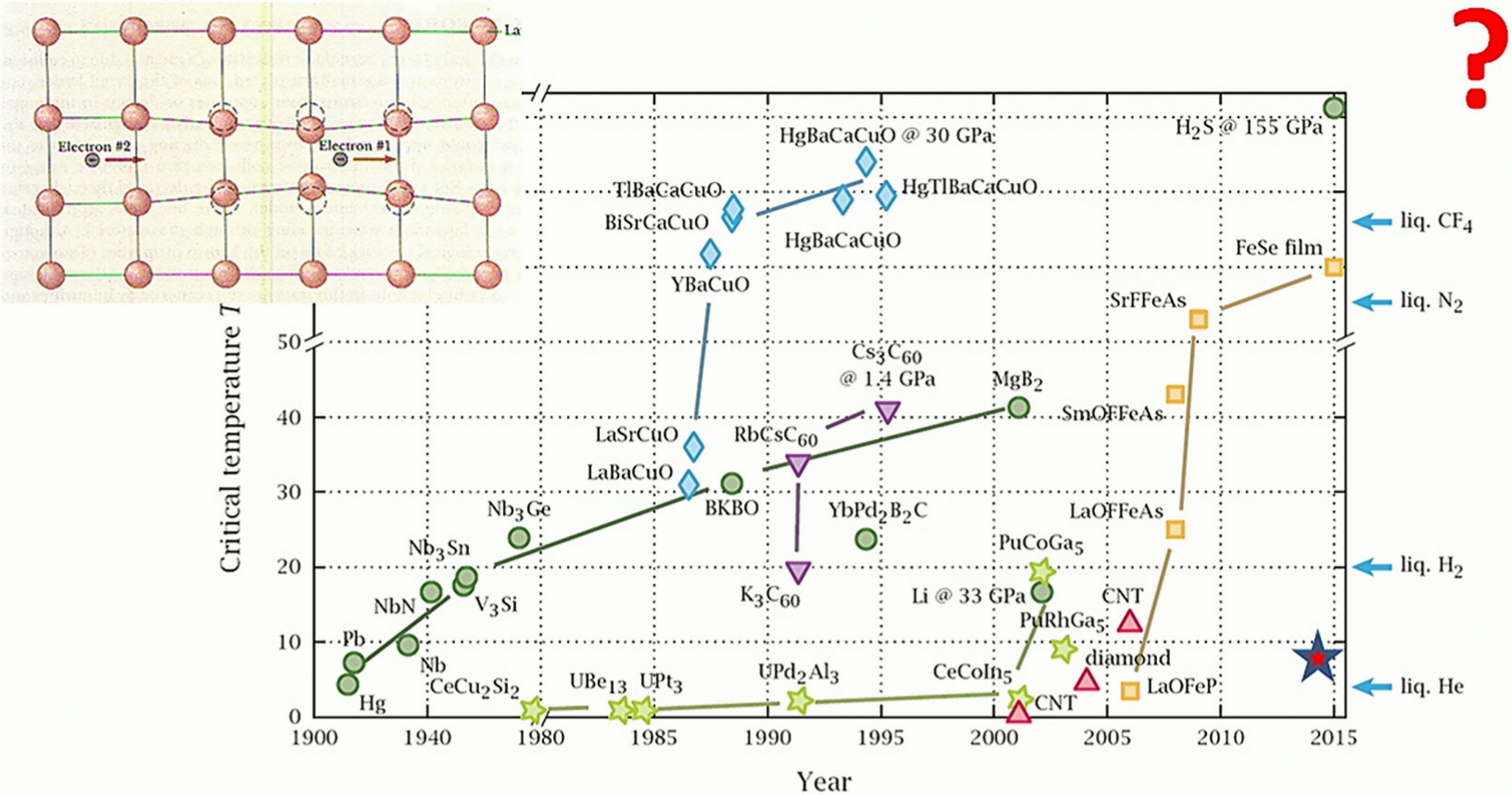
Superconductivity – Electrical Current without Resistance



Superconductivity – Electrical Current without Resistance

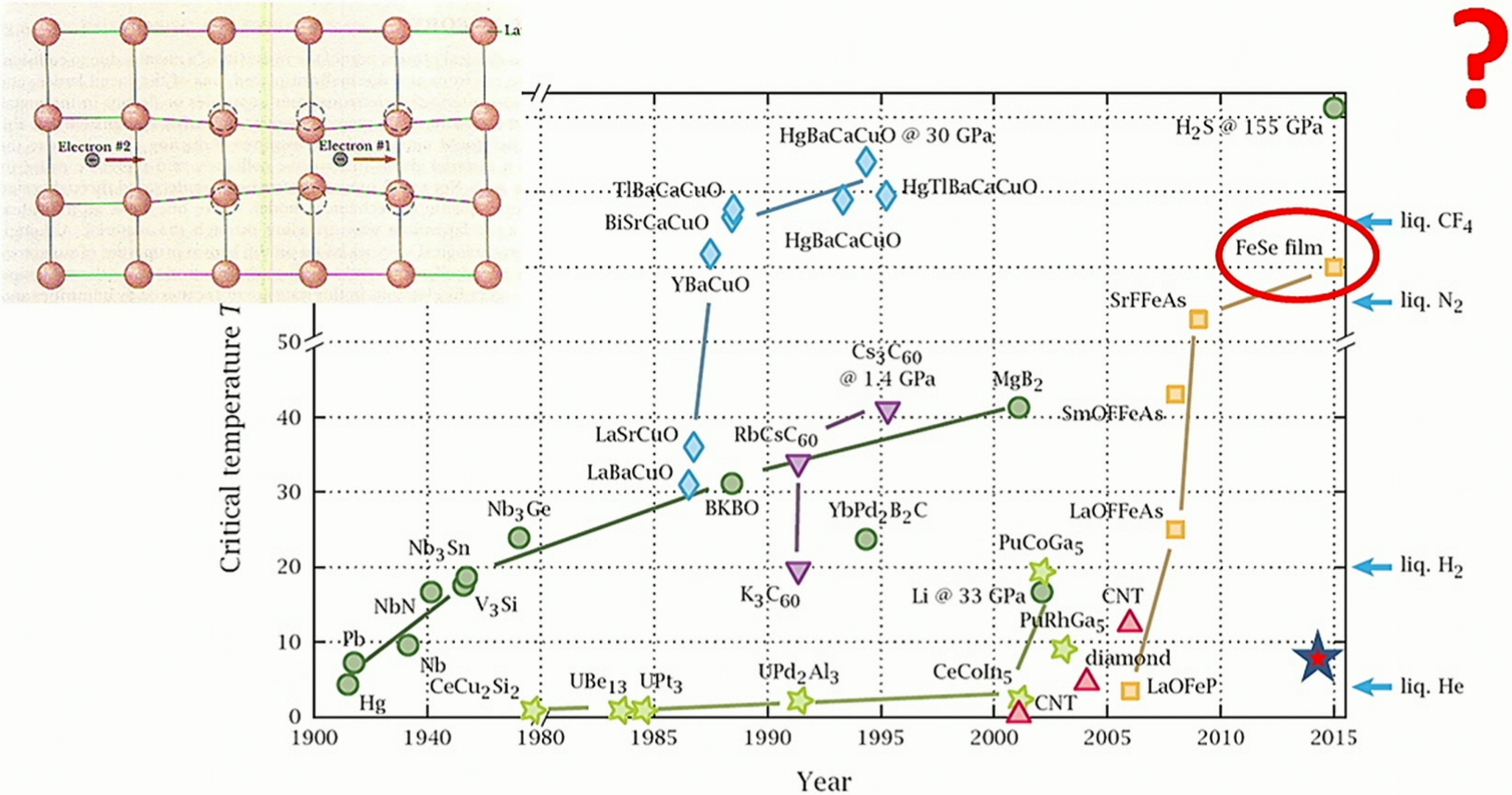


Superconductivity – Electrical Current without Resistance



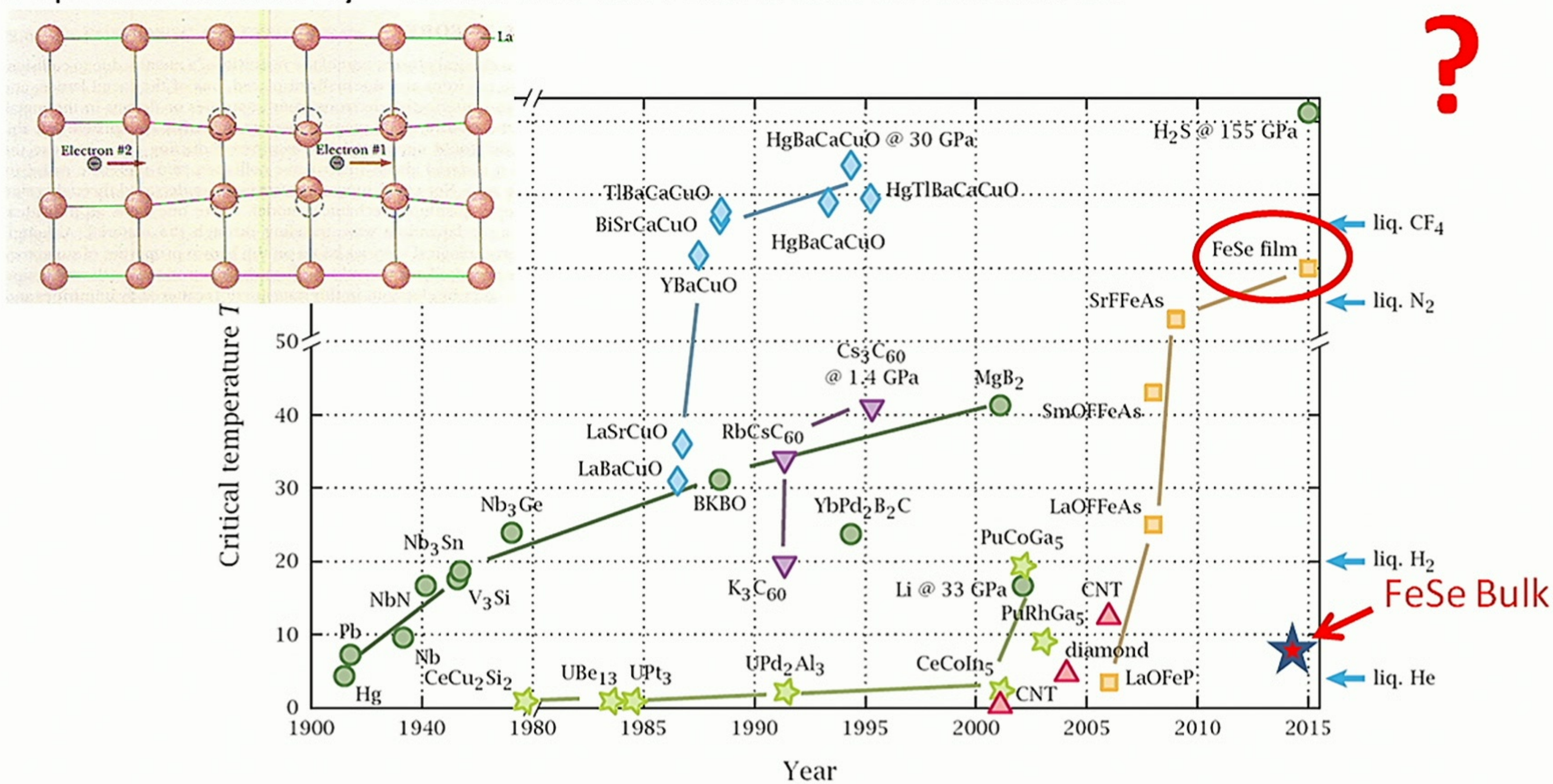
.............still and unsolved mystery

Superconductivity – Electrical Current without Resistance



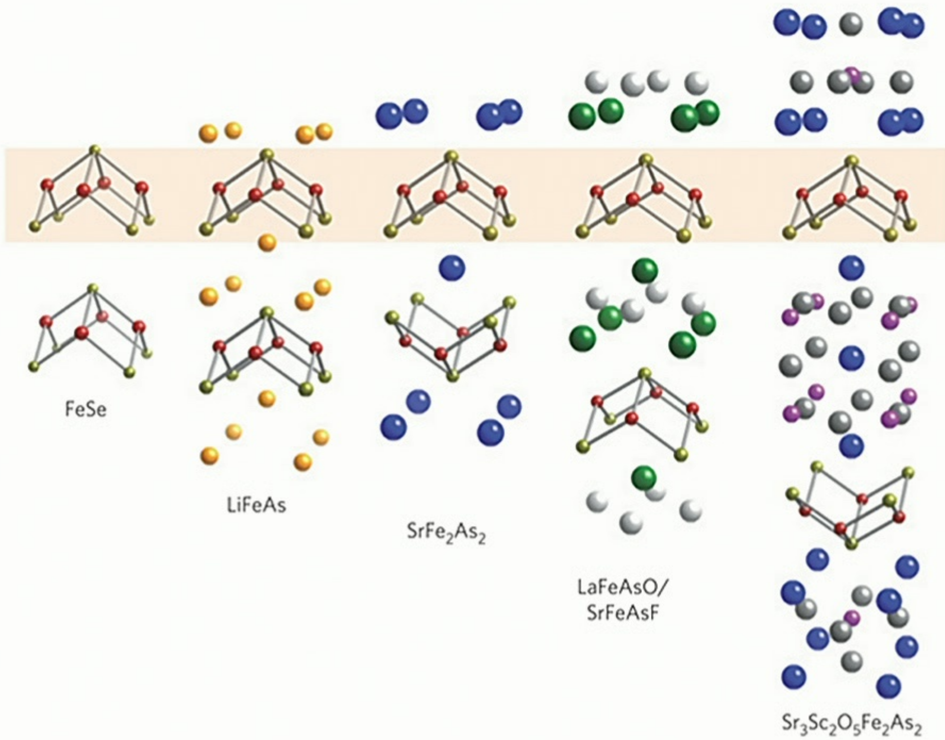
.............still and unsolved mystery

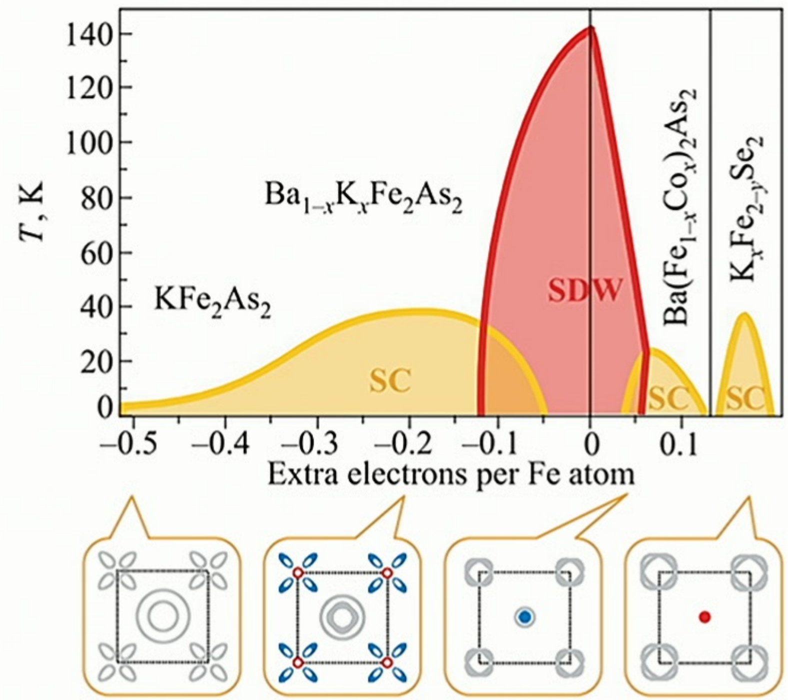
Superconductivity – Electrical Current without Resistance



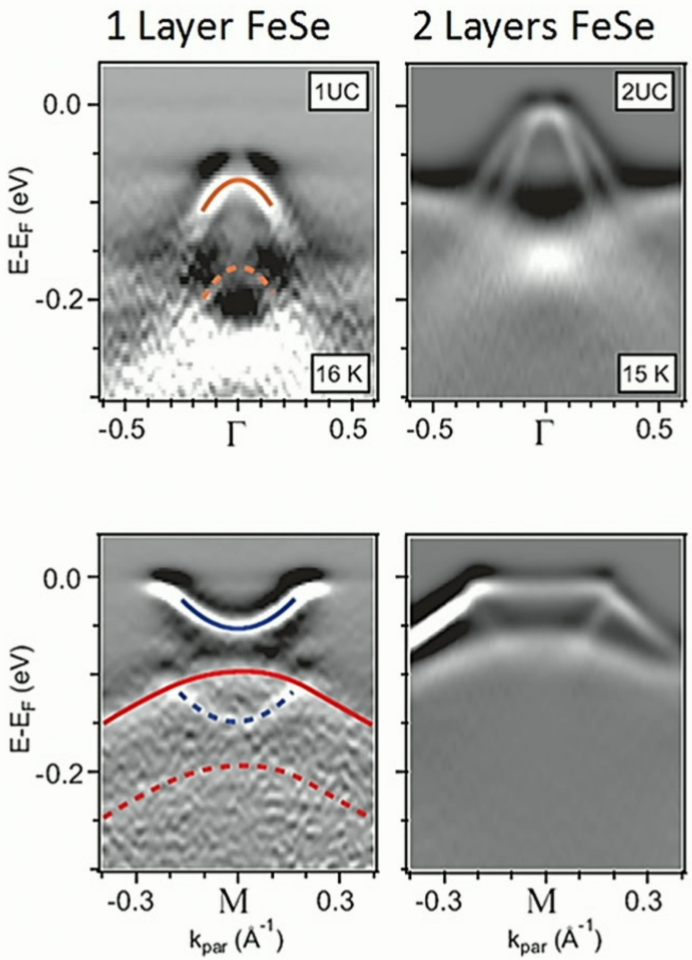
.............still and unsolved mystery

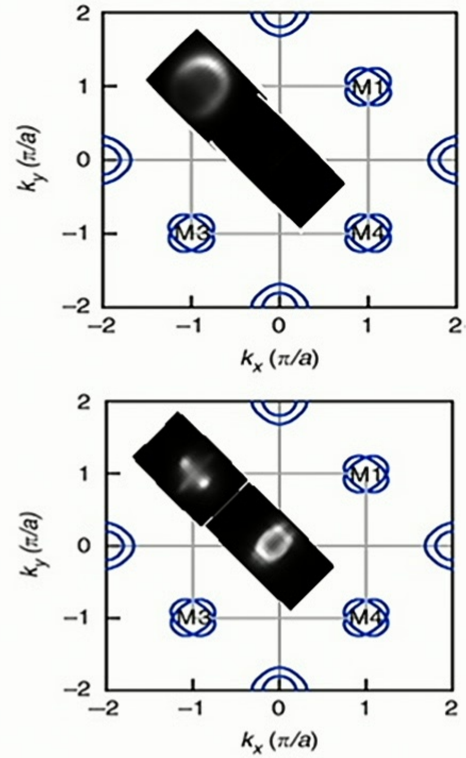
Iron Based High T_c Superconductors





ARPES on FeSe Thin Films

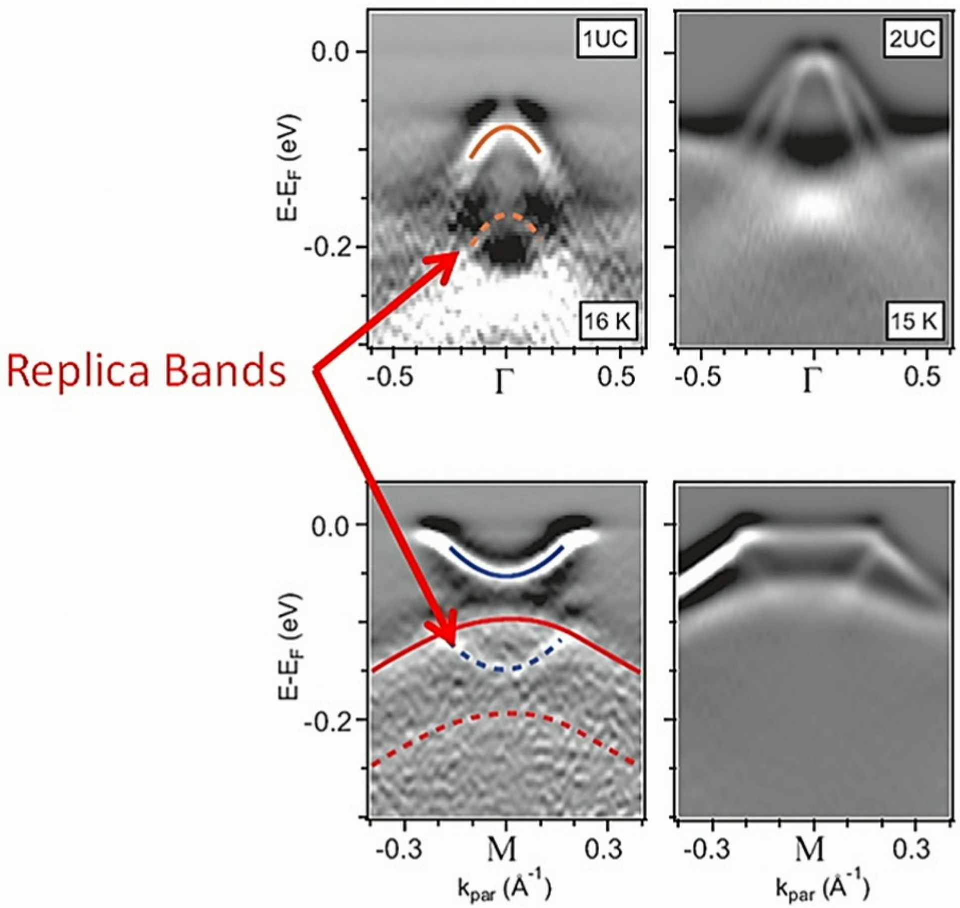


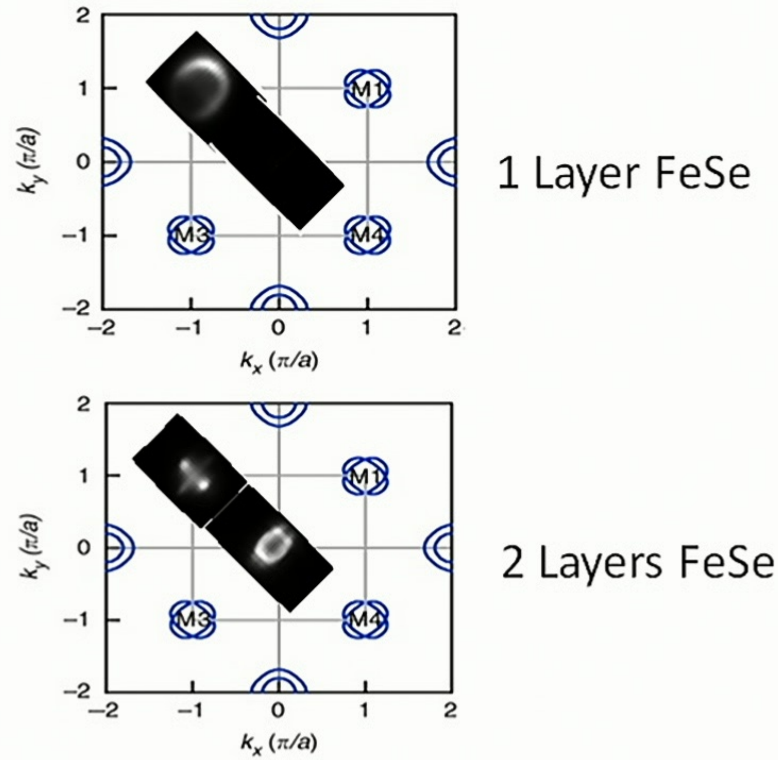


1 Layer FeSe

2 Layers FeSe

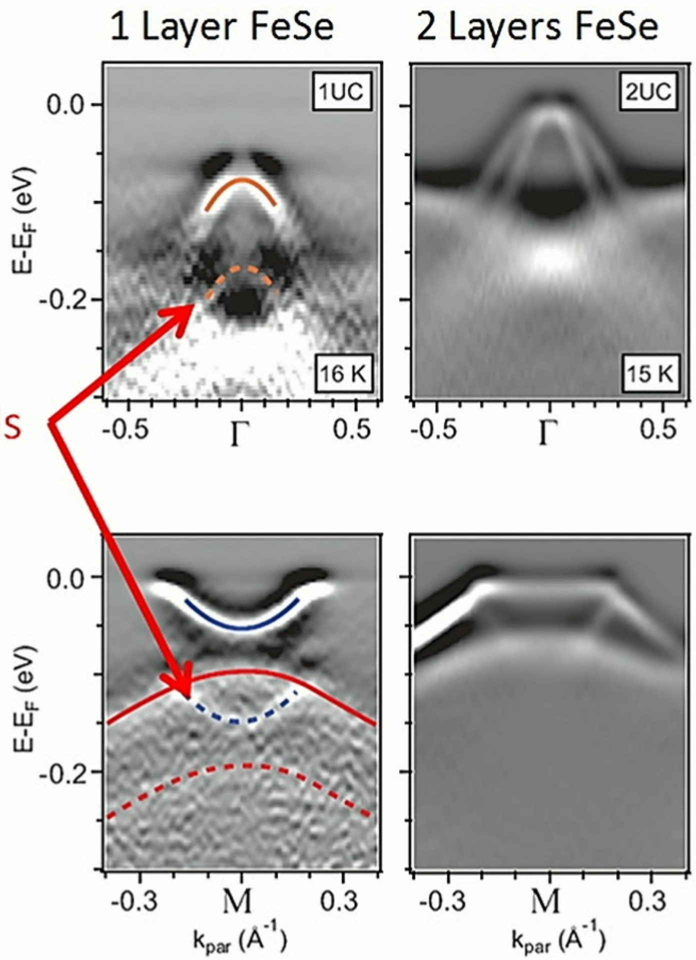
ARPES on FeSe Thin Films

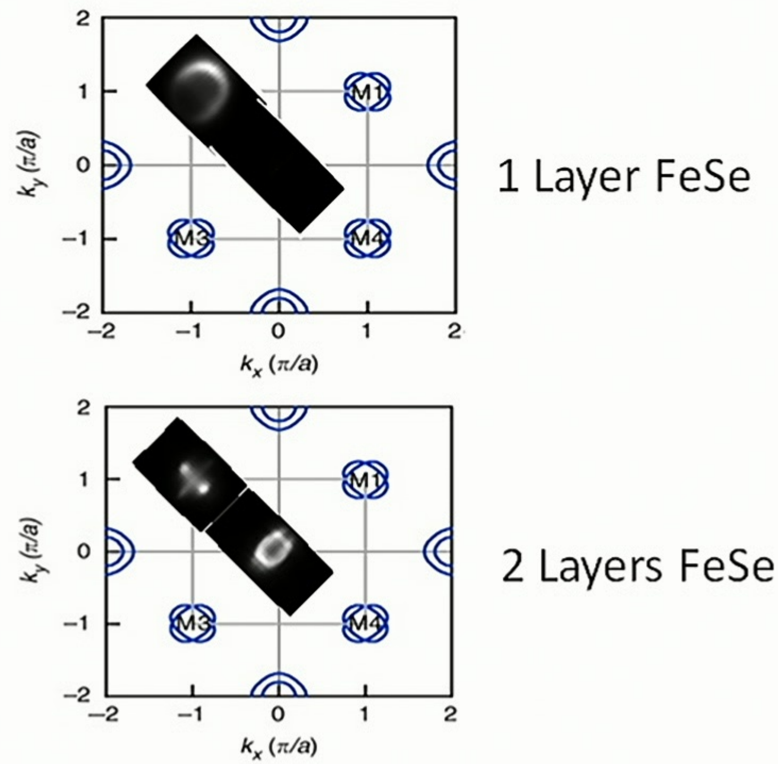




The most ex
science, the
discoveries,
funny...'

ARPES on FeSe Thin Films



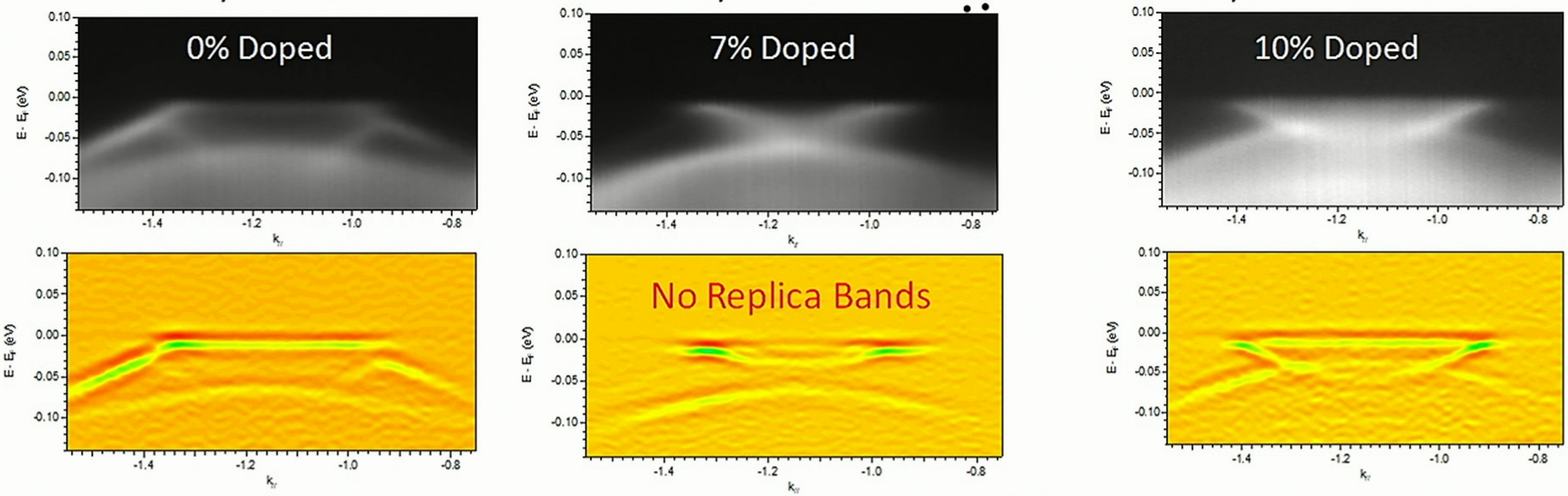


The most exciting phrase to hear in science, the one that heralds new discoveries, is not 'Eureka!' but 'That's funny...'

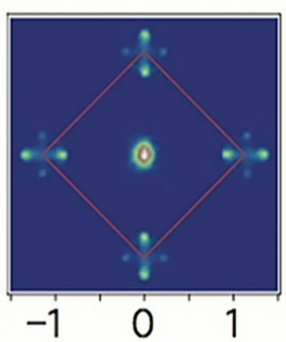
- Isaac Asimov

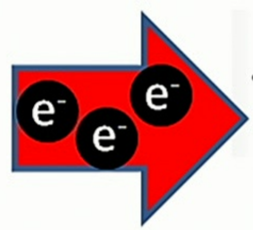
Doping Electrons – Moving E_F

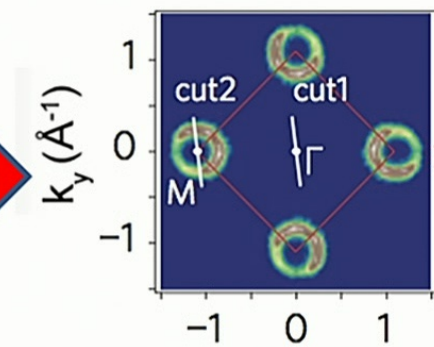
3Layer FeSe | 3Layer FeSe + K | 3Layer FeSe + More K



3Layer FeSe Fermi Surface



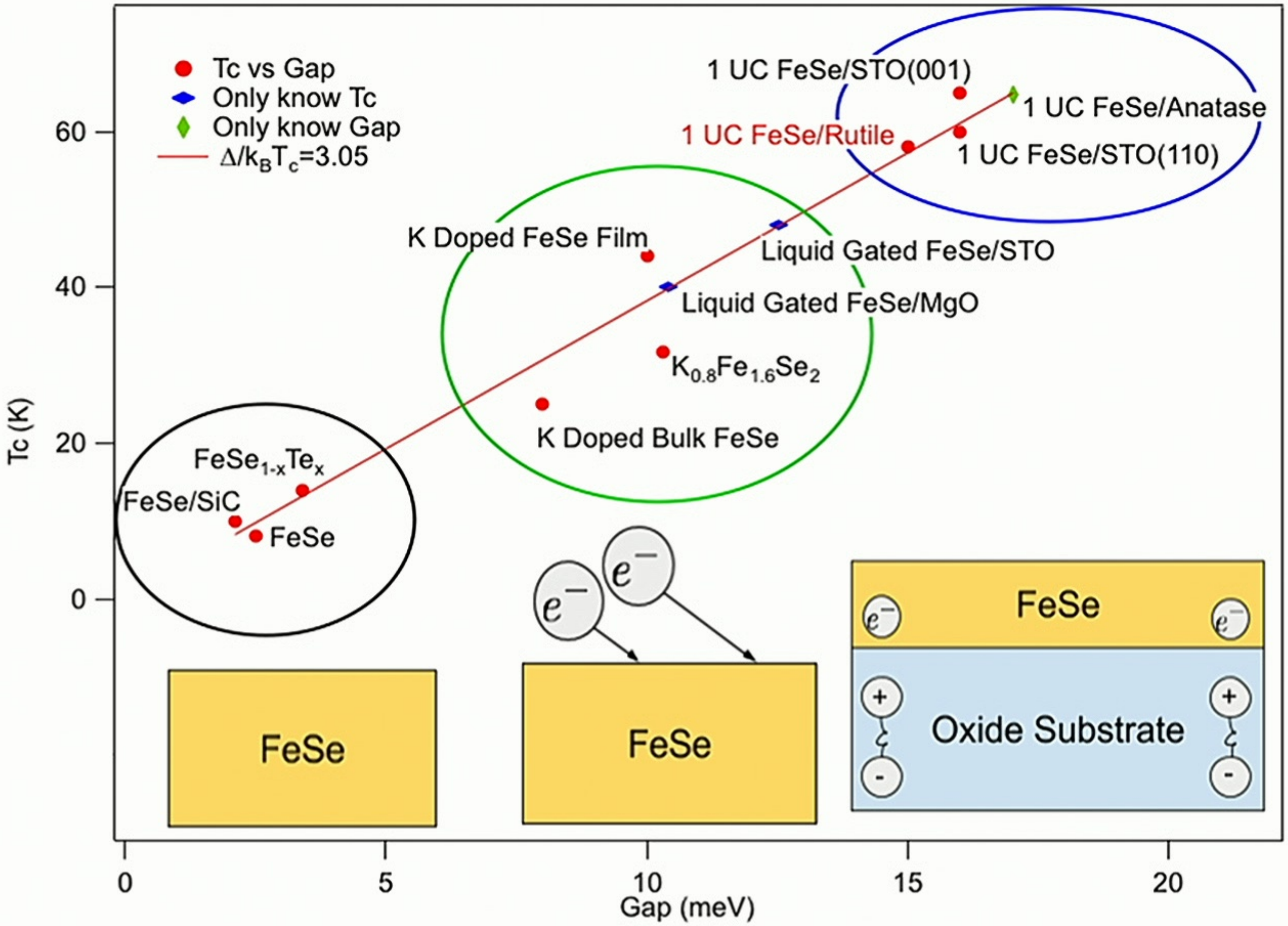




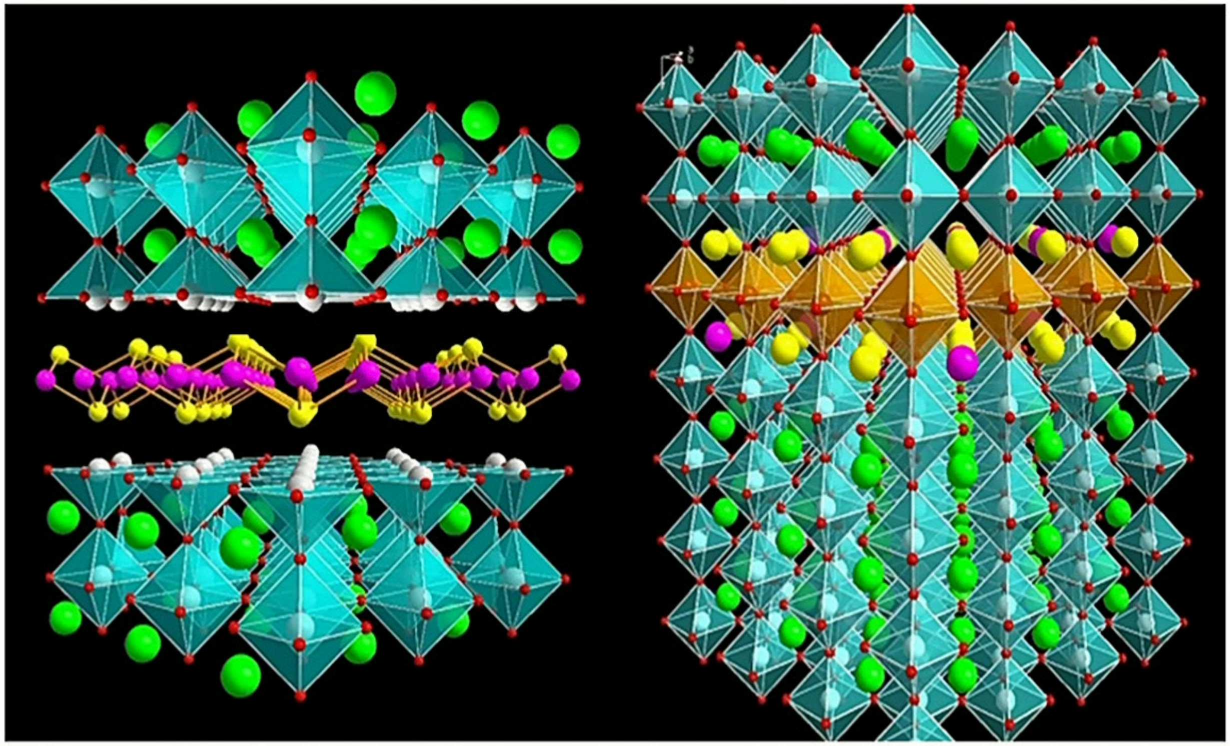
1Layer FeSe Fermi Surface

Kicking Electrons Without Changing Their Momentum

How to Enhance a Superconductor



The Punch line…………..

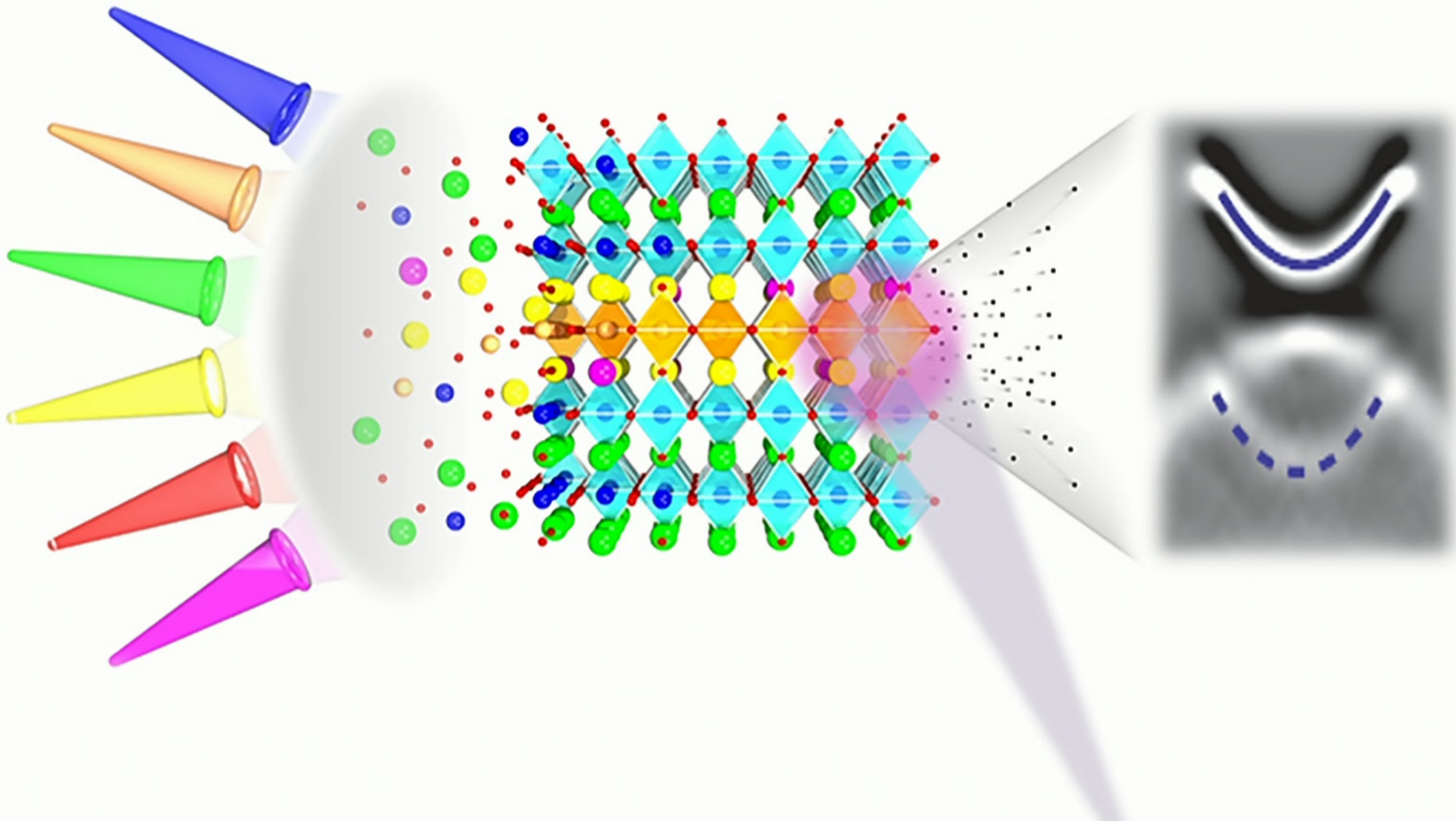


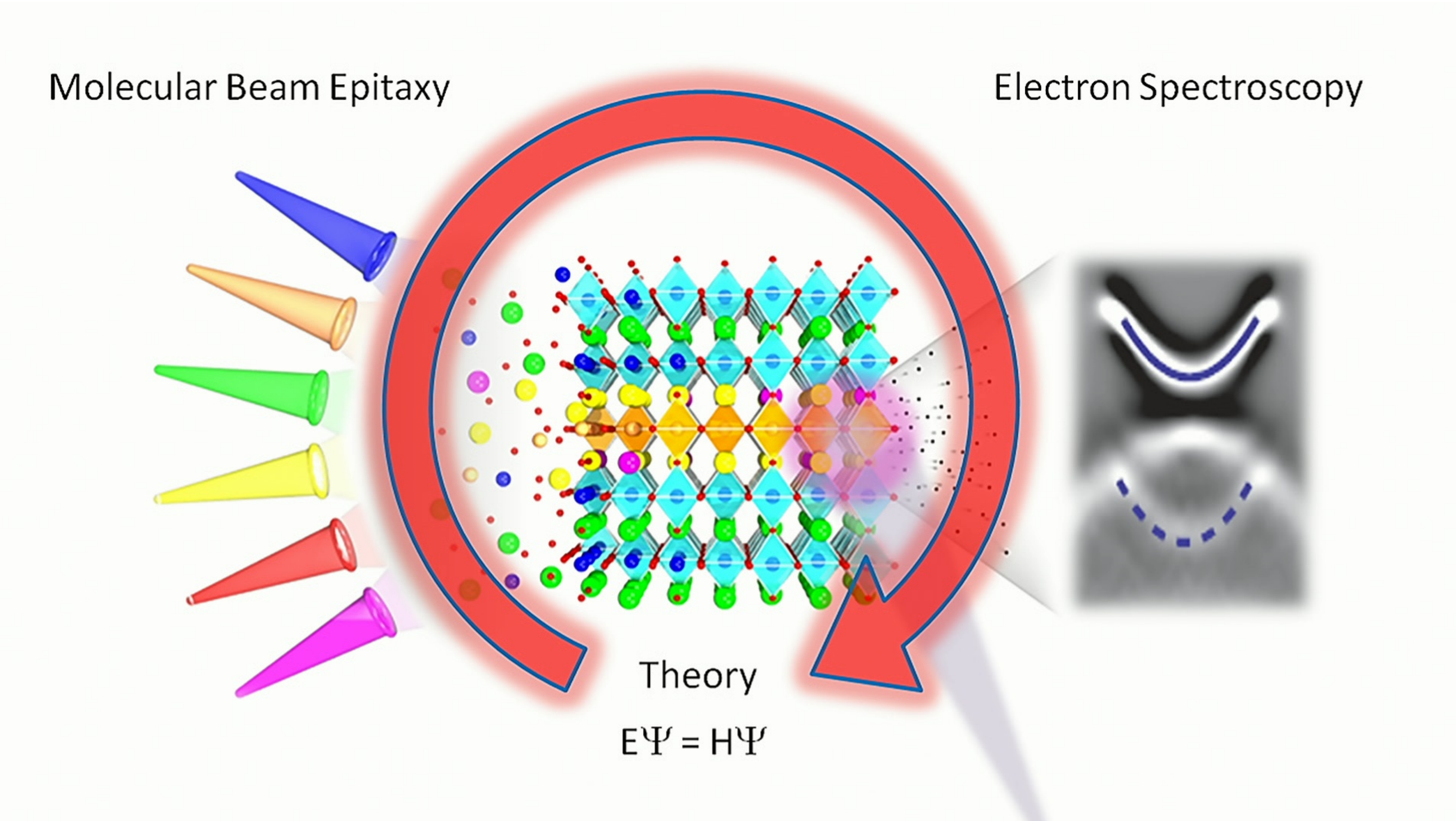
……………there is nothing special about FeSe

It’s a wrap

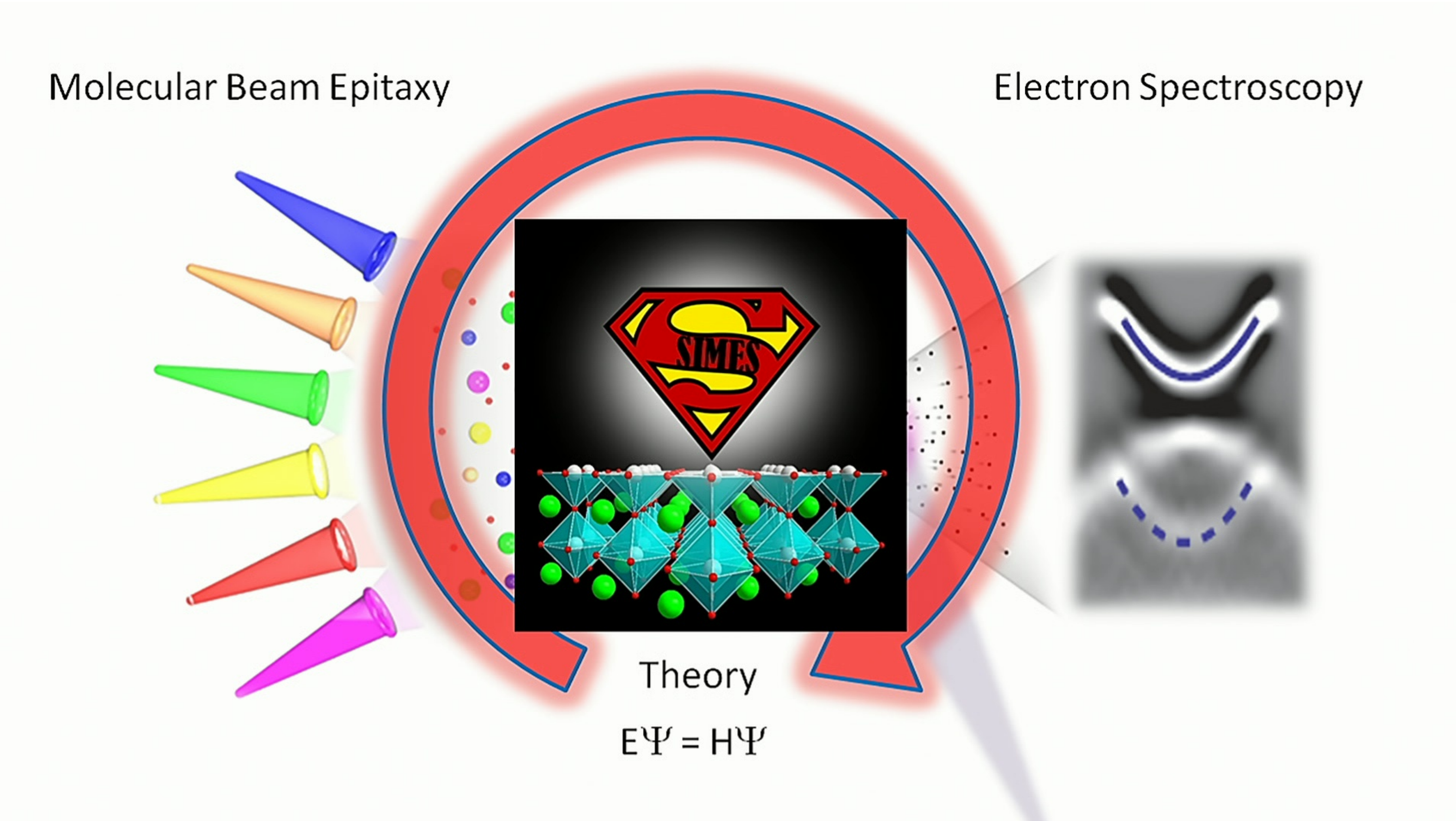
Molecular Beam Epitaxy

Electron Spectroscopy

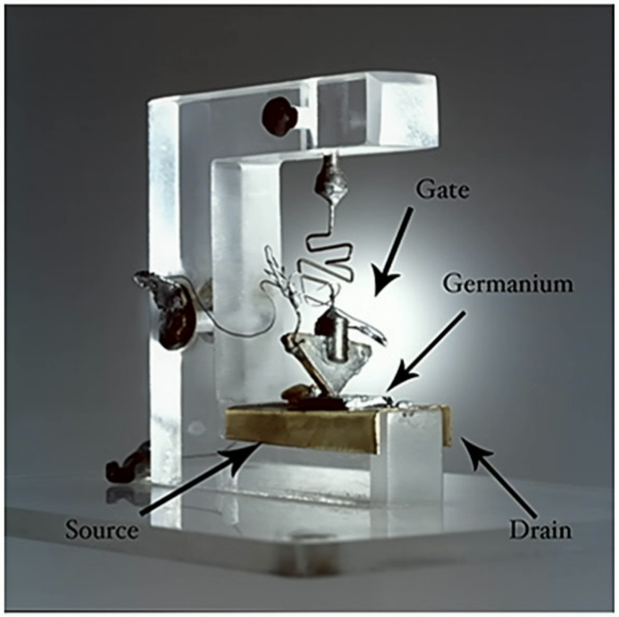




Molecular Beam Epitaxy
Electron Spectroscopy
Theory
$E\Psi = H\Psi$

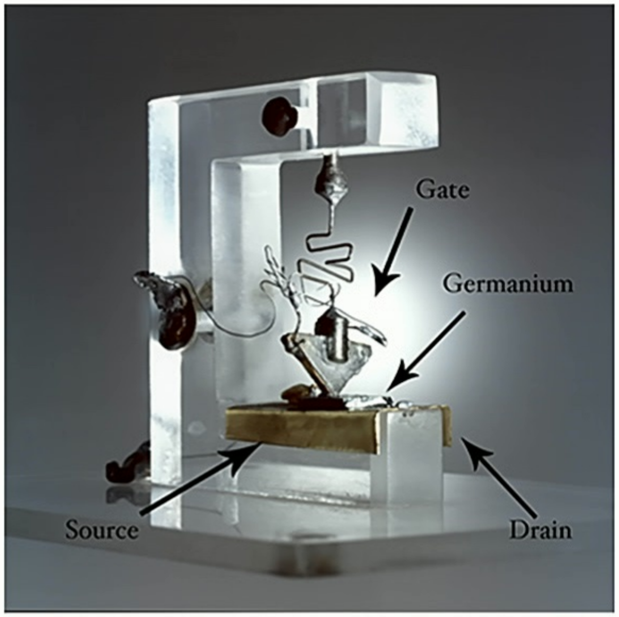

Molecular Beam Epitaxy
Electron Spectroscopy
SIMES
Theory
EΨ = HΨ

Dawn of the Quantum Age



Dawn of the Quantum Age

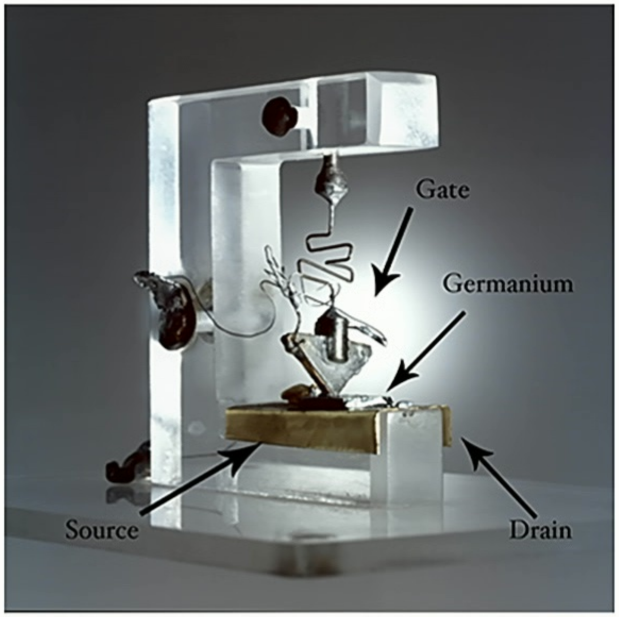
but we need to be realistic............

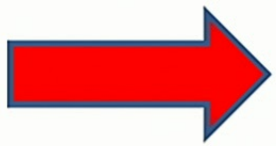


.........because we have just arrived

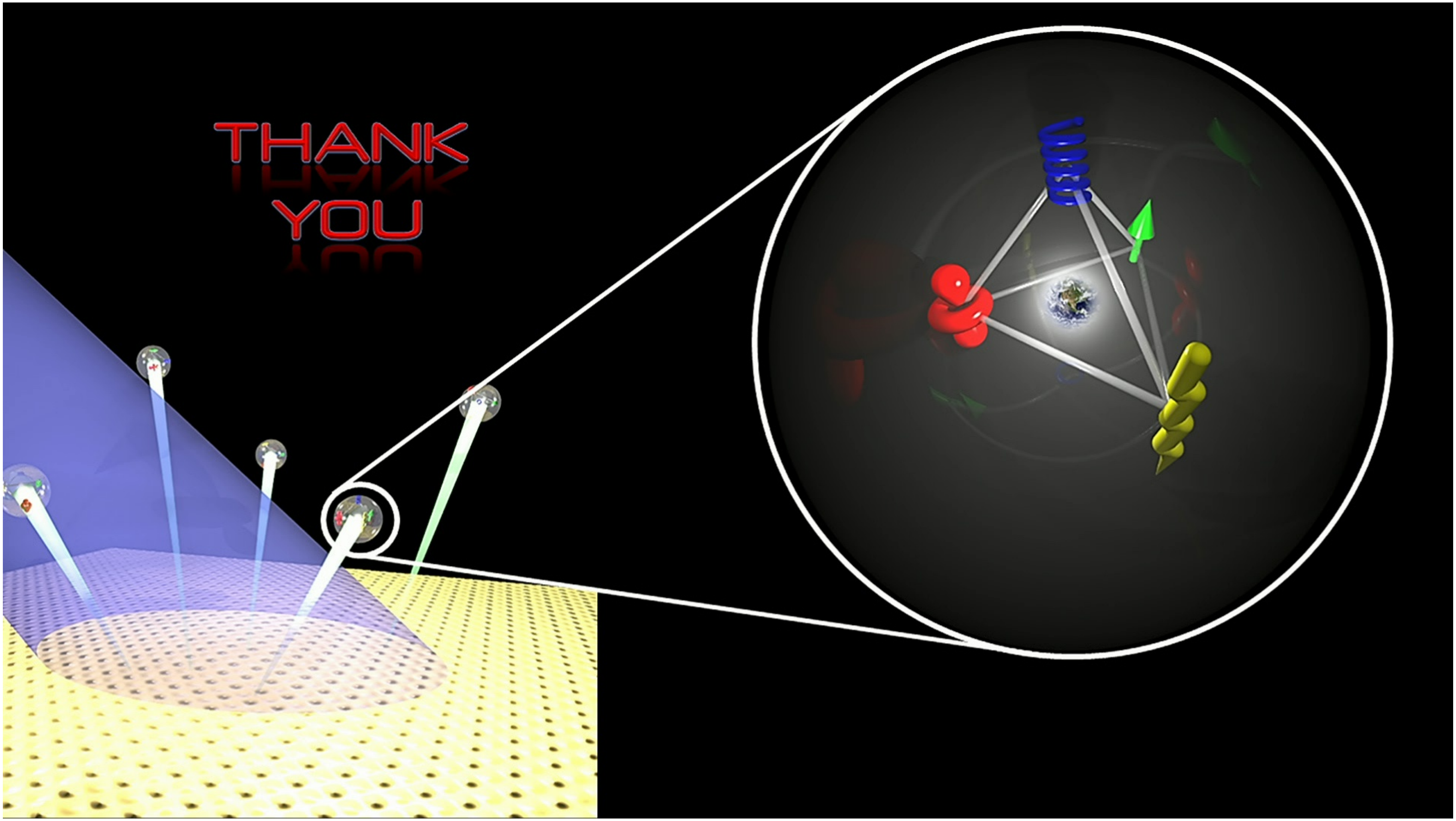
Dawn of the Quantum Age

but we need to be realistic…………





………because we have just arrived


THANK
YOU