Einstein's Photoelectric Effect

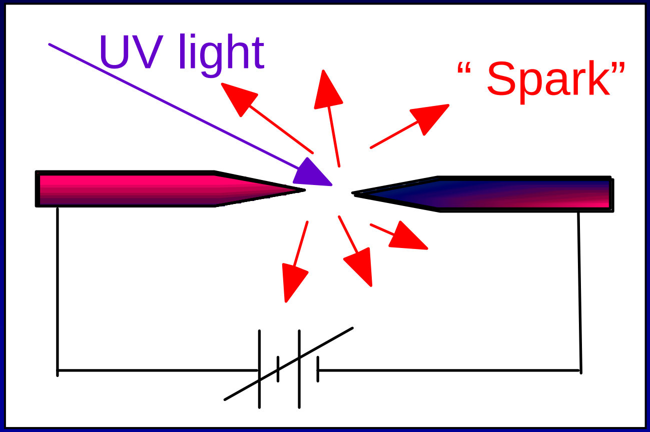
How ONE electron tells the story of GAZILLION electrons

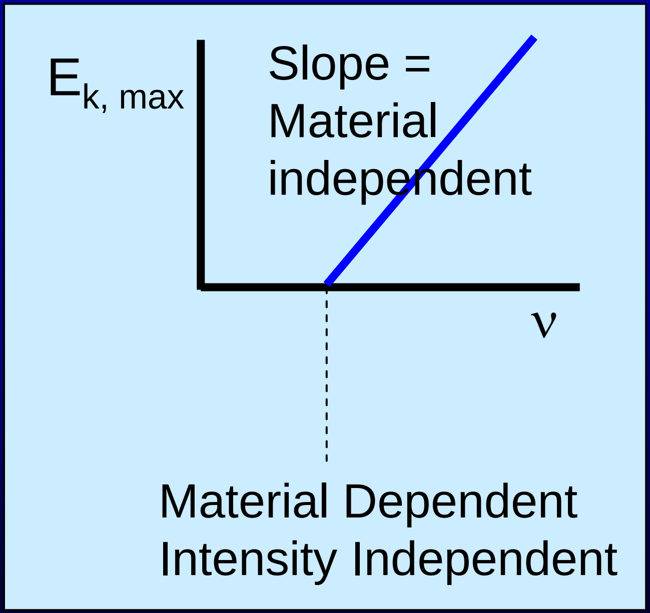
Overview

- Photo-electric effect and Angle Resolved Photo-Electron Spectroscopy (ARPES)
- Emergent behaviors
- High temperature superconductivity and ARPES
- Unconventional emergent behaviors and ARPES

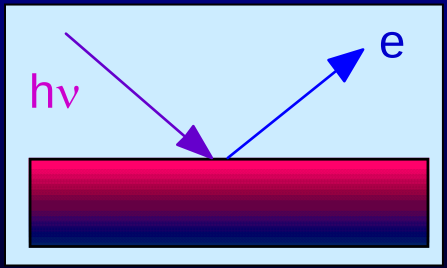
History: The Photoelectric Effect

- Hertz (1887)
- Thompson & Lenard (1897-1902)
  Photo-electrons are involved
- Einstein (1905, 1921 Nobel Prize)
  Quantum theory (Photon)



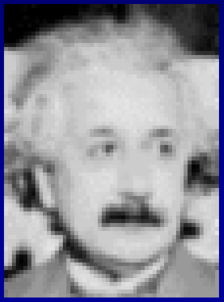


$$E_k = h\nu - E_b - \Phi$$



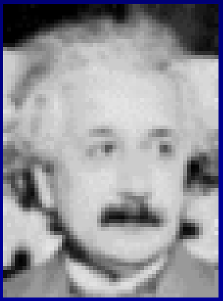
Einstein's Theory – Controversial

Albert Einstein (1879 - 1955) published his theory of the photoelectric effect in 1905, the same year in which he published the Special Theory of Relativity and the paper on molecular dimensions which earned him his PhD from the University of Zurich. However, his reintroduction of the idea of a corpuscular nature for light met with considerable scientific resistance. Even Planck rejected an idea which seemed to set science back one hundred years. As late as 1913, when Einstein was proposed for membership in the Prussian Academy of Science, the nominating committee felt it necessary to apologize for this "mistake" as a singular error in a series of successes. Then, in 1921 Einstein won the Nobel Prize for the theory of the photoelectric effect.



Einstein's Theory – Controversial

In a recommendation for Einstein's membership in the Prussian Academy of Science, the sponsors wrote



"In sum, one can say that there is hardly one among the great problems in which modern physics is so rich to which Einstein has not made a remarkable contribution. <u>That he may sometimes have missed the targeting his speculations, as, for example, in his hypothesis of light-quanta, cannot really be held too much against him,</u> for it is not possible to introduce really new ideas even in the most exact sciences without sometimes taking a risk"

A. Pais, "Subtle is the Lord: The Science and the Life of Albert Einstein," New York: Oxford University Press, 1982, p. 382

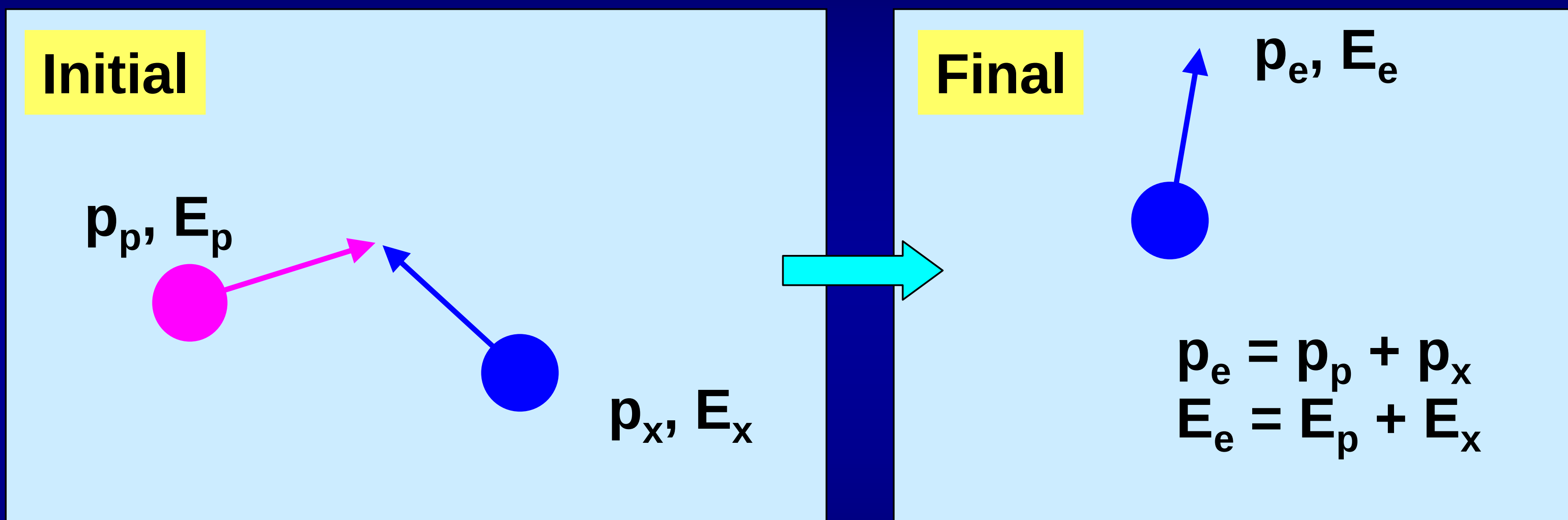
Current Understanding

Quantum Mechanics Governs
Both Light (Photon) and Electron

- Light Wave energy is discrete ($h\nu$, $2h\nu$, $3h\nu$…)
  - The quantum of energy ($h\nu$): Photon Particle
  - Photon Particle is described by a Wave Function
- Electron Particle is described by a Wave Function

Particle Wave Duality

Current Understanding (Particle)

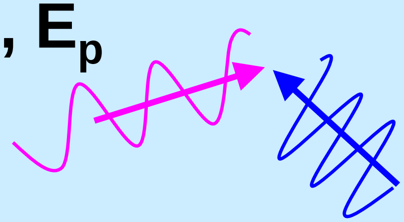


Momentum Conservation
Energy Conservation

Current Understanding (Wave)

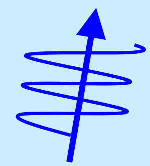
Initial

p_p, E_p



p_x, E_x

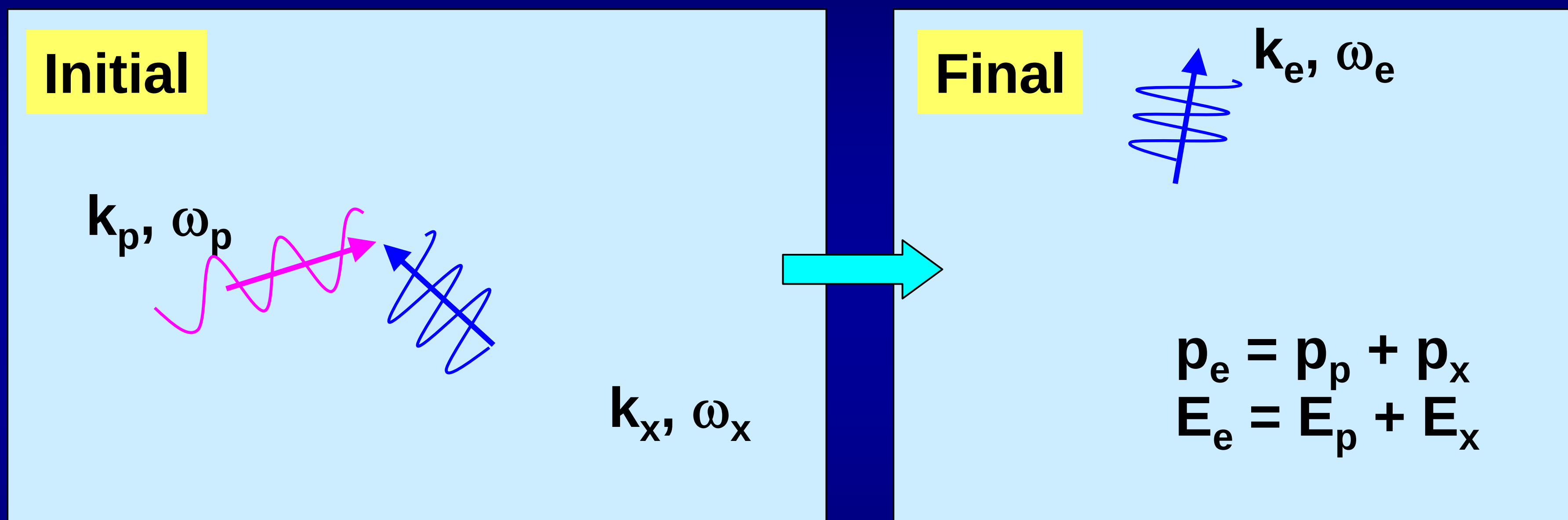
Final



p_e, E_e

$$p_e = p_p + p_x$$
$$E_e = E_p + E_x$$

Current Understanding (Wave)

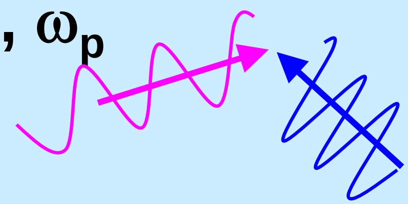


What is measured and what is not

However, ω and k are not independent.
DISPERSION RELATION
For instance, $\omega = ck$ for light (photon).
Homework…

Init

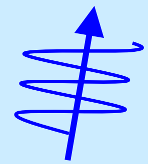
k_p, ω_p



k_x, ω_x

nal

k_e, ω_e



$p_e = p_p + p_x$
$E_e = E_p + E_x$

k = wave number = $2\pi / \lambda$
ω = angular freq. = $2\pi\nu = 2\pi / T$

k = momentum $p = h k / (2\pi)$
ω = energy $E = h \omega / (2\pi)$

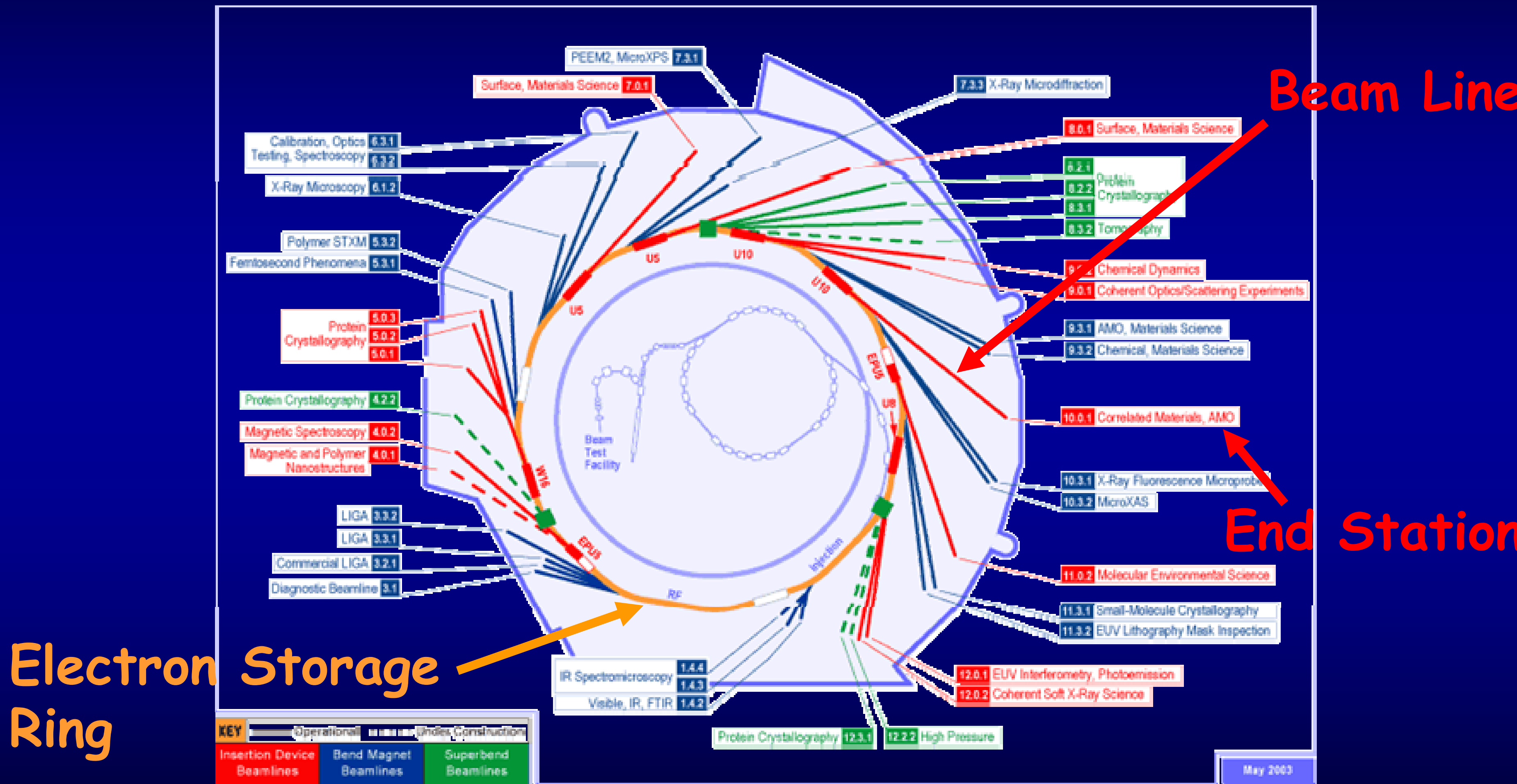
Photo-Electric Effect is Cool

- Photon Detectors
- Digital Camera, Camcorder, Solar Cells, …
- <u>Angle Resolved Photoelectron Spectroscopy</u>

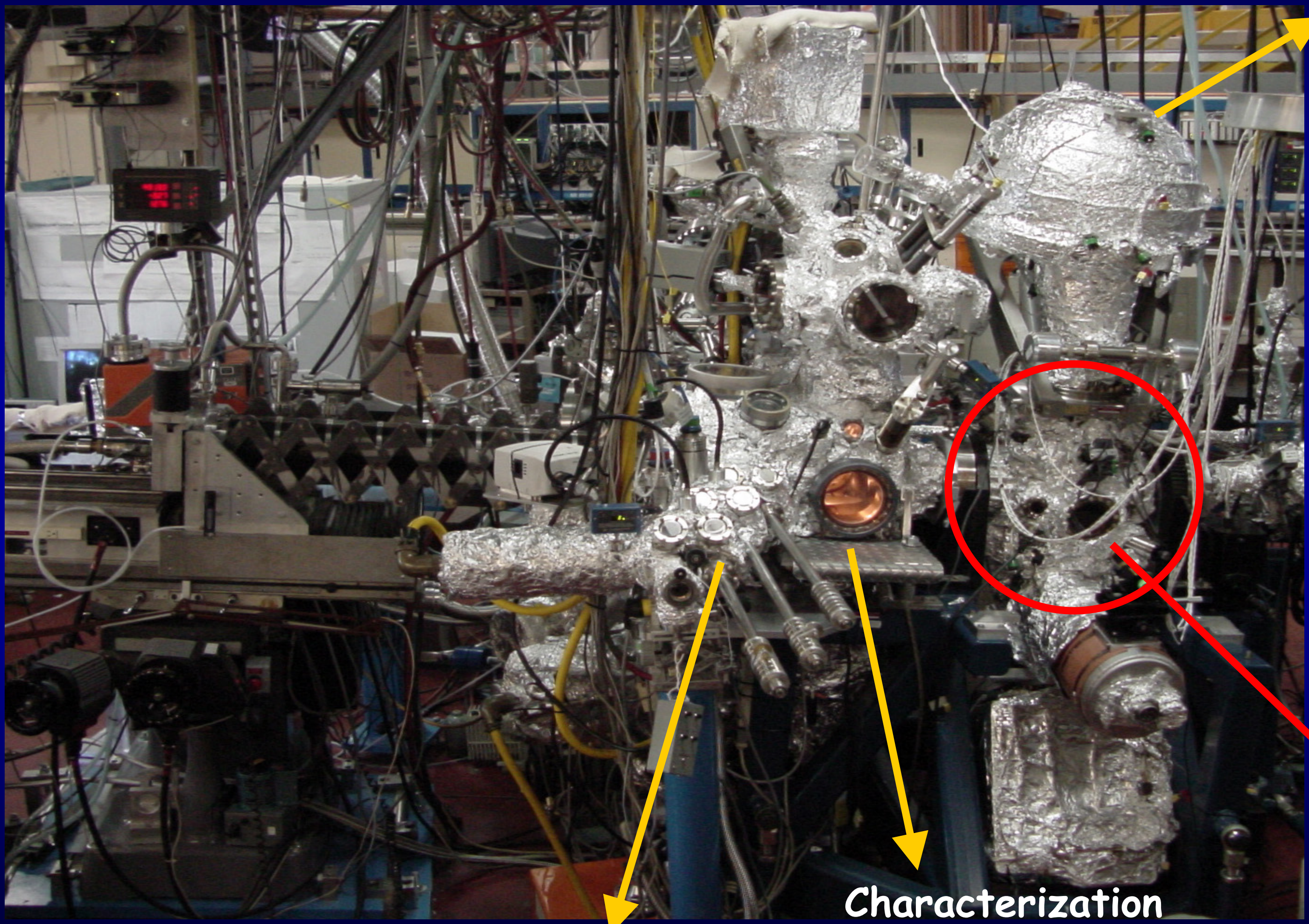
Synchrotron

Advance Light Source
Lawrence Berkeley National Laboratory

Synchrotron = Electron Shaker



ARPES End Station



7.6e2 Torr outside, 3e-11 Torr inside

History of ARPES

- Electron Spectroscopy for Chemical Analysis (ESCA or XPS) (Siegbahn, 1951-, 1981 Nobel Prize)
  - X-ray sources, electron spectrometer, chemical shift
- Photoelectron spectroscopy in UV (UPS) (Spicer, 1955-)
  - UV light sources and vacuum technology
- ARPES (Smith, 1973-)

Emergent Behaviors

R. P. Feynman : QED

"I must clarify something: When I say that all the phenomena of the physical world can be explained by this theory, we don't really know that. Most phenomena we are familiar with involve such *tremendous* numbers of electrons that it's hard for our poor minds to follow that complexity."

Tyranny of Power

- Computer memory of one particle wavefunction : X
- Number of particles: N
- Total memory: X^N

Say, X = 2 (minimum).

$2^{10} = 1024$, $2^{30} = 1.07e9$, $2^{100} = 1.3e30$

$N = 10^{23} \rightarrow X^N \sim 10^{3e22}$

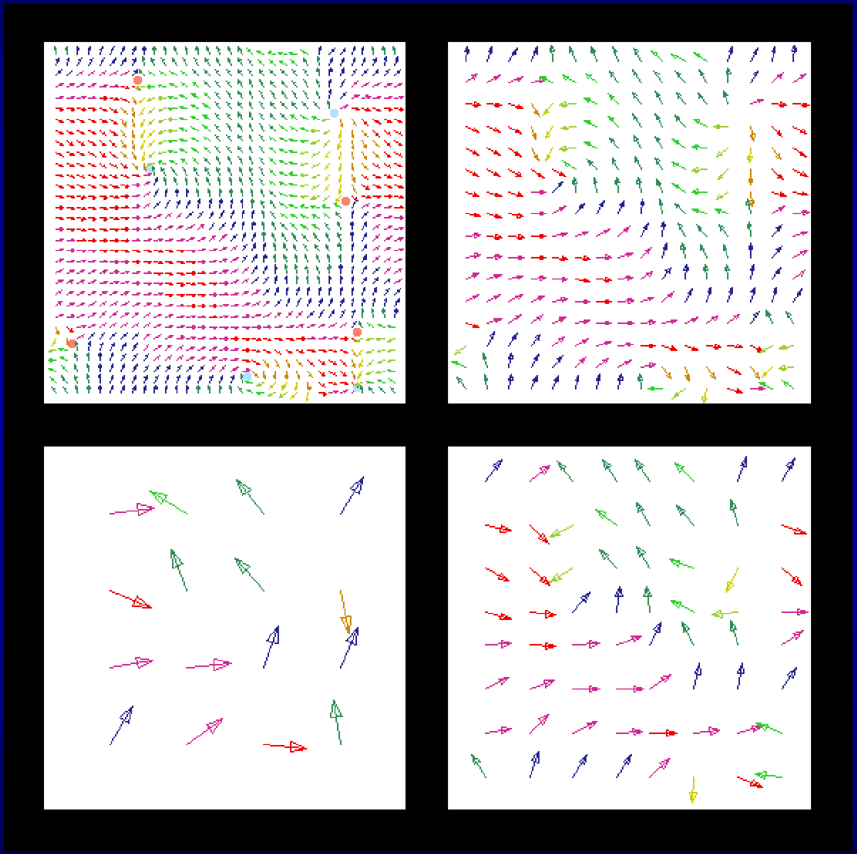
Emergent Behaviors

- More is different (Anderson) – Symmetry Breaking
- Patterns, Life, Brain, Colony, …
  Phases, Temperature, Heat, Friction, …
  Laws, Particles …
- Physics, Chemistry, Biology, Psychology, Social Sciences …

Renormalization Group

- Start with the full Hamiltonian
- Integrate out the high energy dynamics
- Obtain effective low energy Hamiltonian

E.g., "block spin" transformation



ccmp1.phys.metro-u.ac.jp/ccmp/simulation/xy.gif

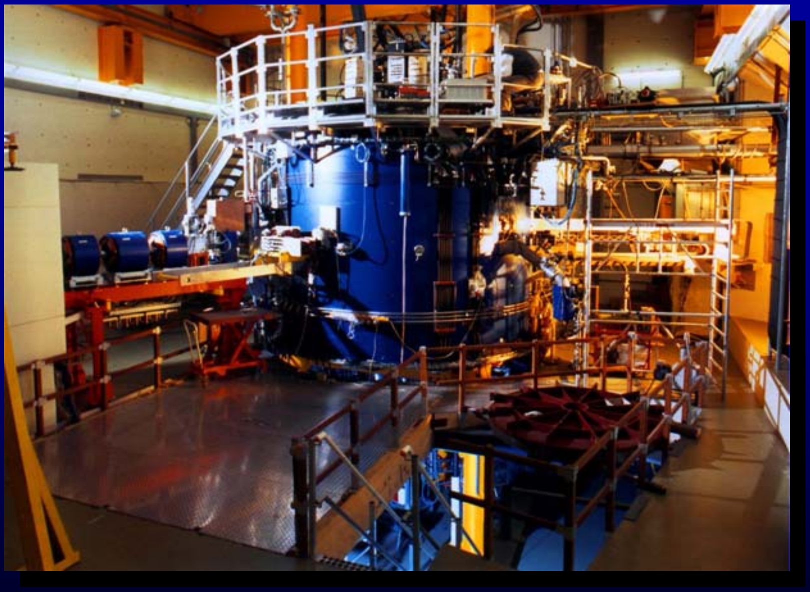
High Temperature Superconductivity

No problem in physics in our time has received more attention, and with less in the way of concrete success, than that of the behavior of the cuprate superconductors, whose superconductivity was discovered serendipitously, and whose properties, especially in the underdoped region, continue to surprise. As the high-Tc community has learned to its sorrow, deduction from microscopics has not explained, and probably cannot explain as a matter of principle, the wealth of crossover behavior discovered in the normal state of the underdoped systems, much less the remarkably high superconducting transition temperatures measured at optimal doping. Paradoxically high-Tc continues to be the most important problem in solid-state physics, and perhaps physics generally, because this very richness of behavior strongly suggests the presence of a fundamentally new and unprecedented kind of quantum emergence.

Laughlin and Pines, "The Theory of Everything," PNAS vol. 97, 28 (1999)

Applications of Superconductivity

- Magnetic Levitation Devices—Trains (Superconducting Coil)
- Magnetic Resonance Imaging (MRI)
- Power Lines
- Particle Accelerators
- Motors
- SQUIDs

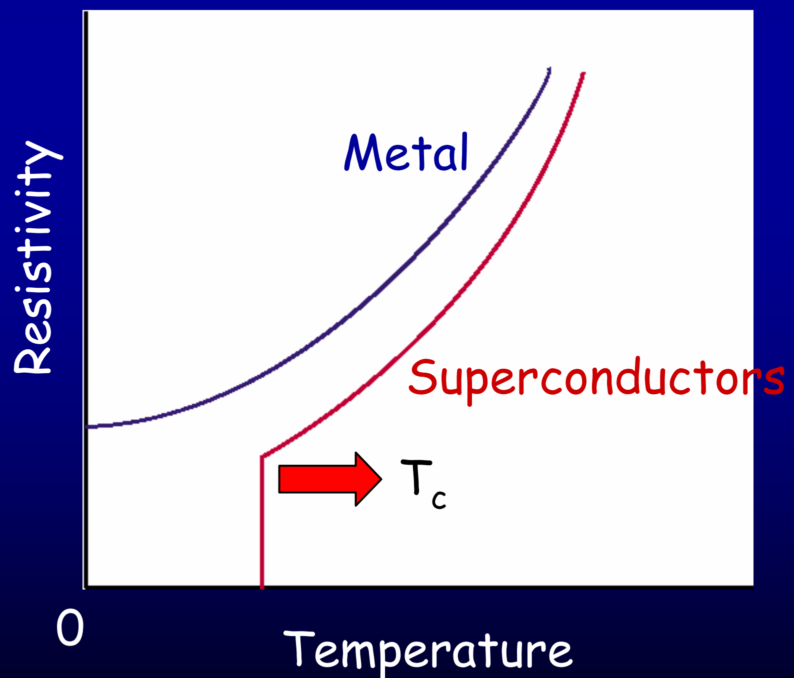


What is Superconductivity?

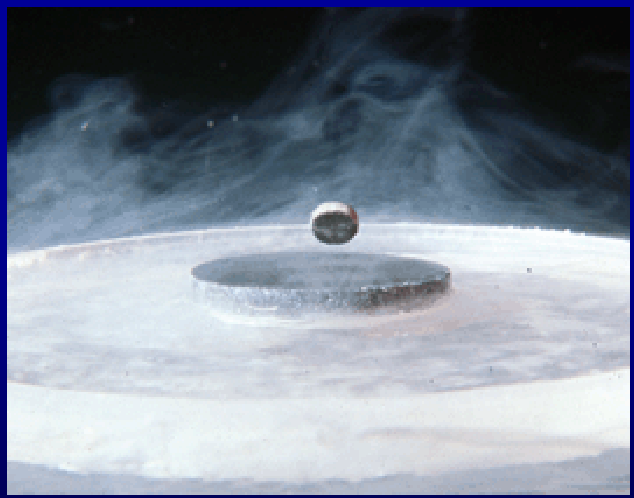
1911 K. Onnes Superconductivity in Hg

1933 Meissner effect

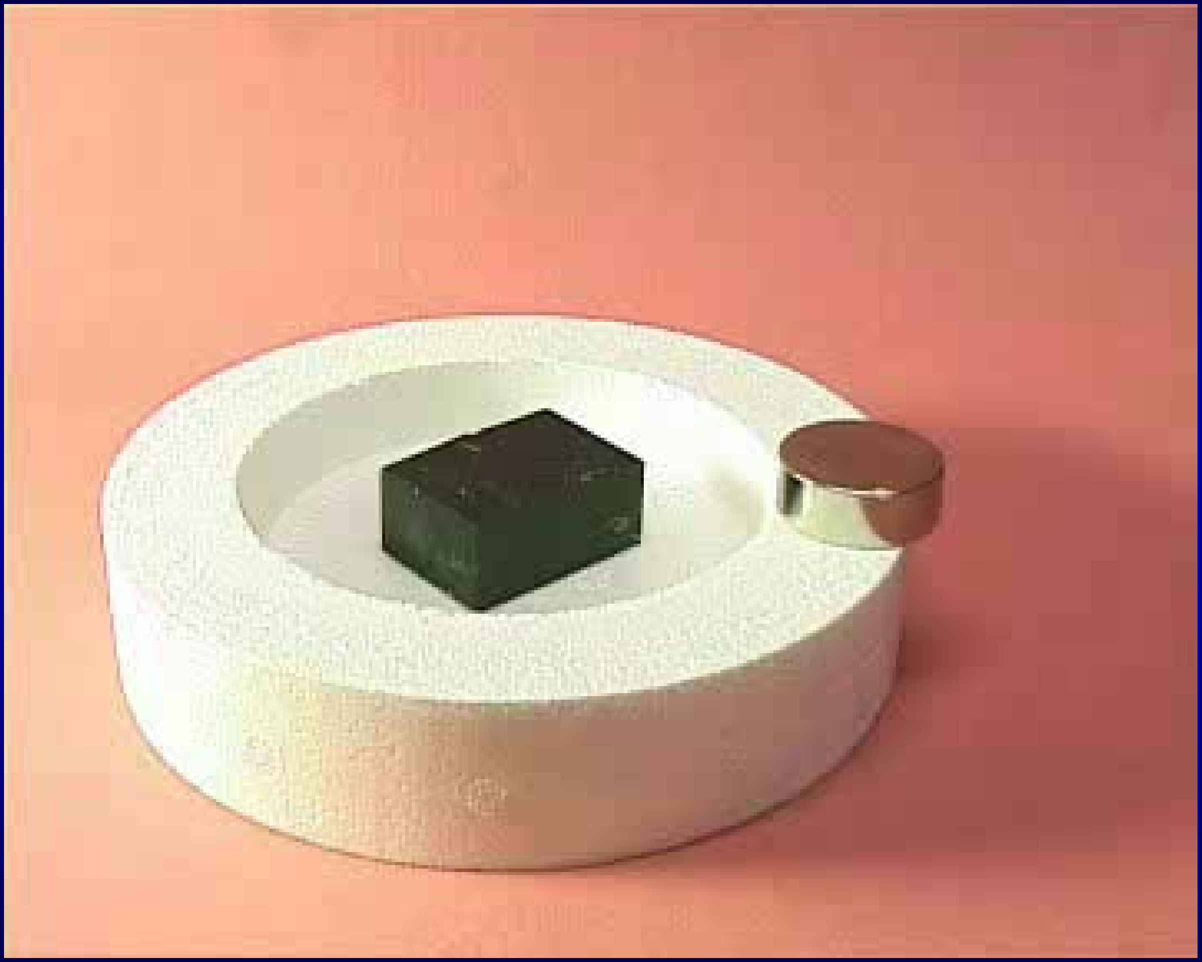
RESISTANCELESS CONDUCTION



MEISSNER EFFECT:
Perfect diamagnetism

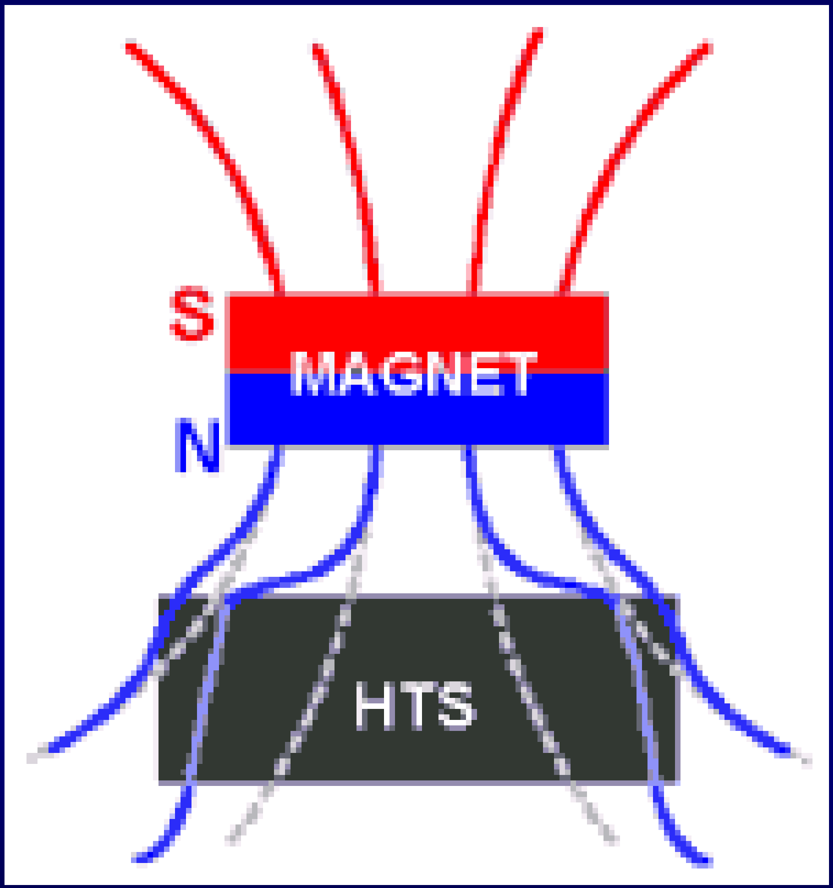


Meissner Effect



http://www.fys.uio.no/super/levitation/

Meissner Effect



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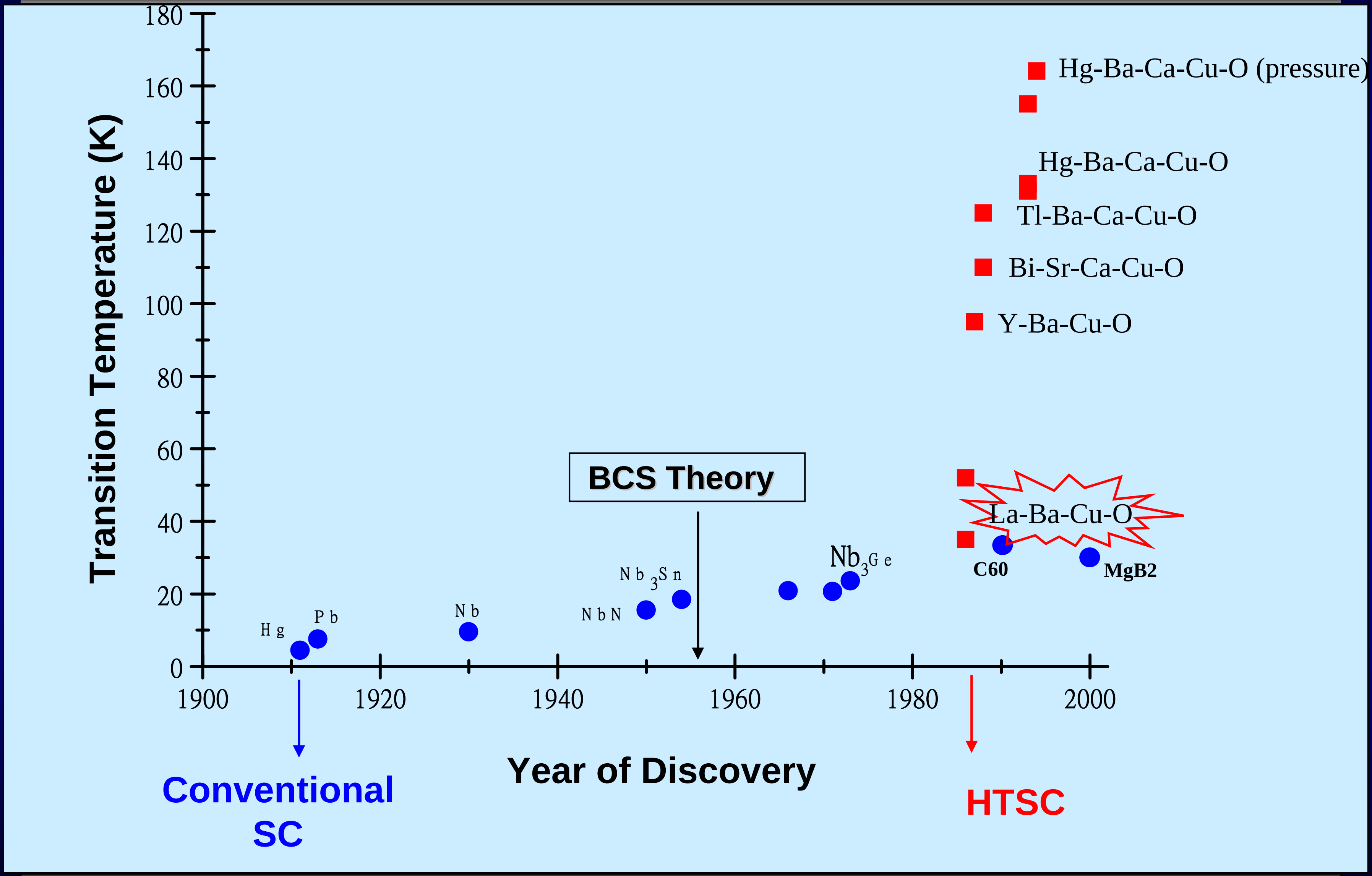
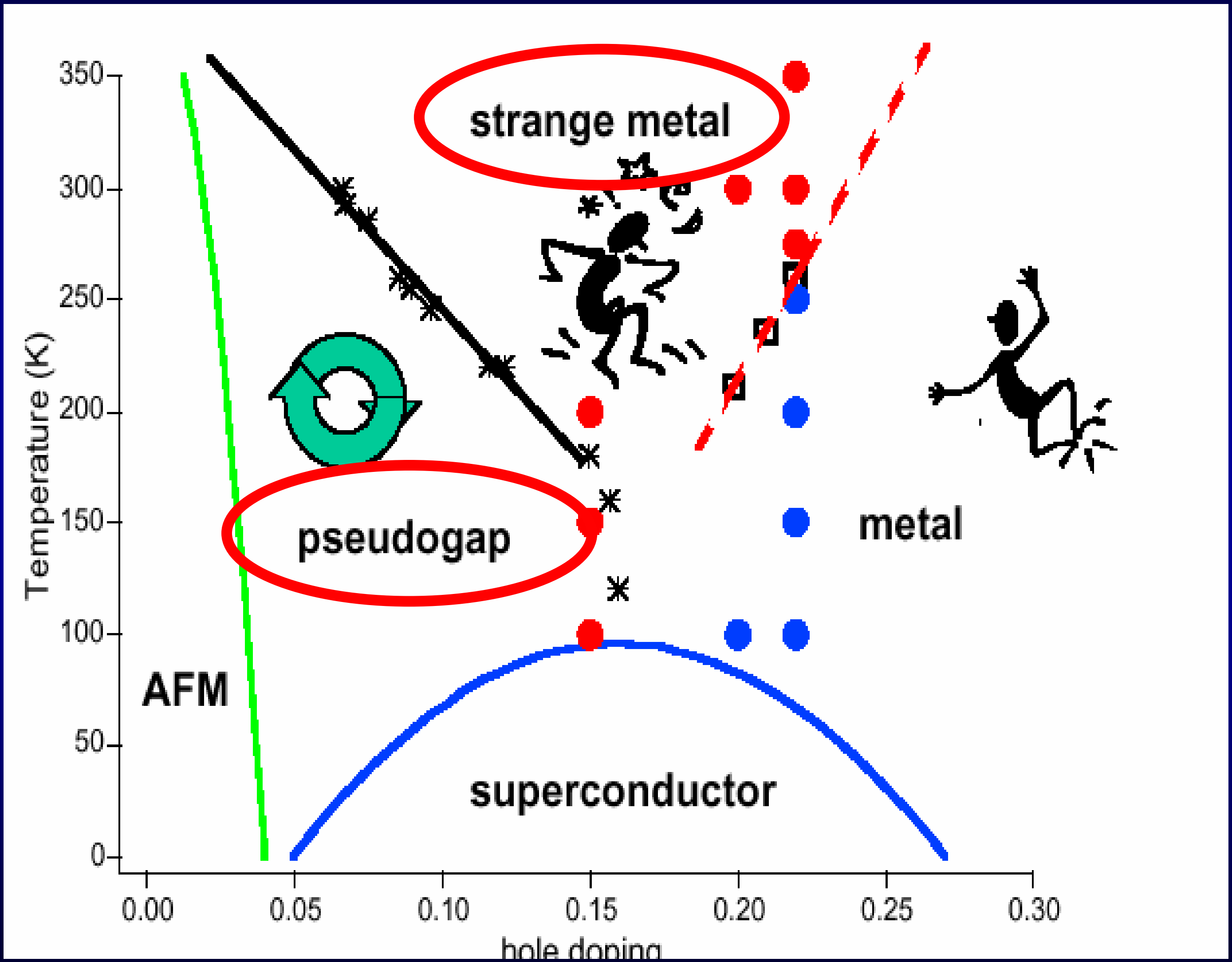
High Temperature Superconductivity



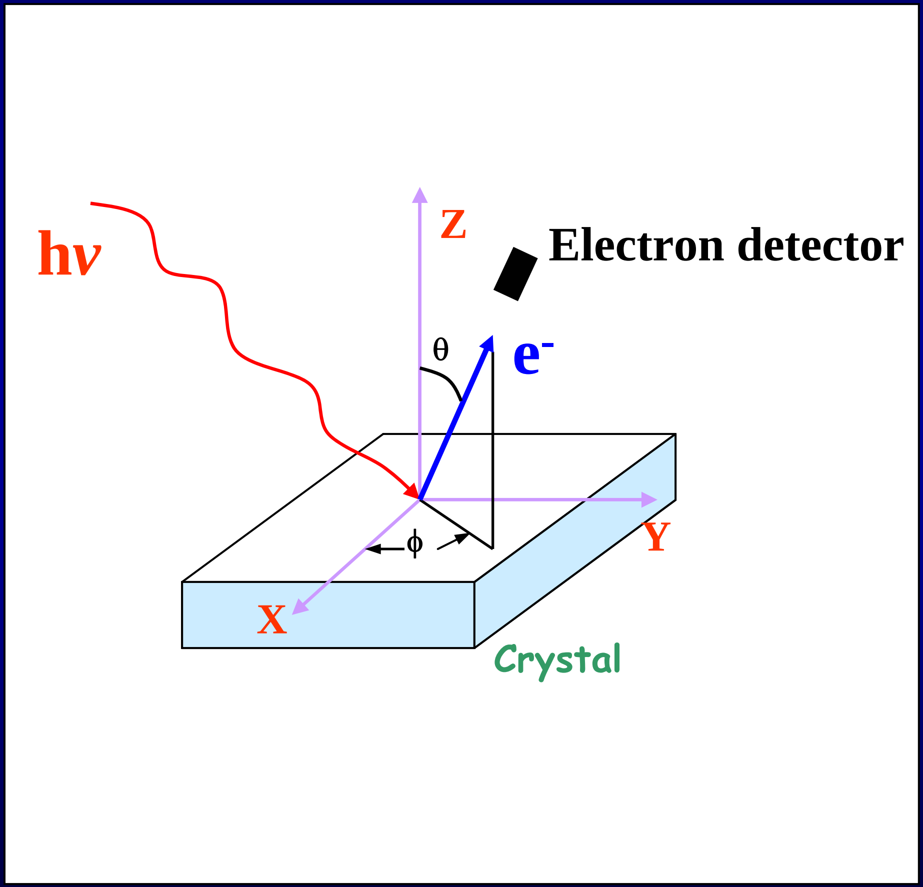
High Tc is Complicated - Work in Progress

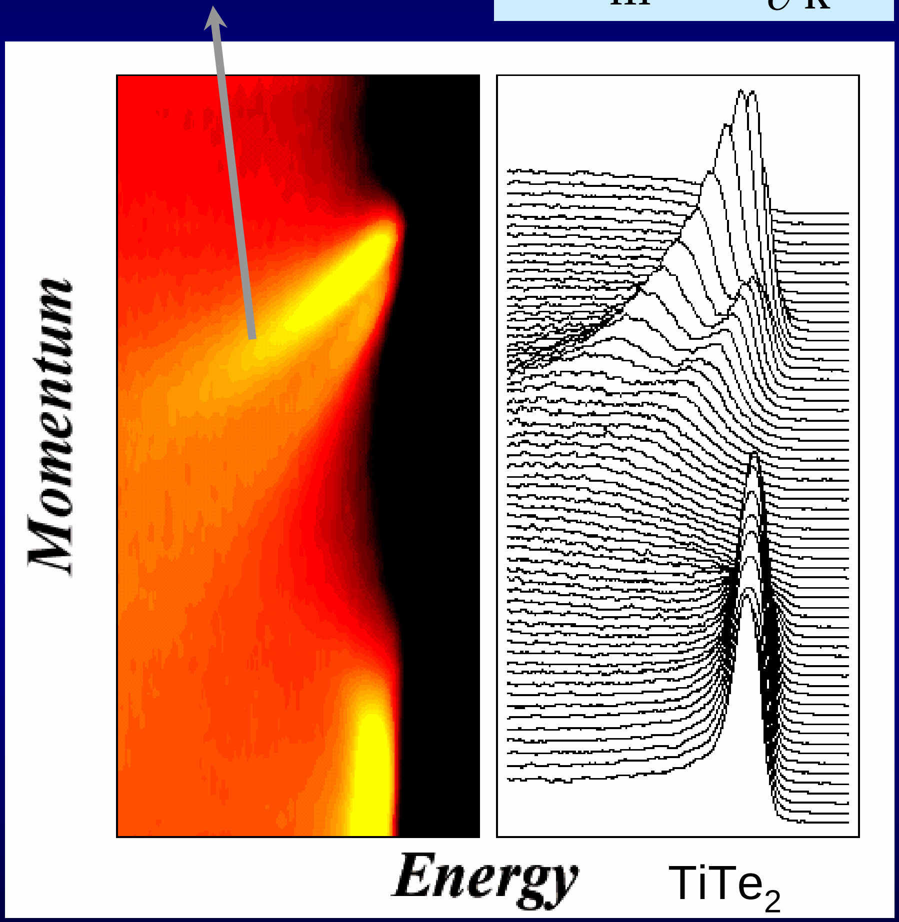


What can ARPES do?

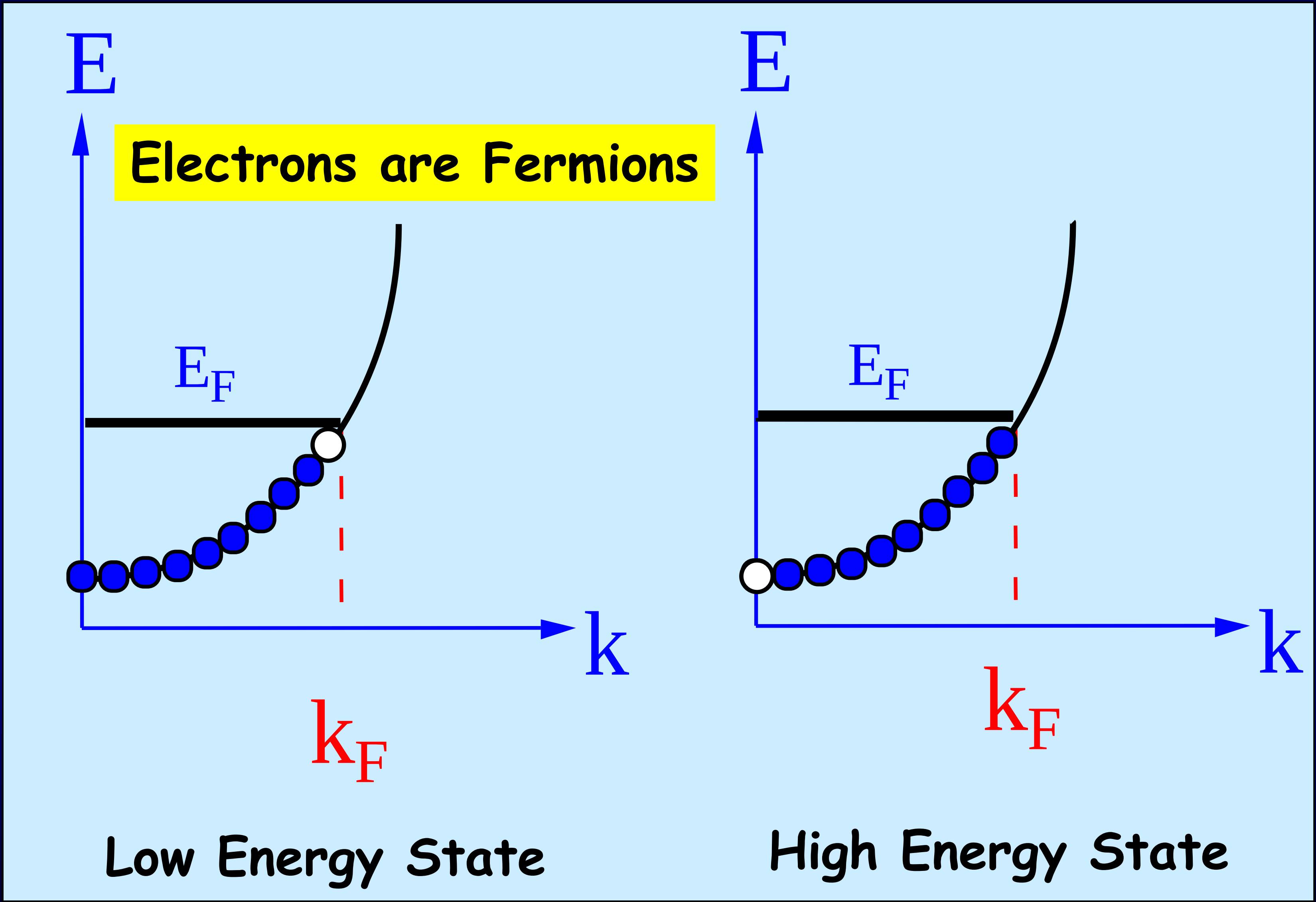
Slope = Velocity

$$V \sim \frac{1}{m^*} \sim \frac{\partial\, \omega(k)}{\partial\, k}$$



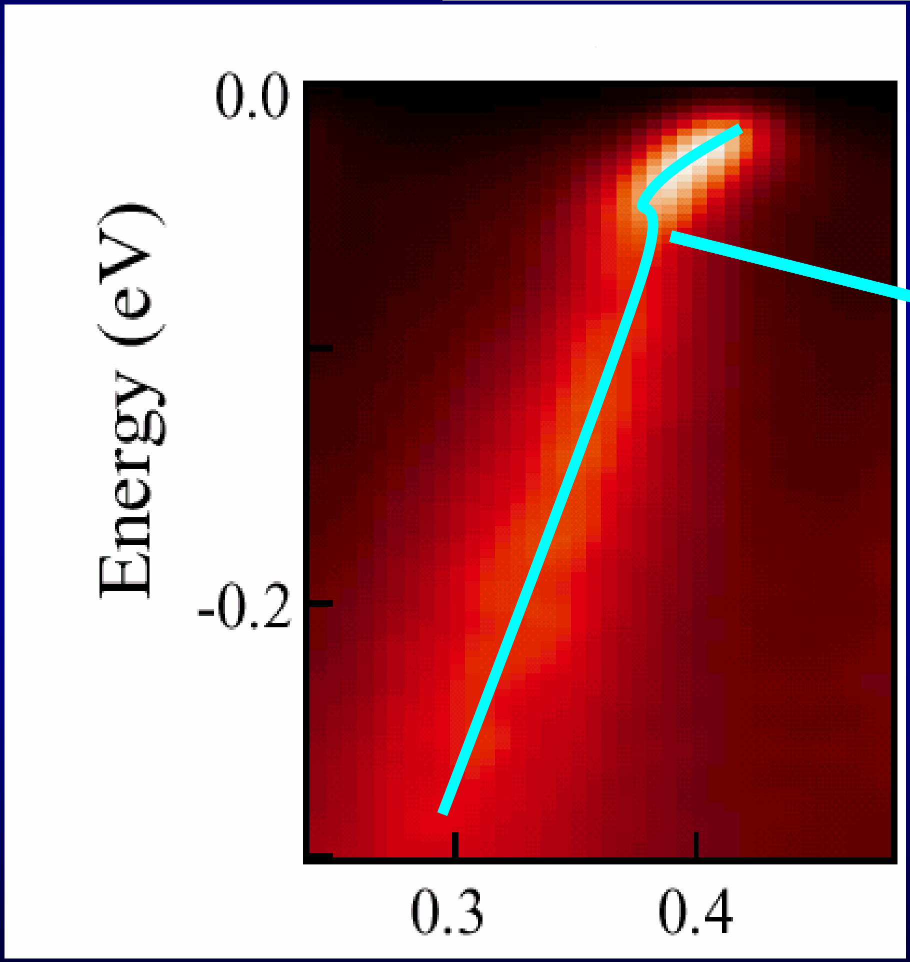


Statistics, High and Low Energy



ARPES, High and Low Energy

$Bi_2Sr_2CaCu_2O_8$ (Bi2212)



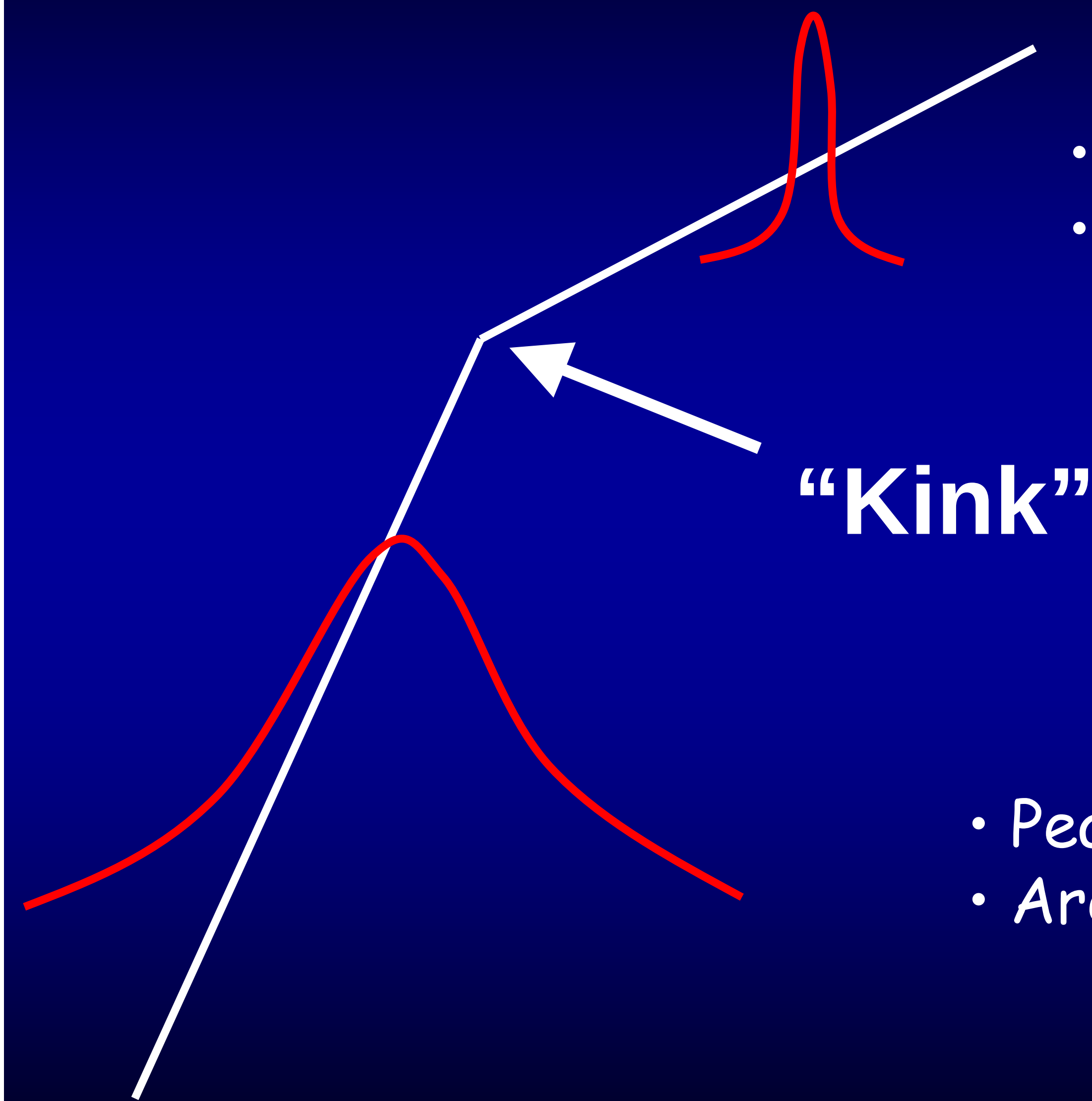
Momentum

Why does the velocity change suddenly??

"Kink"

$$V \sim \frac{1}{m^*} \sim \frac{\partial E(k)}{\partial k}$$

Qualitative Understanding



- Peak is sharp – Stable
- Area Under Curve << 1
  (Many body state)

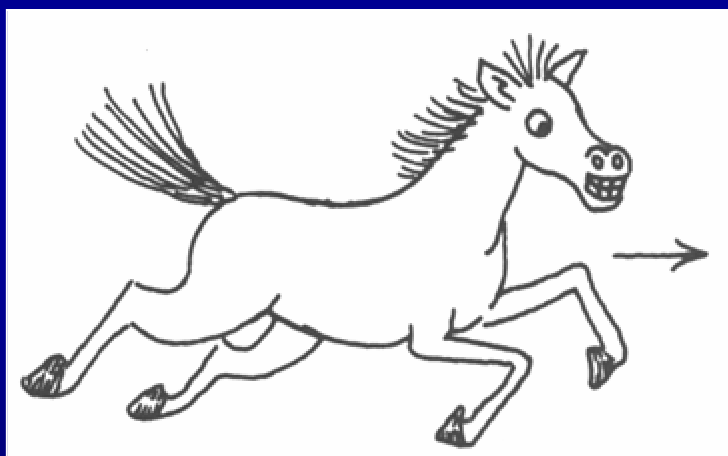
- Peak is broad – Unstable
- Area under curve ~ 1
  (Electron like state)

Qualitative Understanding

Renormalization : Emergence of Heavy Electron

Landau '56
Mattuck '67

Bare Electron
Free Electron
Non-interacting Horse



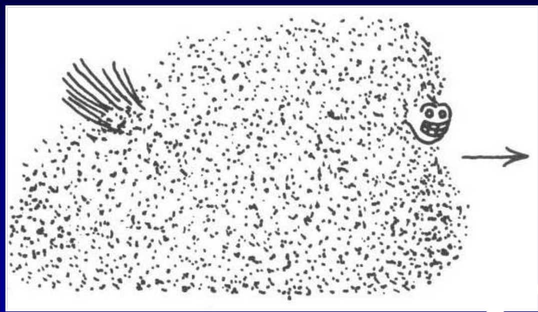
Real Electron
Heavy Electron
Bare Electron + All Others

Electron

Feynman Diagram

Real Excitation = Electron + **<u>Other Stuff</u>**

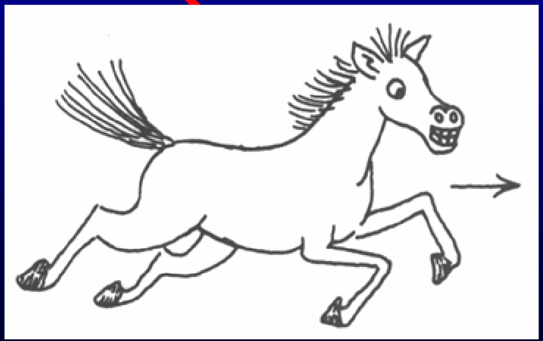
Qualitative Understanding



- Peak is sharp – Stable
- Area Under Curve << 1
  (Many body state)

Eigenstates of Low E Effecitve Hamiltonian

ARPES measures bare electron, i.e. bare horse, one at a time.



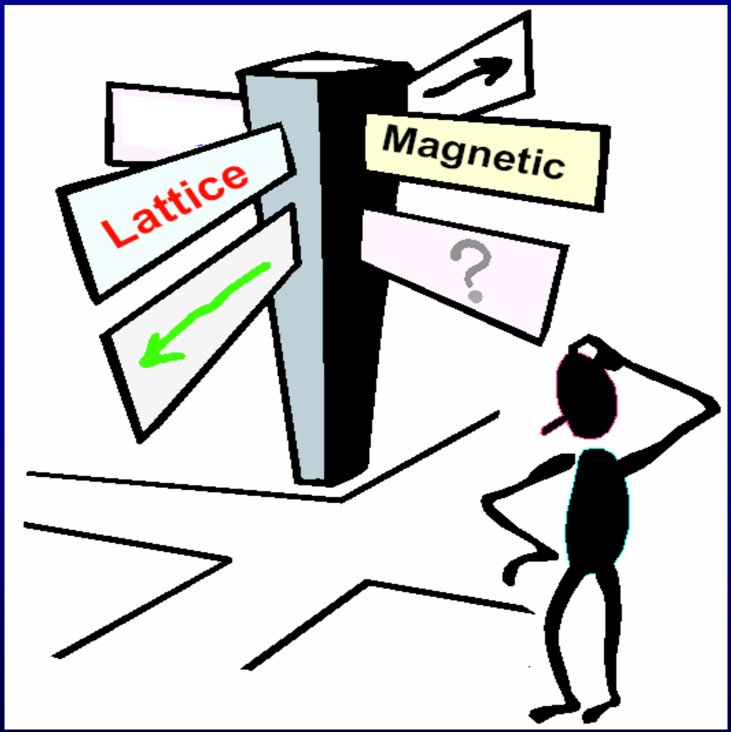
- Peak is broad – Unstable
- Area under curve ~ 1
  (Electron like state)

Eigenstates of High E Hamiltonian

Why care about Kink?

Renormalization, Emergence

Kink = Interaction
Interaction mediates SC



Two Kinks

Low E Kink = Lattice
(~ 70 meV)

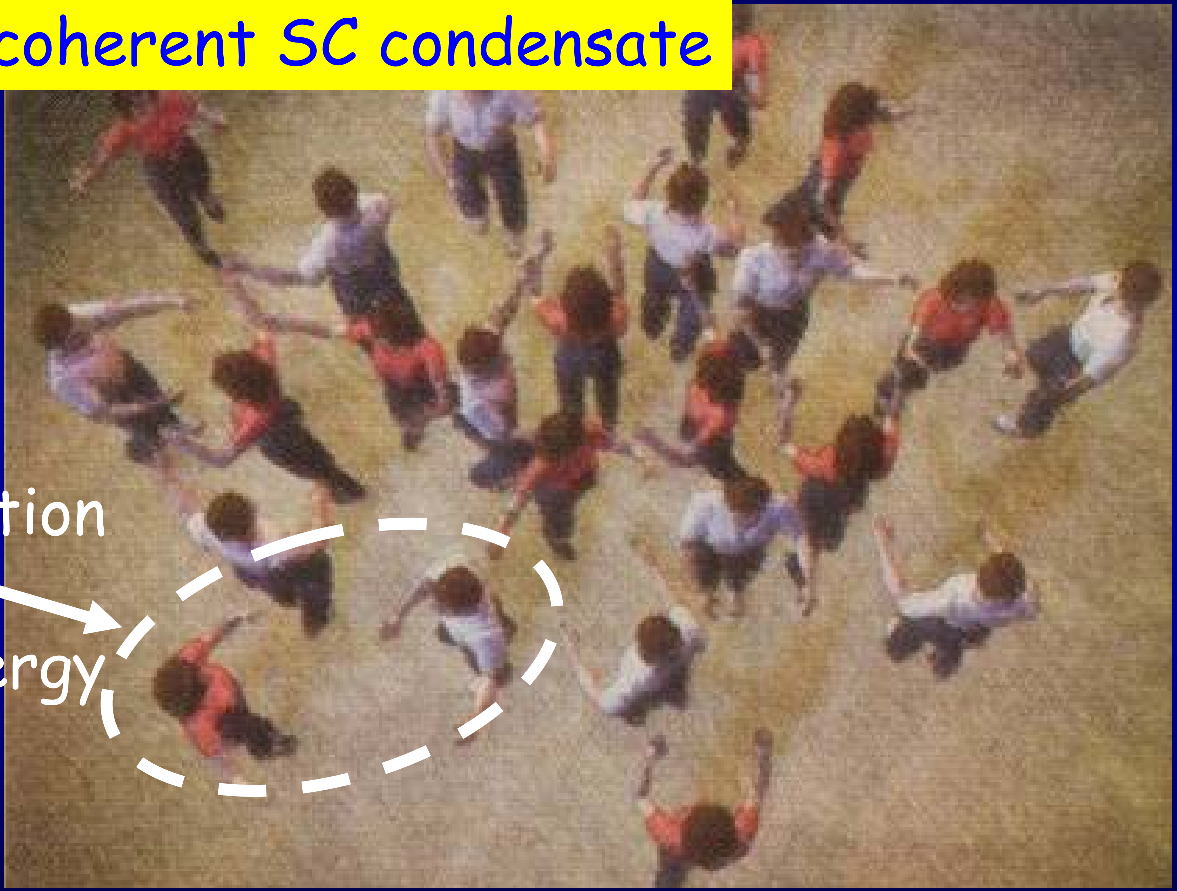
GHG et al.,
Nature 430, 187 (04)
GHG et al.,
PRL 97, 227001 (06)

High E Kink = Spin
(~ 600 meV)

Graf, GHG et al.,
cond-mat/0607319

SC is dance of electron pairs

All to the same tune!
Phase coherent SC condensate



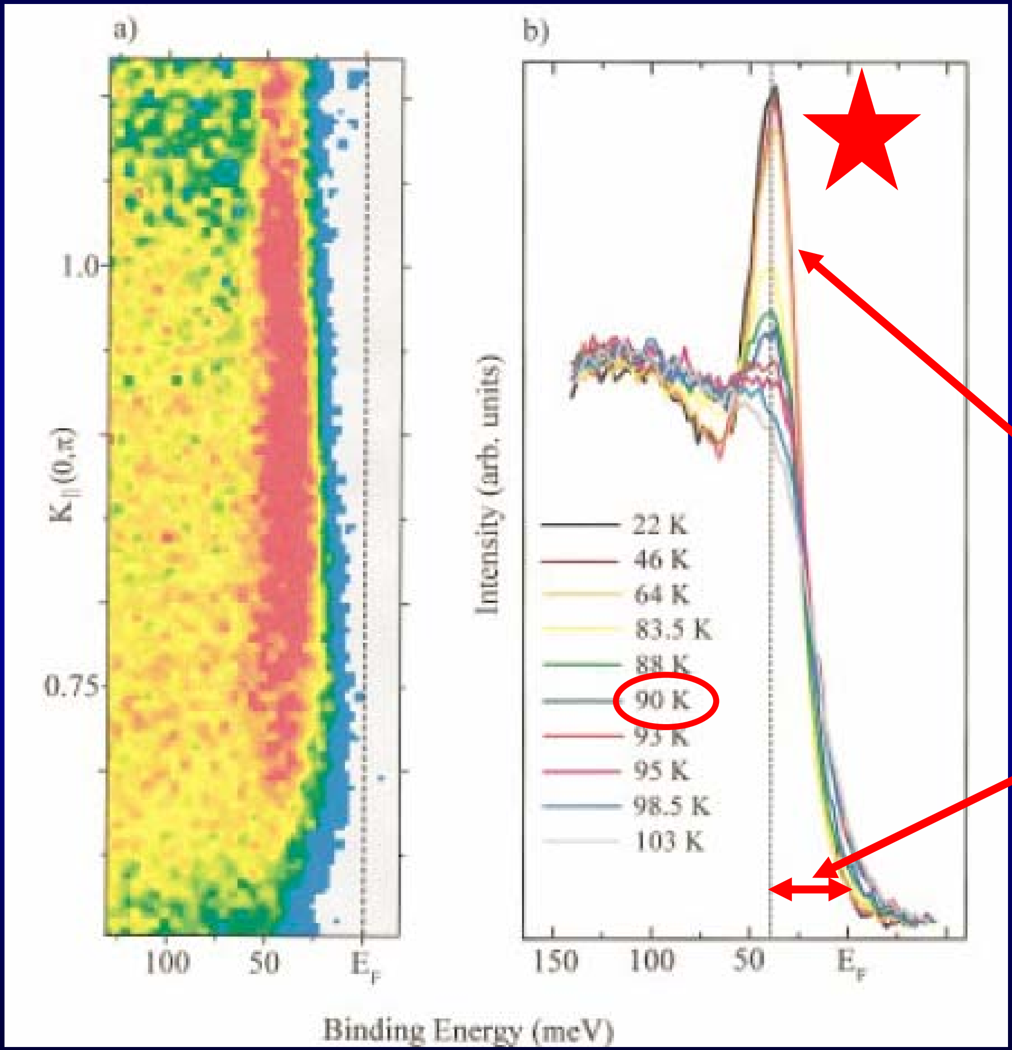
Bound Pair
by Interaction

Binding energy
= SC gap

Signature of this emergence?

Phys. Today, March '04

Signature of SC Condensate

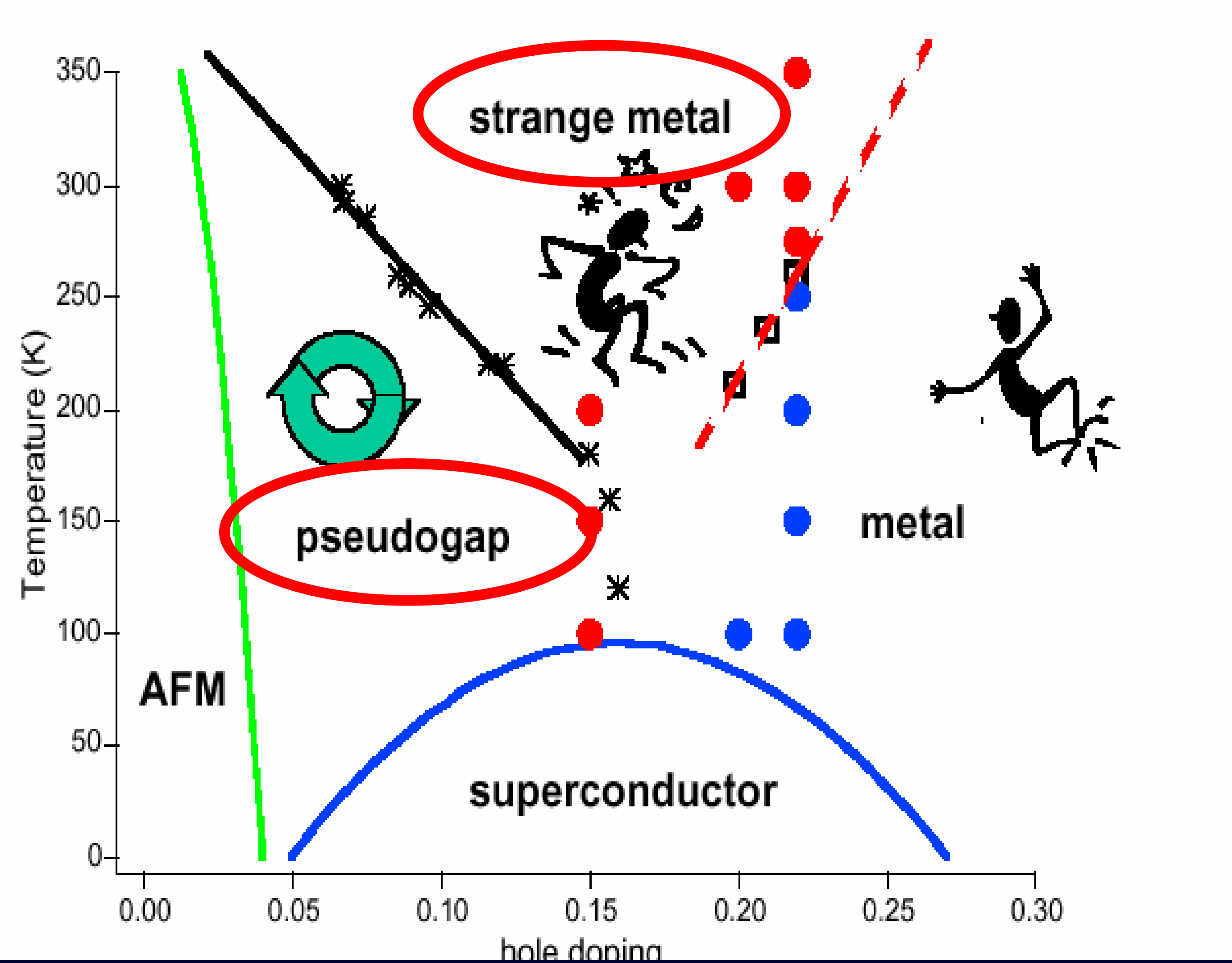


Intensity
~ SC Condensate Size

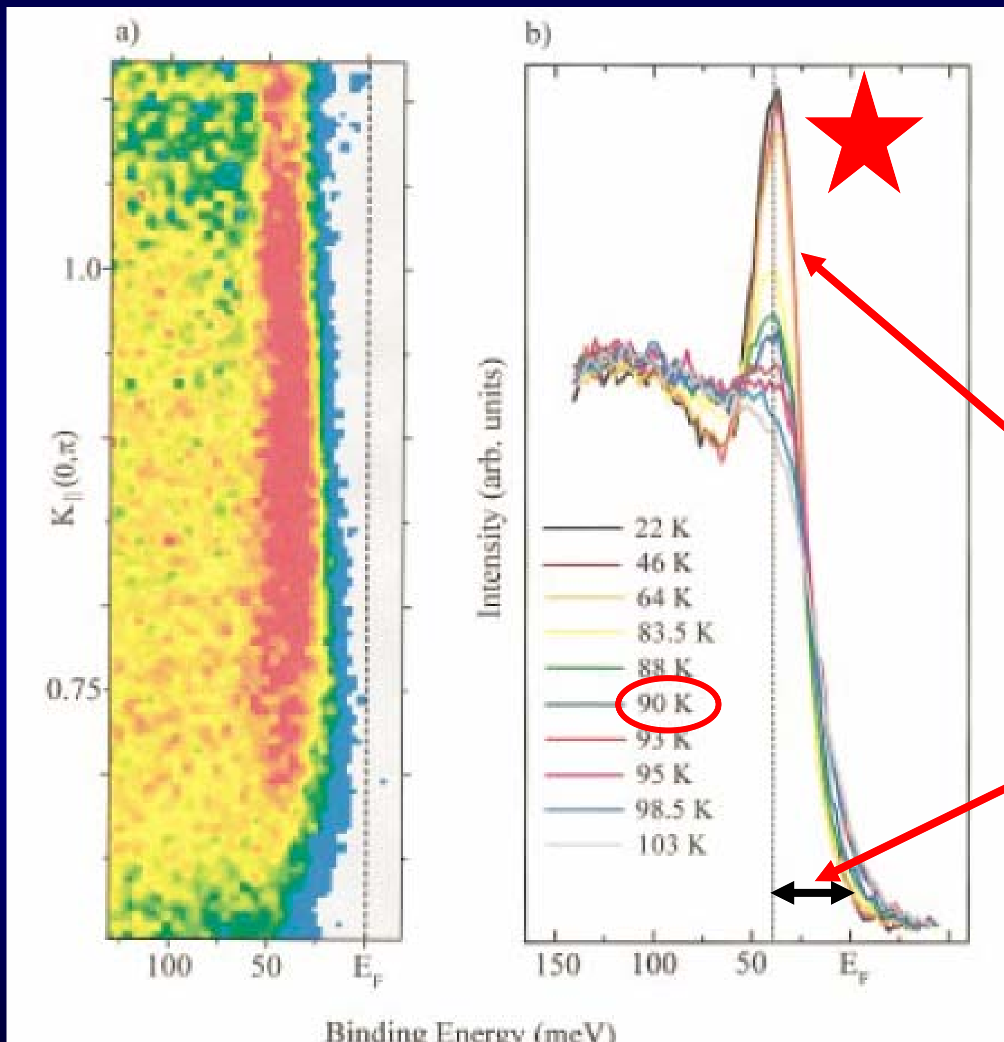
Pair Binding Energy
SC Gap

Fedorov et al.
PRL '99

High Tc is Complicated - Work in Progress



Signature of SC Condensate



The real mystery is normal state!

Intensity
~ SC Condensate Size

Pair Binding Energy
SC Gap

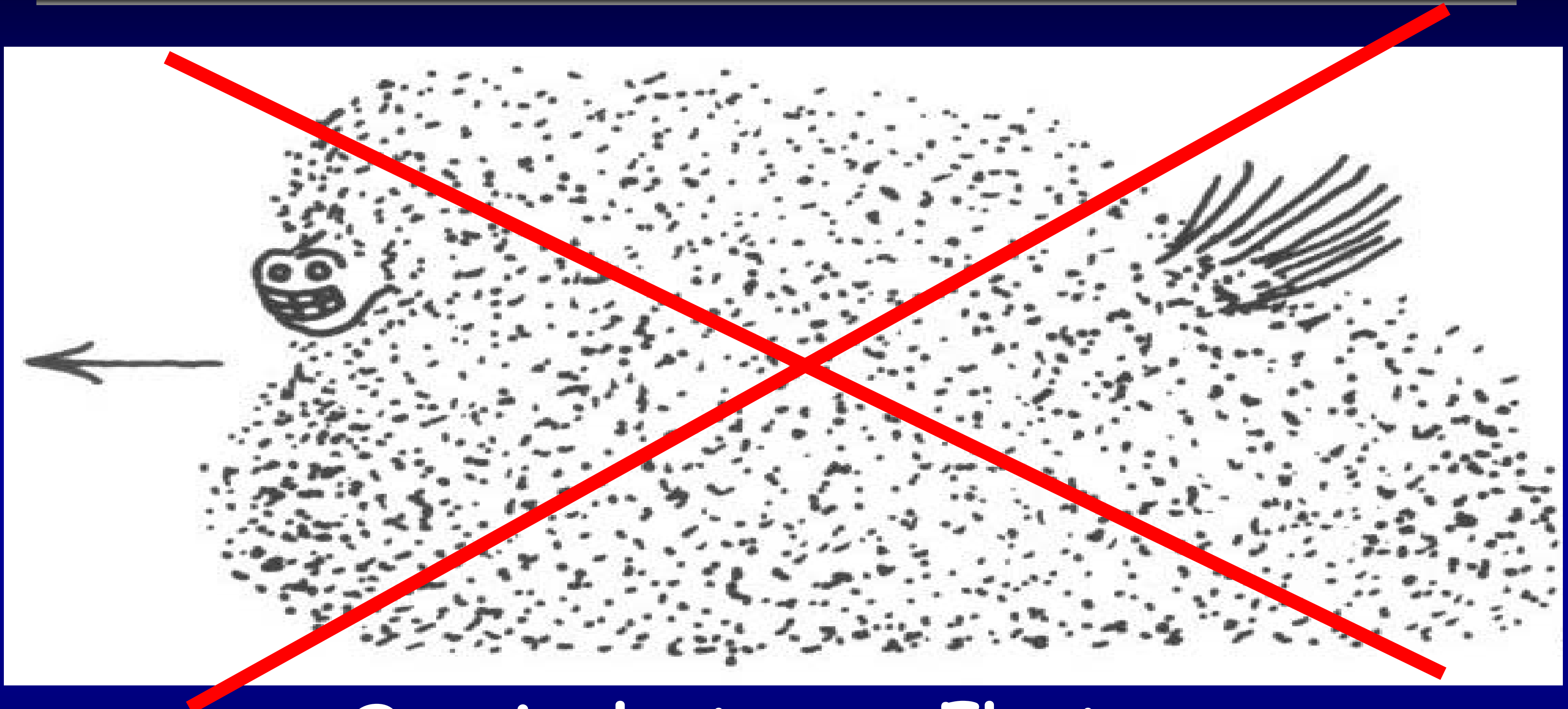
Fedorov et al.
PRL '99

Another Emergent Behavior

Electron Fractionalization

High Tc
Low-Dimensional Metals

Fractionalization?

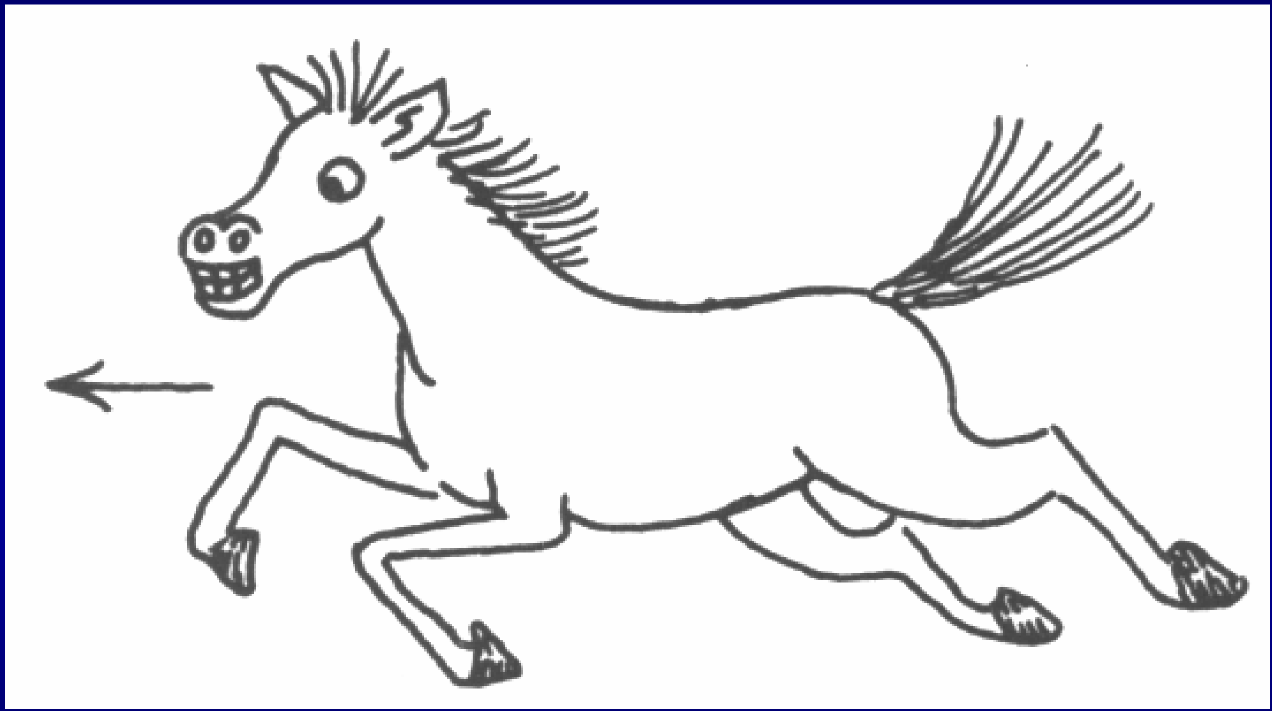


Quasi-electron ≈ Electron

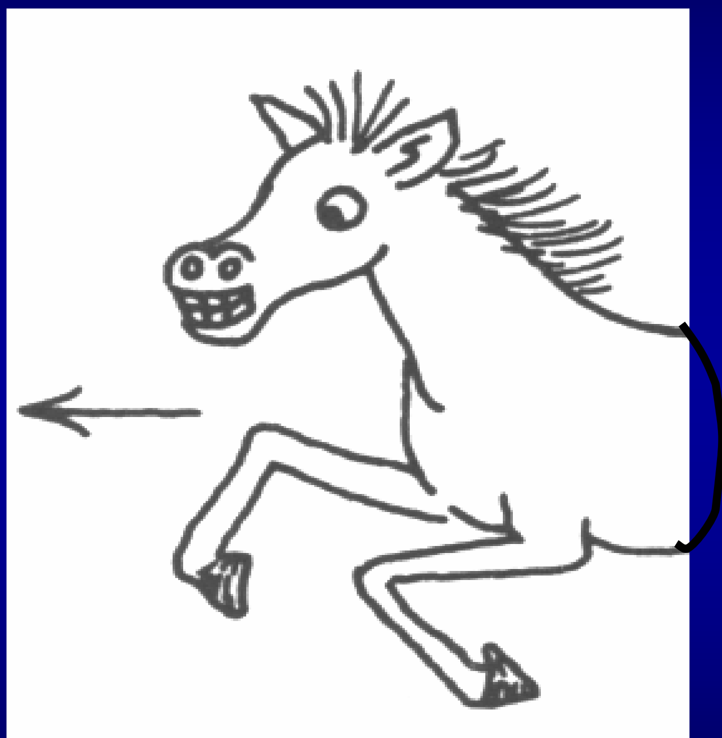
Opposite of Fractionalization

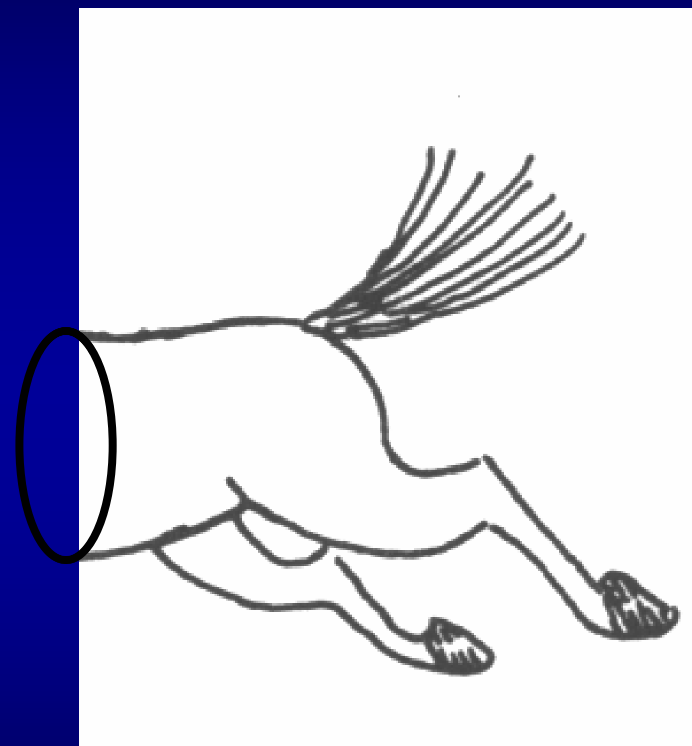
Fermi Liquid

Fractionalization?

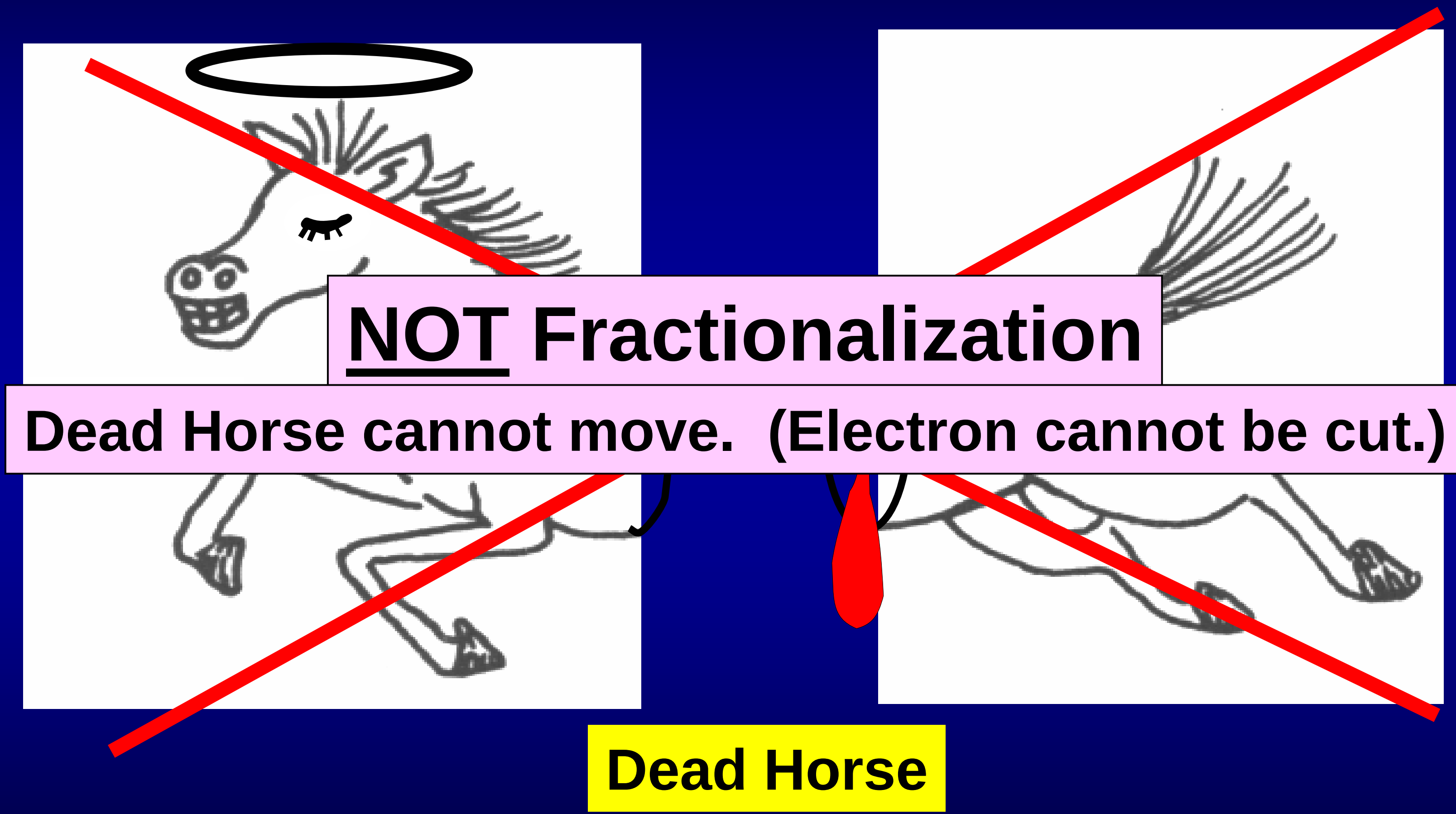


Fractionalization?

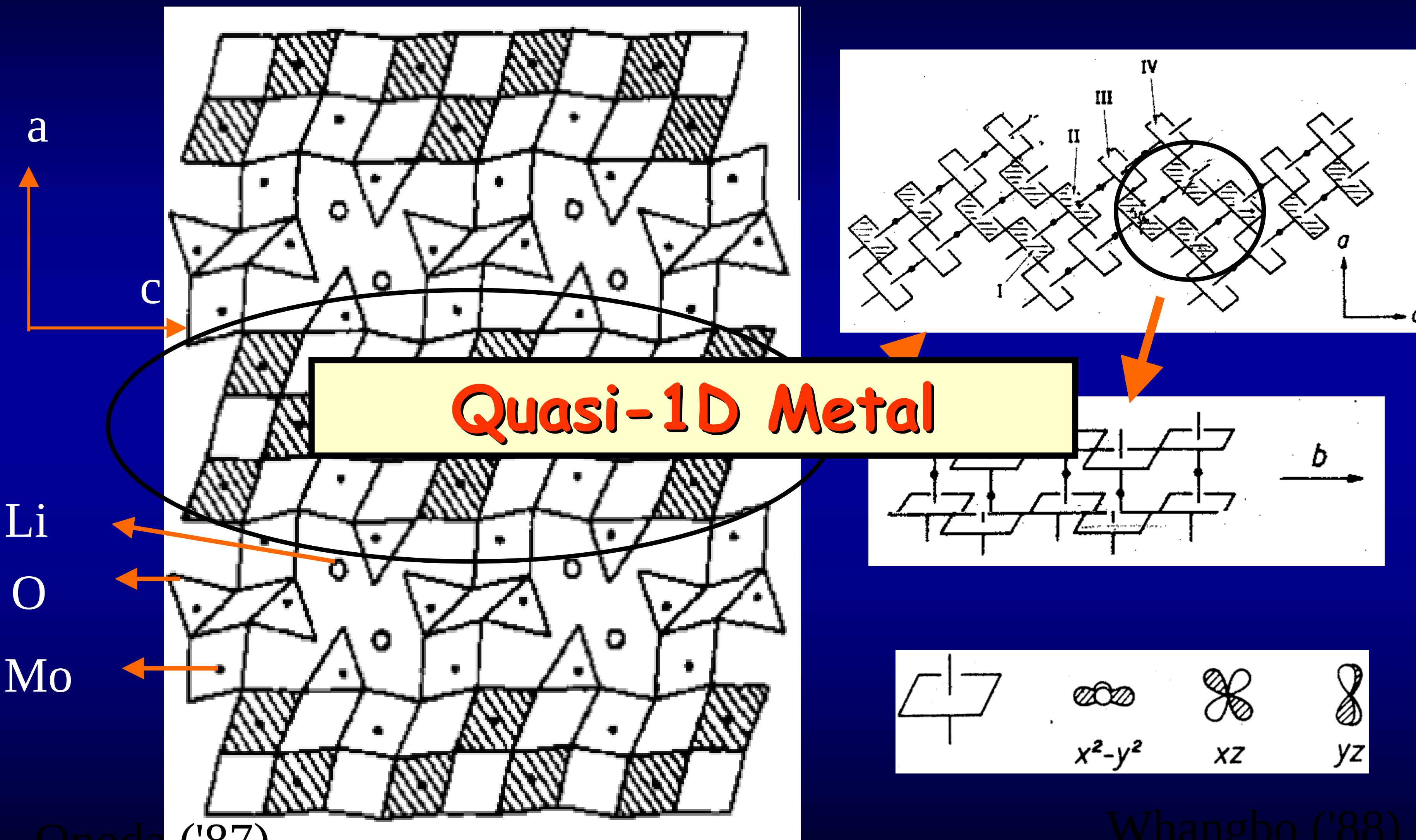




Fractionalization?



Low-D Metal Example – Li Purple Bronze

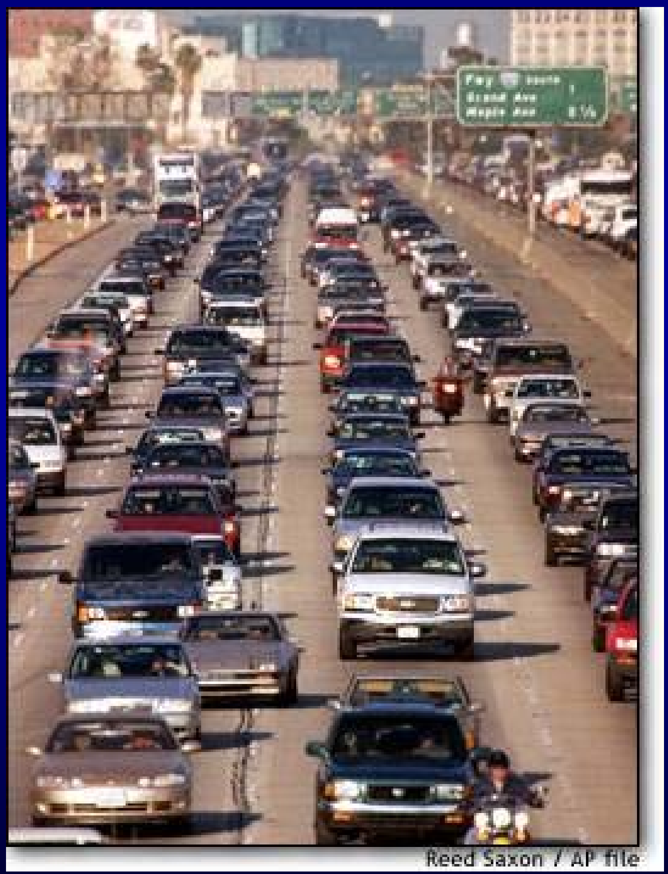


Onoda ('87)

Whangbo ('88)

Dimensionality Matters

New State of Matter beyond Landau Fermi Liquid



No individual particle motion, but only collective density wave motion

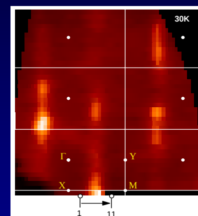
Quantum world → Charge and Spin wave

Charge and Spin propagate separately due to different charge-charge and spin-spin interaction

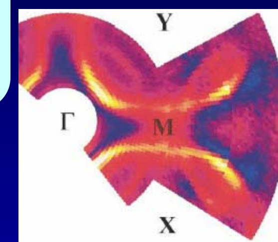
Low Dimensional Metals

“Strangeness”

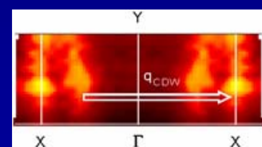
$Li_{0.9}Mo_6O_{17}$
(Li Purple Bronze)



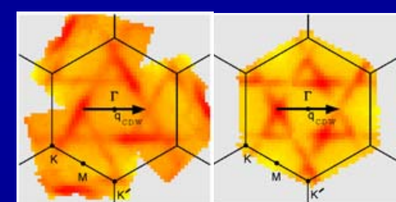
HTSC cuprates



$K_{0.3}MoO_3$
(K Blue Bronze)

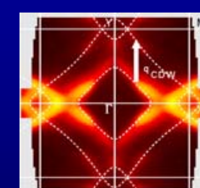


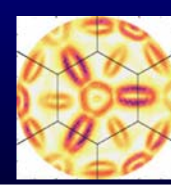
AMo_6O_{17} (A=Na,K)
(Purple Bronze)



Fermi Surface

$SmTe_3$

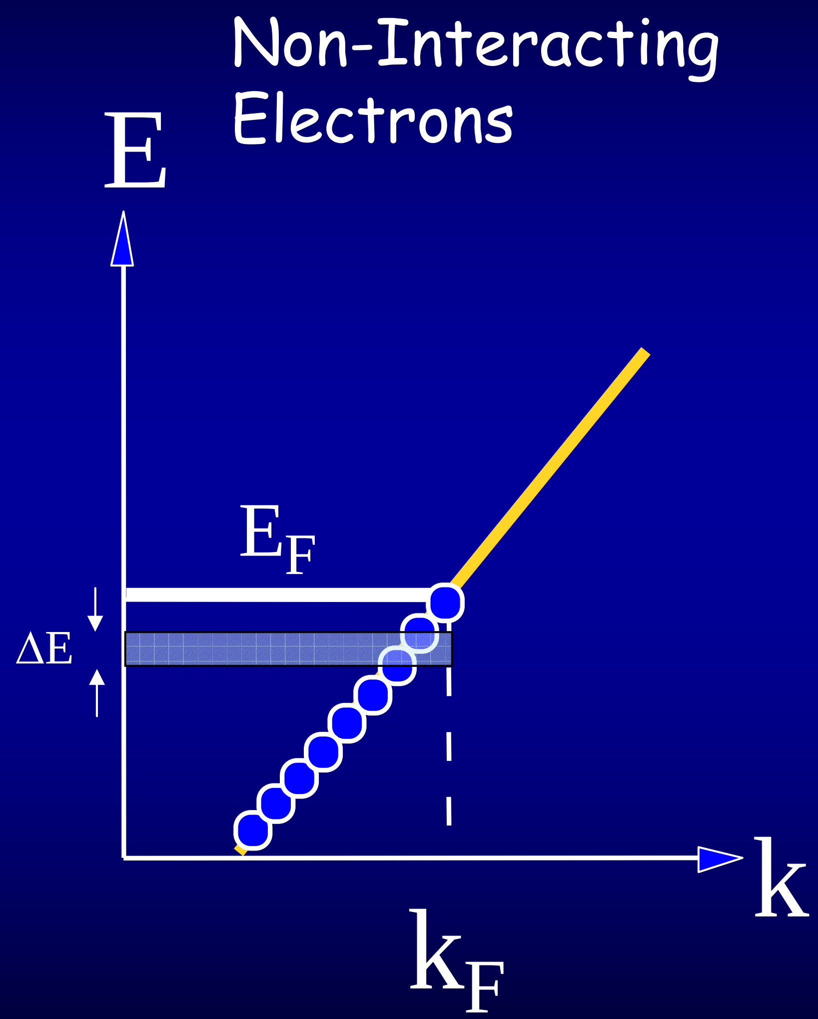




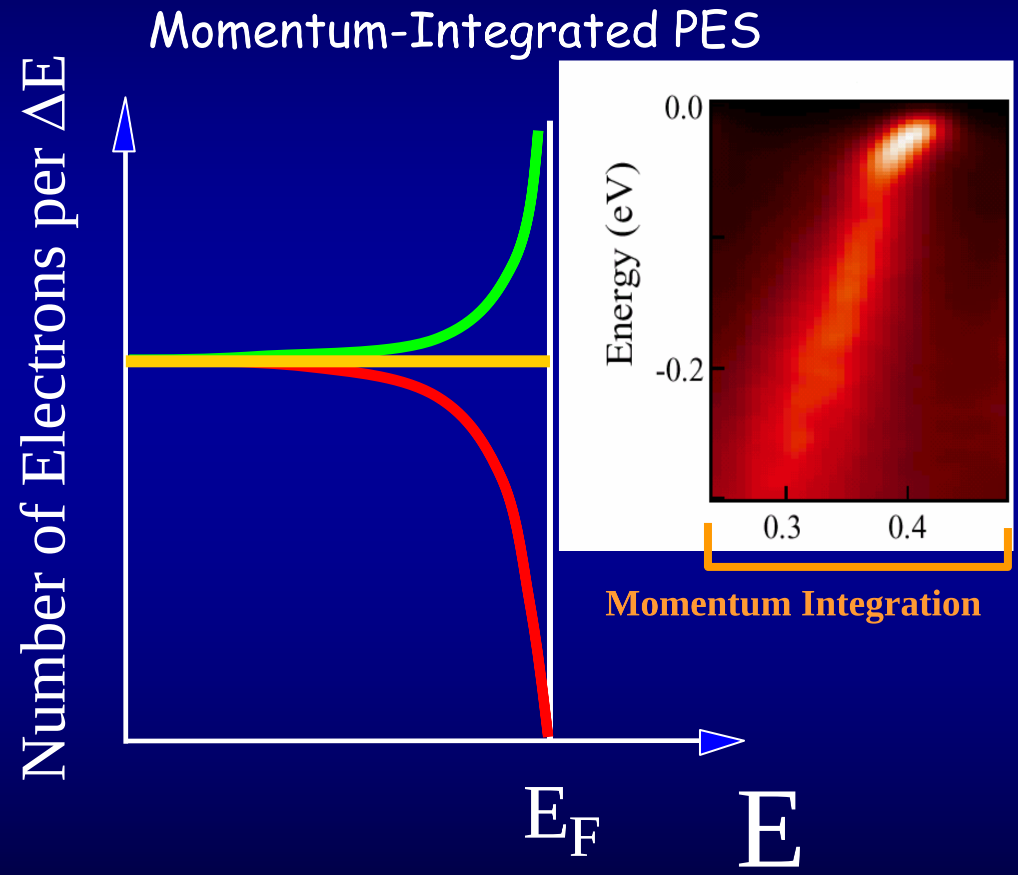
$TiTe_2$

1 Dimensionality of E_F Electronic Structure 2

Signature of Electron Fractionalization

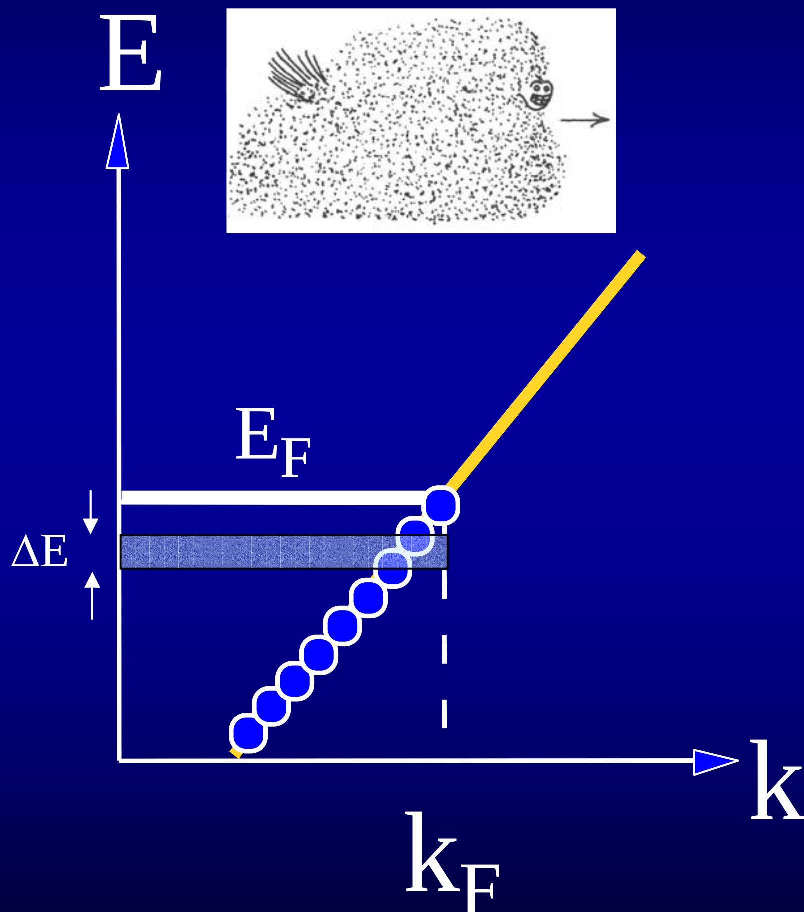


Density of States (DOS)



Signature of Electron Fractionalization

Fermi Liquid



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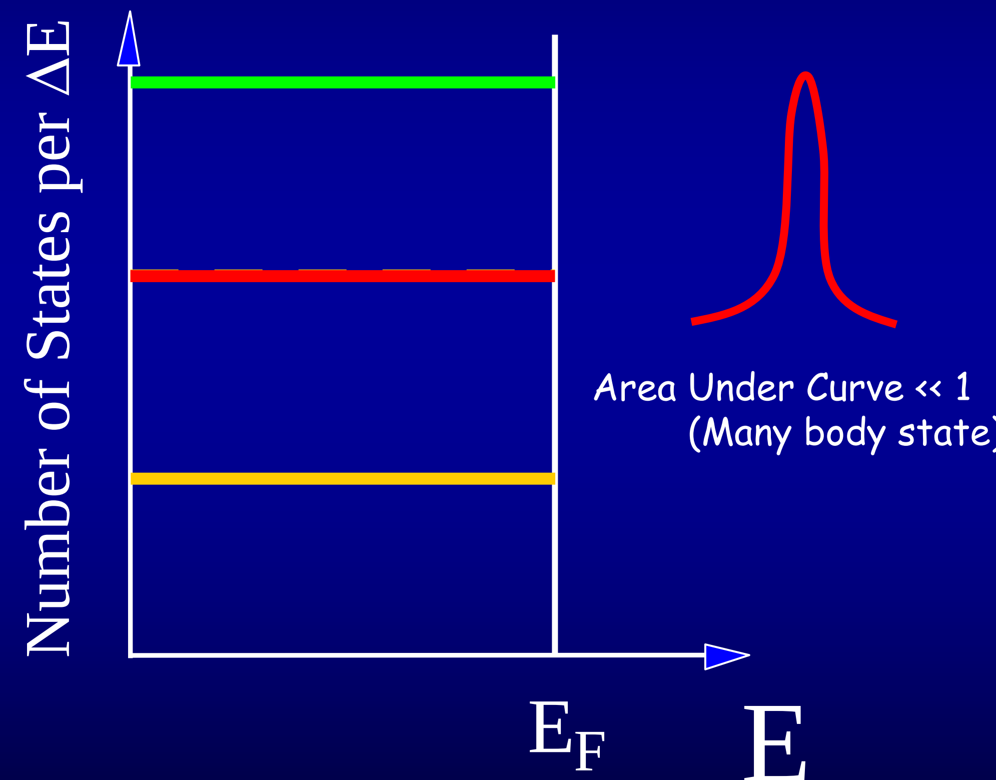
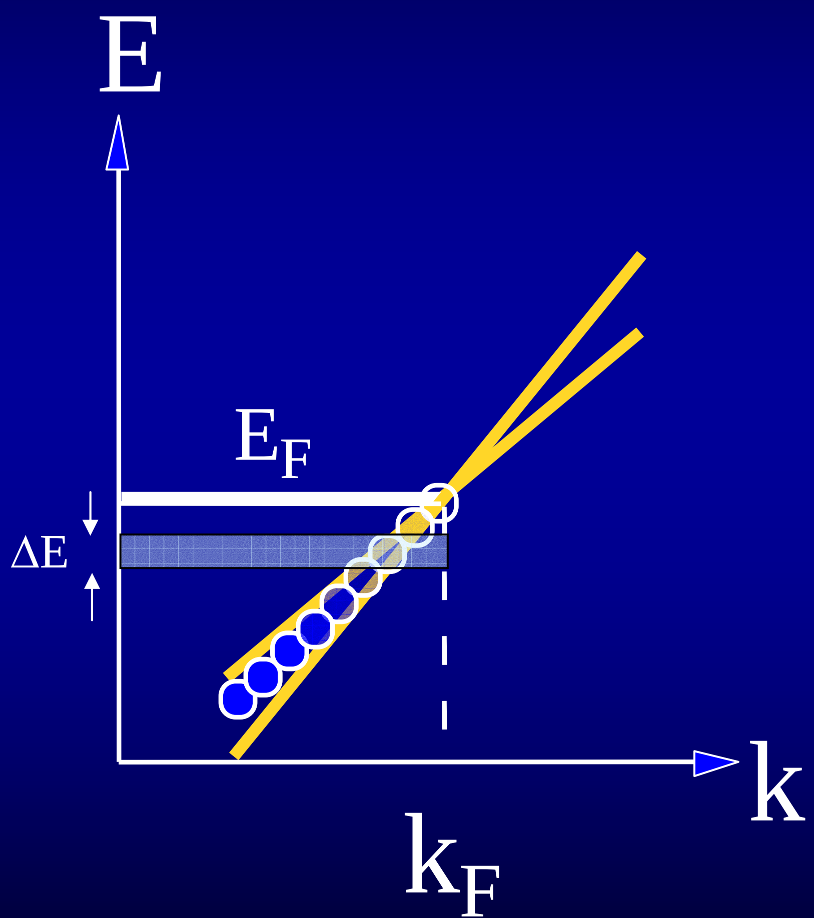


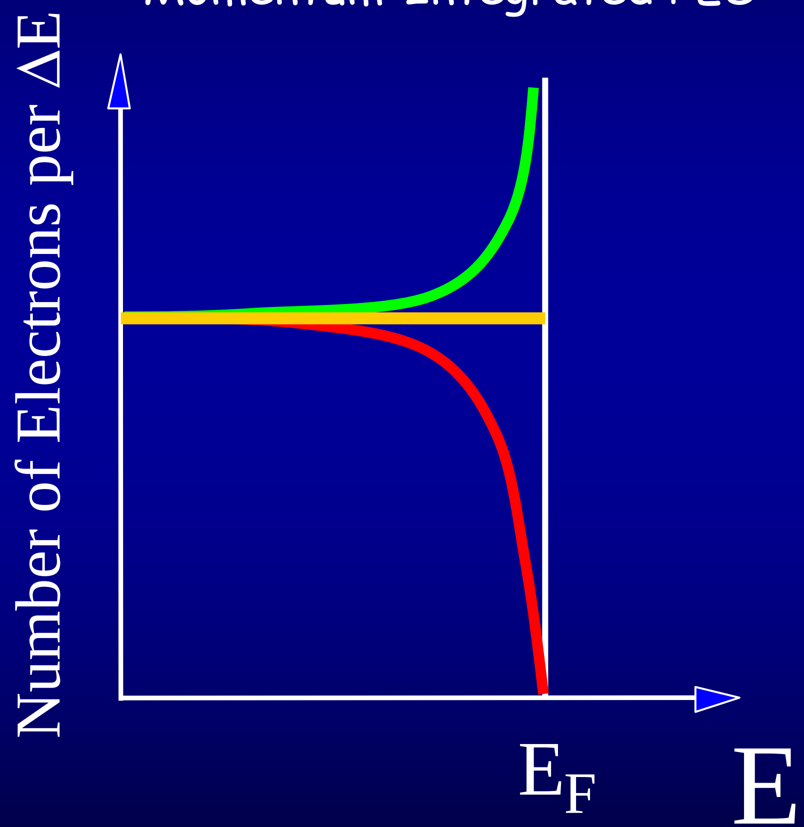
Signature of Electron Fractionalization

Fractionalization



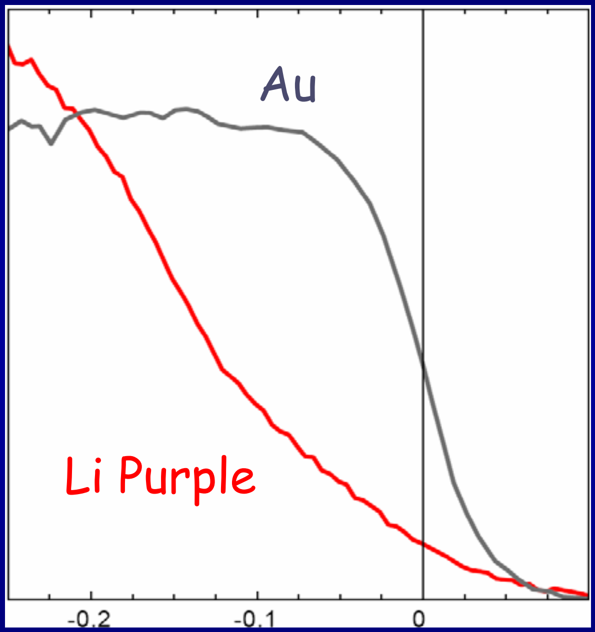
Density of States (DOS)

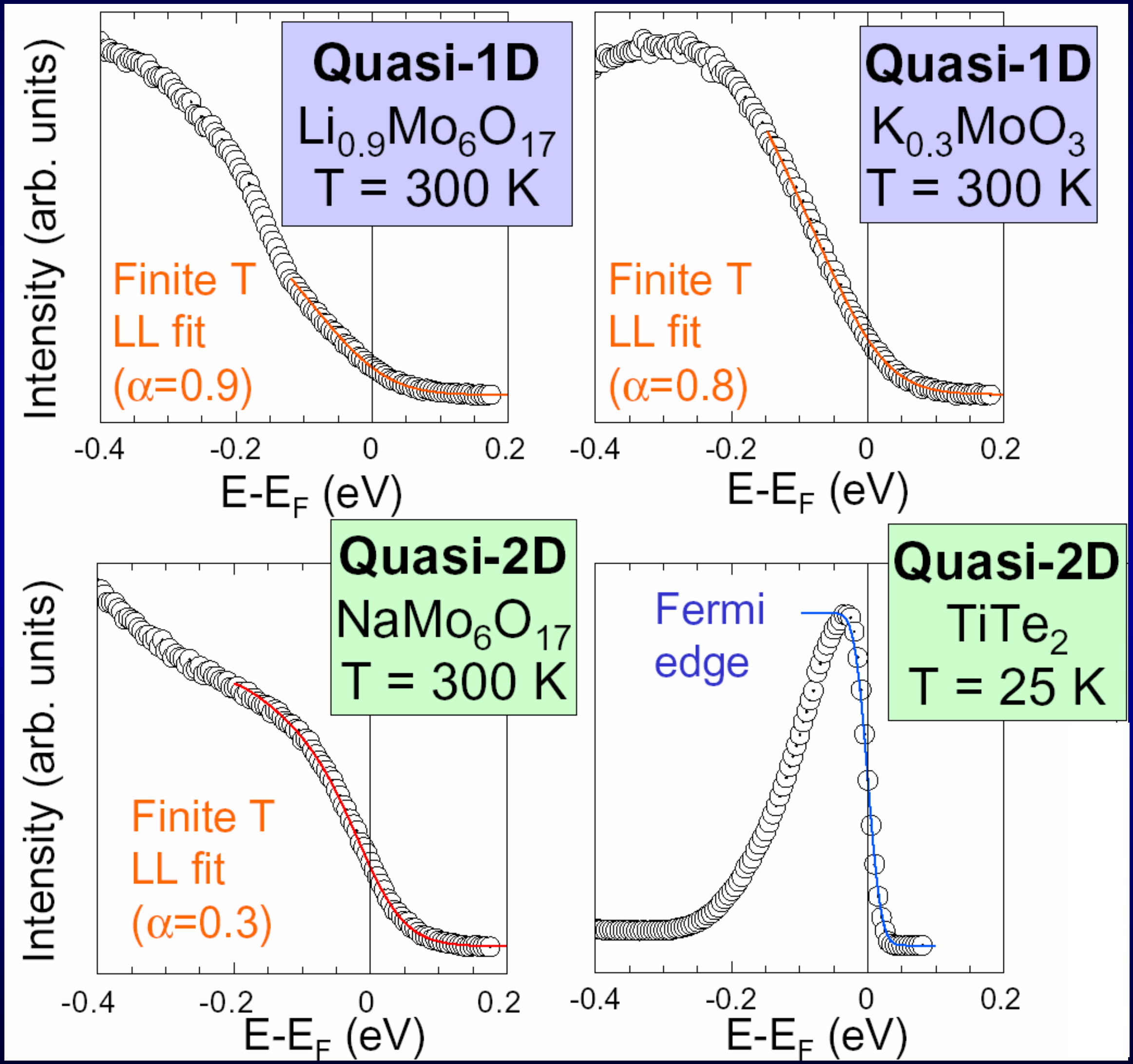
Momentum-Integrated PES



"Pseudo-Gap"

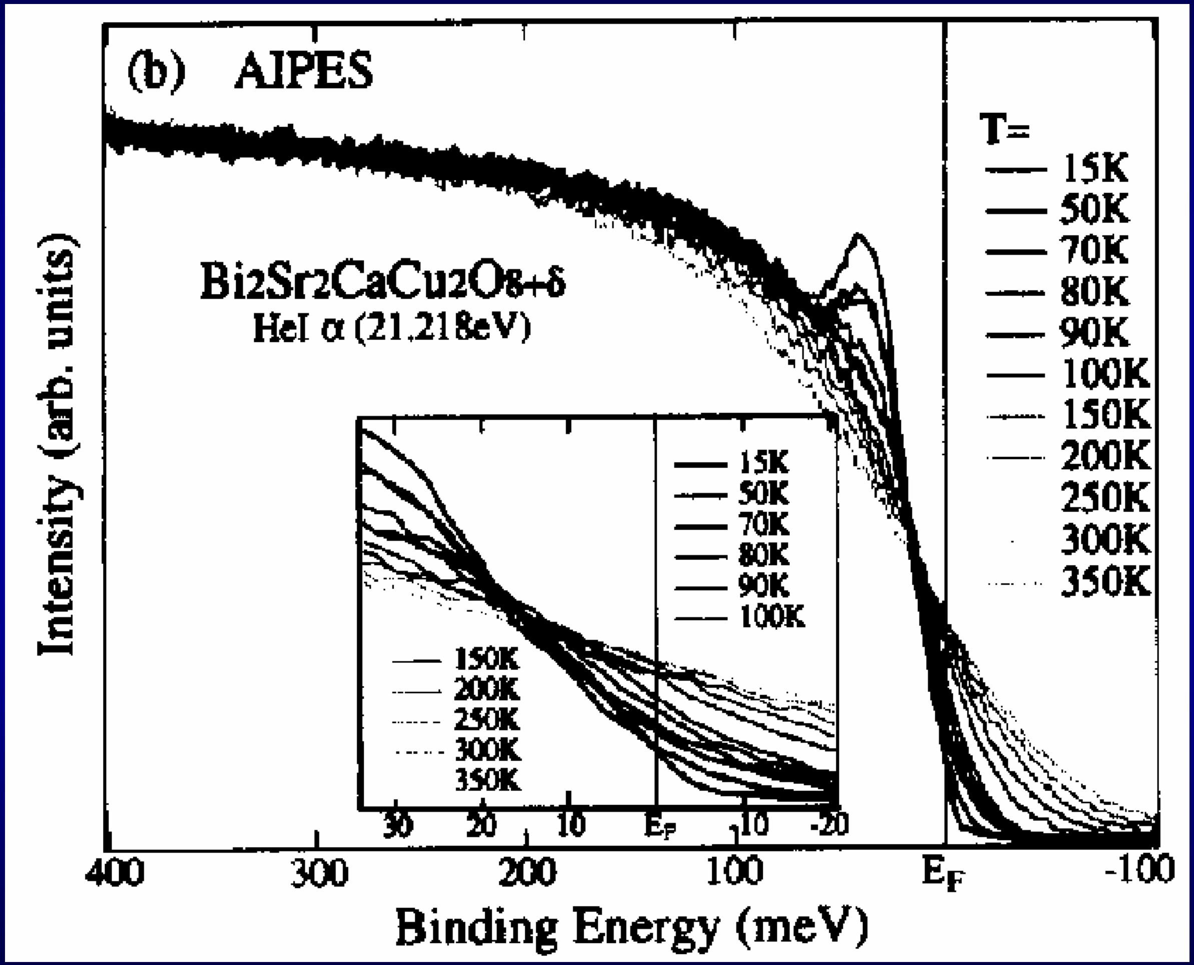
Signature of Electron Fractionalization





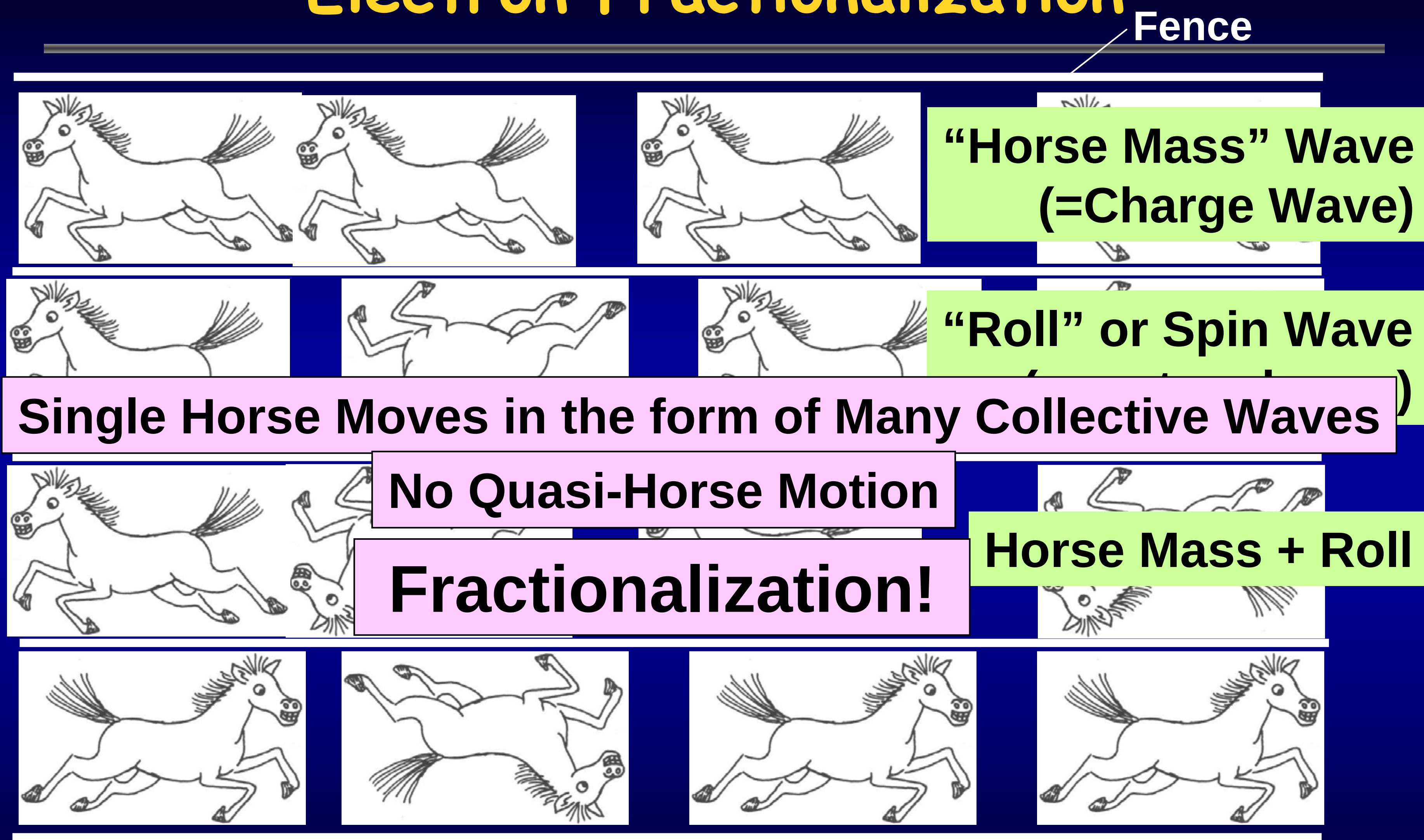
Signature of Electron Fractionalization

Pseudo-Gap



Sato et al, Physica *C* ('00)

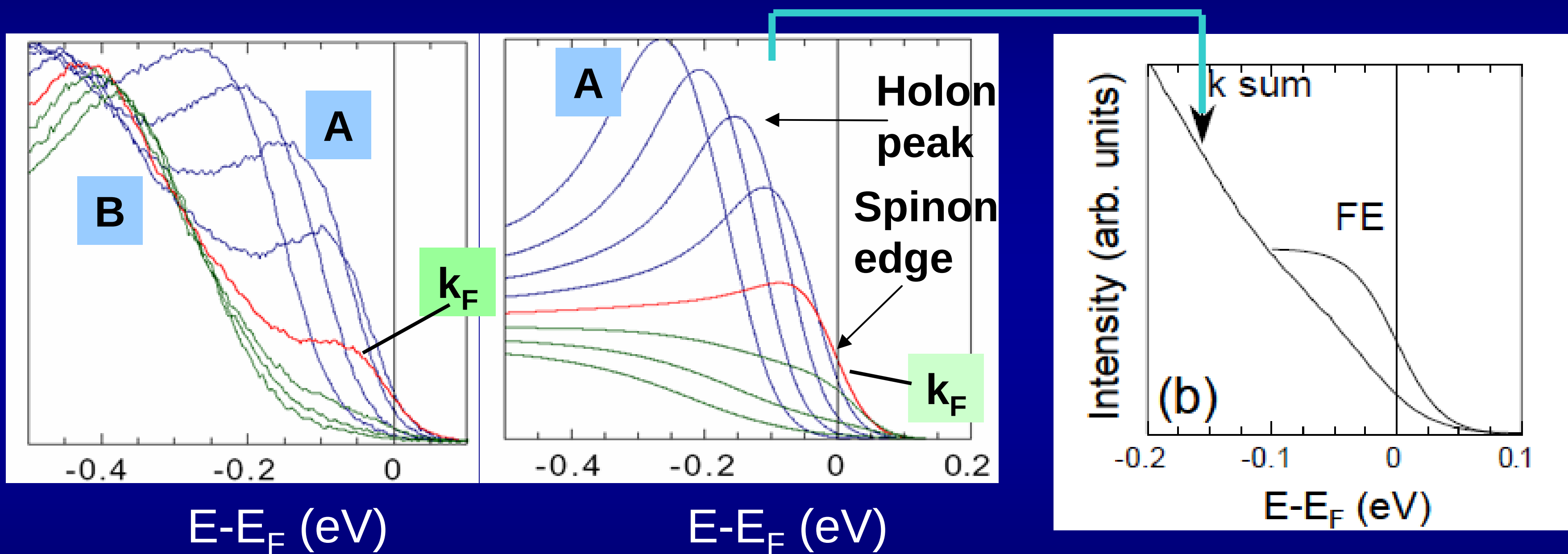
Electron Fractionalization



No Individual Horse Motion (No Quasi-Electron) !

Charge Wave ("Holon") and Spin Wave ("Spinon")

Spin Charge Separation – suggestive but not definite

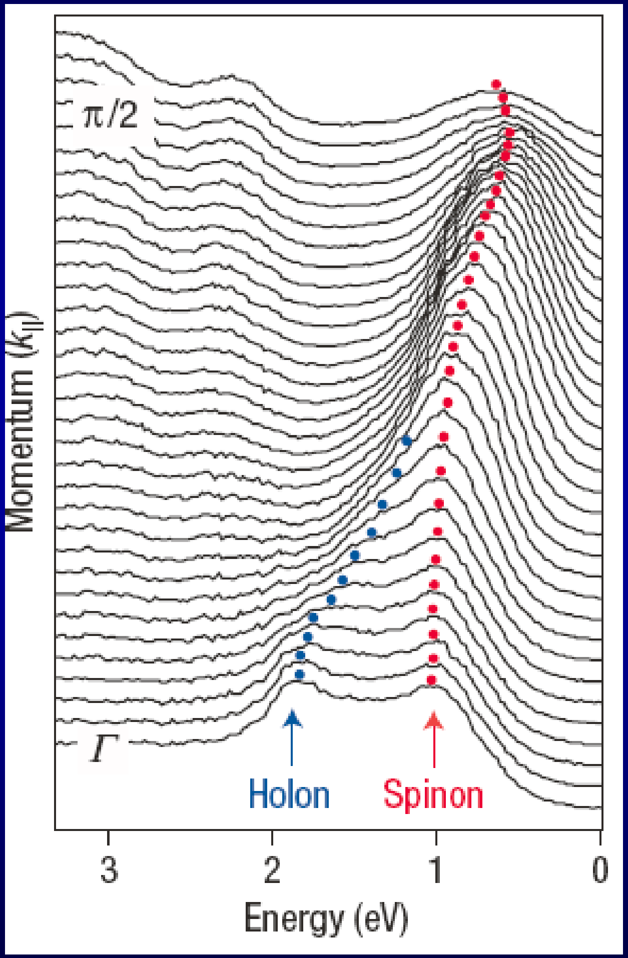


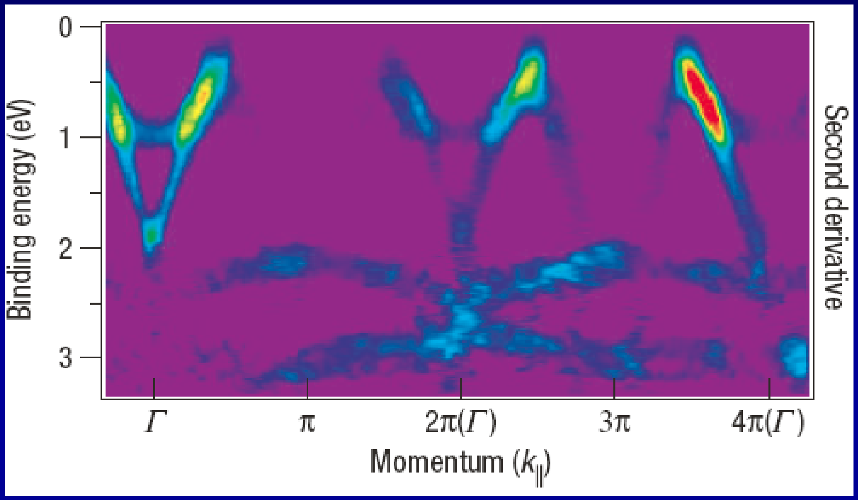
1D Li Purple Bronze ($Li_{0.9}Mo_6O_{17}$) – Luttinger Liquid

J. D. Denlinger, GHG et al, PRL 99
GHG et al., PRB 03; F. Wang et al., PRL 06

Almost an emergence?

$SrCuO_2$



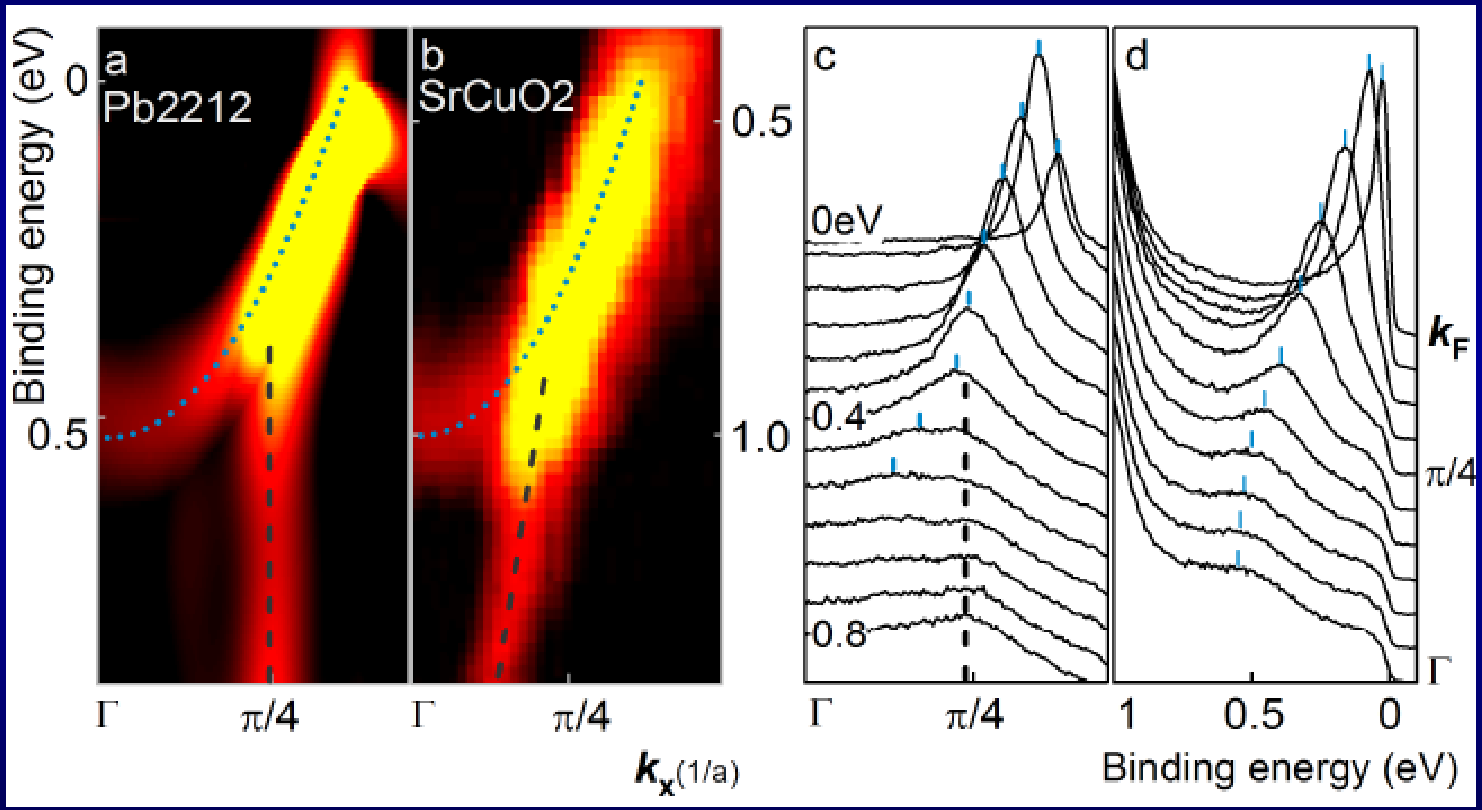


Kim et al., Nature Physics, 2, 397 (2006)

Also, see TTF-TCNQ
Claessen et al., 88, 096402 (2002)

Two dispersing things but at high energy!

Spin Charge Separation in Cuprates



Graf, GHG, et al., PRL in review

Conclusions

- Complex physics in condensed matter systems (High Tc, Low-D conductors, etc)
- Signatures of various types of emergence – New era of condensed matter physics beyond simple Landau Fermi Liquid paradigm
- One electron carries the message of emergence of gazillion electrons through wave function overlaps

Further Reading

- R. Feynman, "**QED: The Strange Theory of Light and Matter,**" Princeton University Press (1988)
- R. D. Mattuck, "A Guide to Feynman Diagrams in the Many-Body Problem," Dover (1976)
- P. W. Anderson, "More is different," Science vol. 177, 393 (1972)
- R. B. Laughlin and D. Pines, "The Theory of Everything," Proceedings of the National Academy of Science, vol. 97, 28 (2000)
- R. B. Laughlin, "A Different Universe – Reinventing physics from bottom down," Basic Books (2006)
- P. W. Anderson, "When electron falls apart," Physics Today 50 (10): 42-47 OCT 1997