

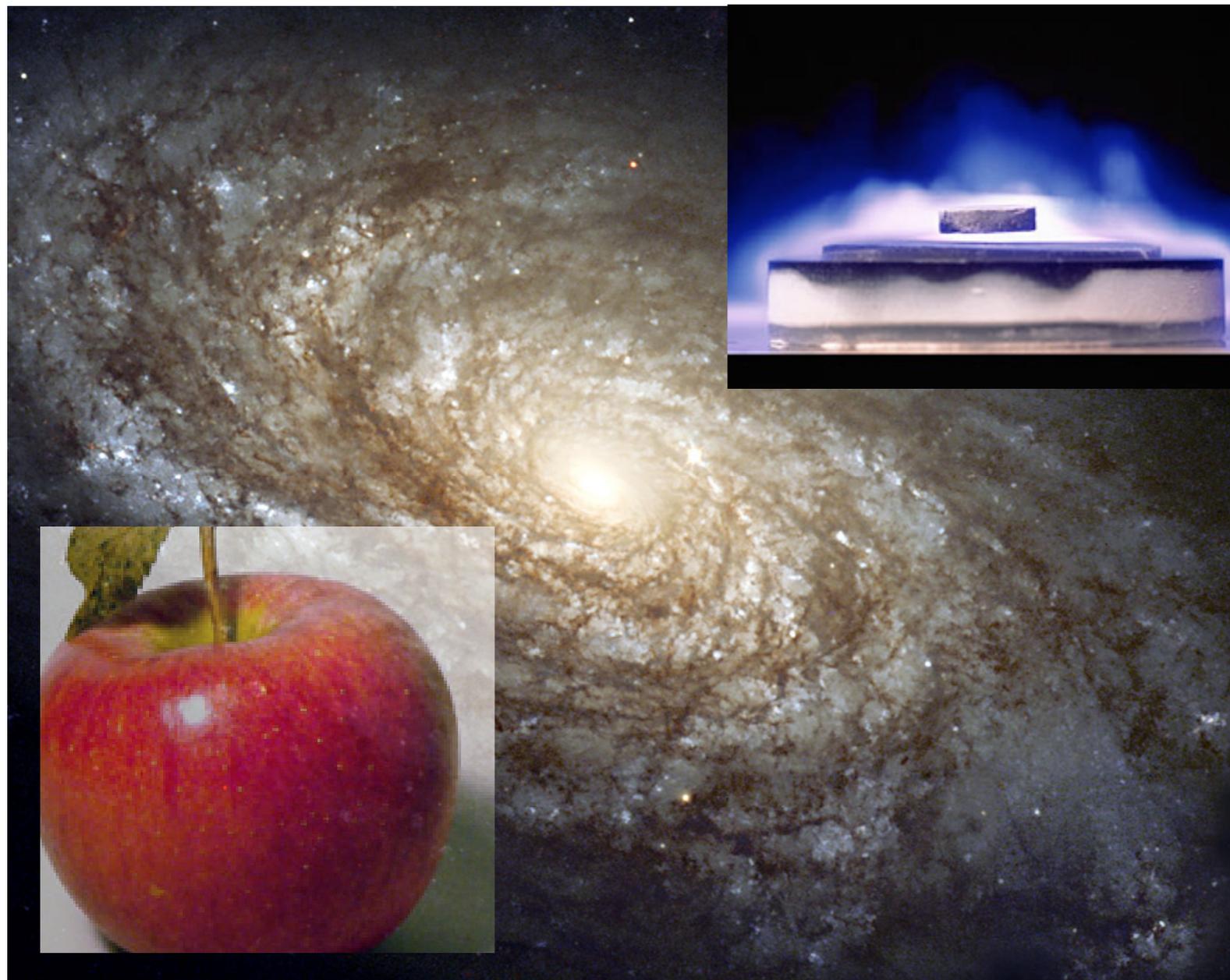
Emergence and Reductionism: an awkward Baconian alliance.

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Center for Materials Theory, Rutgers, USA
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Veldhoven, Holland
Jan 22, 2019



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musicofthequantum.rutgers.edu

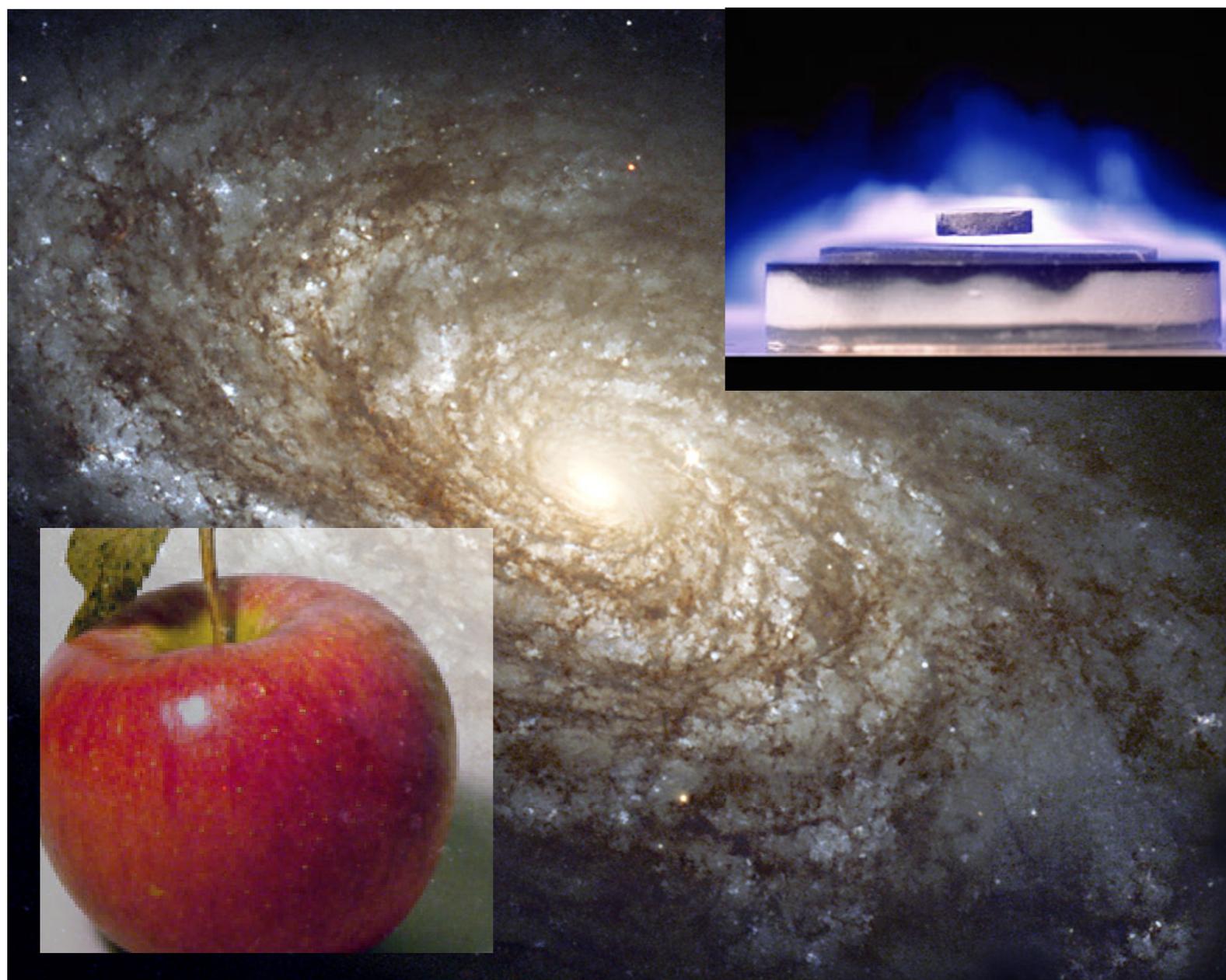
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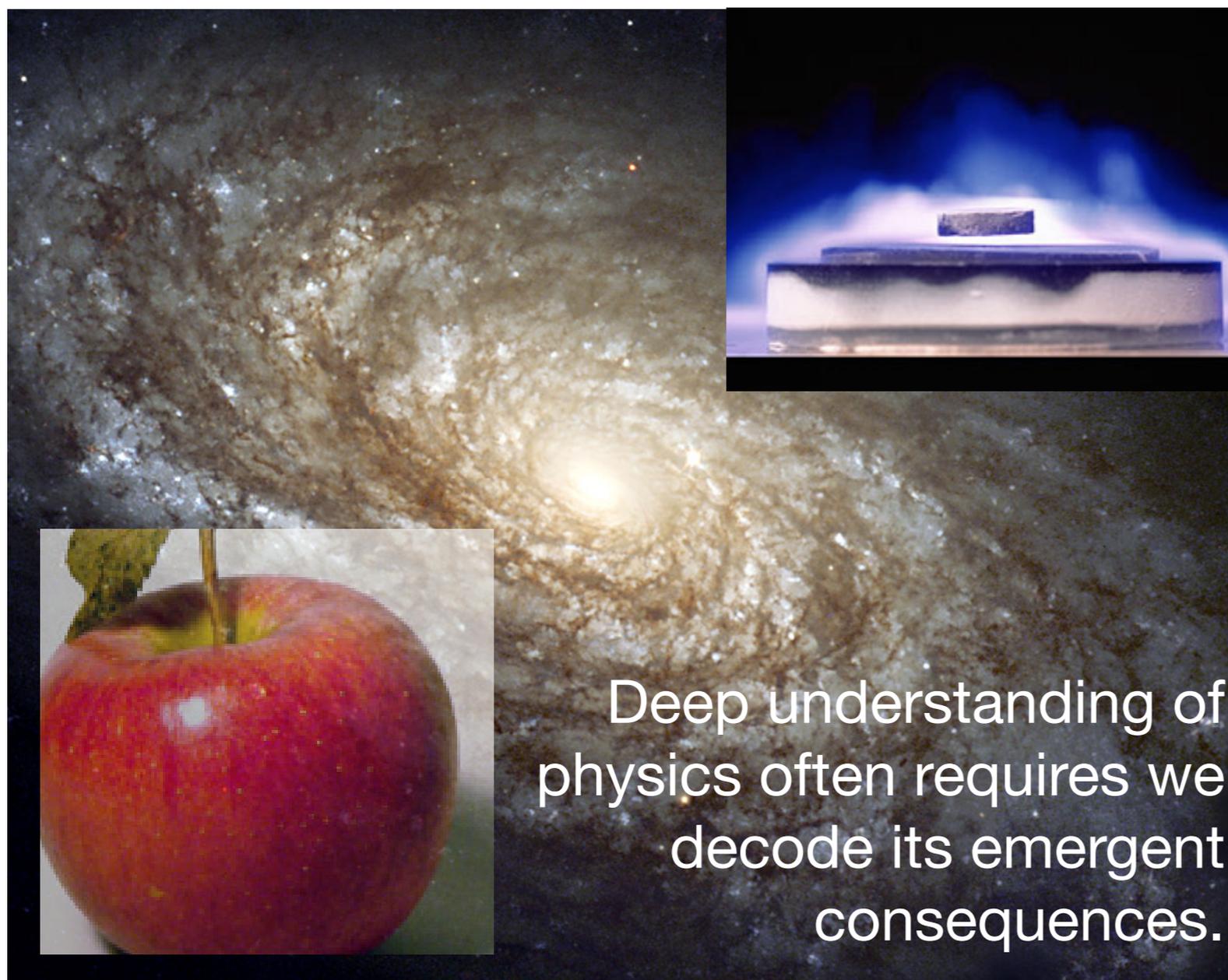
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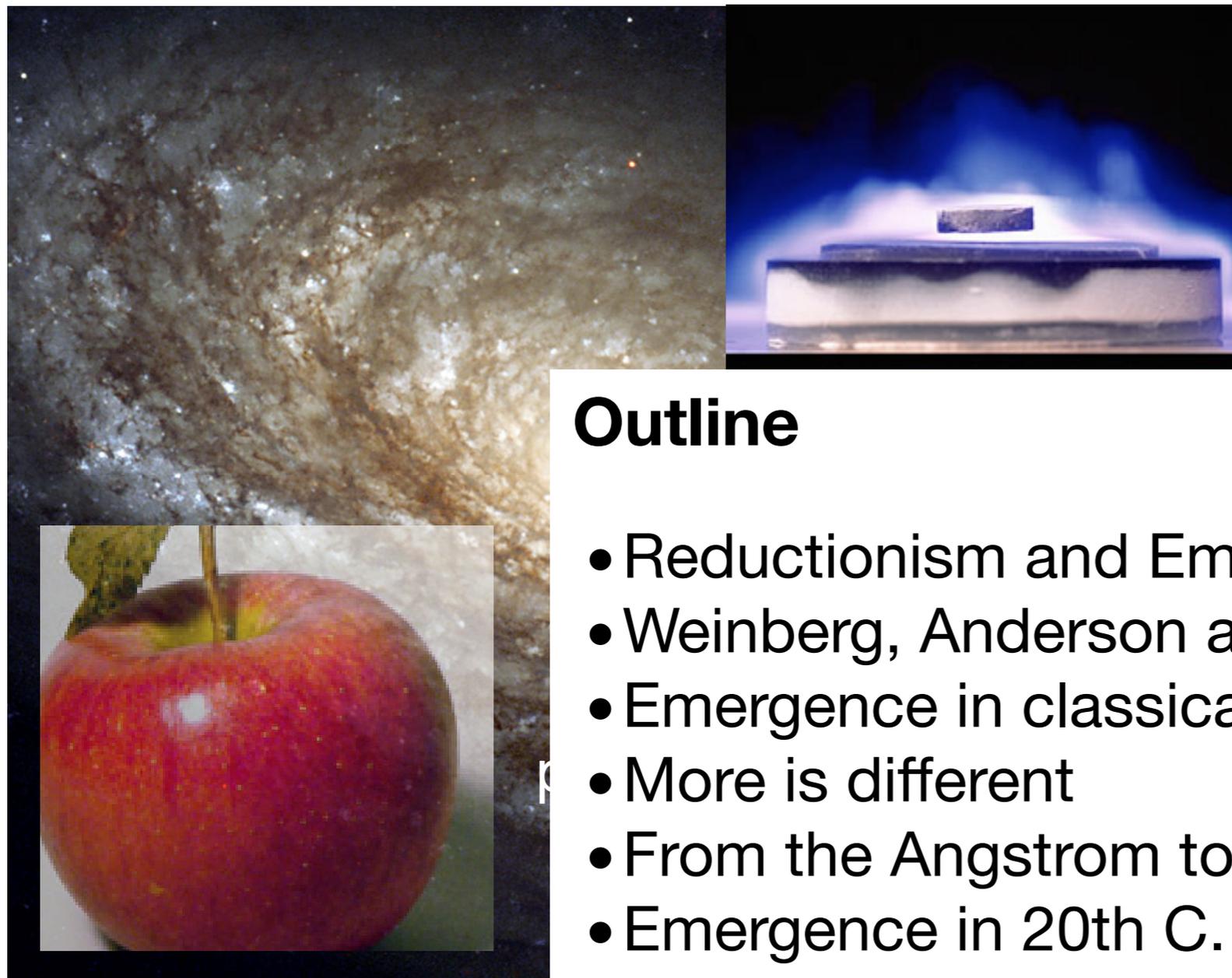
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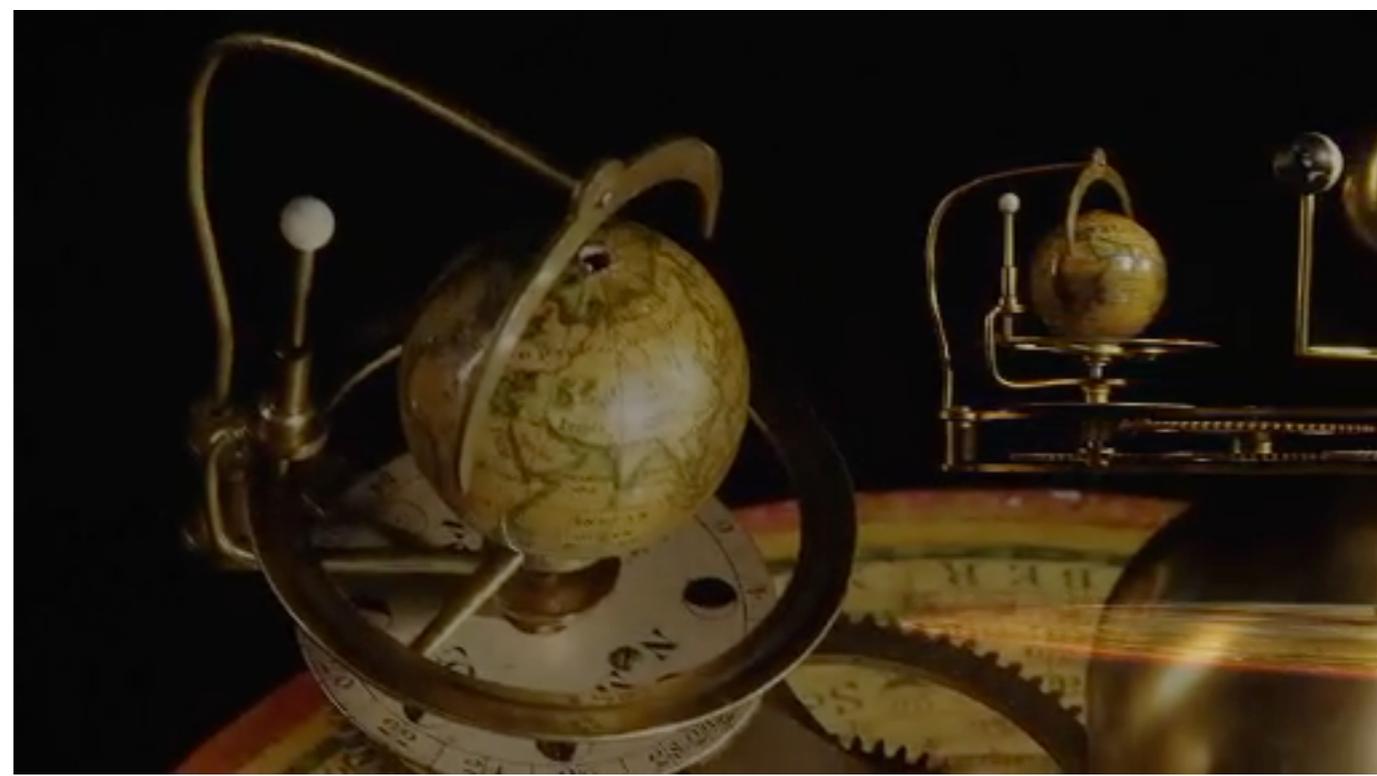
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Outline

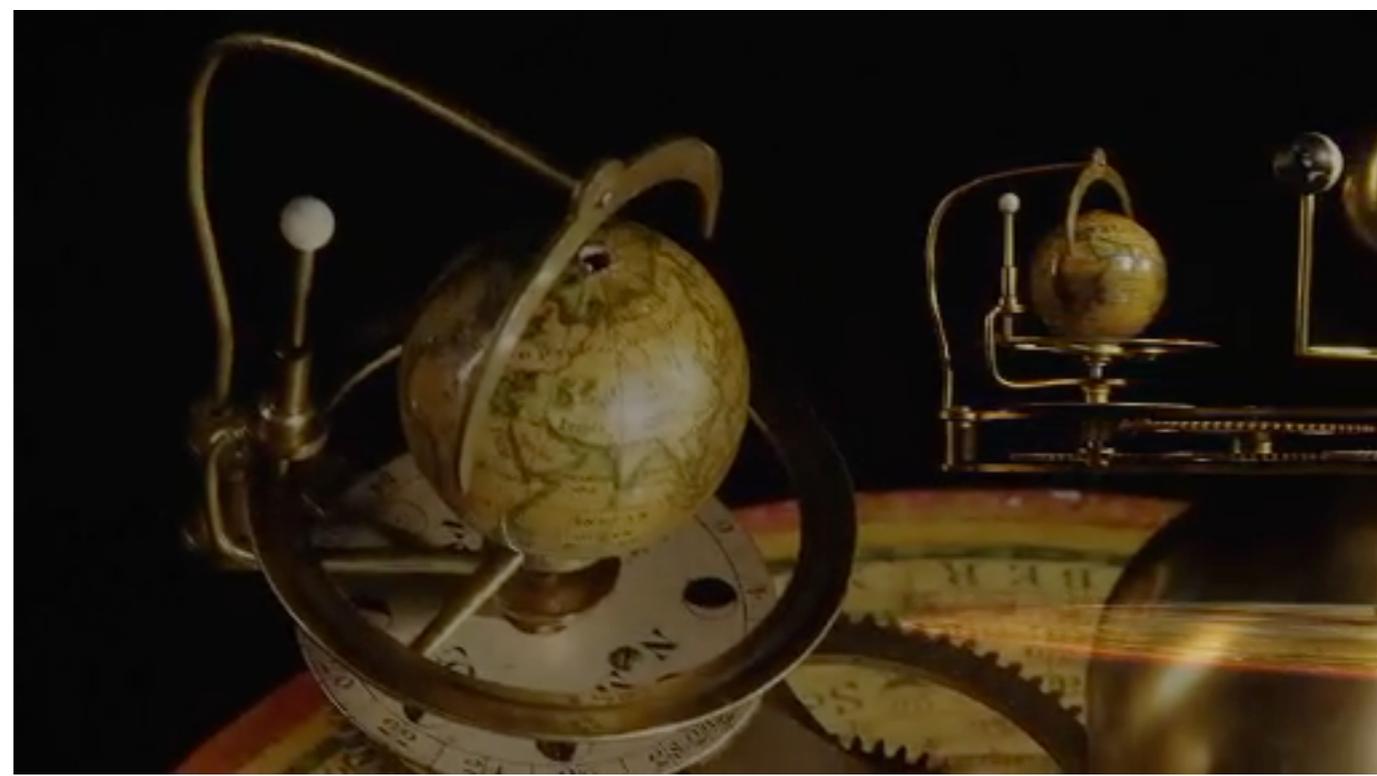
- Reductionism and Emergence
- Weinberg, Anderson and Bacon
- Emergence in classical physics
- More is different
- From the Angstrom to the Micron
- Emergence in 20th C. Condensed Matter Physics

Reductionism and Emergence

Reductionism and Emergence



Reductionism and Emergence

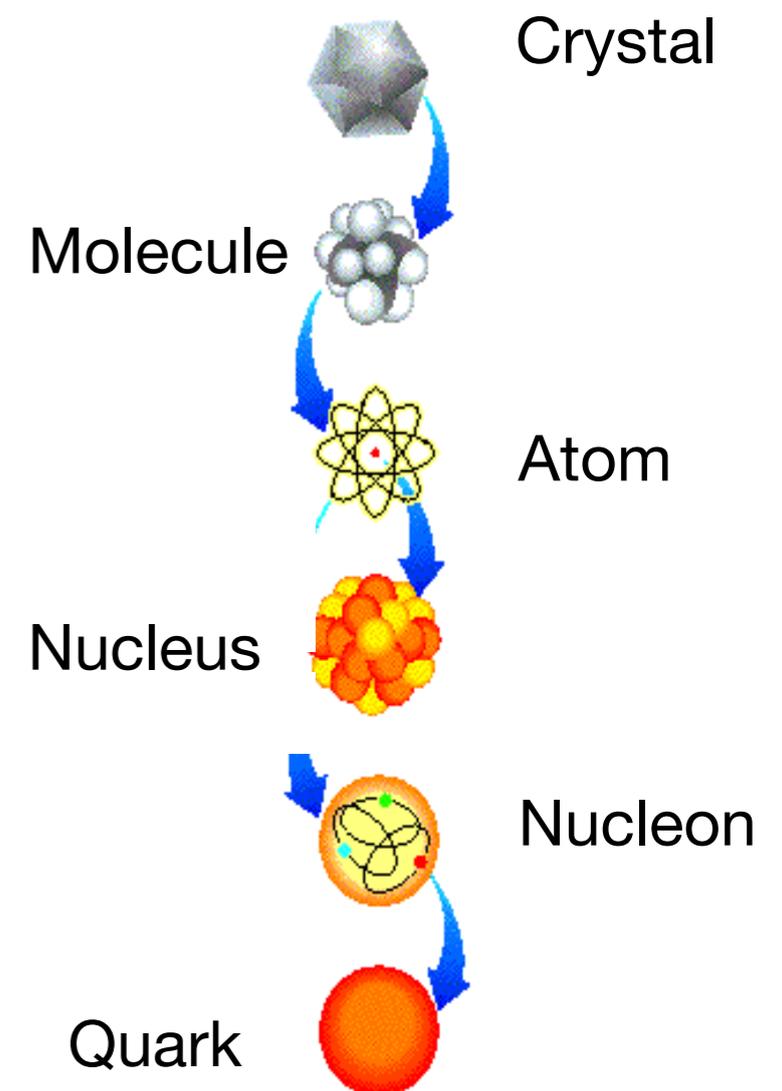


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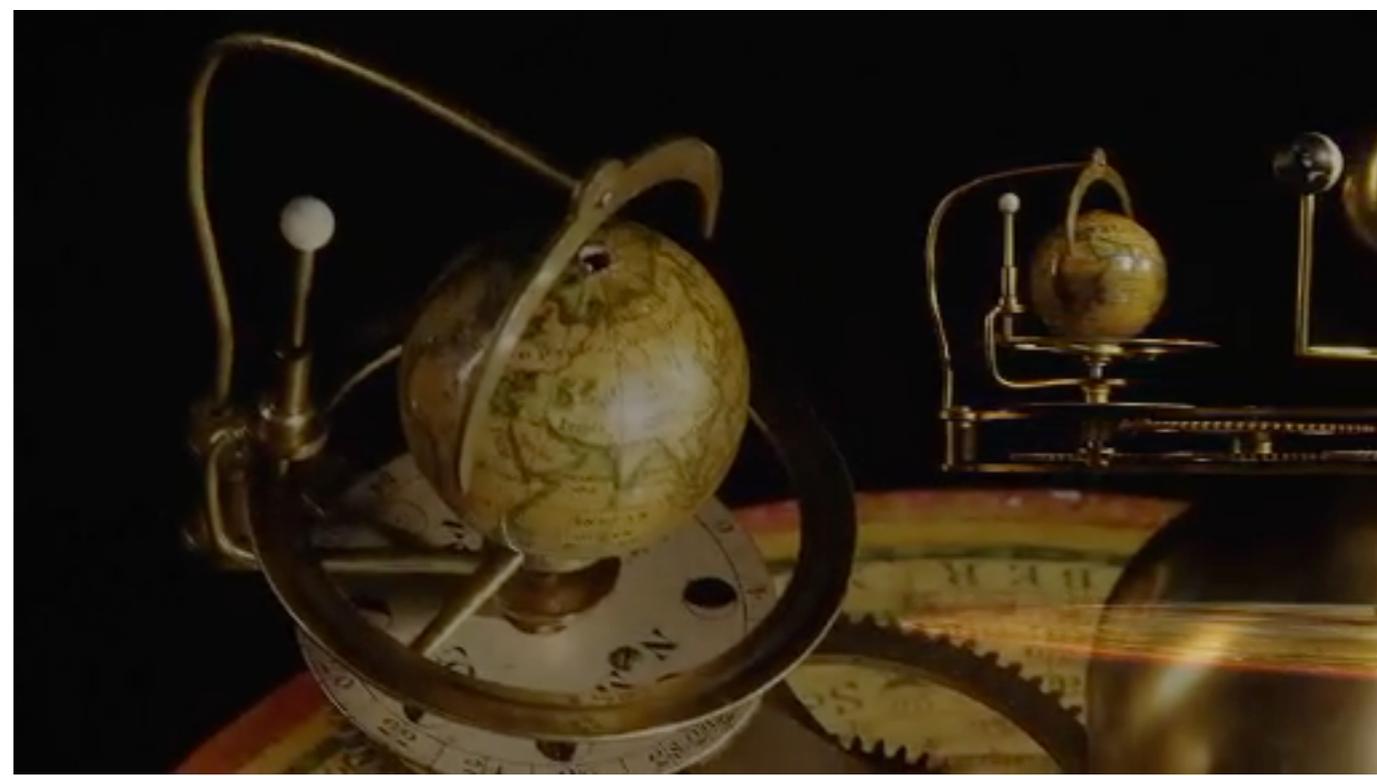


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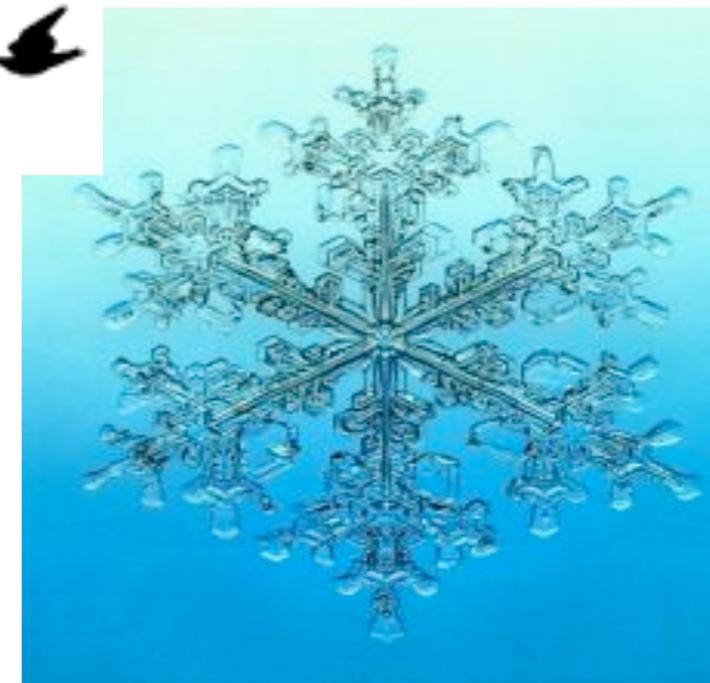
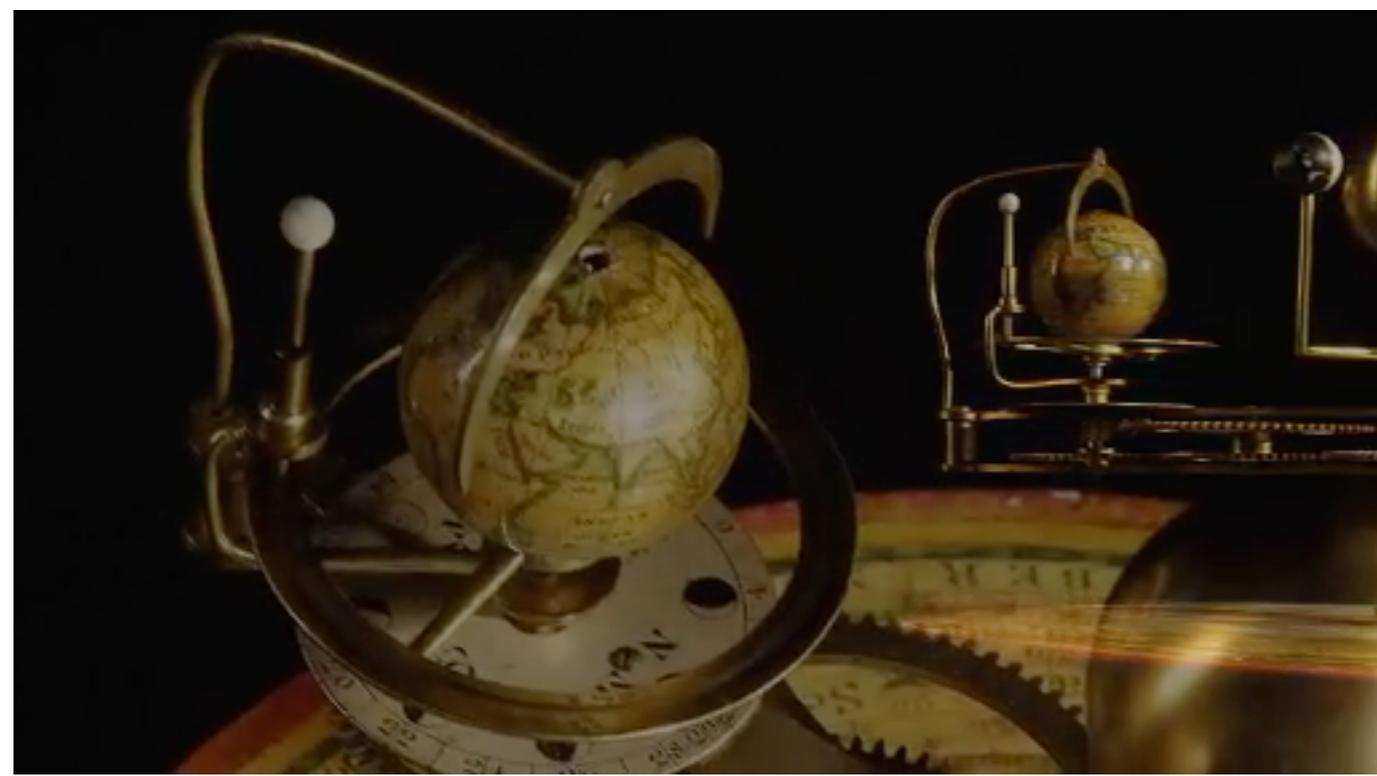
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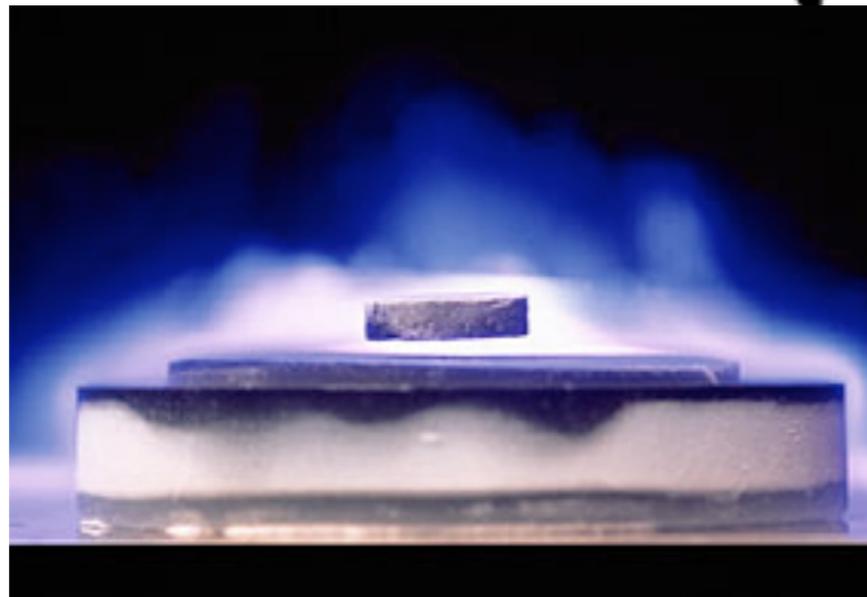
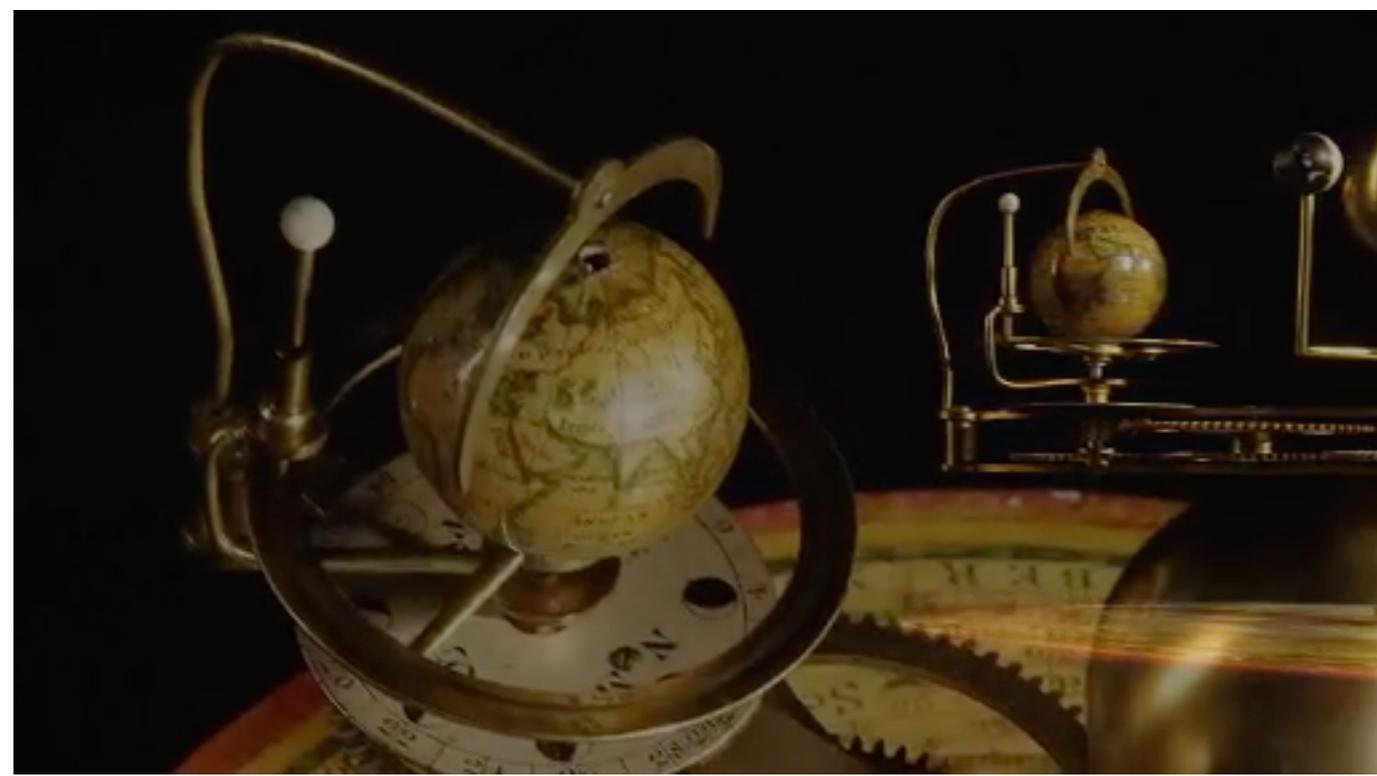
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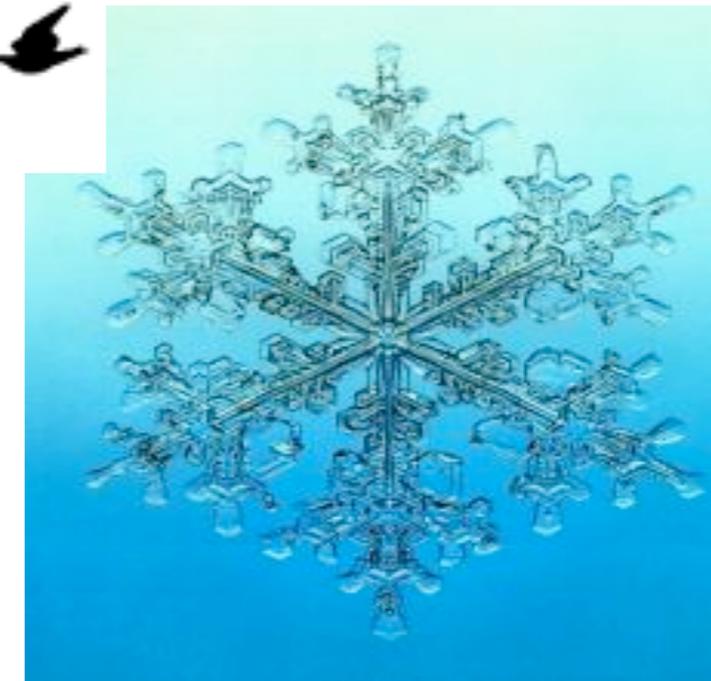
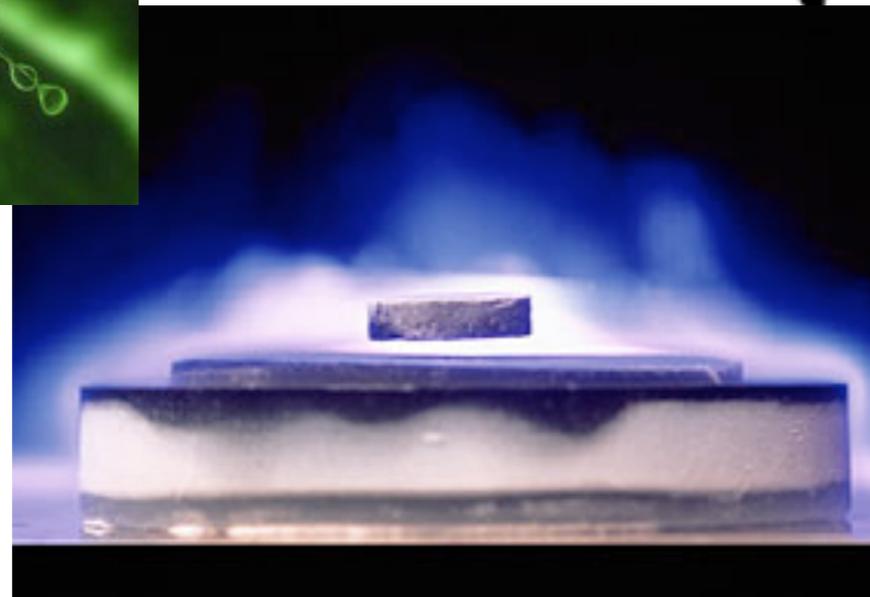
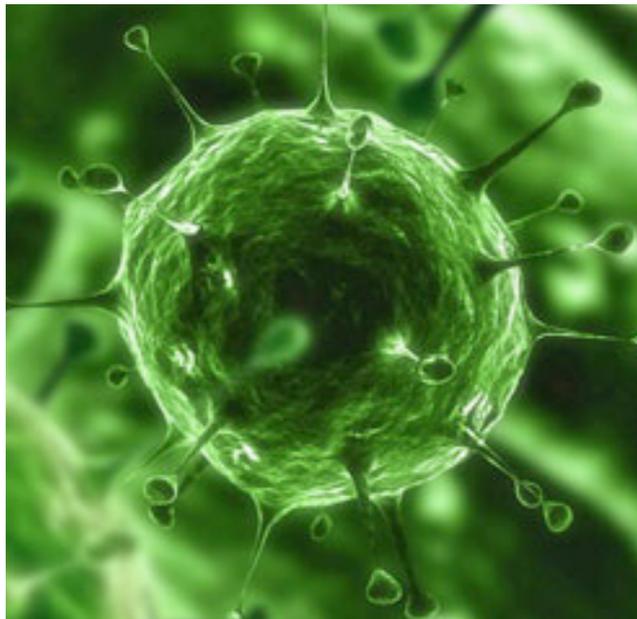
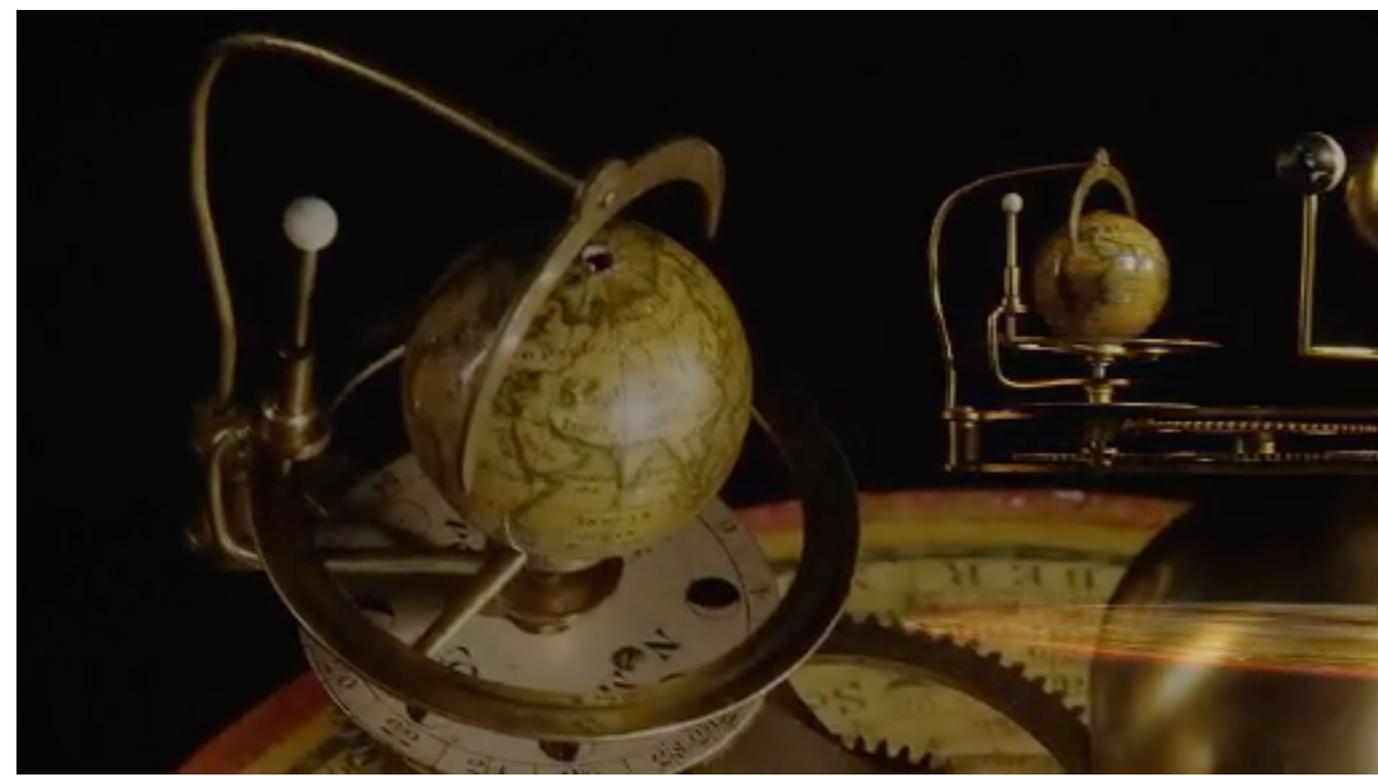
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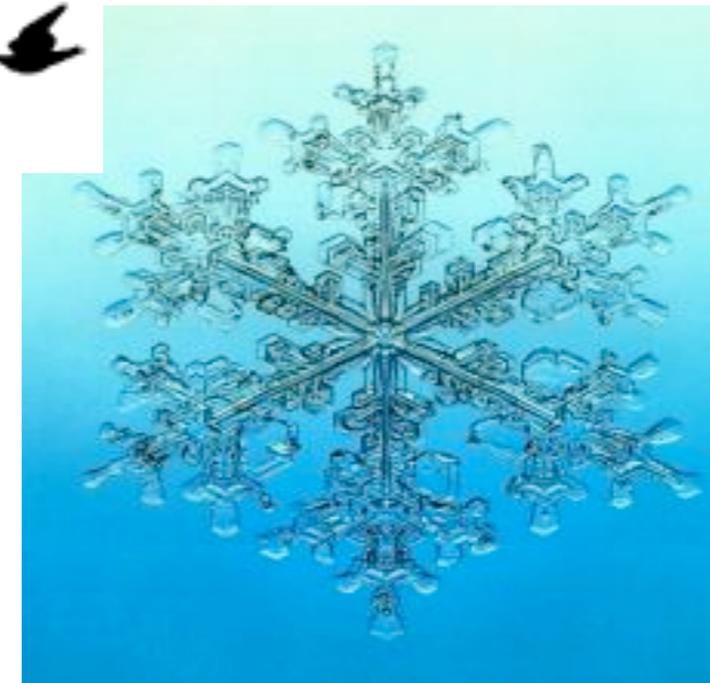
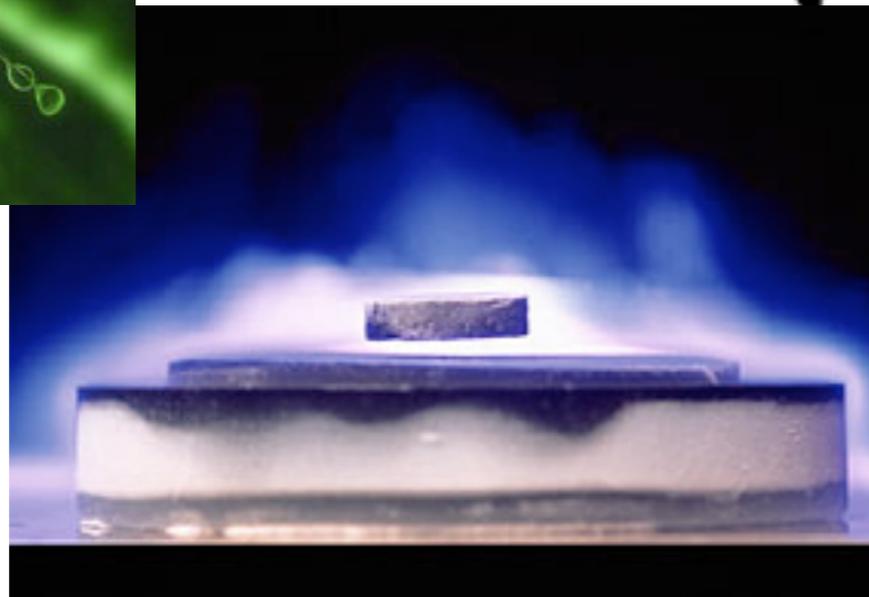
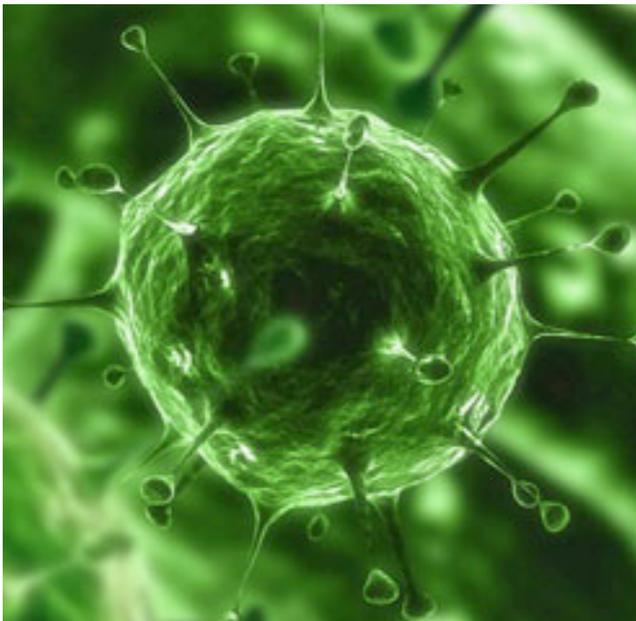
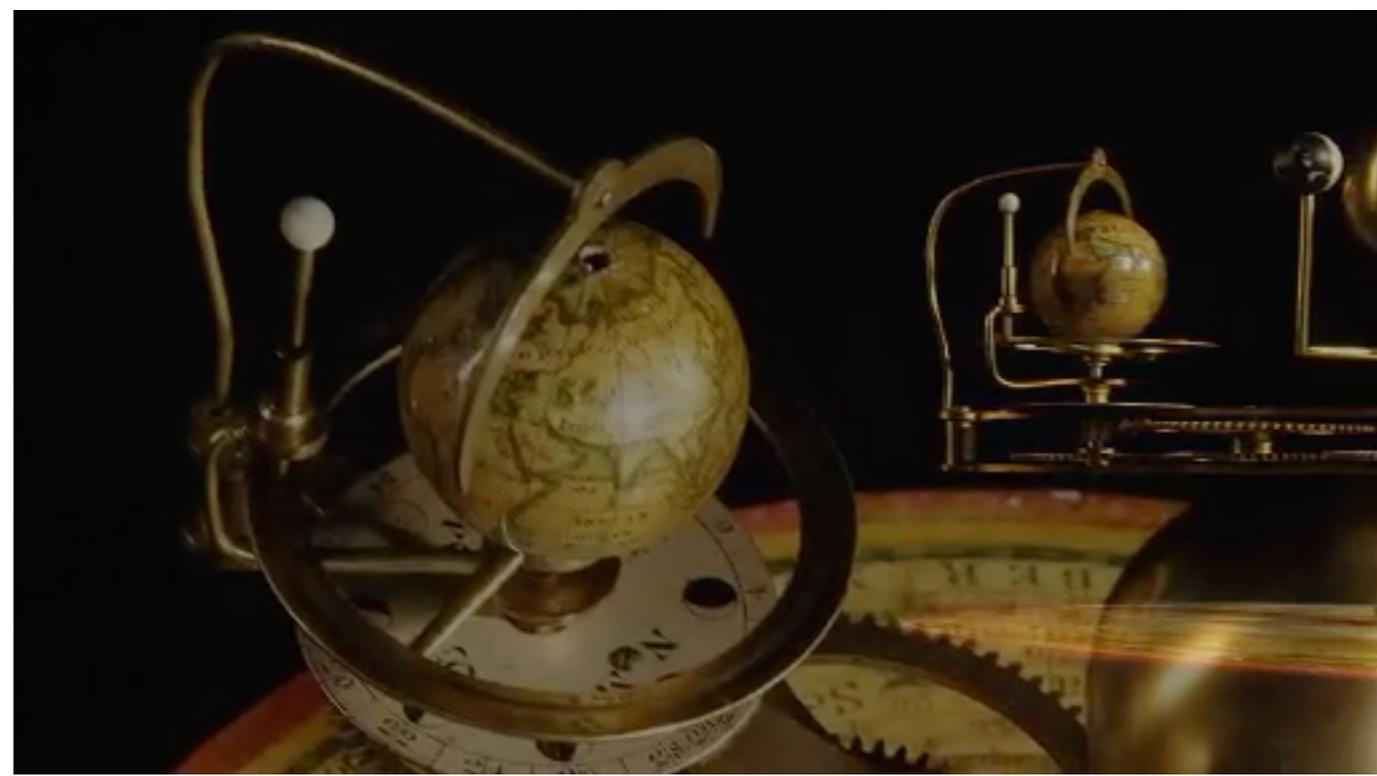
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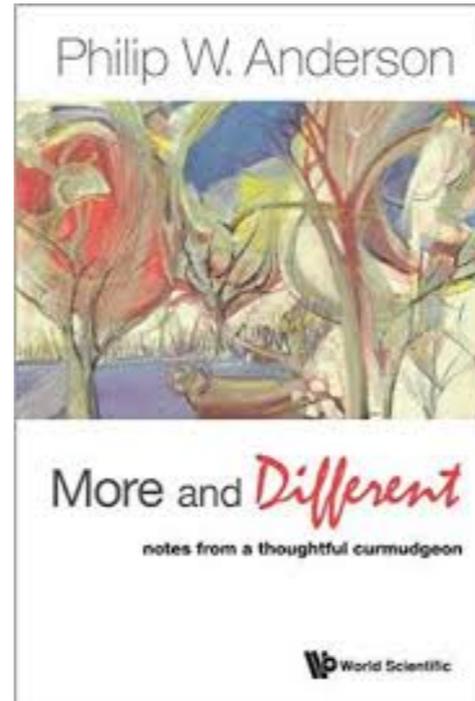
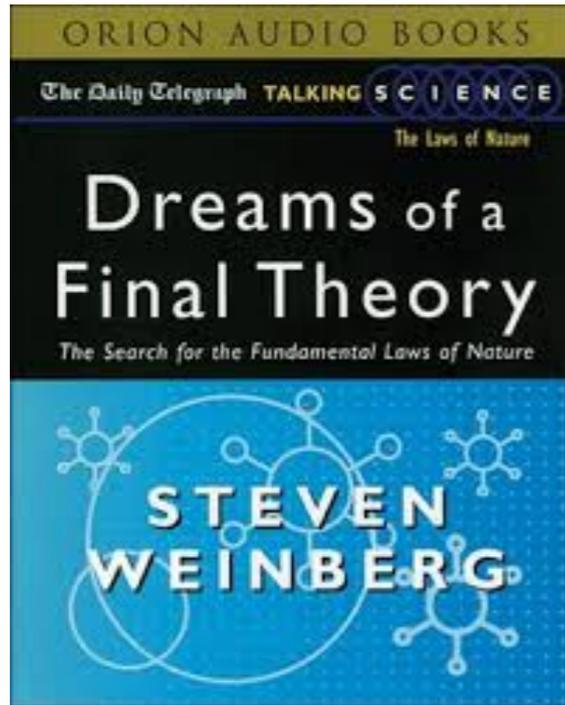


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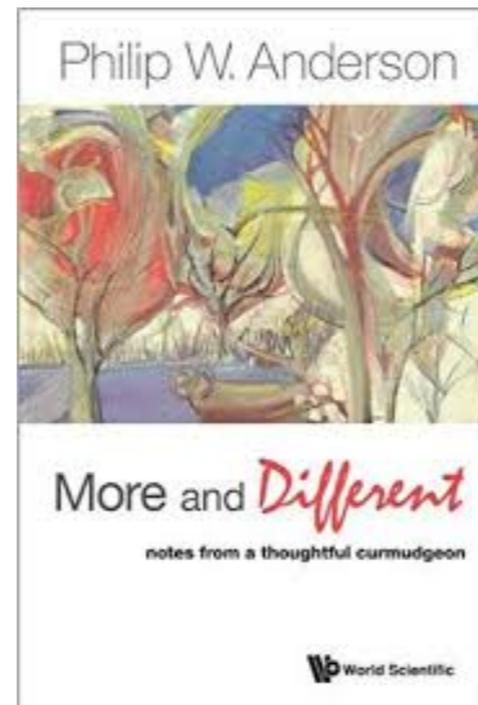
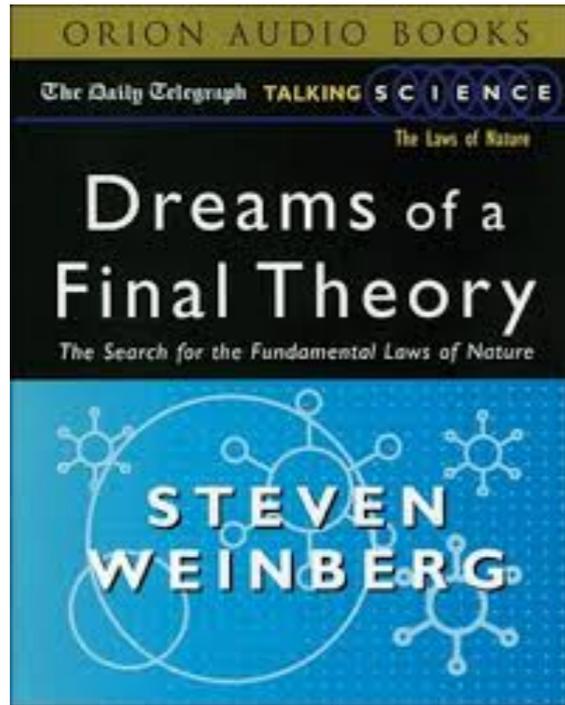
These are all examples of natural science that are not simple extrapolations of the microscopic laws, and that often require new concepts to be understood.



Weinberg, Anderson and Bacon

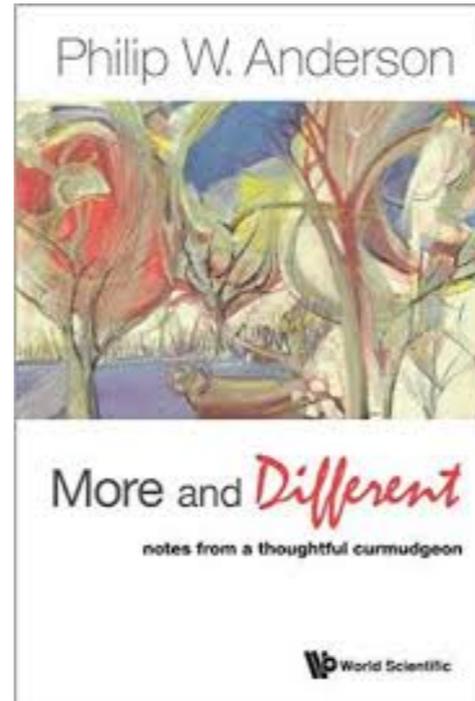
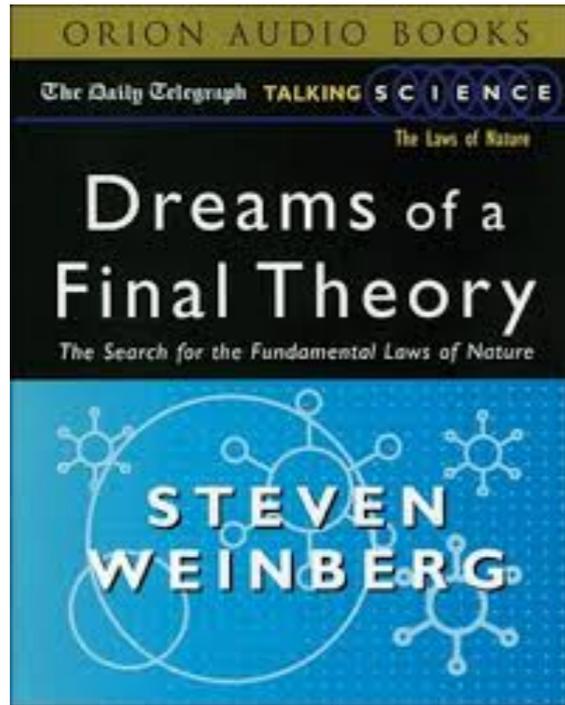


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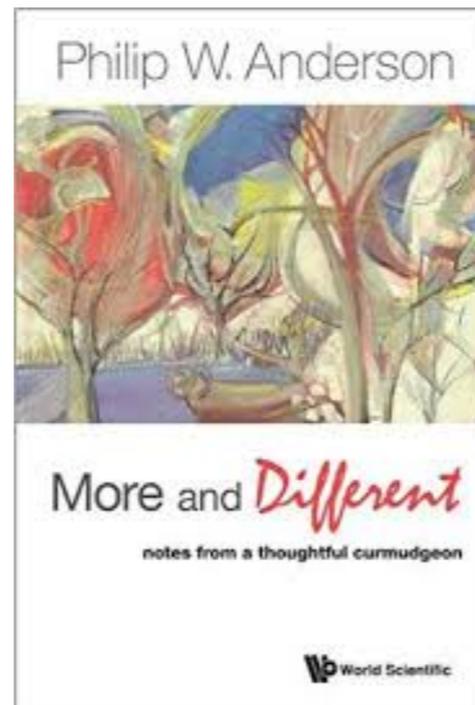
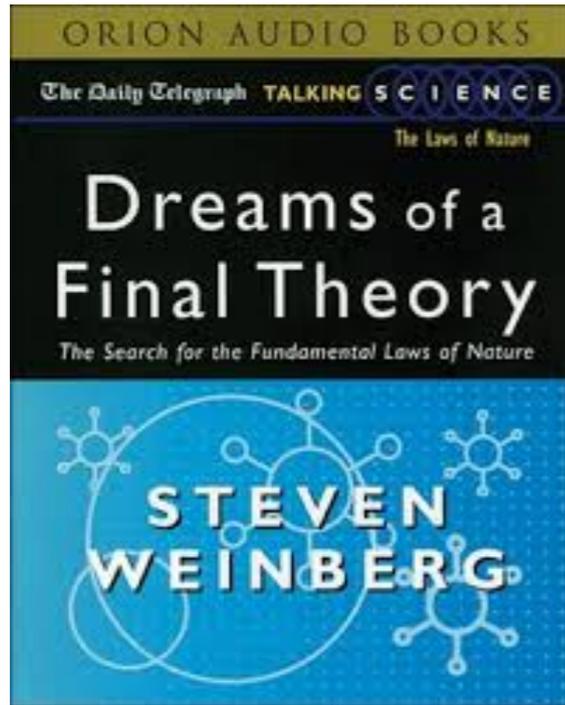
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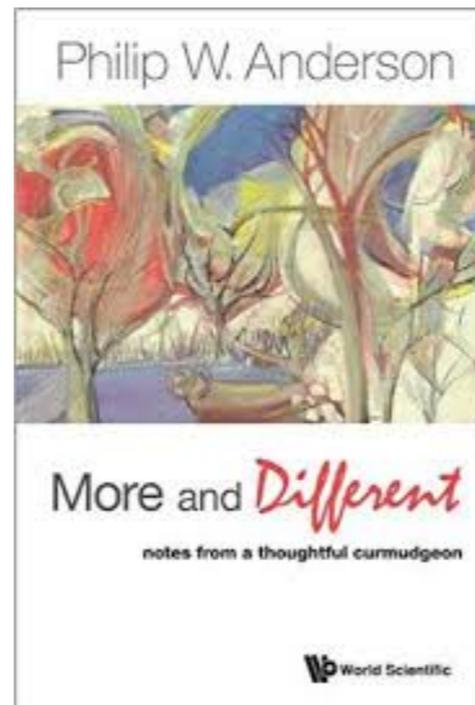
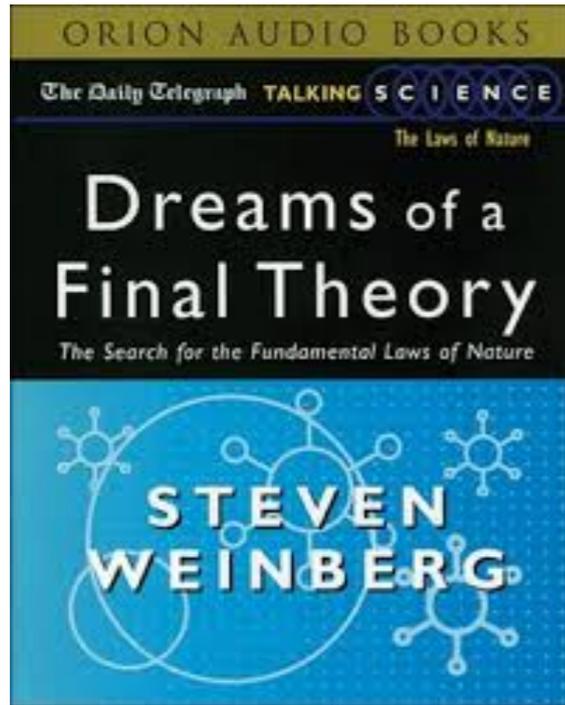
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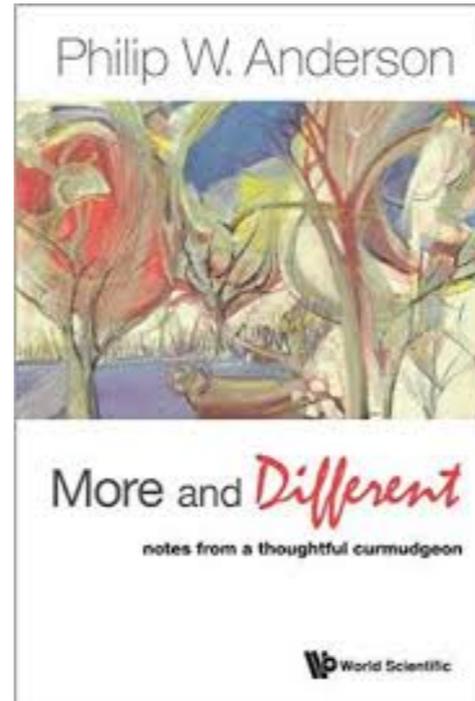
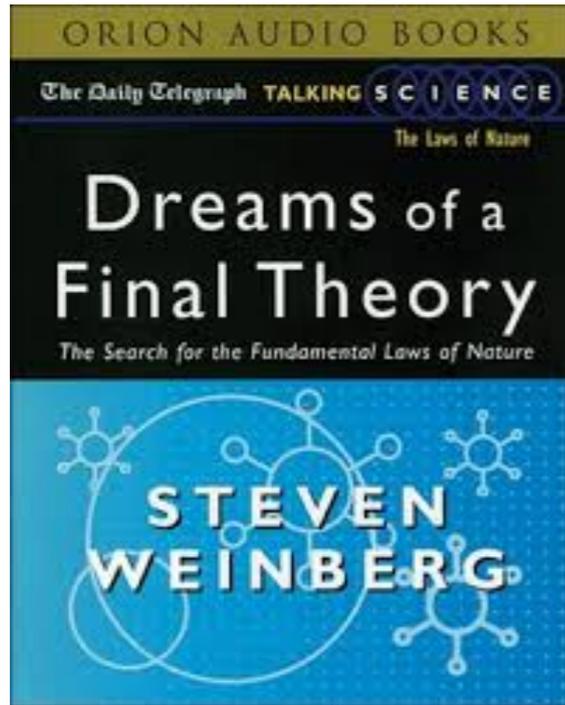
Yet neither repudiates
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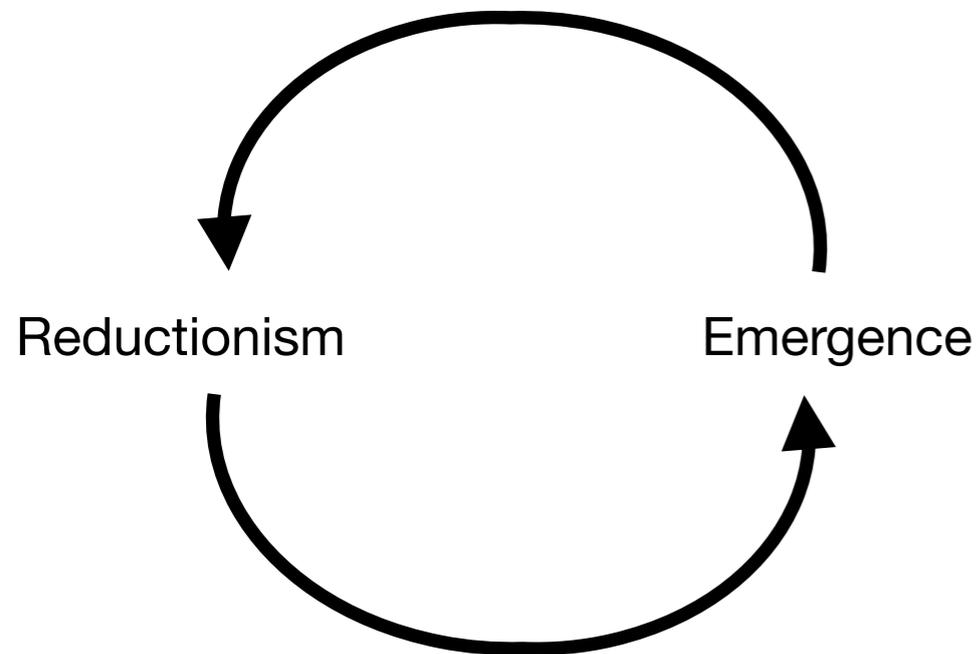
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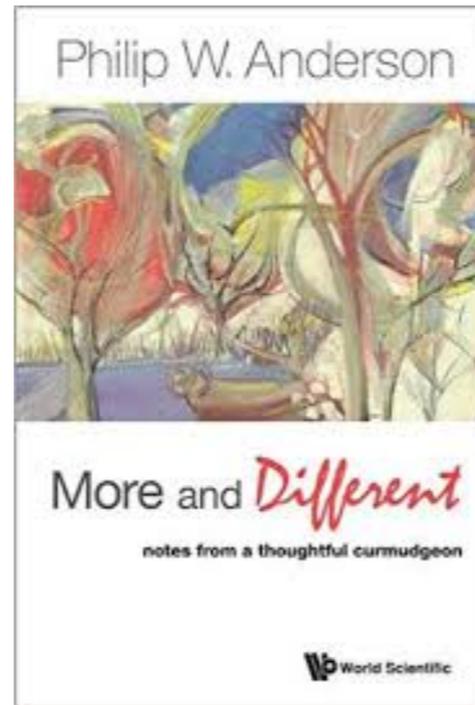
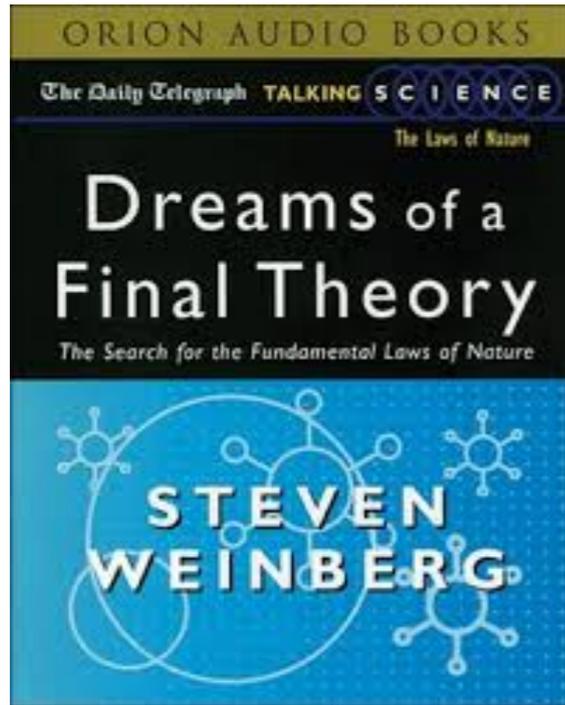


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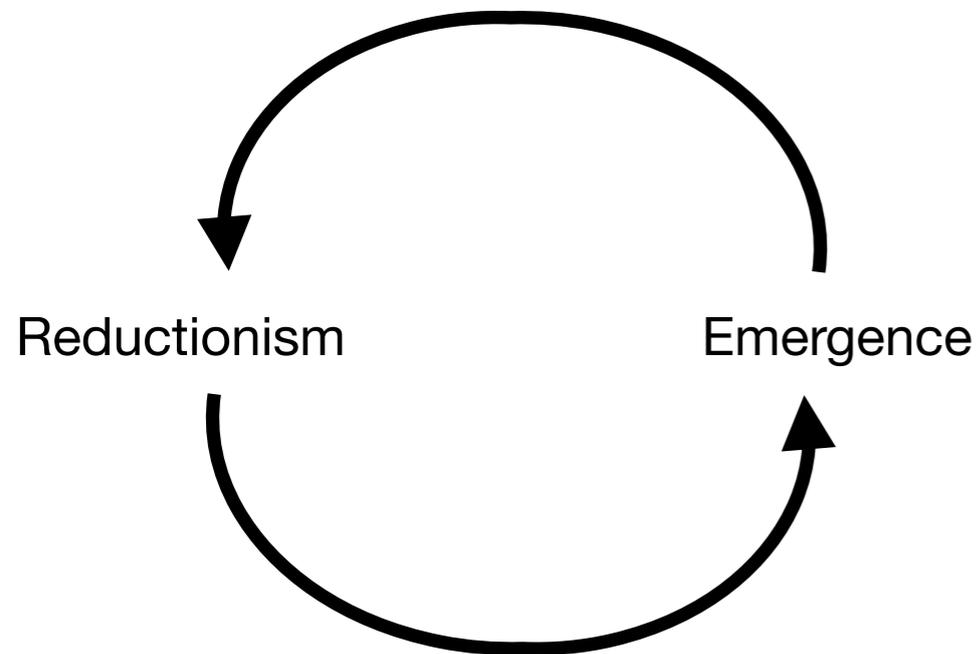


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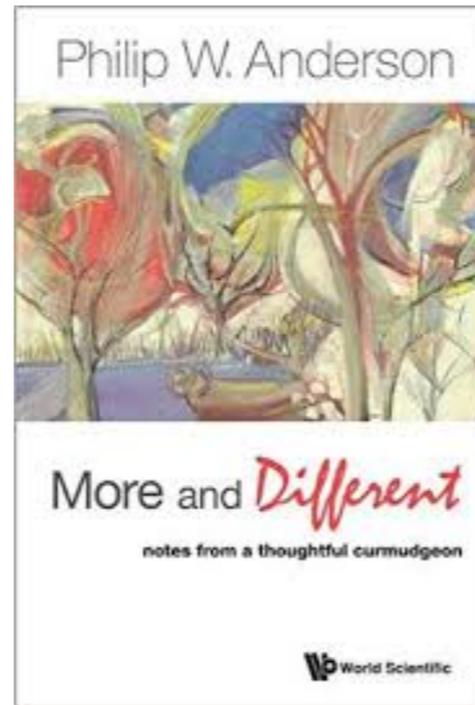
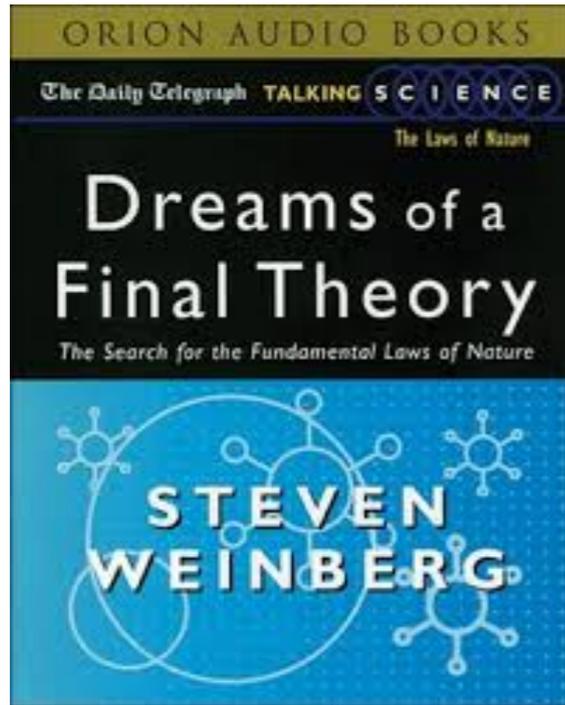
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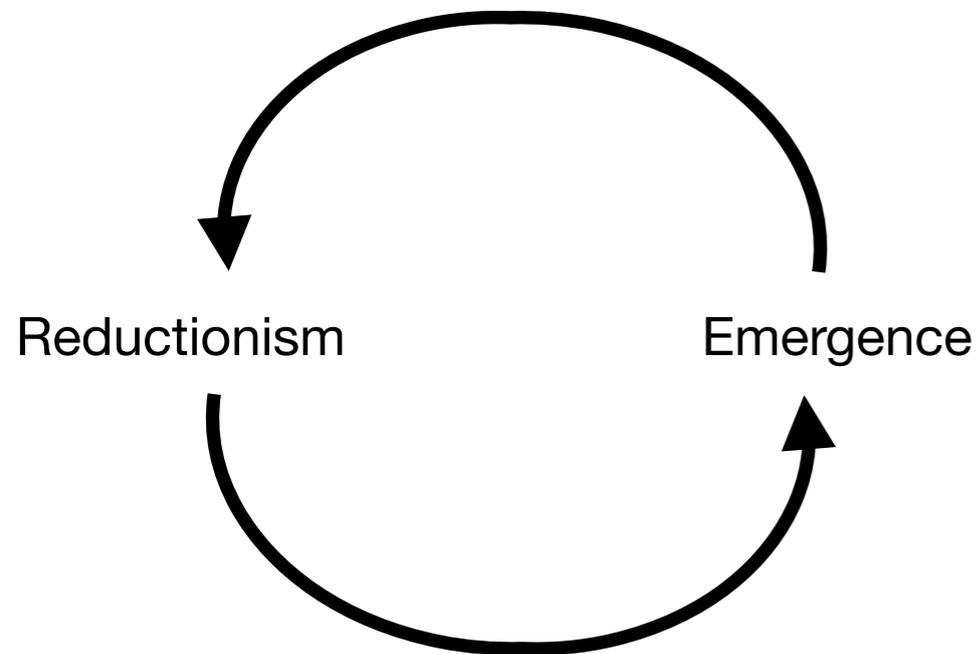
Pragmatic middle ground:

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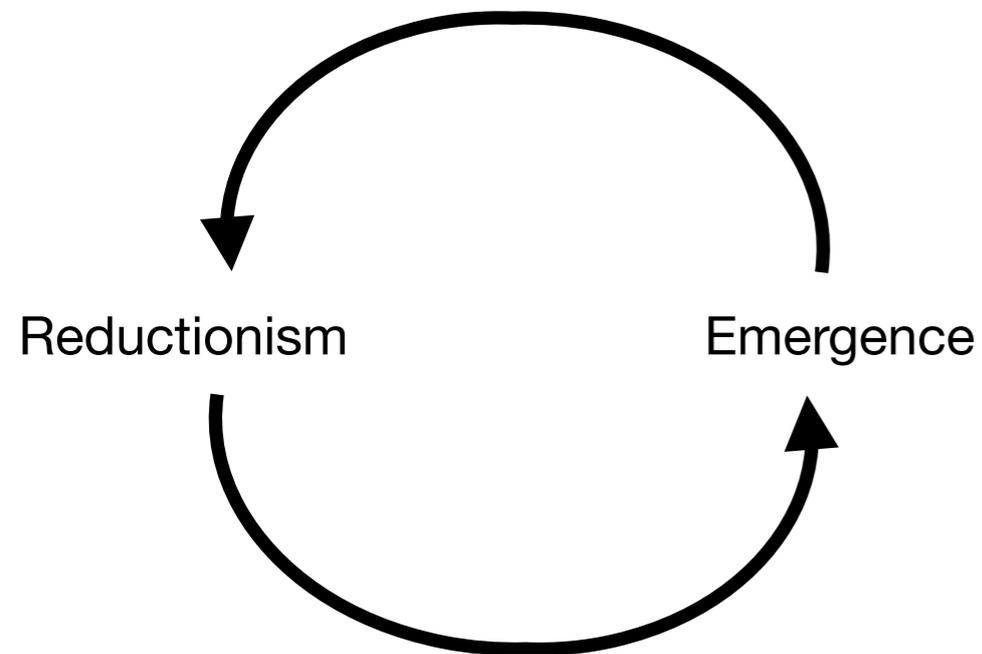
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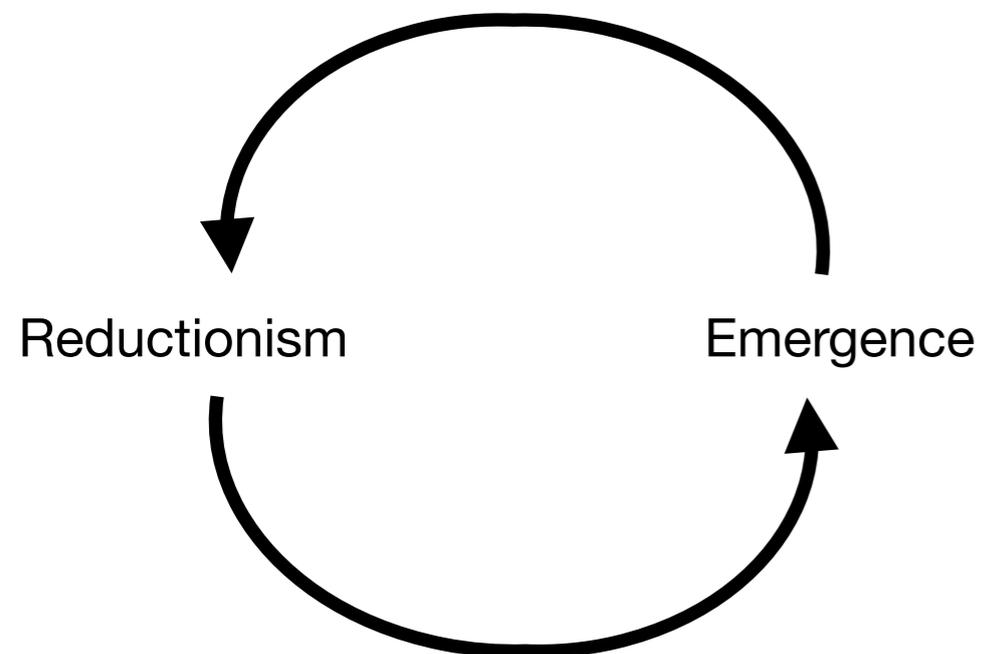


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The one hurries on rapidly from the senses and particulars to the most general axioms, and from them, as principles and their supposed indisputable truth, derives and discovers the intermediate axioms.



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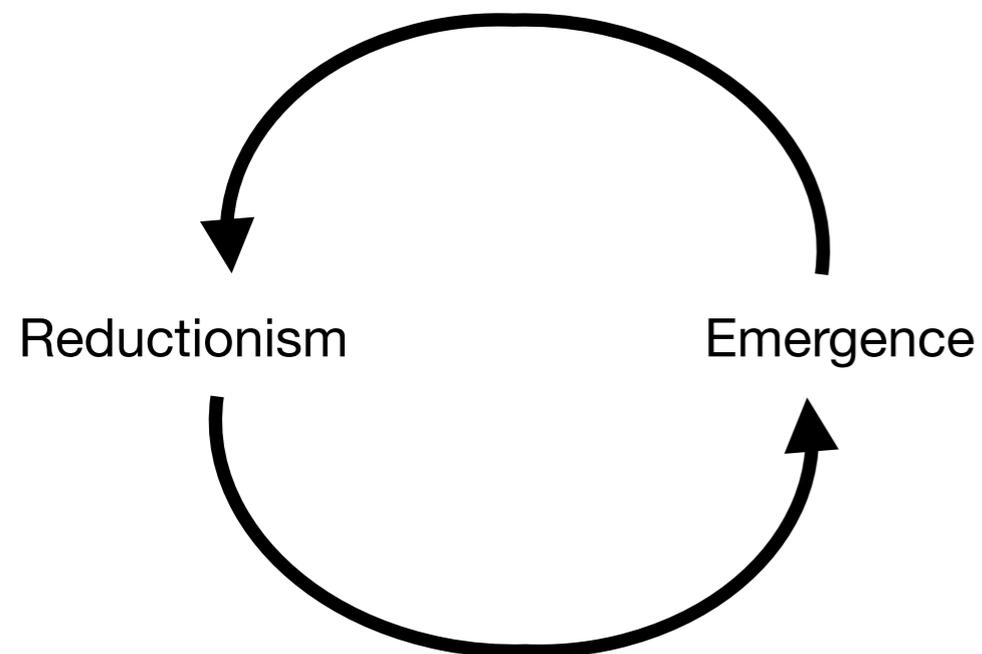
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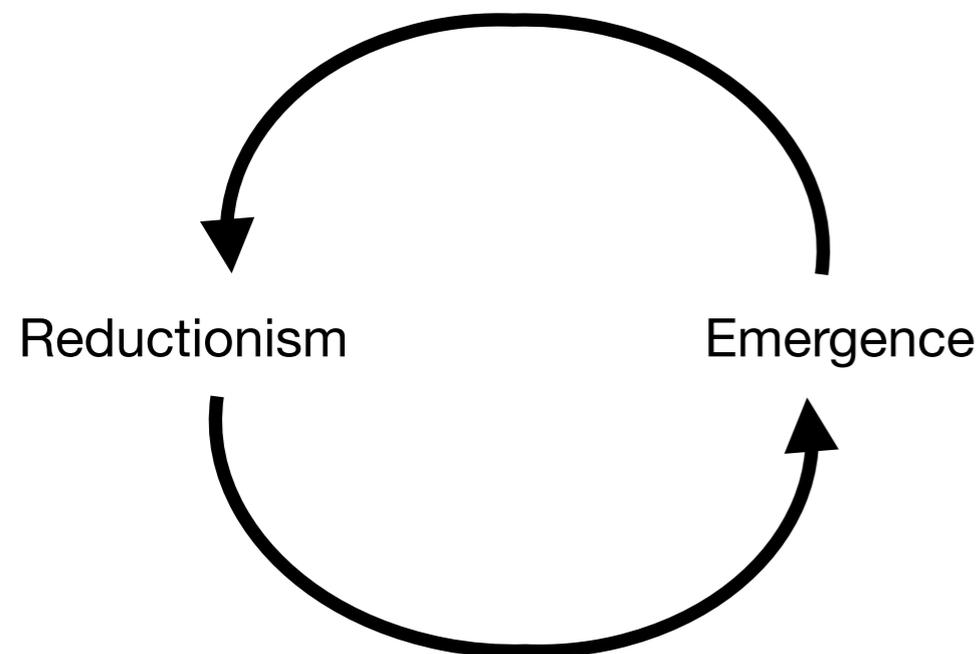
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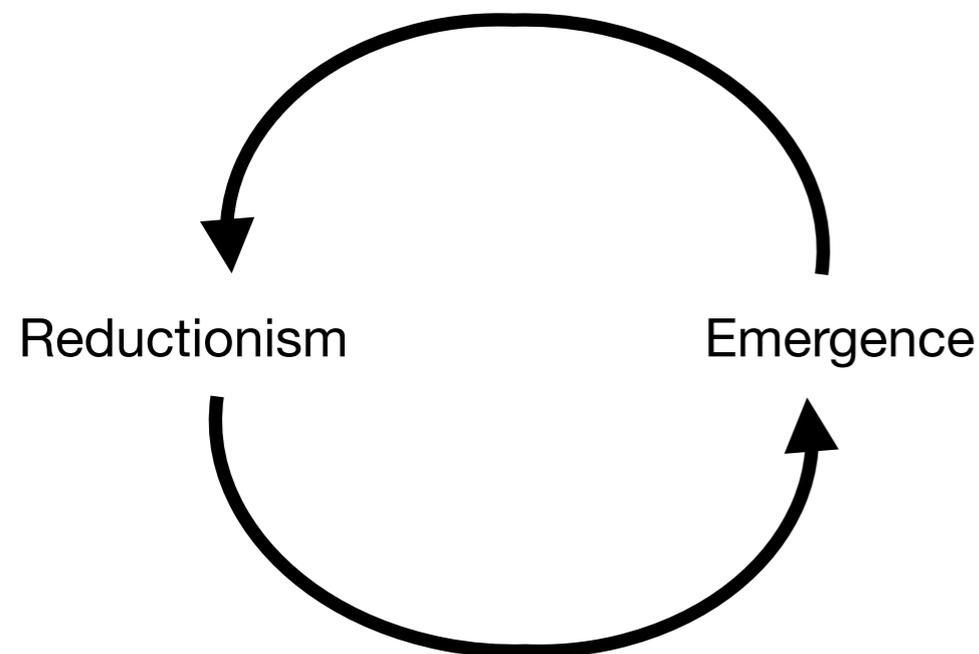
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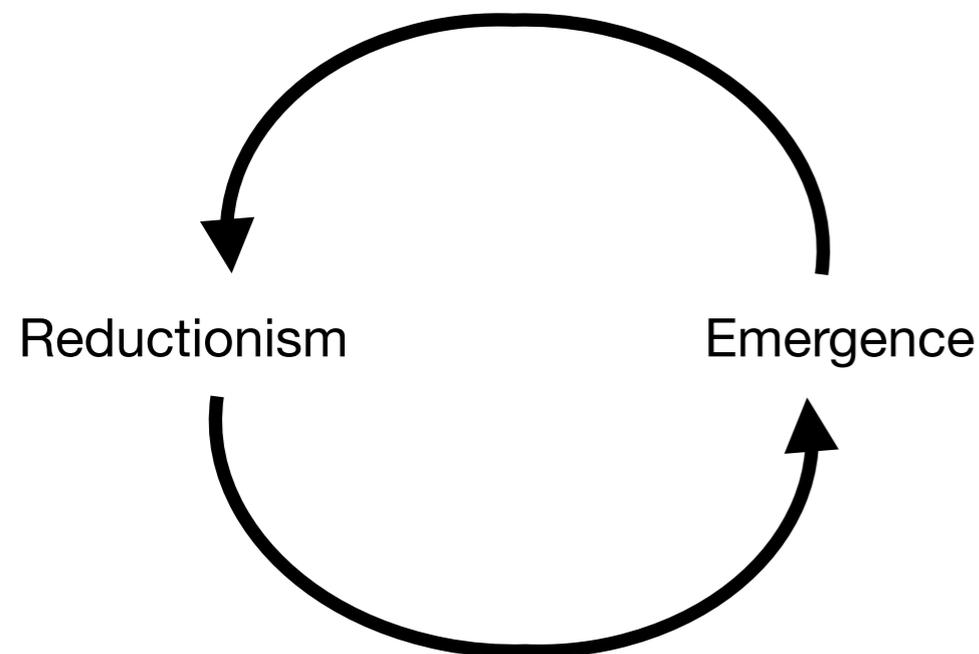
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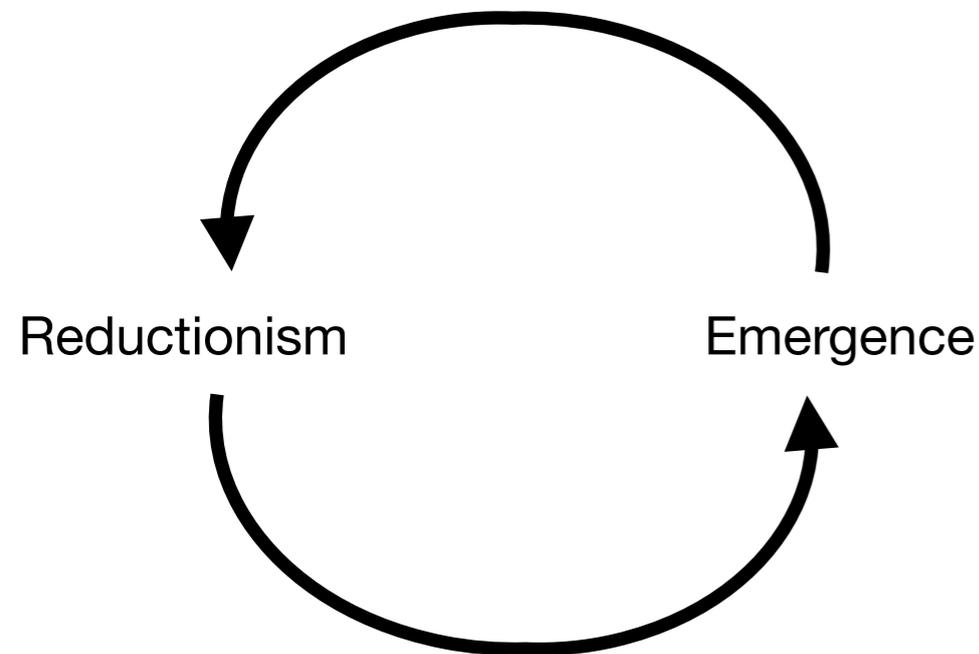
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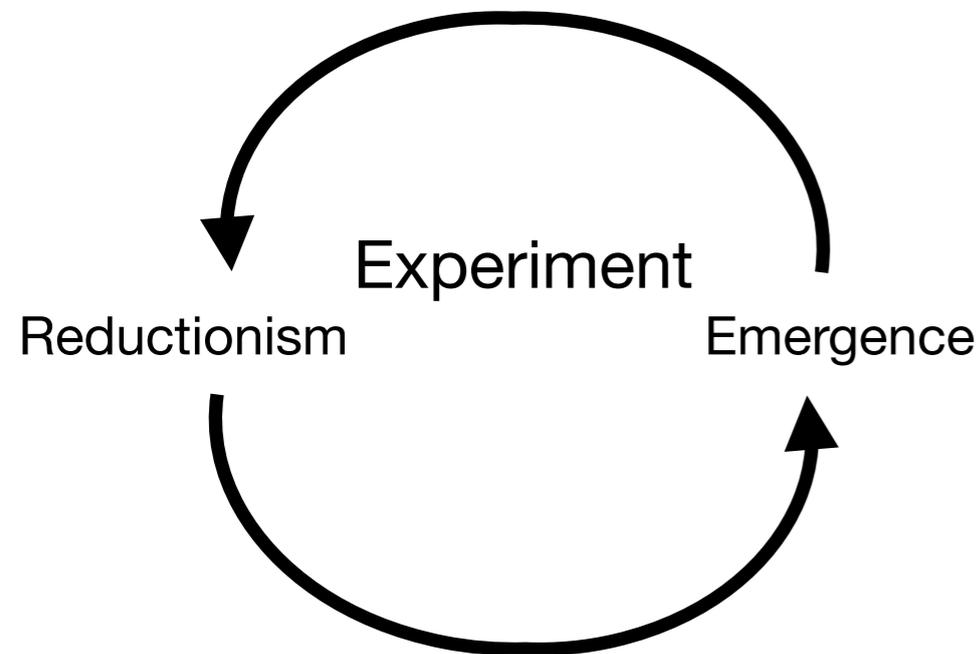
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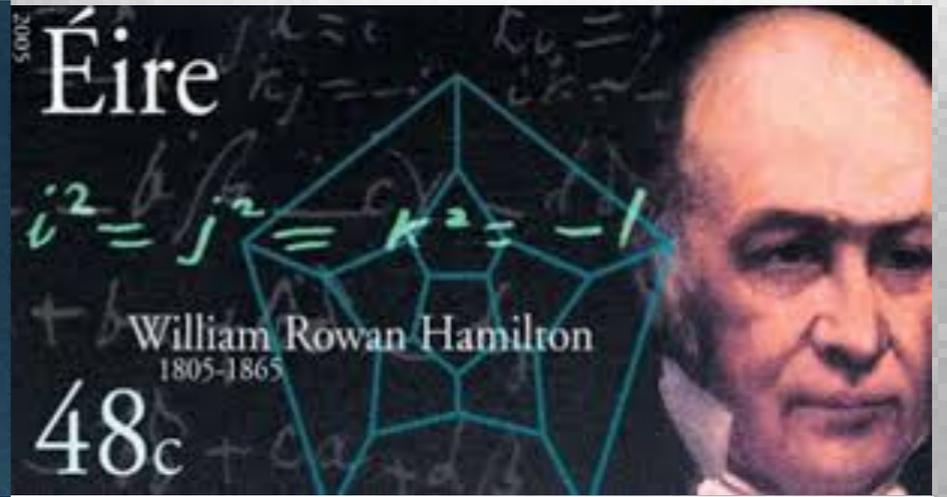
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Emergence in the classical world

The incompleteness of Classical Mechanics



Isaac Newton

Gottfried Leibniz

J. Louis Lagrange

W. Rowan Hamilton

The incompleteness of Classical Mechanics



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1758 in Paris: 72 years after “Principia”

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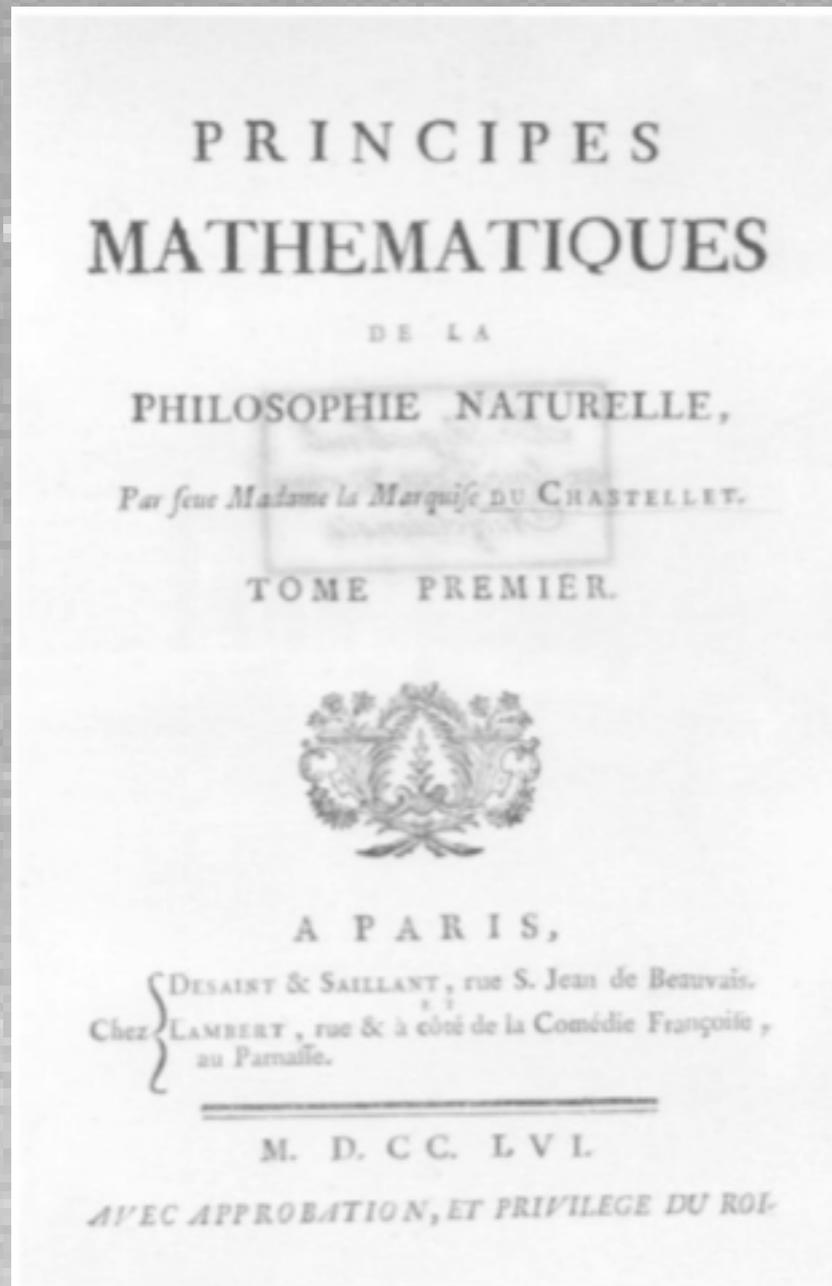
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Par son Excellence la Marquise du CHÂTELET.

TOME PREMIER.



A PARIS,

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Leibniz’ “vis vivre”

$$\sum_i m_i (v_i)^2$$

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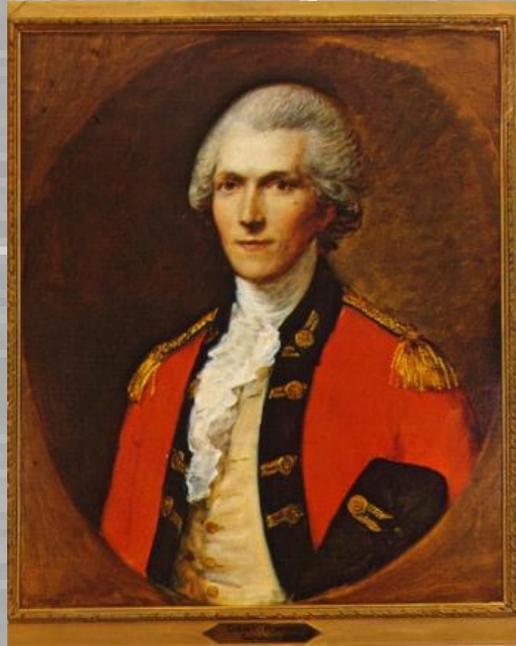
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Resolution of the controversy required understanding of an emergent phenomenon: heat.

The incompleteness of Classical Mechanics



Count Rumford (1753-1814)

Double agent, Military expert, inventor and physicist.

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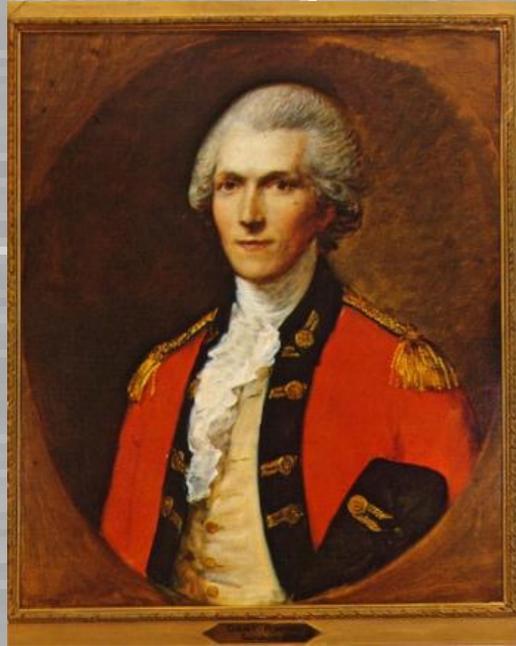
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The incompleteness of Classical Mechanics



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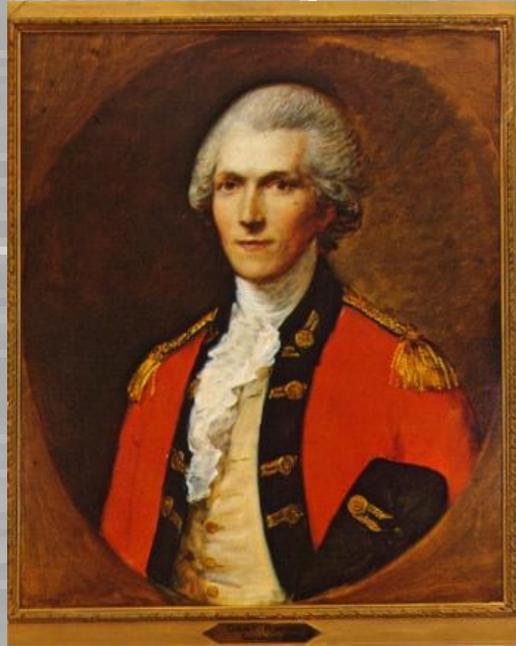
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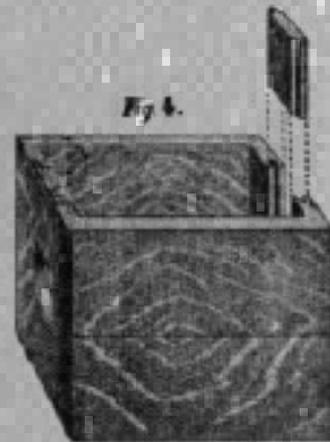
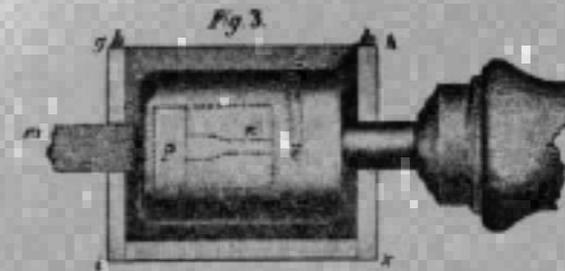
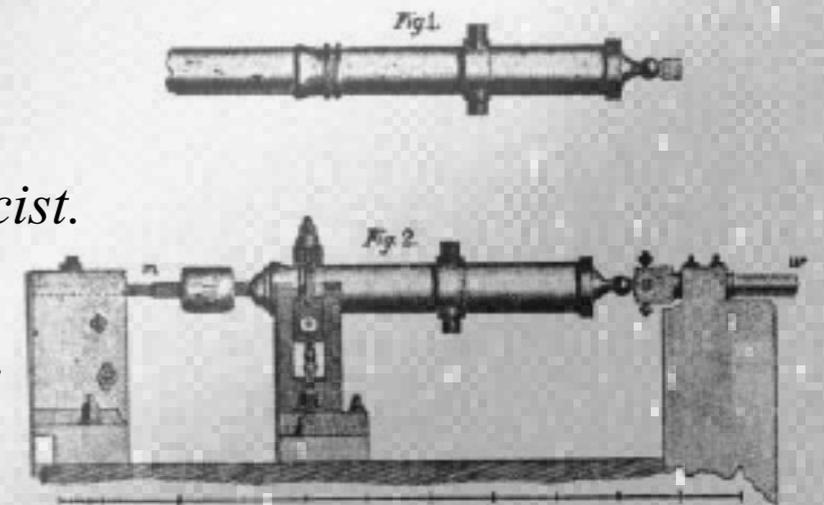
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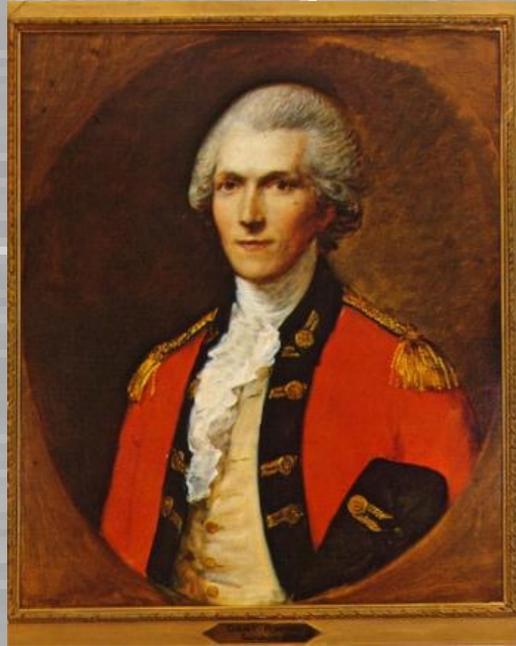
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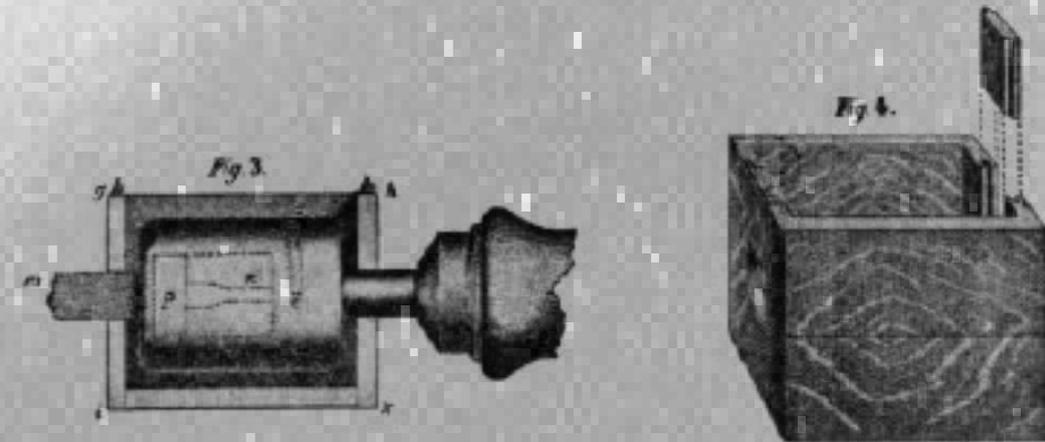
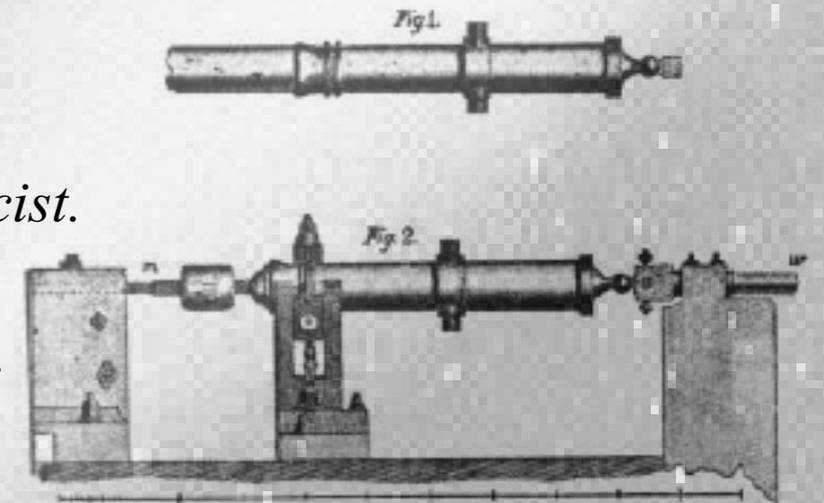
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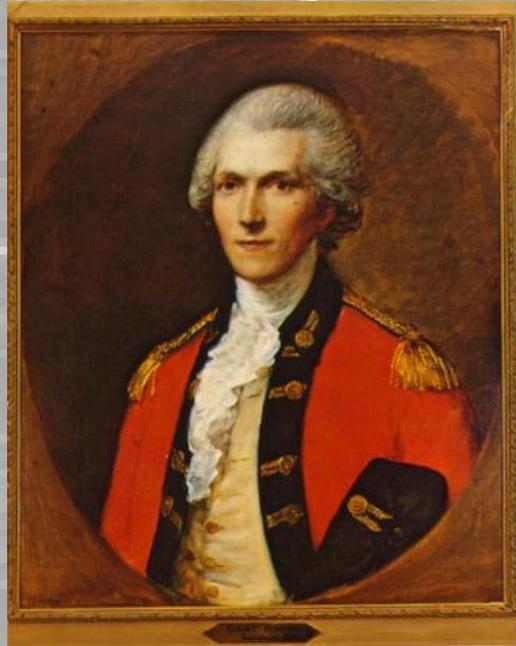
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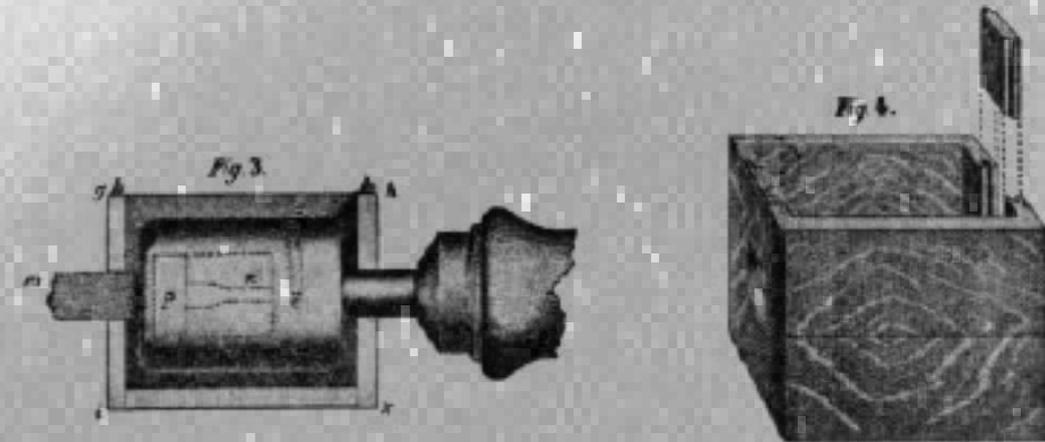
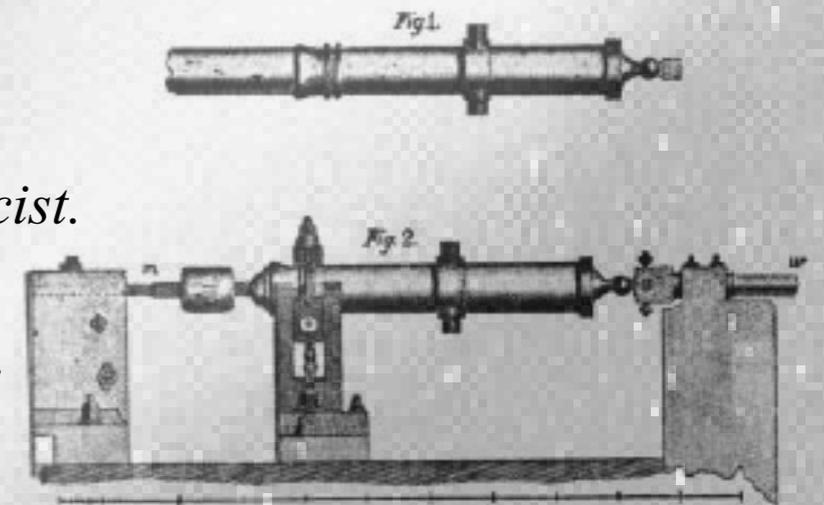
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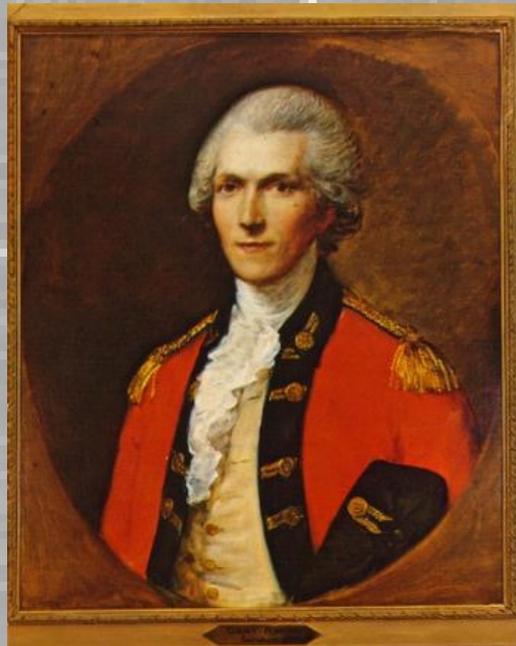
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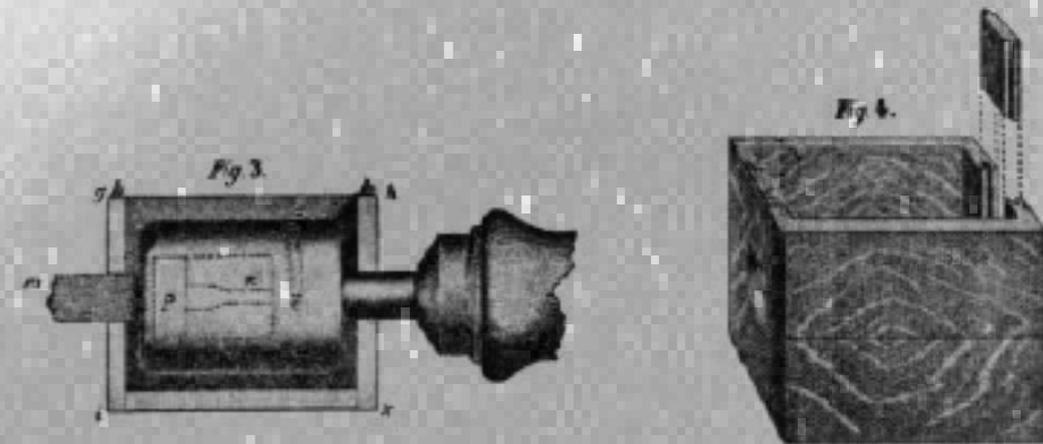
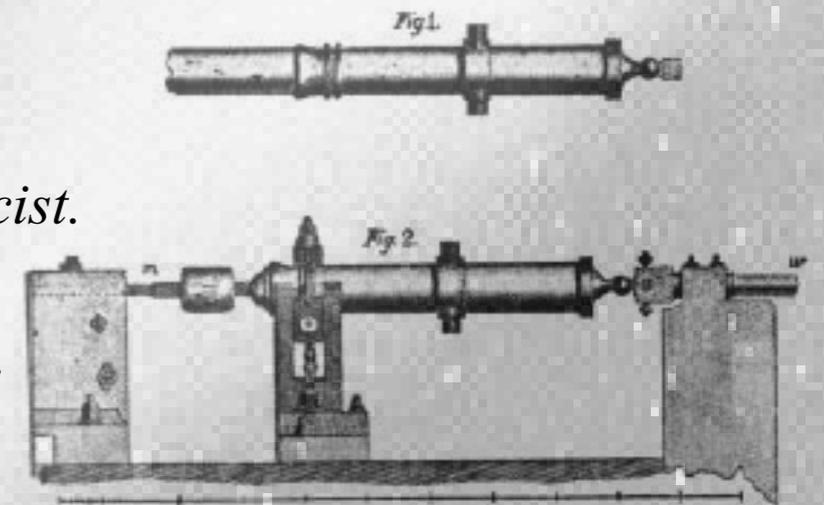
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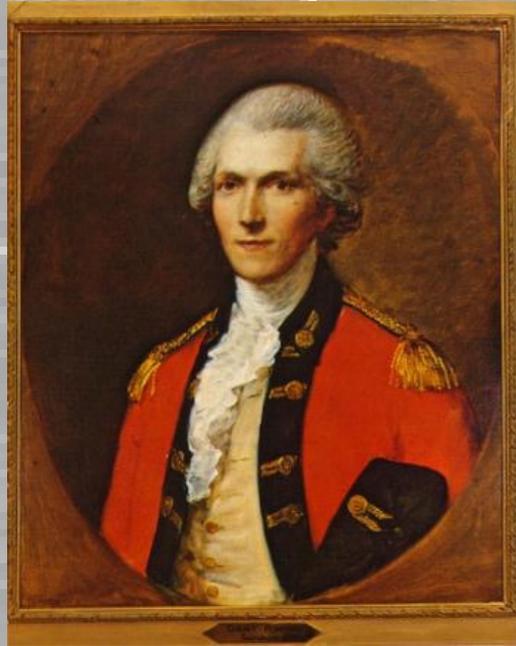
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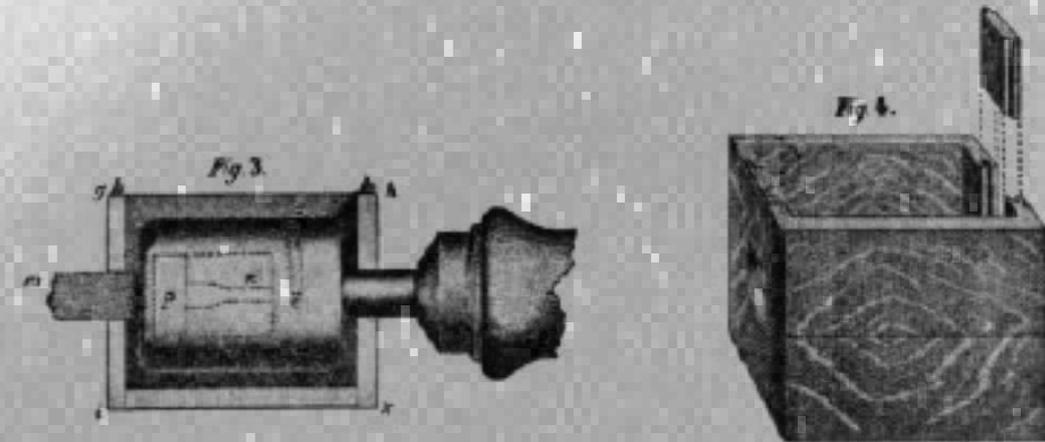
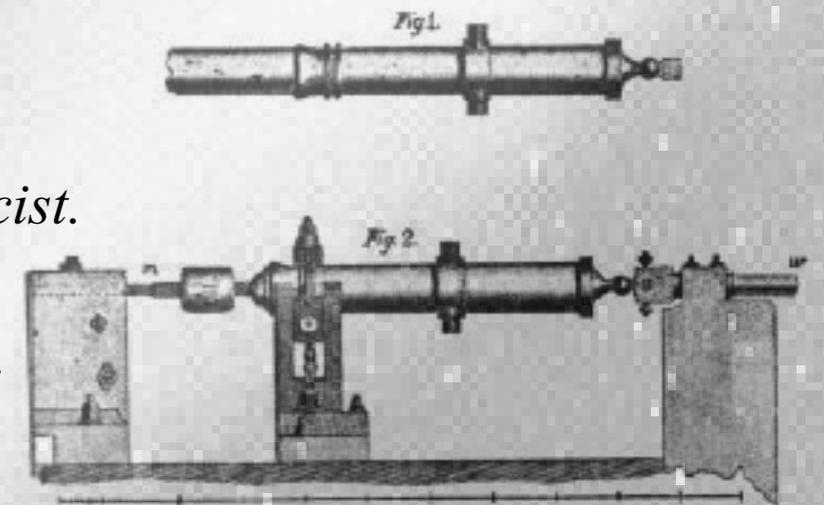
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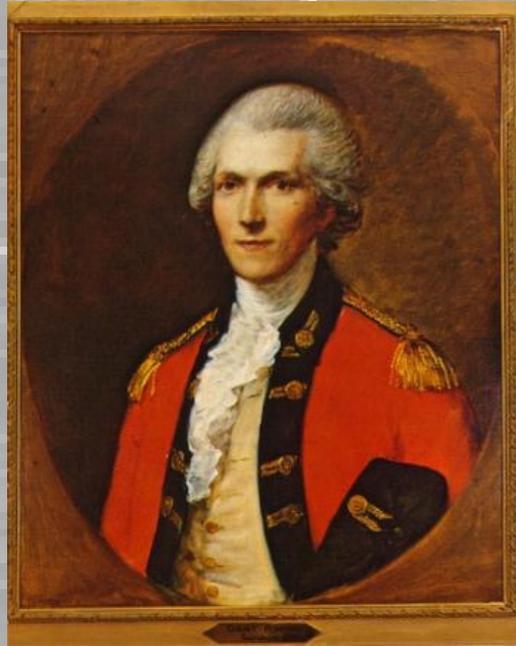
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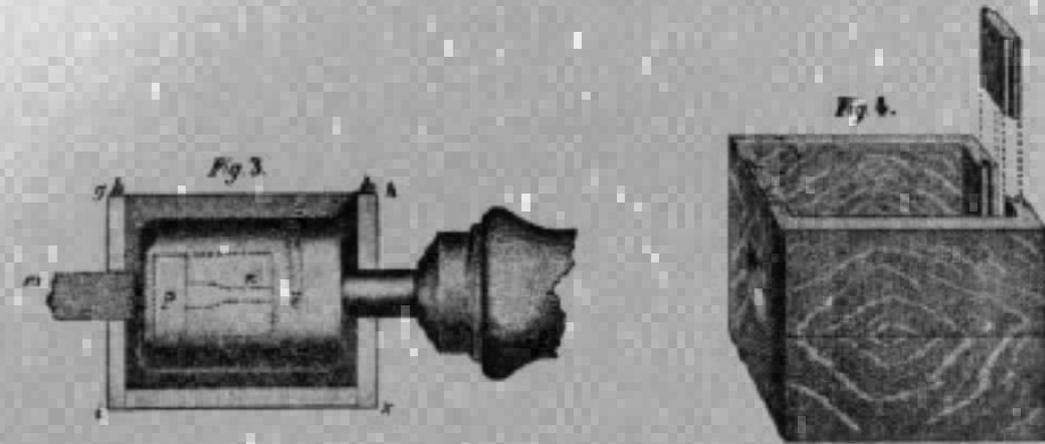
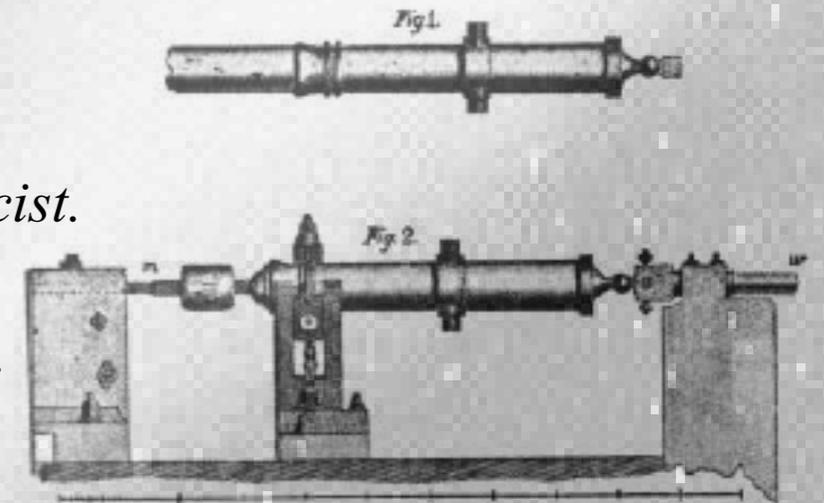
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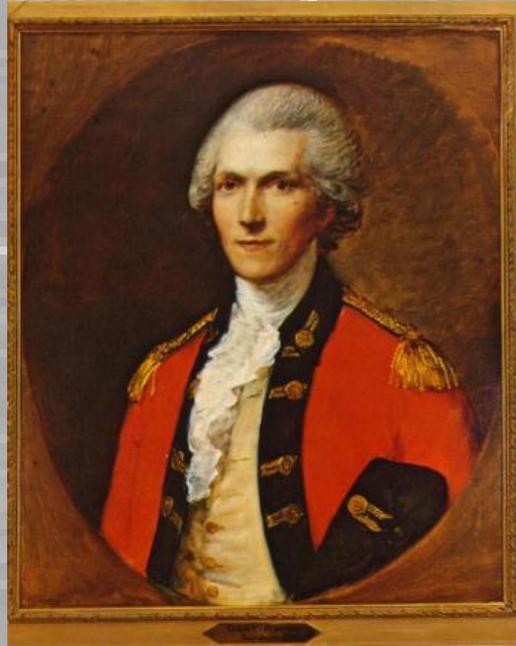
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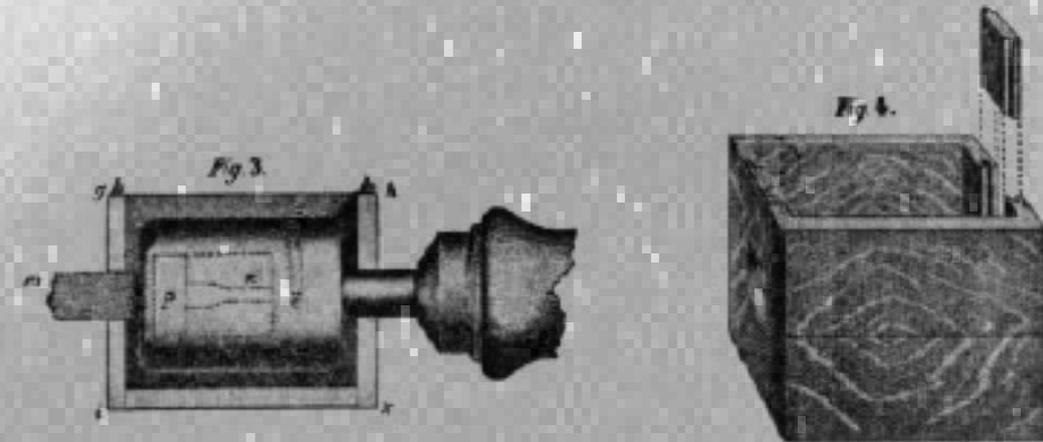
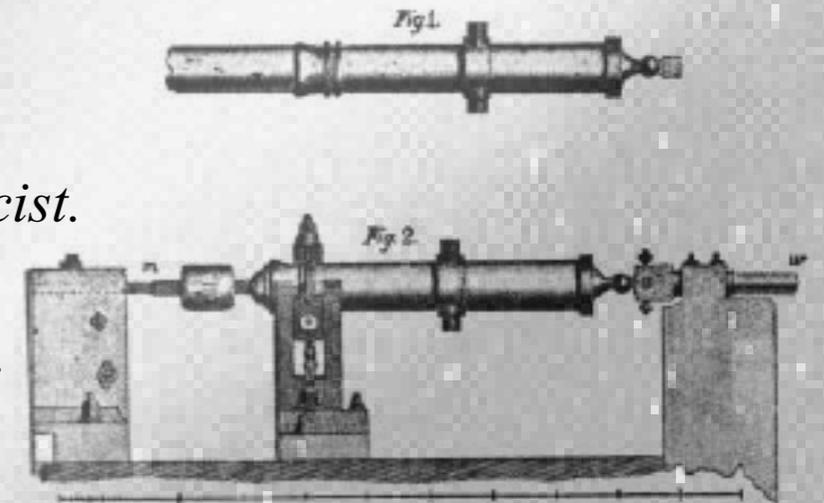
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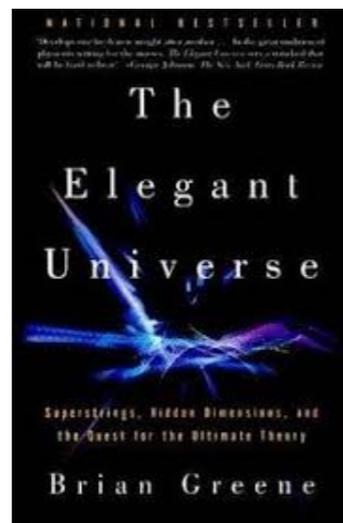
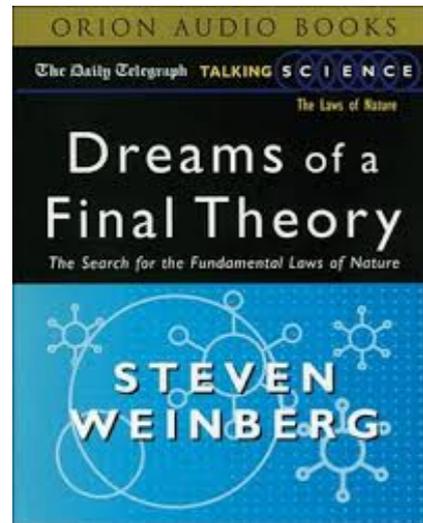
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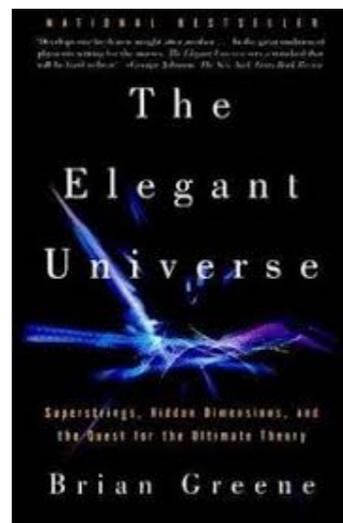
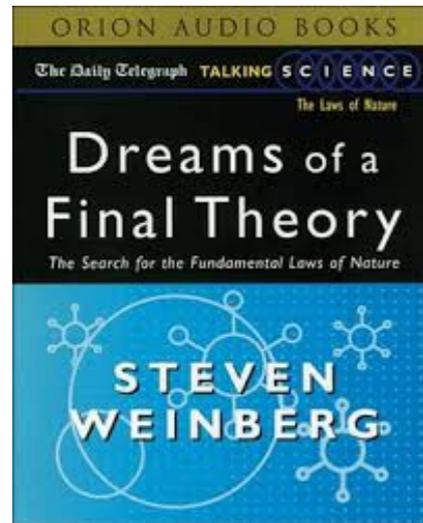


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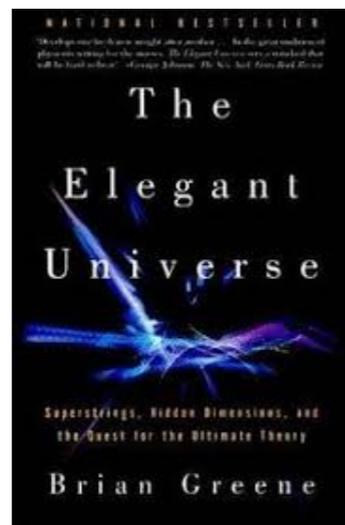
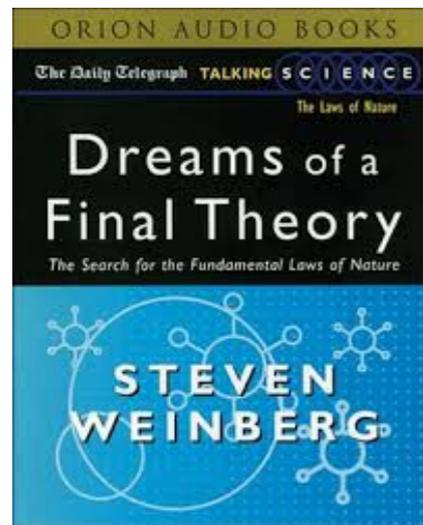


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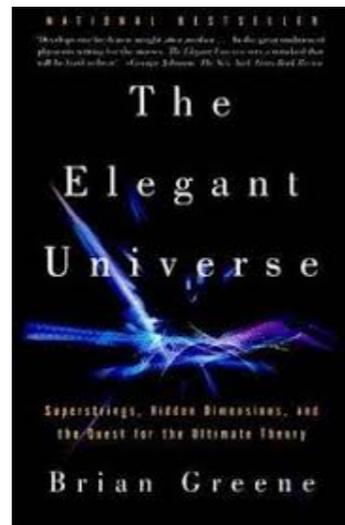
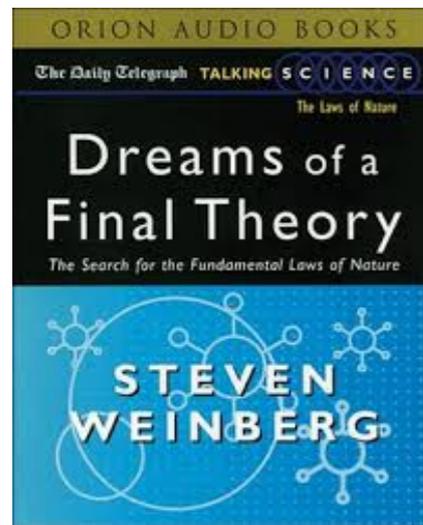


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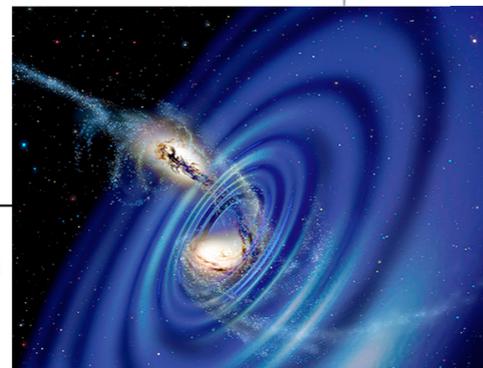
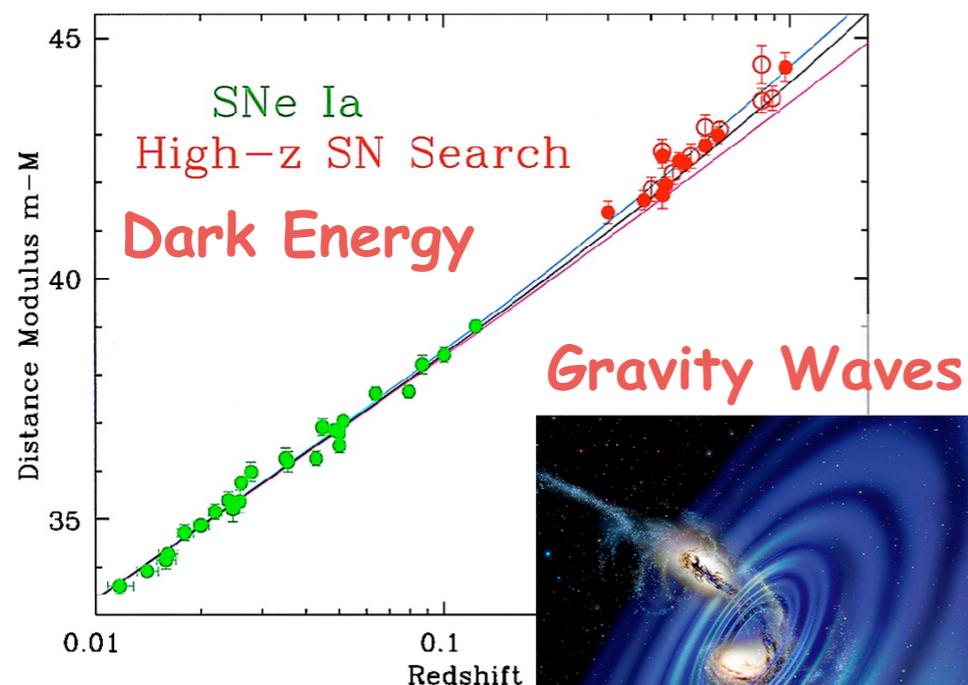
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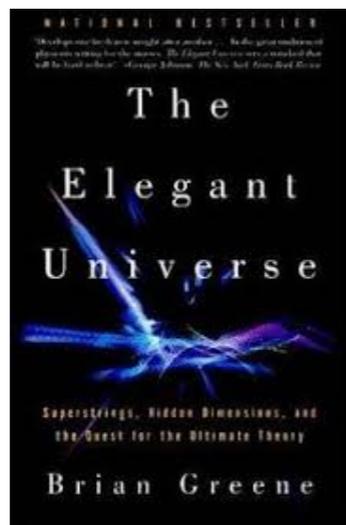
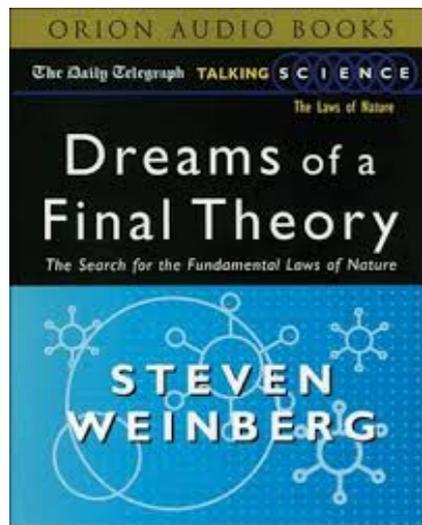
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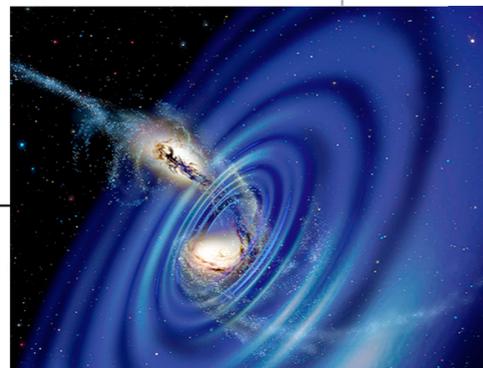
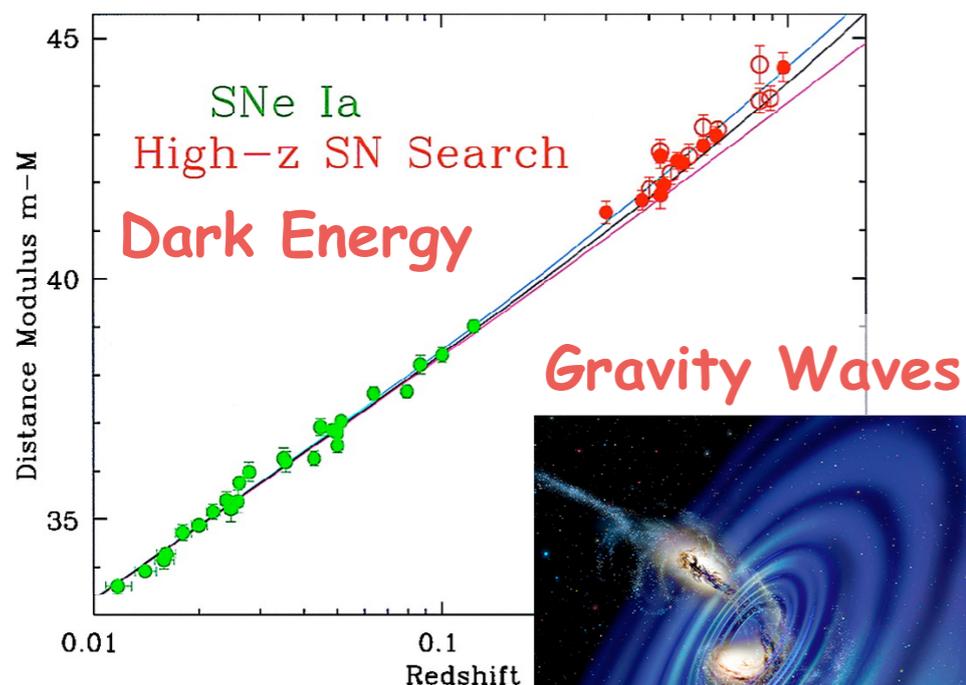
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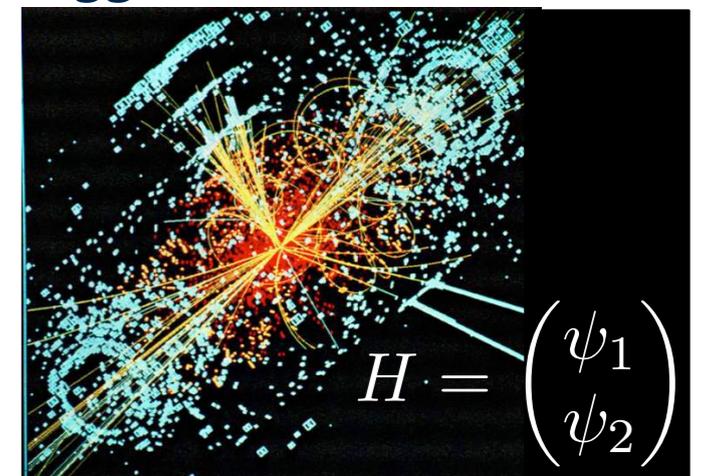
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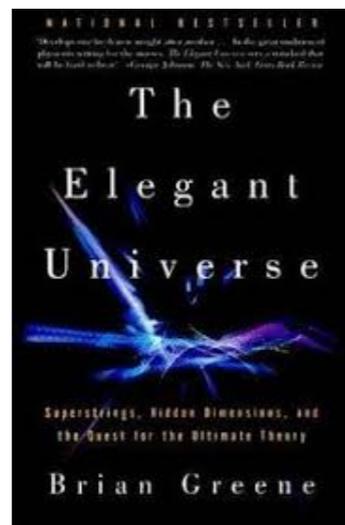
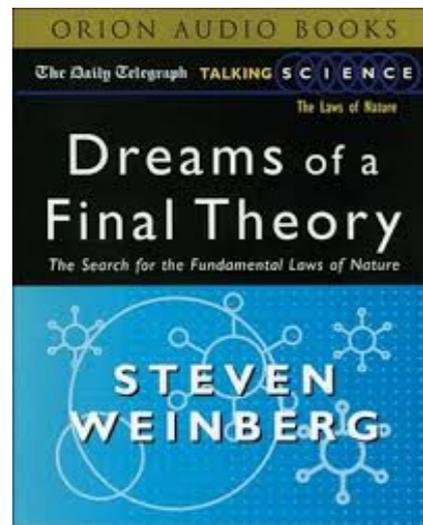
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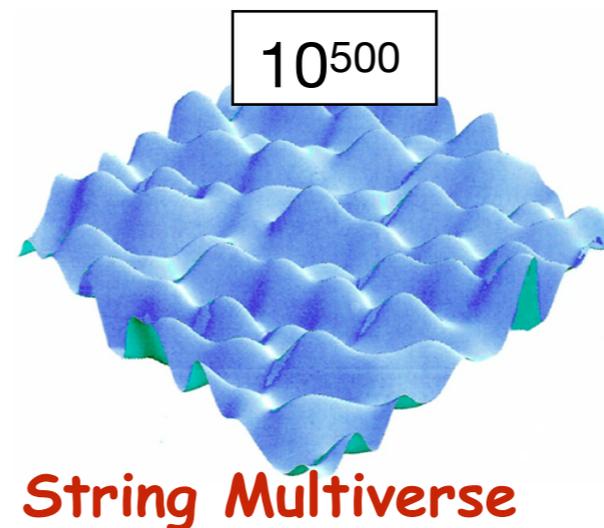
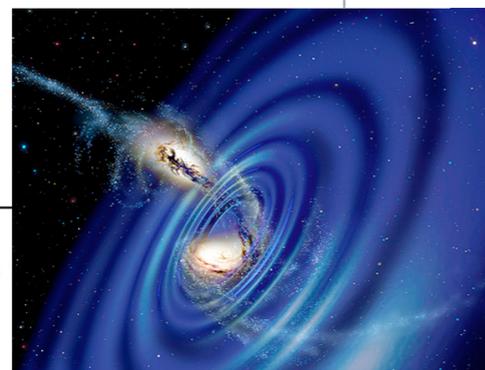
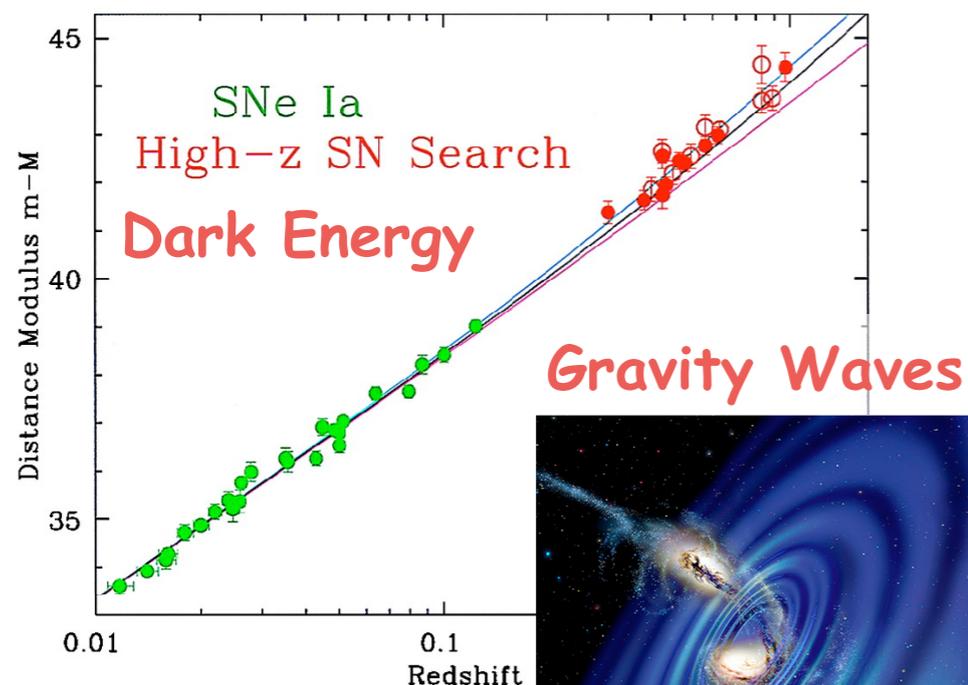
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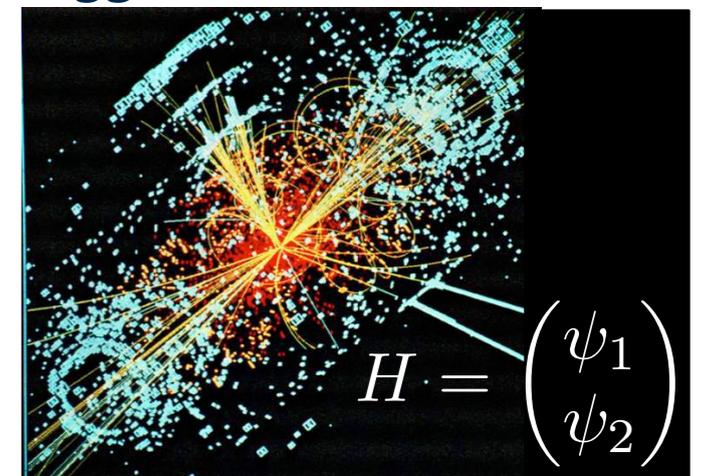
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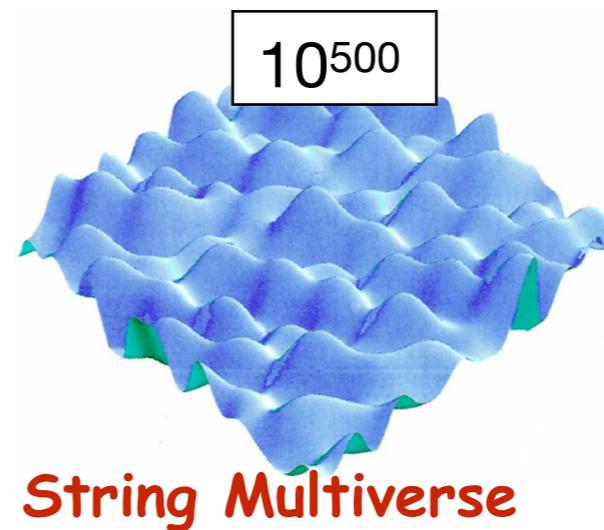
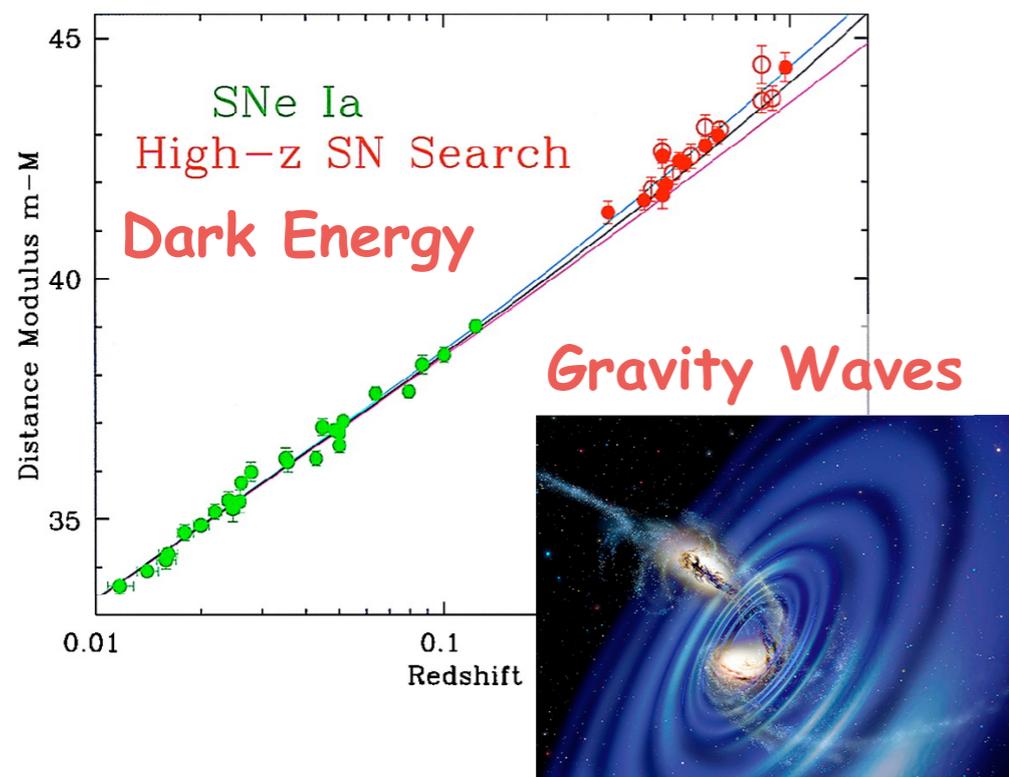
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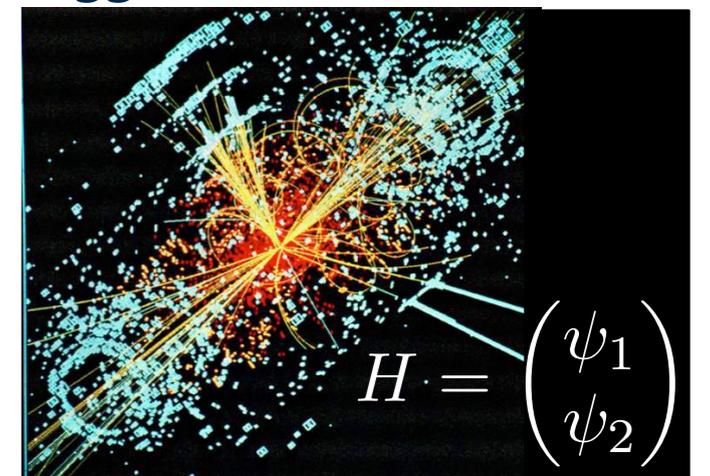
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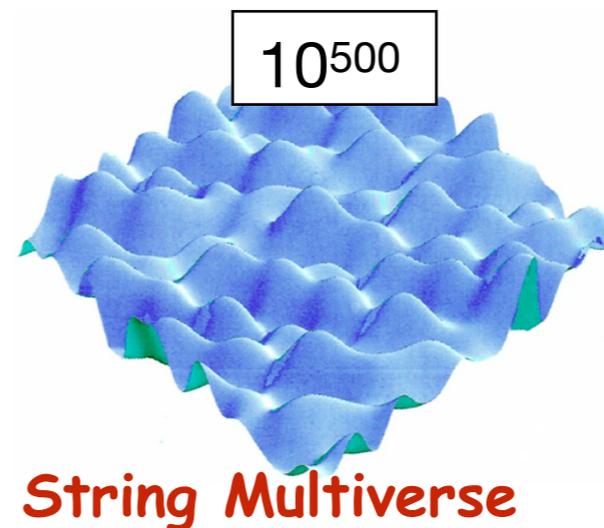
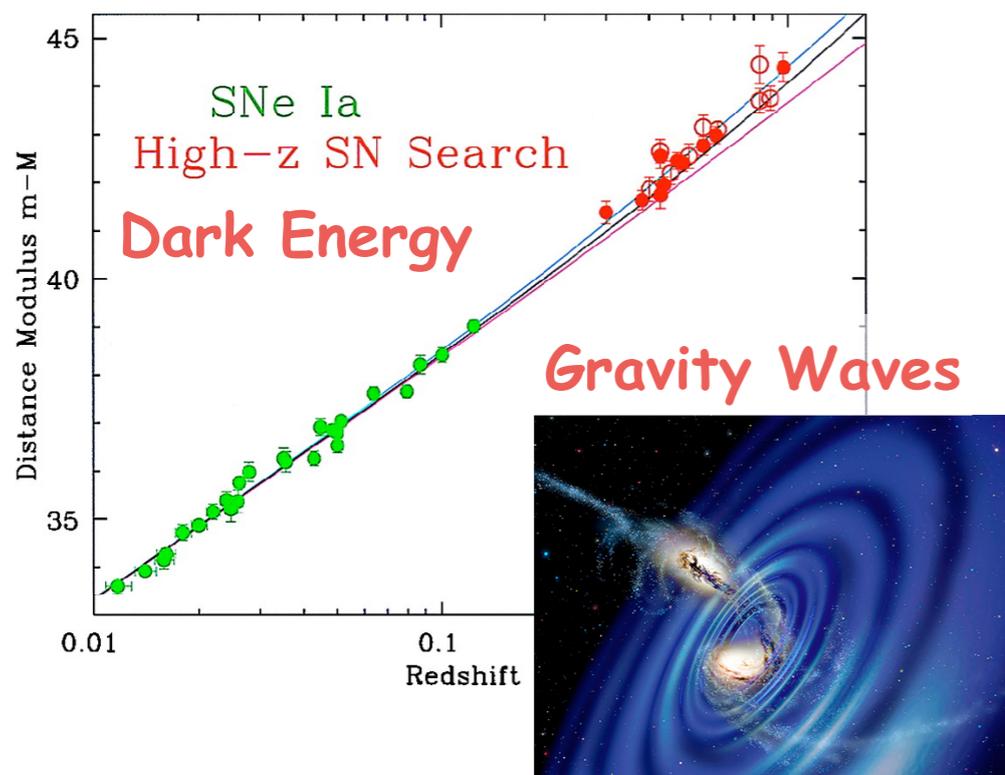
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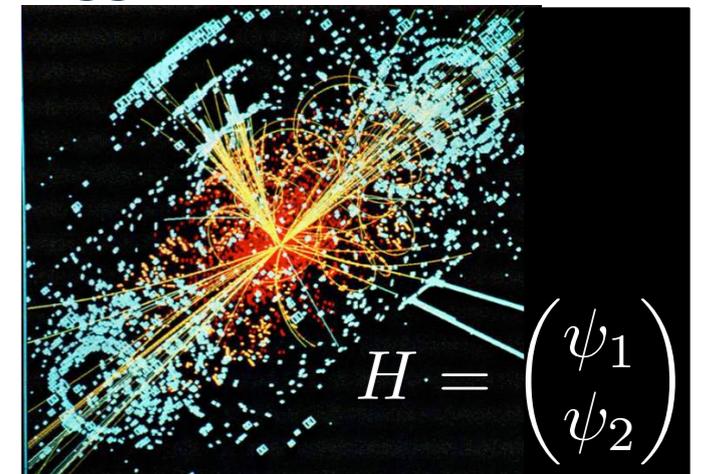
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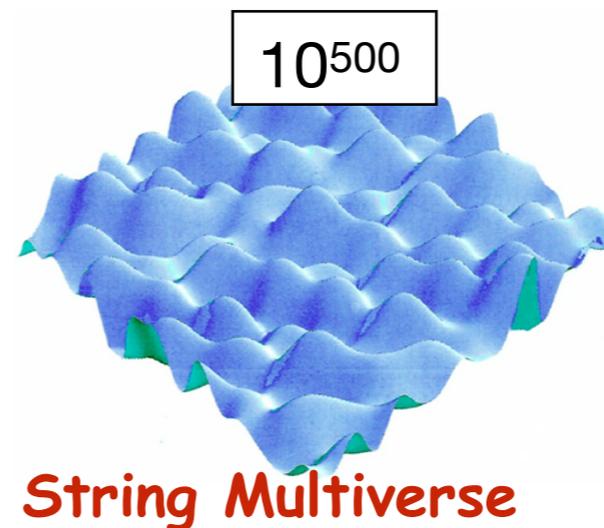
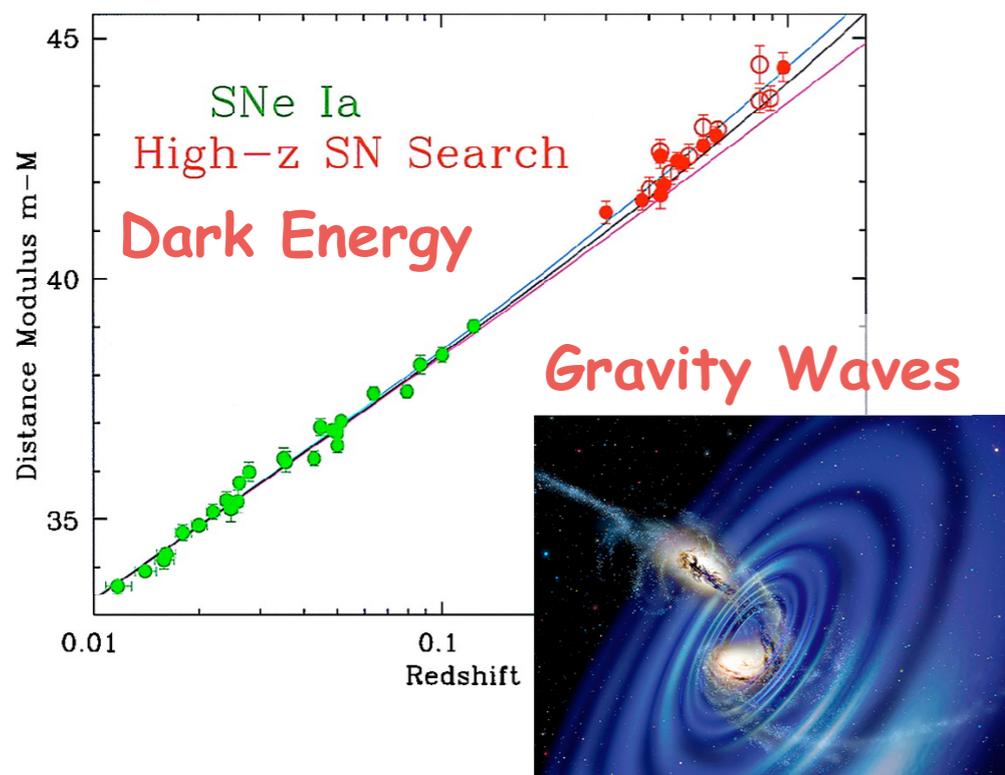
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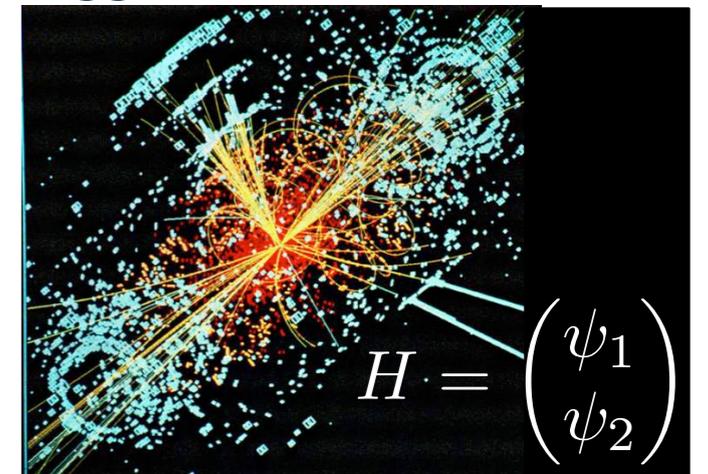
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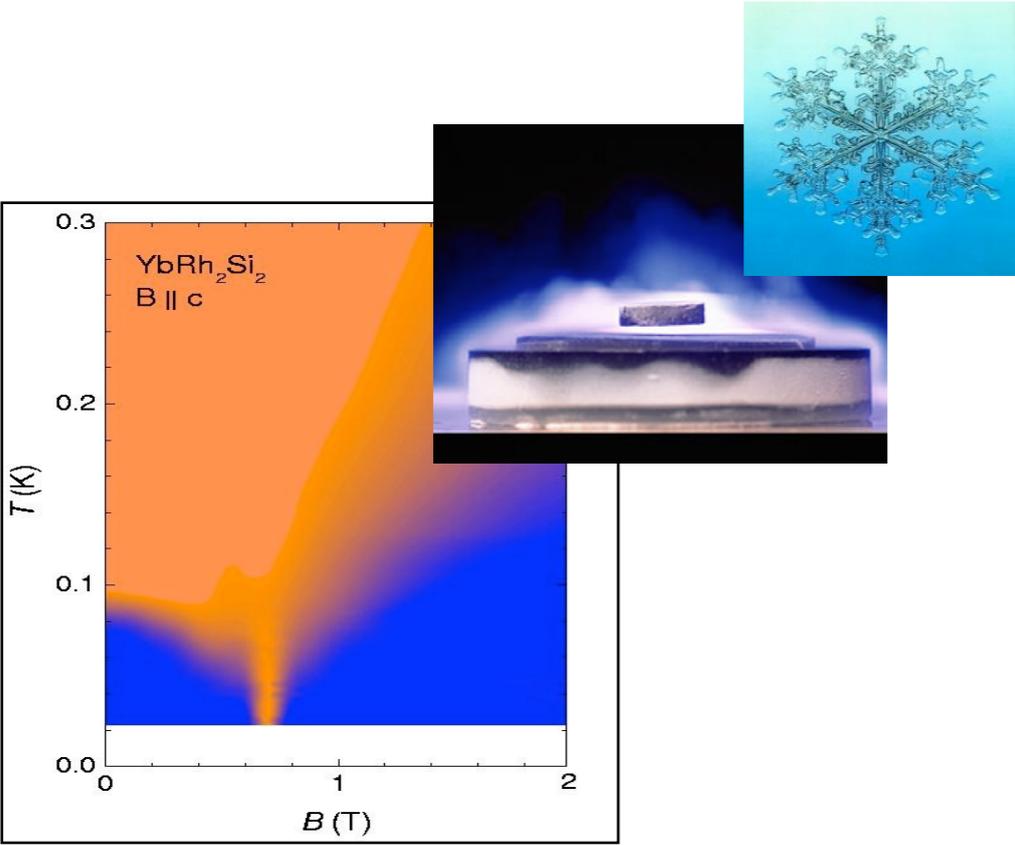
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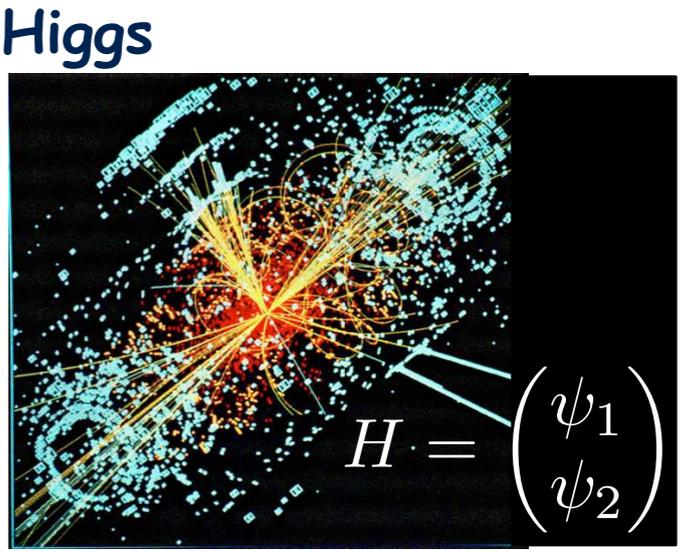
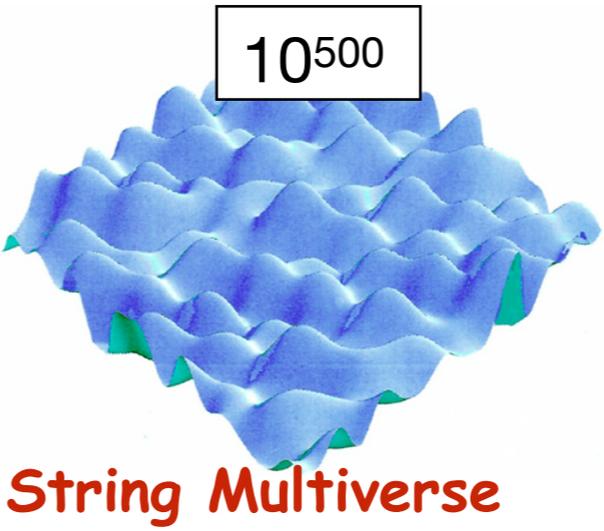
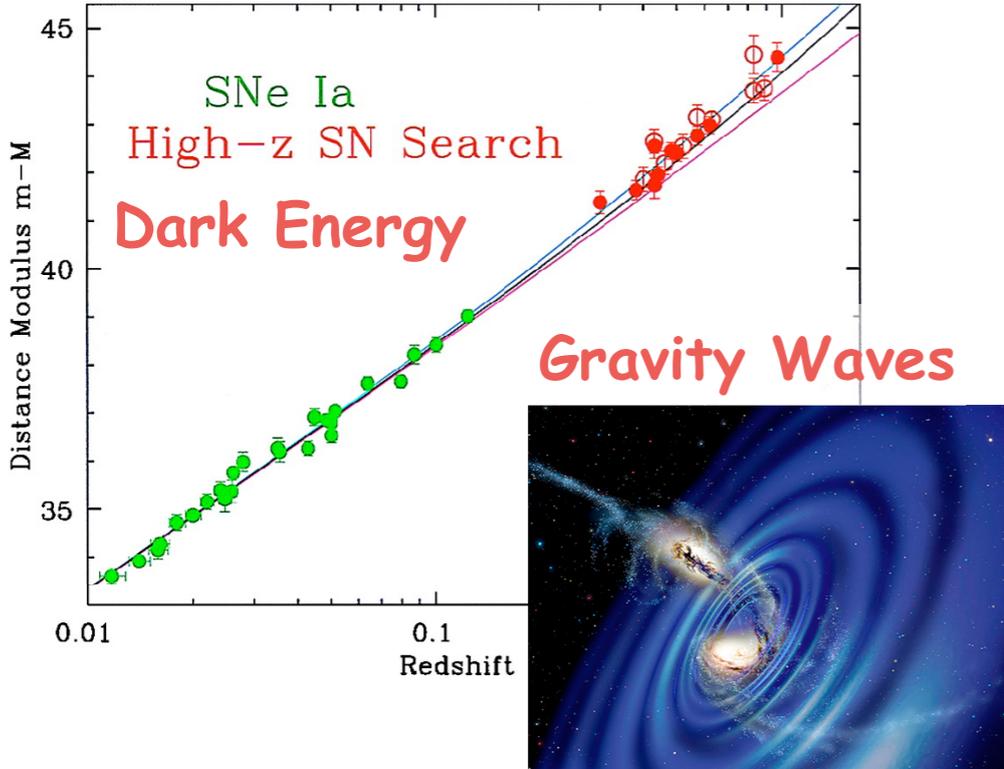
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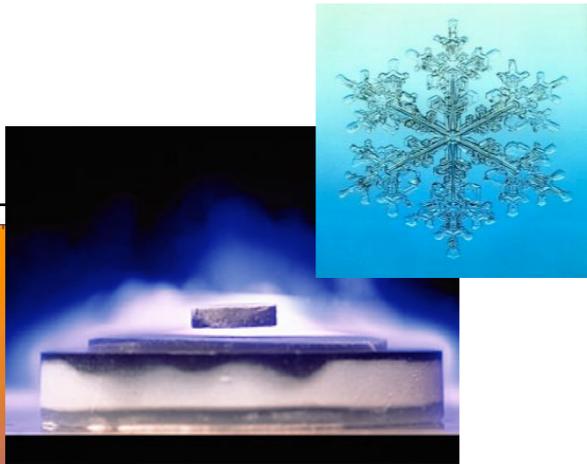
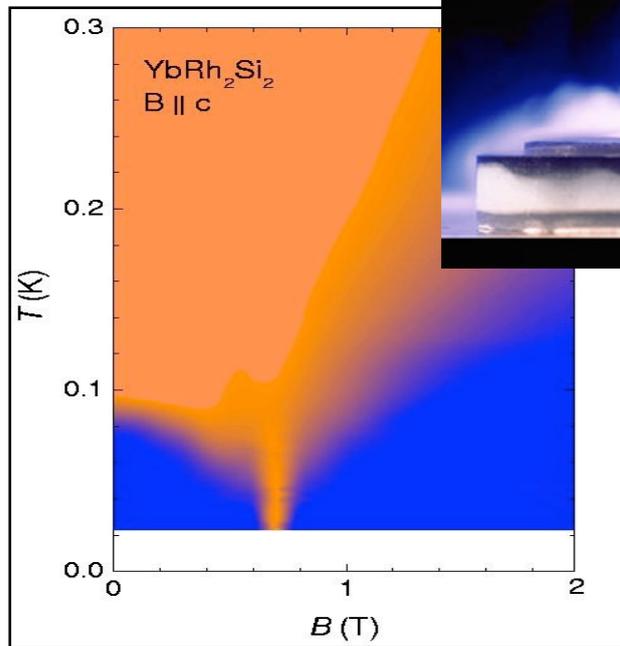
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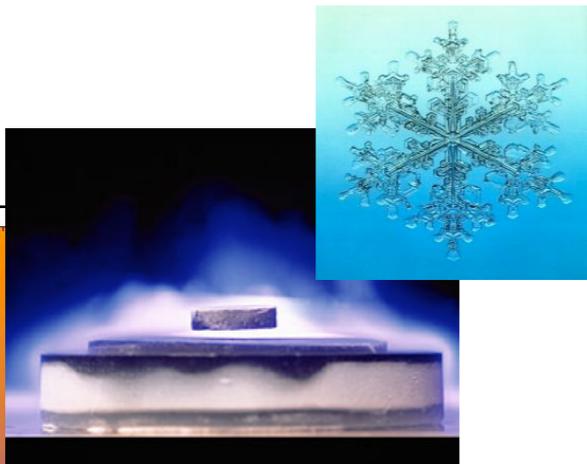
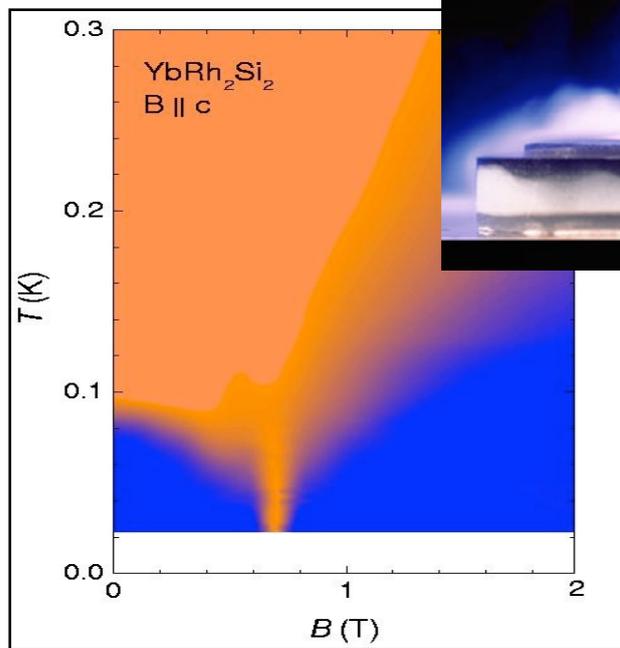


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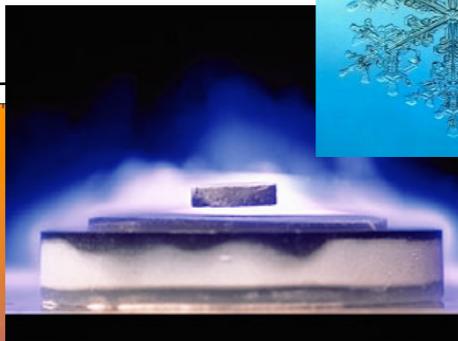
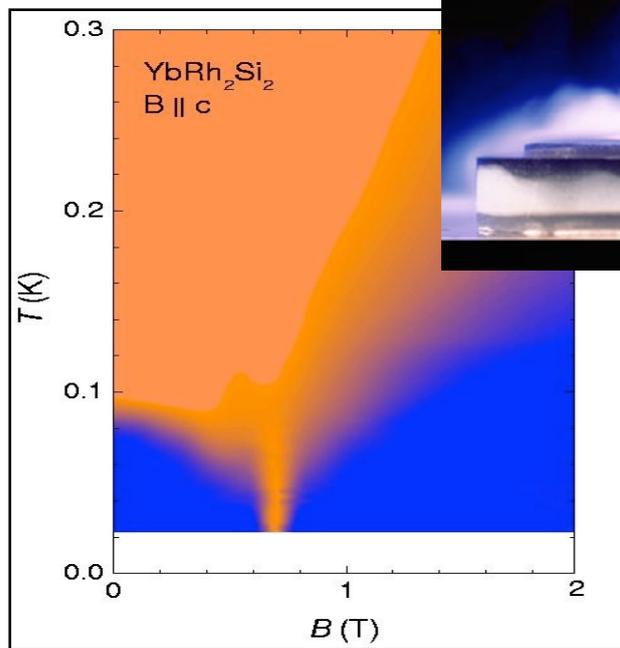
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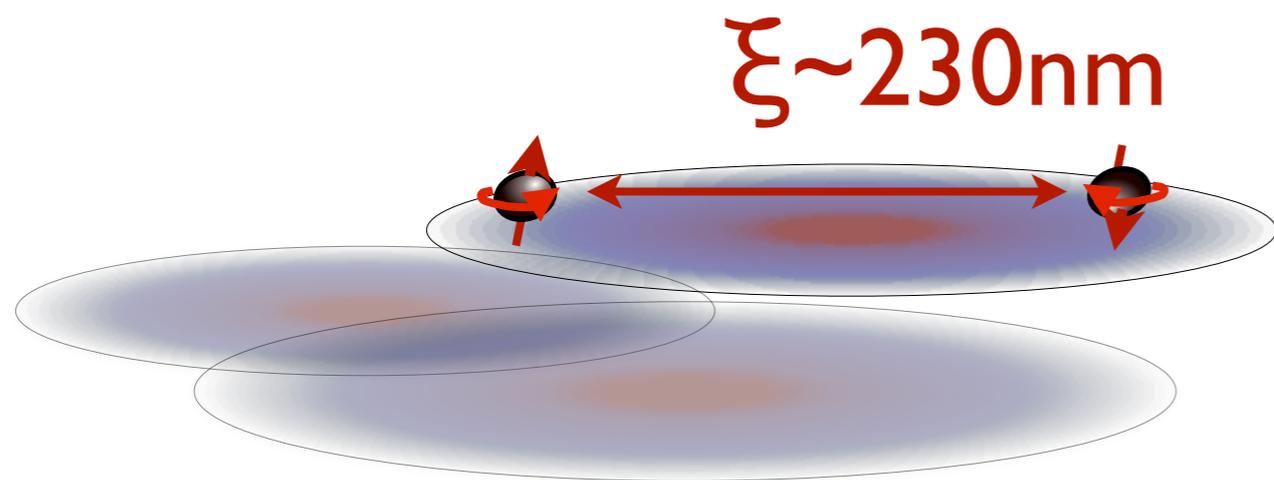
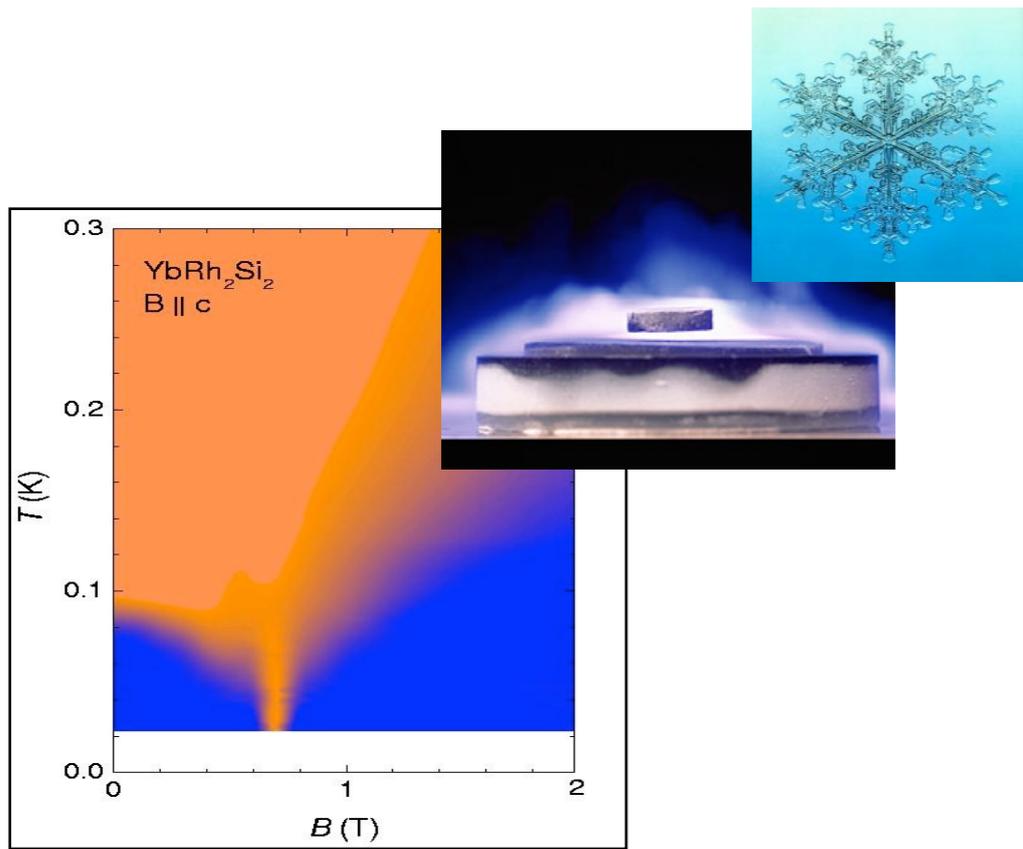
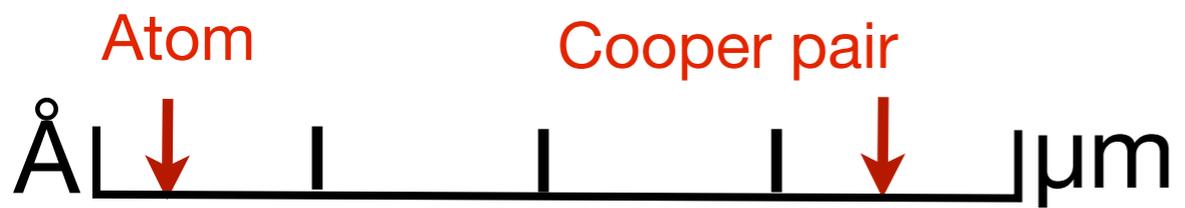
From the Angstrom to the Micron

Atom



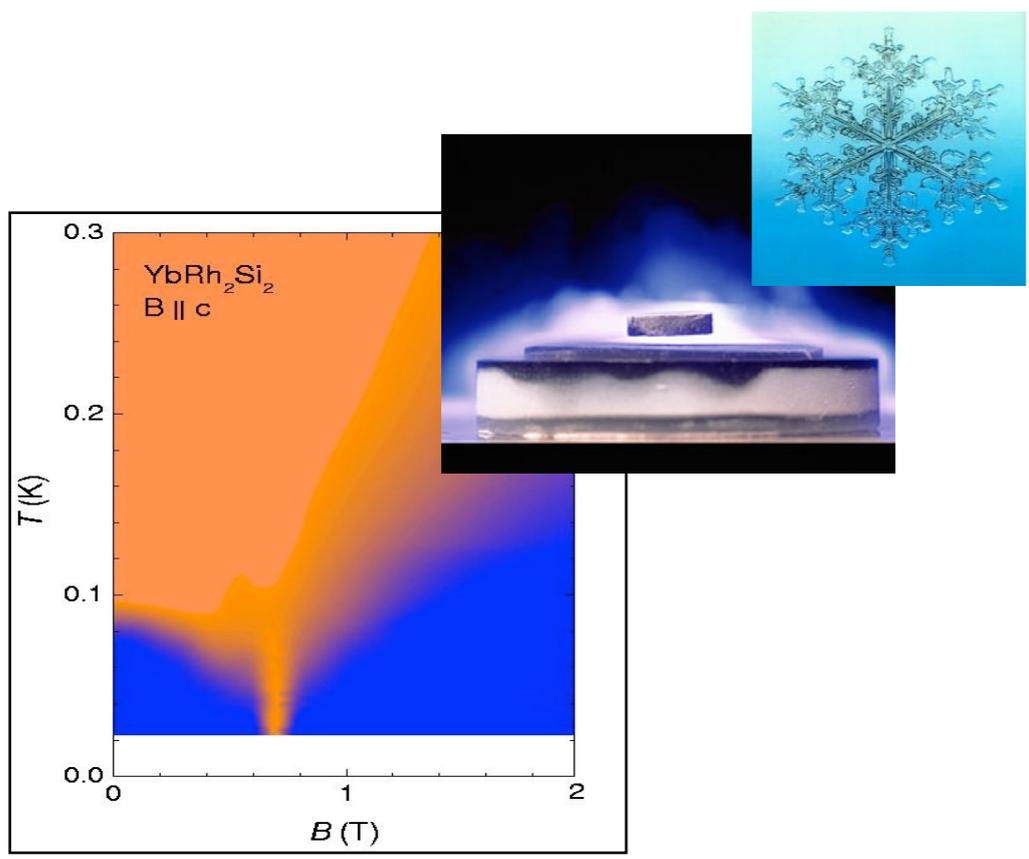
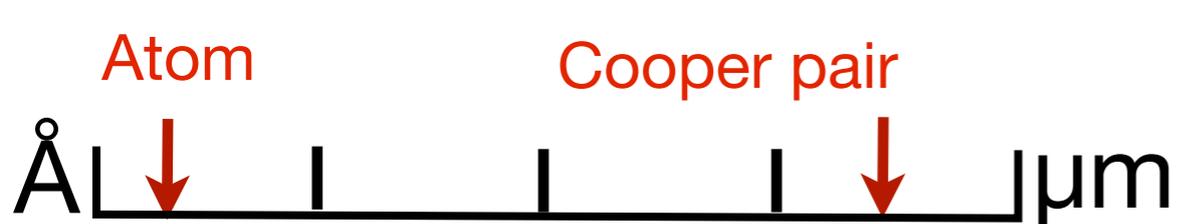
“The behavior of large and complex aggregations of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other.” Philip. W. Anderson “More is Different”, 1967.

From the Angstrom to the Micron



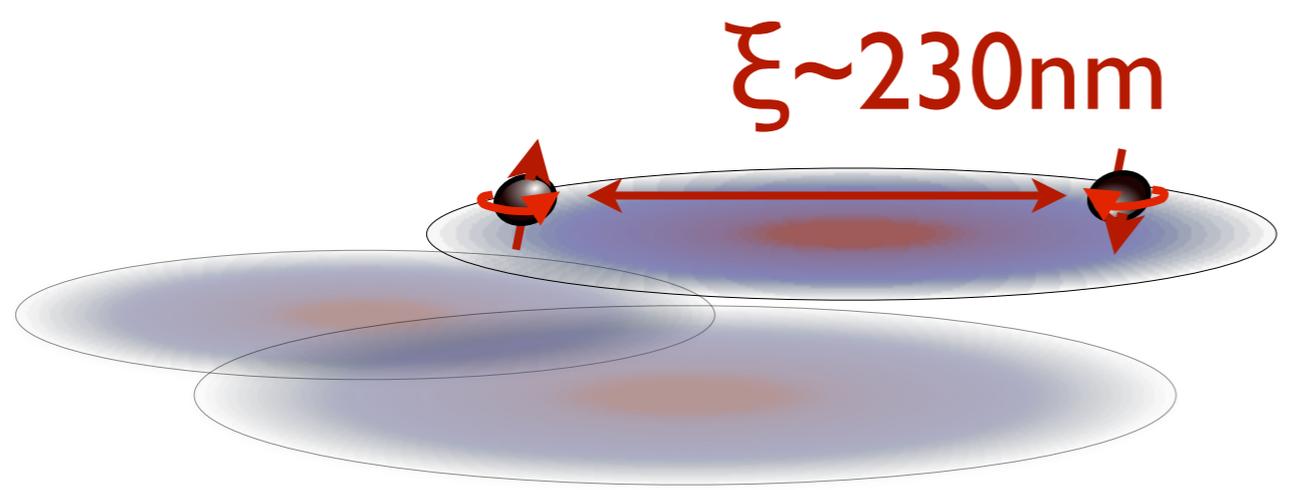
Cooper Pair in Sn

From the Angstrom to the Micron



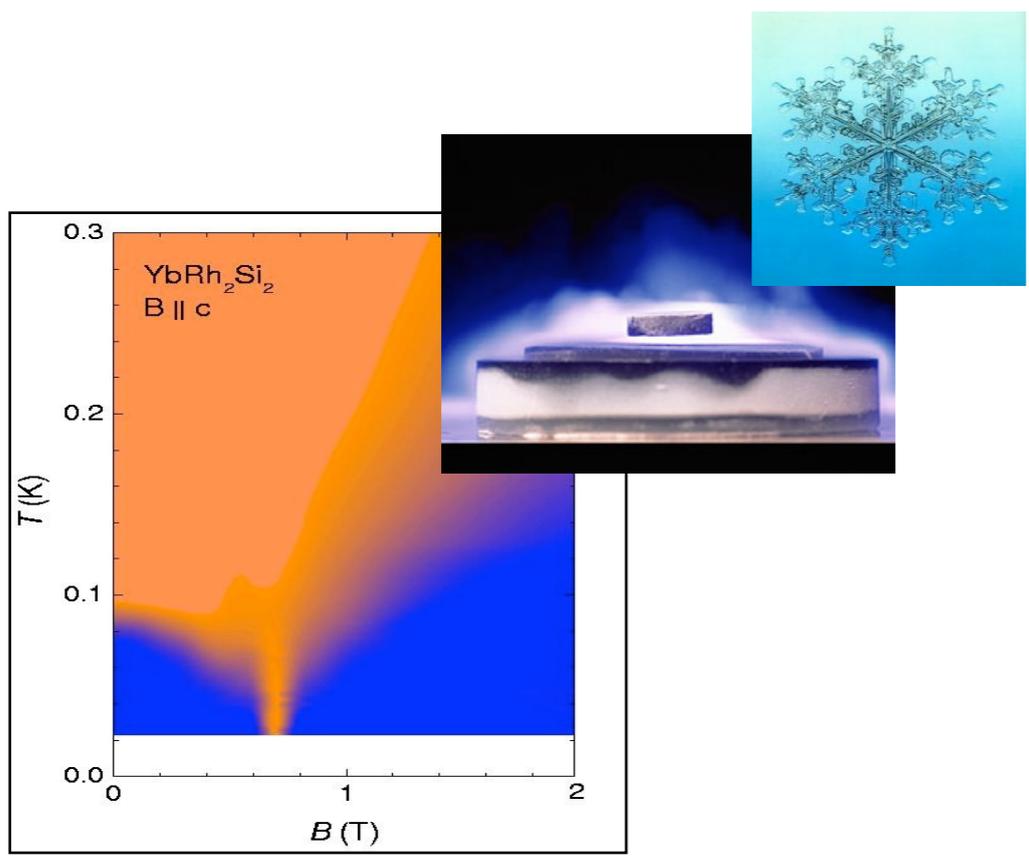
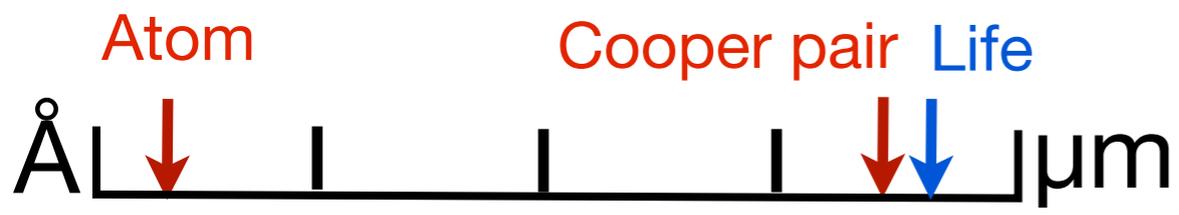
4f	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb
5f	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No
3d	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu				
4d	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag				
5d	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au				

Universe of Quantum Materials



Cooper Pair in Sn

From the Angstrom to the Micron

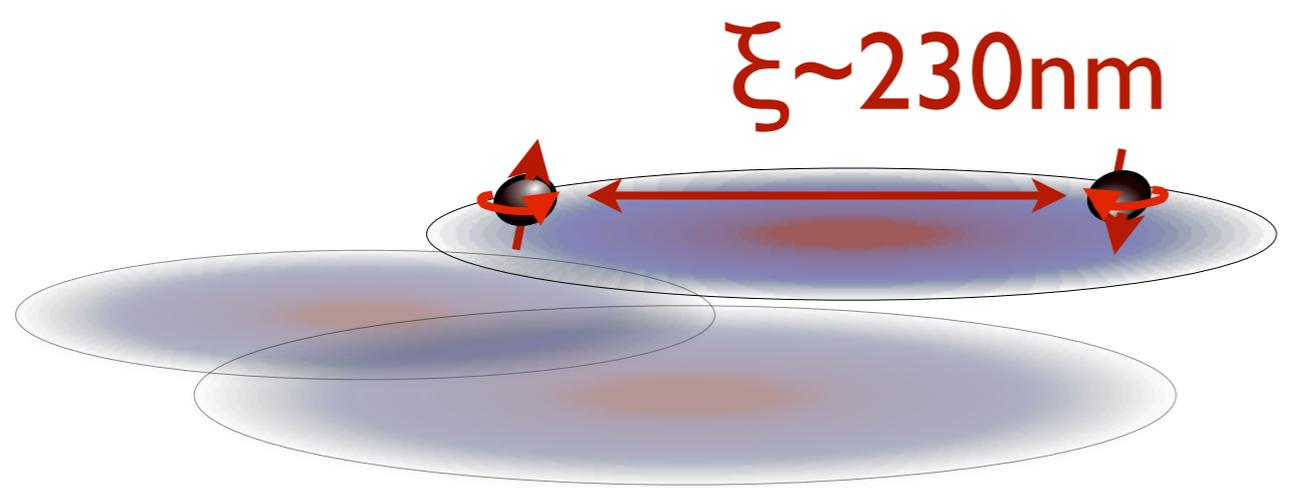


4f	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb
5f	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No
3d	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu				
4d	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag				
5d	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au				

Universe of Quantum Materials

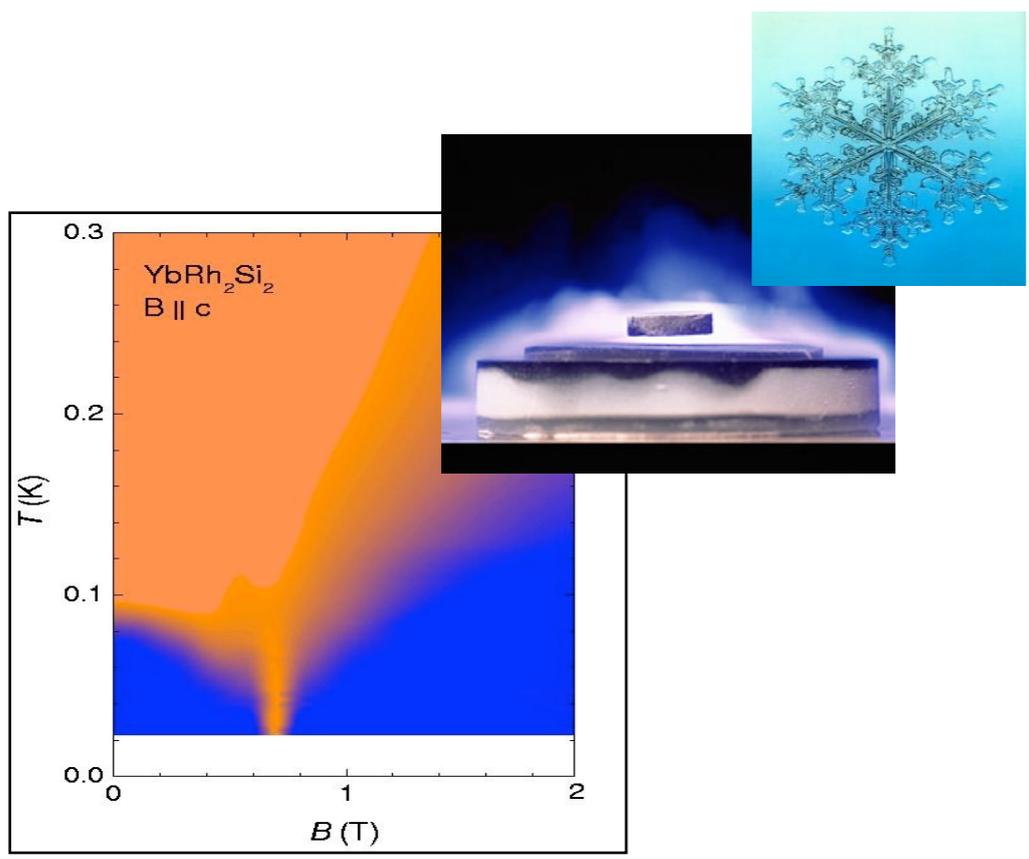
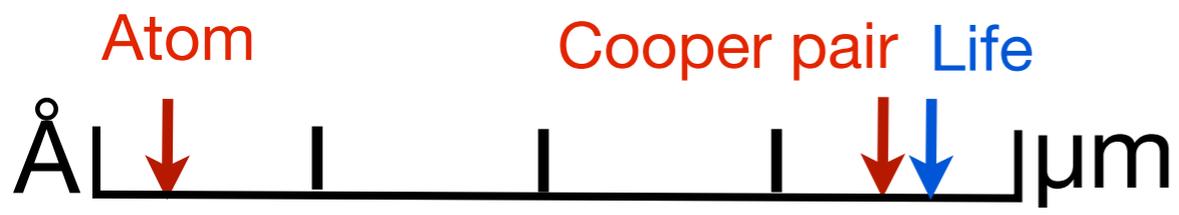
$$|\Psi_A + \Psi_B|^2 \neq |\Psi_A|^2 + |\Psi_B|^2$$

Compounds are different to the sum of their components

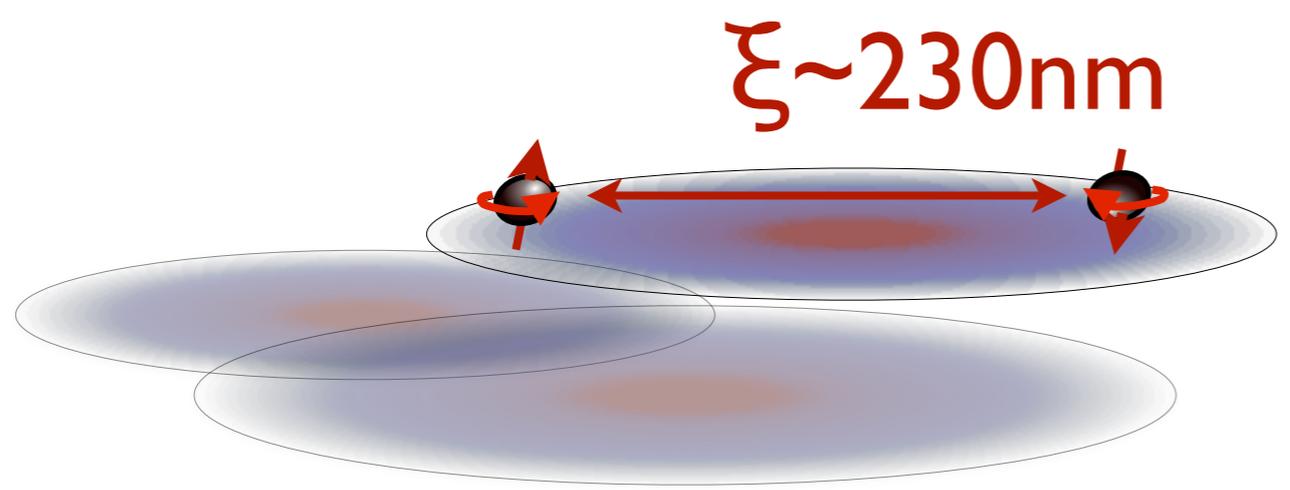
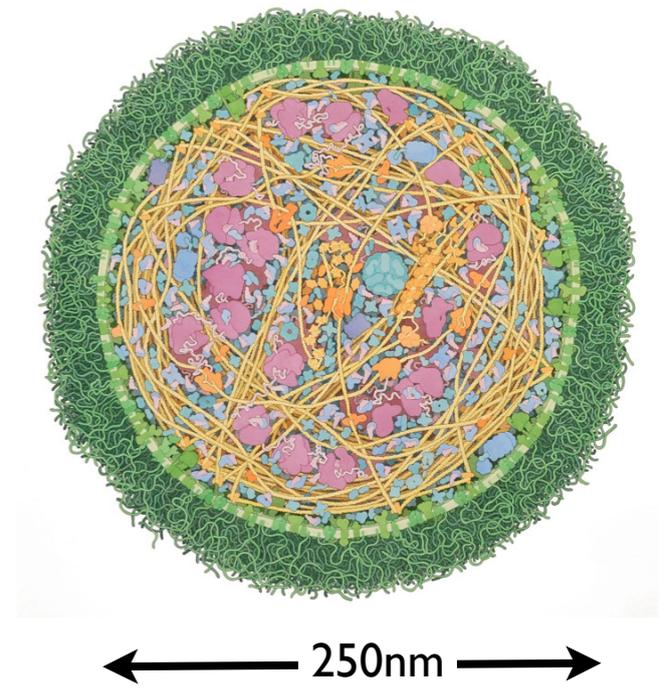


Cooper Pair in Sn

From the Angstrom to the Micron

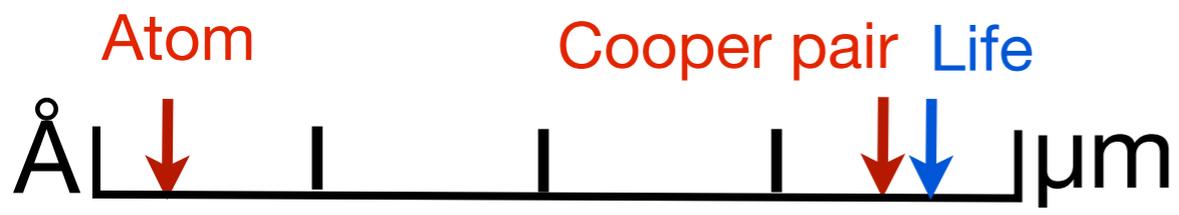


Mycoplasma mycoides

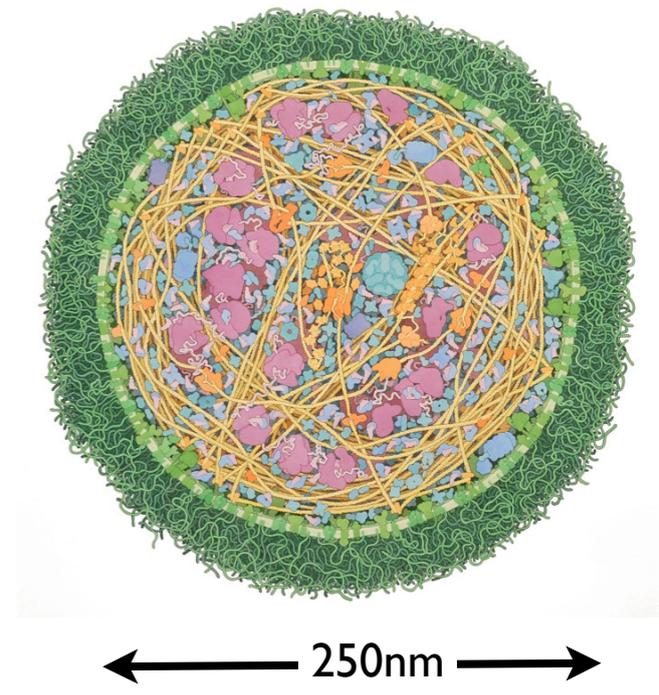


Cooper Pair in Sn

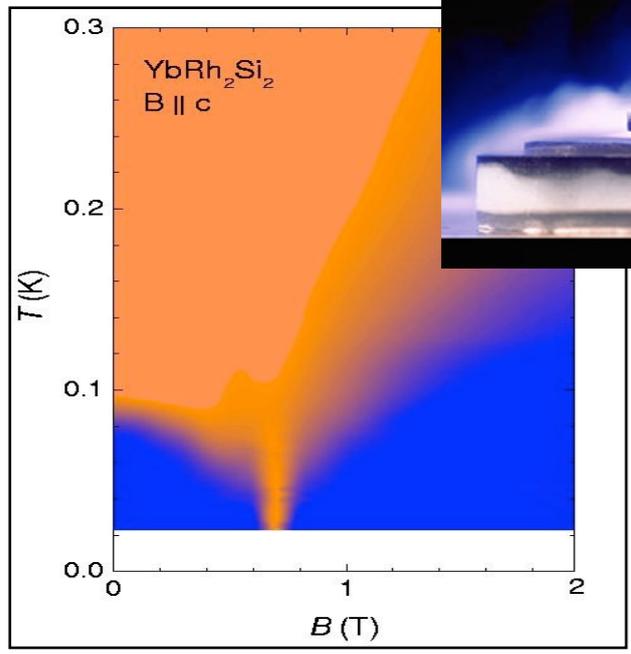
From the Angstrom to the Micron



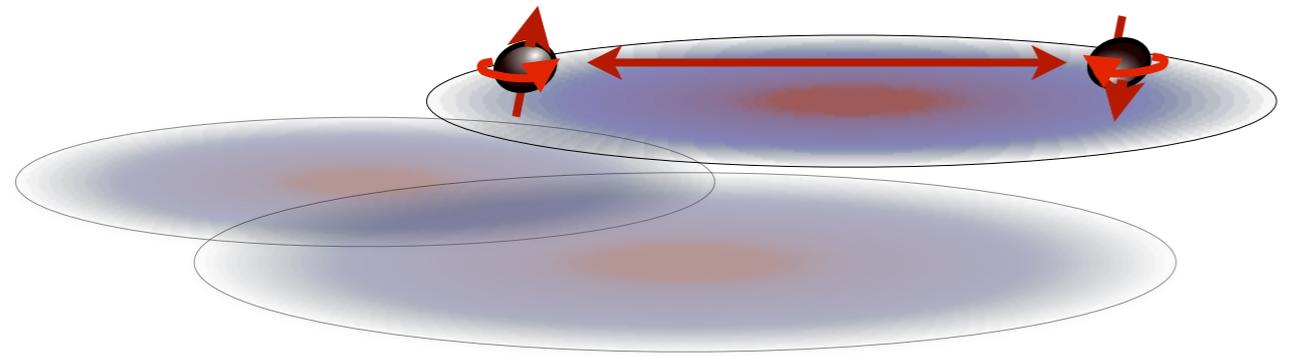
Mycoplasma mycoides



“Emergence”

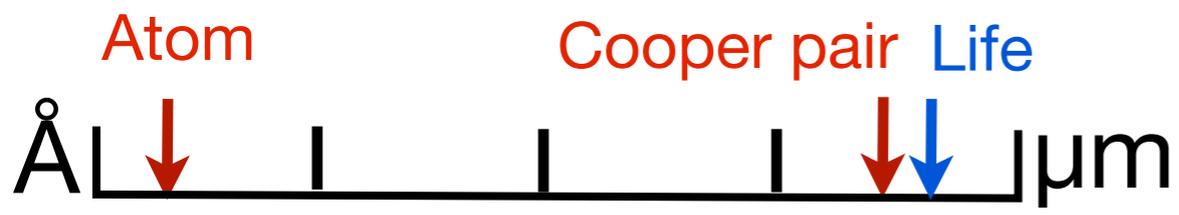


$\xi \sim 230\text{nm}$

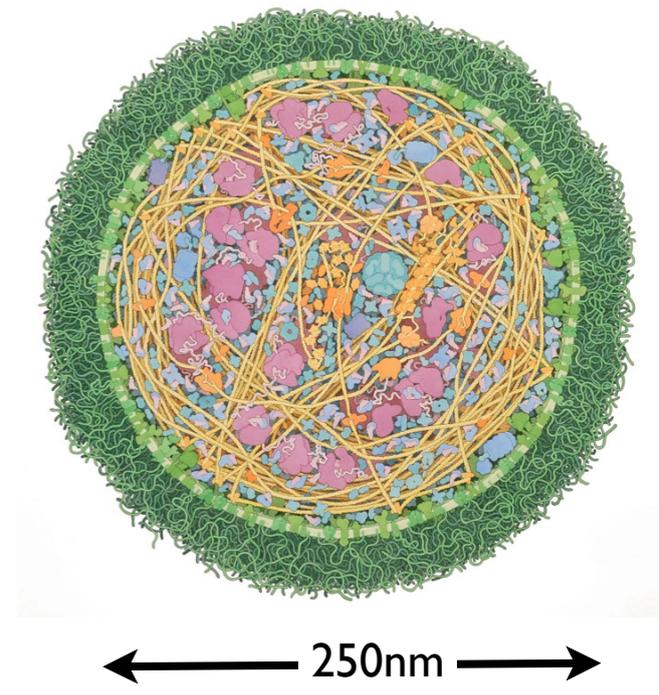


Cooper Pair in Sn

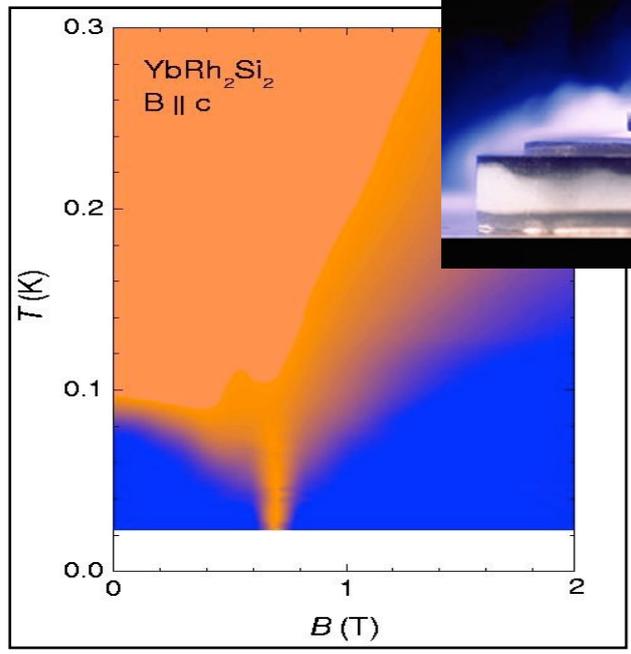
From the Angstrom to the Micron



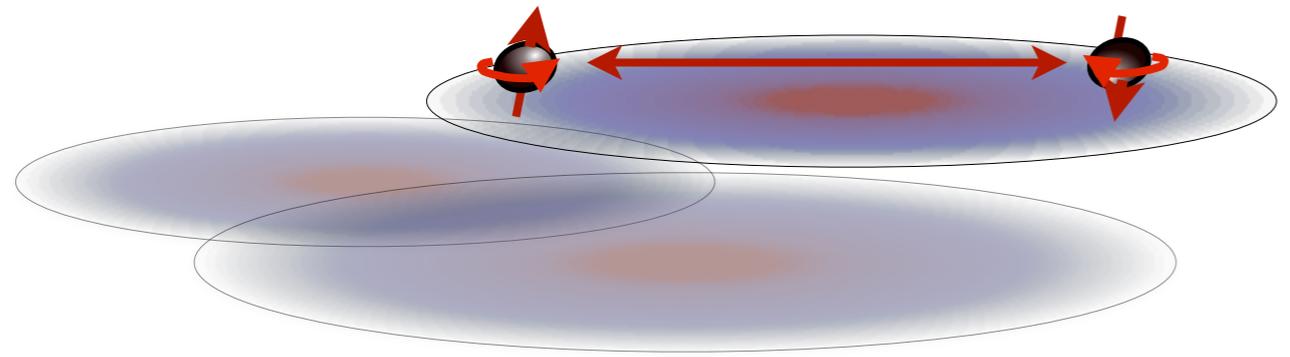
Mycoplasma mycoides



“Emergence”



$\xi \sim 230\text{nm}$



Cooper Pair in Sn

What are the principles that govern the emergence of collective behavior in matter between the Angstrom and the Micron?

From the Angstrom to the Micron

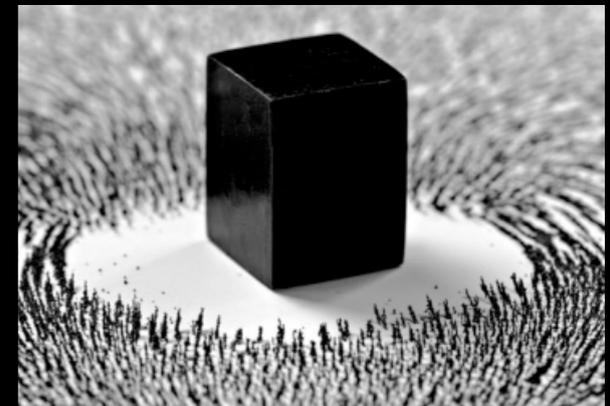
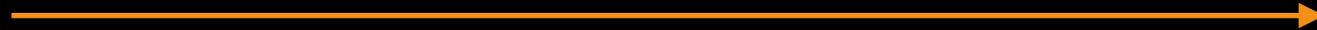
Selected History of Emergence and Reductionism in CMT.

Emergent
Physics

Selected History of Emergence and Reductionism in CMT.



Emergent
Physics



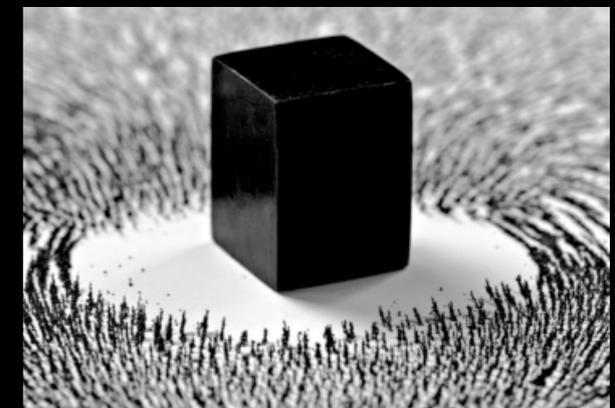
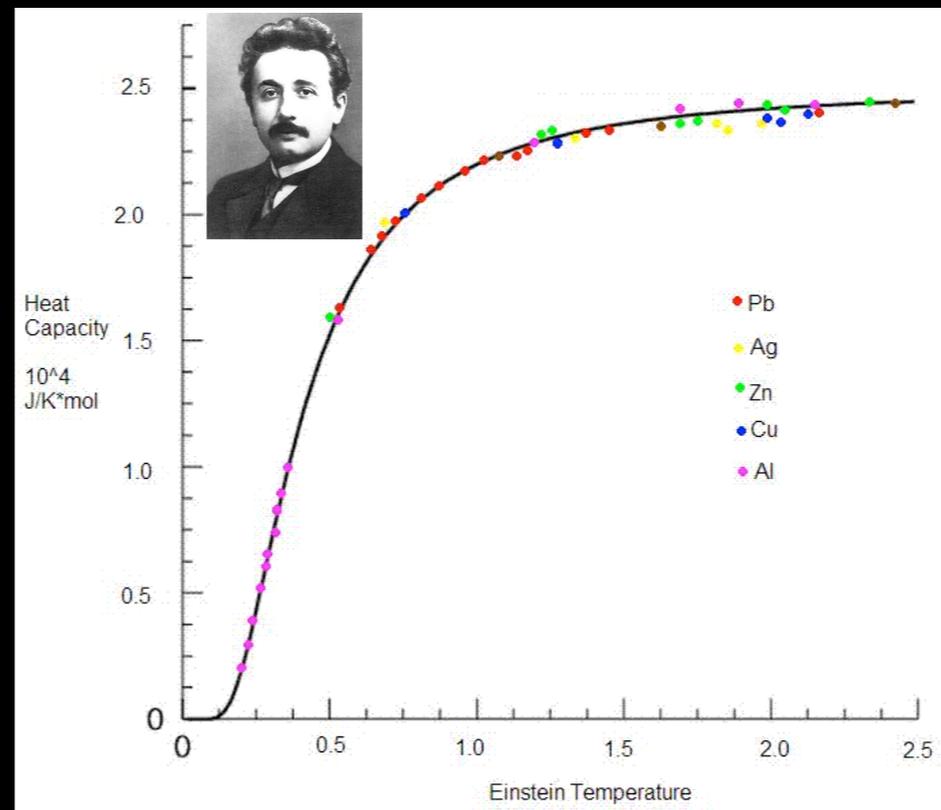
Selected History of Emergence and Reductionism in CMT.



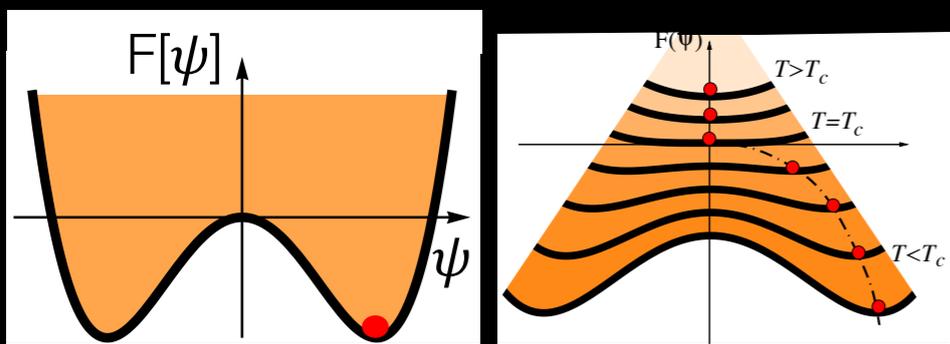
Einstein's phonons=
emergent quanta of
the solid state.

Emergent
Physics

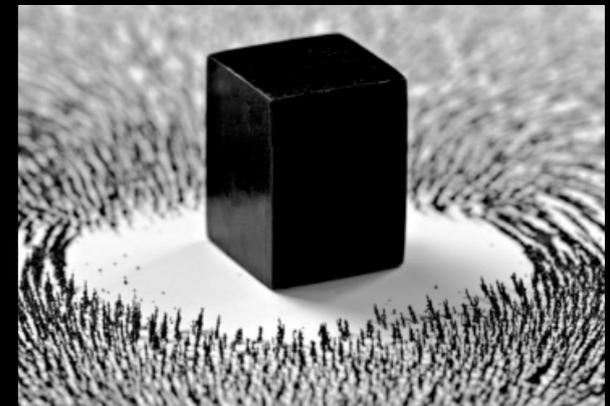
Einstein
Phonons
(1906)



Selected History of Emergence and Reductionism in CMT.



Broken Symmetry

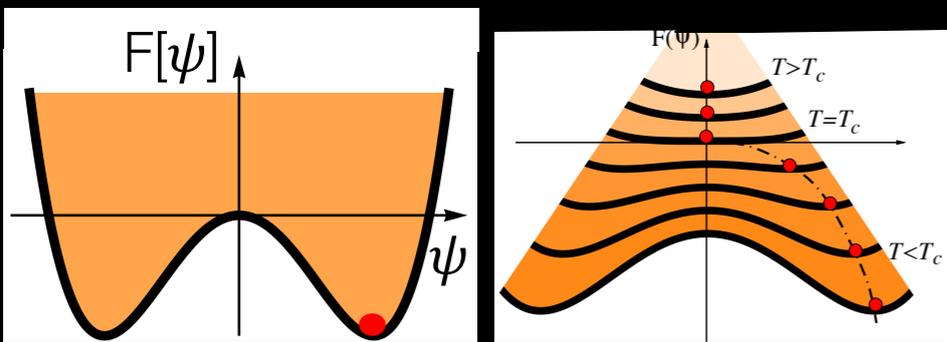
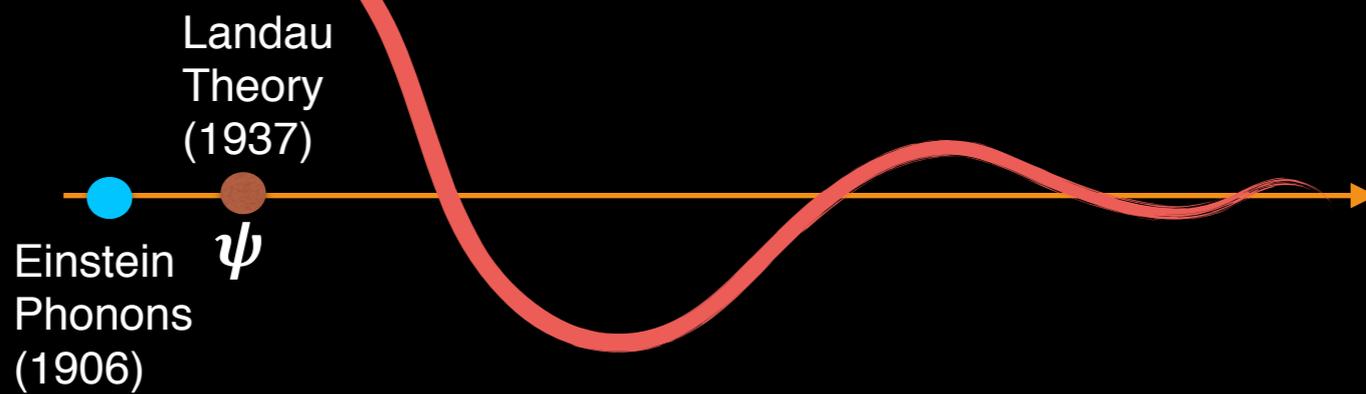


Selected History of Emergence and Reductionism in CMT.

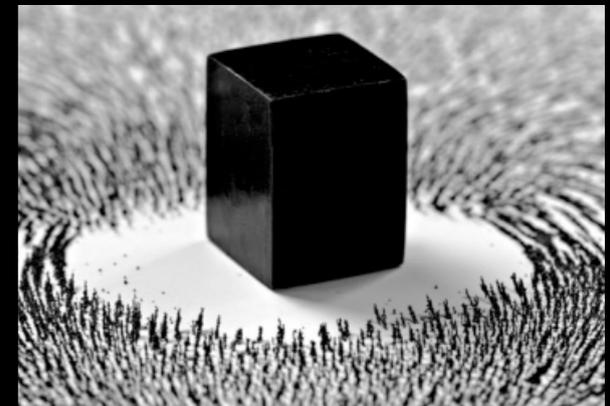


Reductionist

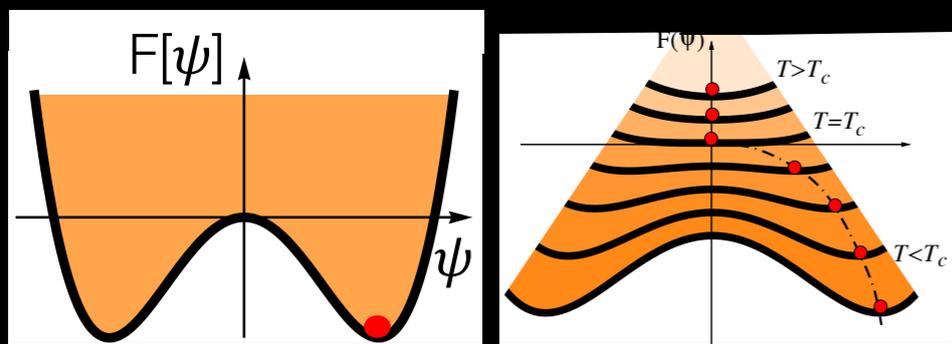
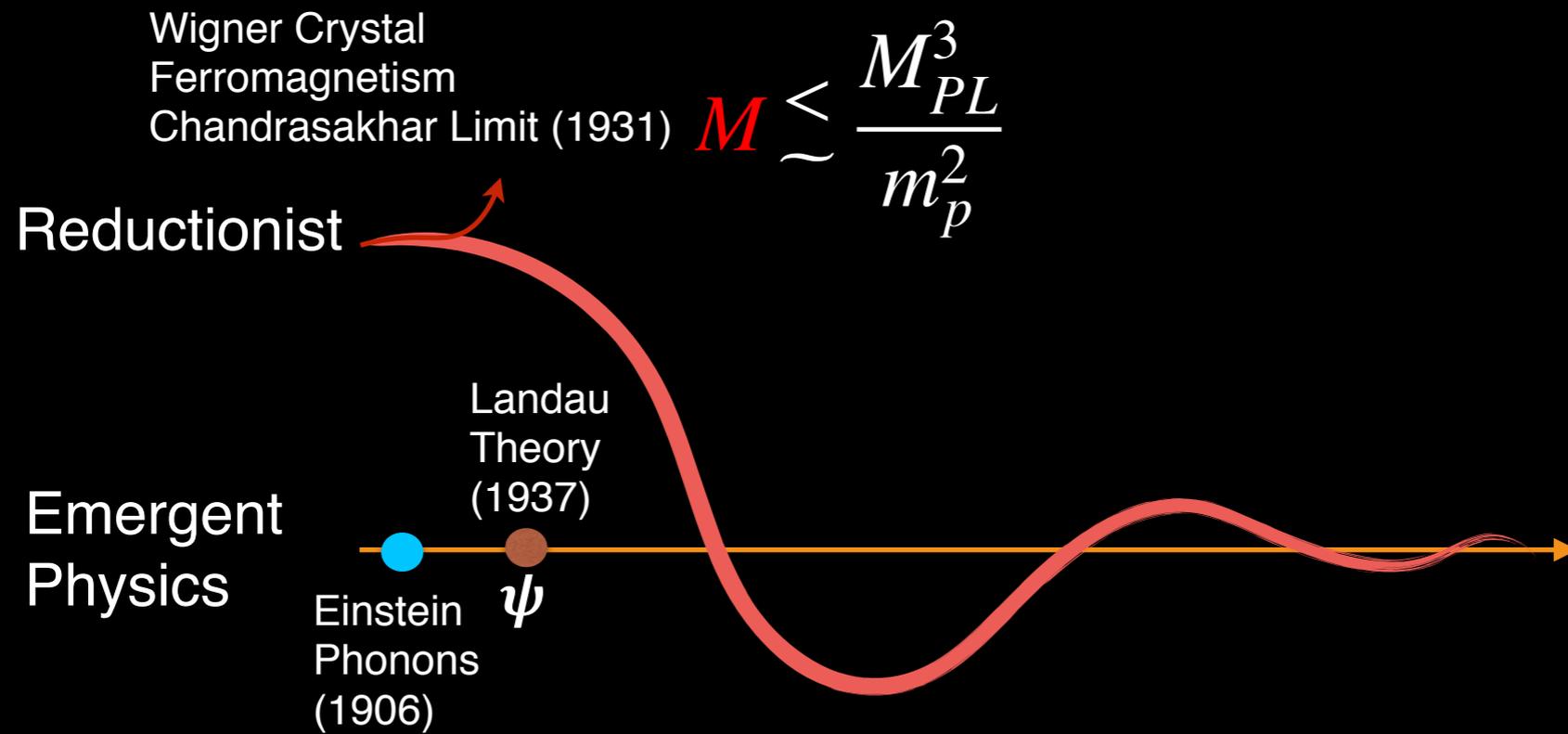
Emergent
Physics



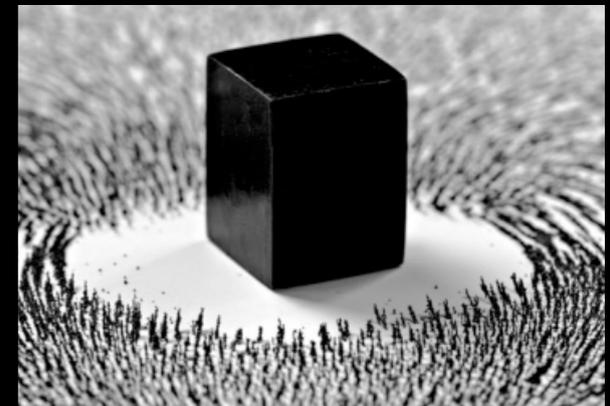
Broken Symmetry



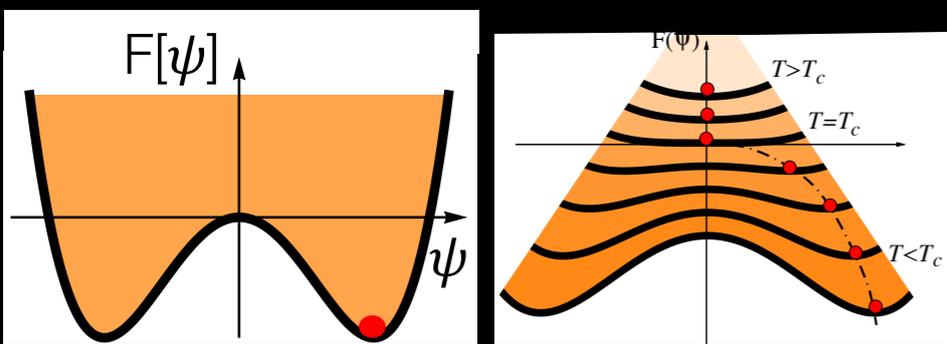
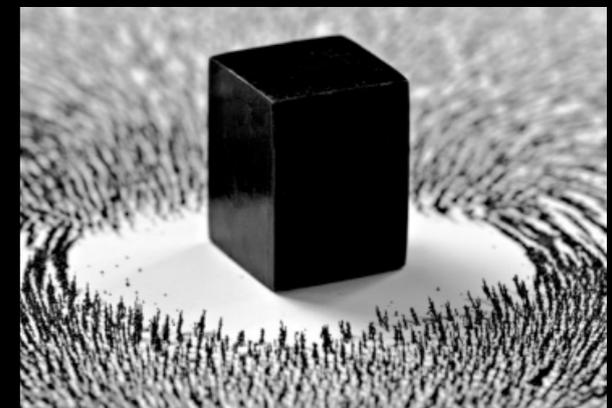
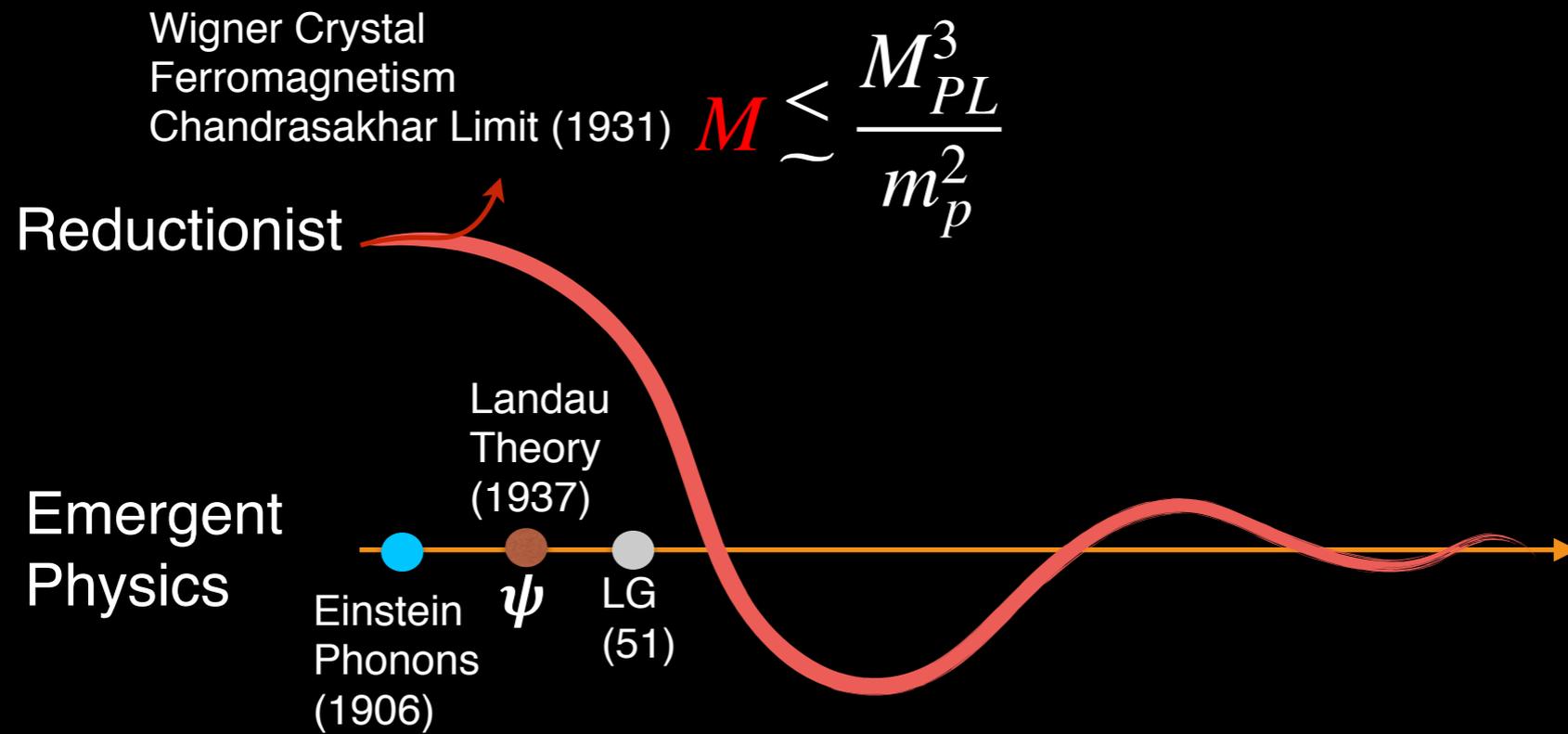
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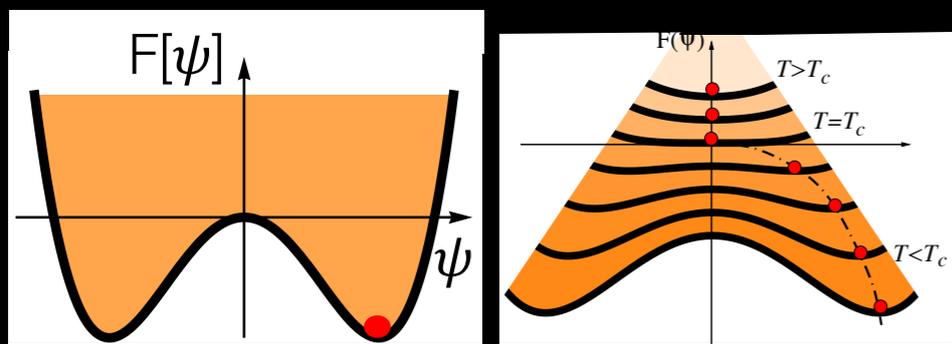
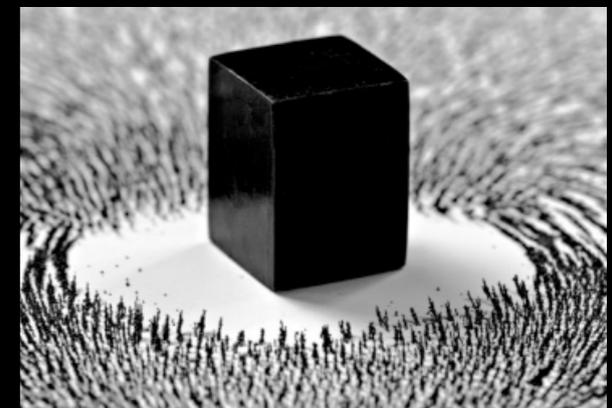
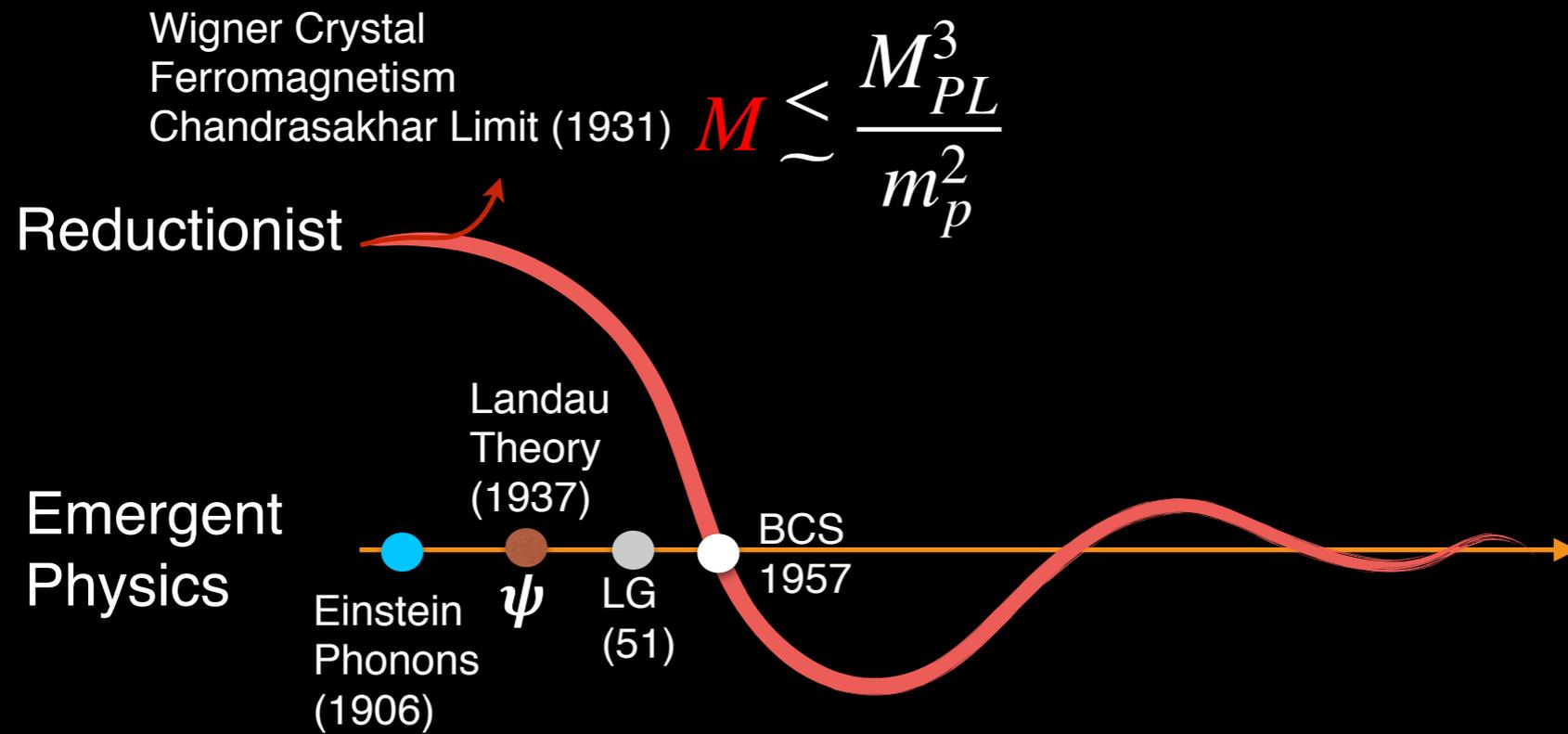


Selected History of Emergence and Reductionism in CMT.



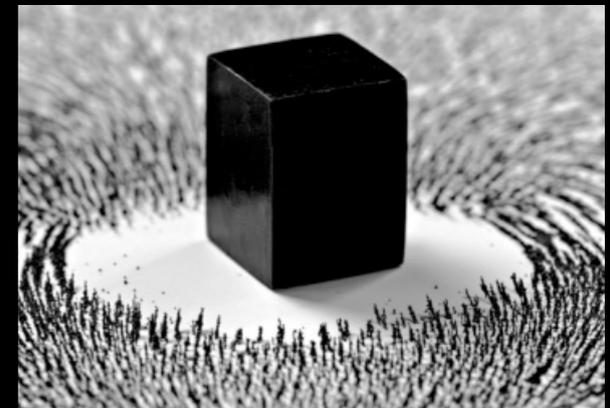
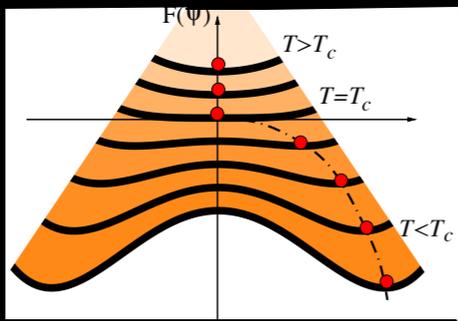
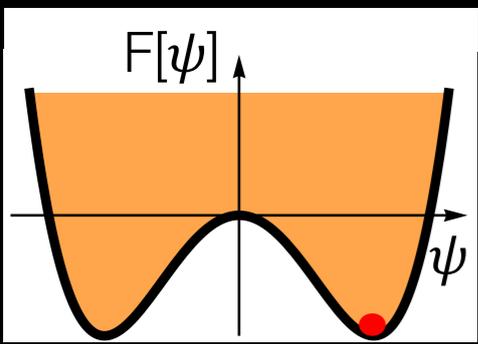
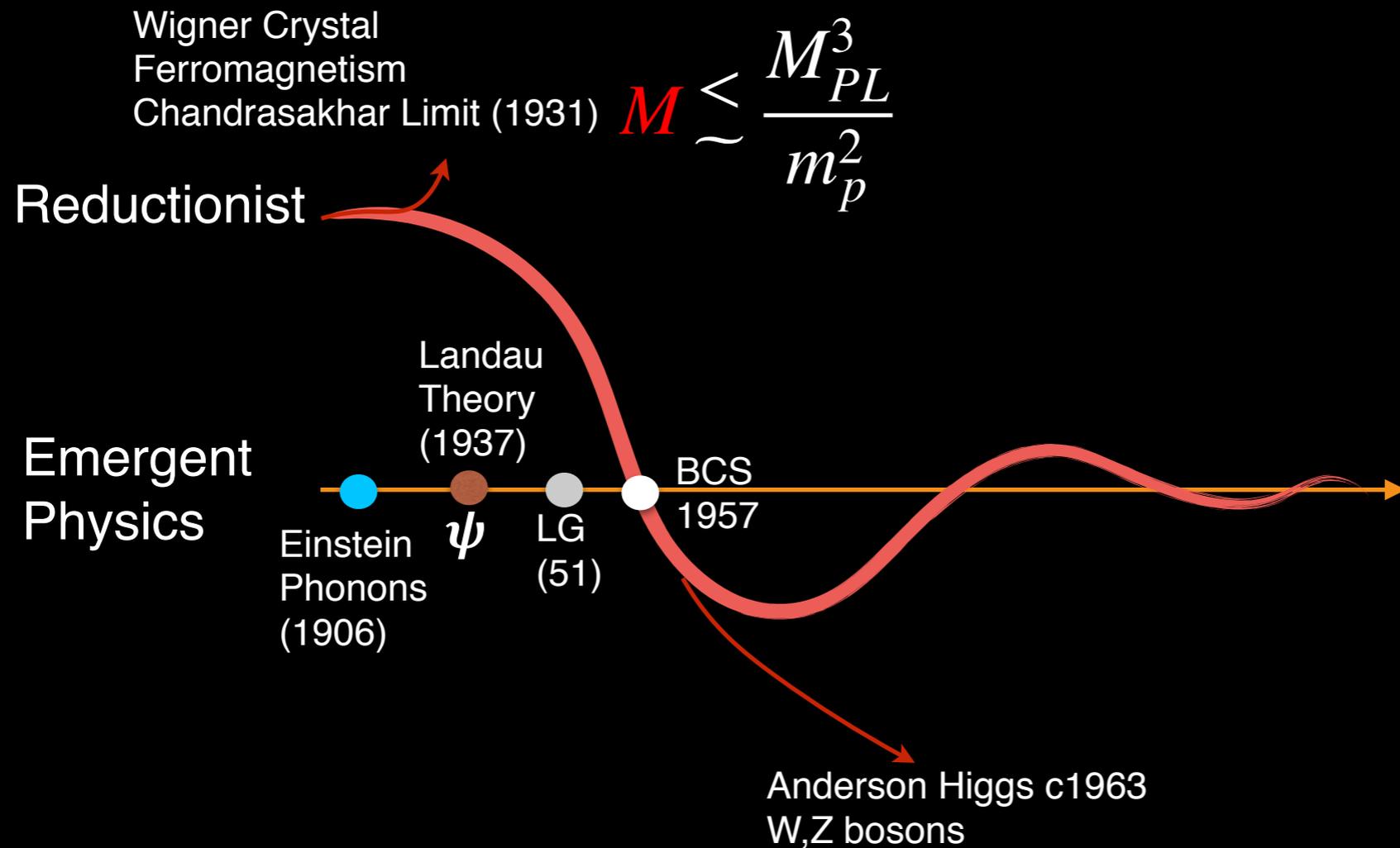
Broken Symmetry

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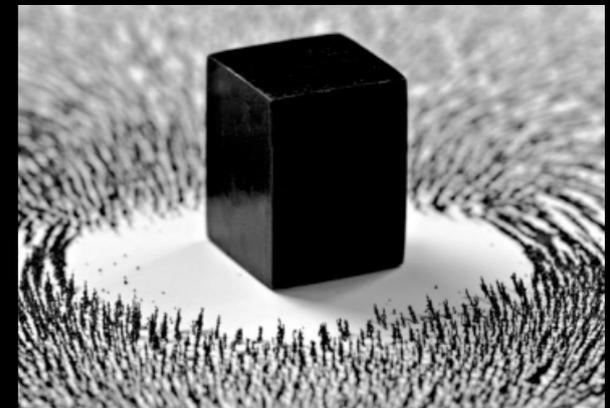
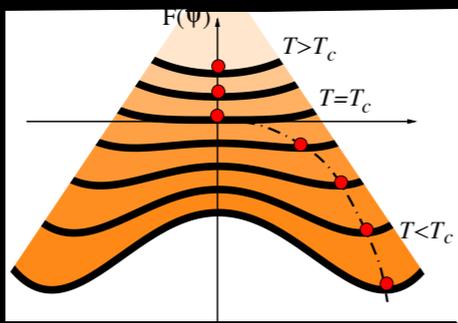
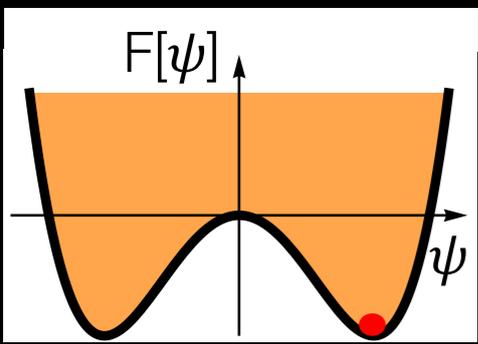
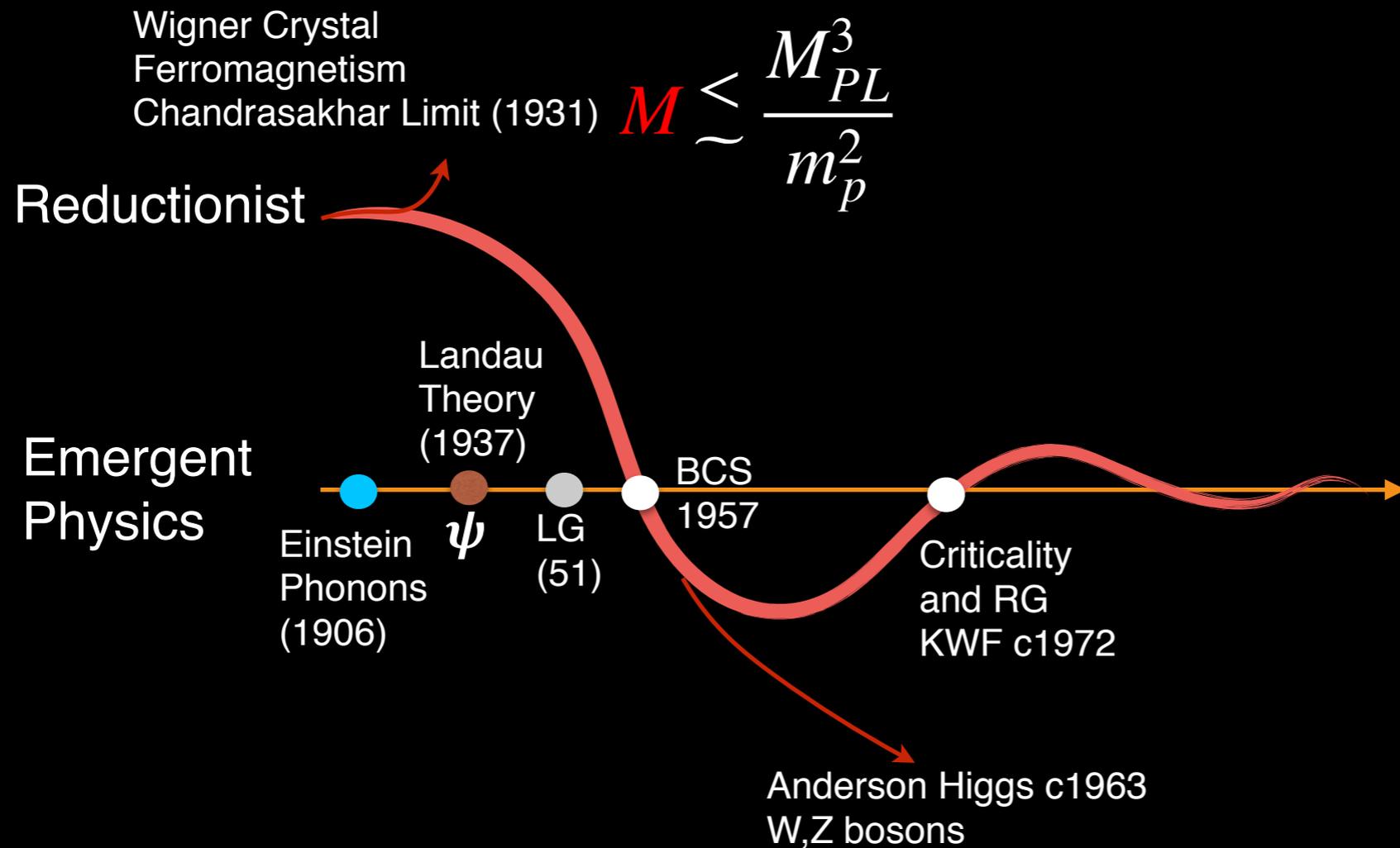
Broken Symmetry

Selected History of Emergence and Reductionism in CMT.



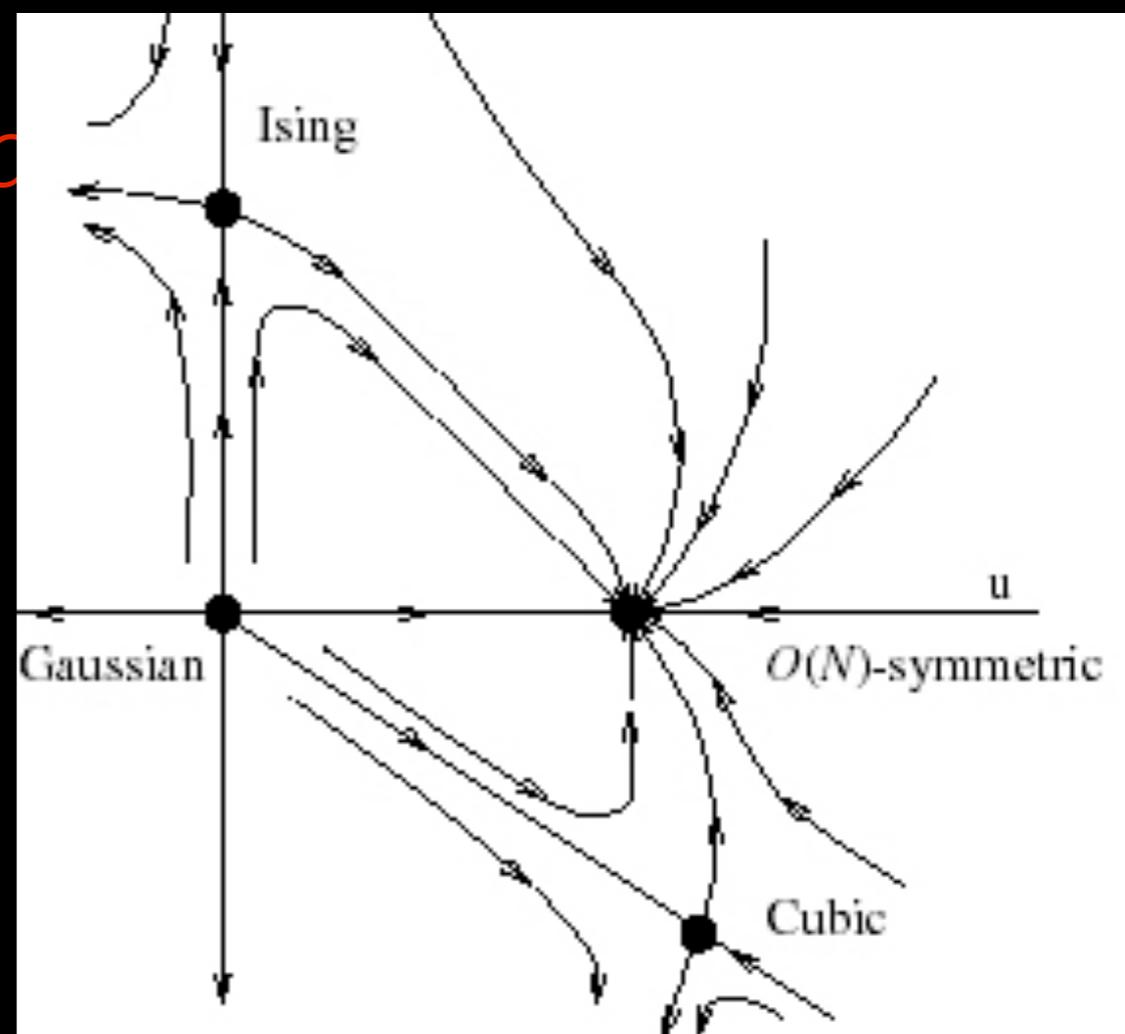
Broken Symmetry

Selected History of Emergence and Reductionism in CMT.



Broken Symmetry

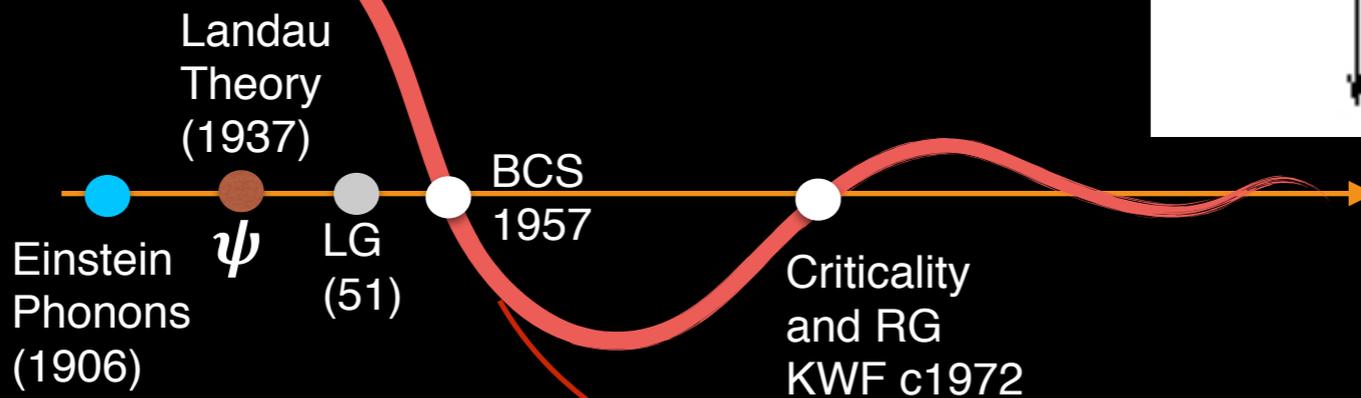
Selected History of Emergence and



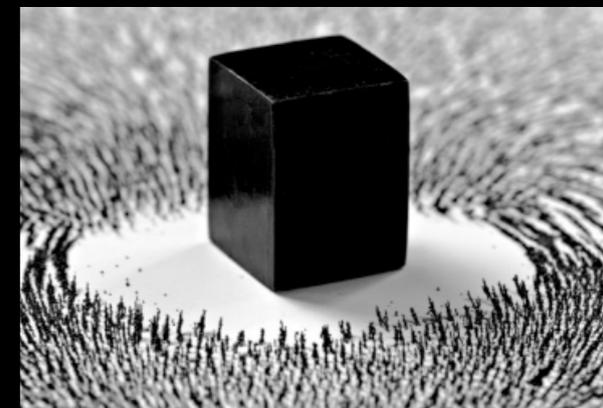
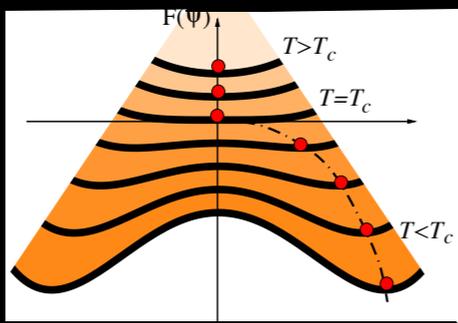
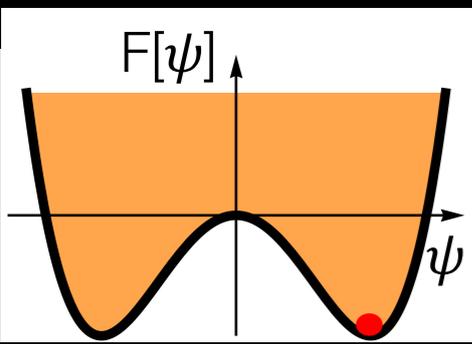
Wigner Crystal
 Ferromagnetism
 Chandrasakhar Limit (1931) $M \lesssim \frac{M_{PL}^3}{m_p^2}$

Reductionist

Emergent Physics

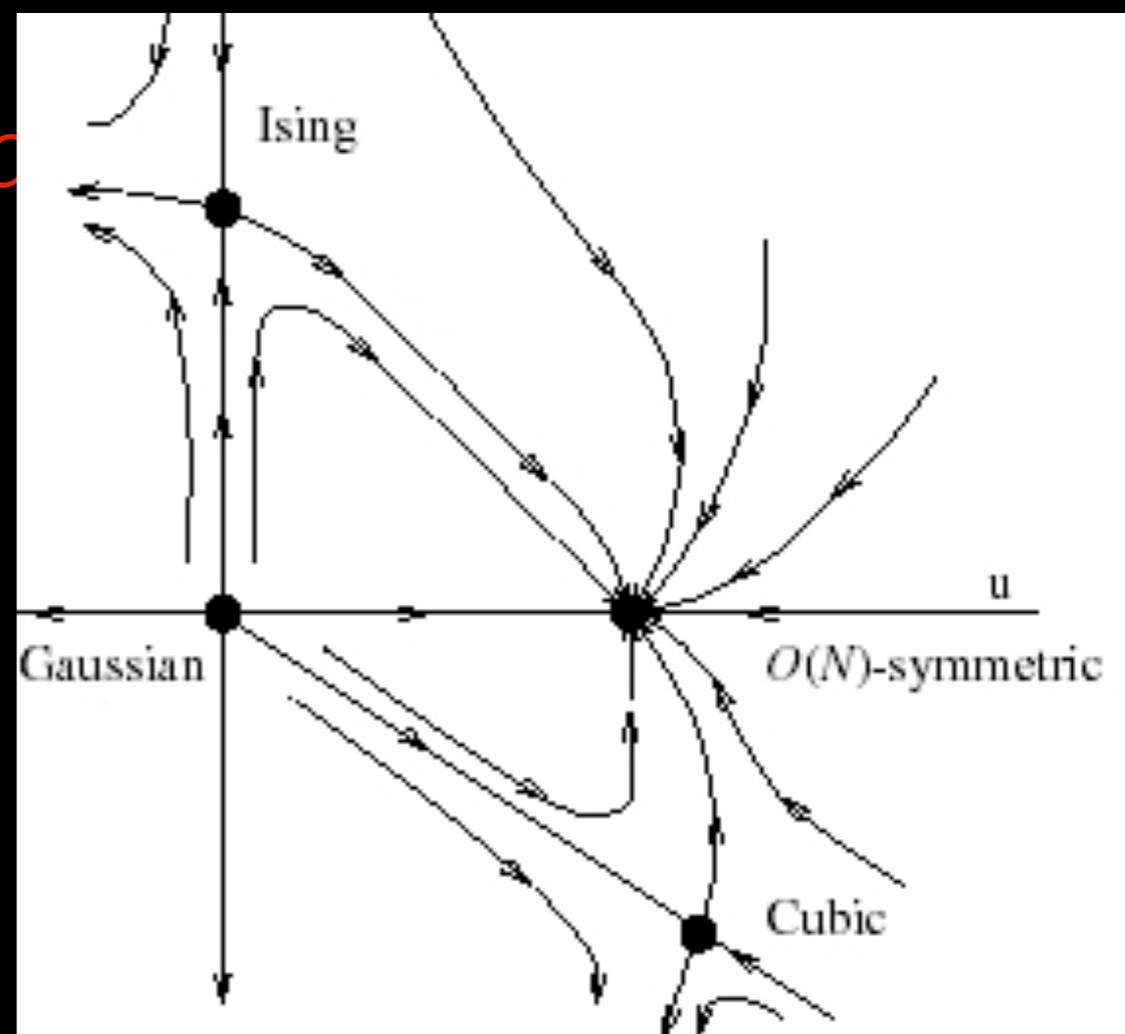


Anderson Higgs c1963
 W,Z bosons



Broken Symmetry

Selected History of Emergence and



Wigner Crystal
 Ferromagnetism
 Chandrasakhar Limit (1931) $M < \frac{M_{PL}^3}{m_p^2}$

Reductionist

Emergent
 Physics



Einstein
 Phonons
 (1906)

Landau
 Theory
 (1937)

ψ

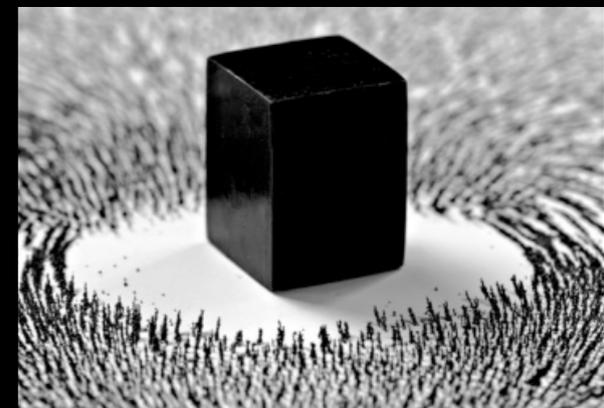
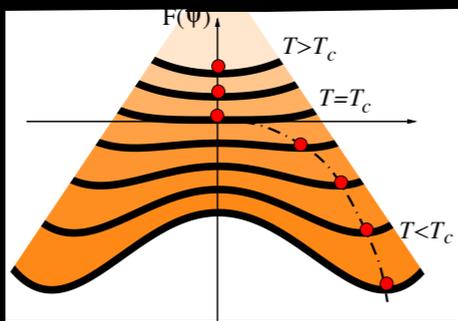
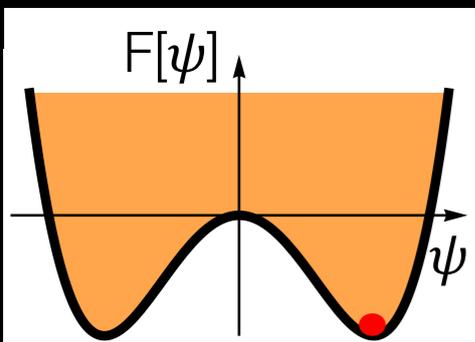
LG
 (51)

BCS
 1957

Criticality
 and RG
 KWF c1972

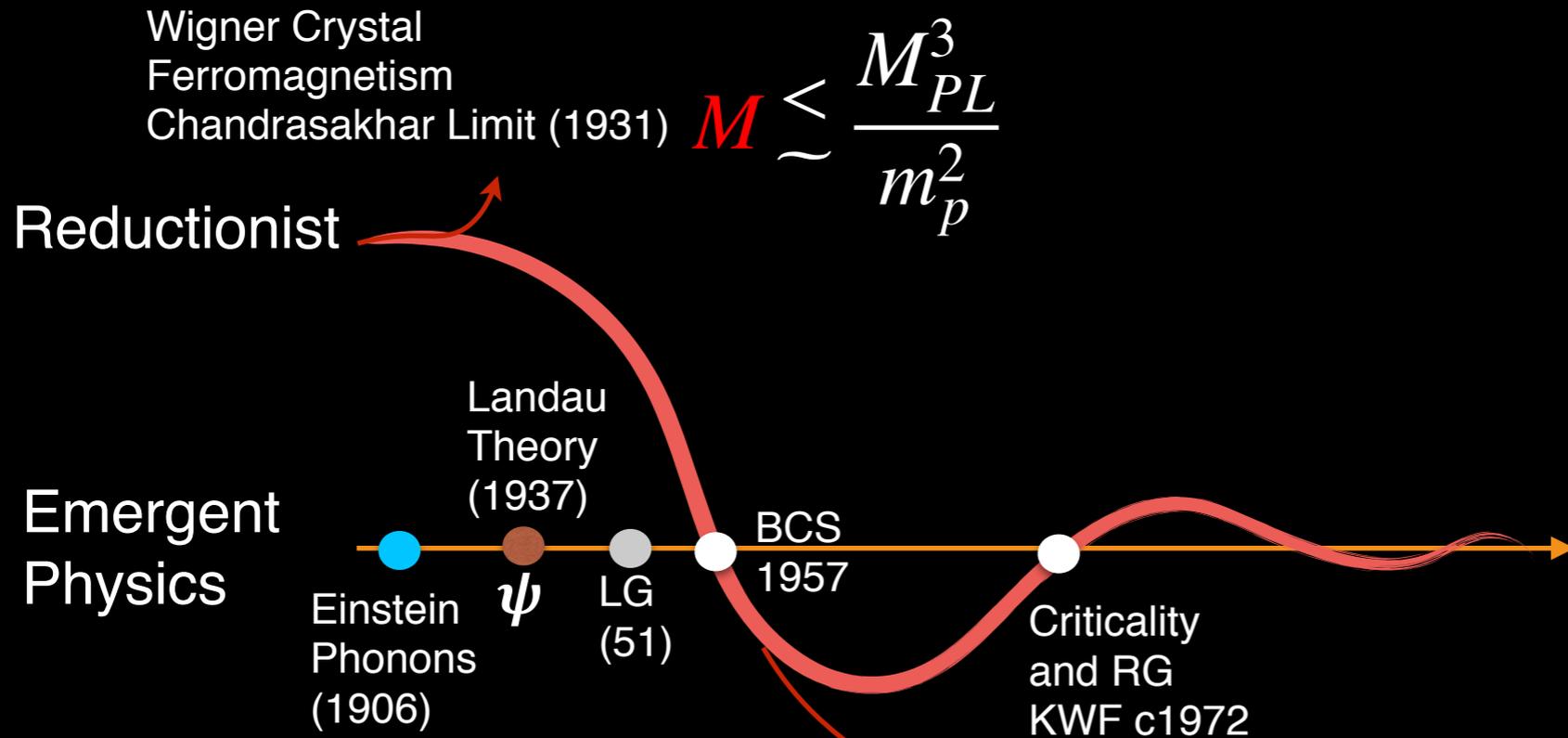
Anderson Higgs c1963
 W,Z bosons

$$\frac{\partial H}{\partial l} = \beta[H]$$



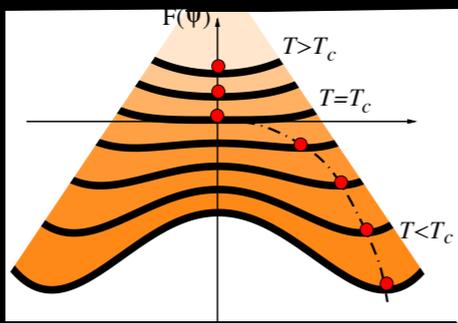
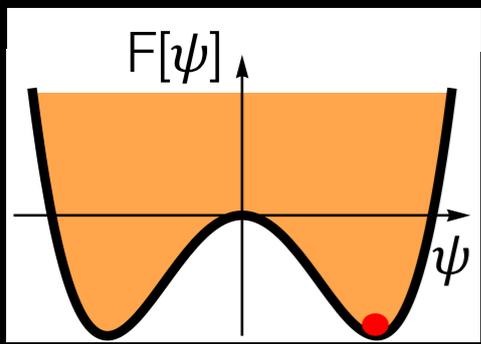
Broken Symmetry

Selected History of Emergence and Reductionism in CMT.

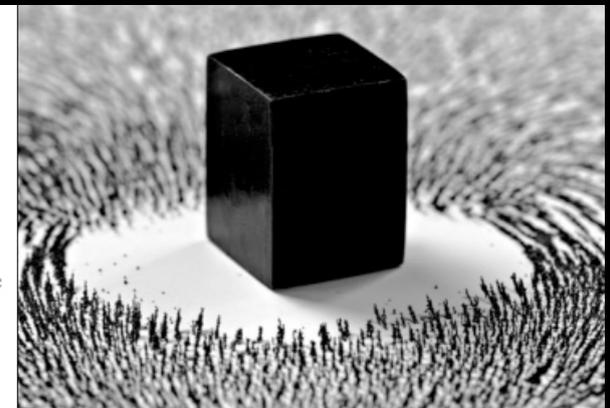
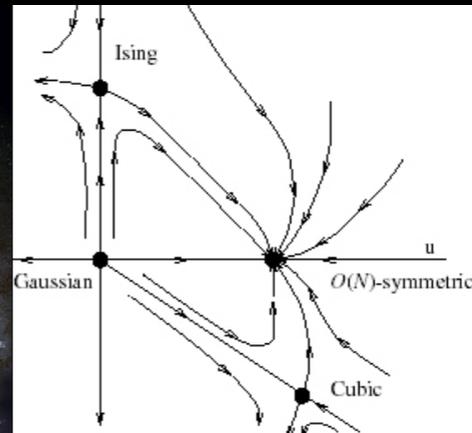


Anderson Higgs c1963
 W,Z bosons

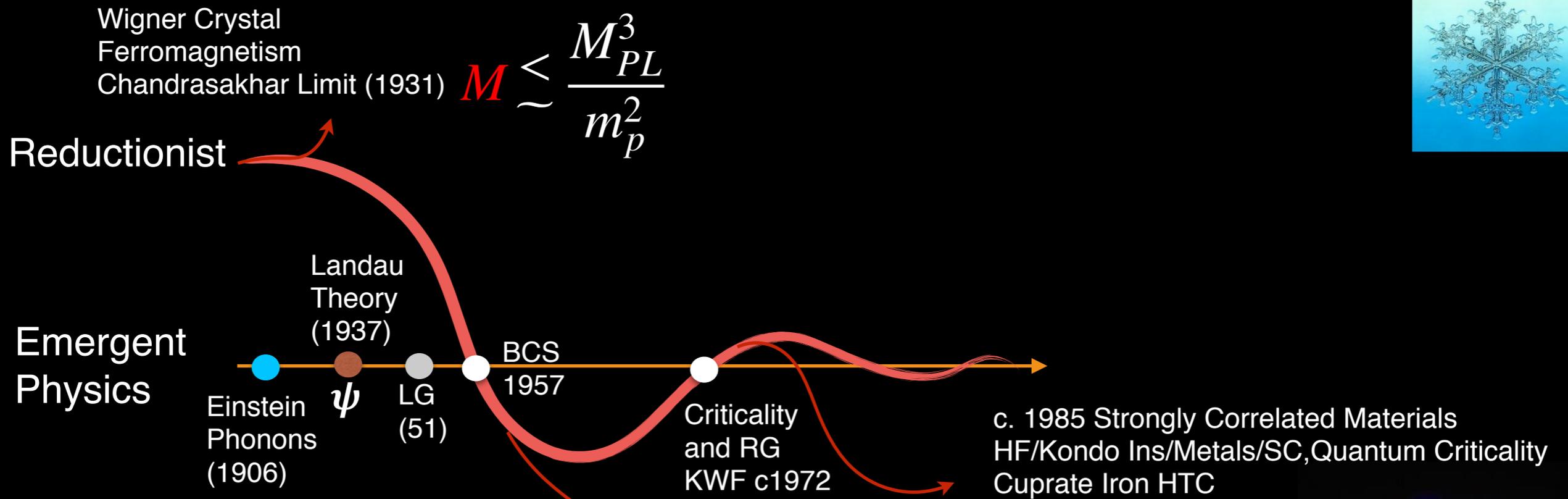
$$\frac{\partial H}{\partial l} = \beta[H]$$



Broken Symmetry

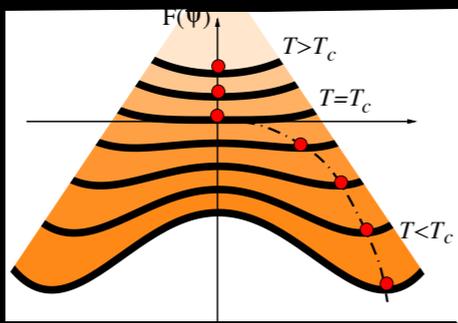
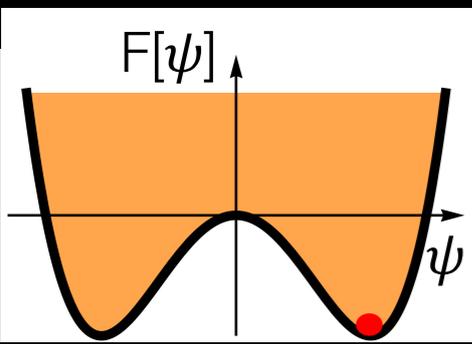
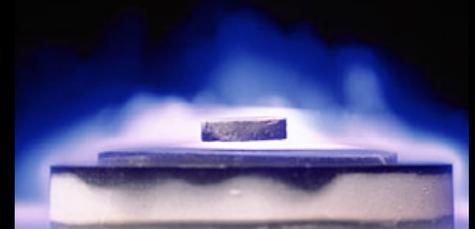


Selected History of Emergence and Reductionism in CMT.

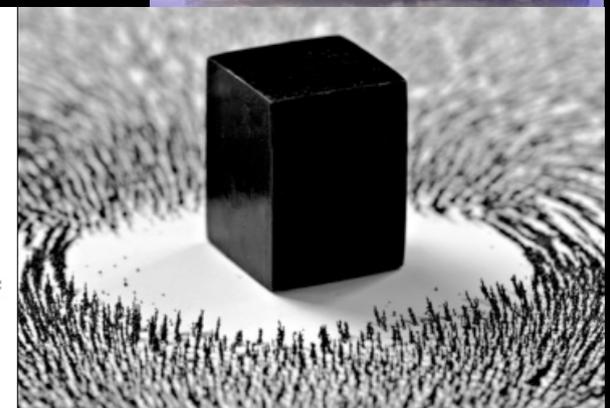
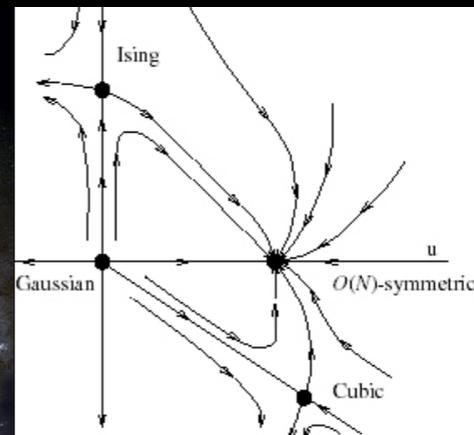


Anderson Higgs c1963
W,Z bosons

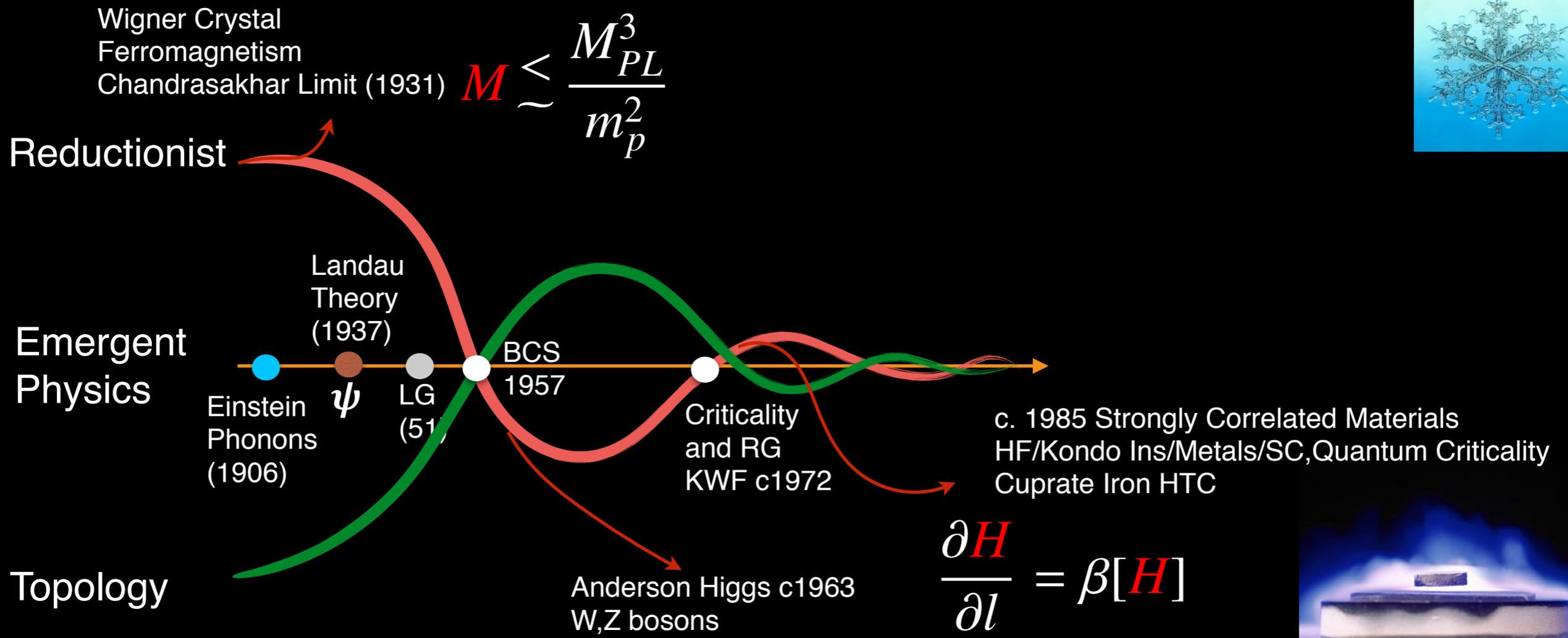
$$\frac{\partial H}{\partial l} = \beta[H]$$



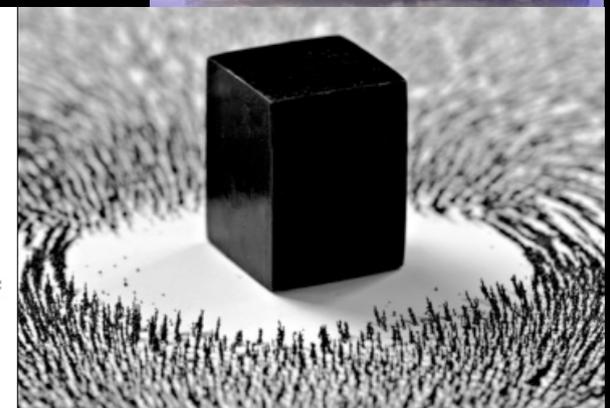
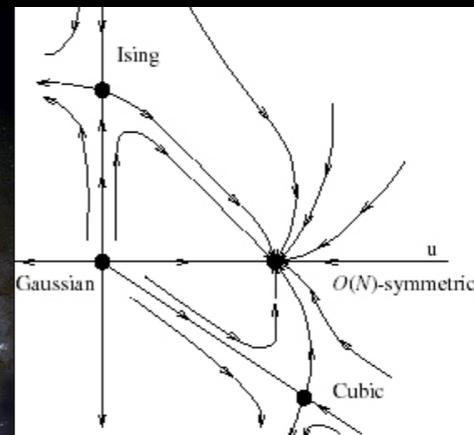
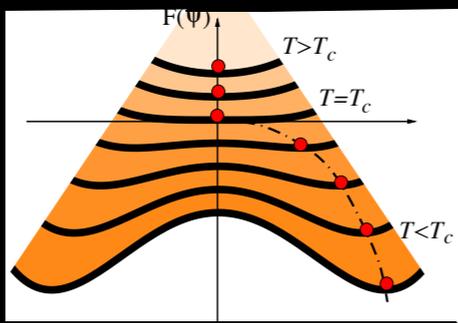
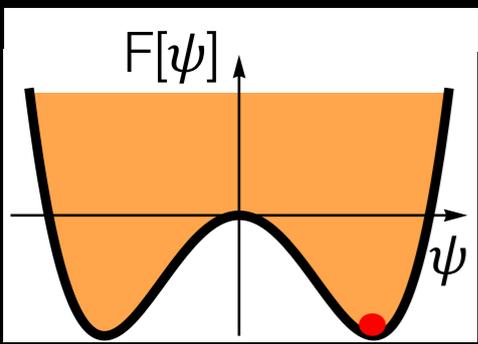
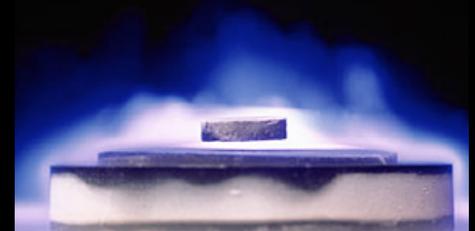
Broken Symmetry



Selected History of Emergence and Reductionism in CMT.

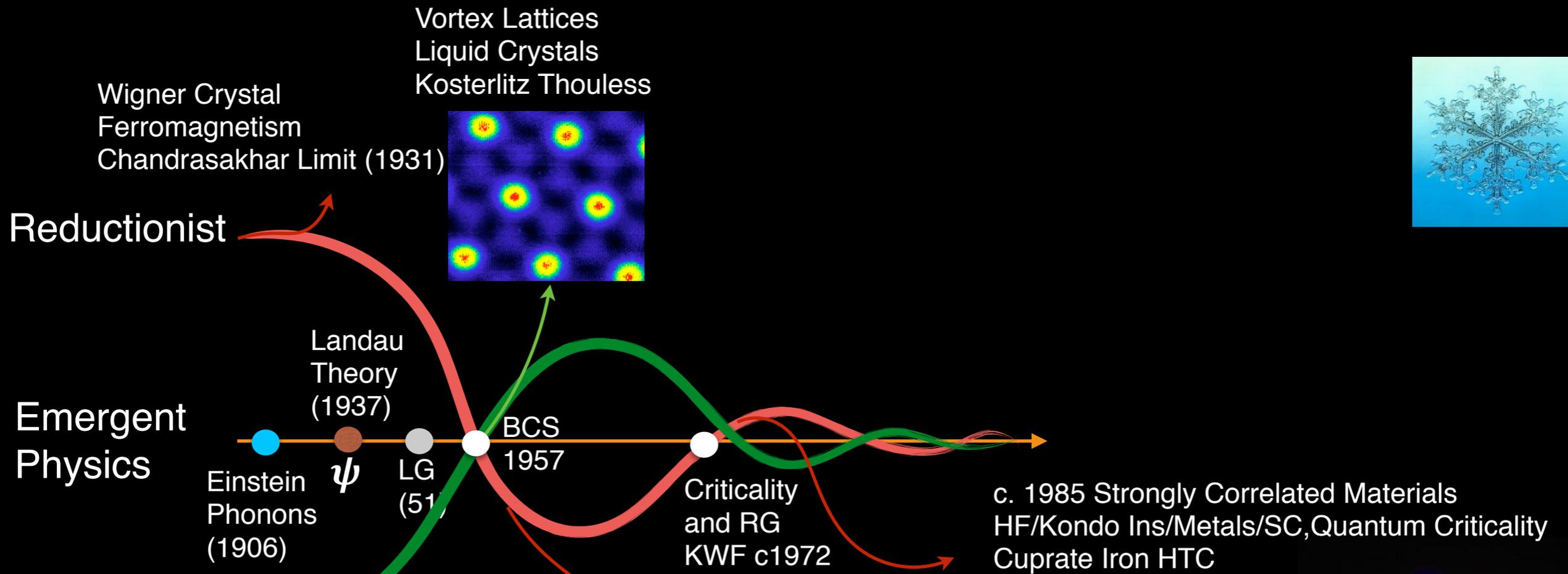


Topology



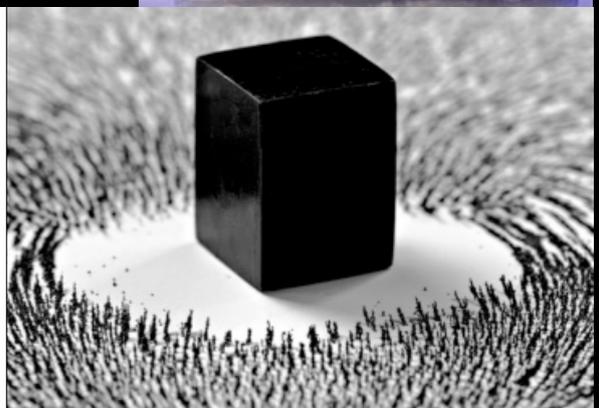
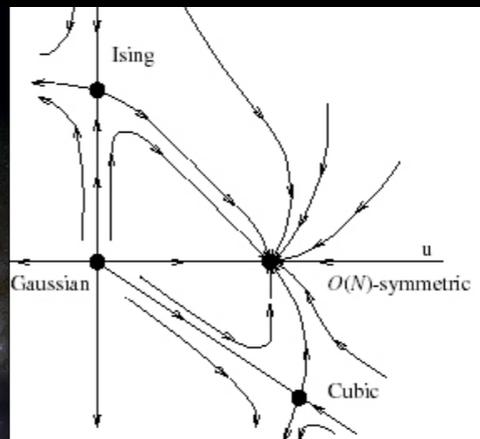
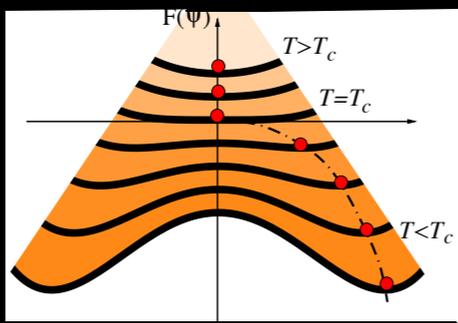
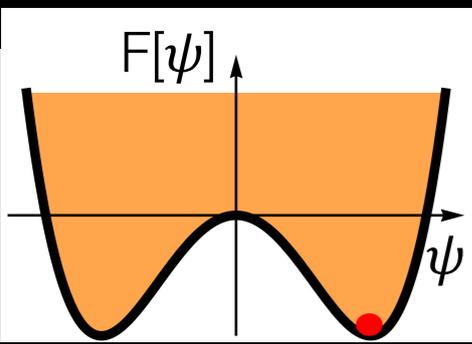
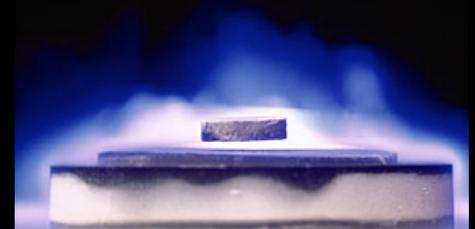
Broken Symmetry

Selected History of Emergence and Reductionism in CMT.



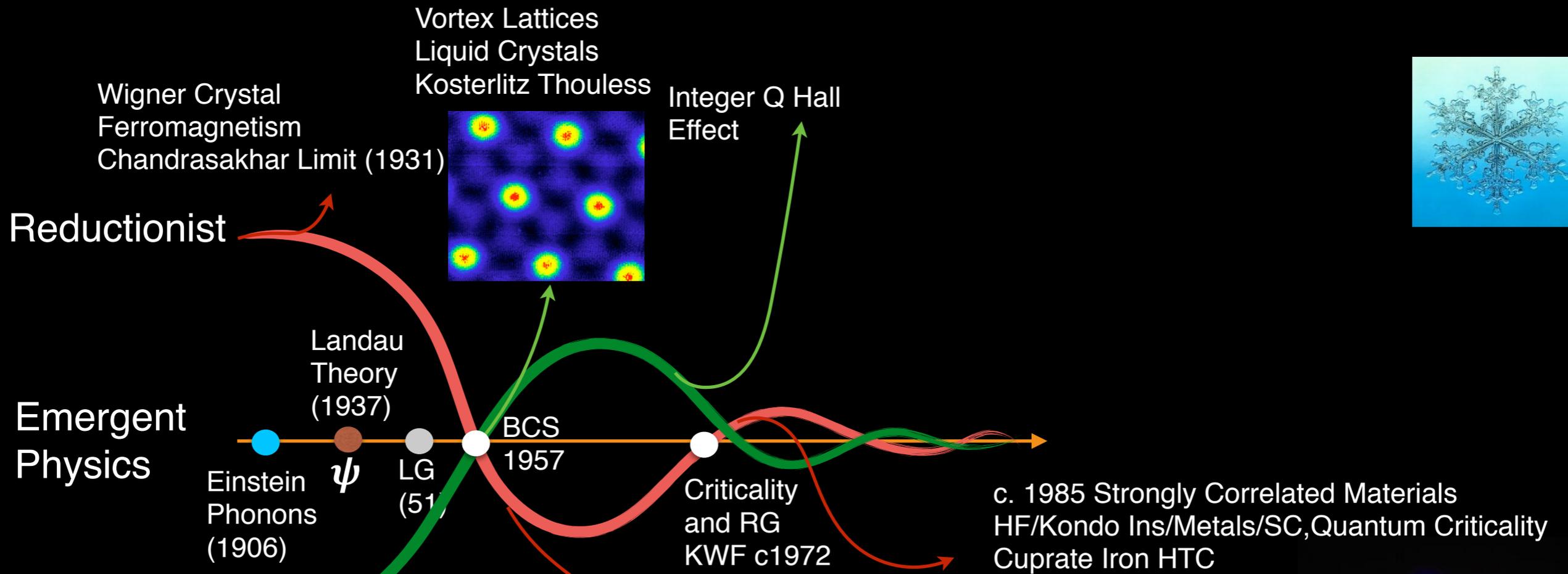
Topology

$$\frac{\partial H}{\partial l} = \beta[H]$$



Broken Symmetry

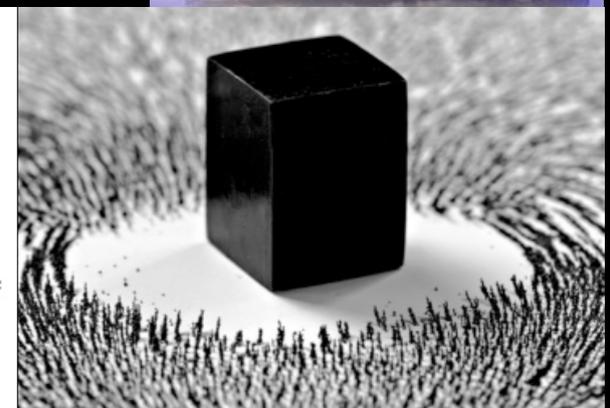
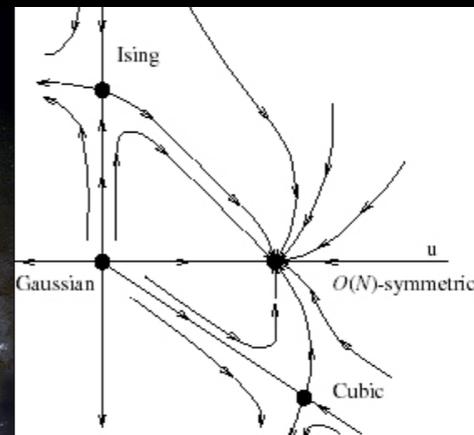
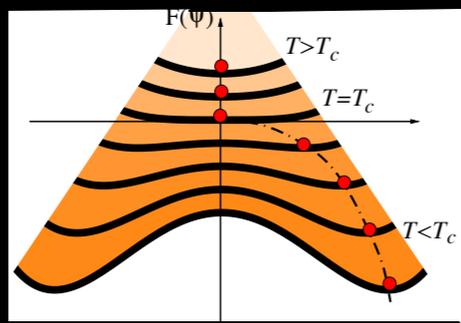
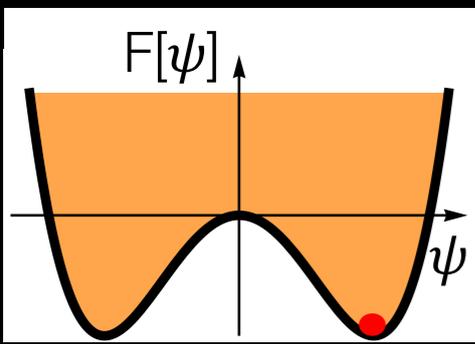
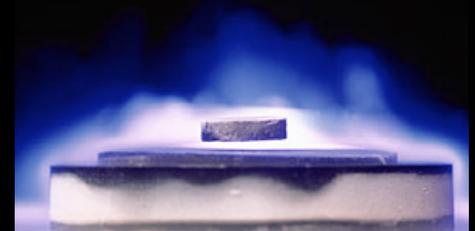
Selected History of Emergence and Reductionism in CMT.



Topology

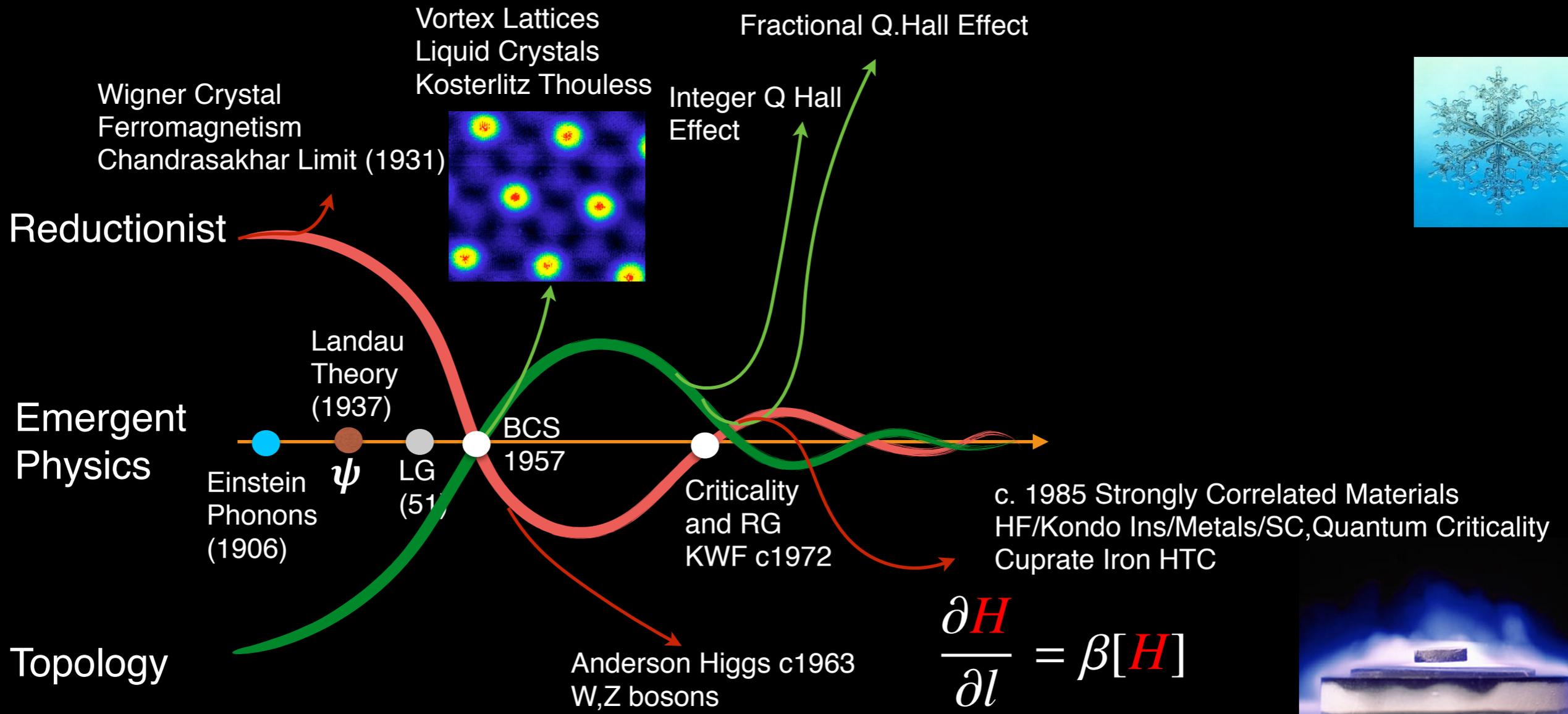
Anderson Higgs c1963
W,Z bosons

$$\frac{\partial H}{\partial l} = \beta[H]$$

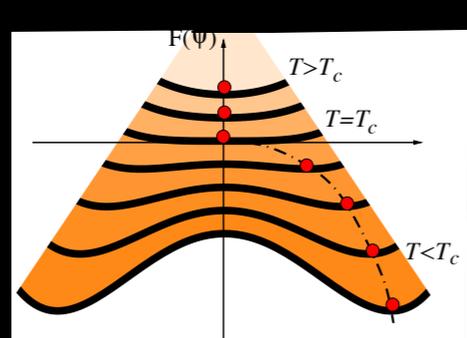
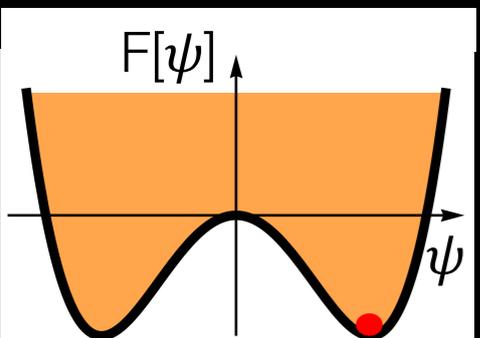
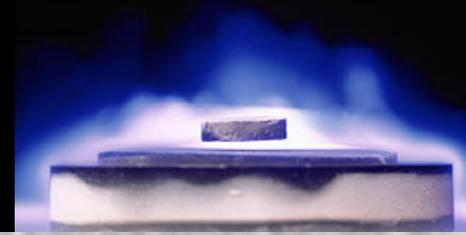


Broken Symmetry

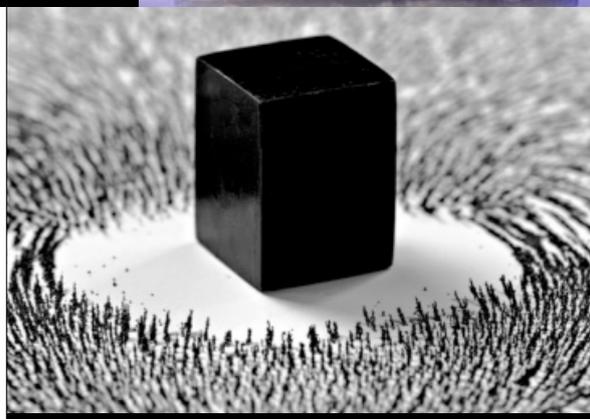
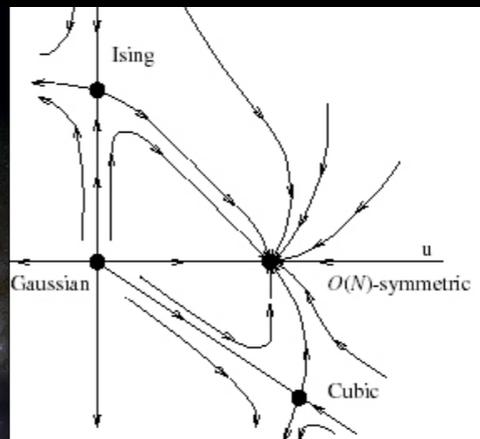
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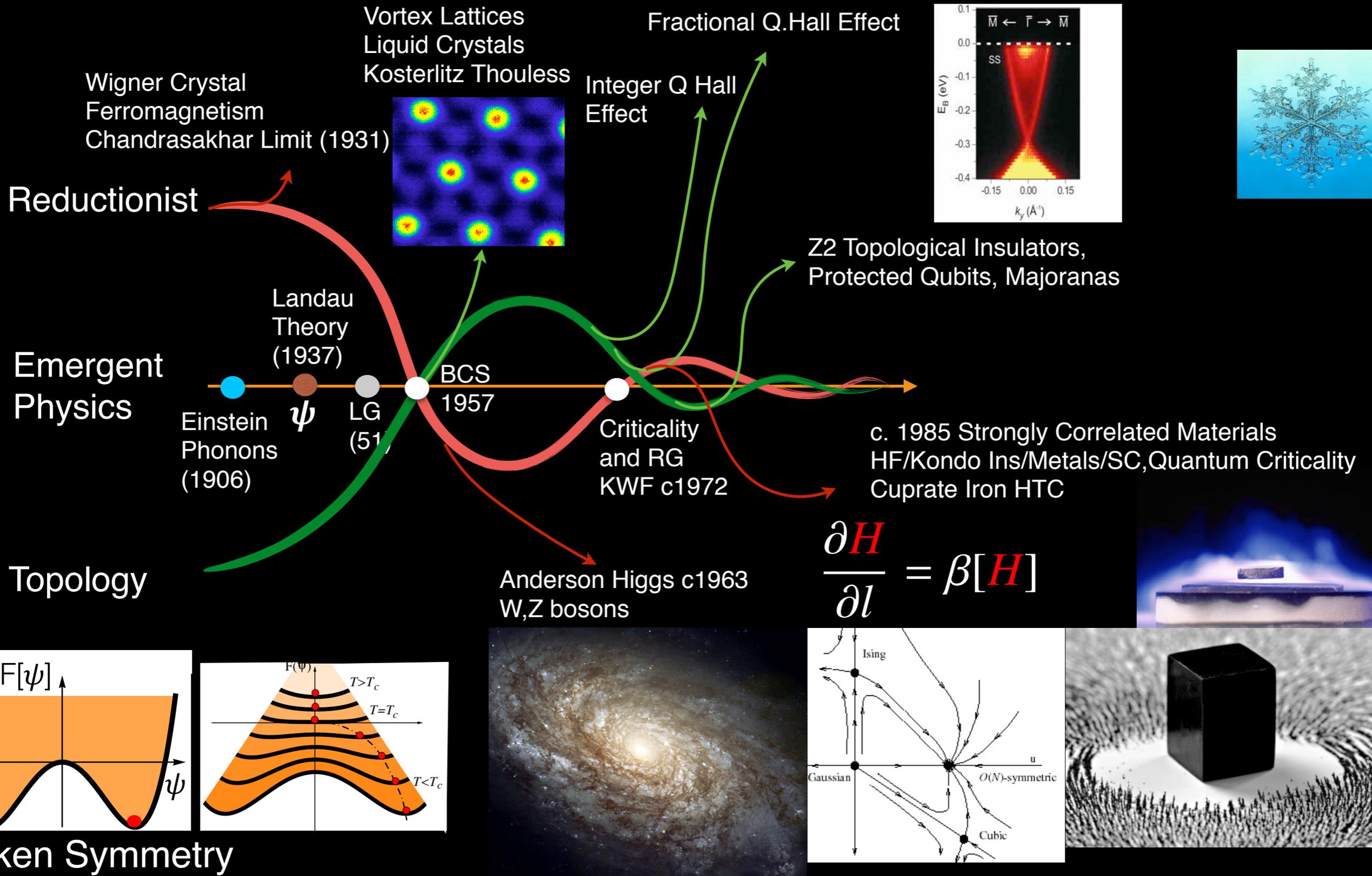
$$\frac{\partial H}{\partial l} = \beta[H]$$



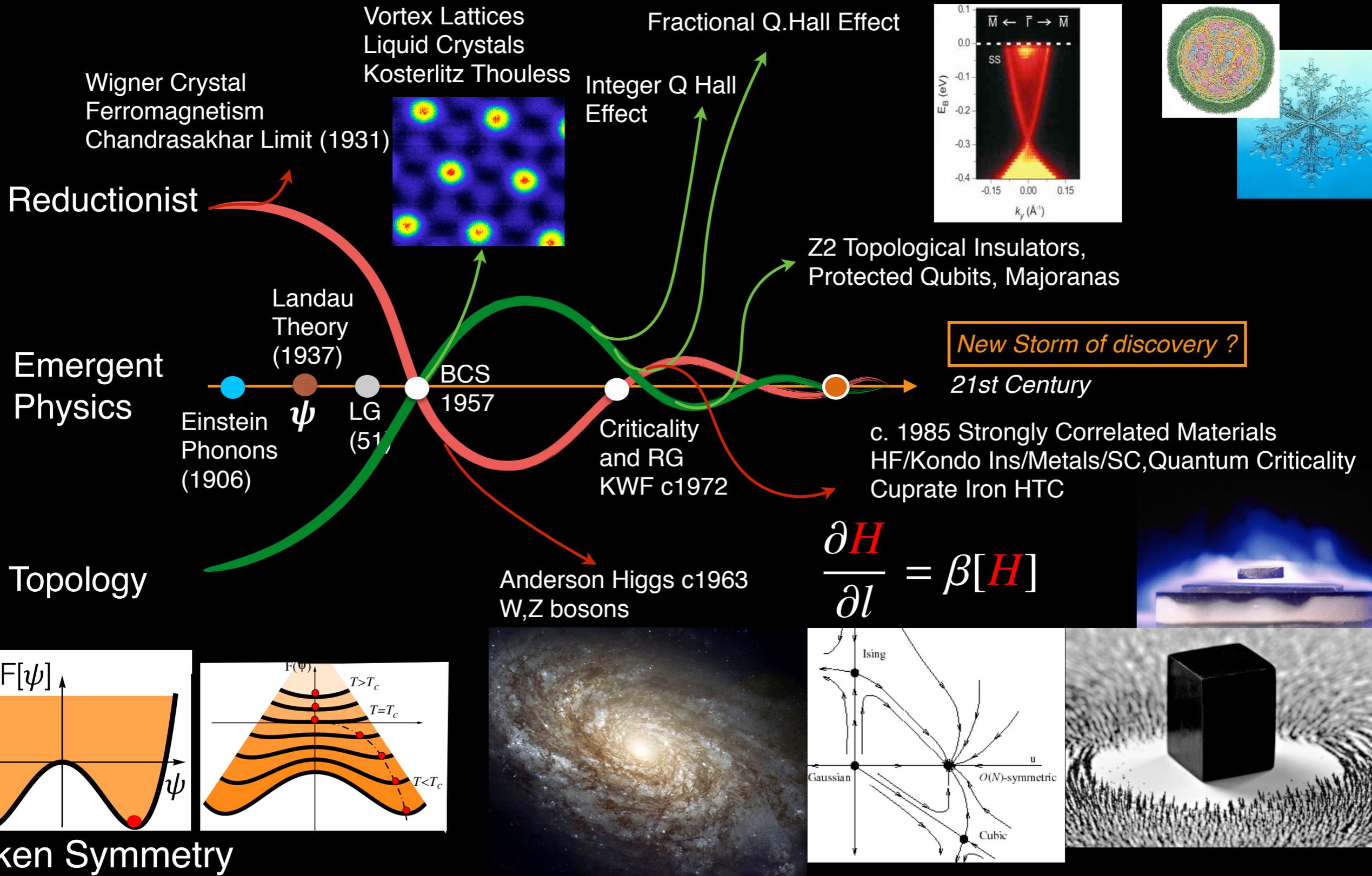
Broken Symmetry



Selected History of Emergence and Reductionism in CMT.



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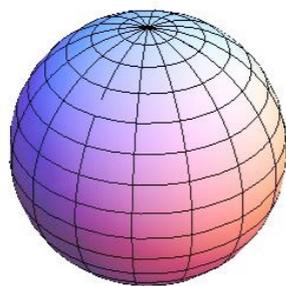
Two examples of emergence in current Condensed Matter Physics

The Rise of Topology

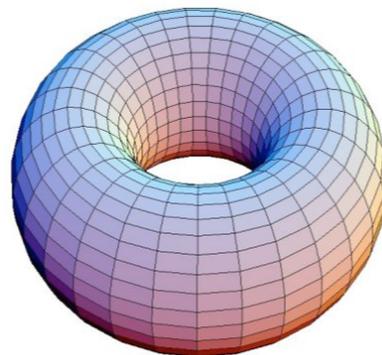
Strange Metals

The rise of Topology.

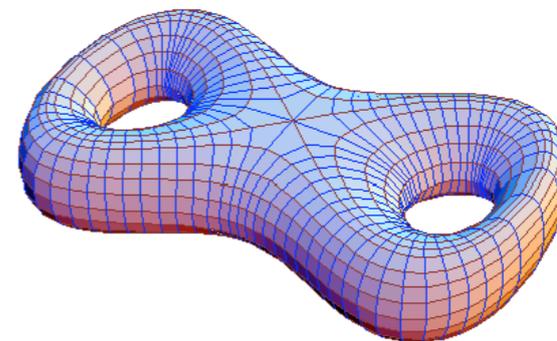
The rise of Topology.



$g=0$



$g=1$

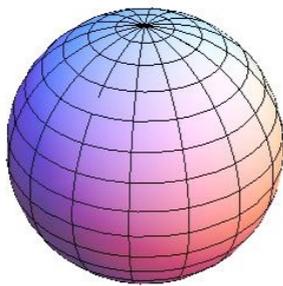


$g=2$

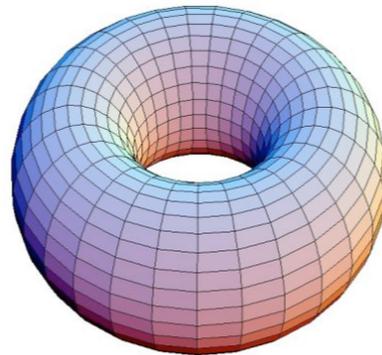
g =genus

The rise of Topology.

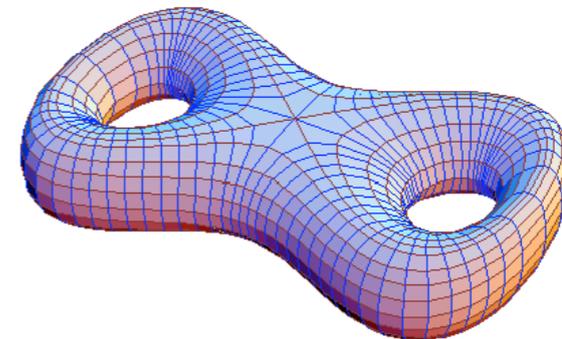
Differential Geometry \longleftrightarrow Topology



$g=0$



$g=1$



$g=2$

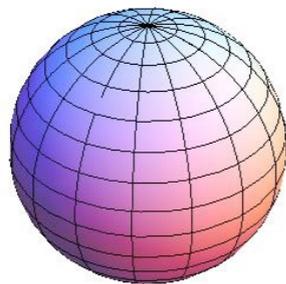
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The rise of Topology.

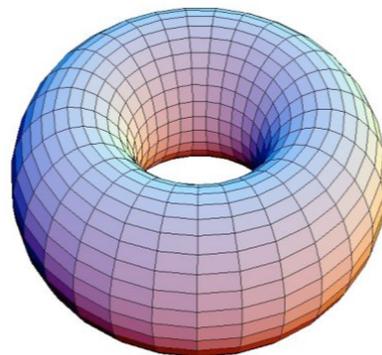
“Gauss-Bonnet Theorem” Gauss (unpublished), Bonnet (1848)

Differential Geometry \longleftrightarrow Topology

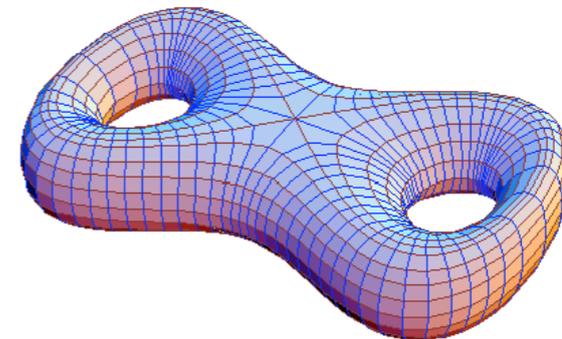
$$\frac{1}{4\pi} \int \kappa dA = \frac{\Omega}{4\pi} = (1 - g)$$



$g=0$



$g=1$



$g=2$

g =genus

The rise of Topology.

Differential Geometry
of the wavefunction



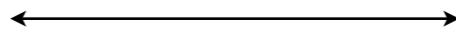
Topological
order

Berry v. Klitzing Laughlin Thouless Haldane

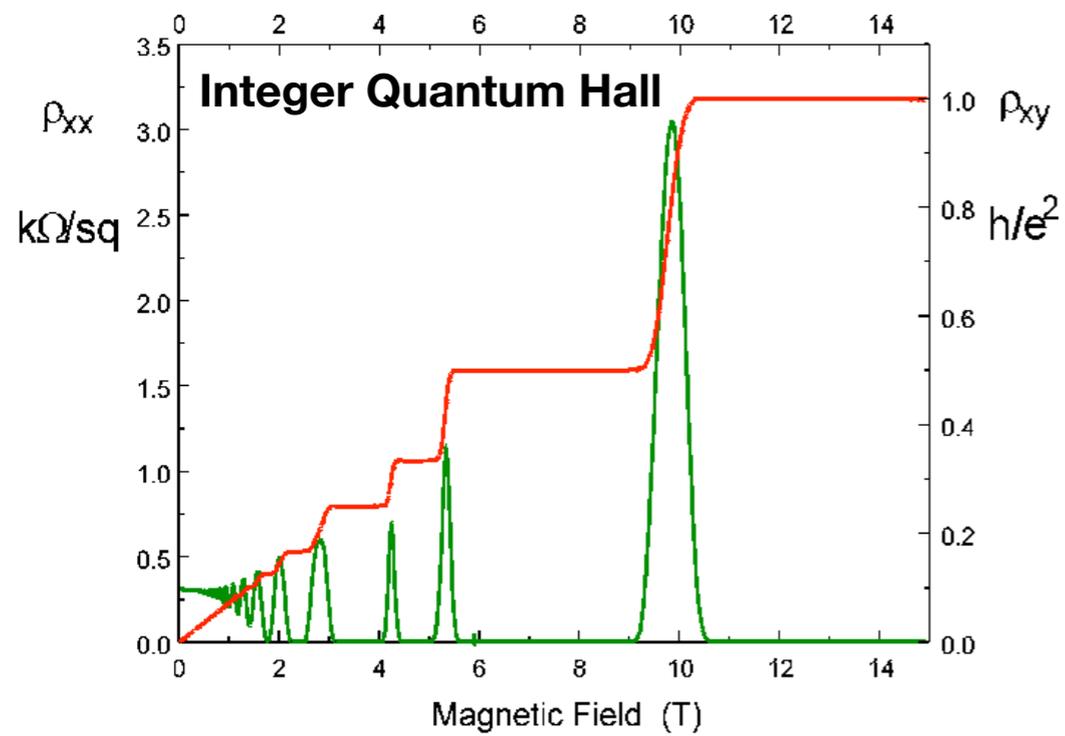


The rise of Topology.

Differential Geometry
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Topological
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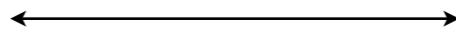
von Klitzing, Dorda & Pepper (1980)

Berry v. Klitzing Laughlin Thouless Haldane

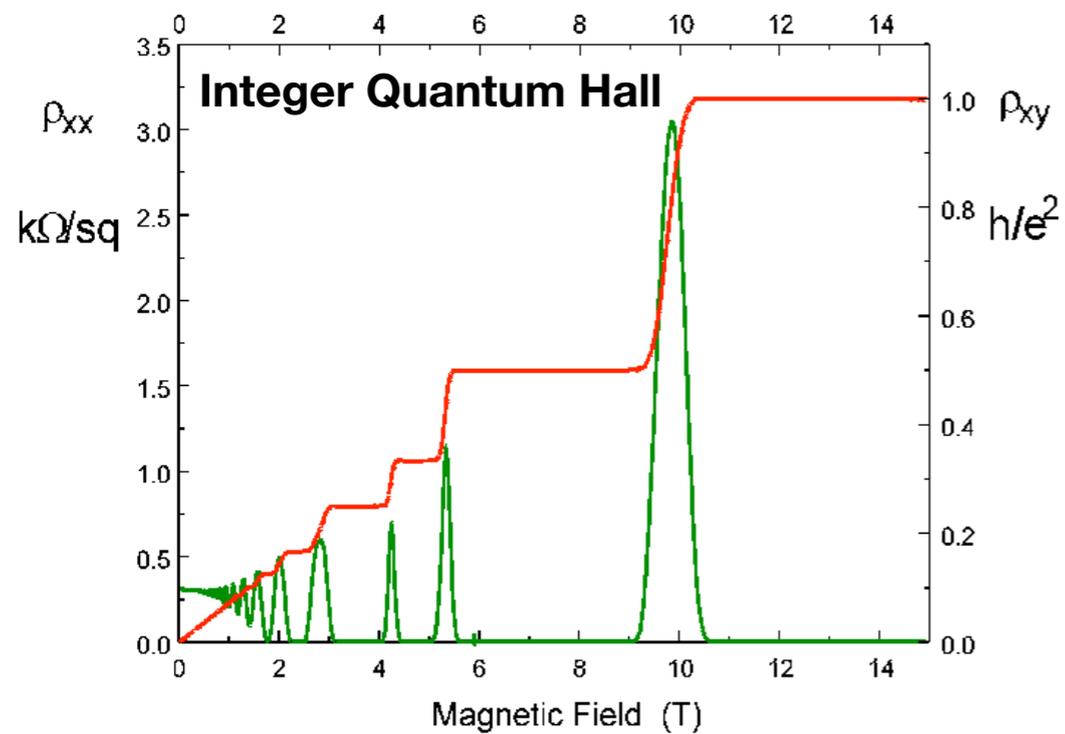


The rise of Topology.

Differential Geometry
of the wavefunction



Topological
order



BERRY CONNECTION
Thouless et al, (1982)

$$\vec{a}_{\mathbf{k}} = i \sum_{n=1,2N} \langle u_{n,\mathbf{k}} | \nabla_{\mathbf{k}} | u_{n,\mathbf{k}} \rangle$$

von Klitzing, Dorda & Pepper (1980)

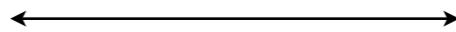


BERRY CONNECTION
Thouless et al, (1982)

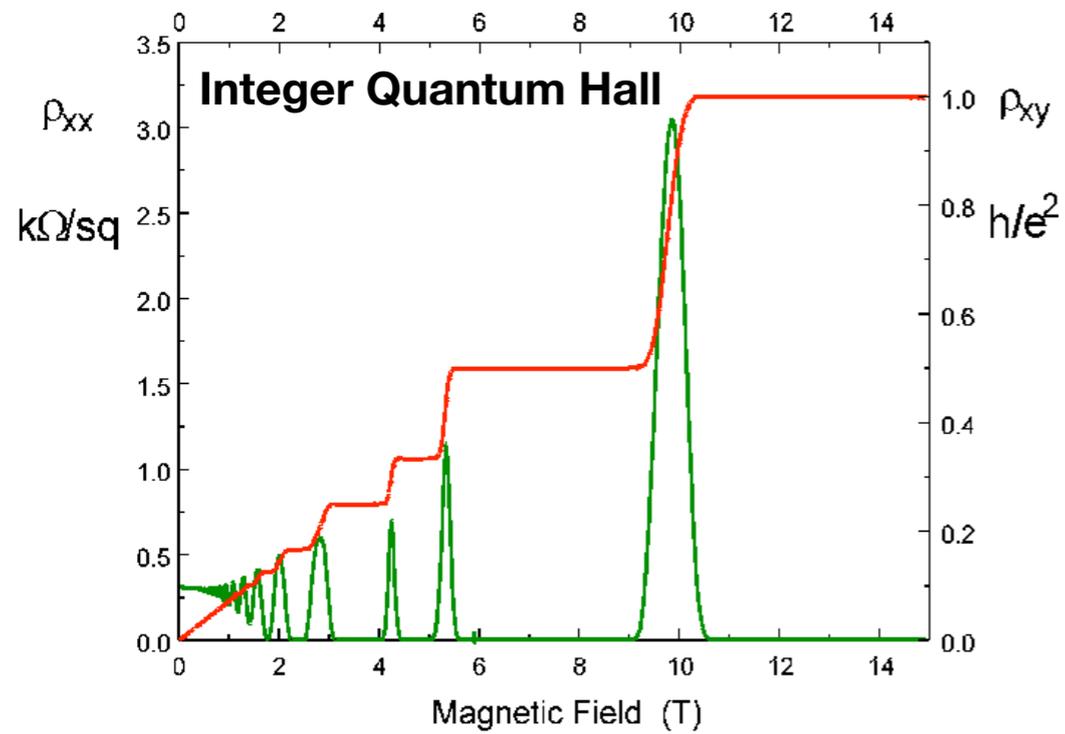
$$\vec{a}_{\mathbf{k}} = i \sum_{n=1,2N} \langle u_{n,\mathbf{k}} | \nabla_{\mathbf{k}} | u_{n,\mathbf{k}} \rangle$$

The rise of Topology.

Differential Geometry
of the wavefunction



Topological
order



von Klitzing, Dorda & Pepper (1980)

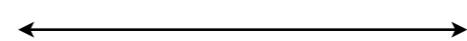


BERRY CONNECTION
Thouless et al, (1982)

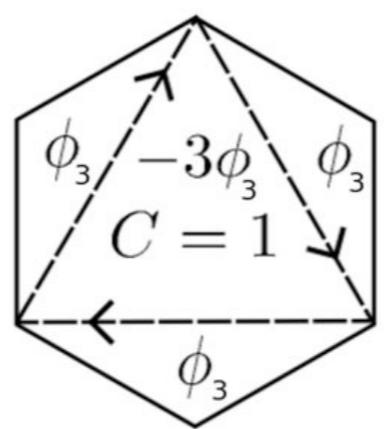
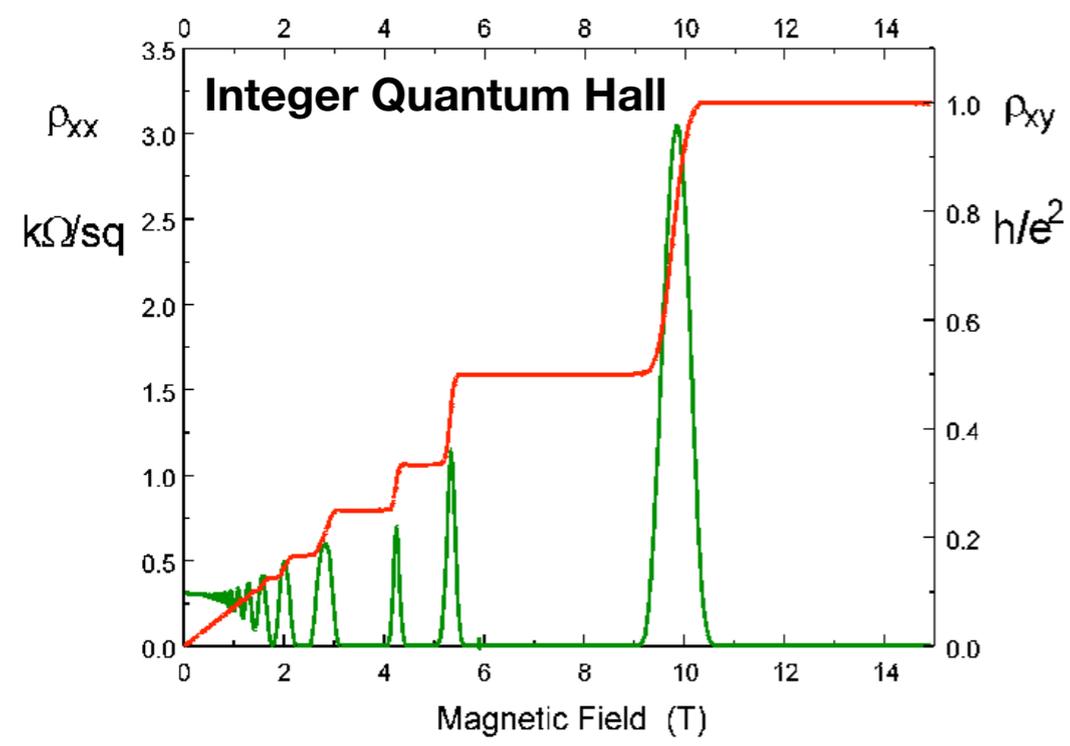
$$\vec{a}_{\mathbf{k}} = i \sum_{n=1,2N} \langle u_{n,\mathbf{k}} | \nabla_{\mathbf{k}} | u_{n,\mathbf{k}} \rangle$$

The rise of Topology.

Differential Geometry
of the wavefunction



Topological
order



Haldane (1988)
no net field

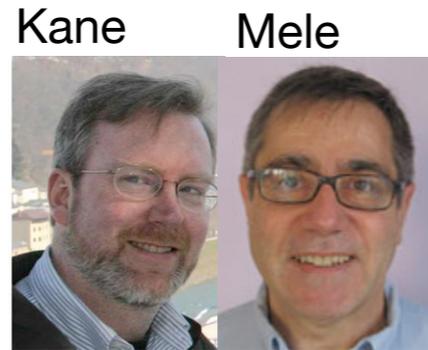
von Klitzing, Dorda & Pepper (1980)



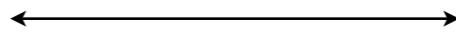
BERRY CONNECTION
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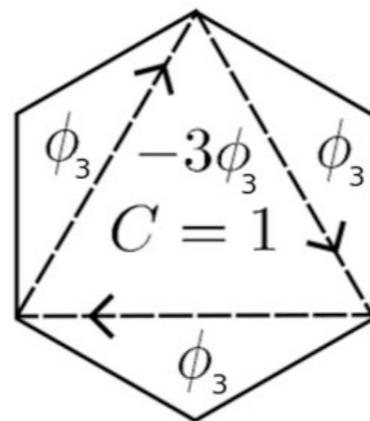
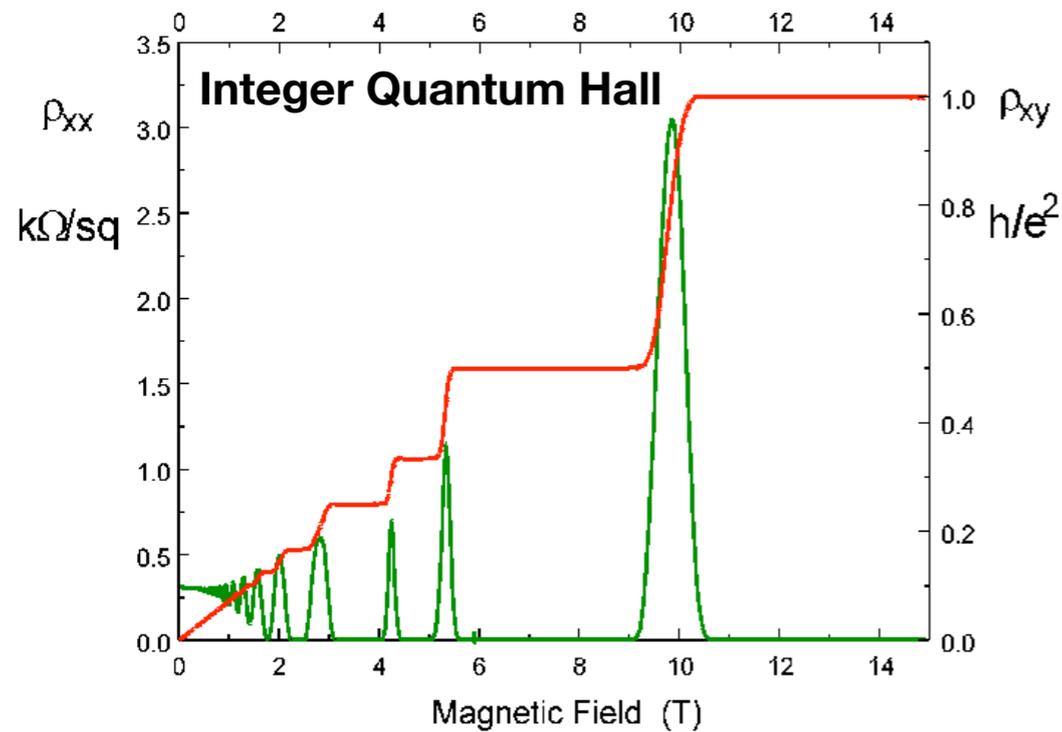
The rise of Topology.



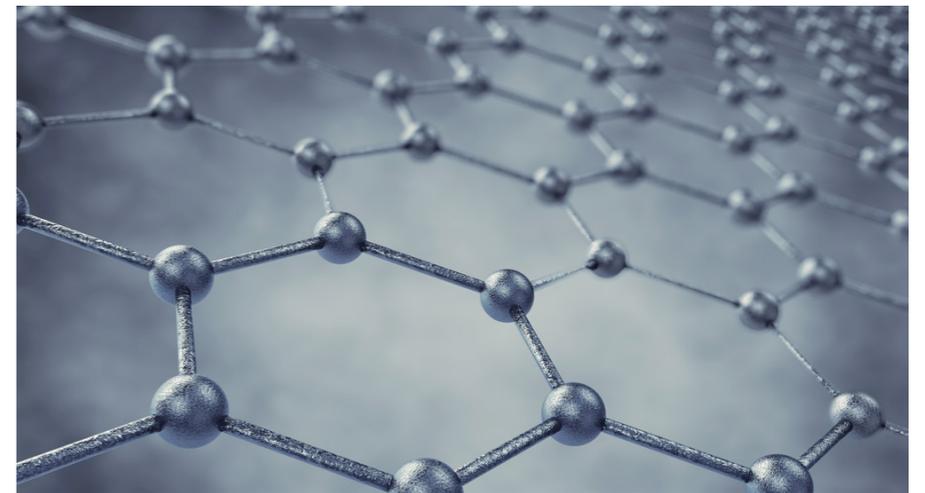
Differential Geometry
of the wavefunction



Topological
order



Haldane (1988)
no net field



Graphene + Haldane's model:
Inspiration for Kane Mele 2005

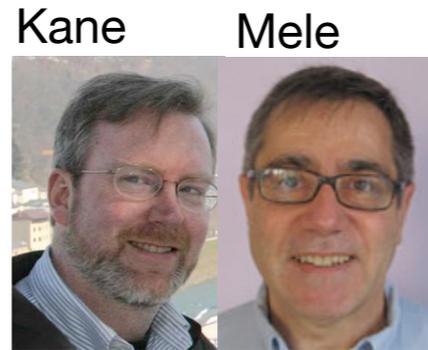
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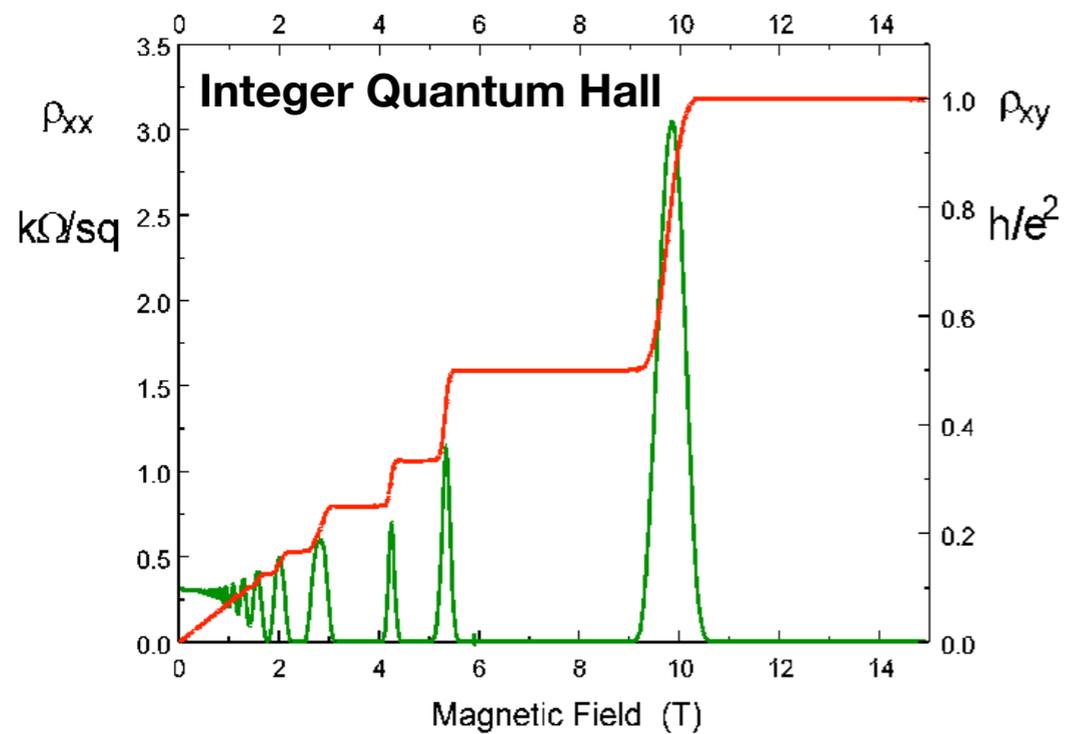
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Differential Geometry
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Topological
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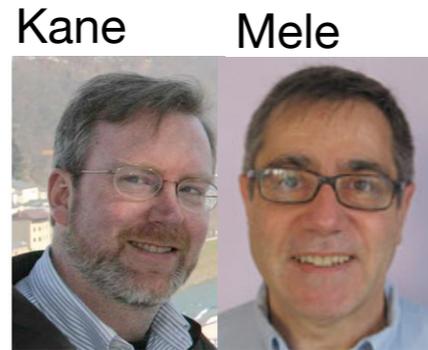
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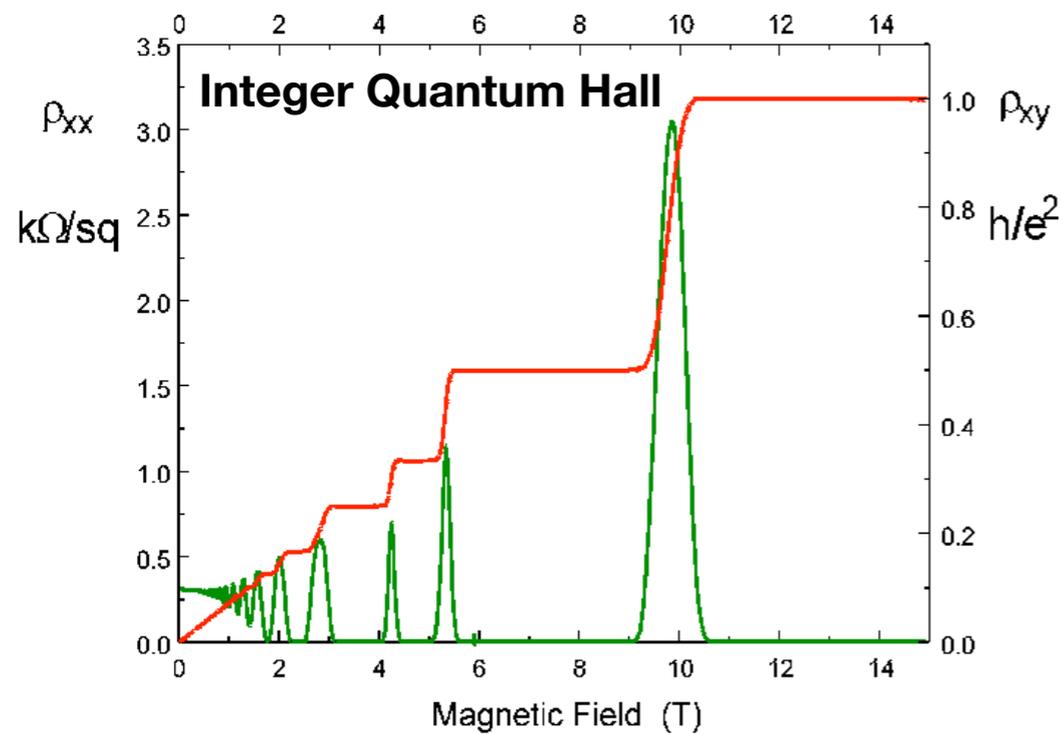
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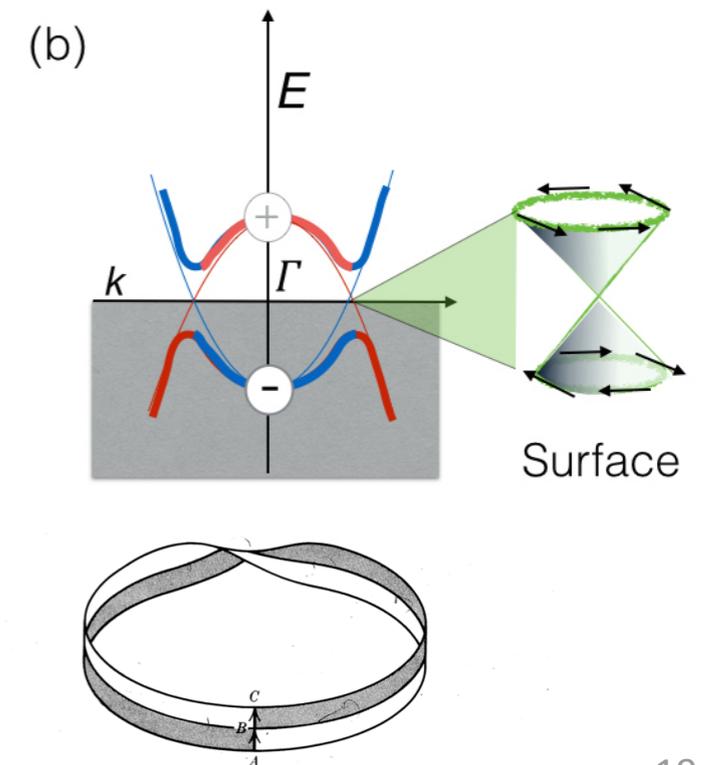
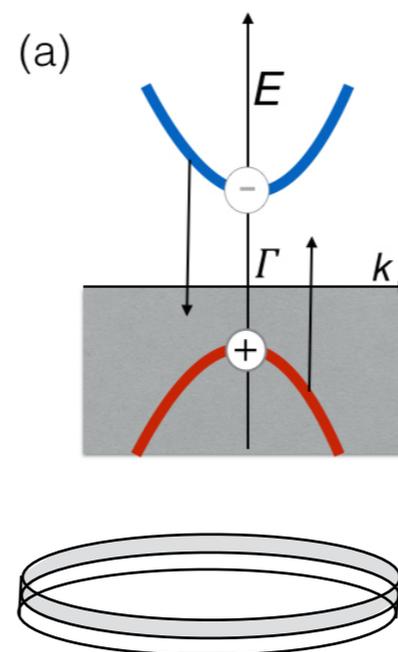
Differential Geometry
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Topological
order



von Klitzing, Dorda & Pepper (1980)



Topological Texture of Berry Connection



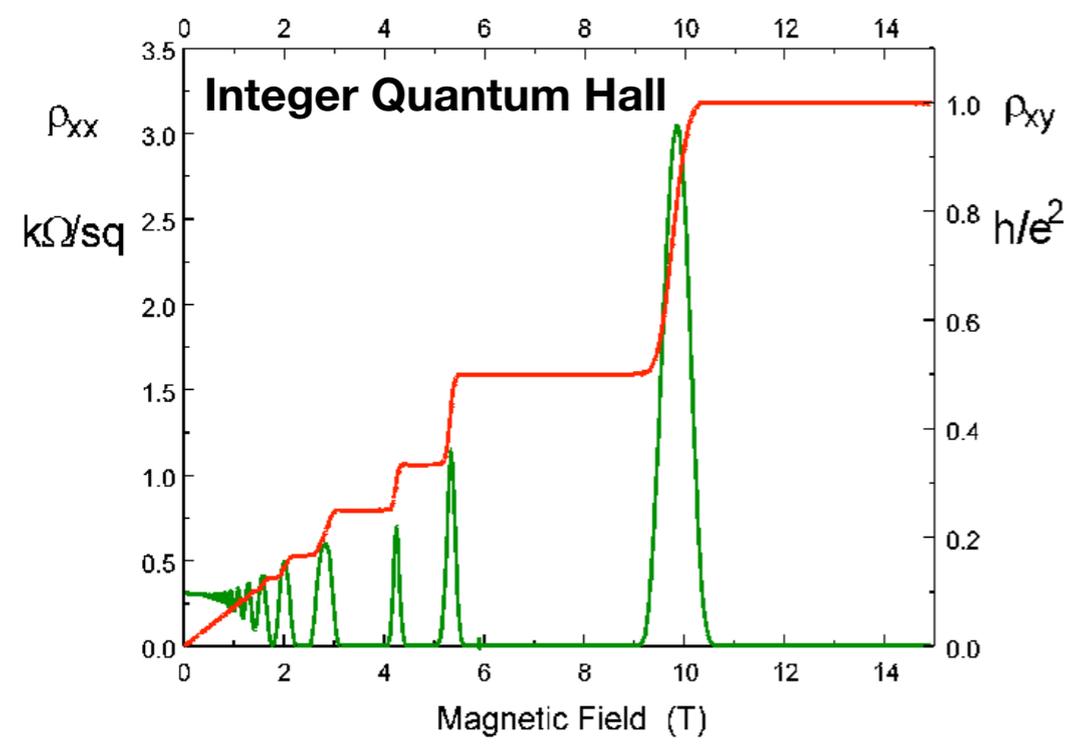
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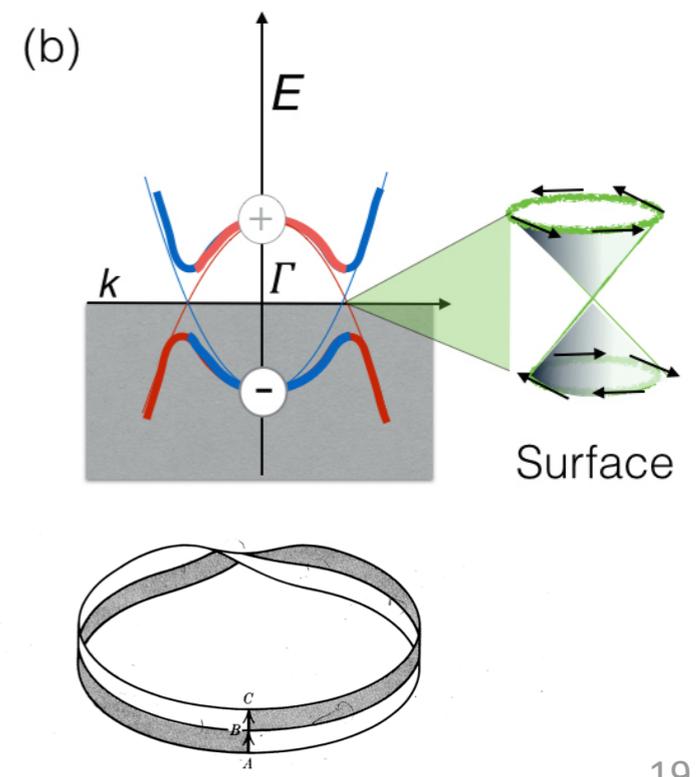
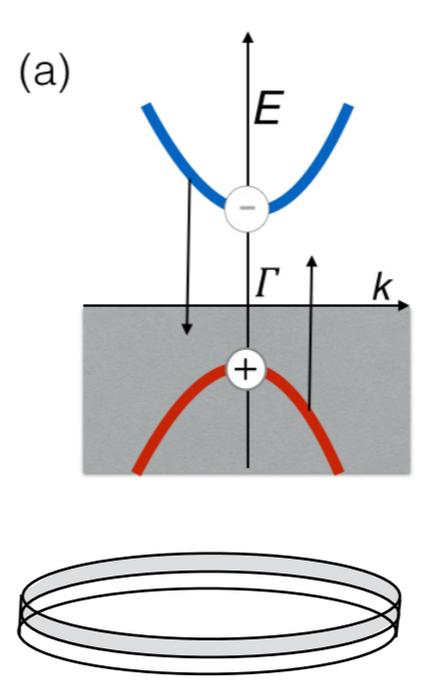
The rise of Topology.



Differential Geometry of the wavefunction \longleftrightarrow Topological order



von Klitzing, Dorda & Pepper (1980)





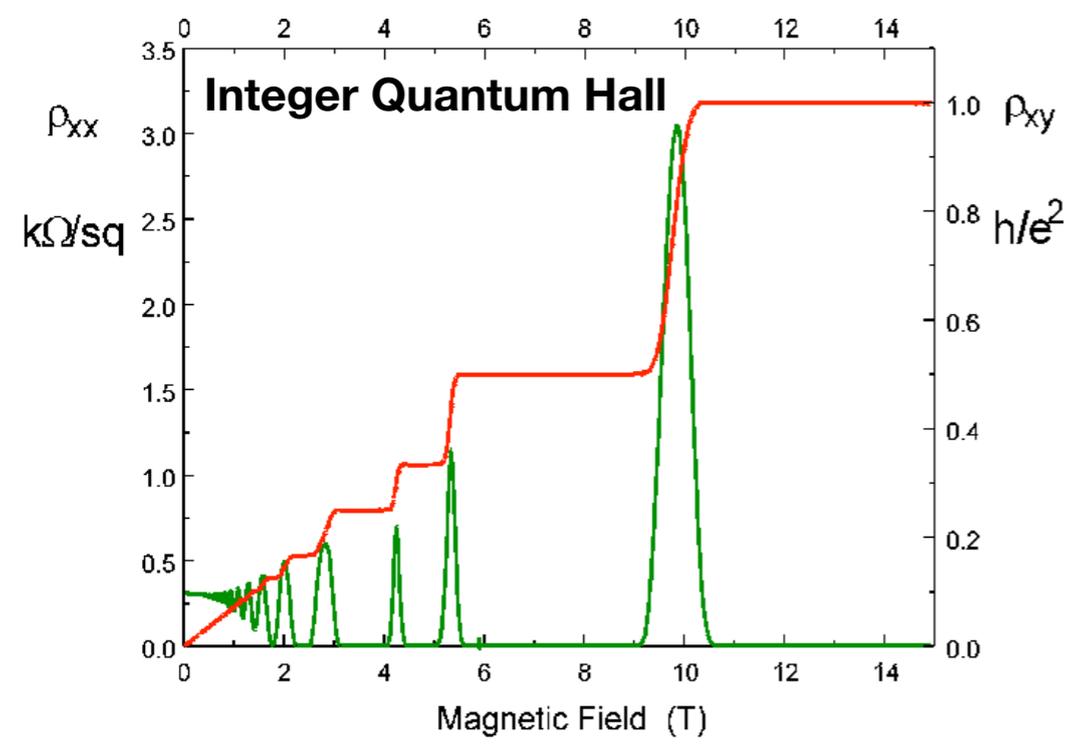
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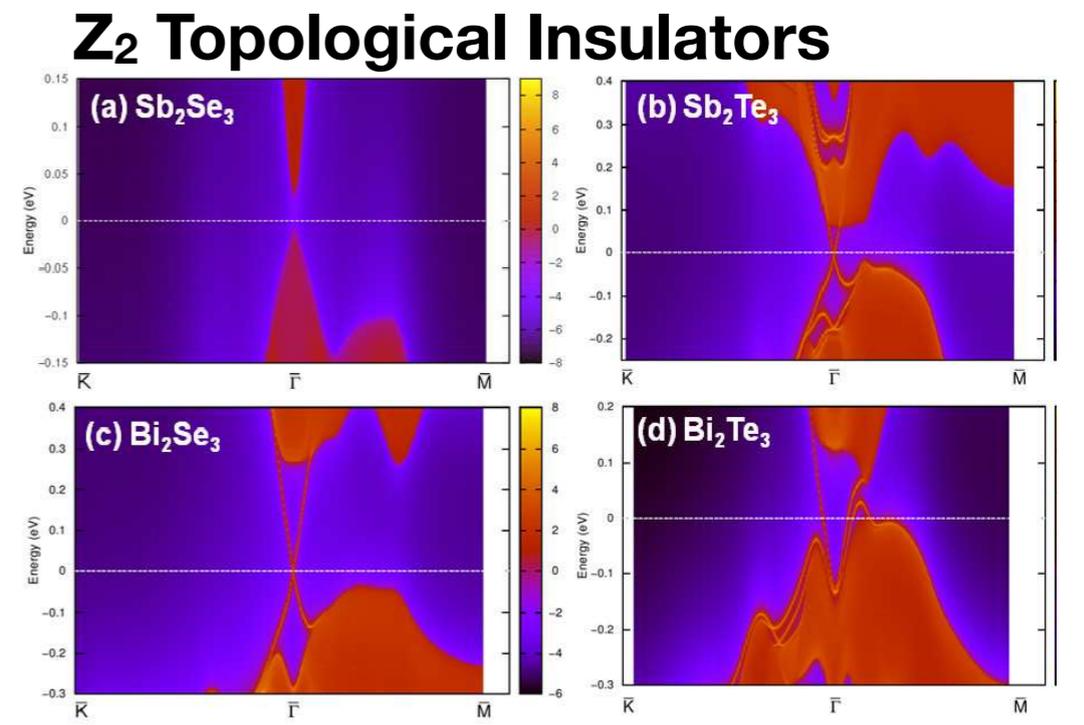
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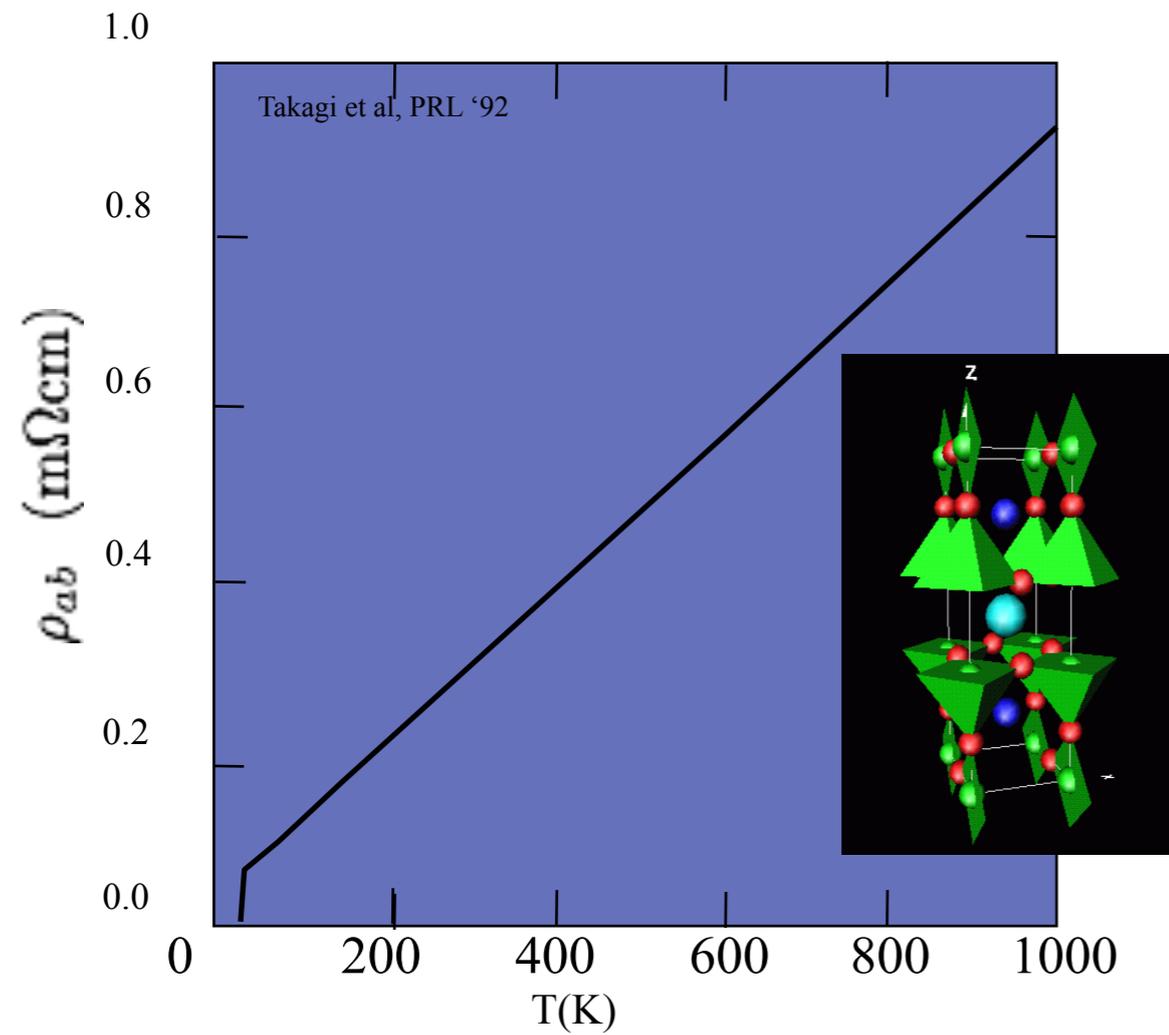


von Klitzing, Dorda & Pepper (1980)



Qi and Zhang, Rev. Mod Phys (2010).

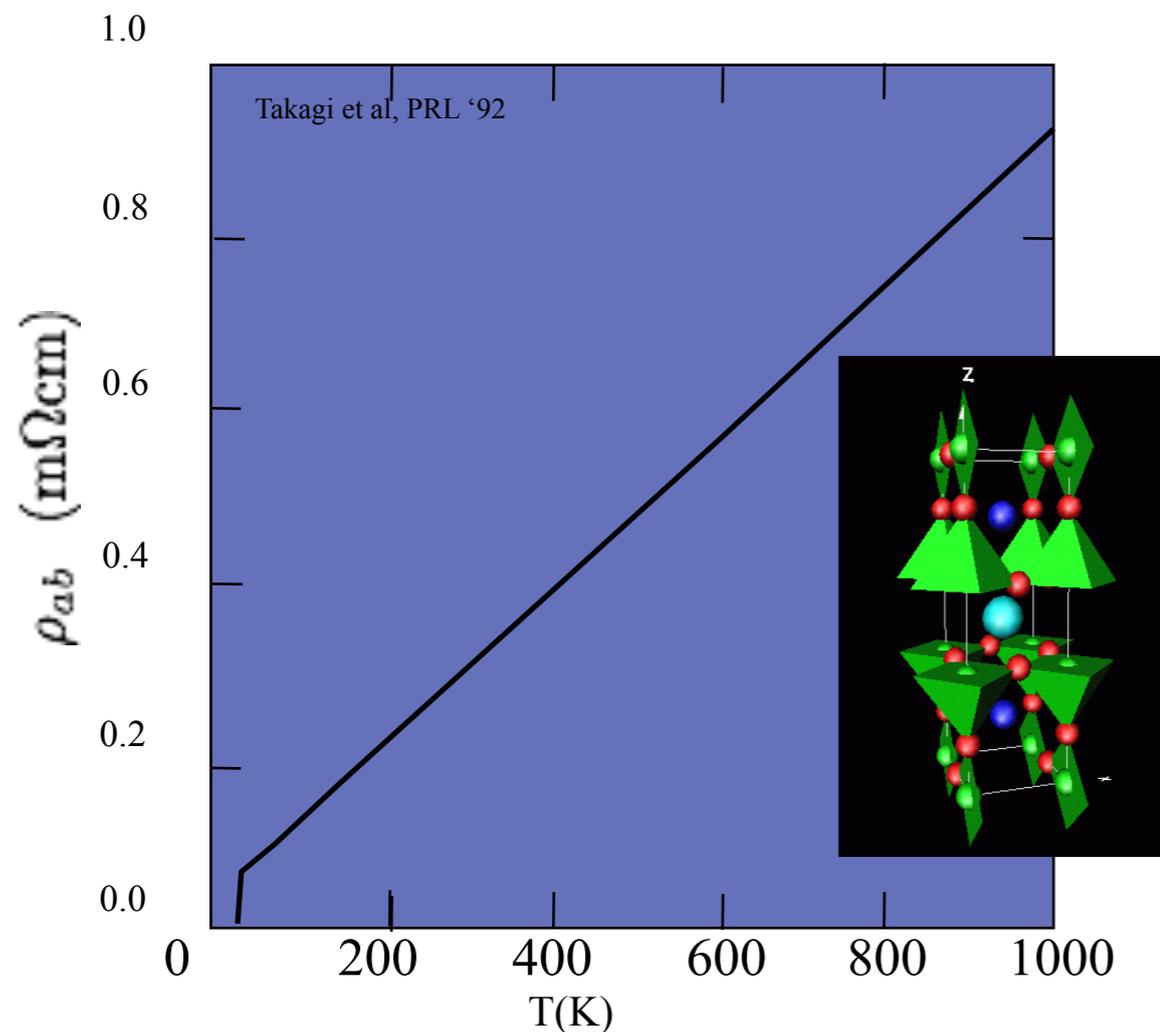
Strange Metals.



Cuprates $T_c=11-92\text{K}$

The normal state is stranger than the superconductor!

Strange Metals.



Cuprates $T_c=11-92K$

The normal state is stranger than the superconductor!

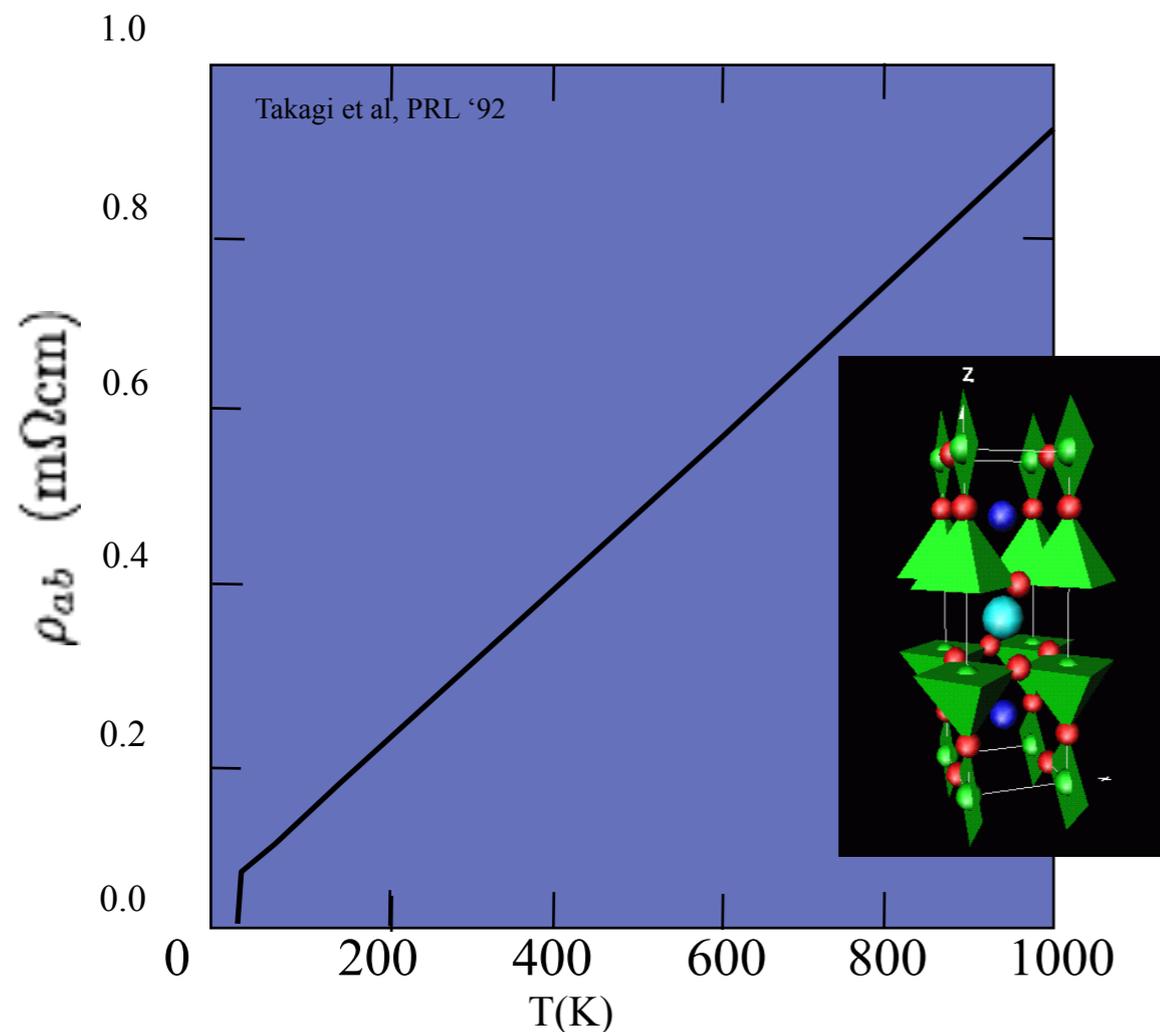


“One of the most striking dilemmas about the high- T_c superconducting cuprates is that they only seem to obey the standard BCS quasiparticle theory when they are superconducting— after all is said and done and in a restricted sense—but that the normal state is undoubtedly not the Fermi liquid on which BCS theory is based.

Philip. W. Anderson

“Hidden Fermi Liquids’ , 2008.

Strange Metals.



Cuprates $T_c=11-92\text{K}$

The normal state is stranger than the superconductor!

Conventional metal: one T^2 relaxation time
Strange metals: two relaxation times - T and T^2

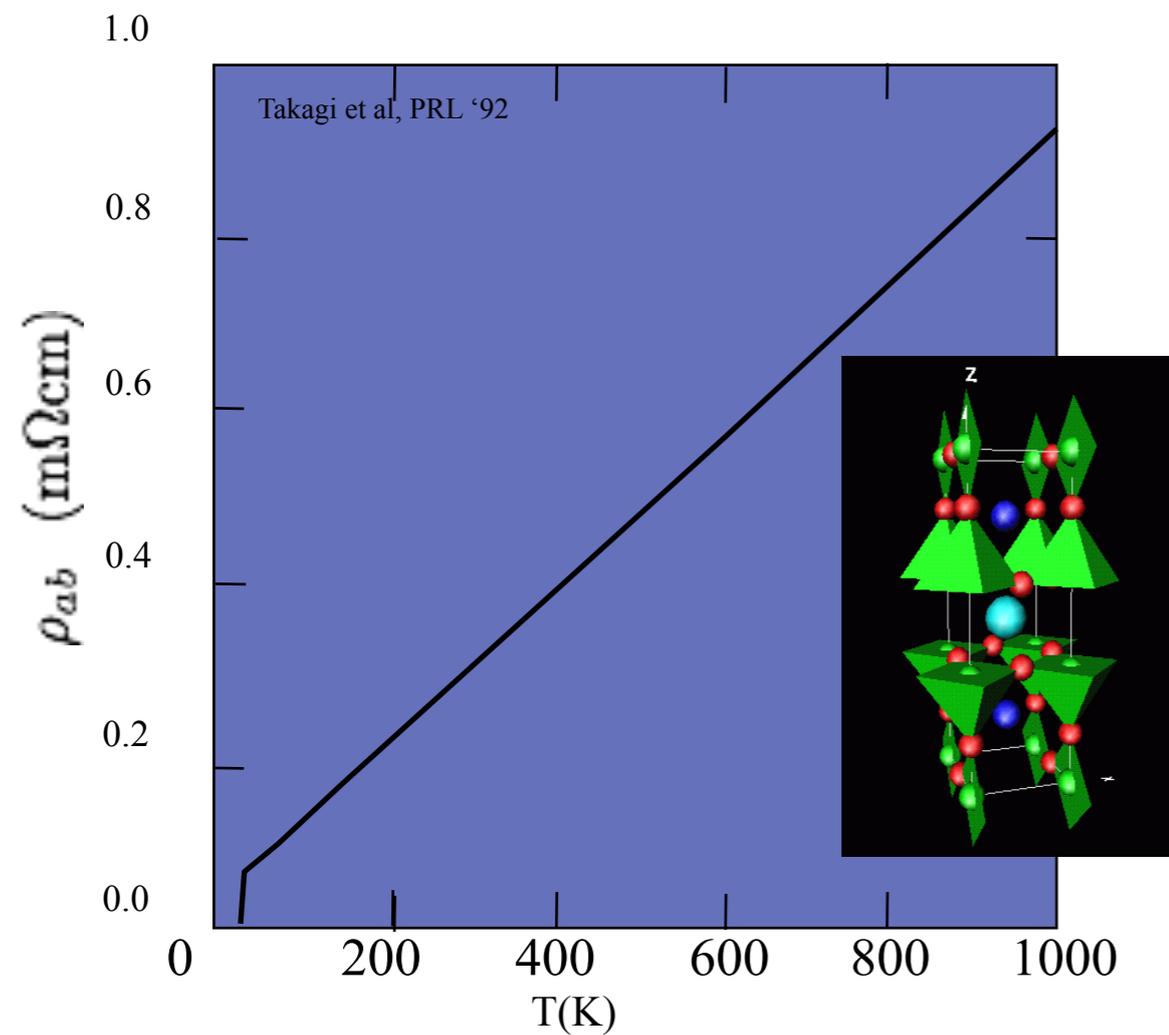


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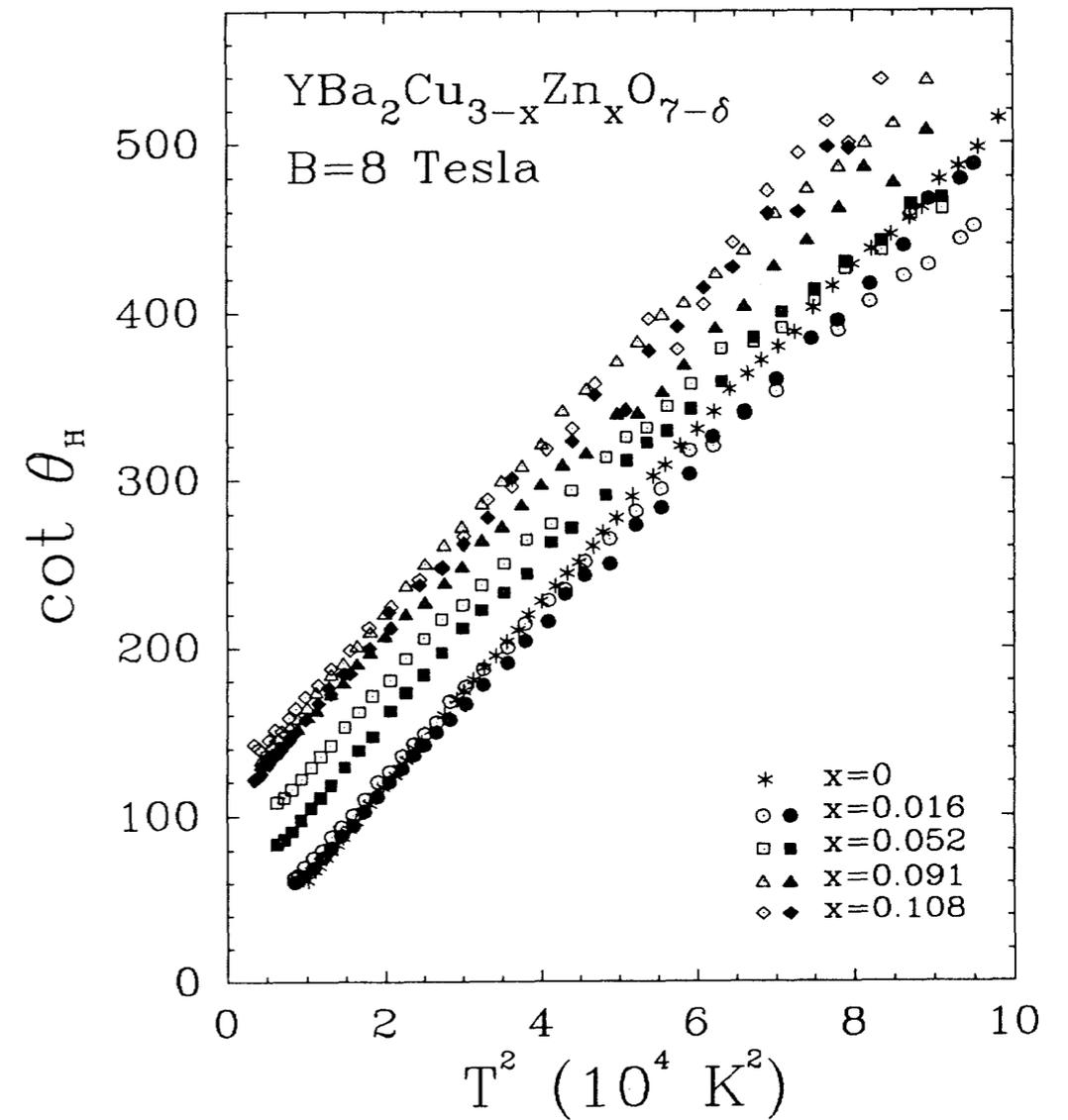
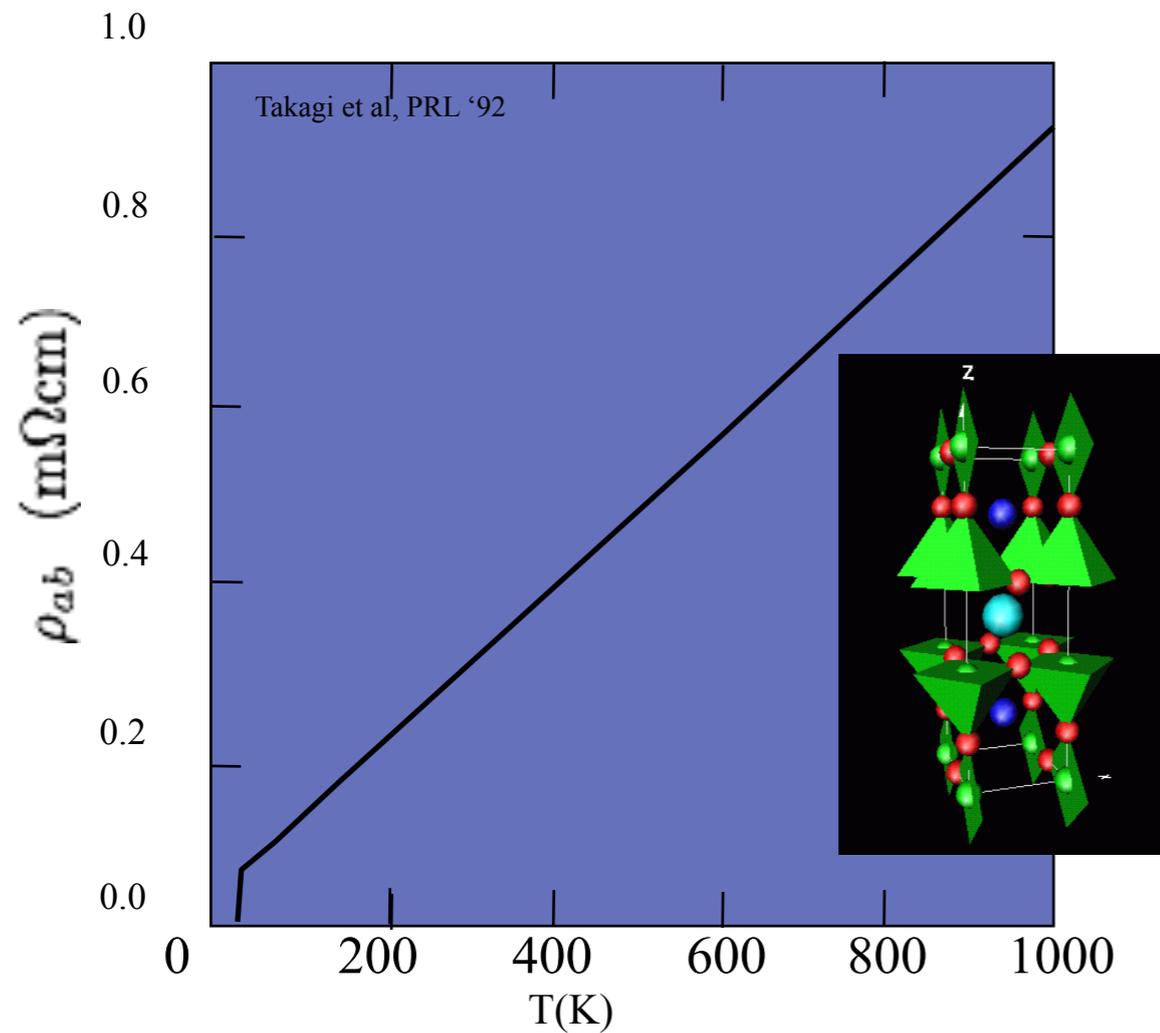
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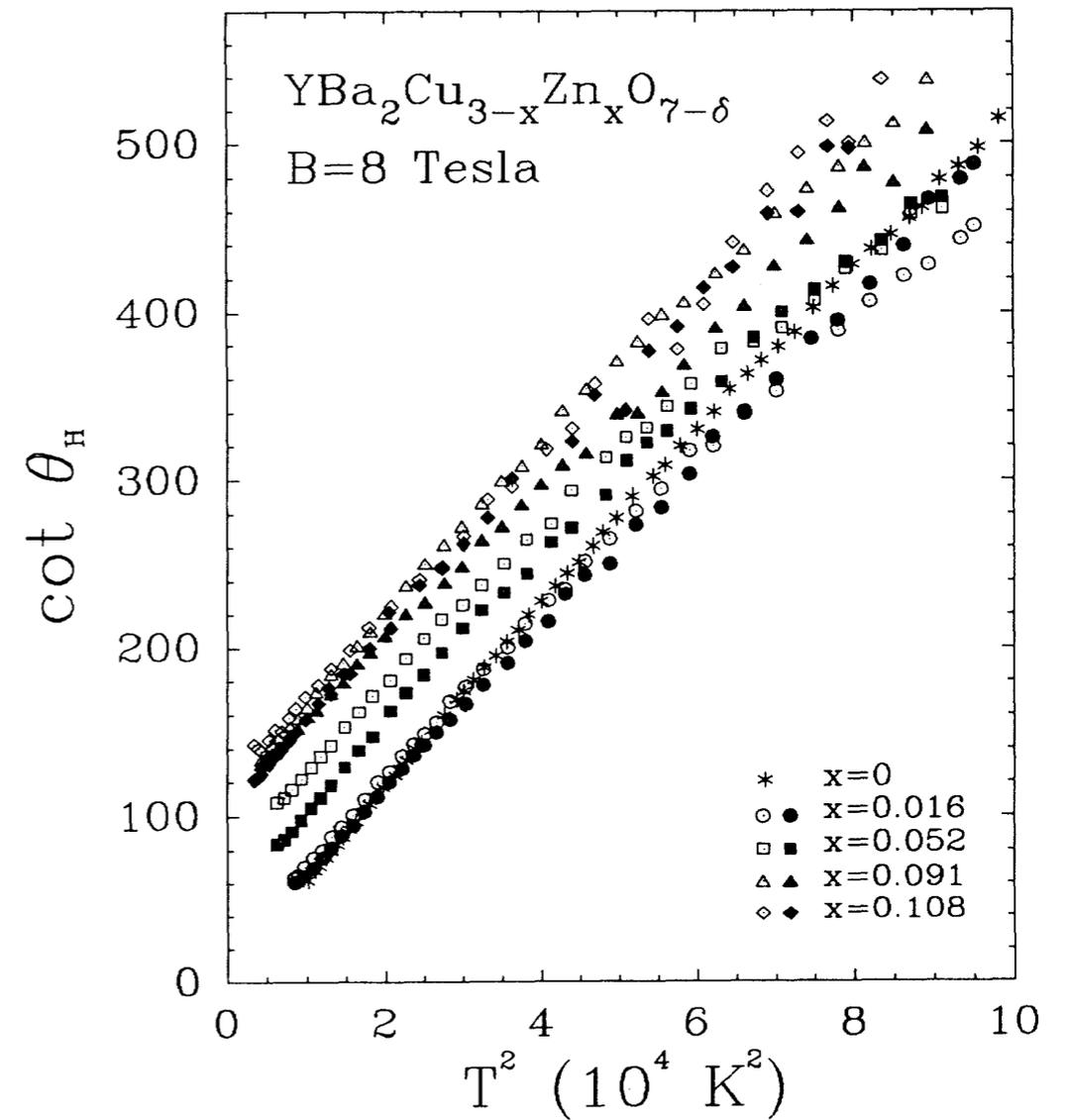
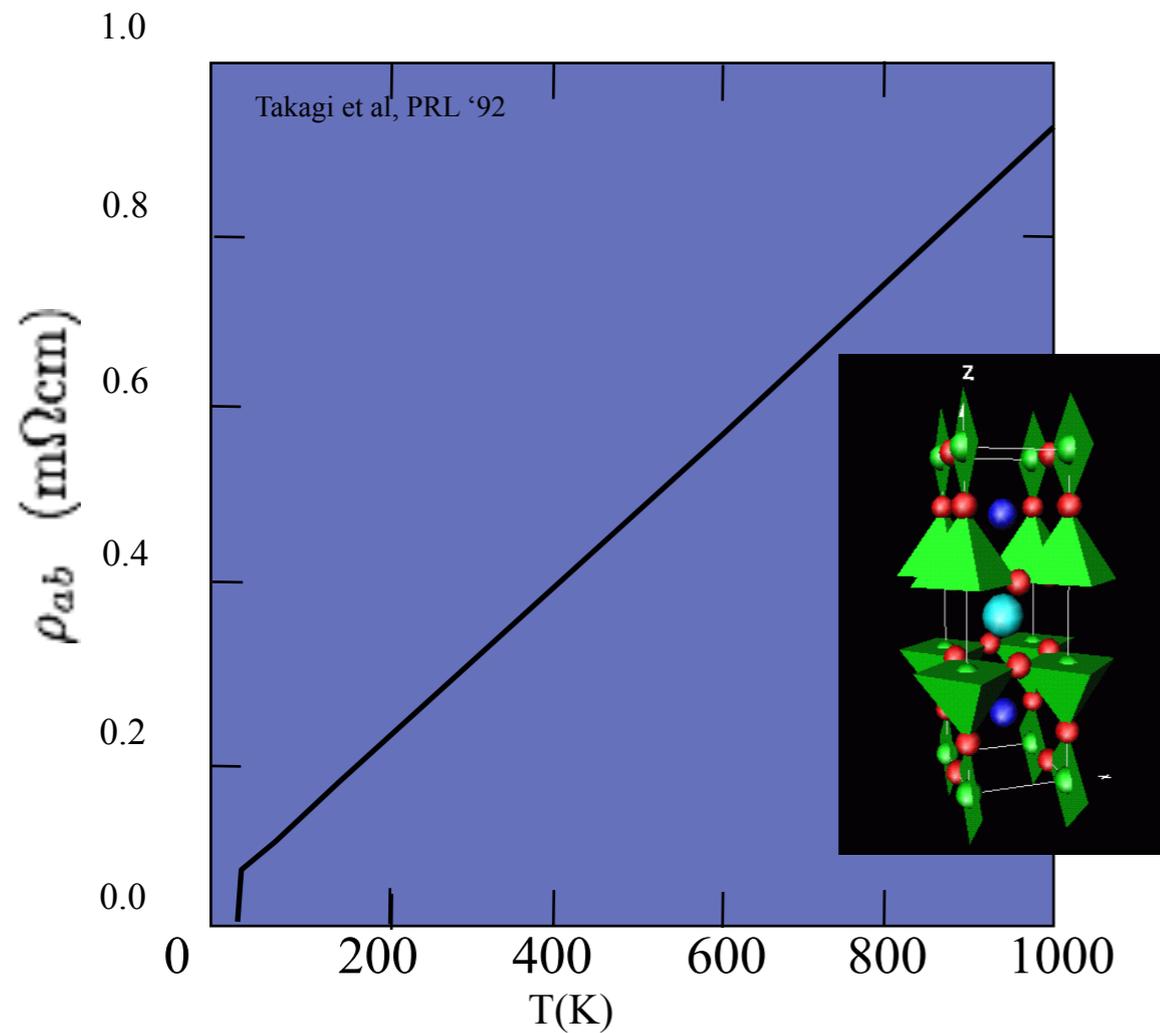
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A 30 year old mystery.

Conclusions

Emergent physics, combined with experiment, continues to yield important insights into our ongoing reductionist understanding.

Condensed matter physicists are looking to the tools of particle physics, such as the holographic principle to make new progress on the many-body problem

Similarly, particle-astro physicists are looking to emergence/condensed matter for inspiration eg is space time an emergent property? (next talk).

90 years after Heisenberg, Schrödinger and Dirac, we are likely still in the quantum revolution, and perhaps like Classical Mechanics, a more complete understanding awaits new perspectives from emergence.