Lecture 1: Physics as Natural Philosophy

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Outline

- Physics as natural philosophy
- The Feynman lectures on Physics.
- History of Physics: from ancient to modern time
- Contemporary physics – high energy, astrophysics, AMO, and condensed matter
- Reductionism v.s. emergentism
- Energy (mass, temperature), length, time scales

Etymology of physics: To be or not to be ☺

Proto-Indo-European: bheue “to be, exist, grow”

Greek: φυσικός (*physikos*) ``of nature” by Aristotle

↓

Latin: physica (study of nature)

↓

Proto-Germantic : beuna

↓

Old English: beon

↓

English : be (存在)

English: physic **(医学)**

physics **(物理学：研究一切存在事物的学问)**

Physics studies how the universe works

- Principles of matter, motions in space and time, and inseparable relations among them.

1. Cognitive revolution: celestial objects (Sun, Moon, planets) are not propelled by angels, but obey the same laws of mundane objects like apples.
2. Understand the birth, evolution, and fate of the universe
3. Lay foundations for the optoelectronic and information era
4. Explore organization principles of complex matter, including superconductivity, magnetism, life, and society.




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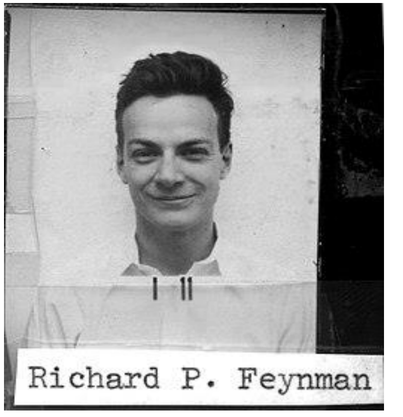
Richard P. Feynman



- 1918, born in New York
- 1942, Ph. D of Princeton
- 1943-1945, the Manhattan Project
- 1945-1949, Cornell
- 1952-1987, Caltech
- 1988, died of cancer

- 1961-1963, general physics teaching for undergrads
- 1965, Nobel Prize in physics for establishing quantum electrodynamics (shared with Schwinger and Tomonaga)
- 1986, commission member for the Challenger disaster

- Path integral method for quantum mechanics
- Theory of superfluid helium
- Theory of beta-decay for weak interaction
- Parton model for strong interaction
- Autobiography and popular science writings

The Feynman Lectures on Physics (Vol I, II, III)

- https://www.feynmanlectures.caltech.edu/
- "Tough, but nourishing and full of favor. After 25 years it is the guide for teachers and for the best of beginning students" – Scientific American
- Reformulating physics, reducing deep ideas into simple, understandable terms

The Feynman Lectures on Physics including Feynman's *Tips on Physics: The Definitive and Extended Edition* (2nd edition, 2005)

- "The lectures… are very serious. I thought to address them to the most intelligent in the class, …, and even the most intelligent student was unable to completely encompass everything… "
- "Many of the students and faculty… said that having 2 years of physics with Feynman was the experience of a lifetime. But that's not how it seemed at that time. Many of the students dreaded the class, and as the course wore on, attendance by the registered students start dropping alarmingly.

Feynman's writing – an elegant prose style

- If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generations of creatures…. I believe it is the *atomic hypothesis* … that *all things are made of atoms*
  --- The *Feynman lectures on physics* Vol I Chapter I

- A poet said, "The whole universe is in a glass of wine" ….
- There are the things of physics: the twisting liquid which evaporates depending on the wind and weather … and our imagination adds the atoms. The glass is a distillation of the earth's rocks, and in its composition we see the secrets of the universe's age, and the evolution of stars.
- If our small minds, for some convenience, divide this glass of wine, this universe, into parts—physics, biology, geology, astronomy, psychology, and so on— remember that nature does not know it! So let us put it all back together, not forgetting ultimately what it is for.…Let it give us one more final pleasure: drink it and forget it all!
  --- The Feynman lectures on physics Vol I Chapter 3

Feynman’s Epilogue

- Finally, may I add that the main purpose of my teaching has not been to prepare you for some examination….

- I wanted most to give you some appreciation of the wonderful world and the physicist’s way of looking at it, which, I believe, is a major part of the true culture of modern times. (There are probably professors of other subjects who would object, but I believe that they are completely wrong.)

- Perhaps you will not only have some appreciation of this culture; it is even possible that you may want to join in the greatest adventure that the human mind has ever begun.

费曼，（Richard Phillips Feynman，1918--1988），因对量子电动力学的贡献，1965年获得诺贝尔物理学奖。

物理学家中的另类，以特立独行著称。

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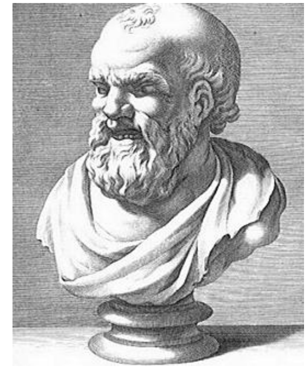
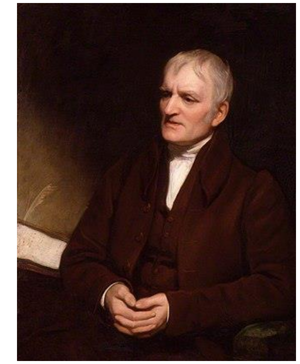
The atomic hypothesis

- The modern concept of atom is inspired by the fact that the appearance of integer numbers in chemical reactions

- Small particles in motion even at zero temperature (thermal and quantum motions). Repulsion when inter-particle distances are small, and attraction when large.

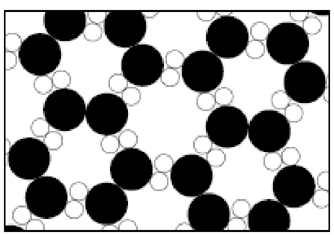


Democritus
(460BC-370BC)

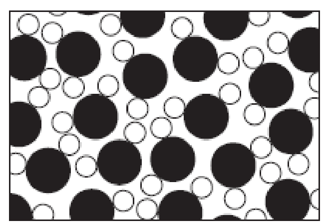


John Dalton
(1766-1844)

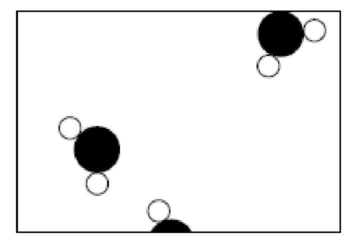
- Phase transitions.



increase T →



increase T →



ice crystal: long-range ordered, rigidity; comparisons to glass, porcelain (ceramics)

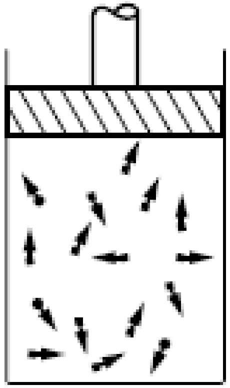
water: long-range disordered

vapor: volume expansion ~ 1000 times

The kinetic theory of gases

- Pressure comes from collisions of atoms on walls.

Gas in vessel: P(T, n/V)



- Ideal Boltzmann gas (A good approximation)

$$P = k_B T N/VT$$
$$T \propto \langle E_k \rangle = \langle \frac{1}{2} m v^2 \rangle$$

Question: Why does $P \propto v$^2?

- Question: What happens if the piston is pushed inward adiabatically, which means the process is very slow and has no heat exchange with the environment?

- Question: What happens if the gas expands adiabatically?

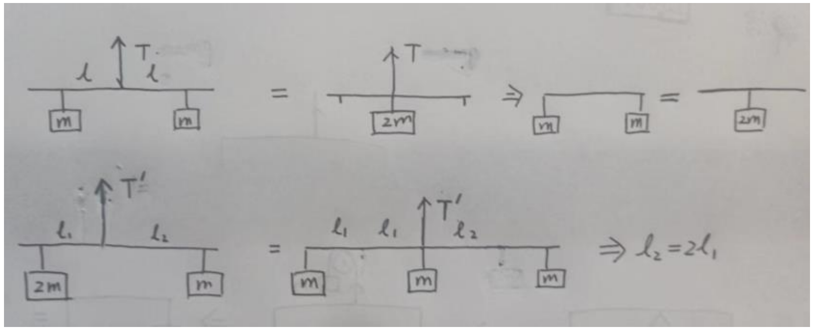
Aristotle and Archimedes

- *Physics (Aristotle): A pioneer rather than an anti-hero.*

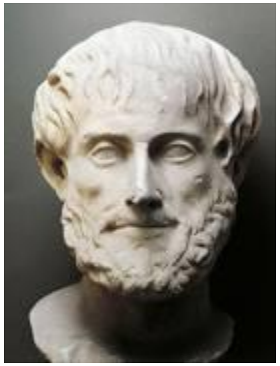
  Q: Why was Aristotle not able to develop Newton's law of dynamics?
  A: Lack of precision measurement of time.

- Statics: the equilibrium condition of lever

  Can you prove that $F_1 l_1 = F_2 l_2$?



- Archimedes' principle:
  buoyant force = weight of displaced fluid



Aristotle
(384BC-322BC)

Archimedes of Syracuse (287BC-212BC)

Galileo: The first modern physicist

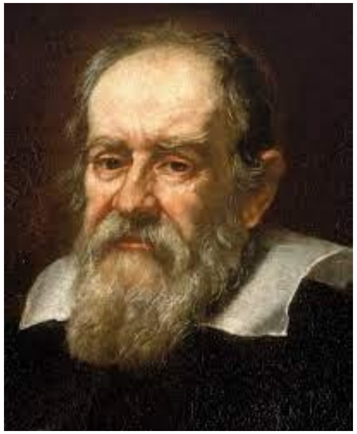
- Galileo – the father of modern physics – indeed of modern science. – A. Einstein

- Scientific methodology: Design experiments to test hypothesis and discover new phenomena.

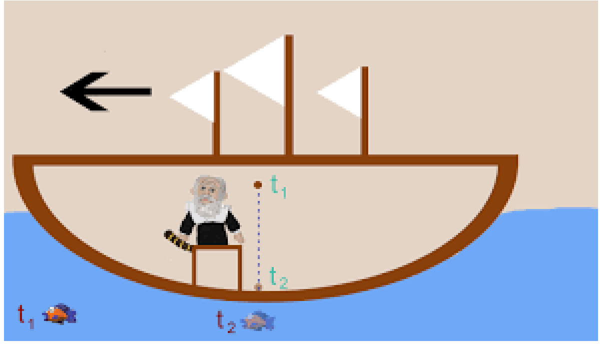
- Motion with variable speed – free fall, projectile

- Galileo's ship:

why do we not feel the motion of the earth?
"*Dialogue Concerning the Two Chief World Systems*" --



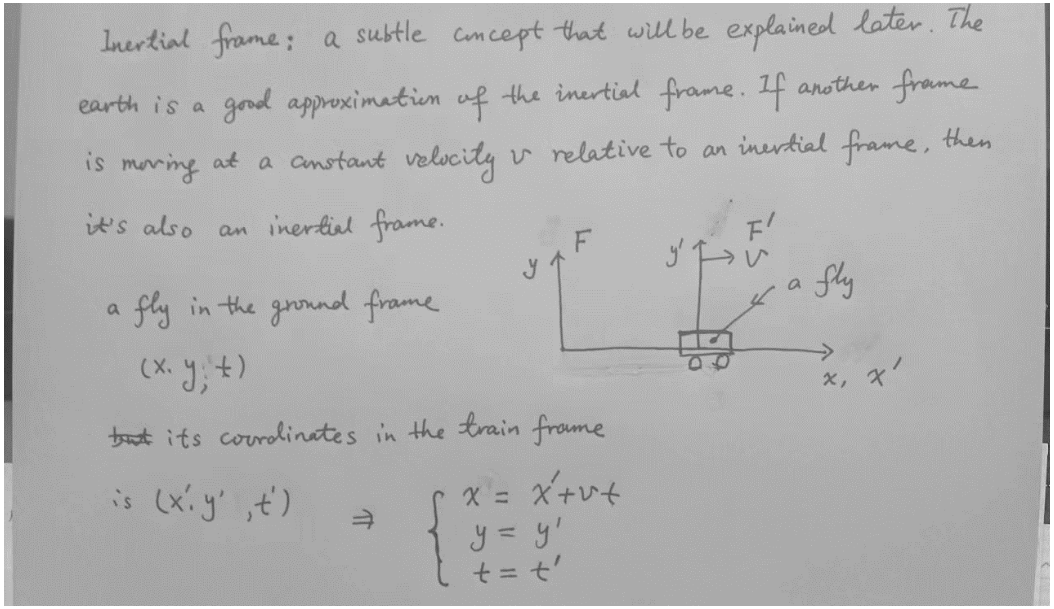
Galileo (1564 – 1642)



A Gedanken experiment:

- Newton's first law of motion (the law of inertia) is actually by Galileo – the existence of the inertial frame.

- Inertial frame and Galilean transformation



- **Galileo's relativity principle:** The mechanical laws are exactly the same in all of the inertial frames. No one is special from any other.

- **Homogeneity in space and time.**

丁仪说着拿起黑白两个球，将黑球放到洞旁，将白球放到距黑球仅十厘米左右的位置，问汪淼，“能把黑球打进去吗？”

“这么近谁都能。”

“试试。”

汪淼拿球杆，轻击白球，将黑球撞入洞内。

“很好，来，我们把球桌换个位置。”丁仪招呼一脸迷惑的汪淼，两人抬起沉重的球桌，将它搬到客厅靠窗的一角。放稳后，丁仪从球袋内掏出刚才打进去的黑球，将它放到洞边，又拾起那个白球，再次放到距黑球十厘米左右的地方，“这次还能打进去吗？”

“当然。”

“打吧。”

汪淼再次轻而易举地将黑球打入洞内。

“搬。”丁仪挥手示意，两人再次抬起球桌，搬到客厅的第三个角，丁仪又将黑白两个球摆放到同样的位置，“打吧。”

“我说，我们……”

“打吧。”

汪淼无奈地笑笑，第三次将黑球击入洞内。

他们又搬了两次台球桌，一次搬到了客厅靠门的一角，最后一次搬回了原位。丁仪又两次将黑白球摆到洞前的位置，汪淼又两次将黑球击入洞内。这时两人都有些出汗了。

“好了，实验结束，让我们来分析一下结果。”丁仪点上一枝烟说，“我们总共进行了五次试验，其中四次在不同的空间位置和不同的时间，两次在同一空间位置但时间不同。您不对结果震惊吗？”他夸张地张开双臂，“五次，撞击试验的结果居然都一样！”

“你到底想表达什么？”汪淼喘着气问。

“你现在对这令人难以置信的结果做出解释，用物理学语言。”

“这……在五次试验中，两个球的质量是没有变化的；所处位置，当然是以球桌面为参照系来说，也没有变化；白球撞击黑球的速度向量也基本没有变化，因而两球之间的动量交换也没有变化，所以五次试验中黑球当然都被击入洞中。”

丁仪拿起搁在地板上的一瓶白兰地，把两个脏兮兮的杯子分别倒满，递给汪淼一杯，后者谢绝了。“应该庆祝一下，我们发现了一个伟大的定律：物理规律在时间和空间上是均匀的。人类历史上的所有物理学理论，从阿基米德原理到弦论，以至人类迄今为止的一切科学发现和思想成果，都是这个伟大定律的副产品，与我们相比，爱因斯坦和霍金才真是搞应用的俗人。”

“我还是不明白你想表达什么。”

“想象另一种结果：第一次，白球将黑球撞入洞内；第二次，黑球走偏了；第三次，黑球飞上了天花板；第四次，黑球像一只受惊的麻雀在房间里乱飞，最后钻进了您的衣袋；第五次，黑球以接近光速的速度飞出，把台球桌沿撞出一个缺口，击穿了墙壁，然后飞出地球，飞出太阳系，就像阿西莫夫描写的那样[①]。这时您怎么想？”

丁仪盯着汪淼，后者沉默许久才问：“这事真的发生了，是吗？”

Newton's *Principia* (1687)

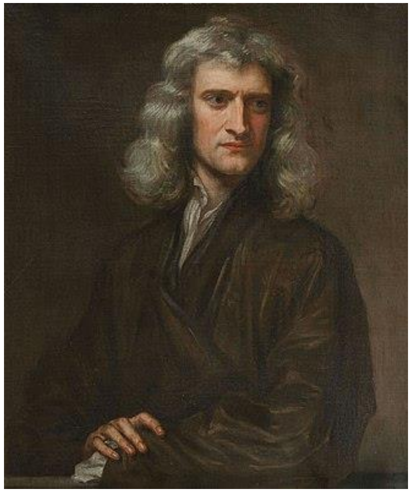
- Nature and Nature's laws lay hid in night:
God said, "Let Newton be! And all was light."
— Alexander Pope

- Victory of rationality: the first complete scientific theoretical system that mankind has mastered.

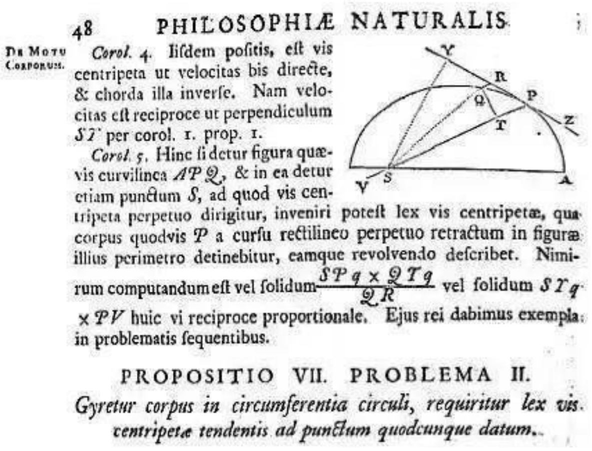
1. Confidence to explore the unknown;
→ the 1st industry revolution

2. Abstraction of phenomenological laws as fundamental principles
   Concepts of mass, force,
   Newton's laws I, II, III, gravity

3. Ingenious mathematical capability: invention of calculus



Isaac Newton
(1642--1726)



48 PHILOSOPHIÆ NATURALIS

DE MOTU CORPORUM.

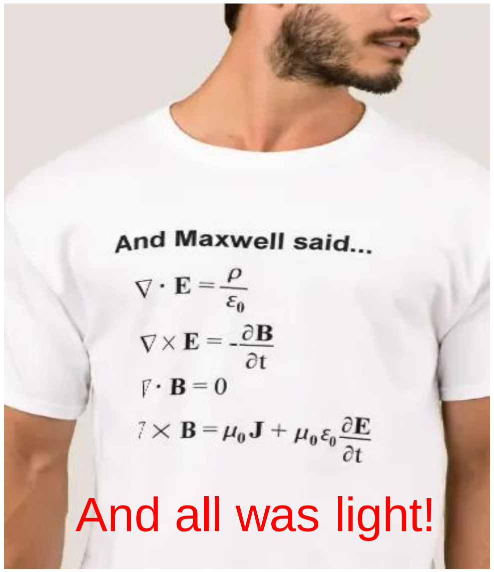
Corol. 4. Iisdem positis, est vis centripeta ut velocitas bis directe, & chorda illa inverse. Nam velocitas est reciproce ut perpendiculum *ST* per corol. 1. prop. 1.

Corol. 5. Hinc si detur figura quævis curvilinea *APQ*, & in ea detur etiam punctum *S*, ad quod vis centripeta perpetuo dirigitur, inveniri potest lex vis centripetæ, qua corpus quodvis *P* a cursu rectilineo perpetuo retractum in figuræ illius perimetro detinebitur, eamque revolvendo describet. Nimirum computandum est vel solidum $\frac{SPq \times QTq}{QR}$ vel solidum $STq \times PV$ huic vi reciproce proportionale. Ejus rei dabimus exempla in problematis sequentibus.

PROPOSITIO VII. PROBLEMA II.

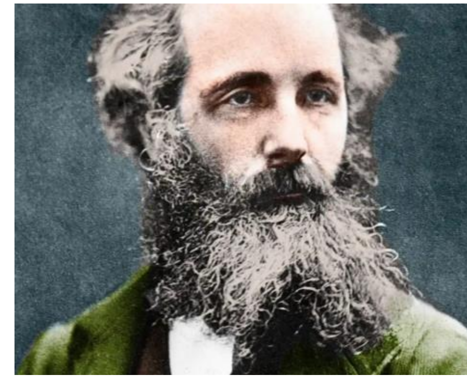
Gyretur corpus in circumferentia circuli, requiritur lex vis centripetæ tendentis ad punctum quodcunque datum.

Maxwell's "A treatise on electricity and magnetism" (1873)



And all was light!

"I stand on the shoulders of Maxwell" -- A. Einstein



James C. Maxwell (1831--1879)

From a long view of the history of mankind — seen from, say, ten thousand years from now — there can be little doubt that the most significant event of the 19th century will be judged as Maxwell's discovery of the laws of electrodynamics. The American Civil War will pale into provincial insignificance in comparison with this important scientific event of the same decade.

--- *Feynman's lecture notes for physics* Vol II Chapter I

Einstein's special relativity (1905)

A 16-year-aged young man dreamed for chasing a light …..

A. Einstein (1879-1955)

If I pursue a beam of light with the light velocity, I should observe such a beam of light as an electromagnetic field at rest though spatially oscillating.

There seems to be no such thing, however, neither on the basis of experience nor according to Maxwell's equations.

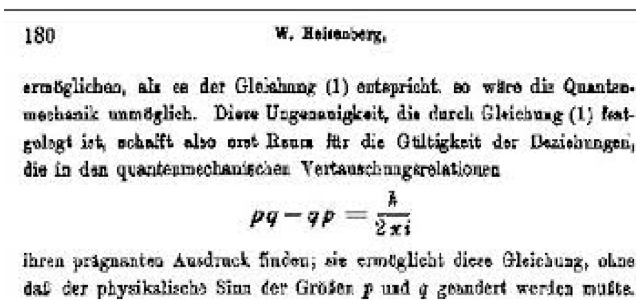
From the very beginning it appeared to me intuitively clear that, judged from the standpoint of such an observer, everything would have to happen according to the same laws as for an observer who, relative to the earth, was at rest. …… One sees in this paradox the germ of the special relativity theory is already contained.

To change the Maxwell equation, or, to the view of space-time?

The existence of magnetic field is a test to relativity.

The epic quantum era (1925---)

"Quantum theoretical re-interpretation of kinematic and mechanical relations", Z. Phys, 33, 879-893 (1925).



180 W. Heisenberg,

ermöglichen, als es der Gleichung (1) entspricht, so wäre die Quantenmechanik unmöglich. Diese Ungenauigkeit, die durch Gleichung (1) festgelegt ist, schafft also erst Raum für die Gültigkeit der Beziehungen, die in den quantenmechanischen Vertauschungsrelationen

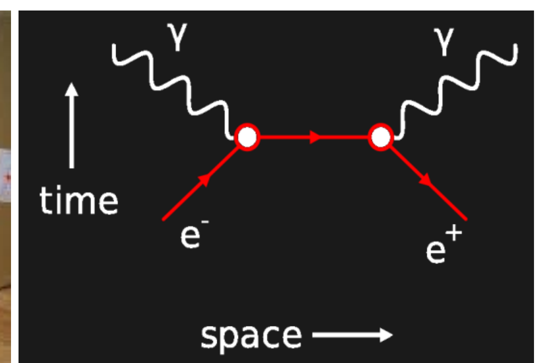
$$pq - qp = \frac{h}{2\pi i}$$

ihren prägnanten Ausdruck finden; sie ermöglicht diese Gleichung, ohne daß der physikalische Sinn der Größen p und q geändert werden müßte.

W. Heisenberg (1901-1976) E. Schrödinger (1887-1961) Paul Dirac (1902-1984)

$$i\hbar\partial_t\psi = -\frac{\hbar^2}{2m}\nabla^2\psi$$

"i" and $\hbar$, which one is more important?



anti-particle

Objective v.s. subjective (Chuang Tzu's fish)

- Quantum world is probabilistic rather than deterministic
- 庄子与惠子游于濠梁之上。庄子曰："鯈鱼出游从容，是鱼之乐也？"惠子曰："子非鱼，安知鱼之乐？"庄子曰："子非我，安知我不知鱼之乐？"惠子曰："我非子，固不知子矣；子固非鱼也，子之不知鱼之乐，全矣"…《庄子·秋水》
- 庄惠问答关乎科学的合理性和实证性，看来惠子的论证方法远比庄子理路清晰 …… 是接近于科学的传统立场的。但是，尽管我是一名科学家，却对庄子所要说的这一方面有更强烈的同感。-- 汤川秀树《知鱼乐》

(钟离→濠梁→安徽凤阳临淮关

濠河与淮河的交汇处)

汤川秀树(Hideki Yukawa)

核力的介子理论，1949年诺贝尔物理奖

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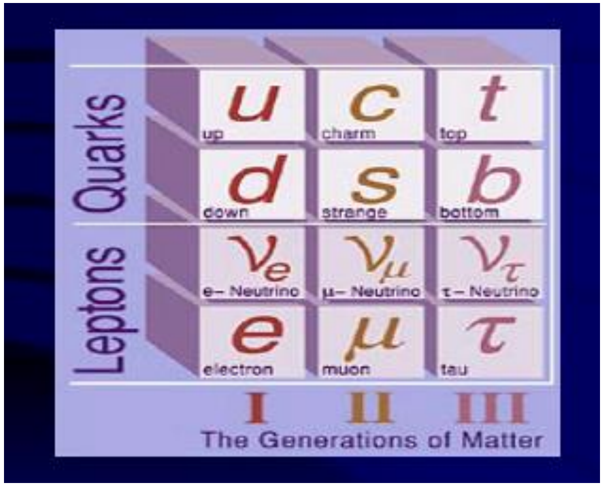
High energy and particle physics

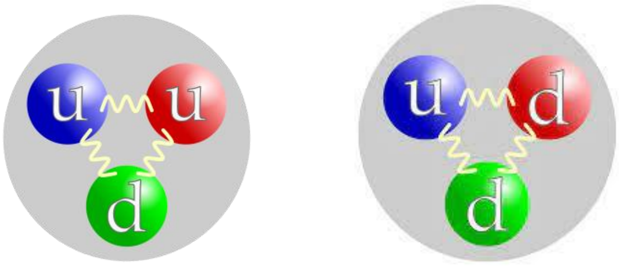
- Physics at the **smallest** space-time scales.

Microscopic structure of space-time, fundamental particles/interactions.



Nucleon: proton, neutron)

Quark color: R, G, B



Leptons: electron, muon, tauon, neutrino

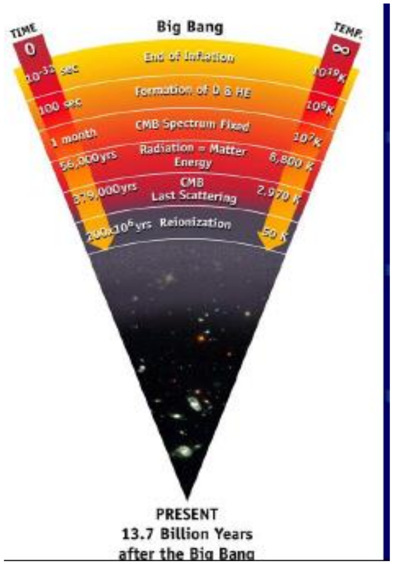
Quark flavors: (fractional charge)

+2/3e	-e/3
up	down
charm	strange
top	bottom

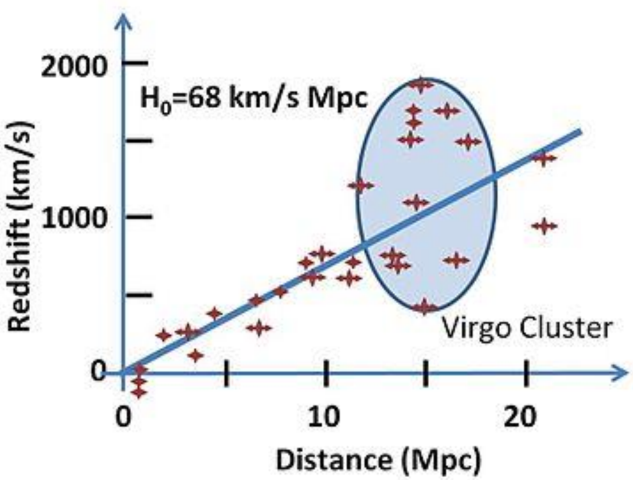
Gauge bosons mediate interactions: photon (EM), W+, W-, Z0 (weak interaction), gluon (Strong interaction)

Higgs particle – mass generation

Astrophysics – the largest space-time scales



- **The birth, evolution and fate of the universe.**
- **Big bang (Gamow) – 3K cosmic background radiation**
- Stellar evolution: collapse of nebula → proptostar → main sequence star → red giant, white dwarf / supernova, neutron star, black hole …



Mass (solar masses)	Time (years)	Spectral type
60	3 million	O3
30	11 million	O7
10	32 million	B4
3	370 million	A5
1.5	3 billion	F5
1	10 billion	G2 (Sun)
0.1	1000s billions	M7

- **Universe expansion – Hubble's law**
- **Dark matter, dark energy**

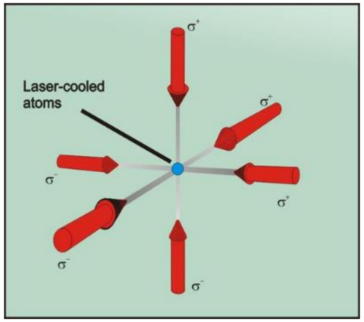
Atom, molecular, and optical physics

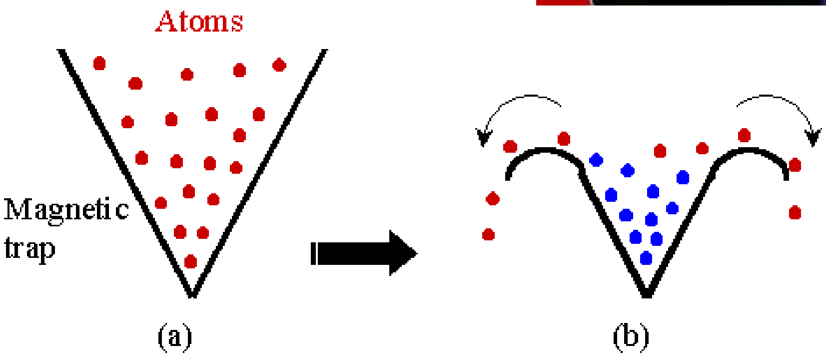
• The most **precise controllability –** Laser, atomic clock

• Bose-Einstein condensation of alkali atoms: Li, Na, K, Rb, Cs. Nearly all atoms condense into a single quantum state.

Laser cooling to 10^{-5}K, evaporative cooling to below 10^{-6}K.

• Quantum entanglement, information, computation



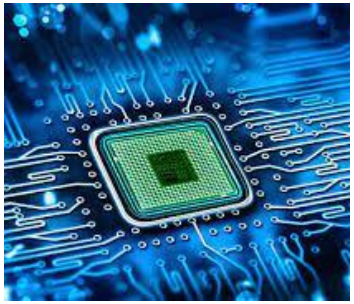


Condensed matter physics – fundamental or applied?

- Old name: solid state physics (actually sounds better).

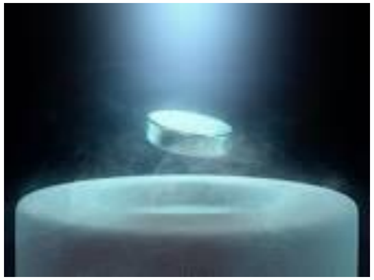
- Close relation to daily life:

semiconductor physics -- electronic industry



solid, liquid, gas

metal, insulator, magnetism, superconductivity/superfluidity ..

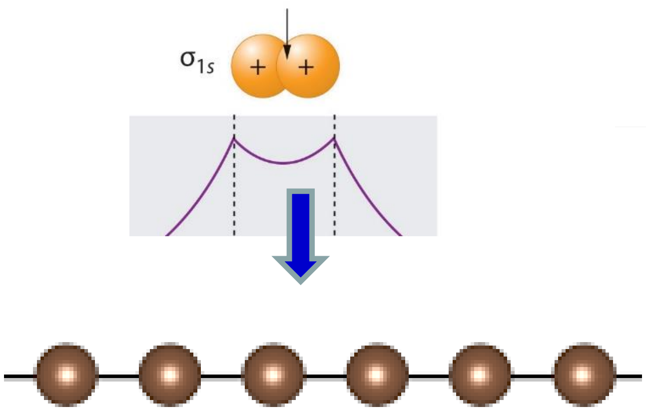


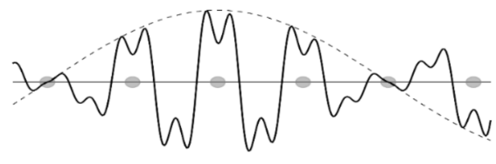
soft condensed matter: polymer, protein, membrane, jamming, packing, avalanche….

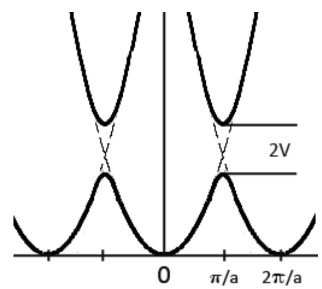
Quantum nature of solids - Bloch theorem, Nobel Prize (1952)

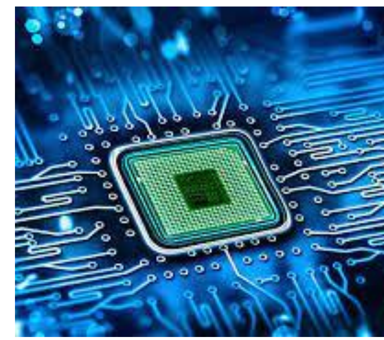
- Bond (chemistry) → band (solid state physics).

Local → global viewpoint: Fourier transform









Foundation to semiconductor physics -- electronic industry

- Are there new principles beyond applying quantum mechanics to complicated systems?

Outline

- Physics as natural philosophy
- The Feynman lectures on Physics.
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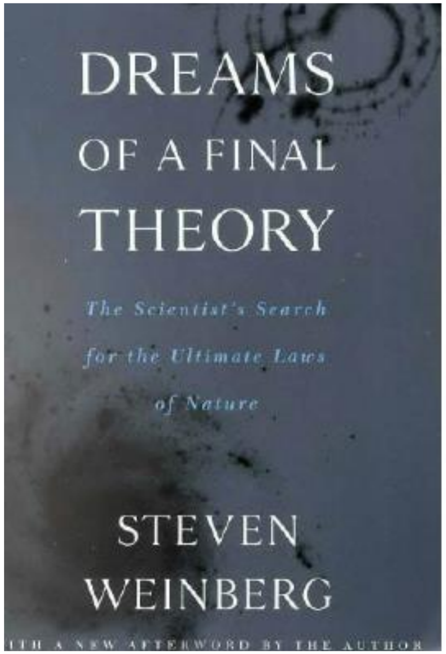
Reductionism: Divide and Conquer

- Success: standard model and beyond

Atom → nucleus and electron → proton, neutron → quark → superstring

… reductionism is a sense of hierarchy, that some truths are less fundamental than others to which they may be reduced… -- S. Weinberg



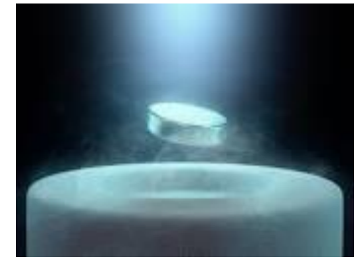
- Theory of everything or nothing?

失败：超导，超流，液氦相图，量子霍耳效应，
约瑟夫逊效应……高温超导体的性质……
更不要说预言蛋白质的功能，人脑的行为……

我们能按古希腊人的理想把一切复杂的系统分解成最基本的单元，了解这些单元的行为，但对于复杂系统本身却一无所知！！

Condensed Matter: Sociology of Particles

- Key features:



Huge amount of particles: 10^{22} per cm^3 (electrons, molecules) of matter!

Strong interactions!

- Organization leads to success! -- New states of matter

human: crowd v. s. army

H_2O molecules: vapor, water, and ice.

- **Social behavior of particles (e.g. electrons) and the underlying organizing principles.**

Particles (electrons) as "citizens" of a big society

More is different! -- Emergentism

"The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles.

L. D. Landau

(1908-1968)

P. W. Anderson

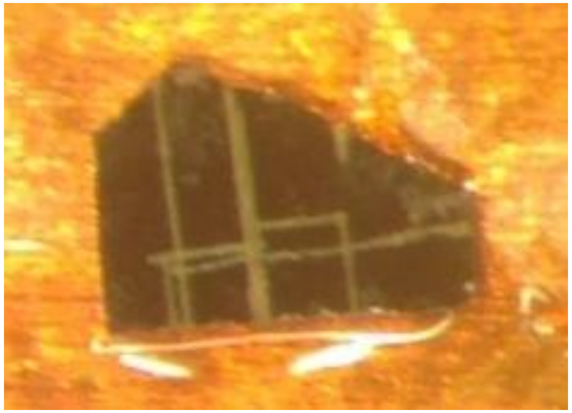
(1923--2020)

"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".

X	Y
solid state or many-body physics	elementary particle physics
chemistry	many-body physics
molecular biology	chemistry
cell biology	molecular biology
•	•
•	•
•	•
psychology	physiology
social sciences	psychology

Outstanding problems? New principles?

- Every sample is a universe, and the universe is just one sample.



To see a World in a Grain of Sand, And a Heaven in a Wild Flower,

一沙一世界，　　一花一天国

电子社会学——凝聚态物理的内容和风格

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力，广泛地应用于处理磁通涡旋、边界和杂质问题等。

另一方面，在 ^{4}He超流的研究中，F. London注意到 ^{4}He是玻色原子，把超流和玻色—爱因斯坦凝聚联系了起来。^{4}He原子形成了一个相干的凝聚体，所谓“相干”，就是指每个原子的行为都协调起来了，而不是各行其是。这部分相干的原子占到了系统的一个宏观的比例。原子在凝聚体中，就像是士兵处于一个军阵中，彼此协调一致，组成了一个整体。

当一个军阵开始运动以后，对行进道路上的磕磕碰碰是具有免疫力的。中性的玻色原子系统具有类似的性质，用行话说，凝聚体具有广义刚度(generalized rigidity)，在这里表现为非零的超流密度。一个

了束缚态的重要性。在费米面的背景上，放上两个费米子(电子)。如果它们之间的相互作用是吸引势的话，他发现不论多弱，都会形成束缚态。这就是著名的库珀配对(Cooper pairing)。

单个库珀对还只是个两体问题，而费米面上有亿万个电子。如何将其推广成相干的多体配对波函数是高度非平庸的。Schrieffer写下了著名的BCS变分波函数，完成了至关重要的一步。他把基态多体波函数分解成了一系列库珀对波函数的乘积。

库珀对由两个电子组成，其统计性质变成了玻色型，可以发生相

避开了瞬时的静电排斥。

BCS理论的核心是著名的能隙方程。在零温下，求解能隙方程可以得到超导能隙 Δ，

$$\Delta = 2\hbar\omega_D \exp[-1/(N_0 g)]\quad,$$

其中 ω_D 是晶格振动的德拜频率，N_0

图3　超流体中原子组成了相干的玻色—爱因斯坦凝聚体，就像是士兵组成了军阵。行进中的军阵不会散开，相干的凝聚体在流动时，对于弱的杂质散射，也不受其影响

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Mass ~ energy ~ frequency ~length ~ temperature

Relativity (mass-energy) $E \sim mc^2$
Quantum mechanics (frequency-energy) $E \sim h\nu = hc/\lambda$
Statistical Mechanics: temperature-energy $E \sim k_B T$

Electron rest mass: $m_e = 9 \times 10^{-31}$kg
Energy: $E = 0.5 Mev$
Frequency: $\nu_\gamma = 1.2 \times 10^{20} Hz,$
length: $\lambda_{cmptn} \approx 2 \times 10^{-12} m$
Temperature: $T \approx 6 \times 10^9 K$

$h = 6.62 \times 10^{-34} J/s$
$k_B = 1.38 \times 10^{-23} J/K$
$1eV = 1.6 \times 10^{-19} J \sim 1.2 \times 10^4 K$

Energy (mass, temperature) scales

$<\mu K$	Ultra-cold atom physics – Bose-Einstein condensation
3K	Cosmic microwave background
<30K	Conventional superconductivity
~90K	High temperature superconductivity YBaCuO (boiling point of N_2)
300K	Room temperature
~1000K	Fe's Curie temperature
1~10eV	Atomic transition, quantum behavior of electrons in metal, chemical bond energy
1Mev	Quantum Electrodynamics (QED) scale - electron's mc^2 -- electron-positron pair-creation
1GeV	Quantum Chromodynamics (QCD) energy scale, Proton's mc^2
100GeV	Electro-weak symmetry scale
125Gev	Higgs boson's mc^2
10^{19}GeV	Planck energy – gravity energy $\sim mc^2$

Length scales $\lambda \sim h/(mc)$

$1.6 \times 10^{-35} m$	Planck length -- gravity becomes strong
$1fm = 10^{-15} m$	Proton radius
$1 \times 10^{-2}\, A^{\circ}$	Electron Compton wavelength, QED length scale
$1A^{\circ} = 10^{-10} m$	Hydrogen atom Bohr radius $0.5A^{\circ}$, crystal lattice constant
$1nm = 10^{-9} m$	molecules, atom clusters, chemistry
$1\mu m = 10^{-6}\, m$	visible light wavelength
$1m$	daily life
$10^{4}\mathrm{km}$	Earth size (R=6400km)
$1.5 \times 10^{8}\mathrm{km}$	Astronomical unit (AU) – the earth-Sun distance (8 light minutes)
40AU	Sun-Pluto distance
100AU	Heliosphere (heliopause)

$1 \times 10^{13} km$ light year (ly)

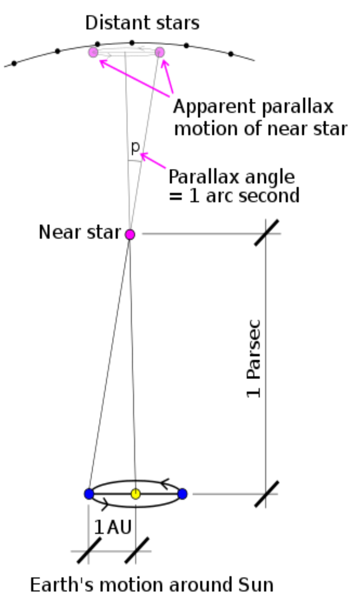
3.26 ly 1 parsec (pc) -- the nearest star (Proxima Centauri, 1.3pc)

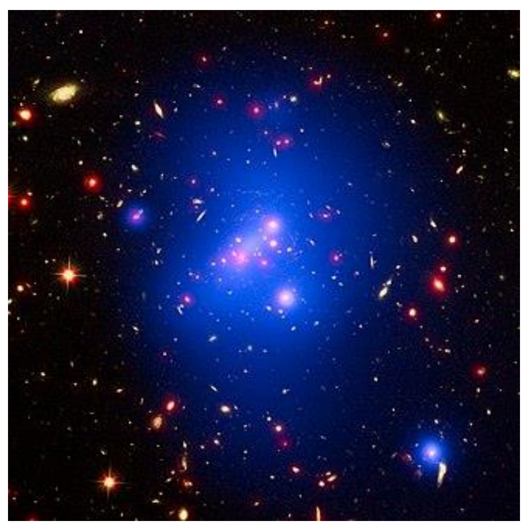
10^5 ly diameter of the milky way (thickness 1000 ly)

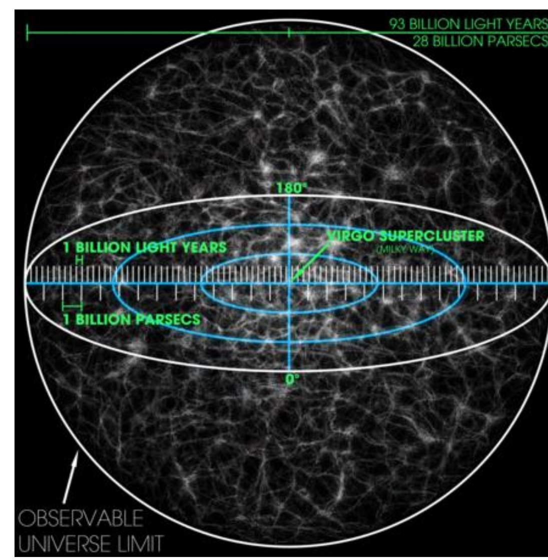
10^6 ly galaxy groups; galaxy clusters

10^8 ly supercluster

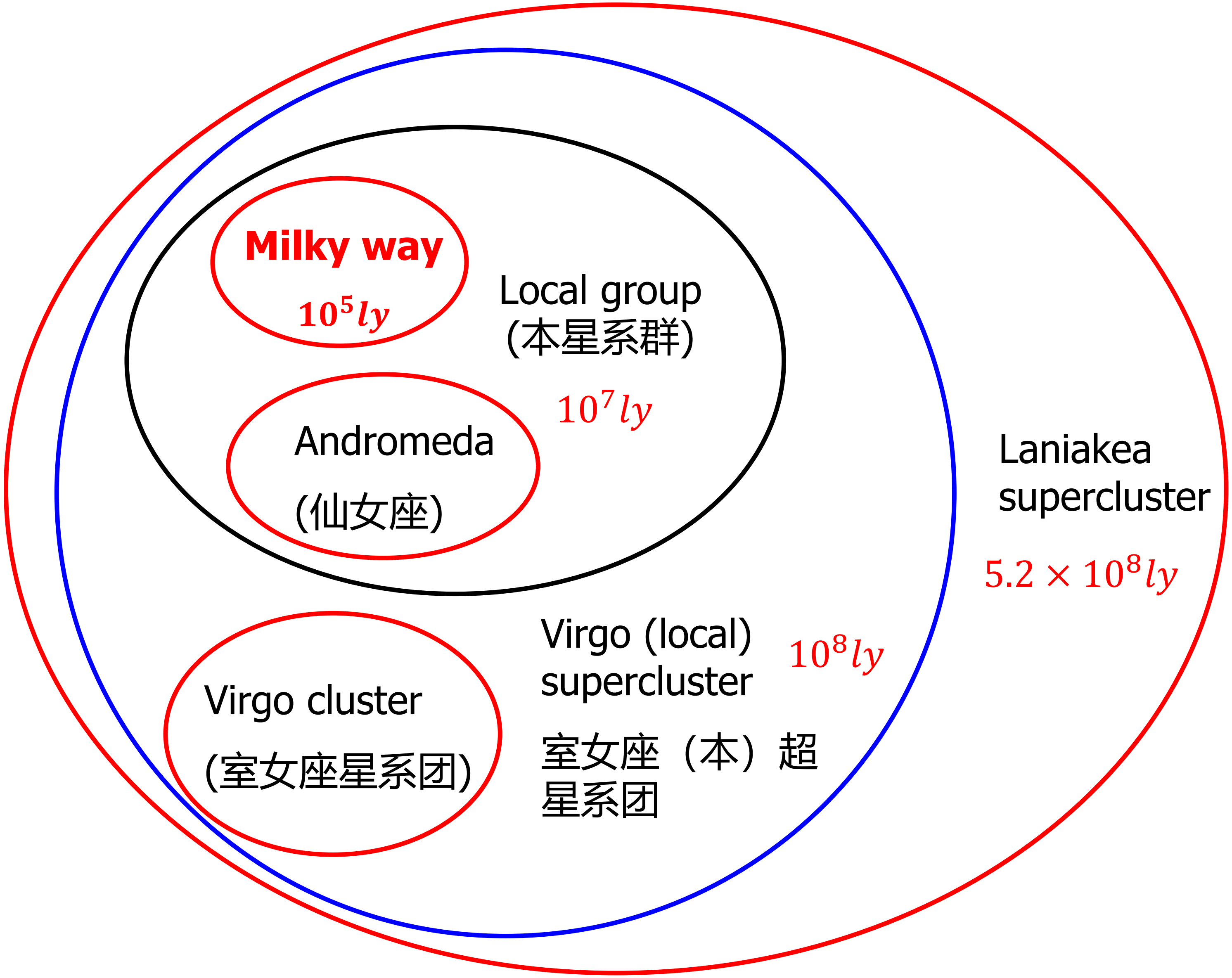
4.6×10^{10} ly the radius of the visible universe







Our location in the universe



Time scales

1.4×10^{10} y	age of the universe
5×10^{9} y	age of the sun, and the earth
1 year	period of the earth orbit
1 month	period of the moon orbit
1 day	period of the earth spin
1s	daily life
$20Hz - 20KHz$	audible frequency

Light comparison[9]

Name	Wavelength	Frequency (Hz)	Photon energy (eV)
Gamma ray	less than 0.01 nm	more than 30 EHz	more than 124 keV
X-ray	0.01 nm – 10 nm	30 PHz – 30 EHz	124 keV – 124 eV
Ultraviolet	10 nm – 400 nm	750 THz – 30 PHz	124 eV – 3.3 eV
Visible	400 nm – 700 nm	430 THz – 750 THz	3.3 eV – 1.7 eV
Infrared	700 nm – 1 mm	300 GHz – 430 THz	1.7 eV – 1.24 meV
Microwave	1 mm – 1 meter	300 MHz – 300 GHz	1.24 meV – 1.24 µeV
Radio	1 meter and more	300 MHz and below	1.24 µeV and below

Further readings

- Feynman lectures on physics Vol (I) Chapters 1, 2, and 3, and listen to the lectures recordings.

- Wiki page of Galileo

- Anderson, P. W.'s "More is different"

究时空之际，
通物我之变，
成明理之言。