

真空

與共振

Vacuum & Resonance

耿朝強
國立清華大學物理系

(民國九十六年十月十七日)

粒子

與 場

Particles & Fields

耿朝強

國立清華大學物理系

(民國九十六年十月十七日)

Outline

- 引言
- 尺度
- 對稱性
- 基本粒子及交互作用力
- 大統一場理論
- 尚未解決之問題
- 未來展望

● 引言

People have long asked:

物質是由什麼組成的？

"What is the world made of?"

是什麼結合它在一起？

"What holds it together?"



Why do physicists want to study particles?

Because we are made of them ...

... and so is everything else in the Universe!





We now know that just **four kinds** of building block are needed to account for all of **ordinary matter**.

They are particles called:

- up-quarks and down-quarks 上和下夸克
- electrons 電子
- electron-neutrinos 電子中微子

Particles are stuck together by forces: **four kinds of forces**

- gravity 重力
- strong 強作用力
- electromagnetic 電磁作用力
- weak 弱作用力

大 尺 度

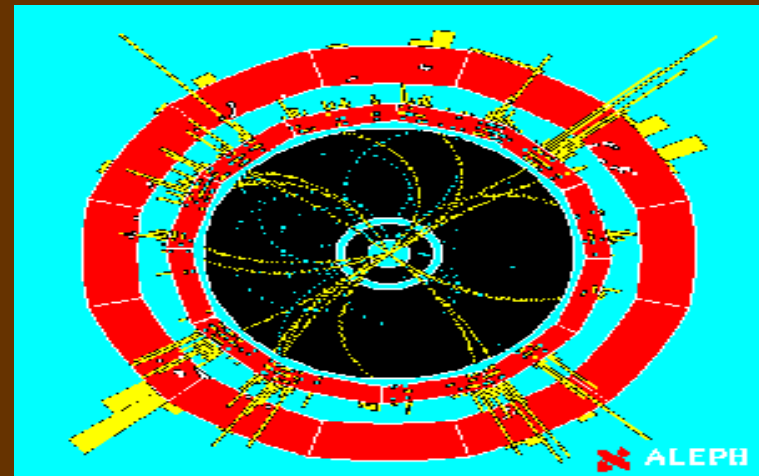


The Andromeda galaxy

Looking into outer space means looking back in time. When you look at a galaxy a million light years away, you are looking at it as it was a million years ago. Looking at the sky at night is like reading the history of the Universe.

小 尺 度

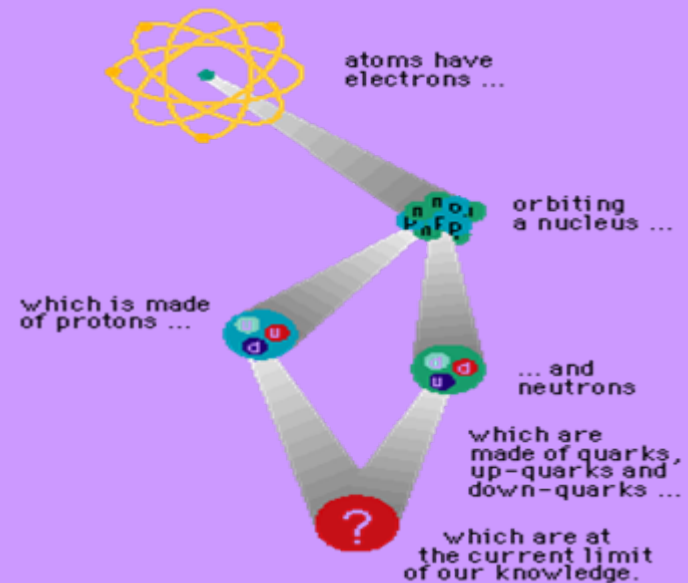
Looking into inner space - into the structure of matter - also provides a view back in time. Experiments today collide together particles at the highest possible energies in order to penetrate into the deepest layers of matter. The enormous concentration of energy leads to the creation of new matter just as when matter was first created in the initial instants after the Big Bang with which the Universe began.



Studies of the smallest structures in the Universe, in high energy particle physics are therefore intimately linked with observations in astronomy of the largest structures. This meeting point between particle physics and cosmology is one of the most fascinating aspects of modern physics. Indeed, through the scenario of the Big Bang, observations in astronomy have testable consequences in particle physics and vice versa.

高能粒子物理 ↔ 天體物理

The world about us and the Universe beyond are built from a huge diversity of materials, and further forms of matter were common in the first instants of the early Universe. Surprisingly, however, this wide variety of matter is made from relatively few simple building blocks.



ordinary matter 普通物質

cosmic matter 宇宙物質

High-energy matter 高能物質

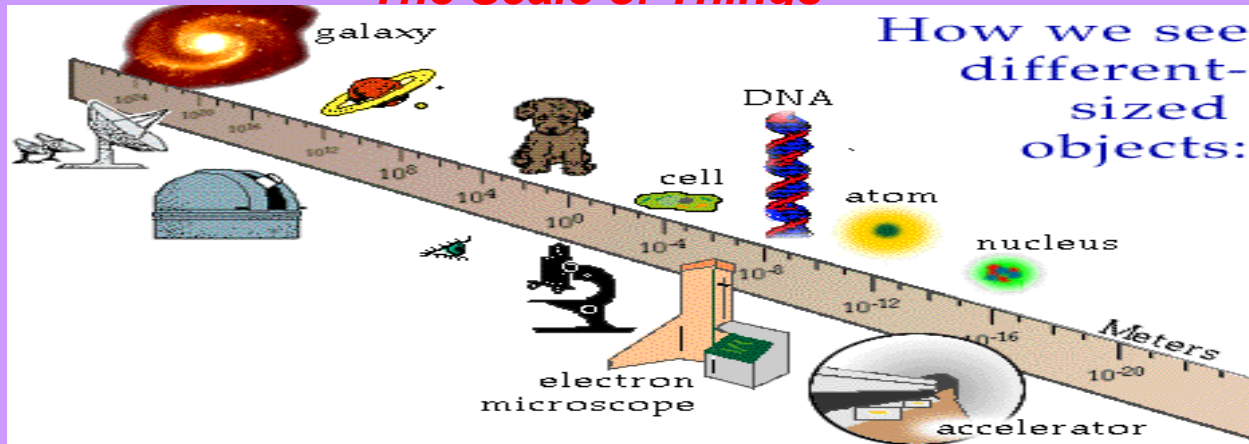
Antimatter 反物質

近代粒子物理之發展可分為六個階段：

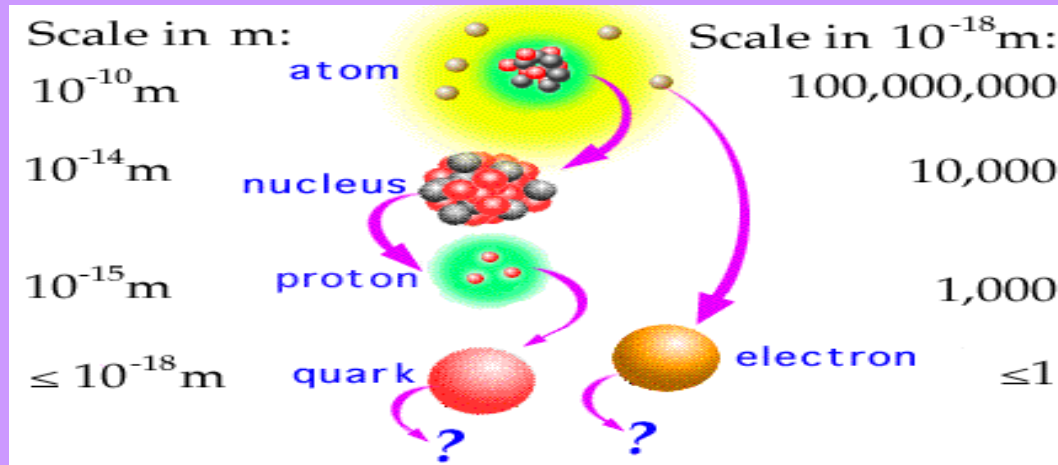
1. *1945之前 -- Pre-Modern Particle Physics Period*
2. *Startup Period (1945 -- 1960) : Early contributions to the basic concepts of modern particle physics.*
3. *Heroic Period (1960 -- 1975): Formulation of the standard model of strong and electroweak interactions.*
4. *Period of Consolidation and Speculation (1975 -- 1990): Precision tests of the standard model and theories beyond the standard model.*
5. *“Frustration” and “Waiting” Period (1990 -- 2005)*
6. *Super-Heroic Period (2005 –2020)*

尺度

The Scale of Things



Scale of the Atom



In summary, we know that **atoms** are made of **protons**, **neutrons**, and **electrons**. **Protons** and **neutrons** are made of **quarks**, which are possibly made of more fundamental objects. (Yikes! Will it never end?)

From an Electron-Volt to Trillions of Electron-Volts

Energies are often expressed in units of "electron-volts". An electron-volt (eV) is the energy acquired by a electron (or any particle with the same charge) when it is accelerated by a potential difference of 1 volt.

- *Typical energies involved in atomic processes (processes such as chemical reactions or the emission of light) are of order a few eV. That is why batteries typically produce about 1 volt, and have to be connected in series to get much larger potentials.*
- *Energies in nuclear processes (like nuclear fission or radioactive decay) are typically of order one million electron-volts (1 MeV).*
- *The highest energy accelerator now operating (at Fermilab) accelerates protons to 1 million million electron volts (1 trillion electron volts, 1 TeV = 10^{12} eV).*
- *The Large Hadron Collider (LHC) at CERN will accelerate each of two counter-rotating beams of protons to 7 TeV per proton.*



● 對稱性

Symmetry is a crucial concept in mathematics, chemistry, and biology. Its definition is also applicable to art, music, architecture and the innumerable patterns designed by nature, in both animate and inanimate forms. In modern physics, however, symmetry may be the most crucial concept of all. Fundamental symmetry principles dictate the basic laws of physics, control structure of matter, and define the fundamental forces in nature.

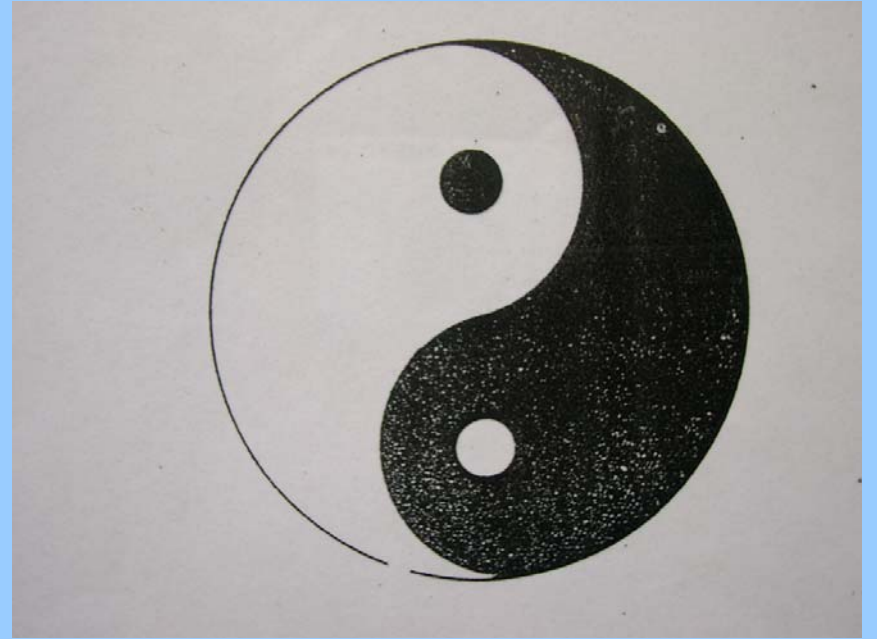
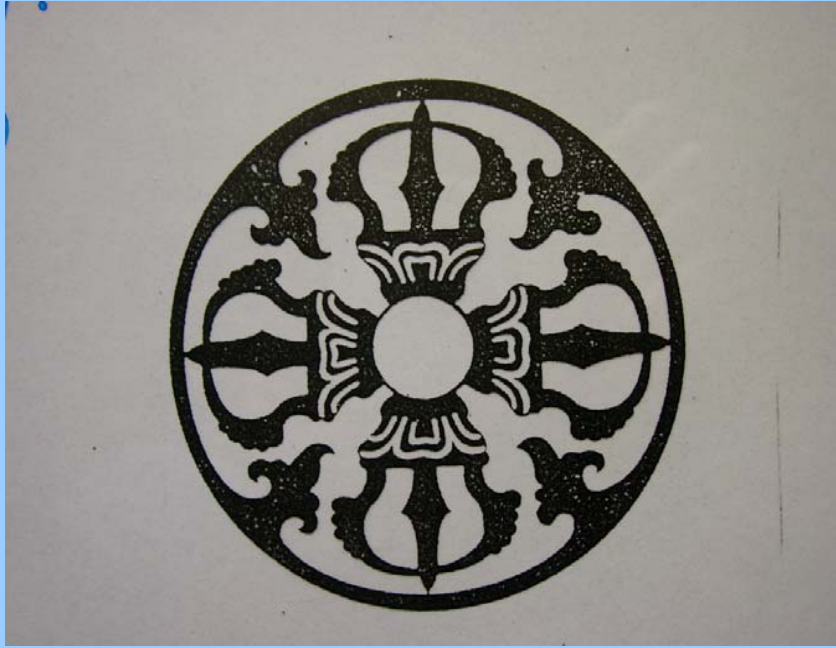
"I aim at two things: On the one hand to clarify, step by step, the philosophic-mathematical significance of the idea of symmetry and, on the other, to display the great variety of applications of symmetry in the arts, in inorganic and organic nature."
And "Symmetry....is an idea which has guided man through the centuries to the understanding and the creation of order, beauty and perfection. "

對稱性是一種觀念，這種觀念在幾千年來一直引導人類理解和創造世界上各種事物之規律，美妙，及完善。

Hermann Weyl (in his book "Symmetry")

"I heave the basketball; I know it sails in a parabola, exhibiting perfect symmetry, which is interrupted by the basket. Its funny, but it is always interrupted by the basket." *Michael Jordan (former Chicago Bull)*

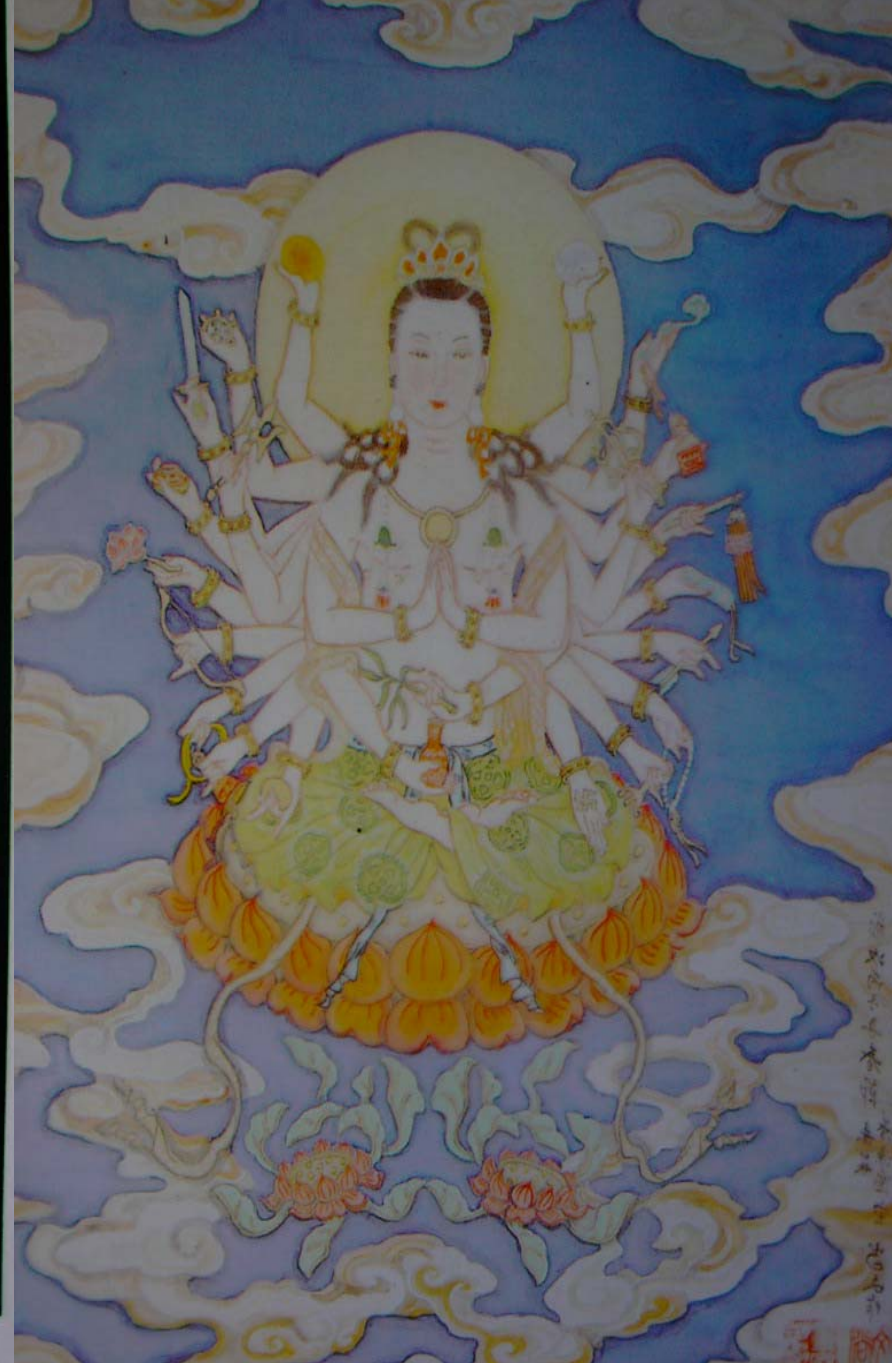
Symmetries ↔ Conservation Laws



中國文學：

舉頭望明月

低頭思故鄉







台北市音樂季

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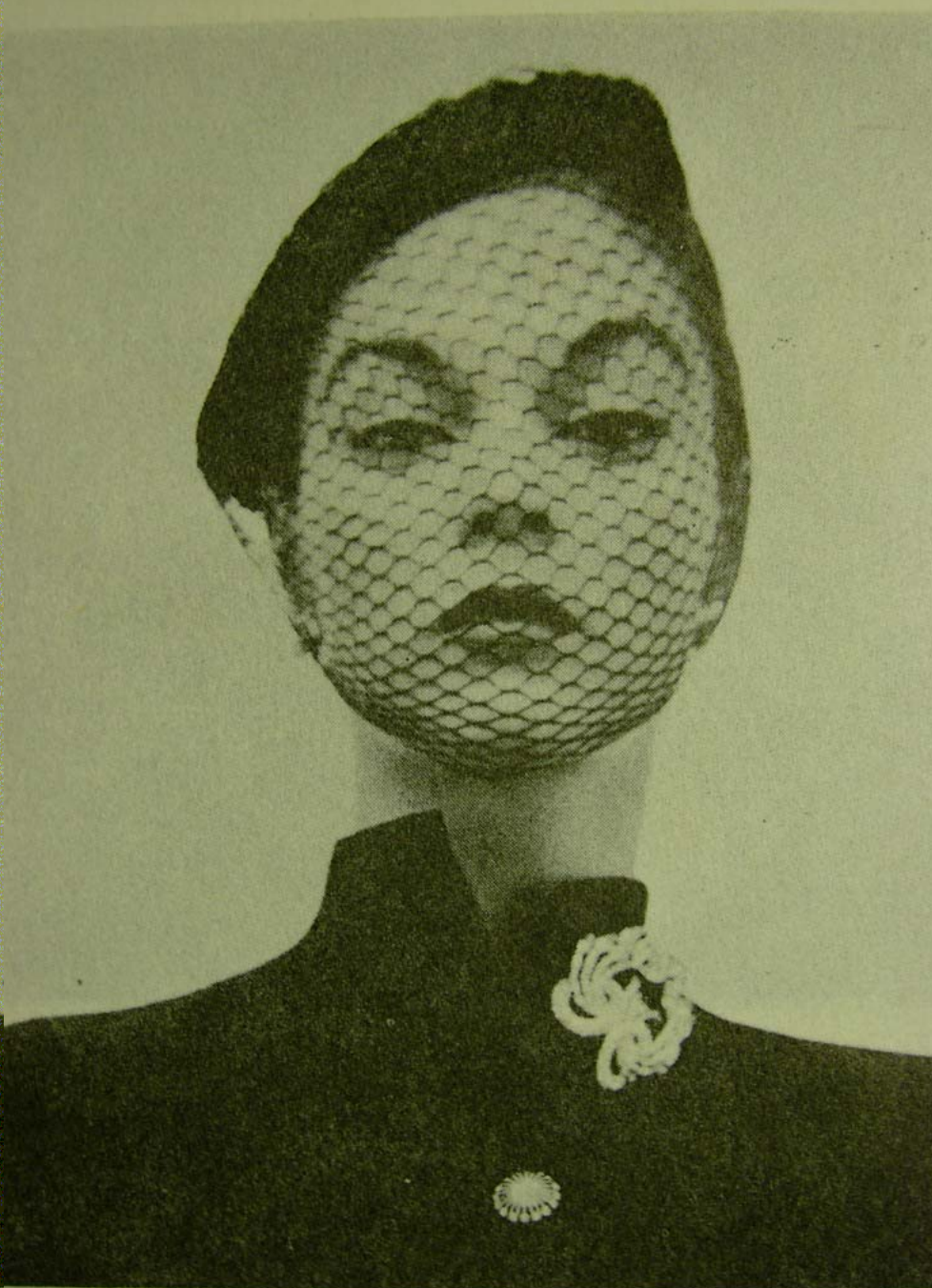
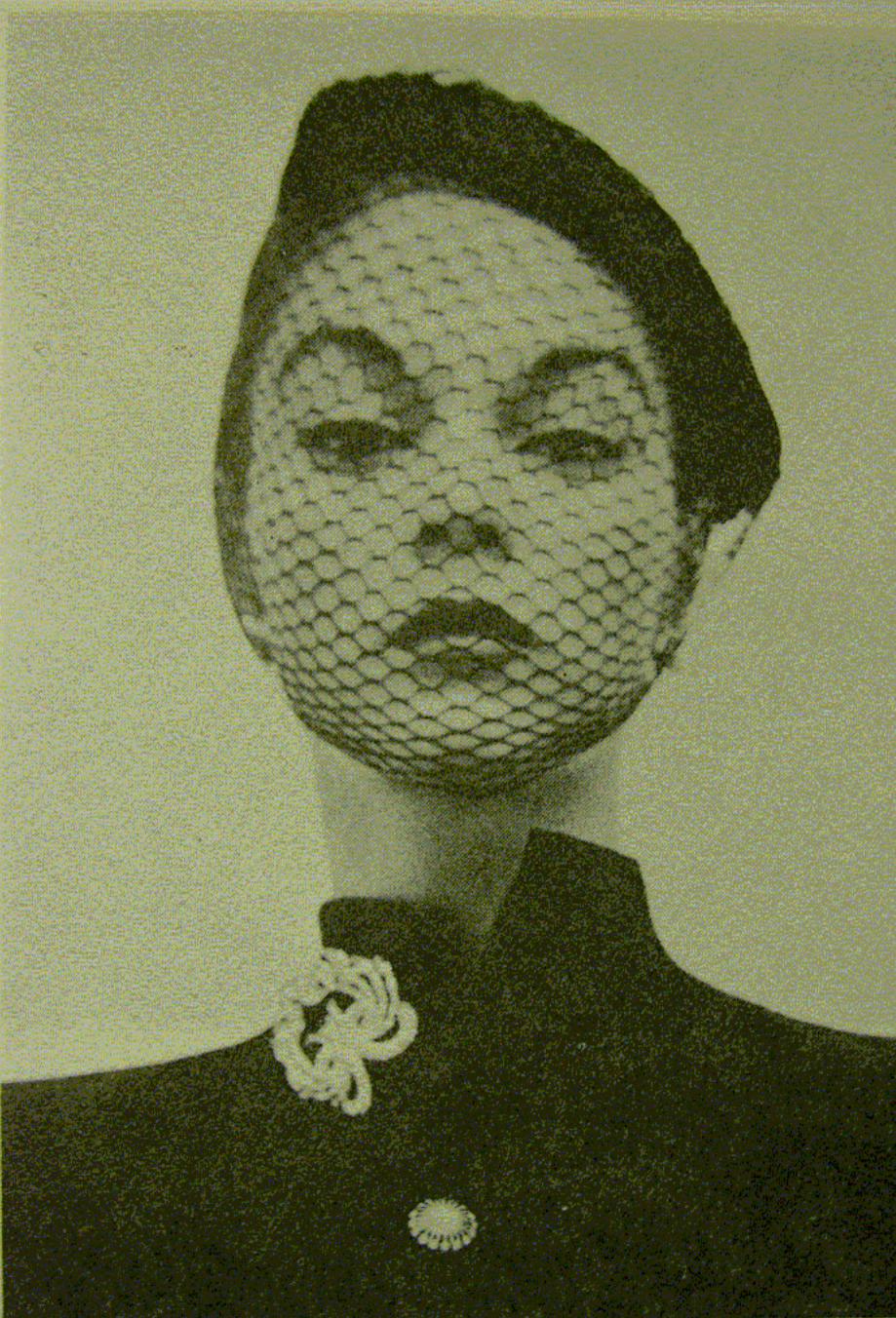
第二屆
 中華民國89年

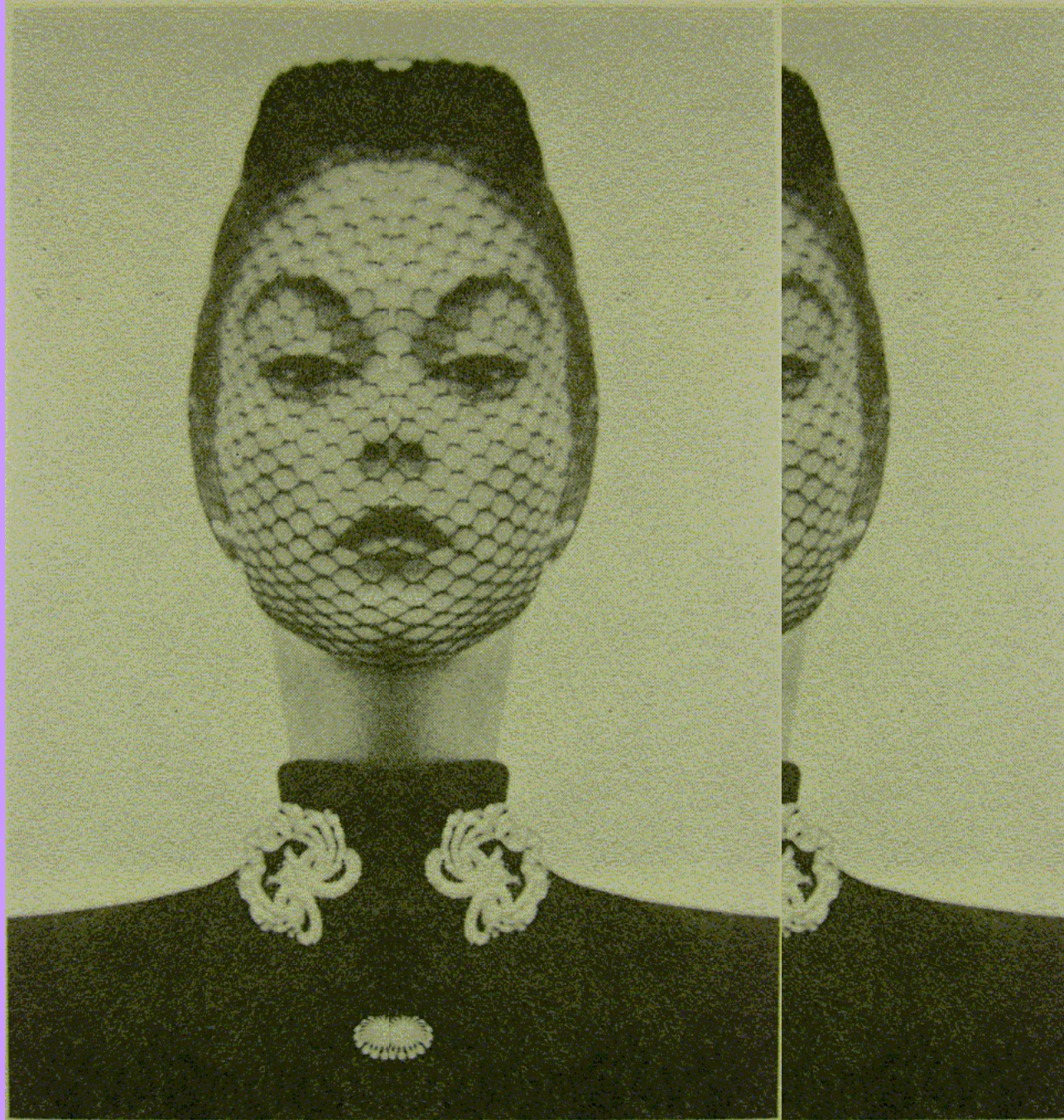
開幕日期：
 中華民國89年8月11日起

開幕地點：
 國立台北立交響樂團
 國中國家音樂廳
 國山樂社：博愛堂、臺灣戲院
 國字音樂節
 國立台北交響樂團
 (7) 國樂、古箏、琵琶、揚琴
 國山樂社：新生戲院
 國山樂社：國山樂社
 國山樂社：國山樂社

對稱一定會美嗎？

左 ↔ 右





美麗嗎？

完全左右對稱

王菲



No.156

2000年10月28日~11月03日

每套100元

精采生活

八卦糾紛特集

李靖打官司

明星跑法院高人

演唱會 王菲

主辦單位要

謝霆鋒全裸

對稱的王菲



張柏芝



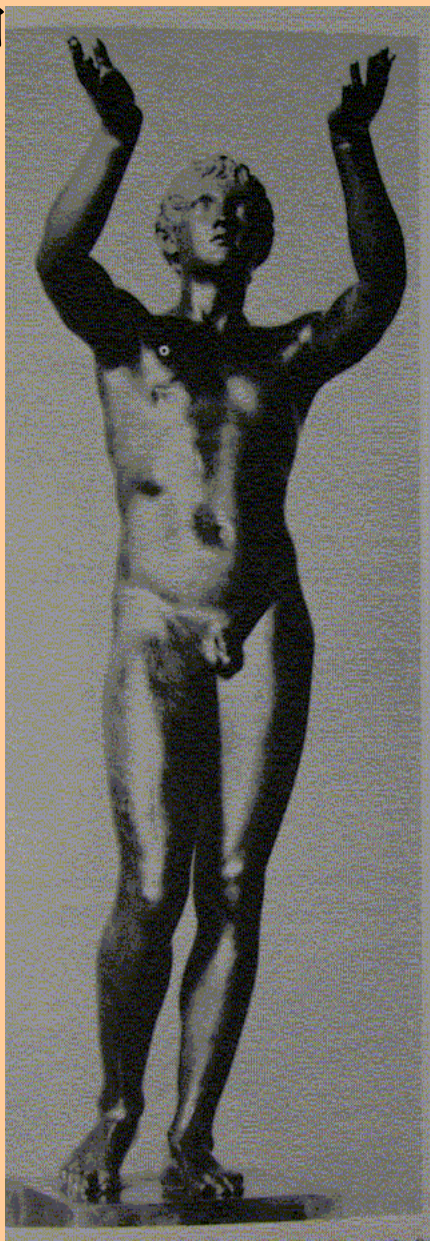
張柏芝 = 林青霞 + 張曼玉

對稱的張柏芝



還美麗嗎？

右



右

右



左

右

對稱性 → 不可區分性

對稱性破壞 → 可區分性

粒子物理：三種非常重要的分立對稱性 -- **C**, **P**, 和 **T** 宇稱

- **P**：宇稱 或 空間反演 $x \longleftrightarrow -x$
- **T**：時間反演 $t \longleftrightarrow -t$
- **C**：粒子和反粒子交換 或 電荷共軛
 $粒子 \longleftrightarrow 反粒子$

很多年來，物理學的規律被認為是 P ， C ，和 T ，守恆的

在電磁作用中， P ， C 和 T 是守恆的！
同樣在強作用中， P ， C 和 T 也是守恆的！

在弱作用中，它們是守恆的嗎？

眾所周知，美國著名華人物理學家李政道和楊振寧博士

在1956年指出：在弱作用力中， P 和 C 是破壞的
為此他們榮獲1957年的NOBEL物理學獎

1964年，在美國BNL國家實驗室，Fitch和Cronin等人發現了反常的中性K介子弱衰變： $\rightarrow CP$ 破壞。

--Fitch和Cronin榮獲了1980年的NOBEL物理學獎

1998年，在FNAL (KTeV) 和CERN (CPLEAR) 分別觀測到了在弱作用 T 破壞現象。

弱交互作用力： P ， C ， CP 和 T 都是破壞的



In 1966 --- Cabibbo



Is the weak interaction God's mistake?

Creation of Adam (Michelangelo, in Sistine Ceiling)



上帝創造的第一個男人
：亞當

God's right hand, on the right, touches life into Adam's left.

Right=對, Left 拉丁文 Sinister = Evil 邪惡, 罪過

● 基本粒子及交互作用力

What is the World Made of?

Why do so many things in this world share the same characteristics?

People have come to realize that the matter of the world is made from a few fundamental building blocks of nature.

The word "**fundamental**" is key here. By fundamental building blocks we mean objects that are **simple and structureless** -- not made of anything smaller.

Even in ancient times, people sought to organize the world around them into fundamental elements, such as **earth, air, fire, and water.**

古代中國文明：世界是由五種星組成

金，木，水，火，土

What is Fundamental?

物質是無限可分的嗎？

一尺之捶，日取其半，萬世不竭

莊子天下篇第三十三（300 B.C.）



Ordinary matter

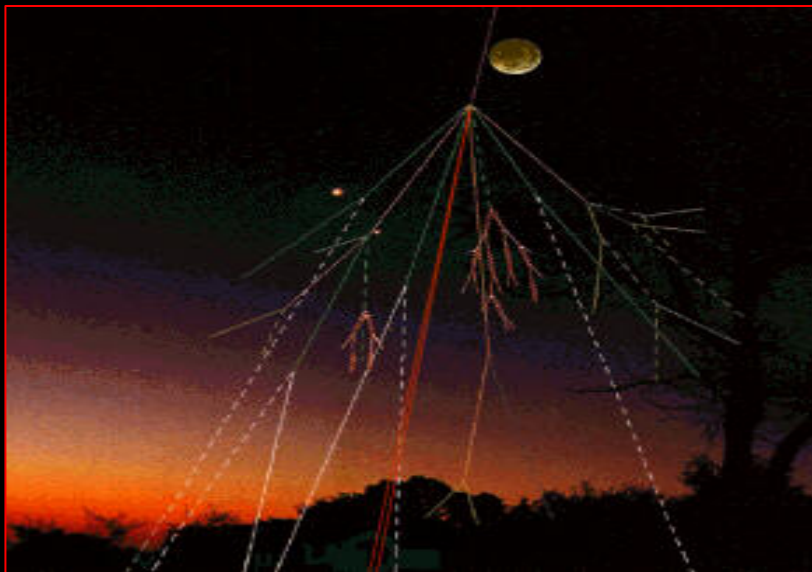
Periodic Table of the Elements

1	IA																0																		
1	H																	He																	
2	3	4																	10																
	Li	Be																	Ne																
3	11	12	13	14	15	16	17	18																	18										
	Na	Mg	Al	Si	P	S	Cl	Ar																											
4	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36																	36
	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr																	
5	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54																	54
	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe																	
6	55	56	57	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86																	86
	Cs	Ba	*La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn																	
7	87	88	89	104	105	106	107	108	109	110	111	112																	112						
	Fr	Ra	+Ac	Rf	Ha	106	107	108	109	110	111	112																							

Naming conventions of new elements

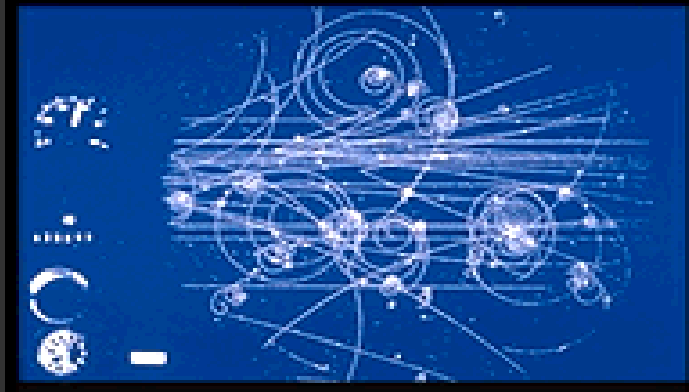
* Lanthanide Series	58	59	60	61	62	63	64	65	66	67	68	69	70	71
	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
+ Actinide Series	90	91	92	93	94	95	96	97	98	99	100	101	102	103
	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Cosmic Matter



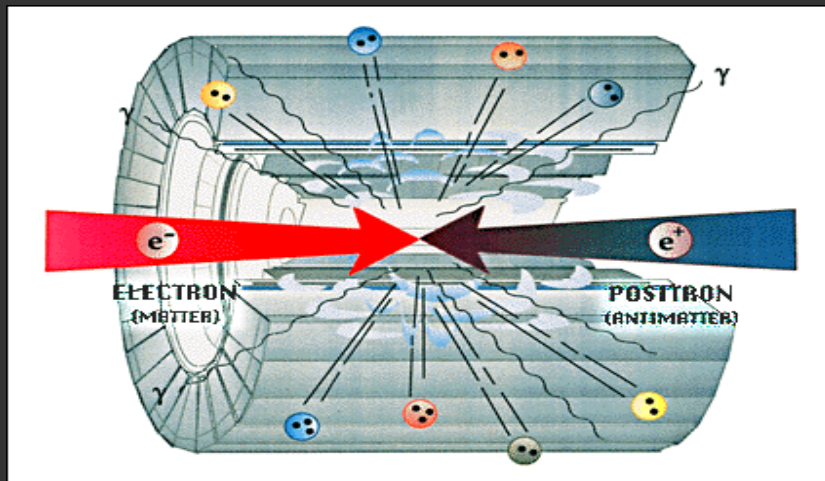
*So to understand the matter that exists as cosmic rays, we need more components than we need to make atoms. In addition to the electron, electron-neutrino, up quark and down quark, we need the **muon**, the **muon-neutrino** and the **strange quark**.*

High Energy Matter



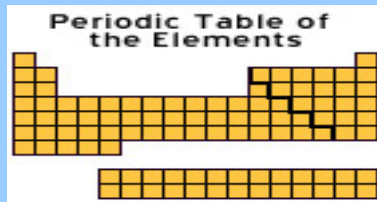
To study high energy particle collisions under more controlled conditions, particle physicists use laboratories such as CERN, where high-energy particle colliders mimic the actions of cosmic rays in the atmosphere. Nowadays, these experiments reach energies that were common in the Universe only in the first instants of its existence.

Antimatter



For each of the basic particles of matter, there also exists a "mirror" version - or antiparticle - in which properties such as electric charge are reversed.

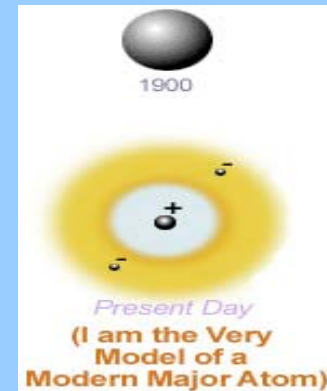
Is the Atom Fundamental ?



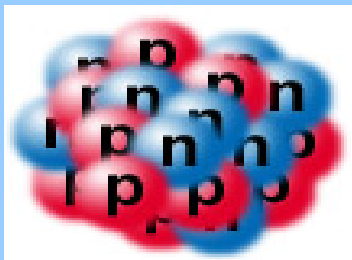
People soon realized that they could categorize atoms into groups that shared similar chemical properties (as in the Periodic Table of the Elements). This indicated that atoms were made up of simpler building blocks, and that it was these

simpler building blocks in different combinations that determined which atoms had which chemical properties.

Moreover, experiments which "looked" into an atom using particle probes indicated that **atoms had structure** and were not just squishy balls. These experiments helped scientists determine that **atoms have a tiny but dense, positive nucleus and a cloud of negative electrons (e^-)**.

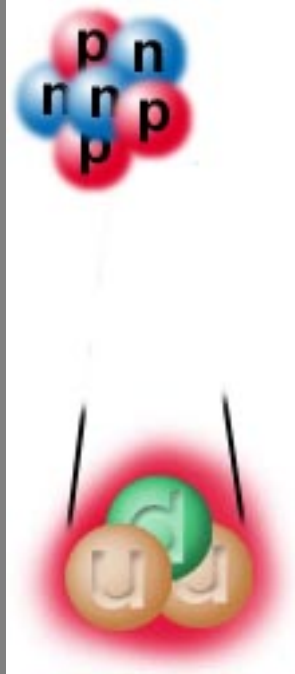


Is the Nucleus Fundamental?



Because it appeared small, solid, and dense, scientists originally thought that the nucleus was fundamental. Later, they discovered that **it was made of protons (p^+)**, which are positively charged, **and neutrons (n)**, which have no charge.

So, then, are protons and neutrons fundamental?



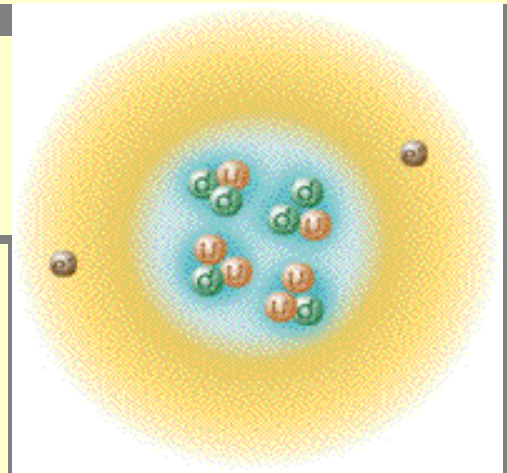
Physicists have discovered that protons and neutrons are composed of even smaller particles called quarks.

As far as we know, quarks are like points in geometry. They're not made up of anything else.

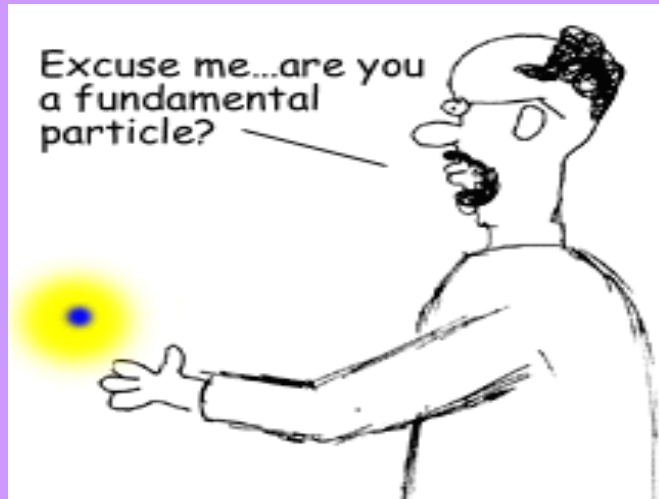
After extensively testing this theory, scientists now suspect that quarks and the electron (and a few other things we'll see in a minute) are fundamental

The Modern Atom Model

Electrons are in constant motion around the nucleus, protons and neutrons jiggle within the nucleus, and quarks jiggle within the protons and neutrons.



This picture is quite distorted. If we drew the atom to scale and made protons and neutrons a centimeter in diameter, then the electrons and quarks would be less than the diameter of a hair and the entire atom's diameter would be greater than the length of thirty football fields! 99.999999999999% of an atom's volume is just empty space!



Physicists constantly look for new particles. When they find them, they categorize them and try to find patterns that tell us about how the fundamental building blocks of the universe interact.

We have now discovered about two hundred particles (most of which aren't fundamental).

To keep track of all of these particles, they are named with letters from the Greek and Roman alphabets.

Of course, You should not be discouraged if you have trouble remembering them. Take heart: even the great **Enrico Fermi** once said to his student (and future Nobel Laureate) **Leon Lederman**,

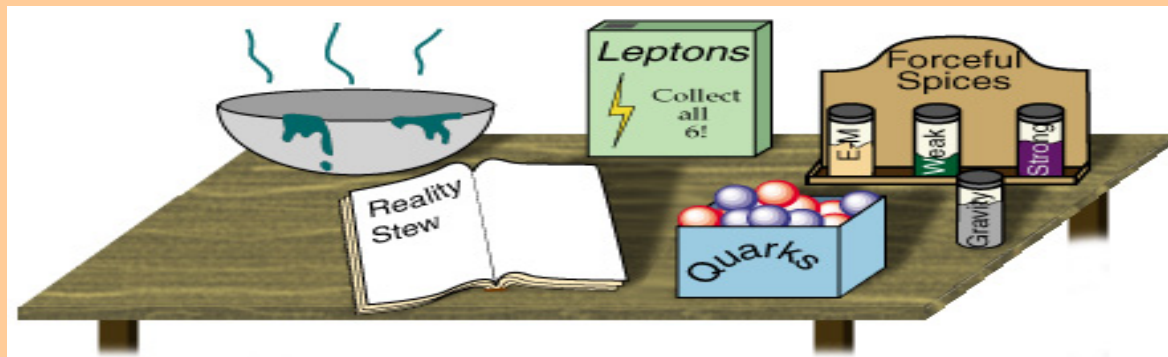
"Young man, if I could remember the names of these particles, I would have been a botanist!"

The Standard Model

Physicists have developed a theory called **The Standard Model** that explains what the world is and what holds it together. It is a simple and comprehensive theory that explains all the hundreds of particles and complex interactions with only:

- **6 quarks.**
- **6 leptons.** The best-known lepton is the electron.
- **Force carrier particles,** like the photon.

All the known matter particles are composites of quarks and leptons, and they interact by exchanging force carrier particles.



The Standard Model is a good theory. Experiments have verified its predictions to incredible precision, and all the particles predicted by this theory have been found. But it does not explain everything. For example, gravity is not included in the Standard Model.

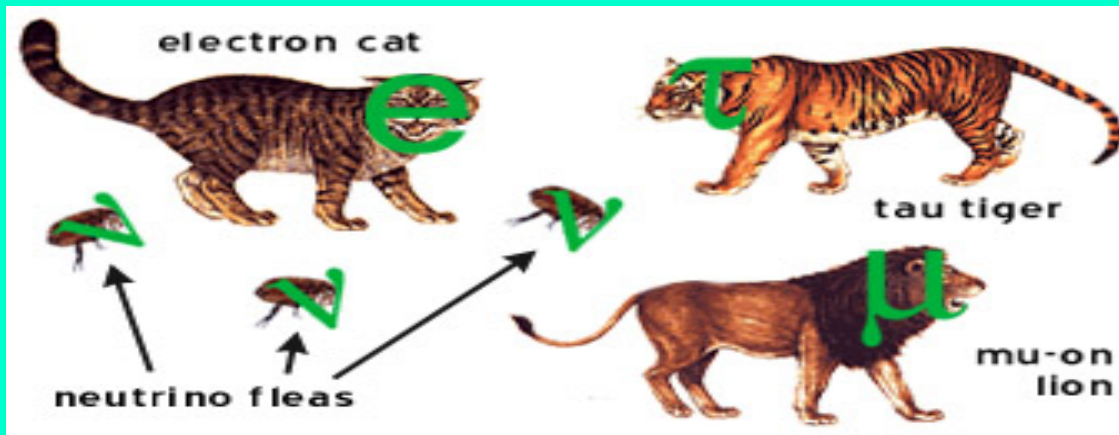
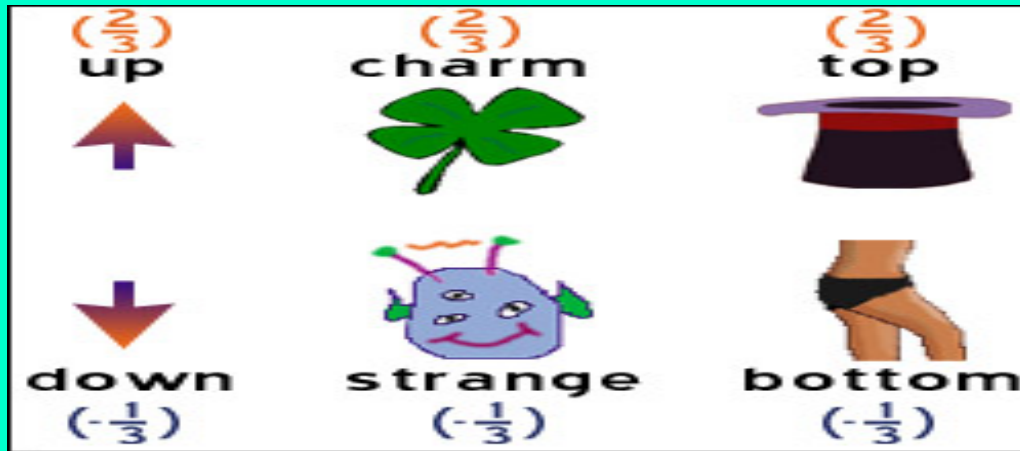
What is the World Made of?

Quarks and Leptons




As you have read, everything from galaxies to mountains to molecules is made from **quarks** and **leptons**. But that is not the **whole story**. Quarks behave differently than leptons, and for each kind of matter particle there is a corresponding antimatter particle.





Particle	Mass (Gev/c ²)	Electr. Charge	Particle	Mass (Gev/c ²)	Electr. Charge
U (up)	.005	+2/3	electron-neutrino	<7x10 ⁻⁹	0
D (down)	.01	-1/3	electron	.000511	-1
C (charm)	1.5	+2/3	muon-neutrino	<.0003	0
S (strange)	0.2	-1/3	muon	0.106	-1
T (top)	180	+2/3	tau-neutrino	<.03	0
B (bottom)	4.7	-1/3	tau	1.7771	-1

Quarks	u up	c charm	t top
	d down	s strange	b bottom
Leptons	ν_e e- Neutrino	ν_μ μ - Neutrino	ν_τ τ - Neutrino
	e electron	μ muon	τ tau
 I II III The Generations of Matter			

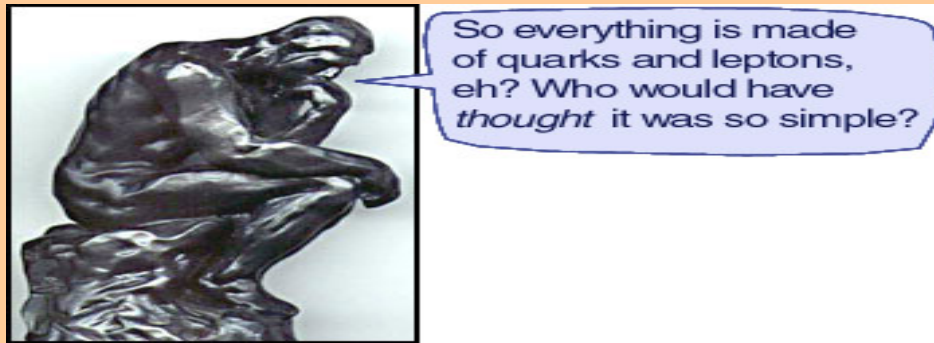
In fact, when the **muon** was discovered physicist **I.I. Rabi** asked,



So why do we have generations of matter at all? Why three of them?

爲什麼物質要有代呢？爲什麼又只有三代？

We don't know. And without understanding why the second and third generation particles exist, we cannot rule out the possibility that there are yet more quarks and leptons that we have not discovered yet.



What Holds it Together? The Four Interactions

	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	$W^+ W^- Z^0$	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and $W^+ W^-$	Quarks and Gluons

Fermions (費米子, 自旋=1/2....): Quarks & Leptons

Bosons (玻色子, 自旋=0,1,....): W^+, W^-, Z^0 , 光子, 膠子

The Pauli Exclusion Principle

Particles that do obey the Pauli Exclusion Principle are called **fermions**, and those that do not are called **bosons**.

Imagine there is a large family of identical fermion siblings spending the night at the Fermion Motel, and there is another large family of identical boson siblings spending the night at the Boson Inn. (Since fermions rent more rooms than bosons, motel owners prefer doing business with fermions. Some motels even refuse to rent rooms to bosons!)



Elementary Particles								
Quarks	u up	c charm	t top	g gluon	Force Carriers			
	d down	s strange	b bottom				γ photon	
Leptons	ν_e e neutrino	ν_μ μ neutrino	ν_τ τ neutrino	W W boson				
	e electron	μ muon	τ tau	Z Z boson				
3 \rightarrow	I	II	III	\leftarrow Generations				

A Lot to Remember



We have answered the questions, "What is the world made of?" and "What holds it together?"

The world is made of six **quarks** and six **leptons**. Everything we see is a conglomeration of quarks and leptons.

There are four fundamental forces and there are **force carrier particles** associated with each force.

These are the essential aspects of the Standard Model. It is the most complete explanation of the fundamental particles and interactions to date.

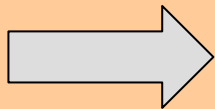
Substructure ?

物質是無限可分的嗎???

夸克和輕子也有結構嗎?

夸克

輕子



Preon 先子

本人1987年的博士論文

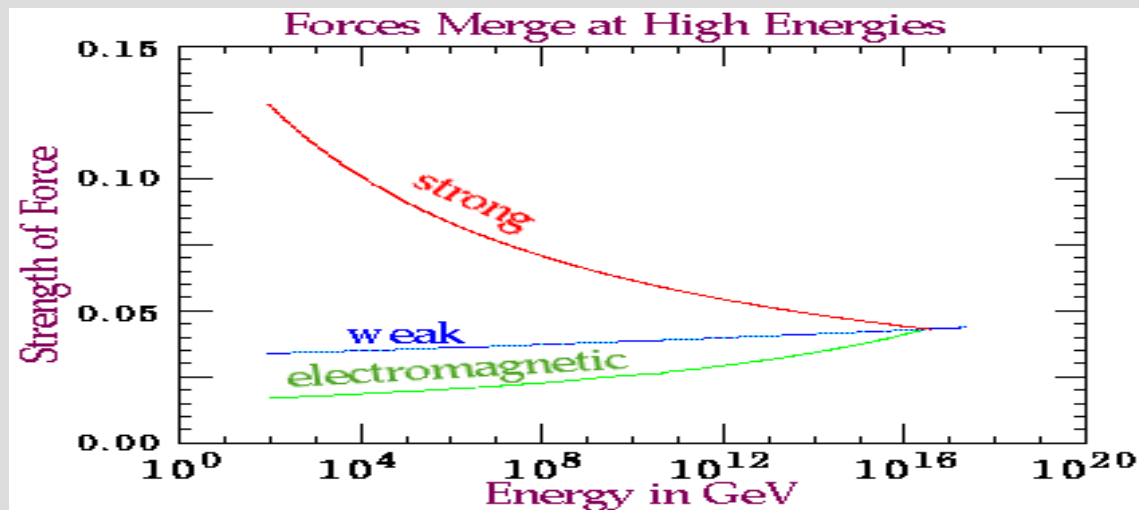
導師：R.Marshak（弱作用理論的創造者之一）

結論：（到目前為止）理論：沒有任何可信之模型
實驗：沒有任何跡象（ 10^{-16} cm）

● 大統一場理論

Grand Unified Theories

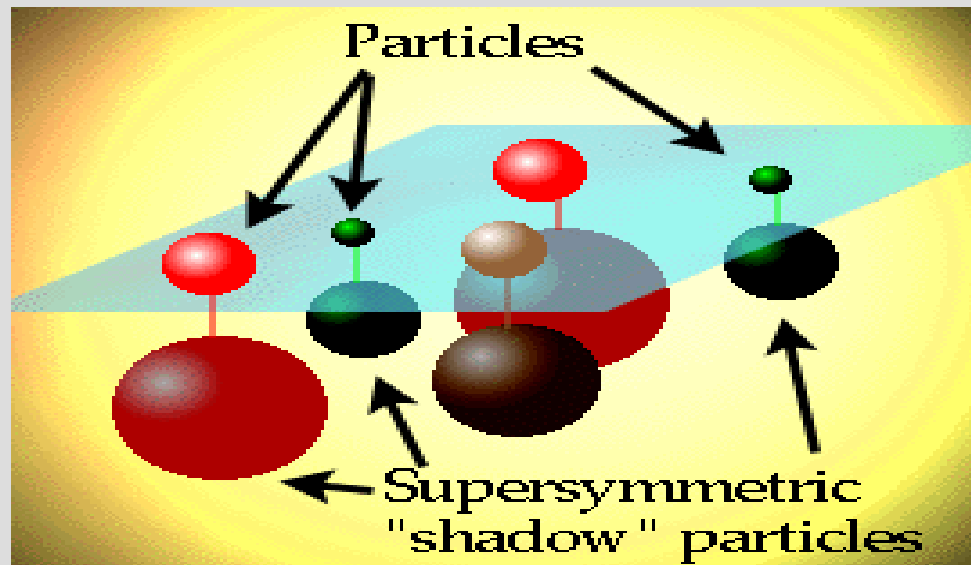
The theory which (we hope!) will unify the **strong, weak, and electromagnetic interactions** is called the "Grand Unified Theory." If a Grand Unification of all the interactions is possible, then all the interactions we observe are all different aspect of the same, unified interaction. However, how can this be the case if strong and weak and electromagnetic interactions are so different in strength and effect? Strangely enough, current data and theory suggest that these varied forces merge into one force when the particles being affected are at a high enough energy.



Contemporary work on GUT also suggests new force-carrier particles that could cause the proton to decay. Such decays must be extremely rare; otherwise our world would not exist today. Measurement tells us the lifetime of the proton is greater than 10^{32} (10 to the power of 32) years!

Supersymmetry 超對稱

Many physicists have developed theories of **supersymmetry**, particularly in the context of Grand Unified Theories. The supersymmetric theories postulate that every particle we observe has a massive "shadow" particle partner. For example, for every quark there may be a so-called "**squark**" tagging along.



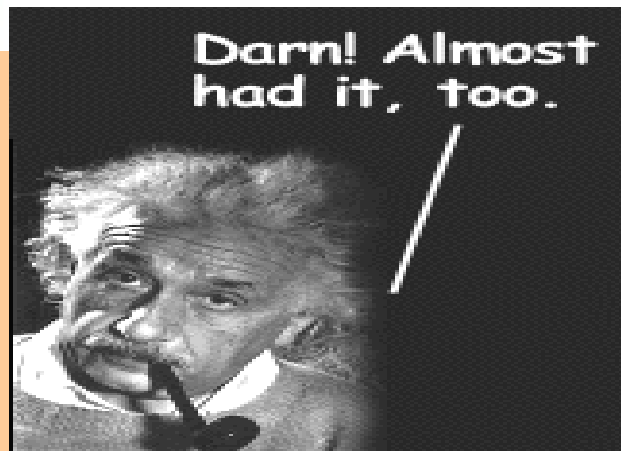
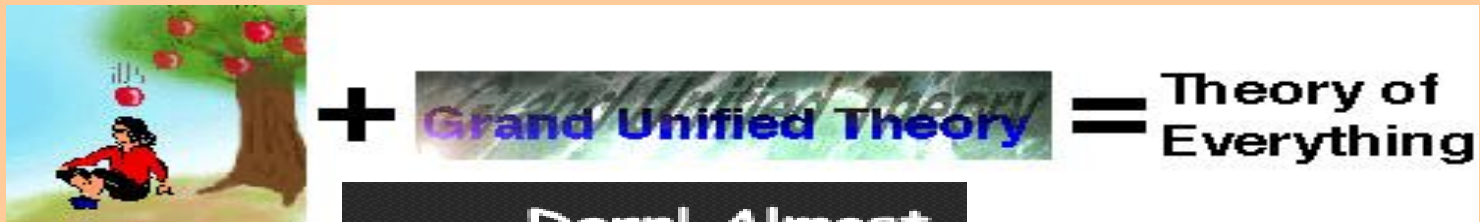
No supersymmetric particle has yet been seen, but experiments underway at CERN are searching for the partner of the W boson, and experiments at Fermilab are looking for the partners of the quarks and gluons. One of the supersymmetric particles (the "**neutralino**") might make up the missing **dark matter** in the universe.

The Theory of Everything (TOE)

The long range goal of physics is to unify all the forces, so that gravity would be combined with the future version of the Grand Unified Theory. Then the gravitational interaction would be thought of as quantized, like the other forces, so that the gravitational force is transmitted by particles called *gravitons*.

This poses a formidable problem. Einstein showed us that the gravitational force arises due to curvature in the fabric of spacetime. Thus, the task is to quantize spacetime to produce the desired gravitons. Achieving this type of quantum field theory is quite a challenge both conceptually and mathematically.

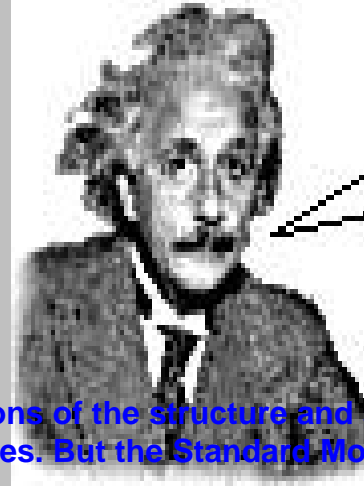
The HEP Experiment may guide us toward a Grand Unified Theory, so that ultimately humankind will understand a complete, unified Theory of Everything.



● 尚未解決之問題

What Questions Remain?

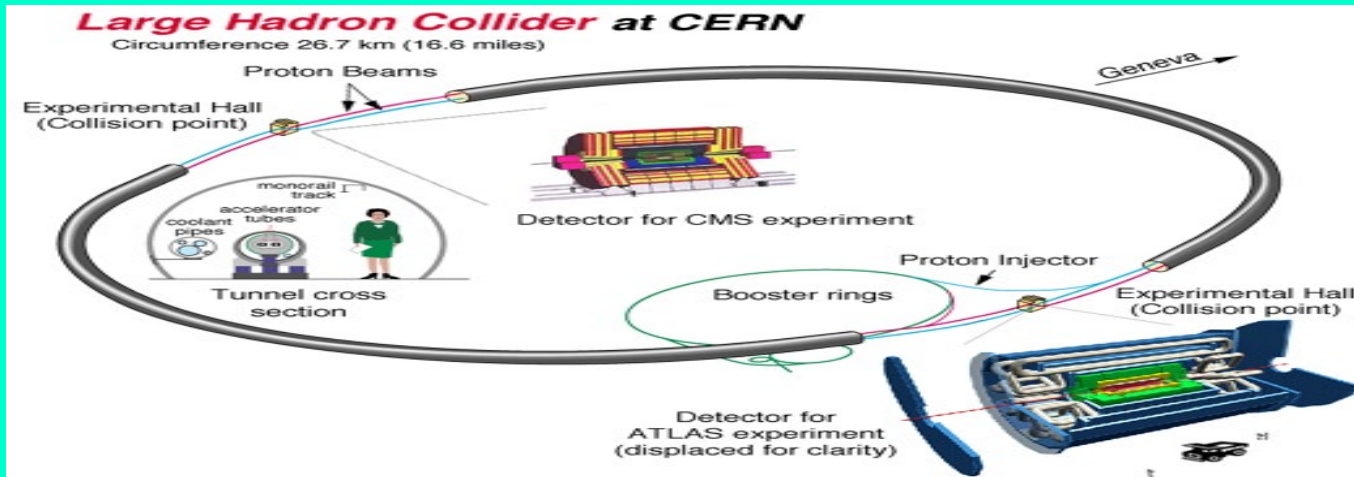
The Standard Model answers many of the questions of the structure and stability of matter with its six types of quarks, six leptons, and the four forces. But the Standard Model leaves many other questions unanswered:



Hmm...The ATLAS Experiment will provide some answers.

- *Why are there three types of quarks and leptons?*
- *Is there some pattern to their masses?*
- *Are there more types of particles and forces to be discovered at yet higher energy accelerators?*
- *Are the quarks and leptons really fundamental, or do they, too, have substructure?*
- *How to understand dark matter and dark energy in the universe?*
- *How to include the gravitational interactions in the SM?*

未來展望



Physics with LHC: **The Higgs Particle**

One of the main goals of the **LHC** program is to discover and study the Higgs particle. The Higgs particle is of critical importance in particle theories and is directly related to the concept of particle mass and therefore to all masses.

A recent campaign in US congress:

*Protons, neutrons and electrons
need unifying,
we should go in and unify them!*