

*What is everything made of?*

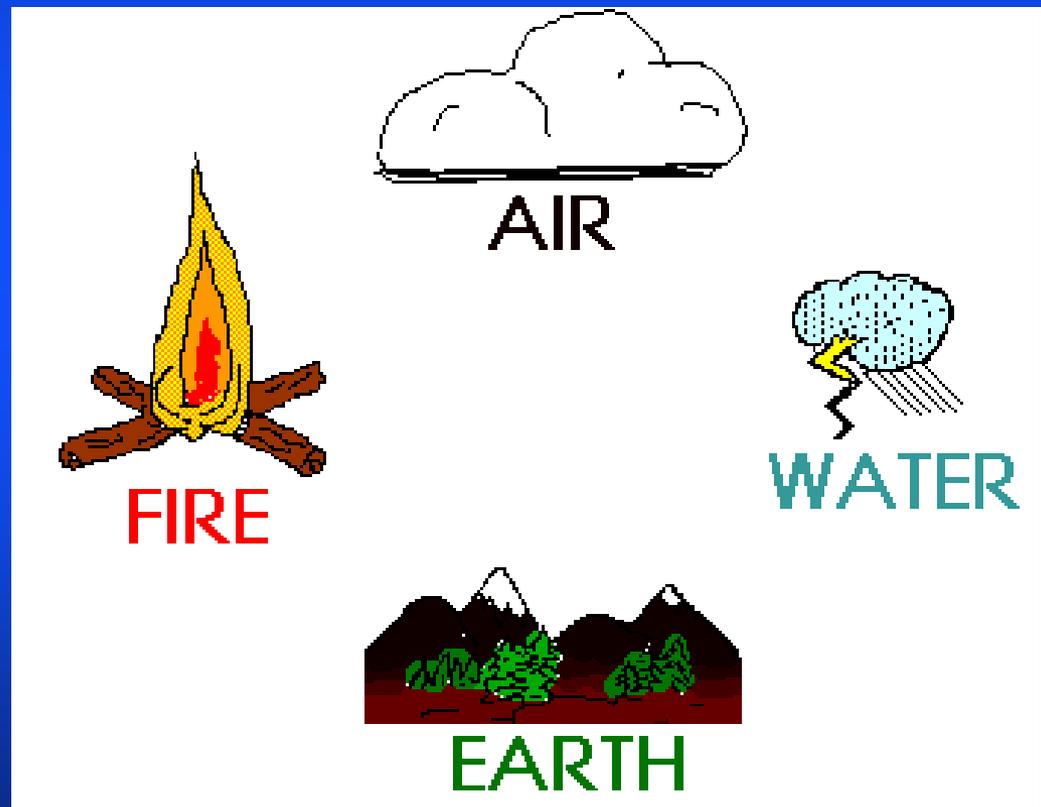
*The quest for the ultimate building blocks  
of the physical universe.*

Soren Sorensen  
*Department of Physics and Astronomy  
University of Tennessee, Knoxville*

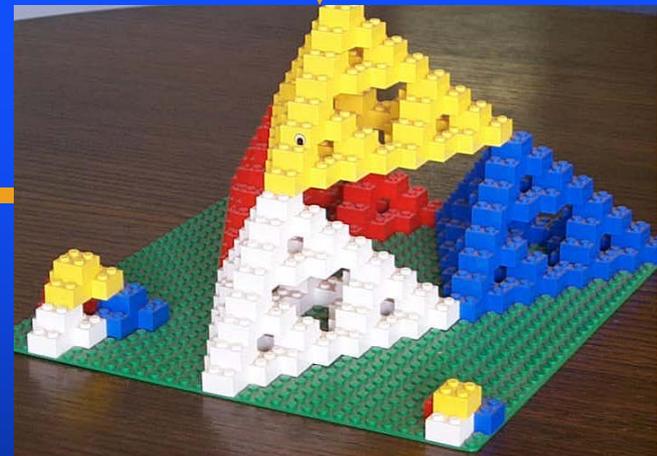
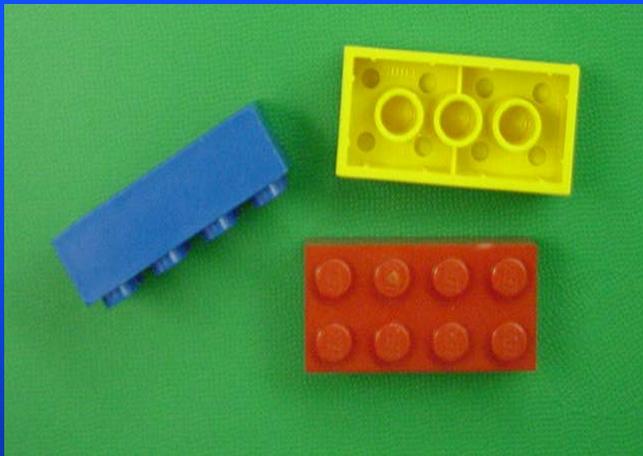
# What is the World made of?

Probably the most fundamental question one can ask next to  
"Does God Exist?"

Thales of Miletus (~624 - ~547 BC)  
Start of philosophy and science.  
Everything is made of water



## *The Lego Block Approach*



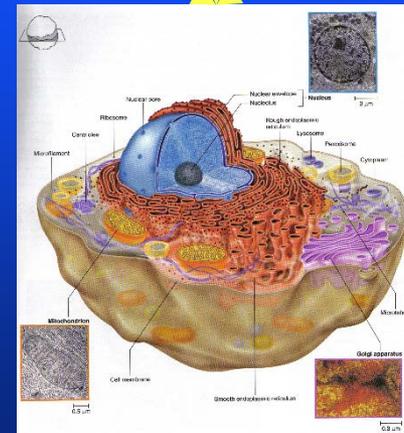
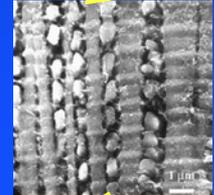
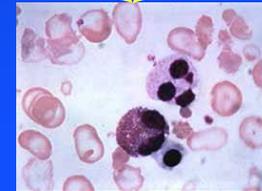
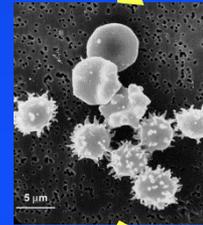
Reduce the complex forms and materials to one (or a few) fundamental building blocks

# The Layers of Science

In a given field of science we can use a particular set of fundamental building blocks.

Usually the number and diversity of the building blocks tends to increase as we learn more and more about the particular layer of science.

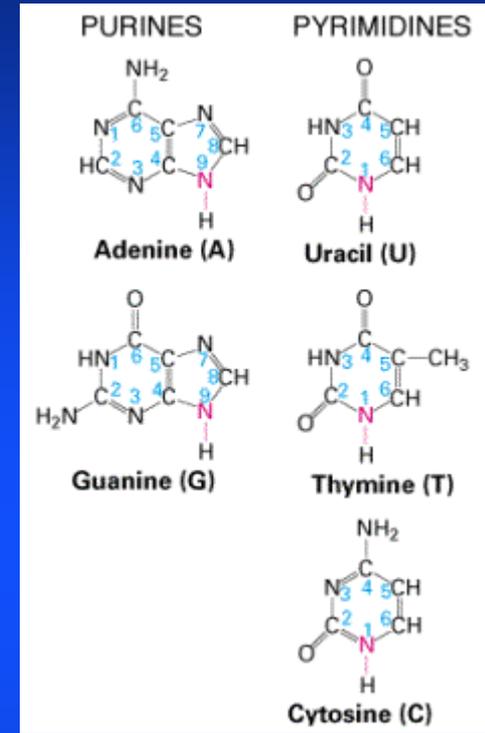
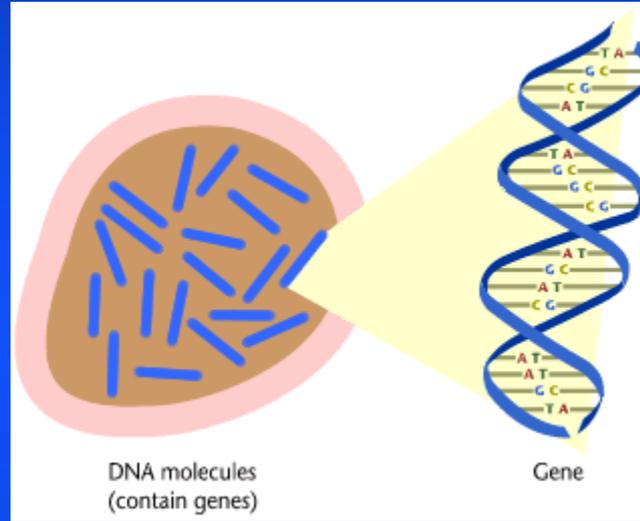
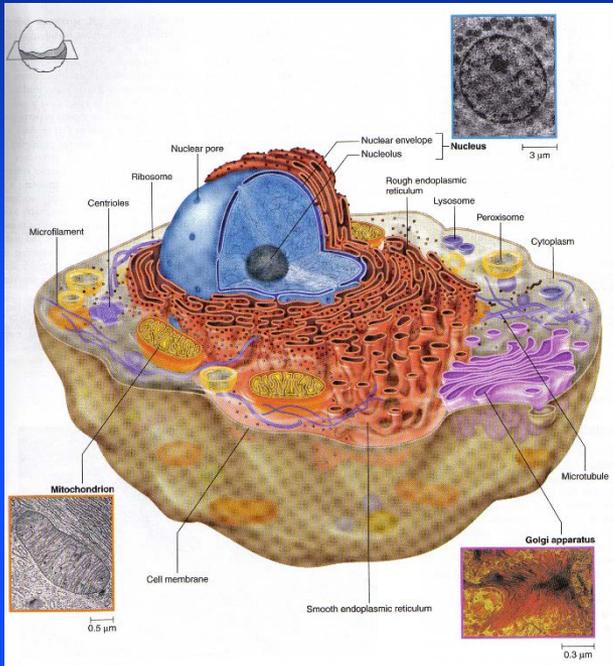
Eventually we realize that all the building blocks have an internal structure and can be described by a much smaller set of more fundamental entities, which then become the new fundamental building blocks



# *The Quantum Ladder*



# Biological Cells → Molecules



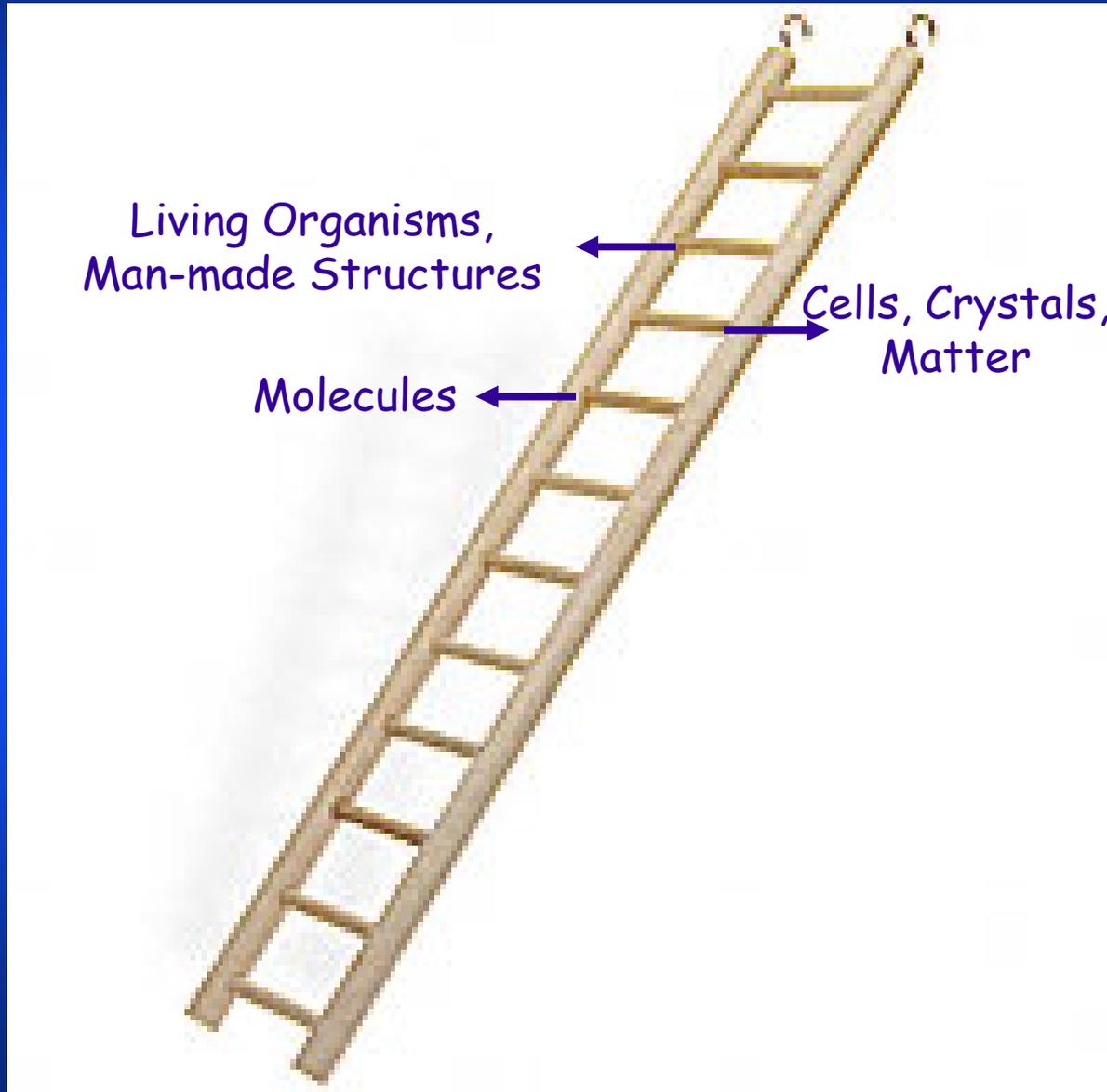
Cells have an internal structure:

Nucleus, Ribosomes, Centrioles, Cytoplasm, Membranes, Axions, etc.

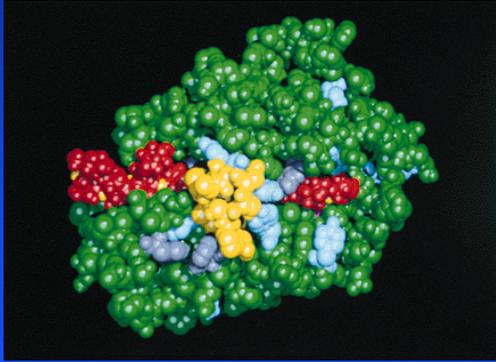
These cell "building blocks" are in turn made of:

Molecules

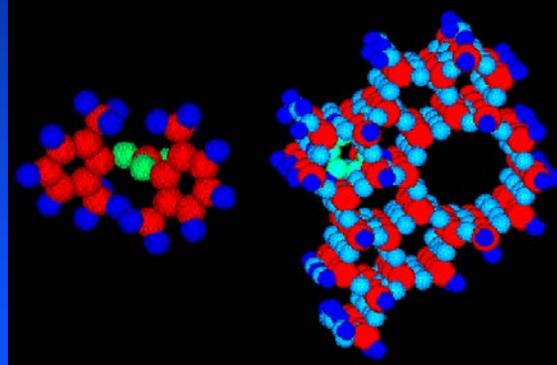
# The Quantum Ladder



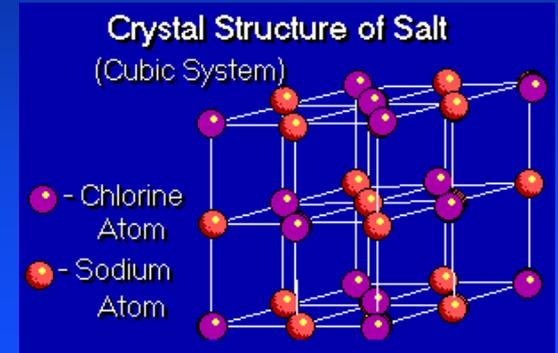
# Molecules → Atoms



Proteins



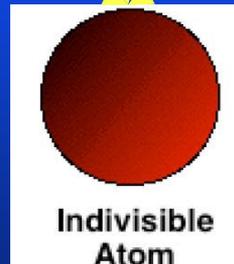
Complex Benzene Rings



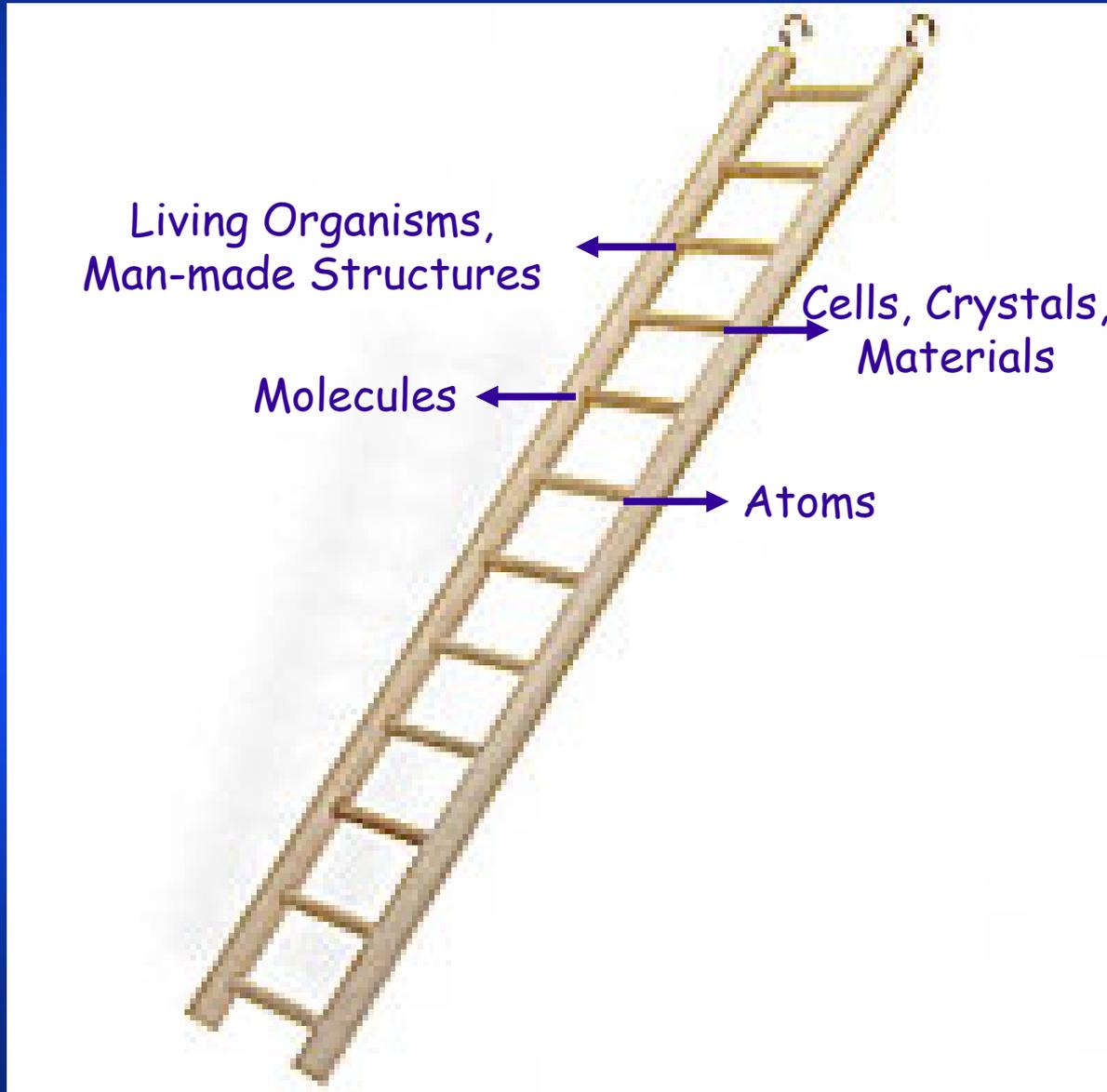
NaCl - "Salt"

The building blocks for all molecules are:

**Atoms**



# The Quantum Ladder



## Atoms

# The Periodic Table

|          |          |          |           |           |           |           |           |           |           |           |           |           |           |           |           |           |           |  |
|----------|----------|----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|--|
| 1<br>H   |          |          |           |           |           |           |           |           |           |           |           |           |           |           |           |           | 2<br>He   |  |
| 3<br>Li  | 4<br>Be  |          |           |           |           |           |           |           |           |           |           | 5<br>B    | 6<br>C    | 7<br>N    | 8<br>O    | 9<br>F    | 10<br>Ne  |  |
| 11<br>Na | 12<br>Mg |          |           |           |           |           |           |           |           |           |           | 13<br>Al  | 14<br>Si  | 15<br>P   | 16<br>S   | 17<br>Cl  | 18<br>Ar  |  |
| 19<br>K  | 20<br>Ca | 21<br>Sc | 22<br>Ti  | 23<br>V   | 24<br>Cr  | 25<br>Mn  | 26<br>Fe  | 27<br>Co  | 28<br>Ni  | 29<br>Cu  | 30<br>Zn  | 31<br>Ga  | 32<br>Ge  | 33<br>As  | 34<br>Se  | 35<br>Br  | 36<br>Kr  |  |
| 37<br>Rb | 38<br>Sr | 39<br>Y  | 40<br>Zr  | 41<br>Nb  | 42<br>Mo  | 43<br>Tc  | 44<br>Ru  | 45<br>Rh  | 46<br>Pd  | 47<br>Ag  | 48<br>Cd  | 49<br>In  | 50<br>Sn  | 51<br>Sb  | 52<br>Te  | 53<br>I   | 54<br>Xe  |  |
| 55<br>Cs | 56<br>Ba | 57-71    | 72<br>Hf  | 73<br>Ta  | 74<br>W   | 75<br>Re  | 76<br>Os  | 77<br>Ir  | 78<br>Pt  | 79<br>Au  | 80<br>Hg  | 81<br>Tl  | 82<br>Pb  | 83<br>Bi  | 84<br>Po  | 85<br>At  | 86<br>Rn  |  |
| 87<br>Fr | 88<br>Ra | 89-103   | 104<br>Rf | 105<br>Db | 106<br>Sg | 107<br>Bh | 108<br>Hs | 109<br>Mt | 110<br>Ds | 111<br>Rg | 112<br>Cn | 113<br>Nh | 114<br>Fl | 115<br>Mc | 116<br>Lv | 117<br>Ts | 118<br>Og |  |
|          |          | 57<br>La | 58<br>Ce  | 59<br>Pr  | 60<br>Nd  | 61<br>Pm  | 62<br>Sm  | 63<br>Eu  | 64<br>Gd  | 65<br>Tb  | 66<br>Dy  | 67<br>Ho  | 68<br>Er  | 69<br>Tm  | 70<br>Yb  | 71<br>Lu  |           |  |
|          |          | 89<br>Ac | 90<br>Th  | 91<br>Pa  | 92<br>U   | 93<br>Np  | 94<br>Pu  | 95<br>Am  | 96<br>Cm  | 97<br>Bk  | 98<br>Cf  | 99<br>Es  | 100<br>Fm | 101<br>Md | 102<br>No | 103<br>Lr |           |  |

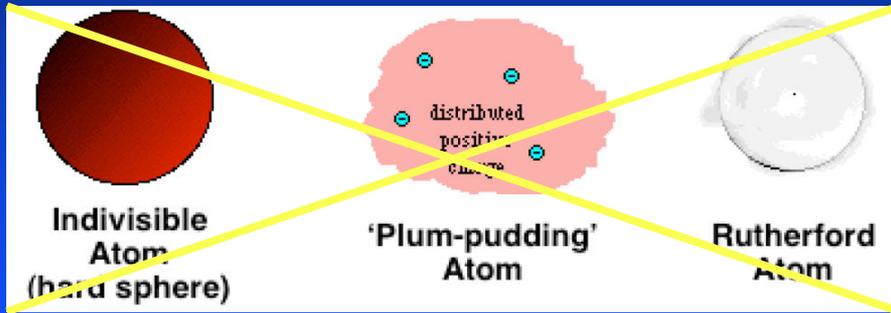
Each element in the Periodic Table corresponds to a particular atom.

Mendeleev discovered how to order the atoms in the Periodic Table, but he did not understand WHY the table had this structure.

Currently we know ~118 different elements.

Problem: There are too many different building blocks.

# Internal Structure of the Atom

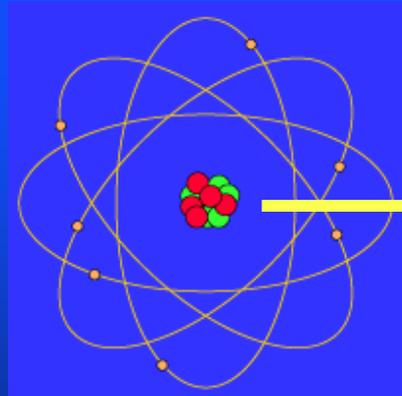


Early models of the Atom

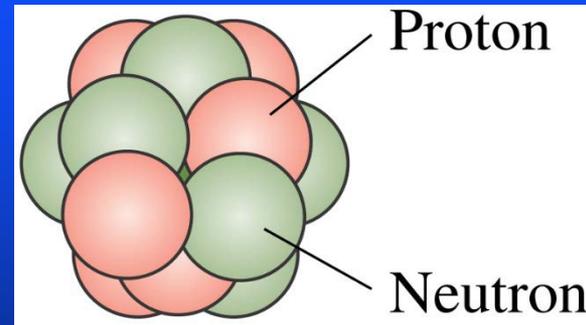
All atoms can be constructed from only three fundamental building blocks:

- Electrons
- Protons
- Neutrons

The atom consists of negative electrons orbiting a positive nucleus



Bohr - Rutherford Atom

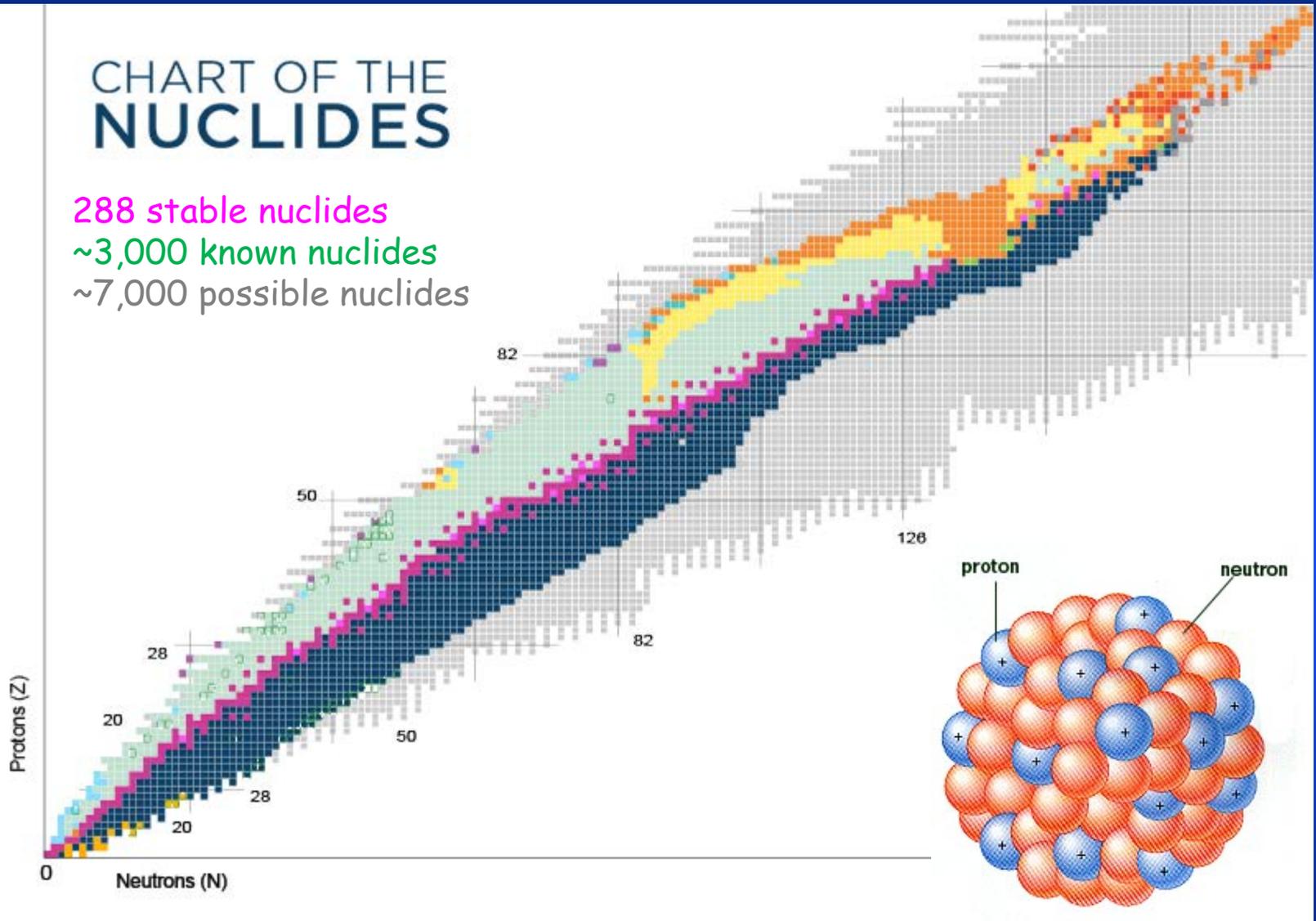


The atomic nucleus consists of positive protons and neutral neutrons

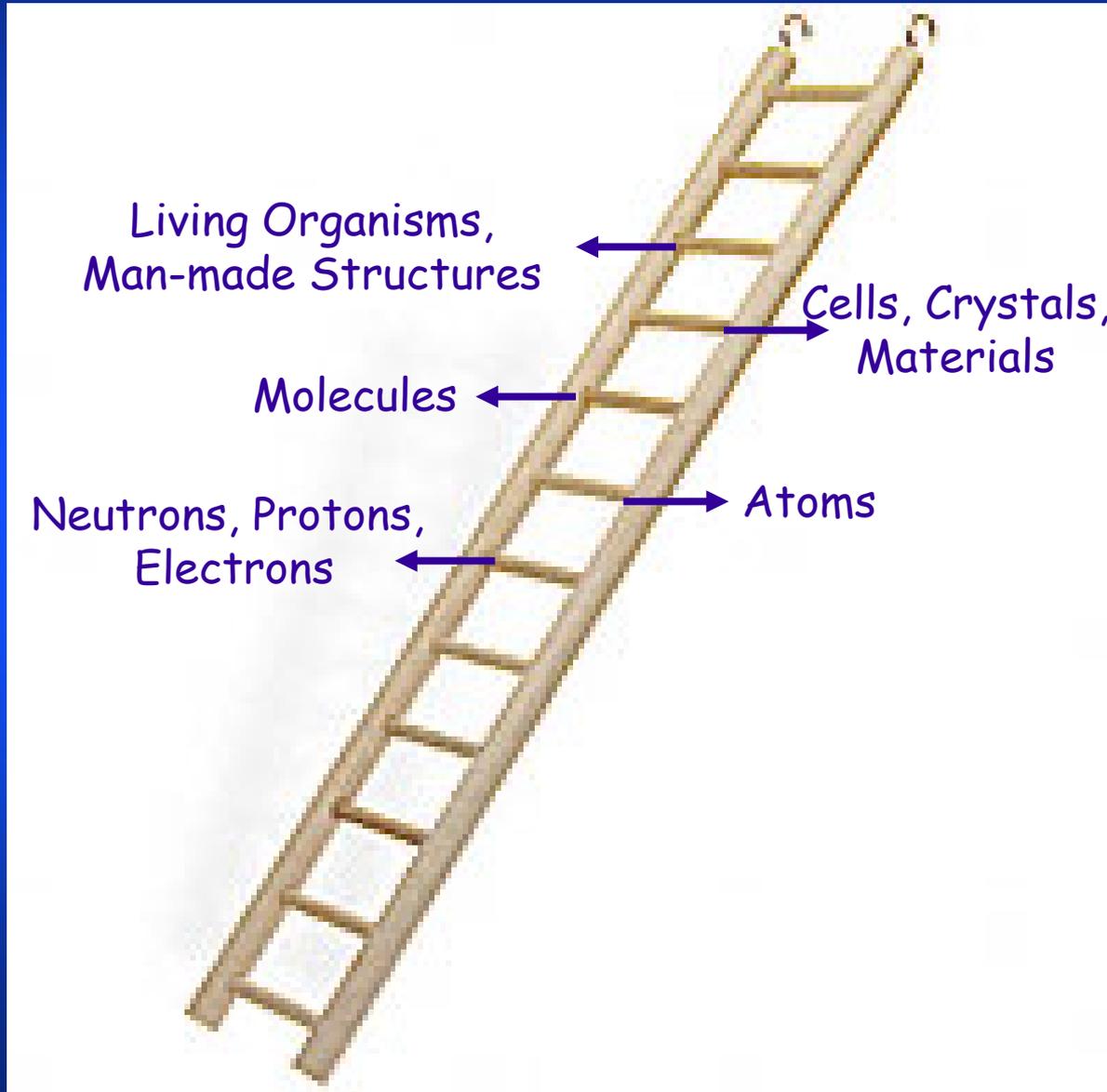
# Combining protons and neutrons into atomic nuclei

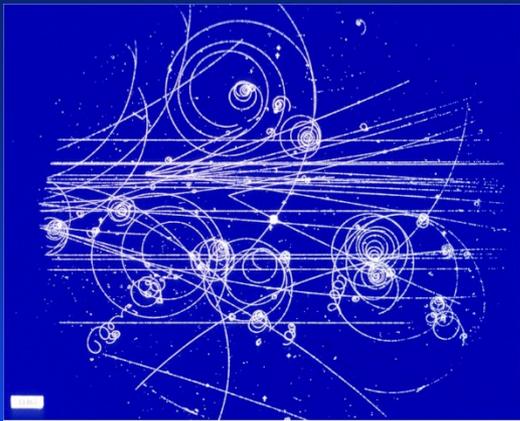
## CHART OF THE NUCLIDES

288 stable nuclides  
~3,000 known nuclides  
~7,000 possible nuclides



# The Quantum Ladder



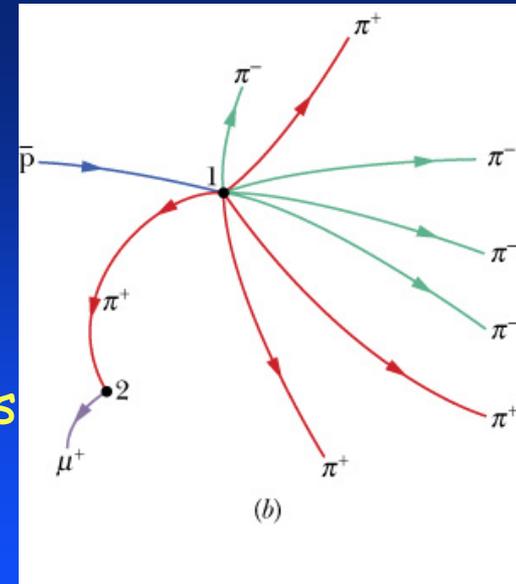


# "Elementary" Particles

In the period 1930 - 1970 hundreds of new "elementary" particles were discovered.

**Problem:**

Too many "elementary" particles



**TABLE 44-2 The Leptons<sup>a</sup>**

| Family   | Particle                       | Symbol         | Mass (MeV/c <sup>2</sup> ) | Charge <i>q</i> |
|----------|--------------------------------|----------------|----------------------------|-----------------|
| Electron | Electron                       | e <sup>-</sup> | 0.511                      | -1              |
|          | Electron neutrino <sup>b</sup> | ν <sub>e</sub> | ≈ 1 × 10 <sup>-7</sup>     | 0               |
| Muon     | Muon                           | μ <sup>-</sup> | 105.7                      | -1              |
|          | Muon neutrino <sup>b</sup>     | ν <sub>μ</sub> | ≈ 1 × 10 <sup>-7</sup>     | 0               |
| Tau      | Tau                            | τ <sup>-</sup> | 1777                       | -1              |
|          | Tau neutrino <sup>b</sup>      | ν <sub>τ</sub> | ≈ 1 × 10 <sup>-7</sup>     | 0               |

The **Lepton** Family (6):  
Heavy Electrons and nearly undetectable neutrinos

**Nine Spin-Zero Mesons<sup>a</sup>**

| Particle  | Symbol          | Mass (MeV/c <sup>2</sup> ) | Quantum Numbers |                      |
|-----------|-----------------|----------------------------|-----------------|----------------------|
|           |                 |                            | Charge <i>q</i> | Strangeness <i>S</i> |
| Pion      | π <sup>0</sup>  | 135.0                      | 0               | 0                    |
| Pion      | π <sup>+</sup>  | 139.6                      | +1              | 0                    |
| Pion      | π <sup>-</sup>  | 139.6                      | -1              | 0                    |
| Kaon      | K <sup>+</sup>  | 493.7                      | +1              | +1                   |
| Kaon      | K <sup>-</sup>  | 493.7                      | -1              | -1                   |
| Kaon      | K <sup>0</sup>  | 497.7                      | 0               | +1                   |
| Kaon      | K̄ <sup>0</sup> | 497.7                      | 0               | -1                   |
| Eta       | η               | 547.5                      | 0               | 0                    |
| Eta prime | η'              | 957.8                      | 0               | 0                    |

The **Baryon** Family (~120):  
heavy protons and neutrons

**Eight Spin-½ Baryons**

| Particle | Symbol         | Mass (MeV/c <sup>2</sup> ) | Quantum Numbers |                      |
|----------|----------------|----------------------------|-----------------|----------------------|
|          |                |                            | Charge <i>q</i> | Strangeness <i>S</i> |
| Proton   | p              | 938.3                      | +1              | 0                    |
| Neutron  | n              | 939.6                      | 0               | 0                    |
| Lambda   | Λ <sup>0</sup> | 1115.6                     | 0               | -1                   |
| Sigma    | Σ <sup>+</sup> | 1189.4                     | +1              | -1                   |
| Sigma    | Σ <sup>0</sup> | 1192.5                     | 0               | -1                   |
| Sigma    | Σ <sup>-</sup> | 1197.3                     | -1              | -1                   |
| Xi       | Ξ <sup>0</sup> | 1314.9                     | 0               | -2                   |
| Xi       | Ξ <sup>-</sup> | 1321.3                     | -1              | -2                   |

The **Meson** Family (~140):  
Similar to Baryons, but lighter



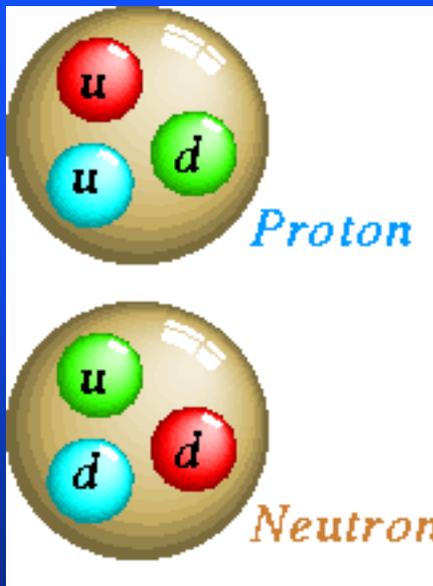
# The Quarks

The solution:

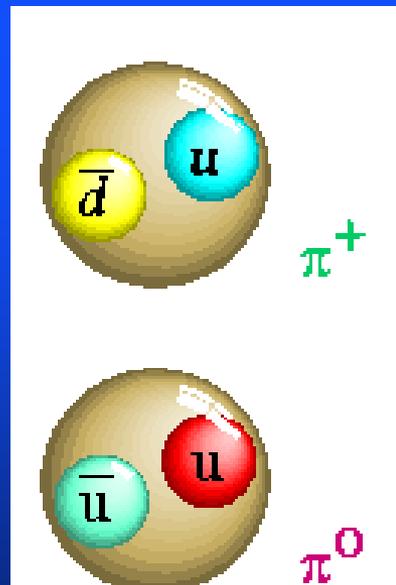
Three simple building blocks called Quarks (1964)

| Quark   | Sym-<br>bol | Charge<br>$e$ | Strange-<br>ness |
|---------|-------------|---------------|------------------|
| Up      | u           | 2/3           | 0                |
| Down    | d           | -1/3          | 0                |
| Strange | s           | 2/3           | -1               |

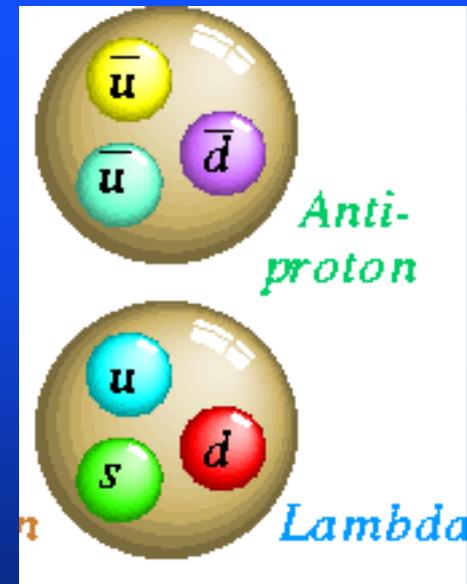
| Anti-Quark   | Sym-<br>bol | Charge<br>$e$ | Strange-<br>ness |
|--------------|-------------|---------------|------------------|
| Anti-Up      | $\bar{u}$   | -2/3          | 0                |
| Anti-Down    | $\bar{d}$   | 1/3           | 0                |
| Anti-Strange | $\bar{s}$   | -2/3          | 1                |



Baryons: qqq

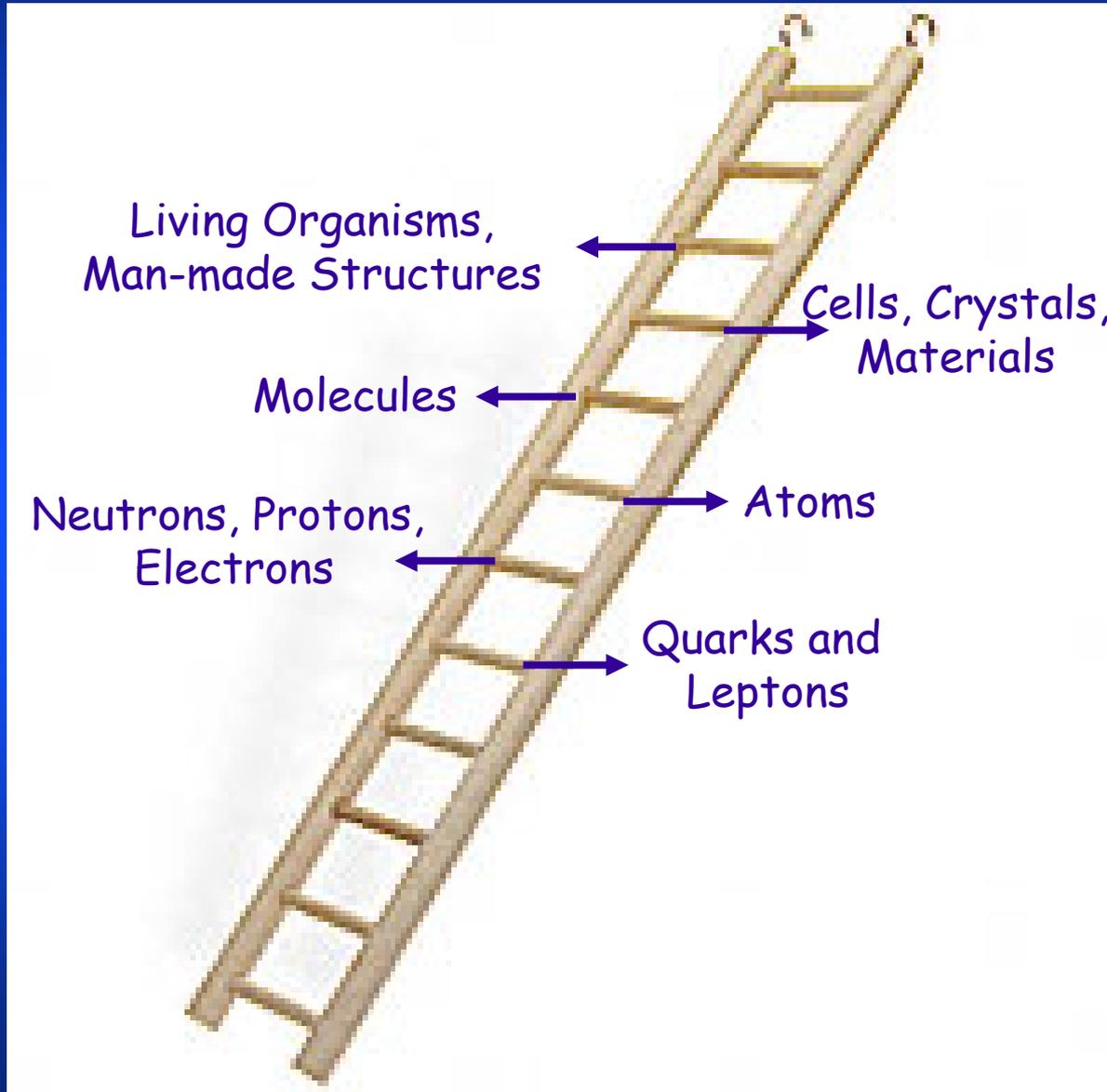


Mesons:  $q \bar{q}$

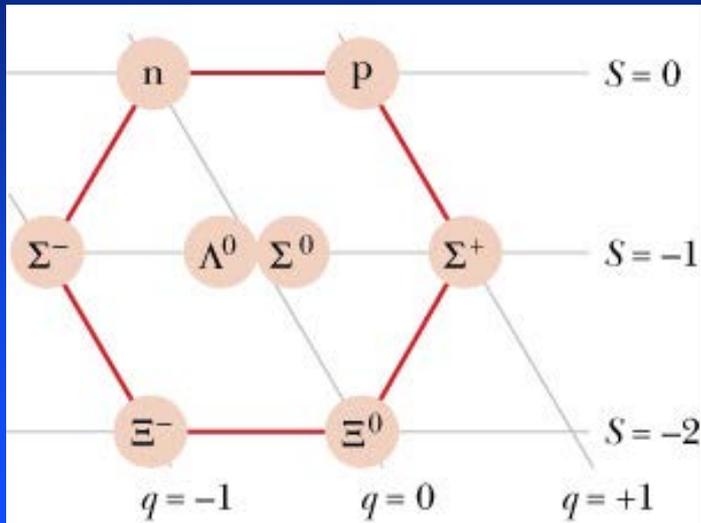


Baryons: qqq or  $q \bar{q} q \bar{q} q \bar{q}$

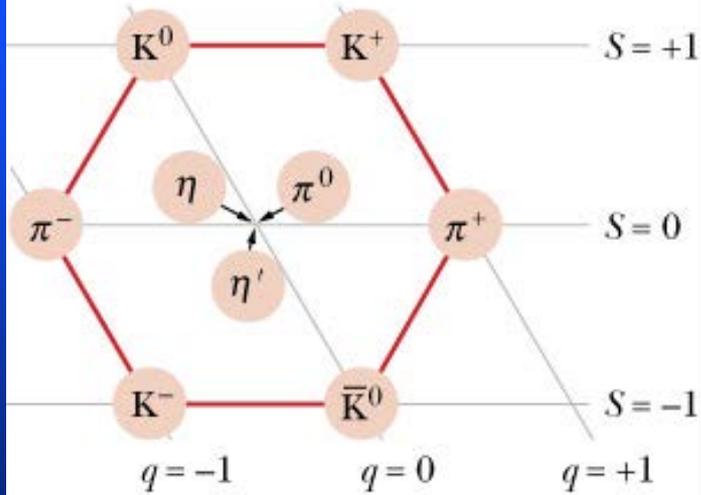
# The Quantum Ladder



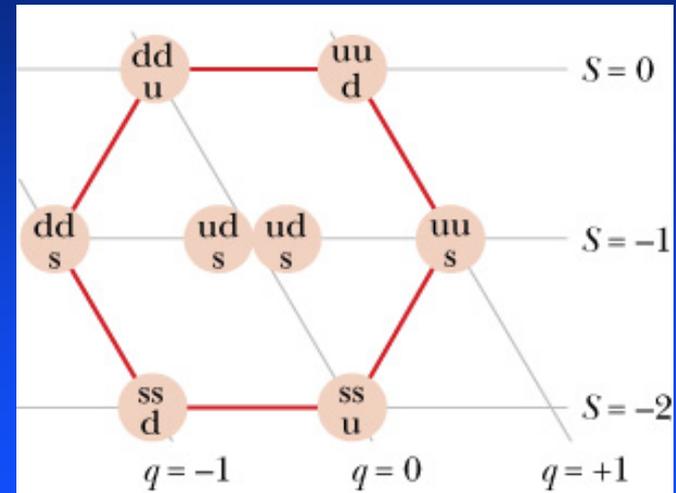
# The Eightfold Way Explained



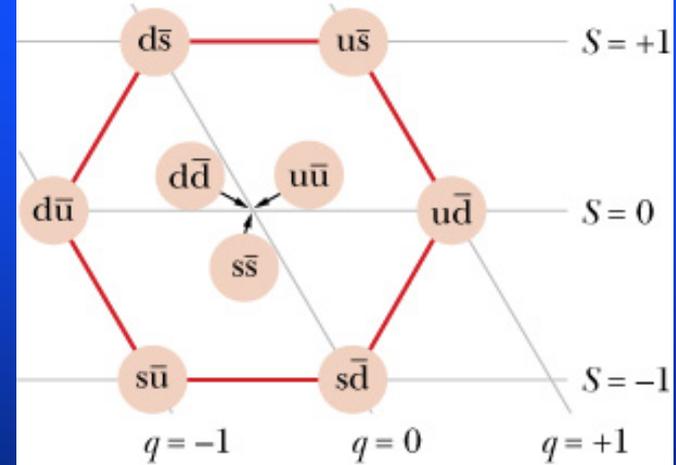
(a)



(b)



(a)



(b)

# The Standard Model

## Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

### FERMIONS

**matter constituents**  
spin = 1/2, 3/2, 5/2, ...

| Leptons spin = 1/2        |                         |                 | Quarks spin = 1/2 |                                 |                 |
|---------------------------|-------------------------|-----------------|-------------------|---------------------------------|-----------------|
| Flavor                    | Mass GeV/c <sup>2</sup> | Electric charge | Flavor            | Approx. Mass GeV/c <sup>2</sup> | Electric charge |
| $\nu_e$ electron neutrino | $<1 \times 10^{-8}$     | 0               | <b>u</b> up       | 0.003                           | 2/3             |
| $e$ electron              | 0.000511                | -1              | <b>d</b> down     | 0.006                           | -1/3            |
| $\nu_\mu$ muon neutrino   | $<0.0002$               | 0               | <b>c</b> charm    | 1.3                             | 2/3             |
| $\mu$ muon                | 0.106                   | -1              | <b>s</b> strange  | 0.1                             | -1/3            |
| $\nu_\tau$ tau neutrino   | $<0.02$                 | 0               | <b>t</b> top      | 175                             | 2/3             |
| $\tau$ tau                | 1.7771                  | -1              | <b>b</b> bottom   | 4.3                             | -1/3            |

**Spin** is the intrinsic angular momentum of particles. Spin is given in units of  $\hbar$ , which is the quantum unit of angular momentum, where  $\hbar = h/2\pi = 6.58 \times 10^{-25} \text{ GeV} \cdot \text{s} = 1.05 \times 10^{-34} \text{ J} \cdot \text{s}$ .

**Electric charges** are given in units of the proton's charge. In SI units the electric charge of the proton is  $1.60 \times 10^{-19}$  coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in  $\text{GeV}/c^2$  (remember  $E = mc^2$ ), where  $1 \text{ GeV} = 10^9 \text{ eV} = 1.60 \times 10^{-10} \text{ joule}$ . The mass of the proton is  $0.938 \text{ GeV}/c^2 = 1.67 \times 10^{-27} \text{ kg}$ .

### BOSONS

**force carriers**  
spin = 0, 1, 2, ...

| Unified Electroweak spin = 1 |                         |                 | Strong (color) spin = 1 |                         |                 |
|------------------------------|-------------------------|-----------------|-------------------------|-------------------------|-----------------|
| Name                         | Mass GeV/c <sup>2</sup> | Electric charge | Name                    | Mass GeV/c <sup>2</sup> | Electric charge |
| $\gamma$ photon              | 0                       | 0               | <b>g</b> gluon          | 0                       | 0               |
| $W^-$                        | 80.4                    | -1              |                         |                         |                 |
| $W^+$                        | 80.4                    | +1              |                         |                         |                 |
| $Z^0$                        | 91.187                  | 0               |                         |                         |                 |

#### Color Charge

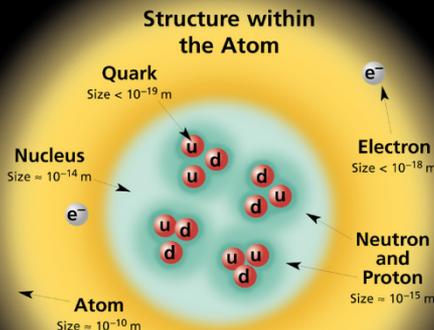
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and  $W$  and  $Z$  bosons have no strong interactions and hence no color charge.

#### Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons**  $q\bar{q}$  and **baryons**  $qqq$ .

#### Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

## PROPERTIES OF THE INTERACTIONS

| Property  | Interaction   | Gravitational                          | Weak (Electroweak)            | Electromagnetic      | Strong                                |                                      |
|---|---|--|-------------------------------|----------------------|---------------------------------------|--------------------------------------|
|   |   | Mass - Energy                          | Flavor                        | Electric Charge      | Fundamental                           | Residual                             |
| <b>Acts on:</b>   |   | All                                    | Quarks, Leptons               | Electrically charged | Color Charge                          | See Residual Strong Interaction Note |
| <b>Particles experiencing:</b>                              |   | All                                    | Quarks, Leptons               | Electrically charged | Quarks, Gluons                        | Hadrons                              |
| <b>Particles mediating:</b>                                 |   | Graviton (not yet observed)            | $W^+$ $W^-$ $Z^0$             | $\gamma$             | Gluons                                | Mesons                               |
| <b>Strength</b> relative to electromag for two u quarks at: | $10^{-18} \text{ m}$<br>$3 \times 10^{-17} \text{ m}$ | $10^{-41}$<br>$10^{-41}$<br>$10^{-36}$ | 0.8<br>$10^{-4}$<br>$10^{-7}$ | 1<br>1<br>1          | 25<br>60<br>Not applicable to hadrons | Not applicable to quarks<br>20       |

| Baryons $qqq$ and Antibaryons $\bar{q}\bar{q}\bar{q}$                |             |                         |                 |                         |      |
|--|-------------|-------------------------|-----------------|-------------------------|------|
| Baryons are fermionic hadrons. There are about 120 types of baryons. |             |                         |                 |                         |      |
| Symbol   | Name        | Quark content           | Electric charge | Mass GeV/c <sup>2</sup> | Spin |
| <b>p</b>   | proton      | <b>uud</b>              | 1               | 0.938                   | 1/2  |
| $\bar{p}$  | anti-proton | $\bar{u}\bar{u}\bar{d}$ | -1              | 0.938                   | 1/2  |
| <b>n</b>   | neutron     | <b>udd</b>              | 0               | 0.940                   | 1/2  |
| $\Lambda$  | lambda      | <b>uds</b>              | 0               | 1.116                   | 1/2  |
| $\Omega^-$   | omega       | <b>sss</b>              | -1              | 1.672                   | 3/2  |

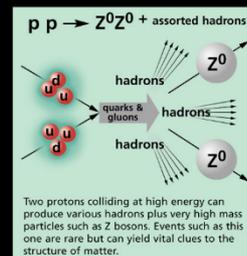
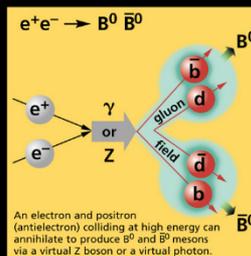
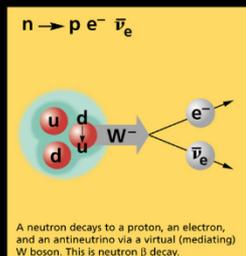
| Mesons $q\bar{q}$  |        |                              |                 |                         |      |
|--|--------|------------------------------|-----------------|-------------------------|------|
| Mesons are bosonic hadrons. There are about 140 types of mesons. |        |                              |                 |                         |      |
| Symbol   | Name   | Quark content                | Electric charge | Mass GeV/c <sup>2</sup> | Spin |
| $\pi^+$  | pion   | <b>u<math>\bar{d}</math></b> | +1              | 0.140                   | 0    |
| $K^-$  | kaon   | <b>s<math>\bar{u}</math></b> | -1              | 0.494                   | 0    |
| $\rho^+$   | rho    | <b>u<math>\bar{d}</math></b> | +1              | 0.770                   | 1    |
| $B^0$  | B-zero | <b>d<math>\bar{b}</math></b> | 0               | 5.279                   | 0    |
| $\eta_c$   | eta-c  | <b>c<math>\bar{c}</math></b> | 0               | 2.980                   | 0    |

#### Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or - charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g.,  $Z^0$ ,  $\gamma$ , and  $\eta_c = c\bar{c}$ , but not  $K^0 = d\bar{s}$ ) are their own antiparticles.

#### Figures

These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



#### The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at <http://ParticleAdventure.org>

This chart has been made possible by the generous support of:

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U.S. National Science Foundation  
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**BURLE** INDUSTRIES, INC.

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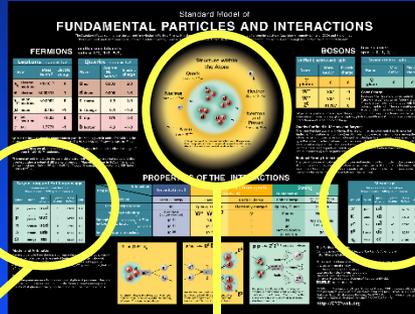
<http://CPEPweb.org>

# Quark Structure of Matter

## Baryons $qqq$ and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.  
There are about 120 types of baryons.

| Symbol     | Name        | Quark content           | Electric charge | Mass $\text{GeV}/c^2$ | Spin |
|------------|-------------|-------------------------|-----------------|-----------------------|------|
| $p$        | proton      | $uud$                   | 1               | 0.938                 | 1/2  |
| $\bar{p}$  | anti-proton | $\bar{u}\bar{u}\bar{d}$ | -1              | 0.938                 | 1/2  |
| $n$        | neutron     | $udd$                   | 0               | 0.940                 | 1/2  |
| $\Lambda$  | lambda      | $uds$                   | 0               | 1.116                 | 1/2  |
| $\Omega^-$ | omega       | $sss$                   | -1              | 1.672                 | 3/2  |

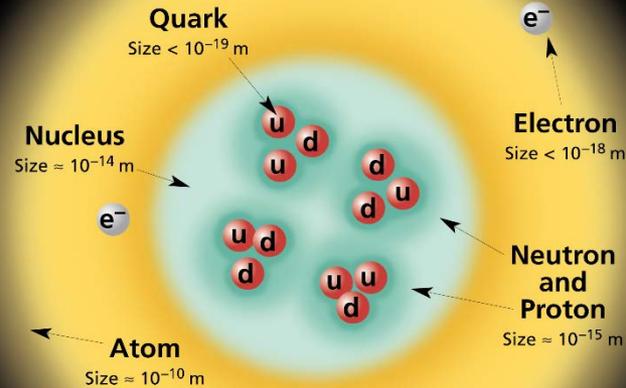


## Mesons $q\bar{q}$

Mesons are bosonic hadrons.  
There are about 140 types of mesons.

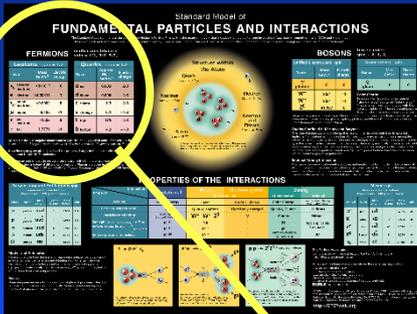
| Symbol   | Name   | Quark content | Electric charge | Mass $\text{GeV}/c^2$ | Spin |
|----------|--------|---------------|-----------------|-----------------------|------|
| $\pi^+$  | pion   | $u\bar{d}$    | +1              | 0.140                 | 0    |
| $K^-$    | kaon   | $s\bar{u}$    | -1              | 0.494                 | 0    |
| $\rho^+$ | rho    | $u\bar{d}$    | +1              | 0.770                 | 1    |
| $B^0$    | B-zero | $d\bar{b}$    | 0               | 5.279                 | 0    |
| $\eta_c$ | eta-c  | $c\bar{c}$    | 0               | 2.980                 | 0    |

## Structure within the Atom



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

# More than just quarks



## FERMIONS

matter constituents  
spin = 1/2, 3/2, 5/2, ...

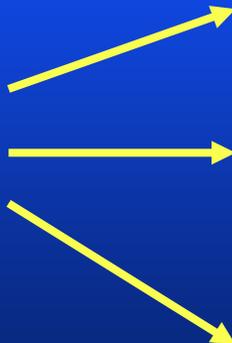
### Leptons spin = 1/2

| Flavor                    | Mass GeV/c <sup>2</sup> | Electric charge |
|---------------------------|-------------------------|-----------------|
| $\nu_e$ electron neutrino | $<1 \times 10^{-8}$     | 0               |
| $e$ electron              | 0.000511                | -1              |
| $\nu_\mu$ muon neutrino   | $<0.0002$               | 0               |
| $\mu$ muon                | 0.106                   | -1              |
| $\nu_\tau$ tau neutrino   | $<0.02$                 | 0               |
| $\tau$ tau                | 1.7771                  | -1              |

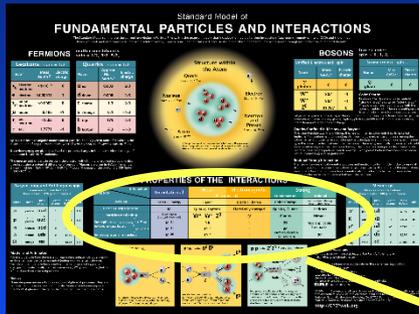
### Quarks spin = 1/2

| Flavor      | Approx. Mass GeV/c <sup>2</sup> | Electric charge |
|-------------|---------------------------------|-----------------|
| $u$ up      | 0.003                           | 2/3             |
| $d$ down    | 0.006                           | -1/3            |
| $c$ charm   | 1.3                             | 2/3             |
| $s$ strange | 0.1                             | -1/3            |
| $t$ top     | 175                             | 2/3             |
| $b$ bottom  | 4.3                             | -1/3            |

3 Families



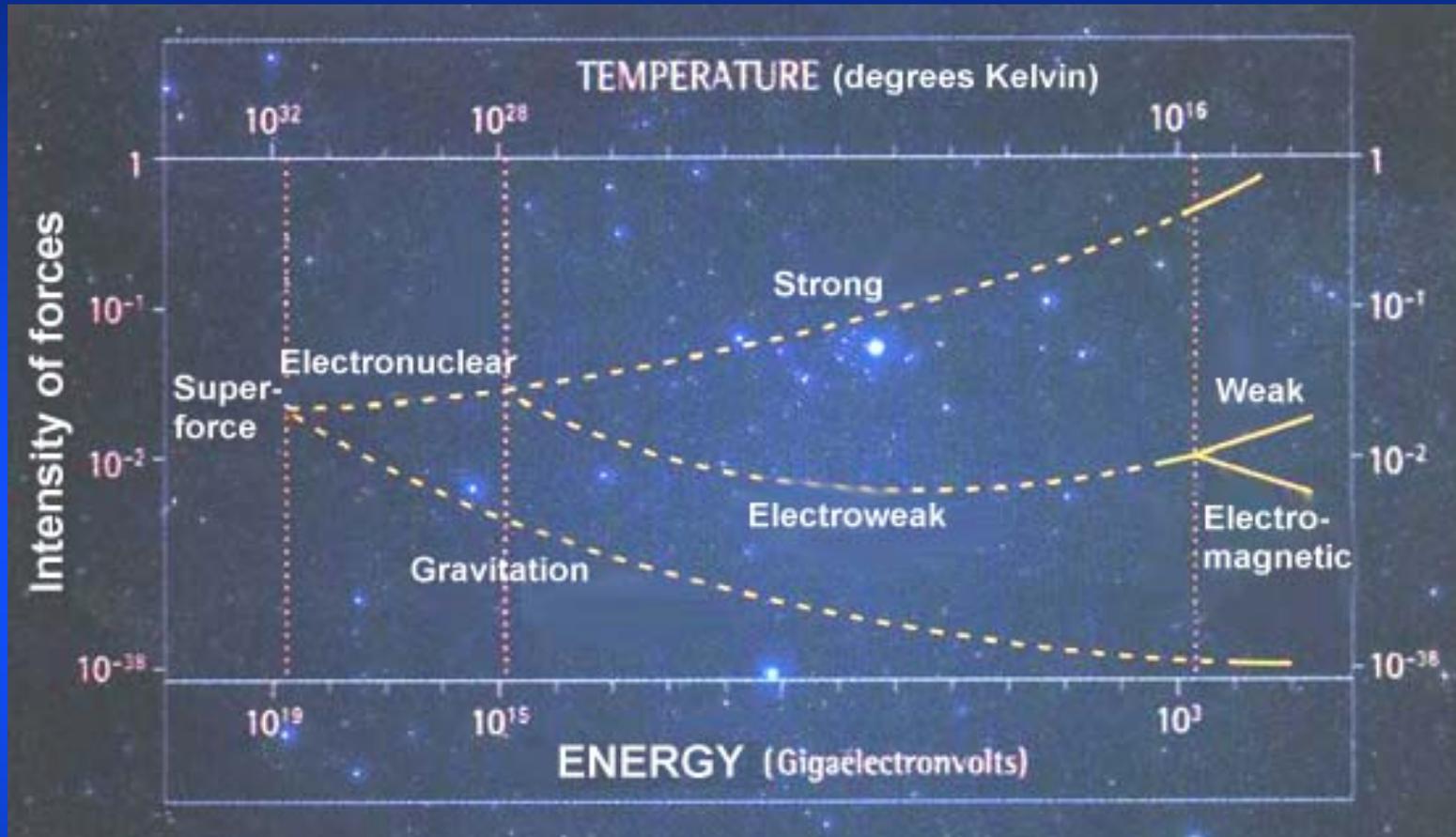
# More than just quarks and leptons: Force Particles



## PROPERTIES OF THE INTERACTIONS

| Property \ Interaction  | Gravitational                     | Weak<br>(Electroweak) |           | Electromagnetic      | Strong         |                                      |        |
|---|-----------------------------------|-----------------------|-----------|----------------------|----------------|--------------------------------------|--------|
|   |                                   |                       |           |                      | Fundamental    | Residual                             |        |
| <b>Acts on:</b>   | Mass – Energy                     | Flavor                |           | Electric Charge      | Color Charge   | See Residual Strong Interaction Note |        |
| <b>Particles experiencing:</b>  | All                               | Quarks, Leptons       |           | Electrically charged | Quarks, Gluons | Hadrons                              |        |
| <b>Particles mediating:</b>   | Graviton<br>(not yet observed)    | $W^+$                 | $W^-$     | $Z^0$                | $\gamma$       | Gluons                               | Mesons |
| <b>Strength</b> relative to electromag<br>for <b>two u quarks</b> at: | $10^{-41}$                        | 0.8                   |           | 1                    | 25             | Not applicable<br>to quarks          |        |
|   | $10^{-41}$                        | $10^{-4}$             |           | 1                    | 60             |                                      |        |
|   | for <b>two protons</b> in nucleus | $10^{-36}$            | $10^{-7}$ |                      | 1              | Not applicable<br>to hadrons         | 20     |

# One Force ??

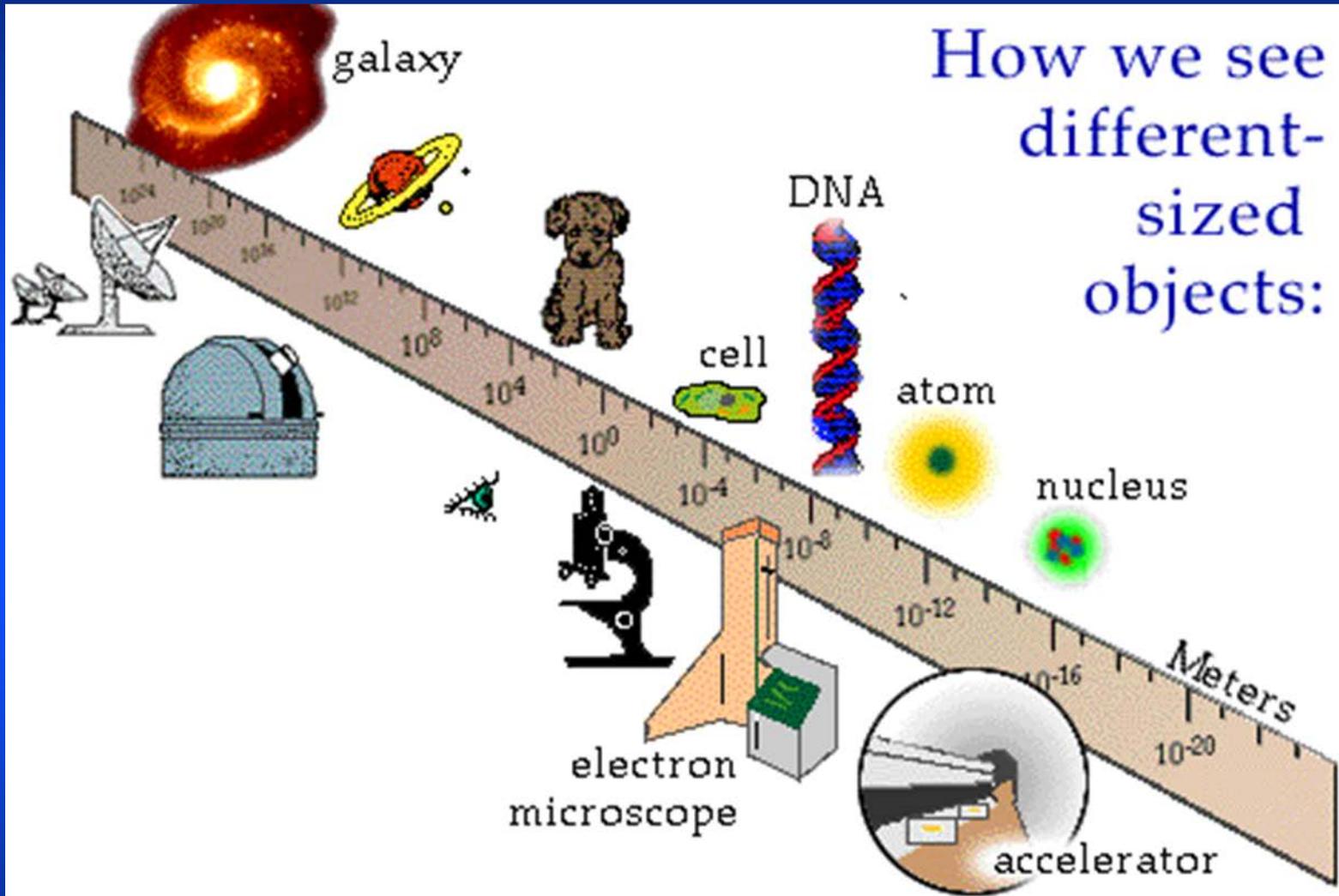


Distance:  $10^{-35}$  m

$10^{-19}$  m

At very small distances (equivalent to very high temperatures) it seems as if all the known forces might be unified into ONE FORCE.

# How can we study quarks?



To study small objects, like quarks, we need large accelerators.

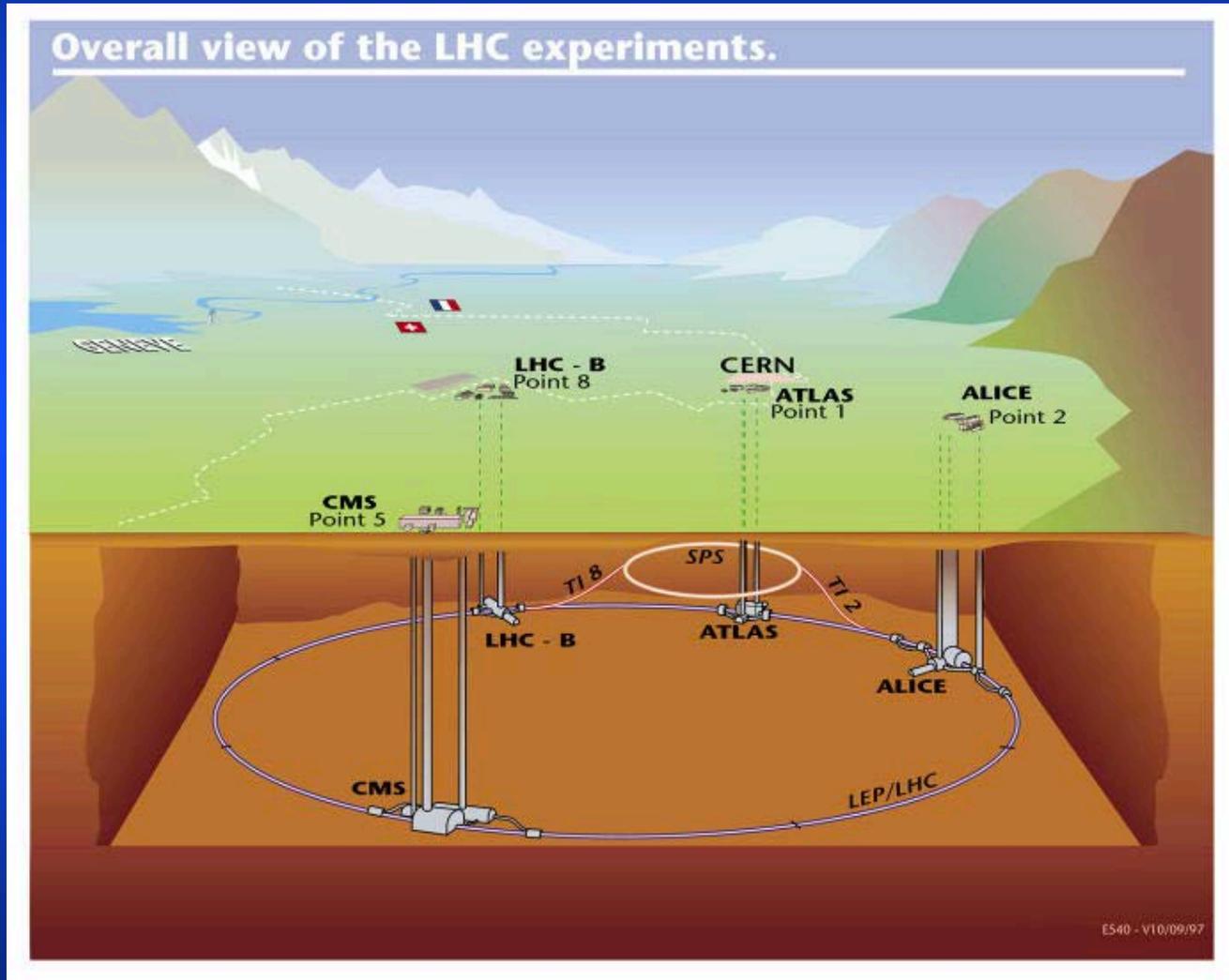
# *How can we study quarks?*

## *Large Hadron Collider in Switzerland/France*



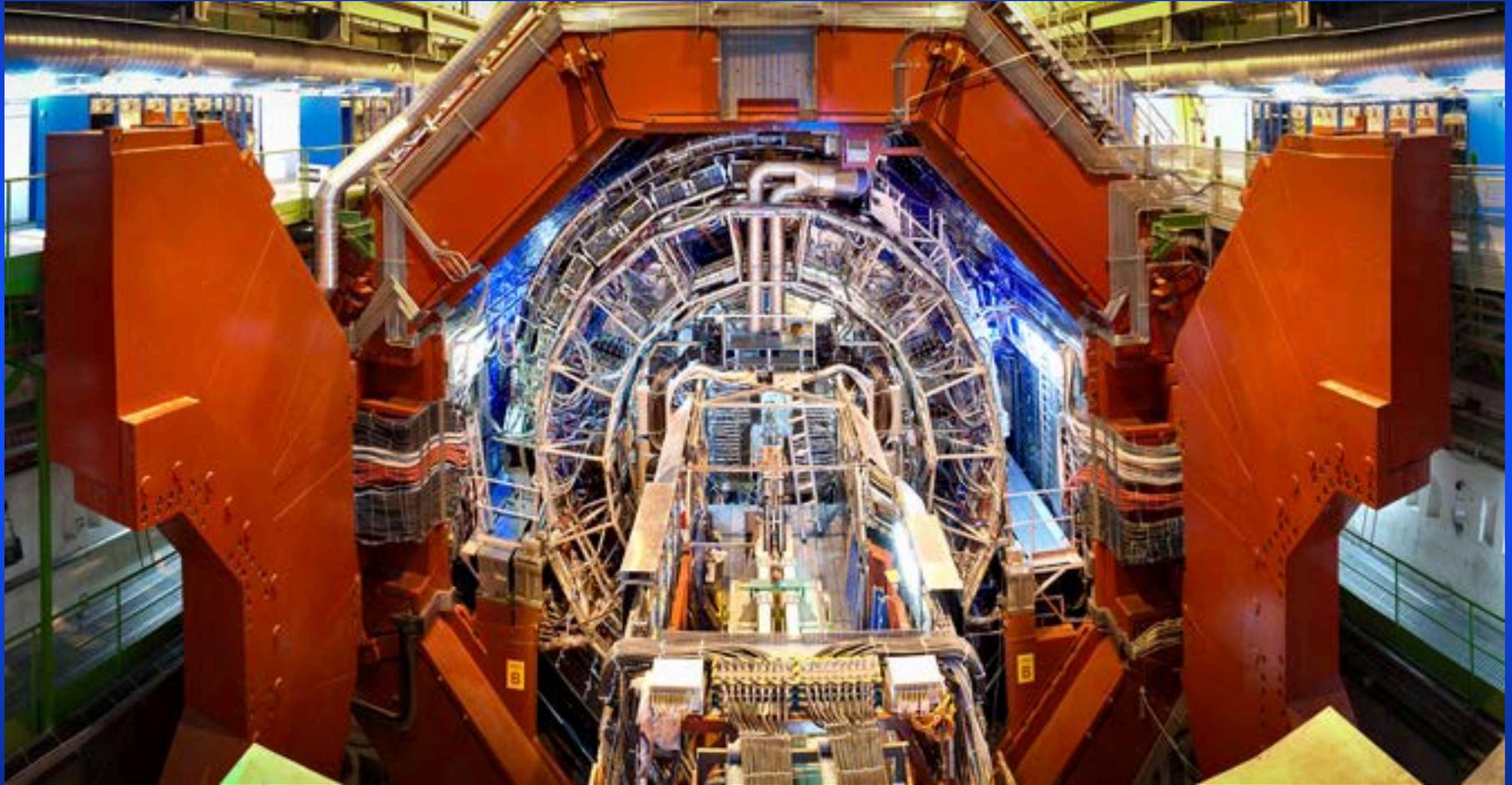
# How can we study quarks?

## Large Hadron Collider in Switzerland/France



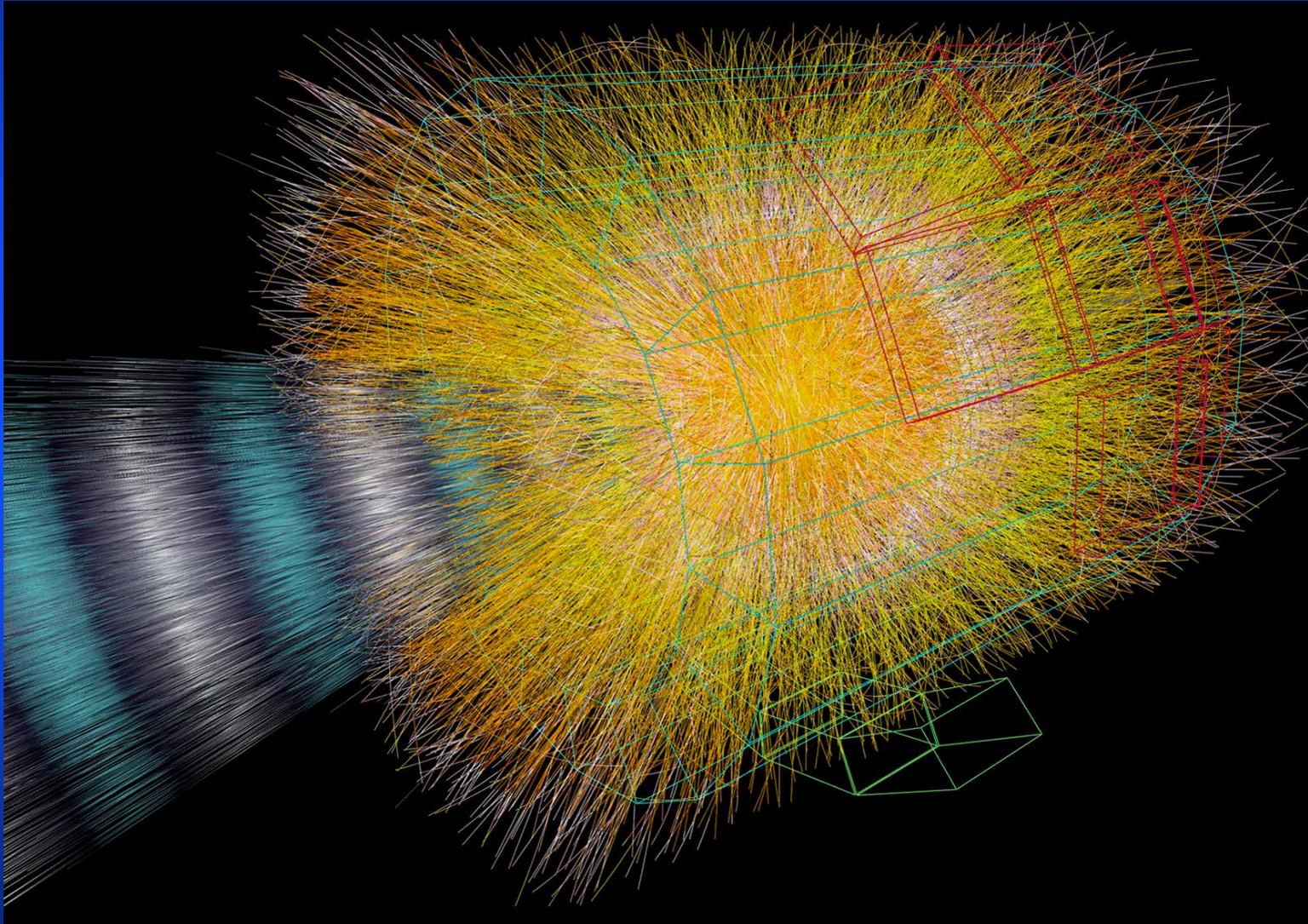
*How can we study quarks?*

*The ALICE Detector*



*How can we study quarks?*

*Result of collision of two heavy atomic nuclei*



# *It starts to be "messy"*

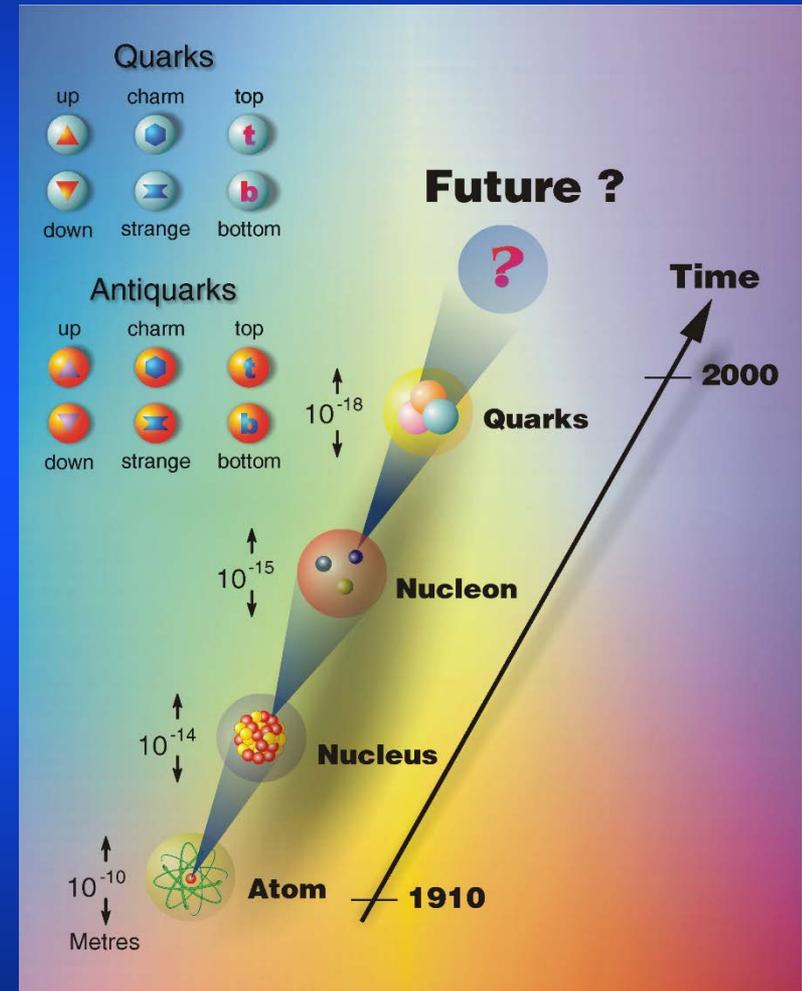
"Fundamental" Particles as of today:

6 quarks  
6 anti-quarks  
6 leptons  
6 anti-leptons  
graviton  
photon  
3 weak-force carriers ( $W^+$ ,  $W^-$ ,  $Z$ )  
8 gluons

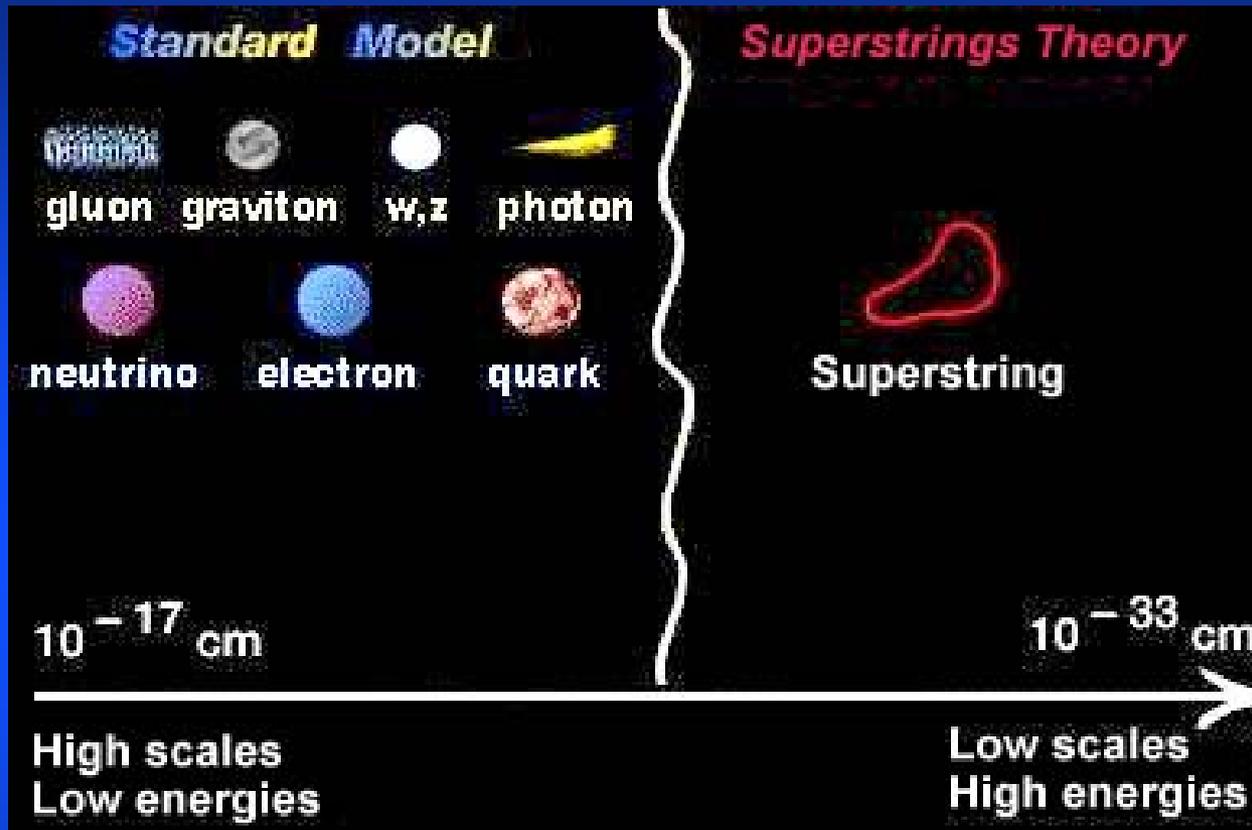
= 37 "fundamental" particles

Problem:

Can we explain all these "fundamental" particles in terms of something even simpler ???



## Maybe: Superstrings

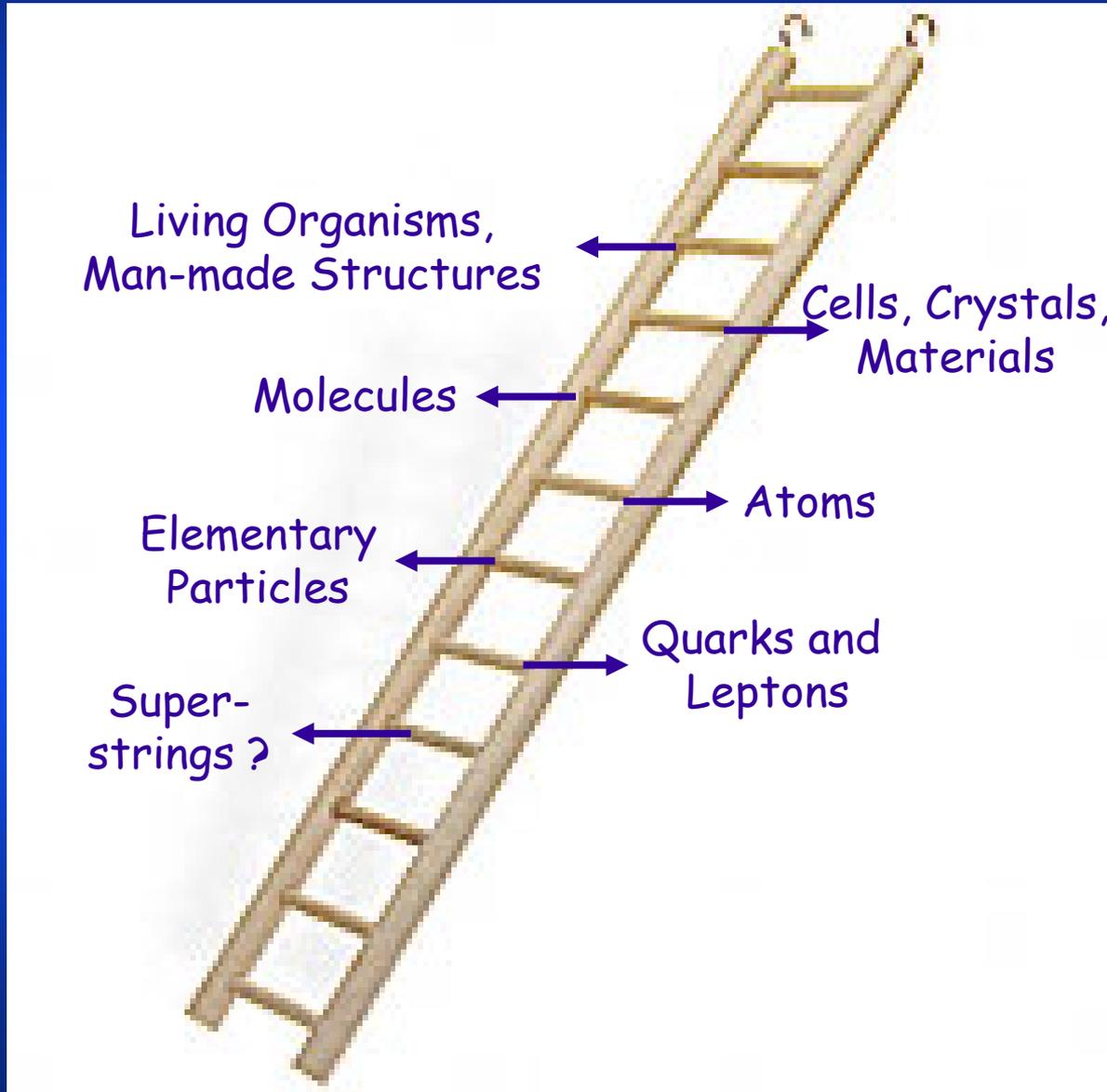


Hypothesis:

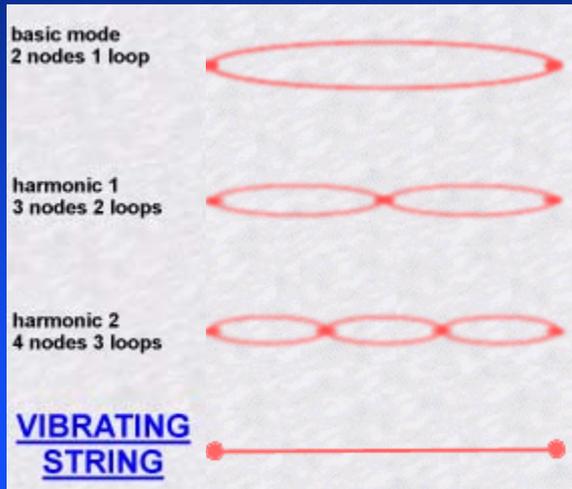
All fundamental particles are different vibrational modes (excitations) of a fundamental entity:

## The Superstring

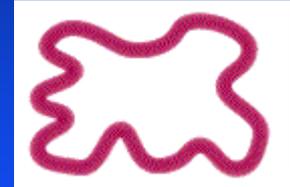
# The Quantum Ladder



# Vibrating and Colliding Superstrings

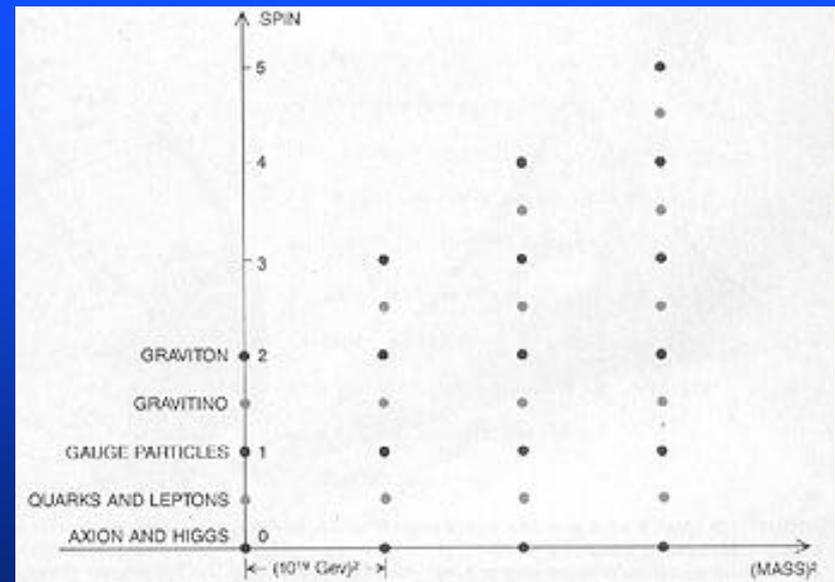


Two types of strings:  
Open strings and Closed Strings

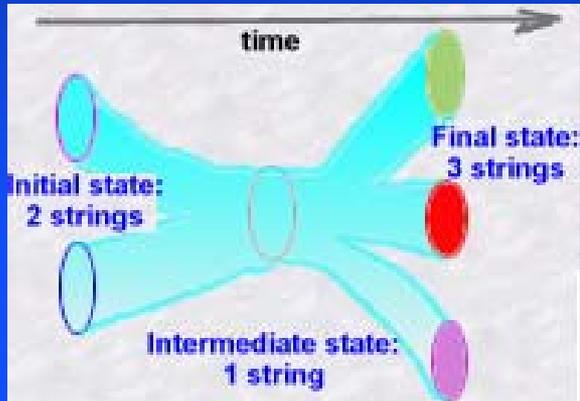


Different modes of vibration (excitation) will correspond to different types of fundamental particles.

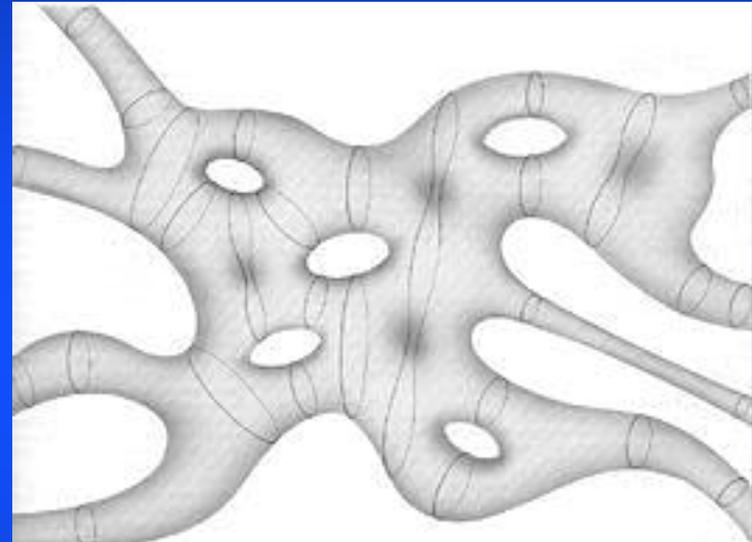
However, at the moment we don't really understand the connection between the vibrations of the string and the fundamental particles



# ALL Interactions



All interactions are just  
merging of strings  
or  
splitting up of a string



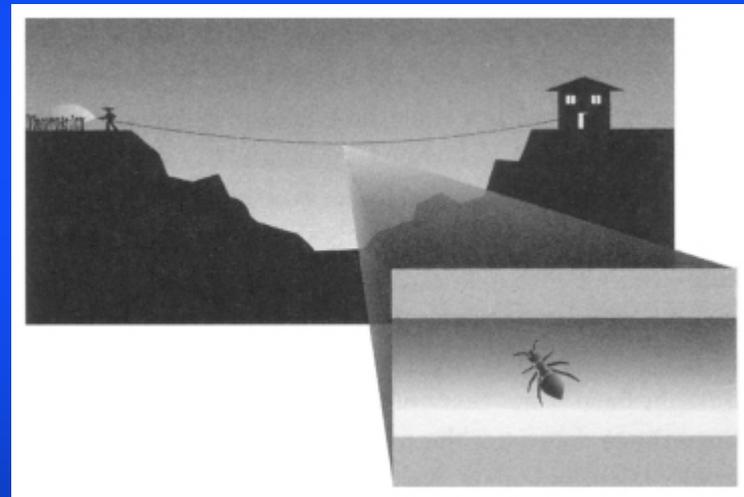
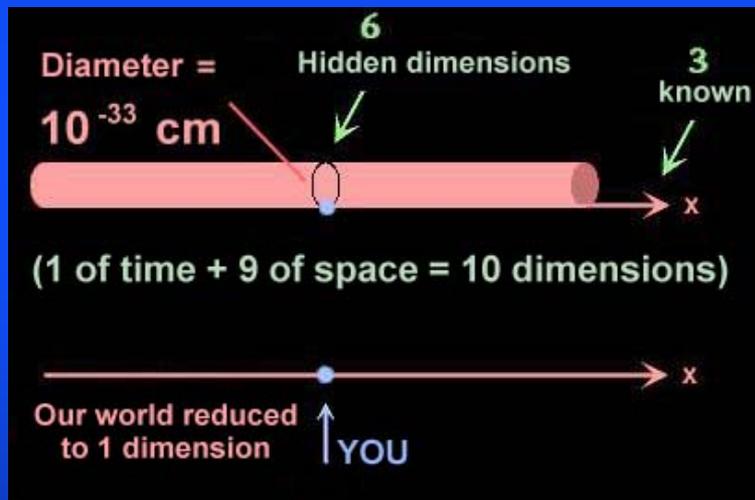
What the world might look like  
at the smallest possible scales

## *Rolled-up dimensions*

The Superstring model is extremely complicated mathematically

We think we live in a 3-dimensional space (+ 1 time dimension)

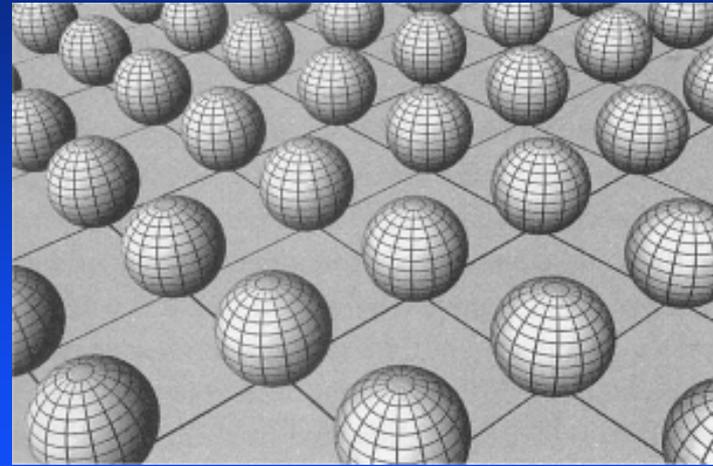
But the Superstring model requires that we live in a 9-dimensional space, but with 6 dimensions "rolled up" (+ 1 time dimension)



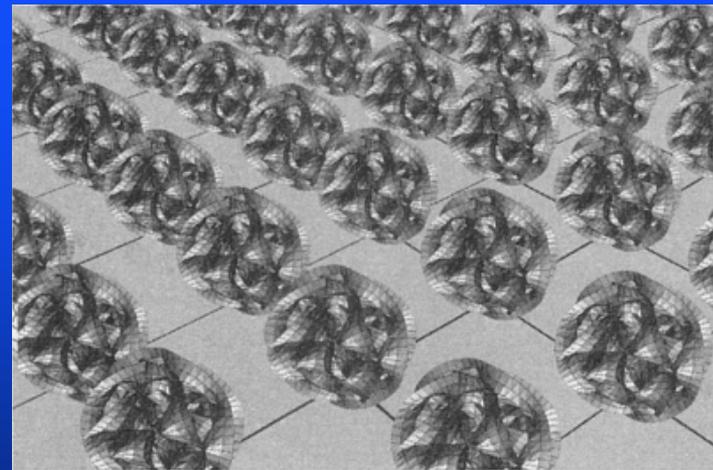
A 1-dimensional string (a rope) is really 2-dimensional when viewed at high resolution (small distances)

## *Superstrings in many dimensions*

Every point in our normal 3-dimensional space is really a 6-dimensional space (Calabi-Yau Space)



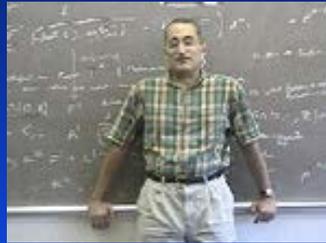
2-dim space with 2 curled-up dimensions (a sphere) in each point



2-dim space with 6 curled-up dimensions (Calabi-Yau Space) in each point

# Superstrings: Pro and Con

Pro:



Edward Witten  
Princeton



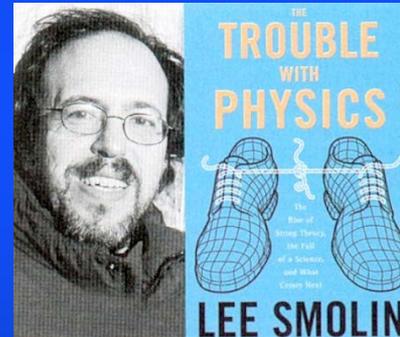
Brian Greene  
Columbia

The concept of the superstring is physically and mathematically appealing  
The superstring model can explain many theoretical problems in modern physics

Con:



Phil Anderson  
Princeton



Lee Smolin  
Perimeter Institute

The superstring model is just a theoretical construction that can not be experimentally verified. It could be "The Ether Theory" of the 21<sup>st</sup> century.

The superstring model is just one of several exciting possibilities for new physics. Quantum Gravity.

Very controversial model. The physicists are having heated debates as to whether this model makes sense.

# Summary



*Will there be an end?*