

# What If the Particle World Were Different?

Andrei Gritsan

Johns Hopkins University



August, 2008

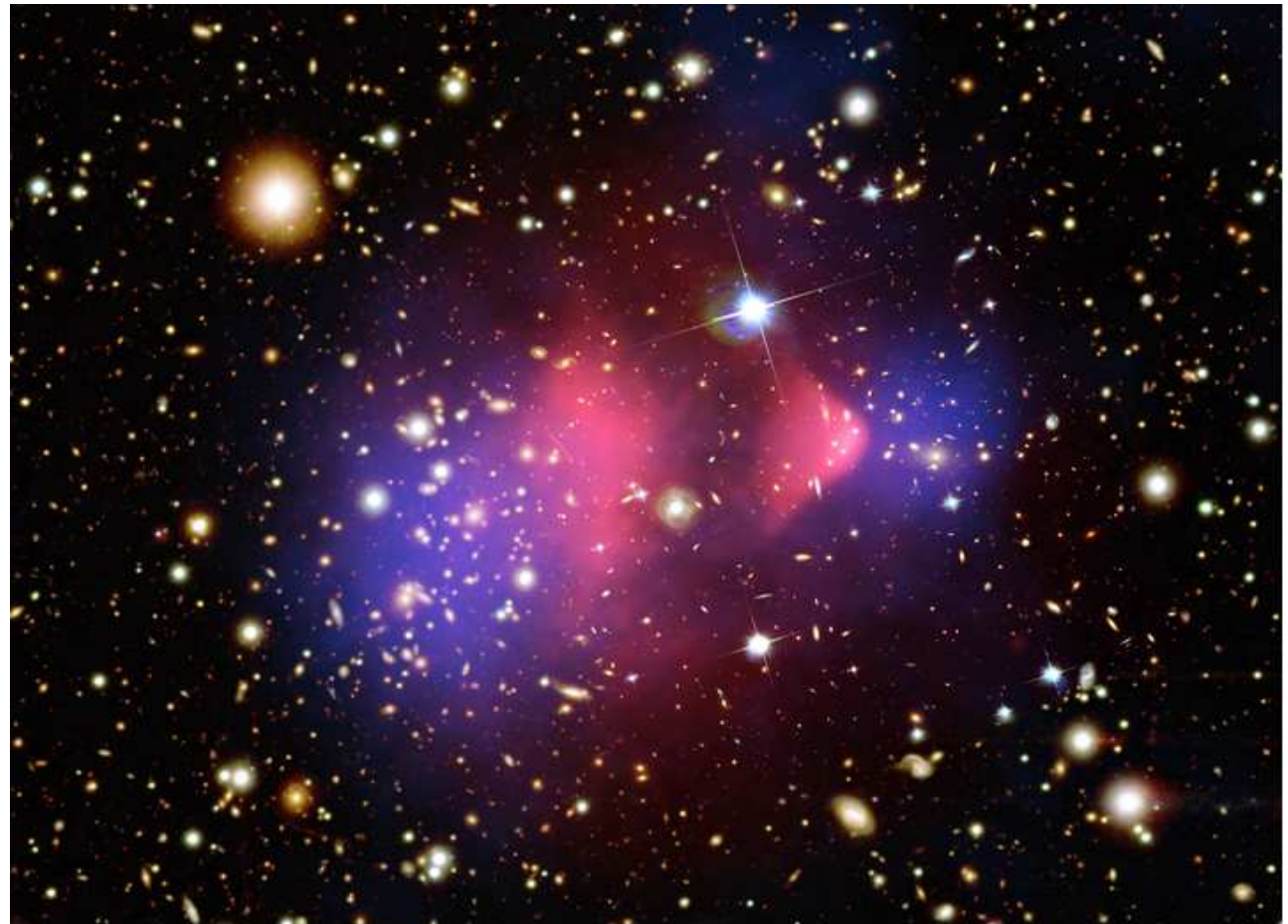
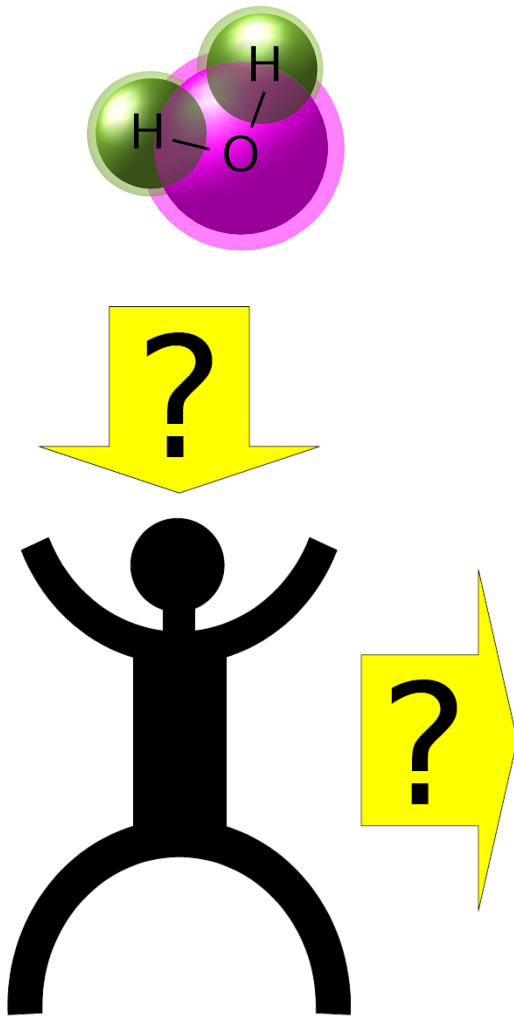
JHU Quarknet Meeting

# The Particle World: the Smallest to the Largest

---

- On the **smallest** and **largest** scale:

**what** are we made of and **why**

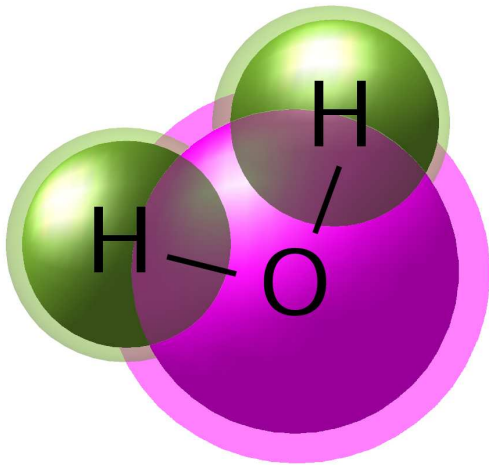


(Galaxy cluster 1E 0657-66: X-ray, Optical, Grav. Lensing)

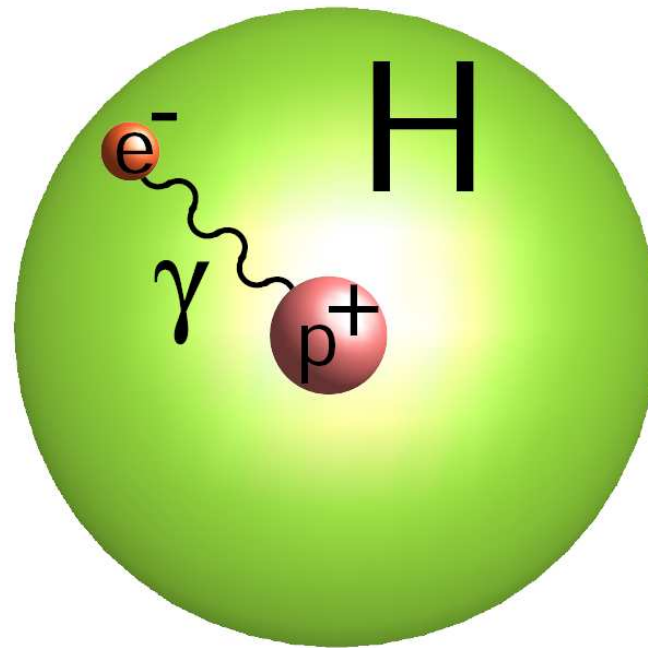
# From Molecules to Quarks

---

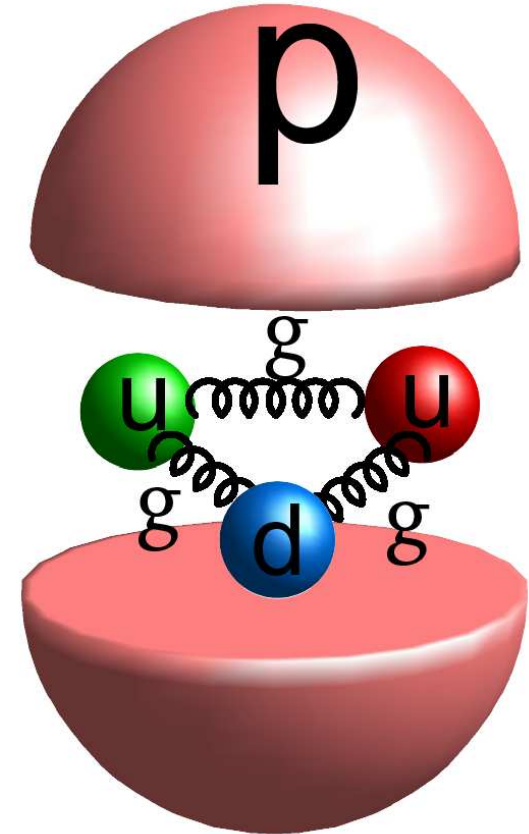
- XXth century: reaching deep into matter, **Quarks**



Chemistry



Atomic Physics

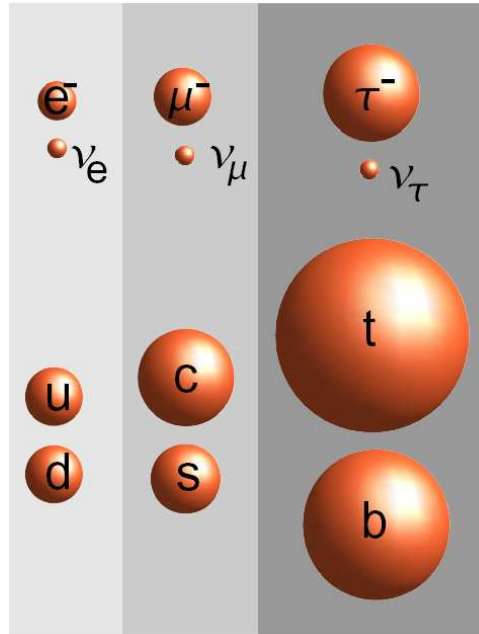


Particle Physics

# Elementary Particles

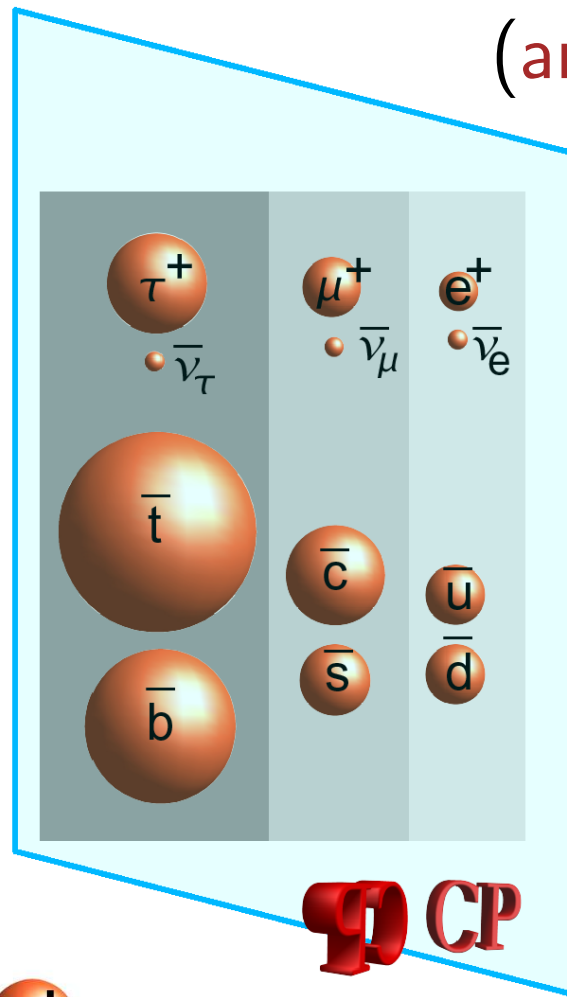
- Fermions  $S = \frac{\hbar}{2}$  (matter)

leptons

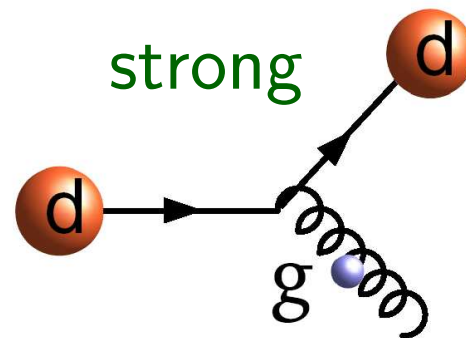
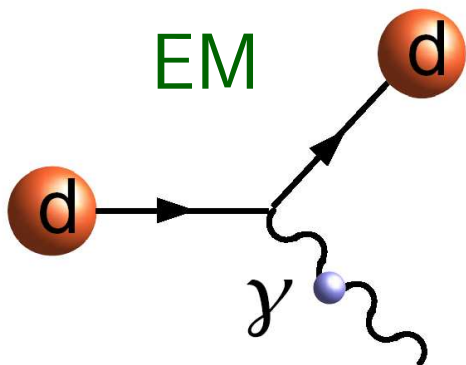


quarks

(anti-matter)



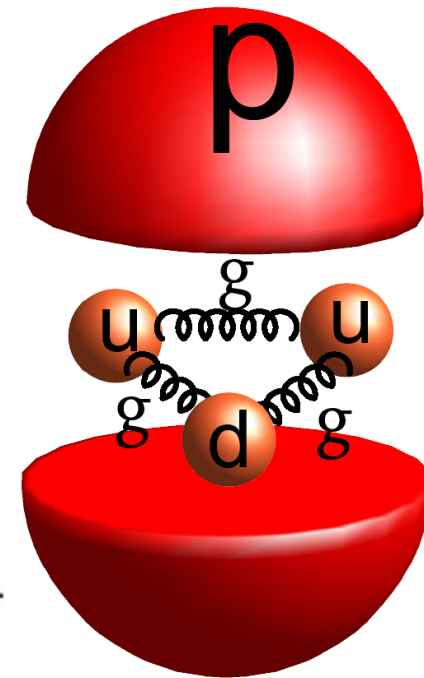
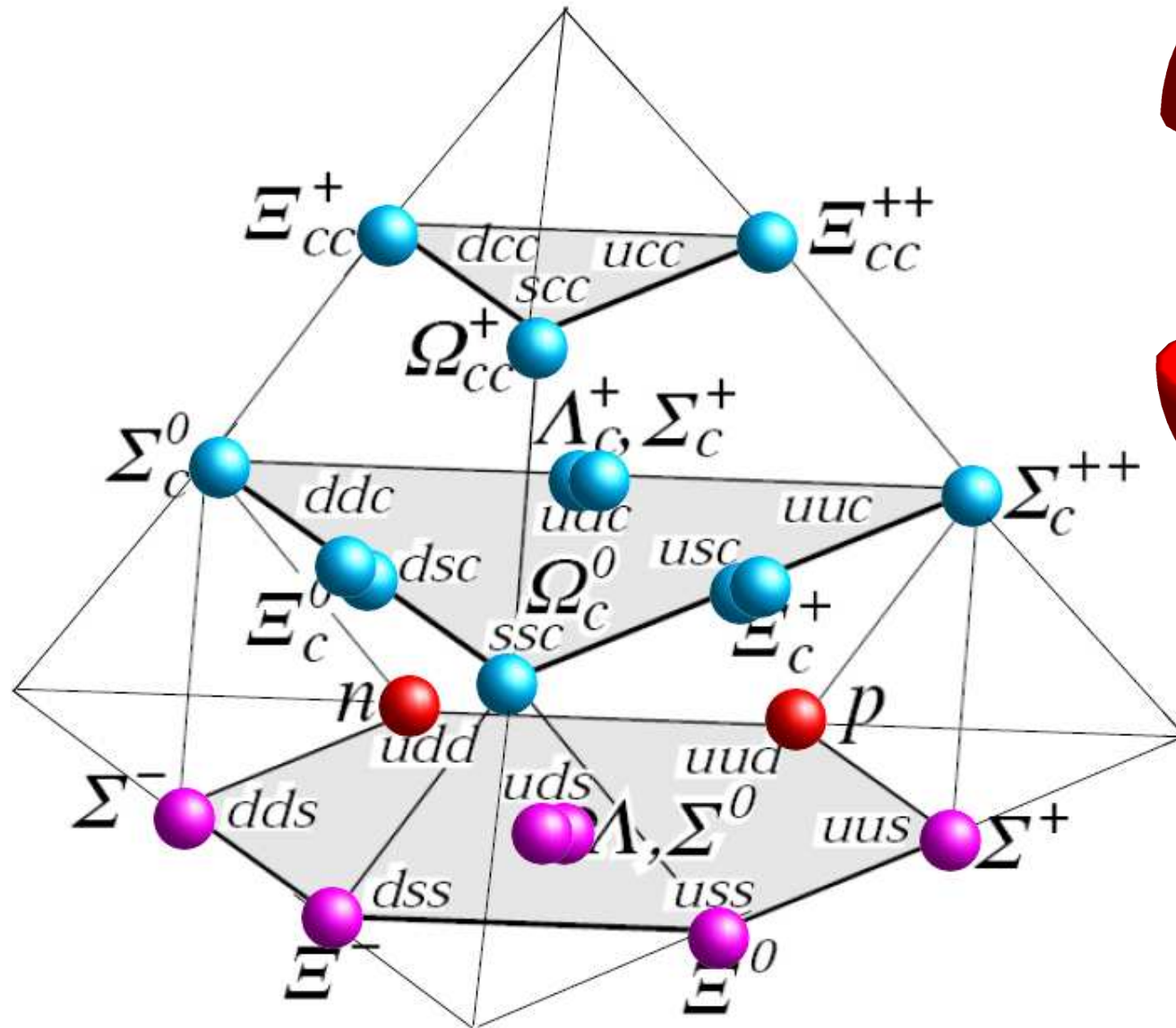
- Bosons  $S = \hbar$  (force carries):



(weak force later)

# “Periodic Table” of Baryons: Proton, Neutron,...

- Three quarks make up a **Baryon**:





# Like Periodic Table of Atoms

**PERIODIC TABLE**  
**Atomic Properties of the Elements**

**NIST**  
National Institute of Standards and Technology  
Technology Administration, U.S. Department of Commerce

18  
VIII

Physcis Laboratory  
[physics.nist.gov](http://physics.nist.gov)

Standard Reference Data Group  
[www.nist.gov/srd](http://www.nist.gov/srd)

Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
IA	IIA-VIII												IIIA	IVA	VA	VIA	VIIA	VIIIA	
1	<b>H</b> Hydrogen 1.00794 1s																		<b>He</b> Helium 4.002602 1s <sup>2</sup>
2		<b>Li</b> Lithium 6.941 1s <sup>2</sup> 2s <sup>1</sup>	<b>Be</b> Beryllium 9.012182 1s <sup>2</sup> 2s <sup>2</sup>										<b>B</b> Boron 10.811 1s <sup>2</sup> 2s <sup>2</sup> 2p <sup>1</sup>	<b>C</b> Carbon 12.0107 1s <sup>2</sup> 2s <sup>2</sup> 2p <sup>2</sup>	<b>N</b> Nitrogen 14.0067 1s <sup>2</sup> 2s <sup>2</sup> 2p <sup>3</sup>	<b>O</b> Oxygen 15.9994 1s <sup>2</sup> 2s <sup>2</sup> 2p <sup>4</sup>	<b>F</b> Fluorine 18.9984032 1s <sup>2</sup> 2s <sup>2</sup> 2p <sup>5</sup>	<b>Ne</b> Neon 20.1797 1s <sup>2</sup> 2s <sup>2</sup> 2p <sup>6</sup>	
3		<b>Na</b> Sodium 22.989770 [Ne]3s <sup>1</sup>	<b>Mg</b> Magnesium 24.3050 [Ne]3s <sup>2</sup>										<b>Al</b> Aluminum 26.981538 [Ne]3s <sup>2</sup> 3p <sup>1</sup>	<b>Si</b> Silicon 28.0855 [Ne]3s <sup>2</sup> 3p <sup>2</sup>	<b>P</b> Phosphorus 30.973761 [Ne]3s <sup>2</sup> 3p <sup>3</sup>	<b>S</b> Sulfur 32.065 [Ne]3s <sup>2</sup> 3p <sup>4</sup>	<b>Cl</b> Chlorine 35.453 [Ne]3s <sup>2</sup> 3p <sup>5</sup>	<b>Ar</b> Argon 39.948 [Ne]3s <sup>2</sup> 3p <sup>6</sup>	
4	<b>K</b> Potassium 39.0983 [Ar]4s <sup>1</sup>	<b>Ca</b> Calcium 40.078 [Ar]4s <sup>2</sup>	<b>Sc</b> Scandium 44.955910 [Ar]3d <sup>1</sup> 4s <sup>2</sup>	<b>Ti</b> Titanium 47.887 [Ar]3d <sup>2</sup> 4s <sup>2</sup>	<b>V</b> Vanadium 50.9415 [Ar]3d <sup>3</sup> 4s <sup>2</sup>	<b>Cr</b> Chromium 51.9961 [Ar]3d <sup>5</sup> 4s <sup>1</sup>	<b>Mn</b> Manganese 54.938049 [Ar]3d <sup>5</sup> 4s <sup>2</sup>	<b>Fe</b> Iron 55.845 [Ar]3d <sup>6</sup> 4s <sup>2</sup>	<b>Co</b> Cobalt 58.933200 [Ar]3d <sup>7</sup> 4s <sup>2</sup>	<b>Ni</b> Nickel 58.6934 [Ar]3d <sup>8</sup> 4s <sup>2</sup>	<b>Cu</b> Copper 63.546 [Ar]3d <sup>10</sup> 4s <sup>1</sup>	<b>Zn</b> Zinc 65.409 [Ar]3d <sup>10</sup> 4s <sup>2</sup>	<b>Ga</b> Gallium 69.723 [Ar]3d <sup>10</sup> 4s <sup>1</sup> 4p <sup>1</sup>	<b>Ge</b> Germanium 72.64 [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p <sup>2</sup>	<b>As</b> Arsenic 74.92160 [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p <sup>3</sup>	<b>Se</b> Selenium 78.96 [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p <sup>4</sup>	<b>Br</b> Bromine 79.904 [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p <sup>5</sup>	<b>Kr</b> Krypton 83.798 [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p <sup>6</sup>	
5	<b>Rb</b> Rubidium 85.4678 [Kr]5s <sup>1</sup>	<b>Sr</b> Strontium 87.62 [Kr]5s <sup>2</sup>	<b>Y</b> Yttrium 88.90585 [Kr]4d <sup>1</sup> 5s <sup>2</sup>	<b>Zr</b> Zirconium 91.224 [Kr]4d <sup>2</sup> 5s <sup>2</sup>	<b>Nb</b> Niobium 92.90638 [Kr]4d <sup>4</sup> 5s <sup>1</sup>	<b>Mo</b> Molybdenum 95.94 [Kr]4d <sup>5</sup> 5s <sup>1</sup>	<b>Tc</b> Technetium (98) [Kr]4d <sup>5</sup> 5s <sup>2</sup>	<b>Ru</b> Ruthenium 101.07 [Kr]4d <sup>7</sup> 5s <sup>1</sup>	<b>Rh</b> Rhodium 102.90550 [Kr]4d <sup>8</sup> 5s <sup>1</sup>	<b>Pd</b> Palladium 106.42 [Kr]4d <sup>10</sup>	<b>Ag</b> Silver 107.8682 [Kr]4d <sup>10</sup> 5s <sup>1</sup>	<b>Cd</b> Cadmium 112.411 [Kr]4d <sup>10</sup> 5s <sup>2</sup>	<b>In</b> Indium 114.818 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>1</sup>	<b>Sn</b> Tin 118.710 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>2</sup>	<b>Sb</b> Antimony 121.760 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>3</sup>	<b>Te</b> Tellurium 127.60 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>4</sup>	<b>I</b> Iodine 126.90447 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>5</sup>	<b>Xe</b> Xenon 131.293 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>6</sup>	
6	<b>Cs</b> Cesium 132.90545 [Xe]6s <sup>1</sup>	<b>Ba</b> Barium 137.327 [Xe]6s <sup>2</sup>		<b>Hf</b> Hafnium 178.49 [Xe]4f <sup>14</sup> 5d <sup>2</sup> 6s <sup>2</sup>	<b>Ta</b> Tantalum 180.9479 [Xe]4f <sup>14</sup> 5d <sup>3</sup> 6s <sup>2</sup>	<b>W</b> Tungsten 183.84 [Xe]4f <sup>14</sup> 5d <sup>4</sup> 6s <sup>2</sup>	<b>Re</b> Rhenium 186.207 [Xe]4f <sup>14</sup> 5d <sup>5</sup> 6s <sup>2</sup>	<b>Os</b> Osmium 190.23 [Xe]4f <sup>14</sup> 5d <sup>6</sup> 6s <sup>2</sup>	<b>Ir</b> Iridium 192.217 [Xe]4f <sup>14</sup> 5d <sup>7</sup> 6s <sup>2</sup>	<b>Pt</b> Platinum 195.078 [Xe]4f <sup>14</sup> 5d <sup>9</sup> 6s <sup>1</sup>	<b>Au</b> Gold 196.96655 [Xe]4f <sup>14</sup> 5d <sup>10</sup> 6s <sup>1</sup>	<b>Hg</b> Mercury 200.59 [Xe]4f <sup>14</sup> 5d <sup>10</sup> 6s <sup>2</sup>	<b>Tl</b> Thallium 204.3833 [Hg]6p <sup>1</sup>	<b>Pb</b> Lead 207.2 [Hg]6p <sup>2</sup>	<b>Bi</b> Bismuth 208.98038 [Hg]6p <sup>3</sup>	<b>Po</b> Polonium (209) [Hg]6p <sup>4</sup>	<b>At</b> Astatine (210) [Hg]6p <sup>5</sup>	<b>Rn</b> Radon (222) [Hg]6s <sup>2</sup> 6p <sup>6</sup>	
7	<b>Fr</b> Francium (223) [Rn]7s <sup>1</sup>	<b>Ra</b> Radium (226) [Rn]7s <sup>2</sup>		<b>Rf</b> Rutherfordium (261) [Rn]5f <sup>14</sup> 6d <sup>2</sup> 7s <sup>2</sup>	<b>Db</b> Dubnium (262) [Rn]5f <sup>14</sup> 6d <sup>3</sup> 7s <sup>2</sup>	<b>Sg</b> Seaborgium (266) [Rn]5f <sup>14</sup> 6d <sup>4</sup> 7s <sup>2</sup>	<b>Bh</b> Bohrium (264) [Rn]5f <sup>14</sup> 6d <sup>5</sup> 7s <sup>2</sup>	<b>Hs</b> Hassium (277) [Rn]5f <sup>14</sup> 6d <sup>6</sup> 7s <sup>2</sup>	<b>Mt</b> Meitnerium (268) [Rn]5f <sup>14</sup> 6d <sup>7</sup> 7s <sup>2</sup>	<b>Uun</b> Ununnilium (281) [Rn]5f <sup>14</sup> 6d <sup>8</sup> 7s <sup>2</sup>	<b>Uuu</b> Unununium (272) [Rn]5f <sup>14</sup> 6d <sup>9</sup> 7s <sup>2</sup>	<b>Uub</b> Ununbium (285) [Rn]5f <sup>14</sup> 6d <sup>10</sup> 7s <sup>2</sup>		<b>Uuq</b> Ununquadium (289) [Rn]5f <sup>14</sup> 6d <sup>10</sup> 7s <sup>2</sup> 7p <sup>1</sup>		<b>Uuh</b> Ununhexium (292) [Rn]5f <sup>14</sup> 6d <sup>10</sup> 7s <sup>2</sup> 7p <sup>2</sup>			
			<b>Lanthanides</b>	<b>La</b> Lanthanum 138.9055 [Xe]5d <sup>1</sup> 6s <sup>2</sup>	<b>Ce</b> Cerium 140.116 [Xe]4f <sup>1</sup> 5d <sup>1</sup> 6s <sup>2</sup>	<b>Pr</b> Praseodymium 140.90765 [Xe]4f <sup>3</sup> 6s <sup>2</sup>	<b>Nd</b> Neodymium 144.24 [Xe]4f <sup>4</sup> 6s <sup>2</sup>	<b>Pm</b> Promethium (145) [Xe]4f <sup>5</sup> 6s <sup>2</sup>	<b>Sm</b> Samarium 150.36 [Xe]4f <sup>6</sup> 6s <sup>2</sup>	<b>Eu</b> Europium 151.964 [Xe]4f <sup>7</sup> 6s <sup>2</sup>	<b>Gd</b> Gadolinium 157.25 [Xe]4f <sup>7</sup> 5d <sup>1</sup> 6s <sup>2</sup>	<b>Tb</b> Terbium 158.92534 [Xe]4f <sup>9</sup> 6s <sup>2</sup>	<b>Dy</b> Dysprosium 162.500 [Xe]4f <sup>10</sup> 6s <sup>2</sup>	<b>Ho</b> Holmium 164.93032 [Xe]4f <sup>11</sup> 6s <sup>2</sup>	<b>Er</b> Erbium 167.259 [Xe]4f <sup>12</sup> 6s <sup>2</sup>	<b>Tm</b> Thulium 168.93421 [Xe]4f <sup>13</sup> 6s <sup>2</sup>	<b>Yb</b> Ytterbium 173.04 [Xe]4f <sup>14</sup> 6s <sup>2</sup>	<b>Lu</b> Lutetium 174.967 [Xe]4f <sup>14</sup> 5d <sup>1</sup> 6s <sup>2</sup>	
			<b>Actinides</b>	<b>Ac</b> Actinium (227) [Rn]6d <sup>1</sup> 7s <sup>2</sup>	<b>Th</b> Thorium 232.0381 [Rn]6d <sup>2</sup> 7s <sup>2</sup>	<b>Pa</b> Protactinium 231.03688 [Rn]5f <sup>2</sup> 6d <sup>1</sup> 7s <sup>2</sup>	<b>U</b> Uranium 238.02891 [Rn]5f <sup>3</sup> 6d <sup>1</sup> 7s <sup>2</sup>	<b>Np</b> Neptunium (237) [Rn]5f <sup>4</sup> 6d <sup>1</sup> 7s <sup>2</sup>	<b>Pu</b> Plutonium (244) [Rn]5f <sup>6</sup> 7s <sup>2</sup>	<b>Am</b> Americium (243) [Rn]5f <sup>7</sup> 7s <sup>2</sup>	<b>Cm</b> Curium (247) [Rn]5f <sup>7</sup> 6d <sup>1</sup> 7s <sup>2</sup>	<b>Bk</b> Berkelium (247) [Rn]5f <sup>9</sup> 7s <sup>2</sup>	<b>Cf</b> Californium (251) [Rn]5f <sup>10</sup> 7s <sup>2</sup>	<b>Es</b> Einsteinium (252) [Rn]5f <sup>11</sup> 7s <sup>2</sup>	<b>Fm</b> Fermium (257) [Rn]5f <sup>12</sup> 7s <sup>2</sup>	<b>Md</b> Mendelevium (258) [Rn]5f <sup>13</sup> 7s <sup>2</sup>	<b>No</b> Nobelium (259) [Rn]5f <sup>14</sup> 7s <sup>2</sup>	<b>Lr</b> Lawrencium (262) [Rn]5f <sup>14</sup> 7s <sup>2</sup> 7p <sup>1</sup>	

**Frequently used fundamental physical constants**  
For the most accurate values of these and other constants, visit [physics.nist.gov/constants](http://physics.nist.gov/constants)  
1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of <sup>133</sup>Cs

speed of light in vacuum	<i>c</i>	299 792 458 m s <sup>-1</sup> (exact)
Planck constant	<i>h</i>	6.626 1 × 10 <sup>-34</sup> J s ( <i>h</i> = <i>h</i> 2π)
elementary charge	<i>e</i>	1.6022 × 10 <sup>-19</sup> C
electron mass	<i>m<sub>e</sub></i>	9.1094 × 10 <sup>-31</sup> kg
	<i>m<sub>e</sub>c<sup>2</sup></i>	0.5110 MeV
proton mass	<i>m<sub>p</sub></i>	1.6726 × 10 <sup>-27</sup> kg
fine-structure constant	<i>α</i>	1/137.036
Rydberg constant	<i>R<sub>∞</sub></i>	10 973 732 m <sup>-1</sup>
	<i>R<sub>∞</sub>c</i>	3.289 842 × 10 <sup>15</sup> Hz
	<i>R<sub>∞</sub>hc</i>	13.6057 eV
Boltzmann constant	<i>k</i>	1.3807 × 10 <sup>-23</sup> J K <sup>-1</sup>

Solids  
 Liquids  
 Gases  
 Artificially Prepared

**Atomic Number**: 58  
**Symbol**: Ce  
**Name**: Cerium  
**Atomic Weight**: 140.116  
**Ground-state Configuration**: [Xe]4f<sup>1</sup>5d<sup>1</sup>6s<sup>2</sup>  
**Ionization Energy (eV)**: 5.5387  
**Ground-state Level**: 1G<sub>4</sub><sup>o</sup>

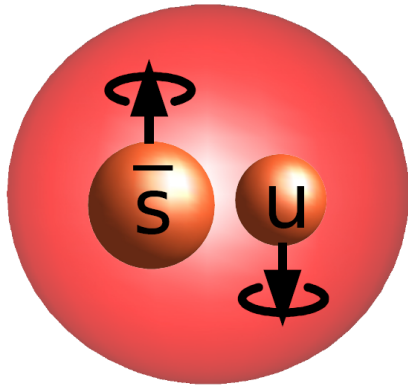
†Based upon <sup>12</sup>C. () indicates the mass number of the most stable isotope.

For a description of the data, visit [physics.nist.gov/data](http://physics.nist.gov/data)

NIST SP 966 (September 2003)

# “Periodic Table” of Mesons

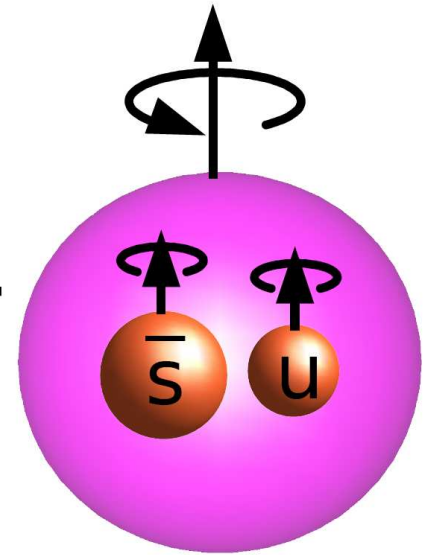
- Quark-antiquark make up a Meson:



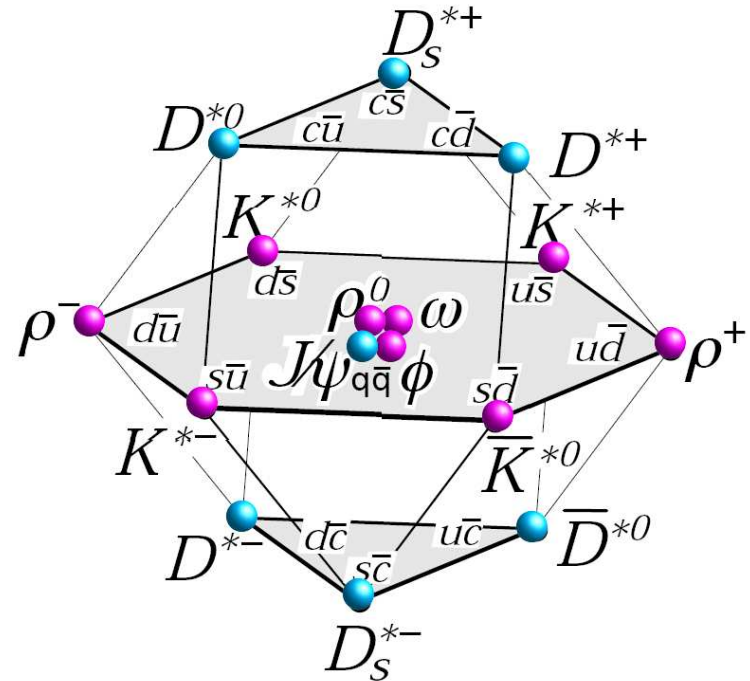
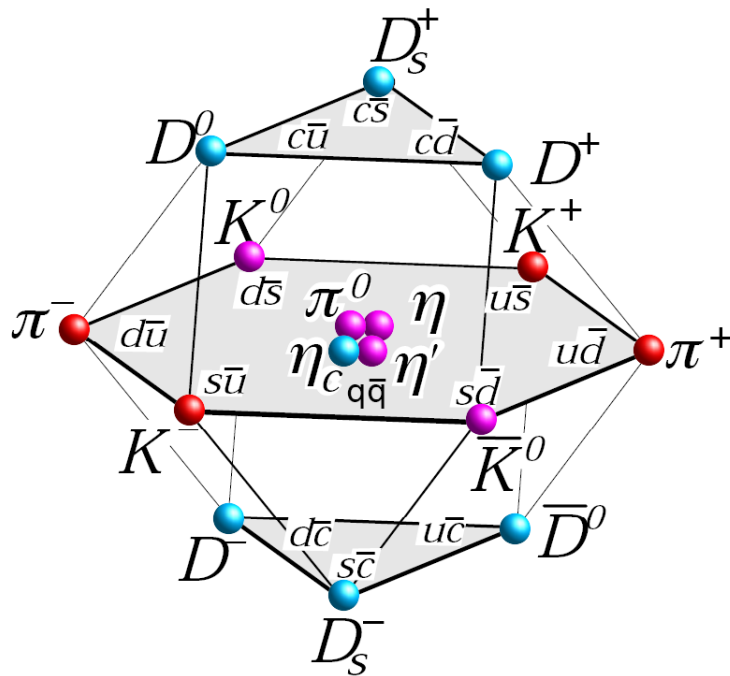
$K^+$

ground state ( $L=S=0$ )

$K^{*+}$

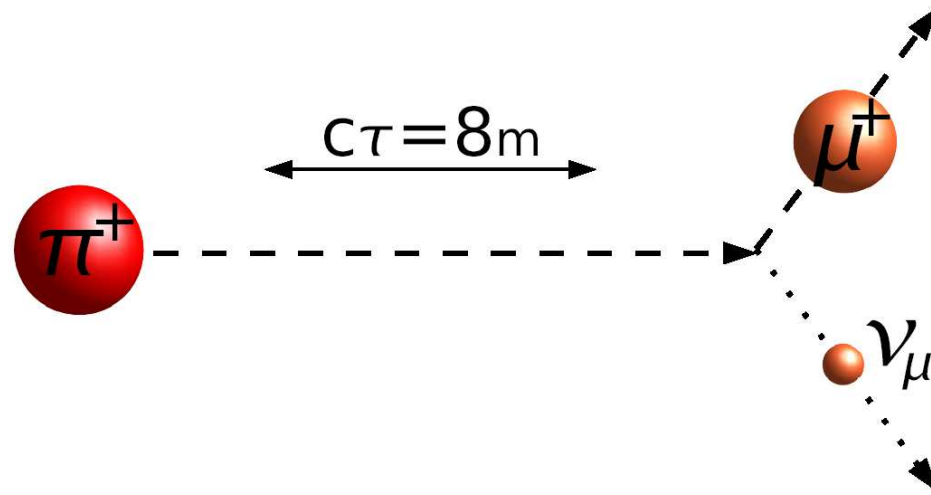


Vector meson  $S=1\hbar$

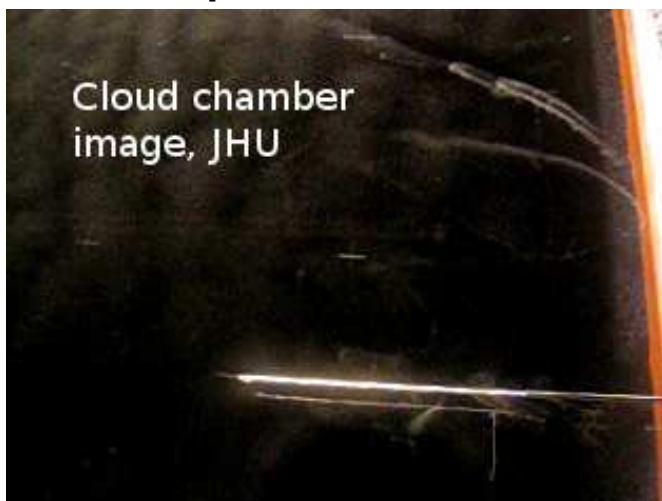


# How do We “See” Particles

- We “see” semi-stable particles by “tracks” in matter:



- Table-top illustrations



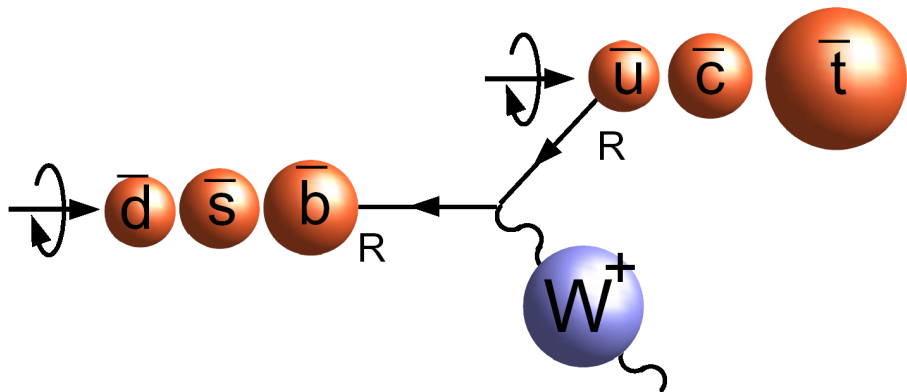
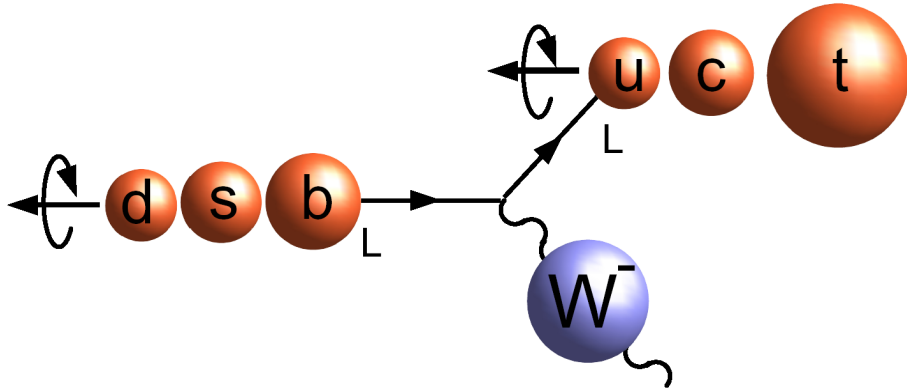
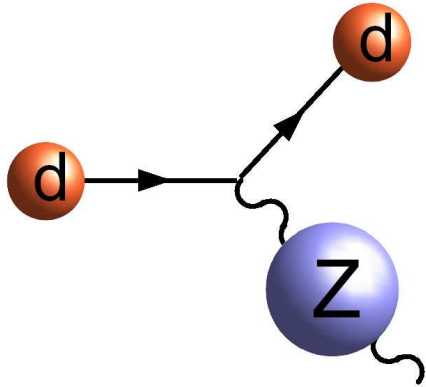
- Complex multi-ton detectors





# Weak Interactions

- Massive carriers  $\Rightarrow$  **weak** (short-range)  
mass  $\sim 80\text{-}90$  GeV



- Special interactions:

change **type** of quark

change **families**

**left-handed** fermions

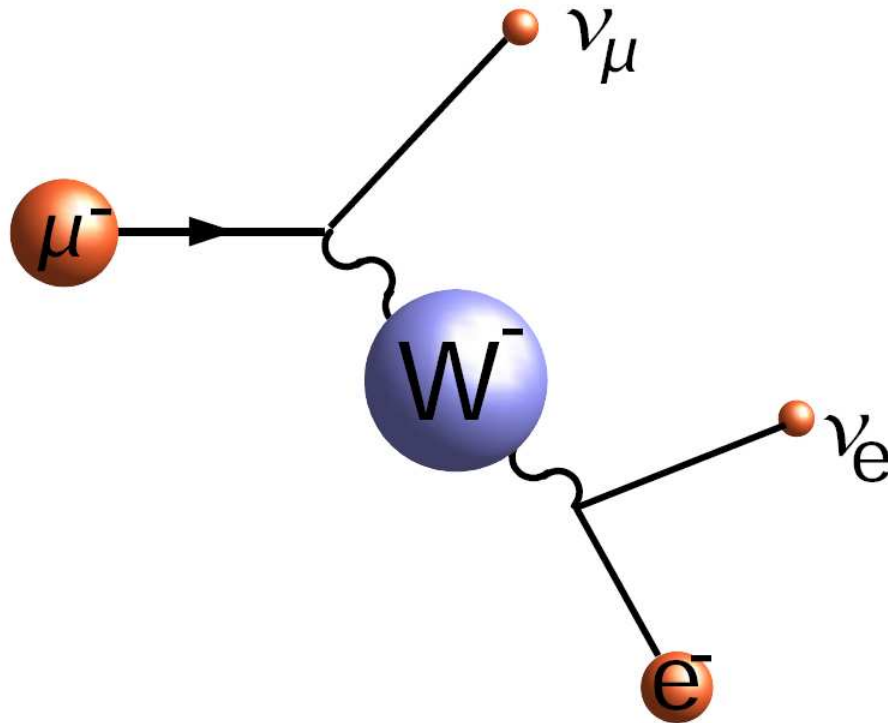
violate ***P***arity and ***C***

violate ***CP*** symmetry

# (1) Scenario: Muonic World

---

- What if muon were the lightest fermion (no electron)
- Normally muon decays:

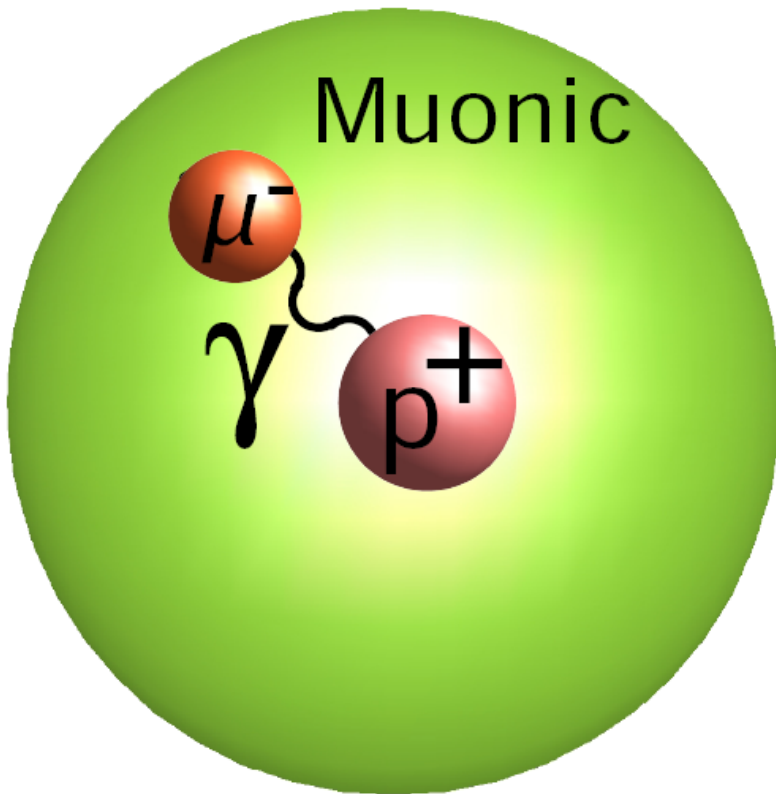


- Now muon is stable

# (1) Scenario: Muonic World

---

- We would get a muonic atom:



- Size changes:

radius  $r = \frac{4\pi\epsilon_0\hbar^2}{m_\mu e^2}$ , 200 smaller !

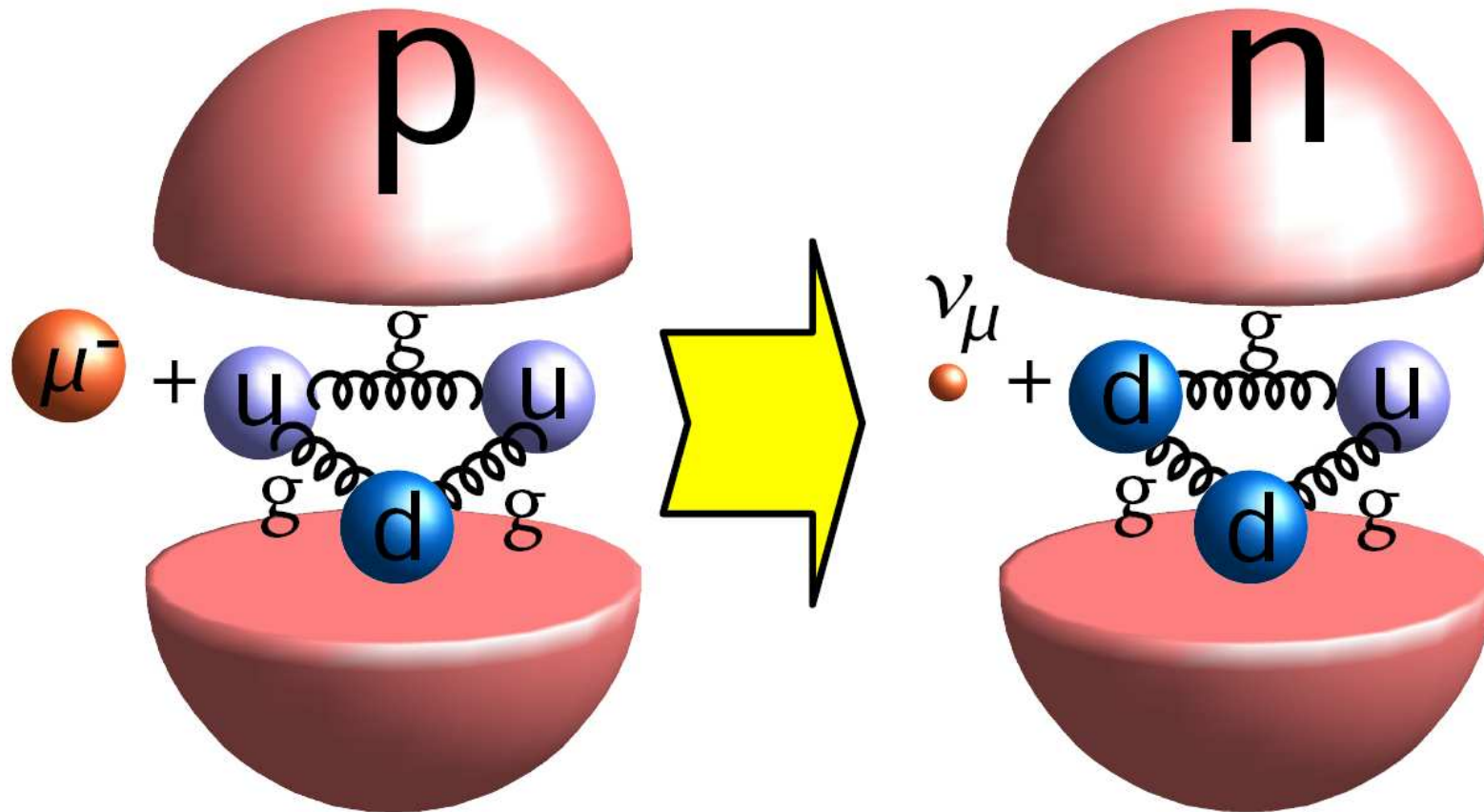
Hydrogen radius

$$r = \frac{4\pi\epsilon_0\hbar^2}{m_e e^2} = 5 \times 10^{-11} \text{ m}$$

# (1) Scenario: Muonic World

---

- However muonic hydrogen would decay:



- Not very interesting universe
  - filled with neutral “balls” of neutrons and neutrinos

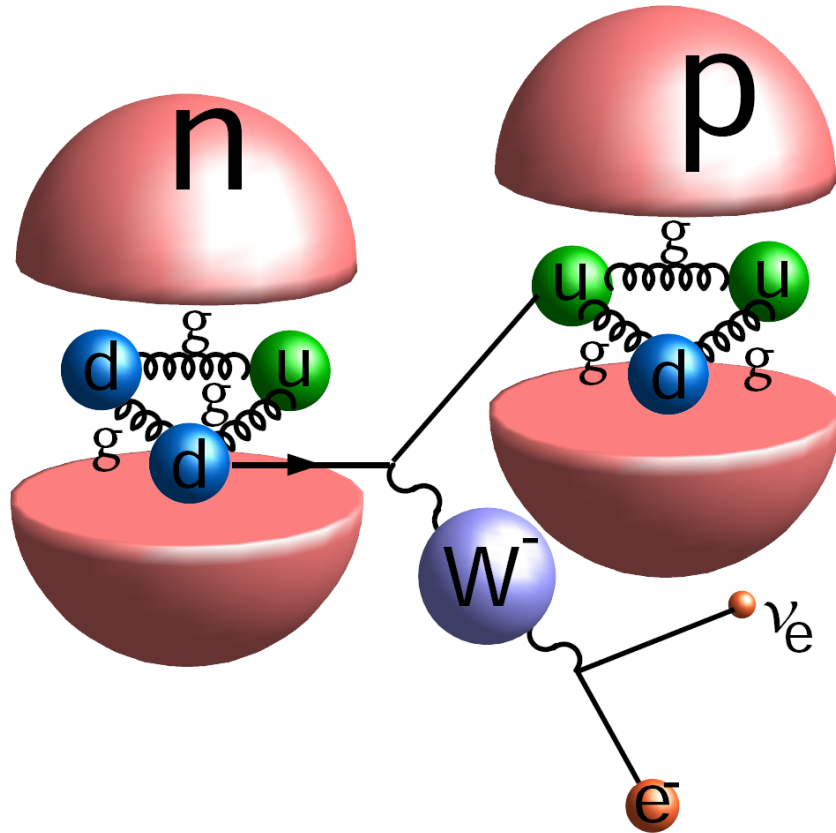


# (1) Scenario: Muonic World

---

- Normally neutron is not stable (life  $\tau \sim 886$  seconds)

$$m(n) > m(p) + m(e) + m(\nu_e)$$



- But stable in the muonic world:

$$m(n) < m(p) + m(\mu) + m(\nu_\mu)$$

## (2) Scenario: Another Neutron World

---

- Again, normally proton is stable and neutron decays:

$$m(n) > m(p) + m(e) + m(\nu_e)$$

- Why is  $m(n) > m(p)$

- $m(p) = 938 \text{ MeV}$ ,  $m(n) - m(p) = 1.3 \text{ MeV}$

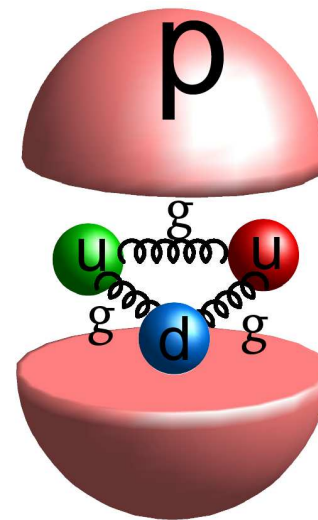
- tiny difference makes a big difference!

- naively expect  $m(p) > m(n)$  if  $u$  and  $d$  were the same

- but  $m(d) > m(u)$

- **New scenario:**

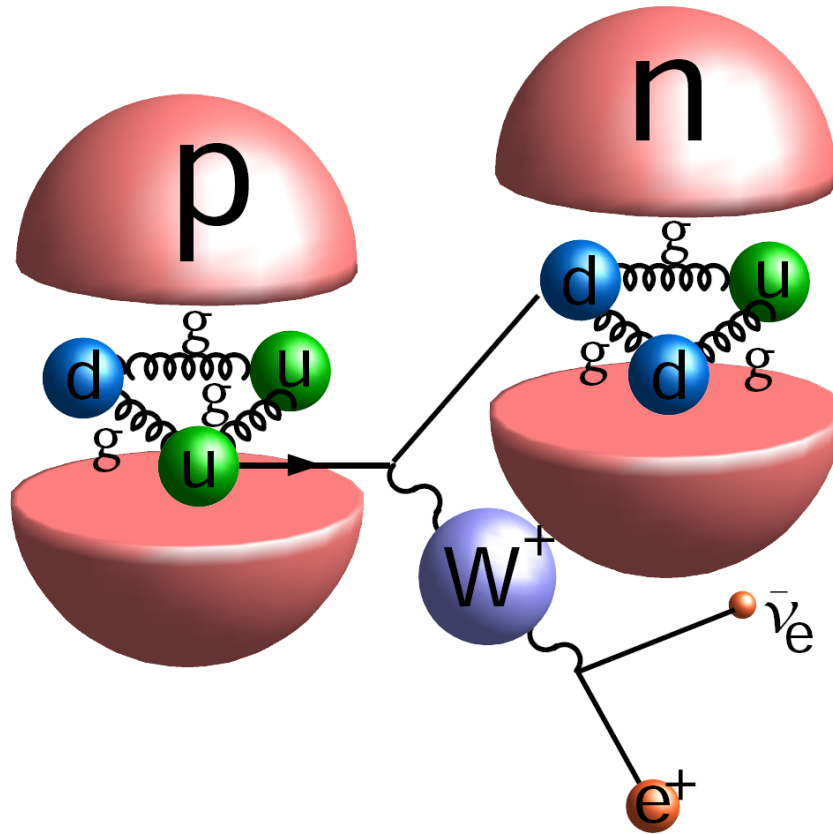
- what if  $m(d) < m(u)$



## (2) Scenario: Another Neutron World

---

- If  $m(d) < m(u)$ , proton decays:

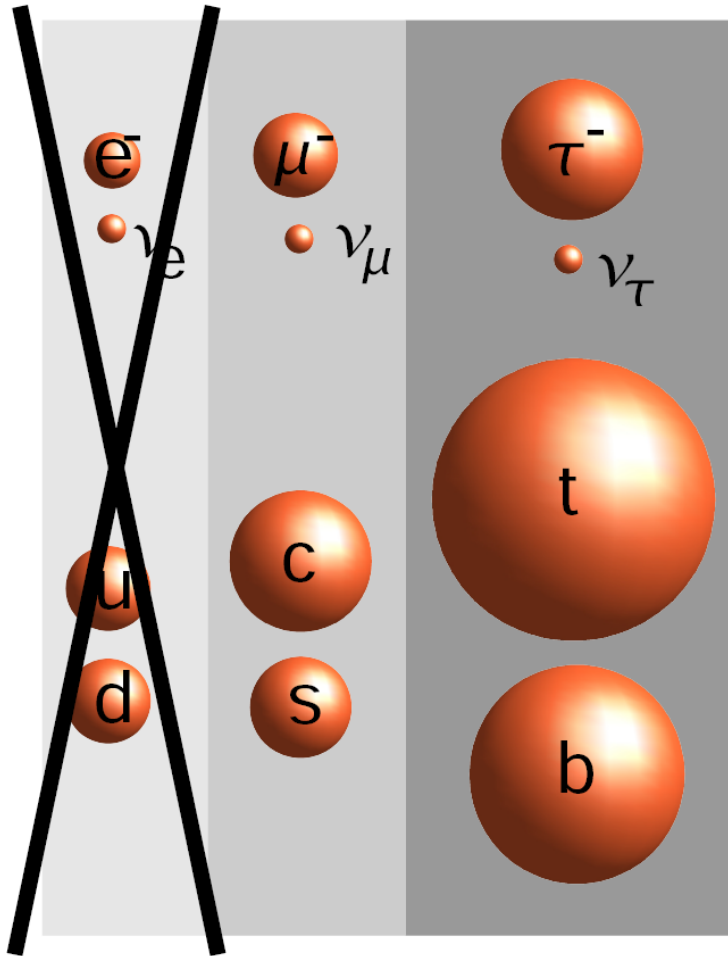


- Consequence: no Hydrogen, no  $H_2O$ 
  - still have  $He^4$ , rapid  $nn$  fusion, instead of slower  $pp$

### (3) Scenario: No First Family

---

- What if the second family of fermions were the first?



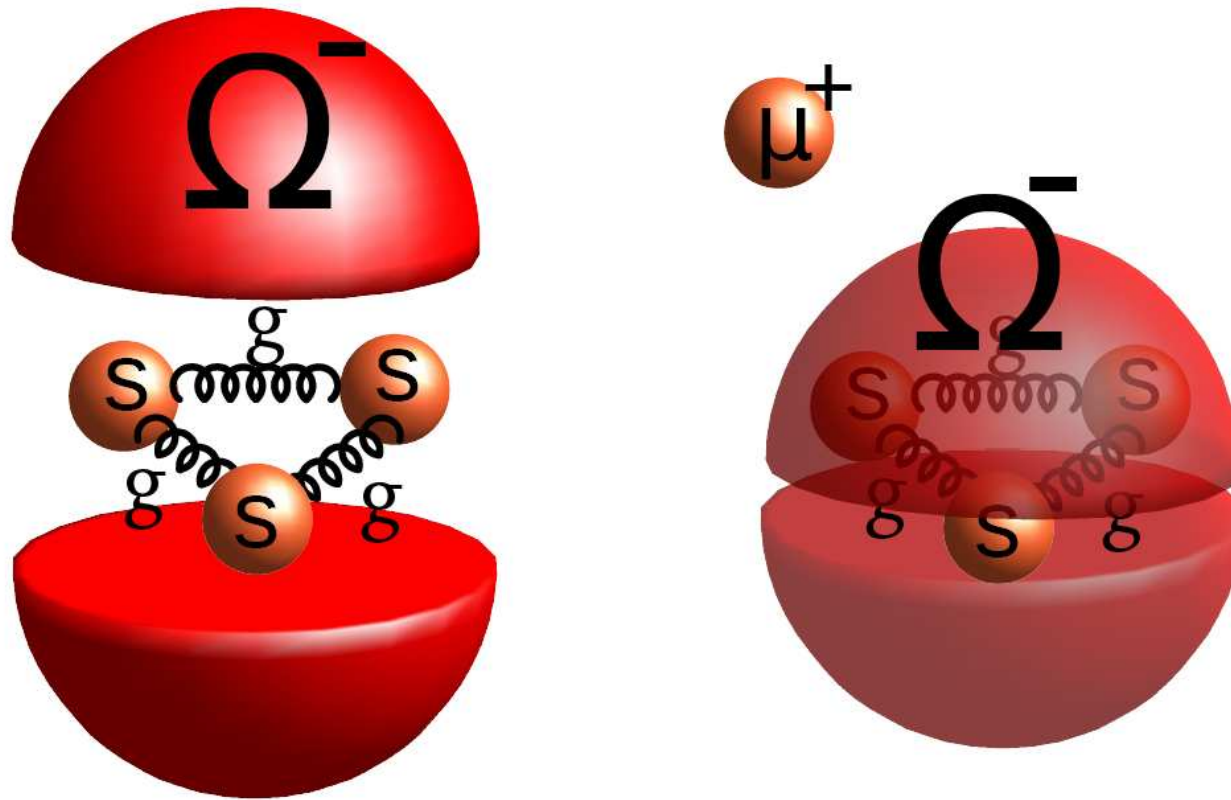
- Would we get muonic atoms?



### (3) Scenario: No First Family

---

- Would we get muonic atoms?
  - probably yes, but only one of them...

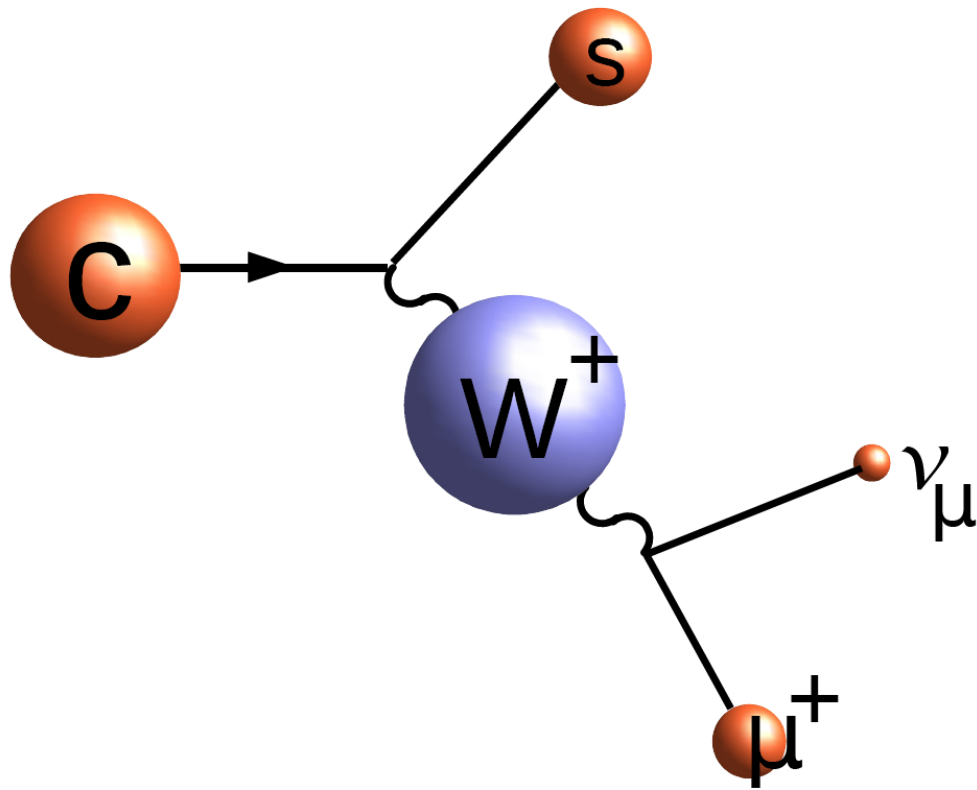


- No atoms, molecules, or anything bigger...

### (3) Scenario: No First Family

---

- Only one baryon with an  $s$  quark
  - because  $c$  is much heavier (unlike  $u$  and  $d$ )

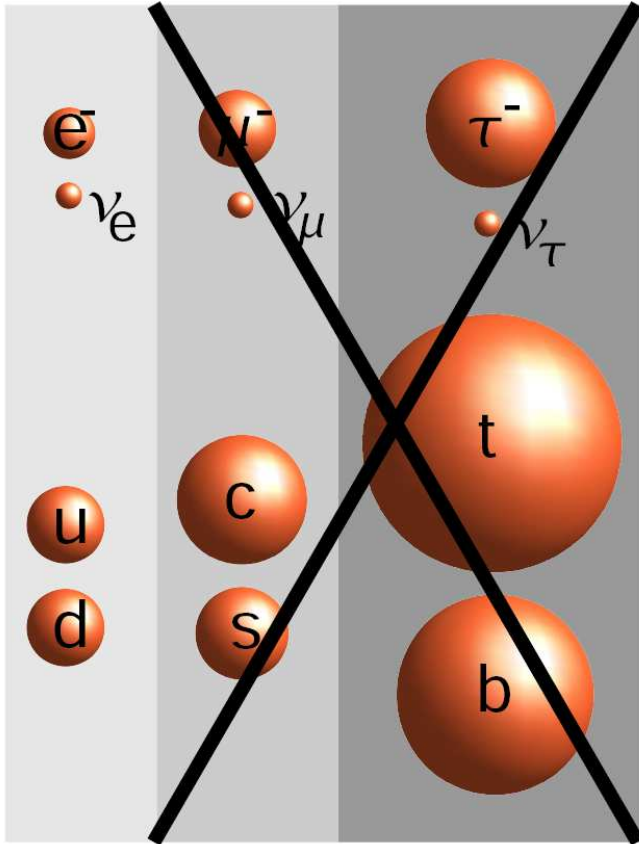


- No stable baryons with  $c$  quarks

## (4) Scenario: Only First Family

---

- What if we had only first family of fermions?

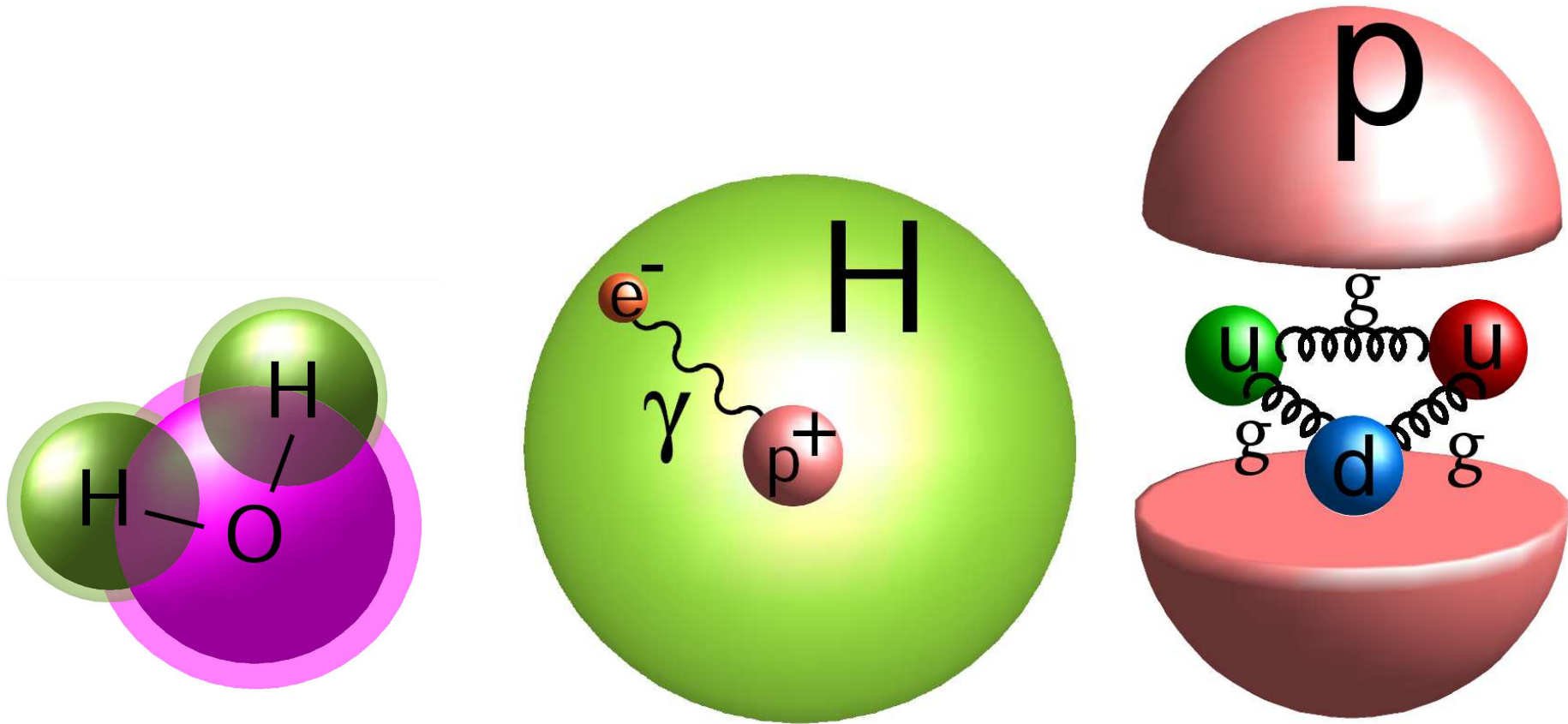


- Would the world around us be the same?

## (4) Scenario: Only First Family

---

- Would the world around us be the same?



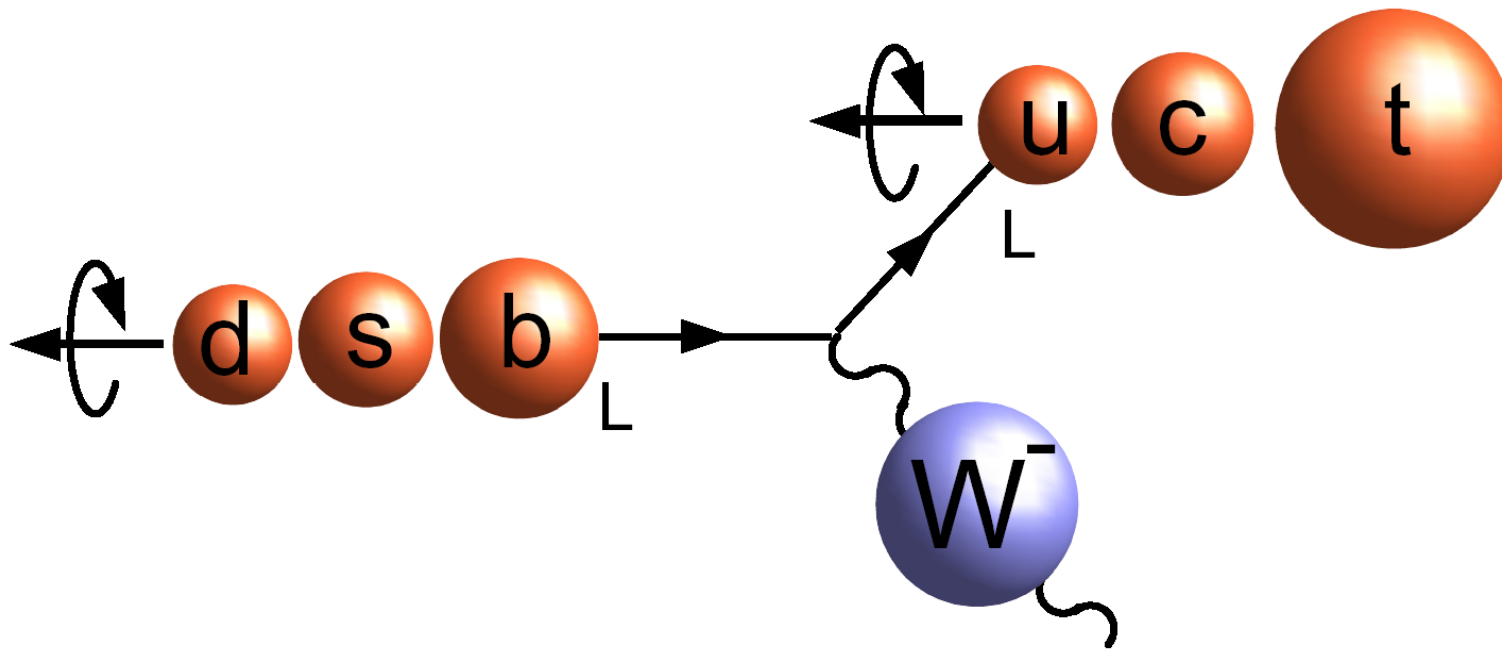
- Yes, if it already existed, almost no difference.



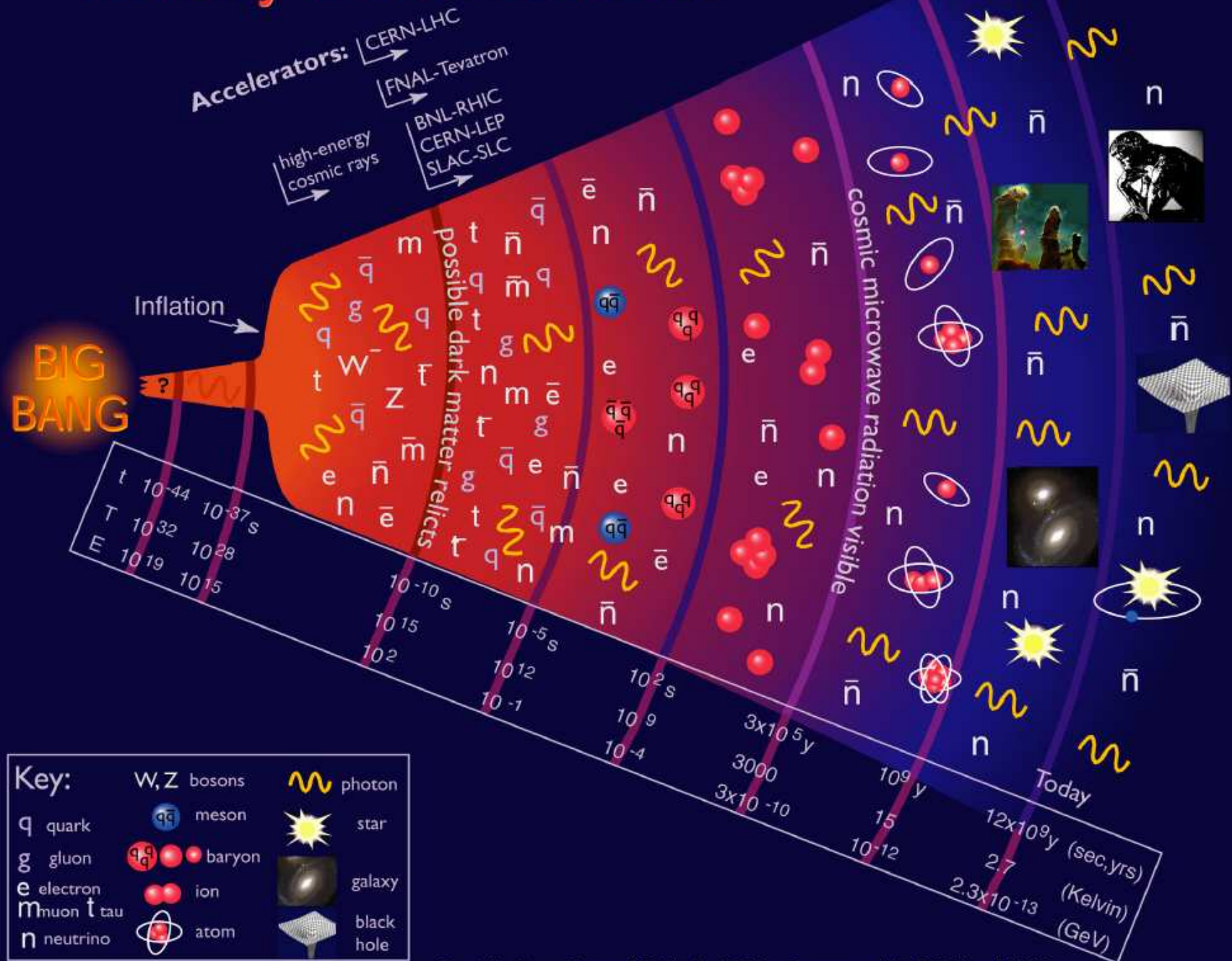
## (4) Scenario: Only First Family

---

- However:
  - laws of physics different in Universe evolution
  - in early moments all families equal
  - $\Rightarrow$  matter-antimatter asymmetry



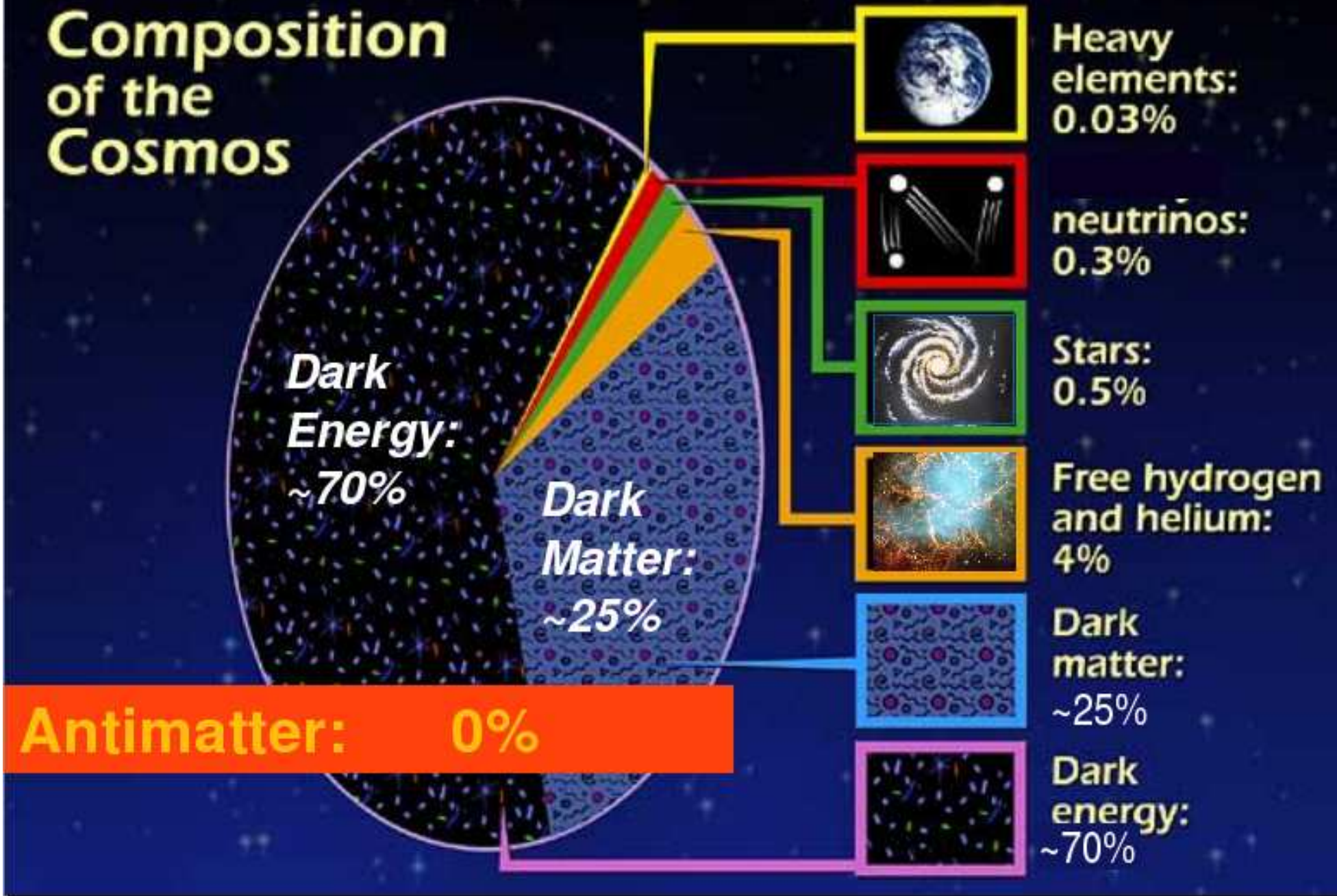
# History of the Universe



Particle Data Group, LBNL, © 2000. Supported by DOE and NSF



# Composition of the Cosmos



## (4) Scenario: Only First Family

---

- With only first family we will not have much
  - everything annihilate to photons...

# What Have We Learned?

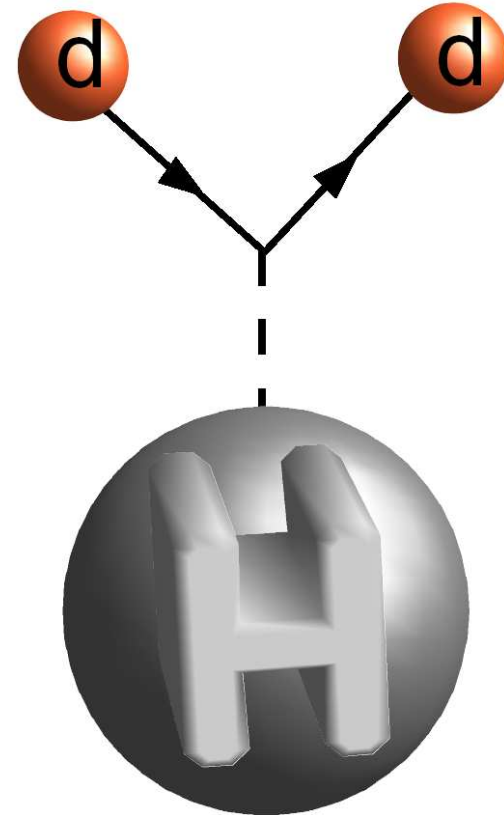
---

- Parameters of elementary particles are essential
- Small change in mass leads to dramatic change in universe
  - electron mass
  - proton and neutron ( $u$  and  $d$  quark) mass
  - fermion families
- Do we understand these parameters?
  - unfortunately not yet
  - but believe secrets of the universe are behind them
  - and believe we are about to uncover them...

# Look Beyond the Standard Model

---

- Mysterious *Higgs* field
  - gives mass to particles
  
- Need something *beyond* the SM
  - large *matter*-dominance
  - *dark matter*
  - light *Higgs*





# Possible Extension: Super-Symmetry

- New (**super**)symmetry:

$$Q|\text{fermion}\rangle = |\text{boson}\rangle$$

$$Q|\text{boson}\rangle = |\text{fermion}\rangle$$

- Solve:

(1) natural light

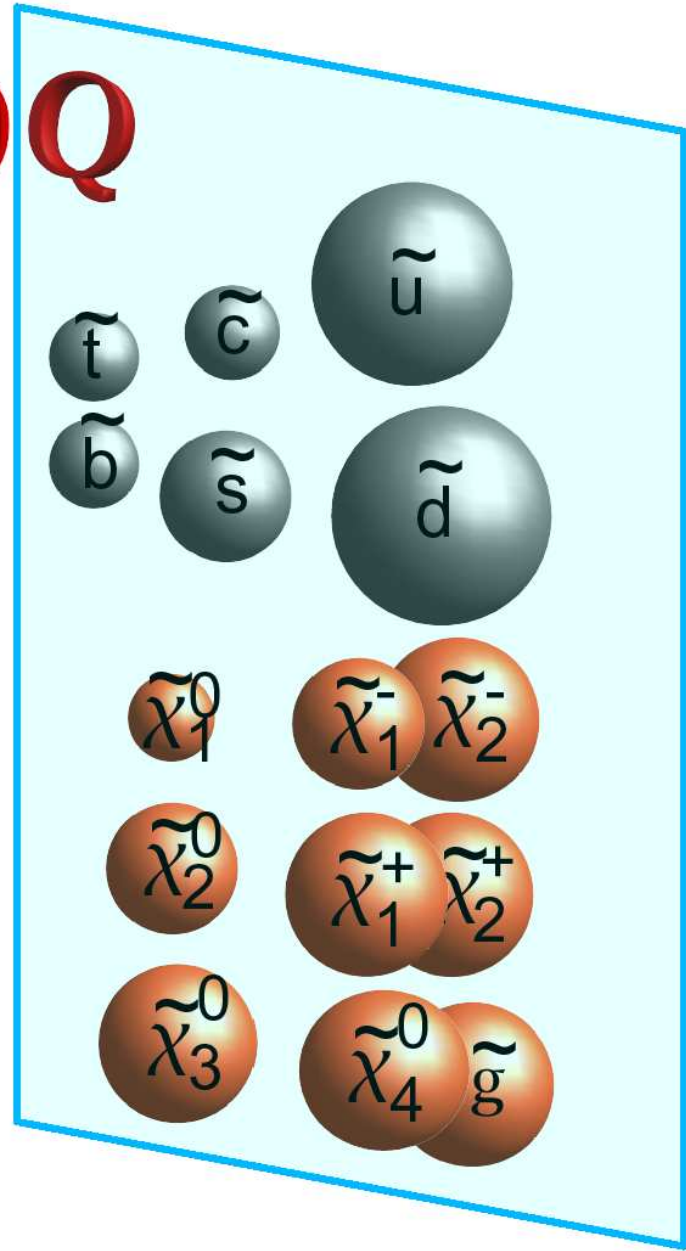
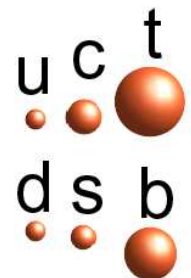
*Higgs*

(2) dark matter

lightest  $\tilde{\chi}_1^0$

(3) large **matter**/antimatter

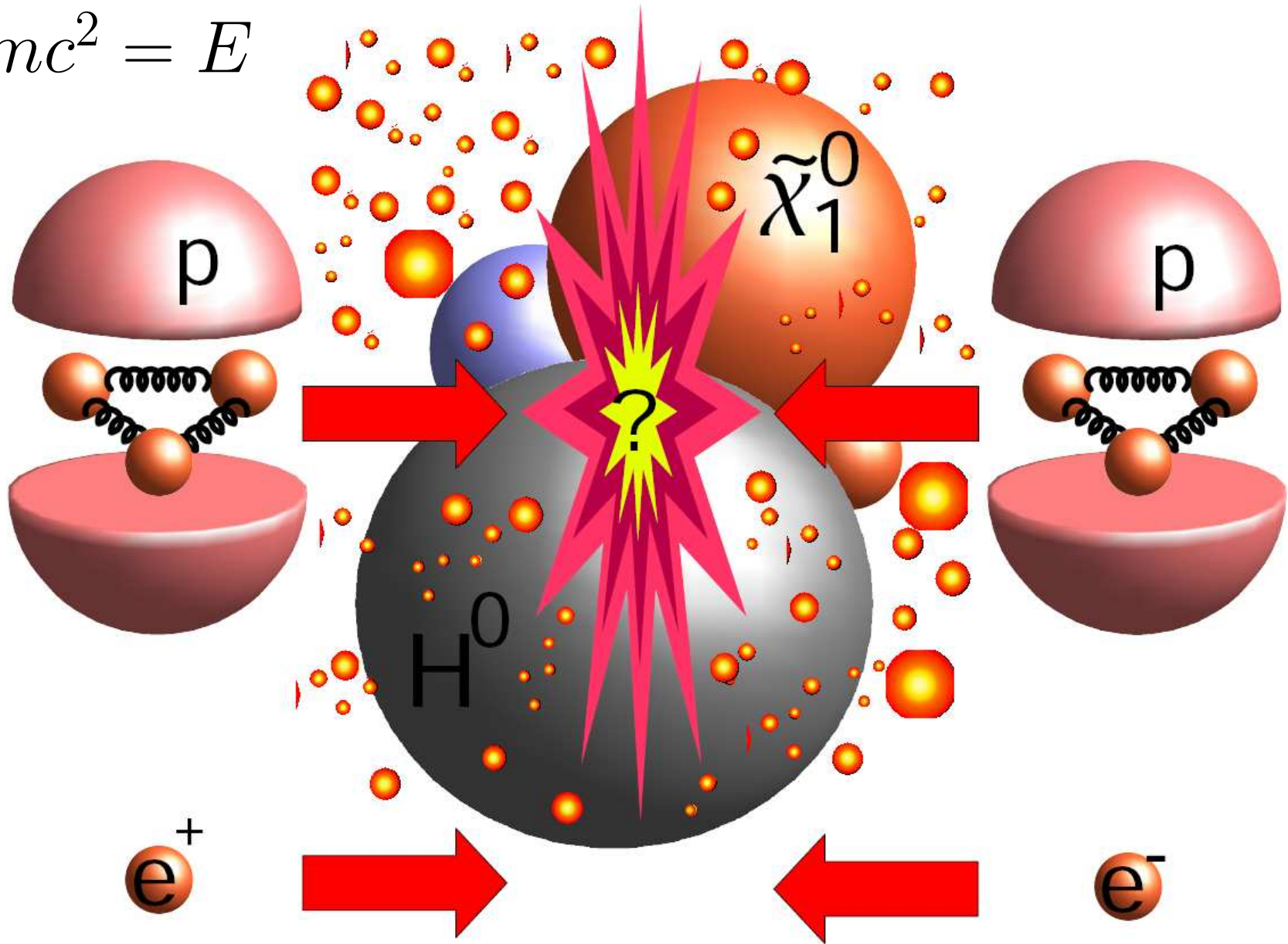
$g \quad \gamma$



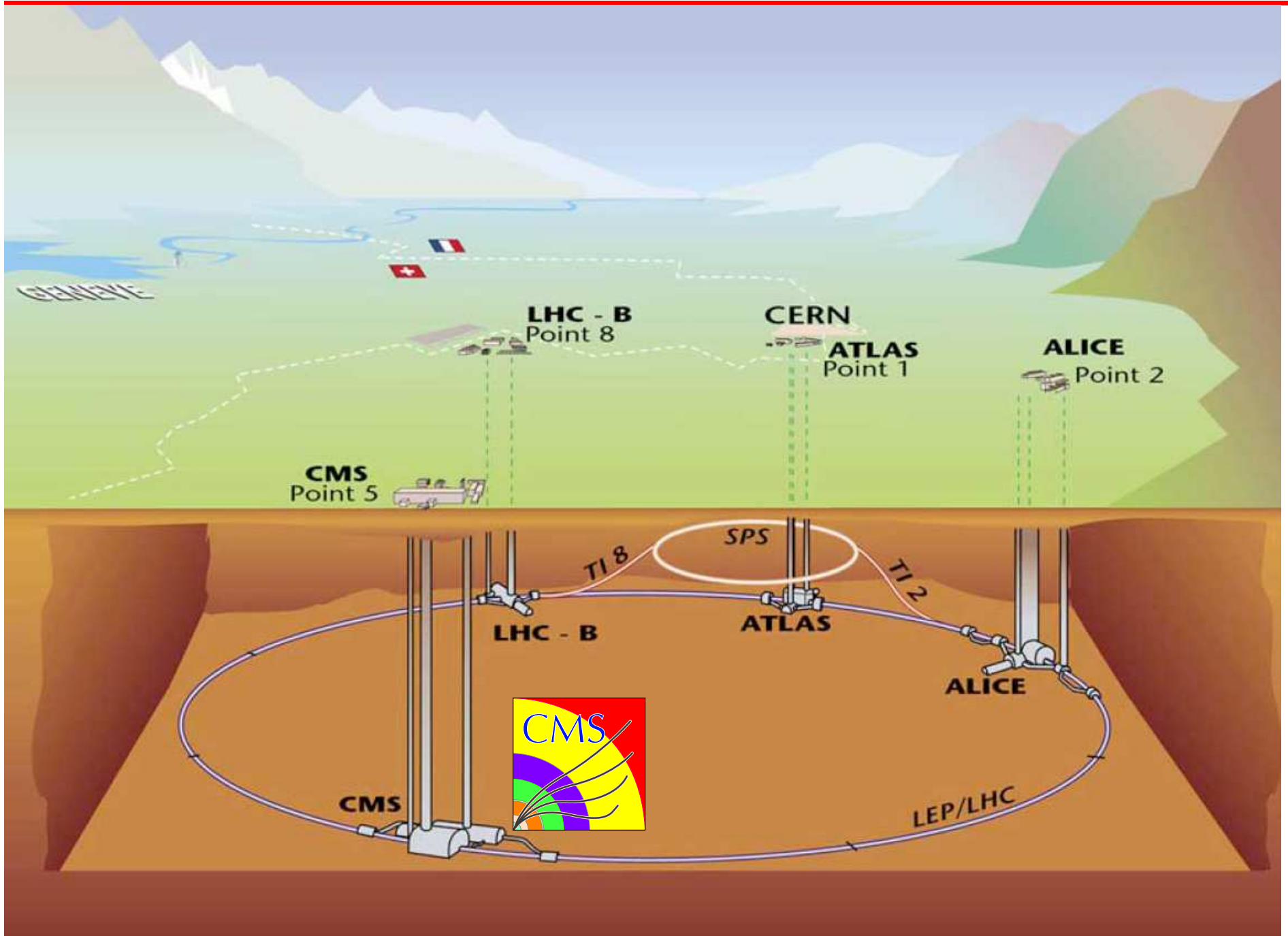
- Just around the corner in mass...

# Reaching Highest Energy

- $mc^2 = E$



# Large Hadron Collider: Fall 2008



# Thanks

---

Thanks to my mentor at LBNL: Robert N. Cahn  
for inspiring ideas

about standard model parameters in everyday life, see

*Reviews of Modern Physics, Vol. 68, No. 3, July 1996*