

# PHYS12 CH:23 The Building Blocks of Reality

## From Quarks to the Universe

Mr. Gullo

December 2025

# Outline

- 1 23.1 The Four Fundamental Forces
- 2 23.2 Quarks
- 3 23.3 The Unification of Forces
- 4 Summary

# Learning Objectives

By the end of this section, you will be able to:

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- **23.1:** Explain how particle accelerators probe nature

## 23.1 The Mystery: How Many Forces Exist?

How many forces exist in the universe?

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Friction, gravity, tension, normal force, magnetic force, electric force, spring force, air resistance...

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### The Physicist's Truth

Four. Just four fundamental forces explain EVERYTHING.



# 23.1 The Four Forces That Run Everything

## The Universal Forces

- 1 **Gravity** - weakest, infinite range
- 2 **Electromagnetic** - charges and magnets, infinite range
- 3 **Weak Nuclear** - radioactive decay, tiny range
- 4 **Strong Nuclear** - binds nucleus, tiny range

# 23.1 The Four Forces That Run Everything

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## The Nail Paradox

Earth's entire mass pulls nail down. Small magnet lifts it up.

## 23.1 Gravity: The Cosmic Sculptor

- Acts on all mass
- Always attractive
- Infinite range
- Weakest force
- Shapes galaxies

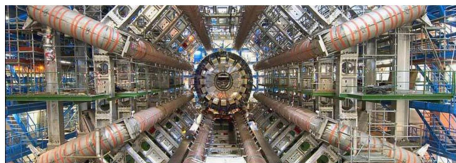


Figure: \*

Large Hadron Collider

# 23.1 Electromagnetic: The Force of Everyday Life

## Hidden in Plain Sight

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- Attractive AND repulsive
- Infinite range (inverse square law)
- Responsible for chemistry, friction, normal force

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## The Mental Model

When you sit in chair: electrons in your atoms repel electrons in chair.  
That's the "normal force."

## 23.1 The Nuclear Paradox

### Civilian View vs. Reality

**Civilian:** "Protons stuck together in nucleus by gravity."

**Physicist:** "Gravity too weak. Protons REPEL electromagnetically. Something else must hold them."

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## The Strong Nuclear Force

- Strongest force at short range ( $< 10^{-15}$  m)
- Acts on protons AND neutrons
- Overcomes EM repulsion
- Drops to zero beyond nuclear diameter

# 23.1 The Weak Nuclear Force: The Decay Master

## Nature's Transformer

- Causes beta decay
- Range:  $< 10^{-18}$  m
- Weaker than strong and EM
- Stronger than gravity
- Acts on quarks and leptons

Beta decay:





## 23.1 The Weak Nuclear Force: The Decay Master

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Beta decay:



### The Name Game

It's called "weak" but it's stronger than gravity. Scientists named it before measuring carefully!

## 23.1 The Universal Law: Force Comparison

Force	Relative Strength	Range	Acts On
Strong	1	$10^{-15}$ m	Nucleons
EM	$10^{-2}$	Infinite	Charged
Weak	$10^{-13}$	$10^{-18}$ m	Quarks/Leptons
Gravity	$10^{-39}$	Infinite	All mass

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### Nature's Source Code

Four forces. That's it. They explain stars, atoms, chemistry, galaxies, YOU.

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### Einstein's Dilemma

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### Yukawa's Solution (1935)

Forces transmitted by **carrier particles** - real particles that carry force between objects.

## 23.1 Carrier Particles: Force Messengers

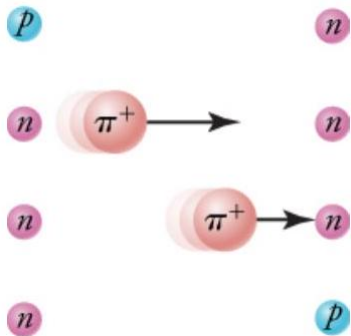


Figure: \*

Pion exchange between proton and neutron

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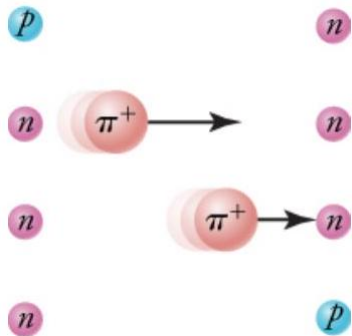


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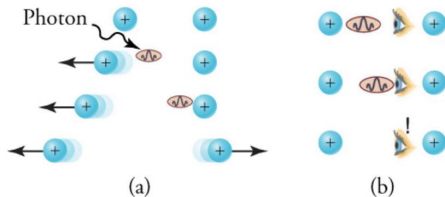
Pion exchange between proton and neutron

### Yukawa's Pion

Proton emits pion  $\rightarrow$  neutron absorbs it  $\rightarrow$  strong force transmitted.  
Particle identities switch!



## 23.1 Virtual Particles and Feynman Diagrams

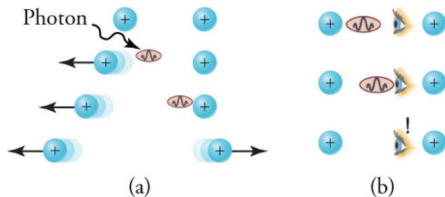


- Carrier particle is **virtual**
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- Exists briefly via uncertainty
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Virtual photon exchange

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Virtual photon exchange

## Reading a Feynman Diagram

Time flows UP. Particles move, exchange virtual particle, trajectories change.

# 23.1 The Four Carrier Particles

## Force Carriers

- **Photon** - EM force, massless
- **Gluon** - Strong force, massless (8 types)
- **$W^+$ ,  $W^-$ ,  $Z^0$  bosons** - Weak force, very massive
- **Graviton** - Gravity, not yet found (predicted massless)

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## Mass and Range Connection

Massless carriers → infinite range (photon, graviton)

Massive carriers → short range (W, Z bosons)

## 23.1 Searching for the Graviton



Figure: \*

LIGO - Laser Interferometer Gravitational-Wave Observatory

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### The Missing Carrier

Expected: massless, chargeless, spin-2 particle traveling at speed of light

## 23.1 Particle Accelerators: Creating Matter from Energy

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## The Particle Physicist's Favorite Indoor Sport

"Smash things together and see what comes out."

## 23.1 Van de Graaff and Cyclotron

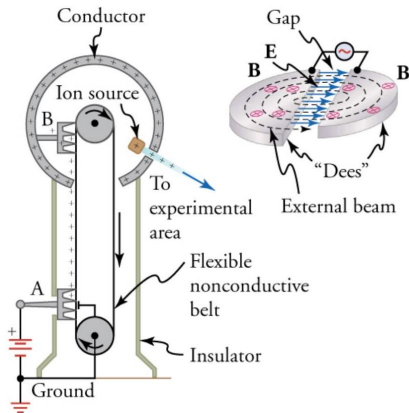


Figure: \*

Van de Graaff (left) and Cyclotron (right)

## 23.1 Van de Graaff and Cyclotron

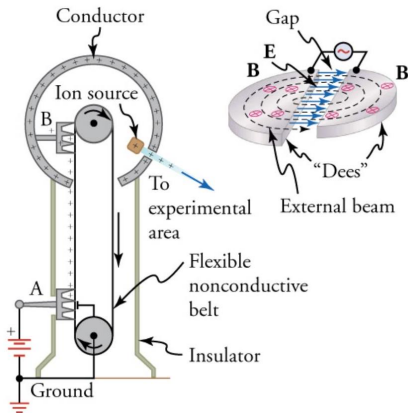


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Van de Graaff (left) and Cyclotron (right)

**Van de Graaff:** Linear acceleration, up to 50 MV

**Cyclotron:** Spiral path, fixed frequency, higher energies

## 23.1 Synchrotron: The Modern Workhorse

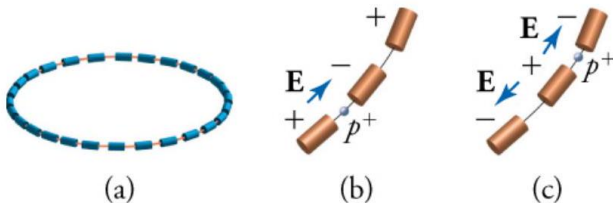


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Synchrotron ring with accelerating tubes

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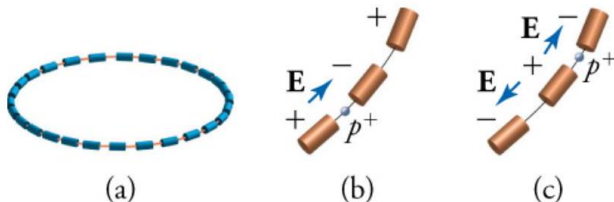


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Synchrotron ring with accelerating tubes

- Particles travel fixed-radius ring
- Magnetic field increases to keep radius constant
- Voltage synchronized with particle speed
- Very large for very high energies

## 23.1 Colliding Beams: Maximum Energy



Figure: \*

Fermilab's proton-antiproton collider

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Fermilab's proton-antiproton collider

### Why Collide Head-On?

Stationary target: much energy lost to recoil

Colliding beams: particles created with near-zero momentum

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- **23.2:** Distinguish matter from antimatter
- **23.2:** Describe the Standard Model
- **23.2:** Define Higgs boson and its importance

## 23.2 The Ancient Quest

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"The first principles of universe are atoms and empty space. Everything else is merely thought to exist."

The search for fundamental particles is nothing new.

- 1930s: proton, neutron, electron discovered
- Scientists thought: "We found smallest pieces!"
- They were only partially correct...

## 23.2 The Discovery That Shattered the Proton

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Results showed three point-like charges *inside* proton!

Protons are NOT fundamental - they have substructure

## 23.2 Electron Scattering Evidence

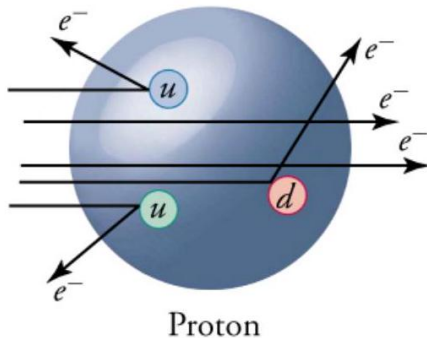


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SLAC scattering experiment

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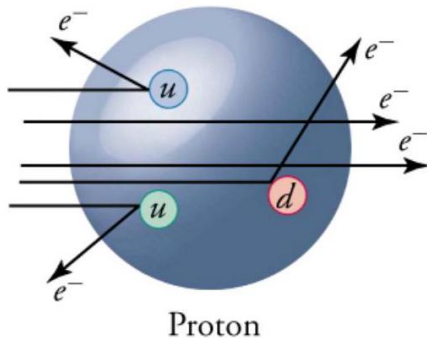


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SLAC scattering experiment

Three point-like charges consistent with quark model

## 23.2 The Six Quark Flavors

### The Quark Family

Quark	Symbol	Charge
Up	u	$+\frac{2}{3}e$
Down	d	$-\frac{1}{3}e$
Charm	c	$+\frac{2}{3}e$
Strange	s	$-\frac{1}{3}e$
Top	t	$+\frac{2}{3}e$
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### The Illusion

**Expected:** Charge is discrete (multiples of  $e$ )

**Reality:** Quarks have fractional charge!

## 23.2 Color Charge: The Hidden Property

**Quarks have three colors:** Red, Green, Blue



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All hadrons must have colors that sum to **white**

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**Example:** Proton = red up + green up + blue down = white

## 23.2 Gluon Exchange Between Quarks

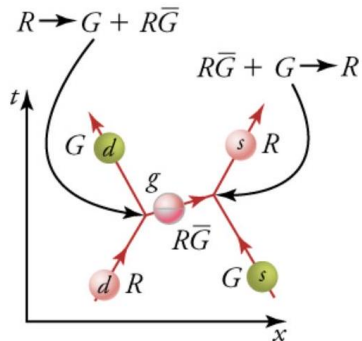


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Gluon changes quark color

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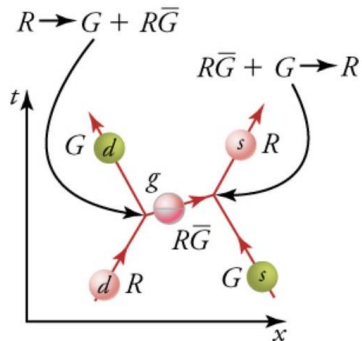


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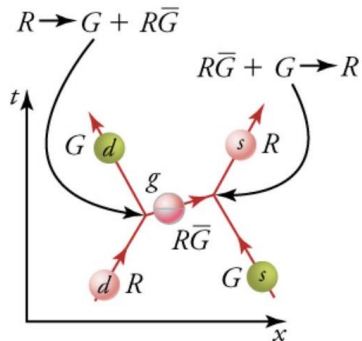


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Gluon changes quark color

Gluon carries strong force AND changes quark color  
Quark flavor does NOT change, only color

## 23.2 Building a Proton

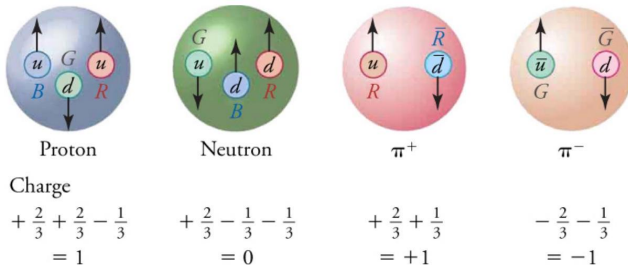


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Proton structure: uud

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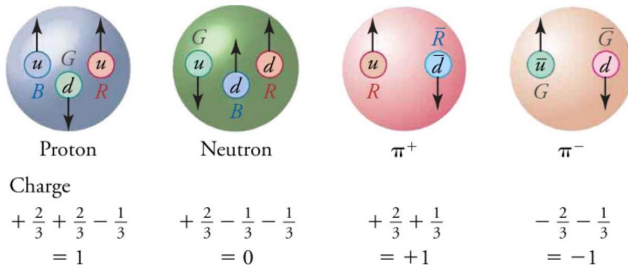


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Proton = two up quarks + one down quark



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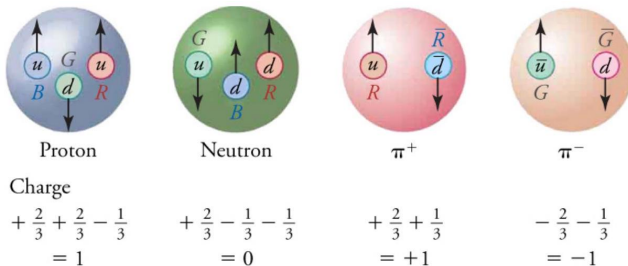


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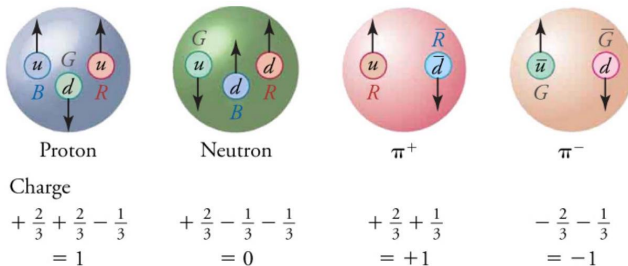


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Color: red + green + blue = white ✓

## 23.2 Hadrons and Leptons

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- Feel strong force
- Composed of quarks
- Baryons: 3 quarks
- Mesons: quark-antiquark
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### The Mental Model

Hadrons are composite. Leptons are fundamental.

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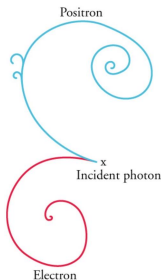


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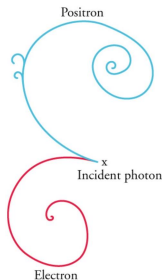


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Positron and electron tracks curve opposite directions

Same mass as electron, opposite charge = antielectron



## 23.2 Pair Production and Annihilation

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Both mass-energy and charge conserved!

## 23.2 Why Antimatter Is Rare

### The Paradox

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If matter and antimatter created equally in Big Bang, where is all antimatter?

When matter meets antimatter: **instant annihilation**

**Evidence:** Tiny excess of matter over antimatter in early universe  
We are made of leftover matter!

# 23.2 The Standard Model of Fundamental Particles

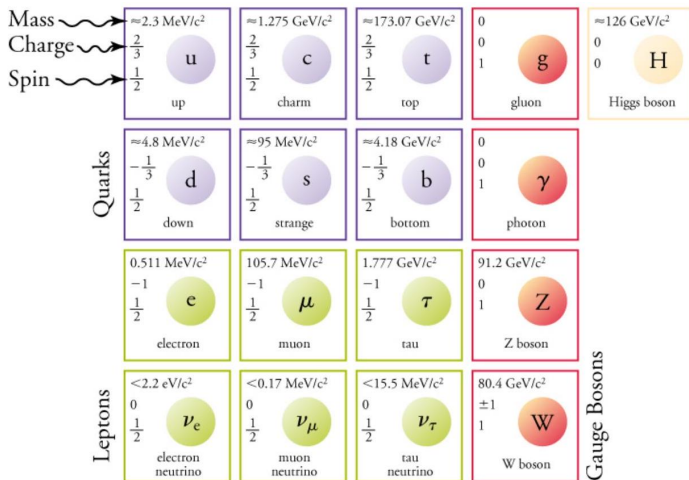


Figure: \*

The Standard Model



## 23.2 Reading the Standard Model

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**Pattern:** Mass increases left to right

**Trend:** Higher mass = less stable = faster decay

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Higgs field is like water. Some particles swim through easily (photon), others slowed down (W, Z bosons).



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**Peter Higgs (1960s):** All particles pass through **Higgs field**

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The slowing creates mass!

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**October 2013:** Peter Higgs wins Nobel Prize

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- **23.3:** Explain evolution of four forces from Big Bang
- **23.3:** Explain how unification theories can be tested

## 23.3 The Dream of Unification

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- Future: All four forces unified → **Theory of Everything**

## 23.3 The Dream of Unification

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### The Pattern

At higher energies, forces become more similar

## 23.3 Force Strength Versus Energy

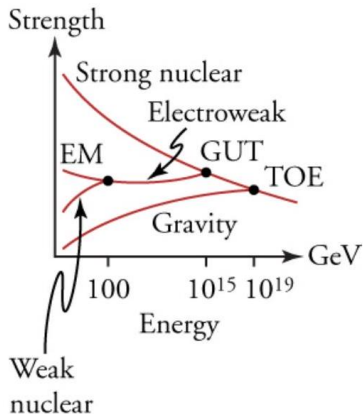


Figure: \*

Force strengths converge at high energy

## 23.3 Force Strength Versus Energy

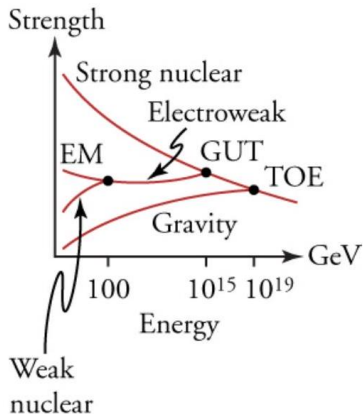


Figure: \*

Force strengths converge at high energy

At low energies: forces very different

At high energies: forces become similar!



## 23.3 Electroweak Unification

**Weinberg, Glashow, Salam (1960s):** EM and weak forces identical at high energies

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**1983:** All three particles discovered at CERN with exact predicted masses!

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Cannot test directly with accelerators

## 23.3 Testing GUT Indirectly: Proton Decay

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**Result (2014):** No decay observed - proton lifetime  $> 5.9 \times 10^{33}$  years

## 23.3 The Big Bang and Force Evolution

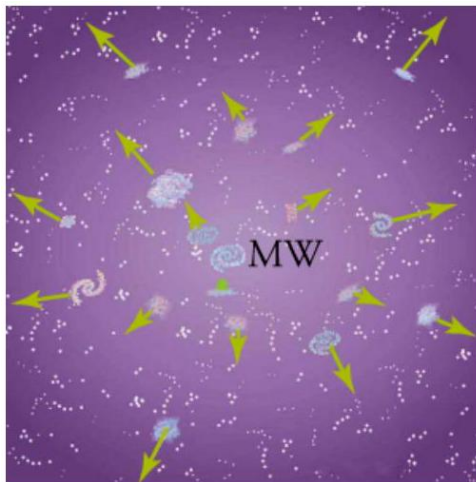


Figure: \*

Universe evolution from Big Bang



## 23.3 The First Trillionth of a Second

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**Electroweak Epoch** ( $10^{-32} \rightarrow 10^{-11}$  s): Strong force separated

**Quark Era** ( $10^{-11} \rightarrow 10^{-6}$  s): All four forces separated, quarks form

## 23.3 The Universe as Our Laboratory

### The Connection

Particle accelerators recreate Big Bang conditions

Cosmology tests particle physics theories

The smallest and largest scales are connected

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### The Connection

Particle accelerators recreate Big Bang conditions

Cosmology tests particle physics theories

The smallest and largest scales are connected

### The Cosmic Connection

Understanding quarks helps us understand first seconds after Big Bang.  
Understanding Big Bang helps us understand quarks.

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- 8 Particle physics explains Big Bang evolution

# Key Concepts

**Four Forces:** Gravity, EM, Weak nuclear, Strong nuclear

**Carrier Particles:** Graviton\*, Photon, W/Z bosons, Gluon

**Quarks:** Six flavors, three colors, fractional charge

**Hadrons:** Baryons (3 quarks), Mesons (quark-antiquark)

**Leptons:** Fundamental particles (electron, muon, tau, neutrinos)

**Standard Model:** 6 quarks + 6 leptons + 4 carriers + Higgs = 17

**Unification:** Forces become similar at high energies

Complete the assigned problems  
posted on the LMS