Goodell Award Presentation

SUNY Institute of Technology, October 28, 2004

High Energy Physics:

An Overview of Objectives, Challenges and Outlooks

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Outline

Introduction

Objectives:

- Elementary Particles
- Fundamental Forces
- Unification

Means and Techniques:

- Experimental
- Theoretical

Strong Interaction

- Hadrons, and their Strong Interaction
- Models for the Physics of Hadrons

Future Outlooks

Introduction:

- What is an elementary particle?

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  A particle that is not consist of other particles

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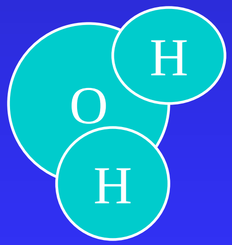
  A particle that is not consist of other particles

Ex. Water molecule is NOT elementary

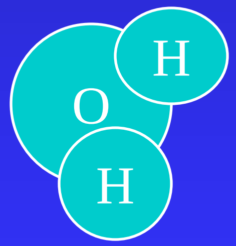


Introduction:

- What is an elementary Particle?

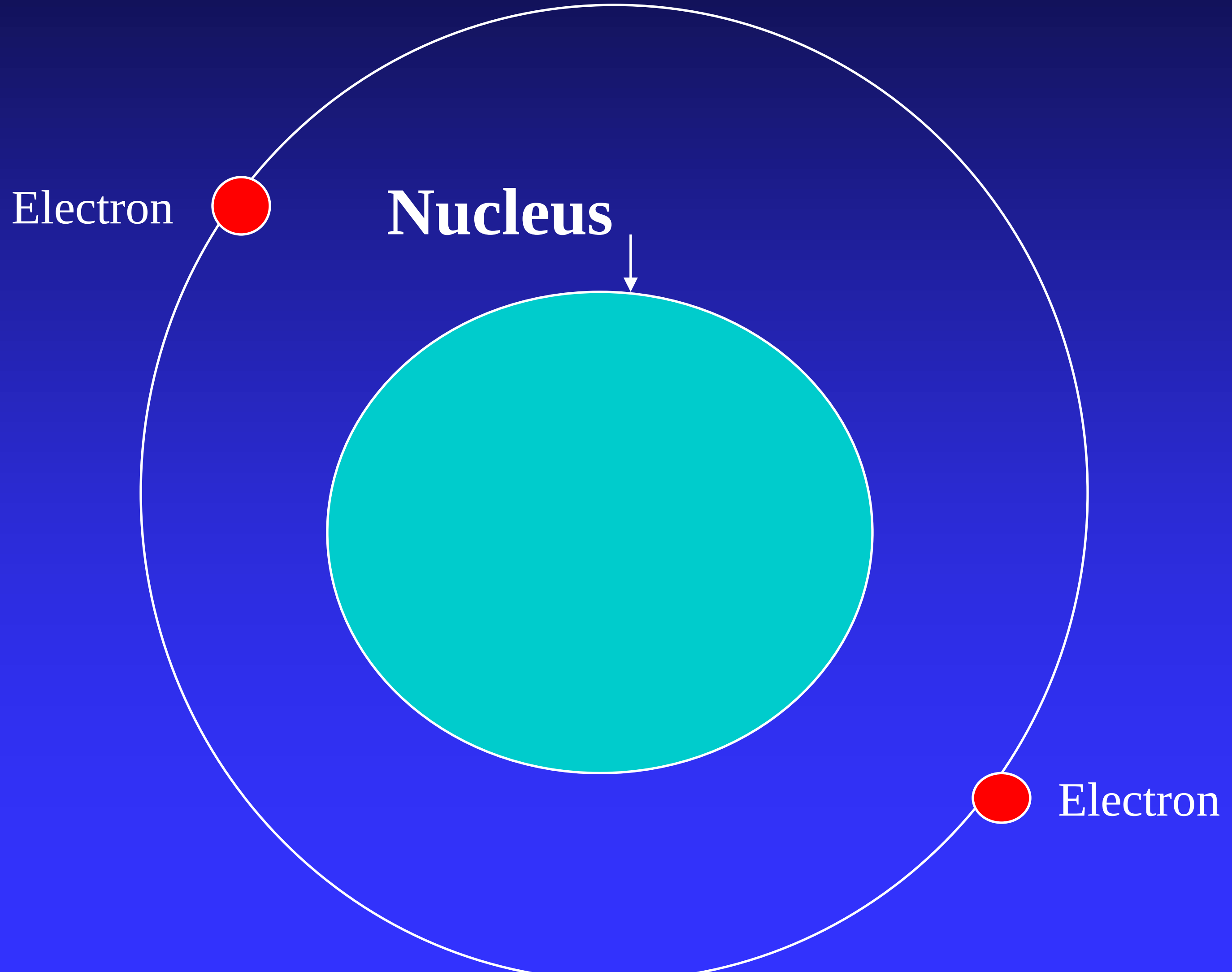
  A particle that is not consist of other particles

Ex. Water molecule is NOT elementary



Atoms and molecules are not elementary.

General structure of atoms:



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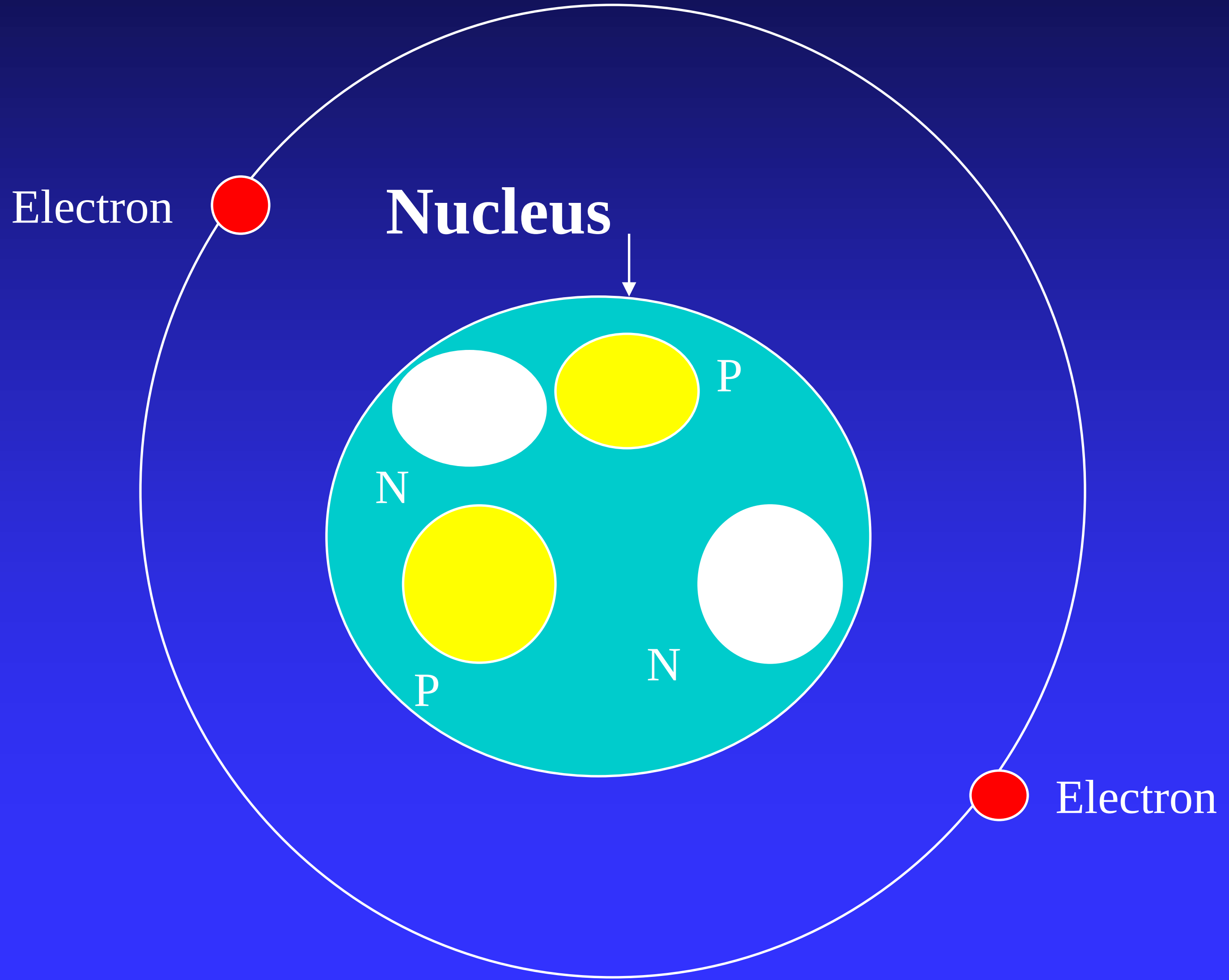

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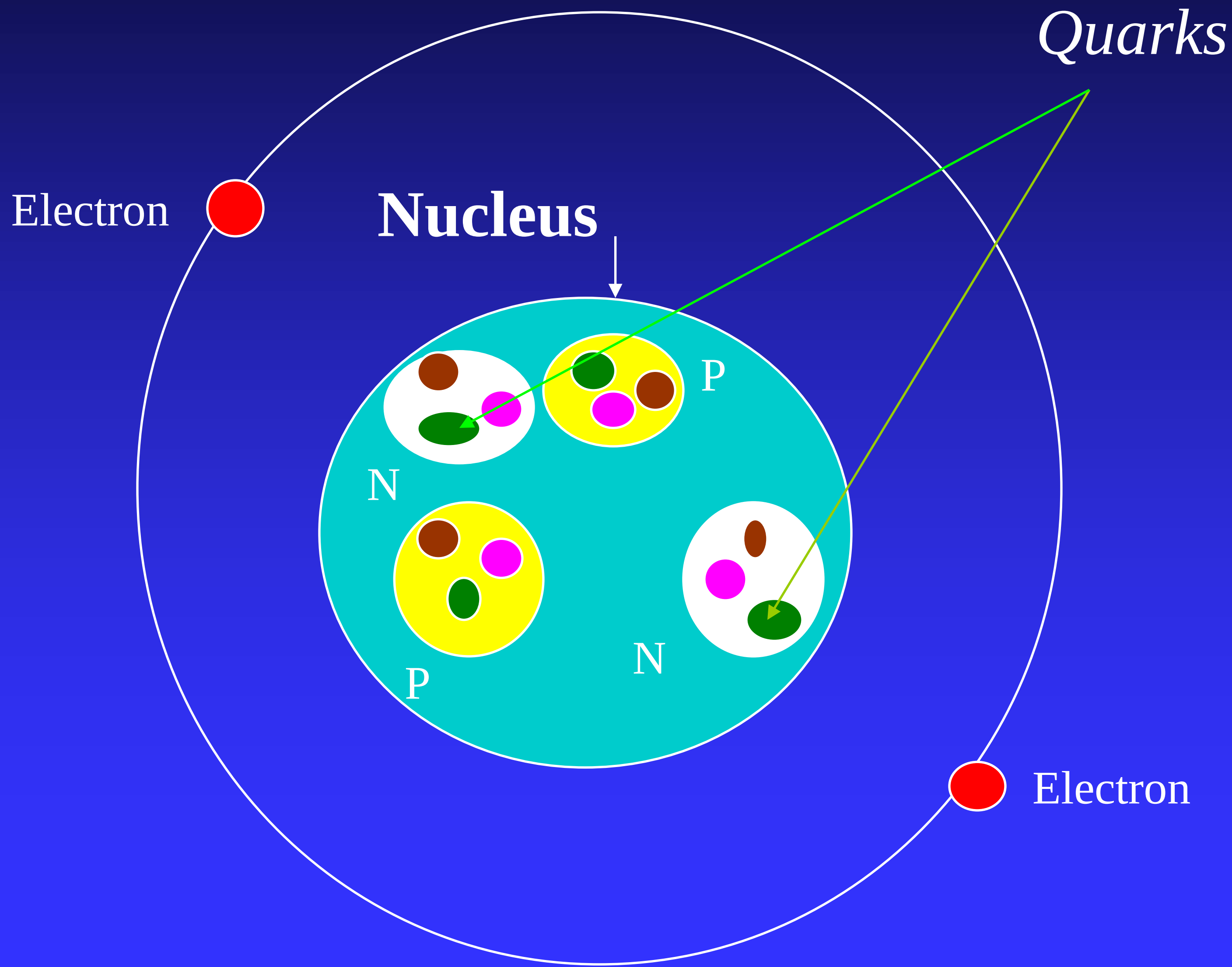

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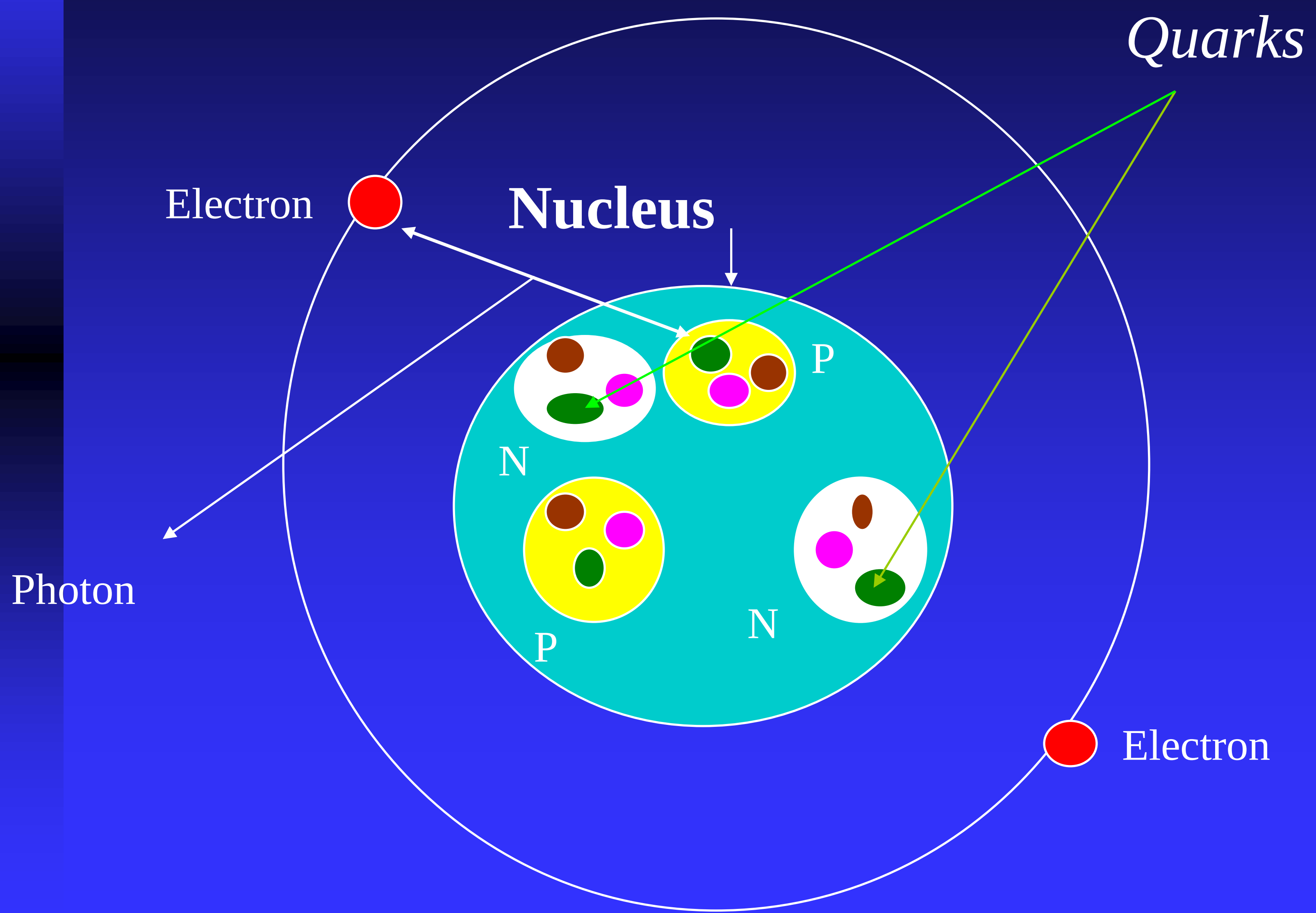

Elementary Particles:

- Quarks (S=1/2)
- Leptons (S=1/2)
- Gauge Bosons (S=1)

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- Quarks:

u* d

u u d

Flavor	Charge (e)	Mass (MeV/C^2)	
u	2/3	< 10	200 - 400
d	-1/3	< 15	200 - 400
s	-1/3	100-300	200 - 400
c	2/3	~ 1,500	
b	-1/3	~ 5,200	
t	2/3	~ 180,000	

Elementary Particles:

- Quarks (S=1/2)
- Leptons (S=1/2)
- Gauge Bosons (S=1)

- Leptons:

	Charge (e)	Mass (MeV/C^2)
e	-1	0.5
ν_e	0	?
μ	-1	~105
ν_μ	0	?
τ	-1	~ 1,700
ν_τ	0	?

Elementary Particles:
- Quarks (S=1/2)
- Leptons (S=1/2)
- Gauge Bosons (S=1)

Gauge Bosons:

	Charge (e)	Mass (MeV/C^2)
Photons	0	0
$W^{+(-)}$	+1 (-1)	80,000
Z	0	91,000
Gluons	0	0

Fundamental Forces:

- Gravitational (10^{-39})
- Electromagnetic (1)
- Nuclear
  - Weak (10^{-11})
  - Strong (10^{3})

Objectives of HEP:

- Identify and classify the elementary particles
- Understand the fundamental forces among the elementary particles
- Unify the fundamental forces into a single theory:

“Theory of Everything”

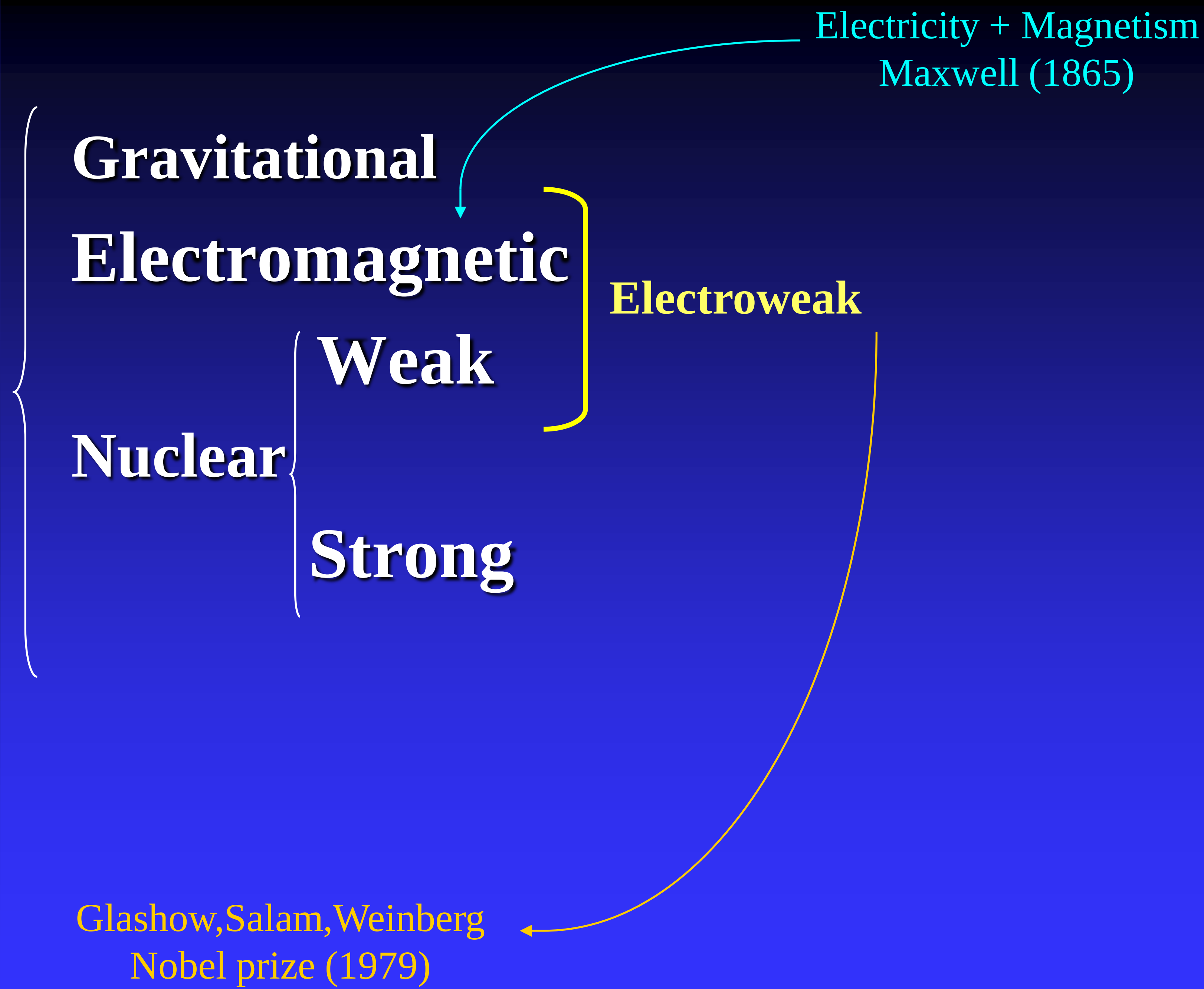
Gravitational

Electromagnetic

Nuclear
- Weak
- Strong

Electricity + Magnetism
Maxwell (1865)

- **Gravitational**
- **Electromagnetic**
- **Nuclear**
  - **Weak**
  - **Strong**


Electricity + Magnetism
Maxwell (1865)
Gravitational
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Electroweak
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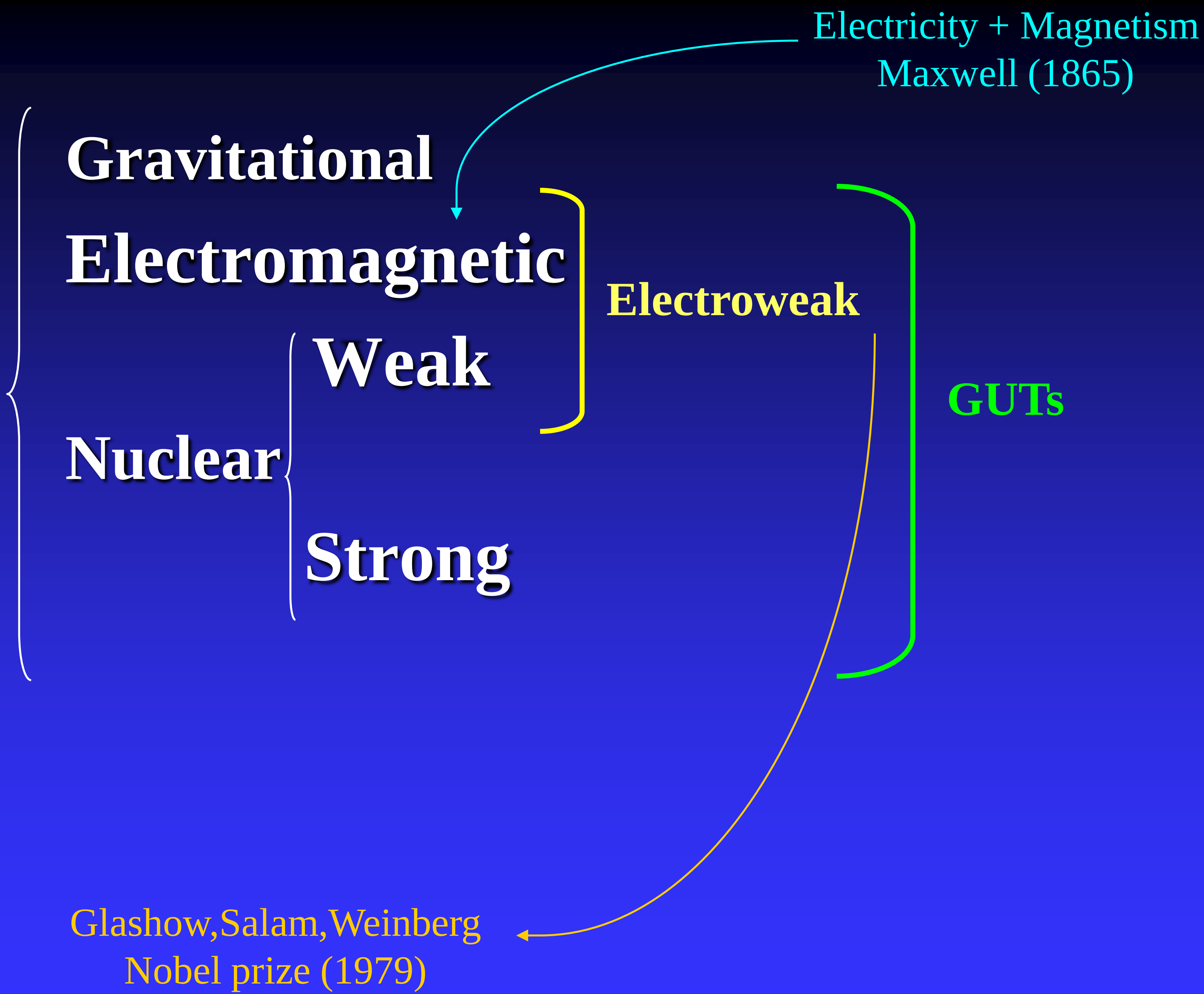
Glashow,Salam,Weinberg
Nobel prize (1979)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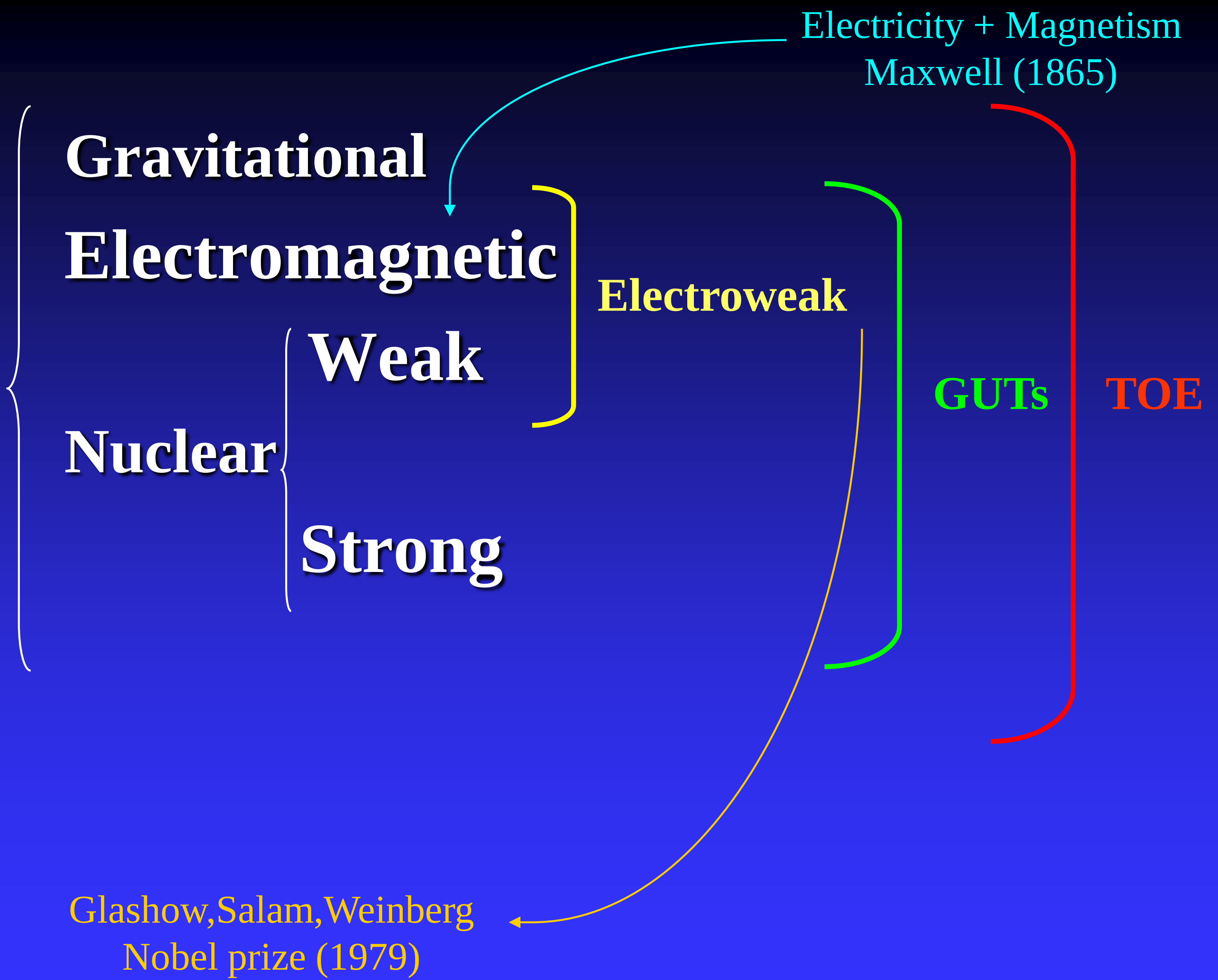
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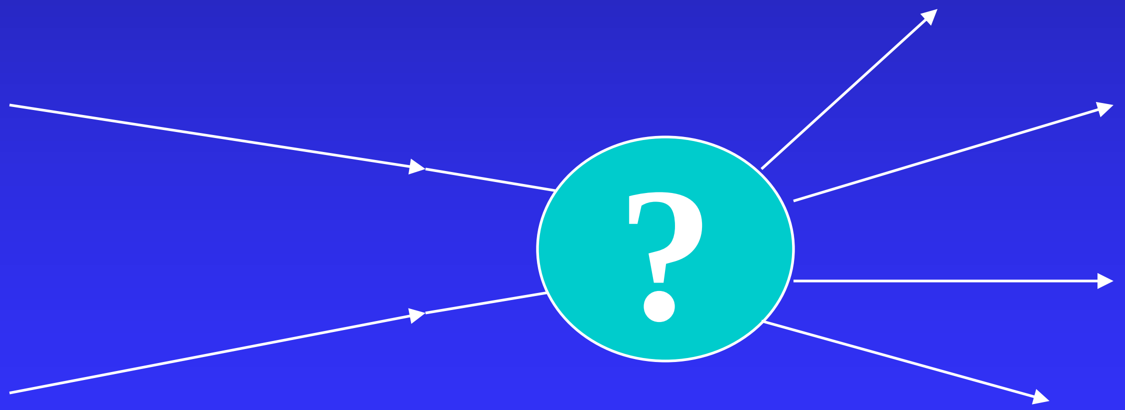
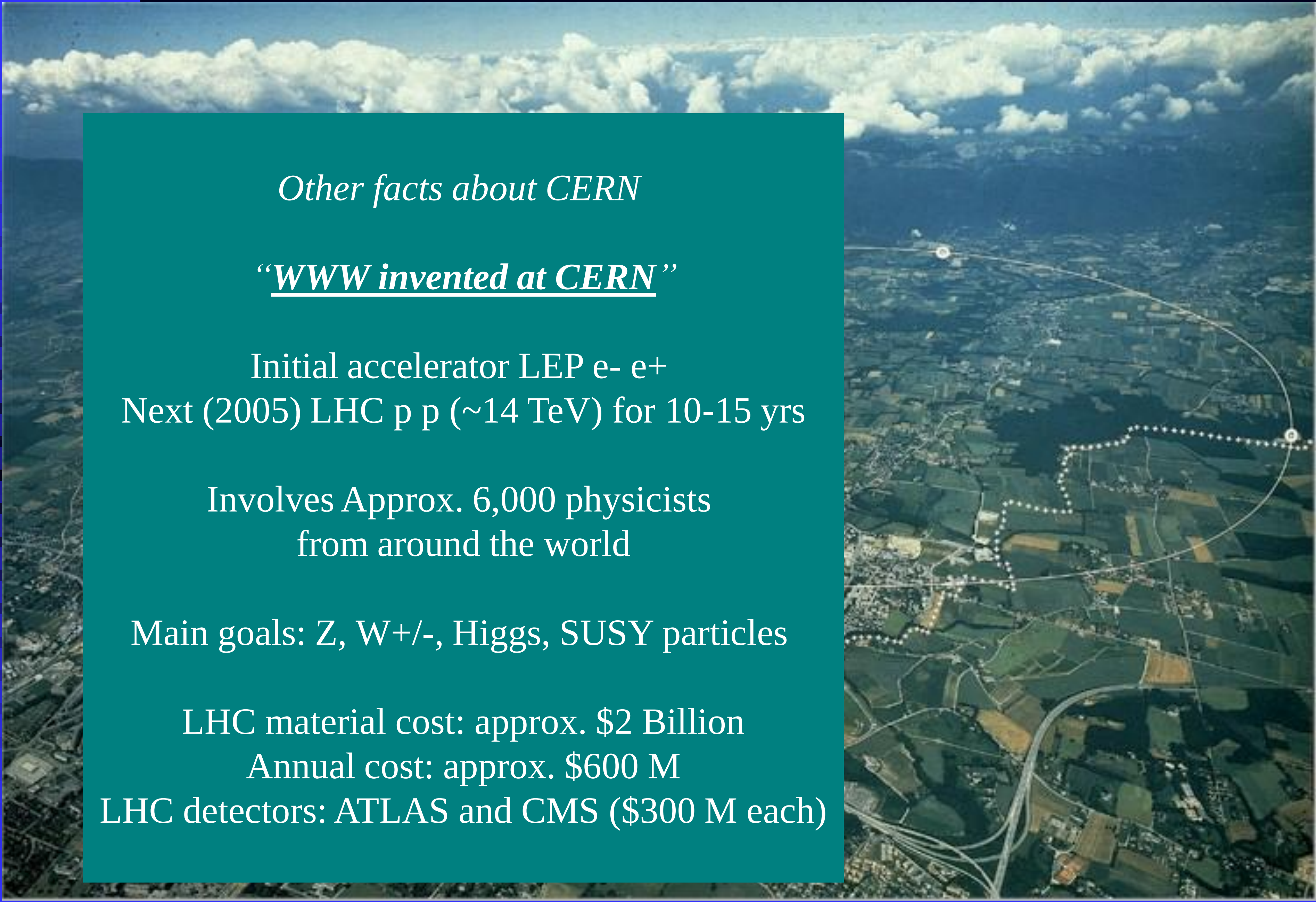
Means and Techniques of HEP:

- **Experimental:**

Particles are accelerated and collided at high speeds (comparable to the speed of light)




Detector:
Approx. 10 m high
Several thousands of tones
Approx. 5.3 mi



Other facts about CERN

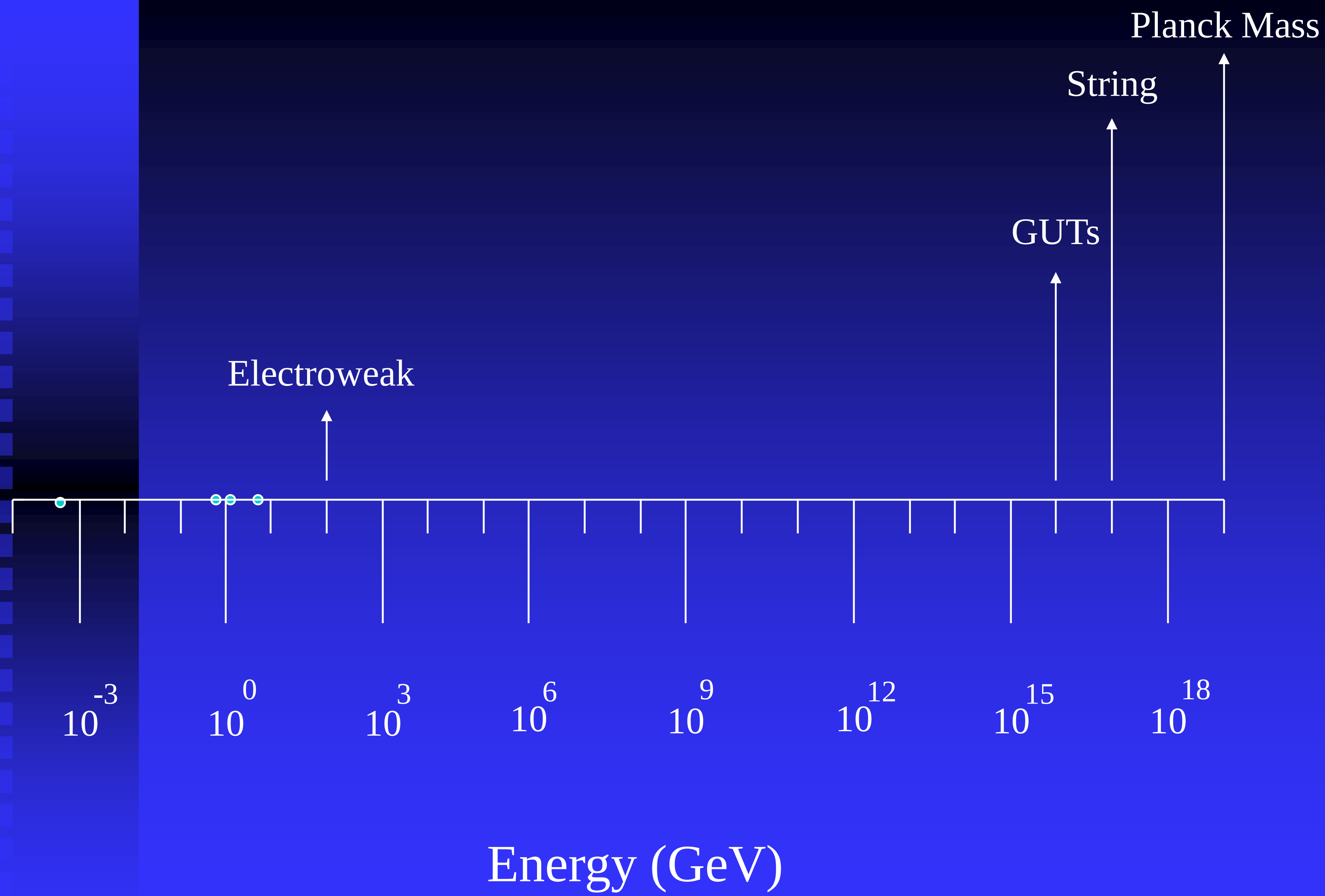
*“**WWW invented at CERN**”*

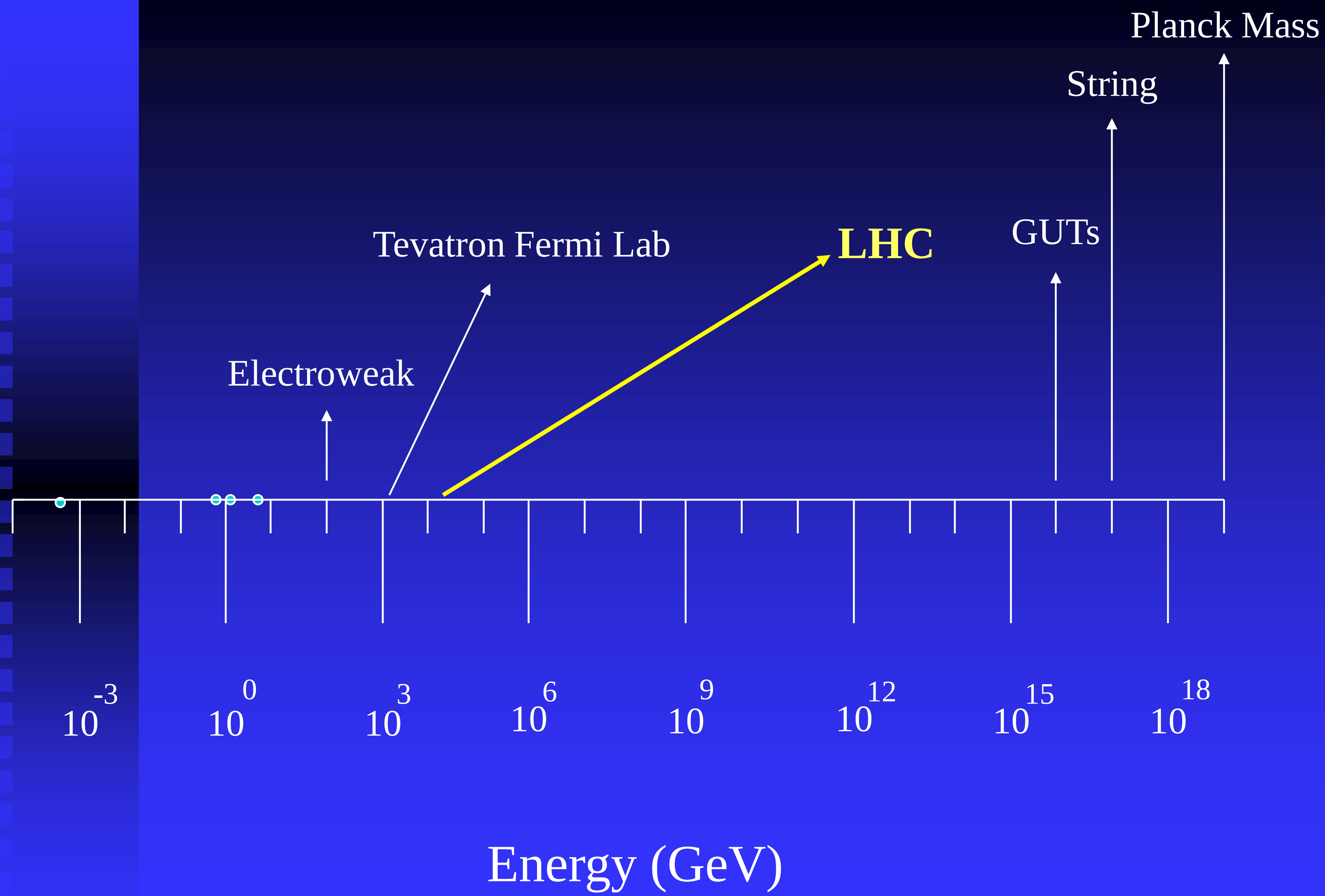
Initial accelerator LEP e- e+
Next (2005) LHC p p (~14 TeV) for 10-15 yrs

Involves Approx. 6,000 physicists
from around the world

Main goals: Z, W+/-, Higgs, SUSY particles

LHC material cost: approx. $2 Billion
Annual cost: approx. $600 M
LHC detectors: ATLAS and CMS ($300 M each)


Planck Mass
String
GUTs
Electroweak
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
Energy (GeV)



Planck Mass
String
GUTs
LHC
Tevatron Fermi Lab
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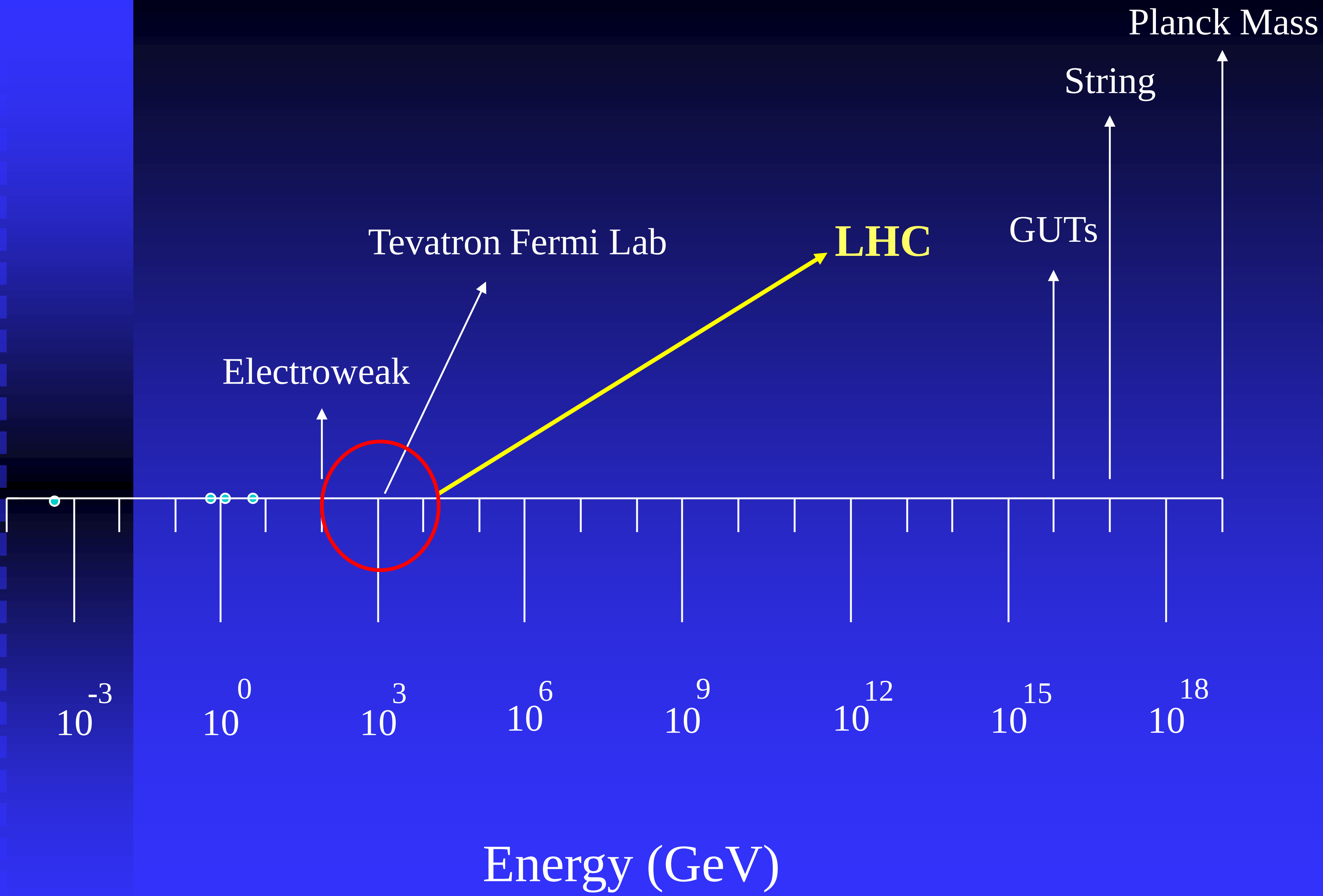
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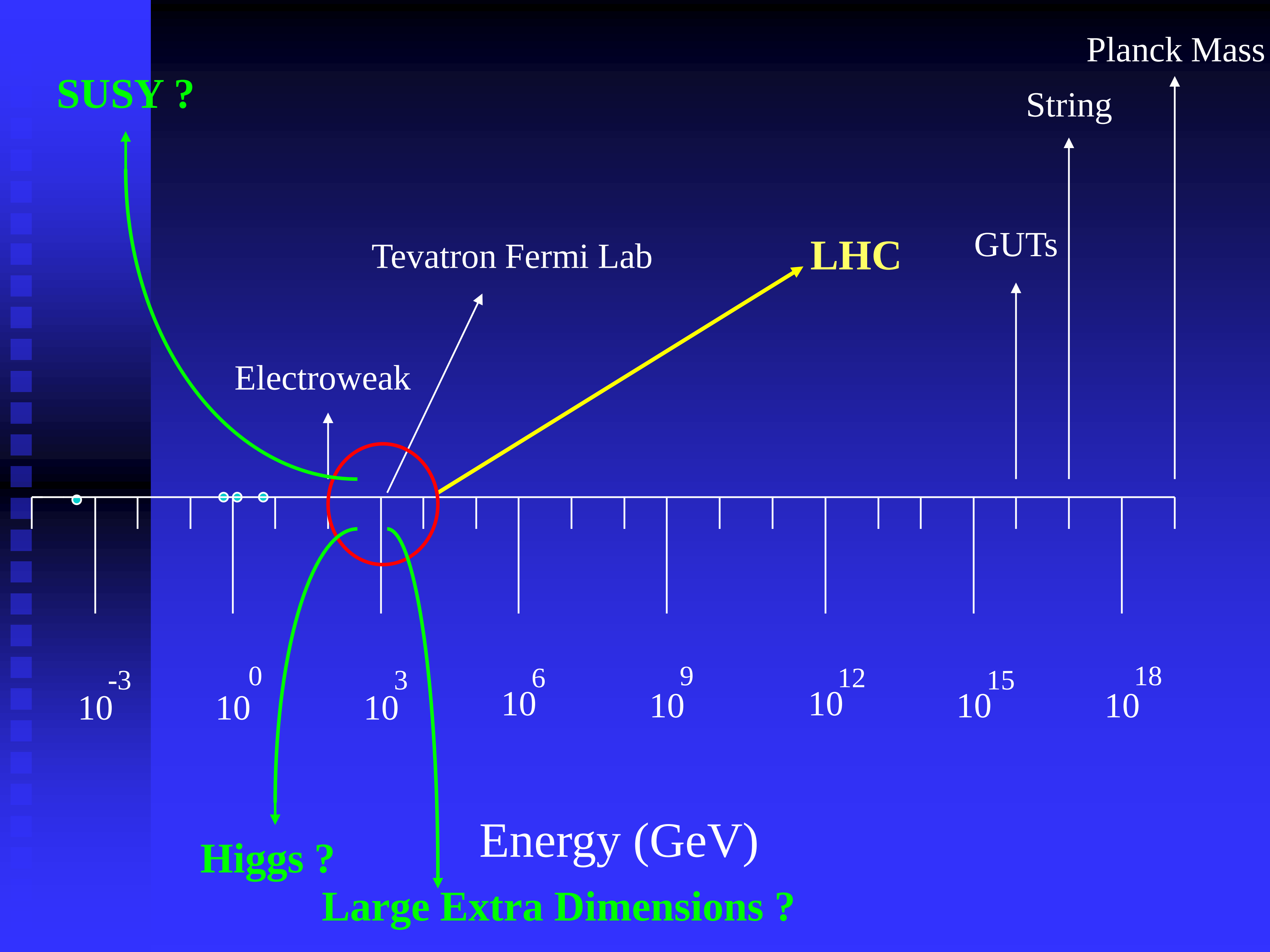

Planck Mass
SUSY ?
String
Tevatron Fermi Lab
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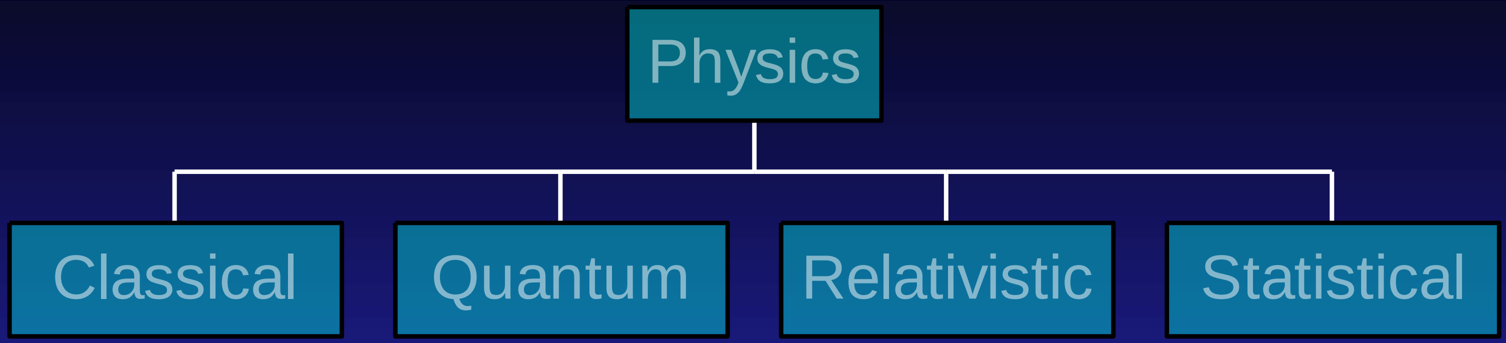
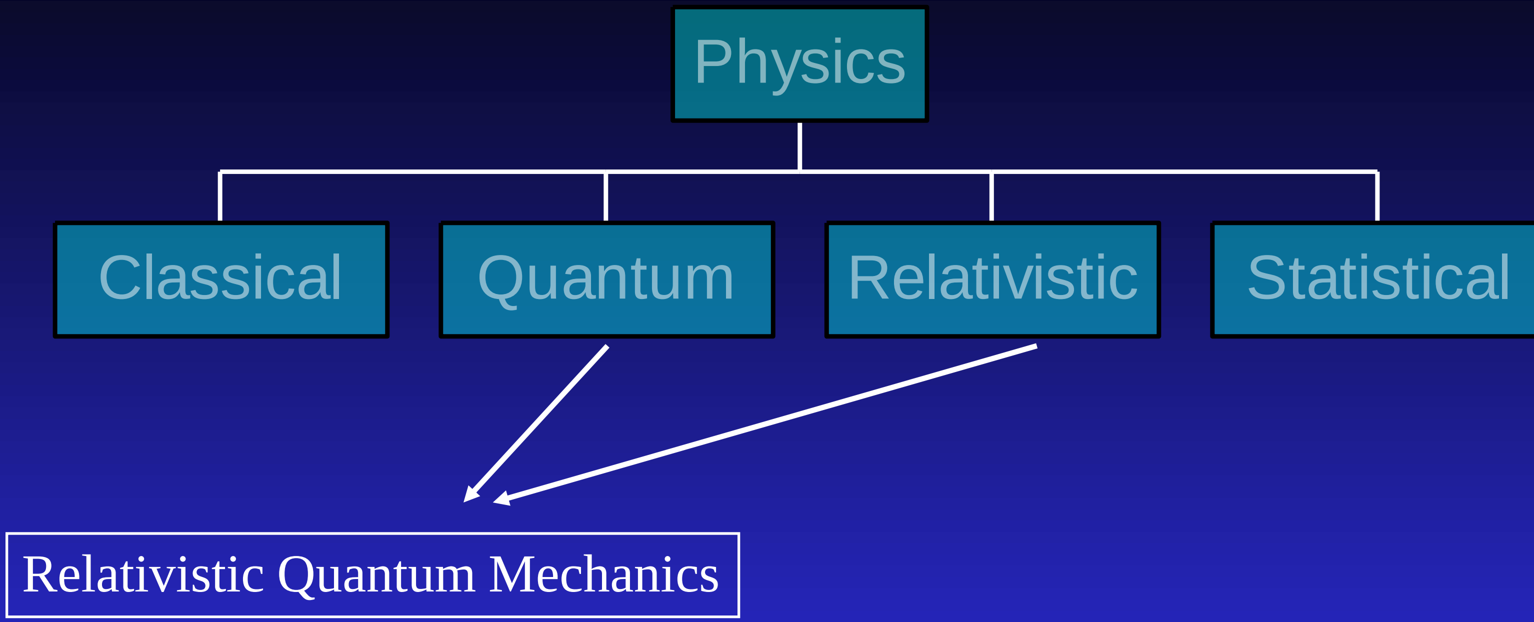
Energy (GeV)
Higgs ?
Large Extra Dimensions ?

Means and Techniques of HEP:

- **Theoretical:**

What is going on here


Physics
Classical
Quantum
Relativistic
Statistical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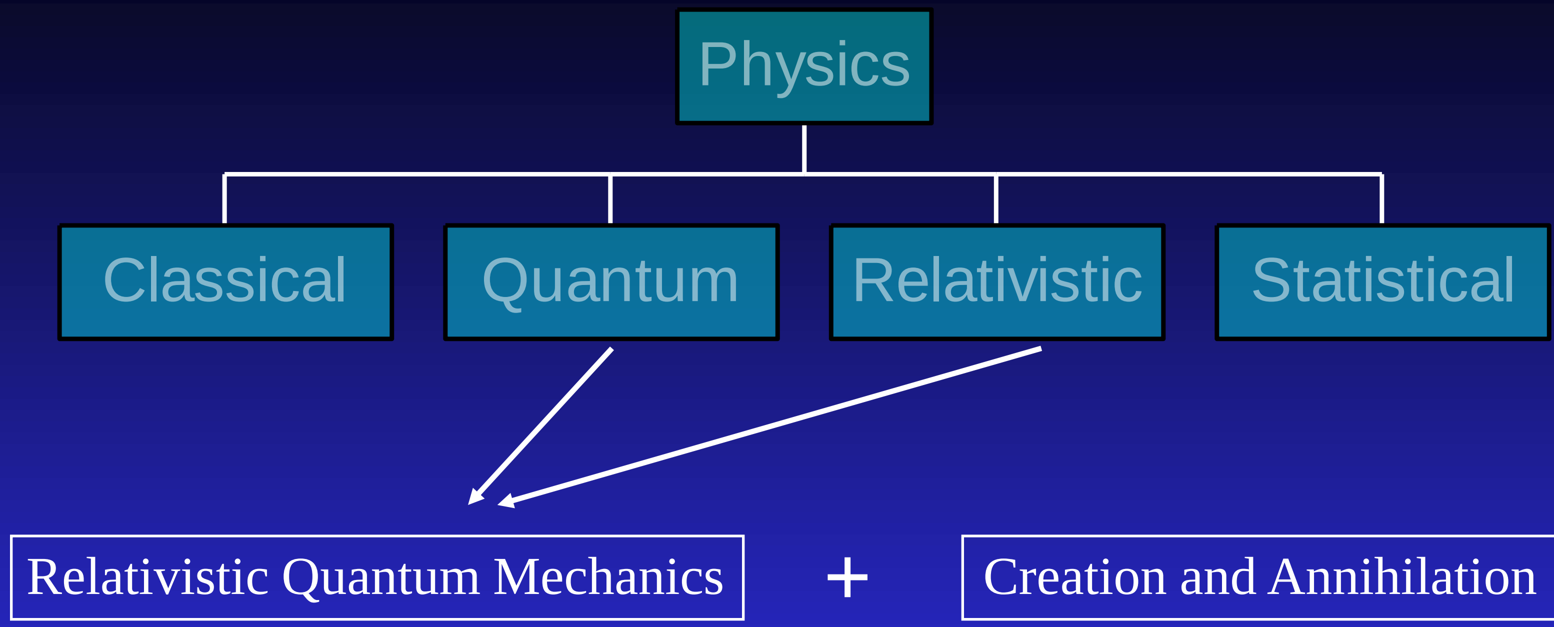
Relativistic Quantum Mechanics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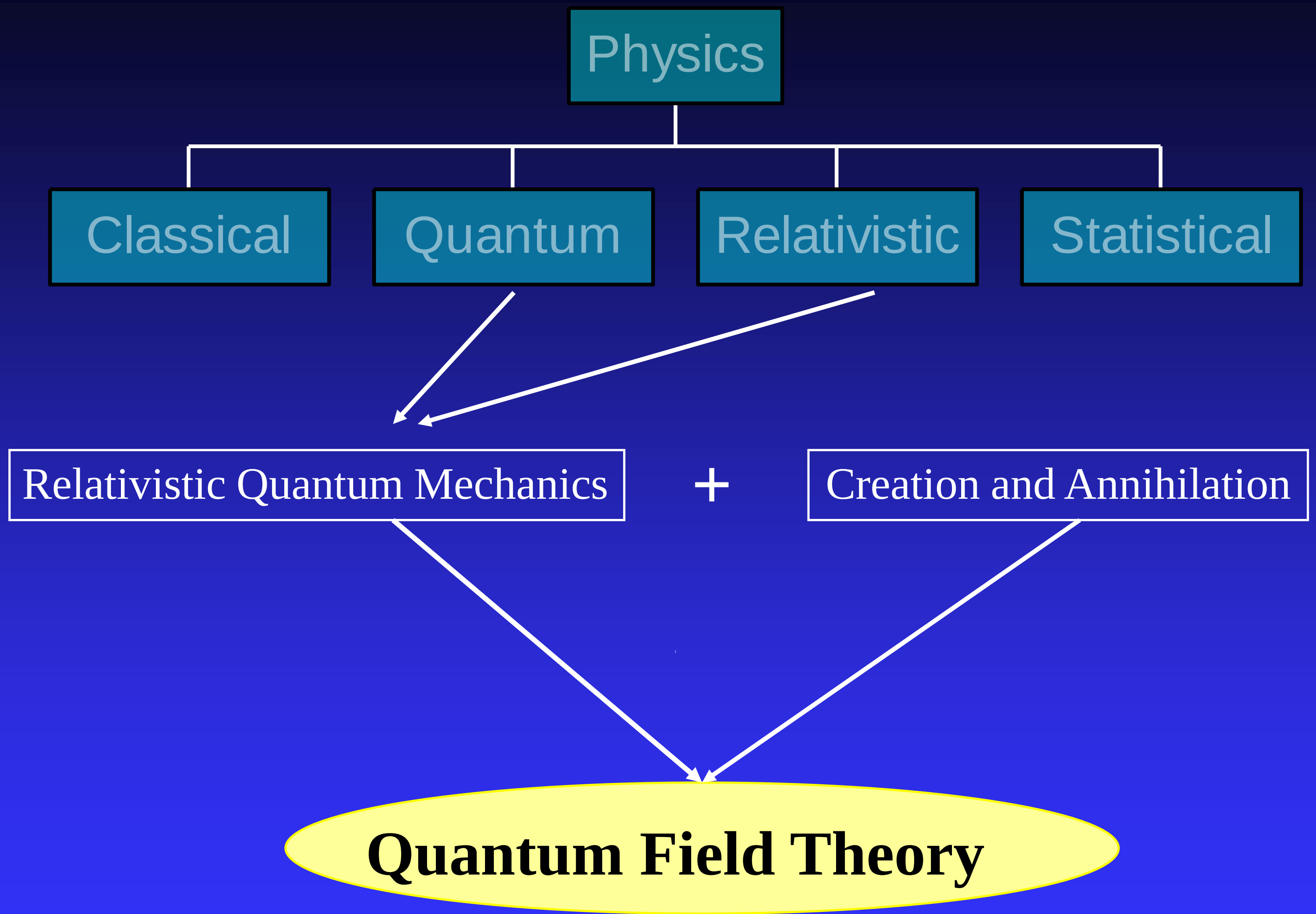
+
Creation and Annihilation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Creation and Annihilation
Quantum Field Theory

Strong Interaction:

- Bounds protons and neutrons inside the nucleus

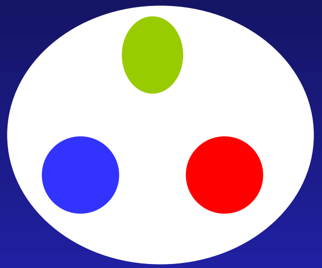
Strong Interaction:

- Bounds protons and neutrons inside the nucleus
- Protons and neutrons $\in$ Hadrons

$$\text{Hadrons}\begin{cases}\text{Baryons } (s = \tfrac{1}{2}, \ldots) \\ \\ \text{Mesons } (s=0,1,\ldots)\end{cases}$$

Simplest internal structure of hadrons in terms of quarks:

<u>Baryons</u>: QQQ



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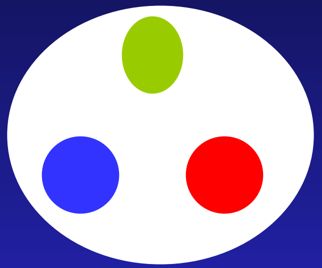

p : uud

charge = 2(2/3e) + (-1/3e) = e

n : udd

charge = (2/3e) + 2 (-1/3e) = 0

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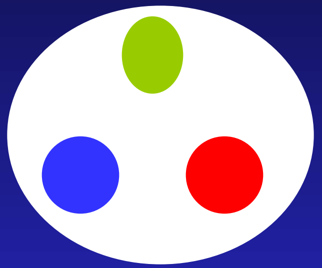

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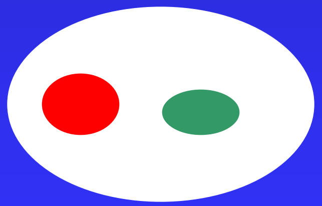
Mesons: QQ*



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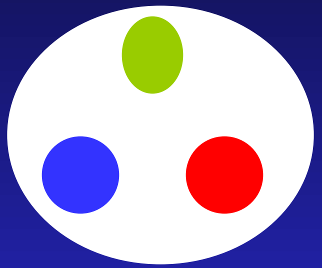

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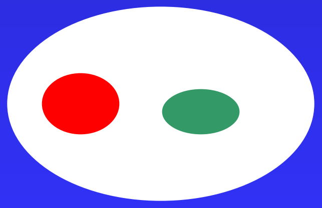

π^+ : u d*

charge = (2/3e) + (1/3 e) = e

Exotic structure of hadrons:

Baryons: QQQQQ*

(Physics Today, Feb. 2004)

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Baryons: QQQQQ*

(Physics Today, Feb. 2004)

Mesons: QQQ*Q*

Hybrid: …QQ* …QQQ*Q* … G

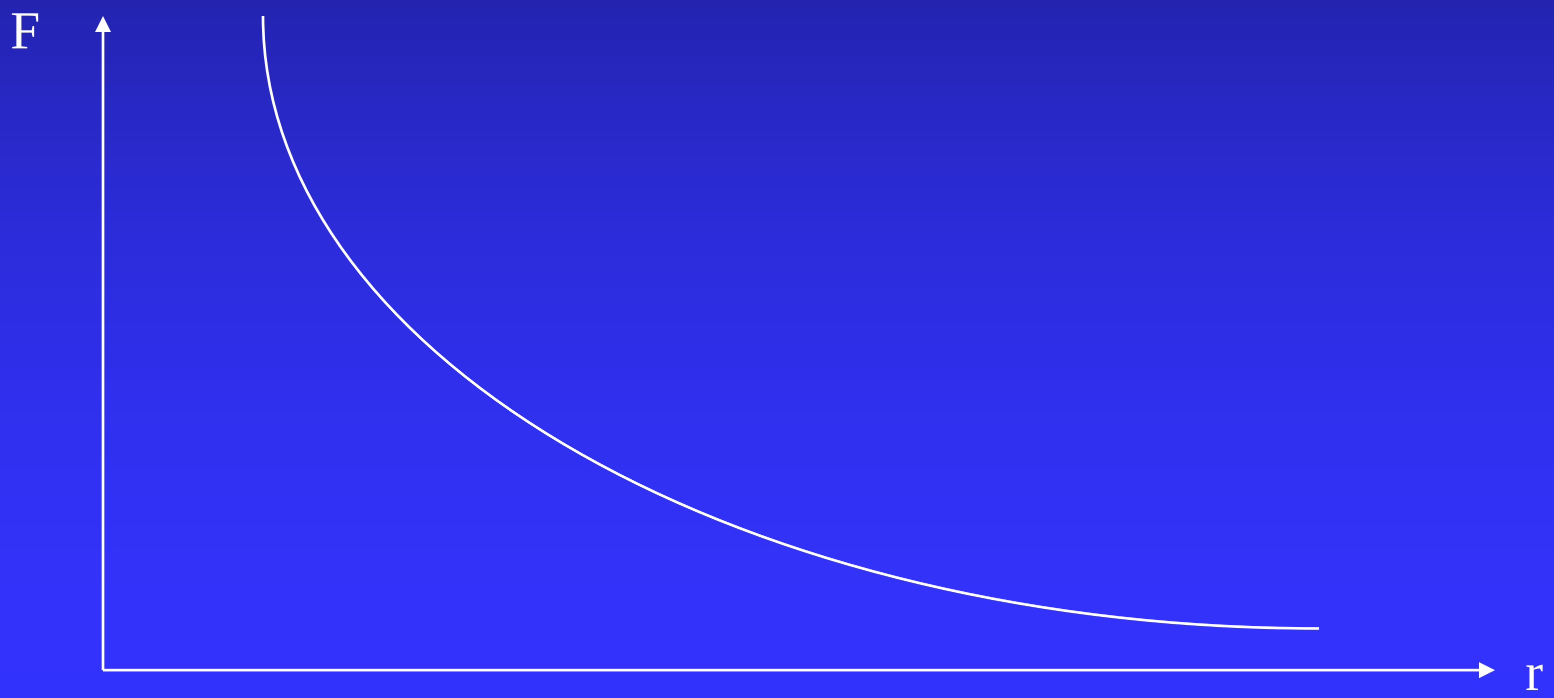
*[A.F., Int.J.Mod.Phys. A **19**,2095 (2004)]*

Basic Properties of the Strong Interaction:

- <u>**Confinement**</u>: Quarks are bounded inside the hadrons (no free quarks)
- <u>**Asymptotic Freedom**</u>: The strength of the interaction decreases with energy

Coulomb's Force:

$$|F| = 1/(4\pi\varepsilon)\ qQ/r^2$$



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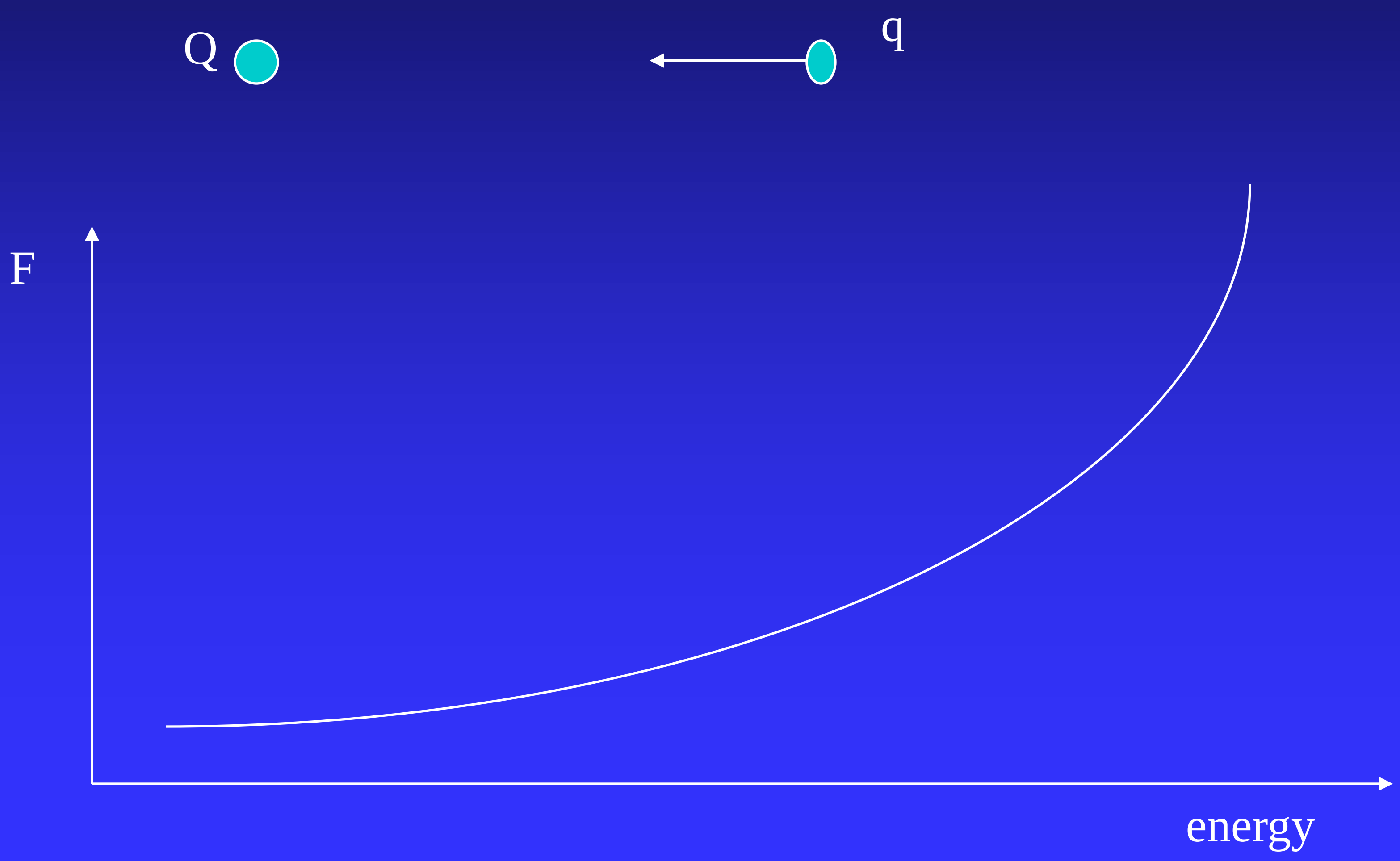
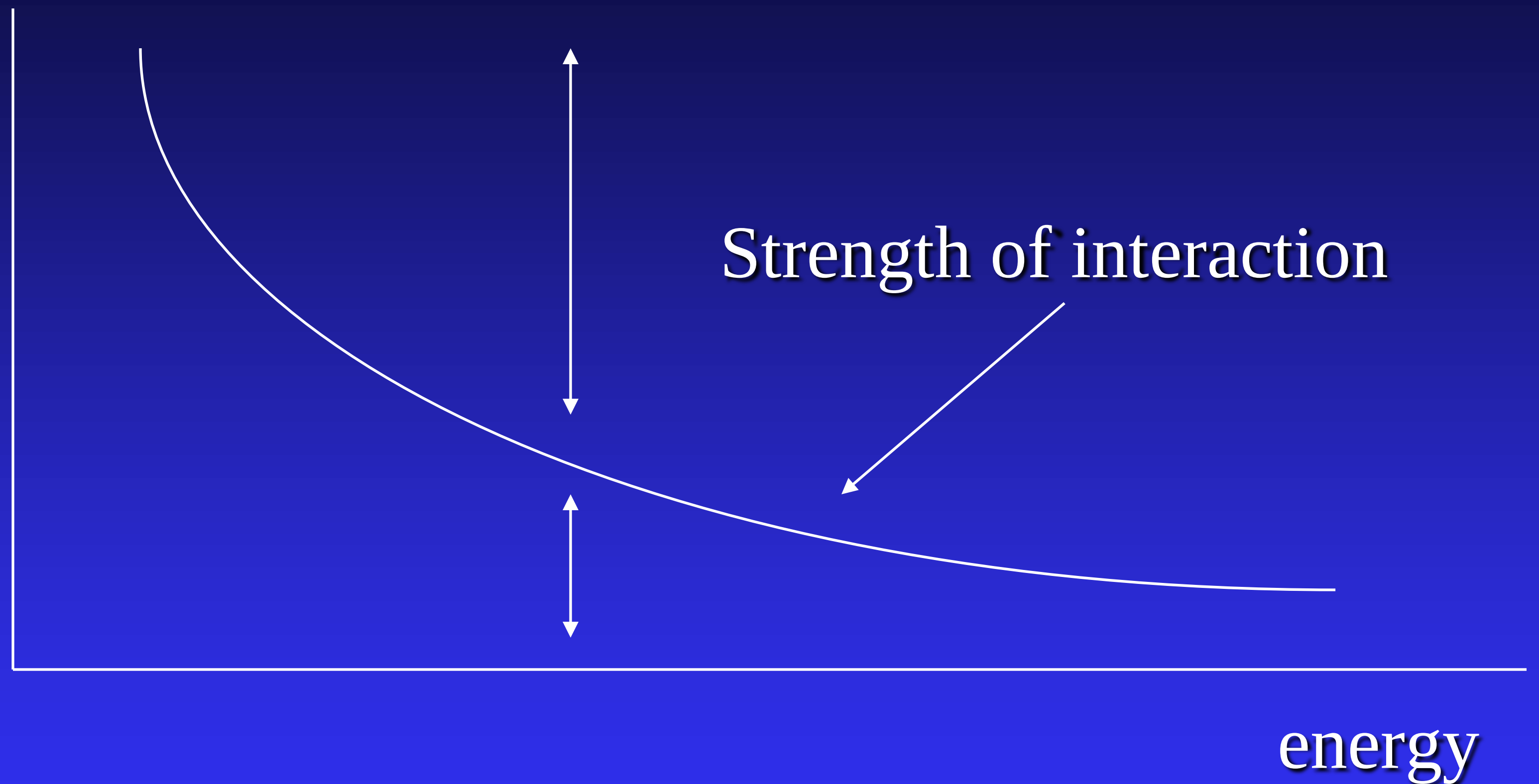


Strong Interaction:



<u>**Experimental Observation**</u>

Physics Nobel Prize (1990)

Friedman, Kendall & Taylor

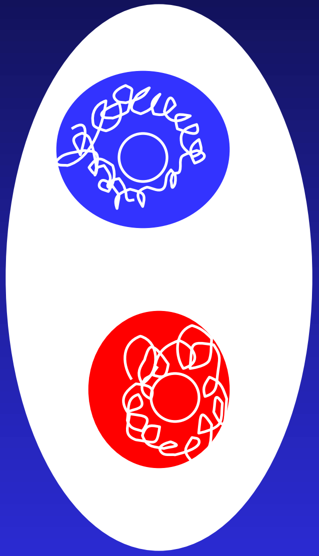
<u>**Theoretical Explanation**</u>

Physics Nobel Prize (2004)

Gross, Politzer & Wilczek

Why are there two different types of mass for light quarks?

Low energy processes:



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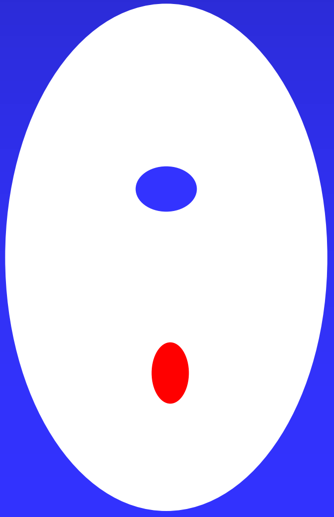

The computational difficulty:

A simple description:

$$F(\mathbf{a}) = F(0) + F'(0)\,\mathbf{a} + \tfrac{1}{2} F''(0)\,\mathbf{a}^2 + \ldots$$

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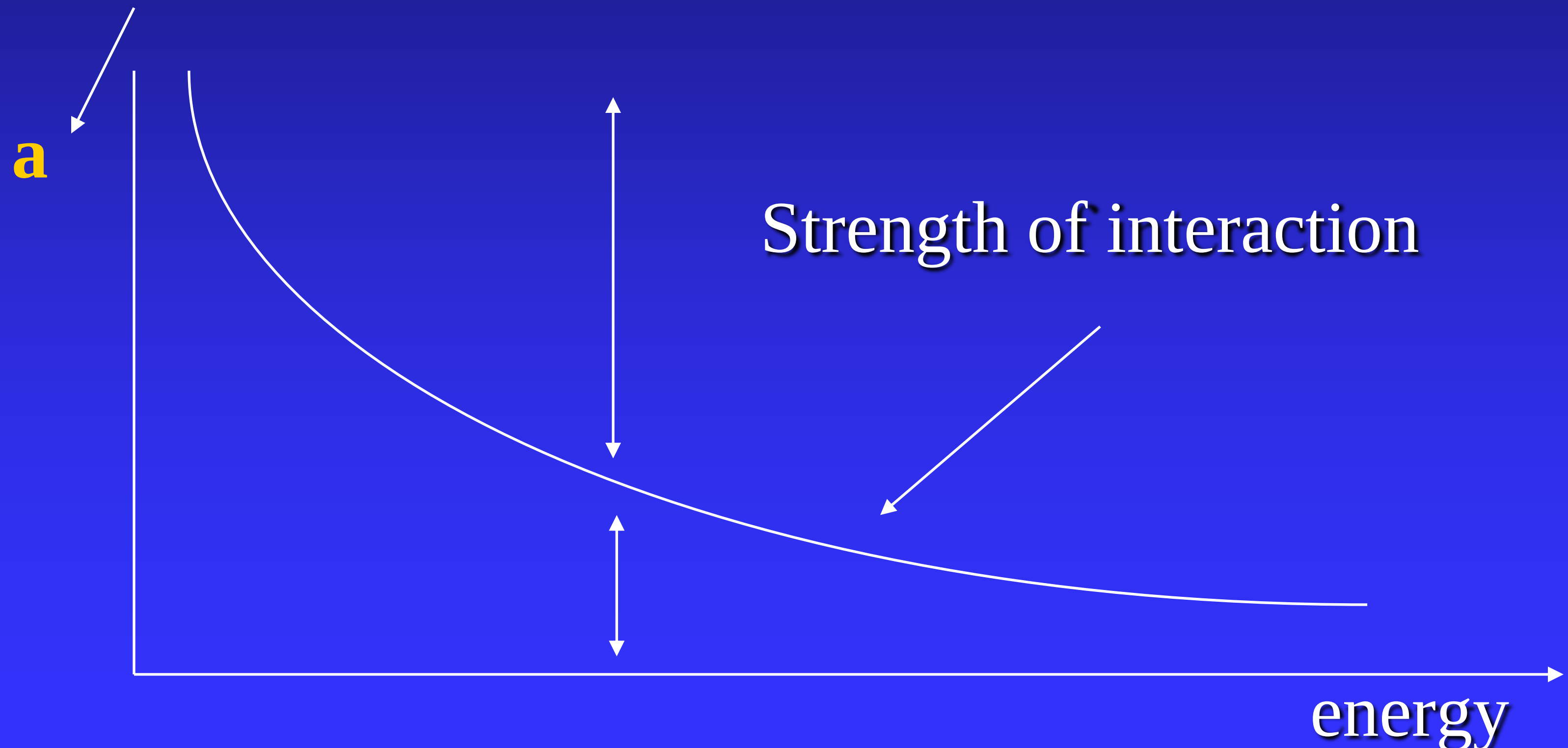
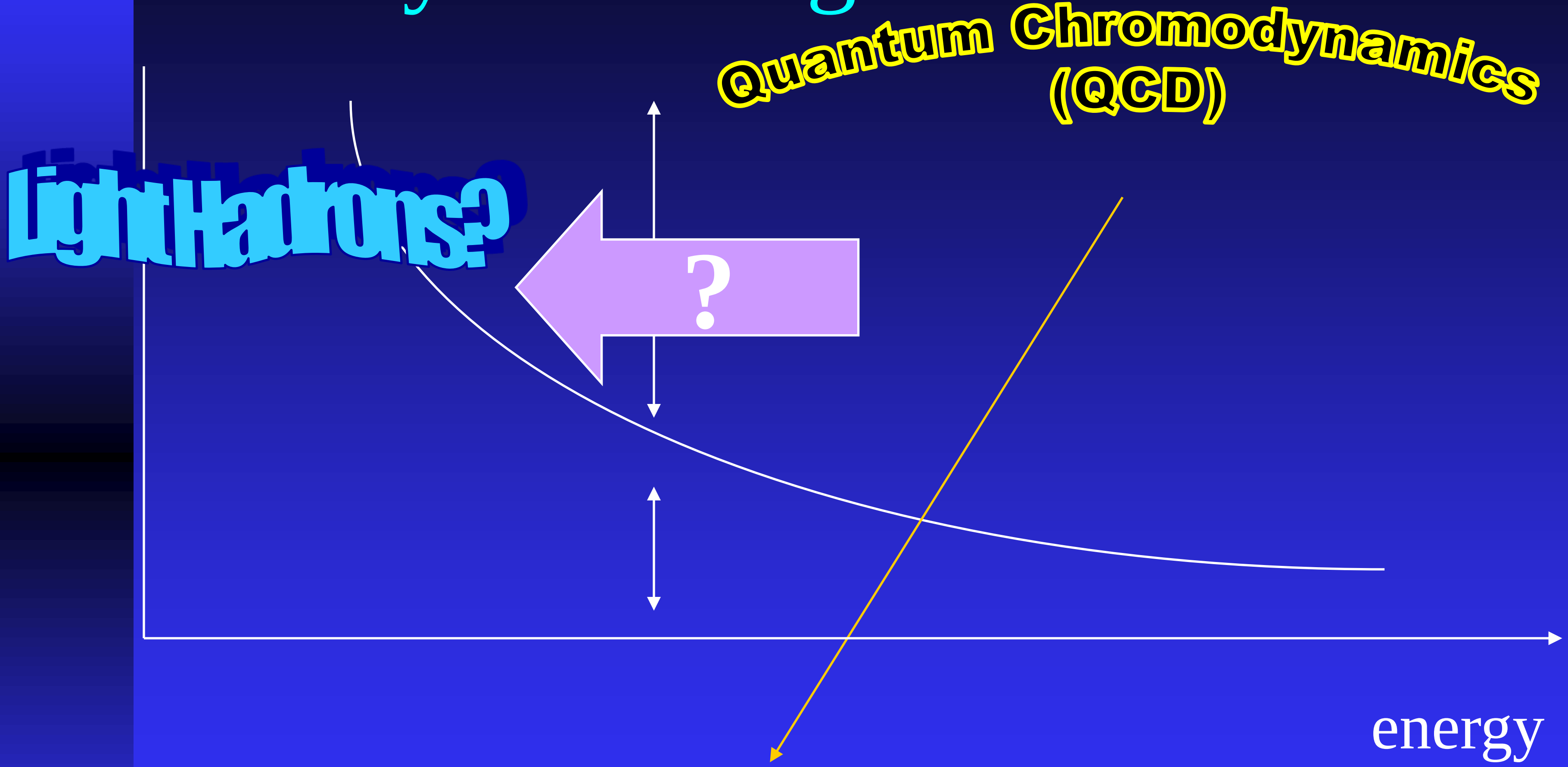
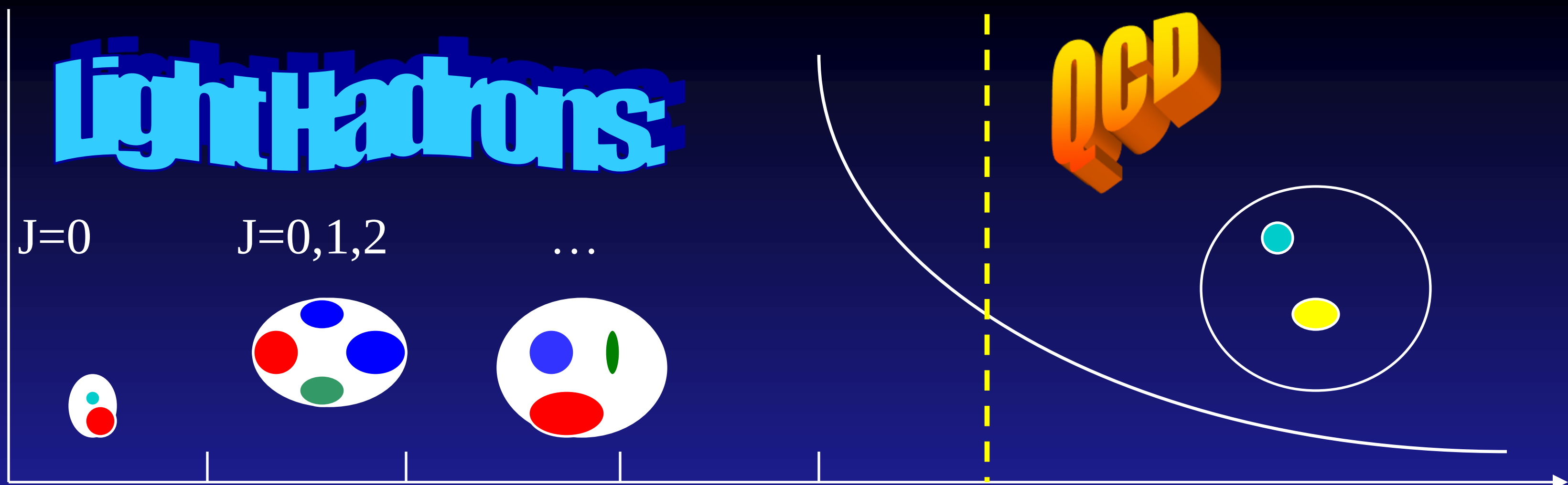


Theory of Strong Interactions:



QCD is a non abelian gauge field theory based on the color quantum number of quarks



Effective theories: Models that are formulated in terms of hadrons

Chiral perturbation theory (< 500 MeV)

Chiral Lagrangians (< 2 GeV)

…

Lattice QCD: Computes physical quantities by directly working with the quark fields

QCD Sum-rules: Provides a bridge between QCD and the physics of hadrons

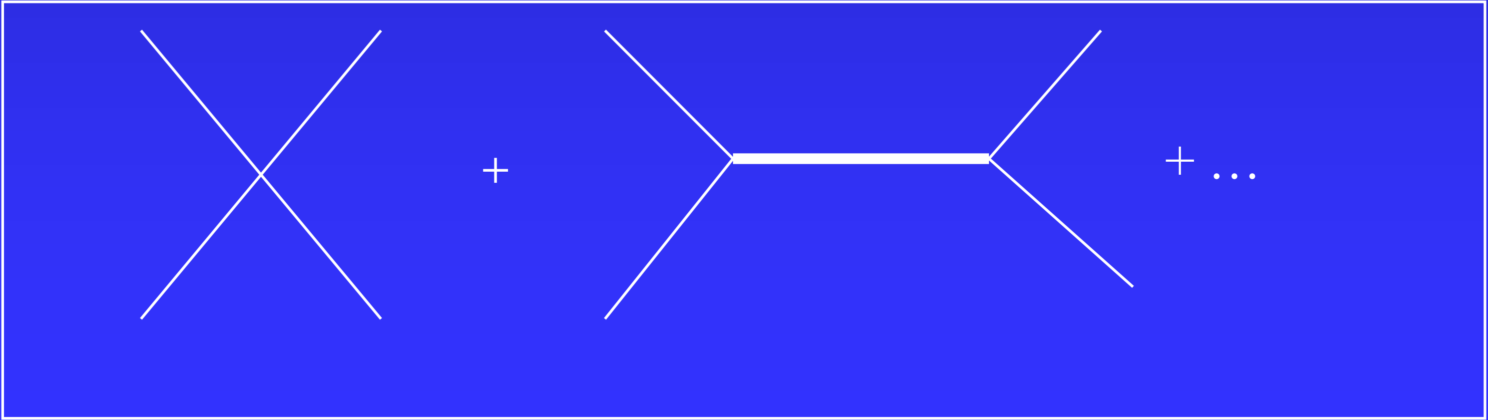
Chiral Lagrangian probe of intermediate states:

Symmetries of the low energy strong interaction

↓

Lagrangian

↓



Future Outlook:

- A number of important experiments will be performed within the next 10-15 years

- Exciting directions for research in HEP, such as neutrino physics, CP violation, beyond the SM, SUSY, Higgs physics, …

- Students can participate at different levels, from undergraduate projects to Ph.D. theses

Appendix

Why should quarks have color?

Why should quarks have color?

Experiment:

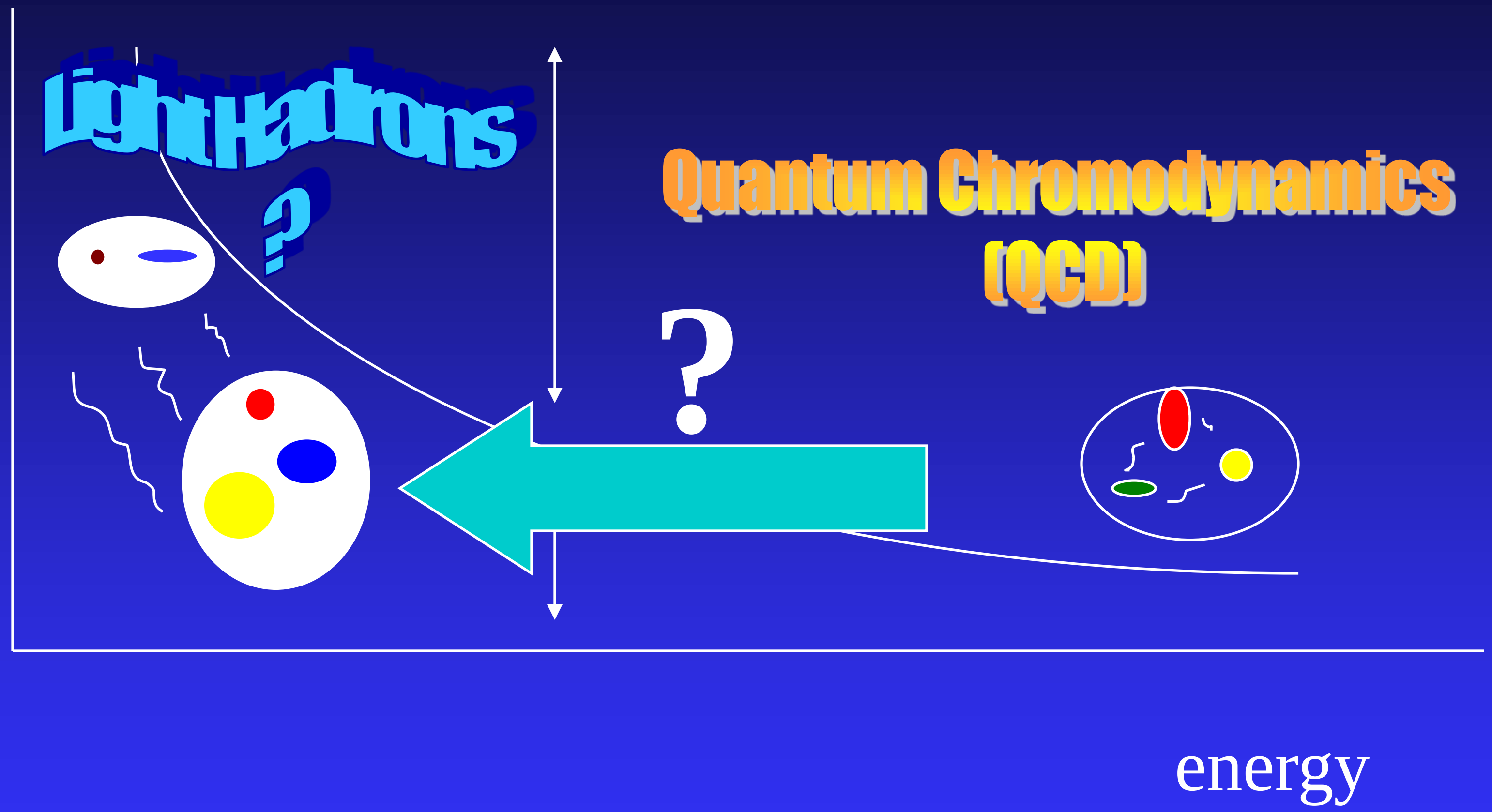
- Δ^{++} :

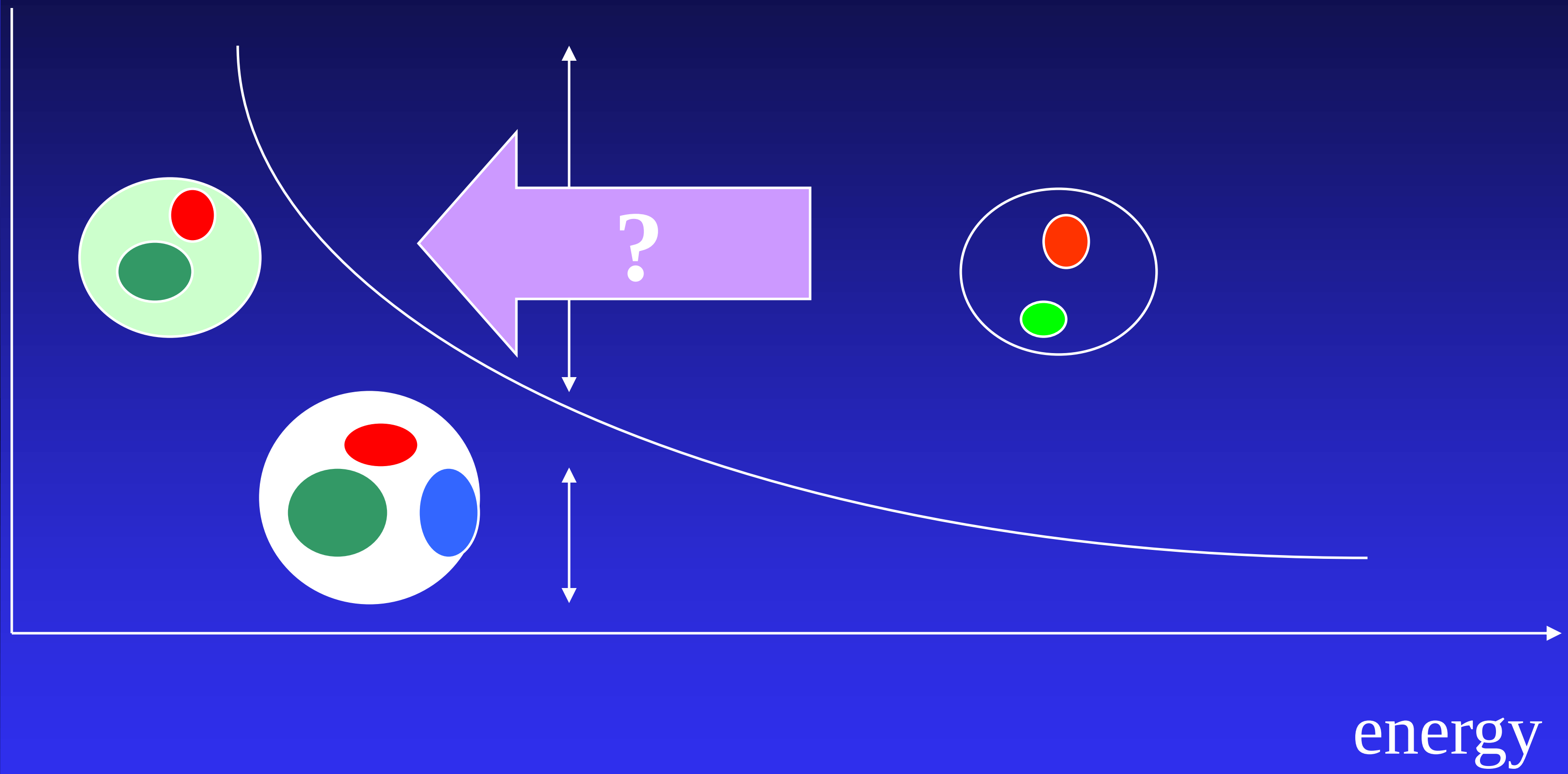
  Spin = 3/2

  Charge = +2e

⟹ Δ^{++} : $U\uparrow U\uparrow U\uparrow$

Theory of Strong Interactions:




?
energy