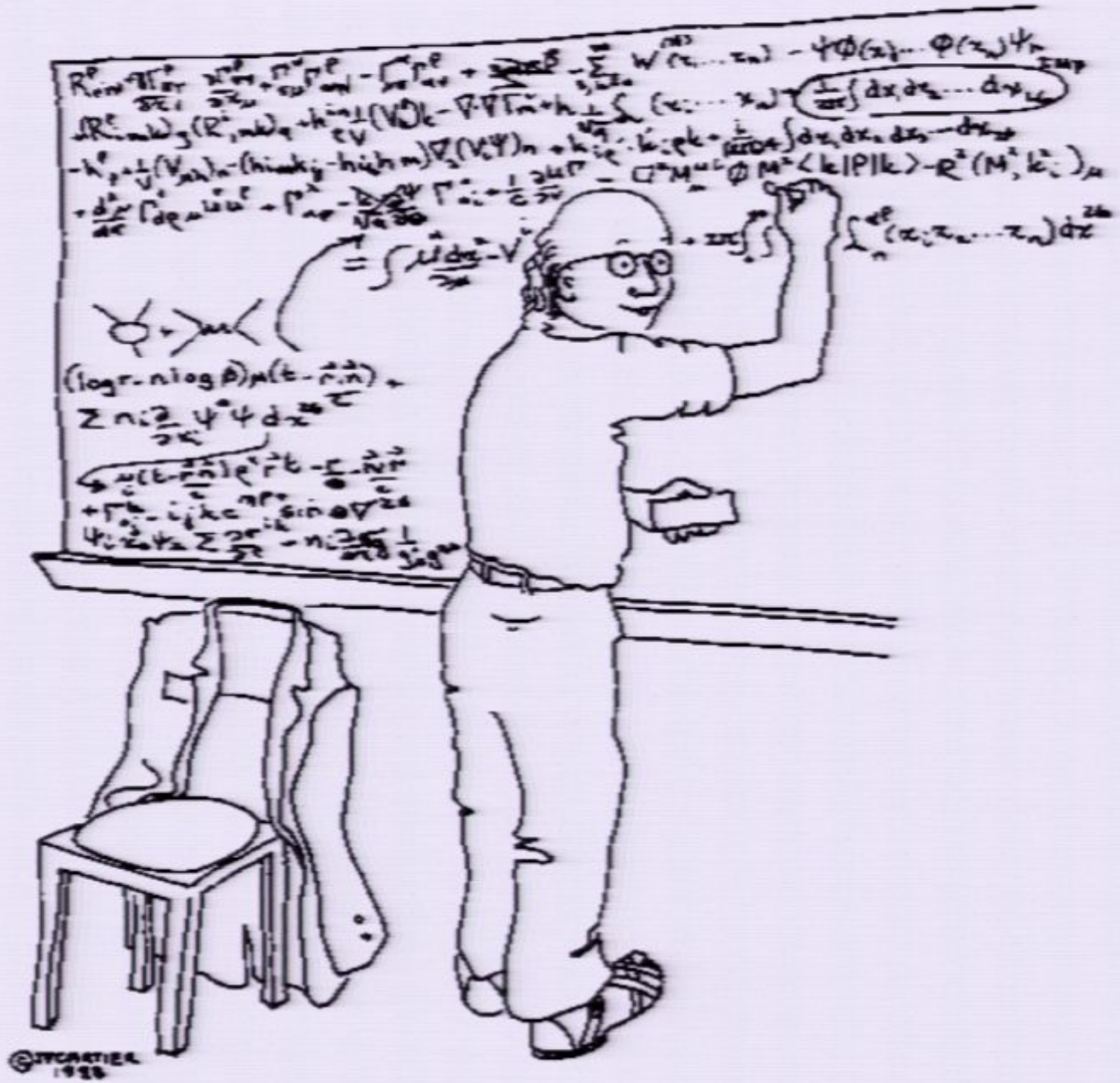
Title: Adventures in Superstrings

Date: Jul 21, 2010 10:30 AM

URL: http://pirsa.org/10070033

Abstract: Physics emerged from the twentieth century with two remarkably successful descriptions of nature which stand in striking contrast. Quantum mechanics describes the subatomic realm with intrinsic uncertainties and probabilities. On the other hand, Einstein's general relativity describe gravitational phenomena in an exacting geometric arena. Theoretical physicists have struggled for over fifty years trying to combine these views in a single unified framework. More recently, superstring theory has drawn a huge amount of interest as a leading contender to provide such a unification. Superstring theory is a theory of strings, branes, extra spacetime dimensions and much more. In my lecture, I will try to give a flavour for what superstring theory is all about and why physicists, like myself, continue to be so excited about this, perhaps the final theory.



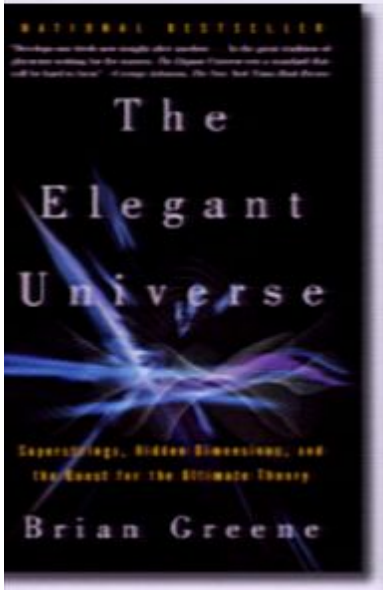
"At this point we notice that this equation is beautifully simplified if we assume that space-time has 92 dimensions."

The Superstring Adventure

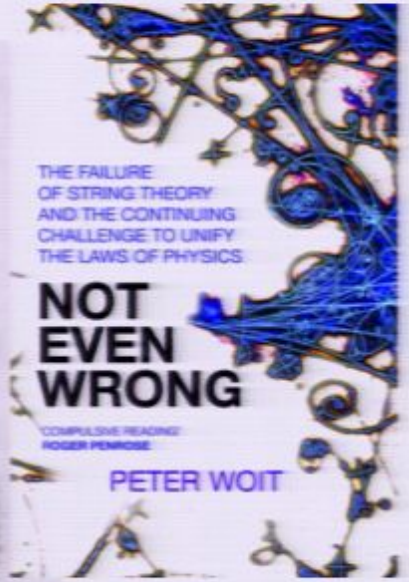
Robert Myers

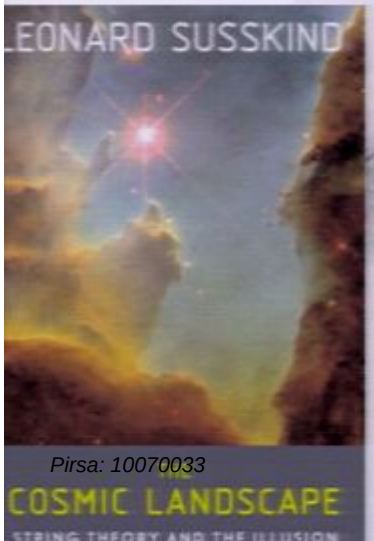
(ISSYP: July 21, 2010)

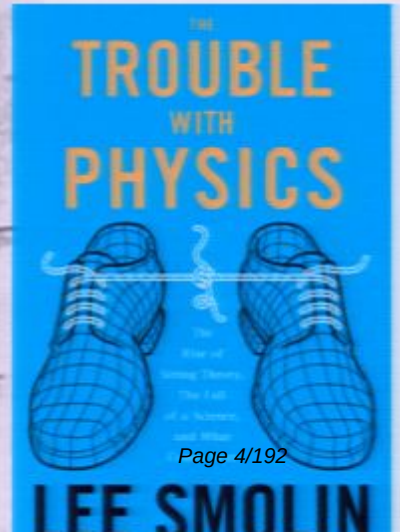
New Yorker magazine:



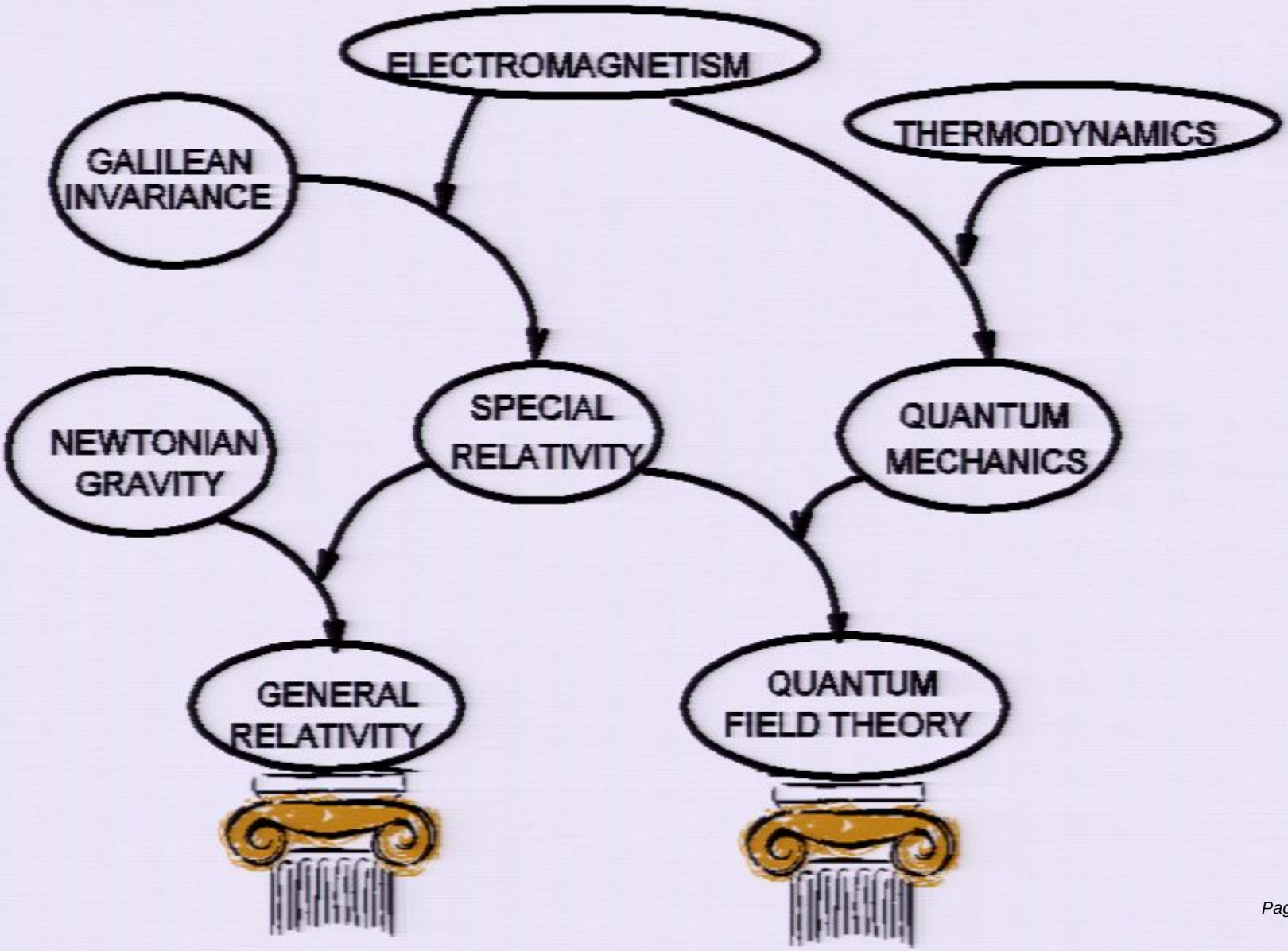
"It's all string theory to me."







Physics of the 20th century: A grand synthesis and progression of ideas!



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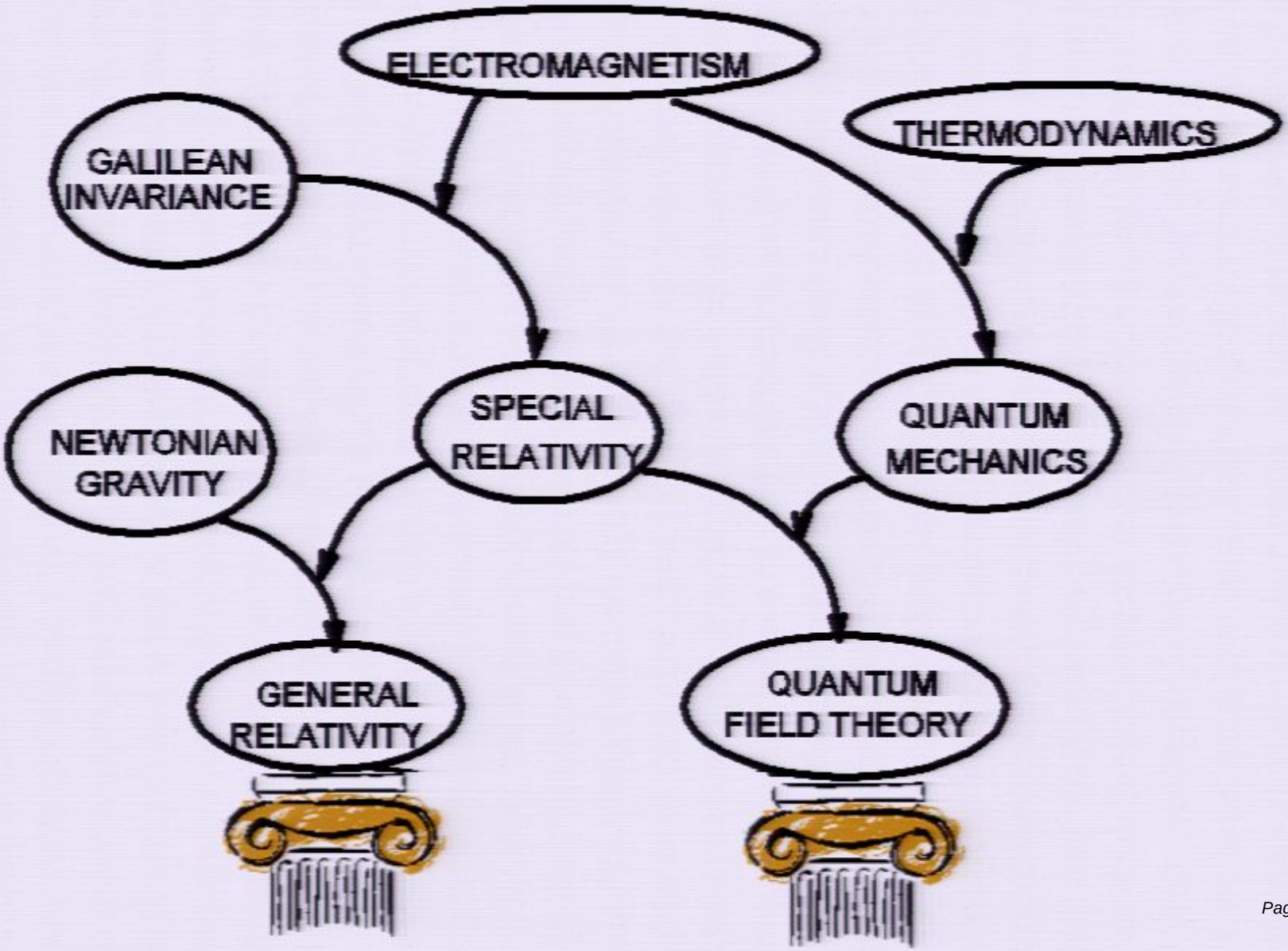

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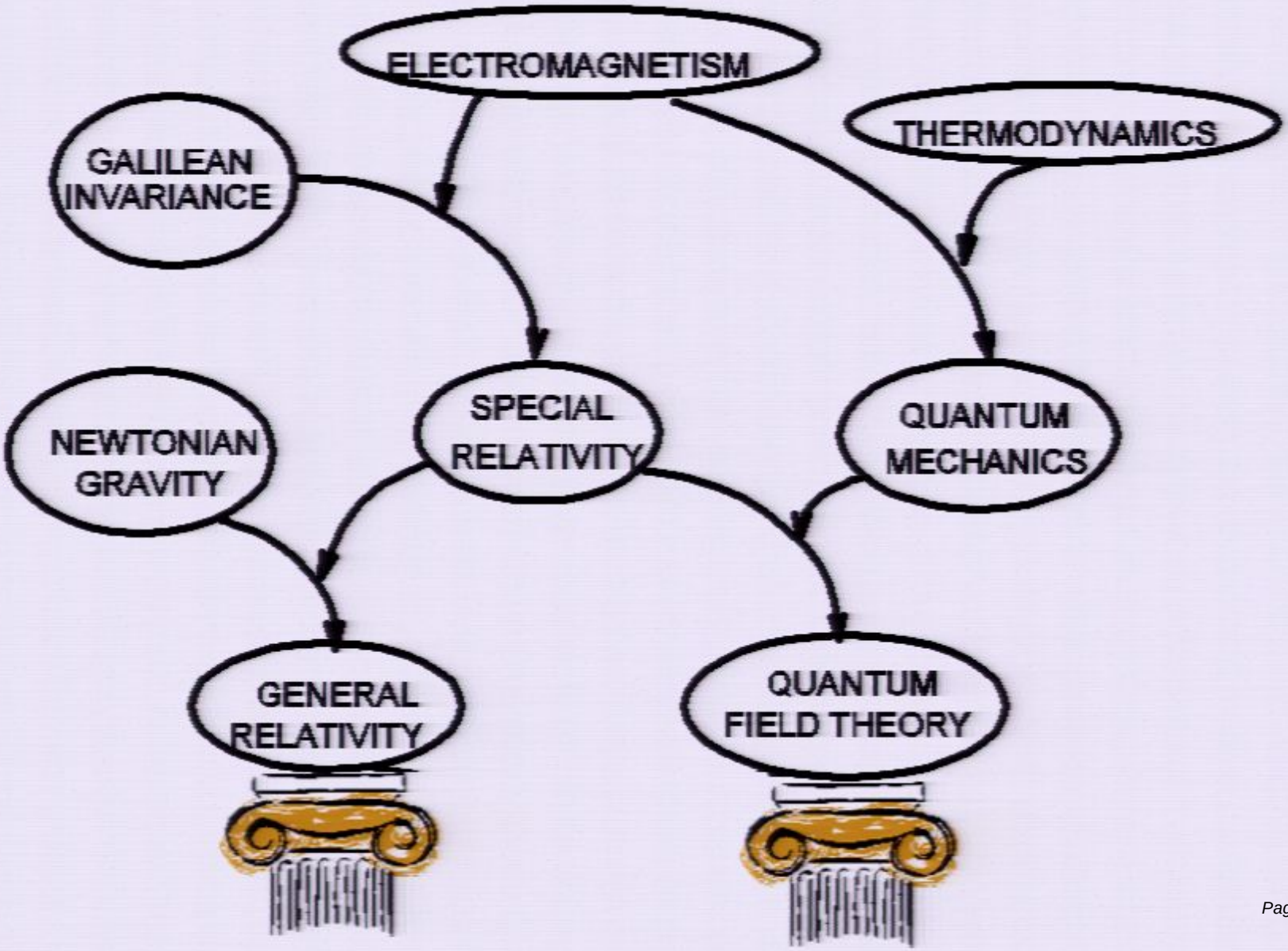

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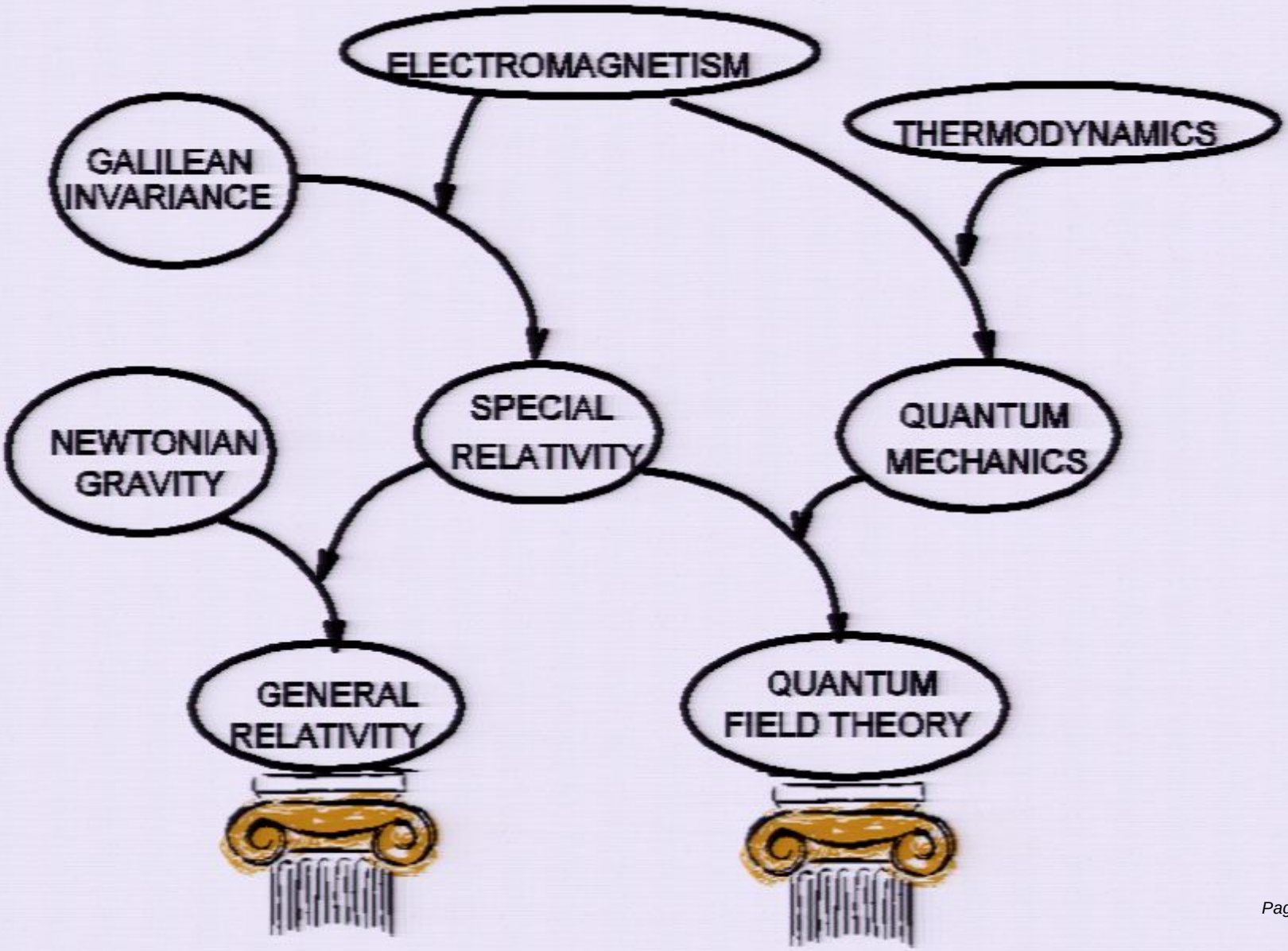

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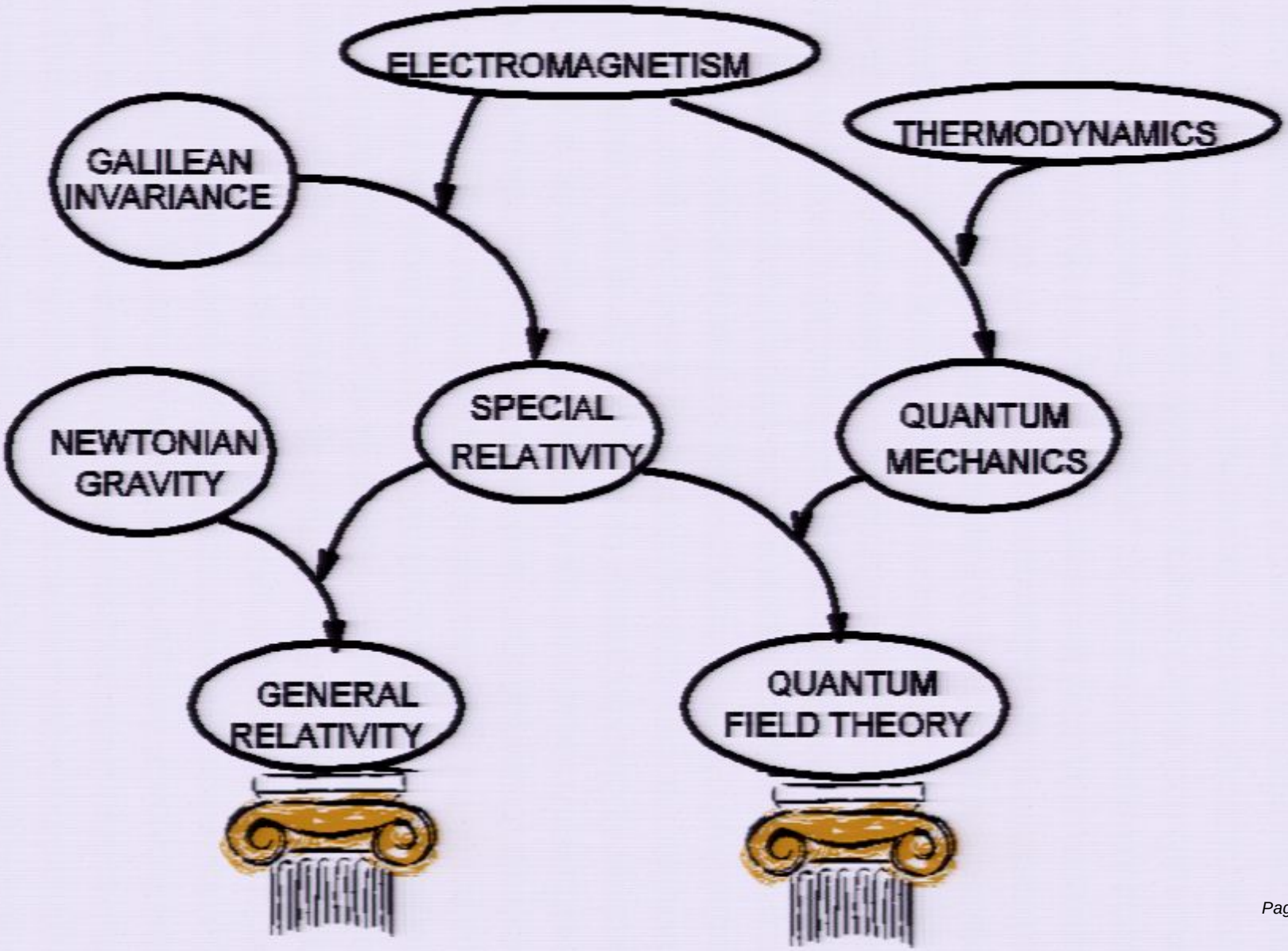

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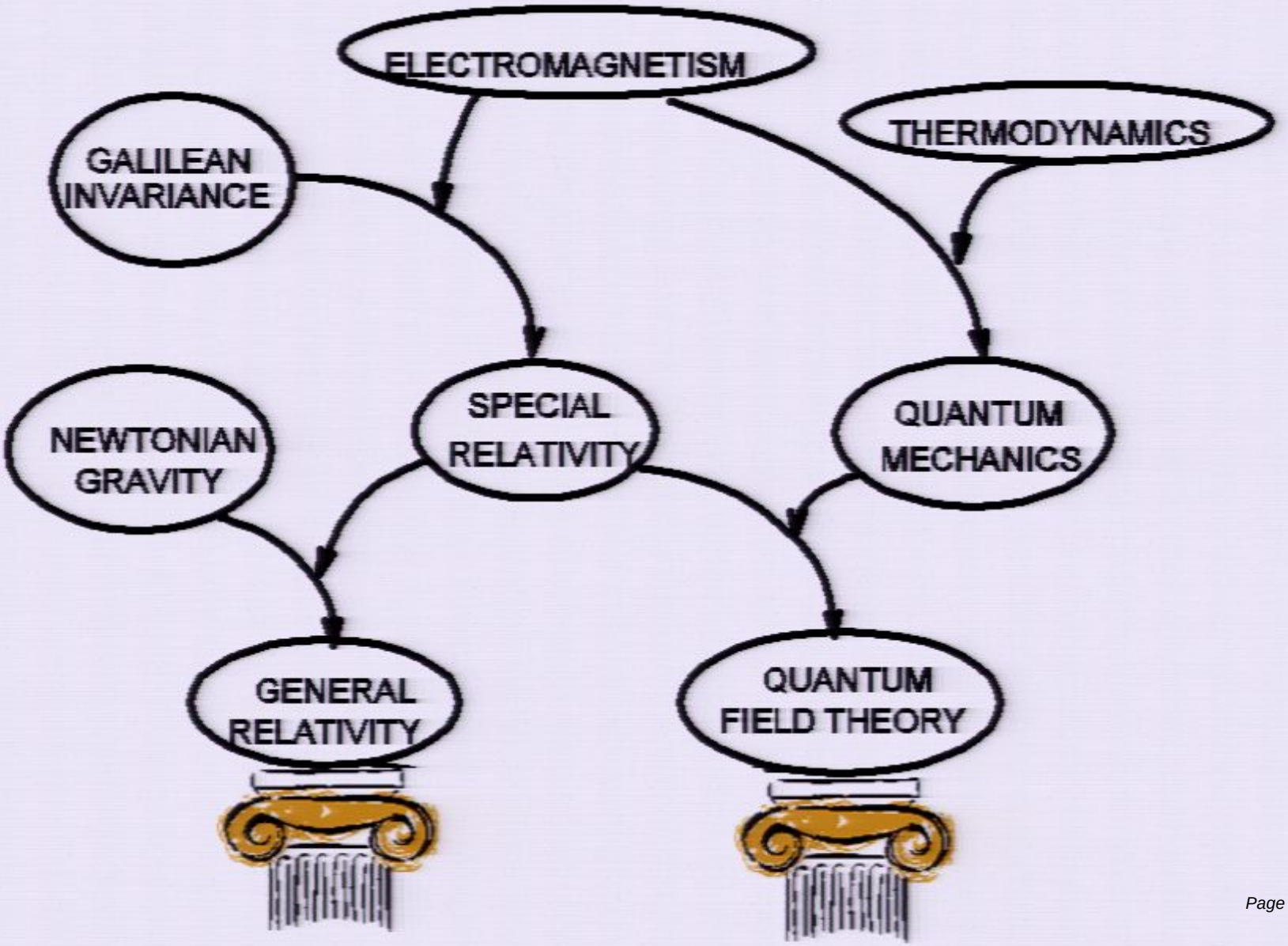

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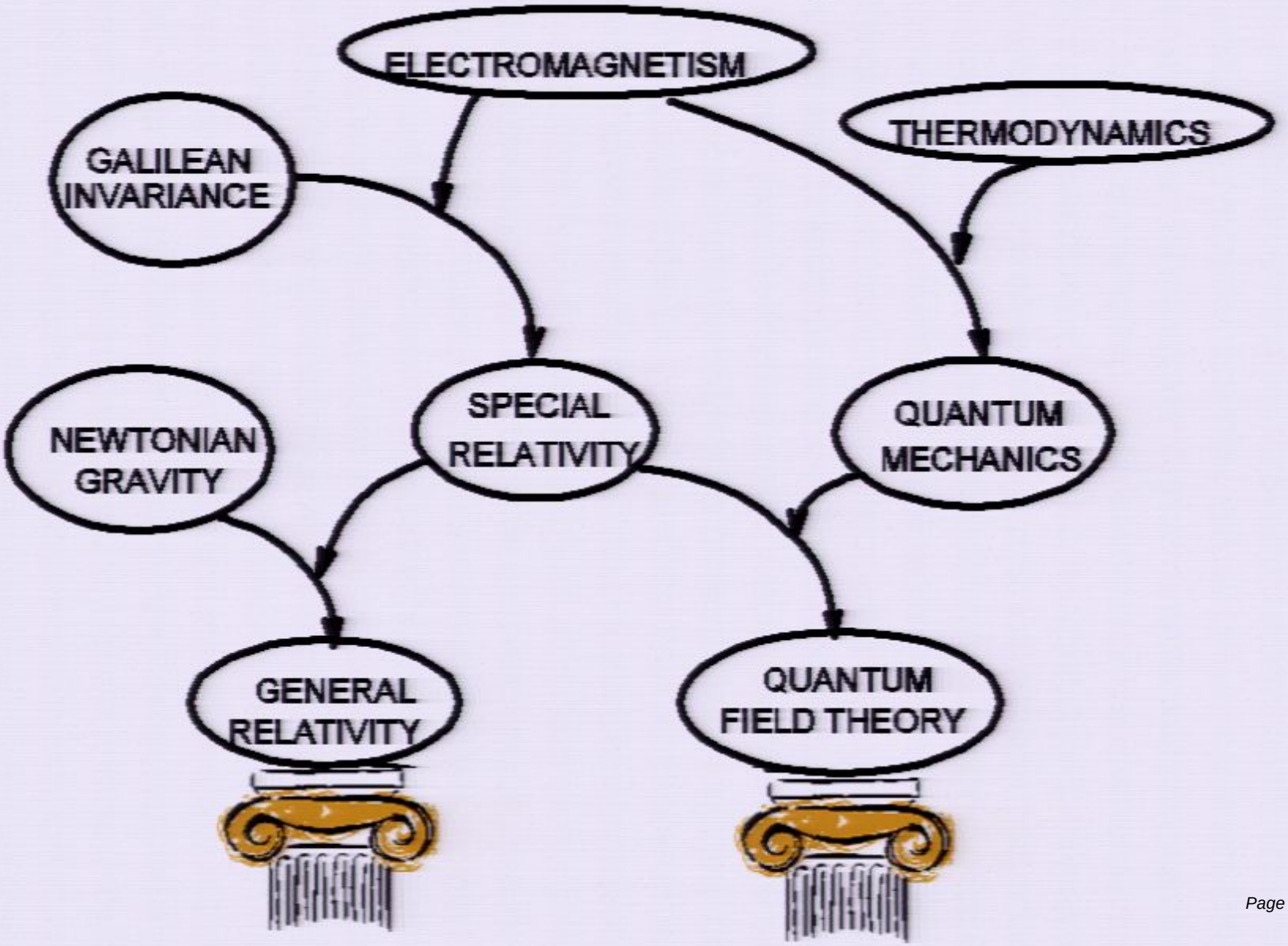

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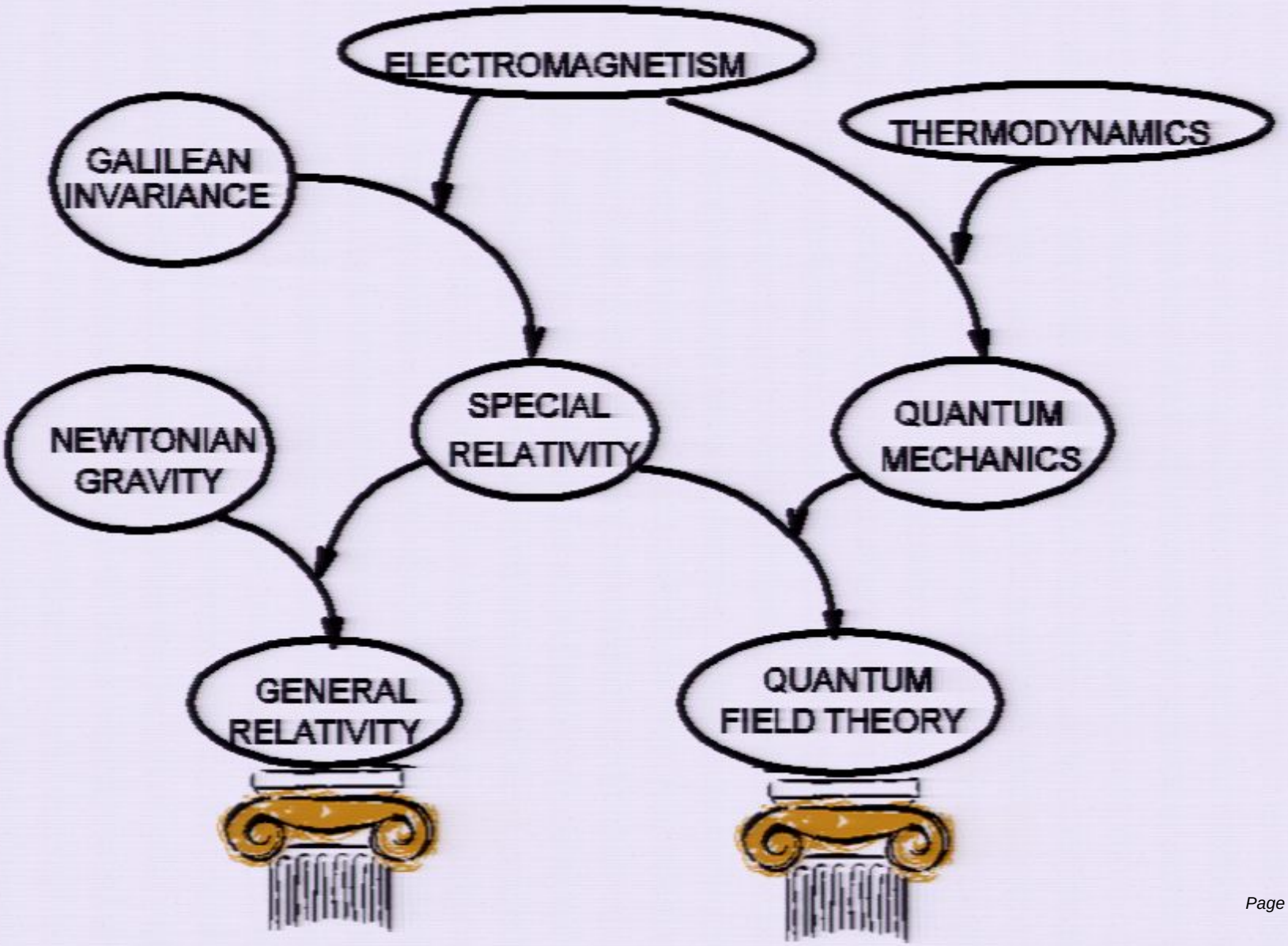

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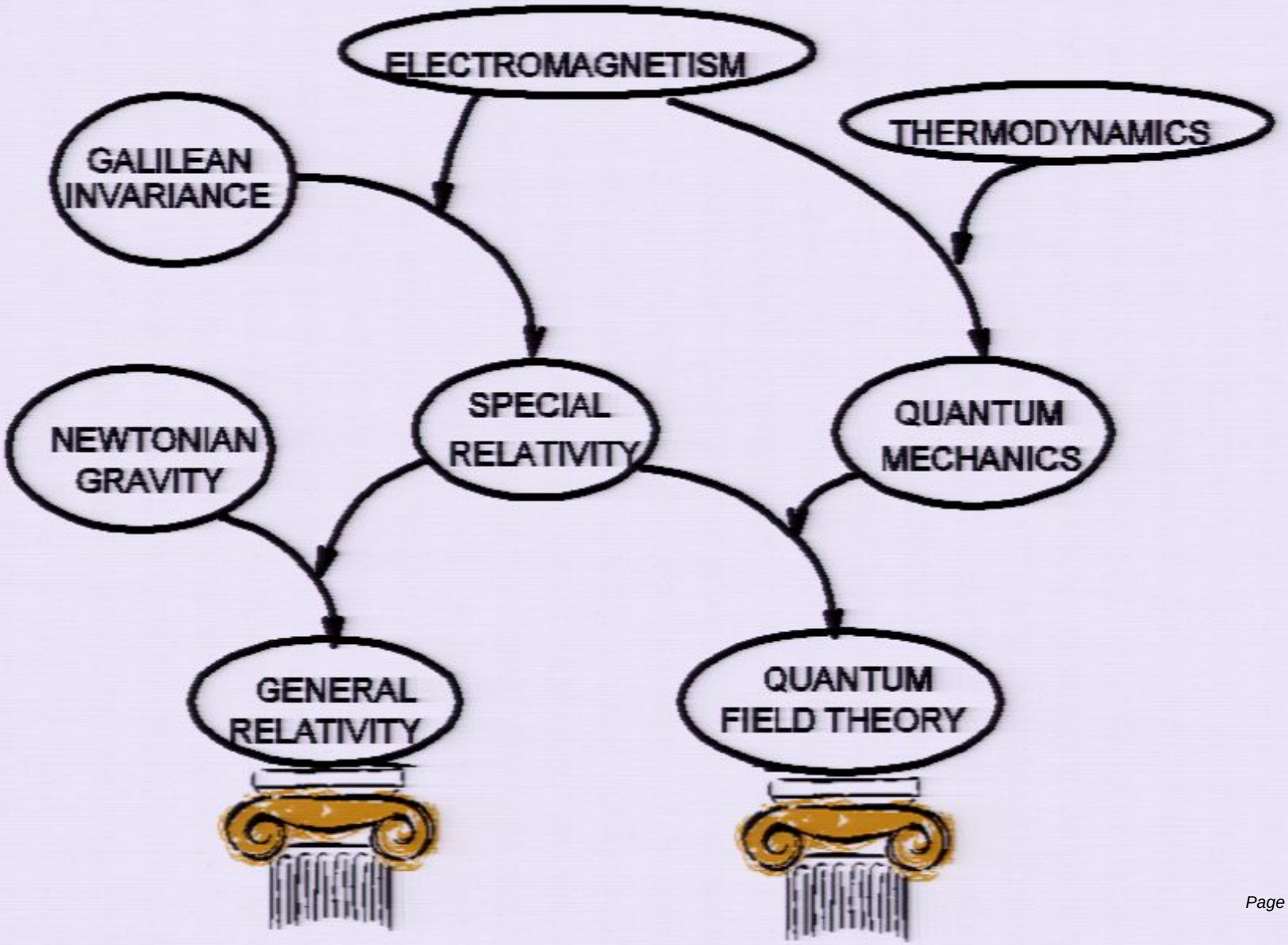

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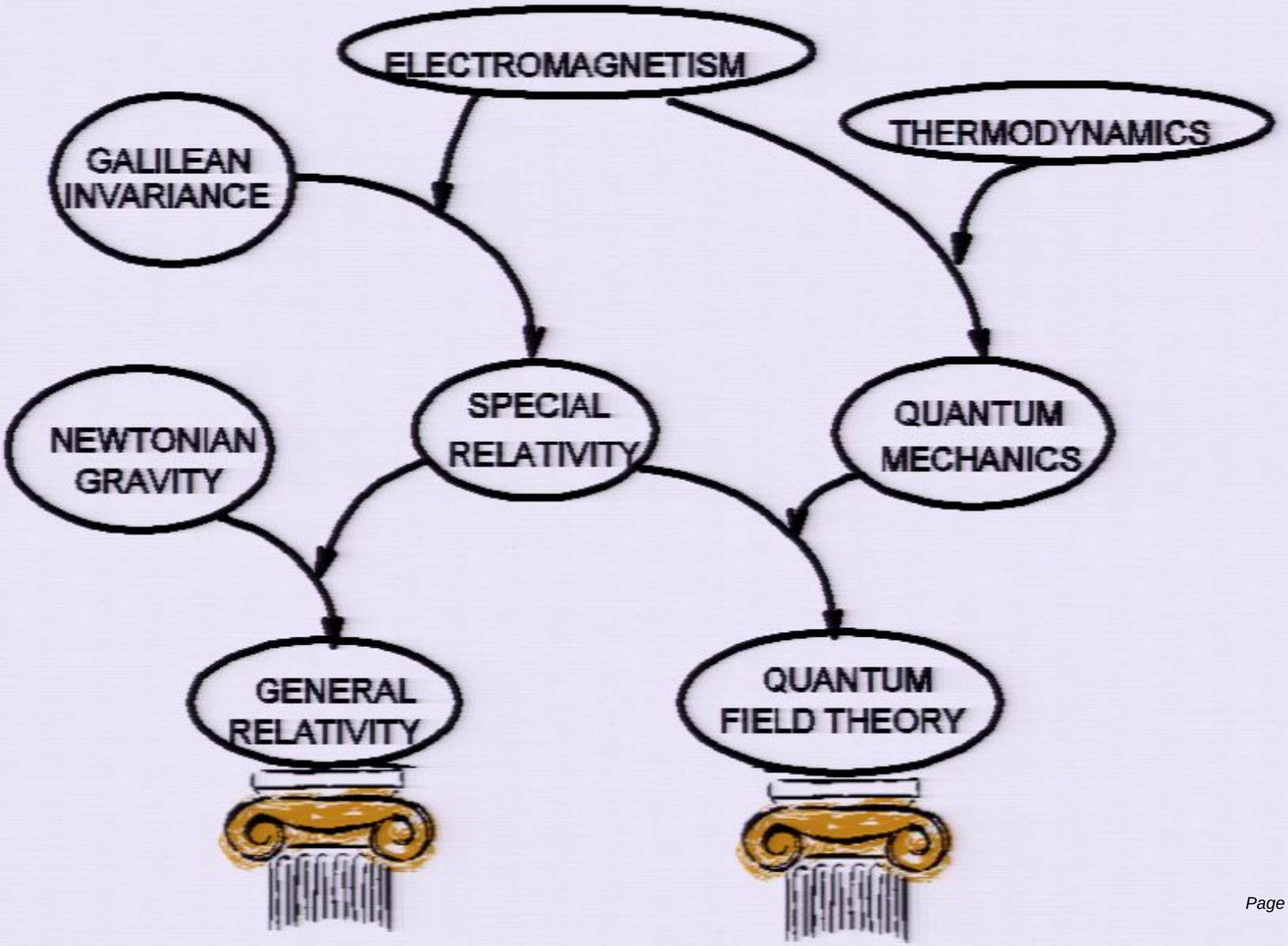

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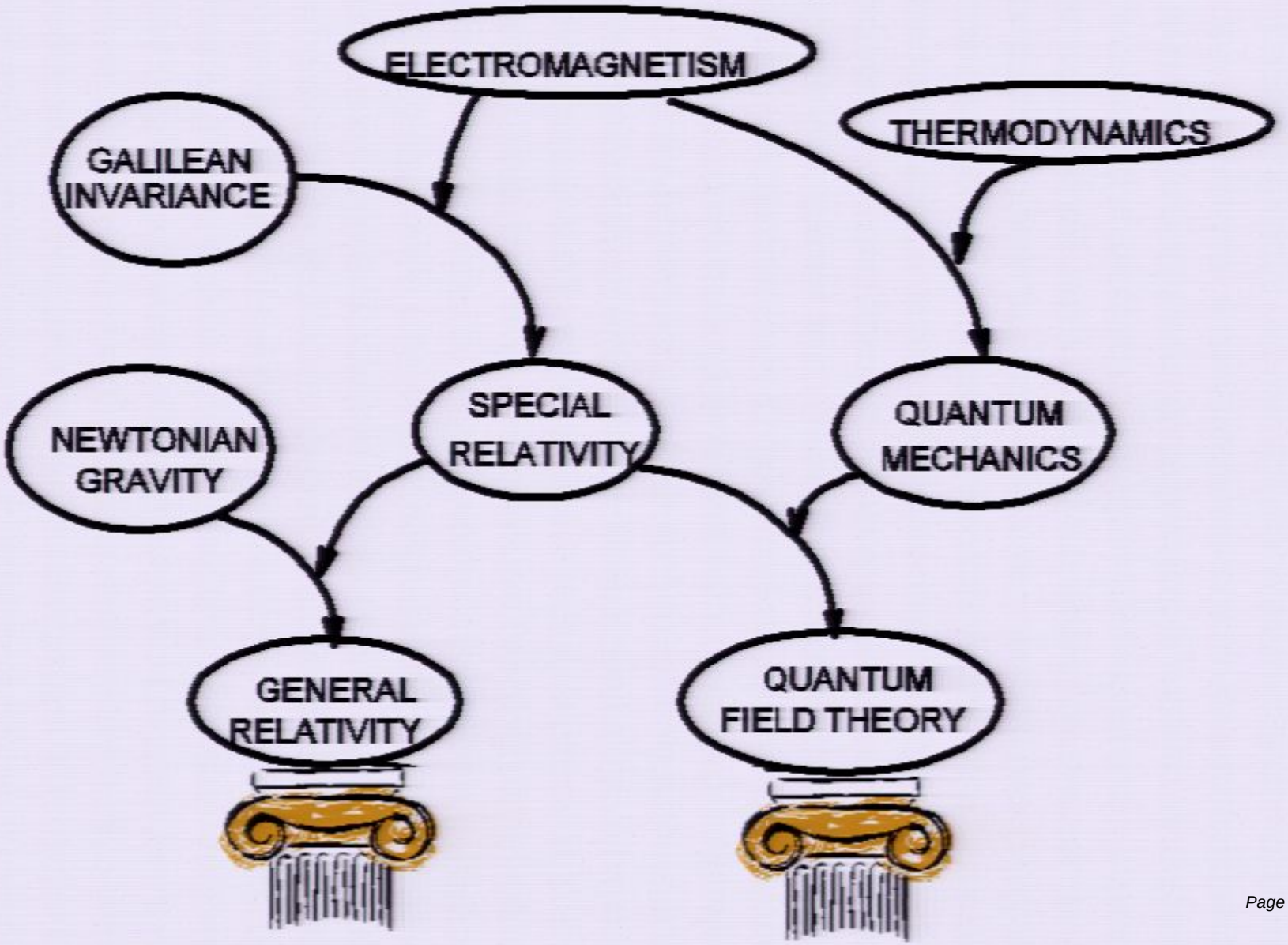

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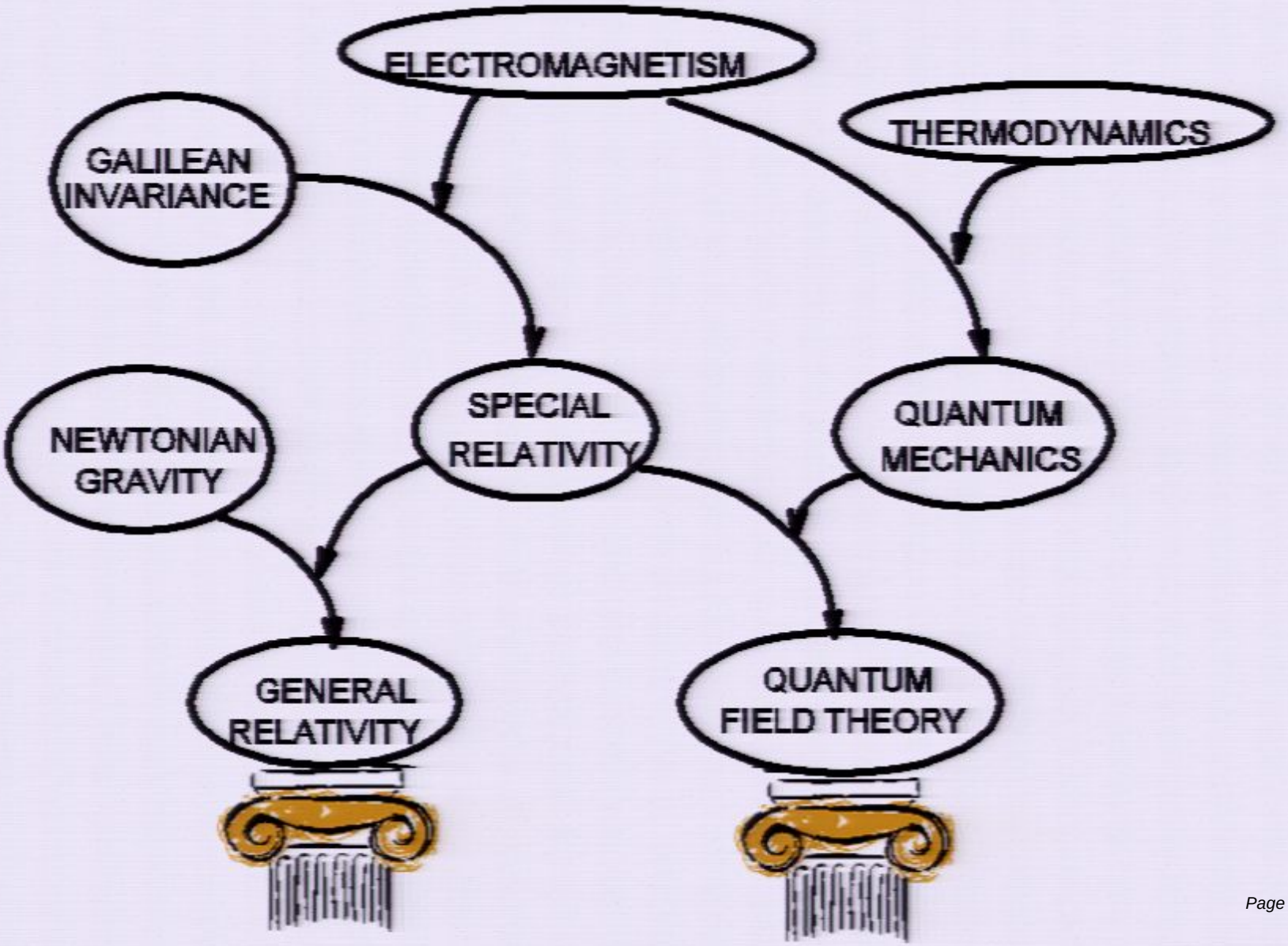

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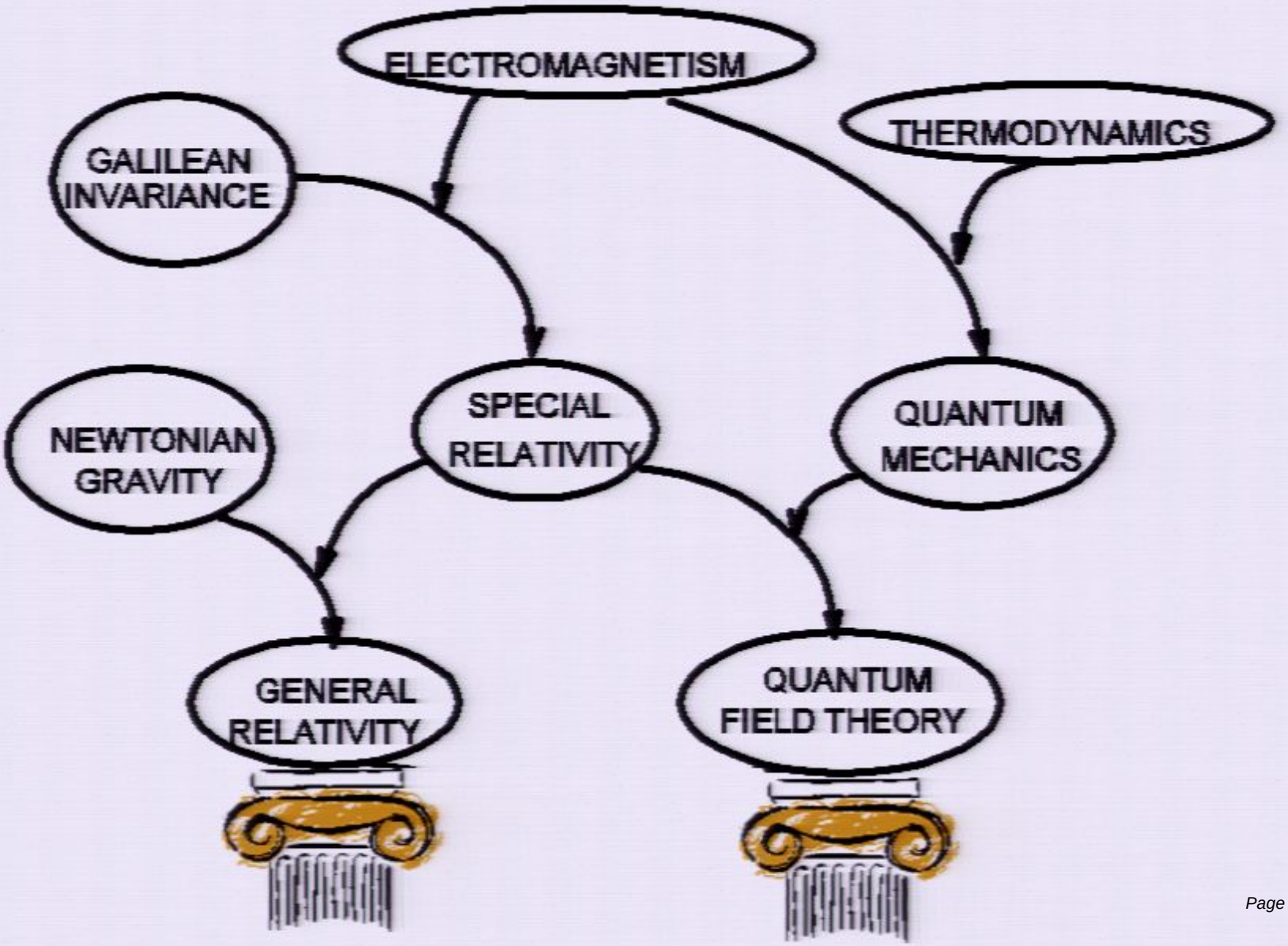

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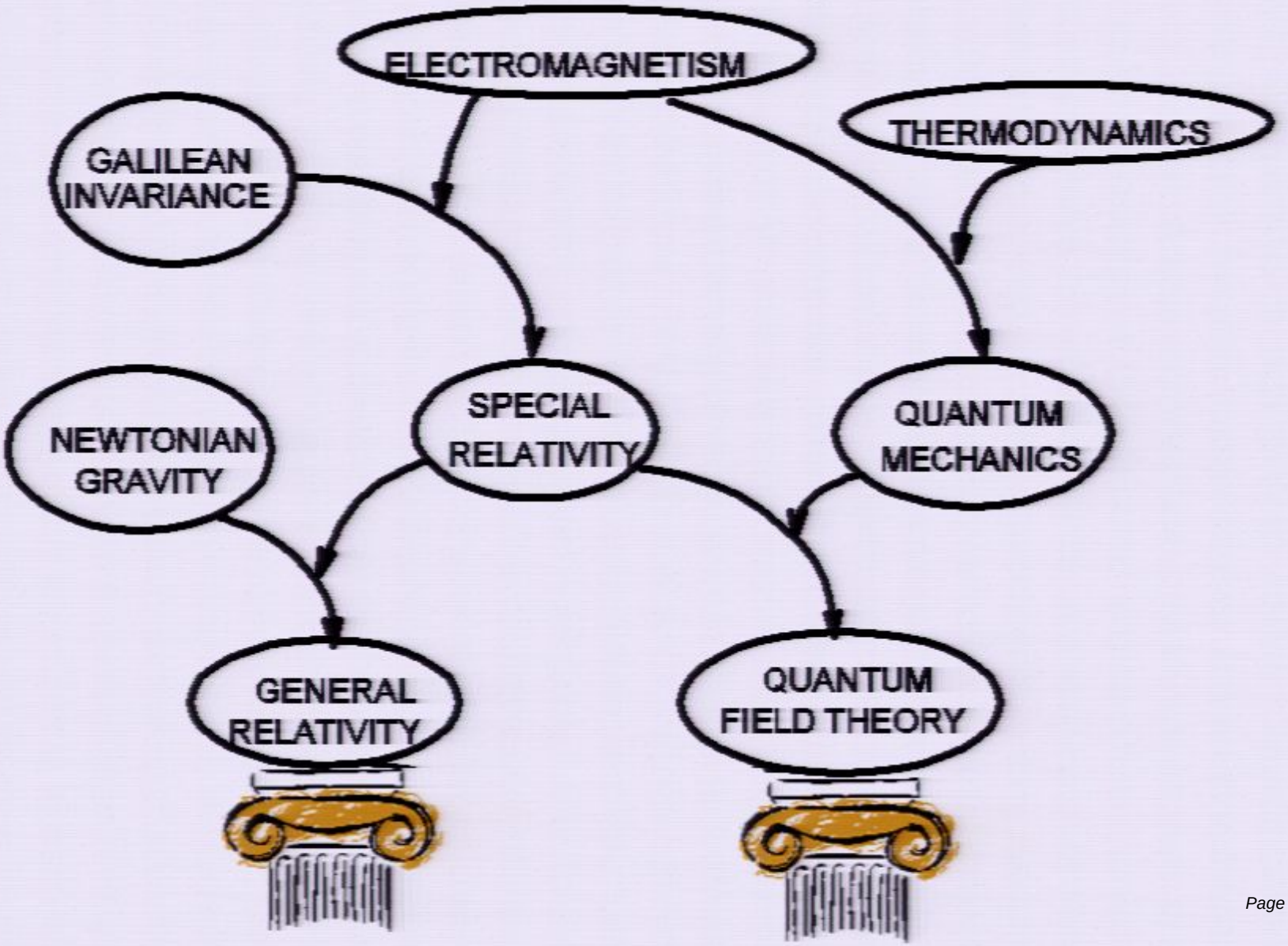

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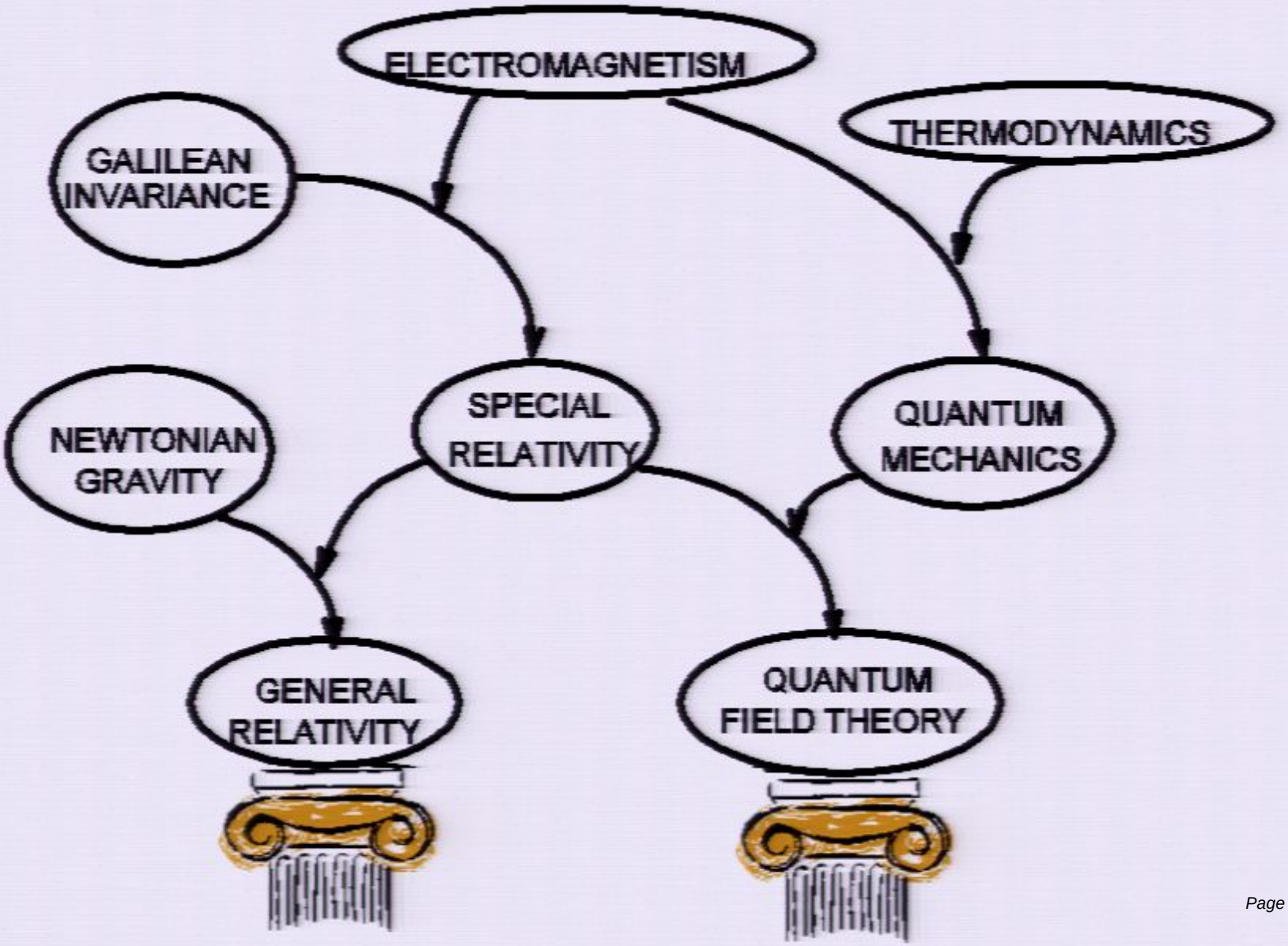

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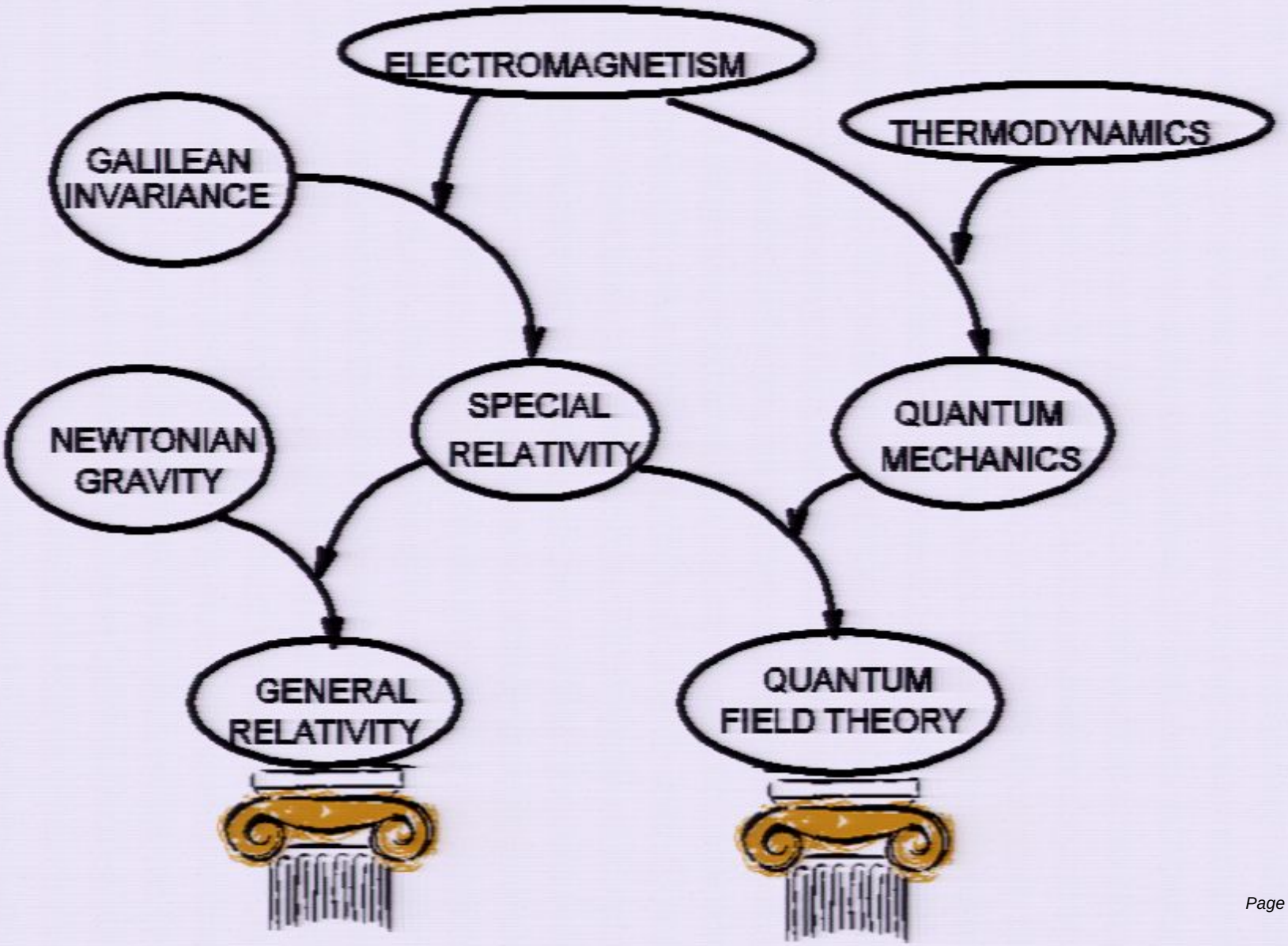

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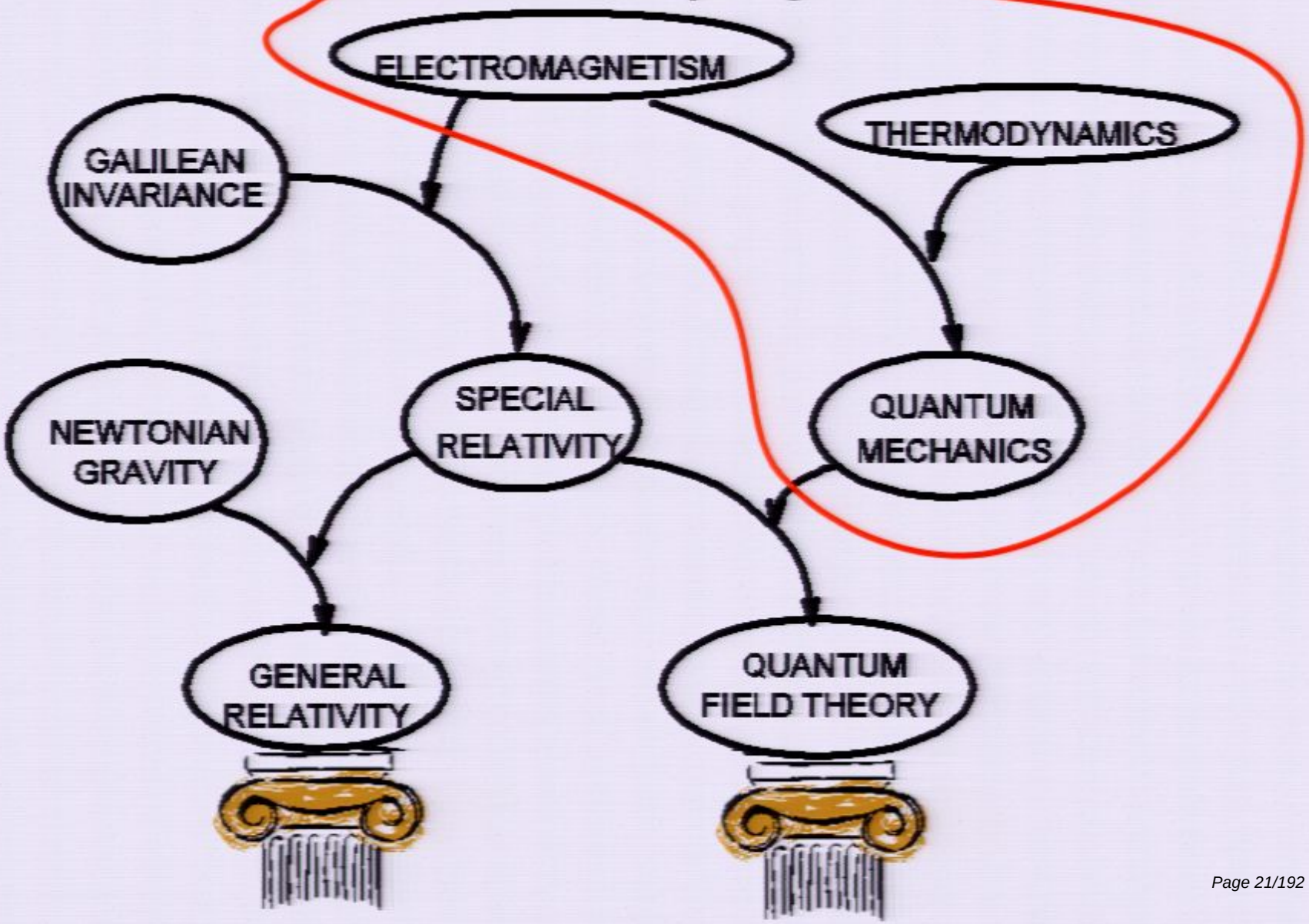

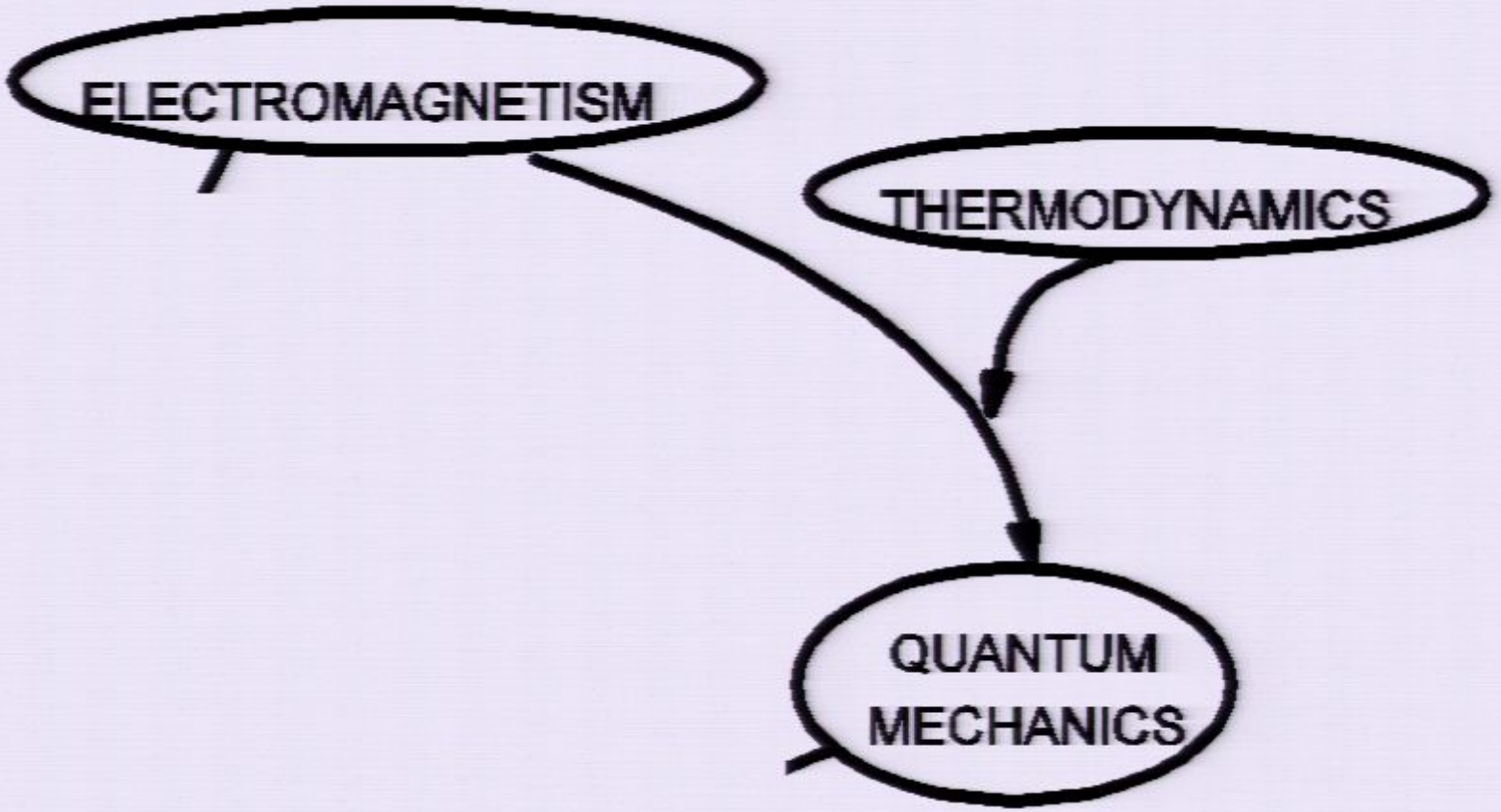
ELECTROMAGNETISM
THERMODYNAMICS
QUANTUM
MECHANICS

ELECTROMAGNETISM

THERMODYNAMICS

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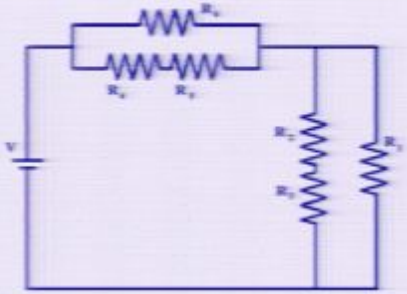

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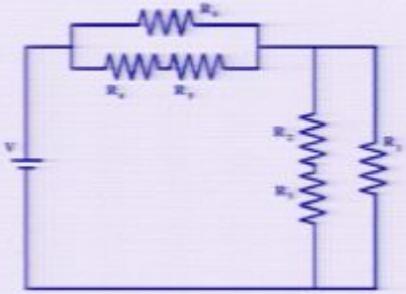

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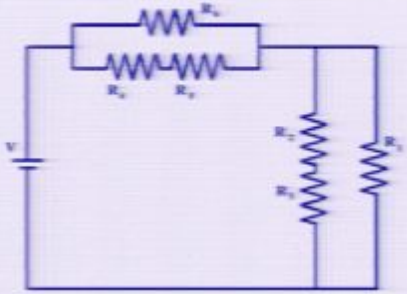

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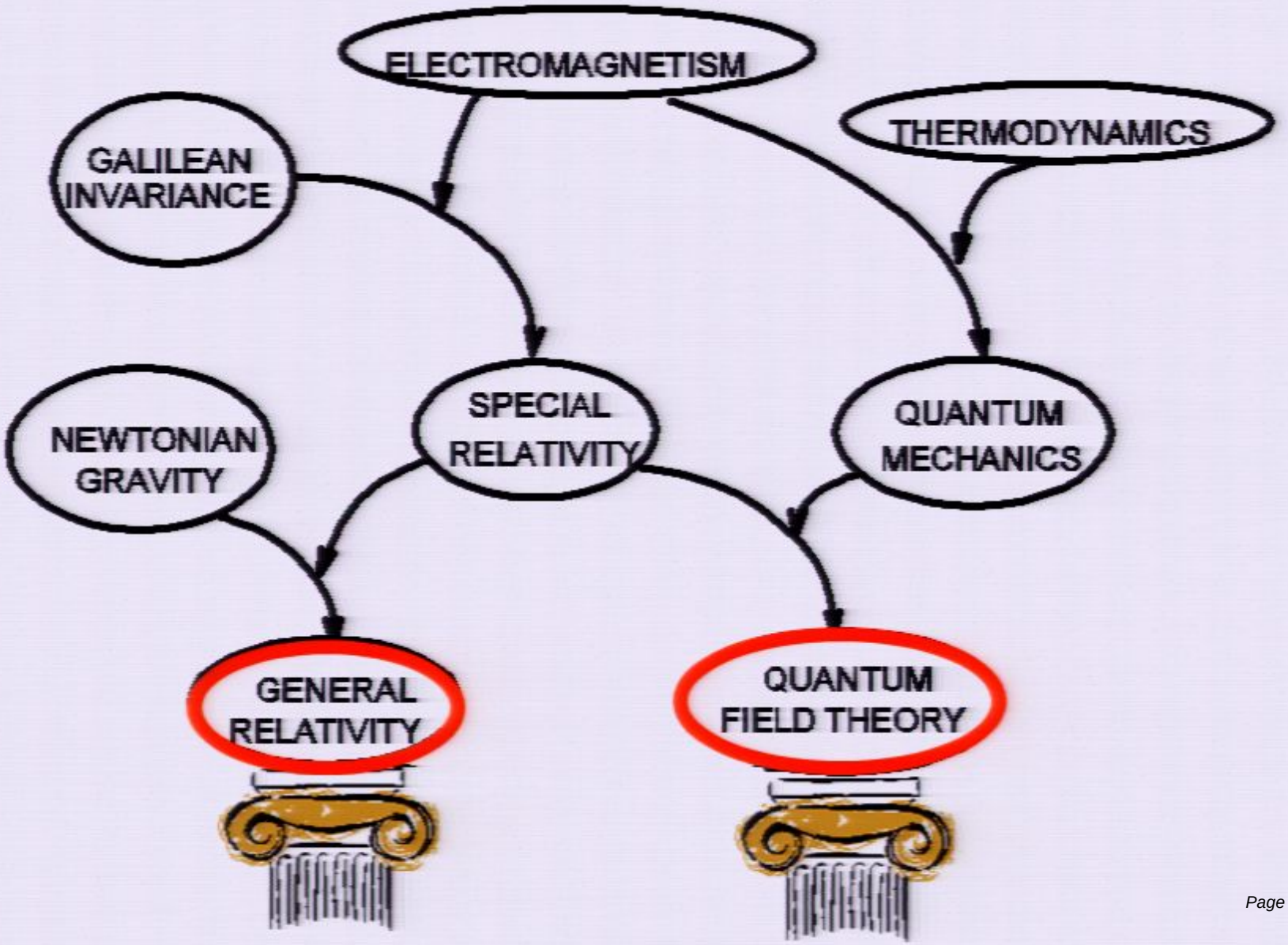

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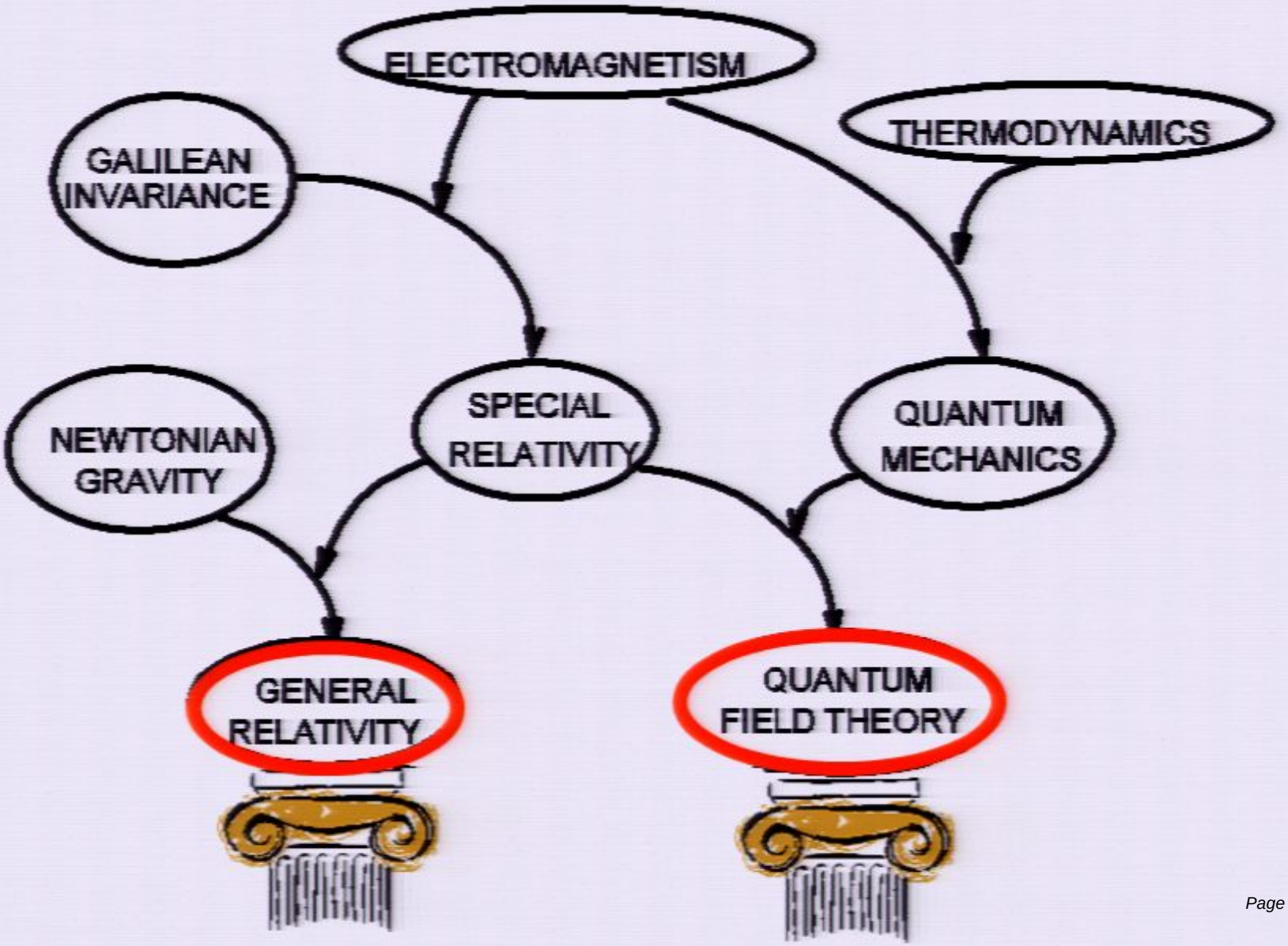

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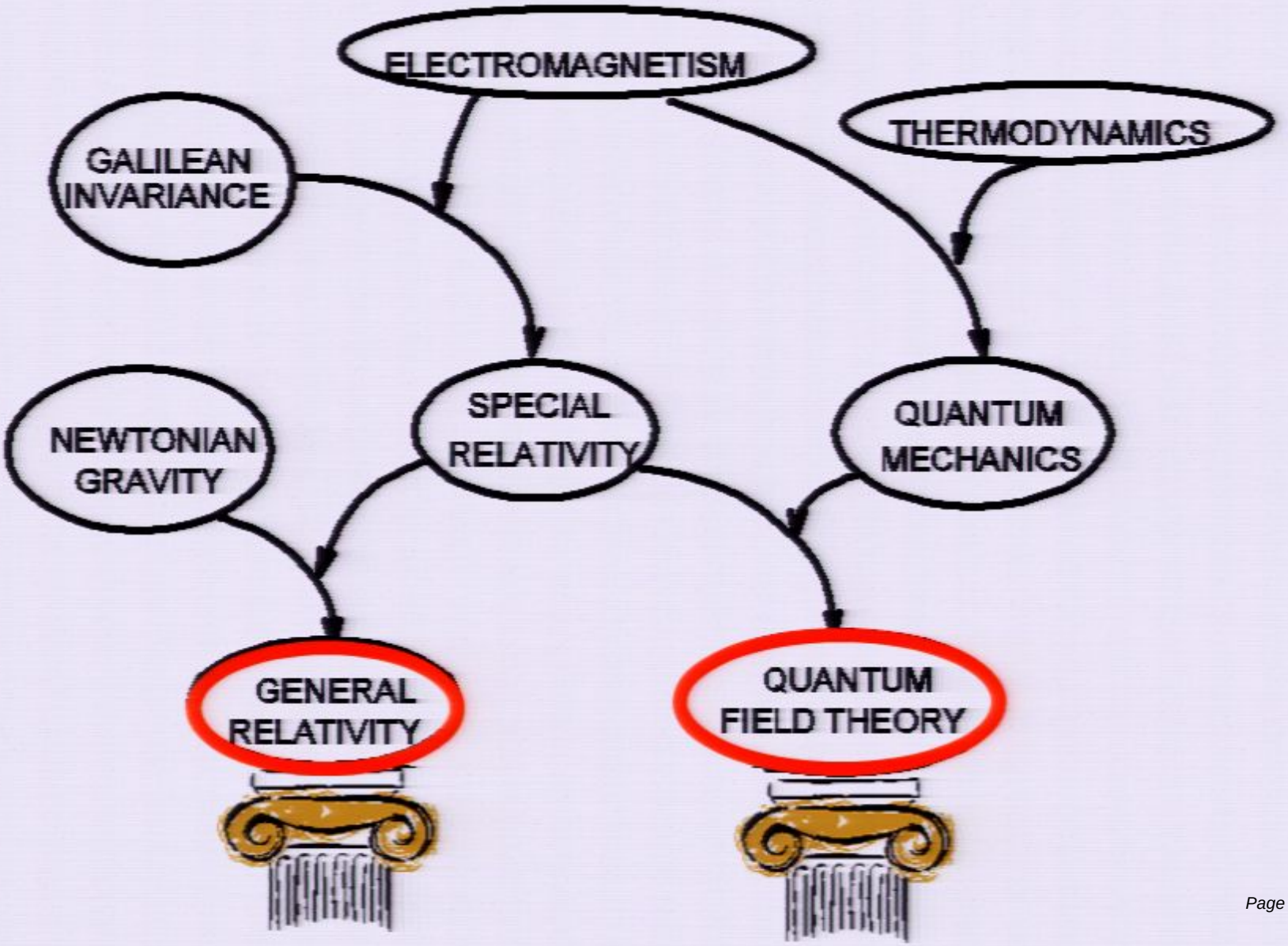

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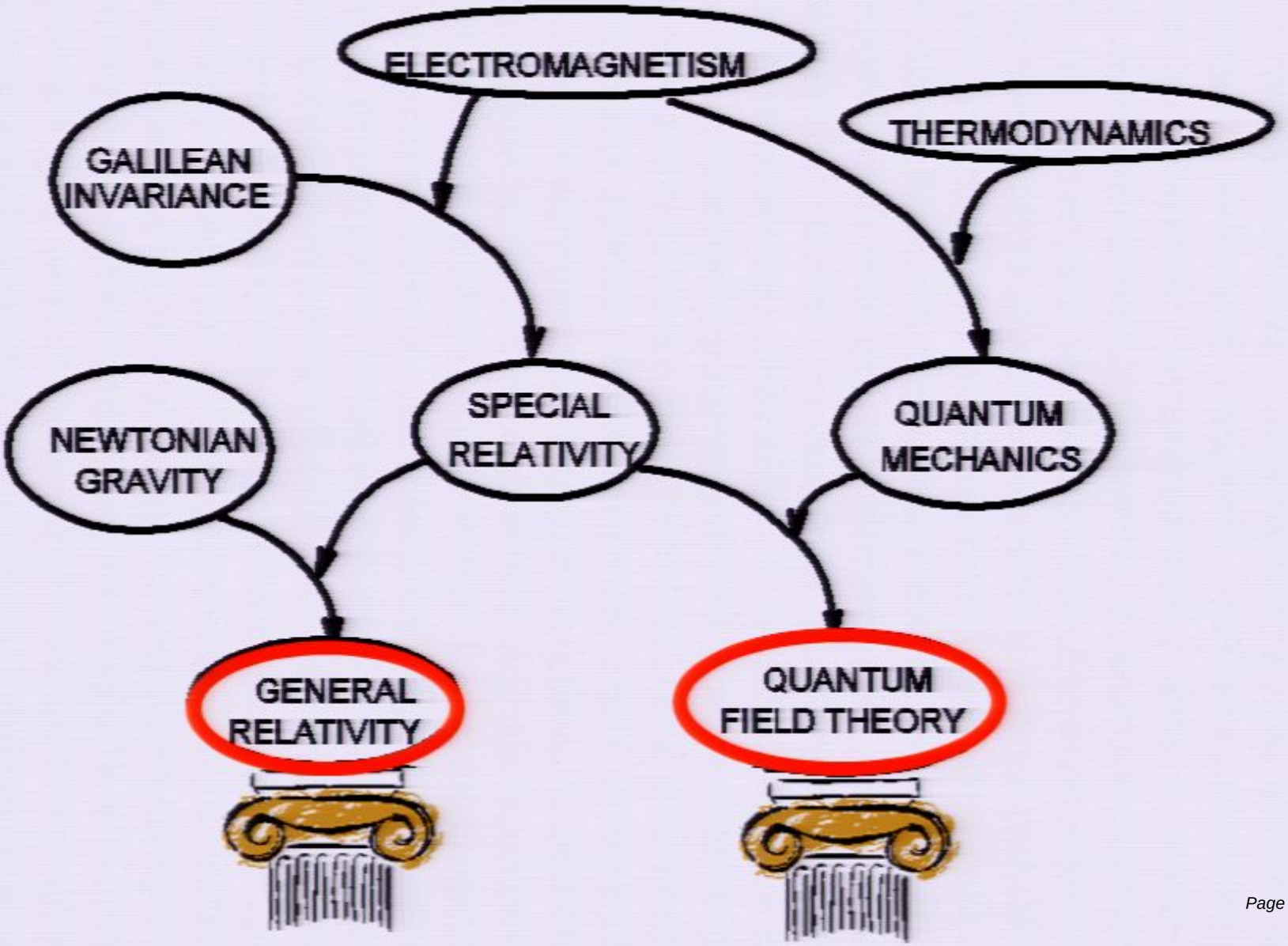

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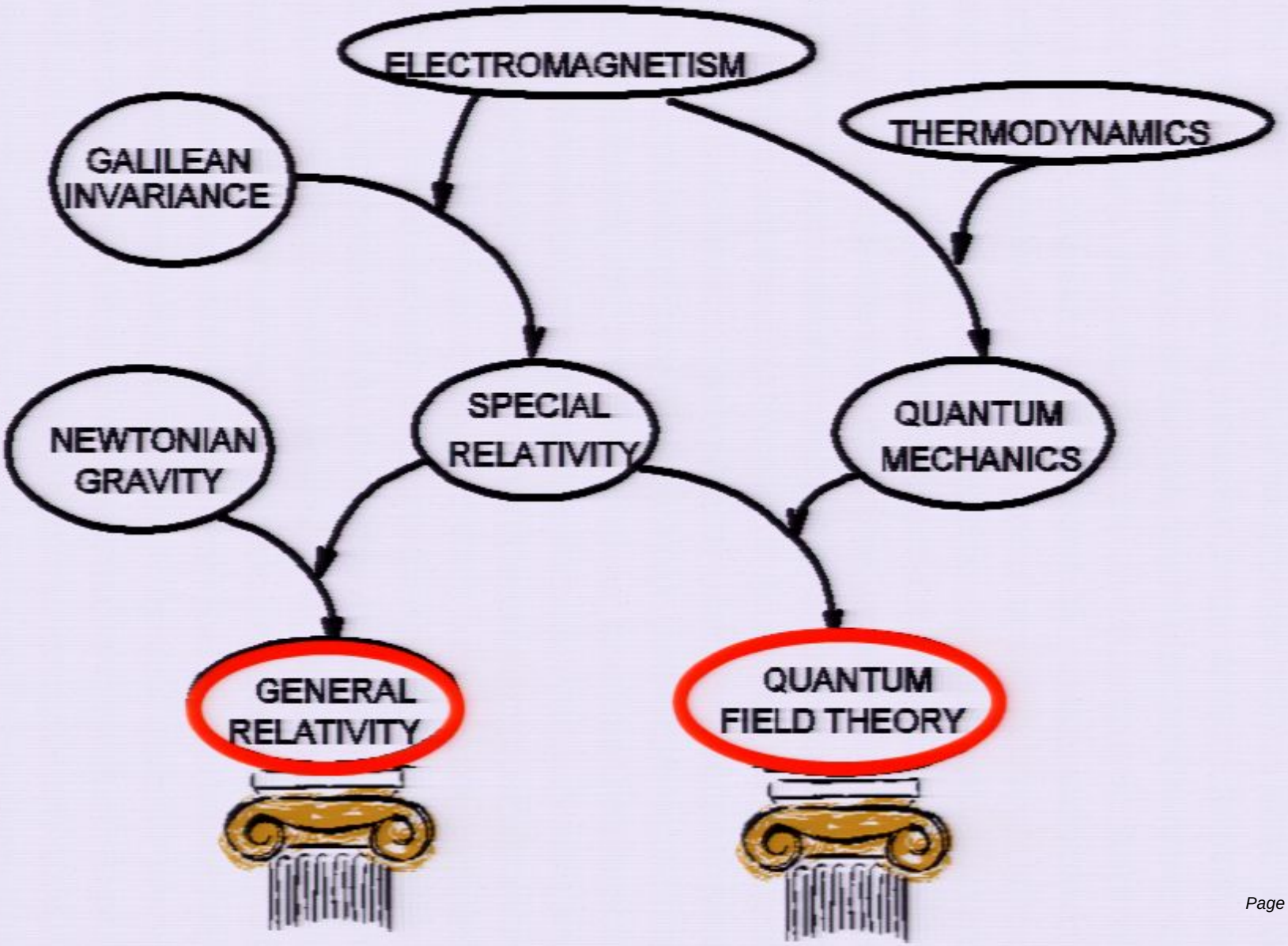

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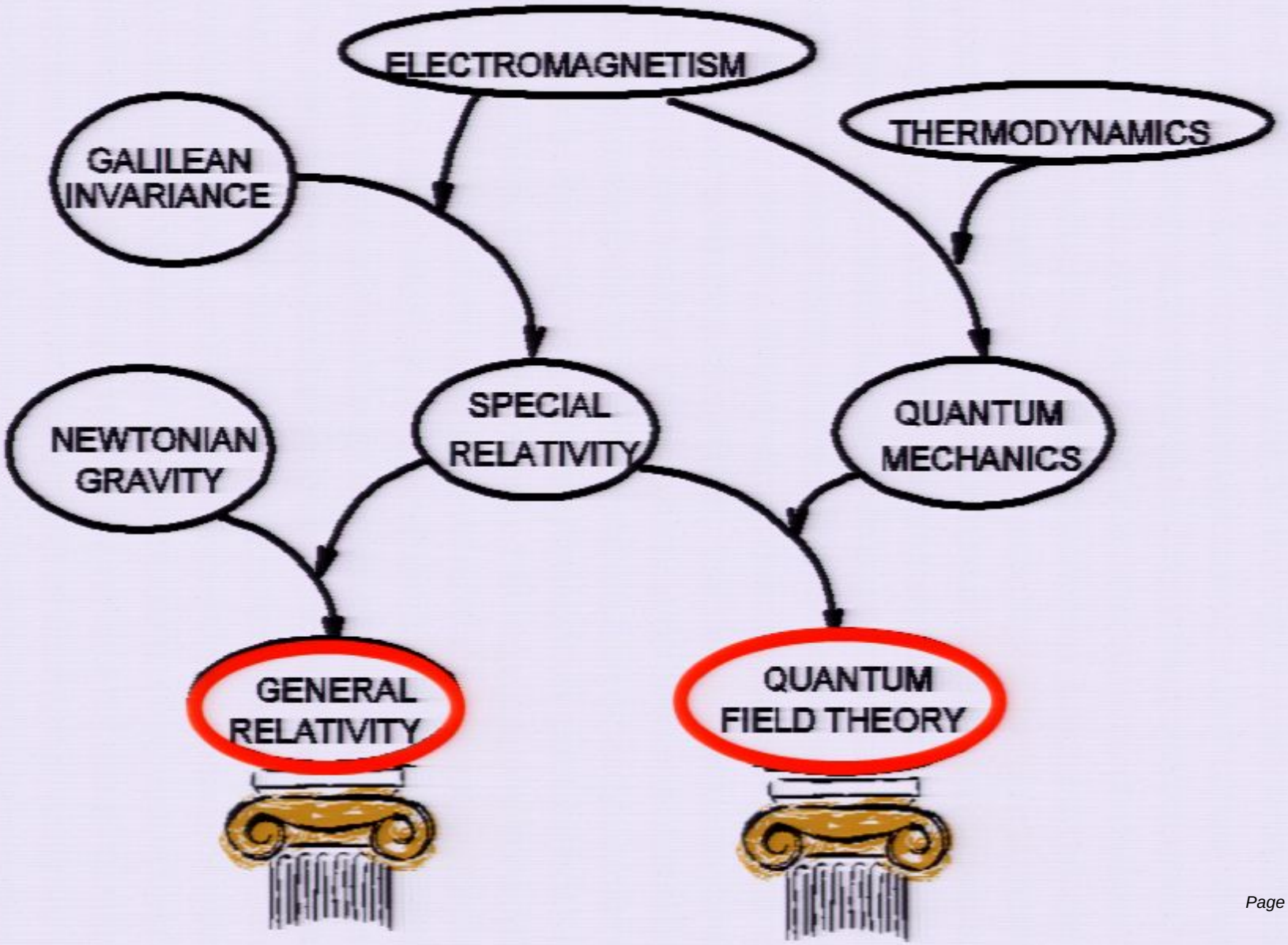

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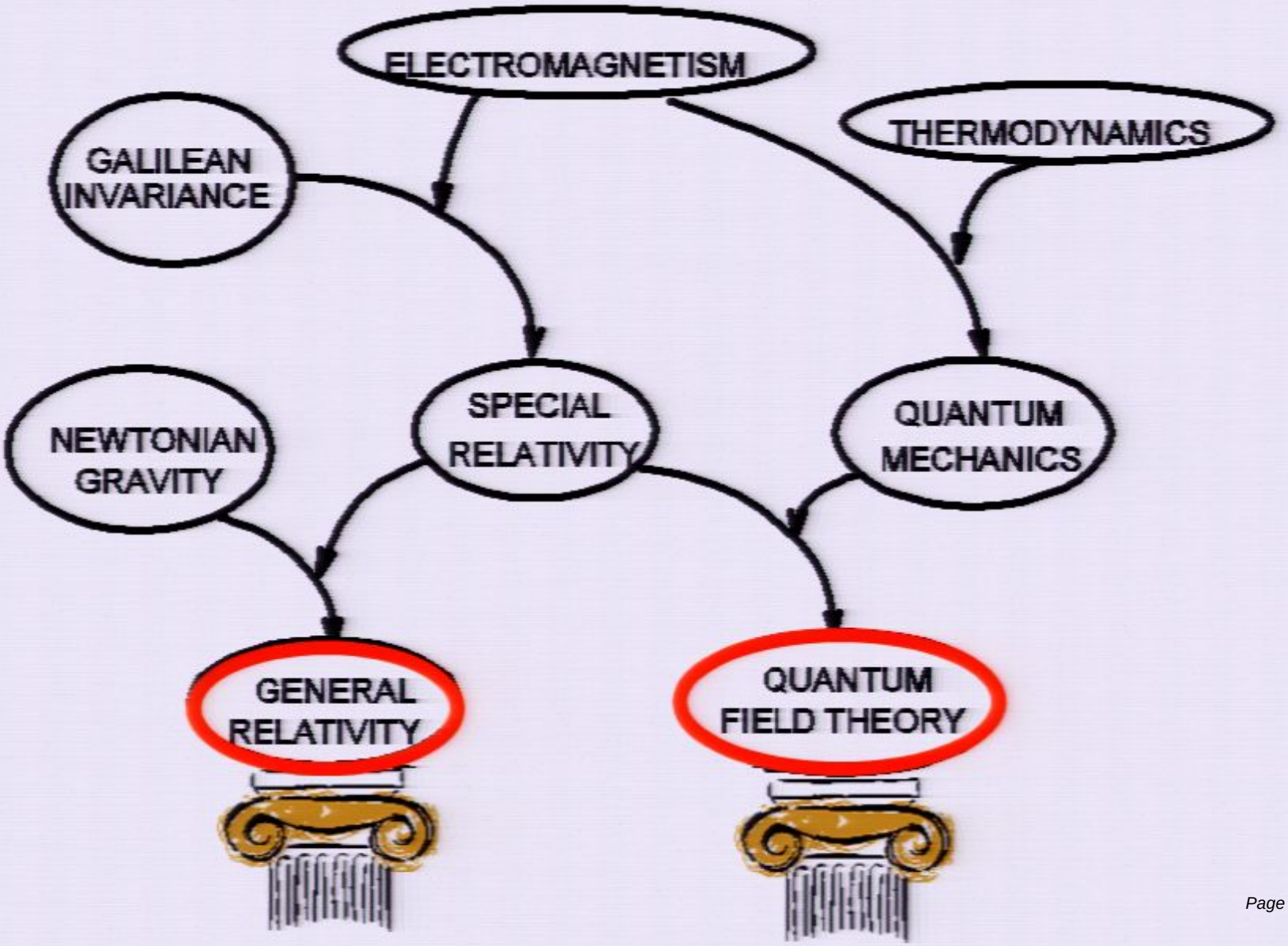

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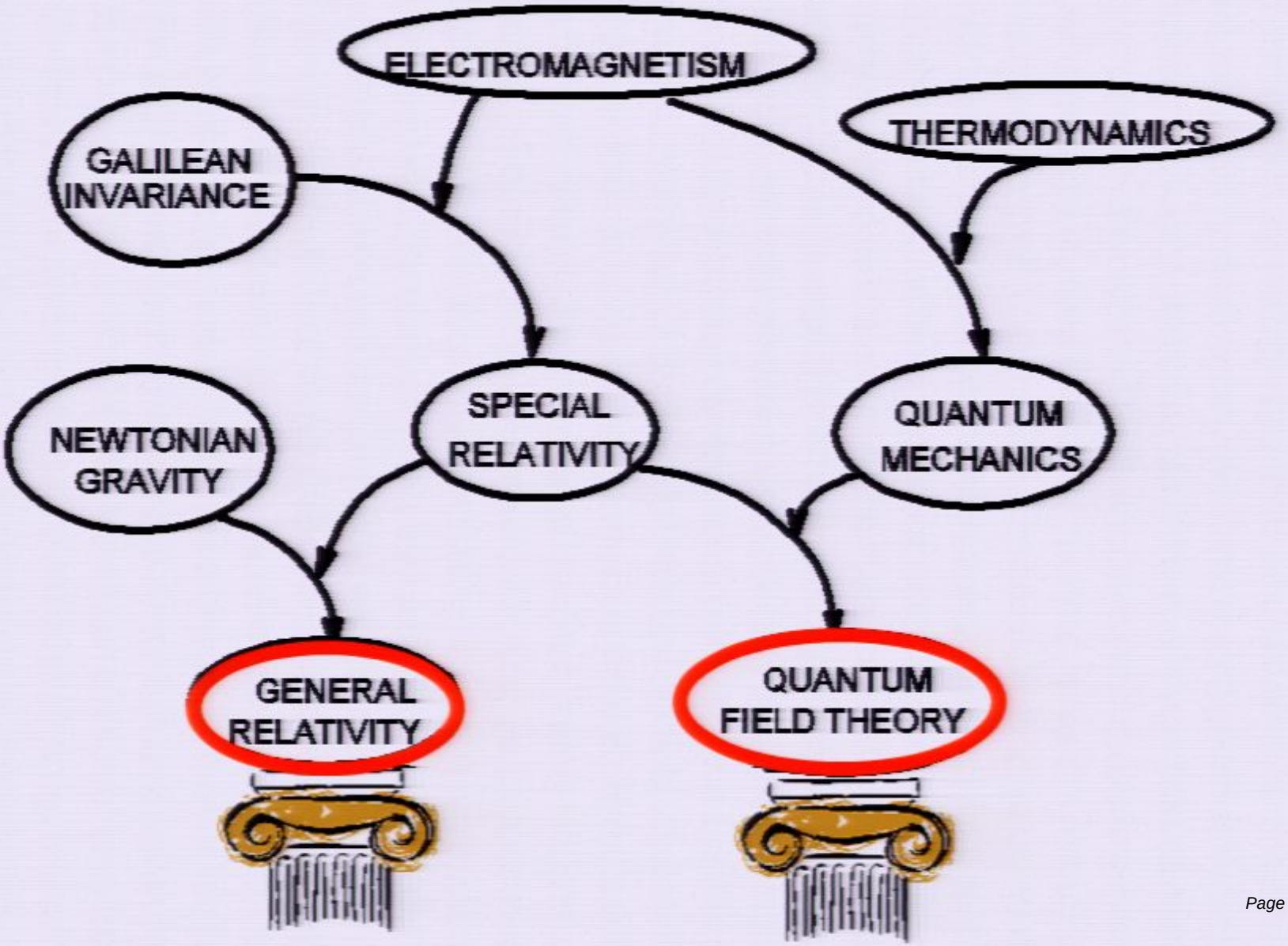

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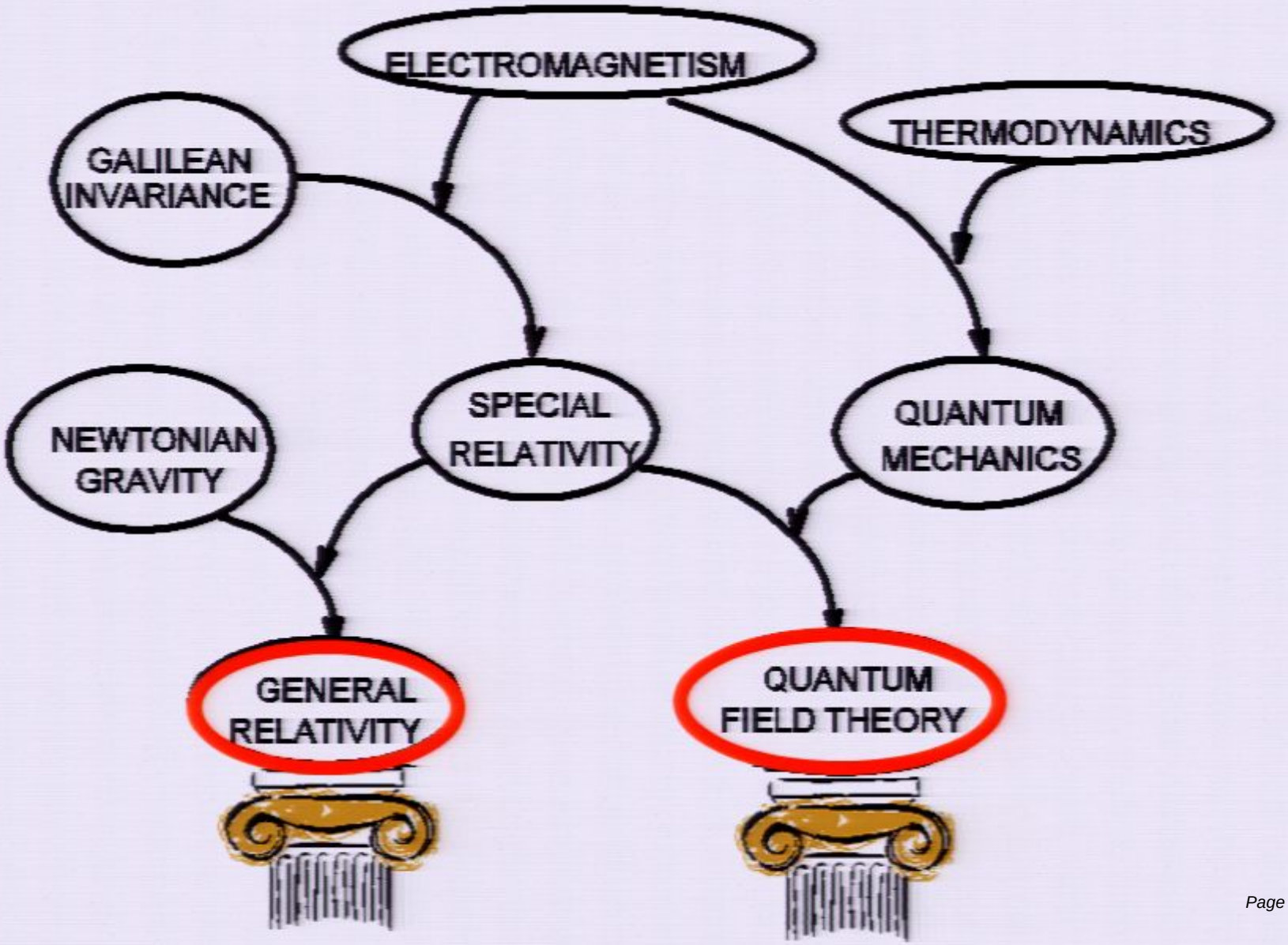

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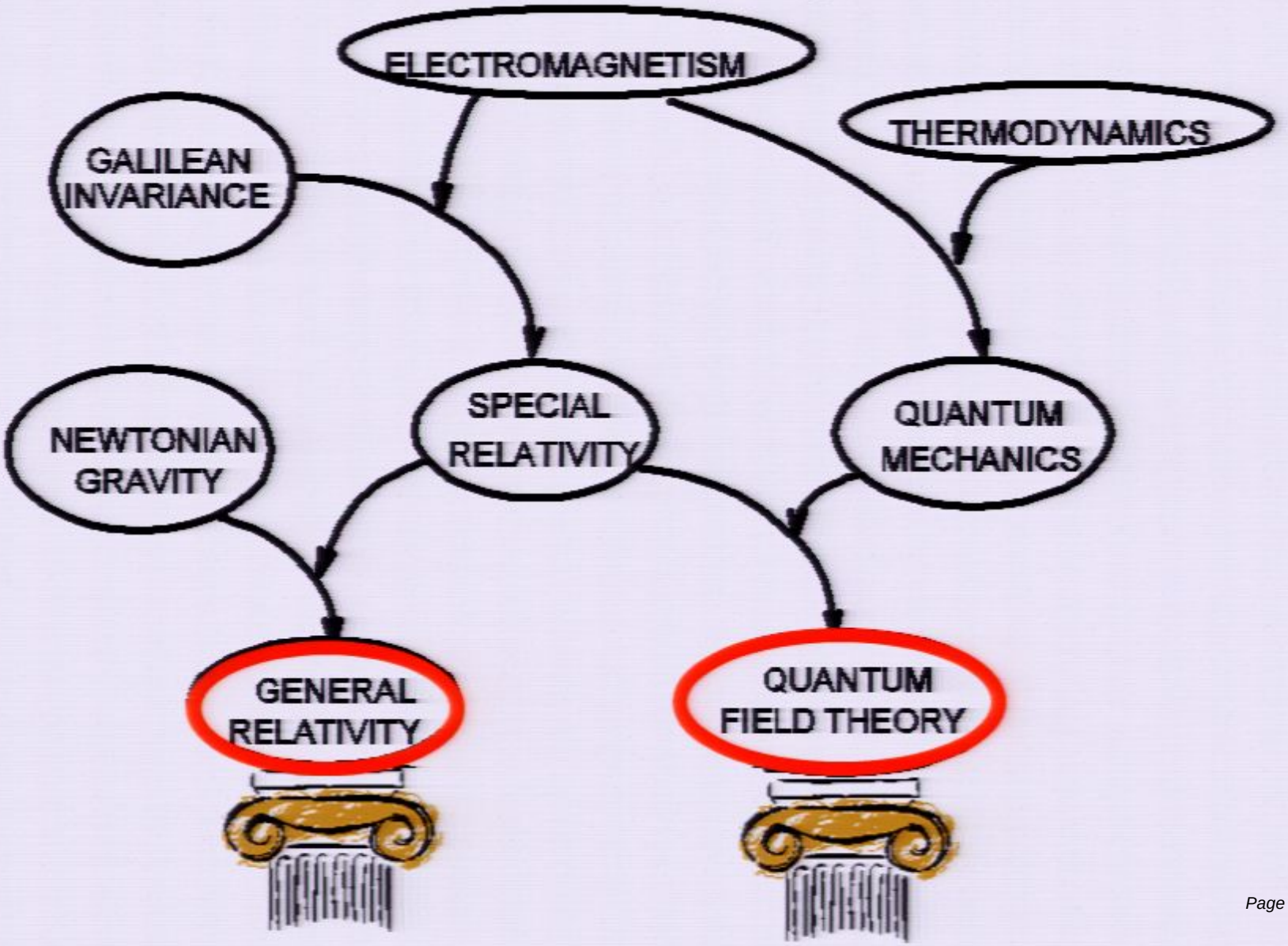

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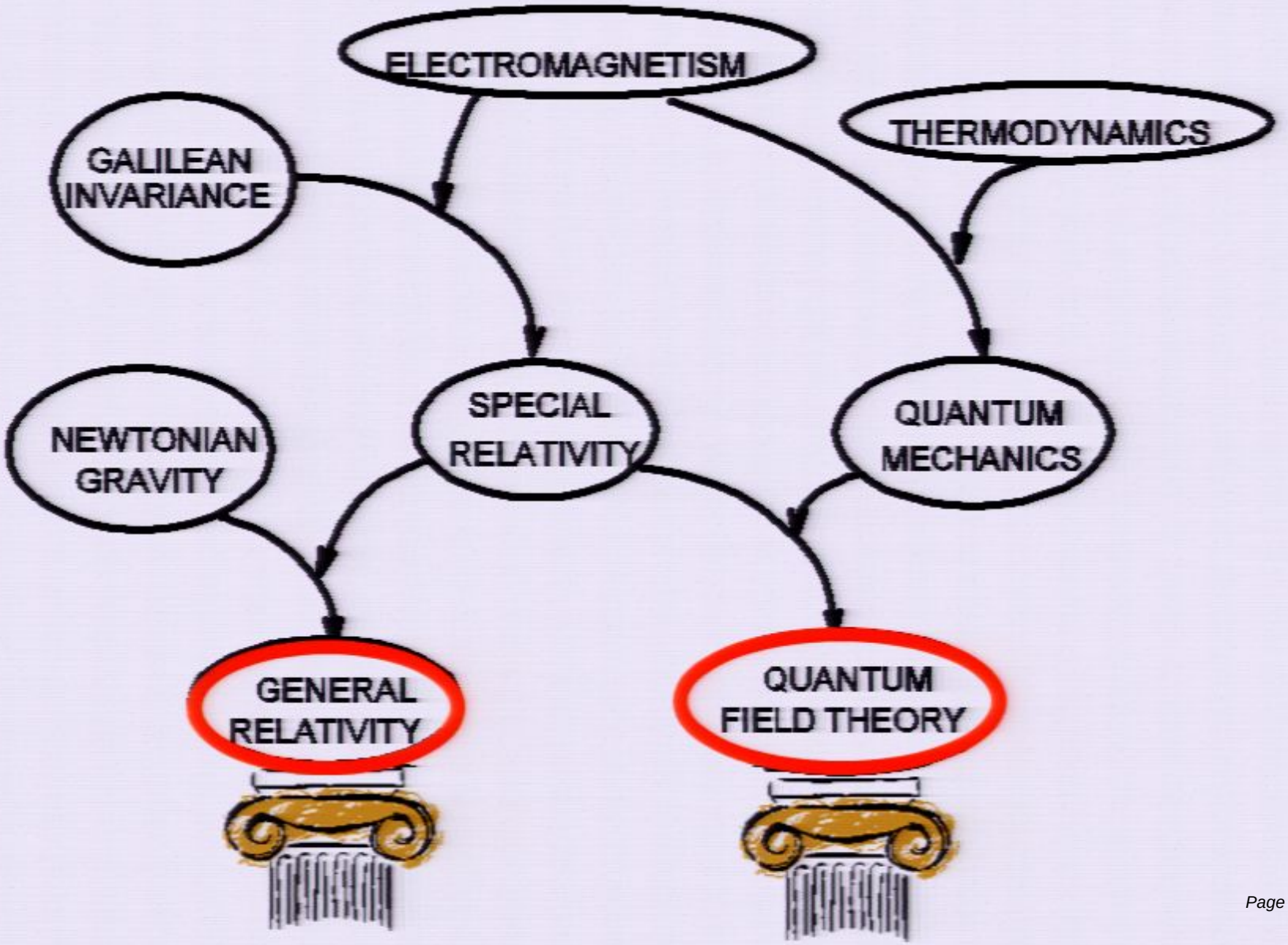

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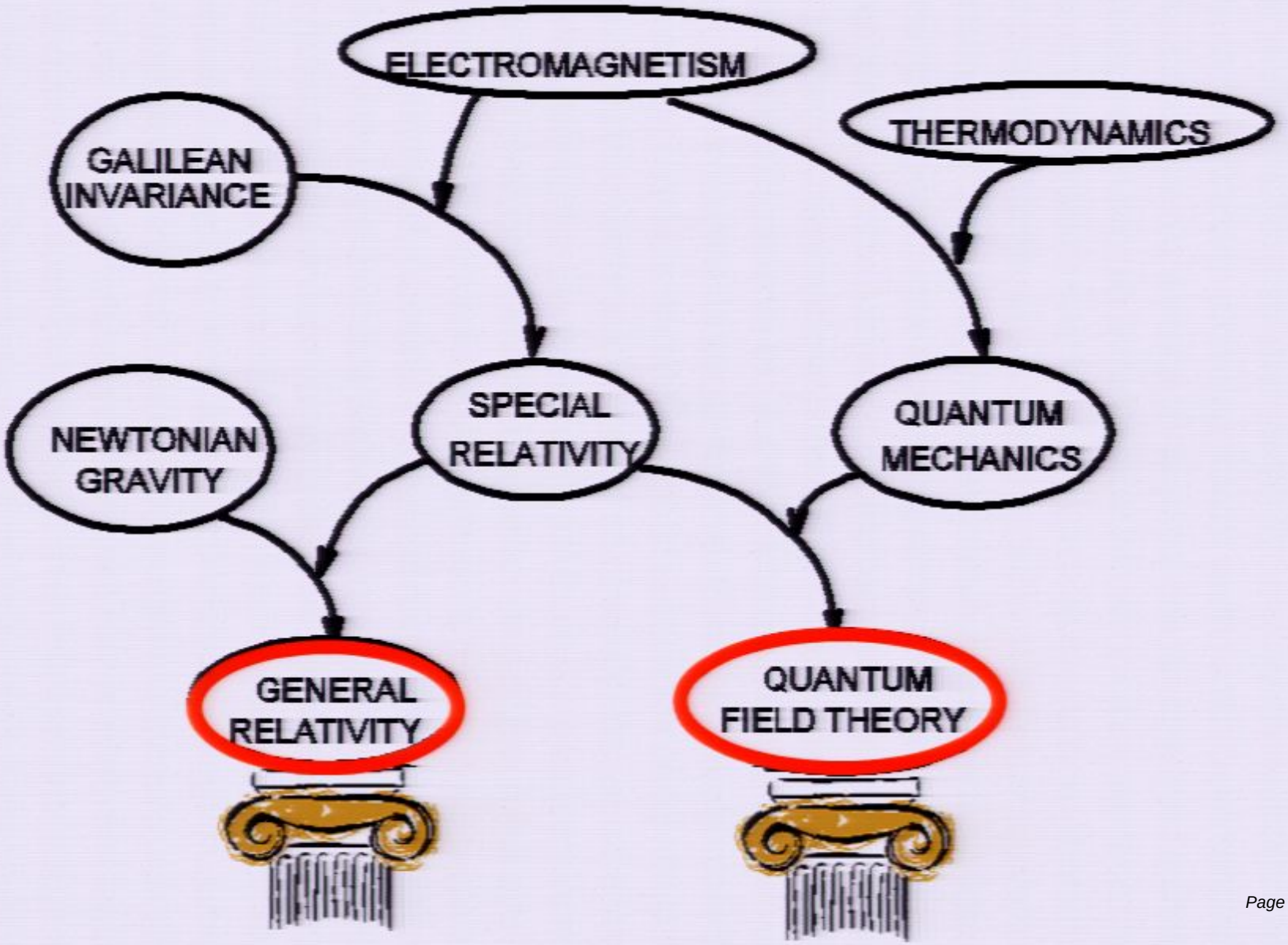

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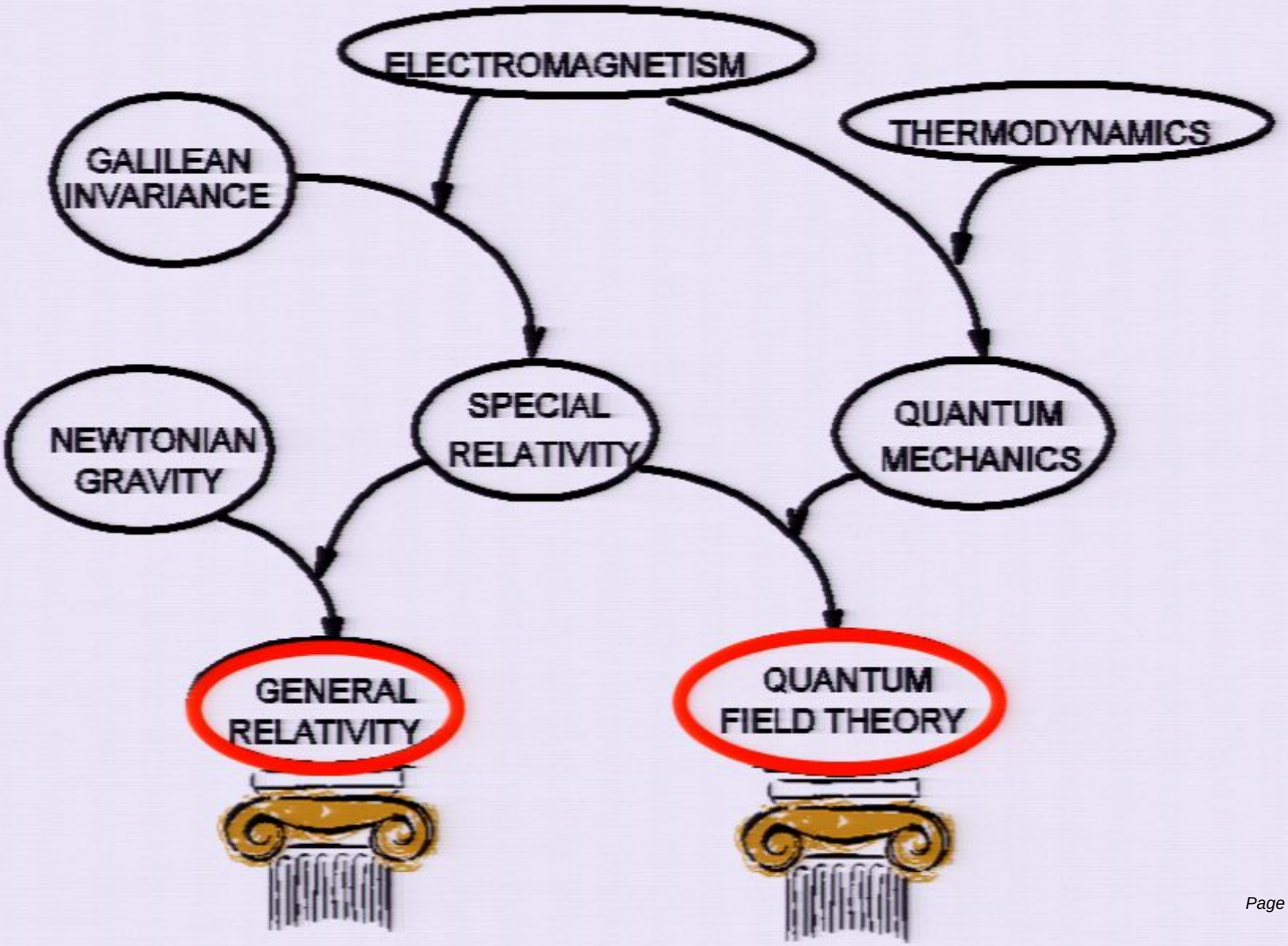

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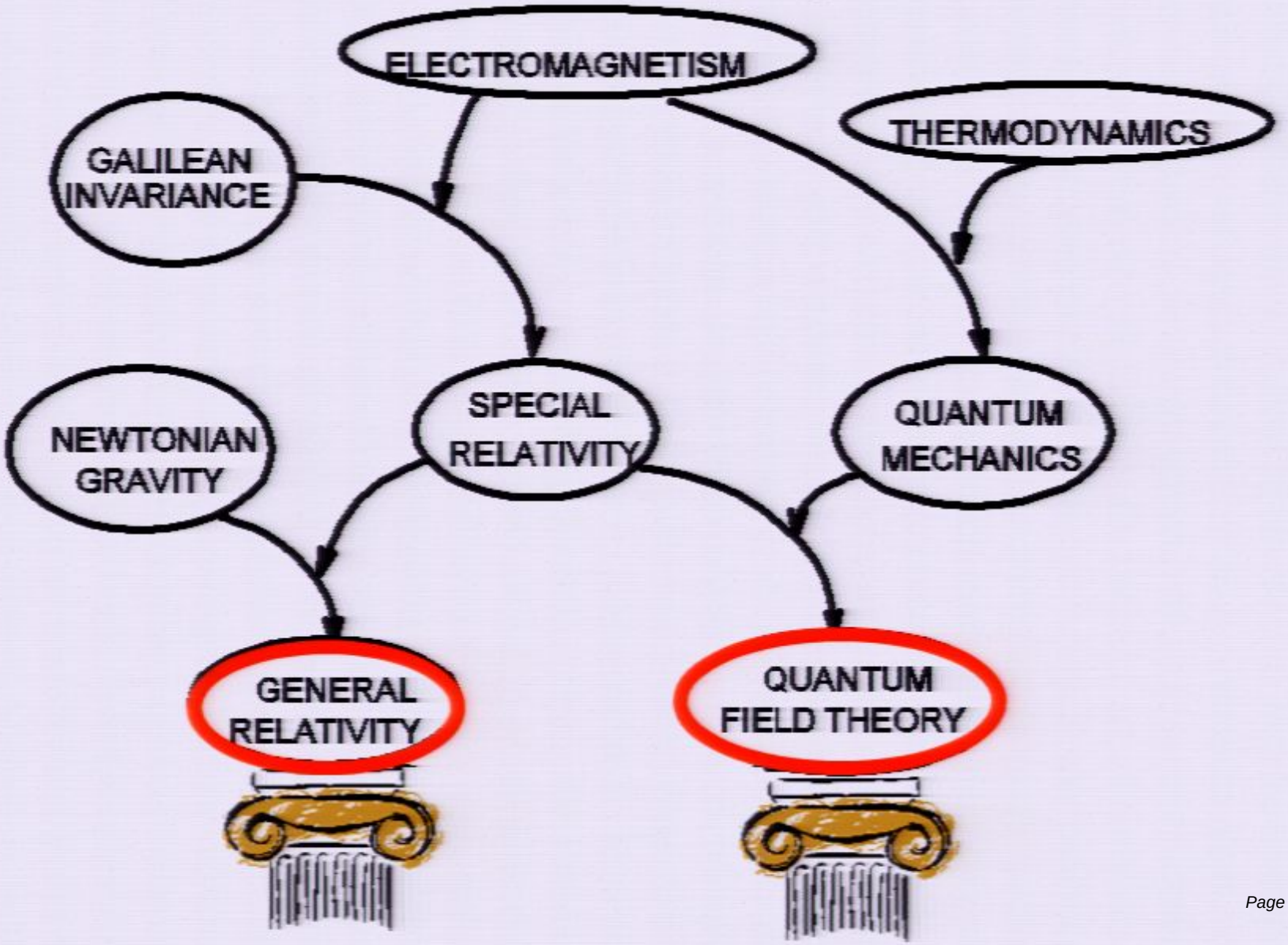

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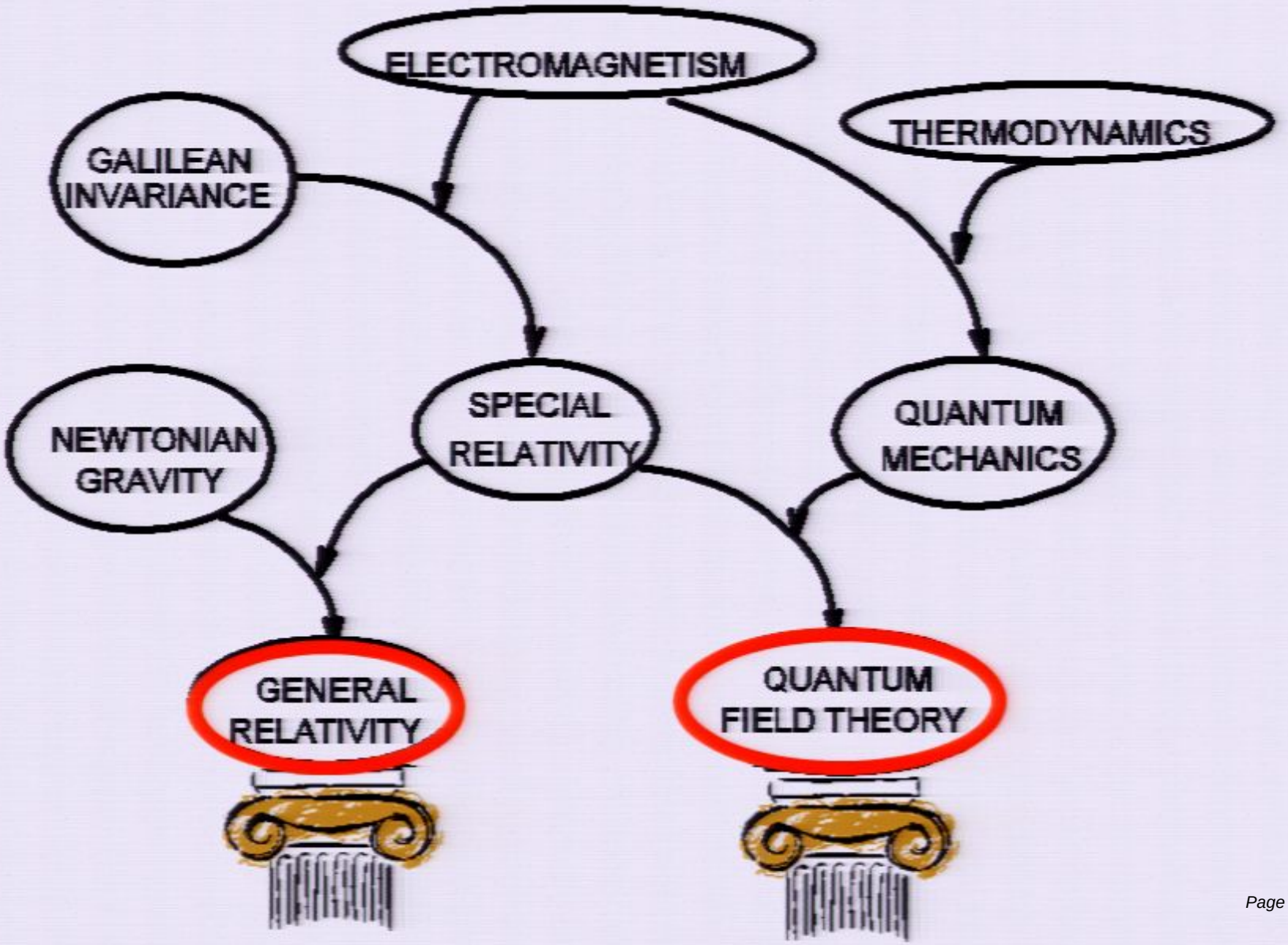
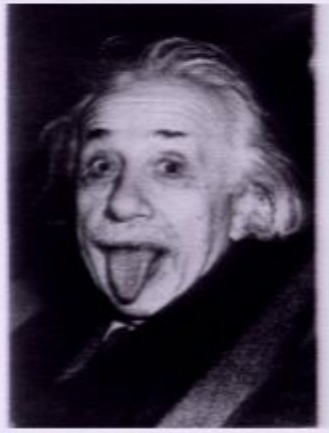


Einstein:



Gravity: It's all just straight lines!

Special Relativity (1905):

Space and time are inextricably linked ➡ Spacetime

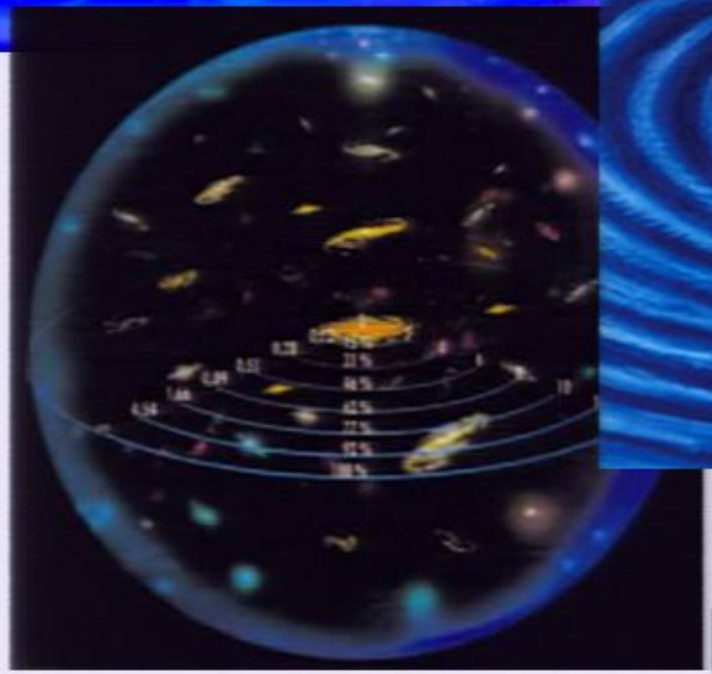
General Relativity (1915):

Gravity is a manifestation of spacetime curvature.

General Relativity: a rich source of new ideas

Black holes

Gravitational waves

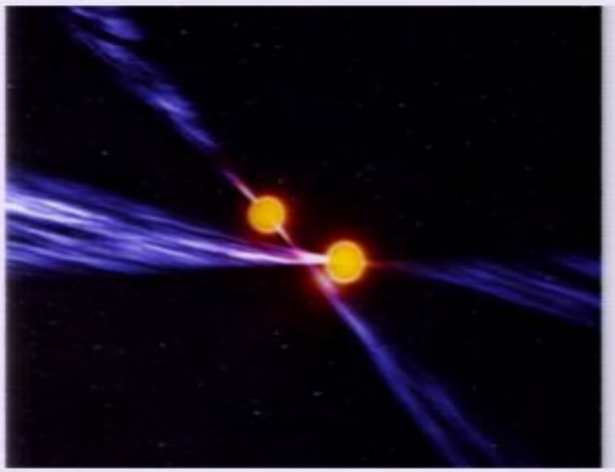


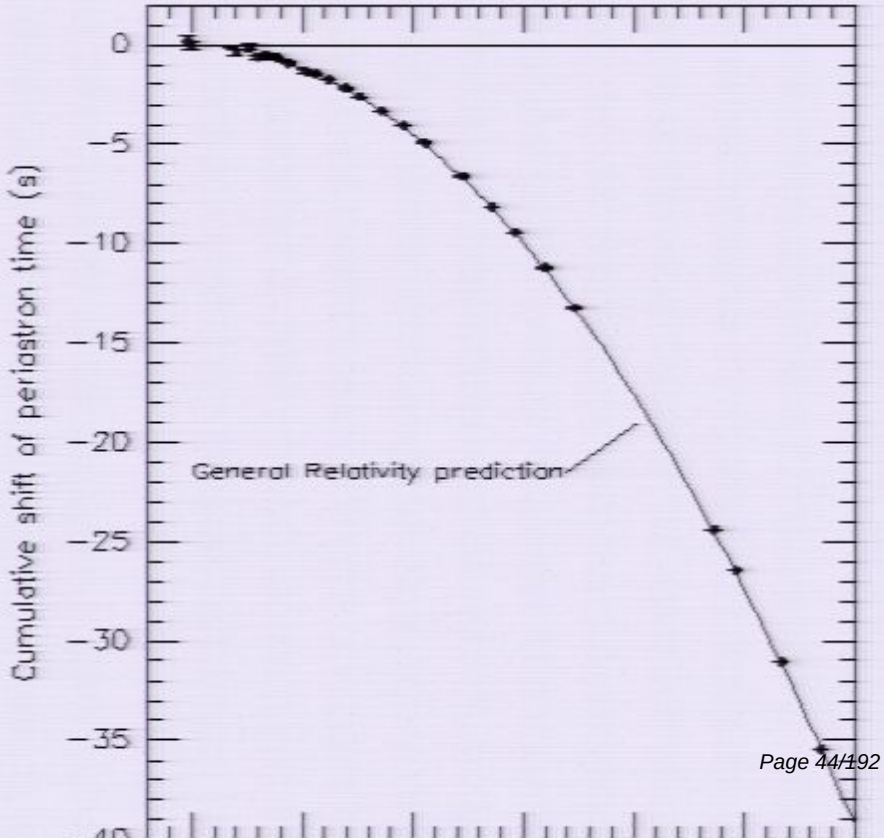
Expanding universe

General Relativity is rigorously tested!!

- Deflection of Light by the Sun
- Gravitational Redshift
- Precession of the Perihelion of Mercury
- Time Delay of Light, ...

Hulse and Taylor: Nobel Prize in 1993!!

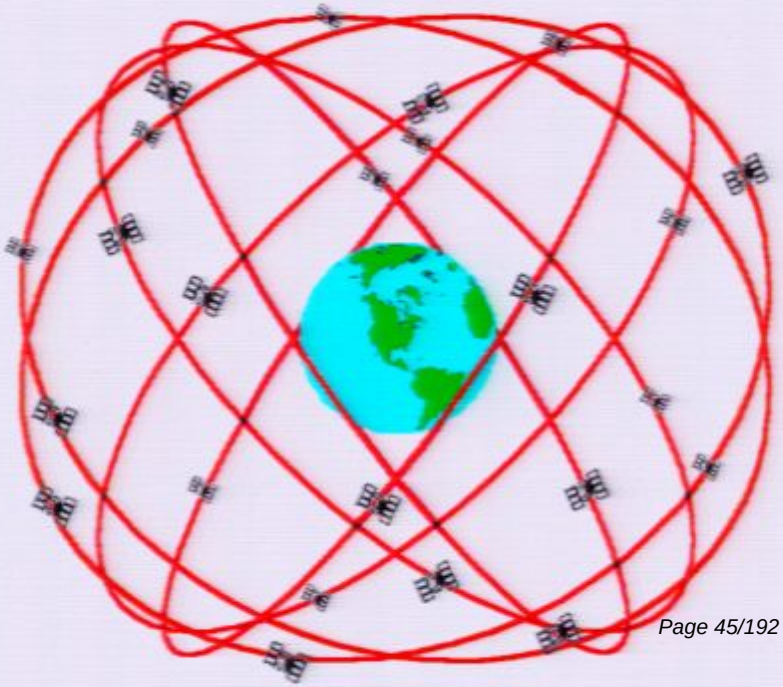




General Relativity is rigorously tested!!

Global Positioning System (GPS):

Accurate positioning requires accounting for affects of general relativity on clocks in orbit and on earth



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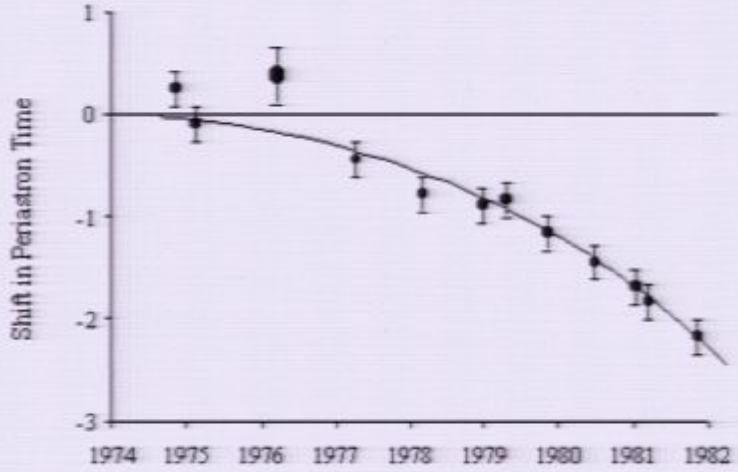
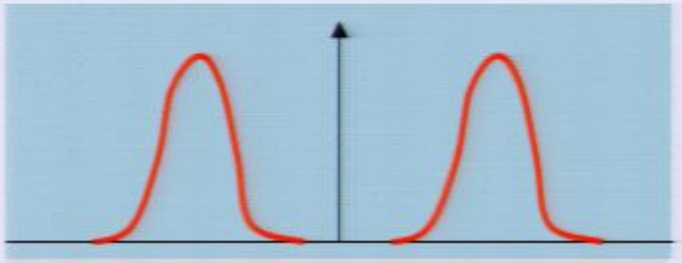


General Relativity is the geometric arena of physics on very large scales:

planets, stars, galaxies, cosmology

Quantum Mechanics (or Quantum Field Theory) is the probabilistic arena of physics on very small scales

Particles can act like waves!



de Broglie wavelength: $\lambda = \frac{2\pi\hbar}{p}$ ← Planck's constant

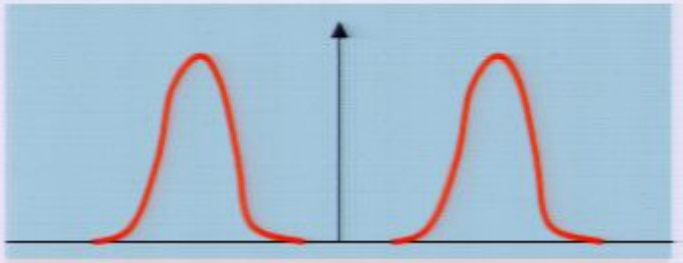
$$\lambda_{\text{rain drop}} \approx 4 \times 10^{-30}\,\text{m}$$

water jet

Positions are uncertain for the very small !

Quantum Mechanics (or Quantum Field Theory) is the probabilistic arena of physics on very small scales

Particles can act like waves!



de Broglie wavelength: $\lambda = \frac{2\pi\hbar}{p}$ ← Planck's constant

$$\lambda_{\text{rain drop}} \approx 4\times10^{-30}\,\text{m}$$
$$\approx .000000\cdots000004\,\text{m}$$

30 digits

water jet

Positions are uncertain for the very small !

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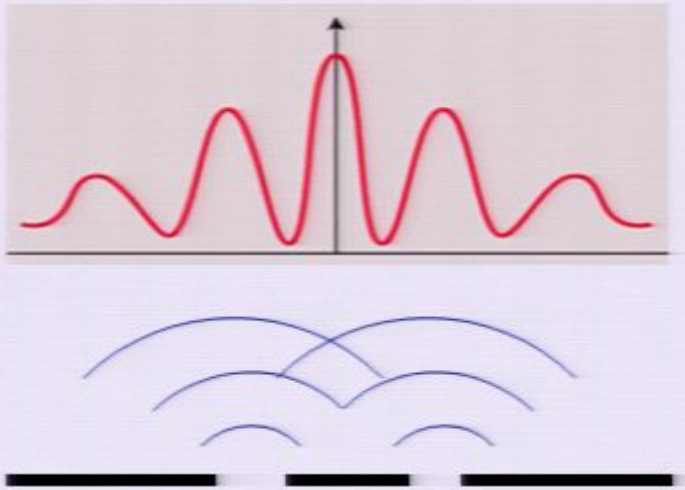
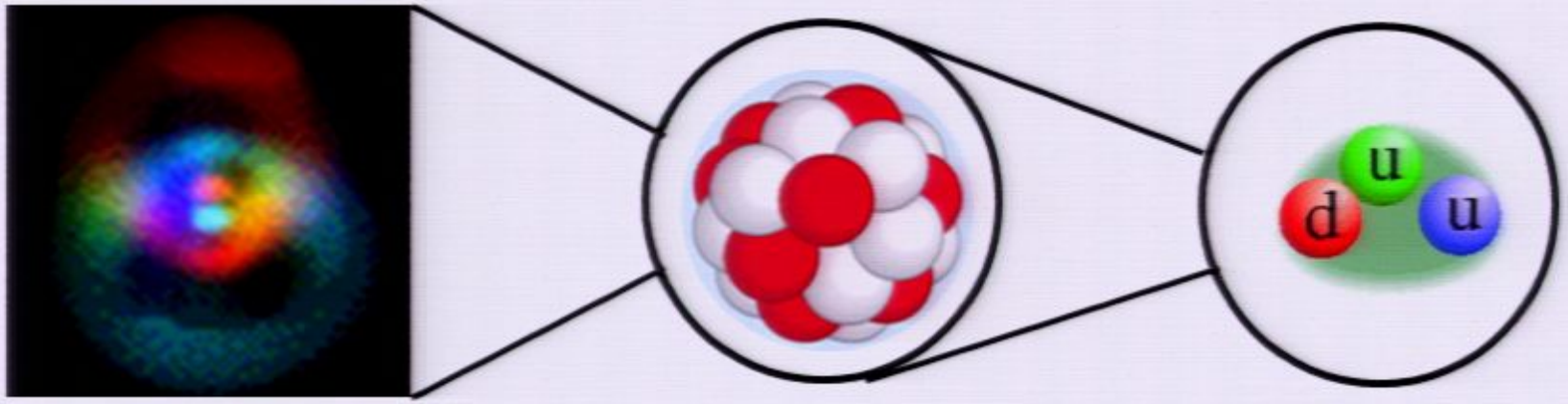


$$\lambda_{\text{rain drop}} \approx 4\times10^{-30}\,\text{m}$$

$$\lambda_{\text{electron}} \approx 3\times10^{-10}\,\text{m} = 3\ \text{Å}$$

Quantum fluctuations are manifest in behavior of subatomic particles

Quantum Field Theory is the probabilistic arena of physics on very small scales



10^{-10} m 10^{-14} m 10^{-15} m

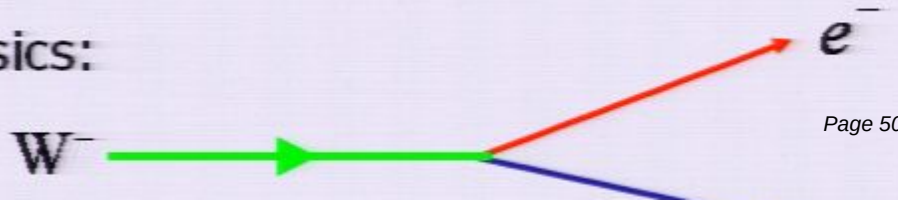
Elementary Particles (10^{-17} m)

Fermions:
- electron, muon, tauon
- neutrinos (3 flavors)
- quarks - up, down, strange, charm, bottom, top

Bosons (Force Mediators):
- photon (electromagnetism)
- gluon (strong)
- $W^{\pm}$, Z (weak)
- Higgs particle

Standard Model of Subatomic Physics:

above particles plus interactions (and ~20 free parameters)



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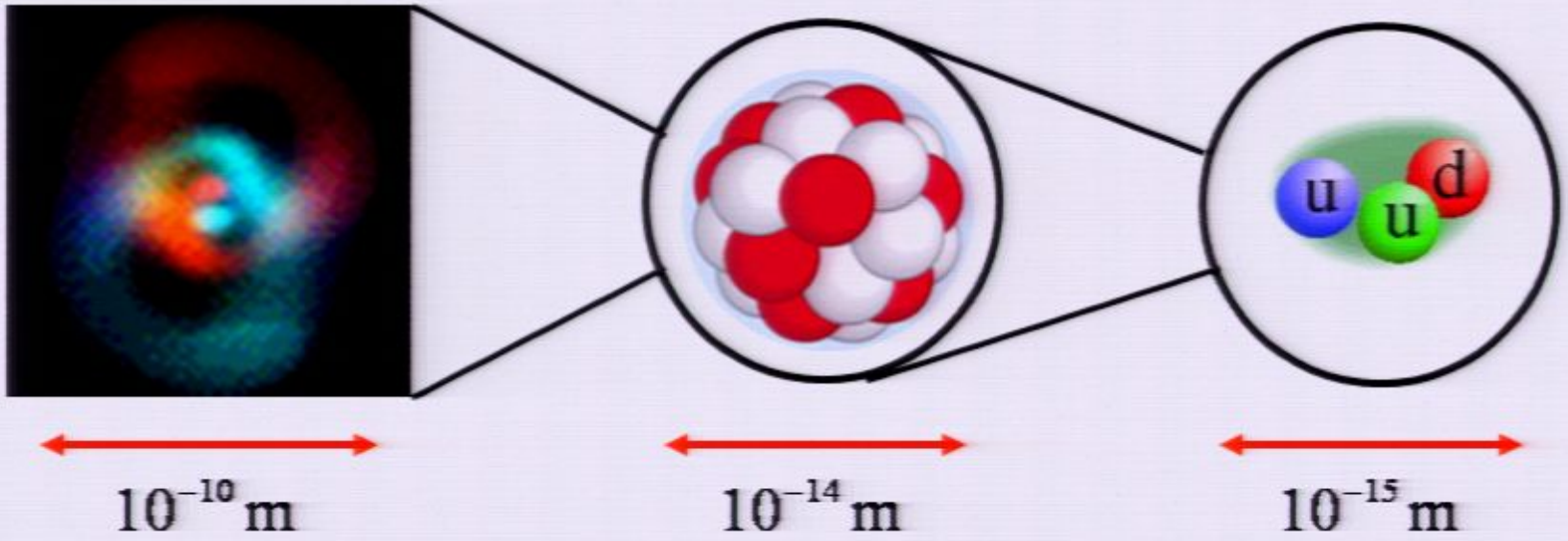

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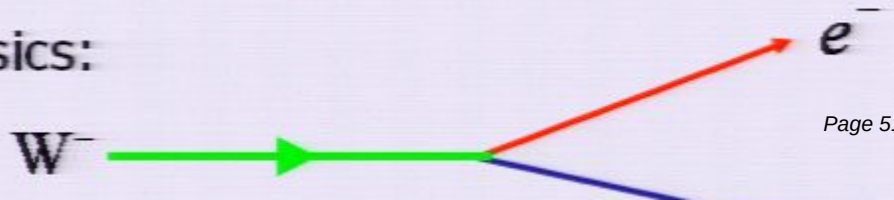

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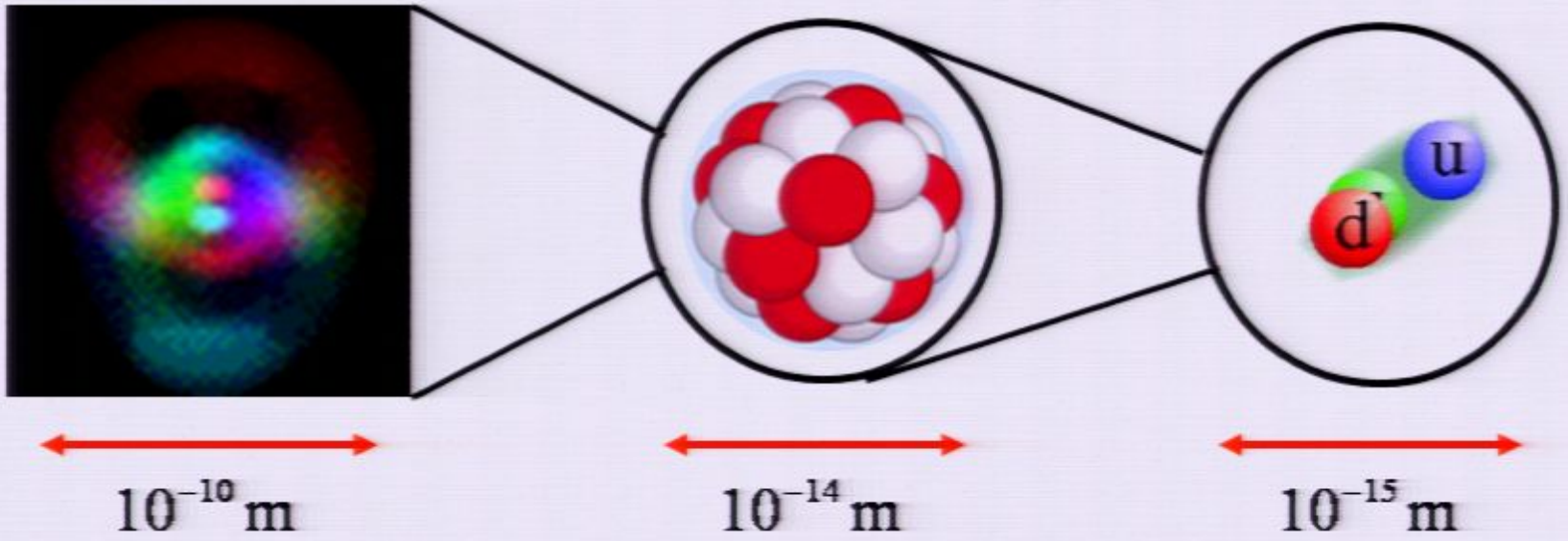

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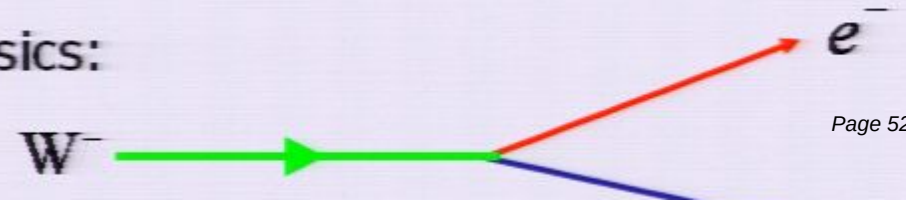

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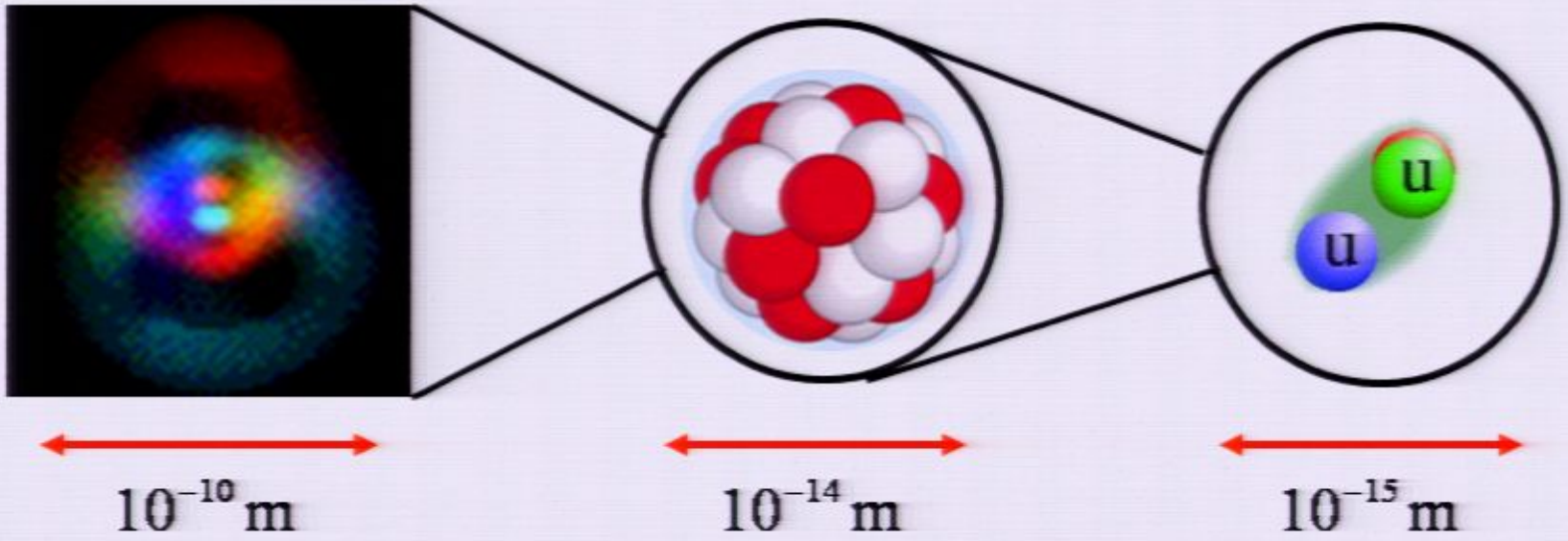

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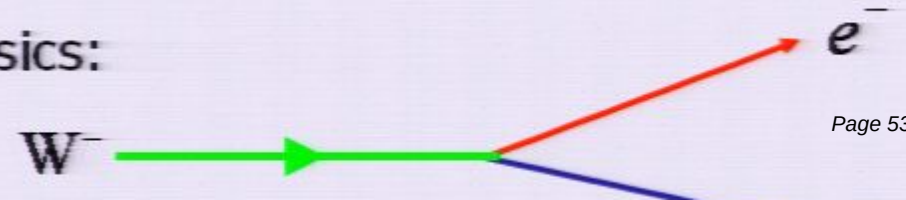

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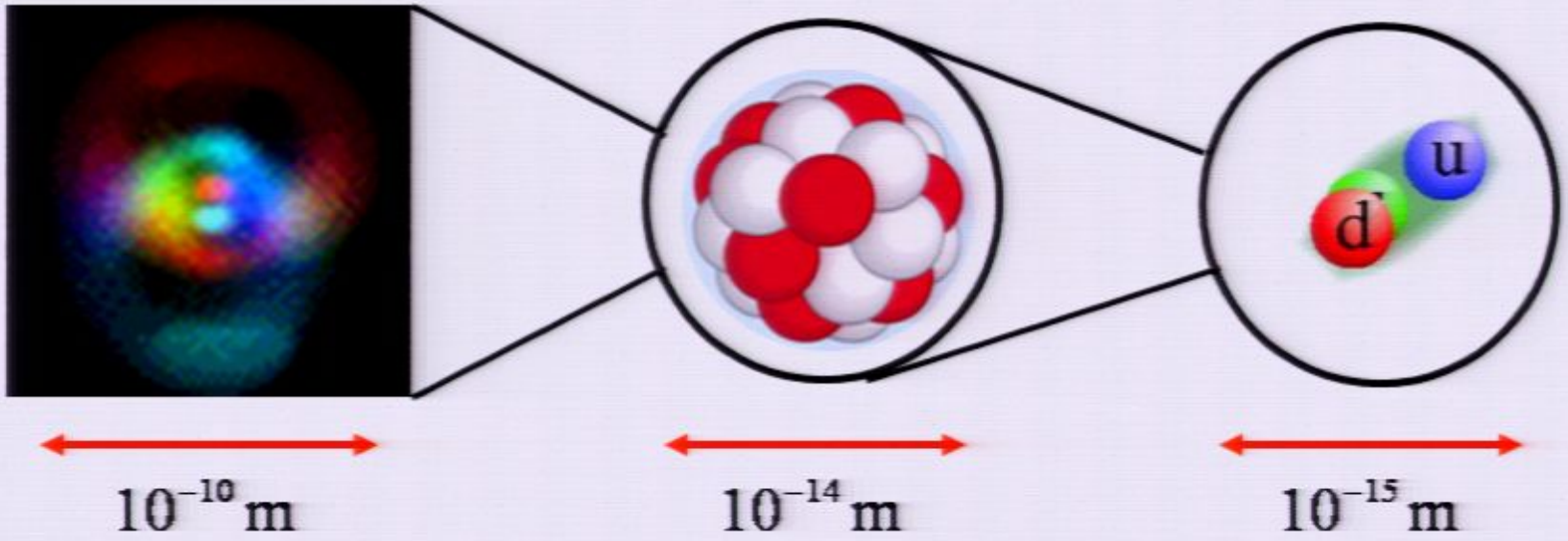

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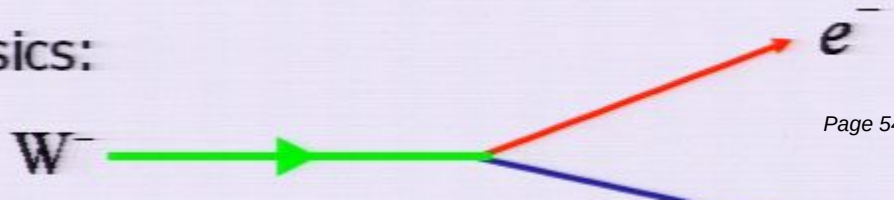

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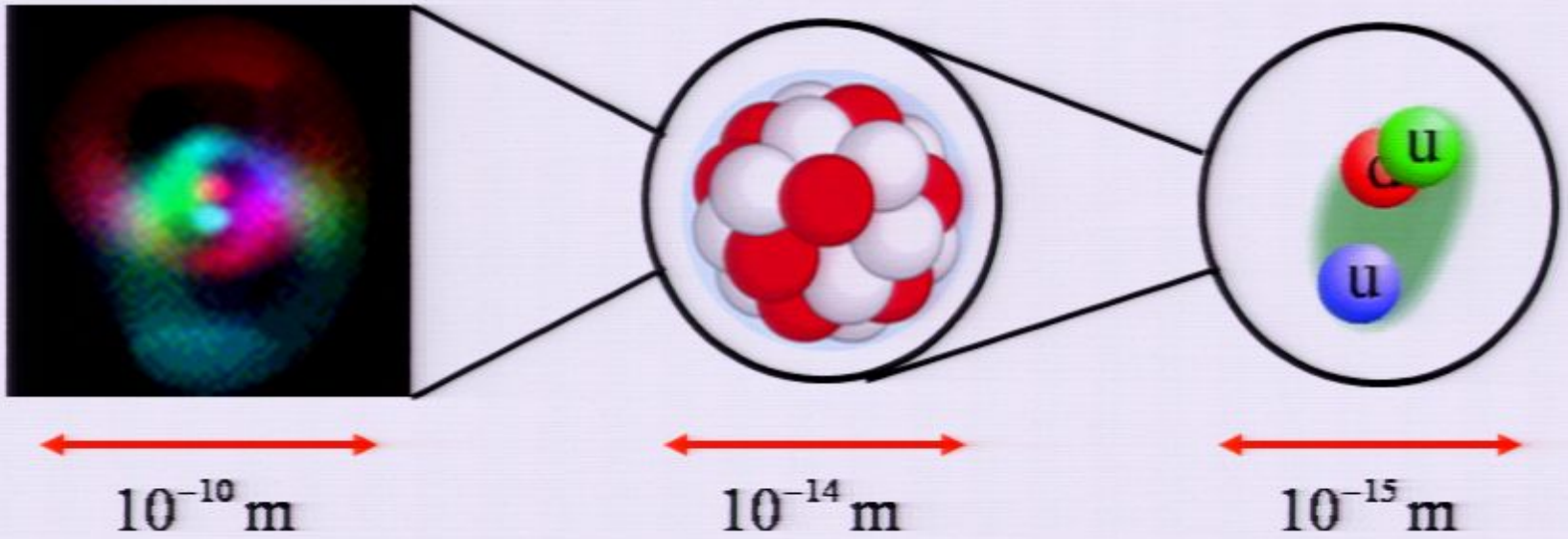

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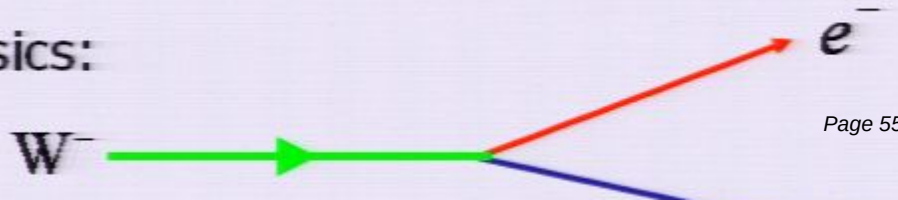

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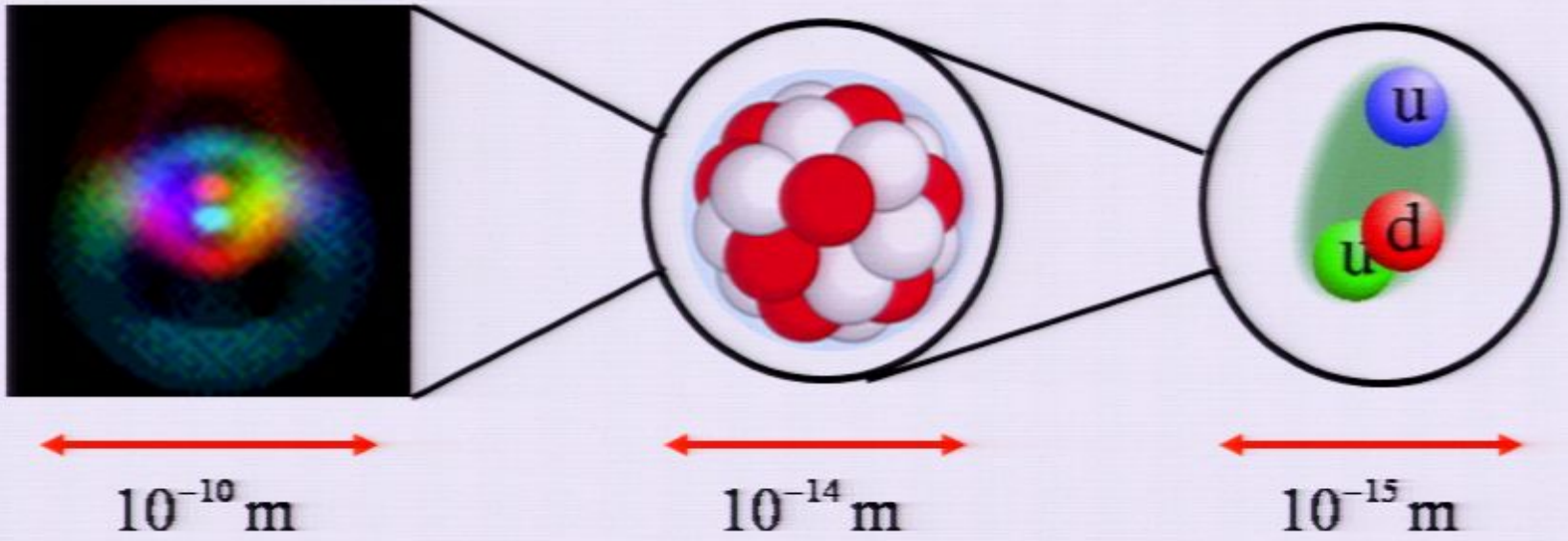

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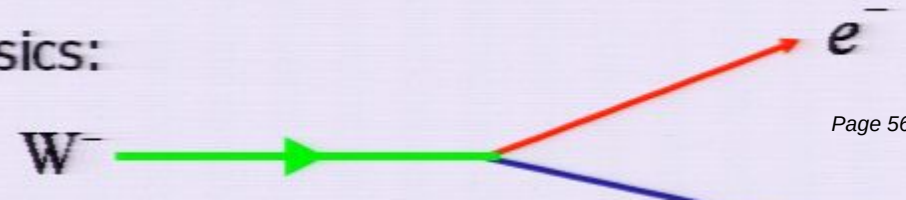

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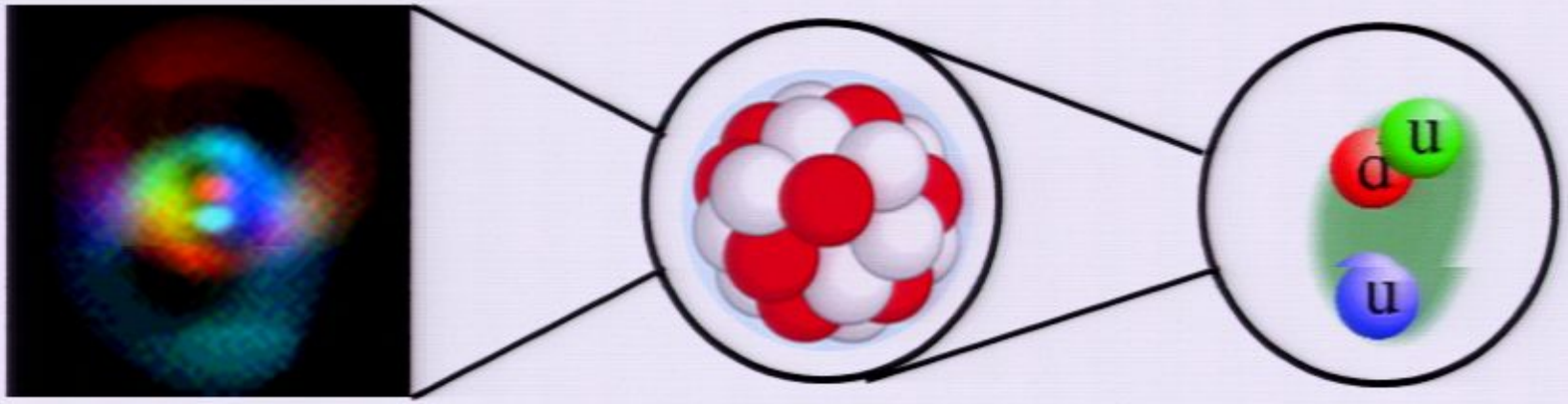

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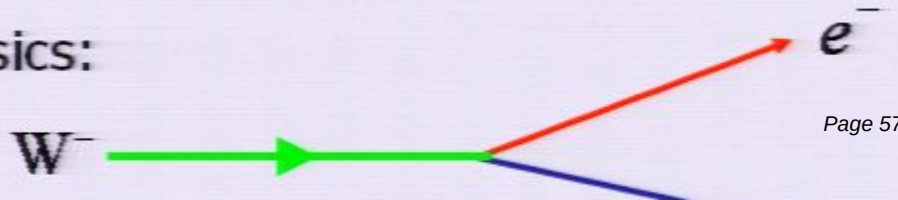

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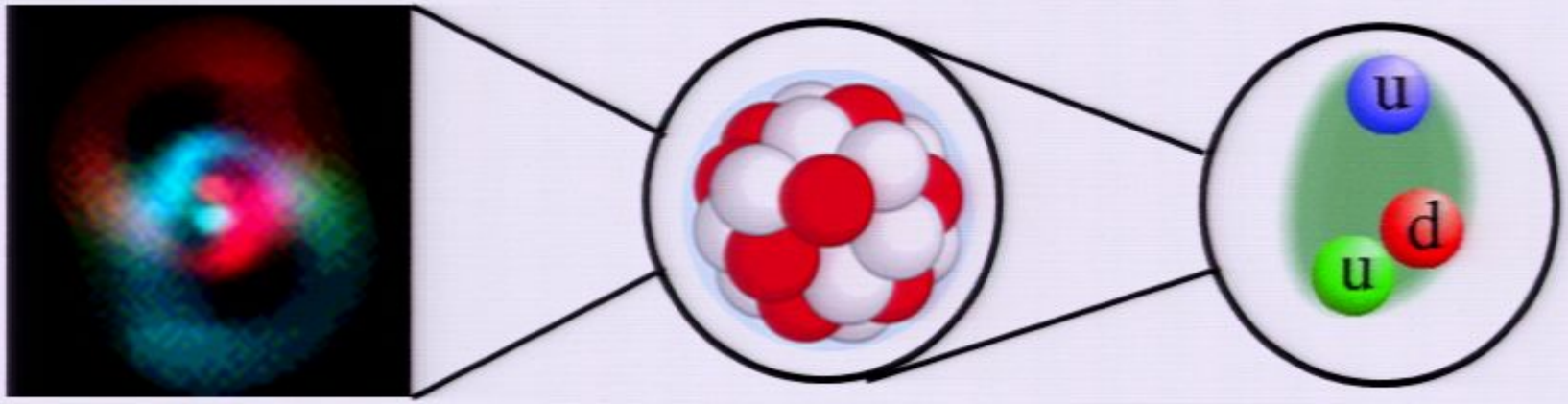

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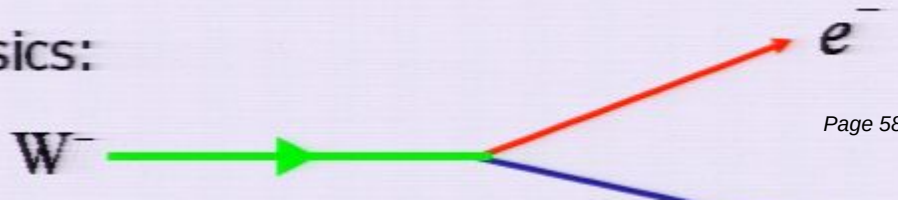

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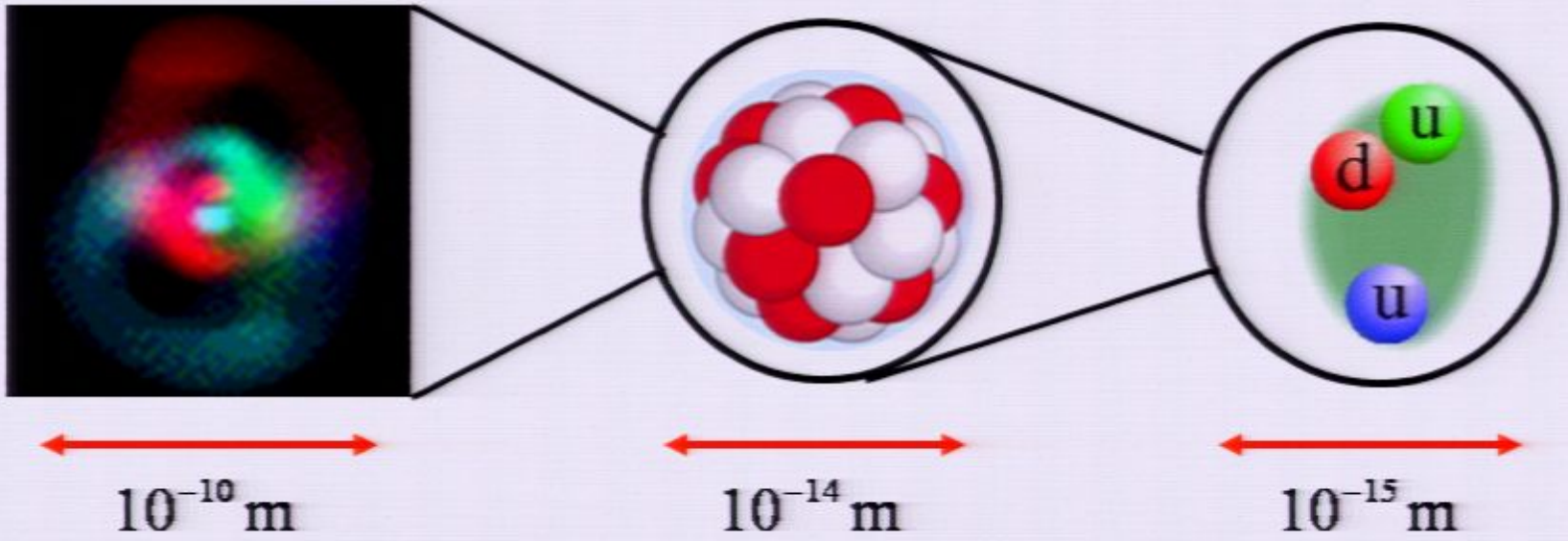

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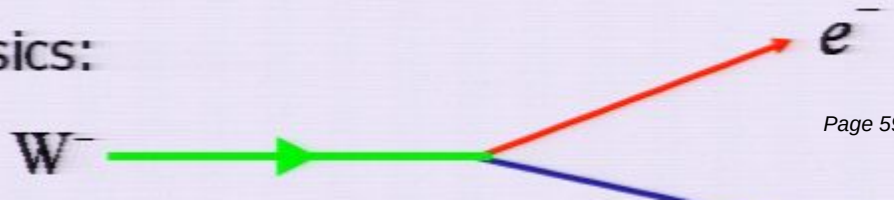

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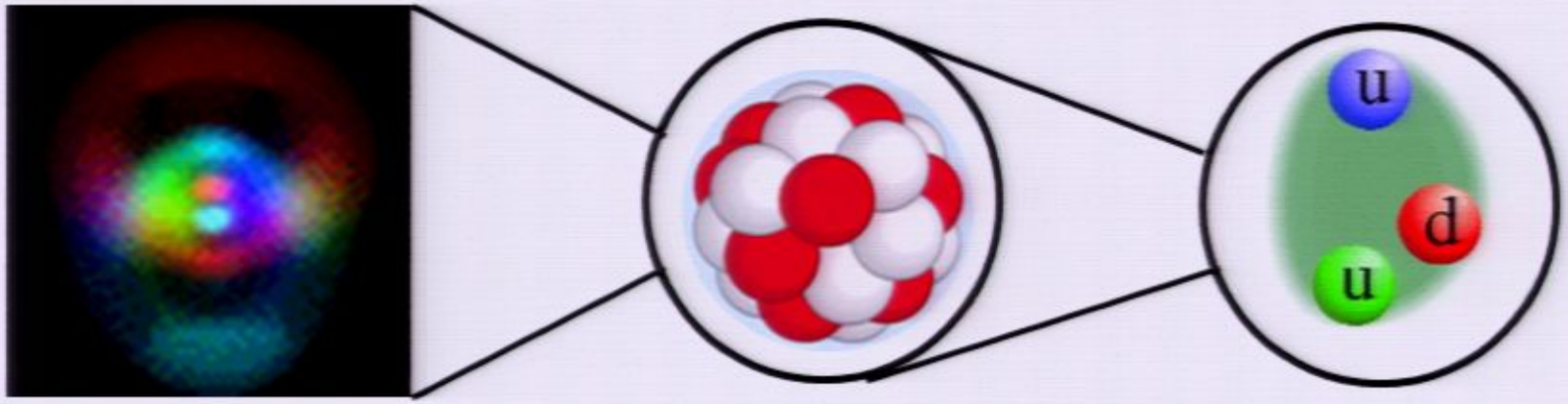

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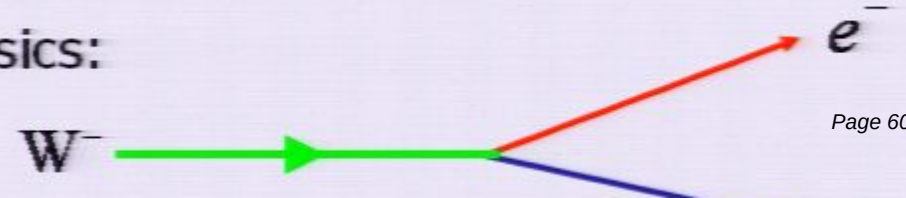

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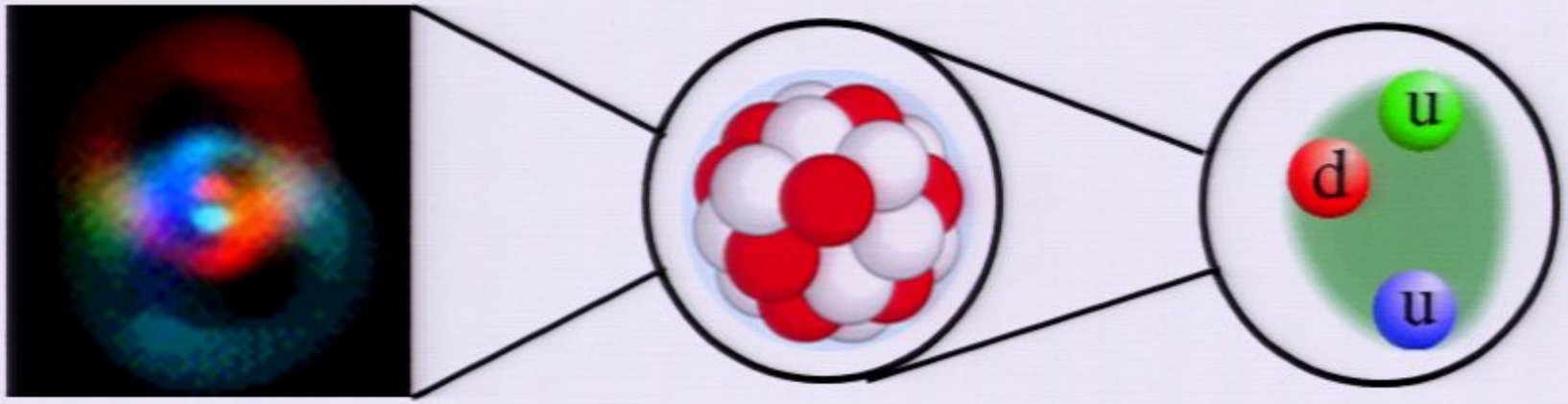

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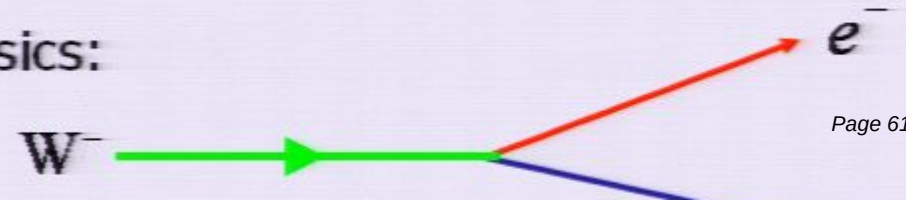

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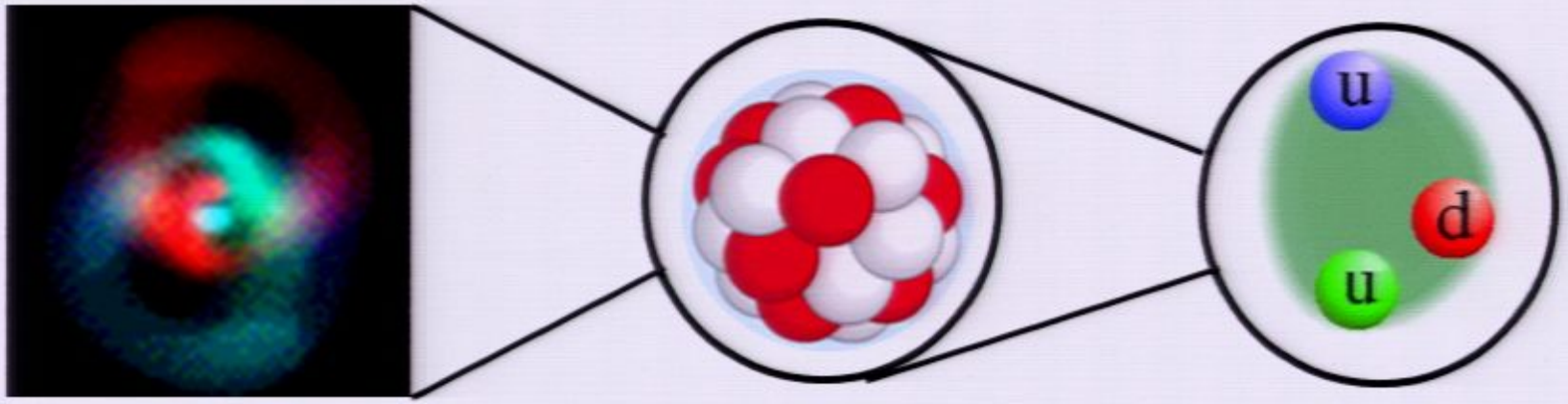

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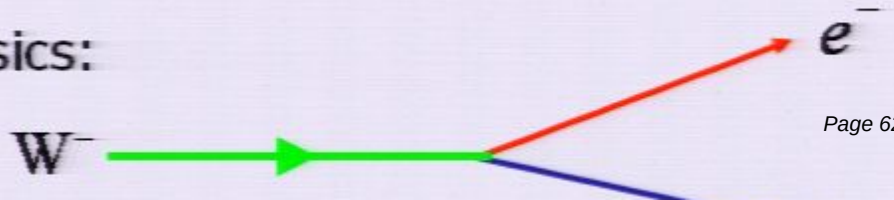

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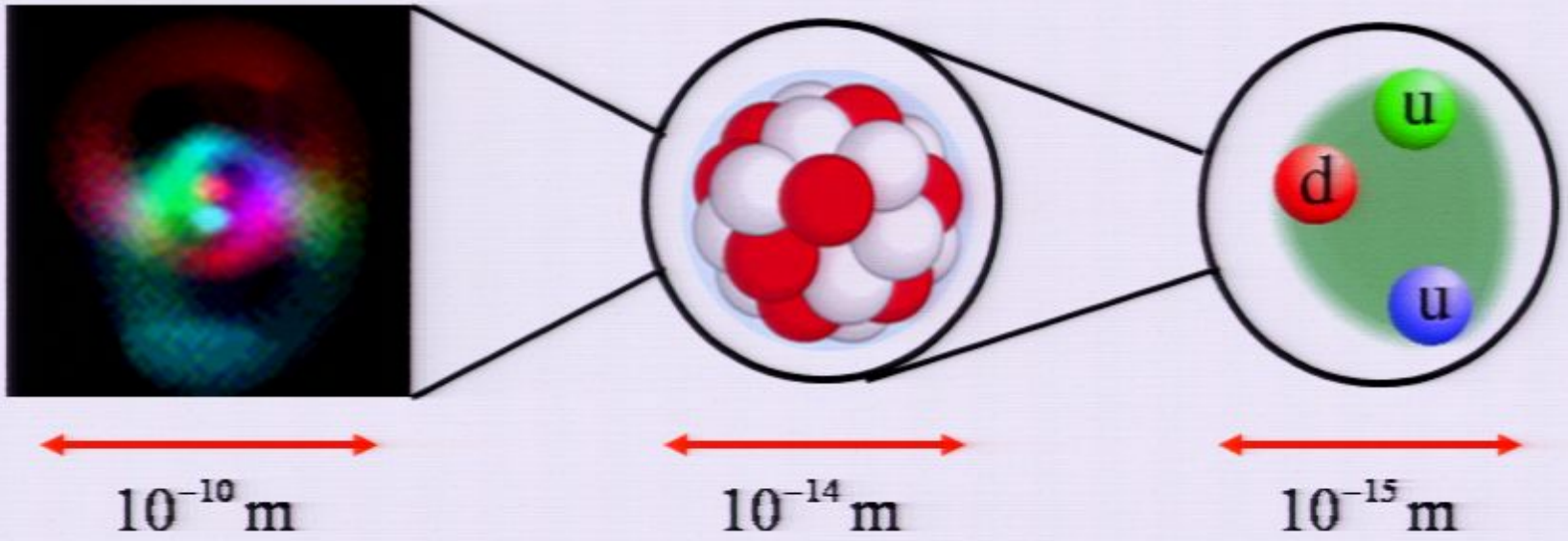

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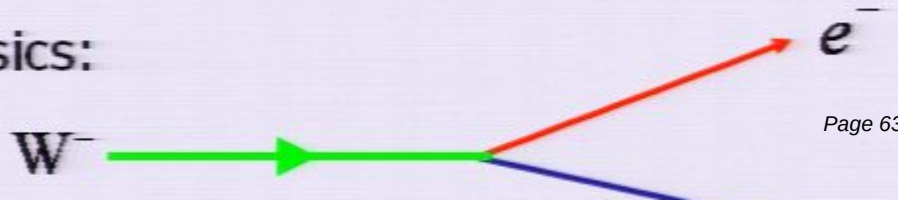

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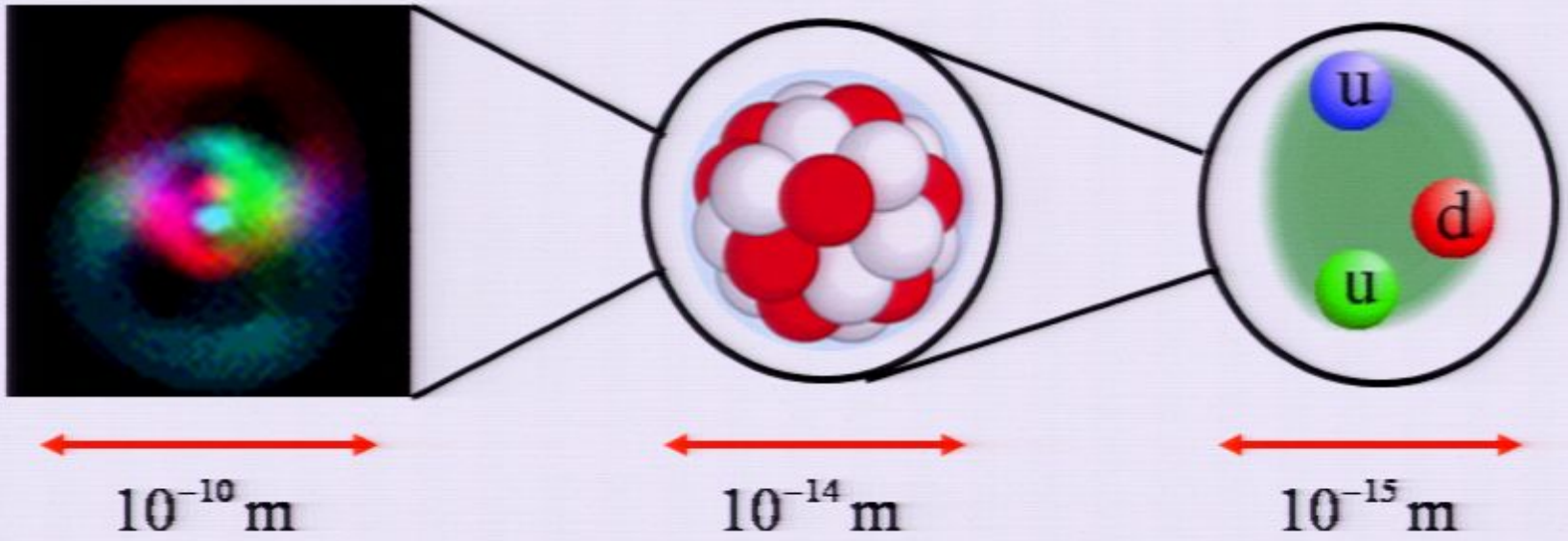

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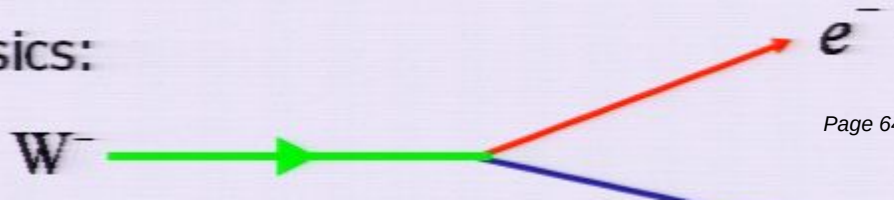

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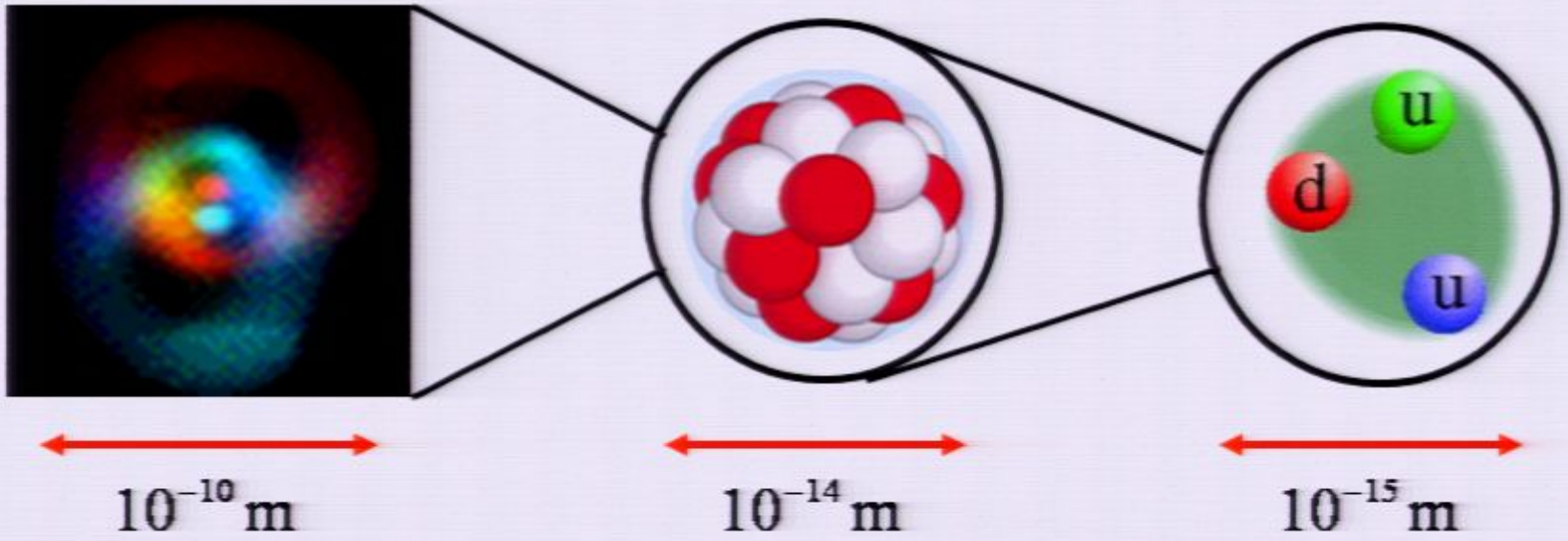

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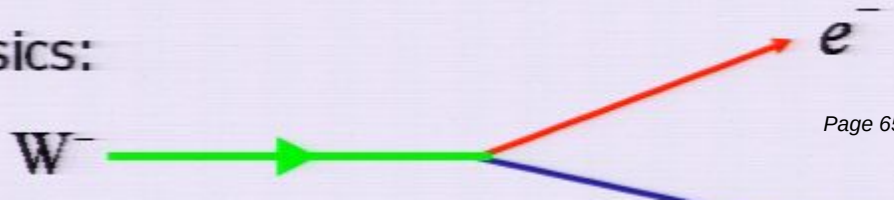

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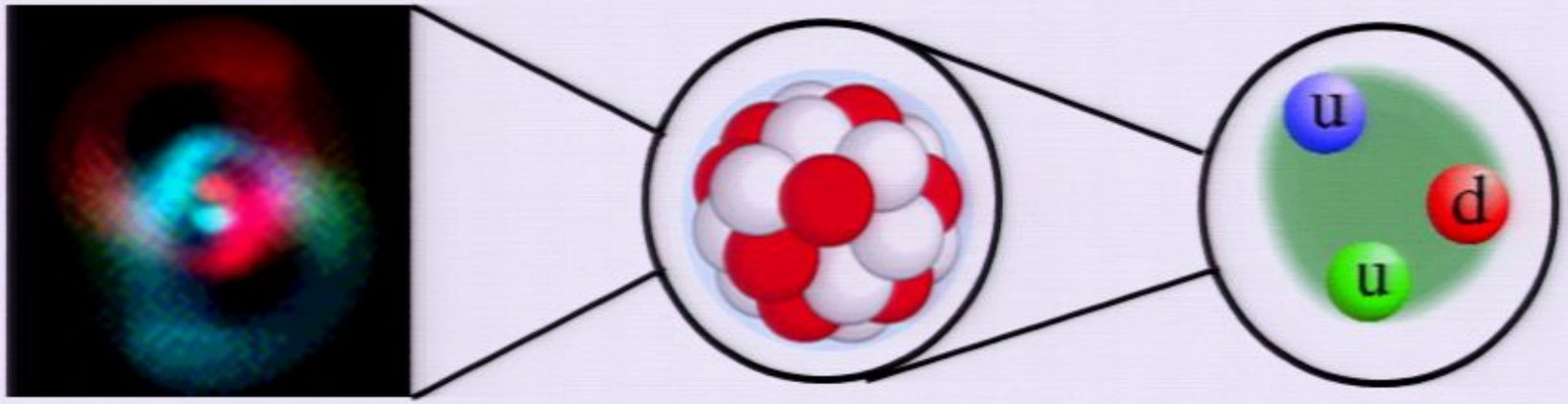

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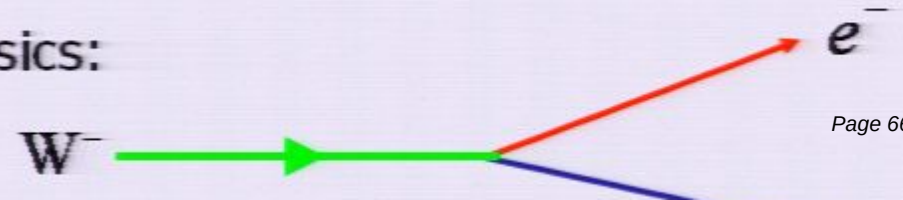

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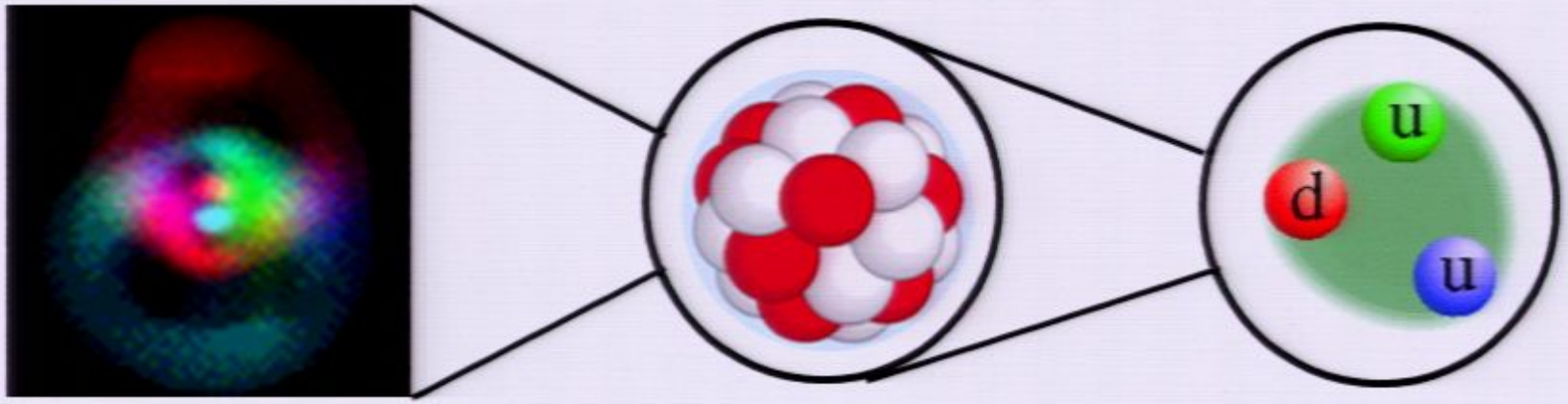

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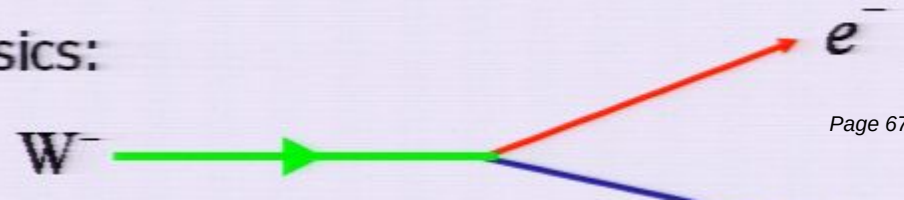

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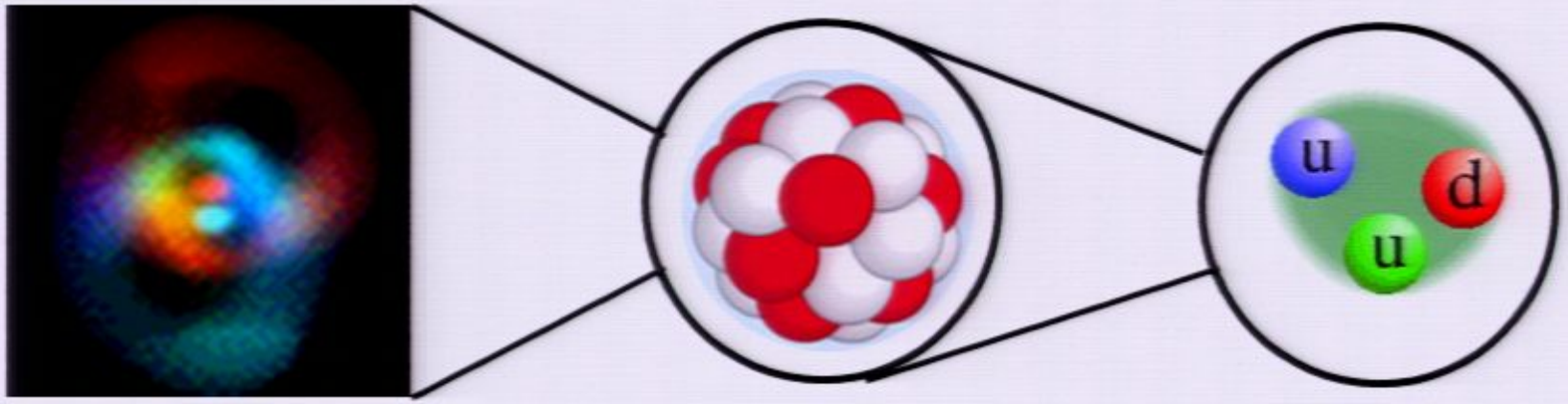

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Fermions:
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- neutrinos (3 flavors)
- quarks - up, down, strange, charm, bottom, top

Bosons (Force Mediators):
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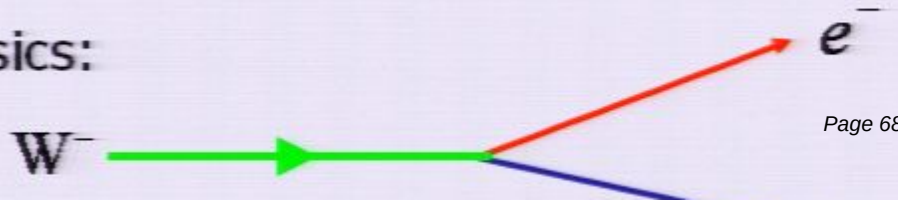
Standard Model of Subatomic Physics:

above particles plus interactions (and ~20 free parameters)



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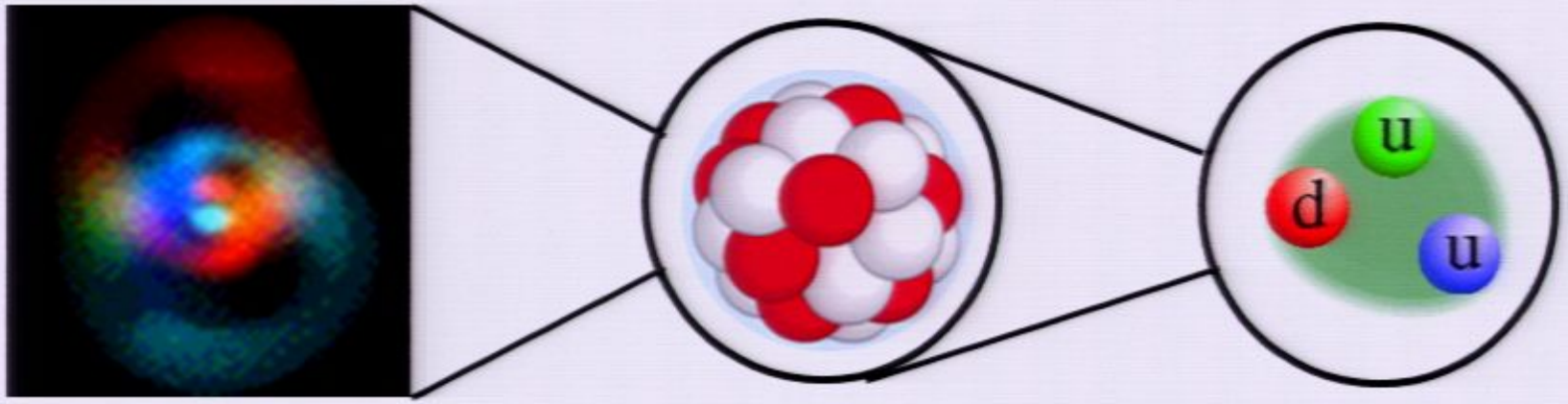

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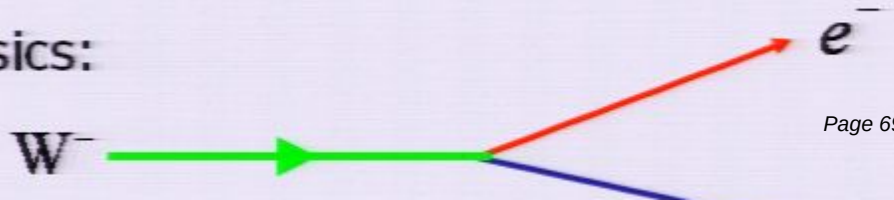

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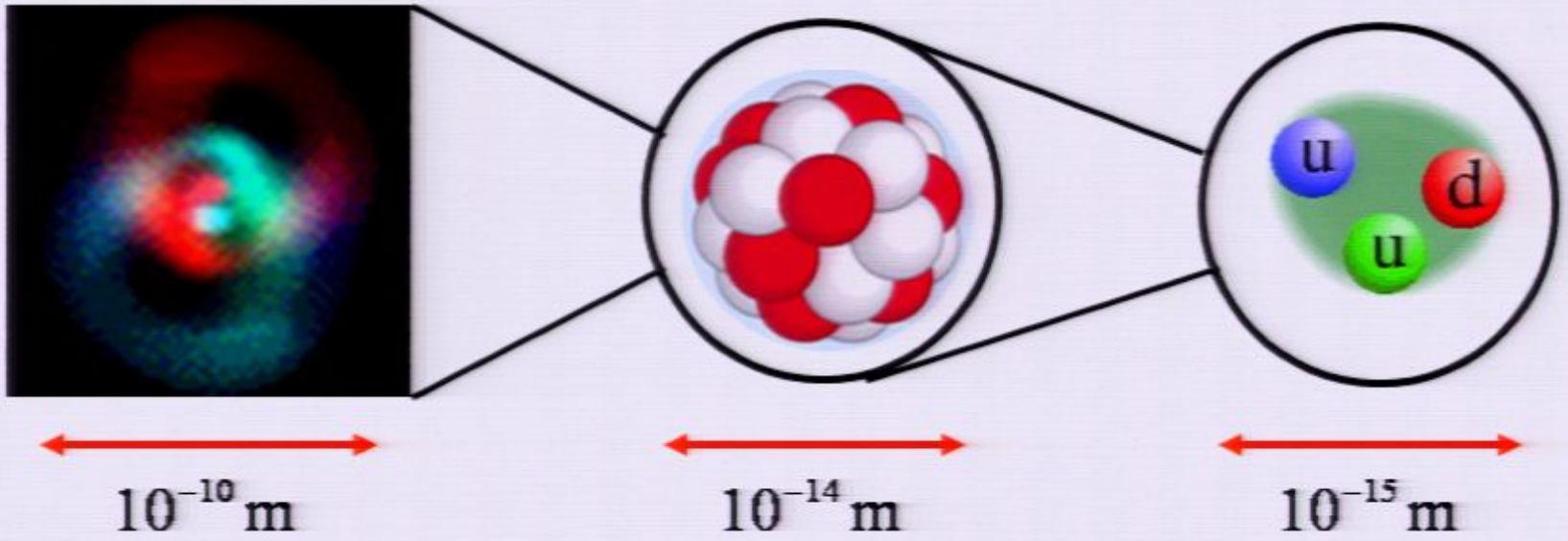

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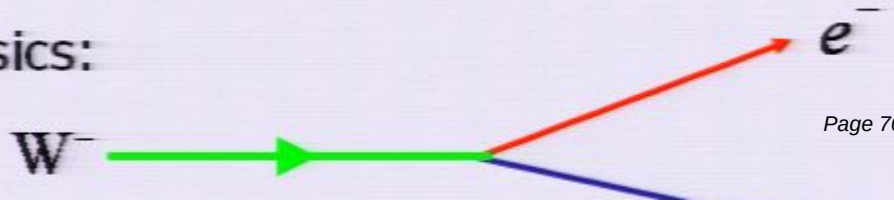

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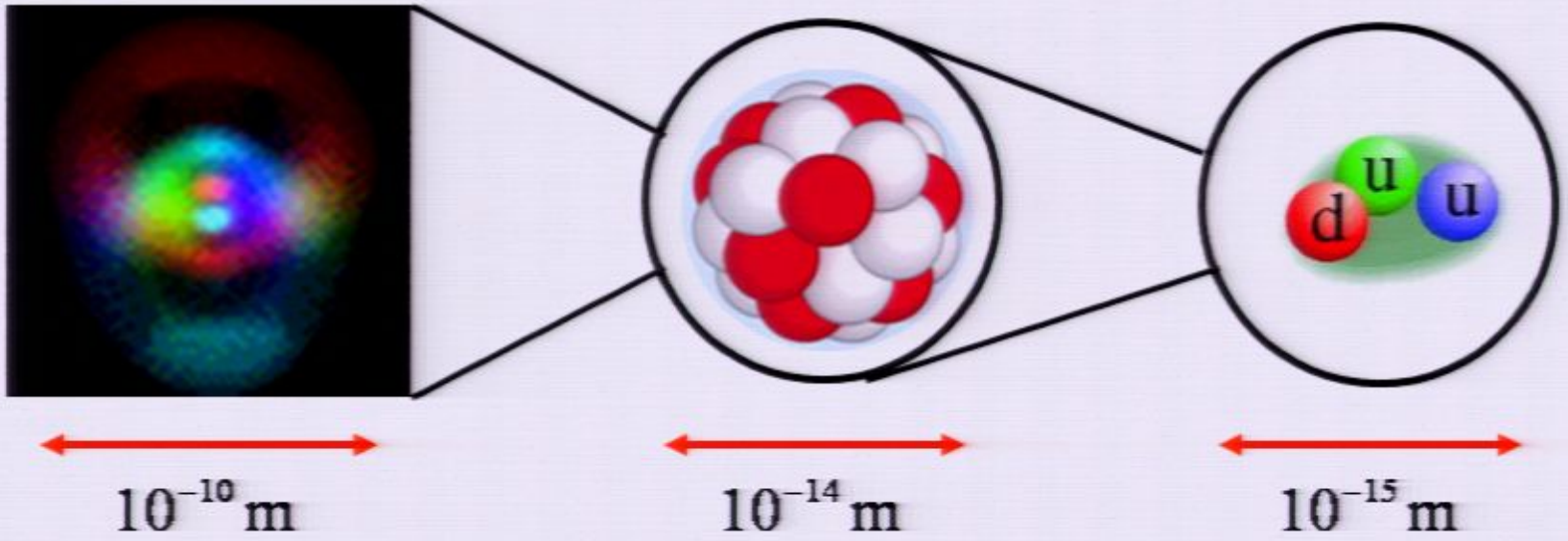

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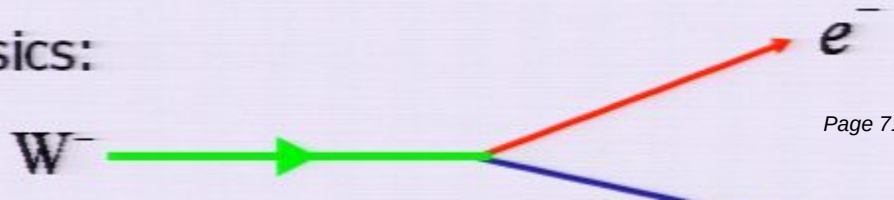

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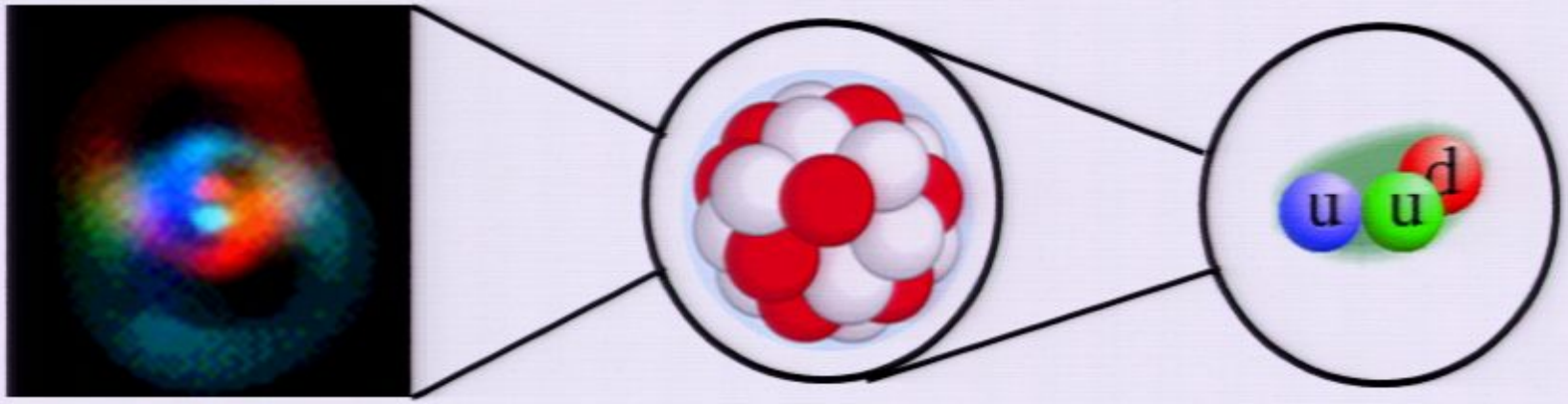

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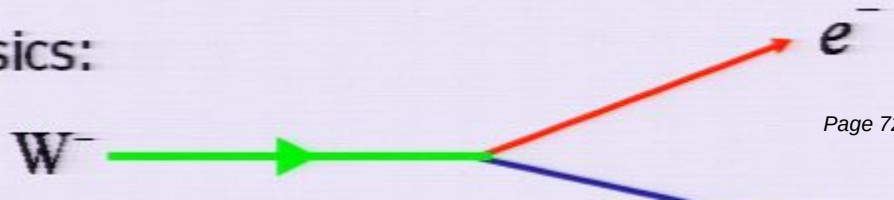

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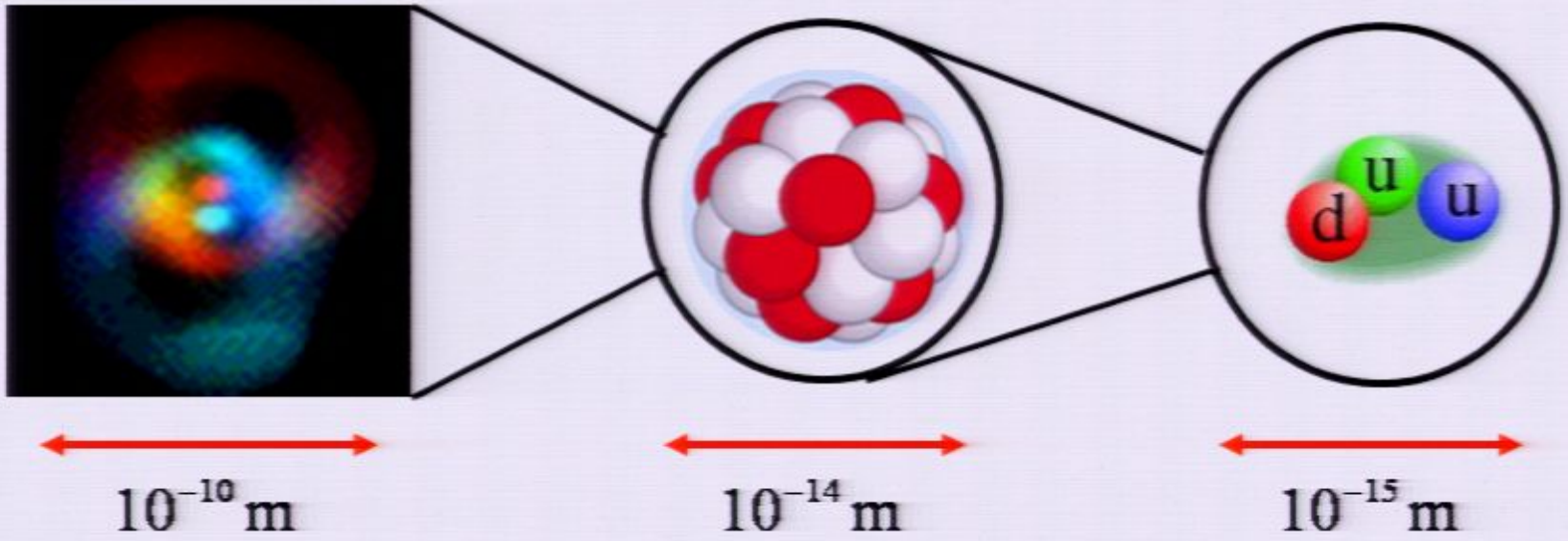

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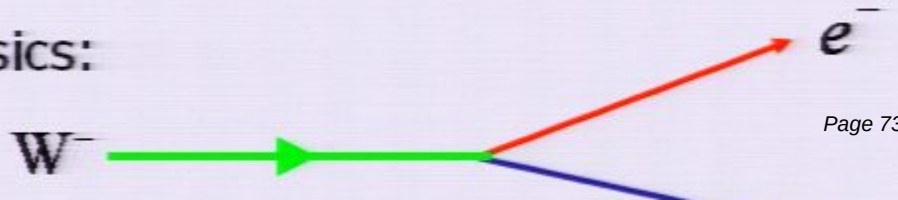

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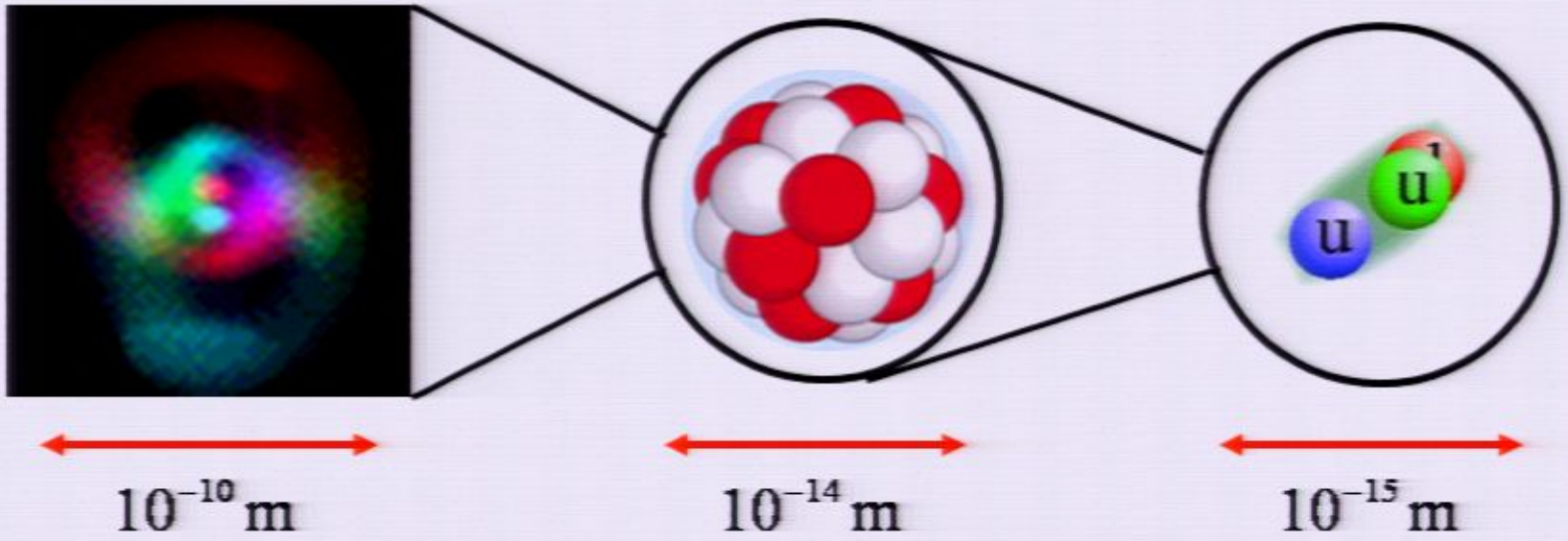

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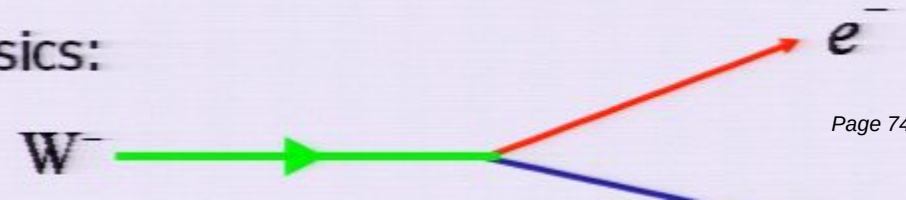

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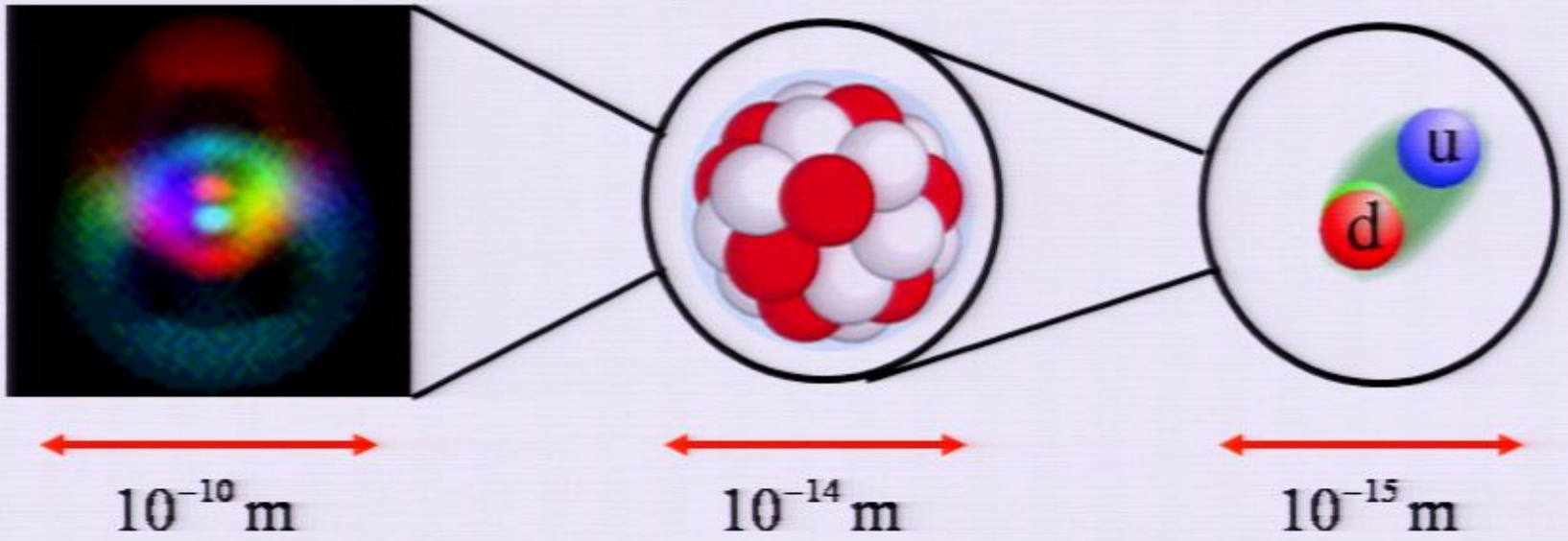

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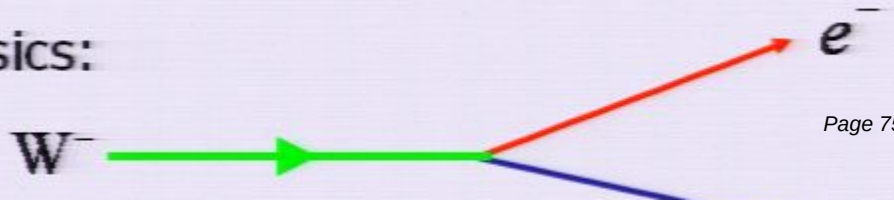

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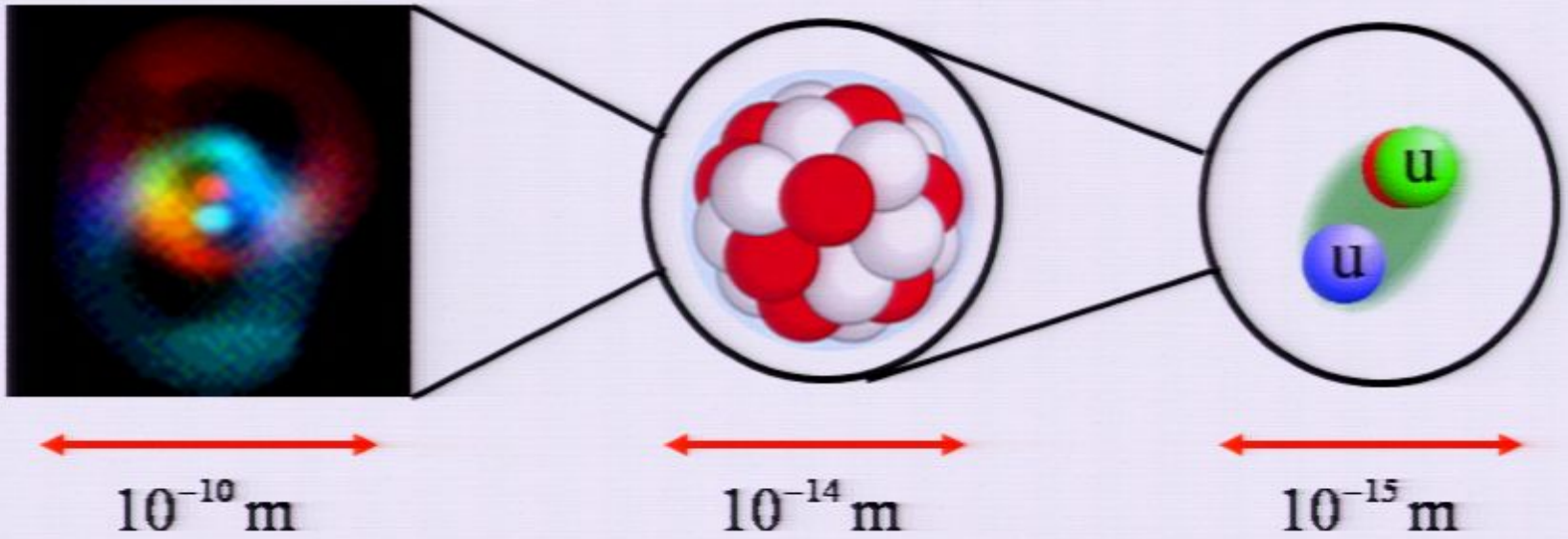

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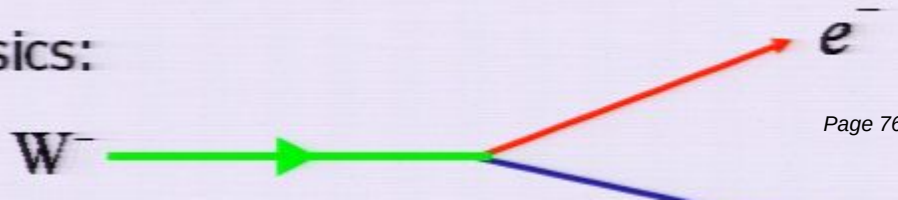

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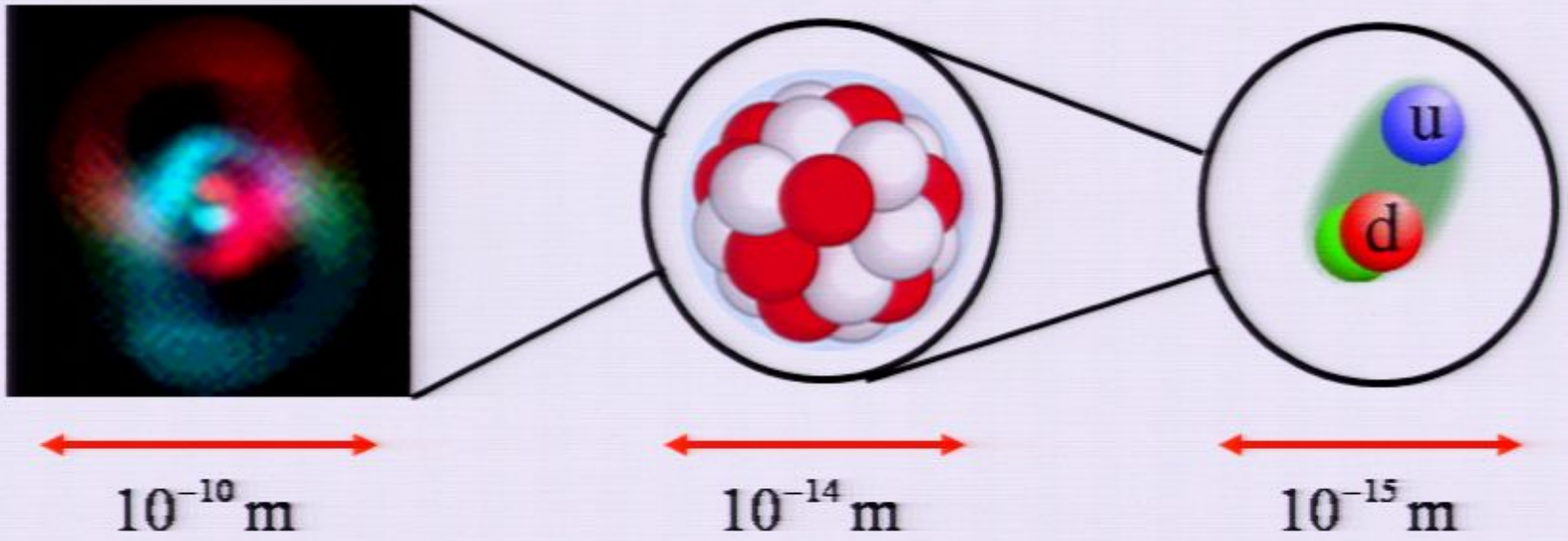

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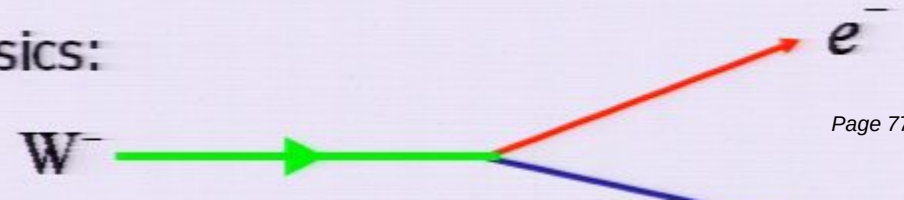

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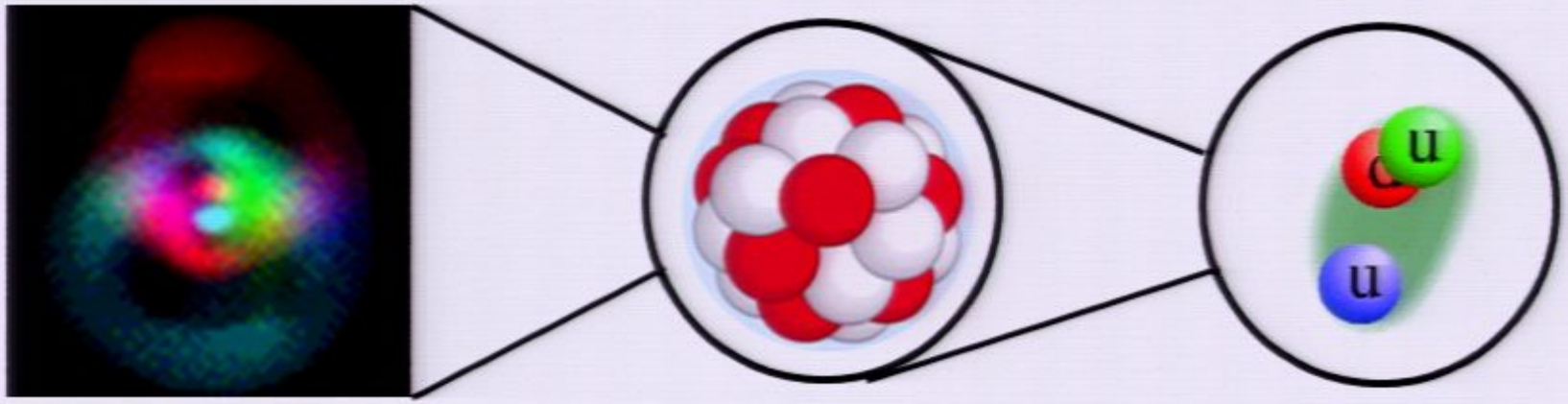

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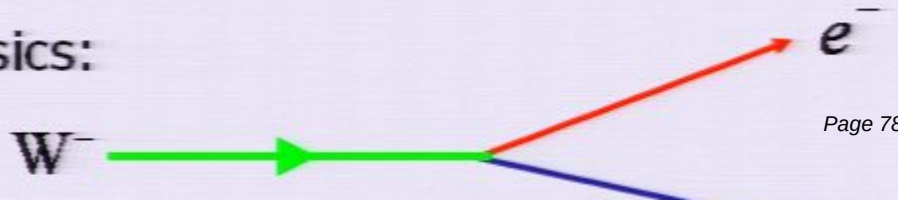

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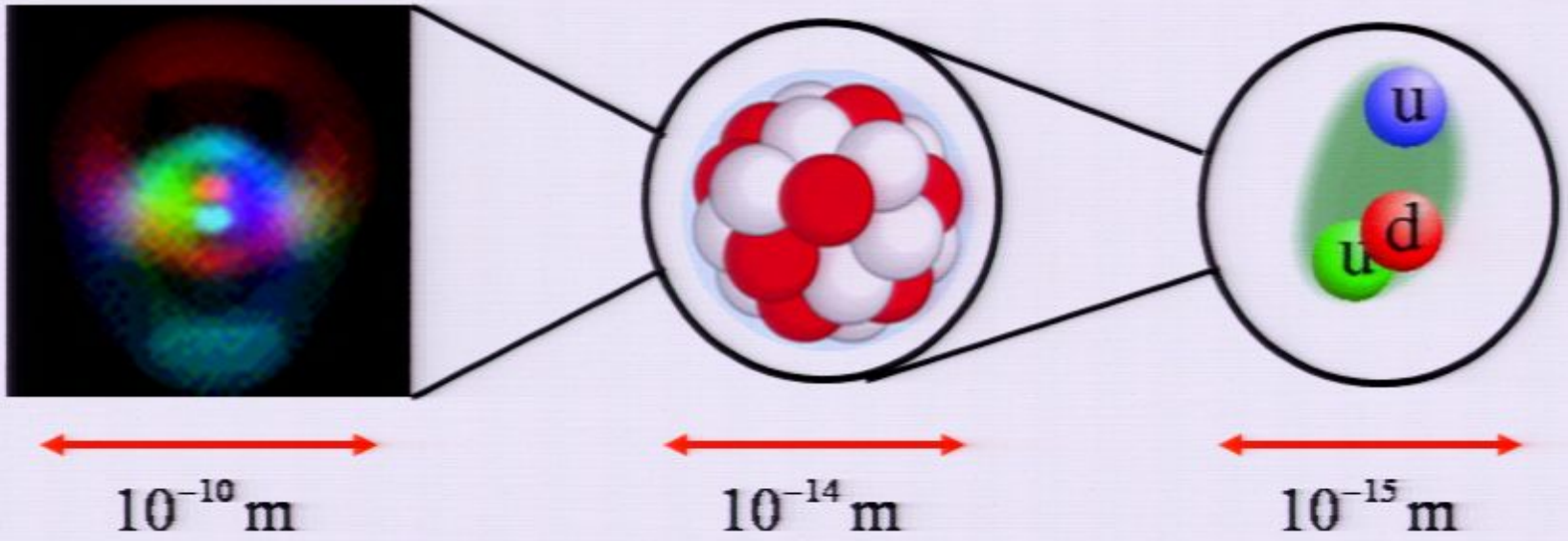

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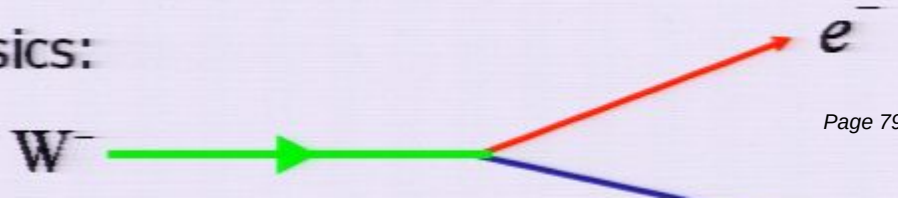

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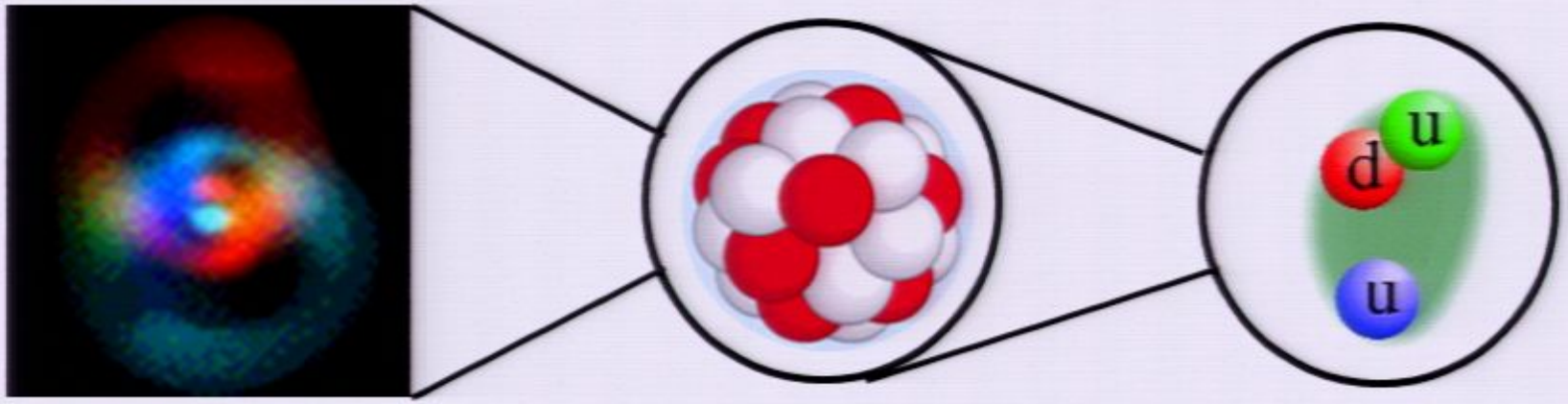

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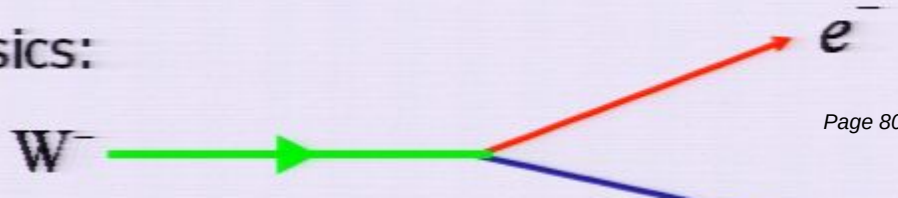

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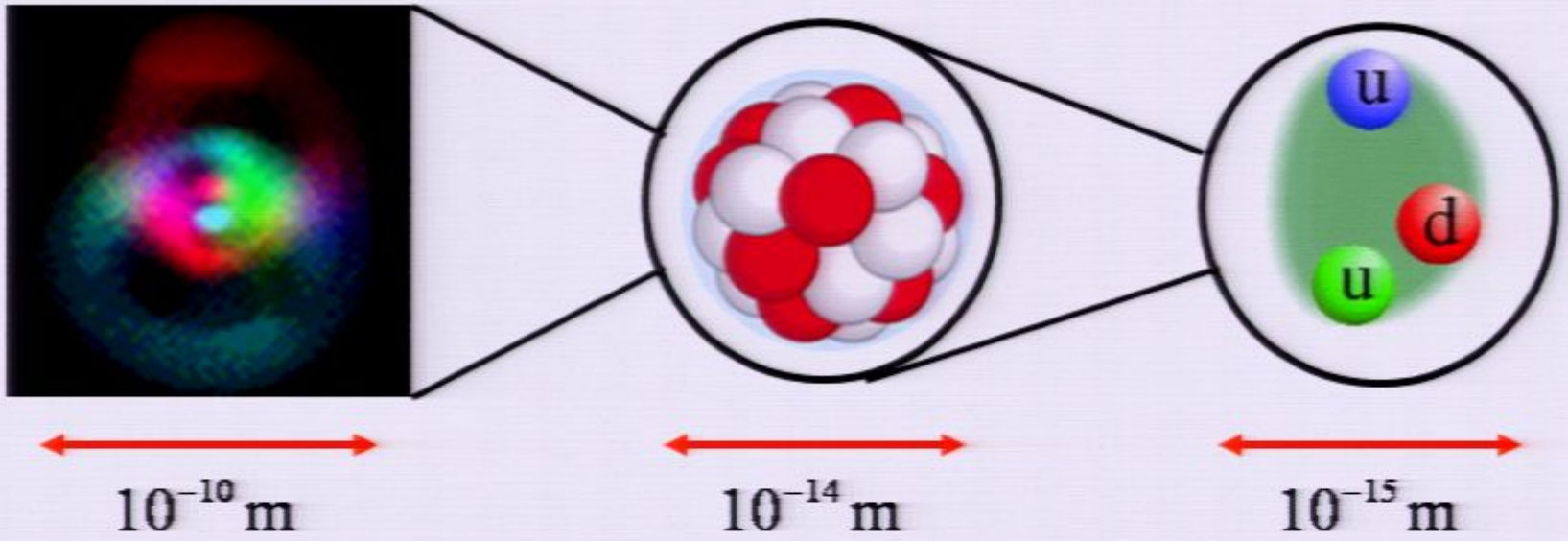

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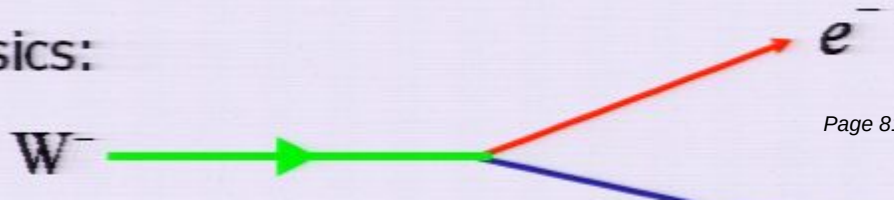

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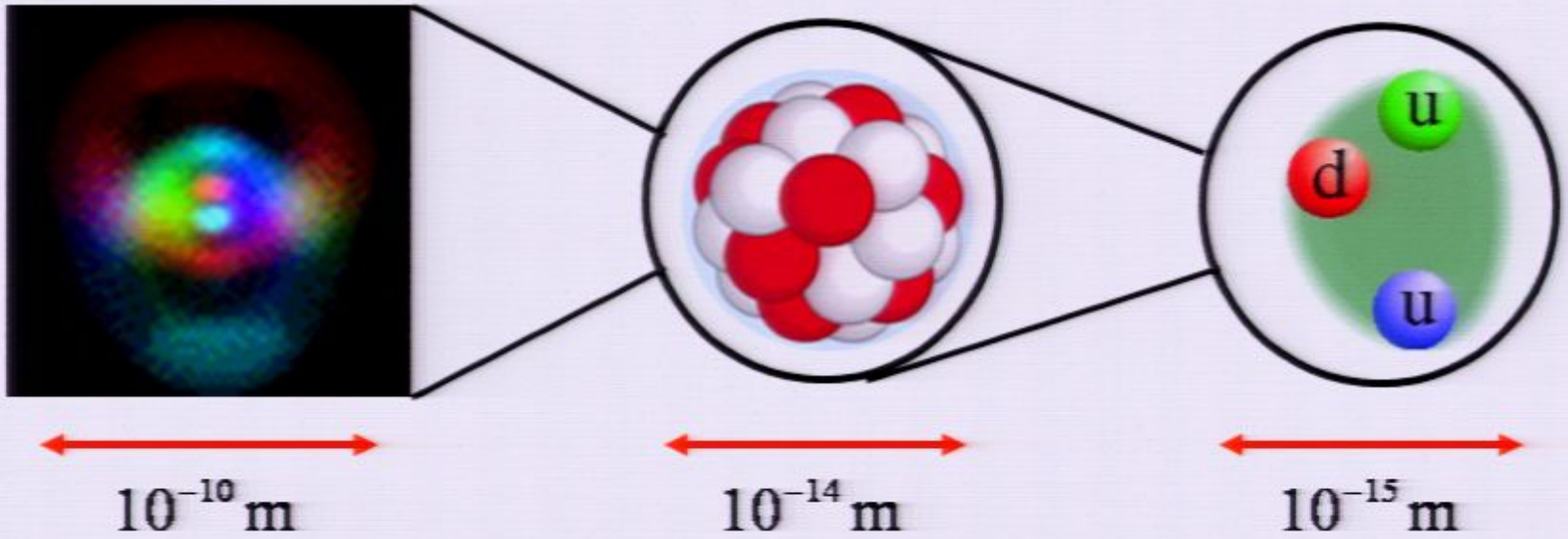

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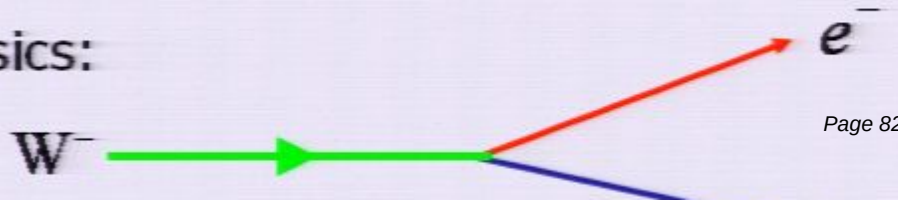

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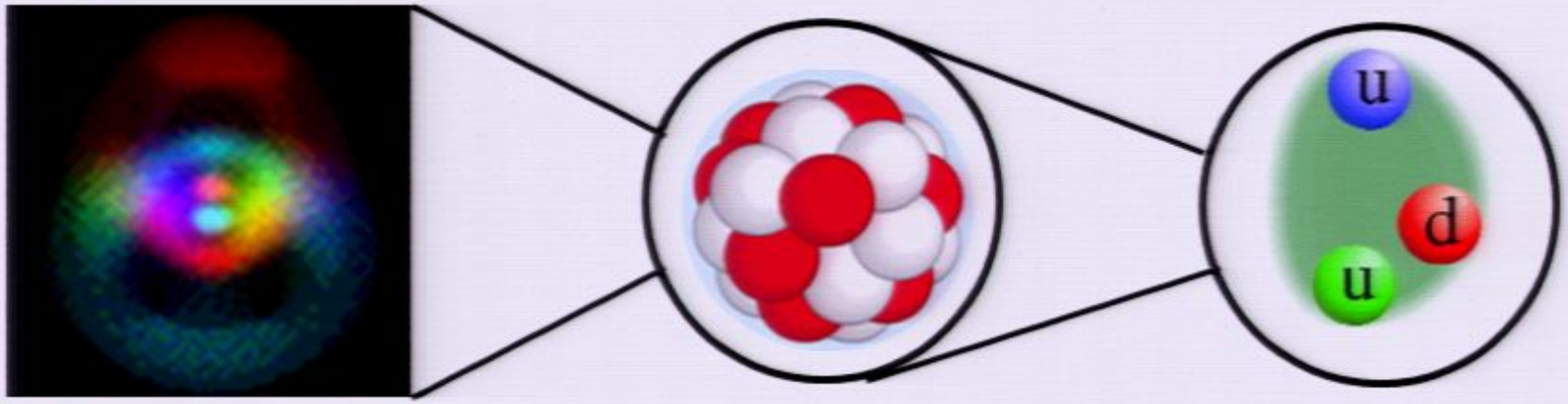

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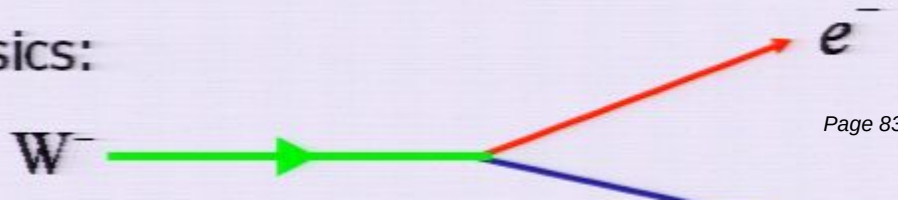

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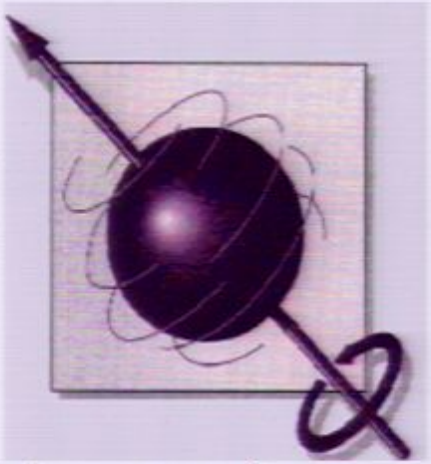

Example: electrons are tiny magnets

$$\mu_e = g\, e\hbar/4m_e \quad \text{with} \quad g \approx 2$$

precise value of magnetic moment depends on quantum fluctuations

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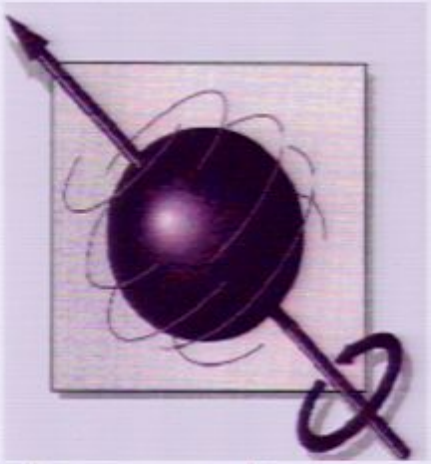

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$$\mu_{\text{measured}} = 2.00231930\,43738$$

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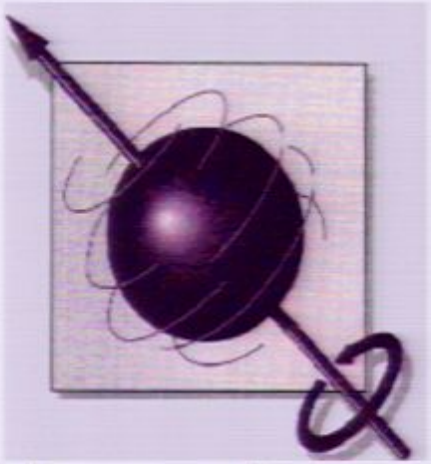

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$$\mu_e = g\ e\hbar/4m_e \quad \text{with} \quad g \approx 2$$

precise value of magnetic moment depends on quantum fluctuations

$$\mu_{\text{measured}} = 2.00231930437\,38$$

$$\mu_{\text{calculated}} = 2.00231930430\,70$$

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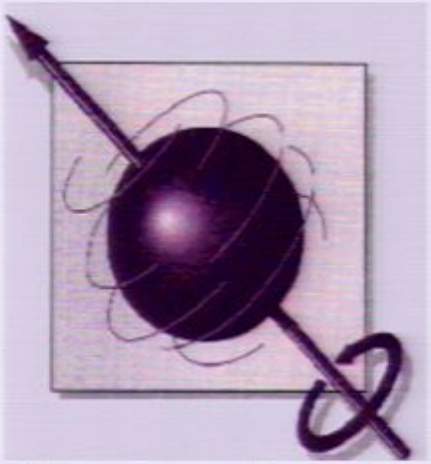

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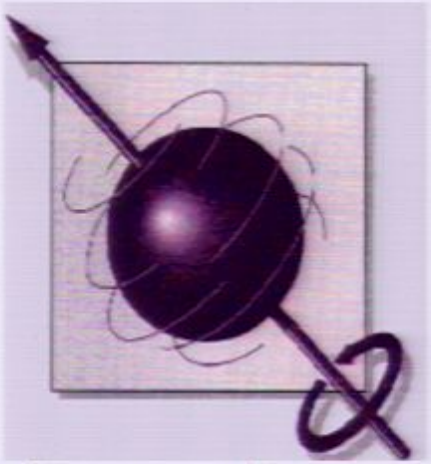
$$\mu_{\text{measured}} = 2.00231930\,43738$$

$$\mu_{\text{calculated}} = 2.00231930\,43070$$

$$\left| \frac{\mu_{\text{calculated}} - \mu_{\text{measured}}}{\mu_{\text{measured}}} \right| < 10^{-10}$$

Quantum theory is rigorously tested!!



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$$\mu_{\text{measured}} = 2.00231930\,43738$$

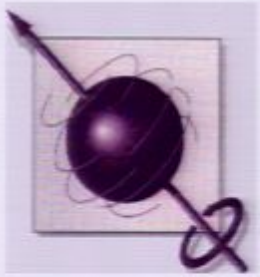
$$\mu_{\text{calculated}} = 2.00231930\,43070$$

(neither answer absolutely correct)

Quantum theory is rigorously tested!!

e.g., magnetic moment of the electron, $\mu_e = g\frac{e\hbar}{4m_e}$,
is modified by quantum fluctuations

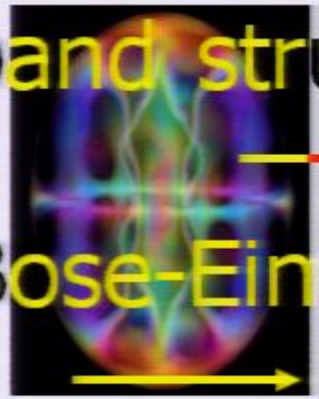
$$\left|\frac{\mu_{\text{theory}} - \mu_{\text{experiment}}}{\mu_{\text{experiment}}}\right| \leq 10^{-10}$$



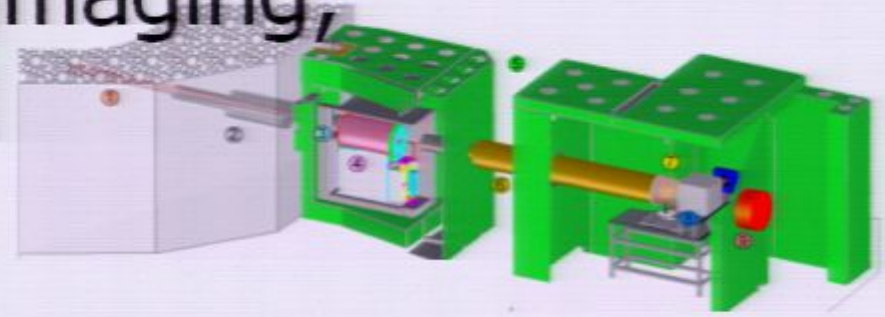
e.g., Lamb shift: shift between $2S_{1/2}$ and $2P_{1/2}$
energy levels of hydrogen atom (f = 1057 MHz)

$$\left|\frac{f_{\text{theory}} - f_{\text{experiment}}}{f_{\text{experiment}}}\right| \leq 10^{-6}$$

Quantum Theory: a rich source of new ideas



- band structure in materials → semiconductor technology
- Bose-Einstein condensation → superfluids, superconductors
- quantum Hall effect, neutron diffraction, electron microscopy, lasers, magnetic resonance imaging, ...



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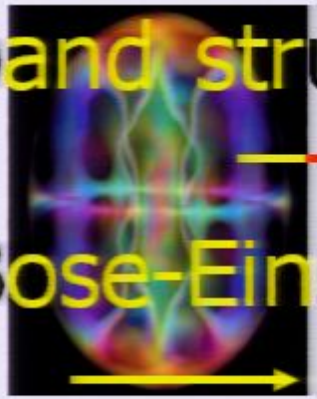

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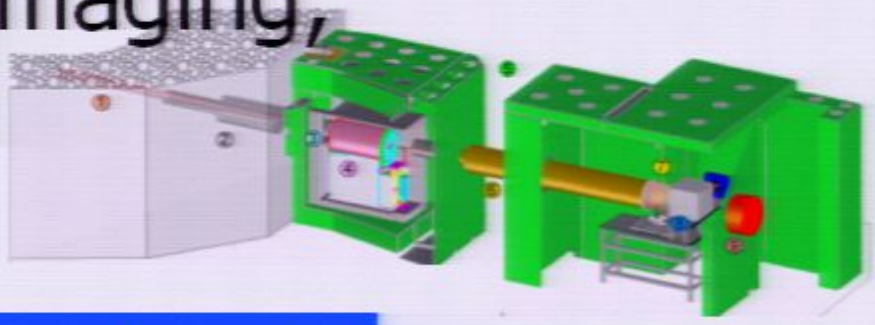
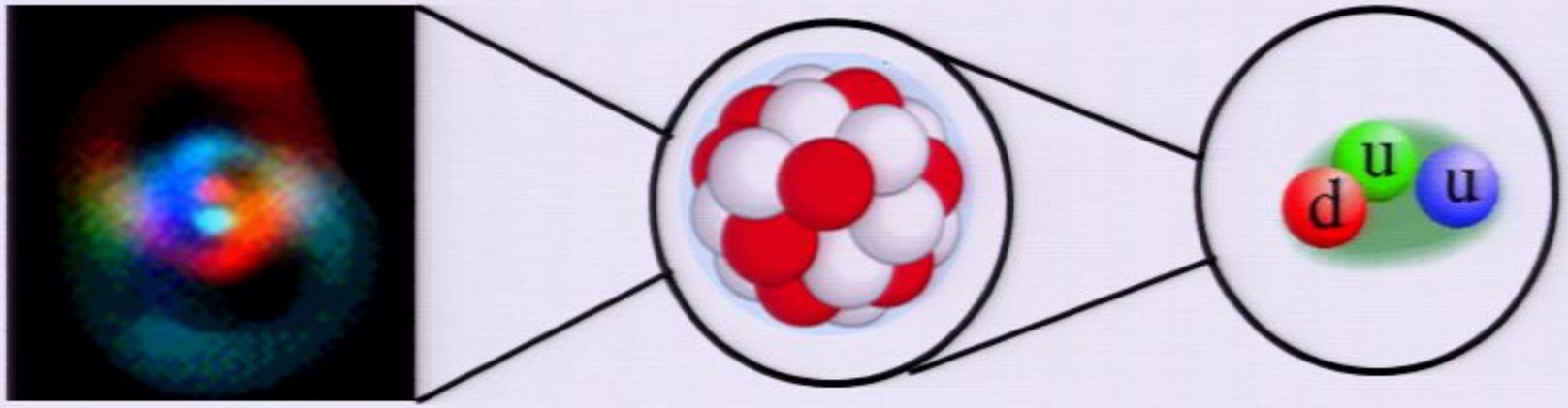


Nobel prizes galore!!

Subatomic Physics



Elementary Particles (10^{-17} m)

Fermions:
- electron, muon, tauon
- neutrinos (3 flavors)
- quarks - up, down, strange, charm, bottom, top

Bosons (Force Mediators):
- photon (electromagnetism)
- gluon (strong)
- $W^{\pm}$, Z (weak)
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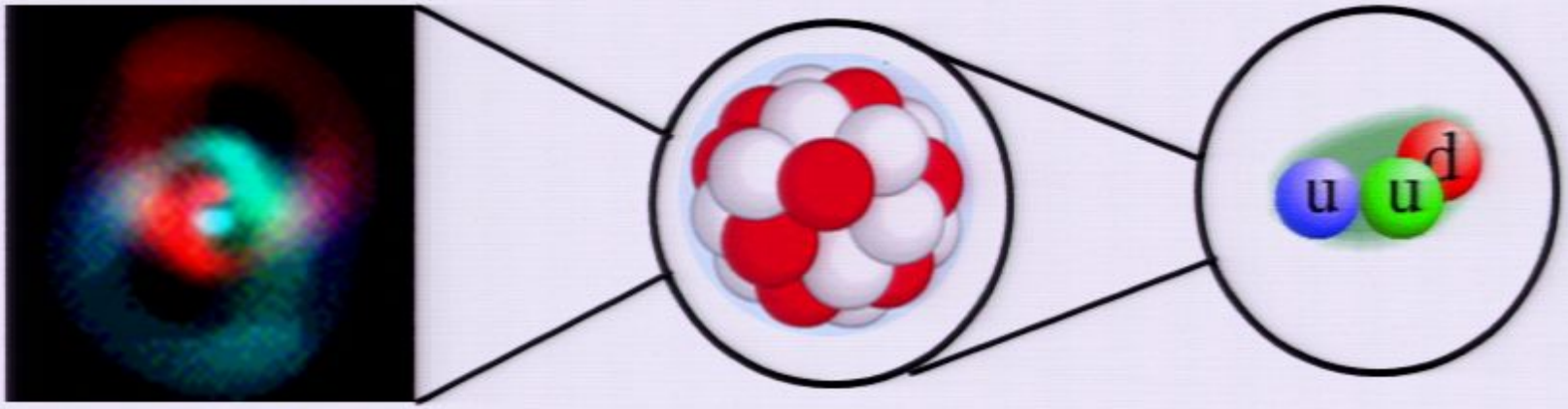

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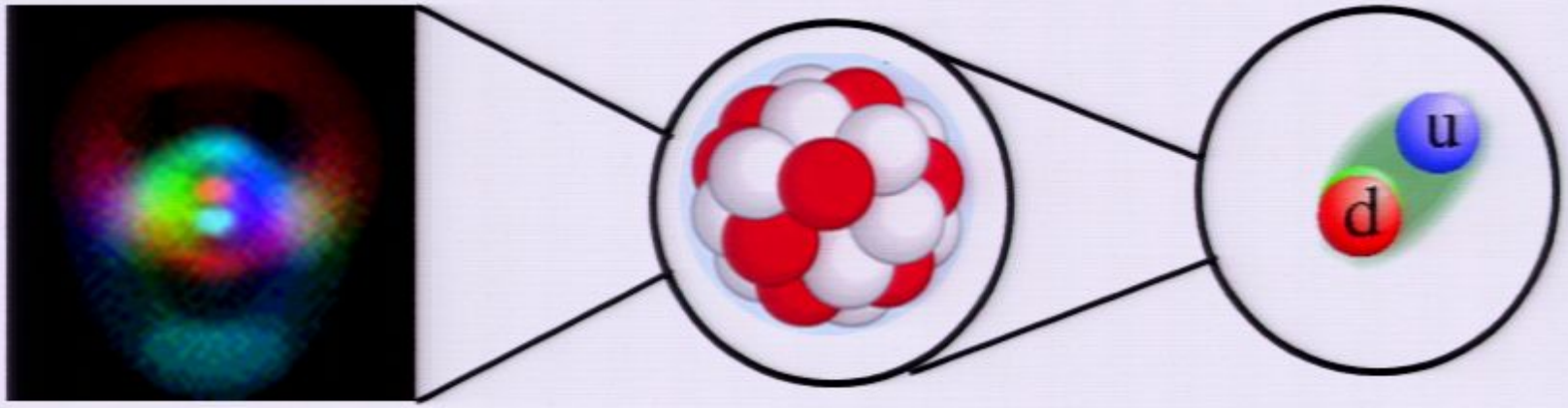

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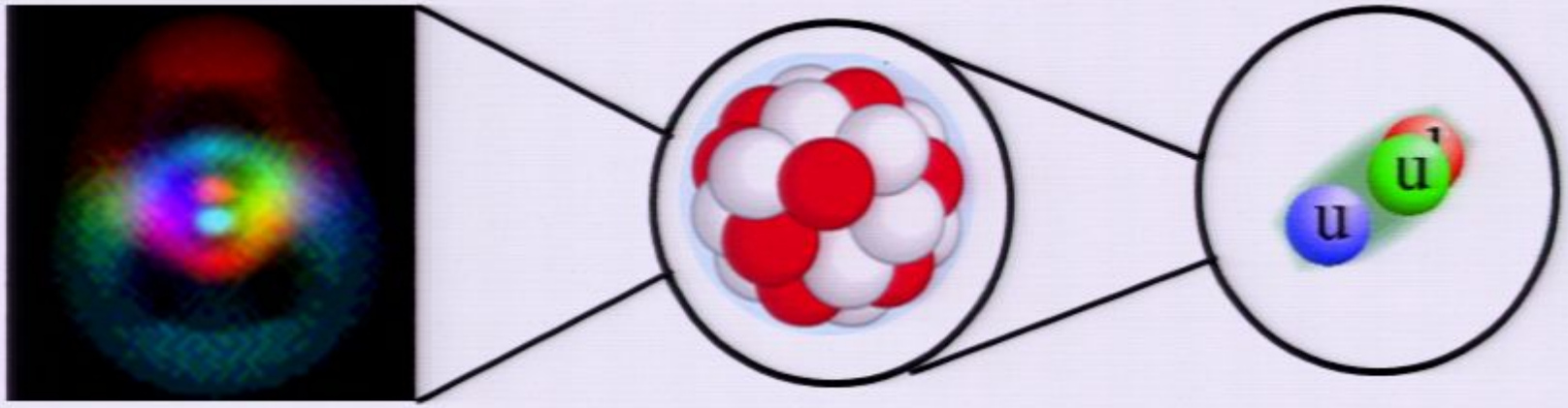

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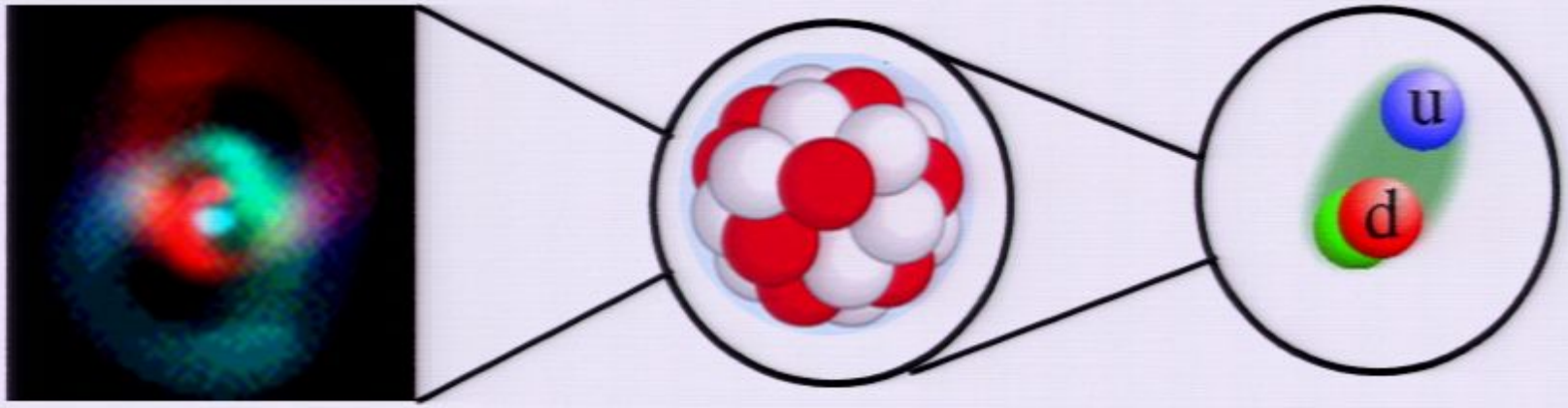
Subatomic Physics → a theory of strings!



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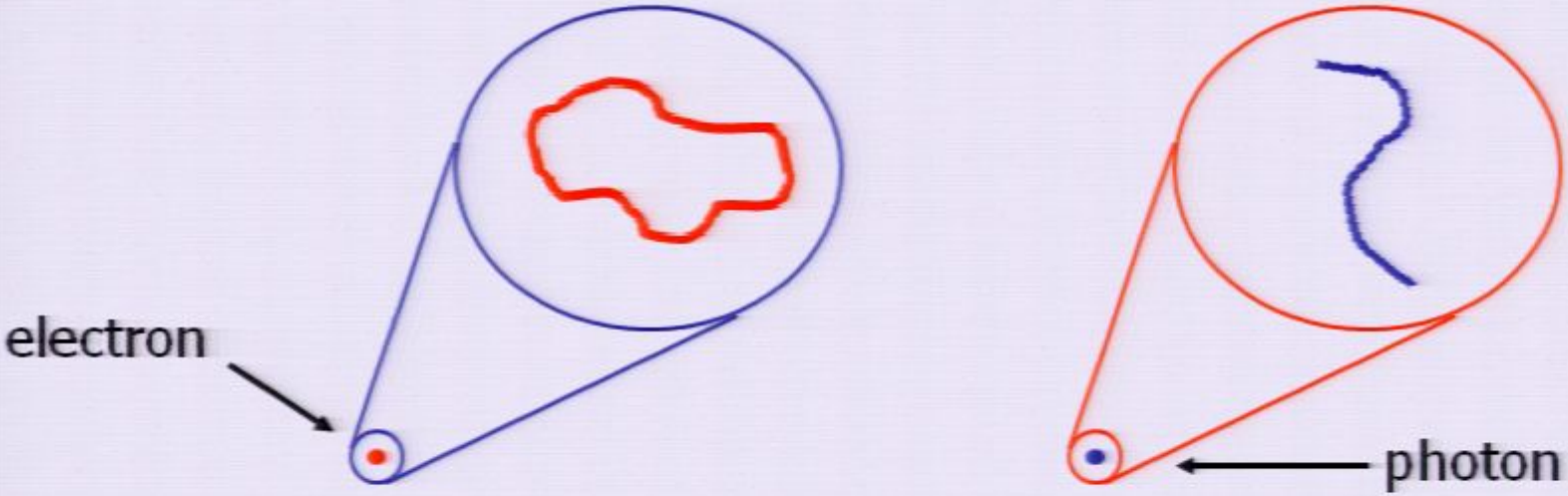
10^{-35} m

Strings tame the particle zoo!

Superstrings: the theory of subatomic physics

The essential idea:

with sufficient resolution, all elementary particles are one-dimensional objects (strings)



all particle types are the same kind of string vibrating or rotating in different ways

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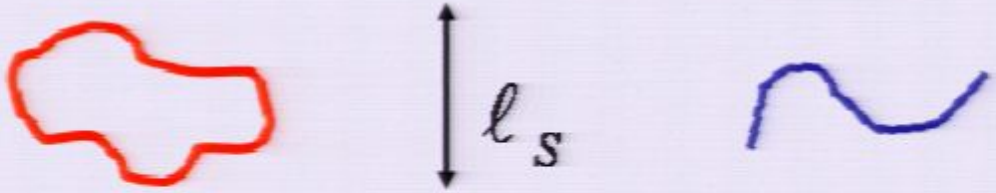

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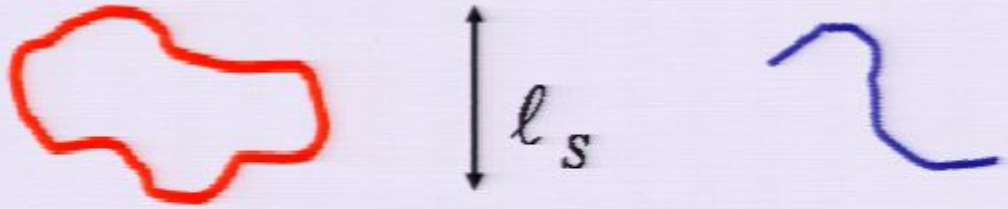

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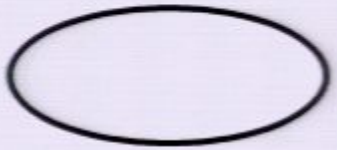
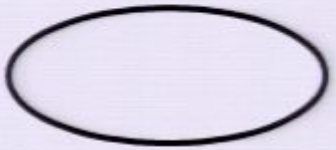
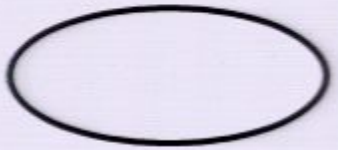
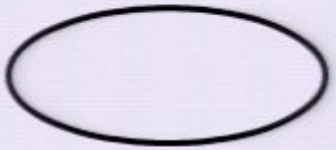
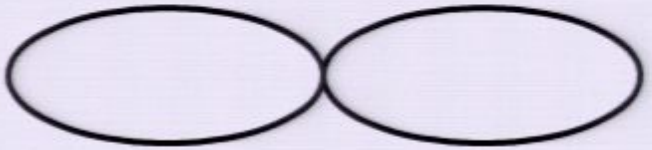
Interactions?

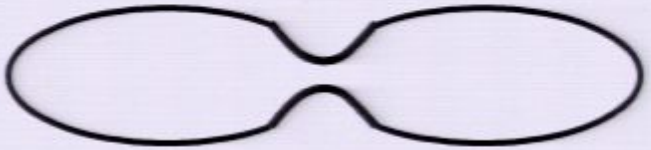


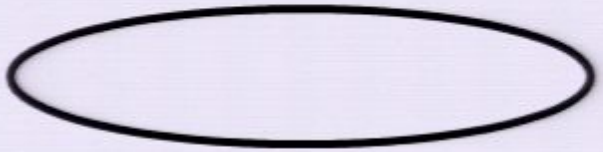


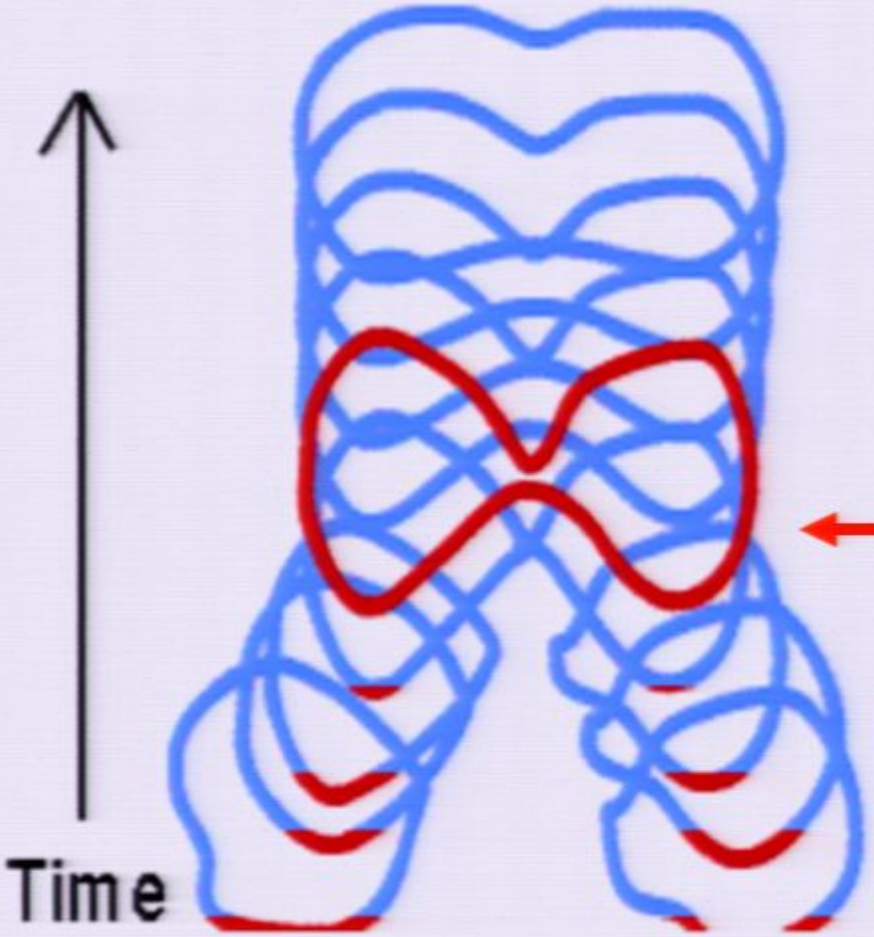




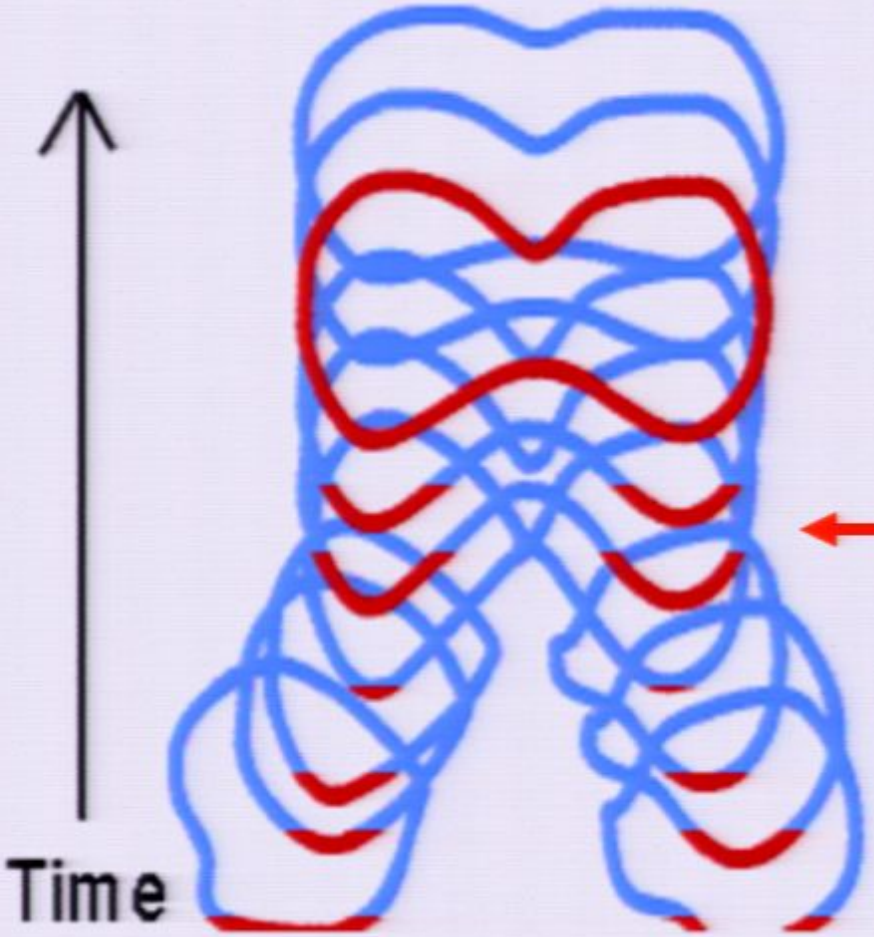








coupling constant, g,
determines probability
of interaction



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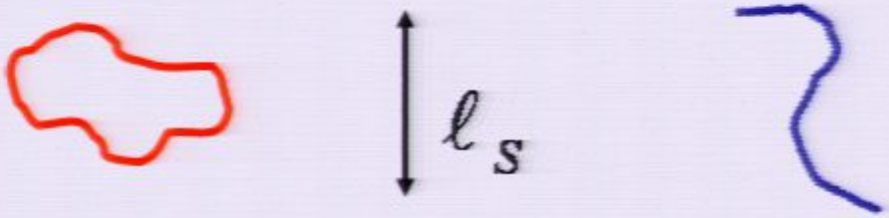
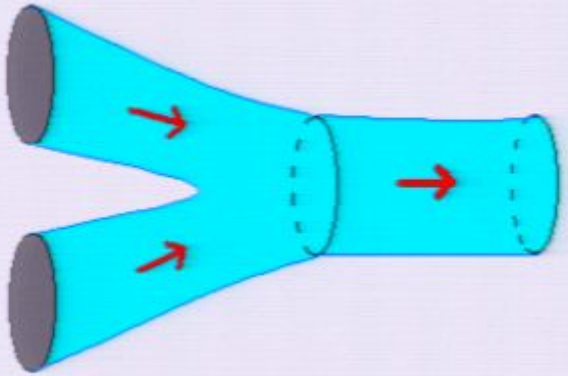
Superstrings: the theory of subatomic physics

with resolution, $\ell_s = 10^{-35}\,\mathrm{m}$, all elementary particles are one-dimensional objects (strings)

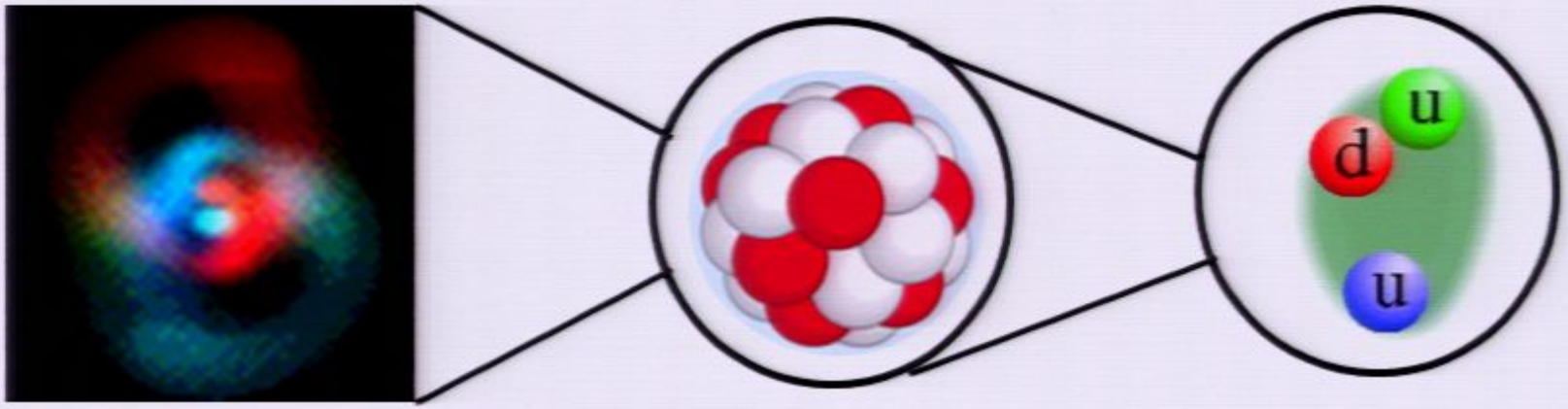


interactions are geometric joining and splitting governed by coupling constant, g



with these simple rules get appropriate particle species and interactions to match Standard Model

Subatomic Physics → a theory of strings!



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What's missing here?

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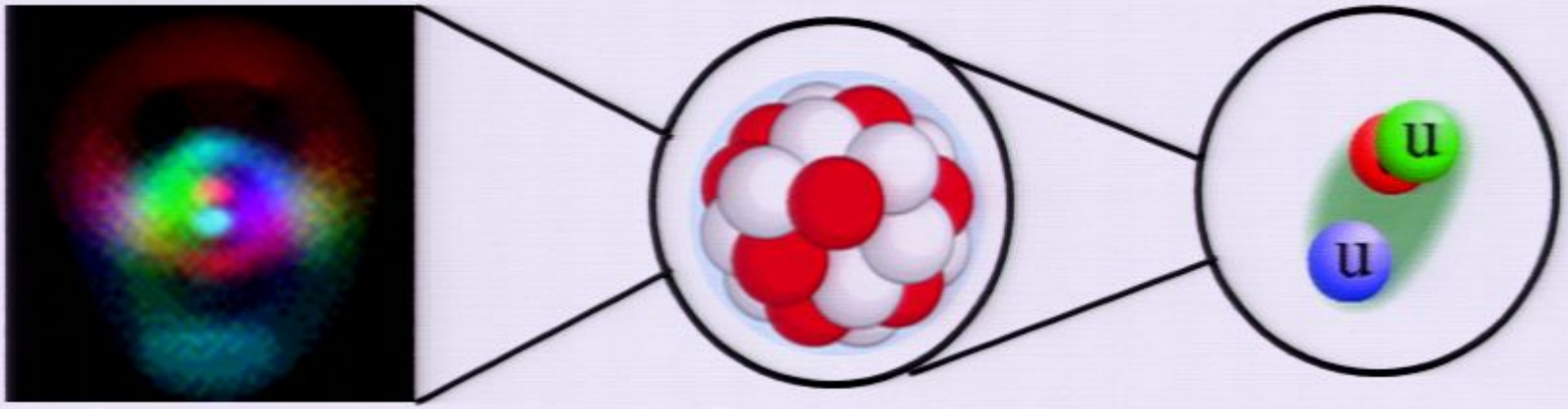

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consistency requires appearance of the graviton!

at long distances much greater than ℓ_s, reproduces Einstein's gravitational equations

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Superstrings naturally provides a unified framework for Quantum Field Theory and General Relativity

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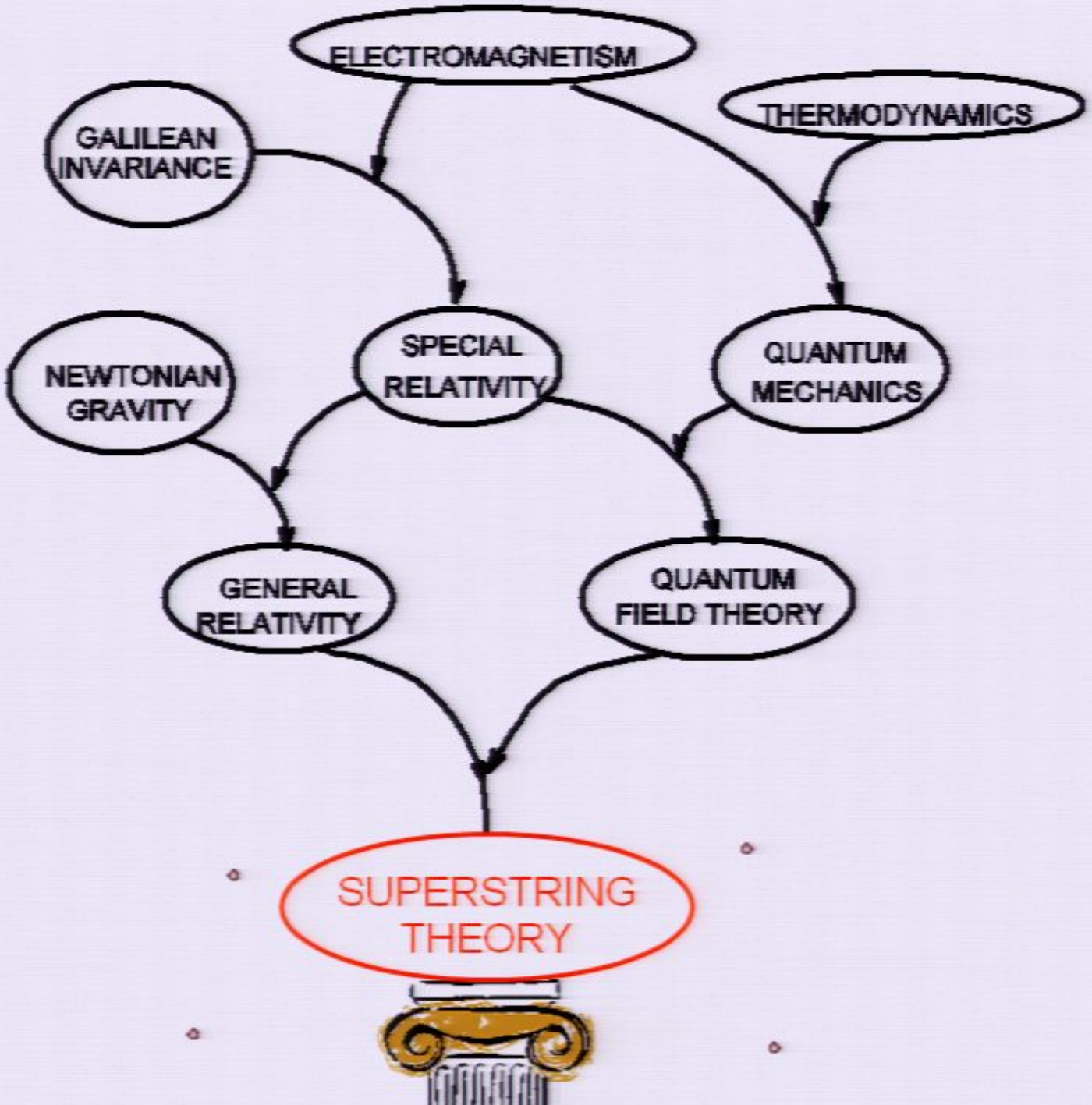
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NEWTONIAN GRAVITY
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QUANTUM MECHANICS
GENERAL RELATIVITY
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SUPERSTRING THEORY

Superstring theory: The devil is in the "details"

- Predicts we live in 10 spacetime dimensions!!

Experimental update: we live in 4 dimensions!
(1 time and 3 space)

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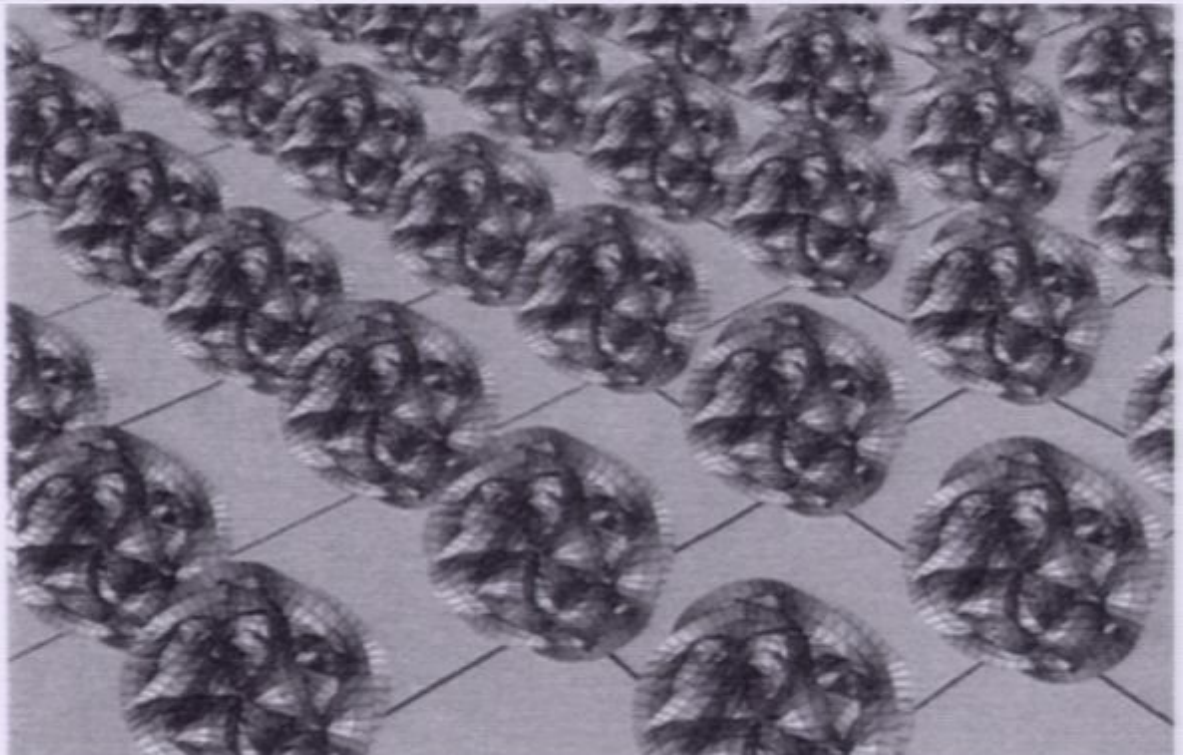

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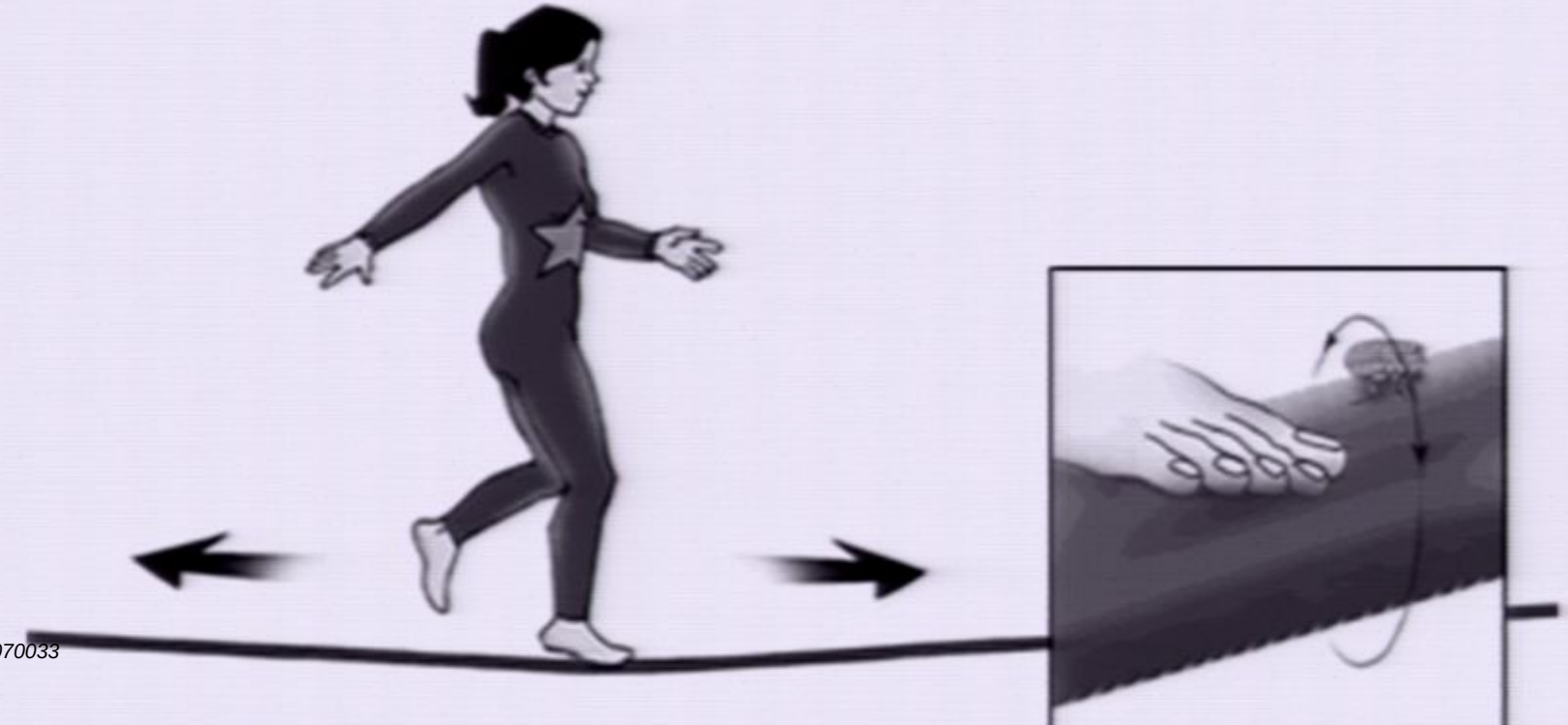

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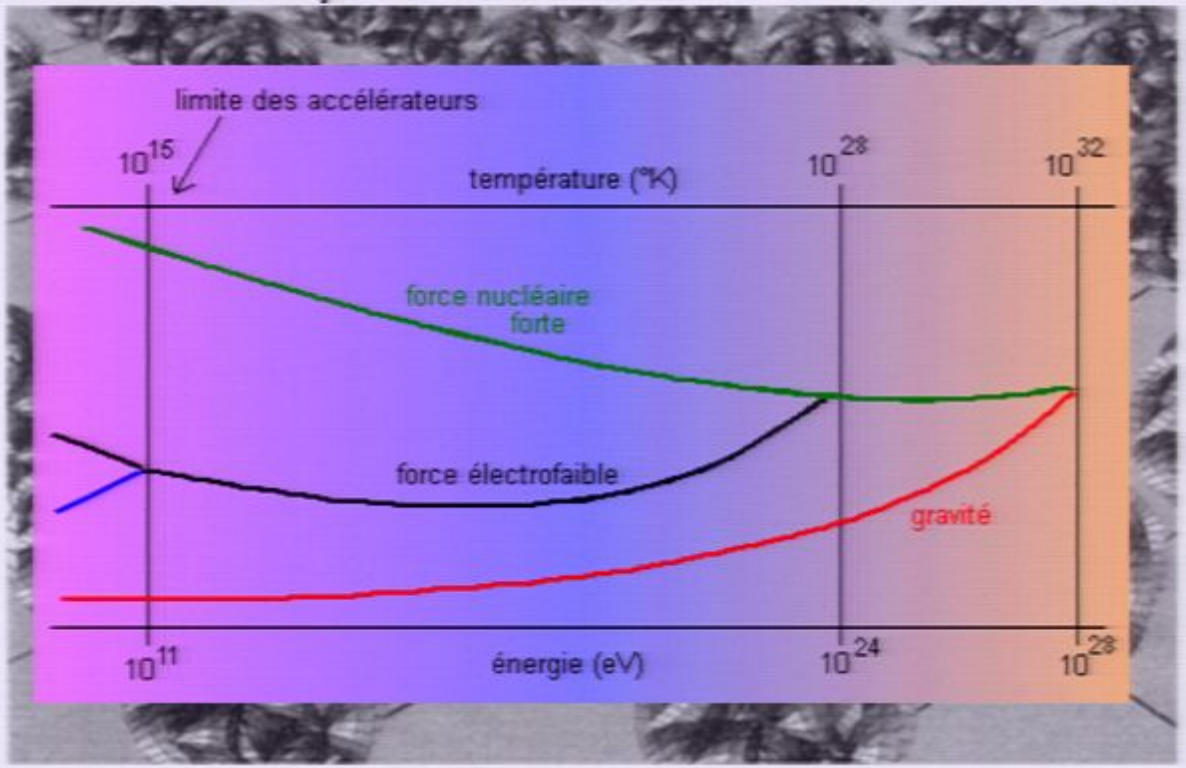

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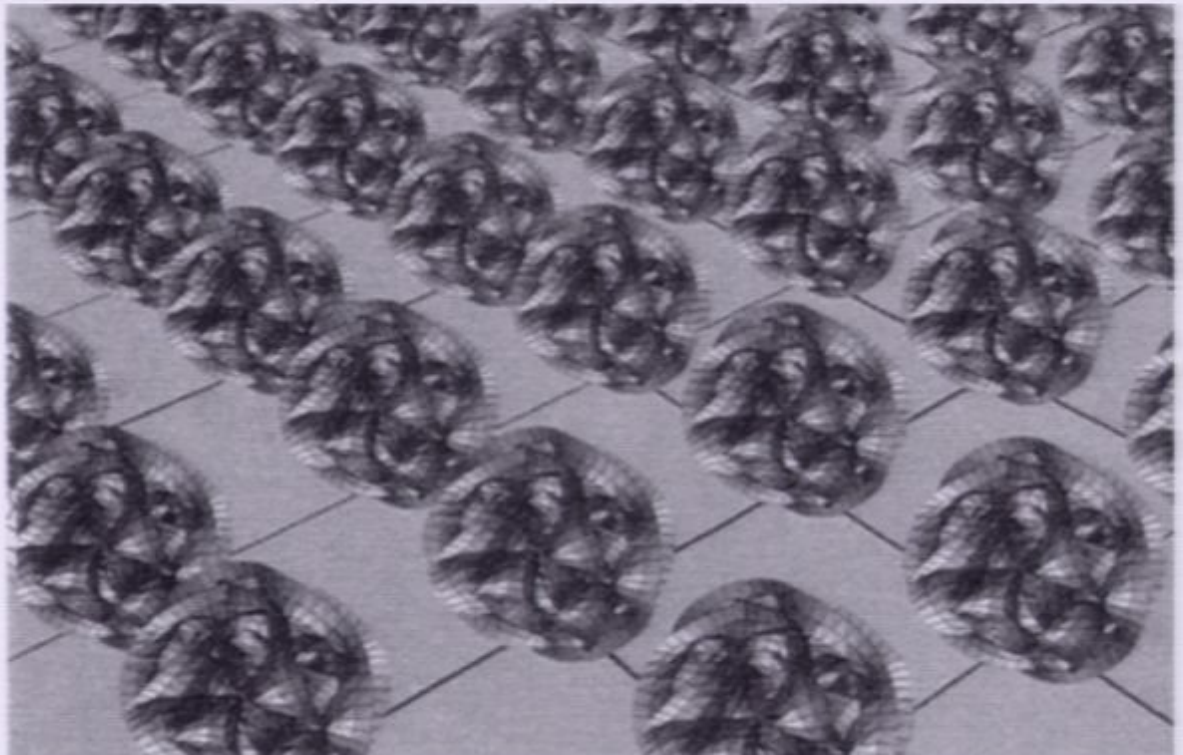

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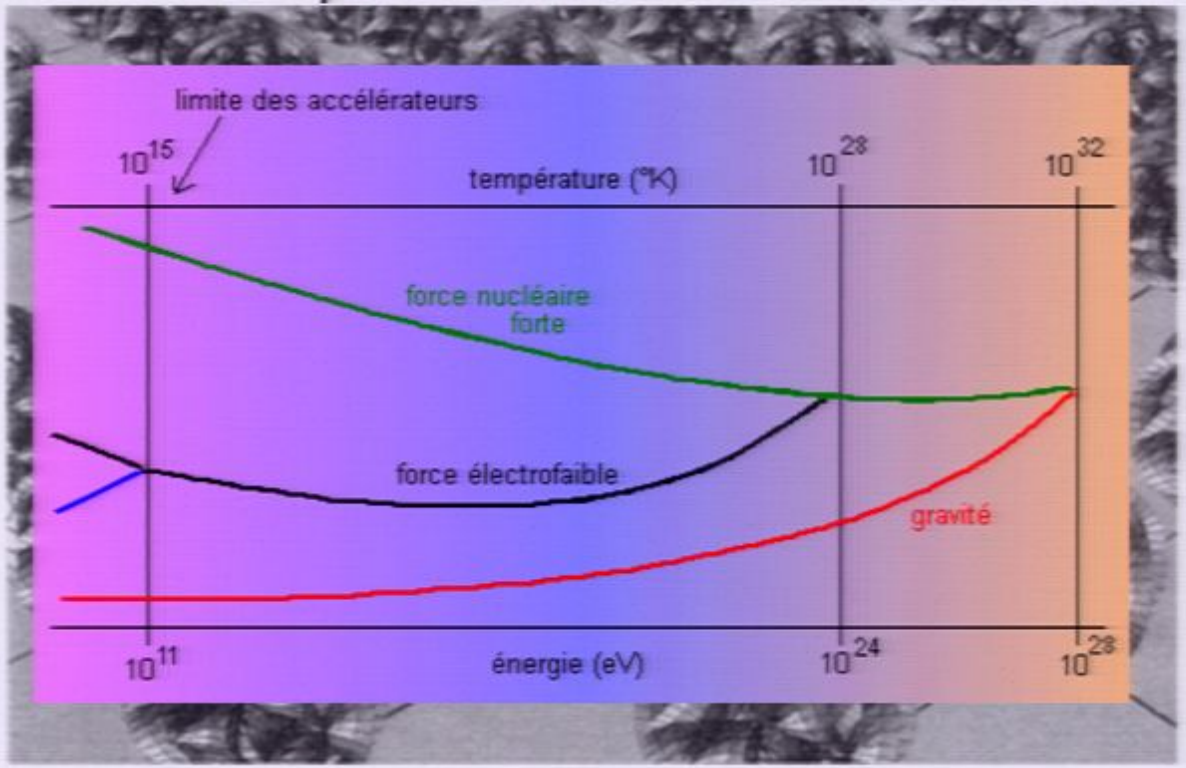

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Big fix: Perhaps we should look harder.

Benefit: SUSY tames the short distance (quantum) fluctuations of the theory

Superstring theory: Details, details, details, ...

- Have five consistent superstring theories:
  Type I, Type IIA, Type IIB,
  Heterotic E_8 X E_8, Heterotic SO(32)

one universe ⟶ four too many theories?!?

Superstring theory: Details, details, details, ...

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- New perspective: all known string theories are different phases of single fundamental theory

→ M-theory

Essential ingredients for M-theory conjecture:

- Dualites: two mathematical descriptions describe identical physical phenomena

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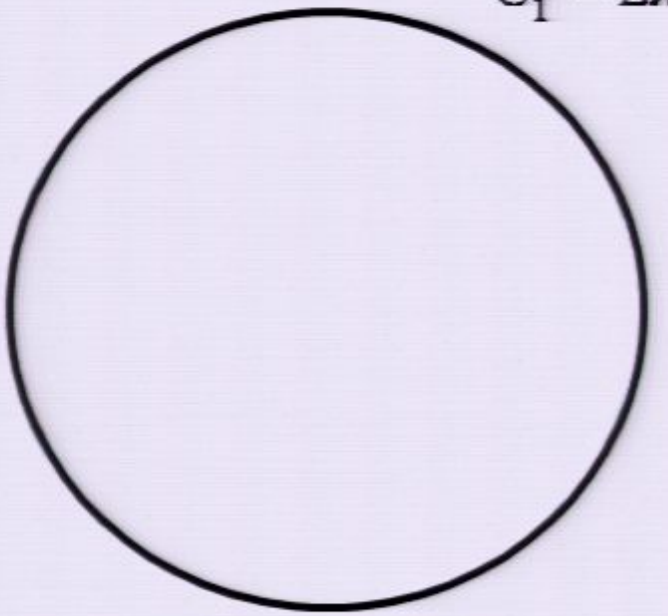
Eg, T-duality relates large and small circle compactifications

$$C_1 = 2\pi R$$



$$C_2 = \frac{2\pi \ell_s^2}{R}$$

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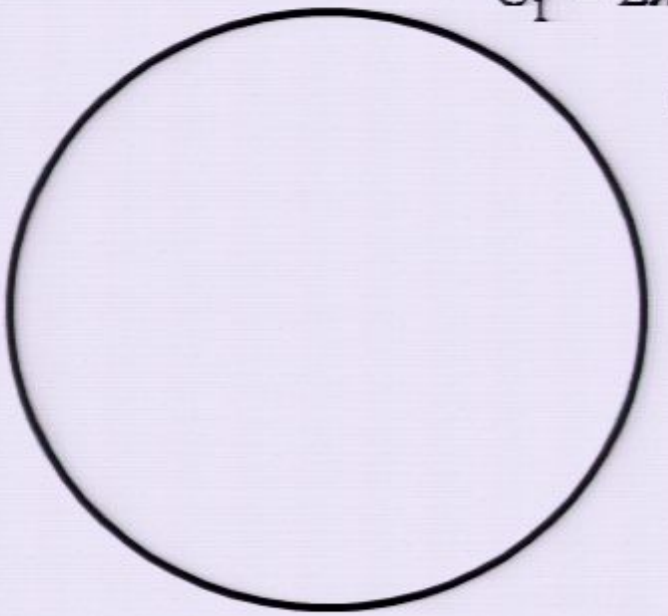

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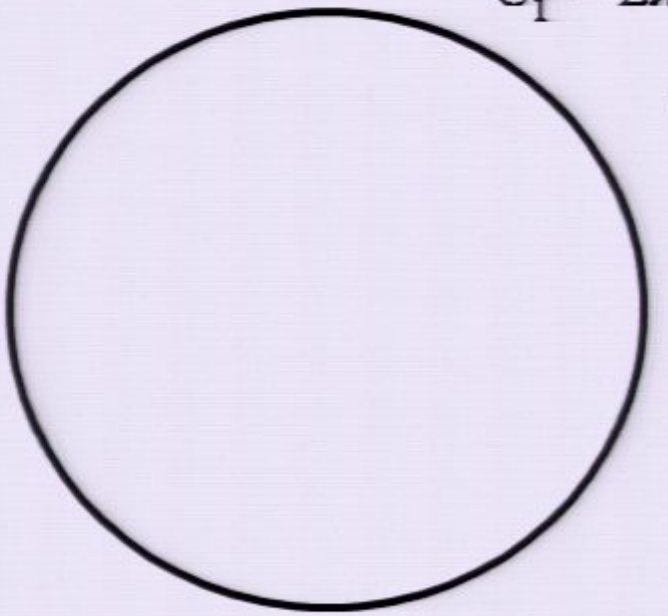

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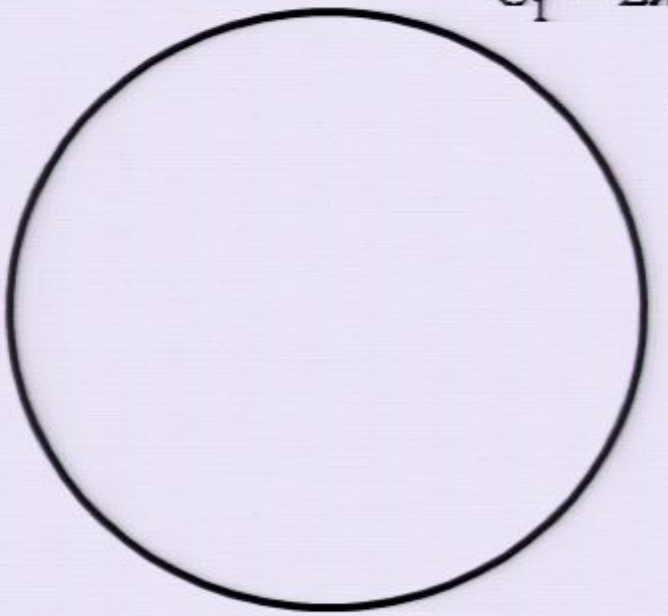

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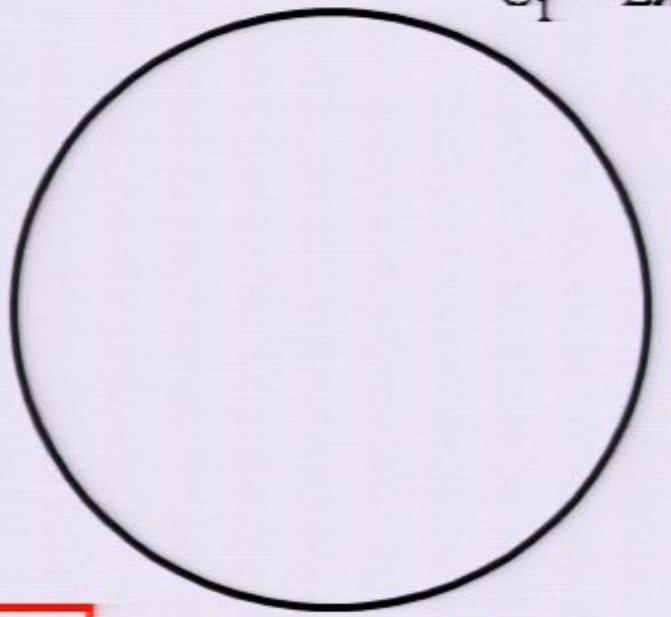

$$E_p = \frac{n}{R}$$

$$E_p = m\frac{R}{\ell_s^2}$$

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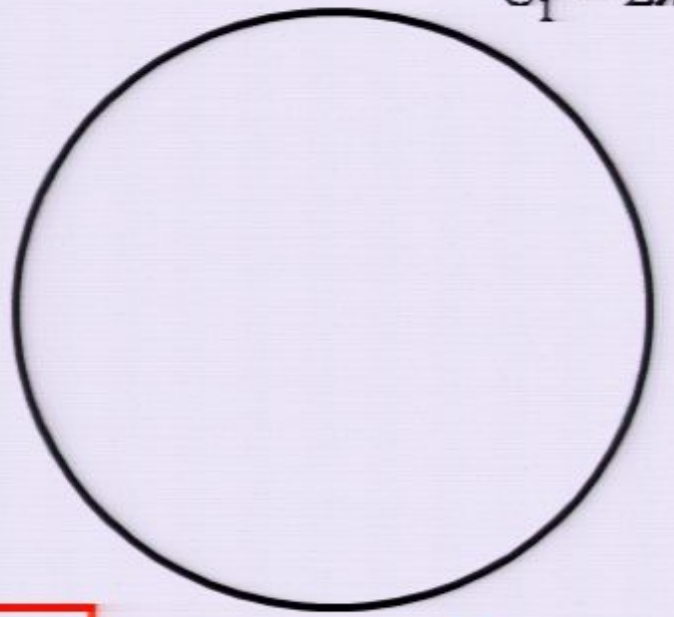

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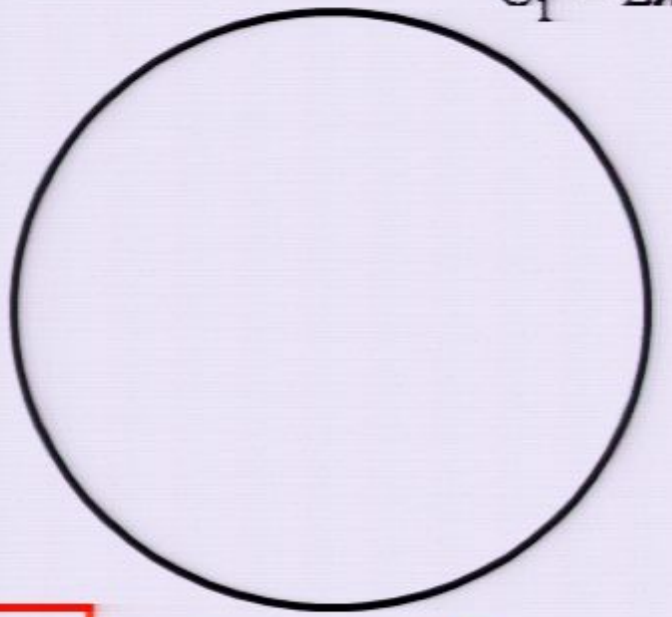

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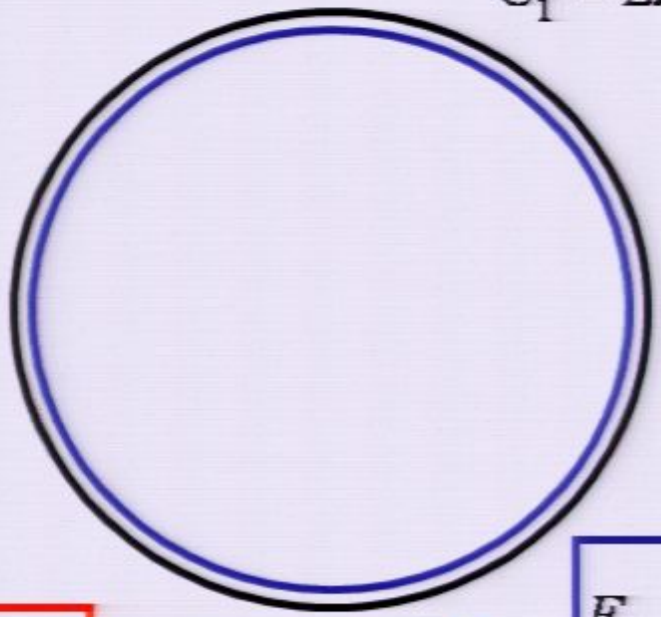

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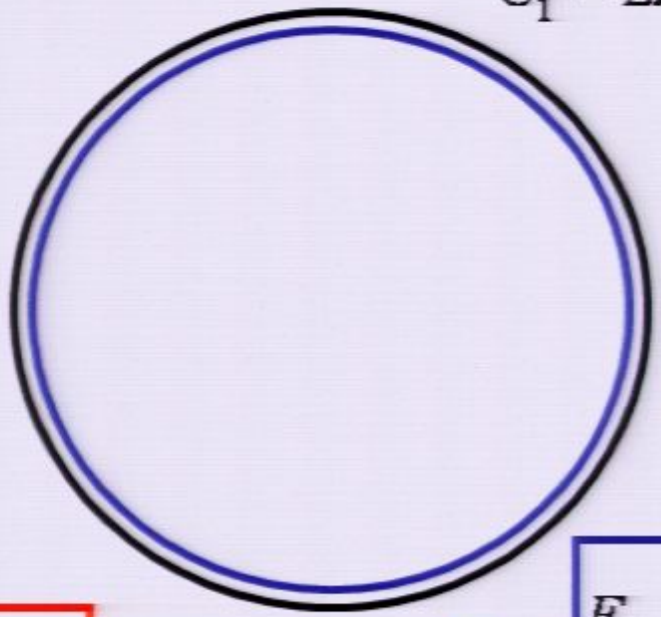

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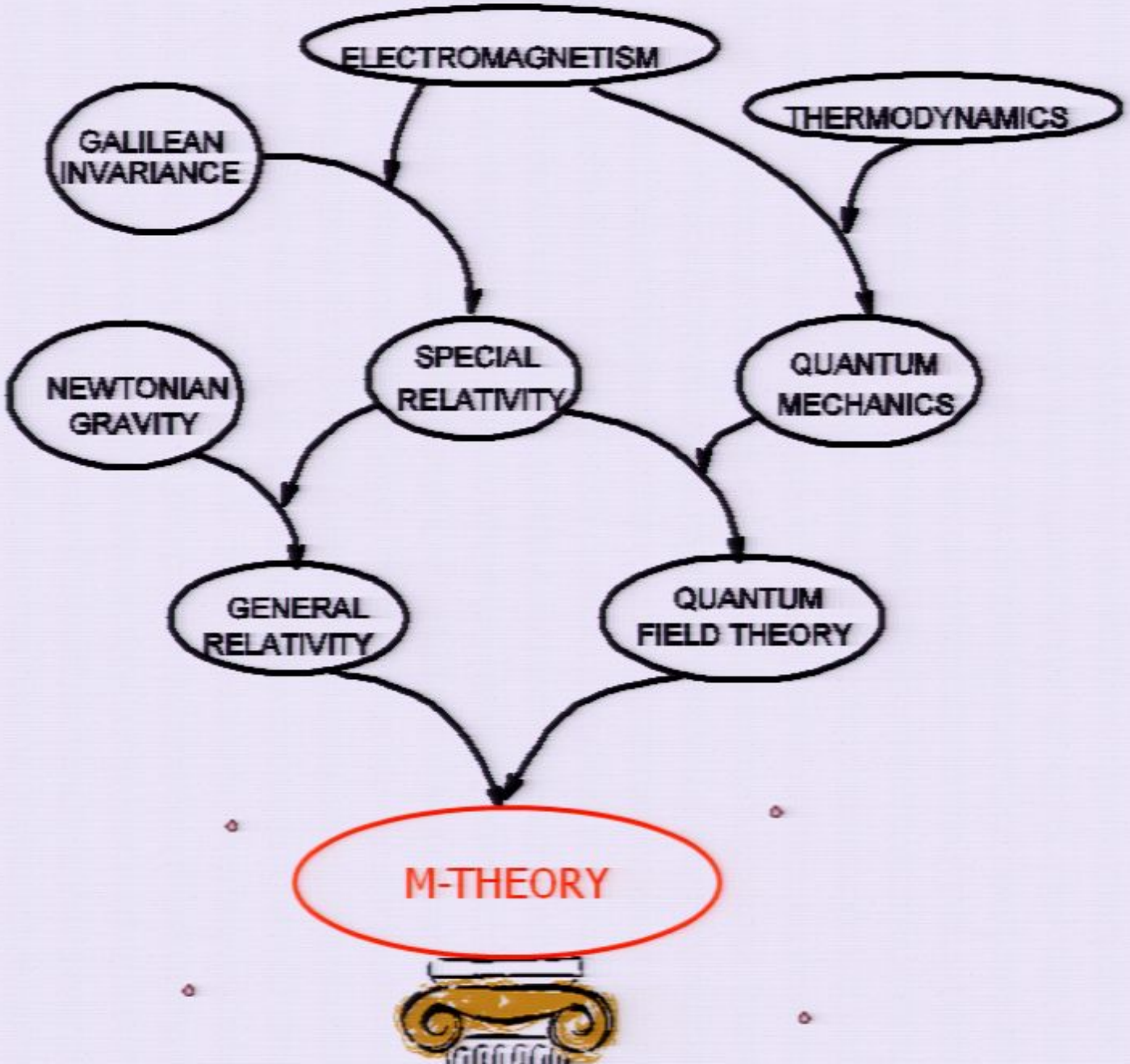
M-theory also includes 11-dimensional supergravity!

String/M-theory is a rich source of new ideas



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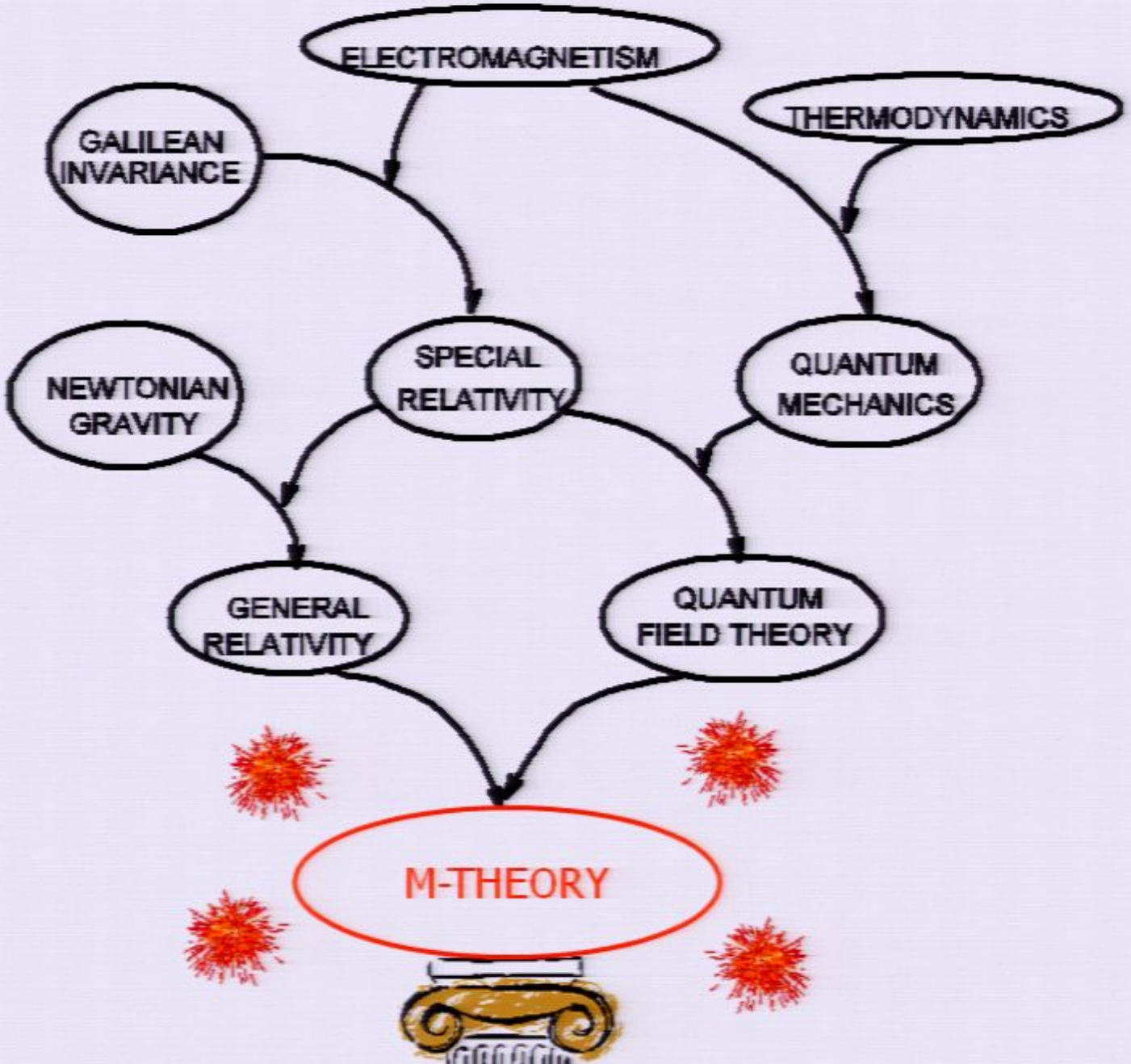

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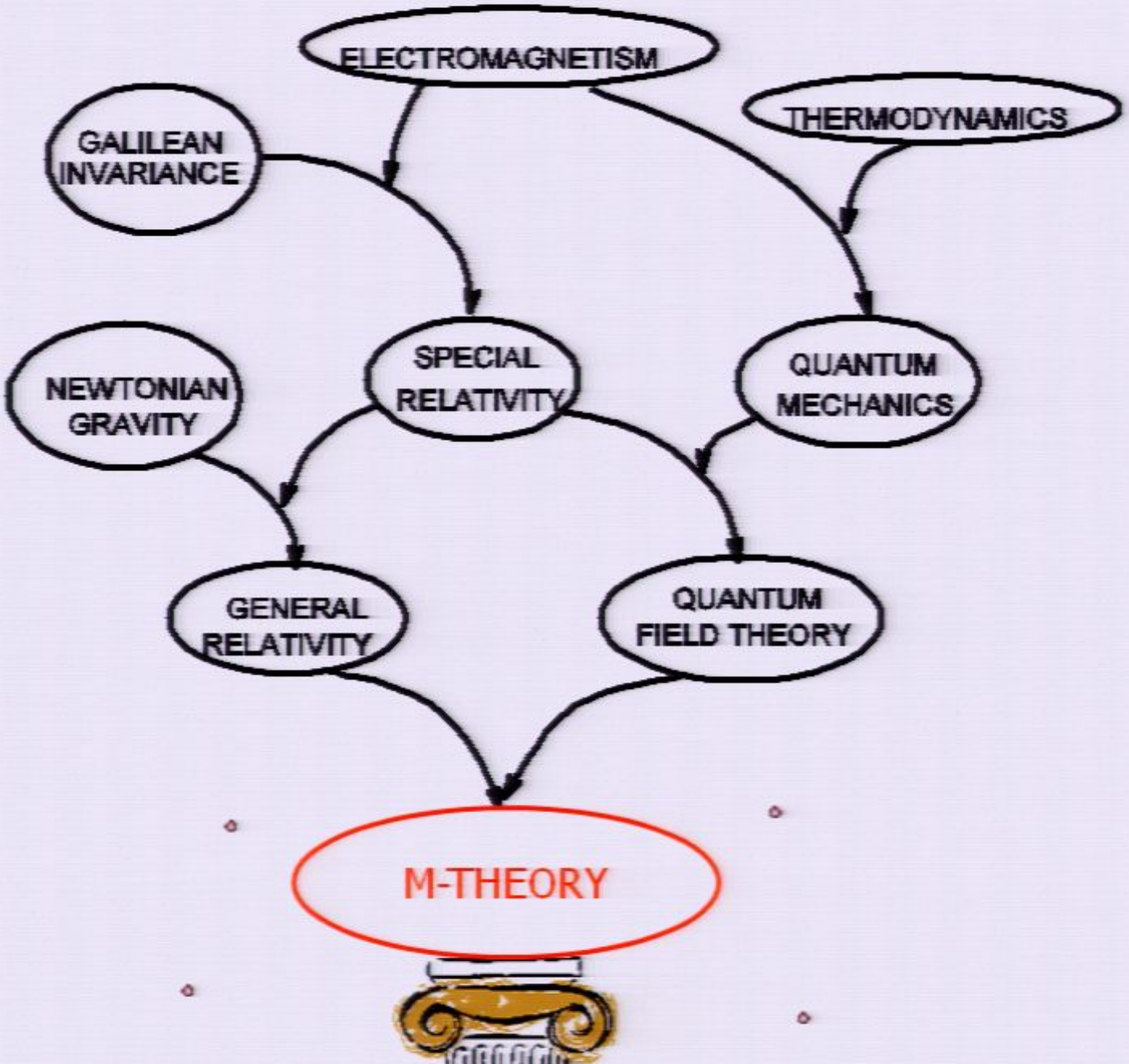

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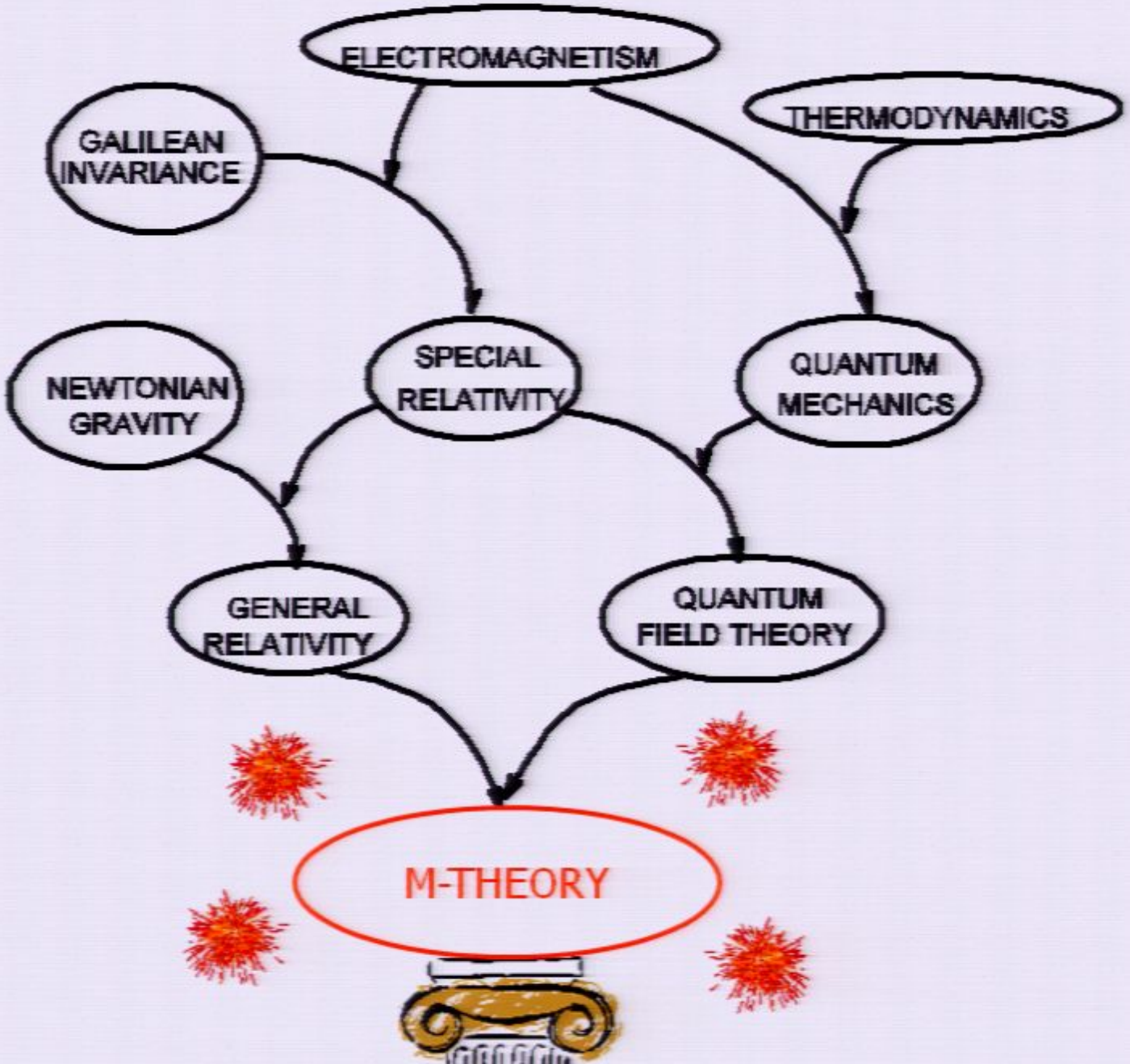

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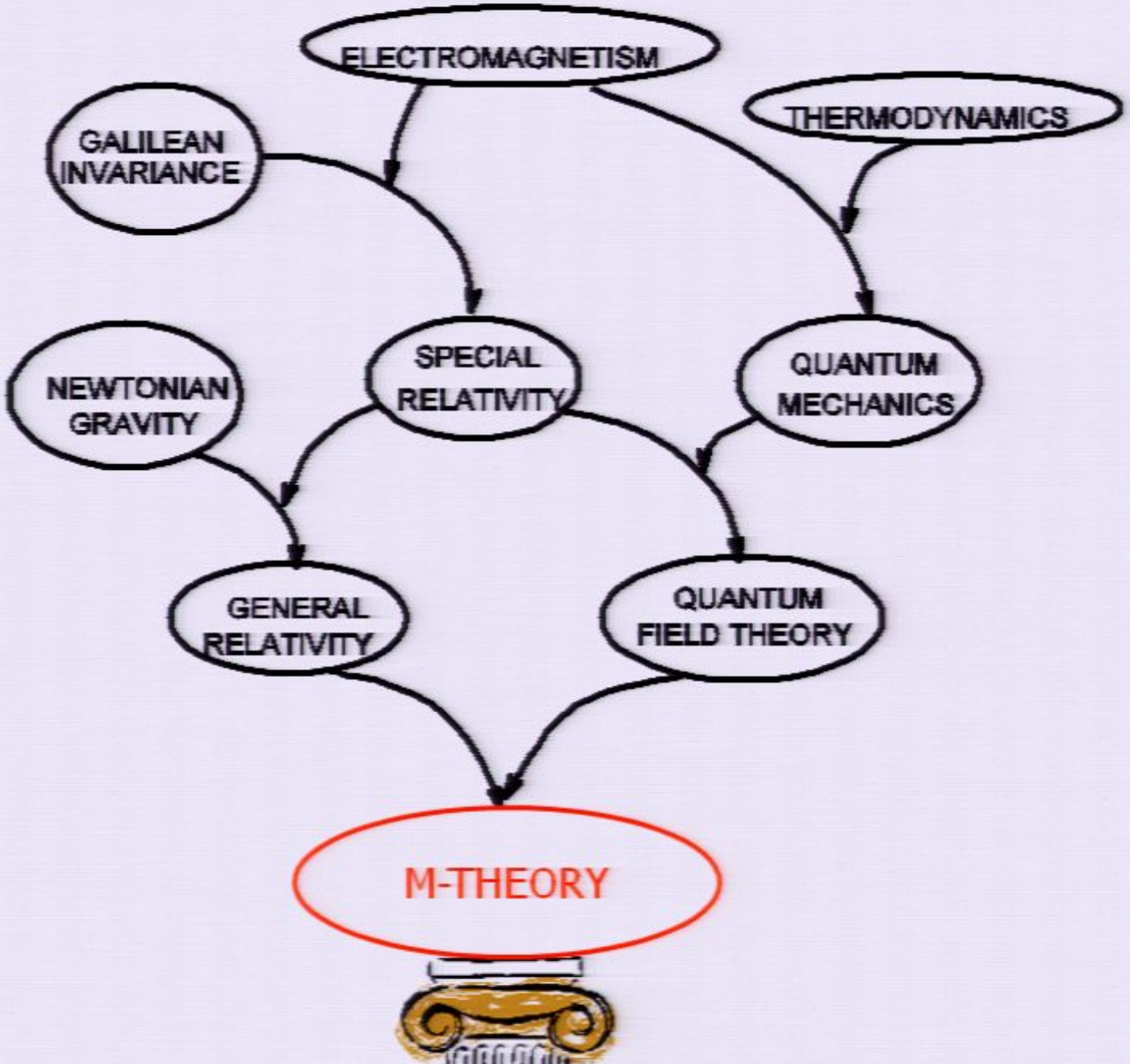

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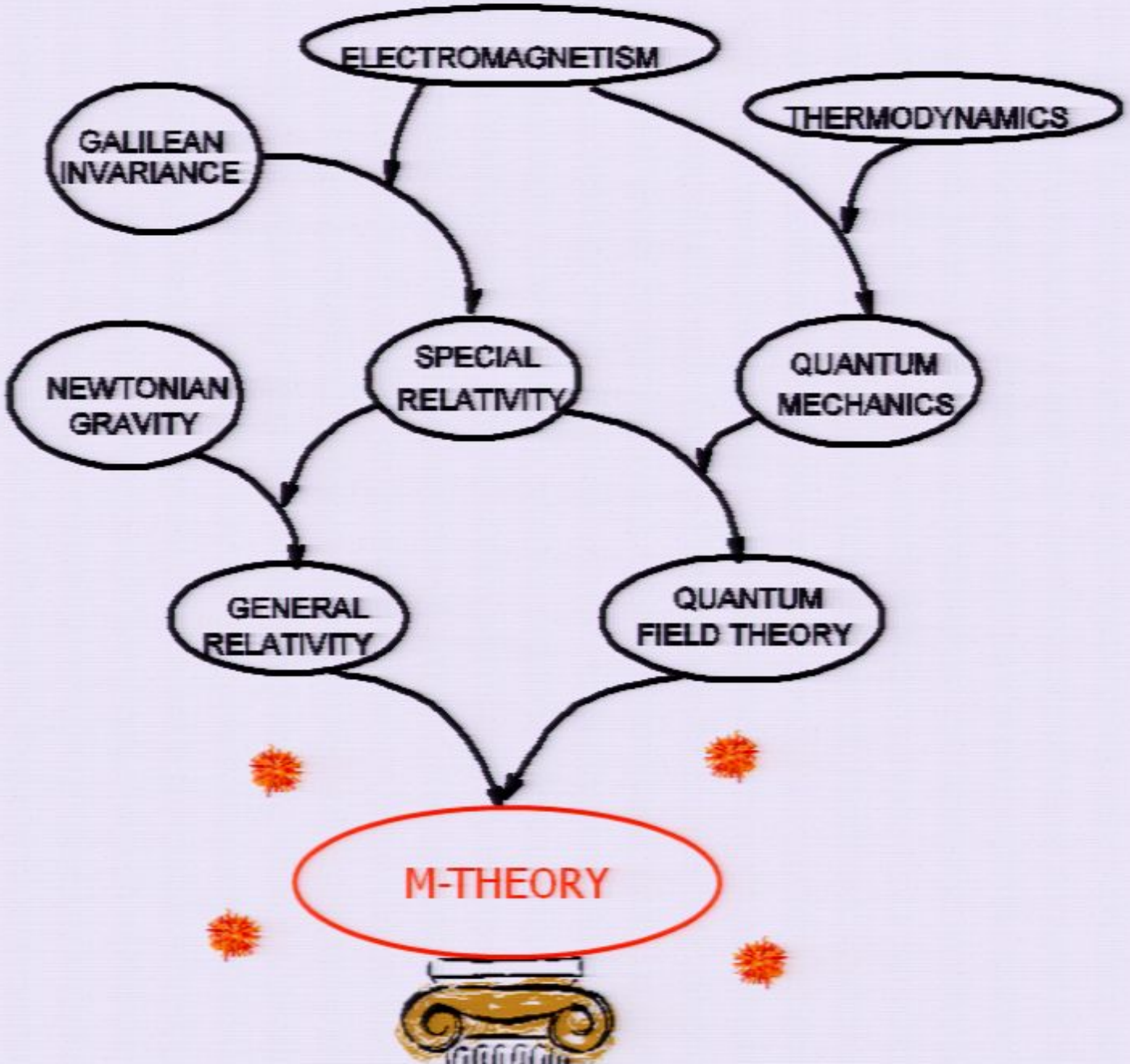

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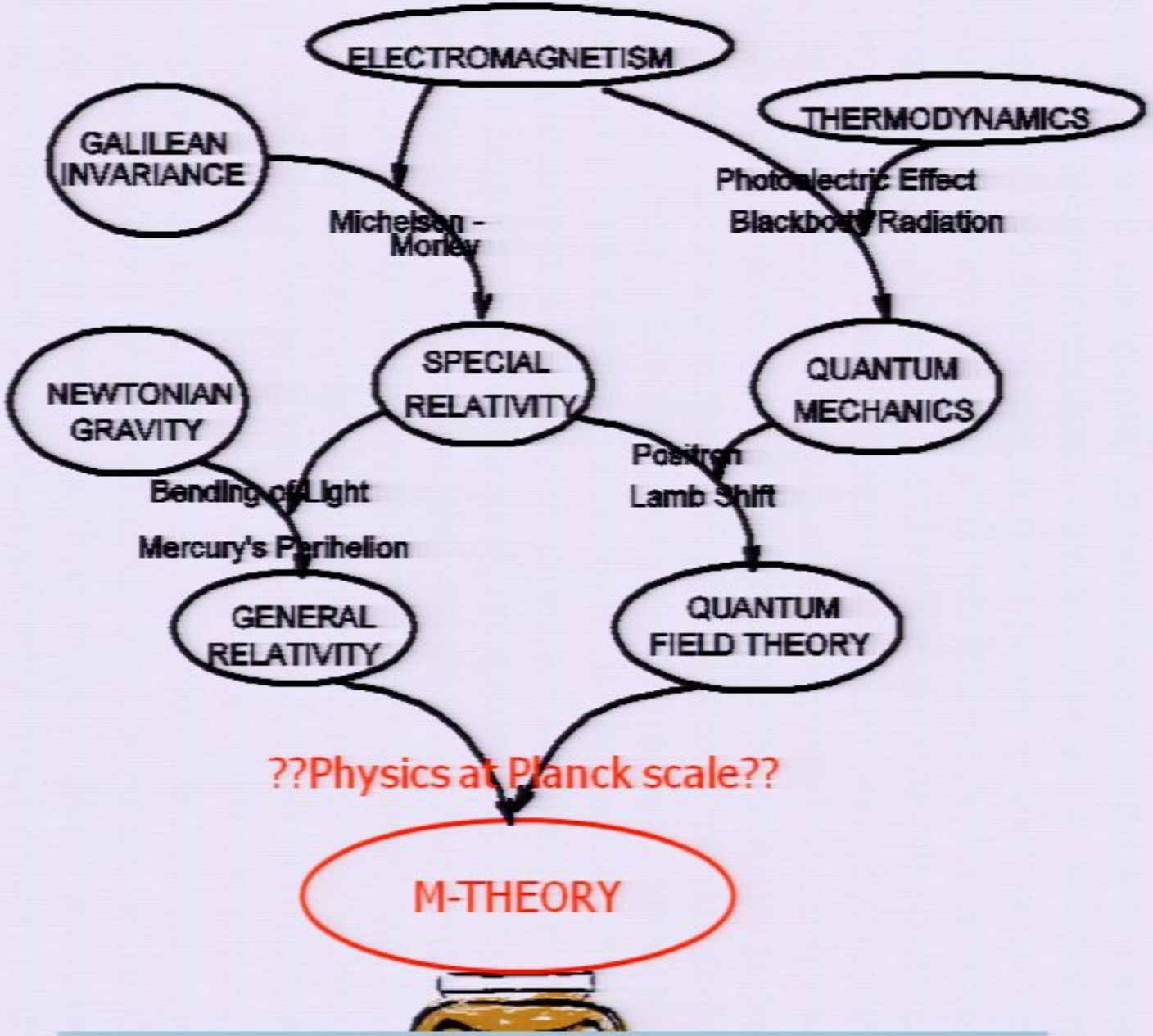

But contact with experiment is crucial

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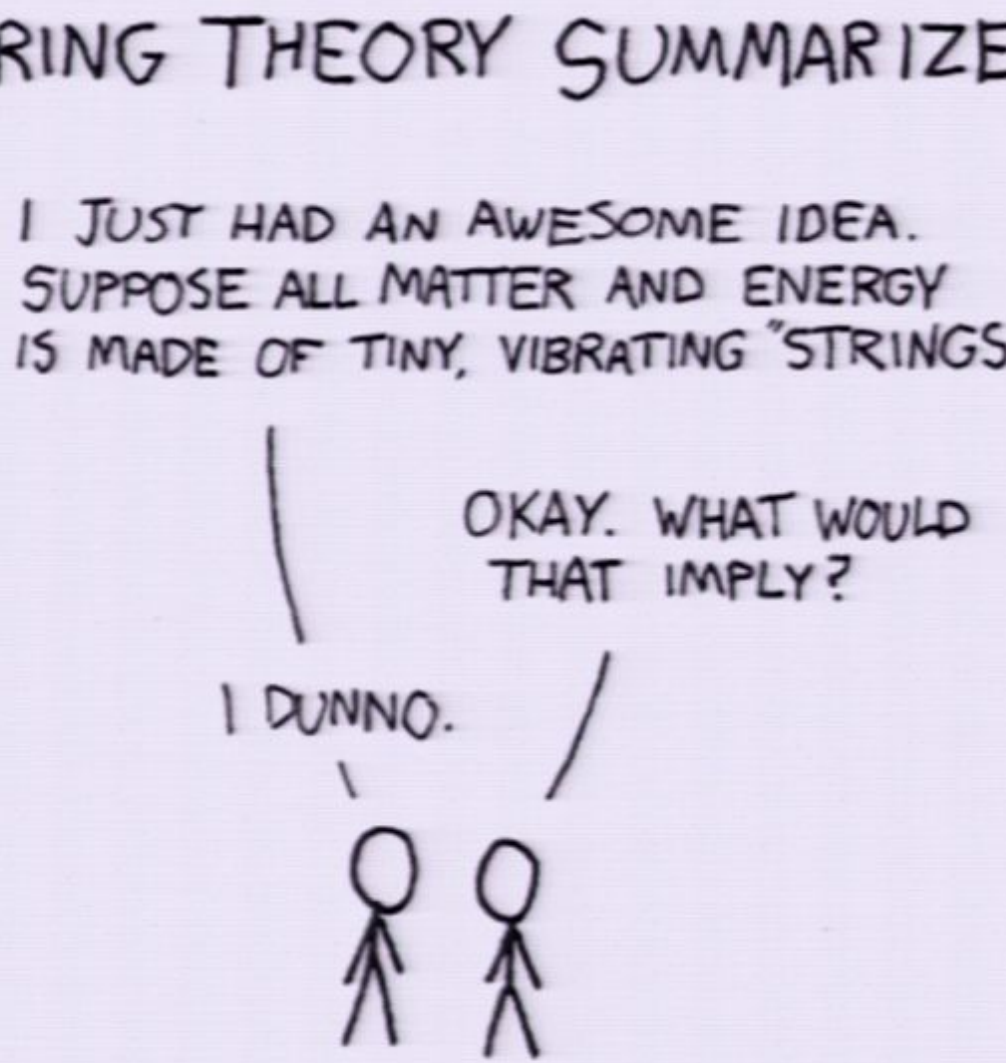

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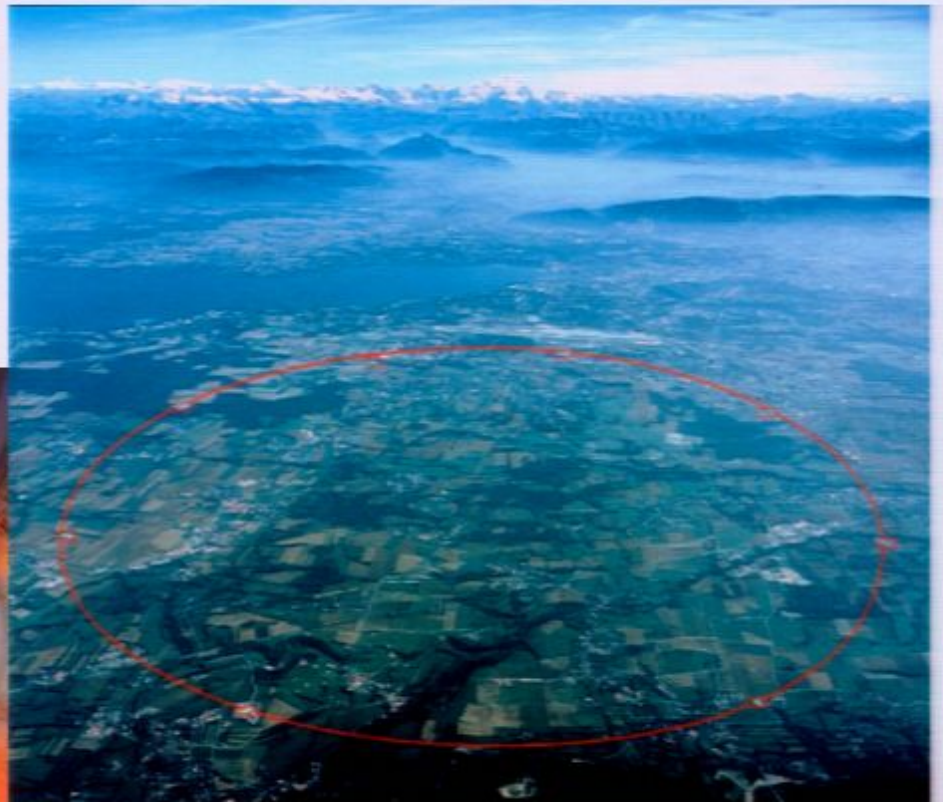

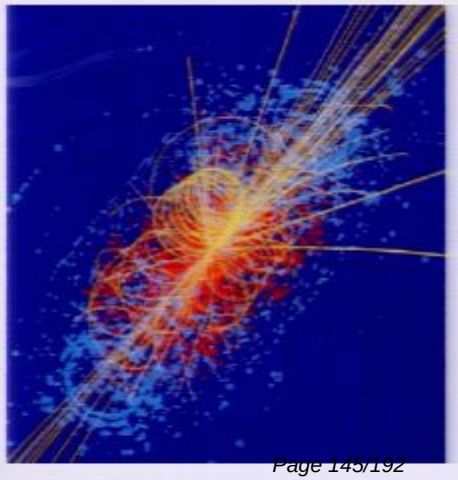

How far away is the Planck scale really?

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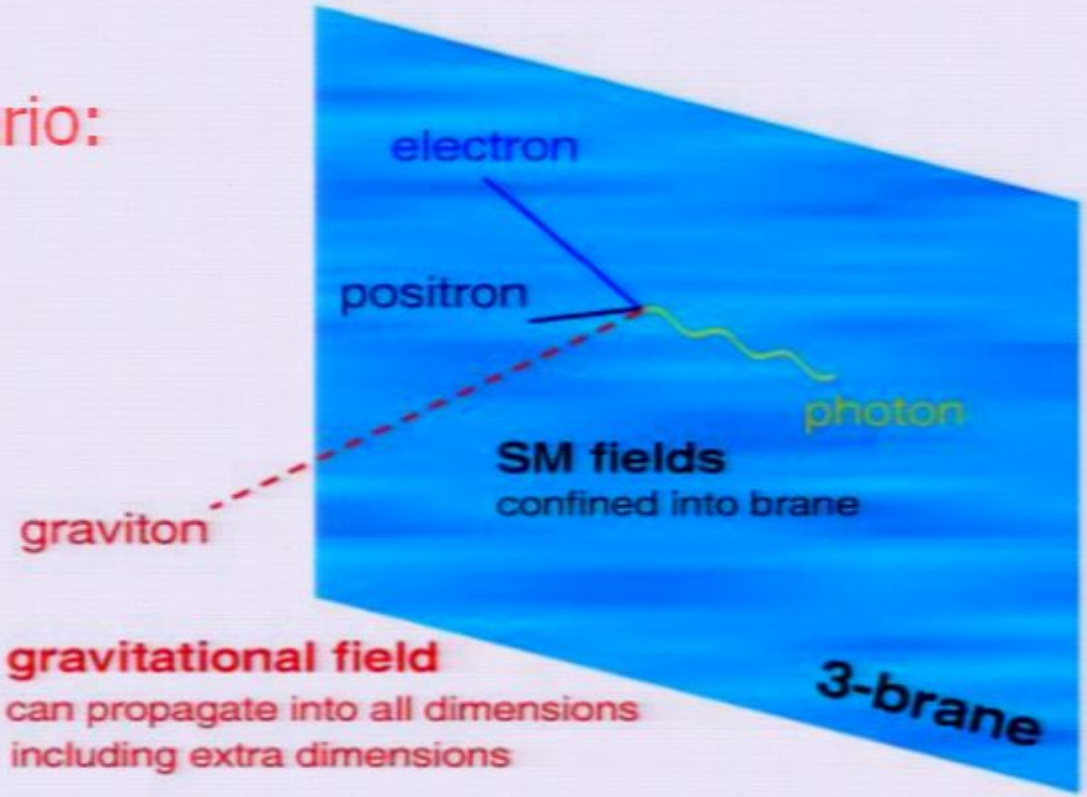

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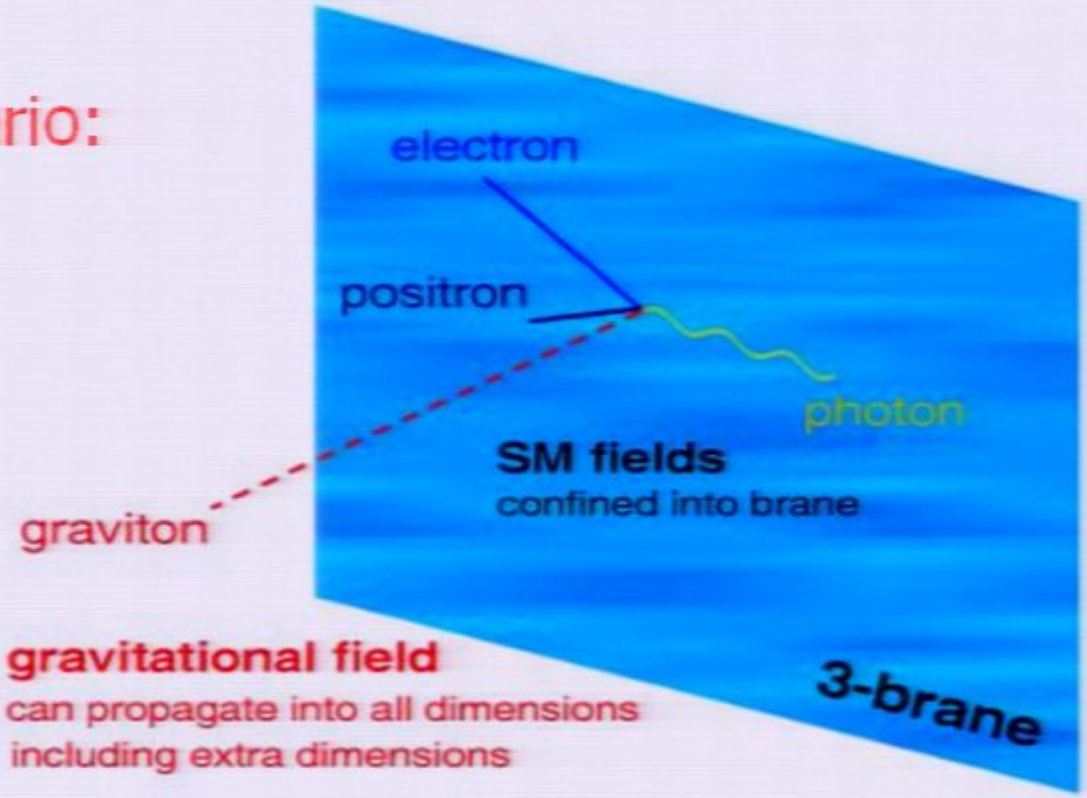

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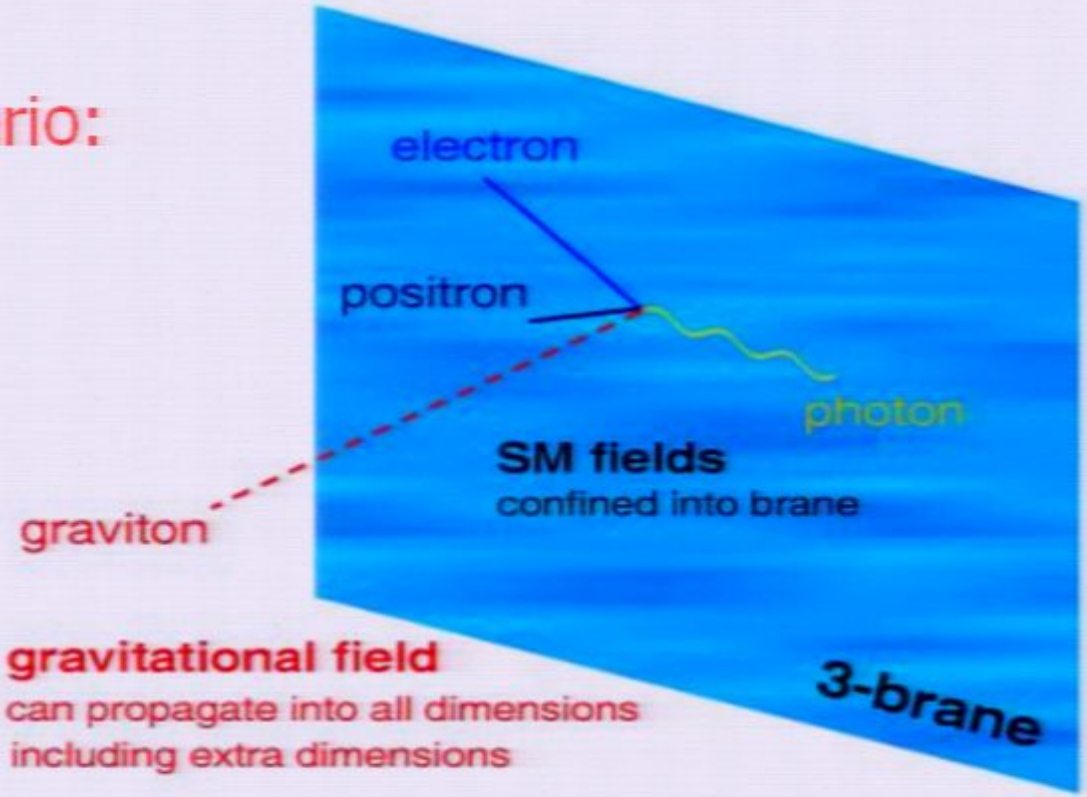

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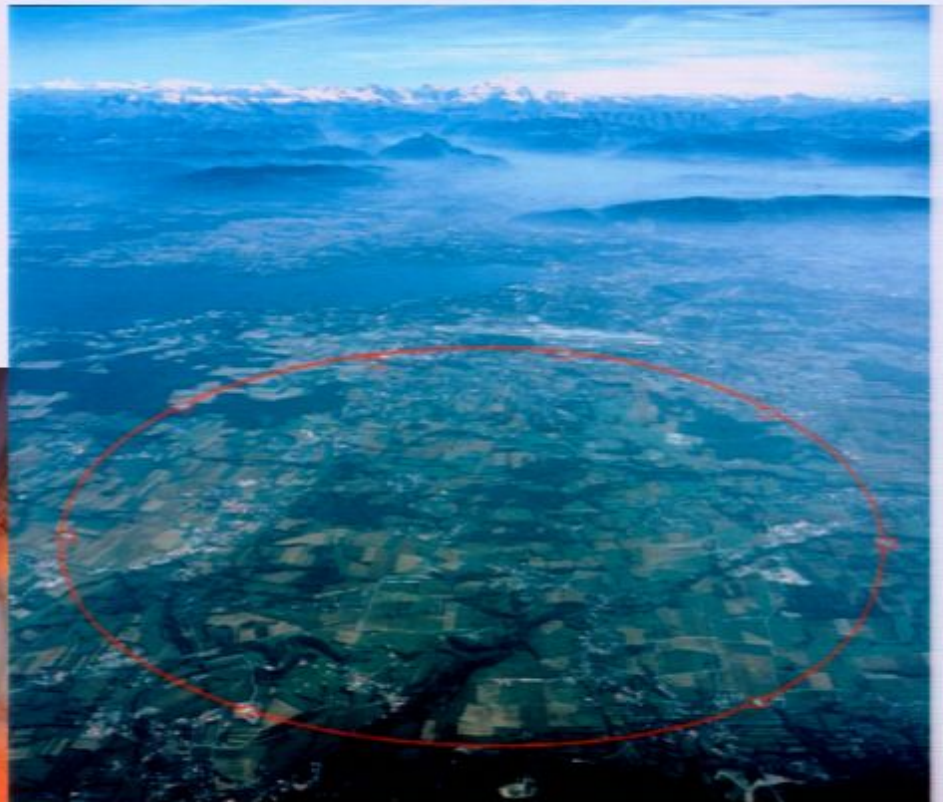

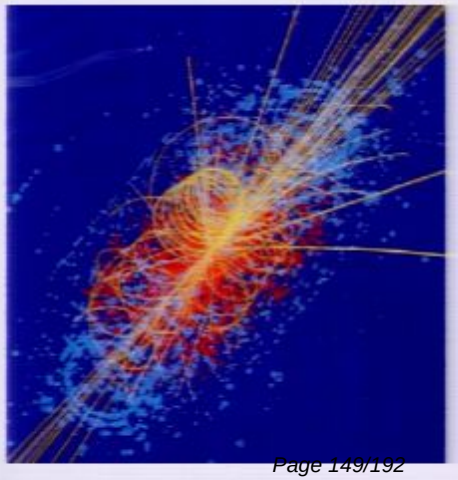

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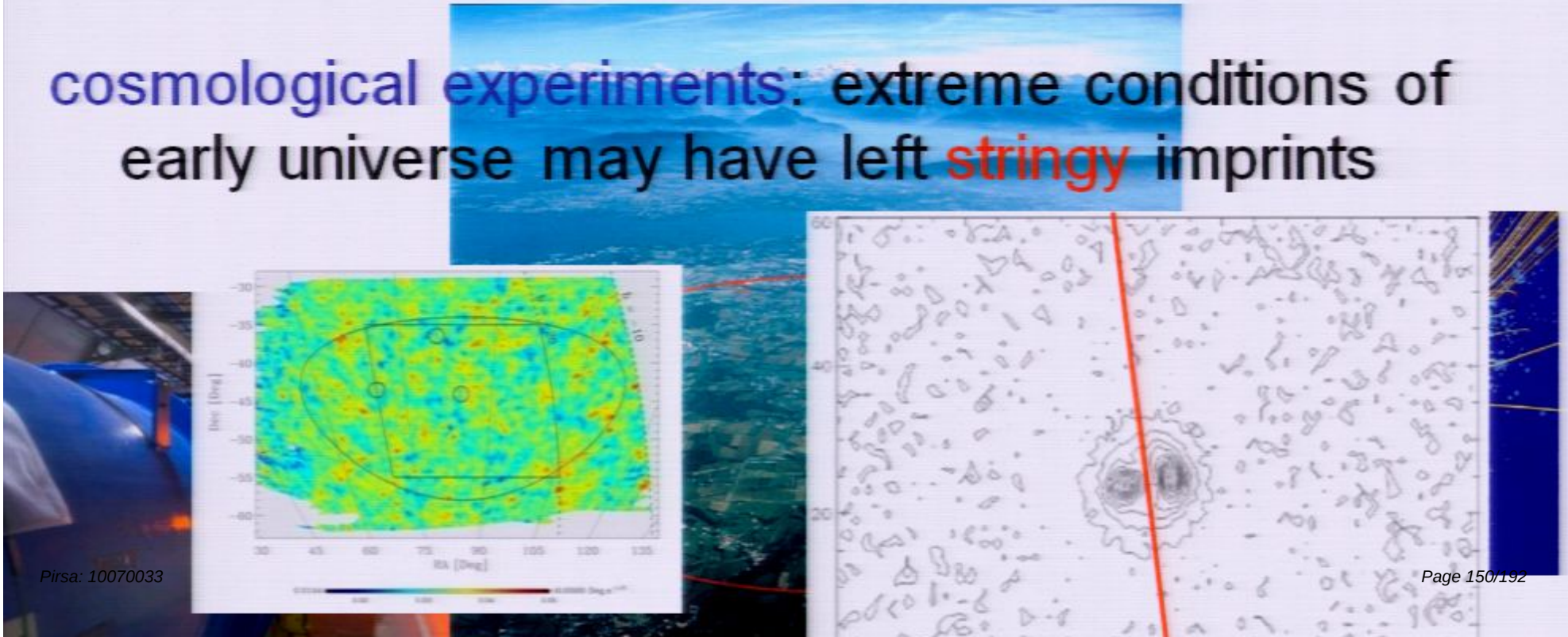

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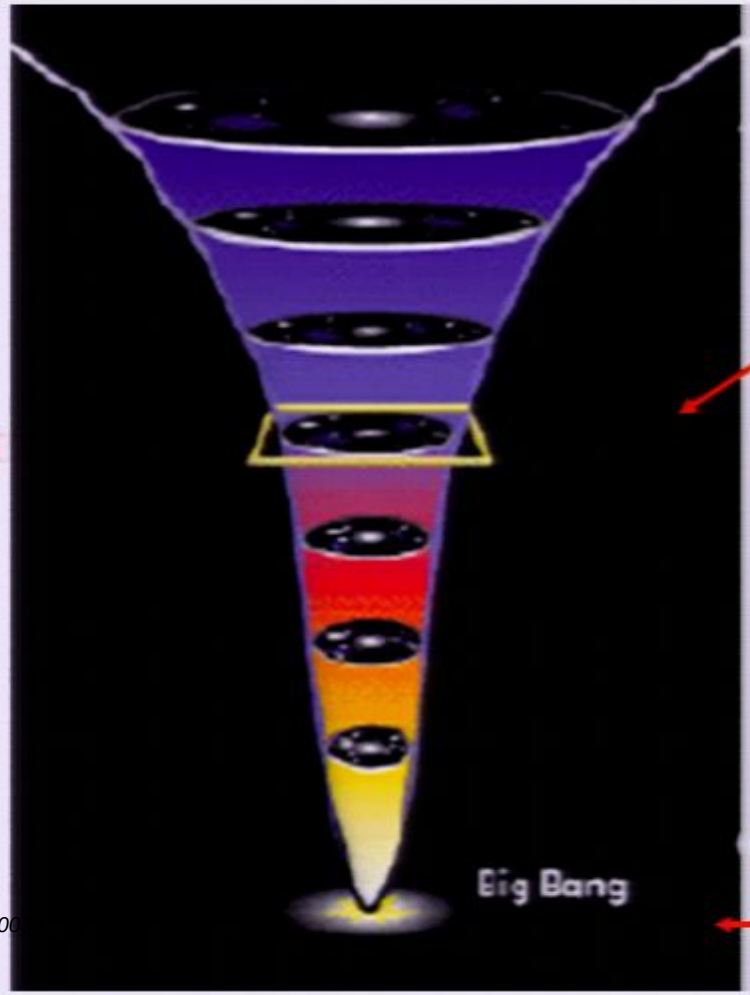

Stringy relics or imprints now?

We need to understand the optics of our "microscope"

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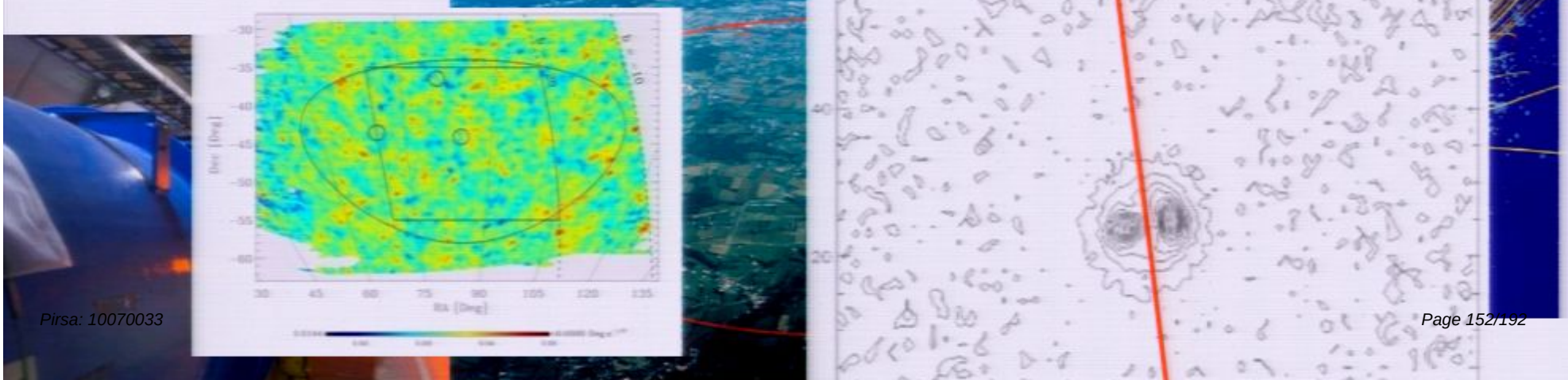

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Ernst Mach: "atoms are physically unverifiable entities"

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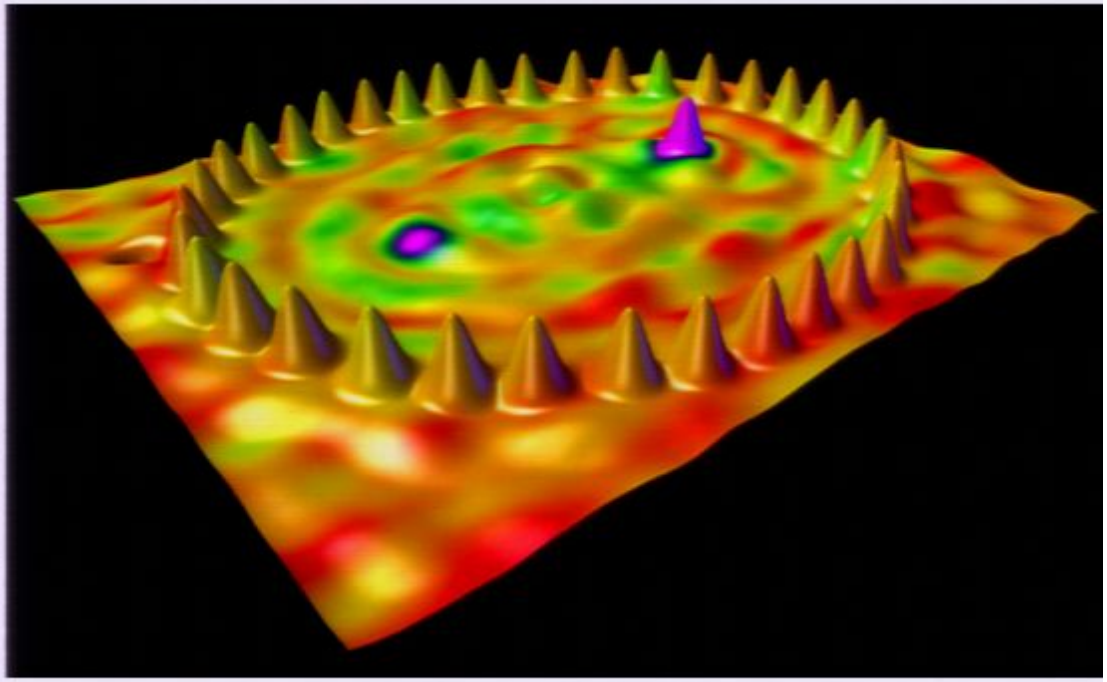

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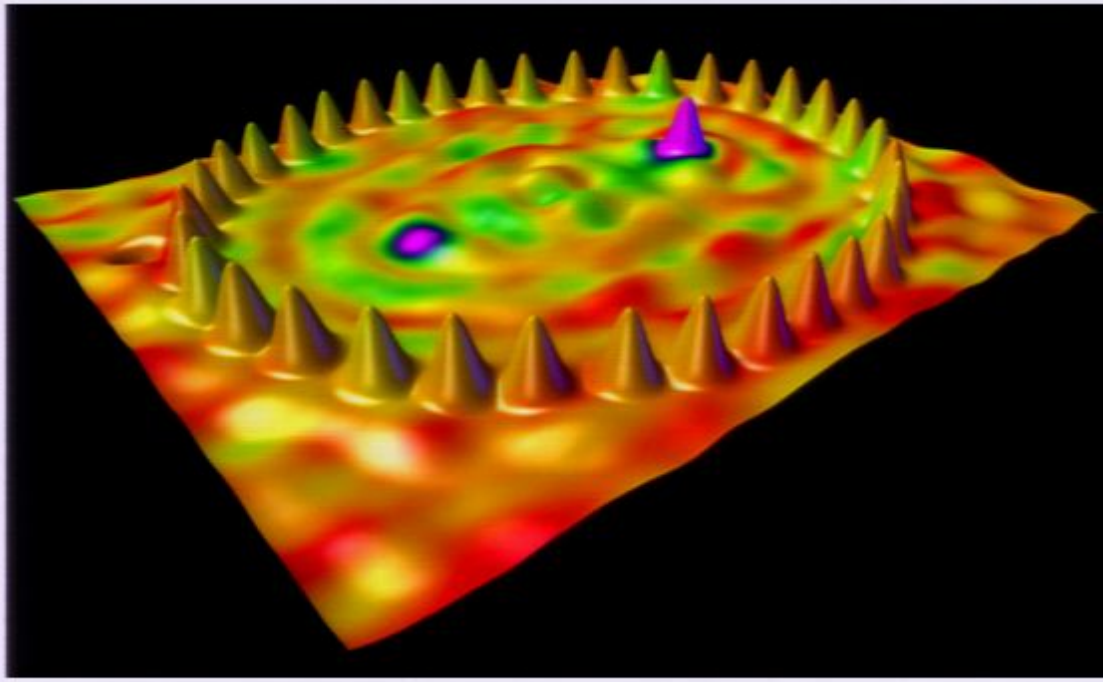

For superstrings,
the adventure is still only beginning!

More strings on the web:

"The Elegant Universe"
Brian Greene
http://www.pbs.org/wgbh/nova/elegant/

Superstrings!
http://www.sukidog.com/jpierre/strings/

The Official String Theory Web Site:
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"It's the 21st century—
time to feed your brain!"

Traffic
Map
Satellite
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RHIC
relativistic heavy ion collider
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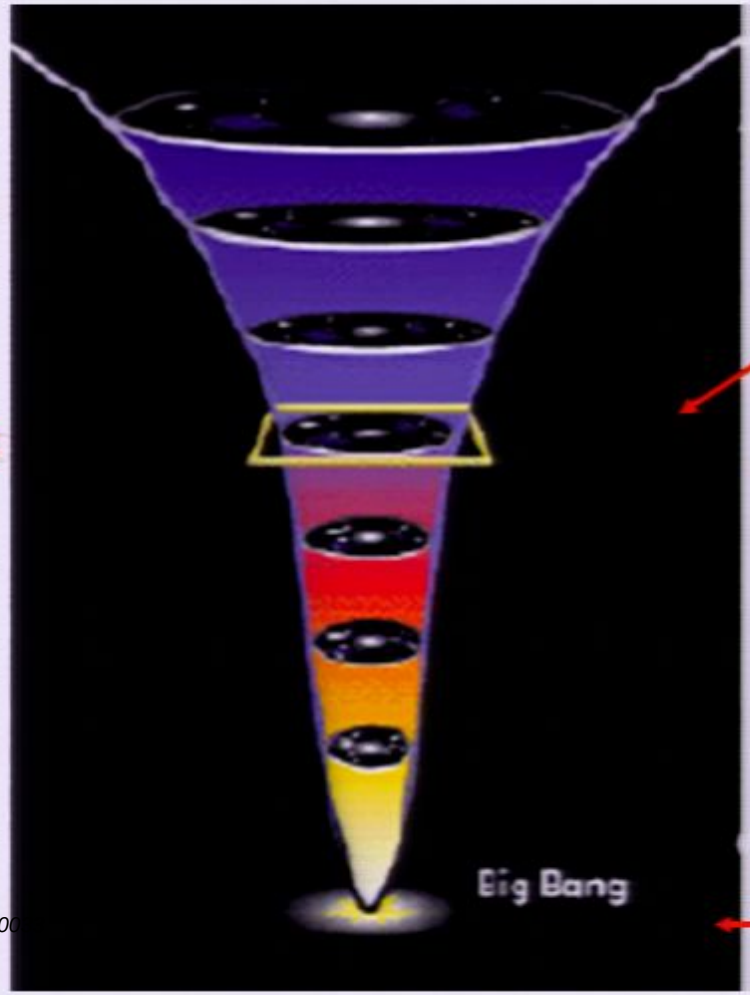

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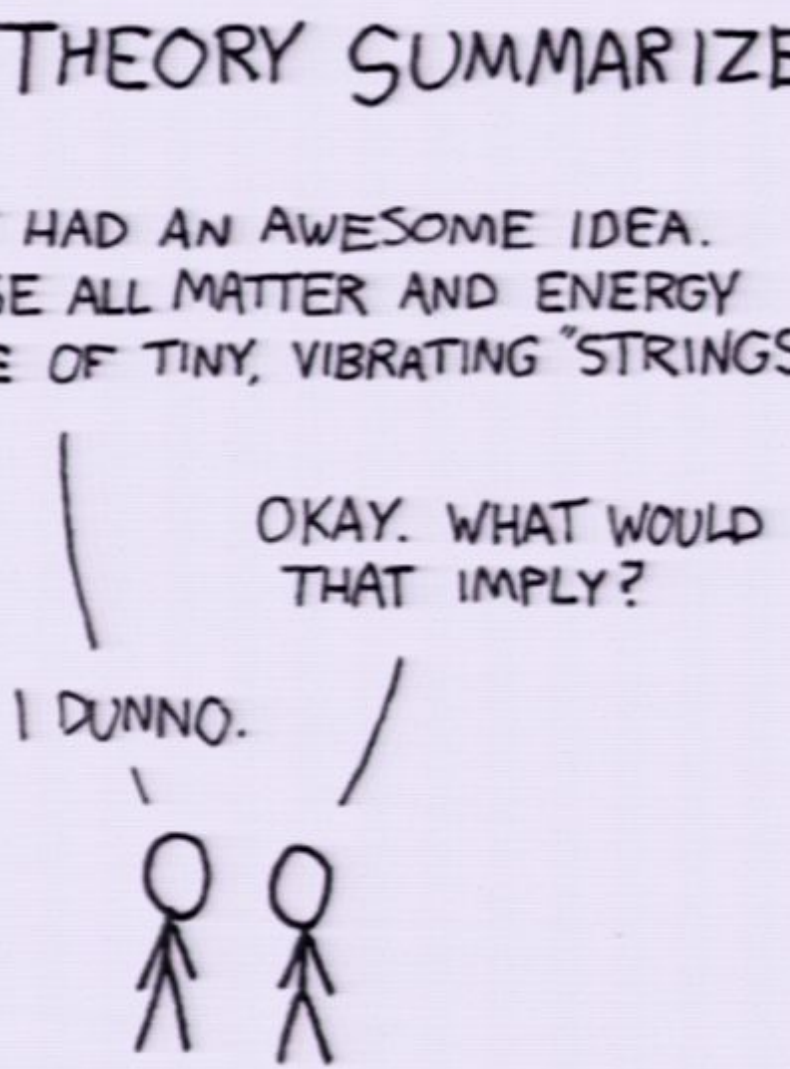

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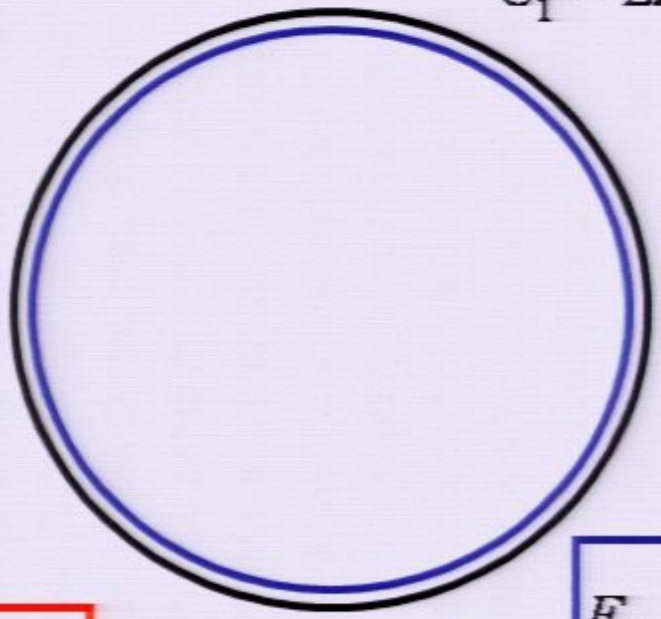

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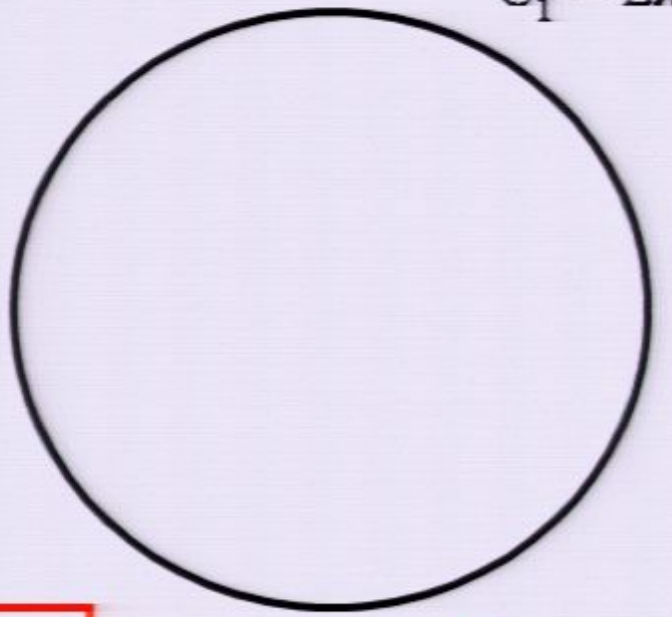

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Superstring theory: The devil is in the "details"

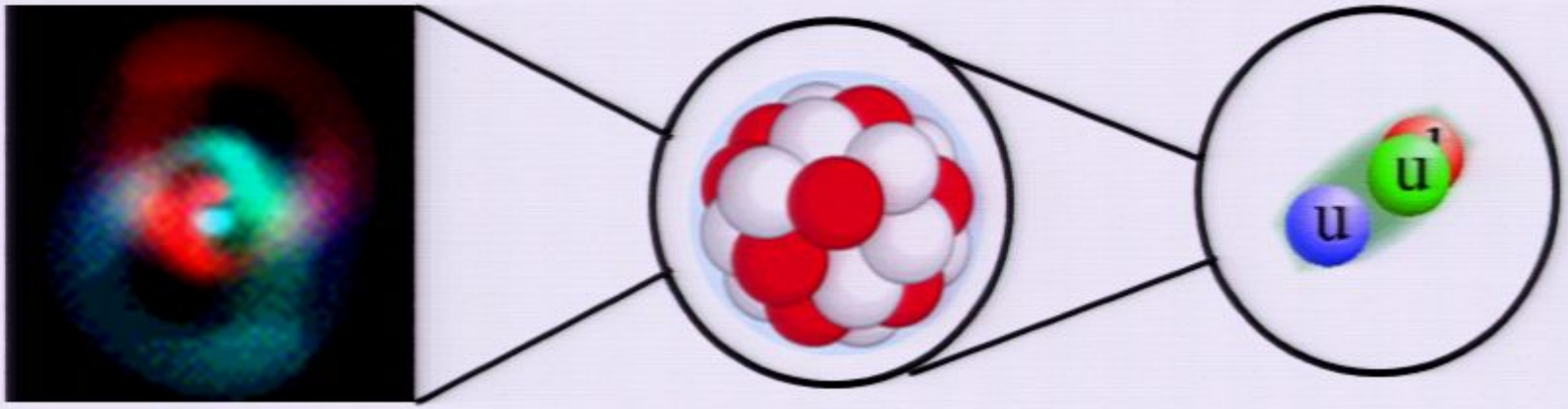
- Predicts we live in 10 spacetime dimensions!!

  Experimental update: we live in 4 dimensions!

- Predicts extra particles we haven't seen yet!

(Supersymmetry: each fermion is accompanied by a bosonic partner of the same mass)

Subatomic Physics → a theory of strings!



Elementary Particles (10^{-17} m)

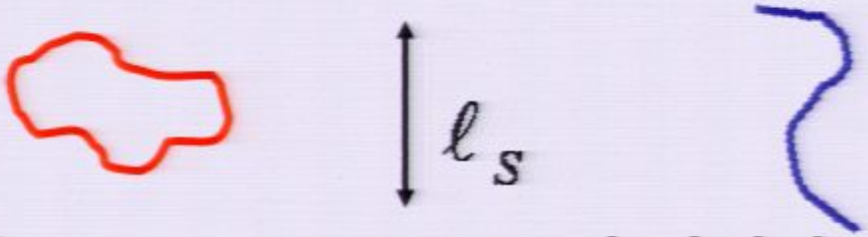
Fermions:
- electron, muon, tauon
- neutrinos (3 flavors)
- quarks - up, down, strange, charm, bottom, top

Bosons (Force Mediators):
- photon (electromagnetism)
- gluon (strong)
- $W^{\pm}$, Z (weak)
- Higgs particle

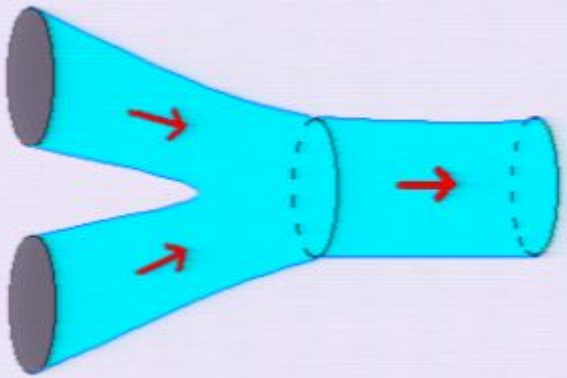
What's missing here?

Superstrings: the theory of subatomic physics

with resolution, $\ell_s = 10^{-35}\mathrm{m}$, all elementary particles are one-dimensional objects (strings)



interactions are geometric joining and splitting governed by coupling constant, g



with these simple rules get appropriate particle species and interactions to match Standard Model

Superstrings: the theory of gravitational physics

consistency requires appearance of the graviton!

at long distances much greater than ℓ_s, reproduces Einstein's gravitational equations

$$R_{\mu\nu} - \tfrac{1}{2} R\, g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

Newton's constant

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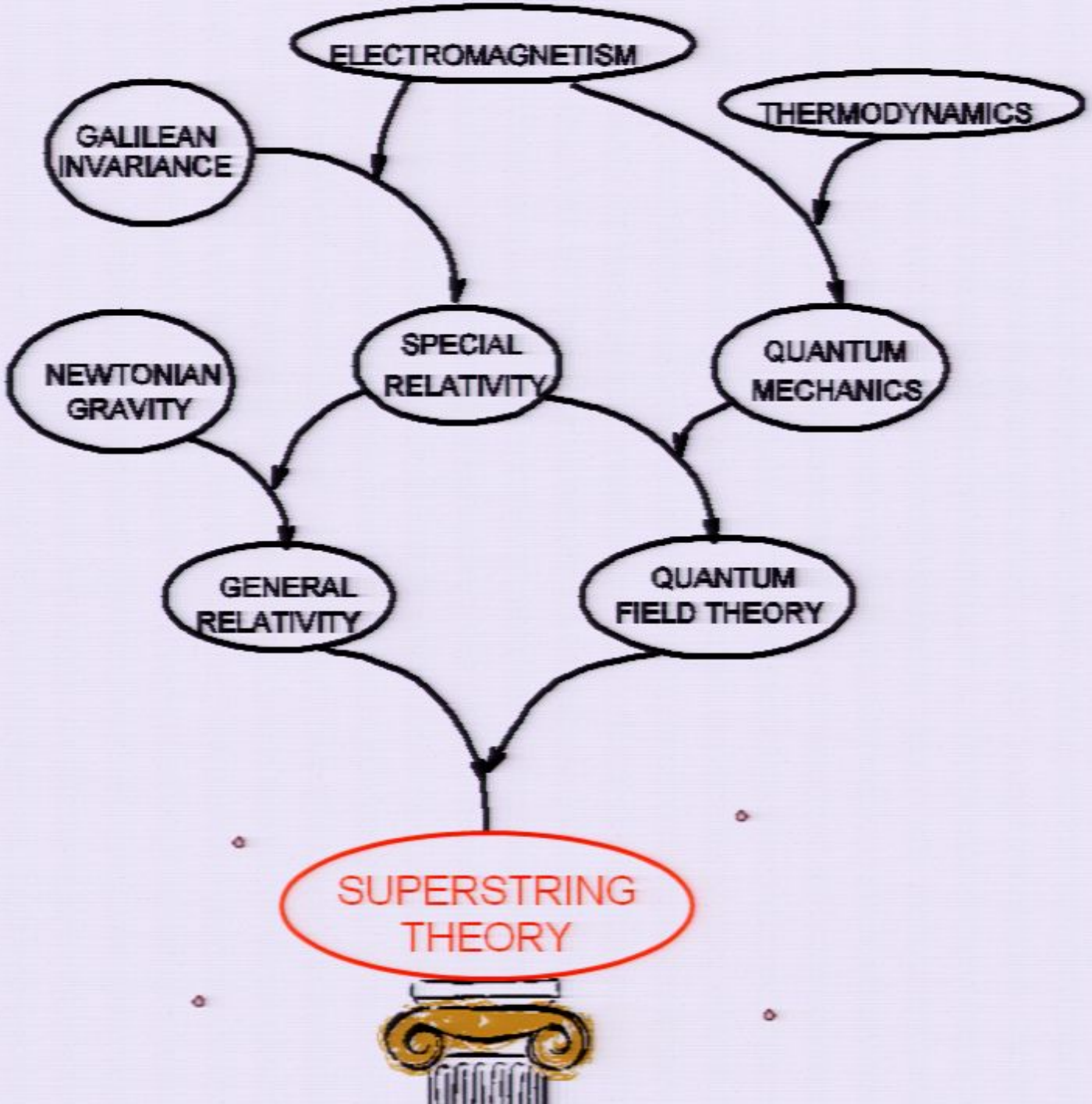
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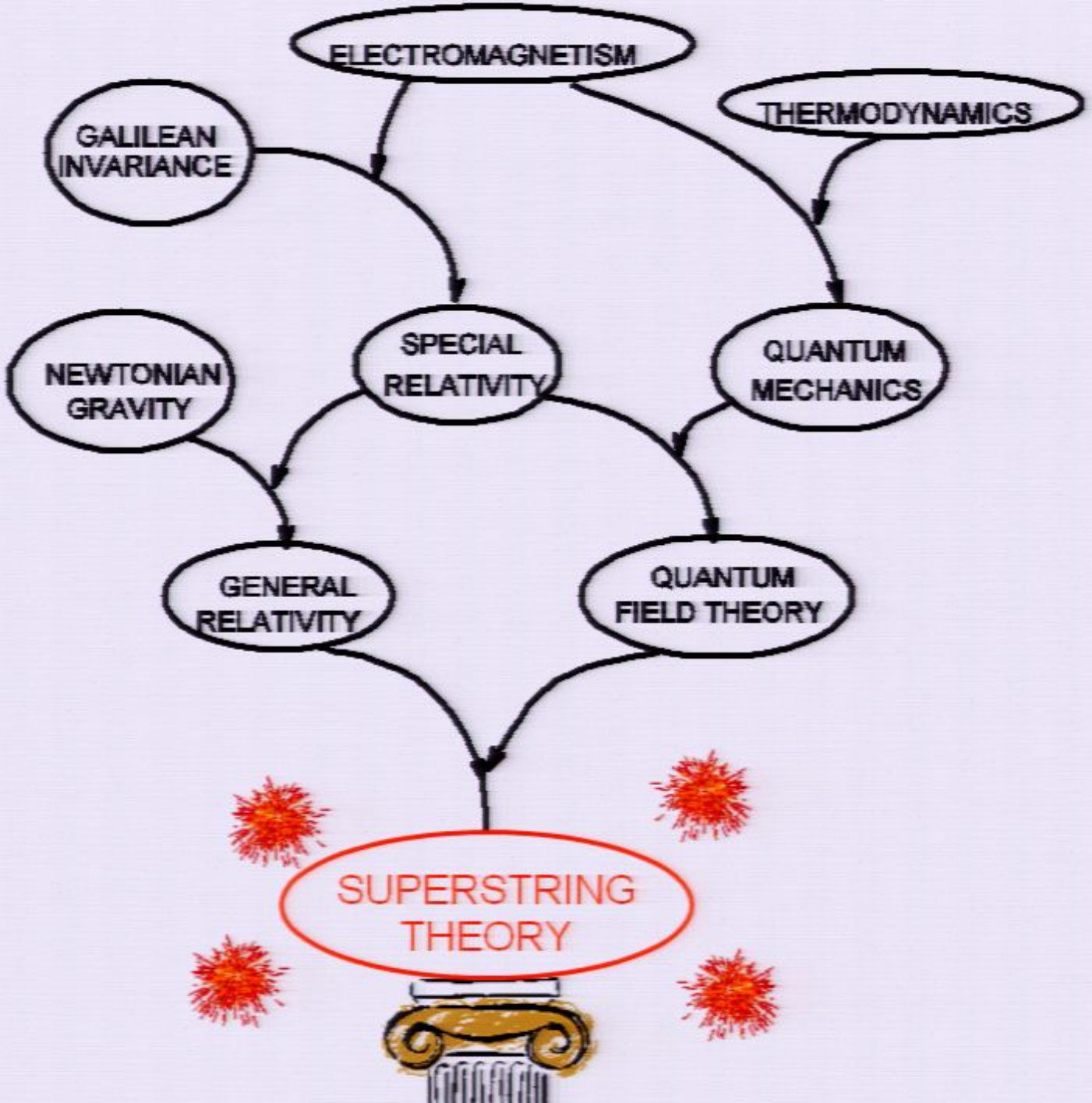
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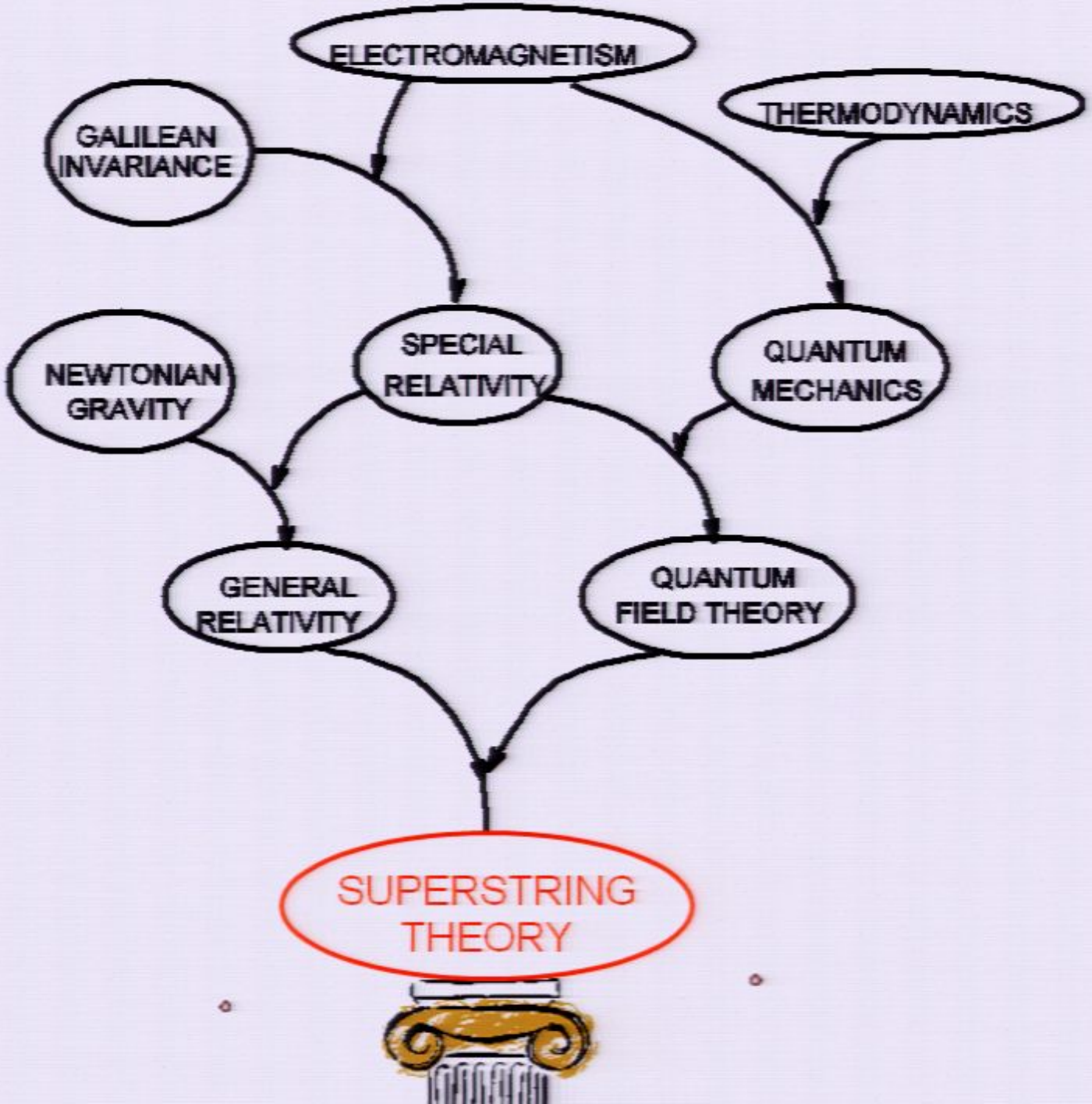
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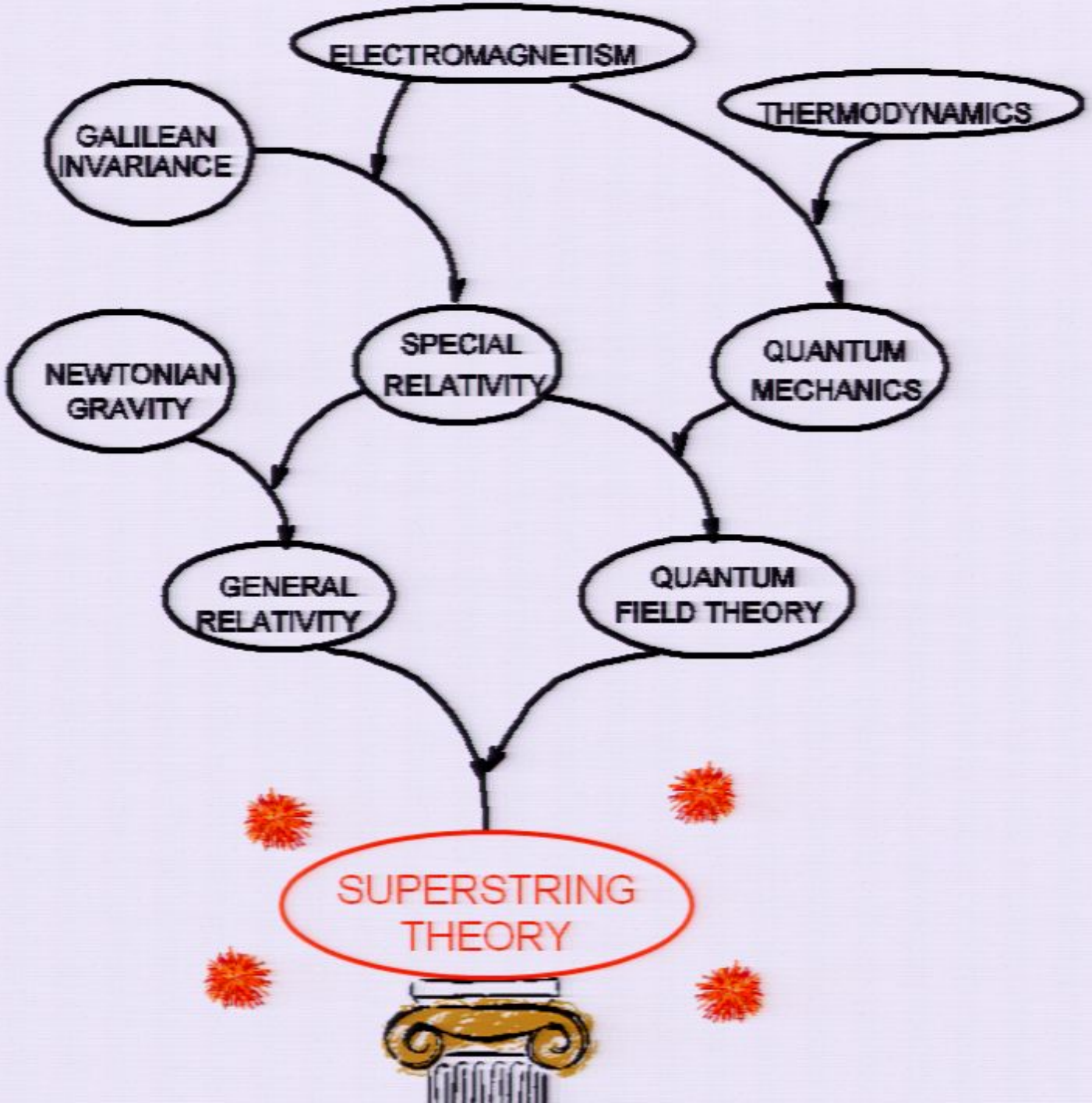
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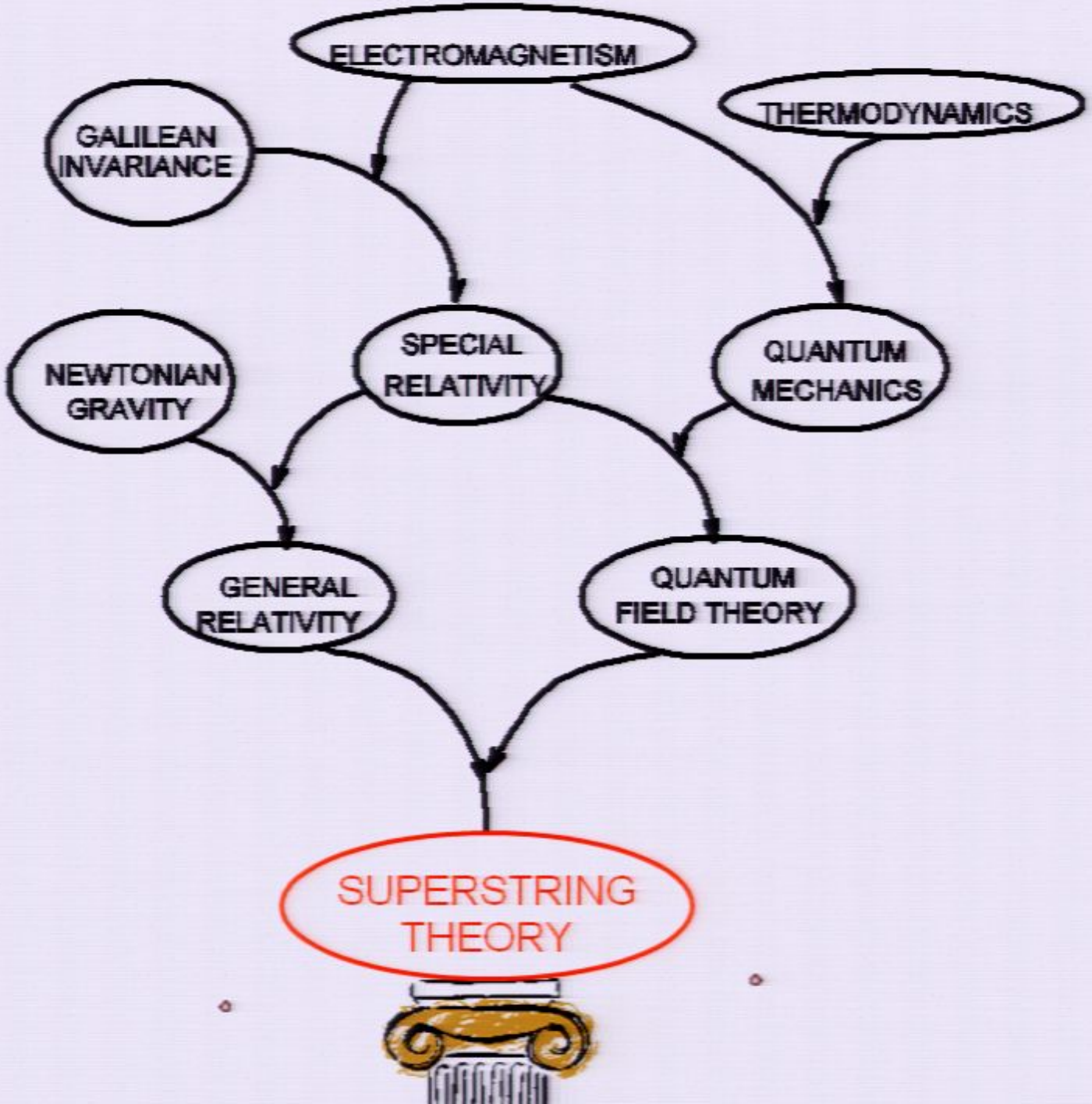
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Superstring theory: The devil is in the "details"

- Predicts we live in 10 spacetime dimensions!!

Experimental update: we live in 4 dimensions!
(1 time and 3 space)

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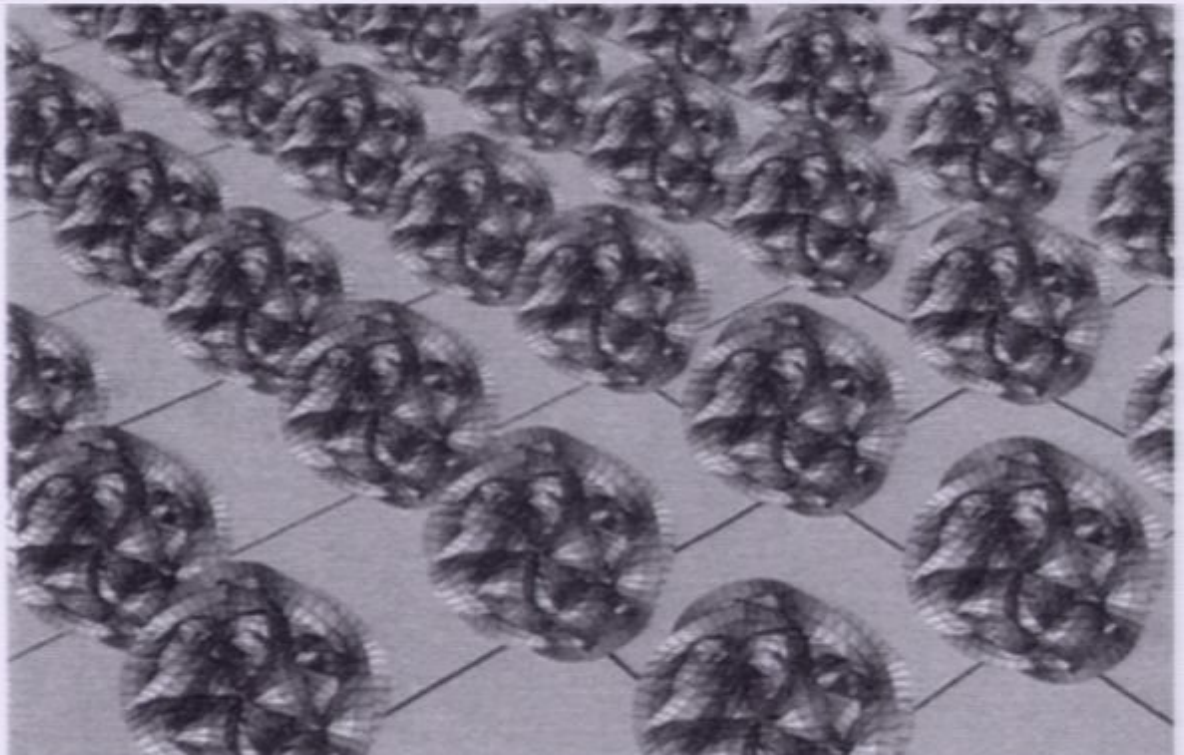


Essential ingredients for M-theory conjecture:

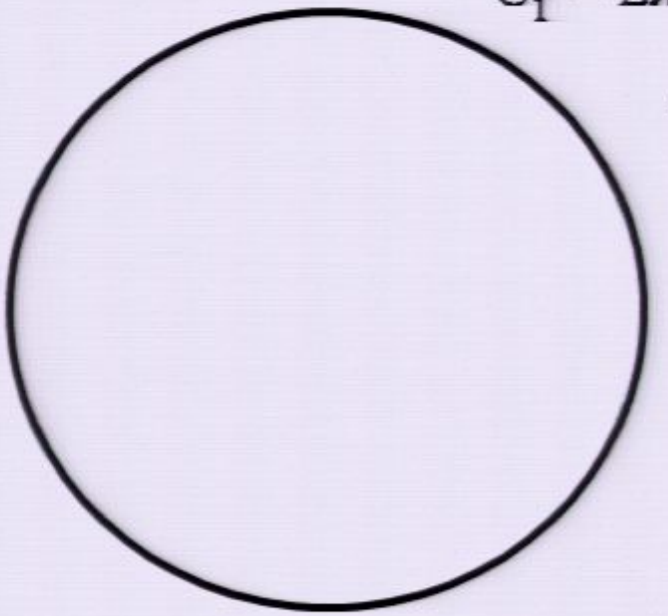
- Dualites: two mathematical descriptions describe identical physical phenomena

Eg, T-duality relates large and small circle compactifications

$$C_1 = 2\pi R$$

$$C_2 = \frac{2\pi \ell_s^2}{R}$$

de Broglie wavelength: $\lambda = \frac{2\pi}{E_p}$



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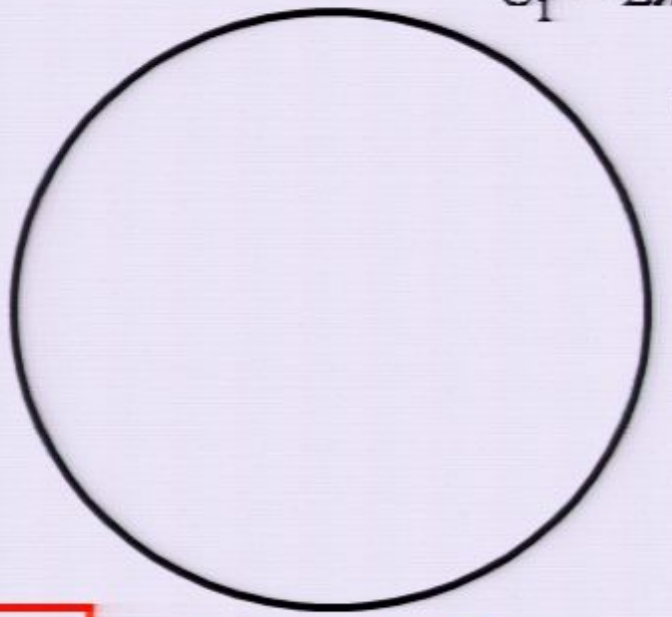

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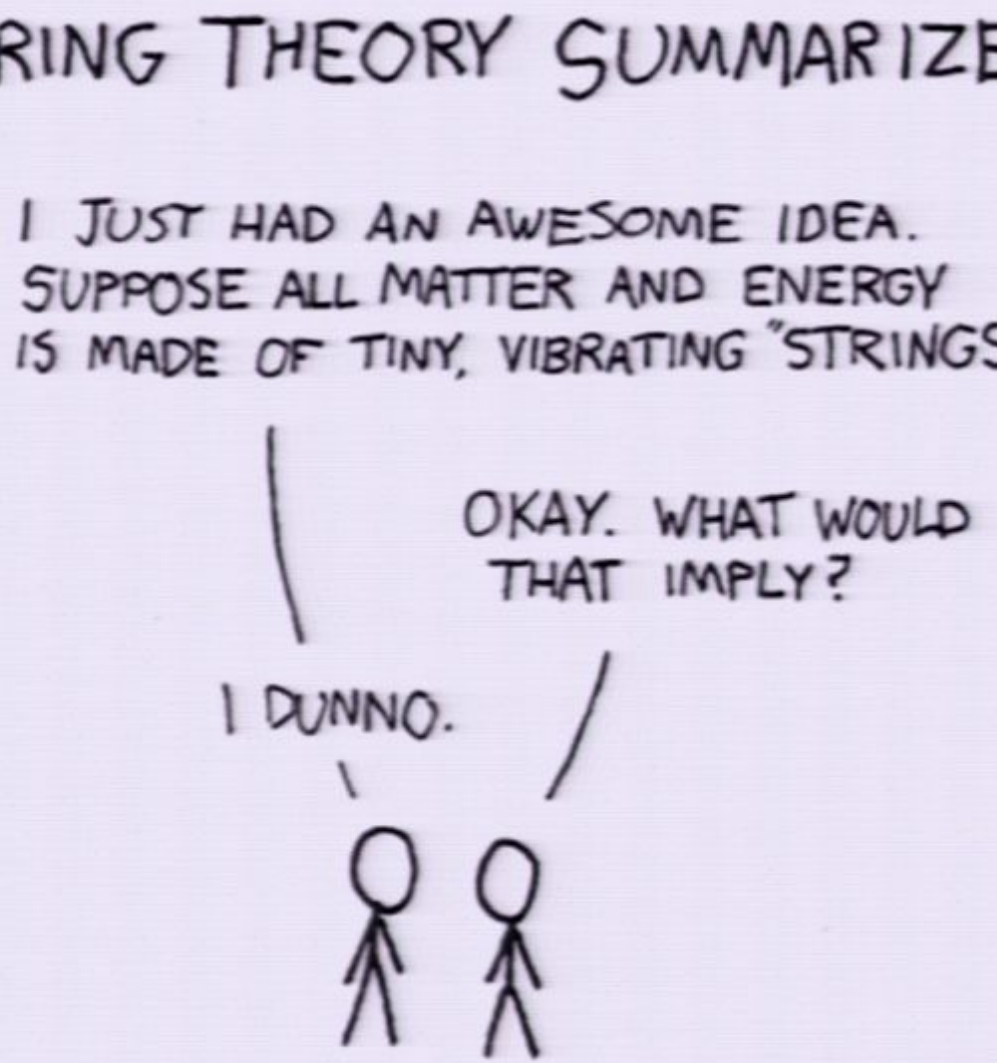
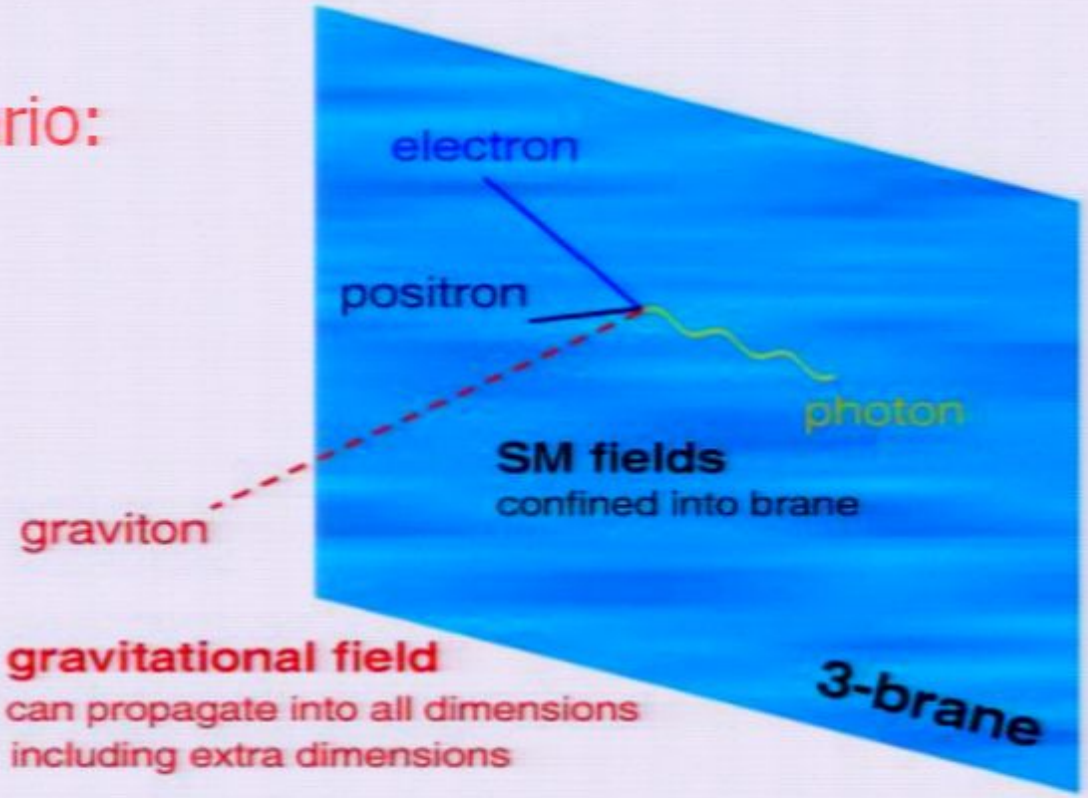
STRING THEORY SUMMARIZED:



How far away is the Planck scale really?

Brane-world scenario:

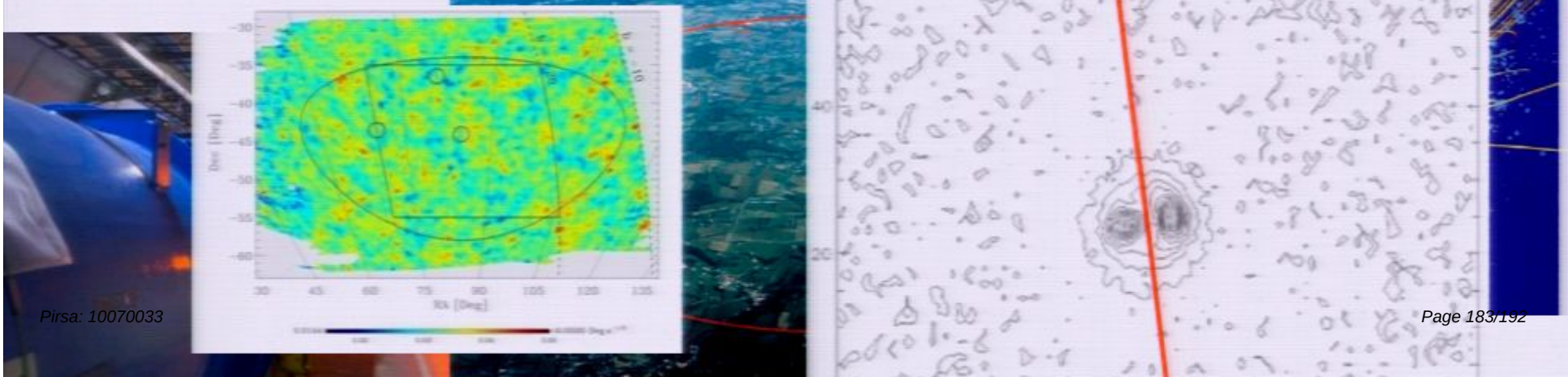


(Some) Extra dimensions may be very large!

Superstring theory: a theory looking for a good experiment

accelerator experiments: probe 10^{12} eV and beyond
Tevatron, Large Hadron Collider, ….

cosmological experiments: extreme conditions of early universe may have left stringy imprints



Cosmology: extreme conditions of early universe give a window on small scales and high energies

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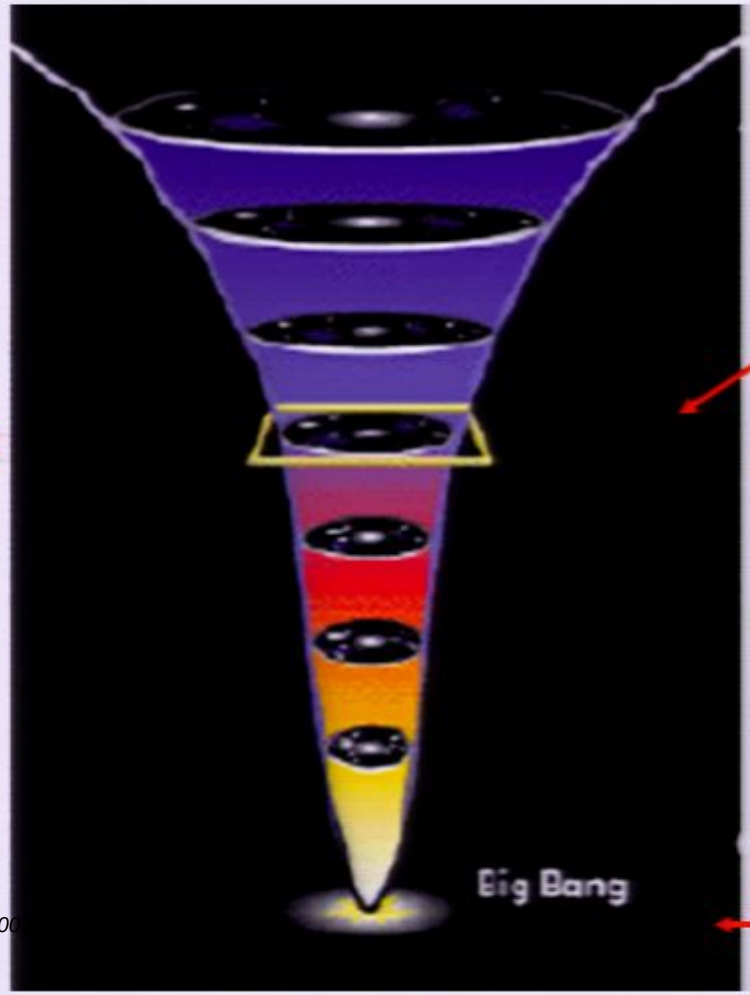
resent

Past



Stringy relics or imprints now?

We need to understand the optics of our "microscope"

String physics is manifest

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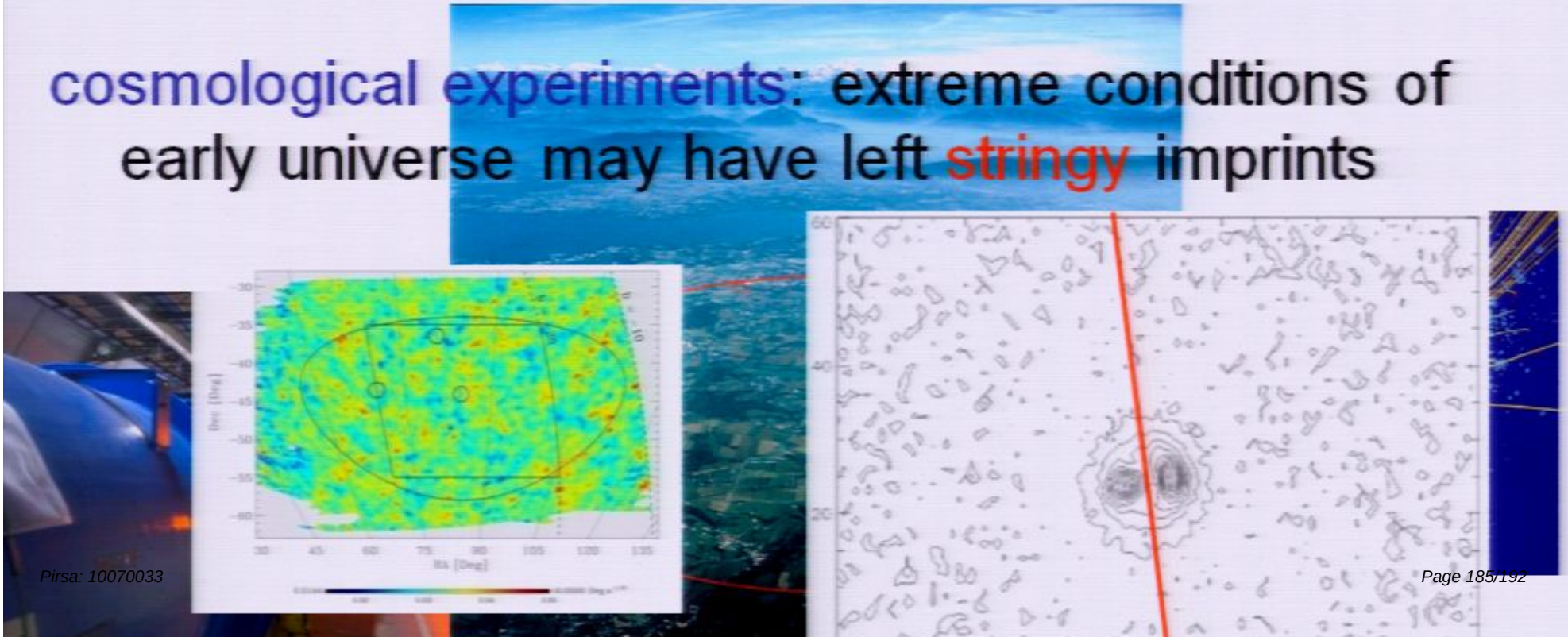

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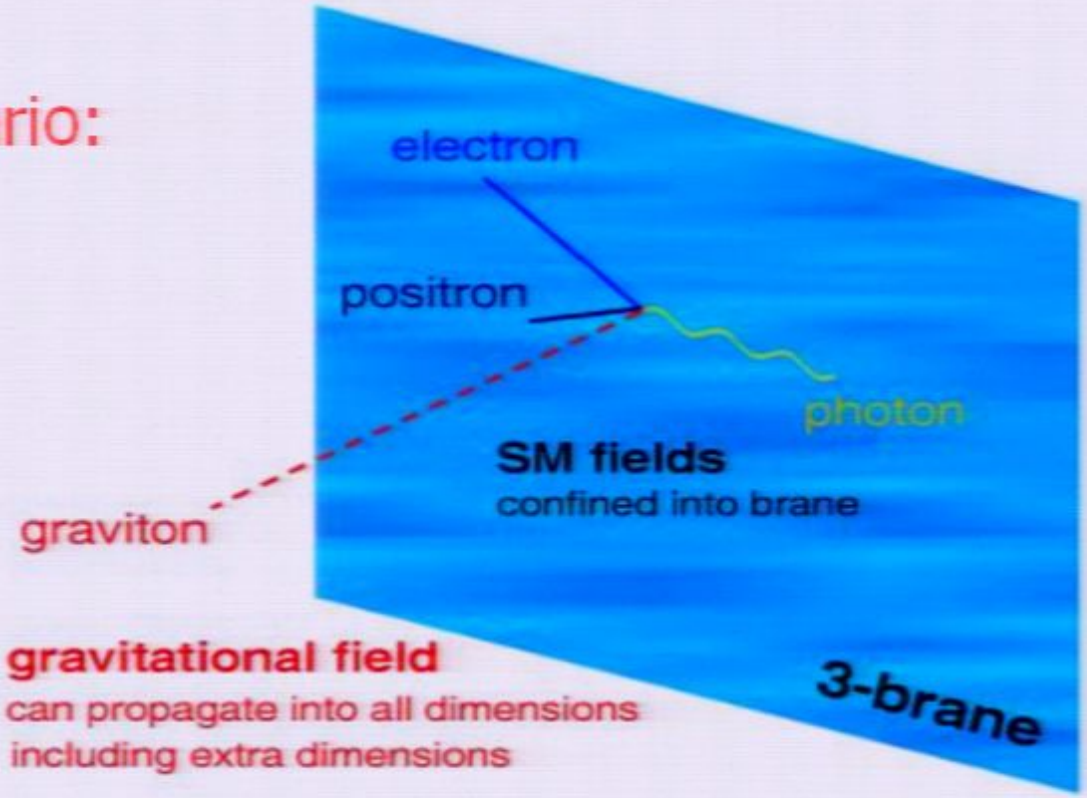

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Advantage: $G_4 = G_{10}/V_6$

Superstring theory: Unique theory of everything

- M-theory Conjecture: all known string theories are different solutions of single fundamental theory

M-theory also includes 11-dimensional supergravity!

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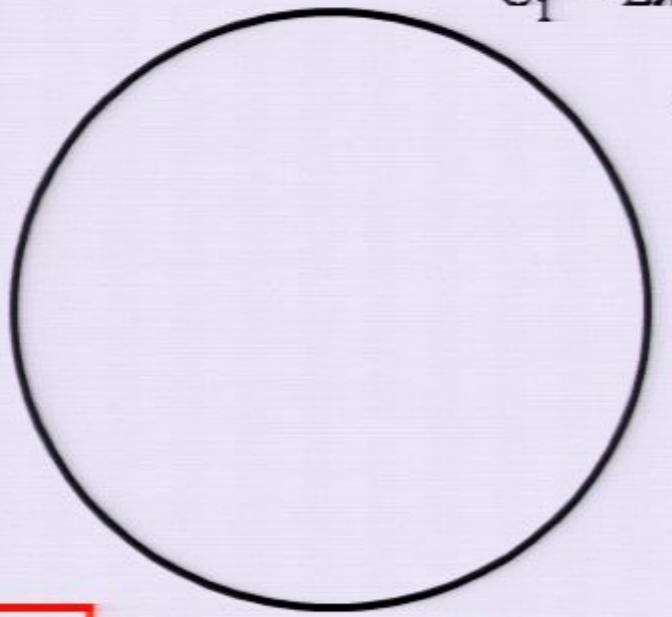

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  Experimental update: we live in 4 dimensions!

- Predicts extra particles we haven't seen yet!

(Supersymmetry: each fermion is accompanied by a bosonic partner of the same mass)

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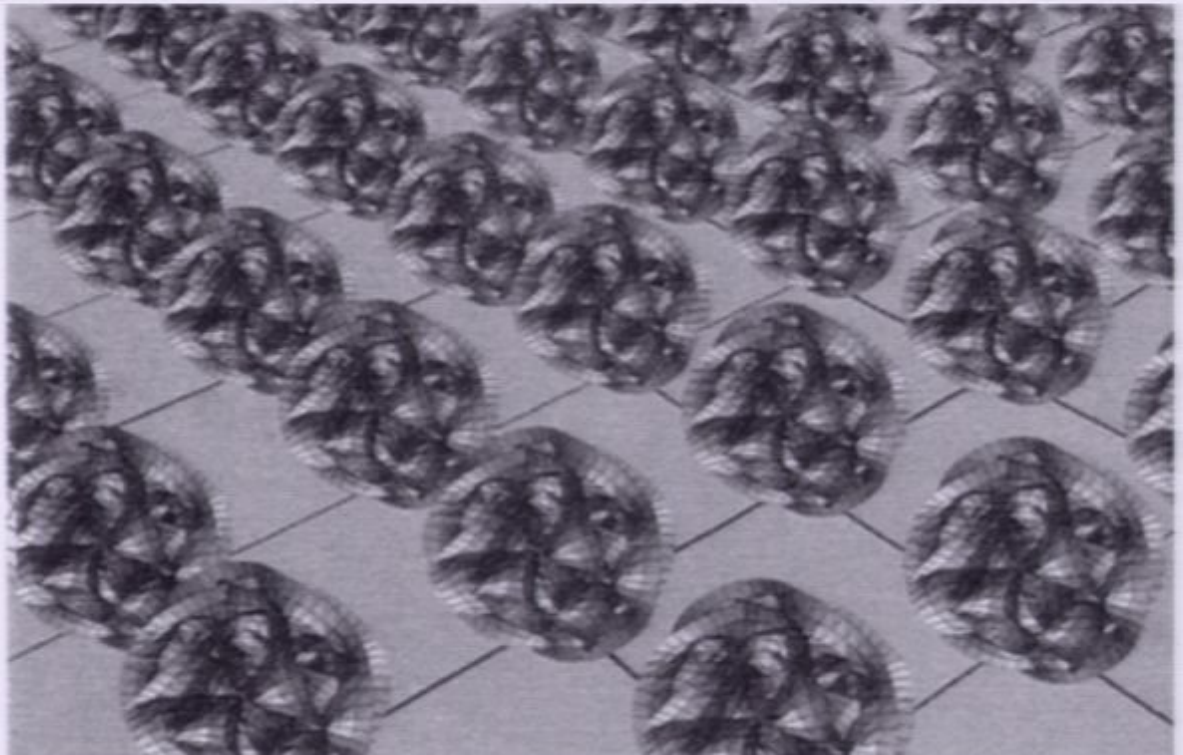

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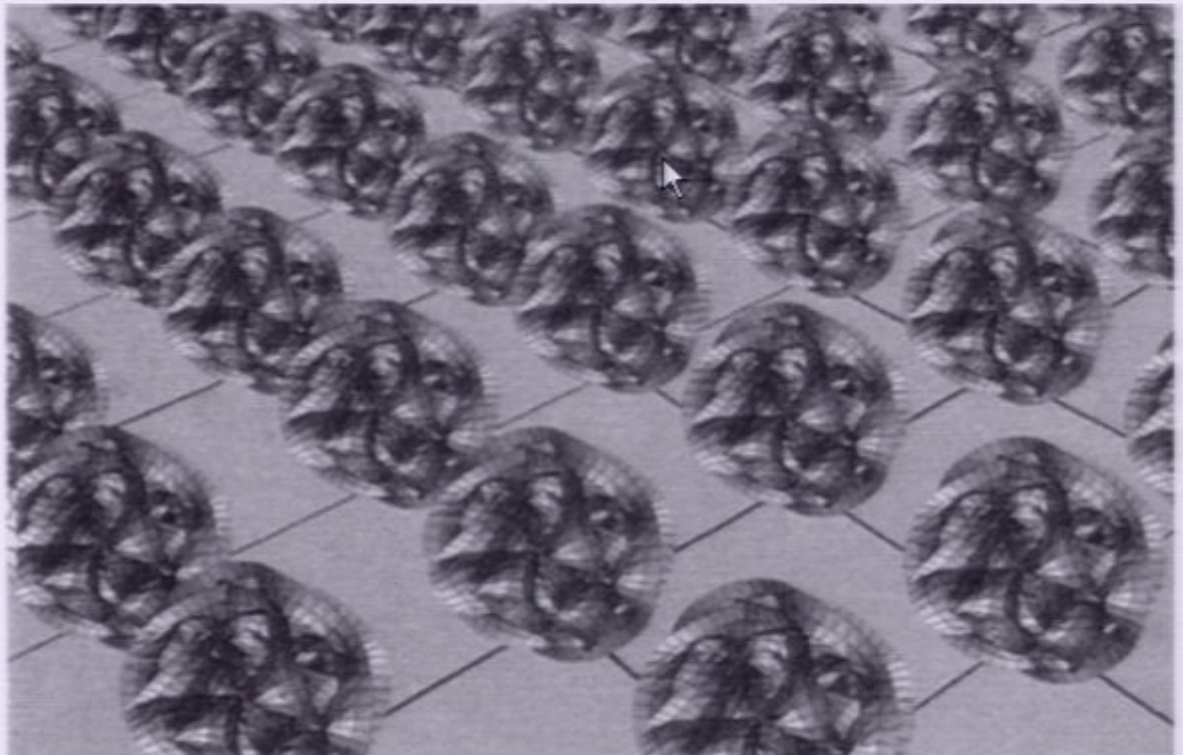
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