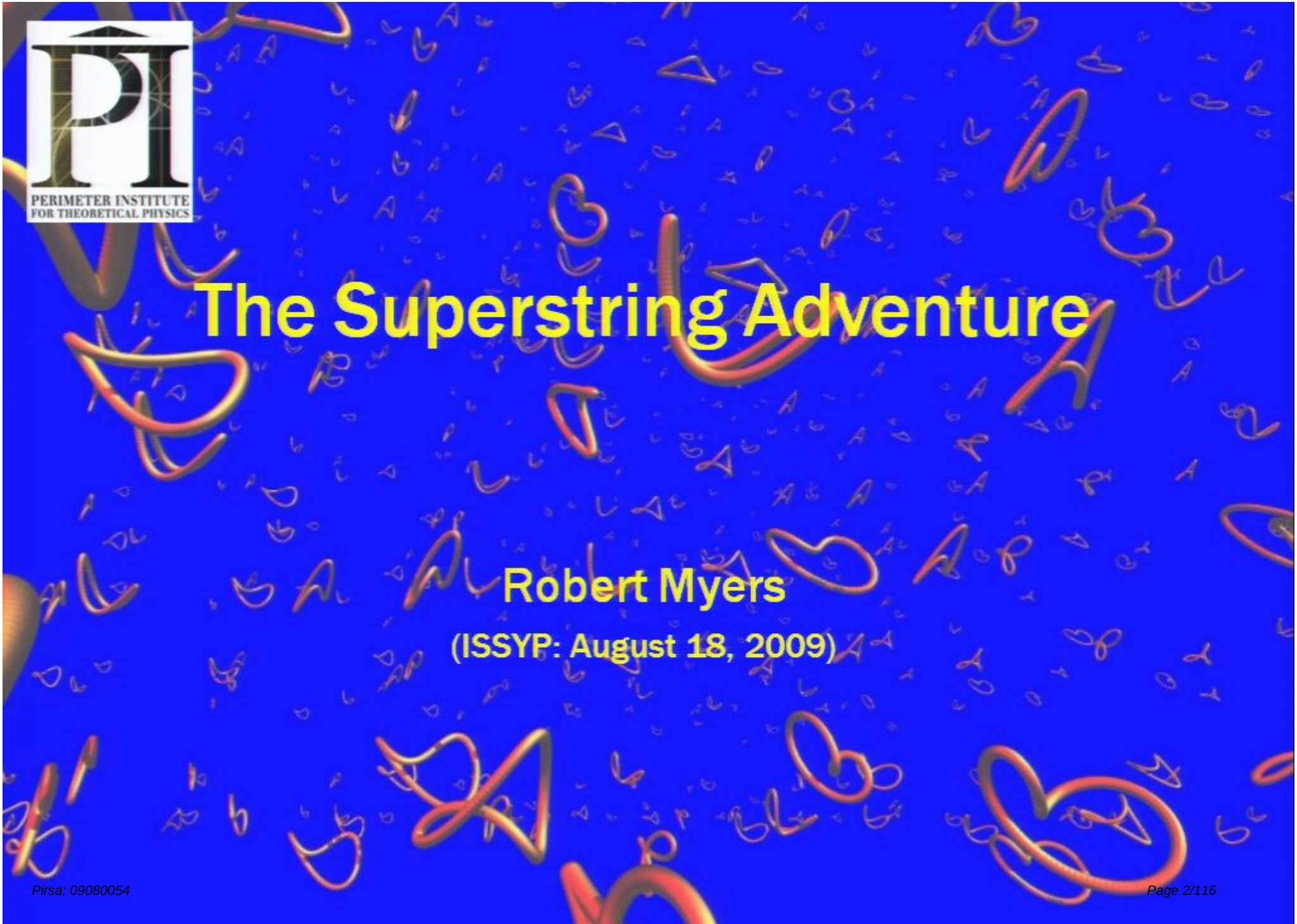
Title: Adventures with Superstrings

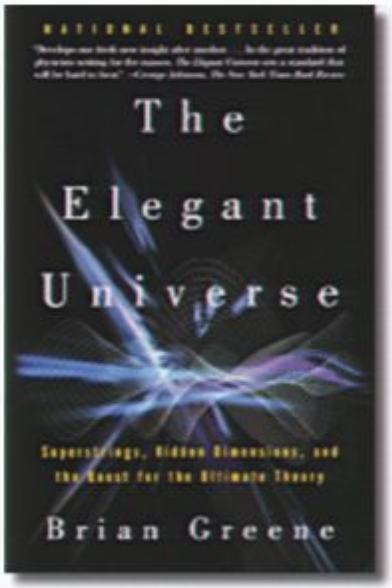
Date: Aug 18, 2009 01:05 PM

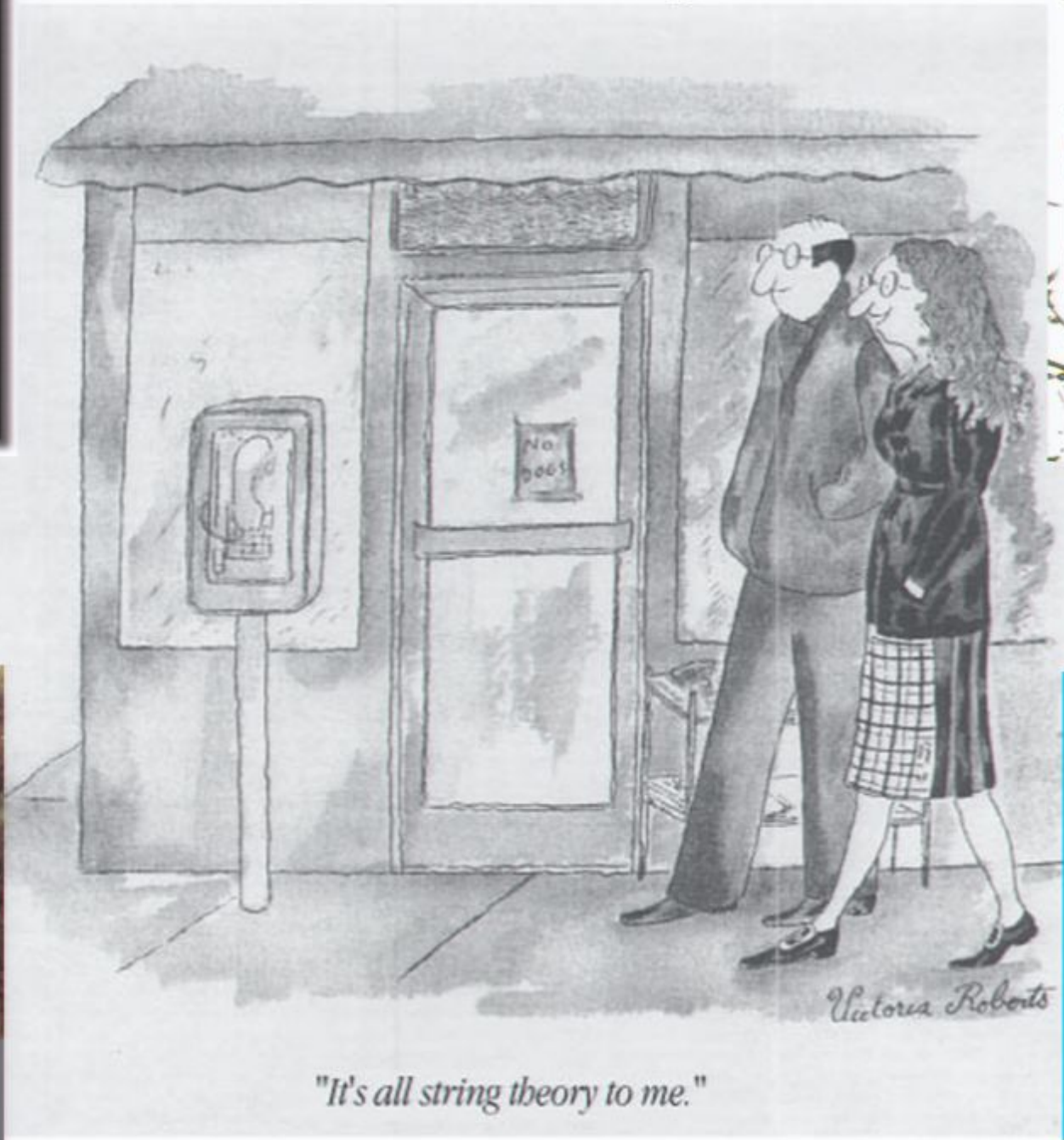
URL: http://pirsa.org/09080054

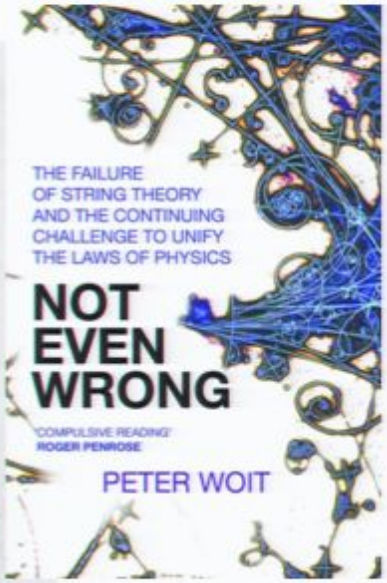
Abstract: Physics emerged from the twentieth century with two remarkably successful descriptions of nature which stand in striking contrast. Quantum mechanics describes the subatomic realm with intrinsic uncertainties and probabilities. On the other hand, Einstein's general relativity describe gravitational 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.

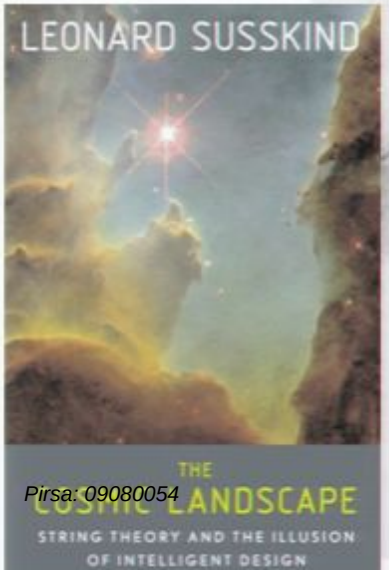

PERIMETER INSTITUTE
FOR THEORETICAL PHYSICS
The Superstring Adventure
Robert Myers
(ISSYP: August 18, 2009)

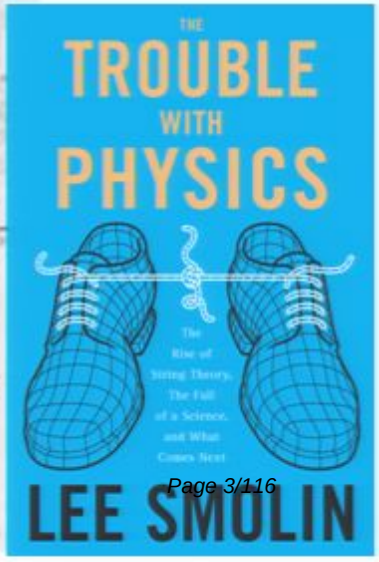
New Yorker magazine:



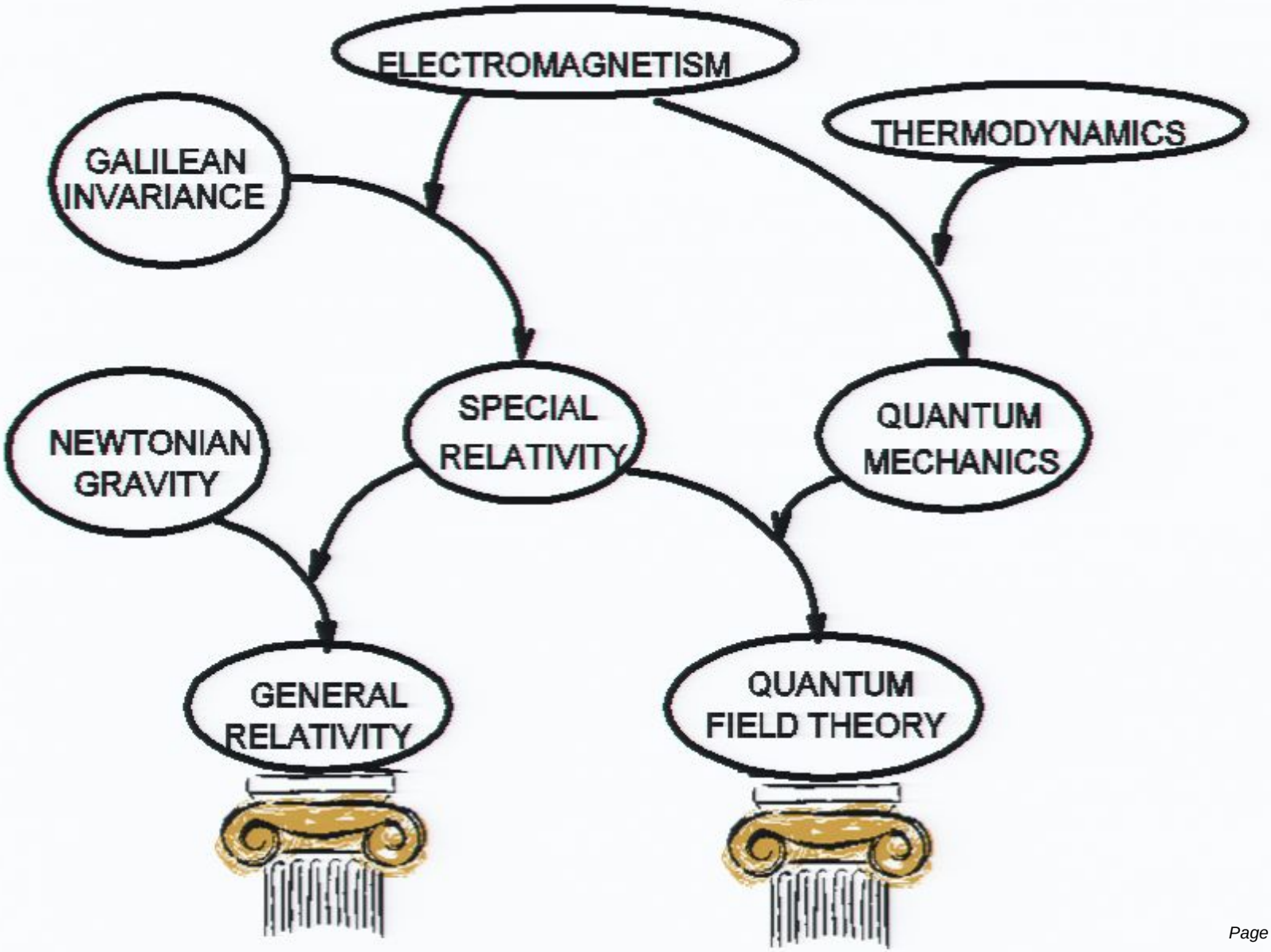








Physics of the 20th century: A grand synthesis and progression of ideas!



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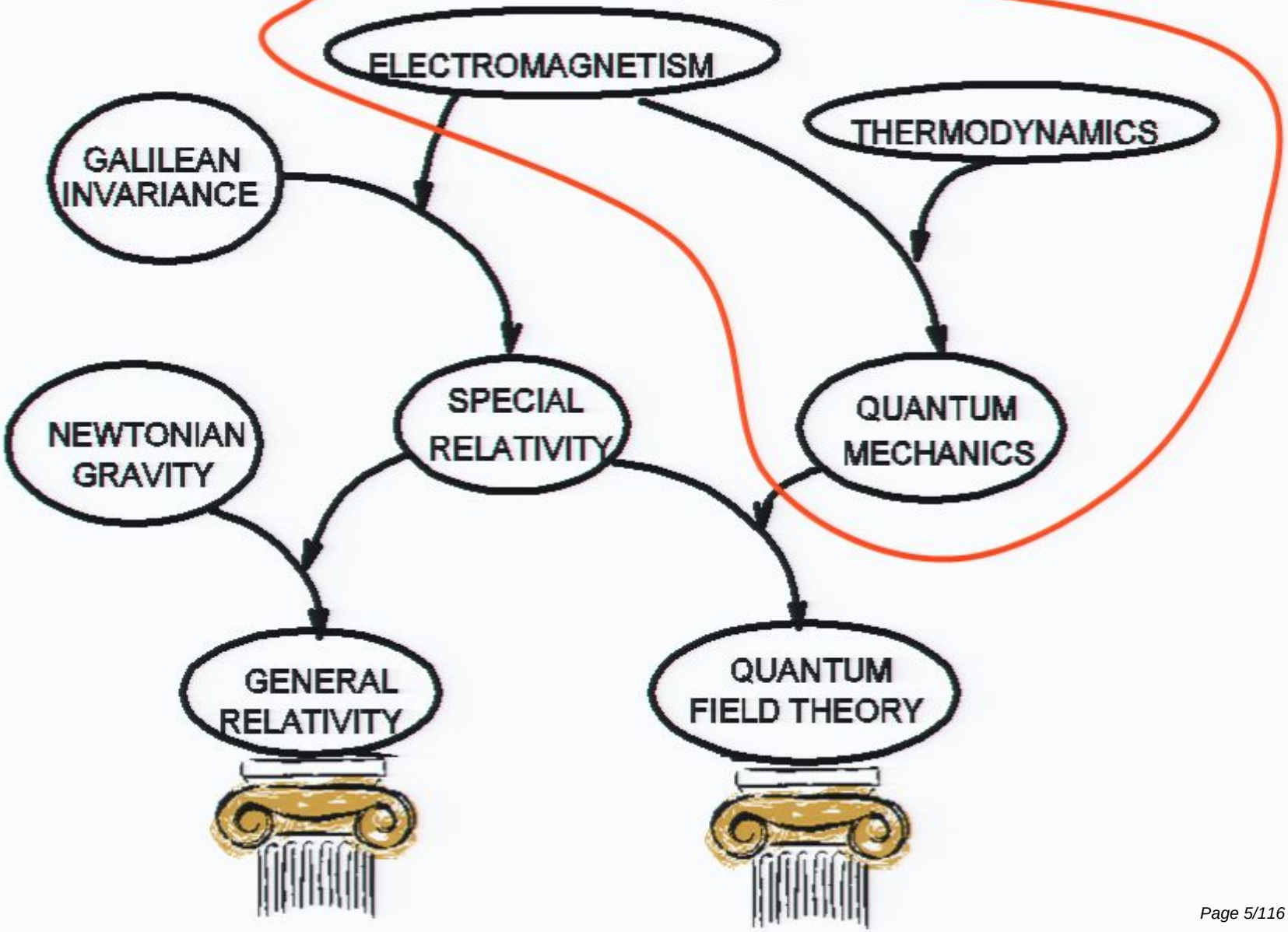
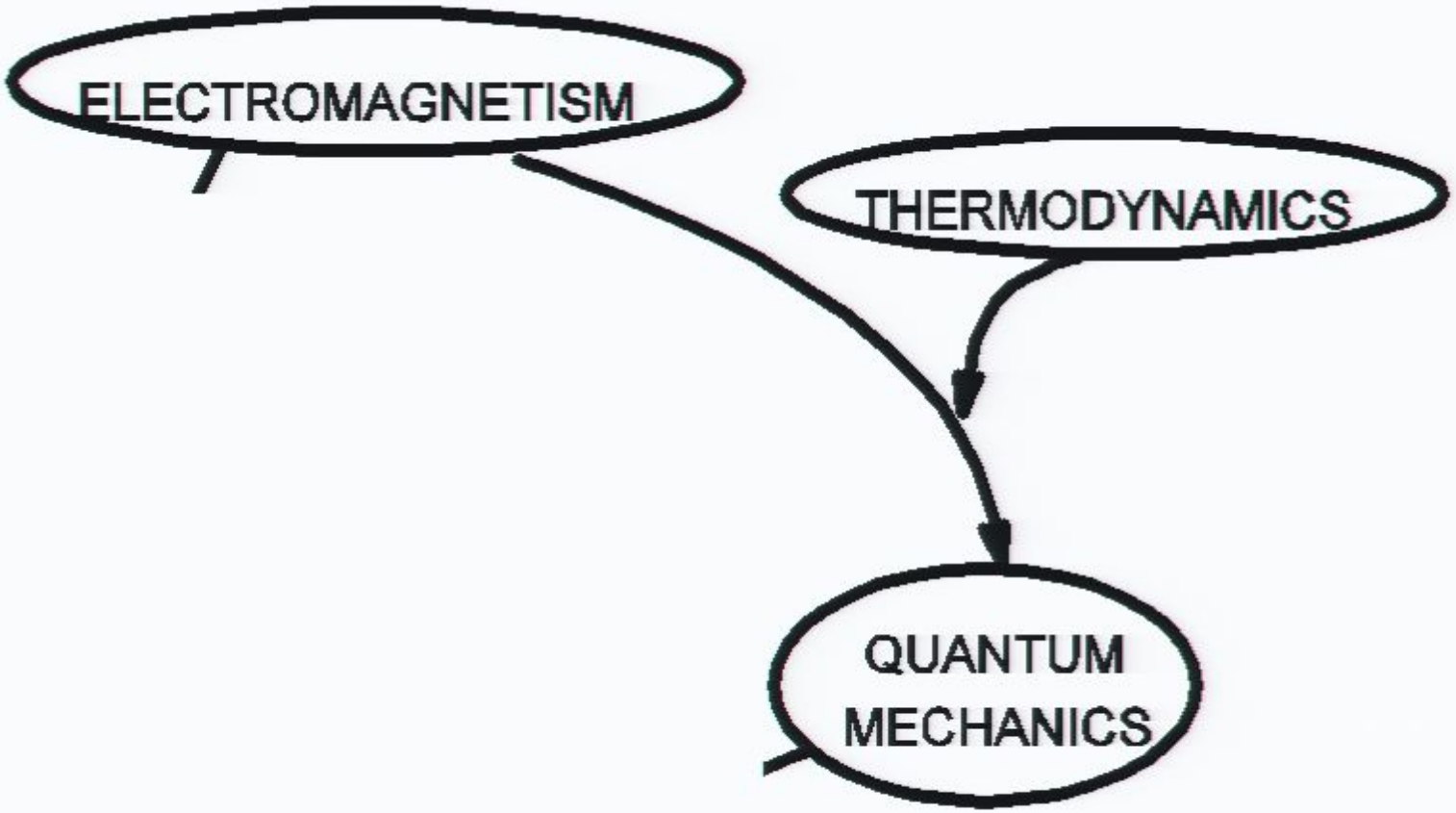
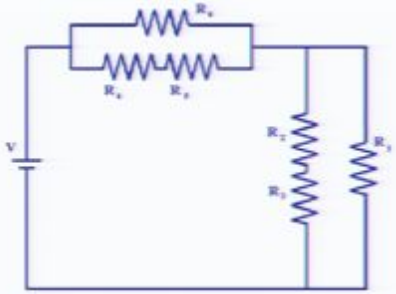



ELECTROMAGNETISM
THERMODYNAMICS
QUANTUM
MECHANICS

ELECTROMAGNETISM

THERMODYNAMICS

QUANTUM MECHANICS



ELECTROMAGNETISM

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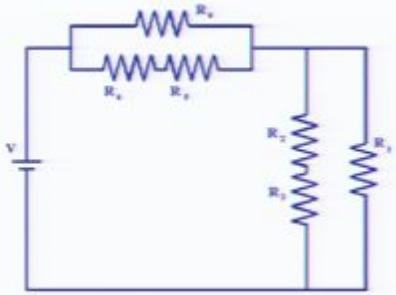

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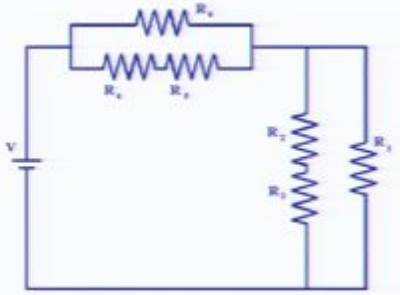

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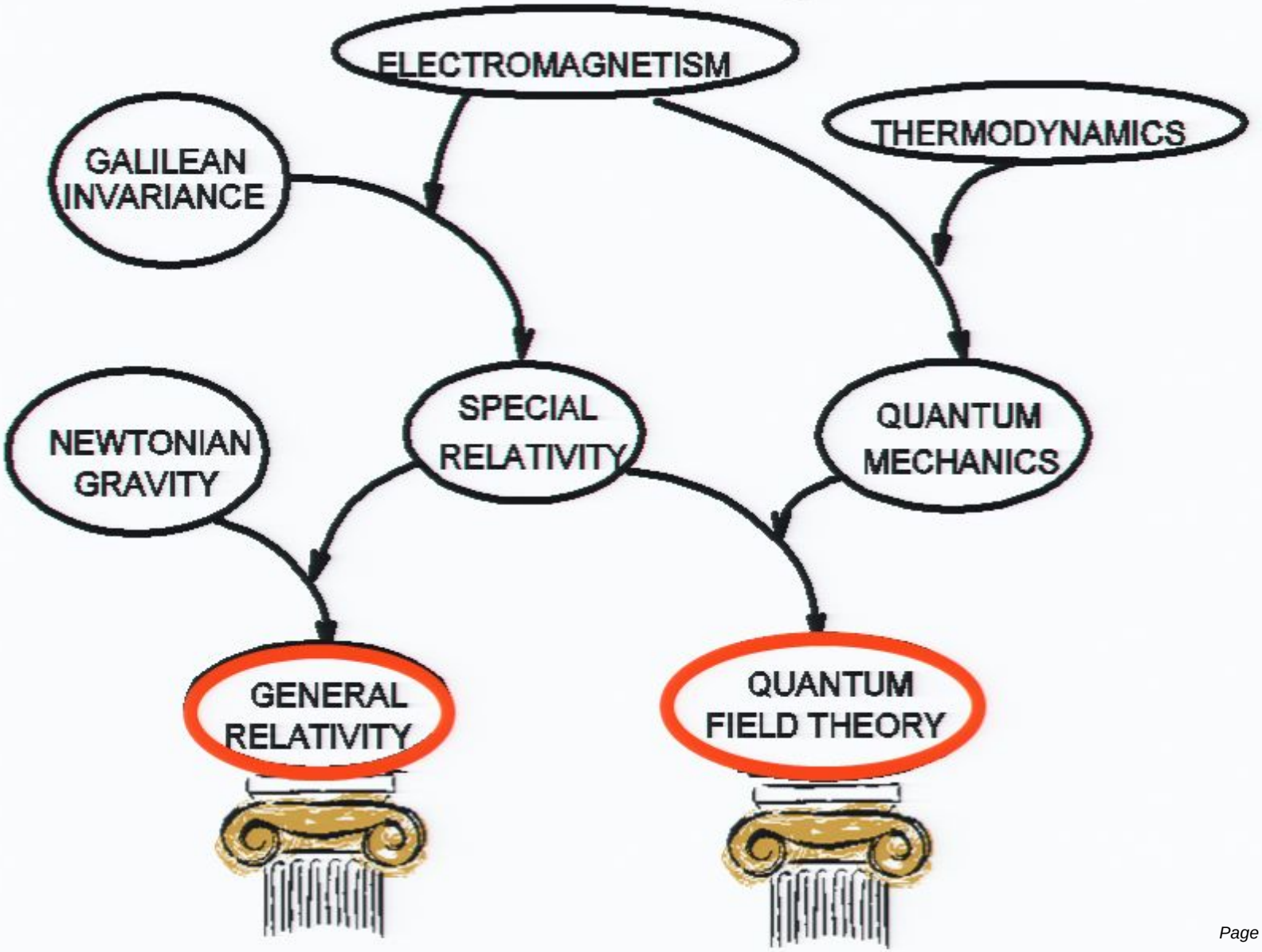
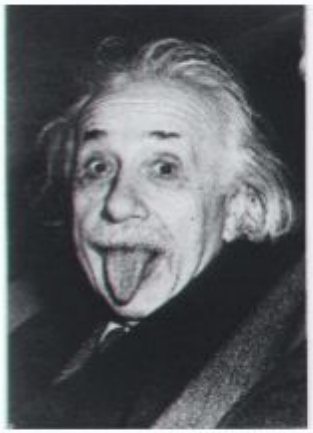


Einstein:



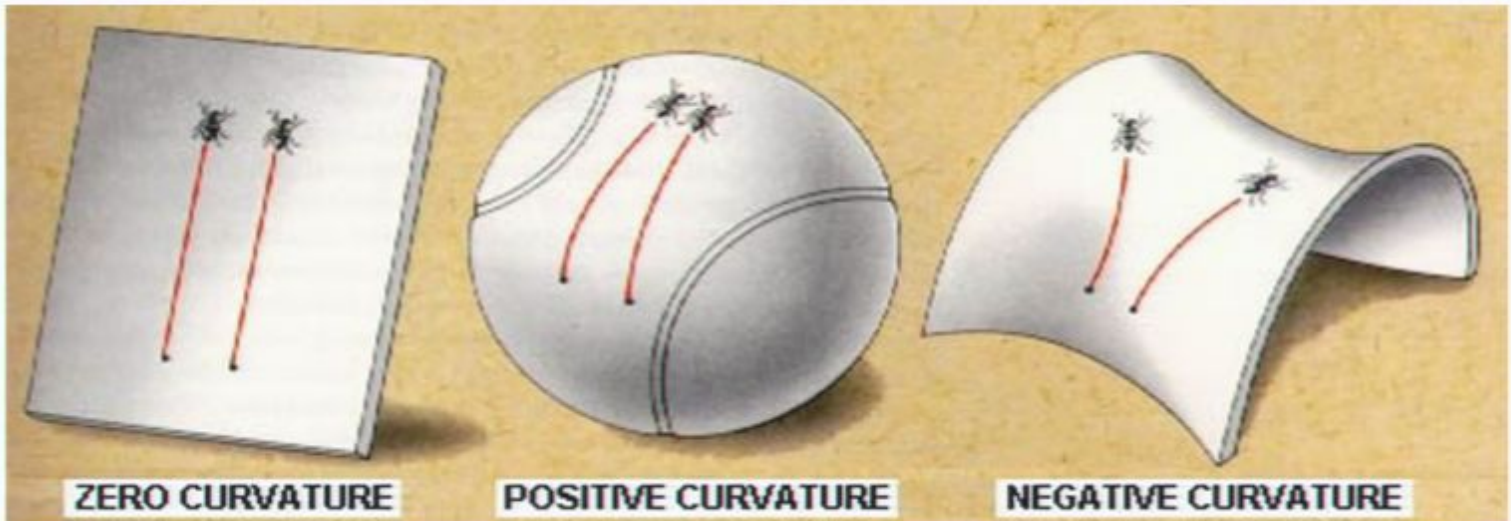
Gravity: It's all just straight lines!

Special Relativity (1905):

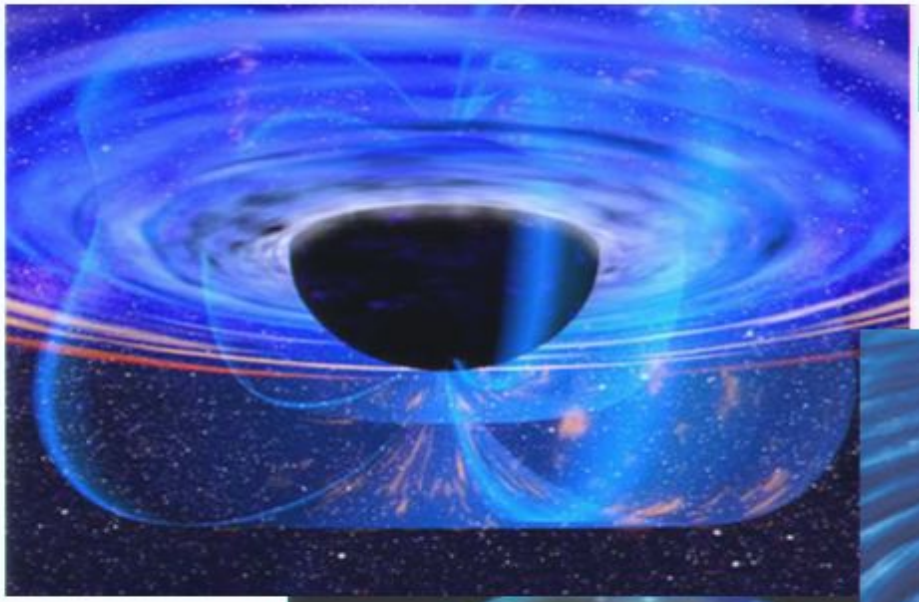
Space and time are inextricably linked ➡ Spacetime

General Relativity (1915):

Gravity is a manifestation of spacetime curvature.

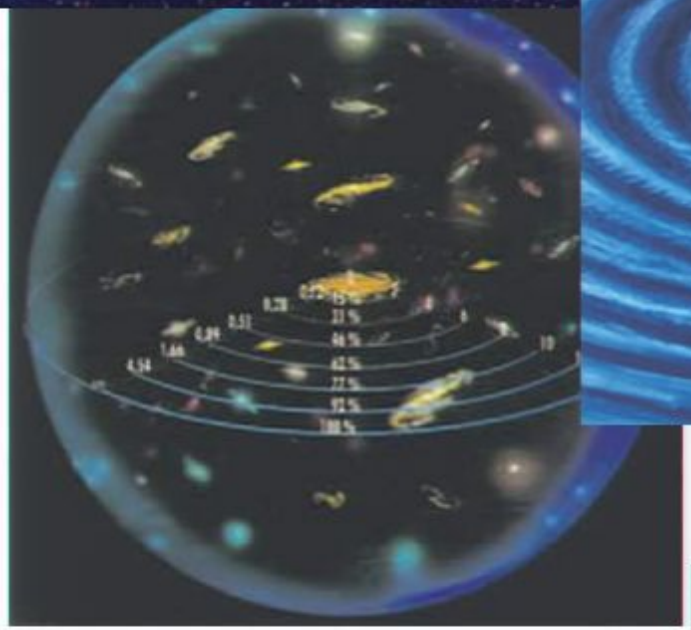


General Relativity: a rich source of new ideas



Black holes

Gravitational waves

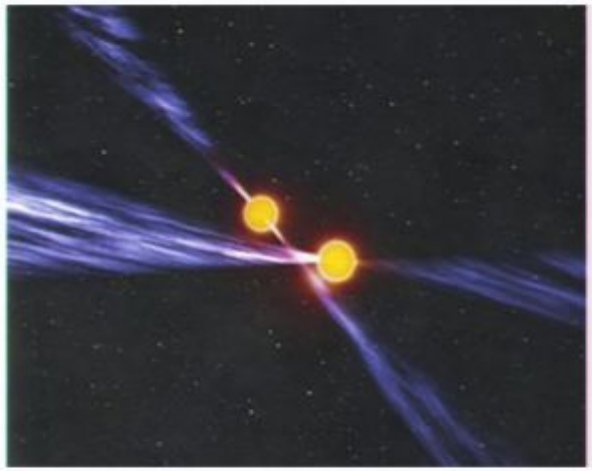


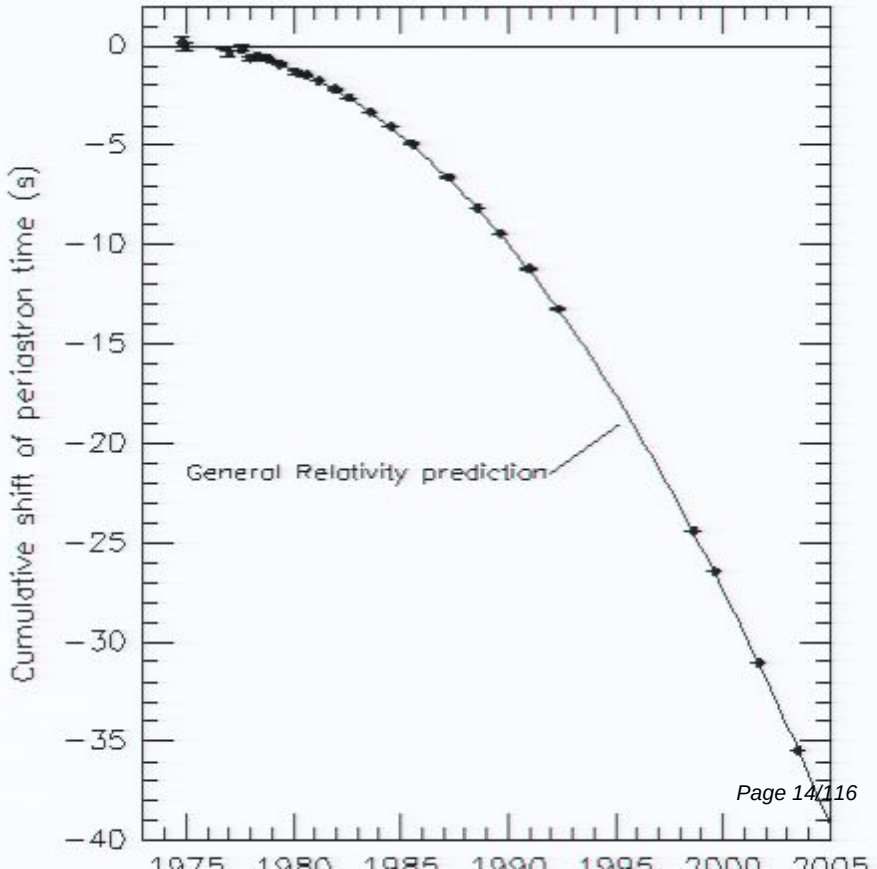
Expanding universe

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!!

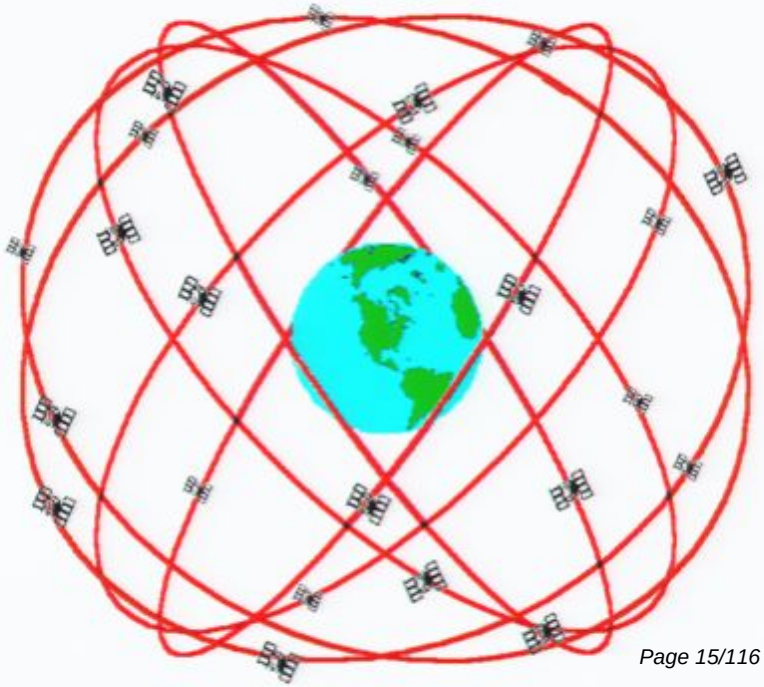




General Relativity is rigorously tested!!

Global Positioning System (GPS):

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



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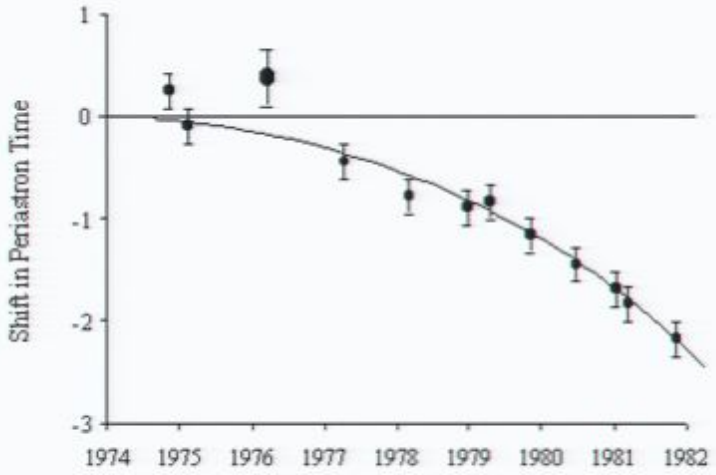
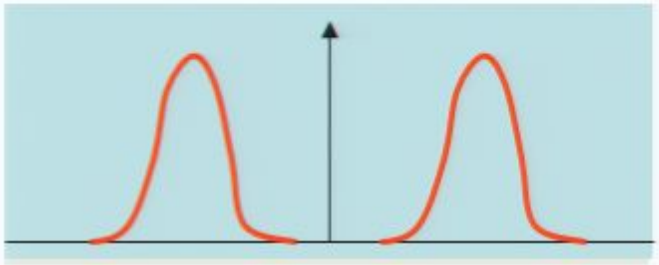


General Relativity is the geometric arena of physics on very large scales:

planets, stars, galaxies, cosmology

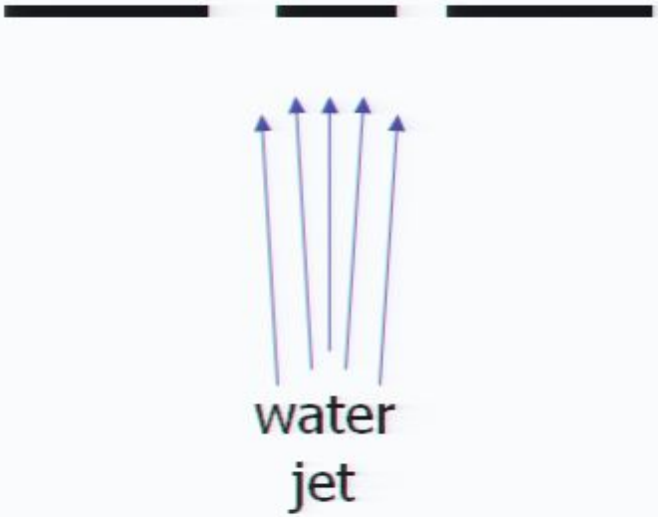
Quantum Mechanics (or Quantum Field Theory) is the probabilistic arena of physics on very small scales

Particles can act like waves!



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

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



Positions are uncertain for the very small !

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

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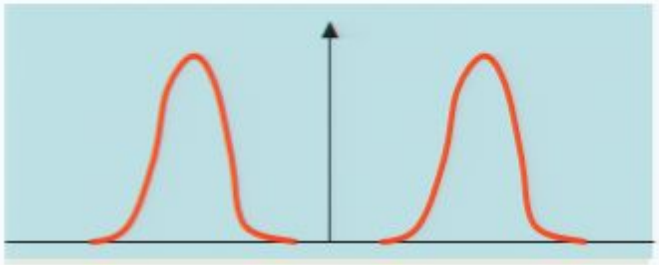

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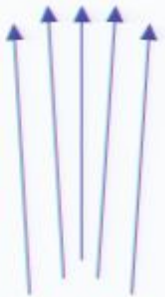
$$\approx .000000\cdots000004\,\text{m}$$

30 digits



water jet

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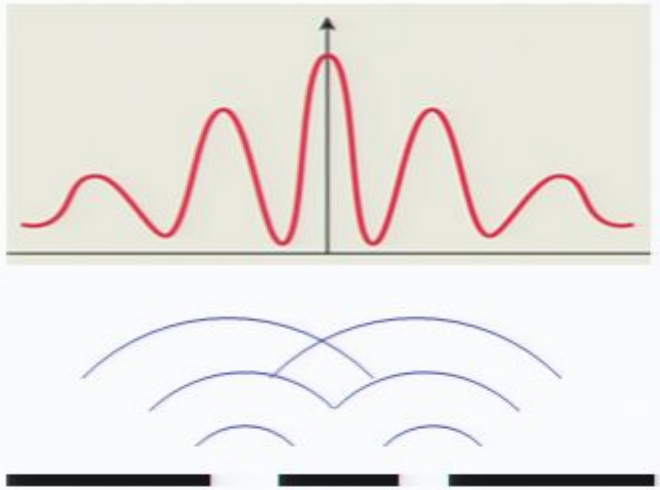
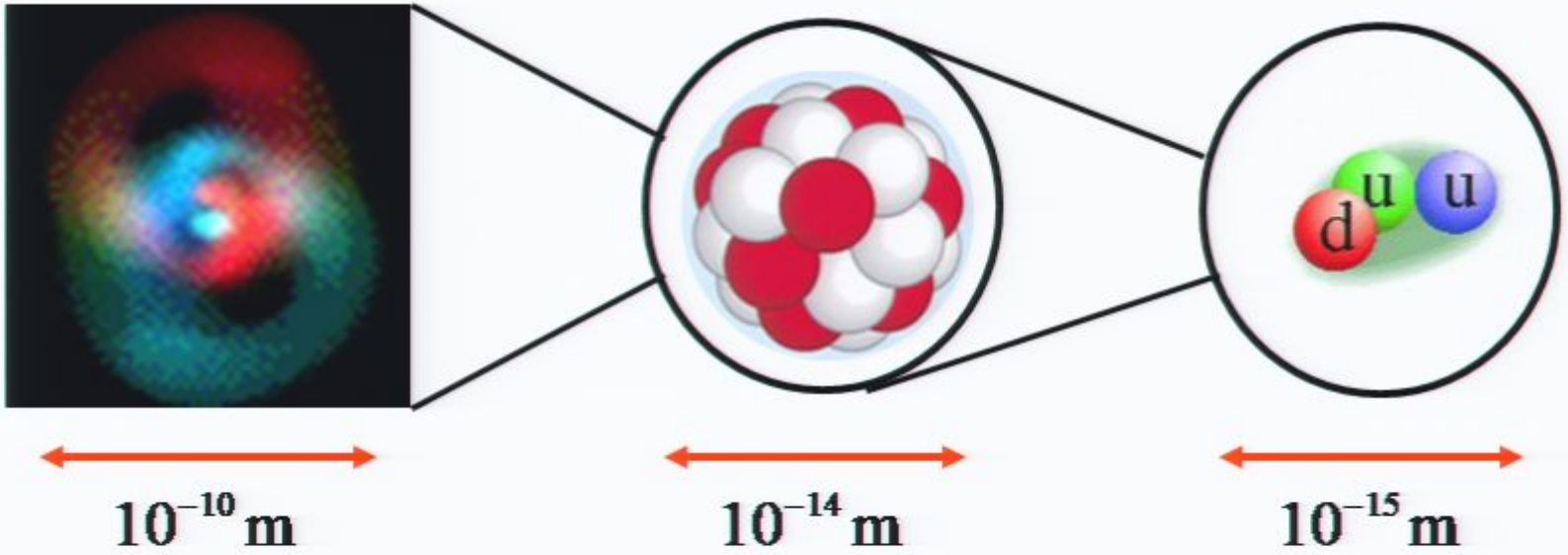


$$\lambda_{\text{rain drop}} \approx 4\times10^{-30}\,\text{m}$$

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

Quantum fluctuations are manifest in behavior of subatomic particles

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



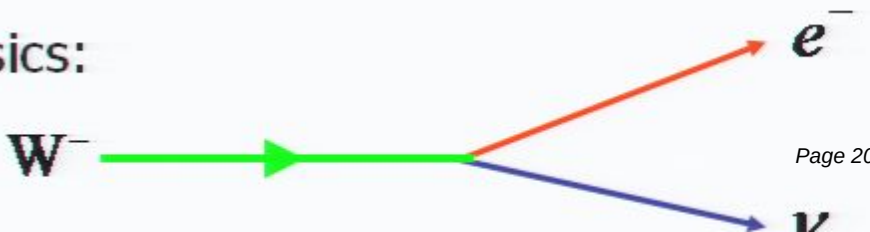
Elementary Particles (10^{-17} m)

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

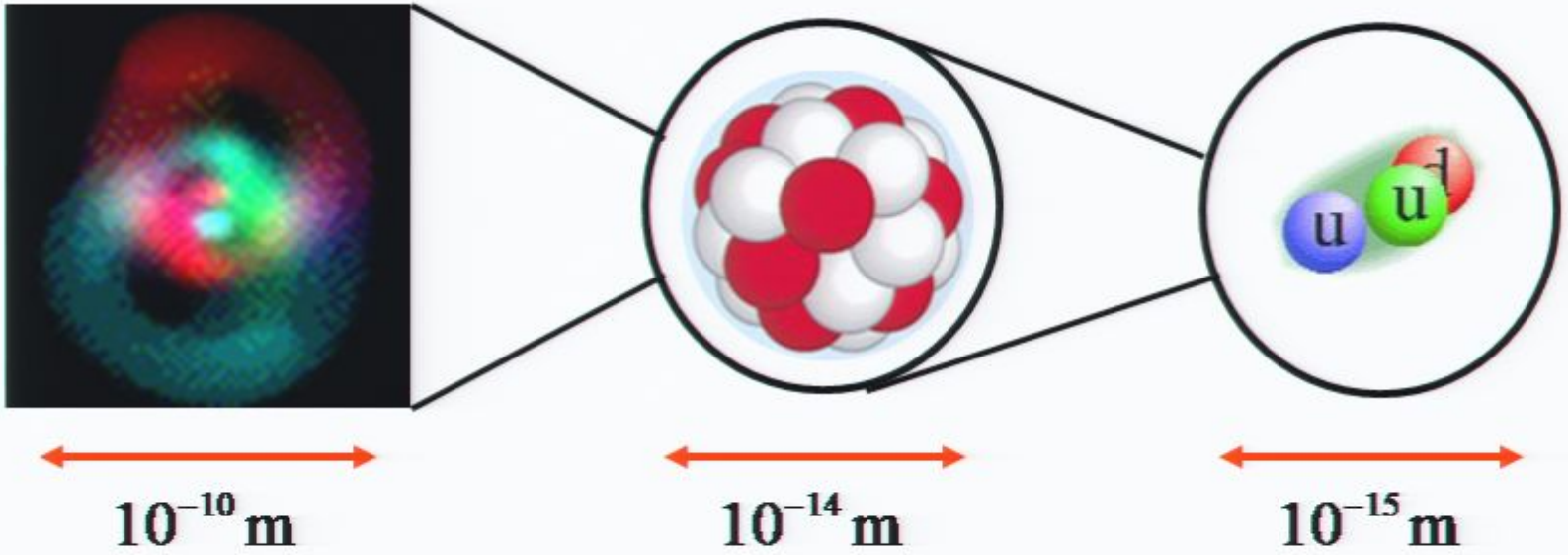
Bosons (Force Mediators):
- photon (electromagnetism)
- gluon (strong)
- $W^{\pm}$, Z (weak)
- Higgs particle

Standard Model of Subatomic Physics:

above particles plus interactions
(and ~20 free parameters)



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



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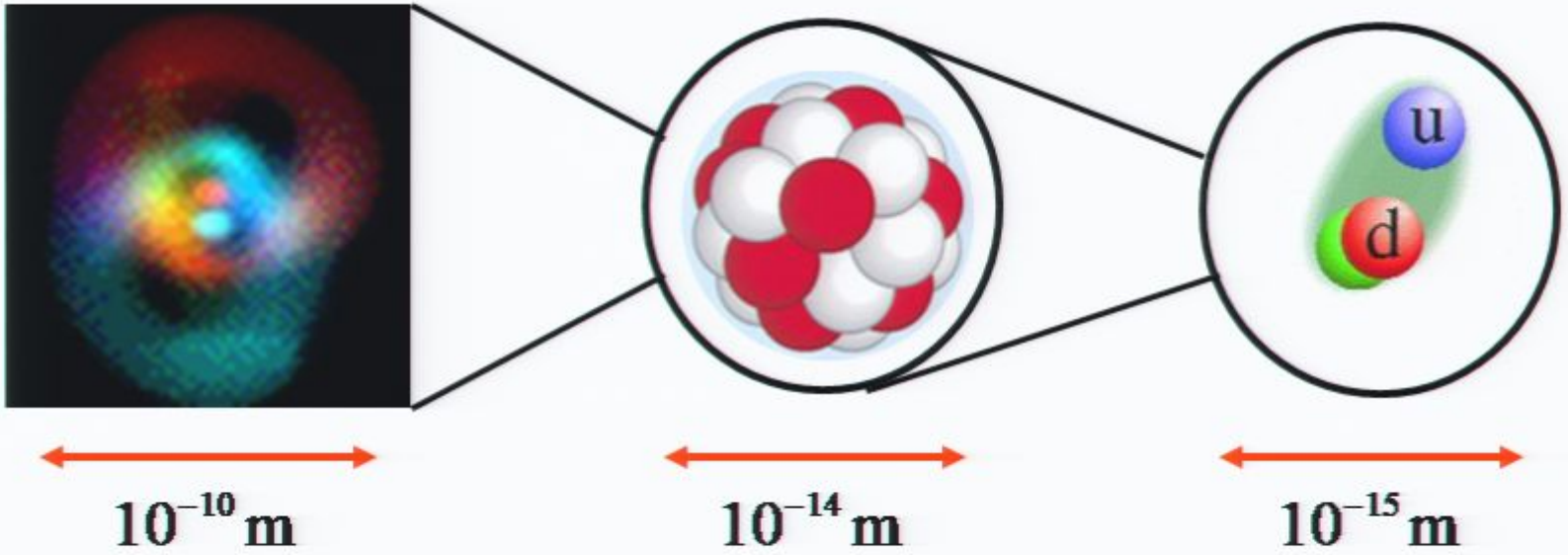

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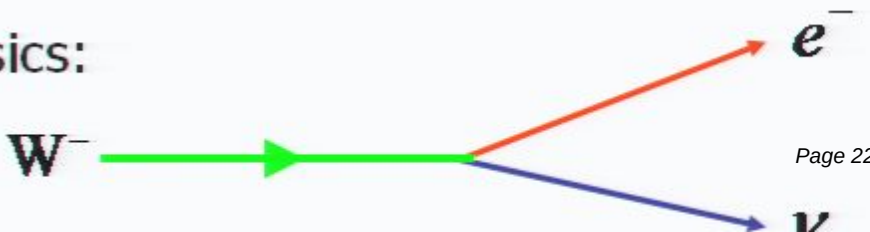

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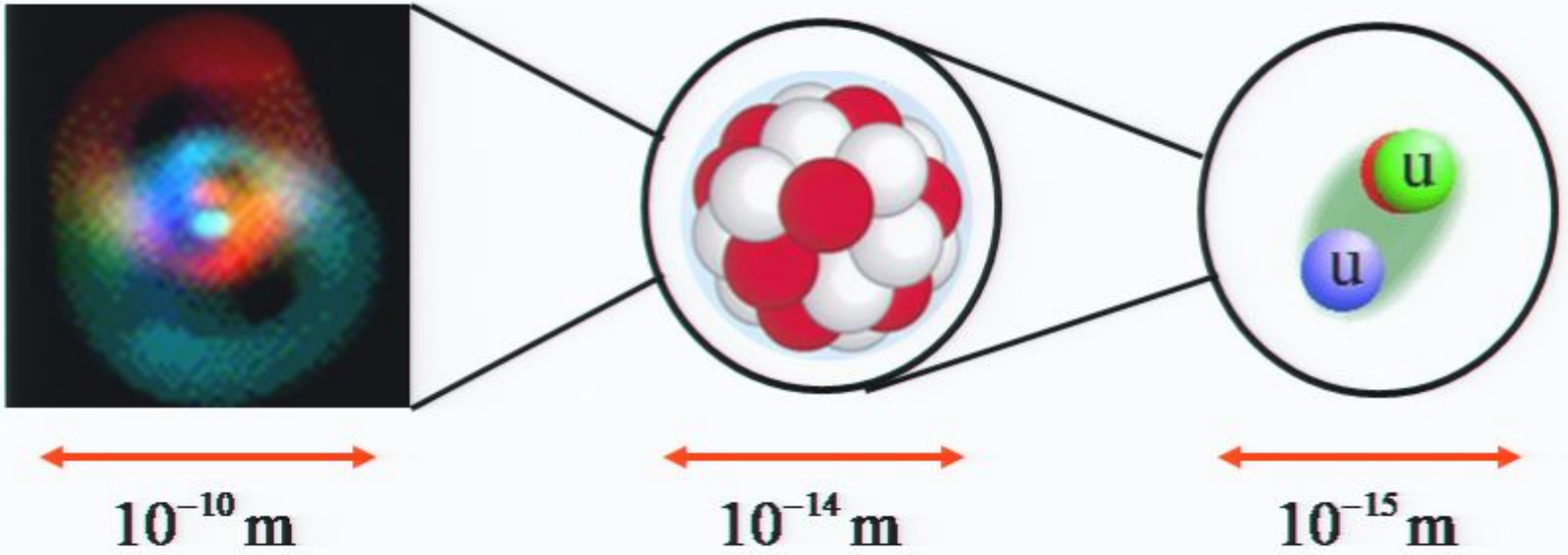

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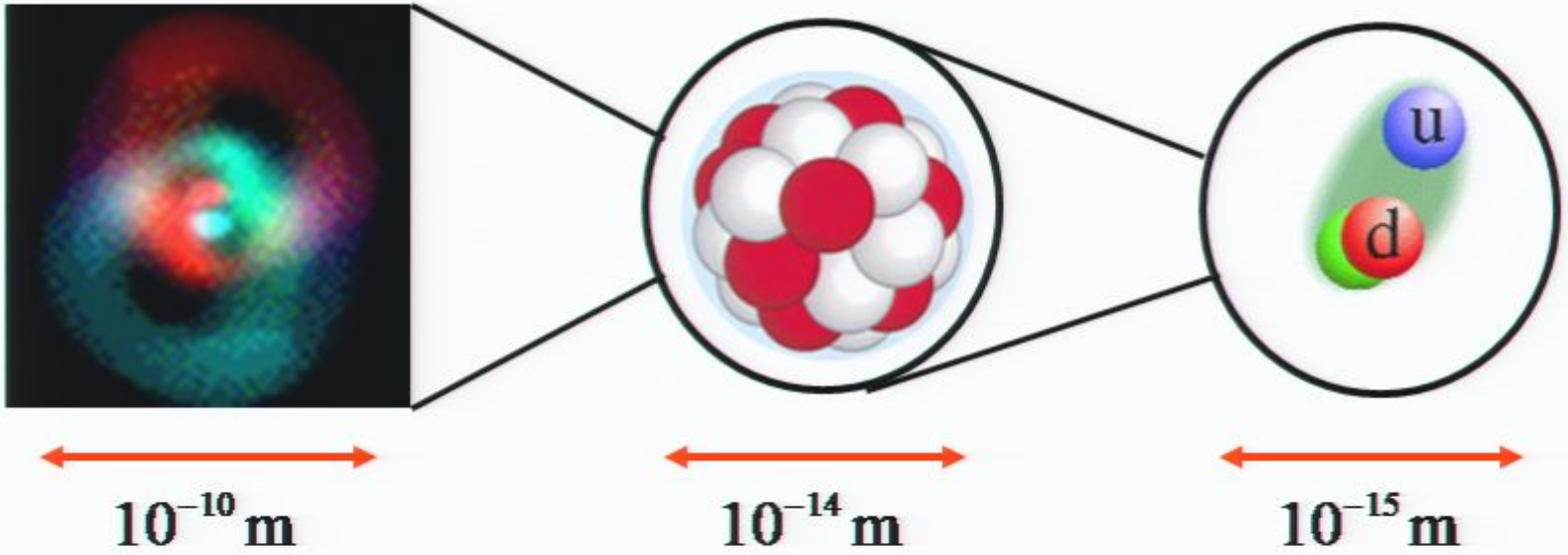

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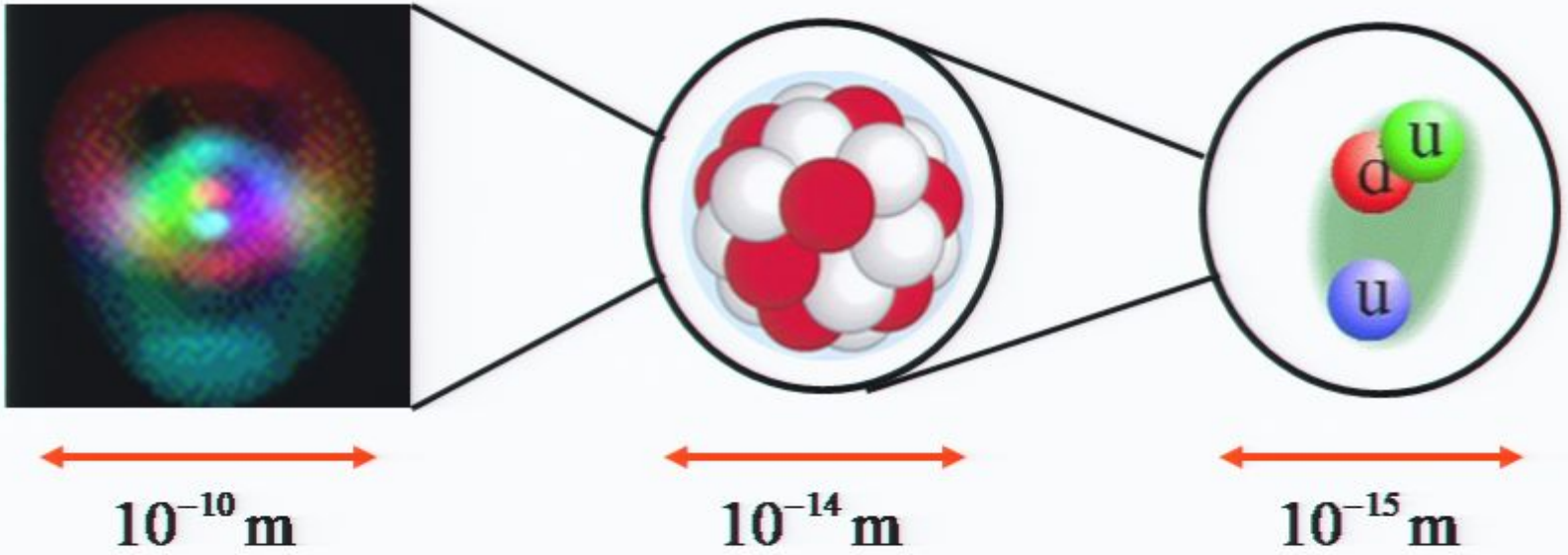

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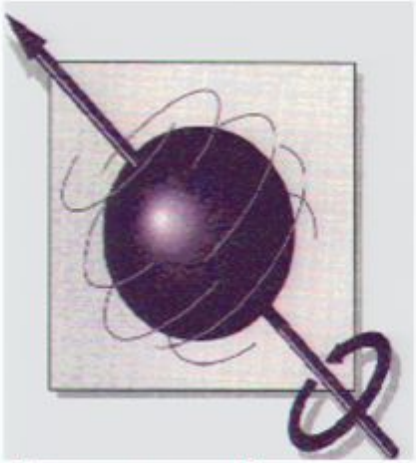
Quantum theory is rigorously tested!!

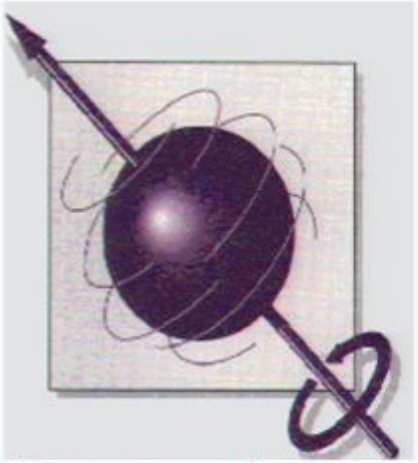


Example: electrons are tiny magnets

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

precise value of magnetic moment depends on quantum fluctuations

Quantum theory is rigorously tested!!



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

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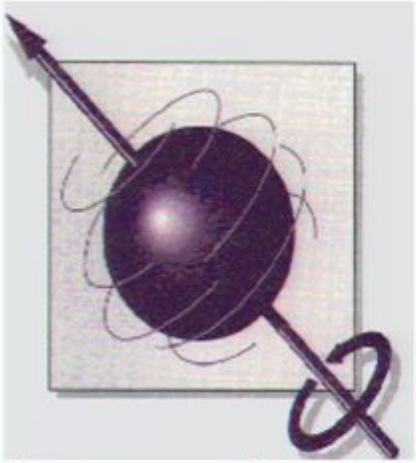

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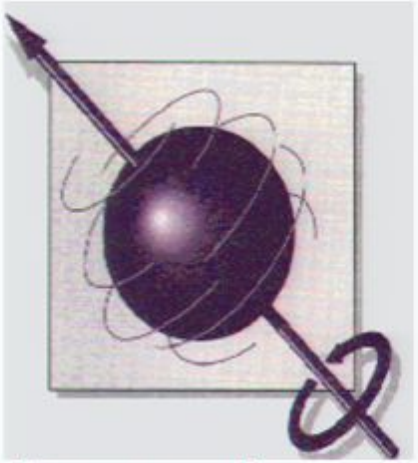
$$\mu_{\text{measured}} = 2.00231930437\,38$$

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

Quantum theory is rigorously tested!!



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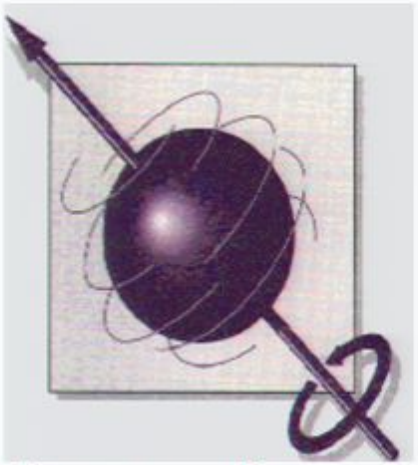
$$\mu_{\text{calculated}} = 2.00231930430\,70$$

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

Quantum theory is rigorously tested!!



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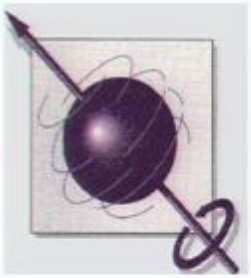
(neither answer absolutely correct)

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

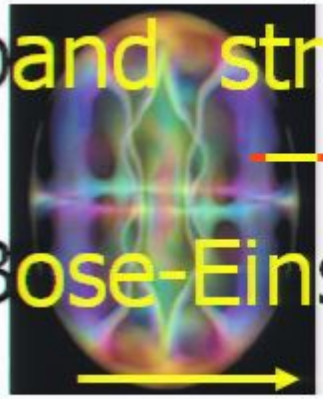
$$\left|\frac{\mu_{\text{theory}} - \mu_{\text{experiment}}}{\mu_{\text{experiment}}}\right| \leq 10^{-10}$$



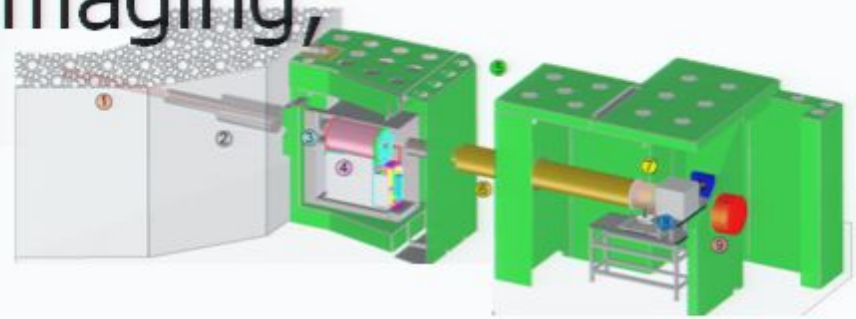
e.g., Lamb shift: shift between $2S_{1/2}$ and $2P_{1/2}$
energy levels of hydrogen atom (f = 1057 MHz)

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

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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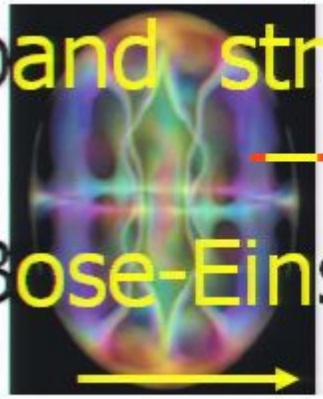

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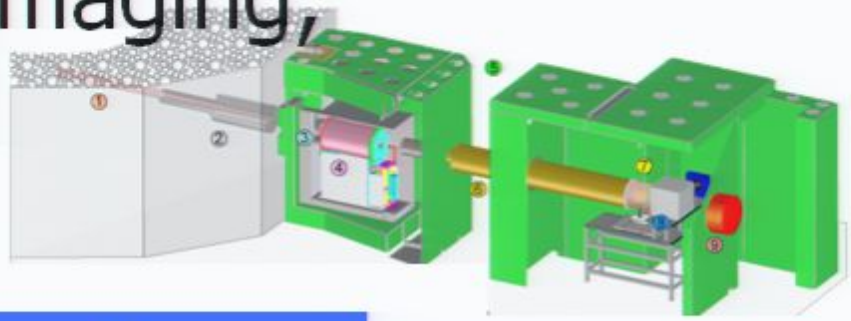
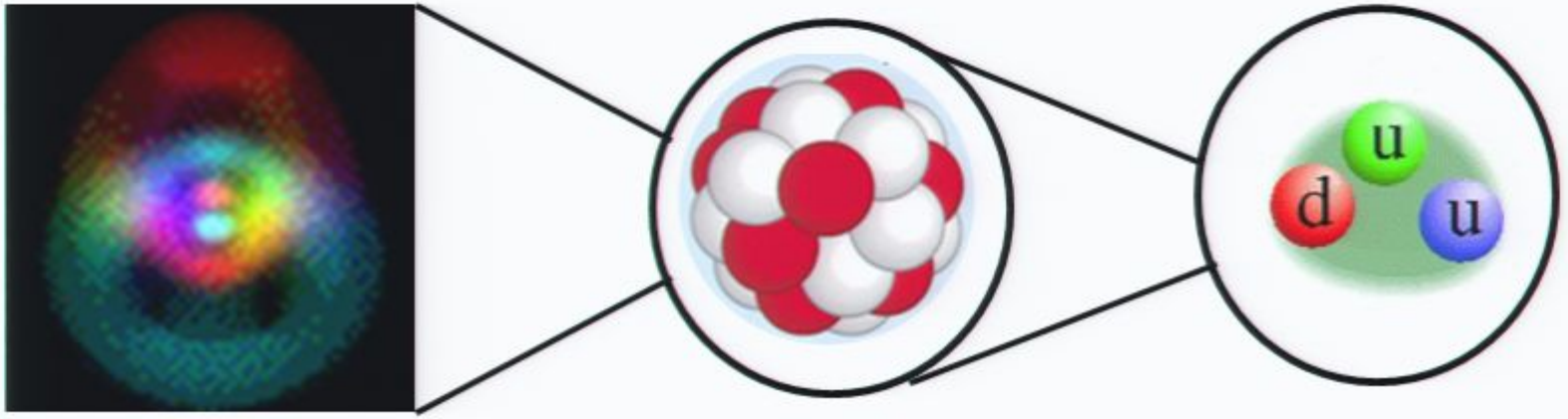


Nobel prizes galore!!

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)
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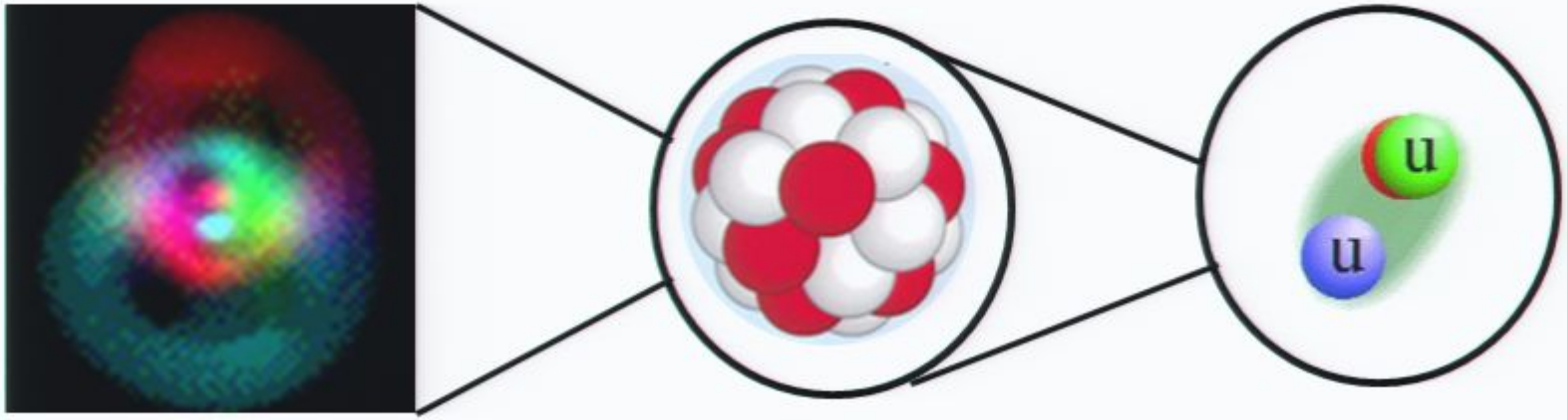
- $W^{\pm}$, Z (weak)
- Higgs particle

Subatomic Physics ⟶ a theory of strings!



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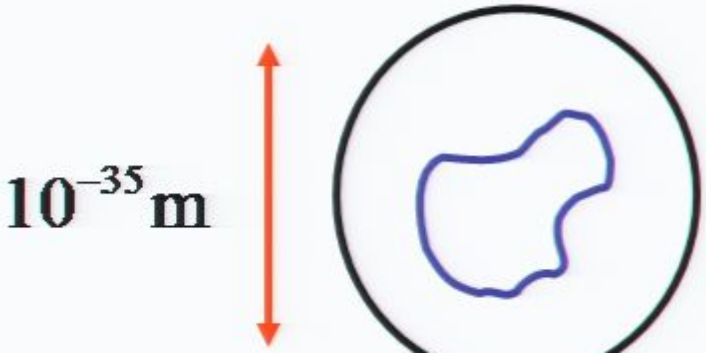
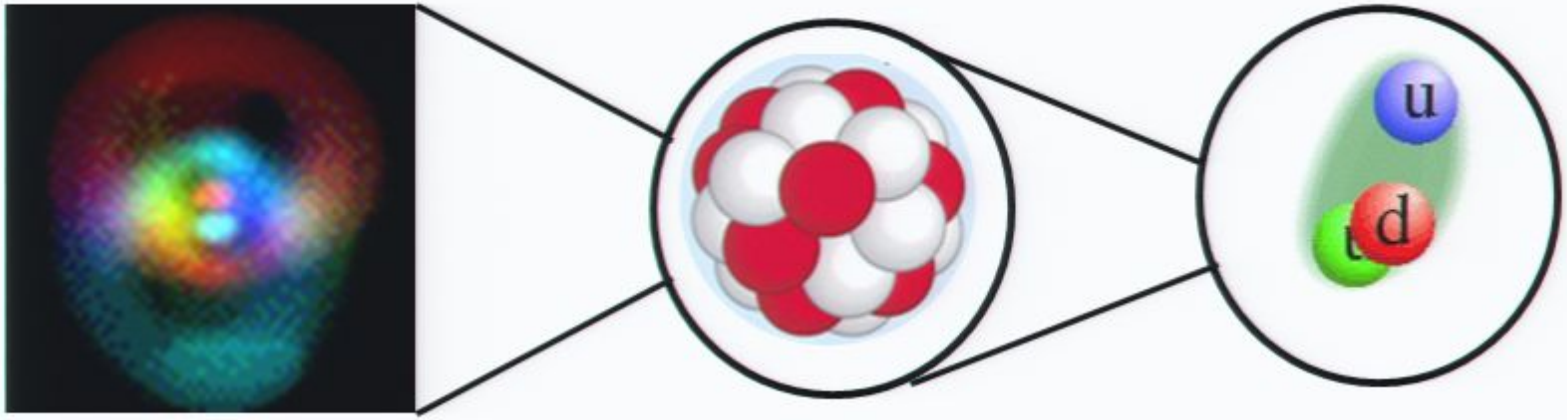


Strings tame the particle zoo!

Subatomic Physics → a theory of strings!



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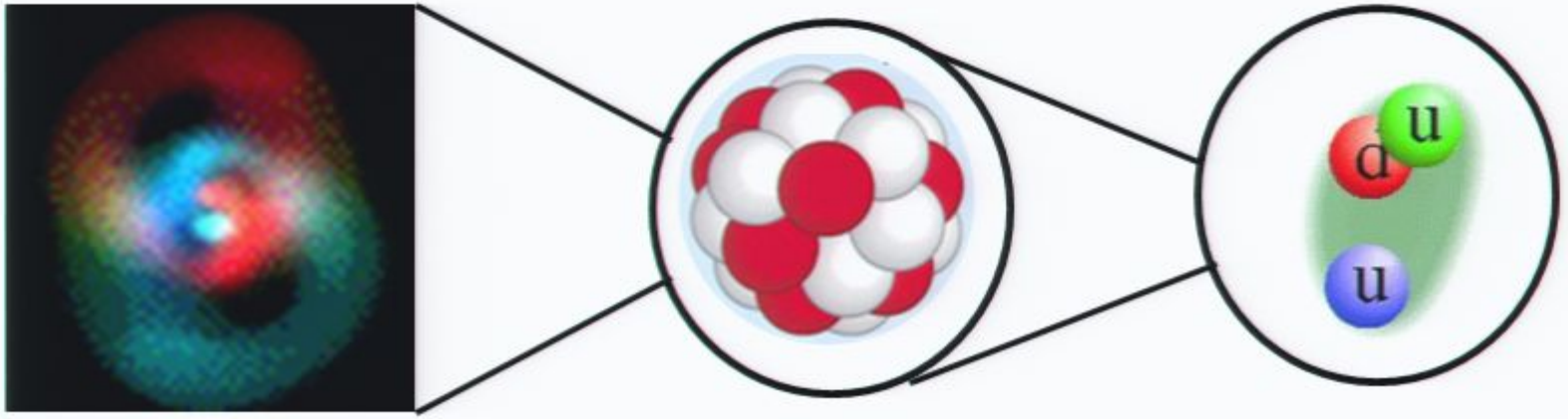

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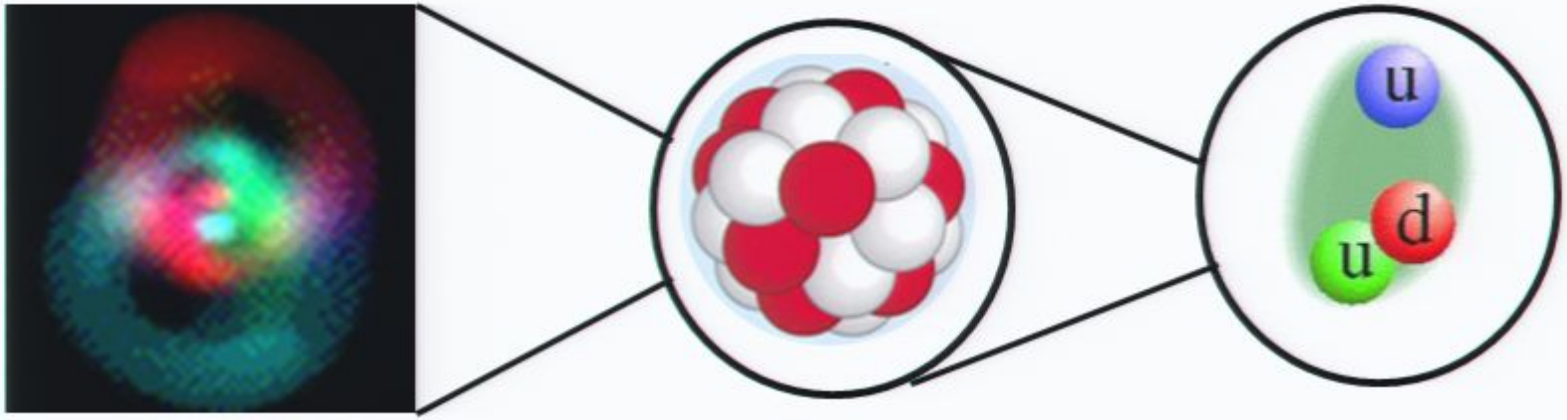

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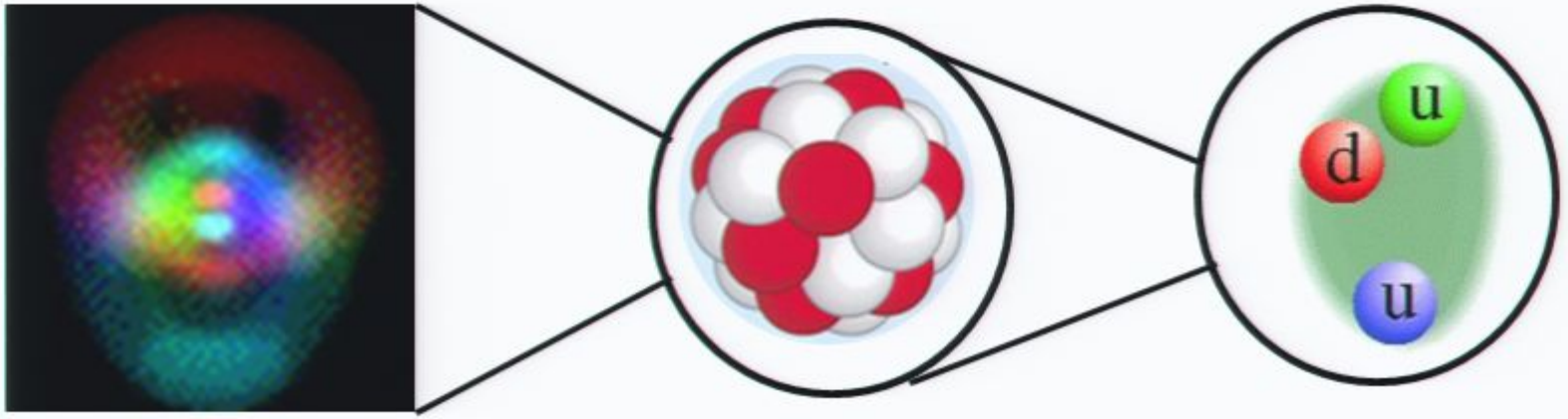

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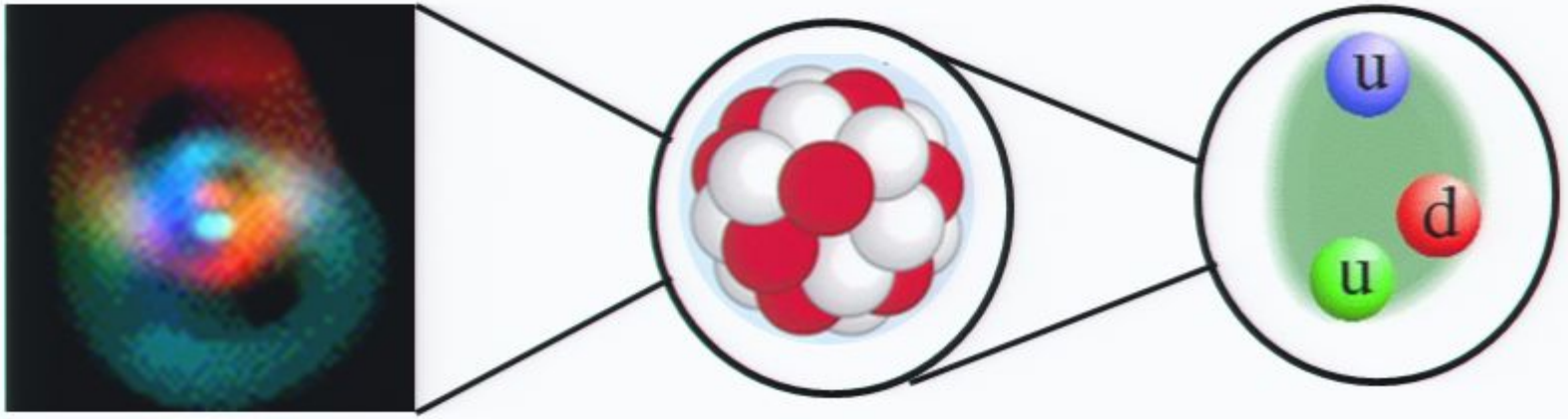

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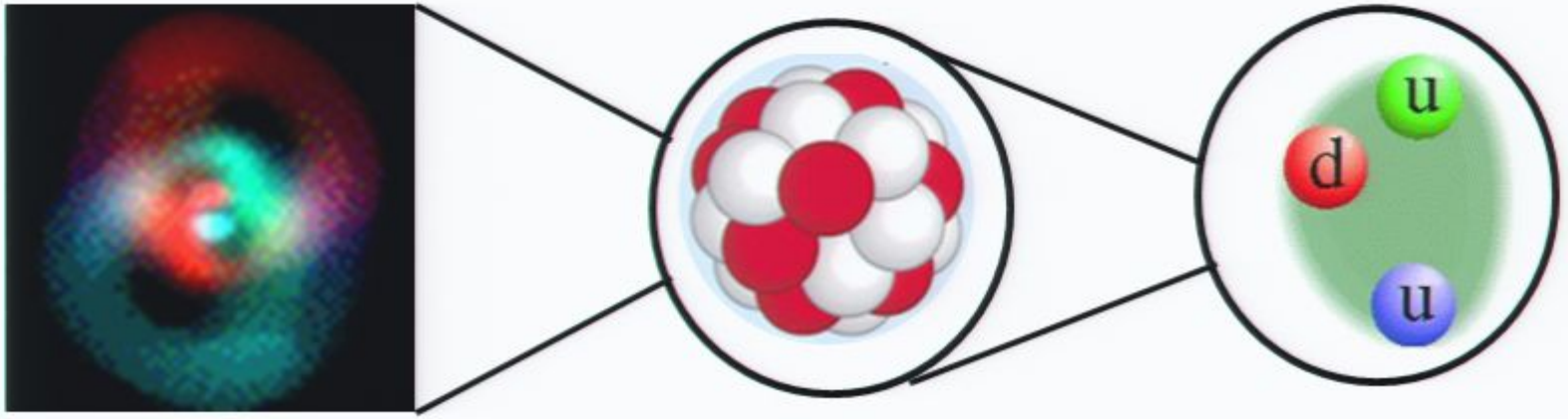

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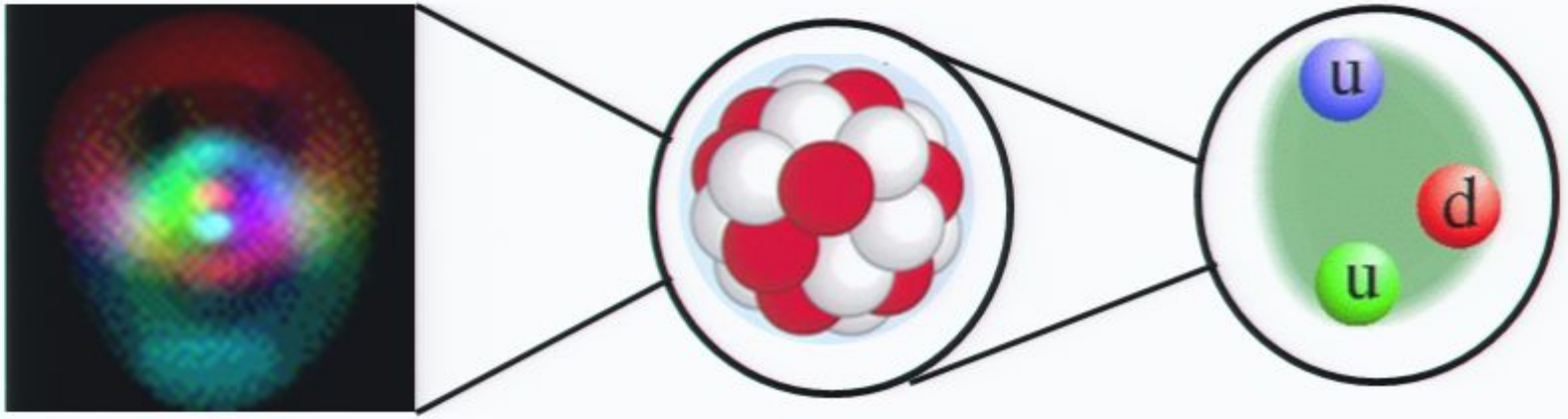

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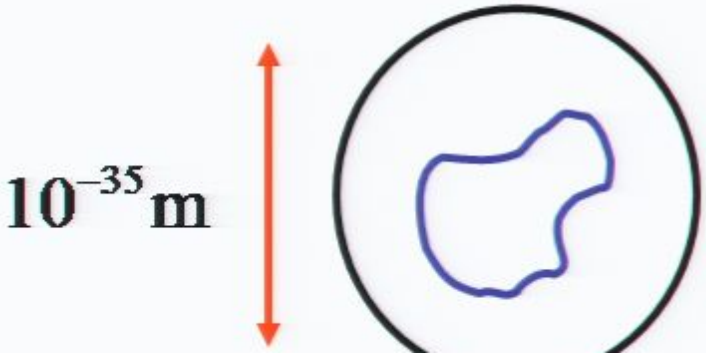

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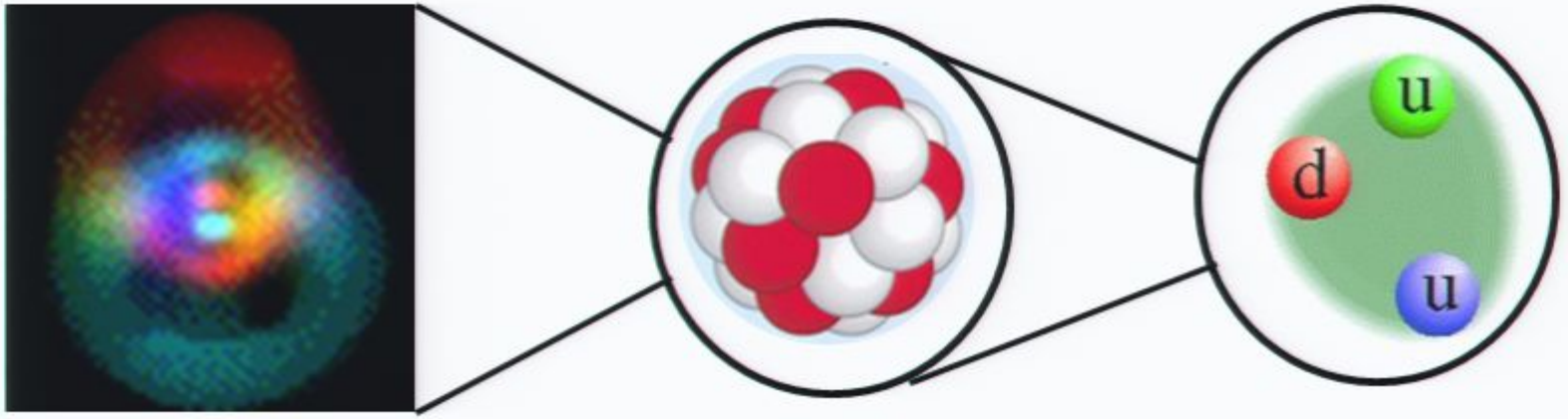

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Superstrings: the theory of subatomic physics

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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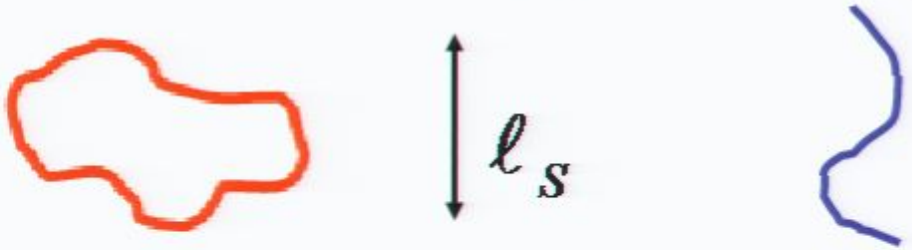

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the typical size of the strings is the fundamental scale of the theory, $\ell_s = 10^{-35}\,\mathrm{m}$

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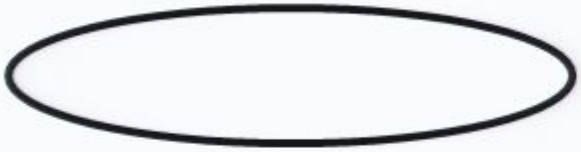
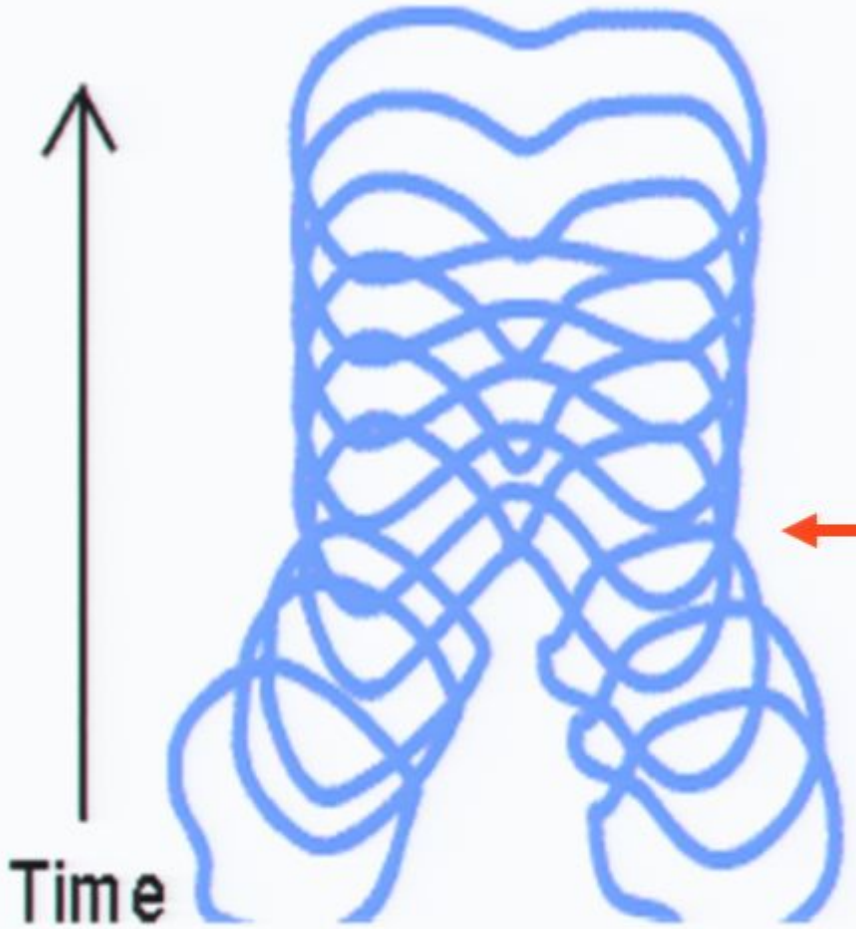
Interactions?





coupling constant, g, determines probability of interaction

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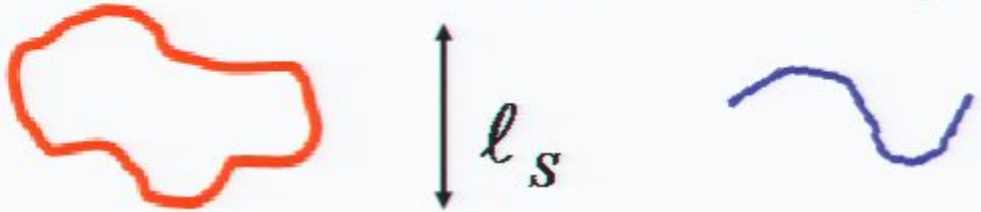
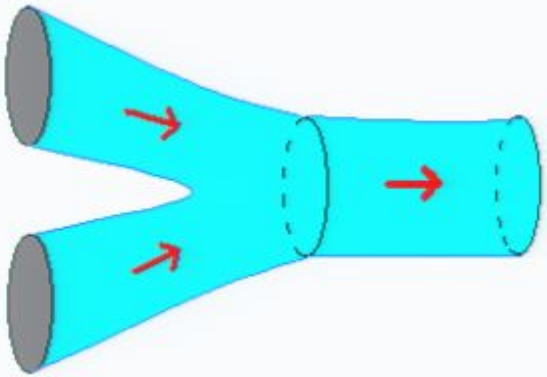
with resolution, $\ell_s = 10^{-35}\,\mathrm{m}$, all elementary particles are one-dimensional objects (strings)

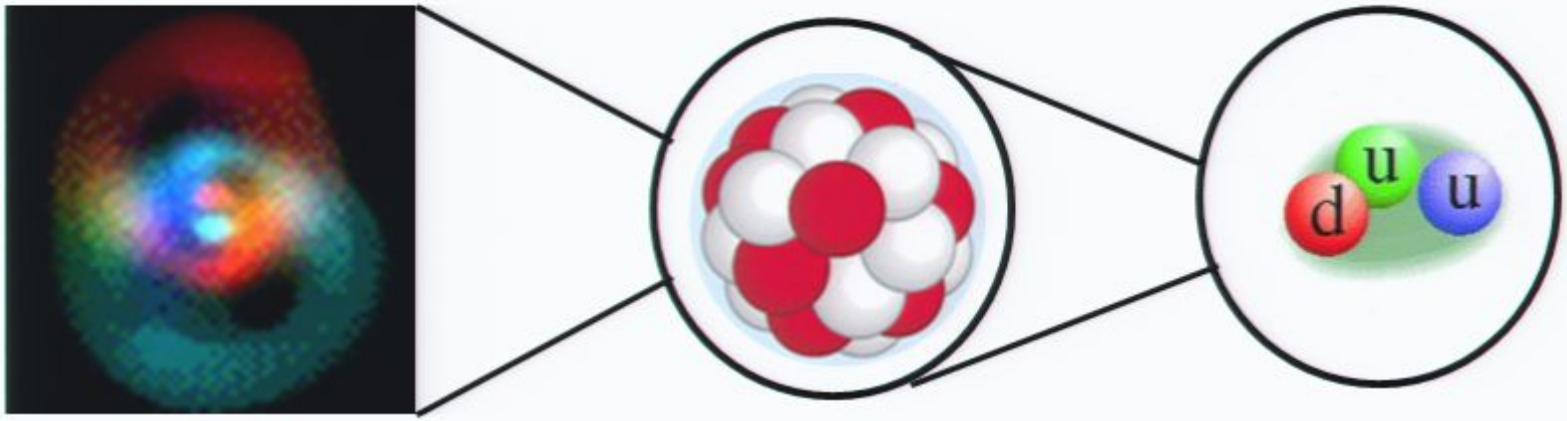


interactions are geometric joining and splitting governed by coupling constant, g



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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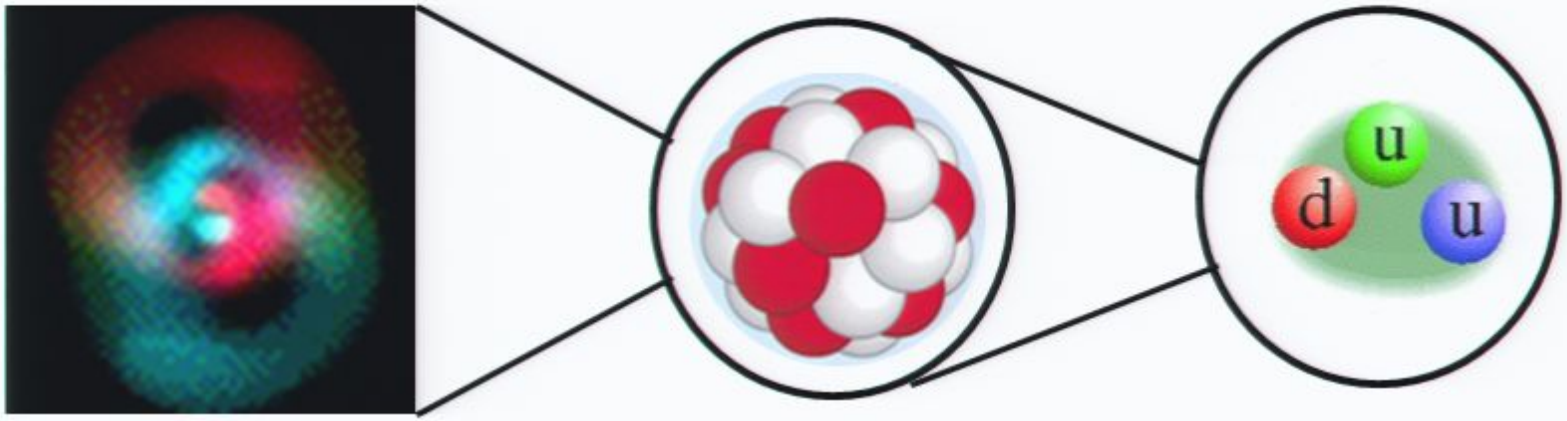

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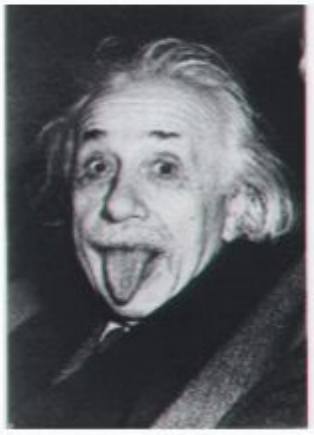
Graviton (gravity!!)



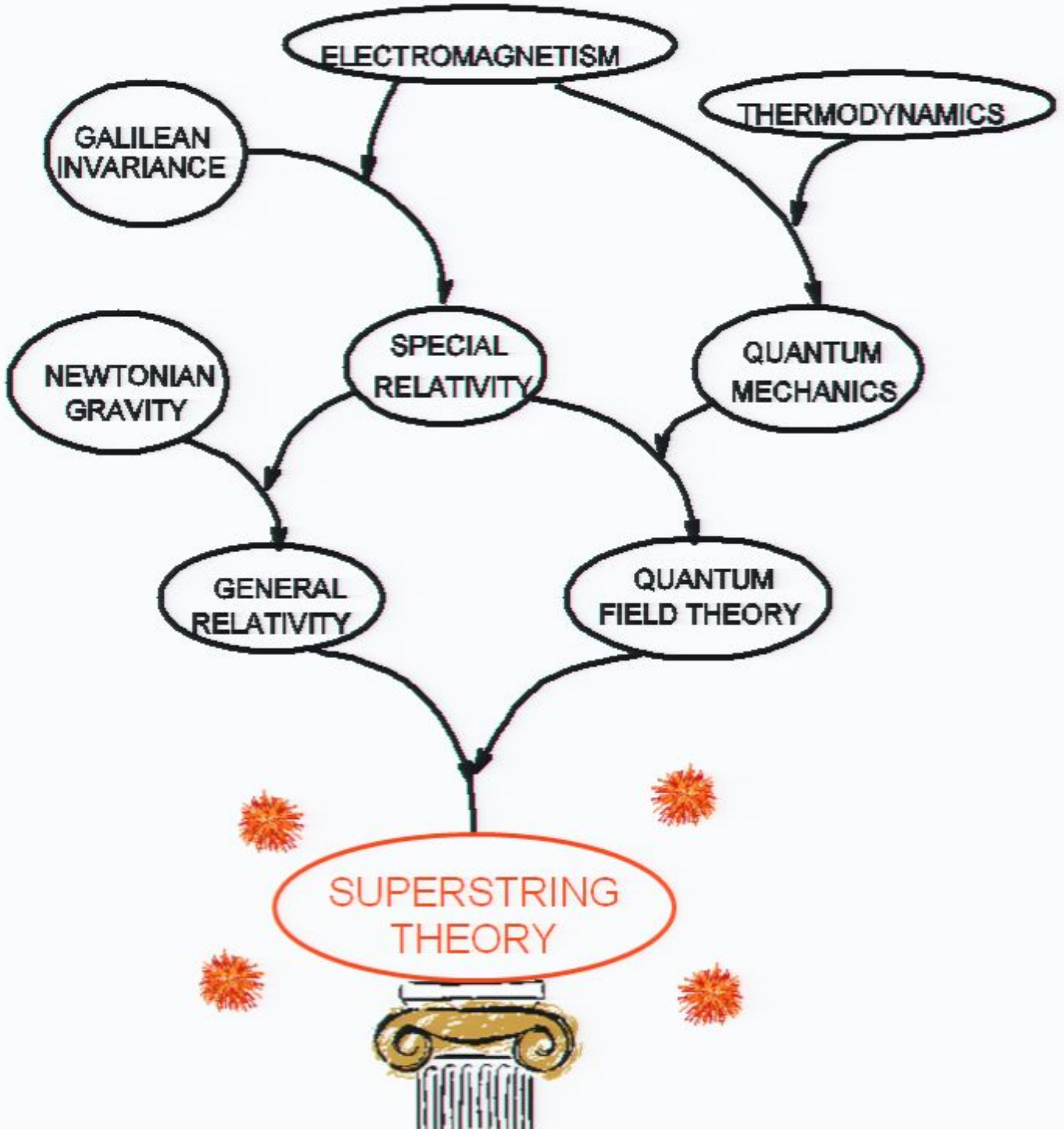
Superstrings: the theory of gravitational physics

consistency requires appearance of the graviton!

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

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

Superstrings naturally provides a unified framework for Quantum Field Theory and General Relativity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THERMODYNAMICS
NEWTONIAN GRAVITY
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QUANTUM MECHANICS
GENERAL RELATIVITY
QUANTUM FIELD THEORY
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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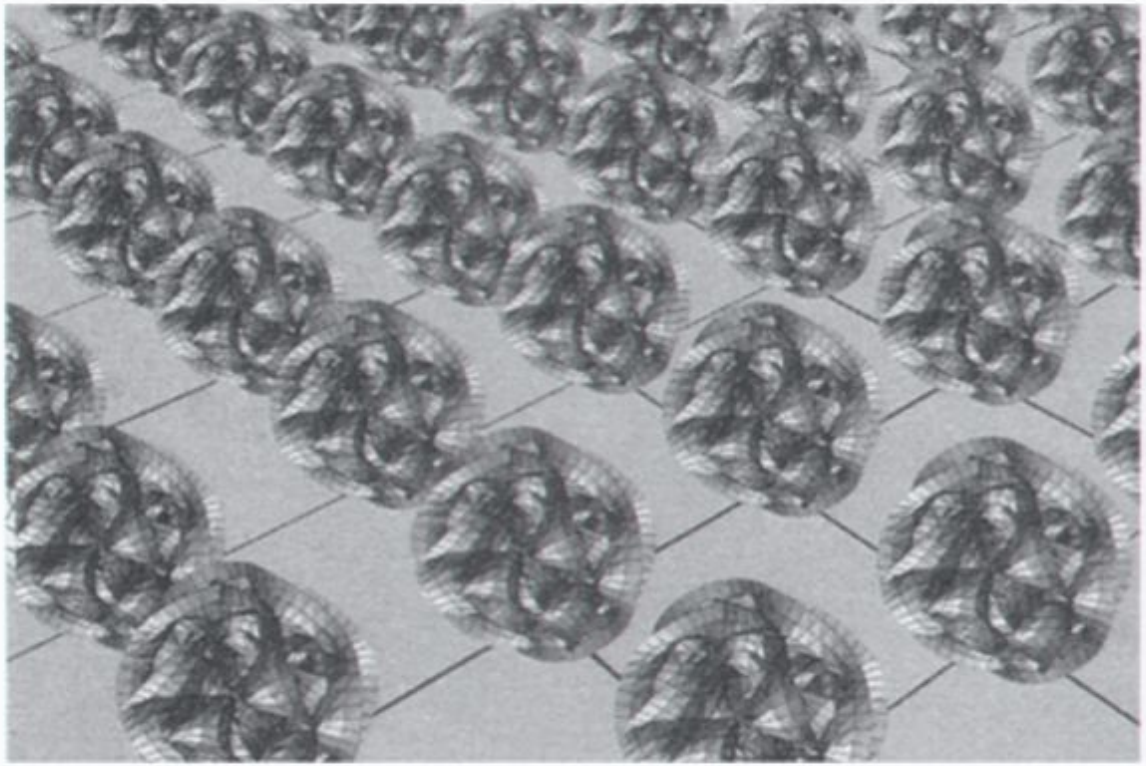
Big fix: Perhaps we haven't seen the extra dimensions yet.



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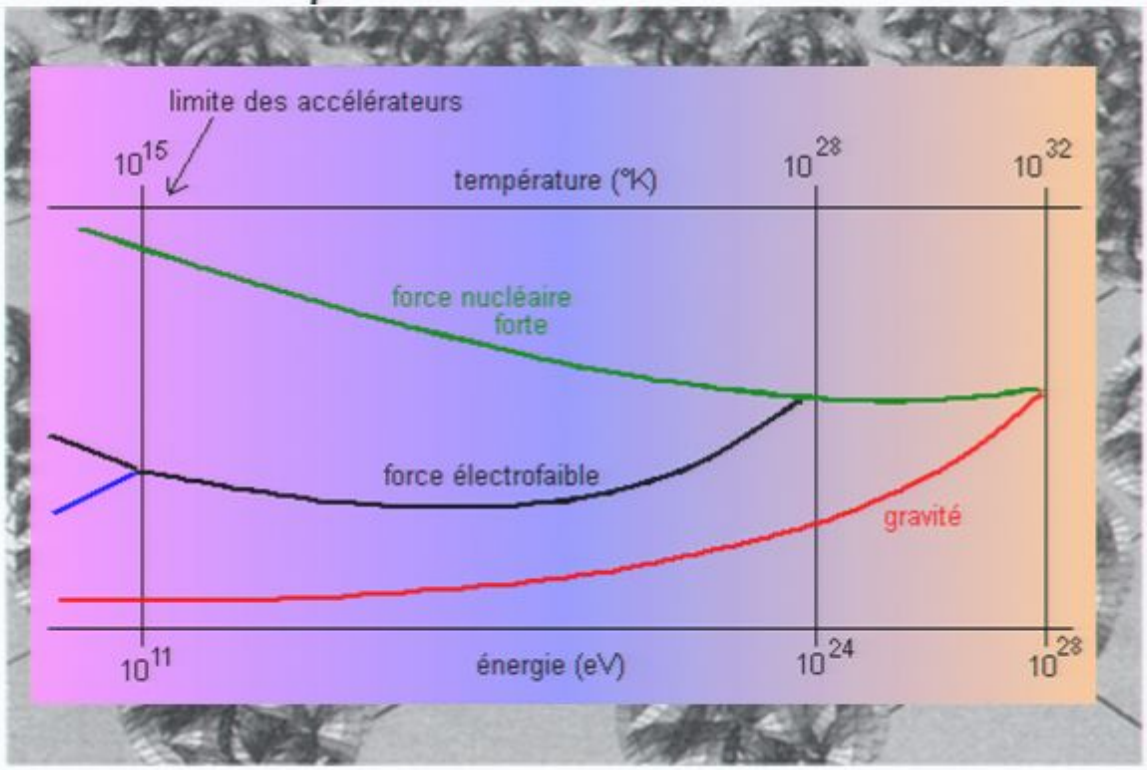

Benefit: richness of four-dimensional physics comes from geometry of the extra dimensions

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

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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, ….

- Have five consistent superstring theories:
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- Conjecture: all known string theories are different solutions of single fundamental theory

→ M-theory

Essential ingredients for M-theory conjecture:

- Dualites: two mathematical descriptions describe identical physical phenomena

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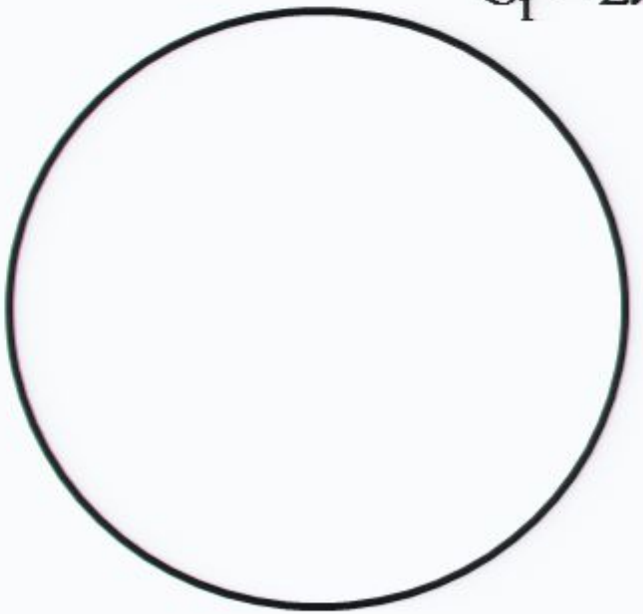
Eg, T-duality relates large and small circle compactifications

$$C_1 = 2\pi R$$



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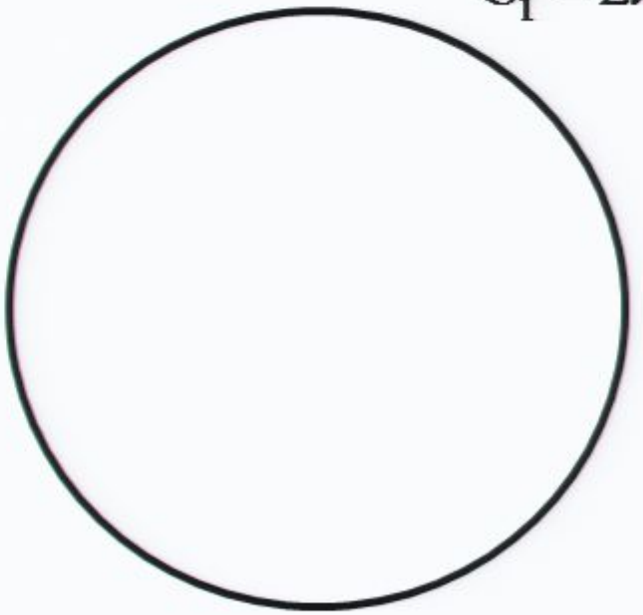

de Broglie wavelength: $\lambda = \frac{2\pi\hbar}{p}$

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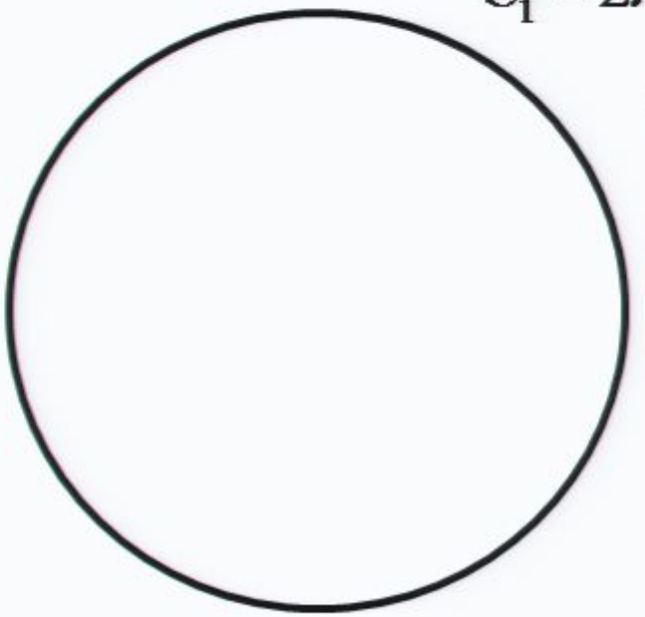

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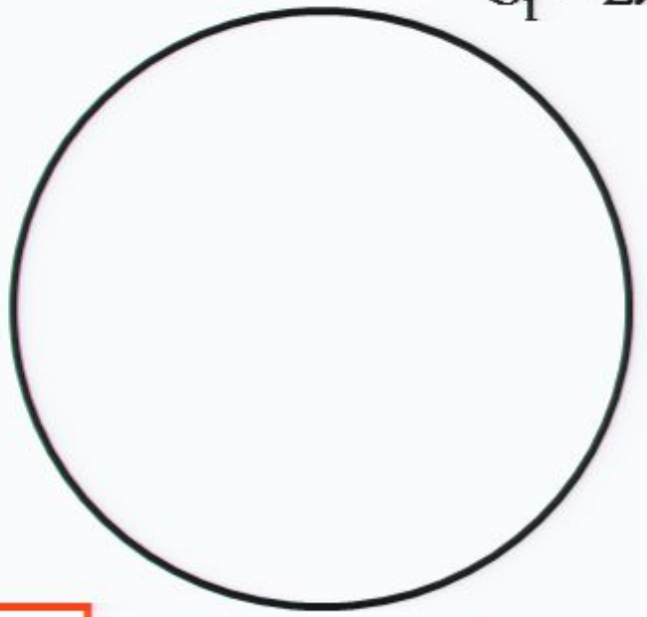

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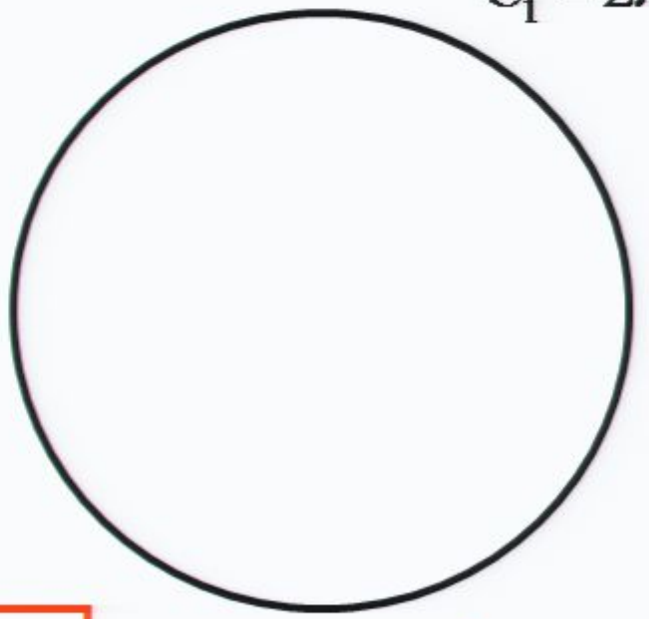

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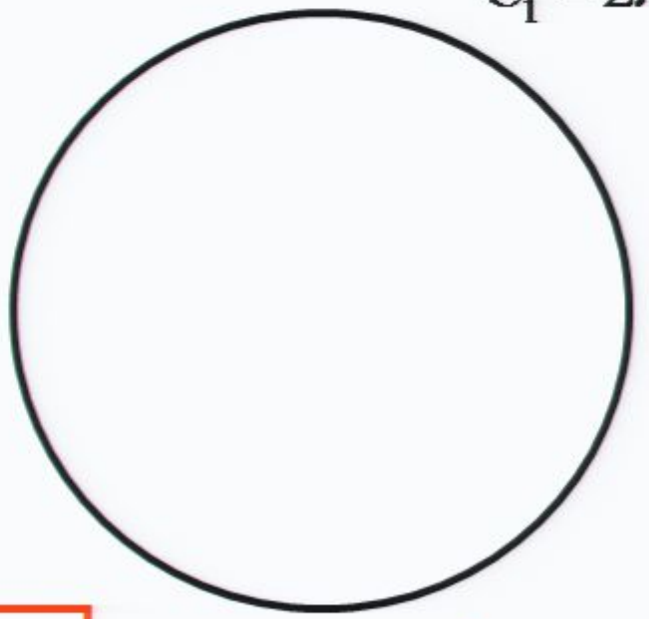

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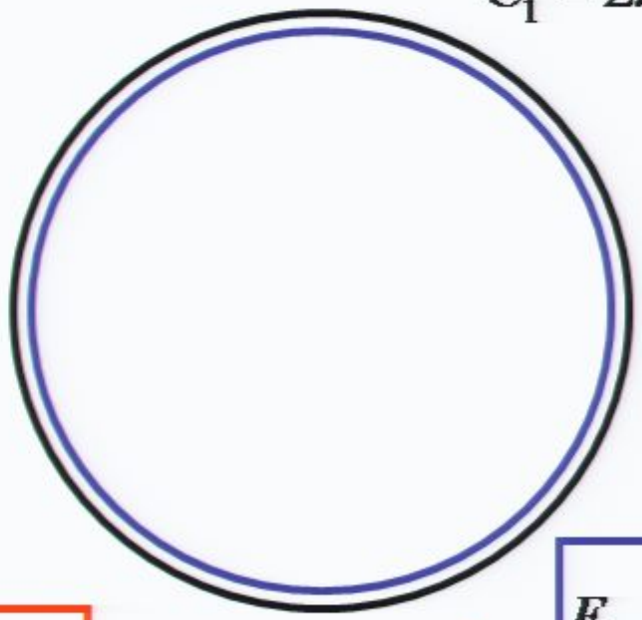

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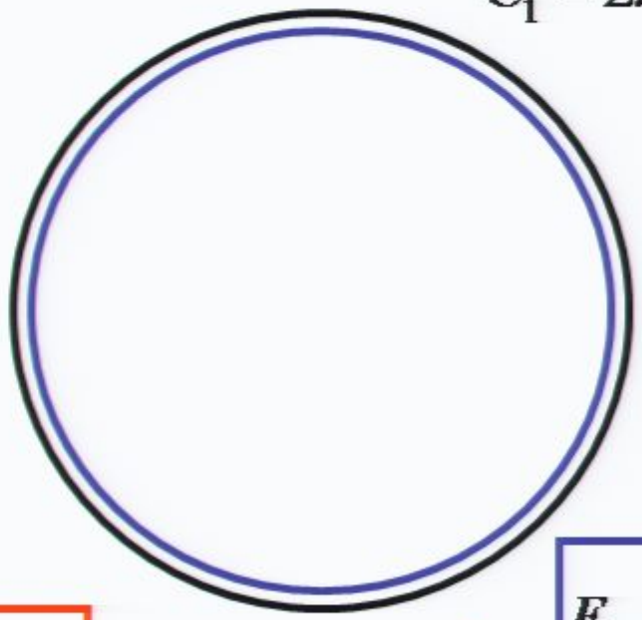

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String theory is more than a theory of strings!

- D-branes: string theory contains other kinds of objects extended in 0, 1, 2, . . . dimensions

particles strings membranes p-branes

$$T_p = \frac{2\pi}{(2\pi\ell_s)^{p+1} g}$$

← extremely heavy in weak coupling

← extremely important in strong coupling

Superstring theory: Unique theory of everything

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

Superstring theory: Unique theory of everything

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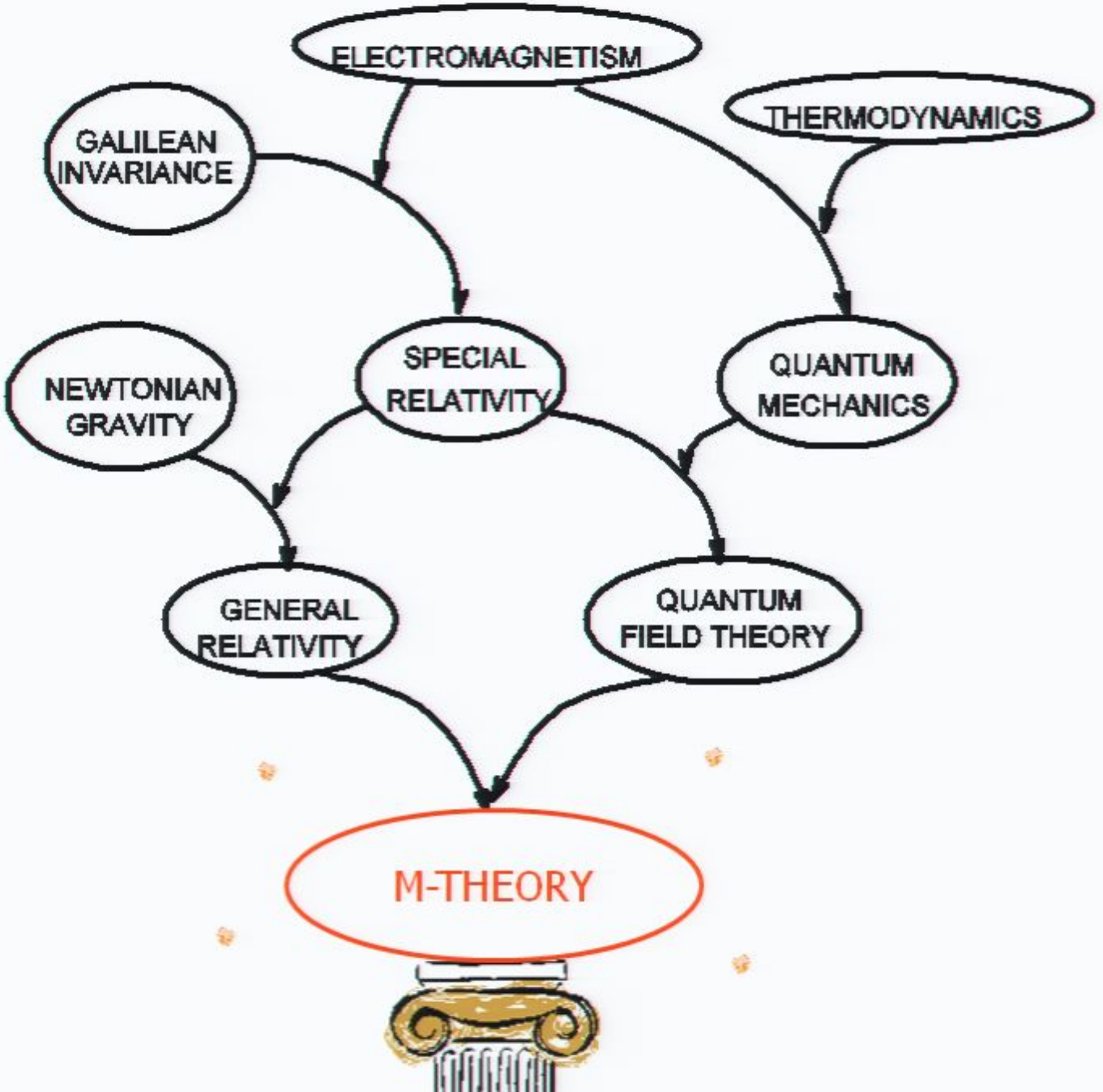
M-theory also includes 11-dimensional supergravity!

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



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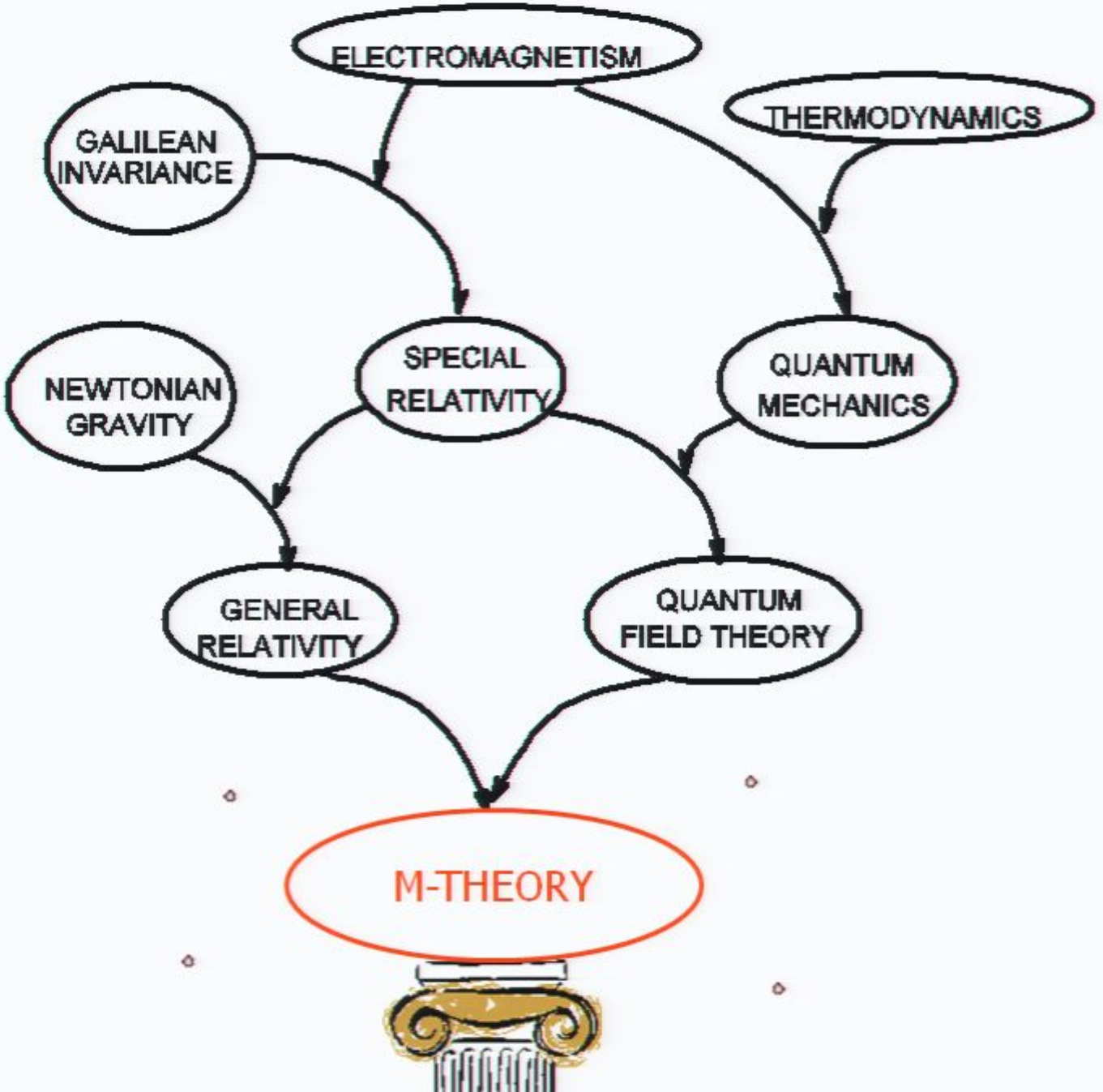

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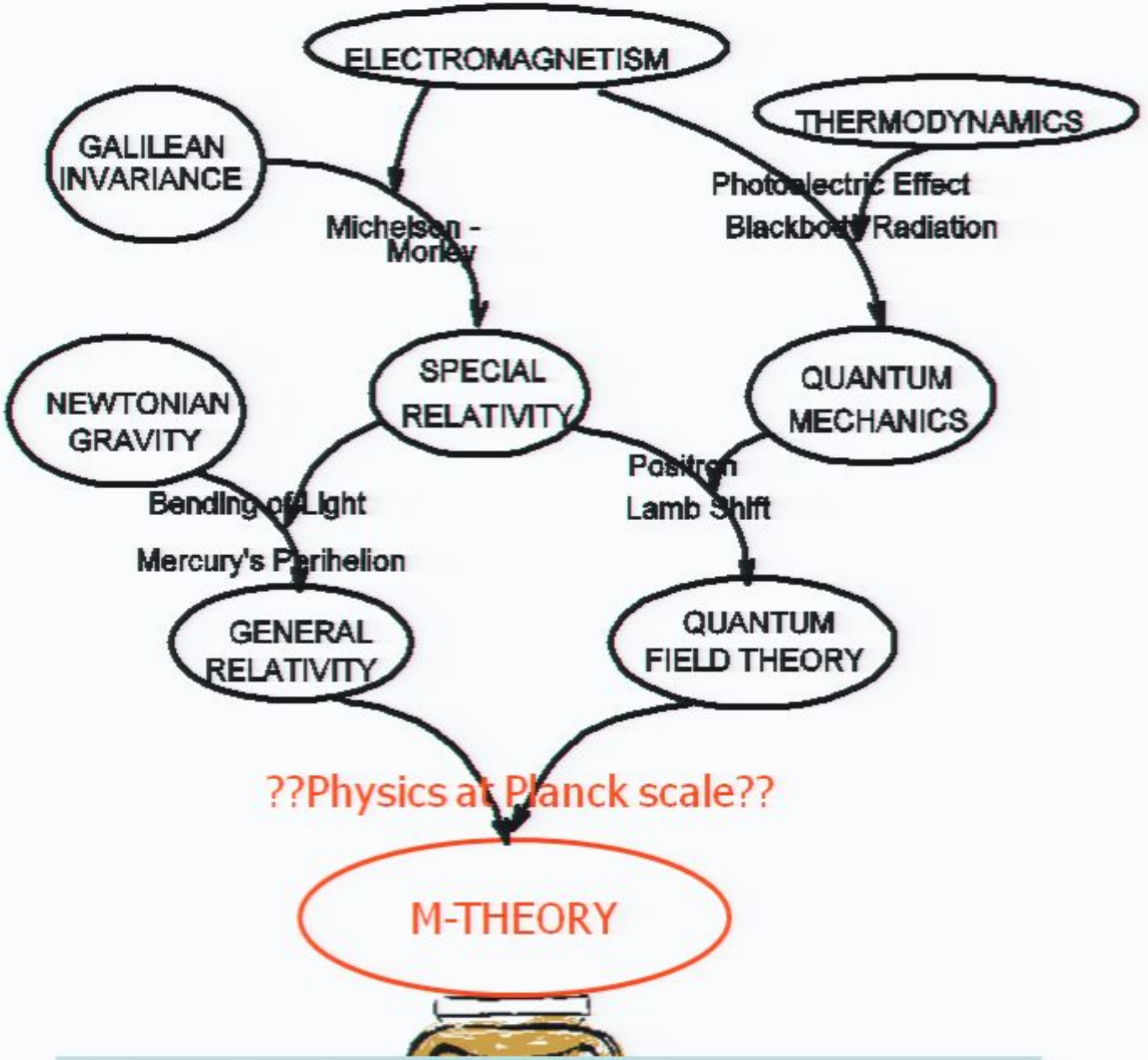
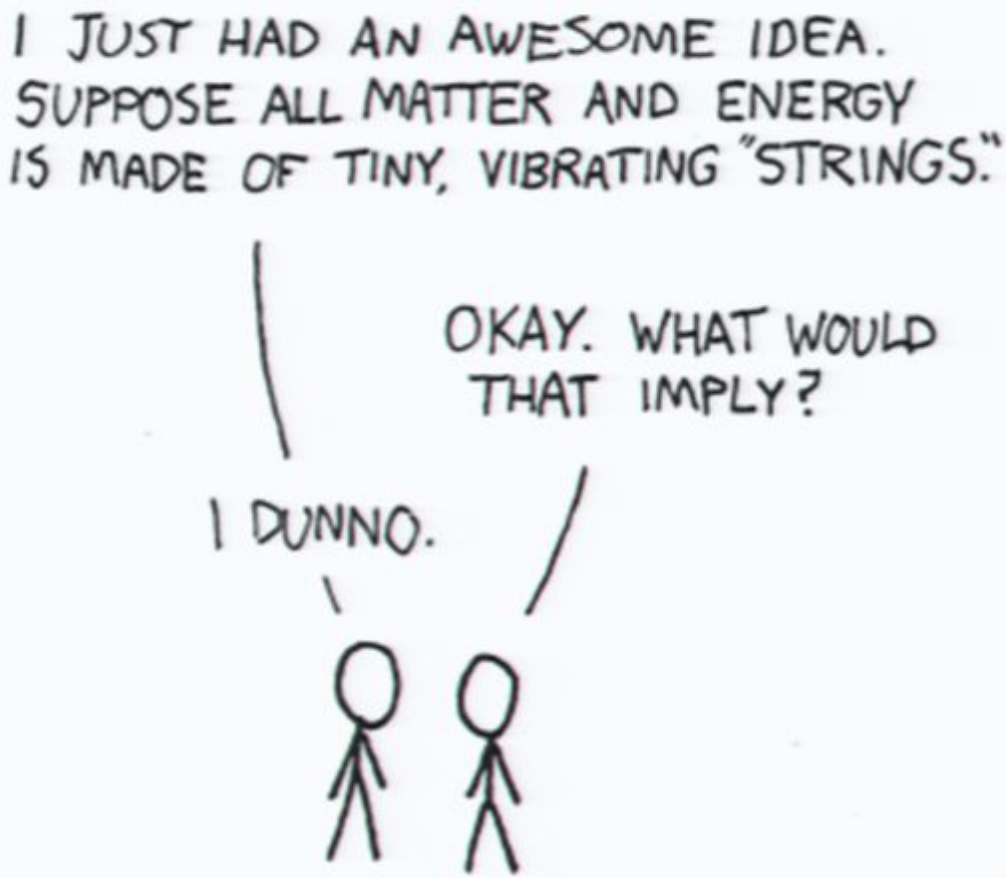


But contact with experiment is crucial

STRING THEORY SUMMARIZED:



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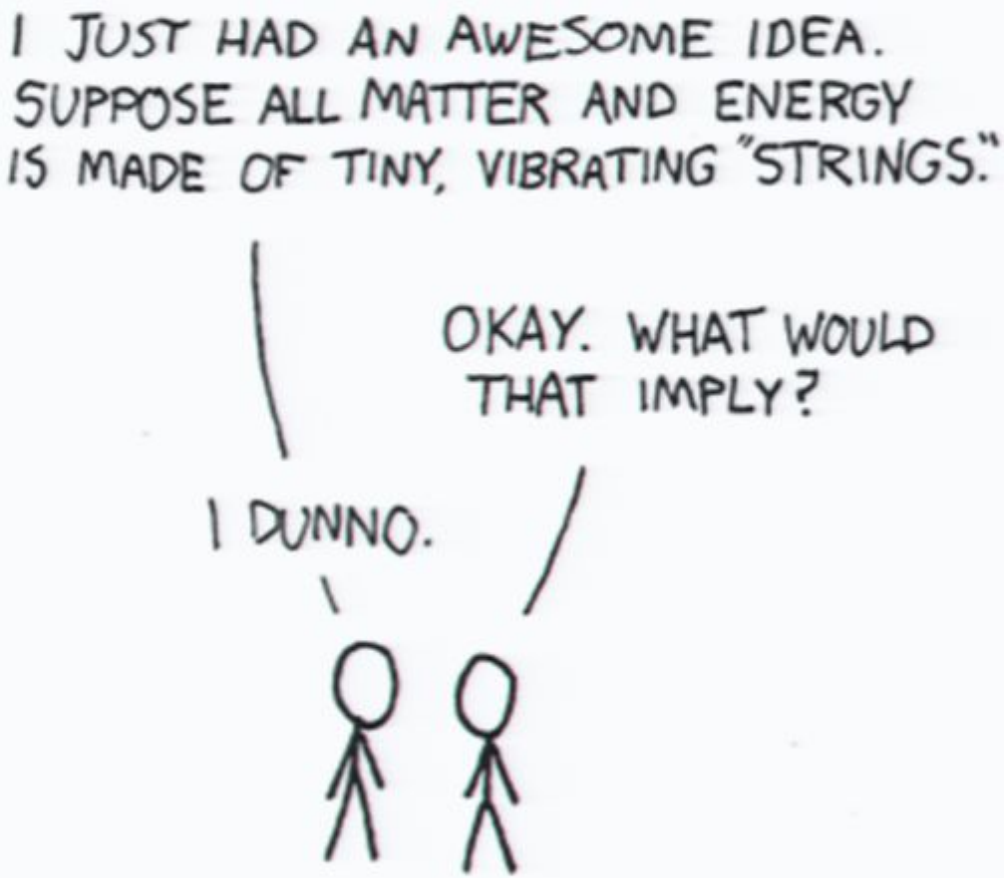
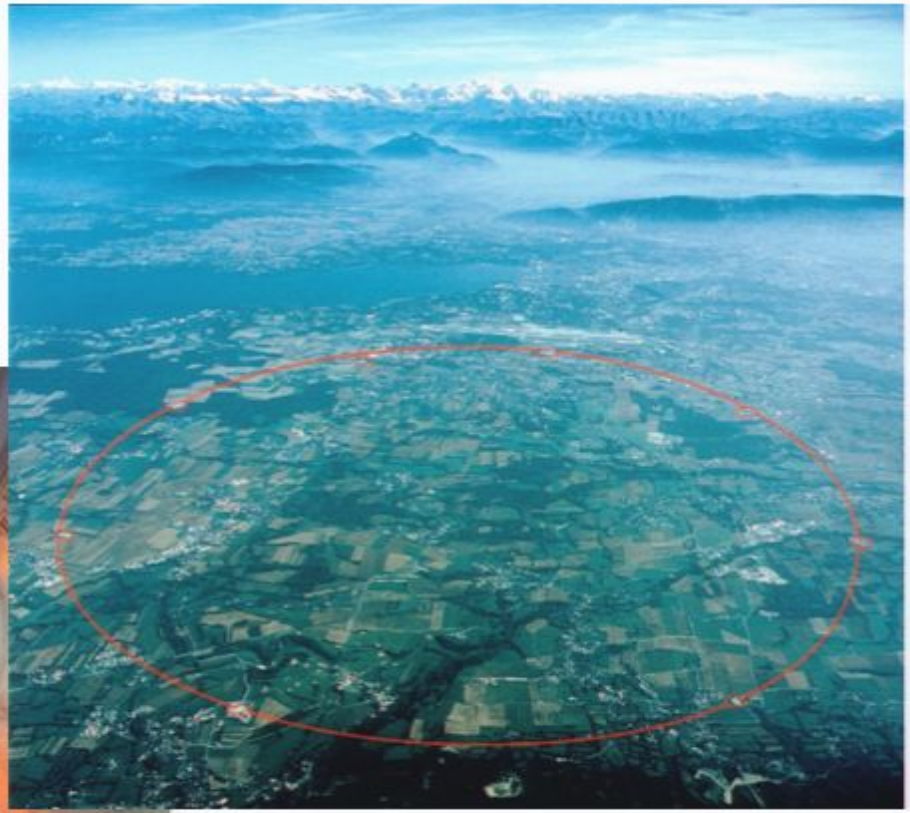
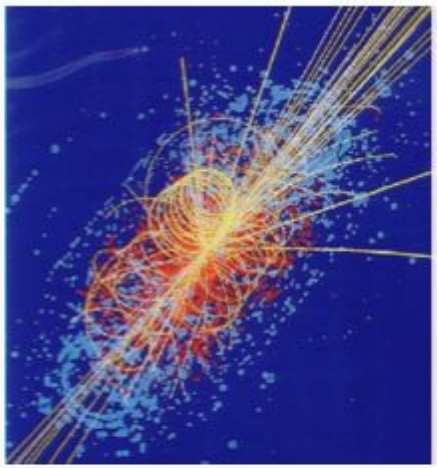


Superstring theory: a theory looking for a good experiment

accelerator experiments: probe 10^{12} eV and beyond

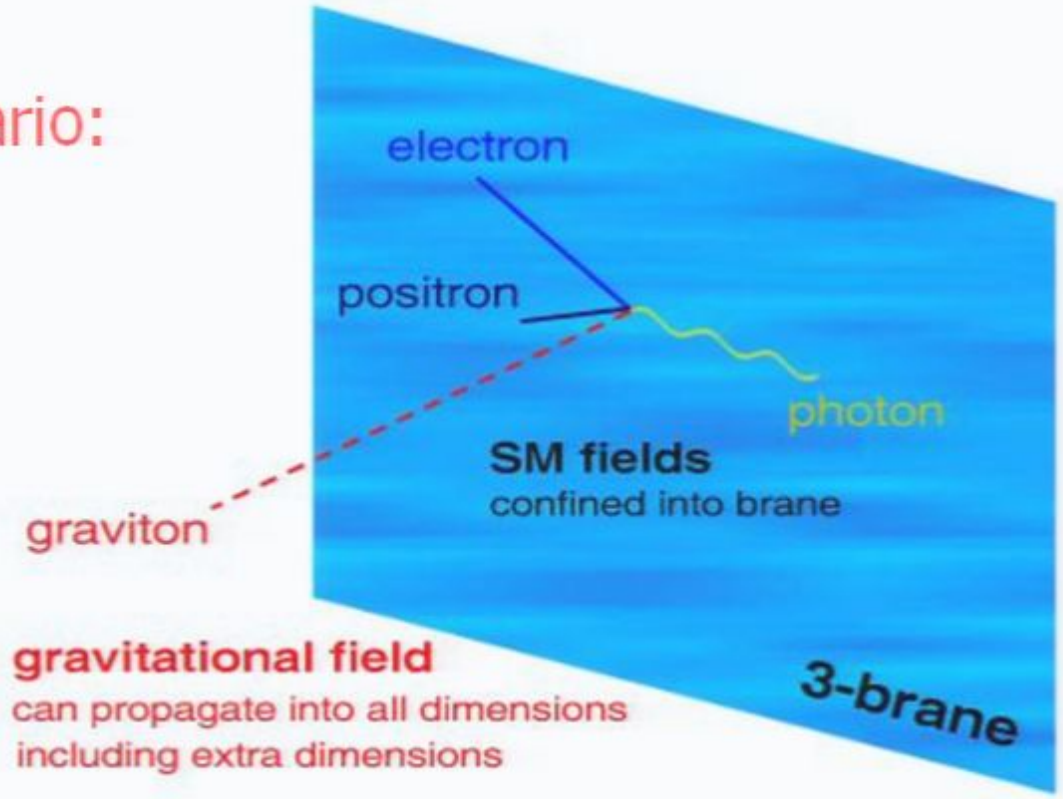
Tevatron, Large Hadron Collider, ...





How far away is the Planck scale really?

Brane-world scenario:



(Some) Extra dimensions may be very large!

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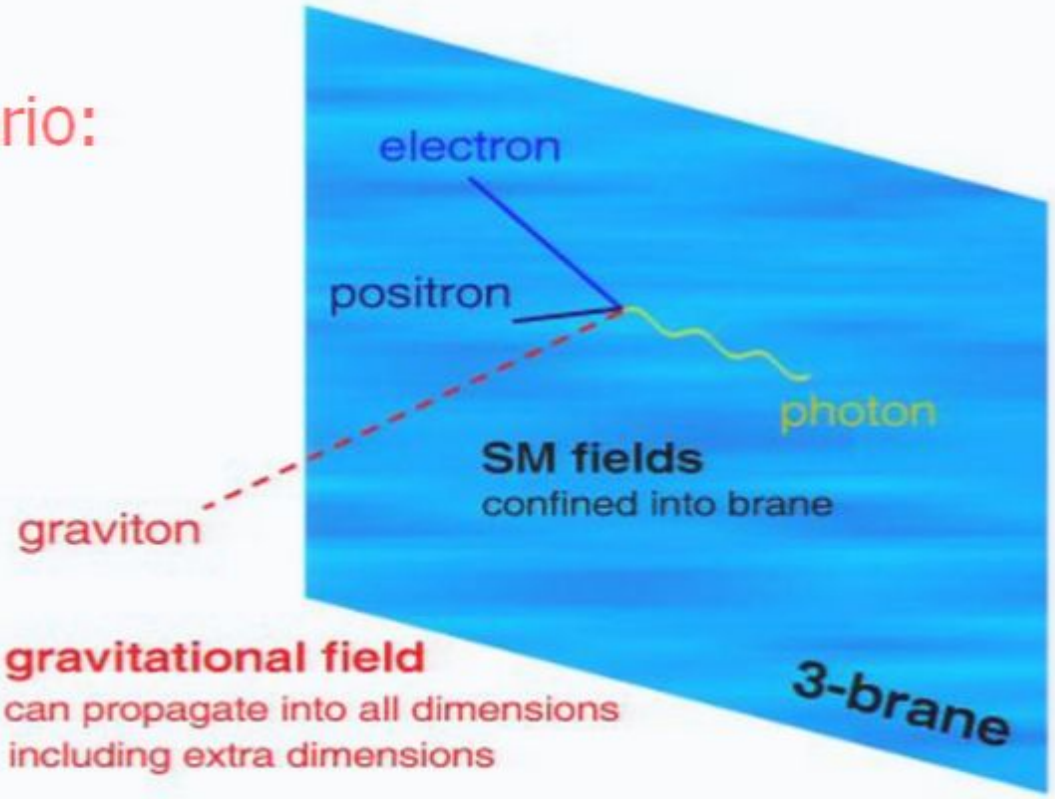

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Advantage: $G_4 = G_{10}/V_6$

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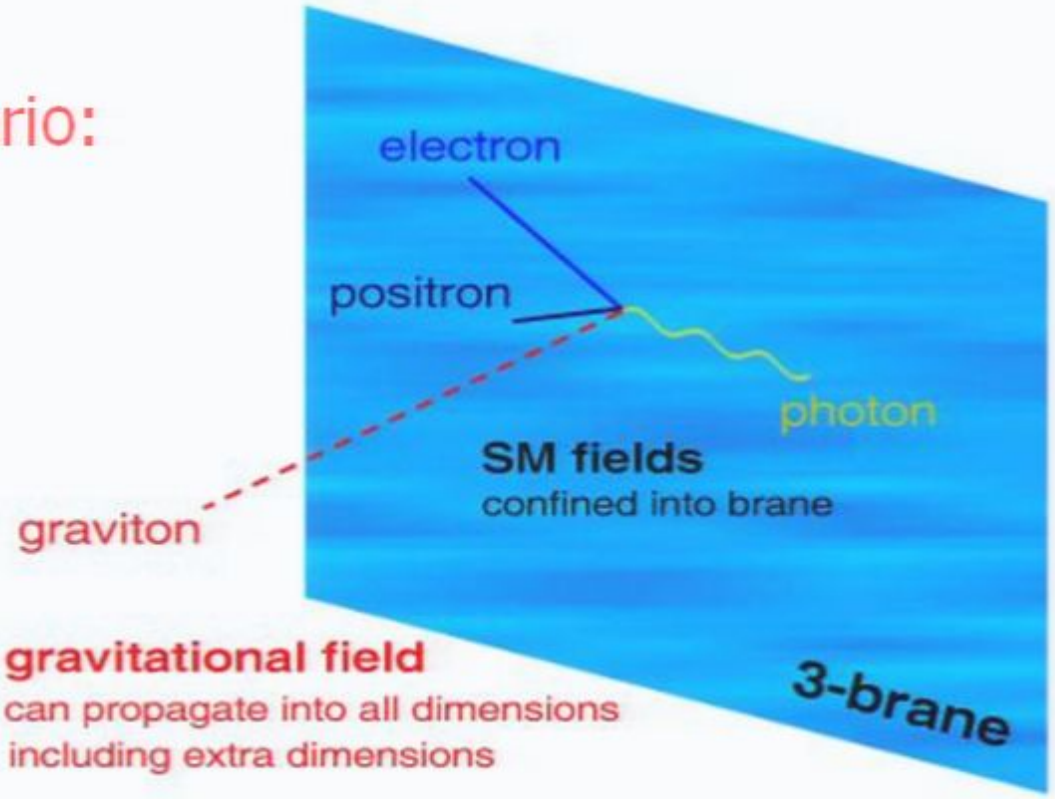

(Some) Extra dimensions may be very large!

Advantage: $\ell_{P,10}^{8} = V_6 \, \ell_{P,4}^{2}$

Planck scale may be within reach!!

Superstring theory: a theory looking for a good experiment

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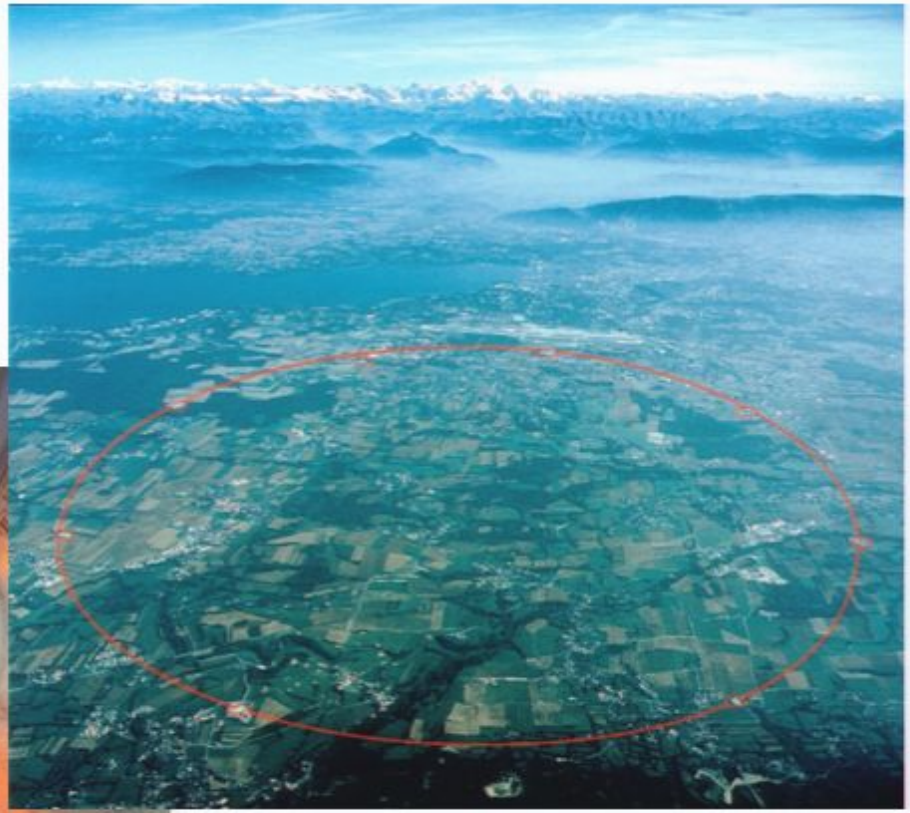

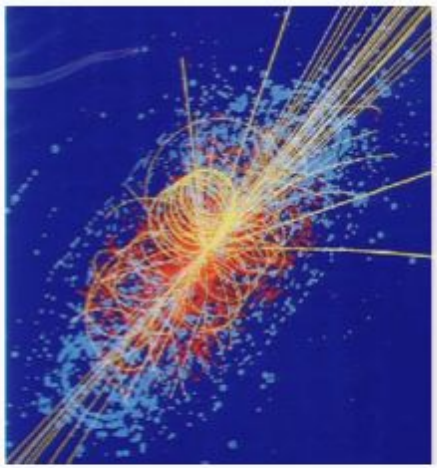

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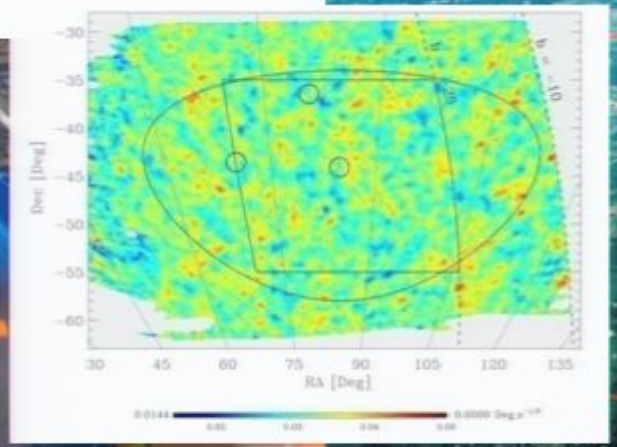
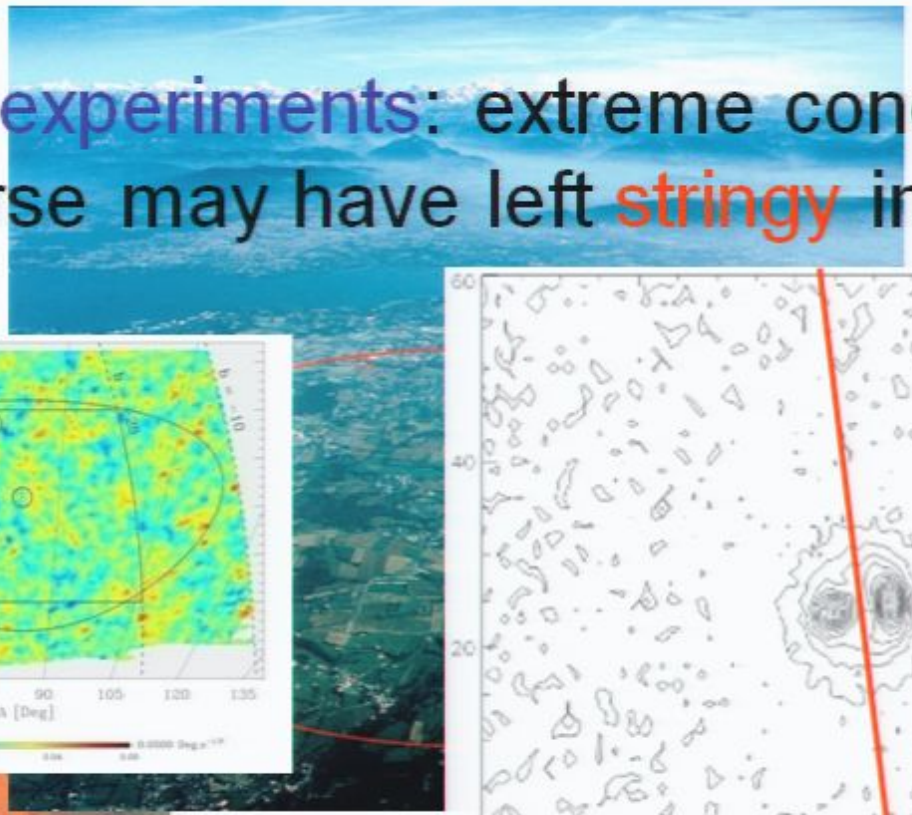
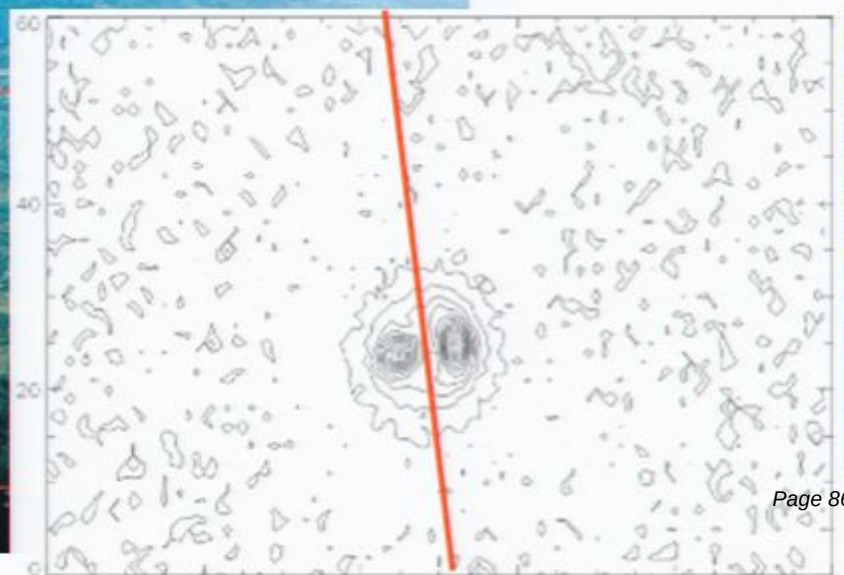
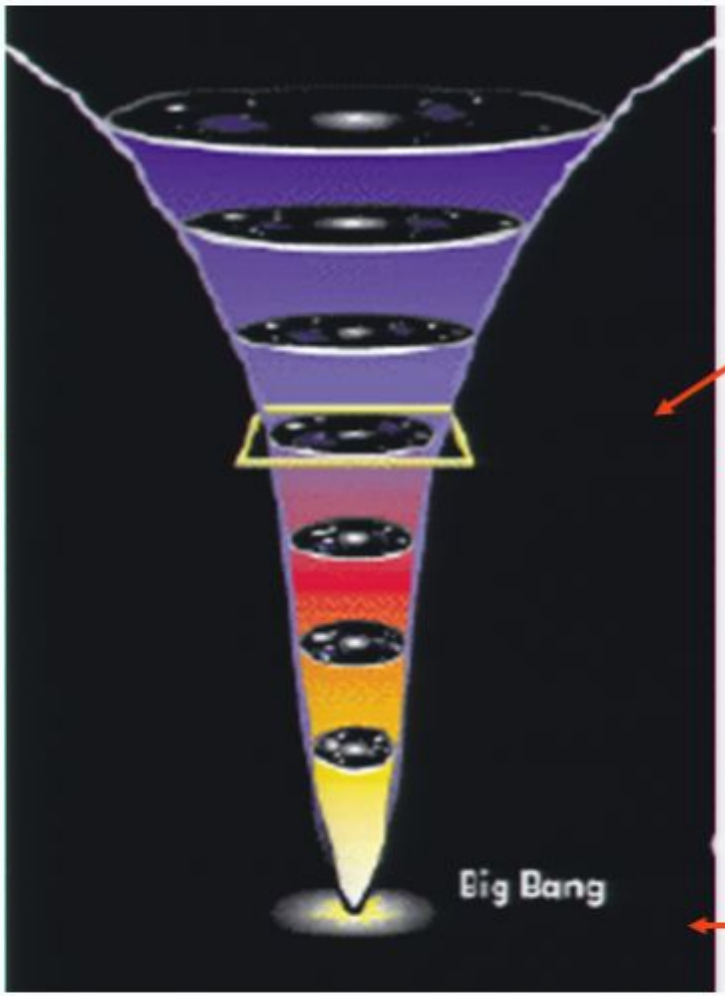






Cosmology: extreme conditions of early universe give a window on small scales and high energies



Future

Present

Past

Stringy relics or imprints now?

We need to understand the optics of our "microscope"

String physics is manifest

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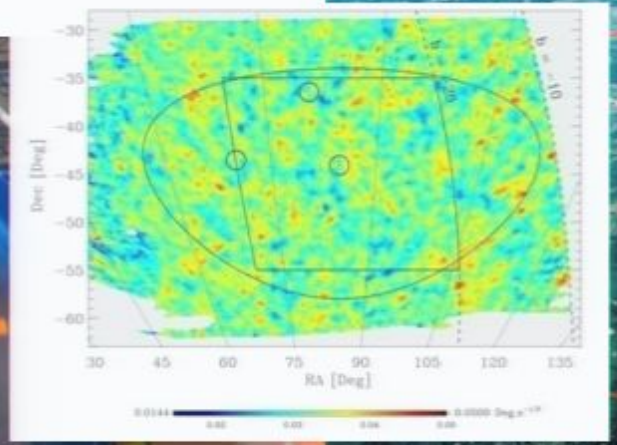

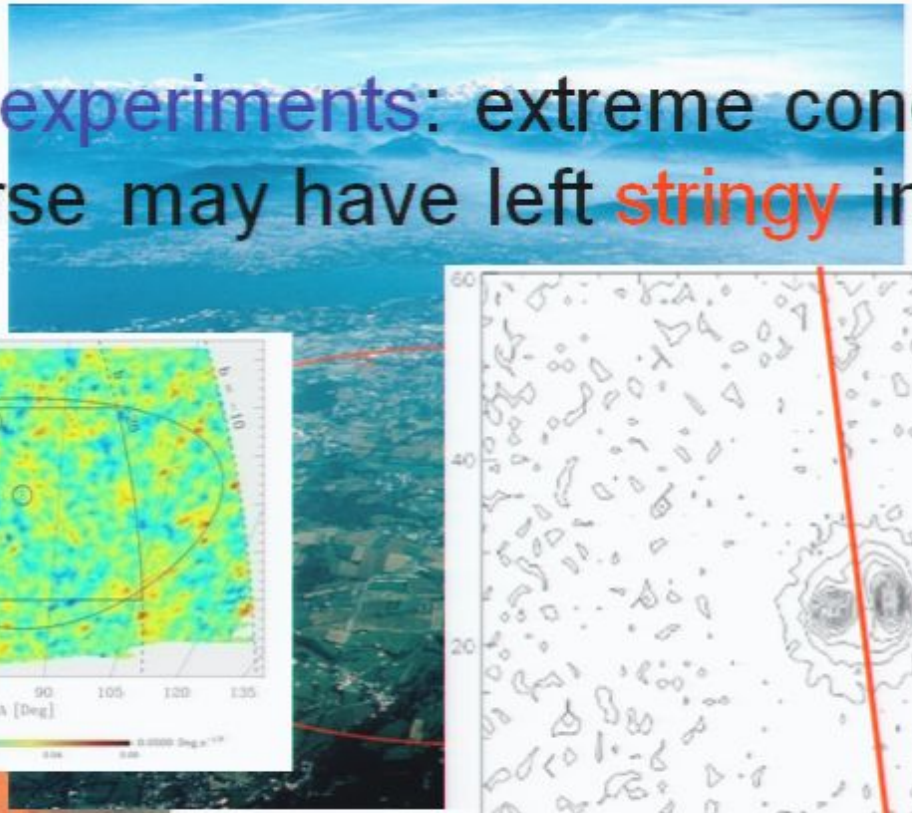

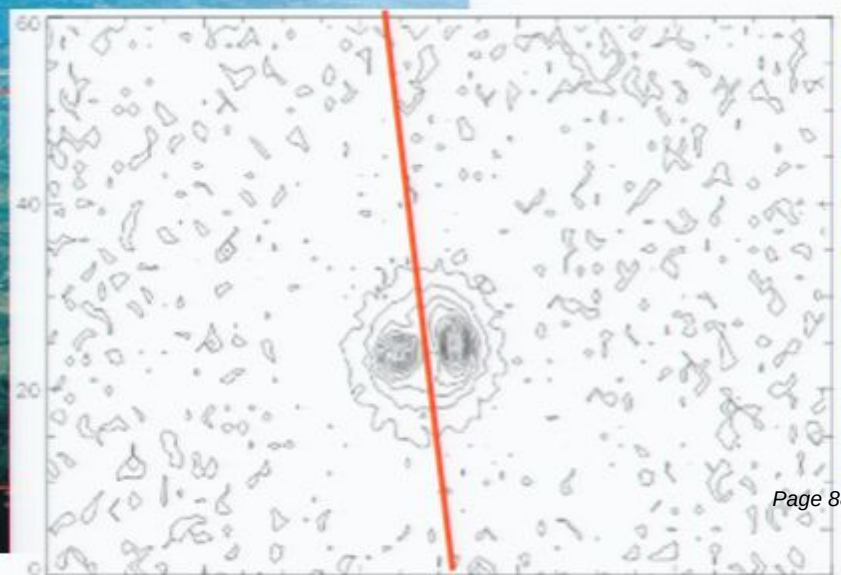

Superstrings:

a mathematical model of our physical universe

Studies of string theory draw upon an enormous range of modern mathematics:

complex analysis, group theory, fibre bundles, gerbes, topology, differential geometry, mirror symmetry, K-theory, derived categories, noncommutative geometry

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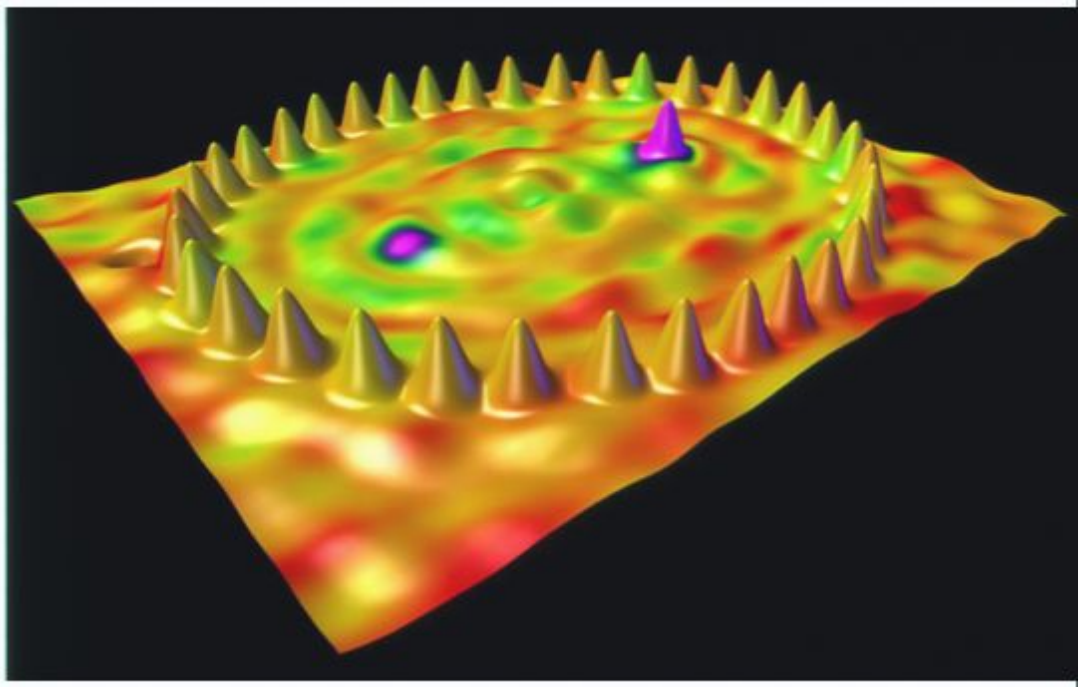
Ernst Mach: "atoms are physically unverifiable entities"

early 1990's –

individual atoms are manipulated using atomic force microscopy



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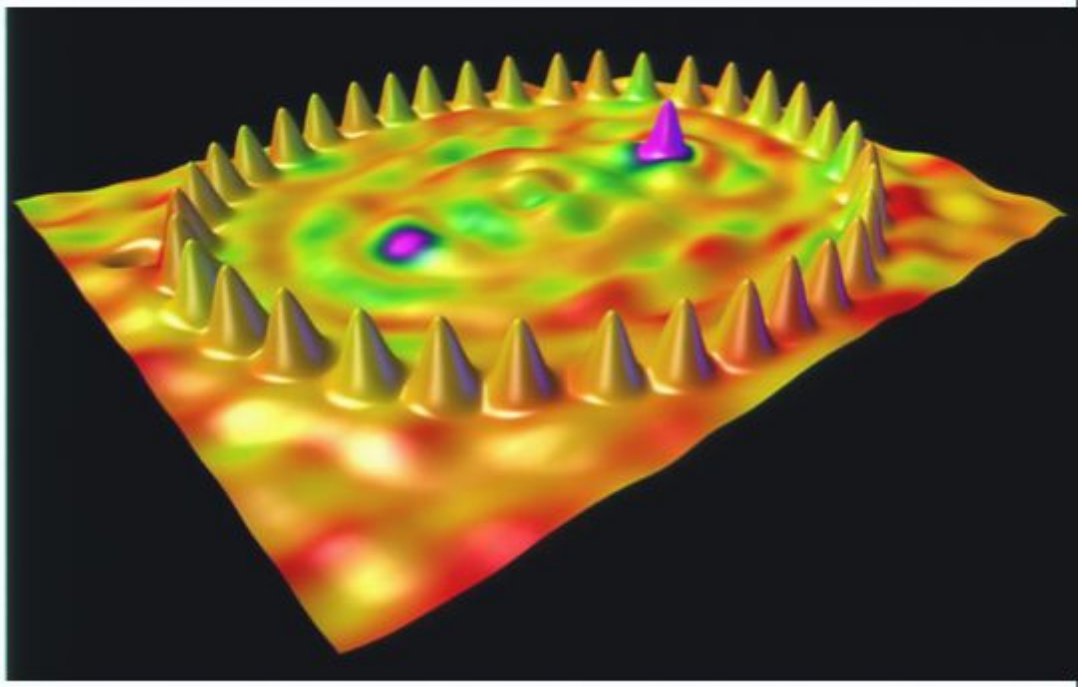

For superstrings,
the adventure is still only beginning!

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:
http://superstringtheory.com/

"It's the 21st century—
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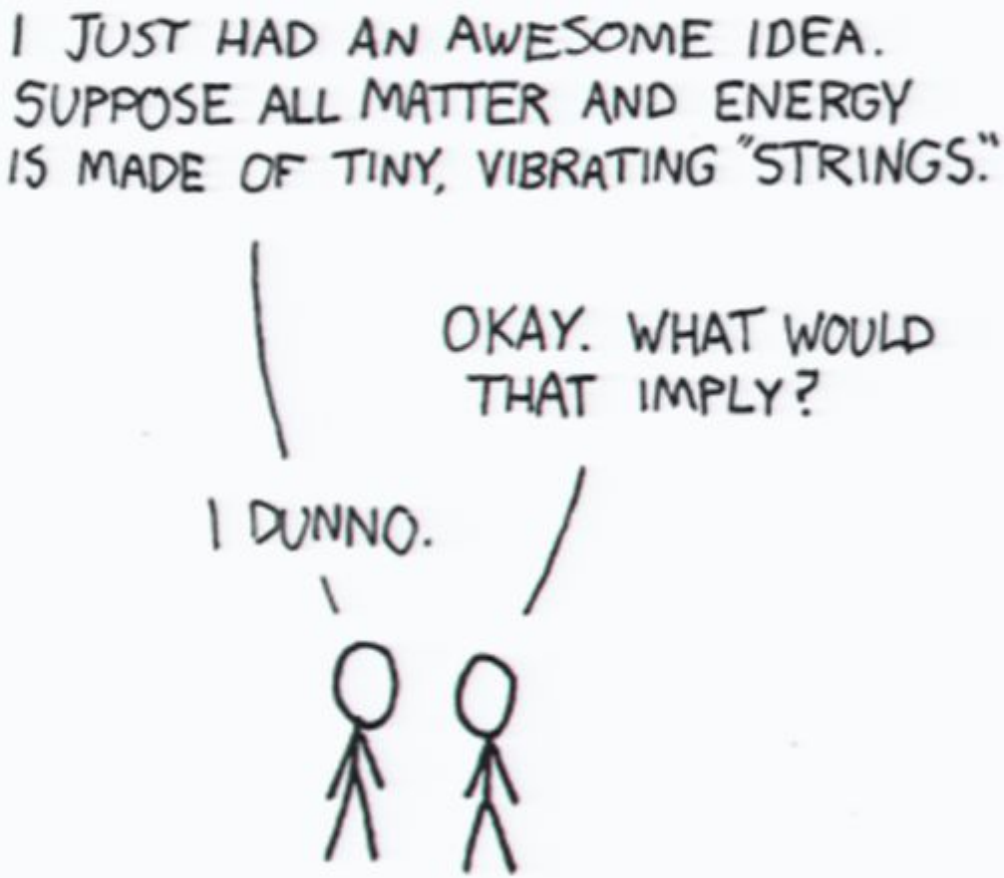

Essential ingredients for M-theory conjecture:

- Dualites: two mathematical descriptions describe identical physical phenomena

Eg, T-duality relates large and small circle compactifications

$$C_1 = 2\pi R$$

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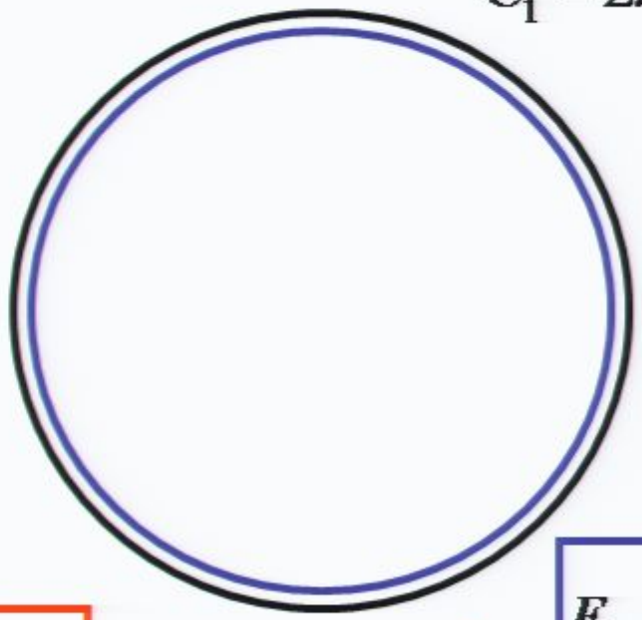

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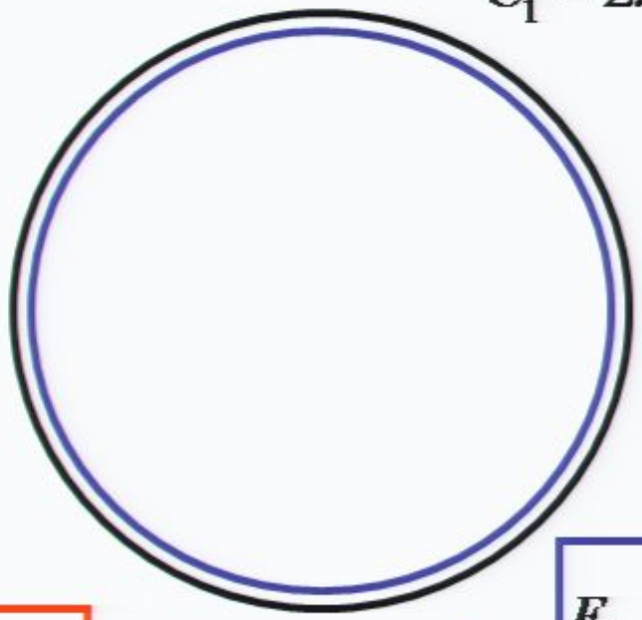

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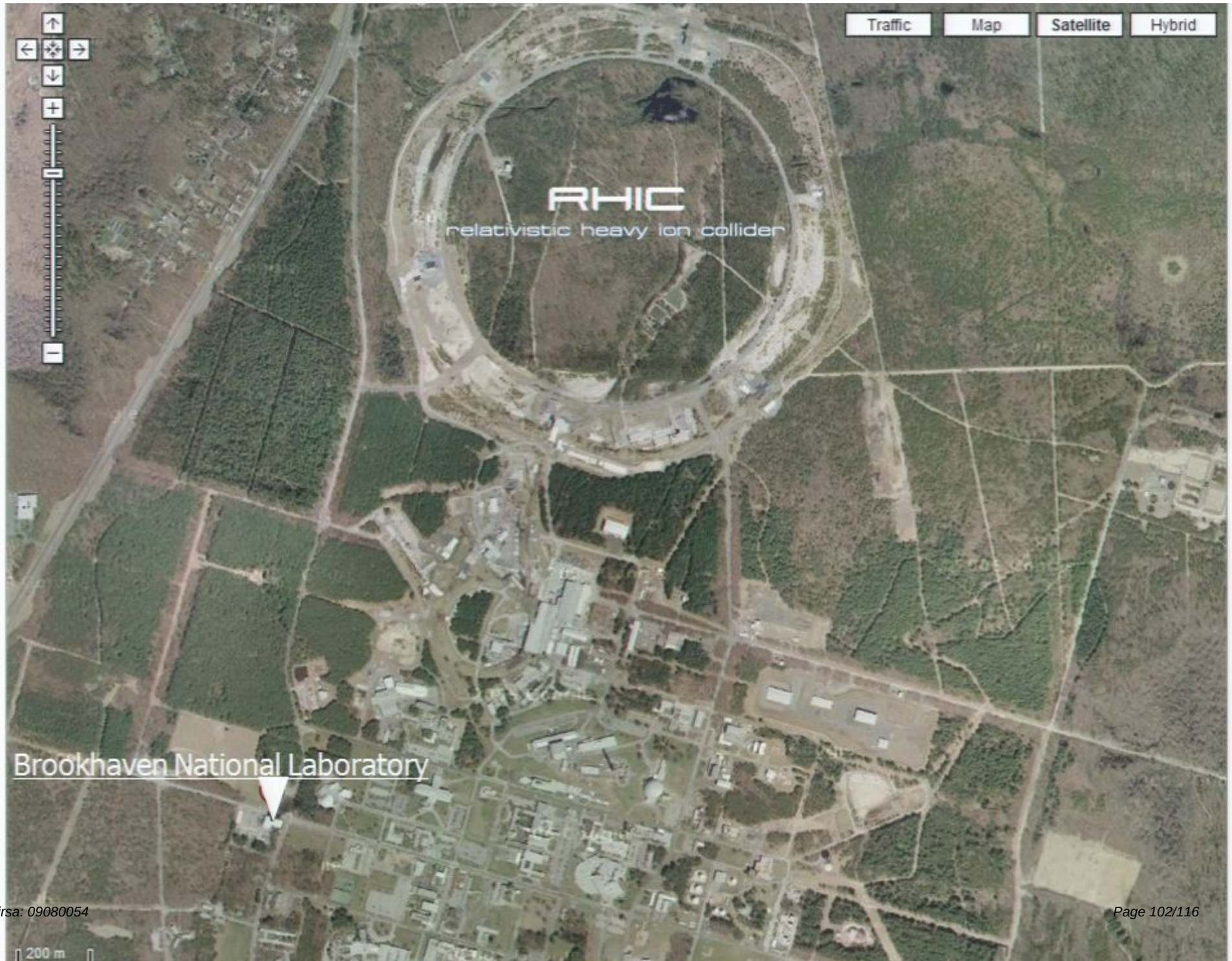
Traffic
Map
Satellite
Hybrid
RHIC
relativistic heavy ion collider
Brookhaven National Laboratory
200 m

Traffic
Map
Satellite
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PHOBOS
BRAHMS
RHIC
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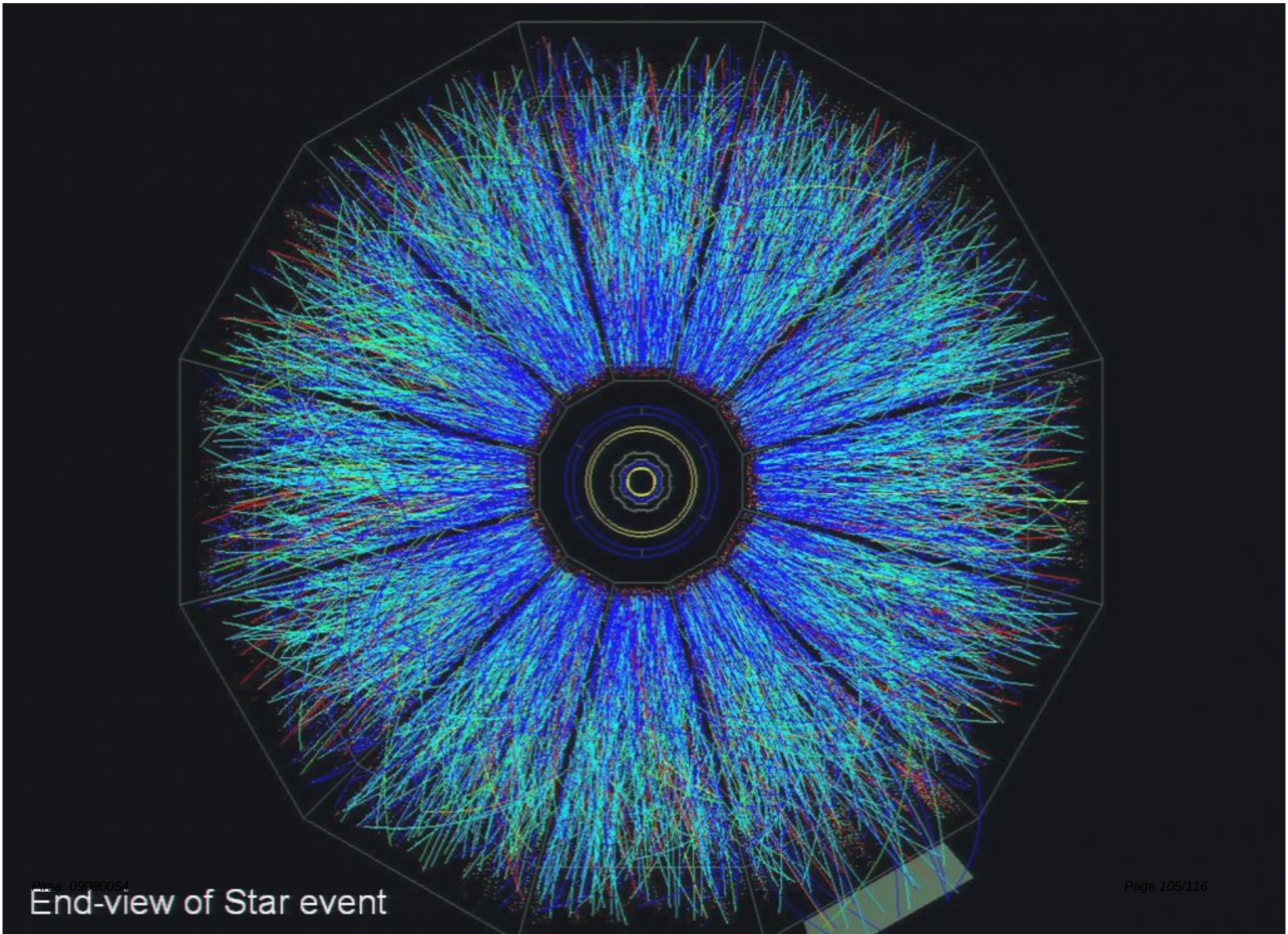

End-view of Star event

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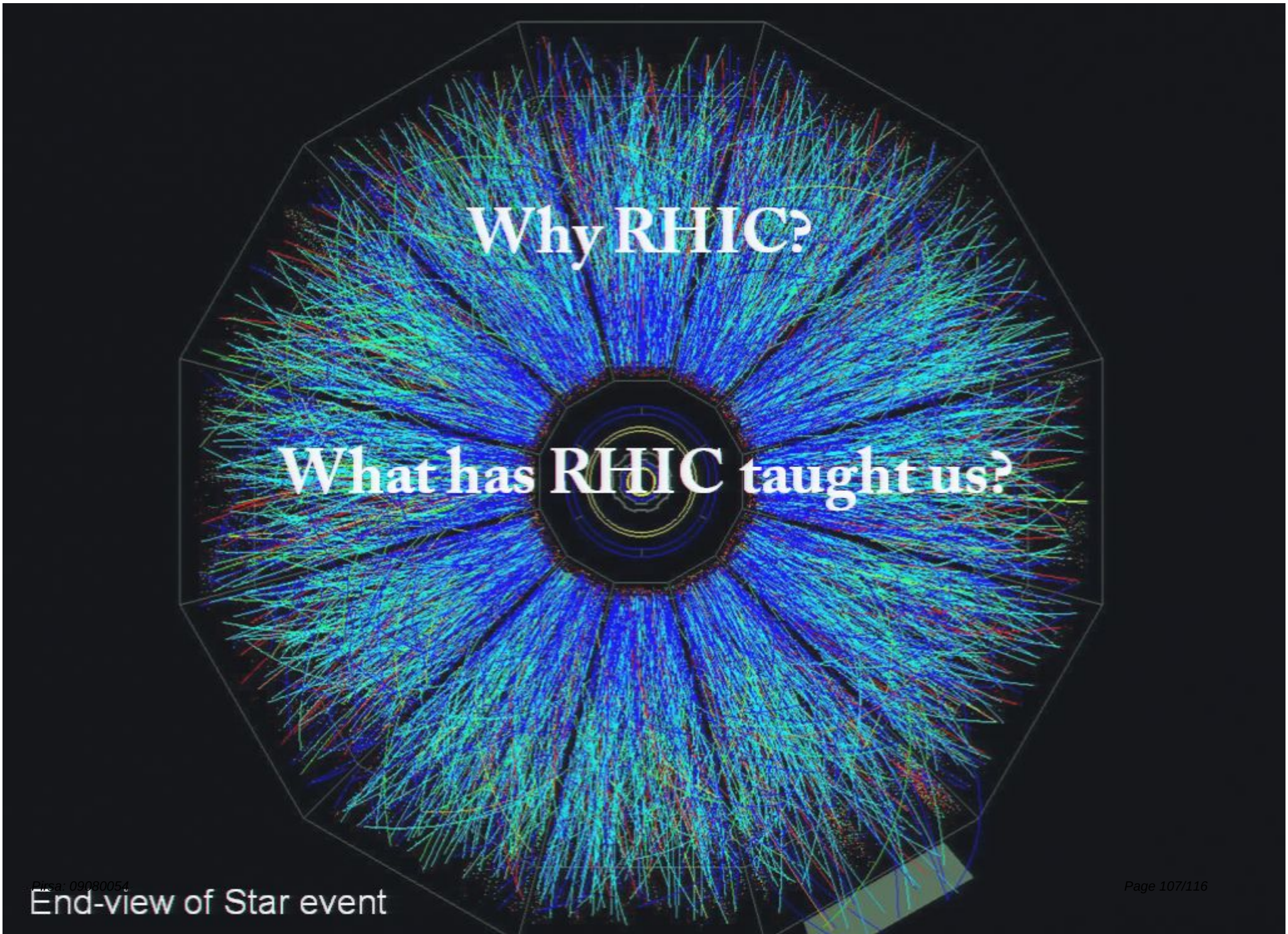

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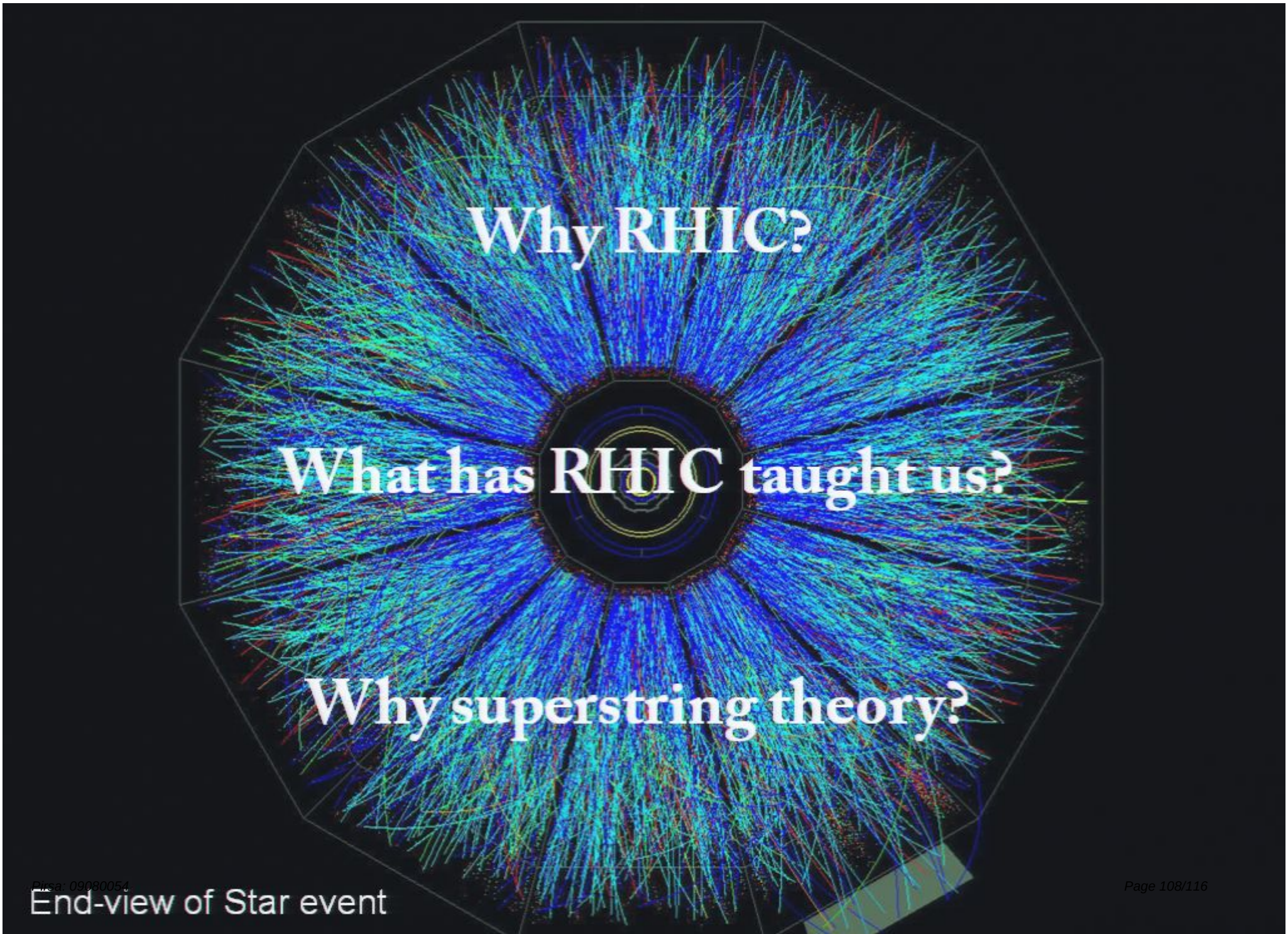
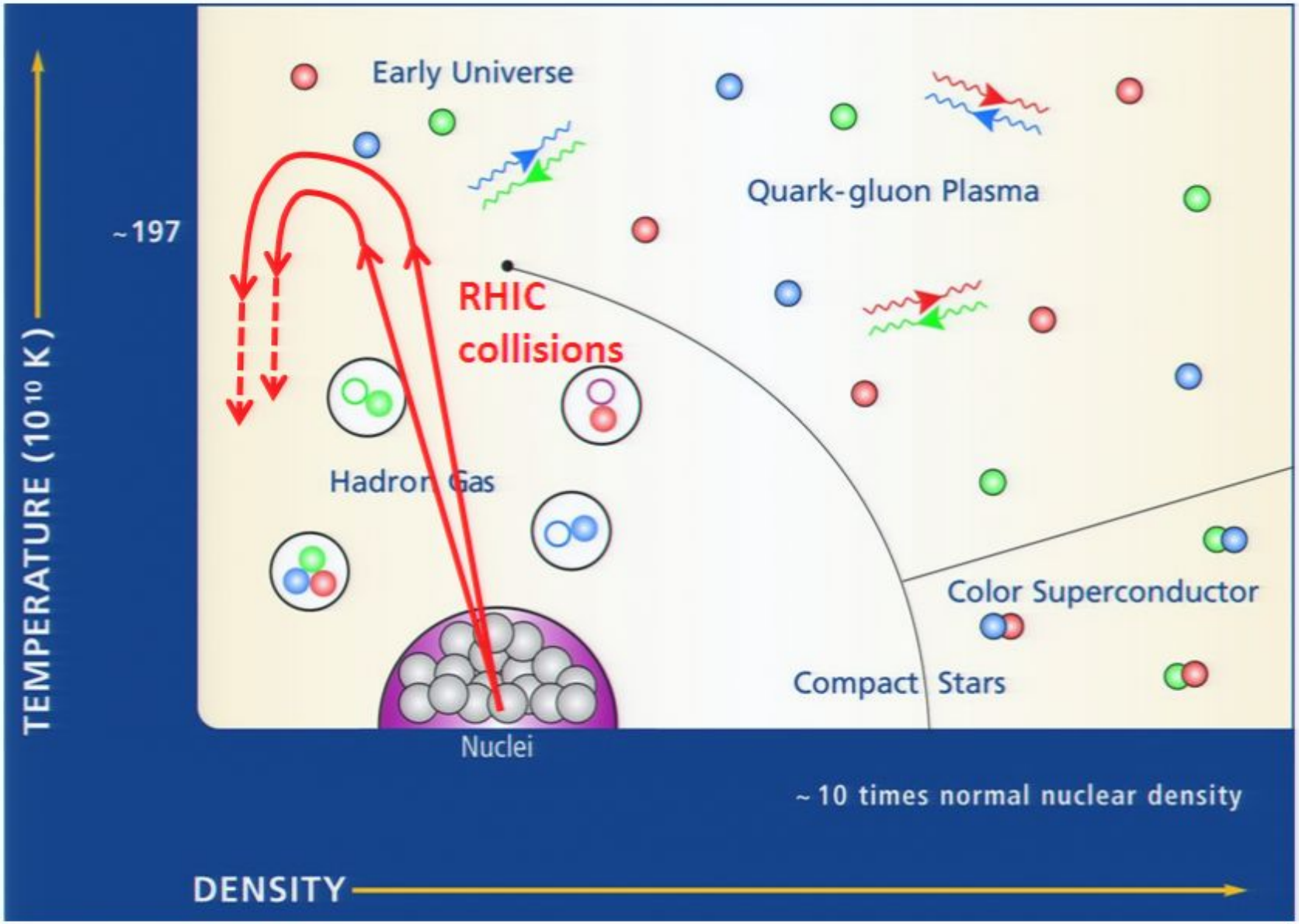
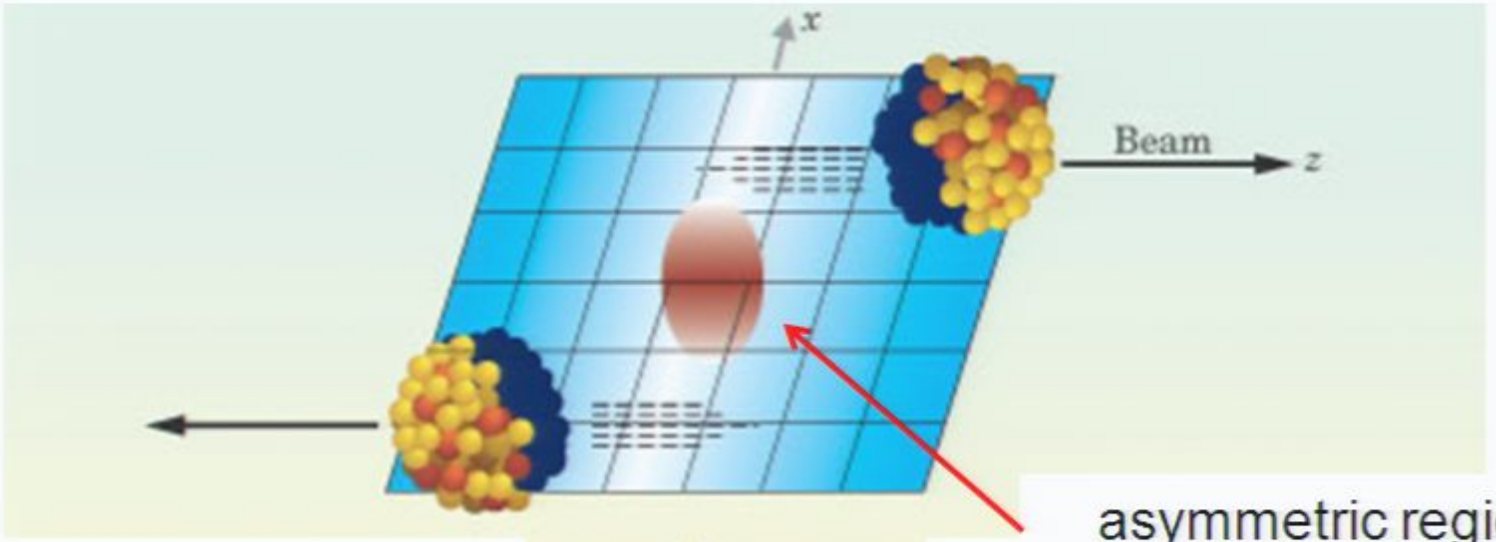


End-view of Star event

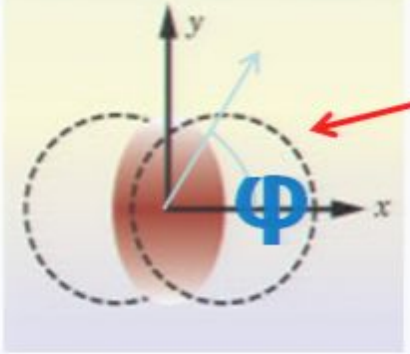
QCD Phase Diagram (according to theorists):



Elliptic flow: consider collision which is not head-on



asymmetric region participates in collision; almond shape



Elliptic flow:

Collective flow:
pressure gradients generate
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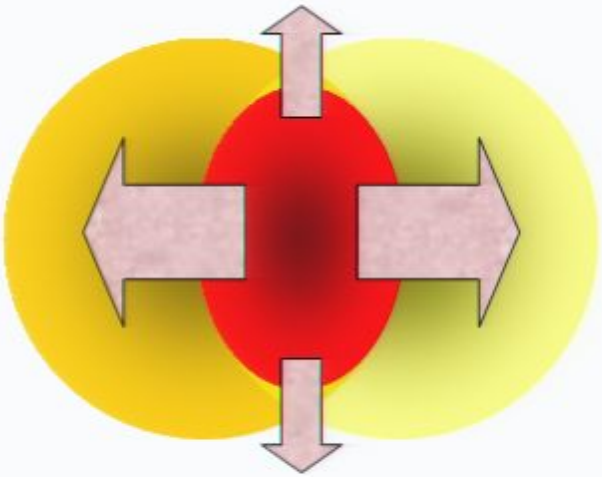
$$v_2 \sim \langle \cos 2\phi \rangle \neq 0$$



→ "**near ideal** fluid"

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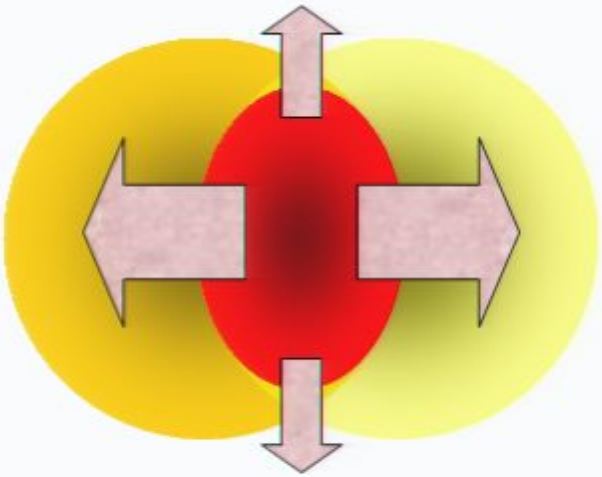

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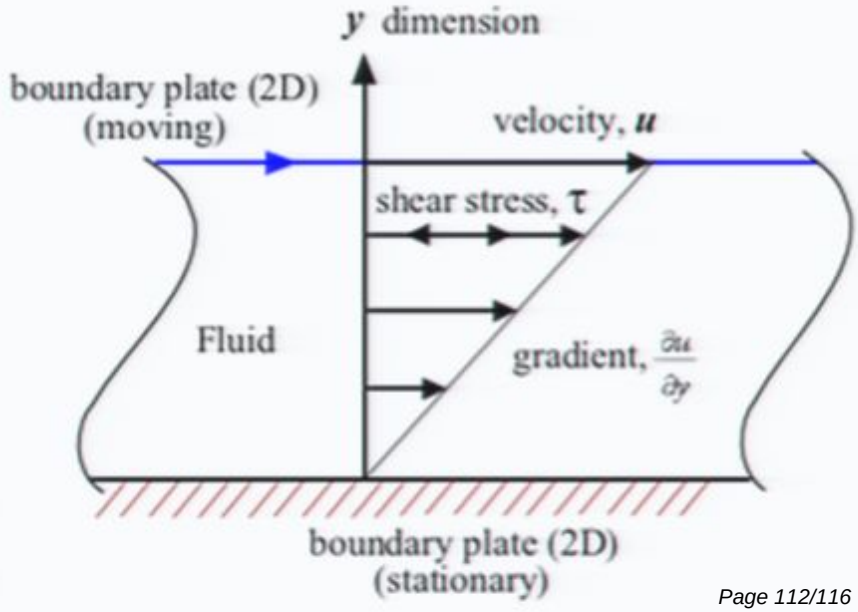
$$\tau = \eta \frac{\partial u}{\partial y}$$



large shear viscosity would even out flow and produce uniform distribution

Surprise: Just above critical temperature, quark-gluon plasma behaves like a **near ideal fluid** with:

$$\eta/s \simeq .08 - .16$$

Theoretical challenge: **both** perturbative analytic and computer techniques fail for strong-coupling dynamics!

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What does superstring theory have to say about the quark-gluon plasma?

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