FUNDAMENTAL PHYSICS AND THE FIFTH DIMENSION

Raman Sundrum
University of Maryland
ANCESTRY OF FUNDAMENTAL FORCES

MOTHER FORCE
  Superstrings?

GRAND UNIFIED FORCE
  Strong Nuclear Force
  Electroweak Force
  Gravity

Electromagnetism
Weak Nuclear Force
ANCESTRY OF FUNDAMENTAL FORCES

MOTHER FORCE
  Superstrings ?
  └── GRAND UNIFIED FORCE
    └── Strong Nuclear Force
        └── Electro- Magnetism
            └── Electroweak Force
                └── Weak Nuclear Force
                └── GRAVITY
          └── DARK MATTER/ FORCES/ENERGY
GENERAL RELATIVITY

Einstein 1915

Consistent with Electromagnetic Laws:
  Light Speed is finite & Fastest

$\Rightarrow$ Spacetime is Curved & Dynamic!

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$
Can curved space curl back on itself?

$\Rightarrow$ Seeing the back of your head!
Can curved space curl back on itself?

⇒ Seeing the back of your head, NO EVIDENCE
NEW DIMENSIONS
MICROSCOPICALLY CURLED?

How to tell in principle?

microscopic circular "5th dimension"
NEW DIMENSIONS?

MICROSCOPICALLY CURLED?

3D

microscopic circular “5th dimension”

↑ 3D

What 5th dimension?

standard light

ultraviolet light needed to see 5th dimension
5D Curved Spacetime (5D Gravity)

Macrosopic 3D Gravity (General Relativity)

Macrosopic 3D Electromagnetism

"Kaluza-Klein" Theory (1930's)
BUT UNREALISTIC!

Mass \rightarrow \text{BLACK HOLES}

"Planck Mass" \sim 10^{80} \times \text{proton mass}

Prediction of Kaluza-Klein Theory for charged particles
Subtler, but more realistic, Kaluza-Klein variants...

Macroscopic 3D Gravity (General Relativity)

Macroscopic 3D Electromagnetism!!

...in modern SuperString Theories
"INTERNAL SPACES"

Symmetry determines the emergent macro forces.

3D

microscopic 5\textsuperscript{th} dimension

"internal space" at a single 3D point

1D circle

\Rightarrow Electromagnetism
"INTERNAL SPACES" can be higher-dimensional. Symmetry determines the emergent macro forces.

3D

microscopic 5th+6th dimensions

"internal space" at a single 3D point

2D sphere

⇒ ElectroWeak Forces

symmetries
“INTERNAL SPACES” can be higher-dimensional. Symmetry determines the emergent macro forces.

3D dimensions

“internal space” at a single 3D point

Higher dimensional symmetric internal space

⇒ Strong Nuclear Force, “Quantum Chromodynamics”
Quantum Mechanics $\Rightarrow$ Force fields comprised of particles

- **Planck Mass**
  - Photon
    - Electromagnetism
  - Photon, $W^+, W^-$
    - Electroweak
  - Photon
    - DATA

- **Mass**
  - Planck Mass
  - 100 proton
"INTERNAL SPACES" can be higher-dimensional. Symmetry & its Breaking determines emergent forces.

OBLATE 2D sphere ➞ Electromagnetism + (short-range) Weak Nuclear Force.

Microscopic 5th+6th dimensions

"internal space" at a single 3D point
The Vacuum & the Higgs Field

Vacuum = Lowest Energy State

3D

5th+6th dimensional oblate sphere

Higgs Field Wave

less oblate
more oblate
less oblate
more oblate
less oblate

3D
“STANDARD MODEL” of Gravity, Electromagnetism, Weak & Strong Nuclear Forces in full realism is written in mathematics of external & internal spaces agnostic about whether or not internal space relates to extra dimensions or string theory. It is in fantastic accord with enormous body of experimental data.
The Hierarchy Problem

- **Strongly Oblate Mass**: Planck Mass $W^+, W^-$
- **Perfect Sphere Mass**: Planck Mass
- **Very, Very Slightly Oblate Mass**: Planck Mass

**Robust** vs **Very Delicate**
Quantum Mechanics $\Rightarrow$ Higgs Waves comprised of particles $\equiv$ Higgs Bosons
Quantum Mechanics + Relativity $\Rightarrow$

Anything is possible to create, given enough Energy:

$$E = mc^2$$

↑ Energy, ↑ mass of thing you want to create, ↑ Light-speed

Planck Mass

Mass

DATA

Higgs boson $w^+, w^-$

100. proton
PARTICLE COLLIDERS

Colliding Proton beams traveling close to light-speed

Detectors

photon Higgs nuclear jets

Mass

Planck Mass

100 proton 0 photon DATA

Higgs boson $W^+, W^-$
LARGE HADRON COLLIDER

Overall view of the LHC experiments.

ATLAS & CMS giant detectors

far under ground
Franco-Swiss Border

Higgs Boson Discovery (2012)

Candidate Higgs event (CMS)
Is newly discovered Higgs boson truly pointlike ("elementary") or COMPOSITE?

PREDENTS
The "indivisible" ATOM is really a composite of electrons "orbiting" a central nucleus.
The nucleus is a composite of protons & neutrons
The proton is a composite of quarks & gluons
Higgs Boson Compositeness would (help) resolve the Hierarchy Problem. The Higgs constituents would have to be very tightly bound in a novel manner. Composite Higgs Theory is very challenging. But there is an indirect approach via an emergent 5th dimension...
CHARACTERISTIC SHAPES & SIZES OF COMPOSITES

electron

Car

Atom

$10^{-12}$ m

Shapes & Size can be correlated.
THE ILLUSION OF DEPTH
THE ILLUSION OF DEPTH
THE ILLUSION OF DEPTH
THE ILLUSION OF DEPTH

2D → “3D”
Theoretically, “SCALE-INVARIENT” QUANTUM SYSTEMS can produce same characteristic shapes over large range of sizes ...
3D → "Holography" → "4D Space"

↑

3D

"5th dimension"
Times rescale with Lengths like the (mis)behavior of clocks & aging near a black hole horizon

3D

“tick tick tick”

“5th dimension”

“t-i-c-k – t-i-c-k – t-i-c-k”
**Conformal Symmetry**

rotates "5th dimension" with usual real 3D space.

\[ \Rightarrow \text{AdS/CFT Duality} \quad \text{Maldacena '97; Gubser, Klebanov, Polyakov '98; Witten '98} \]
"Holographic" Composite Higgs Theory

3D

\[ \frac{1}{\text{protein size}} \times \text{proton size} \]

minimal size in Quantum Gravity

5th dimension

\[ \frac{\text{maximal size of Higgs composite}}{10000 \times \text{proton size}} \]

is an INTERVAL
Warped 5D Spacetime is natural "stage" for particle physics

Randall, Sundrum '99
5D GEOGRAPHY

Quantum fields of different particle species naturally have different characteristic profiles in 5th dimension.

Species with larger overlap are more likely to interact. This helps explain otherwise mysterious patterns in the observed interaction strengths.
5D GEOGRAPHY
Solves the HIERARCHY PROBLEM!
(W mass from) Higgs mechanism gravitates only very weakly.

graviton

5th dimension, MICROSCOPIC

Higgs

W

mass

BLACK HOLES

Planck Mass
EXTRA-DIMENSIONAL PERCEPTION

↑3D

What 5th dimension?

standard light

ultraviolet light needed to see 5th dimension

microscopic interval 5th dimension
EXTRA-DIMENSIONAL PERCEPTION

Quantum Energy

$E_{\text{photon}} \sim \frac{1}{\text{wavelength}}$

What 5th dimension?

- Standard light
- Ultraviolet light needed to see 5th dimension

$\uparrow^{3D}$

Microscopic interval 5th dimension
EXTRA-DIMENSIONAL PERCEPTION

- Top
- Warped light wave
- $E_{\text{photon}}$ requires Large Hadron Collider
- 5th dimension
- What 5th dimension?
- Ultraviolet light needed to see
- Microscopic interval
- Standard light
- 5th dimension
**Extra-Dimensional Perception**

- Warped light wave
- Eventually "splatters" into top quarks

- What 5th dimension?
- Standard light
- Ultraviolet light needed to see
- Microscopic interval
- 5th dimension
BUT COMPETES WITH STANDARD TOP QUARK PRODUCTION
PRECISION TESTS
of STANDARD PROCESSES

- Higgs boson properties
- species-changing processes
- time-reversal asymmetric processes

also provide powerful but indirect probes of 5th dimension

sensitive to details of theoretical model

Also yet to make a discovery...
FUTURE COLLIDERS?
at high precision & high energy Frontiers

Proposed in China...

...And in Europe (environs of CERN)

$O(10)$ improvements in $E$ & Higgs precision!
VERY EARLY UNIVERSE

The Universe is expanding:

galaxies

space stretching
VERY EARLY UNIVERSE

The Universe is expanding:
V E R Y  E A R L Y  U N I V E R S E

The Universe is expanding
Just after Big Bang it was
far denser, hotter
& expanding much faster

No galaxies, stars, atoms then.
Just thick opaque hot cosmic soup
of subatomic particles & antiparticles.
Early Universe: Warped 5D Phase Transition

High Temperature after Big Bang

Expansion

5th dimension

Black Event Horizon

"veiling" Higgs, Electroweak Unified Forces operate

Cremenelli, Nicolis, Ratlazzi '02
Later, Universe cools a bit until...

Bubbles of Higgs Boundary "peek" through horizon & expand, collide

Gravitational Waves!

Randall, Servant '06

Agashe, Du, Ekhteraachian, Kumar, Sundrum, in progress
TODAY the Universe is very cold

Bubbles have coalesced & "taken over" Electromagnetism & Weak Force are distinct
LOOKING BACK IN TIME

Few minutes ago

Cosmic Microwave Background

13 billion years ago

Few years ago

Cosmic soup of subatomic particles

First (neutral) atoms formed
WRINKLES IN SPACETIME

Proposed LISA GW detector

Cosmic Gravity Wave Background

Frequency Spectrum ➔ Transition Dynamics

Kosowsky, Turner, Watkins 92
GRAND UNIFICATION

There is circumstantial evidence that the Electroweak Force & Strong nuclear Force emerge from a highly symmetric internal space (symmetry of 9D sphere!) again somewhat “oblate.”
GRAND UNIFICATION

Interaction strength

Quantum Theory extrapolation

Electromagnetism

Strong nuclear force

Weak nuclear force

Data

Energy of interacting particles

$E_{LHC}$

million $E_{LHC}$

billion $E_{LHC}$

$E_{LHC}$
GRAND UNIFICATION

Quantum Theory

Electromagnetism

Strong nuclear force

(Near) Coincidence predicted by Grand Unification

Energy of interacting particles

$E_{LHC}$

$\text{million \times } E_{LHC}$

$\text{billion \times } E_{LHC}$

Data

Interaction strength

$\frac{1}{\text{interaction strength}}$
GRAND UNIFICATION

Interaction strength

Quantum Theory

Electromagnetism

Strong nuclear force

(Near) Coincidence predicted by Grand Unification

Energy of interacting particles

Energies needed to test Unification!
“Orbifold”

Grand Unification
of EM + Weak + Strong interactions

Analogous to Electroweak Higgs mechanism...

Grand Unification Higgs

5th dimension
unified fields &
gravitons orders of magnitude beyond terrestrial colliders!

$\sim \frac{1}{\text{proton size}}$
CMB is almost, but not perfectly spherically symmetric due to microscopic quantum fluctuations stretched to cosmic size by Universe's growth spurt, "Inflation" as seen by Planck Satellite
RECALL

PARTICLE COLLIDERS

Detectors

Colliding Proton beams

Traveling close to light-speed

photon

Higgs

W

nuclear jets
COSMOLOGICAL COLLIDER
PHYSICS  Chen, Wang ’10
Arkani-Hamed, Maldacena ’15

Recall we need $E \sim \frac{1}{\text{wavelength}}$ to create waves to look inside the 5th dimension.

The expansion of space itself during cosmic inflation can supply this energy!

The CMB (and its future successors) act as detectors of the “splatler” of the 5th dimensional gravitational & unified waves

Kumar, Sundrum ’18
DECODED BY STATISTICS OF QUANTUM FLUCTUATIONS TO SEE THE 5D WAVES
CONCLUSION

Fundamental Physics is strangely beautiful, driven by geometric & symmetry principles.

Fundamental forces are members of a family, descended from unified ancestors at the dawn of time.

Extra-dimensional spacetime structure can play a central role in this physics.

A diverse range of ambitious, titanic experiments will probe this physics this century.