### The Search for the Fundamental Theory of the Universe

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# Are we on the verge of a new revolution in science?

### **Greatest Recent Discoveries**

- Fluctuations of Cosmic Microwave Background (1992) (Nobel Prize 2006)
- Dark Energy (1998) (Nobel Prize 2011)
- Accolerating expansion Slowing expansion Beg Expanding universe





- Higgs Discovery (2012) (Nobel Prize 2013)
- Gravitational waves (2016!) (Nobel Prize 2017)



# Why are these discoveries important ?

#### (Wait a few minutes/slides!)

### Some Science History Highlights (Understanding from Unification)

\* Book recommend: S. Weinberg ``To Explain the World"

### **Science Goals and Techniques**

- Explanations of physical phenomena
- Asking well defined questions
- Making predictions, testing predictions with experiment

### **Science Tools**

Human senses

- Human brain:
  - 1. Curiousity
  - 2. Technology to go beyond our senses
  - 3. Analytic thinking including mathematical techniques





### Newton's Unification: Gravity (XVII-XVIII Century)

#### **Gravity on earth**



#### **Gravity on space**



#### Newton's law of gravity



 $G = 6.67 \times 10^{-11} \frac{N \cdot m^2}{Kg^2}$ 



### Electricity + Magnetism Unification

Faraday and Maxwell (XIX Century)

#### Electricity



Magnetism



#### **Electromagnetism (Maxwell 1876)**

$$\nabla \cdot E = 4\pi\rho$$
$$\nabla \cdot B = 0$$
$$\nabla \times E = -\frac{1}{c}\frac{\partial B}{\partial t}$$
$$\nabla \times B = \frac{4\pi}{c}J + \frac{1}{c}\frac{\partial E}{\partial t}$$

**Optics** 





= Light!!

### Thermodynamics-Mechanics Unification (XVIII-XIX Century)



### e.g. Temperature = average kinetic energy!!





### Microscopic origin of macroscopic quantities !

# e.g. Entropy from number of states

#### Boltzmann constant: k=1.38 x 10<sup>-23</sup> J/K

### Unification of Space and Time (Einstein's Theory of Relativity XX Century)

### **Special Relativity**



#### Minkowski Spacetime

Maximum (constant) speed: 'speed of light'

c=3x10<sup>8</sup> m/s

### Unification of Gravity and Spacetime Geometry (Einstein 1915)

### **Gravity and Geometry of Spacetime**

Einstein 1915



### Unification of Particles and Waves (Quantum Mechanics XX Century)





### **Quantum Fluctuations**

 $\Delta x \, \Delta p \ge \frac{\hbar}{2}$ 



Naïve Expectation (ordinary experience)



Quantum Fluctuation (imperfect representation)

### **On the Atomic Hypothesis**

IF, IN SOME CATACLYSM, ALL OF SCIENTIFIC KNOWLEDGE WERE TO BE DESTROYED, AND ONLY ONE SENTENCE PASSED ON TO THE NEXT GENERATION OF CREATURES, WHAT STATEMENT WOULD CONTAIN THE MOST INFORMATION IN THE FEWEST WORDS? I BELIEVE IT IS THE ATOMIC HYPOTHESIS (OR THE ATOMIC FACT, OR WHATEVER YOU WISH TO CALL IT) THAT ALL THINGS ARE MADE OF ATOMS – LITTLE PARTICLES THAT MOVE AROUND IN PERPETUAL MOTION,

ATTRACTING EACH OTHER WHEN THEY ARE A LITTLE DISTANCE APART, BUT REPELLING UPON BEING SQUEEZED INTO ONE ANOTHER. IN THAT ONE SENTENCE, YOU WILL SEE, THERE IS AN ENORMOUS AMOUNT OF INFORMATION ABOUT THE WORLD, IF JUST A LITTLE IMAGINATION AND THINKING ARE APPLIED.

- RICHARD FEYNMAN -



#### Periodic Table

### Unification of Special Relativity and Quantum Mechanics

1930's...



Dirac (+ Jordan Heisenberg, ..).

# e.g. Quantum Electrodynamics (1948)



Sin-Itiro Tomonaga

Julian Schwinger

Richard P. Feynman

### e.g. Electroweak Unification



Glashow, Salam, Weinberg 1960's

### **The Standard Model**

	M	119

matter	con	stitu	ents	
spin =	1/2,	3/2,	5/2,	

S

Approx.

Mass

GeV/c<sup>2</sup>

0.003

0.006

1.3

0.1

175

4.3

spin = 1/2

Electric

charge

2/3

-1/3

2/3

-1/3

2/3

-1/3

Leptons spin = 1/2			Quark
Flavor	Mass GeV/c <sup>2</sup>	Electric charge	Flavor
ν <sub>e</sub> electron neutrino <b>e</b> electron	<1×10 <sup>-8</sup>	0 -1	U up d down
$ u_{\mu}^{muon}$ neutrino $\mu$ muon	<0.0002 0.106	0 -1	C charm S strange
$m{ u}_{ au}^{ ext{ tau}}_{ ext{neutrino}}$ $m{ au}$ tau	<0.02 1.7771	0 -1	t top b bottom

#### 4 forces 3 Families + Higgs 3+1 Dimensions

### BOSONS

#### force carriers spin = 0, 1, 2, ...

<b>Unified Electroweak</b> spin = 1			
Name	Mass GeV/c <sup>2</sup>	Electric charge	
γ photon	0	0	
W-	80.4	-1	
W+	80.4	+1	
Z <sup>0</sup>	91.187	0	

Strong (color) spin = 1			
Name	Mass GeV/c <sup>2</sup>	Electric charge	
<b>g</b> gluon	0	0	

- Higgs H spin=0
- Graviton G spin=2 (Classical!?)

#### Forces



The particle drawings are simple artistic representations

#### THE STANDARD MODEL



### Some Properties of the SM

- Arguably greatest theoretical achievement in past 75 years.
- It is simple (not the simplest)
- It is 'ugly' (elegant principles but many free parameters)
- Not complete (baryogenesis, dark matter, gravity)

### **Standard Model + Gravity**

Our Universe...

# An Example: Our Universe!



### Cosmic Microwave Background



### **Open Questions**

- Why? (3+1 (dimensions, families, interactions);
   + some 20 parameters (masses, couplings))
- Naturalness (hierarchy, cc, strong CP)
- 'Technical' (confinement,...)
- Cosmology (dark matter, baryogenesis, density perturbations of CMB, origin/alternatives to inflation,..., big-bang)
- Consistency (gravity)

#### Dark Energy (Accelerating Universe 1998)

17-1

### Energy Distribution of the Universe



### **Dark Matter**

Observed vs. Predicted Keplerian





### FUNDAMENTAL PROBLEM Quantum Gravity











 $= 10^{19} \text{ GeV}$ 

 $h/2\pi = \hbar = 1.0546 \times 10^{-34}$  kg m<sup>2</sup> sec<sup>-1</sup>  $G_{\rm N} = 6.672 \times 10^{-11} {\rm m}^3 {\rm kg}^{-1} {\rm sec}^{-2}$ 

 $c = 2.99792458 \times 10^8$  m/sec

21.8 µg

 $\frac{\hbar c}{G}$ 

### Planck Units

# String Theory?

### **String Theory**

- Particles 'look like' strings
- Gravity is included
- Can unify all particles and interactions (Einstein's dream)
- Universe lives in 10 (11) dimensions !!!
- For our universe 10d = 4d+6d (6d very small?)
- Branes
- New 'fermionic' dimensions (supersymmetry!).





### SUPERSYMMETRY



### SUSY particles mass 1TeV solve hierarchy problem!!!





#### United forces



### **Brane World**



### **The Theory is Unique**



#### But many possible solutions or 'vacua' Each solution a different universe!!!

### Size and shape of extra dimensions fixed!

### Landscape of Solutions



### **Multiverse**





### Anthropic explanation of dark energy??







- Field is broad: Mathematics, cosmology, phenomenology, computer,...
- After the Higgs it is one of the main guides to Beyond Standard Model.
- Continuous 'cumulative' progress (inflation, dark matter candidates, etc.)
- The 'Swampland'?





- Realistic Model Building: Many quasi-realistic models (local and global) but not fully realistic yet.
- SUSY Breaking and Moduli Stabilisation: A handful of 'scenarios' (generically scalars much heavier than gauginos)
- Inflation and postinflation cosmology: (Few scenarios with concrete predictions).



### Gravity/No-Gravity correspondence!



### **Some Implications of Holography**

- Proper definition of quantum gravity theory!
- Black hole entropy/area! S<sub>BH</sub>= (kc<sup>3</sup>/4Għ) A
- Information loss paradox 'solved'!?

# Future?

- Experimentally driven? (LHC, axion search, post-Planck/experiments, Gravitational waves) (SUSY? Z'? non-gaussianities?, DR settled? Tensor modes?)
- Accelerators: ILC, 100Km/100TeV hadron collider!?
- Evidence for String (GUT) scale physics?? (proton decay, cosmic strings, tensor modes, bubble collisions?...)

• Properly define the theory!!

### **String Models**

Too many string models?
 (>>10<sup>500</sup>)

 Or too 'few' models?
 (Not fully Realistic model yet!!!)

### Machine learning?





- **Typical statement:** "We do not understand well enough string theory to try to extract its physics implications"
- **Bold answer:** "We may understand the theory better than we think (at low energies and weak couplings) using all foreseeable ingredients: geometry, branes, fluxes, perturbative, nonperturbative effects, etc."

'...our mistake is not that we take our theories too seriously, but that we do not take them seriously enough. It is always hard to realise that these numbers and equations we play with at our desks have something to do with the real world.'

Steven Weinberg

