Abstract: Prepare to be amazed. Nima Arkani-Hamed is one of the world's most innovative scientists, with an infectious enthusiasm for decoding the mysteries of the universe. Renowned for his dynamic and accessible speaking style, Arkani-Hamed is among the most sought-after experts on topics including dark matter, extra dimensions, particle colliders, and the interconnectedness of them all. He was featured prominently in the critically acclaimed 2013 documentary <em>Particle Fever</em>, chronicling the search at the LHC for the Higgs boson. Arkani-Hamed will explore how recent research into quantum mechanics (nature's most fundamental forces and phenomena) promises to shed new light on our understanding of the universe's fabric of time and space.
Quantum Mechanics + Space-Time

in the 21st Century
Triumph of 20th Century

Relativity + Quantum Mechanics

Universe is Inevitable
Central to Dramas of 21st Century
End of Space-time [Gravity]
Limitations of QM [Cosmology]

Why is the Universe BIG, with BIG in it?
* Shockingly constrained by what we already know - unlike ever before!

[Almost impossible to]
20th Century Redux
Relativity + QM

“Quantum Field Theory”
Gravity + Electromagnetism

\[ e^- \quad e^- \quad \text{photon} \]

\[ e^- \quad e^- \quad \text{graviton} \]
Strong + Weak: Same Structure
\[ \begin{align*}
\text{long-range force} \\
(\sim 10^{-16} \text{ cm})
\end{align*} \]
Particles have "Spin"

\[
\frac{1}{2} \times h
\]
electron

\[
1 \times h
\]
W boson

\[
2 \times h
\]
graviton

Allowed:

\[
0, \frac{1}{2}, 1, \frac{3}{2}, 2, \frac{5}{2}, 3, \ldots \times h
\]
Particles we see extremely simple!

Just: \( \frac{1}{2}, 1, 2 \)
The Menu

Gluons

$SU(3)_c \times SU(2)_L \times U(1)_Y$

$\begin{array}{ccc}
Q & 3 & 2 \\
U^c & \frac{3}{3} & - \\
D^c & \frac{3}{3} & - \\
L^c & - & 2 \\
E^c & - & - \\
\end{array}$

$\begin{array}{c}
\frac{1}{6} \\
\frac{-2}{3} \\
\frac{1}{3} \\
\frac{-1}{2} \\
1 \\
\end{array}$

$W^\pm$, Photon
Why So Simple?
Why simple fundamental interaction?

Why not?

Why such a tiny menu of spins?
Whatever the Ultimate Theory

Relativity $\rightarrow$ Quantum Mechanics

At "Long" distances, particles interacting with spins $0, \frac{1}{2}, 1, \frac{3}{2}, 2$. Unique "gravity"
Units!

\[
\text{Time} = \frac{\text{distance}}{c}
\]

\[
\text{Energy} = \frac{\hbar}{\text{time}}
\]

Put \( \hbar = c = 1 \)

\[
(m_p c^2) = 1 \text{ GeV}
\]

\[
10^{16} \text{ GeV}^{-1}
\]

\[
\text{LHC Energies}
\]

\[
7000 \text{ GeV}
\]

\[
\text{Mass} \sim 10^{29} \text{ GeV}
\]

\[
\text{Lecture time} \sim 10^{27} \text{ GeV}^{-1}
\]

\[
10^{14} \text{ cm} \sim 10 \text{ GeV}^{-1}
\]
**Electric Force**

\[
q^2 \sim \frac{1}{137} \quad \text{[a pure number!]} 
\]

\[
e^2 \sim \frac{1}{r^2} 
\]

**Gravitational Force**

\[
\text{grav} \sim - G_N \frac{m_e^2}{r^2} 
\]

\[
\approx (10^{-33} \text{ cm})^2 \sim (L_{\text{Planck}})^2 
\]

\[
\frac{1}{r} \sim (10^{19} \text{ GeV}) 
\]
Quantum Mechanics

\[ \text{Probability} = (\text{Amplitude})^2 \]

Amplitude \( \sim z^2 \sim 1\% \) small
Mystery of "Quantum Gravity"

Amplitude $\sim G_N \times E^2$

Tiny for $E \ll (10^{19} \text{GeV})$ Plank Energy

Bigger than $1$ (!) for $E \gg (10^{19} \text{GeV})$
"Effective Theories"

\[ e \rightarrow e, \quad q^2 \sim \frac{1}{137} \]

- Gluon
- Strong

\[ g^2 \sim \frac{1}{10} \]

- Strength (Length)
- Irrelevant at "long" distances

Only @ low energies!
At high energies $\rightarrow$ approximate particles as massless

Energy $= |\text{momentum}|$

Spin $\rightarrow$ "helicity"
Amplitude depends on (Energy, Angle), complicated!
$S_A \quad S_B \quad S_C$

**NO** (Energy, Angle) $\rightarrow$ **COMPLETELY FIXED** (up to strength) by helicities!
B

C

D

gets
big

A

E

Again, completely known
... 1 yr of Grad School...
All Consistent Theories

Spins

\[ \{ 0, \frac{1}{2}, 1, \frac{3}{2}, 2 \} \]

+ some unit's for strength of interaction!
What About The Higgs?
Important difference between massive and massless particles:

Massive:
- $S = 1$
- Spin 3

Massless:
- 2 helicities

One extra guy!
Amplitude \sim q^2 \sim 1\% \\
Amplitude \sim q^2 \times \left(\frac{\text{Energy}}{\text{Mass W}}\right)^2 \\
\uparrow \quad \uparrow \quad \uparrow \\
1\% \quad 80\text{ GeV} \\
\rightarrow 1(!) \quad \text{if Energy} \geq 1200\text{ GeV}
Need Something New!

Spin of X:
- XXXX
- MUST BE SPIN 0
- X = Higgs

Strengths nailed
TRIUMPH FOR EXPERIMENT
TRIUMPH FOR THEORY
PHYSICS WORKS
Belief in Principles Paid Off

$0, \frac{1}{2}, 1, \frac{3}{2}, 2$

Higgs is first "really new" particle we've seen!
With the discovery of the Higgs, for the first time in our history, we have a self-consistent theory that can be extrapolated to exponentially higher energies.
21st Century Frontiers
Space-Time is Doomed

What Replaces It?
\[ \Delta E \sim \frac{1}{\Delta t} \rightarrow \text{eventually make Black Hole!} \]

No Operational meaning to distance \( < 10^{-33} \) cm, times \( < 10^{-43} \) s, ....

Energy needed \( \sim 10^{19} \) GeV

( L.H.C. Energies \( \sim 10^3 \) GeV...)
Amplitude $\sim (G_N \times E^2)$

- Tiny for $E \ll (10^{19} \text{GeV})$
- Bigger than $1 (!!!)$ for $E \gg (10^{19} \text{GeV})$

Planck energy
Our theories just break down when gravity is strong and quantum gravity effects are dominant.
A First Challenge in Quantum Gravity

Graviton Scattering

\[ \text{Amp} = G_N \frac{\langle 12 \rangle \langle 34 \rangle}{stu} \]

Correct at low energies
\[ s,t,u < \frac{1}{G_N} \]

Wrong at high energies!
\[ s,t,u > \frac{1}{G_N} \]
Naive Attempts Fail

\[ G_N (\langle 12 \rangle [34])^4 \frac{1}{stu} \]

Standard

* \[ \left( \frac{1}{1 - \frac{S}{M^2}} \right) \left( \frac{1}{1 - \frac{T}{M^2}} \right) \left( \frac{1}{1 - \frac{U}{M^2}} \right) \]

Modification to Suppress high Energy Growth

Violate "Unitarity" \rightarrow Negative Probabilities
Discovery of Miraculous Formula

\[ G_N \frac{\langle 12 \rangle [34] \rangle^4}{stu} \times \frac{\Gamma \left( 1 - \frac{s}{M^2} \right) \Gamma \left( 1 - \frac{t}{M^2} \right) \Gamma \left( 1 - \frac{u}{M^2} \right)}{\Gamma \left( 1 + \frac{s}{M^2} \right) \Gamma \left( 1 + \frac{t}{M^2} \right) \Gamma \left( 1 + \frac{u}{M^2} \right)} \]

\[ \Rightarrow \Gamma(n) = (n - 1)! \]

Incredibly: No NEG. Prob!

Where did STRING
No Local Observables!
Observables on "Boundary at Infinity"
(Quantum Gravity)_{D+1} = (Quantum Field Theory)_D

Emergent Space, Gravity, Strings ... → time

"Anti-de Sitter Space"

String Theory = Particle Physics
Emergent Space-Time

What are the correct observables?

$10^{10}$ light years
Why Is There A

Macroscopic Universe?
Vacuum is Too Exciting

Even Vacuum has energy!

Energy

$E_{\text{min}} = 0$

Classical

$E_{\text{min}} \neq 0$

Quantum

Bigger Fluctuations at Shorter Distances
Estimating $A$

"Vacuum Energy Density" $\sim$ Energy $\sim \left[ \frac{\text{Planck}}{\text{Planck Volume}} \right]$

Explosive Acceleration - Doubling size every $10^{-43}$ s!
What We Do

\[ \Lambda_{\text{observed}} = \Lambda_{\text{classical}} + \Lambda_{\text{quantum}} \]

\[ \begin{array}{c}
-2.6493781 \ldots 526 \\
120 \text{ decimals}
\end{array} \]

\[ + 2.6493781 \ldots 534 \]

120 decimals

SEEMS LUDICROUS
An Obvious Gap!

\{0, \frac{1}{2}, 1, \frac{3}{2}, 2\}

↑ Possible, very special!

"Supersymmetry"
Supersymmetry

"Quantum" dimensions

"superpartner" of electron

\[
\begin{align*}
\text{Quantum, Quantum} \\
\frac{dQ}{dx} \frac{dQ}{dy} = & -\frac{dQ}{dy} \frac{dQ}{dx} \\
(d\frac{Q}{x,y})^2 = & 0
\end{align*}
\]
Violent
Quantum
Fluctuations

Gone
Unification of the Forces - Gravity not far behind!
SUSY at the LHC

Quantum dimensions

Squark

"Missing" Energy

Ephoton

Ephoton
LHC By 2018

“Natural”
See major new physics except SUSY

“Fine-Tuned”
Nothing but Higgs, or unusual SUSY
Bigger Paradigm Shift
Is there a deeper structure underlying space-time + QM?
Sometimes, the most crucial clues are "hiding in plain sight", as funny features of existing theoretical framework.
\[ m_{\text{grav}} = m_{\text{inertial}} \]

\[ \downarrow \text{Principle of Equivalence} \]

G. R.
# events \uparrow

"known" physics

gl

gen

gl

gl

New physics

Energy

Rates:
\sim 1 \text{ billion collisions/sec}
\sim 10 \text{ top quarks/sec}
\sim 1 \text{ squark minute.}
Result of a brute force calculation:
Feynman's way of doing physics makes usual rules of spacetime + QM just look like obviously hiding...
Sitting Under our Noses for 60 yrs

String Theory

New Formulation of standard physics—emergent spacetime, QM
Many Other Threads of This Sort

Mining "Theoretical Data":

Amazing Physical + Mathematical
[Speculation]

We will come to see that QM + Spacetime emerge hand-in-hand from more primitive ideas.
This is a singular time in the development of Fundamental Physics.
The questions on the Table are the deepest ones — underpinnings of space + time, origins +
These questions couldn’t have even been meaningfully articulated 50 yrs ago. Today, we have finally have the theoretical framework to let us...
We also have fantastic experimental probes on a number of fronts, that may give us important clues.
Exhilarating Time

To Be Doing Physics:

“Next Step” will likely