String Theory: Physics from the Ultra-Small to the Universe

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Motivation …

The Popular Perception

New Yorker magazine

String Theory: a Sub-Discipline of Physics

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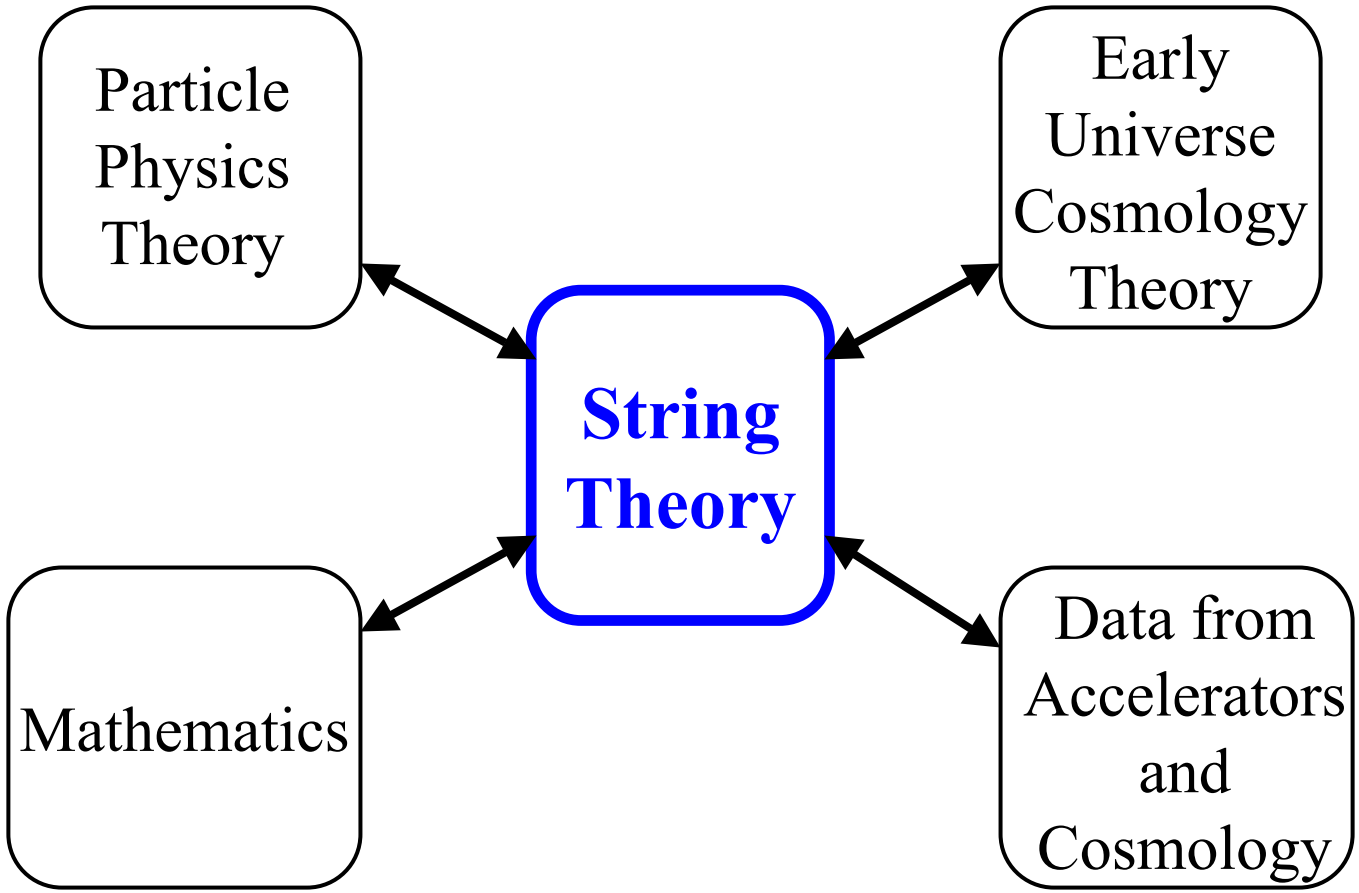

Enormous Dynamic Range

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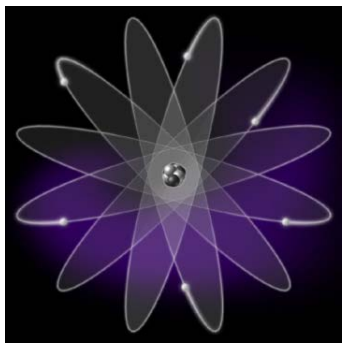
- String Theory is ambitious program!
- Aim: to explain origin and structure of fundamental matter and interactions, from subatomic to cosmological scales.

$10^{-33}\,cm$ ⇨  ⇨  ⇨ $10^{+28}\,cm$

- An underlying idea:
  - at low energy (today), broken symmetries
  - at high energy (past), restored symmetries.

How We Do Research

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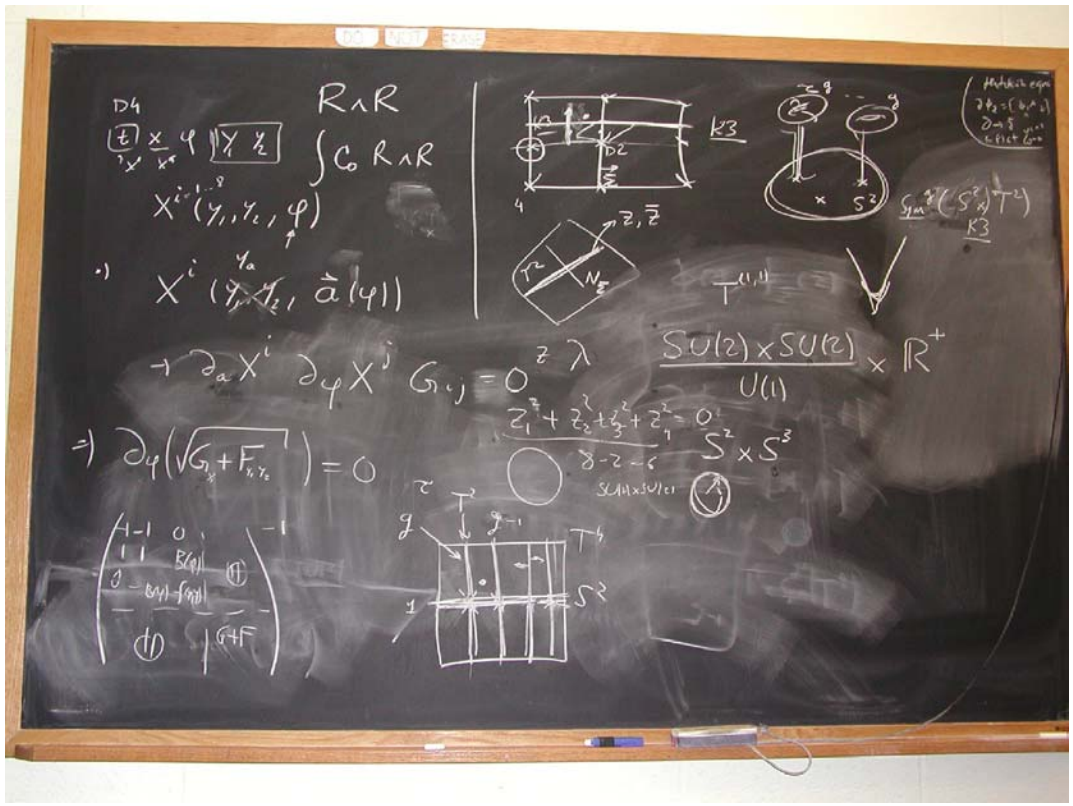
Tools: Pen, paper, computer, collaborators, blackboard.
Speed: Very fast-moving.
Preprints: Electronic since 1991 (http://arxiv.org/)
Topics: ***"Why?"*** questions



What Came Before String Theory …

Standard Model of Particle Physics

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- Two types of fundamental matter seen, so far:
  - Leptons: $(e, \nu_e), (\mu, \nu_\mu), (\tau, \nu_\tau)$
  - Quarks: $(u, d), (c, s), (t, b)$

- Four fundamental interactions:

	Gravi-tational	Electro-magnetic	Weak Nuclear	Strong Nuclear
Leptons:	✓	✓ (+,-)	✓	✗
Quarks:	✓	✓	✓	✓
Range:	Infinite	Infinite	10^{-16} cm	10^{-13} cm
Strength now:	Weakest	Weak	Weaker	Strong

Unification Hints

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- Fundamental "constants" describing strengths of interactions are *not* actually constant, but vary with energy:
  - Strong Nuclear gets weaker at higher energy,
  - Electromagnetic, Weak Nuclear, Gravity all get stronger.

- Variation effect involves
  - Special Relativity: Physics of the Very Fast,
  - Quantum Mechanics: Physics of the Very Small.

- Extrapolating upwards suggests unification at ultra-high-energy.
- Unification at String scale $10^{16}\ {}^{o}C < \mathit{Temp.} < \underline{10^{32}\ {}^{o}C}$
- *Extreme* Physics! Beginning of Universe / Inside Black Holes.

Cartoon of Evolution of Universe

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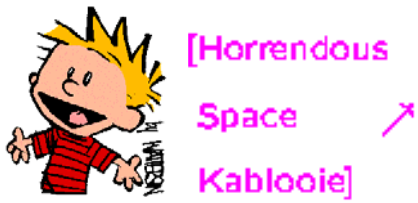

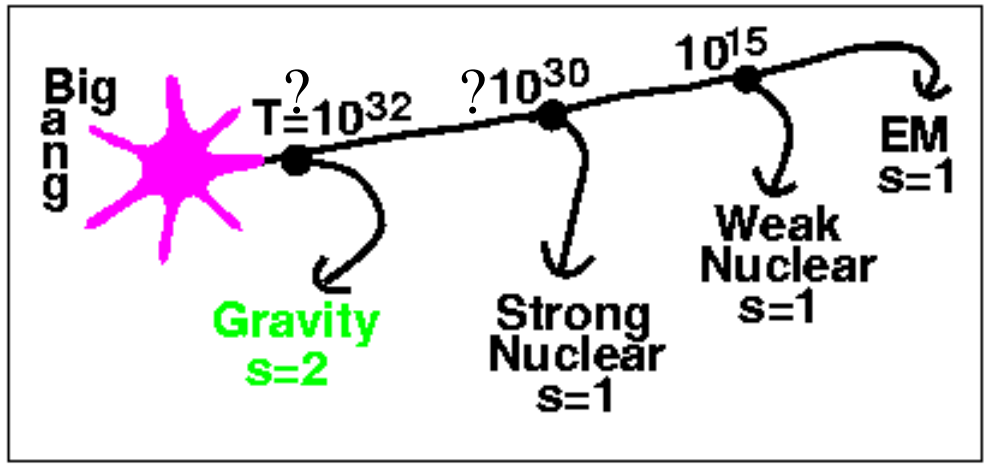

- At beginning:
  - incredibly hot tiny universe
  - no atoms, or even protons or neutrons: no binding possible
  - quarks and leptons interchangeable
  - all interactions same, and of same strength

- Soon afterwards –
  Universe inflated very fast, particle creation, leftover radiation...

Kofman

Unity of Interactions and Matter

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- Fundamental particles in Nature
  labelled by mass, and (intrinsic) spin.

- Dichotomy in Standard Model of Particle Physics:
  - Matter particles: s=½ "fermions" ,
  - Interaction-transmitting particles: spin s=0,1,2 "bosons".

- Theoretical unity via supersymmetry: boson-fermion pairing.
  - Unique and natural extension of symmetries of Nature.
  - Useful for helping solve other problems as well.

- Supersymmetry broken at low-energy: no sparticles seen yet.

Superpartners

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- Massive effort underway in theory and experiment communities to hunt for superparticles!

Particle	spin	Super("mirror world")partner	spin
leptons, quarks	s=½	sleptons, squarks	s=0
Higgs	s=0	Higgsino	s=½
photon,W,Z, gluon	s=1	photino, Wino, Zino, gluino	s=½
graviton	s=2	gravitino	s=3/2

- All extra particles have cosmological consequences.
  - Sparticles may provide "dark matter" of universe.

Accountability …

Accelerators

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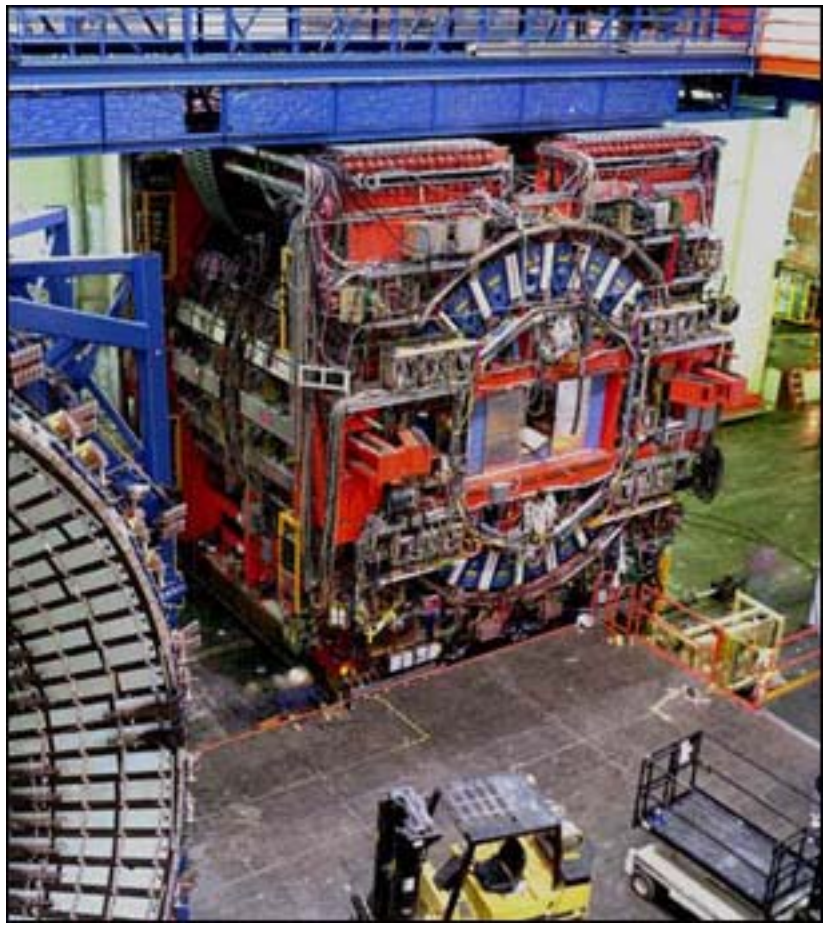
Particle physics: probe shorter distance with higher energy

ring 6 km across



detector several metres tall

CMB (etc.)

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Astrophysics: probe early universe by looking back in time
(universe expanding fast; speed of light finite)

Netterfield

Bond

What Led To String Theory …

The Asymmetrical Treatment of Gravity

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- Quantum Field Theory (QFT) is mathematical framework for Standard Model of Particle Physics: 3 interactions + particles.
- In Particle Physics, gravitational interaction is
  - largely ignored, because so weak;
  - treated only classically.
- Gravity last force to go quantum-mechanical, because *weakest*. Quantum gravity inaccessible in today's accelerators.

- Einstein's General Theory of Relativity (GR) is mathematical framework for classical theory of gravitational interaction. *Very* different than classical theories of other 3 interactions.
- GR describes space-time as a dynamical fabric, which is warped by matter, and causes matter to move.

A Theoretical Disaster and How to Fix It

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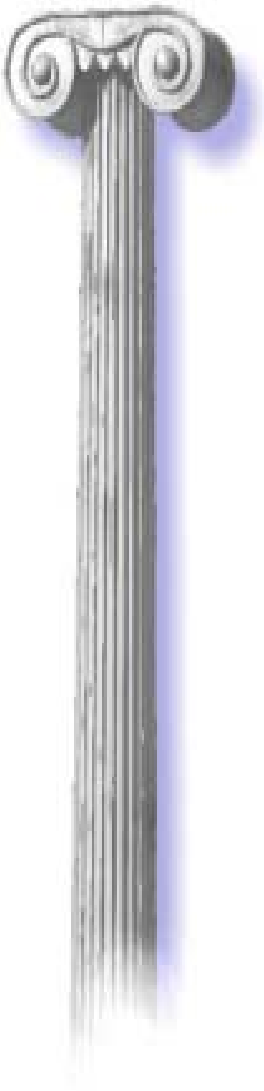

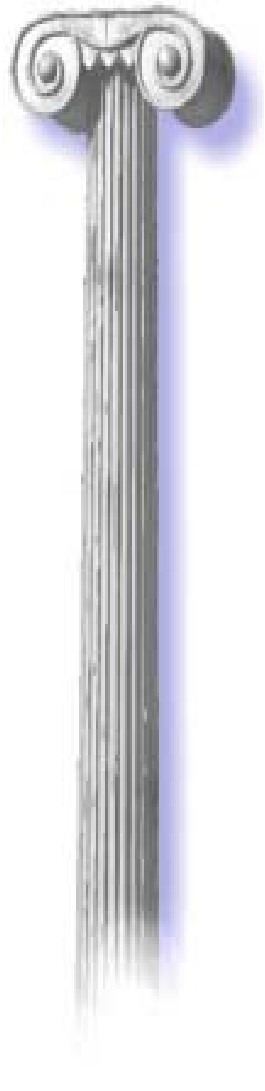

- Twin pillars of 20th C. experimental physics, Quantum Field Theory & General Relativity, are fundamentally incompatible. Oops!!
- Need *quantum* theory of gravity that:
  - predicts *sensible* physics in extreme regimes, e.g. birth of universe, black holes;
  - reduces back to Einstein's theory in ordinary regimes, e.g. solar system;
  - is internally consistent - strong constraint!;
  - unifies all forces and matter together.
- *Unique* theory which does all this (as of now) is SUPERSTRING THEORY.

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String Theory!

(... At Last!)

Aboriginal String

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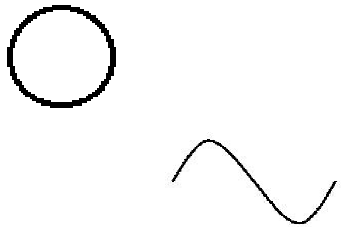
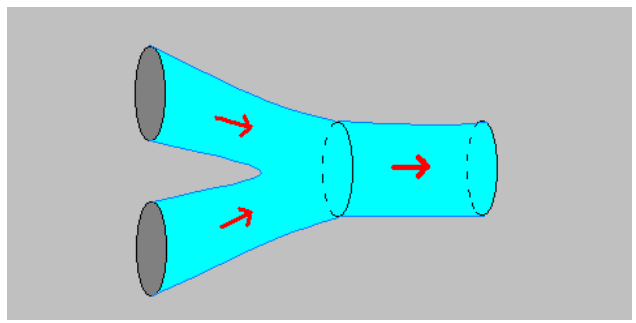
- All "particles" – matter and force-carriers (e.g. electron, quark, photon) are actually tiny vibrating *superstrings*, a.k.a. strings.



- String theory naturally lives in ten dimensions of spacetime. Necessary to roll up other six, inaccessible at low-energy now. Properties of internal space enable differentiation of "particles".

- Interactions described solely by splitting and joining of strings. Smooth process. Gravity automatic!



Extra Dimensions of Space

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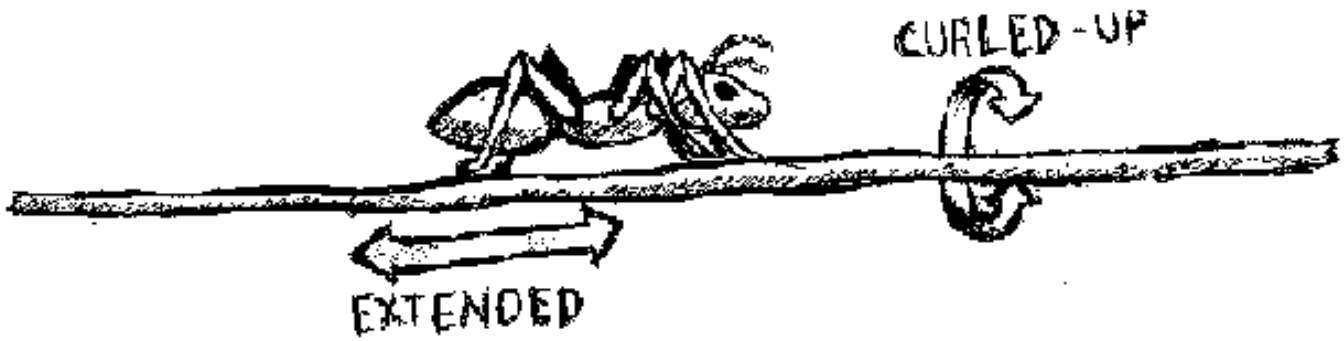
- Theories incorporating this idea go back over 80 years.



- Macroscopic ant can walk in only *one* direction - the second one is just curled up so small it goes unnoticed.
- Microscopic ant would think twig surface is *two*-dimensional.

- State-of-the-art experiment says:
  - if we're allowed in, extra dimensions must be $< 10^{-17}\,cm$
  - if only gravity is allowed in, they must be $< 0.15mm$

Spacetime as Quantum and Dynamical

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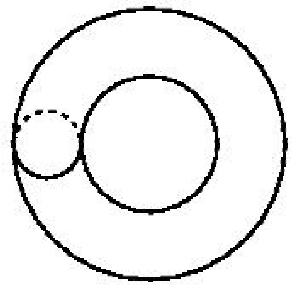
- Spacetime used to be the playing field of particles, interactions.
- But in string theory, we can smoothly:
  - tear the fabric of space, change its topology;
  - change the number of dimensions of space.



- So spacetime as a fundamental idea is probably doomed!
  Big spacetimes >> string size must arise *dynamically* – how?

- Some of the remaining, intriguing questions:
  - Why does time run forwards?
  - Was there anything before the Big Bang?
  - Should quantum theory be applied to the whole universe?
  - Is our Universe a lucky cosmological accident?

String Theory: Where the Buck Stops

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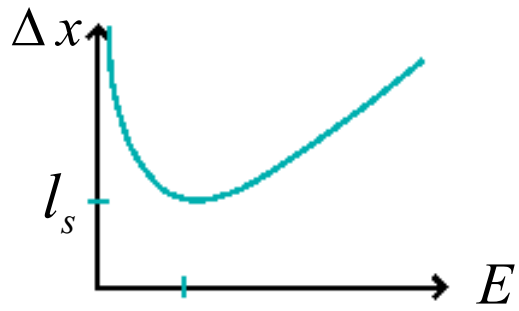
- Are there more layers of the onion?
- We reckon No – have strong indicators that the buck stops here: At ultra-high energy, things get *big* again.

$$\Delta x = \frac{hc}{E} + l_s^{\,2}\,\frac{E}{hc}$$



- Minimum distance ~ string scale
- Want to understand
  - Fundamental degrees of freedom of string theory, and dynamical principles that govern them
  - Particle Physics applications: proton decay (diamonds aren't forever!), quark confinement (this is US$1M question!), …
  - Early Universe Cosmology applications: dark matter, dark energy, particle/antiparticle excess, birth of universe…

Some Recent Progress We've Made

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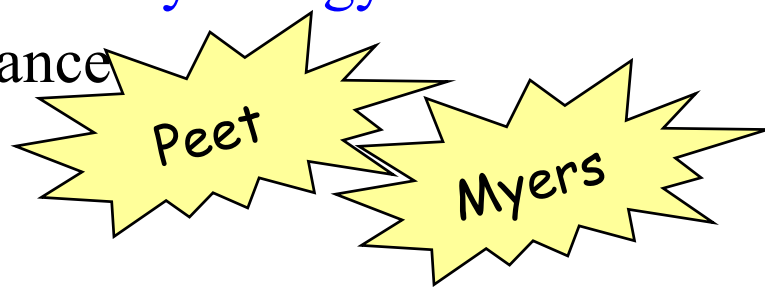
- Black hole is big fat classical spacetime in string theory
  - Event horizon = place of no return for infalling observer,
  - Singularity at centre – where GR+QFT breaks down.
- Near singularity, advantage of having string theory is that we know how to *calculate* there using full quantum string theory.

- Some spacetime singularities are so bad that whole spacetime must be thrown away. Others get resolved by stringy effects:
  - "enhançon": stringy minimum-distance phenomenon in different clothing
  - "dielectric-brane" expansion
  - "spacelike branes" may help resolve spacelike (unavoidable) singularities; most progress to date on avoidable singularities



The End …

Where to Learn More

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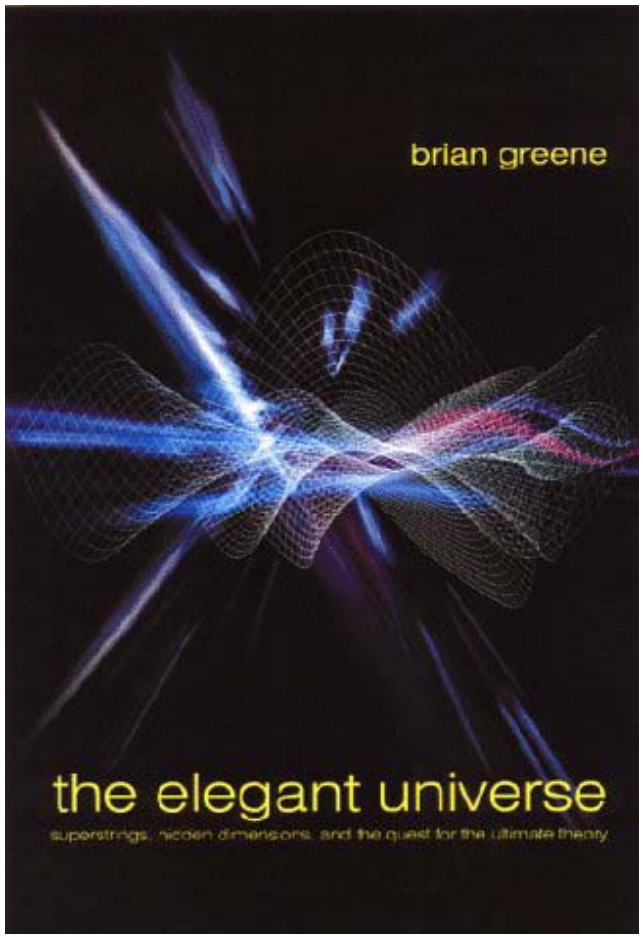

The Official STRING THEORY Web Site

www.superstringtheory.com

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