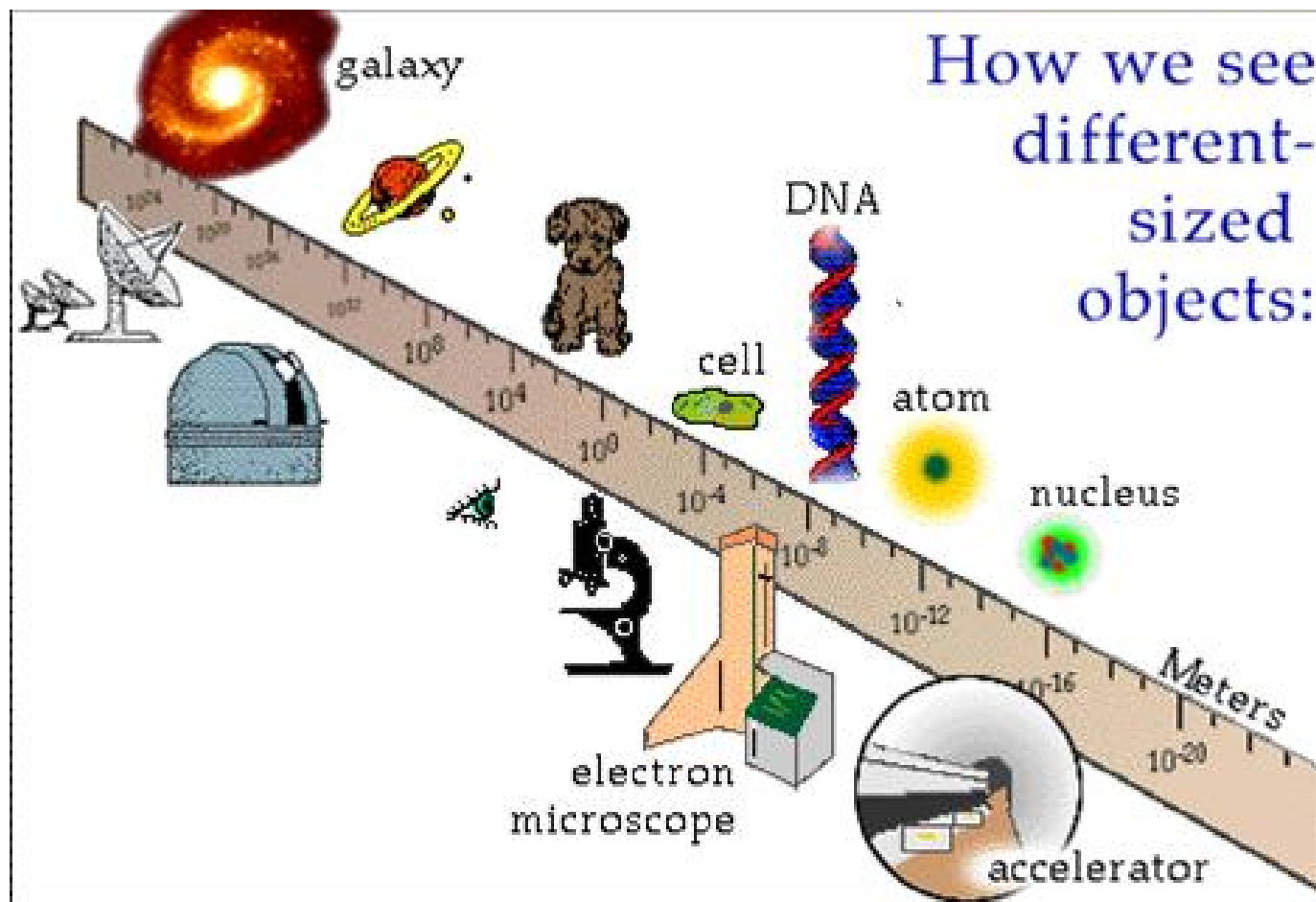


String Theory: the Popular Perception



Enormous Dynamic Range

Our aim: understand fundamental structure of matter and interactions from [sub-]subatomic to cosmological scales: $10^{-33}\text{cm} \rightarrow 10^{28}\text{cm}$.



Data: Particle Physics

Particle theory: highly successful description of particle physics to date.

Two kinds of fundamental matter seen, so far:

- leptons: $(e, \nu_e), (\mu, \nu_\mu), (\tau, \nu_\tau)$;
- quarks: $(u, d), (c, s), (t, b)$.

Four kinds of fundamental interactions seen, so far:

	Gravitational	Electromagnetic	Weak Nuclear	Strong Nuclear
Carrier particle?	graviton	photon	W^\pm, Z^0	gluon
Felt by leptons?	yes	yes/no	yes	no
Felt by quarks?	yes	yes	yes	yes
Range now?	infinite	infinite	subnuclear	nuclear
Strength now?	weakest	weak	weaker	strong

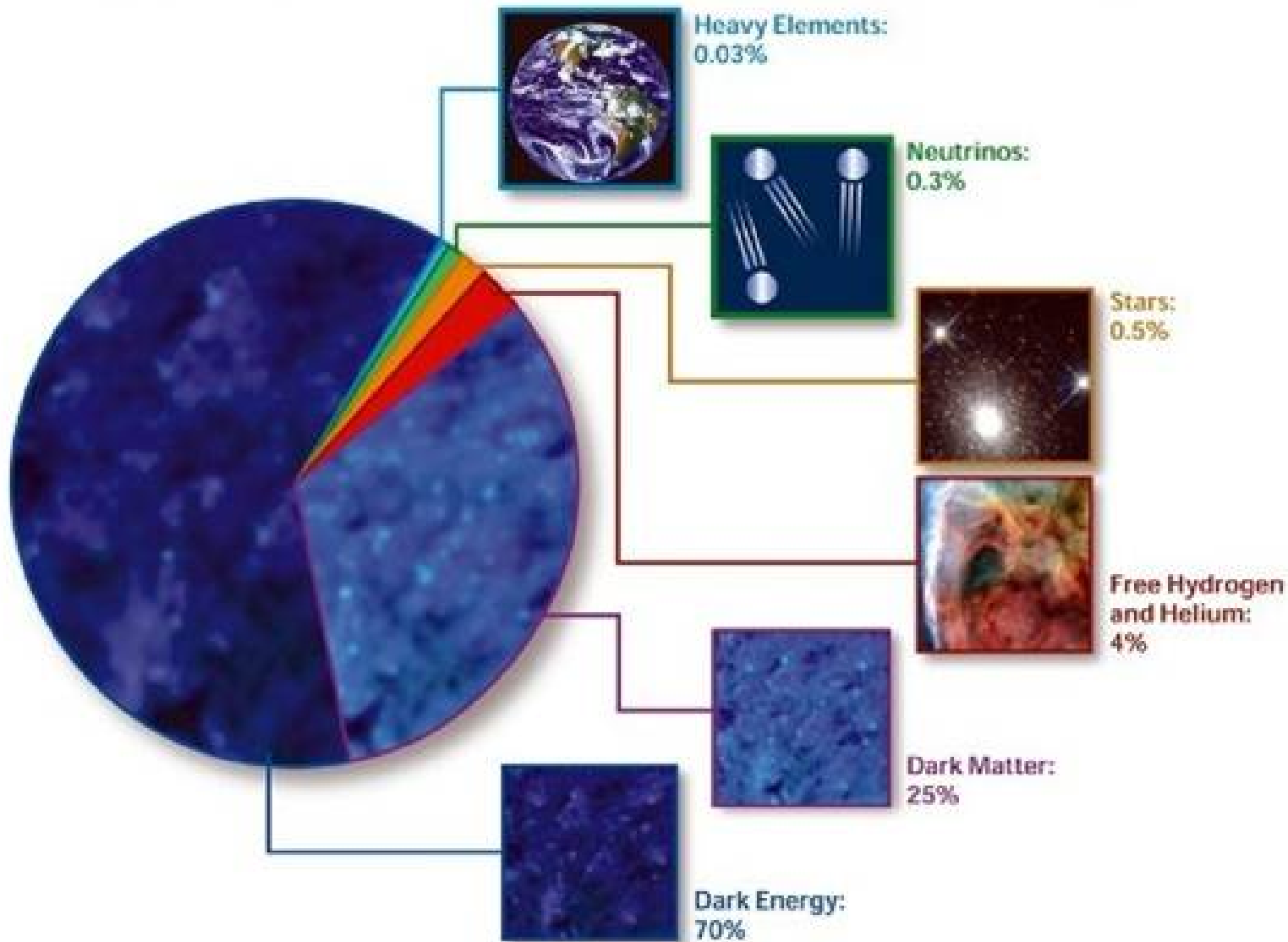
Chinks in armour of Standard Model of Particle Legos:-

- what explains neutrino masses?
- where is the Higgs? graviton?

Data: Cosmology

Weighing the universe:

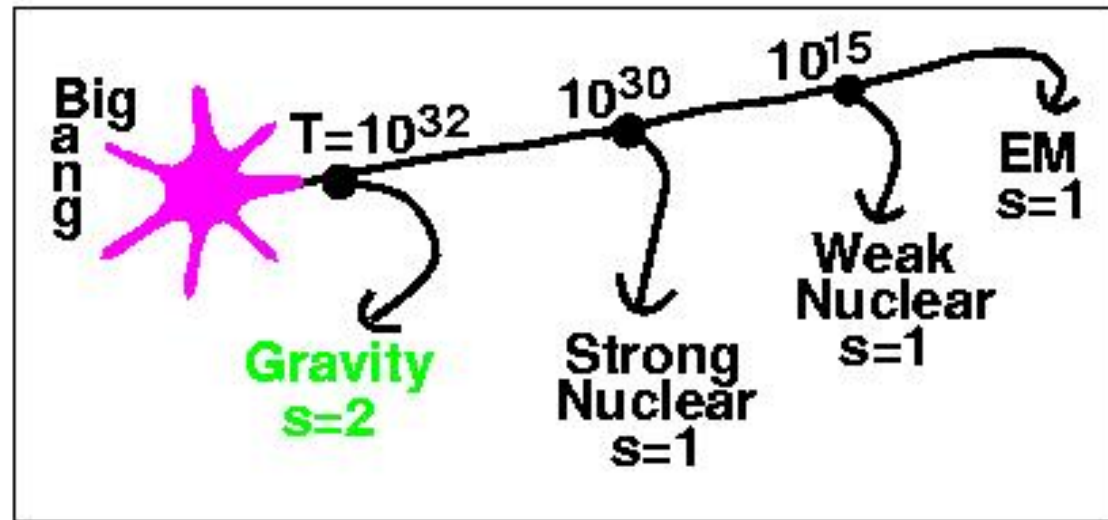
[more shortly re: how]



A Very Brief History of the Last 13.6 Billion Years



[Horrendous
Space
Kablooie]



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 expanded super-fast,
- particle creation, leftover radiation

Pushing the Energy Frontier: Cosmology Experiment

Speed of light finite; universe expanding. Faint, faraway light and other radiation enables tracing back over 10 billion years ago. Satellite, balloon-borne, ground-based detectors.



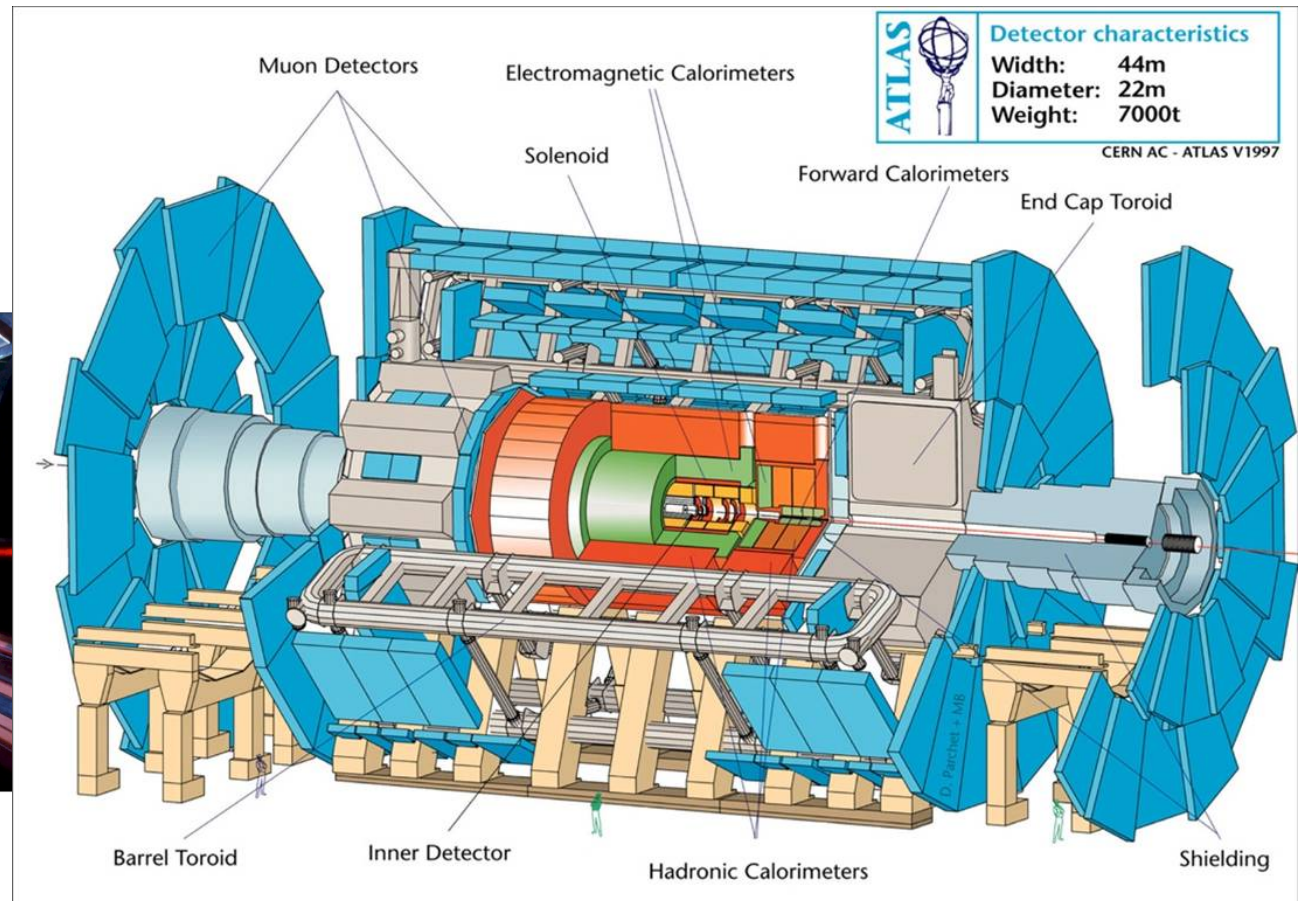
Ripples in CMB radiation left over from big bang (now: polarization), SN Ia, etc.: weigh constituents of universe. Exquisite precision.

Pushing the Energy Frontier: Particle Experiment

Quantum Mechanics teaches us that better resolution in space-time is obtained using probes with higher CM energy:

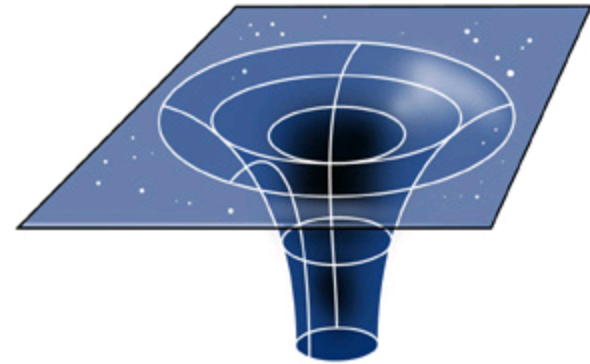
$$\Delta x \propto \frac{1}{E} \quad (\text{QM})$$

So we build bigger and bigger accelerators: LHC 2007/8–



Gravity Weighs In Theoretically

General Relativity [classical] says: if focus too much energy into bounded region, **black hole *always* forms!** Puts fundamental limits even on *thought* experiments.



Length scale associated to [quantum] gravity is the Planck scale ℓ_P , derived from fundamental constants of Nature for gravity, quantum mechanics, and relativity:

$$\ell_P = \left(\frac{G_N \hbar}{c^3} \right)^{\frac{1}{(d-2)}}$$

Black hole radius grows with CM energy E , limiting resolution:

$$\frac{\Delta x}{\ell_P} \propto (E \ell_P)^{\frac{1}{(d-3)}} \quad (\text{GR})$$

Therefore, with all *four*, quantum, interactions

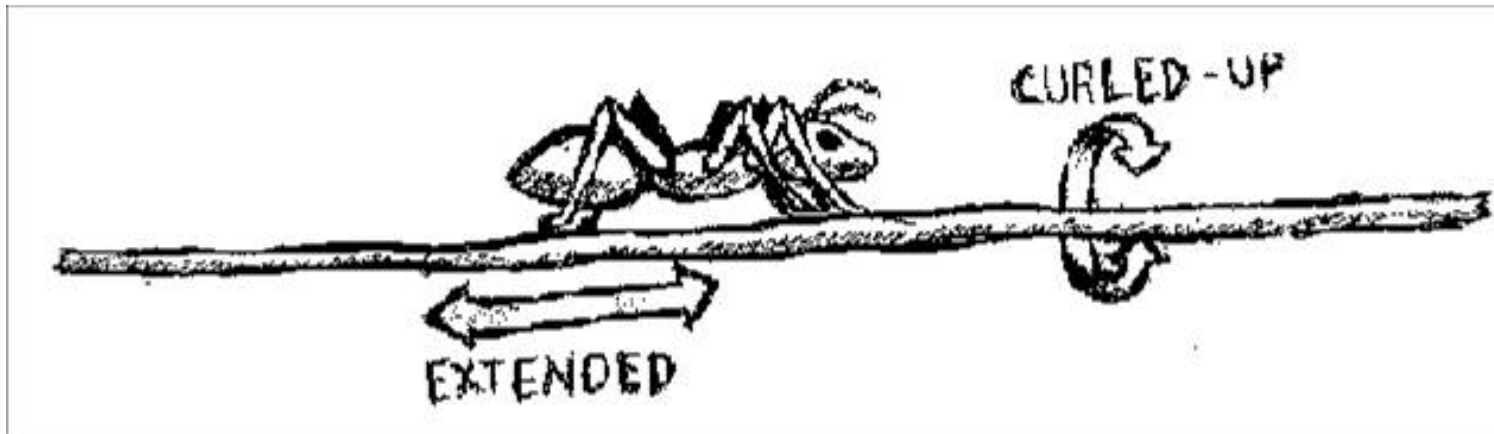
$$\frac{\Delta x}{\ell_P} \sim \frac{1}{(E \ell_P)} + (E \ell_P)^{\frac{1}{(d-3)}}$$

So more \$\$\$ \Rightarrow more results only to a certain extent.

Extra Dimensions of Space

So... How Big is That Planck Scale In The Window? ℓ_P derived from fundamental scale *and* depends on whether there are extra dimensions of space-time beyond the four we can currently see.

Theories incorporating extra dimensions idea go back over 80 (!) years. Simplest case: one extra [*spatial*] dimension curled up on a circle:

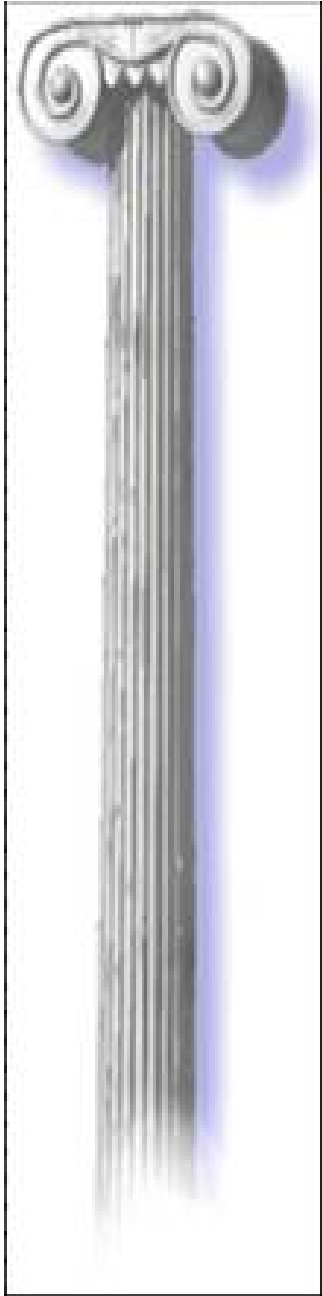


Big ant sees only one direction - circle dimension too small. Wee ant sees twig surface as two-dimensional. Lesson: 'size' seen depends on probe size; also depends on interaction (type, strength) used by probe.

State-of-the-art experiment says:

- democratic extra dimensions must be $< 10^{-18}$ cm;
- gravity-only extra dimensions must be $< 10^{-1}$ cm (!).

Twin Pillars and a Theoretical Emergency



Quantum Mechanics & General Relativity both hold up to exquisite experimental testing, to date. Many investigators looking for chinks in armour of QM+GR standard canon via data. Actually... Fundamental theoretical incompatibility!

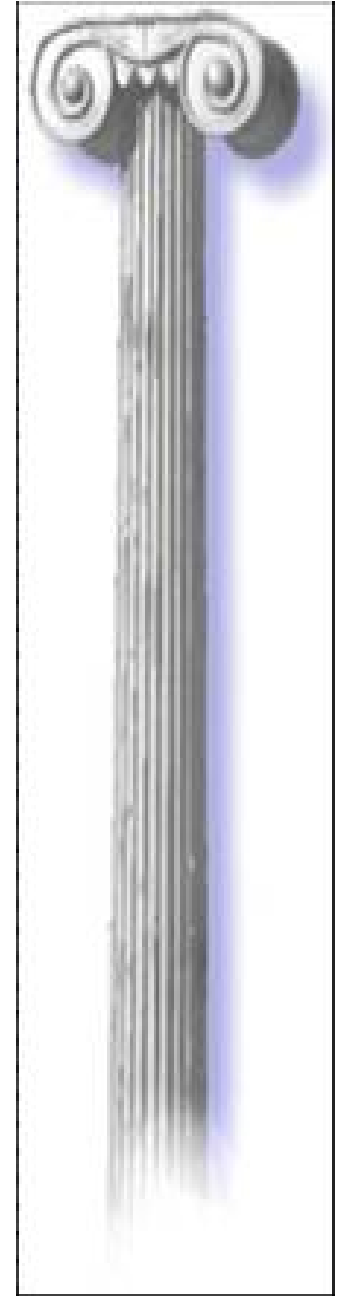
QM



GR

Want predictivity in extreme physical regimes, like birth of universe and black holes. New theory must be internally consistent (no mathematical anomalies); unify; explain patterns/differences; reduce to known theories in non-extreme regimes.

Unique theory with potential to do all this is **SUPERSTRING THEORY**.



Aboriginal string

Always wise to ask: “How well do we know what we think we know?”
Do you really know that electrons are – infinitely – pointlike?

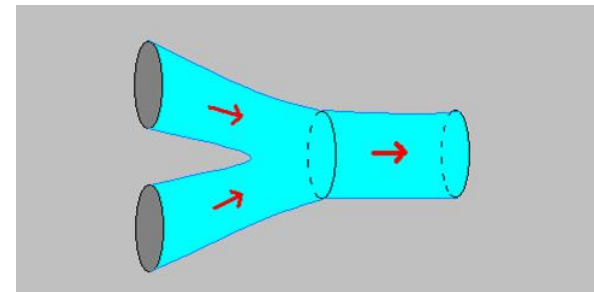
Basic idea: everything you thought was a pointlike particle is actually a tiny vibrating strand of energy called a *string*.



String oscillations obey wave equation, in the two dimensional space-time swept out by string as it moves. Quantizing a string actually amounts to studying infinite tower of simple harmonic oscillators. Non-trivial parts: constraints; infinite number of gauge invariances.

Massless (lowest) state of closed string has two spacetime indices and includes graviton; for open string get gauge boson.

Even more interestingly, interactions of strings described *smoothly* by splitting and joining. Hence, gravity falls out for free!



Why Pick One-Dimensional Objects?

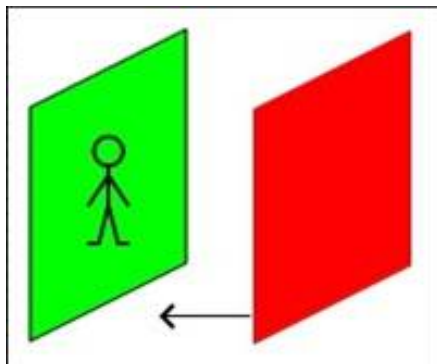
Why choose a string over some other thing? In particular, why not two-dimensional, three-dimensional, etc. objects as fundamental?

First, because strings can be quantized off the bat. Second, multi-dimensional objects called [mem]branes arise *naturally* in string theory.

D-branes: places where open strings end. Dynamical objects, with precise, calculable tension. Heavy when perturbation theory for strings is valid. Figure out dynamics of D-branes induced from string dynamics.

New options with D-branes (and NS5-branes, O_p -planes, . . .)

Good for model-building. e.g. was the big bang a big brane crash?



Duality

Maxwell's equations in vacuum

$$\begin{aligned}\vec{\nabla} \times \vec{E} + \frac{\partial \vec{B}}{\partial t} &= 0, & \vec{\nabla} \cdot \vec{E} &= 0; \\ \vec{\nabla} \times \vec{B} - \frac{\partial \vec{E}}{\partial t} &= 0, & \vec{\nabla} \cdot \vec{B} &= 0;\end{aligned}$$

have an equivalence:

$$\vec{E} \rightarrow \vec{B}, \quad \vec{B} \rightarrow -\vec{E}.$$

Physics expressed in two different disguises is the *same*. Finding examples of duality with matter harder; string duality more complex still.

D-branes play crucial roles in string duality, matching up spectra and states. (Previously missed). Spacetime no longer fundamental; see dualities growing more space dimensions! Gravitational theories dual to gauge field theories. “Deerskin diagram”.



Onion layers

When will the atomistic quest of the Greeks finally end? Are there more layers of the onion? None? One? Infinitely many??



We derived, from twin pillars of 20th century physics,

$$\frac{\Delta x}{\ell_P} \sim \frac{1}{(E\ell_P)} + (E\ell_P)^{\frac{1}{(d-3)}}$$

Minimizing this gives smallest distance scale that can possibly be probed in a unified theory of quantum gravity - such as string theory

$$\Delta x_{\min} \sim \ell_P$$

Indeed, spacetime itself gets challenged. Not fundamental; emergent.

In string theory (see next page!), explicit realization of minimum distance concept, sans hand-waving. Evidence that [the buck stops at string theory](#): theory itself provides indications that there is nothing at a deeper layer.

Stringy Minimum Distance Phenomenon

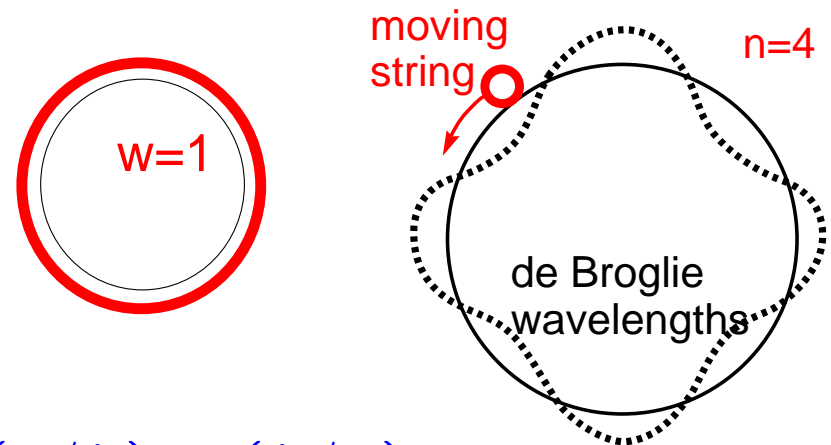
Imagine flat space-time with one dimension curled up i.e. $\mathbb{R}^{1,8} \times S^1$

$$m^2 \ell_s^2 = \frac{n^2 \ell_s^2}{R^2} + \frac{w^2 R^2}{\ell_s^2} + 2(N_L + N_R - 2)$$

Oscillator numbers for left- and right-movers must obey constraint

$$N_R - N_L = n \cdot w$$

n is the momentum number, i.e. the number of de Broglie wavelengths of the string that fit to the circle; and w is the number of times the string wraps around the circle.



T-duality symmetry: swap $n \leftrightarrow w$ and $(R/\ell_s) \leftrightarrow (\ell_s/R)$.

Stringy minimum distance phenomenon. No radii smaller than ℓ_s !

At special radius $R = \ell_s$, two wrapped string states $|n, w, N_R, N_L\rangle$

$$|1, 1, 1, 0\rangle \quad \text{and} \quad |1, -1, 0, 1\rangle,$$

vectors in $d=1+8$, become massless. For dual system of D-branes wrapped on K3, phenomenon yields singularity resolution “enhancement”.

Black Holes and their Thermodynamics

Not all massive objects should be thought of as black holes. Defining characteristic of black hole: *event horizon*. To qualify, object needs its Schwarzschild radius larger than its Compton wavelength – so we can consider it truly corralled within its event horizon. In d -dimensions,

$$(Gm)^{\frac{1}{(d-3)}} > \frac{1}{m}, \quad \text{i.e.} \quad m > m_P.$$

In $d = 4$, $m_P \sim 10^{-5}g$, so the electron, with $m_e \sim 10^{-23}m_P$, does not qualify as a BH. Earth-mass BH has radius of ping-pong ball.

Laws of black hole mechanics much like laws of thermodynamics.

- Zeroth: surface gravity constant over horizon
- First: $dM = TdS -$ (work terms)
- Second: surface area of black hole always increases [classically]

In general, finding new gravity geometries very difficult – eqns of motion horribly nonlinear from math p.o.v. But new solutions keep getting found in string context! New insights like black rings.

“Matter tells spacetime how to warp, and spacetime tells matter how to move.” One big consistency equation in string theory...

Statistical Mechanics of Strings

For strings, as the mode number increases, the number of ways of making a mode of a given mass increases – exponentially! See qualitative idea by looking at free massive states on $\mathbb{R}^{1,9}$: $N_L = N_R$ and

$$m^2 \ell_s^2 = 2(N_L + N_R - 2) \quad (1)$$

For groundstate, two directions to point oscillators in: few ways of doing this.

For N oscillators, rapidly increasing number of ways. Exponential.

[If we do not specify the spacetime spin, degeneracy larger because oscillators can point in any direction in spacetime. If specify spacetime spin, then degeneracy smaller but still exponentially large.]

Find (e.g. in Zwiebach new text)

$$\text{At large } m, \quad \rho_{\text{string}} \sim \exp(\ell_s m) \sim \exp\left(\ell_s \sqrt{N_L + N_R}\right)$$

Hagedorn transition

Suppose we consider a gas of strings in the canonical ensemble:

$$Z(T) = \int dE \rho_{\text{string}}(E) e^{-E/T} \sim \int dE (\dots) e^{E\ell_s} e^{-E/T}$$

Immediately, we notice that this integral does not make sense above the temperature

$$T_{\text{Hag}} \sim \frac{1}{\ell_s}$$

This is known as the Hagedorn temperature. It is the limiting temperature for an ensemble of strings; if more energy is pumped into the system, the energy goes into producing longer and longer pieces of string – which also actually interact with each other a great deal at this temperature – rather than raising the temperature.

Actually, the high-energy density of states of string theory is really *dominated by black holes* – the BH density of states ρ_{BH} grows more quickly at higher energy than ρ_{string} .

Strominger-Vafa

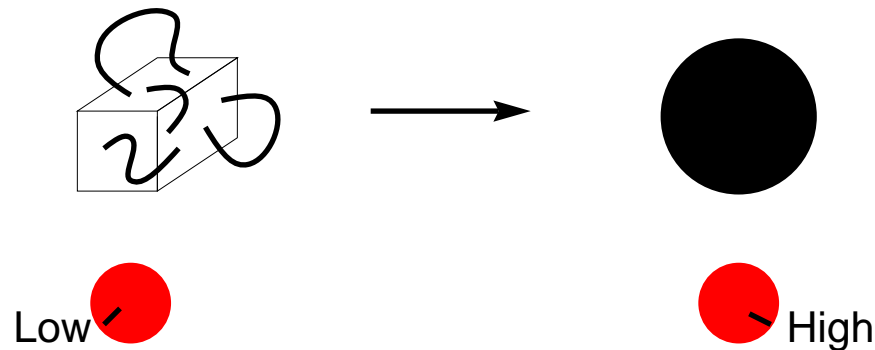
One of biggest results of second superstring revolution was Jan'96 counting of entropy of special black holes, using D-braney stringy statistical mechanics.

Special technical tool: *supersymmetric nonrenormalisation theorems*.

With enough supersymmetry,

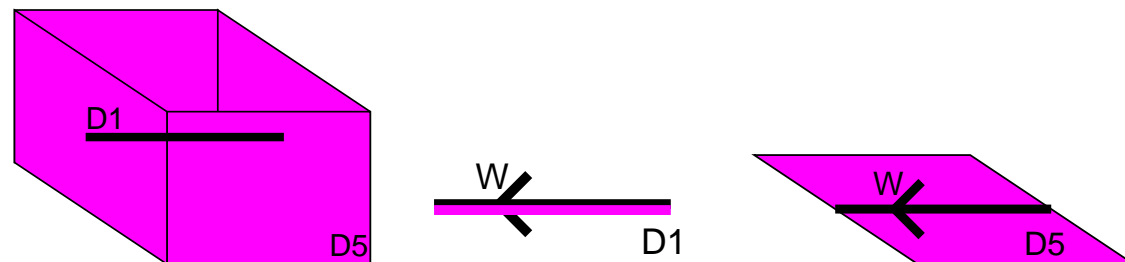
weak coupling degeneracy

= strong coupling degeneracy



Red: coupling constant knob on God's stove (- female, and cooks!)

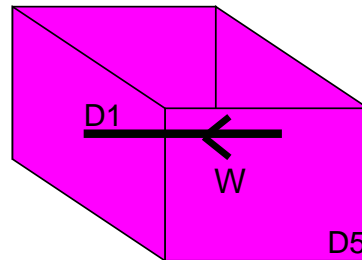
No-force pairs:



Strominger-Vafa II

Need just-right recipe:-

- if D1 is wrapped on circle S^1 , its gravity wants to shrink the circle to zero size at the horizon;
- if D1 joined by D5 wrapped on $T^4 \times S^1$, D1 pressure balances D5 tension and T^4 stays finite size at horizon. But S^1 shrinks even more!;
- if add gravitational wave W moving along circle at c . This pushes out with enough pressure along S^1 to make it also stay finite size at horizon.



$$S_{\text{BH}} = 2\pi\sqrt{N_1 N_5 N_m}$$

Harder cases of finite temperature, unstable branes under active research.