Review Sheet 5
Quantum Gravity, Strings, Branes, and Hyperspace

Conflict between Gravity and Quantum Theory – Need quantum gravity to understand the singularity at the birth of Big Bang and in black holes, and quantum foam.

Planck scale – the tiny scale (10^{-33} cm, 10^{-43} s, 10^{93} gm/cm^3) where Einstein's theory and quantum theory are predicted to collide, the implied "size" of the singularity. Strings are somewhat larger than this.

"Quantum Foam" – word description (in absence of quantitative mathematical theory) of the expected nature of space-time on the smallest level (Planck scale) where quantum effects compete with space-time curvature.

At the quantum foam level it is not just the position of an object in otherwise uniform space that is uncertain (the classic quantum view), but the nature of space itself must be quantum uncertain.

Classic quantum theory – particles are points (electrons) that also have quantum wave-like properties, or are made up of point particles (protons are made of three quarks). The notion of particles as strings changes that picture in a fundamental way.

String Theory – "particles" are actually strings in a space of 10 dimensions plus time. The theory "contains" Einstein's General Relativity and has been used to compute the entropy and temperature of a black hole from basic theory.

Fundamental forces – according to string theory all the basic forces, electricity, magnetism, strong force, weak force – are confined to regular three-dimensional space. Gravity – the creature of space-time – can "leak" into higher dimensions, if they exist.

Early history of string theory – recognition that equations that corresponded to the strong nuclear force also described entities, strings, that could stretch and wiggle.

Quantum View of Forces – the quantum theory views (mathematically) all forces as resulting from an exchange of particles, with different particles representing different forces (electromagnetic, weak, strong).

Strings and space – the shape of the wrapped-up spaces determine how the strings can vibrate and hence what particle they represent.

Extra dimensions – in the first version of string theory, all the extra dimensions were "wrapped up" on a scale comparable to the Plank Scale. Thought to be necessary so that gravity would have inverse-with-distance-squared behavior.

Calabi Yau – a space – special 6-dimensional geometry that could be the shape of the wrapped-up dimensions.

Finite extra dimensions – the realization, guided by string theory, that some of the extra dimensions could be "large." Only gravity could go there.

Branes – surfaces or membranes in higher dimensional space suggested in string theory. Any 2D surface is a 2-brane in our 3D space. In higher dimensional spaces, higher dimensional "slices" are possible, "P" is the dimension of the brane, hence P-brane.

Bulk – the large (not wrapped-up) *extra* dimension in which our 3D Universe is hypothesized to exist. There could be parallel 3D universes (3-branes) floating in the 4D bulk (with 6 wrapped-up dimensions at each point in those spaces).

Forces – the forces of standard quantum theory (electromagnetic, weak, strong), are stuck on branes (string loops with both footprints on the brane), hence within the 3-brane of our Universe.

Gravity is a creature of space, it can leak into the 4D bulk. This could make gravity seem weaker than the other forces.

Graviton – a "closed" loop of string that can leave our 3D brane and float in the 4D bulk.

Small leakage of gravity – just as gravity declines like r^{-2} in 3D space, it could decline like r^{-3} in 4D space (clearly wrong!). Recent realization that it could leak more slowly even if the 4D bulk existed brought a revolution in thinking about large extra dimensions.

Brane world – further work showed that even if one of the extra dimensions is very large, gravity might still be nearly confined to the 3-dimensional brane of our Universe. Our Universe could be a 3-D brane floating in a huge surrounding 4-D bulk. Our Universe might be expanding into this 4-D bulk.

Ekpyrotic Universe - the idea that another 3-D brane floating in the 4-D bulk collided with ours creating the huge, but finite, temperatures that launched the Big Bang without requiring any "singularity."

Brane-world theories – models of our Universe and cosmology exploring the possible existence and effects of a large extra dimension.

Tests of string theory – traces left over from Big Bang, evidence of extra dimensions, the bulk.

Newton had concept of "force" of gravity, Einstein's theory (which is mathematically the same as Newton's for weak gravity), had concept of gravity as curved space, string theory (which is mathematically the same as Einstein for safe distances from any singularity) has concept of gravity as a quantum force for which the messenger particles are gravitons propagating in 10 spatial dimensions.

String theory cannot yet tell us what the "singularity" is within black holes or at the beginning of the Big Bang. One idea, the singularity within a black hole represents the birth of a new Universe.

Dark Energy – the space-time fluctuations of the quantum foam might give an energy to empty space, but simple estimates give the wrong answer for the Dark Energy by a factor of 10^{120}. Recent theories explore whether the Dark Energy could be some manifestation of the 4D bulk, other 3D branes?

TERM-SPANNING THEMES

Quantum uncertainty – quantum pressure, vacuum energy, Hawking radiation, Dark Energy, quantum gravity

Stars to Cosmology – binary star evolution → white dwarfs → Type Ia supernovae → accelerating Universe → Dark Energy

Core collapse – thermal pressure, massive stars, supernovae, neutron stars, black holes, gamma-ray bursts, first stars, end of Dark Ages

Gravity – stellar evolution, curved space, black holes, singularities, quantum gravity

Dimensions – zero, one, two, three, four, ten, embedding diagrams, curved space, hyperspace

Theories of Physics – Newton's gravity, Einstein's gravity, quantum theory, string theory, quantum gravity

Accretion disks – cataclysmic variables, dwarf novae, classical novae, x-ray transients, x-ray bursts, black hole x-ray novae, jets