Review for Test #4
Black Holes, Gamma-Ray Bursts, Cosmology, and Quantum Gravity

Milky Way Galaxy – contains a 4 million solar mass black hole as determined by orbits of stars near the center.

Galaxy/Black Hole connection – The velocity of stars that respond to the bulge mass of a galaxy are correlated with the mass of the central supermassive black hole despite the fact that they are presently much too far from the black hole to sense its gravity. The bulge mass is always about 800 times the black hole mass. This suggests that the processes that cause the development of whole galaxies are nevertheless closely linked to the growth of the black hole when both first formed.

Intermediate mass black holes – 1000 to 10,000 solar mass black holes. First suspected from very bright X-ray sources in other galaxies requiring large masses so the Eddington limit would not be violated. More recent evidence is based on the motion of stars near the center of old globular star clusters. The mass of the black hole is deduced to be about one thousandth of the cluster mass, suggesting that globular clusters and their black holes formed by the same combined mechanism as whole galaxies and their supermassive black holes.

Gamma-ray bursts – flashes of gamma-ray energy detected by satellites about once per day lasting about 10 to 30 seconds.

Optical Counterparts – discovered only in 1997, these allow gamma-ray bursts to be associated with other phenomena. They are in galaxies at cosmological distances.

After-glow – fading radiation in radio, optical, and x-ray lasting for weeks or months after main burst, collision of ejected material with matter surrounding the star.

Gamma-ray bursts occur in star-forming regions in spiral galaxies, so associated with massive, short-lived stars and hence core collapse.

The energy of a gamma-ray burst is focused in a jet moving at near the speed of light, with an energy comparable to a supernova.

A gamma-ray burst in March of 2003 proved that at least this burst was associated with a Type Ic supernovae. Several others have been associated with Type Ic since then.

The most popular idea is that gamma-ray bursts represent the birth of black holes, but the birth of magnetars is also considered.

Gamma-ray bursts and cosmology - gamma-ray bursts are so bright they might be the first objects observable as stars first began to form and die at the end of the “Dark Ages” after the Big Bang cooled off.

Big Bang – the initial expansion of the Universe from a condition of very high density and temperature (“singularity”).

Expansion of the Universe – space expands and pulls all distant galaxies apart with a speed that increases with distance. There need not be a 3-D center, a 3-D edge nor a 3-D outside to our 3-D Universe.

Age of the Universe is about 13.7 billion years, determined from the distance to supernovae (and other things) and the velocity of recession as measured by the Doppler shift.

Traditional Types of Universes – "flat" infinite in extent, will expand forever approaching zero velocity; "open" infinite in extent, will expand forever at a finite velocity; "closed" finite in extent and volume, will recollapse (neglecting Dark Energy).

Dark Matter – the vast majority of the gravitating material in the Universe emits no detectable radiation and is not, nor has ever been, composed of "ordinary" gravitating matter as we know it composed of protons, neutrons and electrons.

Clumping of Dark Matter was critical to convert smoothly spread matter into clumps and hence the galaxies and stars we see today.

Supernovae as sign posts – comparing the apparent brightness to the known intrinsic brightness allows a measure of distances.

Type Ia supernovae – best current tool for measuring distances. Exploding white dwarf in a binary system.

Accelerating Universe – measurement of supernovae has suggested that the expansion of the Universe is not decelerating at all at the current time, but accelerating.

Dark Energy– if the Universe is accelerating, there seems to be an extra force associated with empty space. In the context of Einstein's theory of gravity, this force could be provided by the cosmological constant. Physically, this quantity is associated with an energy of the vacuum of space, a Dark Energy that anti-gravitates.

Composition of the Universe – about 2/3 Dark Energy, about 1/3 Dark Matter, only a few percent "ordinary" matter.

Shape of the Universe – flat in three dimensions. The sum of the Dark Energy, Dark Matter and "ordinary" matter is exactly right, within observational uncertainty, to render the Universe flat.

With the Dark Energy, the Universe could expand to become a dark void, everything could be pulled apart in a Big Rip, or the Universe could recollapse to a singularity.

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.

Wormholes and time machines – according to Einstein's theory it is possible, in principle, to construct wormholes from once place in 3D space to another. They will also automatically be time machines. We will not truly know whether they can exist or not without a theory of quantum gravity.

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 temperature of a black hole from basic theory.

Quantum View of Forces – the quantum theory views (mathematically) all forces as resulting from an exchange of particles, with different exchange 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 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 penetrate 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 gravity could penetrate only a little into 4D, even if the 4D bulk existed. This brought a revolution in thinking about large extra dimensions.

Brane world – 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.

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

Tests of string theory – evidence of extra dimensions, the bulk, in the strength of gravity or in particle accelerators.

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 – Recent theories explore whether the Dark Energy could be some manifestation of the 4D bulk, other 3D branes.

Multiverse – the idea that there could be many 3-D universes separated in hyper space.

String landscape – the notion that string theory may have 10^{500} solutions, each with a different value of the physical constants, only a few of which are suitable for life.

Bubble universes – the individual universes created in the multiverse

Eternal Inflation – the notion that universes are constantly being "born" or "inflated" out of the "quantum foam" of Planck or string-like conditions.

Chaotic Inflation – variation of eternal inflation in which new bubble universes are constantly born "elsewhere" in hyperspace and the multiverse is fractal on large scales.

Black holes and the multiverse – when a "singularity" forms in a collapsing black hole, a new bubble universe might be born "elsewhere".