Black Holes

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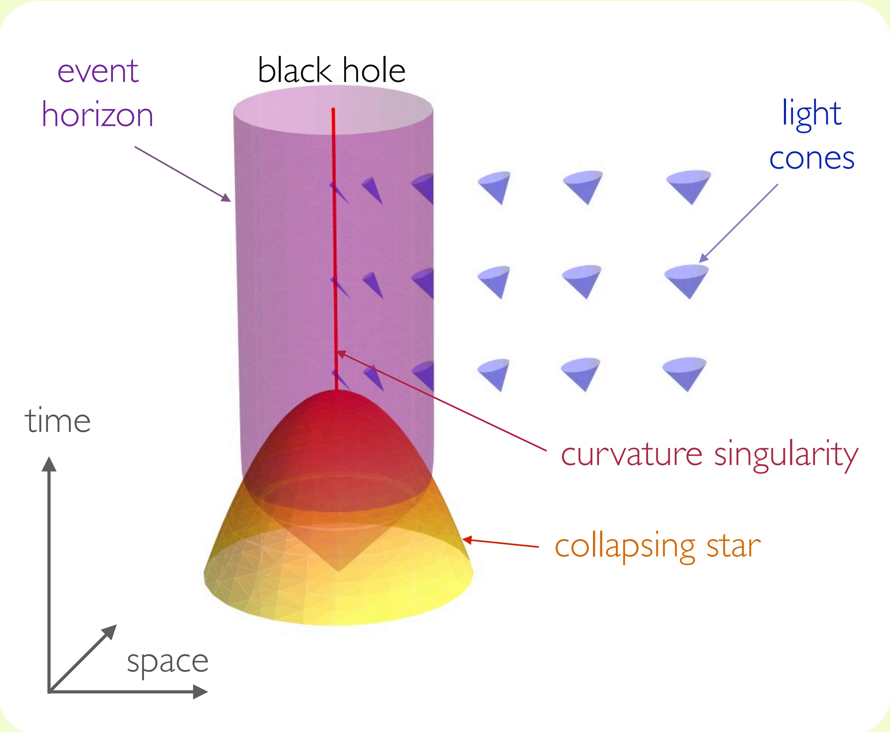
Mathematical description:

- Set within Einstein's theory of gravity, General Relativity = { • gravity = spacetime curvature • matter curves spacetime
- Spacetime can become curved enough to create regions of no-return: gravity is so strong that nothing, not even light, can escape! Such regions are called black holes.
- Though far out of every-day experience, the spacetime structure of black holes can be exemplified by a spacetime diagram:



Collapse of a star to form a black hole:

- ✦ Each horizontal slice corresponds to one instant in time.
- ✦ Bottom: star at early times.
- ✦ Top: late time black hole.
- ✦ Middle: the entire star implodes to a curvature singularity.
- ✦ Since nothing travels faster than light, the light cones indicate the `causal structure' of the spacetime: no signal can reach from inside to outside.
- ✦ Hence outside observers cannot see past the event horizon – this is why black holes are black.

Building blocks of theoretical physics:

- Black holes have astonishingly simple & elegant description. They are arguably the most perfect macroscopic objects in the universe [as noted by Chandrasekhar].
- Hence they provide useful theoretical laboratories: instead of doing experiments, we can calculate, and the mathematics itself reveals remarkable consequences.
- Indeed, black holes lie at the heart of profound dualities, such as the AdS/CFT correspondence (which relates a string theory to a lower-dimensional quantum field theory). This has been one of the major scientific advances of the last half century.
- Through this correspondence, higher-dimensional black holes turn out to describe more familiar objects.
  - ✦ In certain respects, black holes behave like lumps of fluid. This is best-understood in the context of the fluid/gravity correspondence.
  - ✦ Remarkably, the event horizon of a black hole can exhibit the phenomenon of turbulence, one of the richest and least understood types of dynamics.
  - ✦ Black holes are in fact relevent for extremely diverse systems in nature, ranging from ultra-cold atoms to the hot quark-gluon plasma created at colliders.

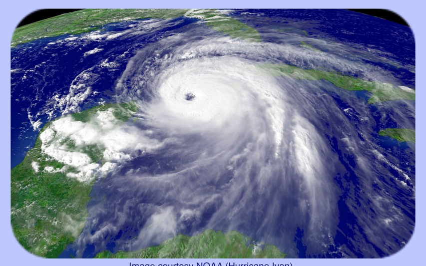


Image courtesy NOAA (Hurricane Ivan)

- Even more amazingly, recent advances suggest profound connections to concepts in quantum information theory, such as entanglement.
- Black holes have many guises. Though apparently esoteric, they appear everywhere!

What are black holes?

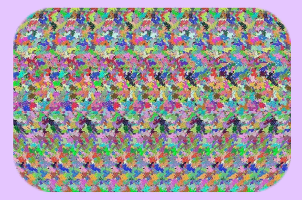
Astrophysical objects:

- Although light cannot escape from black holes (so that we can't see them directly), they can be detected through their influence on surrounding objects. In this way, many black holes have already been observed.
- It is believed that each galaxy contains at least one supermassive black hole (with mass equivalent of several billion Suns), and thousands of Solar-mass black holes.
- The latter arise through stellar collapse: As the star implodes under its own gravity, it becomes increasingly dense. Eventually the inward pull overcomes the outward radiative pressure and the star shrinks rapidly to zero size and infinite density, resulting in a curvature singularity enveloped by an event horizon (see above).
- Black holes are densest possible objects:
  - ✦ Solar-mass black hole has horizon radius 2 miles.
  - ✦ If the entire Earth collapsed to form a black hole, its size would be less than an inch.
- Due to their extreme attributes, black holes are responsible for some of the most energetic processes in our Universe.
  - ✦ As matter falls toward a black hole, its angular momentum causes it to form an accretion disk.
  - ✦ Differential rotation heats up the disk enough to emit powerful radiation.
  - ✦ In addition, electromagnetic fields around a spinning black hole produce collimated jets.

Image courtesy http://ffden-2.phys.uaf.edu/webproj

Key to quantum gravity:

- Black holes are mathematically well defined in classical (i.e. non-quantum) setting. Yet, ultimately, our world is quantum mechanical.
- Our formulation using the continuum fabric of spacetime ceases to be valid when quantum effects become important. Hence spacetime is an emergent construct. More fundamental description requires developing a complete and consistent theory of Quantum Gravity.
- Black holes provide good testing ground for any putative theory of quantum gravity, since they manifest strongly gravitational regions where quantum effects are important.
- But black holes do much more: they provide deep hints for what ingredients quantum gravity should have.



  - ✦ Entropy (or amount of information one can store) is maximized for black holes, and is proportional to horizon area (rather than volume).
  - ✦ So our 3+1 dimensional world should be described by a theory living in 2+1 dimensions.
  - ✦ Analogy: stereogram (3-d image emerges from 2-d one due to correlations…)
  - ✦ Concrete realization: AdS/CFT correspondence
- Through these hints we learn that black holes act as most efficient information storate devices and fastest computers.
- Black holes are fascinating and multifaceted, yet we've barely scratched the surface in our explorations. Many more marvels await us. Join in the quest!