Lecture 1
Gravitation and Astrophysics: Last Frontiers of Physics

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Gravitation

- Gravitation is the oldest field in physics, yet is still not completely understood.

  Newton's law of gravitation (1687)

  Einstein's General Relativity (1915)

- Theoretical challenge:

  There is no quantum theory of gravitation yet, and gravity has not been unified with the rest of physics.

- Experimental challenge:

  Gravity is the weakest force in nature, and the tests of gravitation theories require the most precise, often beyond the state of the art, instrumentation.

Astrophysics

- Astrophysics is the cradle of physics.

  Tycho Brahe's observation of planetary motions (16th century)

  $\Rightarrow$ Kepler's phenomenological laws of planetary motion

  $\Rightarrow$ Newton's inverse-square law of gravitation (17th century)

- Black holes and galactic centers are the regions of the strongest gravitational fields, and stars are the most energetic particle accelerators.

  $\Rightarrow$ The universe is the best laboratory for extreme energy physics where GR and the SM of particle physics can be tested.

  $\Rightarrow$ Advancements in space, measurement, and information technologies are enabling great discoveries in astrophysics.

- Astrophysics may be where the last word for physics can be found.

Nobel prizes in gravitation and astrophysics (1)

Year	Recipient(s)	Topics
1907	Albert Michelson	for his optical precision instruments and the spectroscopic and meteorological investigations carried out with their aid
1921	Albert Einstein	for his services to theoretical physics, and especially for his explanation of the photoelectric effect
1936	Victor Hess	for his discovery of cosmic radiation
1948	Patrick Blackett	for his development of the Wilson cloud chamber method, and his discoveries therewith in the fields of nuclear physics and cosmic radiation
1967	Hans Bethe	for his contributions to the theory of nuclear reactions, especially his discoveries concerning the energy production in stars
1974	Sir Martin Ryle Antony Hewish	for their pioneering research in radio astrophysics: Ryle for his observations and inventions, in particular of the aperture synthesis technique, and Hewish for his decisive role in the discovery of pulsars

Nobel prizes in gravitation and astrophysics (2)

Year	Recipient(s)	Topics
1978	Arno Penzias Robert Wilson	for their discovery of cosmic microwave background
1983	S. Chandrasekhar	for his theoretical studies of the physical processes of importance to the structure and evolution of the stars
	William Fowler	for his theoretical and experimental studies of the nuclear reactions of importance in the formation of the chemical elements in the universe
1993	Russell Hulse Joseph Taylor	for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation
2002	Raymond Davis M. Koshiba	for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos
	Riccardo Giacconi	for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources
2006	John Mather George Smoot	for their discovery of the blackbody form and anisotrophy of the cosmic microwave background radiation

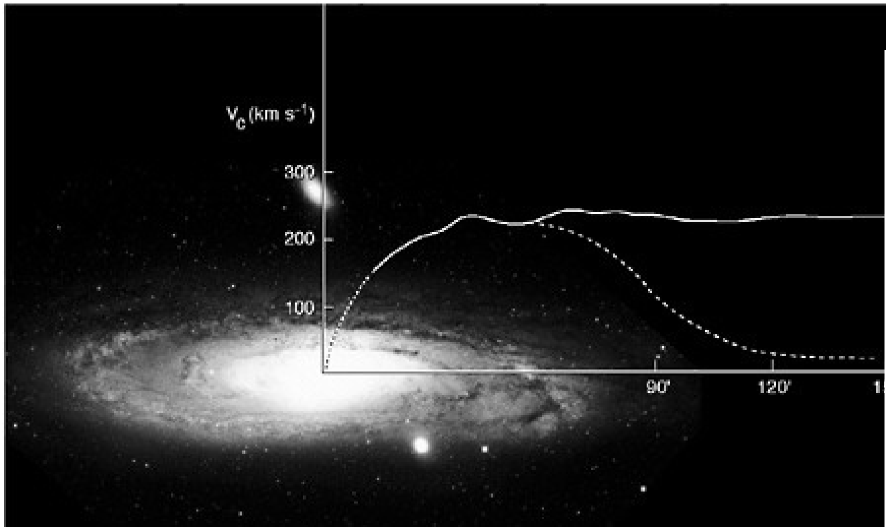
11 science questions for the new century

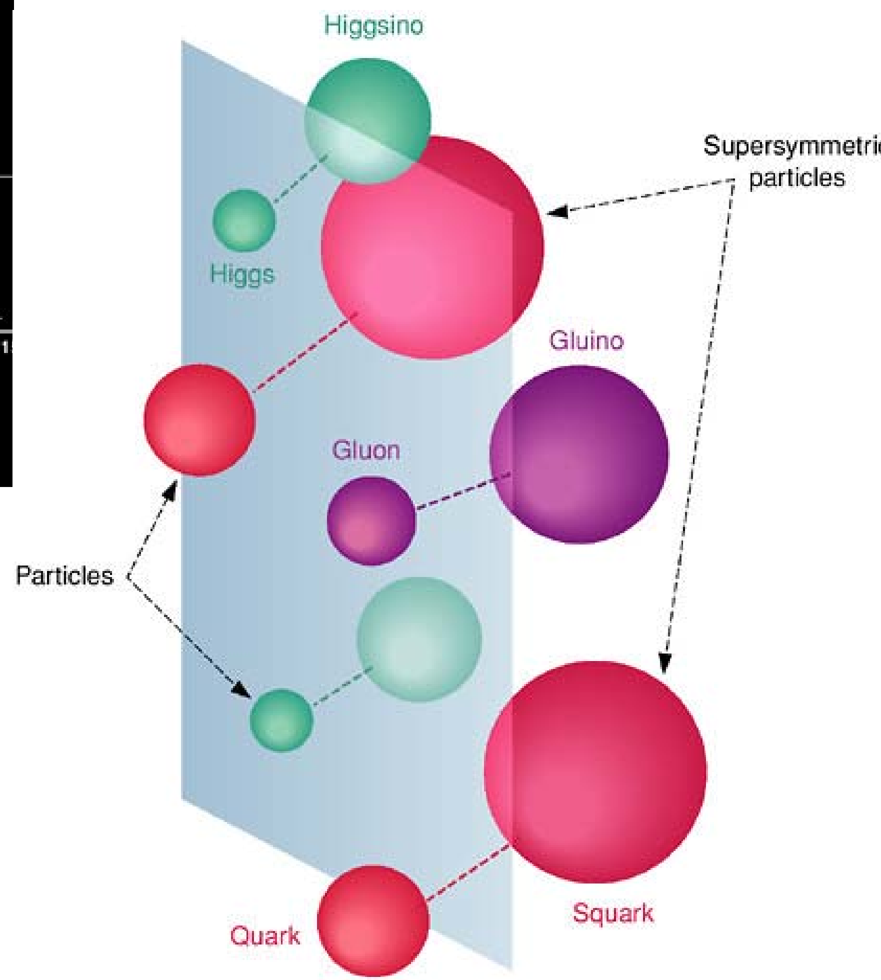
National Academy of Sciences, Committee on the Physics of the Universe, 2002

http://www.nap.edu/books/0309074061/html/1.html

1. What is dark matter?
2. What is the nature of dark energy?
3. How did the universe begin?
4. Did Einstein have the last word on gravity?
5. What are the masses of the neutrinos, and how have they shaped the evolution of the universe?
6. How do cosmic accelerators work and what are they accelerating?
7. Are protons unstable?
8. What are the new states of matter at exceedingly high density and temperature?
9. Are there additional space-time dimensions?
10. How were the elements from iron to uranium made?
11. Is a new theory of matter and light needed at the highest energies?

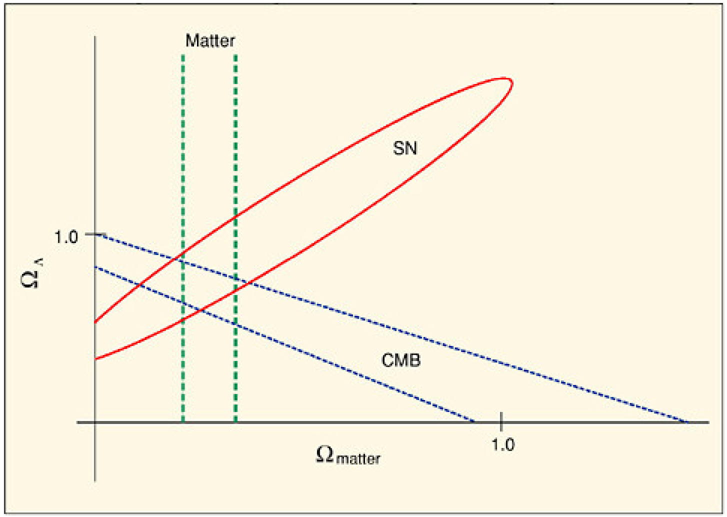
1. What is dark matter?



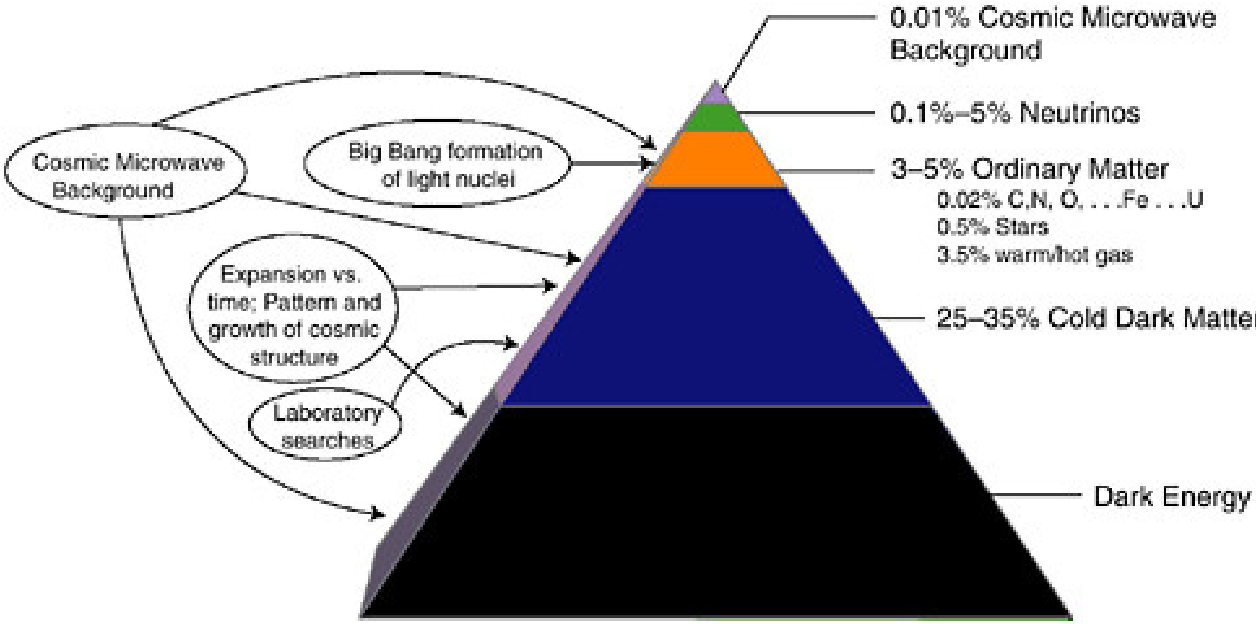


- The objects in the universe are held together by a form of matter different from ordinary matter and that gives off no light.
- This matter probably consists of as-yet-undiscovered particles (neutralinos, axions?).

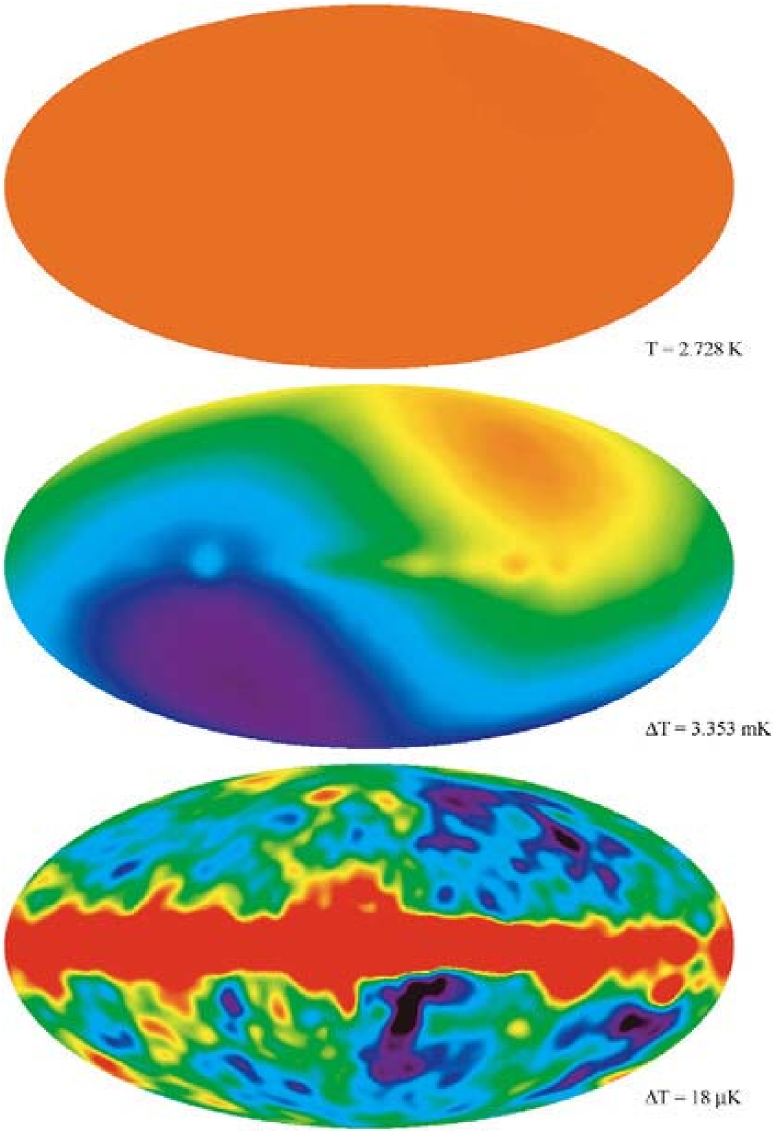
2. What is the nature of dark energy?



- Recent measurements indicate that the expansion of the universe is speeding up, rather than slowing down.
- This calls for the presence of a form of energy, “dark energy,” whose gravity is repulsive and whose nature determines the destiny of our universe.



3. How did the universe begin?



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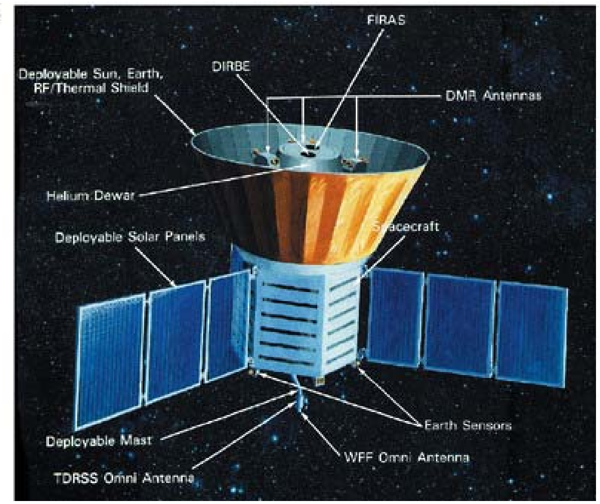
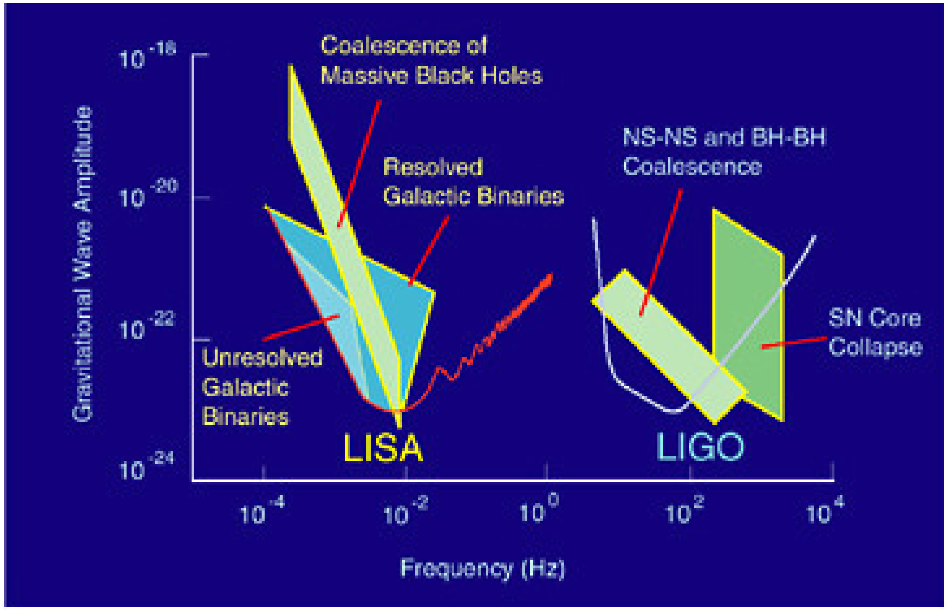
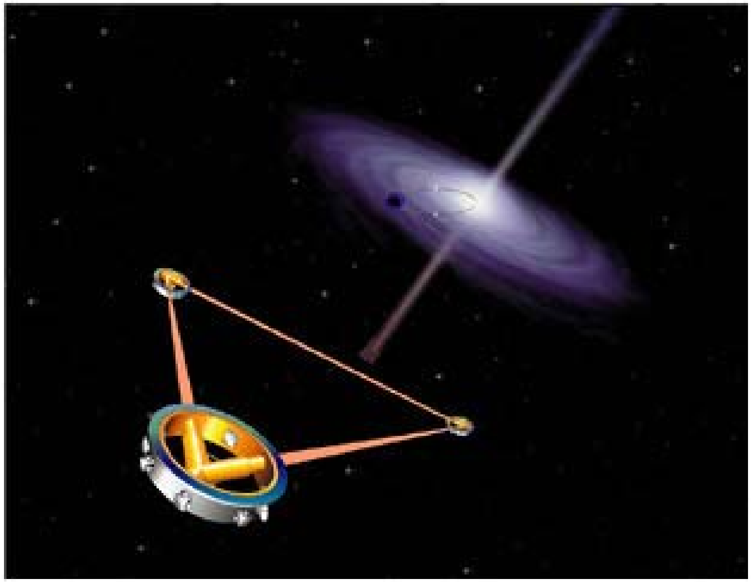


- There is evidence that during its earliest moments the universe underwent a tremendous burst of expansion, “inflation.”
- The largest objects in the universe had their origins in subatomic quantum fuzz.
- The underlying physical cause of this inflation is a mystery.

4. Did Einstein have the last word on gravity?

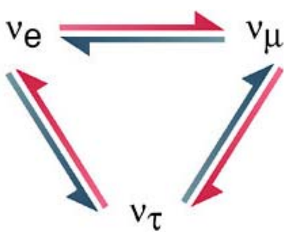
- The effects of strong gravity in the early universe have observable consequences.
- Einstein's theory should work as well in these situations as in the solar system.
- A complete theory of gravity should incorporate quantum effects or explain why they are not relevant.

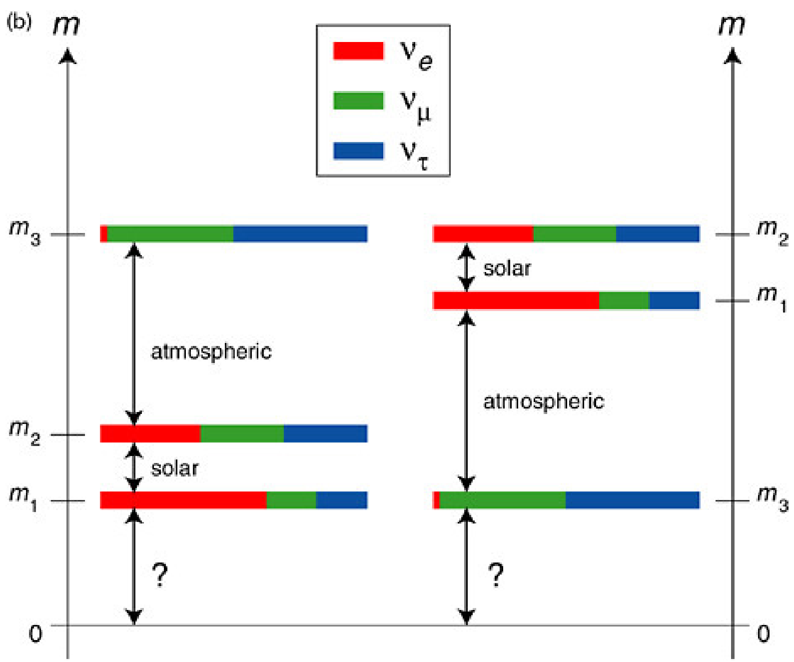


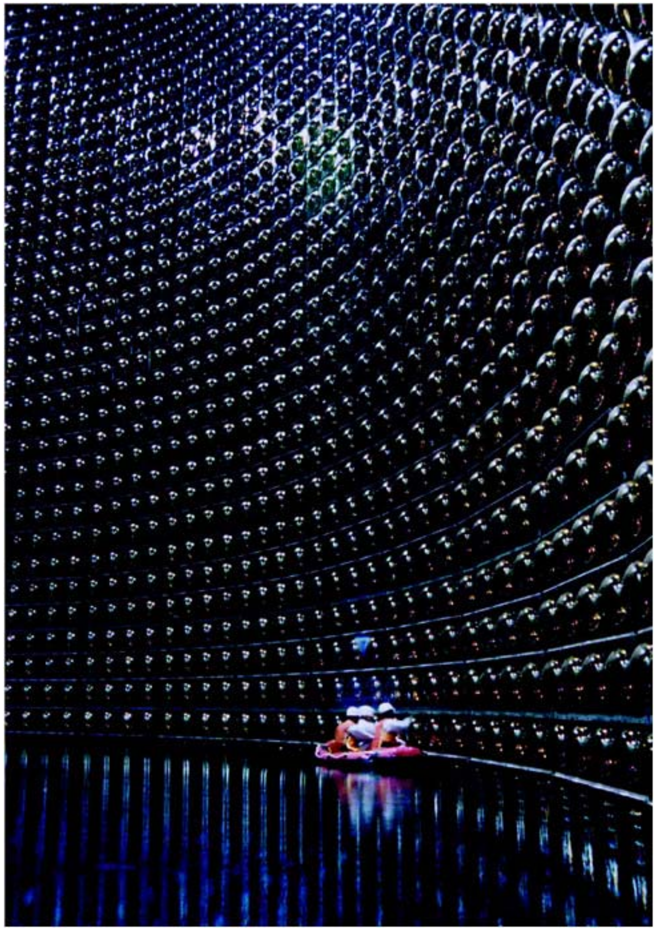


5. What are the masses of neutrinos, how have they shaped the evolution of the universe?

- Neutrinos have a small mass, which implies that cosmic neutrinos account for as much mass as do stars.
- The pattern of neutrino masses can reveal much about how nature's forces are unified, how the elements were made, and possibly even the origin of ordinary matter.

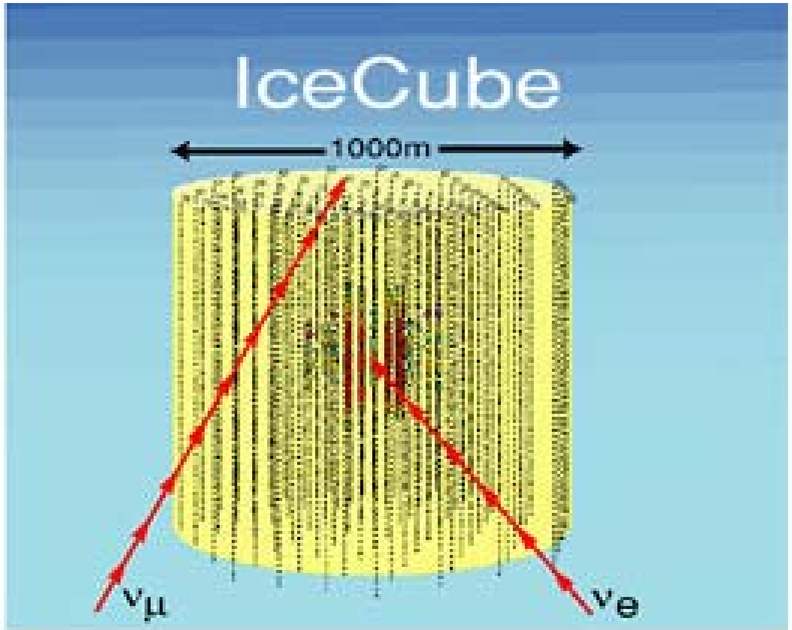


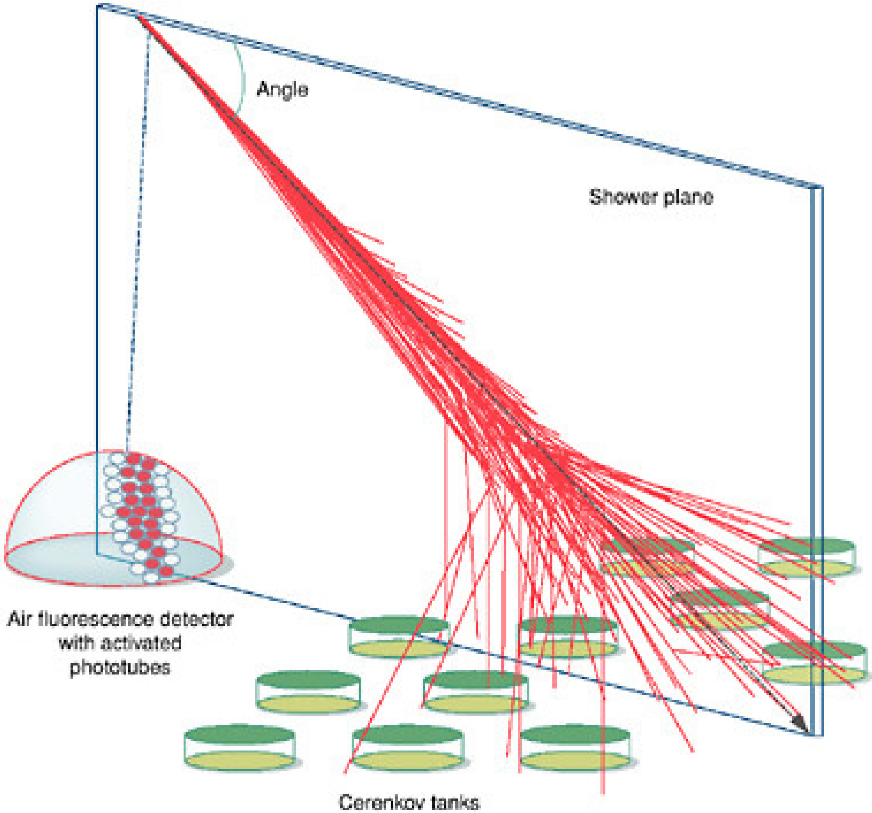




6. How do cosmic accelerators work and what are they accelerating?

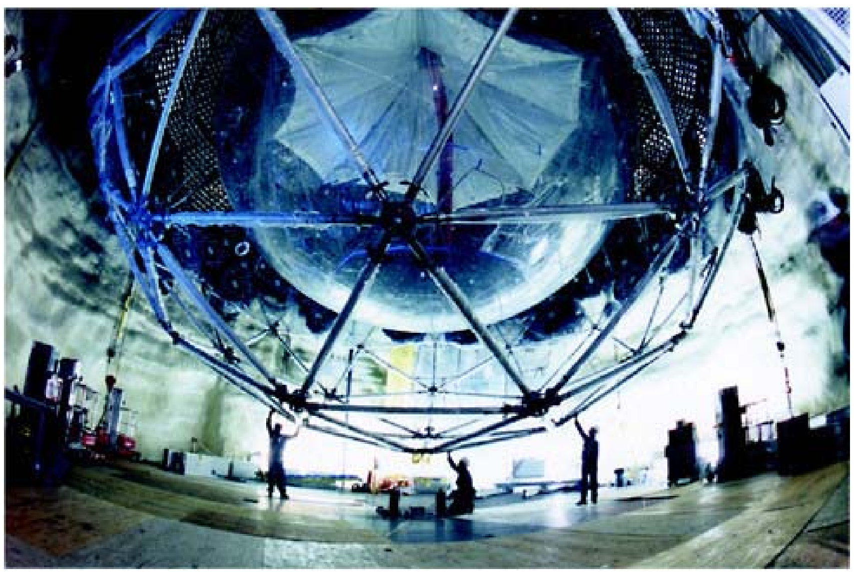
- Physicists have detected an amazing variety of energetic phenomena in the universe, including beams of particles of unexpectedly high energy but of unknown origin.
- The energy of these cosmic beams far exceeds any energies produced on Earth.

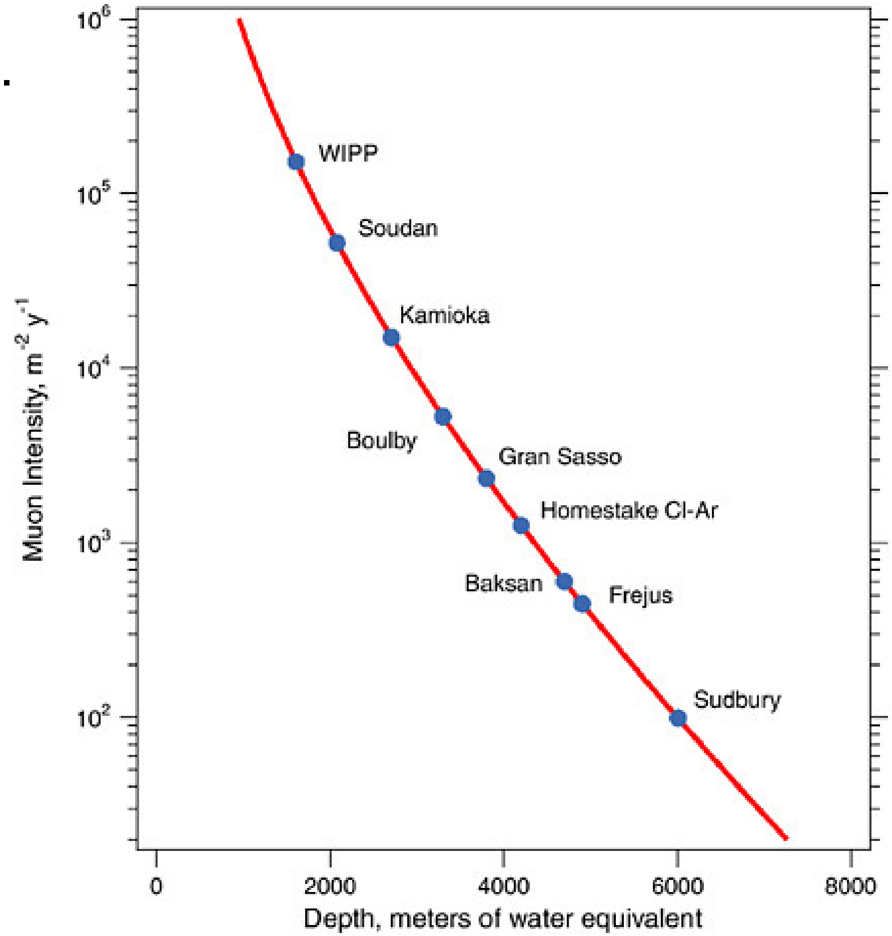




7. Are protons unstable?

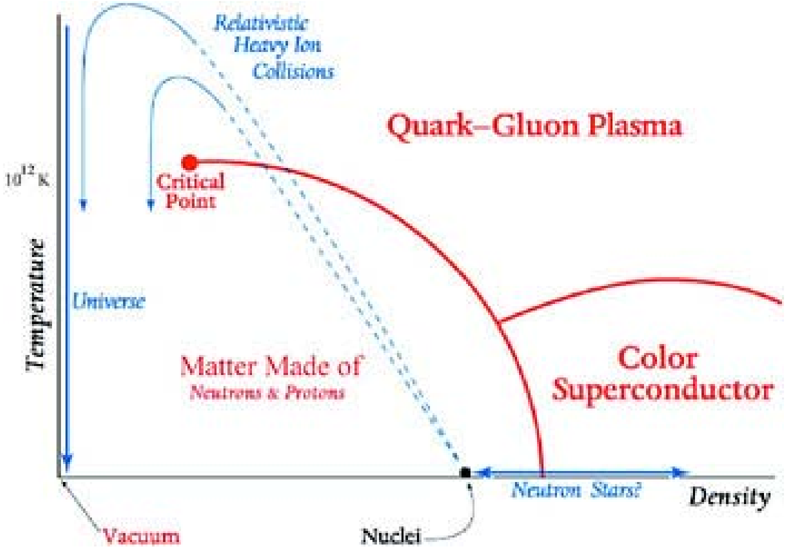
- The ordinary matter is the tiny residue of the annihilation of matter and antimatter in the early universe.
- This tiny imbalance may be due to an instability of protons, and to a slight preference for the formation of matter over antimatter built into the laws of physics.

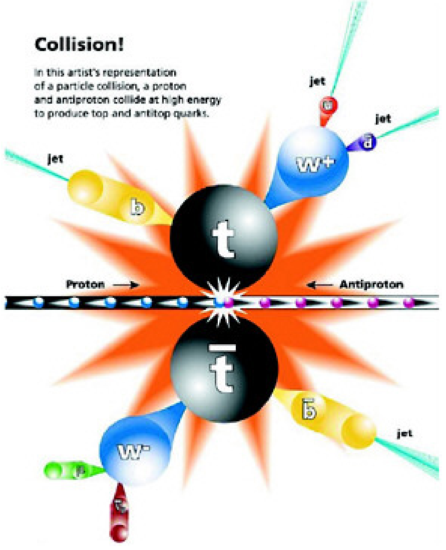


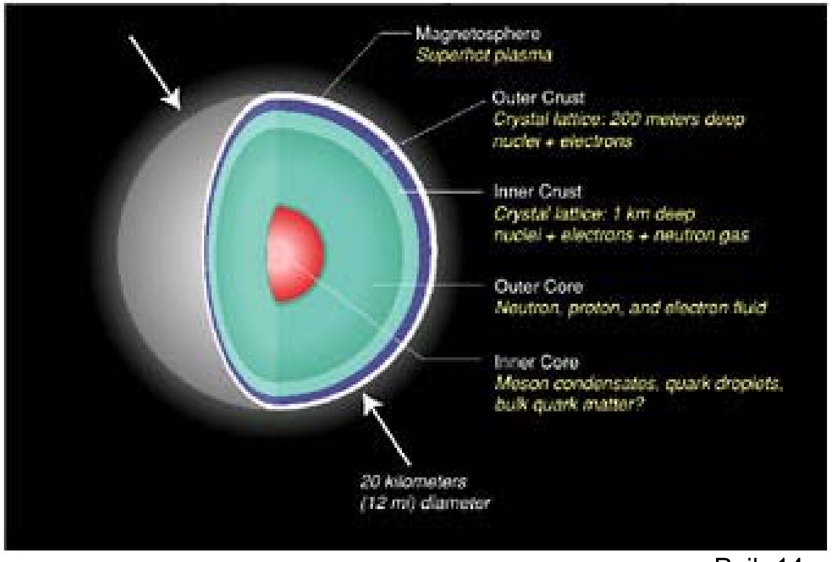


8. What are the new states of matter at exceedingly high density and temperature?

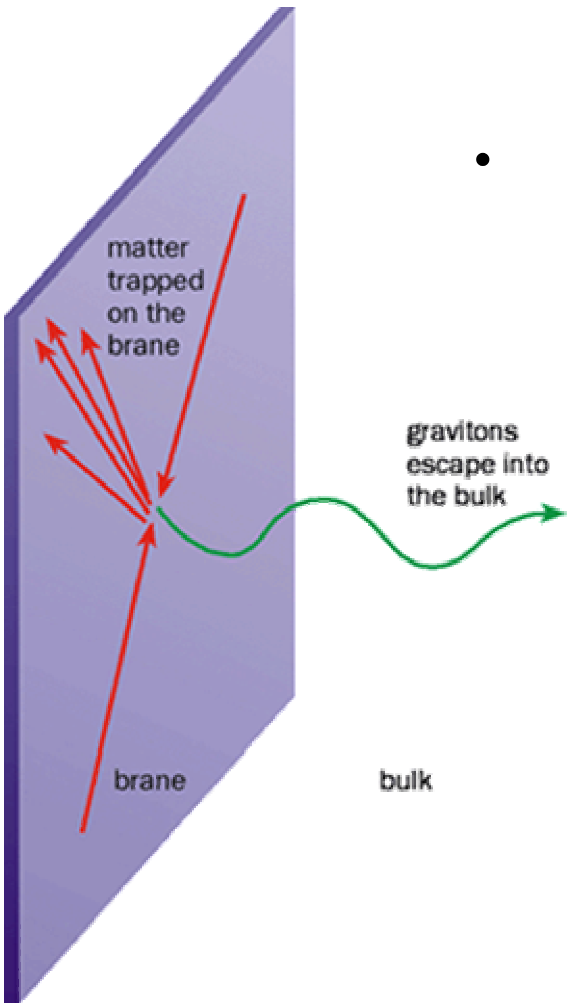
- At high densities, neutrons and protons may dissolve into an undifferentiated soup of quarks and gluons.
- Densities beyond nuclear densities can occur and can be probed in neutron stars, and still higher densities and temperatures existed in the early universe.



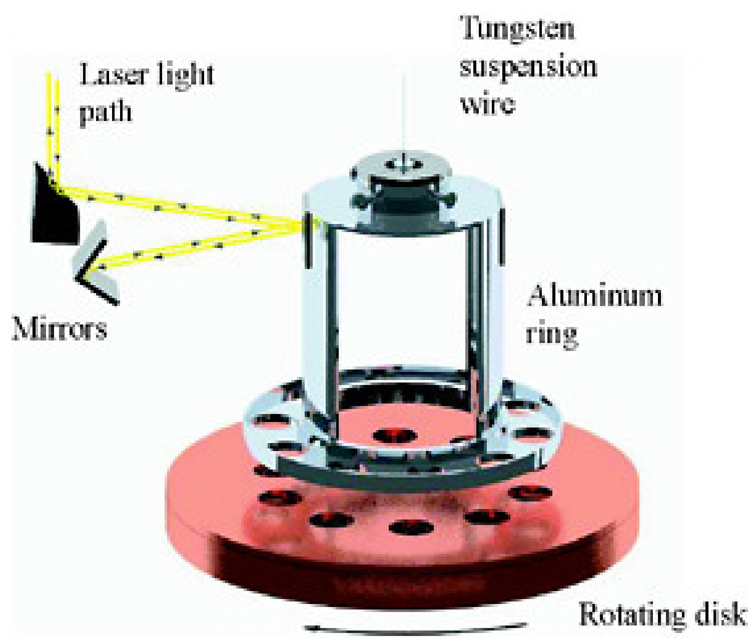




9. Are there additional space-time dimensions?

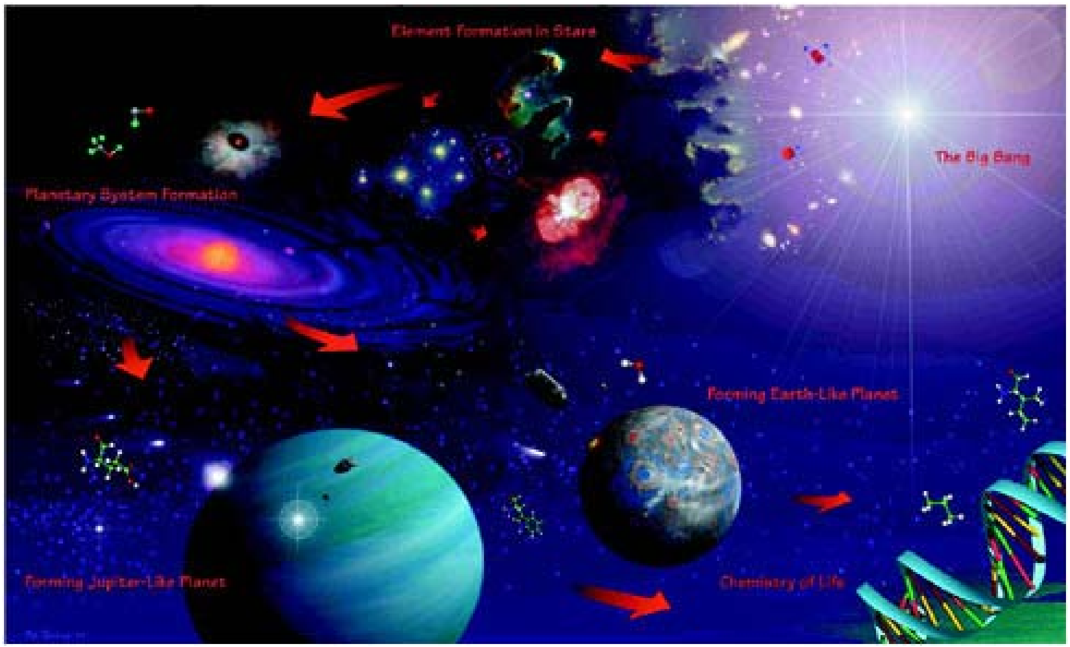


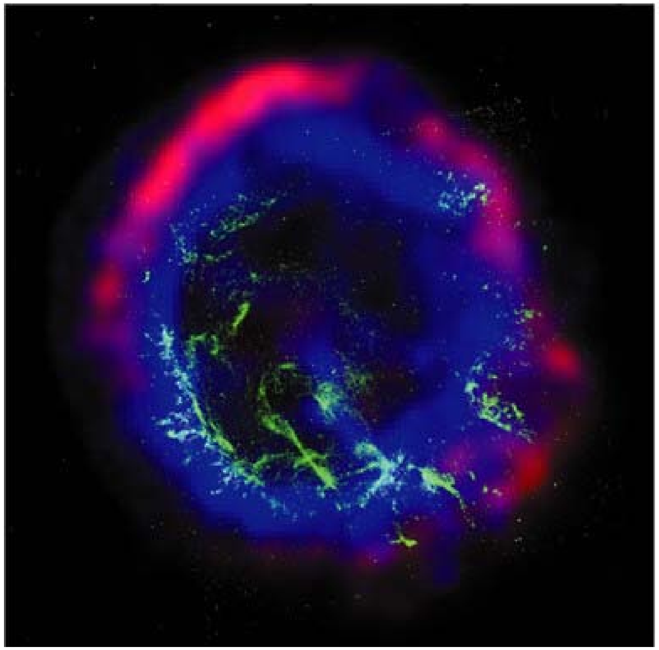
- In trying to extend Einstein's theory, particle physicists have posited the existence of space-time dimensions beyond those that we know.
- Their existence could have implications for the birth and evolution of the universe, could affect the interactions of the fundamental particles, and could alter the force of gravity at short distances.



10. How were the elements from iron to uranium made?

- Our understanding of the production of elements up to iron in stars and supernovae is fairly complete.
- Important details concerning the production of the elements from iron to uranium remain puzzling.





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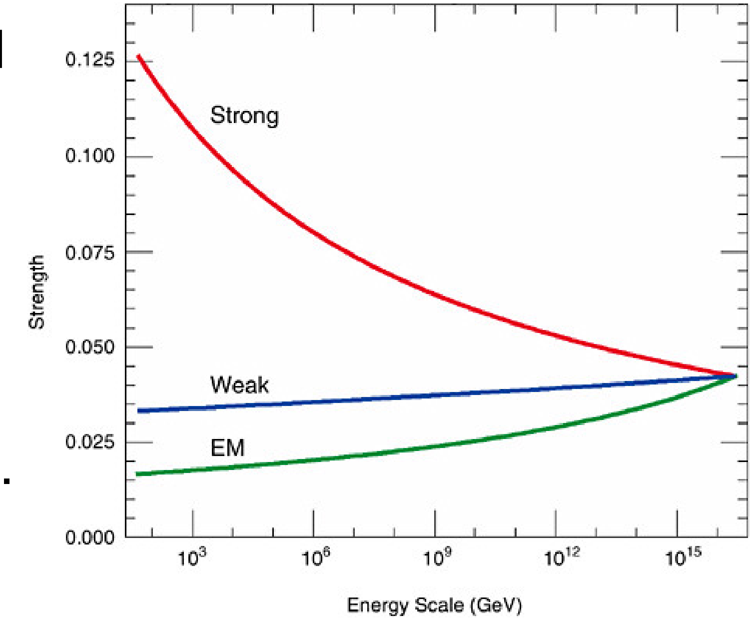
11. Is a new theory of matter and light needed at the highest energies?

- The universe presents us with places and objects, such as neutron stars and the sources of gamma ray bursts, where the conditions are far more extreme than anything we can reproduce on Earth.
- This can be used to test such basic theories as QED and the Standard Model.



FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c²	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c²	Electric charge
g gluon	0	0

Recommendations

1. Measure the polarization of the cosmic microwave background with the goal of detecting the signature of inflation.
2. Determine the properties of dark energy.
3. Determine the neutrino masses, the constituents of the dark matter, and the lifetime of the proton.
4. Use space to probe the basic laws of physics.
5. Determine the origin of the highest-energy gamma rays, neutrinos, and cosmic rays.
6. Discern the physical principles that govern extreme astrophysical environments through the laboratory study of high-energy-density physics.
7. Realize the scientific opportunities at the intersection of physics and astronomy.