QUANTUM MECHANICS

So now we come to the theory which has quite literally revolutionised all our lives- even though most of us are unaware of it. In what follows we will cover the following:

(1) The basic features of Quantum Mechanics- superposition, interference, entanglement; the wave-particle duality; spin, fermions & bosons, & indistinguishability.

(2) The historical development of the subject, and the deep philosophical questions that were and still are raised, about the nature of physical reality, by quantum phenomena.

(3) The way in which quantum mechanics has allowed us to understand how the universe works, from scales ranging from quarks to the universe- a range of some 42 orders of magnitude (10^{42}, or 1 followed by 42 zeroes) in length scale.

BRIEF INTRODUCTORY SURVEY of QUANTUM MECHANICS

Quantum Mechanics is unique in the intellectual history of the world, because

(i) It has no known limits to its validity
(ii) Fundamentally, we do not understand it at all!

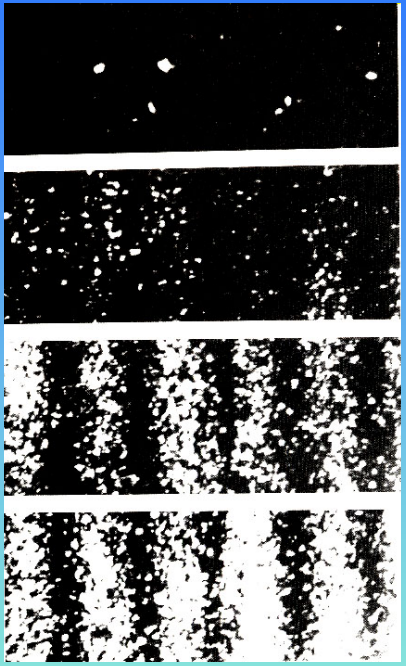
Walt Disney saw it as a Djinni ("genie"), for Good or Bad.

The Fisherman & the Genie (Arabian Nights)

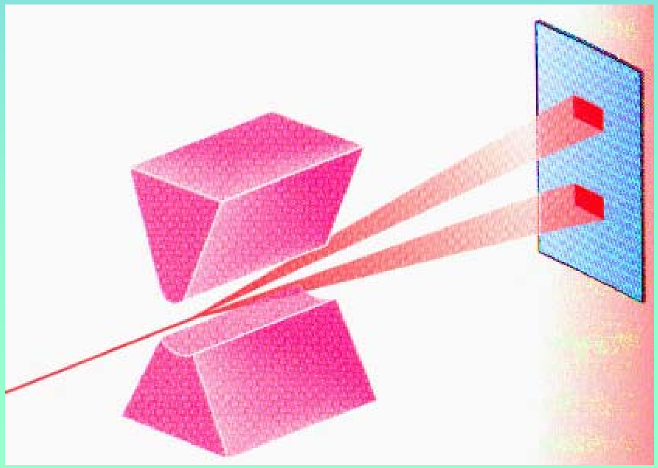
The Genie of Power (Disney)

Q.M. Mysteries: Superposition, Interference, and Spin

The best way to appreciate Quantum Mechanics is to look at it. Here are 2 examples of quantum behaviour.



(1) If one fires electrons through a pair of slits, in the same way as we saw for light, then, we get the result shown at right. The electrons arrive on a screen behind the slits in "lumps" (causing flashes on the screen), as we would expect for particles. However the pattern of arrivals is not what we would expect- in fact they arrive preferentially in band-like regions, as though they were being guided by interfering waves. Even more remarkably, WE SEE THE SAME RESULT FOR LIGHT- the lumps here being called PHOTONS.

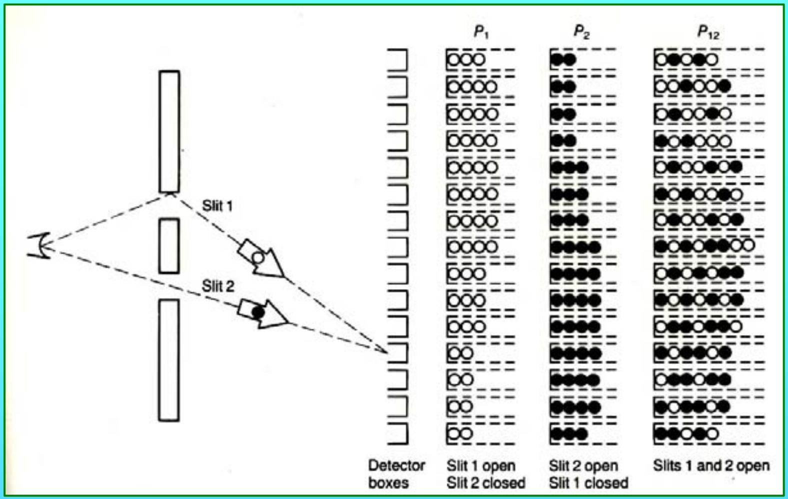


(2) In many cases we also find that only a finite set of states are allowed- this is also completely different from what we are used to in classical physics. At left the famous "Stern-Gerlach" experiment for spin is shown- only 2 values are allowed.

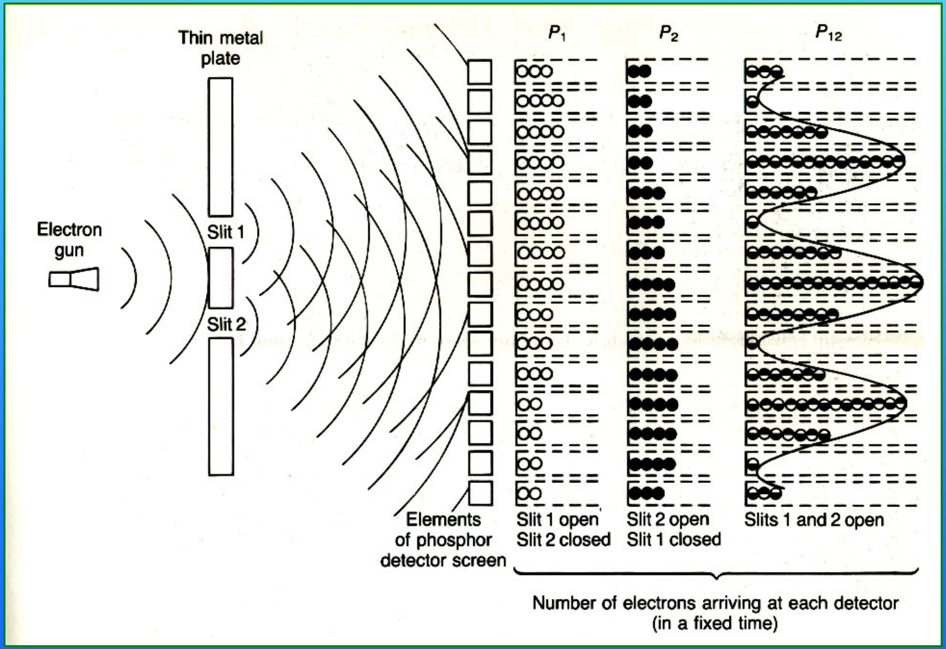
Particles vs Waves

There is NO WAY that one can understand the propagation of the particles through 2 slits as 'particles'.

On the other hand there is no way that one can understand their propagation as mere waves either- the electrons arrive on the screen as discrete "lumps", as do photons. This is the WAVE-PARTICLE DUALITY.



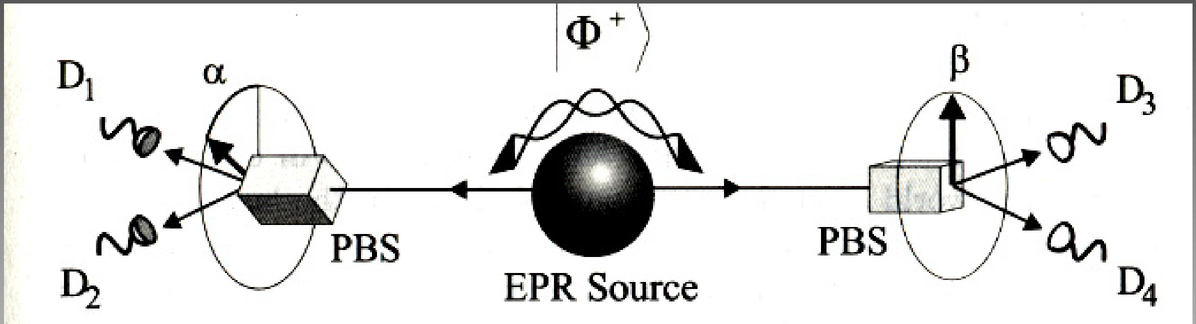
Pattern of arrivals of classical particles when one or other of the slits is open, & when both are open.



Pattern of arrivals of electrons with the same combination of slits open or closed.

In the early days of Quantum Mechanics, a solution to this was proposed by M. Born. According to this idea, the wavelike pattern is a "probability amplitude", which can be used to tell us the probability that a particle will arrive on the screen at some point. In this way it seemed that we had lost the deterministic quality of classical physics.

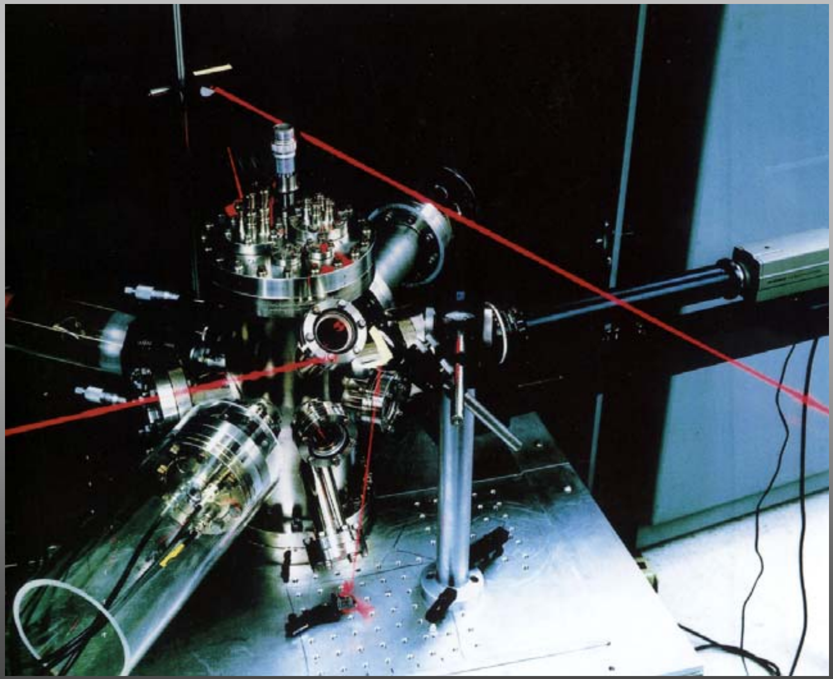
Quantum Entanglement



Just as bizarre is the phenomenon of NON-LOCAL ENTANGLEMENT”

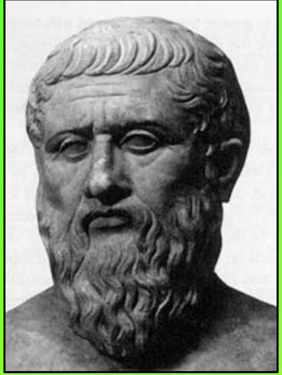
The result here is that the observed behaviour of one of the systems depends on what happens to the other- no matter how far apart they are (such that no signal can propagate between them).

Such experiments are now done in the lab (usually with photons). A major challenge is to achieve this on a larger scale.



A set-up for experiments on EPR-entangled photons

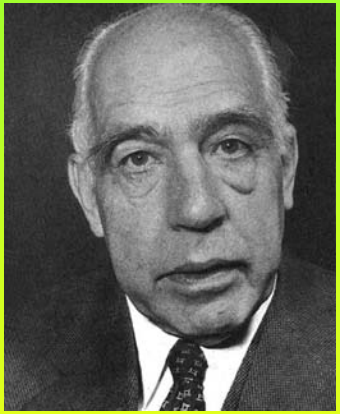
The Philosophical Problem



Plato
(428-348 BC)

Some have thrown up their hands and said that Plato got it right all along- that when it comes to understanding physical reality we are all in the cave...

Some new philosophical approaches have evolved. These will be studied in a whole set of slides later on. The results are quite bizarre. Here are some examples:



N.Bohr (1885-1962)

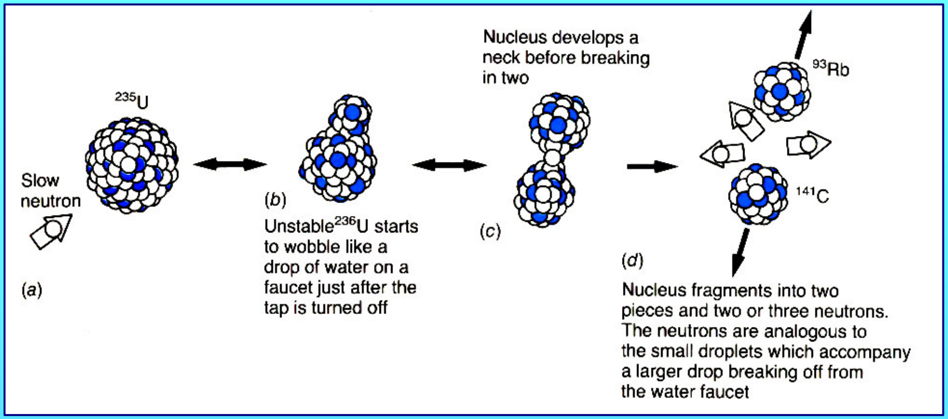
'One may ..limit the use of the word PHENOMENON to refer to observations obtained under specified circumstances, including an account of the whole experiment' (N. Bohr)

There is no quantum world. There is only an abstract quantum description. It is wrong to think that the task of physics is to find out how Nature is. Physics concerns what we can say about Nature.

'We are suspended in Language' (attributed to N. Bohr)

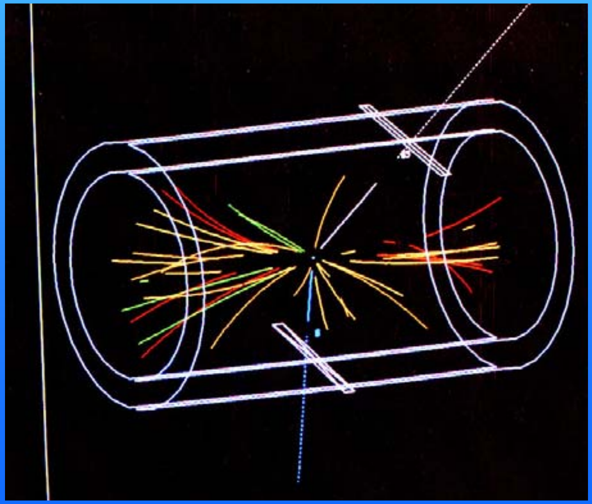
These are just a few examples of the strange ideas that have been forced to the surface by QM. We shall attempt to understand these and others, as we go along.

Q.M. on the Small Scale: I



At the atomic and sub-atomic scales, interference and superposition are everywhere. The physics of the nucleus was unravelled once the existence of the "weak" & "strong" forces was realised- this explained radioactive decay and led to nuclear weapons. In the following years investigations at ever higher energies probed subnuclear processes, culminating in the period 1967-73 with the formulation of the "standard model", which unifies the strong, weak, and EM interactions in a single quantum theory. This allows an explanation of the high-energy processes in astrophysics.

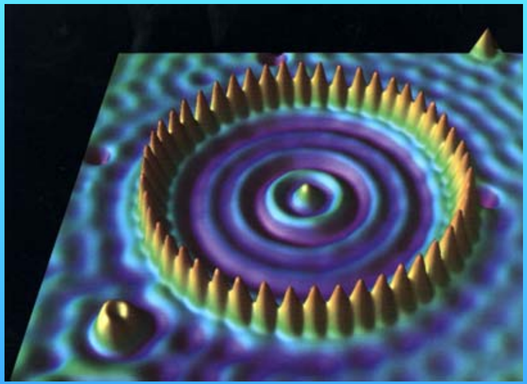
Nuclear fission



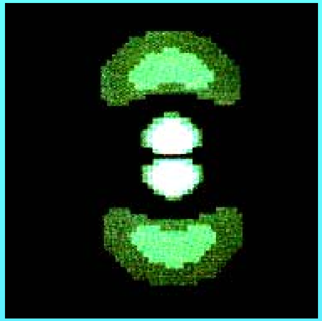
We still have no clear idea how to unify the standard model with gravitation- this is the main goal of modern string theory.

Q.M. on the SMALL SCALE: II

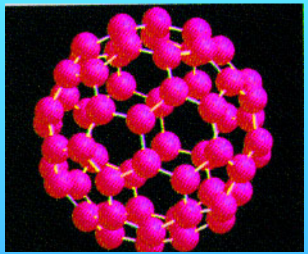
The structure of atoms and molecules is essentially quantum- mechanical- the electrons live in probability amplitude clouds around the central nuclei. As Dirac put it, with the advent of QM, chemistry became a sub-branch of physics- although it is a long way from the QM equations to the structure of, eg., the DNA molecule. Nevertheless QM led to the 20th century revolution in chemistry and biology



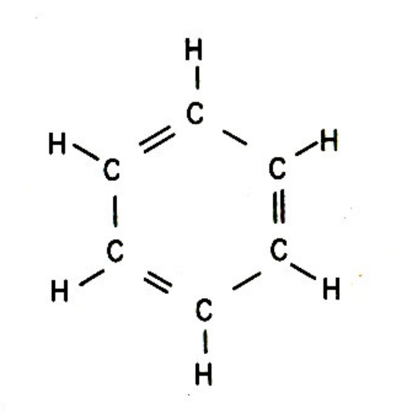
Quantum Corral (Co on metallic Cu surface)



Wave-function for H atom.

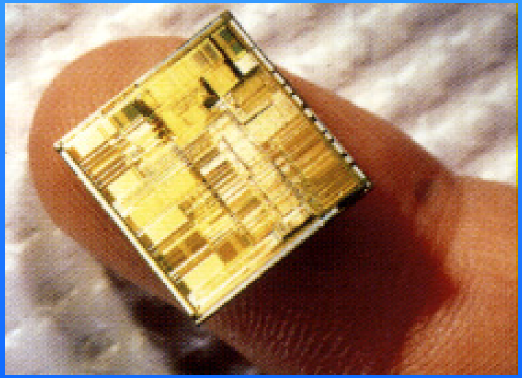


C-60 molecule



Benzene molecule

In the same way QM allowed us to understand the electronic structure of solids, including metals, semiconductors, magnets, polymers, etc., and of liquids from water to liquid crystals. Beginning in the 1960's, this has triggered a massive and continuing techno- revolution

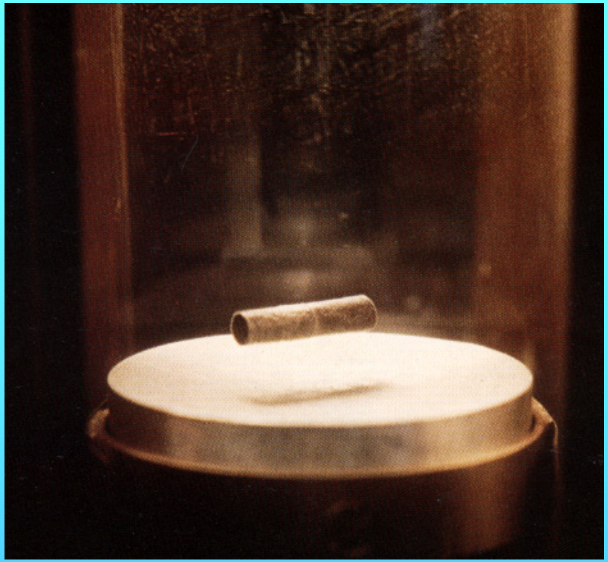


Pentiun 2 chip

DNA molecule

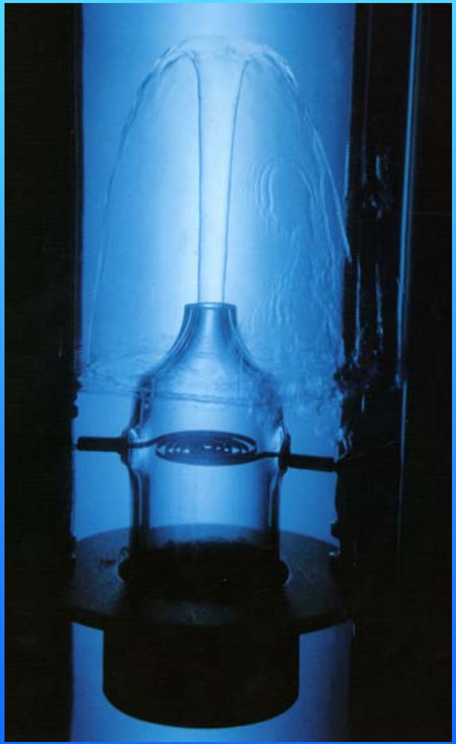
Quantum Mechanics on the Large Scale: I

Although quantum effects like interference and entanglement were not expected at the macroscopic scale by the founders of Q.M., the indirect effect of Q.M. is clear, at scales from the nanoscopic up to our size. In fact, one can’t understand physical processes and structure at the large scale without Q.M.

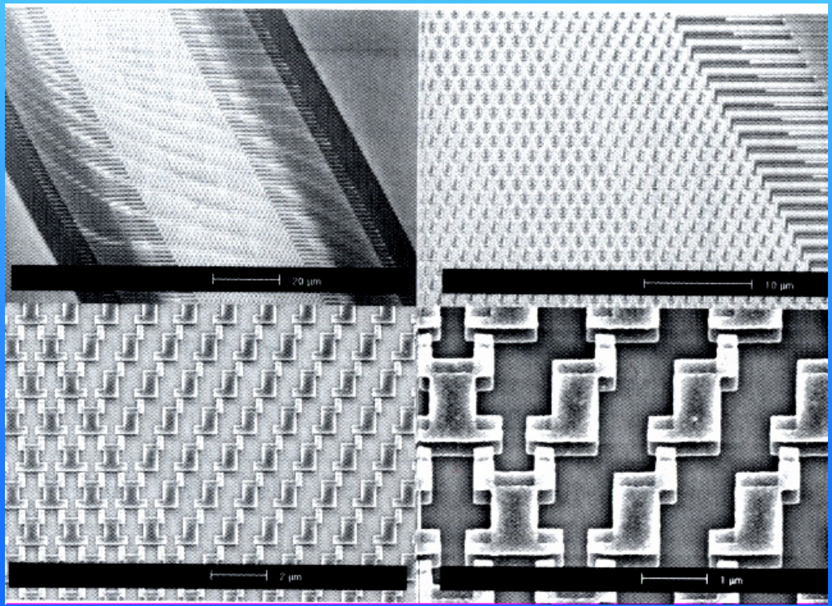


Superconducting levitation effect

However there ARE a few direct effects of QM on the large scale, which are very dramatic (for some, the most dramatic effects of QM anywhere in Nature). These are superfluiditiy and superconductivity, involving the coherent quantum behaviour of huge numbers of particles . These systems can show very strange behaviour.



Superfluid fountain



Large array of Josephson junctions

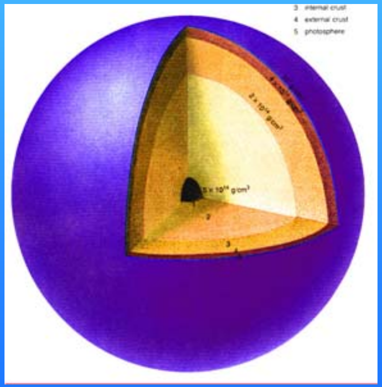
Quantum Mechanics on the Large Scale: II

Until QM, almost all astrophysical processes were beyond our comprehension. We now have an incredibly detailed understanding of how stars function, from birth to death, and of the physics of objects ranging from comets & planets to nebulae and galaxies. Relativistic quantum field theory has opened up the structure of supernovae, neutron stars & black holes, and exposed the story of the universe back to its beginning.

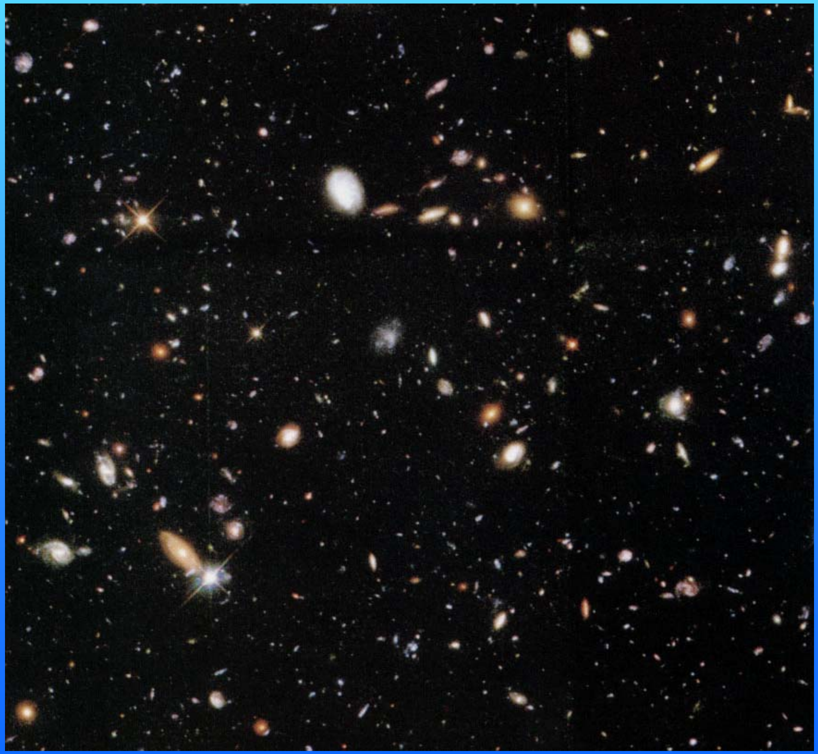
Zeldovich distribution

M16 (Eagle nebula)

Supernova (bottom left) in NGC 5426



Cross-section inside a neutron star (mass ~1.4 suns, diameter ~10 km)



Section of the Hubble deep space probe.