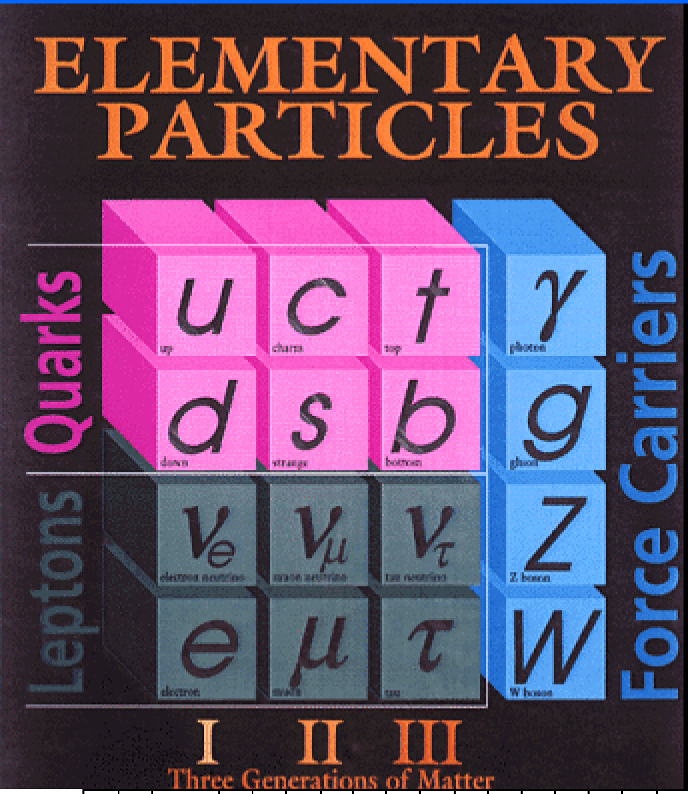
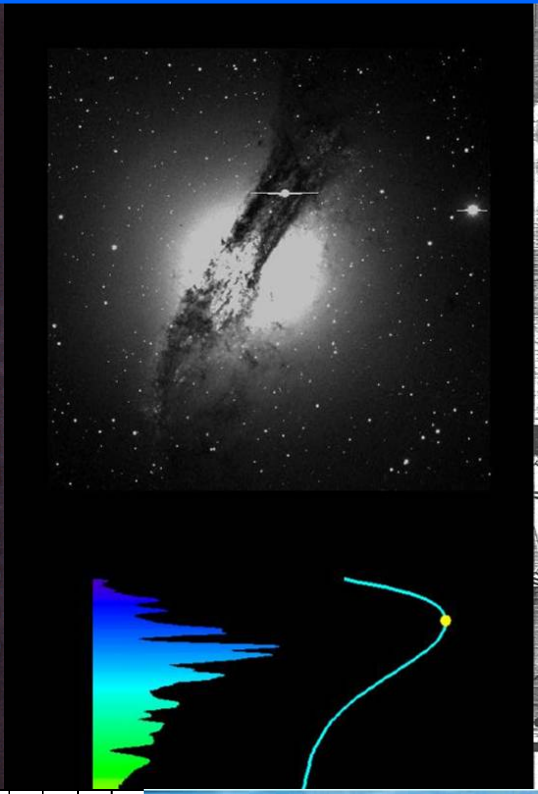
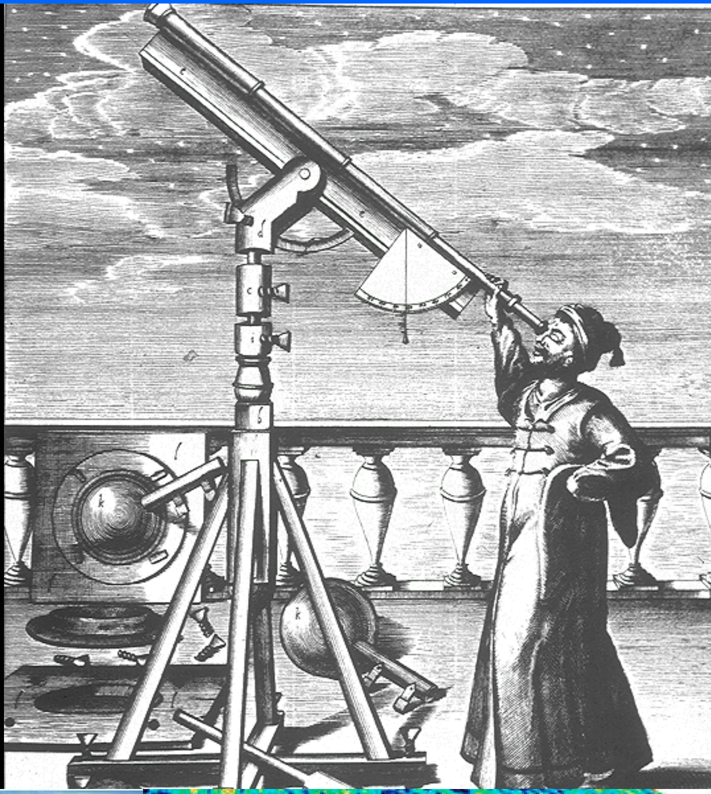
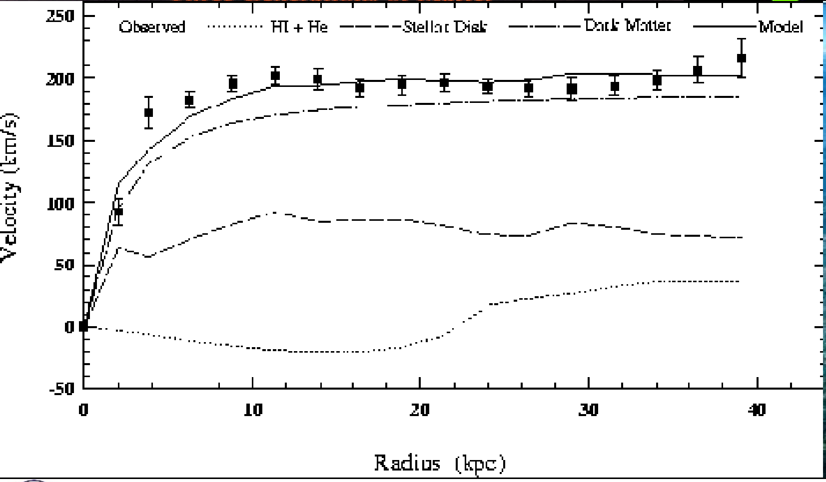
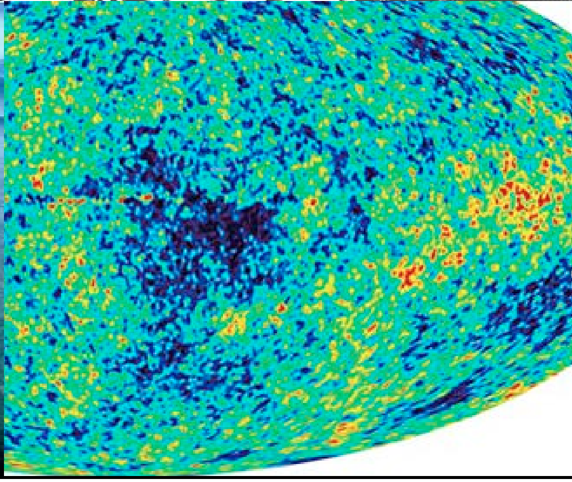
Beyond the Standard Model







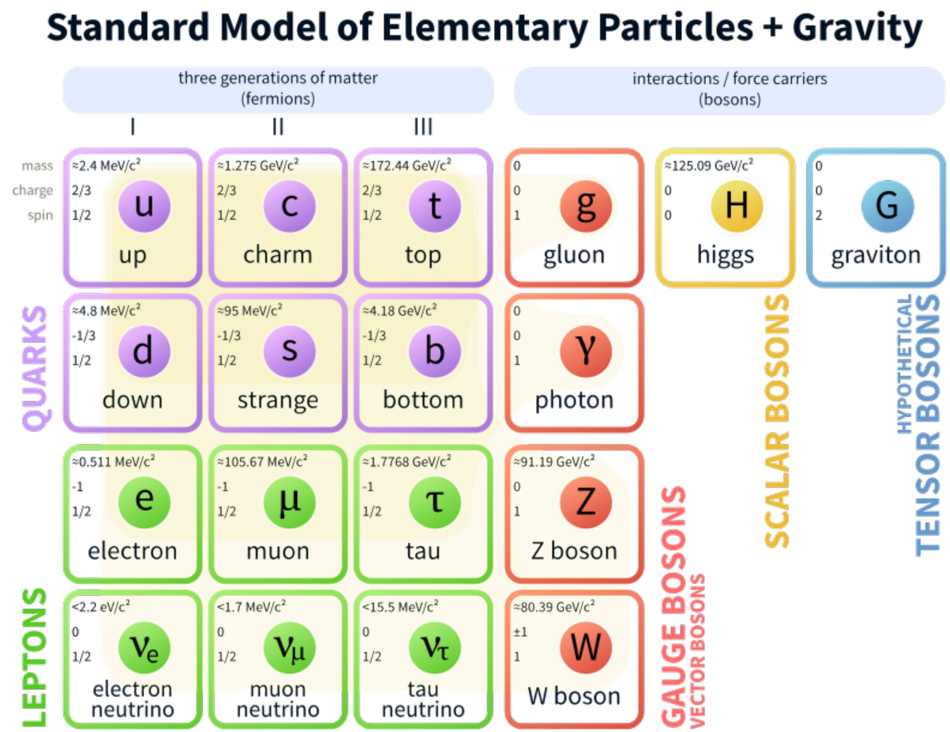


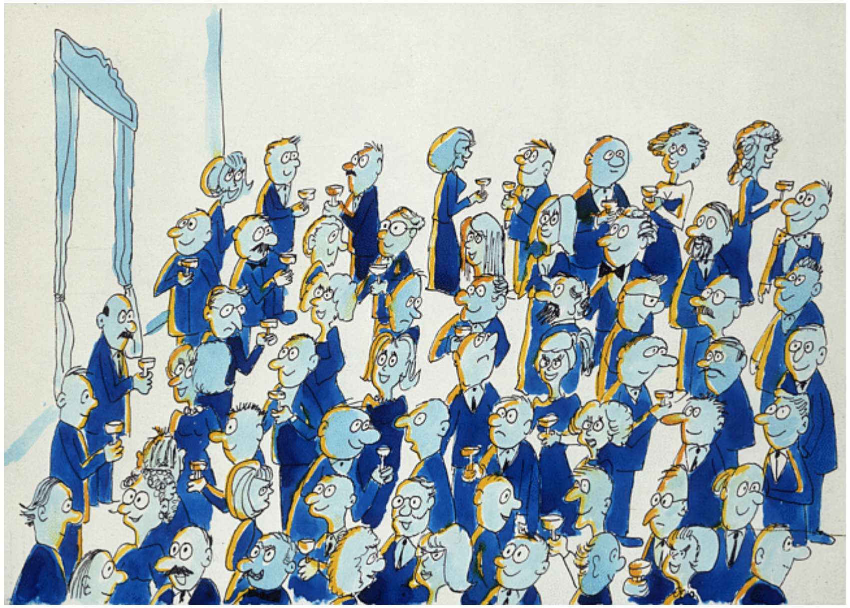


Beyond the Standard Model

The Standard Model is an incomplete theory. It cannot explain why a particle has a certain mass.

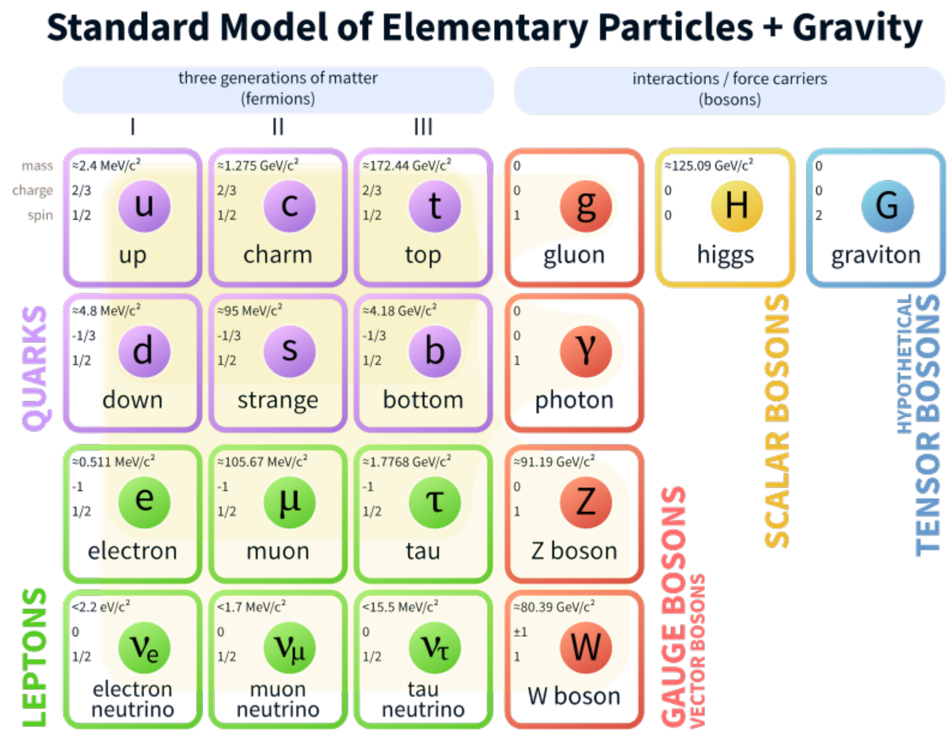
Physicists have theorized the existence of the so-called Higgs field, which in theory interacts with other particles to give them mass. The Higgs field requires a particle, the Higgs boson.





A massless particle moving in a Higgs field is equivalent to a massive particle ⇒ Higgs field "gives mass to all particles"

Beyond the Standard Model

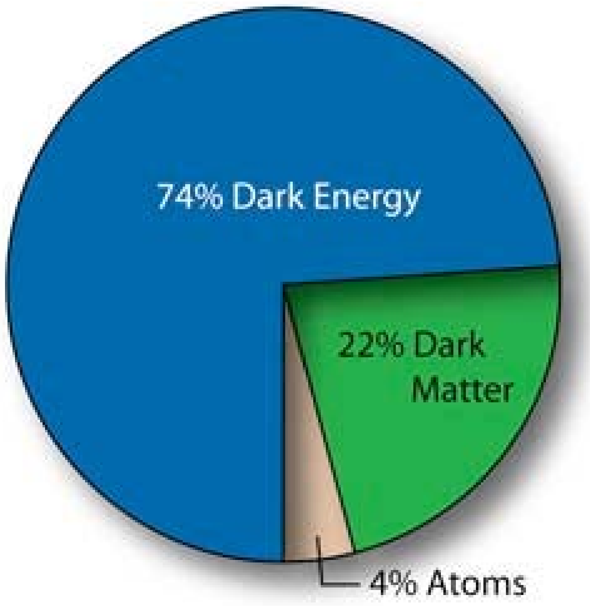


The Standard Model is an incomplete theory. It does not adequately explain:

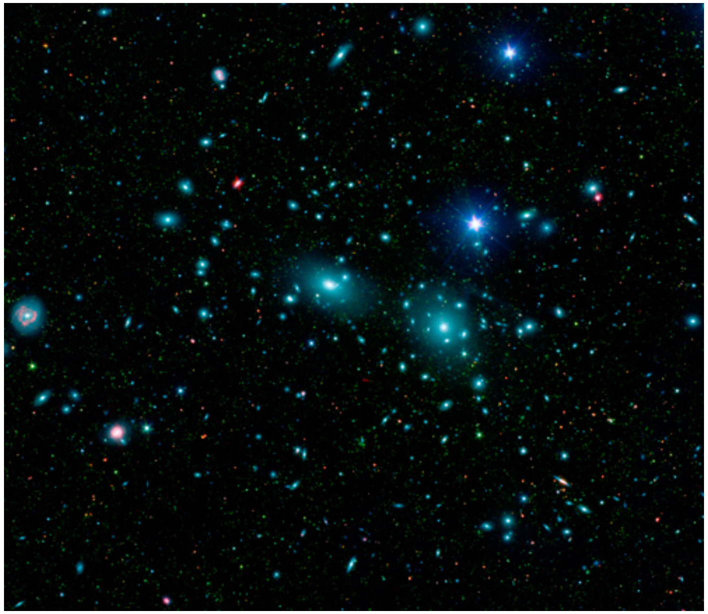
- Gravity (graviton simply added)
- Dark matter (26%) and dark energy (69%)
- Matter – antimatter asymmetry (should be equal)
- Mass of neutrinos (what was their role in the formation of the universe?)
- Superconductivity (how does high T_c work?)
- Quantum theory of gravity (is there a QTG that can describe the universe we live in?
- Number of dimensions in a fundamental theory of nature.

What is the Universe really made of?

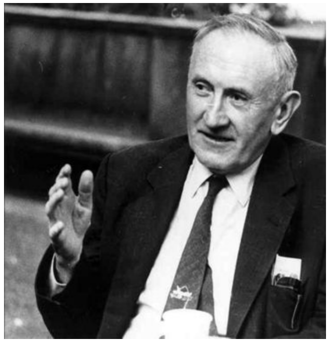
- Particle physicist's answer: stable particles – protons, neutrons, electrons, neutrinos
- (Why not antiprotons, positrons, etc.? another puzzle – may be next time?)
- But astronomical observations indicate that the known particles make only about 4% of the stuff in the Universe!



What is Dark Matter?



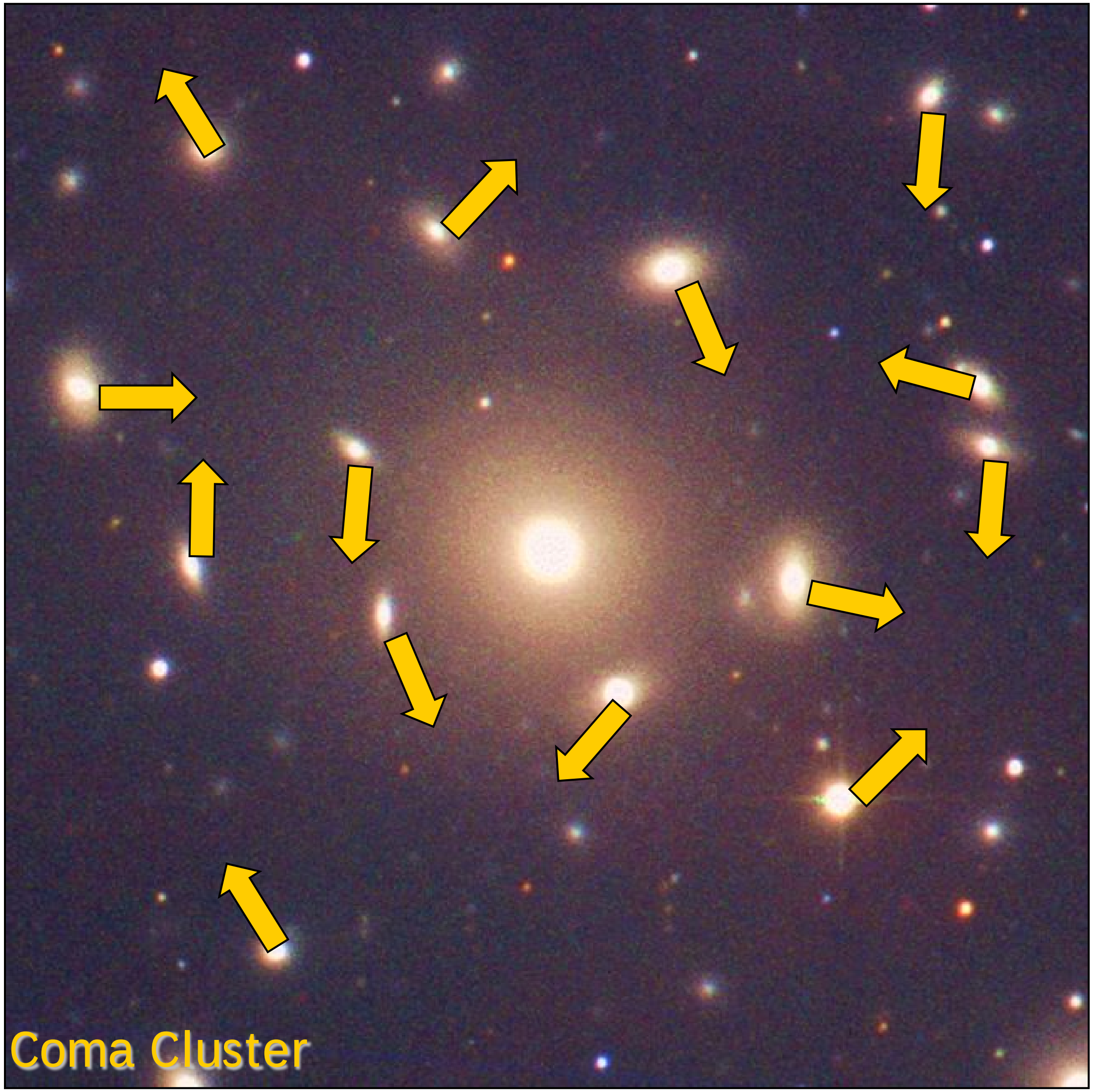
Coma Cluster: By measuring the velocities of all these galaxies Fritz Zwicky realized that galaxies toward the edge of the cluster were moving far too fast.



Fritz Zwicky: Die Rotverschiebung von Extragalaktischen Nebeln
(The redshift of extragalactic nebulae) Helv. Phys. Acta 6 (1933) 110

In order to obtain, as observed, a medium-sized Doppler effect of 1000 km/s or more, the average density in the Coma system would have to be at least 400 times greater than that derived on the basis of observations of luminous matter. If this should be verified, it would lead to the surprising result that dark matter exists in much greater density than luminous matter.

What is Dark Matter?



A gravitational bound system of many 'particles' follows the Virial theorem

$$2\langle E_{kin}\rangle = -\langle E_{grav}\rangle$$

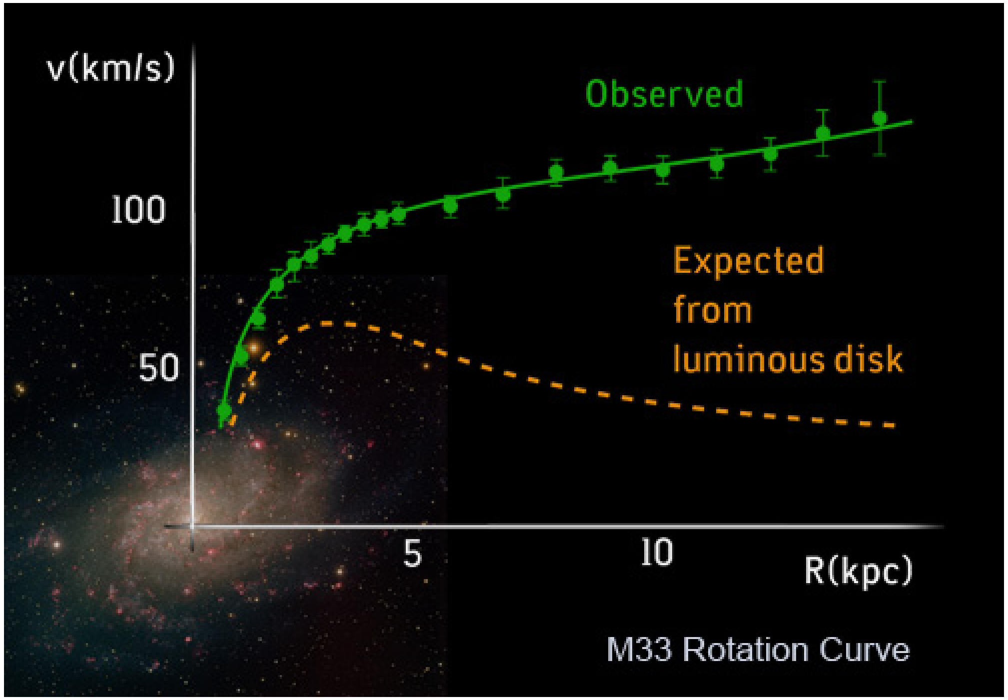
$$2\left\langle \frac{mv^2}{2} \right\rangle = \left\langle \frac{G_N M_r m}{r} \right\rangle$$

$$\langle v^2 \rangle \approx G_N M_r \langle r^{-1} \rangle$$

Velocity measurement via Doppler effect of at least three spectral lines

Mass estimate

What is Dark Matter?



Vera Rubin

Keplerian prediction:

$$m \cdot \frac{v^2}{r} = f \cdot \frac{m \cdot M}{r^2} \quad \rightarrow \quad v^2 = f \cdot \frac{M}{r}$$

Fritz Zwicky: Die Rotverschiebung von Extragalaktischen Nebeln
(The redshift of extragalactic nebulae) Helv. Phys. Acta 6 (1933) 110

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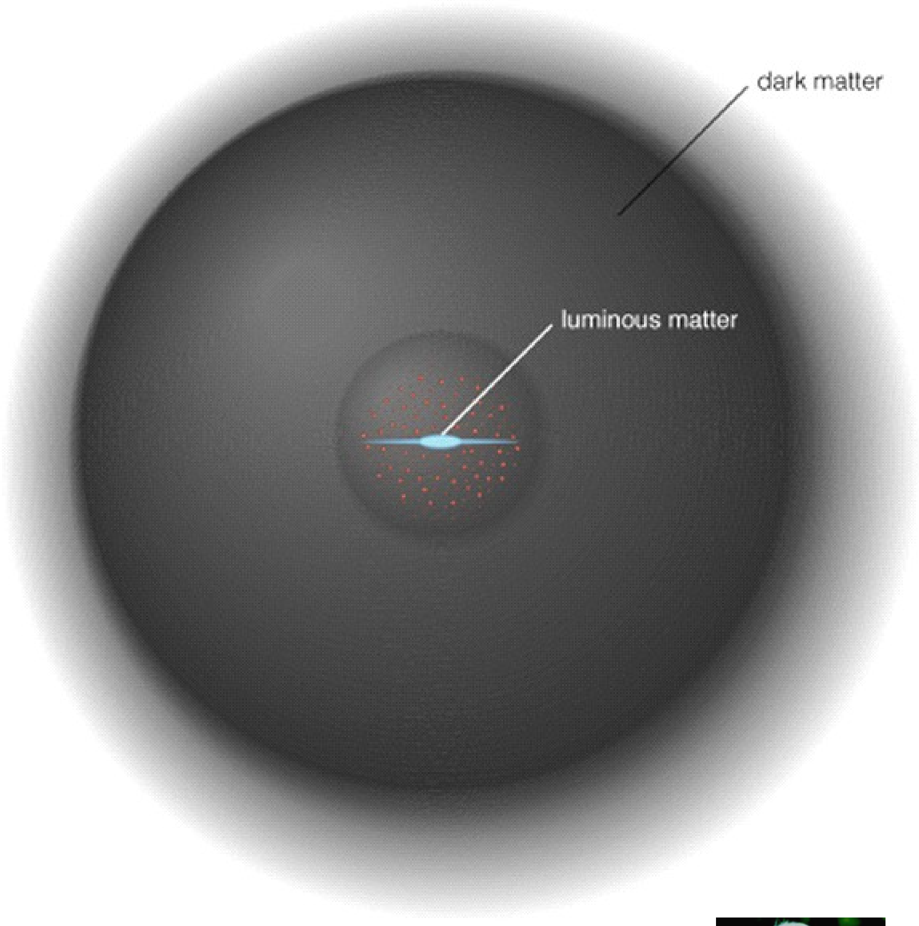
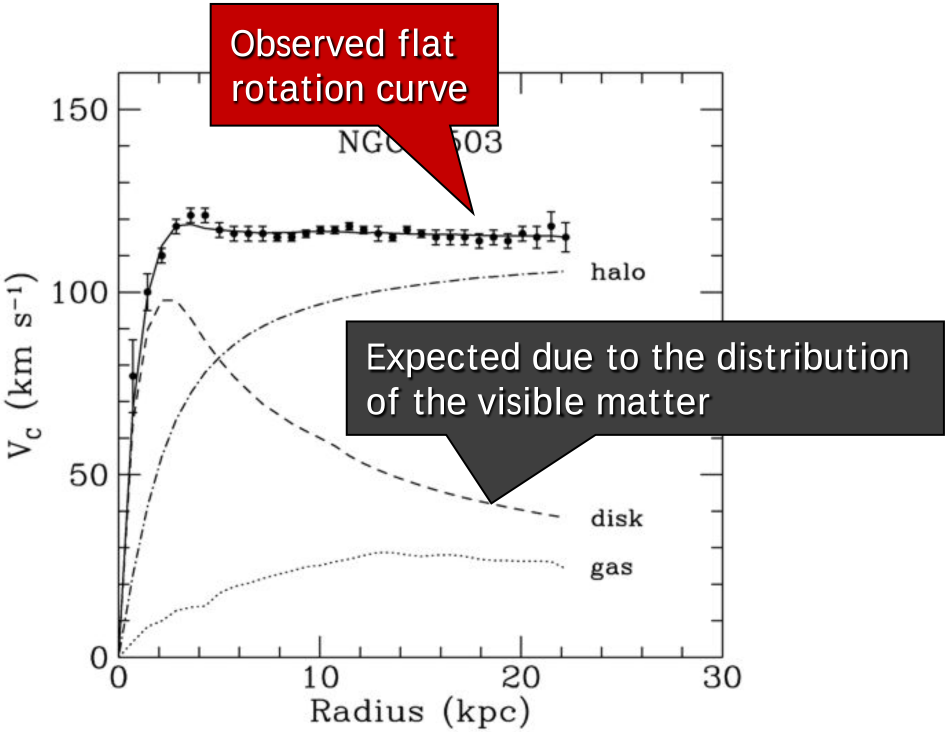
What is Dark Matter?

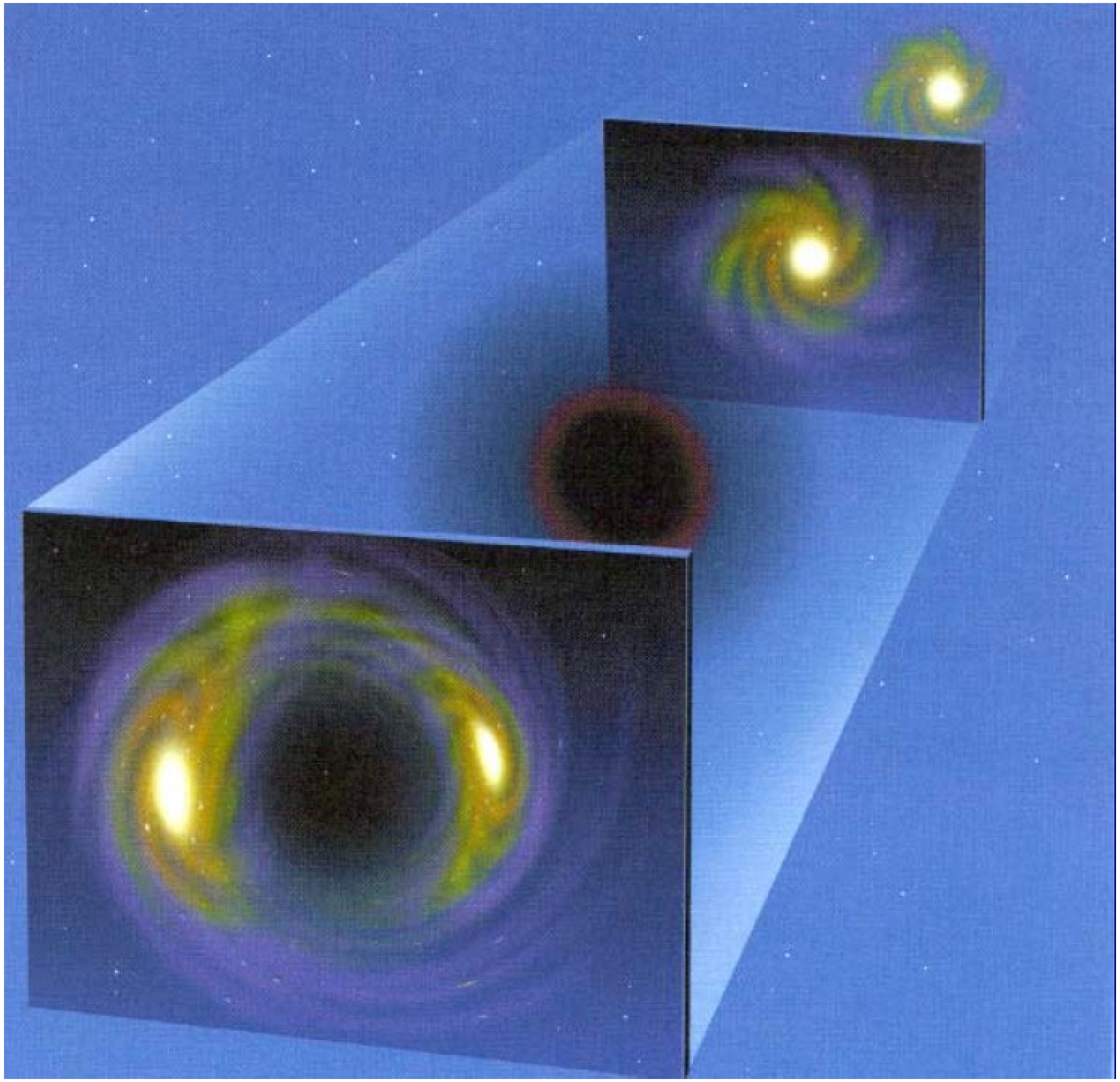


- Dark matter in the Halo around a Galaxy
- Dark matter ~ 10x visible mass

Vera Rubin



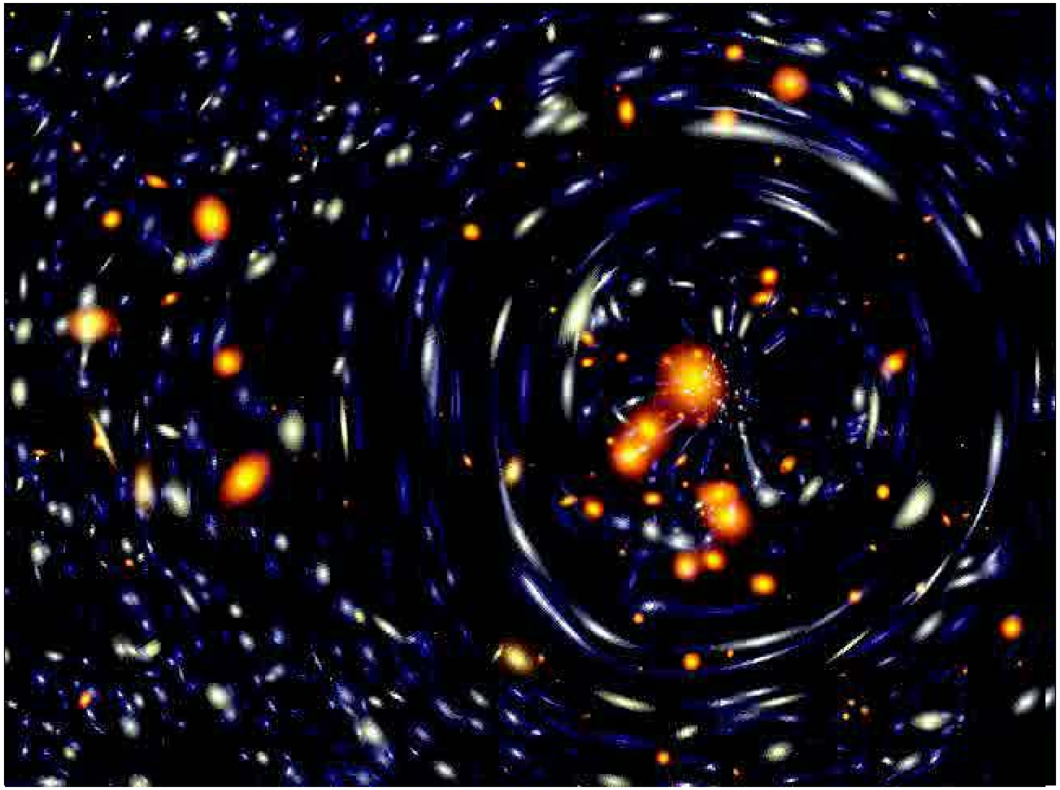
Einstein ring



It is the deformation of light from a source (such as a galaxy or star) into a ring through gravitational lensing of the source’s light by an object with an extremely large mass.

Gravitational lensing effect

Galaxy Cluster Cl 0024+1654
[Hubble Space Telescope]



numerical simulation

Bullet Cluster (1E 0657-56)

Crash of galaxy clusters: Dark matter (blue) creating most of the gravitational potential separated from normal matter (pink).

Big Bang Cosmology: Albert Einstein (1879-1955)

Prediction: The universe is expanding

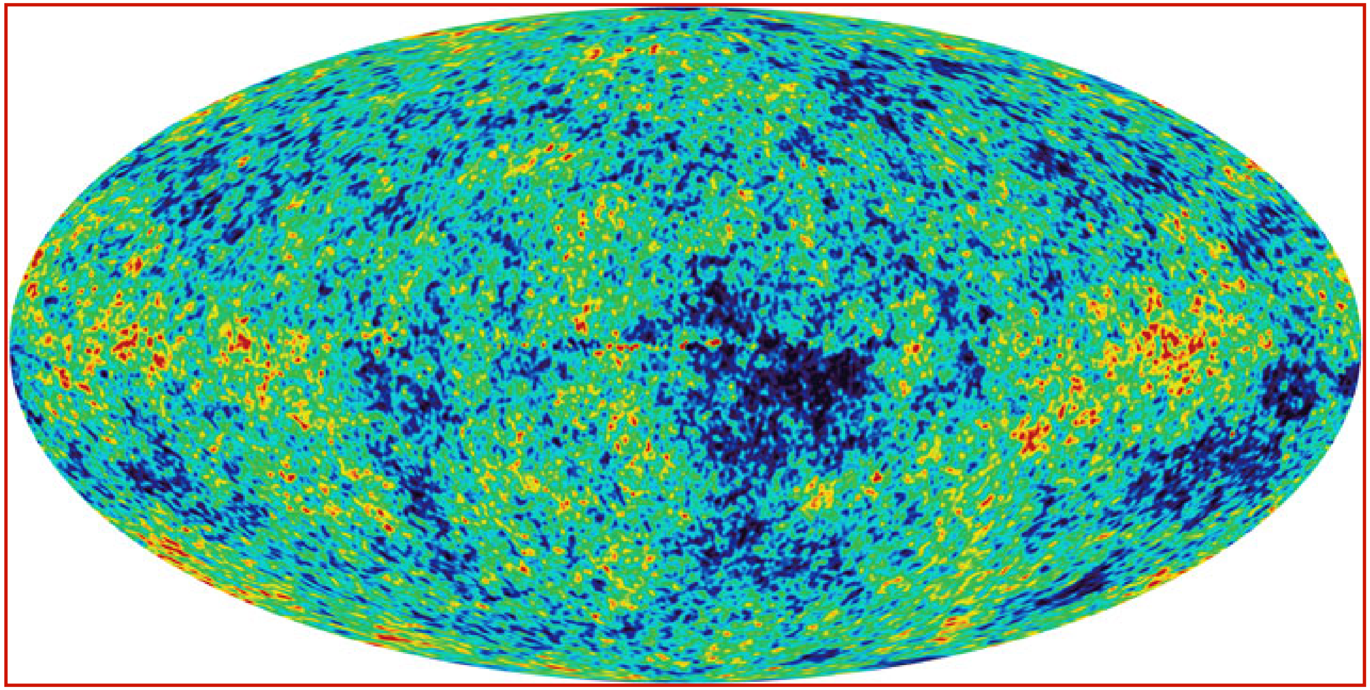
Observation: Galaxies are moving apart from each other (1929)

Red-shift of the spectral lines in stars (Doppler effect)

Testing the Big Bang model

Prediction: If the universe was denser, hotter, in past, we should see evidence of left-over heat from early universe

Observation: Left-over heat from the early universe (Penzias and Wilson, 1965)



What is Dark Energy?

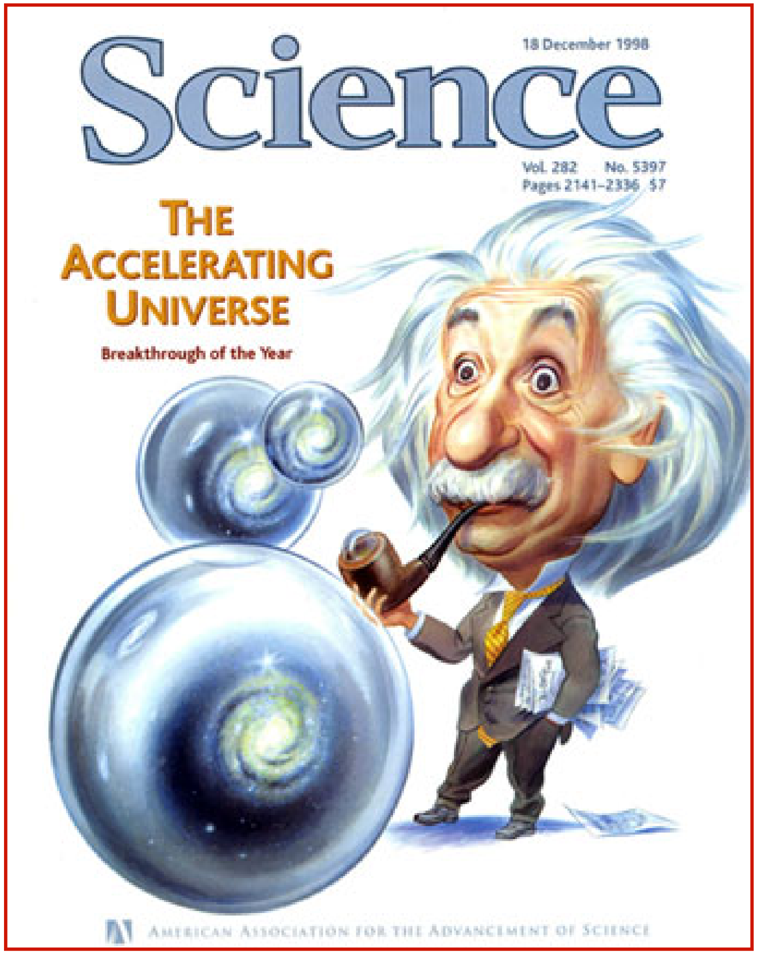
Testing the Big Bang model

Observation: Expansion is accelerating.

Refine: Extra energy content.

A recent discovery and of unknown origin, the concept of Dark Energy is actually an integral part of Einstein's theory of gravity.

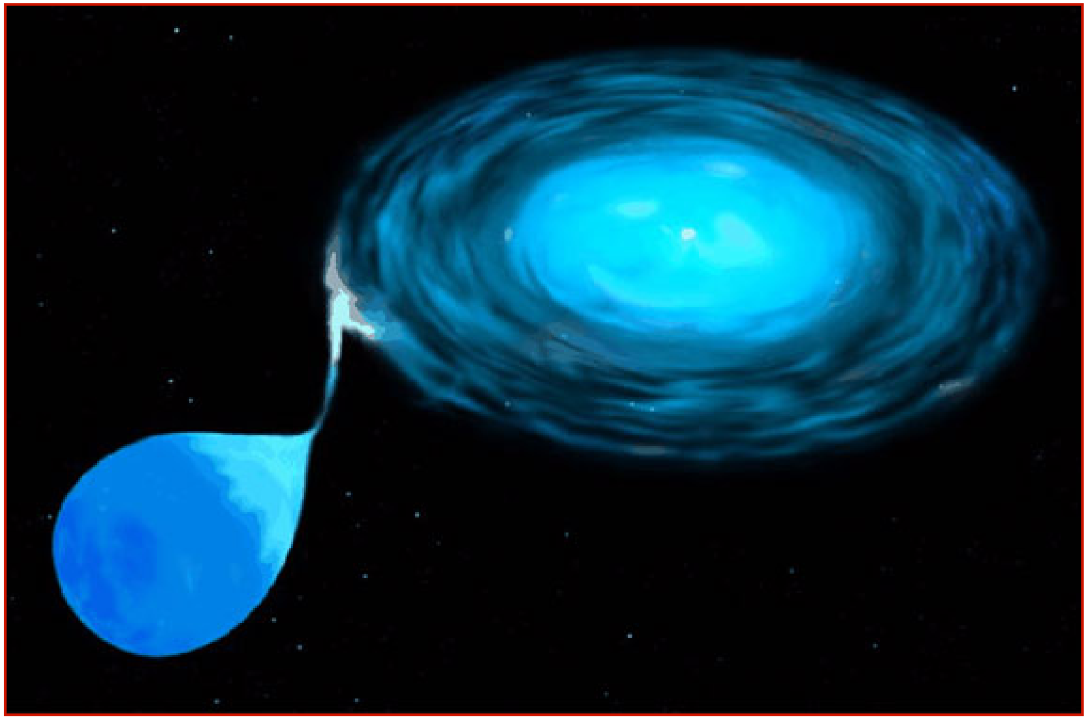
> theory of relativity lies nearest at hand; whether, from the standpoint of present astronomical knowledge, it is tenable, will not here be discussed. In order to arrive at this consistent view, we admittedly had to introduce an extension of the field equations of gravitation which is not justified by our actual knowledge of gravitation. It is to be emphasized, however, that a positive curvature of space is given by our results, even if the supplementary term is not introduced. That term is necessary only for the purpose of making possible a quasi-static distribution of matter, as required by the fact of the small velocities of the stars.



Evidence for Dark Energy

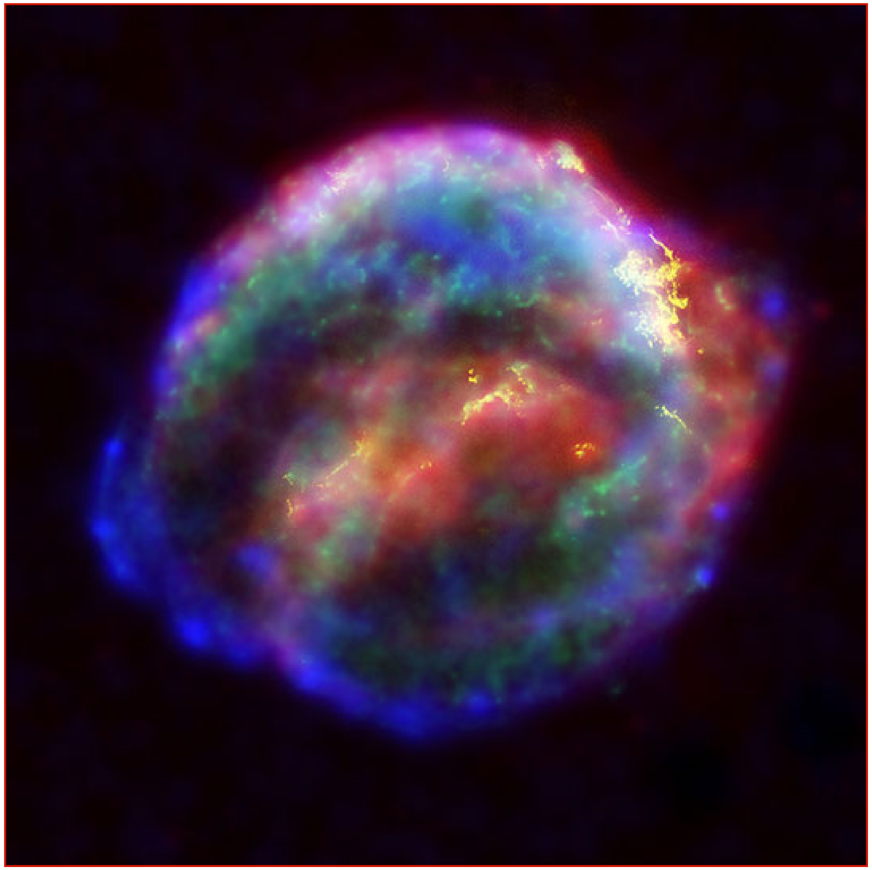
A dying star becomes a white dwarf.

Evidence for Dark Energy



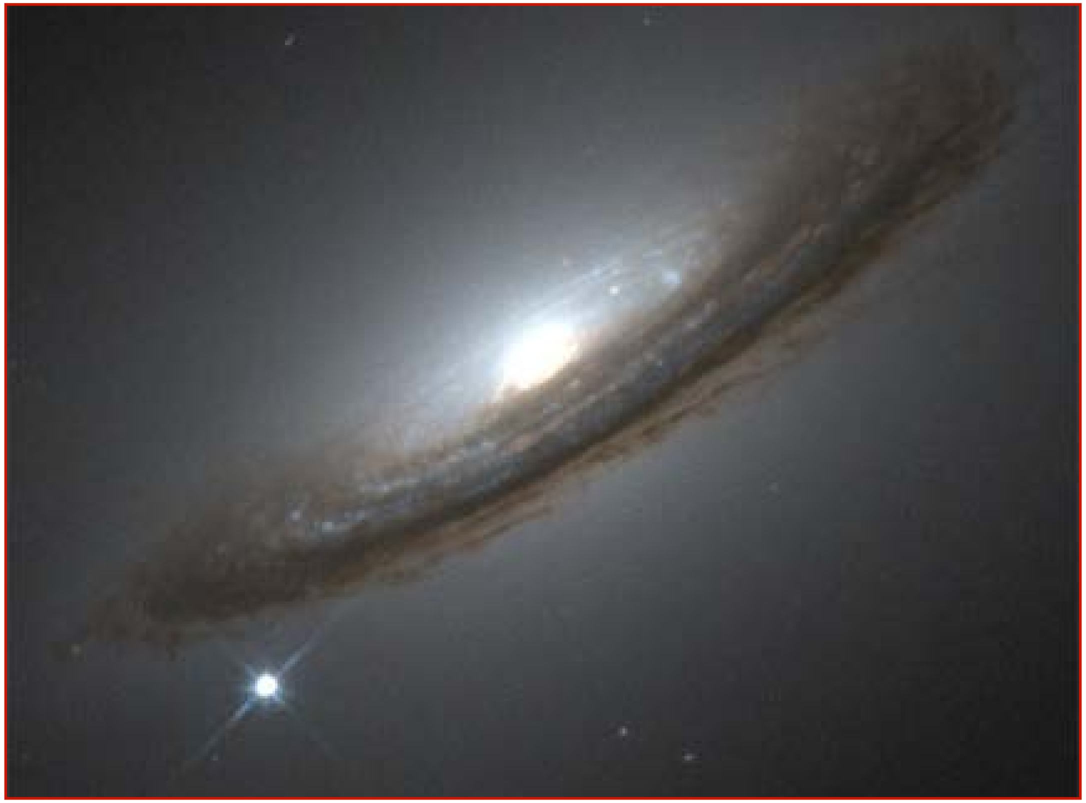
The white dwarf strips gas from its stellar companion …

Evidence for Dark Energy



… and uses it to become a hydrogen bomb. Bang!

Evidence for Dark Energy



The explosion (Supernova Type Ia) is as bright as an entire galaxy of stars

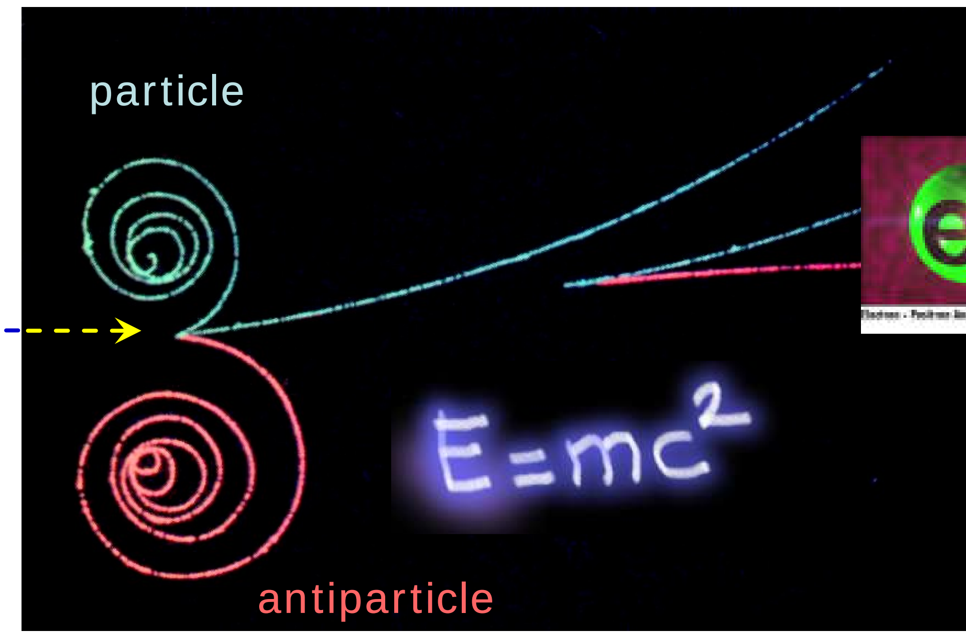
Paul A. M. Dirac

Dirac: Key Discovery

Relativity + Quantum Theory

⇒ ‘Antiparticles’

Energy*



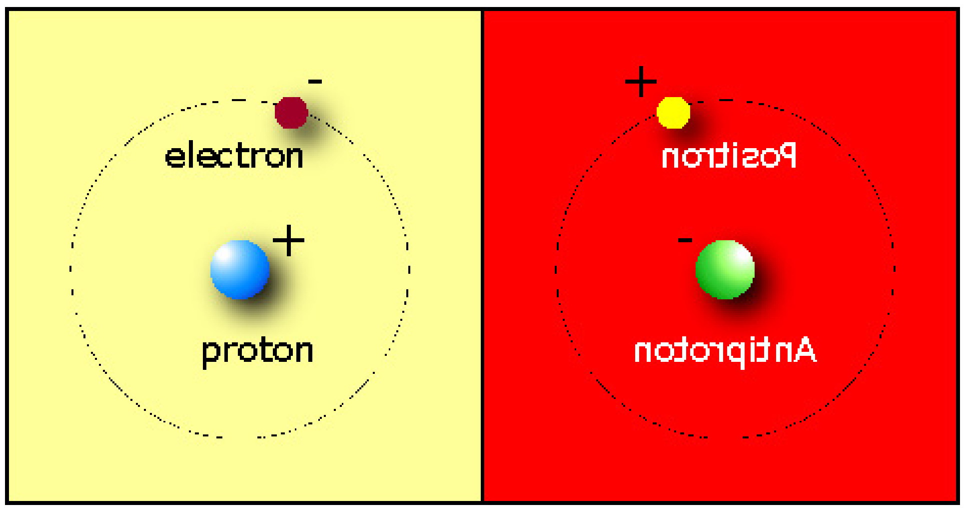
$$(i\gamma^\mu\partial_\mu - m)\psi = 0$$

* gamma rays

Is the Universe symmetric?

1933 Dirac (from his Nobel lecture)

"If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), ***contains a preponderance of negative electrons and positive protons.***



Without asymmetry - we would not be here!!

What kind of asymmetry??

Sakharov's Idea

A.D.Sakharov

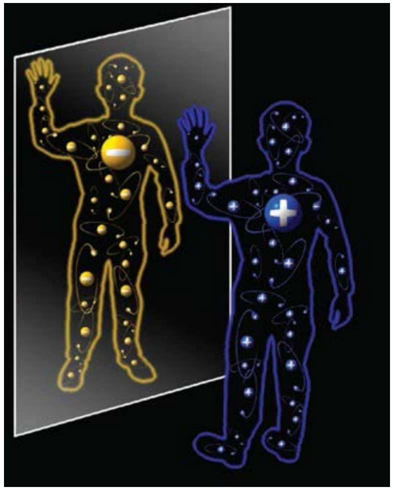
Particles decay (a little) faster than antiparticles*

Small imbalance (1,000,000,001:1,000,000,000)
Occurs during cool-down of Universe

Most particle-antiparticle pairs annihilate to radiation

Galaxies, stars, planets, us = 'left-over'

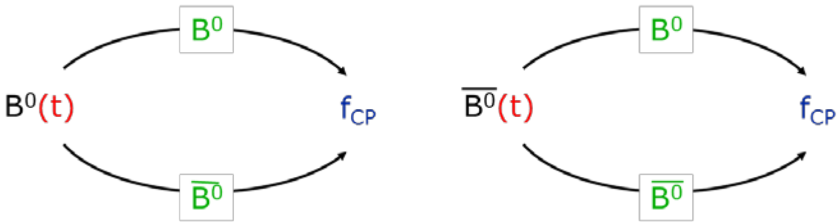
*For experts: this is called 'CP violation'



When we look at our image in a standard mirror, we are looking at the parity transformation of ourselves

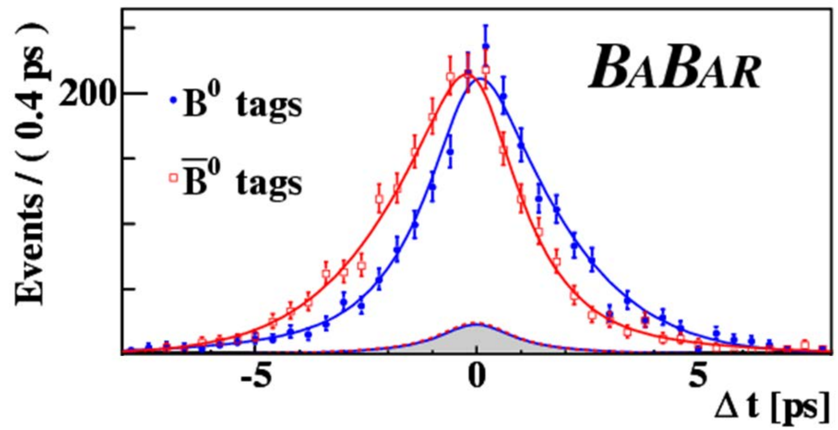
Measuring CP Violation with B^0s

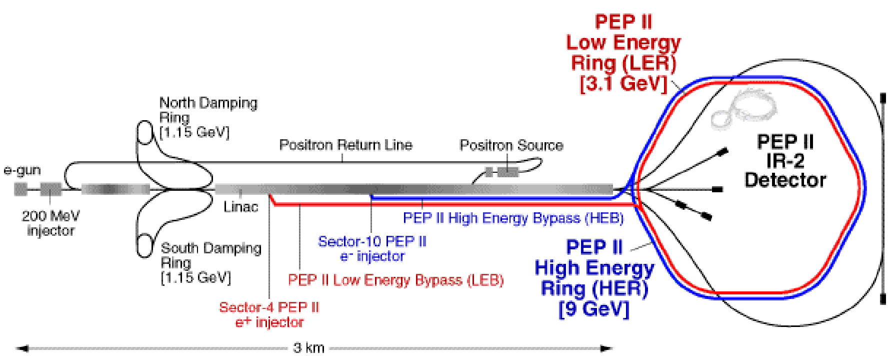
$B^0 = \bar{b}d$



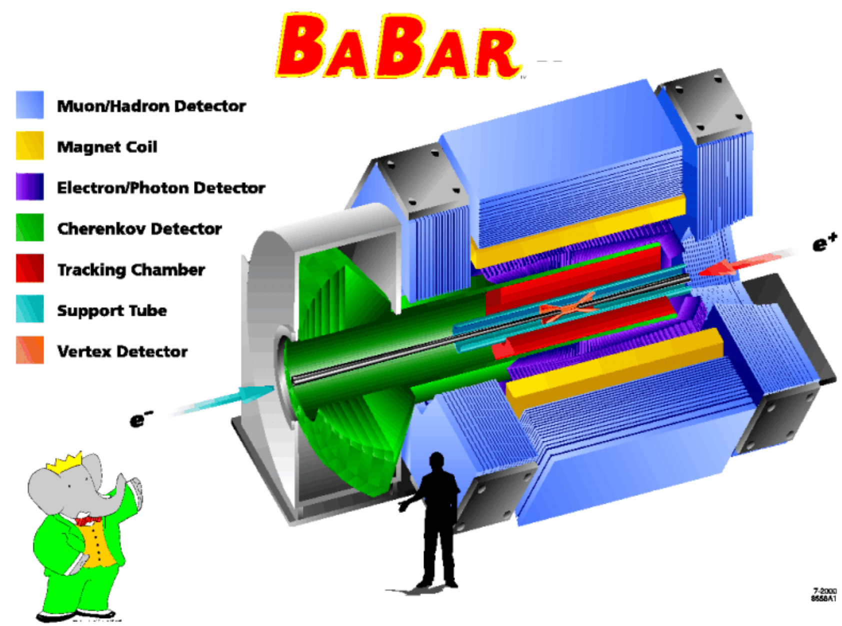
$\overline{B^0} = b\bar{d}$

Not equal –
CP Violation!

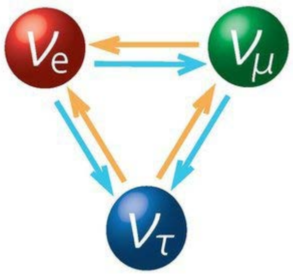




Stanford Linear Accelerator Center



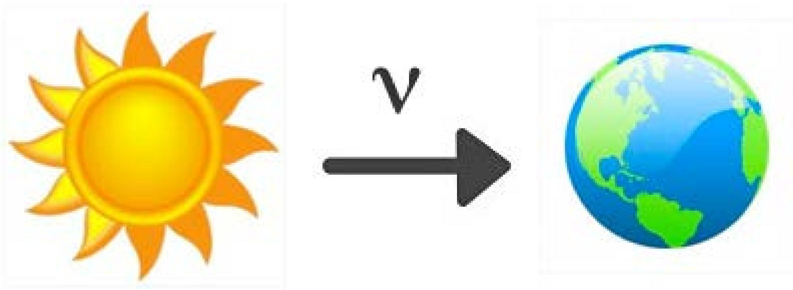
Neutrino masses



The Standard Model was built with the assumption of massless neutrinos

- No right-handed neutrinos, and then no Dirac mass

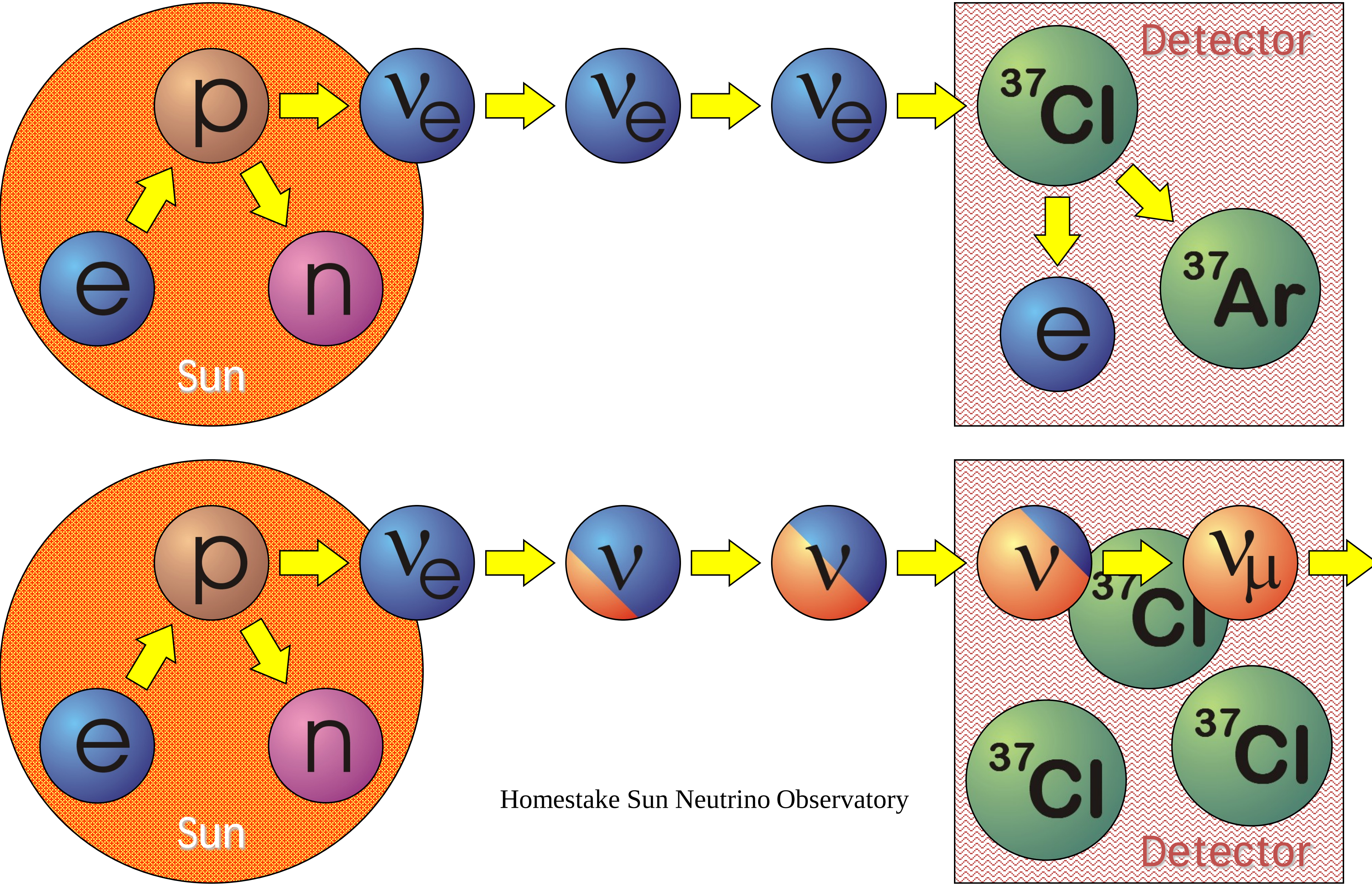
Solar neutrino problem:



$$N_{observed} \cong \frac{1}{3} N_{expected}$$

Where are the missing neutrinos

Solar Neutrino problem



Neutrino Oscillations

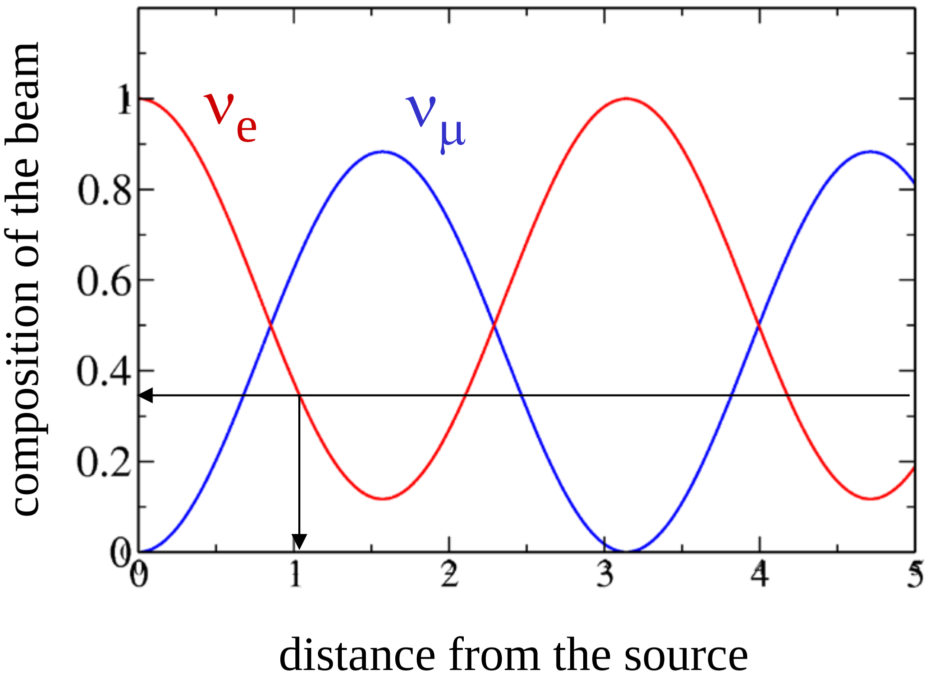
Electron e	Myon μ	Tau τ
e-Neutrino	μ-Neutrino	τ-Neutrino

Idea: if the neutrinos have a non-zero mass, they can interact with each other!

Assumption: Mixture of

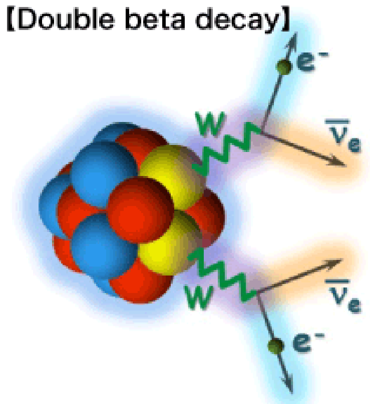
ν_e and ν_μ

changes the composition of the neutrino beam depending on the distance to the neutrino source.

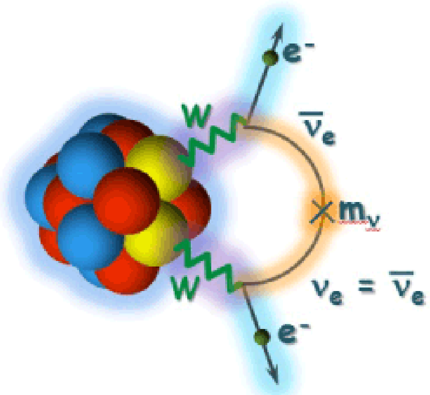


1998: Detection of oscillation between Myon- und Tau-neutrinos with methods of Super-Kamiokande (Myon-Neutrinos from the atmosphere)

Neutrinoless Double Beta Decay



Double beta decay
which emits anti-neutrinos



Neutrinoless
double beta decay

Paul Dirac

Ettore Majorana

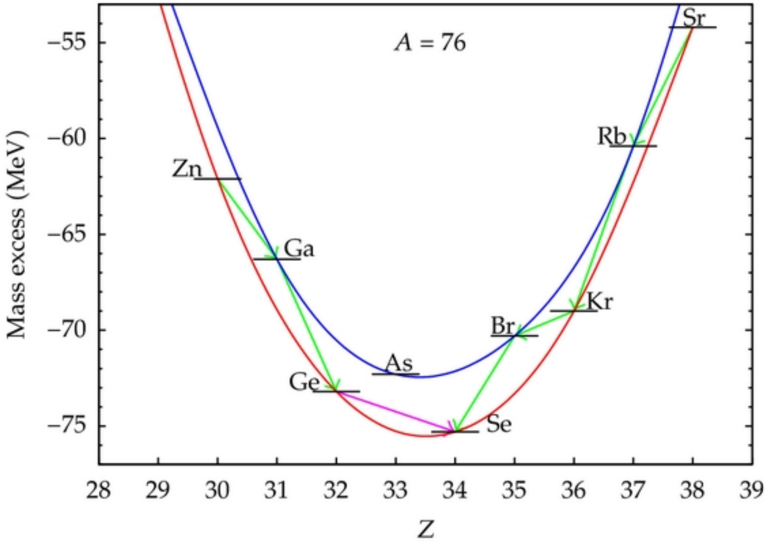
Fermions

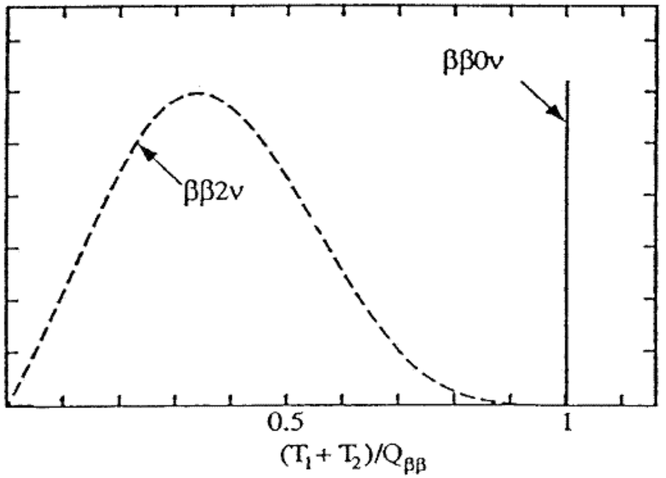
particle-antiparticle pair

Neutral Particles

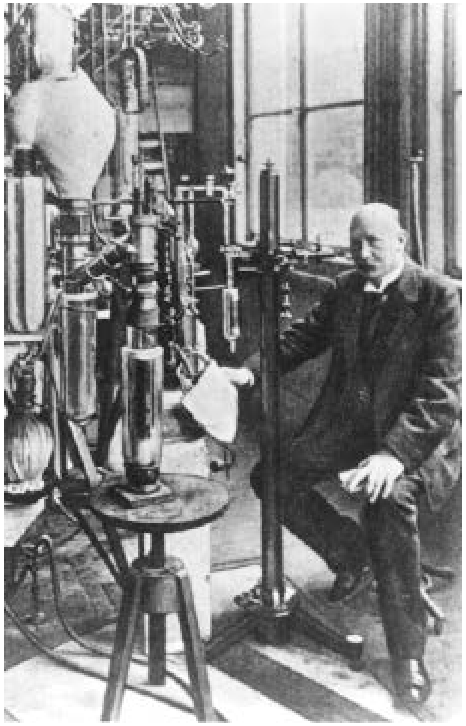
they are their own antiparticles
works for massless neutrinos

$$\nu = \bar{\nu}$$

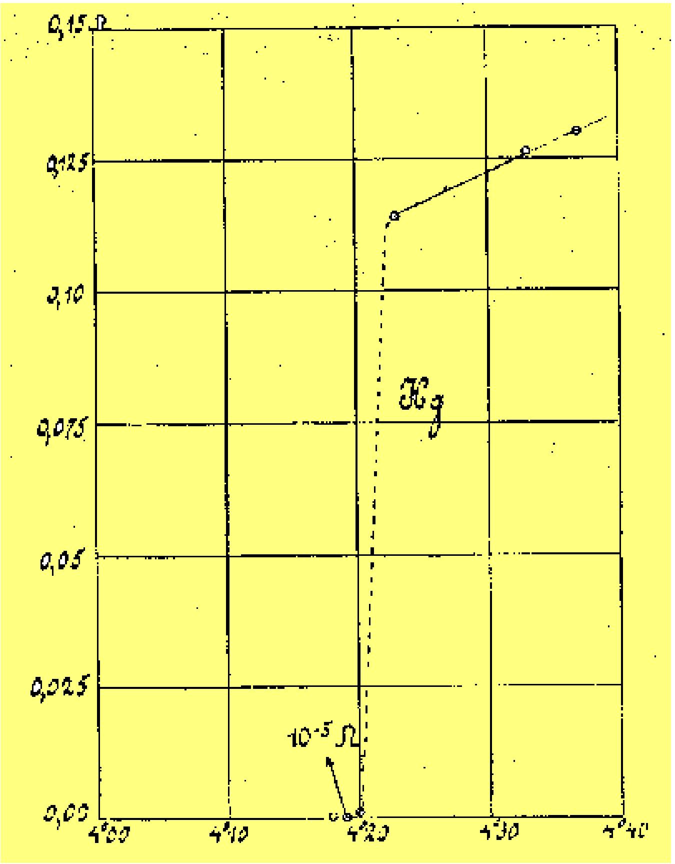




Superconductivity - discovery



- Liquid Helium (4K) (1908) ***Boiling point*** 4.22K
- Superconductivity in Hg $T_C = 4.2K$ (1911)



Resistivity R=0 below T_C; (R<10^{-23} Ω·cm, 10^{18} times smaller than for Cu)

„Mercury has passed into a new state, which on account of its extraordinary electrical properties may be called the superconducting state“

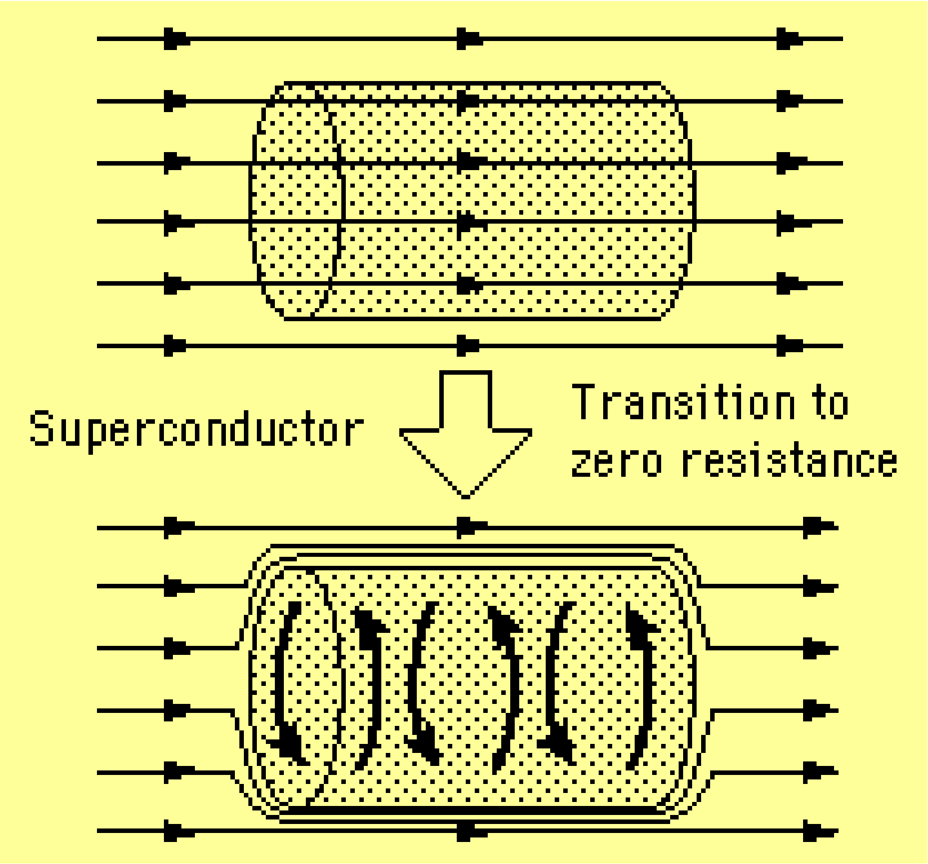
H. Kamerlingh Onnes 1913 (Nobel price 1913)

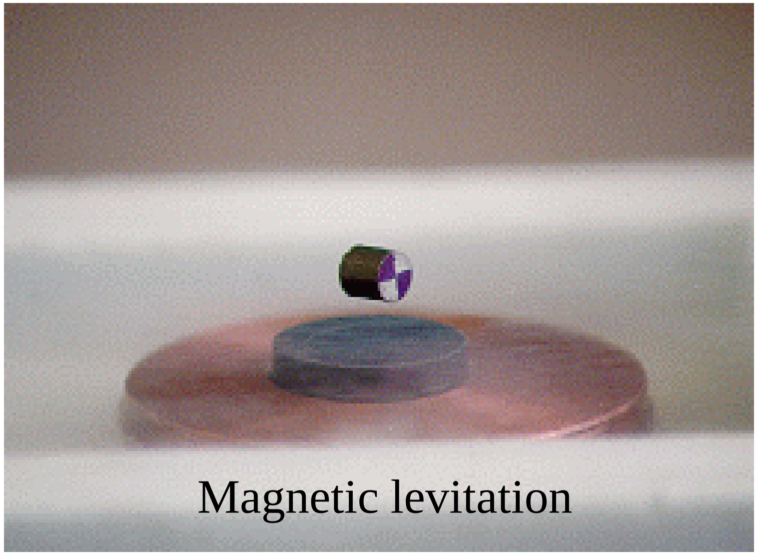
Meissner – Ochsenfeld - effect

A superconductor is a perfect diamagnet. Superconducting material expels magnetic flux from the interior.

W. Meissner, R. Ochsenfeld (1933)

On the surface of a superconductor ($T < T_C$) superconducting current will be induced. This creates a magnetic field compensating the outside one.

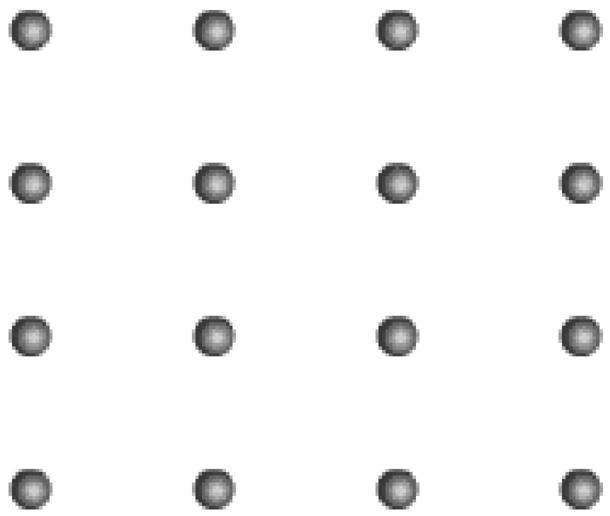




Classical model of superconductivity

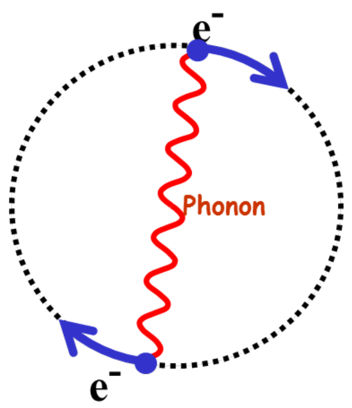
1957 John Bardeen, Leon Neil Cooper and John Robert Schrieffer

An electron on the way through the lattice interacts with lattice sites (cations). The electron produces **phonon**.



The lattice deformation creates a region of relative positive charge which can attract another electron.

During one phonon oscillation an electron can cover a distance of ~10^4Å. The second electron will be attracted without experiencing the repulsing electrostatic force .



Size of Cooper pair 100 nm
Lattice spacing 0.1 – 0.4 nm

Further discoveries

1911-1986: “Low temperature superconductors”
Highest T_C=23K for Nb_3Ge

1986 (January): High Temperature Superconductivity
$(LaBa)_2 CuO_4$ T_C = 35K

K.A. Müller und G. Bednorz (IBM Rüschlikon)
(Nobel price 1987)

1987 (January): $YBa_2Cu_3O_{7-x}$ T_C = 93K

1987 (December): Bi-Sr-Ca-Cu-O T_C = 110K,

1988 (January): Tl-Ba-Ca-Cu-O T_C = 125K

1993: Hg-Ba-Ca-Cu-O T_C = 133K

(A. Schilling, H. Ott, ETH Zürich)

Professor Dr. Dr. h. c. mult. Karl Alex Müller (links) und
Dr. Johannes Georg Bednorz

Z. Phys. B – Condensed Matter 64, 189–193 (1986)
Condensed Matter
Zeitschrift für Physik B

Possible High T_c Superconductivity in the Ba – La – Cu – O System

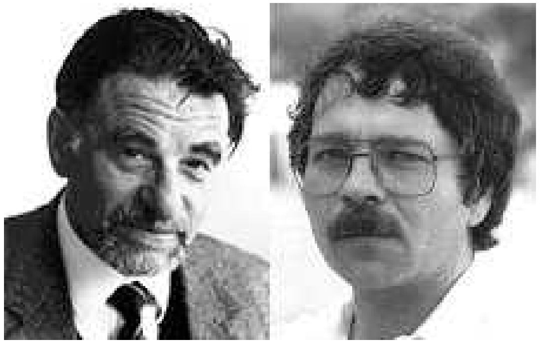
J.G. Bednorz and K.A. Müller
IBM Zürich Research Laboratory, Rüschlikon, Switzerland

Received April 17, 1986

Metallic, oxygen-deficient compounds in the Ba – La – Cu – O system, with the composition $Ba_xLa_{5-x}Cu_5O_{5(3-y)}$ have been prepared in polycrystalline form. Samples with $x=1$ and 0.75, $y>0$, annealed below 900 °C under reducing conditions, consist of three phases, one of them a perovskite-like mixed-valent copper compound. Upon cooling, the samples show a linear decrease in resistivity, then an approximately logarithmic increase, interpreted as a beginning of localization. Finally an abrupt decrease by up to three orders of magnitude occurs, reminiscent of the onset of percolative superconductivity. The highest onset temperature is observed in the 30 K range. It is markedly reduced by high current densities. Thus, it results partially from the percolative nature, bute possibly also from $2D$ superconducting fluctuations of double perovskite layers of one of the phases present.

How does high T_c superconductivity work

- In 1986, Müller and Bednorz found a ceramic compound that superconducted at 30 K, 13 degrees above the highest previously known superconductor. What was so odd about this is that the material (a compound of lanthanum, barium, copper, and oxygen) was a ceramic – normally an insulator – so people *never expected* such materials might be high T_c superconductors.



Müller and Bednorz

- By substituting yttrium for lanthanum, such compounds exceeded 77 K, the temperature of LN2 (a major milestone since LN2 is far cheaper than methods of cooling below this temperature). For the first time, concepts such as Maglev trains, superconducting magnets for accelerators, lossless power transmission, etc. became possibilities.

- The current record holder is 138 K (for $Hg_{0.8}Tl_{0.2}Ba_2Ca_2Cu_3O_{8.33}$). How high will transition temperatures reach? Are there yet-undiscovered materials that might exceed room temperature (which would completely revolutionize the entire electronics and power industries)?

Will it ever be possible to understand high T_c materials on a quantitative level?