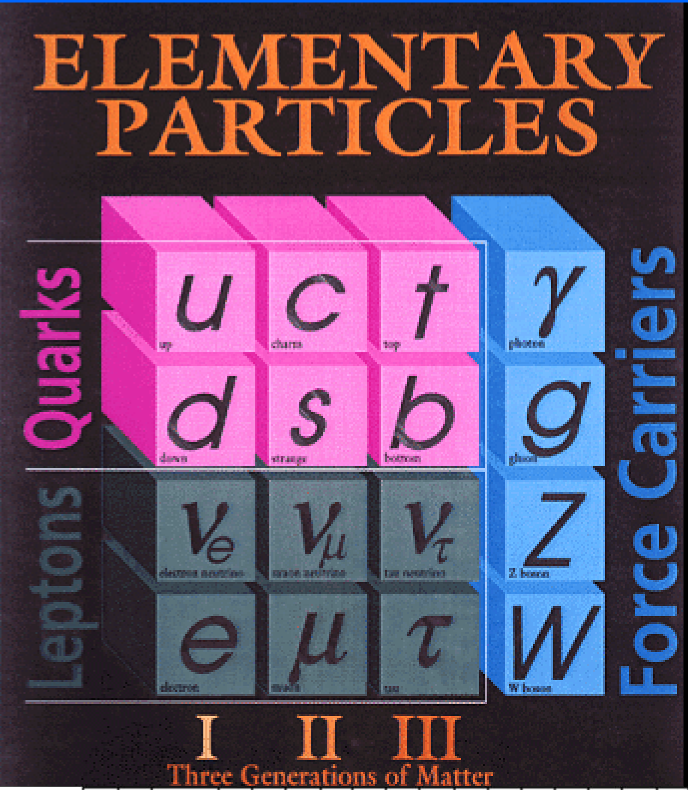
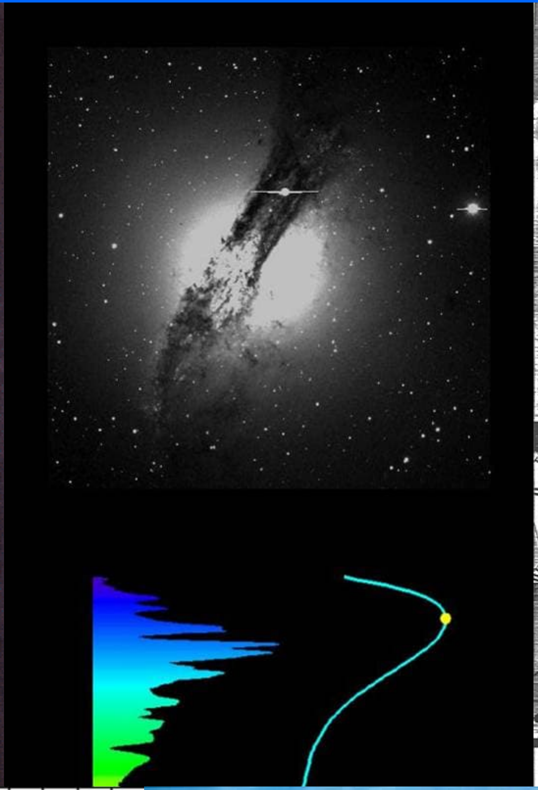
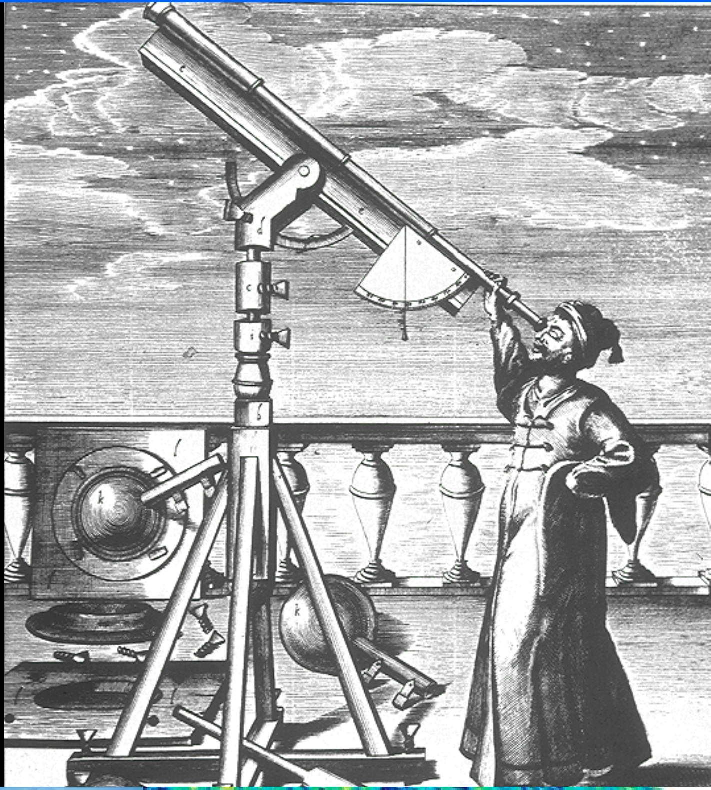
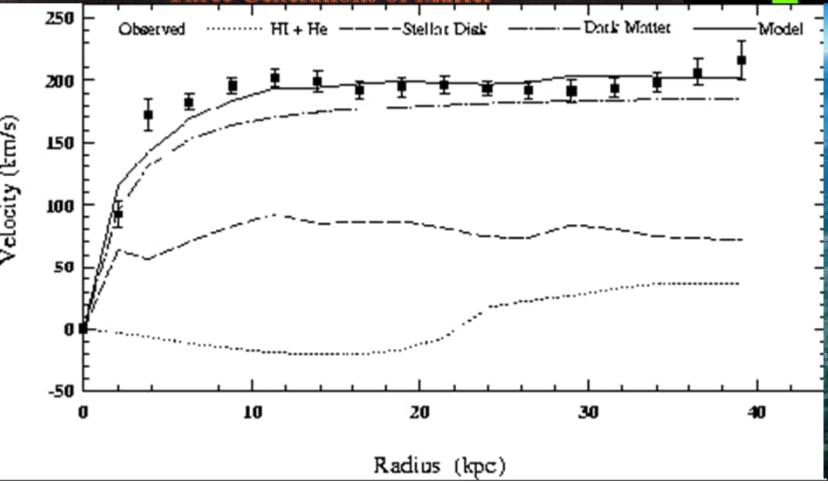
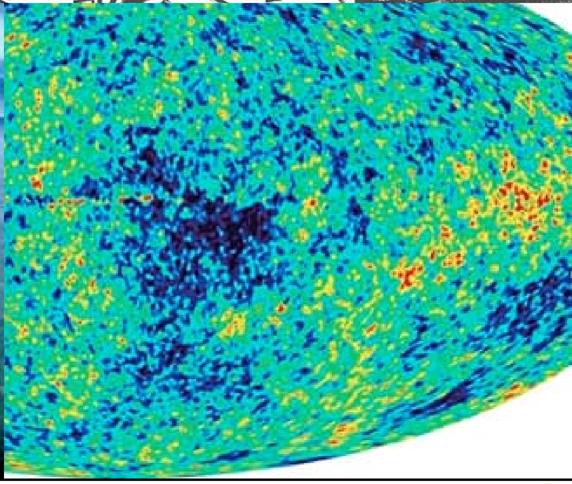
# Beyond the Standard Model



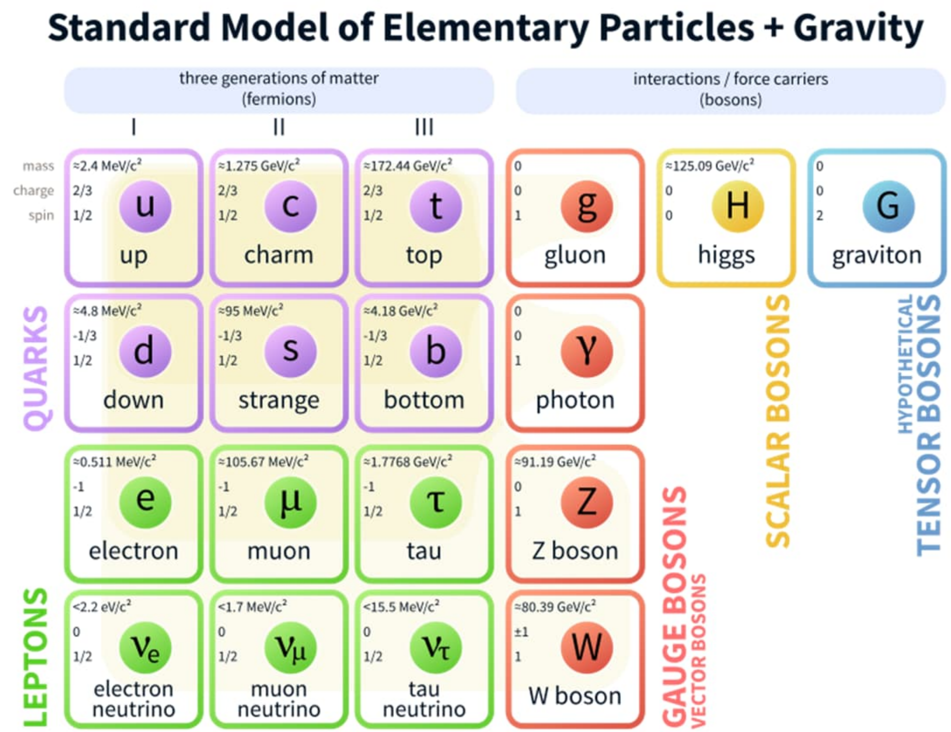




The Standard Model is an incomplete theory. It cannot explain why a particle has a certain mass.


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.



# The Higgs Boson

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

# Higgs Mechanism

To understand the Higgs mechanism, imagine that a room full of physicists chattering quietly is like space filled with the Higgs field …

… a well-known scientist walks in, creating a disturbance as he moves across the room and attracting a cluster of admirers with each step …

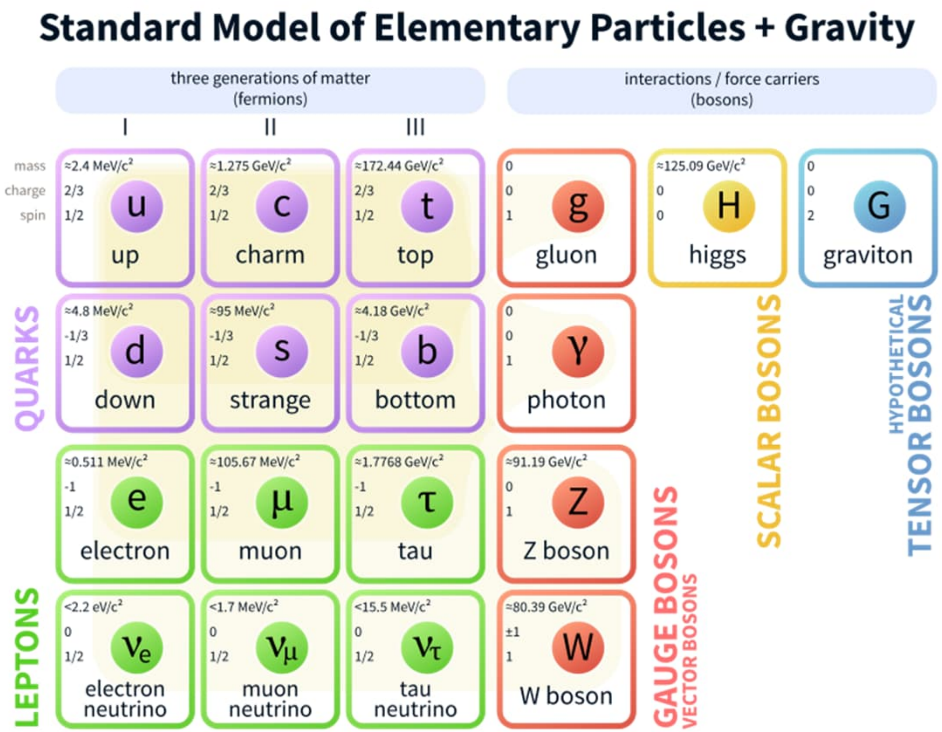
… this increases his resistance to movement, in other words, he acquires mass, just like a particle moving through the Higgs field…

# Higgs Mechanism

… if a rumor crosses the room, …

… it creates the same kind of clustering, but this time among the scientists themselves. In the analogy, these clusters are the Higgs particles.

# Beyond the Standard Model

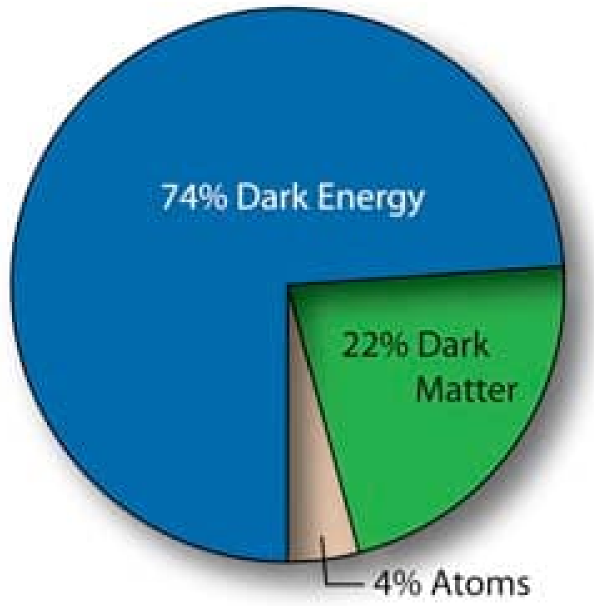



The Standard Model is an incomplete theory. It does not adequately explain:

- 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.

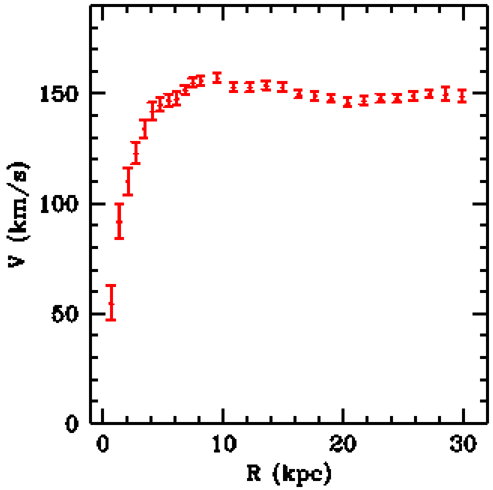
# What is the Universe really made of?

- 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?

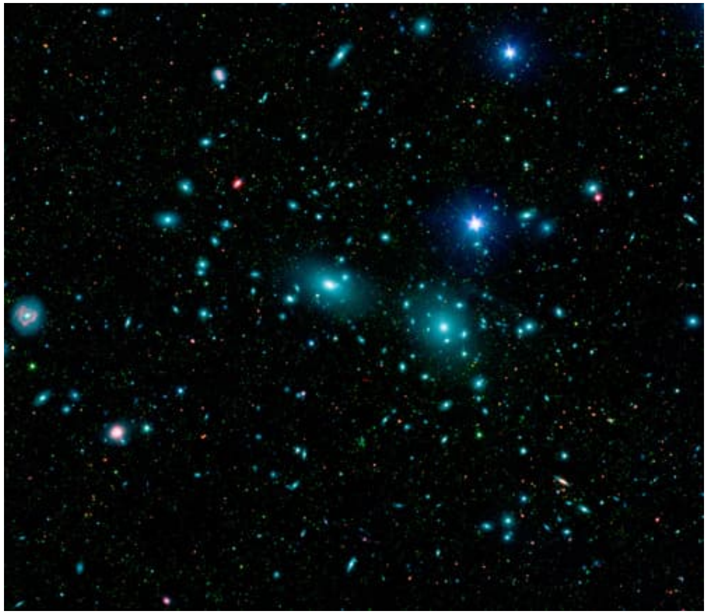
- The first evidence for dark matter was obtained in the 1930s when Zwicky and Smith looked at the velocities of galaxies within clusters and found that they were 10 to 100 times larger than expected from the visible mass. **Larger velocities indicate larger gravitational forces ⇒ larger masses than are visible**.
- This, however, was not strong enough evidence. These observations were particularly susceptible to systematic errors from galaxies that are not truly bound within the cluster, or from galaxies in the foreground.
- Not until the 1970s, when Rubin, Freeman, and others looked at the "rotation curves" of galaxies, was strong evidence obtained.
- Dark matter can have several types of sources. Dark matter could be composed of



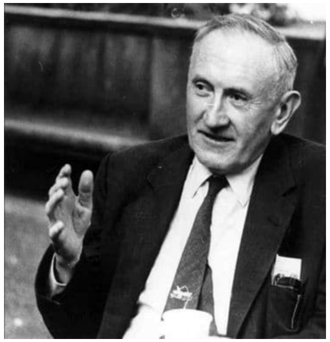

everyday material (protons, neutrons, and electrons) in forms such as planet-sized objects, or as brown dwarf stars. Or it could be composed of other known particles, such as neutrinos. However, as we will discuss *next week*, results over the past decade indicate the majority of DM is likely to be ***neither*** of these two cases. Instead, it strongly appears that dark matter is something ***exotic and unknown***.

Vera Rubin

# What is Dark Matter?



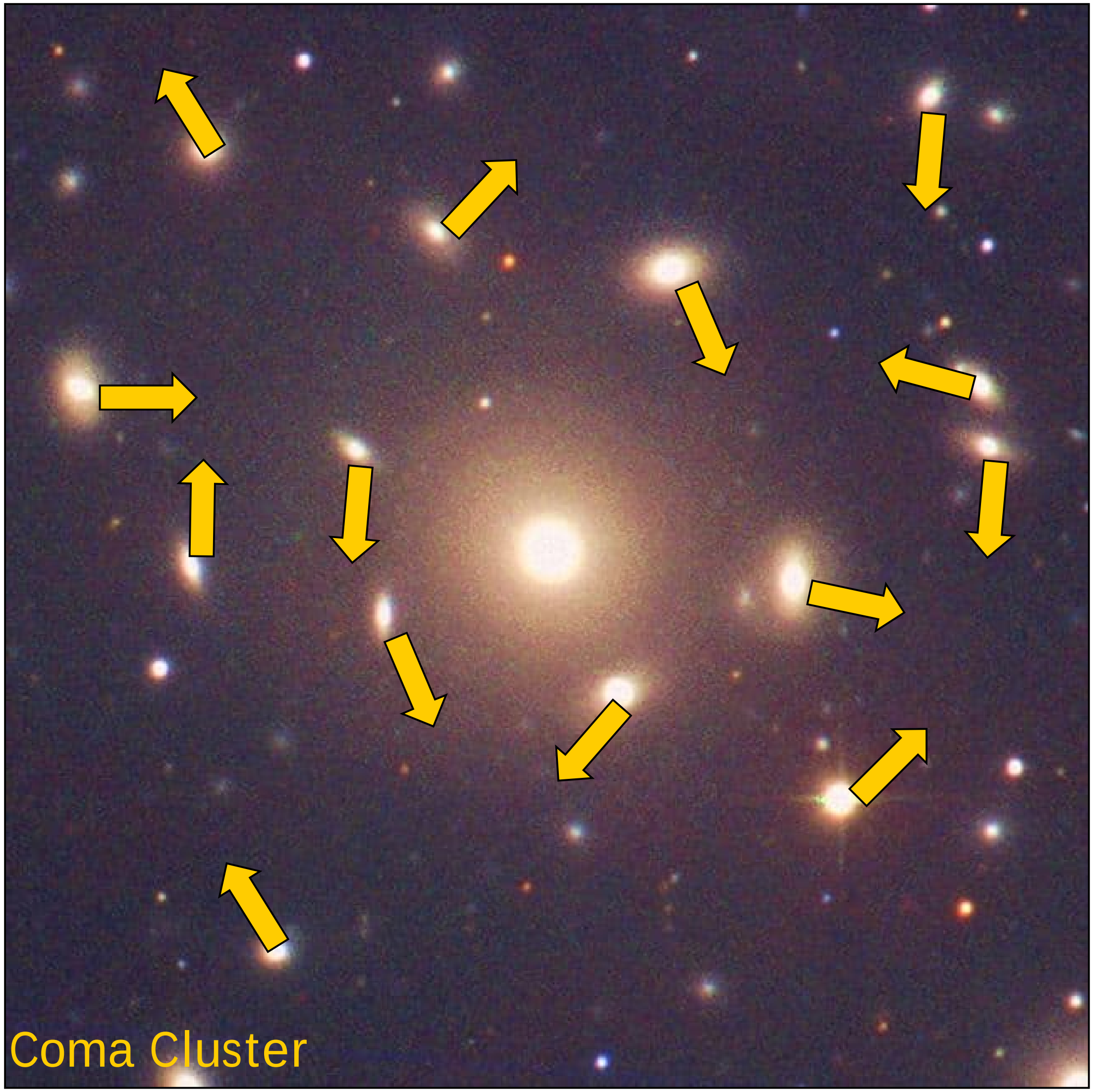
***Coma Cluster***: By measuring the velocities of all these galaxies Fritz Zwicky realized that galaxies toward the edge of the cluster were moving far too fast.



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

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

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

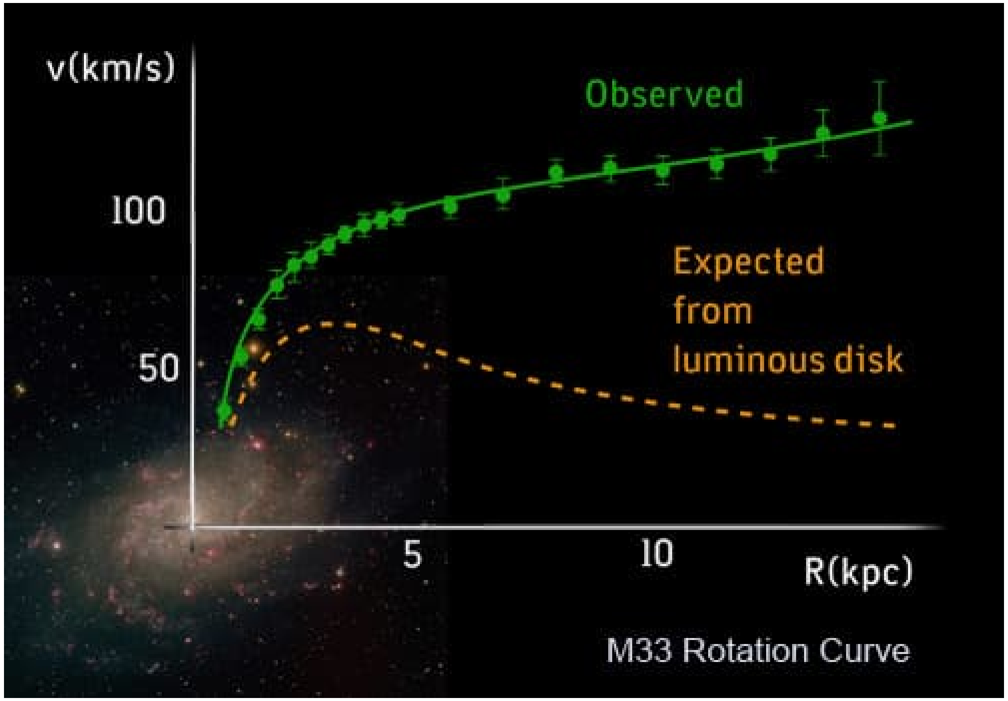
$$\langle v^2 \rangle \approx G_N M_r \langle r^{-1} \rangle$$

Velocity measurement via Doppler effect of at least three spectral lines

↓

Mass estimate

# What is Dark Matter?

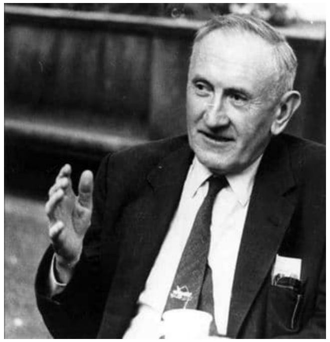



Vera Rubin

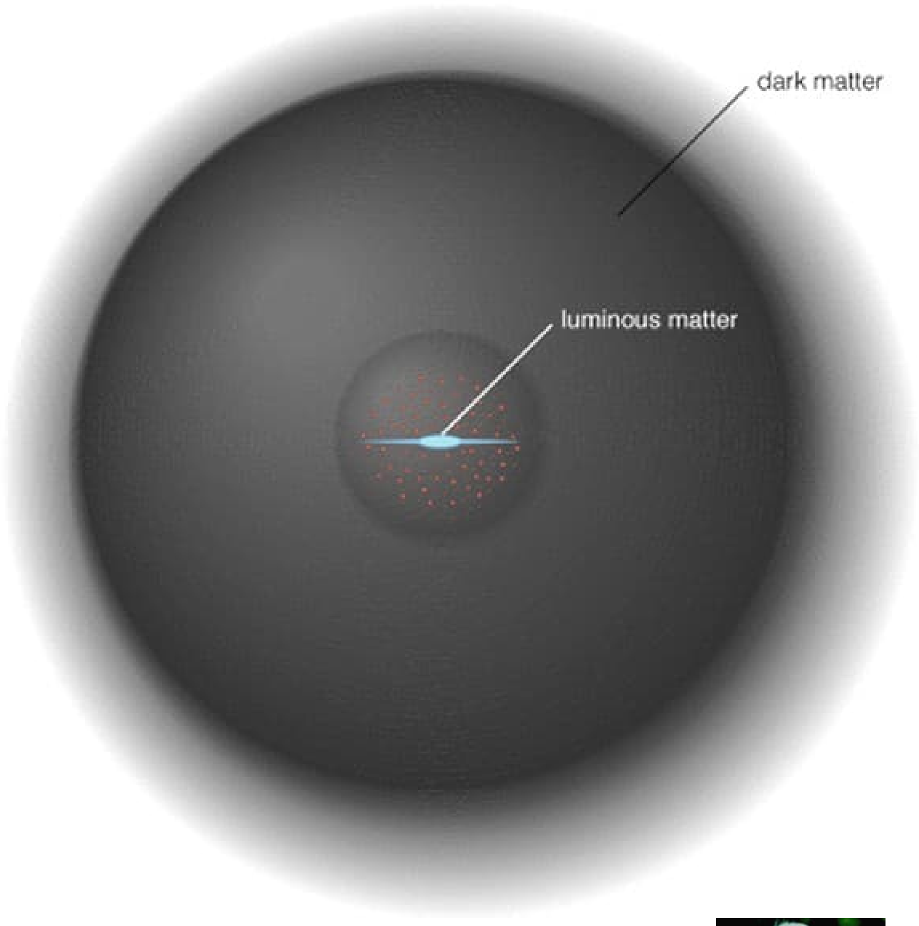
Keplerian prediction:

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

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

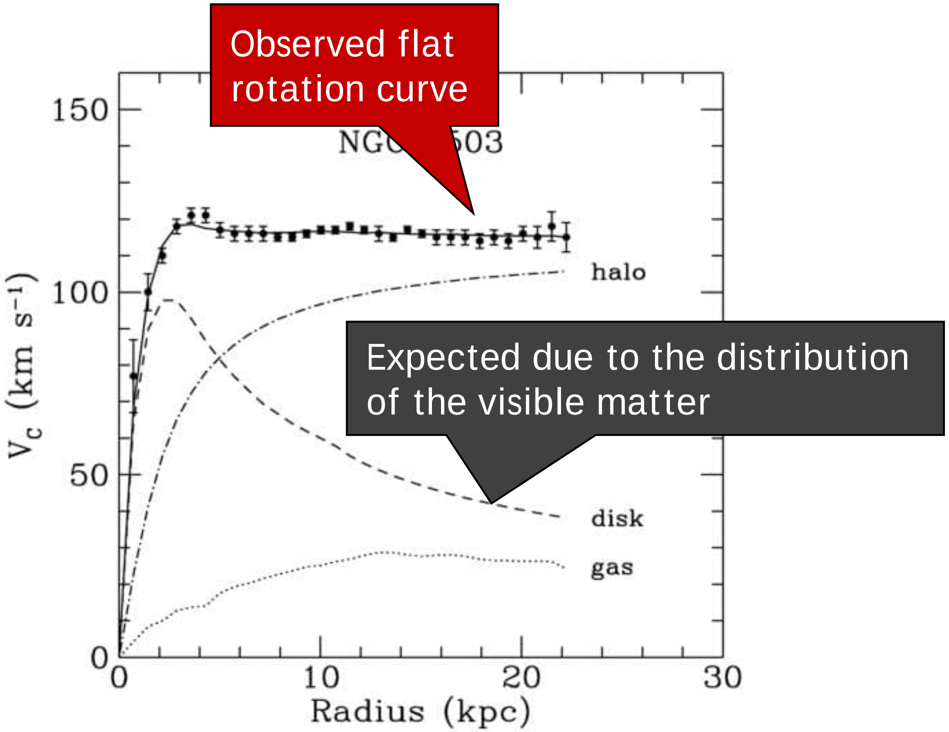


In order to obtain, as observed, a medium-sized Doppler effect of 1000 km/s or more, the average density in the Coma system would have to be at least 400 times greater than that derived on the basis of observations of luminous matter. If this should be verified, it would lead to the surprising result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

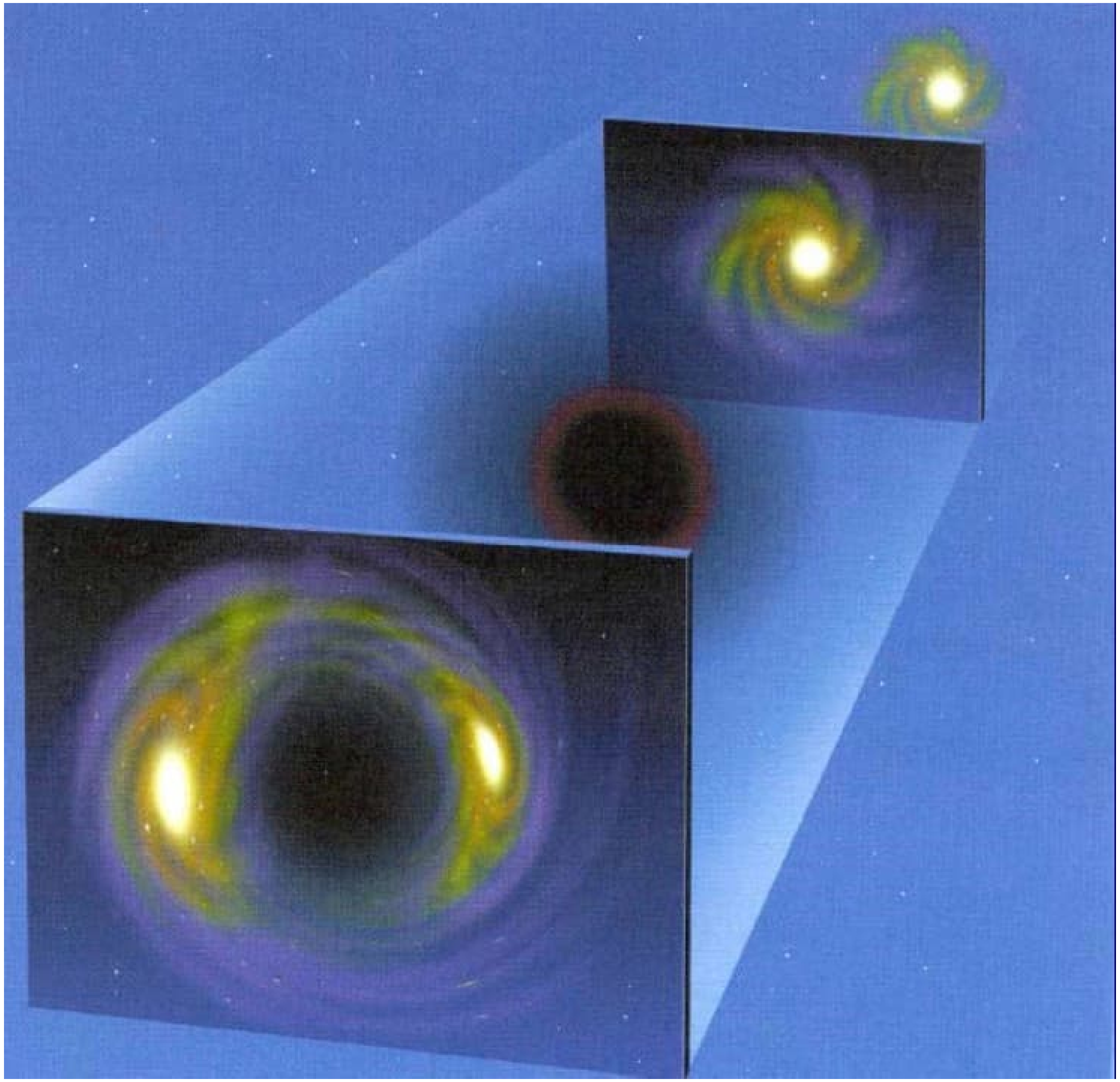



- Dark matter in the Halo around a Galaxy
- Dark matter ~ 10x visible mass

Vera Rubin



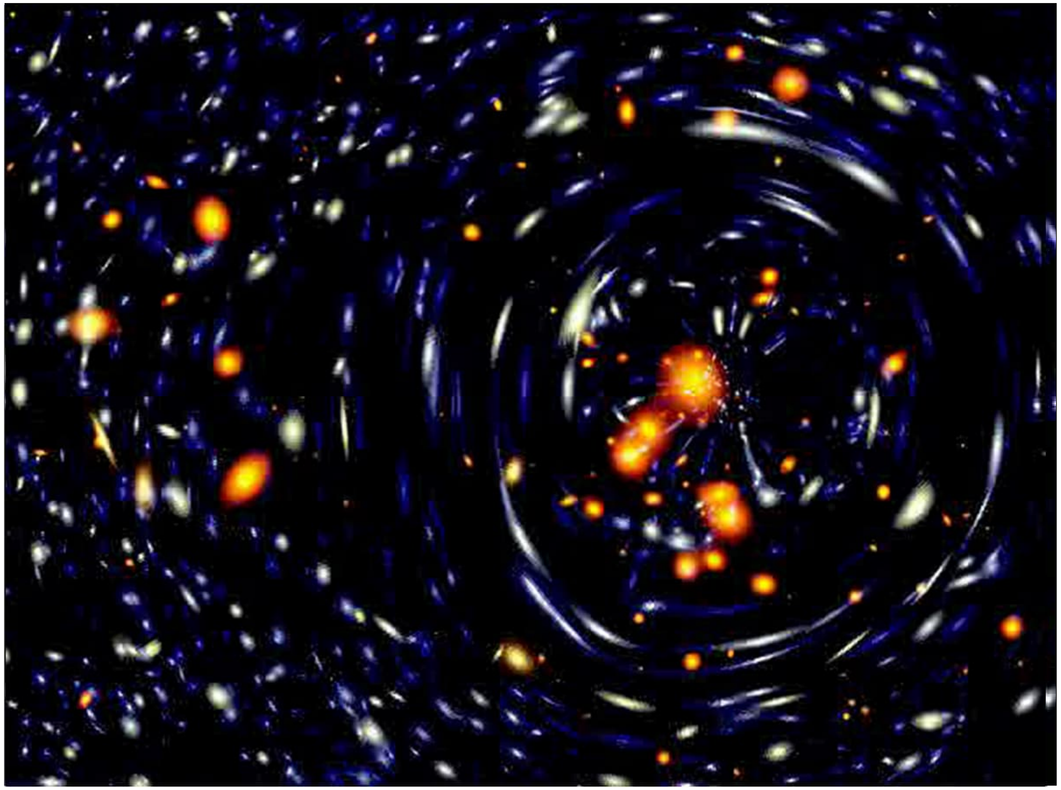
# Einstein ring



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).

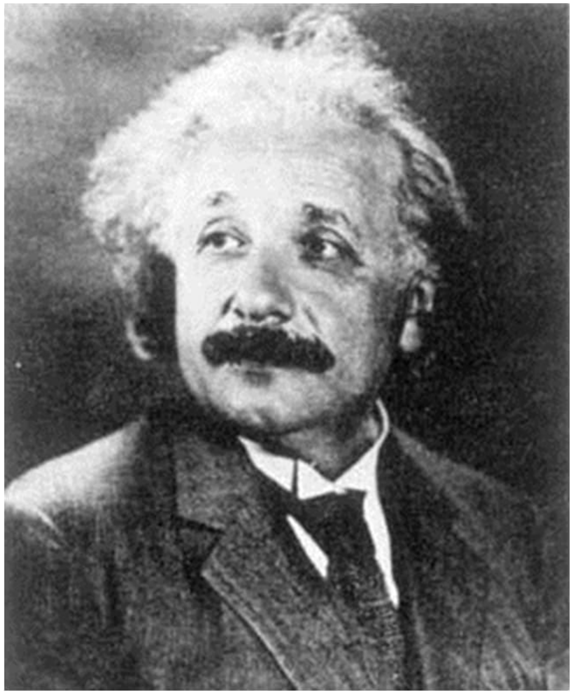
# What is Dark Energy?

- In Einstein's General Theory of Relativity, Einstein included a term called the "*Cosmological Constant*," which represents the energy density of empty space. If the universe were *static* (as Einstein thought it was at the time), the cosmological constant *must be nonzero* in order to counterbalance the attraction of matter in the universe.

- In 1929, when Hubble found the universe to be not static, but *expanding*, Einstein threw away this term.

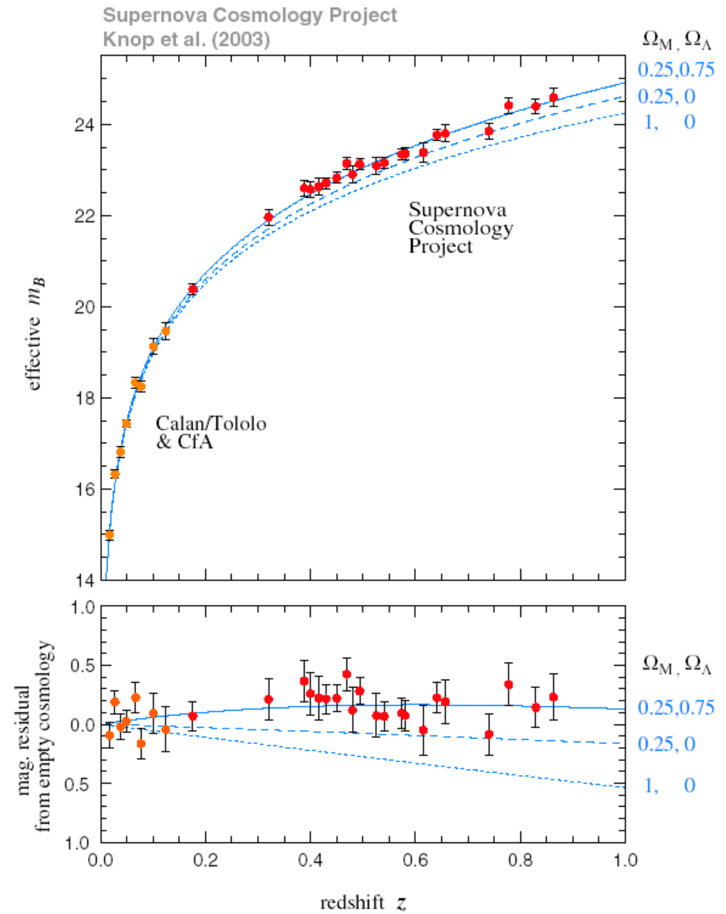
Later on, in the 60's and 70's, when people such as Zel'dovich tried to combine quantum field theory and GR, they noted that this energy of empty space should ***not*** be zero, but actually *unphysically enormous*, due to quantum fluctuations (actually creation and annihilation of particle-antiparticle pairs) that *continuously* occur within the vacuum. This is the so-called **"Cosmological Constant Problem."** It *still* really has no good answer, however things have changed…

- Until the last 5 years, it was thought that there just had to be something – some unknown symmetry of nature – that was offsetting the enormous cosmological constant and causing it to cancel out to zero. *After all*, the entire body of experimental evidence was consistent with a zero cosmological constant…



# What is Dark Energy?

- But in the 1990s evidence began to suggest that there might be a nonzero cosmological constant. Experiments that look at the cosmic microwave background (CMB) were obtaining data that was consistent with there being *just enough* energy density in the universe so that the universe is "flat" (too much and the universe would be "closed," too little and it would be "open"). But experiments looking at galactic cluster densities and gravitational lensing were finding only enough *matter* (*dark* + *light*) to account for about 1/3 of this energy density. Where was the extra energy?




- In 1999, two experiments looking at distant supernovae reported groundbreaking results. The expansion of the universe that they were measuring appeared to be ***accelerating***. This was consistent with a *small, but nonzero*, positive cosmological constant that accounted for the difference above.

- The fact that this is *still* <u>completely inconsistent</u> with the quantum mechanical expectation leads people to believe that there could be more to this than just a cosmological constant. Hence the name ***"Dark Energy."*** Nobody knows why the expansion of the universe is accelerating…

# What is Dark Energy?

Big Bang Cosmology: Albert Einstein (1879-1955)

**Prediction**: The universe is expanding

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

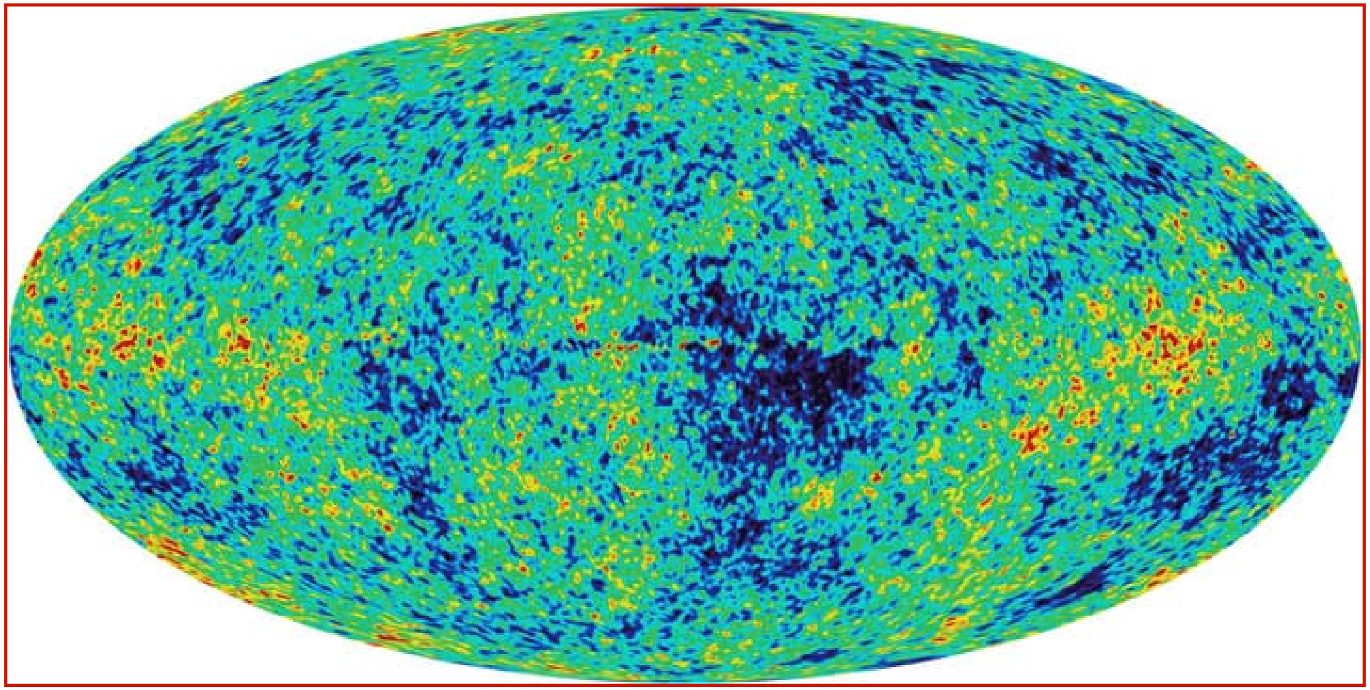
Red-shift of the spectral lines in stars (Doppler effect)

# What is Dark Energy?

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?

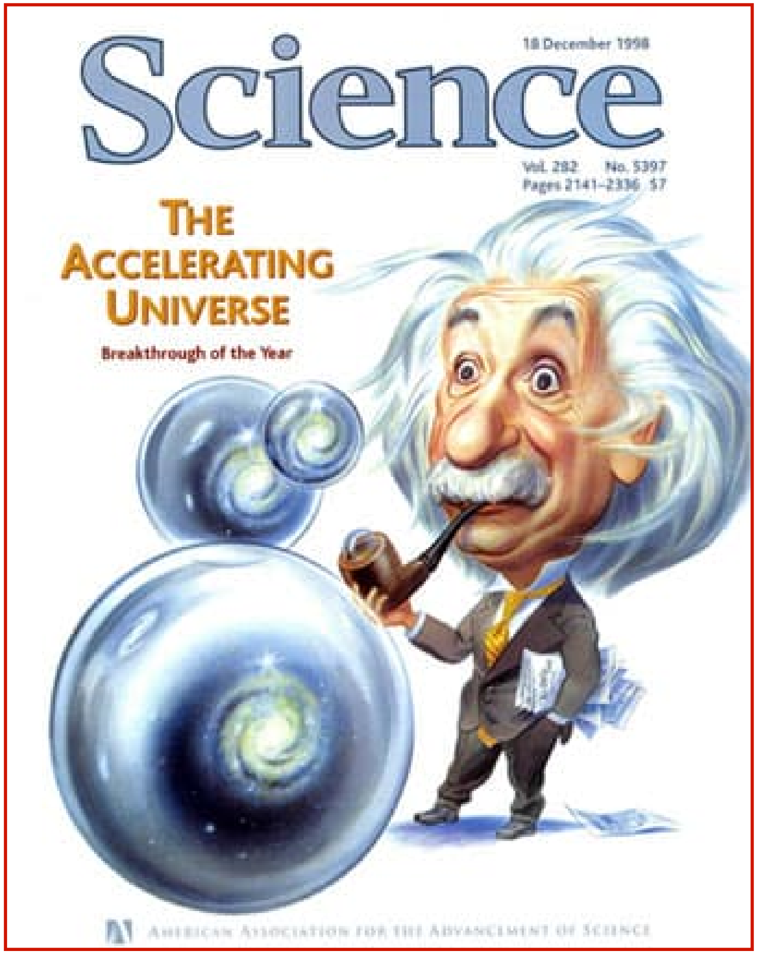
Testing the Big Bang model

**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.

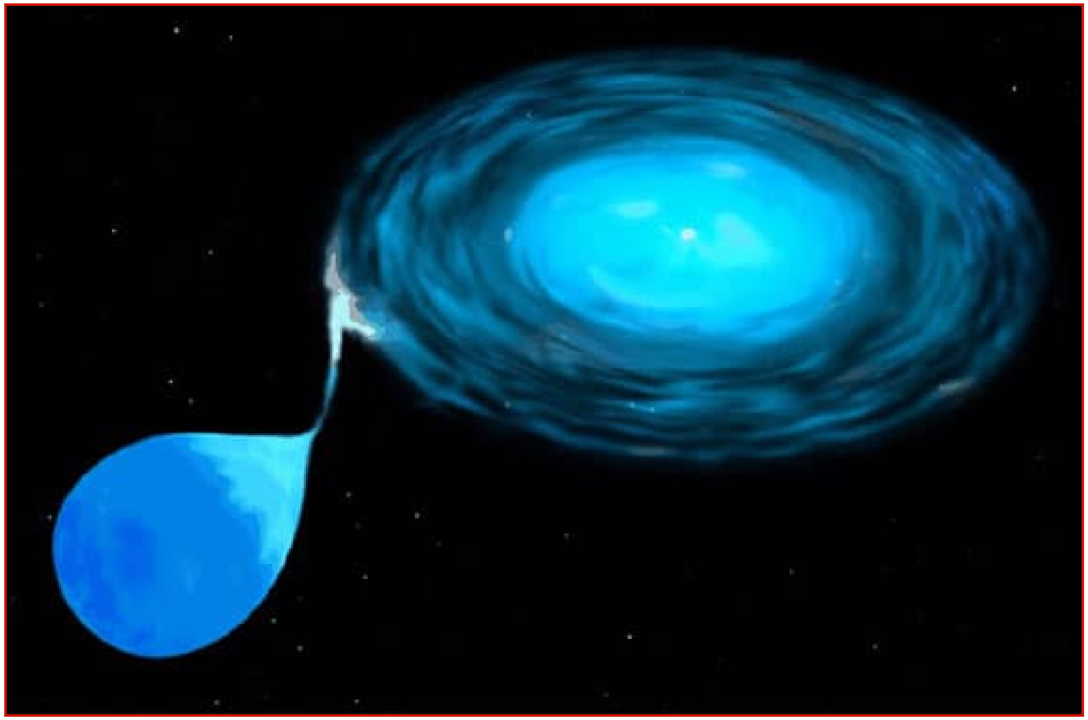
theory of relativity lies nearest at hand; whether, from the standpoint of present astronomical knowledge, it is tenable, will not here be discussed. In order to arrive at this consistent view, we admittedly had to introduce an extension of the field equations of gravitation which is not justified by 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

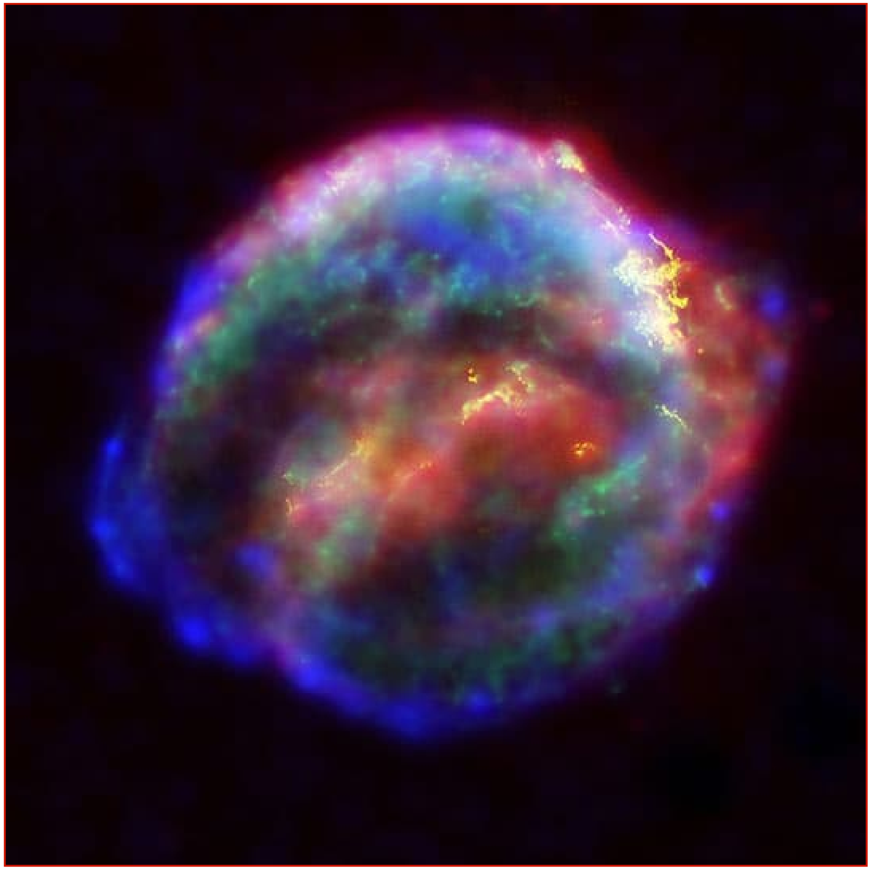
A dying star becomes a white dwarf.

# 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

# Why is there more matter than antimatter?

➢ The existence of antimatter was predicted by Dirac in 1928 and first discovered by Anderson (positrons in cosmic rays) in 1932. Nowadays we make small amounts of antimatter in laboratories *routinely* (for use in colliders, PET scans, etc.).

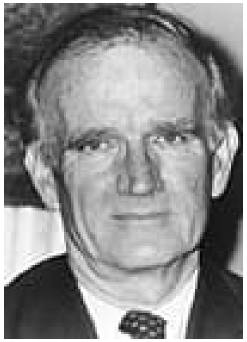
➢ Now note that the *Big Bang was purely energy*. Energy can divide into matter and antimatter, but it should divide into *equal amounts*… Where did all the antimatter go?

➢ Maybe there are big clumps of antimatter elsewhere in the universe? Perhaps we are just inside a big clump of matter, and other huge parts of the universe are really made of antimatter? But experiments looking for both the photons that would be produced when particles and antiparticles annihilate at the clump boundaries, and for antiparticles that would drift across into our matter clump, see nothing. CMB data is also inconsistent with matter-antimatter clumping.
Matter-antimatter clumps (known as domains) are still being looked for, they are *strongly disfavored*.

➢ Back in time. In 1964, Fitch and Cronin discovered a fundamental ***difference** between matter and antimatter*. They found that matter and antimatter behave *slightly* differently with respect to the *weak interaction*, one of the four fundamental forces of nature…

PHYSICAL REVIEW LETTERS

EVIDENCE FOR THE $2\pi$ DECAY OF THE $K_2^0$ MESON*†



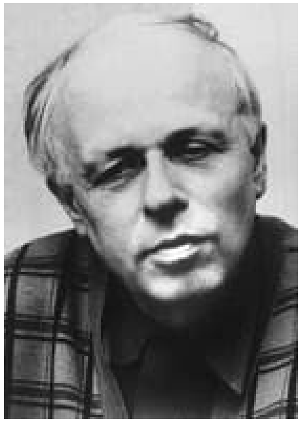
Val Fitch

Jim Cronin

# Why is there more matter than antimatter?

- Was this small difference between matter and antimatter, known as "*CP* violation," (short for *charge-parity* ) *enough* to explain a matter-antimatter asymmetry of the universe?

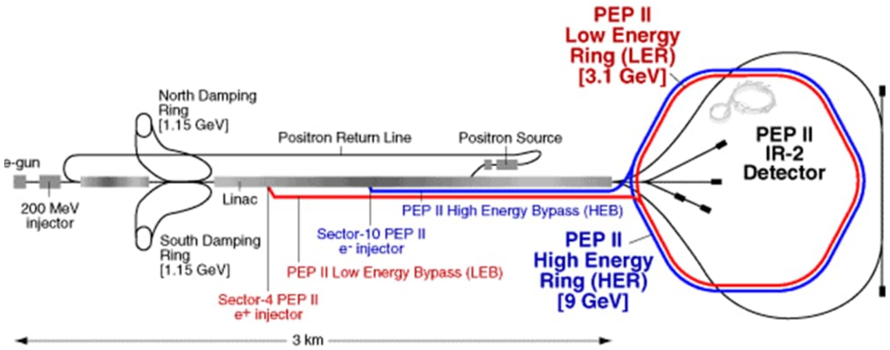
- No, more is needed. In 1967, Sakharov detailed exactly what conditions need to be satisfied for a matter-antimatter asymmetry to develop in the universe. *CP* violation is one of them – it is necessary, but not *sufficient*:



Andrei Sakharov

*Sakharov's conditions for development of matter-antimatter asymmetry*

1) A departure from thermodynamic equilibrium.
2) Non-conservation of "baryon number."
3) *C* and *CP* violation.




- The main problem is that the Standard Model of particle physics does not contain *enough* of these 3 conditions to explain the observed matter-antimatter asymmetry. Thus experiments, for example, *BaBar* (at the Stanford Linear Accelerator Center, shown at left) look for *additional CP* violation *beyond* the Standard Model. *Where will it be found…?*

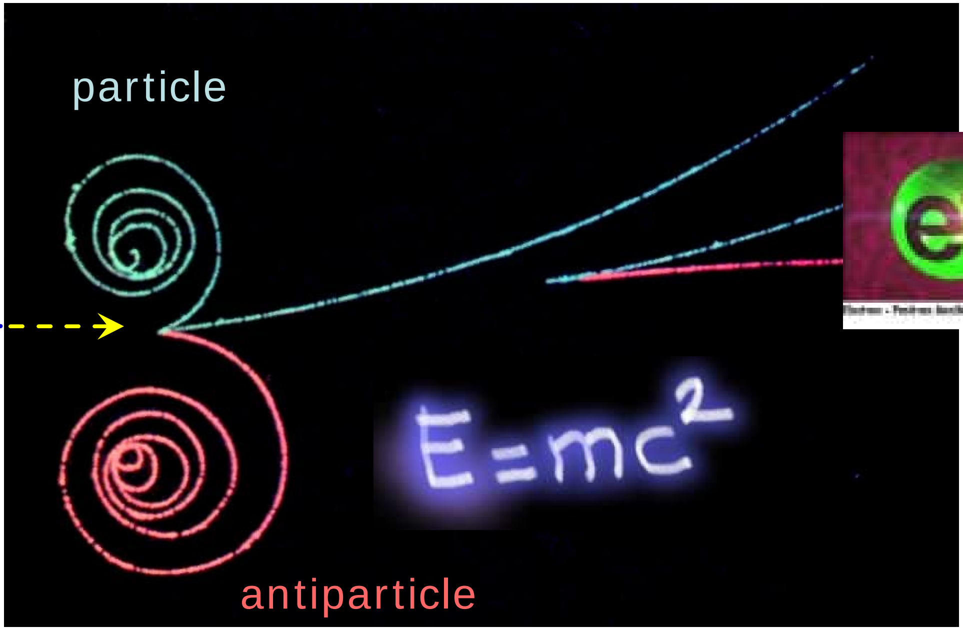
**Dirac: Key Discovery**

Paul A. M. Dirac

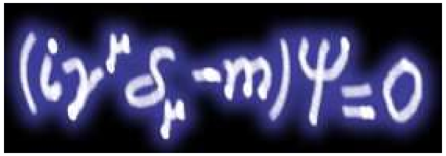
Relativity + Quantum Theory

⇒ ‘Antiparticles’

**Energy***



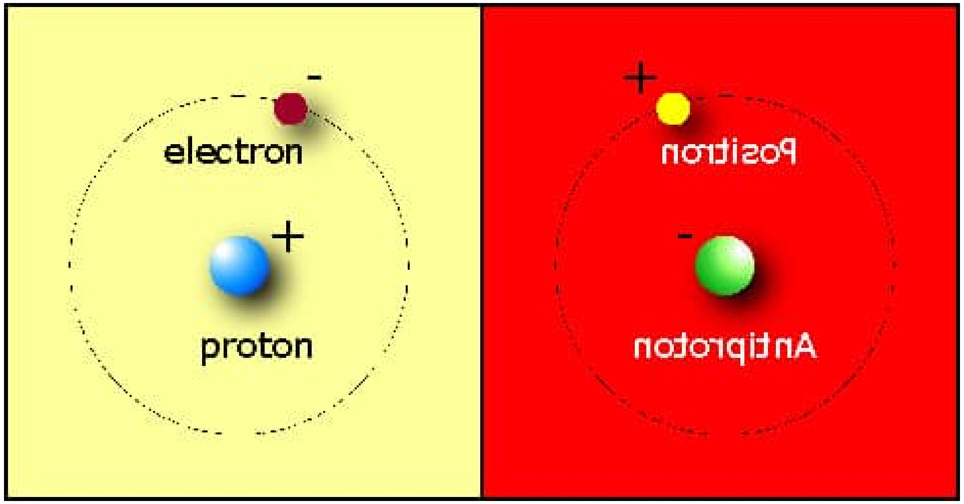





* gamma rays

## 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

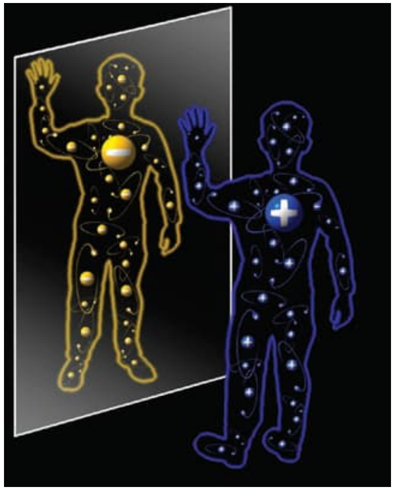
Particles decay (a little) faster than antiparticles*

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'

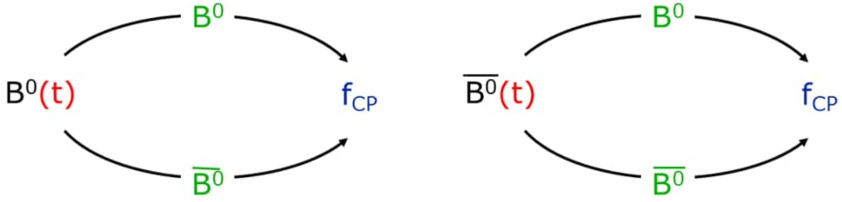
*For experts: this is called 'CP violation'



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

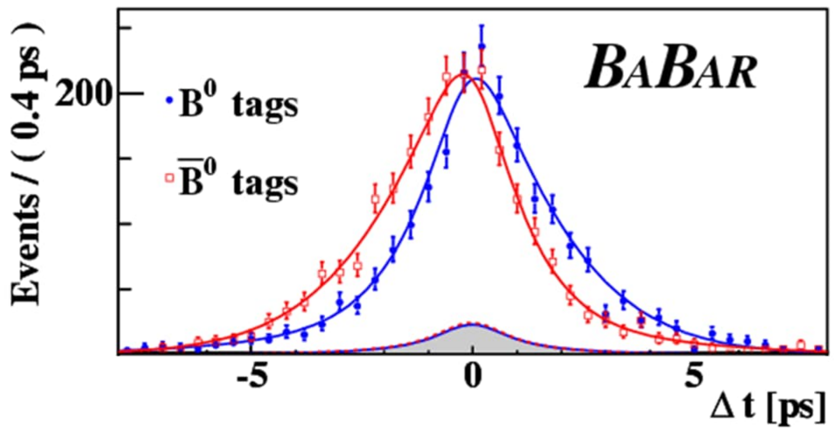
# Measuring CP Violation with $B^0$s

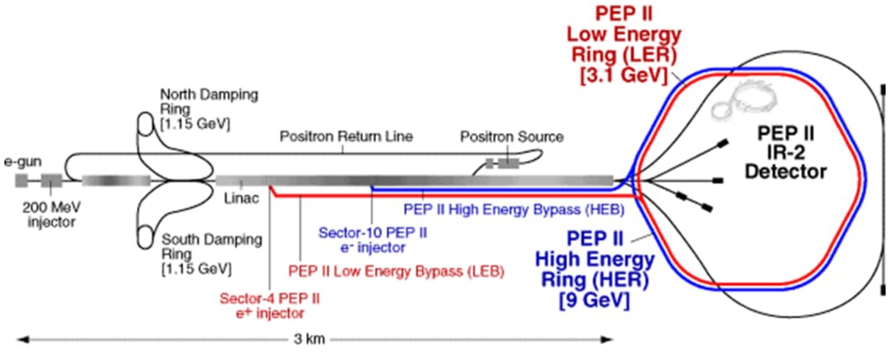
$B^0 = \bar{b}d$



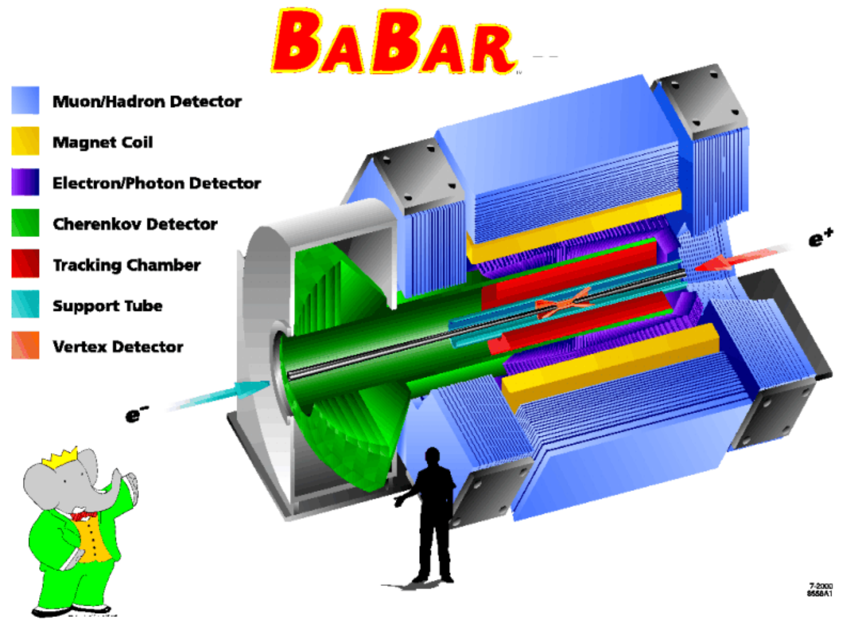

$\overline{B^0} = b\bar{d}$

Not equal –
CP Violation!



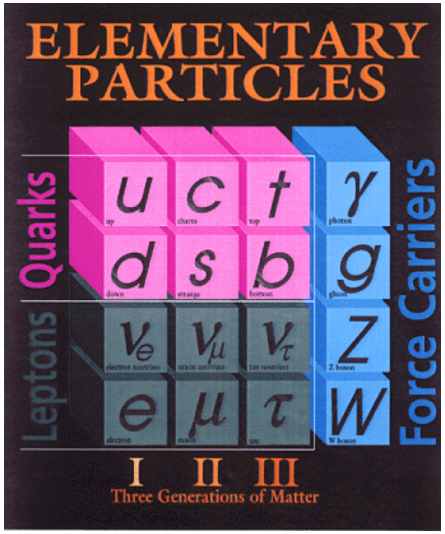

Stanford Linear Accelerator Center



# How heavy are Neutrinos?

Pauli & Fermi

- For nearly 70 years, neutrinos were thought to be massless particles…
- Neutrinos were first postulated in 1930 by Wolfgang Pauli as a solution to the problem of missing energy in nuclear beta decays. A few years later, Fermi named them "neutrinos" and developed the theory of beta decay.
- It was not until 1951 that neutrinos were detected *directly*. This is due to the fact that they tend to just pass through a detector without interacting. In fact (as you've undoubtedly heard) the vast majority of neutrinos can simply pass right through the Earth without interacting at all. As we now know, this is because neutrinos are not subject to either the electromagnetic interaction (because they have no electric charge) nor to the strong nuclear interaction, but only to the weak (and presumably gravitational) interactions.




- However, neutrinos are a type of fermion. All the other fermions have mass – why not neutrinos?
  - (Fermions are fundamental particles with half-integer spin – they include all 6 types of quark as well as the electron, muon, and tau leptons, and the neutrinos.)
- So let's try to detect the mass of a neutrino. How would one do this? Neutrinos are too light to, for example, look at the missing momentum in a nuclear beta decay and determine the mass through conservation of energy… However, we know that the ***quarks*** can occasionally change their flavor – quarks can ***mix***. If (and only if) neutrinos have mass, they should be able to do this too…

# How heavy are Neutrinos?

Raymond Davis, Jr.

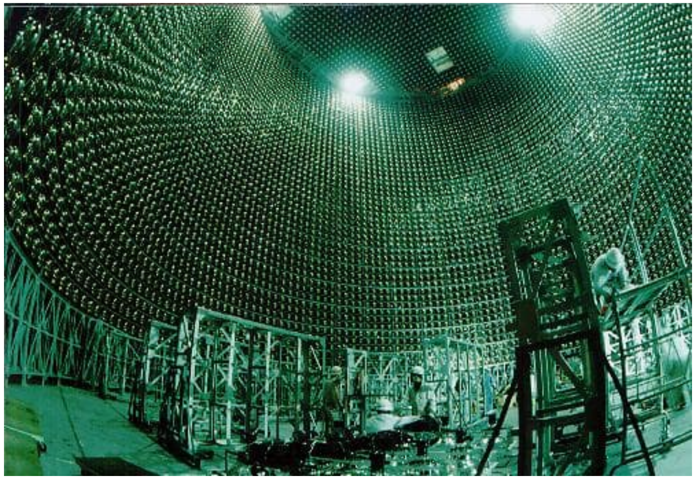
- In 1968, Ray Davis set up a detector 4800 ft. underground in the Homestake Gold Mine in Lead, South Dakota. The detector was a 100,000 gallon tank of perchloroethane. Neutrinos from the sun can interact with the Cl atoms and produce Ar. Davis developed techniques for extracting argon atoms. He detected a **shortage of solar** $\nu_e$ 2/3 below that predicted by John Bahcall's Standard Solar Model. Later experiments confirmed this shortage. Were the neutrinos oscillating (mixing)?

- A similar deficit was observed for $\nu_\mu$ from cosmic rays in the atmosphere. In 1998, the Super-Kamiokande detector (a 12 million gallon tank of purified water, pictured below) detected a zenith angle dependence of this shortage.

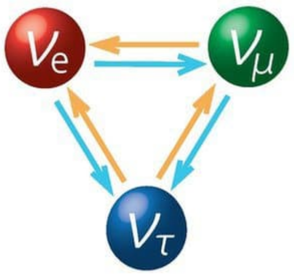
This was very strong indication that neutrinos were oscillating, and thus had mass. In 2002, the Sudbury Neutrino Observatory detected an excess of solar $\nu_\tau$, complete confirmation of neutrino oscillations.

- How do massive neutrinos fit into the Standard Model of particle physics? The original Standard Model, as developed in the 1970s by Glashow, Weinberg, Salam, and others, had massless neutrinos. It is not too difficult to just modify the Standard Model Lagrangian to add mass terms for the neutrinos. But, as we will discuss a few weeks from now, it's not so simple…

- How do neutrinos get their masses, and why are they so much lighter than the other particles?



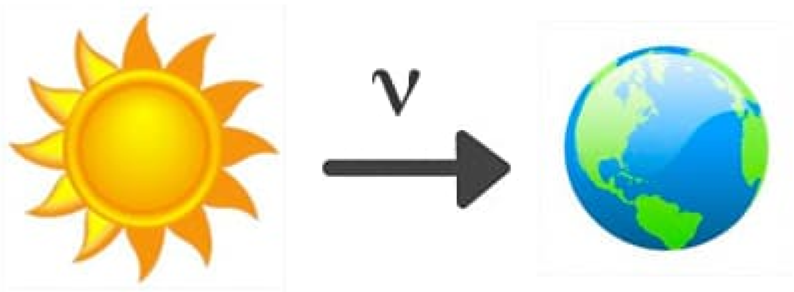
# Neutrino masses




The Standard Model was built with the assumption of massless neutrinos

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

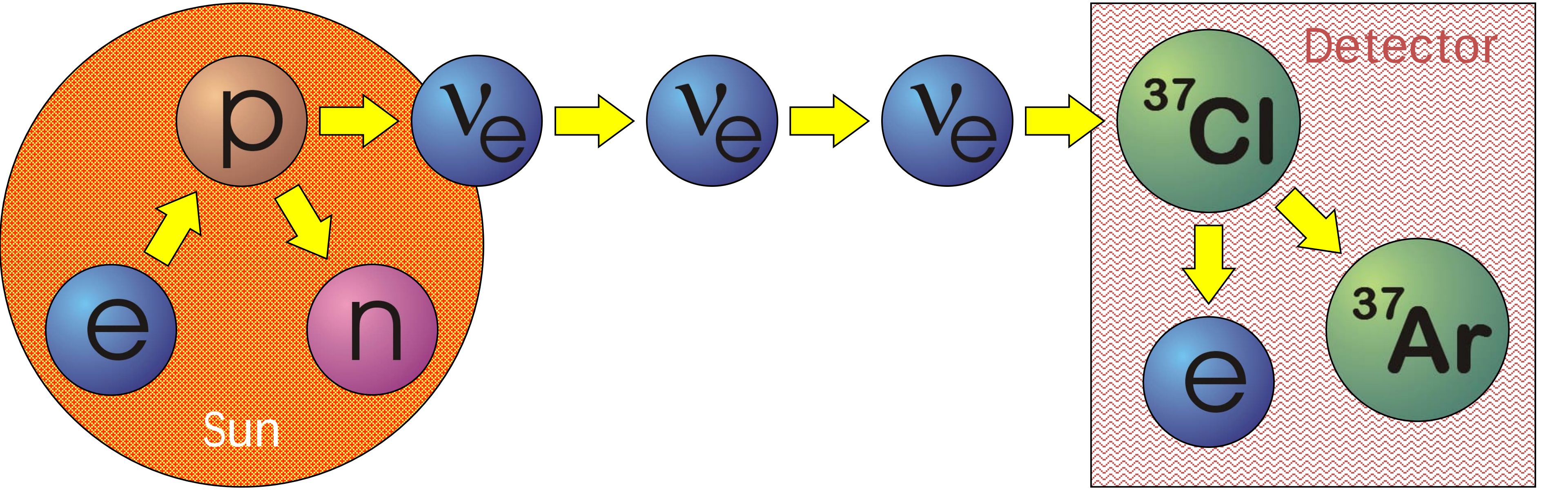
***Solar neutrino problem:***

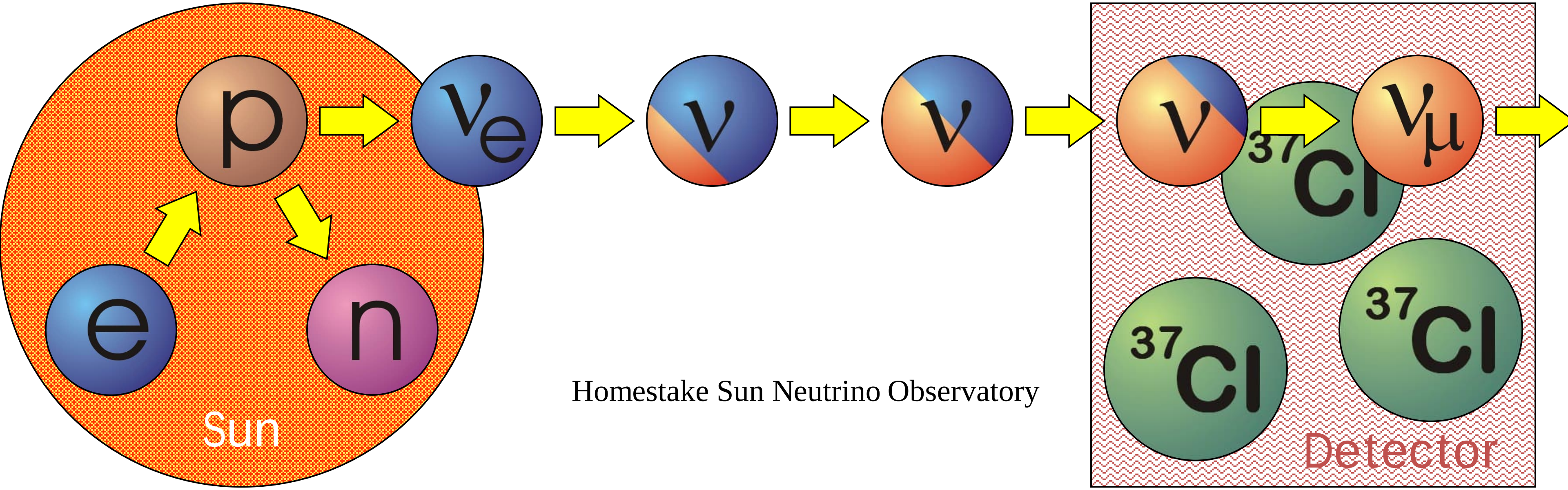



$$N_{observed} \cong \frac{1}{3} N_{expected}$$

Where are the missing neutrinos

# Solar Neutrino problem




Homestake Sun Neutrino Observatory

# Neutrino Oscillations

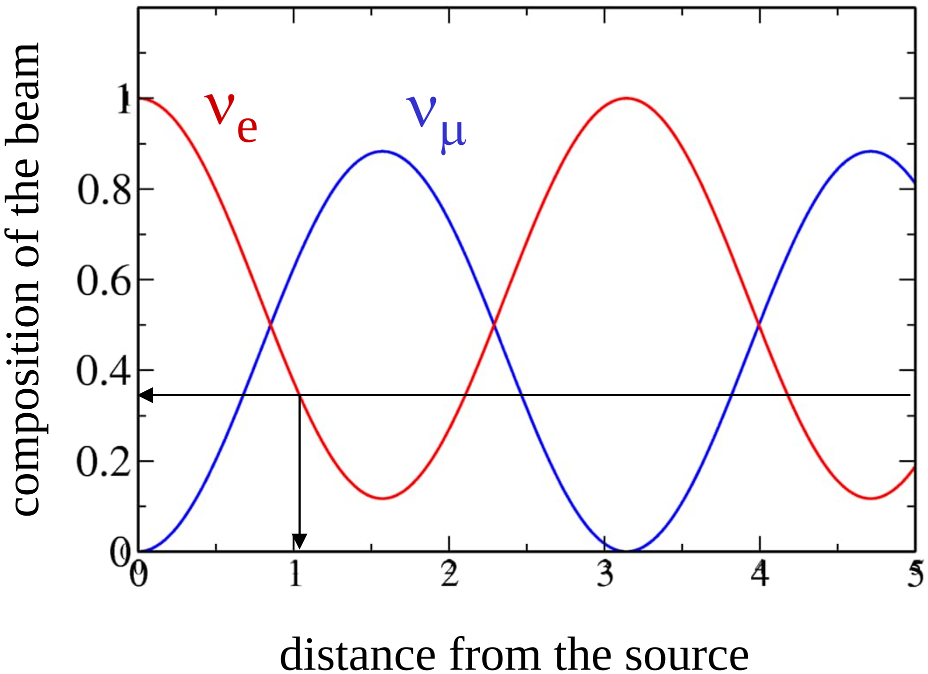
| | | |
|---|---|---|
| Electron e | Myon μ | Tau τ |
| e-Neutrino | μ-Neutrino | τ-Neutrino |

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

Assumption: Mixture of

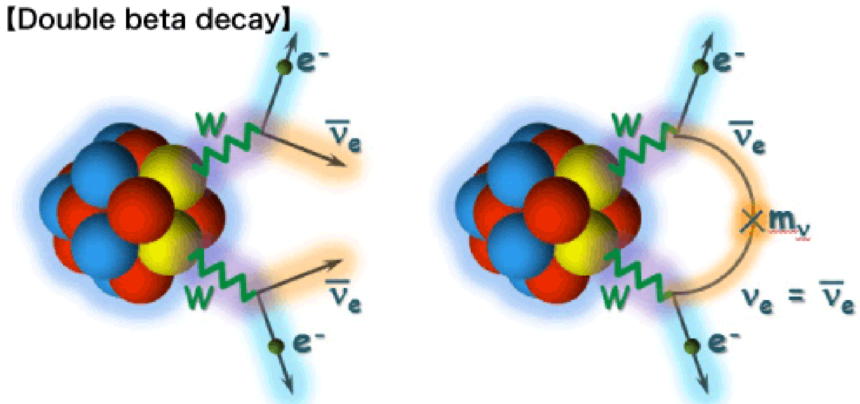
$\nu_e$ and $\nu_\mu$

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



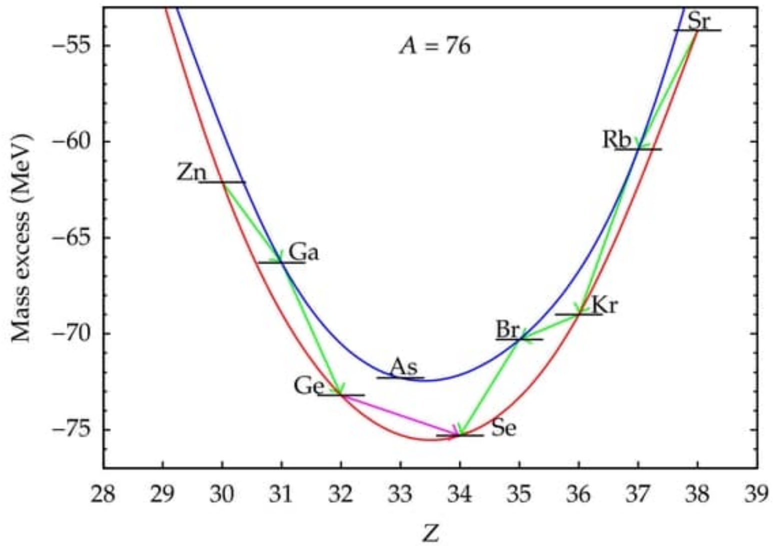

*1998: Detection of oscillation between Myon- und Tau-neutrinos with methods of Super-Kamiokande (Myon-Neutrinos from the atmosphere)*

# Neutrinoless Double Beta Decay



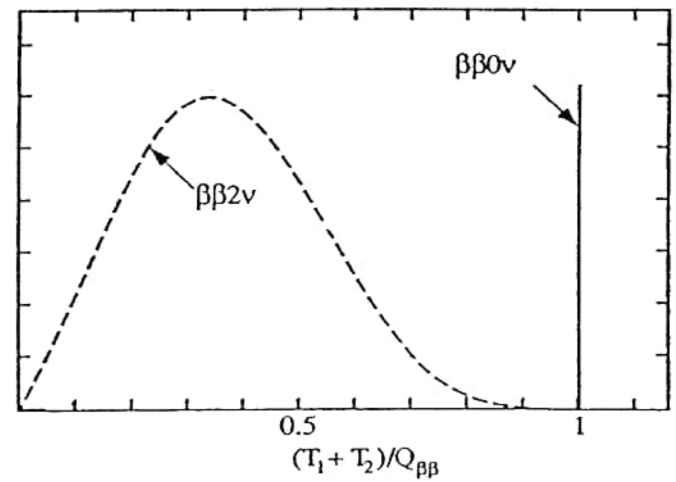

Double beta decay which emits anti-neutrinos

Neutrinoless double beta decay




Paul Dirac

Ettore Majorana




## Fermions

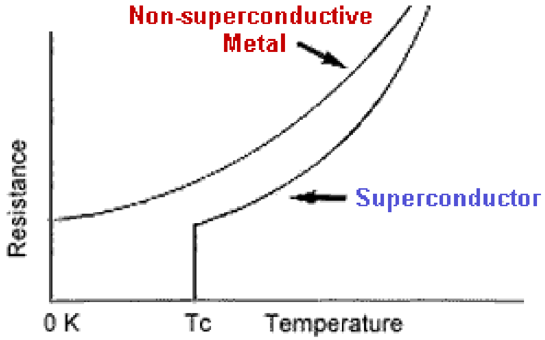
particle-antiparticle pair

## Neutral Particles

they are their own antiparticles
works for massless neutrinos

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

# How does high $T_c$ superconductivity work




- Superconductors were discovered in 1911 by Dutch physicist H.K. Onnes. He cooled mercury to liquid helium temperature (4 K) and saw that its resistance disappeared.
- In 1933, Meissner and Ochsenfeld discovered that superconductors repel magnetic fields, the "Meissner effect."

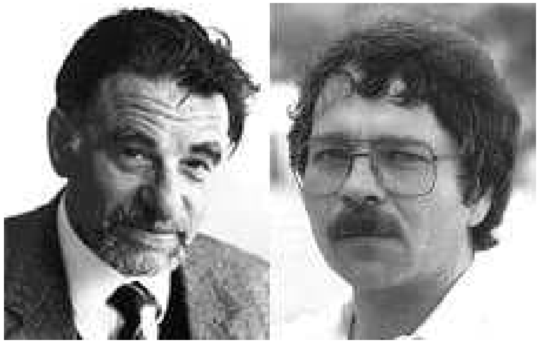
Onnes

- An approximate theory of superconductivity was developed by Landau and Ginzburg in the early 1950s. Their work predicts the maximum magnetic field that can be applied to a superconductor before it changes state, the penetration depth of the field, and other observables.
- In 1957, a more exact description of supercondutors was developed by Bardeen, Cooper, and Schrieffer. The BCS theory allows one to calculate the superconducting transition temperature for elements and simple alloys.

Bardeen, Cooper, and Schrieffer

- With more complicated materials and higher temperatures, however, the BCS theory becomes inadequate to explain the onset of superconductivity.

# How does high $T_c$ superconductivity work



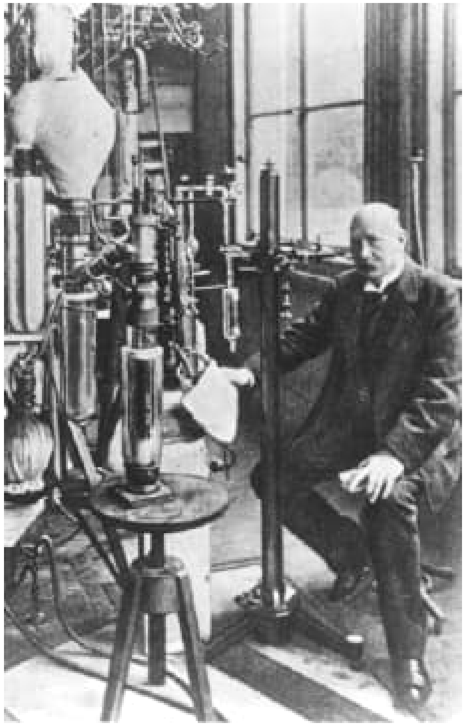
Müller and Bednorz

- 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.

- 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.

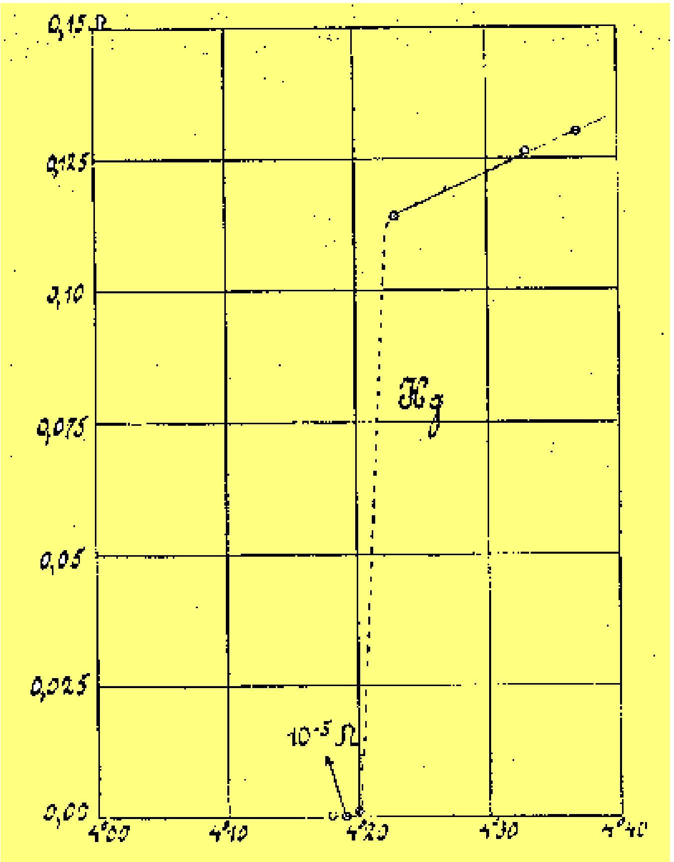
- The current record holder is 138 K (for $Hg_{0.8}Tl_{0.2}Ba_2Ca_2Cu_3O_{8.33}$). How high will transition temperatures reach? Are there yet-undiscovered materials that might exceed room temperature (which would completely revolutionize the entire electronics and power industries)? Will it ever be possible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

# 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“*

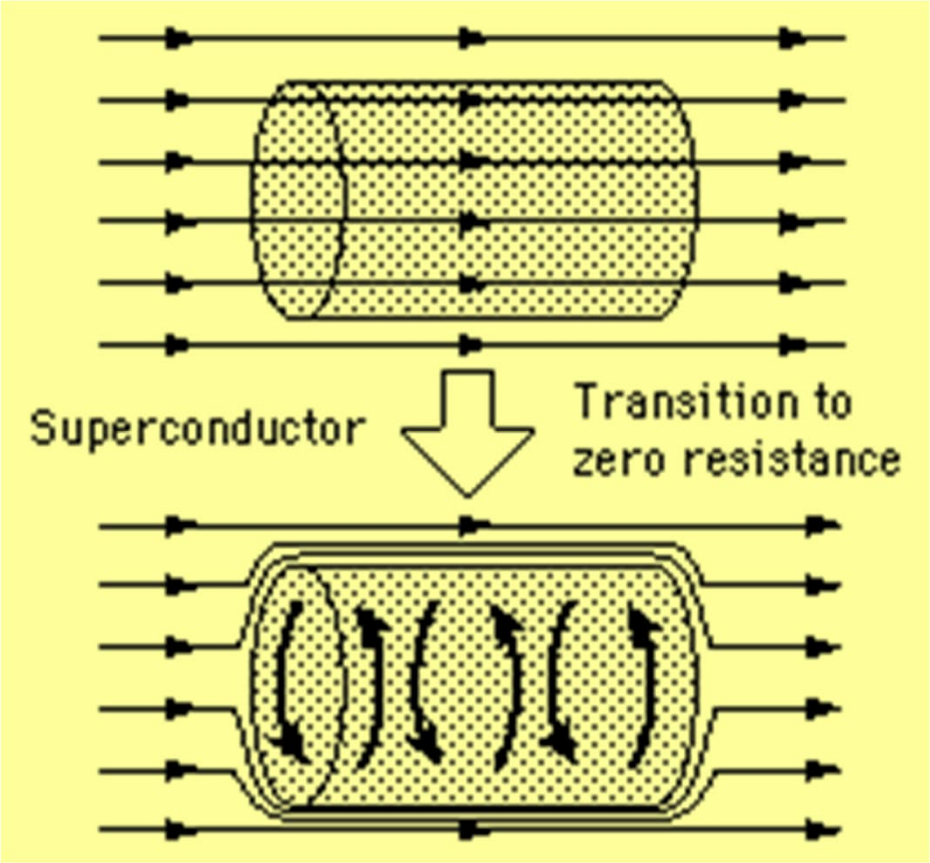
H. Kamerlingh Onnes 1913 (Nobel price 1913)

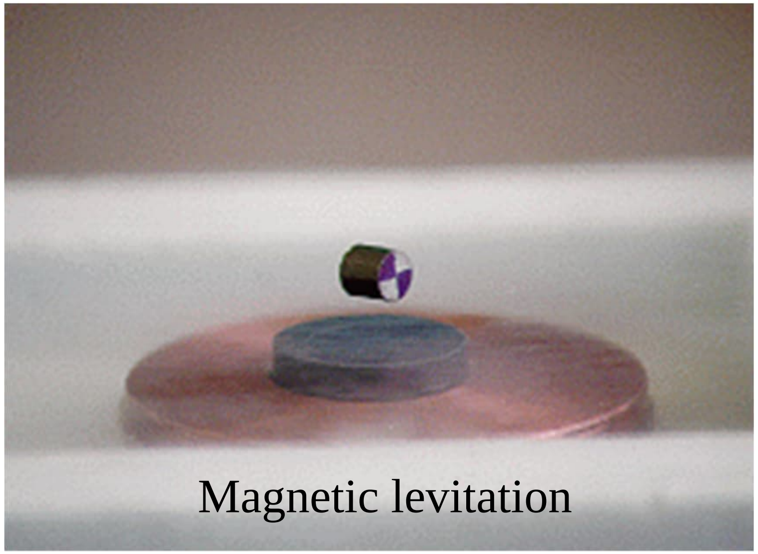
# Meissner – Ochsenfeld - effect

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.



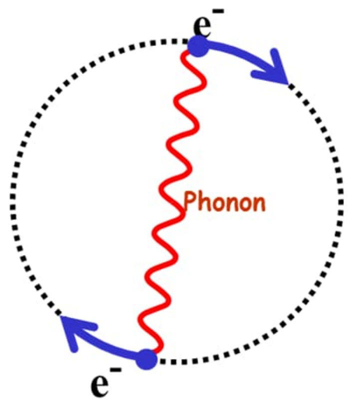
# Classical model of superconductivity

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 ~$10^4$Å. The second electron will be attracted without experiencing the repulsing electrostatic force .

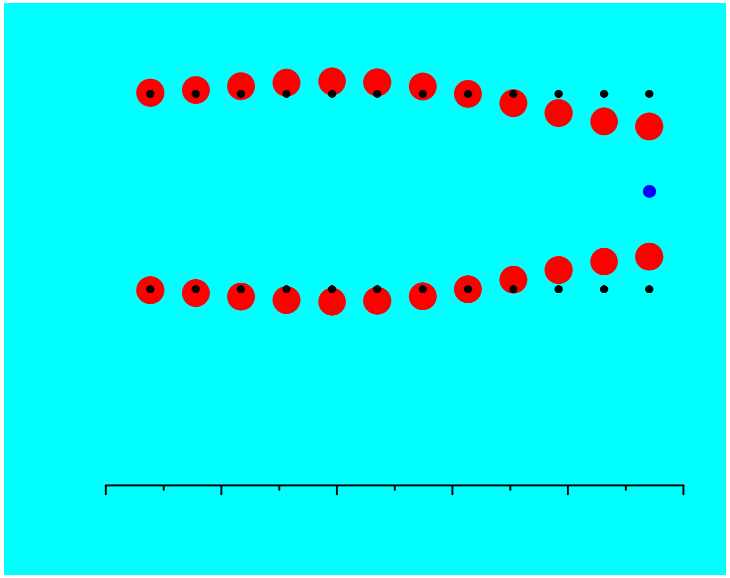



Size of Cooper pair 100 nm
Lattice spacing 0.1 – 0.4 nm

# Classical model of superconductivity

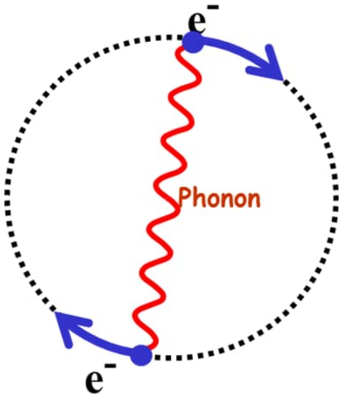
1957 John Bardeen, Leon Neil Cooper and John Robert Schrieffer

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



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

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




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

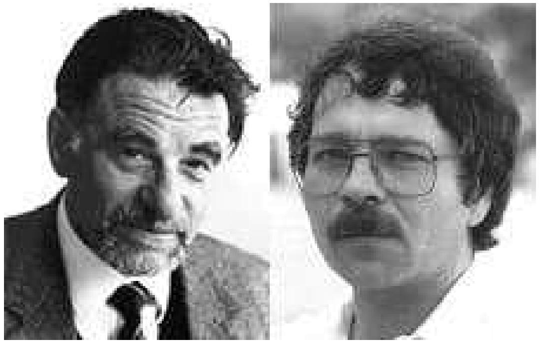

**Possible High $T_c$ Superconductivity in the Ba – La – Cu – O System**

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 2*D* superconducting fluctuations of double perovskite layers of one of the phases present.

# How does high $T_c$ superconductivity work



Müller and Bednorz

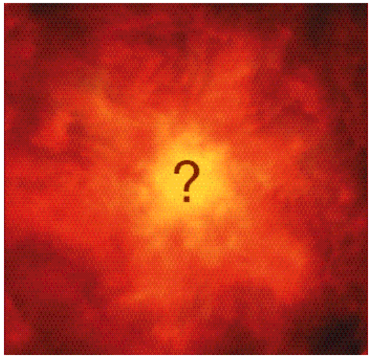
- In 1986, Müller and Bednorz found a ceramic compound that superconducted at 30 K, 13 degrees above the highest previously known superconductor. What was so odd about this is that the material (a compound of lanthanum, barium, copper, and oxygen) was a ceramic – normally an insulator – so people *never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

- 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?

# Is there a testable quantum theory of gravity?




- Since Einstein, theoreticians have been trying to find a quantum theory of the gravitational field – a theory that would answer questions such as what happens at the center of a black hole and in the instant after the Big Bang. Einstein himself died trying to create a unified theory of gravity and electromagnetism…

- The early attempts at quantum theories of gravity always had trouble with the gravitational self-interaction at high field strengths, though. Infinities occurred, and seemed impossible to avoid. In 1972, Deser and Van Nieuwenhuizen used a result from t'Hooft to formally show what had been suspected for a while – that gravity was non-renormalizable, ie. that it was impossible to remove the infinities if gravity is treated as a traditional quantum field theory.

- Four years earlier, Veneziano developed a "dual resonance" model of the strong interaction (completely separate from gravity). Nambu, Susskind, and Nielsen soon realized that what Veneziano's model actually represents is the quantum mechanics of vibrating strings.

- In the early 70's, Ramond, Schwarz, & others expanded this string-based field theory to include the fermions and bosons of particle physics. However, an unidentified massless, spin-2 boson kept popping up and was impossible to get rid of…

- In 1974, Scherk and Schwarz realized that the spin-2 boson could represent the graviton, a single quantum of gravity. They proposed string theory as a quantum theory of the gravitational field.


John Schwarz


Michael Green

# Is there a testable quantum theory of gravity?

- The announcement was largely met with silence in the physics community – primarily because a lot of questions remained to be answered. Was a string-based theory of gravity truly free of all the infinities that plagued traditional attempts at quantizing gravity? In 1981, Green and Schwarz formally proved that it was indeed free of such anomalies, and string theory began to be taken much more seriously.

- In order to be free of spurious fields, string theory requires **supersymmetry**, which implies a doubling (at least) of the number of observable particles. All the particles we observe today should, if supersymmetry exists, have partner particles that differ only in their spin (fermions partner with bosons, and vice-versa) and their mass (the supersymmetric partners must be heavier, or we would have observed them already).

- Supersymmetry has other nice attributes, in that it provides an ingredient for the unification of the other three forces (electromagnetic, weak, and strong), and the supersymmetric partner particles provide a potential source of dark matter.

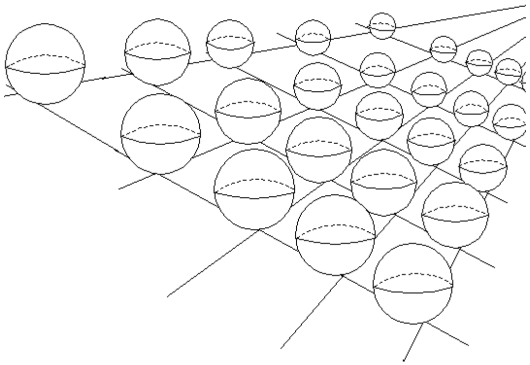
The LHC ring

← 10 km →

- After 20 years of searching, we have not seen indication of it yet. Perhaps the partner particles just live at a higher energy than we've been able to measure? In order for them to help in unification, they must be of order 1 TeV or less. The Large Hadron Collider at CERN, which will be completed in 2007, will reach this level, and we will then have more definitive information on whether supersymmetry (and possibly string theory) represent reality or not.

- Will string theory ever make firm predictions about particle masses, etc.? How does dark energy fit into the picture?

# How many dimensions are in a fundamental theory of the universe?

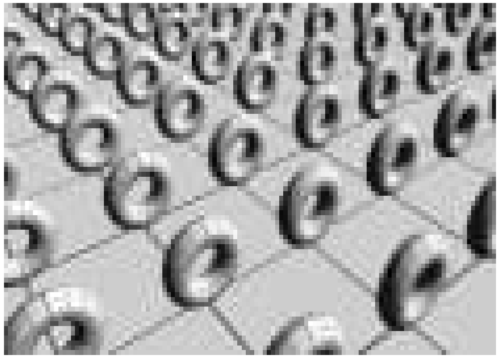


- In 1921, Theodor Kaluza and Oscar Klein independently discovered that if there were an extra spacetime dimension that was periodic (ie. "curled up" into a circle), gravity and electromagnetism would automatically be unified in a single theory.

- Unfortunately, this simple model predicts an additional scalar field that does not exist. However, the concept of adding additional "compactified" dimensions to solve fundamental problems still persists…

- The original version of string theory required 26 spacetime dimensions. Modern versions of string theory (M-theory) contain 11. All but 4 of these dimensions must be compactified at small scales (in a form called a Calabi-Yau manifold).

- But how small are those small scales? They manifestly should be at the scale of quantum gravity, *ie.* the Planck scale.

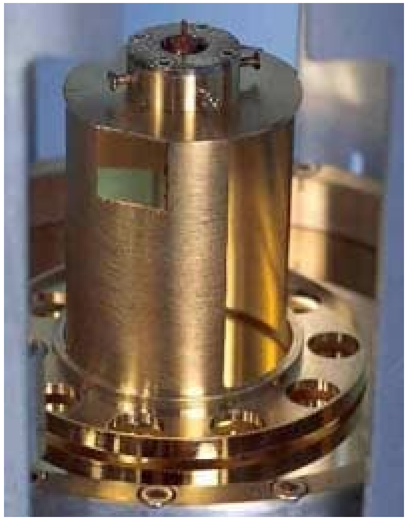


- But if there are extra compactified dimensions, the Planck scale is no longer necessarily down at 1.6 x $10^{-35}$ m! Let's say there is one extra compact dimension, curled up into radius R. We then have the gravitational potential:

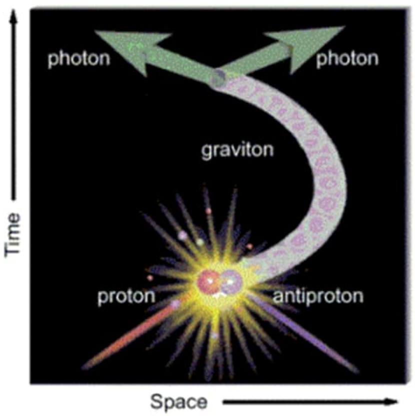
$$V(r) \approx \frac{G' m_1 m_2}{r^2} \quad (r \ll R) \qquad V(r) \approx \frac{G' m_1 m_2}{rR} \quad (r \gg R)$$

$$\frac{1}{m_{Planck}} \propto G' \neq G$$

# How many dimensions are in a fundamental theory of the universe?



- If the actual Planck scale were close to the electroweak scale, ie 1 TeV, this would have several nice features. One, the problem of why the electroweak and gravitational scales are so different (the "hierarchy problem") would cease to exist, and two, this can result in extra dimensions that are at the millimeter scale – large enough to be probed by experiment.
- Until a few years ago, the smallest scale that anyone ever probed the gravitational force law was ~1 m, in important experiments done in the 19th century by Baron von Eötvös of Hungary. Thus, if there were a different force law at smaller scales than ~1 m, no one would have known…
- Recently, a variety of Eötvös-type experiments, primarily at the University of Washington, have lowered this scale to ~100 um. No evidence of extra dimension was seen at this scale.




- Experiments at particle accelerators can also look for evidence of extra dimensions. An excess in the number of events with large amounts of "missing energy" – where the energy of all the visible particles does not come close to the total energy of the collision, could be a signal for the production of gravitons into an "invisible" extra dimension. Studies at the Tevatron and elsewhere are ongoing, but have not seen anything yet…

# Some other major open questions …

- A disadvantage of a course such as this is that the choice of topics to cover is always, to some degree, arbitrary. There are any number of open questions in physics, and one cannot with *any* certainty predict which questions will turn out to have the largest impact on physics in the future. We are leaving many important things out…
- There does, however, exist some degree of general consensus in the physics community about which questions seem most important. We have attempted to choose questions that are on most physicists' lists of critical questions.
- But there are other questions that are also critical. Some **extremely** important ones that we are unfortunately leaving out due to time constraints are:

    1) Will we be able to detect gravitational waves? What impact will they have on our understanding of nature?

    2) Is it possible to build a quantum computer? What materials should best be employed, and how would quantum computers be used in the future?

    3) We understand the theory of the strong nuclear force, but we have great difficulty using it to calculate particle properties. How can one deal with the strong force and other theories that couple strongly, and use them in calculation?

    4) (and beyond) …?