
Beyond the Standard Model

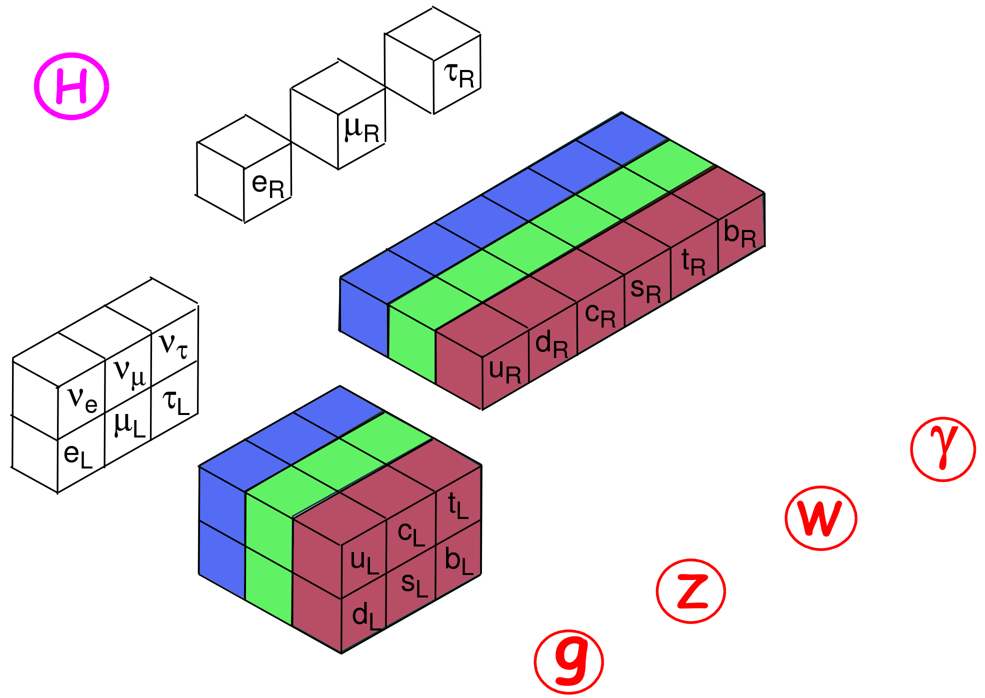
The Standard Model

What is the standard model ?

- The standard model describes the electromagnetic, strong and weak interactions. It is based on the principle of gauge invariance.

- The model has lots of free parameters: lepton and quark masses, coupling constants, quark and neutrino mixing parameters, W, Z and H masses...

- It uses a basic set of fermions and gauge bosons:



The Standard Model

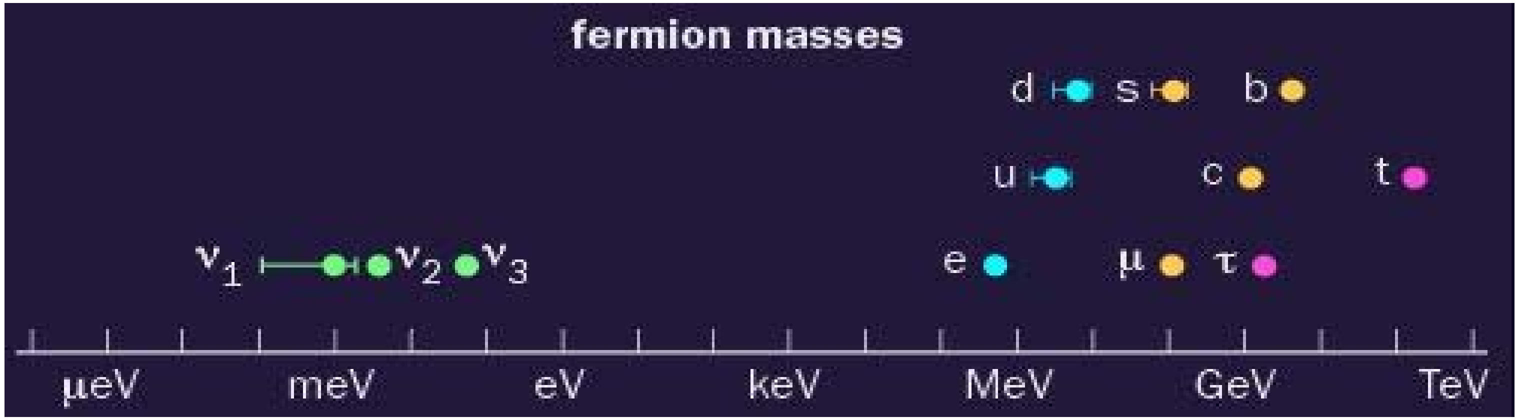
- The Standard Model agrees very well with all experimental data.
- The model has been tested down to 10^{-18} m.
- It has been tested to a precision better than 0.1% .

➡ Problems with the standard model:

- Does the Higgs exist ?
- If neutrinos have mass, are there right-handed neutrinos ?
- Why is there 3 generations ?
- What about gravity ?

The Standard Model

- Why are the masses so different (the hierarchy problem) ?



- Can the strong and electroweak interaction be described by a unified theory ?

- What happened with the anti-matter in the Big Bang ?

- What is dark matter ?

- What is dark energy ?

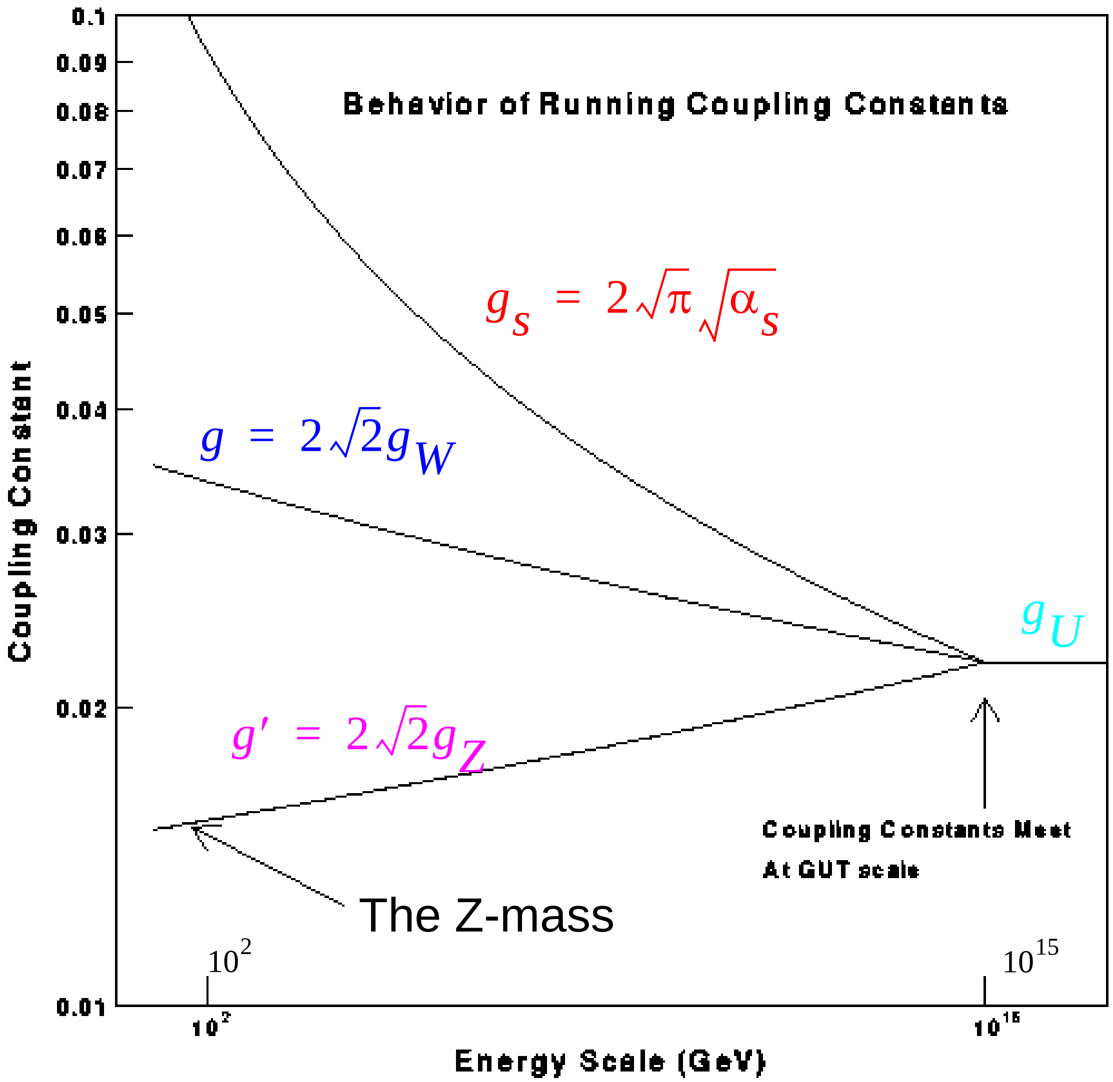
Grand Unified Theories (GUTs)

➡ The Georgi-Glashow model

- **Weak and electromagnetic interactions are unified, why not to add the strong one ?**

- **We know that coupling constants are not truely constant but that they depend on energy (or Q^2) in the interaction.**

- **The basic idea is that at some very high "unification mass" electroweak and strong couplings might become equal.**



Grand Unified Theories (GUTs)

- Grand unified theories can be constructed in **many different ways**.

- One example is the **Georgi-Glashow model**, which combines coloured quarks and leptons in single families, such as

$$(d_r, d_g, d_b, e^+, \bar{\nu}_e)$$

- It is necessary to introduce **two new gauge bosons** in the theory:

  X with **Q=-4/3** and **Y** with **Q=-1/3**

- These gauge bosons would have a mass close to the unification energy and would therefore be extremly heavy: $M_X = 10^{15}$ GeV/c^2

- There is **a single unified coupling constant** (g_U) in the theory with

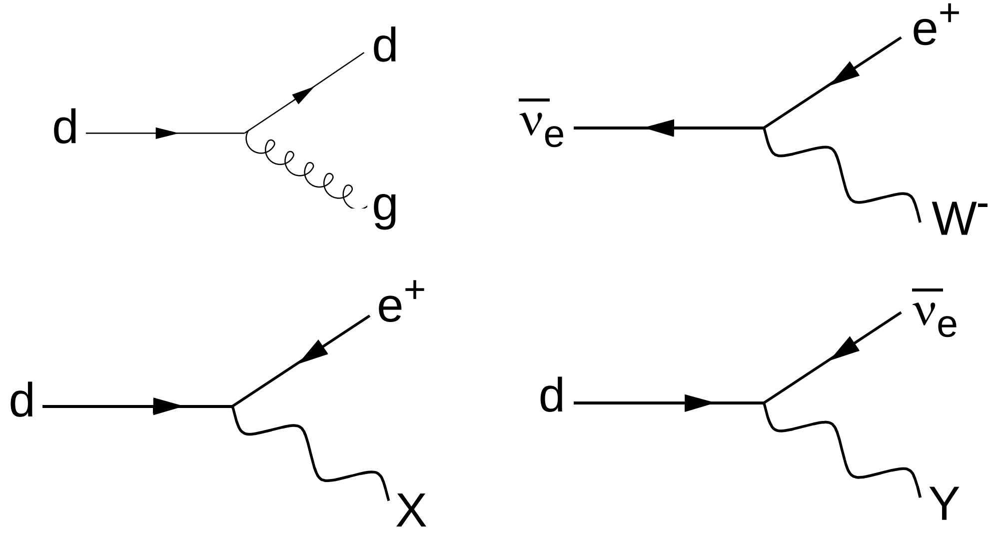
$$\alpha_U \equiv \frac{g_U^2}{4\pi} \approx \frac{1}{42}$$

Grand Unified Theories (GUTs)

- The new gauge bosons would make new processes possible in which quarks could be transformed into leptons by exchanging X and Y bosons:

old processes:

new processes:



- The fact that the model predicts the value of α_U as well as a relationship between g_U, g and g' means that it also predicts a value for the weak mixing angle:

$$\sin^2\theta_W = 0{,}21$$

This is close to the measured value !

Grand Unified Theories (GUTs)

- The model also makes the prediction that the sum of the charges within a family such as $(d_r, d_g, d_b, e^+, \bar{\nu}_e)$ has to be zero:

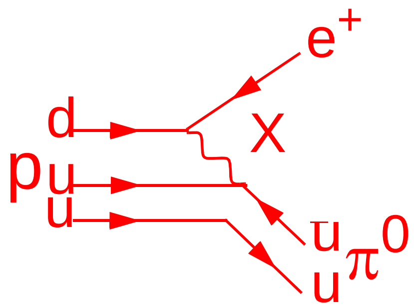
  $3Q_d + e = 0$ where the factor 3 is the number of colours.

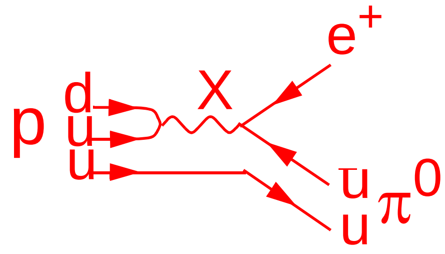
- With other words, if the d-quark did not have the charge -e/3 the model does not work.

- Baryon and lepton numbers are not necessarily conserved in GUT. This makes it possible to use GUT to explain why the world is dominated by baryons although it is assumed that the same amount of baryons and anti-baryons were produced in the Big Bang.

Proton decay experiments

- The **proton** must be **unstable** according to Grand Unified Theories because it can decay by processes involving the X and Y bosons:





- Baryon and lepton numbers are not conserved in these processes but the following combination is:

$$B - L \equiv B - \sum_{\alpha} L_{\alpha} \qquad (\alpha = e, \mu, \tau)$$

- It is possible to **estimate the lifetime** of the proton (τ_p) from a simple zero-range approximation:

$$\tau_p = 10^{32} - 10^{33} \text{ years}$$

(Age of universe = 10^{10} years)

Proton decay experiments

- Many experiments that are doing neutrino physics (Kamiokande, IMB) started out as proton decay experiments.

- The most searched for decay mode is: $p \rightarrow \pi^0 + e^+ \rightarrow \gamma\gamma + e^+$
where the experiments looks for one positron + two electron-positron pairs from photon conversions.

- No clear examples of proton decays have been observed and the upper limit on the proton lifetime is now:

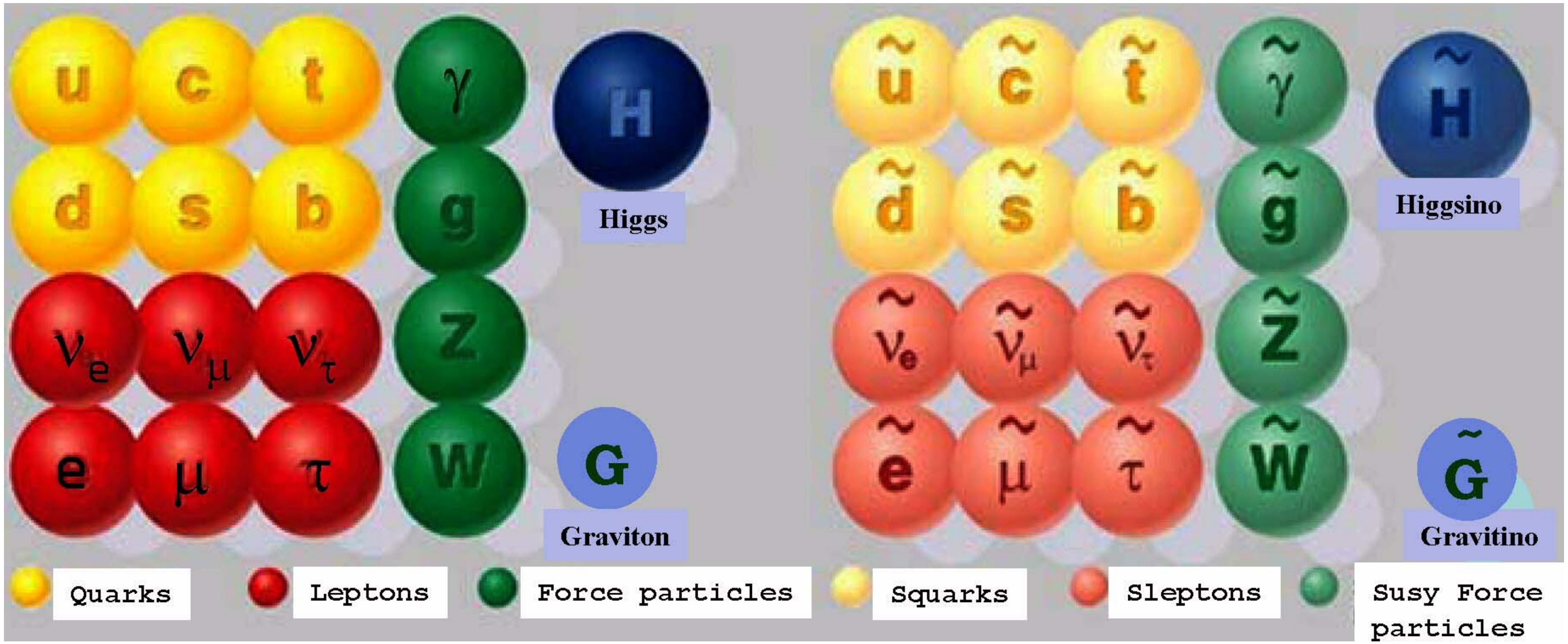
$$\frac{\tau_p}{B(p \rightarrow \pi^0 e)} > 5 \times 10^{32} years$$

- The Georgi-Glashow model predicts this ratio to be only 0.003-0.030 x 10^{32} years in clear disagreement with experiments. Other GUT models, however, predict longer lifetimes.

Supersymmetry

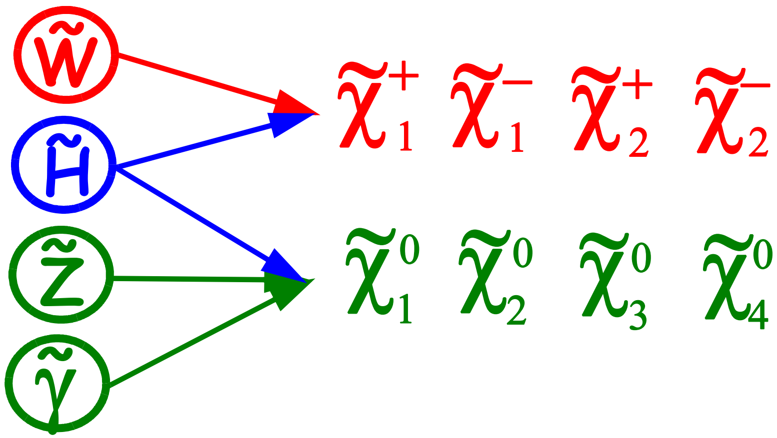
- The most popular GUTs incorporate **supersymmetry** (SUSY) in which the interactions are **symmetric** under the transformation of a **fermion to a boson**.
- Every known elementary particle is predicted to have a super-symmetric partner (**superpartner**) with **different spin**.

Spin = 1/2 1 0 0 1/2 1/2



Supersymmetry

- The new particles are called squarks, sleptons, photinos, gluinos, winos, zinos ..... and use a tilde to denote these particle: $\tilde{e}$ $\tilde{W}$ $\tilde{\gamma}$
- These new particles must be heavier than the known particles since they have not been observed.
- The Lightest Supersymmetric Particle (LSP) is stable in most models.
- New states are predicted due to mixing between some of the super partner states:



"Charginos"

"Neutralinos"

Supersymmetry

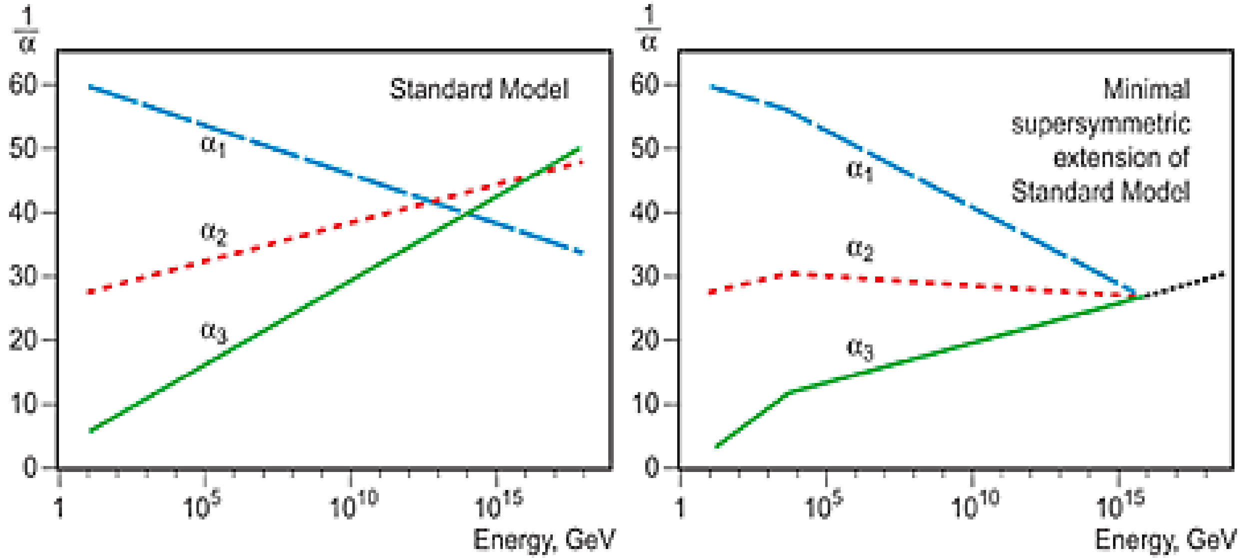
- There are many different supersymmetric models:

Name		LSP	New parameters
MSSM:	Minimal super symmetric standard model	Any	> 100
cMSSM:	Constrained MSSM	$\tilde{\chi}_1^0$	M_0, $M_{1/2}$, A_0, $\tan(\beta)$, $\mathrm{sgn}(\mu)$
mSUGRA:	Minimal Supergravity	$\tilde{\chi}_1^0$	M_0, $M_{1/2}$, A_0, $\tan(\beta)$, $\mathrm{sgn}(\mu)$
AMSB:	Anomaly mediated symmetry breaking	$\tilde{\chi}_1^0$	m_0, $M_{3/2}$, $\tan(\beta)$, $\mathrm{sgn}(\mu)$
GMSB:	Gauge mediated symmetry breaking	$\tilde{G}$	Λ_m, M_m, $\tan(\beta)$, N_5, $\mathrm{sgn}(\mu)$

Supersymmetry

- With SUSY one can shift the grand unification energy to higher values and this means that the prediction for the lifetime of the proton increases. This is more consistent with experimental (non)observations.

- The extrapolation of α to the unification scale works better with SUSY.



- SUSY predicts a value for the weak mixing angle which is closer to the experimental results than the Georgi-Glashow model.

- Some SUSY models even attempt to unify ALL forces (i.e., including gravity) at the Planck mass of 10^{19} GeV by replacing particles with superstrings.

Supersymmetry

SUSY search in the DELPHI experiment

- One possibility to look for SUSY at LEP was to search for selectron production followed by a decay to electrons and neutralinos:

$$e^+ + e^- \rightarrow \tilde{e}^+ + \tilde{e}^-$$

$$\tilde{e}^+ \rightarrow e^+ + \tilde{\chi}_1^0$$

$$\tilde{e}^- \rightarrow e^- + \tilde{\chi}_1^0$$

1) The cross section for producing selectron pairs is comparable to that of producing ordinary charged particles with the same mass.

2) The selectrons decay before they can reach a detector.

3) The neutralinos only interact weakly and they are therefore virtually undetecable.

Supersymmetry

- The signature that one was looking for was events with only an electron and a positron. One required that these
  i) carried only about half of the collision energy;
  ii) were not emitted in the opposite directions in the center-of-mass frame.

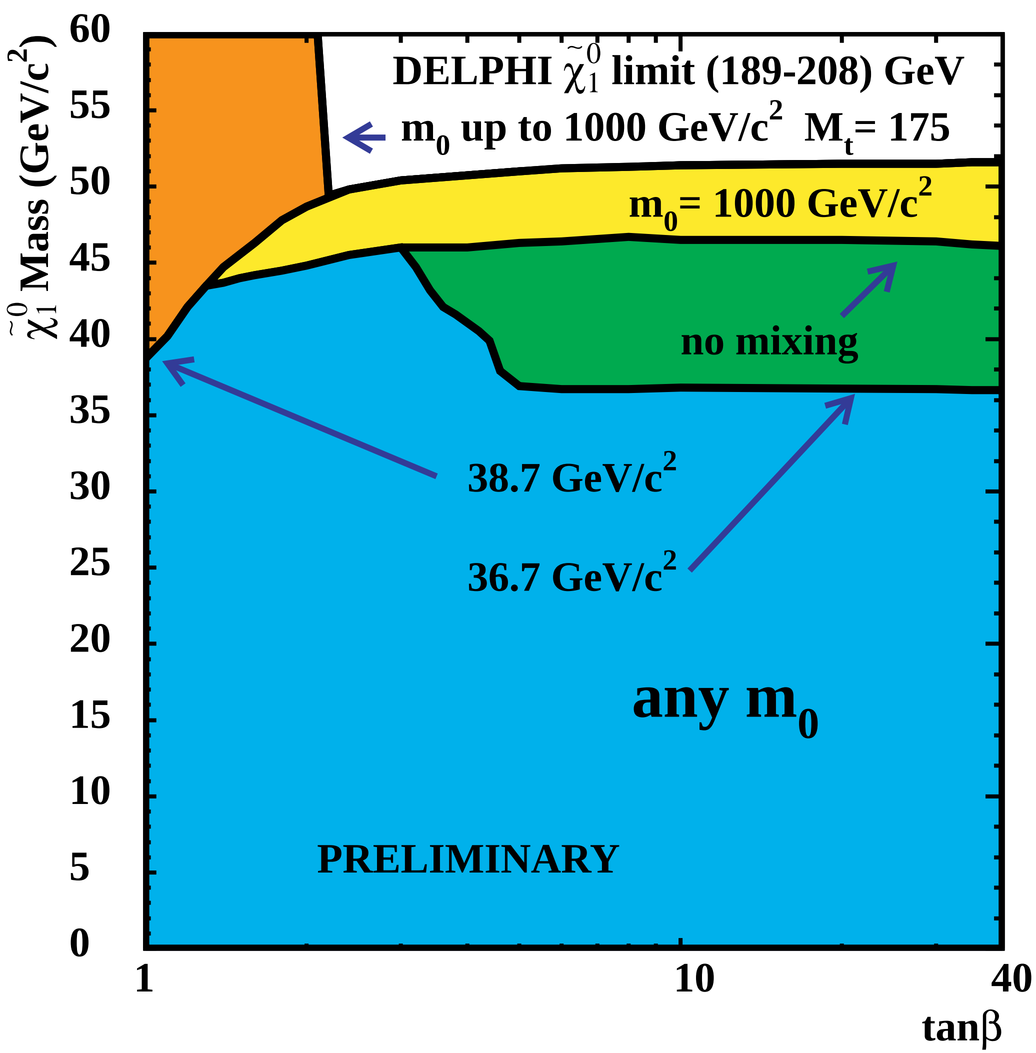
- No events were found with a clear and background free signature.

- Even if no signal was found one could use the results to set lower limits on the mass of the neutralino.

- A complication is that SUSY has many models, each with different sets of unknown parameters. And so the results are often given for different assumptions on models and parameters.

Supersymmetry

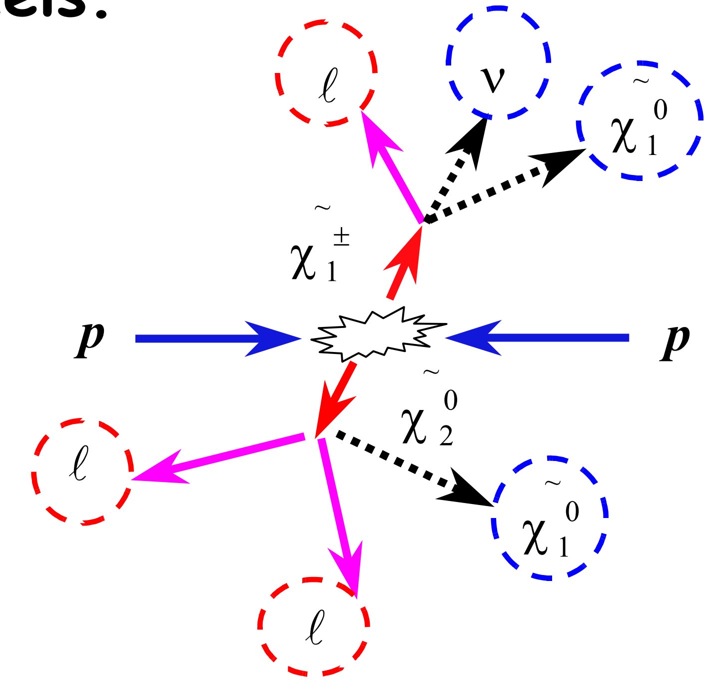
- The results of the slepton searches were combined with other SUSY searches in DELPHI to set limits on the neutralino mass.
- In this plot all the coloured areas are excluded by the seaches: →
- The tan(β) parameter is related to the SUSY Higgs particles and m_0 to the sfermions.
- The result is that the mass of the $\tilde{\chi}_1^0$ > 36.7 GeV for all parameter values.



Supersymmetry

➡ SUSY search in the ATLAS experiment

- One of the main purposes of the LHC experiments are to search for SUSY as predicted by different models.
- The background will be problematic but one of the most promising channels is the production of a chargino and a neutralino that decays to leptons and the lightest neutralino.



- In this search one will be looking for three leptons (electrons and muons) and missing energy due to the neutralinos and neutrinos. Typically one will require P_T>10 GeV for the leptons and atleast 30 GeV of missing energy in the event.
- The main background will come from ZW and $t\bar{t}$ production.

Gravitation and extra dimensions

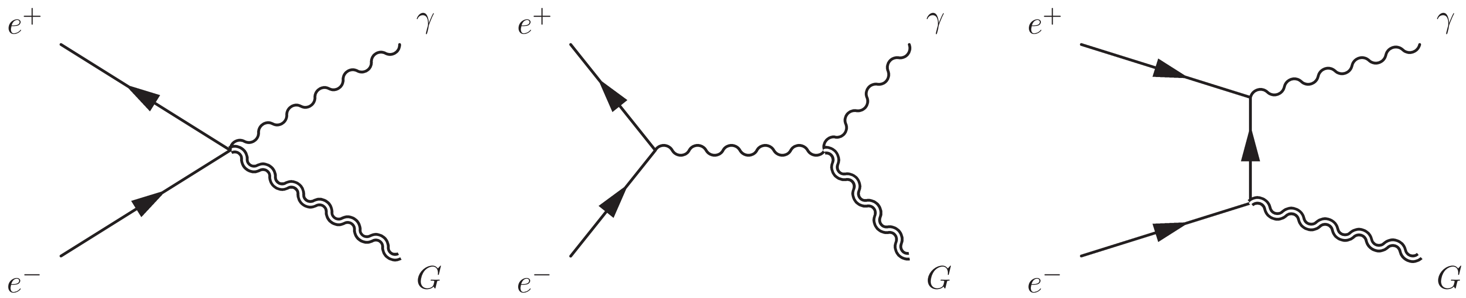
- The gravitational force is much weaker than the electromagnetic and strong interactions and it has therefore not been studied in particle physics.
- One has, however, postulated that there exists graviational force carriers as for the other interactions. These are called Gravitons (G).
- Graviation has only been studied at large distances (>1 mm) and it could be that it is stronger at shorter distances.
- Theories have been proposed in which gravity is unified with other interactions by introducing new dimensions of space in which only gravity can propagate (in addition to the normal 3 space + 1 time dimensions).

Gravitation and extra dimensions

➡ Graviton search in the DELPHI experiment

- **If our accelerators could reach the energy scale where gravity is unified with the other forces one could start see events in which gravitons are produced that escape undetected into the extra dimensions.**

- **The theory predicts that e^+e^- collisions at sufficient energy could produce events with one graviton and one photon:**



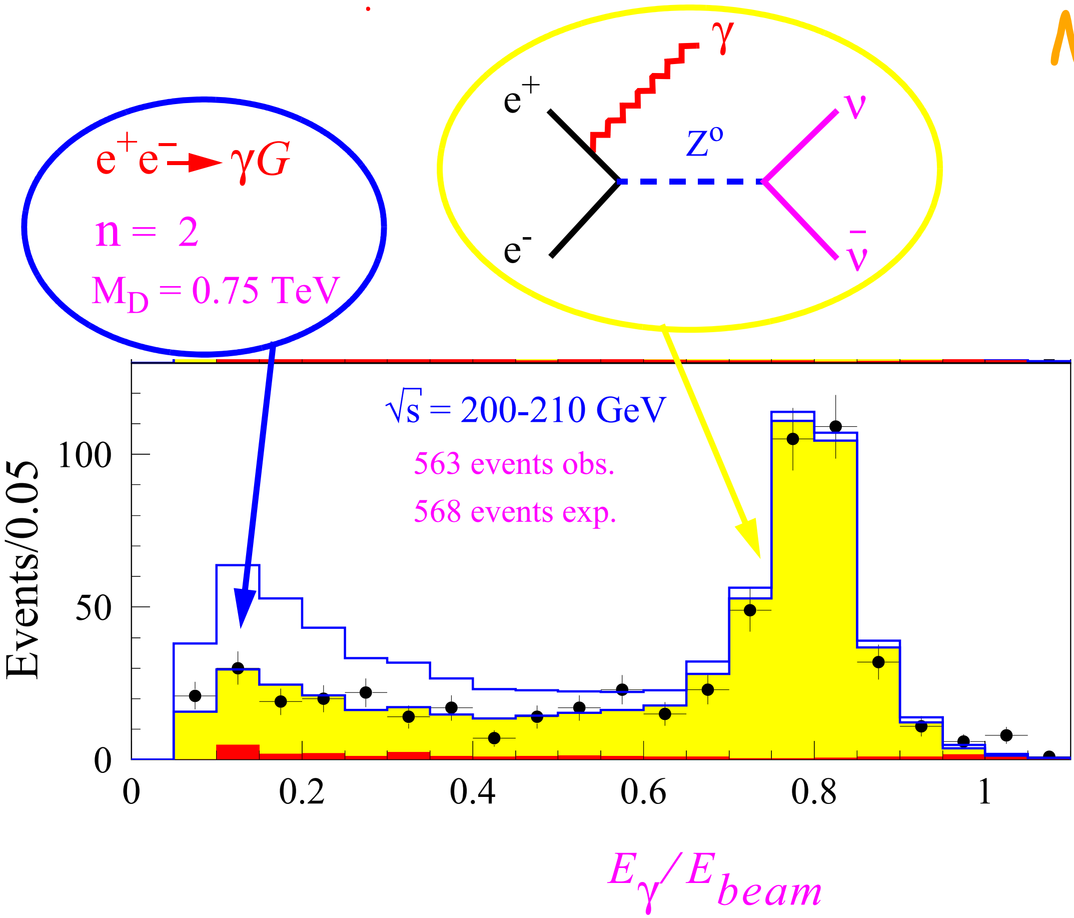
- **Since the Graviton cannot be detected one would only see one photon in the experiments.**

Gravitation and extra dimensions

- Events were selected in the DELPHI experiment with only one photon and nothing else and the energy of the photons were plotted.

Standard Model

New Physics



The extra dimension model predicts that photons with a low energy are produced.

The standard model predicts that sometime photons are radiated off the electrons in events with a Z^0 that decays to neutrinos.

- Conclusion: There is no sign of graviton production in the data !

Gravitation and extra dimensions

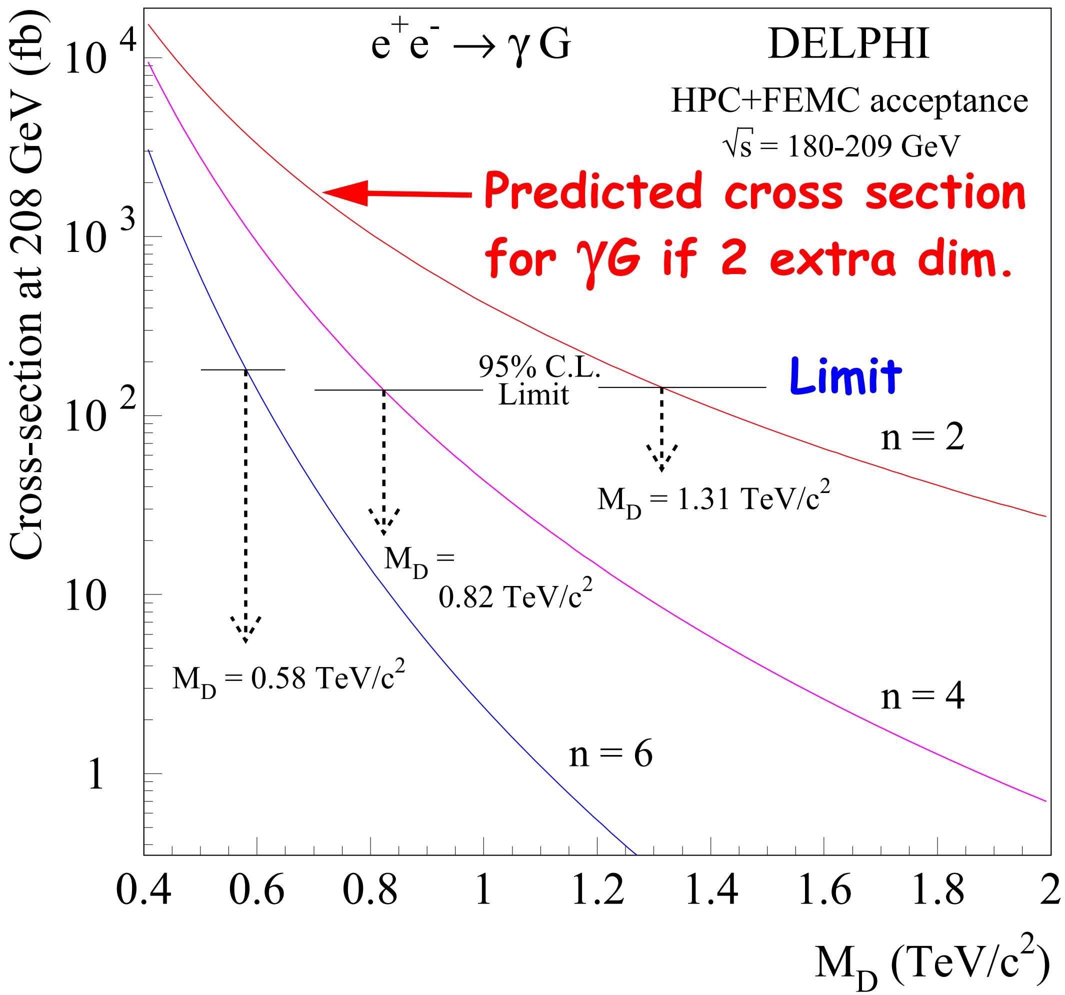
- The measurement could be used to set limits on the parameters in the theory even if no signal was seen.

One parameter was the number of extra dimensions which could be between 1 and 6.

Another parameter was a fundamental mass scale M_D.

The data could be used to set limits on the cross section for γG production and this could be transformed into limits on the parameters.

The final result was M_D > 1.31 TeV for 2 extra dimensions.



Dark matter & energy

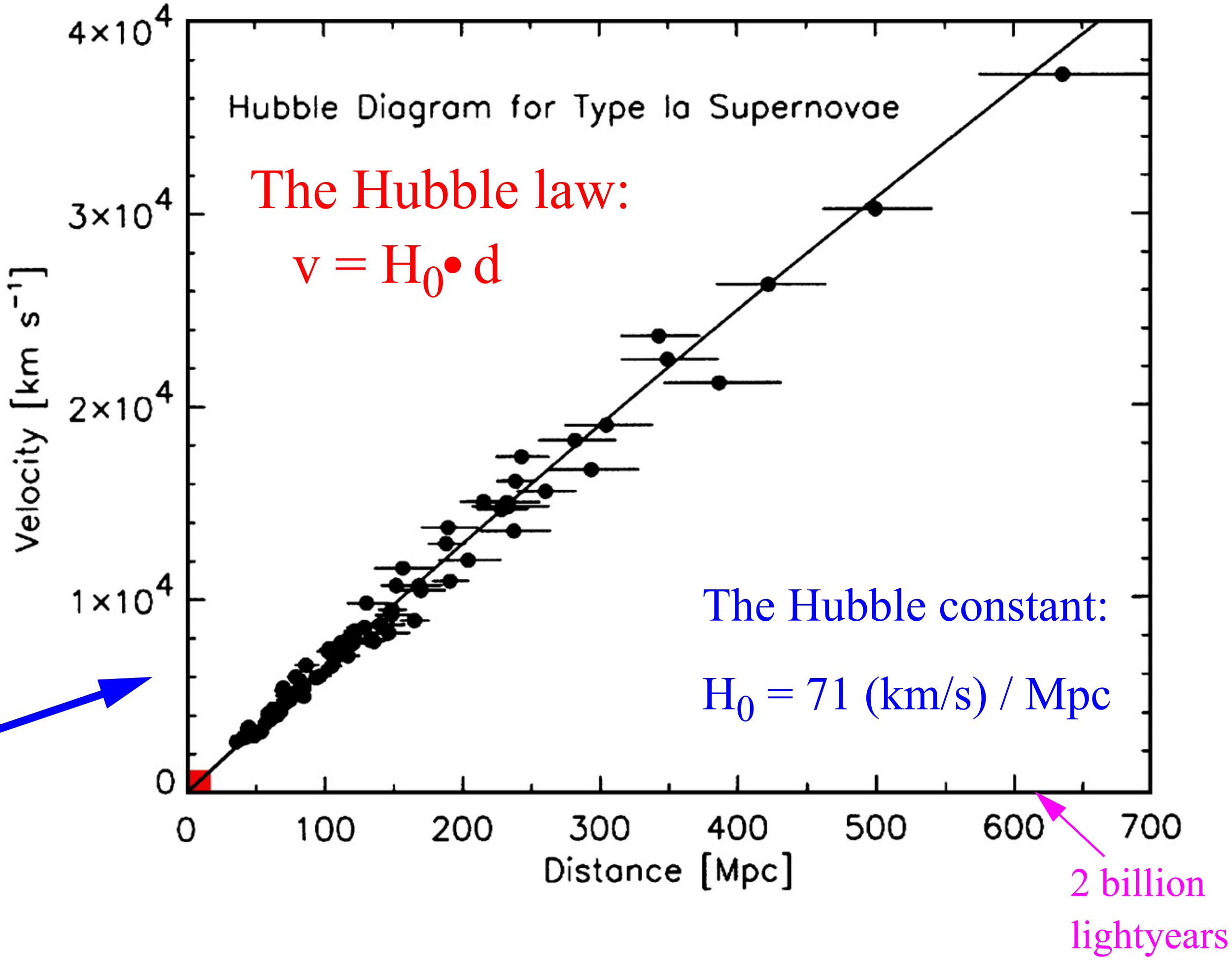
The Big Bang Model

- There is experimental **evidence** for the **Big Bang model**, for example:

1) A nearly **uniform** distribution of **matter** in the universe.

2) An abundance of **light elements** such as He, D and Li.

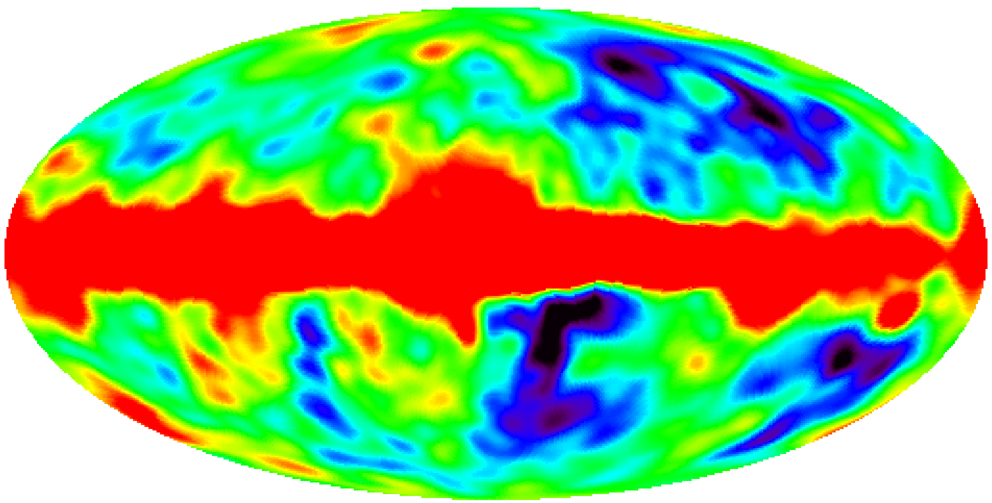
3) The **universe is expanding** and the velocity of super-novas are therefore increasing with their distance to earth.



Dark matter & energy

4) The cosmic background radiation with a temperature of 2.7 K (0.0002 eV) is regarded as a remenant of the Big Bang.

The sky as seen at microwave frequencies by the COBE satellite:



The difference between the hottest regions in red and the coldest in blue are only 0.0002 K while the average temperature is 2.7 K.

Conclusion: The cosmic microwave background radiation is very uniform.

Dark matter & energy

- One has introduced a quantity called the critical density which is defined as:

$$\rho_c = \frac{3H_0^2}{8\pi G} = O(10^{-26})\ \text{kg m}^3$$

"The critical density"

where H_0 is the Hubble constant and G is the gravitational constant.

- The basic idea is that if the density in the universe is larger than the critical density, the expansion of the universe will eventually end. Otherwise it will continue for ever.

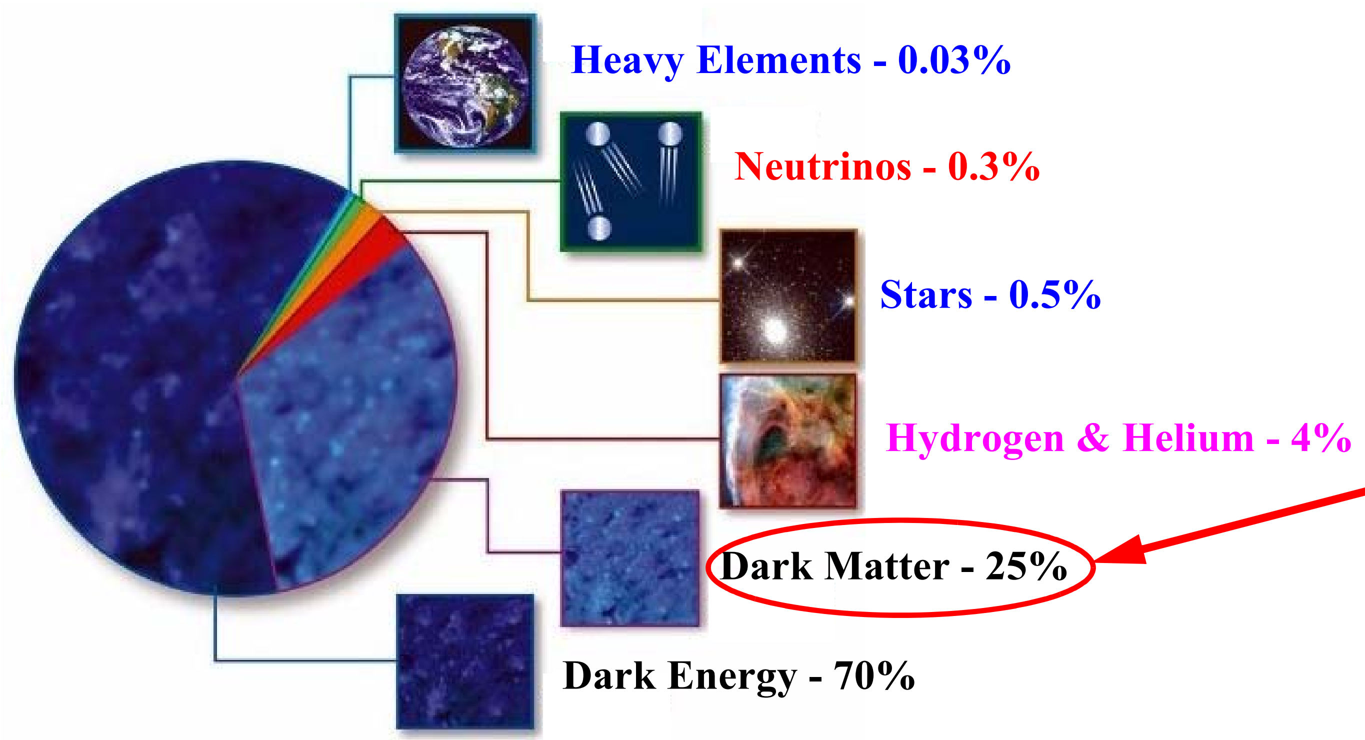
- One has also introduced something called the relative density (Ω) which is defined as:

$$\Omega \equiv \rho / \rho_c$$

Dark matter & energy

➡ Dark Matter

- The density of the universe is estimated in the inflationary Big Bang model to be close to the critical energy.
- One divide the density up into a matter part (Ω_M) and an energy part (Ω_Λ) such that $\Omega = \Omega_M + \Omega_\Lambda$.

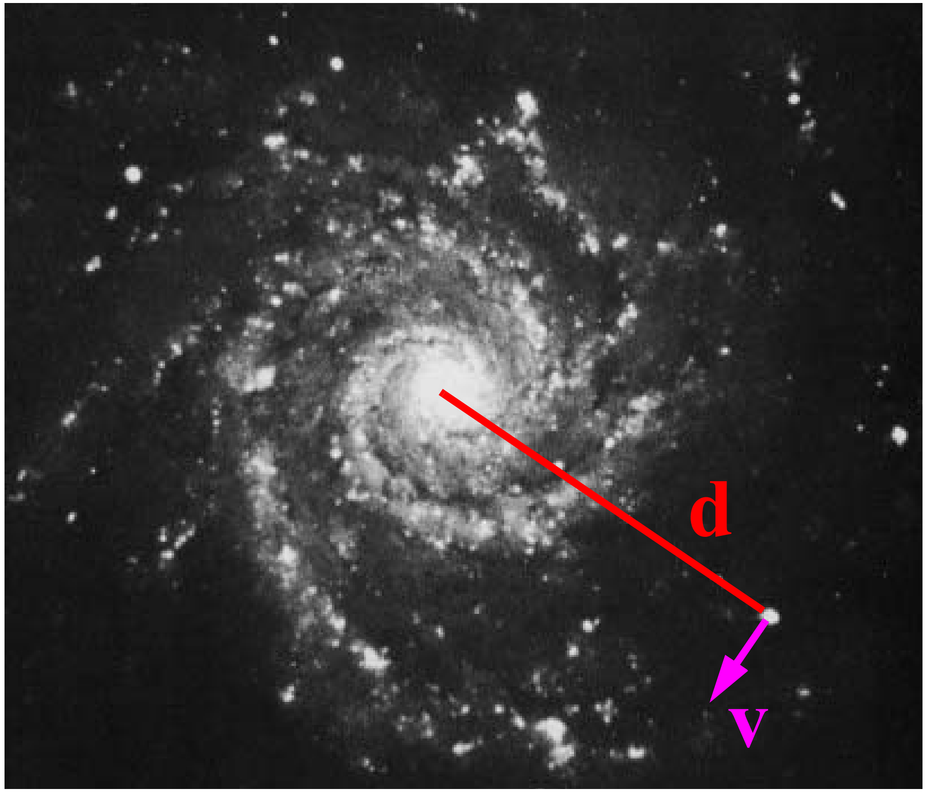


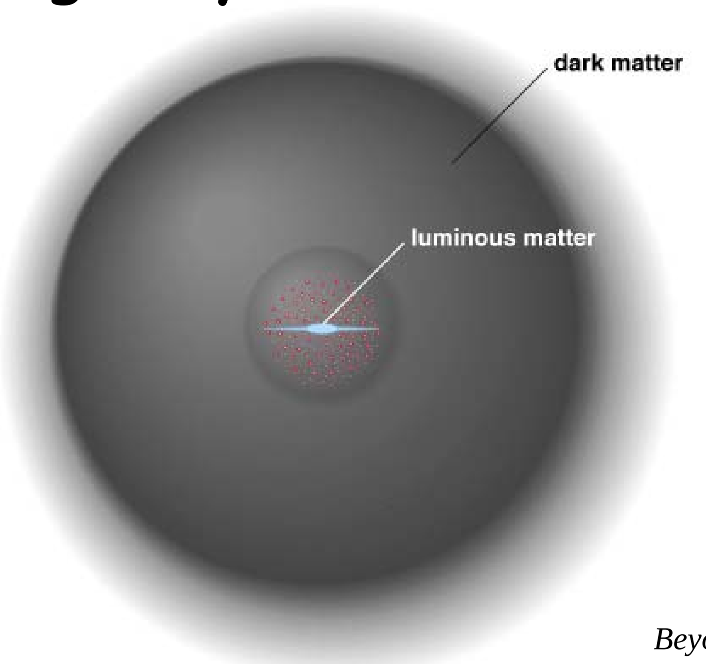
- Most of the matter is of an unkown type that is called "Dark Matter".

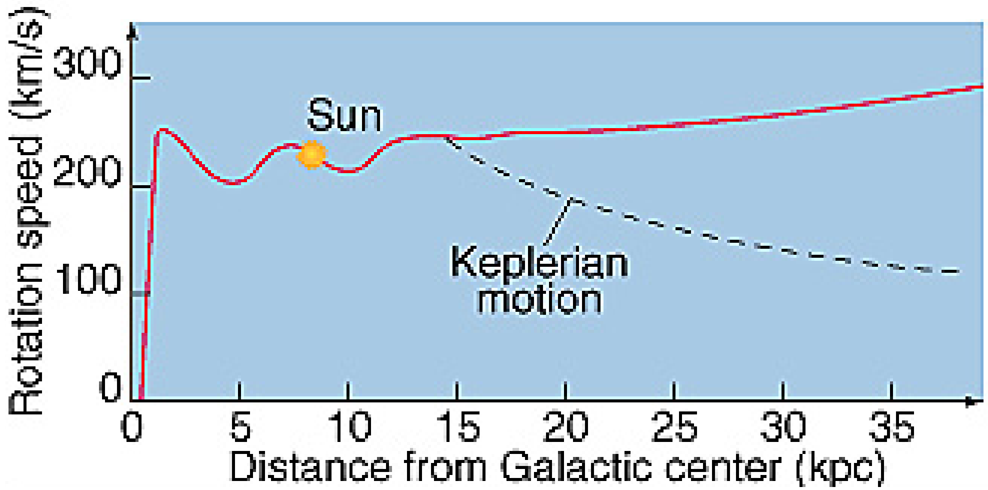
Dark matter & energy

- The evidence for dark matter came originally from measurements of the rotation velocity of stars in galaxies.

- The large rotational velocity of stars in the outer regions of the the Milky way can be explained if the galaxy is full of dark matter.







Dark matter & energy

- The million dollar question: What does dark matter consist of ?

1) Baryonic matter that emits little or no electromagnetic radiation: Brown dwarfs, small black holes - MACHO's (for Massive Compact Halo Object).

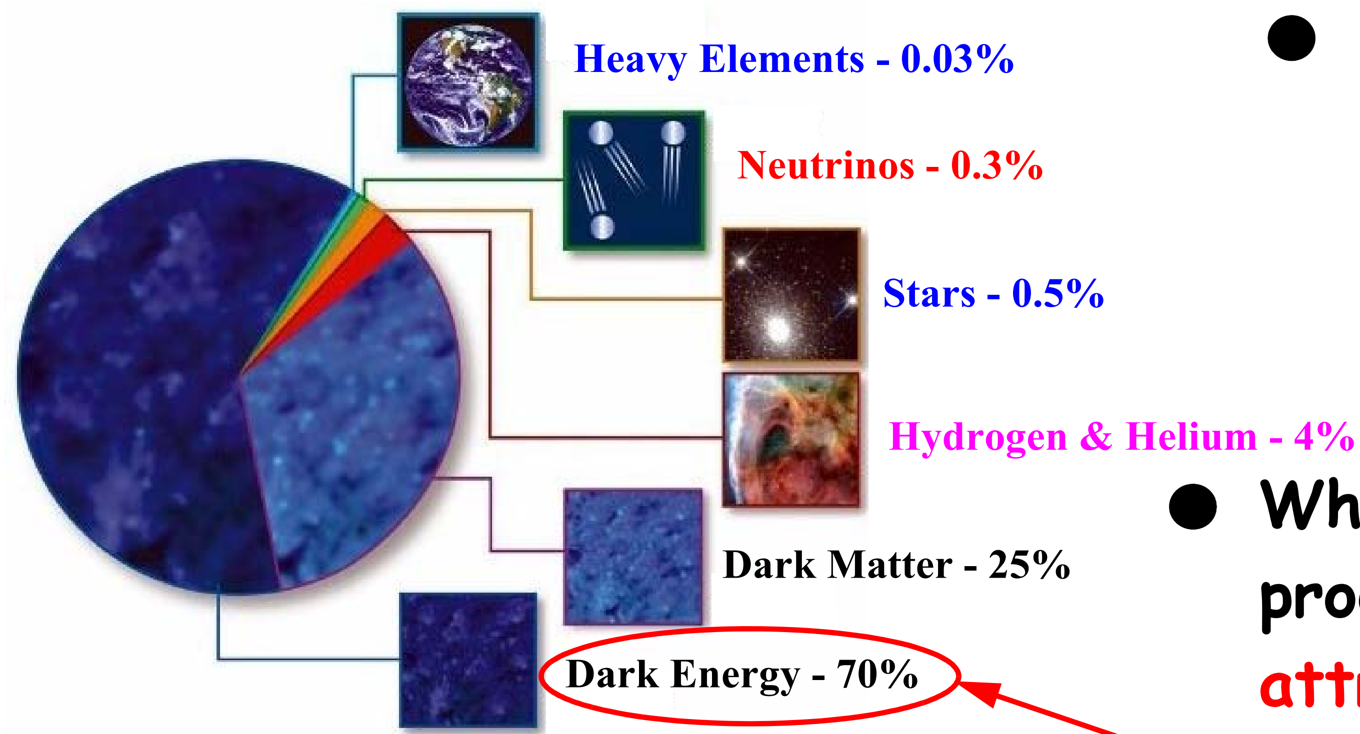
2) Hot dark matter: If neutrinos have a mass > 1 eV they would give a significant contribution to the density of the universe. It is, however, difficult to explain how the galaxies are formed if neutrinos make up the dark matter.

3) Cold dark matter: Weakly Interacting Massive Particles (WIMPs). This is non-baryonic objects that were non-relativistic at the early stages of the evolution of the universe. SUSY particles could be these WIMPs.

Dark matter & energy

➡ Dark Energy

- Studies of the brightness (magnitude) of remote supernovas and their redshifts have indicated that the expansion of the universe is not constant but accelerating.

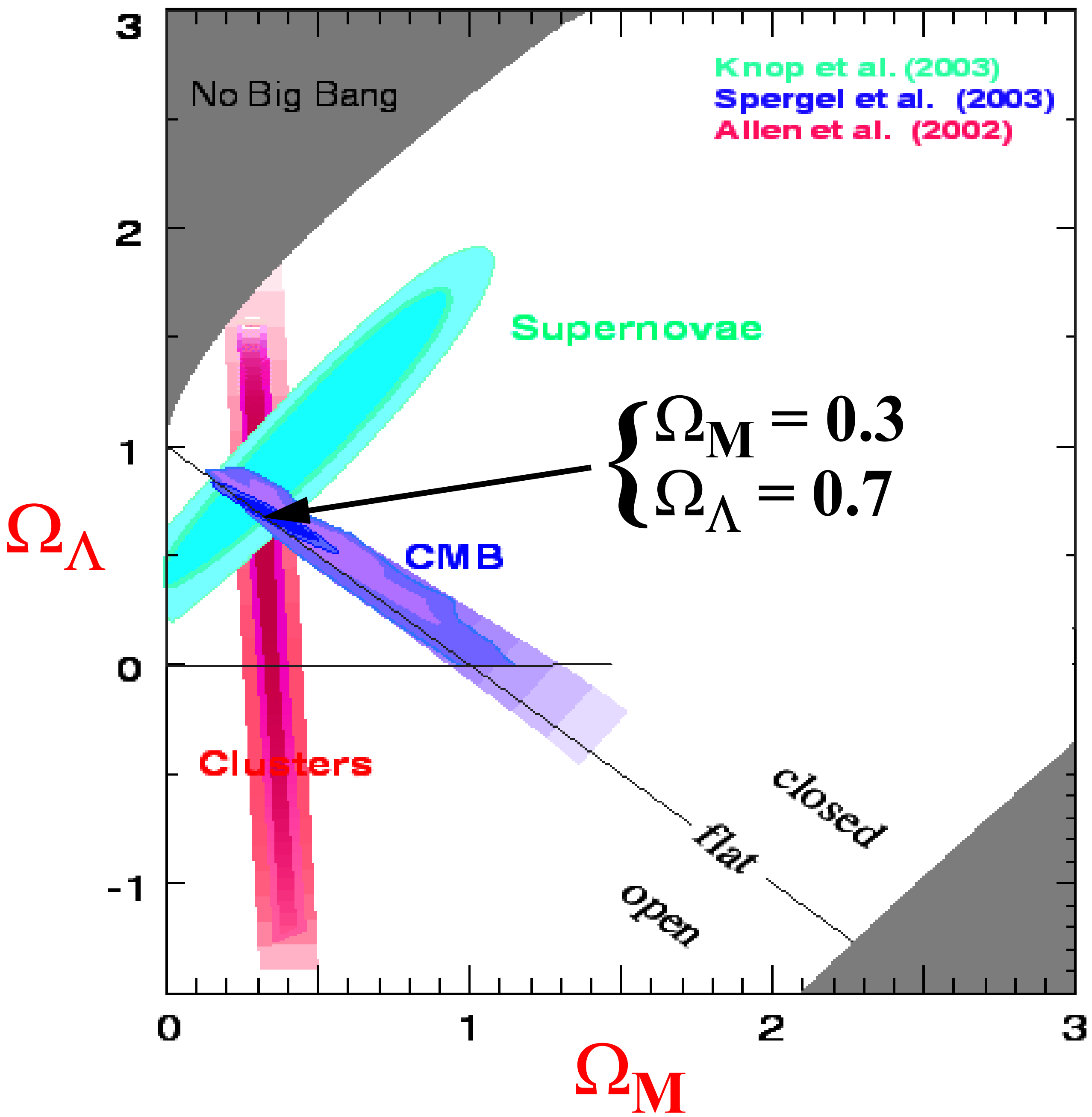


- The suggestion has been made that the universe is full of a mysterious "Dark Energy".

- While Dark Matter is producing a gravitationally attractive force, the Dark Energy is producing a gravitationally repulsive force.

Dark matter & energy

- Other evidence for dark energy has come from studies of the Cosmic Microwave Background (CMB) and the motion of clusters in galaxies.



Dark matter & energy

The two-million dollar question is:

What is causing the Dark Energy ?

There are two main hypothesis:

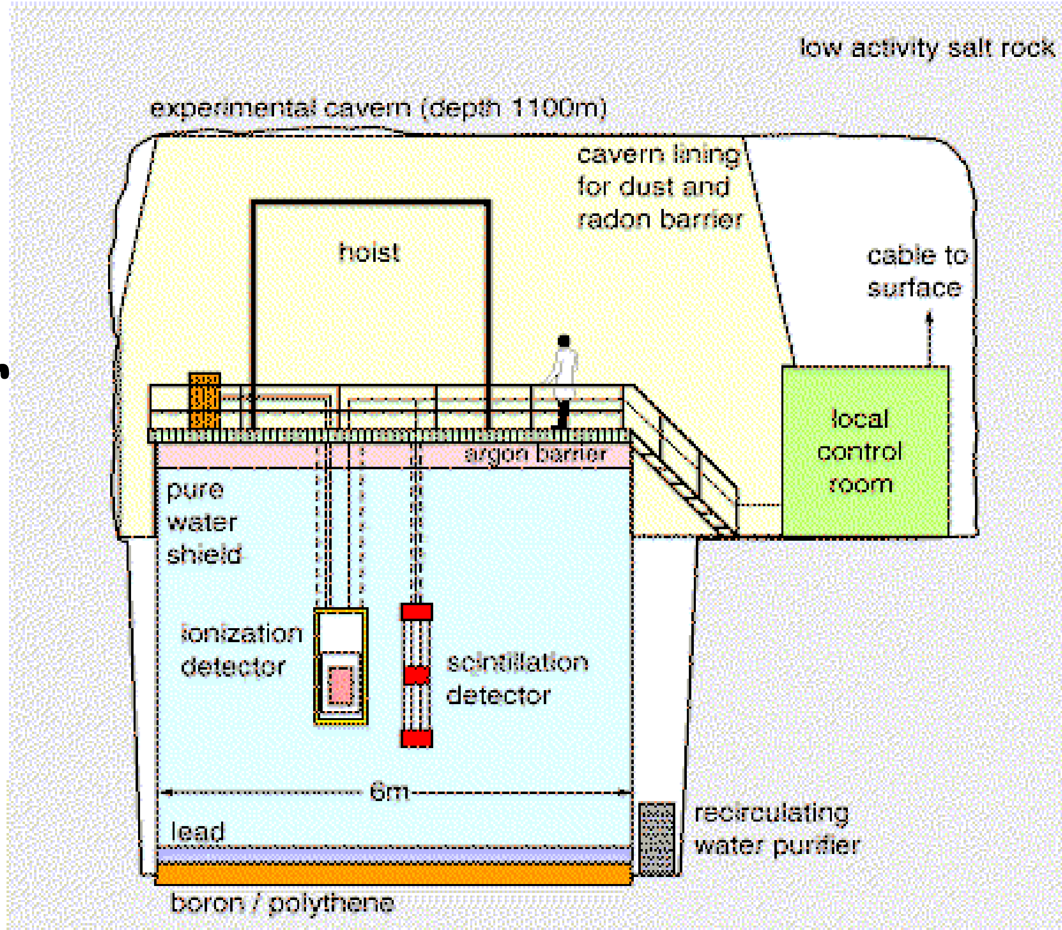
1) The Cosmological Constant: Space has an intrinsic constant fundamental energy (10^{-29} g/cm^3). Calculations of vacuum fluctuations in particle physics give rise to an energy density in vacuum but the calculated value do not agree with astronomical observations.

2) Quintessence: Particle-like excitations in a new dynamical field called quintessence. This field differs from the Cosmological constant in that can vary in space and time.

Dark matter & energy

➡ Direct search for WIMPs

- Interactions between WIMPs and matter has to be very rare. It is estimated that there could be about one WIMP interacting in a kg of matter every day.



- WIMP detectors are typically installed deep underground and surrounded with shielding in order to minimize the background.

- The Boulby experiment uses a NaI detector which produces scintillation light if a WIMP interacts with an atom. 200 tons of ultra pure water is used for shielding.

Dark matter & energy

➡ The Cryogenic Dark Matter Search (CDMSII)

- In 2009 **CDMSII** claimed "a hint" of a dark matter discovery.

The New York Times

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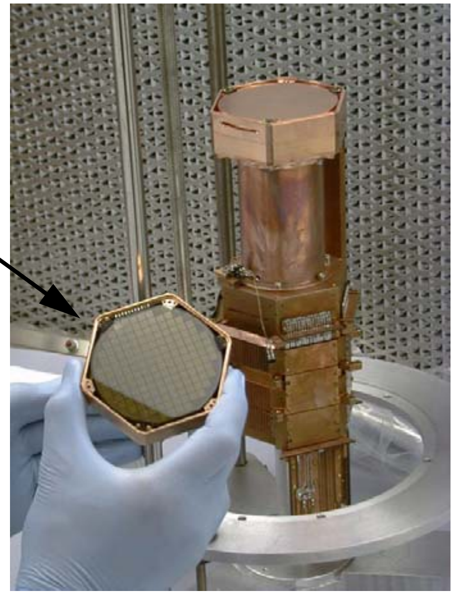
ENVIRONMENT

At a Mine's Bottom, Hints of Dark Matter

By DENNIS OVERBYE
Published: December 17, 2009

An international team of physicists working in the bottom of an old iron mine in Minnesota said Thursday that they might have registered the first faint hints of a ghostly sea of subatomic particles known as dark matter long thought to permeate the cosmos.

- The experiment used Ge detectors at **the Soudan underground laboratory** to look for WIMPs.
- Interactions between WIMPs and the Ge atoms would cause phonons and ionization that could be detected by sensors on the semiconductors.



- The experiment found **two candidate events** with 0.9 expected from background.