

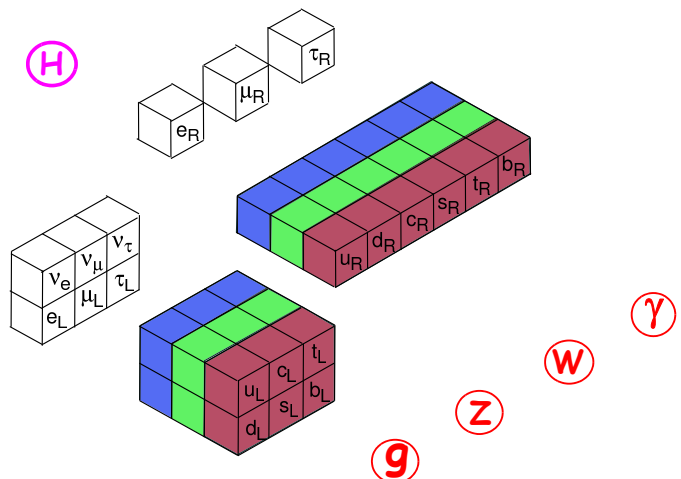
Beyond the Standard Model

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

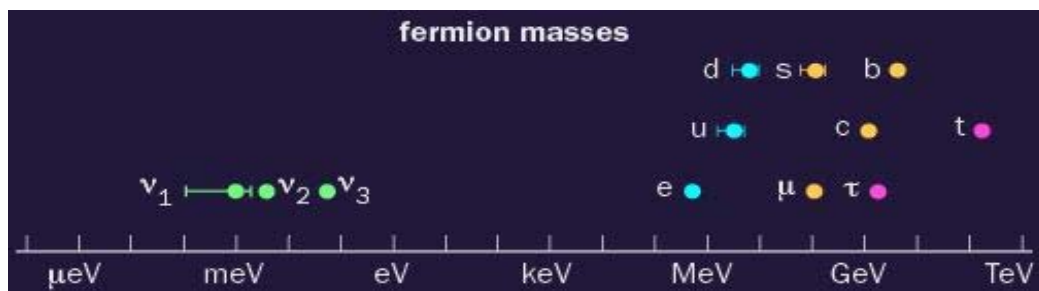
- The Standard Model **agrees** very well with all **experimental data**.
- The model has been tested down to 10^{-18} m.
- It has been tested to a **precision** better than 0.1% .

➔ Problems with the standard model:

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

The Standard Model

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

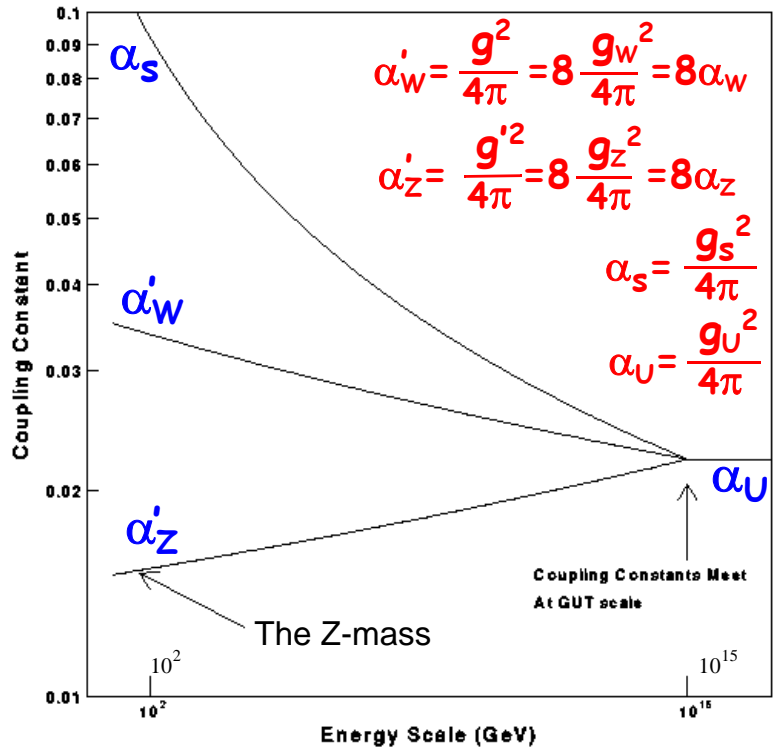


- Can the strong and electroweak interaction be described by a **unified theory** ?
- What happened with the **anti-matter** in the Big Bang ?
- What is **dark matter** ?
- What is **dark energy** ?

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 truly 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**.



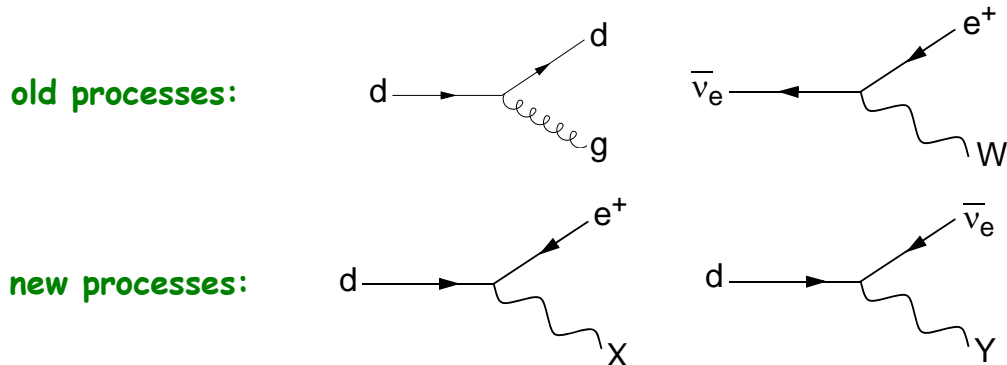
Grand Unified Theories (GUTs)

- 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 extremely heavy: $M_X = 10^{15} \text{ GeV}/c^2$
- 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:



- 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:

$$\sin^2 \theta_W = 0,21 \quad \text{This is close to the measured value !}$$

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:

$$3Q_d + e = 0 \quad \text{where the factor 3 is the number of colours.}$$

- 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:

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

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

$$\tau_p = 10^{32} - 10^{33} \text{ years} \quad (\text{Age of universe} = 10^{10} \text{ years})$$

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 look 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:

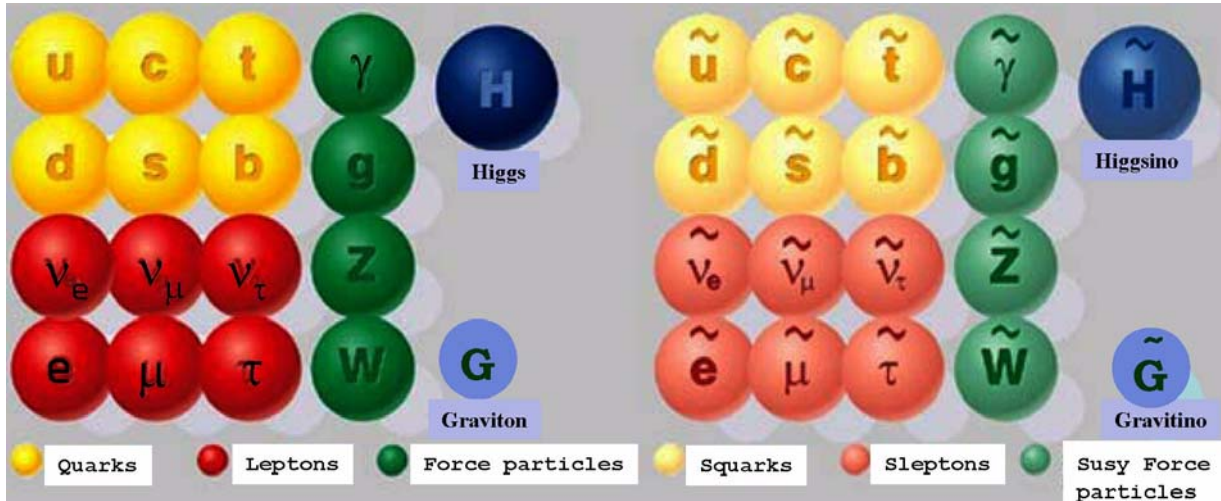
$$\frac{\tau_p}{B(p \rightarrow \pi^0 e)} > 5 \times 10^{32} \text{ years}$$

- The **Georgi-Glashow model** predicts this ratio to be only **0.003-0.030 $\times 10^{32}$ 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



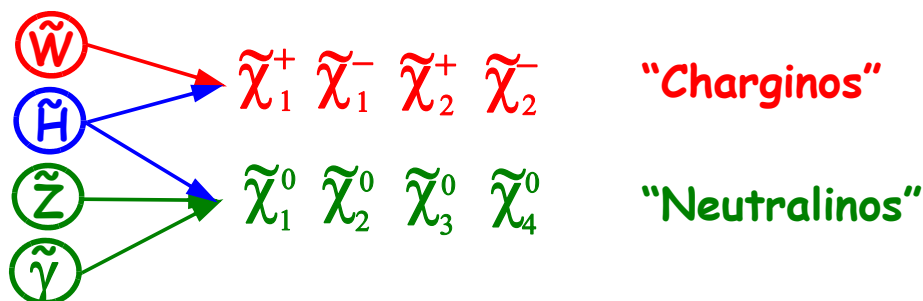
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Supersymmetry

- 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:



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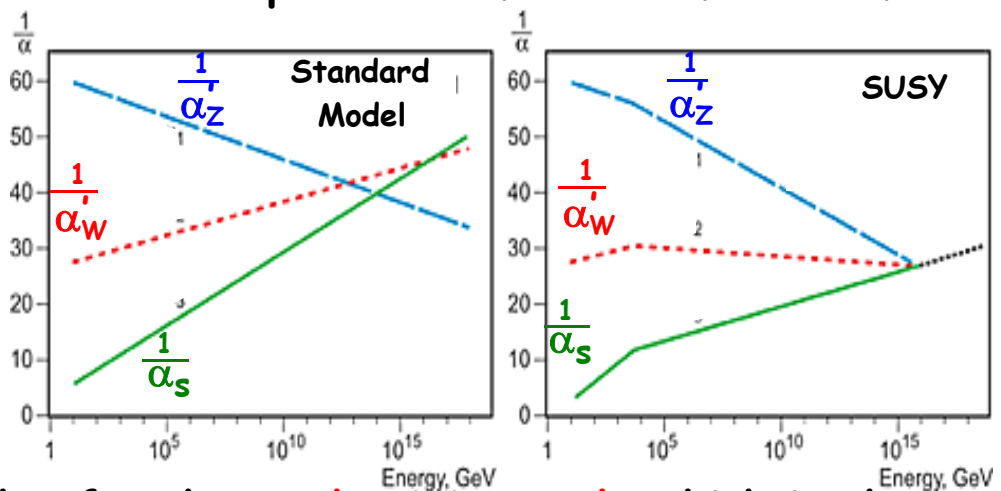
Supersymmetry

- There are many different supersymmetric models:

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

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.



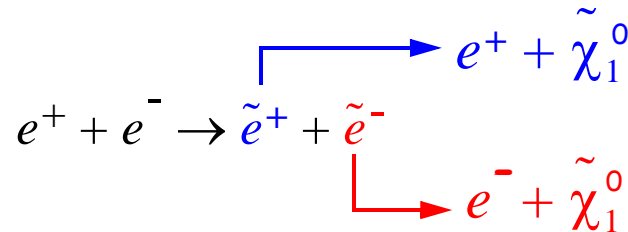
- Extrapolation of α** to the unification scale works better with SUSY.

- 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:




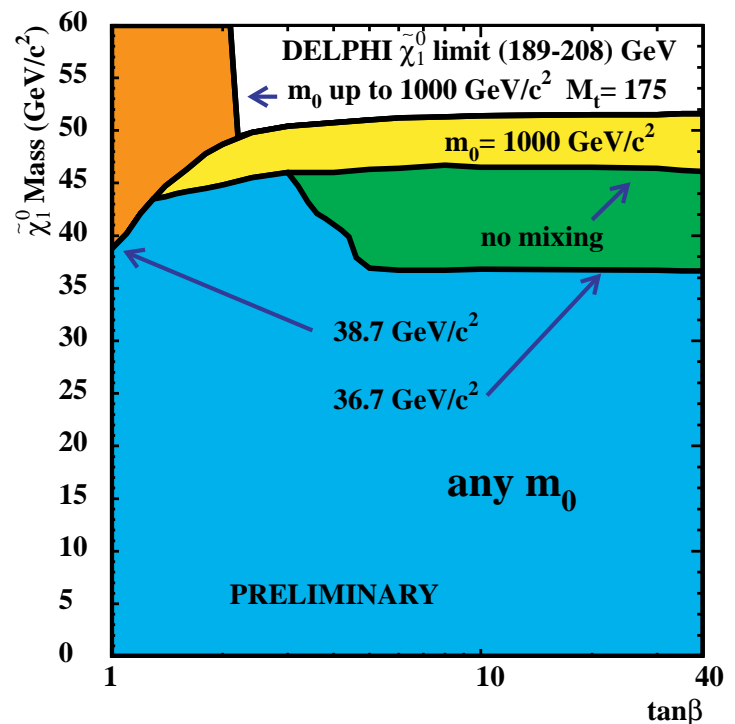
- 1) The **cross section** for producing selectron pairs is comparable to that of producing ordinary charged particles with the same mass.
- 2) The **selectrons decay** before they can reach a detector.
- 3) The **neutralinos** only interact **weakly** and they are therefore virtually undetectable.

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 searches: 
- The $\tan(\beta)$ parameter is related to the **SUSY Higgs** particles and m_0 to the **sfermions**.
- The result is that the mass of the $\tilde{\chi}_1^0 > 36.7 \text{ GeV}$ for all parameter values.



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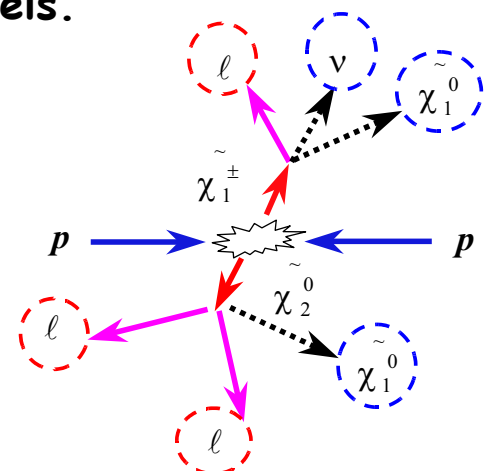
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Supersymmetry

➡ 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 $P_T > 10 \text{ GeV}$ for the leptons and at least 30 GeV of missing energy in the event.
- The main **background** will come from **ZW** and $t\bar{t}$ production.



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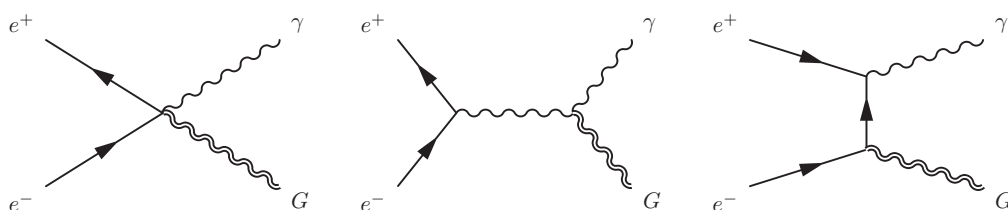
Gravitation and extra dimensions

- 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 gravitational force carriers as for the other interactions. These are called **Gravitons (G)**.
- Gravitation 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**:

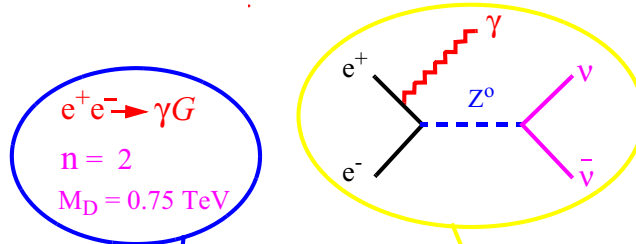


- Since the Graviton cannot be detected one would **only** see one **photon** in the experiments.

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.

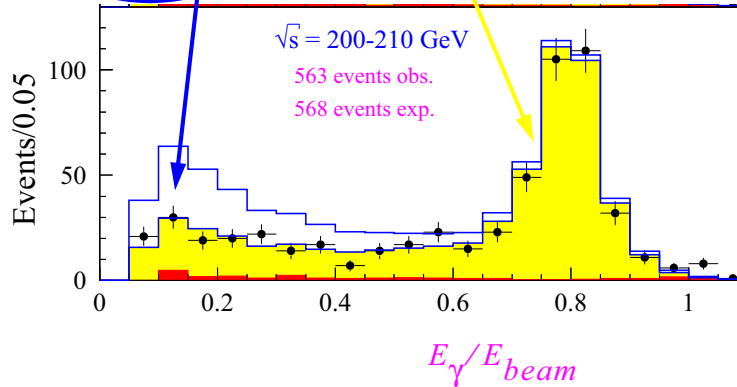
New Physics



Standard Model

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

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



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

Gravitation and extra dimensions

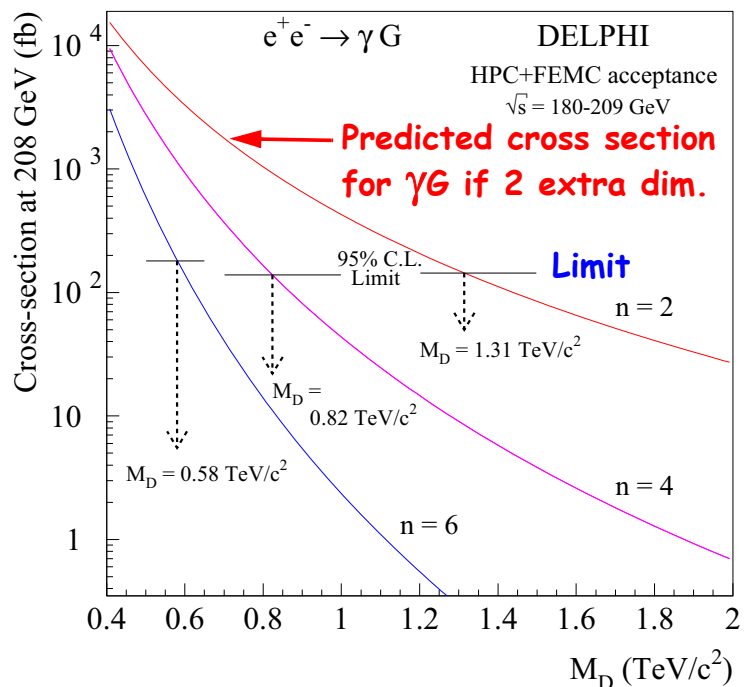
- The measurement could be used to **set limits** on the parameters in the theory even if no signal was seen.

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 $M_D > 1.31 \text{ TeV}$ for 2 extra dimensions.

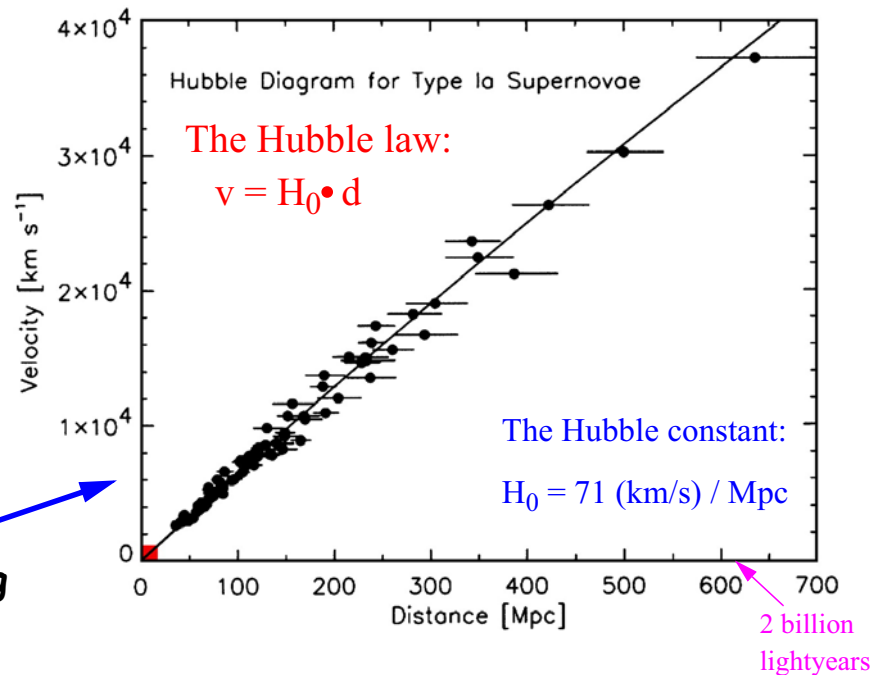


Dark matter & energy

➔ 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 supernovas are therefore increasing with their distance to earth.



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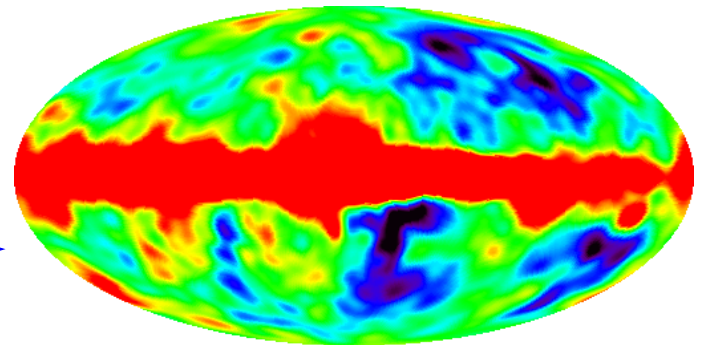
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Dark matter & energy

- 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**.

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Dark matter & energy

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

$$\rho_c = \frac{3H_0^2}{8\pi G} = O(10^{-26}) \text{ kg m}^3 \quad \text{“The critical density”}$$

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

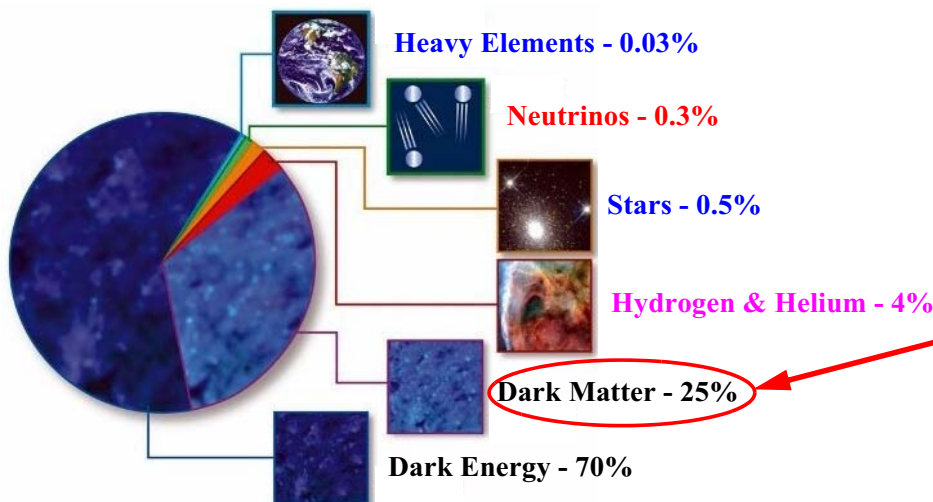
- The basic idea is that if the density in the universe is larger than the critical density, the **expansion** of the universe will eventually **end**. Otherwise it will continue for ever.
- One has also introduced something called the **relative density** (Ω) which is defined as:

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

Dark matter & energy

➔ Dark Matter

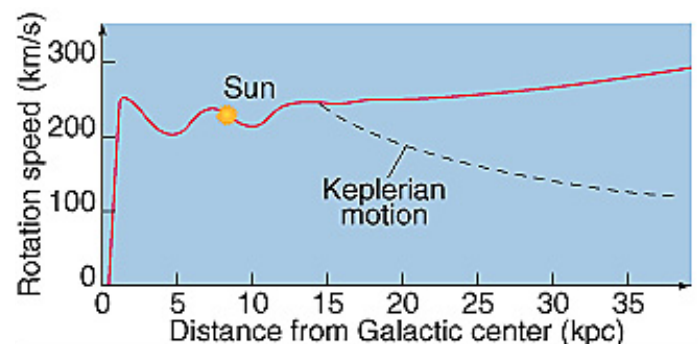
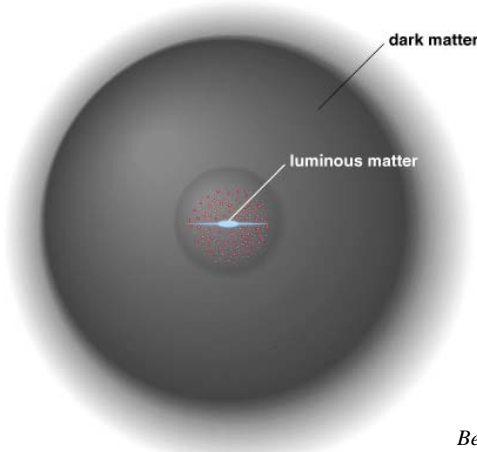
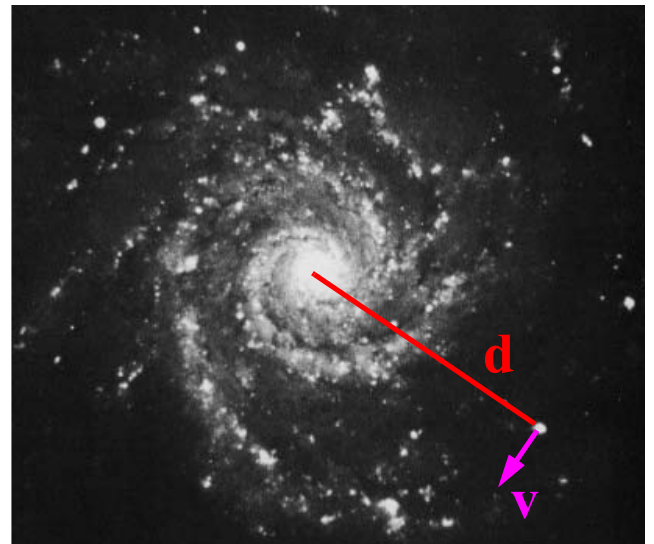
- The density of the universe is estimated in the inflationary Big Bang model to be **close to the critical energy**.
- One divide the density up into a **matter part** (Ω_M) and an **energy part** (Ω_Λ) such that $\Omega = \Omega_M + \Omega_\Lambda$.



- Most of the matter is of an unknown 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**.



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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.

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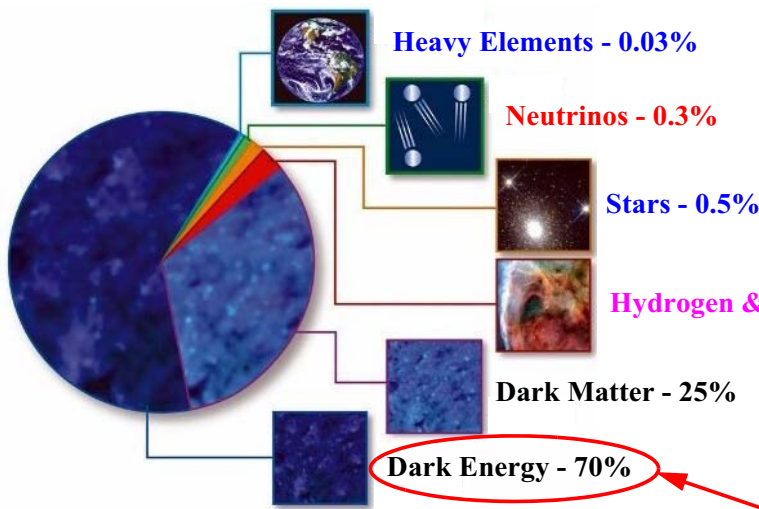
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Dark matter & energy

➔ 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**.

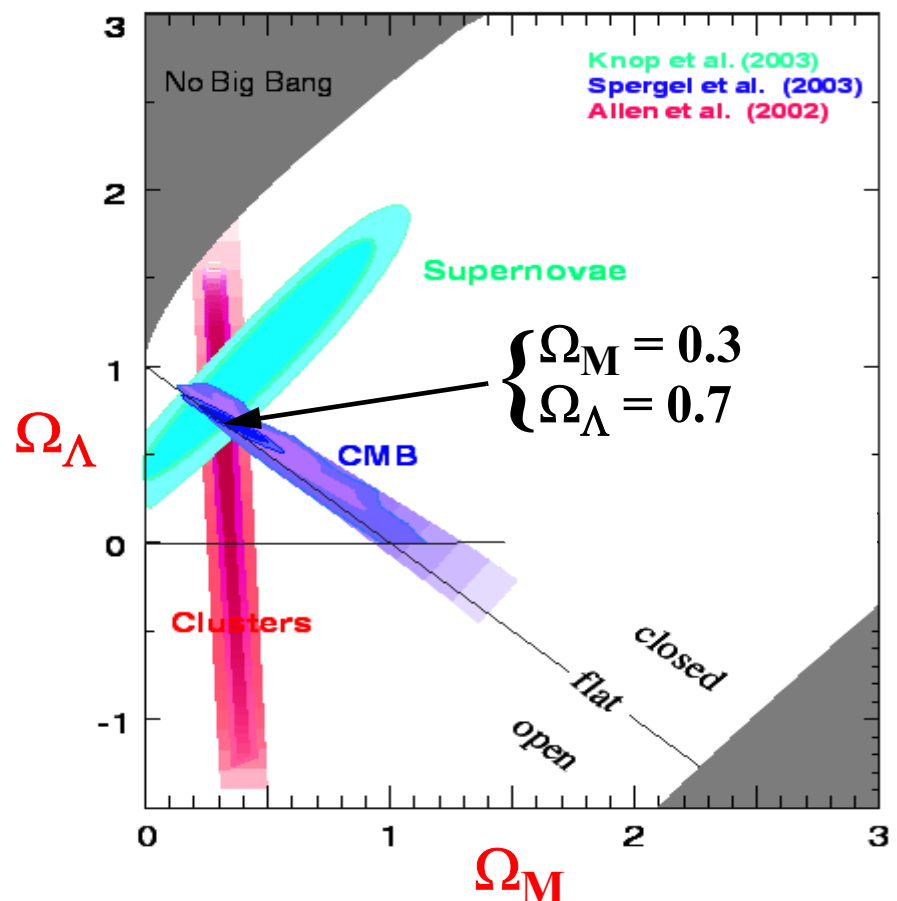
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Dark matter & energy

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



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Dark matter & energy

The two-million dollar question is:

What is causing the Dark Energy ?

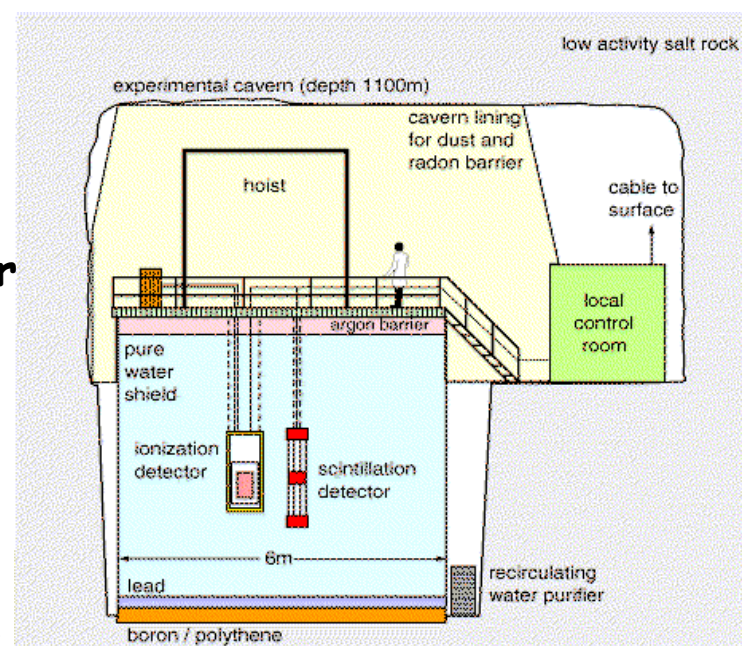
There are two main hypothesis:

- 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 it 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 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.

