Beyond the Standard Model

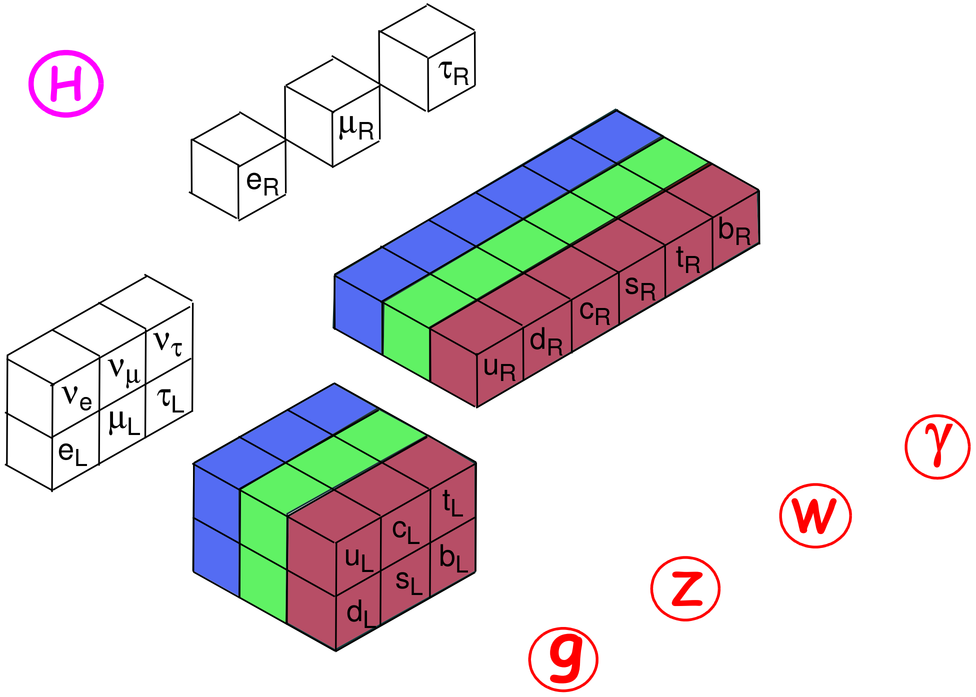
The Standard Model

➡ 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 ?

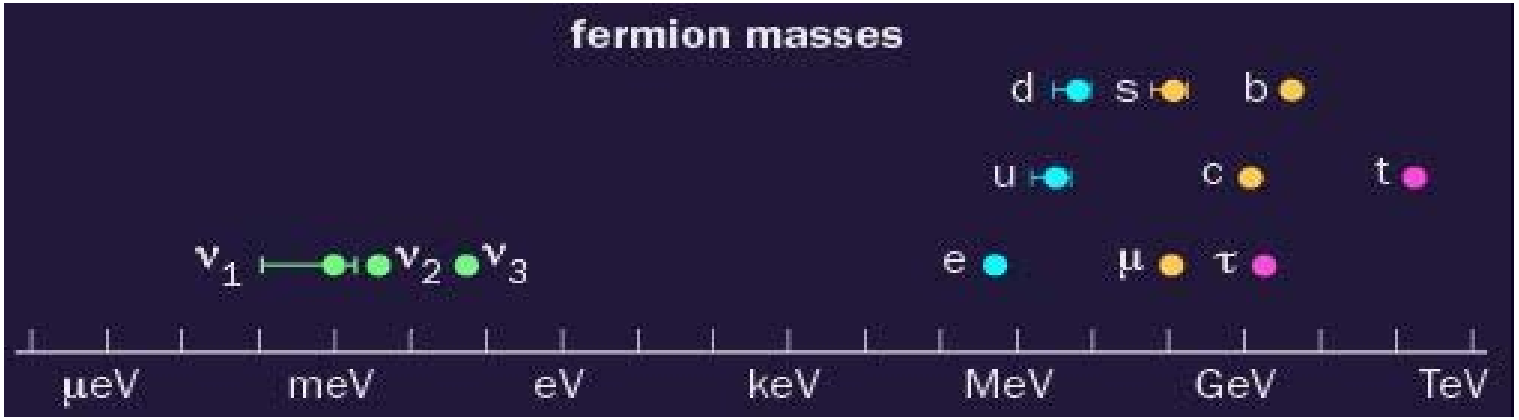
- If neutrinos have mass, are there right-handed neutrinos ?

- 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)

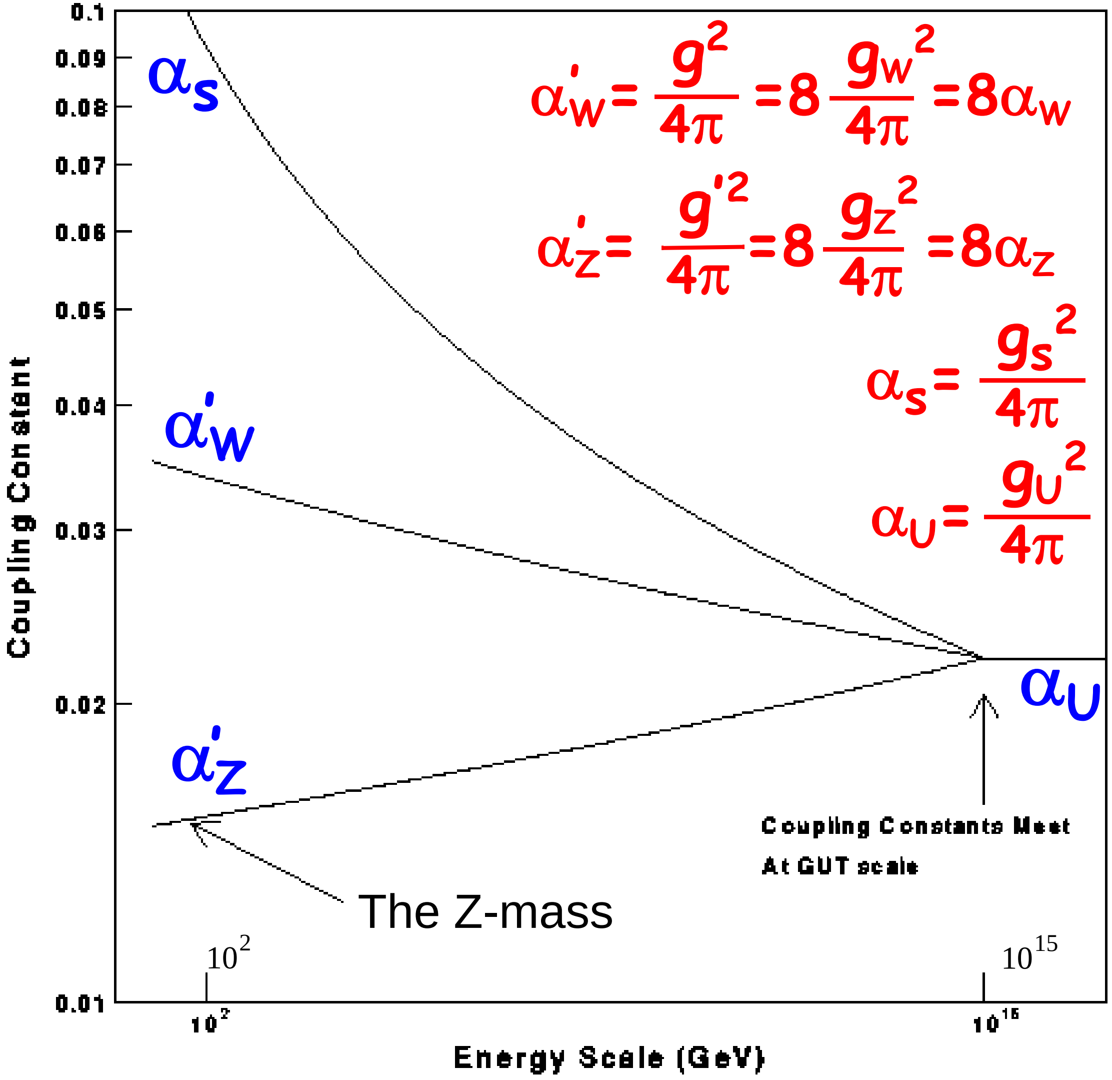
➡ The Georgi-Glashow model

- Weak and electromagnetic interactions are unified.

  ⇨ add the strong one !

- Coupling constants are not truely constant ⇨ they depend on energy (or Q^2) in the interaction.

- Unification at some very high unification mass ⇨ electroweak and strong couplings become equal.



$$\alpha'_W = \frac{g^2}{4\pi} = 8\frac{g_W^2}{4\pi} = 8\alpha_W$$

$$\alpha'_Z = \frac{g'^2}{4\pi} = 8\frac{g_Z^2}{4\pi} = 8\alpha_Z$$

$$\alpha_s = \frac{g_s^2}{4\pi}$$

$$\alpha_U = \frac{g_U^2}{4\pi}$$

Grand Unified Theories (GUTs)

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

- **Example:** The Georgi-Glashow model ⇨ combines coloured quarks and leptons in single families ⇨

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

- Two new gauge bosons are introduced ⇨

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

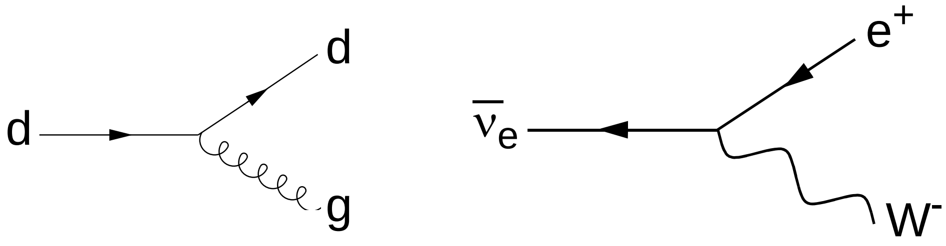
- The gauge bosons have a mass close to the unification energy ⇨ Extremly heavy: $M_X = 10^{15}$ GeV/c^2

- Single unified coupling constant (g_U): $\alpha_U \equiv \frac{g_U^2}{4\pi} \approx \frac{1}{42}$

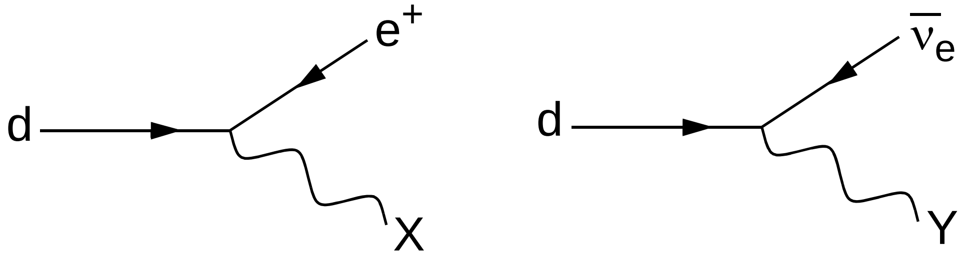
Grand Unified Theories (GUTs)

- New gauge bosons ⇨ processes possible in which **quarks are transformed into leptons** by exchanging X and Y bosons:

old processes:



new processes:



- The model **predicts** a value of α_U & relationship between g_U, g and g' ⇨ it predicts a value for the weak mixing angle:

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

Close to the measured value !

Grand Unified Theories (GUTs)

- The model predicts 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.

- If the d-quark do not have the charge -e/3 the model do not work.

- Baryon and lepton numbers are not necessarily conserved in GUT.

⇒

GUT can explain why the world is dominated by baryons even if the same amount of baryons and anti-baryons were produced in the Big Bang.

Proton decay experiments

- **Grand Unified Theories ⇒ The proton must be unstable !** **It decays 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:**

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

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: $p \to \pi^0 + e^+ \to \gamma\gamma + e^+$
The experiments looks for one positron + two electron-positron pairs from photon conversions.

- No proton decays have been observed ⇨ upper limit:

$$\frac{\text{proton lifetime}}{\text{branching ratio}} = \frac{\tau_p}{B(p \to \pi^0 e)} > 5\times 10^{32}\, years$$

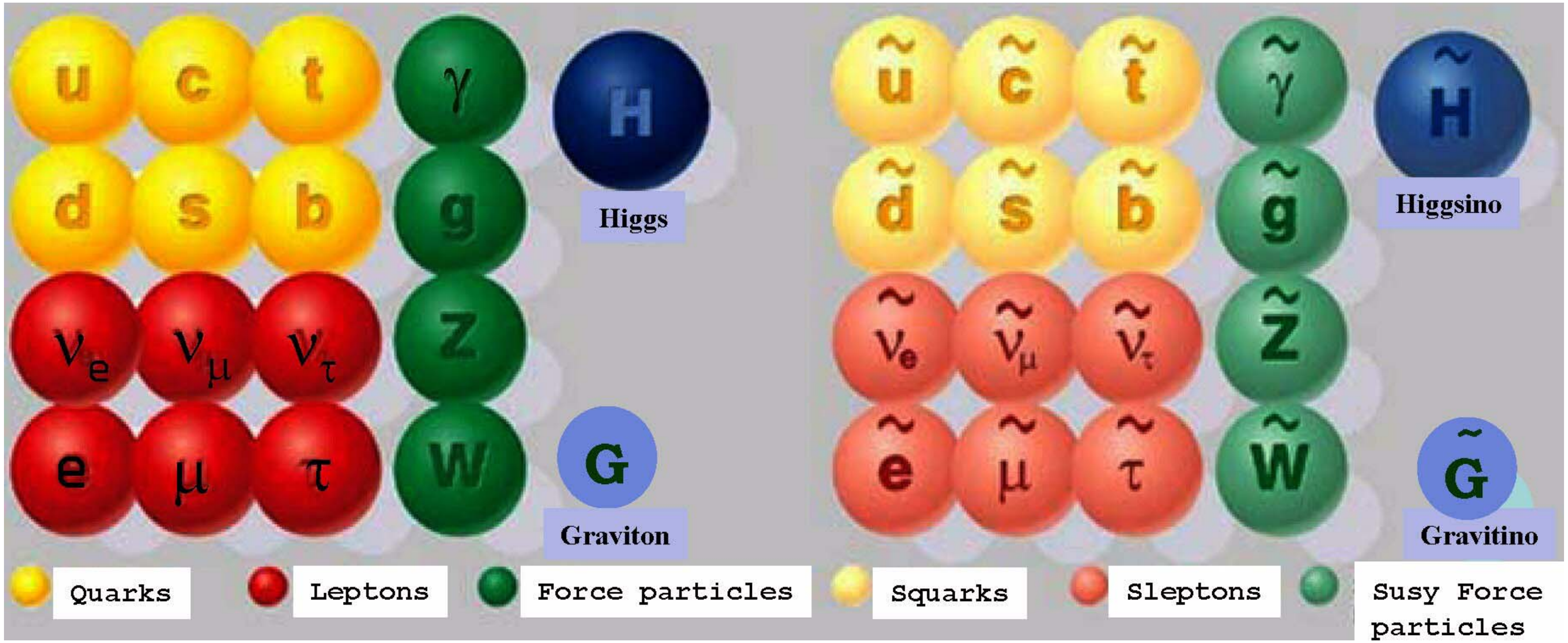
- The Georgi-Glashow model predicts:

$$\frac{\text{proton lifetime}}{\text{branching ratio}} = 0.003\text{-}0.030 \times 10^{32} \text{ years}$$

Supersymmetry

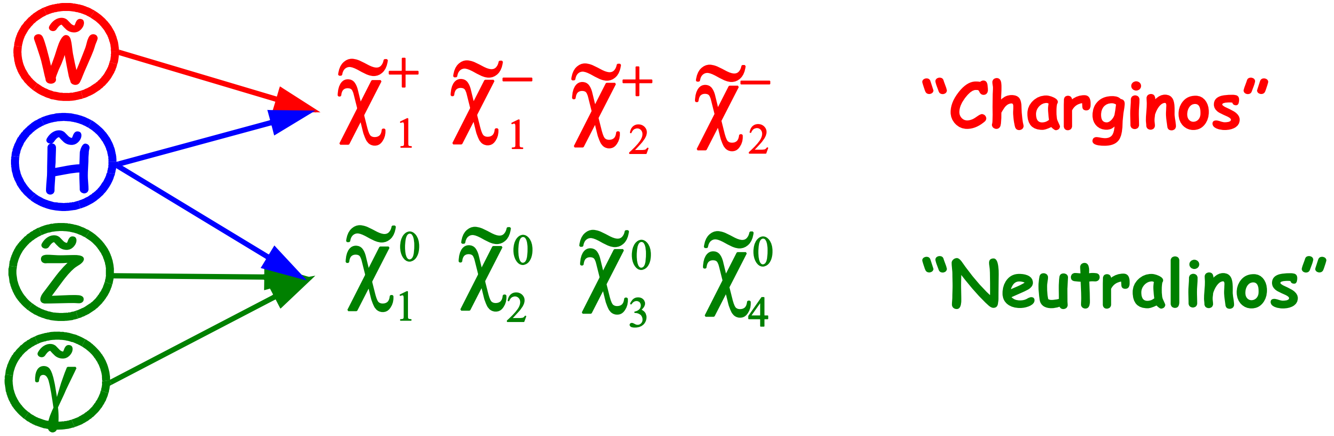
- Supersymmetry (SUSY) ⇨ a GUT in which interactions are symmetric under the transformation of a fermion to a boson.
- Every known elementary particle have a super-symmetric partner (superpartner) with different spin.

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: $\tilde{e}$ $\tilde{W}$ $\tilde{\gamma}$
- New particles must be heavier than the known particles ⇨ otherwise they would already have been discovered.
- The Lightest Supersymmetric Particle (LSP) is stable (in most SUSY models).
- New states are predicted due to mixing between some of the super partner states:



$\tilde{\chi}_1^+$ $\tilde{\chi}_1^-$ $\tilde{\chi}_2^+$ $\tilde{\chi}_2^-$ "Charginos"

$\tilde{\chi}_1^0$ $\tilde{\chi}_2^0$ $\tilde{\chi}_3^0$ $\tilde{\chi}_4^0$ "Neutralinos"

Supersymmetry

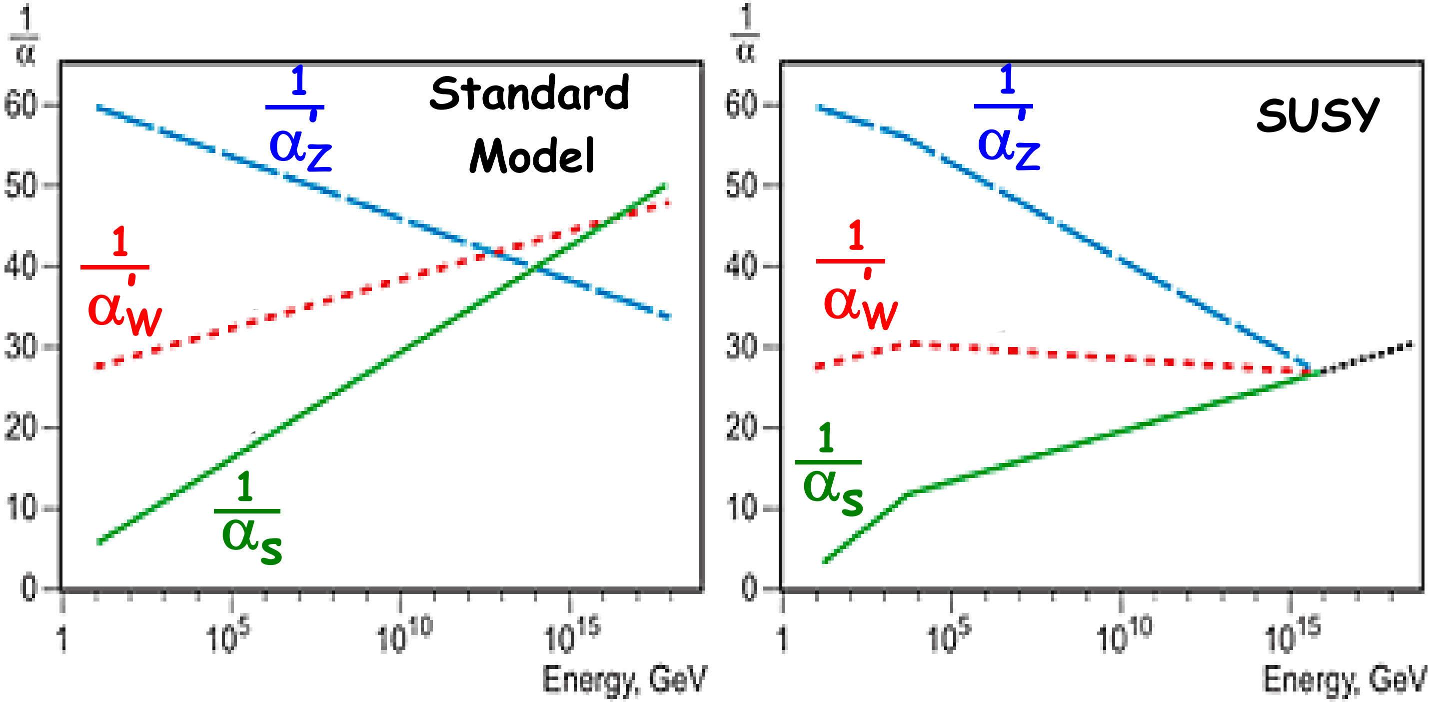
- There are many different supersymmetric models:

	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

- SUSY ⇨ shift the grand unification energy to higher values.
  ⇨ the prediction for the lifetime of the proton increases.

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



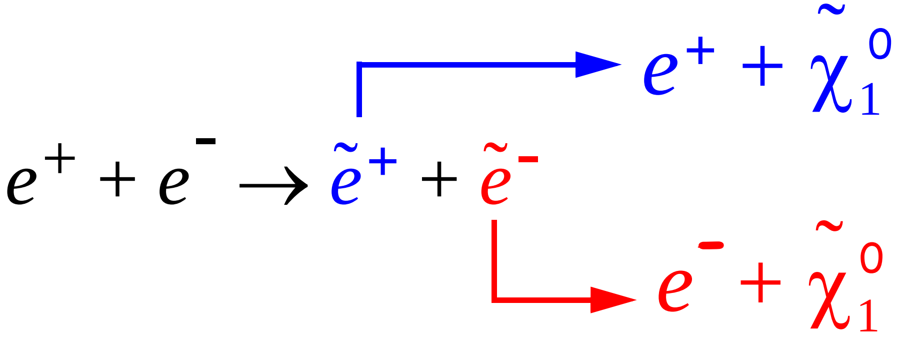
- SUSY predicts a value for the weak mixing angle which is closer to the experimental results than the Georgi-Glashow model.

- Some SUSY models unify ALL forces including gravity at the Planck mass of 10^{19} GeV by replacing particles with superstrings.

Supersymmetry

➡ SUSY search in the DELPHI experiment

- **SUSY at LEP ⇨ Example: selectron production ⇨ decay to electrons and neutralinos:**



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

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

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

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 undetectable.**

Supersymmetry

- Signature ⇨ events with only an electron and a positron.

- Selection:
  i) the e^+ and e^- should carry only half of the collision energy
  ii) the e^+ and e^- are not emitted in the opposite directions

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

- The results ⇨ set lower limits on the mass of the neutralino.

- SUSY has many models, each with different sets of unknown parameters ⇨ the results are given for different assumptions on models and parameters.

Supersymmetry

- The slepton searches were combined with other SUSY searches to set limits on the neutralino mass.

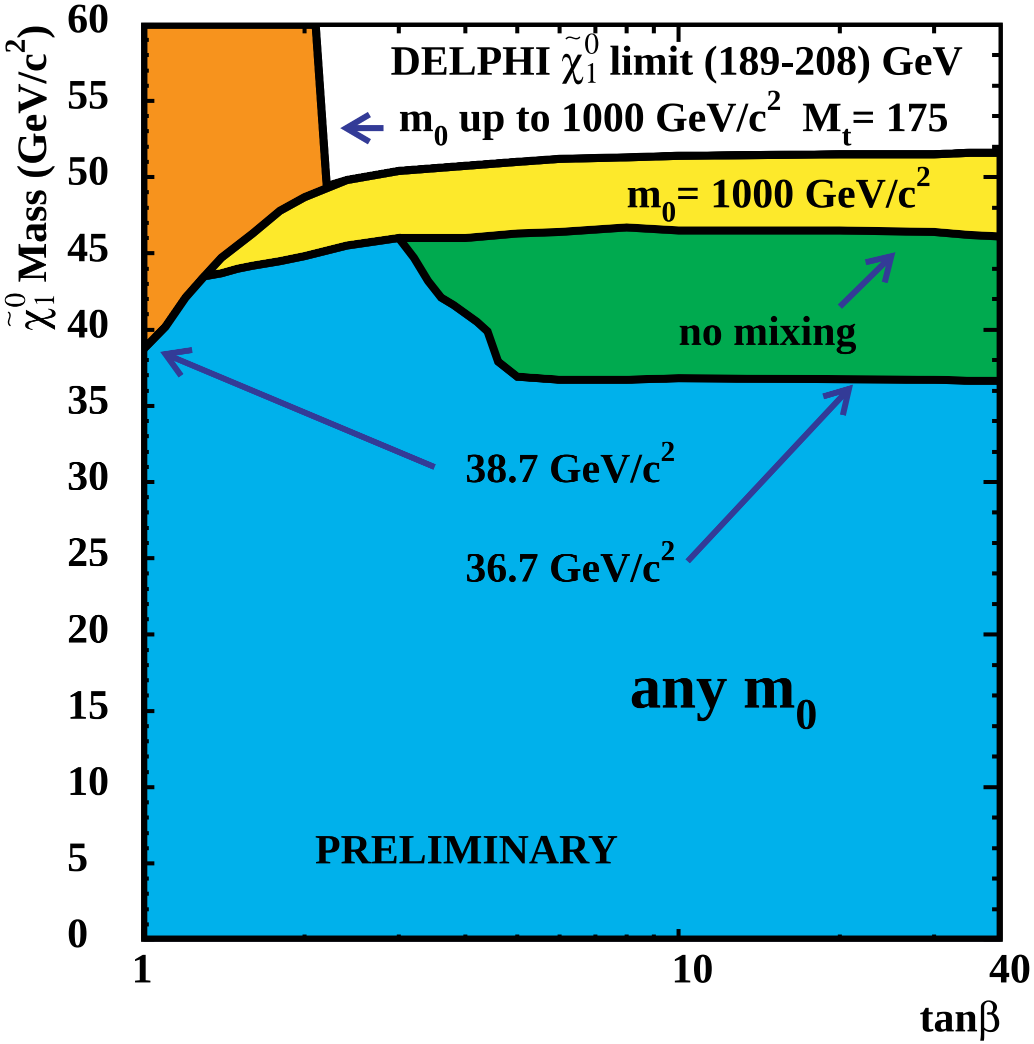
- All the coloured areas are excluded by the searches.

- The tan(β) parameter is related to the SUSY Higgs particles and m_0 to the sfermions mass.

- Result:

$$\tilde{\chi}^0_1 > 36.7\ \text{GeV}$$

for all parameter values.

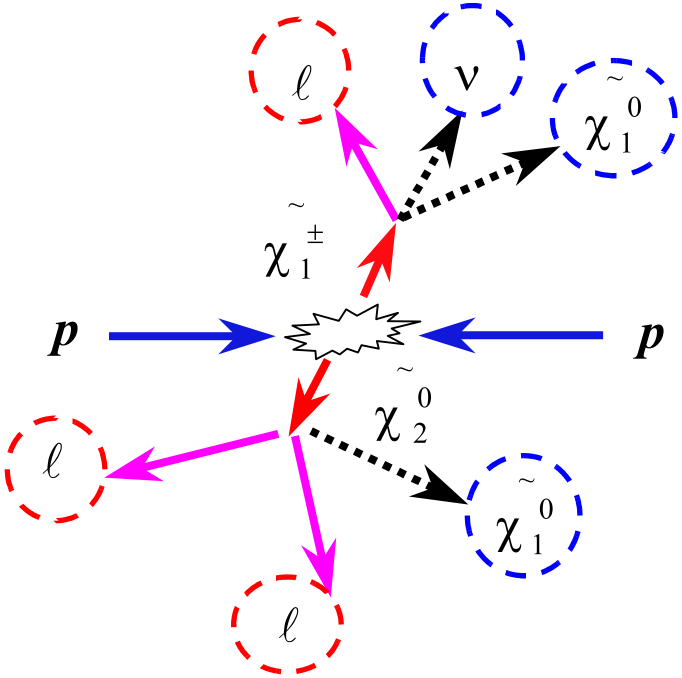


Supersymmetry

➡ 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.

- **Promising channel:** the production of a chargino and a neutralino ⇨ that decays to leptons and the lightest neutralino.



- **Signature: three leptons (electrons and muons)** and **missing energy**.

- **Selection:** P_T>10 GeV for the lepton & Missing energy > 30 GeV.

- **Background: ZW** and **$t\bar{t}$** production.

Gravitation and extra dimensions

- The gravitational force is much weaker than the electromagnetic and strong interactions ⇨ not studied in particle physics.

- Postulated the existance of graviational force carriers ⇨

  Gravitons (G).

- Graviation has only been studied at large distances (>1 mm)

  ⇨ it could be stronger at shorter distances.

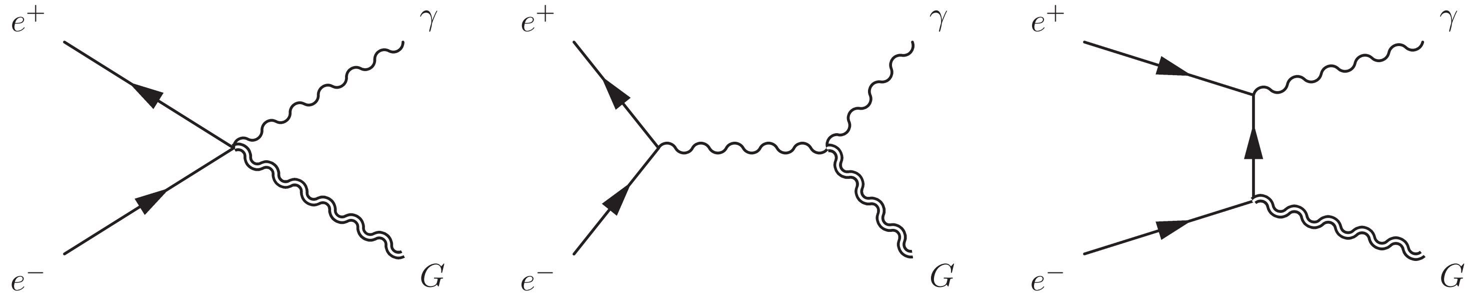
- Theories have been proposed in which gravity is unified with other interactions by introducing new dimensions of space in which only gravity can propagate (in addition to the normal 3 space + 1 time dimensions).

Gravitation and extra dimensions

➡ Graviton search in the DELPHI experiment

- At the energy scale where gravity is unified with other forces ⇨ gravitons are produced in the events that escape undetected into the extra dimensions.

- Prediction: e^+e^- colliders with sufficient energy ⇨ events with one graviton and one photon:

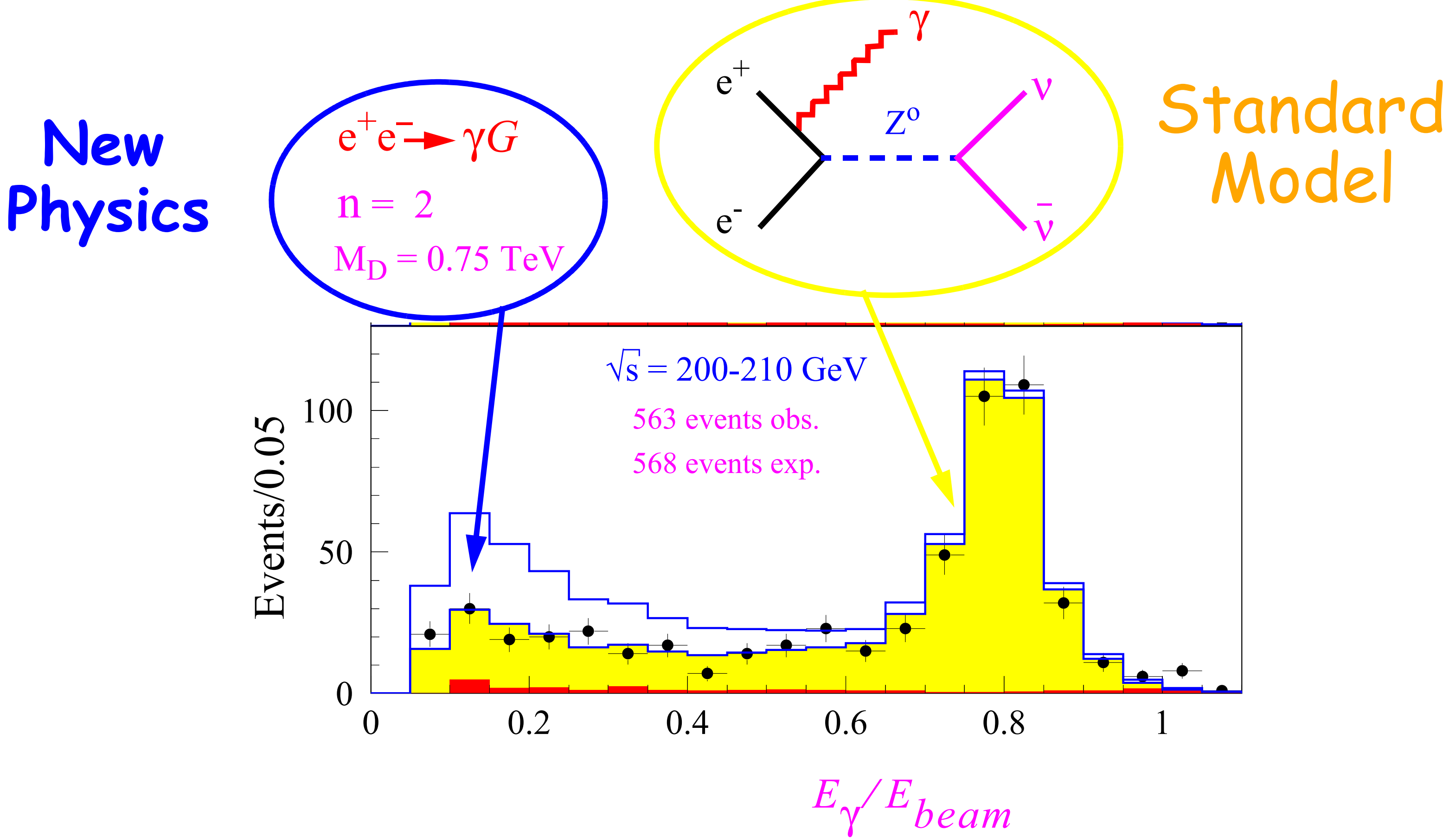


- Gravitons cannot be detected ⇨ only one photon in the experiment.

Gravitation and extra dimensions

- **Selections: Events with only one photon and nothing else.**
  Measurement: The energy of the photon

Standard Model]:



- **Conclusion: No sign of graviton production in the data !**

Gravitation and extra dimensions

- **The measurement ⇨ set limits on the parameters in the theory**
- **Parameters:**

  i) n - the number of extra dimensions

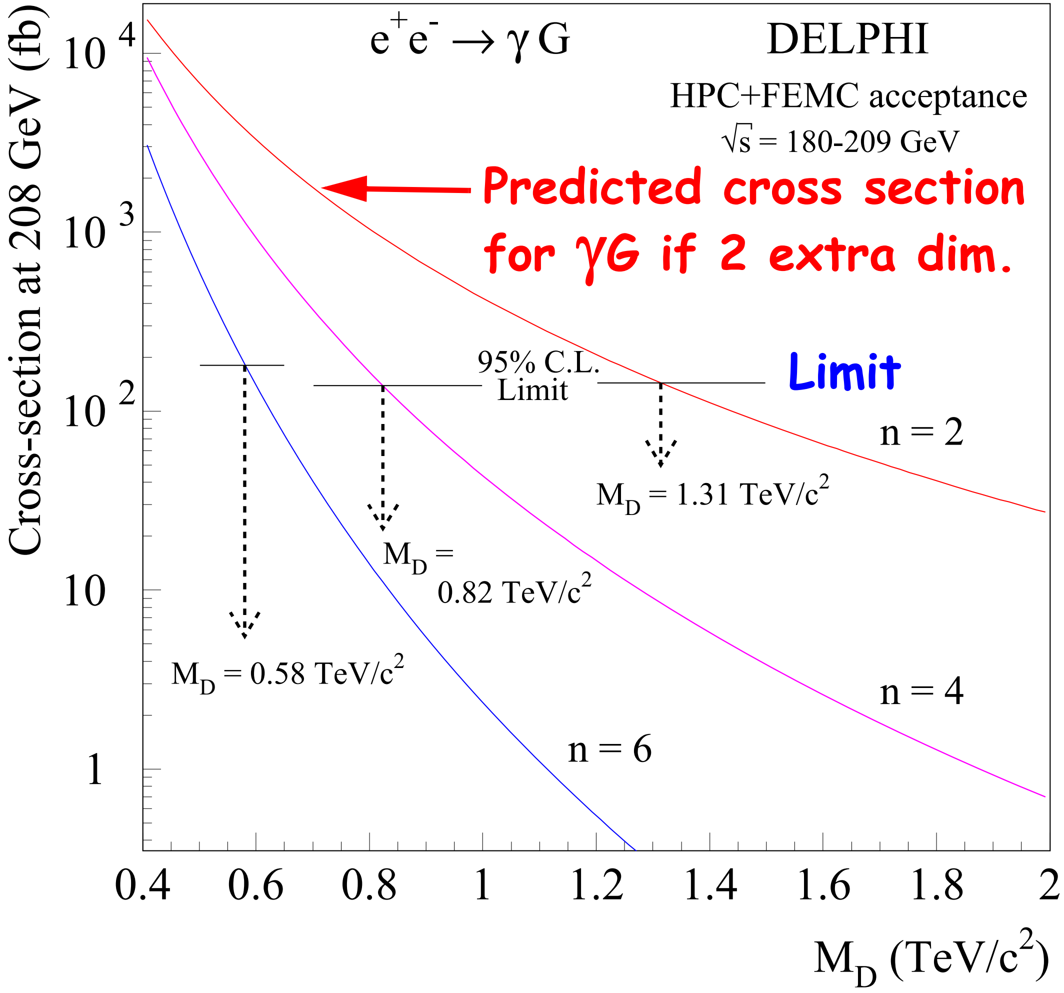
  ii) M_D - a fundamental mass scale.

- **Limits:**

  The data would set limits on the cross section

  ⇨

  limits on M_D and n in the theory



Predicted cross section for γG if 2 extra dim.

Limit

Dark matter & energy

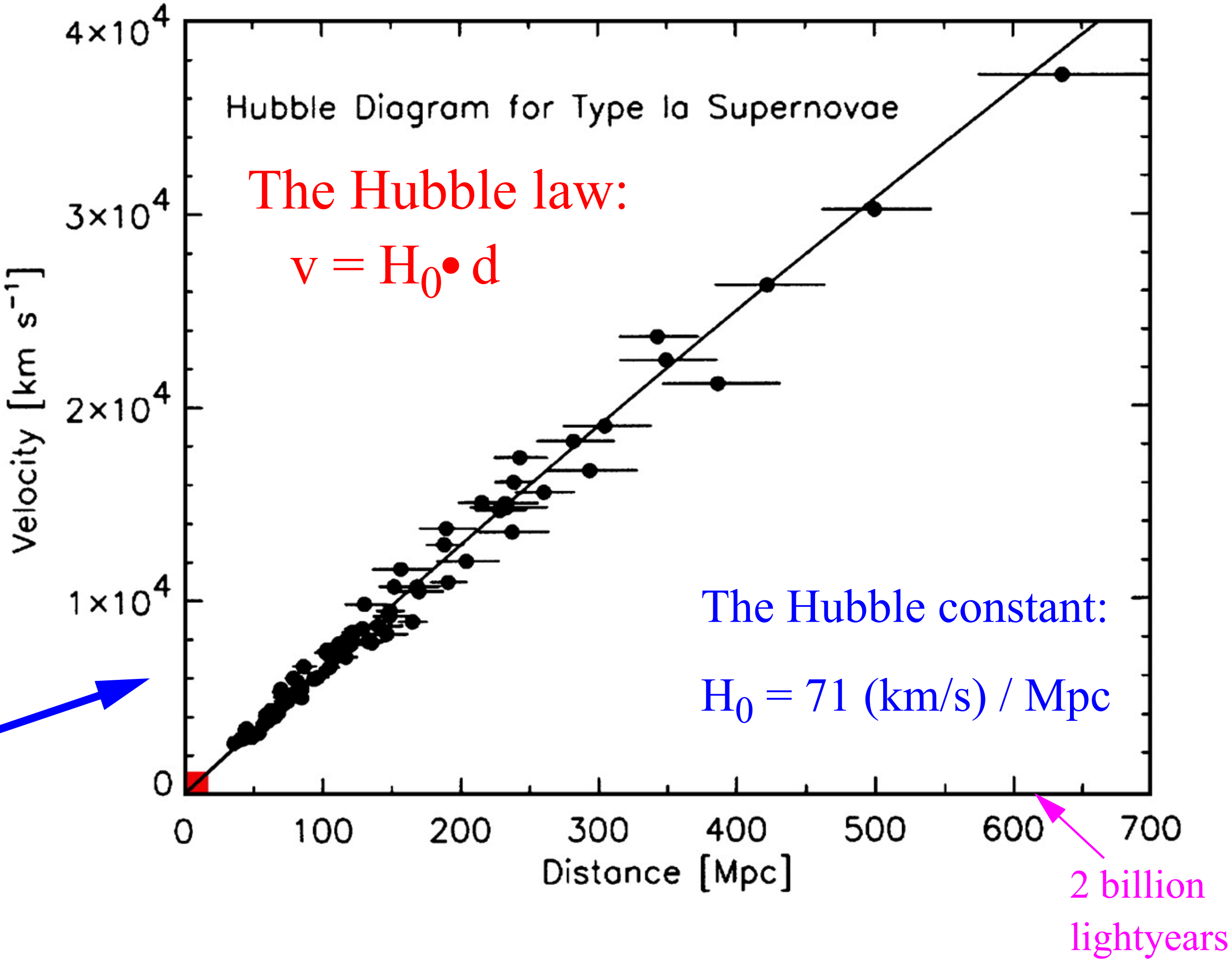
➡ The Big Bang Model

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

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.



The Hubble law:

$v = H_0 \bullet d$

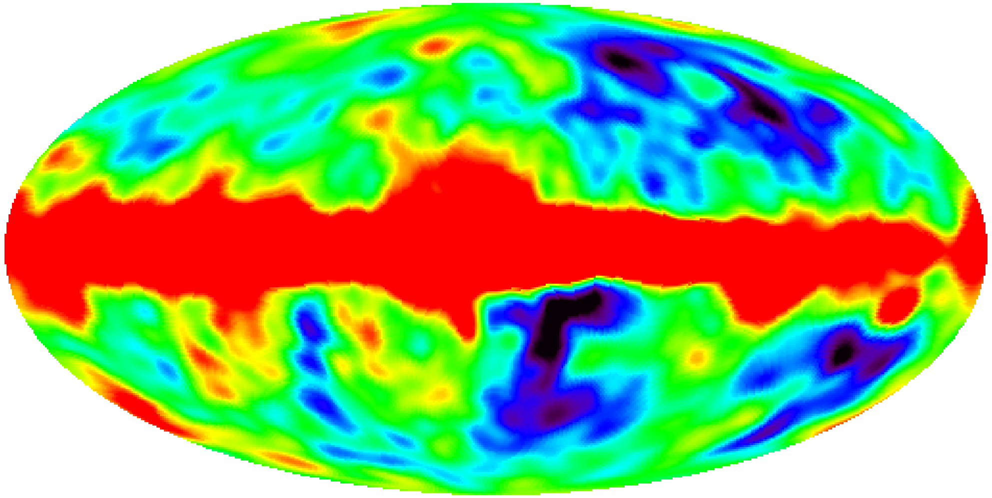
The Hubble constant:

$H_0 = 71$ (km/s) / Mpc

Dark matter & energy

4) The cosmic background radiation with a temperature of 2.7 K (0.0002 eV) ⇨ 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

- **The critical density:** $$\rho_c = \frac{3H_0^2}{8\pi G} = O(10^{-26})\ \mathrm{kg\ m}^3$$

where H_0 is the Hubble constant

G is the gravitational constant

- 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).

- **The relative density:** $$\Omega \equiv \rho/\rho_c = \Omega_M + \Omega_\Lambda$$

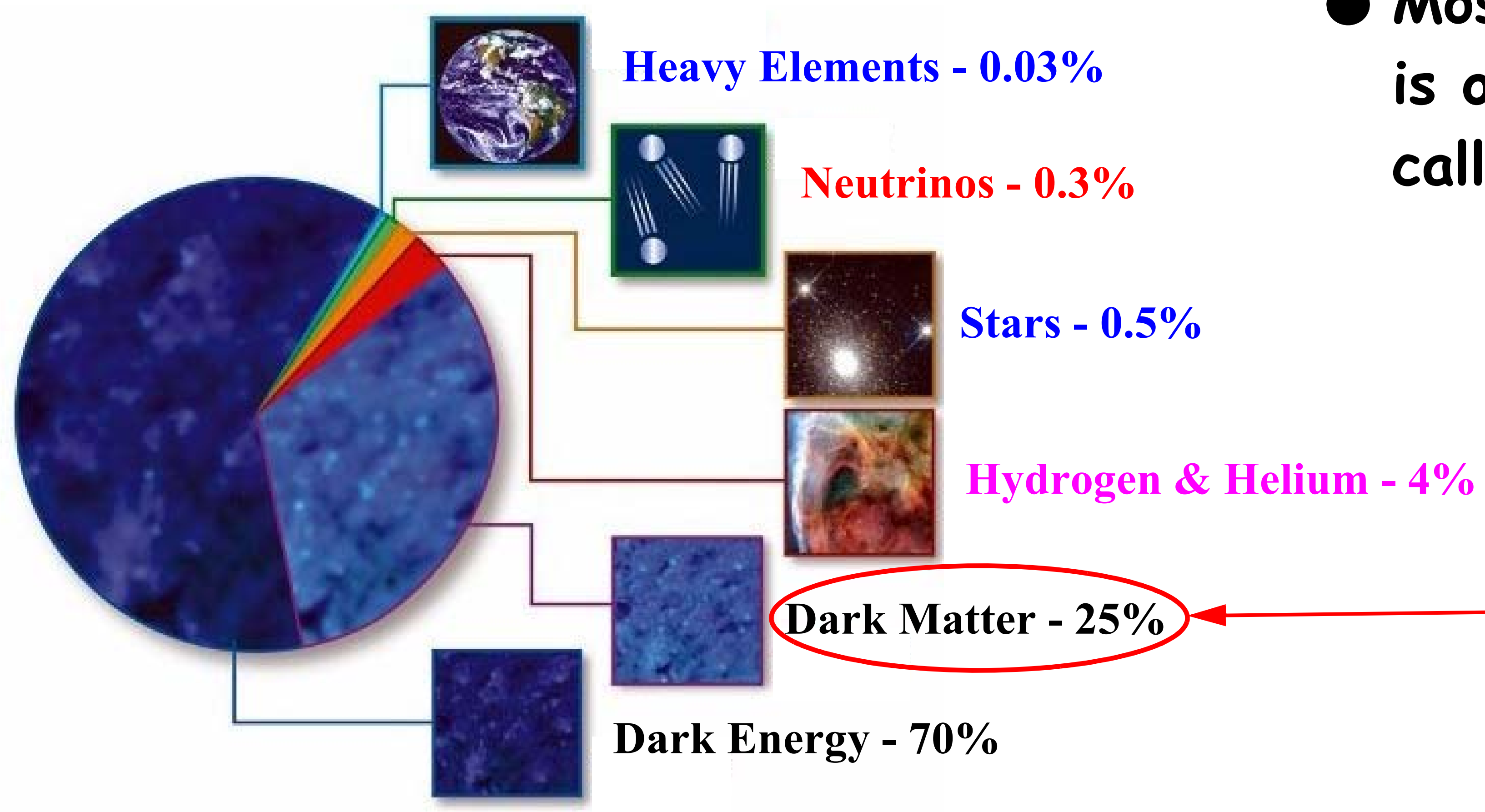
Matter part Energy part

Dark matter & energy

➡ Dark Matter

- The inflationary Big Bang model ⇨ the density is close to the critical density.

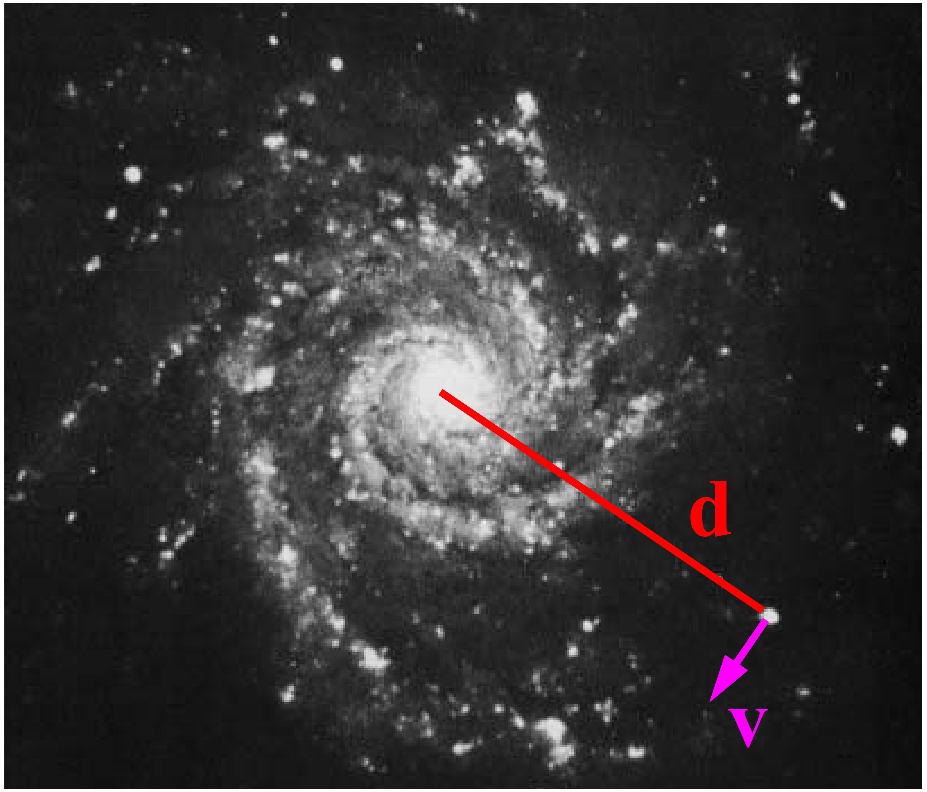
- Most of the matter is of an unkown type called "Dark Matter"

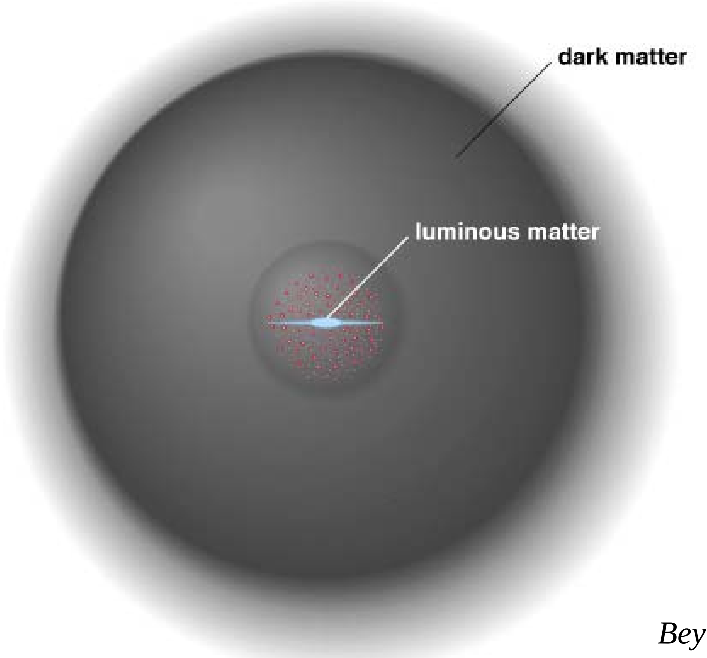


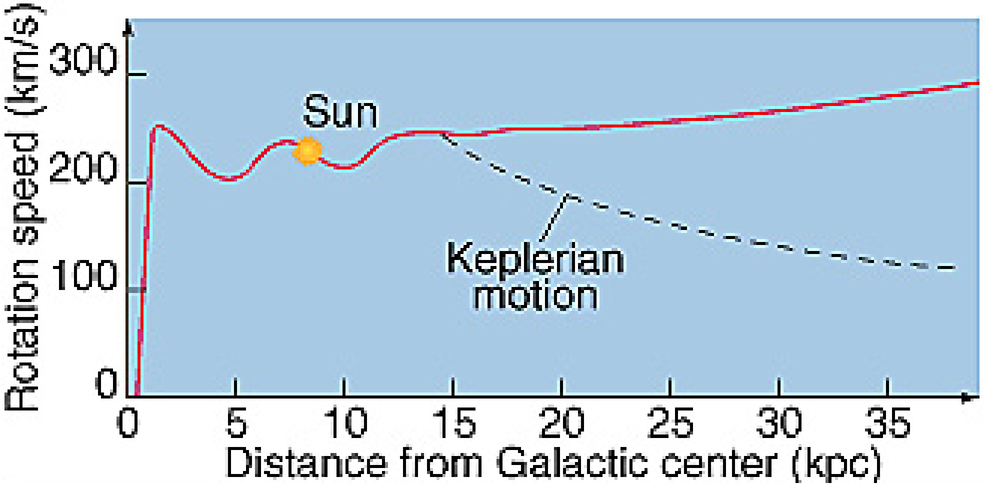
Dark matter & energy

- The evidence for dark matter ⇨ 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).

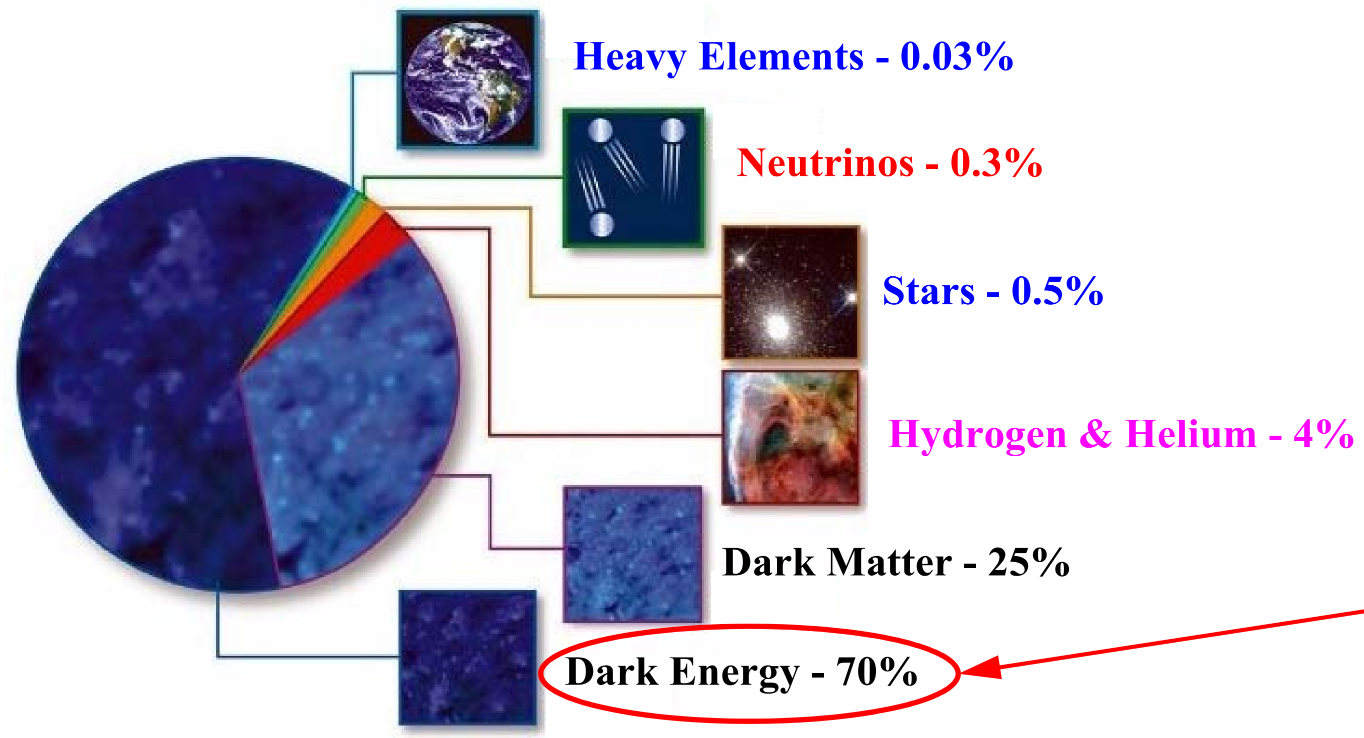
  2) Hot dark matter: If neutrinos have a mass > 1 eV they would give a significant contribution to the density of the universe. But it is difficult to explain how the galaxies are formed if neutrinos make up the dark matter.

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

Dark matter & energy

➡ Dark Energy

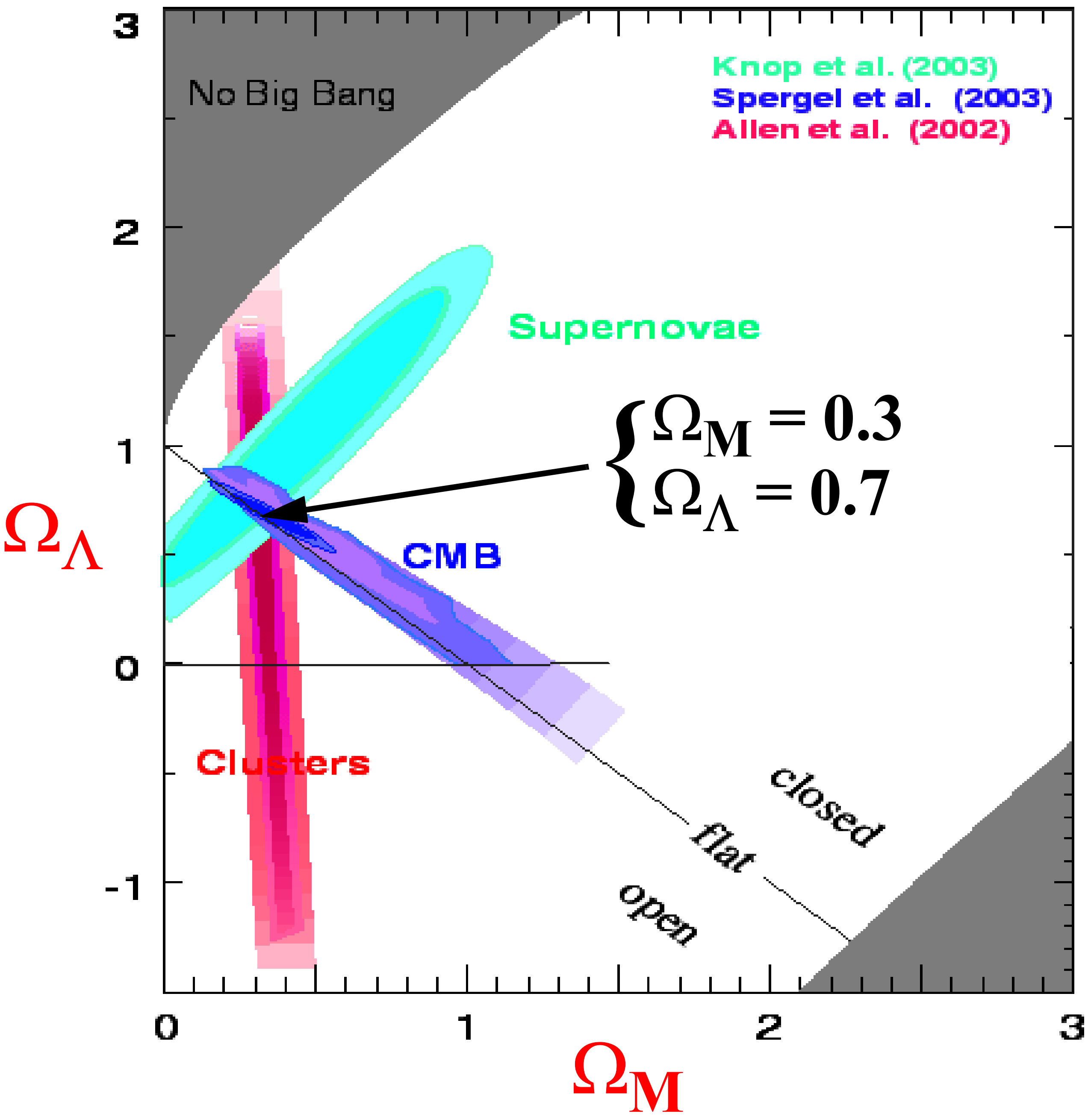
- The brightness (magnitude) of remote supernovas and their redshifts ⇨ the expansion of the universe is not constant but accelerating ⇨ the universe is full of dark energy.



- Dark Matter: gravitationally attractive force
- Dark Energy: gravitationally repulsive force

Dark matter & energy

- Other evidence for dark energy ⇨ studies of the Cosmic Microwave Background (CMB) & the motion of clusters in galaxies.



$$\begin{cases}\Omega_M = 0.3\\ \Omega_\Lambda = 0.7\end{cases}$$

Dark matter & energy

The two-million dollar question is:

What is causing the Dark Energy ?

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.

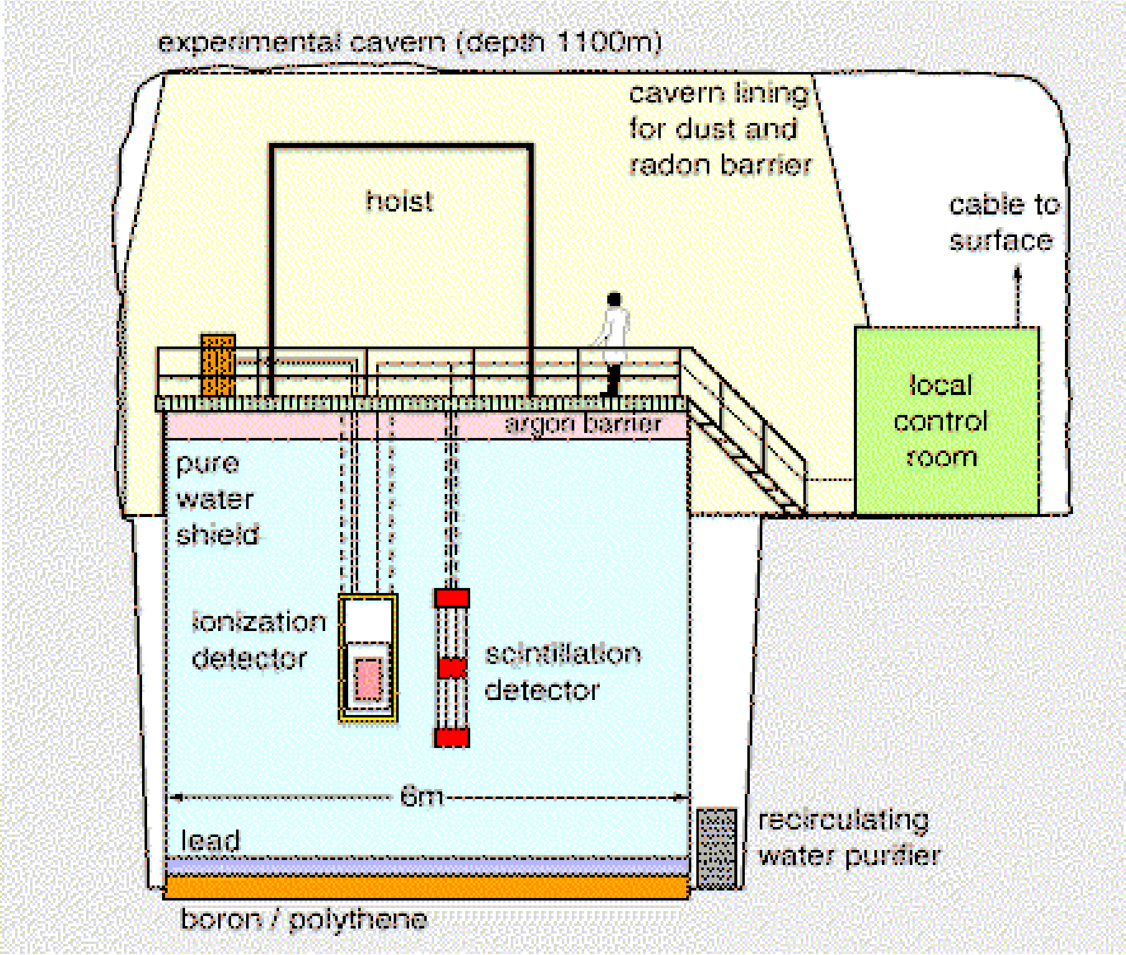
2) Quintessence: Particle-like excitations in a new dynamical field called quintessence. This field differs from the Cosmological constant in that it can vary in space and time.

Dark matter & energy

➡ Direct search for WIMPs

- Interactions between **WIMPs** and matter has to be very **rare**.
  ⇨ about one WIMP interacting in a kg of matter every day.

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



- The **Boulby experiment:** **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

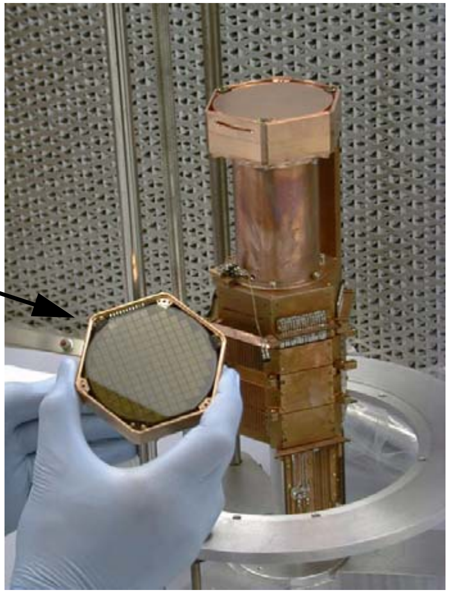
At a Mine's Bottom, Hints of Dark Matter

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.

- **CDMSII: Ge detectors at the Soudan underground laboratory to look for WIMPs.**

- **Interactions between WIMPs and the Ge atoms ⇨ phonons and ionization ⇨ detected by sensors on the semiconductors.**



- **Two candidate events with 0.9 expected from background.**