

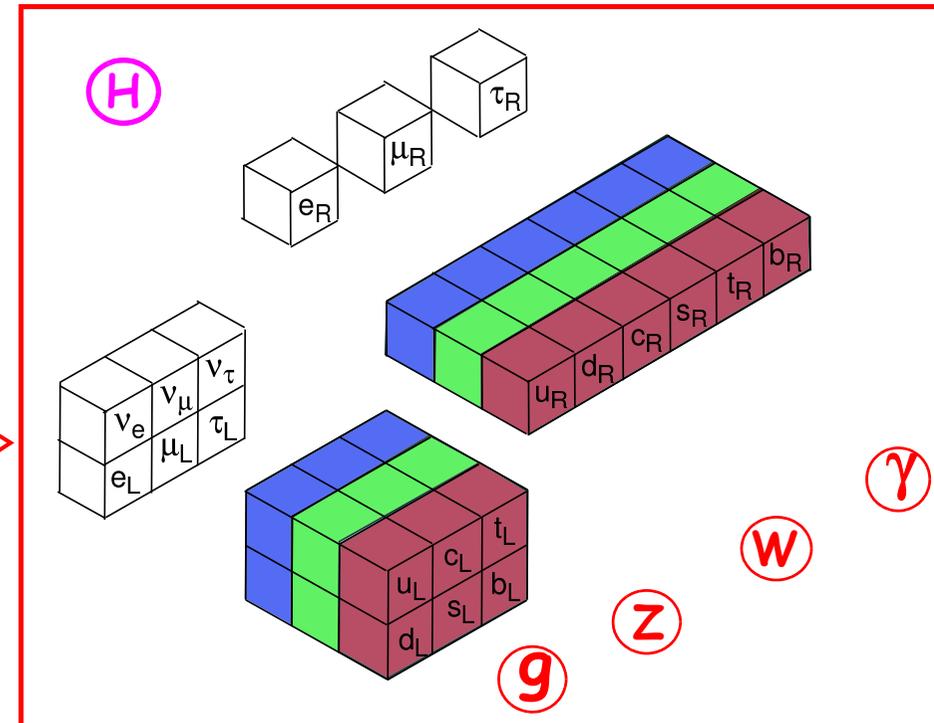


Beyond the Standard Model

The Standard Model

➔ What is the standard model ?

- The standard model ➔ the **electromagnetic, strong and weak interactions** ➔ based on the principle of **gauge invariance**.
- **Lots of free parameters:** quark and neutrino mixing parameters, lepton and quark masses, coupling constants, W , Z and H masses...
- **Basic fermions and gauge bosons** ➔



The Standard Model

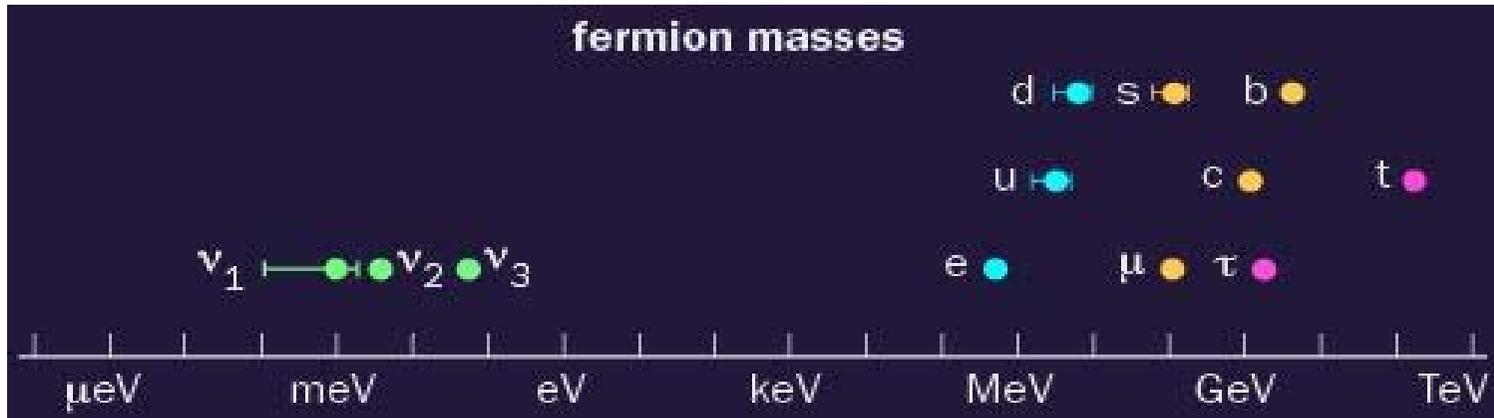
- The Standard Model **agrees** very well with all **experimental data**.
- The model has been tested down to 10^{-18} m.
- It has been tested to a **precision** better than 0.1% .

➔ Problems with the standard model:

- 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)

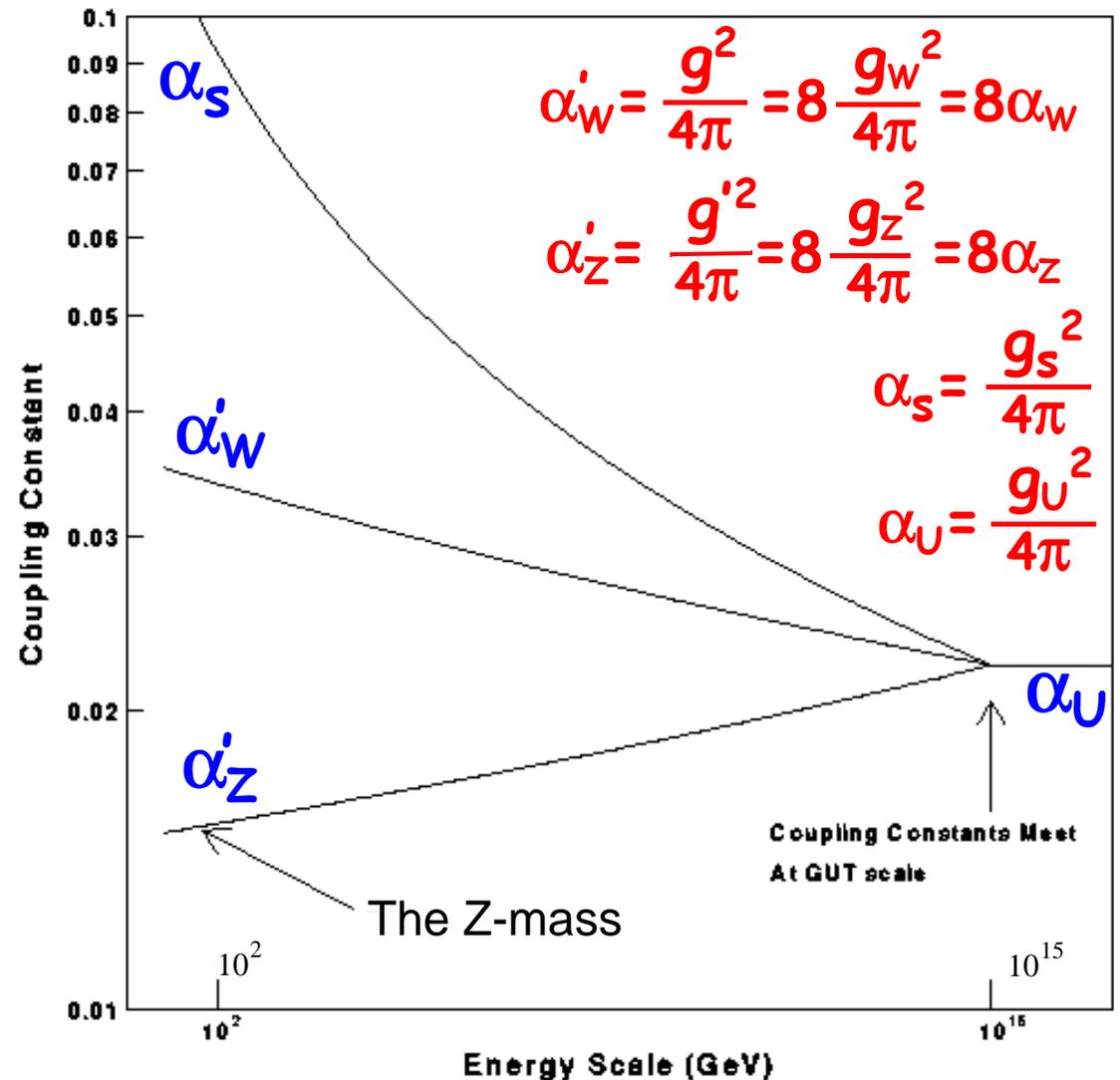
➔ The Georgi-Glashow model

- Weak and electromagnetic interactions are unified.

➔ add the strong one !

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

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



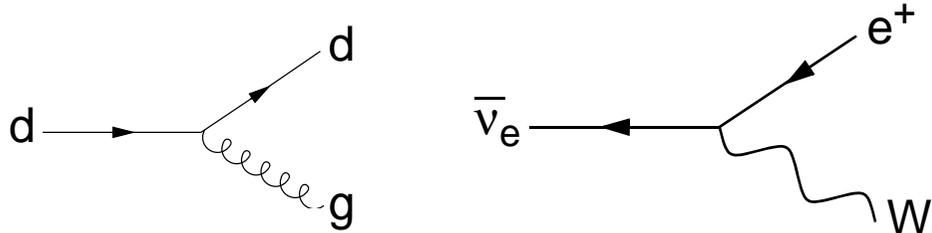
Grand Unified Theories (GUTs)

- Grand unified theories \Rightarrow constructed in **many different ways**.
- **Example:** The **Georgi-Glashow model** \Rightarrow combines coloured quarks and leptons in single families \Rightarrow
 $(d_r, d_g, d_b, e^+, \bar{\nu}_e)$
- **Two new gauge bosons** are introduced \Rightarrow
X with $Q = -4/3$ and **Y** with $Q = -1/3$
- The gauge bosons have a mass close to the unification energy
 \Rightarrow Extremely heavy: $M_X = 10^{15} \text{ GeV}/c^2$
- **Single unified coupling constant (g_U):** $\alpha_U \equiv \frac{g_U^2}{4\pi} \approx \frac{1}{42}$

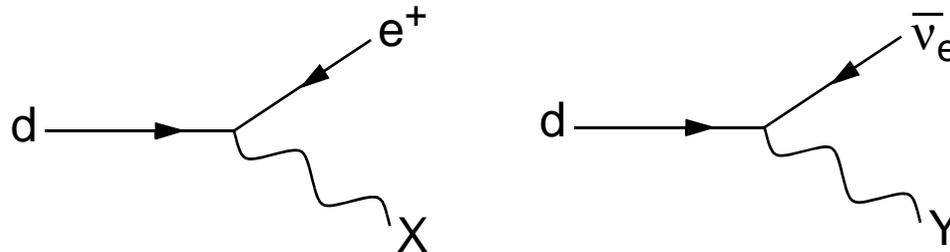
Grand Unified Theories (GUTs)

- New gauge bosons \Rightarrow 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' \Rightarrow it predicts a value for the weak mixing angle:

$$\sin^2 \theta_W = 0.21$$

Close to the measured value !

Grand Unified Theories (GUTs)

- Prediction \Rightarrow the sum of the charges is zero within a family

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

The number of colours

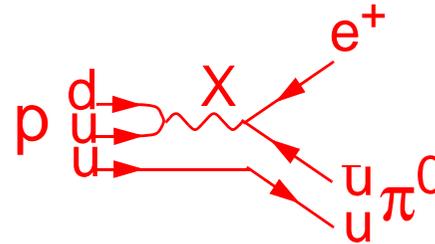
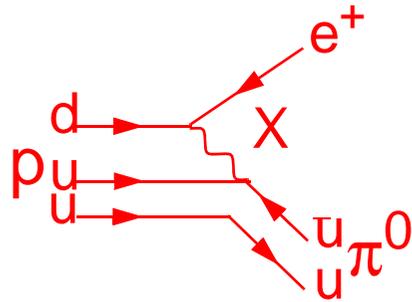
$$3Q_d + e = 0$$

- Since d-quark have the charge $-e/3$ the model works !
- **Baryon and lepton numbers** are **not** necessarily **conserved** in GUT.
- Non-conservation \Rightarrow 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 \Rightarrow 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:

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

- 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** $\Rightarrow p \rightarrow \pi^0 + e^+ \rightarrow \gamma\gamma + e^+$
Look for one positron + two electron-positron pairs (from photon conversions).
- No proton decays have been observed \Rightarrow upper limit:

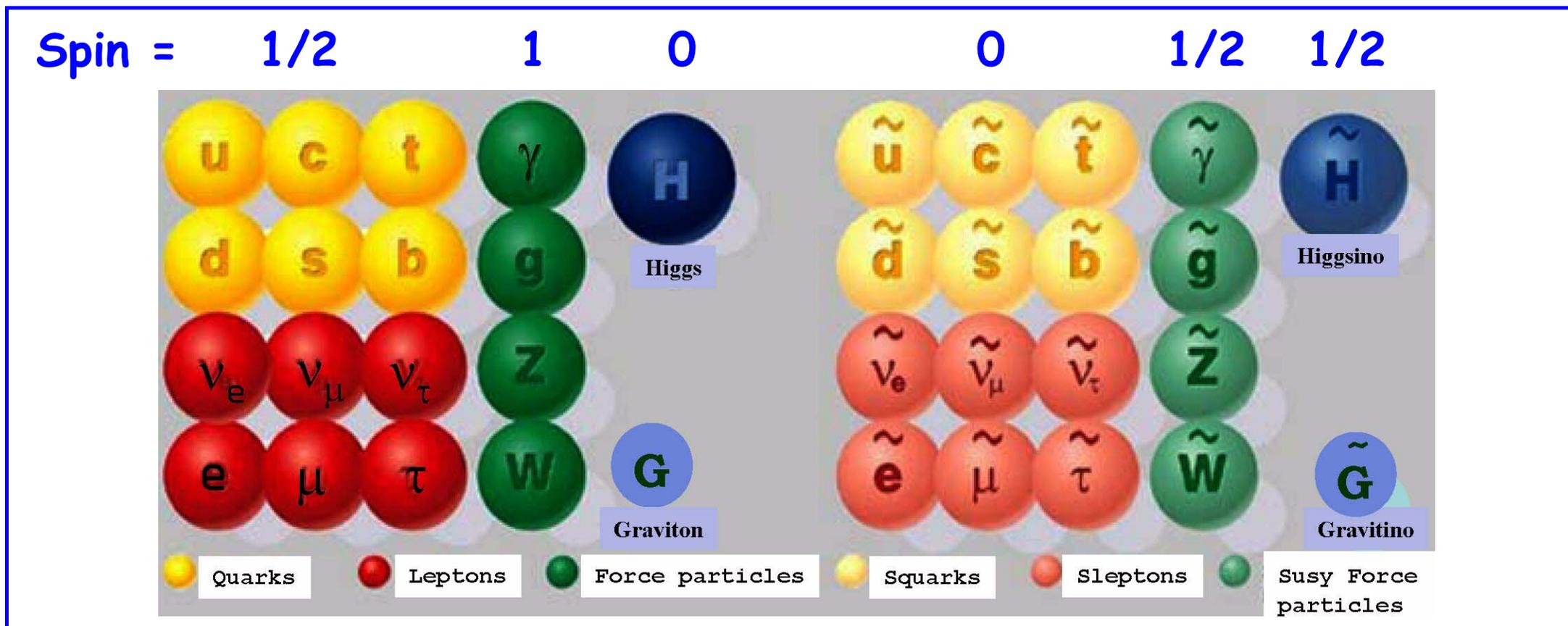
$$\frac{\text{proton lifetime}}{\text{branching ratio}} = \frac{\tau_p}{B(p \rightarrow \pi^0 e)} > 5 \times 10^{32} \text{ years}$$

- The **Georgi-Glashow model** predicts:

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

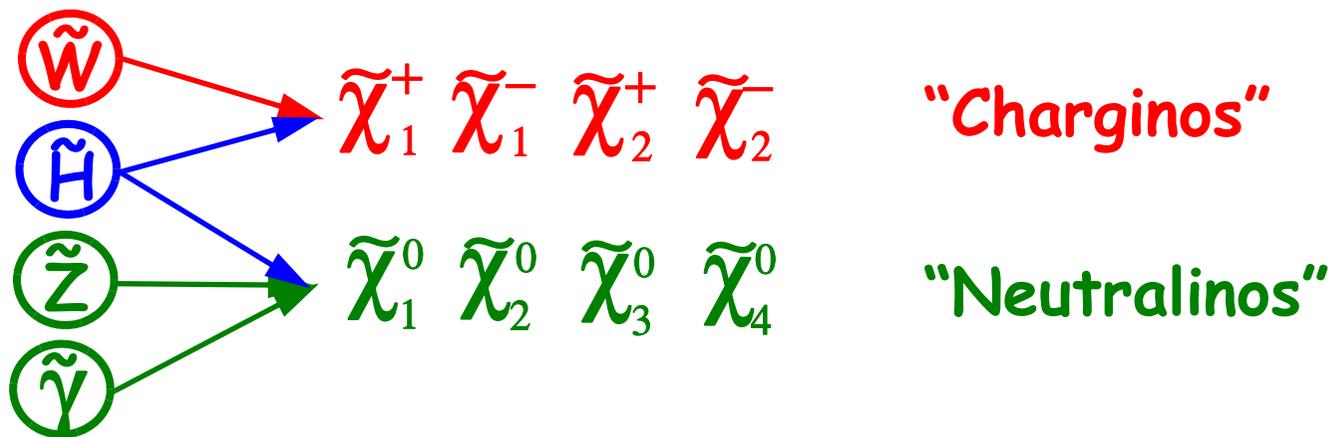
Supersymmetry

- **Supersymmetry (SUSY)** \Rightarrow 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**.



Supersymmetry

- The new particles are called **squarks, sleptons, photinos, gluinos, winos, zinos** a tilde is used to denote these particle: \tilde{e} \tilde{W} $\tilde{\gamma}$
- New particles must be **heavier** than the known particles \Rightarrow 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:



Supersymmetry

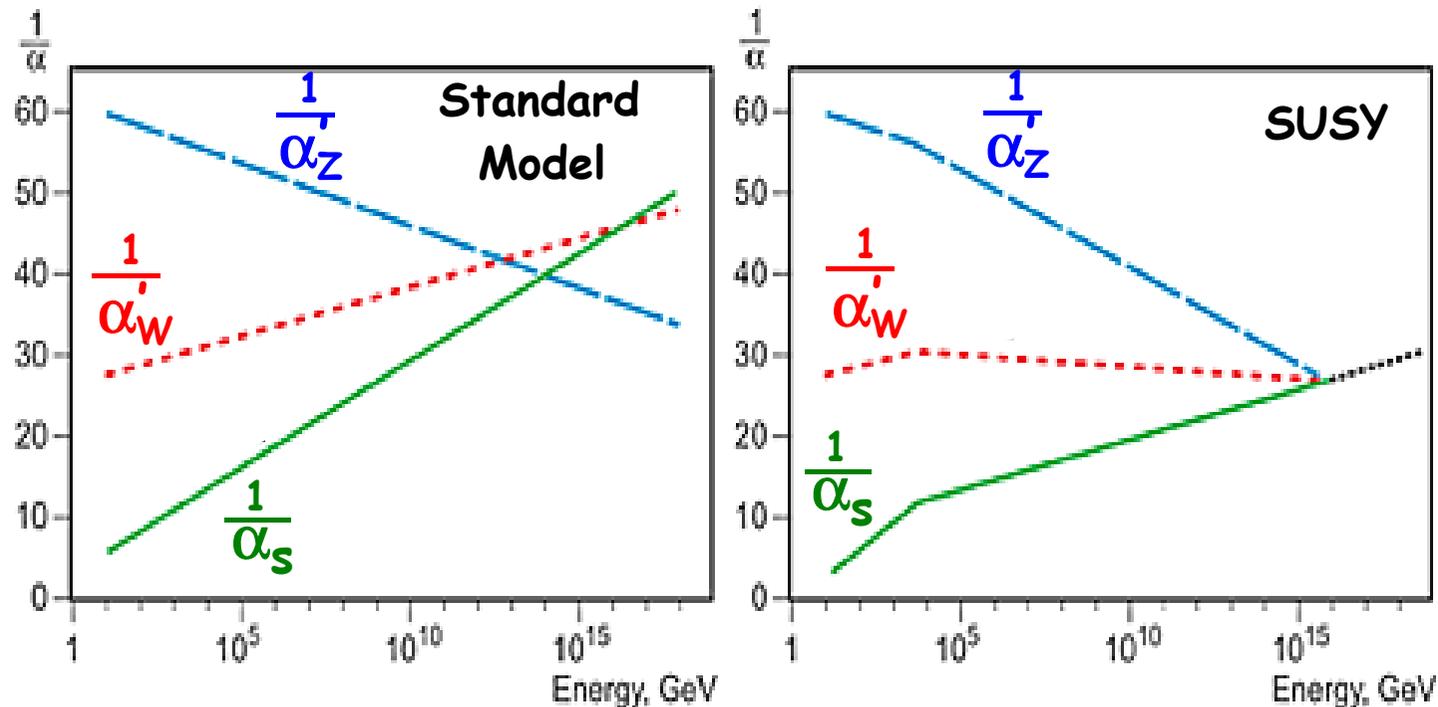
- There are many different supersymmetric models:

	<u>Name</u>	<u>LSP</u>	<u>New parameters</u>
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

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

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

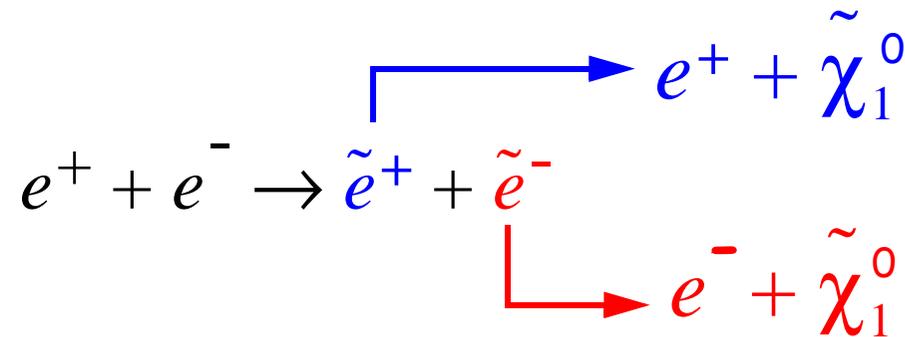


- SUSY predicts a value for the **weak mixing angle** which is closer to the experimental results than the Georgi-Glashow model.
- Some SUSY models **unify ALL forces including gravity** at the Planck mass of 10^{19} GeV by replacing particles with superstrings.

Supersymmetry

➔ SUSY search in the DELPHI experiment

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



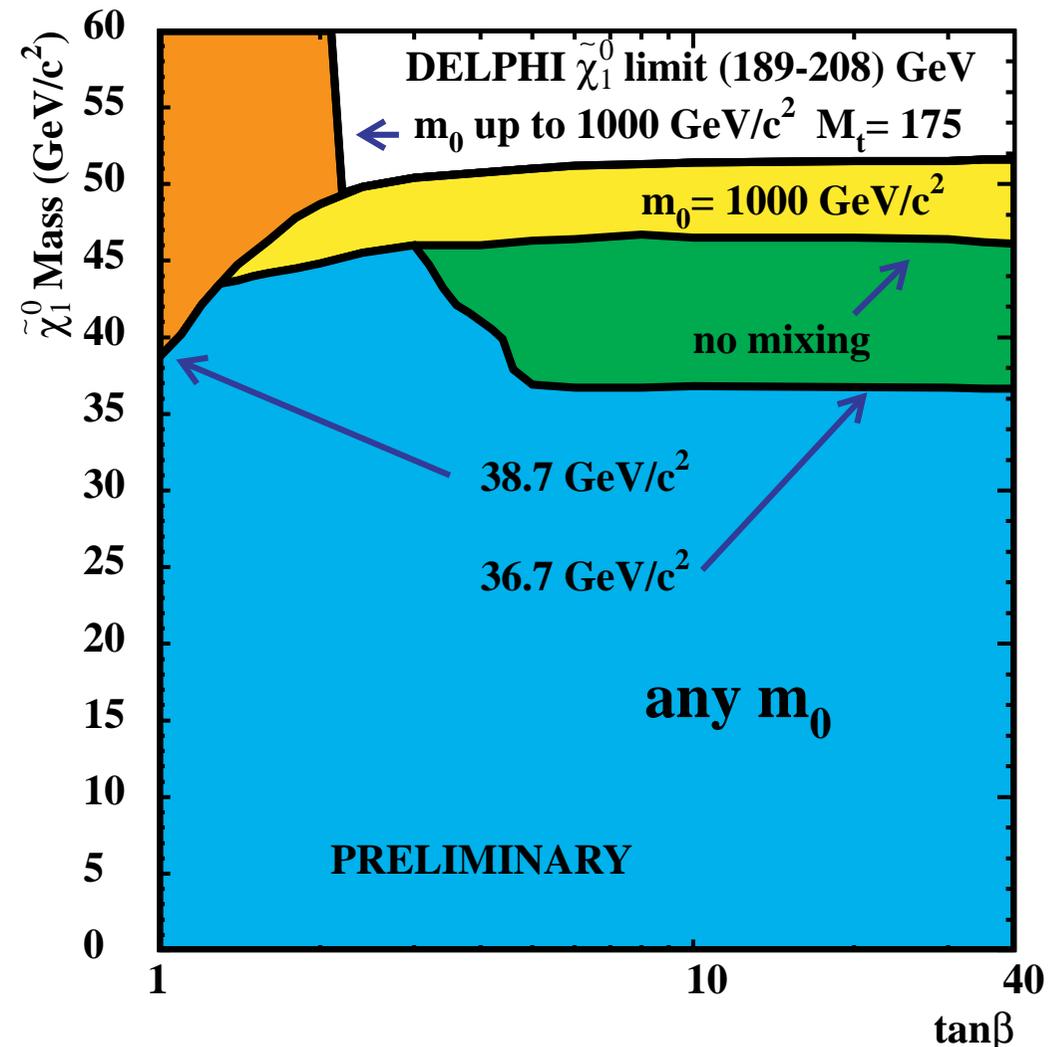
- 1) The **cross section** for producing selectron pairs is comparable to that of producing ordinary charged particles with the same mass.
- 2) The **selectrons decay** before they can reach a detector.
- 3) The **neutralinos** only interact **weakly** and they are therefore virtually undetectable.

Supersymmetry

- **Signature** \Rightarrow 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 \Rightarrow set **lower limits** on the mass of the neutralino.
- SUSY has many models, each with different sets of **unknown parameters** \Rightarrow the results are given for different assumptions on models and parameters.

Supersymmetry

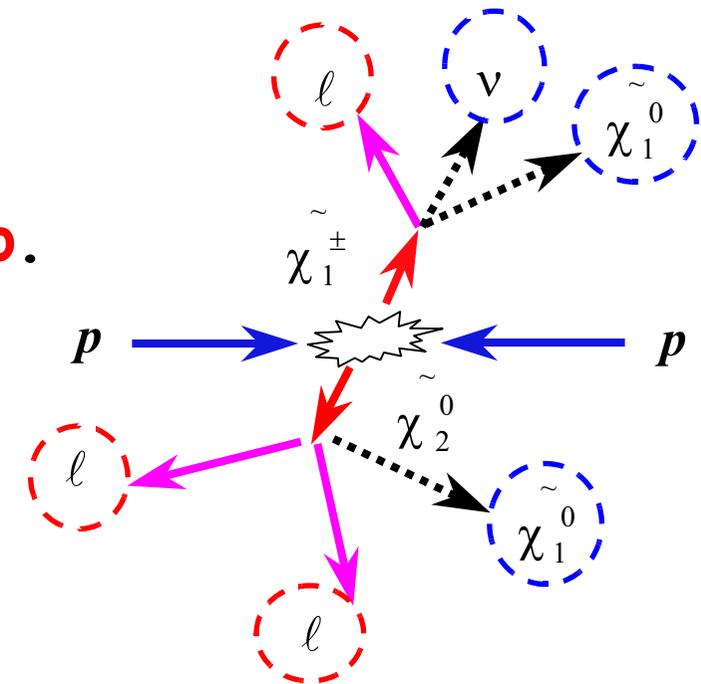
- The slepton searches were combined with other SUSY searches to set **limits on the neutralino mass**.
- All the coloured areas are excluded by the searches.
- The **$\tan(\beta)$** parameter is related to the **SUSY Higgs** particles and **m_0** to the **sfermions mass**.
- Result: **$\tilde{\chi}_1^0 > 36.7 \text{ GeV}$**
for all parameter values.



Supersymmetry

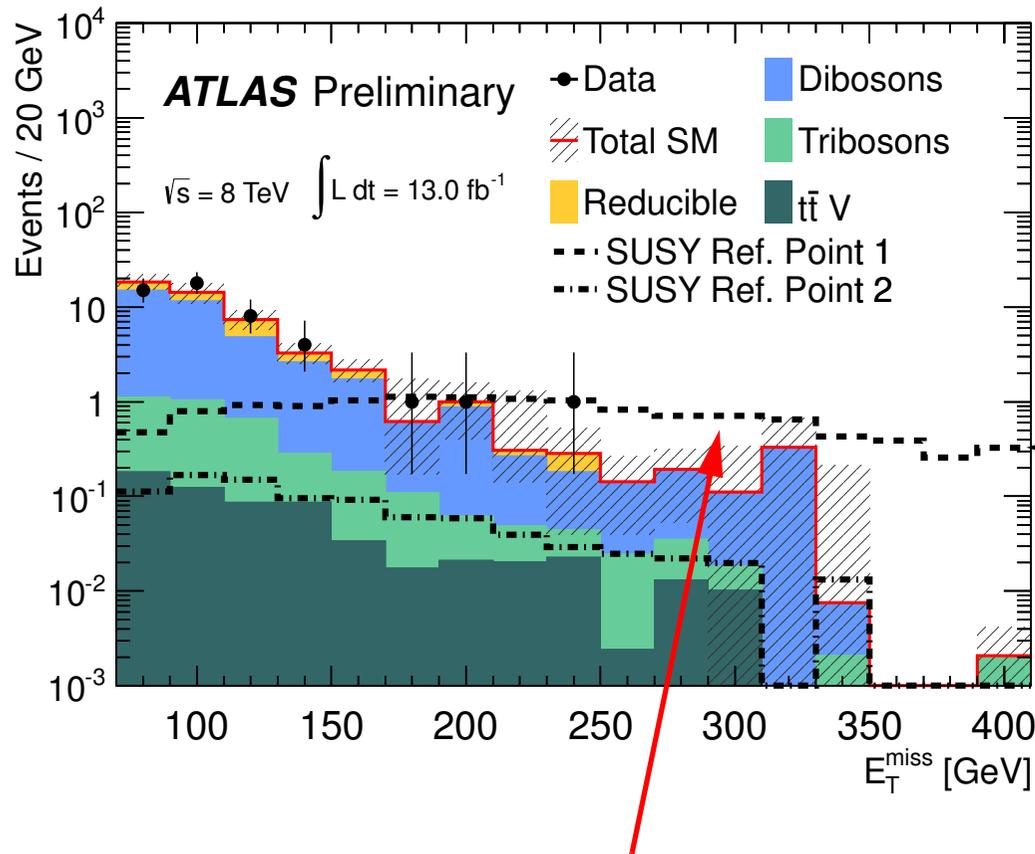
➔ SUSY search in the ATLAS experiment

- One of the main purposes of the LHC experiments are to search for SUSY as predicted by different models.
- **One possible channel:**
the production of a **chargino & neutralino**
➔ decays to **leptons & lightest neutralino**.
- **Signature:** three leptons (electrons & muons) and missing energy.
- **Selection:** $P_T > 10$ GeV for the lepton & Missing energy > 75 GeV.
- **Background:** ZW and $t\bar{t}$ production.



Supersymmetry

- Searches for these processes have been made by ATLAS.



Expected contribution from a SUSY signal with a particular choice of parameters:

Chargino mass = 500 GeV
Lowest neutralino mass = 0 GeV
Next-to-lowest neutralino mass = 500 GeV
Slepton mass = 250 GeV

- Events with large **missing transverse energy** are expected if **neutralinos** have been produced.

Gravitation and extra dimensions

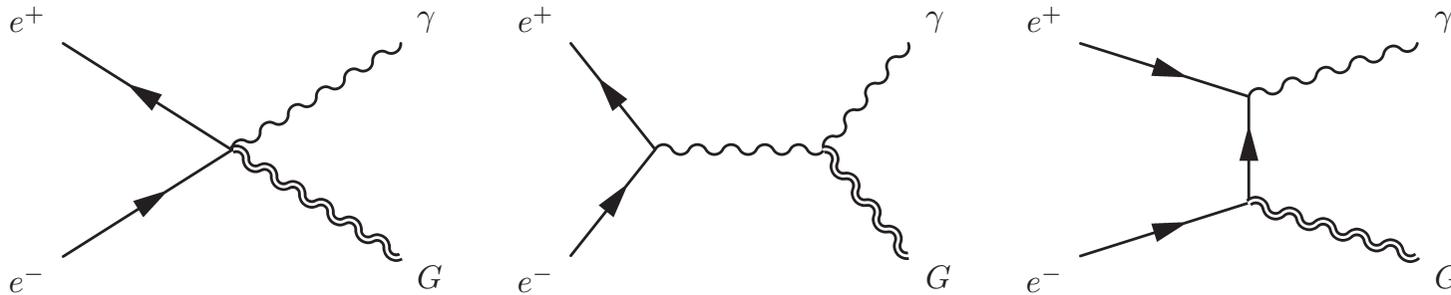
- The **gravitational force** is much **weaker** than the electromagnetic and strong interactions \Rightarrow not studied in particle physics.
- Postulated the existence of gravitational force carriers \Rightarrow
Gravitons (G).
- Gravitation has only been **studied at large distances** (>1 mm)
 \Rightarrow it could be stronger at shorter distances.
- New theories \Rightarrow Gravity is unified with other interactions \Rightarrow
New dimensions of space in which **only gravity can propagate**
(new dimensions 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 high-energy collisions
 - ➔ **but 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.

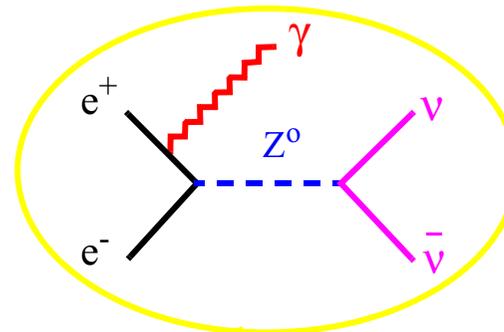
Gravitation and extra dimensions

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

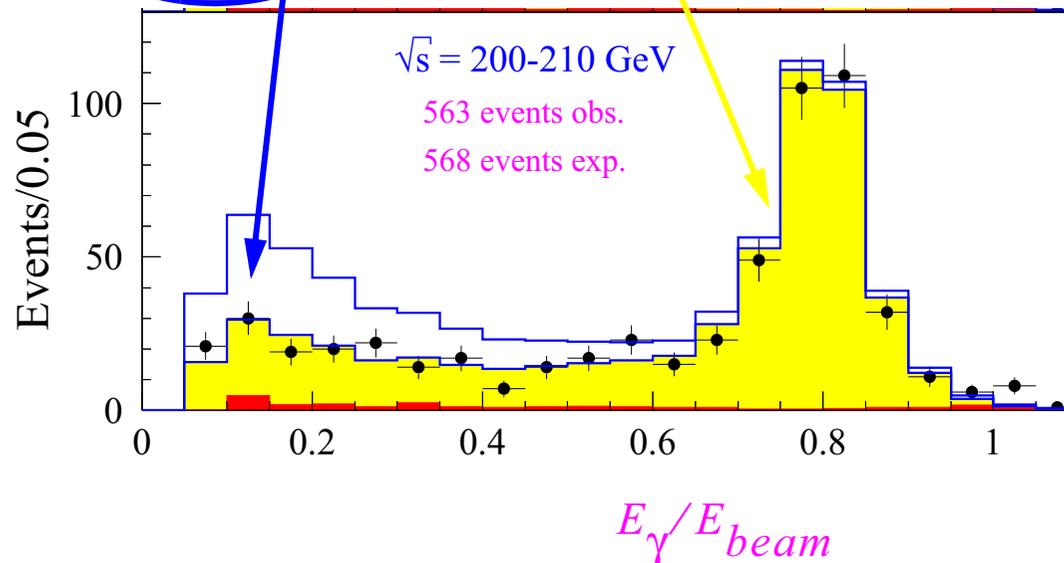
New
Physics

$$e^+e^- \rightarrow \gamma G$$

$n = 2$
 $M_D = 0.75 \text{ TeV}$



Standard
Model



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

Gravitation and extra dimensions

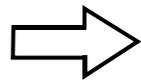
- The measurement \Rightarrow **set limits** on the parameters in the theory

- Parameters:

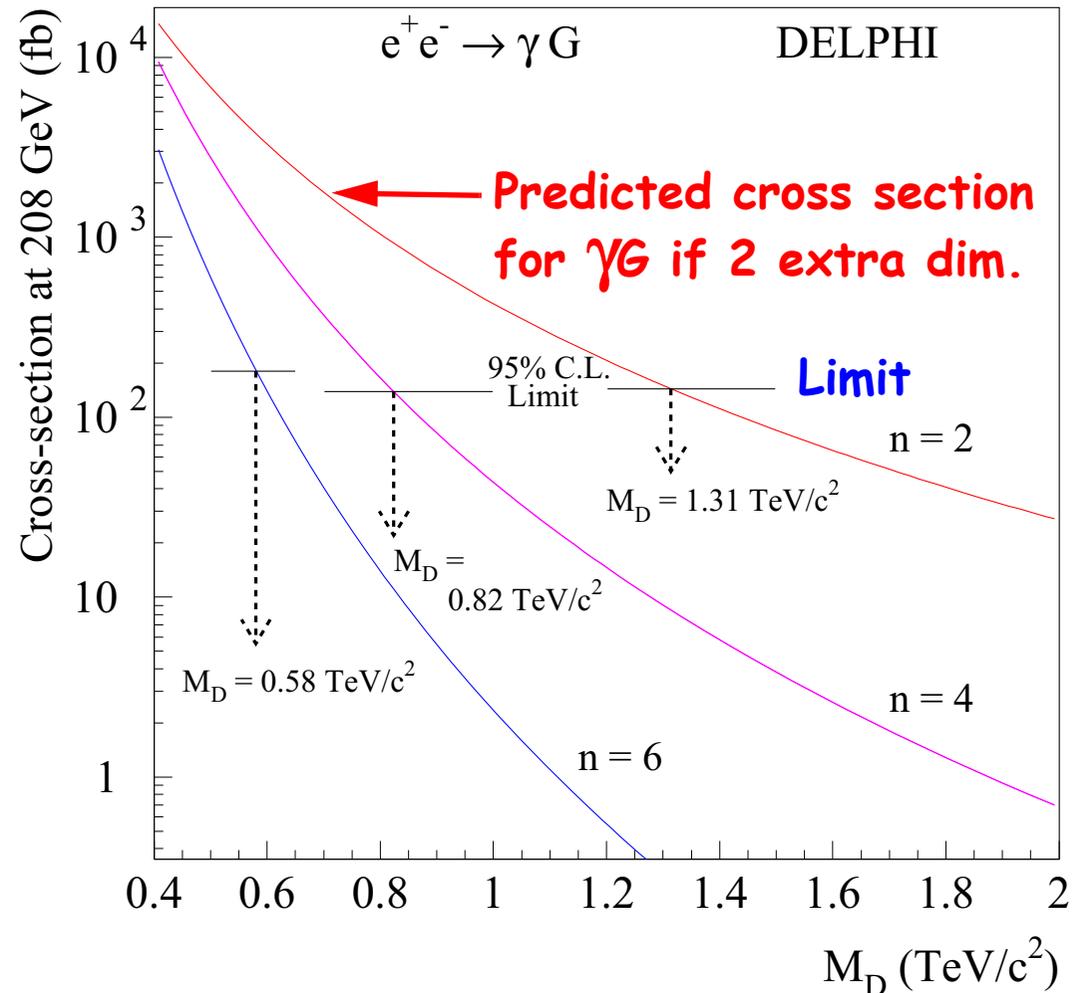
- n - the number of extra dimensions
- M_D - a fundamental mass scale.

- Limits:

The data set limits on the cross section



limits on M_D and n in the theory



Dark matter & energy

➔ The Big Bang Model

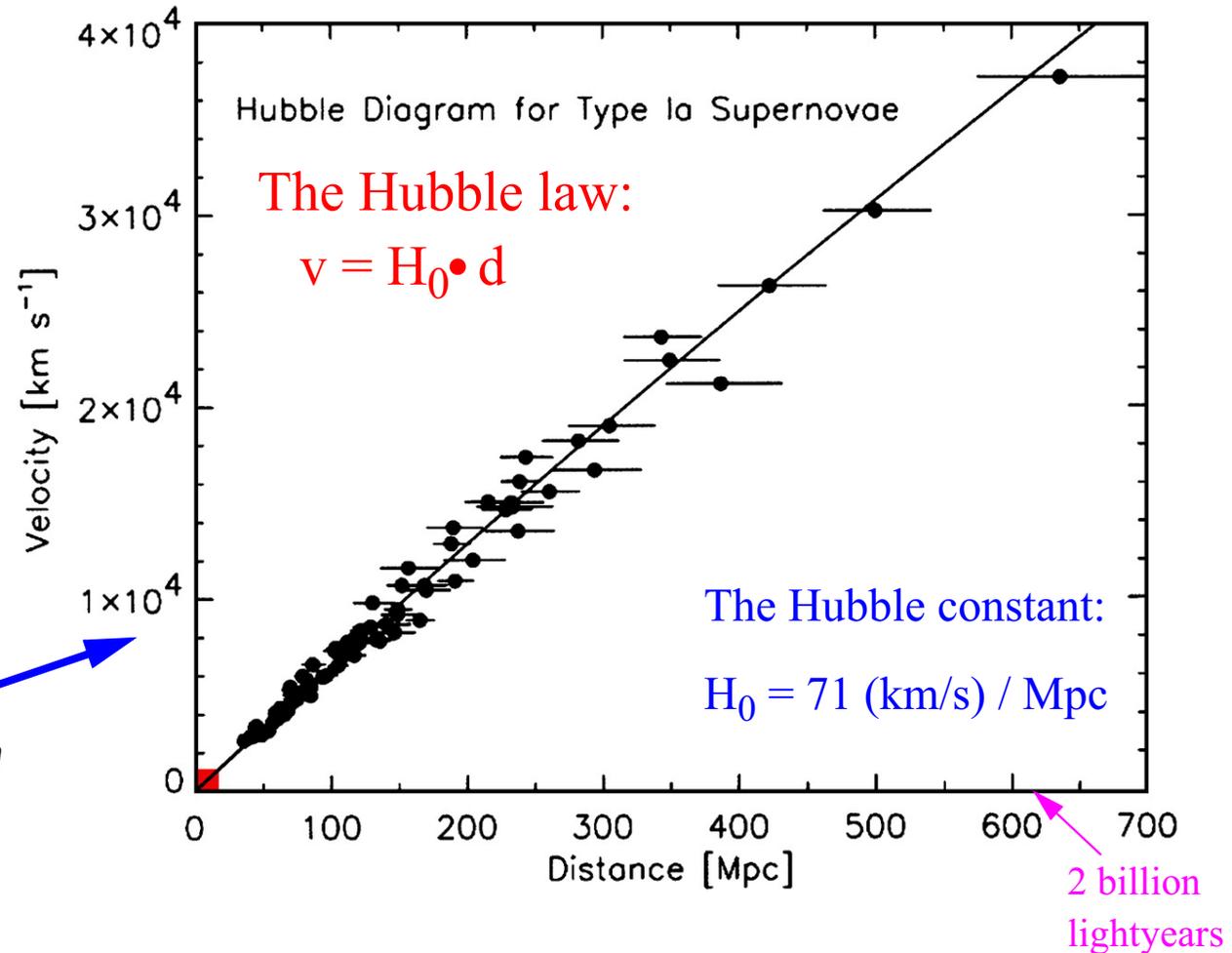
● Experimental **evidence** for the **Big Bang model** ➔

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 supernovas are therefore increasing with their distance to earth.

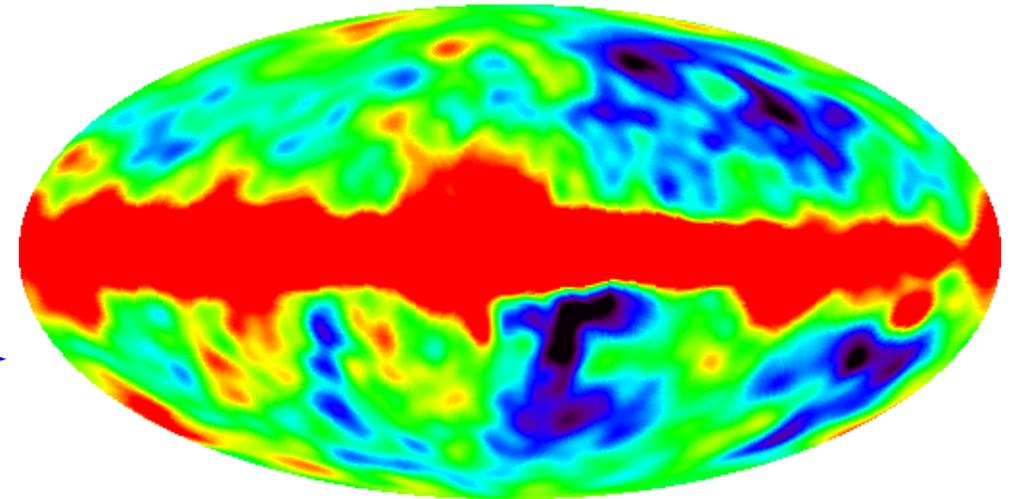
4) The cosmic background radiation.



Dark matter & energy

- **The cosmic background radiation** with a temperature of 2.7 K (0.0002 eV) \Rightarrow remnant 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

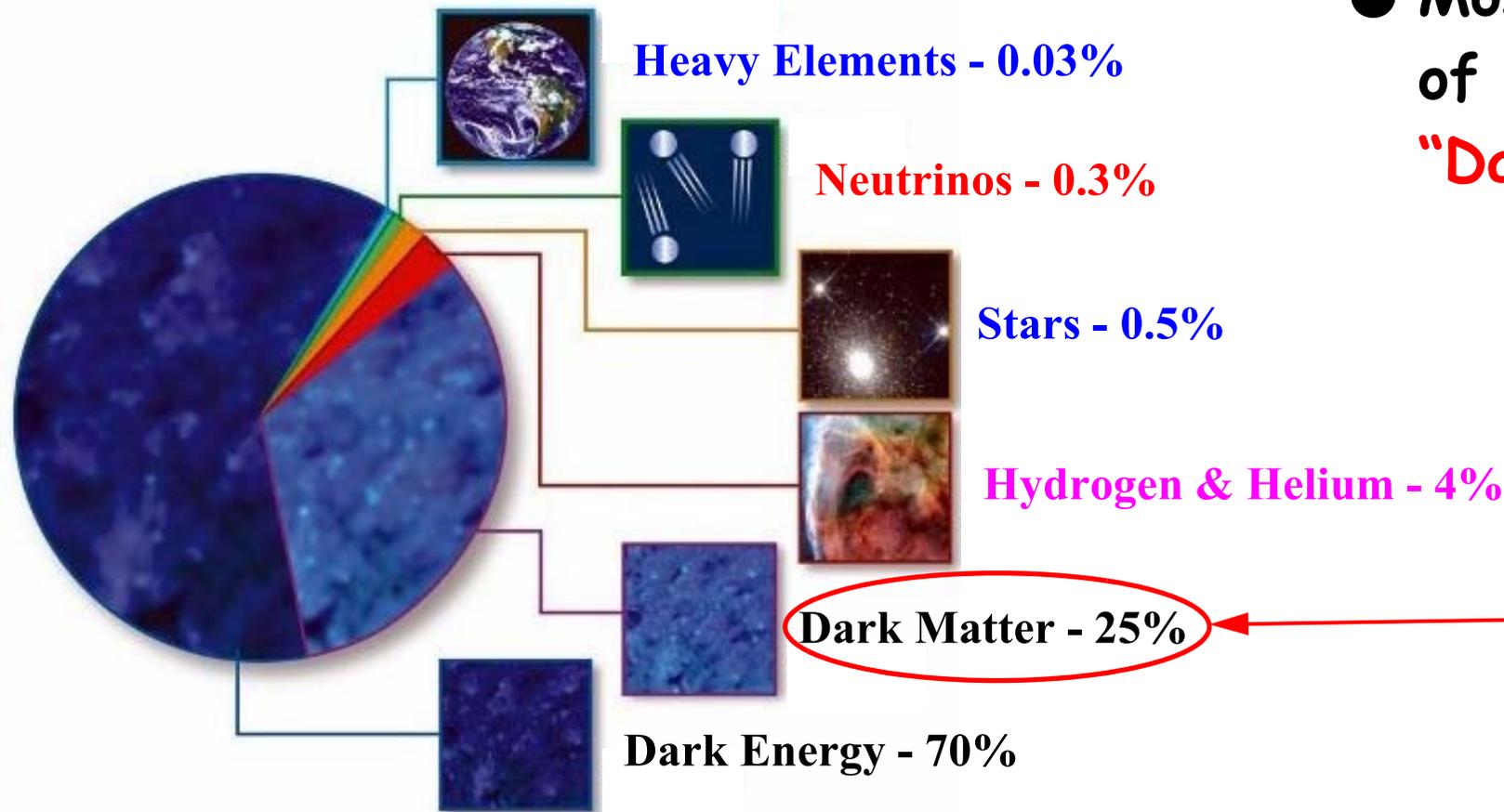
- The critical density: $\rho_c = \frac{3H_0^2}{8\pi G} = O(10^{-26}) \text{ kg m}^3$
Hubble constant
Gravitational constant
- If the density in the universe is larger than the critical density
⇒ the **expansion** of the universe will eventually end.
(otherwise it will continue for ever).

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

Dark matter & energy

➔ Dark Matter

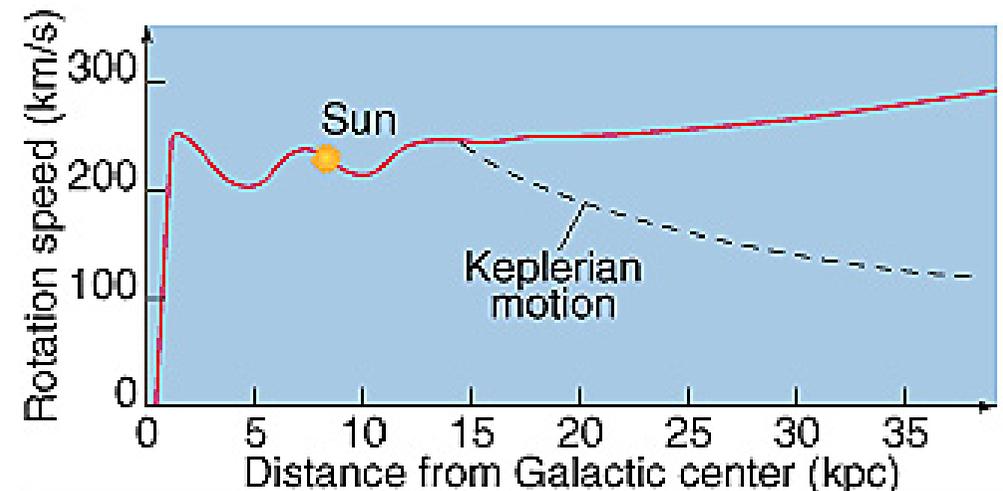
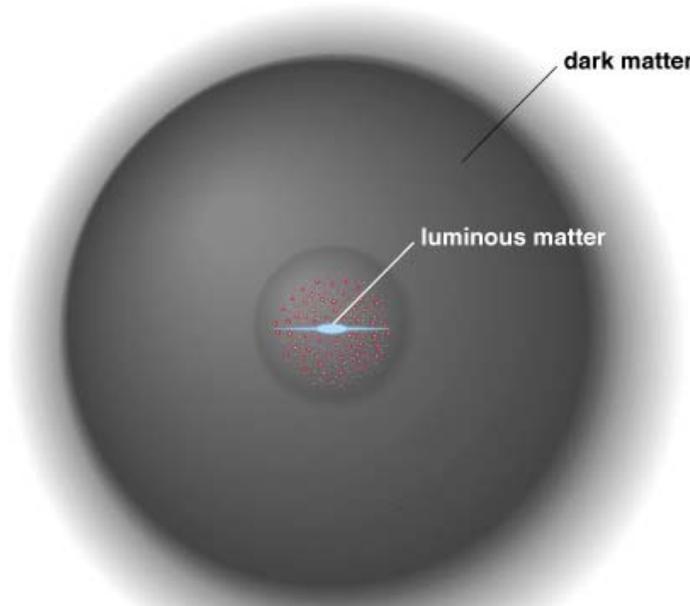
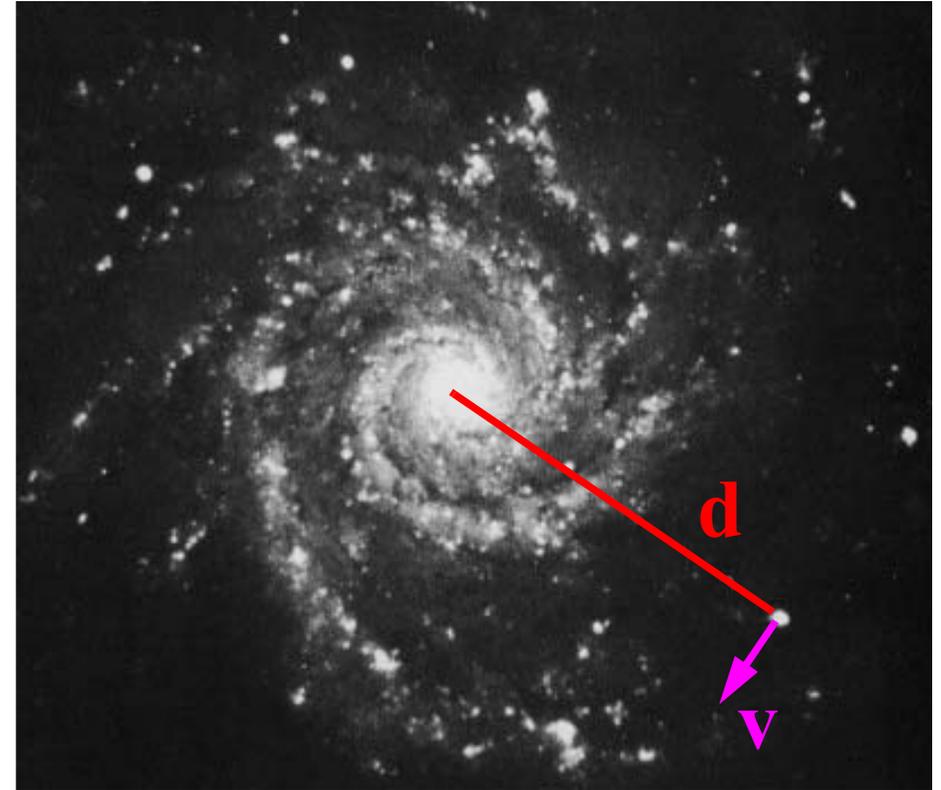
- The inflationary Big Bang model ➔ the density is **close to the critical density**.



- Most of the matter of an unknown type **"Dark Matter"**

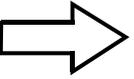
Dark matter & energy

- Evidence for dark matter \Rightarrow measurements of the **rotation velocity of stars** in galaxies.
- The **large rotational velocity** of stars in the outer regions of the Milky way \Rightarrow the galaxy is **full of dark matter**.



Dark matter & energy

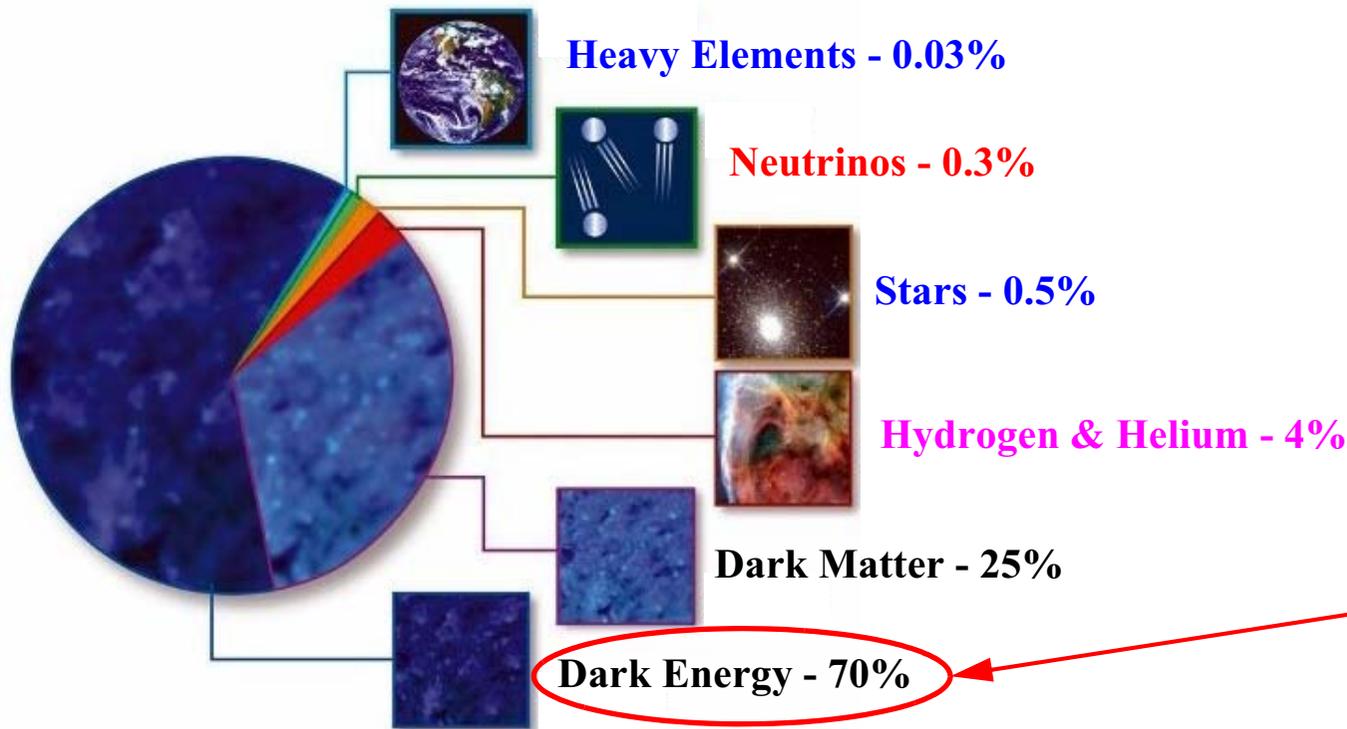
- What does dark matter consist of ?

- 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 $> 1 \text{ eV}$  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

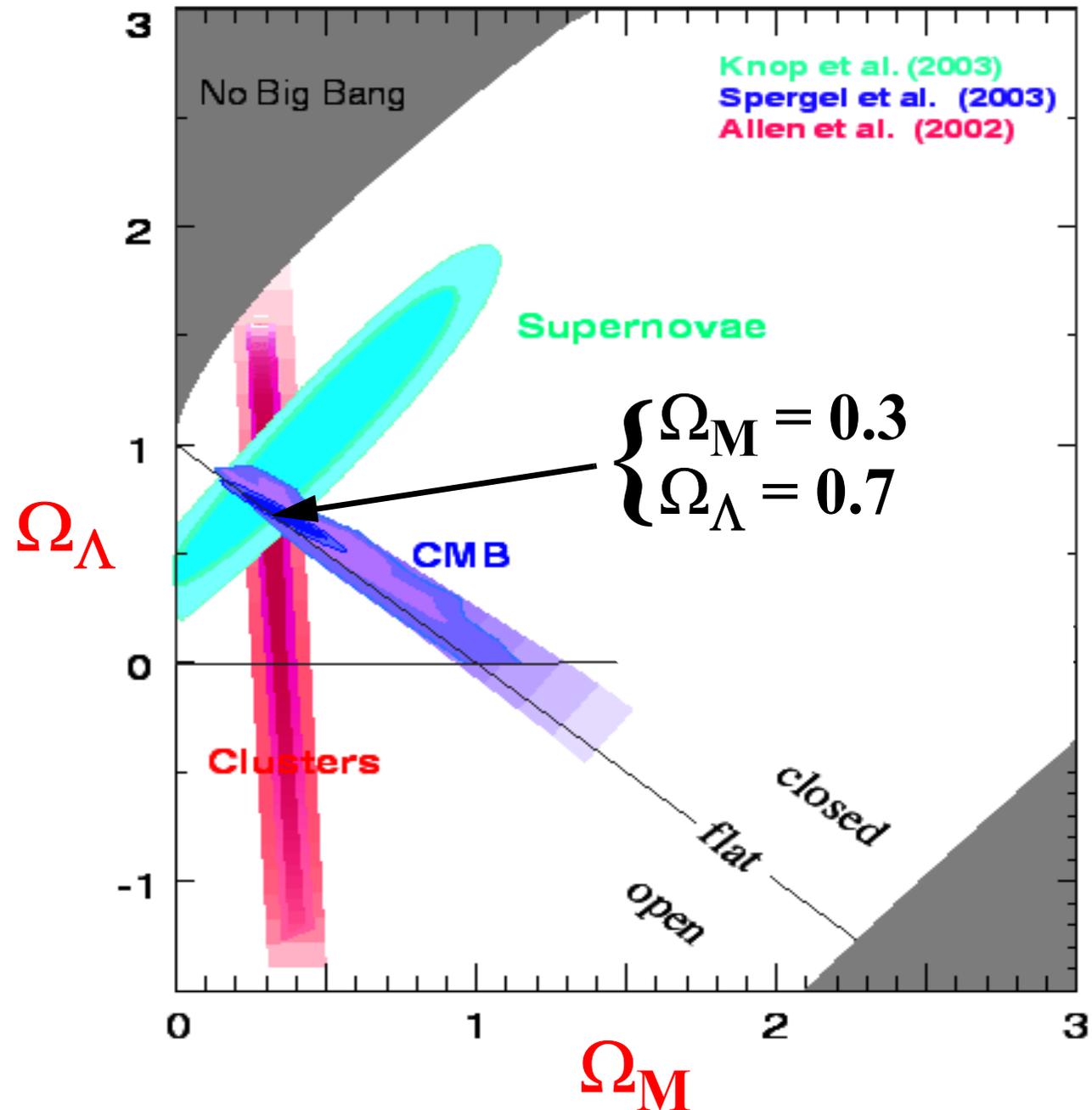
- The brightness (magnitude) of remote supernovas and their redshifts \Rightarrow the **expansion** of the universe is not constant but **accelerating** \Rightarrow the universe is full of **dark energy**.



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

Dark matter & energy

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



Dark matter & energy

- What is causing the Dark Energy ?

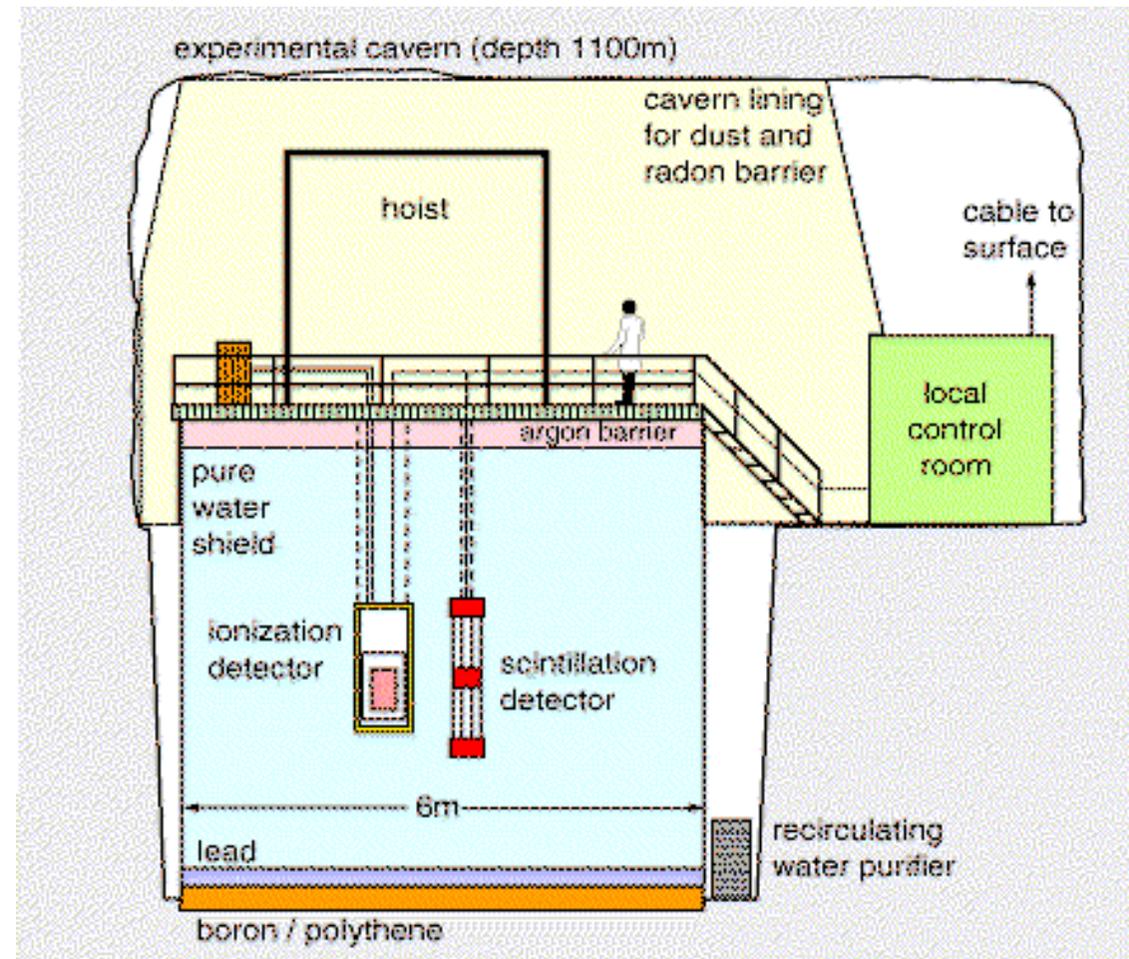
Two main hypothesis:

- 1) **The Cosmological Constant:** Space has an intrinsic **constant fundamental energy** (10^{-29} g/cm³). 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.
- **CDMSII: Ge detectors at the Soudan underground laboratory** to look for **WIMPs**.
- Interactions between **WIMPs** and the **Ge** atoms \Rightarrow phonons and ionization \Rightarrow detected by sensors on the semiconductors.
- **Two candidate events** with 0.9 expected from background.

