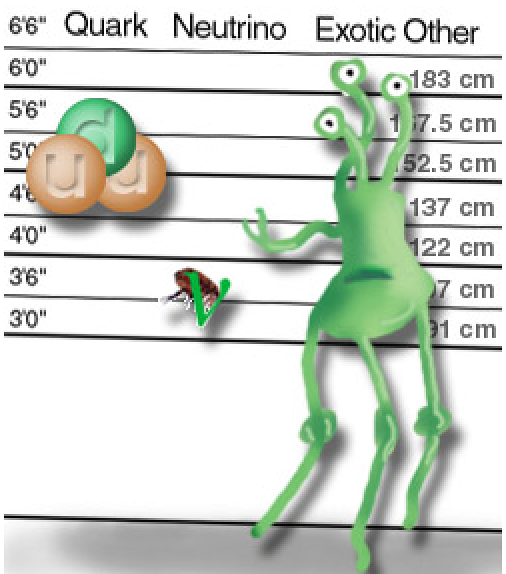
XII. Beyond the Standard Model

- While the Standard Model appears to be confirmed in all ways, there are (quite) some unclear points and possible extensions
  - What is the *Dark Matter*?
  - What is the *Dark Energy*?
  - What about gravity and *Graviton*? Can not ignore it at energies beyond $M_{Planck} = 10^{19}$ GeV.
  - How come there is almost no antimatter?
  - Why there are *three* generations of quarks and leptons?
  - Why all couplings are different?
  - Why so many free parameters (masses, couplings, mixing angles)?
  - Higgs mass actually diverges with corrections from fermion loops!



"All right... which of you punks is responsible for dark matter?"

Grand Unified Theories (GUTs)

- Weak and electromagnetic interactions are unified, why not to add the strong one?
  - At some very high "unification mass" electroweak and strong couplings may become equal, since they all depend on Q^2

$$\alpha_1 \equiv \alpha'_Z = \frac{g'^2}{4\pi} = 8\frac{g_Z^2}{4\pi} = 8\alpha_Z$$

$$\alpha_2 \equiv \alpha'_W = \frac{g^2}{4\pi} = 8\frac{g_W^2}{4\pi} = 8\alpha_W$$

$$\alpha_3 \equiv \alpha_s = \frac{g_s^2}{4\pi}$$

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

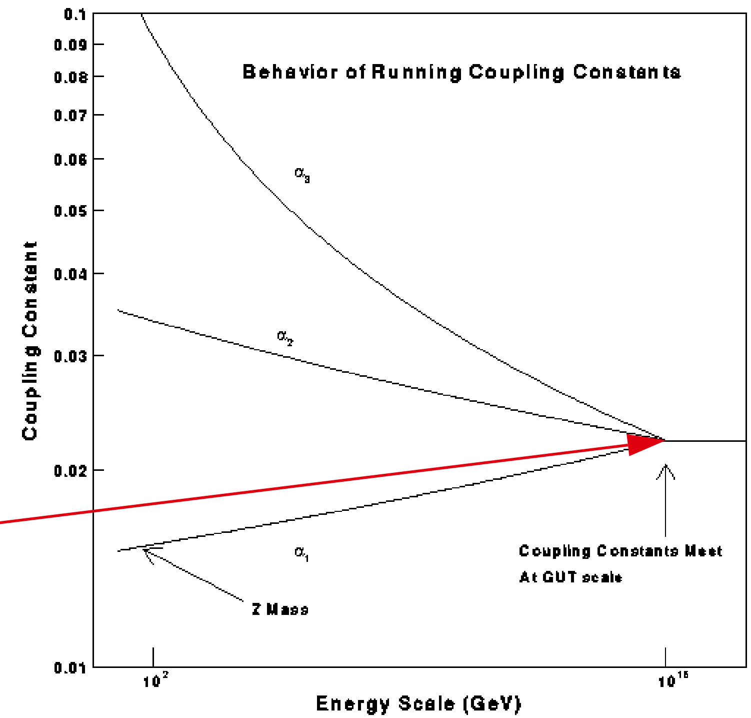


Figure 199: Coupling constants in a GUT; α_1 and α_2 are couplings at Z and W

Grand unified theories can be constructed in many different ways.

❖ *Georgi-Glashow model* combines coloured quarks and leptons in single families, like

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

this leads to introduction of new gauge bosons:

X with $Q=-4/3$ and Y with $Q=-1/3$, $M_X \approx 10^{15}$ GeV/c^2:

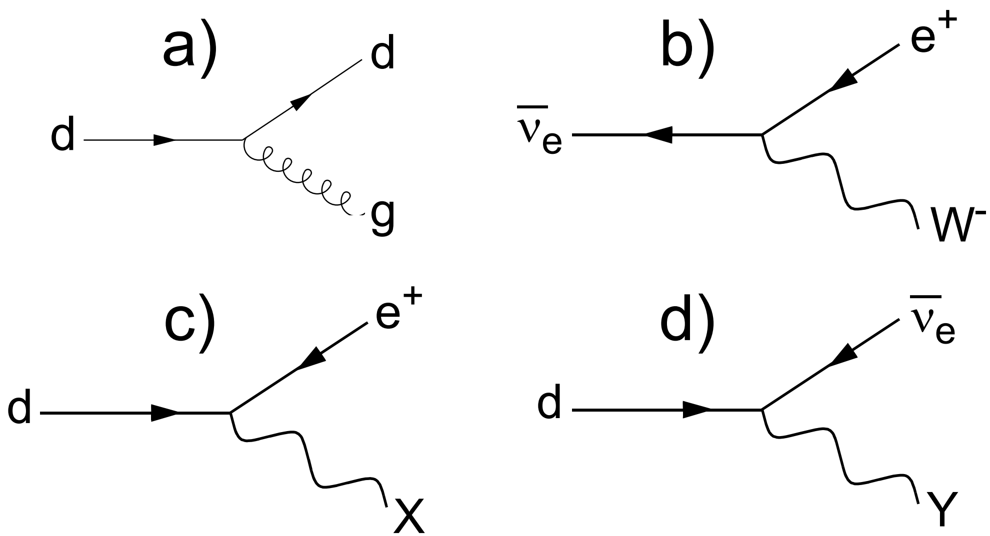


Figure 200: SM processes (a,b) and those predicted by a GUT (c,d)

There is then a single unified coupling constant g_U, and $\alpha_U \equiv \frac{g_U^2}{4\pi} \approx \frac{1}{42}$

- Georgi-Glashow model explains equal magnitudes of electron and proton charge

Sum of electric charges in any given family must be zero $\Rightarrow 3Q_d + e = 0 \Rightarrow$ down-quark has charge $-e/3$.

– Factor of 3 arises naturally from the number of colors

- This model also predicts the weak mixing angle using values of the coupling constants:

$$\sin^2\theta_W = 0.21 \qquad (231)$$

which is very close to experimental results, though not an exact match.

- GUTs predict that the proton is unstable and can decay by a process involving X or Y bosons

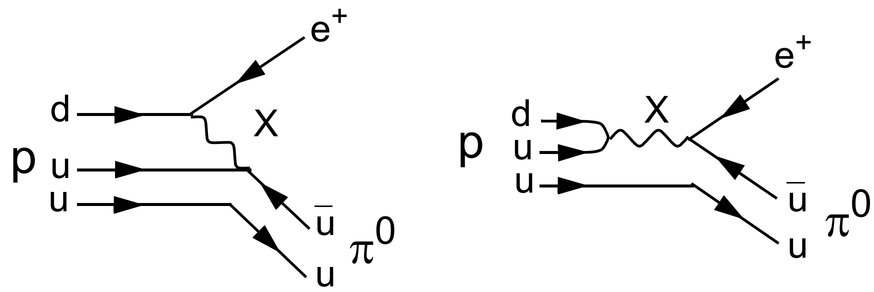


Figure 201: Proton decays in GUT

- In processes like those in Fig.201, *baryon and lepton numbers are not conserved*, but their combination is:

$$B - L \equiv B - \sum_{\alpha} L_{\alpha} \quad (\alpha = e, \mu, \tau) \tag{232}$$

- From the simple zero-range approximation, lifetime of the proton is (from different GUTs):

$$\tau_p = 10^{32} \div 10^{33} \text{ years} \tag{233}$$

while the age of the universe is about 10^{10} years...

- Many detectors used for the neutrino physics (IMB, Kamiokande) started as proton decay experiments, but have not observed a clear example so far
  - The most interesting process is

$$p \to \pi^0 + e^+ \to \gamma\gamma + e^+$$

    where the signature is one positron and two electron-positron pairs from photon conversions

  - The upper measured limit for the proton lifetime is

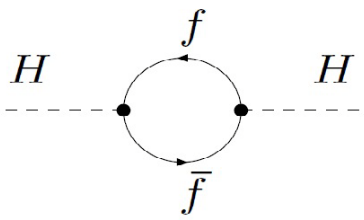
$$\frac{\tau_p}{B(p \to \pi^0 e^+)} > 5 \times 10^{32}\ years$$

    which disagrees with the Georgi-Glashow model prediction of $0.003 \div 0.030 \times 10^{32}$ years; other GUTs can predict longer lifetimes though

- Baryon number non-conservation allows explanation of excess of baryons in the universe as compared to antibaryons. However, CP-violation must be present as well.

Supersymmetry (SUSY)

- Most popular GUTs incorporate SUSY: interactions are symmetric under a transformation from a fermion to a boson
- One of the problems SUSY addresses is the *Hierarchy/Naturalness problem*: Higgs mass diverges with fermion loop corrections:



$$\Delta m_H^2 \sim \frac{\lambda_f^2}{4\pi^2}(\Lambda^2 + m_f^2) + \ldots$$

Figure 202: Corrections to Higgs mass from fermion loop (coupling $-\lambda_f H f f$)

  - In Fig.202, Λ is high-energy cut-off. If $\Lambda \sim M_{Planck}$, corrections explode

- Corrections from a scalar loop $\tilde{f}$ with an opposite sign can cancel the divergence:

$$\Delta m_H^2 \sim -\frac{\lambda_{\tilde{f}}^2}{4\pi^2}(\Lambda^2 + m_{\tilde{f}}^2) + \ldots \qquad (234)$$

- The problem is solved if for every fermion degree of freedom there is a scalar $\tilde{f}$, such that $\lambda^2_{\tilde{f}} = \lambda^2_f$ and $m_{\tilde{f}} = m_f$.
  - In SUSY, every known elementary particle has a supersymmetric partner -"superparticle" - with *different* spin:

Particle	**Symbol**	**Spin**	**Superparticle**	**Symbol**	**Spin**
Quark	q	1/2	Squark	$\tilde{q}$	0
Electron	e	1/2	Selectron	$\tilde{e}$	0
Muon	μ	1/2	Smuon	$\tilde{\mu}$	0
Tau	τ	1/2	Stau	$\tilde{\tau}$	0
W	W	1	Wino	$\tilde{W}$	1/2
Z	Z	1	Zino	$\tilde{Z}$	1/2
Photon	γ	1	Photino	$\tilde{\gamma}$	1/2
Gluon	g	1	Gluino	$\tilde{g}$	1/2
Higgs	H	0	Higgsino	$\tilde{H}$	1/2

In a true supersymmetry, superpartners ought to have the same mass, which contradicts observations, therefore *SUSY is broken*!

- All superpartners have to be much heavier than the SM particles

Adding all breaking terms to the Lagrangian will lead to 105 (!) parameters. This can be reduced to just 19 assuming that all flavor matrices are aligned with the SM ones - *minimal flavor violation*.

In the Minimal Supersymmetric Standard Model (MSSM):

- There are two Higgs doublets and spartners, 5 Higgs bosons: h, H, A, H^+ and H^-
- Sparticles are produced in pairs
- The lightest SUSY particle (LSP) is *stable*, neutral and weekly interacting (much like neutrino, only very heavy)
- *R-parity* is conserved: $P_R=(-1)^{3(B-L)+2S}$ (baryon and lepton numbers are not conserved); all sparticles have R-parity of -1

Mixing between some of spartner states leads to new particles: *charginos* and *neutralinos*

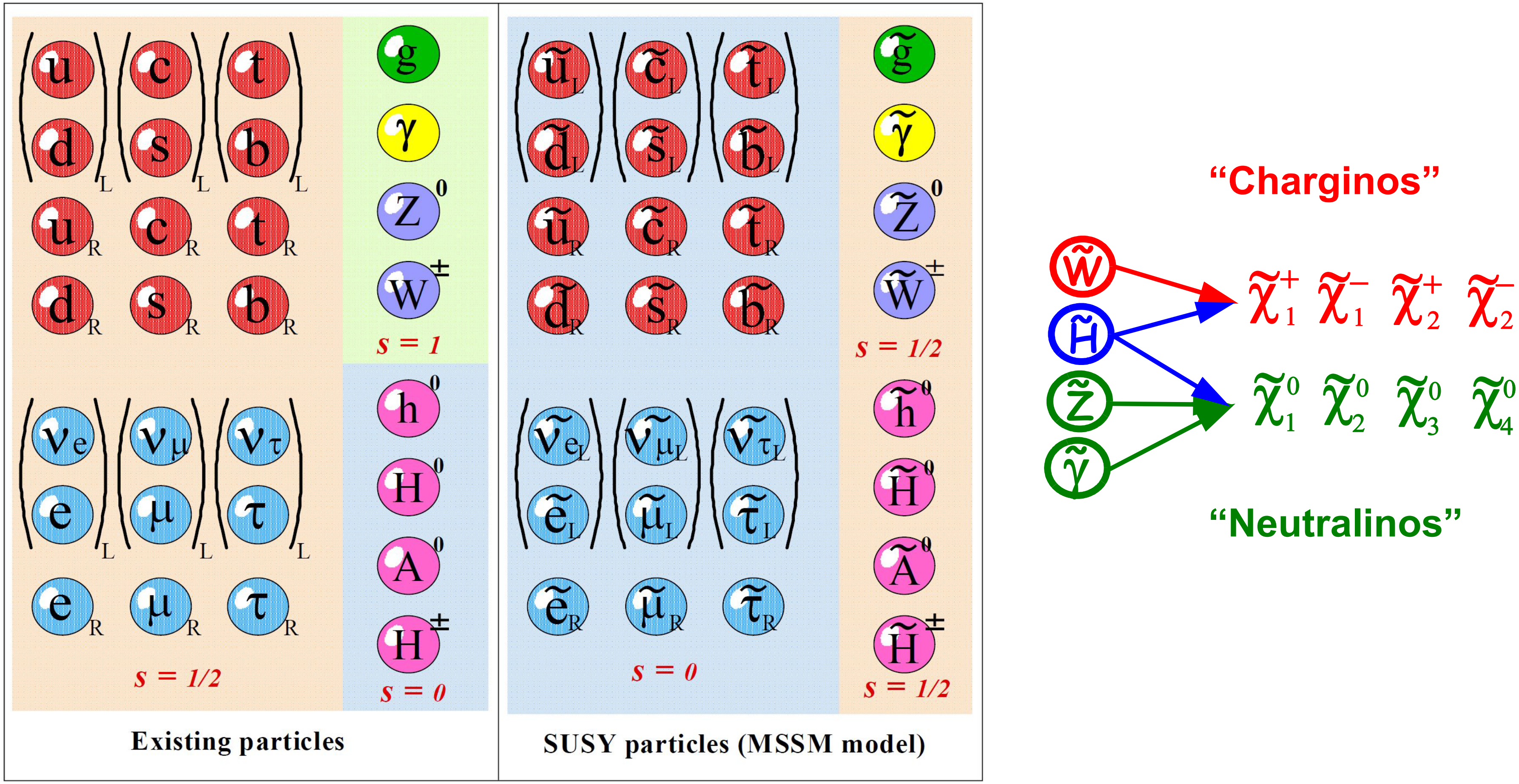


Figure 203: Comparison of SM and MSSM; charginos and neutralinos as gaugino (zino, wino and photino) and higgsino mixings

There are other supersymmetric models:

Model		LSP	New parameters
MSSM	Minimal Supersymmetric Standard Model	Any	>100
cMSSM	Constrained MSSM	$\tilde{\chi}_1^0$	m_0, $m_{1/2}$, A_0, $\tan(\beta)$, sign(μ)
mSUGRA	Minimal Supergravity	$\tilde{\chi}_1^0$	m_0, $m_{1/2}$, A_0, $\tan(\beta)$, sign(μ)
AMSB	Anomaly Mediated Symmetry Breaking	$\tilde{\chi}_1^0$	m_0, $m_{3/2}$, $\tan(\beta)$, sign(μ)
GMSB	Gauge Mediated Symmetry Breaking	$\tilde{G}$	$\Lambda_m=F_m/M_m$, M_m, $\tan(\beta)$, N_5, sign(μ), C_{grav}

- here, parameters are: m_0 - scalar masses, $m_{1/2}$ and $m_{3/2}$ - gaugino and gravitino masses, A_0 - Higgs-sfermion-sfermion coupling constant, $\tan(\beta)$ - ratio of Higgs vacuum expectation values, sign(μ) - sign of the higgsino mass parameter, F_m - SUSY breaking scale, M_m - messenger mass, N_5 - nr of messenger fields, C_{grav} - G mass scale factor

- SUSY models can shift the grand unification energy to higher values. e.g from 10^{15} to 10^{16} GeV/c^2, and hence the proton lifetime increases:

$$\tau_p = 10^{32} \div 10^{33}\ years \qquad (235)$$

which is more consistent with experimental (non)observations.

- SUSY also modifies the value of the weak mixing angle in Eq.(231) to be closer to the experimental results.

- SUSY even attempts at unifying ALL forces, including gravity, at the *Planck mass* of the order of 10^{19} GeV/c^2 by replacing particles with *superstrings*

- LSPs can be candidates for the *cold dark matter*

SUSY searches

- Most SUSY models introduce *neutralino* $\tilde{\chi}_1^0$, which is the mixture of photino, higgsino and zino
- Neutralinos' presence can be observed in selectron production:

$$e^+ + e^- \rightarrow \tilde{e}^+ + \tilde{e}^- \qquad (236)$$

$$\tilde{e}^+ \rightarrow e^+ + \tilde{\chi}_1^0 \qquad \tilde{e}^- \rightarrow e^- + \tilde{\chi}_1^0 \qquad (237)$$

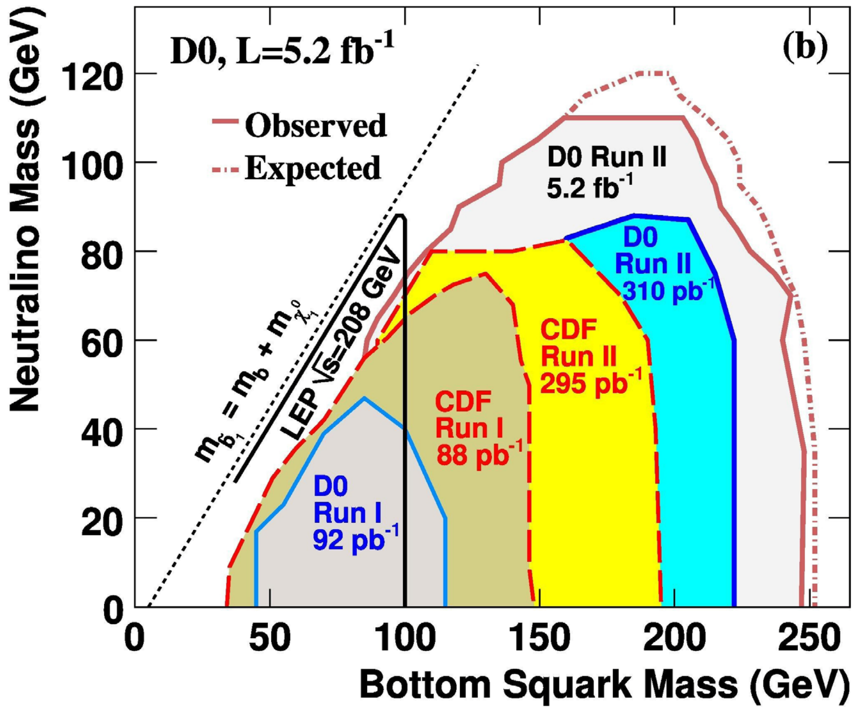
SUSY predictions for reactions 236-237:

1) Cross-section of reaction (236) is comparable with producing ordinary charged particles of the same mass
2) Selectrons decay before they can reach a detector
3) Neutralinos are virtually undetectable due to very weak interaction

- Thus only the final state electrons in decays (237) can be detected, so that they:

(a) carry only half of the initial energy of the initial e^+e^- state,
(b) should not be emitted in opposite directions in CM frame

- No signature of this kind has been observed so far
  - This still allows to define lower mass limits



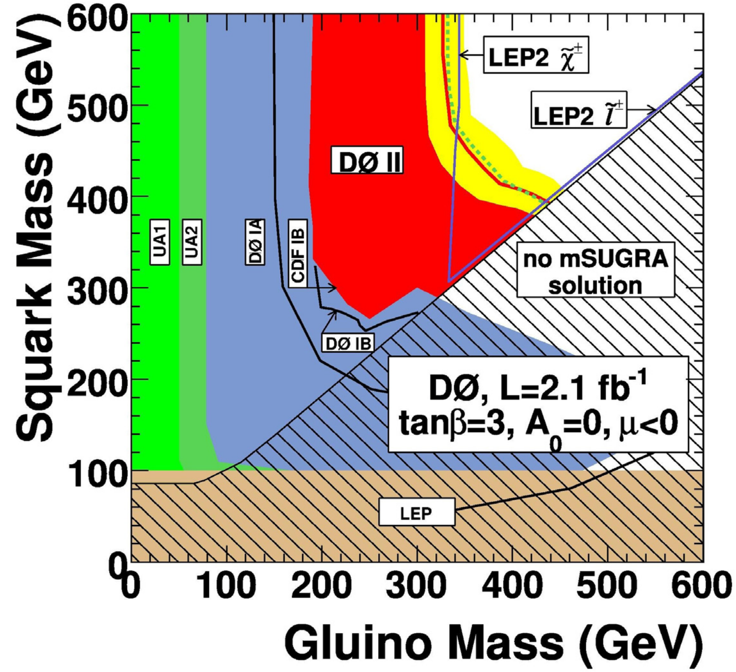
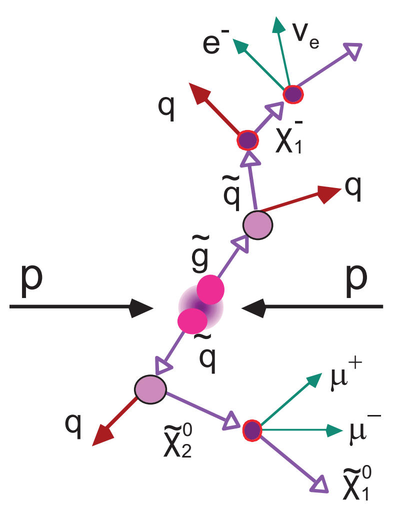


Figure 204: Mass limits on some SUSY particles before LHC. Shaded areas show excluded ranges

  - LEP set model-independent limits for all sparticles coupling to Z^0 (e.g. sleptons, chargino) of ~ 100 GeV

- SUSY searches are among the main goals of the LHC
  - One of the main challenges is the SM background estimation; some can be removed by using tuned selection criteria, and some is irreducible
- cMSSM and mSUGRA with light sparticles was largely excluded already by early LHC data
  - Strong production of gluinos and light squarks is excluded up to ~1.4 TeV, and 13 TeV running bring sensitivity to 2.5-3 TeV
- A lot of other SUSY models still exist



  - Production of sparticles should be detectable via characteristic kinematic spectra, including e.g. missing transverse energy of more than 100 GeV

Figure 205: Possible supersymmetric particles at LHC

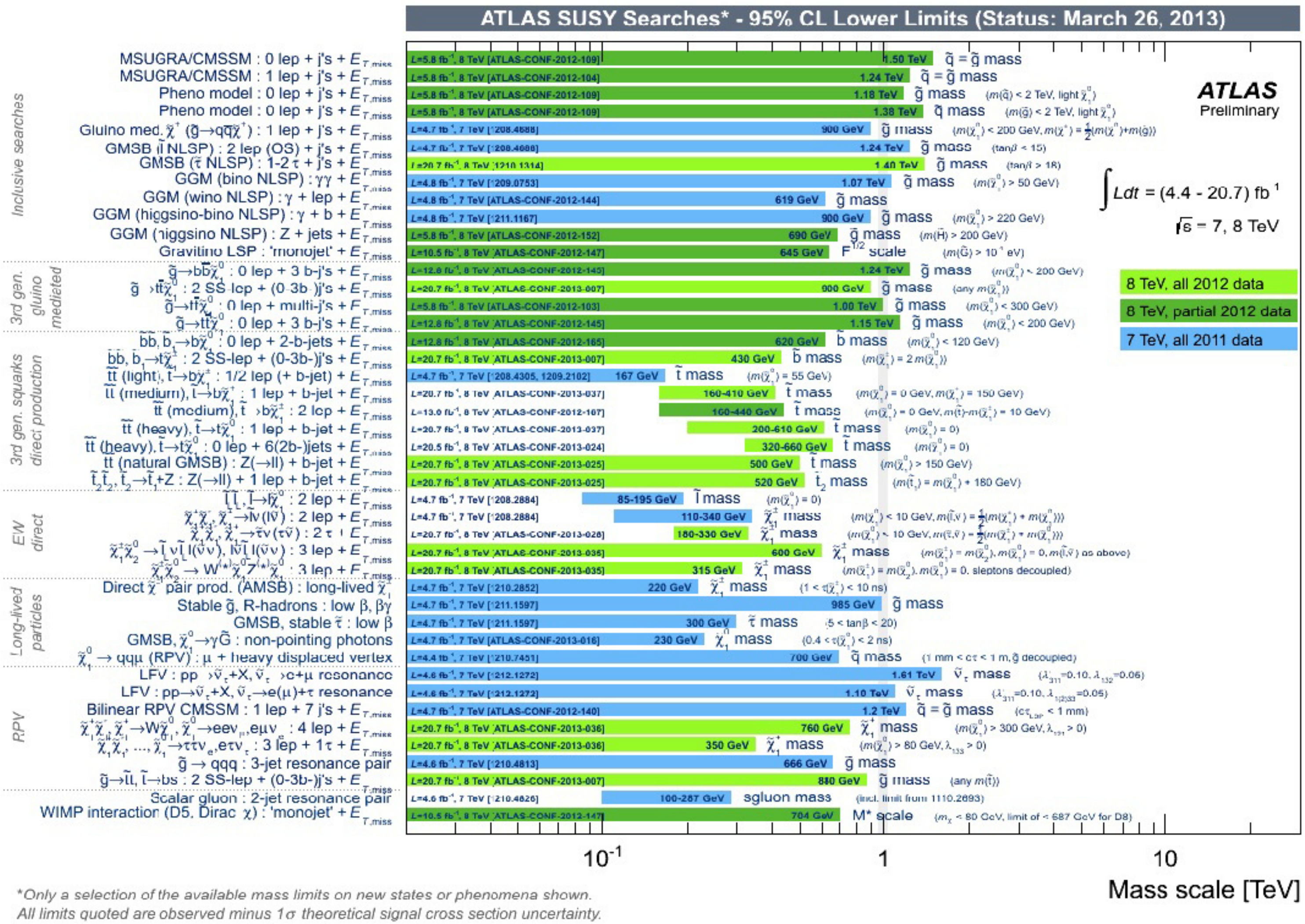


Figure 206: Overview of ATLAS SUSY searches status (shaded areas are excluded)

Gravitation and extra dimensions

- The gravitational force is much weaker than the electromagnetic and strong interactions, and as such it has not been a subject of particle physics studies
- Still, gravitational force carriers (*gravitons*, G) should exist
- Gravitation has only been studied at large distances ($> 1\ mm$), and it could be that it is stronger at subatomic distances
- Unification of gravity with other interactions can be done by introducing *extra dimensions* in space, where only gravity can propagate
- If our accelerators could reach the energy scale where gravity is unified with the other forces, one could start seeing events in which gravitons are produced that *escape undetected* into the extra dimensions

Graviton searches

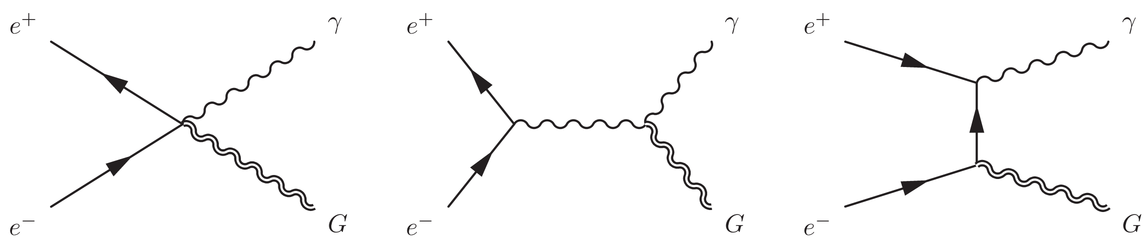


Figure 207: Graviton production channels in electron-positron annihilation

If sufficient energy is available, graviton can be produced together with photon in e^+e^- anihilation

- Events with single photon and nothing else would indicate a graviton
- Extra-dimensions model predicts graviton carrying out most energy and hence a low-energy photon
- A background process: initial state radiation of a photon with a consecutive neutrino decay of the Z^0

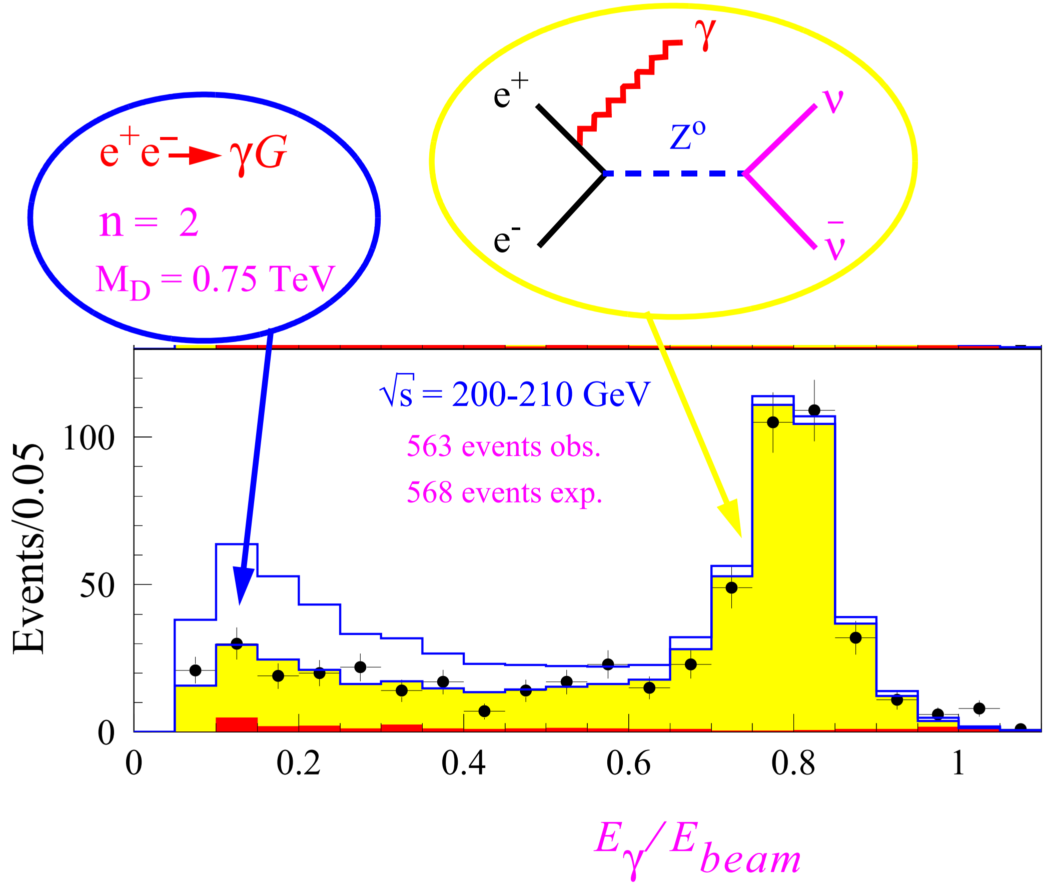


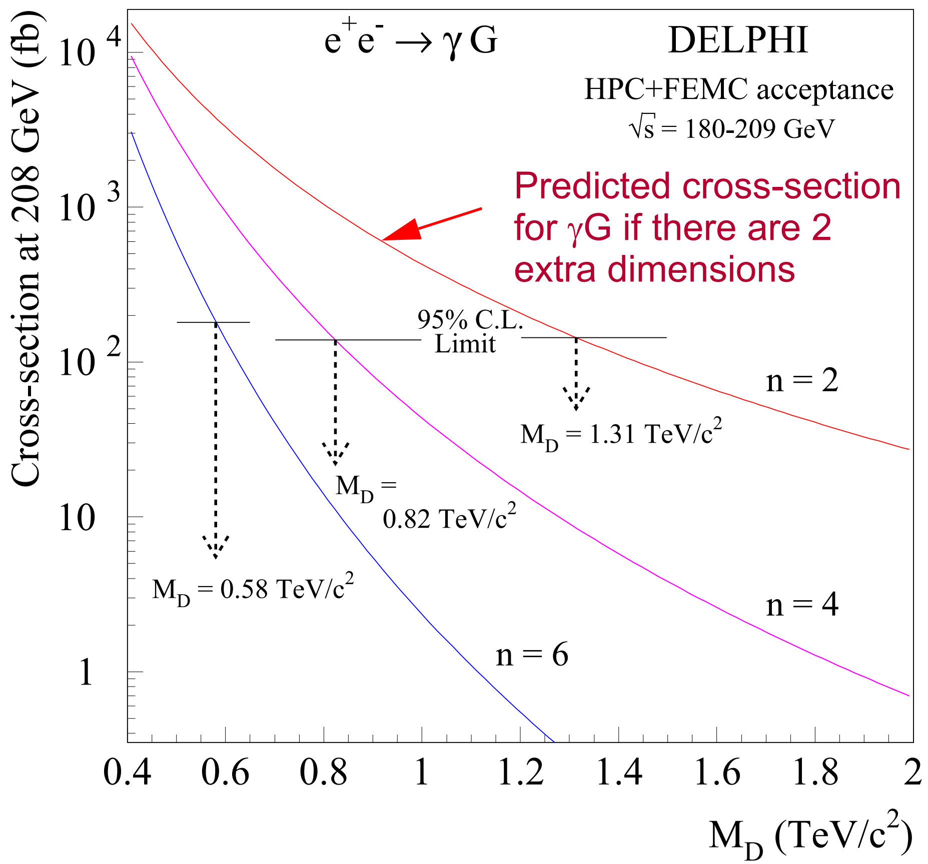
Figure 208: DELPHI measurement of single-photon energy: no extra-dimensions signature

- In Fig.208, n is number of extra dimensions and M_D is the fundamental mass scale in the theory

- We can set limits on:
  - Number of extra dimensions (between 1 and 6)
  - Mass scale M_D
  - Cross section of the γG production and parameters that depend on it

    DELPHI set the limit of
    $M_D > 1.31$ TeV
    for 2 extra dimensions

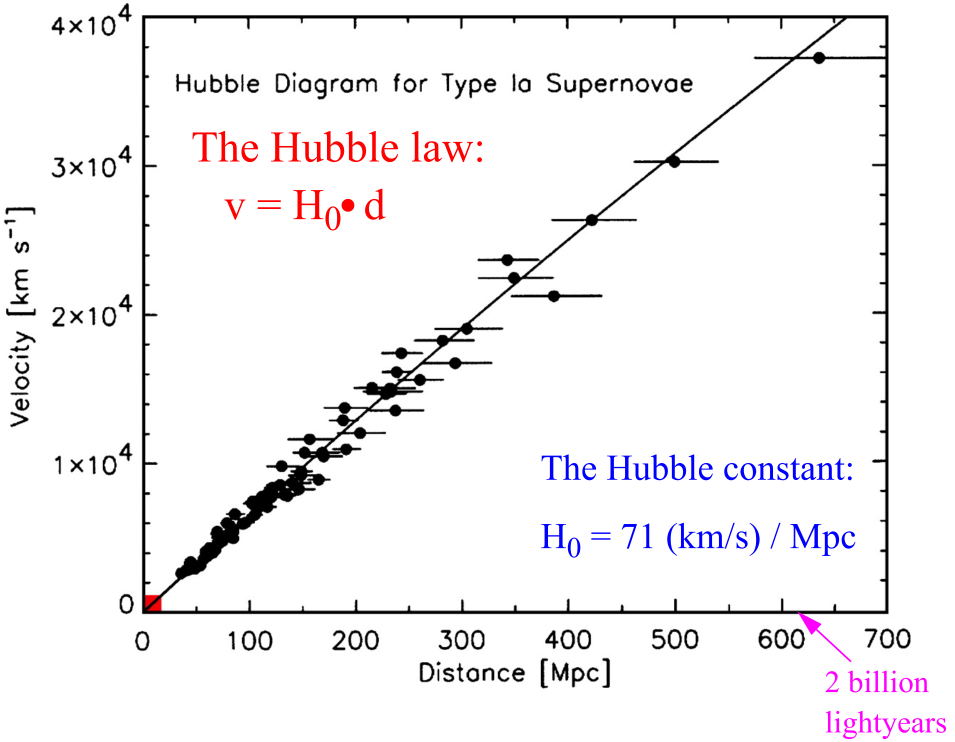
    Cosmological constrains actually lead to much higher limits on M_D



Dark matter and dark energy

Experimental evidence for the Big Bang model:

- Matter distribution in the universe is nearly uniform
- Abundance of light elements, such as He, D and Li
- The universe is expanding, and the velocities of extragalactic objects are increasing with their distance to Earth (the Hubble's law)
- The cosmic background radiation (*cosmic microwave background*) with the temperature of 2.7 K (0.0002 eV) is quite uniform and is regarded as a remnant of the Big Bang



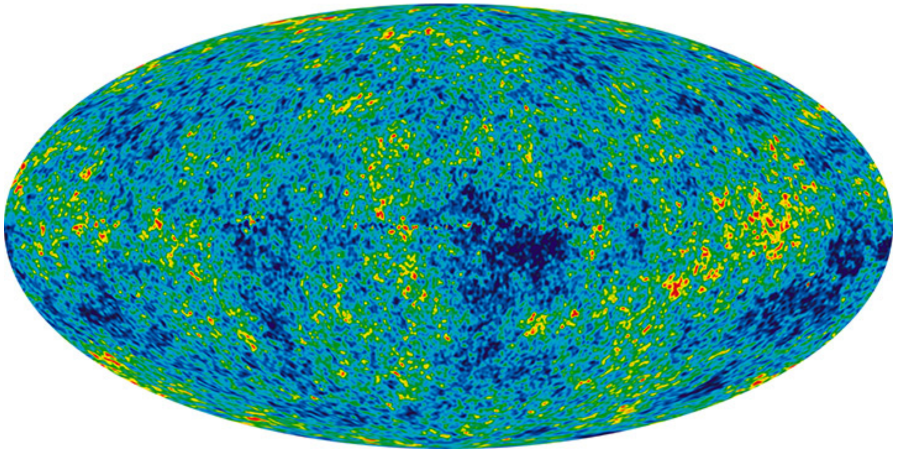


Figure 209: The sky map in microwave frequencies using data from 9 years of the WMAP mission with MilkyWay subtracted; temperature range is ±200 μK

Expansion should halt at the *critical density* ρ_c of the universe:

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

Here H_0 is the *Hubble constant* and G is the gravitational constant. If the density is larger than ρ_c, the expansion ends.

The *relative density* Ω is actually estimated to be close to 1 in the *inflationary* Big Bang model:

$$\Omega \equiv \rho / \rho_c = 1$$

The relative density consists of a matter part Ω_M and an energy part Ω_Λ:

$$\Omega = \Omega_M + \Omega_\Lambda$$

- However, relative density of the *observable baryonic* matter (i.e., the one emitting electromagnetic radiation) in the universe is only few percent!
- The rest is called the "*dark matter*" and the "*dark energy*" (known since 1930ies)

Dark matter

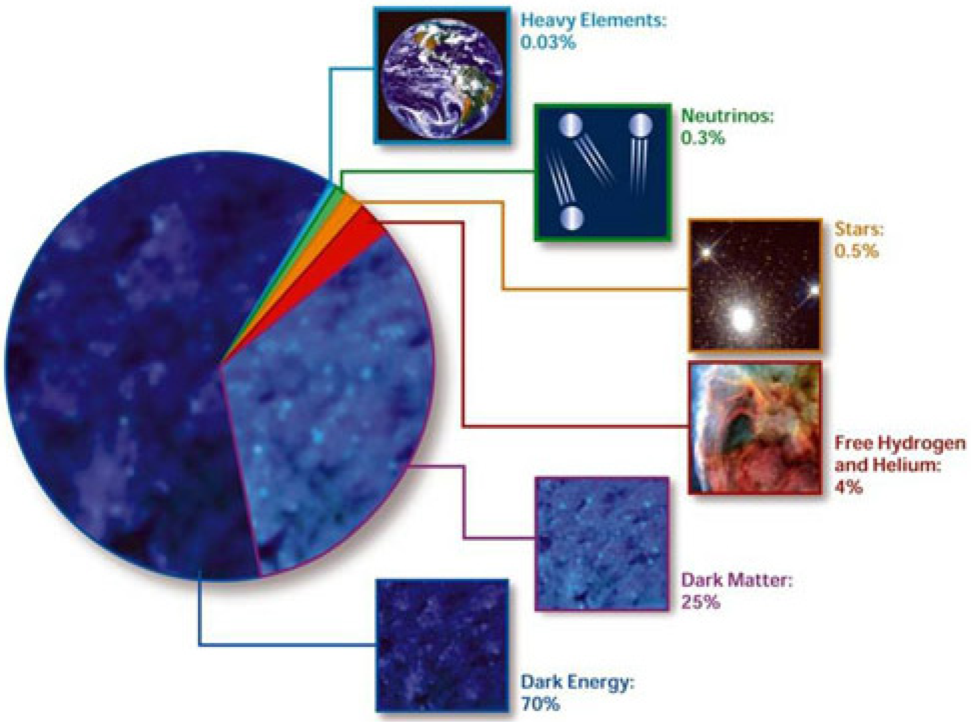


Figure 210: Composition of the Universe

- One of the best evidences for dark matter came from measurements of the rotational velocity of stars in galaxies
  - The large rotational velocity of stars in the outer regions of the Milky Way can be explained if the galaxy is full of invisible dark matter

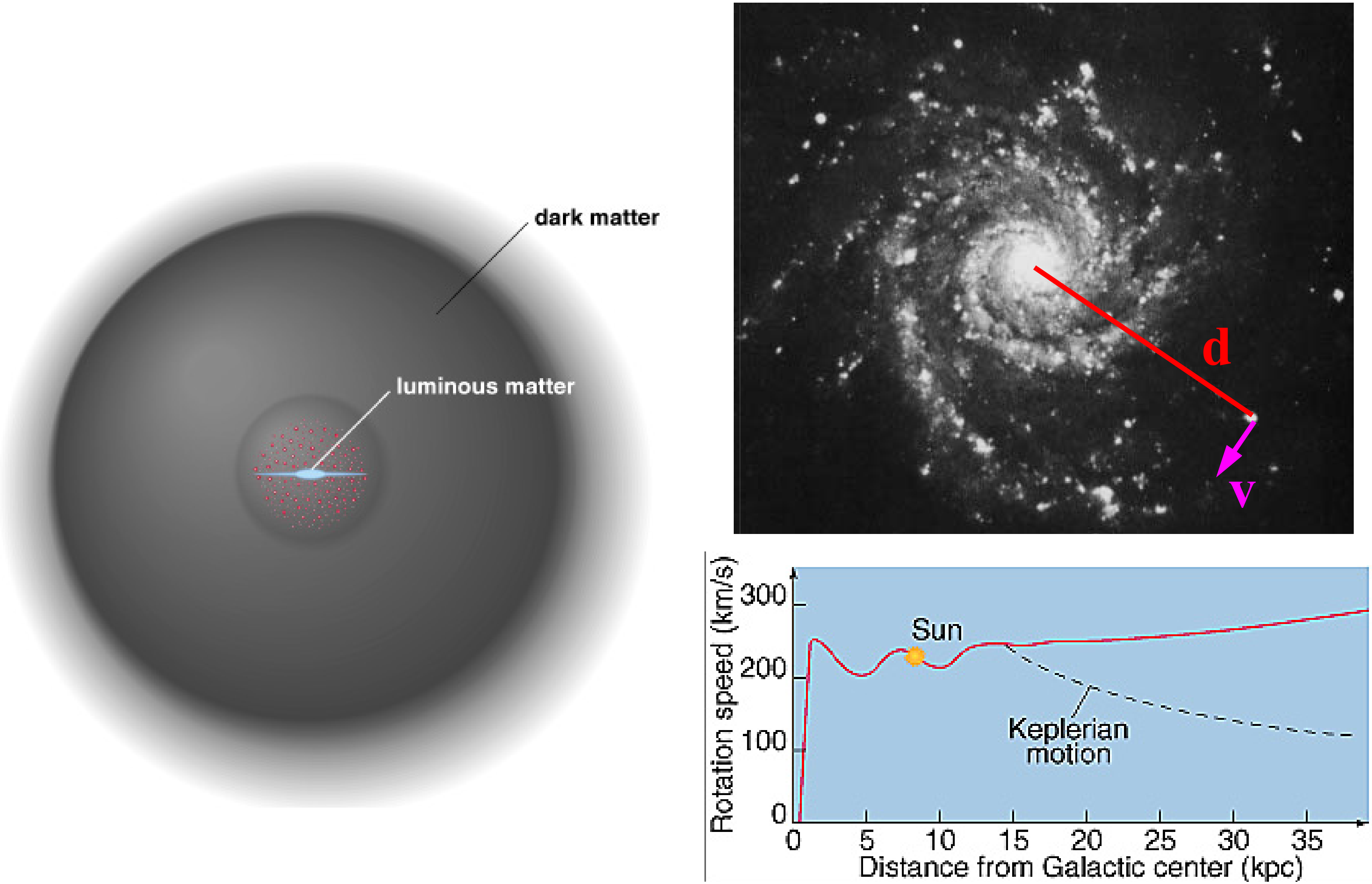


Figure 211: Measurement of rotational speeds of stars in galaxies indicates presence of dark matter

- Possible components of the dark matter:
  - *Baryonic matter* that emits little or no electromagnetic radiation: brown dwarfs, small black holes – MACHO's (for MAssive Compact Halo Object); can not have significant contribution
  - Massive neutrinos ("*hot dark matter*"): at the Big Bang, the rate of neutrino production is the same as of photons $\Rightarrow$ knowing the density of photons, expansion rate of the universe and neutrino masses, one can calculate contribution of hot dark matter, which will be significant if neutrino mass exceeds 1 eV. They however can't constitute a significant part of dark matter, as it will be difficult to explain galaxies formation.
  - "*Cold dark matter*": WIMP's (Weakly Interacting Massive Particles), non-baryonic objects, non-relativistic at early stages of the universe evolution. SUSY particles could be such WIMPS.

Dark energy

- Universe's expansion is actually accelerating
  - Shown by studies of magnitude of supernovas and their red-shifts
  - Such acceleration indicates presence of a repulsive force
  - While dark matter produces attractive force, dark energy is responsible for the *gravitationally repulsive force*
- Cosmic Microwave Background (CMB) measurements estimate matter (observable and dark) at just ~32%
- Motion of galaxy clusters suggests the same
- The rest is then dark energy

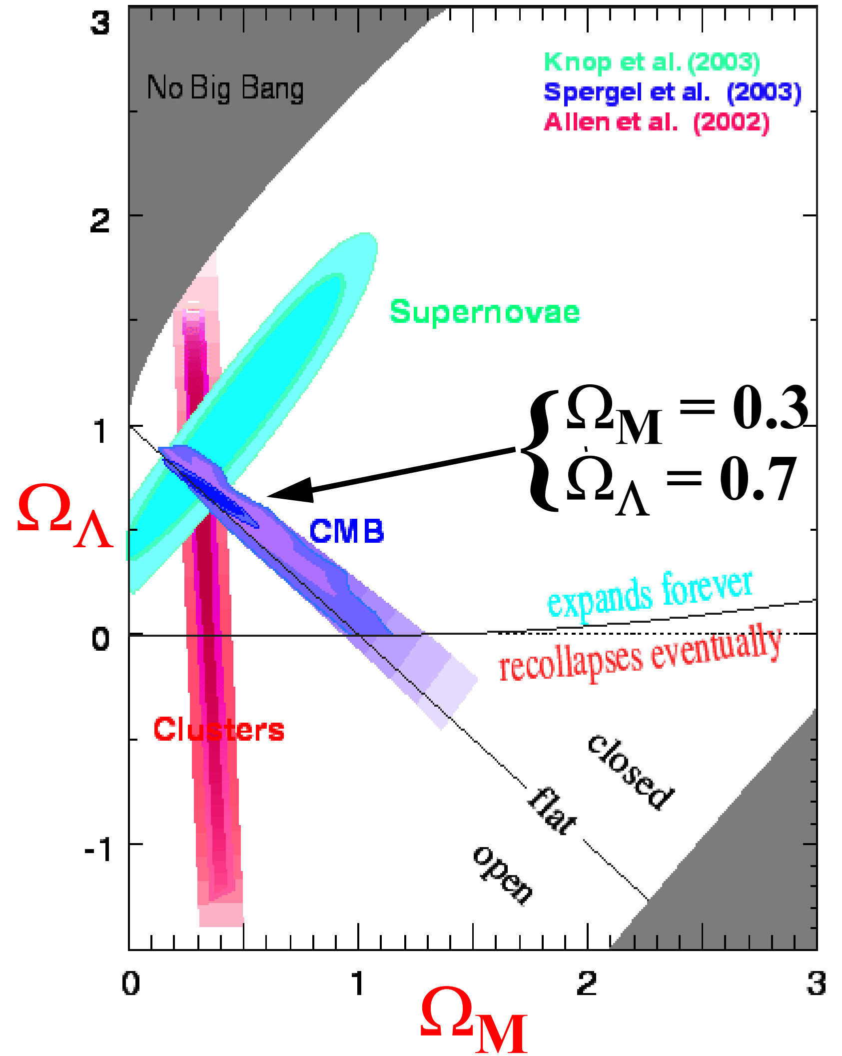


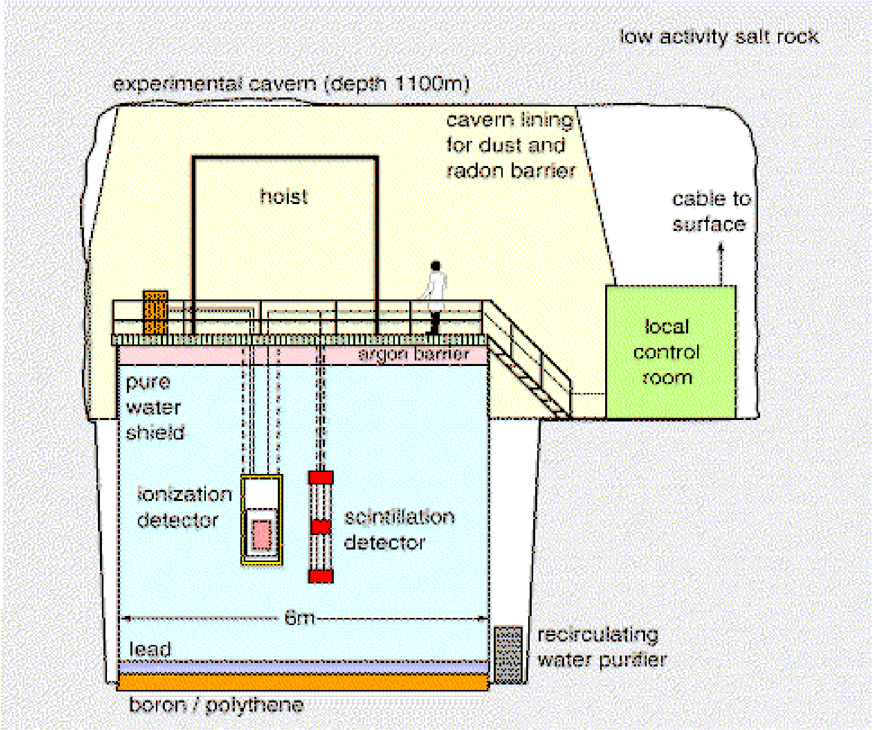
Figure 212: Summary of dark matter and dark energy data

Two main hypotheses for the dark energy:

- The *Cosmological Constant*: space is thought of having 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 is many orders of magnitude larger than astronomical observations
  - While cosmological constant may explain acceleration, it is not quite consistent with dark energy data and models
- *Quintessence*: particle-like excitations in a dynamic field called quintessence. This field differs from the cosmological constant in that it can vary in space and time.
  - No evidence of quintessence has been found yet

Searches for dark matter

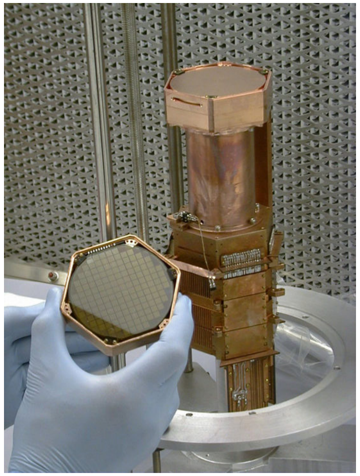
- WIMPs are the obvious target
- Estimates show that there can be 1 WIMP interaction per 1kg of matter per 1 day
- Like neutrino detectors, WIMP experiments have to be shielded from background, located underground



- A number of direct WIMP search experiments are running, including several consecutive detectors in the Boulby mine, UK
  - NaIAD experiment ran in 2000-2003 and produced best limits on WIMP-nucleon cross-section. It used a NaI detector which produced scintillation light if a WIMP interacts with an atom. 200 tons of ultra pure water was used for shielding.
  - Series of DRIFT experiments: *directional* dark matter search

Although the results are still inconclusive, several experiments announced events above predicted background: CoGeNT, CRESST, Edelweiss and CDMS

- CDMS stands for Cryogenic Dark Matter Search, and refers to a number of experiments that make use of semiconductor detectors cooled to milikelvins



  - CDMSII and SuperCDMS were located in the Soudan mine (SuperCDMS moves to Sudbury) and use Ge detectors that would produce phonons upon interaction with WIMPs
  - In April 2013, CDMSII announced 3 events when 0.7 were expected - 3-sigma confidence level
  - The signal is compatible with SUSY neutralinos, but more data are needed