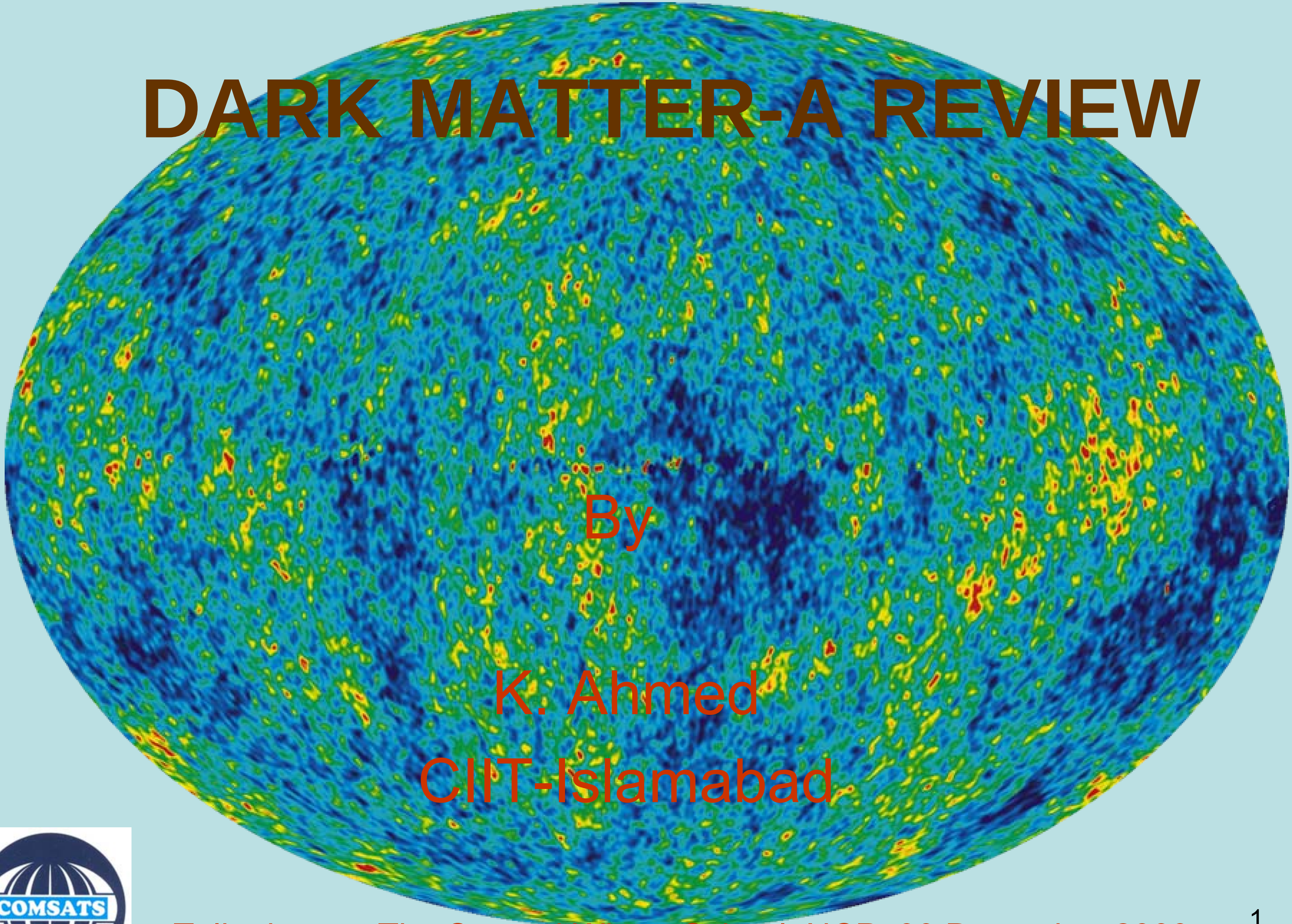


DARK MATTER-A REVIEW

By

K. Ahmed
CIIT-Islamabad

Talk given at The Second Winter School, NCP, 30 December 2009

Layout

- Energy Budget of the Universe
- What is Dark Matter?
- History
- Evidence for Dark Matter
- Gravitational Lensing
- SM and Cosmology
- Supersymmetry
- LSP as Dark Matter candidate
- References

Layout (continued)

- BIG-BANG COSMOLOGY:

  “Einstein-Freedmann- Lemaitre Equations of Motion”:

$$H^2 = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G_N \rho}{3} - \frac{k}{R^2} + \frac{\Lambda}{3},$$

where "H" is the Hubble parameter that varies with time, ρ is the energy density k is the curvature and Λ is the cosmological constant.

- Equation of State:

$$\dot{\rho} = -3H(\rho + p)$$

- Some Cosmological Paramters:

$$\rho_c = \frac{3H^2}{8\pi G_N} = 1.88 \times 10^{-26}\, h^2 kg\, m^{-3}$$

$H = 100$ h km s^{-1} Mpc^{-1}

$\Rightarrow H^{-1} = 9.78\, h^{-1}$ Gyr

Another form of Friedmann Equation

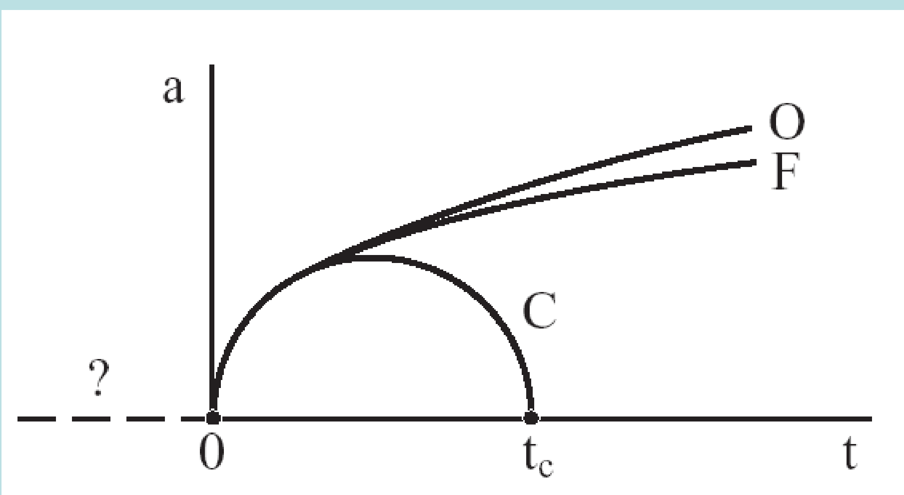
$\Omega_{tot} = \rho / \rho_c;$

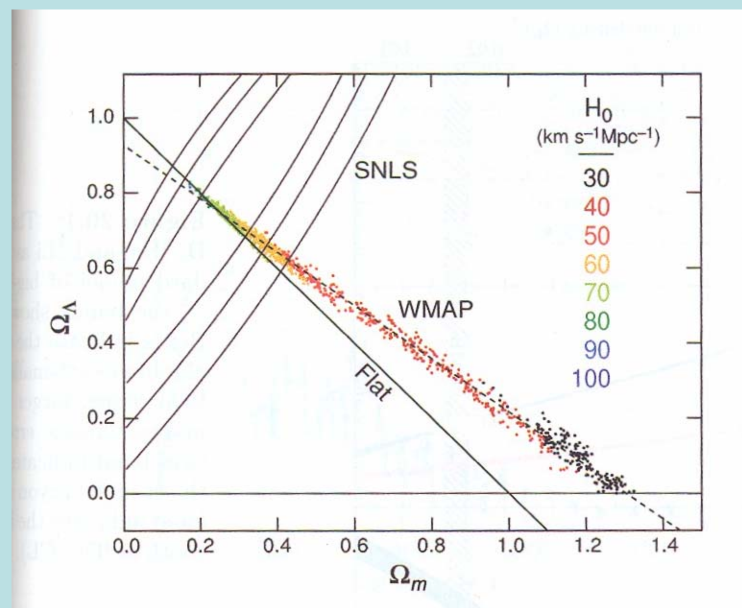
$k / R^2 = H^2(\Omega_{tot} - 1)$

Three scenarios

- Closed universe $\Omega_{tot} > 1, k = +1$
- Open universe $\Omega_{tot} < 1, k = -1$
- Flat universe $\Omega_{tot} = 1, k = 0$

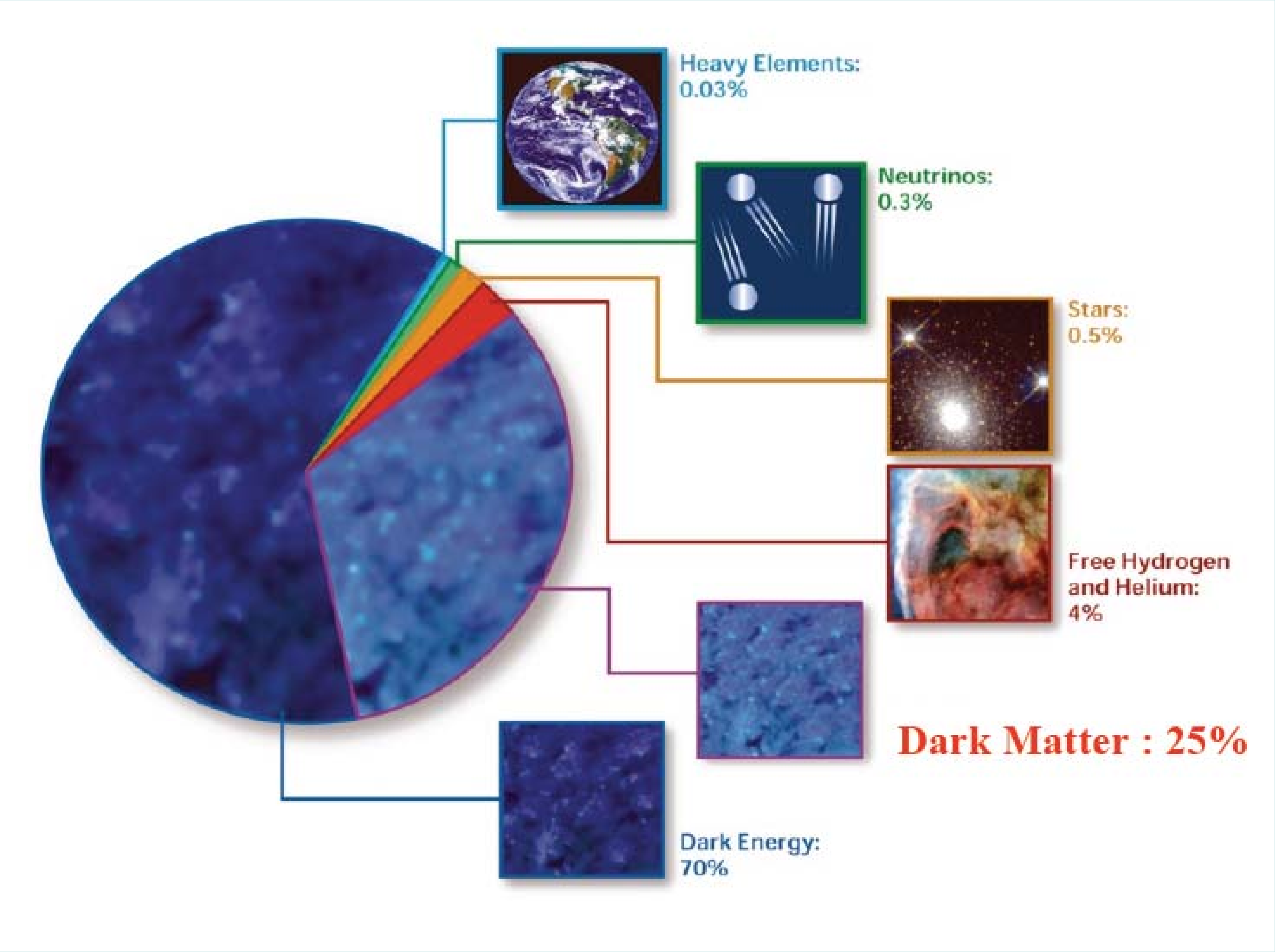
$$\Omega_\Lambda + \Omega_m \approx 1$$





Energy Budget of the Universe

- Stars and galaxies ~0.5%
- Neutrinos ~0.1-1.5%
- Rest of ordinary matter ~4.4%
- **Dark matter ~23%**
- Dark Energy ~73%
- Anti-Matter ~0%


Heavy Elements:
0.03%
Neutrinos:
0.3%
Stars:
0.5%
Free Hydrogen
and Helium:
4%
Dark Matter : 25%
Dark Energy:
70%

What is Dark Matter?

- It consists of neutral, non-luminous and non-interacting stuff(?).
- In astronomy and cosmology, dark matter is hypothetical matter that is undetectable by its emitted radiation, but whose presence can be inferred from gravitational effects on visible matter.

What is DM? (contd.)

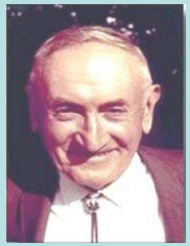
- It is now known that DM is not made up of baryons and is non-luminous/non-radiant and is not “Jupiter-like dust”. It cannot be a light nuclear particle like the neutrino because neutrino being so light cannot $(m_{\nu_e} \lesssim 1\ eV)$ comprise so large energy density as one quarter of the energy density of universe. It is electrically neutral and carries no color charge.

- It is safe to assume that the DM would be found in weak TeV scale provided the DM was in thermal equilibrium with all the species existing after the Big-Bang.

History

Zwicky F., Helv. Phys. Acta **6, 110 (1933)**

1933



- The mass of Coma cluster was first estimated by Zwicky to be $M > 5 \times 1014 M_O$, using the virial theorem. This estimation was based on a value of 1200 km/s for the radial velocity dispersion of the cluster galaxies, not too far from current estimates (e.g. Colless & Dunn).
- The corresponding mass-to-light ratio was large, $M/L > 50 M_O / L_O$, and a form of invisible matter seemed needed. Zwicky suggested that there must be some non-visible form of matter, which would provide enough of mass to hold the cluster together.

Virial Theorem

The virial theorem that more massive galaxies should have faster rotational velocities:

Virial Theorem

(Claussius 1870)

For a bound gravitational system, the long-term average of its kinetic energy is one half that of its potential energy.

Kinetic Energy: 1) orbital kinetic energy (bulk motion)

2) thermal kinetic energy (random motion)

only 1) rotationally supported against gravity
Earth-Moon, Earth-Sun, the Milky Way galaxy (spiral galaxies),....

only 2) `pressure' supported against gravity
stars & gaseous planets, globular clusters of stars

1+2) mixed support
elliptical galaxies, super-cluster of galaxies

Virial Theorem: <1> + <2> = - ½ <U>
(total energy = <1 + 2 + U > = ½ <U> [less than 0])

$$\frac{mv_c^2}{2} - \frac{GMm}{R} = -\frac{GMm}{2R}$$

$$v_c^2 = \frac{GM}{R}$$

$$M = \frac{v_c^2 R}{G}$$

http://www.astro.toronto.edu/~mhvk/AST221/L6/L6_4.pdf

http://odin.physastro.mnsu.edu/~eskridge/astr225/week10.html

- 1970

Spiral Galaxy NGC 4414

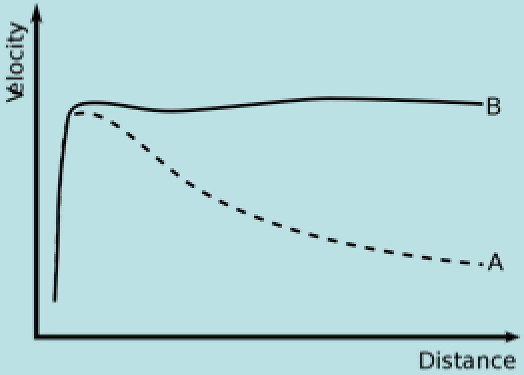


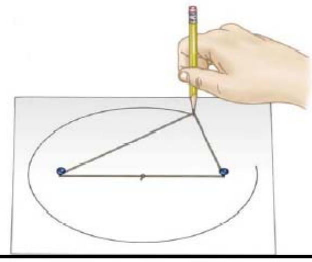
Fig. Rotation curve of a typical spiral galaxy: predicted (A) and observed (B). Dark matter can explain the velocity curve having a 'flat' appearance out to a large radius

- Vera Rubin's made a collection of conclusive data pointing to the presence of dark matter in galaxies. These data are measurements of the orbital velocities of interstellar matter in galaxies. She studied the variation of these velocities with distance from the center of the galaxy.

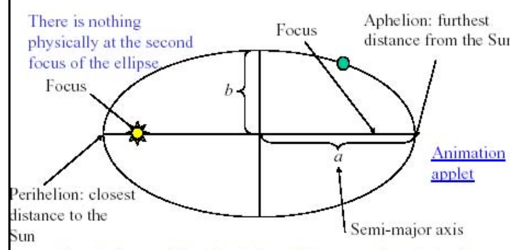
- It is assumed that matter orbits about the center of a galaxy owing to a centripetal force which is the gravitational attraction of other matter in the galaxy. Assuming all other matter in the galaxy is luminous, astrophysicists cannot account for the centripetal accelerations observed. These can be accounted for, however, if additional matter is present.
- It was determined that the velocity varies as a function of distance from the galactic center of clouds of ionized hydrogen. This was done by measurement of the Doppler shift of their H-alpha emission lines. The hydrogen clouds move with the stars and other visible matter in the galaxies. Their velocities are more easily and directly measured than other visible matter.

Kepler's First Law

- The orbit of a planet about the Sun is an ellipse with the Sun at one focus.



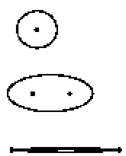
Elliptical Orbit



For the Sun and the planets the orbits are are almost circular.

Eccentricity = Shape of Orbit

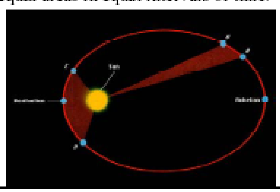
- Values range from 0 to 1
  - 0 = circle
  - 0.5 = ellipse
  - 1 = straight line



$$\varepsilon = \sqrt{1 - \frac{b^2}{a^2}}$$

Kepler's Second Law

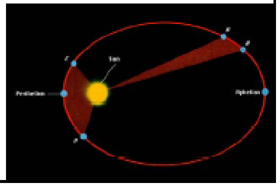
- "The Law of Equal Areas" -- A line joining a planet and the Sun always sweeps out equal areas in equal intervals of time.



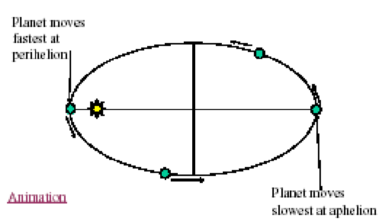
Animation applet

Question

- Does the speed of an object change in an elliptical orbit? If so, where does it move fastest and where does it move slowest?



Speed of Planets in Elliptical Orbits



Animation

Kepler's Third Law

- $P^2 = a^3$
  - P = sidereal period in years
  - a = semi-major axis in AU
    - AU = Astronomical Unit = Average distance between the Earth and the Sun
  - The closer a planet is to the Sun, the less time it takes to go around the Sun.

Example: If $P = 8$ years then

$$P^2 = 64 = a^3$$

$$\Rightarrow a = \sqrt[3]{64} = 4 \text{ AU}$$

http://www.uwsp.edu/physastr/kmenning/Astr311/

- **It was found that the velocities of the clouds did not decrease with increasing distance from the galactic center, and in some cases even increased a little. This is in striking contrast to the decrease in velocity with radius predicted by Keplerian motion, which would occur if all the mass of the galaxy were concentrated in the center of the galaxy**.

- In this case, one has the result that the velocity decreases inversely as the square root of the radius (distance from center); i.e., Of course not all the mass of the galaxy is located in the center. Generally, however, there is a central region where most of the visible matter is located, as the galaxy NGC 4414. The region is called the central bulge. If we assume the mass in the galaxy is distributed as are the luminous regions, the velocities would still be expected to decrease with increasing radius at large radii, though the decrease would not be as rapid as if all the mass were located in the center.

Dark Matter: the most impressive quantative or qualitative evidence

- Latest WMAP & LSS data provides stringent bounds on Ω_{DM} and Ω_B ⇒

Evidence for non-baryonic DM at more than 10 standard deviations!! The SM does not provide any candidate for such non- baryonic DM.

- LSS formation requires DM to be COLD

⇒ New particles not included in the spectrum of the fundamental building blocks of the SM!

Rise and Fall of Neutrinos As Dark matter

- Massive neutrinos are only candidates in the SM to account for DM, starting with the “prejudice” of neutrinos of a few eV to correctly account for DM.

- Neutrinos decouple at temperatures ~1 MeV. Since their mass<< decoupling temperature, neutrinos remain relativistic for a long time. Being very fast, they smooth out any possible growth of density fluctuation forbidding the formation of proto-structures.

- The “weight” of neutrinos in the DM budget is severely limited by the observations disfavoring scenarios, where first super large structures arise and then galaxies originate from their fragmentation.

DARK MATTER SEARCH

- Evidence For DM (non-luminous, non-baryonic, non-radiating) comes from:

  1. Motion of cluster of galaxies where the inward gravitational pull from within the center is insufficient to balance the outward “centrifugal force” of the matter. Without DM the cluster will pull itself apart.

  2. Similar mechanism helps to stabilize individual galaxies when their rotational motion is considered. This balancing ensures that the speed of galaxies in the cluster beyond the bright core should fall inversely *with square root of distance from the center*.

This is contrary to observation. Rotational **curves remain constant at radii** far **exceeding the luminous core** indicating a dark component of mass, i.e., the galaxies **possess a halo of DM**.

DARK MATTER SEARCH (CONTD.)

- Measurement of Cosmic Microwave Background Radiation (CMBR) provides an opportunity to make a precise mapping of the Dark Matter.
- Various new and sensitive technologies have measured variations from uniform CMBR to the tune of $1:10^{-5}$.
- These variations in the CMBR arise from the early universe as quantum fluctuations from an inflationary epoch, in which the universe is assumed to expand exponentially for a very short fraction of a second.
- These fluctuations under gravity and with time can grow into **large scale structures to form galaxies and clusters that we see today**.
- The amount and type of material that clumps under gravity determines the structure.
- Simulations indicate that **substantial DM component is consistent with observations**.
- A universe **without the DM component** grows insufficient structure.

DM and Baryonic Density

- These fluctuations create in homogeneities and anisotropies in the CMBR after passing through the DM background, [PDB 2008]:

$$\Omega_{DM} h^2 = 0.106 \pm 0.008 \qquad (1)$$

$$\Omega_{baryon} h^2 = 0.0223^{+0.0007}_{-0.0009} \qquad (2)$$

$$\rho_{DM}^{local} \simeq 0.3 \frac{GeV}{cm^3} \qquad \mathbf{(3)}$$

- where Ω_{DM} is DM density parameter, and Ω_{baryon} is the matter density of protons and neutrons. (Note (1) is nearly six times (2)). Eq.(3) is our galaxy's dark matter energy density estimate.

- Big bang expansion resulted in cooling that gave rise to light elements (nucleosynthesis). The abundance parameters of hydrogen, deuterium, helium and lithium, can be easily estimated from basic thermodynamics.

- Baryonic density can also be independently measured from nucleosynthesis.

- These measurements imply a baryon density

$$0.017<\Omega_{baryon}h^2<0.024 \quad \text{.........(4)}$$

Gravitational Lensing

- The phenomena of bending of light around intense gravitational sources led to confirm Einstein's general theory of relativity in 1919 by A.R. Eddington, who observed the starlight around the complete solar eclipse, confirming that the sun causes bending. This phenomenon is also used these days to estimate DM component.

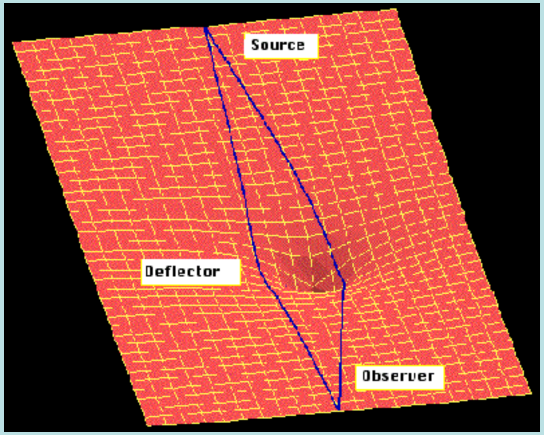


Fig. The deflection of Space-Time by a mass; like a rubber sheet with a cannon-ball on it.

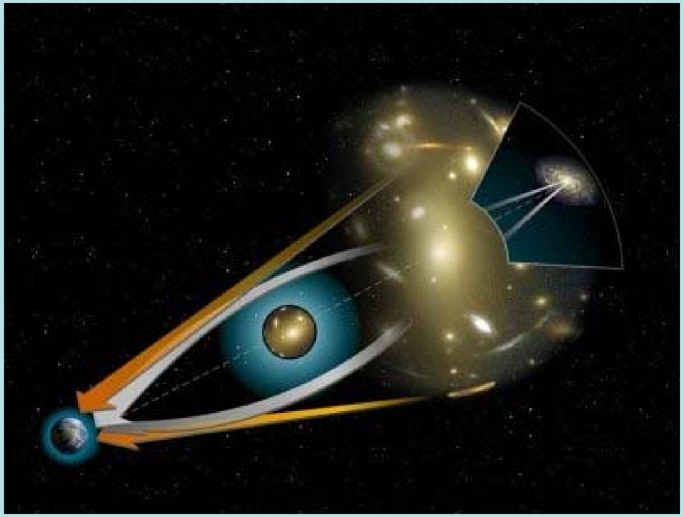


Fig. A gravitational lens at work.

http://plus.maths.org/latestnews/may-aug08/algebra/index.html

Weakly Interacting Massive Particle Annihilation

- One estimates the amount remaining as a “thermal relic” by balancing the expansion rate of the universe against the tendency of WIMP/DM to self annihilate into ordinary matter.

- For sufficiently large expansion rate, DM cannot find other DM particles with which it might annihilate. At this point the **amount of DM** freezes out and annihilation become unimportant.

- This determines the amount of DM in equilibrium balancing the fight between expansion and annihilation, resulting in the equation:

$$\Omega_{DM} h^2 = c \frac{T_o^3}{M_{pl}^3} \frac{1}{< \sigma v >} \qquad (5)$$

where,

T_0 *is temperature and v is the relative velocity of WIMPS annihilating* into *SM particles.*

Using:

$$\Omega_{DM} h^2 = 0.106 \pm 0.008$$

$$< \sigma v > \approx 1\, pb.$$

Approx. mass scale can be calculated from identifying

$$< \sigma v > \approx \frac{\alpha^2}{m^2}, \text{.................(6)}$$

to be Dark matter or WIMP mass:

$$m \approx 100\, GeV\, ! \text{...............(7)}$$

SM & COSMOLOGY

- The gauge theories describe condensation of nuclei (light) from quarks, (nucleosynthesis), with merging of Micro Particle Physics Phenomena and the Macro physics (Cosmology) in terms of Hot Big Bang Standard Model.
- There remain many issues like dark matter, dark energy and matter -anti matter asymmetry.

Cosmology: Need to go Beyond SM(BSM)- SUSY included

- Neutrino Physics:

$$m_{v} \neq 0, \theta_{v} \neq 0$$

- Cosmology –Particle Physics:

Dark Matter

Dark Energy

Baryon-antibaryon asymmetry

Present "Observational" Evidence for New Physics (NP)

- Neutrino Masses ☆ ☆ ☆
- Dark Matter ☆ ☆ ☆

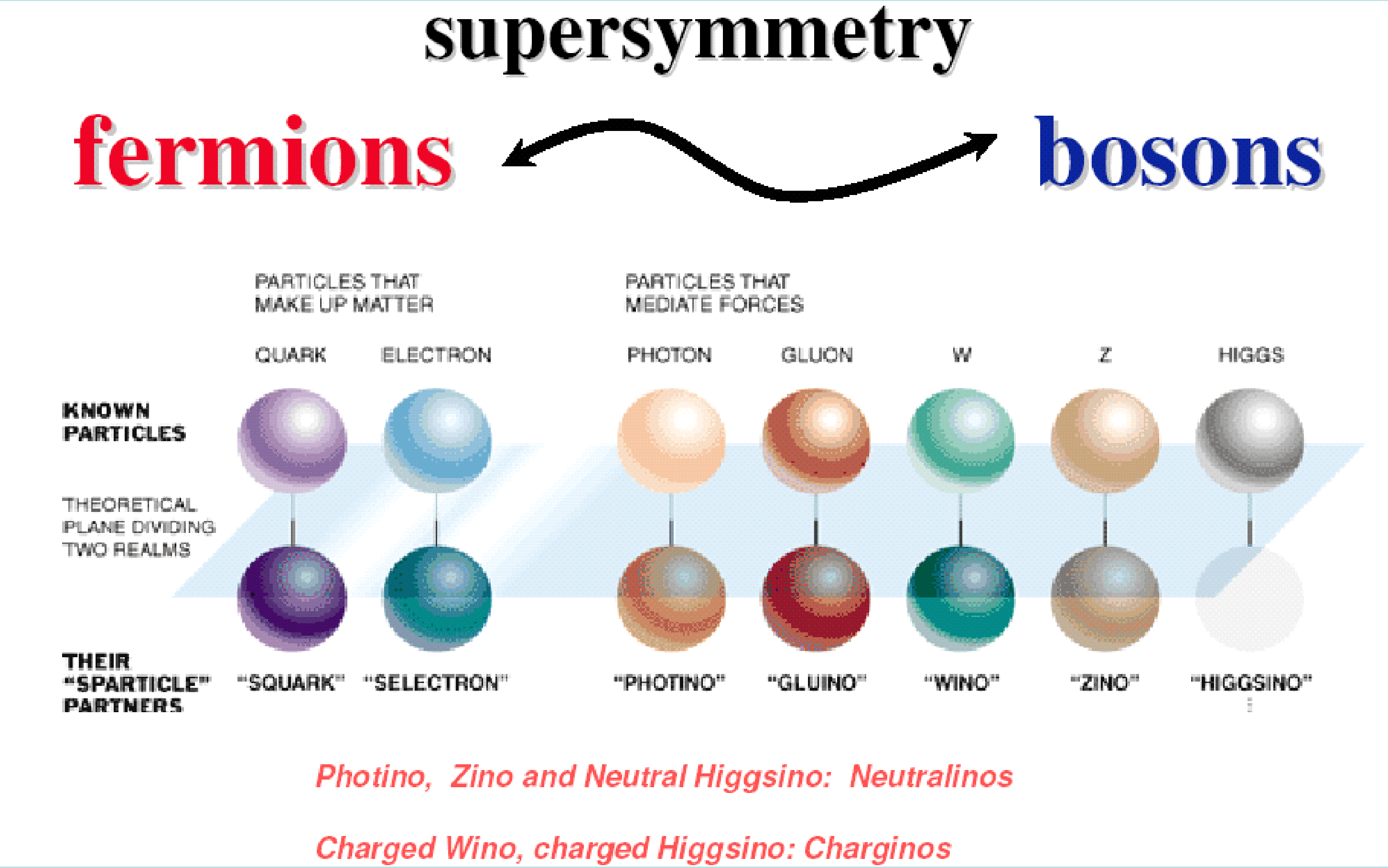
Neutrinos are Massive: New Physics is there!

- Is the above a trivial statement?

  SM built to have massless neutrinos (no RH neutrino, no isospin triplet scalar Higgs),

  find that neutrinos are massive and claim that new physics (NP) discovered!
- No, neutrino mass is “real” NP with a new energy scale associated to it.

WHAT IS SUPERSYMMETRY?



Standard Model Particles		SUSY Partners		
Particles	States	Sparticles	States	Mixtures
Quarks(q) (Spin-1/2)	$\begin{pmatrix} u \\ d \end{pmatrix}_L$, u_{R-}, d_R $\begin{pmatrix} c \\ s \end{pmatrix}_L$, c_{R-}, s_R $\begin{pmatrix} t \\ b \end{pmatrix}_L$, t_{R-}, b_R	Squarks($\tilde{q}$) (Spin-0)	$\begin{pmatrix} \tilde{u} \\ \tilde{d} \end{pmatrix}_L, \tilde{u}_R, \tilde{d}_R,$ $\begin{pmatrix} \tilde{c} \\ \tilde{s} \end{pmatrix}_L, \tilde{c}_R, \tilde{s}_R$ $\begin{pmatrix} \tilde{t} \\ \tilde{b} \end{pmatrix}_L, \tilde{t}_R, \tilde{b}_R$	
Leptons(l) (spin-1/2)	$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L, e_R, \nu_{e_R}$ $\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L, \mu_R, \nu_{\mu_R}$, $\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L, \tau_R, \nu_{\tau_R}$	Sleptons($\tilde{l}$) (spin-0)	$\begin{pmatrix} \tilde{e} \\ \tilde{\nu}_e \end{pmatrix}_L, \tilde{e}_R, \tilde{\nu}_{e_R}$ $\begin{pmatrix} \tilde{\mu} \\ \tilde{\nu}_\mu \end{pmatrix}_L, \tilde{\mu}_R, \tilde{\nu}_{\mu_R}$ $\begin{pmatrix} \tilde{\tau} \\ \tilde{\nu}_\tau \end{pmatrix}_L, \tilde{\tau}_R, \tilde{\nu}_{\tau_R}$	
Gauge/ Higgs bosons (spin-1, spin-0)	g,Z,h,H,A,γ $W^\pm$, $H^\pm$	Gauginos/Higgsinos (spin-1/2)	$\tilde{g}, \tilde{Z}, \tilde{\gamma}, \tilde{H}_1^0$ $\tilde{W}^\pm, \tilde{H}^\pm$	$\tilde{\chi}^0_{1,2,3,4}$ $\tilde{\chi}_{1,2}^\pm$
Graviton	G	Gravitino (spin-3/2)	$\tilde{G}$	

SUSY DM search at LHC

- SUSY is the leading theory of new physics (NP) for physics beyond SM(BSM). SUSY as discussed leads to doubling of spin degrees of freedom.

- However as seen such particles do not exist at low energies, which means SUSY is broken.

- LHC holds a possibility of producing some SUSY particles, especially the LSP (lightest super-symmetric particle).

- LHC will be operating at 14 TeV in the CM for pp-collisions with luminosity ~10^{34}.

LSP Scenarios

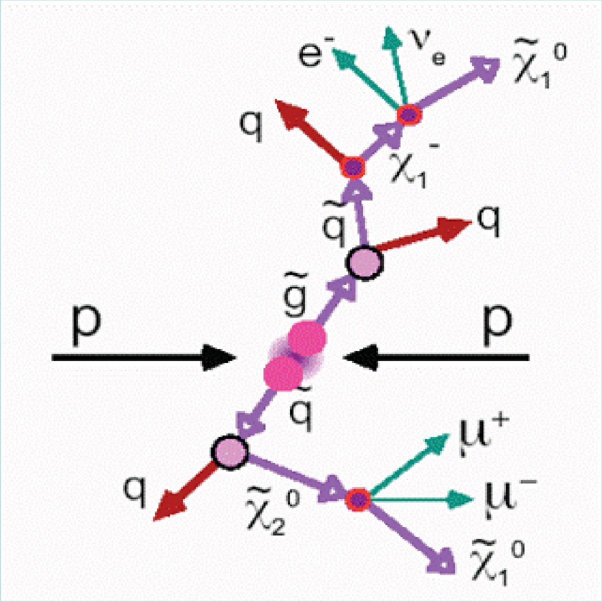
- There are three scenarios, where a neutral sparticle may be found:

1. It may be a SUSY partner of neutrino called sneutrino. This is excluded by the underground detection experiments designed to look for DM by scattering off nuclei.
2. It could be the spartner to the graviton called gravitino. This possibility is still open and under study in Supergravity theory.
3. Another viable possibility is that DM is a neutral superposition of spartners of SM gauge bosons, namely photino, zino, bino and higgsino. This admixture is known as neutralino.
4. One last possibility is that there could be a single scalar particle coupled to the Higgs boson. This will modify the properties of the Higgs boson, which could dominantly decay invisibly and its discovery could occur simultaneously to the discovery of Dark matter.

What if we do not see DM at LHC

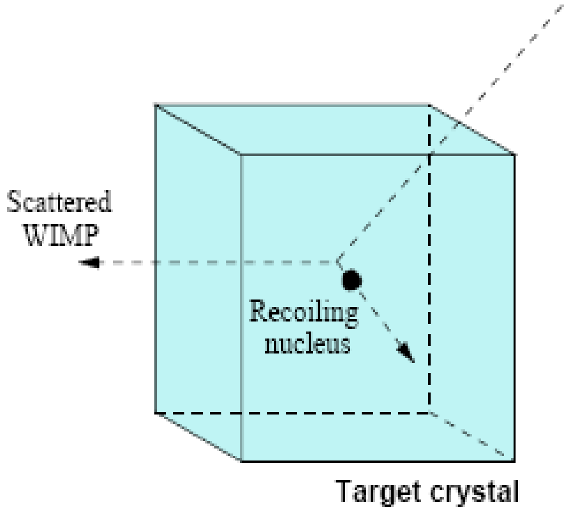
- This may imply that we do not understand DM in terms of TeV scale. One possibility is then axion for dark matter:
- Axion is a particle causing strong CP-violation through violation of Pecci-Quinn symmetry. Axion decay rate through two photons relevant to LHC energies have already been predicted

LSP as Dark Matter Candidate at LHC[CMS,1998 Publication]



Neutralino Dark Matter

If Neutralinos constitute the bulk of dark matter they would cluster with ordinary stars in galactic halos, raising the hope of their direct detection through their elastic scattering with nuclei inside a detector.

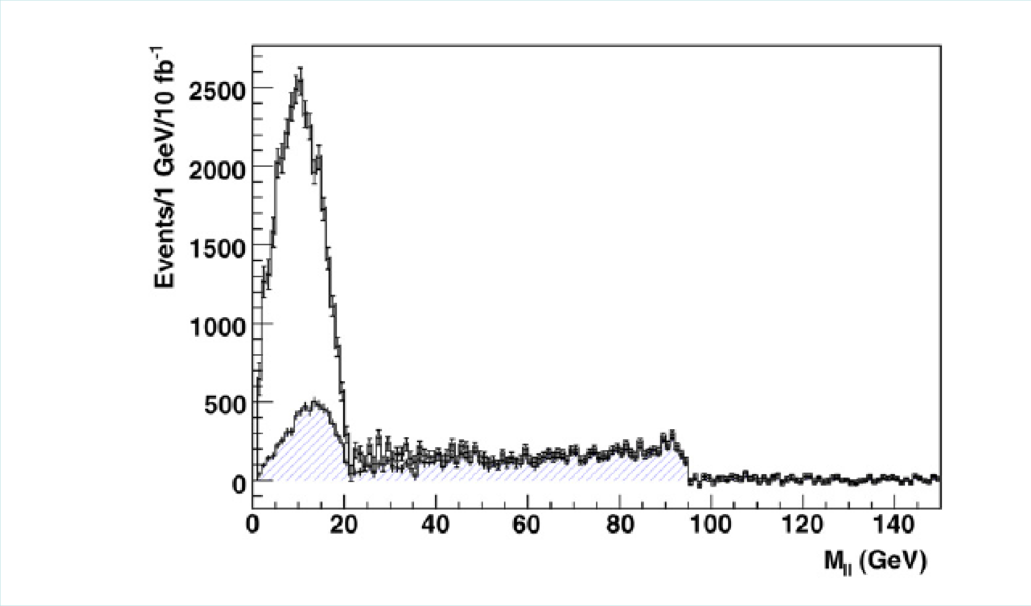


The recoiling energy can be detected by

- Ionization on solids
- Ionization in scintillators (measured by emission of photons)
- Increase in the temperature (measured by the released phonons)

Gravitino Dark Matter

- It is a spin 3/2 partner of graviton. It may be produced at LHC.



K. Hamaguchi , S. Shirai, T.T. Yanagidaa, Physics Letters B 663 (2008) 86–94.

SUSY Signals at LHC/Dark Matter candidate (WIMP)

- The SUSY signals for LHC depend on various models.
- Missing Transverse Energy (MET) for WIMPS
- Five significant (MSSM) models are discussed in "LHC Discoveries Unfolded" by Joseph Lykken and Maria Spiropulu,, Ch.7, in the World Scientific Publication entitled "Perspectives on LHC Physics", p.109, (2008). These particles appearing as missing energy with 5σ and first 100 pb^{-1} cross section. See relevant Figure and Table (pp 124-127 of Lykken & Maria's above article).

MSSMs’ Mass Spectra

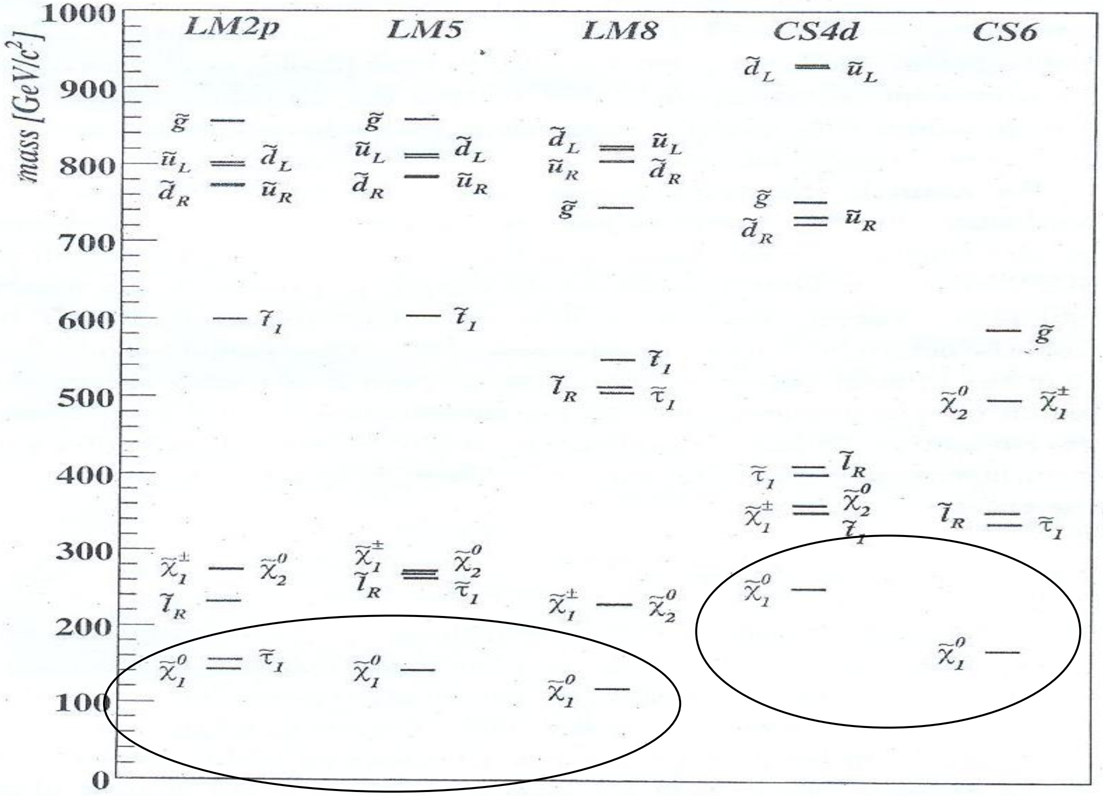


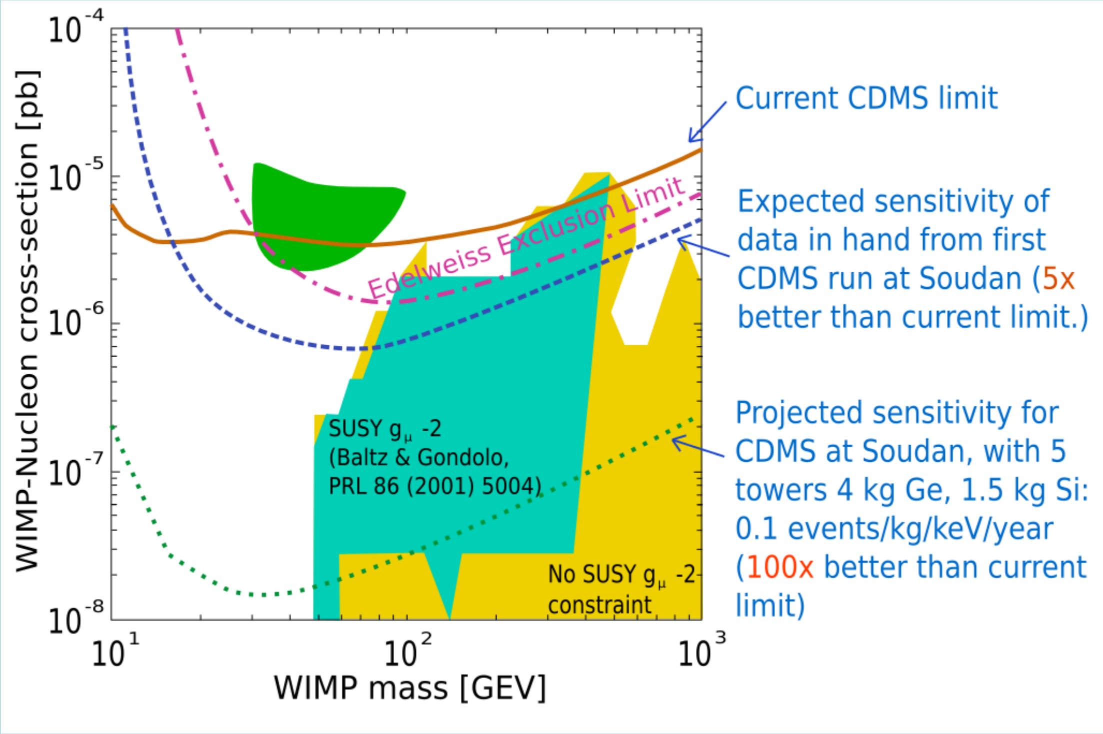
Fig. 7.3. The mass spectra of the MSSM models LM2p, LM5, LM8, CS4d, and CS6 [23]. Only the most relevant particles are shown: the lighter gauginos $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^{\pm}$, the lightest stau $\tilde{\tau}_1$, the right-smuon and selectron denoted collectively as $\tilde{\ell}_R$, the lightest stop $\tilde{t}_1$, the gluino, and the left/right up and down squarks $\tilde{u}_L$, $\tilde{u}_R$, $\tilde{d}_L$ and $\tilde{d}_R$. The very heavy $\simeq$ 2 TeV squarks of model CS6 lie outside the displayed range.

S-particles Decays in Relevant MSSMs'

	LM2p	LM15	LM8	CS4d	CS6
$\tilde{g} \to qq$	45%	45%	-	-	-
$\to \tilde{b}_1 b$	25%	20%	14%	2%	-
$\to \tilde{t}_1 t$	16%	23%	81%	94%	-
$\to q\bar{q}\tilde{\chi}_1^0$	-	-	5%	-	75%
$\tilde{u}_L \to d\tilde{\chi}_1^{\pm}$	64%	64%	55%	-	-
$\to u\tilde{\chi}_1^0$	32%	32%	27%	-	-
$\to u\tilde{g}$	-	-	-	83%	85%
$\tilde{u}_R \to u\tilde{\chi}_1^0$	99%	99%	62%	92%	-
$\to u\tilde{g}$	-	-	38%	-	85%
$\tilde{b}_1 \to t\tilde{\chi}_1^-$	42%	36%	35%	20%	9%
$\to b\tilde{\chi}_2^0$	29%	23%	22%	14%	5%
$\to b\tilde{\chi}_1^0$	7%	2%	1%	50%	-
$\to b\tilde{g}$	-	-	-	-	85%
$\tilde{t}_1 \to b\tilde{\chi}_1^+$	45%	43%	42%	-	-
$\to t\tilde{\chi}_1^0$	22%	25%	30%	-	4%
$\to t\tilde{g}$	-	-	-	-	96%
$\to bW^+\tilde{\chi}_1^0$	-	-	-	100%	-
$\tilde{\chi}_1^{\pm} \to W^{\pm}\tilde{\chi}_1^0$	5%	97%	100%	100%	2%
$\to \tilde{\tau}_1^{\pm}\nu_{\tau}$	95%	-	-	-	77%
$\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0$	1%	11%	100%	100%	-
$\to h\tilde{\chi}_1^0$	3%	85%	-	-	2%
$\to \tilde{\tau}_1\tau$	96%	3%	-	-	77%
$\tilde{\tau}_1 \to \tau\tilde{\chi}_1^0$	100%	100%	88%	98%	100%

WIMPS

- In astrophysics, weakly interacting massive particles**, or WIMPs,** are hypothetical particles These particles interact through the weak nuclear force and gravity, and possibly through other interactions no stronger than the weak force.



CDMS parameter space excluded as of 2004. DAMA result is located in green area and is disallowed

SUSY MASS Spectrum

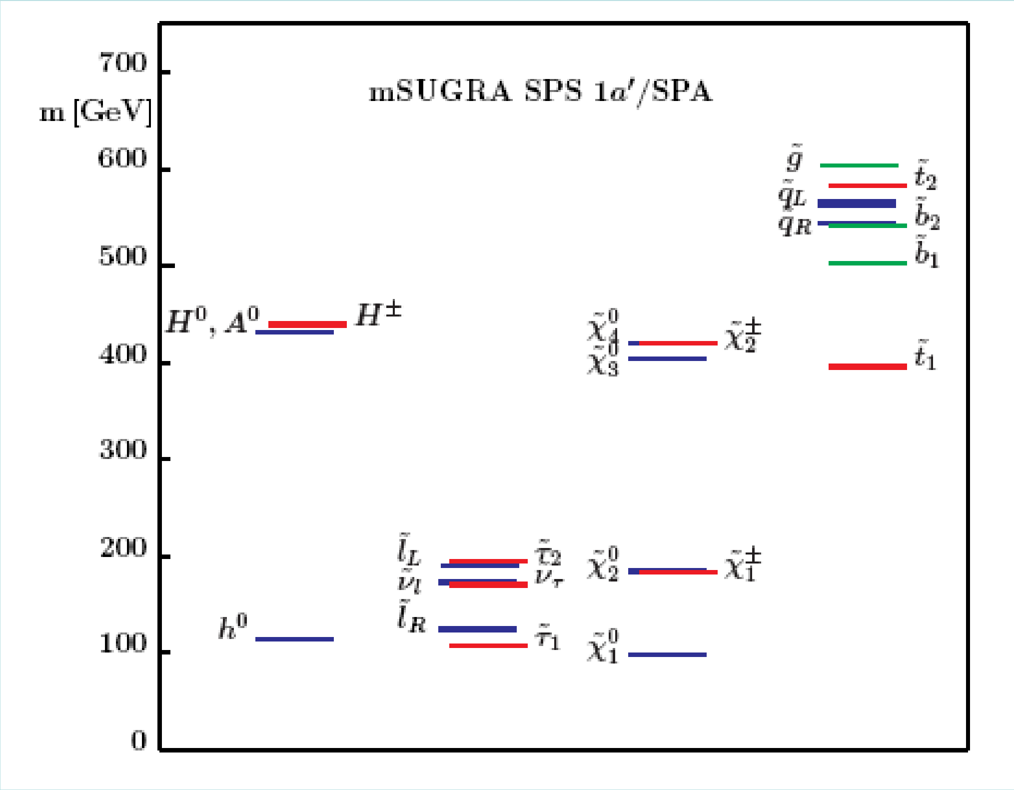


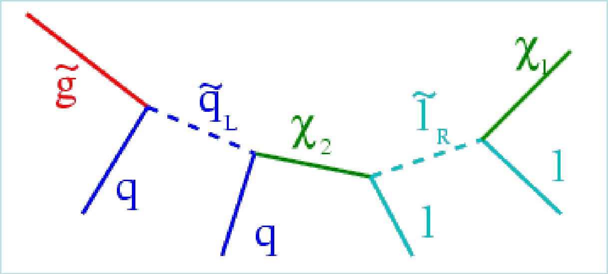
Figure 1:Mass spectrum of sparticles and Higgs bosons for the mSUGRA reference point SPS 1a’.

SUSY Studies, by Jan Kalinowski

Supersymmetry signals at LHC

- LHC is expected to give a copious production of squarks, gluinos.

- Multi-jets and large missing energy may be the signatures of gluino/squark decay chain.



$\tilde{g}$ = gluino

$\tilde{q}_L$ = squark

χ = neutralino

References

- R. Barbier et al., Physics Rep. **420** (2005), 1-195.
- S. P. Martin, A Supersymmetry Primer, hep-ph/9709356v2, March, (1998).
- H. E. Haber, G. L. Kane, Phys. Rep. ***117***, (1985), 175.
- Joseph Lykken and Maria Spiropulu.,“LHC Discoveries Unfolded”,pp-109-131, in “Perspectives on LHC Physics”, eds, Gordon Kane, Aaron Pierce. Published by World Scientific Publishing Co. Pte. Ltd.(2008), and references within.
- H. Murayama, *ArXiv e-prints* (2007), arXiv:0704.2276.

J. M. Overduin, P. S. Wessan, The Light/ Dark Universe, World Scientific, Singapore, (2008).