DARK MATTER PARTICLE PHYSICS

Fiorenza Donato

Dept. Theoretical Physics and INFN, Torino

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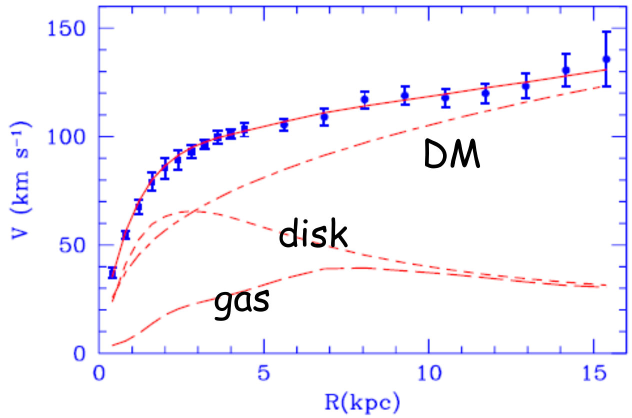
Plan of the lectures

- Dark Matter (DM) candidates
  - Baryonic & non-baryonic
- DM relic density
  - Brief derivation
  - Hot and cold relics
- DM and New Physics
  - Supersymmetric Models (briefly)
  - Neutralino DM
- Direct neutralino DM detection
  - Main formulae
  - Results
- Indirect neutralino DM detection
  - Propagation of chrged particles
  - Gamma-ray
  - Results

Matter & Energy in the Universe

(See Lectures by Goobar and Djorgovski)

M33 RC (Corbelli & Salucci) 1999



Galactic: rotation curves

$\Omega_{lum} \sim 0.01$ (stars&gas)

$\Omega_{halo} \sim 0.1$ (DM)

Extragalactic:

$\Omega_m \sim 0.2\text{-}0.3$

- Clusters of galaxies
  - galaxy motions (optical)
  - temperature of hot cluster gas (X-ray)
  - gravitational lenses to bkgd objects
- Lyman-α (absorption featurs in QSO)

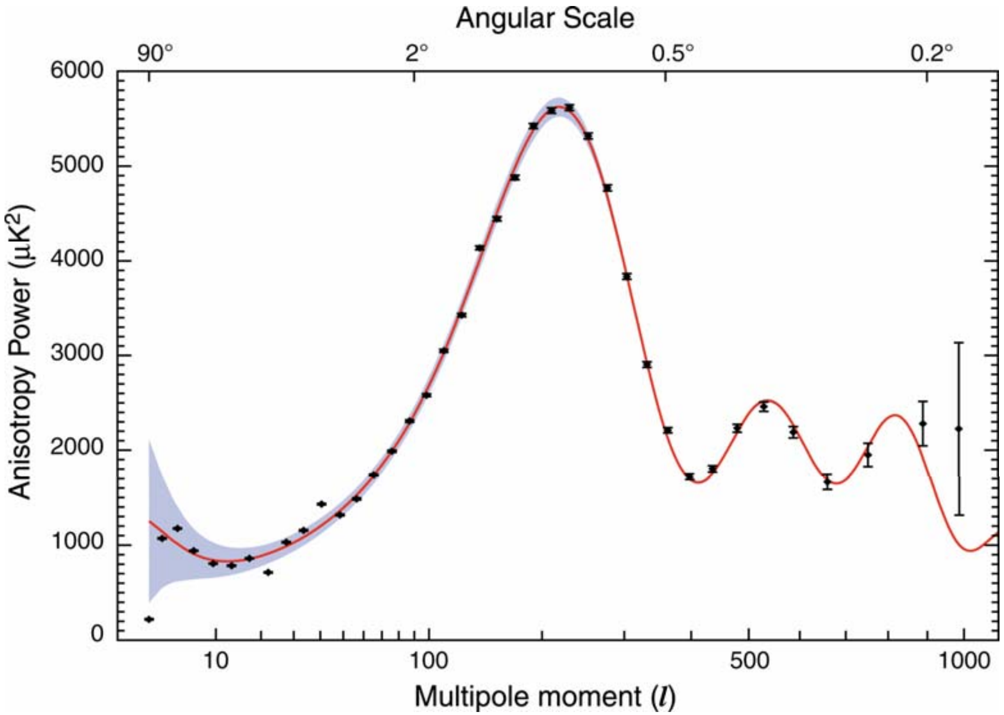
Cosmological scales: CMBR, SNIa, LSS

$\Omega_m h^2 = 0.127^{+0.007}_{-0.013}$ $\Omega_b h^2 = 0.0223^{+0.0007}_{-0.0009}$ (WMAP)

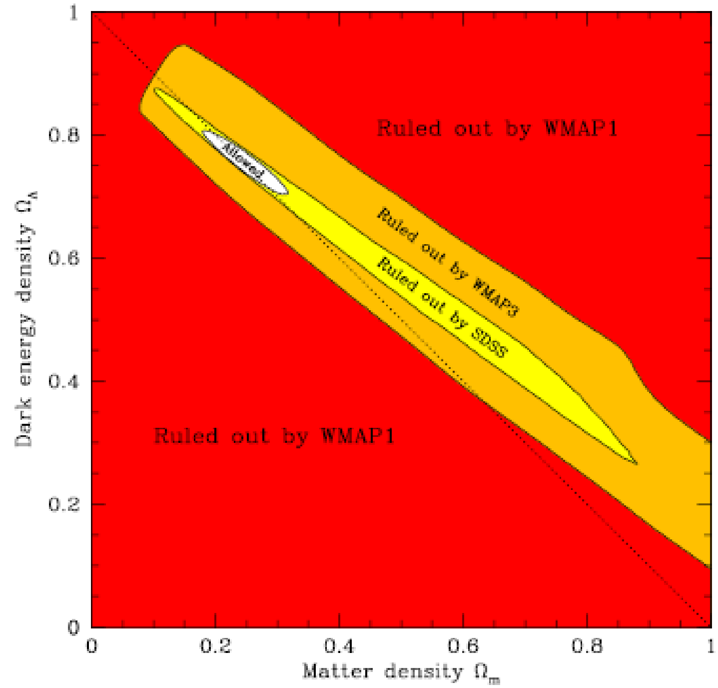
$\Omega_{tot} = 1.003 \pm 0.010$ (WMAP&SDSS)

$\Omega_m \sim 0.24$ $\Omega_\Lambda \sim 0.76$ (WMAP&SDSS)

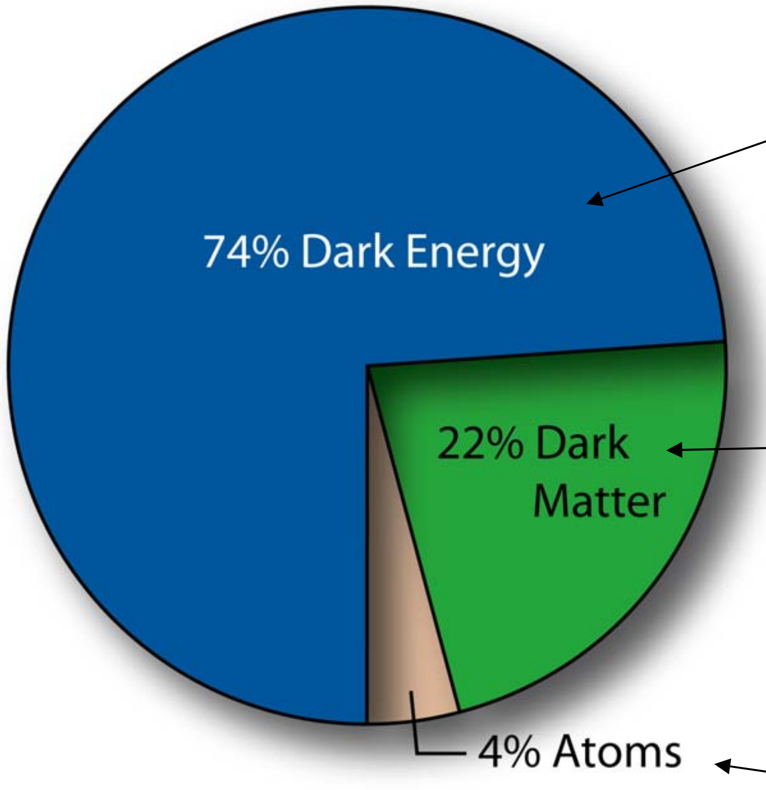
NASA/WMAP Science Team 2006



Tegmark et al. 2006 (SDSS)



Universe Pie



A MISTERY!
See Lectures by Doran...☺

MOSTLY A MISTERY!
Stay with us!
We're going to share
Hopes ☺ and dark thoughts ☹

Standard Model of Particle Physics
MOSTLY UNDERSTOOD...

Candidates to Dark Matter

- Non-"luminous" **baryons**

  Jupiters, white dwarfs, remnants of massive stars:
  MACHOs (gravitational lensing)
  primordial black holes (evaporation products)
  diffused (intragalactic or intracluster) hydrogen (abs. lines)

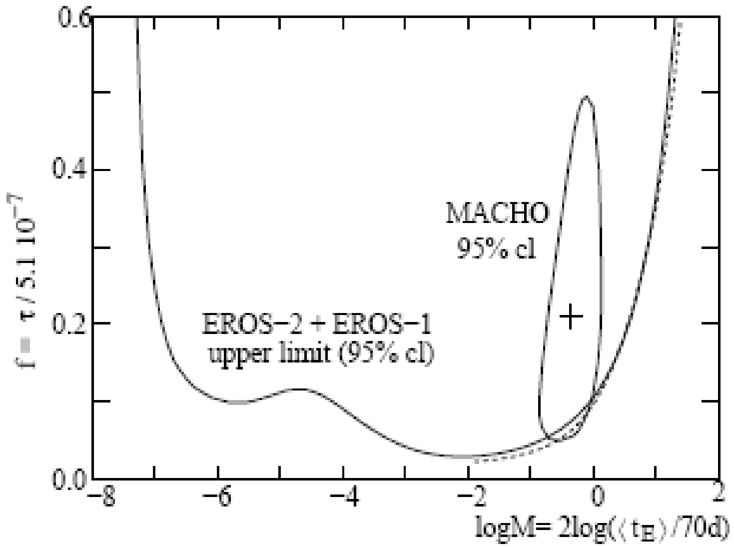
- **Non-baryonic** DM

  Massive neutrino
  Axion
  Neutralino
  Kaluza Klein particle
  Gravitino, axino, sneutrino, ...
  Q-balls, little Higgs, ...
  Ultra heavy ????

  ⇒ **new particles, New Physics!!**

Baryonic DM: limits

EROS Coll. astro-ph/0607207



Baryonic dark matter must be compatible with BBN predictions $0.017 \leq \Omega_b h^2 \leq 0.024$

Neutral hydrogen clouds seen in Lyman-α forests

Density comparable to the one required by BBN

Fraction of dark massive halo objects (machos) is small (< 10%).
MACHO Coll. results different
Self lensing?

Non-baryonic DM

- Relics from early universe
- STABLE on cosmological scales
- Particles in thermal equilibrium with the primordial plasma (**thermal** relics)
  - HOT DM: relativistic when decoupling
  - COLD DM: non-relativistic when decoupling
- WIMP: Weakly Interacting Massive Particles
- Have right relic density

Relic Density

Equilibrium Thermodinamics

A weakly interacting particle gas in thermodynamical equilibrium:

<u>number density</u>: $n = \frac{g}{(2\pi)^3}\int f(\vec{p})d^3p$ <u>energy density</u>: $\rho = \frac{g}{(2\pi)^3}\int f(\vec{p})E(\vec{p})d^3p$

g internal degrees of freedom

f(p) phase space distribution func. $f(\vec{p}) = \frac{1}{e^{(E-\mu)/T} \pm 1}$

$\pm$ Fermi-Dirac/Bose-Einstein, μ chemical potential (assumed to be zero)

Rel. limit (T>>m): $n \propto T^3$, $\rho \propto T^4$

Non-rel. Limit (T<<m): $n \propto T^{3/2}\exp(-m/T)$

Decoupling from the primordial plasma

Consider a stable particle χ

In case of no plasma-χ interaction, the number of χ particles for comoving volume $Y_\chi \equiv n_\chi/s$ is constant. *

<u>Annihilation processes</u> may let Y_χ change: $\chi\bar{\chi} \rightarrow X\bar{X}$

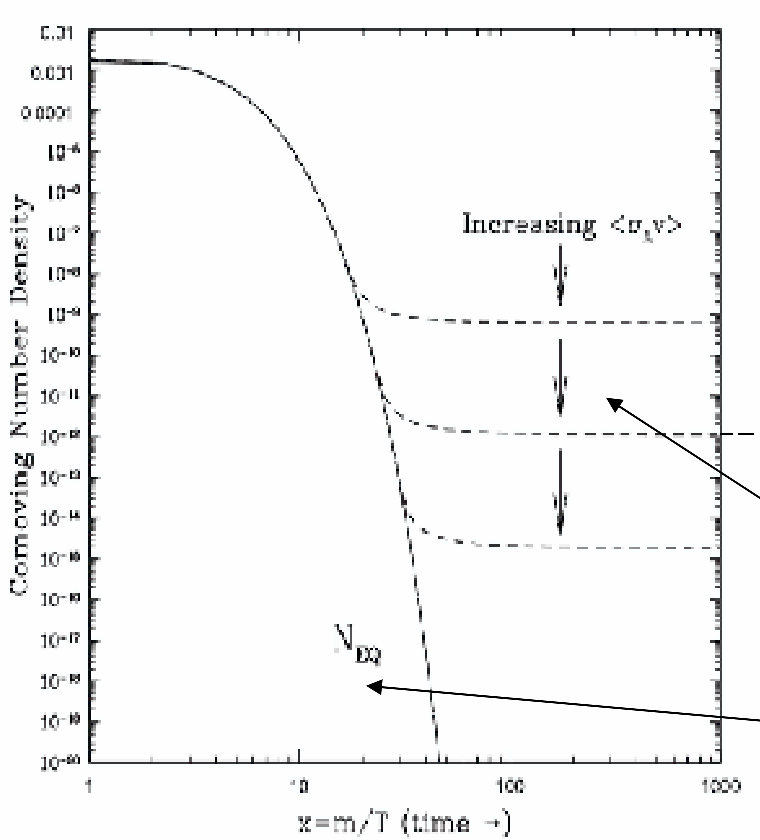
They let the species χ in thermic equilibrium until $\Gamma/H>1$ (Γ is the collision term, H the Hubble parameter)

When $\Gamma/H \ll 1$ expansion dominates and the annihilation freezes, at the **<u>freeze-out</u>** temperature $\mathbf{T_f}$

*Entropy per comoving volume: $S=(p+\rho)R^3/T$

Entropy density: $s \equiv S/R^3$(In thermodynamic equilibrium S is constant)

Decoupling from the plasma takes place when T is sufficiently low, namely when expansion (H) dominates over collissions (Γ).



$\Gamma_{ann} = n_\chi \langle \sigma_{ann} v \rangle$

$n_{EQ} \propto T^3$ relativistic

$n_{EQ} \propto (mT)^{3/2} \exp(-m/T)$ non-relativistic

Departure from equilibrium

Equilibrium

Boltzmann Equation

$$\frac{dn}{dt} + 3Hn = \frac{g}{(2\pi)^3}\int C(f)\frac{d\vec{p}}{E}$$

C(f) collision term → annihilation: $\Gamma_{ann}=n_\chi\langle\sigma_{ann}v\rangle$

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_{ann}v\rangle_{TOT}\,[n_\chi^2 - (n_\chi^{EQ})^2]$$

Dilution effect due to expansion

Destruction rate

Inverse creation Processes at equil.

$$\frac{x}{Y_{EQ}}\frac{dY}{dx} = -\frac{\Gamma_{ann}}{H}\left[\left(\frac{Y}{Y_{EQ}}\right)^2 - 1\right]$$

$x=m/T$

$\Gamma_{ann}/H \ll 1$ **freeze-out** of the species at T_f

$T \ll m$ creation processes are Boltzmann suppressed

Γ_{ann} decreases with T up to when annihilations become ineffective

HOT and COLD relics

HOT relic particles: $x_f \equiv m/T_f \ll 3$ (high T, low m)

Decoupling arrives when particles are still relativisitc $Y = n/s \sim T^3 R^3 \sim$ const
Details of freezing are not much relevant

$$Y(x \to \infty) \equiv Y_{EQ}(x_f) = 0.278 \frac{g_{eff}}{g_{*s}(x_f)}$$

$$\rho_{\chi 0} \equiv s_0 Y_\infty m = 2.97 \cdot 10^3 Y_\infty (m/eV) \quad \text{eV/cm}^3$$

$$\Omega_\chi h^2 = 7.83 \cdot 10^{-2} \frac{g_{eff}}{g_{*s}(x_f)} \frac{m}{eV}$$

For light neutrinos:
g_{*s}=10.75, g_{eff}=2*3/4 →

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{93.1 \text{ eV}}$$

Neutrino relic density

Neutrino DM

Several evidences for neutrinos to be **massive** come from different neutrino oscillation experiments (depending only on mass differencies)

- **atmospheric** neutrinos (Kamiokande, SK, Macro, ...)
  $|\Delta m_{ATM}|^2 \sim 2.5 \cdot 10^{-3}\ eV^2$
- **solar** neutrinos (SNO, SK, Kamiokande, Gallex, GNO, ...)
  $|\Delta m_{SUN}|^2 \sim 8 \cdot 10^{-5}\ eV^2$
- **Reactor** (Chooz) and **accelerator** (K2K, Minos) experiments:
  $|\Delta m|^2 \sim |\Delta m_{ATM}|^2$

Upper limits on neutrino masses come from β decay exps. indicate eV scale masses

Light neutrinos

↓

HOT DARK MATTER

Cosmological neutrinos

Neutrino DM – depending on the mass – washes out the power spectrum of primordial density perturbations, and suppresses the formation of the observed structures at 1-10 Mpc scales.

Limits to Σm_ν from CMBR experimets (WMAP), Large Scale Structures (SDSS, 2dFGRS), Lyman α forests.

Data Set	$\sum m_\nu$ (95% limit for $N_\nu = 3.02$)	N_ν
WMAP	2.0 eV(95% CL)	
WMAP + SDSS	0.91 eV(95% CL)	$5.92^{+0.25}_{-3.45}$
WMAP + 2dFGRS	0.87 eV(95% CL)	$2.68^{+0.26}_{-1.67}$
CMB + LSS +SN	0.68 eV(95% CL)	$3.29^{+0.45}_{-2.18}$

(Spergel et al. astro-ph/0603449)

CMB+Lyman α:

$\Sigma m_\nu < 0.30$ eV

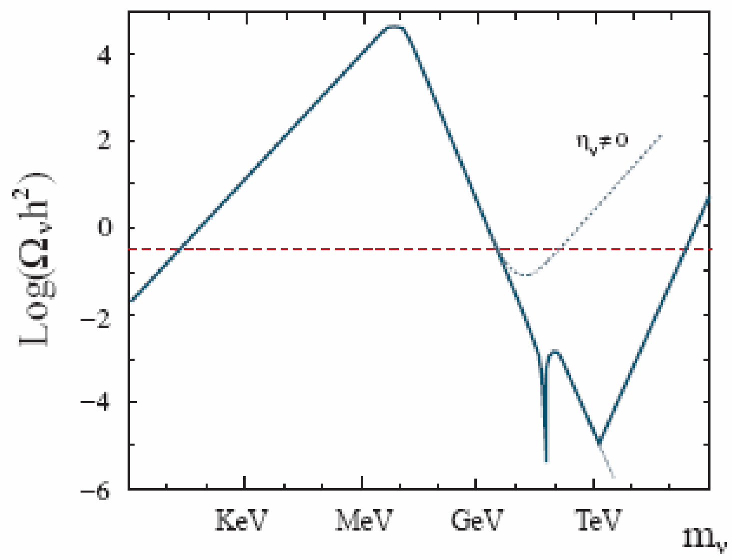
(Goobar et al. 2006)

Kainulaien & Olive astro-ph/0206163

Neutrino relic density

Cosmological limits on neutrino mass

Overdensity for a wide range of mass



From WMAP $\Omega_\nu h^2 = \dfrac{\Sigma m_\nu}{93.1 eV} \leq 0.0073$

Only a very small fraction of Ω can be ascribed to massive neutrinos

WE NEED COLD DARK MATTER (CDM)

The Universe is most probably a mixture of
several kinds of dark components

COLD relic particles: $x_f \equiv m/T_f$ >> 3 (low T, high m)

Decoupling arrives when massive particles are no more relativisitc.

Details of freezing and annihilation are important.

$$\frac{dY}{Y^2} \cong -0.264 \frac{g_{*s}}{g_*^{1/2}} m_{Pl} \frac{m}{x^2} < \sigma v > dx$$

Integrating from T_f to T=0: $$\Omega_\chi h^2 \approx 3.3 \cdot 10^{-38} \frac{g_*(x_f)^{1/2}}{g_* s(x_f)} \frac{cm^2}{< \sigma v >_{\text{int}}}$$

$x_f \approx 20$, $g_*(x_f) \approx g_{*s}(x_f) \approx 60$: $$\Omega_\chi h^2 \approx \frac{4.3 \cdot 10^{-39} cm^2}{< \sigma v >_{\text{int}}}$$

EW size!!

$$\langle \sigma_{ann} v \rangle = \sigma_0 (T/m)^n = \sigma_0 x^{-n}$$

(s wave n=0 p wave n=1)

Particle Physics
...New Physics...!

Supersymmetry & Dark Matter

(See Lectures by A. Masiero)

Fermions $\Leftrightarrow$ Bosons

R=1 R= -1

Leptons & Quarks	*Sleptons, Squarks*
Gauge Fields	*Gauginos*
Higgs Fields	*Higgsinos*

R-parity conservation:

The Lightest Supersymmetric Particle (LSP) is stable on cosmologicl scales and can be the Dark Matter!

Neutralino as the CDM candidate

$$\chi = a_1 \widetilde{B}_0 + a_2 \widetilde{W}_0^3 + a_3 \widetilde{H}_0^1 + a_4 \widetilde{H}_0^2$$

- **Stable** (if R-parity is conserved)
- **Mass**: m_χ~ 10-1000 GeV
- Non-relativistic at decoupling $\Rightarrow$ **CDM**
- **Neutral** & **colourless**
- **Weakly** interacting (WIMP)
- Good relic density $\Omega_\chi \mathbf{h^2}$

Which Supersymmetric Model?

(See Lectures by A. Masiero)

- Theoretical and experimental constraints are too faint to outline a model

- Minimal Supersymmetric extension of the Standard Model **(MSSM)** depends on the SYMMETRY BREAKING mechanism:
  - **Gravity** mediated → **neutralino** DM
  - Gauge mediated → gravitino DM
  - Anomaly mediated → neutralino, stau sneutrino

- The nature and phenomenology of LSP depends on susy breaking and regions of the susy parameter space

Gravity mediated SUSY schemes

Supergravity inspired models (SUGRA)

- Unification conditions occur at the GUT scale (M_{GUT}~10^{16} GeV)

$$M_i(M_{GUT}) = m_{1/2} \qquad (gaugino\ \ masses)$$

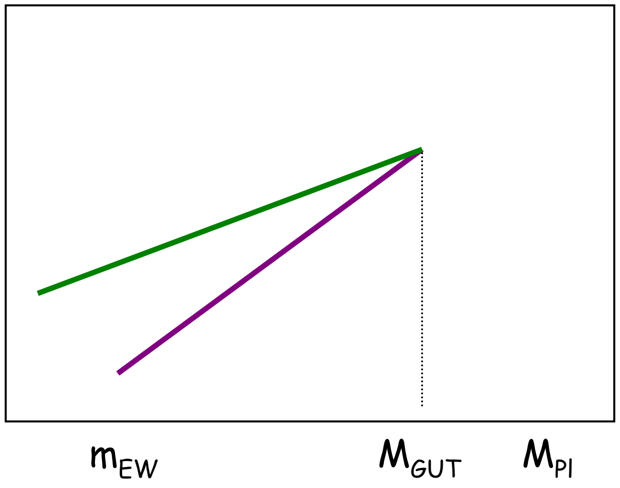
$$m_i(M_{GUT}) = m_0 \qquad (scalar\ \ masses)$$

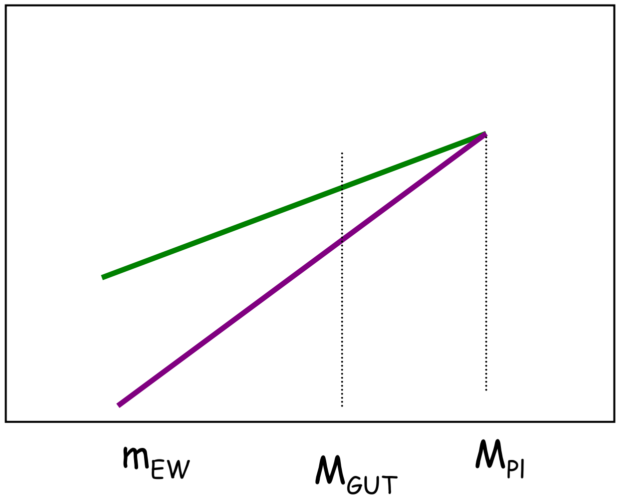
$$A^{u(d,l)}(M_{GUT}) = A_0 m_0 \qquad (trilinear\ \ terms)$$

- Free parameters of the model: $m_{1/2},\ m_0,\ \ A_0,\ \ sign(\mu),\ \ \tan\beta$

- RGE evolution down to EW scale & radiative EW symmetry breaking

SUGRA is severely constrained by unfication assumptions at M_{GUT}.



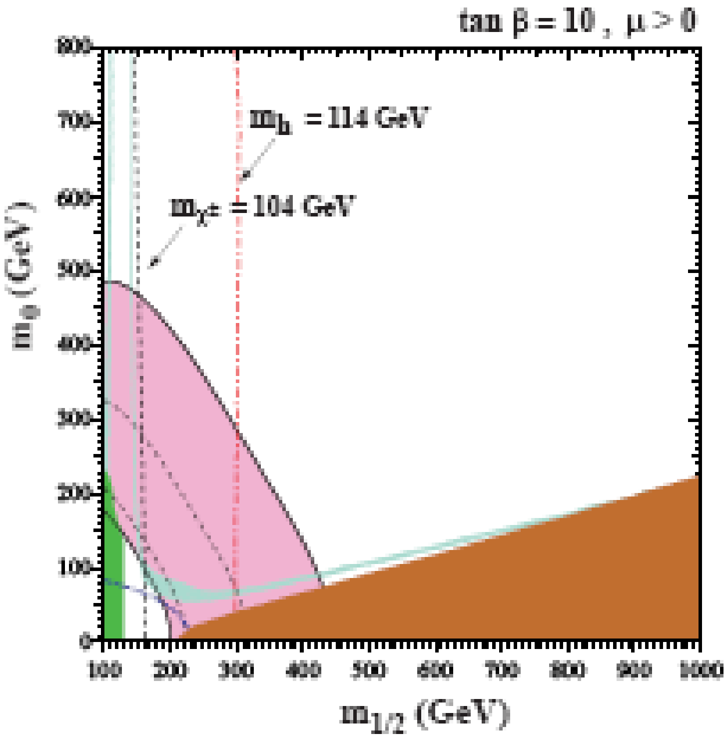


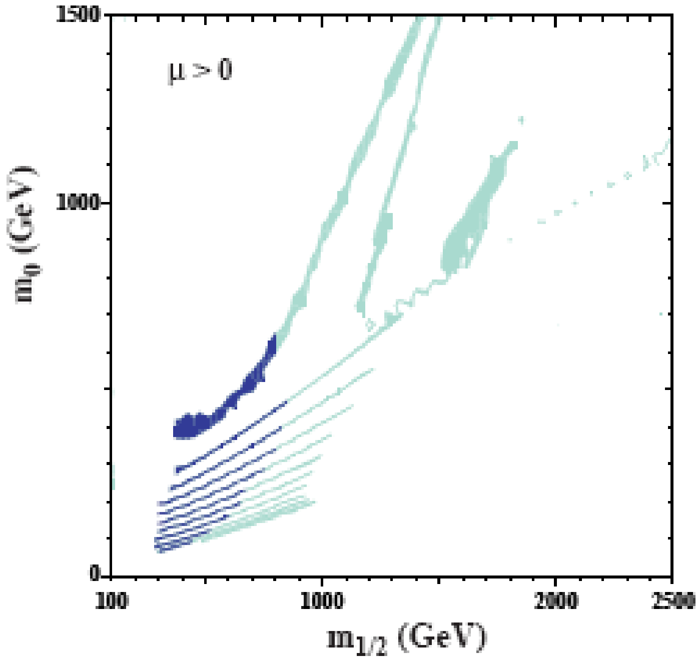
But:

- universality might occur at higher scales (M_{plank}) leading to deviations from universality at M_{GUT}
- the starting point for RGE could begin at a lower scale, between M_{GUT} and M_{EW}

→ non-universal SUGRA

SUGRA models





Different tanβ: 5,10, ...,55

Light blue regions: allowed region

CMSSM Olive astro-ph/0503065

Effective MSSM scheme (effMSSM)

Model (parameters) defined at the EW scale

Independent parameters:

- M_1 U(1) gaugino soft breaking term
- M_2 SU(2) gaugino soft breaking term
- μ Higgs mixing mass parameter
- $\tan\beta$ ratio of two Higgs v.e.v.'s
- m_A mass of CP odd neutral Higgs boson
- m_q soft mass common to all squarks
- m_l soft mass common to all sleptons
- A trilinear parameter ($A_b = A_t \equiv Am_q$; $A_\tau \equiv Am_l$)
- $R \equiv M_1/M_2$ (=0.5 in GUT)

$\tilde{q}$

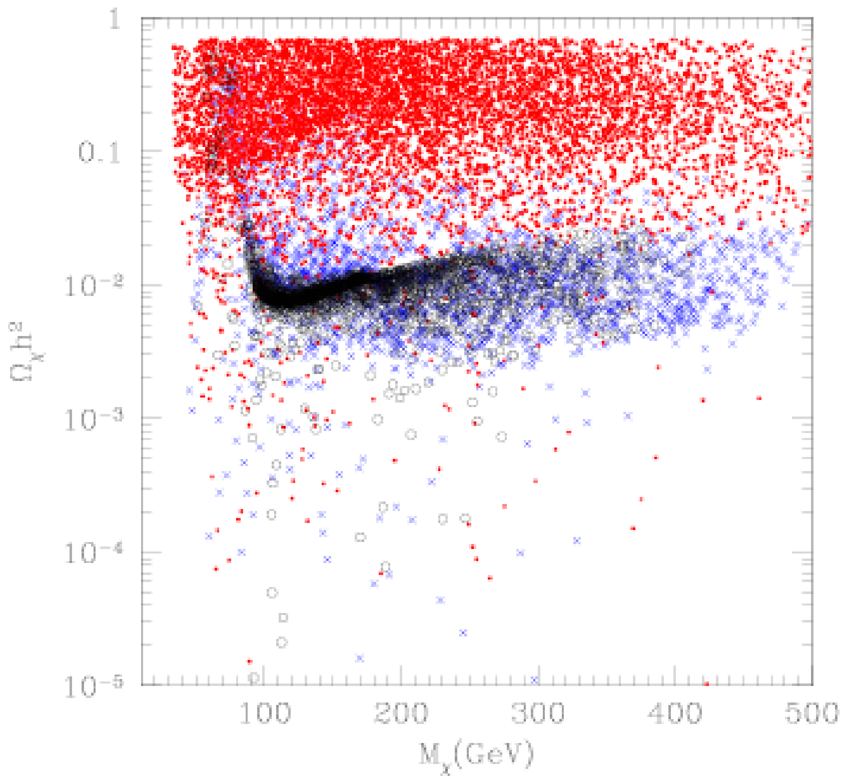
Experimental constraints

- EXPERIMENTAL BOUNDS:
  - Accelerator (LEP & Tevatron) data on Higgs and supersymmetric particle (negative) searches
  - $b \to s\gamma$
  - $B_S \to \mu^+ \mu^-$ $\quad$ ($BR(B_S \to \mu^+ \mu^-) \leq 9.5 \times 10^{-7}$)
  - $a_m \equiv (g_m - 2)/2$ $\quad$ ($-142 \leq \Delta a_m \cdot 10^{11} \leq 474$)

- Requirements that neutralino is the LSP
- No a priori on the relic density $\Omega_\chi h^2$

  Subdominant neutralinos, if detectable, could be very interesting for particle physics (new physics) and cosmology (mixture of candidates)

Neutralino relic abundance



effMSSM Bottino et al. 2001

The Neutralino can be THE DM candidate ($\Omega_\chi h^2 \sim 0.1$), able to explain the whole non-baryonic DM or a subdominant relic Particle

Red: gaugino
Blue: mixed
Black: higgsino

Upper bound on $\Omega_\chi h^2 \Rightarrow$ lower bound on m_χ

Full scanning of effMSSM

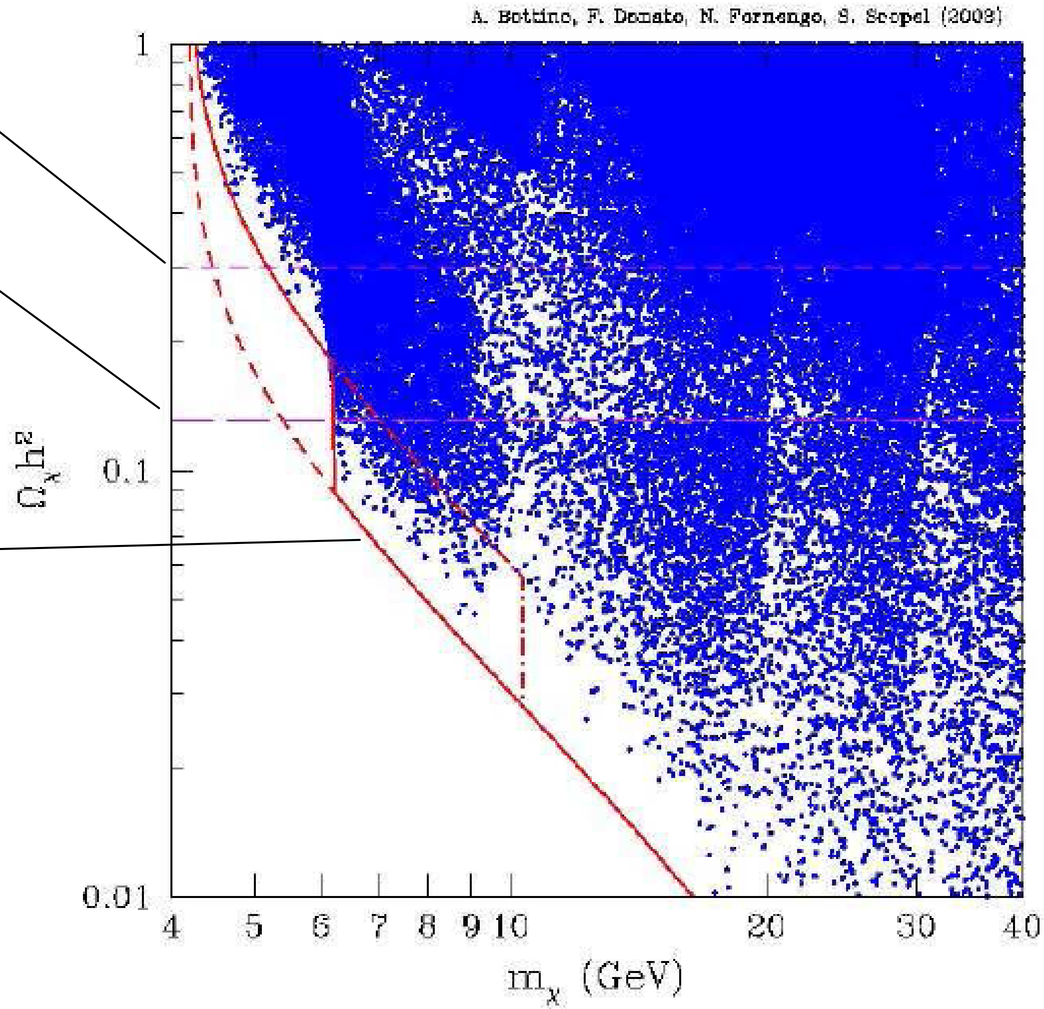
$\Omega_{CDM}h^2 = 0.3$

$\Omega_{CDM}h^2 = 0.131$ ➡ $m_\chi \geq 6.2$ GeV

$(\Omega_\chi h^2)_{min,Higgs} \propto$

$((2m_\chi)^2 - m_A{}^2)^2 / m_\chi{}^2 \sqrt{1-(m_b/m_\chi)^2}$

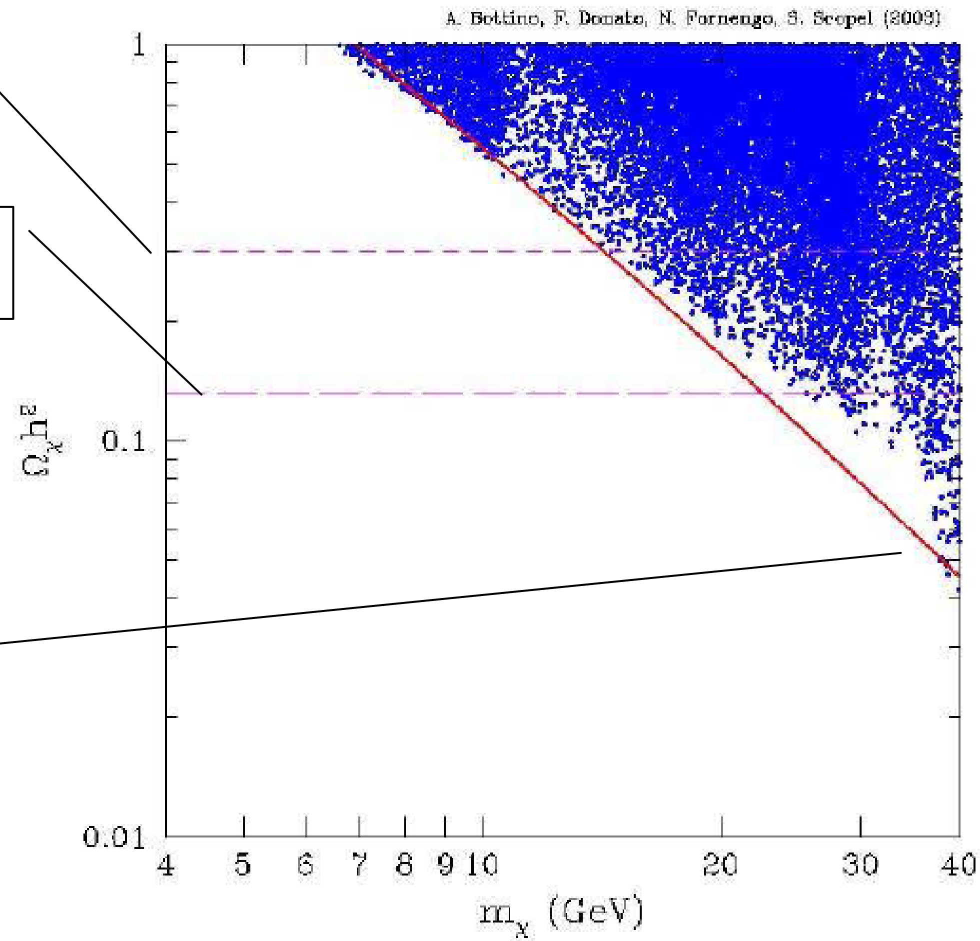
T_{QCD}=300 MeV



Full scanning of effMSSM & m_A > 300 GeV

$\Omega_{CDM}h^2 = 0.3$

$\Omega_{CDM}h^2 = 0.131 \Rightarrow m_\chi \geq 22$ GeV



$(\Omega_\chi h^2)_{min,sfermion} \propto$

$m_{stau} / m_\chi^2 \sqrt{1-(m_\tau/m_\chi)^2}$

T_{QCD}=300 MeV