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DARK MATTER CANDIDATES

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~ D

$p + n \rightarrow D + \gamma$

Nucleosynthesis

PART I

DARK MATTER CANDIDATES

(i) MACHO : faint stars, brown dwarfs,
stellar remnants (white dwarfs, neutron stars, black holes)

At most 20% of galactic halo can be made of stellar remnants $\Rightarrow$ NOT ENOUGH TO ACCOUNT for DM as dictated by CMB.

(ii) Axions : $10^{-(3-6)}$ eV mass Range — Peccei-Quinn solution of Strong CP problem

↘ pseudoscalar

(iii) Weakly Interacting Massive Particles (WIMP)

If present in THERMAL ABUNDANCES in Early Universe annihilate with one another $\Rightarrow$ predictable number of them remain today.

Relic density: $\Omega_X h^2 = \left(3\times10^{-26}\ \frac{cm^3}{s}\right) \frac{1}{\langle\sigma v\rangle_{annih}}$

Reason for being taken very seriously ⟵ { "WIMP MIRACLE" } { weak interaction annihilation cross section automatically give Right answer

(2)

WIMP candidates:

(i) Supersymmetry → lightest neutralino

~~(iii) light Gravitino~~

O

(ii) Superheavy DM particles $M_X > 10^{15}$ GeV

↘ WIMPzillas ↘ Can be non-thermally produced

Can be produced gravitationally

IF THERMAL RELIC, $\Omega_X \leq 1 \Rightarrow m_X < 500$ TeV

Heavier than this must be NON-THERMAL ?

DM might be composed of non-thermal supermassive states

↓

Use partial wave Unitarity of S-matrix

CONDITIONS

① SDM: either stable
or life-time greater than age of Universe
(e.g. gauge mediated SUSY breaking scenarios
... M theory ⇒ CRYPTONS

② SDM must not be in equilibrium when it froze. → sufficient $n\,\sigma|v| < H$ (↳ number density)

4 - production mechanisms of superheavy DM

① Production during Re-heating $\quad \Omega_{SDM} \sim \left(\frac{2000\, M_X}{T_{RH}}\right)^7$

② Pre-heating producting SDM

③ Gravitational production at the end of Inflationary era.

④ SDM ⇒ created in collisions of vacuum bubbles in a first-order phase transition.

X scalar field (M_X)
Coupled to inflaton field

$$S = S_g + S_M \quad \Big| \quad S_g = \int d^4x \sqrt{-g}\, \frac{M_p^2 R}{16\pi}$$

$$S_M = \int d^4x \sqrt{-g} \left(\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - m_\phi^2 \phi^2 \right) + \frac{1}{2} g^{\mu\nu} \partial_\mu X \partial_\nu X - (m_X^2 + \xi R + g^2 \phi^2) X^2$$

(inflaton: ϕ; if $\xi = \frac{1}{6}$ conformal coupling)

Background metric FRW $\quad ds^2 = -dt^2 + a^2(t)\, d\vec{x}^2$

X-sector:

$$\ddot{X} + 3H\dot{X} - \frac{1}{a^2}\vec{\nabla}^2 X + (M_X^2 + g^2\Phi^2)X = 0$$

$H = \frac{\dot{a}}{a}$ Hubble Rate.

Fourier $X = \int \frac{d^3k}{(2\pi)^{3/2} a}\left(a_{\vec{k}} e^{i\vec{k}\cdot\vec{x}} h_k(t) + a_{\vec{k}}^\dagger e^{-i\vec{k}\cdot\vec{x}} h_k^*(t)\right)$

$h_k = X_k a$, $[a_{\vec{k}_1}, a_{\vec{k}_2}^\dagger] = \delta^{(3)}(\vec{k}_1 - \vec{k}_2)$

$\Longrightarrow$ mode equation

$$\ddot{h}_k + H\dot{h}_k + \left[-H^2 - \frac{\ddot{a}}{a} + \left(\frac{k}{a}\right)^2 + M_X^2 + g^2\phi^2\right]h_k = 0$$

Conformal time $ds^2 = a^2(\eta)(d\eta^2 - d\vec{x}^2) \Longrightarrow$

$$h_k''(\eta) + \omega_k^2 h_k = 0$$

$$\omega_k^2 = \sqrt{k^2 + [M_X^2 + g^2\phi^2(\eta)]a^2(\eta)}$$

Particle production during inflation $\rightarrow$ Bogoliubov Coefficients $\Rightarrow$ number density $n_X(t) = \int_0^\infty \frac{dk}{2\pi^2 a^3} k^2 |\beta_k|^2$

β_k ~ Bogolubov coefficient defined via the transformation $h_k^{\eta_1}(\eta) = \alpha_k h_k^{\eta_0}(\eta) + \beta_k h_k^{*\,\eta_0}(\eta)$

$$\alpha_k' = \frac{\omega_k'}{2\omega_k} \exp\left(2i \int \omega_k \, d\eta\right) \beta_k$$

$$\beta_k' = \frac{\omega_k'}{2\omega_k} \exp\left(-2i \int \omega_k \, d\eta\right) \alpha_k$$

B.C α_k, β_k constants as $\eta \to \pm\infty$

$$\beta_k \approx \int d\eta \, \frac{\omega_k'}{2\omega_k} \exp\left(-2i \int^{\eta} \omega_k(\eta') d\eta'\right)$$

$$\omega_k = \sqrt{k^2 + M_X^2 C(\eta)}$$

$$C(\eta) = \left(1 + \frac{g^2 \bar{\phi}^2(\eta)}{M_X^2}\right) a^2(\eta)$$

$$n_X(t) \simeq \frac{a_{eff}^3(r)}{8\pi^{3/2} a^3(t)} \exp\left(-\frac{4M_X}{\sqrt{H_{eff}^2(r) + R_{eff}(r)/6}}\right) \times$$

$$\times \left[\frac{M_X}{4} \sqrt{H_{eff}^2(r) + \frac{1}{6} R_{eff}(r)}\right]^{3/2}$$

$a_{eff} \equiv \sqrt{C}$

$H_{eff}, R_{eff} \rightarrow$

$ds^2 = a_{eff}^2 (d\eta^2 - dx^2$

and r is defined as: $n = r$: → $\frac{c''(r)}{c^2}$ is a maximum.

$$\frac{\mu^2}{6} c'''(r) + c'(r) = 0$$

$$\frac{\mu^2}{2} c''(r) = -\frac{\omega_k^2(r)}{M_X^2}$$

μ ~ purely imaginary

$\tilde{n}_j = r + \mu$ complex plane

GRAVITINO D.M. : Could be LSP

why? | So far nothing (almost) is known about gravitino mass

$m_{3/2} < 1\,\text{keV} \Rightarrow$ hot D.M.

$1\,\text{keV} < m_{3/2} < 15\,\text{keV} \Rightarrow$ warm D.M.

$100\,\text{keV} < m_{3/2} < 10\,\text{MeV} \Rightarrow$ CDM favoured by Gauge mediation Susy Breaking & thermal leptogenesis

$100\,\text{GeV} < m_{3/2} < 1\,\text{TeV} \rightarrow$ CDM gaugino + Gravity mediation Thermal leptogenesis.

GRAVITINO PROBLEM ?

$n_{3/2}$ ~ number density

$$\frac{n_{3/2}}{n_\gamma} \sim \frac{\alpha_3}{M_p^2} T_R$$

(α_3 ← QCD fine structure constant; T_R ← Reheating temperature)

↓ late decay of heavy gravitinos → alters BBN

$\Rightarrow T_R < O(10^5)$ GeV

$\Rightarrow$ incompatible with leptogenesis $T_R \gtrsim 10^9$ GeV

CONFLICT AVOIDED IF GRAVITINO IS THE LSP. BBN constraints apply then to NLSP.

Two processes Contribute to gravitino production:

gravitinos produced in WIMP decays

$$\Omega_{\frac{3}{2}} = \frac{m_{3/2}}{m_{NLSP}} \Omega_{NLSP}$$

Thermal production of gravitinos (by Reheating): dominated by $2 \to 2$ QCD scattering

$$\Omega_{3/2} h^2 = 0.5 \left(\frac{T_R}{10^{10}\text{ GeV}} \right) \left(\frac{100\text{ GeV}}{m_{3/2}} \right) \left(\frac{m_{\tilde{g}}(\mu)}{1\text{ TeV}} \right)^2$$

R-parity conservation $\Longrightarrow$ GRAVITINO $\Rightarrow$ LSP STABLE.

$$\Omega_{gravitino} h^2 = \Omega_{gr}^{thermal} h^2 + \Omega_{gr}^{non\text{-}thermal} h^2$$

WMAP constraints

$$\Omega_{DM}^{WMAP} h^2 = 0.113 \pm 0.004$$

BBN constraints:

	$^7Li/H$	$^6Li/^7Li$
		$\sim 0.01 - 0.15$
observation	$(1-2) \times 10^{-10}$	
BBN(CMB)	$\sim 4 \times 10^{-10}$	$\approx 10^{-4}$ } Discrepancy!

PROPOSED RESOLUTION – USING NEW PHYSICS: through hypothesised metastable particle: → SEE APPENDIX.

PHENOMENOLOGY DEPENDS ON WHAT IS NLSP

arXive: 0903.2860
0907.5003.

↙

NLSP : neutralino
stau
stop
sneutrino

GRAVITINO as CDM: Phenomenology

① neutralino as NLSP $m_\chi = 1$ TeV

$m_{grav} \sim 1$ GeV

↓

life-time $O(1)$ s
longer for smaller masses } → ESCAPE colliders and ~~and~~ trigger missing energy signature.

IF ALL neutralinos decayed to gravitino ⟹

GRAVITINO would not be detectable by WIMP Direct searches
neither indirect astrophysical signal from dark matter annihilation in haloes.

Difficult to prove identity of DM in this case. Need to check if R parity is really conserved.

② Stau as NLSP

massive stable charge ptcle at colliders. Can be stored until it decays → measure its life time.

Stau NSLP → catalytic effect on BBN.

c.f. → Lithium problem solution.

③ Stop NLSP : long-lived stop → hadronize once produced.

↓

can solve Lithium problem → hadronic decay.

④ Sneutrino NLSP : small but non-zero effects on BBN.

Colliders: missing energy signatures
↳ study through cascade decays of heavier Susy particles | SIGNATURES BEST FOR NEUTRALINO LSP ARE NOT GOOD FOR THIS SCENARIO.

AXION DM

Coupling of $\alpha g_\gamma \frac{\phi_a}{4\pi} F_\mu \tilde{F}^\mu \sim g\, \phi_a{}_{\gamma\gamma}\, \vec{E}\cdot\vec{B}$ (α: Fine structure Constant)

$$g_{a\gamma\gamma} \equiv \frac{\alpha\, g_\gamma}{\pi f_a} \qquad g_\gamma \sim 0.97 \text{ or } 0.36$$

$$m_a(\text{eV}) \approx 0.6\ \text{eV}\ \frac{10^7\ \text{GeV}}{f_a[\text{GeV}]}$$

$f_a \sim$ symmetry Breaking scale of $U_{PQ}(1)$ ↓ axion is pseudo-Goldstone Bosons

Accelerator based studies

$$m_a < 10^{-2}\ \text{eV}$$

$$\Omega_a = \frac{\rho_a}{\rho_c} \sim \left(\frac{5\ \mu\text{eV}}{m_a}\right)^{7/6}$$

$$\Omega_a < 1 \implies m_a > 10^{-6}\ \text{eV}$$

$$\implies 10^{-6} < m_a < 10^{-2}\ \text{eV}$$

DARK MATTER & EXTRA DIMENSIONS

Warped extra Dimensions Kaluza-Klein Modes $\Longrightarrow$ neutrino KK mode provide Realistic DM candidate, mass of O(TeV)

arxive 0901-0609 (Carena et al.)

Generic KK decomposition:

Dirac field: $$\psi(x^\mu, y) = \frac{1}{\sqrt{2}R}\left[\psi^{SM}(x^\mu) + \sqrt{2}\sum_{n=1}^{\infty} P_L\, \psi_{L,n}(x^\mu)\cos\left(\frac{ny}{R}\right)\right.$$

$$\left. + P_R\, \psi_{R,n}(x^\mu)\sin\left(\frac{ny}{R}\right)\right]$$

$$\left(P_{L,R} = \frac{(1 \mp \gamma_5)}{2}\right)$$

ONLY KK fermion that could play the role of DM is neutrino

$\swarrow$

Thermal Relic abundance

Review (Phys Rept) hep-ph/0701197.

APPENDIX

Massive Gravitino & $\frac{^6Li}{^7Li}$ problem   arxiv 0907 500

Suggested Resolutions: (1) $d + {}^4He \rightarrow {}^6Li + \gamma$ suppressed by parity!

But if ∃ massive, X^- bound to ^4He by Coulomb
→ absorbed emitted γ → process no longer parity
suppressed. Simultaneously X^- is freed from
bound state with ^4He by energy release →
attached to another ^4He → acting as catalyst for ^6Li
production.

(2) hadronic decay of metastable neutral particle → n, p, T, ^3He
(spallation of ^4He) → interact with ambient nuclei,
e.g. $n + p \rightarrow D, T + {}^3He \rightarrow {}^6Li$ (more ^6Li)
and $^7Be(n,p)\,{}^7Li\,(p, {}^4He)\,{}^4He$ (Reducing ^7Li)

COULD THIS neutral ptcle be the Gravitino ?
Decaying massive gravitino into neutralino D.M ?
~ BUT solution to ^7Li not found...

PART II – CALCULATING ABUNDANCIES

BOLTZMANN EQUATION

THERMAL RELICS

[N.E. MAVROMATOS
DARK-MATTER CANDIDATES]

$$\hat{L}[f] = m_\chi \frac{d}{d\tau} f = m_\chi u^\alpha \partial_\alpha f +$$

$$+ m_\chi \frac{dp^\alpha}{d\tau} \frac{\partial}{\partial p^\alpha} f$$

($u^\alpha \partial_\alpha f$ → use FRW co-moving coordinates)

($\frac{dp^\alpha}{d\tau}$ →) $-\Gamma^\alpha_{\mu\nu} p^\mu p^\nu$

FRW universe: $\Gamma^0_{ii} \sim \frac{\dot{a}}{a}$

homogeneous:

$$\hat{L}[f] = m_\chi \partial_t f - \frac{\dot{a}}{a} |\vec{p}|^2 \frac{\partial f}{\partial E}$$

$$n_\chi = \int d^3p \, f(E,t) \frac{g}{(2\pi)^3}$$

(g ← INTERNAL D.O.F.)

$$\hat{L}[n_\chi] = E \frac{dn_\chi}{dt} - \frac{\dot{a}}{a} \int d|\vec{p}| \, d\Omega \, |\vec{p}|^4 \frac{\partial |\vec{p}|}{\partial E} \frac{\partial f}{\partial |\vec{p}|} =$$

$$= E\frac{dn_\chi}{dt} - E\frac{\dot a}{a}\int d|\vec p|\, d\Omega\, |\vec p|^3 \frac{\partial f}{\partial|\vec p|}$$

(we used $|\vec p|^2 + m_\chi^2 = E^2$) $\quad \frac{\partial|\vec p|}{\partial E} = \frac{E}{|\vec p|}$

$(|\vec p|^2 = p_i p_j h^{ij})$

Then: $$\frac{dn_\chi}{dt} + 3Hn_\chi = \frac{g}{8\pi^3}\int \frac{d^3p}{E} C[f] \quad ; \quad H = \frac{\dot a}{a}$$

Suppose: $\chi + I_1 + I_2 + \dots \rightleftharpoons F_1 + F_2 + \dots$

<u>Collision term:</u>

$$\frac{g}{(2\pi)^3}\int \frac{d^3p_\chi}{E_\chi} = -\int d\Pi_\chi\, d\Pi_1\, d\Pi_2 \dots d\Pi_{F_1}\, d\Pi_{F_2} \dots \times (2\pi)^4 \delta^{(4)}(p_\chi + p_{I_1} + p_{I_2} + \dots$$
$$- p_{F_1} - p_{F_2} \dots)\,(|M|^2_{\chi+I_1+I_2 \to F_1+F_2+\dots})\, f_1 f_2 \dots f_\chi\, (1 \pm f_{F_1})(1 \pm f_{F_2}) \dots$$
$$\dots - |M|^2_{F_1+F_2 \to \chi+I_1+I_2}\, f_{F_1} f_{F_2} \dots (1 \pm f_1)(1 \pm f_2) \dots$$
$$\dots (1 \pm f_\chi)$$

$d\Pi_k = \frac{g_k}{(2\pi)^3}\frac{d^3p_k}{E_k}$ / g_k internal d.o.f. of species k

---

$$f_k = e^{-(E_k - \mu_k)/k_B T}$$

CPT, CP conservation assumption $\Longrightarrow |M|^2_{\chi+I_1 \to F} = |M|^2_{F \to \chi + I}$

Bose-Einstein (Fermi-Dirac): $(k_B = 1)$

$$f(\vec{p}) = \left(e^{(E-\mu)T} \pm 1\right)^{-1}$$

$(-)$ = Bosons

$(+)$ = fermions

chemical potentials in a Reaction: $(k_B = 1)$

$$\mu_i + \mu_j = \mu_k + \mu_e$$

$$n = \frac{g}{2\pi^2} \int_m^\infty \frac{(E^2 - m^2)^{1/2}}{e^{(E-\mu)/T} \pm 1} E\,dE$$

$$\rho = \frac{g}{2\pi^2} \int_m^\infty \frac{(E^2 - m^2)^{1/2} E^2\,dE}{e^{(E-\mu)/T} \pm 1}$$

$$p = \frac{g}{6\pi^3} \int_m^\infty \frac{(E^2 - m^2)^{3/2}}{e^{(E-\mu)/T} \pm 1} dE$$

Radiation: $T \gg m$, $T \gg \mu$

Hence:

$$n = \begin{cases} \frac{\zeta(3)}{\pi^2} g T^3 & \text{Bose} \\ \frac{3}{4} \frac{\zeta(3)}{\pi^2} g T^3 & \text{Fermi} \end{cases} \qquad \rho = \begin{cases} \frac{\pi^2}{30} g T^4 & \text{Bose} \\ \frac{7}{8} \frac{\pi^2}{30} g T^4 & \text{Fermi} \end{cases}$$

$$p = \frac{1}{3}\rho$$

$$\rho_{rad} \simeq \frac{\pi^2}{30} g_* T^4 = T^4 \sum_{i=\text{species}} \left(\frac{T_i}{T}\right)^4 \frac{g_i}{2\pi^2} \int_{x_i}^{\infty} \frac{(\xi^2 - x_i^2)^{1/2}}{e^{\xi_i - y_i} \pm 1} \; (4) \; \xi^2 d\xi$$

$x_i = \frac{m_i}{T}$

$y_i = \frac{\mu_i}{T}$

$$P_{rad} \simeq \frac{1}{3} \rho_{rad} \simeq \frac{\pi^2}{90} g_* T^4$$

$$g_* = \sum_{i=\text{boson}} g_i \left(\frac{T_i}{T}\right)^4 + \frac{7}{8} \sum_{j=\text{fermion}} g_j \left(\frac{T_j}{T}\right)^4$$

$$s = \frac{\rho + p}{T} \quad \text{entropy density}$$

Simple case one stable χ : $\chi\bar{\chi} \rightleftharpoons$ ~~XX~~ Standard Model particles

$$f_\chi = e^{-\frac{E_\chi}{T}}$$

> Energy conservation
> $E_\chi + E_{\bar{\chi}} = E_\chi + E_{\bar{\chi}}$

$$f_\chi f_{\bar{\chi}} = e^{-(E_\chi + E_{\bar{\chi}})/T} = e^{-(E_\chi + E_{\bar{\chi}})T} = f_\chi^{eq} f_{\bar{\chi}}^{eq}$$

hence $f_\chi f_{\bar{\chi}} - f_\chi f_{\bar{\chi}} = f_\chi f_{\bar{\chi}} - f_\chi^{eq} f_{\bar{\chi}}^{eq}$

Hence re-write Boltzman

$$\frac{dn_\chi}{dt} + 3H n_\chi - \langle \sigma_{\chi\bar{\chi}\to X\bar{X}} |v| \rangle (n_\chi^2 - n_\chi^{eq\,2})$$

$$\langle \sigma_{\chi\chi\to X\bar{X}} |v| \rangle = (n_\chi^{eq})^{-2} \int d\Pi_\chi d\Pi_{\bar{\chi}} d\Pi_X d\Pi_{\bar{X}} (2\pi)^4 \delta(p_\chi + p_{\bar{\chi}} - p_X - p_{\bar{X}}) |M|^2 e^{-\frac{E_X}{T}} e^{-\frac{E_{\bar{X}}}{T}}$$

Solving Boltzman: $Y \equiv \frac{n_\chi}{s}$

$$\dot{n}_\chi + 3 H n_\chi = s \dot{Y}$$

$$x = \frac{m_\chi}{T}$$

$$\frac{dY}{dx} = -\frac{x}{H(m_\chi) s} \int d\Pi \ldots d\Pi |M|^2 \delta^{(4)}(\Sigma p) \cdot (f_1 \cdot f - f_F f_F)$$

$H(m_\chi) \simeq 1.67 \cdot g_*^{1/2} \frac{m_\chi^2}{M_{pl}}$ and $H(x) = H(m_\chi) x^{-2}$

$$\frac{dY}{dx} = - \frac{x \langle \sigma_A |v| \rangle s}{H(m_\chi)} \left(Y^2 - Y_{eq}^2 \right)$$

$$\frac{x}{Y_{eq}} \frac{dY}{dx} = - \frac{\Gamma_A}{H(T)} \left(\frac{Y^2}{Y_{eq}^2} - 1 \right)$$

$\Gamma_A \equiv n_{eq} \langle \sigma_A |v| \rangle$ annihilation interaction rate

If $\Gamma > H$ equilibrium is maintained (initially)

If $\Gamma < H \longrightarrow$ species freeze out

Relic abundance

$$(\rho_\chi)_0 = s_0 \, Y(x \to \infty) \, m_\chi$$

or equivalently $\Omega_\chi h^2$ | $H_0 = 2.1332 \, h \, 10^{-42}$ GeV

$0 \leq h \leq 1$

$h_{WMAP} \sim 0.71$

Reduced Hubble constant.

Solving Boltzman's equation

$$\sigma_A |v| \sim v^p$$

$p=0$ s-wave
$p=2$ p-wave

$\langle v^2 \rangle \sim T$
↳ kinetic energy of a particle

$$\langle \sigma_A |v| \rangle = \sigma_0 \left(\frac{T}{m_x}\right)^n \equiv \sigma_0 x^{-n}$$

$$Y_{eq} = 0.145 \left(\frac{g}{g_{*s}}\right) x^{3/2} e^{-x}$$

Early times $Y \sim Y_{eq}$

Calculating <u>FREEZE OUT</u>

$$\Delta \equiv Y - Y_{eq} \Big|_{x=x_f} \sim Y^{eq}(x_f)$$

$$\therefore \quad x_f = \ln\left(0.038\,(n+1)\,\frac{g}{g_{*s}^{1/2}}\,M_{pl}\,m_x\,\sigma_0\right) - (n+\tfrac{1}{2})\ln\left(\ln\left(0.038\,(n+1)\left(\frac{g}{g_{*s}^{1/2}}\right) M_{pl}\,m_x\,\sigma_0\right)\right)$$

$$\Omega_\chi h^2 = \frac{1.07 \times 10^9 (n+1)\, x_f^{n+1}\ \mathrm{GeV}^{-1}}{\left(\frac{g_{*S}}{g_*^{1/2}}\right) M_{pl}\, m_\chi\, \sigma_0}$$

EXTRA SOURCES

$$\frac{dn}{dt} = -3\frac{\dot a}{a} n - \langle \sigma v \rangle (n^2 - n_{eq}^2) + \Gamma n$$

$t < t_f$ equilibrium.

Due to source, $\Gamma = \Gamma(t)$:

$n = n_{eq}^{(0)}$

$$n_{eq}\, a^3 = n_{eq}^{(0)} a^3(t_0) \exp\left(\int_{t_0}^{t} \Gamma dt'\right)$$

t_0 ↳ Exit from inflationary period

$$\boxed{x = \frac{m_x}{T}}$$

$$\frac{dY}{dx} = m_x \langle v\sigma \rangle \left(\frac{45}{\pi} G_N \tilde g_{eff}\right)^{-1/2} \left(h + \frac{x}{3}\frac{dh}{dx}\right)(Y^2 - Y_{eq}^2)$$

$$- \frac{\Gamma}{Hx}\left(1 + \frac{x}{3h}\frac{dh}{dx}\right) Y$$

$\left(G_N = \frac{1}{M_{pl}^2}\right)$ | h = entropy d.o.f.

$$\rho + \Delta\rho = \frac{\pi^2}{30} T^4 \tilde g_{eff}$$

↳ additional due to source → $H^2 = \frac{8\pi G_N}{3}(\rho + \Delta\rho)$

$\rho = \frac{\pi^2}{30} T^4 g_{eff}(T)$ only those thermalized

$$\tilde{g}_{eff} = g_{eff} + \frac{30}{\pi^2} T^{-4} \Delta\rho$$

$$H^2 = \frac{4\pi^3 G_N}{45} T^4 \tilde{g}_{eff}$$

$x > x_f$:

$$Y_{eq} = Y_{eq}^{(0)} \exp\left(- \int_x^\infty \frac{\Gamma H^{-1}}{x} dx \right)$$

$$Y_{eq}^{(0)} = \frac{45}{2\pi^2} \frac{g_s}{h} (2\pi x)^{-3/2} e^{-\frac{1}{x}}$$

$x < x_f$: $Y \gg Y_{eq}^{(0)} \Longrightarrow$

$$\frac{d}{dx}\left(\frac{1}{Y}\right) = -m_\chi \langle v\sigma \rangle \left(\frac{45}{\pi} G_N \tilde{g}_{eff}\right)^{-\frac{1}{2}} h + \frac{\Gamma H^{-1}}{xY}$$

MODIFIED FREEZEOUT:

$$x_f^{-1} = \ln \left[0.03824\, g_s \frac{M_{pl}\, m_\chi}{\sqrt{g_*}} x_f^{1/2} \langle v\sigma \rangle \right] + \frac{1}{2} \ln\left(\frac{g^*}{\tilde{g}_*}\right) + \int_{x_f}^{x_{in}} \frac{\Gamma H^{-1}}{x'} dx'$$

Relic abundance: solve Boltzmann eqn $x_0 \to T_0 = 2.7\,°K$

$$Y^{-1}(x_0) = Y^{-1}(x_f) + \left(\frac{\pi}{45}\right)^{1/2} m_\chi M_{pl}\, \tilde{g}_*^{-1/2}$$

$$h(x_0)J - \int_{x_0}^{x_f} \frac{\Gamma H^{-1}}{x' Y}\, dx'$$

$$J \equiv \int_{x_0}^{x_f} \langle \sigma v \rangle\, dx'$$

$$\therefore \quad \Omega_\chi h^2 = (\Omega_\chi h^2)_{\text{no source}} \left(\frac{\tilde{g}_*}{g}\right)^{1/2} \left(1 + \int_{x_0}^{x_f} \frac{\Gamma H^{-1}}{\mathcal{X}(x')}\, dx'\right)$$

modify

$$(\Omega_\chi h^2)_{\text{no source}} = \frac{1.066 \times 10^9\ \text{GeV}^{-1}}{M_{pl} \sqrt{g_*}\, J}$$

$$\therefore \quad \mathcal{X}(x) = x \exp\left(-\int_{x_0}^{x} \Gamma H^{-1} \frac{dx'}{x'}\right)$$

Gauge mediated susy Breaking:

$$K = S^{\dagger}S - \frac{(S^{\dagger}S)^2}{\Lambda} + \dots \text{(higher orders)}$$

single chiral superfield ↙ ; Λ ↘ Cut-off of theory

$$\boxed{W = m^2 S}$$ superpotential

↓ scale of susy breaking

MSSM couples to susy breaking sector through messenger fields

$$W \ni -\lambda S f \bar{f}$$

potential is minimized: $f\bar{f} = \frac{m^2}{\lambda}$

$S = 0 \rightarrow$ susy unbroken

For broken susy need $\langle f \rangle = \langle \bar{f} \rangle = 0, \; \langle S \rangle \neq 0$

$\langle S \rangle \neq 0$ during inflation $\rightarrow$ coherent oscillations of S

dominate energy density of Universe after inflation

$\rightarrow$ S-decay produce Gravitinos & Radiation.

Couplings in SUSY Lagrangian

$$S = S_R + i S_I$$

~~$\mathcal{L}_{int}^{(\lambda)} = \frac{m_X}{2\langle S\rangle} \frac{1}{2} S_R \lambda\lambda$~~

S-field decays into two gravitinos

Non-thermal production + Boltzmann | MORE COMPLICATED

$$S_{R,I} \to \psi_{3/2}\,\psi_{3/2}$$

if energy density is ~~calculated~~ dominated by a non-relativistic matter ϕ

$$\phi \to X + \gamma$$

$$\dot\rho_\phi = -3H\rho_\phi - \Gamma_\phi \rho_\phi$$

$$\dot\rho_{rad} = -4H\rho_{rad} + \Gamma_\phi \rho_\phi$$

$$\dot n_X = -3H n_X - \langle\sigma v\rangle (n_X^2 - n_X^{eq\,2}) + \Gamma_\phi \frac{\rho_\phi}{m_\phi}\, b$$

COUPLED SYSTEM OF EQUATIONS

$$H^2 = \frac{1}{3M_p^2}\rho_{total} \qquad \rho_{tot} = \rho_\phi + \rho_{rad}$$

$$\rho_X \ll \rho_\phi, \rho_{rad}$$

if $n_X^{eq} < n_X$

$$\Rightarrow \frac{n_X}{s} = N_X \frac{H^{3/2}}{\Gamma_\phi^{1/2} \langle\sigma v\rangle s}, \qquad N_X \equiv \langle\sigma v\rangle \Gamma_\phi^{1/2} \frac{n_X}{H^{3/2}}$$

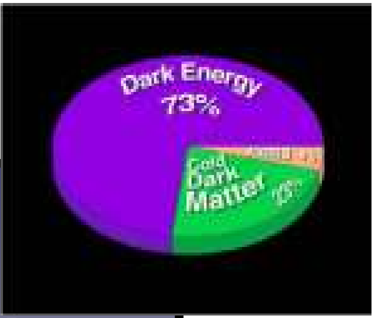
La TROBADA
Cosmo-OLE09 Workshop

N.E. MAVROMATOS

November 10th 2009

IFIC, Valencia

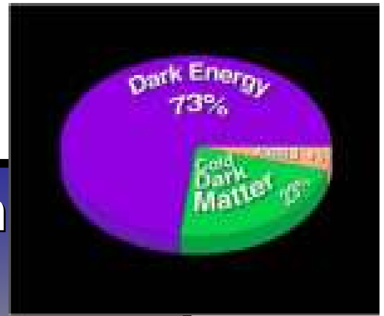
DARK MATTER



Non luminous massive matter: matter of unknown composition that does not emit or reflect enough electromagnetic radiation to be observed directly, but whose presence can be inferred from gravitational effects on visible matter.

Observed phenomena consistent with existence of dark matter: (I) rotational speeds of galaxies and orbital velocities of galactic clusters,
(II) gravitational lensing of background objects by galaxy clusters such as the Bullet cluster, and
(III) the temperature distribution of hot gas in galaxies and clusters of galaxies.
(IV) Dark matter also plays a central role in structure formation and galaxy evolution, and has measurable effects on the anisotropy of the cosmic microwave background.

DARK MATTER



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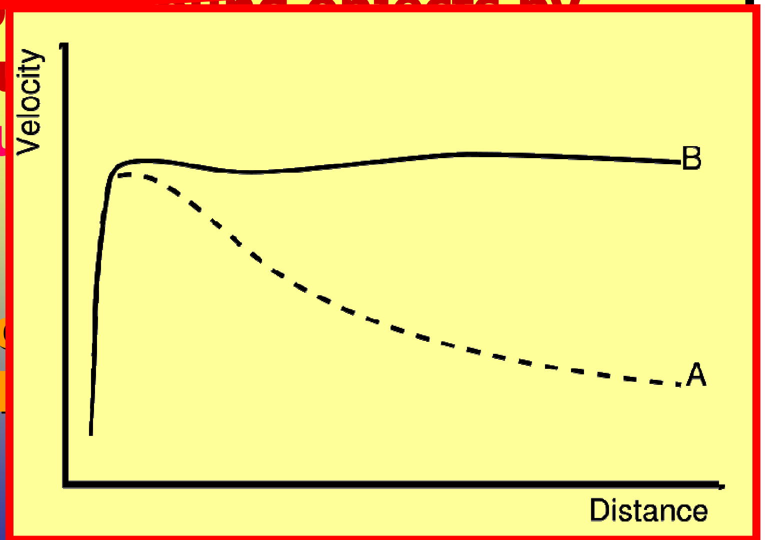

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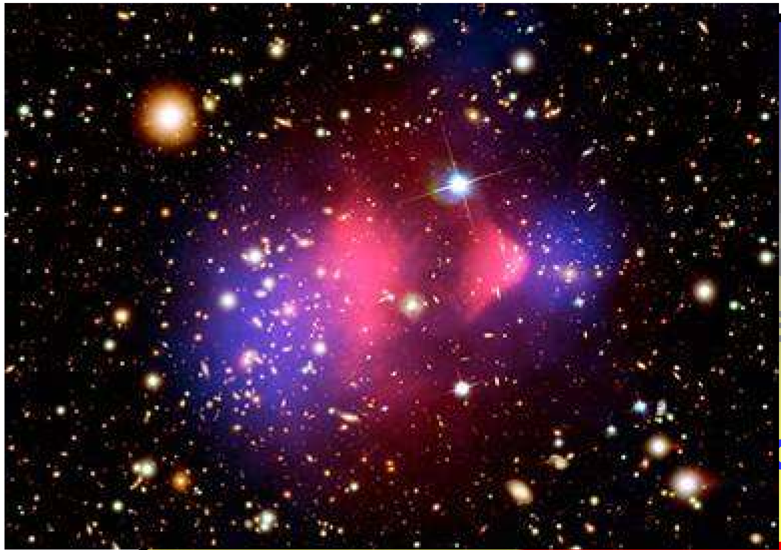
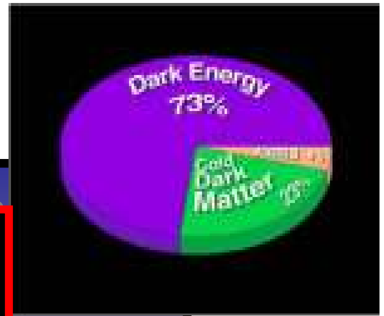


Bullet cluster: blue areas Dark Matter inferred by Gravitational Lensing Techniques



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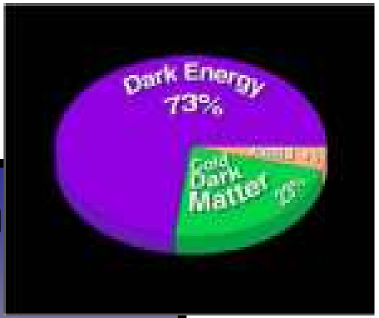

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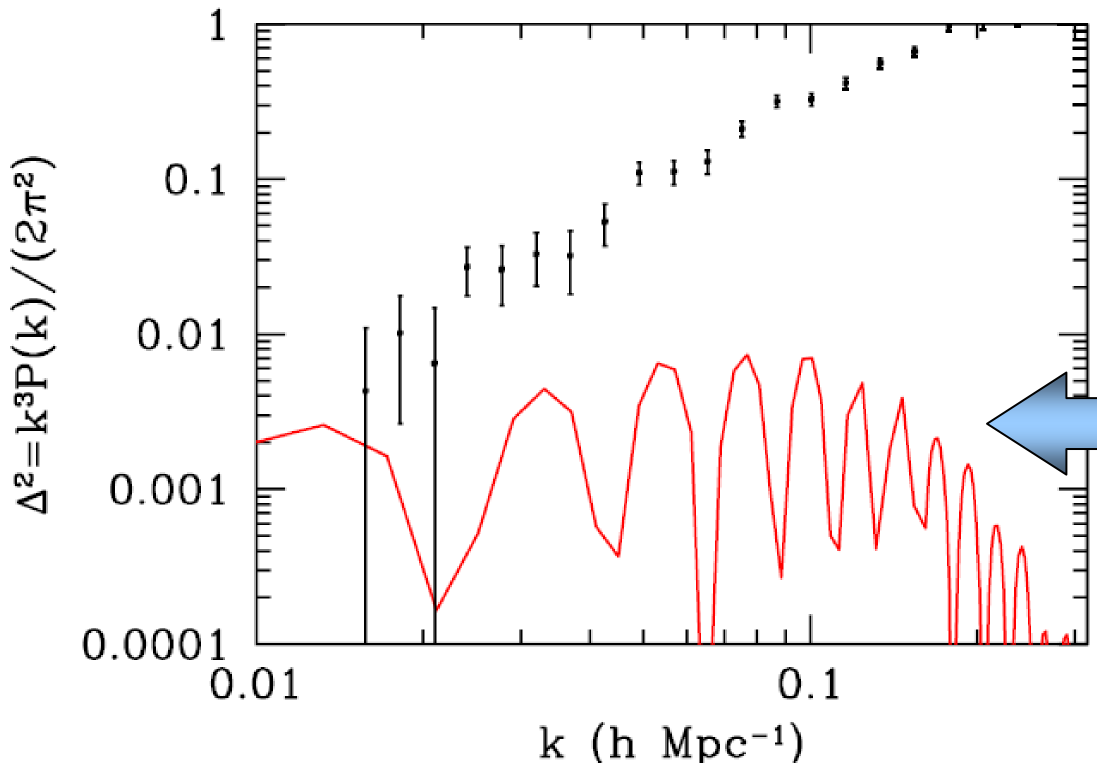
STRUCTURE FORMATION & DARK MATTER

Power Spectrum of Galaxies

$$\Delta^2 = k^3 P(k)/(2\pi^2)$$



Baryon-only Models, without Dark Matter

Gravitational Lensing vs alternative gravity models

$$\vec{F} = m\mu(\frac{a}{a_0})\vec{a} \ ,$$

$$\mu(x) = 1 \ \ |x| >> 1,$$

$$\mu(x) = x \ , \ \ |x| << 1$$

MOdified Newotian Dynamics at galactic scales of Milgrom, introduces universal acceleration constant a_0

Relativistic Field Theory Limit- Tensor-Vector-Scalar

(TEVES) Model of Bekenstein

ALTERNATIVES TO DARK MATTER

$$A_\mu A^\mu = -1$$

Time-like Vector Instabilities (c.f. growth of galaxies, baryon spectrum)

Can fit many rotation curves, but FAIL, in their simplest form at least, to account for certain gravitational lensing observations

Ferreras, Sakellariadou, Yusaf (2008)

Mavromatos, Sakellariadou, Yusaf (2009)

Ferreras, Mavromatos, Sakellariadou, Yusaf (2009)

lternative gravity

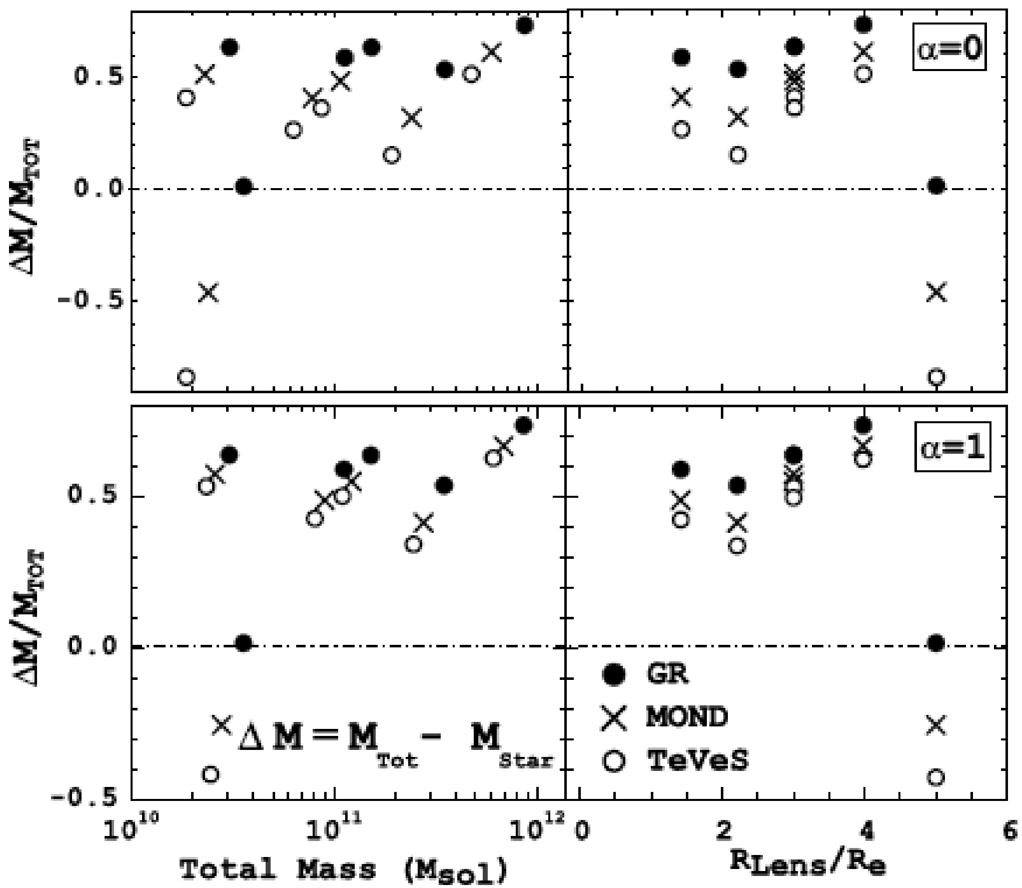


FIG. 2: A comparison of the need for dark matter for the lenses in GR, MOND and TeVeS, for $\alpha = 0$ (top panels) and $\alpha = 1$ (bottom panels). The right hand panels give the dark matter requirements as a function of the ratio R_{lens}/R_e. Any dark matter needed in TeVeS is especially significant for those masses which probe further out, where the modification to gravity is larger.

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nstant a_0
-Scalar
R
growth

Mavromatos, Sakellariadou, Yusaf (2009)

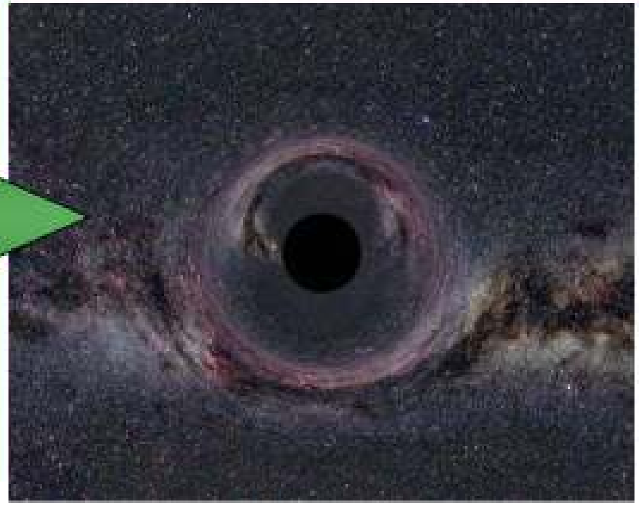
DARK MATTER COMPOSITION

ASTROPHYSICAL OBJECTS:

(i) MAssiveCompactHalo ObectS (MACHOS) :

Dwarf stars and Planets (**Baryonic Dark Matter**) and

Black Holes



(ii) Non-luminous Gas Clouds

PARTICLES (Non-Baryonic Dark Matter)

Weakly Interacting Massive Particles (WIMP) might be the best candidates for it: should not have electromagnetic or strong interactions. May have weak and gravitational interactions.

Why Massive: to make up the "missing mass" in galaxies.

WIMPS: axions,neutrinos
Stable Supersymmetric
Partners (neutralino, etc)

If these WIMPS are **thermal relics** from Big Bang then we can calculate their relic abundance today and compare with CMB and other astrophysical data.

Non thermal relics may also exist in some models...

TYPES OF DARK MATTER

- HOT DARK MATTER (HDM): form of dark matter which consists of particles that travel with ultrarelativistic velocities: e.g. neutrinos

- COLD DARK MATTER (CDM): form of dark matter consisting of slowly moving particles, hence cold,
- e.g. axions, WIMPS (stable supersymmetric particles (neutralinos etc.) or MACHOS.

- WARM DARK MATTER (WDM): form of dark matter with properties between those of HDM and CDM, sterile neutrinos, light gravitinos-partner of gravitons in supergravity theories…)

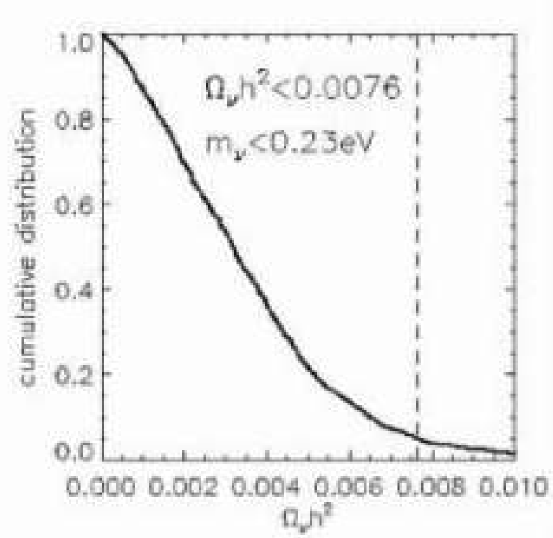
PHYSICS: WMAP and Dark Matter

WMAP results so far:

- Disfavor strongly hot dark matter (neutrinos), $\Omega_\nu h^2 < 0.0076$ ($< m_\nu >_e < 0.23$ eV).
- Warm Dark Matter (gravitino) disfavoured by evidence for re-ionization at redshift $z \sim 20$.
- Cold Dark Matter (CDM) remains: axions, supersymmetric dark matter (lightest SUSY particle (LSP)), superheavy (masses $\sim 10^{14\pm 5}$ GeV)

  WMAP results: $\Omega_m h^2 = 0.135^{+0.008}_{-0.009}$ (matter), $\Omega_b h^2 = 0.0224 \pm 0.0009$ (baryons), hence, assuming CDM is the difference, $\Omega_{CDM} h^2 = 0.1126^{+0.0161}_{-0.0181}$, ($2\sigma$ level).

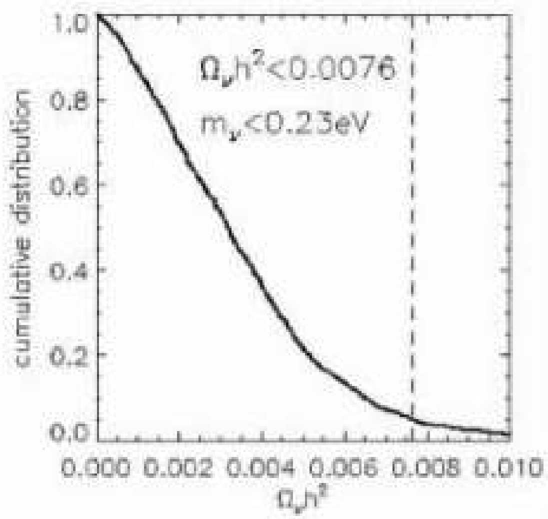
WMAP excludes HOT Dark Matter



Contribution of neutrinos to energy density of Universe: $\Omega_\nu h^2 = \frac{\sum_i m_i}{94.0 \text{ eV}}$
(sum over light neutrino species (decouple while still relativistic)).
WMAP and other experiments (the Lyman α data etc) $\Omega_\nu h^2 < 0.0076 \Rightarrow < m_\nu >_e < 0.23$ eV :
Excludes HOT DM.

NB: WMAP still consistent with Majorana neutrinos, and also marginally with $\beta\beta$-decay (Heidelberg-Moscow Coll.).

WMAP excludes HOT Dark Matter



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Model dependence…

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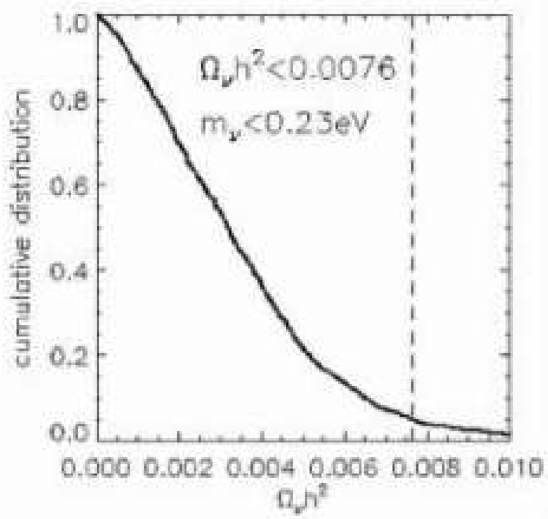
WMAP excludes HOT Dark Matter

Caution:
FRW- Comology &
local Lorentz
invariance **assumed.**
If Lorentz violated (TeVeS)
ν of 2 eV mass could have
$\Omega_\nu \sim 0.15$ to reproduce
CMB spectrum
(Dodelson-Liguori 2006)



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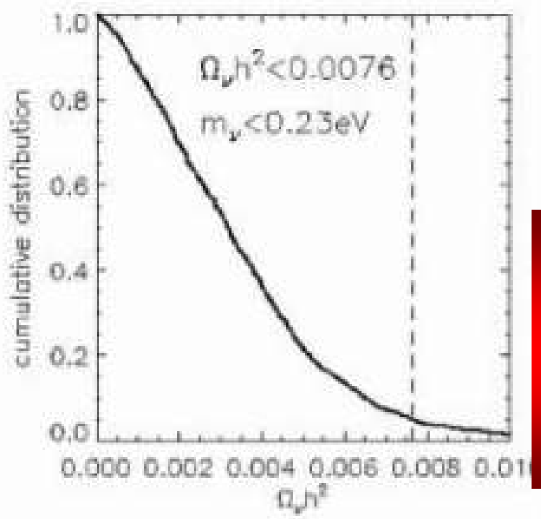

BUT…TeVeS excluded by Gravitational Lensing Data

(Ferreras, Sakellariadou, Yusaf, NM)

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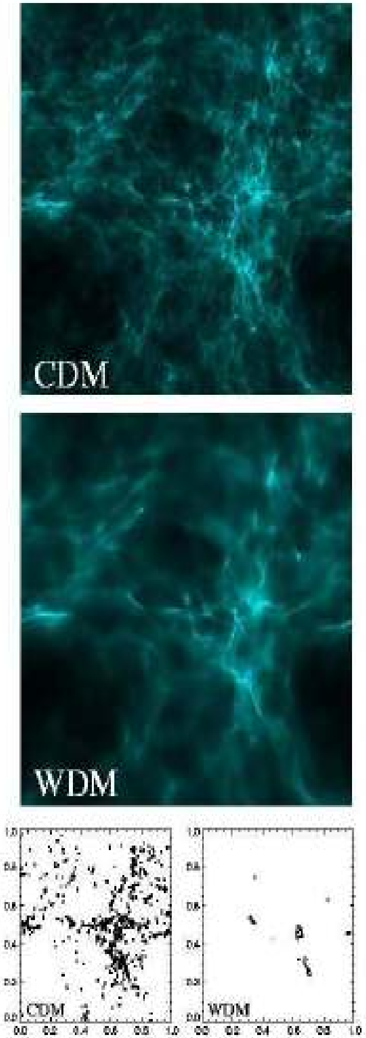

Numerical simulations for structure formation in Cold Dark Matter (CDM) (top) and Warm Dark Matter (WDM) (middle) with mass $m_X = 10$ KeV at $z = 20$. Bottom: Dark halos with mass $> 10^5 M_\odot$ for CDM (left) and for WDM (right).

IMPORTANT COMMENTS:

Such structure formation arguments can only place a lower bound on mass of the WDM candidate: $m_X > 10$ KeV.

Above results exclude Light Gravitino Models ($m_X < 0.5 KeV$) of Particle Physics as DM candidates.

NB! WDM with $m_X \geq 100$ KeV becomes indistinguishable from Cold Dark Matter, as far as structure formation is concerned.

Exotic SM Particles relevant(?) to Cosmology

- **Axions:** massive (neutral) particles (not discovered as yet)
  - Required for a **solution of the so-called strong CP problem:** i.e. why strong interactions (QCD) do not break CP symmetry as the weak interactions do (axion mechanism: Goldstone-Boson of spontaneously broken Peccei Quinn symmetry, acquiring a small mass due to non-perturbative QCD instanton effects)
  - Current Experiments looking for Axions: CAST(CERN), PVLAS
  - Mass range (light masses): $10^{-6} < m < 10^{-2}$ eV/c^2

  (ADMX experiment ruled out very light axion masses 10^{-6})
  - Strong and Weak Interactions Cross section: Very low
  - Change to (and from) photons in the presence of strong magnetic fields , allows detection (c.f. CAST Experiment)
  - Cosmology: Abundant creation of Axions during Big-Bang. Due to their **very low-mass** they may not have other decay modes, thus filling up the Universe with a cold Bose-Einstein condensate

    and (depending on masses and interaction couplings) playing the role of **Dark Matter (DM) candidates.**

    Heavy axions (if allowed) could not survive at late eras of the Universe, hence **cannot contribute to DM**

Beyond SM I: Massive Neutrinos ν

- **In SM Neutrinos ν are massless and come into three "flavours",**

  ν_e , ν_μ , ν_τ .

- **However in the 1990's it was confirmed experimentally (through observed ν - flavour oscillations) that neutrinos have small masses. Actually at present only mass differences can be measured through oscillation experiments. The latest results are:**

$\Delta m_{21}^2 = 0.000079 \text{ eV}^2$ (KamLAND) ,
$\Delta m_{23}^2 = 0.0031 \text{ eV}^2$ (2006, initial MINOS consistent with Super-K)

- **Being weakly interacting and massive neutrinos could be a dark matter candidate** ("Hot DM", as they move at speed close to light speed)**.**

- **But Hot DM cannot cluster around galaxies….**
  …So DM problem is not solved by ν.

- **Moreover, within the FRW-ΛCDM Cosmology, WMAP derived upper bounds for the sum of (light) neutrino masses excluding HOT DM as the dominant DM candidate** via CMB data**.**

WMAP excludes HOT Dark Matter

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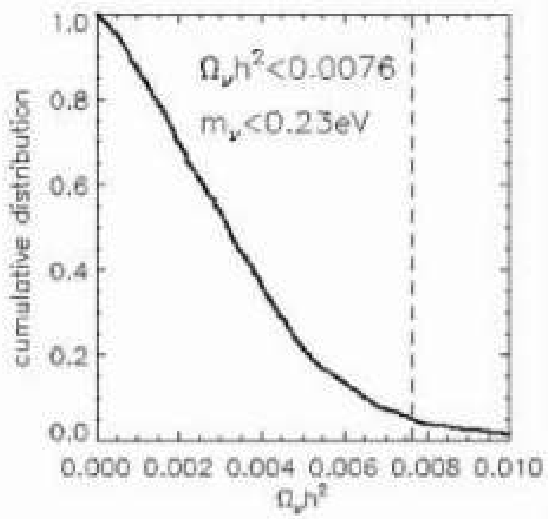

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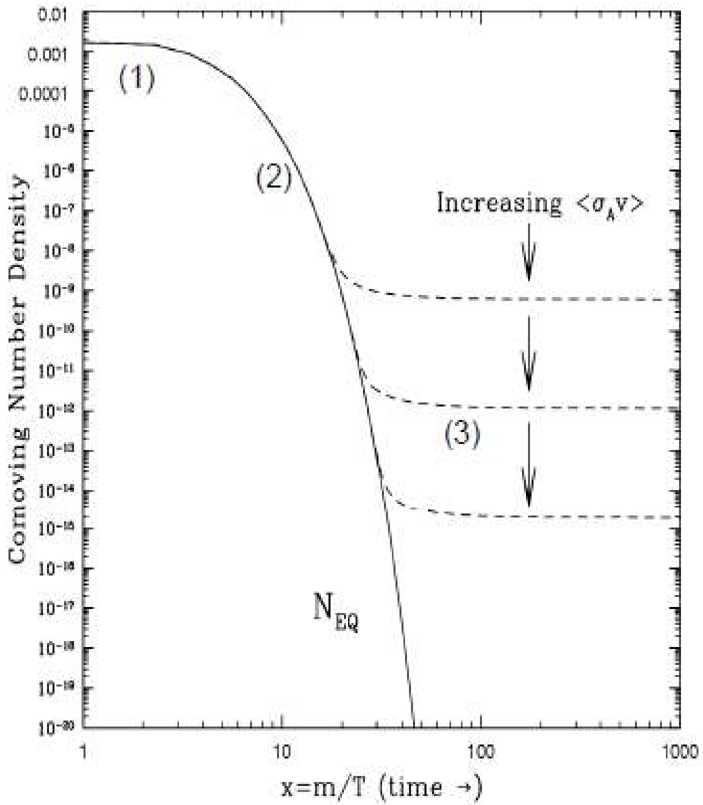
WIMP Dark Matter: thermal properties & relic densities



The full line is the equilibrium abundance; the dashed lines are the actual abundance after freeze-out. As the annihilation cross section $\langle \sigma_A v \rangle$ is increased, the WIMP stays in equilibrium longer, leading to a smaller relic density.

WIMP Dark Matter: thermal properties & relic densities

Standard assumption: the dark matter particle, χ, is a thermal relic of the Big Bang:

When the early Universe was dense and hot, $T \gg m_\chi$, χ was in thermal equilibrium ; annihilation of χ and $\bar{\chi}$ into lighter particles, $\chi\bar{\chi} \to l\bar{l}$, and the inverse process $l\bar{l} \to \chi\bar{\chi}$ proceeded with equal rates.

As the Universe expanded and cooled to a temperature $T < m_\chi$, the number density of χ dropped exponentially, $n_\chi \sim e^{-m_\chi/T}$.

Eventually the temperature became too low for the annihilation to keep up with the expansion rate and χ 'froze out' with the cosmological abundance observed today.

MODEL DEPENDENT

Time evolution of number density $n_\chi(t) \Longrightarrow$ Boltzman equation,

$$\mathrm{d}n_\chi/\mathrm{d}t + 3Hn_\chi = -\langle\sigma_A v\rangle\left[(n_\chi)^2 - (n_\chi^{\mathrm{eq}})^2\right],$$

H=Hubble expansion rate, n_χ^{eq} = equilibrium number density, $\langle\sigma_A v\rangle$ the thermally averaged annihilation cross section summed over all contributing channels.

It turns out that the relic abundance today is inversely proportional to the thermally averaged annihilation cross section, $\Omega_\chi h^2 \sim 1/\langle\sigma_A v\rangle$.

When the properties and interactions of the WIMP are known, its thermal relic abundance can hence be computed from particle physics' principles and compared with cosmological data.

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The equation is modified in Non-equilibrium Cosmologies

$$\boxed{\frac{dn}{dt} + 3\frac{\dot{a}}{a}n = \Gamma(t)n + \int \frac{d^3p}{E}C[f]}$$

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Lahanas, NM, Nanopoulos

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Appropriate source terms, dilaton rates off-shell terms …, see below

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and χ 'froze

Time evoluti

$$\Gamma(t) \equiv \dot{\Phi} + \frac{1}{2}\eta\left(e^{-\Phi} g^{\mu\nu}\,\tilde{\beta}^{\rm Grav}_{\mu\nu} + 2e^{\Phi}\,\tilde{\beta}^{\Phi}\right), \quad \eta = -1$$

$$\mathrm{d}n_\chi/\mathrm{d}t + 3Hn_\chi = -\langle\sigma_A v\rangle\left[(n_\chi)^2 - (n_\chi^{\rm eq})^2\right]$$

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SUSY PARTICLE SPECTRUM

(☐ = superpartners)

spin $\frac{1}{2}$	spin 0	spin 1	spin $\frac{1}{2}$
quark q_L, q_R	squark $\tilde{q}_L, \tilde{q}_R$	W_3, B	$\tilde{W}_3, \tilde{B}$
lepton ℓ_L, ℓ_R	slepton $\tilde{\ell}_L, \tilde{\ell}_R$	$W^\pm$	$\tilde{W}^\pm$
higgsino $\tilde{H}_1, \tilde{H}_2$	Higgs H_1, H_2	gluon g	gluino $\tilde{g}$

graviton (spin 2) ↔ gravitino (spin 3/2)

$$\tilde{W}^\pm, \tilde{H}^\pm \Longleftrightarrow \tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$$ (charginos)

$$\tilde{B}, \tilde{W}_3, \tilde{H}_1, \tilde{H}_2 \Longleftrightarrow \tilde{\chi}_1^0, \ldots, \tilde{\chi}_4^0$$ (neutralinos)

- *R*-parity: $R = (-1)^{3(B-L)+2s}$ → $R = \begin{cases} +1, \text{ for SM particles} \\ -1, \text{ for superpartners} \end{cases}$
  - ***R*-parity conservation hinted but *not required* by proton stability**
  - **not a fundamental symmetry**
- If *R*-parity is conserved:
  - **SUSY-partners are always produced in pairs (*R* is a multiplicative quantum number)**
  - **Lightest SUSY-particle (LSP) is stable**
    - should be colorless and neutral
    - weakly interacting → escapes the detector undetectable → *large missing energy*
    - dark matter candidate

PHYSICS: WMAP and SUSY Dark Matter

SUSY Dark Matter: favorite candidate NEUTRALINO χ as (stable) Lightest SUSY particle.

From WMAP then, assuming $\Omega_{CDM} \simeq \Omega_\chi$, we can infer stringent limits for its relic density:

$$\boxed{0.094 < \Omega_\chi h^2 < 0.129}, \qquad (2-\sigma \quad \text{level})$$

Important: Upper limit is RIGOROUS.
Lower Limit is OPTIONAL (could exist other contributions to overall matter density).

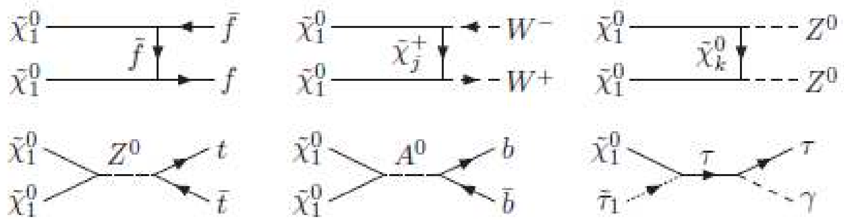
Use this constraint, together with $g_\mu - 2$, $b \to s\gamma$ to **CONSTRAIN SUSY MODELS**, specifically MSSM with universal value for scalars m_0 and gauginos $m_{1/2}$ at some input GUT scale (Constrained MSSM (CMSSM)).

Concentrate on plots $(m_0, m_{1/2})$ for minimal SUGRA model (mSUGRA).

Neutralino dark matter

Neutralino mass matrix in bino–wino–higgsino basis $\psi_j^0 = (-i\lambda', -i\lambda^3, \psi_{H_1}^0, \psi_{H_2}^0)$ is

$$\mathcal{M}_N = \begin{pmatrix} M_1 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\ 0 & M_2 & m_Z c_W c_\beta & -m_Z c_W s_\beta \\ -m_Z s_W c_\beta & m_Z c_W c_\beta & 0 & -\mu \\ m_Z s_W s_\beta & -m_Z c_W s_\beta & -\mu & 0 \end{pmatrix}$$



M_1, M_2: the U(1) and SU(2) gaugino masses, μ: higgsino mass parameter, $s_W = \sin\theta_W$, $c_W = \cos\theta_W$, $s_\beta = \sin\beta$, $c_\beta = \cos\beta$ and $\tan\beta = v_2/v_1$ ($v_{1,2}$ v.e.v. of Higgs fields $H_{1,2}$).

Matrix diagonalized by unitary mixing matrix N,

$N^* \mathcal{M}_N N^\dagger = \mathrm{diag}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_4^0})$, where $m_{\tilde{\chi}_i^0}$, $i = 1, ..., 4$, are the (non-negative) masses of the physical neutralino states with $m_{\tilde{\chi}_1^0} < ... < m_{\tilde{\chi}_4^0}$. The lightest neutralino is then:

$$\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W} + N_{13}\tilde{H}_1 + N_{14}\tilde{H}_2 \, .$$

Neutralino relic densities via Boltzman equation

Without coannihilations: evolution of relic particle number density, n governed by single species Boltzmann equation:

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left[n^2 - (n^{\rm eq})^2 \right].$$

Number density modified by Hubble expansion and by direct and inverse annihilations of the relic particle. Relic particle is assumed stable , so relic decay neglected. Also assumed T invariance to relate annihilation and inverse annihilation processes.

Presence of coannihilators: Boltzmann equation more complicated but can be simplified using stability properties of relic particle and coannihilators (using $n = \sum_{i=1}^{N} n_i$):

$$\frac{dn}{dt} = \; - \; 3Hn - \sum_{i,j=1}^{N} \langle \sigma_{ij} v_{ij} \rangle \left(n_i n_j - n_i^{\rm eq} n_j^{\rm eq} \right).$$

To a very good approximation, can use single species Boltzmann equation for coannihilations case if:

$$\langle \sigma v \rangle = \sum_{i,j} \langle \sigma_{ij} v_{ij} \rangle \frac{n_i^{\rm eq}}{n^{\rm eq}} \frac{n_j^{\rm eq}}{n^{\rm eq}}.$$

Boltzman can be solved numerically, but in most cases even analytically.

Solving the Boltzman equation

Determine freeze-out temperature $x_F = m_\chi / T_F$: $x_F = \ln\left(\frac{0.038\, g\, m_{\rm pl}\, m_\chi \langle\sigma v\rangle}{\sqrt{g_*\, x_F}}\right)$.

$m_{\rm pl}$: Planck mass, g : total number of degrees of freedom of the χ particle (spin, color, etc.),

g_* : total number of effective relativistic degrees of freedom at freeze-out, and the thermally averaged cross section is evaluated at the freeze-out temperature. For most CDM candidates, $x_F \simeq 20$.

Total (co)annihilation depletion of neutralino number density calculated by integrating the thermally averaged cross section from freeze-out to the present temperature:

$$\Omega_\chi {\rm h}^2 = 40\sqrt{\frac{\pi}{5}}\frac{h^2}{H_0^2}\frac{s_0}{m_{Pl}^3}\frac{1}{\left(g_{*S}/g_*^{1/2}\right)\, J(x_F)} = \frac{1.07\times 10^9\ {\rm GeV}^{-1}}{g_*^{1/2}\, m_{\rm pl}\, J(x_F)}, \quad J(x_F) = \int_{x_F}^{\infty}\langle\sigma v\rangle\, x^{-2} dx.$$

g_{*S} number of effective relativistic dof contributing to the entropy of the universe and h is the reduced Hubble parameter: $H_0 = 100\, h\ {\rm km\, sec^{-1}\, Mpc^{-1}}$. Expression one compares with experimental determination of the DM abundance.

NB1: Theoretical assumptions leading to above may not hold: the missing non-baryonic matter in the universe may only partially, or not at all, consist of relic neutralinos.

CMSSM/mSUGRA: MUST KNOW

Parameters:

$m_0, m_{1/2}, A_0$= universal trilinear coupling, μ=Higgs parameter, tanβ= $\frac{<H_2>}{<H_1>}$; H_2 gives mass to u quark, H_1 gives mass to d quark and lepton.

Geometry of Parameter space: two branches

Loop corrections imply constraints on radiative electroweak symmetry breaking for m_0 and a combination $m'_{12} = f(m_{1/2}, A_0, \tan\beta)$:

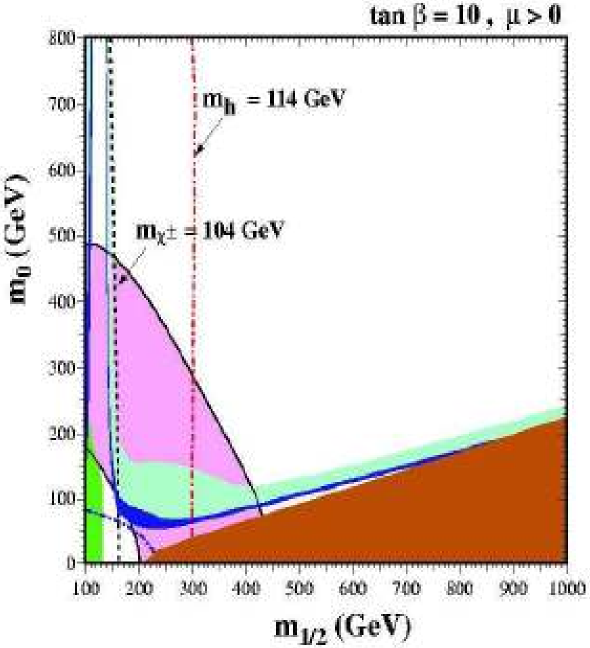
Ellipsoidal Branch (EB) of RSSB: For given μ, and small values of tan$\beta < 7$: $(m_0, m'_{12}) \in$ surface of ELLIPSOID $\rightarrow$ upper bound on sparticle masses for a given value of $\Phi \equiv \mu^2/M_Z^2 + 1/4$

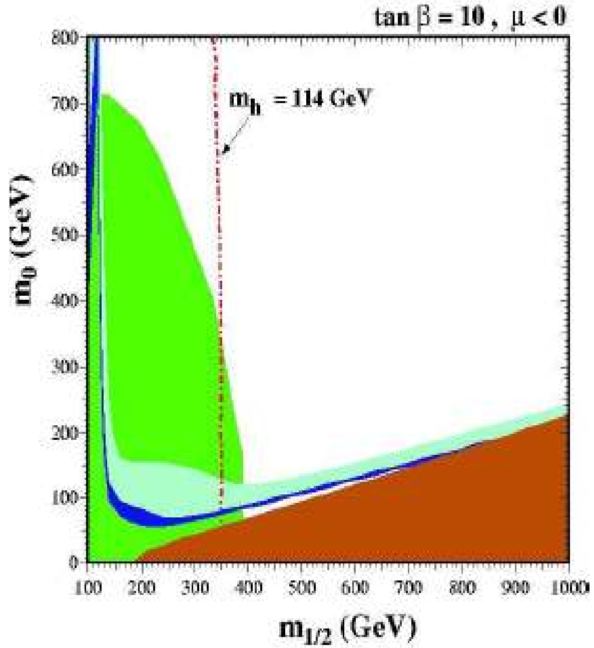
(**Hyperbolic Branch (HB) of RSSB**): For given μ, and large values of tan$\beta \gtrsim 7$: $(m_0, m'_{12}) \in$ surface of HYPERBOLOID: $\frac{{m'_{1/2}}^2}{\alpha^2(Q_0)} - \frac{{m_0}^2}{\beta^2(Q_0)} \simeq \pm 1, \quad Q_0 = 0$ fixed value of running scale, α, β constant functions of Φ, M_Z, A_0. **For fixed A_0 $m_0, m_{1/2}$ lie on hyperbola** $\rightarrow$ can get large for fixed μ or Φ.

WMAP AND SUSY CONSTRAINTS

Ellis, Olive, Santoso & Spanos, arXiv:hep-ph/0303043, Lahanas & Nanopoulos arXiv:he-ph/0303130

mSUGRA

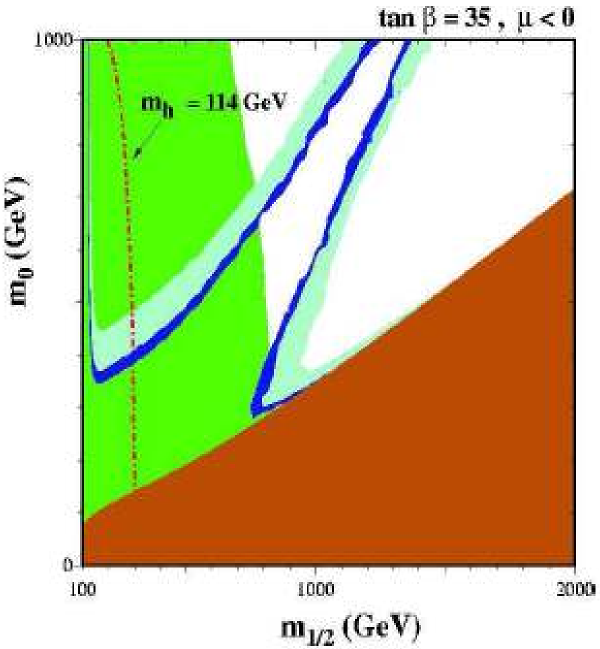


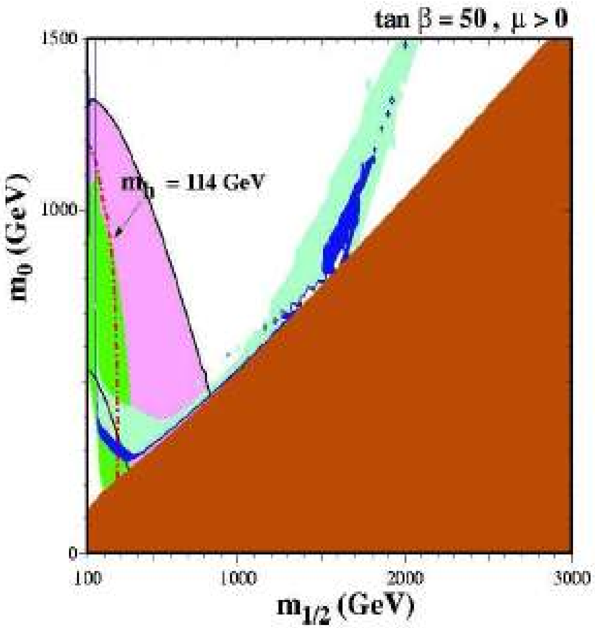


Dark Blue shaded region favoured by WMAP ($0.094 \leq \Omega_\chi h^2 \leq 0.129$). Turquoise shaded: have $0.1 \leq \Omega_\chi h^2 \leq 0.3$. Brick red shaded regions excluded because LSP is charged. Dark green regions: excluded by $b \to s\gamma$. The Pink shaded: $2-\sigma$ effects of $g_\mu - 2$. Dash-dotted line: LEP constraint on $\tilde{e}$ mass.

WMAP AND SUSY CONSTRAINTS (cont'd)

Ellis, Olive, Santoso & Spanos, arXiv:hep-ph/0303043, mSUGRA





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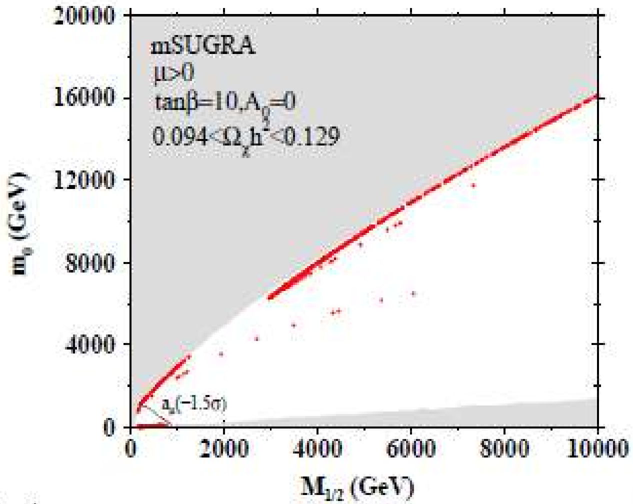
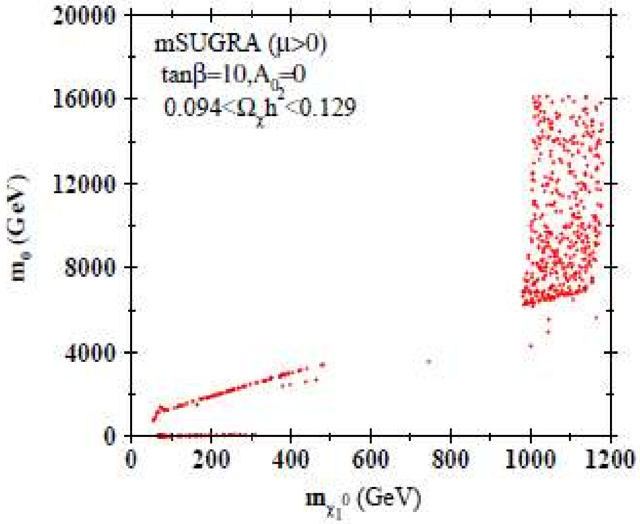
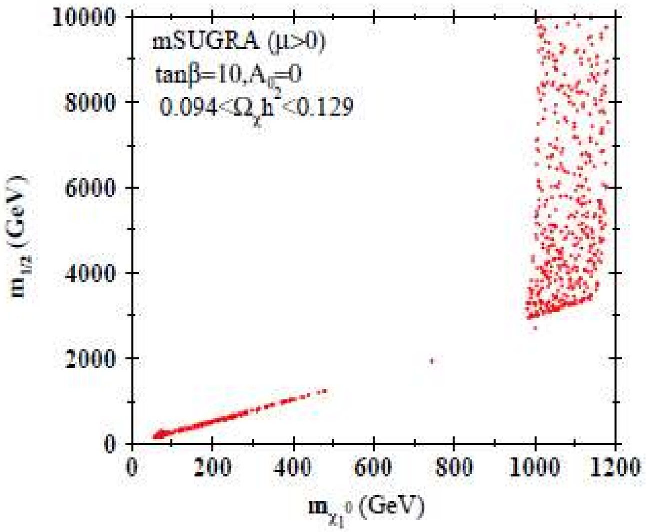
HB/mSUGRA (Chattopadhyay *et al.* arXiv:hep-ph/0303201)







The importance of $g_\mu - 2$ for HB Branch

There are two estimates (due to severe theoretical uncertainties) for the difference of the experimentally measured (E821 Expt) value of $a_\mu = (g_\mu - 2)/2$ from the theoretically calculated one within the standard model (SM) (Narison, arXiv:hep-ph/0303004):

- (I) $a_\mu^{\rm exp} - a_\mu^{\rm SM} = 1.7(14.2) \times 10^{-10}$
- (II) $a_\mu^{\rm exp} - a_\mu^{\rm SM} = 24.1(14.0) \times 10^{-10}$

Estimate (II), has been used in Chattopadhyay *et al.* 2003, at a 1.5σ range. In this case much of the HB Branch and all of Inversion region can be eliminated.

Estimate (I), essentially implies no difference, and hence if adopted leaves intact the HB Branch and the Inversion region.

Imperative to determine unambiguously $g_\mu - 2$ by reducing the errors in the leading order hadronic contribution.

Recent measurement (1σ-level) (Eidelman, talk at ICHEP 2006 Moscow (Russia)):

$$1.91 \times 10^{-9} < \Delta a_\mu < 3.59 \times 10^{-9}$$

(Now deviates from the SM prediction by $3.4\ \sigma$)

Model Independent Dark Matter Tests at Colliders (Birkedal hep-ph/0509199)

Introduce the parameter $\kappa_e \equiv \sigma(\chi\chi \to e^+e^-)/\sigma(\chi\chi \to SM|SM)$

Use crossing symmetries to relate $\sigma(\chi\chi \to e^+e^-)$ to $\sigma(e^+e^- \to \chi\chi)$ and co-linear factorization to relate $\sigma(e^+e^- \to \chi\chi)$ to $\sigma(e^+e^- \to \chi\chi\gamma)$, thus relating astrophysical data on $\sigma_{\rm an}$ to $e^+e^- \to \chi\chi\gamma$:

$$\frac{d\sigma}{dx d\cos\theta}(e^+e^- \to 2\chi + \gamma) \simeq \frac{\alpha\kappa_e\sigma_{\rm an}}{16\pi}\frac{1+(1-x)^2}{x}\frac{1}{\sin^2\theta}2^{J_0}(2S_\chi+1)^2\left(1-\frac{4M_\chi^2}{(1-x)s}\right)^{\frac{1}{2}+J_0},$$

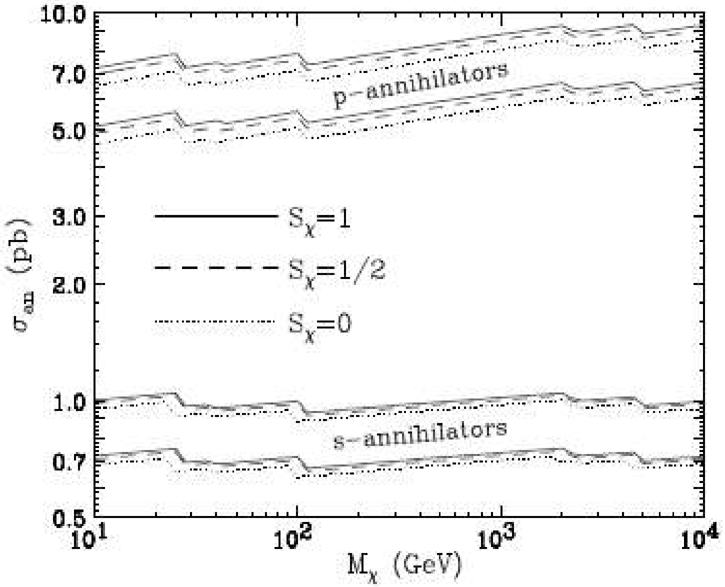
$x = 2E_\gamma/\sqrt{s}$, θ angle between photon & incoming electron, S_χ spin of WIMP, J_0 dominant value of J in velocity expansion of $\langle\sigma v\rangle = \sum_J \sigma_{\rm an}^{(J)} v^{(2J)}$ (commonly $J=0$ dominates, s-annhilator DM).

NB: although model independent, the above process is rarely the dominant collider signature of new physics within a given model.

Important: slepton masses essential for computing relic abundances; without a collider measurement of the slepton mass, there may be a significant uncertainty in the relic abundance calculation. This uncertainty results because the slepton mass should then be allowed to vary within the whole experimentally allowed range.

Measure slepton masses at LHC (direct production challenging due to W^+W^- and $t\bar{t}$ production but possible through $m_{\ell\ell}$ distribution in $\tilde{\chi}_2^0 \to \ell^\pm\ell^\mp\tilde{\chi}_1^0$) and ILC.

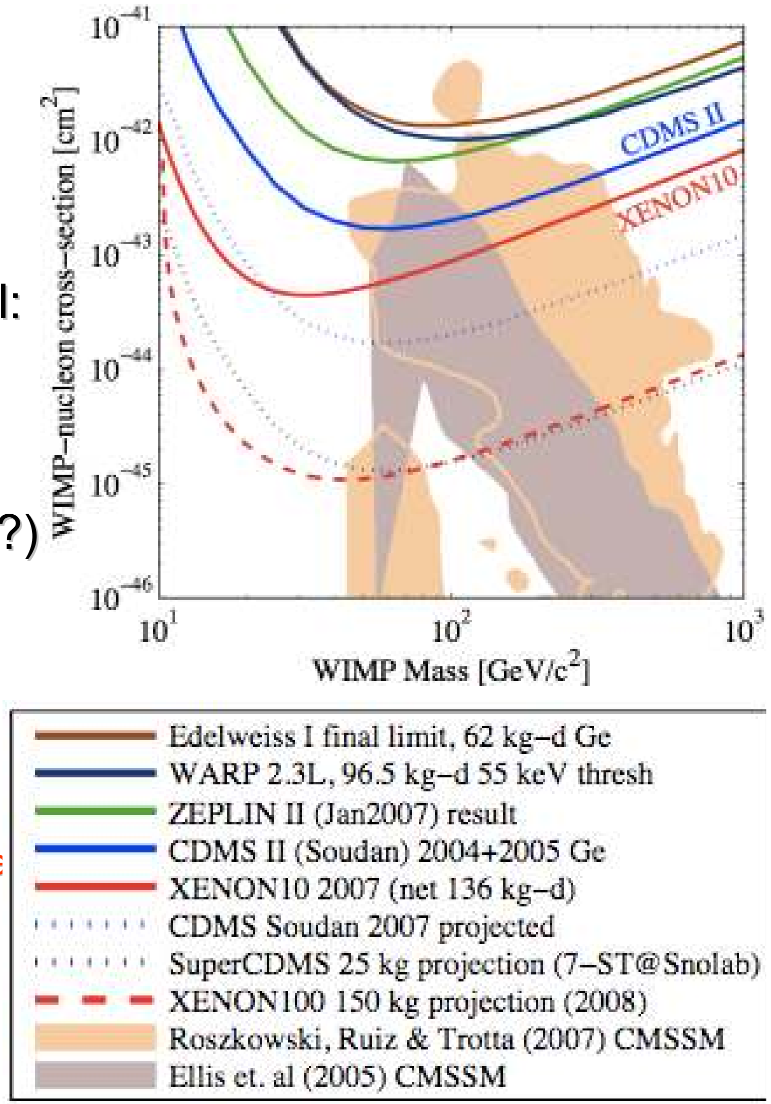
Model Independent Dark Matter Tests at Colliders



Values of the quantity σ_{an} allowed at 2σ level as a function of the dark matter mass. The lower (upper) band is for models where s-wave (p-wave) annihilation dominates. (A. Birkedal hep-ph/0509199). Important: $\sigma_{\rm an}$ virtually insensitive to dark-matter mass and points to cross sections expected from weak-scale interactions (around $0.8\,pb$ for s-annihilators and $6\,pb$ for p-annihilators) $\Longrightarrow$ possibility that DM is connected to WIMPs. Such WIMPs exist not only in supersymmetric theories, but also in theories involving extra dimensions and 'little Higgs' theories.

Dark matter: (in)direct WIMP searches

- **Direct detection**
  - look for elastic scattering of WIMP on nuclei
  - sensitive to WIMP mass m_X and cross section $\sigma_{X\text{-nucleon}}$
  - various techniques applied to observe the recoil: scintillator NaI, cryogenic, noble liquids (Ar, Xe), bubble chamber (superheated liquid)
    ➔ uncorrelated systematics
  - annual modulation observed by DAMA/LIBRA (?)
    - **not confirmed by other experiments**
- Indirect detection
  - look for annihilation products in galactic halo
  - sensitive to DM particle annihilation processes
  - telescopes
    - neutrinos: ANTARES, NESTOR,Amanda, Icecube, Supe
    - γ-rays: MAGIC, HESS, Veritas, Cangaroo
    - γ-rays, antiprotons, e^+: Glast, PAMELA, AMS, HEAT
  - can distinguish different WIMPs: neutralinos, KK states, ...
  - hints of DM annihilation seen by EGRET, HESS , ATIC & PAMELA (but probably excess positrons are due to PULSARS)
- Important for checking compatibility of cosmological and particle physics (LHC) results with SUSY (or other) scenario



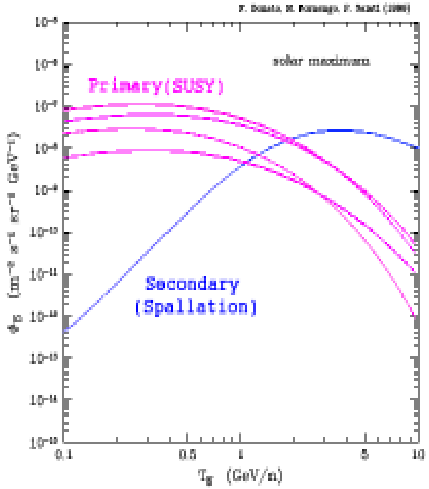
http://dmtools.brown.edu

Other Fields: Nuclear (Astro)Physics of Antimatter

Indirect detectors of SUSY dark matter (searching for cosmic antideuteron (clean signals)) (Hailey, LEAP03, Yokohama (March 2003) talk)

Cosmic antideuterons are an indirect but clear sign of dark matter

Antideuteron flux at the earth (w/propagation and solar modulation)



primary component: neutralino annihilation

$\chi + \chi \rightarrow \gamma, \bar{p}, \bar{D}$

Secondary component: spallation

$p + H \rightarrow p + H + X + \bar{X}$

$p + He \rightarrow p + He + X + \bar{X}$

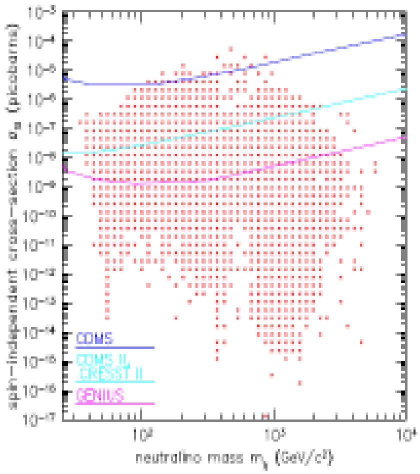
Cleaner signature than antiprotons

Antideuteron flux ~10^{-8} $m^{-2}s^{-1}sr^{-1}GeV^{-1}$

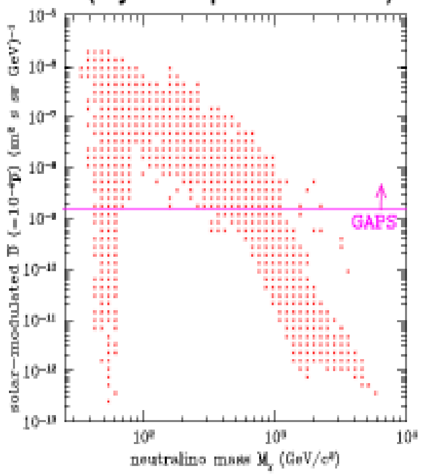
Large grasp AΩ [m^2 sr] required

GAPS measures low energy antideuterons produced by neutralino annihilation in the mass range M_χ~80-350 GeV

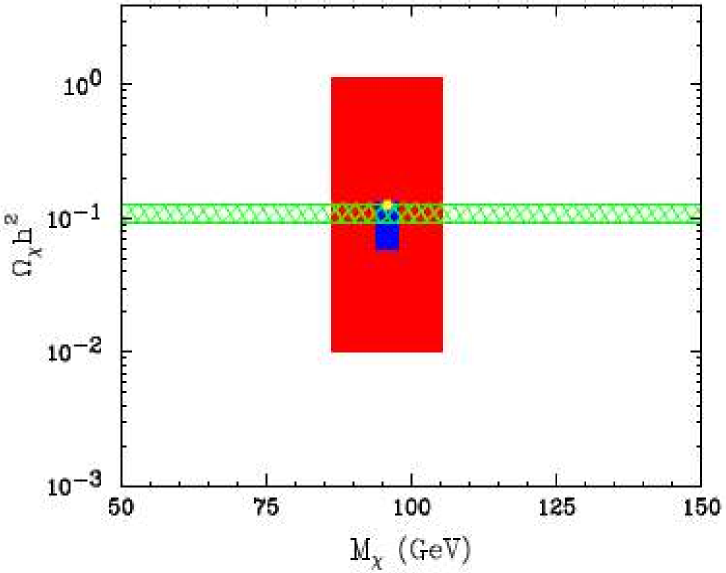
Direct Dark Matter Searches



GAPS (3 year Explorer Mission)



Summary of ACCURACY of determining mSUGRA DM mass in astrophysics & colliders



Accuracy of WMAP (horizontal green shaded region), LHC (outer red rectangle) and ILC (inner blue rectangle) in determining M_χ, the mass of the lightest neutralino, and its relic density $\Omega_\chi h^2$. The yellow dot denotes the actual values of M_χ and $\Omega_\chi h^2$ for point in parameter space of mSUGRA: $m_0 = 57$ GeV, $m_{1/2} = 250$ GeV, $A_0 = 0$, $\tan\beta = 10$ and $\text{sign}(\mu) = +1$ (A. Birkedal *et al.*, arXiv:hep-ph/0507214)

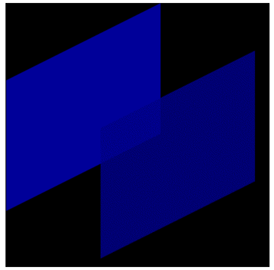
Simplest (Toy) Model: mSUGRA with dilaton Quintessence

Diamandis, Georgalas, Lahanas, NM, Nanopoulos
Papantonopoulos, Pappa

Dissipative Liouville Q-Cosmologies

Robertson-Walker Space times. **Effective 4-d action with matter & radiation (in String Frame)**

$$S^{(4)} = \frac{1}{2\alpha'}\int d^4x\sqrt{-G}[e^{-\Psi(\phi)}R(G) + Z(\phi)(\nabla\phi)^2 + 2\alpha' V(\phi)\dots] - \frac{1}{16\pi}\int d^4x\sqrt{G}\frac{1}{\alpha(\phi)}F^2_{\mu\nu} - I_{\rm m}(\phi, G, {\rm matter}) \ ,$$



including string loops, $e^{\Psi(\phi)} = c_0 e^{-2\phi} + c_1 + c_2 e^{2\phi} + \dots, \ Z(\phi) = 4 + \dots, \dots$

$V(\phi) = 2Q^2 e^{2\phi} + \tilde{V}, \ \tilde{V} = \alpha_3 e^{3\phi} + \beta_4 e^{4\phi} * \dots$

Off-Shell Liouville Equations: $(\rho_\phi = (\dot{\phi})^2 + V(\phi)/2 \ , \ p_\phi = (\dot{\phi})^2 - V(\phi)/2 \ )$

$$3H^2 = \rho_m + \rho_\phi + \frac{e^{2\phi}}{2}\mathcal{J}_\phi \ ,$$

$$2\frac{dH}{dt_E} = -\rho_m - \rho_\phi - p_m - p_\phi + a^{-2}(t_E)\mathcal{J}_{ii} \ , \qquad i = 1, 2, 3,$$

$$\frac{d^2\phi}{dt_E^2} + 3H\frac{d\phi}{dt_E} + \frac{1}{4}\frac{\partial V}{\partial\phi} + \frac{1}{2}(\rho_m - 3p_m) = -\frac{3\ \mathcal{J}_{ii}}{2\ a^2} - \frac{e^{2\phi}\mathcal{J}_\phi}{2} \ ,$$

Off-Shell Terms

$$\mathcal{J}_\phi = e^{-2\phi}(\ddot{\phi} - \dot{\phi}^2 + Qe^{\varphi}\dot{\phi}), \quad \mathcal{J}_{ii} = 2a^2\left(\ddot{\phi} + 3H\dot{\phi} + \dot{\phi}^2 + (1-q)H^2 + Qe^{\varphi}(\dot{\phi} + H)\right) \ .$$

Matter (non) Conservation equations:

$$\dot{\rho}_m + 3H(\rho_m + p_m) + \dot{Q}(\partial V(\phi))/2\partial Q - \dot{\phi}(\rho_m - 3p_m) = 6(H + \dot{\phi})a^{-2}\mathcal{J}_{ii}$$

Off-Shell Terms

Simplest (Toy) Model: mSUGRA with dilaton Quintessence

Diamandis, Georgalas, Lahanas, NM, Nanopoulos

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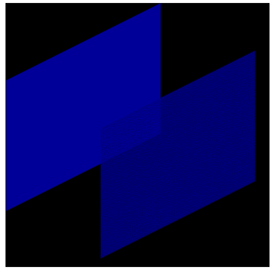
including string loops, $e^{\Psi(\phi)} = c_0 e^{-2\phi} + c_1 + c_2 e^{2\phi} + \dots$, $Z(\phi) = 4 + \dots$, ...

$V(\phi) = 2Q^2 e^{2\phi} + \tilde{V}$, $\tilde{V} = \alpha_3 e^{3\phi} + \beta_4 e^{4\phi} * \dots$



Off-Shell Liouville Equations: $(\rho_\phi = (\dot\phi)^2 + V(\phi)/2\ ,\ p_\phi = (\dot\phi)^2 - V(\phi)/2\ )$

$$3H^2 = \rho_m + \rho_\phi + \frac{e^{2\phi}}{2}\mathcal{J}_\phi\ ,$$

$$2\frac{dH}{dt_E} = -\rho_m - \rho_\phi - p_m - p_\phi + a^{-2}(t_E)\mathcal{J}_{ii}\ , \qquad i = 1, 2, 3,$$

$$\frac{d^2\phi}{dt_E^2} + 3H\frac{d\phi}{dt_E} + \frac{1}{4}\frac{\partial V}{\partial\phi} + \frac{1}{2}(\rho_m - 3p_m) = -\frac{3\,\mathcal{J}_{ii}}{2\,a^2} - \frac{e^{2\phi}\mathcal{J}_\phi}{2}\ ,$$

Off-Shell Terms

$$\mathcal{J}_\phi = e^{-2\phi}(\ddot\phi - \dot\phi^2 + Qe^{\phi}\dot\phi), \quad \mathcal{J}_{ii} = 2a^2\left(\ddot\phi + 3H\dot\phi + \dot\phi^2 + (1-q)H^2 + Qe^{\phi}(\dot\phi + H)\right)\ .$$

Off-Shell Terms

Consistency with Big-Bang Nucleosynthesis (at MeV scales) required, determines exotic scaling and equation of state of part of Dark Matter (due to coupling with dilaton)

Boltzmann equation Modifications for Thermal Dark matter Relics, e.g. Neutralinos

Lahanas, NM, Nanopoulos

$$\frac{dn}{dt} + 3\frac{\dot{a}}{a}n = \Gamma(t)n + \int \frac{d^3p}{E}C[f] \,, \quad \Gamma(t) \equiv \dot{\Phi} + \frac{1}{2}\eta\left(e^{-\Phi}g^{\mu\nu}\tilde{\beta}^{\rm Grav}_{\mu\nu} + 2e^{\Phi}\tilde{\beta}^{\Phi}\right), \ \eta = -1$$

Friedmann equation

$$H^2 = \frac{8\pi G_N}{3}\left(\rho + \Delta\rho\right)$$

$$\rho = \frac{\pi^2}{30}T^4\, g_{eff}(T)$$

$$\varrho + \Delta\varrho \equiv \frac{\pi^2}{30}T^4\,\tilde{g}_{eff}$$

$$\tilde{g}_{eff} = g_{eff} + \frac{30}{\pi^2}T^{-4}\Delta\rho$$

Freeze-out point x_f modification: $[\, g_* \equiv g_{eff}(x_f), \quad \tilde{g}_* \equiv \tilde{g}_{eff}(x_f)]$

$$x_f^{-1} = ln\left[0.03824\, g_s\, \frac{M_{Planck}\, m_{\tilde{\chi}}}{\sqrt{g_*}}x_f^{1/2}\langle v\sigma\rangle_f\right] + \frac{1}{2}\,ln\left(\frac{g_*}{\tilde{g}_*}\right) + \int_{x_f}^{x_{in}} \frac{\Gamma H^{-1}}{x}\,dx$$

Lahanas, NM, Nanopoulos

Modified expression for relic abundance

$$\Omega_{\tilde\chi} h_0^2 = \left(\Omega_{\tilde\chi} h_0^2\right)_{no-source} \times \left(\frac{\tilde g_*}{g_*}\right)^{1/2} \exp\left(\int_{x_0}^{x_f} \frac{\Gamma H^{-1}}{x} dx\right)$$

with $\left(\Omega_{\tilde\chi} h_0^2\right)_{no-source} = \frac{1.066 \times 10^9 \text{ GeV}^{-1}}{M_{Planck} \sqrt{g_*}\, J}$ $\qquad J \equiv \int_{x_0}^{x_f} \langle v\sigma \rangle \, dx.$

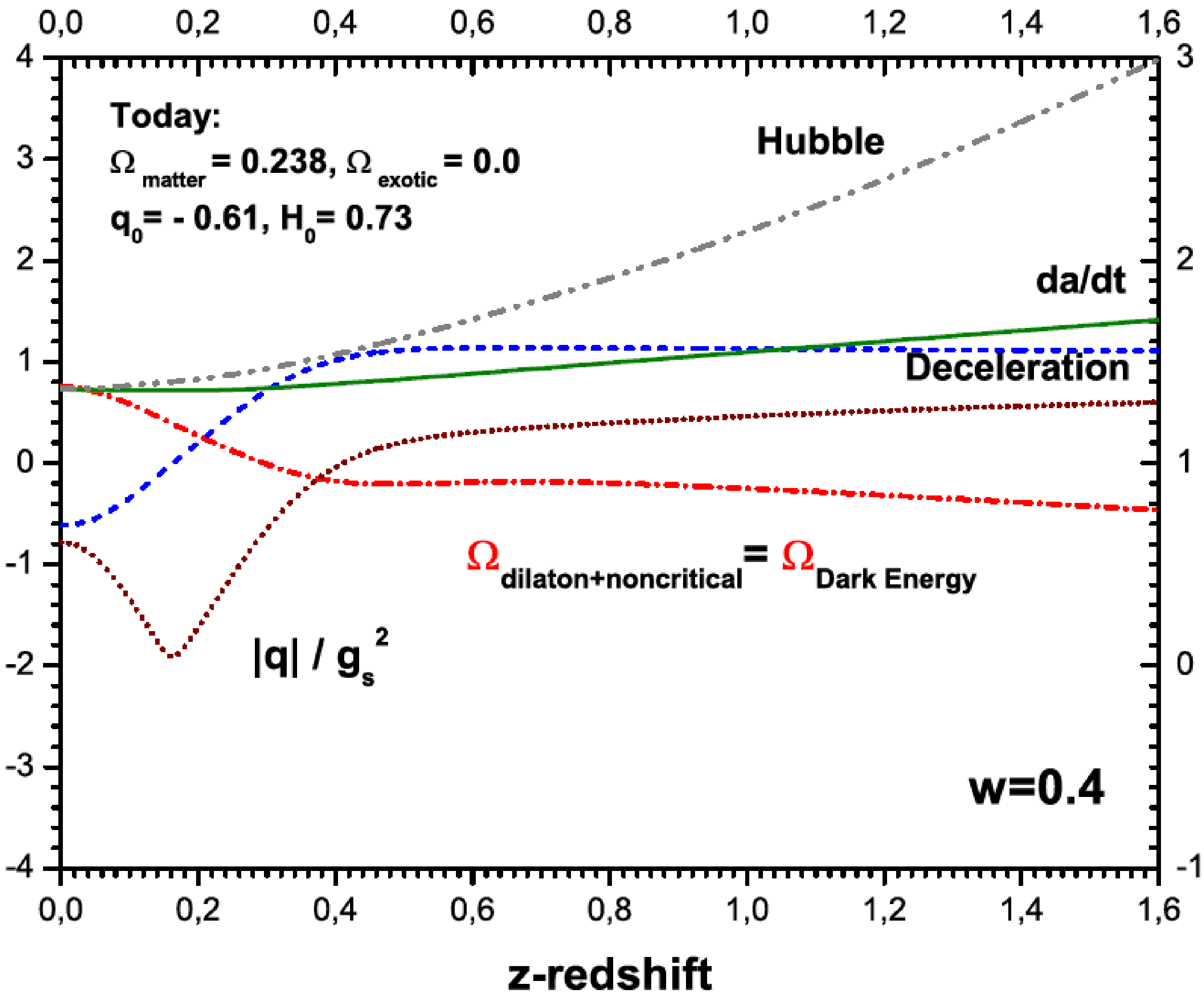
NB: Notice presence of non-critical/dilaton prefactor $R = \left(\frac{\tilde g_*}{g_*}\right)^{1/2} \exp\left(\int_{x_0}^{x_f} \frac{\Gamma H^{-1}}{x} dx\right)$

O(10) Dilution for Dark matter (e.g. neutralinos)
Baryon Density unchanged

$$\int d^4x \sqrt{-g}\, e^{\gamma\Phi} L^{\text{Dark Matter}}$$

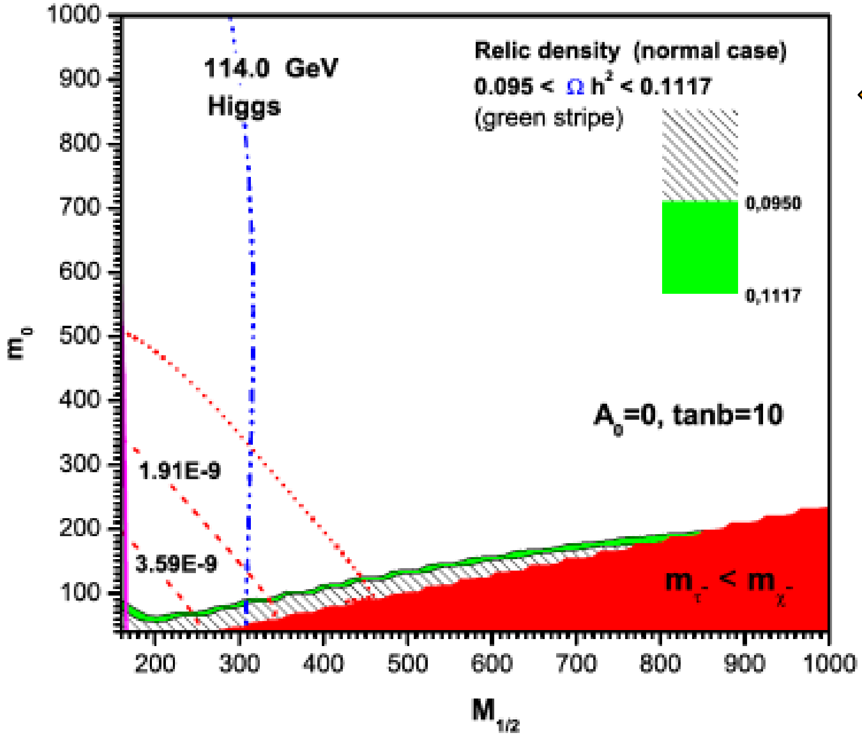
Equation of State (Consistent with BBN)

$p_{DM} \sim 0.4\, \rho_{DM}$

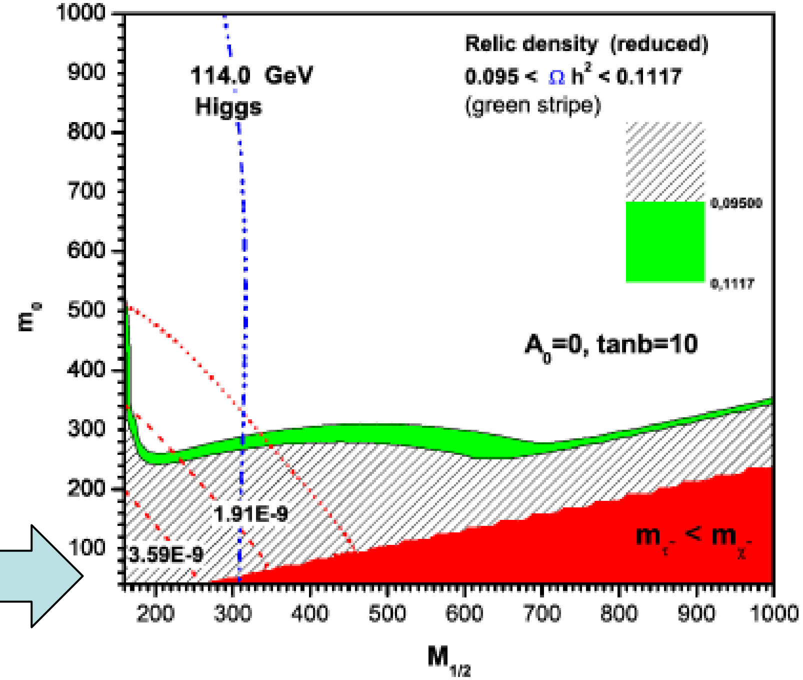


Today:
Ω matter = 0.238, Ω exotic = 0.0
q0= - 0.61, H0= 0.73
Hubble
da/dt
Deceleration
Ω dilaton+noncritical = Ω Dark Energy
|q| / gs2
w=0.4
z-redshift
0,0
0,2
0,4
0,6
0,8
1,0
1,2
1,4
1,6
4
3
2
1
0
-1
-2
-3
-4

More Room for Supersymmetry at Colliders…..

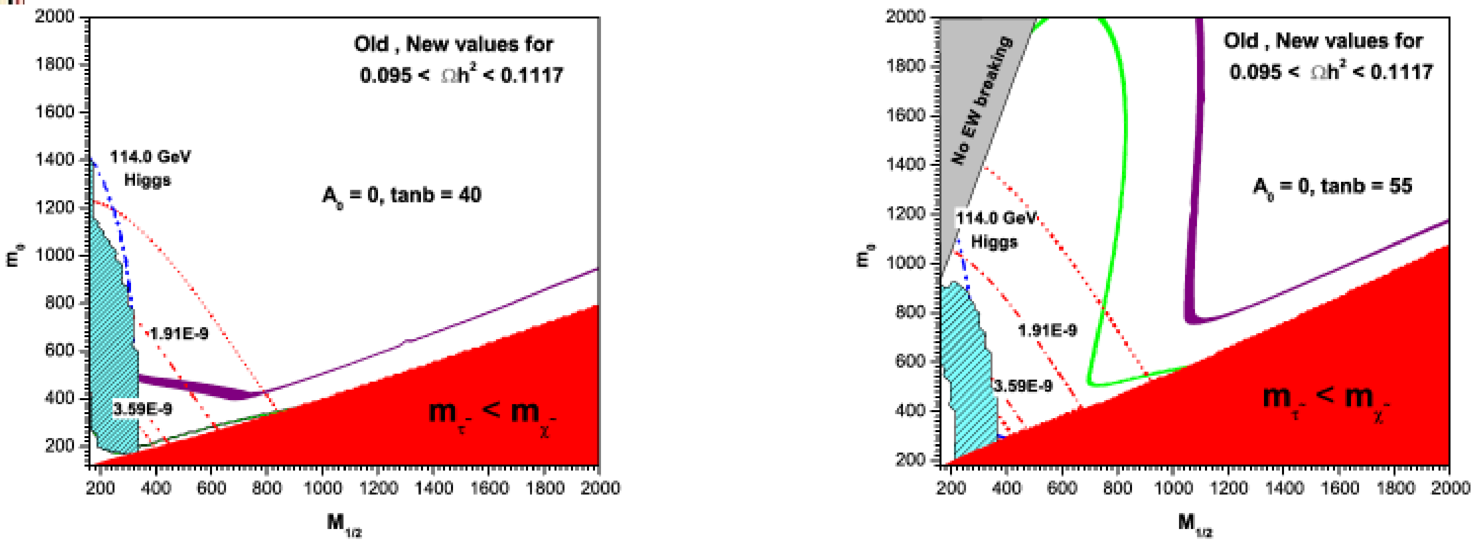


Conventional Cosmology



Supercritical String Cosmology

More Room for Supersymmetry at Colliders…..



Left: In the very thin green (grey) stripe the neutralino relic density is within the WMAP3 limits $0.0950 < \Omega_{CDM} h^2 < 0.1117$, for values of $A_0 = 0$ and $tan\beta = 40$ shown in the figure, according to the conventional calculation. The thin dark (purple) region lying above is the same region according to the non-critical-string calculation with the reduction factor for the MSSM inputs shown in the figure. The remaining Higgs and $g - 2$ boundaries are as in figure 150. The hatched dark (cyan) region on the left is excluded by $b \to s\,\gamma$ data. Right: The same as in left panel, for $A_0 = 0$ and $tan\beta = 55$.

Lahanas, NM, Nanopoulos

New Signals of SSC at LHC

Dutta et al., PRD79 , 055002 (2009)

Unlike Standard mSUGRA scenarios, in toy SSC mSUGRA

Final states consist of:

(i) Z bosons +

(ii) Higgses +

(iii) high-energy taus +

… + jets plus missing energy

Higher values of scalar unification masses m_0 allowed in SSC

Contrast with standard-Cosmology mSUGRA where only low-energy τ exist due to proximity of stau mass to that of lightest neutralino in stau-neutralino co-annihilation region

New Signals of SSC at LHC

Dutta et al., PRD79 , 055002 (2009)

Unlike Standard mSUGRA scenarios, in toy SSC mSUGRA

Final states consist of:

(i) Z bosons +

(ii) Higgses +

(iii) high-energy taus +

… + jets plus missing energy

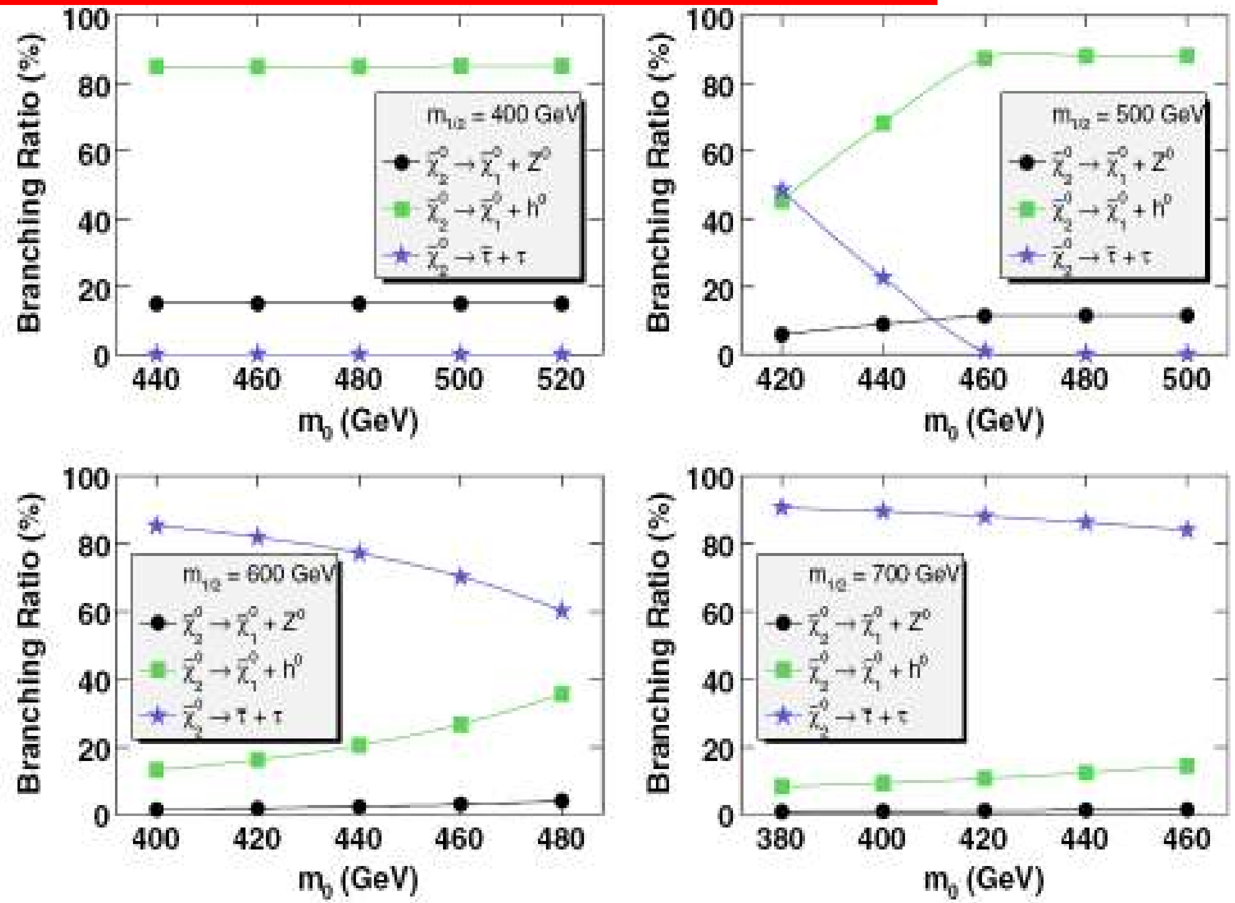


FIG. 2 (color online). The dominant decay branching ratios of decays from the $\tilde{\chi}_2^0$ are shown here. Each of the four plots shows how the branching ratios vary with m_0 at constant $m_{1/2}$. Together they survey the SSC band of parameter space in Fig. 1.

Very Different

Phenomenology from

Standard mSUGRA

New Signals of SSC at LHC

Dutta et al., PRD79 , 055002 (2009)

Unlike Standard mSUG

Final states consist of:

(i) Z bosons +

(ii) Higgses +

(iii) high-energy taus +

… + jets plus missing e

Increasing $m_{1/2}$ leads to shifts from Higgs- to τ-dominant decay chains in SSC. Distinguishable from co-annihilation region due to

LARGE MASS DIFFERENCES between

and

For values of $m_{1/2}$ < 350 GeV

dominates, hence Z production

Very Different

Phenomenology from

Standard mSUGRA

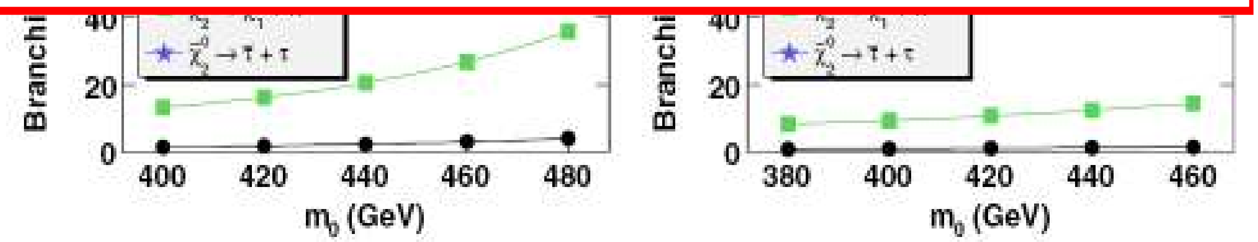


FIG. 2 (color online). The dominant decay branching ratios of decays from the $\tilde{\chi}_2^0$ are shown here. Each of the four plots shows how the branching ratios vary with m_0 at constant $m_{1/2}$. Together they survey the SSC band of parameter space in Fig. 1.

Typical mass spectra

Dutta et al., PRD79 , 055002 (2009)

TABLE I. SUSY masses (in GeV) and dominant branching ratios for $\tilde{\chi}_2^0$ for the point $m_0 = 471$ GeV, $m_{1/2} = 440$ GeV, $\tan\beta = 40$, $A_0 = 0$, and $\mu > 0$. Notice that the $\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau$ is kinematically forbidden. For this point, $\Omega_{\tilde{\chi}_1^0} h^2 = 0.089$ and $\sigma_{p-\tilde{\chi}_1^0} = 2.42 \times 10^{-9}$ pb. The total production cross section for this point is $\sigma = 1.61$ pb.

$\tilde{g}$	$\tilde{u}_L$ / $\tilde{u}_R$	$\tilde{t}_2$ / $\tilde{t}_1$	$\tilde{b}_2$ / $\tilde{b}_1$	$\tilde{e}_L$ / $\tilde{e}_R$	$\tilde{\tau}_2$ / $\tilde{\tau}_1$	$\tilde{\chi}_2^0$ / $\tilde{\chi}_1^0$	$\mathcal{B}(\tilde{\chi}_2^0 \to h^0 \tilde{\chi}_1^0)$ (%) / $\mathcal{B}(\tilde{\chi}_2^0 \to Z \tilde{\chi}_1^0)$ (%)
1041	1044	954	958	557	532	341	86.8
	1017	768	899	500	393	181	13.0

TABLE II. SUSY masses (in GeV) and dominant branching ratios for $\tilde{\chi}_2^0$ for the point $m_0 = 471$ GeV, $m_{1/2} = 320$ GeV, $\tan\beta = 40$, $A_0 = 0$, and $\mu > 0$. We chose this point to examine despite the fact that it is within the region excluded by $b \to s\gamma$. We did this to examine the behavior of $\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0$ at its maximal branching ratio. The total production cross section for this point is $\sigma = 7.10$ pb.

$\tilde{g}$	$\tilde{u}_L$ / $\tilde{u}_R$	$\tilde{t}_2$ / $\tilde{t}_1$	$\tilde{b}_2$ / $\tilde{b}_1$	$\tilde{e}_L$ / $\tilde{e}_R$	$\tilde{\tau}_2$ / $\tilde{\tau}_1$	$\tilde{\chi}_2^0$ / $\tilde{\chi}_1^0$	$\mathcal{B}(\tilde{\chi}_2^0 \to h^0 \tilde{\chi}_1^0)$ (%) / $\mathcal{B}(\tilde{\chi}_2^0 \to Z \tilde{\chi}_1^0)$ (%)
785	838	763	768	519	493	241	0.0
	821	598	708	487	389	129	99.6

TABLE III. SUSY masses (in GeV) and dominant branching ratios for $\tilde{\chi}_2^0$ for the point $m_0 = 440$ GeV, $m_{1/2} = 600$ GeV, $\tan\beta = 40$, $A_0 = 0$, and $\mu > 0$. For this point, $\Omega_{\tilde{\chi}_1^0} h^2 = 0.106$ and $\sigma_{p-\tilde{\chi}_1^0} = 7.19 \times 10^{-10}$ pb. The total production cross section for this point is $\sigma = 0.446$ pb.

$\tilde{g}$	$\tilde{u}_L$ / $\tilde{u}_R$	$\tilde{t}_2$ / $\tilde{t}_1$	$\tilde{b}_2$ / $\tilde{b}_1$	$\tilde{e}_L$ / $\tilde{e}_R$	$\tilde{\tau}_2$ / $\tilde{\tau}_1$	$\tilde{\chi}_2^0$ / $\tilde{\chi}_1^0$	$\mathcal{B}(\tilde{\chi}_2^0 \to h^0 \tilde{\chi}_1^0)$ (%) / $\mathcal{B}(\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau)$ (%)
1366	1252	1153	1153	594	574	462	20.5
	1211	957	1094	494	376	249	77.0

Very Different Phenomenology from Standard mSUGRA

Dutta et al., PRD79 , 055002 (2009)

Hence, question as to whether astrophysical dark matter is the same as particle one, cannot be answered uniquely as it it highly model dependent….

But plethora of data exist and will become available (c.f. LHC, Planck mission …)

So with time we will probably be able to answer such fundamental questions…

Very Different Phenomenology from Standard mSUGRA