What light can Supersymmetry shed on Dark Matter?

(pun intended).

Rob Knegjens

ITF, Utrecht

December 17, 2008

Evidence for Dark-Matter

Rotation curves of spiral galaxies

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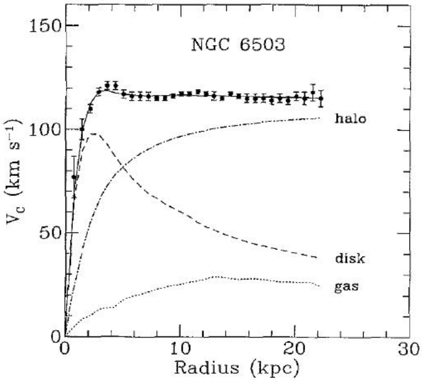
$$\Rightarrow \quad v_c(r)\Big|_{r>r_M} \propto \frac{1}{\sqrt{r}}$$



Rotation curve for the spiral galaxy NGC 6503
(From G. Jungman *et al.*)

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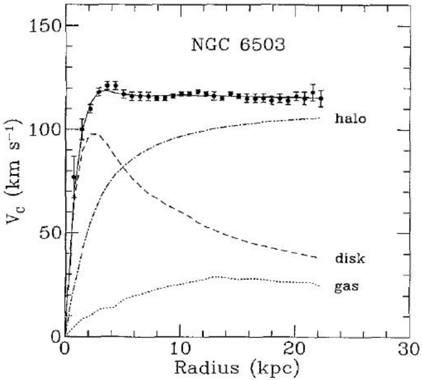

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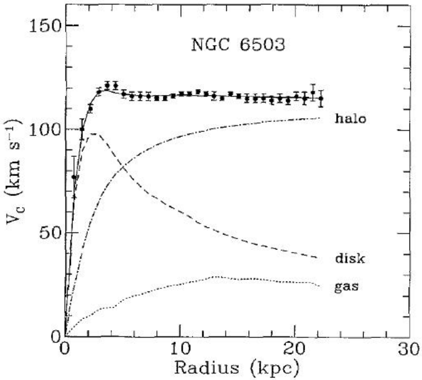
- Spherical DM halo

$$\rho_{\text{halo}}(r) \propto \frac{1}{r^2}$$

$$M'(r)\Big|_{r>r_M} \propto r$$



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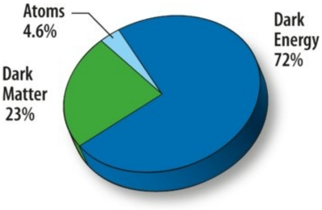
- DM cold and non-baryonic
- Latest CMB data (WMAP) for ΛCDM model ($h = 0.7$)

$$\Omega_{\text{b}} = 4.6 \pm 0.1\%$$
$$\Omega_{\text{nbm}} = 22 \pm 2\%$$



(From NASA/WMAP)

CDM Density from Thermal Freeze Out?

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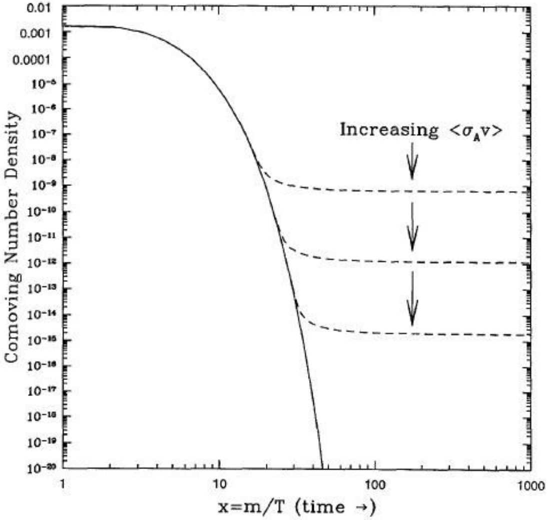
- When $\frac{\Gamma_A}{H} < O(1)$ $\Rightarrow$ annihilation freezes out, N_χ freezes in!

Freeze Out of CDM

For χ cold, $\langle \sigma_A v \rangle = const$, solve after freezeout:

$$N_{\chi 0} \approx \frac{10^{-9}[pb \cdot c][\text{GeV}]}{m_\chi \langle \sigma_A v \rangle}$$



Comoving number density (From Kolb and Turner)

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- CDM particle is Weakly interacting

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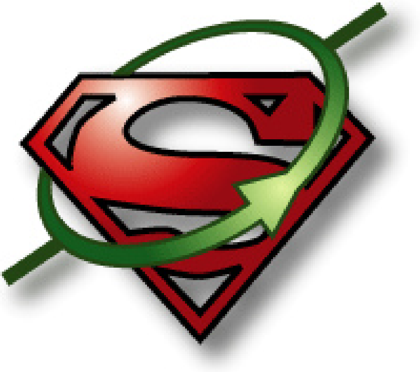
Possible WIMPs:

- ~~Light neutrino~~, ~~heavy 4th gen. neutrino~~
- Lightest Kaluza-Klein mode (Extra Dimensions)
- Stable fermions (Little Higgs models)
- Lightest SUSY Particle (LSP)

SUPERSYMMETRY



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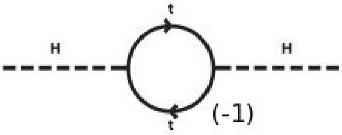
- Solves the naturalness (fine-tuning) problem

$$m_H^2 = m_{\text{tree}}^2 - \frac{\lambda_t^2}{8\pi^2}{\Lambda_{\text{UV}}}^2 + \ldots \sim (200\text{GeV})^2$$



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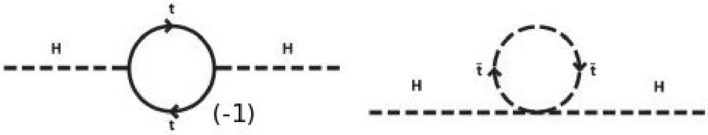

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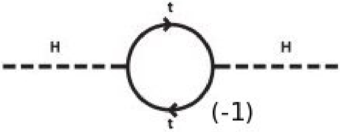
- Broken SUSY theory with R-parity gives a stable DM candidate!



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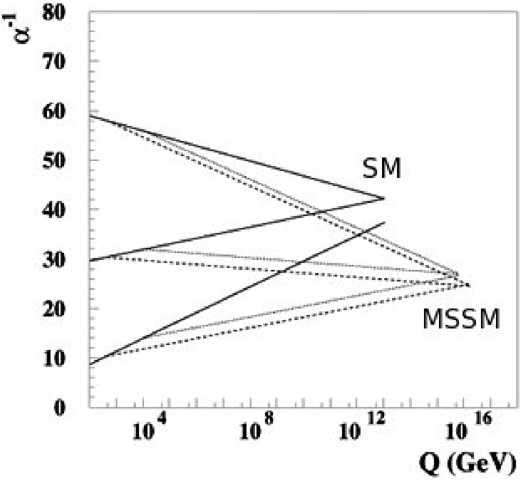

Evolution of $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge couplings for SM (solid) and MSSM (dashed)

(From Braz. J. Phys. vol.34 no.4a So Paulo Dec. 2004)

Poincaré Algebra

- The Poincaré group:
  - Translations generated by P_μ
  - Rotations generated by J_i
  - Boosts generated by K_i

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- The Poincaré *Lie algebra*:

$$\begin{aligned}
[P_\mu, P_\nu] &= 0 \\
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- Restricted Lorentz group sub-algebra:

$$[J_i, J_j] = i\epsilon_{ijk} J_k, \quad [K_i, K_j] = i\epsilon_{ijk} K_k, \quad [K_i, K_j] = -i\epsilon_{ijk} J_k$$

Representations of the Lorentz Group

$$A_i = \frac{1}{2}(J_i + iK_i) \quad \text{and} \quad B_i = \frac{1}{2}(J_i - iK_i),$$

- Decomposes into two $SU(2)$ sub-algebras

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- Dirac spinors $\rightarrow (\frac{1}{2}, 0) \oplus (0, \frac{1}{2})$

$$\psi_D = \begin{pmatrix} \psi_L \\ \chi_R \end{pmatrix} \quad , \quad \psi_M = C\bar{\psi}_M{}^T = \begin{pmatrix} \psi_L \\ -i\sigma_2\psi_L^* \end{pmatrix}$$

Super-Poincaré Algebra

NO-GO Theorem: Coleman and Mandula

The most general Lie algebra for symmetries of an S-matrix for a relativistic 4D QFT can only have as generators those of the Poincare group along with Lorentz scalar generators of a compact Lie group.

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Q: new anti-commuting generators

- Let $Q \equiv (j, j')$ and $\bar{Q} \equiv (j', j)$

$$\Rightarrow \{Q, \bar{Q}\} = X \equiv (j + j', j + j')$$

Super-Poincaré Algebra

- Only X of form $(j+j', j+j')$ is $P_\mu \equiv (\frac{1}{2}, \frac{1}{2})$

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- SUSY states must have the same mass

$$Q(P^2\psi) = Q(m_\psi^2\psi) \quad \Rightarrow \quad P^2(Q\psi) = m_\psi^2(Q\psi)$$

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  - (x^μ, θ) coordinates span superspace
- Define a generic superfield $\hat{\Phi}(x, \theta)$ expanded into a θ basis

$$\hat{\Phi}(x,\theta) = \mathcal{S} - i\sqrt{2}\bar{\theta}\gamma_5\psi - \frac{i}{2}(\bar{\theta}\gamma_5\theta)\mathcal{M} + \frac{1}{2}(\bar{\theta}\theta)\mathcal{N} + \frac{1}{2}(\bar{\theta}\gamma_5\gamma_\mu\theta)V^\mu + i(\bar{\theta}\gamma_5\theta)[\bar{\theta}(\lambda + \frac{1}{\sqrt{2}}\not{\partial}\psi)] - \frac{1}{4}(\bar{\theta}\gamma_5\theta)^2[\mathcal{D} - \frac{1}{2}\Box\mathcal{S}]$$

SUSY Transformation

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- Similarly, Q generates transformations in superspace

$$\delta_\alpha\hat{\Phi} = i[\bar{\alpha}Q, \hat{\Phi}] = (-\bar{\alpha}\frac{\partial}{\partial\bar{\theta}} - i\bar{\alpha}\not{\partial}\theta)\hat{\Phi}$$

SUSY Transformation

- Components of $\delta\hat{\Phi} = i[\bar{\alpha}Q, \hat{\Phi}]$ transform as

$$
\begin{aligned}
\delta\mathcal{S} &= i\sqrt{2}\bar{\alpha}\gamma_5\psi \\
\delta\psi &= -\frac{\alpha\mathcal{M}}{\sqrt{2}} - i\frac{\gamma_5\alpha\mathcal{N}}{\sqrt{2}} - i\frac{\gamma_\mu\alpha V^\mu}{\sqrt{2}} - \frac{\gamma_5\not{\partial}\mathcal{S}\alpha}{\sqrt{2}} \\
\delta\mathcal{M} &= \bar{\alpha}(\lambda + i\sqrt{2}\not{\partial}\psi) \\
\delta\mathcal{N} &= \dots \\
\delta V^\mu &= \dots \\
\delta\lambda &= \dots \\
\delta\mathcal{D} &= \bar{\alpha}\,\underbrace{\partial_\mu(\gamma^\mu\gamma_5\lambda)}_{\text{total derivative}}
\end{aligned}
$$

Irreducible Representations of SUSY

Chiral Scalar Superfield

Setting $\lambda = \mathcal{D} = \psi_R = 0$ etc.

$$\begin{aligned} \delta\mathcal{S} &= -i\sqrt{2}\bar{\alpha}\psi_L \\ \delta\psi_L &= -\sqrt{2}\mathcal{F}\alpha_L s + \sqrt{2}\not{\partial}\mathcal{S}\alpha_R \\ \delta\mathcal{F} &= i\sqrt{2}\bar{\alpha}\ \underbrace{\partial_\mu(\gamma^\mu\psi_L)}_{\text{total derivative}} \end{aligned}$$

$$\boxed{\hat{\mathcal{S}} \equiv \{\underbrace{\mathcal{S}}_{2}, \underbrace{\psi_L}_{4}, \underbrace{\mathcal{F}}_{2}\}}$$

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Real Vector Superfield

Setting $\mathcal{S} = \psi = \mathcal{M} = \mathcal{N} = 0$ via gauge choice

$$\hat{V} \equiv \{\underbrace{V^\mu}_{3}, \underbrace{\lambda}_{4}, \underbrace{\mathcal{D}}_{1}\} = \hat{V}^\dagger$$

Building a SUSY Lagrangian

- Build from combination of superfields

$$\hat{\Phi}\hat{\Phi}' = \hat{\Phi}'', \quad \hat{\mathcal{S}}^{\dagger}\hat{\mathcal{S}} = \hat{\Phi}, \quad \hat{\mathcal{S}}\hat{\mathcal{S}}' = \hat{\mathcal{S}}''$$

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- $\delta\hat{\mathcal{S}} \neq 0$ but $\delta\mathcal{F} = \not{\partial}(\dots)$

$$\textit{Superpotential } \hat{W}(\hat{\mathcal{S}}) \rightarrow \hat{W}\Big|_{\mathcal{F}\text{-term}} \in \mathcal{L}$$

A Master SUSY Lagrangian

$$\mathcal{L} = \sum_i (D_\mu \mathcal{S}_i)^\dagger (D^\mu \mathcal{S}_i) + \frac{i}{2}\sum_i \bar{\psi}_i \not{D} \psi_i + \sum_\alpha \left[\frac{i}{2}\bar{\lambda}_\alpha (\not{D}\lambda)_\alpha - \frac{1}{4} F_{\mu\nu\alpha} F^{\mu\nu}_\alpha\right]$$
$$- \sqrt{2}\sum_{i,\alpha}\left(\mathcal{S}_i^\dagger g_\alpha t_\alpha \bar{\lambda}_\alpha \psi_{Li} + \text{h.c.}\right)$$
$$- \frac{1}{2}\sum_\alpha \left[\sum_i \mathcal{S}_i^\dagger g_\alpha t_\alpha \mathcal{S}_i + \xi_\alpha\right]^2 - \sum_i \left|\frac{\partial \hat{W}}{\partial \hat{\mathcal{S}}_i}\right|^2_{\hat{\mathcal{S}}=\mathcal{S}}$$
$$- \frac{1}{2}\sum_{i,j} \bar{\psi}_i \left[\left(\frac{\partial^2 \hat{W}}{\partial \hat{\mathcal{S}}_i \partial \hat{\mathcal{S}}_j}\right)_{\hat{\mathcal{S}}=\mathcal{S}} P_L + \left(\frac{\partial^2 \hat{W}}{\partial \hat{\mathcal{S}}_i \partial \hat{\mathcal{S}}_j}\right)^\dagger_{\hat{\mathcal{S}}=\mathcal{S}} P_R\right] \psi_j$$

Minimal Supersymmetric Standard Model

- Keep $SU(3)_c \times SU(2)_L \times U(1)_Y$. Promote SM gauge fields to *real vector superfields*

$$\text{e.g } B_\mu \longrightarrow \hat{B} \ni (B_\mu, \lambda_0, \mathcal{D}_B)$$

- Promote SM fermion fields to *chiral scalar superfields*

$$\text{e.g } \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \longrightarrow \begin{pmatrix} \hat{\nu} \\ \hat{e} \end{pmatrix} \equiv \hat{L}_e \qquad \hat{e} \ni (\tilde{e}_L, \psi_{eL}, \mathcal{F}_e) \text{ etc.}$$

$$e_R \longrightarrow \hat{E}^c \ni (\tilde{e}_R^\dagger, \psi_{EL}, \mathcal{F}_E)$$

Minimal Supersymmetric Standard Model

- Higgs potential must enter via superpotential $\hat{W}(\hat{\mathcal{S}})$

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \rightarrow \hat{H}_u = \begin{pmatrix} \hat{h}_u^+ \\ \hat{h}_u^0 \end{pmatrix}$$

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Letting $\hat{H}_u$ be $Y = 1$, also need a $Y = -1$ Higgs field but $\hat{H}_u^\dagger \not\in \hat{W}$

$$\text{add } \hat{H}_d = \begin{pmatrix} \hat{h}_d^- \\ \hat{h}_d^0 \end{pmatrix}$$

- *Minimal* superpotential:

$$\hat{W} = \mu \hat{H}_u \hat{H}_d + \mathbf{f}_u \epsilon \underbrace{\hat{Q}}_{\frac{1}{3}} \underbrace{\hat{H}_u}_{1} \underbrace{\hat{U}}_{-\frac{4}{3}} + \mathbf{f}_d \underbrace{\hat{Q}}_{\frac{1}{3}} \underbrace{\hat{H}_d}_{-1} \underbrace{\hat{D}}_{\frac{2}{3}} + \mathbf{f}_e \hat{L} \hat{H}_d \hat{E}$$

MSSM Particles

SM Particles		Superpartners	
Fermions		Scalar Fermions	
Quarks	u c t d s b	Squarks	$\tilde{u}$ $\tilde{c}$ $\tilde{t}$ $\tilde{d}$ $\tilde{s}$ $\tilde{b}$
Leptons	e μ τ ν_e ν_μ ν_τ	Sleptons	$\tilde{e}$ $\tilde{\mu}$ $\tilde{\tau}$ $\tilde{\nu}_e$ $\tilde{\nu}_\mu$ $\tilde{\nu}_\tau$
Gauge Bosons		Gauginos	
Photon	A_μ	Photino	$\sin\theta_w\lambda_3 + \cos\theta_w\lambda_0$
W,Z Bosons	${W^\pm}_\mu$ Z_μ	W-ino Z-ino	$\frac{1}{\sqrt{2}}(\lambda_1 \mp i\lambda_2)$ $-\cos\theta_w\lambda_3 + \sin\theta_w\lambda_0$
Gluon	$g_{A\mu}$	Gluino	$\tilde{g}_A$
Higgs Bosons		Higgsinos	
h_u^+ h_u^0 h_d^- h_d^0		$\tilde{h}_u^+$ $\tilde{h}_u^0$ $\tilde{h}_d^-$ $\tilde{h}_d^0$	

R-Parity

- MSSM doesn't naturally conserve B/L numbers

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$$\boxed{R = (-1)^{3(B-L)+2s}}$$

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$$R(\text{SM particles}) = 1 \qquad R(\text{Superpartners}) = -1$$

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- So superpartners must occur in pairs: the lightest can't decay!

Breaking of the MSSM

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- *Soft* breaking protects scalar masses

$$
\begin{aligned}
\mathcal{L}_{\text{soft}} = & \left[\tilde{L}_i^\dagger \mathbf{m}^2_{Lij} \tilde{L}_j + \ldots + m^2_{H_u} |H_u|^2 + \ldots \right] \\
& - \frac{1}{2} \left[M_1 \bar{\lambda_0} \lambda_0 + \ldots \right] + \left[(\mathbf{a_e})_{ij} \epsilon_{ab} \tilde{L}_i H_d \tilde{e}^\dagger_{Rj} + \ldots \right] \\
& + \left[(\mathbf{c_e})_{ij} \epsilon_{ab} \tilde{L}_i H_d^* \tilde{e}^\dagger_{Rj} + \ldots \right] + \left[b H_u H_d + h.c \right]
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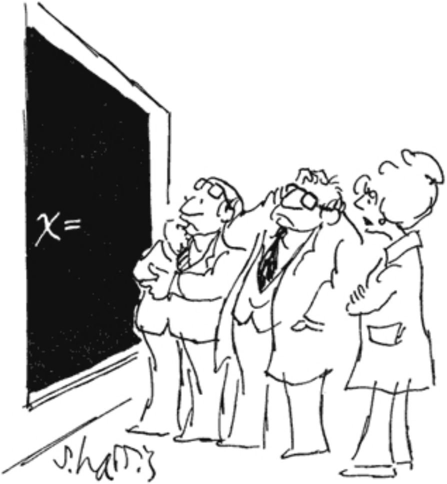
$$\mathcal{L}_{\text{soft}} = \left[\tilde{L}_i^\dagger \mathbf{m}^2_{Lij} \tilde{L}_j + \ldots + m^2_{H_u} |H_u|^2 + \ldots\right] - \frac{1}{2}\left[M_1 \bar{\lambda_0} \lambda_0 + \ldots\right] + \left[(\mathbf{a_e})_{ij} \epsilon_{ab} \tilde{L}_i H_d \tilde{e}^\dagger_{Rj} + \ldots\right] + \left[(\mathbf{c_e})_{ij} \epsilon_{ab} \tilde{L}_i H^*_d \tilde{e}^\dagger_{Rj} + \ldots\right] + [bH_u H_d + h.c]$$

- MSSM with all soft breaking terms: 178 parameters!!
  - Phenomenological assumptions: e.g CMSSM: $\sim 5 - 10$ parameters
  - mSUGRA (local SUSY) has 4 parameters

LIGHTEST SUPERSYMMETRIC PARTICLE (LSP)



(S. Harris)

LSP Candidates

Whish is the stable *Lightest Supersymmetric Particle* (LSP)?

- Charged gaugino/slepton:
  - Moderate relic density ⇒ mixed with ordinary matter
  - Ruled out by searches for anomalously heavy terrestrial protons
- Gluino/Squark:
  - From GUTs; gluino heavier than neutralino, squarks heavier than sleptons
- Sneutrino (WIMP candidate):
  - Most of parameter space ruled out by direct-detection experiments
- Neutralino (WIMP candidate):
  - *Strongest LSP candidate*!

(Or: gravitino, axino?)

Neutralino

- Electroweak breaking of MSSM mixes gauginos and higgsinos

$$\mathcal{L} \ni -\sqrt{2} g \mathcal{S}_i^\dagger g t_A \bar{\lambda}_A \psi_{Li}$$
$$\overset{\not{EW}}{\longrightarrow} \ni g \underbrace{\langle h_u^0 \rangle}_{v_u} \bar{\lambda}_3 \tilde{h}_u^0 + \dots$$

- Physical particles are eigenstates of the mass matrix

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$$\overset{\cancel{EW}}{\rightarrow} \ni g \underbrace{\langle h_u^0 \rangle}_{v_u} \bar{\lambda}_3 \tilde{h}_u^0 + \dots$$

- Physical particles are eigenstates of the mass matrix
- Consider neutral fermions:

$$\hat{W} \ni \mu \hat{H}_u \hat{H}_d \qquad \mathcal{L}_{\text{soft}} \ni -\frac{1}{2} M_1 \bar{\lambda}_0 \lambda_0 - \frac{1}{2} M_2 \bar{\lambda}_3 \lambda_3$$

$$\Rightarrow -\frac{1}{2} \begin{pmatrix} \bar{\tilde{h}}_u^0 & \bar{\tilde{h}}_d^0 & \bar{\lambda}_3 & \bar{\lambda}_0 \end{pmatrix} \begin{pmatrix} 0 & \mu & -\frac{g v_u}{\sqrt{2}} & \frac{g' v_u}{\sqrt{2}} \\ \mu & 0 & \frac{g v_d}{\sqrt{2}} & -\frac{g' v_d}{\sqrt{2}} \\ -\frac{g v_u}{\sqrt{2}} & \frac{g v_d}{\sqrt{2}} & M_2 & 0 \\ \frac{g' v_u}{\sqrt{2}} & -\frac{g' v_d}{\sqrt{2}} & 0 & M_1 \end{pmatrix} \begin{pmatrix} \tilde{h}_u^0 \\ \tilde{h}_d^0 \\ \lambda_3 \\ \lambda_0 \end{pmatrix}$$

Neutralino

- Daigonalizing mass matrix gives *Neutralino* eigenstates

$$\mathcal{M}_D = V^\dagger \mathcal{M}_{\text{neutral}} V$$

$$\begin{pmatrix} \chi_1 \\ \chi_2 \\ \chi_3 \\ \chi_4 \end{pmatrix} = V^\dagger \begin{pmatrix} \tilde{h}_u^0 \\ \tilde{h}_d^0 \\ \lambda_3 \equiv \tilde{W}^3 \\ \lambda_0 \equiv \tilde{B} \end{pmatrix}$$

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- The lightest we call *the Neutralino*

$$\boxed{\chi_0 = V_{10}^* \tilde{h}_u^0 + V_{20}^* \tilde{h}_d^0 + V_{30}^* \tilde{W}^3 + V_{40}^* \tilde{B}}$$

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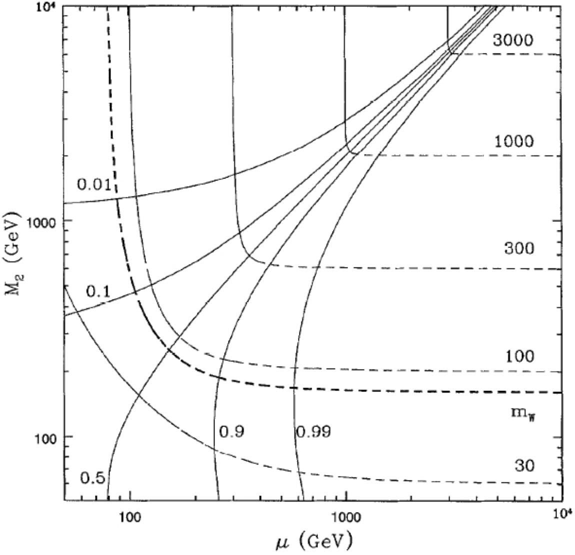
- If $f_g := |V_{30}|^2 + |V_{40}|^2 > 0.5 \Rightarrow$ primarily gaugino etc.

Neutralino Mass Contour Plot

GUT relation:

$M_1 = \frac{5}{3} M_2 \tan^2 \theta_w$

$\Rightarrow f_g(M_2, \mu)$ and $m_\chi(M_2, \mu)$



Broken curves are m_χ (GeV), solid curves f_g (From G. Jungman *et al.*)

WIMP DETECTION

CDMS II, Soudan Mine, Minnesota (From CDMS)

Direct Detection

- WIMP Flux through earth's surface from DM halo: $100 - 1000\text{cm}^{-2}s^{-1}$

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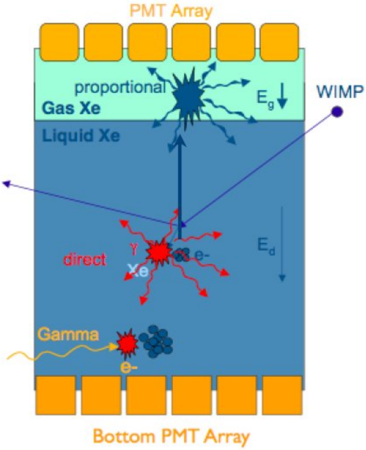
- Cosmic gamma rays with energies KeV-MeV occur with rate $> 100\text{kg}^{-1}/\text{day}$
  $\Rightarrow$ Experiments forced underground

Direct Detection

- CDMS-II Detector (Minnesota)
  - Ge crystal target coupled to thermal calorimeters, $E_T \sim 1\text{KeV}$
- XENON Detector (Gran Sasso)
  - Liquid Xenon target. PMTs detect scintillation and ionization

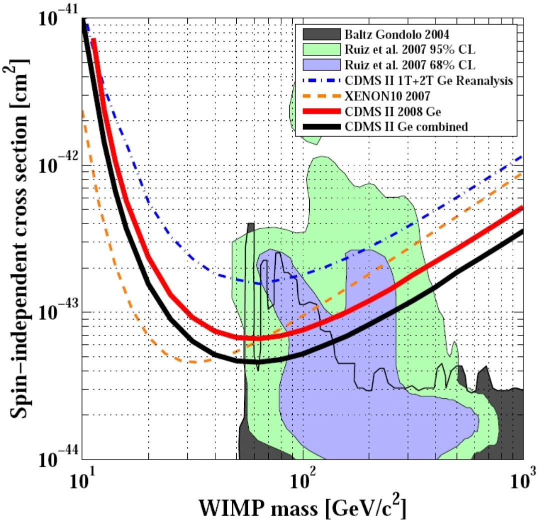


Working principle of XENON detector (From XENON)

Direct Detection

No WIMP signals yet found:

- Gives upper limits to σ
- Reduces *MSSM* parameter space



Spin-independent cross section 90% CL upper limits versus WIMP mass (From CDMS)

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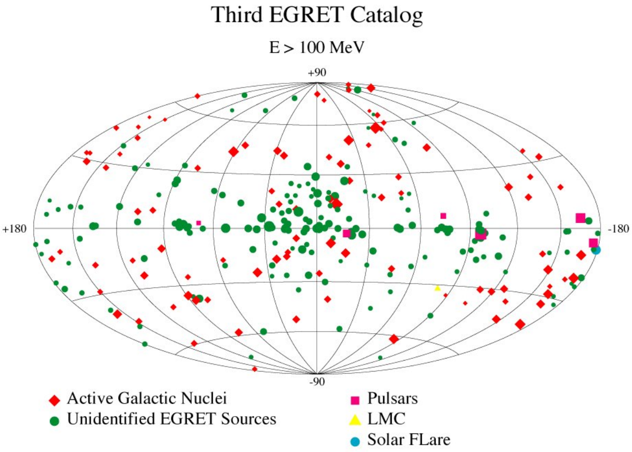
- Neutrino detectors currently under construction (IceCube, ANTARES, Km3net) hope to see energetic DM neutrinos

Energetic Gamma Ray Experiment Telescope

EGRET Detector

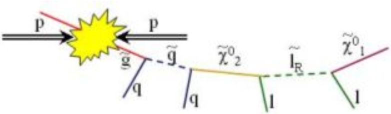
- Gamma rays: 30 MeV to 30 GeV
- Found 271 point sources, 170 unidentified?

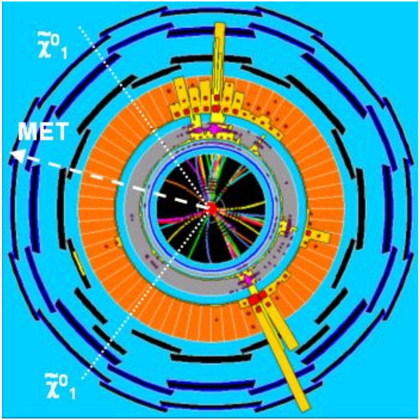


(From CGRO Science Support Center)

Colliders

- Hope to see SUSY at LHC
- Neutralino will pass through LHC undetected: look for missing transverse energy





Example of missing energy in ATLAS detector (From Dorigo's Blog)

Conclusions

- SUSY is a welcome extension to the SM
- Neutralino is a strong DM candidate
- Until we know how SUSY is broken, large parameter space limits further predictions
- Experimental progress is healthy
  - Various methods will give confidence in results
  - Experiments narrow down the MSSM parameter space