Dark Matter Constituents

Lars Bergström
Department of Physics
Stockholm University
lbe@physto.se

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Basic facts:

\[ \Omega_i \equiv \frac{\rho_i}{\rho_{\text{crit}}} \]

\[ \rho_{\text{crit}} = \frac{3H_0^2m_{\text{pl}}^2}{8\pi} = 1.88h^2 \cdot 10^{-29} \text{ g/cm}^3 \]

\[ h \equiv \frac{H_0}{100 \text{ km/s/Mpc}} \]

Observations give \(0.6 < h < 0.8\)

Big Bang nucleosynthesis (deuterium abundance) and cosmic microwave background (WMAP) determine baryon contribution \(\Omega_B h^2 \approx 0.02\), so \(\Omega_B \approx 0.04\)

\(\Omega_{\text{lum}} \approx (4 \pm 2) \cdot 10^{-3}\) (stars, gas, dust) => baryonic dark matter has to exist (maybe as warm intergalactic gas?)

But, if \(\Omega_M > 0.06\), there has to exist non-baryonic dark matter!
Result from best-fit model for WMAP (for flat Universe):

- Only 4.4% baryonic matter, $\Omega_b h^2 = 0.024 \pm 0.0009$
- Around 23% Cold Dark matter, $\Omega_{CDM} h^2 = 0.113 \pm 0.01$
- Around 73% "Dark energy", $\Omega_\Lambda = 0.73 \pm 0.04$
- Age of Universe: $13.7 \pm 0.2$ Gyr
- $\Omega_\nu h^2 < 0.0076$
Large-scale structure is in striking agreement with the Concordance Model, \( \Lambda CDM (\Omega_M = 0.3, \Omega_\Lambda = 0.7) \)

C. Frenk, 2002
Galaxy cluster
CL0024+1654, z = 0.4

Strong + weak lensing reconstruction of density profile (Kneib et al, astro-ph/0307299)

CDM N-body fit (Navarro, Frenk & White)

Singular isothermal sphere

Kneib et al.
Dark matter needed on all scales!

(⇒ MOND and other *ad hoc* attempts to modify Einstein or Newton gravity very unnatural & unlikely)

Galaxy rotation curves

X-ray emitting clusters

NED/STScI; E. Corbelli & P. Salucci (1999)

Cluster 3C295 (Chandra)
Since 1998 (Super-K), we know that non-baryonic dark matter exists! \[ \Delta m_\nu \neq 0 \Rightarrow m_\nu \neq 0 \]

However, neutrinos are not the main component of dark matter (10% at most):
- Pauli principle \( \Rightarrow \) cannot clump in dwarf halos
- Galaxy distribution \( \Rightarrow \) limit on sum of \( \nu \) masses

WMAP: \( \sum m_\nu < 0.7 \text{ eV} \), depends on analysis of Ly-\( \alpha \) forest

Ø. Elgarøy & O. Lahav (2DF Collaboration), 2003; S. Hannestad astro-ph/0303076: \( \sum m_\nu < 1 \text{ eV} \) (depending on priors and \( \nu \) chemical potential)

Allen, Schmidt & Bridle (astro-ph/0306386) find \( \sum m_\nu = 0.56 \pm 0.3 \text{ eV} \) if \( \sigma_8 \approx 0.75 \) (from X-ray luminosity function).

Future galaxy surveys + Planck satellite (CMBR) \( \Rightarrow \) perhaps \( m_\nu \approx \Delta m_\nu^{\text{atm}} \approx 0.06 \text{ eV} \) may be detectable! (Hu, Eisenstein & Tegmark, 1998)

Yoo, Chanamé & Gould, astro-ph/0307437: "The end of the MACHO era" (stability of wide binaries)
• Part of the “Concordance Model”
• Gives excellent description of CMB, large scale structure, Ly-\(\alpha\) forest, gravitational lensing, supernova distances …
• If consisting of particles, may be related to electroweak mass scale: weak cross section, non-dissipative Weakly Interacting Massive Particles (WIMPs). Potentially detectable, directly or indirectly.
• May or may not describe small-scale structure in galaxies: Controversial issue, but alternatives (self-interacting DM, warm DM, self-annihilating DM) seem worse. Probably non-linear astrophysical feedback processes are acting (bar formation, tidal effects, mergers, supernova winds, …). This is a crucial unsolved problem of great importance for dark matter detection rates. See Ben Moore’s talk.
Good particle physics candidates for Cold Dark Matter:

Independent motivation from particle physics; detectable by other means than through gravity only

- **Axions** (introduced to solve strong CP problem)
- Weakly Interacting Massive Particles (WIMPs, \(3 \text{ GeV} < m_X < 50 \text{ TeV}\)), thermal relics from Big Bang:
  - Supersymmetric particles
  - Heavy neutrino-like particles
  - Braneworld and Kaluza-Klein states
  - Mirror particles
  - ”Little Higgs”
  - ...
- Non-thermal (maybe superheavy) relics

"The WIMP miracle": for typical gauge couplings and masses of order the electroweak scale, \(\Omega_{\text{wimp}} h^2 \approx 0.1\) (within factor of 10 or so)
Other WIMP candidate: **Right-handed neutrino** (Krauss, Nasri & Trodden; Baltz & L.B., 2002)

Usual see-saw mechanism \( \Rightarrow M_R = O(M_{GUT}) \Rightarrow \) thermal production not possible (needed annihilation cross section would violate unitarity)

Zee model: neutrino masses generated by loops with new charged scalar. Krauss, Nasri, Trodden: discrete symmetry \( \Rightarrow \) mass generated at 3 loops \( \Rightarrow \) TeV scale \( N_R \) sufficient \( \Rightarrow \) **Leptonic WIMP (“LIMP”)**

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**FIG. 1:** The three-loop diagram through which a nonzero neutrino mass is generated.
Axion: may solve strong CP problem & DM problem

S. Asztalos et al., 2002 (Livermore)

C. Eleftheriadis et al., (CERN) astro-ph/0305534
Supersymmetry

- Invented in the 1970’s
- Necessary in most string theories
- Restores unification of couplings
- Solves hierarchy problem
- Gives right scale for neutrino masses
- Predicts light Higgs ( < 130 GeV)
- May be detected at Fermilab/LHC
- Gives an excellent dark matter candidate (If R-parity is conserved ⇒ stable on cosmological timescales)
- Useful as a template for generic “WIMP” (Weakly Interacting Massive Particle)

The lightest neutralino: the most natural SUSY dark matter candidate

\[ \tilde{\chi}^0 = a_1 \tilde{\nu} + a_2 \tilde{Z}^0 + a_3 \tilde{H}_1^0 + a_4 \tilde{H}_2^0 \]
DM need not necessarily be neutralino

Super-WIMPS (Feng, Rajaraman and Takayama, 2003)

Example: light gravitino, produced through decay by neutralino -> g + SM particle ⇒ only gravitationally interacting DM

FIG. 4: Regions of the \((m_{\text{SWIMP}}, \Delta m)\) plane excluded by BBN, CMB, and diffuse photon constraints. The shaded regions and the regions below the CMB contours are excluded.

This point may explain \(^{7}\text{Li}\) anomaly...

Neutralino decay may be seen at LHC
Model for Neutralino Galactic Halo:

\[ \rho_{\text{local}} \sim 0.3 \text{ GeV/cm}^3, \ v/c \sim 10^{-3}, \ m_\chi \sim 100 \text{ GeV} \]

\[ \Rightarrow \ \text{flux} \ 10^3 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} ! \]
$\Omega_{CDM} \sim 0.2 - 0.3$ in Concordance Model
instead of $\Omega_{CDM} \sim 1$ in the "Standard CDM" of the 1980’s
→ Good news for dark matter searches!
Explanation: $\Omega_{DM} \sim 1/(\sigma_{\text{ann}} v)$ for thermal relics
Crossing symmetry $\Rightarrow \sigma_{\text{scatt}} \sim \sigma_{\text{ann}}$

Thus, low $\Omega_{DM}$ (if enough to make up galaxy halos) means higher
annihilation & scattering rates (cf. G. Gelmini et al., 2002)
One tool for calculation: DarkSUSY fortran code,
www.physto.se/~edsjo/darksusy

P. Gondolo, J. Edsjö, L.B., P. Ullio,
Mia Schelke and E. A. Baltz
DarkSUSY scan

- $\Omega > 0.95$
- $\Omega h^2 = 0.11 \pm 0.01$ (WMAP)

MSSM is a low-energy effective theory whereas mSUGRA sets values of parameters at GUT scale. Radiative EW symmetry breaking $\Rightarrow$ value of $\mu$ fixed in mSUGRA, but sign is free.

cf. J. Ellis & al, H. Baer et al, J. Edsjö et al
Methods of WIMP Dark Matter detection:

- Discovery at accelerators (Tevatron II, LHC,..)
- Direct detection of halo particles
- Indirect detection of neutrinos, gamma rays, radio waves, antiprotons, positrons

The basic process for indirect detection is annihilation, e.g, neutralinos:

\[ \frac{d\sigma_{si}}{dq} = \frac{1}{\pi v^2} \left[ Zf_p + (A-Z)f_n \right]^2 F_A(q) \propto A^2 \]

Neutralinos are Majorana particles

\[ \Gamma_{ann} \propto n_{\chi}^2 \sigma v \]

Enhanced for clumpy halo; near galactic centre and in Sun & Earth
Direct "detection" by DAMA – controversial issue since TAUP 1997...

R. Bernabei et al, astro-ph/0307403
107 800 kg days, 6σ effect!

Direct detection: a field in rapid development - see talks by Seidel and Morales
To match WMAP precision on $\Omega_{CDM} h^2$, high-precision relic density calculations are needed. Example: coannihilations in mSUGRA

Edsjö, Gondolo, Schelke & Ullio, 2003 ⇒ DarkSUSY now accurate to 1%.

A. Bottino et al, 2003: Low mass (M < 50 GeV) window (relaxing standard GUT assumption $M_1 \approx M_2/2$)

Hooper & Plehn, 2002
Usually, the heaviest kinematically allowed final state dominates (b or t quarks; W & Z bosons)

Note: equal amounts of matter and antimatter in annihilations - source of antimatter in cosmic rays?

Decays from neutral pions: Dominant source of continuum gammas in halo annihilations
Antiprotons at low energy can not be produced in pp collisions in the galaxy, so that may be DM signal?

However, p-He reactions and energy losses due to scattering of antiprotons \( \Rightarrow \) low-energy gap is filled in. BESS data compatible with conventional production by cosmic rays. Antideuterons better signal – but rare? (Donato et al., 2000)

L.B., J. Edsjö and P. Ullio, 2000 
Bieber & Gaisser, 2000

F. Donato et al., 2003
Positrons from neutralino annihilations – explanation of feature at 10 – 30 GeV?

Baltz, Edsjö, Freese, Gondolo 2002; Kane, Wang & Wells, 2002

New experiments will come: Pamela (2004) and AMS (2005)
Kaluza-Klein Dark Matter (Universal extra dimensions)


Main new effect: bosonic DM, no chirality suppression

Direct detection and positrons are best methods (but mass degeneracies are crucial to get detectable signals)

Cheng, Feng & Matchev PRL 2002

Spin-dep

Positrons

Spin-indep
Indirect detection through $\gamma$-rays. Two types of signal: Continuous (large rate but at lower energies, difficult signature) and Monoenergetic line (small rate but at highest energy $E_\gamma = m_\chi$; ”smoking gun”).

Advantage of gamma rays: point back to the source. Enhanced flux possible thanks to halo density profile and substructure (as predicted by CDM).

L.B., P. Ullio & J. Buckley 1998
Loop-induced $2\gamma$ (or $Z\gamma$) final state: source of nearly monoenergetic photons

\[ v/c \approx 10^{-3} \Rightarrow E_\gamma \approx m_\chi \]

(for $\gamma \gamma$) or

\[ E_\gamma \approx m_\gamma \left(1 - \frac{m_Z^2}{4m_\chi^2}\right) \]

(for $Z\gamma$)

Rates are remarkably large (B.R. $\propto 10^{-3} - 10^{-2}$) for higgsino-like neutralinos (in particular, also for TeV-scale higgsinos). New calculation of higher order effects by Hisano, Matsumoto & Nojiri, PRD 2003.
At $m_\chi = 1$ TeV, EW interactions get strong

\[
\mathcal{L} = \frac{1}{2} \Phi^T(r) \left( \left( E + \frac{\nabla^2}{m} \right) 1 - V(r) + 2i\Gamma \delta^3(r) \right) \Phi(r)
\]

\[
\Gamma = \frac{\pi \alpha_s^2}{m^2} \left( \frac{3}{2} \frac{1}{2\sqrt{2}} \right)
\]

\[
(\sigma v)_{VV'} = c_i \sum_{ab} \Gamma_{ab} |V_{VV'}| \times A_a A_b^*
\]

Short distance | Long distance

**Gamma-ray line cross sections enhanced by large factors**
USA-France-Italy-Sweden-Japan (-Germany) collaboration, launch 2006

GLAST will also likely detect a few thousand new GeV blazars …
Major uncertainty for gamma-ray detection from galactic center: Halo dark matter density distribution.

Fits to N-body simulations

\[ \rho_{\text{Moore}}(r) = \frac{c}{r^{3/2}(a^{3/2} + r^{3/2})}; \]

\[ \rho_{\text{NFW}}(r) = \frac{c}{r(a + r)^2}; \]

Fits to rotation curves

\[ \rho_{\text{Burkert}}(r) = \frac{c}{(r + a)(a^2 + r^2)}; \]

Fit to lensing (elliptical galaxies)

\[ \rho_{\text{CIS}}(r) = \frac{c}{a^2 + r^2}; \]

\[ \rho_{\text{SIS}}(r) = \frac{c}{r^2}; \]

Berezinsky, Gurevich, Zybin model

\[ \rho_{\text{BGZ}}(r) = \frac{c}{r^{1.8}}; \]
Note large uncertainty of flux for nearby objects (Milky Way center, LMC, Draco, ...)

In this region (at cosmological distances), the uncertainty is much less

\( \bar{J}(\hat{n}; \Delta \Omega) \equiv \frac{1}{\Delta \Omega} \int d\Omega \int \frac{dl}{(8.5 \text{ kpc})} \left( \frac{\rho(\vec{r})}{0.3 \text{ GeV/cm}^3} \right)^2 \)

FIG. 4: Scaling of the collected \( \gamma \)-ray flux with the distance \( d \) between the detector and the center of a halo, for three different halo profiles. The angular acceptance of the detector is assumed to be \( \Delta \Omega = 10^{-3} \text{ sr} \). The plot is for a \( 10^{12} M_\odot \) halo, the arrows indicate the position on the horizontal axis for the Milky Way and Andromeda; the case for other masses is analogous.
Gamma-ray excess towards Galactic center may be explained by WIMP annihilation

A. Cesarini et al, astro-ph/0305075
Simultaneous fit to radio emission (408 MHz) and EGRET γ-ray spectrum possible if halo is mildly singular $\rho(r) \propto 1/r^{0.1}$, enhanced by formation of spike.

Sub-mm bump due to processes in accretion disk?

Figure 1. Required values of the magnetic field, relative to the equipartition field (see eq. 6) to reproduce the observed spectrum of Sgr A* at a frequency of 408 MHz. Each point represents a different supersymmetric "model" consistent with cosmological relic abundance and accelerator constraints.

Figure 2. Expected gamma-ray flux for the same set of supersymmetric models and $\gamma=0.05$ (triangles), $\gamma=0.12$ (diamonds), $\gamma=0.2$ (dots), $\gamma=1.0$ (squares), along with EGRET data (Narayan et al. 1998) and expected sensitivities for GLAST (1 month observation time) and MAGIC (50 hours).
'Milky Way' simulation, Helmi, White & Springel, 2002

Stoehr, White, Springel, Tormen, Yoshida, astro-ph/0307026,
Hofmann, Schwarz, Stöcker, 2001; Gnedin & Primack, 2003
Problems with WIMP interpretation of detected gamma-rays from Galactic center:

• What is the cause of the background distribution (SNR’s, inverse Compton & bremsstrahlung, …)? How parametrize it?

• Are there other point sources in the vicinity (Hooper & Dingus, 2002)?

• What is the WIMP halo profile (cusp, spike, core, …)? Effects of interaction with black hole, dense stellar cluster, …

• Is there an excess beyond EGRET’s measurements (CANGAROO reports TeV excess …)?

GLAST and new Air Cherenkov Telescopes may perform a more convincing angular and spectral mapping. Gamma-ray line would be spectacular, but rate uncertain
Diffuse cosmic gamma-rays

Idea: Redshifted gamma-ray line gives peculiar energy feature – may be observable for CDM-type (Moore profile) cuspy halos and substructure

FIG. 13: Extragalactic gamma-ray flux (multiplied by $E^2$) for two sample thermal relic neutralinos in the MSSM (dotted curves), summed to the blazar background expected for GLAST (dashed curve). Normalizations for the signals are computed assuming halos are modelled by the Moore profile, with 5% of their mass in substructures with concentration parameters 4 times larger than $c_{\text{vir}}$ as estimated with the Bullock et al. toy model.
Predicted gamma-ray signal towards galactic center for leptonic WIMP (NFW profile assumed)

Only coupling to leptons $\Rightarrow$ no direct detection, no neutrino signal from Earth & Sun, no antiproton signal. Gamma-rays (and perhaps positrons) are the only hope for detection. Air Cherenkov Telescopes (HESS) & GLAST provide "window of opportunity".
Conclusions

• Existence of nonbaryonic dark matter more certain than ever
• CDM favoured
• Neutrinos and MACHOs only small part of dark matter
• Supersymmetric particles (neutralinos) are among the best-motivated candidates
• New direct and indirect detection experiments will reach deep into SUSY parameter space
• DAMA still sees annual modulation
• Indications of gamma-ray excess from Galactic center
• The various indirect detection methods are complementary to each other and to direct detection
• SUSY WIMPs are generic, but there exist alternatives
• The hunt is going on – many new experiments coming!