DARK MATTER AND THE WEAK SCALE

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INPAC- Berkeley-May 4, 2007
Physics beyond the SM is required by Dark Matter, and expected at the EW scale.
Dark Matter: We know a lot!

- We know DM exists (no modified gravity!)
- We know its abundance in the Universe: $0.097 < \Omega \chi h^2 < 0.115$
- We know most of it is not in MACHOS
- We know most is not baryonic
- We know it is NOT explained by the Standard Model of EP
Dark Matter exists! "bullet cluster" August 2006

The visible mass, hot gas detected by Chandra in X-rays (pink), is not where the mass of the cluster seen through gravitational lensing (blue) is.
Dark Matter: not MACHOS

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EROS, 2003

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Dark Matter: not MACHOS


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Dark Matter: not baryons

from P. Gondolo- adapted from L. Verde

\[ \Omega_{\Lambda} = 0.73 \pm 0.04, \quad \Omega_m = 0.27 \pm 0.04 \]
Dark Matter: is cold or warm

Hot dark matter (only < 0.02 of total)
  relativistic at galaxy formation \( (T \sim 1\text{keV}) \)

Warm dark matter
  semi-relativistic at galaxy formation \( (T \sim 1\text{keV}) \)

Cold dark matter
  non-relativistic at galaxy formation \( (T \sim 1\text{keV}) \)
Only SM DM candidates: $\nu$’s

Laboratory data

$m_1 < 2.8$ eV

$\Delta m_{23}^2 \sim 3 \times 10^{-3}$ eV$^2$

$\Delta m_{12}^2 \sim 7 \times 10^{-5}$ eV$^2$

$\rightarrow m_2, m_3 < 2.8$ eV

But Hot DM

and $0.0012 < \Omega_\nu < 0.015$
No CDM or WDM in the SM!

But many in extensions of the SM!

Warm dark matter:

• sterile neutrino, gravitino, non-thermal neutralino...

Cold dark matter:

• WIMPs (LSP or variants LKP, LZP, LTP), axion, WIMPZILLAs, solitons (Q-balls)…
New physics at the EW scale
Expected because of Spontaneous Symmetry Breaking arguments (totally independently of the DM issue)

Radiative corrections to the SM Higgs: $\delta m_H^2 = \alpha_H \Lambda_{SM}^2$
($\Lambda_{SM}$: maximum energy scale that the SM describes)

“Naturalness problem”: to keep $m_H$ we need a fine-tuning

of order: $\Delta \equiv \left| \frac{\partial \ln m_H^2}{\partial \ln \Lambda_{SM}^2} \right|^{-1} \approx \left( \frac{0.5 \text{TeV}}{\Lambda_{SM}} \right)^2 \left( \frac{m_H}{130 \text{GeV}} \right)^2$

Thus $\Lambda_{SM} \approx 5 \text{TeV}$: $\Delta \approx 10^{-2}$, but $\Lambda_{SM} \approx M_P$: $\Delta \approx 10^{-32}$!
New physics at the EW scale
Naturalness implies $\Lambda_{SM} \approx O(\text{TeV})$ above which the
cancellation in $\Delta$ is due to a new theory....

- supersymmetry (with or without a composite Higgs boson)
- technicolor (walking or top assisted TC)
- large extra spatial dimension (possibly warped)
- “Little Higgs” model (Higgs is a pseudo-Goldstone boson) which provides main potential discoveries at the LHC and DM candidates...
  - LSP, Lightest Technibaryon, LKP (Lightest KK Particle) or LZP (in Warped SO(10) with Z3 model), LTP (the Lightest T-odd heavy photon in Little Higgs with T-parity...)
New physics at the EW scale?
Could $\Lambda_{SM} \gg O(\text{TeV})$?

Djouadi 05- adapted from Hambye, Riesselam 97

- Triviality (upper) bound
- Vacuum stability (lower)
- Unitarity $< 700$ GeV

For $\Lambda_{SM} \approx M_P$:
- $115 \text{GeV} < m_h < 180 \text{GeV}$

Same as 95\%C.L. experimental LEP range:
- $114 \text{GeV} < m_h < 198 \text{GeV}$
New physics at the EW scale?

Could the LHC see just a Higgs boson? YES, if we accept fine tuning through the anthropic principle

- $\Lambda_{SM} \approx M_{\text{GUT}}$: SM + anthropic pple in landscape of vacua.

  The LHC will only see the SM Higgs in the LEP range! (+ multistage GUT unification?).
New physics at the EW scale?

Could the LHC see just a Higgs boson and little else? YES

- $\Lambda_{SM} > 100 \text{ TeV}$: split-SUSY + anthropic principle in landscape of vacua. The LHC will only see the SM-like Higgs in the LEP range (and a long lived hadronizing gluino)!

- $\Lambda_{SM} \approx 1.5 \text{ TeV}$: small modification of the SM, e.g. Inert Doublet Model. The LHC will only see the SM Higgs with $m$ up to 500 GeV (other inert components with mass from 60 GeV to 1 TeV but produced in pairs and not coupled to fermions may not be seen at the LHC)!
Physics beyond the SM is required by Dark Matter, and expected at the EW scale, and both physics may or may not be related!

Thus LHC and DM searches are independent and complementary.
Large Hadron Collider at CERN
**LHC:** 14 TeV pp collider- completion 2007-2008-
start L=10 fb⁻¹-design L=100 fb⁻¹

- May find charged particles up to $\sim$ 2 TeV.
- May find DM candidates of up to $\sim$ 2 TeV in missing energy events.

**ILC:** 0.5 TeV (1 TeV) $e^+e^-$ linear collider

- Lower mass reach.
- Precision measurements.
WIMP DM searches:

- **Direct Detection**: looks for energy deposited within detector
  
  **Signature**: same $\sigma$ and $m$ + annual modulation and/or recoil direction, seen by different experiments with different nuclei (CDMS, Edelweiss, Cresst, Zeplin, Xenon...)

- **Indirect Detection**: looks for WIMP annihilation products
  
  **Signature**: no other possible sources or complementary to other searches
  
  - neutrinos from Sun/Earth (AMANDA, Icecube, Antares)
  - anomalous cosmic rays and $\gamma$-rays from galactic halo(s) (AMS, Pamela)
  - neutrinos, gamma-rays, radio waves from galactic center (Glast, Hess, Veritas, Heat)
DM-searches + LHC: all is possible!

- LHC sees many new particles and the DM particle mass range, which is simultaneously detected in Direct/Indirect Searches (e.g. MSSM neutralino?)
- LHC sees many new particles and finds the NLSP, DM searches cannot detect the LSP (e.g. a it is the gravitino)
- LHC finds only the Higgs, but DM is detected in Direct/Indirect DM Searches (e.g. Split SUSY, IDM?)
- LHC sees new physics but DM is not related to it (e.g. axions, sterile neutrinos?)
- Any other combination you may imagine...
DM-searches + LHC:

- LHC sees many new particles and the DM particle mass range, which is simultaneously detected in Direct/Indirect Searches (e.g. MSSM neutralino?)
Supersymmetry Most studied model

- Models are completely calculable
- Hierarchy: maintains EW scale $\ll$ GUT scale
- One stage unification of fundamental forces
- Every known particle has supersymmetric partner(s)
- If R-parity is conserved, the Lightest Supersymmetric Partner is good dark matter candidate (if neutral):
  - sneutrino (partner of neutrino)
  - gravitino (partner of graviton)
  - neutralino (gaugino/ higgssino, partner of neutral gauge boson/Higgs boson)
- Requires two Higgs doublets minimum.
MSSM

• Minimum number of particles (SUSY partners + two Higgs doublets)
• Number of parameters: 18 of the SM + 106!!!
• Parameter reduction:
  – wMSSM: simplified weak-scale MSSM: 18 + 7 p. \((M_2, \mu, \tan \beta, m_A, \tilde{m}, A_b, A_t)\)
  – CMSSM: constrained MSSM: 18+6 parameters \((m_0, A_0, m_{1/2}, \tan \beta, \mu)\)
  – mSUGRA: minimal supergravity: 18+5 parameters \((m_0, A_0, m_{1/2}, \tan \beta, \text{sign of } \mu)\)

NMSSM

• Non Minimum number of particles (extra singlet Higgs, etc)
WIMPs as Dark Matter

With standard cosmological assumptions before BBN

- WIMPs reach thermal equilibrium
- Chemical decoupling when \( \Gamma_{\text{ann}} = \langle \sigma v \rangle n \leq H \),
- No entropy change in matter + radiation

\[ \Omega h^2 \approx \frac{2 \times 10^{-10} \text{GeV}^{-2}}{\langle \sigma v \rangle} \]

Weak \( \sigma \) for \( \Omega \sim 1 \)!
Dark Matter constraint: Within the standard cosmology neutralinos in CMSSM are the CDM only in the blue narrow bands (e.g. J. Ellis et.al.2005)
LHC typical SUSY decay chain

Typical topology:

- missing energy
- multiple hadronic jets
- number of leptons

2 isolated leptons
+ 2 b-jets
+ 4 jets
+ $E_t^{\text{miss}}$
LHC SUSY spectroscopy

First evidence could come from dilepton “edges”:

- gluino, sbottom and squark reconstruction
  \[ \tilde{g} \to \tilde{b} \tilde{b}, \tilde{b} \to b\chi_2^0, \]
  \[ \chi_2^0 \to \ell^+ \ell^- \chi_1^0 \]

reconstruction starts with \( \chi_2^0 \): sharp \( M_{\ell\ell}^{max} \) given by

- \( m_{\chi_2^0} \), \( m_\ell \) and \( m_{\chi_1^0} \)
LHC/LC and DM searches: Baer et.al 04
Dark Matter constraint: narrow regions

Benchmarks in DM regions: A’ to L’
(Battaglia, DeRoeck, Ellis, Gianotti, Olive, Pape 03)

SPS 1a’, 1b, 2, 3, 4, 5
(Snowmass Points and Slopes) (Allanach et al. 02)

LCC 1, 2, 3, 4
(Linear Collider Cosmo) (White paper on ILC)

SPS1a’, LCC2, D’, LCC4 ... 
(ILC World-wide study) (Battaglia et al 2006)
Example LCC2:  (Baltz, Battaglia, Peskin, Wisansky 2006)

- squark, slepton too heavy for LHC,
- chargino neutralino of 100-300 GeV, gluino of 850 GeV
- \( \chi \rightarrow WW, ZZ, \chi\chi \) annihilate through neutralino/chargino exchange
- LHC sees most gauginos/higgsinos, one Higgs boson (ILC sees all others and cross sections).
- LHC gives the DM mass to 10% and relic density (ILC:10%)
- By 2012, same DM mass is seen also in Direct (\( \sim 70 \) events in SuperCDMS 25Kg?) and Indirect detection (GLAST sees \( \gamma \) from DM clusters?)
Example LCC2: (Baltz, Battaglia, Peskin, Wisansky 2006)
DM-searches + LHC:

- LHC sees many new particles and finds the NLSP, DM searches cannot detect the LSP (e.g. it is the gravitino)
**SuperWIMPs** *(Feng, Rajaraman, Takayama 2003)*

NLSP sleptons with weak annihilation cross section get the right DM density

After one month decays into gravitinos LSP! which inherit the right density (although interact only gravitationally)

LSP can be Warm Dark Matter *(Cembranos et al 2006)*

DM searches: NO HOPE *(couplings suppressed by 10^{-16})*

In Accelerators, NLSP could be trapped in kton water tanks and observed decay

*(Feng, Smith 04, Hamaguchi et al. 04, Ellis et al 2005)*
DM-searches + LHC:

- LHC finds only the Higgs, but DM is detected in Direct/Indirect WIMP DM Searches (e.g. Split SUSY, IDM?)
Split-SUSY (Dimopoulos, Arkani-Hamed; Giudice, Romanino 2004)
Forget fine tuning - think landscape of vacua
Keep DM and one stage GUT unification.
Scalars heavy, except light SM-like higgs > 140 GeV
Neutralinos/charginos “light” but the best LHC background rejection \( M_{\ell\ell} \) gone (no squarks, sleptons incascades)
Long lived-hadronizing gluino, R-hadron, is best LHC signal
(Killian, Plehn, Richardson, Schmidt 2005)
Neutralino DM in Split-SUSY

Profumo, Ullio 2004

$$\Omega h^2 > 0.13$$

Direct Detection
Muon Flux/Sun
Antideuterons (?)
Antiprotons
Positrons

Future Direct Searches at LEP
Detection Reach
Long-lived Gluinos at LHC (AMSB relation)

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The Inert Doublet Model

Barbieri, Hall, Rychkov, 2006

The LHC may see just a Higgs boson or little else?

SM-like Higgs can be heavy, 500 GeV, without violating electroweak precision bounds (new physics above LHC scale).

Model: SM + one Higgs doublet not coupled to fermions and with no VEV, unbroken discrete parity implies that the **Lightest Inert Particle (LIP)** is good DM candidate, which could be detected in Direct /Indirect Searches.
LIP-MSSM abundance

Honorez et al, 2007
LIP-MSSM searches

Honorez et al, 2007

light colors: $0.01 < \Omega_{DM} h^2 < 0.3$, dark colors: $0.094 < \Omega_{DM} h^2 < 0.129$
DM-searches+LHC:

- LHC sees new physics but DM is not related to it (e.g. sterile neutrinos, axions?)

- Sterile neutrinos are not related to the EW scale. For example, see-saw models point to scales larger than TeV
  \[ M \sim \text{GeV}^2 / m_s \text{ thus } m_s = \text{keV} \text{ implies } M \sim 1000 \text{ TeV} \]

- The “Invisible axion models” have two Higgs doublets (plus a singlet but at a higher scale) whose components should be found at the LHC. But the DM is the axion.
Sterile Neutrinos

$\nu_s$ produced via oscillations with active neutrinos

Can be Warm DM or Cool DM (with large Lepton Asymmetry L).

$\nu_s \rightarrow \nu \gamma$ produces X-rays and lower bounds on $m_s$

SDSS Power Spectrum of Ly-$\alpha$ clouds at $z = 4$ provides upper bound on $m_s$

$m_s > 14$ keV (Seljak et al) or $m_s > 7$ keV (Viel et al)

reject $\nu_s$ unless large L (but possible systematic errors in Ly-$\alpha$ argument?)

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Axions

• introduced to solve the “strong CP problem” Peccei & Quinn

• invisible axion
  Kim; Shifman, Vainshtein, Zakharov (KSVZ)
  Dine, Fischler, Srednicki; Zhitnitsky (DFSZ)

• Good CDM candidate for $1\mu$eV $\leq m \leq 1$meV

• Produced cold: alignment, strings

• Axion DM is about to be detected or to be ruled out experimentally!
Axions (Duffy et al 2006)

Axion Dark Matter eXperiment (ADMX) uses a Sikivie microwave cavity detector to search for $a\gamma\gamma$

“Medium Resolution” (MR) assumes velocity dispersion is $\leq 10^{-3}c$ (axion escape velocity is $2 \times 10^{-3}c$.)

“High Resolution” (HR) uses the possible existence of discrete flows, or streams (smaller velocity dispersion) 97.7% CL limits
DM-searches + LHC:

About Dark Matter abundance: Underabundance, Overabundance, Just Right-abundance?

- Underabundant WIMPS: direct detection can reach them (indirect detection is harder)

- Overabundant: should they be rejected? Should LHC concentrate on candidates with Just Right abundance?
Underabundant WIMPs

- Small thermal relic density
- Large annihilation cross section
- Large scattering cross section
- Similar direct detection rate

Duda, Gelmini, Gondolo 2001
Dark Matter constraint: narrow bands

(Battaglia, De Roeck, Ellis, Gianotti, Olive, Pape 2003)

Benchmarks in regions with $0.094 < \Omega \chi h^2 < 0.129$

mSUGRA with $\mu > 0$ and (bottom to top) $\tan \beta = 5, 10, 20, 35$ and 50,

But bands depend on cosmology before BBN, where we cannot observe the Universe!!
Standard or Non std cosmologies?

Standard cosmological assumptions before BBN, i.e. at $T > 4$ MeV

- $T_{RH}$, highest temperature of the most recent radiation dominated epoch of the Universe, is large,
- neutralinos are produced thermally and reach equilibrium before decoupling
- the entropy of matter and radiation is conserved

Imply neutralinos can be the DM only in narrow bands

In non-standard cosmologies, can the neutralino be the cold dark matter in all of the parameter space?
How to get a non-std abundance

- **Decrease** the density by producing radiation after freeze out [entropy dilution].
- **Increase** the density by creating neutralinos from particle decays (or topological defects) [non-thermal production], or by decreasing the expansion rate at freeze-out [e.g. quintessence].

Late decaying scalar field $\phi$
(e.g. a modulus field in string theory models or an inflaton)\textsuperscript{(G.G. and P. Gondolo, hep-ph/0602230)}\textsuperscript{(G.G., P. Gondolo, A. Soldatenko and C. E. Yaguna, hep-ph/0605016)}

which reheats the Universe to a low reheating temp. $T_{RH}$, above BBN and below the standard freeze-out of neutralinos

$$5\text{MeV} < T_{RH} < m_\chi/20$$

and produces $b$ neutralinos per $\phi$ decay, due to the branching ratio of the scalar field into SUSY partners

$$\eta = b(100\text{TeV}/m_\phi)$$
Std vs Non-std cosmology

In non-std cosmology, the narrow band can be anywhere in the parameter space, provided right $T_{RH}$, $\eta$
Standard $\Omega$: forbids blue region
Direct Detection: Std/Non-Std

![Graph showing the relationship between Neutralino Mass (GeV) and the SI cross section for generic and standard models.](image)
Neutralino warm dark matter

Zhang, Brandenberger 2001; Hisano, Kohri and Nojiri 2001, Gelmini, Yaguna 2006

Cold dark matter may have problems with structure at small scales. Dark matter may be warm.....Warm dark matter requires speed now (if $p_\chi$ only redshifts):

$$v_0 = \frac{T_0 E_I}{T_{RH} m_\chi} \simeq 10^{-7},$$

$E_I$: energy at production at $T_{RH}$

Thus: $\chi$ must be produced hot + late+ must not lose energy in interactions with thermal bath, i.e. must not interact $\Gamma_{\text{scat}} < H$

Late decaying scalar + Split SUSY ($\mu(m_\tilde{\nu}) > 5(20) \text{TeV}$) allow O(100GeV) mass Bino to be warm dark matter

Difficult for DM searches!
WIMP density cosmology probe
The neutralino density may be used to find out about the cosmology before BBN. This is not a new idea

Thermal relics: Do we know their abundances?

Marc Kamionkowski and Michael S. Turner
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and NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500
(Received 25 May 1990)

The relic abundance of a particle species that was once in thermal equilibrium in the expanding Universe depends upon a competition between the annihilation rate of the species and the expansion rate of the Universe. Assuming that the Universe is radiation dominated at early times the relic abundance is easy to compute and well known. At times earlier than about 1 sec after the bang there is little or no evidence that the Universe had to be radiation dominated, although that is the simplest—and standard—assumption. Because early-Universe relics are of such importance both to particle physics and to cosmology, we consider in detail three nonstandard possibilities for the Universe at the time a species' abundance froze in: energy density dominated by shear (i.e., anisotropic expansion), energy density dominated by some other nonrelativistic species, and energy densi-
WIMP density cosmology probe

The neutralino density may be used to find out about the cosmology before BBN. This is not a new idea.

Massive Particles as a Probe of the Early Universe

John D. Barrow

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Received 29 January 1982
(Revised 30 March 1982)

The survival density of stable massive particles with general annihilation cross section is calculated in a cosmological model that expands anisotropically in its early stages \((t < 1 \text{ s})\). It is shown that the faster average expansion rate leaves a larger present density of surviving particles than in a model that expands isotropically. This allows particle survival calculations to be employed as a probe of the dynamics of the early universe prior to nucleosynthesis. Several examples of heavy lepton, nucleon and monopole survival are discussed.
Conclusions

In most scenarios one can think of the LHC should find at least a hint of the new physics...

Whatever the LHC finds will lead to a set of possible Dark Matter candidates and reject others...

DM searches are independent and complementary to collider searches in multiple ways...

Direct and Indirect DM searches are complementary between them...

All possibilities are still open.... hopefully not for long!