Dark Matter Particle Candidates

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Evidence for cold dark matter

- Cold dark matter: $535 \pm 7 \text{ pJ/m}^3$
- Ordinary matter: $37.6 \pm 0.2 \text{ pJ/m}^3$
- Neutrinos: $1 \text{ to } 4 \text{ pJ/m}^3$
- Photons: $0.04175 \pm 0.00004 \text{ pJ/m}^3$

The observed energy content of the Universe

- Matter: $p \ll \rho$
- Radiation: $p = \rho/3$
- Vacuum: $p = -\rho$

Planck (2015) $TT,TE,EE+lowP+lensing+ext$

$\rho_{\text{crit}} = 1688.29 \ h^2 \ \text{pJ/m}^3$

$1 \ \text{pJ} = 10^{-12} \ \text{J}$
Is cold dark matter an elementary particle?

No known particle can be nonbaryonic cold dark matter!
What particle model for cold dark matter?

• It should have the cosmic cold dark matter density

• It should be stable or very long-lived ($\gtrsim 10^{24}$ yr)

• It should be compatible with collider, astrophysics, etc. bounds

• Ideally, it would be possible to detect it in outer space and produce it in the laboratory

• For the believer, it would explain claims of dark matter detection (annual modulation, positrons, X-ray line, $\gamma$-ray excess, etc.)
Particle dark matter

- SM neutrinos (hot)
- lightest supersymmetric particle (cold)
- lightest Kaluza-Klein particle (cold)
- sterile neutrinos, gravitinos (warm)
- Bose-Einstein condensates, axions, axion clusters (cold)
- solitons (Q-balls, B-balls, ...) (cold)
- supermassive wimpzillas (cold)

**Mass range**

- $10^{-22}$ eV ($10^{-59}$ kg) B.E.C.s
- $10^{-8} M_\odot$ ($10^{+22}$ kg) axion clusters

**Interaction strength range**

- Only gravitational: wimpzillas
- Strongly interacting: B-balls
Particle dark matter

**Hot dark matter**
- relativistic at kinetic decoupling (last scattering, start of free streaming)
- big structures form first, then fragment
  - light neutrinos

**Cold dark matter**
- non-relativistic at kinetic decoupling
- small structures form first, then merge
  - neutralinos, axions, WIMPZILLAs, solitons

**Warm dark matter**
- semi-relativistic at kinetic decoupling
- smallest structures are erased
  - sterile neutrinos, gravitinos
Particle dark matter

**Thermal relics**
- in thermal equilibrium with the plasma in the early universe
- produced in collision of plasma particles
- insensitive to initial conditions
  
  neutralinos, other WIMPs, ....

**Non-thermal relics**
- not in thermal equilibrium with the plasma in the early universe
- produced in decays of heavier particles or extended structures
- have a memory of initial conditions
  
  axions, WIMPZILLAs, solitons, ....
# Particle dark matter

| DM production | - in plasma reactions  
|               | - from decays of decoupled species  
|               | - emitted from extended objects | collider searches cosmic density |
| DM–DM annihilation $\chi^+\chi^\rightarrow$anything | - self-conjugate DM  
|               | - asymmetric DM | indirect detection cosmic density |
| DM–SM scattering $\chi^+\text{SM}^\rightarrow\chi'^+$SM | - elastic/inelastic scattering  
|               | - short-/long-range interactions | hot/cold/warm halo (sub)structure direct detection |
| DM–DM scattering $\chi^+\chi^\rightarrow\chi^+\chi$ | - collisionless  
|               | - self-interacting | dark halo structure |
| DM decay $\chi^\rightarrow$anything | - stable  
|               | - long-lived  
|               | - ensemble of short-lived particles | indirect detection |
Particle dark matter

Some factors affecting the particle dark matter cosmic density

— Production mechanism:
  • produced in reactions of plasma (thermal) particles
    - reaching reaction equilibrium
    - not reaching reaction equilibrium
    - coannihilating with similar mass particles
  • produced in decays of non-thermal particles
  • emitted from extended objects

— Dark matter-antimatter asymmetry:
  • self-conjugate
  • not self-conjugate

— Hubble expansion rate before nucleosynthesis:
  • standard vs nonstandard cosmology
The magnificent WIMP
(Weakly Interacting Massive Particle)

- One naturally obtains the right cosmic density of WIMPs
  
  *Thermal production in hot primordial plasma.*

- One can experimentally test the WIMP hypothesis
  
  *The same physical processes that produce the right density of WIMPs make their detection possible*
The power of the WIMP

Indirect detection

Cosmic density

Direct detection

Large scale structure

Colliders

Cosmic density

Production

Annihilation

Scattering
Neutrinos
Cosmic density of massive neutrinos

Active neutrinos

Excluded as cold dark matter (1991)

Lee & Weinberg 1977

~ few GeV preferred cosmological mass

Direct Searches

LEP bound $Z \rightarrow \nu\bar{\nu}$
Sterile neutrino dark matter

Standard model + right-handed neutrinos

Active and sterile neutrinos oscillate into each other.

Sterile neutrinos can be warm dark matter (mass > 0.3 keV)

Dodelson, Widrow 1994; Shi, Fuller 1999; Laine, Shaposhnikov 2008
Sterile neutrino dark matter

An unidentified 3.5-keV X-ray line has been reported in galaxy clusters and the Andromeda galaxy.

Bulbul et al 2014; Boyarski et al 2014; Iakubovskyi et al 2015

Radiative decay of sterile neutrinos

\[ \nu_s \rightarrow \gamma \nu_\alpha \quad E_{\gamma} = m_s / 2 \]

\[ m_v = 7.1 \text{ keV} \quad \sin^2(2\theta) = 7 \times 10^{-11} \]
Neutralinos
Supersymmetric models

The CMSSM* is in dire straights, but there are many supersymmetric models

*Constrained Minimal Supersymmetric Standard Model
Neutralino dark matter: impact of LHC

“the only pMSSM models remaining [with neutralino being 100% of CDM] are those with bino coannihilation”

pMSSM (phenomenological MSSM)

\[ \mu, m_A, \tan \beta, A_b, A_t, A_\tau, M_1, M_2, M_3, \]
\[ m_{Q_1}, m_{Q_3}, m_{u_1}, m_{d_1}, m_{u_3}, m_{d_3}, \]
\[ m_{L_1}, m_{L_3}, m_{e_1}, m_{e_3} \]

(19 parameters)

only a few red points have 100% CDM
Neutralino dark matter: impact of LHC

Kowalska et al 1211.1693 [PRD 87(2013)115010]

CNMSSM: Alive and well!

NMSSM (Next-to-MSSM)

\[ W = \lambda S H_u H_d + \frac{\kappa}{3} S^3 + (\text{MSSM Yukawa terms}), \]

\[ V_{\text{soft}} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 \]

\[ + \left( \lambda A_\lambda S H_u H_d + \frac{1}{3} \kappa A_\kappa S^3 + \text{H.c.} \right), \]

Constrained NMSSM

\[ m_0, m_{1/2}, A_0, \tan \beta, \lambda, \text{sgn}(\mu_{\text{eff}}), \]

GUT & radiative EWSB

Marginalized 2D posterior PDF of global analysis including LHC, WMAP, \((g-2)_\mu\), \(B_s \rightarrow \mu^+ \mu^-\) etc.
Neutralino dark matter

Neutralino dark matter with decoupled (heavy) sfermions

Excluded by LEP, HESS, LUX

All can be tested by LZ, CTA, and a 100-TeV pp collider

Bramante, Desai, Fox, Martin, Ostdiek, Plehn 2015
QCD axions
QCD axions as dark matter

Hot

Produced thermally in early universe

*Important for* $m_a > 0.1\text{eV}$ ($f_a < 10^8$), *mostly excluded by astrophysics*

Cold

Produced by coherent field oscillations around minimum of the axion potential

*(Vacuum realignment)*

Produced by decay of topological defects

*(Axionic string decays)*

Still a very complicated and uncertain calculation!

*e.g. Hiramatsu et al 2012*
QCD axions as cold dark matter

Expansion rate at end of inflation

\[ m_a = \left(71 \pm 2\right) \mu \text{eV} \left(1 + \alpha_d\right)^{6/7} \]

PQ symmetry breaks before inflation ends

PQ symmetry breaks after inflation ends

Visinelli, Gondolo 2009, 2014

Sikivie (today), Carosi, Brubaker, Baer (Thursday)
Anapole dark matter
Anapole dark matter

The anapole moment is a C and P violating, but CP-conserving, electromagnetic moment

*First measured experimentally in Cesium atoms*

Zeldovich 1957

Wood et al 1997

Anapole dark matter

spin-1/2 Majorana fermion

\[
\mathcal{L} = \frac{g}{2\Lambda^2} \bar{\chi} \gamma^\mu \gamma^5 \chi \partial^\nu F_{\mu\nu}
\]

\[
H = -\frac{g}{\Lambda^2} \bar{\sigma} \cdot \nabla \times \vec{B}
\]

Direct detection limits with standard dark halo

*Del Nobile, Gelmini, Gondolo, Huh 2014*
Anapole dark matter

\[
\frac{d\sigma}{dE_R} = \frac{2m e^2 g^2}{\pi v^2 \Lambda^2} \left[ (v^2 - v_{\text{min}}^2) F_L^2(E_R) + F_T^2(E_R) \right]
\]

For anapole dark matter, the lowest DAMA bins may be compatible with null searches.

The modulation amplitude would need to be large.

Del Nobile, Gelmini, Gondolo, Huh 2014
Scalar phantoms
Scalar phantom dark matter

“Gauge singlet scalar dark matter”
“Singlet scalar dark matter”
“Scalar singlet dark matter”
“Scalar Higgs-portal dark matter”
“The minimal model of dark matter”

Minimalist dark matter

do not confuse with minimal dark matter

Gauge singlet scalar field $S$ stabilized by a $\mathbb{Z}_2$ symmetry $(S \rightarrow -S)$

$$\mathcal{L} = \frac{1}{2} \partial^\mu S \partial_\mu S + \frac{1}{2} \mu_S^2 S^2 - \frac{\lambda_S}{4} S^4 - \lambda_{HS} H^\dagger H S^2$$

Silveira, Zee 1985
Andreas, Hambye, Tytgat 2008
Djouadi, Falkowski, Mambrini, Quevillon 2012
Cline, Scott, Kainulainen, Weniger 2013

“Scalar phantom” is the original 1985 name
Scalar phantom dark matter

Feng, Profumo, Ubaldi 2015

If density is rescaled according to $\Omega_S$, LUX and FERMI exclusion regions are very different

Cline, Scott, Kainulainen, Weniger 2013

Not excluded by LUX at $m_S \approx 60$ GeV and $m_S > 1$ TeV

No density rescaling
750-GeV portal
A possible spin-0 resonance decaying into a pair of photons

There are many models and analyses relating the 750-GeV resonance to dark matter, too numerous to list here.
750-GeV portal with Majorana dark matter

**Scalar resonance**

\[ gg \to S \to \gamma\gamma \]

\[ c_{\chi S} S \bar{S} \chi + \frac{c_{GG}}{\Lambda} S G^a_{\mu\nu} G^a_{\mu\nu} \]

- **Strongest constraints from invisible width, jets, and LUX**
- **Can be fully probed by LZ**

**Pseudoscalar resonance**

\[ gg \to P \to \gamma\gamma \]

\[ c_{\chi P} P \bar{\chi} i\gamma_5 \chi + \frac{c_{GG}}{\Lambda} P G^a_{\mu\nu} G^a_{\mu\nu} \]

- **Strongest constraints from invisible width and FERMI**
- **Hard to probe > 350 GeV**
Self-interacting dark matter
Self-interacting dark matter

Proposed as solution to ‘cusp vs core’ and ‘too big to fail’ puzzles in collisionless dark matter simulations. Spergel, Steinhardt 1999

Tested on cluster and galaxy collisions

\[ \frac{\sigma}{m} < 0.7 \text{ cm}^2/\text{g} \quad \text{mass loss in Bullet Cluster} \quad \text{Randall et al } 2008 \]
\[ \frac{\sigma}{m} < 0.47 \text{ cm}^2/\text{g} \quad \text{72 cluster collisions} \quad \text{Harvey et al } 2015 \]
\[ \frac{\sigma}{m} = (1.7 \pm 0.7) \times 10^{-4} \text{ cm}^2/\text{g} \quad \text{in Abell 3827 (?)} \quad \text{Massey et al } 2015 \]

Several particle models exist

Light mediator Feng, Kaplinghat, Yu; Buckley, Fox 2009; Tulin, Yu, Zurek 2013

Hidden vector dark matter (HVDM) Hambye 2008

Dark matter is 3 gauge bosons of a hidden SU(2) group spontaneously broken by a hidden Higgs doublet coupled to the SM Higgs.

Allowed in some regimes Bernal et al 2015

Yu, Bullock, Boddy (Thursday)

1 barn/GeV = 0.6 cm$^2$/g
Dynamical dark matter
Dynamical dark matter

Dienes, Thomas 2011, 2012
Dienes, Kumar, Thomas 2012, 2013

A vast ensemble of fields decaying from one to another

Example: Kaluza-Klein tower of axions in extra-dimensions

Phenomenology obtained through scaling laws

\[ m_n = m_0 + n \delta \Delta m, \]
\[ \rho_n \sim m_n^\alpha, \tau_n \sim m_n^{-\gamma} \]

This model can fit the positron excess and has no cut off.
Asymmetric dark matter
Asymmetric dark matter

- Dark matter in a hidden mirror sector ("dark sector")
- Dark matter asymmetry similar to baryon asymmetry, generated by similar mechanisms
  \[ n_\chi \approx n_p \]
- Dark matter mass is a few times the proton mass
  \[ \Omega_\chi \approx \frac{m_\chi}{m_p} \Omega_p \approx (\text{a few}) \Omega_p \]

Model-agnostic dark matter
All particle physics models

- Consider all possible interactions between dark matter and standard model particles
- This program has been carried out in some limits (e.g., contact interactions, non-relativistic kinematics)

Four-particle effective operators

\[ O \]

\[ q, g \]

\[ q, g \]

There are many possible operators. Interference is important although often neglected. Long-distance interactions are often not included.
Effective operators: LHC & direct detection

<table>
<thead>
<tr>
<th>Name</th>
<th>Operator</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>$\bar{\chi}\chi\bar{q}q$</td>
<td>$m_q/M_3^*$</td>
</tr>
<tr>
<td>D2</td>
<td>$\bar{\chi}\gamma^5\chi\bar{q}q$</td>
<td>$i m_q/M_3^*$</td>
</tr>
<tr>
<td>D3</td>
<td>$\bar{\chi}\chi\gamma^5\bar{q}q$</td>
<td>$i m_q/M_3^*$</td>
</tr>
<tr>
<td>D4</td>
<td>$\bar{\chi}\gamma^5\chi\gamma^5\bar{q}q$</td>
<td>$m_q/M_3^*$</td>
</tr>
<tr>
<td>D5</td>
<td>$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma^\mu q$</td>
<td>$1/M_2^*$</td>
</tr>
<tr>
<td>D6</td>
<td>$\bar{\chi}\gamma^\mu\gamma^5\chi\gamma^\mu\bar{q}q$</td>
<td>$1/M_2^*$</td>
</tr>
<tr>
<td>D7</td>
<td>$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma^5\gamma^\mu q$</td>
<td>$1/M_2^*$</td>
</tr>
<tr>
<td>D8</td>
<td>$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma^\mu\gamma^5 q$</td>
<td>$1/M_2^*$</td>
</tr>
<tr>
<td>D9</td>
<td>$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$</td>
<td>$1/M_2^*$</td>
</tr>
<tr>
<td>D10</td>
<td>$\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta} q$</td>
<td>$i/M_2^*$</td>
</tr>
<tr>
<td>D11</td>
<td>$\bar{\chi}\chi G_{\mu \nu} G^{\mu \nu}$</td>
<td>$\alpha_s/4M_3^*$</td>
</tr>
<tr>
<td>D12</td>
<td>$\bar{\chi}\gamma^5\chi G_{\mu \nu} G^{\mu \nu}$</td>
<td>$i \alpha_s/4M_3^*$</td>
</tr>
<tr>
<td>D13</td>
<td>$\bar{\chi}\chi G_{\mu \nu} \tilde{G}^{\mu \nu}$</td>
<td>$i \alpha_s/4M_3^*$</td>
</tr>
<tr>
<td>D14</td>
<td>$\bar{\chi}\gamma^5\chi G_{\mu \nu} \tilde{G}^{\mu \nu}$</td>
<td>$\alpha_s/4M_3^*$</td>
</tr>
</tbody>
</table>

Table of effective operators relevant for the collider/direct detection connection

Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu 2010
Effective operators: LHC & direct detection

LHC limits on WIMP-quark and WIMP-gluon interactions are competitive with direct searches

Beltran et al, Agrawal et al., Goodman et al., Bai et al., 2010; Goodman et al., Rajaraman et al. Fox et al., 2011; Cheung et al., Fitzpatrick et al., March-Russell et al., Fox et al., 2012......

These bounds do not apply to SUSY, etc.

Complete theories contain sums of operators (interference) and not-so-heavy mediators (Higgs)

Fox, Harnik, Primulando, Yu 2012
Effective operators: direct detection

All non-relativistic contact operators classified

\begin{align*}
1, \quad & \vec{S}_X \cdot \vec{S}_N, \quad v^2, \quad i(\vec{S}_X \times \vec{q}) \cdot \vec{v}, \quad i\vec{v} \cdot (\vec{S}_N \times \vec{q}), \quad (\vec{S}_X \cdot \vec{q})(\vec{S}_N \cdot \vec{q}) \quad i\vec{S}_N \cdot \vec{q}, \quad i\vec{S}_X \cdot \vec{q}, \\
& \vec{v}^\perp \cdot \vec{S}_X, \quad \vec{v}^\perp \cdot \vec{S}_N, \quad i\vec{S}_X \cdot (\vec{S}_N \times \vec{q}). \quad (i\vec{S}_N \cdot \vec{q})(\vec{v}^\perp \cdot \vec{S}_X), \quad (i\vec{S}_X \cdot \vec{q})(\vec{v}^\perp \cdot \vec{S}_N).
\end{align*}

Global analysis

Catena, Gondolo 2014

Experimental limits

Schneck et al. (SuperCDMS) 2015

LUX \quad m = 10 \text{ TeV}
Summary

• There have been many candidates for nonbaryonic dark matter over the years. There seem to be even more now.

• Particle physicists do not lack ideas and are able to escape stronger and stronger experimental constraints.

• The time is ripe for experiments to conclusively find a particle of dark matter.