Theory of low mass WIMPs

Light dark matter
Weakly-interacting
2-10 GeV/c^2 mass

Paolo Gondolo
University of Utah
The original WIMP

Light since 1977
Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee(a)
Fermi National Accelerator Laboratory, (b) Batavia, Illinois 60510

and

Steven Weinberg(c)
Stanford University, Physics Department, Stanford, California 94305
(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of $2 \times 10^{-29}$ g/cm$^3$, the lepton mass would have to be greater than a lower bound of the order of 2 GeV.

2 GeV/c$^2$ for $\Omega_c=1$
Now 4 GeV/c$^2$ for $\Omega_c=0.25$
Cosmic density of thermal WIMPs

- At early times, WIMPs are produced in $e^+e^-$, $\mu^+\mu^-$, etc collisions in the hot primordial soup [thermal production].
  $$\chi + \chi \leftrightarrow e^+ + e^-, \mu^+ + \mu^-, \text{etc}.$$  

- WIMP production ceases when the production rate becomes smaller than the Hubble expansion rate [freeze-out].

- After freeze-out, the number of WIMPs per photon is constant.
The original WIMP

• Lee and Weinberg’s heavy neutrinos were Dirac neutrinos
  \[ \text{WIMP} \neq \text{antiWIMP} \]
  In this case, an asymmetry is possible in their density
  \[ n_{\text{WIMP}} \neq n_{\text{antiWIMP}} \quad (\text{asymmetric dark matter}) \]
  Lee and Weinberg set it to zero

• Many other dark matter candidates (Majorana neutrinos, neutralinos, gauge singlet scalars) are self-conjugate
  \[ \text{WIMP} = \text{antiWIMP} \]
  In this case, no asymmetry is possible
**Cosmic density of thermal WIMPs**

\[
\Omega_{\chi} h^2 \simeq \frac{3 \times 10^{-27} \text{cm}^3/\text{s}}{\langle \sigma v \rangle_{\text{ann}}}
\]

\[
\Omega_{\chi} h^2 = \Omega_{\text{cdm}} h^2 \simeq 0.1143
\]

for \( \langle \sigma v \rangle_{\text{ann}} \simeq 3 \times 10^{-26} \text{cm}^3/\text{s} \)

This is why they are called **Weakly Interacting Massive Particles** (WIMPless candidates are WIMPs!)
Cosmic density of massive neutrinos

Fourth-generation Standard Model neutrino

![Diagram showing the relationship between the logarithm of the neutrino density and the logarithm of the neutrino mass, with regions labeled as 'dark matter', 'overabundant', and 'underabundant'.]
Cosmic density of massive neutrinos

Fourth-generation Standard Model neutrino
Connection to direct detection

Annihilation $\nu \bar{\nu} \rightarrow q \bar{q}$

Scattering $\nu q \rightarrow \nu q$

Crossing

For example, for a $\sim 4 \text{ GeV}/c^2$ dark matter neutrino, the scattering cross section is

$$\sigma_{\nu n} \approx 0.01 \frac{\langle \sigma v \rangle}{c} \approx 10^{-38} \text{ cm}^2$$
Cosmic density of massive neutrinos

Fourth-generation Standard Model neutrino

~ few GeV
preferred cosmological mass
Lee & Weinberg 1977
Cosmic density of massive neutrinos

Fourth-generation Standard Model neutrinos

Excluded as dark matter (1991)

~ few GeV
preferred cosmological mass
Lee & Weinberg 1977

Direct Searches

LEP bound $Z \rightarrow \nu\bar{\nu}$

Wednesday, February 22, 12
Supersymmetric neutralinos
Supersymmetric neutralinos

> 1.5 GeV photinos

\[ T^* = 1 \text{ GeV} \]

\[ T^* = 400 \text{ MeV} \]

Goldberg 1983

> 4 GeV neutralinos

\[ \text{Total rate (events/kg/day)} \]

\[ m_x \text{ (GeV)} \]

(a)

Griest 1988
The DAMA annual modulation

\[ S = S_0 + S_m \cos[\omega(t - t_0)] \]

Bernabei et al 1997-10

Drukier, Freese, Spergel 1986
WIMP interpretation of the DAMA modulation

\[ m > 25 \text{ GeV}/c^2 \]

Theoretical prejudice

Bernabei et al, TAUP 1997
WIMP interpretation of the DAMA modulation

The theoretical prejudice from supersymmetry..........

![Graphs showing spin-independent and spin-dependent cross sections](image)

- **Spin-independent cross section**
  - The shaded areas indicate regions of parameter space that are allowed by DAMA.
  - The cross sections are shown as functions of the neutralino mass $m$.
  - Regions above certain thresholds (e.g., $m > 45$ GeV/$c^2$) are allowed.

- **Spin-dependent cross section**
  - Similar graph showing cross sections for different values of $\tan \beta$.
  - Regions above certain thresholds (e.g., $m > 50$ GeV/$c^2$) are allowed.

*References*
- Baltz, Gondolo 2001
- Ellis, Ferstl, Olive, Santoso 2003
The theoretical prejudice from supersymmetry...........
............ continued into 2003

\[ m > 25 \text{ GeV}/c^2 \]

Belli, Cerulli, Fornengo, Scopel 2002

\[ m > 10 \text{ GeV}/c^2 \]

Benoit et al 2002; Akerib et al 2003
The theoretical prejudice from supersymmetry..........
............... continued into 2003
...............when 7-10 GeV neutralinos were resurrected

No limits were yet available below 10 GeV

Bottino, Donato, Fornengo, Scopel 2003
WIMP interpretation of the DAMA modulation

The theoretical prejudice from supersymmetry.........

............... continued into 2003

............... when 7-10 GeV neutralinos were resurrected

............... and light WIMPs examined in the light of DAMA

Gondolo, Gelmini 2004
“Los muertos que vos matáis gozan de buena salud.”


Light WIMPs in the Maxwellian halo model are possible!


CoGeNT hunts for light WIMPs

At first no signal

\[
\sigma_{\text{SI}} \text{(cm}^2\text{)} \quad 10^{-38} \rightarrow 10^{-41}
\]

\[
m_\chi \text{(GeV/c}^2\text{)} \quad 0 \rightarrow 10
\]

\[
\text{DAMA–96, DAMA ann. mod., DAMA–98, This work}
\]

\[\chi^2/dof = 31.9/25\]

\[\text{cosmogenic } ^{68,71}\text{Ge (1.298 keV)}\]

\[\text{counts/keV day} \quad 0 \rightarrow 200\]

\[\text{energy (keVee)} \quad 0 \rightarrow 4\]

Aalseth et al 2008
CoGeNT hunts for light WIMPs

At first no signal

then an “irreducible background” interpreted as light WIMPs

Light WIMPs become more interesting!

Aalseth et al 2010
CoGeNT hunts for light WIMPs

At first no signal

then an “irreducible background” interpreted as light WIMPs

then an annual modulation similar to DAMA’s

Light WIMPs become even more interesting!
CoGeNT hunts for light WIMPs

At first no signal
then an “irreducible background” interpreted as light WIMPs
then an annual modulation similar to DAMA’s
then extra surface events in the “irreducible background”

---

**CoGeNT** hunts for light WIMPs

**At first no signal**
then an “irreducible background” interpreted as light WIMPs
then an annual modulation similar to DAMA’s
then extra surface events in the “irreducible background”

---

**Collar at TAUP 2011**

---

**Kelso, Hooper, Buckley 2011**
CRESST sees an excess too

67 events observed cannot all be explained by background at 4σ

Adapted from Angloher et al 2011

Light WIMPs couldn’t be more interesting!
Many see light WIMPs in outer space

Diffuse γ-ray and microwave excess near the Galactic Center

Finkbeiner 2004
Hooper et al 2007
Hooper, Goodenough 2010
Hooper, Linden 2010-11
CoGeNT & DAMA vs. XENON, CDMS, et al

Akerib et al (CDMS) PRD82, 122004, 2010
CoGeNT & DAMA vs. XENON, CDMS, et al

![Graph showing WIMP-nucleon cross-section versus WIMP mass for various experiments.]

**Not compatible**

*Aprile et al (XENON-100) 1104.2549*
CoGeNT & DAMA vs. XENON, CDMS, et al

![Graph showing WIMP mass vs. scattering rate](image)

**Spin-independent $L_{\text{eff}}$ constant below 3.9 keVnr**

**Barely compatible**

**Savage, Gelmini, Gondolo, Freese 2010**
then convolved with its a second convolution with the quadrature difference be-

candidate event energies. The 10 (4) individual probability
construct a cumulative probability that describes how

within each energy interval defined by that detector's

D. S. AKERIB

The limit was calculated for 75 WIMP masses
channel when the hardware and software threshold effi-
hardware trigger and software phonon thresholds depend

masses. In hindsight, this turned out to be true for WIMP

WIMP sensitivity resides. Trading exposure for cleaner

particular care was taken to include the effect of nonzero
combined Ge and Si (Si only) optimum interval upper limit

Q

The resulting limit reflects only a fraction of the exposure,
distributions were serialized as described above, and a
-corrected keV for each detector was used to

-200 GeV

200 GeV

-200 GeV

-200 GeV

-200 GeV

-200 GeV

-200 GeV

-200 GeV

-200 GeV
CoGeNT & DAMA vs. XENON, CDMS, et al

\[ v_0 = 230 \text{ km/s} \]
\[ v_{\text{esc}} = 600 \text{ km/s} \]

\[ \sigma_{\text{DM-N}} \text{ (pb)} \]

\[ \sigma_{\chi p} \text{ (pb)} \]

\[ m_{\text{DM}} \text{ (GeV)} \]

DAMA (90%, 99% CL)

CoGeNT (90%, 99% CL)

Quite compatible

Hooper, Collar, Hall, McKinsey 2010
The comparison depends on the model!

- astrophysics model
  \textit{local density, velocity distribution}
- particle physics model
  mass, cross section (dependence on spin, velocity, energy, couplings)
- detector response model
  energy resolution, quenching factors, channeling fraction
Astrophysics model

**Analytic models**

![Velocity distribution graph](image)

**N-body simulations**

- **Read et al 2008**
- **Kuhlen et al**

**Warning:** NO BARYONS!!!

Very very uncertain.
Detector response model

Quenching factor \[ E_{ee} = Q \cdot E \]

This is where one can tweak to make experiments compatible.

Lin et al (TEXONO) 2007

Chagani et al 0806.1916

Aprile et al (XENON100), 1104.2549
Detector response model

**Channeling fraction**

- **Channeling**
- **Blocking**

Very small because of blocking

**Channeling**

- 40% at 2 keV

**Blocking**

- 0.4% at 2 keV

**Graphs**

- Bernabei et al. 2008
- Bozorgnia, Gelmini, Gondolo 2010

Wednesday, February 22, 12
Model-independent approach?
Astrophysics-independent approach

Fox, Liu, Weiner 2011

**Astrophysics factor**

\[
\frac{\rho \sigma_{xp} c^2}{m_\chi} \int_0^\infty \frac{f(v')}{v'} dv'
\]

Fox, Kopp, Lisanti, Weiner 2011

**Figure 14:** Astrophysics independent comparison of CoGeNT and DAMA modulation amplitudes. Such comparisons are only in the context of SI scattering proportional to \(Z v\).

**Figure 7:** A comparison of measurements and constraints of the astrophysical observable \(Q = 1\) by form factor as in (8). Thus, unlike CDMS-Si SUF, XENON10-S2, XENON100, CDMS Ge low, and SIMPLE for XENON10-MED, XENON10, CDMS Ge, CDMS Si SUP, CRESST-II, CoGeNT, DAMA, and CDMS-Ge, with a Poisson limit on the integral of (8) from the experimental threshold to \(t\).

Fox, Kopp, Lisanti, Weiner 2011

**Figure 7:** A comparison of measurements and constraints of the astrophysical observable \(Q = 1\) by form factor as in (8). Thus, unlike CDMS-Si SUF, XENON10-S2, XENON100, CDMS Ge low, and SIMPLE for XENON10-MED, XENON10, CDMS Ge, CDMS Si SUP, CRESST-II, CoGeNT, DAMA, and CDMS-Ge, with a Poisson limit on the integral of (8) from the experimental threshold to \(t\).

Frandsen et al 2011

**Figure 7:** A comparison of measurements and constraints of the astrophysical observable \(Q = 1\) by form factor as in (8). Thus, unlike CDMS-Si SUF, XENON10-S2, XENON100, CDMS Ge low, and SIMPLE for XENON10-MED, XENON10, CDMS Ge, CDMS Si SUP, CRESST-II, CoGeNT, DAMA, and CDMS-Ge, with a Poisson limit on the integral of (8) from the experimental threshold to \(t\).
What particle model for light WIMPs?
What particle model for light WIMPs?

- It should have the cosmic cold dark matter density
- It should be stable or very long-lived ($\gtrsim 10^{24}$ yr)
- It should account for the CoGeNT and DAMA modulations
- It should be compatible with collider, astrophysics, etc. bounds
- Ideally, it would justify apparent incompatibilities between direct detection experiments
- Ideally, it would explain some excessive emissions possibly observed in Galactic gamma-ray and radio maps
CLOSED
2008

29 W 125th St, New York, NY 10027

Endorsed by Oprah
# A few particle models for light WIMPs*

<table>
<thead>
<tr>
<th>Models</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSSM neutralino</td>
<td>Goldberg 1983; Griest 1988; Gelmini, Gondolo, Roulet 1989; Griest, Roszkowski 1991; Bottino et al 2002-11; Kuflik, Pierce, Zurek 2010; Feldman et al 2010; Cumberbatch et al 2011; Belli et al 2011; .....</td>
</tr>
<tr>
<td>SUSY beyond-MSSM neutralino</td>
<td>Flores, Olive, Thomas 1990; Gunion, Hooper, McElrath 2005; Belikov, Gunion, Hooper, Tait 2011; Belanger, Kraml, Lessa 1105.4878; .....</td>
</tr>
<tr>
<td>sneutrino</td>
<td>.....; An, Dev, Cai, Mohapatra 1110.1366; Cerdeno, Huh, Peiro, Seto 1108.0978; .....</td>
</tr>
<tr>
<td>minimalist dark matter</td>
<td>Silveira, Zee 1985; Veltman, Yndurain 1989; McDonald 1994; Burgess, Pospelov, ter Veldhuis 2000; Davoudiasl, Kitano, Li, Murayama 2004; Andreas et al 2008-10; He, Tandean 1109.1267; .....</td>
</tr>
<tr>
<td>technicolor and alike</td>
<td>.....; Lewis, Pica, Sannino 1109.3513; .....</td>
</tr>
<tr>
<td>kinetically-mixed U(1)’</td>
<td>.....; Foot 2003-10; Kaplan et al 1105.2073; An, Gao 1108.3943; Fornengo, Panci, Regis 1108.4661; Andreas, Goodsell, Ringwald 1109.2869; Andreas 1110.2636; Feldman, Perez, Nath 1109.2901; .....</td>
</tr>
<tr>
<td>(Higgs portal)</td>
<td></td>
</tr>
<tr>
<td>baryonic U(1)’</td>
<td>Gondolo, Ko, Omura ; Cline, Frey 1109.4639; .....</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* 1-10 GeV WIMP; very incomplete references.
Phenomenological approach
Break the annihilation/scattering relation

**Annihilation** \( \nu \bar{\nu} \rightarrow q \bar{q} \)

**Scattering** \( \nu q \rightarrow \nu q \)

For example, for a \( \sim 4 \text{ GeV}/c^2 \) dark matter neutrino, the scattering cross section is

\[
\sigma_{\nu n} \sim 0.01 \frac{\langle \sigma v \rangle}{c} \sim 10^{-38} \text{ cm}^2
\]
For example, for a ~4 GeV/c² dark matter neutrino, the scattering cross section is

$$\sigma_{\nu n} \approx 0.01 \frac{\langle \sigma v \rangle}{c} \approx 10^{-38} \text{ cm}^2$$
Break the annihilation/scattering relation

**Annihilation** $\nu \bar{\nu} \rightarrow q \bar{q}$

**Scattering** $\nu q \rightarrow \nu q$

**Crossing**

4-GeV neutrino

![Diagram with interactions and spectral analysis](image)

**CDMS shallow-site**

**DAMA**

**CoGeNT/DAMA**

Akerib et al (CDMS) 2010
Break the annihilation/scattering relation

Annihilation $\nu \bar{\nu} \rightarrow q \bar{q}$

Crossing

Scattering $\nu q \rightarrow \nu q$

Resonant when $m_\nu \approx m_Z/2$

$$\sigma_{\nu n} \approx \frac{0.02}{1 + m_n/m_\nu} \left( 1 - \frac{4m_\nu^2}{m_Z^2} \right)^2 \frac{\langle \sigma v \rangle}{c}$$

$\sigma_{\nu n}$ would perhaps match DAMA/CoGeNT if $m_Z$ were $\approx 2m_\nu$

Try a new particle $\chi$ and a new vector boson $Z'$
Break the annihilation/scattering relation

Example: Leptophobic $Z'$

- An extra $U(1)$ gauge boson $Z'$ coupled to quarks but no leptons, with no significant kinetic mixing
- Works for $m_{Z'} \sim 10$-20 GeV and $\alpha' \sim 10^{-5}$

Gondolo, Ko, Omura 2011
Modify the scattering cross section

The recoil spectrum (scattering rate per unit target mass)

\[
\frac{dR}{dE} = \frac{1}{m_A} \frac{\rho_X}{m_\chi} \int \frac{d\sigma}{dE} \nu f(\mathbf{v}) d^3\mathbf{v}
\]

Recoil energy

\[
= \frac{\rho_X}{2\mu^2 m_\chi} \int E_{\text{max}} \frac{d\sigma}{dE} \frac{f(\mathbf{v})}{\nu} d^3\mathbf{v}
\]

\[
E_{\text{max}} = \frac{2\mu^2 \nu^2}{m_A}
\]
Modify the scattering cross section

The recoil spectrum (scattering rate per unit target mass)

\[
\frac{dR}{dE} = \frac{1}{m_A m_\chi} \int \frac{d\sigma}{dE} v f(v) d^3v
\]

\[
= \frac{\rho_\chi}{2\mu^2 m_\chi} \int E_{\text{max}} \frac{d\sigma}{dE} \frac{f(v)}{v} d^3v
\]

Traditionally, \( E_{\text{max}} \frac{d\sigma}{dE} = \text{const} \times \) (nuclear form factor), with the same coupling to protons and neutrons (spin-independent case)

Put additional velocity or energy dependence in \( E_{\text{max}} \frac{d\sigma}{dE} \)

Set different couplings to neutrons and protons (“isospin-violating”)

\[
E_{\text{max}} = \frac{2\mu^2 v^2}{m_A}
\]
Modify the scattering cross section

Energy and/or velocity dependent scattering cross sections

<table>
<thead>
<tr>
<th>nucleus</th>
<th>DM</th>
<th>$E_{\text{max}} , d\sigma/dE$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>light mediator</td>
</tr>
<tr>
<td></td>
<td></td>
<td>heavy mediator</td>
</tr>
<tr>
<td>“charge”</td>
<td>“charge”</td>
<td>$1/E^2$</td>
</tr>
<tr>
<td>“charge”</td>
<td>dipole</td>
<td>$1/E$</td>
</tr>
<tr>
<td>dipole</td>
<td>dipole</td>
<td>const + $E/v^2$</td>
</tr>
</tbody>
</table>

All terms may be multiplied by nuclear or DM form factors $F(E)$

See e.g. Barger, Keung, Marfatia 2010; Fornengo, Panci, Regis 2011; An et al 2011
Modify the scattering cross section

Example:
a 1 GeV mediator can bring CoGeNT, DAMA, and CRESST together

---

Fornengo, Panci, Regis 2011
Isospin-violating dark matter

Spin-independent couplings to protons stronger than to neutrons allow modulation signals compatible with other null searches

Kurylov, Kamionkowski 2003; Giuliani 2005; Cotta et al 2009; Chang et al 2010; Kang et al 2010; Feng et al 2011; Del Nobile et al 2011; .....
Isospin-violating dark matter

Spin-independent couplings to protons stronger than to neutrons allow modulation signals compatible with other null searches

Kurylov, Kamionkowksi 2003; Giuliani 2005; Cotta et al 2009; Chang et al 2010; Kang et al 2010; Feng et al 2011; Del Nobile et al 2011; ....

coupling $N f_n + Z f_p \approx 0$ for $f_n/f_p \approx -Z/N$

Why $f_n/f_p = -0.7$ suppresses the coupling to Xe
Isospin-violating dark matter

Spin-independent couplings to protons stronger than to neutrons allow modulation signals compatible with other null searches

Kurylov, Kamionkowskii 2003; Giuliani 2005; Cotta et al 2009; Chang et al 2010; Kang et al 2010; Feng et al 2011; Del Nobile et al 2011; ..... 

Models with $f_n/f_p = -0.7$ are possible through e.g. interference of two Higgs boson mediators, but require a new physics scale of 1-20 GeV..........

Compositeness? Mirror baryons?

Del Nobile et al 2011
Light neutralinos
Light neutralinos

Bottino, Donato, Fornengo, Scopel 2003-2011  Non-GUT MSSM

~10 GeV neutralinos may account for DAMA, CoGeNT, and CRESST

Fornengo at TAUP 2011

Belli et al 1106.4667
Light neutralinos
Bottino, Donato, Fornengo, Scopel 2003-2011  Non-GUT MSSM

~10 GeV neutralinos may account for DAMA, CoGeNT, and CRESST

negative LHC Higgs searches impose \( m_\chi > 18 \) GeV

Fornengo at TAUP 2011

Bottino et al 1112.5666
Minimalist dark matter
Minimalist dark matter

do not confuse with minimal dark matter

Gauge singlet scalar field $S$, stabilized by $Z_2$ symmetry

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

Silveira, Zee 1985

Minimalist dark matter

Andreas et al 2010

CoGeNT

DAMA (no chann.)

DAMA (chann.)

CDMS-Si

CDMS

XENON10

XENON100

CRESST

Higgs mass

$\sigma_{el}$ (cm$^2$)

$\sigma_n$ (cm$^2$)

$m_S$ (GeV)

$m_D$ (GeV)

115 GeV

150 GeV

200 GeV

450 GeV

He, Tandeon 2011

Wednesday, February 22, 12
Minimalist dark matter

*do not confuse with minimal dark matter*

Constraints from the LHC: none

A Higgs mass of 125 GeV works!

For DM, let Higgs mass > 115 GeV

For Higgs mass < 150 GeV, Higgs is 99.2% invisible

He, Tandeau 2011
Minimalist dark matter

Constraints from diffuse Galactic gamma-rays

Very sensitive to unknown properties of small dark subhalos
# A few models of light dark matter*

<table>
<thead>
<tr>
<th>Models</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSSM neutralino</td>
<td>..........; Griest 1988; Gelmini, Gondolo, Roulet 1989; Griest, Roszkowski 1991; Bottino et al 2002-11; Kuflik, Pierce, Zurek 2010; Feldman, Liu, Nath 2010; Cumberbatch et al 2011; Belli et al 2011; ..........</td>
</tr>
<tr>
<td>SUSY beyond-MSSM neutralino</td>
<td>Flores, Olive, Thomas 1990; Gunion, Hooper, McElrath 2005; Belikov, Gunion, Hooper, Tait 2011; Belanger, Kraml, Lessa 1105.4878; ..........</td>
</tr>
<tr>
<td>sneutrino</td>
<td>..........; An, Dev, Cai, Mohapatra 1110.1366; Cerdeno, Huh, Peiro, Seto 1108.0978; ..........</td>
</tr>
<tr>
<td>minimalist dark matter (SM + real singlet scalar)</td>
<td>Veltman, Ydnurain 1989; Silveira, Zee 1985; McDonald 1994; Burgess, Pospelov, ter Veldhuis 2000; Davoudiasl, Kitano, Li, Murayama 2004; Andreas et al 2008-10; He, Tandean 1109.1267; ..........</td>
</tr>
<tr>
<td>technicolor and alike</td>
<td>..........; Lewis, Pica, Sannino 1109.3513; ..........</td>
</tr>
<tr>
<td>kinetically-mixed U(1)'</td>
<td>..........; Foot 2003-10; Kaplan et al 1105.2073; An, Gao 1108.3943; Fornengo, Panci, Regis 1108.4661; Andreas, Goodsell, Ringwald 1109.2869; Andreas 1110.2636; Feldman, Perez, Nath 1109.2901; ..........</td>
</tr>
<tr>
<td>baryonic U(1)'</td>
<td>Gondolo, Ko, Omura; Cline, Frey 1109.4639; ..........</td>
</tr>
<tr>
<td>dynamical DM</td>
<td>Dienes, Thomas 1106.4546, 1107.0721</td>
</tr>
</tbody>
</table>

* 1-10 GeV WIMP; very incomplete references.
So many theoretical models!

My suggestion: pay theorists more, so they do not need to work so much.