LIGHT DARK MATTER

A NEW INTERACTION?

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Workshop "Dark Side of the Universe"
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What is DARK MATTER?

(Assuming it exists!)

- Assuming it is made of **PARTICLES**

  presumably (even necessarily)

  having some **INTERACTIONS**

→ **NON-BARYONIC DARK MATTER**

( $\Omega_{dm} \simeq .23$ )
DARK MATTER PARTICLES

- Normally: **WIMPS**
  - Weakly Interacting Massive Particles
  
  Best candidate:
  
  Spin $\frac{1}{2}$ **NEUTRALINO**

  of SUSY extensions of Standard Model

  Stable from **R. PARITY** conservation

  with
  
  $$R_p = (-1) \quad (-1)$$

  $$\Rightarrow \text{L.S.P. Stable}$$

  { Ordinary particles: $\oplus$ SUSY
    Superpartners: $\ominus$ SUSY }
BUT....

NEUTRALINOS have not been seen (yet)

LEP + ... results ⇒

\[ m_{\text{Neutralino}} > \sim 30 \text{ GeV} \]

presumably also \( \leq \) few hundred GeV in most cases

if it is to be a good Dark Matter candidate

• Compute relic abundance

\[ \Omega_{\text{dm}} h^2 \sim \frac{1}{\Gamma_{\text{annihilation}}} \]

\( \sim \) \( \rightarrow \) \( \Sigma_{\text{am}} V \approx 3 \times 10^{-26} \text{ cm}^3/\text{s} \)

i.e. \( \approx \) WEAK INTERACTION
Discuss possible new candidates for dark matter.

There is still room for unconventional possibilities.
HOW COULD LIGHT DARK MATTER PARTICLES exist?

should be:

- NEUTRAL
- STABLE

new quantum number

- No direct coupling to the Z
  (otherwise, would have been "seen" in Z decays at LEP)

- Annihilation cross-sections
  \[ \text{dm} + \text{dm} \rightarrow f \bar{f} \]

should lead to

CORRECT RELIC DENSITY

knowing that

\[ \frac{\Omega_{\text{dm}} h^2}{\nu} = \frac{1}{\sigma_{\text{ann}} v_{\text{rel}}} \]

\[ \sim 1 \]
Evaluate required **ANNIHILATION CROSS-SECT.** for **LIGHT D.M.**

\[
\begin{align*}
\Gamma \chi \chi & \rightarrow H \\
\downarrow \\
\n_{\text{at freeze out}} \\
(T_F = \frac{m}{x_F})
\end{align*}
\]

\[
\sigma_{\text{ann}} V_{\text{rel}} \approx \sqrt{g_*} \frac{T_F^2}{m_{\text{pl}}}
\]

Now:

\[
N_{\text{dm}} = (2) n_{\text{dm}} = (2) \left[ \frac{4}{11} \right] \left( \frac{T_{\text{re}}}{T_F} \right)^3 \sqrt{g_*} n_{\text{dm}}
\]

\[\text{if } m_{\text{dm}} \neq m_{\text{dm}}^* \]

\[\text{if } m_{e} < T_F < m_{\text{pl}} \]

\[\Rightarrow \rho_{\text{dm}} = (2) n_{\text{dm}} m_{\text{dm}}\]

\[\Rightarrow \Omega_{\text{dm}} h^2 \sim (2) \left[ \frac{4}{11} \right] \ldots \sqrt{g_*} \frac{T_F}{\langle \sigma_{\text{ann}} V_{\text{rel}} \rangle} \]

\[\Omega_{\text{dm}} h^2 \sim 0.11 \]

\[\langle \sigma_{\text{ann}} V_{\text{rel}} \rangle \sim 2 \text{ to } 10 \text{ pb} \]

\[\text{depending on}\]

\[\begin{align*}
\text{if } m_{\text{dm}} = m_{\text{dm}}^* & \Rightarrow \sigma \neq \sigma^* \\
\text{if } m_{\text{dm}} \neq m_{\text{dm}}^* & \Rightarrow T_F < \sim m_{e} \text{ or } T_F > \sim m_{e} \text{ } \frac{m_{\text{pl}}}{x_F} \text{ } g^*
\end{align*}\]

\[\Rightarrow \text{energy dep. of } \sigma \text{ at threshold.}\]
Recall:

"Lee-Weinberg" limit

on a heavy neutrino mass:

A weakly-interacting heavy neutrino
should be heavier than $\approx 2 \text{ GeV}$

$$m_L \gtrsim 2 \text{ GeV}$$

to have

$$\Omega_{dm} \ h^2 \lesssim 1$$

given that

$$\Omega_{dm} \ h^2 \propto \frac{1}{<\sigma_{ann} \nu>}$$

with a weak-interaction annihilation cross section

$$\sigma_{ann} \nu \approx \frac{G_F^2}{(2\pi)} \ m_L^2 \ldots$$
More precisely:

- $\rho_{dm} = (2) n_{\sigma dm} m_{dm}$

$\Rightarrow$ Factor 2 present

if Dark Matter particles differ from antiparticles

- $n_{\sigma dm} = \left[ \frac{4}{11} \right] \frac{T_{\sigma \gamma}^3}{T_F^3} n_{dm}$

$\Rightarrow \left[ \frac{4}{11} \right]$ dilution factor present IF $m_e \lesssim T_F \lesssim m_\mu$

This dilution factor is ABSENT, however, for

Lighter Dark Matter particles

$(\lesssim$ a few MeV)

decoupling (at $T_F = m/x_F$)

after most electrons have annihilated.

- $n_{\sigma dm} \left[ \frac{11}{4} \right] \frac{T_F^3}{T_{\sigma \gamma}^3} < \sigma_{ann} v_{rel} > \simeq 1.66 \sqrt{g_*} \frac{T_F^2}{m_{pl}}$

with $g_*$ depends on $T_F$ and therefore on $m_{dm}$

- Further factor $\approx 2$ of enhancement

of required annihilation cross section

for $P$-wave annihilation, for which

$\sigma_{ann} v_{rel} \propto v^2$

(case of interest to us here)
Altogether – in the case of

$$\sigma_{\text{ann}} v_{\text{rel}} \propto v^2$$

($P$-wave annihilation cross section)

we get:

- for self-conjugate spin-1/2 **Majorana particles**:
  $$< \sigma_{\text{ann}} v_{\text{rel}} / c > \simeq 4 - 5 \text{ pb}$$

- for non-self-conjugate **spin-0 scalars**:
  $$< \sigma_{\text{ann}} v_{\text{rel}} / c > \simeq 8 - 10 \text{ pb}$$

[self-conjugate scalars cannot have a $P$-wave pair annihilation cross section!]

Remember that:

$$1 \text{ pb} = 10^{-36} \text{ cm}^2$$

$$1 \text{ pb} \times c \simeq 3 \times 10^{-26} \text{ cm}^3 / \text{s}$$

These are in fact

"relatively large" annihilation cross section!

... yes, but as compared to what??
LARGE ANNIHILATION CROSS SECTIONS REQUIRED!

Usually:

Interaction \sim G \bar{x}\ldots \bar{x} f \ldots f

\sigma V \sim \frac{G^2}{2\pi} m_x^2

Weak interactions: \quad G = G_F = 10^{-5} \text{ GeV}^{-2}

\frac{G_F^2}{2\pi} \left(1 \text{ GeV}\right)^2 \sim 10^{-38} \text{ cm}^2 = \frac{1}{100} \text{ pb}

WEAK INTERACTION CROSS SECTIONS

by far TOO SMALL

for correct relic abundance
Too much dark matter!!

How can we have a sufficient annihilation rate for light dark matter particles?

Questions:

New annihilation mechanisms needed

Discuss new situations, in particular scalar dark matter

New particles + possibly new interactions required

[Spin \(-\frac{1}{2}\) D.M. also possible]

... as in all extensions of the standard model

(supersymmetric theories, axions, GUTs, extra dimensions, strings .... !)
SCALAR DARK MATTER

[ Spin $\frac{1}{2}$ Light DM
also possible:

2 possibilities:

I

Exchange of MIRROR FERMIONS

\[ \sigma V \sim \frac{c^2 f^2}{(4E^2 - m^2)^2} \quad \text{can be large} \]

II

Virtual production of LIGHT NEUTRAL NEW GAUGE BOSON

\[ \sigma V \sim \frac{c^2 f^2 E^2}{(4E^2 - m^2)^2} \quad \text{can be large} \]
But: if large $\sigma$'s

Why have such new particles and processes not shown up in

- particle physics accelerators
- astrophysical processes

? 

In particular, large annihilation cross sections

$\text{dm} \cdot \text{dm} \rightarrow \bar{f}f$

dangerous, since could lead to

Excessive Gamma ray production
dangerous:

Seems to be **EXCLUDED** for

\[ m_{\text{dm}} \leq 100 \text{ MeV} \]

C. BOEHM. T. ENSSLIN J. SILK

(depending on how \( \gamma \)-ray production is evaluated)

UNLESS ....

CROSS-SECTIONS ARE

ENERGY DEPENDENT

\[ \sigma_{\text{ann}} V_{\text{rel}} \sim v^2 \]

(P-wave annihilation)

(at least at freeze-out)

Then

\( (\sigma v) \)

residual annihilations

\[ \sim 10^{-5} (\sigma v) \]

primordial annihilations at freeze-out

SMALL ENOUGH!
NEED

\[ \langle \Gamma_{\text{ann}} V_{\text{rel}} \rangle \propto v^2 \]

This is not the case for

annihilation through

\[ \text{MIRROR EXCHANGES} \]

(\text{S-wave annihilation})

\[ \text{could still contribute to halo annihilations} \]

This is the case for annihilations through

\[ \text{SPIN-1 U-BOSON} \]

\[ \text{virtual production} \]

(\text{P-wave annihilation})

New Gauge Interaction


\[ SU(3) \times SU(2) \times U(1) \times \text{Extra } U(1) \]

\[ \downarrow \]

Gluons, \( W^\pm, Z, \gamma \), \( U \)
A GAMMA RAY SIGNATURE

from the GALACTIC CENTER

at low energy

could be due to a

LIGHT NEW GAUGE BOSON

C. Boehm - P.F

(May 2003)

→ Nucl. Phys. B, 2004
INTEGRAL Observes

BRIGHT 511 KeV $\gamma$ RAY LINE

FROM GALACTIC CENTER

Signals decays of

POSITRONIUM $\rightarrow \gamma\gamma$

Where are the $e^+$ coming from?

- Apparently not so easy to get them from astrophysical processes.
- Could be a sign of light dark matter annihilations into $e^+e^-$

(C. BOEHM, M. CASSE PRL 2004
D. HOOPER, J. SILK, J. PAUL)
WHY has such a NEW PARTICLE and corresponding NEW INTERACTION not been observed?

especially if NEW INTERACTIONS are STRONGER than WEAK INT.

as necessary to provide for SUFFICIENT ANNIHILATIONS of LIGHT DARK MATTER particles

?
yes, U-Interactions are stronger than weak interactions but only at lower energies

when weak interactions are really weak \( \sim G_F^2 E^2 \)

but they are weaker than weak at higher energies when weak interactions are "strong" as they are damped by U-propagator effects
\[ \sigma_{\text{ann. red}} \sim V^2 \left( \frac{E^2}{(m_u^2 - 4E^2)^2} \right) \]

\[ \sim \text{a few pb} \]

P wave annihilation

very small:

typically \( c_\delta \sim 10^{-6} \)

\( U \)-interactions significantly STRONGER than WEAK

but only at lower energies
POSSIBLE EFFECTS ON:

- NEUTRINO scattering CROSS SECTIONS
- DIRECT PRODUCTION of U-BOSONS
- Anomalous MAGNETIC MOMENTS of e⁻, µ⁻
- PARITY VIOLATION in Atomic physics
- NUCLEOSYNTHESIS etc.
**Neutrino Scattering**

\[ A \sim \frac{f_{\nu} f_{\ell}}{m_u^2 - q^2} = \frac{f_{\nu} f_{\ell}}{m_u^2} \cdot \frac{m_u^2}{m_u^2 - q^2} \]

\[ \ll 1 \]

\[ \text{if } m_u < \sqrt{1941} \]

- No constraints at high-energy
- Constraint from $\nu + e$ at low $q^2$

\[ \frac{f_{\nu} f_{e}}{m_u^2} \leq G_F \]
Direct production of $U$-boson

- Couplings to matter $f \ll e$
  (by several orders of magnitude)

- Production cross-sections:
  \[ \sigma_{\text{prod.}} \propto f^2 \]

Very small?
Naïvely tend to vanish if $f \to 0$

But:

THIS IS WRONG!!
For a U with longitudinal polarization:

\[ \varepsilon_\ell \sim \frac{q \, k^\mu}{m_U} \rightarrow \text{small} \]

Amplitudes:

\[ A \sim f \frac{q \, k^\mu}{m_U = g' F} \sim \frac{k^\mu}{F} \]

\( \sim \text{small extra U(1)} \)

\( \text{gauge coupling} \)

\( \text{independent of coupling } g' \)

\( F = \text{extra U(1) boson scale} \)

If the U-current has an (non-conserved) **axial part**

the U-boson would behave much like a **spin-0 axion**

\( \downarrow \)

unobserved!
AMPLITUDE

\[ g'' \sim \frac{k^\mu}{m_u} \]

for longitudinally polarized $U$ boson

very small \rightarrow very large \rightarrow \text{finite}

\[ g'' = \frac{1}{m_u} \]

extra $U(1)$ breaking scale

(\sim \text{electroweak scale})

"EQUIVALENCE THEOREM"

A VERY LIGHT SPIN-1 $U$-BOSON IS PRODUCED AND INTERACTS AS AN AXIONLIKE SPIN-0 PARTICLE

(P.F. 1980)
BUT PARTICLE PHYSICS EXPERIMENTS

\[
\begin{align*}
\psi & \rightarrow \gamma + \text{axion} < 1.4 \times 10^{-5} \\
\gamma & \rightarrow \gamma + \text{axion} < 1.5 \times 10^{-5}
\end{align*}
\]

EXCLUDED THE STANDARD AXION!

WHAT ABOUT A SPIN-1 U-BOSON?

Is it excluded?

Not necessarily, as for the axion.

(USE LARGE SCALE SYMMETRY BREAKING)

THE AXION CAN BE MADE "INVISIBLE"

THE U-BOSON ALSO CAN BE MADE "INVISIBLE"

(USING LARGE HIGGS SINGLET V.E.V.)

P.F. 1980

(you could make this longitudinal part almost "invisible", but you still want the U to interact significantly with ordinary matter)

Consider U-couplings to MATTER that are almost purely VECTORIAL

(OR: INVISIBLE U-BOSON MECHANISM
LARGE SYMMETRY BR. SCALE \( F \)
for EXTRA \( U(1) \)

Through Large Higgs singlet v.e.v.)

\[
\begin{align*}
\Psi, \gamma & \rightarrow \Psi U: \quad \frac{g a_{\Psi}^2}{m_\Psi^2} < G_F 110 \\
K^+ & \rightarrow \pi^+ U: \quad \frac{g a_{K}^2}{m_{K}^2} < G_F 1300
\end{align*}
\]

\( 04.08.357 \)
OTHER CONSTRAINTS

- $g - 2$
  - $m_e < m_u < m_\mu$
  - $\delta \pi_e \leq 2 \times 10^{-4}$ $m_u$ (MeV)
  - $\delta \pi_\mu \leq 6 \times 10^{-4}$

- Neutrino scatterings at lower energies

- Nucleosynthesis
  - Like 1 extra $\nu$ flavor??
  - but: ... !

- Searches in $e^+e^-$
Funny effects in Nucleosynthesis etc:

Light Dark Matter particles annihilating after Neutrino decoupling would ultimately heat up photons relatively to Neutrinos.

\[ T_\nu \leq T_{\text{standard}}^8 \left( \frac{4}{11} \right)^{1/3} \]

Neutrinos contribute less to \( g^* \)!!

\[ g^*_\nu \leq g^*_{\text{standard}} \]

- Influence on Dark Matter residual abundance.
- Allows for less primordial helium than in Standard Model!

- Serpico, Raffelt - astro-ph.0403417

BBN constraints \( \Rightarrow \)

\[ m_{dm} \geq 2 \text{ MeV} \]
PARITY VIOLATION

in ATOMIC PHYSICS

\[ Q_W = \begin{cases} 
-72.74 \pm (29) \pm (36) & \text{exp.} \\
-73.19 \pm 0.13 & \text{SM} 
\end{cases} \]

\[ \Delta Q_W = 0.45 \pm 0.48 \]

\[-10^{-3} G_F < \frac{-e + e}{2} \ll 3 \times 10^{-3} G_F\]

C. Bouchiat, P.F. (\(m \mu \gg \text{few MeV's}\))

(m\(\mu\) no axion like particle)

\(\Rightarrow\) favors VECTOR COUPLING of U boson
FIG. 1: Diffuse background spectrum as a function of photon energy. The crosses (HEAO), stars (COMPTEL) and diamonds (EGRET) correspond to the observations [1, 2]. At low energy, Seyfert galaxies (dashed line) are the main contributors [1]. At intermediate energy, SNIa (continuous line), as calculated in this article, dominates. At high energy blazars (dot-dashed line) explain the observed cosmological gamma-ray background [4]. Altogether the sum of the three contributions (dotted line) reproduces it rather well. However, an additional contribution from light Dark Matter particles, of up to about 4 keV cm$^{-2}$ s$^{-1}$ sr$^{-1}$, is not excluded near 511 keV (indicated by an arrow).
FIG. 4: Diffuse background spectrum. Crosses: HEAO data; stars: COMPTEL observations. The three dotted lines correspond to the contributions from Seyferts, SNIa and blazars. The dot-dot-dot-dashed line represents the new positron contribution to the cosmological gamma-ray background, for a $S$-wave cross-section. This contribution for a $P$-wave cross-section is also given for a NFW (dashed line) or Moore profile (long dashed line). (The background as computed in [13], significantly higher, is also shown for comparison, as a dot-dashed line.)
Constraints on LDM in the $a - m_X$ plane, with $a$ the velocity-independent part in $\sigma_{\text{ann}} v_{\text{rel}}$. $b$ is fixed by the relic density, so that $(\sigma v_{\text{rel}})_F \approx < a + b v^2 >_F \approx 10^{-25} \text{ cm}^3 \text{ s}^{-1}$ at freeze-out. The upper line $a \approx 10^{-25} \text{ cm}^3 \text{ s}^{-1}$ corresponds to a purely $S$-wave cross-section, and the lower part of the diagram to a $P$-wave dominated one. We limit ourselves to the mass interval $\frac{1}{2}$ to 100 MeV.

The grey region is the one compatible with the galactic constraint, based on the total level of emission, using the (Moore or NFW) dark-matter distributions of Table I (its upper part corresponds to a Milky-Way emission $S$-wave-dominated, with a behaving like $1/m_X^2$).

The dot-dashed line is associated with a LDM-induced background (for a NFW profile) that would correspond to the missing 4 keV cm$^{-2}$ s$^{-1}$ sr$^{-1}$, the top left-hand corner above this line being excluded on the basis of the cosmic background data. (Same for the dashed line with Moore profiles.)
Constraints on Light Dark Matter
from SUPERNOVAE

with D. Hooper and G. Sigl

LDM particles can play a role in core-collapse supernovae if relatively large annihilation and scattering cross-sections (compared to neutrinos)

- Neutrinos stay in equilibrium (through weak interactions) down to \( \approx 8 \text{ MeV} \) in supernovae explosion \( (\nu_\mu, \nu_\tau) \)

- LDM particles annihilate staying in equilibrium until they decouple (occurs at \( T_f \approx \frac{m_X}{17} \), during expansion of Universe)

- LDM particles can influence behavior of neutrinos in supernova by having relatively "large" interactions with them
LDM decoupling temperature
(as a function of LDM-nucleon cross-sections):

\[ T_{\text{dec (massive } \nu)} \]

\[ T_{\text{dec (LDM)}} \]
(dependending on \( \sigma_{\text{int}} \))

\[ \implies \text{Neutrinos may be kept longer in equilibrium} \]

due to stronger-than-weak interactions with LDM particles
$\nu$ decoupling temperature in supernova
case possibly lower than in Standard Model
if DM particles
1) are sufficiently light
2) interact sufficiently with neutrinos

Crucial ingredient: magnitude of
neutrino/LDM scattering cross-section

Lighter LDM masses $\lesssim 10$ MeV
are practically excluded

UNLESS neutrino-LDM interactions
remain relatively small
compared to electron-LDM interactions

"small" neutrino-LDM cross-sections possible if:
• spin-0 LDM coupled through heavy fermions exchanges
due neutrino chirality
and/or
• small (or 0) coupling of $U$ boson to neutrinos
CONCLUSIONS

LIGHT DARK MATTER -

Viable possibility, to be confronted to

Standard WIMP (neutrino) scenarios

$\text{Spin 0} \quad \frac{1}{2}$

- LARGE $\sigma_{\text{ann}} \propto v^2$

- New Interactions responsible for

  Dark Matter annihilations

- Annihilations due to a

  New light SPIN-1 boson $\chi$

  have the required characteristics: $\sigma_{\text{ann}} v^2$

  $\left\{\begin{array}{ll}
  \text{Stronger than weak at low energy} \\
  \text{Weak than weak at high energy}
  \end{array}\right.$

- 511 KeV line a possible signature

- Consequences in Particle Physics/Astrophysics to be further explored.