Indirect dark matter search at Super-Kamiokande

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A. Takeda (ICRR, Univ. of Tokyo) for the Super-K collaboration
Experimental searches for dark matter particles

Weakly interacting massive particles (WIMPs) are leading candidates for non-baryonic cold dark matter.

WIMP searches are categorized in main three methods:
- **Hadron collider**: using mono-jet and mono-photon signatures.
- **Direct**: scattering interactions of WIMPs with nuclei in the detector.
- **Indirect**: detection of the final products from WIMP annihilation. Possible target objects are Galactic Center, Milky Way halo, dwarf galaxies, and the Sun and the Earth.
Super-Kamiokande detector

- The world largest pure water Cherenkov detector located in Kamioka mine (36° 25’ N, 137° 18’ E).
- 50 kton pure water (22.5 kton fiducial, 2m from the walls of the inner detector)
- 1,000 m (2,700 m w.e.) underground
- 11,129 20-inch PMTs in inner detector (ID)
- 1,885 8-inch PMTs in outer detector (OD)

Many physics targets:
- Neutrino oscillation: atmospheric ν, solar ν, T2K beam
- Nucleon decay
- Astrophysics: **WIMP search**, Supernova Relic Neutrino, Supernova burst, monopole search, etc.
Indirect WIMP search by Super-Kamiokande

- The Sun: WIMP particles are scattered elastically and trapped in the deep solar core. Neutrinos produced by pair annihilation may be detected in terrestrial detector.
- Galaxy: diffuse signal from entire Galaxy, peaked from Galactic center.

(*) The picture of Galaxy was taken from http://www2.nhk.or.jp/zero
Solar WIMP search

- Huge gravity allows enough captures to achieve equilibrium between capture and annihilation.
- The capture process of WIMPs inside the Sun is same with direct detection.

Typical neutrino energies are $\sim 1/3 - 1/2$ of the WIMP mass or lower.

Super-K’s sensitivity to few-GeV neutrinos makes it suitable for $\sim 10$ GeV WIMP search and results are compared with direct detection on WIMP-nucleon elastic scattering cross section.

Expected sensitivity of Super-K

WIMP capture rate inside the Sun

- **Spin-dependent (SD):** main contribution comes from hydrogen. Owing to hydrogen-rich composition (~74% of total mass) of the Sun, high capture rate is expected.
- **Spin-independent (SI):** Owing to coherent enhancement $\propto A^2$ and mass-matching factor, even small composition of heavy elements have large contribution to capture rate. (depends on solar composition model, then evaluation of uncertainty is important. It was considered in this analysis.)

The sensitivity for SI as well as SD for light WIMPs is expected to be competitive with direct detection.

Capture rate inside the Sun

Capture rate for SI coupling


Data analysis

- **Real data:**
  Accumulated during the SK I–IV run periods.
  - SK-I (1996–2001),
  - SK-II (2002–2005, with half PMT coverage)

- **MC simulation**
  Generated for primary atmospheric neutrino flux was divided into below 2 samples
  1. Atmospheric neutrino background:
     250-year MC sample per SK run period was normalized to the live time of each SK run period and oscillated ($\sin^2 \theta_{13} = 0.025$, $\sin^2 \theta_{12} = 0.304$, $\sin^2 \theta_{23} = 0.425$, $\Delta m^2_{21} = 7.66 \times 10^{-5} \text{eV}^2$, $\Delta m^2_{32} = 2.66 \times 10^{-3} \text{eV}^2$)

  2. WIMP neutrino signals:
     Other 250-year MC sample per SK run period was reweighted by the ratio of WIMP neutrino flux to original atmospheric neutrino flux.
     **WIMPSIM 3.01** was used to simulate the neutrino flux from WIMP annihilation in the Sun at Super-K. ($\chi \chi \rightarrow \tau^+ \tau^- / b\bar{b} / W^+ W^- \text{ channels from 4 to 200 GeV/c}^2$)

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**Live time [days]**

<table>
<thead>
<tr>
<th>period</th>
<th>FC + PC</th>
<th>Upmu</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK-I</td>
<td>1489</td>
<td>1646</td>
</tr>
<tr>
<td>SK-II</td>
<td>799</td>
<td>828</td>
</tr>
<tr>
<td>SK-III</td>
<td>518</td>
<td>636</td>
</tr>
<tr>
<td>SK-IV</td>
<td>1096.7</td>
<td>1096.7</td>
</tr>
<tr>
<td>Total</td>
<td>3902.7</td>
<td>4206.7</td>
</tr>
</tbody>
</table>
WIMP induced neutrino events at Super-K

- Example of reconstructed angle to the Sun \((\cos\theta_{\text{sun}})\) and momentum distribution

SK data (I–IV)
BG MC (normalized by live time)
Signal MC (6 GeV/c^2 bb)
Signal MC (200 GeV/c^2 \(\tau^+\tau^-\))

(*) WIMP MC for \(bb\) and \(\tau\tau\) at 90% upper limit are magnified 30 times for visibility

-> Excess neutrinos in the direction from the Sun were searched.
WIMP contribution by pulled $\chi^2$ method

Data was fitted with “atmospheric neutrino + WIMP induced neutrino” to find best fit value of WIMP contribution

$$
\chi^2 = \min_{\{\epsilon_j\}} \left[ 2 \sum_{i=1}^{N} \left\{ N_{i,\text{exp}} - N_{i,\text{data}} + N_{i,\text{data}} \ln\left( N_{i,\text{data}} / N_{i,\text{exp}} \right) \right\} + \sum_{j=1}^{J} \left( \frac{\epsilon_j}{\sigma_j} \right)^2 \right]
$$

$$
N_{i,\text{exp}} = N_{i,\text{BG}} \left( 1 + \sum_{j=1}^{J} f_j^i \epsilon_j \right) + \beta N_{i,\chi} \left( 1 + \sum_{j=1}^{J} g_j^i \epsilon_j \right)
$$

- $\sigma_j$ 1σ value of j-th systematic uncertainty
- $\epsilon_j$ $\sigma_j$'s pull
- $f_j^i / \sigma_j$ ($g_j^i / \sigma_j$) $\sigma_j$'s predicted fractional change of the # of BG (signal) events in the j-th bin due to 1σ change.

- The data and MC calculations are distributed into 480 bins based on reconstructed momentum and $\cos \theta_{\text{sun}}$.
- It makes full use of the energy, angle, and flavor information.
Conversion from flux limit to WIMP-nucleon scattering cross section limit

Simulation package **DarkSUSY 5.0.6** was used for conversion

- Capture/annihilation of WIMPs in the Sun
- Propagation inside the Sun, vacuum, and inside the Earth considering oscillation and interaction

Assumptions

- WIMPs have only a single type of interaction with nucleus (SI or SD)
- For SI interaction, 2 cases are considered:
  1. isospin-invariant (coupling to neutrons ($f_n$) = coupling to protons ($f_p$))
  2. isospin-violating dark matter (IVDM) with destructive interference ($f_n/f_p = -0.7$)
- Standard DM halo ($\rho=0.3$ GeV/cm$^3$, $v_{\text{rms}}=270$ km/s, $v_{\text{sun}}=220$ km/s)
- Solar composition is based on BS2005-OP model.
- Pair annihilation to fermion or boson with mono channel (bb, $\tau^+\tau^-$, $W^+W^-$)
- Equilibrium between capture and annihilation
90% C.L. upper limits on the SD WIMP-proton cross section

Solid red line: 90% C.L. upper limit calculated at default DarkSUSY. The shadowed red bands show consideration of uncertainties in the capture rate.

Below 100 GeV/c^2, we set the current best limits on the SD cross section.

90% C.L. upper limits on the SI WIMP-nucleon cross section (1/2)

In the case of Isospin conservation \((f_p/f_n = 1)\)

Solid red line: 90% C.L. upper limit calculated at default DarkSUSY. The shadowed red bands show consideration of uncertainties in the capture rate.

We ruled out some fraction of WIMP allowed regions.

\[ K.\, Choi, \, et. \, al., \, Phys. \, Rev. \, Lett. \, 114, \, 141301 \, (2015) \]
Isospin conservation ($f_p/f_n = 1$) is not guaranteed in more general scenarios. Isospin violating dark matter (IVDM) arises from recent CDMS-II Si result which can be reconciled with other conflicting null results.

The entire CDMS-II Si 90% C.L. signal region (blue in left figure) was ruled out with 100% annihilation to $\tau^+\tau^-$. 

Expected sensitivity by next generation detector

- Total mass: 0.99 Mton
- Fiducial mass: 0.56 Mton
  x 25 of Super-K

Sensitivity x 3–5 of Super-K is expected (10 years, 5.6 Mton·year).

WIMP-proton SD cross section

WIMP-nucleon SI cross section

Hyper-Kamiokande

Hyper-Kamiokande

Hyper-Kamiokande

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Hyper-Kamiokande
Galactic WIMP search

- WIMP contribution was derived with $\chi^2$ method same as solar WIMP search.
- Data sample is 4223 days of SK data (1996–2014)
- NFW halo model is assumed.

- Fit results are consistent with zero.
- 90% CL upper limit on WIMP self annihilation cross section <$\sigma_A V$>

100 GeV WIMPs $b\bar{b}$ channel

- DATA SK1–4
- MC ATM+WIMP
- - WIMP signal shape before fit
90% CL upper limit on $<\sigma_A V>$

- **Solid line**: global fit.
- **Dotted line**: ON- and OFF-source search by using data only. Related systematic error as they should equally affect ON- and OFF-source are cancel out.
- Assuming NFW halo model.
- A new statistical approach is now being prepared.
Conclusion

- Indirect WIMP searches by Super-Kamiokande were conducted.
- Solar WIMP search
  - No significant excess for 4–200 GeV WIMP hypotheses gives upper limits on the WIMP-nucleon elastic scattering cross sections.
    - **SD interaction**: most stringent constraint was derived (< 100 GeV) even for the softest (bb) annihilation channel.
    - **SI interaction**: assuming 100% $\tau^+\tau^-$ channel, we excluded the entire DAMA/CoGeNT-claimed signal region and most parts of CDMS-II Si signal region.
  - Uncertainties in capture process were studied in detail and considered.
- Galactic WIMP search
  - No significant excess from 1 GeV–10 TeV WIMP gives 90% CL upper limit on WIMP self-annihilation cross $<\sigma_A\,\sigma_V>$.
  - ON- and OFF-source analysis also gives same level of limits.
Backup
EARTH WIMP SEARCH

For the Earth, the SI interaction dominates in the capturing process. If the mass of DM almost matches one of the heavy elements in the Earth, the capture rate will increase considerably.

Capture rate in the Earth

The peaks correspond to resonant capture on the most abundant elements $^{16}\text{O}$, $^{24}\text{Mg}$, $^{28}\text{Si}$ and $^{56}\text{Fe}$ and their isotopes.

Preliminary results from sensitivity studies

Dashed lines show 90% CL limits for background only scenario.
**Relative strength of limits from Sun and Earth**

- Expected muon neutrino flux [/km$^2$/year] by WimpSim
  (Assuming SI cross section is $10^{-40}$ cm$^2$)

- Capture rate

$^{16}\text{O}$, $^{24}\text{Mg}$, $^{28}\text{Si}$, and $^{56}\text{Fe}$ and their isotopes enhance capture rate.
History of solar WIMP searches in Super-K

- 2004: 1679.6 days (SK-I), upward through-going muon events were used. *S. Desai et al., PRD79 (2004) 083523*
- 2011: 3109.6 days (SK-I, II, III), upward-going muon events and their energy information were used. *T. Tanaka et al., Astrophys. J. 742 (2011) 78*

In previous WIMP searches (2004 and 2011), only upward going muon events were used to avoid contamination of atmospheric neutrinos which have an $E^{-2.7}$ power-law spectrum.

To search for light WIMPs below 10 GeV, events with interaction vertices in the detector (contained events) were included in this analysis.


Search for the light solar WIMPs in Super-K

Event categories in Super-K

- Contained events
- Upward-going muons (upmu)

For light WIMPs < 10GeV, most of the signals are detected as contained events (FC + PC)
**Systematic errors**

- Sources of systematic uncertainties considered in this analysis

<table>
<thead>
<tr>
<th>Categories</th>
<th>Background MC</th>
<th>Signal MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino interactions in Super-K</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Event reduction</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Event reconstruction and selection</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Prediction of atmospheric neutrino flux including $1\sigma$ uncertainties on oscillation parameters</td>
<td>25</td>
<td>–</td>
</tr>
<tr>
<td>Oscillation of WIMP neutrinos during propagation through the Sun, vacuum, and Earth</td>
<td>–</td>
<td>7</td>
</tr>
<tr>
<td><strong>Total number of systematic sources</strong></td>
<td><strong>66</strong></td>
<td><strong>48</strong></td>
</tr>
</tbody>
</table>

- Total systematic uncertainty is $\sim 10\%$ effect on the WIMP sensitivity.
- The largest contributions come from **neutrino interaction** and atmospheric neutrino flux uncertainty.
90% upper limit on neutrino flux from WIMP annihilation

- The 90% upper limit on muon-neutrino flux from WIMP annihilation in the Sun at Super-K

For all tested WIMP hypothesis, no significant excess over expected atmospheric neutrino BG and 90% upper limit was set. Number of events was converted to flux considering detection efficiency, cross section and live time. The shadowed regions in left figure show 1σ bands of the sensitivity study results.

Uncertainties in capture process

Following uncertainties were taken into account in conversion to WIMP-nucleon (or WIMP-proton) scattering cross section limit

<table>
<thead>
<tr>
<th></th>
<th>Solar model</th>
<th>Form factor</th>
<th>Solar evaporation</th>
<th>Velocity distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD</td>
<td>4%</td>
<td>1%</td>
<td>&lt; 1%</td>
<td>40%</td>
</tr>
<tr>
<td>SI</td>
<td>25%</td>
<td>45%</td>
<td>&lt; 1%</td>
<td>25%</td>
</tr>
</tbody>
</table>

(1) **Solar model**: uncertainty in the composition of the Sun was estimated by comparing the DarkSUSY default choice BS2005-OP with other model (BS2005-AGS,OP).

(2) **Form factor**: For SD interaction, form factor is not considered. For SI interaction, the DarkSUSY default choice Helm-Gould form factor was compared with other parameter (the effective radius used in Helm-Lewin-Smith form factor).

(3) **Solar evaporation** is expected to have no impact > 4GeV WIMPs.

(4) **Velocity distribution of WIMPS**: uncertainty was determined in K. Choi, C.Rott, and Y.Itow, J. Cosmol. Astropart. Phys. 05 (2014) 049

(*) The effects of the planets on the capture rates is negligible.

(*) Uncertainty in the local WIMP density is not considered because it will make a similar effect both for direct and indirect searches.
WIMP annihilation in the galactic center


Claimed signals and conflicting null results for light (~10GeV/c²) WIMPs from direct searches

Annual modulation signals and some event excesses have been reported from direct searches:

- Allowed regions from annual modulation signals and event excesses are conflicting with other null results.
- A new result from CRESST-II doesn’t confirm their previous event excess.


- The significance of CoGeNT excess becomes < 2σ level with the maximum likelihood analysis.

arXiv:1401.6234

Complemental searches for ~10GeV WIMPs are necessary.
Experimental model-independent residual rate of the single-hit scintillation events measured by DAMA/NaI over 7 and by DAMA/LIBRA over 6 annual cycles.

Energy distribution of the modulation amplitudes $S_m$ for the total cumulative exposure 1.17 ton years.

- DAMA/NaI
- DAMA/LIBRA: 250 kg NaI(Tl) crystals
- Total 13 annual cycles from DAMA/NaI and DAMA/LIBRA
- 1.17 ton years
- 8.9 $\sigma$ modulation

DAMA/LIBRA result

R. Bernabei et al., arXiv: 1301.6243
CDMS-II Si result


- Si Z-sensitive ionization and phonon (ZIP) detector. Total 8 detectors out of 11 were used for data analysis.
- July 2007–September 2008 (140.2 kg days)
- Three WIMP-candidate events were observed.
- Number of expected surface-event BG is $0.41 \pm 0.20 - 0.08$ (stat) + 0.28 - 0.24 (syst).
- Neutrons and 206Pb are limited to < 0.13 and < 0.08 events (90% C.L.)

CDMS-II Si: light blue contours (68% and 90% C.L.)
CoGeNT: yellow contours
CRESST: light red contours
DAMA/LIBRA: light brown contours
CRESST-II result

Spin-independent WIMP-nucleon 90% C.L. limit

- CRESST-II phase 1 (2009–2011, 730 kg days)
  Allowed regions were set in above light blue contours.

- CRESST-II phase 2 (2013 Aug. – 2014 Jan., 29.35 kg days)
  Previous allowed region was excluded by above red line.

• CaWO₄ crystals
• Gran Sasso

Energy spectrum (phase-II, 29.35 kg days)
CoGeNT result

Red contour is good fit to CoGeNT data with models including WIMP signal with $m_\chi \sim 7 – 11$ GeV.


- Updated CoGeNT data (arXiv: 1401.6234):
  1136 live days as of Apr. 23, 2013
- Maximum likelihood signal extraction uses 2 dimensional probability density function. significance level become 1.7$\sigma$.  


Capture rates inside the Sun

Spin independent interaction

Capture rates of WIMPs as a function of WIMP mass. In $C^{\text{CNO}}$ (the sum of C, O, and N), oxygen is the most important of the CNO elements. For heavier elements like iron, due to form factor suppression, capture rate become low rapidly for higher WIMP mass.

WIMP capture rate inside the Sun

- Spin-dependent (SD): main contribution comes from hydrogen. Owing to hydrogen-rich composition (~74% of total mass) of the Sun, high capture rate is expected.
- Spin-independent (SI): Because of the capture rate is boosted $\propto A^4$ (coherent enhancement $\propto A^2$ and mass-matching factor $\propto \sim A^2$), even small composition of heavy elements have large capture rate. (depends on solar composition model, then, evaluation of uncertainty is important. It was considered in this analysis.)

→ The sensitivity for SI as well as SD for light WIMPs is expected to be competitive with direct detection.

Capture rate inside the Sun

Capture rate for SI coupling

Neutrino production in the Sun

- In the SD (SI) case, the thermalization time exceeds the age of the solar system if $\sigma_{SD} (\sigma_{SI}) < 10^{-48}$ cm$^2$ ($10^{-51}$ cm$^2$) for 100 GeV WIMP. However, they are low enough compared to the expected sensitivity of indirect detection. Then, it is OK to assume equilibrium between capture and annihilation.
- The thermalized WIMPs are predicted to distribute within 1% of the radius of the Sun.
- By decays of the annihilation products, neutrinos and anti-neutrinos can be produced as final products and escape the Sun and detected by the terrestrial detector.
  - **bb channel**: WIMPs hadronize and produce B mesons, which interact in the solar medium before decay. This channel gives “softest” spectrum.
  - **W$^+$$W^-$ channel**: the high and low-energy peaks correspond to the prompt decay of the W boson and decay products of hadrons.
  - **$\tau^+\tau^-$ channel**: largest number of tau neutrinos are produced than other flavors of neutrinos. This channel gives most energetic (“hardest”) spectrum.
  - **vv channel**: this channel is helicity-suppressed for Majorana particle. This channel is not included in our study.
- The propagation of the neutrinos through the Sun and vacuum:
  In the sun, a charged current (CC) interaction reduce the amount of the flux and a neutral current (NC) interaction reduce the energy of the neutrino. In the case of CC, only tau leptons produced by tau neutrino can produce secondary neutrinos. (electrons are stable, muons are stopped before decay)
(1) Setting of model space. Possible constrains from recent accelerators and CMB measurements for CMSSM and other sources are set as much as possible. Then, DarkSUSY scan possible WIMP scenarios which are randomly chosen within the model space we set. We ran it for about 5,000,000 scenarios first, and collected the models which have WIMP masses close to our region of interest, and made the “mode” files which are summary of SUSY parameters for each WIMP scenario.

(2) Running DarkSUSY in “read model mode” for each WIMP scenario made in (1). DarkSUSY analytically calculate the capture rate.
  - SI and SD coupling are considered independently. (for calculation of SI, SD is set to be zero, and vice versa)
  - Assuming of equilibrium for any chosen model.
  - Force the annihilation into a specified single channel.

In summary, a neutrino flux corresponding to a certain WIMP mass, annihilation channel and WIMP-nucleus scattering cross section was calculated by DarkSUSY.
Effect of the velocity distribution of dark matter in our Galaxy on capture rate in the Sun.

(1) Orbital speed of the Sun
(2) Escape velocity of dark matter from the halo
(3) Dark matter velocity distribution functions
(4) Existence of a dark disc.

-> even extreme case do not decrease the sensitivity of indirect detection because the capture rate is achieved over a broad range of the velocity distribution by integration over the velocity distribution.
Impact of the dark matter velocity distribution on capture rates in the Sun (2/3)

K. Choi, C. Rott and Y. Itow, Journal of Cosmology and Astroparticle Physics

- The capture boosts as a function of WIMP mass for variation of several parameters

<table>
<thead>
<tr>
<th>Orbital speeds of sun</th>
<th>Escape speed of the Milky Way</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity distribution functions (VDFs)</td>
<td>Dark disc scenarios</td>
</tr>
</tbody>
</table>

1. Orbital speeds of sun
2. Escape speed of the Milky Way
3. Velocity distribution functions (VDFs)
4. Dark disc scenarios
The sources and descriptions of the velocity distribution functions (VDFs)

<table>
<thead>
<tr>
<th>Name &amp; reference</th>
<th>Description of simulation</th>
<th>Description of VDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vogelsberger et al.</td>
<td>Largest dark matter only simulation of a Milky Way-sized dark matter halo</td>
<td>Median of the velocity modulus distributions for 2 kpc boxes centered between 7 and 9 kpc from the Galactic center</td>
</tr>
<tr>
<td>Ling et al.</td>
<td>Cluster re-simulation project</td>
<td>Standard velocity distribution for 96 halos at $r/r = 0.15$, peaks at low-velocity</td>
</tr>
</tbody>
</table>
New limits on dark matter from Super-Kamiokande

Rolf Kappl\textsuperscript{a,b}, Martin Wolfgang Winkler\textsuperscript{a,*}

\textsuperscript{a} Physik-Department T30, Technische Universität München, James-Franck-Straße, 85748 Garching, Germany
\textsuperscript{b} Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany

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Abstract

The signals observed at the direct detection experiments DAMA, CoGeNT and CRESST could be explained by light WIMPs with sizeable spin-independent cross sections with nucleons. The capture and subsequent annihilation of such particles in the Sun would induce neutrino signals in the GeV range which may be observed at Super-Kamiokande. We determine the rate of upward stopping muons and fully contained events at Super-Kamiokande for various possible WIMP annihilation channels. This allows us to provide strong constraints on the cross section of WIMPs with nucleons. We find that the DAMA and CoGeNT signals are inconsistent with standard thermal WIMPs annihilating dominantly into neutrino or tau pairs. We also provide limits for spin-dependent WIMP nucleus scattering for masses up to 80 GeV. These exclude the DAMA favored region if WIMPs annihilate even subdominantly into neutrinos, taus, bottoms or charms.

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Capture rate in the Sun

- Solar capture rate for spin-independent and spin-dependent WIMP nucleus scattering

\[
C_\odot = 4\pi \sum_i \int_0^{R_\odot} dr \, r^2 \frac{dC_\odot,i}{dV},
\]

\[
\frac{dC_\odot,i}{dV} = \rho_X \rho_\odot,i(r) \frac{\sigma_i}{2m_X \mu_i^2} \int_0^\infty du \frac{f(u)}{u} \int_{E_{R,\text{min}}}^{E_{R,\text{max}}} dE_R |F(E_R)|^2.
\]

\[\rho_\odot,i(r)\] is the mass density of nuclei \(i\) at radius \(r\) in the Sun.

- Spin-independent: The sum runs over all types of nuclei in the Sun.
  They considered from hydrogen to nickel.

- Spin-dependent case: only capture at hydrogen is relevant.

\[\rho_X \approx 0.3 \text{ GeV cm}^{-3}\]
\[v_\odot = 220 \text{ km s}^{-1}\]
\[|F(E_R)|^2 = e^{-E_R/E_i}\] (Gaussian form factors)

\[E_i = \frac{3}{2m_i R_i^2}, \quad R_i = (0.9A^{1/3} + 0.3) \text{ fm}\]

\((*) F(E_R)=1\) for hydrogen

The velocity distribution \(f(u)\) of WIMPs:

\[
\frac{f(u)}{u} = \frac{1}{\sqrt{\pi} v_\odot^2} \left( e^{-(u-v_\odot)^2/v_\odot^2} - e^{-(u+v_\odot)^2/v_\odot^2} \right)
\]

The WIMP nucleus cross section \(\sigma_i\):

(assuming equal coupling to p and n)

\[\sigma_i = \sigma_p A_i^2 \frac{\mu_i^2}{\mu_p^2},\]
Capture rate in the Sun

- Solar capture rate for spin-independent and spin-dependent WIMP nucleus scattering

For the spin-independent case, coherent enhancement $\propto A^2$
the mass-matching factor becomes approximately $\propto A^2$
resulting in the capture rate being boosted $\propto A^4$
However, due to form factor suppression, the capture rate scattering off heavy element (ex. iron) can be suppressed by several orders of magnitude for WIMPs with mass of several hundred GeV. Therefore, dominant element is oxygen.
WIMPs which are trapped in the Sun thermalize and, follow a Maxwellian velocity distribution with temperature $T_\chi$:

$$f(v) = \frac{2m_\chi^3}{\pi T_\chi^3} v^2 e^{-(m_\chi v^2)/(2T_\chi)}.$$

It turns out that for all relevant masses the WIMPs reside close to the center of the Sun. In this region the variations of the solar temperature and density are small and one can approximate both quantities by constants.

Annihilation rate is given by $\Gamma_\odot = A_\odot N^2 / 2$

$$A_\odot = \frac{1}{N^2} \int dr \, 4\pi r^2 n_\chi^2(r) \langle \sigma v_{\text{rel}} \rangle_\odot = \left( \frac{\sqrt{2}}{\pi \bar{r}} \right)^3 \langle \sigma v_{\text{rel}} \rangle_\odot.$$

For WIMP masses $m_\chi > 1\text{GeV}$

$$A_\odot = 4.5 \cdot 10^{-30} \text{ cm}^{-3} \left( \frac{m_\chi - 0.6 \text{ GeV}}{10 \text{ GeV}} \right)^{3/2} \langle \sigma v_{\text{rel}} \rangle_\odot.$$
Evaporation

- Trapped WIMPs may escape from the Sun if their energy is increased by scattering with nuclei in the Sun (called as evaporation). The evaporation rate can be estimated as

$$E_{\odot} \sim \frac{8}{\pi^3} \frac{\sigma_{evap}}{\bar{r}^3} \bar{v} \frac{E_{esc}}{T_\odot(\bar{r})} \exp \left[ -\frac{E_{esc}}{2T_\odot(\bar{r})} \right]$$

where:
- $E_{esc}$: the escape energy at the center of the Sun
- $\sigma_{evap}$: the evaporation cross section
- $\bar{v} = \sqrt{\frac{8T_\odot(\bar{r})}{\pi m_\chi}}$: the mean WIMP speed for the thermal distribution

Although the estimation of evaporation rate is only accurate to within a factor of three, this precision is sufficient for our purpose as it translates into an uncertainty in the evaporation mass of only 3%.

$$m_{evap} = m_0 + 0.32 \text{ GeV} \log_{10} \left( \frac{\sigma_p}{10^{-40} \text{ cm}^2} \right)$$

$m_0 = 3.5 \text{ GeV} (3.02 \text{ GeV})$ in the case of SI (SD) interaction
The evolution of the total WIMP number \((N)\) in the Sun is described following differential equation using capture rate \(C\), related annihilation rate \(A\) and evaporation rate \(E\),

\[
\dot{N} = C_{\odot} - A_{\odot} N^2 - E_{\odot} N
\]

In case of negligible evaporation with \(m\chi\) is larger than evaporation mass.

\[
N = \sqrt{\frac{C_{\odot}}{A_{\odot}}} \tanh(\sqrt{C_{\odot} A_{\odot}} t)
\]

Total annihilation rate is \(\Gamma_{\odot} = \frac{1}{2} A_{\odot} N^2 = \frac{1}{2} C_{\odot} \tanh^2(\sqrt{C_{\odot} A_{\odot}} t_{\odot})\)

If \(\sqrt{C_{\odot} A_{\odot}} t_{\odot} \gg 1\), the equilibrium between capture and annihilation is reached, then

\[
\Gamma_{\odot} = C_{\odot}/2
\]

In the SD (SI) case, the thermalization time exceeds the age of the solar system if \(\sigma_{SD} (\sigma_{SI}) < 10^{-48} \text{ cm}^2 (10^{-51} \text{ cm}^2)\) for 100 GeV WIMP. However, they are low enough compared to the expected sensitivity of indirect detection. Then, it is OK to assume equilibrium.
The Super-K 90% upper limits on the SI WIMP nucleon cross section

- SK I–III data (1996–2007) were used.
  FC events: 8596 in 2906 days
  upward stopping muon events: 53 (θ_{μ_{sun}} < 30 degrees) in 2828 days

Spin independent
Assuming equal coupling to protons and neutrons

(*) This channel (νν) should be helicity-suppressed for Majorana particle, then, it is not included in our result.

Left: s-wave annihilation. Right: p-wave annihilation
At low WIMP mass the limits arise from FC events, at higher WIMP mass from stopping upmu. Below the evaporation mass all constraints disappear rapidly.
The Super-K 90% upper limits on the SD WIMP nucleon cross section

Spin dependent

Assuming only coupling to protons.

(*) This channel (νν) should be helicity-suppressed for Majorana particle, then, it is not included in our result.

(Left plot) s-wave annihilation. (right plot) p-wave annihilation.
At low WIMP mass the limits arise from FC events, at higher WIMP mass from stopping upμμ. Below the evaporation mass all constraints disappear rapidly.
Navarro–Frenk–White (NFW) halo model

THE STRUCTURE OF COLD DARK MATTER HALOS

JULIO F. NAVARRO
Steward Observatory, The University of Arizona, Tucson, AZ 85721

CARLOS S. FRENK
Physics Department, University of Durham, Durham DH1 3LE, England

AND

SIMON D. M. WHITE
Max-Planck-Institut für Astrophysik, Karl-Schwarzschild Strasse 1, D-85740, Garching, Germany

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ABSTRACT

We use $N$-body simulations to investigate the structure of dark halos in the standard cold dark matter cosmogony. Halos are excised from simulations of cosmologically representative regions and are resimulated individually at high resolution. We study objects with masses ranging from those of dwarf galaxy halos to those of rich galaxy clusters. The spherically averaged density profiles of all our halos can be fitted over two decades in radius by scaling a simple "universal" profile. The characteristic overdensity of a halo, or equivalently its concentration, correlates strongly with halo mass in a way that reflects the mass dependence of the epoch of halo formation. Halo profiles are approximately isothermal over a large range in radii but are significantly shallower than $r^{-2}$ near the center and steeper than $r^{-2}$ near the virial radius. Matching the observed rotation curves of disk galaxies requires disk mass-to-light ratios to increase systematically with luminosity. Further, it suggests that the halos of bright galaxies depend only weakly on galaxy luminosity and have circular velocities significantly lower than the disk rotation speed. This may explain why luminosity and dynamics are uncorrelated in observed samples of binary galaxies and of satellite/spiral systems. For galaxy clusters, our halo models are consistent both with the presence of giant arcs and with the observed structure of the intracluster medium, and they suggest a simple explanation for the disparate estimates of cluster core radii found by previous authors. Our results also highlight two shortcomings of the CDM model. CDM halos are too concentrated to be consistent with the halo parameters inferred for dwarf irregulars, and the predicted abundance of galaxy halos is larger than the observed abundance of galaxies. The first problem may imply that the core structure of dwarf galaxies was altered by the galaxy formation process, and the second problem may imply that galaxies failed to form (or remain undetected) in many dark halos.

Subject headings: cosmology: theory — dark matter — galaxies: halos — methods: numerical