Searches for dark matter with the Super-Kamiokande detector
Indirect dark matter detection
- Search for the products of WIMP annihilation or decay

Produced ν's provide very good information about:
- source position
- generated energy spectra
- flavor composition

Where we are searching:
Diffuse signal from entire Galaxy, peaked from Galactic Center
Sun, consider as point source
Earth core
Super-Kamiokande

Detector measures solar, atmospheric, cosmic, and accelerator neutrinos

- 50 000 tons of water (22.5 kton FV)
- located in Mozumi mine, 1 km underground
- ID ~11 000 PMTs, OD ~1 800 PMTs
- far detector for T2K experiment

Detected Cherenkov light allows to reconstruct energy, direction, and flavor of produced lepton.
Atmospheric neutrinos

- Main background for WIMP searches
- ~10 events/day
- Data period 1996-2016
- ~50,000 events in total

Data samples at SK

Katarzyna Frankiewicz
DPF meeting, 2017/08/01
Signal simulation

DarkSUSY - package for supersymmetric dark matter calculations  P. Gondolo et al., JCAP 07, 008 (2004)

WimpSim - code calculates the annihilation of WIMPs inside the Earth/Sun and propagates products to the detector  M. Blennow et al., arXiv: 0709.3898 (2008)

- Example: muon neutrino flux produced in WIMP annihilation in the Earth core

- Energy spectra and angular distribution for each neutrino flavor are calculated for given annihilation channel and assumed WIMP mass

- Neutrino interactions and oscillations in a fully consistent three-flavor way are included
Analysis

Search for excess of neutrinos from the **Milky Way/Earth/Sun** as compared to atmospheric neutrino background

→ For each tested WIMP mass, find the best configuration of **ATM MC + WIMP SIGNAL** that would match **DATA** the best

**Example:** signal for 6 GeV WIMPs annihilating into $b\bar{b}$ for one of data samples

- **Galactic WIMP search** - diffuse search
  - **MultiGeV $\mu$-like**

- **Earth WIMP search** - diffuse search
  - **MultiGeV $\mu$-like**

- **Solar WIMP search** - point-like search
  - **MultiGeV $\mu$-like**

- **Each analysis is performed in the coordinate system in which the expected signal is peaked and possible to distinguish from the atmospheric neutrino background**

Katarzyna Frankiewicz  
DPF meeting, 2017/08/01
Diffuse signal from entire Galaxy, peaked from Galactic Center

GC visibility with SK:
~71% with UPMU, 100% FC/PC

Search constrains DM self-annihilation cross section \(<\sigma_A v>\)


Expected signal intensity strongly depends on halo model
NFW is considered as a benchmark model in this analysis
Galactic WIMP search – data

- FIT based on lepton mom. & $\cos\theta_{GC}$ distributions
- NFW halo model is assumed
- Fit results are consistent with zero
- 90% upper limits on DM self-annihilation cross section $<\sigma_A V>$

Example for: 5 GeV WIMPs, bb ann. channel
Galactic WIMP search – fitted number of DM-induced neutrinos

SK preliminary

- FIT based on lepton mom. & $\cos\theta_{\text{GC}}$ distributions
- NFW halo model is assumed
- Fit results are consistent with zero
- 90% upper limits on DM self-annihilation cross section $<\sigma_A V>$
**Galactic WIMP search – WIMP self-annihilation cross section**

- FIT based on lepton mom. & $\cos\theta_{GC}$ distributions
- NFW halo model is assumed
- Fit results are consistent with zero
- 90% CL upper limits on DM self-annihilation cross section $<\sigma_A V>$

For each considered annihilation channel 100% BR is assumed

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Katarzyna Frankiewicz

DPF meeting, 2017/08/01
Earth WIMP search

For the Earth, the spin-independent interactions dominate in the capturing process.
→ scalar interaction in which WIMPs couple to the nucleus mass

If the mass of DM almost matches one of the heavy elements in the Earth, the capture rate will increase considerably.

Capture rate for DM particles captured to the Earth core. The peaks correspond to resonant capture on the most abundant elements $^{16}$O, $^{24}$Mg, $^{28}$Si and $^{56}$Fe and their isotopes.

WIMP-nucleon SI scattering cross section $\sigma_{\chi n}$ can be constrained and compared with other results from direct DM detection.
Earth WIMP search – data

- **FIT based on lepton mom. & \( \cos \theta_{\text{ZENITH}} \) distributions**

- Fit results are consistent with zero

- 90% upper limits on SI WIMP-nucleon scattering cross section \( \sigma_{\chi n} \)

Katarzyna Frankiewicz

DPF meeting, 2017/08/01
Earth WIMP search – fitted number of DM-induced neutrinos

- FIT based on lepton mom. & $\cos\theta_{\text{zenith}}$ distributions
- Fit results are consistent with zero
- 90% upper limits on SI WIMP-nucleon scattering cross section $\sigma_{\chi n}$

Katarzyna Frankiewicz
DPF meeting, 2017/08/01
Earth WIMP search – WIMP-nucleon SI cross-section limit

FIT based on lepton mom. & $\cos \theta_{\text{zenith}}$
distributions

Fit results are consistent with zero

90% upper limits on SI WIMP-nucleon scattering cross section $\sigma_{\chi n}$

$\rightarrow$ scalar interaction in which WIMPs couple to the nucleus mass
Solar WIMP search

- DM particles passing through the Sun can elastically scatter with a nucleus and lose energy.

- WIMP density increases in the core, leading to DM annihilation until equilibrium is achieved: 
  capture rate = annihilation rate

- Scattering cross section $\sigma_\chi n$ can be constrain and compare with results from direct DM detection.


more: G. Wikström, J. Edsjö
JCAP 04, 009 (2009)
Solar WIMP search – data

- FIT based on lepton mom. & $\cos\theta_{\text{SUN}}$ distributions
- Fit results are consistent with zero
- 90% upper limits on SD and SI WIMP-nucleon scattering cross section $\sigma_{\chi n}$

Example for: 200 GeV WIMPs, $\tau^+\tau^-$ ann. channel

- SubGeV angle
- MultiGeV angle
- SubGeV energy
- MultiGeV energy
- PC + stopping muon angle
- Through-going muon angle
**Solar WIMP search – WIMP-nucleon SD & SI cross-section limit**

**Spin-dependent interactions**

- SK I-IV, $b\bar{b}$
- SK I-IV, $\tau^+\tau^-$
- SK I-IV, $W^+W^-$

**Spin-independent interactions**

- DAMA/LIBRA (2008)
- JCAP 0904:010,2009
- LUX, WS2013+WS2014-16
- PICO-60, 2016-2017

(In)direct dark matter detection?

Cone search: 8 cones from 5° to 40° around GC
→ No clusters visible

\[ (GC) \]

\[ (Lab) \]

\[ \chi_A \]

\[ \chi_B \]

\[ e^- \]

\[ e^- \]

\[ B \]

\[ g' \]

\[ \gamma' \]

SK very forward scattering
- electromagnetic shower
- no hadrons → no decay e, no neutrons

Limit for \( m_{\gamma'} = 20 \text{ MeV} \)

SK preliminary

Katarzyna Frankiewicz
DPF meeting, 2017/08/01
Summary

No excess of DM induced $\nu$'s has been observed at SK so far

Galactic WIMP search
- upper limits on $<\sigma_A v>$ for wide range of WIMPs masses (1 GeV to 10 TeV)

Earth WIMP search
- upper limits on SI WIMP-nucleon cross-section
- high sensitivity to resonant capture region

Solar WIMP search
- strong constrains for low WIMP masses
- results published in 2015

Boosted dark matter search
- alternative DM models can also be tested with SK detector
Dark matter candidates

- Dynamics of galaxy clusters
- Galaxy rotation curves
- Gravitational lensing
- Cosmic Microwave Background
- Structure formation

Weekly Interacting Massive Particle (WIMP):
- neutral
- long livetime
- massive (10 GeV - 10 TeV)
- weekly interacting with matter

Many possibilities, various detection techniques, many experiments..

most popular WIMP candidate:
the lightest supersymmetric particle (LSP)
neutralino $\chi$ - Majorana fermion
FIT result – brazil plot

ANNIHILATION, NFW PROFILE

$b\bar{b}$
- Observed upper limit 90% CL
- Sensitivity upper limit 90% C.L.
- $\pm 1\sigma$ sens. uncertainty
- $\pm 2\sigma$ sens. uncertainty

$\mu^+\mu^-$
- Observed upper limit 90% CL
- Sensitivity upper limit 90% C.L.
- $\pm 1\sigma$ sens. uncertainty
- $\pm 2\sigma$ sens. uncertainty

ANNIHILATION, NFW PROFILE

$W^+W^-$
- Observed upper limit 90% CL
- Sensitivity upper limit 90% C.L.
- $\pm 1\sigma$ sens. uncertainty
- $\pm 2\sigma$ sens. uncertainty

$\nu\bar{\nu}$
- Observed upper limit 90% CL
- Sensitivity upper limit 90% C.L.
- $\pm 1\sigma$ sens. uncertainty
- $\pm 2\sigma$ sens. uncertainty

Livetime: FC/PC 5325.8 days, UPMU 5629.1 days

1200 TOY MCs
RESIDUAL 5GeV BB-BAR

\[ \cos \theta_{GC} \]
\[ M_{\chi} = 5.0 \text{ GeV/c} \]

points: TOY MC data set  
blue line: ATM MC (with pulls)  
red dashed line: best fitted signal with ATM MC (all with pulls)

\[ \chi^2_{\text{total}} = \chi^2_{\text{data}} + \chi^2_{\text{syst}} \]
\[ 604.0 = 566.9 + 37.0 \]  
\[ 601.6 = 564.9 + 36.7 \]  
\[ \Delta \chi^2 = 2.4 = 2.0 + 0.4 \]
\( \langle \sigma V \rangle \) limit – brazil plot

1200 TOY MCs
**Example:** 6 GeV WIMPs, b̅b̅ ann. channel - spectra at detector position

- very similar shape of energy spectra from Sun and Earth
**Example:** 10 GeV WIMPs, $b\bar{b}$ ann. channel - spectra at detector position

- very similar shape of energy spectra from Sun and Earth
**Example:** 50 GeV WIMPs, $b\bar{b}$ ann. channel - spectra at detector position

- similar shape of energy spectra from Sun and Earth
**Example:** 200 GeV WIMPs, $b\bar{b}$ ann. channel - spectra at detector position

![Graphs showing neutrino and antineutrino fluxes at detector position](Generated with WimpSim, www.physco.se/~adjp/wimpsim/)
DM-induced neutrino signal
differential $\bar{\nu}_\mu \nu_\mu$ energy spectra per DM annihilation for $M_\chi=300$ GeV
(oscillated throughout Galaxy)
Signal illustration for Earth WIMP search

\( \tau^+ \tau^- \text{ ann. channel} \)

WIMP mass = 3 GeV

DATA
SK1,2,3,4

WIMP
SIGNAL

- Sub-GeV e-like 1-dcy e
- Sub-GeV e-like 0-dcy e
- Sub-GeV \( \mu \)-like 0-dcy e
- Sub-GeV \( \mu \)-like 1-dcy e
- Sub-GeV \( \pi^0 \)-like 1-R
- Sub-GeV \( \pi^0 \)-like 2-dcy e
- Sub-GeV \( \pi^0 \)-like M-R
- Multi-GeV e-like \( \nu_e \)
- Multi-GeV e-like \( \bar{\nu}_e \)
- Multi-GeV \( \mu \)-like
- Multi-Ring e-like \( \nu_e \)
- Multi-Ring e-like \( \bar{\nu}_e \)
- Multi-Ring \( \mu \)-like
- Multi-Ring Unclassified

lepton momentum (MeV)  
\( \cos \text{ zenith} \)
Signal illustration for Earth WIMP search

$\tau^+\tau^-$ ann. channel
WIMP mass = 6 GeV
Signal illustration for Earth WIMP search

τ⁺τ⁻ ann. channel
WIMP mass = 10 GeV

DATA
SK1,2,3,4

WIMP
SIGNAL
Signal illustration for Earth WIMP search

$\tau^+\tau^-$ ann. channel
WIMP mass = 25 GeV

DATA
SK1,2,3,4
WIMP
SIGNAL

lepton momentum (MeV)
cos zenith

Signal illustration for Earth WIMP search

$\tau^+\tau^-$ ann. channel
WIMP mass = 25 GeV

DATA
SK1,2,3,4
WIMP
SIGNAL

lepton momentum (MeV)
cos zenith
Signal illustration for Earth WIMP search

τ⁺τ⁻ ann. channel
WIMP mass = 50 GeV

DATA
SK1,2,3,4

WIMP
SIGNAL
Signal illustration for Earth WIMP search

$\tau^+\tau^-$ ann. channel
WIMP mass = 1 TeV

DATA SK1,2,3,4

WIMP
SIGNAL

lepton momentum (MeV)

$\cos$ zenith

$\cos$ zenith

$\cos$ zenith
Earth WIMP search – muon neutrino flux limit

- FIT based on lepton mom. & \( \cos\theta_{\text{ZENITH}} \) distributions,

- No excess of \( \nu \)'s from the EARTH as compared to atm bkg is observed

- 90% CL upper limit on total integrated muon-neutrino flux from WIMP annihilations in the Earth core for \( \tau^+\tau^- \), \( b\bar{b} \) and \( W^+W^- \) channels

- 90% CL upper limit on SI WIMP-nucleon scattering cross section \( \sigma \chi n \)
Solar WIMP search – muon neutrino flux limit

- FIT based on lepton mom. & $\cos\theta_{\text{SUN}}$ distributions, 3903 days of SK data used

- No excess of $\nu$'s from the SUN as compared to atm bkg is observed

- 90% CL upper limit on total integrated muon-neutrino flux from WIMP annihilations in the Sun for $\tau^+\tau^-$, $b\bar{b}$ and $W^+W^-$ channels

- 90% CL upper limit on WIMP-nucleon scattering cross section $\sigma_n$ for WIMP mass

The shadowed regions show 1σ bands of the sensitivity study results
Ice Cube + Deep core effective area:

- **Effective area**: The effective area $A_{eff}$ relates a measured event rate $R_{exp}(\theta)$ to the total incident flux $\Phi$:

$$dR_{exp}(\theta) = A_{eff}(\theta, E) \cdot \frac{d\Phi}{dE} dE$$  \hspace{1cm} (5.1)$$

Here $\theta$ is the event zenith angle. The energy dependence of $A_{eff}$ is introduced through the energy dependence of the detector efficiency. In IceCube $A_{eff}$ is typically given related to a neutrino or a muon flux. The concept of an effective area is based on the assumption of infinite tracks (where only the projection of the detector volume into the plane perpendicular to the event direction is of importance). This is well justified for muons with a few 100 GeV as these can cross the whole detector, but at the lowest energetic events effective volumes pose a clearer definition.
Comparison with SK:

Super-Kamiokande effective area for 10 GeV WIMPs
\sim 10^{-1} \text{ m}^2

IceCube + Deep Core effective area for 10 GeV WIMPs
\sim 10^{-4} \text{ m}^2

Livetime:
IceCube 327 days
SK FC/PC 5325.8, UPMU 5629.2

Comparison for 10 GeV WIMPs, $\tau^+\tau^-$ ann. channel:
$10^{-1} \times 5500 / 10^{-4} \times 327 \sim 16000 \rightarrow 100x$ better limit

Super-K limit: $1.4 \times 10^{-40}$
IceCube limit: $2.5 \times 10^{-38}$
Boosted dark matter search

Somewhere near the Galactic Center

Inside SK

electron is elastically scattered by B
Analysis Technique

• Divide into three energy ranges, by evis
  – Sub GeV: 100 MeV*-1.33 GeV
  – Mid Energy: 1.33 GeV-20 GeV
  – High Energy: >20 GeV

• For 8 cones from 5 to 40 degrees around Galactic Center, count number of events and compare to estimated background

*evis>30 MeV
amome>100 MeV
4 Simple Cuts

Total Data Events (Sep 16)

<table>
<thead>
<tr>
<th></th>
<th>Evis&lt;1.33 GeV</th>
<th>1.33 GeV&lt;Evis&lt;20 GeV</th>
<th>20 GeV&lt;Evis</th>
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<tr>
<td>FCFV</td>
<td>15206</td>
<td>4908</td>
<td>97</td>
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<td>and single ring</td>
<td>11367</td>
<td>2868</td>
<td>53</td>
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<tr>
<td>and e-like</td>
<td>5655</td>
<td>1514</td>
<td>53</td>
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<tr>
<td>and 0 decay-e</td>
<td>5176</td>
<td>1134</td>
<td>17</td>
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<tr>
<td>and 0 tagged neutrons</td>
<td>4132</td>
<td>683</td>
<td>4</td>
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</table>
Mid Energy

Grey are 8 cones from 5° to 40° around GC

No clusters visible
## Results

162 kton yrs

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<thead>
<tr>
<th>Evis&lt;1.33GeV</th>
<th>1.33GeV&lt;Evis&lt;20GeV</th>
<th>Evis&gt;20GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bckg</strong></td>
<td><strong>Data</strong></td>
<td><strong>Signal</strong></td>
</tr>
<tr>
<td>GC 5° cone</td>
<td>8.6 ± 0.7</td>
<td>7</td>
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<tr>
<td>GC 10° cone</td>
<td>32.9 ± 1.9</td>
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<tr>
<td>GC 15° cone</td>
<td>74.4 ± 3.6</td>
<td>70</td>
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<tr>
<td>GC 20° cone</td>
<td>129.5 ± 5.5</td>
<td>127</td>
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<tr>
<td>GC 25° cone</td>
<td>201.4 ± 7.7</td>
<td>211</td>
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<tr>
<td>GC 30° cone</td>
<td>290.3 ± 10.2</td>
<td>292</td>
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<tr>
<td>GC 35° cone</td>
<td>394.1 ± 13.0</td>
<td>387</td>
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<tr>
<td>GC 40° cone</td>
<td>511.2 ± 16.0</td>
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<tr>
<td></td>
<td><strong>Bckg</strong></td>
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<tr>
<td>GC 5° cone</td>
<td>1.6 ± 0.3</td>
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<tr>
<td>GC 10° cone</td>
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<td>GC 20° cone</td>
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<td></td>
<td><strong>Bckg</strong></td>
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<tr>
<td>GC 35° cone</td>
<td>0.49 ± 0.15</td>
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<tr>
<td>GC 40° cone</td>
<td>0.63 ± 0.19</td>
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</tr>
</tbody>
</table>

No evidence of excess in any energy region or cone