Dark Matter Searches at Super-Kamiokande

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Indirect searches for dark matter induced neutrinos at Super-Kamiokande:

1. Galactic Center & Halo 2017
2. Sun 2015
3. Earth 2017
Super-Kamiokande

@ Kamioka Observatory (ICRR, University of Tokyo), Japan

- Super-Kamiokande runs from 1996
- T. Kajita → Nobel Prize 2015
- Measures solar, atmospheric, cosmic & accelerator neutrinos

- ~11k ID, ~1.8k OD
- Located 1km underground
- 50 kton of pure water (22.5 kton FV)
- Inner (ID) & outer/veto (OD) detection regions
- PMTs detect Cherenkov light

Located in Japan.
Detected Cherenkov light allows for reconstruction of:

- lepton momentum (neutrino energy)
- lepton direction
- lepton flavor (e-like vs. µ-like, good separation possible)

\[ \nu_e + N \rightarrow e^- + N' \]
Atmospheric neutrinos: main background in DM-induced $\nu$ searches

- ~10 events/day
- data period: 1996-2016
- ~50 000 events in total

Monte Carlo

Events / 4600 Days

FC
PC
UPMU

- $\nu_e$
- $\nu_\mu$
- WIMPs

atmospheric neutrinos at SK

$E^2 \Phi$ [GeV cm$^{-2}$ sr$^{-1}$ sec$^{-1}$] vs. $\log_{10}(E_\nu / \text{GeV})$

Super-Kamiokande I-IV $\nu_\mu$
Frejus $\nu_\mu$
IceCube $\nu_\mu$ unfolding
IceCube $\nu_\mu$ forward folding
AMANDA-II $\nu_\mu$ unfolding
AMANDA-II $\nu_\mu$ forward folding
ANTARES $\nu_\mu$
HKKM11 $\nu_\mu \nu_\mu$ (w/ osc.)

- $\nu_e$
- $\nu_\mu$
- Frejus $\nu_e$
- IceCube/DeepCore 2013 $\nu_e$
- IceCube 2014 $\nu_e$
- HKKM11 $\nu_e \nu_e$ (w/ osc.)
Dark matter searches at Super-Kamiokande

• Search for excess of neutrinos from Earth/Sun/Milky Way
• **FIT:** for each tested WIMP mass, find configuration of ATM $\nu + DM$ signal that would match DATA the best

Galactic WIMP search  
Earth WIMP search  
Solar WIMP search

- **MultiGeV $\mu$-like**
- $\cos \theta_{GC}$  
- $\cos \theta_{ZENITH}$  
- $\cos \theta_{SUN}$

• In these coordinate systems, signal is easy to distinguish from atmospheric neutrino background

Detector  
$\theta_{GC}$, $\theta_{SUN}$ or $\theta_{zenith}$  
lepton direction  
Galactic Center, Sun  
Earth  
SK

DATA  
ATM MC (BKG) with oscillations  
WIMP signal enhanced for illustration
Galactic WIMP search

- 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 $\langle \sigma v \rangle$

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. & $\cos\theta_{\text{GC}}$ distributions, 5326-5629 live-days, 1996-2016
- NFW halo model assumed
- Fit results are consistent with null WIMP contribution
- 90% CL upper limit on DM self-annihilation cross section $<\sigma_A V>$

proportions of the signal in various samples are reflected
Galactic WIMP search: fitted number of DM-induced $\nu$'s

- FIT based on lepton mom. & $\cos\theta_{GC}$ distributions, 5326-5629 live-days, 1996-2016
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SK preliminary points on the plots are not independent

$\sim$150 systematic uncertainty terms included in the fit p-values in backup
Galactic WIMP search: DM self-annihilation cross section

- FIT based on lepton mom. & \( \cos \theta_{\text{GC}} \) distributions, 5326-5629 live-days, 1996-2016
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- 90% CL upper limit on DM self-annihilation cross section \( <\sigma_A V> \)

\[
\frac{d\phi_{\Delta\Omega}}{dE} = \frac{1}{2} \left\langle \sigma_A \cdot V \right\rangle J_{\Delta\Omega} \frac{R_{sc} \rho_{sc}^2}{4\pi M^2_\chi} \frac{dN}{dE}
\]

90% CL upper limit on DM self-annihilation cross section
Solar WIMP search

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

- WIMP density increases in core, leading to DM annihilation until equilibrium is achieved: 
  \[ \text{capture rate} = \text{annihilation rate} \]

- Scattering cross section \( \sigma_{\chi n} \) can be constrained and compared with results from direct DM detection.


Solar WIMP search

- FIT based on lepton mom. & \( \cos\theta_{\text{SUN}} \) distributions, 3903 days of SK data (1996-2012)
- No excess of \( \nu \)'s from the SUN as compared to atm bkg
- 90% CL upper limit on WIMP-nucleon scattering cross section \( \sigma_{Xn} \) for \( \tau^+\tau^- \), \( bb \) and \( W^+W^- \) channels

**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**

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Solar WIMP search: WIMP-nucleon SI & SD cross section limit

90% CL upper limit

**spin dependent interactions**

**spin independent interactions**

Earth WIMP search

- Spin-independent interactions dominate in the capturing process → scalar interaction in which WIMPs couple to the nucleus mass
- If the mass of DM matches given heavy element, the capture rate increases considerably

![Graph showing capture rate in the Earth vs WIMP mass](image)

\[ \sigma_{SI} = 10^{-42} \text{ cm}^2 \]

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

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

- FIT based on lepton mom. \& $\cos^2\theta_{\text{zenith}}$ distributions, 5326-5629 live-days, 1996-2016
- Fit results are consistent with null WIMP contribution
- 90 % upper limits on SI WIMP-nucleon scattering cross section $\sigma_{\chi-n}$

Example: 50GeV WIMPs $bb$ ann. channel

Proportions of the signal in various samples are reflected
Earth WIMP search: fitted number of DM-induced $\nu$s

- FIT based on lepton mom. & $\cos\theta_{\text{zenith}}$ distributions, 5326-5629 live-days, 1996-2016

- Fit results are consistent with null WIMP contribution

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

- FIT based on lepton mom. & $\cos\theta_{\text{zenith}}$ distributions, 5326-5629 live-days, 1996-2016
- Fit results are consistent with null WIMP contribution
- 90% upper limits on SI WIMP-nucleon scattering cross section $\sigma_{\chi-n}$
Summary

• DM induced neutrinos has not been observed at Super-Kamiokande so far

• Galactic WIMP search (2017)
  • upper limits on $<\sigma_A V>$ for wide range of WIMPs masses (1 GeV to 10 TeV)
  • strongest limits $< 20$-$100$GeV among $\nu$ experiments

• Solar WIMP search (2015)
  • strongest limits $< 20$-$100$GeV among $\nu$ experiments

• Earth WIMP search (2017)
  • upper limits on spin-independent WIMP-nucleon cross-section
  • high sensitivity to resonant capture region $\rightarrow$ currently the strongest limits from $\nu$ experiments
Thank you!

... we keep looking

SK will be re-open for upgrade this year!!!
supplementary slides
Signal simulation

Simulate DM signal before detection \(\rightarrow\) DarkSUSY & WimpSim

P. Gondolo et al., JCAP 07, 008 (2004)

EXAMPLE: Galactic WIMP search

differential \(\bar{\nu}_\mu \nu_\mu\) energy spectra per DM annihilation for \(M_\chi = 100\) GeV (oscillated throughout Galaxy)

EXAMPLE: Earth WIMP search

muon neutrino flux produced in WIMP annihilation in the Earth’s core

PARAMETERS:
- WIMP mass = 100 GeV
- Annihilation channel:
  - \(b\bar{b}\)
  - \(\tau^+\tau^-\)
  - \(W^+W^-\)

Angular distribution of muon neutrinos from the Earth’s core

\(E_\nu\) [GeV]

\(d^2N/dE\) [per ann. GeV]
Super-K data samples

**Fully-contained**
- ν energy reconstruction
- ν direction info
- e/μ identification possible

**Partially-contained**
- partial E_ν info (lepton leaves detector)
- ν direction info

**Upward-going muons**
- no E_ν info
- excellent ν direction info
- downward-going muons are neglected (mainly cosmic ray μ)
 Galactic WIMP search: **ON-/OFF-source**

**Different approach**: search for large-scale anisotropy due to DM-induced $\nu$'s from Milky Way

\[
\Delta N \approx N_{on}^{\text{sig}} - N_{off}^{\text{sig}} = \Delta N^{\text{sig}} \propto \langle \sigma_A \nu \rangle
\]

- Analysis uses ON-/OFF-source concept to estimate background directly from data
- Independent on MC simulations and related systematic uncertainties
ON- & OFF-source results

SKI-IV, 1996-2016

\[ A = \frac{(N_{ON} - N_{OFF})}{(N_{ON} + N_{OFF})} \]
Galactic WIMP search: p-value’s
Galactic WIMP search: signal illustration 10GeV bb-bar

\[ \cos \theta_{GC} \]

\[ M_\chi = 10.0 \text{ GeV/c} \]
Galactic WIMP search: signal illustration 100GeV bb-bar

\cos \theta_{GC}

M_\chi = 100.0 \text{ GeV/c}

Data
SK1-4, 1996-2016

ATM MC+WIMP
at best fit point

WIMP
before fit
 Galactic WIMP search: signal illustration 1000GeV bb-bar

\[ \text{cos} \theta_{GC} \]

\[ M_\chi = 1000.0 \text{ GeV/c} \]

DATA
SK1-4, 1996-2016

ATM MC+WIMP at best fit point

WIMP before fit
Galactic WIMP search: residuals for 5GeV bb-bar best fit

\[ \chi_2^{\text{total}} = \chi_2^{\text{data}} + \chi_2^{\text{syst}} \]

\[ 604.0 = 566.9 + 37.0 \]

\[ 601.6 = 564.9 + 36.7 \]

\[ \Delta \chi_2 = 2.4 = 2.0 + 0.4 \]

points: data set  
red line: only ATM MC (with pulls)  
color line: best fitted WIMP + ATM MC (all with pulls)  

\[ \cos \theta_{GC} \]

\[ M_\chi = 5.0 \text{ GeV/c} \]
‘Boosted’ dark matter search

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

limit for $m_\gamma=20$ MeV