Searches for Neutrinos from WIMP Dark Matter

- Potential Sources
- The IceCube Neutrino Detector
- Results from IceCube
- Future Prospects

July 29 - August 6 · Snowmass on the Mississippi · U. Minnesota, Minneapolis, MN
IceCube includes about 250 researchers from 39 institutions around the world. Prof. Francis Halzen, University of Wisconsin – Madison is the principal investigator and Prof. Olga Botner from Uppsala University serves as the collaboration spokesperson.
Candidate WIMP Accumulators

• Earth (ν-accessible only)
  • Capture depends on WIMP velocity distribution
    • Only slow, light (M_χ < 50 GeV) WIMPs accessible
  • Unlikely to be in capture-annihilation equilibrium
    • Hard to link to physical quantities
  • Focus on spin-independent (SI) interactions

• Sun (ν only)
  • Wide range of WIMP masses accessible
    • WIMP evaporation for M_χ <~ 4 GeV
    • ν absorption in sun for M_χ >~ 1 TeV
  • In equilibrium (Γ_{Ann} = (1/2)Γ_C)
    • extract σ_{χ-p}
  • Access both spin-dependent (SD) and SI interactions
Candidate WIMP Accumulators

• Galactic Center (ν plus γ, antimatter)
  • WIMPs collisionless
  • Inner halo cusp/core structure not well known:
    • extract $<\sigma_{\text{Ann}} \cdot v>$
      • average is over expected WIMP velocity distribution
    • or look for spectral lines

• Galactic Halo (ν plus γ, antimatter)
  • WIMPs collisionless
  • matter density known pretty well
    • extract $<\sigma_{\text{Ann}} \cdot v>$

• Dwarf spheroidal galaxies, galaxy clusters (ν plus γ)
  • attractively high mass-to-light ratio (dSph’s)
    • extract $<\sigma_{\text{Ann}} \cdot v>$
  • lots of mass, possible clumpiness
WIMP → Neutrino Channels

• Consider “extrema” to bracket possible neutrino energy spectrum
  • Hard channel
    • e.g., $\chi\chi \rightarrow W^+W^-$ and $\chi\chi \rightarrow \tau^+\tau^-$
    • Average $E_\nu \sim M_\chi/3$
  • Soft Channel
    • e.g., $\chi\chi \rightarrow bb$
    • Average $E_\nu \sim M_\chi/6$
  • Line Search
    • $\chi\chi \rightarrow \nu\nu$
    • $E_\nu \sim M_\chi$

• Search for $\nu_\mu$-induced muons in detector
Summary of IceCube Searches

Search for dark matter annihilations to $\nu$ at $E_\nu$ from 10 GeV – 10 TeV

Local sources: Sun (& Earth)
* IceCube-79 limits (PRL 110 (2013) 131302)

Galactic Halo
* IceCube-22 limits (PRD 84 (2011) 022004)
* IceCube-79 limits

Dwarf spheroidal galaxies
* IceCube-59 limits

Galaxy clusters

Galactic Center
* IceCube-79 sensitivity

Image: M. Strassler
The IceCube Detector

- First operating km-scale neutrino detector
  - ~5000 10” PMTs
  - 78 strings: 125 m horiz., 17 m vert.
- Originally optimized for TeV-PeV energies
  - now also sensitive to ~10 GeV scale with DeepCore in-fill
    - 8 in-fill strings mostly 72 m & 7 m
- Sensitive to $M_\chi$ from below ~50 GeV to above ~100 TeV
- Physics-quality data taken with partially completed detector
  - IC-22, IC-40, IC-59, IC-79
    - IC-79 volume is about 1 km$^3$
Earth WIMPs

• Assumptions/Issues/Observations
  • Assumed velocity distribution matters
  • Earth is a shallow gravitational well
  • Neutrino oscillations can be relevant
  • “Dark disk” can increase Earth’s accumulation

Minimum velocity for WIMP to be captured by Earth after scattering off iron
Results and Predicted Sensitivity: Earth WIMPs

- Earth WIMPs
  - Dedicated online trigger/filter in place at Pole
    - selects vertically upward-going events w/low E threshold
  - No “off-source” region: analysis more challenging
    - atmospheric neutrinos are main background
    - can’t check with data
  - AMANDA analysis (published 2006)
    - Expected IceCube 10-yr sensitivity overlaid
    - Below: With and without “dark disc” assumption

IceCube Solar WIMP Search

- **Solar WIMPs**
  - extract neutrino sample, vetoing downgoing cosmic ray muons
    - sample dominated by atmospheric neutrinos
  - maximize efficiency for ~horizontal events
    - sun is ±23° from horizon
  - striking signature: high energy $\nu$ excess from direction of sun
Solar WIMPs

• Assumptions/Issues/Observations
  • In equilibrium: $\Gamma_{\text{Ann.}} = (1/2)\Gamma_{\text{Cap.}}$.
    • annihilation rate depends only on capture rate, i.e., on scattering cross sections
    • analyses can place limit on $\sigma_{\text{scatt.}}$.
  • Daughter neutrinos’ oscillations can be relevant
  • Daughter neutrinos’ absorption can be relevant
  • No known astrophysical source can mimic neutrino signal
**IceCube Solar WIMP Search**

- **Solar WIMPs**
  - **Recent (IC-79) analysis improvements:**
    - Uses full year’s data, including summer (317 days livetime)
    - Uses DeepCore to reach neutrino energies of 10-20 GeV

![Diagram](Image: M. Danninger)

**Case 1 (WH):**
- high energy
- up-going
- no containment

**Case 2 (WL):**
- low energy
- up-going
- strong containment

**Case 3 (SL):**
- low energy
- down-going
- strong containment
IceCube Solar WIMP Search

- Solar WIMPs
  - Recent (IC-79) analysis improvements:
    - Uses full year’s data, including summer (317 days livetime)
    - Uses DeepCore to reach neutrino energies of 10-20 GeV

Expected atmospheric neutrino flux.

Contained events (WinterLow) have lower energies than uncontained events (WinterHigh):

Probe different $M_{\chi}$
IceCube Solar WIMP Search

- **Solar WIMPs**
  - Use shape of distribution of space angle ($\psi$) w.r.t. sun
  - Estimate background using off-source data
  - Systematics include
    - ice properties
    - module efficiencies
    - $\nu$ cross sections
IceCube Solar WIMP Search

• Solar WIMPs
  • Use shape of distribution of space angle ($\psi$) w.r.t. sun
  • Estimate background using off-source data
  • Systematics include
    • ice properties
    • module efficiencies
    • $\nu$ cross sections

\[
f(\psi | \mu) = \frac{\mu}{N_{\text{obs}}} f_s(\psi) + \left(1 - \frac{\mu}{N_{\text{obs}}} \right) f_{\text{bg}}(\psi)
\]

Space Angle w.r.t. Sun

(Angle between event track & direction from the Sun)

IceCube Searches for Neutrinos from Dark Matter
IceCube Solar WIMP Search: Results

• Solar WIMPs
  • final sample
  • final limits (with expected sensitivity overlaid)

Unblinded events in different samples

Expected sens. vs. observed result

- Expected (b5)
- Expected (W'W')
- Observed (b5)
- Observed (W'W')

\( \cos(\Psi) \)

\( \log_{10}(\sigma_{SD, \text{cm}^2}) \)

\( \log_{10}(m_\chi/\text{GeV}) \)
IceCube Solar WIMP Search: Results

• Solar WIMPs
  • Final limits

**SI WIMP-proton cross-section limit**

- Most stringent $\sigma_{SD}$ limit for most models (reaches $M_\chi \sim 20$ GeV)
- Complementary to direct detection efforts
- Different (and fewer) astrophysical uncertainties
• Assumptions/Issues/Observations
  • Halo: predict $\rho$(dark matter)
    • N-body simulations
    • Gravitational lensing observations
    • Models agree at $r \sim 3$-30 kpc
  • Galactic Center: unknown $\rho$
    • simulations can’t get there
    • no direct measurements
    • but can still look for excess neutrinos therefrom
  • Interplay of decay channel and neutrino oscillations is relevant

FIG. 3. Differential muon neutrino energy spectrum per annihilation, taking neutrino oscillations into account. In this example we assume a WIMP mass of 300 GeV and 100% branching fraction into the corresponding annihilation channel.
IceCube GC & Halo WIMP Searches

• Galactic Center and Halo
  • 90% CL limits for several annihilation channels (assuming 100% BRs)
  • Early IC-22&40 analyses shown
IceCube GC WIMP Search

• Galactic Center
  • Extend previous search, adding IC-79 data with DeepCore
  • Two independent analyses:
    • Low energy ($M_\chi < 300$ GeV)
    • High energy ($M_\chi > 300$ GeV)
IceCube GC WIMP Searches

• Galactic Center
  • Extend previous search, adding IC-79 data with DeepCore
  • Two independent analyses:
    • Low energy ($M_\chi < 300$ GeV)
    • High energy ($M_\chi > 300$ GeV)
  • “Starting events” sample opens up southern sky
    • relies on muon vetoing
IceCube GC WIMP Sensitivity

• Galactic Center: IC-79 sensitivity
  • first time IceCube can reach <100 GeV masses for GC
    • 4 orders of magnitude improvement at this scale
  • unblinding of analysis underway
IceCube Halo WIMP Result

• Galactic Halo: IC-79 result
  • multipole analysis focuses on large scale anisotropies ($\ell<100$)
  • small halo-model dependencies
  • results compatible with background-only hypothesis
IceCube Dwarf Galaxy & Cluster WIMP Result

- Dwarf galaxy and galaxy clusters: IC-59 results
  - IC-59 dwarf galaxy (stacking analysis)
  - IC-59 galaxy cluster (point source search)
Future Work: IceCube/DeepCore

- IceCube/DeepCore can use cascade channel to test possible signals in PAMELA and Fermi data
  - Background from downward-going neutrino-induced muons is reduced
- (Highly effective veto and low energy reconstructions will keep muon neutrinos competitive, though.)
Conclusions

• Neutrinos are sensitive probes for detecting dark matter

• Searches for WIMP→ν signatures from distinct sources are “self-complementary,” and complementary to searches using other astrophysical messengers

• Solar WIMP annihilations to neutrinos would provide a “smoking gun” signature with minimal model assumptions

• Clever new ideas for detection channels and sources spur new analyses

• Future detectors with lower energy thresholds will probe region of parameter space made interesting by direct detection experiments
  • See PINGU talk, next.
PINGU & WIMPs

• PINGU: Precision IceCube Next Generation Upgrade
  • New IceCube in-fill array, to be proposed in fall 2013
  • Main physics goal: neutrino mass hierarchy with atmospheric neutrinos
    • see talk by T. DeYoung
      • 11:00 Weds., Anderson 250
  • But also has sensitivity to WIMPs, especially at lower WIMP masses
- Further increase sensor density relative to DeepCore
  - Baseline geometry has ~40 additional strings @ 60 DOMs
    - IceCube-based technology plus R&D modules
    - Include new low-E calibration devices
    - Geometry optimization underway
- Aims:
  - Physics program at $E_{\text{thr}} \sim$ few GeV
    - Neutrino mass hierarchy
    - Low mass WIMPs ($M_\chi \sim$10-100 GeV)
  - R&D: Cherenkov ring segment reco.?
• Below $E_\nu \sim 20$ GeV, PINGU provides gain in fiducial mass relative to the existing low $E_\nu$ in-fill, DeepCore
PINGU vs. DeepCore

- Simulated event:
  - 9.3 GeV neutrino
    - 4.4 GeV initial cascade
    - 4.9 GeV muon
  - Showing physics hits only
    - no noise shown, but noise is not hard to remove

DeepCore Only

DeepCore + PINGU
Predicted PINGU WIMP Sensitivities

• Solar WIMP sensitivity
  • PINGU can probe interesting WIMP mass range

• GC Line sensitivity
  • Again, PINGU reaches interesting masses

• N.B. Plots at trigger level
  • somewhat optimistic
PINGU Details

• Letter of Intent out in next 1-2 months
• Proposal submissions in fall
• Detector time frame
  • Could start full-detector data taking as early as 2019
• Detector cost estimate
  • $8-12M startup costs for drill
  • $1.25M per string
Conclusions

• PINGU can probe solar WIMPs with masses as low as 10 GeV

• Surrounding IceCube (and DeepCore) modules veto cosmic ray muons, giving PINGU access to downward-going starting events
  - solar WIMPs during austral summer
  - galactic center

• If approved, PINGU can be up and running in ~6 years
IceCube Dwarf Galaxy & Cluster WIMP Results

- **Dwarfs**

  ![Graph showing WIMP mass (GeV) vs. $\langle A \rangle$ for dwarfs.]

  Luenemann & Rott, ICRC 2011

  100% WW, NFW profile

- **Virgo with subclusters**

  ![Graph showing WIMP mass (GeV) vs. $\langle A \rangle$ for Virgo Cluster.]

  IceCube Preliminary

  - Best Limit obtained for Virgo Cluster

- **Galaxy clusters**

  ![Graph showing WIMP mass (GeV) vs. $\langle A \rangle$ for galaxy clusters.]

  IceCube Preliminary

  - Virgo with subclusters
  - Coma Cluster NFW and Sub
  - Virgo Cluster NFW and Sub
  - Andromeda NFW and Sub

  100% WW, NFW profile

D. Cowen/Penn State 36

Searches for Neutrinos from Dark Matter
Future Results: IceCube

- Perform line search for neutrinos motivated by
  - 130 GeV gamma ray line discussion
  - general principles
    - it's a new way to search

![Graph showing signal counts and p-value](Weniger (2011))

![Graph showing photon energy spectrum](Su, Finkbeiner (2012))

![Graph showing spectrum of unassociated 2FGL sources](Su, Finkbeiner (2012))

Rott, Astroteilchenphysik in Deutschland 2012
IceCube Results

- WIMP Decay: Assumptions
  - Dark matter is thermal relic and unstable
  - For them still to be here
    - \( \tau(\chi) > \tau(\text{universe}) = \) 4 x 10^{17} s
  - Line spectrum from \( \chi \rightarrow \nu \nu \)

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{lifetime_vs_mass}
\caption{Lifetime \( \tau \) vs. mass \( m_\chi \).}
\end{figure}
• Assumptions/Issues/Observations

• Dwarf galaxies:
  • attractive due to high mass-to-light ratio
  • many newly identified by Sloan
  • assume profile for dark matter (e.g. NFW*)

• Galaxy clusters:
  • factor in presence of substructures

• Neutrinos can probe higher WIMP masses than photons
  • Effective area for neutrinos increases with neutrino energy

Solar WIMPs

- Global SUSY analysis with IceCube
- Contours show 1-2σ credible regions

- Grey regions are without IceCube data
- Colored regions are with IceCube (but indicate relative probability only, not goodness of fit)
Challenges: Event Reconstruction

- The ice could have been designed a little better for us.
  - Photon scattering and absorption lengths are high below 2100 m
    - $\langle \lambda_{\text{eff}} \rangle \sim 50 \text{ m}$
    - $\langle \lambda_{\text{abs}} \rangle \sim 150 \text{ m}$
  - ...but they vary with depth throughout.
  - Our simulations must include all these variations in as much detail as we can measure.

- Be nice to be able to move in a calibrated light source next to each deployed DOM. Instead, use
  - muons
  - DOM LEDs