Dark Matter in a dark place:
DM annihilation in IceCube

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IceCube
Indirect Detection with neutrinos
Local Sources: the Sun and the Earth
The galactic halo & galactic center
Future prospects
Conclusions
IceCube & DeepCore

- 1 km³ neutrino detector
- 5,160 optical modules
  - 10” PMT + Complete DAQ system
- 78 ‘standard’ strings
  - 125 m string spacing
  - 17 m DOM spacing
  - ~100 GeV energy threshold
- 8 DeepCore Infill strings
  - with denser spacing
  - 50/60DOMs w/7 m spacing
  - In clearest, deepest ice
  - ~ 10 GeV energy threshold
From light to particle tracks

- All data is sent to surface
- Trigger requires 8 hit HLC (paired) DOMs within 5 µs
- 1\textsuperscript{st} guess algorithms fit light pattern to plane.
- Maximum likelihood fits find final tracks
  - Optical scattering & absorption length of ice vary with depth.
- Background from coincident overlapping events is removed by splitting event in time/space & reconstructing separately.
- Resolution & pointing checked with cosmic-ray \(\mu\) Moon shadow, horizon…

Stochastic loss

The Moon from 1 mi underground
Neutrinos from dark matter - assumptions

- What we measure is a limit on the neutrino flux from different dark matter ‘reservoirs.’ These limits are then interpreted in terms of a dark matter model.

- Dark matter spatial & velocity distributions
  - Maxwellian distribution usually assumed
  - Different halo matter distributions do not give very different answer for matter abundance at Earth

- Searches for dark matter capture (via inelastic interactions) and annihilation in Sun/Earth
  - Sun is the best place to probe spin-dependent couplings

- Searches for dark matter annihilation in the galactic halo and core.

- These assumptions apply to Super-K equally.
  - Many also apply to PAMELA, Fermi results.
Capture in the Sun - rate uncertainties

- Capture rate depends on inelastic cross-section
- 15-20% variation from velocity profile variations
- For heavy WIMPs, 3-body calculations find a large capture rate decrease caused by the presence of Jupiter.
  - Capture takes a long time.
  - Compensated by WIMPs scattered by Jupiter into the Sun?
- These effects also pertain to Earth WIMPs

C. Rott et al., JCAP 09, 029 (2011); Sivertsson & Edsjo, arXiv:1201.1895
WIMPs build up in Sun & annihilate

- At equilibrium: annihilation rate = capture rate

\[
\frac{dN}{dt} = C_C - C_A N^2 - C_E N. \quad \text{Evaporation is negligible}
\]

- For most of considered SUSY parameter range, the Sun has reached equilibrium

- Dark matter annihilates (must be Majorana particle) or decays

- Mass and final states are unknown. Final state choices:
  - \( \chi \chi \rightarrow \bar{\nu} \nu \)
  - “Hard” \( \chi \chi \rightarrow W^+W^- \) (\( \tau^+\tau^- \) for \( M_\chi \) below threshold)
  - “Soft” \( \chi \chi \rightarrow b\bar{b} \)
  - Dark matter decay also considered.

- Consider these variables by scanning over different possibilities (mass, decays), or as systematic uncertainties
Solar analyses - I

- The sun is dense enough so that neutrinos with $E > \sim 200$ GeV interact before escaping
  - NC & some CC interactions produce lower energy $\nu$
  - Neutrino energy spectrum is of lesser diagnostic value
- Sun is below horizon 6 months/year
- Combined analysis
  - IceCube 40-string +AMANDA 2008/9
  - AMANDA-II data 2001-2006
    - Denser string spacing, so better for lower masses
      - DeepCore will perform same function in future
- Results from separate analyses were combined.

Solar analyses - II

- Initial straight cuts, followed by machine learning (boosted decision tree/support vector machine)
  - Final cut was optimized to maximize model discovery potential/sensitivity
    - Different optimizations for different masses and hard/soft decays
    - Led to relatively loose cuts
- Background determined by time-scrambling data
- The shape of the space angle distribution ($\psi$) wrt. the sun was used to determine the size of the signal
- Systematic uncertainties due to optical properties of ice, sensitivity of optical modules, $\nu$ cross-sections
Solar results

- No excess seen at small $\psi$

IC40+ AMANDA only

100 GeV $\chi \rightarrow b\bar{b}$

1 TeV $\chi \rightarrow W^+W^-$
90% CL $\nu$ flux combined limits

- A model-independent flux limit is obtained for the 2 analyses.
  - Then combined, including IC22 limits.
- Limits are put on the $\nu$ flux for specific annihilation products
  - Mass and branching mode
- These limits are compared with the range of predictions from a 7-parameter MSSM scan using DarkSUSY (shaded area)
  - Incorporates LEP, CDMS(2010) and Xenon100 (2011) limits
Cross-section limits

- Assuming equilibrium, these limits are converted to spin-dependent (SD, left) & spin-independent (SI) limits
  - Independent of WIMP model.
- Shaded band shows predictions based on MSSM scans
  - Already, IceCube is sensitive to new regions of MSSM parameter space.
Kaluza-Klein dark matter

- The IC22 & IC40 analyses were also used to put limits on Kaluza-Klein dark matter
  - Probes allowed phase space for LKPs
- Same data, reinterpreted in different parameter space

\[ \Delta q \] is the mass splitting between \( q \) and \( \gamma \)

The Earth

- Best for lighter WIMPs
- Mostly spin-independent couplings
- AMANDA analysis set limits from 50 GeV to 5 TeV
- IC79/86 analysis is in progress

Galactic halo search

- Search for $\nu$ from WIMP annihilation in the galactic halo
- 1 year of IC22 data
- 4 models of halo density profile
- Sets limits on $<\sigma_A \cdot \nu>$
- Distant enough for full mixing

$$\frac{d\Phi_\nu}{dE} = \frac{<\sigma_A \nu>}{2} \frac{J(\psi)}{4\pi m^2_\chi} \frac{R_{sc} \rho_{sc}^2}{dN_\nu/dE}$$

Measure

Constrain

Galaxy

SUSY

IceCube – Phys. Rev. D84, 022004 (2011)
IceCube field of view

- The galactic center is above the horizon at the South Pole
- This search is limited to the outer that is in the Northern hemisphere
- For each direction in the sky, integrate annihilation likelihood $\sim \text{density}^2$ along line of sight.
- On-source region is within 80 degrees of galactic center
  - Only portion below IceCube horizon
- Off-source region is the same declination but shifted 180 degrees in RA
Galactic halo results

- 1367 on-source,
- 1389 off-source
- Limits conservatively assume that dark matter is evenly distributed
  - Substructure will increase the annihilation rate by boosting $<\rho^2>$
    - Accounting for substructure might ‘boost’ the limits by a factor of $\sim 2$
  - Not very sensitive to size of galactic halo & choice of halo model.
    - Widths of lines to right show uncertainty due to halo model.
- “Natural Scale” == consistency with thermal relics
IceCube, PAMELA & Fermi

- PAMELA, Fermi & HESS report excess positrons, electrons & electrons respectively from the galactic center.
  - If from leptophilic dark matter, annihilation should also produce $\nu$.
  - Due to $e^\pm$ energy loss, the annihilation must be nearby (1 kpc)
  - IceCube can constrain the masses of this dark matter

![Graphs showing $\sigma_A$ versus $m_\chi$ for different final states](image)
WIMP decay

- The same analysis set limits on WIMP decay, $\chi \rightarrow \nu \nu$
- Lifetimes $>10^{24}$ s
IC40 galactic center analysis

The galactic center is above the horizon, so there is a much larger background from muons from downgoing cosmic rays

- Reduce rate by using top/sides of detector to veto incoming particles
- Select events in $\pm 8^0 (\Delta \delta)$ by $\pm 9^0 (\Delta \alpha)$ box around the galactic center
- 798842 events in signal region
- 798819 (scaled) events in background region
- Same declination, all azimuth, less ‘guard’ region

The galactic center provides a similar constraint as the halo analysis.

N.b. IC40 $\sim 2^*$ the data of IC22.
Future plans

- More data
  - IC86 > 2 * IC40
- DeepCore will provide a huge increase in sensitivity down to 10 GeV
- Using the rest of IceCube as a veto, DeepCore should have good sensitivity to neutrinos coming from above the horizon.
  - More sensitive galactic center search
  - 12 month/year solar search
- IceCube Earth WIMP search
- Studies with $\nu_e$
  - Lower backgrounds & good energy resolution
  - Hard because of very limited angular resolution
- Search for $\nu$ from dwarf spheroidal galaxies
Sensitivity vs. energy

- Effective area increases with energy.
  - Neutrino cross-section and μ range both increase with energy
- At energies from 10-100 GeV DeepCore provides orders-of-magnitude improvement in sensitivity.
- In longer term, the proposed PINGU/MICA may push this down to ~1 GeV

Filter level effective area for IC40 & IC79 low-energy & high-energy filters.

ν from WIMP annihilation in nearby dwarf spheroidal galaxies

- Dwarf spheroidal galaxies have a high mass to light ratio, so may be a particularly promising place to search for dark matter annihilation.
  - 13 Northern hemisphere galaxies
    - within 417 kpc of Earth
    - from Sloan digital sky survey
- Quasi-point sources
- Stack sources for improved sensitivity
- Current search uses 1 year of IC59 data
- Will set limits on ν flux and $<\sigma_A \nu>$
Conclusions

- Searches for $\nu$ from WIMP annihilation with $\frac{1}{4}$ or $\frac{1}{2}$ of IceCube have already yielded interesting limits on WIMP annihilation in the Sun, the galactic halo and the galactic center.
- IceCube limits on $\nu$ from the Sun set the best limits on WIMPs with spin-dependent coupling to matter.
- Over the next few years, IceCube analyses using the full power of the full detector will either see a signal or set much tighter limits, while DeepCore will push down to lower masses.
Backups
Equilibrium Times vs. $T_{\text{Sun}}$