Cline meeting 2016

• IceCube
• atmospheric and cosmic neutrinos
• the search for dark matter
IceCube

5160 PMs in 1 km³
muon track: time is color; number of photons is energy
up-going muon track from muon neutrino (9 PeV)

date: June 11, 2014
most probable energy: 9 PeV
topology: track
shower initiated inside the detector by electron neutrino (1 PeV)

date: August 9, 2011
energy: 1.04 PeV
topology: shower
nickname: Bert
muons detected per year:

- **atmospheric**\( \mu \sim 10^{11} \)
- **atmospheric**\( \nu \rightarrow \mu \sim 10^5 \)
- **cosmic**\( \nu \rightarrow \mu \sim 10 \)

* 3000 per second
** 1 every 6 minutes
neutrino flavors in IceCube

**CC Muon Neutrino**

\[ \nu_\mu + N \rightarrow \mu + X \]

track (data)

factor of \(\approx 2\) energy resolution

\(< 1^\circ\) angular resolution at high energies

**Neutral Current / Electron Neutrino**

\[ \nu_\circ + N \rightarrow e + X \]

\[ \nu_\times + N \rightarrow \nu_\times + X \]

cascade (data)

\(\approx 15\%\) deposited energy resolution

\(\approx 10^\circ\) angular resolution (in IceCube)

(at energies \(\geq 100\) TeV)

**CC Tau Neutrino**

\[ \nu_\tau + N \rightarrow \tau + X \]

“double-bang” (\(\approx 10\) PeV) and other signatures (simulation)

(not observed yet: \(\tau\) decay length is \(50 \text{ m/PeV}\))
• IceCube

• atmospheric and cosmic neutrinos

• the search for dark matter
above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

\[
dN/dE \sim E^{-2}
\]

10–100 events per year for fully efficient 1 km\(^3\) detector

100 TeV
confirmation! flux of muon neutrinos through the Earth

neutrinos of all flavors interacting inside IceCube
muon neutrinos through the Earth → 6 sigma

**Assuming best-fit power law:**

- Unfolding
- Conv. atmospheric $\nu_\mu + \bar{\nu}_\mu$
- Astrophysical $\nu_\mu + \bar{\nu}_\mu$

**IceCube Preliminary**

Events per bin

$\log_{10}$ (median neutrino energy / GeV)
2 year HESE
• we observe a diffuse and isotropic flux of neutrinos from extragalactic sources or the Galactic halo!

• where do they come from? Dark matter!
late decay of PeV-mass dark matter

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3 year HESE

ICECUBE PRELIMINARY

Galactic

TS = 2 \log(L/L_0)

0 11.2917
4 year HESE

ICECUBE PRELIMINARY

where do they come from?
The spectrum is not a power.
• IceCube
• atmospheric and cosmic neutrinos
• the search for dark matter
IceCube targets for dark matter annihilation

- Sun
- Galactic Centre
- Dwarf galaxies
- Earth
- Galactic Halo
- Galaxy clusters
Galactic center and halo
dwarfs and clusters of Galaxies
$\chi\chi \rightarrow \tau^+ \tau^-$

NFW
WIMP Capture and Annihilation

1. Halo WIMPs scatter on nuclei in the Sun
2. Some lose enough energy in the scatter to be gravitationally bound
3. Scatter some more, sink to the core
4. Annihilate with each other, producing neutrinos
5. Propagate + oscillate their way to the south pole, convert into muons in the ice

$$\chi + \chi \rightarrow W^+ + W^- \rightarrow \nu + \nu$$

$$b + b \rightarrow \nu + \nu$$
\[
\frac{dN_\chi}{dt} = C_{sun} = \varphi_\chi \sigma_{sun}
\]

- \(\varphi_\chi = \left[ \frac{\rho}{m_\chi} \right] v_\chi\)

- \(\sigma_{sun} = \frac{M_{sun}}{m_p} \sigma_{\chi p}\)

- \(C_{sun} = 2 C_{annihilation} \quad \text{(equilibrium)}\)

Given a cross section on protons and a branching ratio of the annihilation products into neutrinos (via \(\tau, b\) or \(W\) for instance) the model is seen or ruled out.
\[ \frac{dN_{\chi}}{dt} = C_{\text{sun}} = \varphi_{\chi} \sigma_{\text{sun}} \]

- \[ \varphi_{\chi} = \left[ \frac{\rho}{m_{\chi}} \right] \nu_{\chi} \]
- \[ \sigma_{\text{sun}} = \left( \frac{M_{\text{sun}}}{m_p} \right) \sigma_{\chi p} \]
- \[ C_{\text{sun}} = 2 C_{\text{annihilation}} \quad \text{(equilibrium)} \]

Given a cross section on protons and a branching ratio of the annihilation products into neutrinos (via \( \tau, b \) or \( W \) for instance) the model is seen or ruled out.
detection is a smoking gun

- indirect rates are dictated by the interaction cross section of WIMPS with hydrogen.
  → no unknown astrophysics

- in the neutrino case there is a direct connection between theory and observation and the background is understood.
IceCube 79 data

- Up-going 1
- No containment

Starting events → lower energy

- Up-going 2
- Strong containment

- Down-going 3
- Strong containment

Graph showing L2 filter rate (Hz) vs. run number with a 'Summer' period indicated.
\[ \mu = 1 \text{ TeV} \]

\[ m_\chi = 50 \text{ GeV} \]
1 TeV wimp signal at 90% CL limit

event selection 1 (winter, high energy)

50 GeV wimp

event selection 2 (winter, low energy)

event selection 3 (summer, low energy)

background expectation from data

observation

signal simulation (e.g. 1000 GeV)
perform your own IceCube dark matter search

http://arxiv.org/abs/1601.00653

- software to test your own model (cross section/branching ratios)
- IceCube data available
wimp annihilation in the center of the Earth

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

![Graph showing capture rate in the Earth vs WIMP mass and cross section vs mass](image)
Limits after 3 years (6 soon)  
spin independent ($A^2$ handicap)
Limits after 3 years (6 soon) spin dependent ($A^2=1$)

*IceCube Preliminary*
conclusions

• far from the square root regime

• we are designing a next-generation detector with a larger volume at higher energy and a lower threshold at low energy

• we want to deploy DMice at the South Pole (see talk by Reina Maruyama)
The IceCube–PINGU Collaboration

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Swedish Polar Research Secretariat
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US National Science Foundation (NSF)
IceCube drilling to best low background site on Earth:

→ radio-pure ice
→ no seasonal variations (temperature, humidity,…)
→ shielded from cosmic rays by IceCube veto

• DM-ice, DeepCore upgrades

• $1.25M per string of 60 ten inch PMTs (data to your pc, includes logistics)