The IceCube Neutrino Observatory

IceCube Array
86 total strings, including 8 DeepCore strings

60 optical sensors on each string

5160 optical sensors
The IceCube Neutrino Observatory - Canadian activities

IceCube Array
86 total strings, including 8 DeepCore strings

60 optical sensors on each string
5160 optical sensors

IceCube Lab
Skiway
Amundsen-Scott South Pole Station

Digital Optical Module

DeepCore
Foundation of the Canada effort (2010); measurements of atmospheric neutrino oscillations and WIMP indirect searches
The IceCube Neutrino Observatory - Canadian activities

IceCube Array
86 total strings, including 8 DeepCore strings

60 optical sensors on each string

5160 optical sensors

IceCube Lab
Skiway
Amundsen-Scott South Pole Station

Canadian focus added in 2014 on high energy neutrino searches; tests of neutrino flavor ratios and Lorentz invariance

DeepCore
Foundation of the Canada effort (2010); measurements of atmospheric neutrino oscillations and WIMP indirect searches
- 78 Strings
- 125m string spacing
- 17m DOM spacing
High Energy Neutrino Searches

IceCube Preliminary

*Darren R. Grant - University of Alberta*

C. Kopper/ C. Weaver - UofA
Tests of neutrino flavour ratio

C. Kopper/ C. Weaver - UofA
IceCube

- 78 Strings
- 125m string spacing
- 17m DOM spacing
IceCube

- 78 Strings
- 125m string spacing
- 17m DOM spacing
IceCube

- 78 Strings
- 125m string spacing
- 17m DOM spacing
IceCube-DeepCore

- 78 Strings
- 125m string spacing
- 17m DOM spacing
- Add 8 strings
- 75m string spacing
- 7m DOM spacing
IceCube-DeepCore

Atmospheric neutrino oscillations  S. Nowicki/C. Krauss - UofA/ K. Clark UofT
Atmospheric neutrino oscillations

S. Nowicki/C. Krauss - UofA / K. Clark UofT
Atmospheric neutrino oscillations

**IceCube-DeepCore**

S. Nowicki/C. Krauss - UofA/ K. Clark UofT

**PRELIMINARY**

Normal mass ordering assumed, 90% CL contours

| $|\Delta m^2_{31}| [10^{-3} eV^2]$ |
|------------------|------------------|
| 0.30             | 0.35             |
| 0.40             | 0.45             |
| 0.50             | 0.55             |
| 0.60             | 0.65             |
| 0.70             |                  |

| $\sin^2(\theta_{23})$ |
|------------------|
| 0.20             |
| 0.25             |
| 0.30             |
| 0.40             |
| 0.50             |
| 0.60             |
| 0.70             |

**DeepCore**

**IceCube**
IceCube-DeepCore

Indirect dark matter searches

R. Moore - UofA/ K. Clark UofT

Spin-dependent

Spin-independent

Darren R. Grant - University of Alberta
Indirect dark matter searches

IceCube-Preliminary

Darren R. Grant - University of Alberta
The IceCube Neutrino Observatory - Generation 2 (Gen2)

IceCube Lab
Skiway
Amundsen-Scott South Pole Station
Surface Veto Array
High Energy Array (astrophysical neutrinos)
IceCube
DeepCore
PINGU (neutrino mass ordering, tests of maximal mixing, indirect dark matter)

Darren R. Grant - University of Alberta
IceCube-Gen2

the High Energy Array (goal of 10x sensitivity to high energy neutrinos)

- ~120 new strings
- up to 250m string spacing
- 80 modules/string at 17m spacing
IceCube-Gen2

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- up to 250m string spacing
- 80 modules/string at 17m spacing

Darren R. Grant - University of Alberta
IceCube-Gen2

- Add 40 strings (baseline target)
- ~20m string spacing
- 3-5m DOM spacing
- ~15x higher photocathode density
PINGU sensitivity to the neutrino mass ordering (3 sigma in 3-4 years)
IceCube-Gen2

PINGU sensitivity to the neutrino mass ordering (3 sigma in 3-4 years)
IceCube-Canada Long Range Planning (2017 - 2021)
1. Physics and other research goals:

- Exploit the full capability of the current IceCube-DeepCore arrays, including leading measurements for:
  - neutrino oscillations
  - dark matter
  - atmospheric neutrino fluxes
  - particle physics at the highest energy sources (including acceleration mechanism)
  - tests of long-baseline vacuum oscillation flavour ratios
  - tests of Lorentz invariance with high energy neutrinos
  - supernova neutrinos
  - beyond standard model searches

- Complete the design of PINGU and the High Energy Array

- Complete the design and fabrication of Gen2 optical modules; first deployments 2020/21; first data of new detector arrays.
2. Expected HQP training:

The IceCube program has proven very popular with students and has attracted scholarship students and a number of students from high-ranking international programs.

With an increase in total FTE researchers (currently forecast and anticipated) we expect student (PDF) numbers to increase by 75% (200%) in 2018 and again by 65% (33%) in 2021.

The graph shows the breakdown of FTE for Postdoctoral Fellows, Graduate students, Undergraduate students, and Faculty from 2010 to 2020. The aggressive ramp-up post-2017 assumes successful international Gen2 project funding starting in 2018.
3. Equipment needs:

- Anticipate the need for a large-scale cold test facility for next generation optical modules (and potential water test facility at SNOLAB) (CFI; ~$1.5M, 2017/18)

- Electronics shop time (TRIUMF and UofA) for next generation module design and testing of main boards, calibration systems, front-end DAQ (CFI; ~$3.5M; 2017/19)

- Potential optical module fabrication facility (CFI; ~$1.5M; 2018)

- Photosensor development facility (jointly with TRIUMF) (NSERC/CFI; see Fabrice’s talk)

- (plans for request ~30% Gen2 DOMs from CFI)

- total CFI requests planned ~$12M-15M
4. Computing needs anticipated:

- ~25 TB per user for storage (based on average IceCube analysis sets)
- approximately steady increases in CPU with increase in group size
- large increase of GPU-years (~100x CPU) in 2016 (proposed *illume* cluster - Kopper CFI JELF)
5. Technical support requirements:

- CPP+ (MRS - Alberta/Toronto) is absolutely vital for the long-term Gen2 plans

- TRIUMF electronics and detector shops are essential to the proposed detector developments during this period

- SNOLAB facilities (space and expertise in low-background counting) are planned for use (calibrations, detector operation/verification, R&D)
6. Relationships with other projects:

- common elements are being explored with HyperK-Canada. In particular potential design and development of a multi-PMT optical module, simulations, PMT characterization

- planned photosensor development activities have potential overlap with long term SNOLAB program (nEXO, DEAP-50T, SNO++); synergies with Queen’s-led CFREF under review
IceCube-Canada Long Range Planning (2017 - 2021)

7. Relationships with international partners (primarily via the IceCube collaboration):

- USA (WIPAC leadership of the IceCube operations including the data/computing facility; new US collaborators joining for Gen2 including Columbia, MIT, Notre Dame)

- Europe (Belgium, Germany - particular overlap with Erlangen and DESY for module development, Sweden; significant increased activity in UK and Denmark for Gen2)

- Japan and S. Korea (Chiba, University of Tokyo, SKKU; collaborating on activities for module development)
Summary and Outlook

IceCube-Canada has matured into a vibrant program in the past 5 years with established leadership in the core analyses of the project (neutrino oscillations, high energy neutrinos, dark matter)

Canadian researchers currently hold guiding roles in the collaboration, including chair publications committee, co-conveners of the diffuse, the oscillations and PINGU-analysis working groups, co-lead scientist for future upgrades

Current projection is the Canadian group will have tripled in size in 2016 (since 2011) with estimates that could see this double again by 2021

Future planning for Gen2 (lead by Canadian researchers) is developing rapidly; current timeline is limited by funding planning.

Design Phase

- Y1: CDR
- Y2: PDR
- Y3: FDR

Prototyping Phase

Procurement/production

Construction Phase

Y5 - Y13:
- PINGU ~3 yrs
- High Energy Array ~6 yrs

target 2020 start
Backup slides
cascade events only
p-value = 18 %
Neutrinos

Antineutrinos

\[ P(\nu_e \rightarrow \nu_e)_{\text{PREM}} = \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) \]

\[ \Delta m^2_{32} = 2.32 \times 10^{-3} \text{ eV}^2 \]

\[ \sin^2(2\theta_{23}) = \frac{\pi}{4} \]
Neutrinos

\[ P(\nu_e \rightarrow \nu_\mu)_{\text{PREM}} \]

Antineutrinos

\[ P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)_{\text{PREM}} \]

Normal hierarchy

\[ \Delta m^2_{32} = 2.32 \times 10^{-3} \text{ eV}^2 \]

\[ \sin^2(2\theta_{23}) = \frac{\pi}{4} \]

Inverted hierarchy

\[ P(\nu_e \rightarrow \nu_\mu) = \sin^2(2\theta) \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) \]
Using atmospheric neutrinos to measure the NMO

Up to 20% differences in $\nu_\mu$ survival probabilities for various energies and baselines, depending on the neutrino mass hierarchy.
PINGU and the NMO

• Cannot distinguish $\nu$ from $\overline{\nu}$ directly – rely instead on differences in fluxes, cross sections (and kinematics)

• Differences clearly visible in expected atm. muon ($\nu + \overline{\nu}$) rate even with 1 year’s data

• Note: detector resolutions not yet included here
PINGU and the NMO

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- Differences clearly visible in expected atm. muon ($\nu + \overline{\nu}$) rate even with 1 year’s data

  - Note: detector resolutions not yet included here
Distinctive (and quite different) hierarchy-dependent signatures are visible in both the track and cascade channels.

- Quantity shown is an illustration of statistical significance per bin (as per Akhmedov et al. arXiv:1205.7071)
- Full MC for detector efficiency, reconstruction, and particle ID included

In Fig. 13 we show the distinguishability metric evaluated for the track channel and cascade channel, where the energy-dependent PID efficiency for separating the two channels is parametrized using Fig. 9, based on a full simulation and reconstruction of simulated data.

4.1.2. Analysis Method

Three different independent analyses were employed in this study. Full details of the statistical methods are given in Appendix A, where we show that the approaches agree at the 5% level. The most detailed method, using a library of simulated events to generate the distribution of observables ($E_\nu$ and $\cos(\theta)$) expected from different possible combinations of true oscillation parameters, generates ensembles of pseudo-experiments for these scenarios and uses a likelihood ratio method to determine the degree to which one hierarchy is favored. Although this approach is currently too computationally intensive to incorporate the full range of systematics under investigation, it provides a benchmark to ensure that the statistical approximations used in the other two methods are valid.
PINGU and the NMO - predicted sensitivity

- With baseline geometry, a determination of the mass hierarchy with 3σ significance appears possible with ~3.5 years of data
  - Primary estimate uses parametric detector response model based on simulations
  - Vetted against full Monte Carlo studies with more limited statistics and range of systematics
- Optimization of detector geometry & analysis techniques and more detailed treatment of systematics nearing completion
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![Graph showing PINGU livetime vs. NMH significance](arXiv:1401.2046)
Optimized PINGU and the NMO - predicted sensitivity

- Studies of the PINGU geometries reviewed a very broad maximum for optimizing the signal to the mass hierarchy.

- Selected geometry (40 strings, 96 modules per string) optimizes performance as a function of overall estimated cost.

- The optimized geometry is remarkably robust to the remaining systematics under study.

after Blennow et al., arXiv:1311.1822