Neutrinos at the South Pole -
The PINGU Detector

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The IceCube Neutrino Telescope

- **IceCube Lab**
- **IceTop**
  - 81 Stations
  - 324 optical sensors
- **IceCube Array**
  - 86 strings including 8 DeepCore strings
  - 5160 optical sensors
- **DeepCore**
  - 8 strings spacing optimized for lower energies
  - 480 optical sensors
- **Eiffel Tower**
  - 324 m
- **Bedrock**
The IceCube Neutrino Telescope

- IceCube Lab
- IceTop 81 Stations 324 optical sensors
- IceCube Array 86 strings including 8 DeepCore 5160 optical sensors
- DeepCore 8 strings-spacing optimized 480 optical sensors
- Eiffel Tower 324 m
- Bedrock
- Cables and DOMs

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How do we Detect Neutrinos?

- IceCube separates neutrino interactions into two types:
Events in the Detector

- Events are separable using their signature in the detector

**CC Muon Neutrino**

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

“Track”

**NC Neutrino**

\[ \nu_X + X \rightarrow \nu_X + X \]

“Cascade”
• 78 Strings
• 125m string spacing
• 17m DOM spacing

IceCube

10 T eV
1 EeV
1 T eV
100 GeV
10 GeV
1 GeV
100 MeV
10 MeV
100 MeV
10 GeV
100 GeV
1 TeV
10 TeV
1 EeV

IceCube

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IceCube Results
IceCube + DeepCore

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

- Approximately 1 year of data analyzed
- High rate in detector provides large event sample
- No-oscillation hypothesis rejected at 5.6σ
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Even Lower Energies

- Deep Core is a success, but we get access to more physics with a lower threshold

- muon neutrino disappearance

- maximal $\theta_{23}$ measurement

- lower energy dark matter

- neutrino mass hierarchy
IceCube + DeepCore + PINGU

- 78 Strings
- 125m string spacing
- 17m DOM spacing
- Add 8 strings
  - 75m string spacing
  - 7m DOM spacing
- Add 40 strings
  - 20m string spacing
  - 5m DOM spacing
Mass Hierarchy Determination

- Experiments use the difference in MSW effect for $\nu$ and anti-$\nu$
- Combine with difference in $\nu$ and anti-$\nu$ cross-section
Neutrino Oscillograms

- The cross-section and flux are different for $\nu_\mu$ and $\bar{\nu}_\mu$
- The patterns are therefore different!
Mass Hierarchy Determination

Cascade-Like Events

Track-Like Events

- Difference in counts between hierarchies illustrates distinguishability
- Event selection, reconstruction not included here
The Bottom Line

- Most important question is how long does it take to make a measurement?
Future of the NMH Measurement

- **MANY** caveats
  - median outcome shown
  - width indicates effect of main uncertainty ($\delta_{CP, \theta_{23}}$)
  - dates are also bound to change as time goes on

after Blennow et al., arXiv:1311.1822
Conclusion

- IceCube and DeepCore have been very successful and have shown that particle physics is possible in ice
- PINGU will provide insight into the nature of the NMH
- Canada has taken a leading role in the development of PINGU, responsible for all simulation while contributing to analysis and reconstruction
Backup
IceCube + DeepCore

- Addition of extra strings in closer proximity lowers the detection threshold energy
IceCube + DeepCore

• Addition of extra strings in closer proximity lowers the detection threshold energy

• This allows for sensitivity at the energy of an oscillation minimum
Distinguishability

\[
\frac{N_{IH} - N_{NH}}{\sqrt{N_{NH}}}
\]

- Add in the proper reconstruction of the events