IceCube, DeepCore and beyond

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for the IceCube Collaboration

September 2018 TMEX18, Warsaw



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- Ice Cherenkov \mathbf{v} detector
- 1.5 2.5 km under ice
- 5,160 **DOMs**
- 86 strings
- Spacing: 17m in z, 125 in x-y
- 1 km3 volume
- LE extension: DeepCore
 - 7m in z
 - 40-70m in x-y



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Large, sparsely instrumented V

*approx. to scale

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Neutrino signatures

• Above a few GeVs it's all Deep Inelastic Scattering



- Hadrons, e and most taus are point like
 → cascades
- Muons and PeV+ taus have a *long range*→ tracks

Muon-track events



Muon-track events



Cascade-like events



Cascade-like events



Neutrinos accessible



Neutrinos accessible



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The low energy side of IceCube

Towards precision physics in ice

Atmospheric neutrinos

• Some people's background is another people's signal





Atmospheric neutrinos

• Free beam of neutrinos. Wide E range, varying travel distance.



Analysis strategy

- Background
 - Aggressive vetoing to **reject muons**
 - Select starting events only
- Reconstruction
 - 8D likelihood w/track+cascade
 - Using detailed ice description
- Particle identification
 - Ratio of track+cascade/cascade only fit
- Parameterize systematic effects
 - Fit together with physics parameters



Atmospheric neutrinos

Free beam of neutrinos. Wide E range, varying travel distance.



Standard oscillations in matter

Survival probabilities for atmospheric neutrinos (no approximations)



Results: NuMu disappearance

- Analysis in L vs E space
- 48k events in 3 years
- $\chi^2 = 117.4/119$ dof
- Data driven background



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Phys. Rev. Lett. 120, 071801 (2018)

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Results: NuTau appearance

- Let tau neutrino component float
- Slightly below expected value (1.0)
- Not significant yet



Sterile neutrino flux modifications

For a higher mass difference
 → higher E

$$P^{2\nu}_{\nu_{\alpha} \to \nu_{\beta}}(L, E) = \sin^2 \left(2\theta\right) \sin^2 \left(\frac{\Delta m^2}{4E}L\right)$$

 Additional sterile mixing + matter enhancements changes oscillation amplitudes also at low energies



Results: Sterile neutrinos - LE

• How would a sterile neutrino affect the sample?



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Results: Sterile neutrinos - HE

 How would a sterile neutrino affect the high energy sample?

$$\begin{vmatrix} \mathbf{v}_{e} \\ \mathbf{v}_{\mu} \\ \mathbf{v}_{\tau} \\ \mathbf{v}_{s} \end{vmatrix} = \begin{vmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\mu 1} & U_{\tau 2} & U_{\tau 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{vmatrix} \mathbf{v}_{4}$$

Phys. Rev. Lett. 117, 071801 (2016)



Summary from the low energy side

- Atmospheric neutrinos used for **particle physics** studies
- Events are hard to reconstruct, but we have thousands per year
- Measurements of **standard oscillations** improving rapidly
- Tau neutrinos from oscillations beginning to appear
- Exotic BSM ongoing: **steriles**, non-standard interaction, decoherence

Studies start to be limited by systematics

we need more calibration sources

The high energy side of IceCube

Will come on Friday

Looking into the future



The IceCube Upgrade



- More sensors in same volume
 - Lower DeepCore E threshold
 - Better oscillation physics
- New calibration sources
 - Controlled light emission
 - Improved ice description
 - Better pointing at HE by factor 2
 - Re-analysis of current HE data

The IceCube Upgrade



- Example of reanalysis of data with improved reconstruction
- Results from 2015 and 2017 used roughly same detector livetime



And at high energies

Potential for better resolution





A step further: IceCube Gen-2



A step further: IceCube Gen-2

Main detector

- +120 strings
- 240m inter-string distance
- 80 Oms per string
- 8 km³ volume

Extensions

- Surface array (CR and veto)
- Radio array (EHE neutrinos)



Final words

IceCube: a neutrino observatory from GeV to PeV energies

- <u>Neutrino oscillations</u>
- <u>Sterile neutrinos</u>
- Astrophysical neutrinos
- Dark matter
- Cosmic ray physics
- ...

More data and better calibration \rightarrow constantly improving results

Upgrades proposed: maximize the science output at all energies

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International Funding Agencies

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