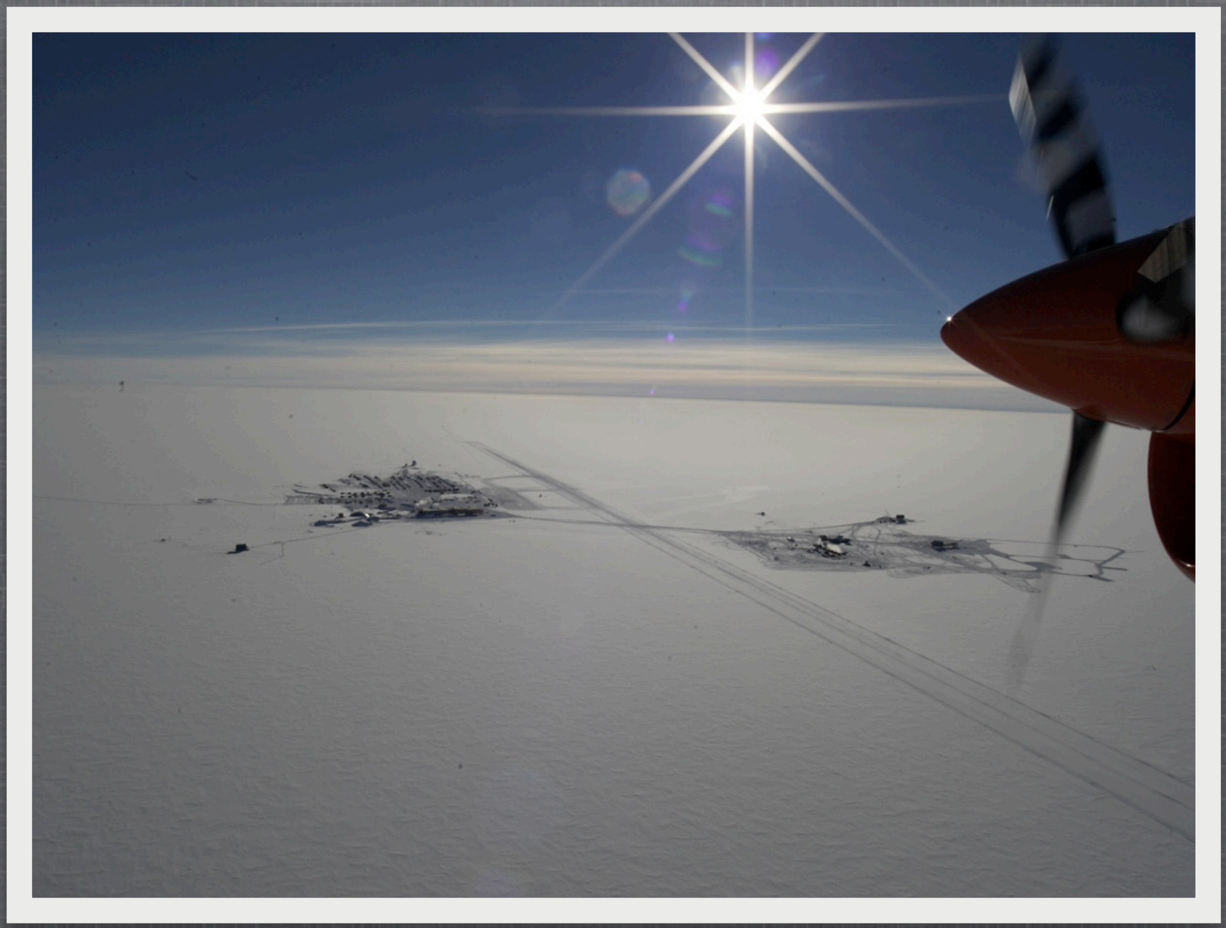
THE PHYSICS POTENTIAL OF ICECUBE'S DEEP CORE SUB-ARRAY



D. Cowen/Penn State & Humboldt U.

Outline

- Introduction to IceCube and IceCube Deep Core (ICDC)
- Design of IceCube Deep Core
- Physics Reach
  - Full list
  - Effective areas
  - Specific physics examples
    - WIMPs
    - Southern sky sources
    - Neutrino oscillations

Introduction

- Deep Core originally conceived as a way to improve IceCube's sensitivity to solar WIMPs
  - About 2 years ago, our Swedish collaborators proposed a denser sub-array as a way to lower IceCube's neutrino energy threshold
- That a dense sub-array could do that and much more soon became clear to the following people:

The IceCube Collaboration

- Bartol Research Inst.
- Anchorage University
- Pennsylvania State U.
- UC Berkeley
- UC Irvine
- Clark-Atlanta University
- Georgia Tech.
- University of Maryland
- U. Wisconsin-Madison
- U. Wisconsin-River Falls
- LBNL, Berkeley
- University of Kansas
- University of Alabama
- Southern U., Baton Rouge
- Ohio State University

- University of Oxford
- Uppsala University
- Stockholm University
- Universite Libre de Bruxelles
- Vrije Universiteit Brussel
- Universite de Mons-Hainaut
- Universiteit Gent
- University Utrecht
- EPF Lausanne
- RWTH Aachen
- Humboldt Univ., Berlin
- Universitat Dortmund
- MPIK Heidelberg
- Universitat Mainz
- Universitat Wuppertal
- DESY, Zeuthen

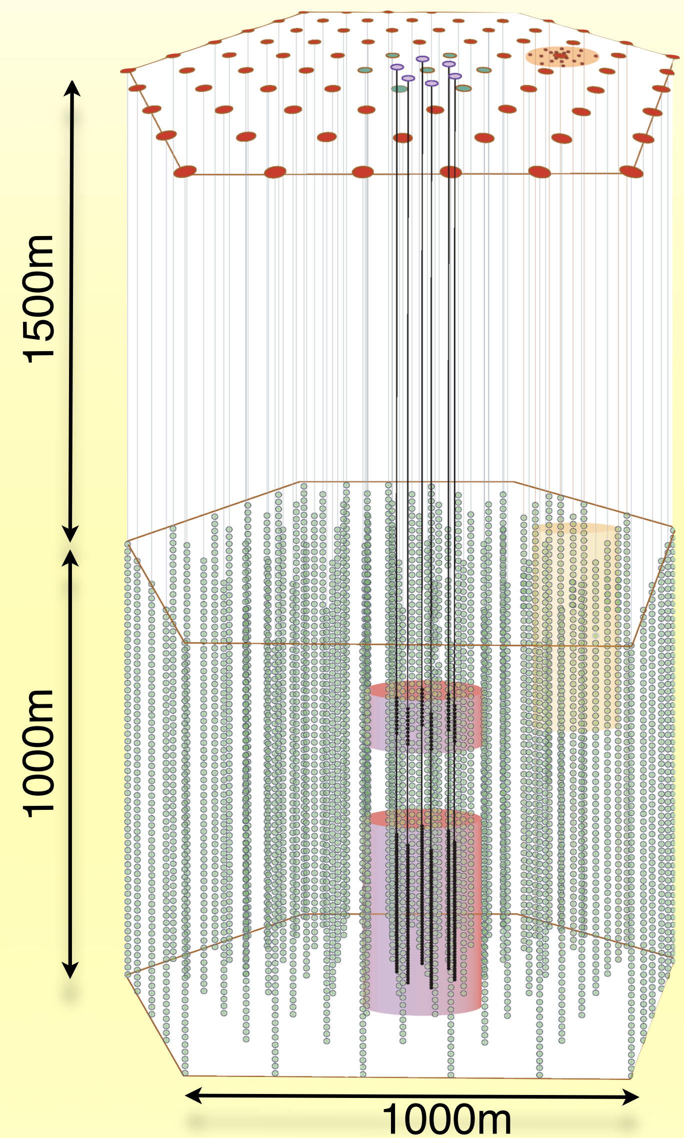
- Chiba University

- University of Canterbury, Christchurch

Approximately 250 winter-loving people from 33 Institutions

IceCube Deep Core ("ICDC")

- ICDC extends low energy reach by ~1 order of mag.
- Design:
  - 6 special strings + 7 nearby IceCube strings
    - 72m interstring spacing
    - 7m vertical spacing
      - 10x higher DOM density
  - high QE Hamamatsu PMTs
  - primarily in clearest deep ice
    - λ_{eff} ~ 40-50m
  - surrounding strings serve as highly effective active veto
- Funding for hardware (PMTs, strings, etc.) from Europe



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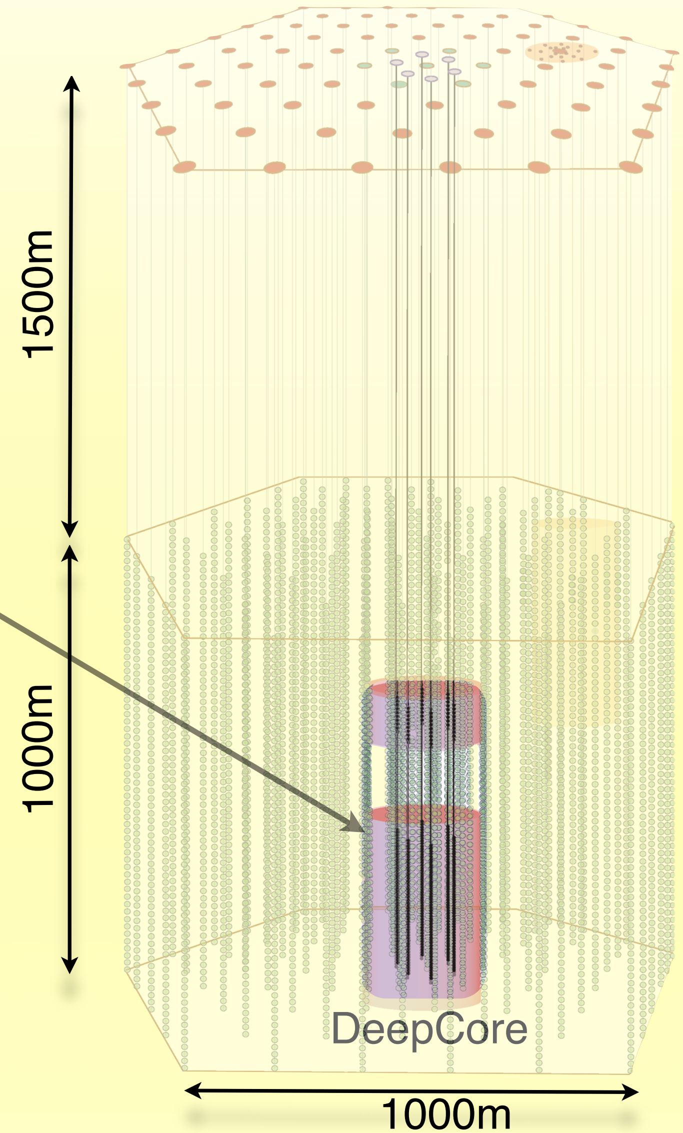

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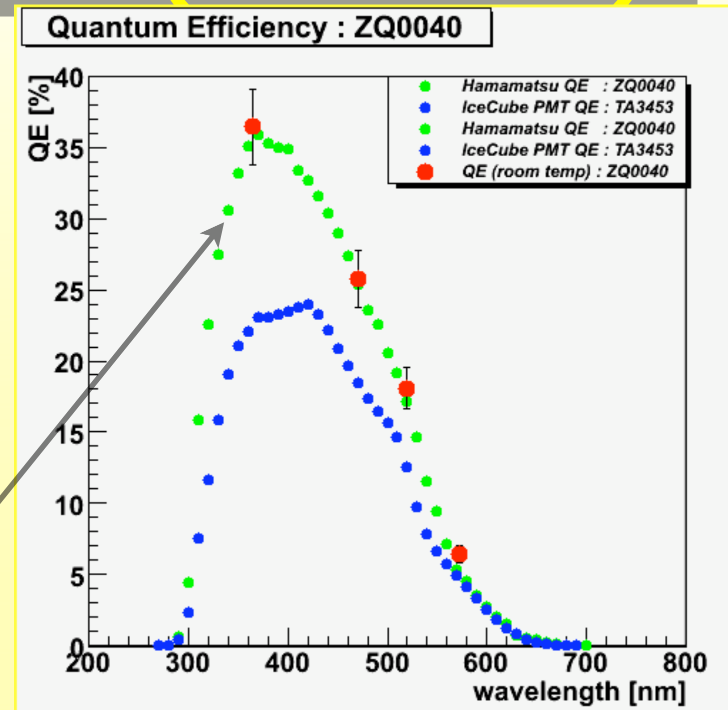

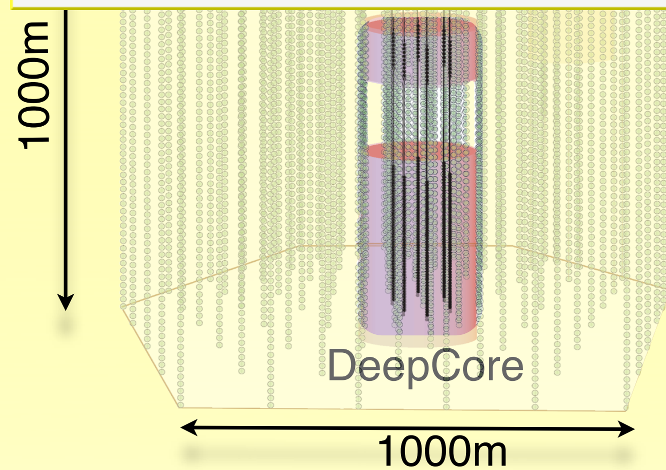

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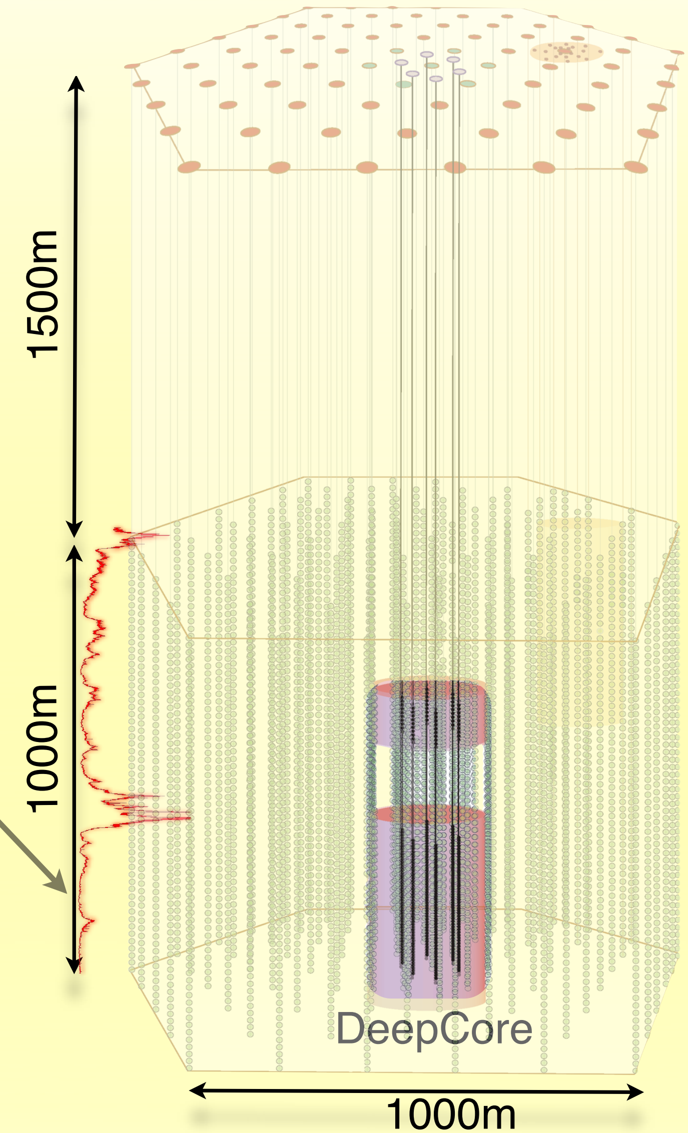

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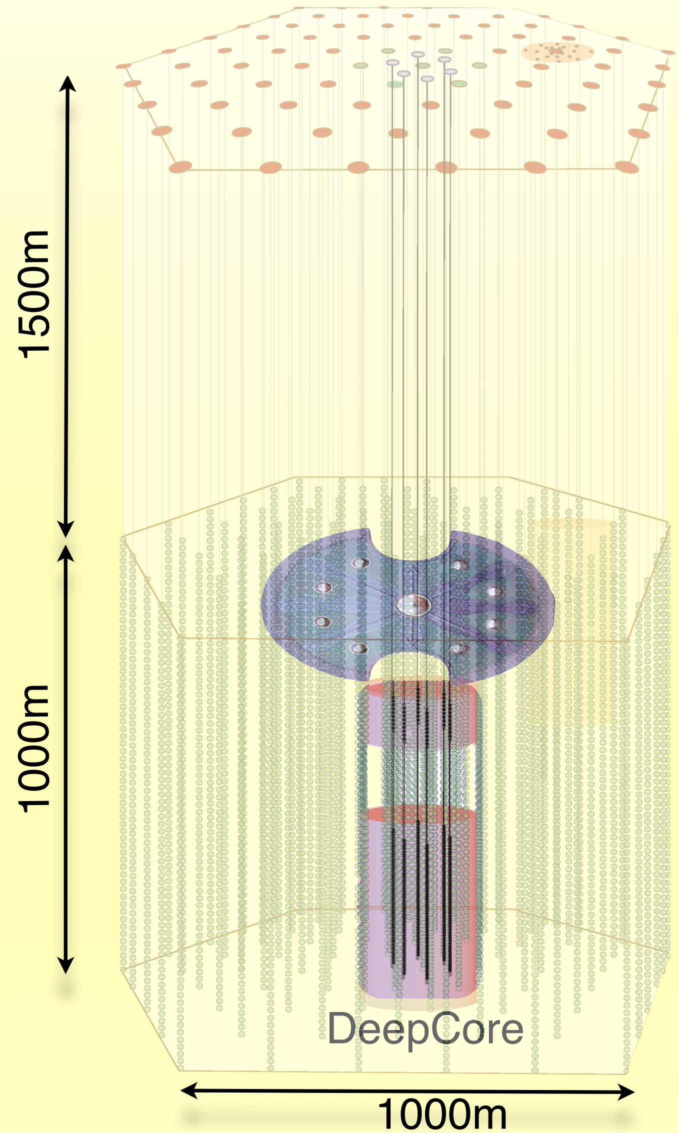

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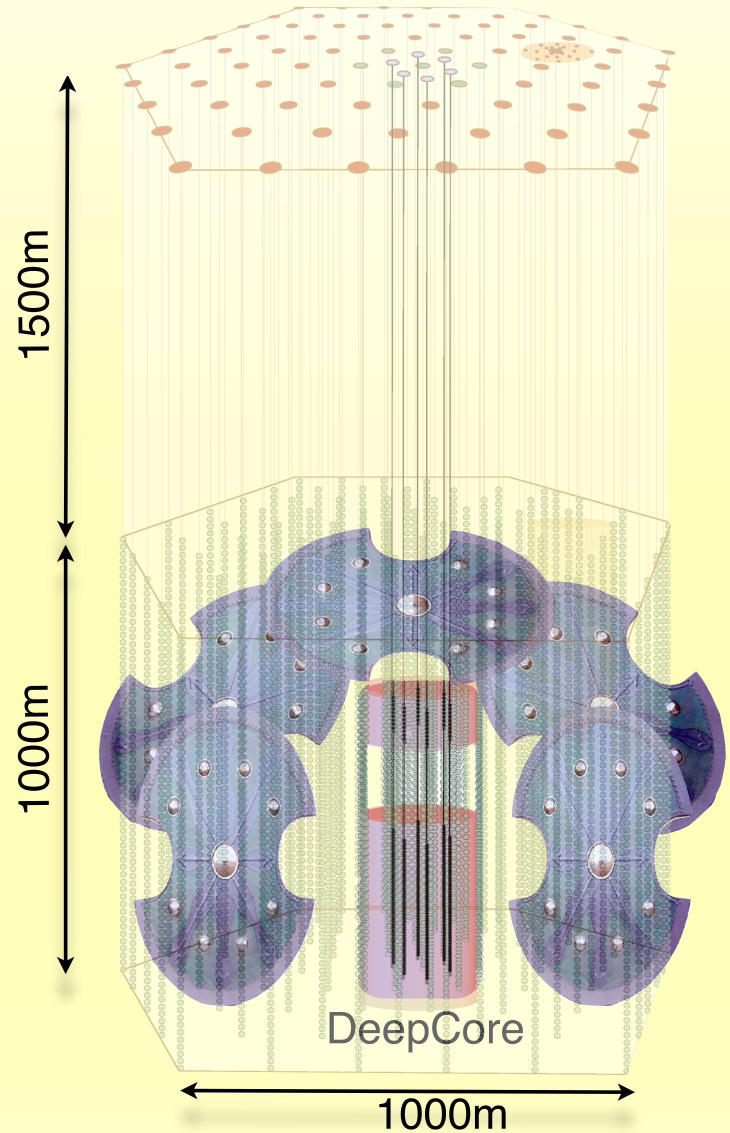

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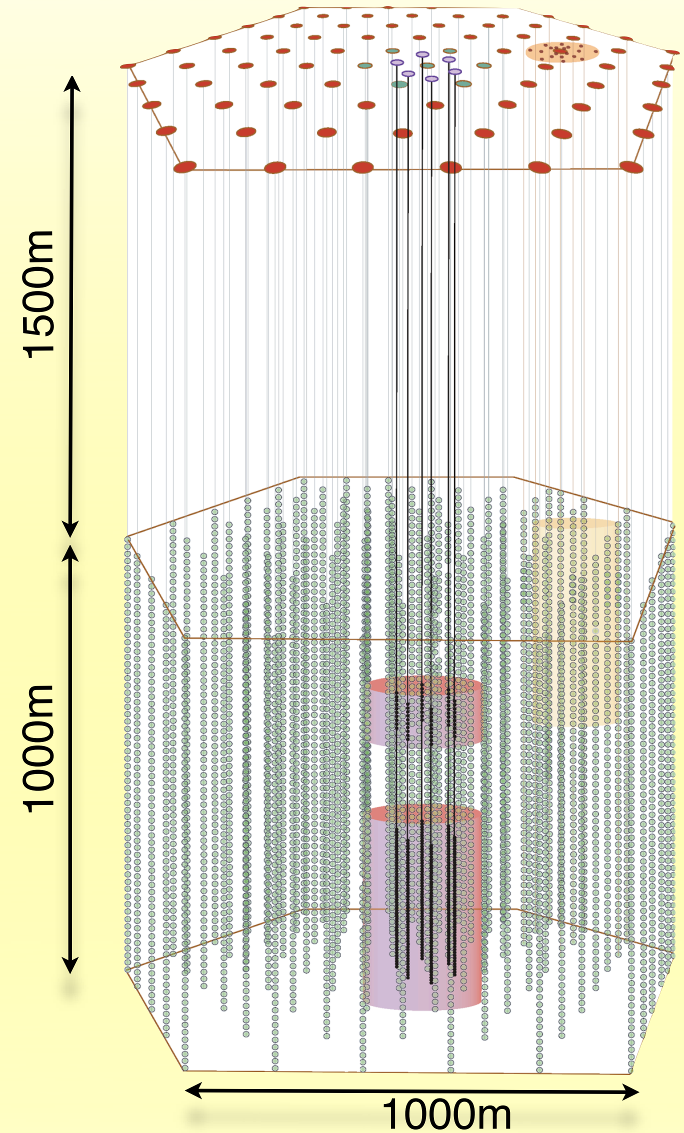
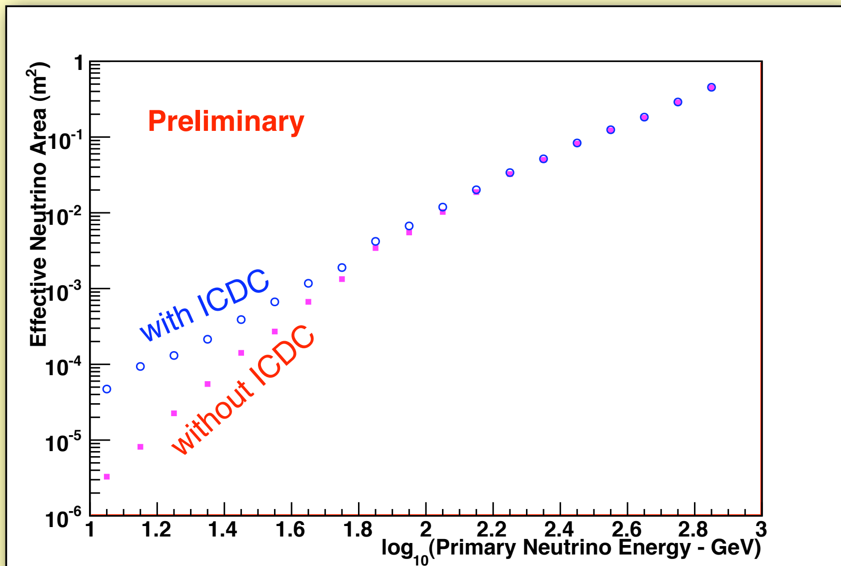


ICDC A_{eff} and V_{eff}

A_{eff}: For downgoing muon neutrinos following E^{-2} spectrum that trigger the detector ("SMT4", no reconstruction efficiencies included yet!)

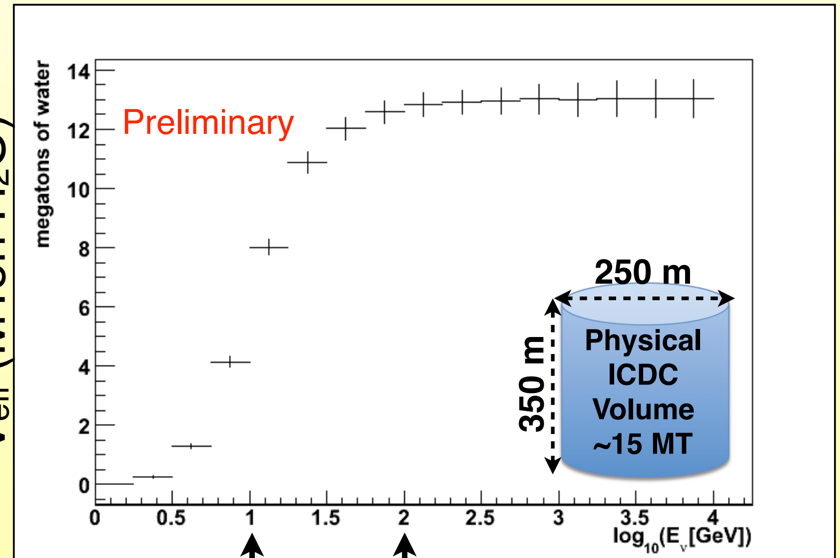
$A_{eff}(m^2)$



10 GeV

100 GeV

V_{eff} (MTon H_2O)



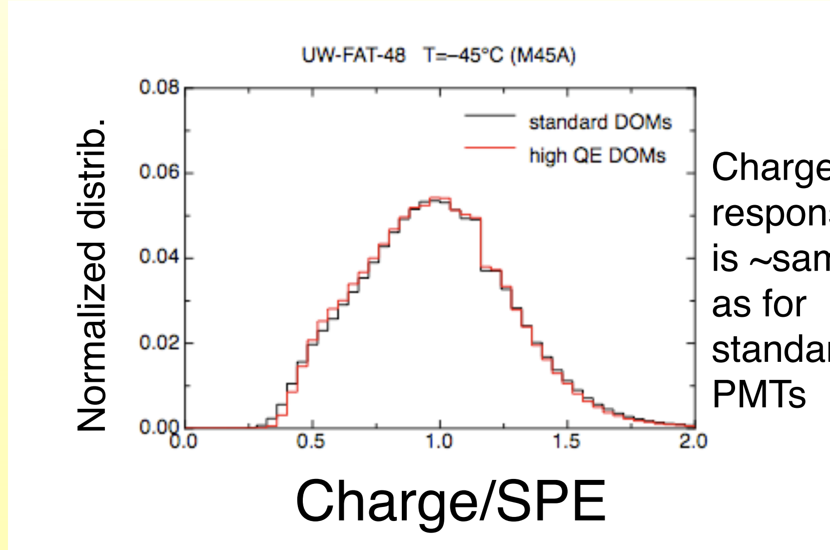
10 GeV

100 GeV

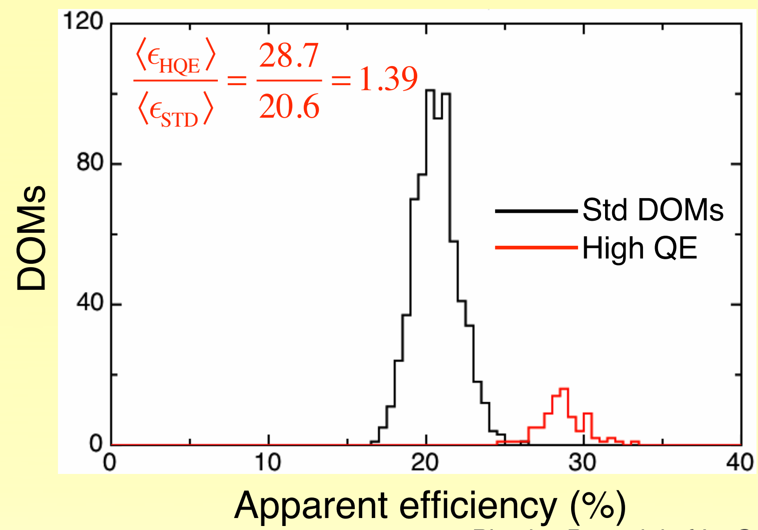
V_{eff}: For contained downgoing muon neutrinos that interact in the fiducial volume and trigger the detector ("SMT4", no reconstruction efficiencies included yet!)

High QE PMTs

- New photocathode material
  - Almost everything else about the PMT is the same (except price and intrinsic noise)
- Lab measurements show about 40% improvement in QE
- In situ measurements have thus far validated lab measurements (see next slide)



Charge response is ~same as for standard PMTs



Optical efficiency measured in lab at 405 nm (relative to 2" PMT)

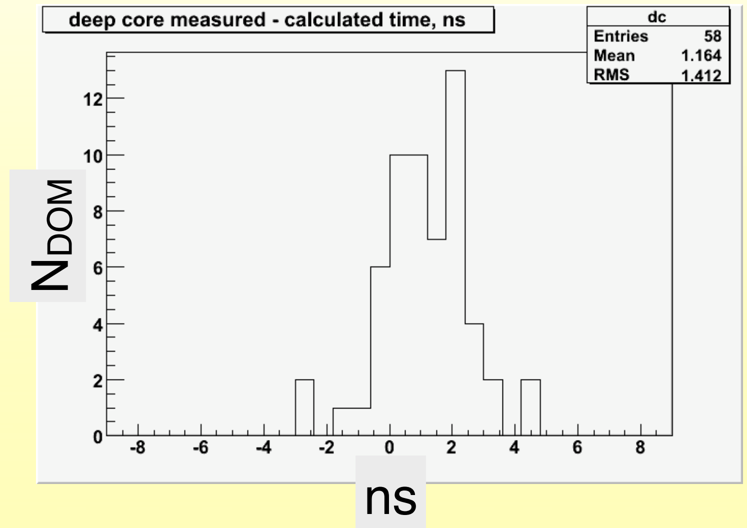
Performance of New DOMs*

*Digital Optical Module

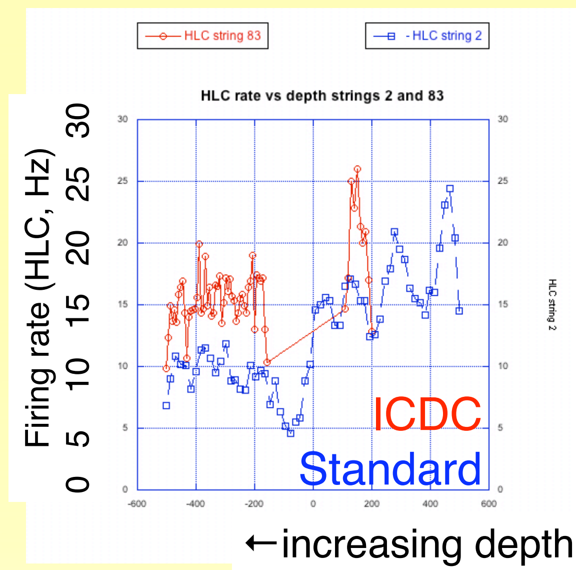
The first Deep Core string was deployed this past season.

Will be fully deployed next year.

- Timing resolution is as expected: few ns



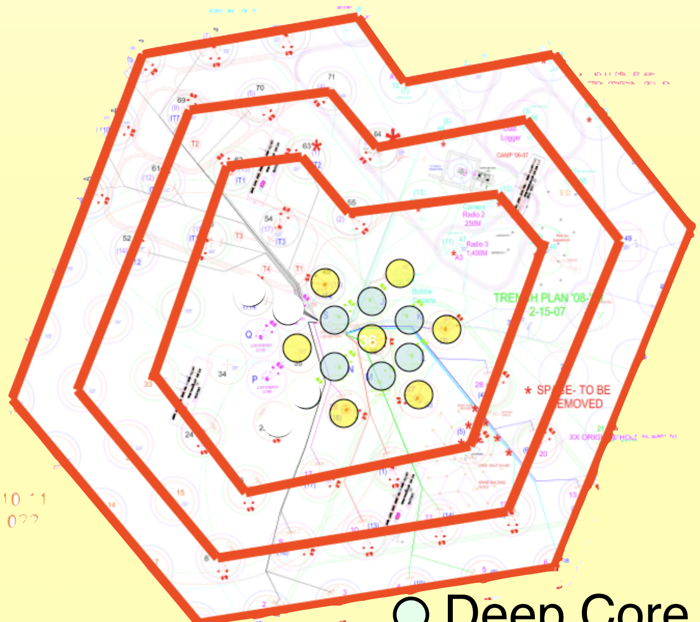
- Noise rate higher, also as expected



ICDC Cosmic-Ray Veto

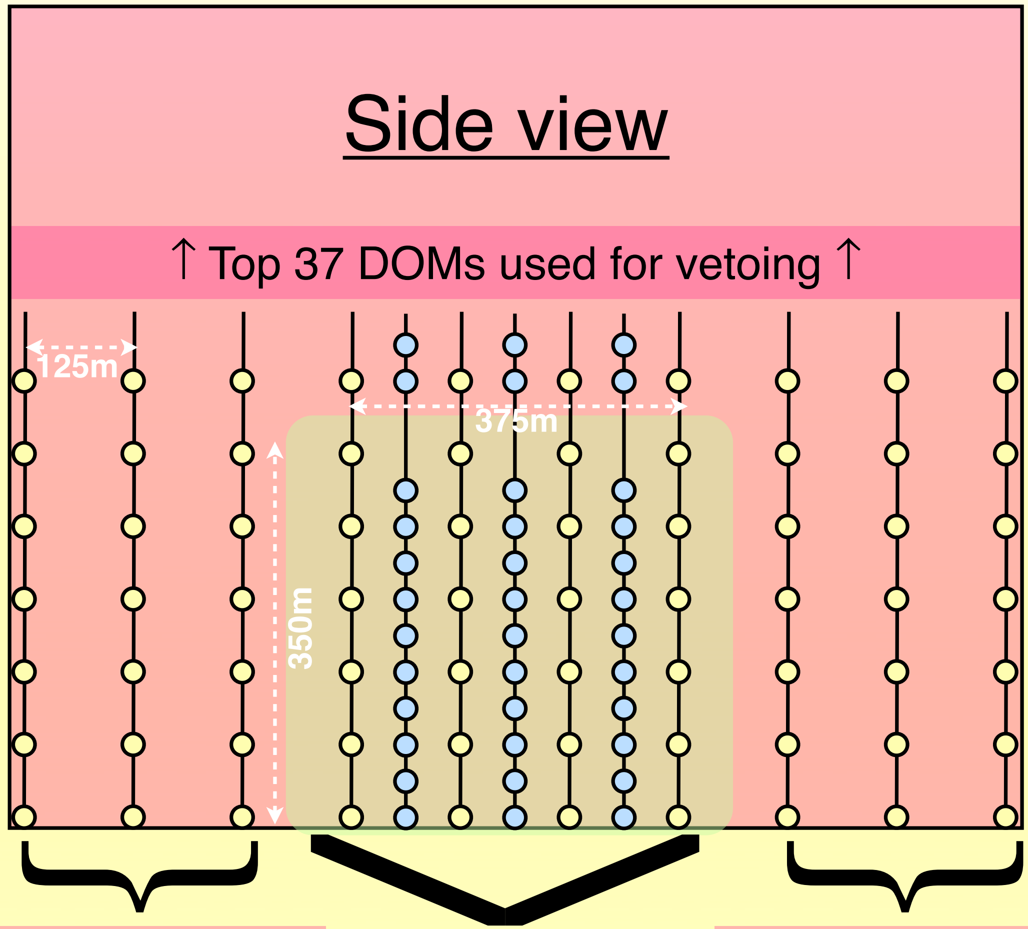
$$\phi(\mu)\,/\,\phi(\nu_{\text{atm}}) \simeq 10^{6}$$

Top view



Deep Core
IceCube

375 m thick active veto:
3 full IceCube DOM
layers surround ICDC



Side 3 strings used for vetoing

ICDC fiducial volume

Side 3 strings used for vetoing

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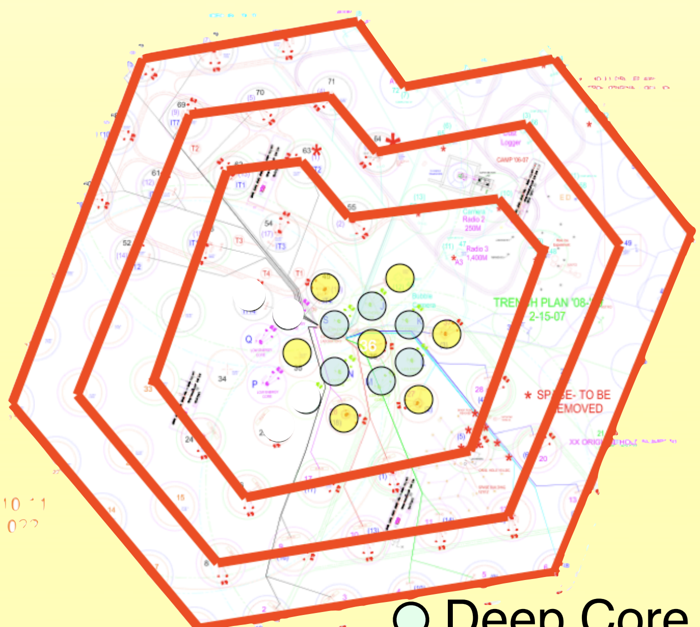

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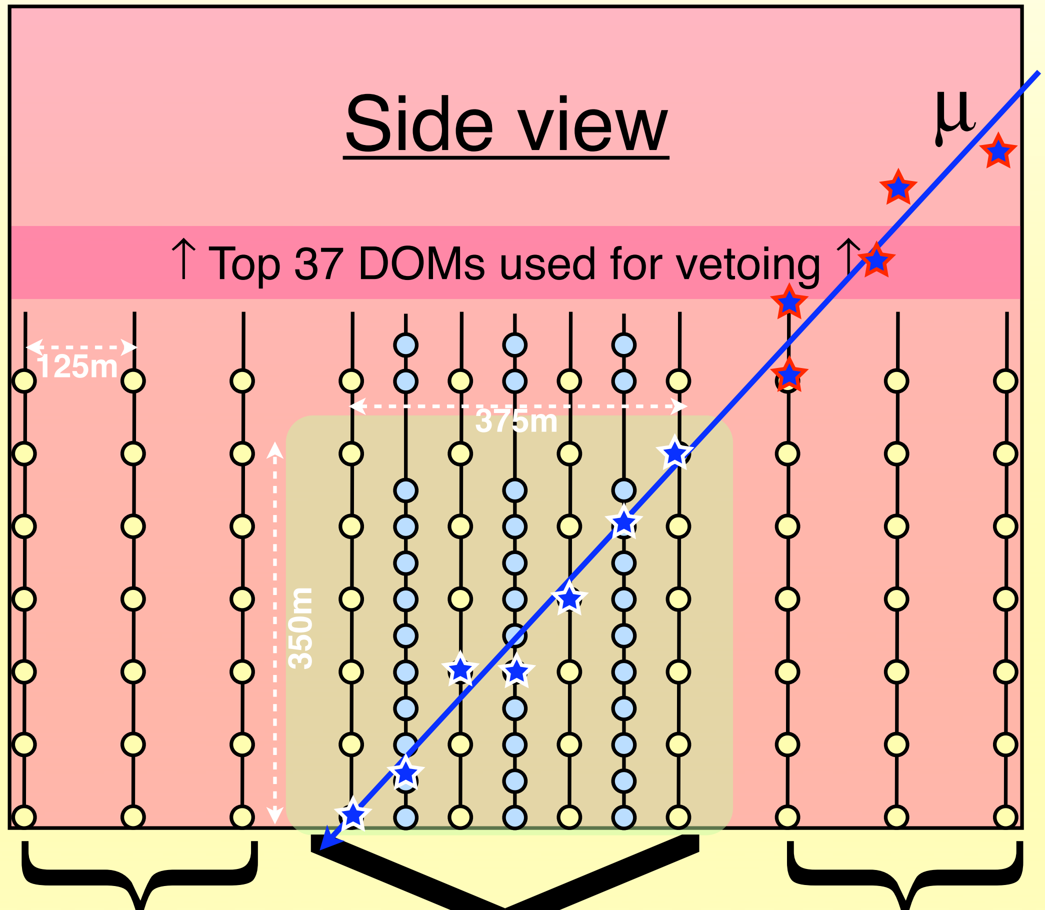

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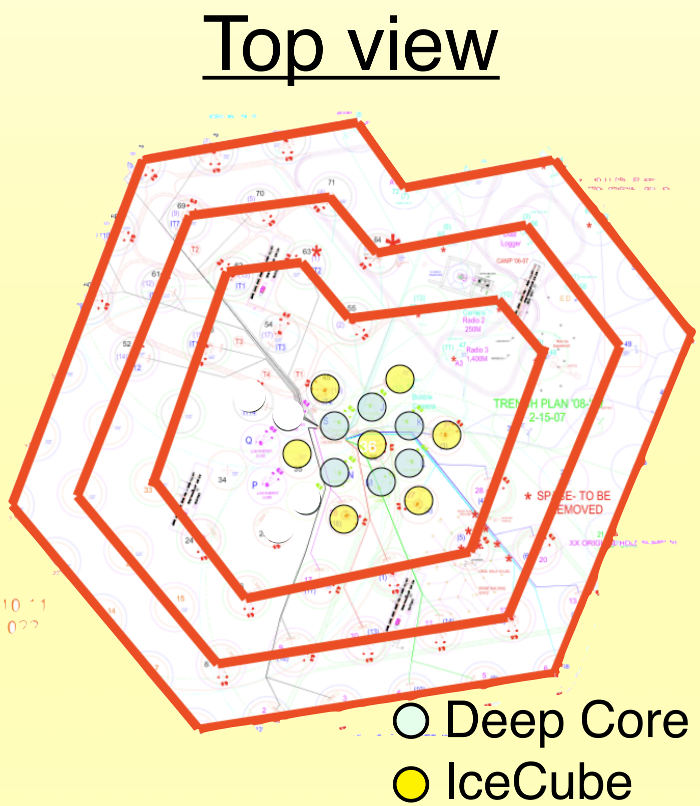

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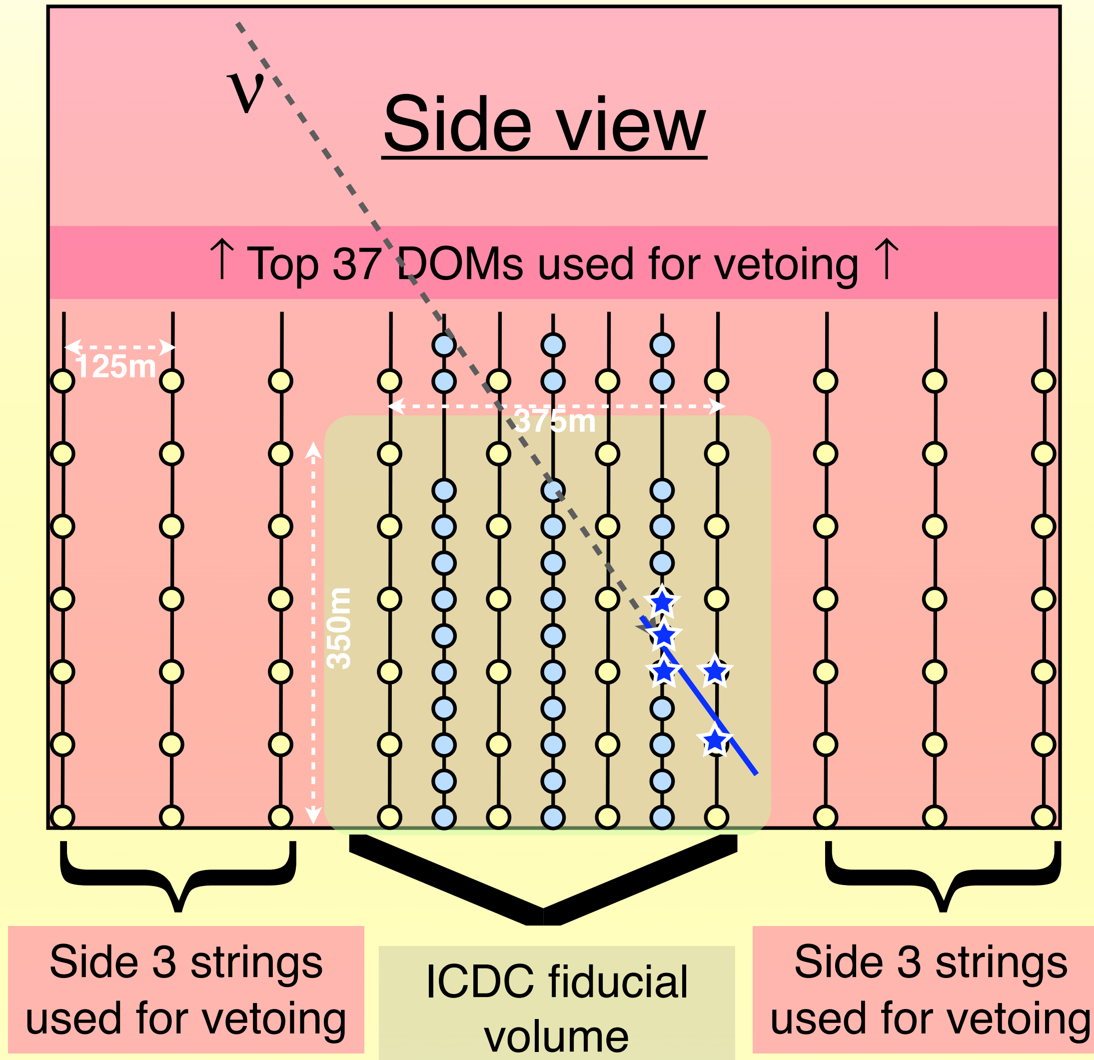

ICDC Veto Algorithms

- Online algorithm (preliminary)
  - Find event's light-intensity-weighted center-of-gravity and start time
    - Look at DOMs outside ICDC and calculate

$$v = \left|\vec{r}_{\mathrm{CoG}} - \vec{r}_{\mathrm{DOM}}\right| \Big/ \left(t_{\mathrm{CoG}} - t_{\mathrm{DOM}}\right)$$

    - If too many hits give v~c, veto event
      - Gives ~5×10^4 rejection with ~90% signal acceptance

ICDC Veto Algorithms

- <u>Offline</u> algorithm (preliminary)
  - Hit kept only if close in (r,t) with another hit
  - Calculate weight $w(r_{ICDC})$ for each hit
    - more distant hits get higher weight
    - require small summed weight
    - Gives 10^4 rejection of cosmic-rays
  - Next require event "vertex" in V_{ICDC}
    - Gives 10^6 rejection (with low signal efficiency)
      - This rejection factor brings us close to 1:1 ratio of (cosmic-ray background):(atmospheric neutrinos)

ICDC Veto Algorithms

- Future algorithms
  - Online algorithm already has high enough rejection and signal efficiency for satellite bandwidth
  - Offline algorithm can and will be improved through use of reconstructions tailored for short tracks that start in ICDC fiducial volume
    - Goal: better than 10^6 rejection with high signal efficiency

ICDC Physics

- ICDC enhances sensitivity to
  - WIMPs
  - southern sky ν sources
  - neutrino oscillations
  - tau neutrinos
  - atmospheric neutrinos
  - monopoles

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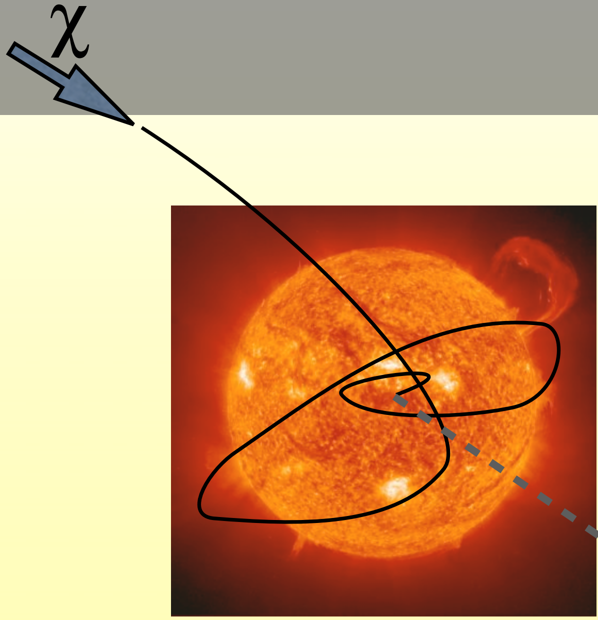
WIMPs



- Indirect detection from WIMP–WIMP annihilation in the
  - Earth's core
  - Solar core
  - Galactic center

$$\chi\chi \rightarrow \begin{matrix} q\bar{q} \\ l\bar{l} \\ W^{\pm}, Z, H \end{matrix} \rightarrow \cdots \rightarrow \nu_\mu$$

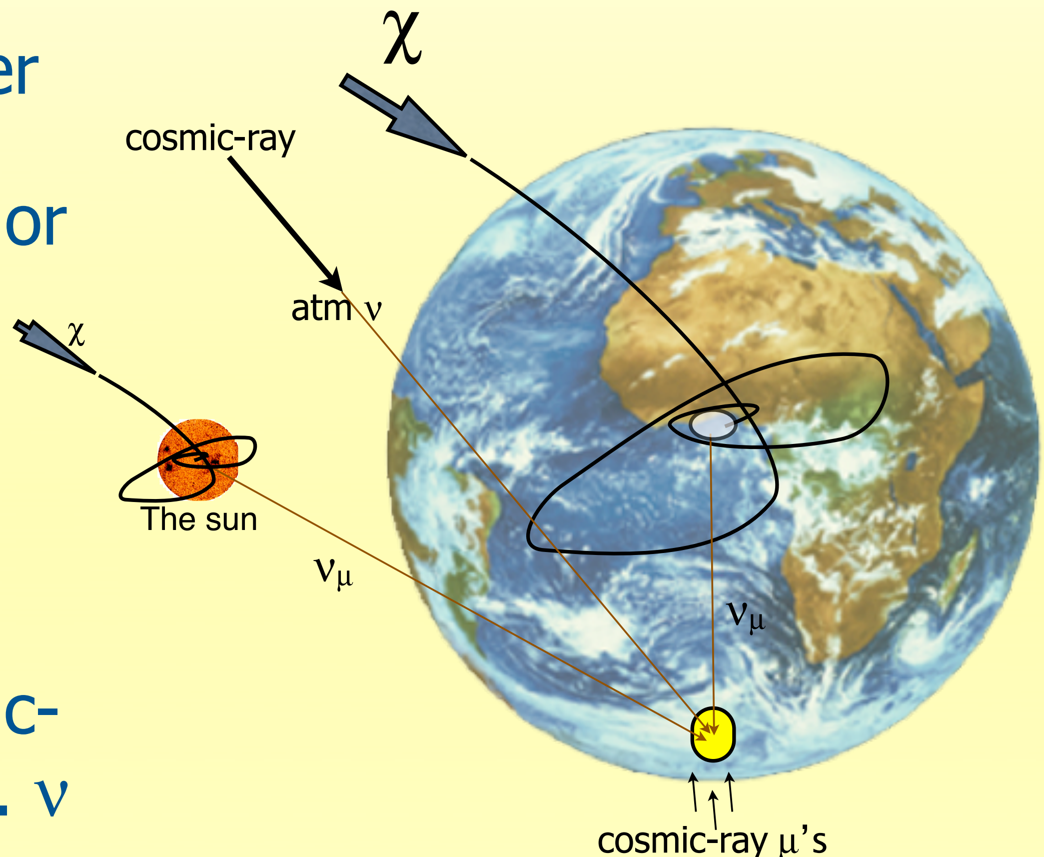
ν_μ

Indirect vs. direct searches:
- longer cosmological integration time
- sensitive to lower $\bar{v}_{WIMP}$
- sensitive to σ_{SD} (solar)

$\chi\chi \rightarrow \bar{b}b(\tau^+\tau^-) \rightarrow \nu$	soft E_ν spectrum
$\chi\chi \rightarrow W^+W^- \rightarrow \nu$	hard E_ν spectrum

Detecting a WIMP Signal

- Look for:
  - few signal events per year from the direction of the sun or earth
    - Soft:
      - $E_\mu \sim 0.01M_\chi - 0.06M_\chi$
    - Hard:
      - $E_\mu \sim 0.03M_\chi - 0.3M_\chi$
  - Bkgd: $\sim 5 \cdot 10^{10}$ cosmic-ray μ and $\sim 10^5$ atm. ν bkgd events per year



WIMPs and IC22*

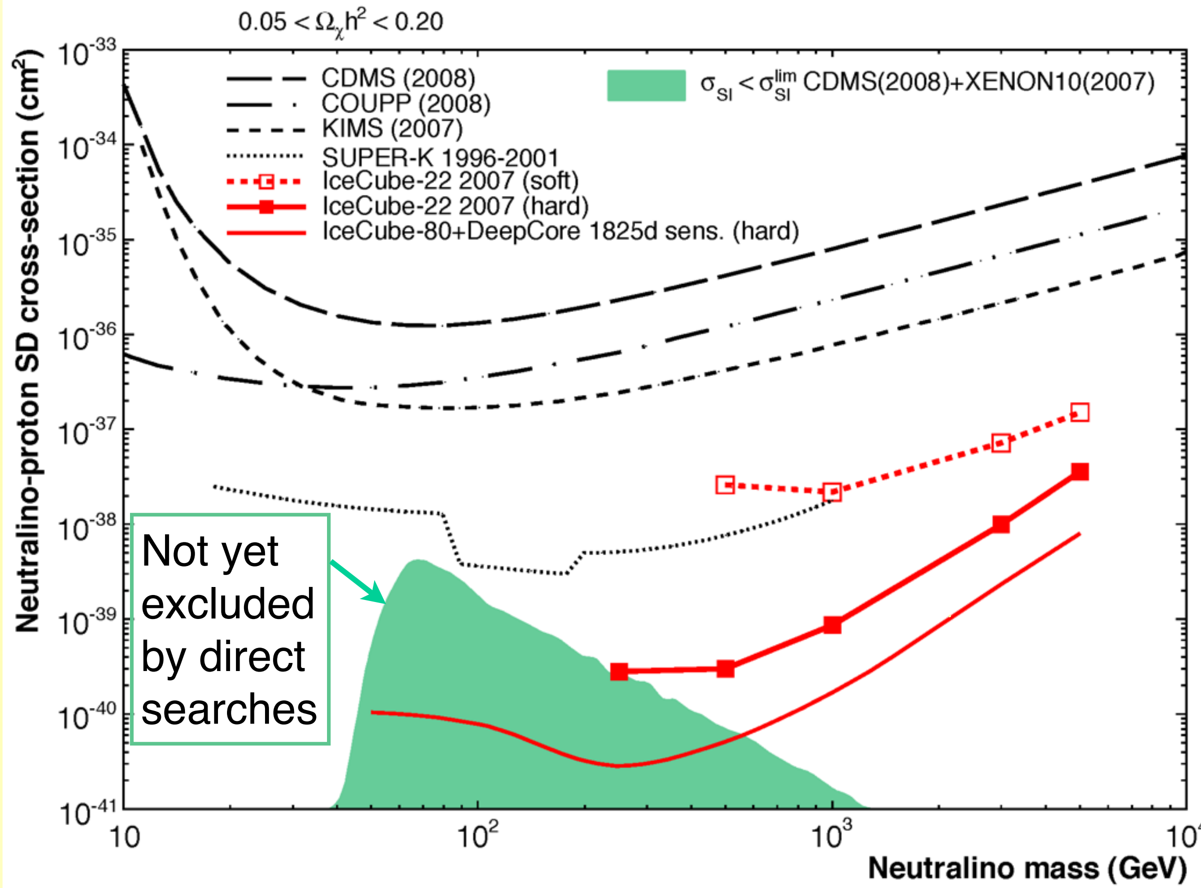
- A WIMP analysis was performed with IC22
- Achieved background rejection of 10^6, signal efficiency of ~20%
  - 3^o angular resolution
  - only used data with sun below horizon
- Observed flux with 250 days live time consistent with background expectation
  - background estimated from off-source data
- Set limit on σ_{SD} by assuming $R_{annih} = R_{capture}$, local $\rho_{WIMP} = 0.3 GeV/cm^3$ and Maxwellian v_{WIMP}

*IceCube ran with 22 strings in 2007: "IC22"

WIMPs and IC22

- IC22 result improves existing limits on σ_{SD}

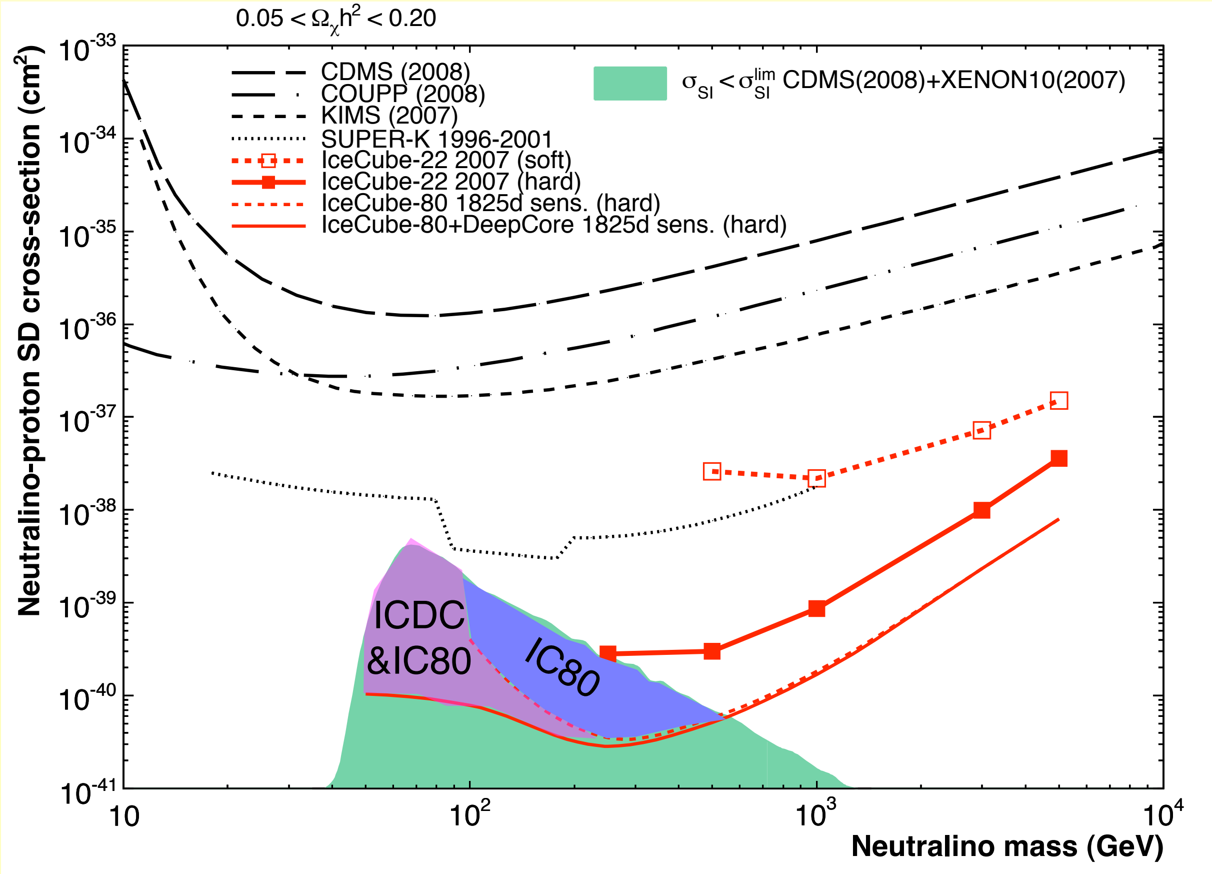
ArXiv:0902.2460v1



WIMPs and ICDC

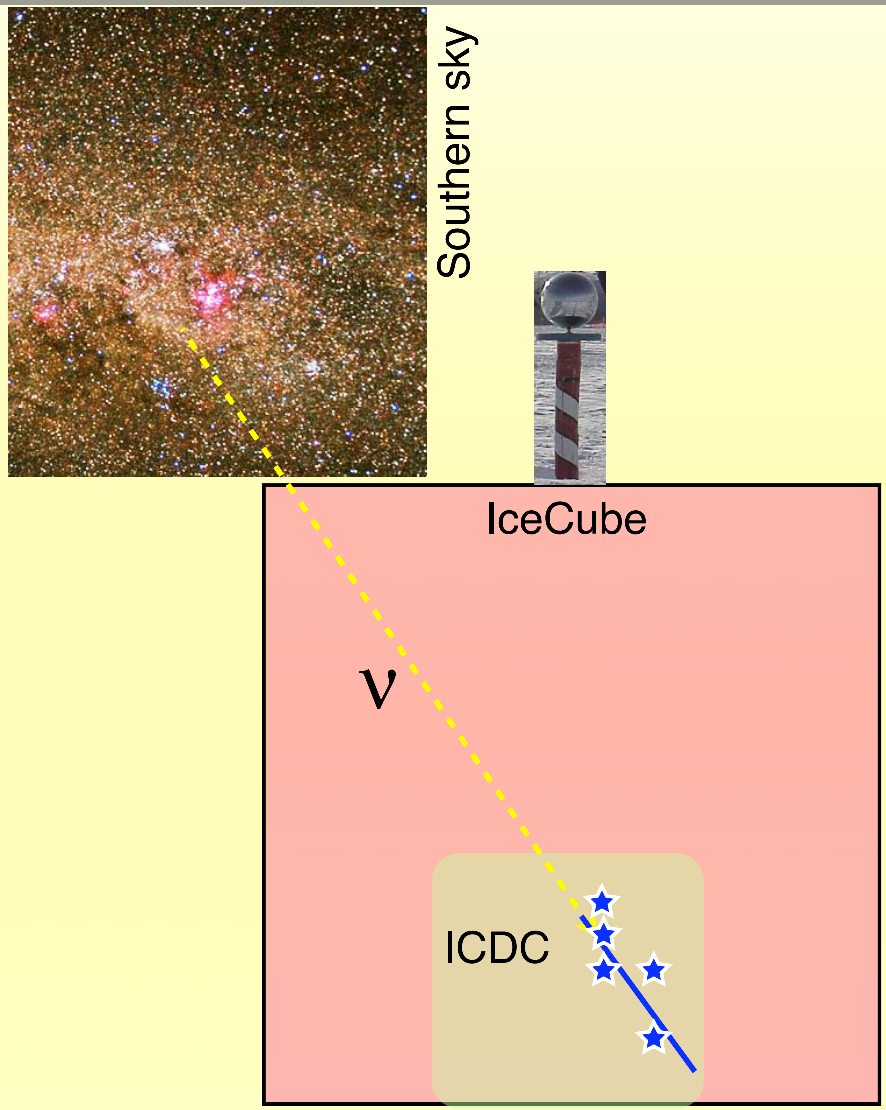
- IC22 result improves existing limits on σ_{SD}
- ICDC (& IC80) will extend sensitivity into region not yet excluded by direct searches based on σ_{SI}
  - region shown uses less powerful earlier design for ICDC
  - will improve, both in E_{thres} and exposure

ArXiv:0902.2460v1



Southern Sky ν Sources

- Potential sources:
  - AGN, PWNe, SNR, GRBs
- Enabled by vetoing capability
  - Thus far, all neutrino telescopes have only tried to look down
  - Focus on tracks that start in the ICDC fiducial volume
    - Will need specialized reconstruction algorithms to handle starting cascade (and use it for energy estimation) as well as fully contained tracks
- Work in progress...



ICDC & ν Oscillations

- To be sensitive to Δm^2(atm) $\sim 10^{-3}$, require L(km)/E(GeV)$\sim 10^3$
- At its design sensitivity of $E_\nu \sim$1TeV, IceCube needs L$\sim 10^6$ km
  - There are no TeV neutrino sources at that distance
- Atmospheric neutrinos, with L$\sim 10^4$ km, can be used by IceCube...
  - ...but only if IceCube has sensitivity to $E_\nu \sim$10 GeV

ICDC & ν Oscillations

- Preliminary studies performed using full detector simulation
  - assume high level of background suppression
  - only at trigger level
    - signal reco. algorithms under development
  - low energy response of ICDC is crucial
- Three possible measurements
  - ν_μ disappearance
  - ν_τ appearance (inclusive msmt.)
  - neutrino hierarchy

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  - ν_μ disappearance [Feasible.]
  - ν_τ appearance (inclusive msmt.) [Maybe?]
  - neutrino hierarchy [Hard.]

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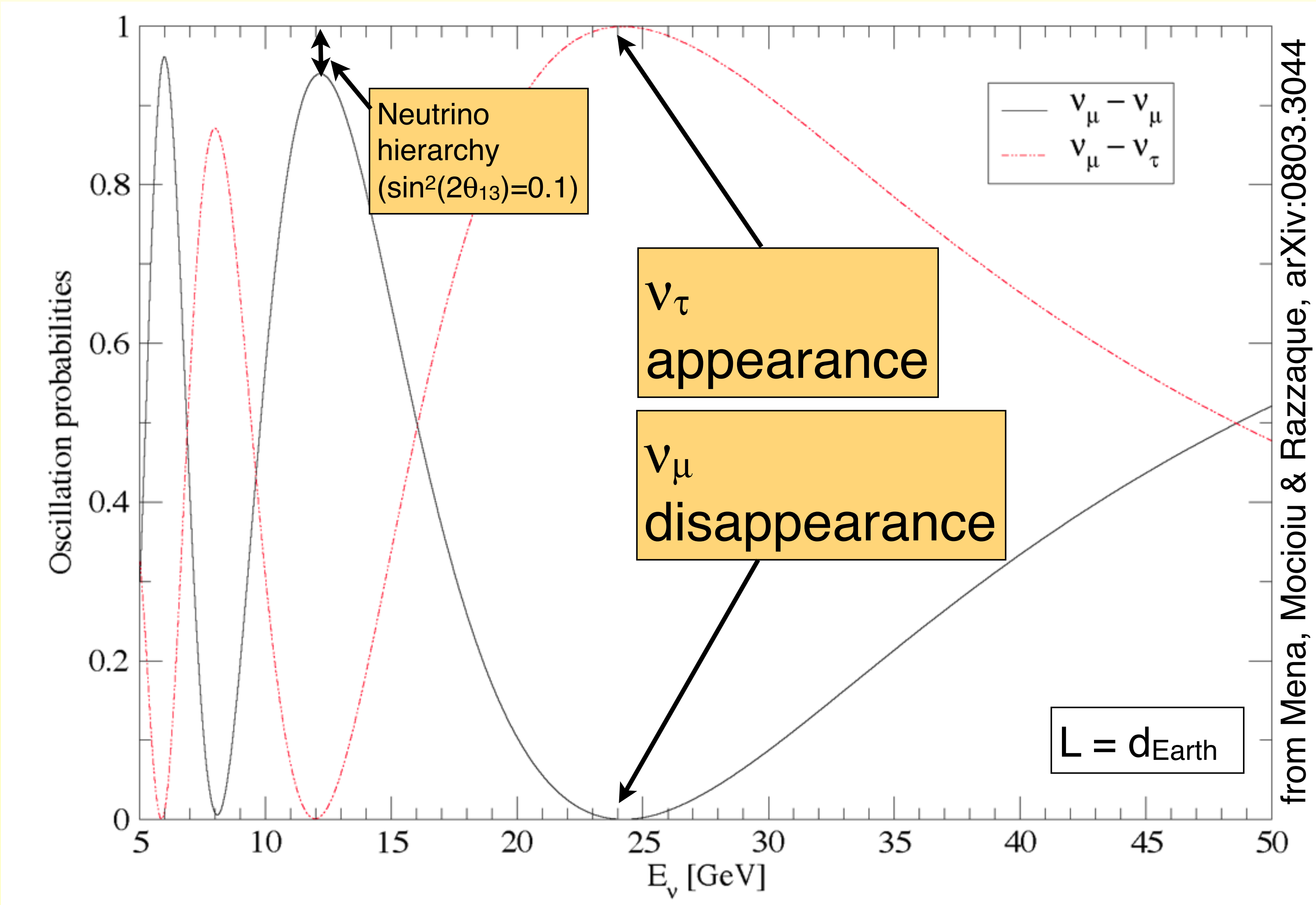

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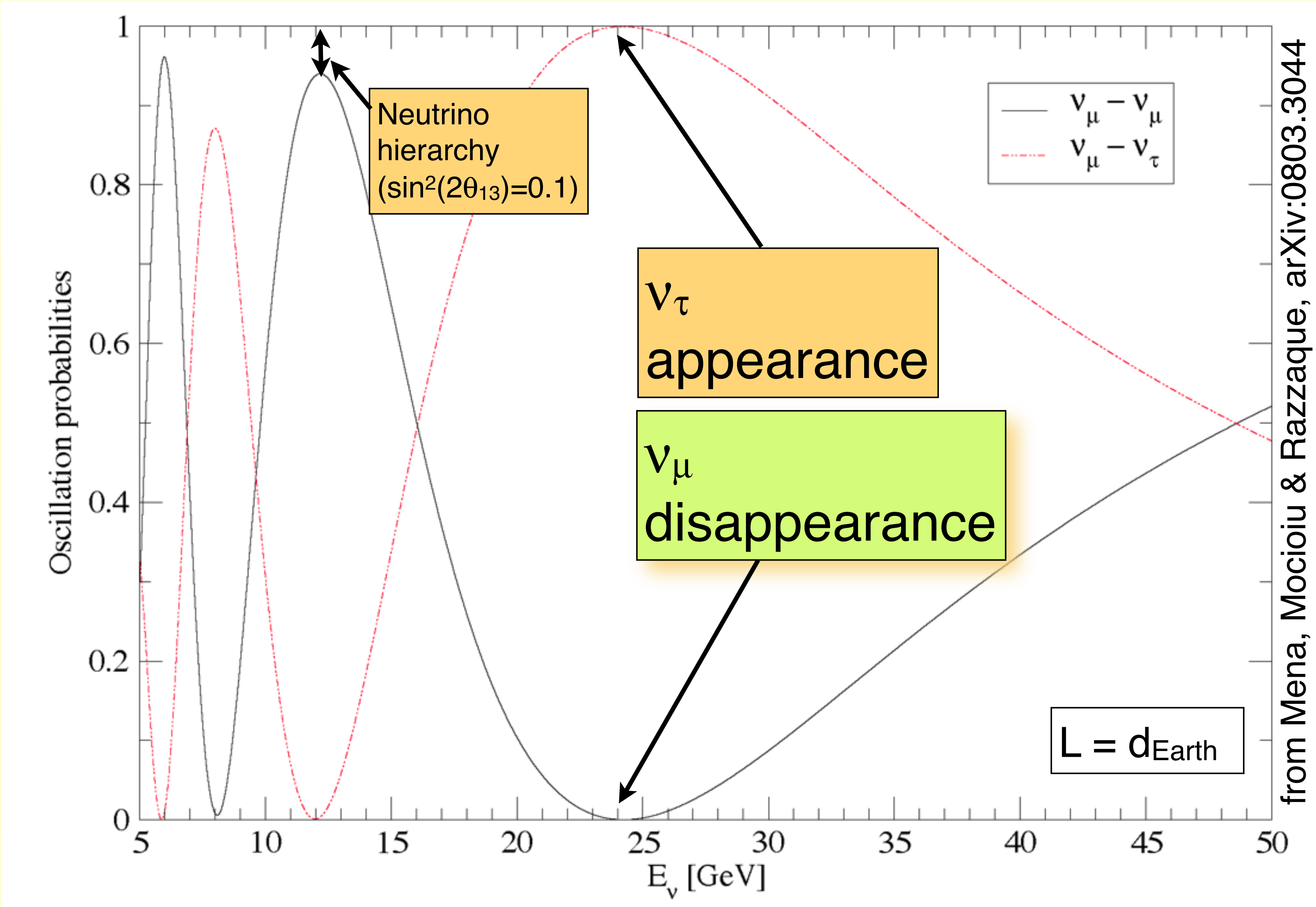
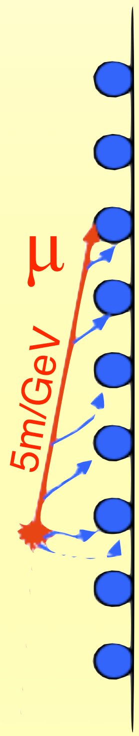
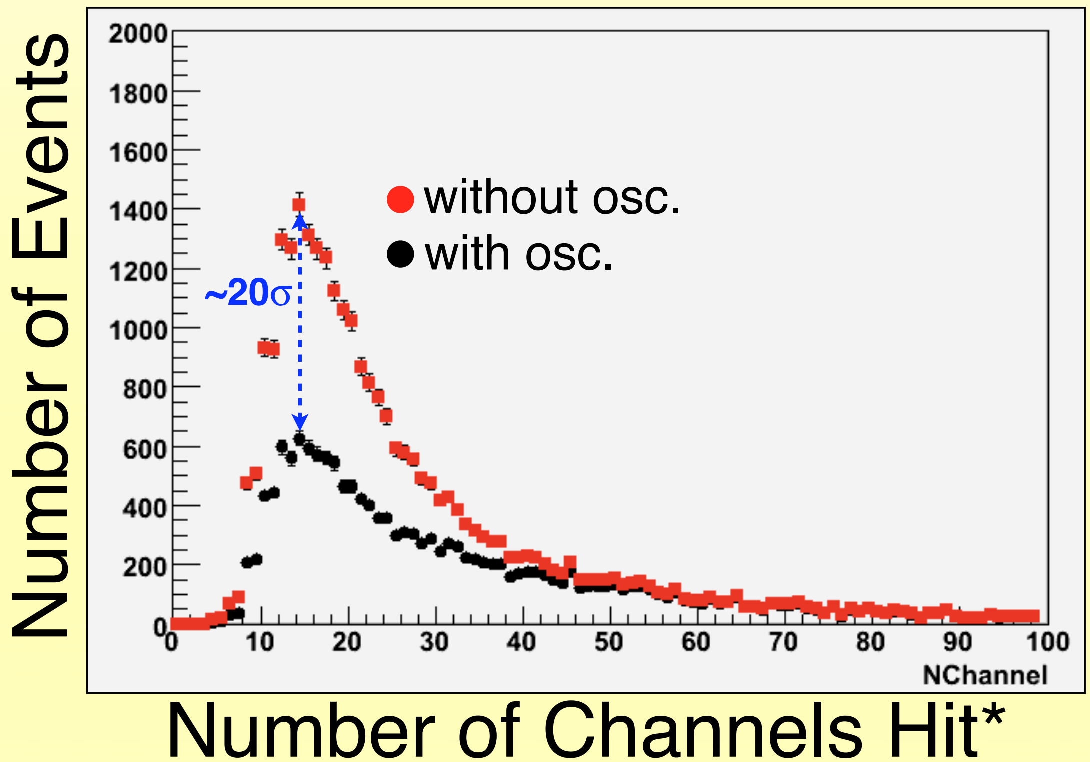


ICDC & ν_μ Disappearance

- Effect is simplest to measure for vertically upgoing ν_μ-induced μ (analysis already underway w/IceCube)





- Full 3-ν oscillations
- PREM (earth model)
- Only at trigger level
- Only statistical errors; no systematics
- 1 yr ICDC
- $\cos\Phi < -0.6$

- These initial studies yield a >20σ effect with one year of ICDC data: lower E_{thr}, more statistics

*Crude energy estimator

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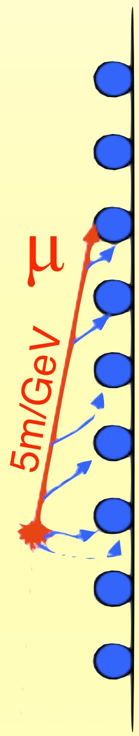

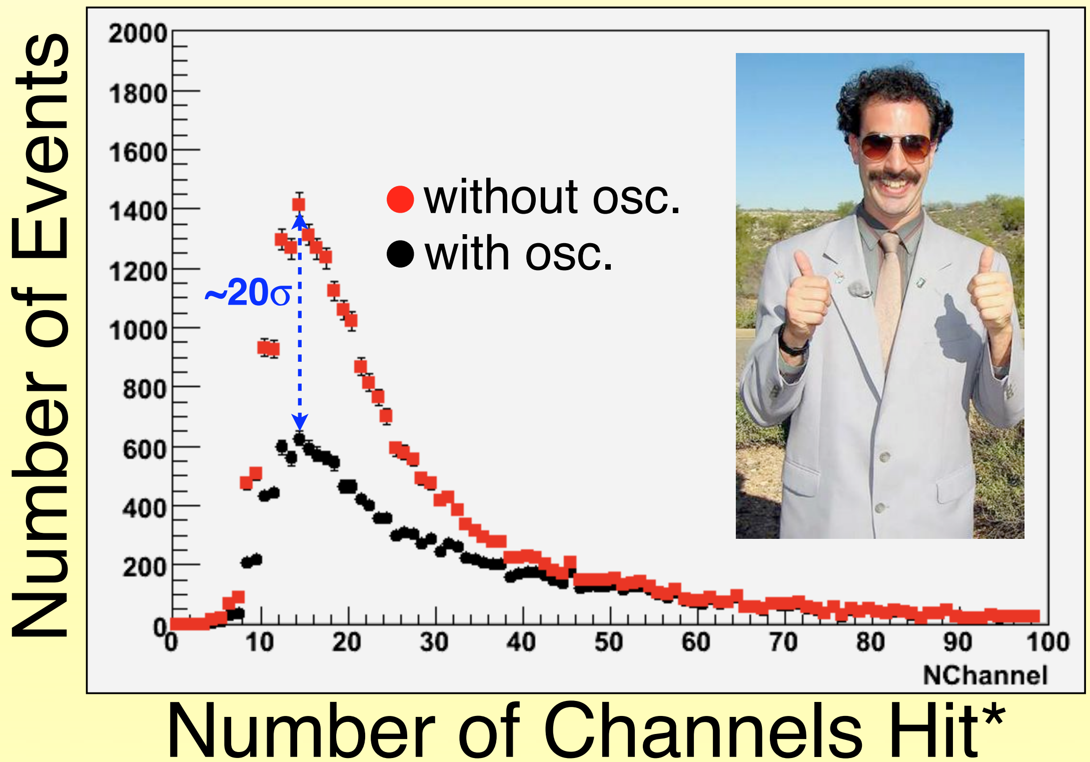

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Conclusions

- IceCube and IceCube Deep Core can analyze data at much lower E_ν than previously imagined or foreseen
  - Improves energy overlap with other experiments
  - Expect that veto will be powerful enough to remove most of cosmic-ray background
  - Expect energy resolution for all flavors of neutrinos to be sufficient to do interesting neutrino oscillation studies
  - This talk has covered only a fraction of the physics potentially opened up by ICDC
    - Advertisement: Workshop 19-20 March (next week) at Penn State on "Low Energy" Neutrino Physics and Astrophysics with IceCube's Deep Core Sub-Array
      - http://gravity.psu.edu/events/LowENu_workshop

Conclusions, cont'd.

- IceCube Collaborators also play a vital role in keeping the Earth from experiencing a major catastrophe:

Anna "Atlas" Franckowiak

Conclusions, cont'd.

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The End