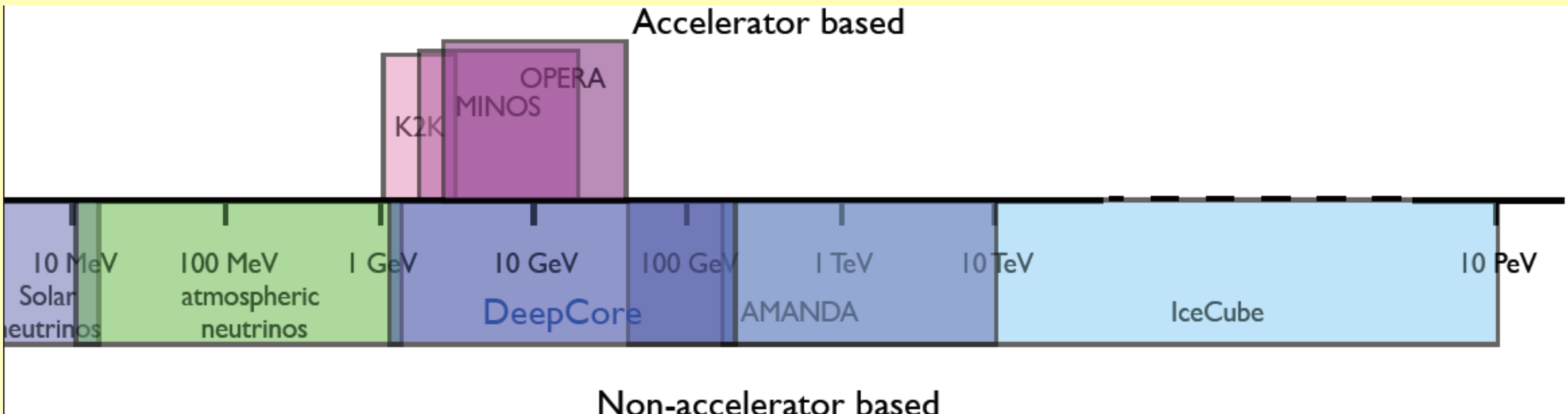
Low E_ν & WIMPs with DeepCore

- Deep Core design
- Initial studies of first DeepCore string
- Predicted DeepCore performance
- Status of low energy analyses
  - WIMPs
  - Neutrino oscillations
- Enhancing DeepCore with two additional strings ("79&80")

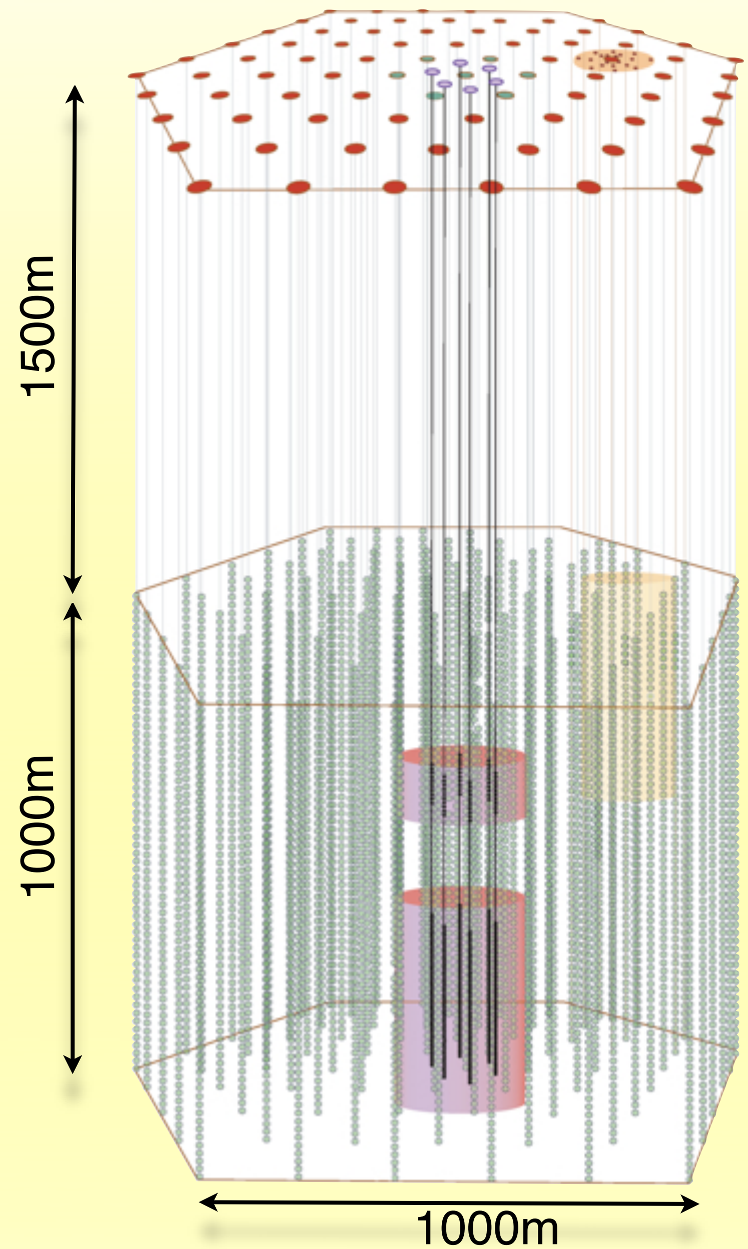
IceCube DeepCore

- IceCube: Optimized for 1 TeV < E_ν < 1 PeV
  - "map ν sky": search for high energy astrophysical ν's from GRBs, SNe, AGN; search for WIMP dark matter,...
  - also use these ν's to study fundamental ν properties: oscillations, decay,...
- DeepCore: Sensitivity as low as E_ν ~ 10 GeV
  - also "map low-E_ν sky"; search for WIMP dark matter
    - access more potential sources; lower mass WIMPs
  - also study fundamental ν properties
    - but with a guaranteed source: atmospheric ν's



IceCube DeepCore

- DeepCore 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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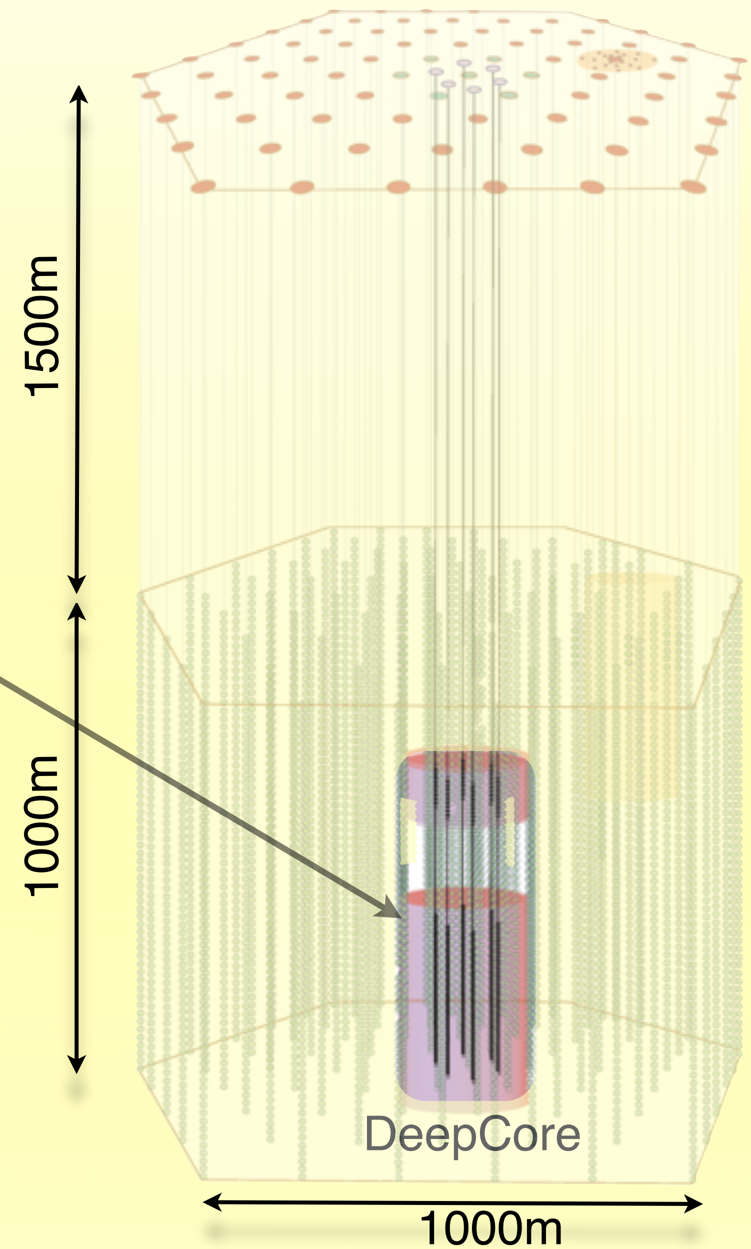

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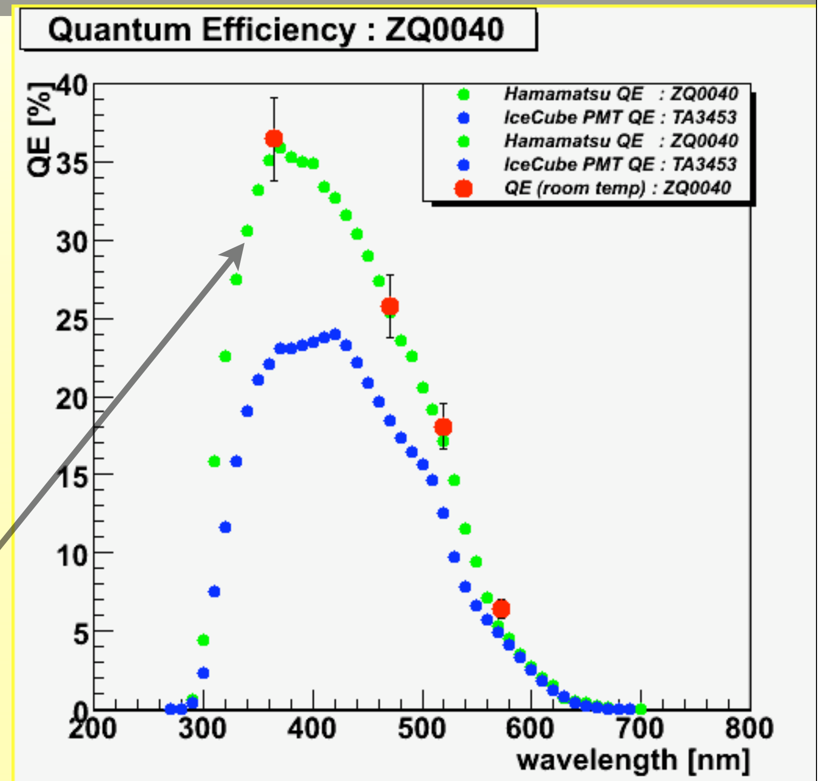

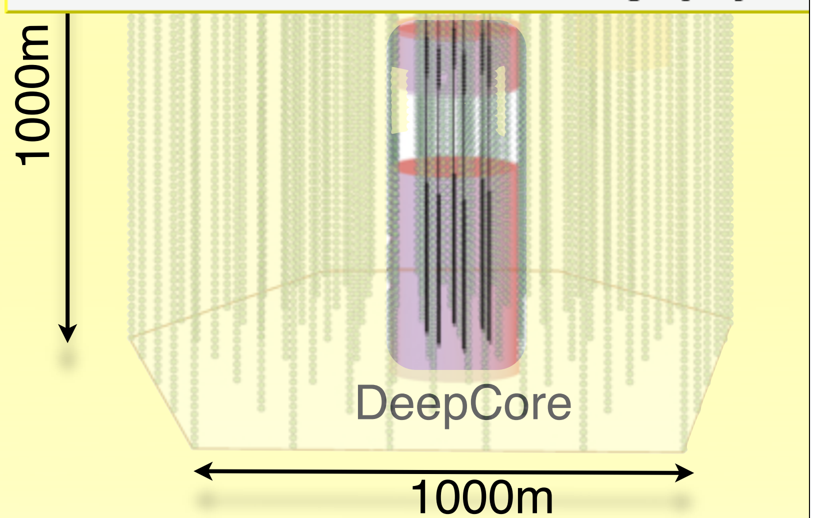

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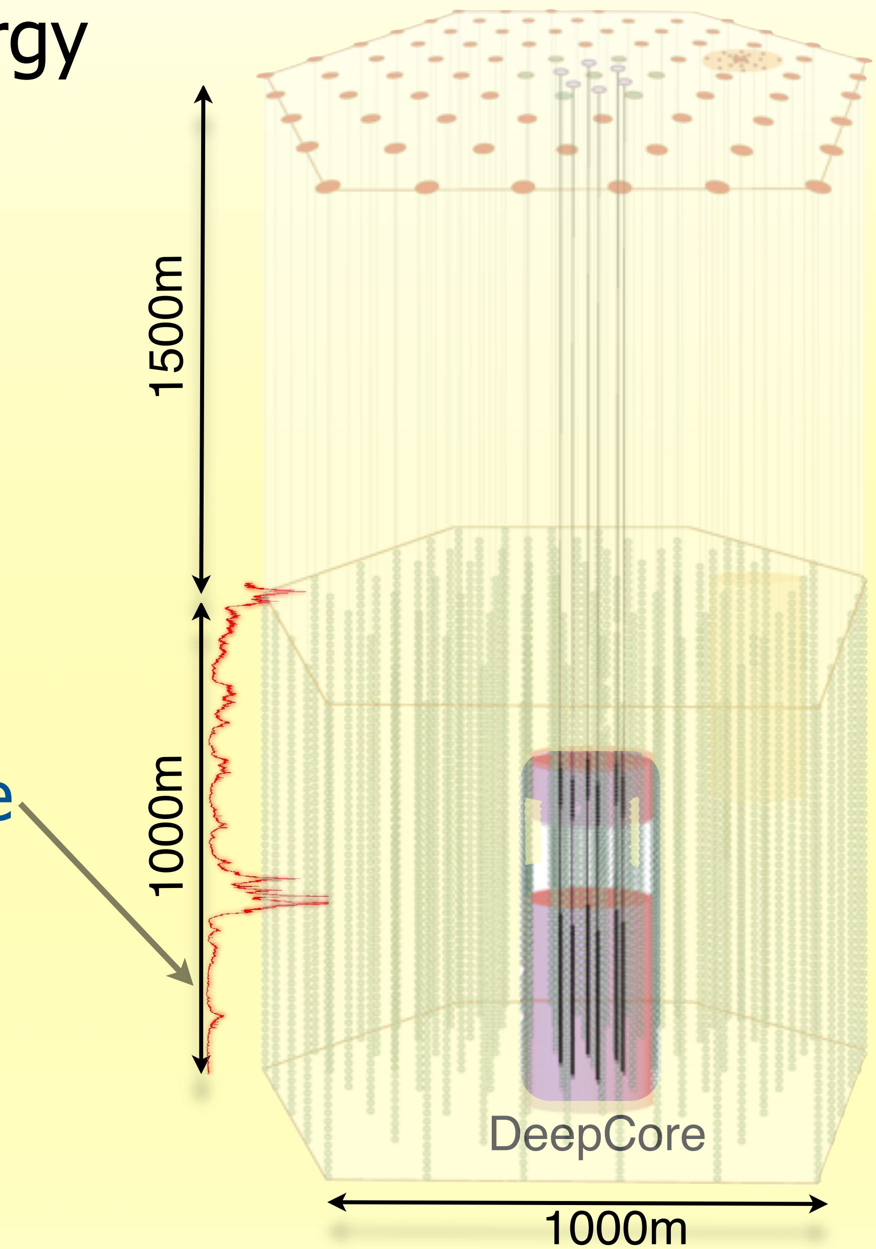

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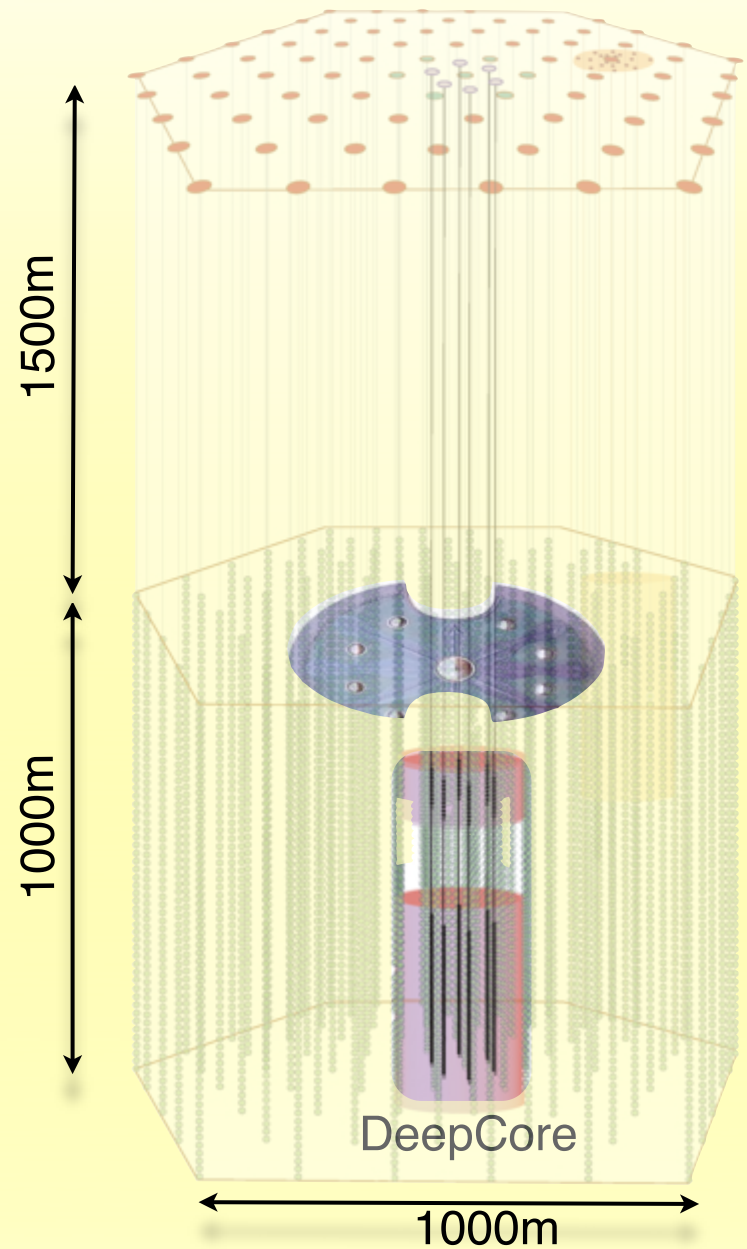

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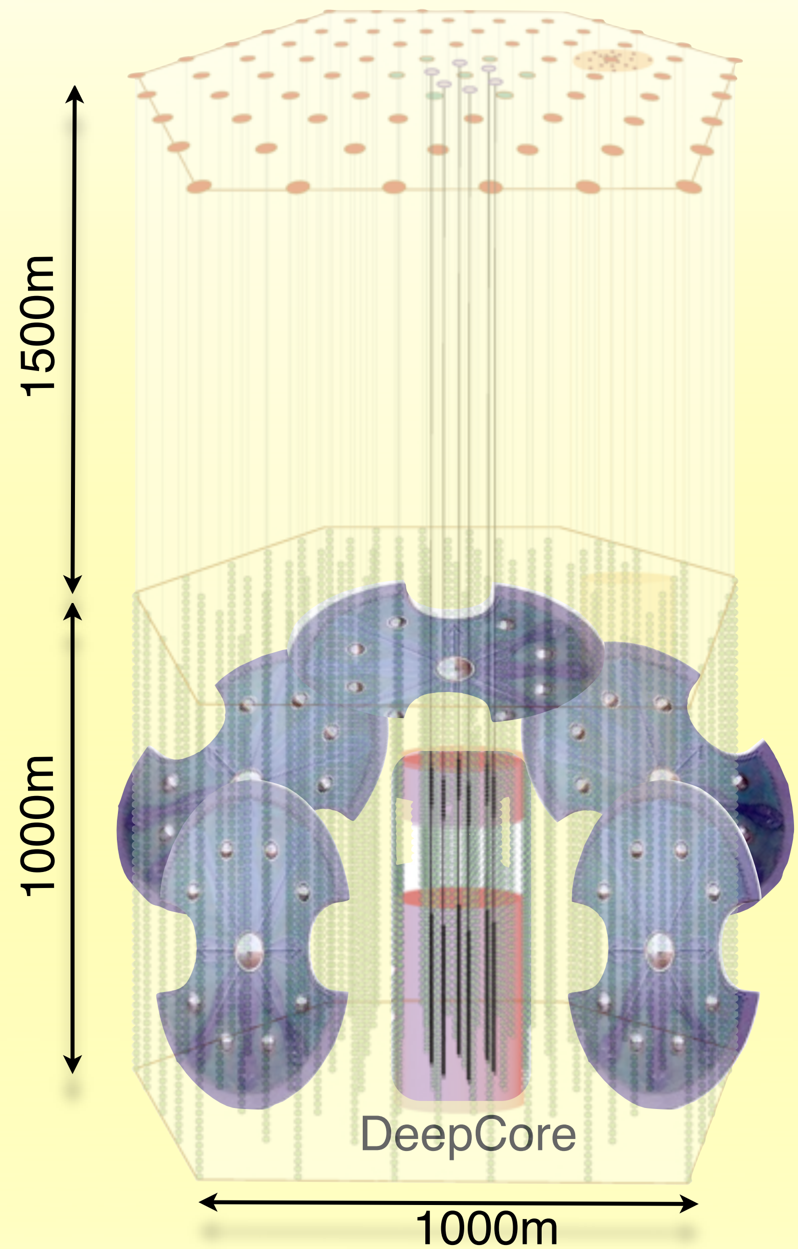

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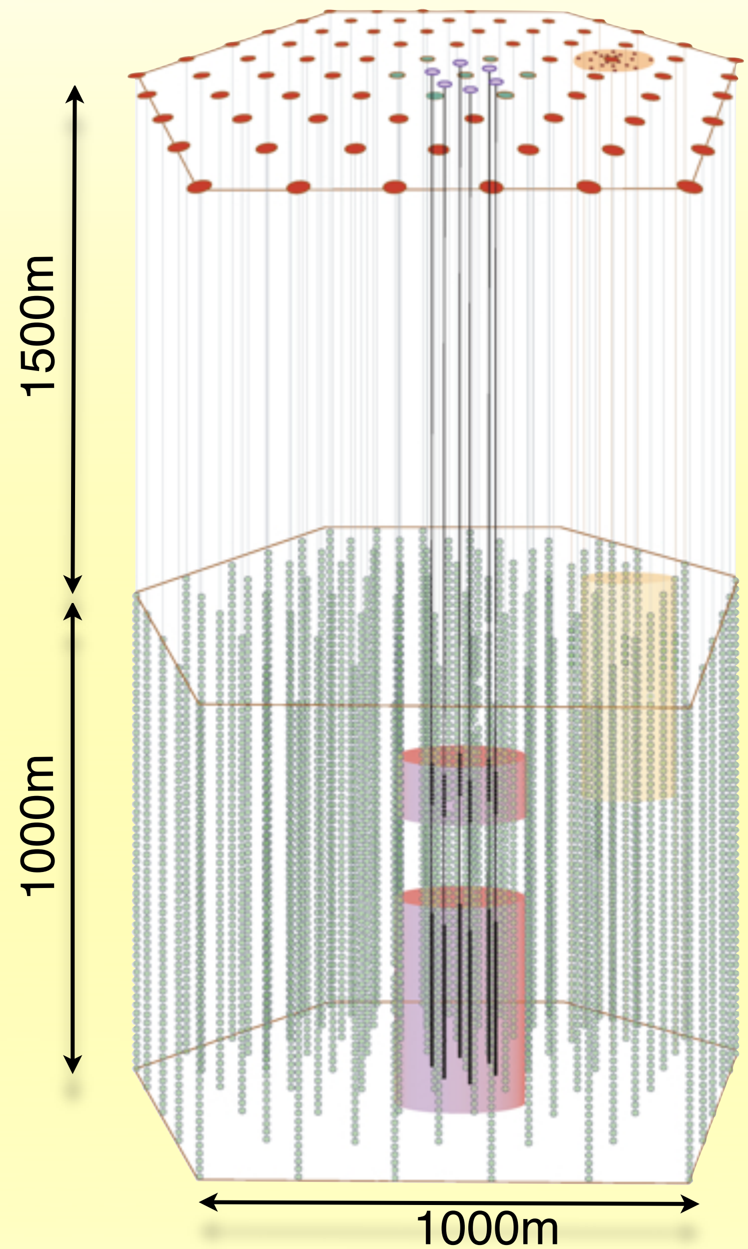
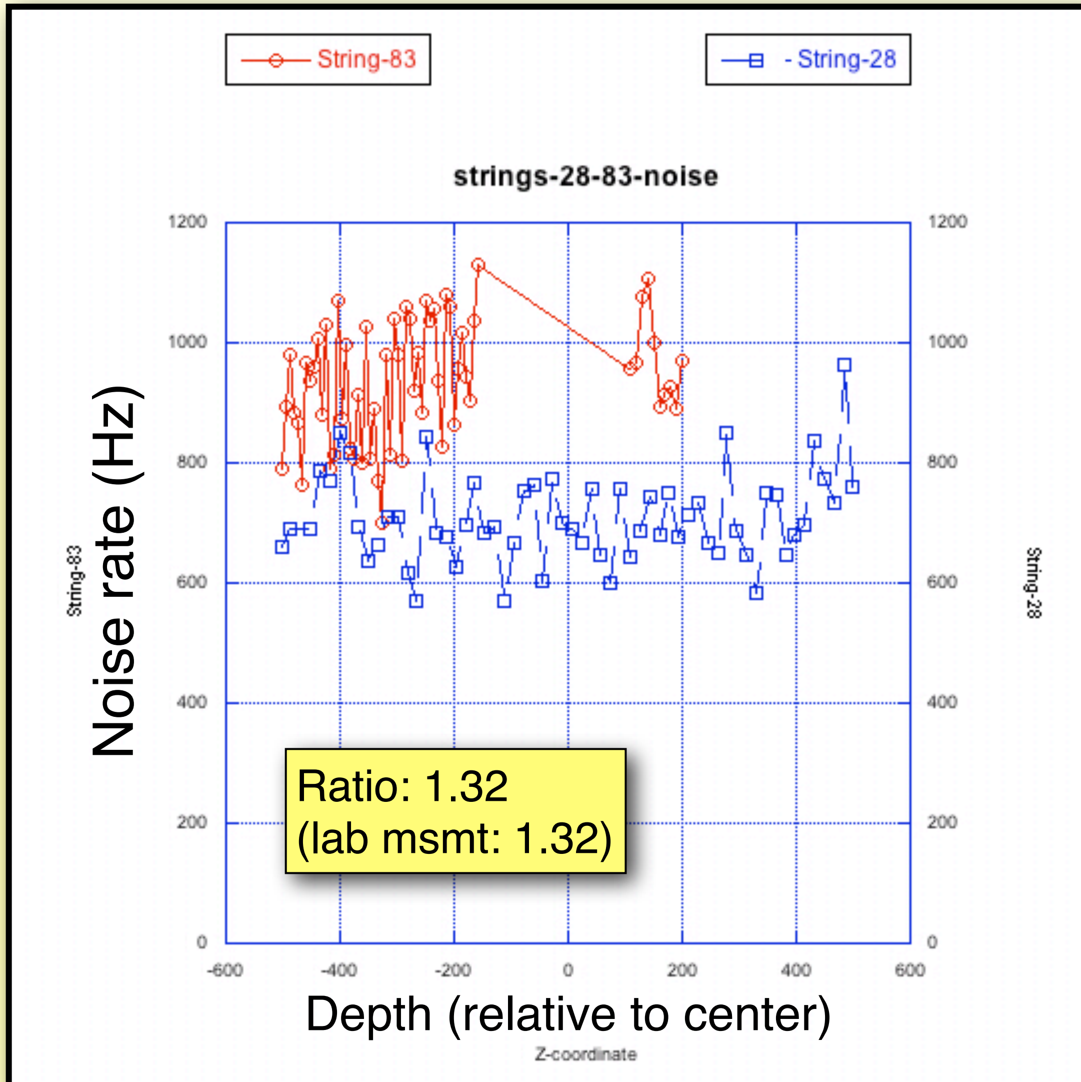
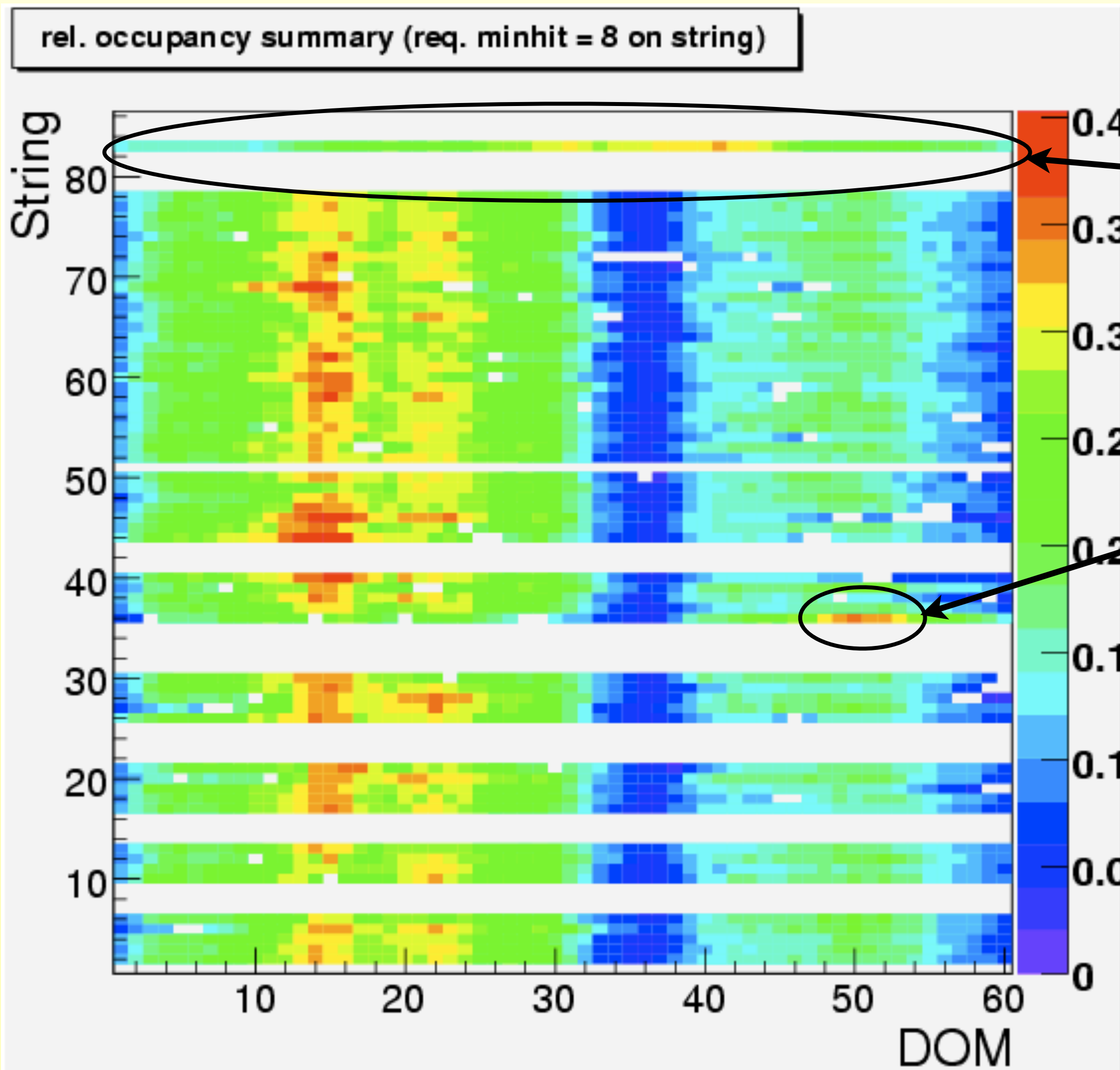


DeepCore Performance

- First string already deployed; balance to be deployed next season
  - also, standard IceCube strings completing full veto will be deployed
- Performance of first string matches laboratory predictions for noise



DeepCore Performance



"Track-based" occupancy shows enhancements where high quantum efficiency DOMs are located (strings 83 and 36)

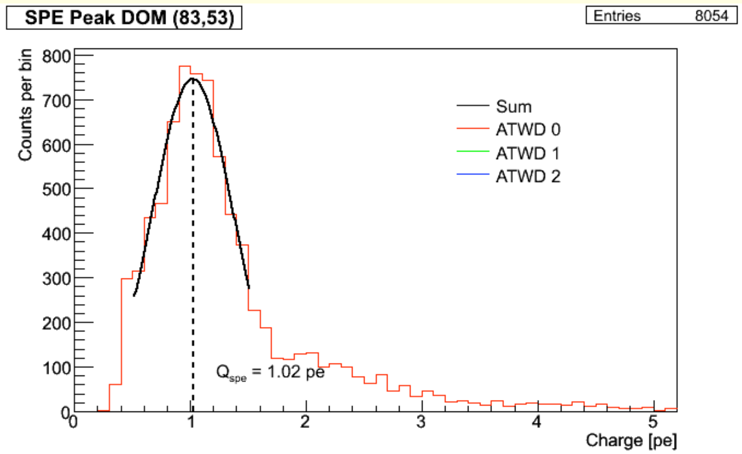
Note that x-axis scaling is with DOM number, not depth. Compare string 83 (topmost horizontal bar in plot) to DOMs 40-60 of other strings.

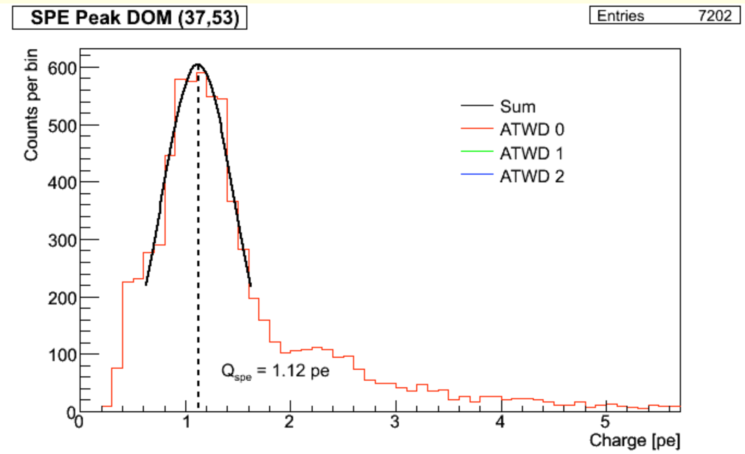
DeepCore Performance

DeepCore String

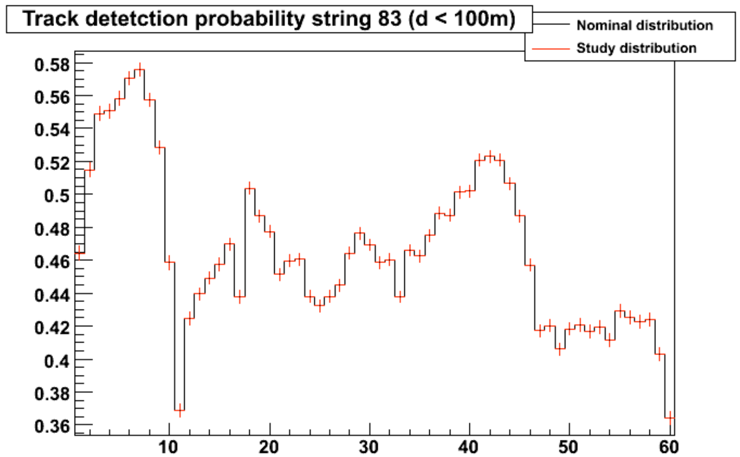
Standard String

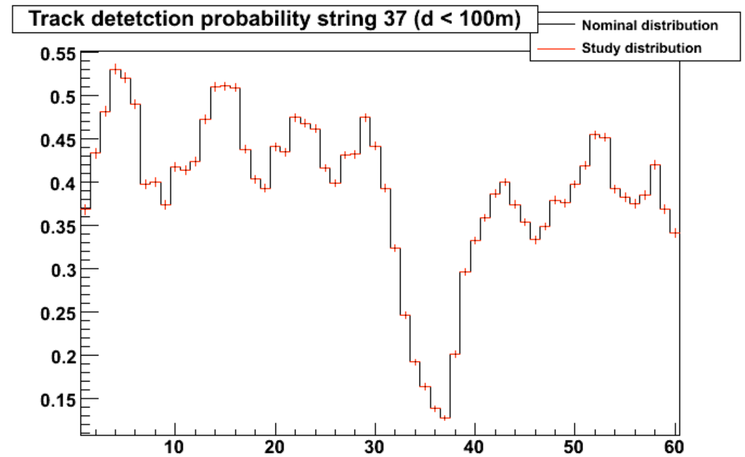
SPE peak:



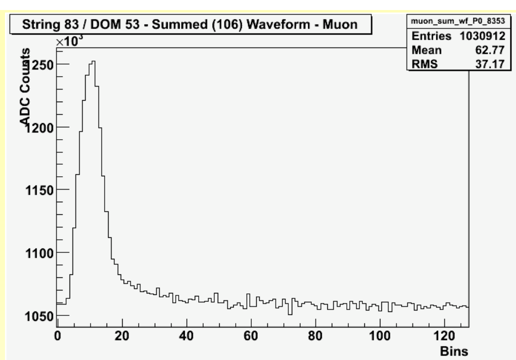


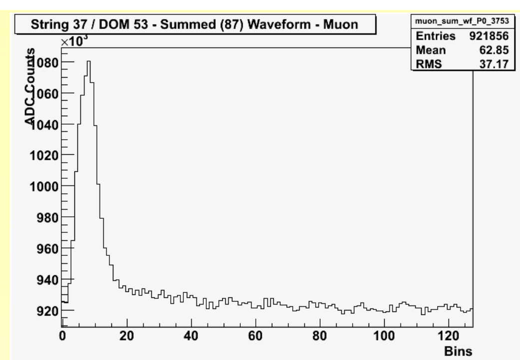
Track Detection Probability:





Average Waveform:

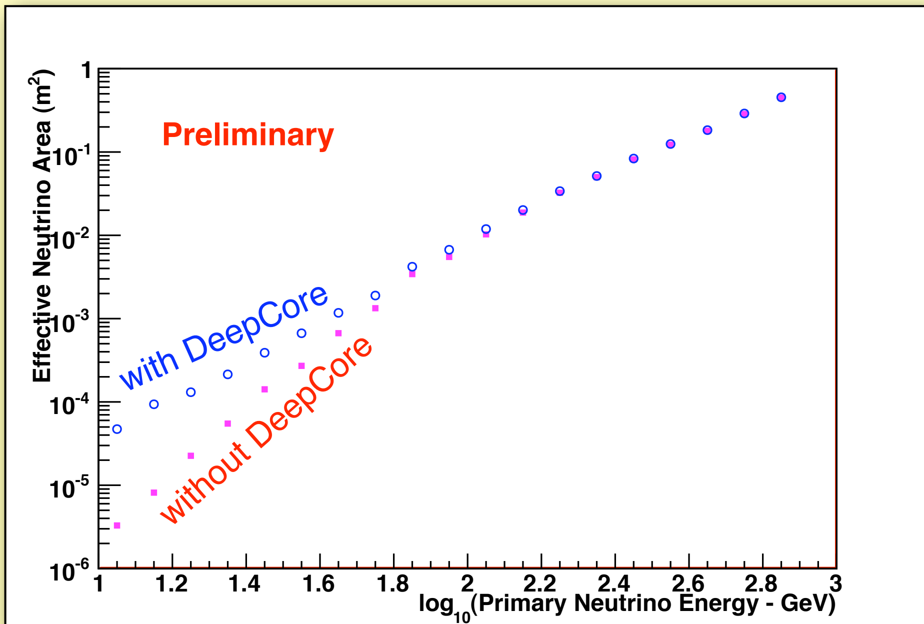




DeepCore A_{eff} and V_{eff}

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

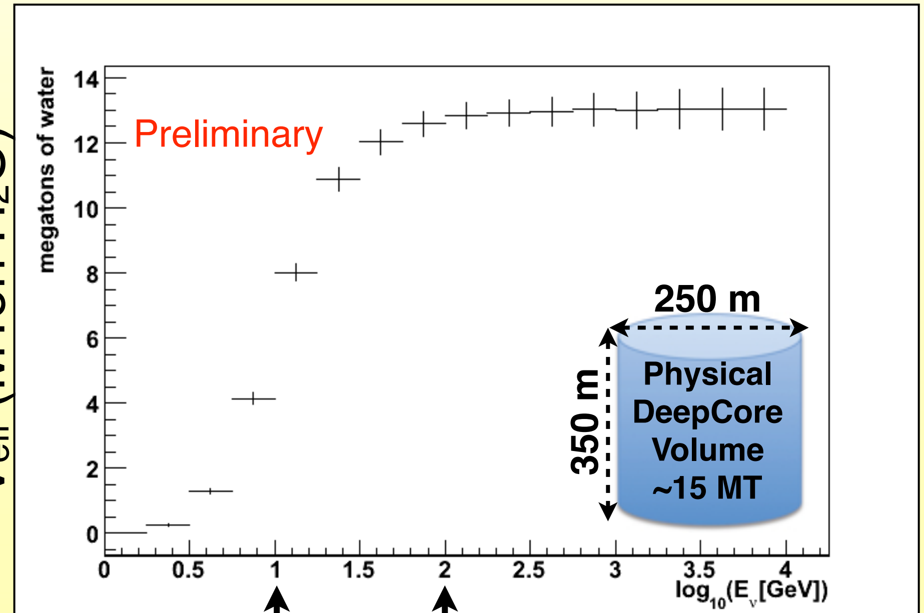
$A_{eff}(m^2)$



10 GeV

100 GeV

V_{eff} (MTon H_2O)



10 GeV

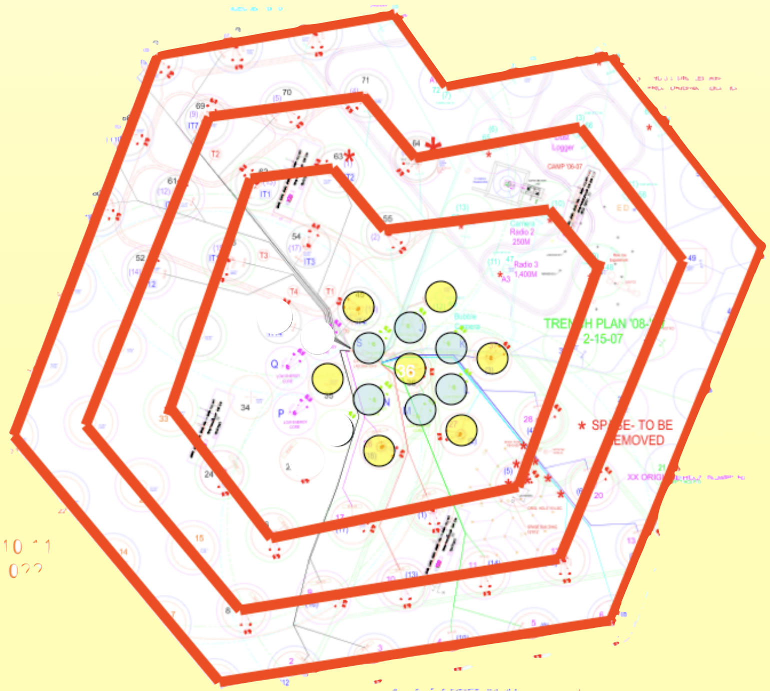
100 GeV

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

DeepCore Cosmic-Ray Veto

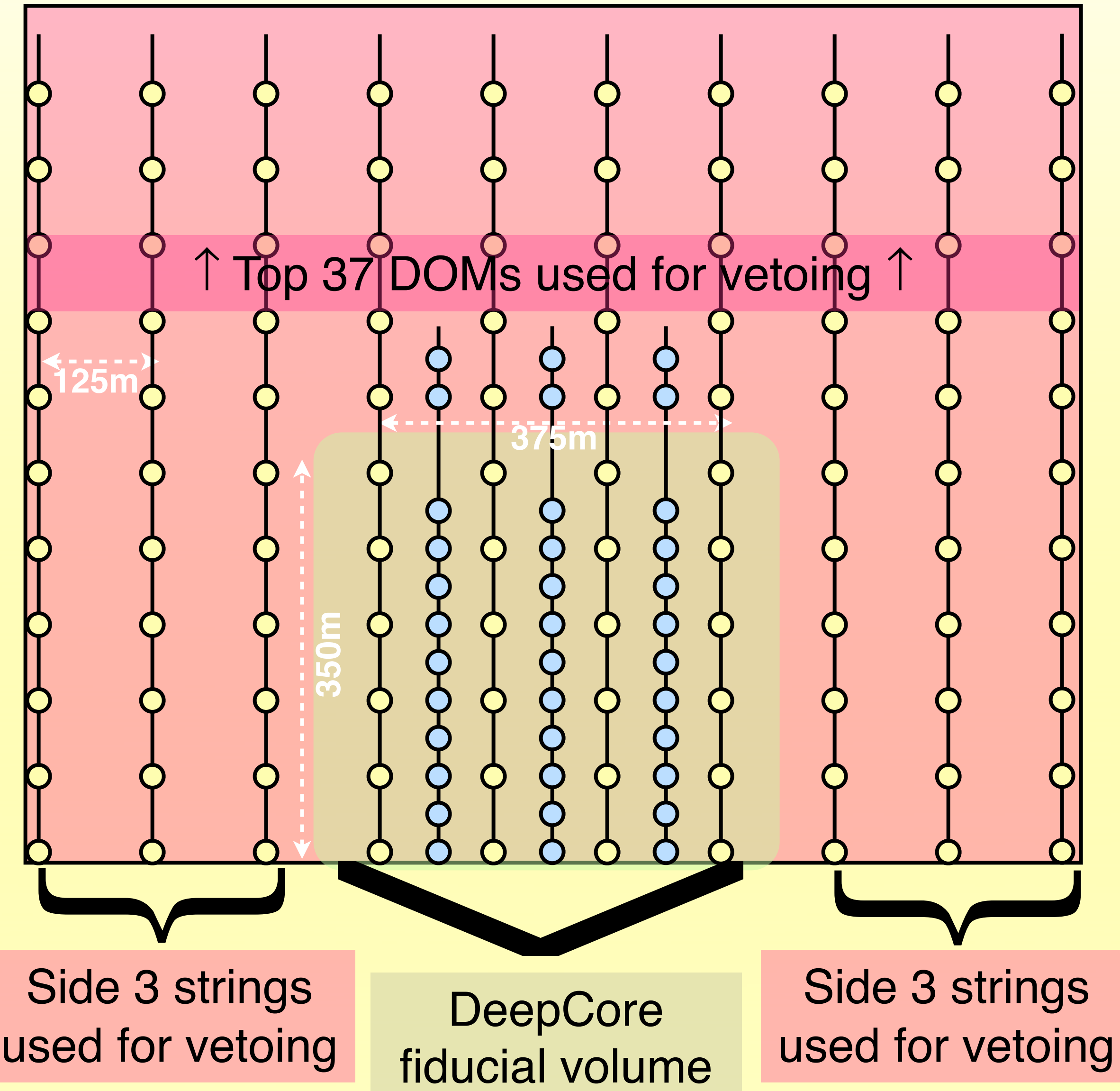
$$\phi(\mu)/\phi(\nu_{atm}) \simeq 10^6$$

Top view



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

Side view



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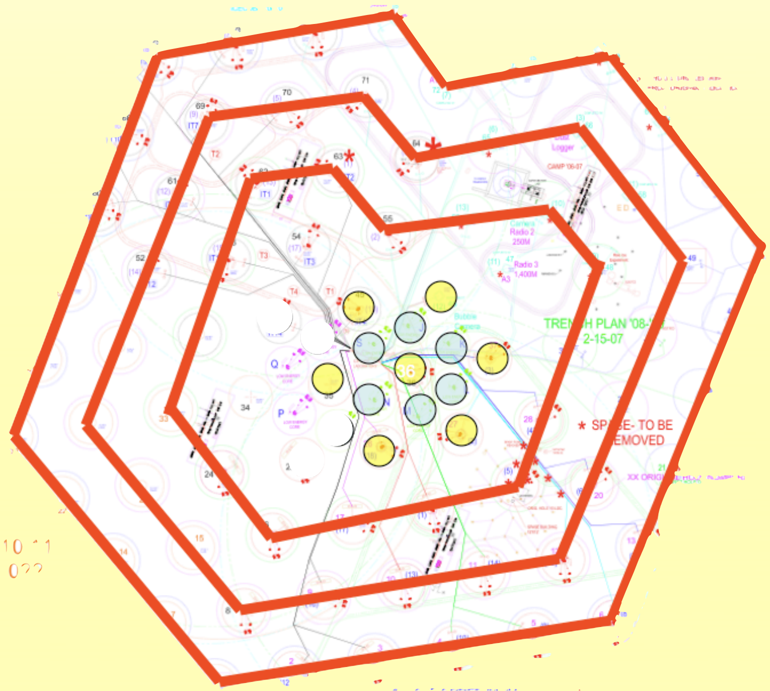

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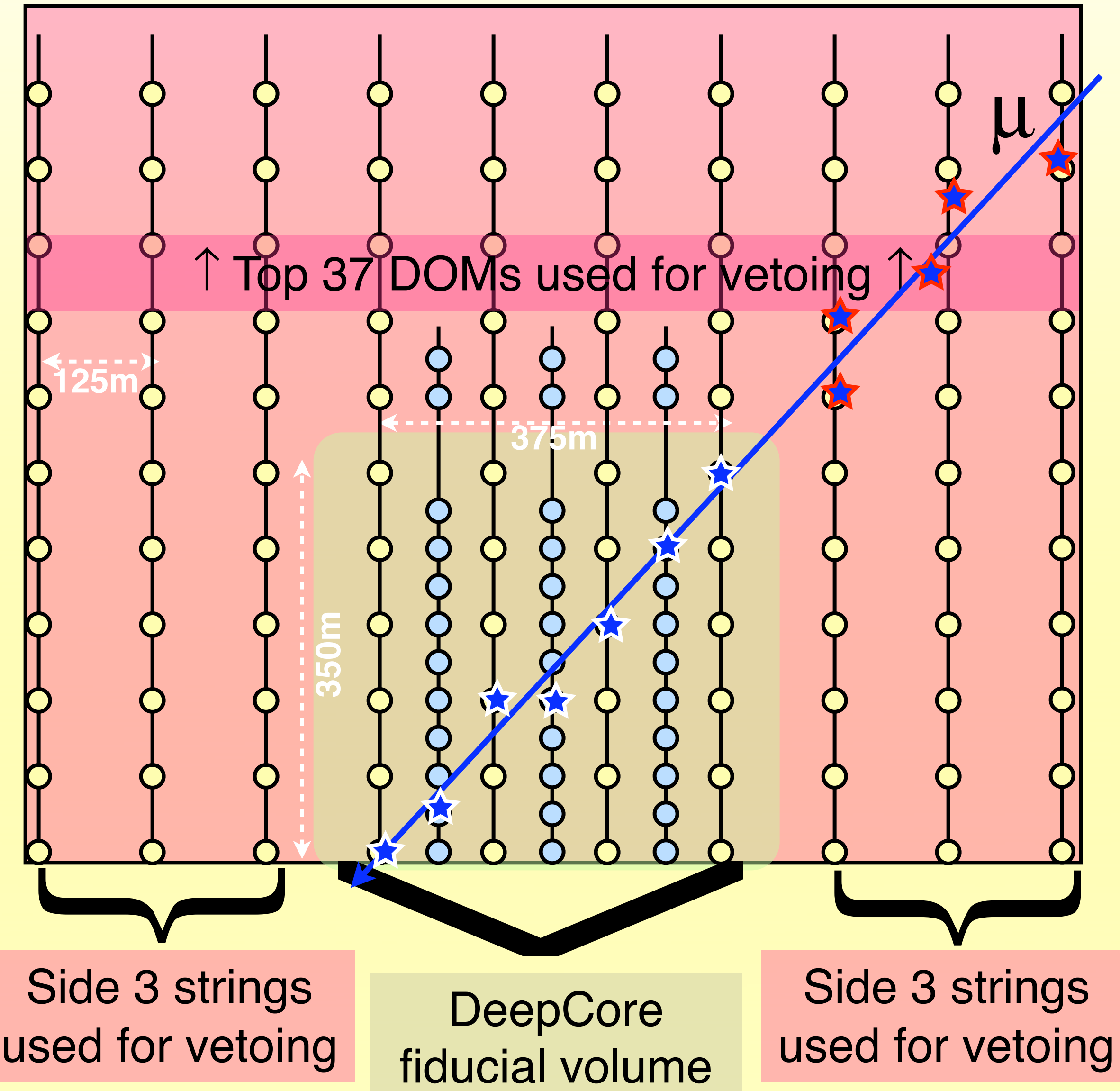

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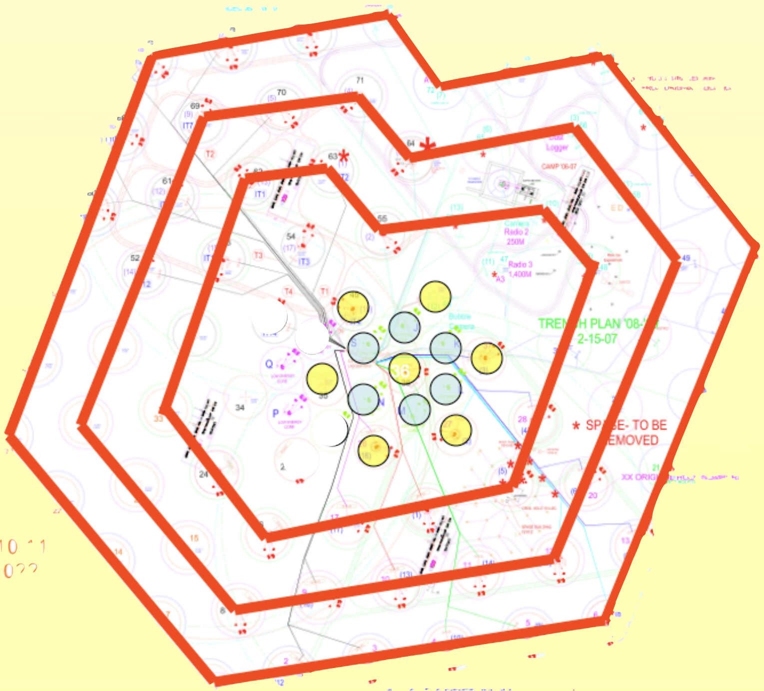

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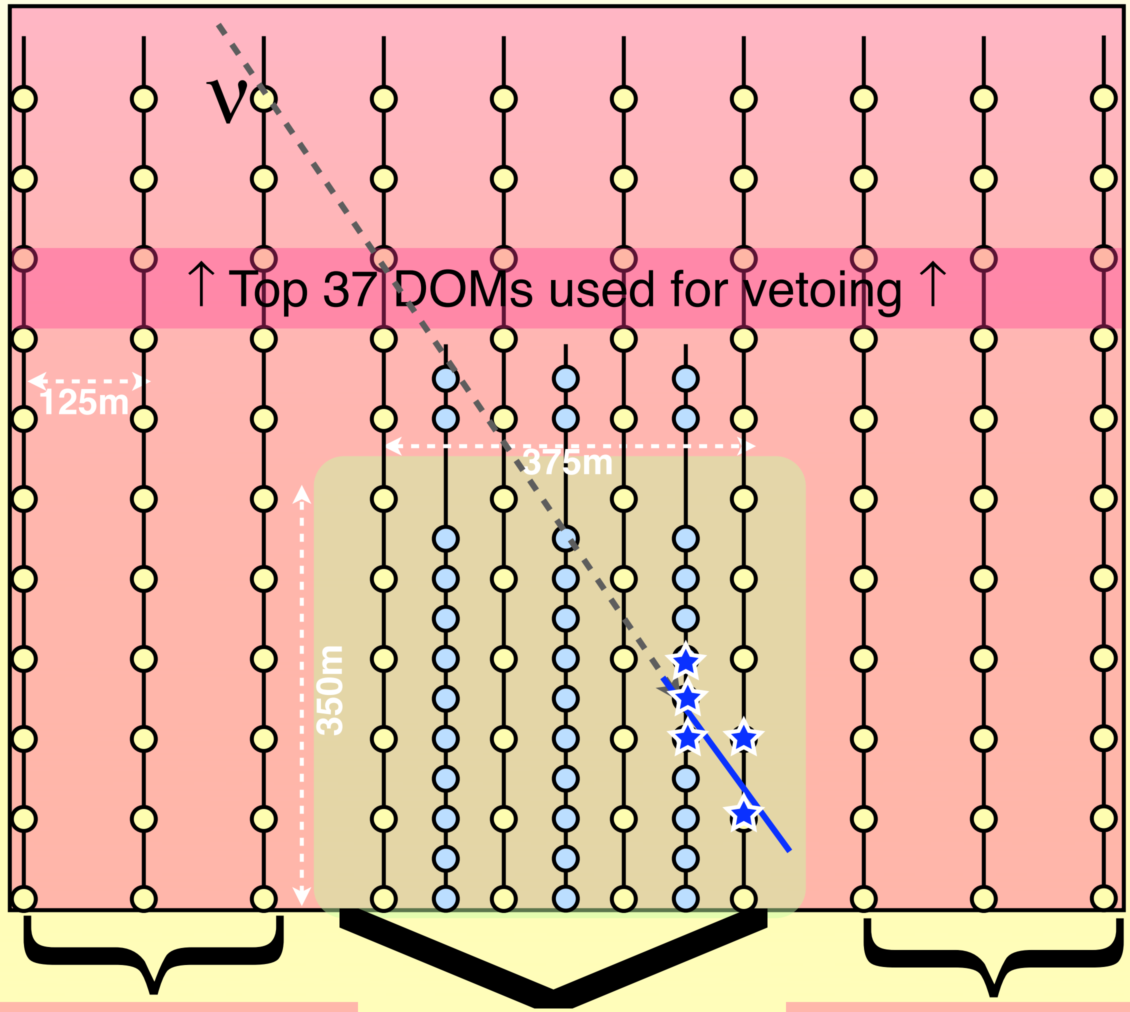


Side 3 strings used for vetoing

DeepCore fiducial volume

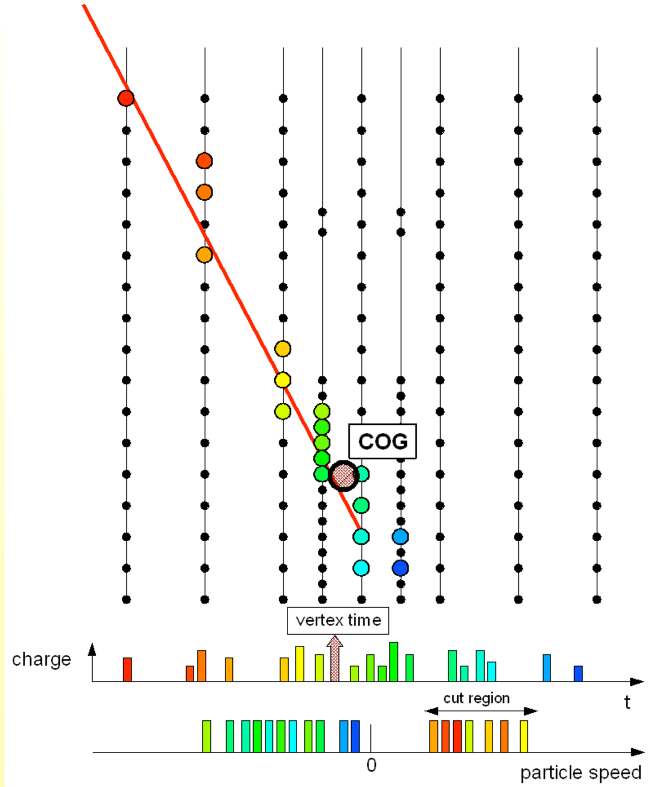
Side 3 strings used for vetoing

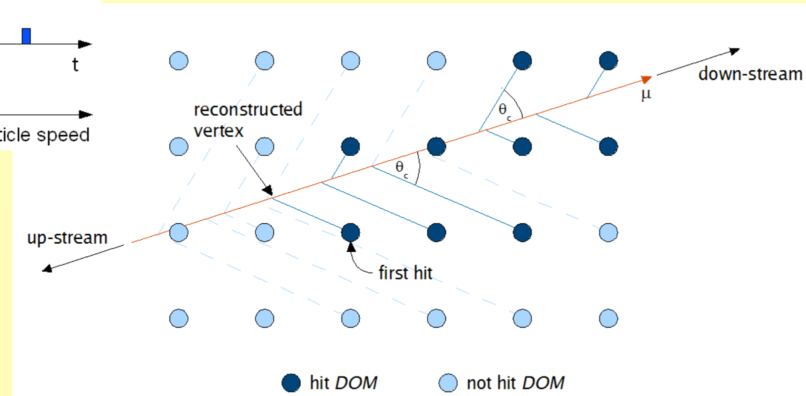
18-hole 09/10 season: Full veto

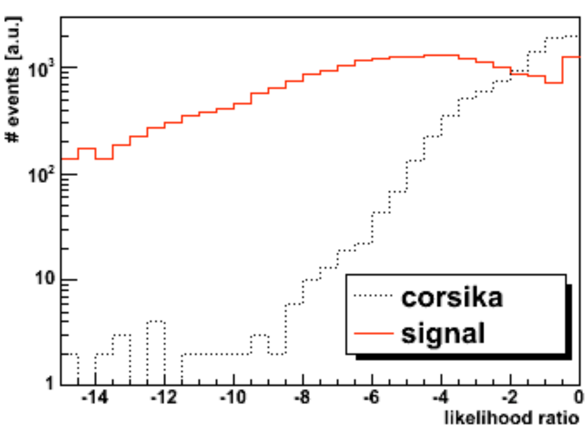
~10^6 rejection factor attainable

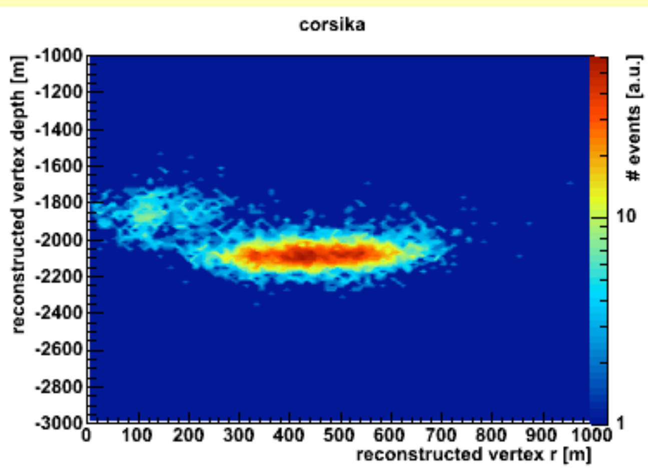
Veto Details

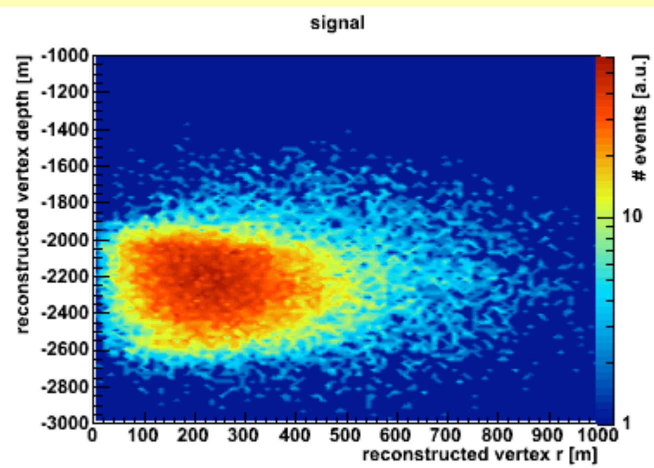
- Depth
- Veto events with hits outside fiducial volume consistent with a cosmic-ray muon
- Evaluate likelihood of event to have been produced by a neutrino vs. a muon
- Require event vertex to be in DeepCore fiducial volume











DeepCore Physics

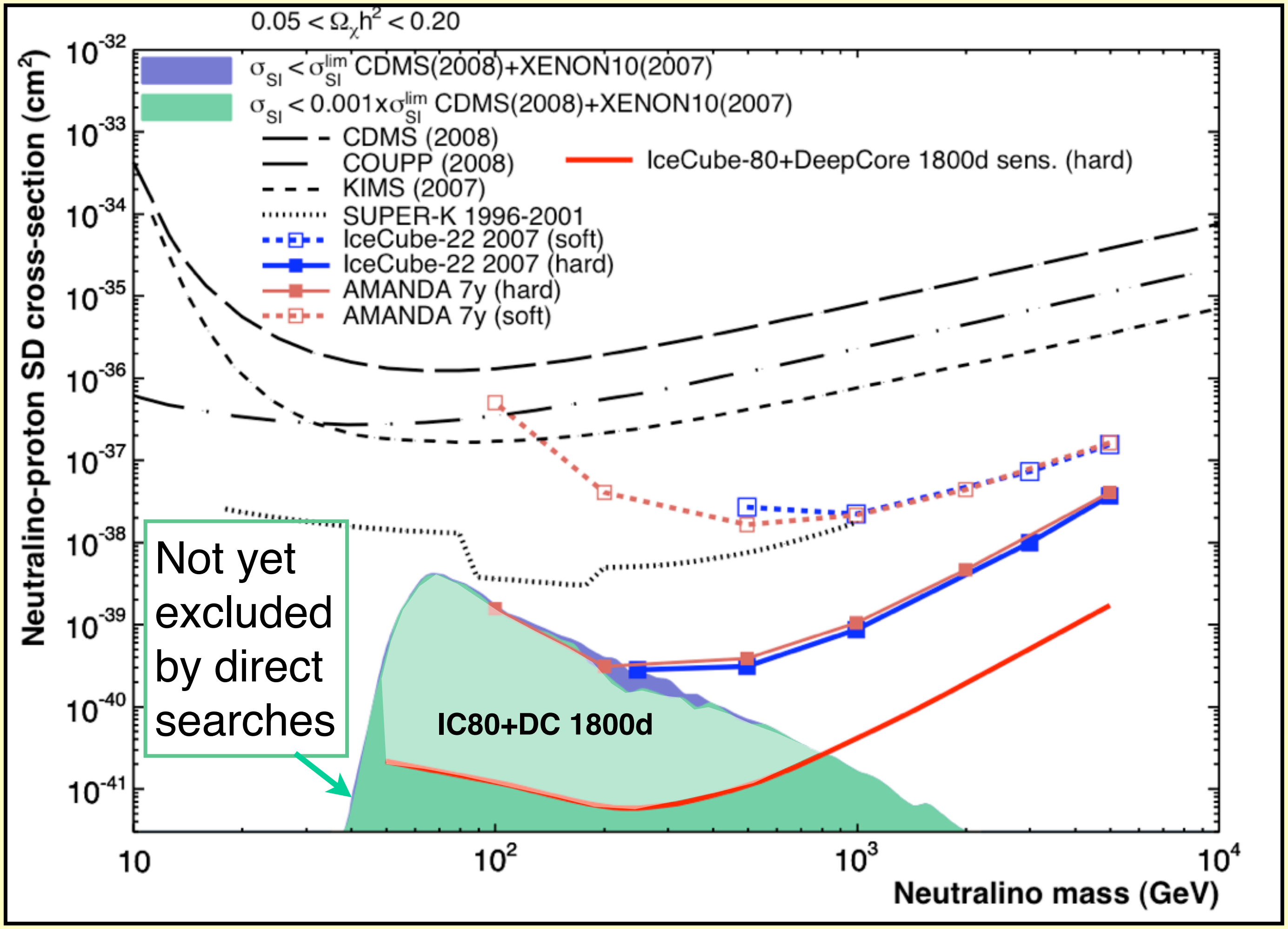
- Main topics:
  - WIMPs
  - Neutrino Oscillations
  - Southern Sky Sources
  - Exotica
- Studies performed with full detector simulation
  - WIMPs: basic reconstructions used
  - Oscillations: just at trigger level

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 104 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}

WIMPs and DeepCore

- IC22 result improves existing limits on σ_{SD} (ArXiv: 0902.2460v1, accepted by PRL)
- Main systematic uncertainties (~20%):
  - photon propagation in the ice
  - absolute DOM efficiency
- DeepCore (& IC80) will extend sensitivity into region not yet excluded by direct searches based on σ_{SI}

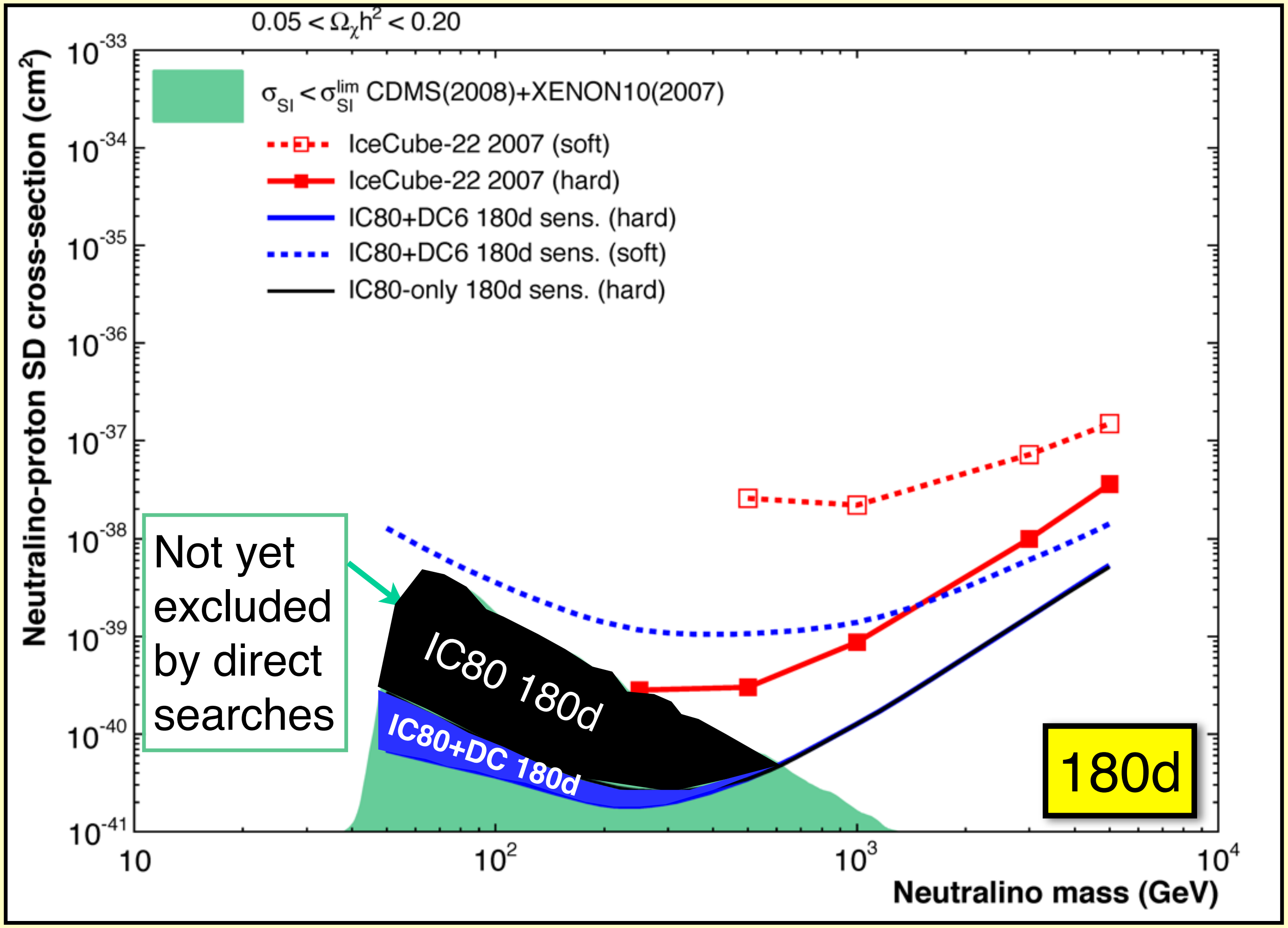


DeepCore and WIMPs

- Significant improvement in expected solar WIMP sensitivity relative to last SAC meeting:
  - final geometry & high QE PMTs included
  - 10x more 1μ and atm ν background
  - coincident 2μ and 3μ background used
  - updated ice model
  - better trigger and updated reconstruction
  - improved analysis method (multivariate) and additional cuts
- N.B.: Our studies focused thus far on solar WIMPs
  - later will also study DeepCore response to Earth WIMPs and possibly WIMPs from galactic cente

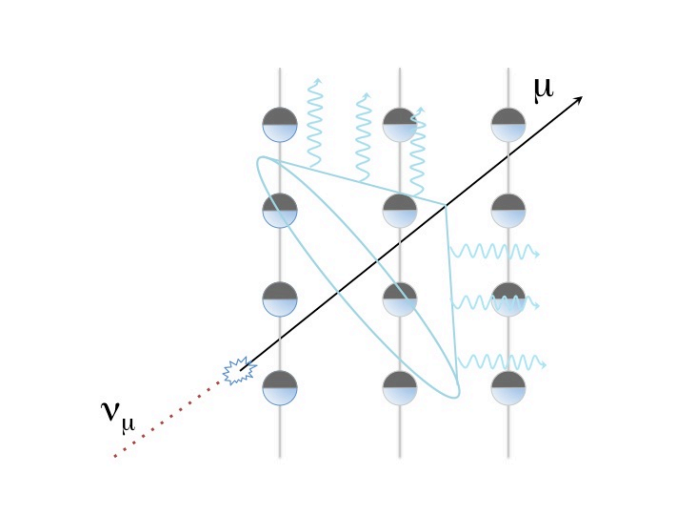
WIMPs and DeepCore

- Same expected sensitivity as before, only in 1/10 the time
- Very conservative DeepCore contribution at low energies
  - minimizing reconstruction systematics etc. will be key to exploiting DeepCore's potential

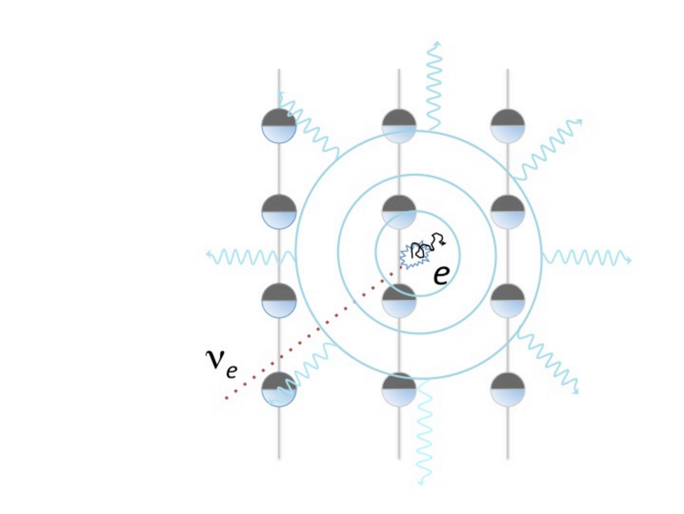


DeepCore & ν Oscillations

- Preliminary studies performed using full detector simulation
  - assume high level of background suppression provided by veto
  - <u>done only at trigger level</u>
    - signal reconstruction algorithms to identify low energy neutrino flavor and energy are under development
- Three possible measurements
  - ν_μ disappearance
  - ν_τ appearance
  - neutrino hierarchy



"Track"



"Shower" or "Cascade"

DeepCore & ν Oscillations

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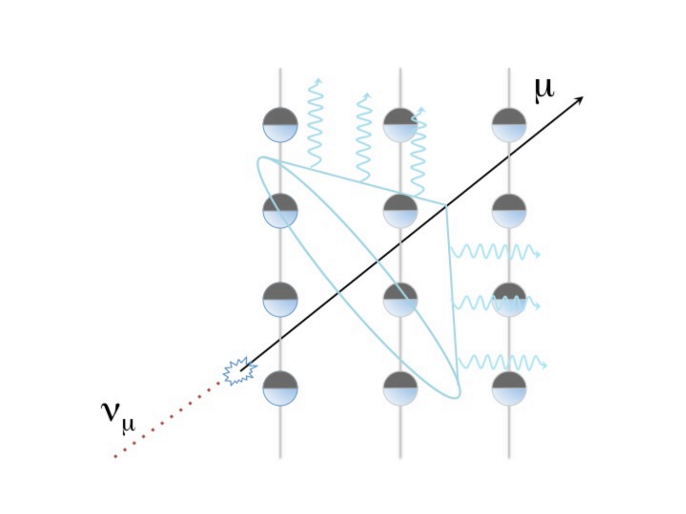
  - assume high level of background suppression provided by veto
  - done only at trigger level
    - signal reconstruction algorithms to identify low energy neutrino flavor and energy are under development
- Three possible measurements
  - ν_μ disappearance [Feasible.]
  - ν_τ appearance [Maybe.]
  - neutrino hierarchy [Very hard.]



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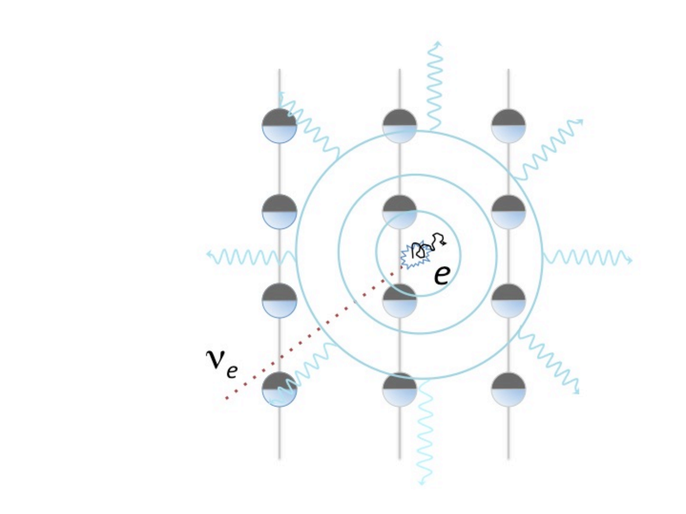

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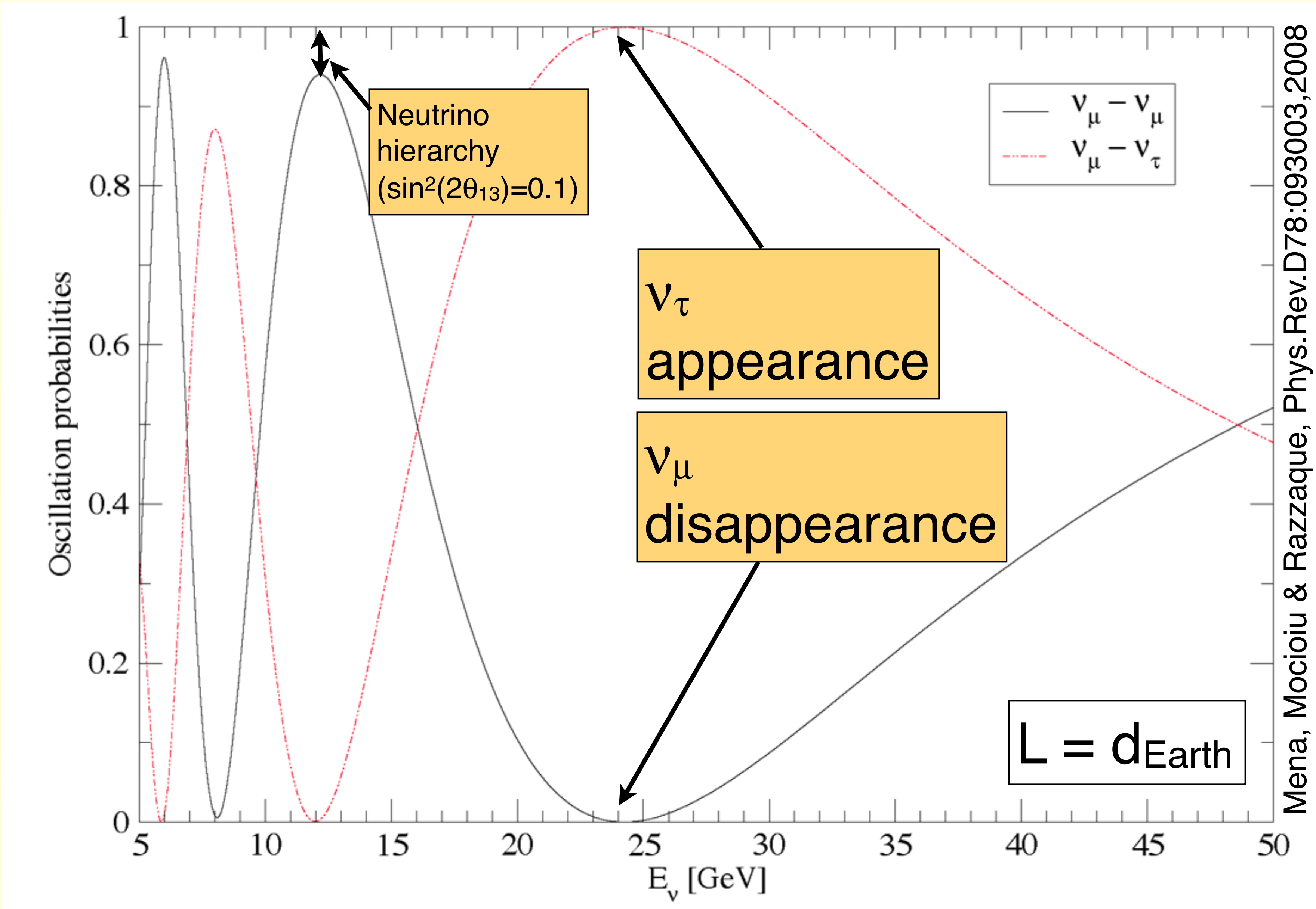
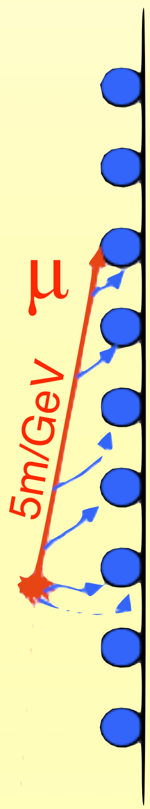
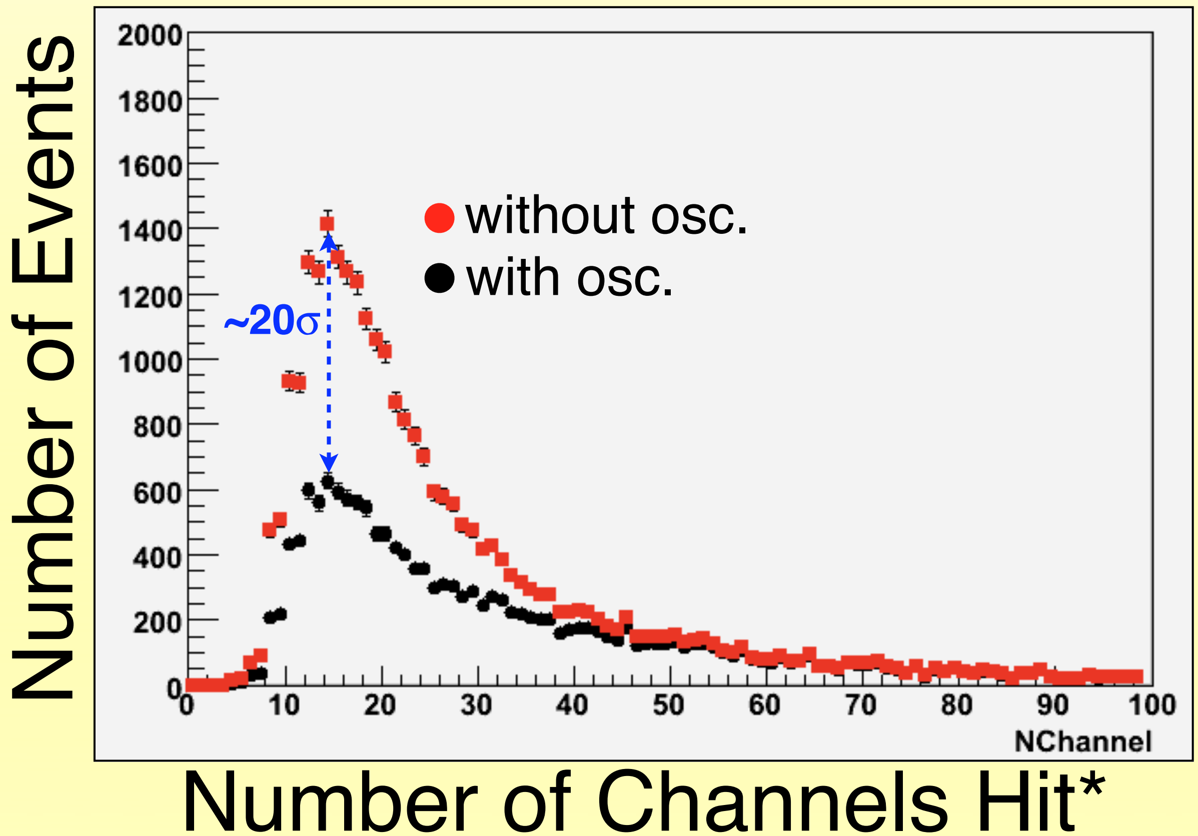


DeepCore & ν_μ Disappearance

- Use ~vertically upgoing ν_μ-induced muons



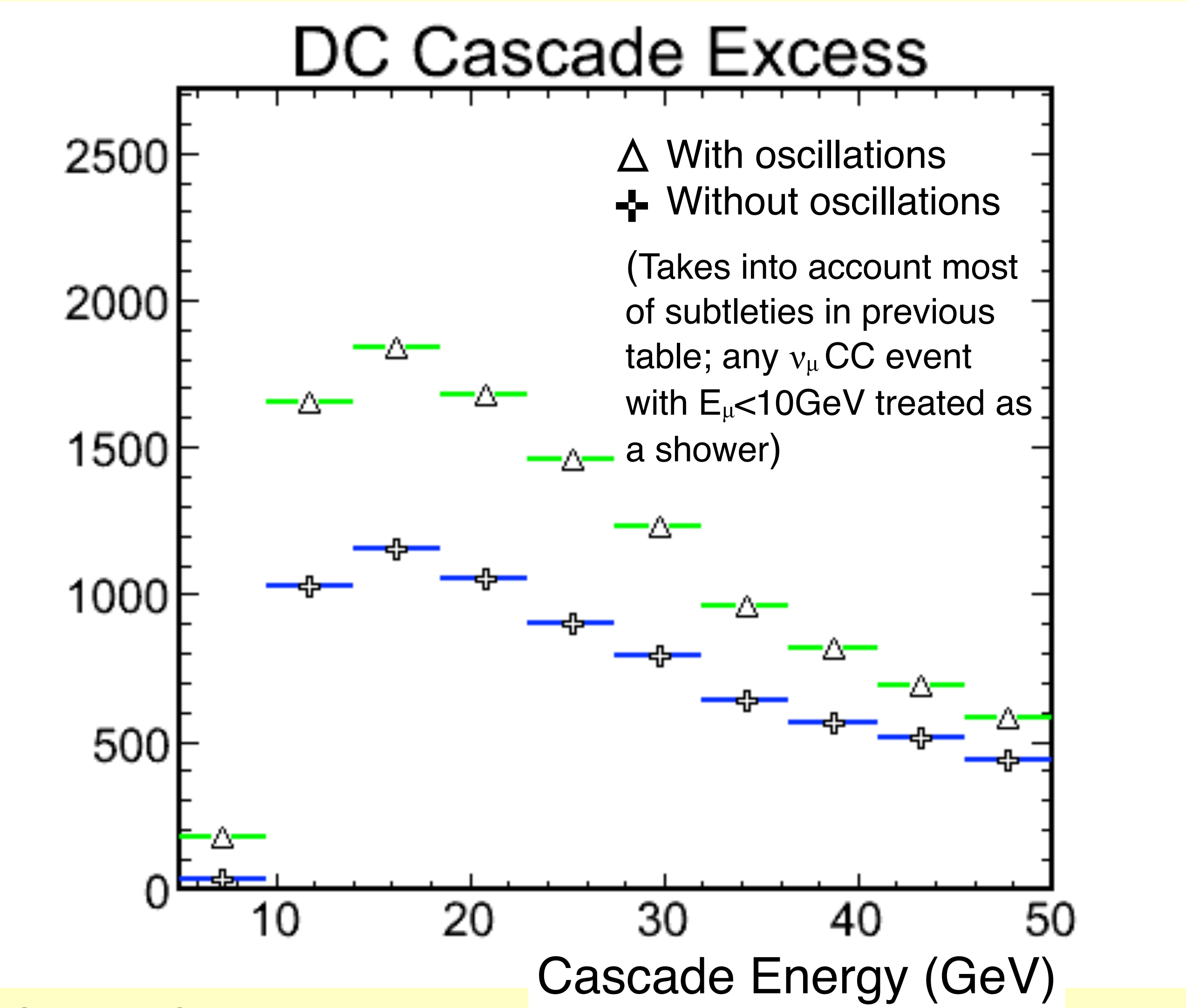


- full 3-ν oscillations
- PREM (earth model)
- trigger level (SMT4)
- full simulation
- no systematics
- 1 yr DeepCore
- $\cos(\theta) < -0.6$

*Crude energy estimator

- These initial studies yield a large effect with just one year of DeepCore data

ν_τ Appearance: Ultra-Preliminary Study

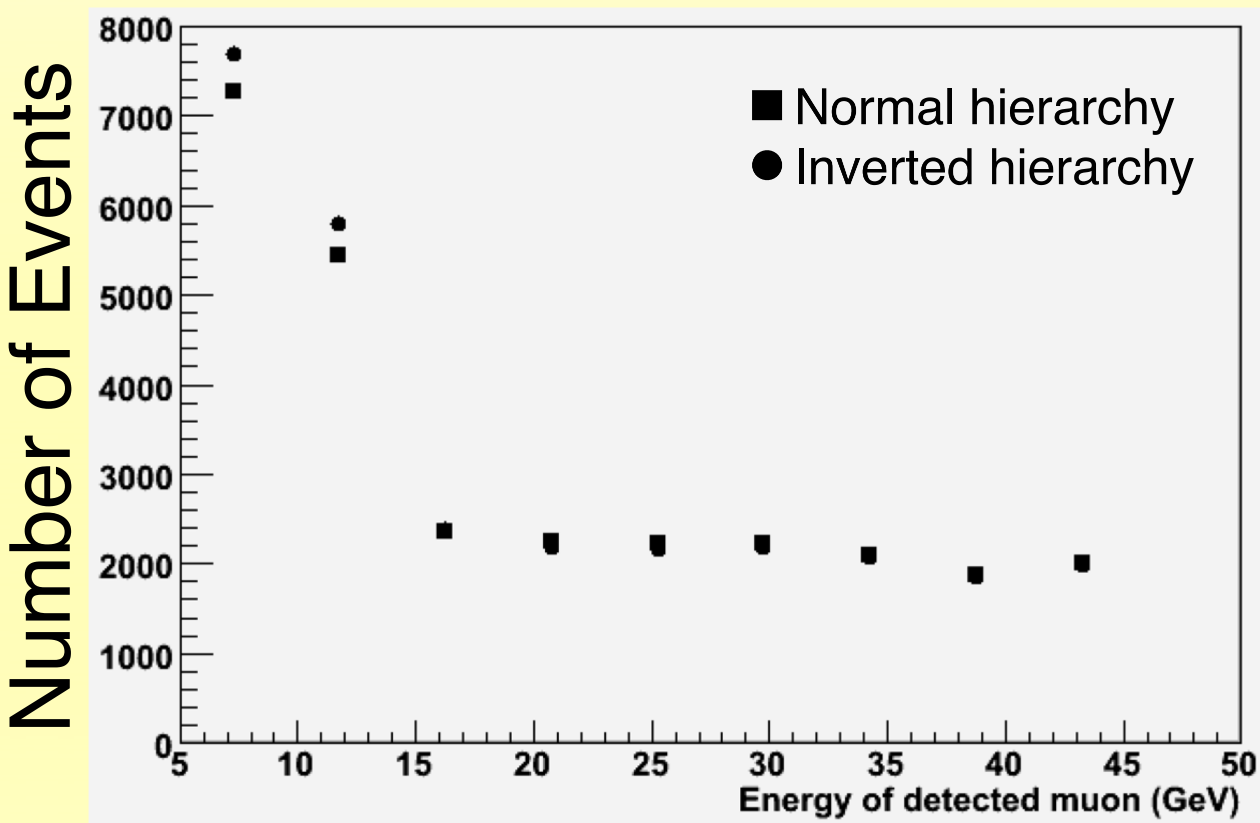


- full 3-ν oscillations
- PREM (earth model)
- trigger level (SMT4)
- full simulation
- no systematics
- 1 yr DeepCore

Conclusion: Worth pursuing.

DeepCore & Hierarchy: Sensitivity

- Perform study with full IceCube simulation at trigger level (no reconstruction)



True E_{μ} (GeV)

- full 3-ν oscillations
- PREM (earth model)
- trigger level (SMT4)
- full simulation, no reconstruction
- no systematics
- 5 yrs DeepCore
- $\cos(\theta) < -0.7$

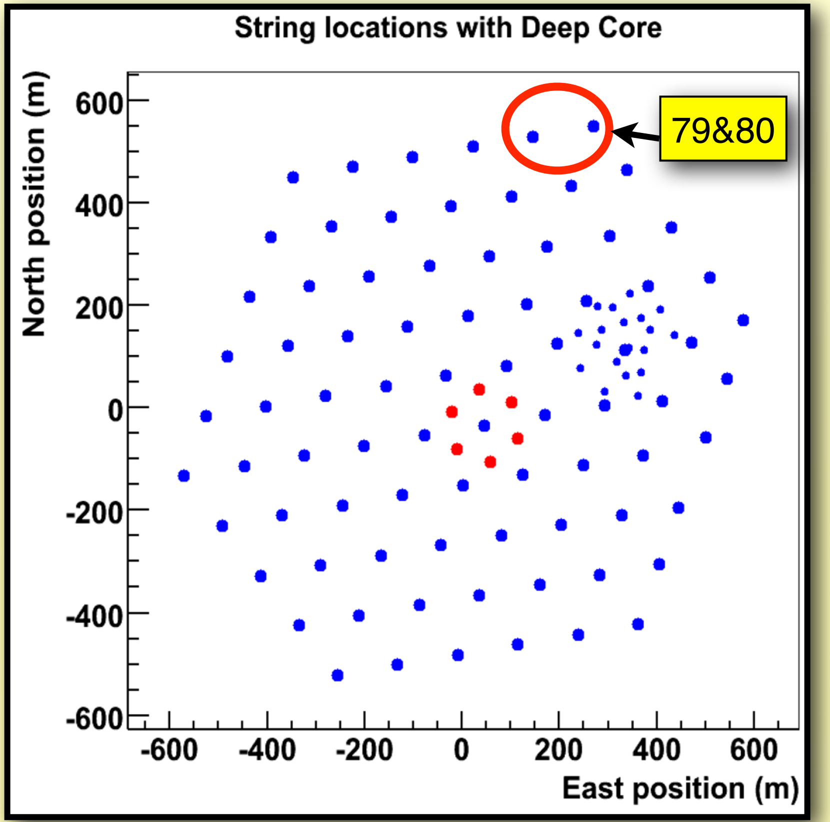
Conclusion: Worth pursuing.

Low Energy Reconstruction

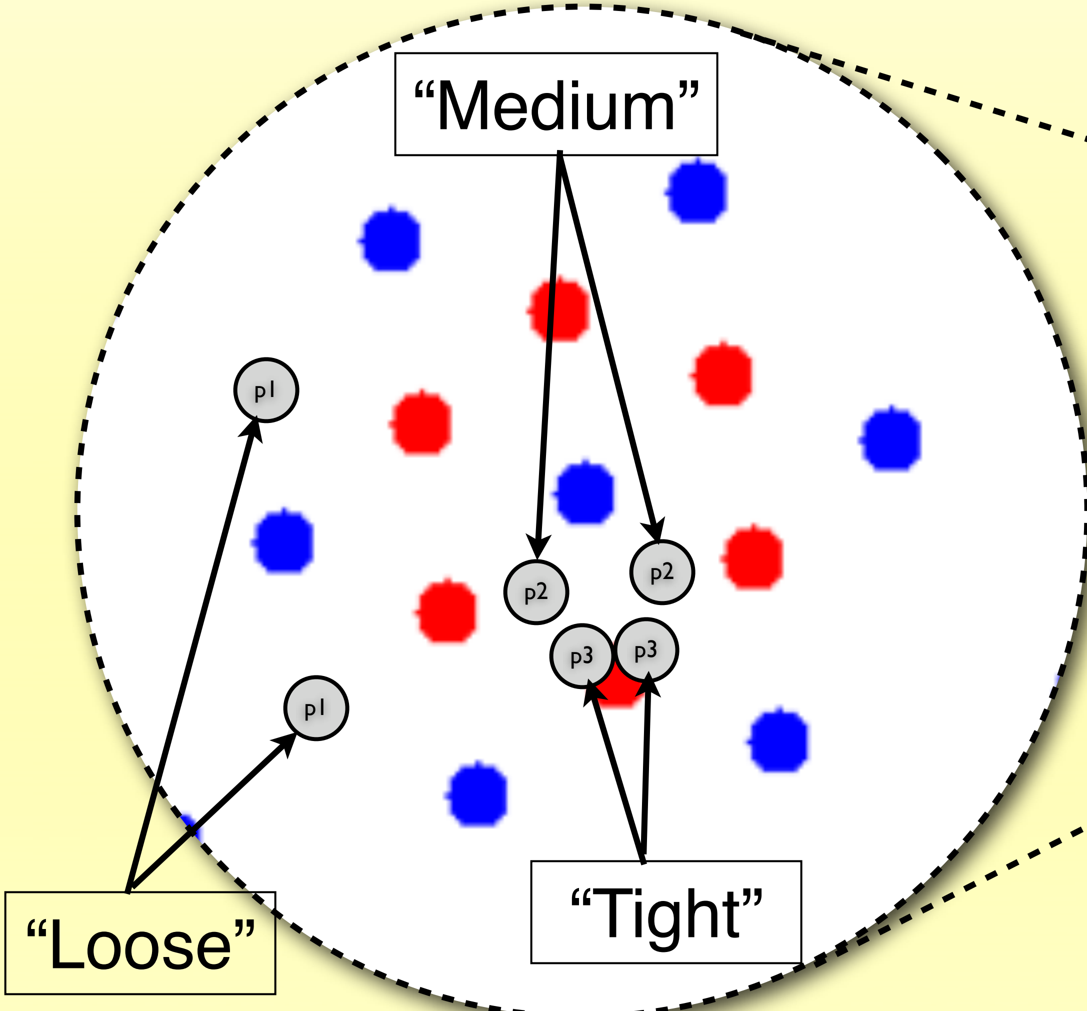
- Existing reconstruction algorithms for muon neutrinos assume “infinite” length
- At energies of interest to DeepCore, this is not a very good approximation
  - Must take into account both finite track length and hadronic shower at creation vertex
- Week-long mini-workshop planned for early June at Heidelberg to accelerate progress on this front
- Once have traction on reconstruction, will finish partially-completed DeepCore “detector paper”

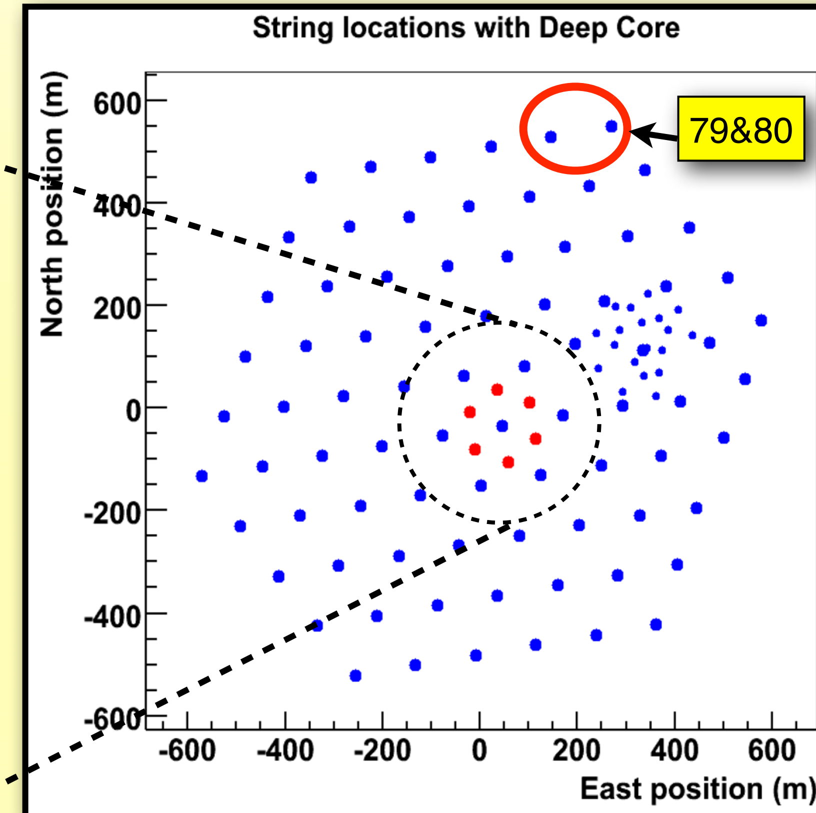
Strings 79 & 80

- We have performed a study of the advantages of adding two strings to the DeepCore array
  - studied 3 possible geometries
  - see marked improvement in:
    - basic reconstruction quantities
    - sensitivities
  - studies assumed strings would have the DeepCore DOM geometry
    - decision on breakouts before 1 July 2009
- Note: Any two strings could be used; 79&80 historically were first two available and started us thinking about them in DeepCore context

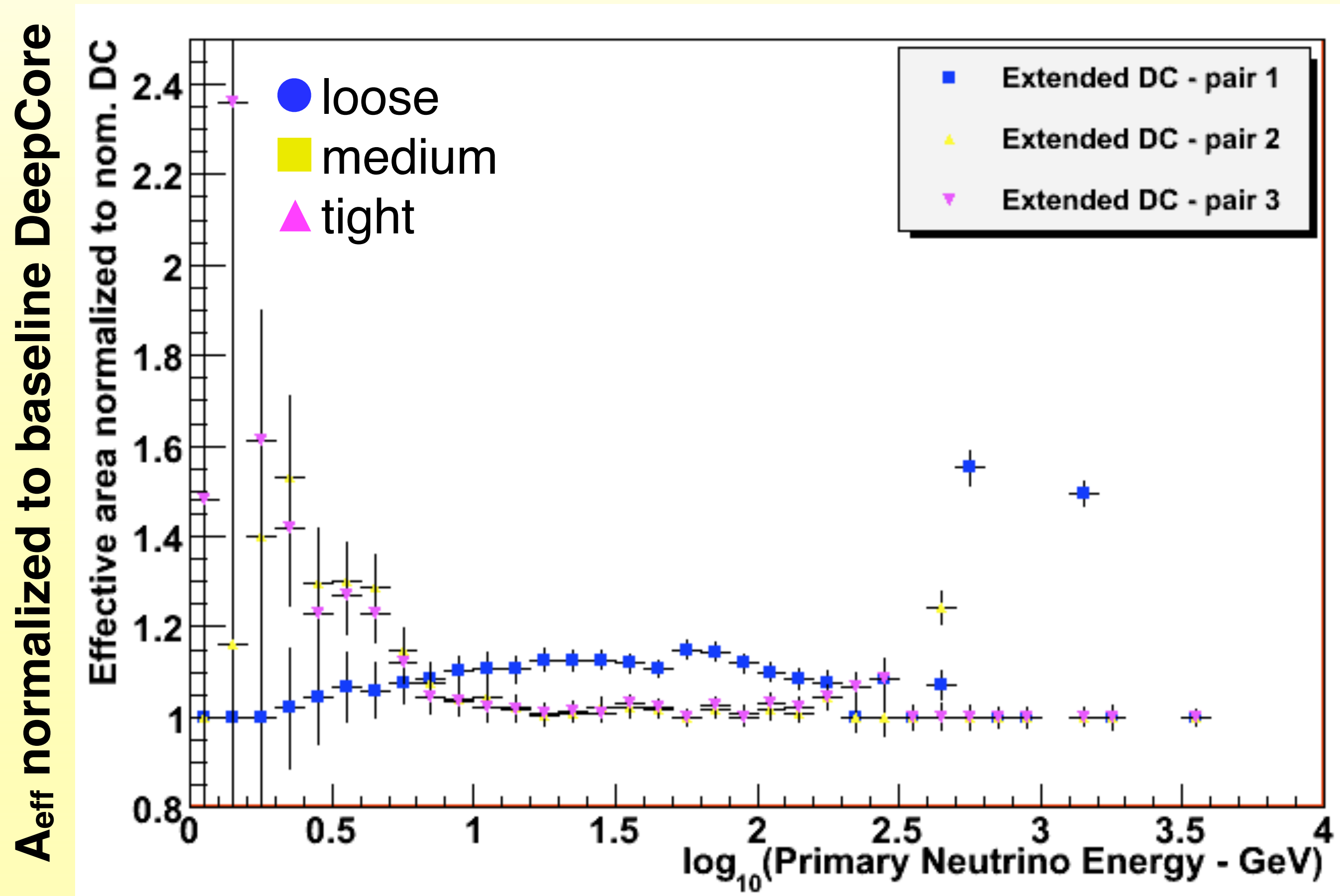


Strings 79 & 80





DeepCore + 79&80

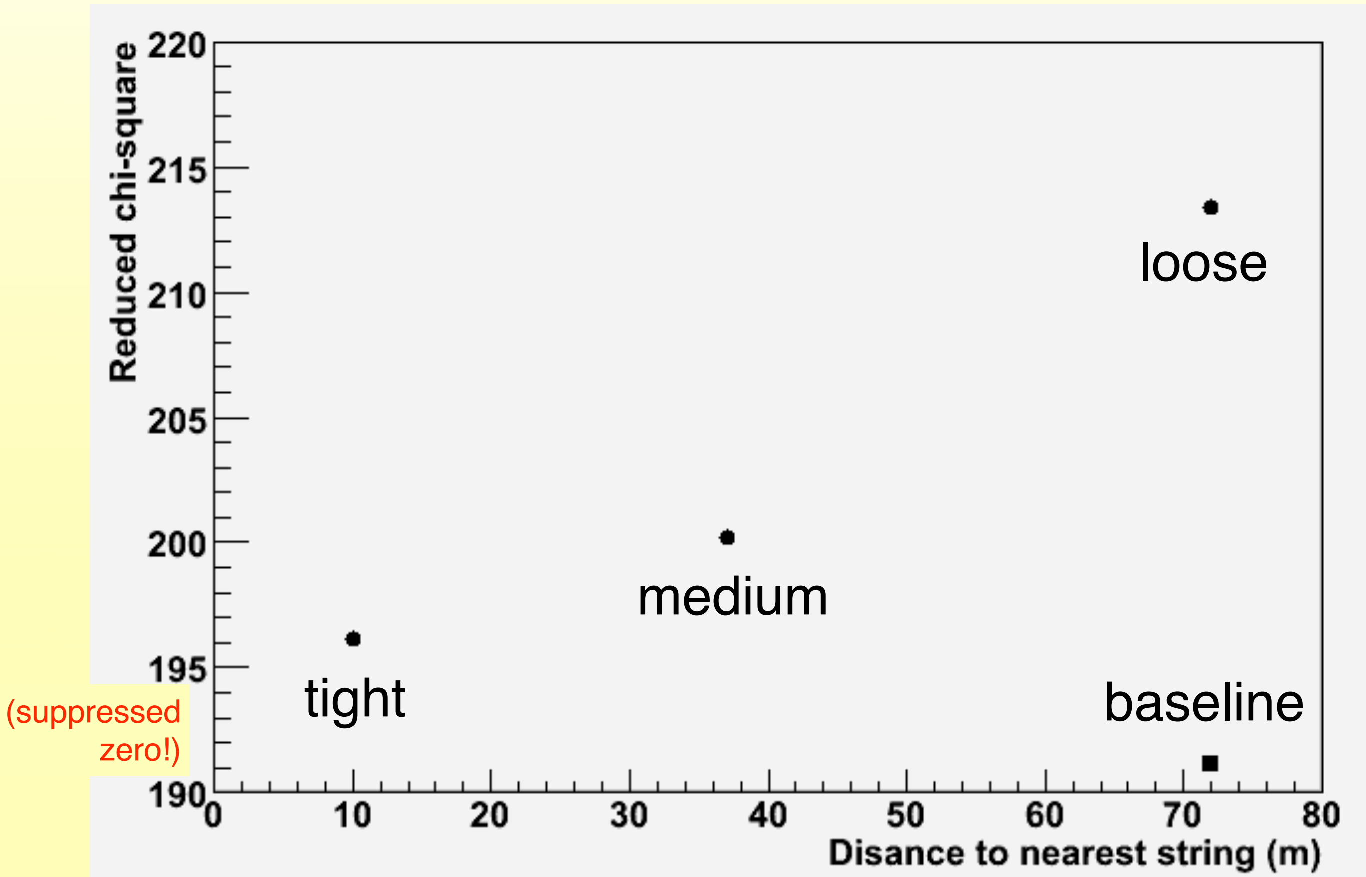


Effective Area normalized to the nominal DeepCore geometry for ν_μ events. Trigger condition is SMT4 in the given geometry. Significant increases are seen for pairs 2 and 3 below 10 GeV. Nominal increases of 10-15% are seen for pair 1 between 10 GeV and 300 GeV.

See significant gain in the effective area for ν_μ events, especially at low energies. Similar gains for ν_e.

Associated improvements:
N_{str}: up to 200%
N_{ch}: up to 30%
N_{dir}: up to 40%

DeepCore + 79&80



See improvement in statistical separation between null and oscillation hypotheses for ν_μ disappearance (at trigger level)

Reduced chi-square calculated for the binned nchannel distributions of the expected (null hypothesis - no oscillations) and observed (numu disappearance) event rates. Trigger condition is SMT4 in the given detector geometry, normalized for 1 year of livetime. Circles- extended DeepCore geometries (pair 3 - 10m nearest string; pair 2 - 37m nearest string; pair 1 - 72m nearest string). Square - nominal DeepCore. Larger values of chi-square represent improved separation between the oscillation/no oscillation scenarios.

Disposition of 79&80

- We think we have a compelling case to use 79&80 to augment DeepCore
  - improves N_{str}, N_{ch}, and N_{dir}, all markers for improved reconstruction capability
  - reconstruction is probably going to be the key challenge faced by low energy analyses
- However, strings 79 & 80 are also of interest to the High Energy Extension
- Have some indications that HEE works nearly as well without 79&80 as with (i.e., with 7 strings vs. 9)
  - concern: we may be near a “critical edge” and MC is not accurate enough to tell us

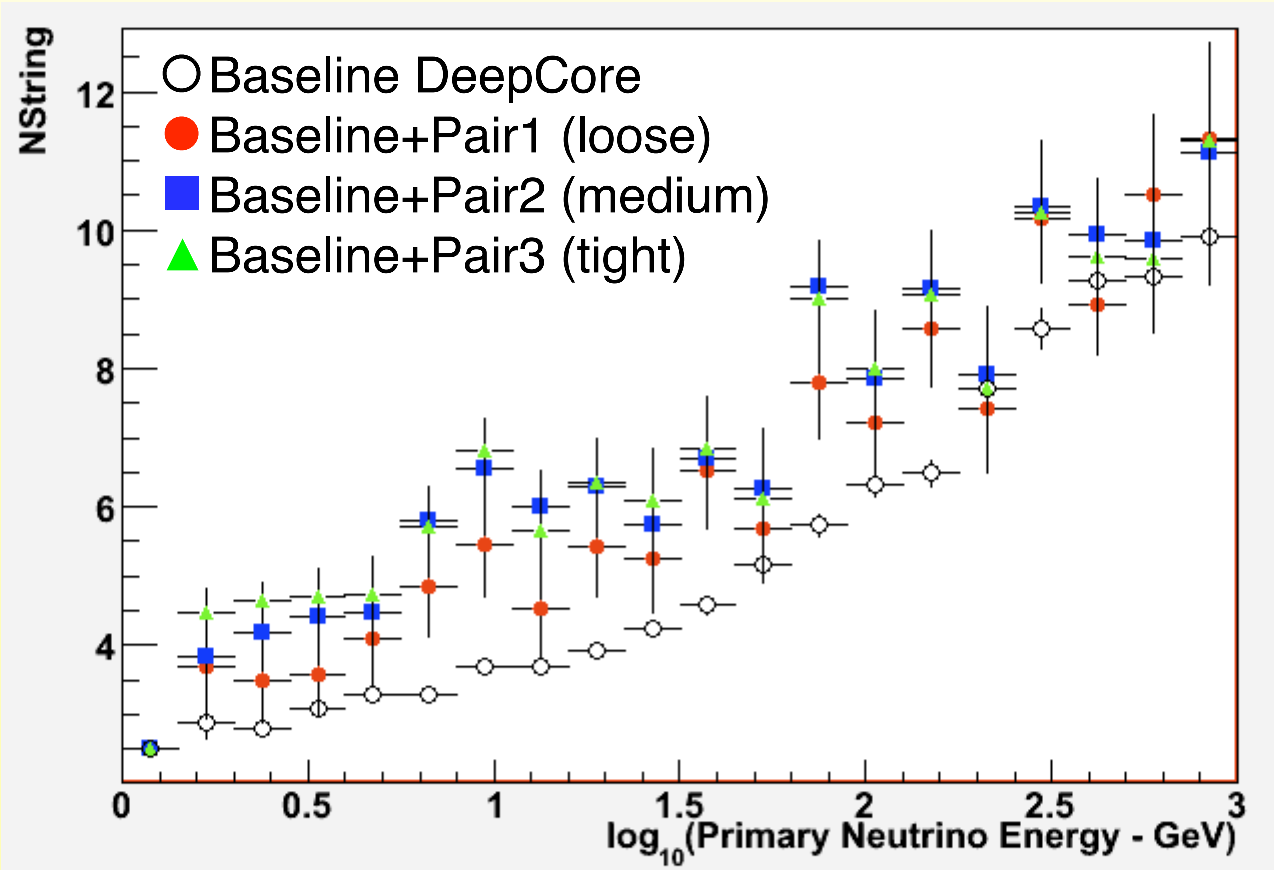
Conclusions

- Need to settle on location of strings 79&80 soon
  - SAC input requested
- Work on improving the S/N of the veto is ongoing
  - Cosmic-ray muon events tagged by IceTop can be used to estimate leakage systematics
- Efforts on new reconstruction algorithms tailored for low energy events are starting in earnest
- More exhaustive studies of the first DeepCore string 83 have begun:
  - need to fully characterize new PMTs (overall efficiency, charge response, linearity, noise, stability...)
  - need to understand photon propagation in deep ice better (not unique to DeepCore/Low Energy)

The End

Backup Slides

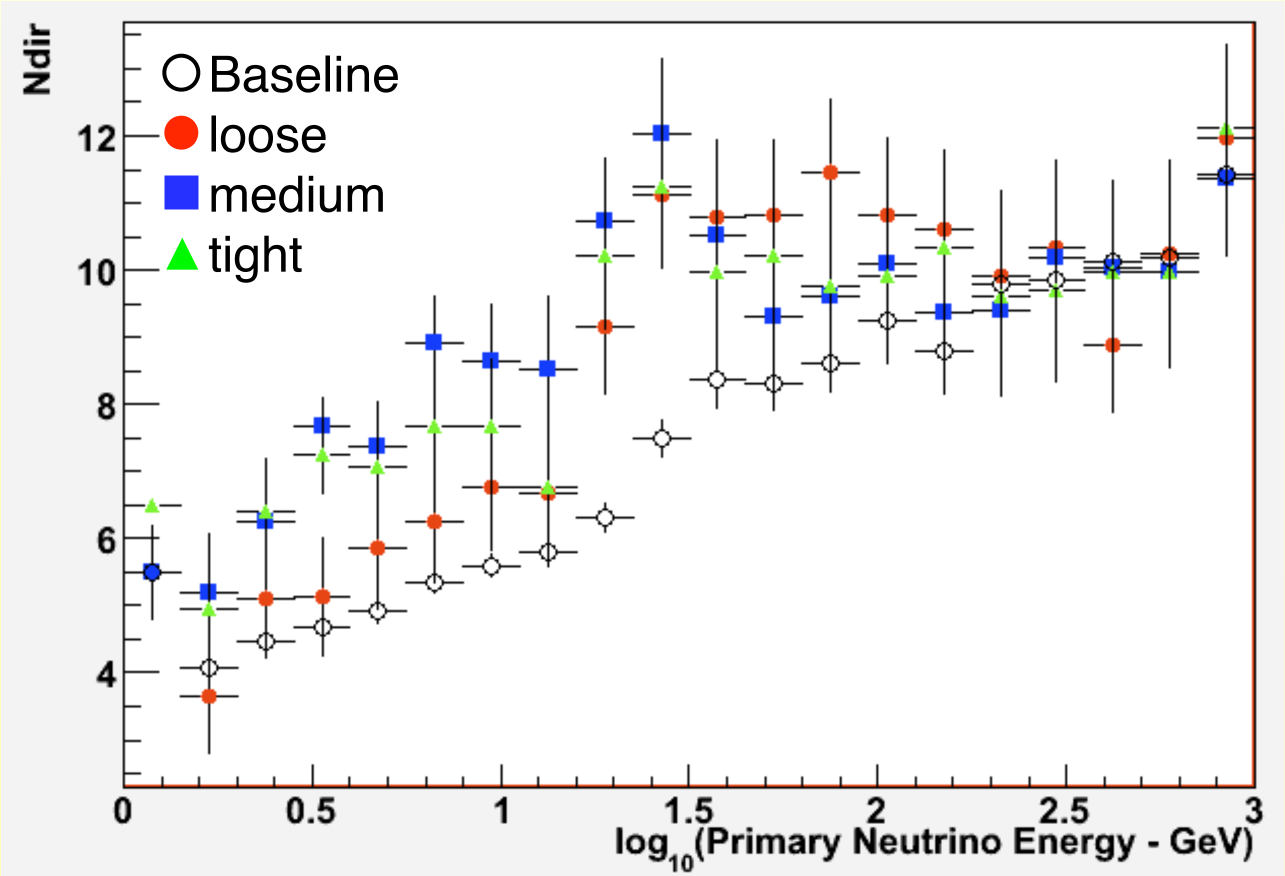
DeepCore + 79&80



See significant gain in the number of strings per event

Profile distribution for NString vs. Primary Neutrino Energy of NuMu events. Trigger condition is SMT4 in the given geometry. Pair 1 - red circles; Pair 2 - blue squares; Pair 3 - Green triangles; Nominal DeepCore - black open circles.

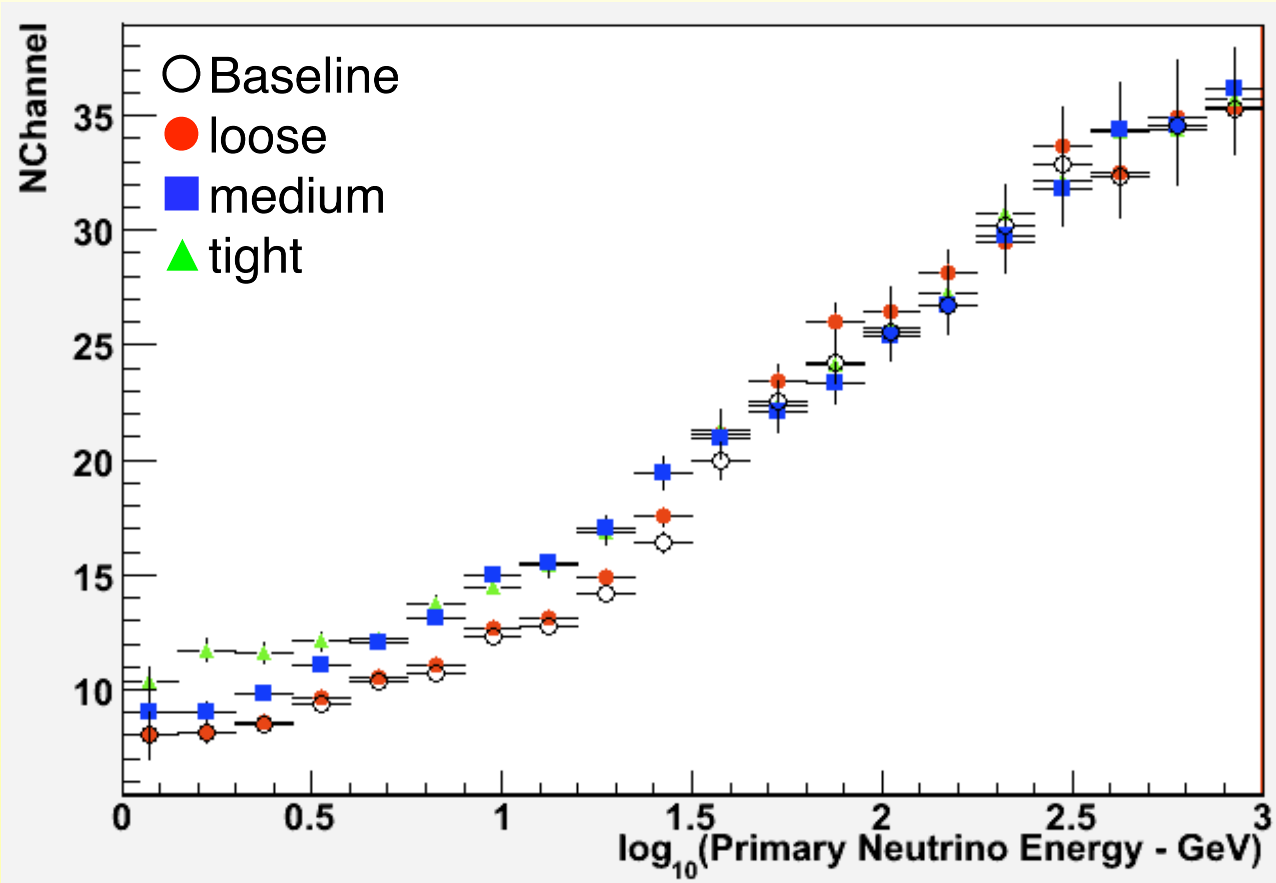
DeepCore + 79&80



Profile distribution for NDir vs. Primary Neutrino Energy of NuMu events. Trigger condition is SMT4 in the given geometry. Pair 1 - red circles; Pair 2 - blue squares; Pair 3 - Green triangles; Nominal DeepCore - black open circles. Used MC truth for track position and direction.

See significant gain in the number of direct (unscattered) hits per event

DeepCore + 79&80



See significant gain in the number of channels hit per event

Profile distribution for NChannel vs. Primary Neutrino Energy of NuMu events. Trigger condition is SMT4 in the given geometry. Pair 1 - red circles; Pair 2 - blue squares; Pair 3 - Green triangles; Nominal DeepCore - black open circles.

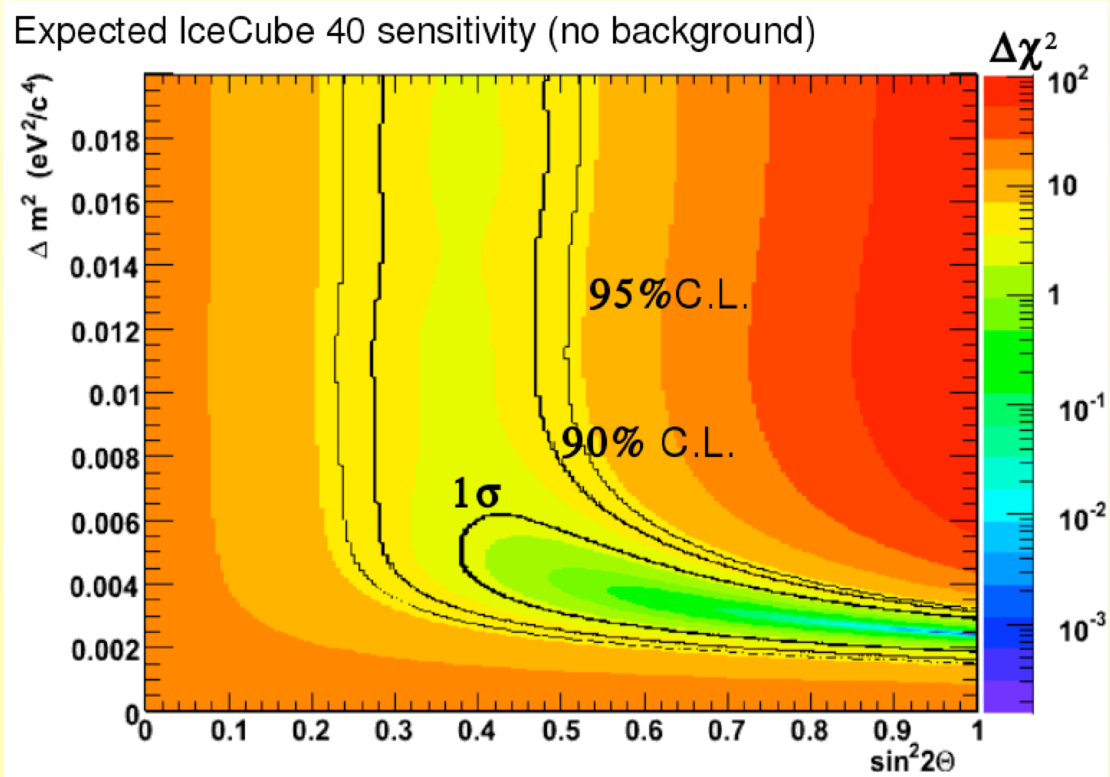
ν_μ Disappearance: IceCube Preliminary Study Results

- 1.45 days of MC background yielded zero events
  - good, but need more MC statistics! ...Being generated
- Used a 12.85-day subsample of IC22 data (requiring $\geq$ 8 hits, not $\geq$ 5...yet)
  - expected 1.8 signal events without oscillations; 1.4 with oscillations
  - saw 3: reasonable agreement so far...
  - E_ν > ~25 GeV
- For full 200+ day IC22 dataset
  - predict 35.3 without oscillations; 27.7 with

Next Steps: IC40, IC59

- Use data from larger IC40 detector
  - 3x more "central" strings
  - minimum 5 instead of 8 hits
- Expect about a 10-fold improvement in statistics:
  - 353 events without oscillations, 277 with: a 4σ effect (optimistic: 0 background assumed)

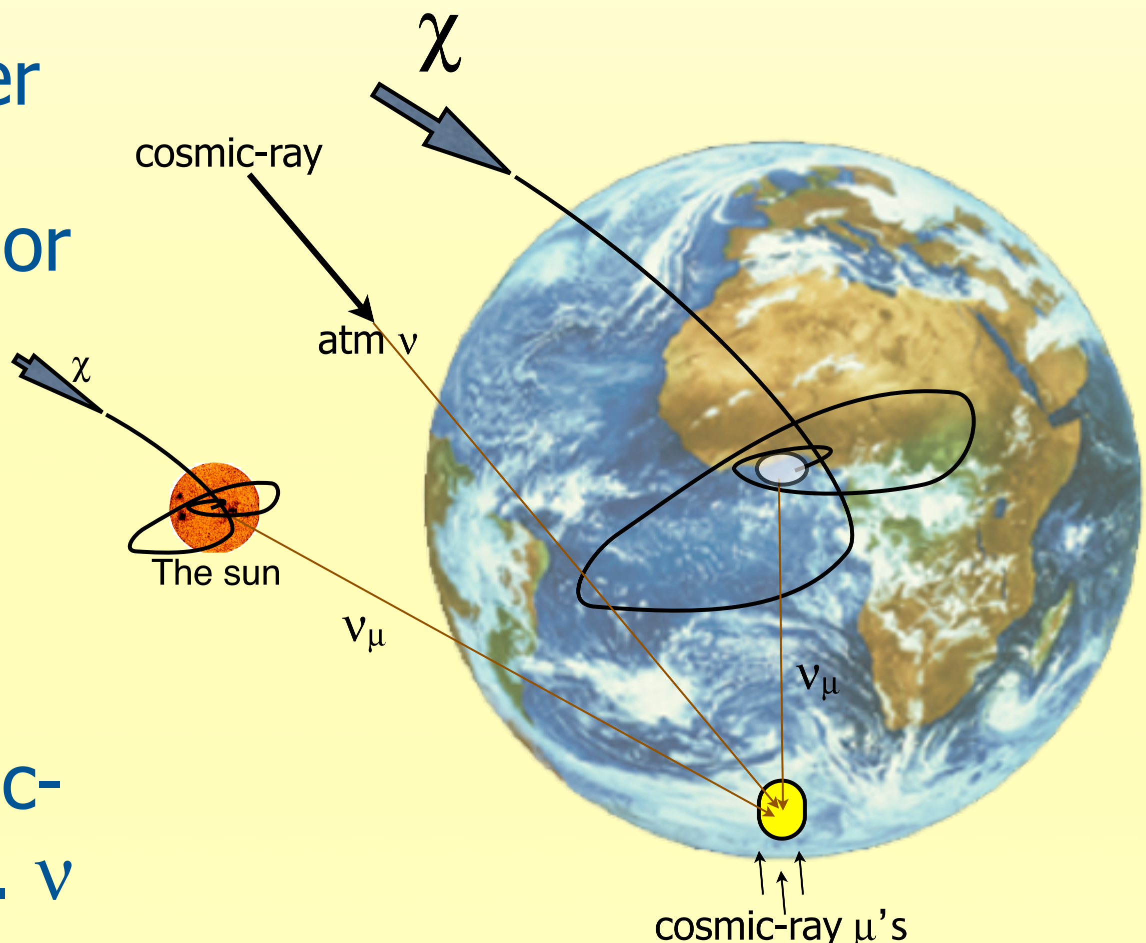
Carsten Rott, OSU/IceCube



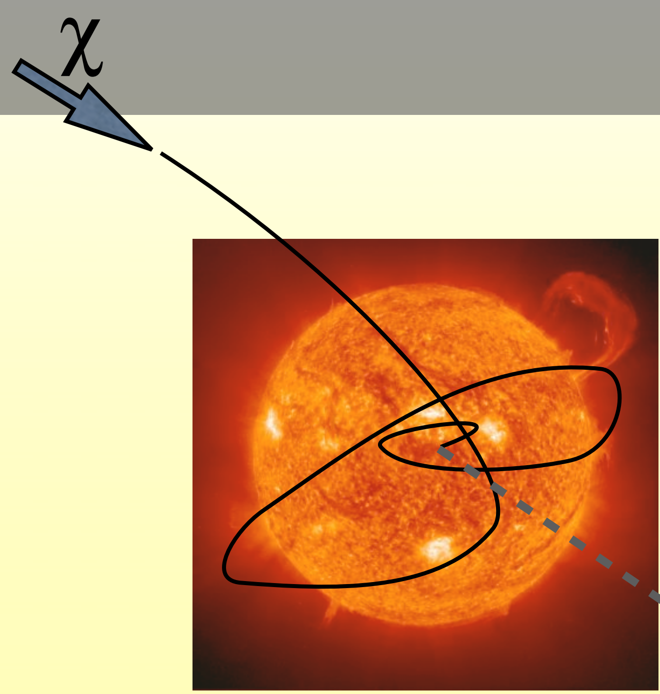
- Repeat with IC59
- Move on to DeepCore...

Detecting a WIMP Signal

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



WIMPs

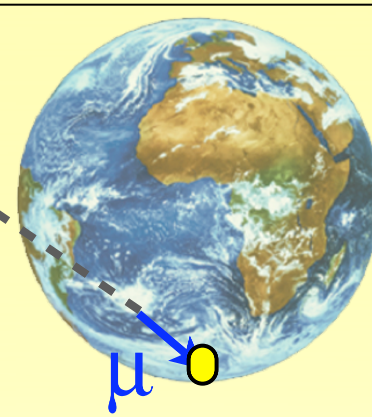


- Indirect detection from WIMP–WIMP annihilation in the
  - Earth's core
  - Solar core
  - Galactic center

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

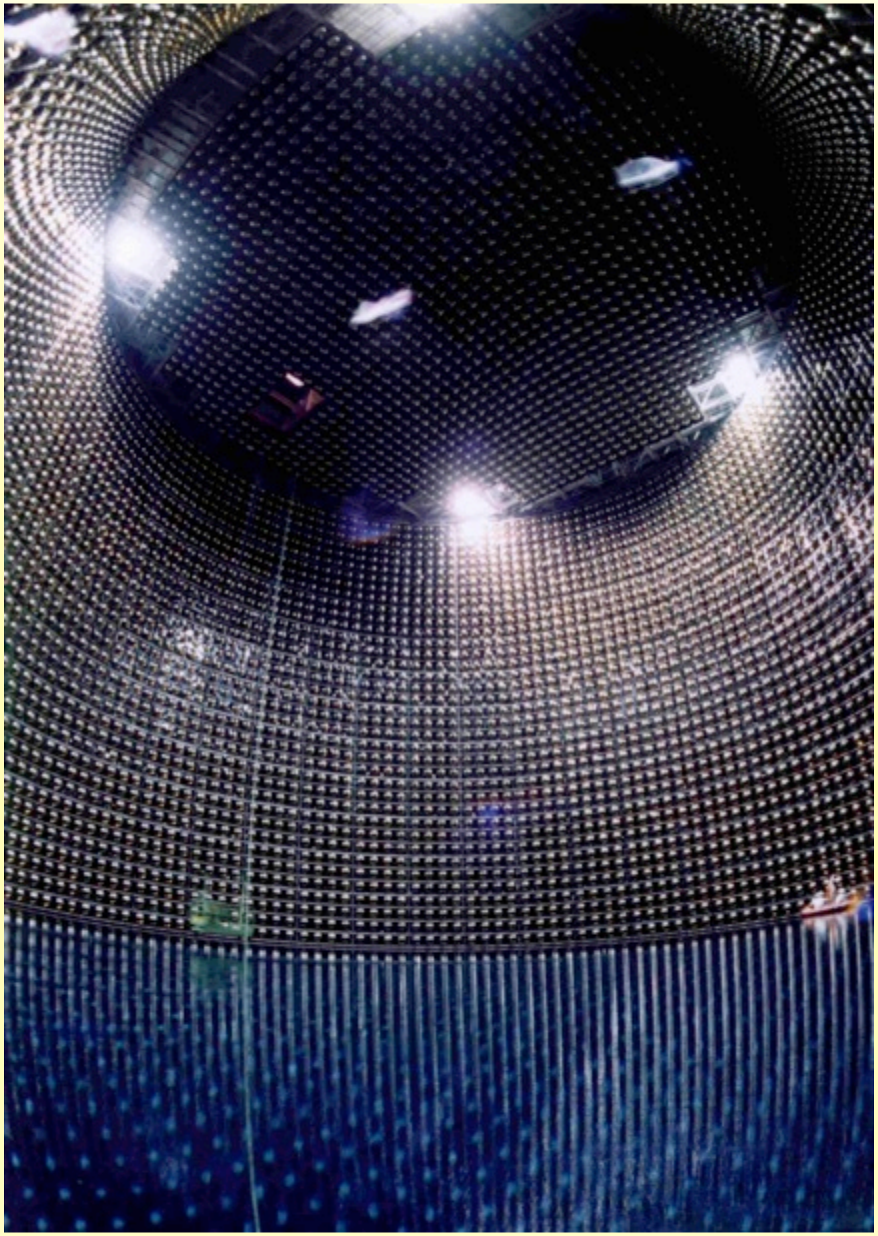
ν_μ

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



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

ν_μ Disappearance: SuperK



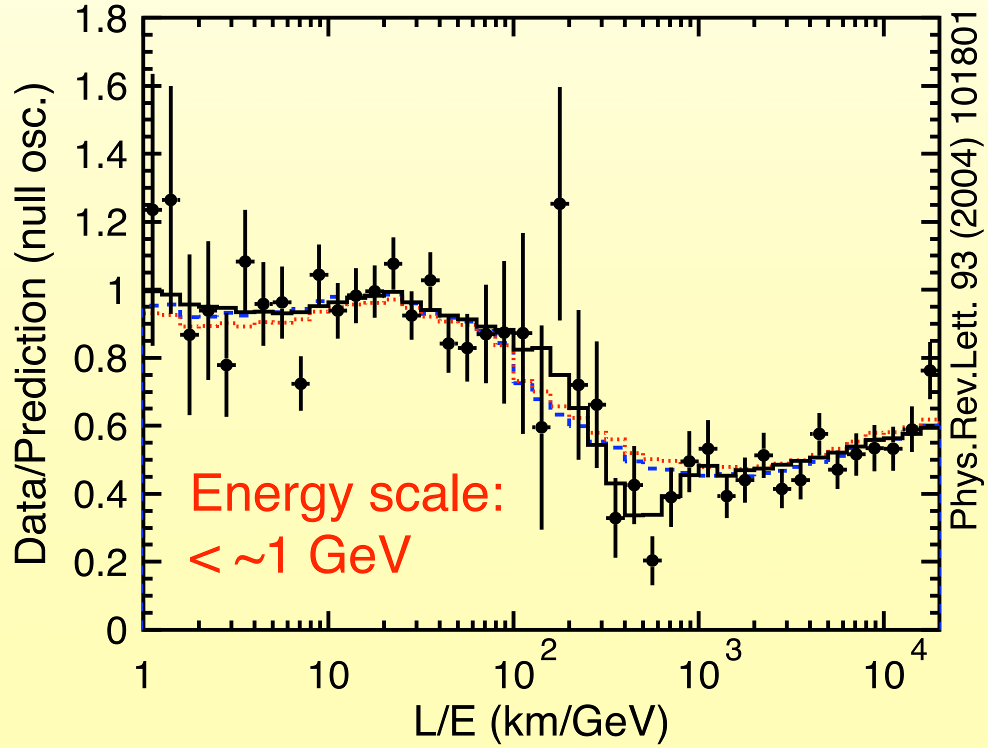
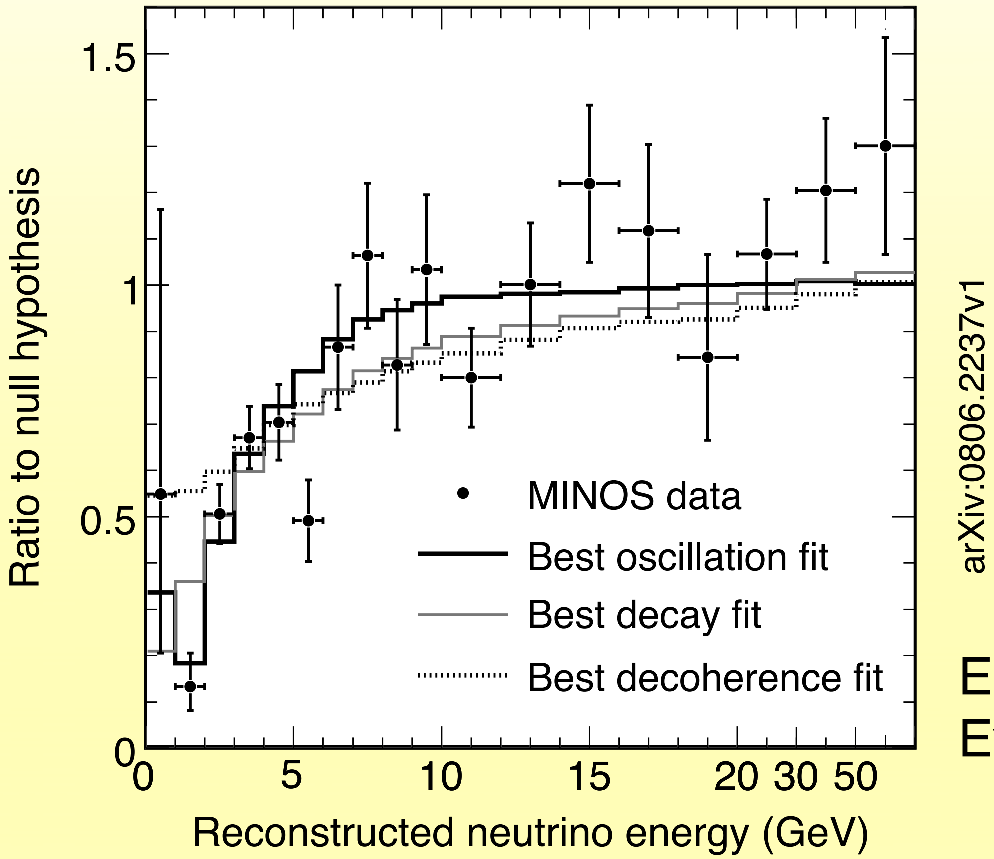


FIG. 4: Ratio of the data to the MC events without neutrino oscillation (points) as a function of the reconstructed L/E together with the best-fit expectation for 2-flavor $\nu_\mu \leftrightarrow \nu_\tau$ oscillations (solid line). The error bars are statistical only. Also shown are the best-fit expectation for neutrino decay (dashed line) and neutrino decoherence (dotted line).

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2[1.27 \Delta m^2 (L/E)]$$

ν_μ Disappearance: MINOS



Energy scale: 10's of GeV
Event sample: 848

- Measured:
  - $\Delta m^2 = (2.32 \pm 0.16 \times 10^{-3})$ eV^2 and
  - $\sin^2 2\theta = 1.0$

DeepCore & ν Oscillations

- To be sensitive to Δm^2(atm) ~10^{-3}, require L(km)/E(GeV)~10^3
- At its design sensitivity of E_ν~1TeV, IceCube needs L~10^6 km
  - There are no TeV neutrino sources at that distance
- Atmospheric neutrinos, with L~10^4 km, exist in abundance and can be used by IceCube...
  - ...but only if IceCube has sensitivity to E_ν ~10 GeV
- [Note: Astrophysical neutrinos from distant sources give us sensitivity to oscillations, decay, ... but we need to find one or more sources first!]

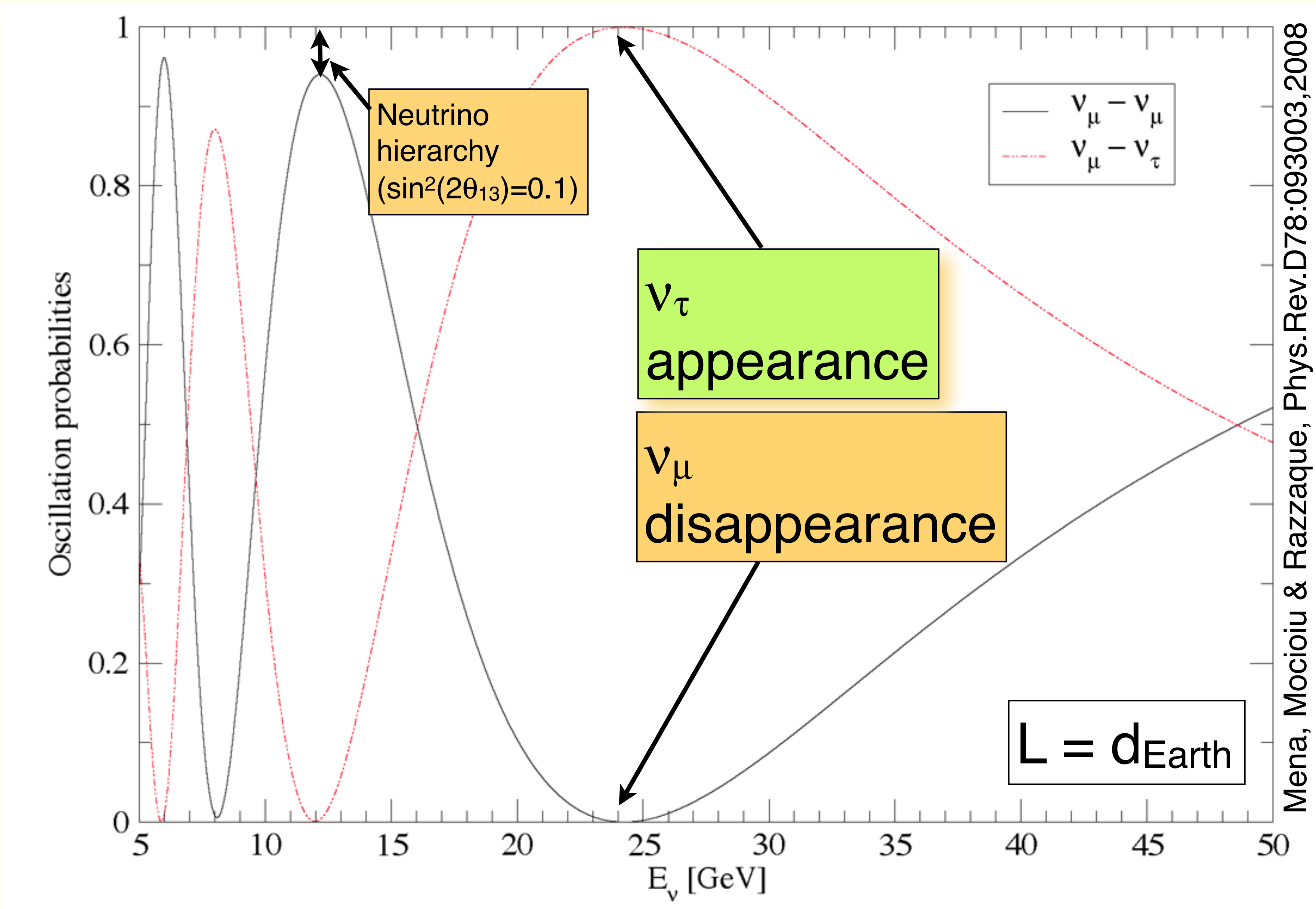
ν_τ Appearance

- Indications are that $\nu_\mu \rightarrow \nu_\tau$, but ν_τ not yet seen directly
  - Difficult to measure:
    - τ has short lifetime, difficult to identify unambiguously
    - If try to compensate for short lifetime with larger E, then need very large L to get L/E in range
- CHORUS ('97) and NOMAD ('98) attempted to detect ν_τ from $\nu_\mu \rightarrow \nu_\tau$ oscillations
  - placed limits
- SuperK "disfavors absence" of atmospheric $\nu_\mu \rightarrow \nu_\tau$ at 2.4σ
- OPERA (CNGS) has started running
  - expects ~2 ν_τ per year

ν_τ Appearance: Technique

- Veto cosmic-ray background
- Reconstruct shower position and energy in DeepCore
- Use MC to correct for shower-like events from non-ν_τ-CC interactions
- Compare to null oscillation hypothesis, normalizing to higher energies

DeepCore & ν Oscillations



DeepCore & ν_τ Appearance

- Try to detect ν_τ signal from ν_μ oscillations
  - Look for enhancement in number of shower events around E_ν~25 GeV (<E_{vis}>~10-15 GeV)
  - Must distinguish shower-like from track-like events
- Showers are produced in many ways, and we must take into account all of them:

DeepCore & ν_τ Appearance

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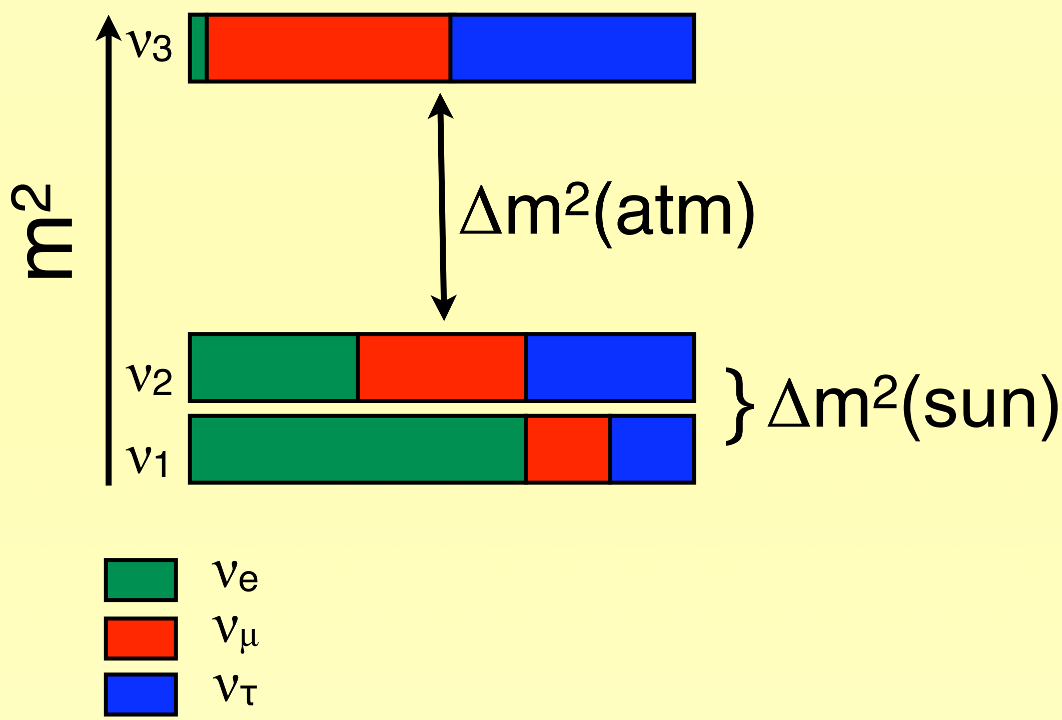
	CC	NC	Comment
ν_e	E_W+E_e	E_Z	$\Phi(\nu_e)$~$0.1\Phi(\nu_\mu)$; indep. of $\nu_\mu \rightarrow \nu_\tau$
ν_μ	veto(visible μ) OR E_W+E_μ	E_Z	CC & NC mimic signal; reduce significance
ν_τ	$E_W+E_{e/\mu/h}-E_{(2/2/1\ \nu\text{'s})}$ OR veto($\tau \rightarrow \mu\nu\nu$)	E_Z	Will veto some τ signal that mimics CC ν_μ

Neutrino Hierarchy

- One way to encapsulate the solar, reactor and atmospheric neutrino oscillation results is with this figure:



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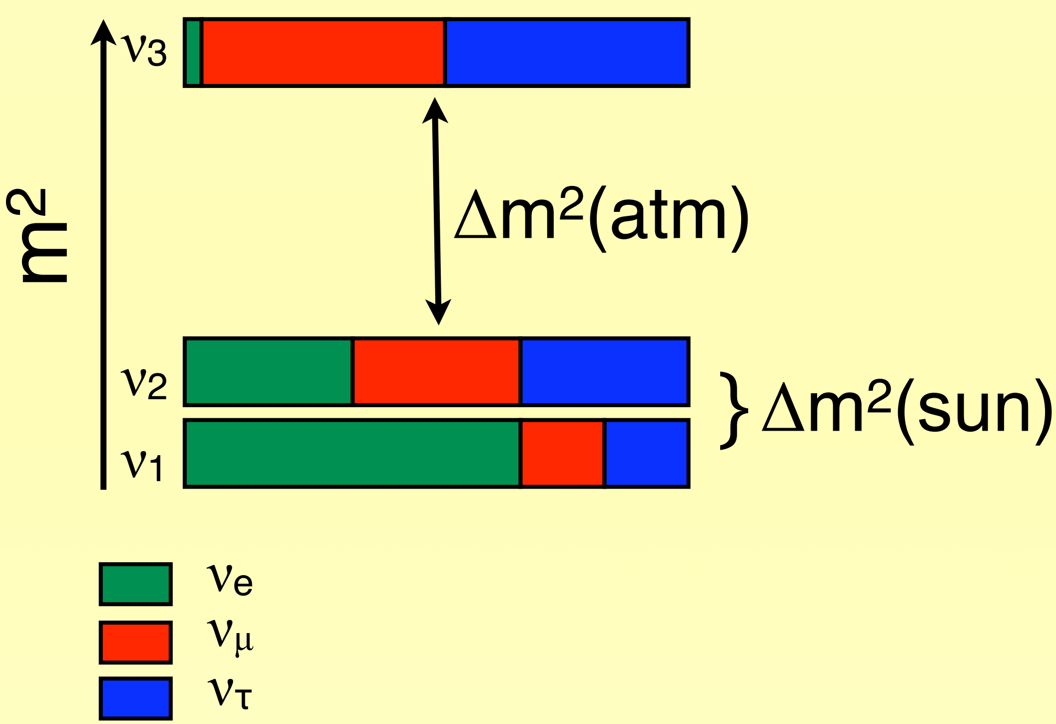

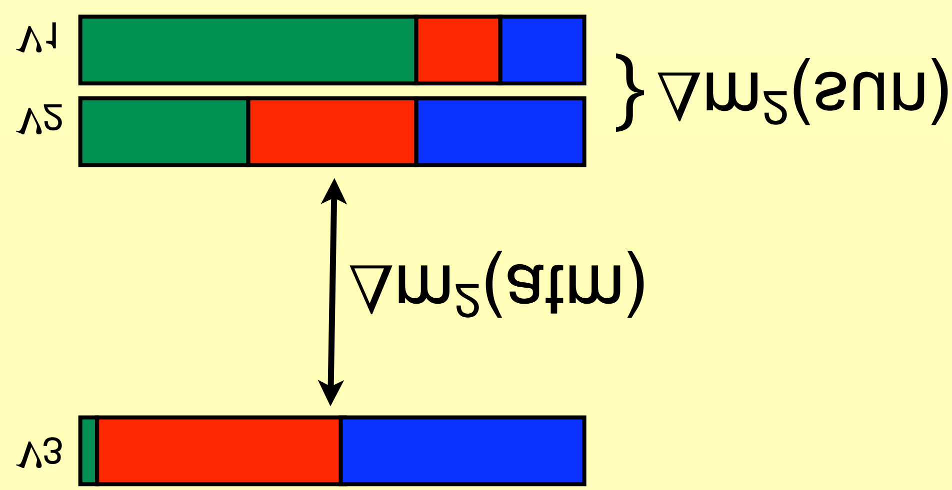

Or this one.

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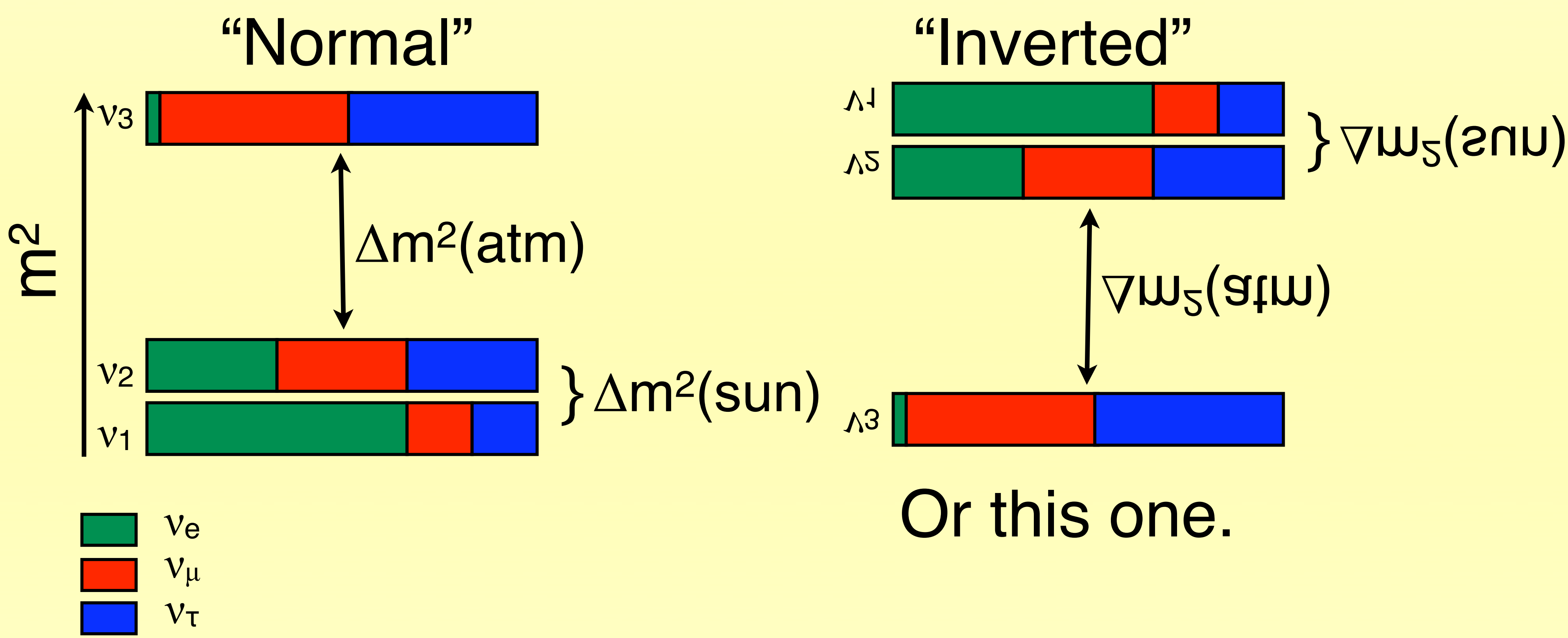

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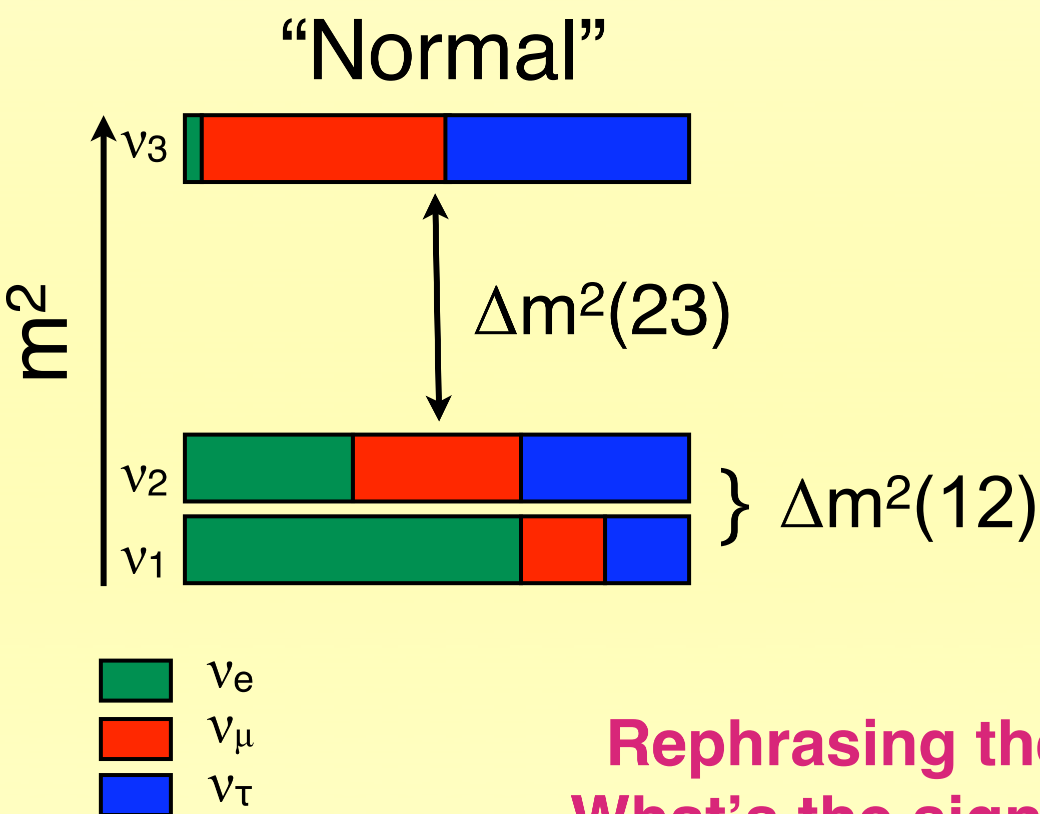
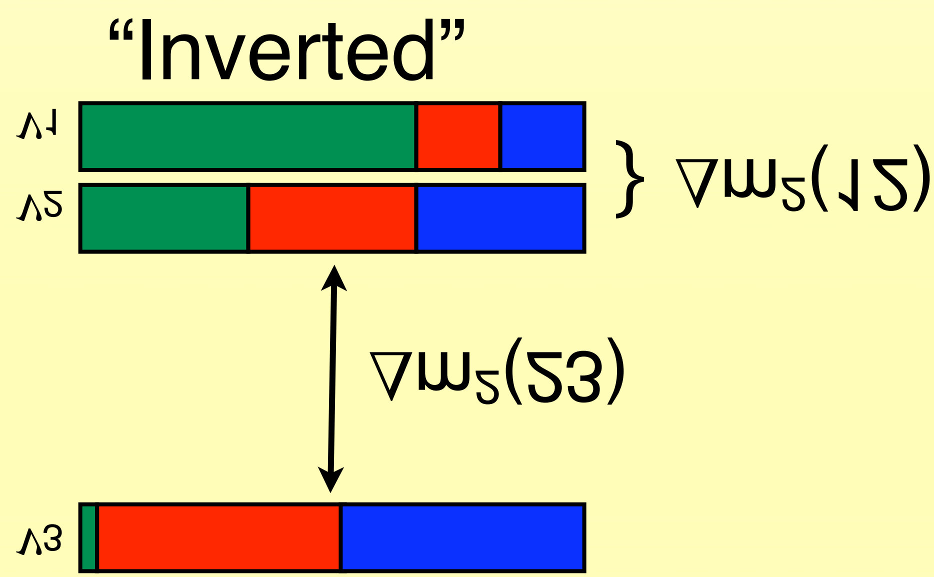




Or this one.

Rephrasing the question:
What's the sign of $\Delta m^2(23)$?

Neutrino Hierarchy

- No experiment built so far can distinguish between “normal” and “inverted” hierarchies
  - need to be able to measure difference between ν and $\bar{\nu}$ interactions
    - rely on matter effects
- The NOνA experiment (under construction) may have sensitivity, provided Nature cooperates
  - Ditto for IceCube

DeepCore & Neutrino Hierarchy

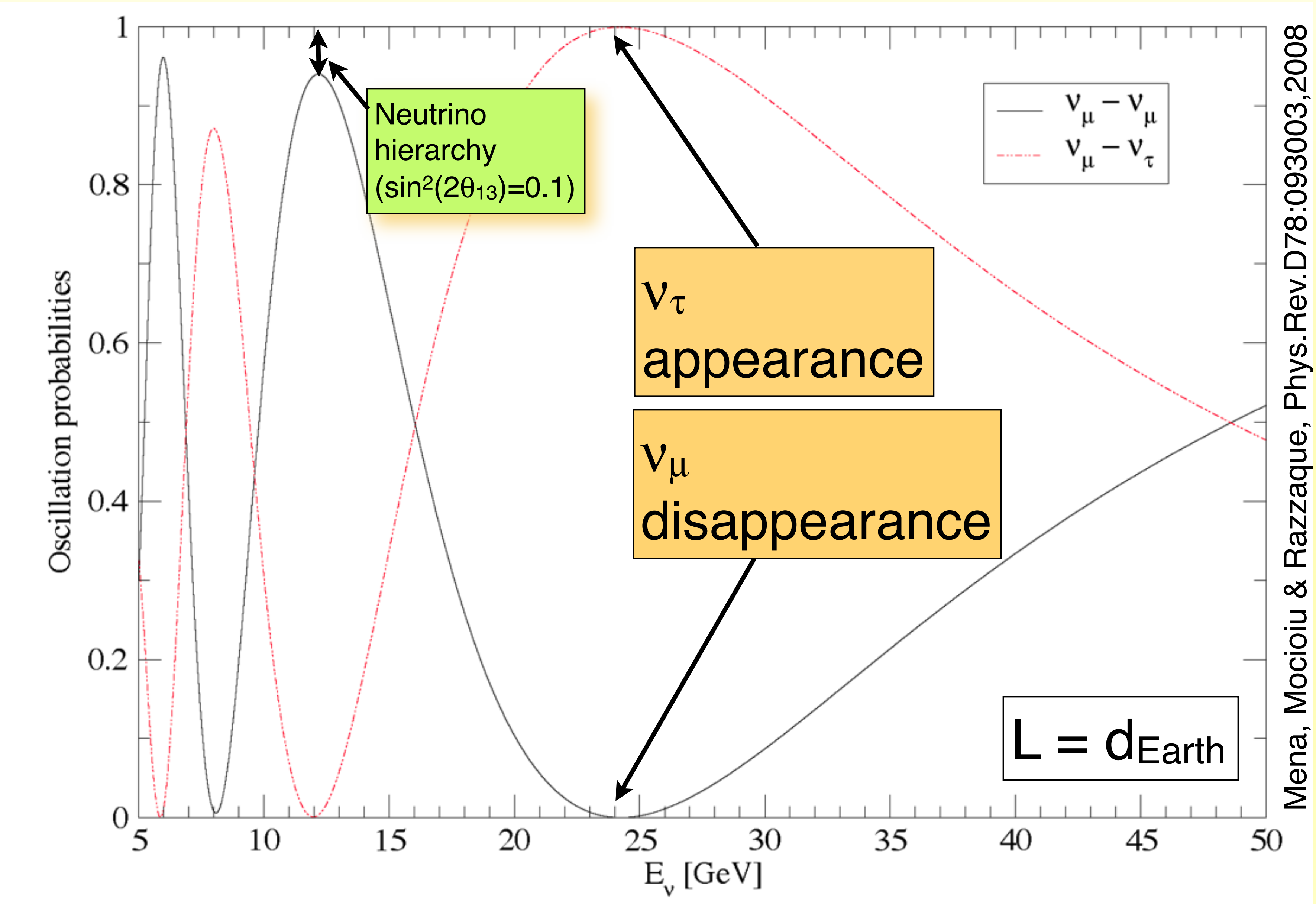
- Measurements use the fact that the effective θ_{13} angle in matter is given by

$$\sin^2 2\theta_{13}^{\mathrm{m}} = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13} + \left(\cos 2\theta_{13} \mp \frac{\sqrt{2}G_F N_e}{\Delta_{31}}\right)^2}$$

  - With "-" for ν, "+" for $\overline{\nu}$; $\Delta_{31} \equiv (\Delta m_{31})^2/2E$
- At what E_ν are we on resonance?
  - For L ~ d_E, with N_e for the earth:
    - E_ν(resonance) = ~ 10 GeV!
- So:
  - Look at low E, upgoing ν_μ-induced μ
  - Should see difference in disappearance for ν_μ vs. $\overline{\nu}_\mu$

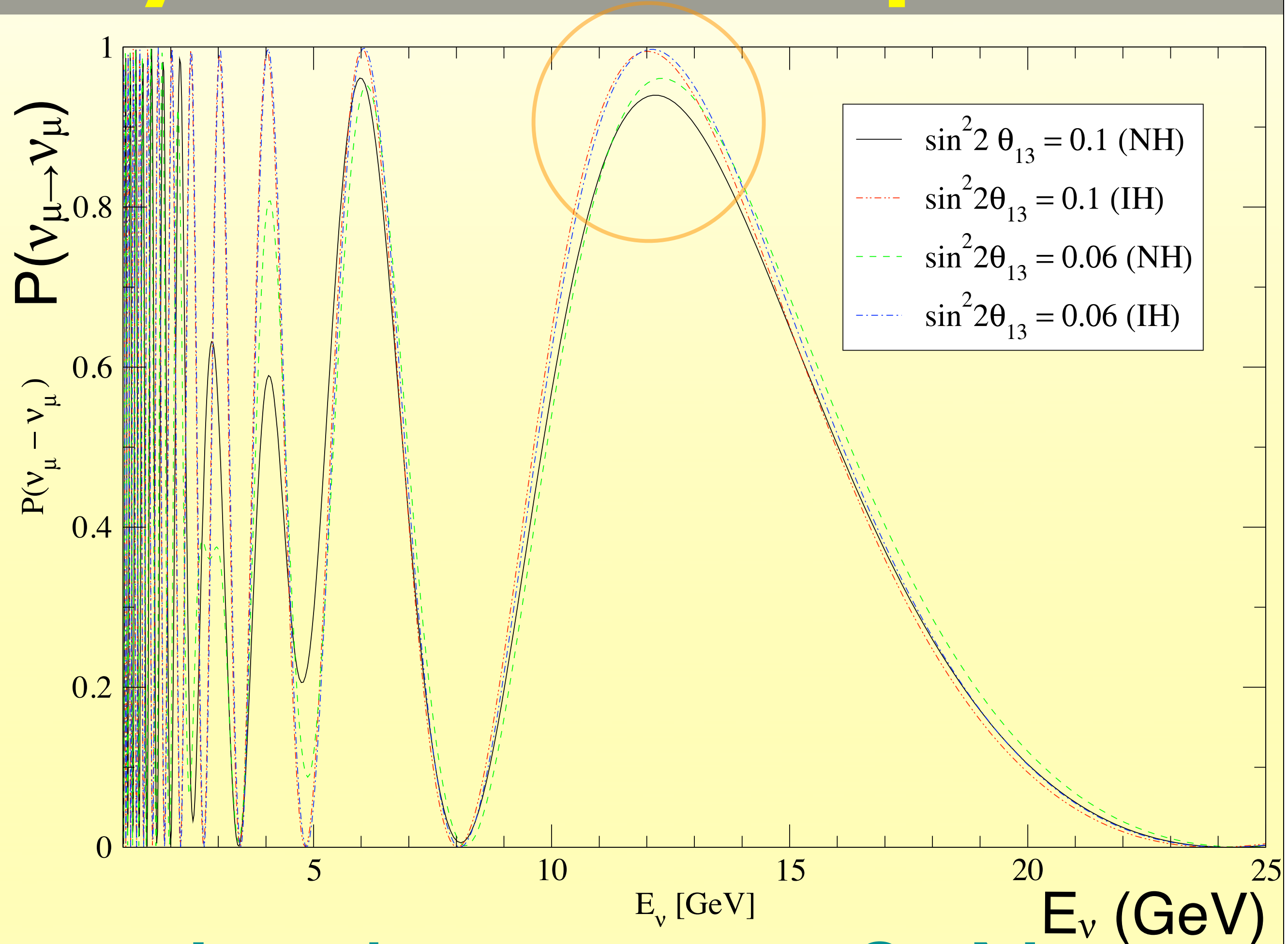
Mena, Mocioiu & Razzaque, Phys.Rev.D78:093003,2008

DeepCore & ν Oscillations



Hierarchy: Technique

- For ν's:
  - Normal Hierarchy:
    - $P_{\mu\mu}$ suppressed at ~12 GeV
  - Inverted Hierarchy:
    - $P_{\mu\mu}$ enhanced at ~12 GeV



- Look too easy? Not the whole story

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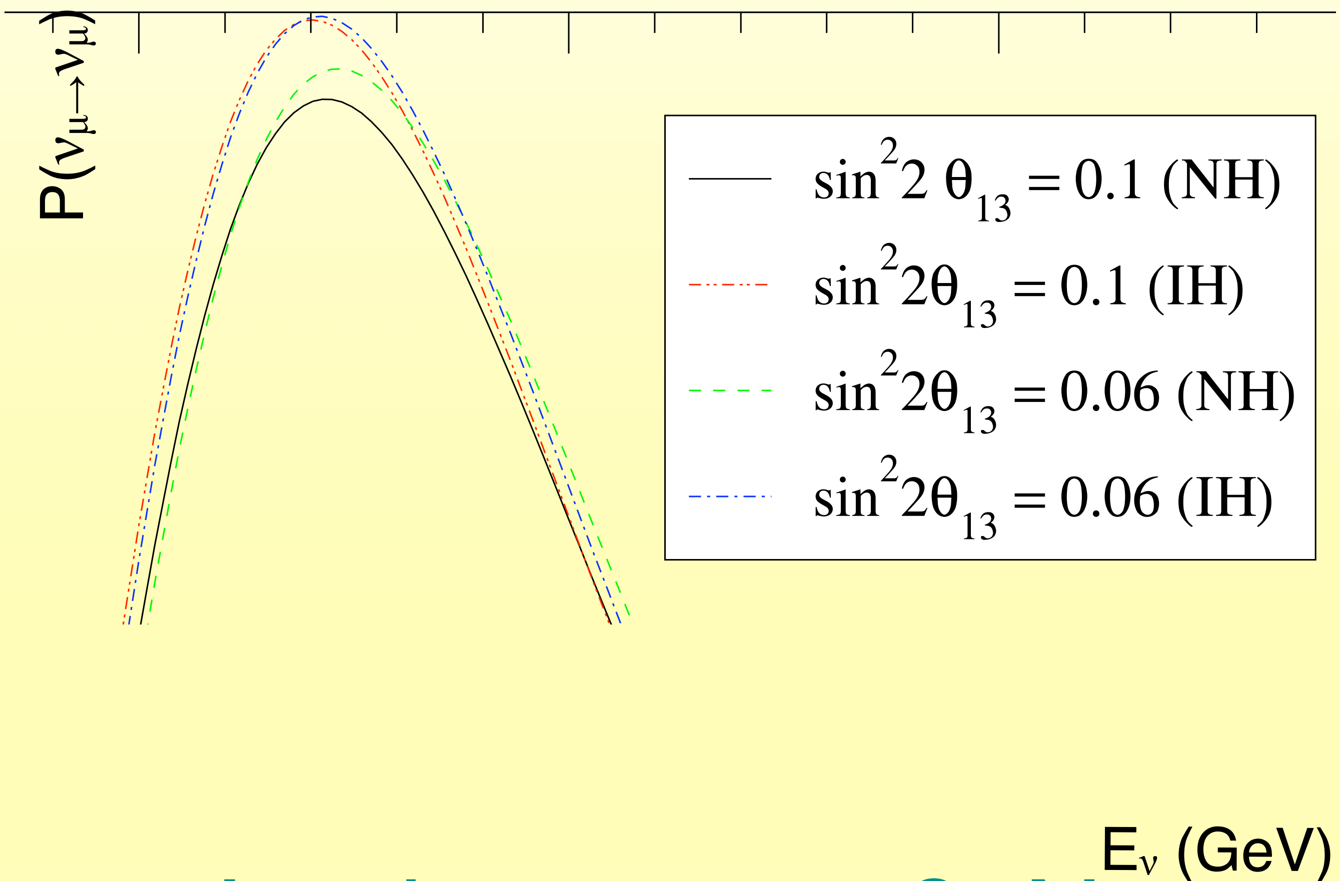

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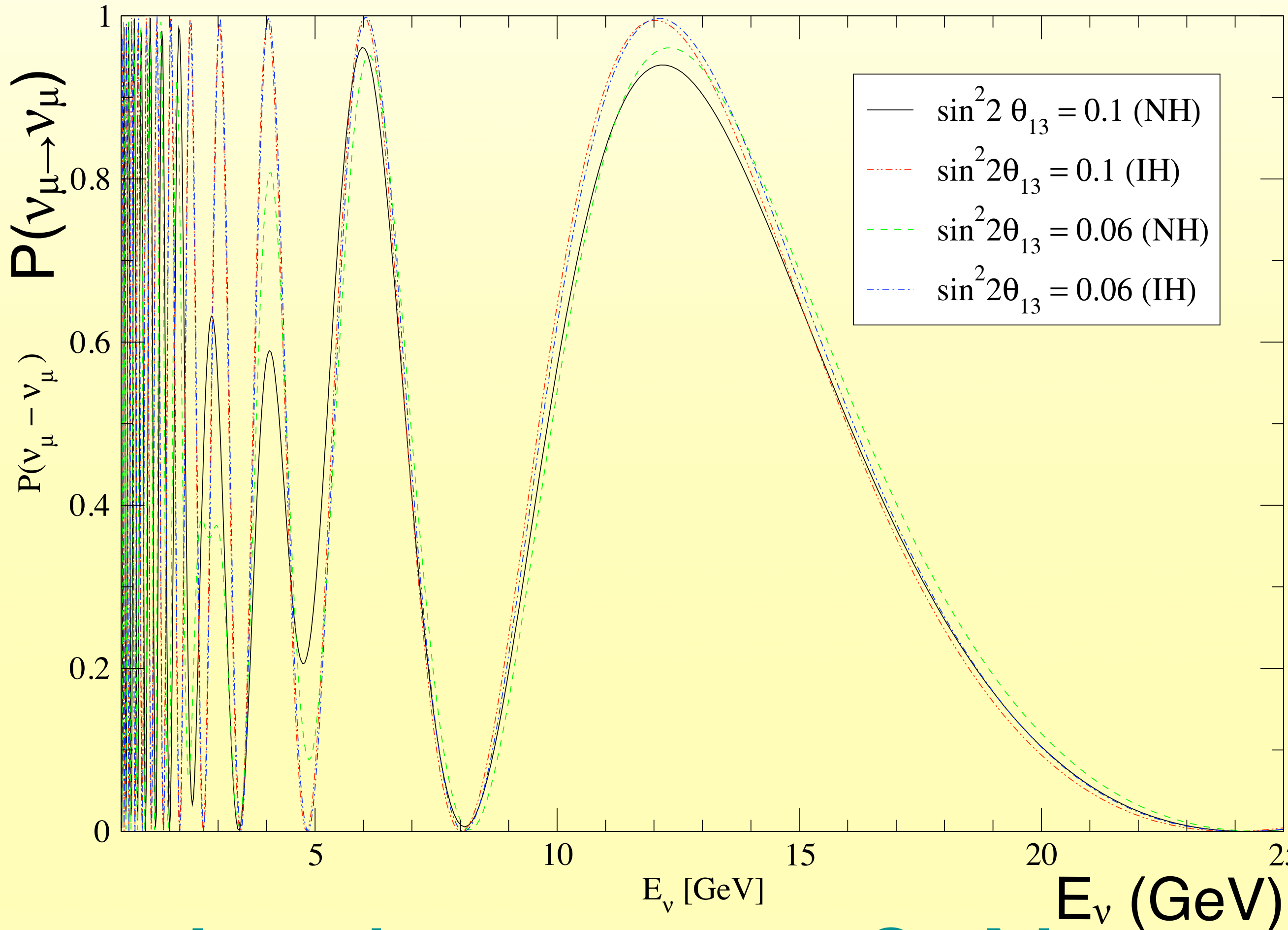

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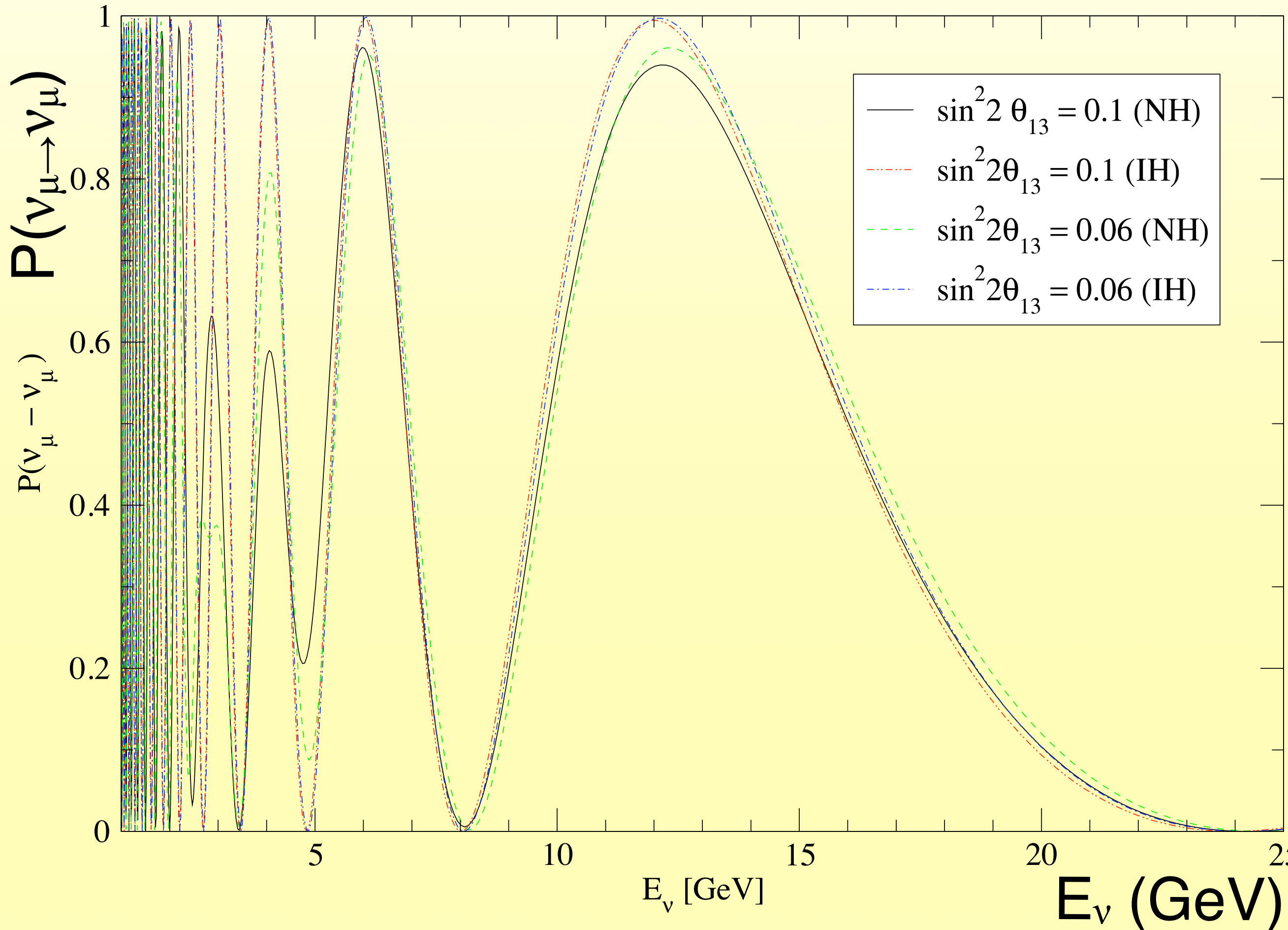


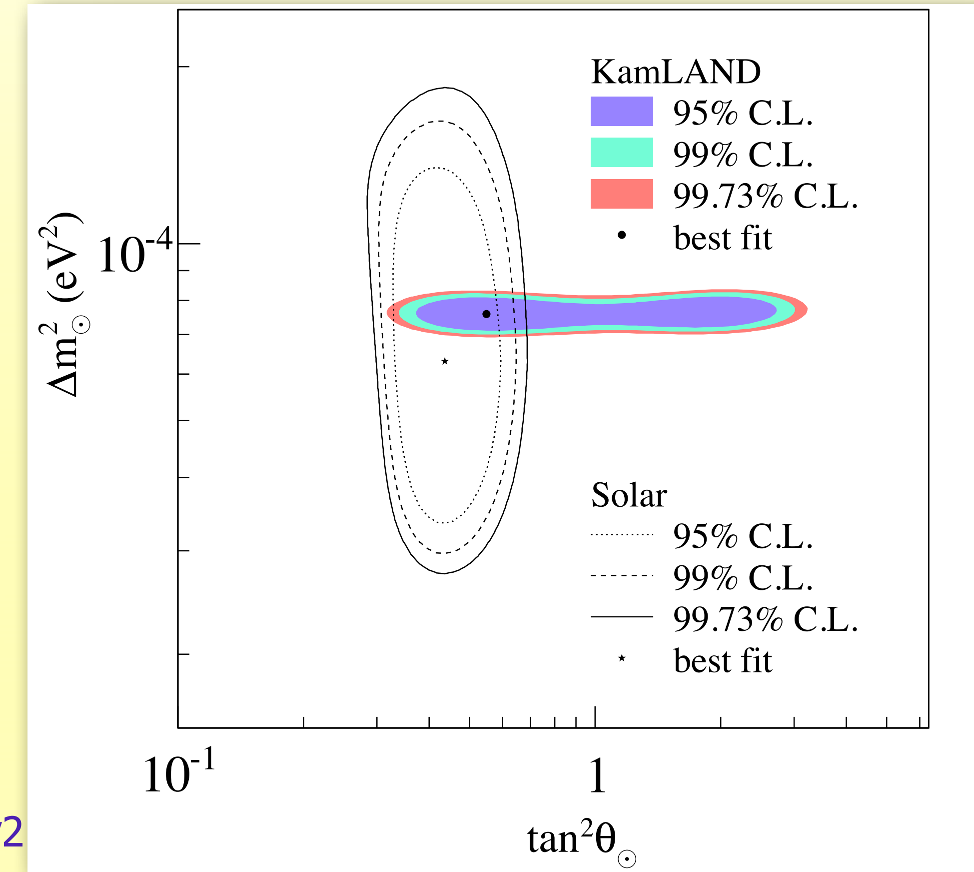
- For anti-ν's:
  - ~Symmetrical; exchange IH↔NH labels in figure

DeepCore & Hierarchy: Technique

- Can DeepCore tell the difference between ν_μ and $\bar{\nu}_\mu$?
- It can't tell the difference between μ^+ and μ^-…
- But at E ~ 12 GeV:
  - $\sigma(\nu_x) \sim 2\sigma(\bar{\nu}_x)$
    - (effect diminished a bit by higher E_μ of $\bar{\nu}_\mu$ interactions)
- Thus we can get *statistical* discrimination between NH and IH

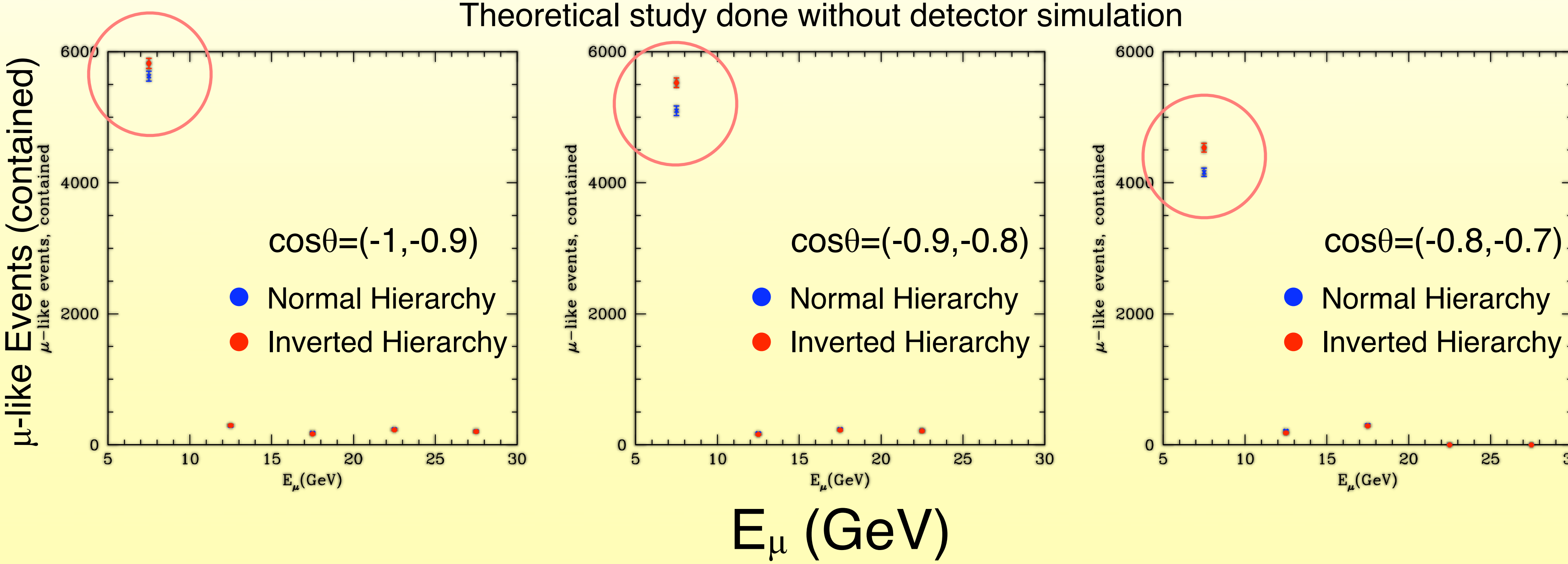
Neutrino Hierarchy

- (First, some preliminaries)
- Need to show the other main neutrino oscillation result, from solar and reactor neutrino experiments
  - These experiments measured ν_e or $\overline{\nu}_e$ disappearance
    - $\Delta m^2 = (7.6 \pm 0.2 \times 10^{-5})$ eV^2
    - $\tan^2\theta = 0.47 \pm 0.06$



DeepCore & Hierarchy: Technique

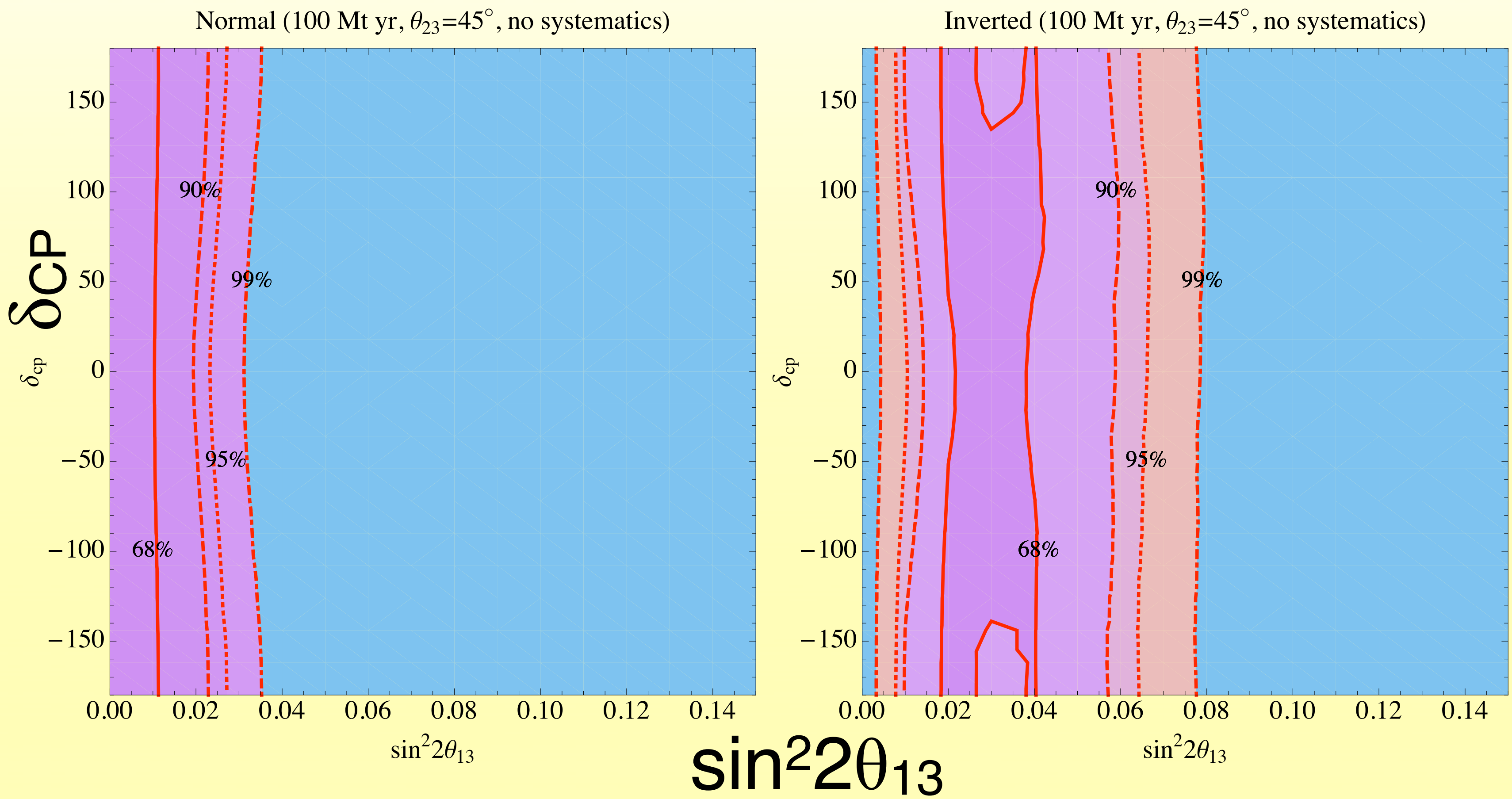
Theoretical study done without detector simulation



- 5 MTon detector, 10 yrs of running, $E_{th} \sim 5$ GeV, $\theta_{13} = 0.1$ ($\sin^2 2\theta_{13} = 0.04$)*
  - 5 GeV μ? L = 25 m, within 1.2 scattering lengths of 10-12 DOMs (↑, centered)
- DeepCore physical volume is ~14 MTon
  - fiducial volume will be somewhere between 5 and 13 MTon

*CHOOZ: $\sin^2 2\theta_{13} < 0.17$ (90%CL)
(Daya Bay/2011: $\sin^2 2\theta_{13} \sim 0.01$)

DeepCore & Hierarchy: Sensitivity



Assumes 100 Mton-yrs

- Shows rejection level of wrong model
- Effect is easier to see if have NH due to difference in cross sections for ν's and $\overline{\nu}$'s