Future Instruments: PINGU

Snowmass Workshop, SLAC
6-8 March, 2013
Doug Cowen
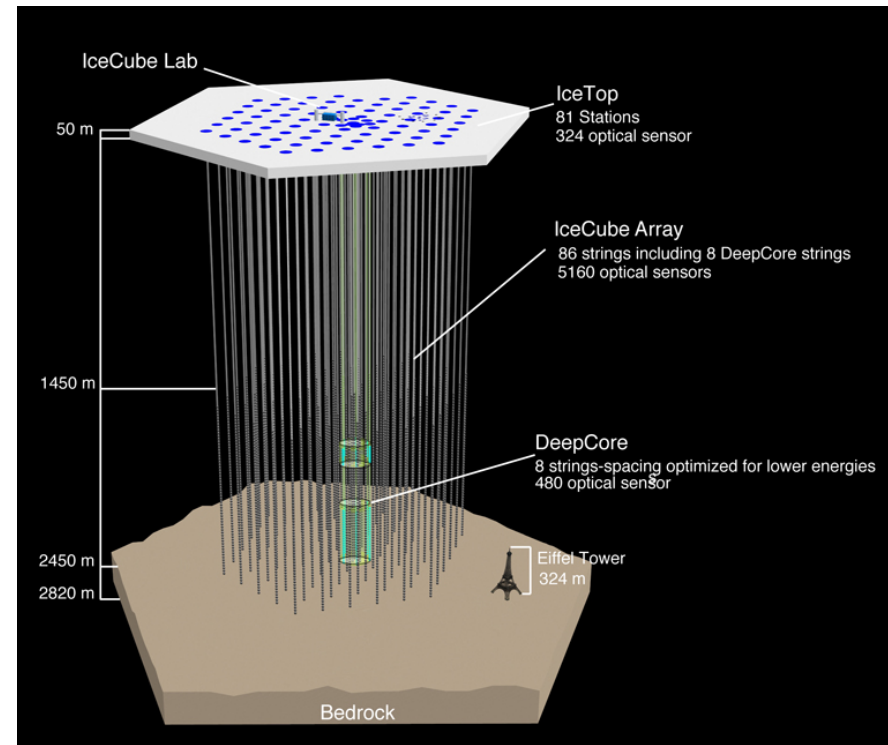Penn State & IceCube

PINGU (Precision IceCube Next Generation Upgrade)

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- Design concept:
  - Add in-fill strings to IceCube/DeepCore array
    - further increase module density
      - current detector shown at right...
    - continue to exploit 2km depth and surrounding array as active cosmic ray muon veto
    - optimize and simplify IceCube module design for ~5 GeV E_ν events, reduced cost
    - co-deploy new calibration devices tuned for lower E_ν
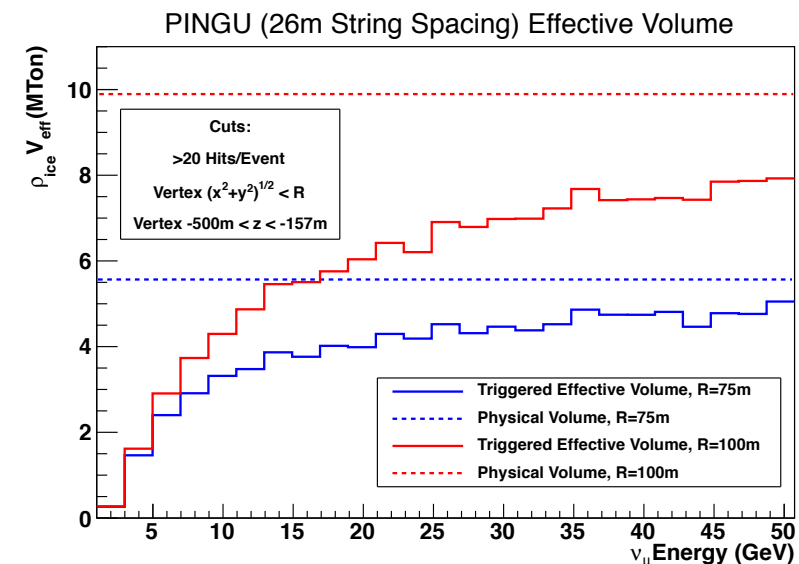   - improve refrozen hole ice clarity
  - Goal: reach few GeV E_ν threshold

The current IceCube/DeepCore detector

IceCube Lab

PINGU

(Precision IceCube Next Generation Upgrade)

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- Design concept:
  - Add in-fill strings to IceCube/DeepCore array
    - further increase module density
      - ...sample new geom. shown at right; V ~ few Mt
    - continue to exploit 2km depth and surrounding array as active cosmic ray muon veto
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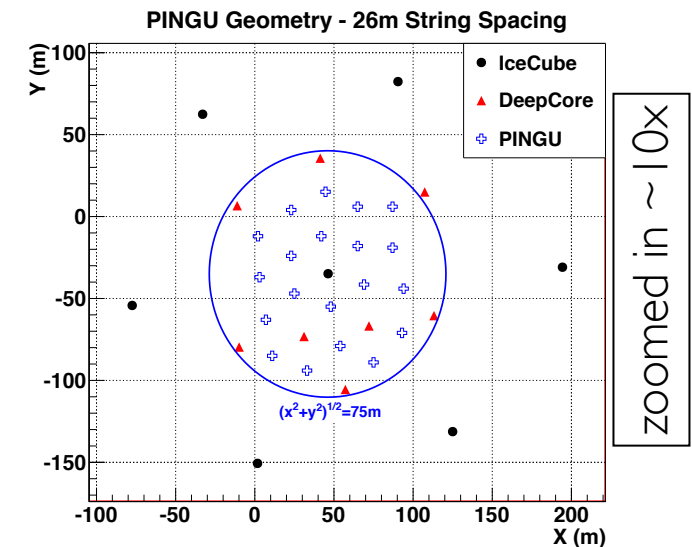   - improve refrozen hole ice clarity
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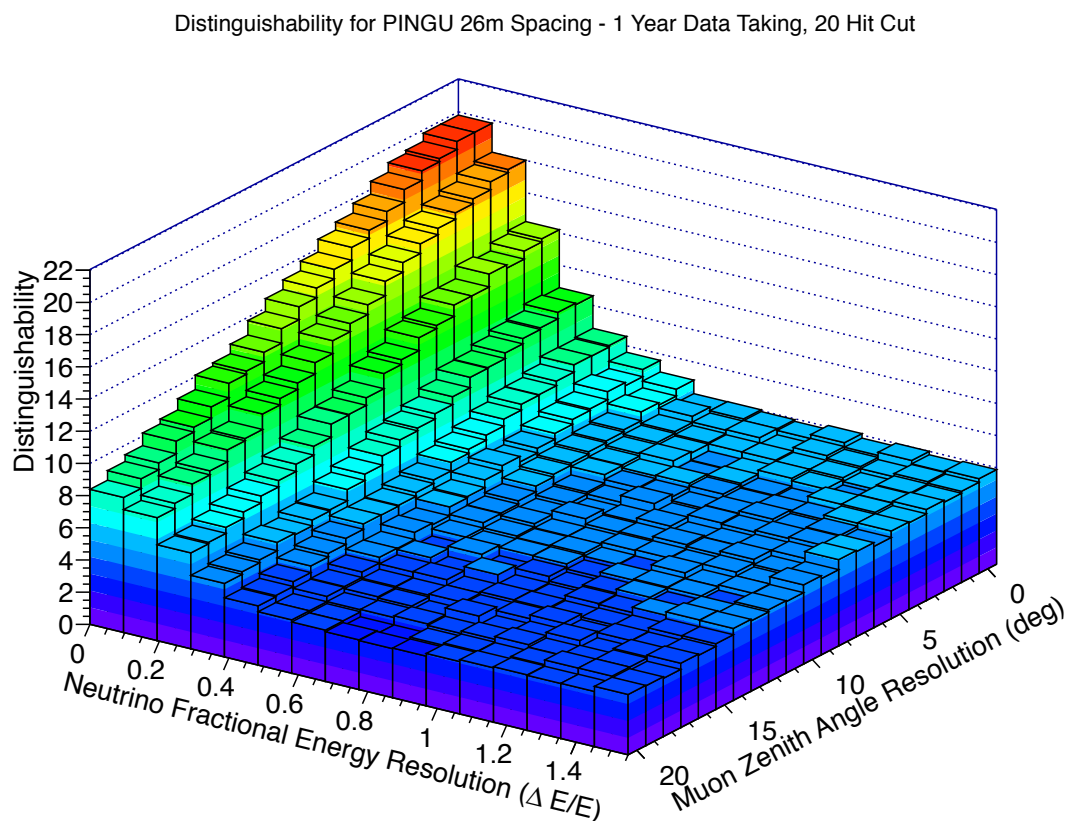
PINGU Geometry - 26m String Spacing

- IceCube
- DeepCore
- PINGU

$(x^2+y^2)^{1/2}=75m$

zoomed in ~10x

PINGU (26m String Spacing) Effective Volume

Cuts:

>20 Hits/Event

Vertex $(x^2+y^2)^{1/2} < R$

Vertex -500m < z < -157m

Triggered Effective Volume, R=75m
Physical Volume, R=75m
Triggered Effective Volume, R=100m
Physical Volume, R=100m

$\rho_{ice} V_{eff}$ (MTon)

ν_μ Energy (GeV)

PINGU Physics Goals

- Neutrino mass hierarchy determination with ~5-15 GeV atmospheric neutrinos

  - First detection of parametric oscillations "for free"

- Other neutrino oscillation physics: maximal θ_{23}, ν_τ appearance

- Low mass WIMP dark matter detection via neutrinos

- Point source search for $E_\nu \gtrsim 10$ GeV neutrinos

- R&D for possible megaton-scale Cherenkov ring-imaging detector: "MICA"

PINGU

- Current status

  - Actively working on reco. & geom. optimization to estimate σ's from sim.

    - As a *proxy* for reco. efficiency, require at least 20 detected Cherenkov γs

- Near–future work

  - Evaluate impact or mitigation of anticipated systematics (uncertainties in ice properties, module efficiencies, energy scale, angular reconstruction, cross sections, atm nu fluxes, earth profile, ...)

- Theoretical issues

  - δ_{CP} : small (but with a beam[4], PINGU might *measure* δ_{CP})

  - $\Delta(m_{31})^2$: non-negligible degeneracy with NMH, but manageable

Distinguishability for PINGU 26m Spacing - 1 Year Data Taking, 20 Hit Cut

θ_{23} Maximal?

- External feasibility study of a sin(θ_{23}) measurement in a DeepCore/PINGU-like detector

  - 10 years of exposure, various threshold and resolution assumptions up to $\sigma_E = 5$ GeV, $\sigma_{cos(\theta)} = 0.25$, 5% systematic; $\sin^2(2\theta_{13}) = 0.08$
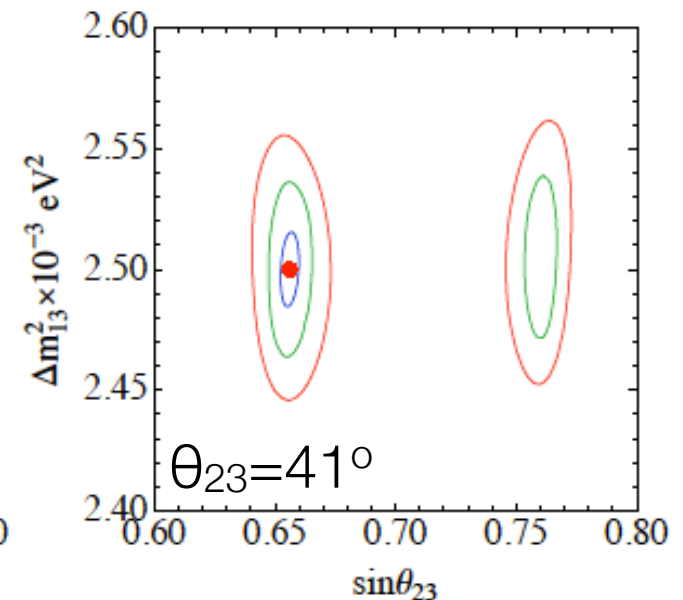
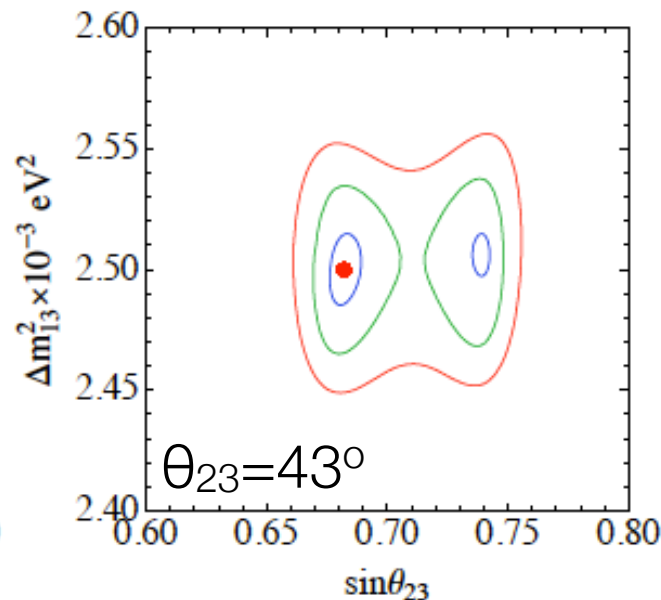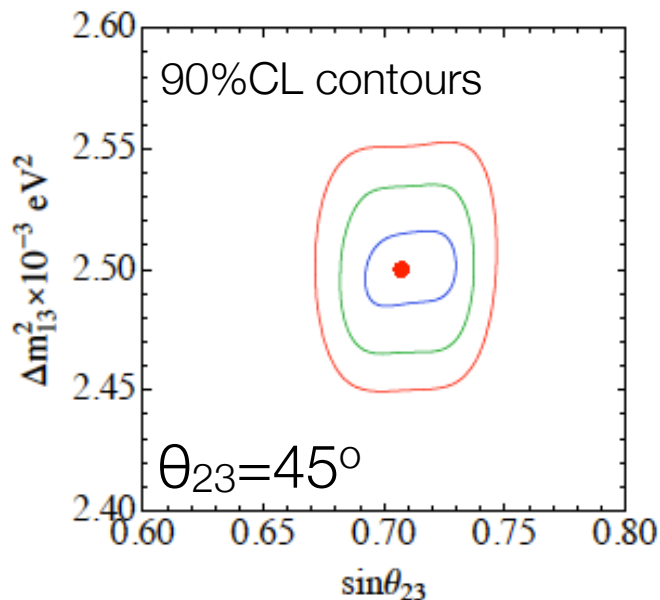 - Requirements not dissimilar to those for hierarchy

Observable energies of 5 to 50 GeV
10 energy bins, 4 angular bins
vs.
1st energy bin, 1 angular bin +
9 energy bins, 4 angular bins
vs.
Exclude first 2 energy bins:
8 energy bins, 4 angular bins

90%CL contours
$\theta_{23}=45^\circ$
$\theta_{23}=43^\circ$
$\theta_{23}=41^\circ$

Tau Neutrino Appearance

- $P(\nu_\mu \rightarrow \nu_\tau) \propto |U_{\tau 3}|^2$

  - test for unitarity

    - do the three fractions of $\nu_{e,\mu,\tau}$ making up ν_3 sum to 1.0?

- <u>Lots</u> of statistics

  - ~1 month DeepCore shown; ~30x more data in hand; PINGU will have greater efficiency

  - Key: control of systematics

- Similar to SuperK msmt

  - PRL 97:171801 (2006)

  - "disfavors the no tau neutrino appearance hypothesis by 2.4 sigma" (closer to 4σ now)
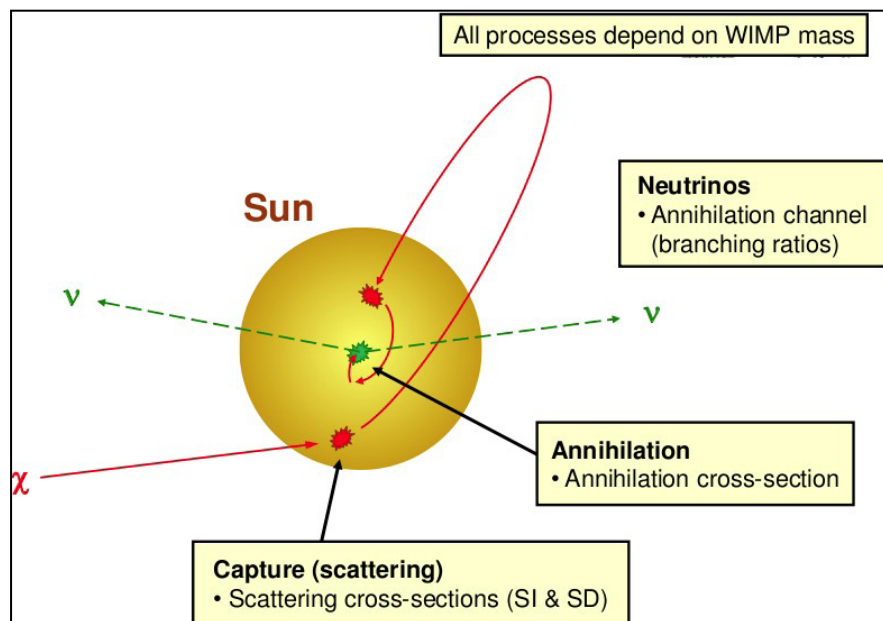
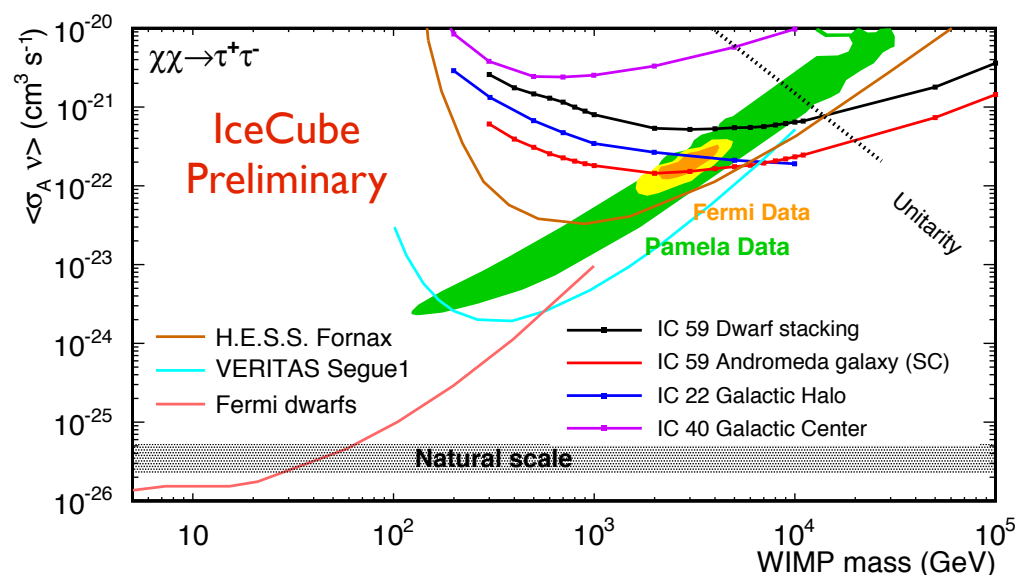Mena, Mocioiu & Razzaque, *Phys. Rev.* D**78**, 093003 (2008)
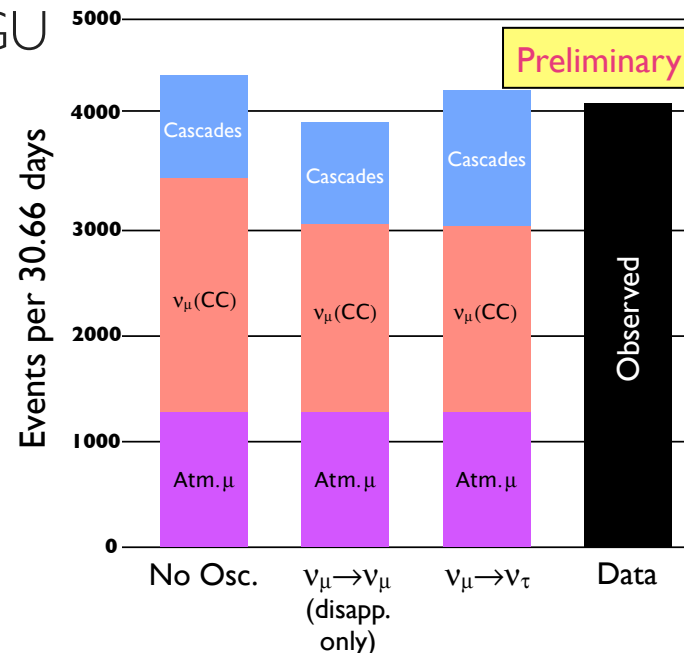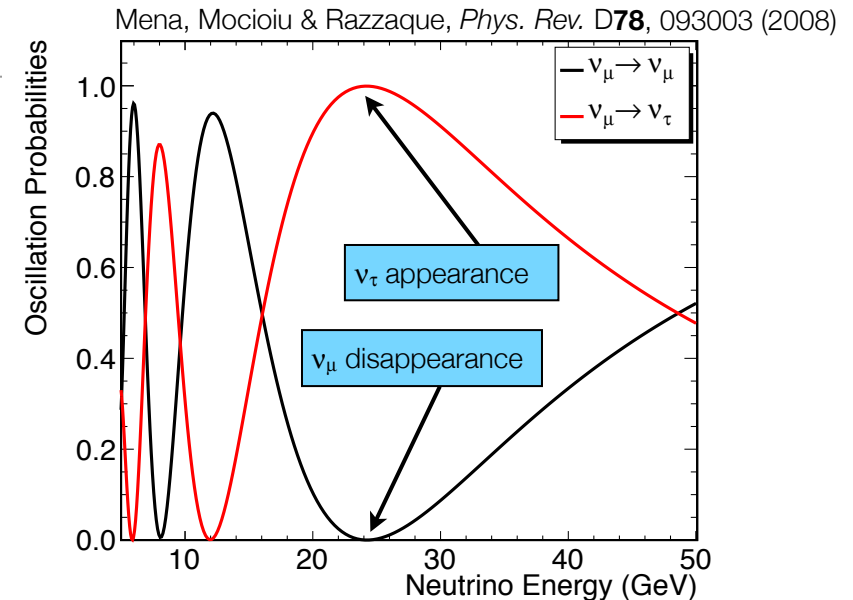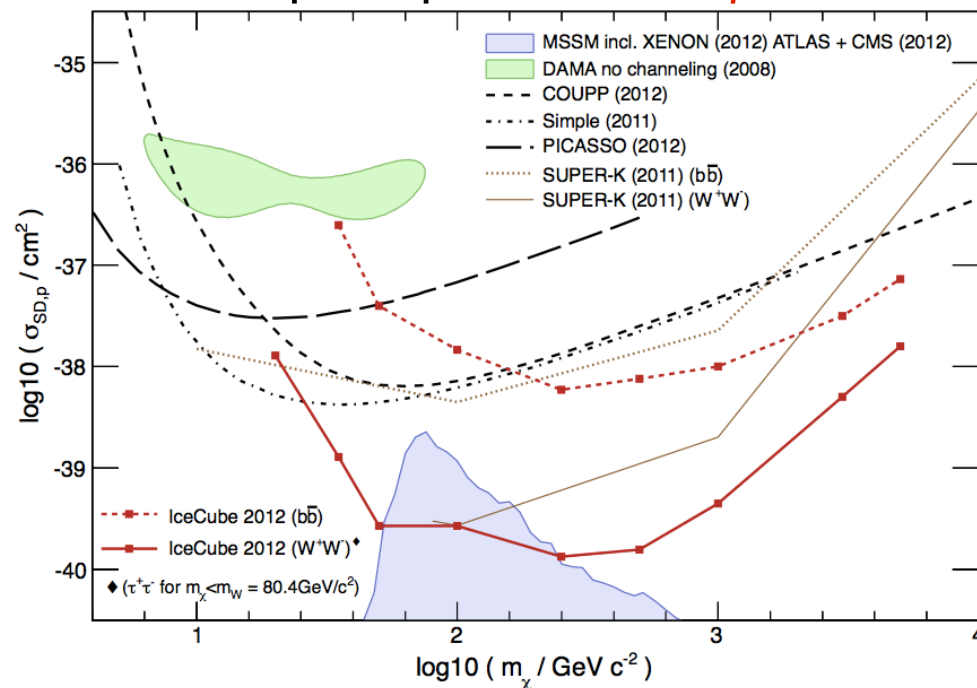

Statistical power:

- 80k cascade-like events in 2 years.
- 10% decrease due to ν_μ disappearance.
- 2/3 of those reappear as ν_τ cascades.

5333/sqrt(80000) = 18σ

IceCube-DeepCore indirect WIMP searches
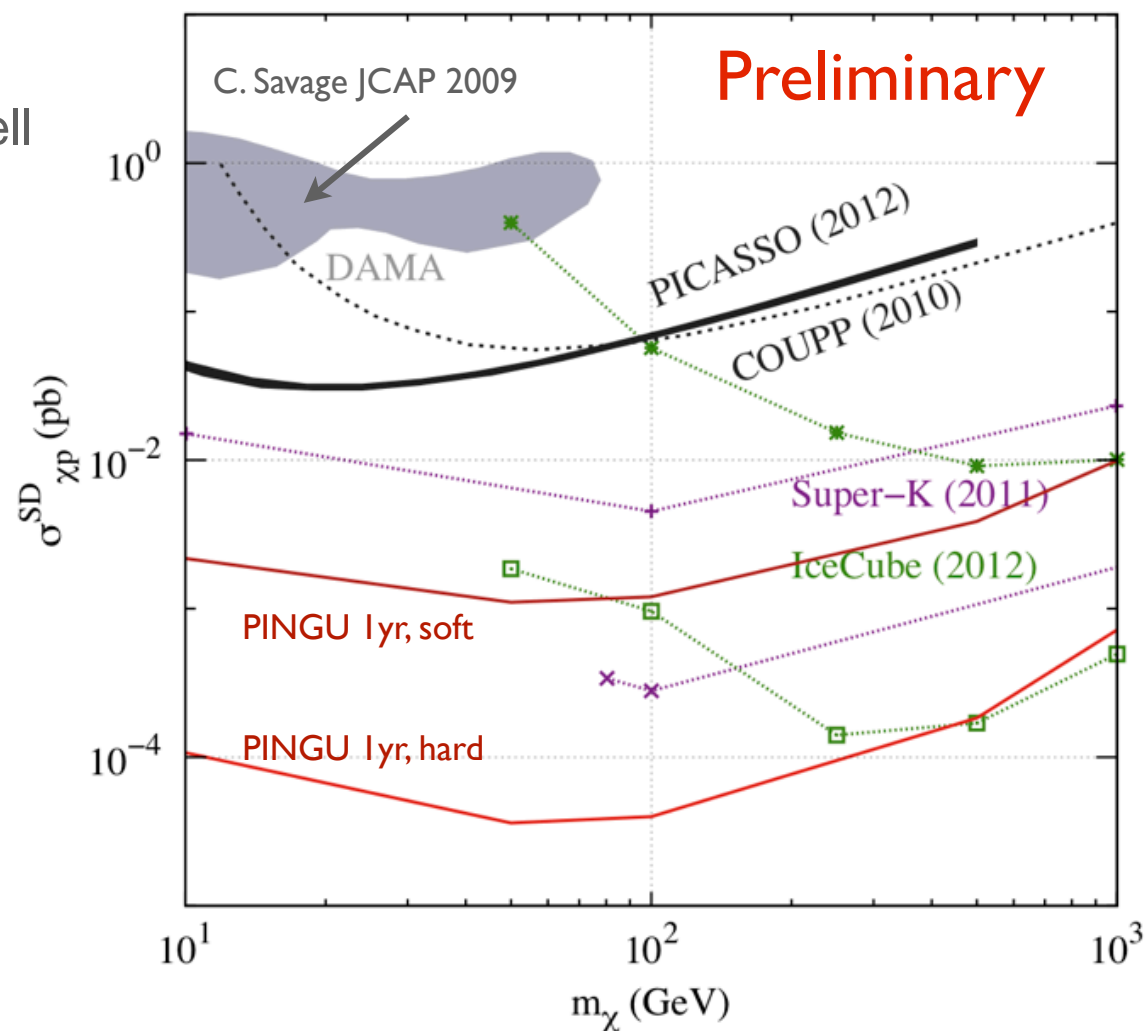
PINGU indirect WIMP searches

- Low-mass WIMP scenarios well testable at trigger level

- Next steps:

  - Detailed study with full PINGU simulation

  - More sophisticated event reconstruction
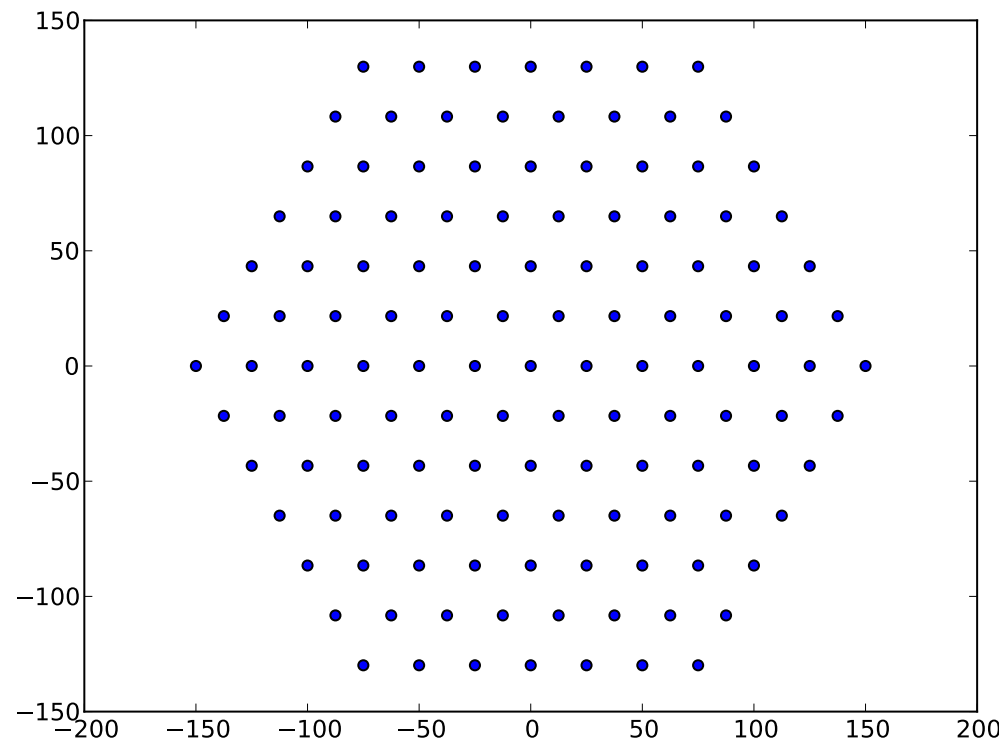
  - Check atmospheric muon background

Adapted Rott, Tanaka, Itow JCAP09(2011)029 to PINGU.

MICA Conceptual Detector

"Anything worth doing is worth overdoing" M. Jagger

- Up to a few hundred strings of "linear" detectors within DeepCore fiducial volume

- Goals: ~5 MTon scale with energy sensitivity of:

  - O(10 MeV) for bursts

  - O(50MeV) for single events

- Physics extraction from Cherenkov ring imaging in the ice

- Annual supernovae neutrinos to 10 MPc; New 10-MeV scale detection channels for Solar WIMPs become available; potential proton decay sensitivity

- IceCube and DeepCore provide the active veto

- No excavation necessary: detection medium is the support structure

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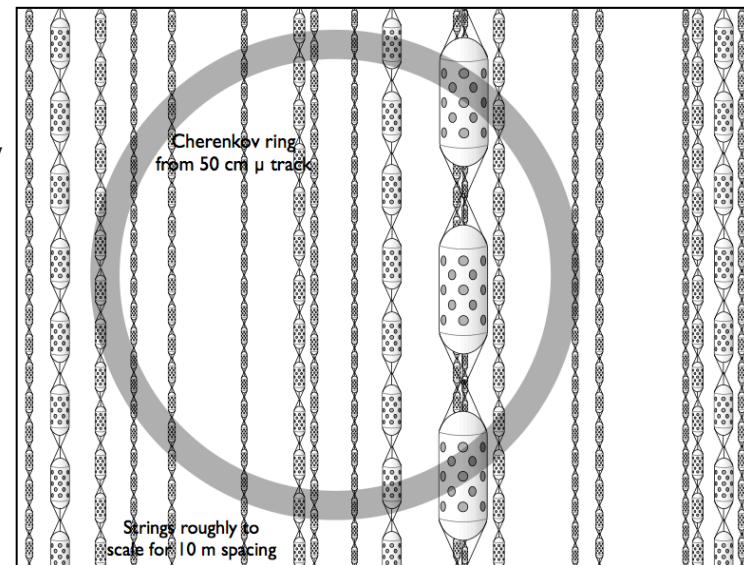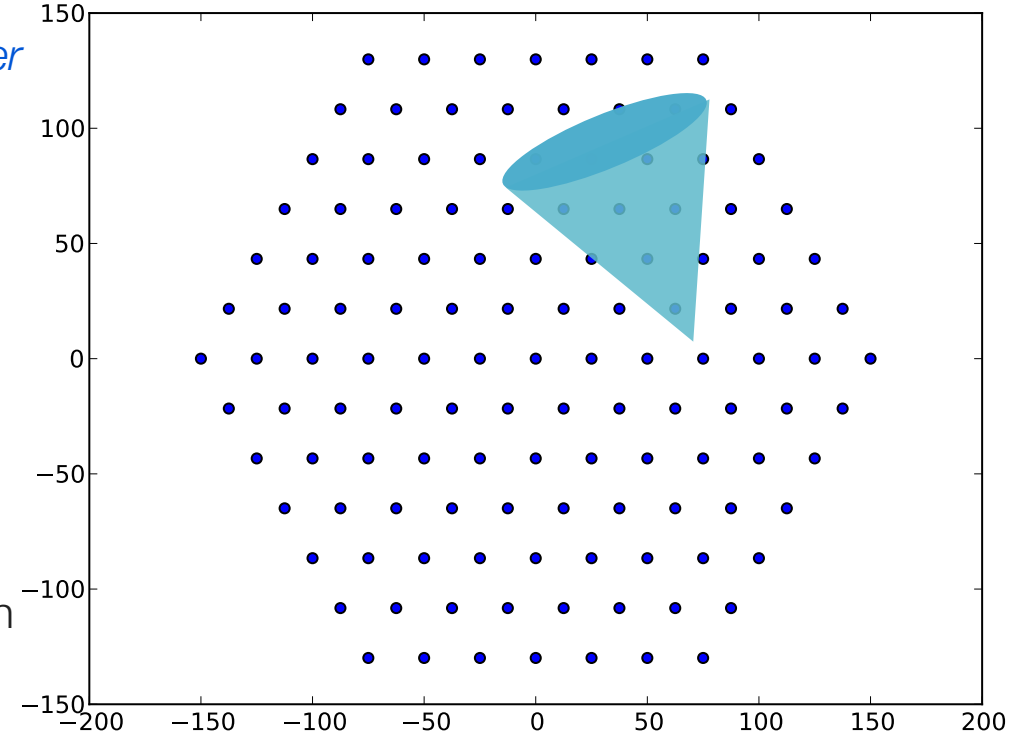
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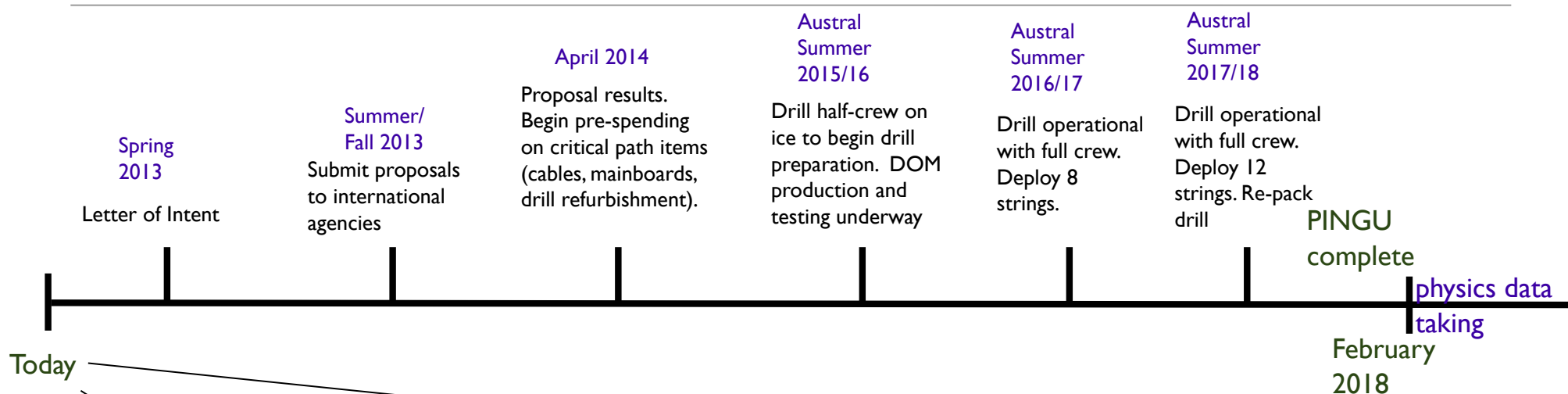- No excavation necessary: detection medium is the support structure

Cherenkov ring from 50 cm μ track

Strings roughly to scale for 10 m spacing

PINGU: Timescale & Cost

Spring 2013

Letter of Intent

Summer/ Fall 2013

Submit proposals to international agencies

April 2014

Proposal results. Begin pre-spending on critical path items (cables, mainboards, drill refurbishment).

Austral Summer 2015/16

Drill half-crew on ice to begin drill preparation. DOM production and testing underway

Austral Summer 2016/17

Drill operational with full crew. Deploy 8 strings.

Austral Summer 2017/18

Drill operational with full crew. Deploy 12 strings. Re-pack drill

PINGU complete

physics data taking

February 2018

Today

Current Status
- Detailed MC simulations nearing completion
- Enhanced low-E reconstruction algorithms from DeepCore being applied to simulated PINGU events
- Estimation of sensitivity to NMH with full reconstruction and estimation of systematics underway
- Letter of Intent in prepration

- Rough cost estimate
  - Drill setup costs: $10M
  - Per-string hardware + deployment cost: $1.25M
    - A 20-string in-fill would cost roughly $35M, shared between NSF and European agencies

Conclusions

- Huge neutrino statistics achieved by instrumenting megatons of optically clear ice

- IceCube/DeepCore and its potential new infill array PINGU may be able to measure a variety of neutrino oscillation parameters and explore low-mass WIMP parameter space with
  - gratifyingly short time scale and modest cost
  - straightforward construction and low overall risk

- Currently addressing reconstruction and systematics challenges–we know these won't be trivial!

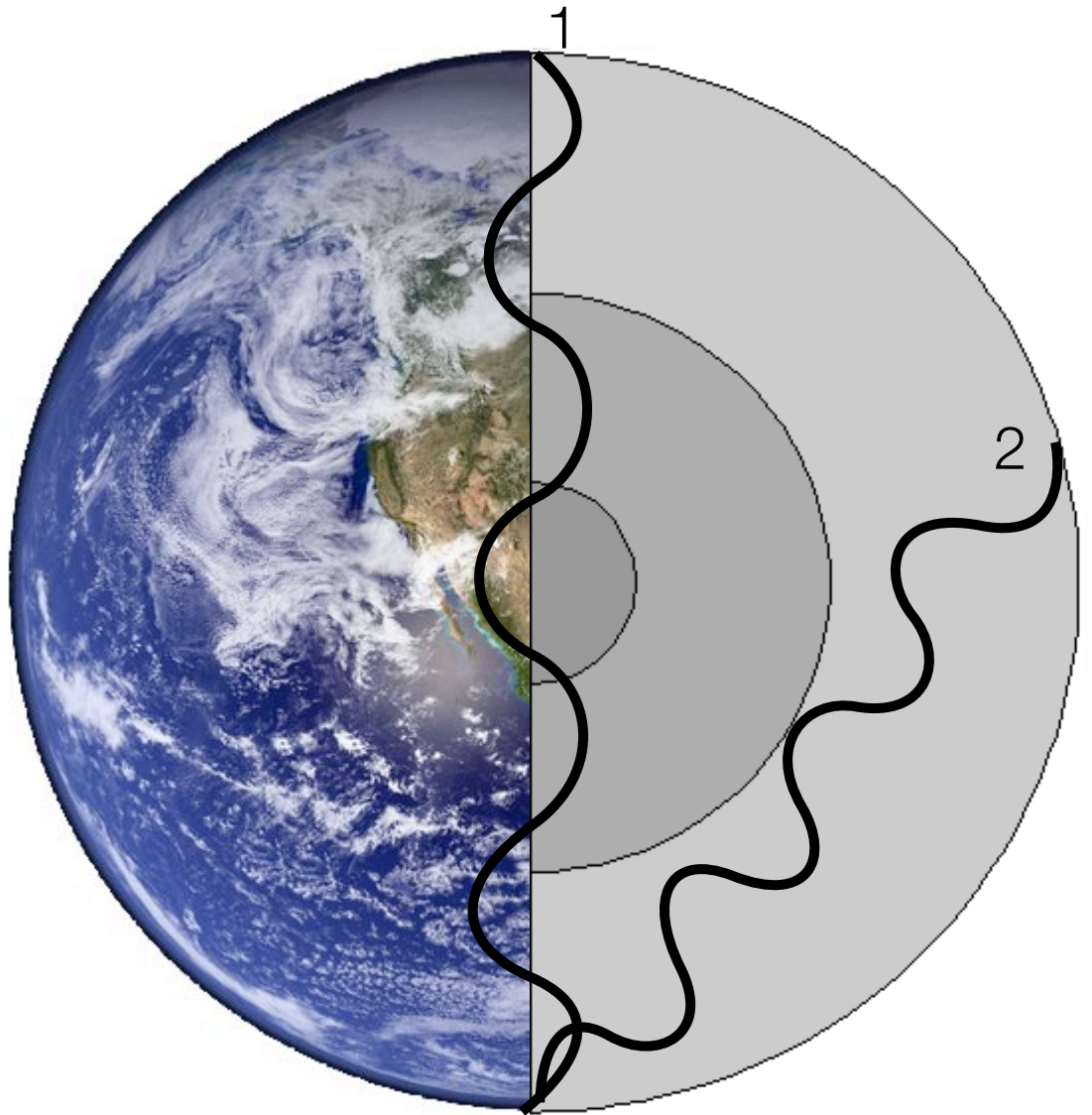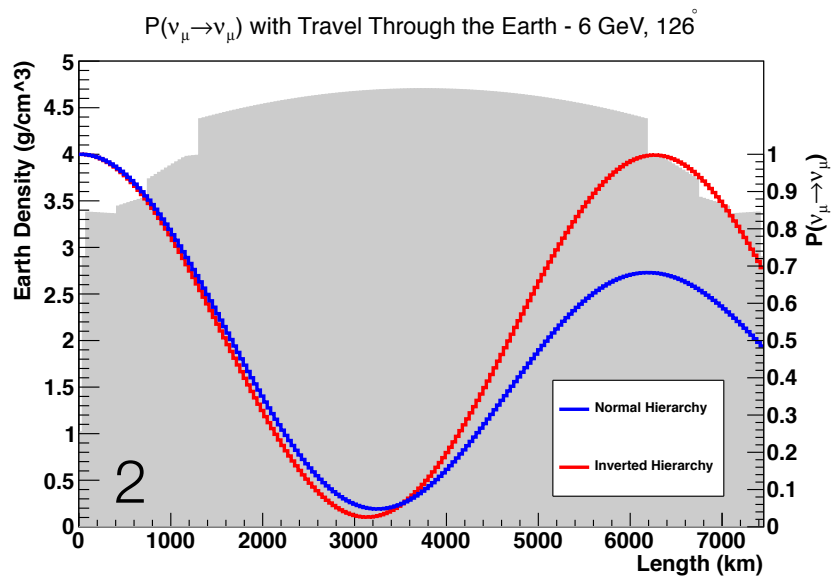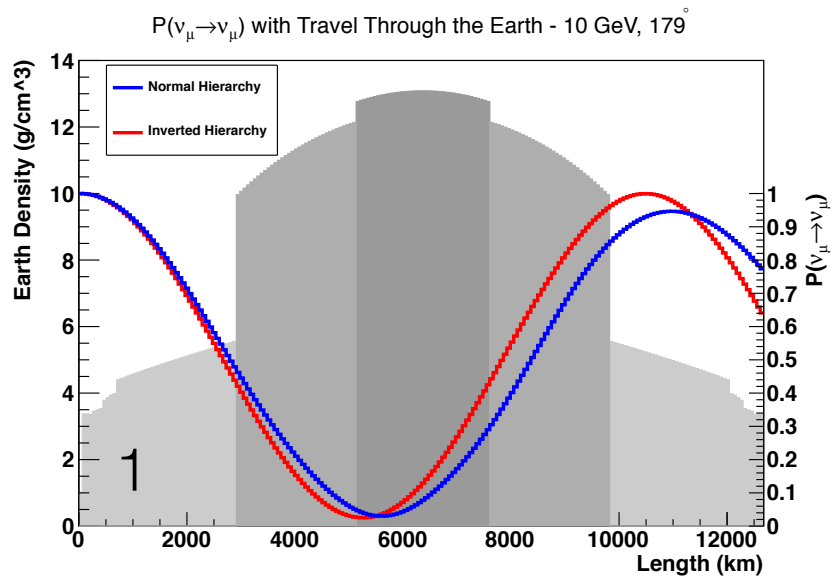- R&D modules co-deployed with PINGU may point way to megaton-scale Cherenkov-ring-imaging detector in the ice

The End

NMH and Atmospheric Neutrinos

- Few-GeV atm. ν could provide sensitivity to NMH via matter effects

  - Resonant MSW and parametric oscillations for few-GeV earth-crossing neutrinos

  - NMH determines character of oscillations and it is different for ν vs $\bar{\nu}$

    - At these energies, use $\sigma(\nu) \sim 2\sigma(\text{anti-}\nu)$

  - Degeneracy with δ_{CP} is minimal

Neutrino Hierarchy and Parametric Resonances

- Parametric resonances can occur as neutrinos cross regions of distinct density
  - Flavor transitions enhanced due to matter-induced modifications in oscillation <u>phase</u>
    - (MSW occurs through modifications in neutrino mixing <u>angle</u>)
  - If travel through periodically varying density, transition probabilities can add up and become large, but generally speaking need lots of periods

- Relevant Exception: For matter densities close to MSW resonance densities, can have parametric enhancement of oscillations with a very small number of periods
  - This is the case for Earth and neutrinos at ~5 GeV(!!) *and*
  - The character of the effect depends strongly on the hierarchy. 🙂

E. Kh. Akhmedov, *Pramana* 54:47-63,2000 or hep-ph/9907435

P($\nu_\mu \to \nu_\mu$) with Travel Through the Earth - 10 GeV, 179°

P($\nu_\mu \to \nu_\mu$) with Travel Through the Earth - 6 GeV, 126°

Matter Effects & Hierarchy

Up to 20% differences in ν_μ survival probabilities for various energies and baselines, depending on the neutrino mass hierarchy

PINGU

- Following Ref. [2], define "distinguishability" as

$$S_{tot} = \sqrt{\Sigma_{ij} \frac{(N_{ij}^{IH} - N_{ij}^{NH})^2}{N_{ij}^{NH}}}$$

$$N_{i,j}^{NH} = P(\nu_\mu)_{i,j}^{NH} * \Phi(\nu_\mu)_{i,j} * \sigma(\nu_\mu)_j * V_{i,j}^{eff} + P^{NH}(\overline{\nu_\mu})_{ij} * \Phi(\overline{\nu_\mu})_{i,j} * \sigma(\overline{\nu_\mu})_j * V_{i,j}^{eff}$$

- From Ref. [2]: