Neutrino Oscillations : An Outlook

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Accidental Tourist into the HEP conference

HKUST Conference 23/1/2019

Preamble for collider-centric audience

- 10% information exchange better than zero
- We all know that neutrinos have mass
- We all know the 3x3 PMNS matrix
  - relating weak eigenstates to mass eigenstates

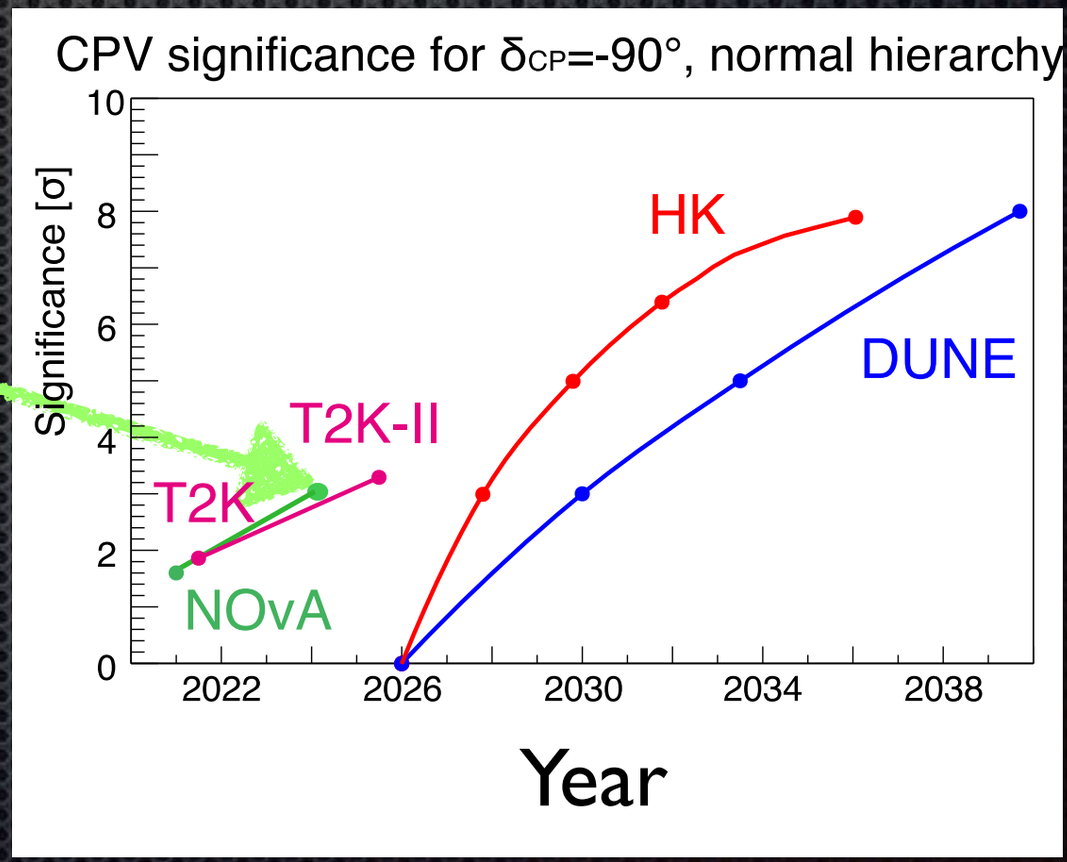
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- We should be reminded that disappearance and appearance are different
  - disappearance has no CPV
  - appearance has CPV (potentially) as 3 states involved
- Next steps in LB oscillation measurements rely on νe appearance
  - MH related to νe forward scattering but unrelated to
  - CPV even though both look for $\nu\mu \rightarrow \nu e$

Preamble for collider-centric audience

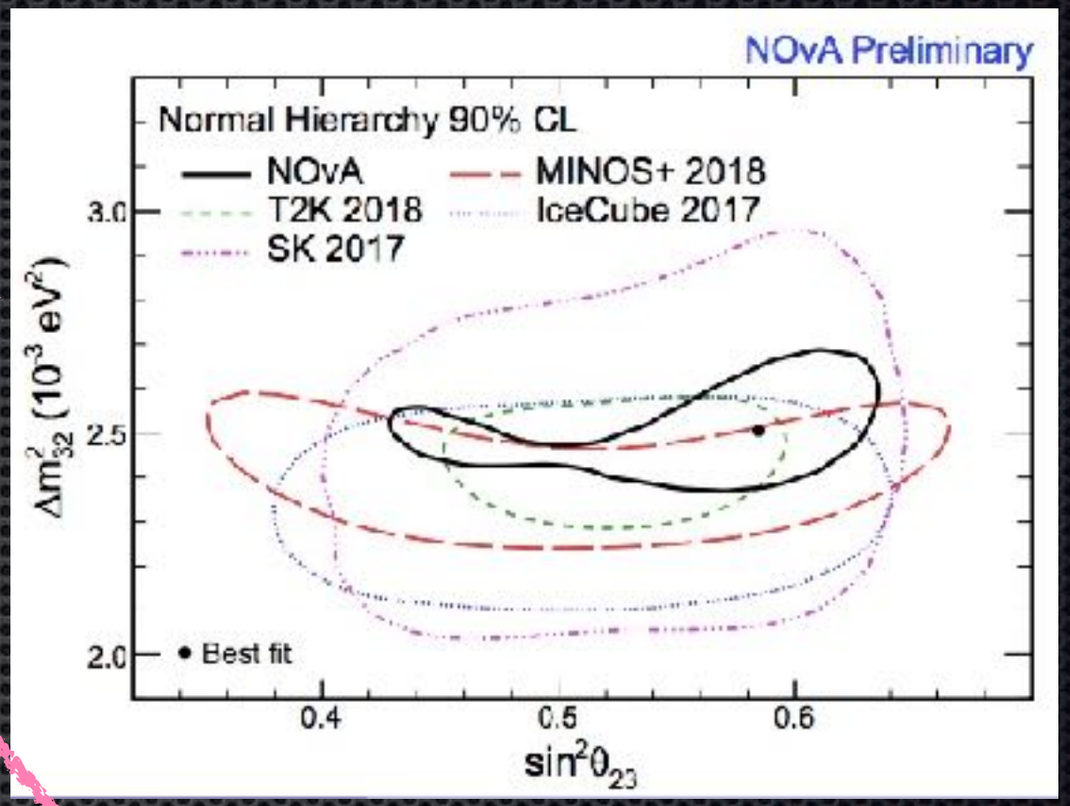
- We should be reminded that
  - Δm^2_{23}, Δm^2_{13}, $\sin^2 2\theta_{23}$, $\sin^2 2\theta_{13}$ all "precisely" measured via disappearance
- We need to study appearance for future knowledge
- The "known unknowns" are the target of the next experiments
  - dCP and MH, potentially low hanging fruit
- We need events for precision
  - thwarted by neutrino's weak interaction preference
- DUNE, Hyper-K will make the next steps and catch up by 2031
- JUNO will open a new window on θ_{12}

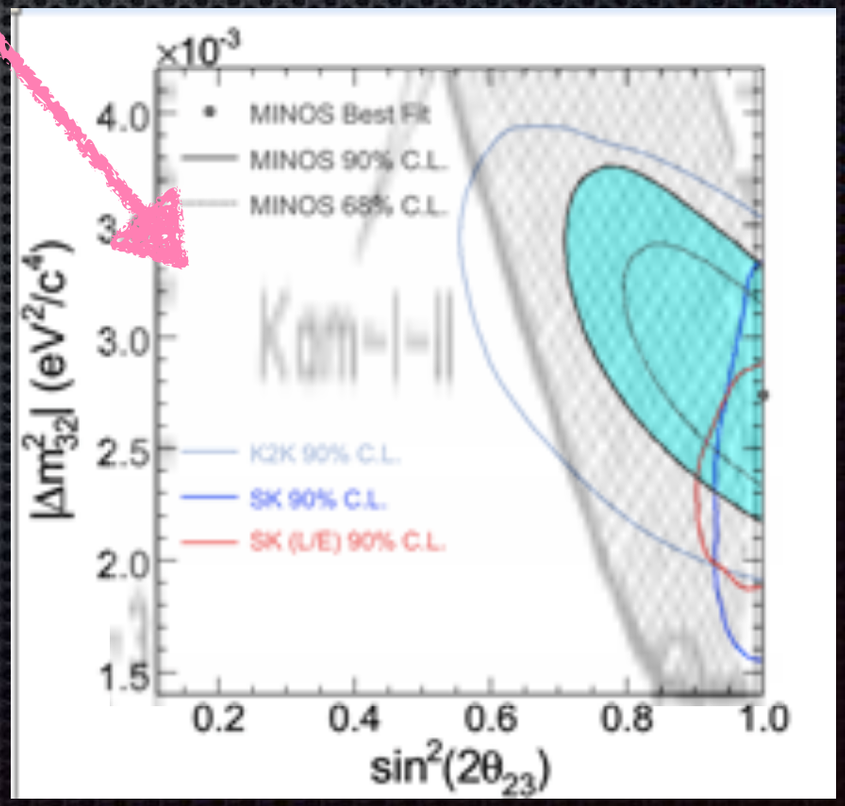
$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_{i=1}^{3} U^*_{\alpha i} U_{\beta i} e^{-im_i^2 L/2E} \right|^2$$



The potential for new insight

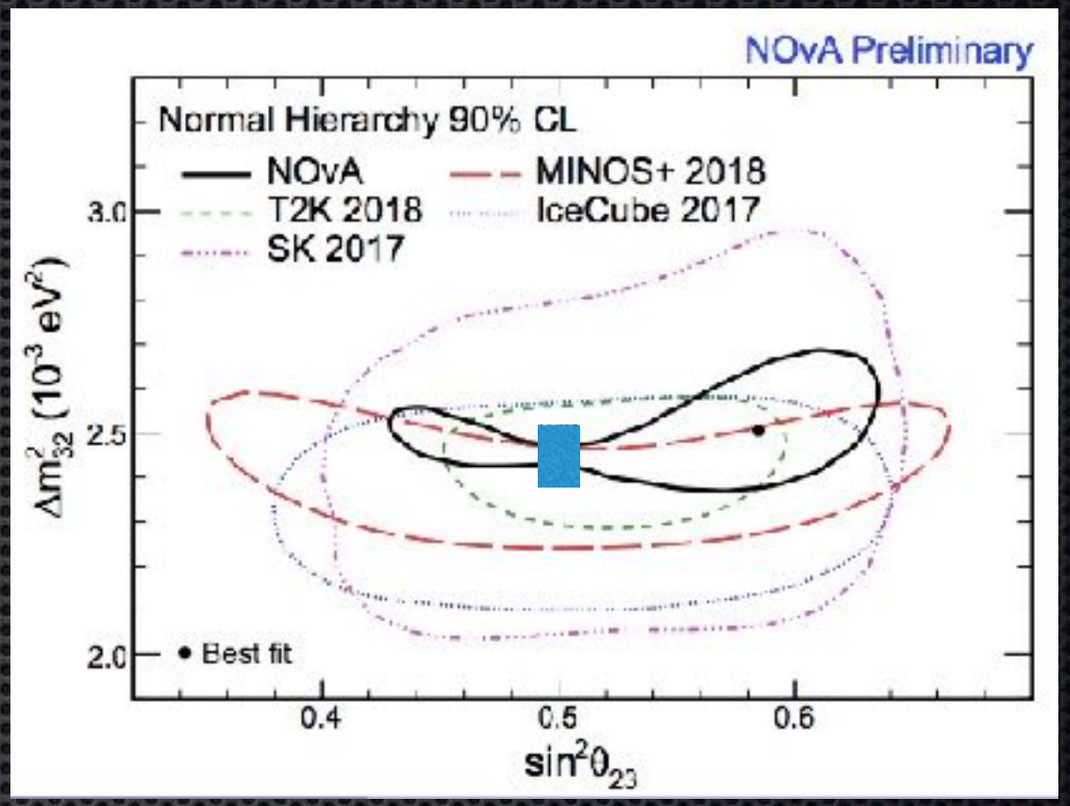
- What if $\sin^2\theta_{23}$ is maximal?
- This plot has taken more than 20 years to achieve (1994-now)
  - Is this evidence of a new symmetry? A Big Thing?
  - Are there any theoretical insights that would tell us what to do next?
  - Is the tension between T2K and NOνA real? Water vs Plastic? Beam modelling uncertainty?
  - What is the next step?

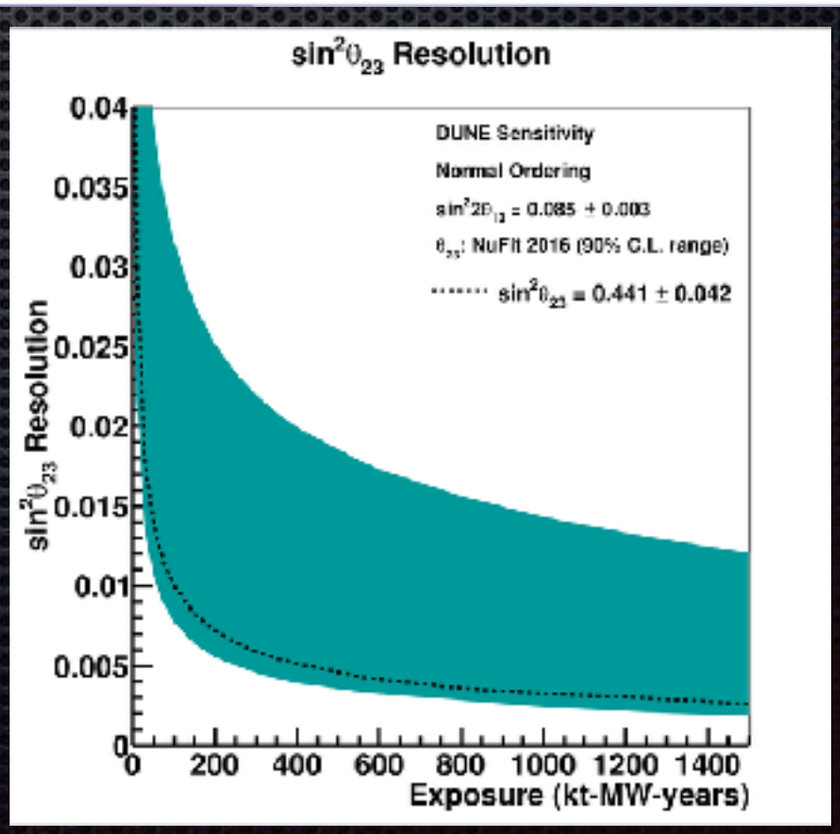




The potential for new insight

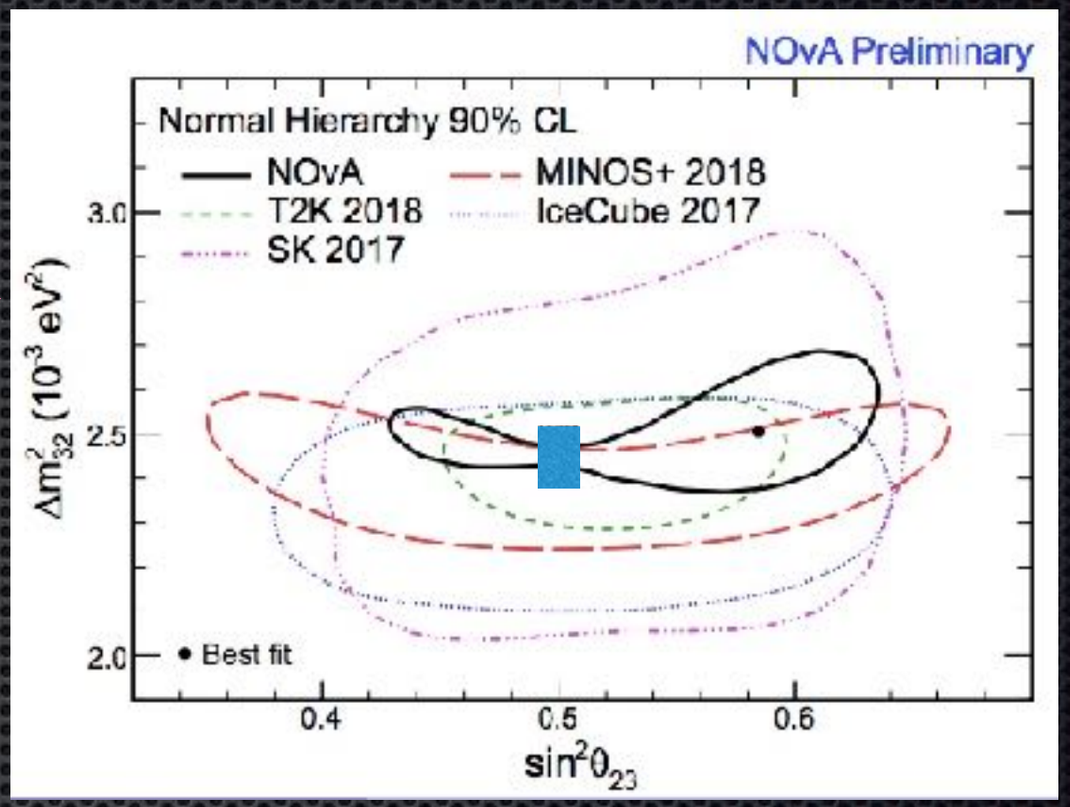
- DUNE can measure θ_{13}, θ_{23} to 1°
- Starts to be limited by systematics after "only" 400 kt-MW-years
  - that would be 2036 at the earliest
  - Its too late to realise we need more mass by then
  - About 10^{21} neutrinos will fly into space each year - a waste
- Will this be enough precision?
- What do the theorists say?





The potential for new insight

- As an experimentalist, and in the absence of direction →
  - The next step is MegaTon scale
  - The next challenge is how to afford it!
- "Cheap as CHIPS" idea is a possible way
- Avoid systematics limitation



Cheap as CHIPS is an idea for a way forward!

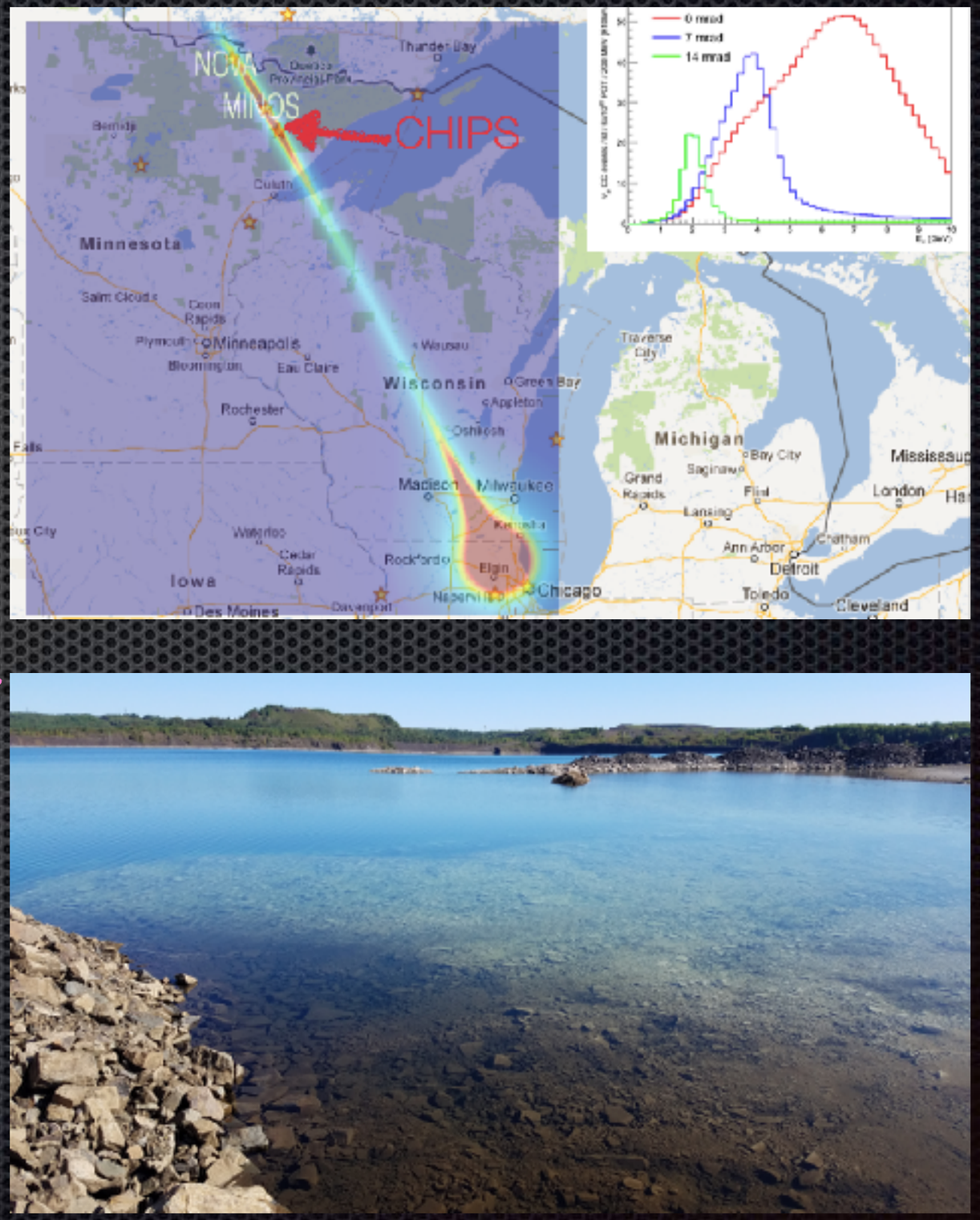
The CHIPS concept

- Big vision is a Mton array of 100kton CWC (CHIPS Water Cherenkov) detectors
- Profit from systematics cancellation instead of systematics limitation
- 7 kton prototype under construction in a flooded quarry in the path of the NuMI beam
- Potential demonstration of $200k/kilo-ton

5 steps to "cheap as CHIPS"

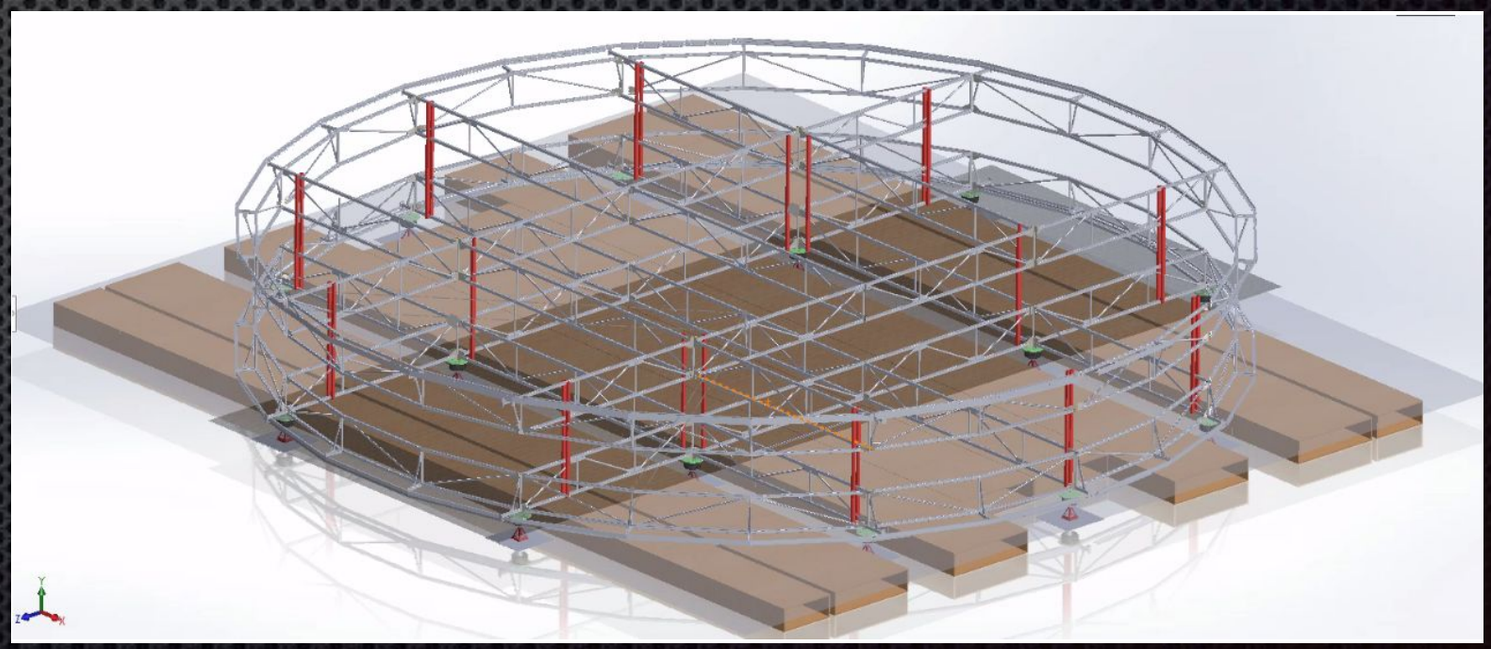
- Location
  - Sunk in a flooded mine pit in the path of the NuMI neutrino beam, will make use of the water for cosmic overburden and mechanical support
- Structure Design
  - Will allow it to grow in size with time but with no financial penalty beyond the instrumentation costs
- PMT Choice and Layout
  - 3"PMT's good position and time resolution and beam optimized layout
- Electronics
  - will make use of ubiquitous mobile phone and communications technology and already developed KM3Net Solutions
- Water Purification
  - Simple water purification plant will use filtering to maintain water clarity together with natural coldness of 4°C

1. Location



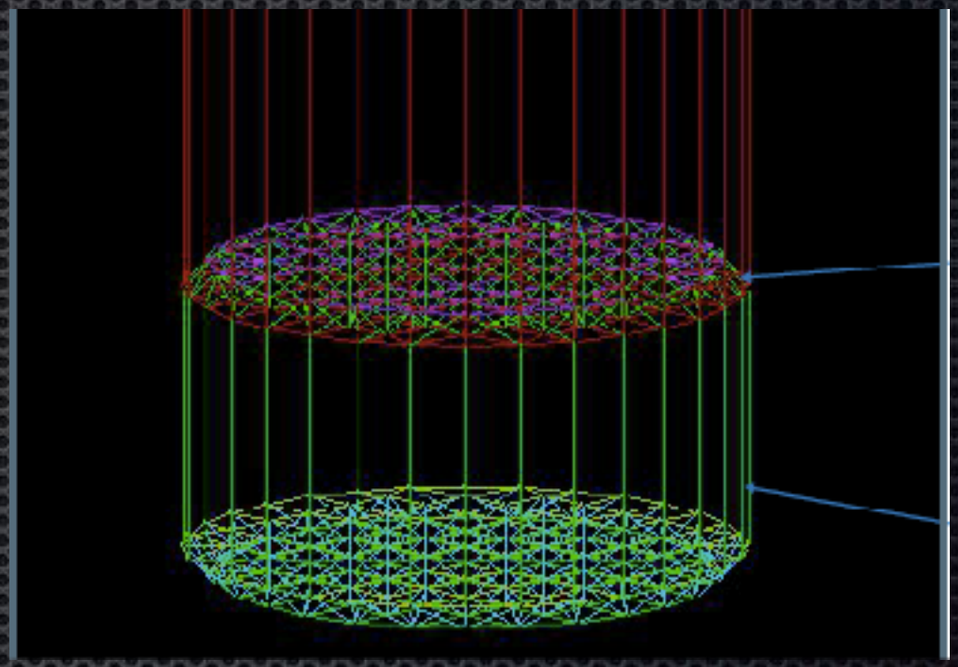
- Polymet Mining site, secure and friendly lab space in the main building
- Wentworth pit is ex-taconite flooded quarry
- 50-60m at deepest point
- 7 milliradians off axis in the NuMI muon-neutrino beam

1. Location



2. Structure

- Two steel end caps will be strung together
- Detector can grow in height for cost of cables and instrumentation
- Bottom cap will be suspended by top cap floatation



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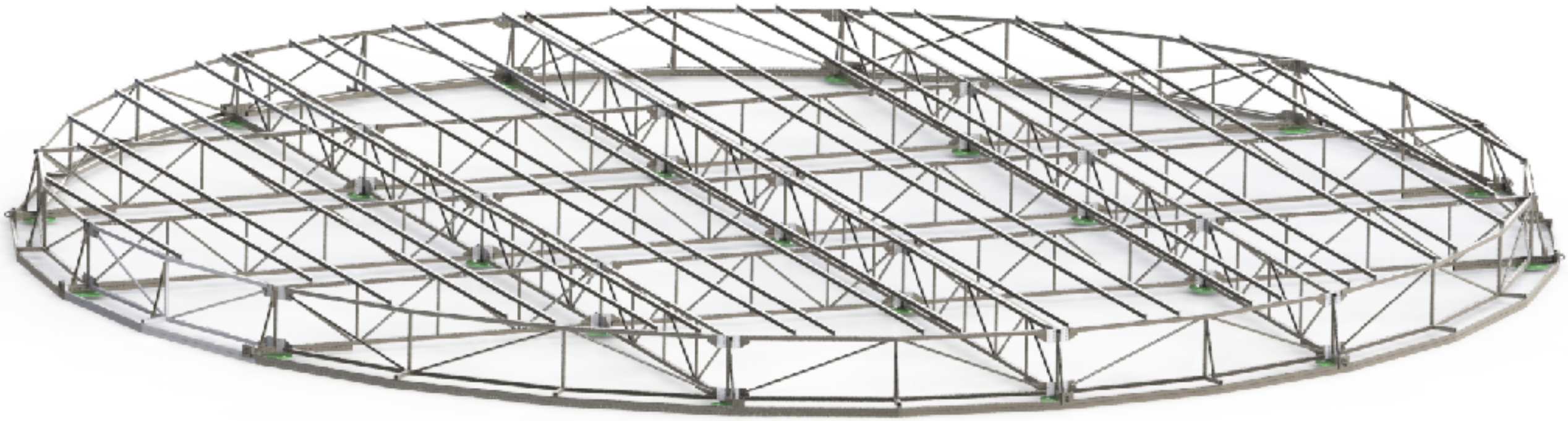
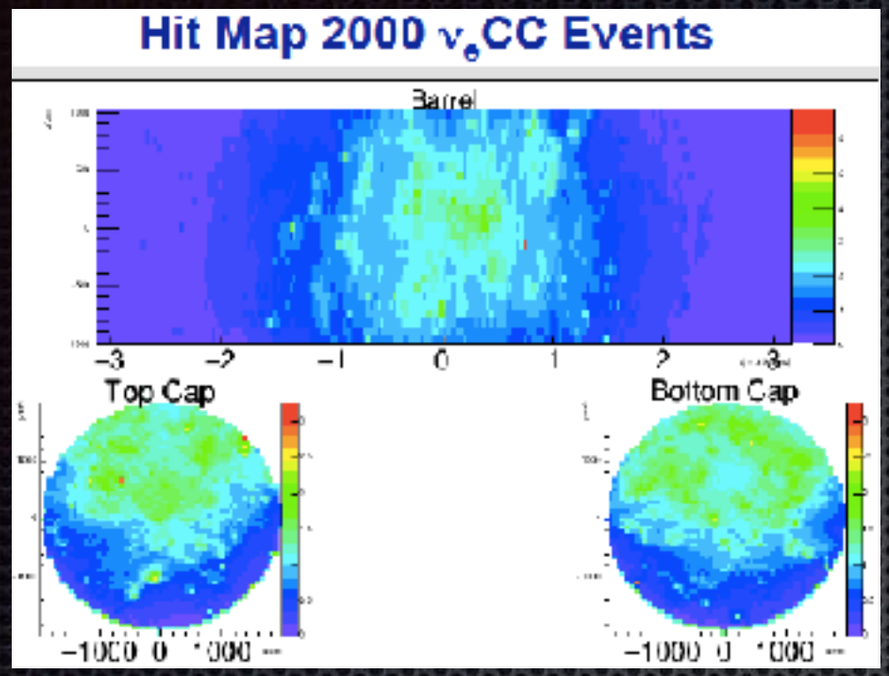
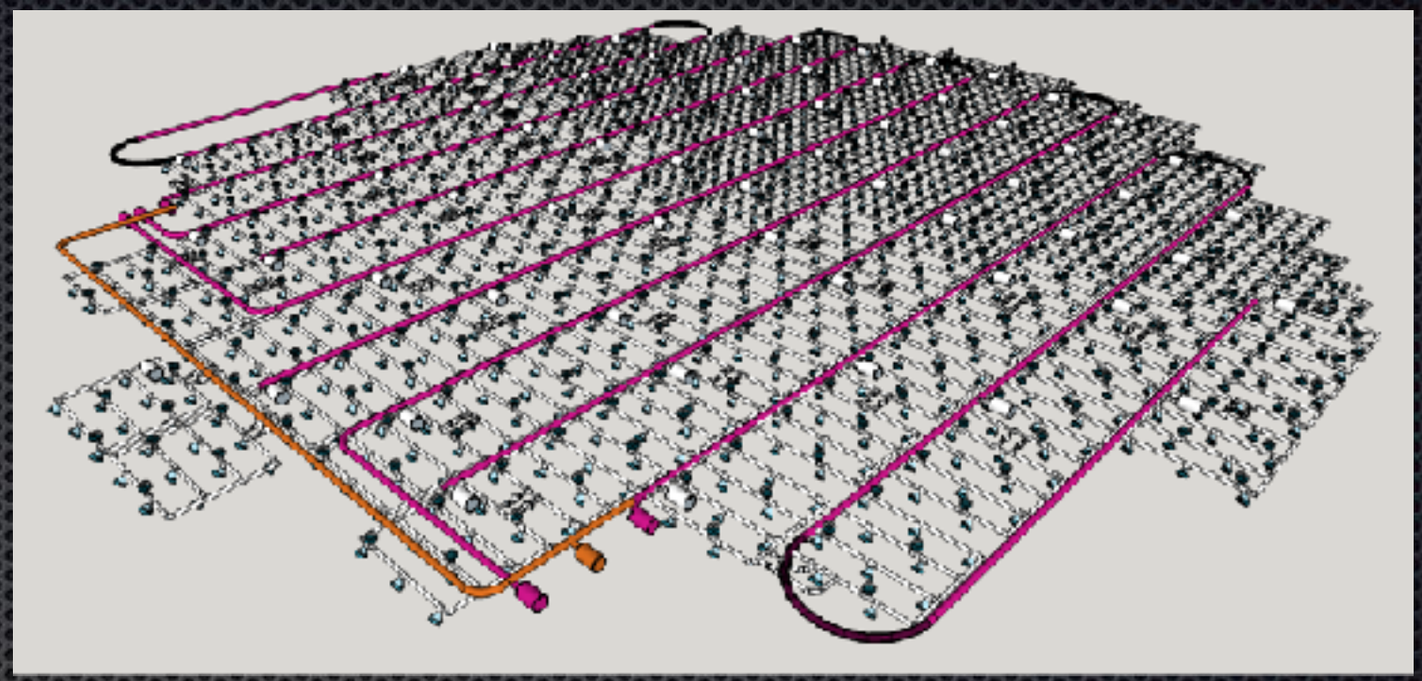
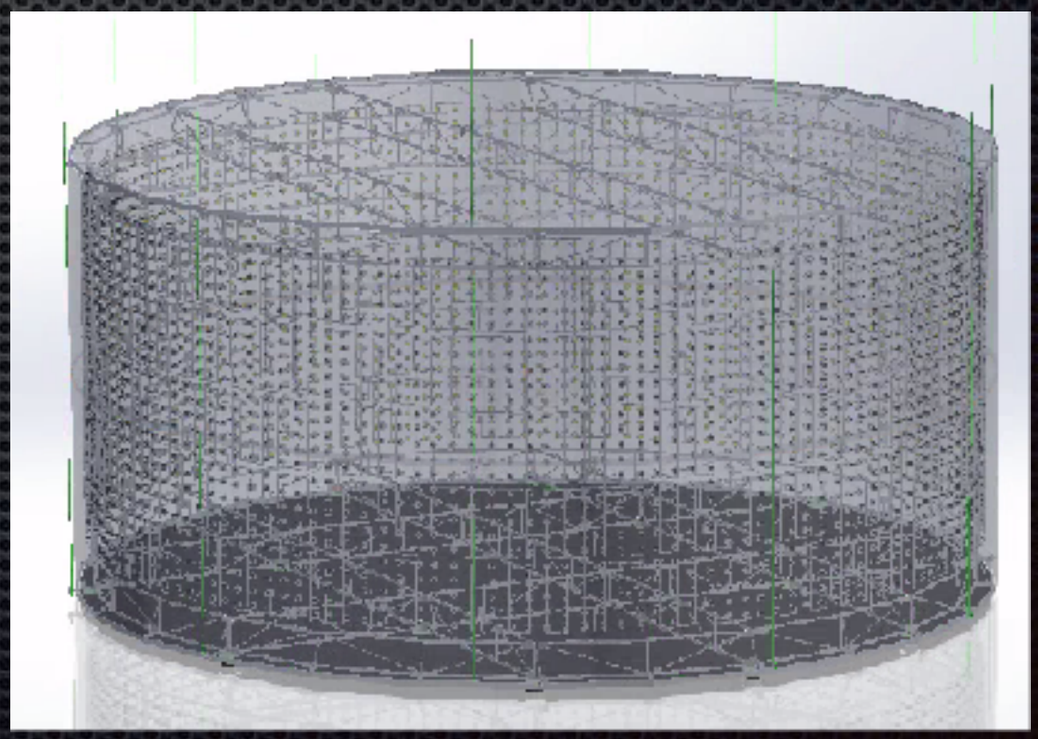


3. PMT Choice and Layout





- Layout will involve high and low density planes
- A big part of the instrumentation will just implement (almost) KM3Net technology
  - HZC 3.5" PMTs at 6% coverage in front and end caps, and 4% coverage back end cap region
- Low density wall planes will be made with NEMO-III 3" PMTs and Madison electronics.
  - Old 3" PMTs at 4% coverage in back



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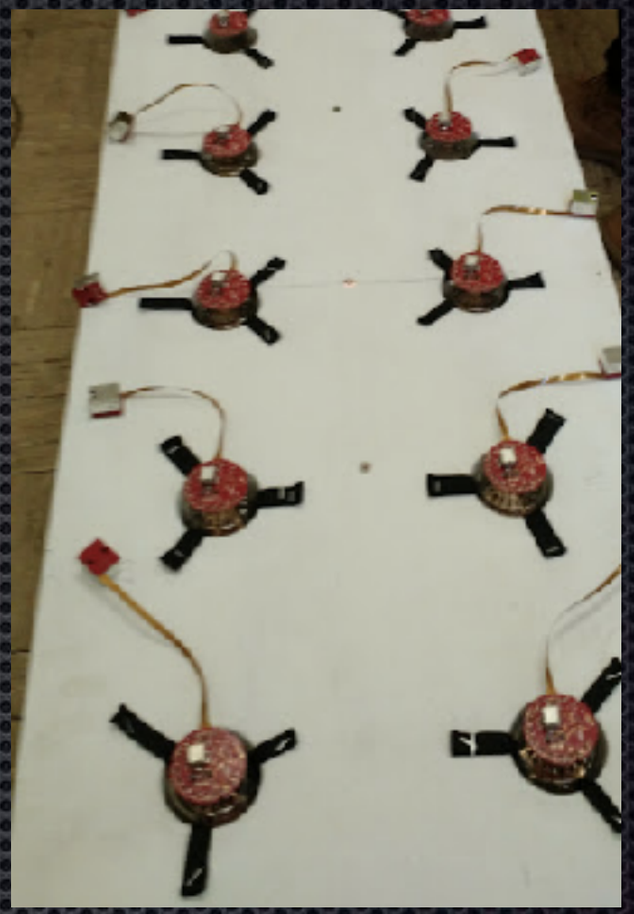


- 150 PMTs could be potted per day in 5 story jig constructed
- Potting mixed, pumped and 15ml put in inverted domes, PMTs held in jig lowered into the domes
- ~4000 PMTs were potted
- Took a few days to perfect the process, thereafter it took a few hours every day for 3-4 people
- 1500 HZC PMTs left to pot

3. PMT Choice and Layout

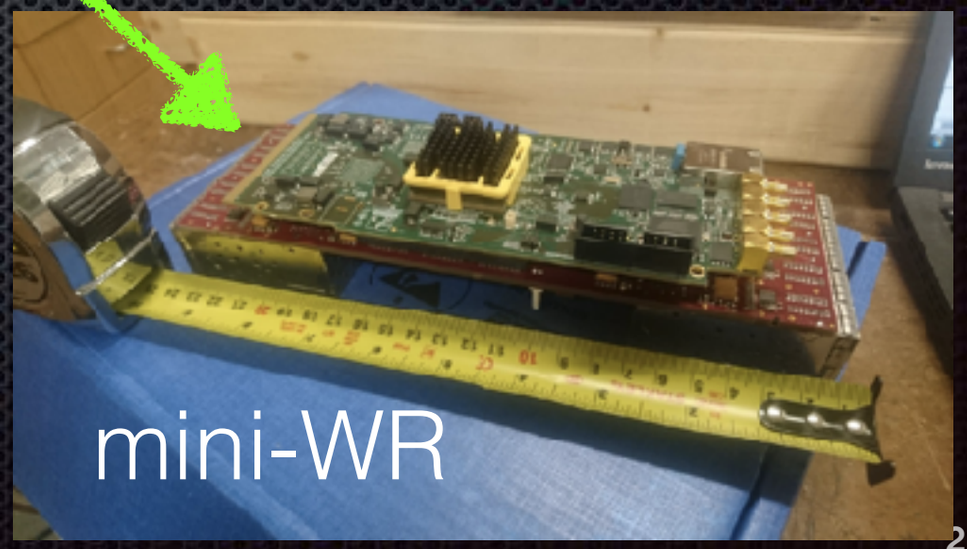
Purpose built PMT storage locker

Detector Plane Construction

- Detector Planes made out of schedule 40 PVC
- Keeps electronics dry, withstands 6 ATM
- reflective cones increase light collection
- Undergrad involvement essential

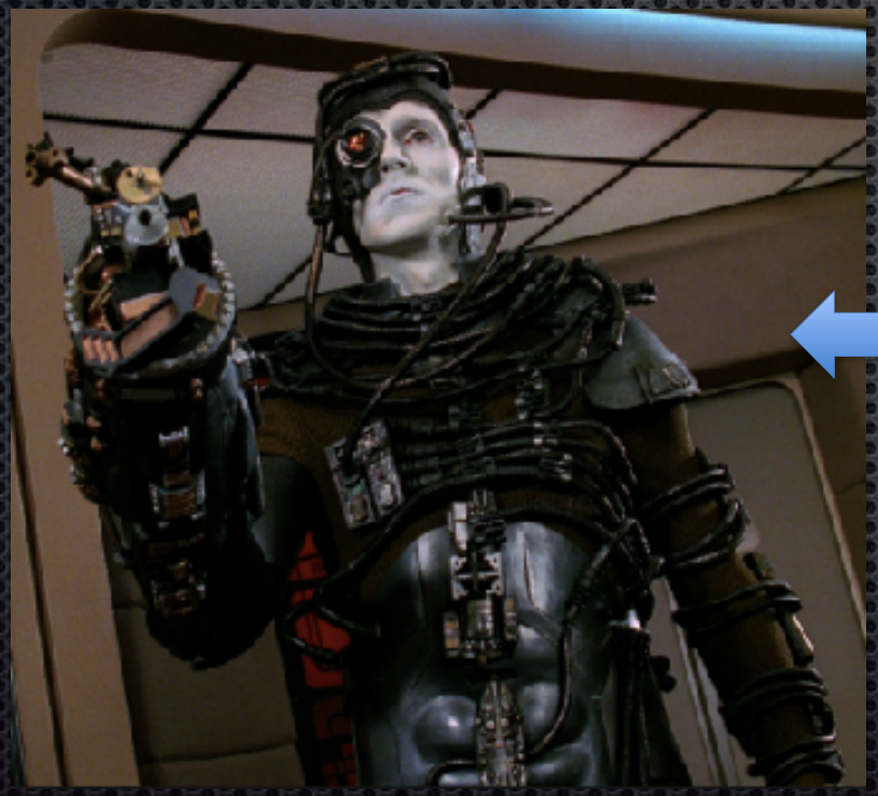
4. Electronics

- KM3Net electronics takes advantage of many millions of euros of electronic design
- Blazes the trail of multi-small-pmts : no long heavy cables, -ve HV CW bases
  - 30 PMTs talk to one central logic board, gets timing from CHIPS miniature White Rabbit timing board (1ns-over-ethernet)
  - All standard cat-5 interconnecting cables
  - CWDM (Coarse Wavelength Division Multiplexing) on fibres out of the planes
- SFPL (Small Format Pluggable Lasers) on WR
- Power cable down, fibre cable up to surface, no other racks or modules!



4. Electronics: Madison Planes

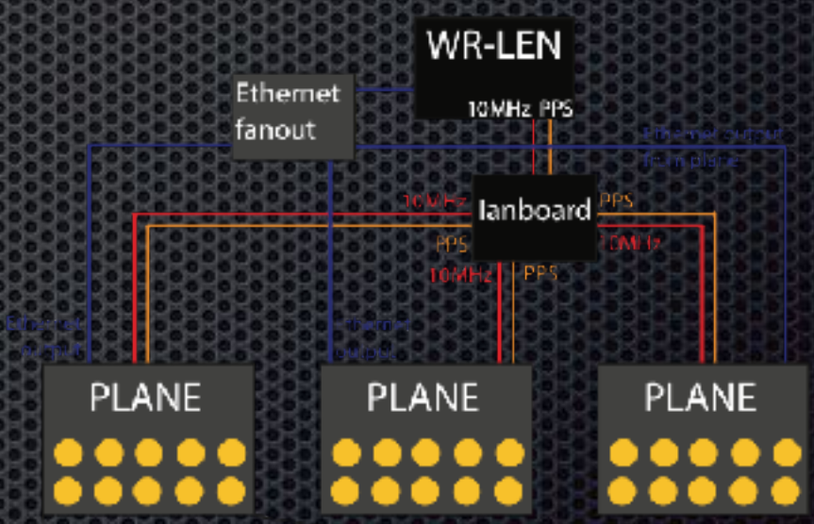
- We are riding a revolutionary wave in development
- Microprocessors on each PMT provide ToT and receive clock from WR system
- Each one knows the time to 1ns
- $40 for a BBG to collect signals and transmit to Ethernet
- Reduce cost to minimum
- Designed at Madison

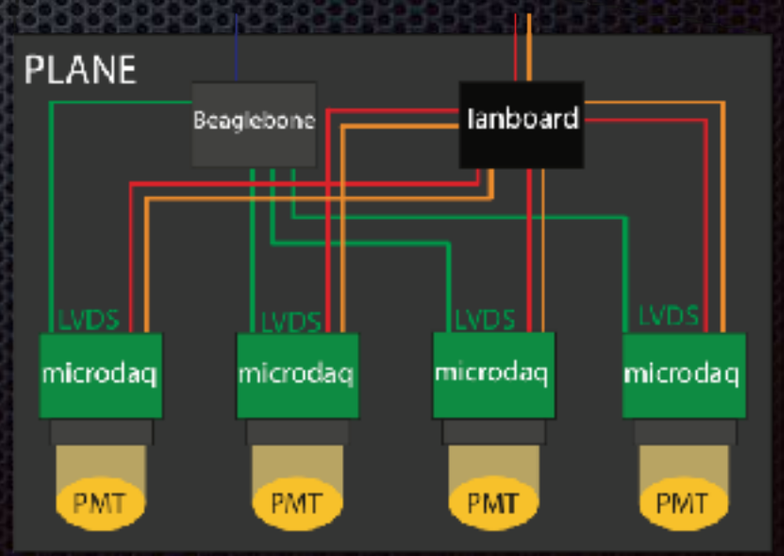


- Side comment: Industrially available ASICs in version 100 (ish): home grown electronics is typically in version 2-5the combination of cheap processors such as Raspberry Pi, BeagleBone and Arduino combined with the WWW means progress goes incredibly fast as solutions are known instantaneously
- Developers are like the Borg: and resistance is futile..

4.Electronics: **Madison** Planes

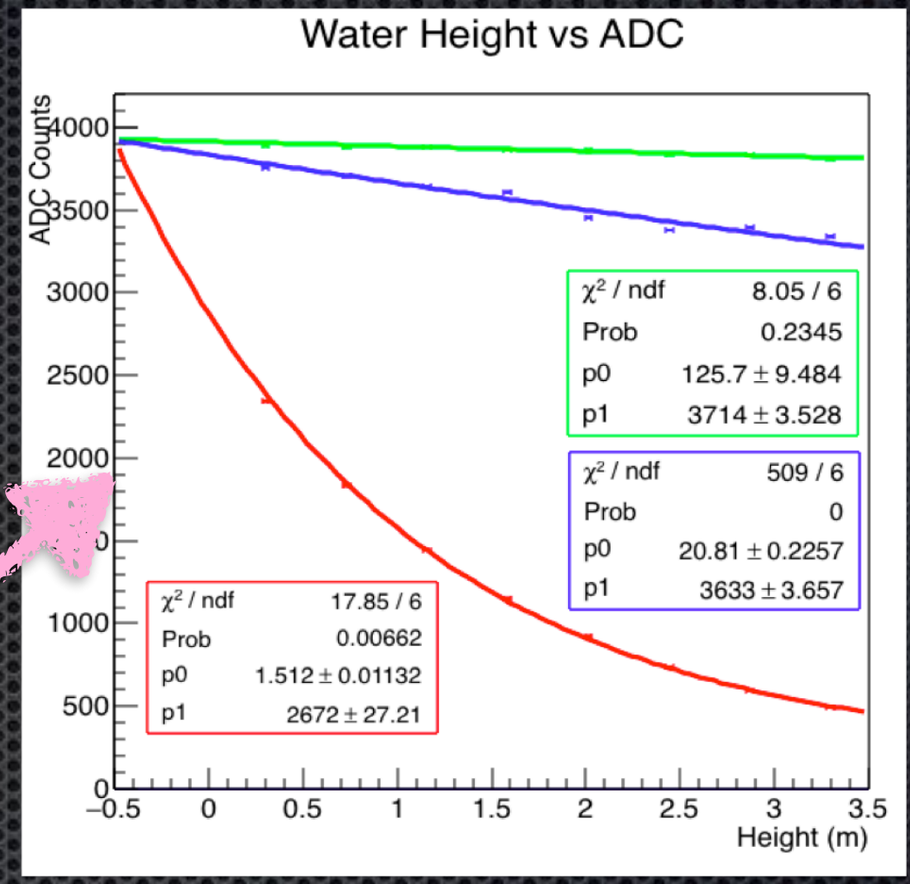
- Top level fanout provides power, 10MHz, PPS and ethernet on cat-5
- Communication software between BB and micro-daq demonstrates 1Mbps on RS485/D
- Rate of 1-10kHz per tube means scope for local filtering (maybe) or at least buffering during spills
- Total cost, $25+PMT, data->disk



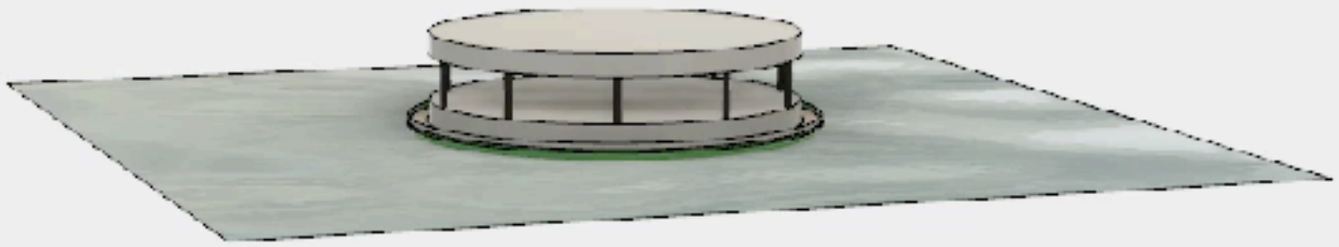


5. Water Clarity

- CHIPS has advantage of being under about 6 bar pressure and at 4-8°C :
  - Good for crushing bubbles and bacterial blooms respectively
- Filters provide
  - a raking of the particulates in the water down to 0.2 micron
- We used a small model of CHIPS-M (micro-CHIPS) on surface
  - Using 405nm laser and 3m upright column, we watched the water clarity over 3 months
  - This is likely worse than in reality because it is not pressurized or cold
- Needed to know how clear we can make the water with simple filtering, for simulation benchmarking, and for system design



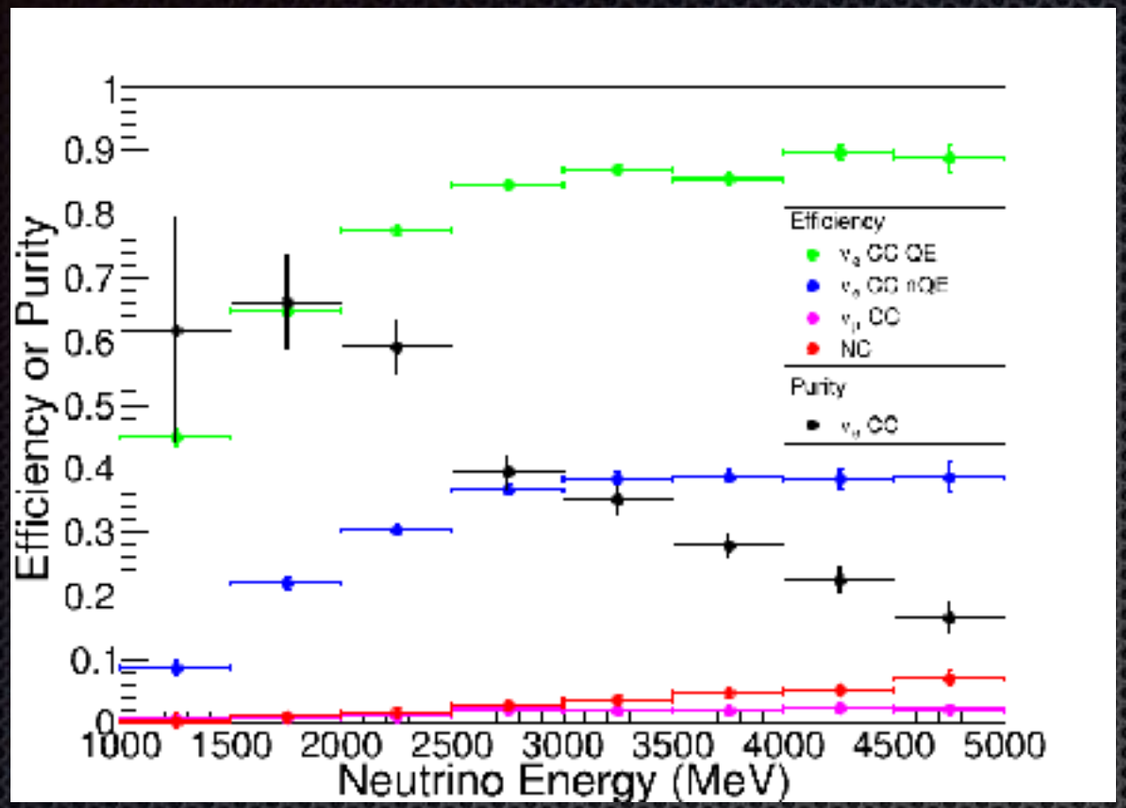
DEPLOYMENT

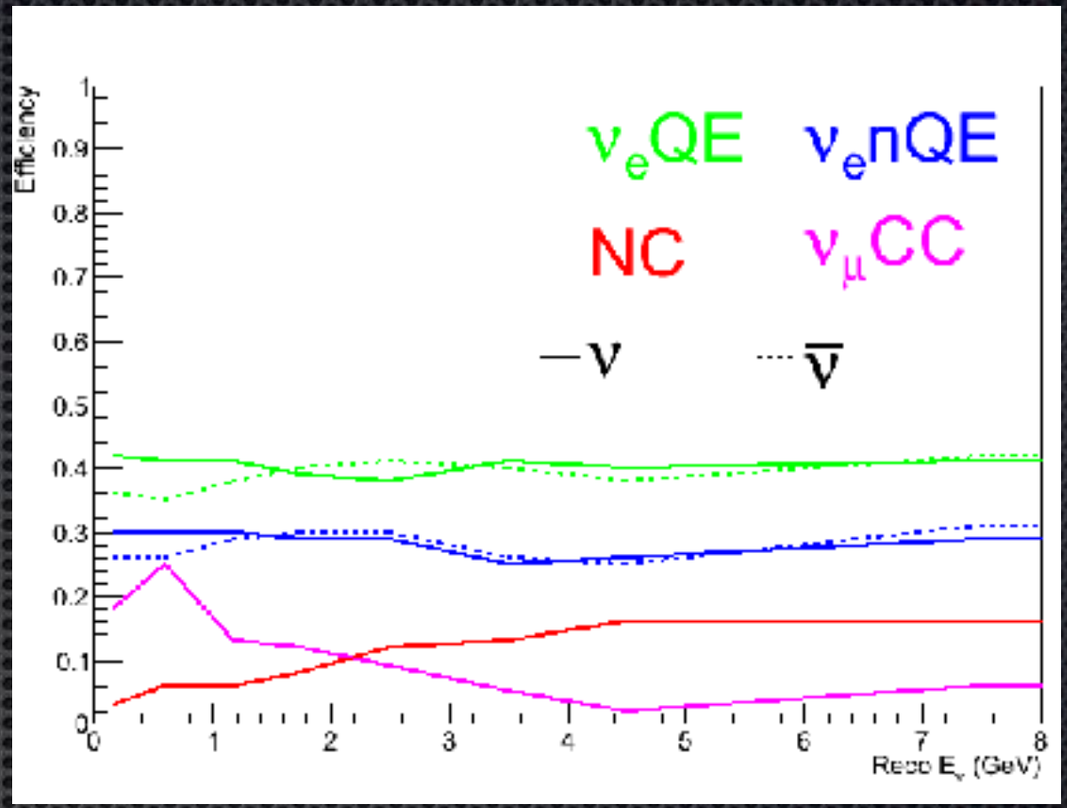


Reconstruction

- No self-respecting new experiment will go without machine learning!
- Our first stab at this has improved our event efficiency and purity by 30%
- It has sped up the reconstruction from 2.5 minutes to 1sec / event

Reconstruction

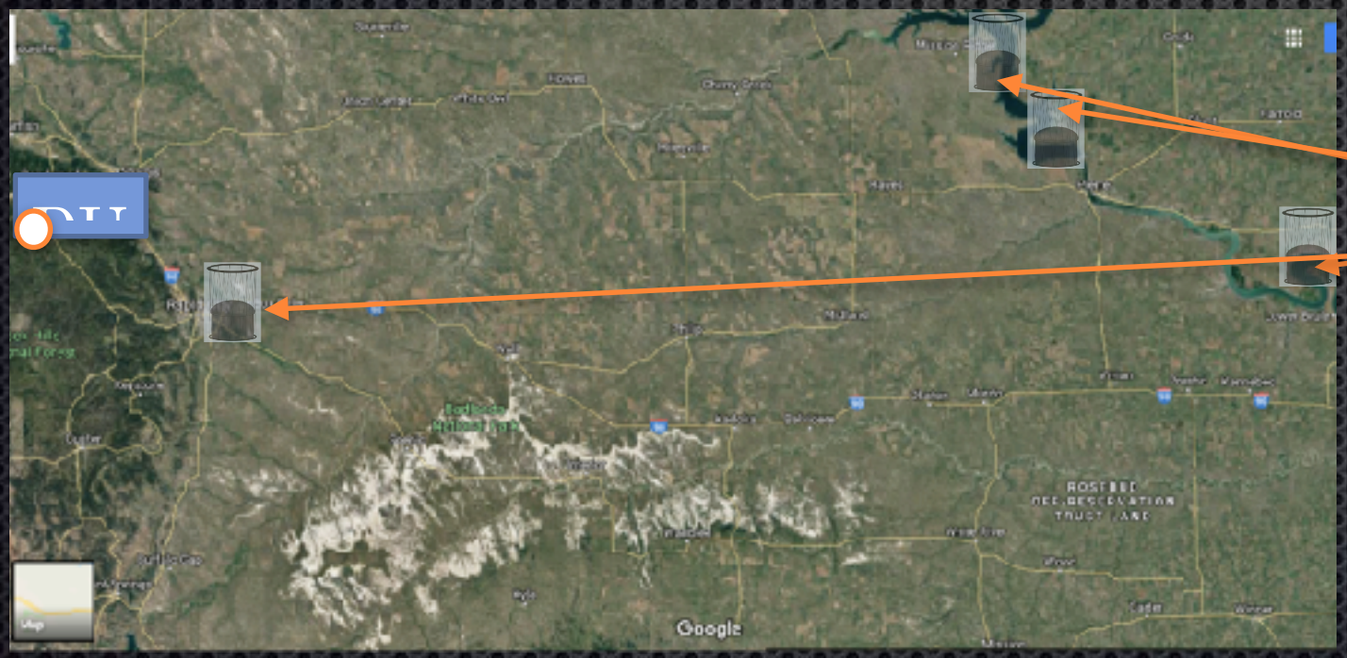




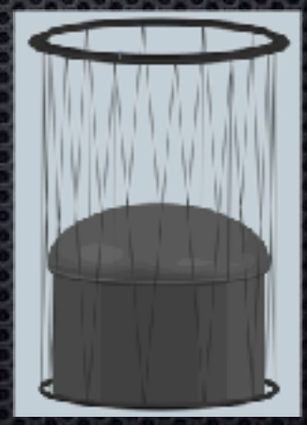
- Originally based on MiniBOONE approach, several innovations from that point (time) but…
- Deep learning tools improved all aspects to be competitive with new Super-K
- Pretty good basic bottom line so far, more improvements on the way

CHIPS Fleet : future view

- Idea is to use several CHIPS 100kt detectors to gain higher precision on oscillation parameters
- systematics will cancel between them, small changes in L and/or E from different positions could lead to higher precision on the oscillation probability measurement



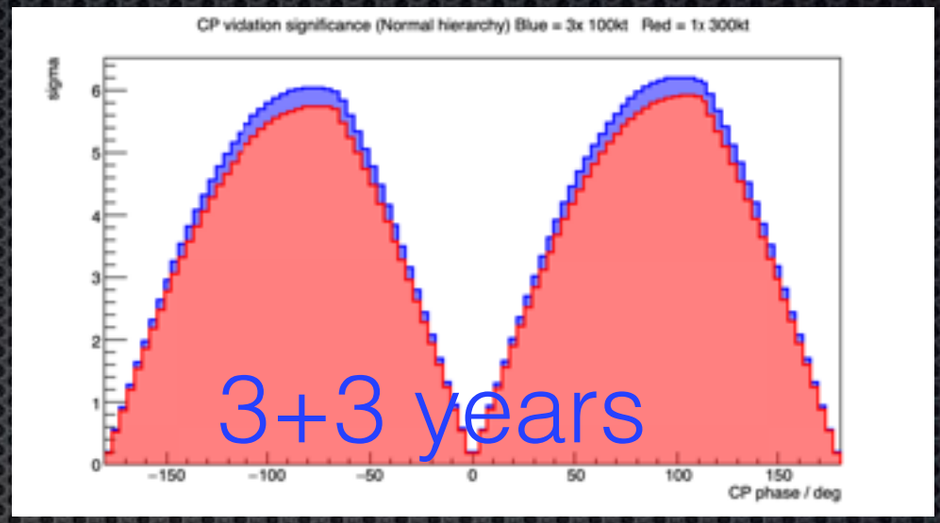
S.Dakota..scene of the new LBNF neutrino beam

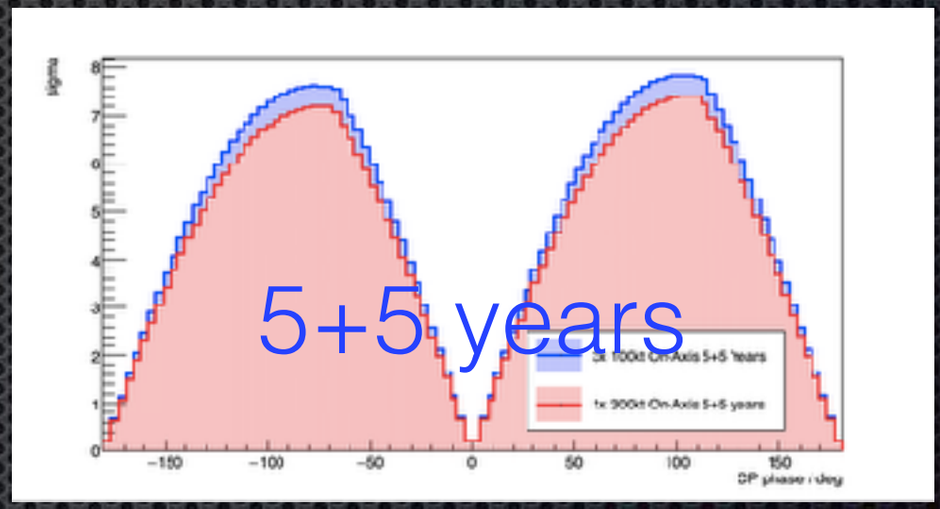


Big Canyon through the country called Missouri River…eg

CHIPS array @ LBNF

- Initial studies of the precision advantage of several identical detectors show promise
- Plot at right shows the difference between 3x100 kiloton detectors (1290km,1300km,1310km) compared to one 300 kiloton detector using GLOBES framework
- As statistics increase, the advantage of systematic cancellations becomes apparent...study in its infancy
- We will see whether this can become a compelling argument for a complimentary detector (array) to DUNE





Summary

- There could still be a lot to learn but we always need more mass
- If CHIPS successful we will have shown:
  - $200-300k/kton (compared to $20M/kiloton)
  - cheap electronics concept for distributed PMT systems
  - Potentially shine light on tension between T2K and NOVA (same beam as NOVA, same target as T2K)
  - measurements along the way to help the race to dCP
- Precise measurement of the oscillation shape could provide new clues....
  - called a fishing expedition