Cheap as CHIPS

Large water Cherenkov detectors: faster and cheaper

or

R&D of Water **CH**erenkov Detectors **I**n Mine **P**it**S**

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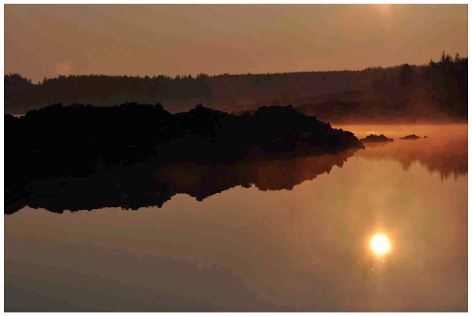
LAL/APC, April 7-8, 2015



Outline:

1. The context & the premise
2. CHIPS idea:
   - physics reach
   - challenges
3. R&D
4. Future

Abstract

CHIPS is an R&D program focused on designing and fabricating a cost-effective large water Cherenkov detector (WCD) to study neutrino oscillations. Traditional WCD's with a low energy threshold have been built in special large underground caverns. Civil construction of such facilities is costly and the excavation phase significantly delays the detector installation although, in the end, it offers a well-shielded apparatus with versatile physics program.

Following concepts developed for the LBNE WCD (arXiv:1204.2295), we propose to submerge a detector in a deep water reservoir, which avoids the excavation and exploits the directionality of an accelerator neutrino beam for optimizing the detector. Following the LOI (arXiv:1307.5918), we have submerged a small test detector in a mine pit in Minnesota, 7 mrad off NuMI axis. Borrowing technical ideas and solutions from IceCube and KM3Net, we are now focusing on designing a large (10-20kt) isolated water container to house photodetectors with underwater readout and triggering. We will describe the CHIPS concept and its physics potential in more detail, and will present the ongoing R&D activities.

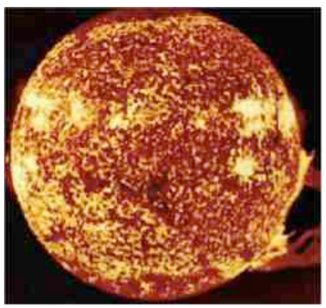
Remarkable "Neutrino Years"

(painted with a broad brush)

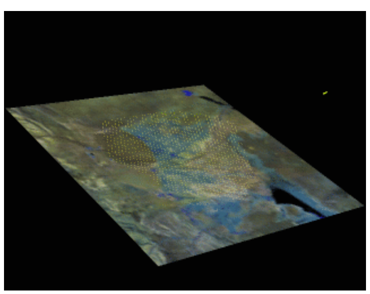
< 1998

- $m_\nu = 0, \qquad \nu = e, \mu, \tau$

  - *solar* neutrinos *deficit*



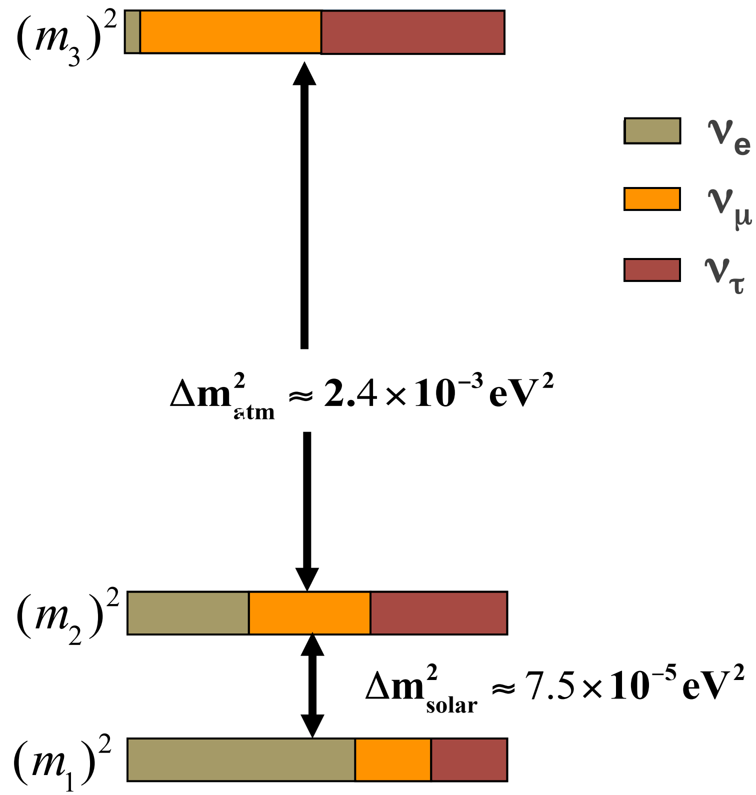
  - *atmospheric* neutrinos *anomaly*



$$\frac{N(\nu_\mu)}{N(\nu_e)} \neq 2$$

> 1998

- *neutrino oscillations* $\rightarrow m_\nu \neq 0$
- *measured* Δm^2_{sol} *and* Δm^2_{atm}
- *measured* 3 *out of* 4 *mixing angles*



Neutrino mixing and oscillations

Pontecorvo – Maki – Nakagawa - Sakata (PMNS) matrix

weak eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

mass eigenstates

3 mixing angles + 1 CP phase

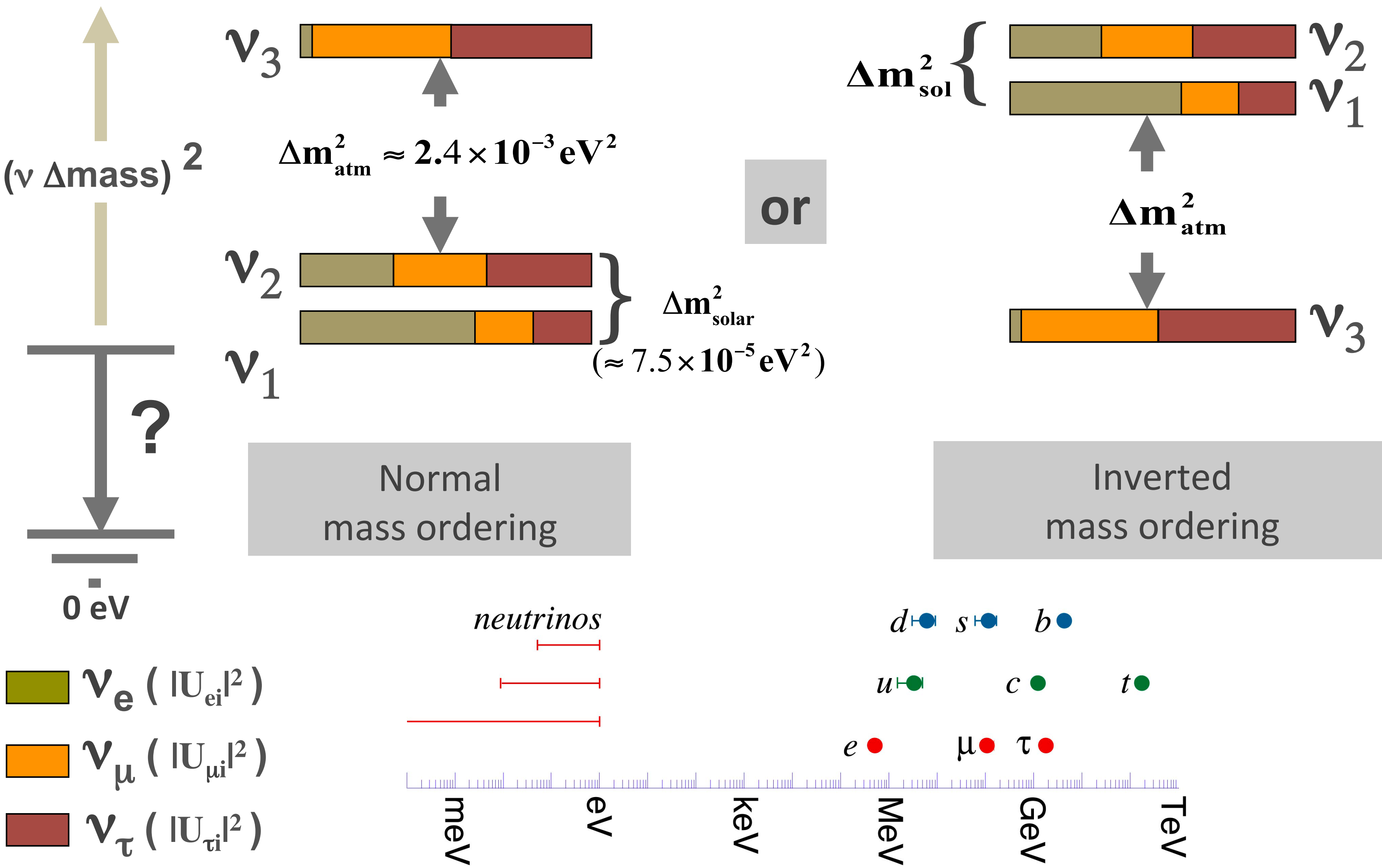
If neutrinos are Majorana particles: $\nu \equiv \bar{\nu}$

$(c_{ij} \equiv \cos\theta_{ij},\ s_{ij} \equiv \sin\theta_{ij})$

$$U = \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}\cdot e^{i\delta} \\ & 1 & \\ -s_{13}\cdot e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

Solar	Atmospheric Reactor $\nu_e \leftrightarrow \nu_\mu, \nu_\tau$	Atmospheric $\nu_\mu \leftrightarrow \nu_\tau$	Majorana Phases $0\nu\beta\beta$

Present neutrino landscape



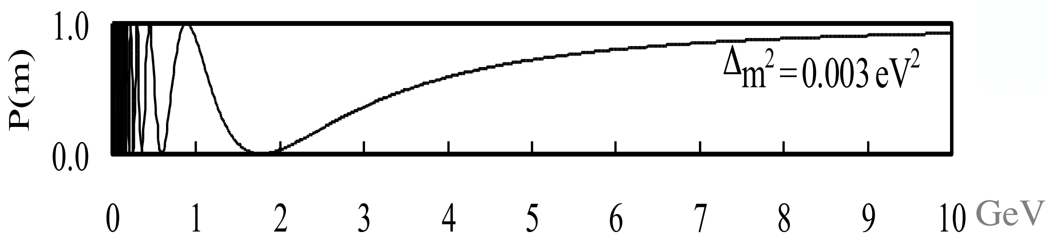
Neutrino oscillations - MINOS

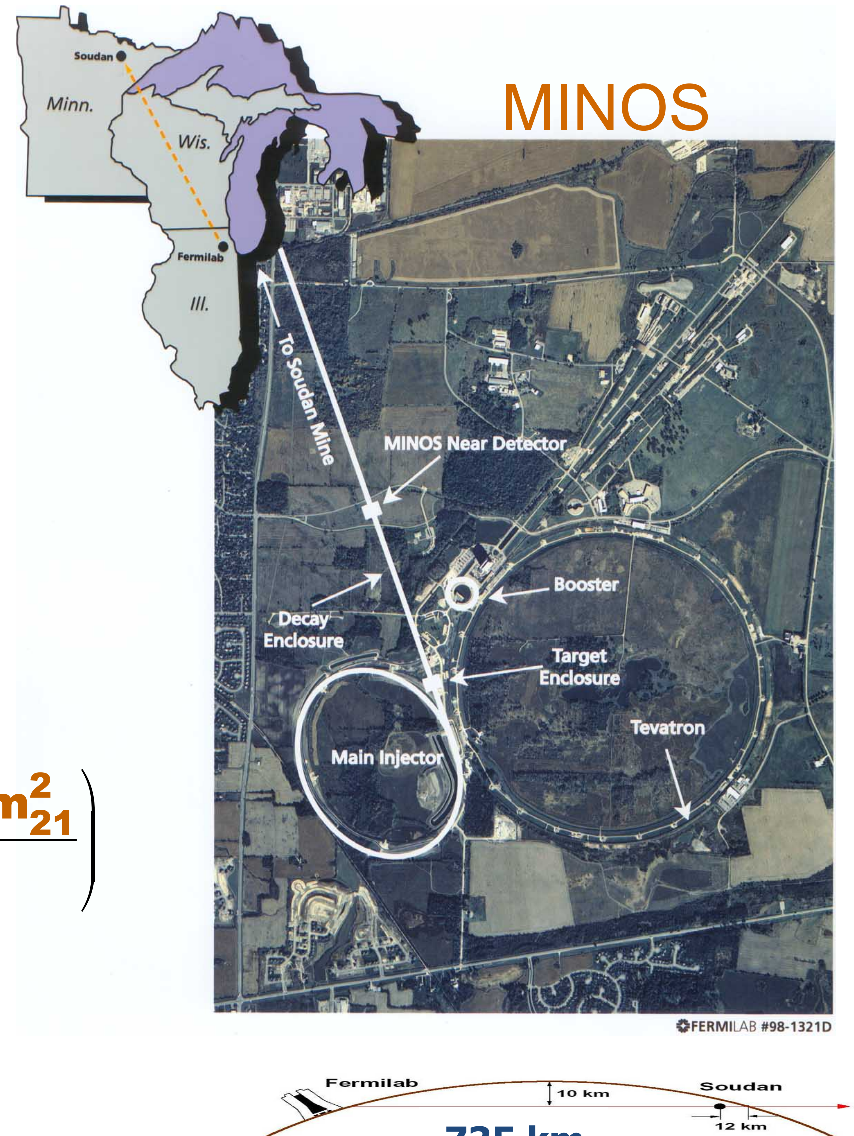
- Two-detector measurement
  - ✓ long baseline (735km)
- High intensity beam
  - ✓ (120 GeV from Main Injector)

$$|\nu(t=0)\rangle = |\nu_a\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

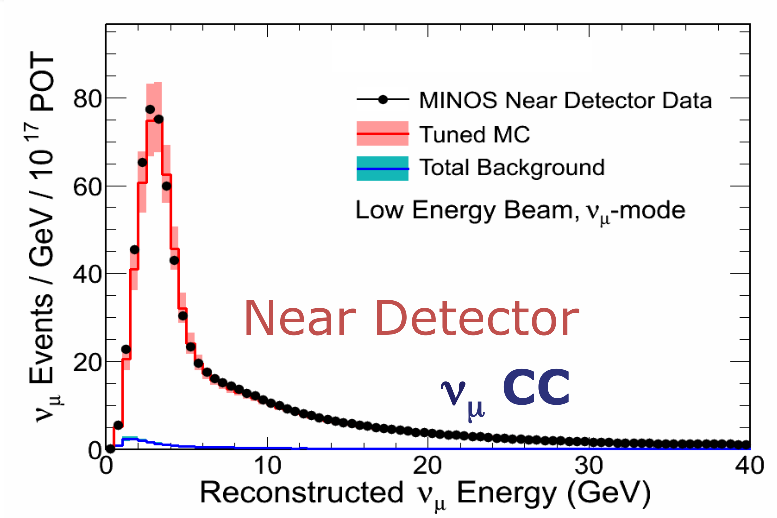
$$\begin{pmatrix}\nu_a\\ \nu_b\end{pmatrix}_{weak} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}_{mass}$$

$$P(\nu_a \to \nu_a) = 1 - \sin^2(2\theta)\cdot\sin^2\left(\frac{1.27\cdot L\cdot\Delta m^2_{21}}{E}\right)$$





MINOS recent results



Normal ordering

$|\Delta m^2_{32}| = 2.34^{+0.09}_{-0.09} \times 10^{-3}\mathrm{eV}^2$

$\sin^2\theta_{23} = 0.43^{+0.16}_{-0.04}$

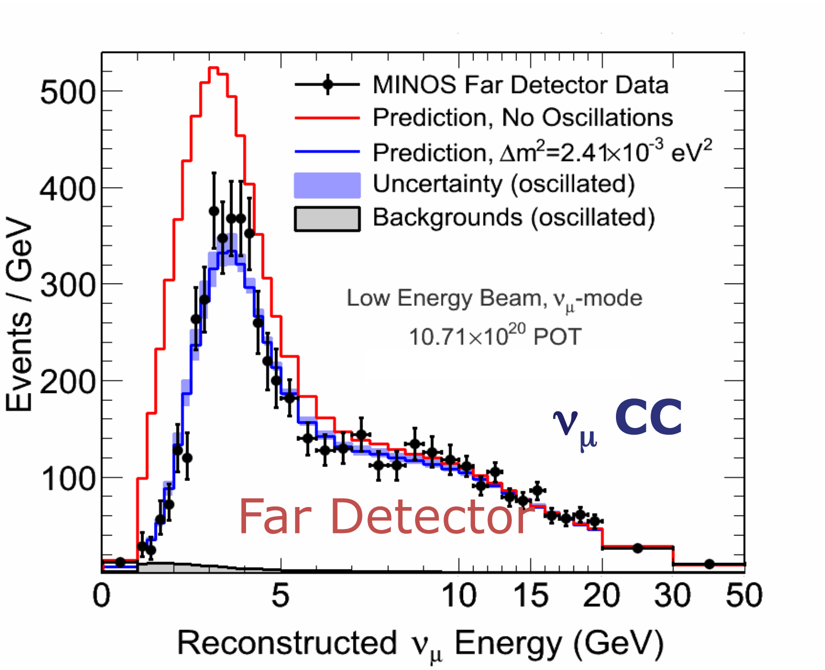
$0.37 < \sin^2\theta_{23} < 0.64$ (90% C.L.)

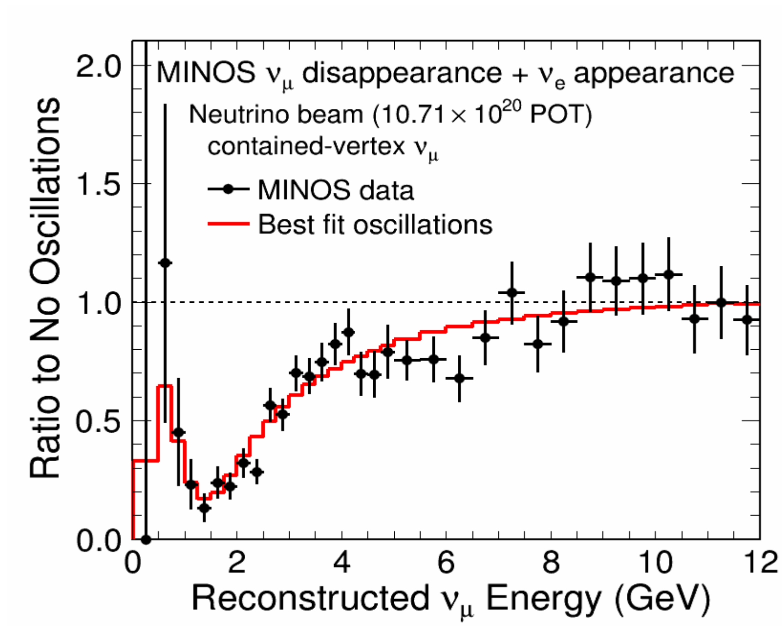
Inverted ordering

$|\Delta m^2_{32}| = 2.37^{+0.11}_{-0.07} \times 10^{-3}\mathrm{eV}^2$

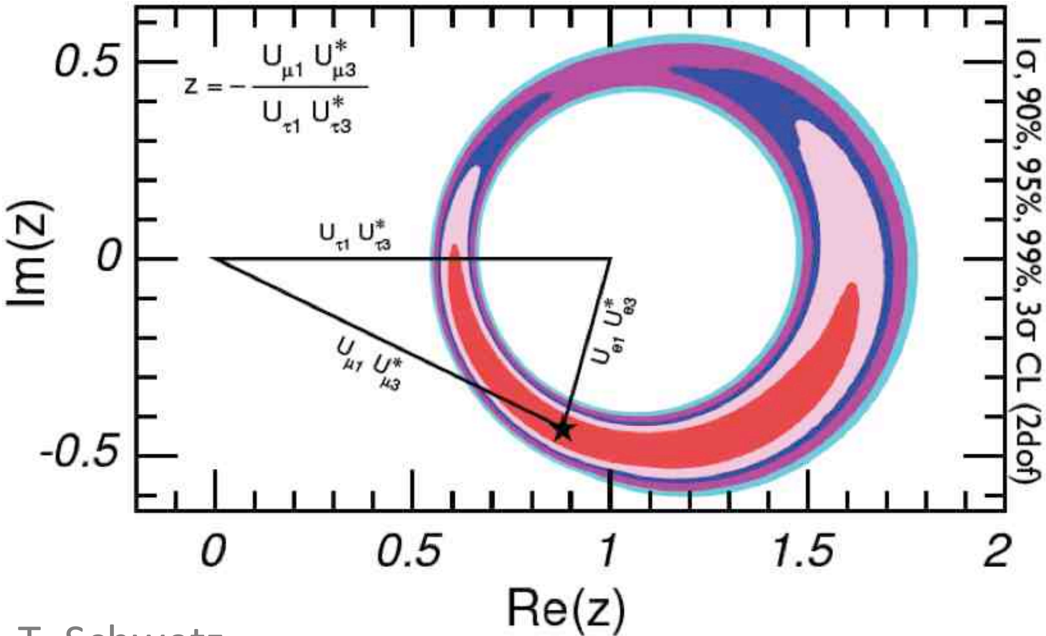
$\sin^2\theta_{23} = 0.43^{+0.19}_{-0.05}$

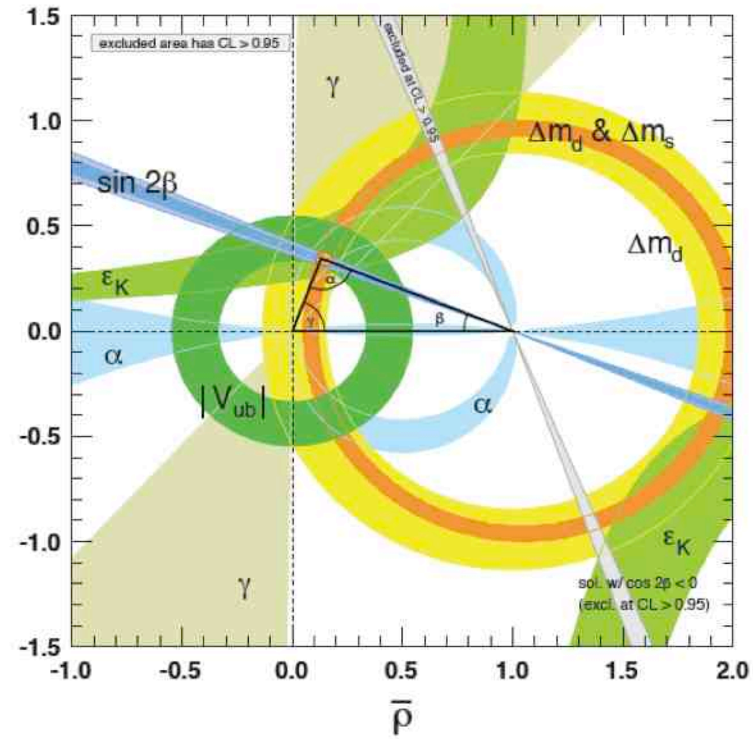
$0.36 < \sin^2\theta_{23} < 0.65$ (90% C.L.)





The CKM matrix:
Inspiration and aspiration for the PMNS matrix





T. Schwetz
@ NuFact 2014

$$\approx \begin{pmatrix} 0.82 & 0.55 & 0.15 \\ 0.37 & 0.57 & 0.70 \\ 0.39 & 0.59 & 0.68 \end{pmatrix}$$

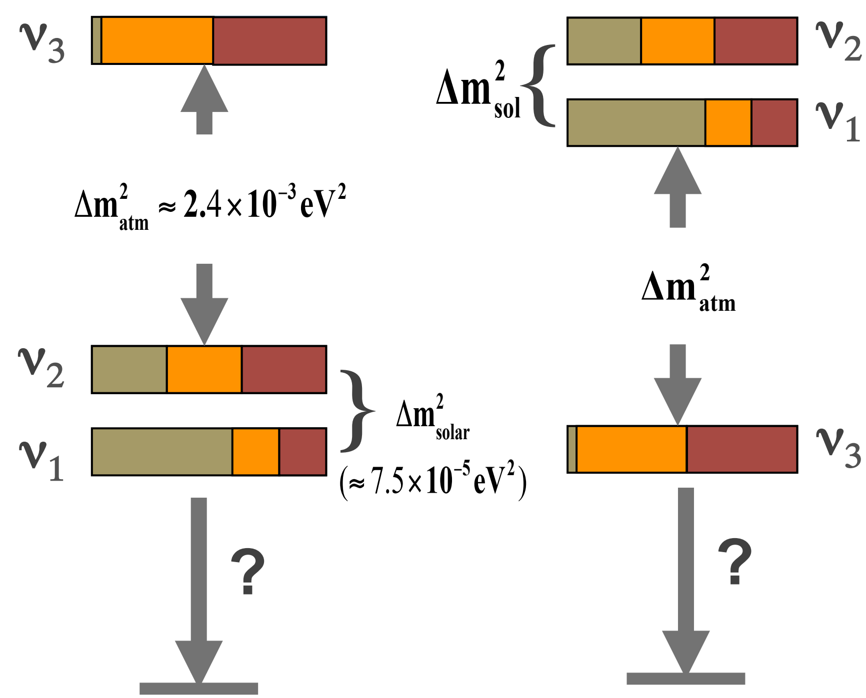
$$\approx \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

www.nu-fit.org (2014)

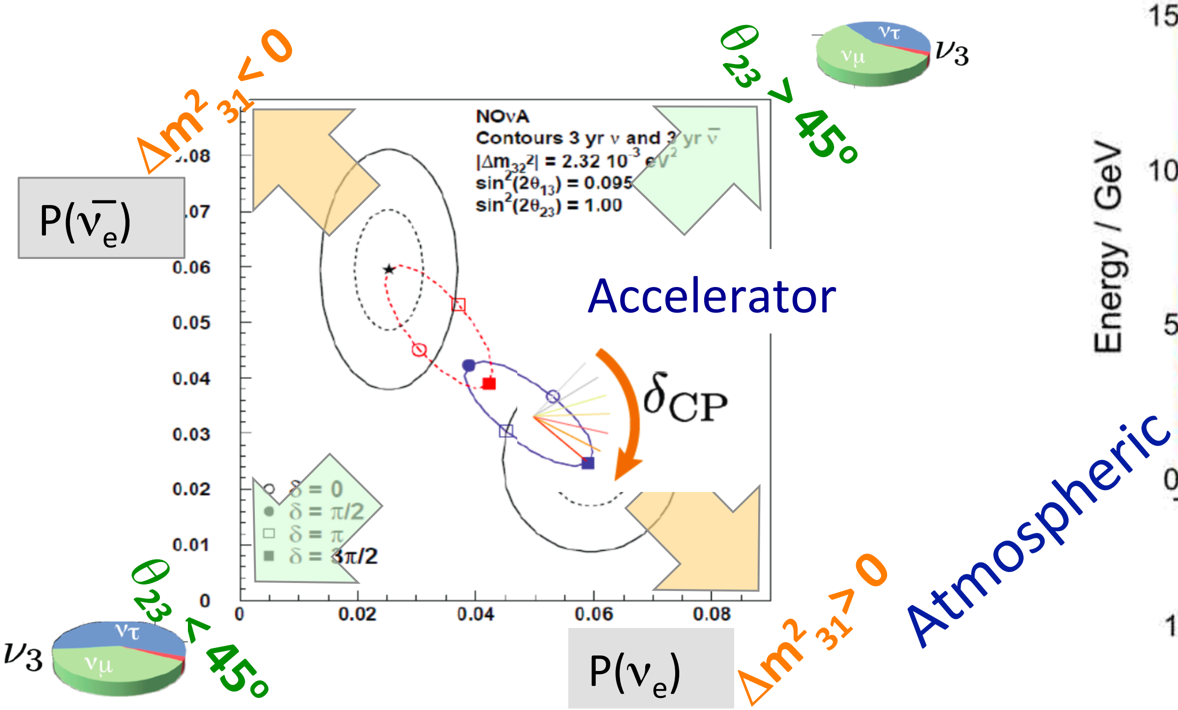
$\lambda \sim 0.22$

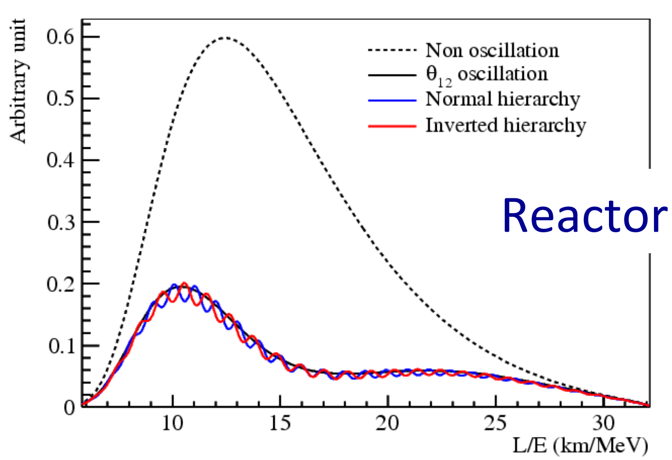
The main open ν questions

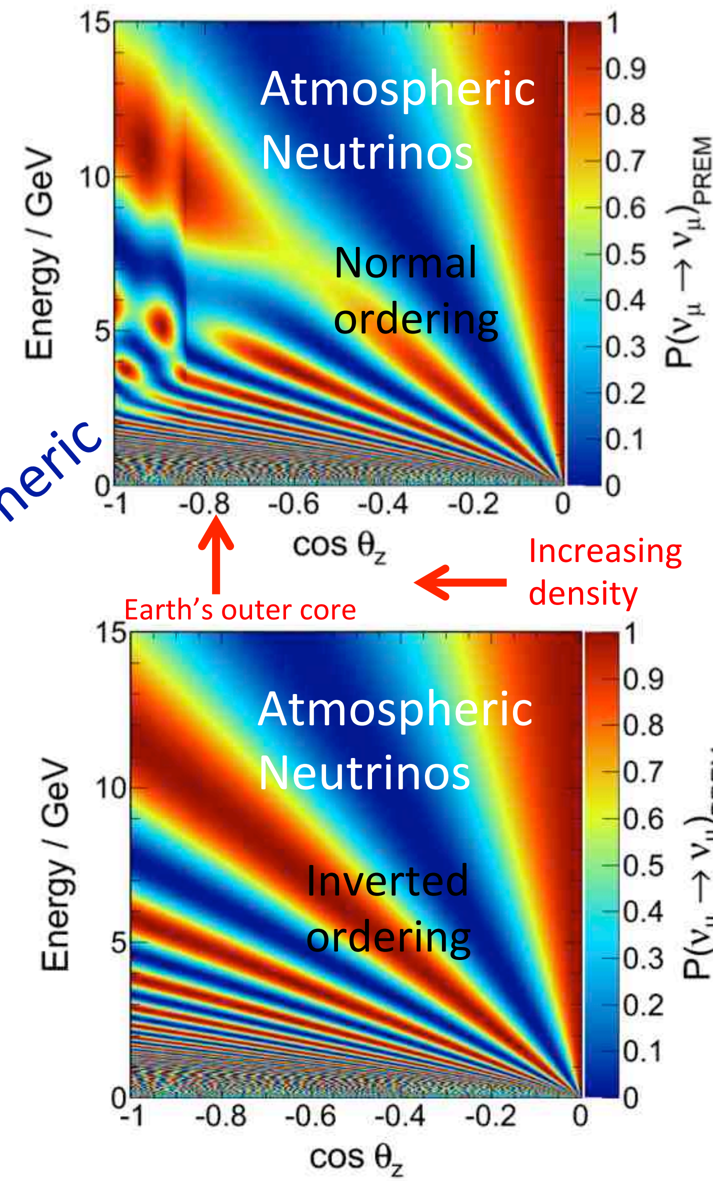
- What is the mass ordering of neutrino masses?
  - ✓ Neutrinos are fundamental constituents
  - ✓ Must know their properties
  - ✓ May affect the Majorana transition
- Do neutrinos violate CP?
  - ✓ Fundamental parameter of νSM
  - ✓ Why is there more matter than anti-matter?
  - ✓ Can we explain via CPV in the leptonic sector?
  - ✓ There may be connections to dark matter
- What is the absolute neutrino mass?
- What is the nature of neutrinos:
  - ✓ Dirac ?
  - ✓ Majorana ?
- Is θ_{23} = 45° or which octant is it in ?
  (i.e., is the mixing maximal?)



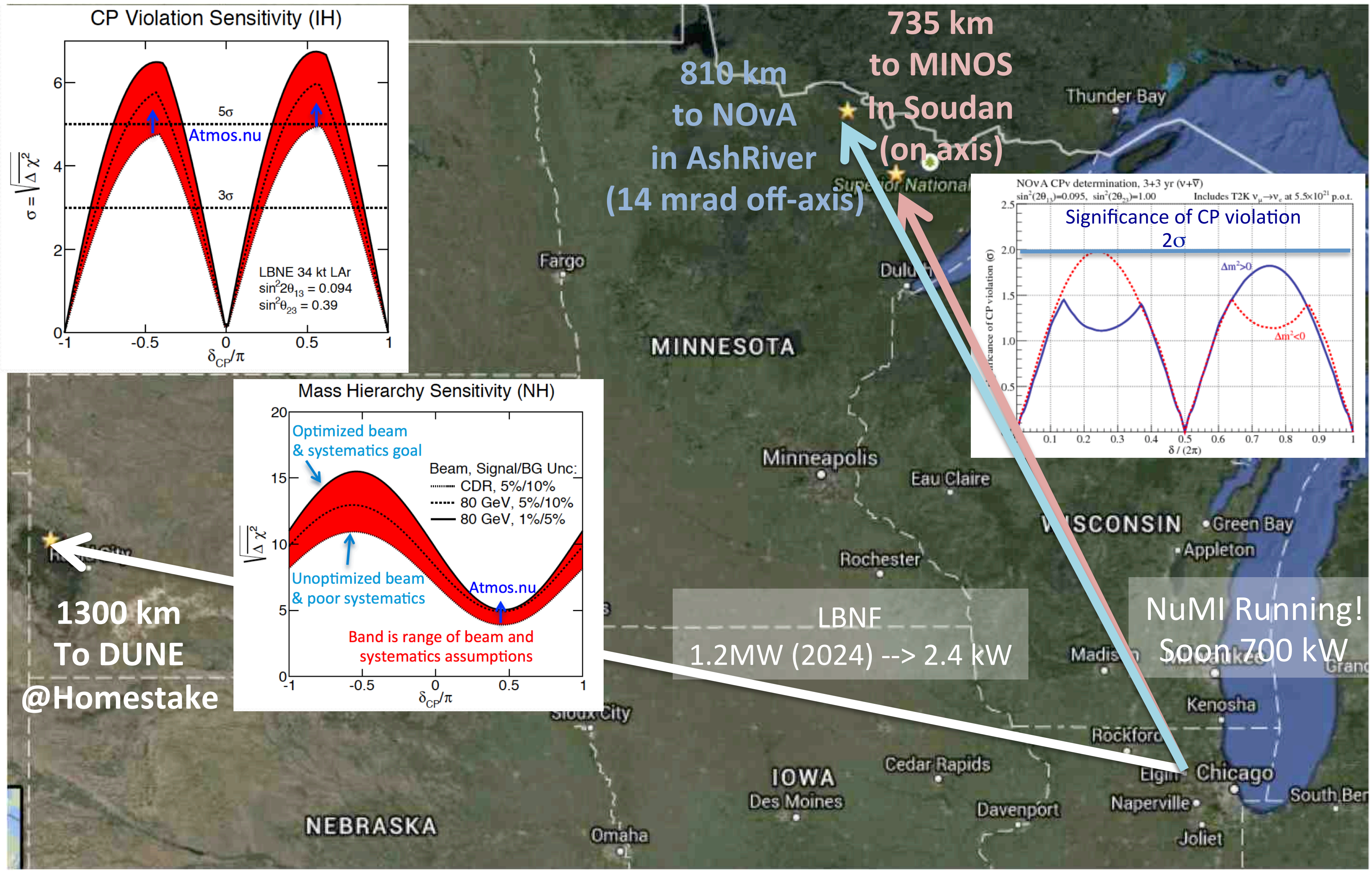
The principles of measuring MO and δ_{CP}



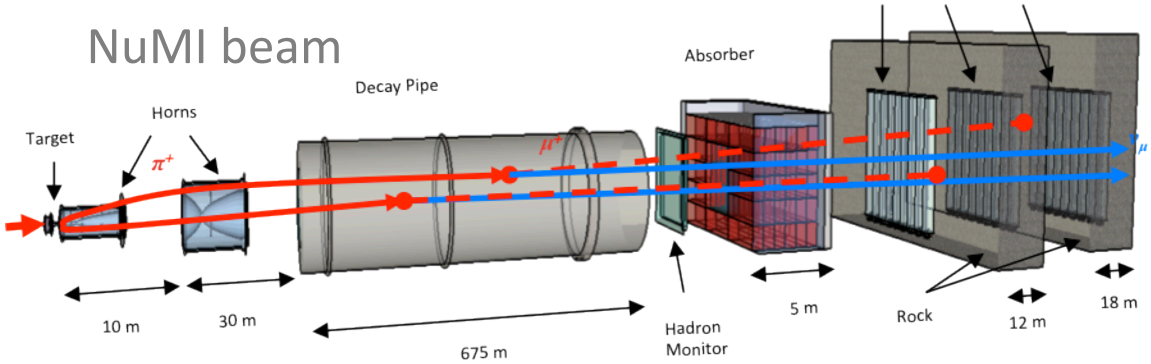


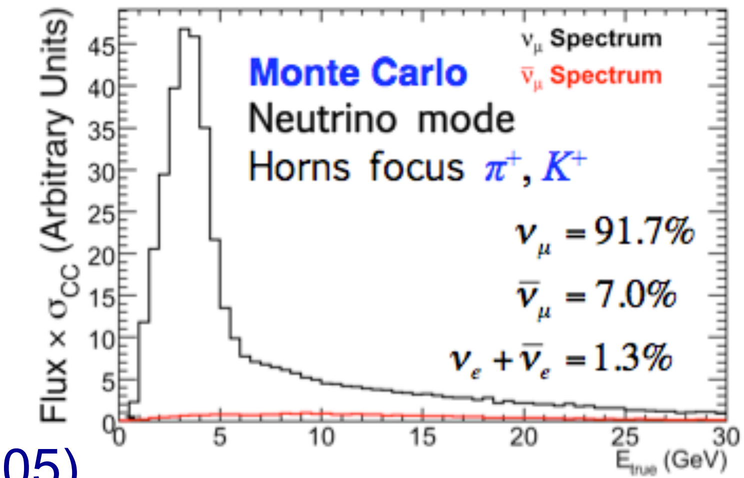


The context:
Long-term phases of long baseline neutrino program in the US

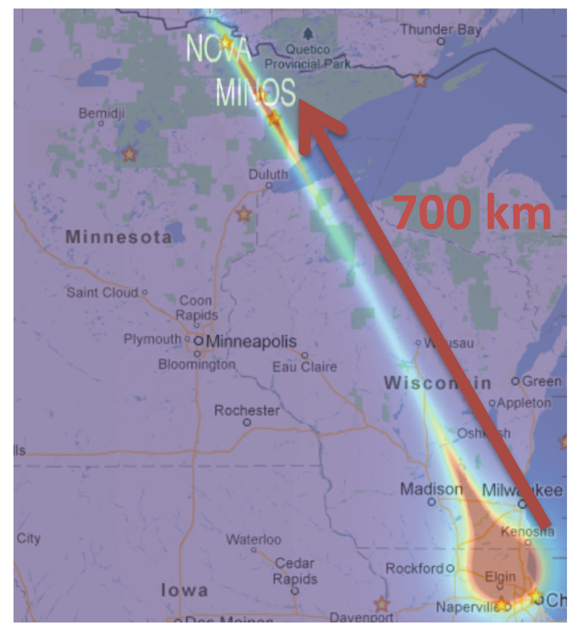


Meanwhile: NuMI





- High intensity, flexible beam (running since 2005)
  - ➪ Movable target / 2 horns (→ adjustable energy spectrum)
  - ➪ ~3.5 x 10^{13} protons/pulse (~420 kW, 120 GeV beam)
  - ➪ Recently reached 453 kW
  - ➪ Proton Improvement Plan (PIP) underway (700 kW)
  - ➪ 2.2sec. → 1.7sec. → 1.33sec. cycle time
  - ➪ Flux constrained by MINOS, MINOS+/NOvA, MINERvA, microBooNE → NuMI-X consortium



- Medium energy beam since 2013 for the off-axis NOvA

Protons-on-target (POT) history of NuMI

May 1
2005

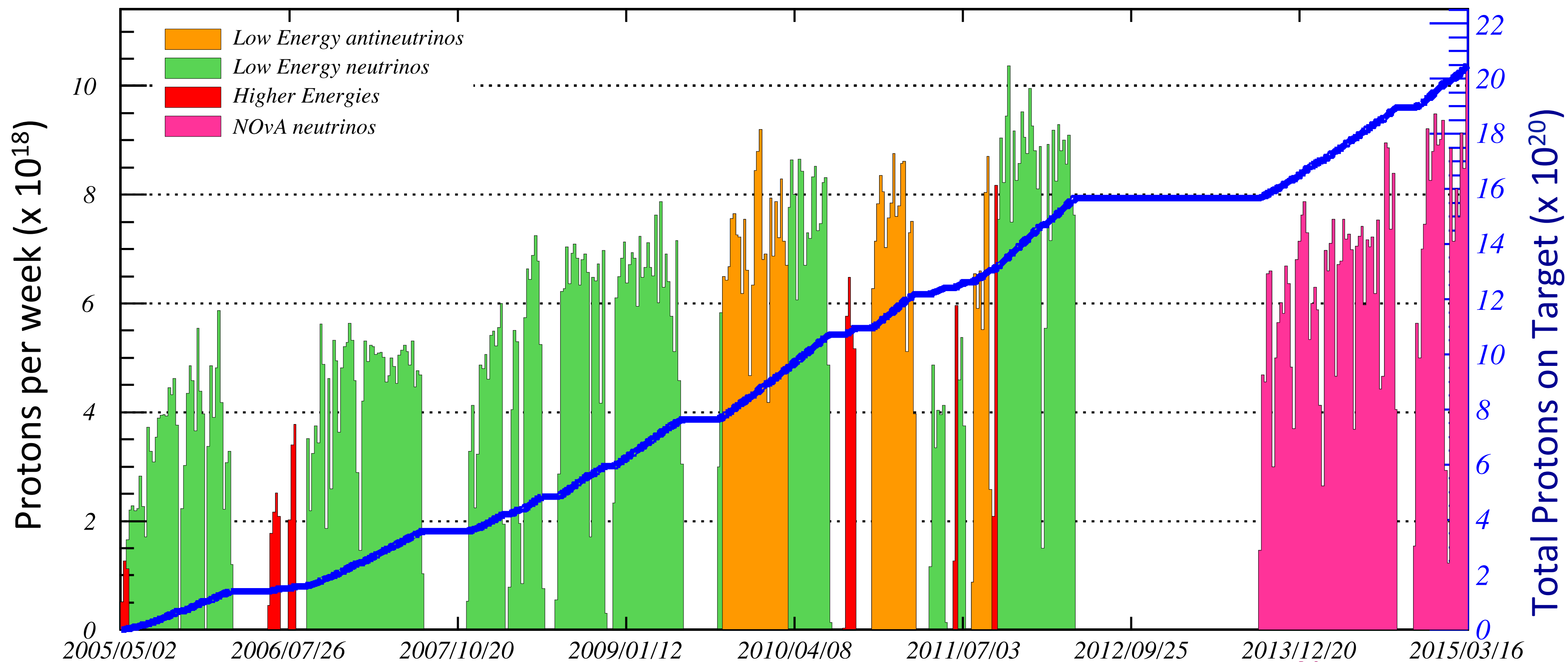
15.6×10^20 POT

April 30
2012

~4.5 ×10^20 POT

NOvA era
MINOS+

Atmospheric 48.67 kt year (since 2003)



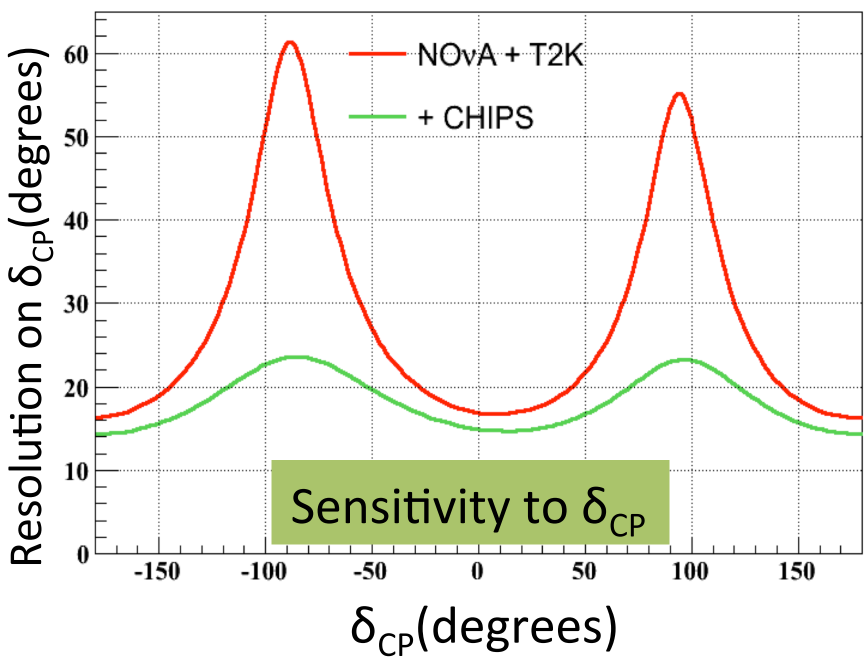
7 years, 7 targets, 2 horns

New target
Horn 1

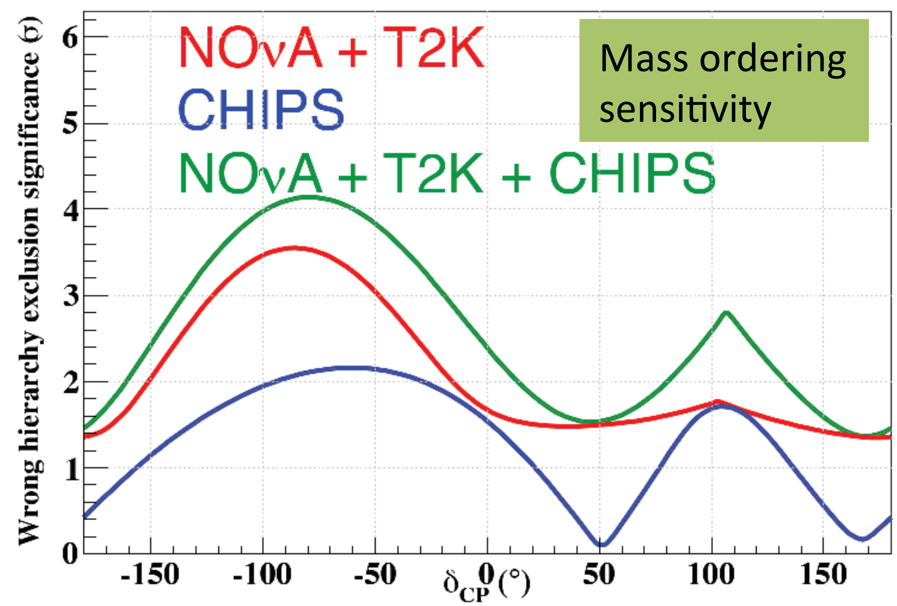
Idea: Extend the reach of NuMI and exploit/fill the time gap

- NuMI will be the most powerful neutrino beam (700kW) for years (Could be upgraded to 1.2MW)
- Adding a large detector extends the δ_{CP} reach of NOvA and T2K

GLoBES calclulations assume MH is known



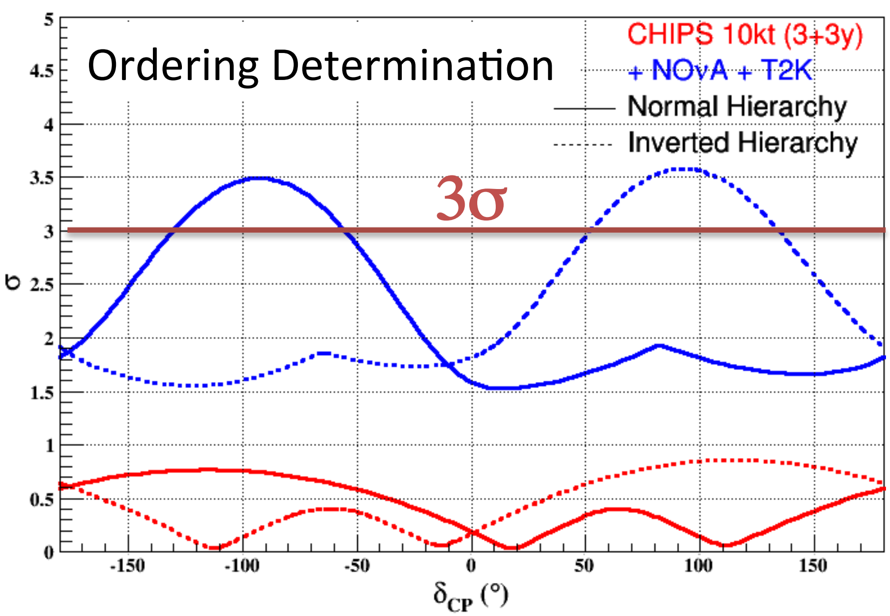
100 kt CHIPS: 3+3 years
Neutrino + antineutrino

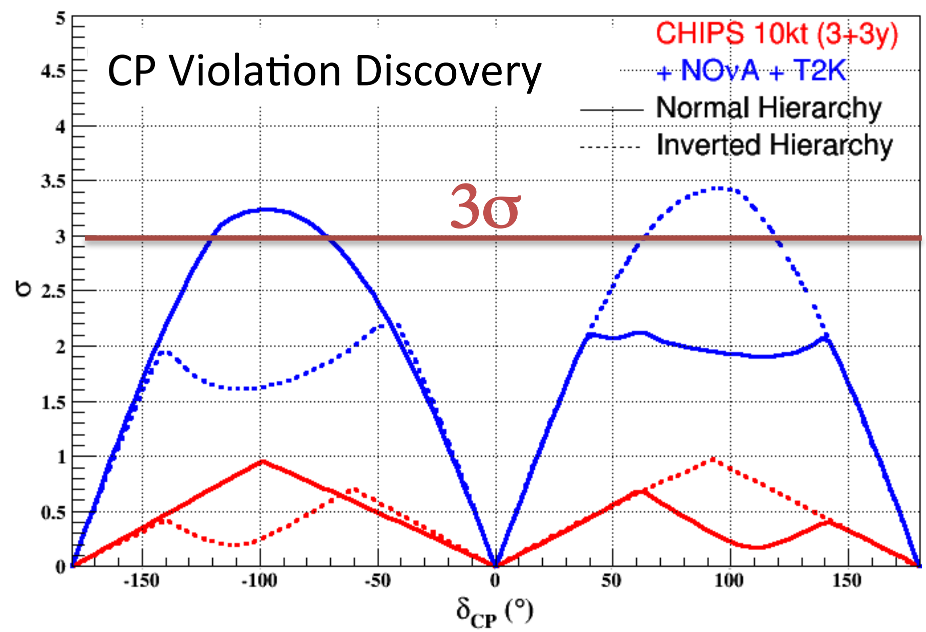


Looking into the future: NOvA & T2K & CHIPS-10

- 10 kt CHIPS: 2024
- 10kt CHIPS + NOVA + T2K can push both mass ordering and CPV discovery past 3-sigma

Need large detectors!

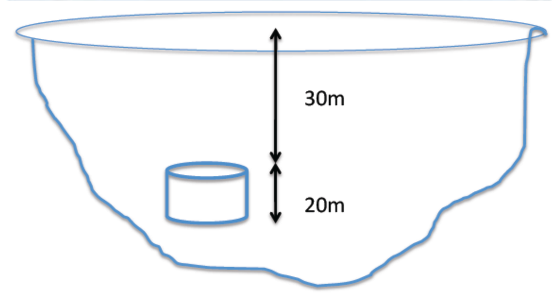


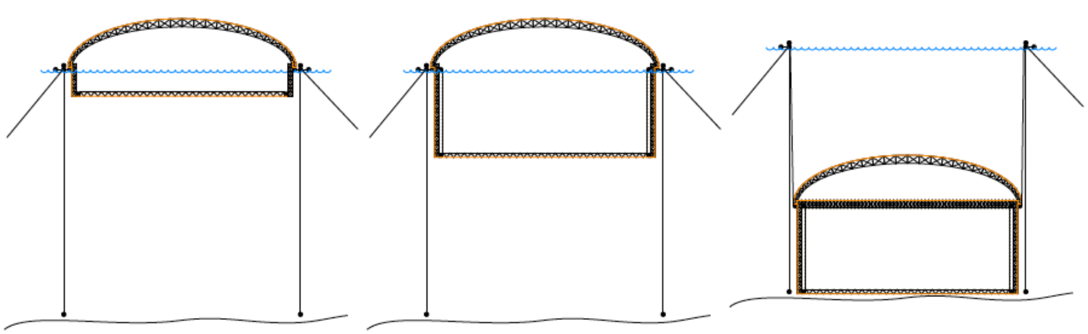


CHIPS (Water CHerenkov In Mine PitS) concept

- Explore (R&D) a new technique for a water Cherenkov detector under shallow water overburden
  - ✓ Large mass detector with a cost-saving construction
  - ✓ No conventional civil construction/excavation
  - ✓ Concept (advanced in earlier studies for LBNE)
  - ✓ Use applicable ideas (fisheries floating platforms, light structures, …), IceCube PMT (DOM) deployment
  - ✓ Benefits from earlier studies for
    - GRANDE, MEMPHYS, PMM2, KM3NeT,….
  - ✓ Optimize for a 10 μs long beam window and direction
  - ✓ Goal: ~$200k/kt (presently about $1M/kt)
- Challenge the "Super-K paradigm"

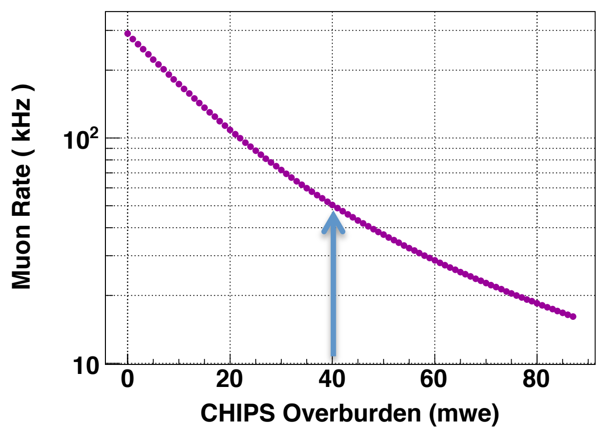
Aqualine FrøyaRing Sinker Tube

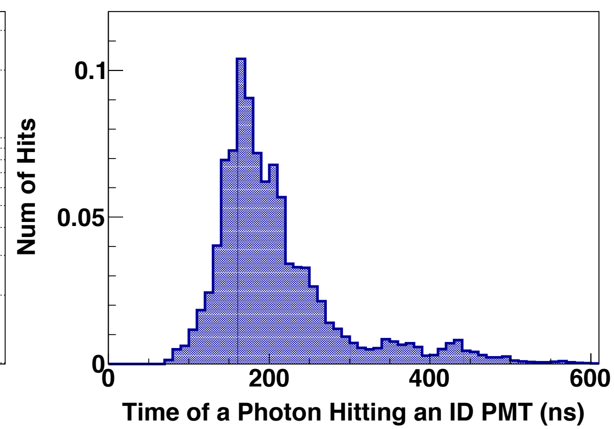


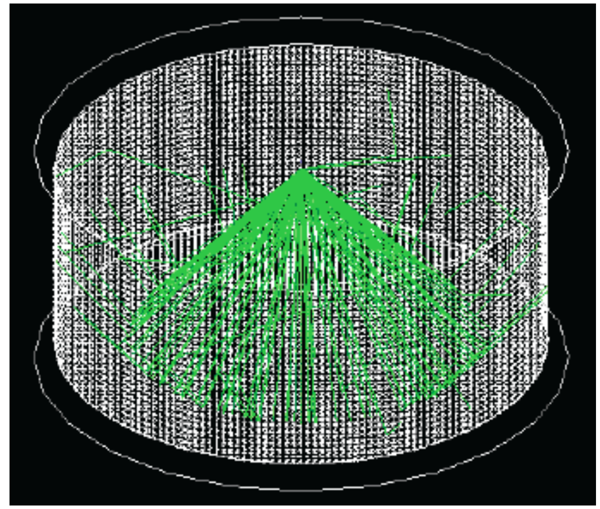


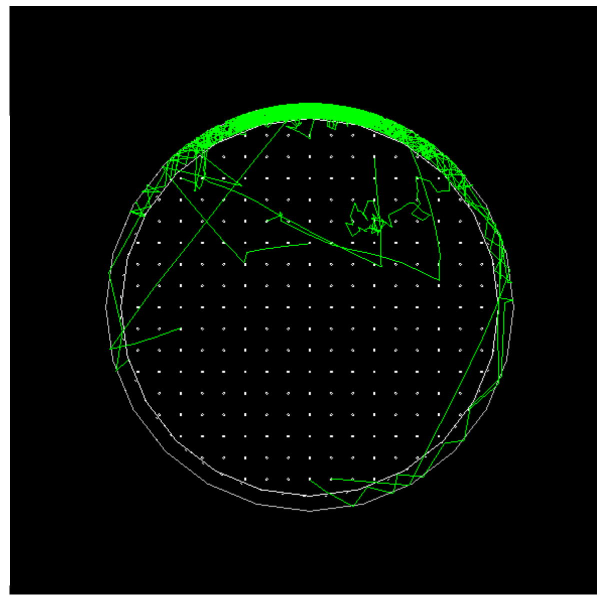
Cosmic rays background with shallow overburdens

- GEANT4/CRY simulation of cosmic muons
- Muon rate expected to be 30-50kHz
  (for large volumes, depending on details)
- Inside detector events last up to 500ns
- Expected (conservative) dead time 2.5% during a beam spill of 10μs
- High efficiency veto tag (outer detector)



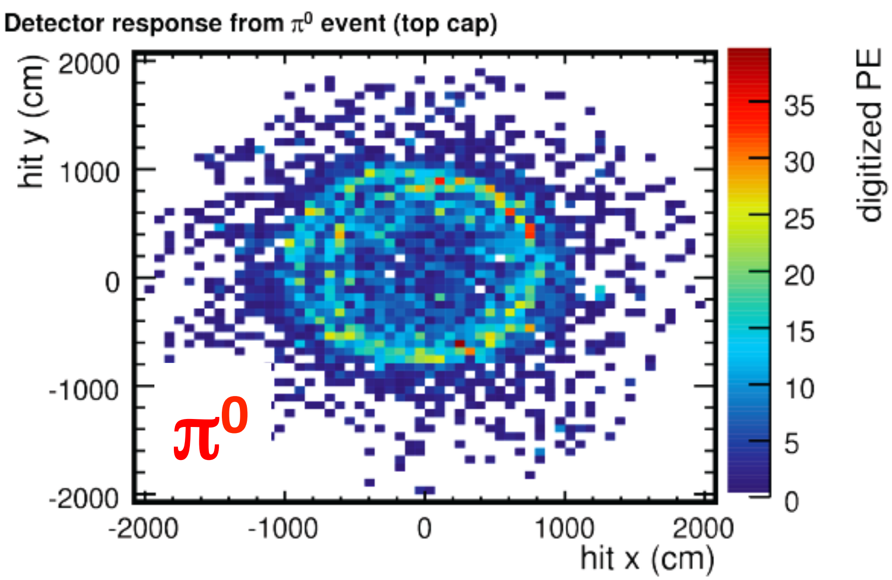


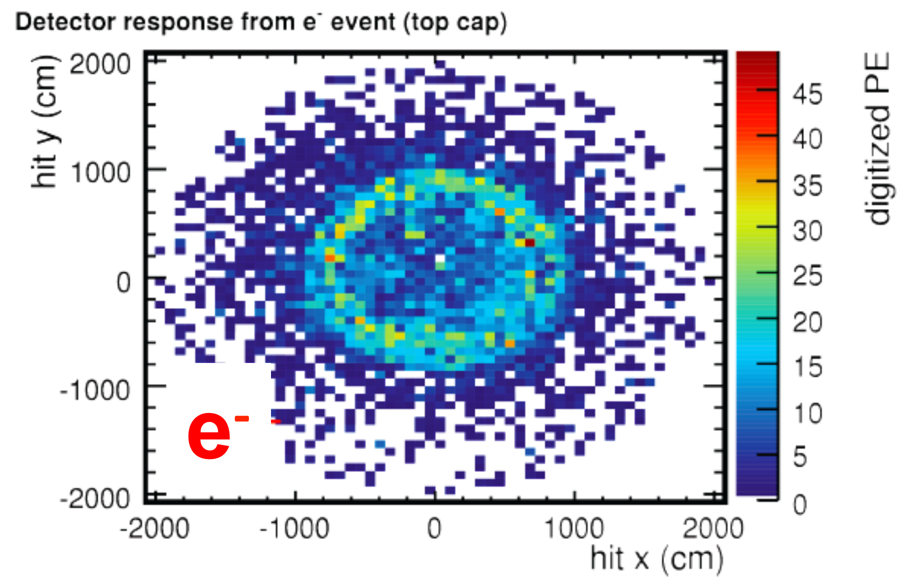




The challenge: π^0 versus ν_eCC

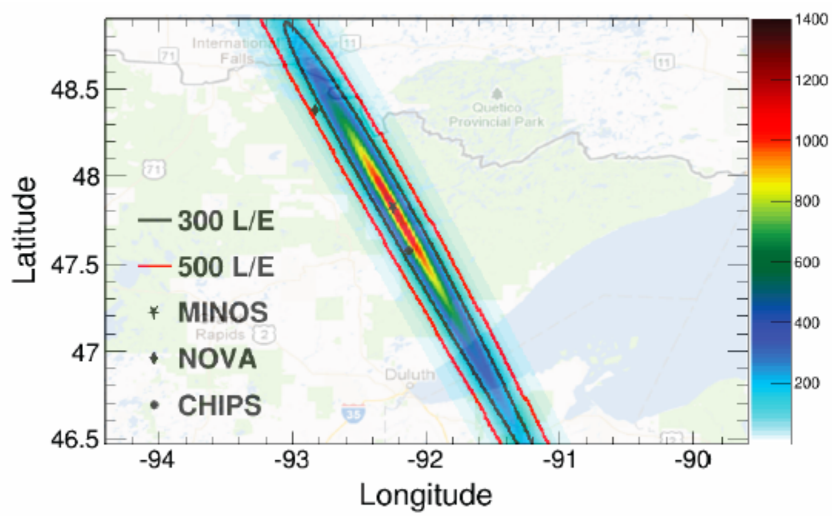
- The goal: find and reconstruct ν_e produced from the ν_μ beam
- The main background to ν_eCC appearance is π^0--> $\gamma\gamma$ in NC
- Reject NC background: discriminate between e^- and $\gamma\gamma$
- Then compare ν_e in ν_μ beam with $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam

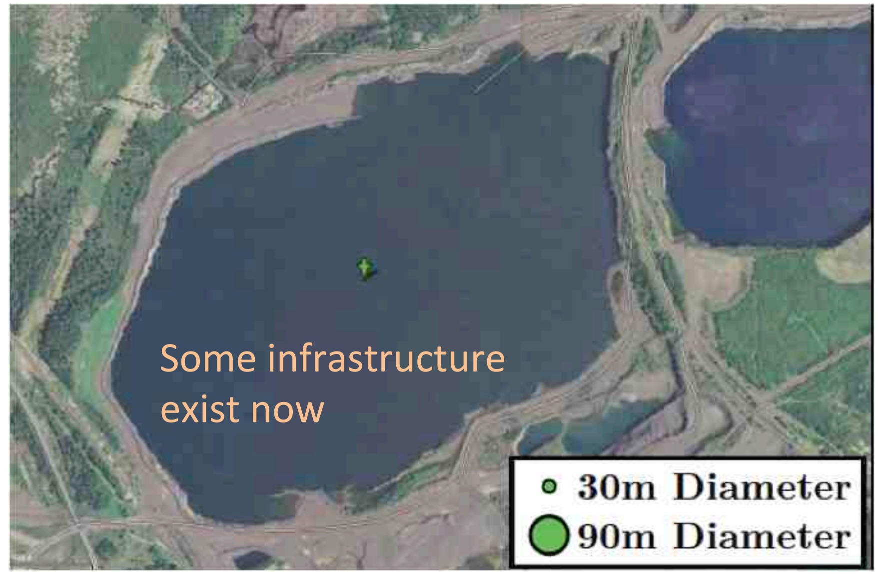




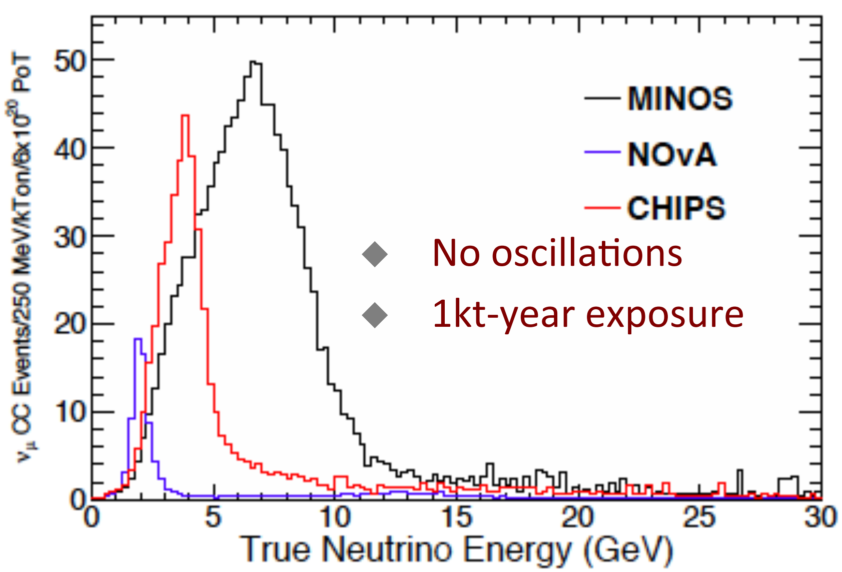
A suitable location: Wentworth Mine Pit 2W

site of Cliffs Natural Resources





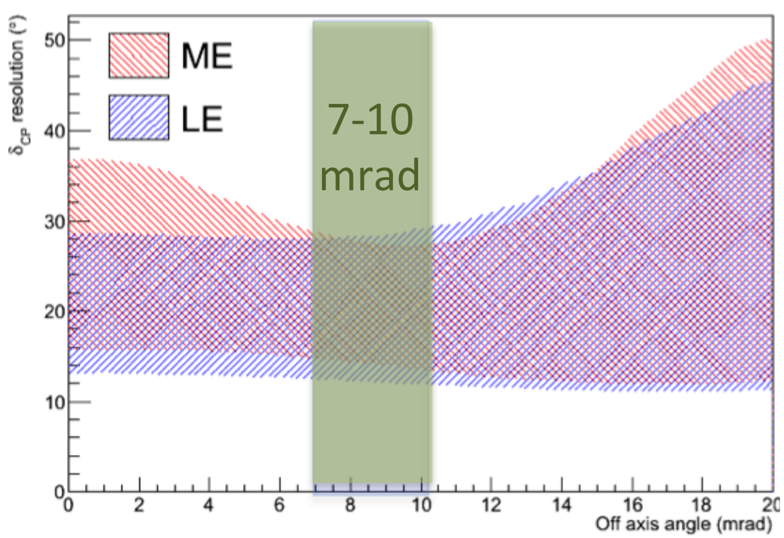
Some infrastructure exist now

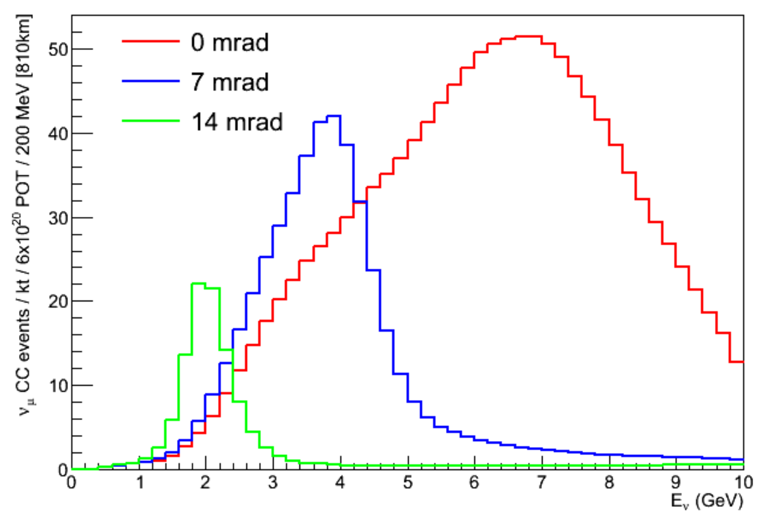


- No oscillations
- 1kt-year exposure

Wentworth pit: 7 mrad off NuMI axis

- GLoBES calculations
  - ✓ Figure of Merit: resolution on δ_{CP}
  - ✓ 20% photocathode coverage of standard QE 10” PMTs, equivalent to 12% coverage of HQE 12”
- Assume Super-K old-style efficiencies
  - ✓ New algorithms a la MiniBooNE better for efficiency and background rejection are now available
- Off-axis between 7-10mrad gives best reach in δ_{cp}
  - ✓ More on-axis increases background, more off-axis reduces rate
- Ability to run in both ME and LE beam





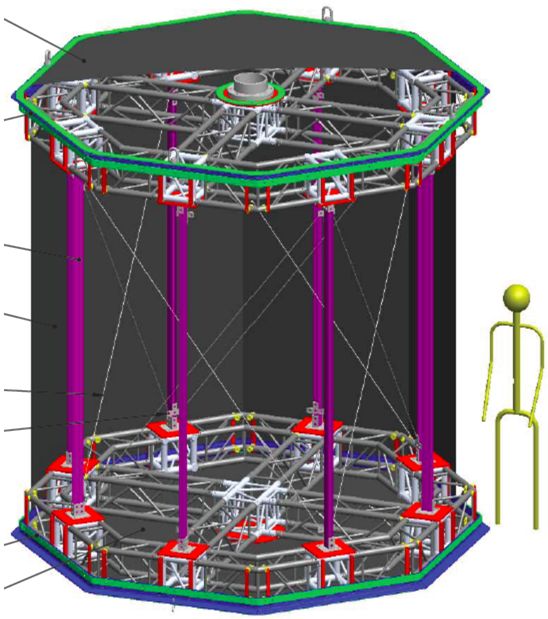
PMTs & underwater front-end readout & logic

- PMTs and front-end electronics are the major cost drivers
- Cost & time savings: learn, borrow, adopt, and adapt from recent/past R&D
- Discussions & visits with LBNE, KM3NeT, IceCube, MEMPHYS, PMm2 teams
- Small(er) PMTs offer an attractive segmentation (topology) option
  - simulations and reconstruction work in progress

IceCube DOM

KM3NeT OM

To get our feet wet: CHIPS-M



Spring 2014

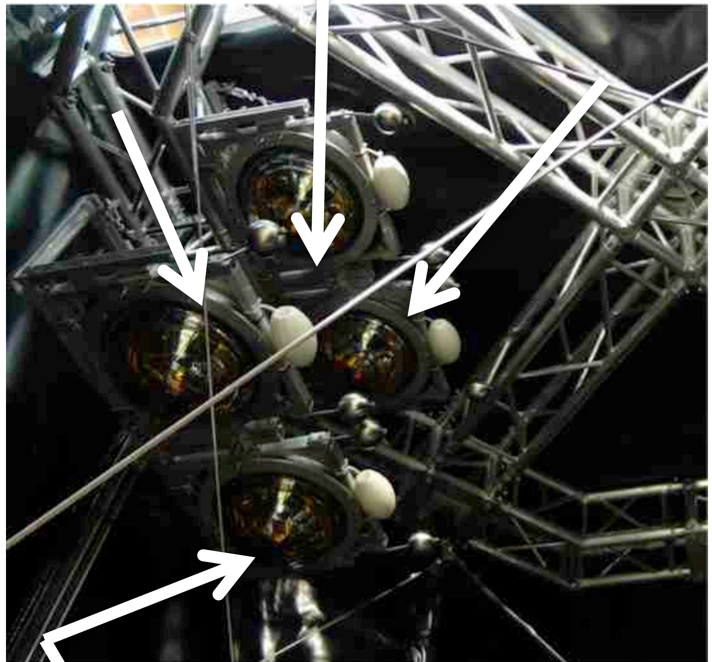
June-July 2014

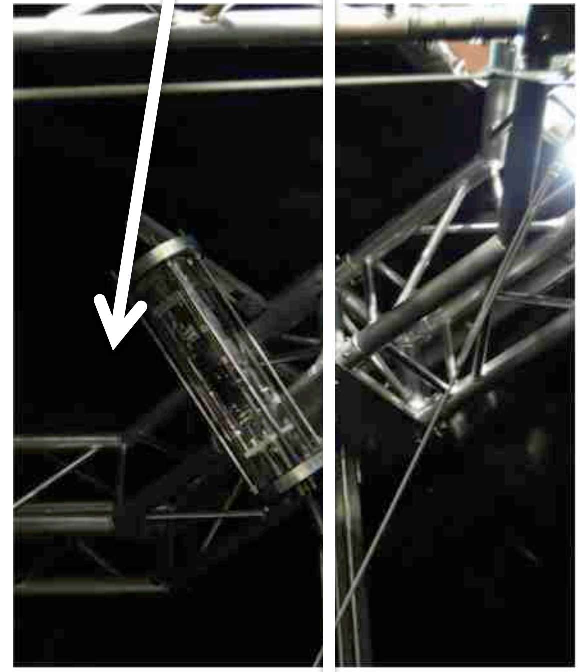
August 8, 2014

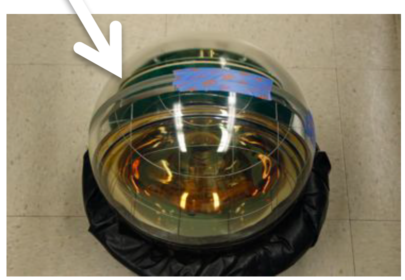
Construction accomplished mostly by students and postdocs!

CHIPS-M elements

IceCube DOMs (on loan) + "environmental tubes"
with a camera (inside and outside)





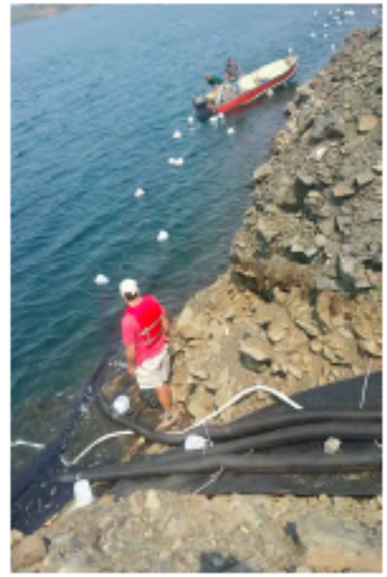


Liner

Deployment Day

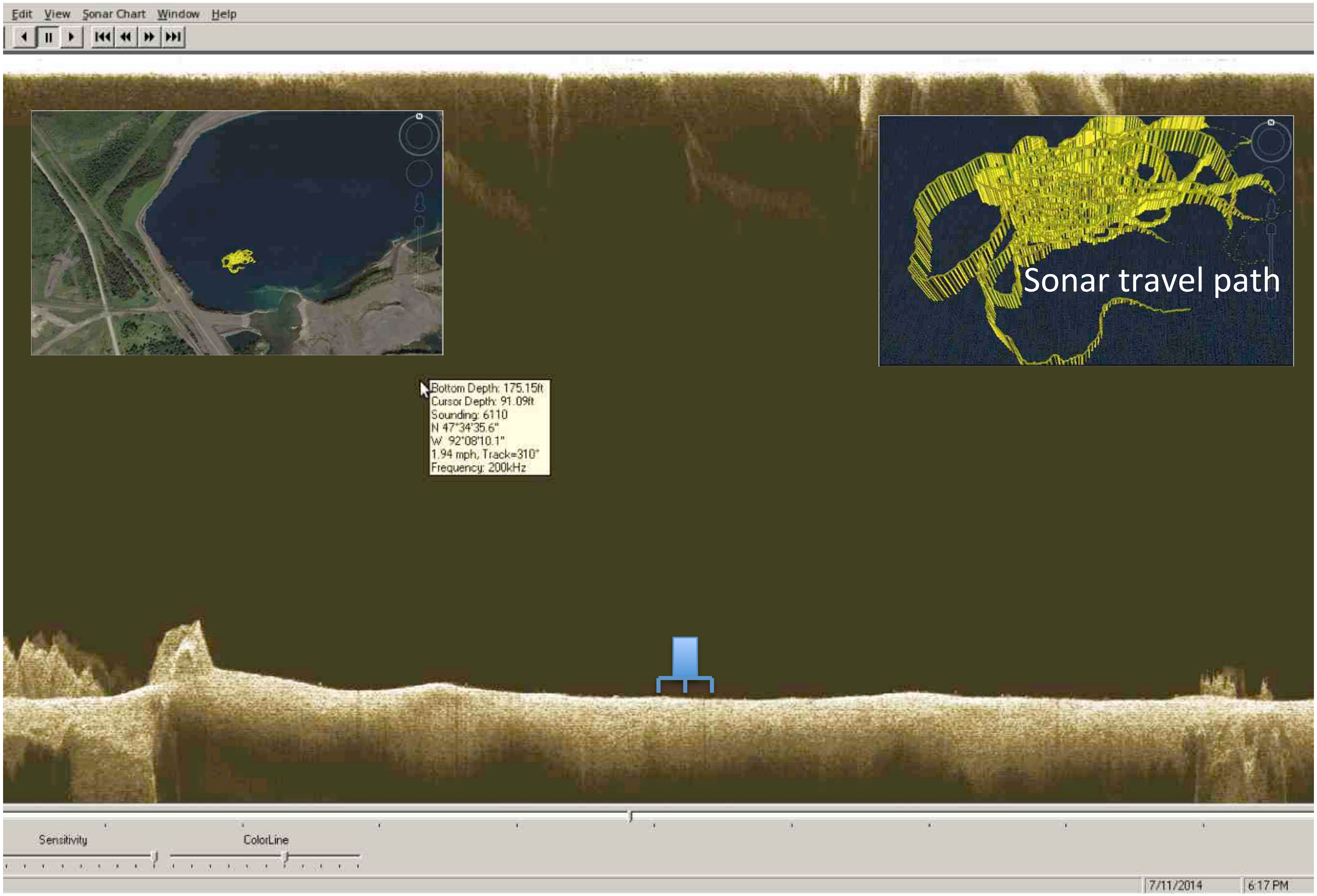
August 8, 2014

Umbilical: carries water and signals


Tugging CHIPS-M

Sonar at the Wentworth mine pit



Now (winter) at the pit

Water filtration

- CHIPS – under ~6 bar pressure
  - ✓ Bubbles (produce scattering centers increasing light attenuation) are squeezed
  - ✓ Scattering attenuation length difficult to measure in the lab as the bubbles expand
    - Super-K biggest problem is bubbles, not a problem deep-see detectors
- Water filtering
  - ✓ Need to remove particulates in the
  - ✓ Need a carbon filter to eliminate life + a UV sterilizer to make sure
  - ✓ Need reverse osmosis and de-ionizing filter
- CHIPS-M with in-situ LED's
  - ✓ Presently LEDs on the IceCube DOM's can be flashed
- Attenuation length important for simulations / benchmarking

Shortly after submerging… (overnight changes)

Water changed the color

Camera view from the bottom up

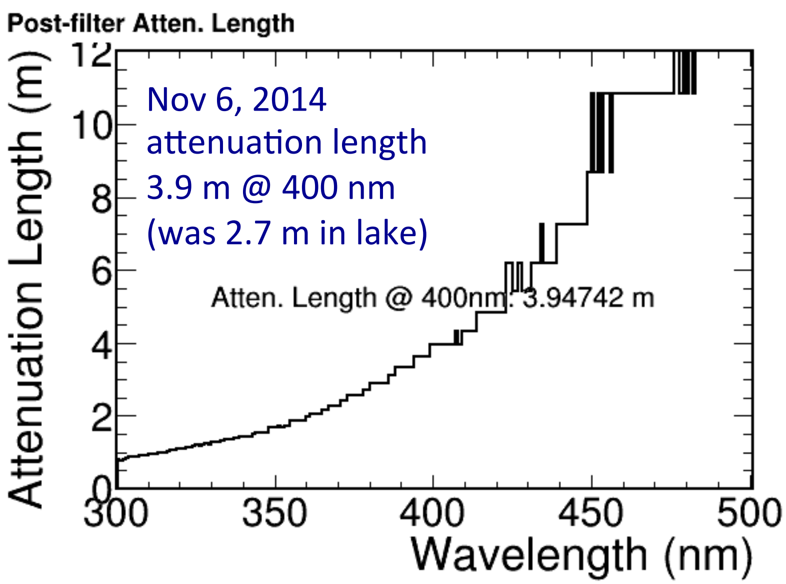
Unfriendly water…

- Investigating the reasons for (too) slow improvement despite continuous filtration

  (A light leak implies water leak)

- This is (obviously) one of critical parameters --> increasing the R&D effort

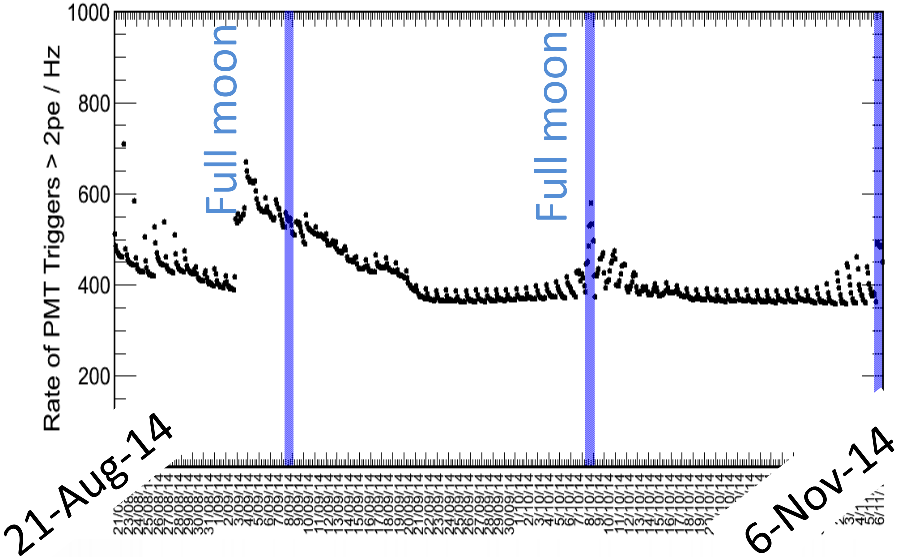
- Need to improve reversed osmosis and deionization stages



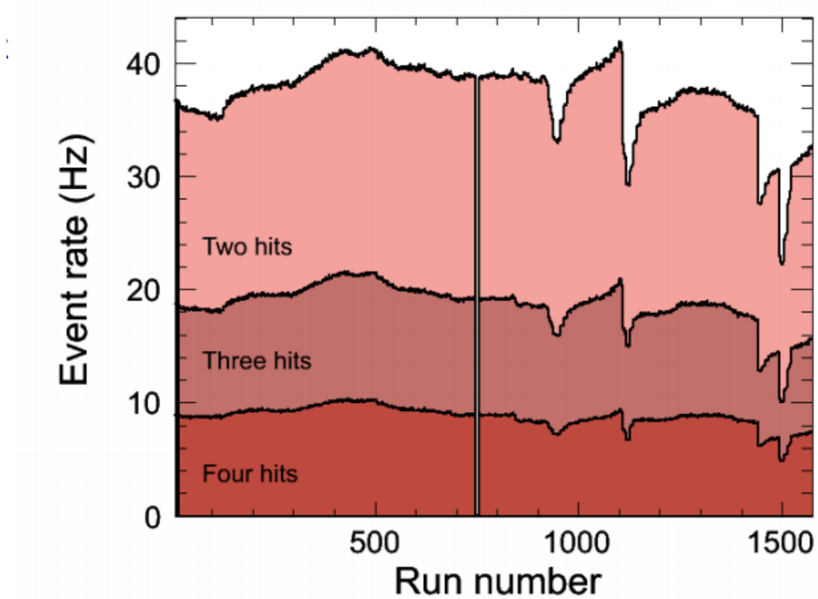
- Filters getting very dirty
  - ✓ Zinc sulfide
- Yet to be fully understood …

Some data analysis

- Trigger rate
  - ✓ Light leak apparent
  - ✓ Jumps coincide with full moon
  - ✓ Run overnight only



- Events rate
  - ✓ 4 PMTs hit in coincidence
  - ✓ Slow rise could be effect of water
  - ✓ Sudden reduction in event rate is correlated with pump stop/start



CHIPS-M and beyond

CHIPS-M

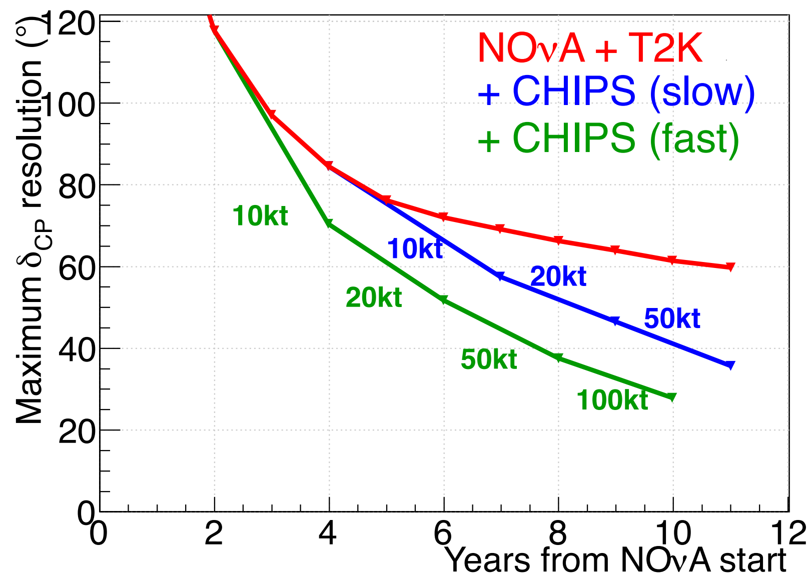
- Bring up and inspect
- Understand what went right and wrong

CHIPS-M+

- Fix/improve environmental monitoring units
- Test underwater photodetector assembly modules
  - ✓ KM3NeT FE board (31 x 3" PMT's)
  - ✓ PARISROC FE board (16 x 12" PMT's)
- Test structural ideas

CHIPS-10

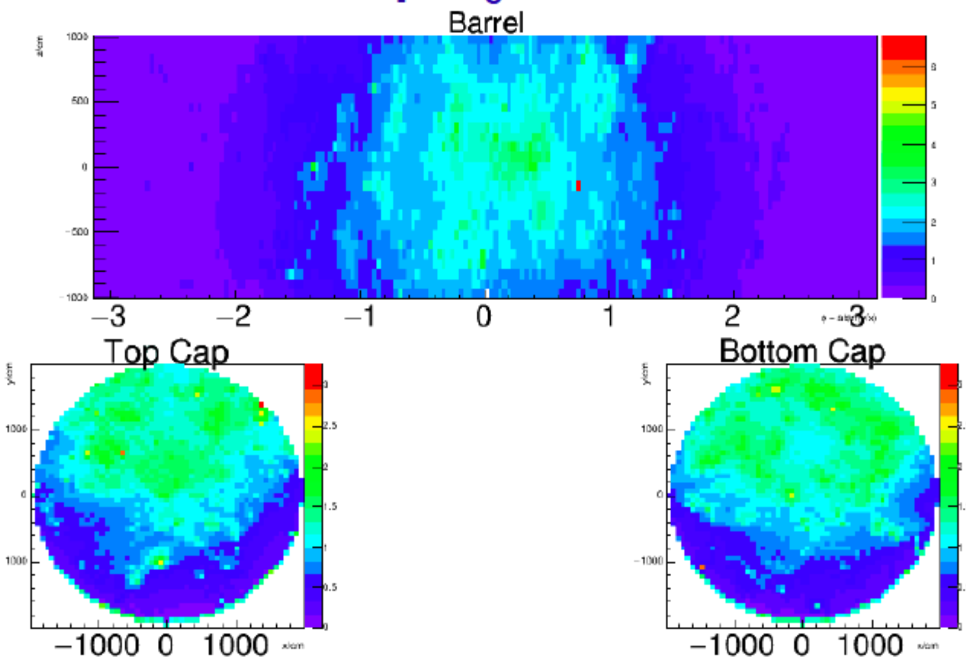
- Main prongs of effort
  - ✓ Simulations and reconstruction
  - ✓ Mechanical design and installation
  - ✓ Water filtration
  - ✓ Underwater front-end electronics and daq
  - ✓ Environmental monitoring
- Possible time line



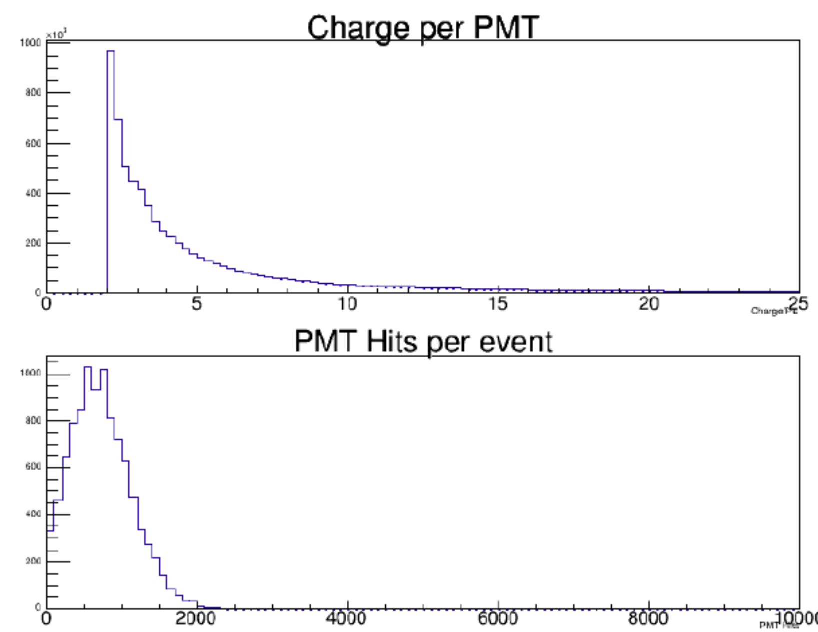
Simulations / reconstruction

- Simulations
  - ✓ WCSIM package (based on GEANT4) - relatively easy, although needs photodetector details (unknown at this point)
  - ✓ Non-homogeneous PMT distribution, including different size PMT's
  - ✓ Guide geometry optimization for a directional neutrino beam
- Reconstruction - much more challenging

Hit Map ν_eCC Events



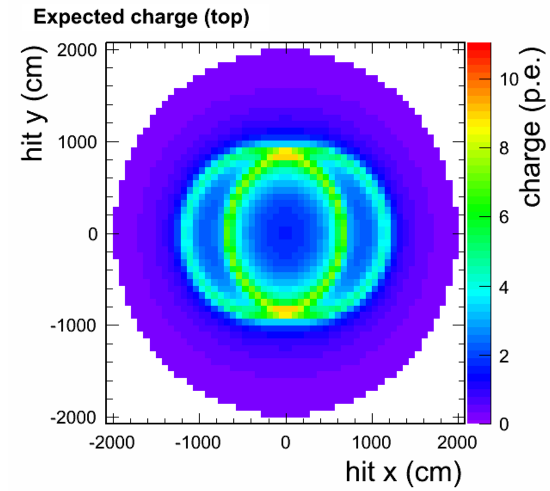
PMT Charge Distribution for Electrons, λ=40m



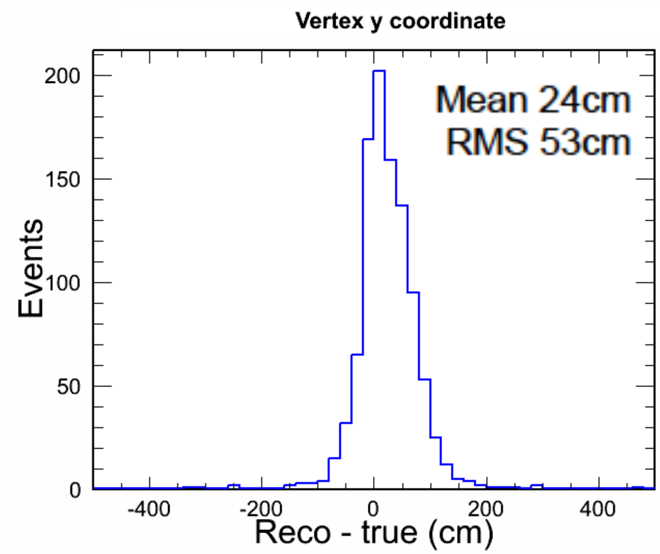
Reconstruction

- State of the SK/T2K art: APFit --> fitQun
  - ✓ fitQun significantly improves low energy reco
  - ✓ Based on the miniBooNE algorithm
  - ✓ Includes charge and time likelihood
  - ✓ Improves efficiency for π^0 and resolutions
  - ✓ MC calculates the likelihood for a given combination of track hypothesis and hit pattern
- CHIPS reco – builds upon fitQun ideas
  - ✓ Non-uniform PMT size and their distribution
  - ✓ Flexibility in geometry
  - ✓ A lot of new code
- Preliminary fitter is working

… Will soon start helping guide our choices



Charge expectation for two simultaneous electron tracks

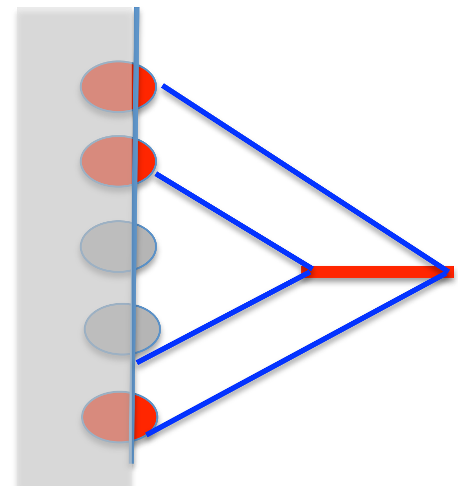


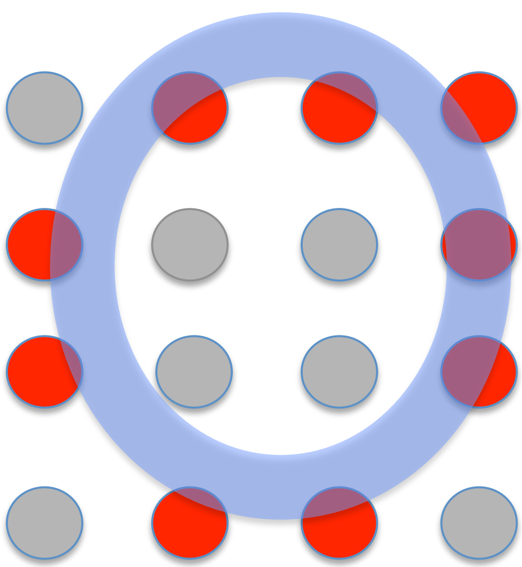
Electron vertex

Ideas

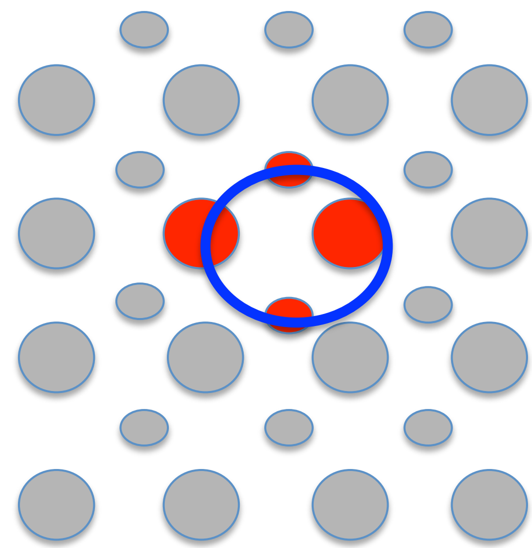
- We optimize for the beam direction
- Including smaller PMT's ?
  - ✓ Has additional topological info
  - ✓ Increase the effective fiducial volume
  - ✓ New reconstruction code can cope with it

Side view of the wall with PMT's





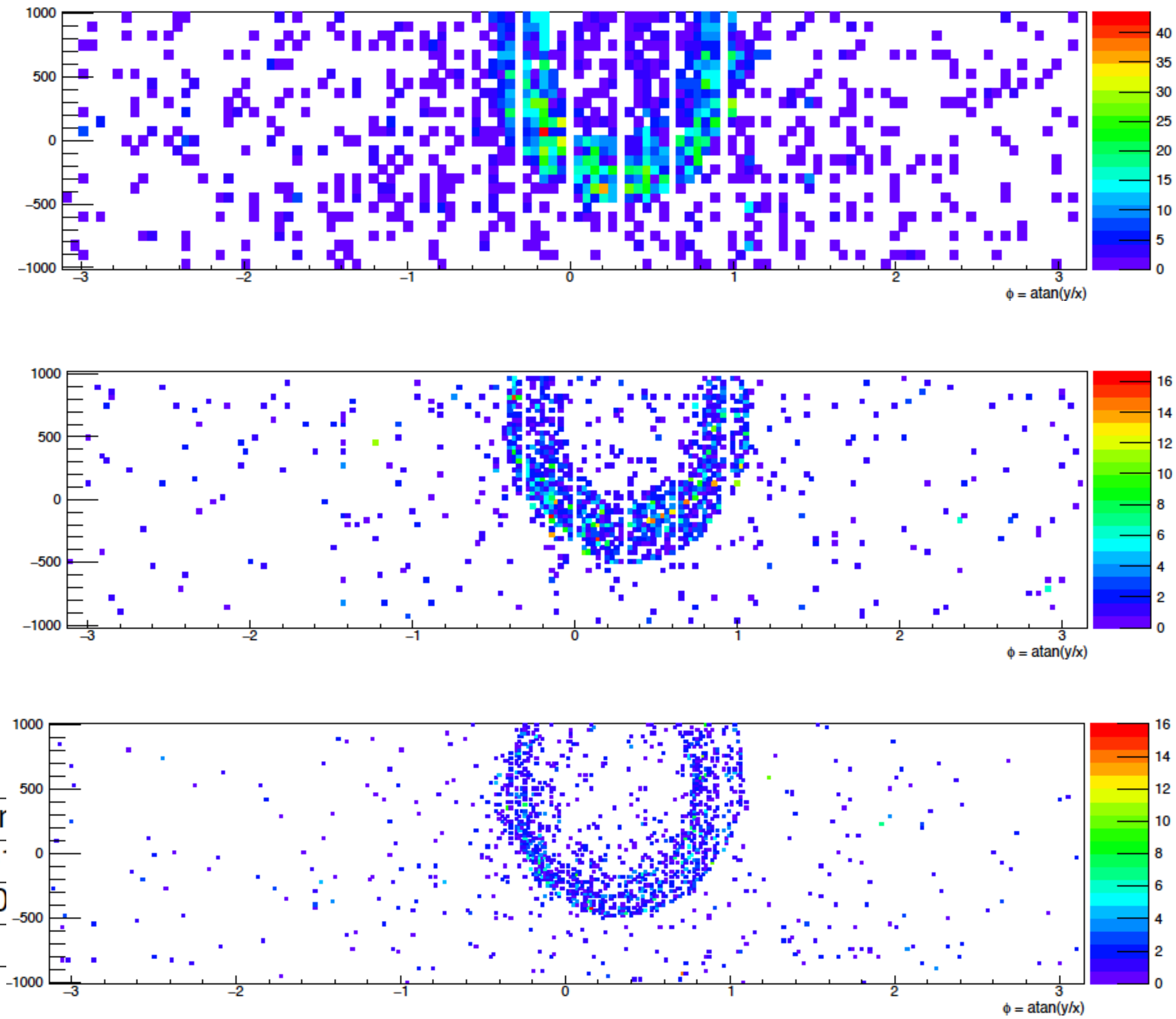
En-face view of the wall
homogenous PMT's
and
non-homogenous PMT's



10”, 5”, and 3” PMT diameter – ν_μ event (crisp ring)

E_ν=5.7 GeV

- The same event in three PMT sizes (all at 10% surface coverage)
- Clear topological difference
- PMT numerology for FULL coverage of the surface (overkill, likely will need ½)



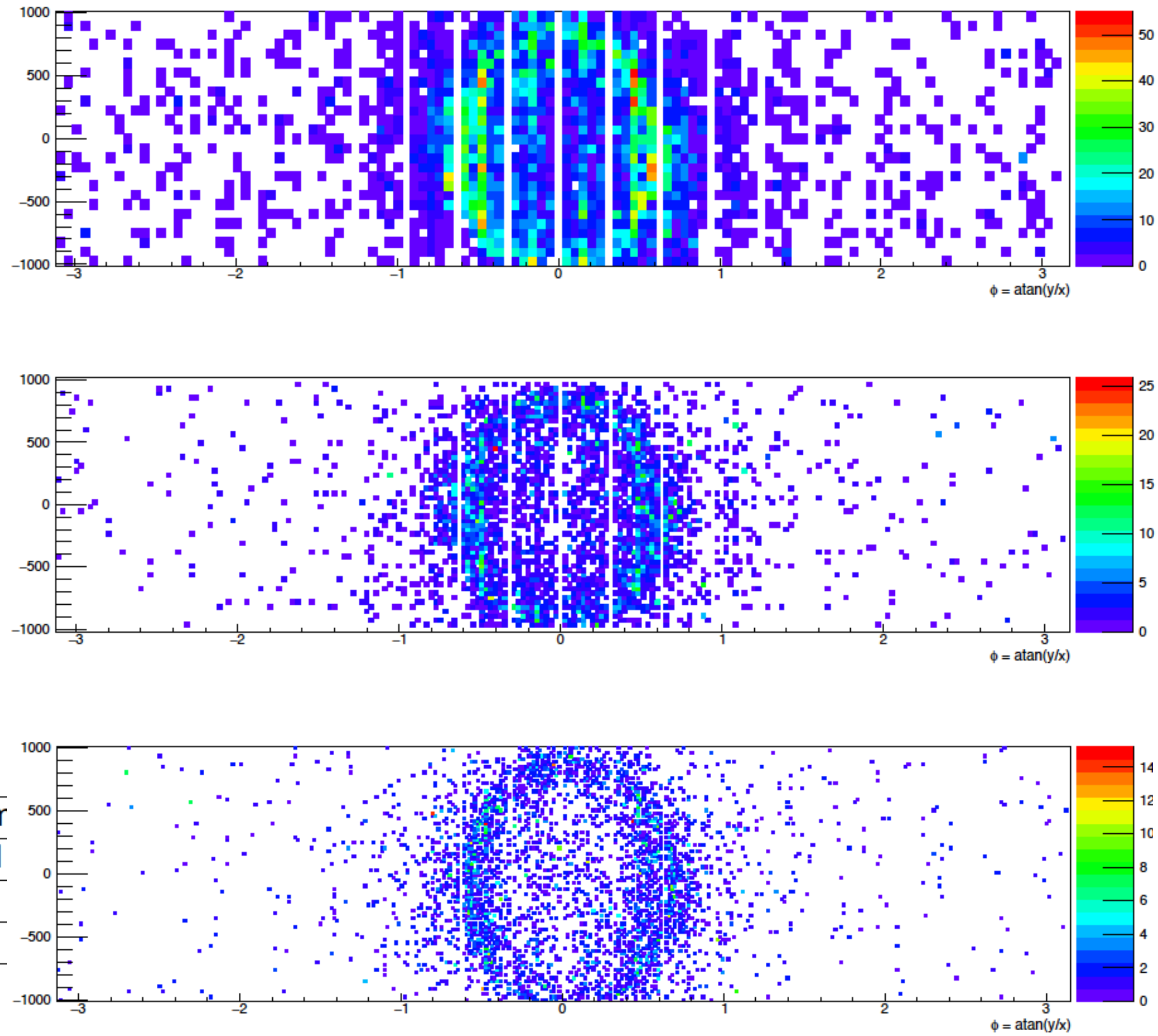
Size	Total PMTs	Barrell	Top	Bottor
3”	54742	33840	10451	1045
5”	19680	12320	3680	3680
10”	5026	3240	893	893

10”, 5”, and 3” PMT diameter – ν_e event (fuzzy ring)

E_ν=3.6 GeV

- The same event in three PMT sizes (all at 10% surface coverage)
- Clear topological difference
- PMT numerology for FULL coverage of the surface (overkill, likely will need ½)

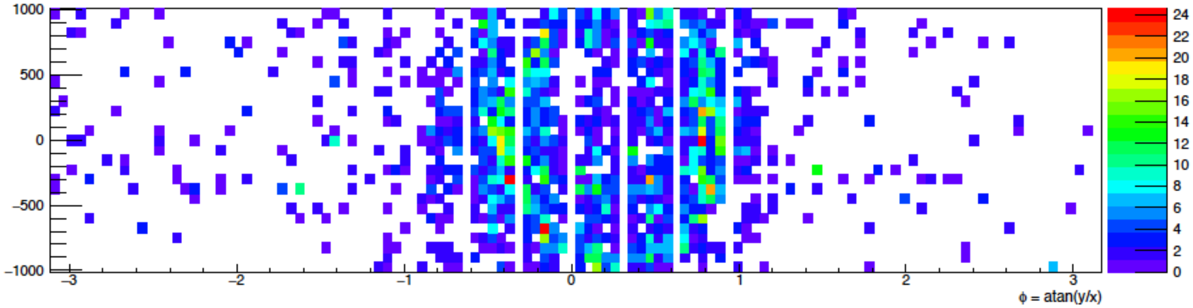
Size	Total PMTs	Barrell	Top	Bottom
3”	54742	33840	10451	10451
5”	19680	12320	3680	3680
10”	5026	3240	893	893



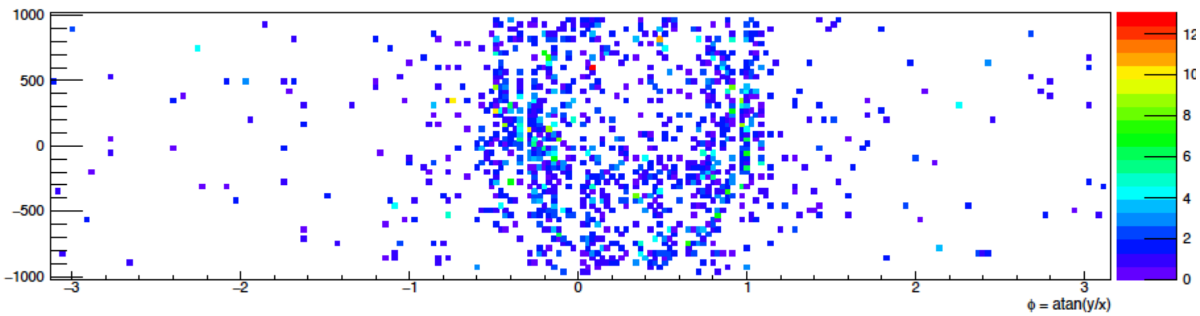
10", 5", and 3" PMT diameter – NC w/ π^0 event (2 rings)

E_ν=3.1 GeV

- The same event in three PMT sizes (all at 10% surface coverage)

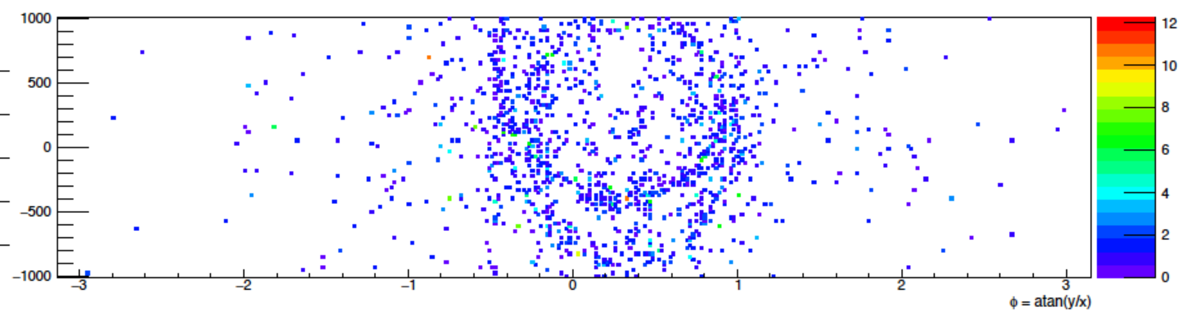


- Clear topological difference



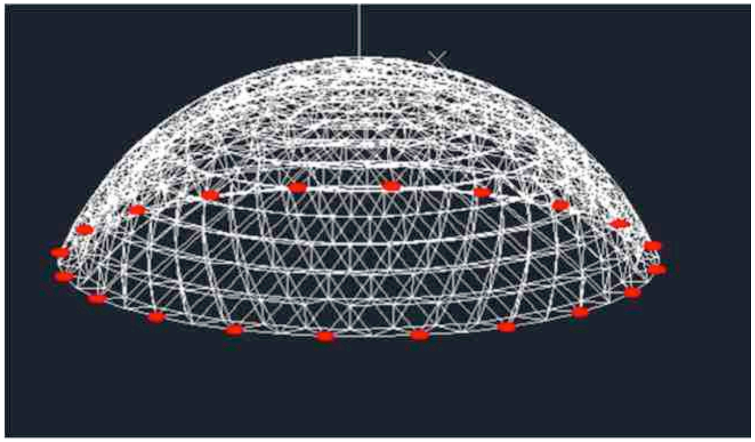
- PMT numerology for FULL coverage of the surface (overkill, likely will need ½)

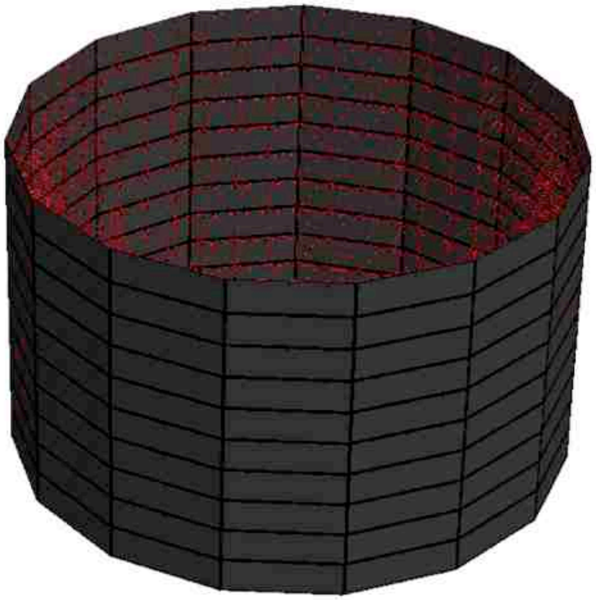
Size	Total PMTs	Barrell	Top	Bottom
3"	54742	33840	10451	10451
5"	19680	12320	3680	3680
10"	5026	3240	893	893



Mechanics

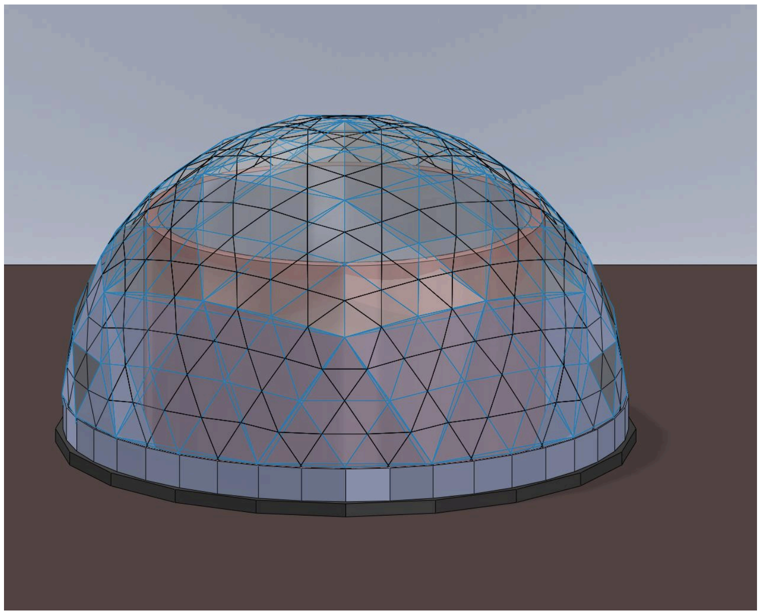
- Large structure ("space frame")
  - ✓ Need to be modular for assembly
  - ✓ Need a veto volume
- Wall material
  - ✓ Flexible liner (a la CHIPS-M) ?
  - ✓ More rigid (fiber glass) panel ?
- Buoyancy issue
  - ✓ Choose neutral as much as possible

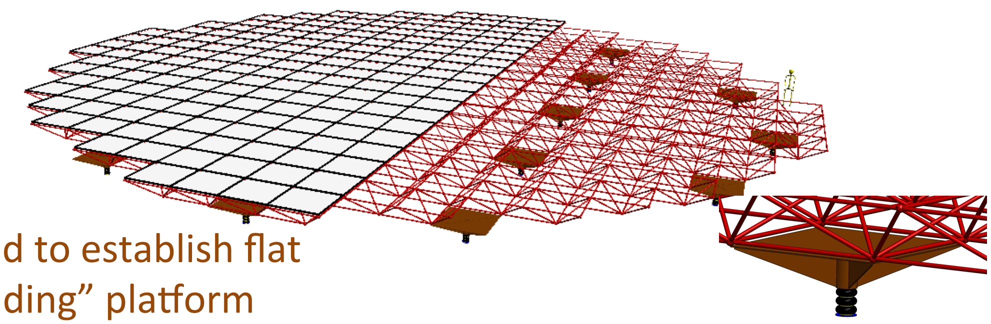




Spaceframe

- Radome (radar dome)?
- Contacting manufacturers

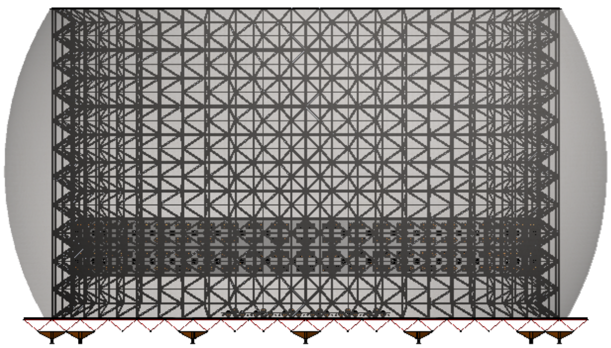


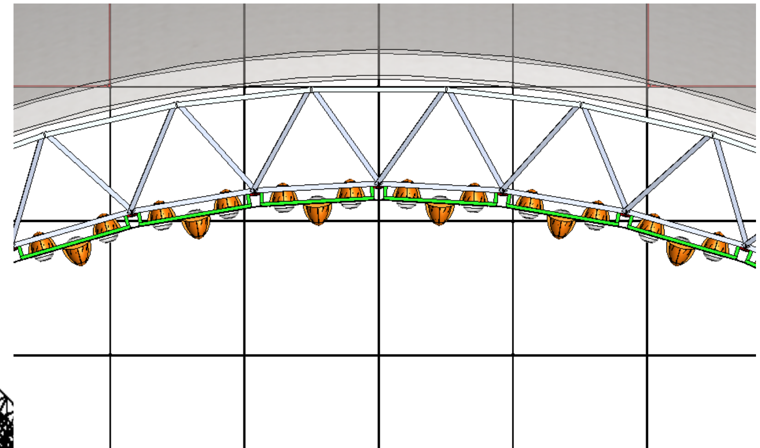


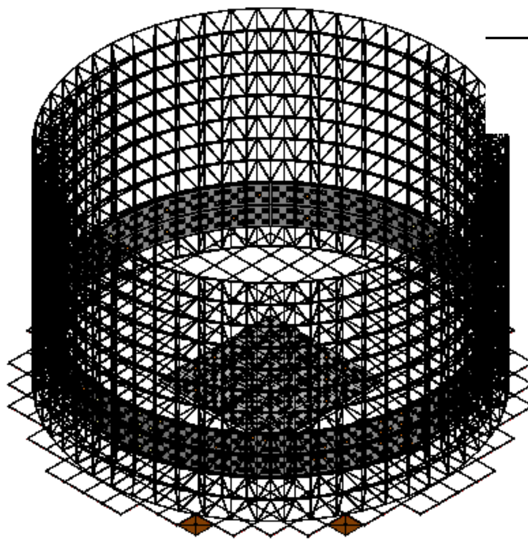
Need to establish flat "landing" platform for the bottom of pit

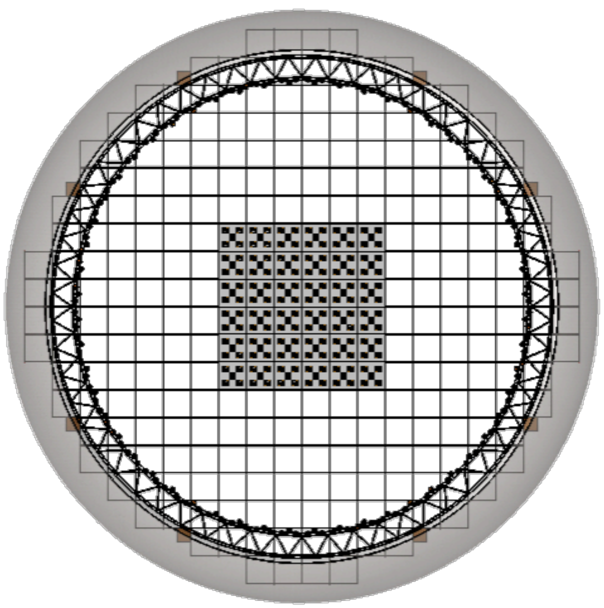
Heydar Aliyev Cultural Centre
Baku, Azerbaijan

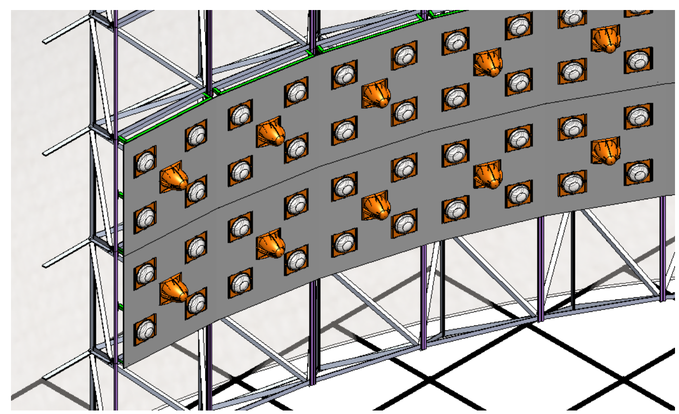
Conceptual development







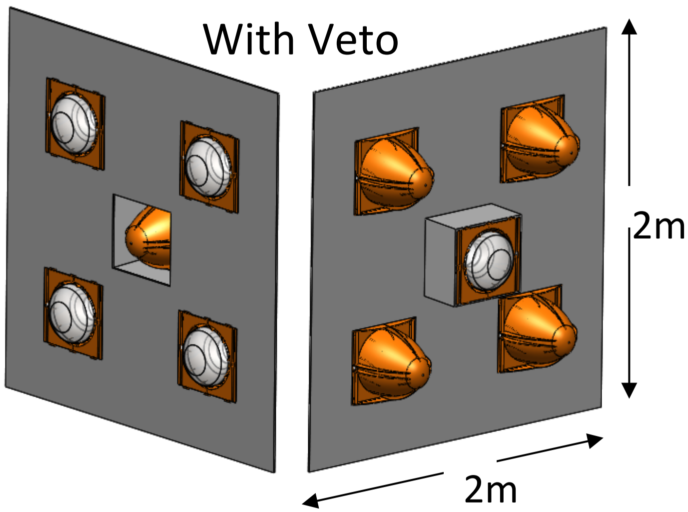


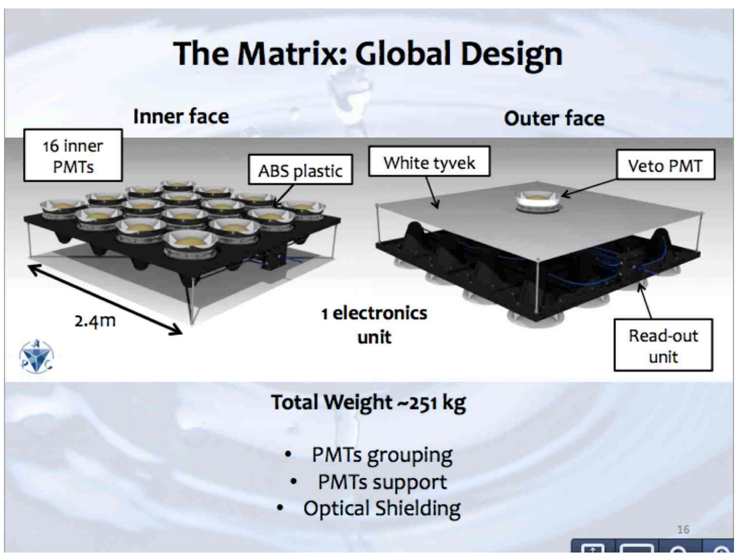


Possible staging …

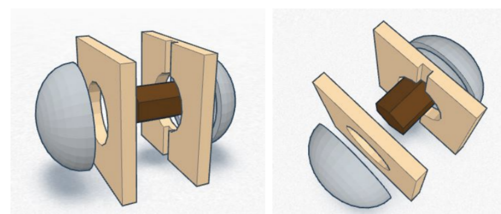
Wall panels (options)

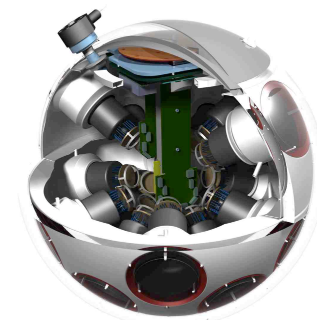
- A la MEMPHYS (below)

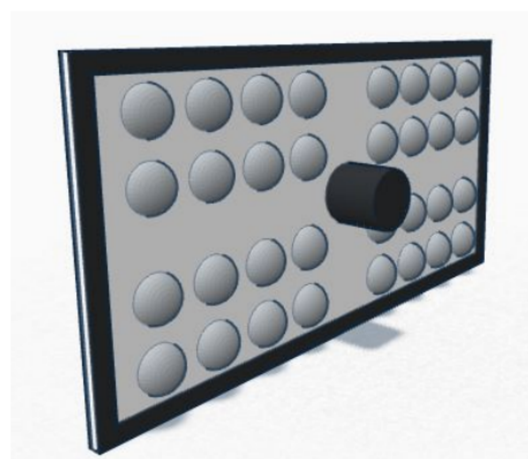




- NIKHEF idea (Paul Koojimans)
- Masters students with a UCL student will build one plane of KM3NeT tubes and electronics (“unfolded” OM)

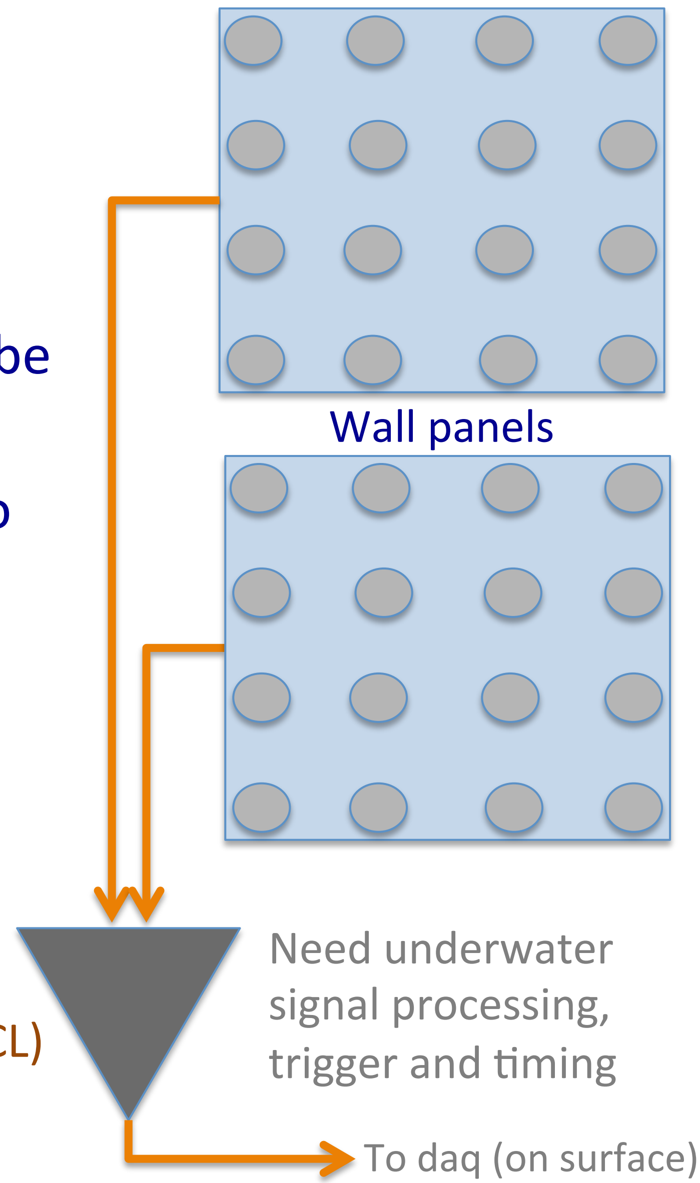






The front-end challenge: underwater intelligence

- Bringing individual signals to surface is too expensive (and cumbersome)
- Signals, time stamping etc. must be performed underwater
- "Intelligent" hit information packets must be (multiplexed) to an on-shore daq PC
- Underwater connections are a challenge to cost
- Integration of front-end and mechanics under 6 bars may be also demanding
- Examining/pursuing three ASIC's / approaches
  - ✓ KM3NeT
  - ✓ PARISROC (from MEMPHYS, 100 ASIC's--> UCL)
  - ✓ SAMPIC (from SuperNEMO, …)

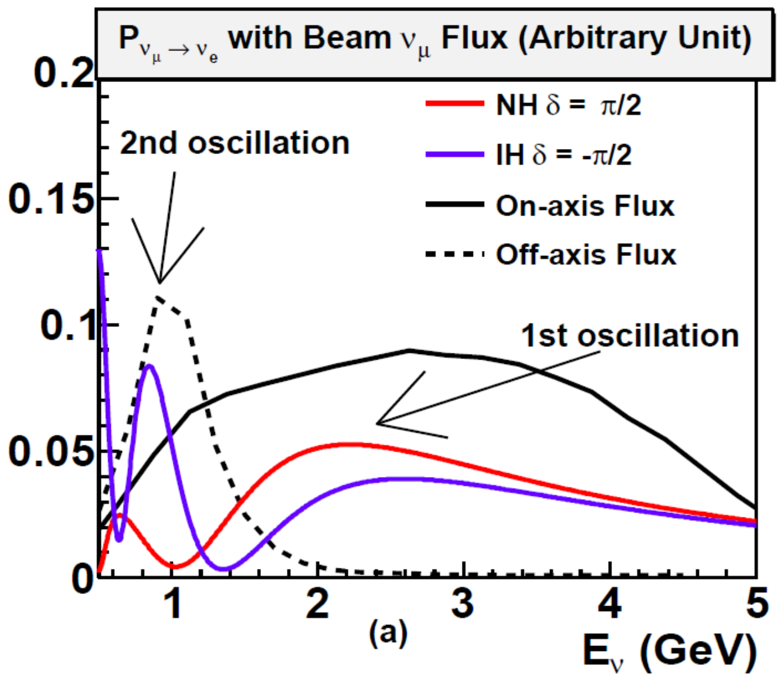


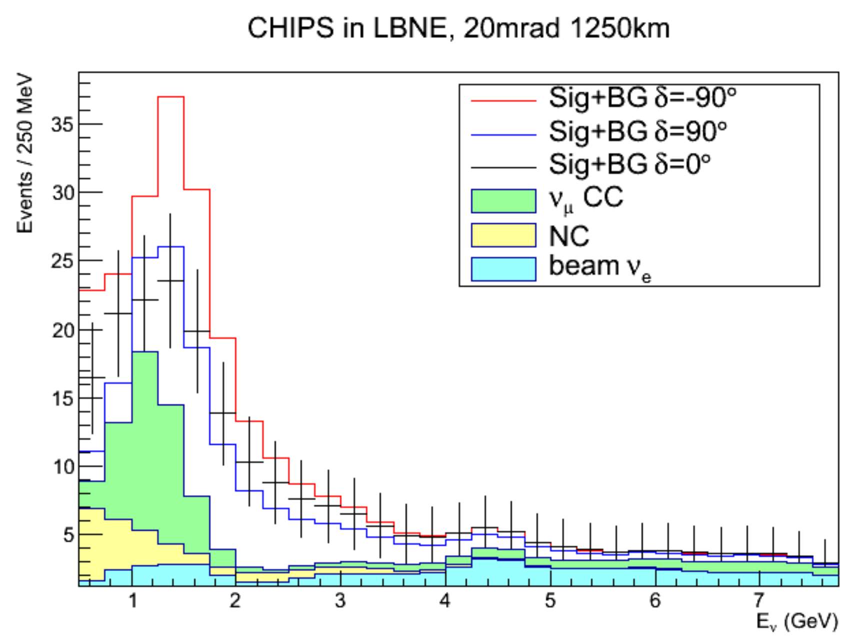
PMTs landscape: Hamamatsu, HZC, ADIT/ETL

- Hamamatsu (new and old)
  - ✓ KM3NeT will use 3" PMTs in their OMs
  - ✓ We have 400 of old 3" PMTs from NEMO-3
  - ✓ We have worked extensively with an 8" (R5912) for SuperNEMO
- HZC ('The Chinese Photonis')
  - ✓ Recently received a 3" PMT
  - ✓ They are working on large PMT's
- ADIT/ETL (Sweetwater, TX and Uxbridge, London)
  - ✓ Developing large PMT's (for the Watchman Experiment, a new 11" PMTs (w/ 12 stages)
    - Pressure resistant to 8 bars
    - Water resistant
    - Low radioactivity ("Borexino" glass)
  - ✓ Developing 5" with similar features
  - ✓ Their 3" competes well with Hamamatsu
    - Has a short stem

HPK
R 12199
(80mm)

Future off axis CHIPS at LBNF (20 mrad) – reuse most hardware



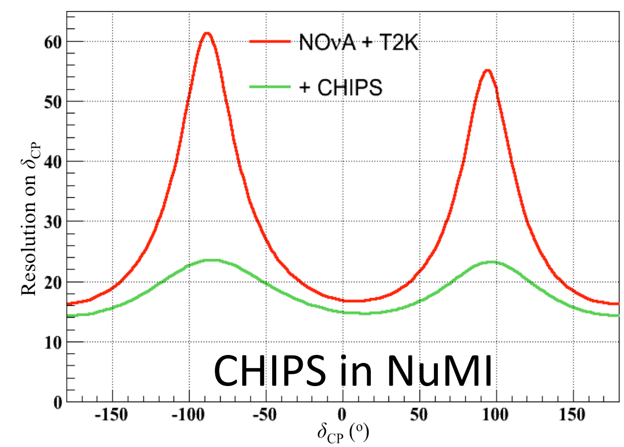


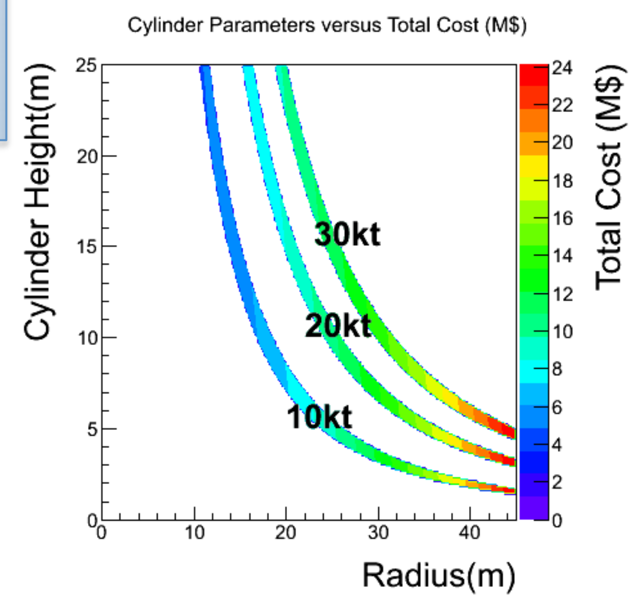
- 2[nd] oscillation maximum at ~ 0.8 GeV
- 2[nd] oscillation maximum will be a valuable augmentation to LAr
- Large QE cross-section suitable for water Cherenkov detectors
  - ✓ High efficiency for QE events

Summary and outlook

- NuMI era (soon at 700 kW) offers unique capabilities until DUNE is built ca.2024
- Adding massive detectors extends its physics reach
- New construction would fill the time gap and advance
  - ✓ Physics
  - ✓ Technology
  - ✓ Training of younger generation

  (It's a win-win-win situation)
- R&D on-going --> are the goals achievable?
- Great time to join and shape the future





○ Support acknowledgements: Leverhulme Trust, U. of Minnesota, UCL, U. of Texas at Austin, U. of Manchester, Royal Society, DOE, STFC

○ Post Scriptum: P5 endorses this R&D program although not the experiment (yet).

○ LOI: arXiv:1307.5918v3 [physics.ins-det] 23 Sep 2013

Disclaimer

It's tough to make predictions,
especially about the future.

Lawrence Peter "Yogi" Berra
(baseball player)