# CHIPS AND THE NEW IDEA

Nikhef, UCL, UM, UW

- Introduction
  - Preamble
  - Oscillations in practice
  - What is CHIPS?
  - Why should you care about CHIPS?
- The fun part
  - Construction of the detector (life in the Gulag)
- The future vision towards an array of detectors

Supported by ERC, Leverhulme Trust, UW Madison, UM (Minn), UCL
Contributors: UM Duluth, Czech Technical University,
UA (Canada)

# April 17th

2019

# Introduction

## GENERAL

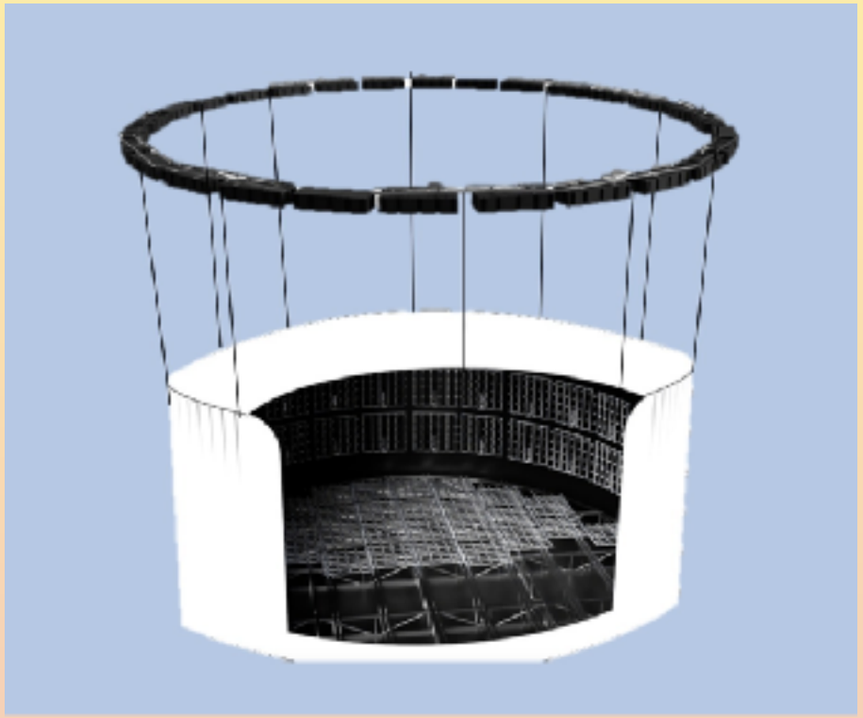
- Neutrino oscillation study needs to measure neutrinos at-a-distance
- Neutrinos interact only with the Weak Interaction
- At low energy ($E << m_W$) the interaction x-sec is rather low
- Need to increase the flux (beam) or increase the target mass (detector)
  - Increase flux by maximum factor 2 (1-2 MW) over present (its hard)
  - Increase in mass is expensive (10M-100M money units/kton)

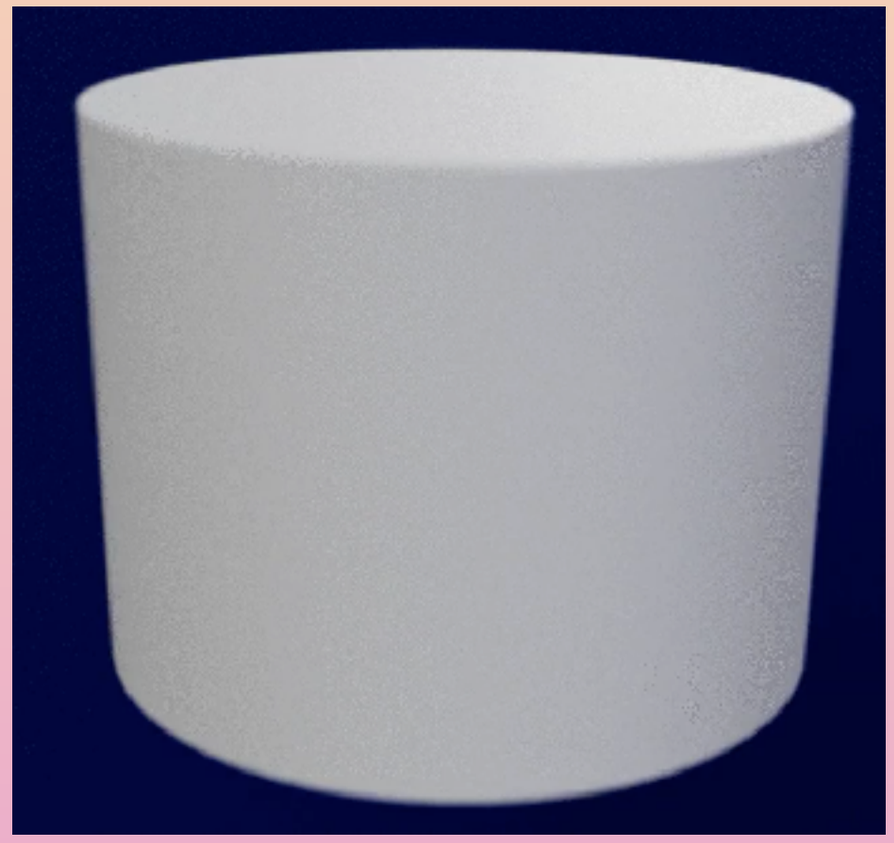
## SPECIFIC

- Mass Hierarchy needs a long baseline to be accessible
- CP violation needs lots of events to be measured
- $\sin^2\theta_{23}$ remains the big uncertainty in trying to measure the first two
  - also potentially is the most interesting….maximal?

# CHIPS : Cherenkov Detectors in Mine PitS

- The CHIPS goal was to prove that a water Cherenkov detector can do oscillation physics for a fraction of the cost of present neutrino detectors
  - to $200k/kt (presently $2-10M/kt water, $10-50M/kt Liquid Ar
  - and with all the technical challenges that go with it
- ~5-15 kt CHIPS was submerged (end of 2019) in a flooded mine pit in the path of the NuMI beam : in 4 months!



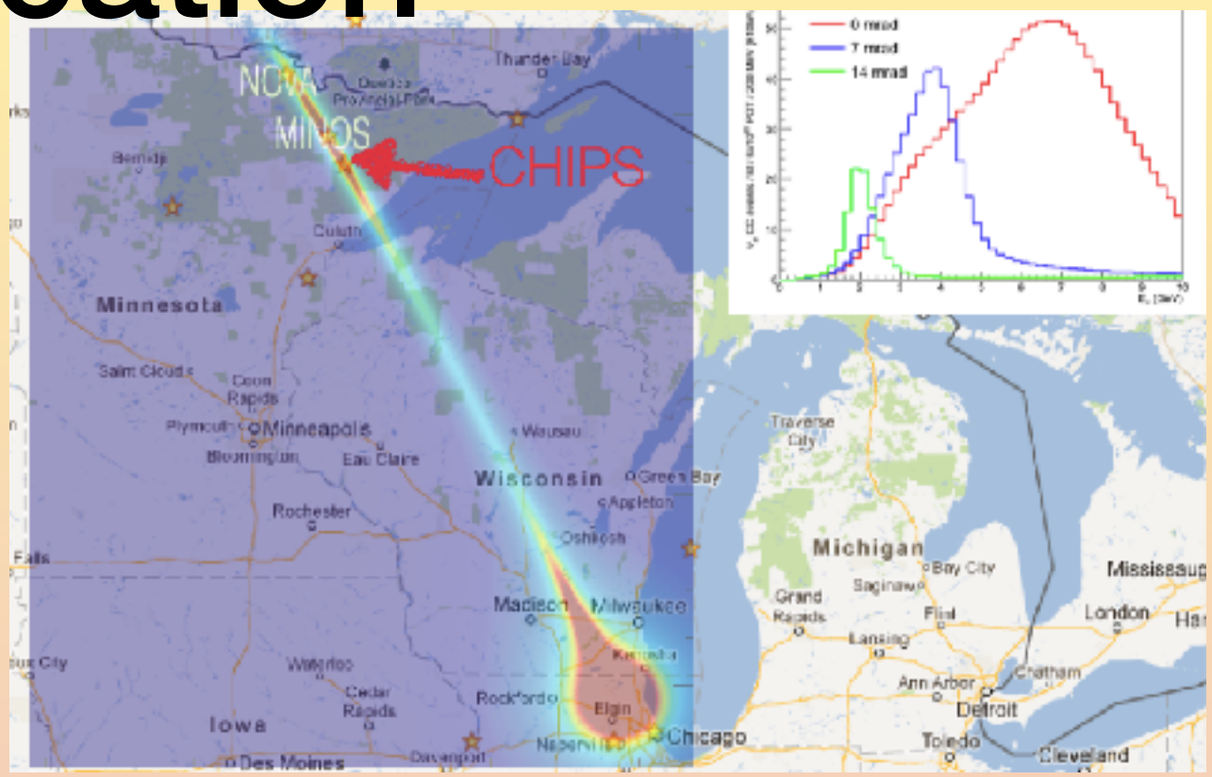


# SOMETHING NEW AND RISKY

- 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 $4^{o}$C

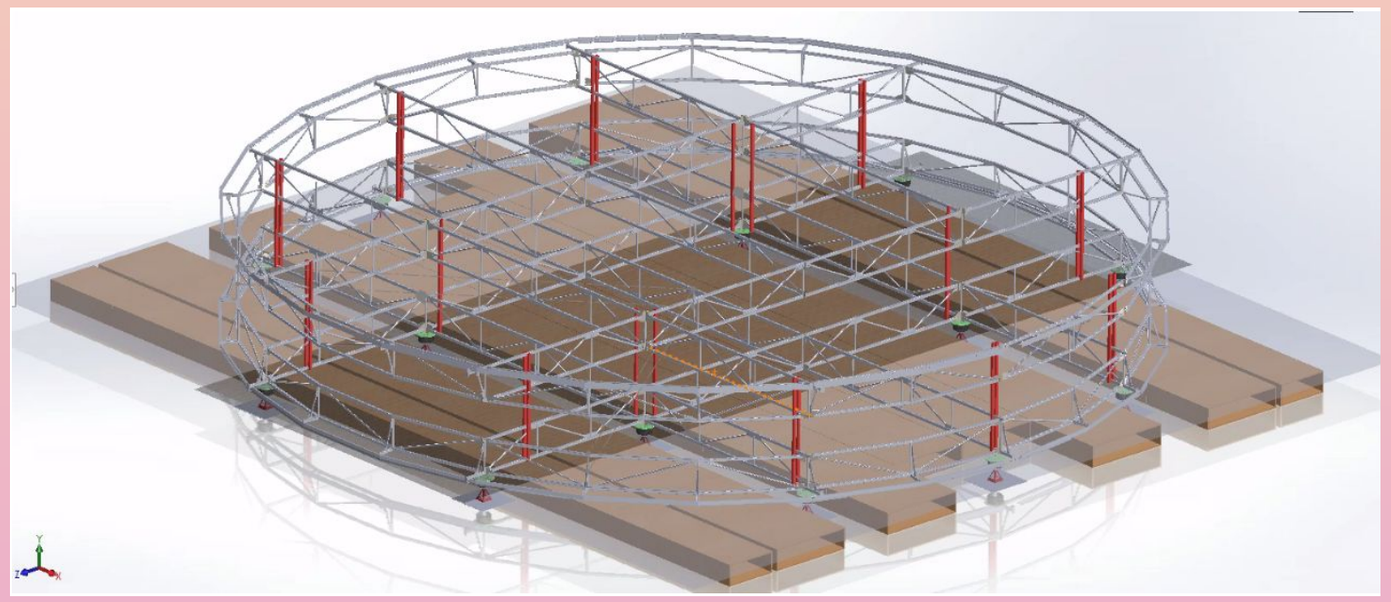
with support from ERC, Leverhulme Trust, UCL, UW, Nikhef, UM, U.Alberta, UC, UMD, Marseille, MSU, Czech TU, W&M

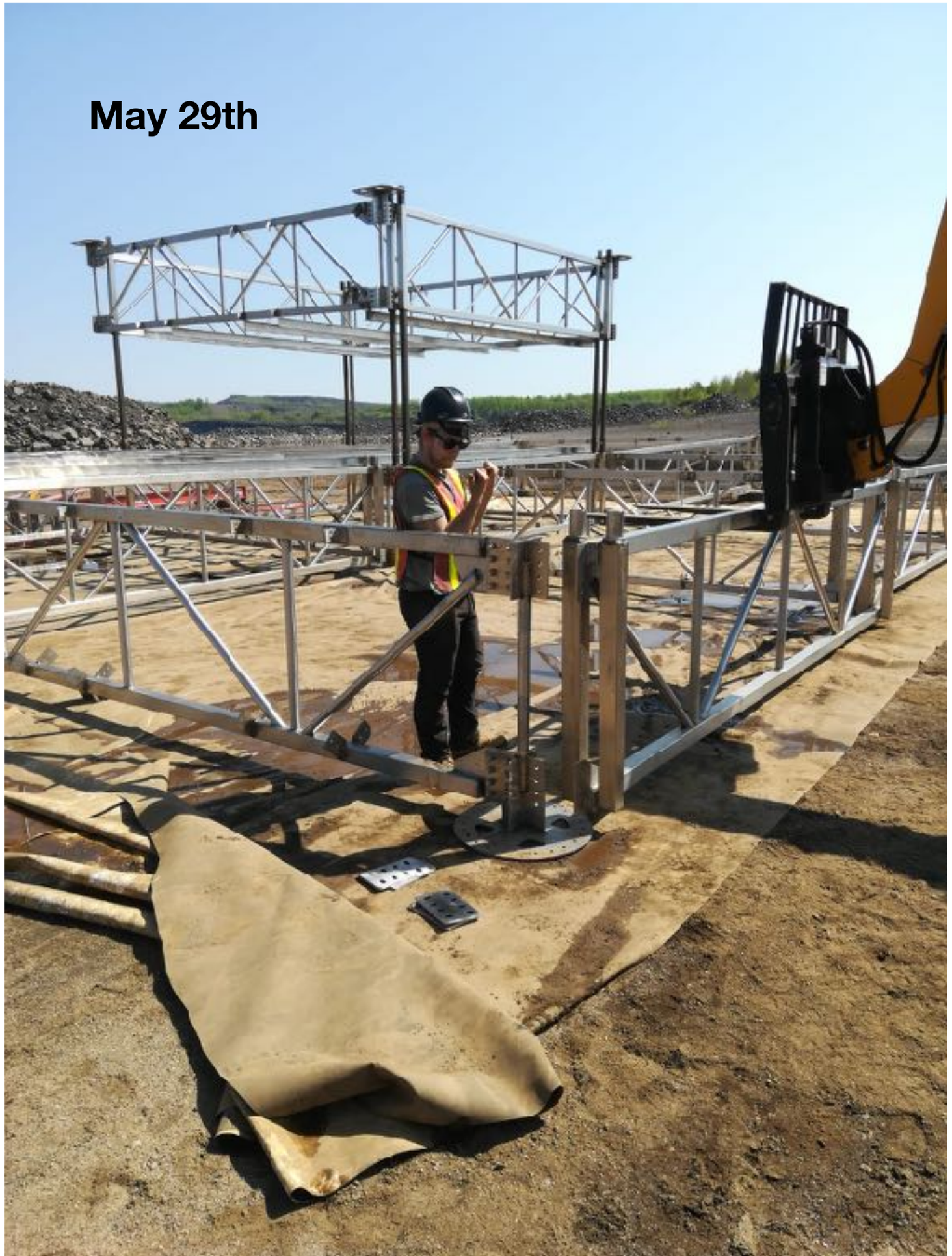
# 1.Location




- Polymet Mining site, secure and friendly lab space in the main building
  - (reminds one of the twilight zone)
- Wentworth pit is ex-taconite flooded quarry
- 50-60m at deepest point
- 7 milli-radians off axis in the NuMI muon-neutrino beam

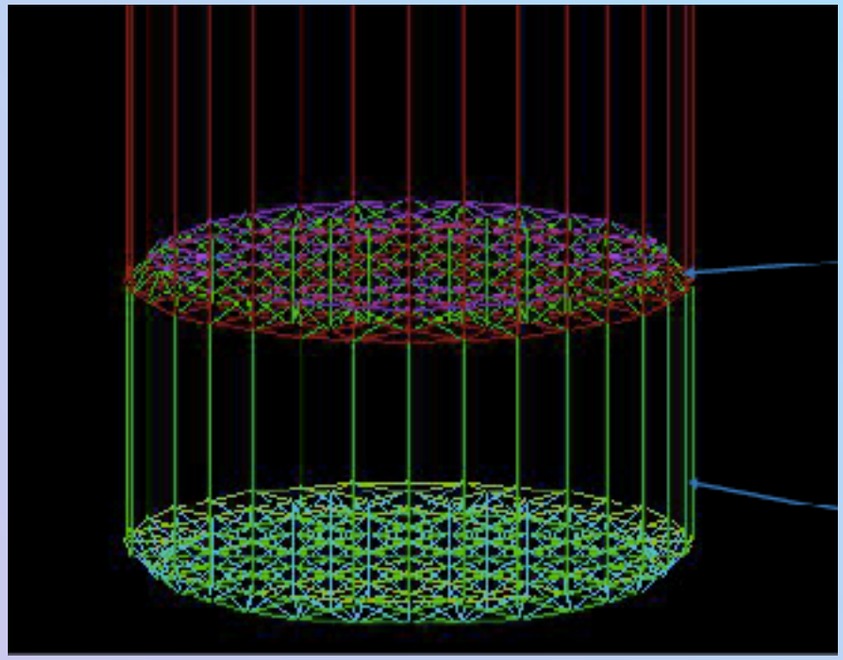
# 1.Location




May 29th

# 2.Structure

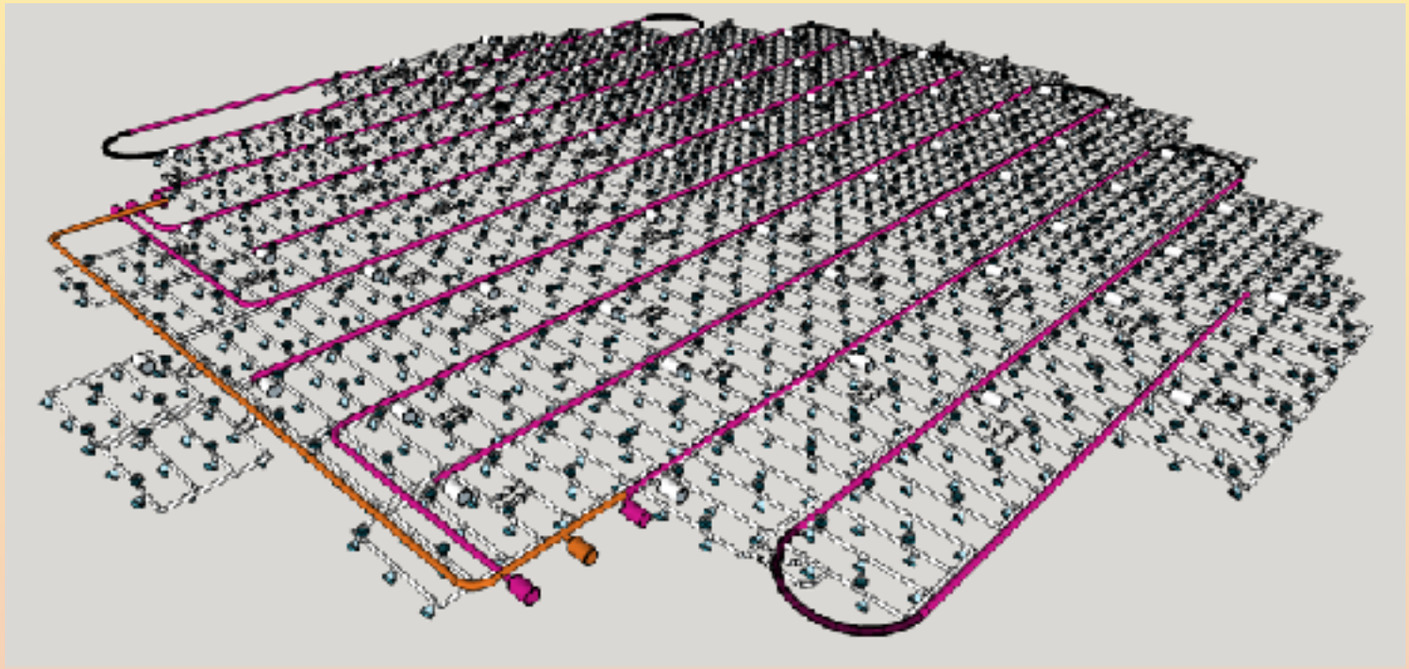
- Two 25m steel end caps are held together by Dyneema cables
- Detector can grow in height for cost of cables and instrumentation
- Top cap is buoyant wrt bottom cap
- Bottom cap will rest on ground
- Top cap will be held down by Dyneema cables

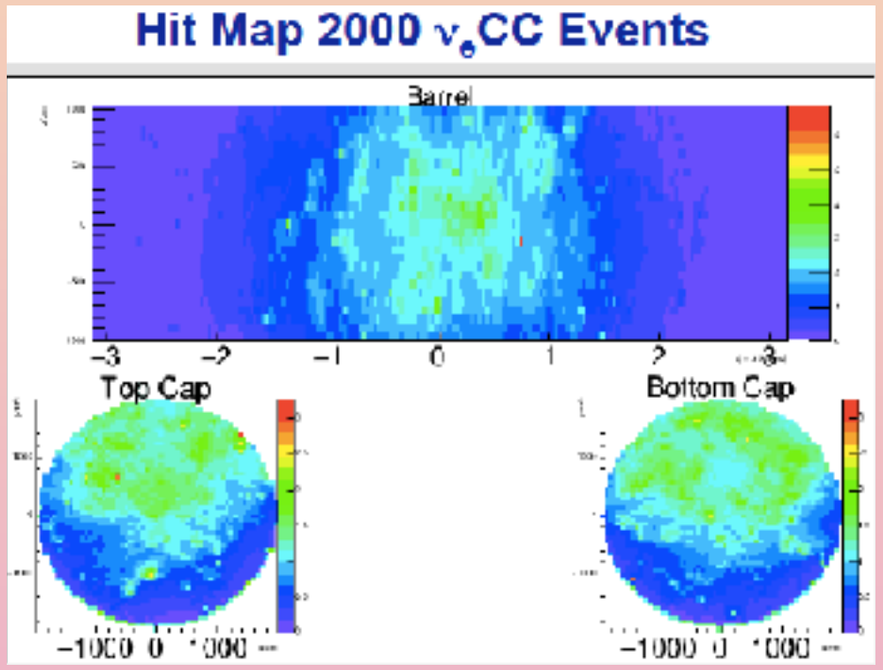


June 21st

# 3. PMT Choice and Layout

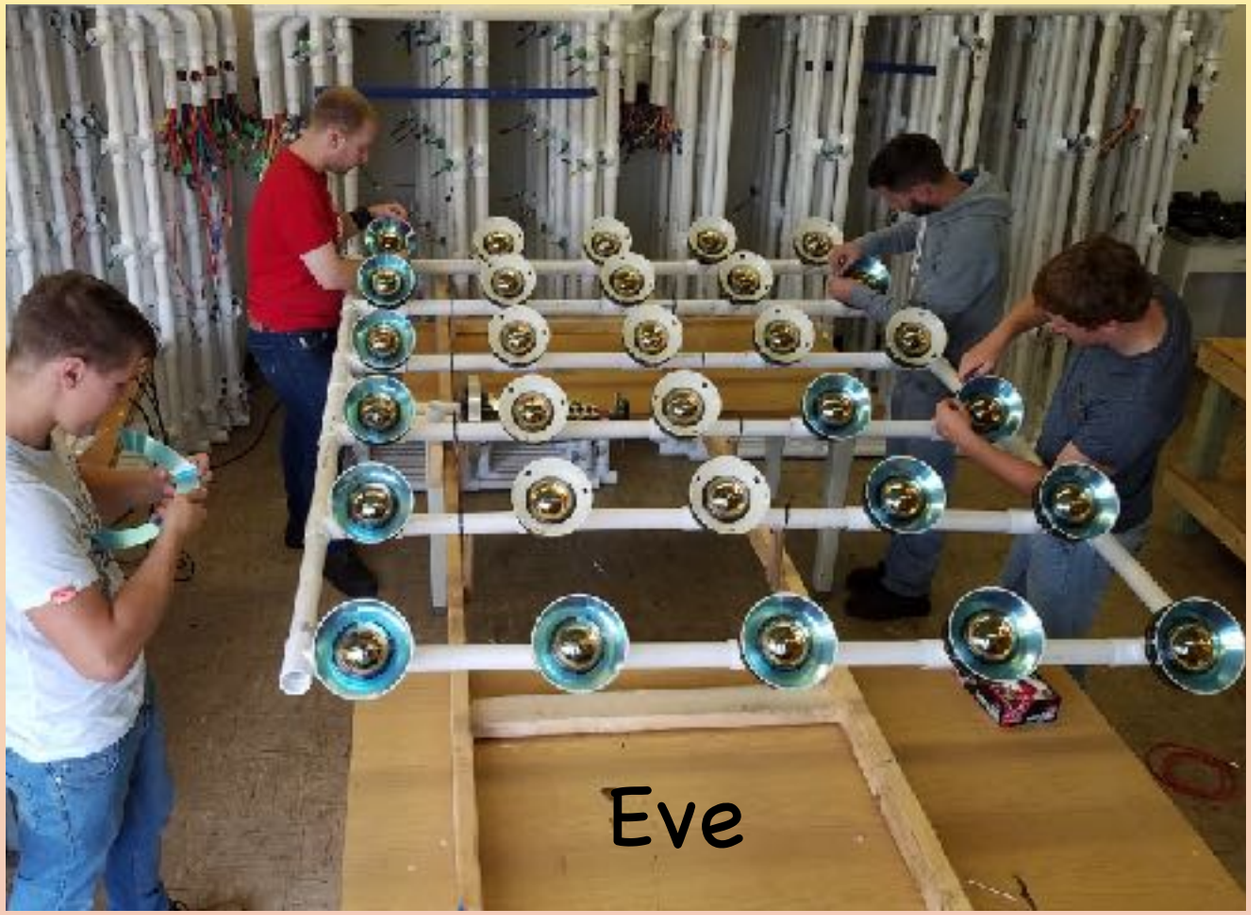
- Layout involves high and low density planes
- A big part of the instrumentation just implemented (almost) KM3Net technology
  - HZC 3.5” PMTs at 6% coverage in front wall and front of end caps, and 4% coverage back end cap region
  - KM3Net uses -ve CW-HV base, PMTs must be protected from water
- Low density wall planes will be made with NEMO-III 3” PMTs and Madison electronics.
  - Old 3” PMTs at 4% coverage in back
  - Madison electronics uses +ve CW HV base, PMTs are in contact with water





- very good clarity achieved with the potting compound
- Only failure mode was flat cables to J45 connector
- Acrylic dome protects PMT from high pressure and also from contact with water

# Detector Plane Construction (2018)

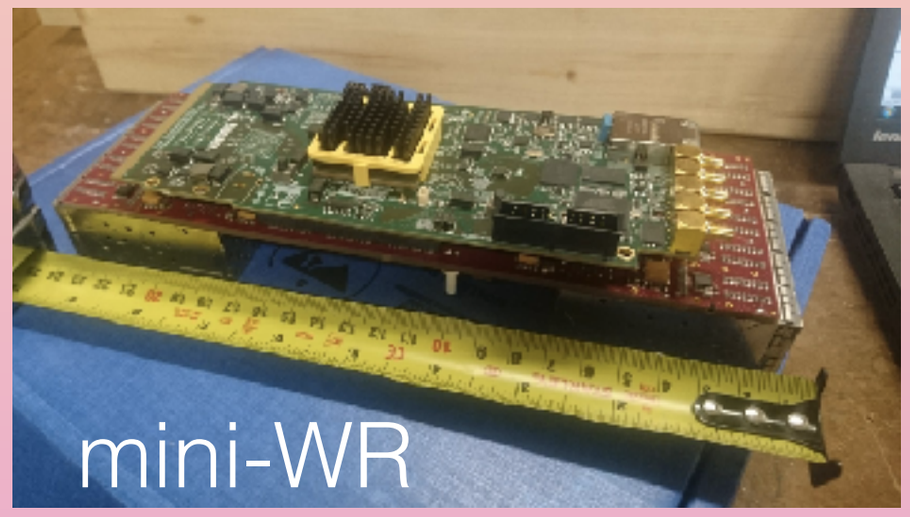


- Detector Planes made out of schedule 40 PVC, (lots of) glued joints
- Keeps electronics dry, withstands 6 ATM (in most cases)
- Tested with air pressure (DO NOT DO THIS AT HOME)
- Inside cat-6 cables run though PVC pipe from PMT to Electronics
- Reflective (Winston approximation) cones increase light collection
- Undergrad involvement essential!!!
- 8 in 2018, 8 in 2019
- Planes built in just-in-time fashion as no storage possible

**July 2nd**

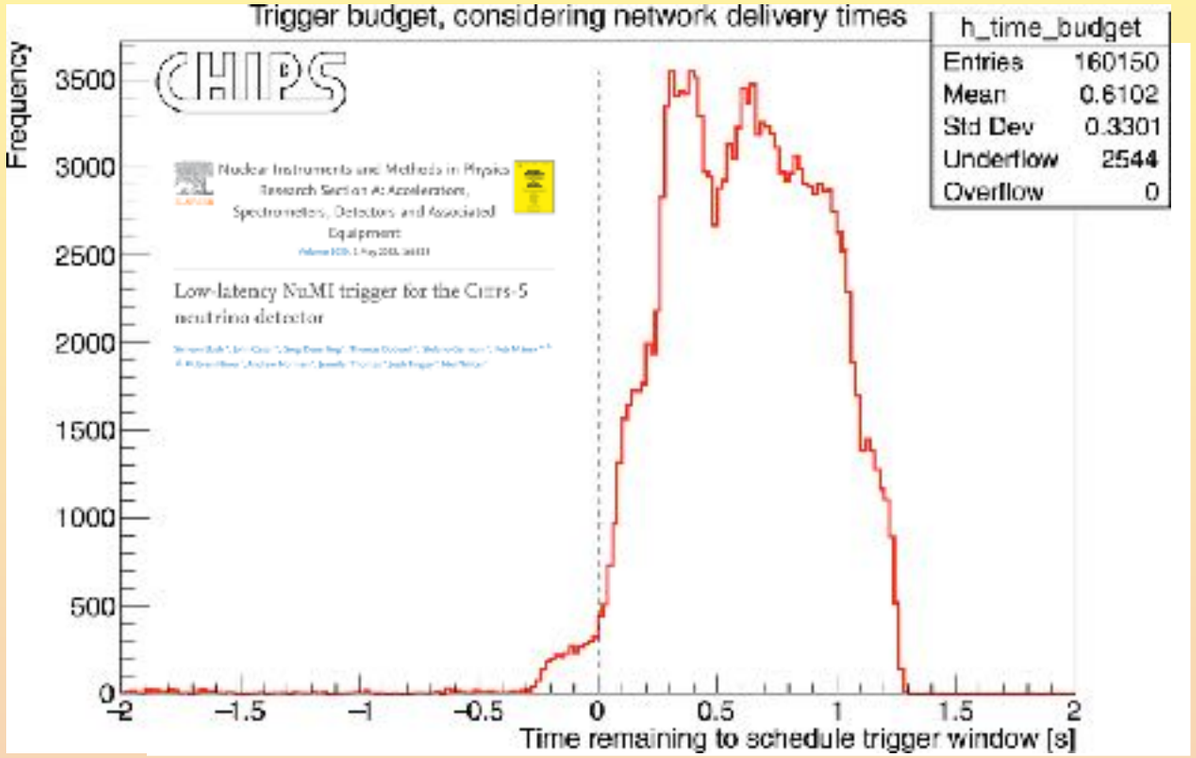
# 4.Electronics : Nikhef planes

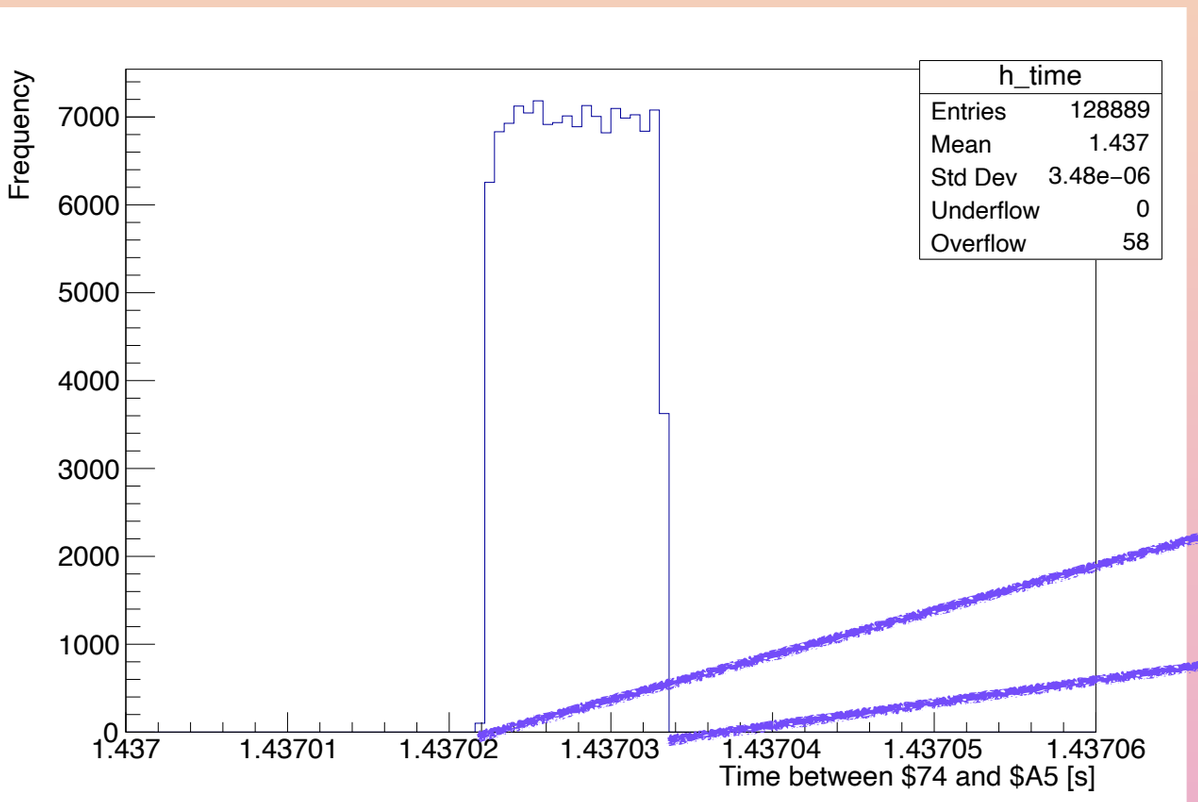
- KM3Net electronics takes advantage of some millions of euros of electronics design effort
- Blazes the trail of multi-small-PMTs : no long heavy cables, -ve HV CW bases
  - 30 PMTs talk to one central logic board (CLB), gets timing from CHIPS miniature White Rabbit timing board (1ns-over-ethernet)
  - CW uses 3.3V, AC/DC converter on CLB
  - All standard cat-5 interconnecting cables
  - CWDM (Coarse Wavelength Division Multiplexing) on fibres out of the planes
- SFPL (Small Format Pluggable Lasers) on WR at each fan-out box
- 2 cables: Power cable down, fibre cable up to surface via 5 fan-out boxes inside the detector
  - Fanned out along manifolds between boxes and planes
- No other racks or modules!
- Spill time served over ethernet from MI $74 : proved to arrive in time

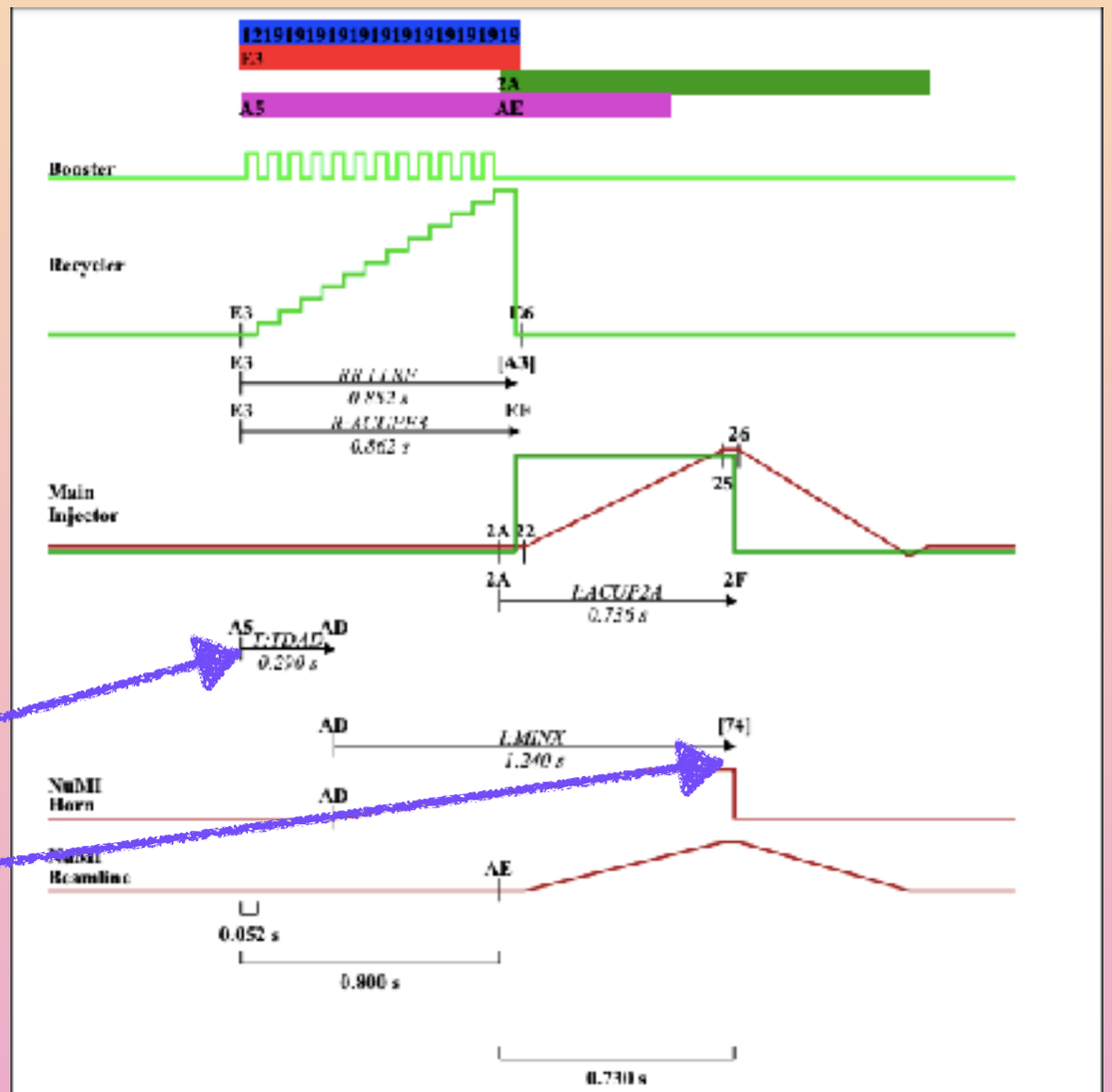


# Spill Server results!

- Using NOVA TDU (Time Distribution Unit) we have served the spill from FNAL to the internet
- 96% of the spill signals arrive up at CHIPS within 1.3 sec (time from $A5 to $74 NuMI spill)
- Jitter on $A5 compared to $74 is the remaining 4%, use previous spill time.
- Potentially useful for DUNE?



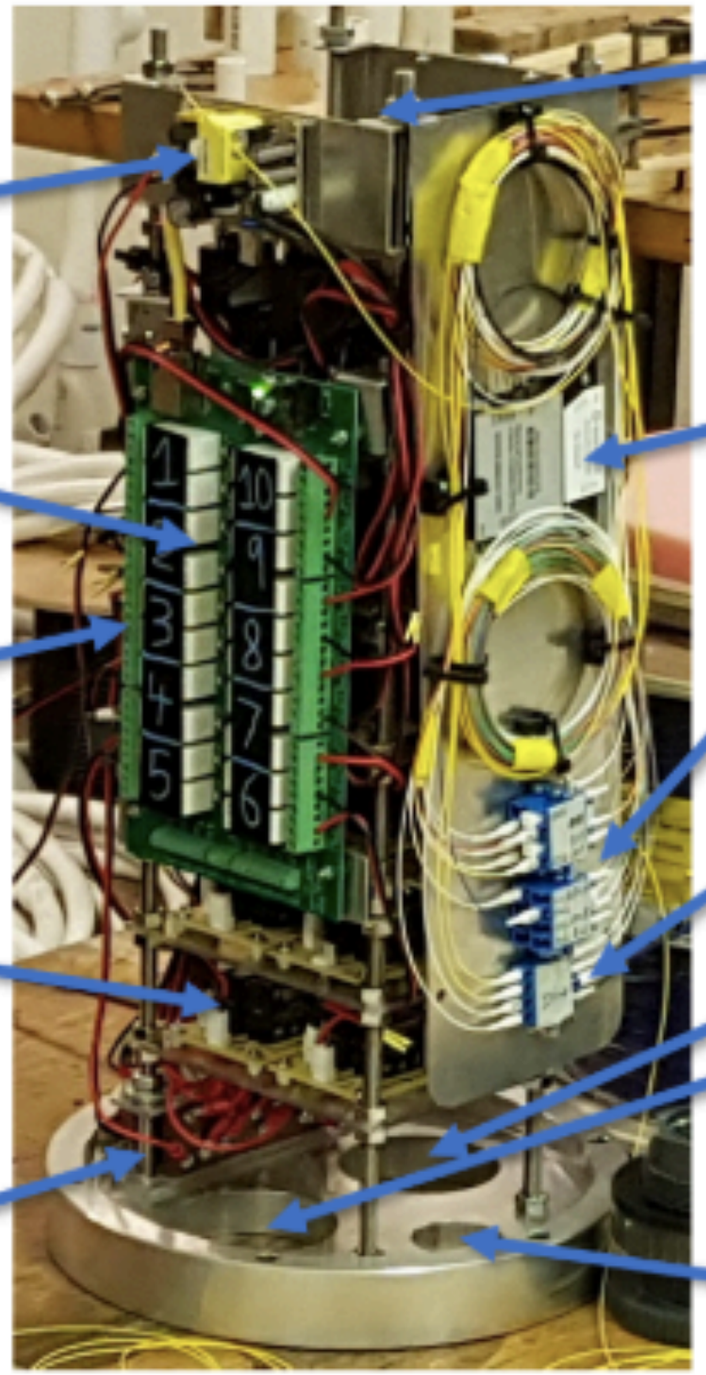



# 4.Electronics : Nikhef planes

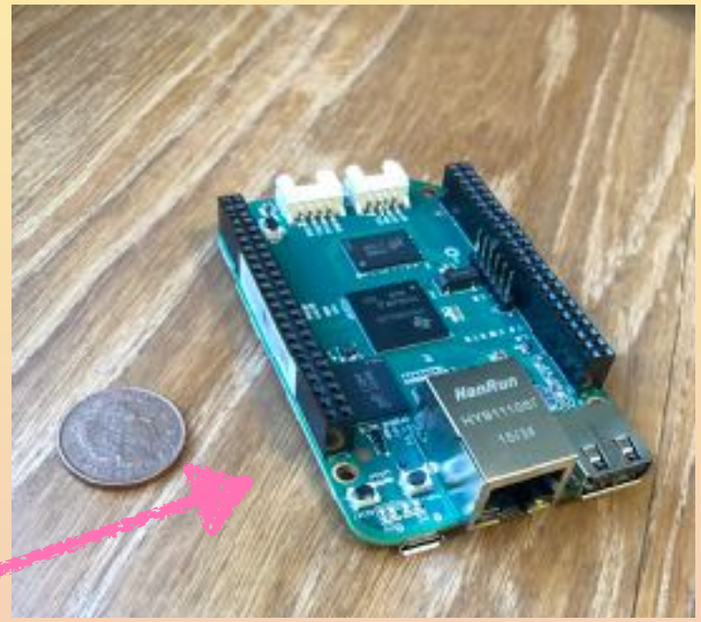
**~~Junction~~ Box** Jelly

The junction box takes both the power and fiber input from the shore hut and distributes these to the five Nikhef containers and single Madison container.



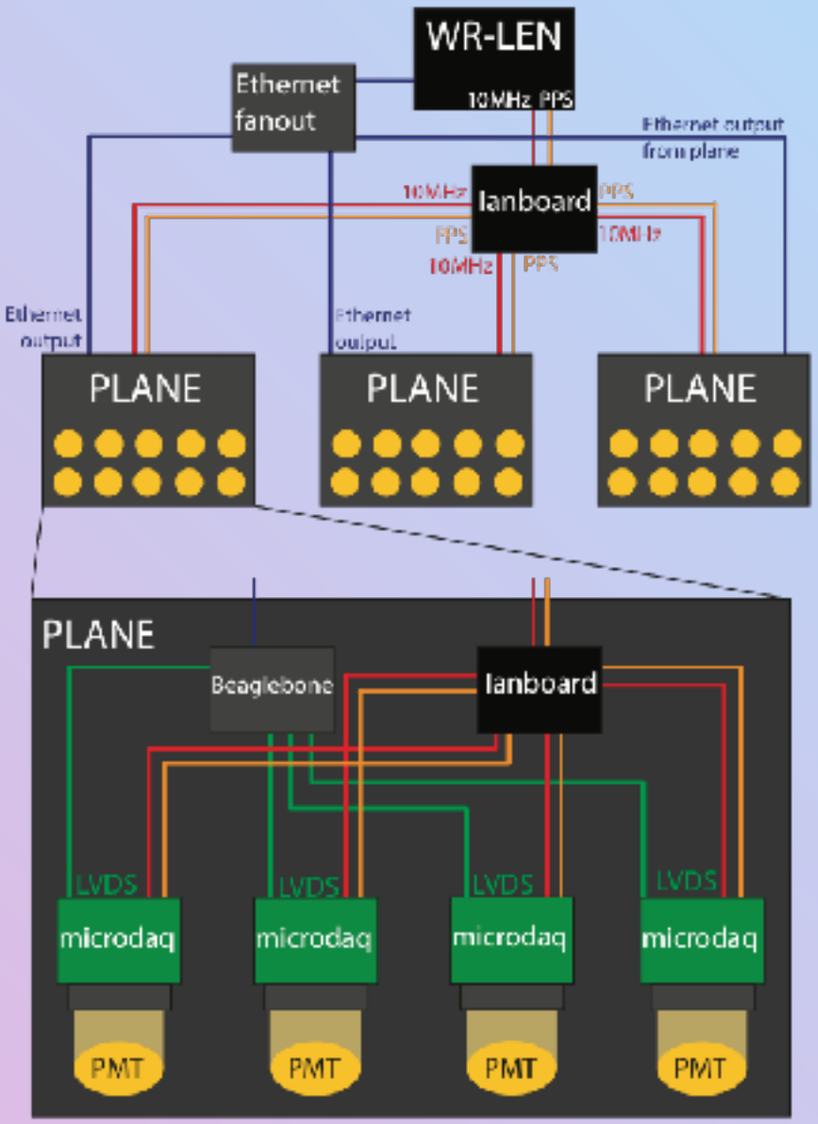
# 4. Electronics: Madison Planes

- We are riding a revolutionary wave in development
- Microprocessors on each PMT are possible, cheap and available!
- provide ToT and receive clock from WR system
  - Each PMT knows the time to 1ns
  - 24V, 10MHz, PPS and Ethernet all on the cat-6
- $40 for a BBG to collect (many) signals and transmit to Ethernet
- Reduce cost to minimum
- Designed at Madison, standing on giant shoulders



# 4.Electronics: Madison Planes

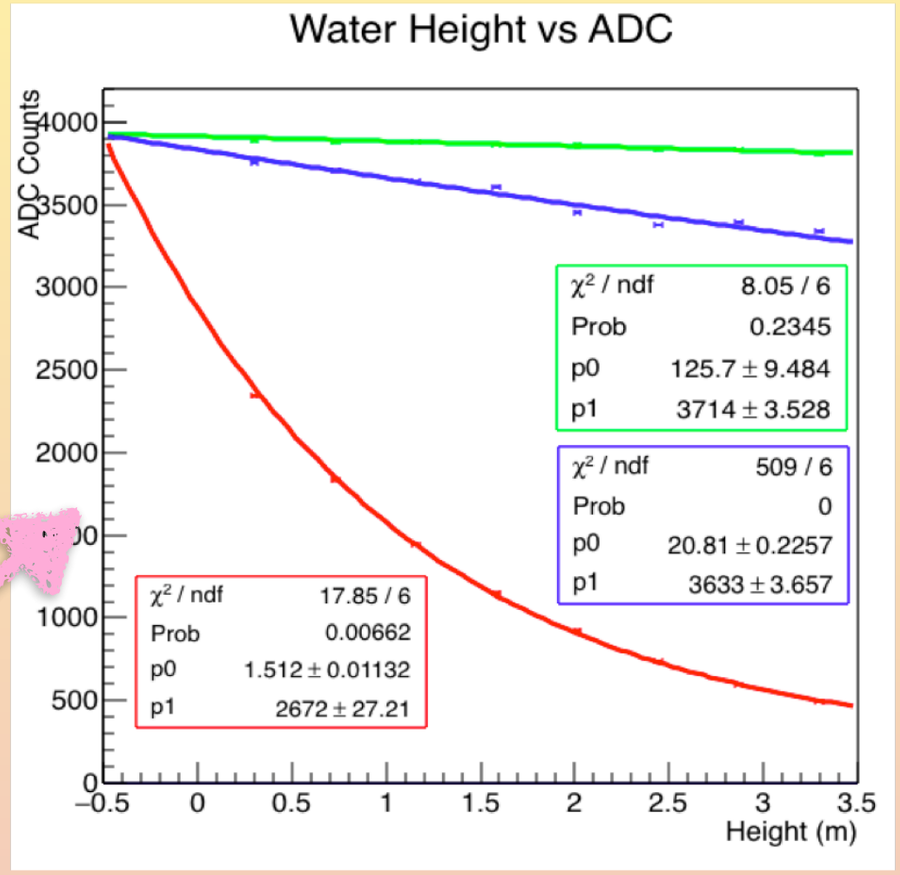
- Top level fanout provides power, 10MHz, PPS and ethernet on cat-6
- Communication software between BBG and micro-daq demonstrates 1Mbps on RS485/D
- Rate of 1-10kHz per tube means scope for local filtering (maybe) or at least buffering during spills
- Total cost, $25+PMT, data->disk



July 23rd

# 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, bacteria mostly > 1 μm
- 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
- 60m attenuation length was attainable and reproducible



## July 31st

August 9th

CHIPS detector: September 11th 2019

Buoyancy pipes hold top cap above the bottom cap via 28 dyneema strings

Veto PMTs look upwards

**August 28th**

August 28th

August 31st

CHIPS detector: September 2019

62 total detector planes installed in top and bottom end-caps

total of 1770 Photo-multiplier tubes

# View from the air of CHIPS detector construction, September 2019

# Water level was rising every day….October 6th

- This was a surprise, but everything was OK and we towed it back like an errant child with steel cable and the fork-lift

- she became anthropomorphic

CHIPS detector: October 10th 2019

62 total detector planes installed in top and bottom end-caps

total of 1770 Photo-multiplier tubes

will enclose ~5 kilotons of water

- CHIPS being towed out to position, October 14th 2019
- Finally was submerged 22nd November

WYZE
2019-10-14 10:19:48

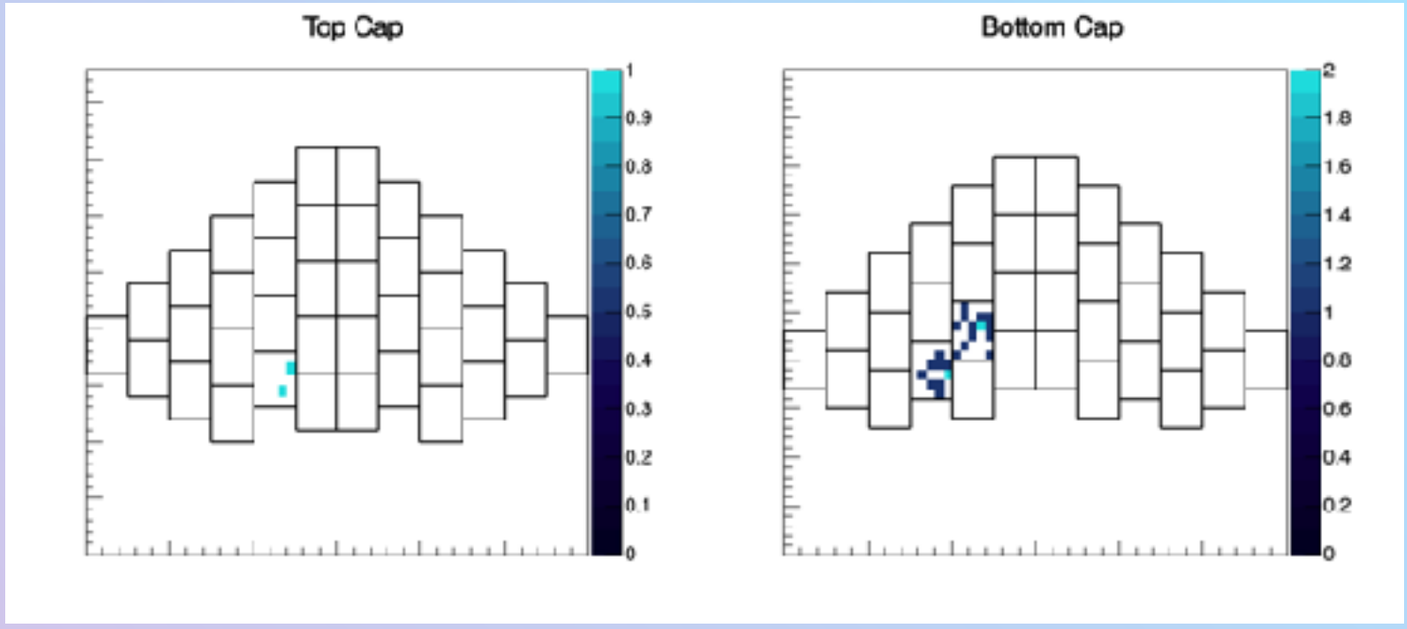
**what's missing from g_lag?**

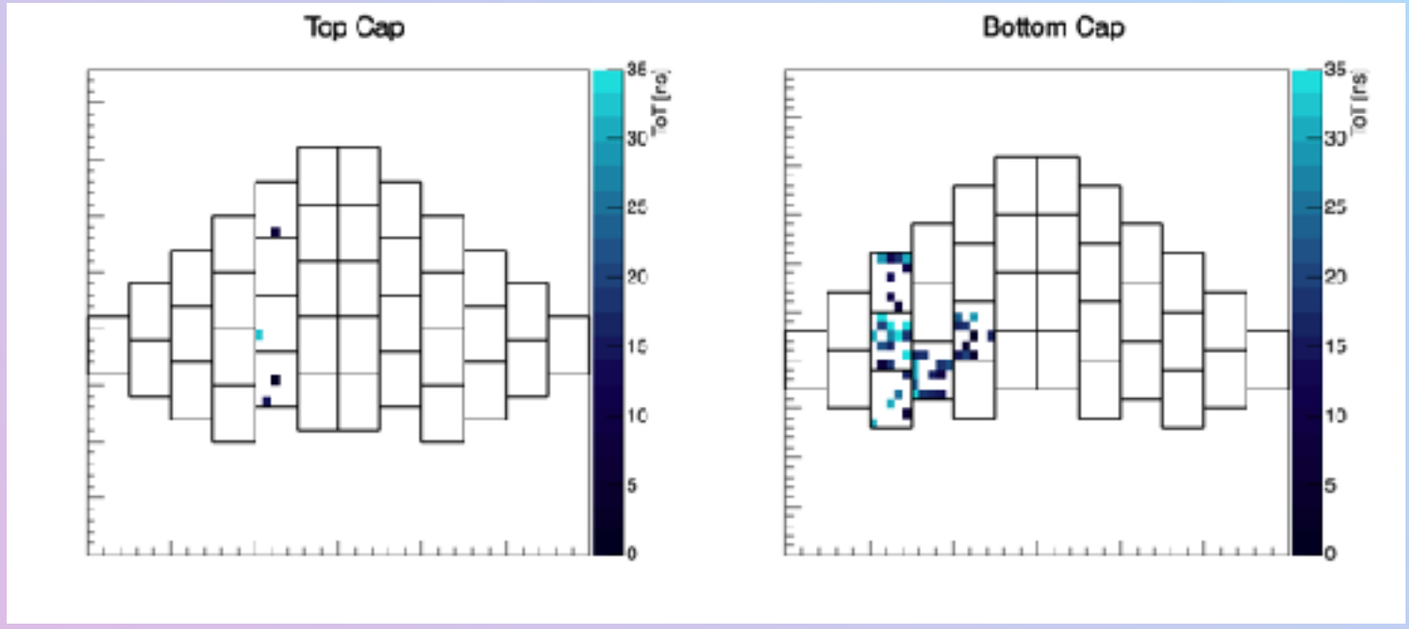
**+Jerry**

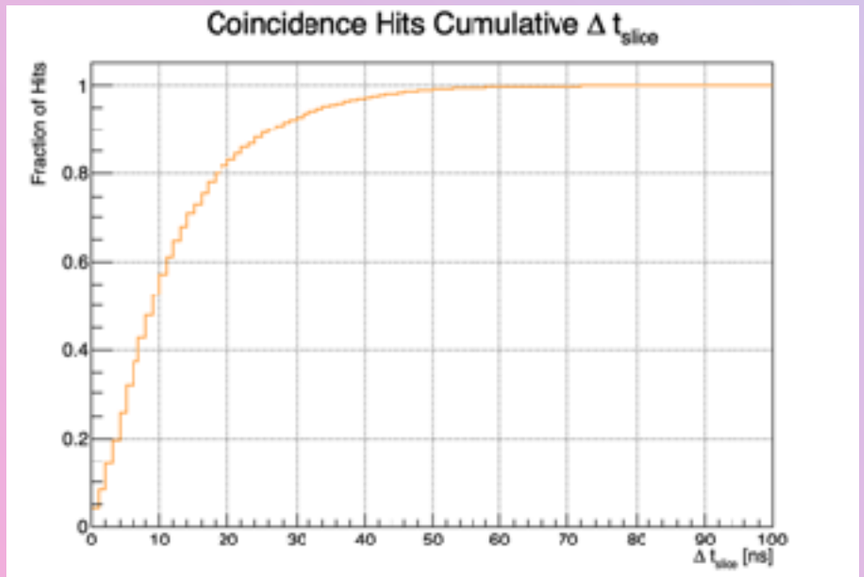
- We have 7 full time people
- 7 part time people
- 8 undergrad volunteers in 2019
- This group built the whole thing…

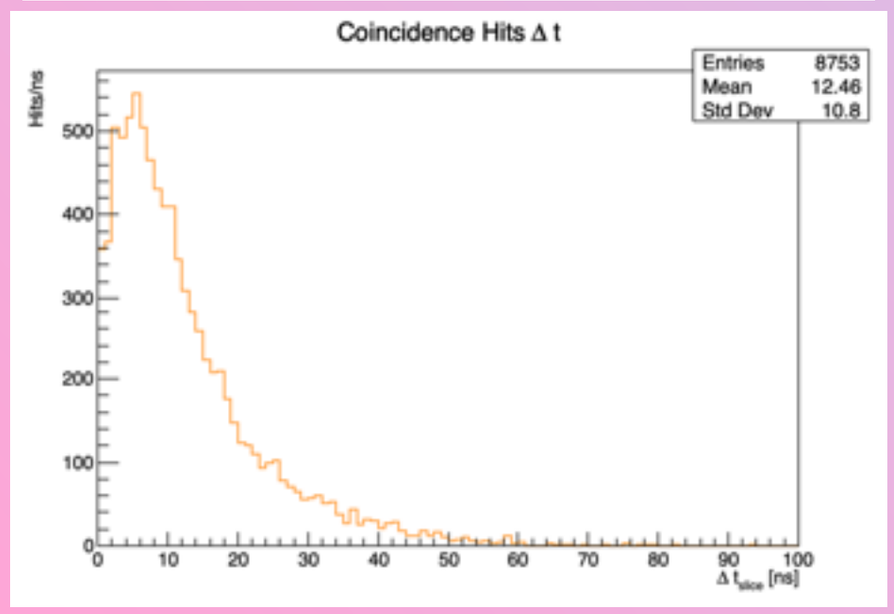
# Some first events

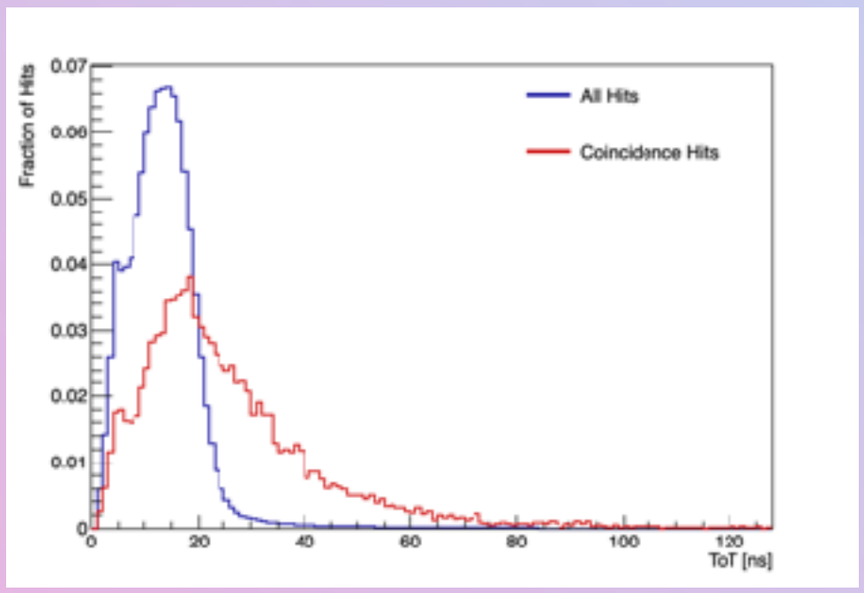
- First efforts to search for events in coincidence
- 35ns sliding window
- looks like we are seeing comics!



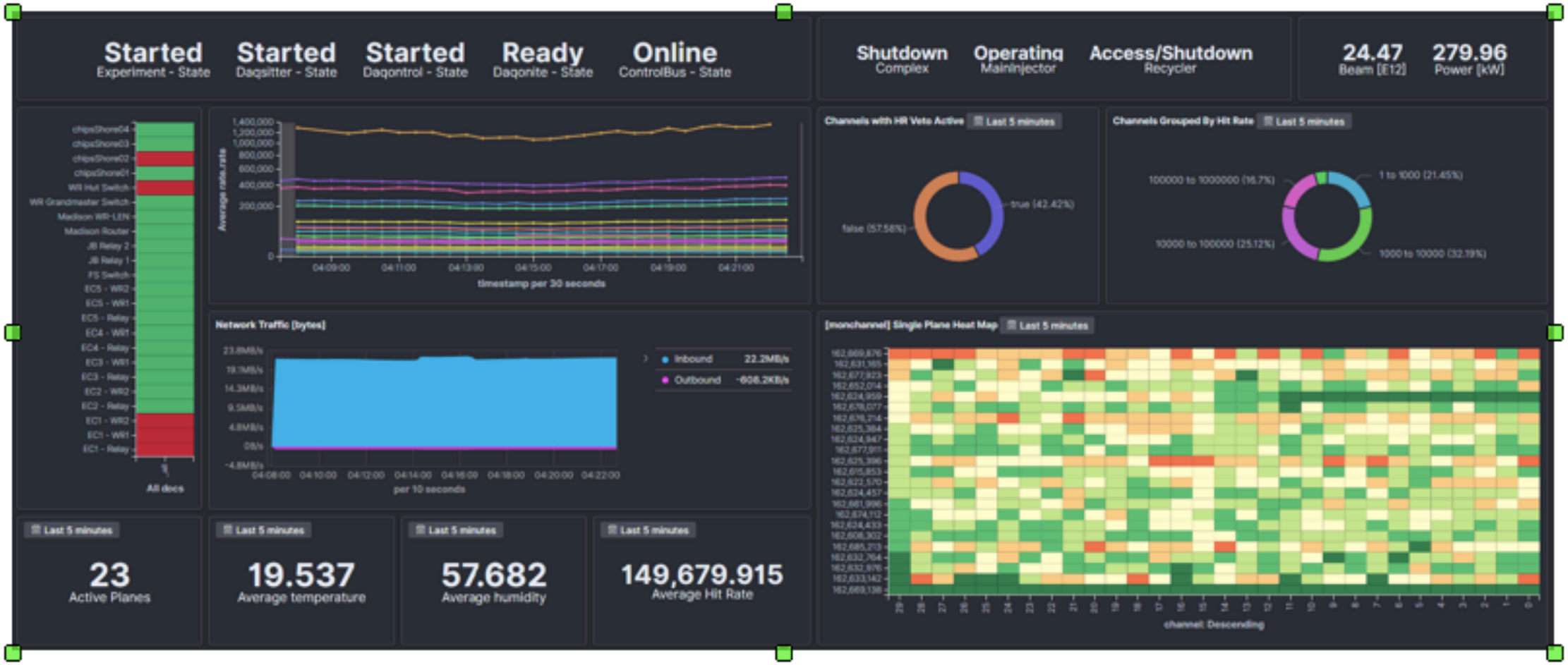



# DAQ Monitoring

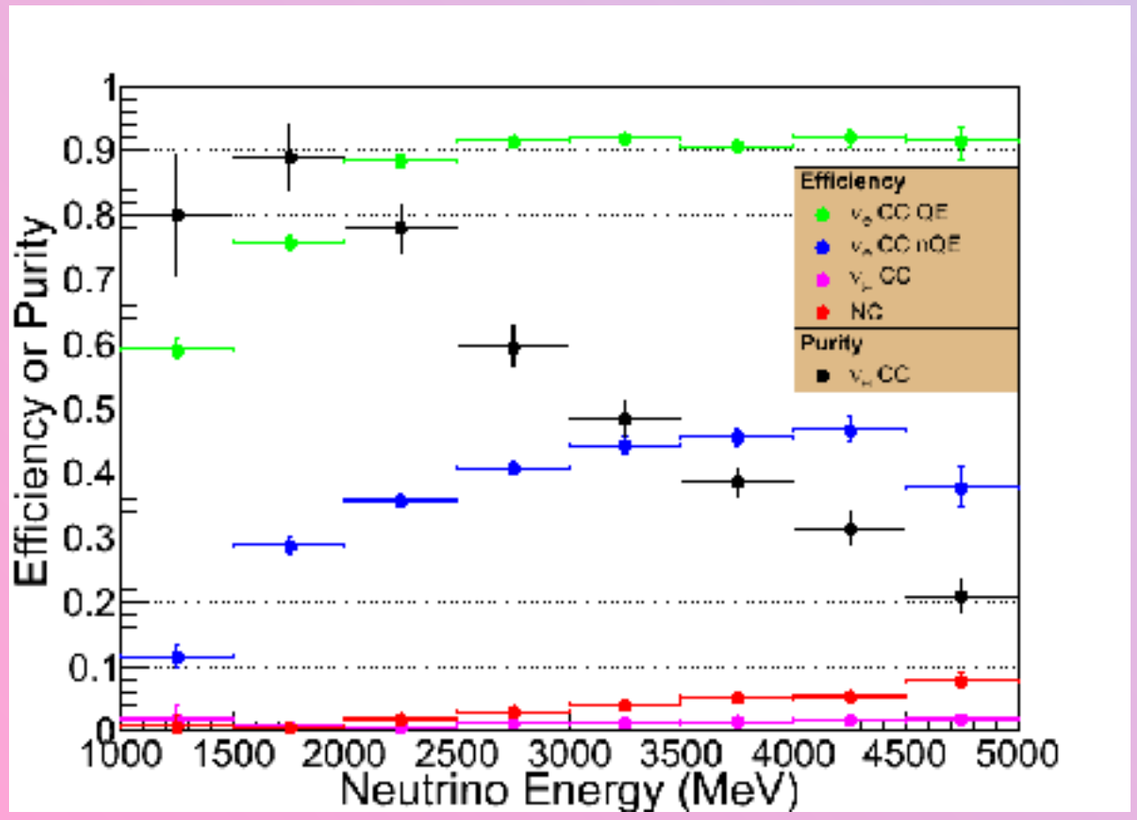
## Monitoring

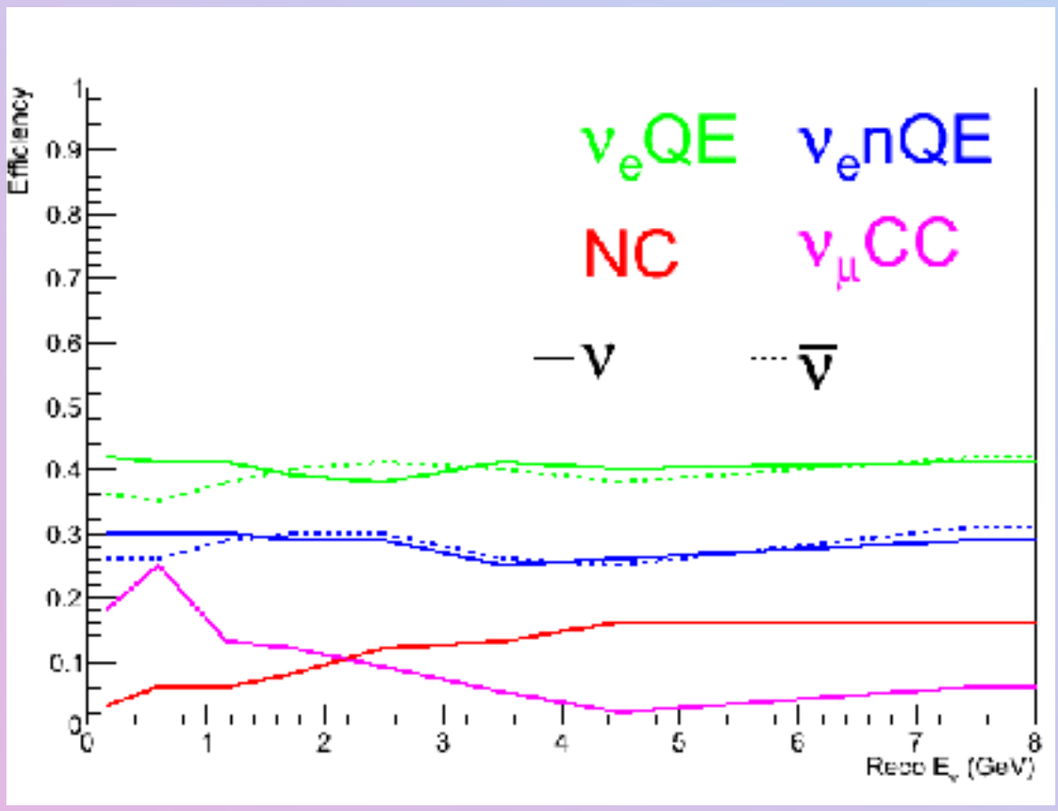
- All DAQ monitoring data (data quality, networking status, application status etc…) is stored in Elasticsearch, an open source, noSQL database, which accepts JSON data from many sources throughout the detector and DAQ machines.
- All monitoring is then done through a series of dashboards on the web based Kibana UI
- Flexible and extensible with plenty of extensions available for any input data type.



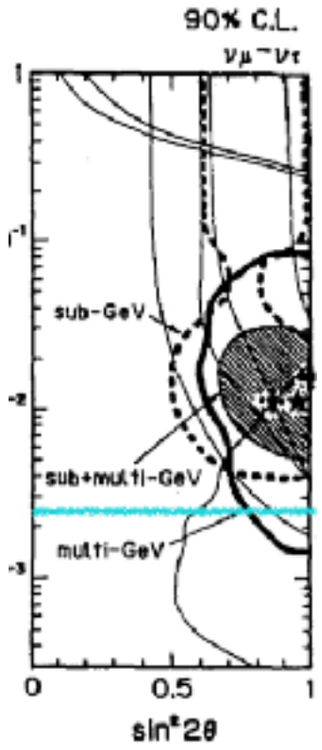
# Reconstruction

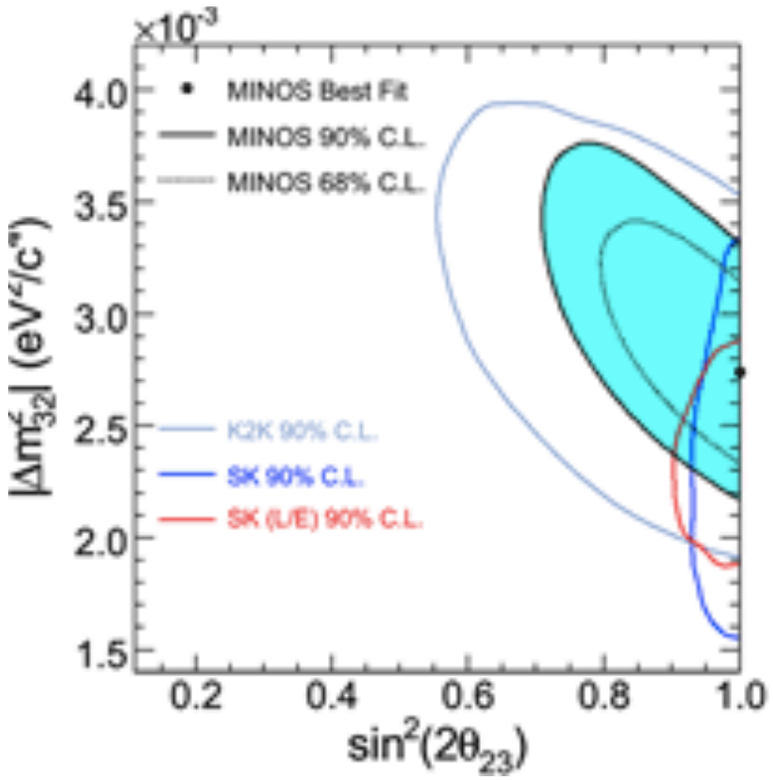
- Deep learning improved all aspects of the reconstruction to compete favourably (in simulations) with “old" Super-K reconstruction
  - No self-respecting new experiment will go without machine learning!
- Our first stab at this has improved our event efficiency and purity by $30\%$ over old approach based on MiniBooNE algorithm
- It sped up the reconstruction from $2.5$ minutes to $1$sec / event!
- Pretty good basic bottom line, paper submitted to journal.

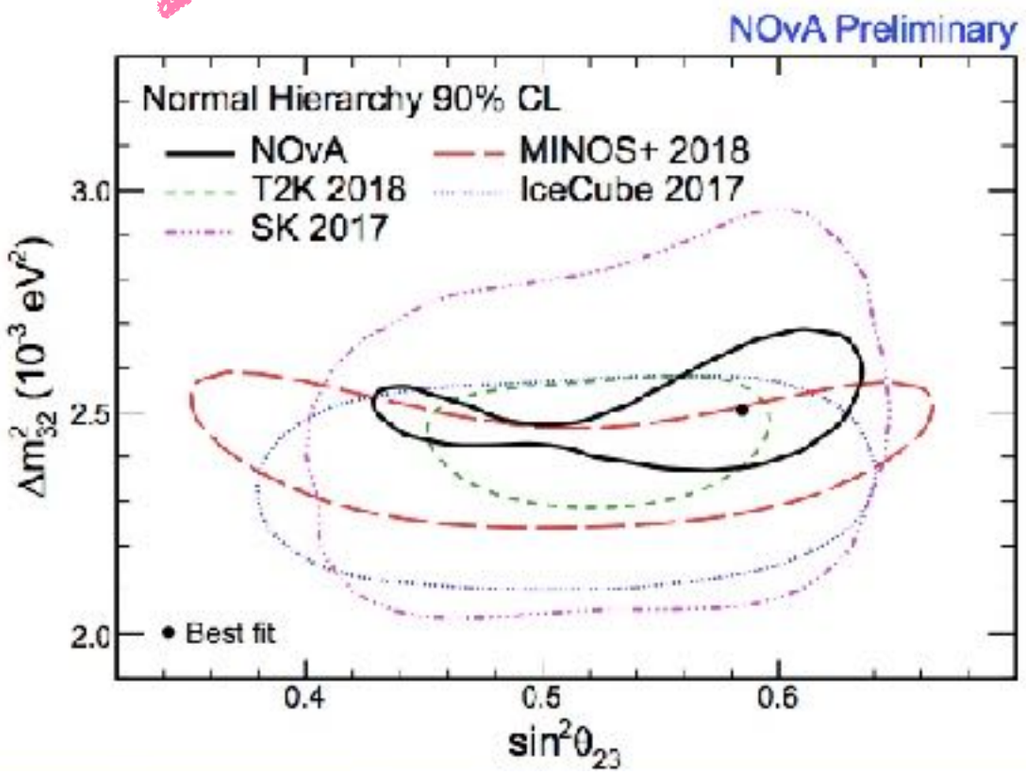


# 2018

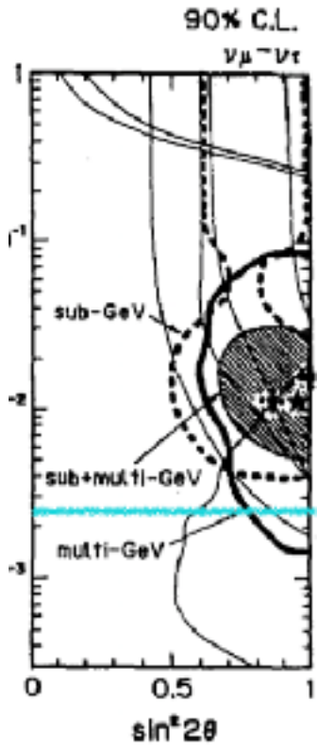


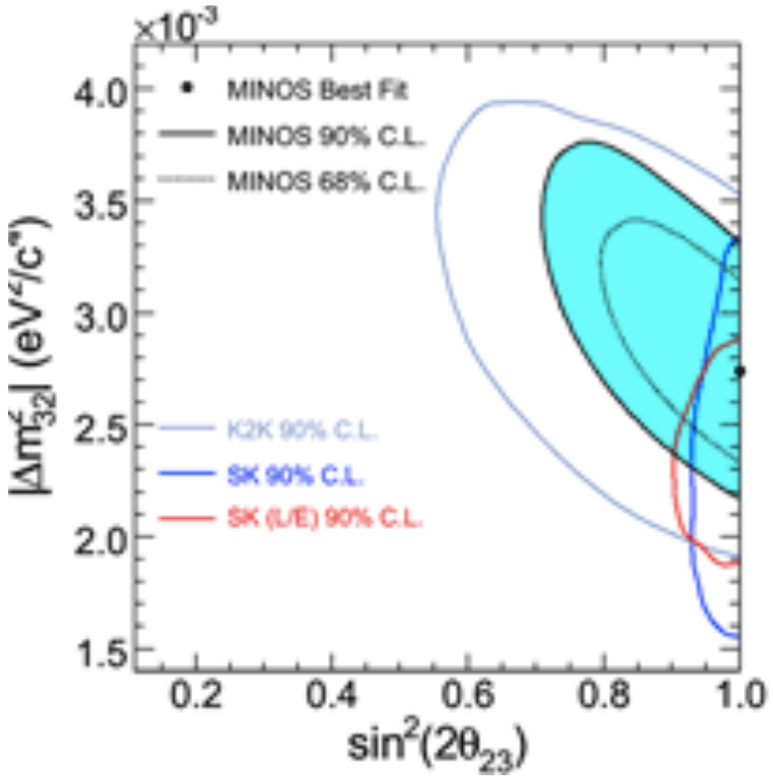



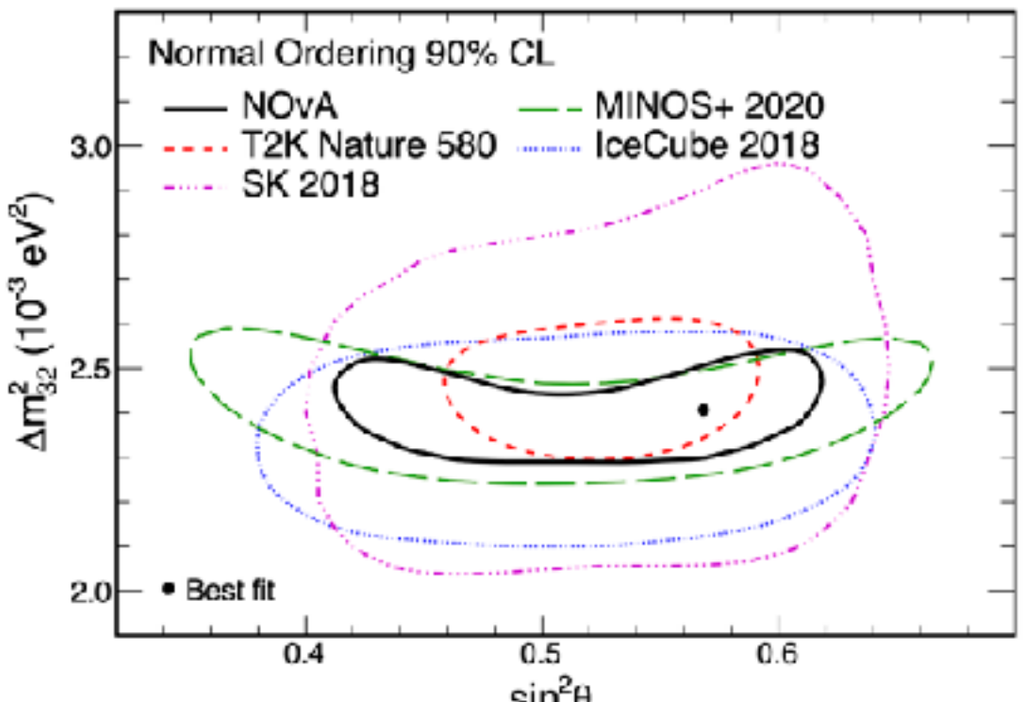




- This plot has taken almost 30 years to achieve (1994-now)

# 2020



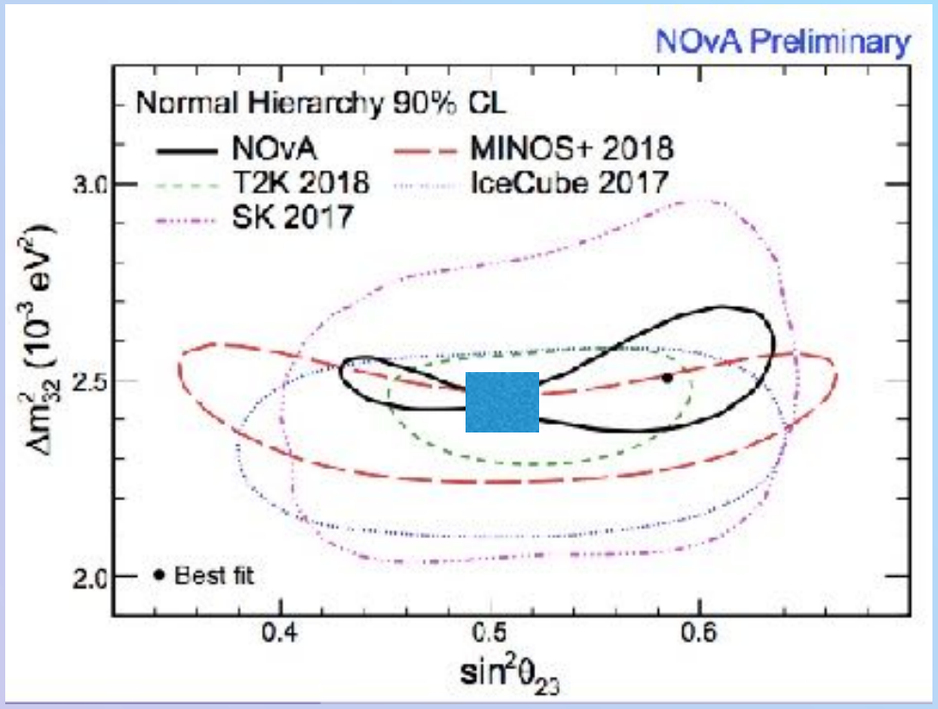



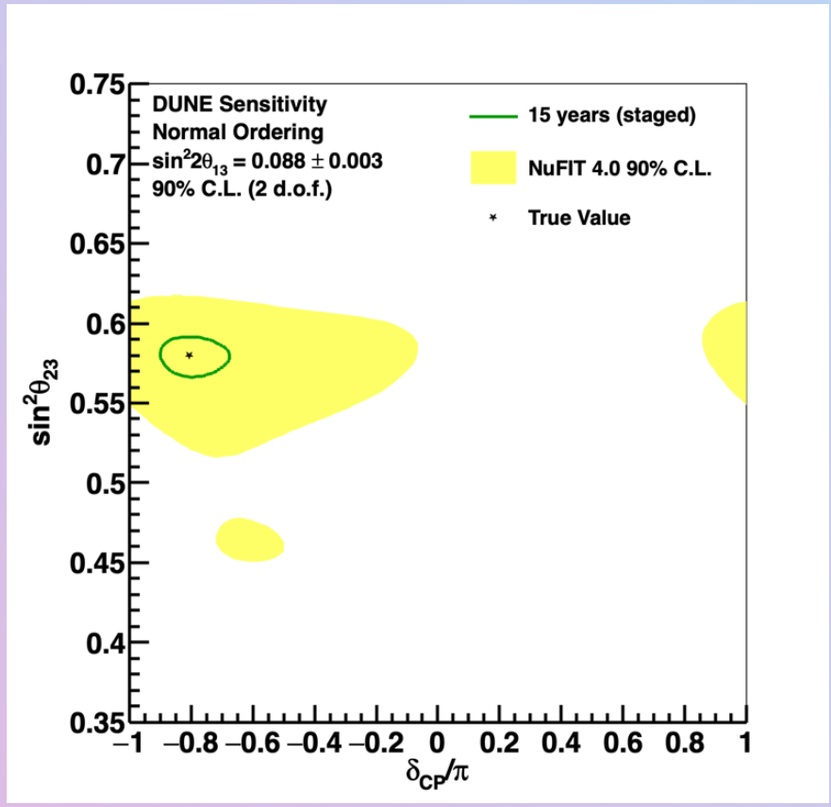




- This plot has taken almost 30 years to achieve (1994-now)
  - And it is still changing…a lot!
- What if $\sin^2\theta_{23}$ is maximal?
  - Is this evidence of a new symmetry? A Big Thing?
  - Are there any theoretical insights that would tell us what to do next?
    - no.

# The potential for new insight

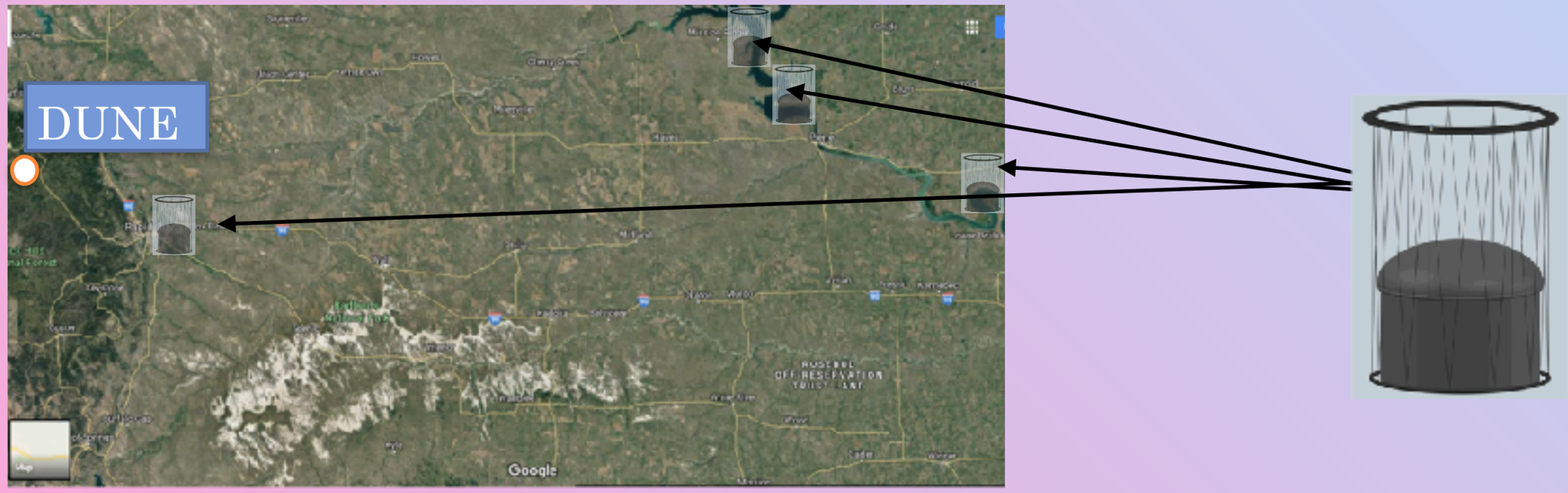
- DUNE can measure $\theta_{13}$, $\theta_{23}$ to 1°
  - this is a ~3% total error
  - current experiments have 3-4% systematic error!
- Starts to be limited by systematics after "only" 400 kt-MW-years
  - that would be 2036 at the earliest
  - Its too late to realise we need more mass by then
  - About $10^{21}$ neutrinos will fly into space each year - a waste!
- Will this be enough precision?
  - will we ever be able to say $\sin^2\theta_{23}$ is maximal and there is a symmetry that says so?
- What do the theorists say?
  - not enough on this topic IMHO



# The idea

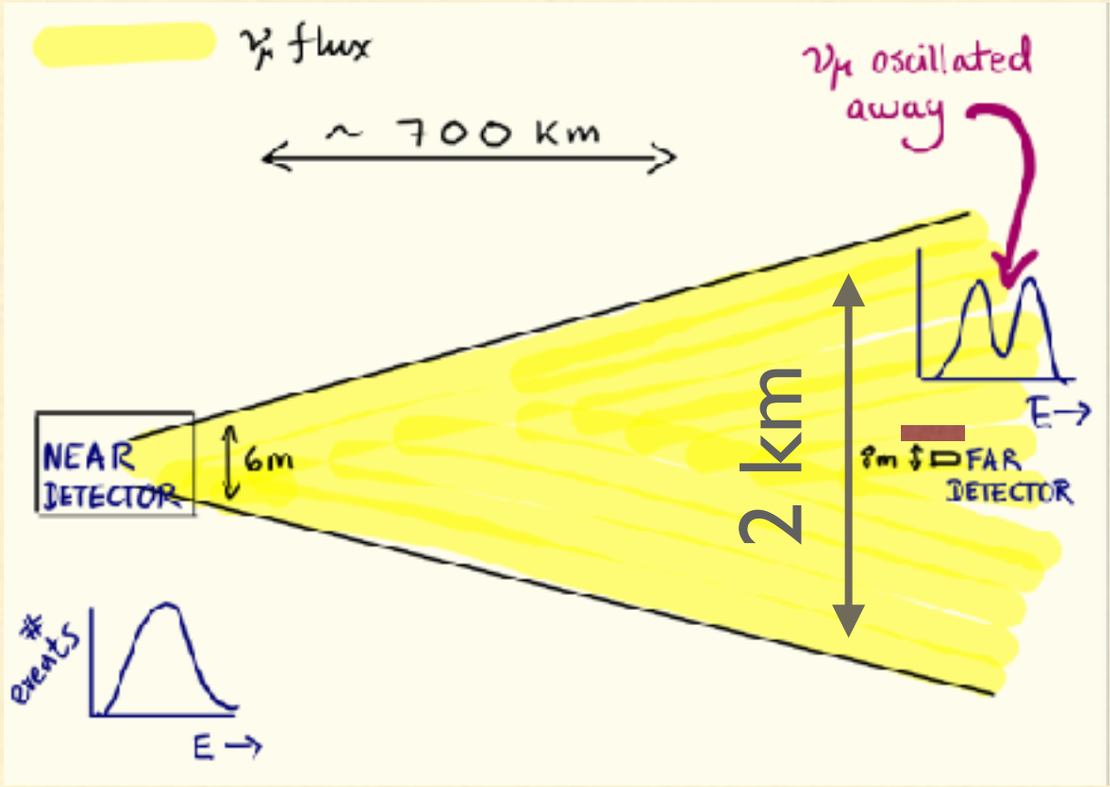
- Overarching idea is a Mton array of $100$ kton CWCs (CHIPS Water Cherenkov) detectors
- Profit from systematics cancellation instead of systematics limitation
- Profit from large detector mass for “faster” measurements
  - nothing is fast in neutrino physics
- Profit from relatively simple and speedy construction
  - $14$ people built first $5$kiloton CHIPS in about $6$ months
- Use reservoirs near Lead, S. Dakota (Oahe Lake, Pactola Lake as examples)
  - look for others when time permits (ROAD TRIP!!!!)




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

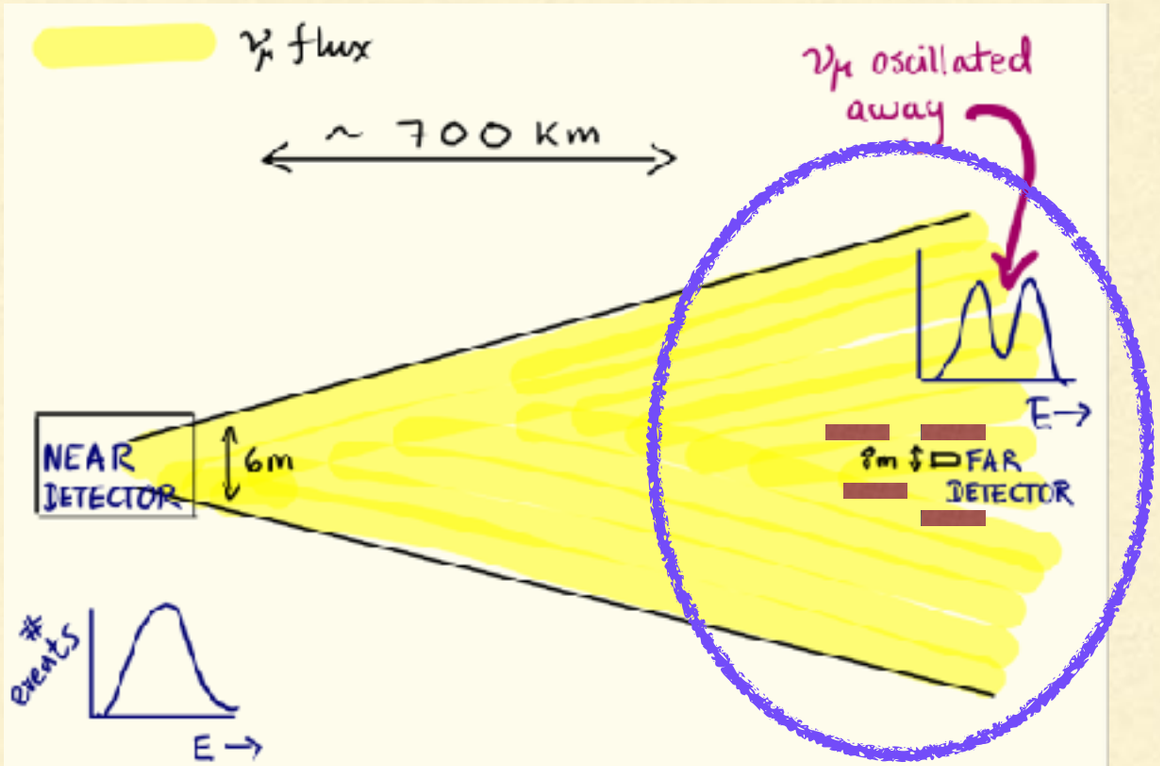
# . . . WE CAN DREAM!

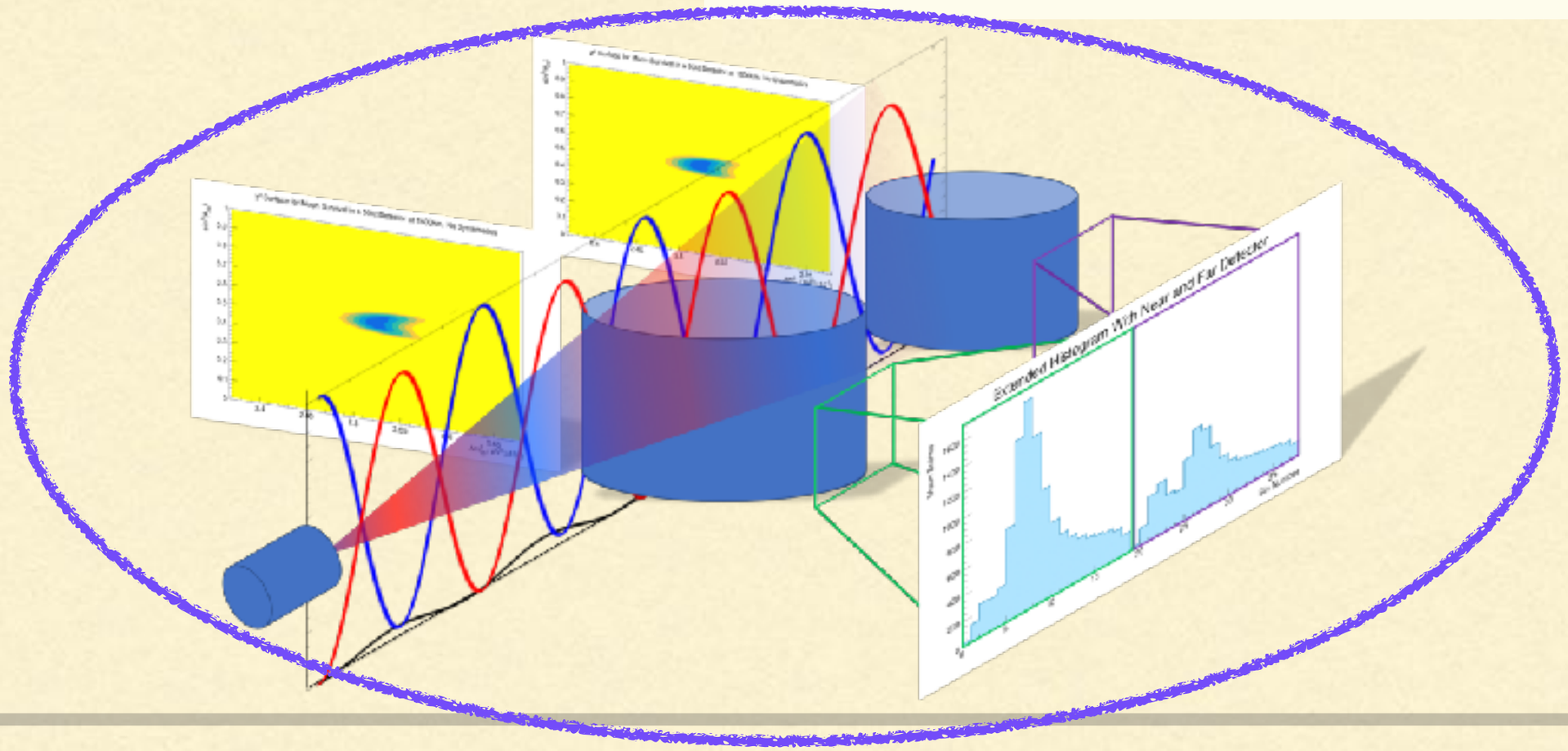
- The standard way to measure neutrino oscillations, like the MINOS experiment, was to have as-similar-as-possible near and far detectors, and look at the difference
- beam small compared to detector at ND, large compared to detector at FD
  - differences in flux, acceptance, reconstruction and energy measurement between the two detectors limit precision to ~4%
  - very high rate in ND requires different electronics and selection criteria and different detector technology at DUNE!
- This approach has outlived its usefulness : we no longer have to prove neutrino oscillations exist



# NOW WE CAN DREAM!

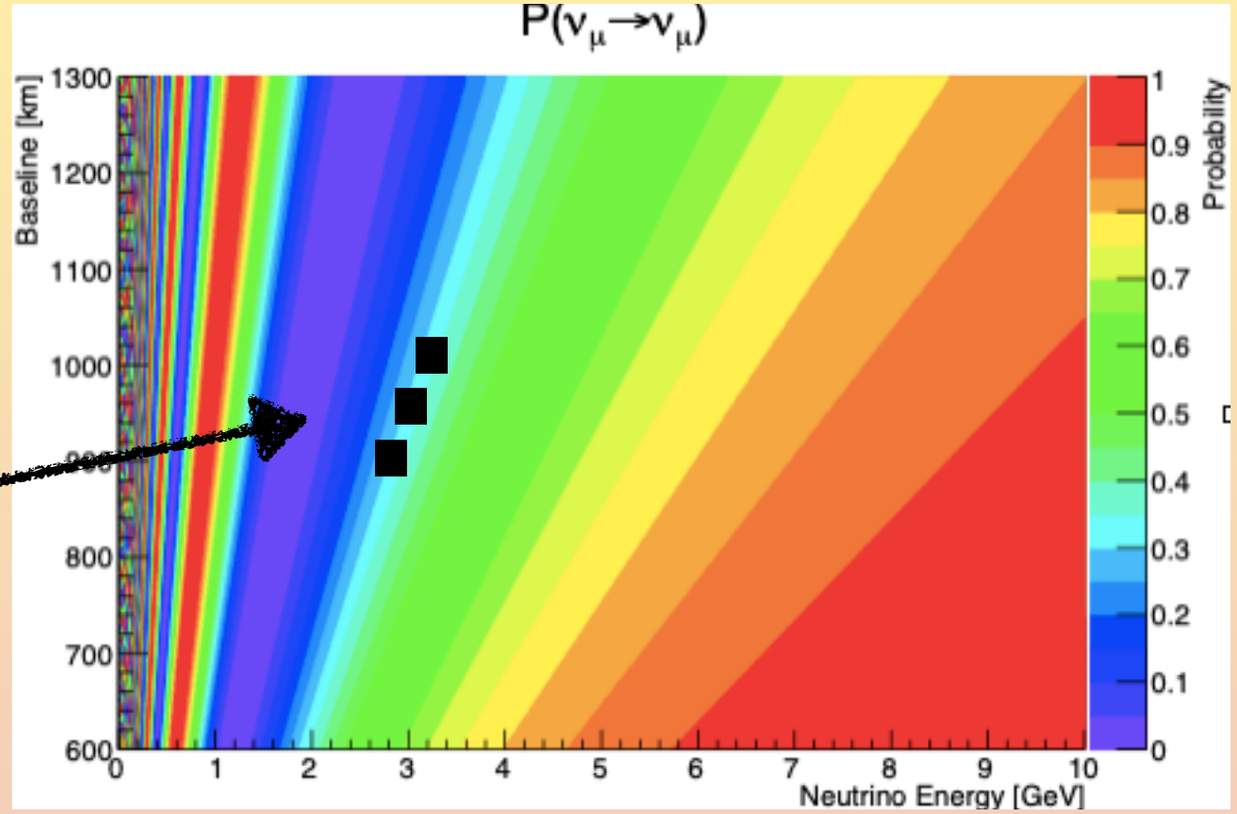
- Move to a new paradigm, where we accept oscillations take place and use an array of large identical detectors to measure small differences in oscillation in identical Far detectors, and *almost* identical beam
- These will **cancel** the dominant systematic errors, while at the same time record a very large number of events

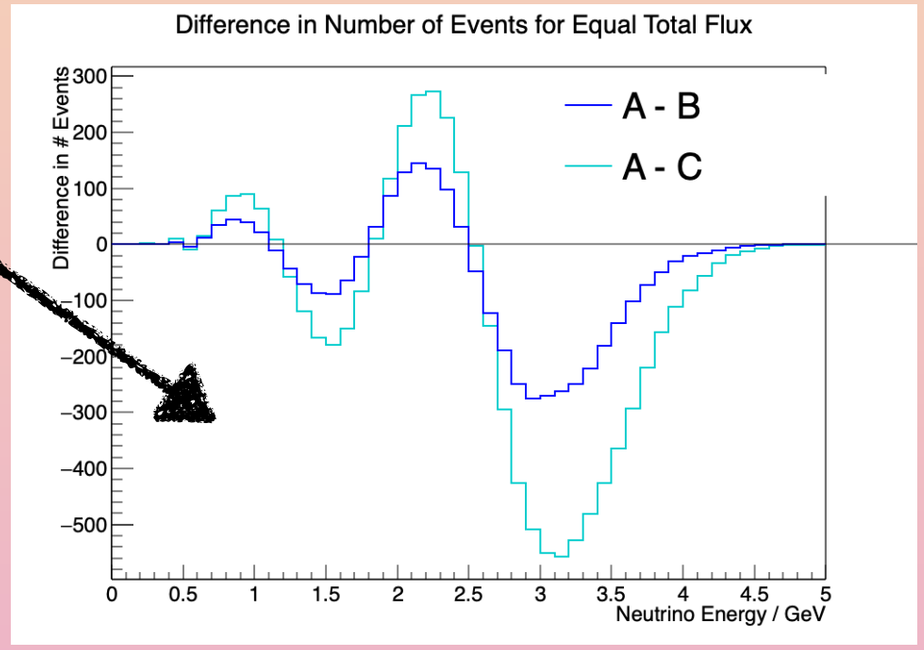


# CHIPS array @ LBNF

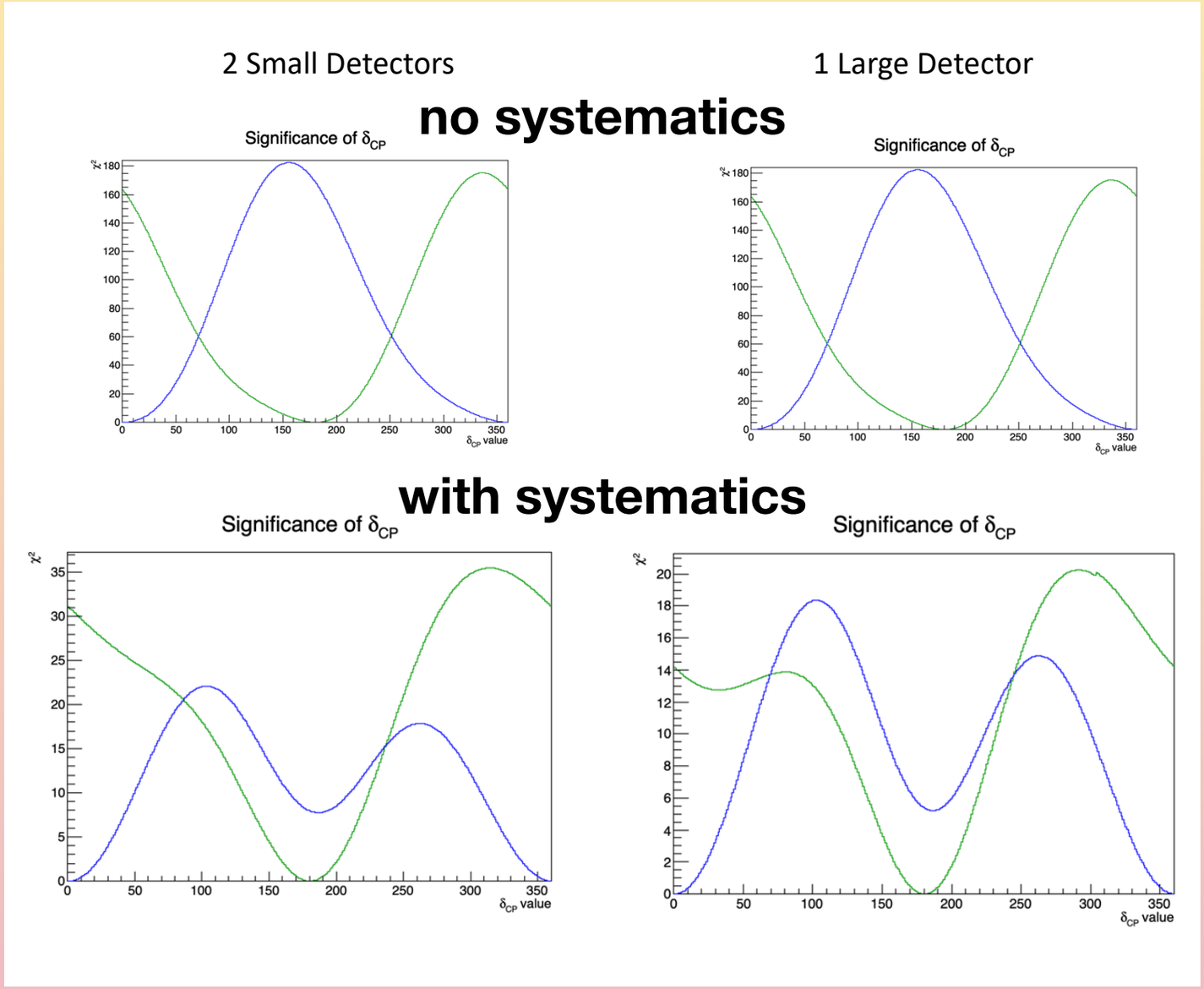
- Initial studies of the precision advantage of several identical detectors show promise
- Simple construction (always good) such that $P_1$-$P_2$ = 0, $P_2$-$P_3$=0, all systematics cancel
- Plot at right shows the difference between 3x100 kiloton detectors at 900km,950km,1000km, corrected for $1/r^2$
- We will see whether this can become a compelling argument for a complimentary detector (array) to DUNE



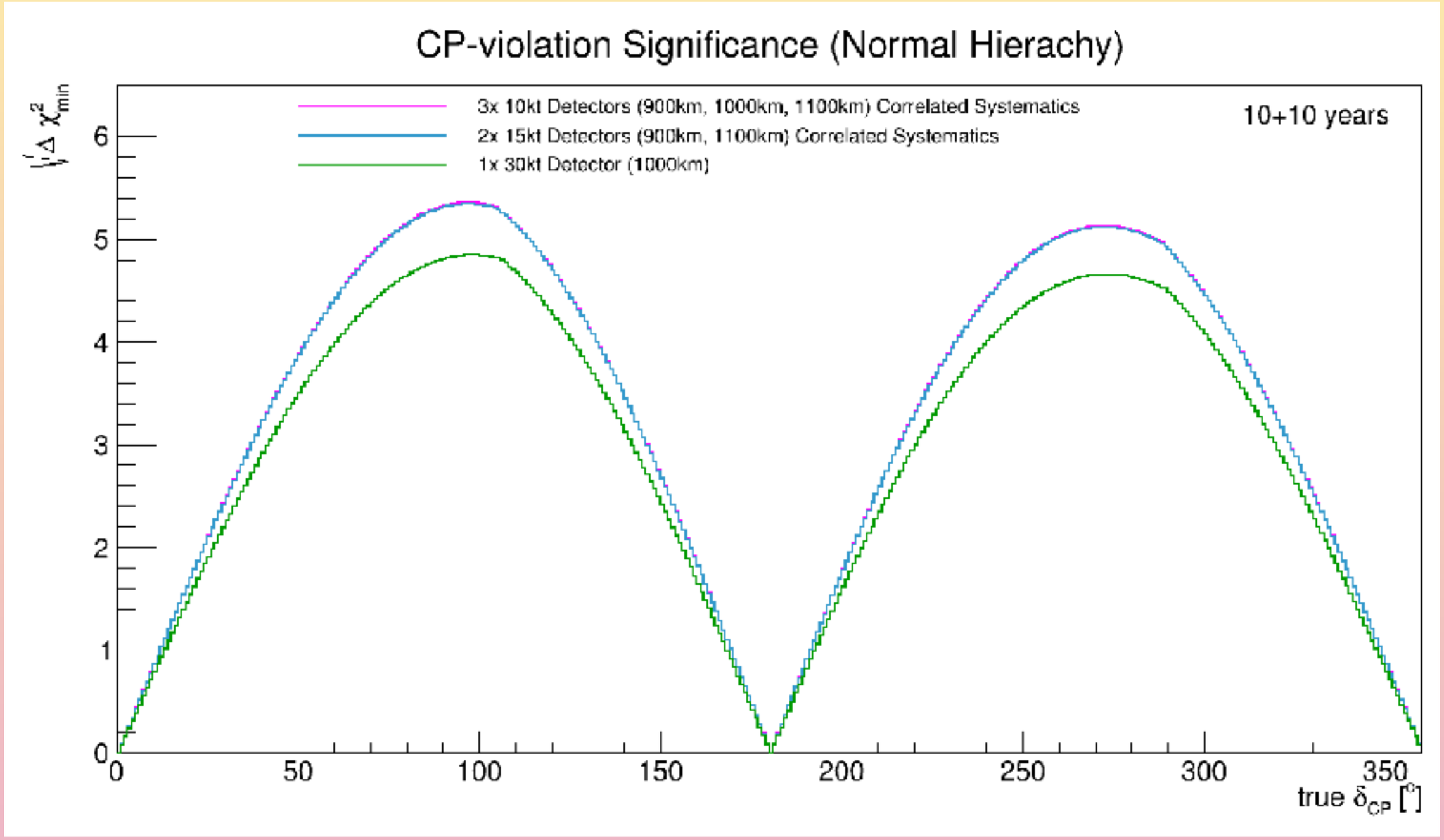



# CHIPS array in principle: SANITY CHECK

- Look at 2 detectors compared to 1:
- Usual (GLOBES) approach is to add systematics in quadrature for different detectors
  - This isn't correct here, as beam, x-sec etc are correlated
    - very conservative but useful for different detectors with different measurements
- More work to be done to make this argument concrete
- Checking this out with MINOS and NOVA
  - First look at two far detectors in the same beam



# Proper systematic treatment in globes



# Meanwhile, back at the Gulag

# Then what happened??

- In early 2020, COVID happened
- US closed borders to non-US
- Lease on land running out
- ERC AdV grant funding running out

- The biggest machine I had ever seen was delivered
- Sad pictures…..
- Detector chopped up and scrapped

April 29th

2022

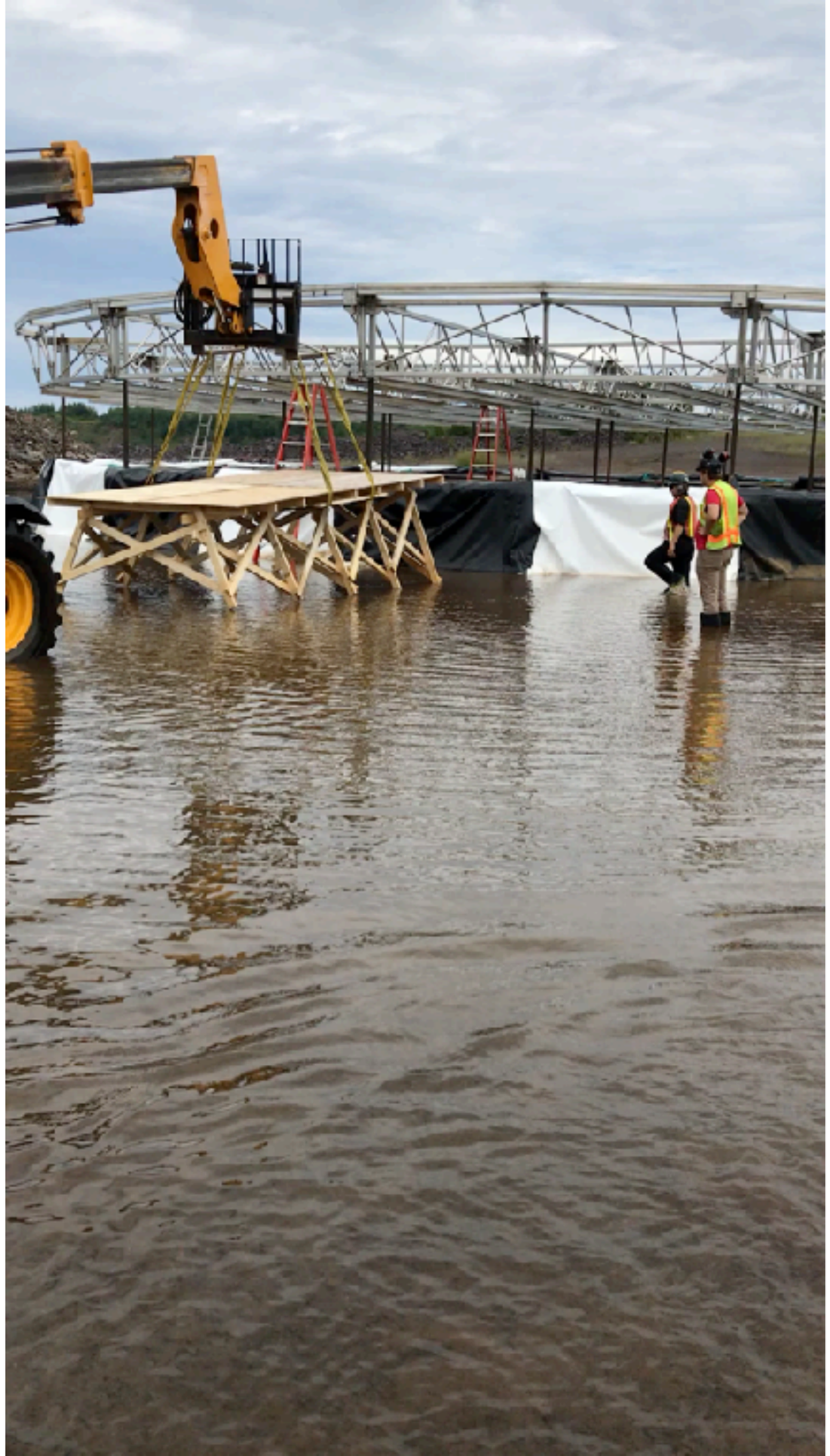
3 years later almost to the day....

# The Outcome

- We showed that you COULD build a detector fast, cheaply and with a small number of people
  - $200-300k/kton (compared to $20M/kiloton)
- After salvaging the detector we found all planes on bottom cap were in tact (PMTs, Electronics, Planes)
- Developed cheap electronics concept for distributed PMT systems
  - $25/channel PMT to disk (excluding PMT of course)
  - development of small format White Rabbit module
- We showed that low density coverage adequate for neutrino beam physics with simulations
- We showed we can trigger a long baseline experiment over the internet

- We did not get any neutrino data with the detector
- The floating dock failed and would need to be re-engineered
- We would be more economical with glued joints in future
  - Time consuming and each one a potential single point of failure

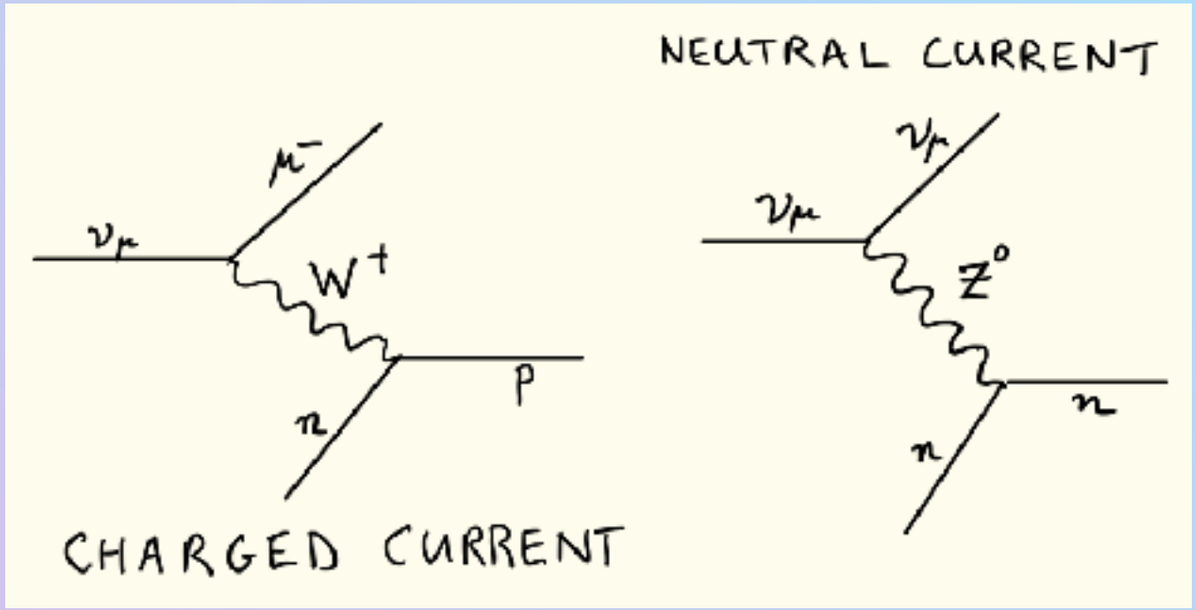
- To **learn** more about neutrino oscillations we need to **be** more (massive) in the future
  - More mass, but smarter than just that!
  - Is a detector array a better way to reach high precision?
  - A ND at short distance adds more systematics and is unnecessary



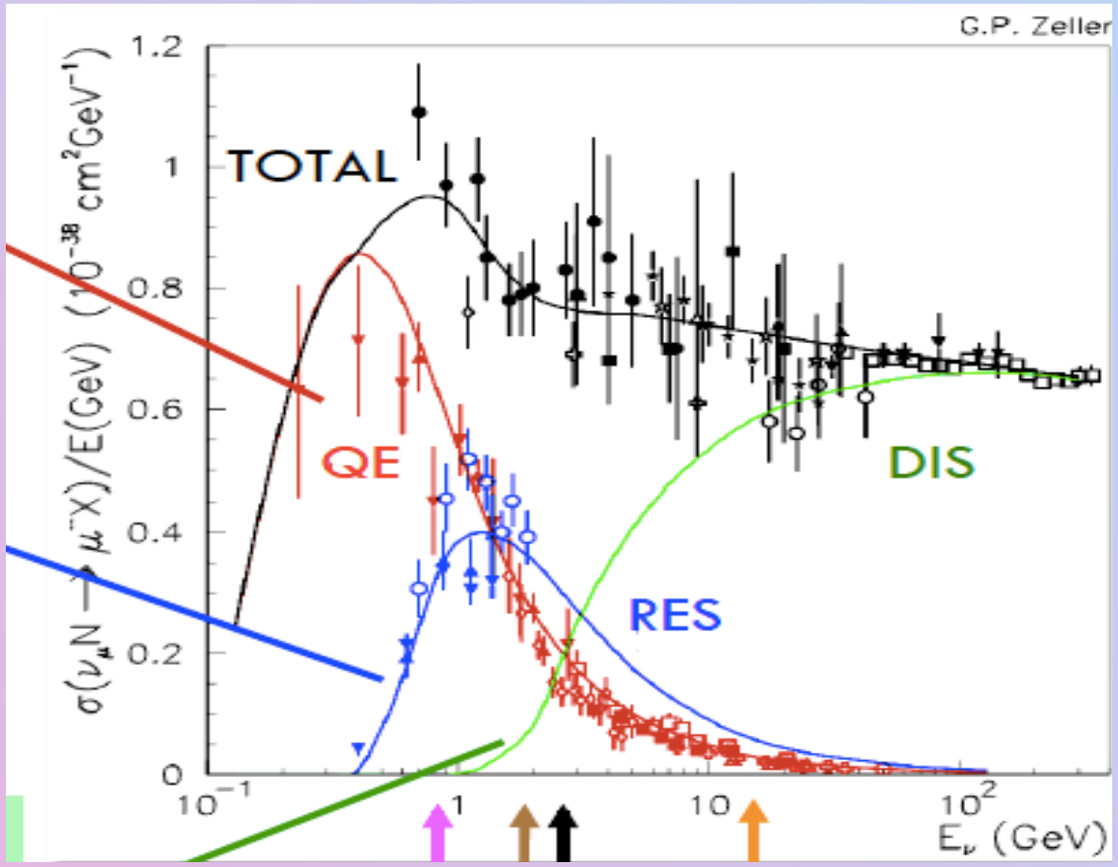
## August 12th

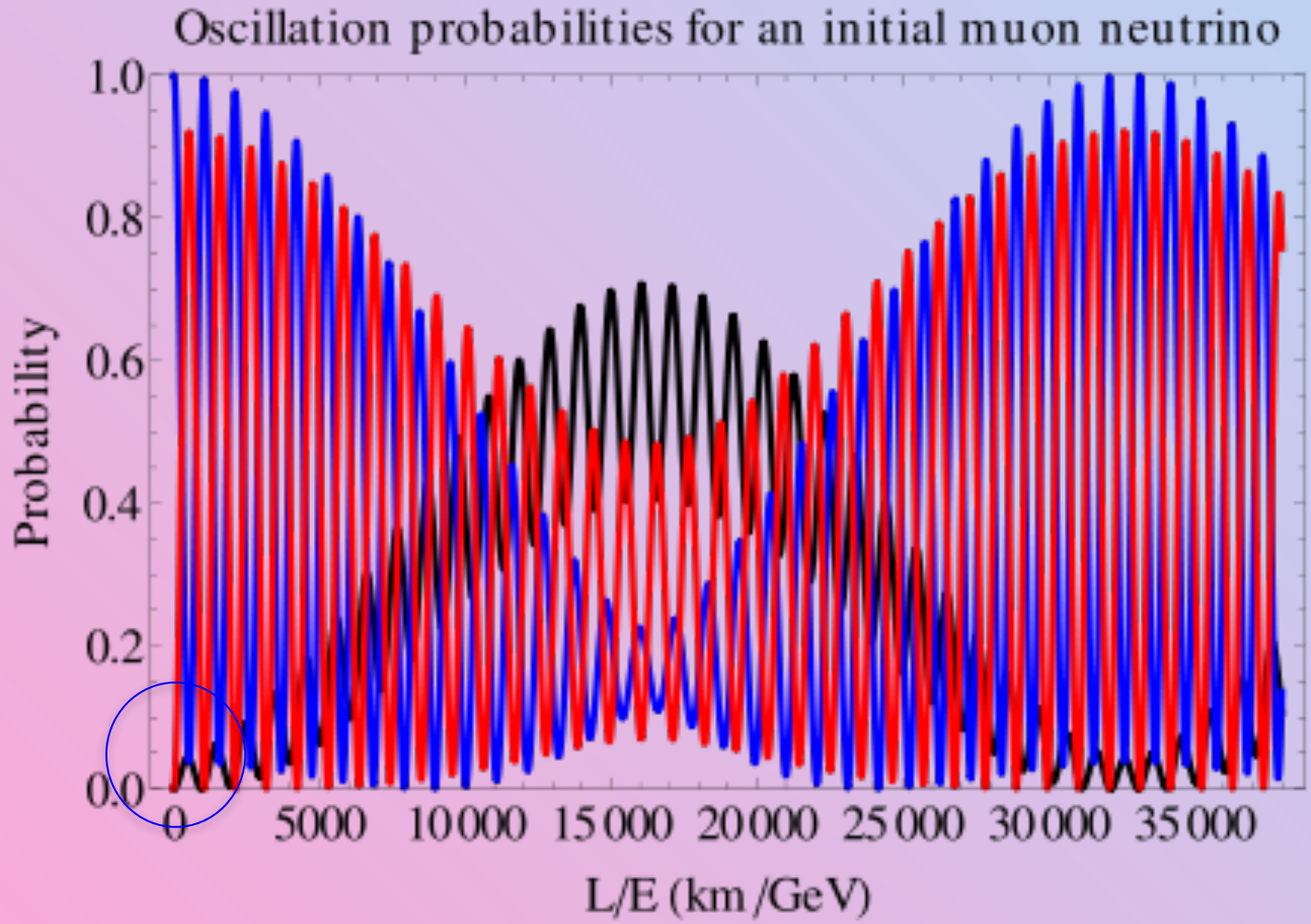
# TO CATCH A NEUTRINO

- Neutrinos are simple things
- They only have two types of interactions
- Its just they don't like to have them




- You need LOTS of n and p if you want to catch a neutrino
- Steel and water are cheap and heavy
- But no amount of measuring them was going to ever give us the insight that their oscillations have



# Neutrino Oscillations in practice

- The **disappearance experiments** start off with $\nu_{\mu,e}$ and look for disappearance of $\nu_{\mu,e}$ (no CP violation allowed)
- The **appearance experiments** start with $\nu_{\mu}$ and look for appearance of $\nu_{e}$ (CP violation IS allowed)
- L/E is (time) the experiment variable, for the known $\Delta m^2$s as shown