Questions in Experimental Neutrino Physics

- part 2: The Known Unknowns

Andrzej M. Szelc
University of Manchester

"known" Questions in ν-physics

(answered or being answered)

- Experimental neutrino physics in the last decades was driven by the following questions:

- why do we see less neutrinos from the sun?

- where are the atmospheric νs?

- could this be due to oscillations?

- What are the parameters of Oscillation ?

- Especially, is θ_{13} non-zero?

- Is the θ_{23} mixing maximal?

- what is going on with neutrino interactions?!

Yesterday's news.
Or lecture.

Big Questions in ν-physics

•Experimental neutrino physics in the next decade (and beyond) will be driven by the following questions:

- ***how much do neutrinos weigh?***
- ***what is the nature of the ν?***

β decay and 0νββ decay

- ***which neutrino is the heaviest and which is the lightest (MH)?***
- ***do neutrinos violate CP?***

long-baseline neutrinos

- ***is our picture correct?***
- ***are there more than 3 kinds of neutrinos?***

short-baseline neutrinos

$\nu_\mu \rightarrow \nu_e$

(0.1-10)GeV En. range

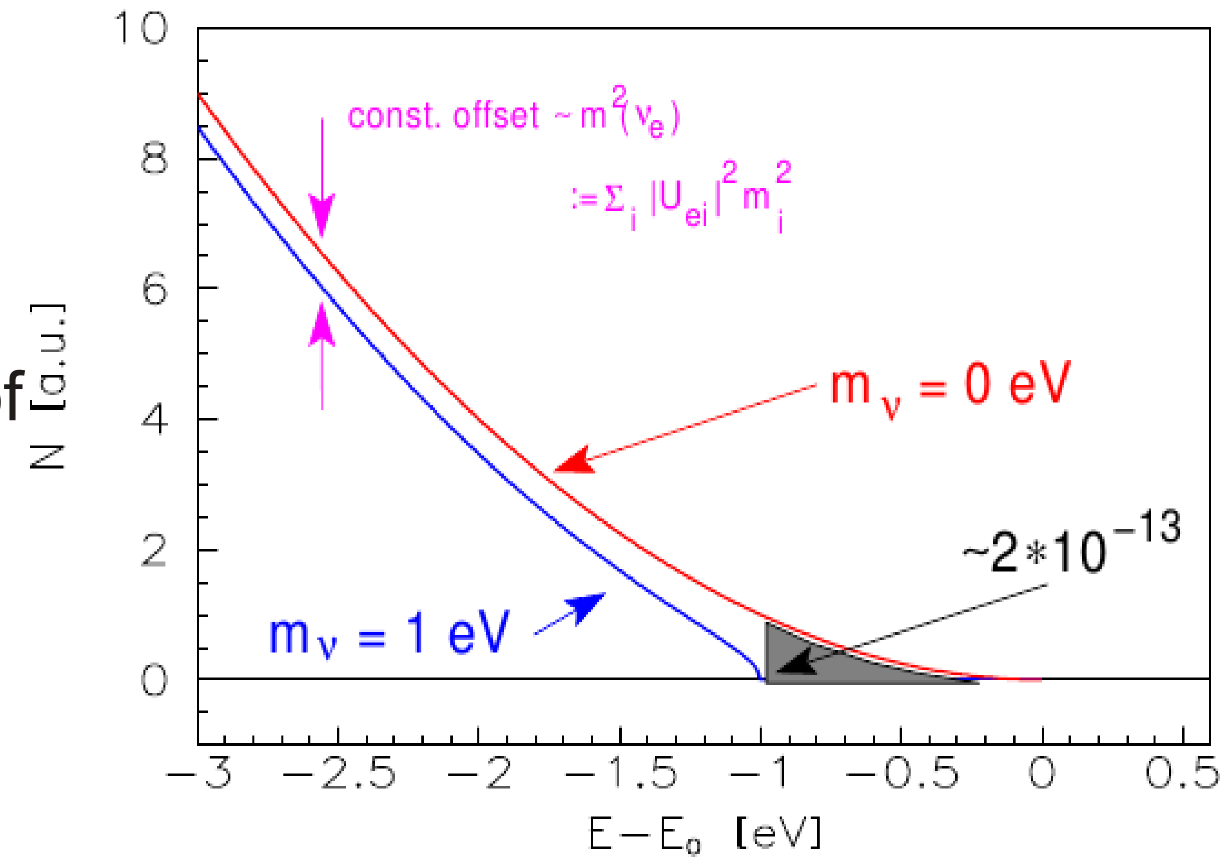
Neutrino masses

- **Known constraints:**
  - Non zero (at least one must be > 0.05eV)
  - Direct measurements put it < 2eV
  - If Inverted Hierarchy $\Sigma m\nu > 0.1$eV
  - Cosmological constraints (model dependent?) $\Sigma m\nu < 0.23$ eV
- **Why are they so light?**

β-decay to measure ν-mass

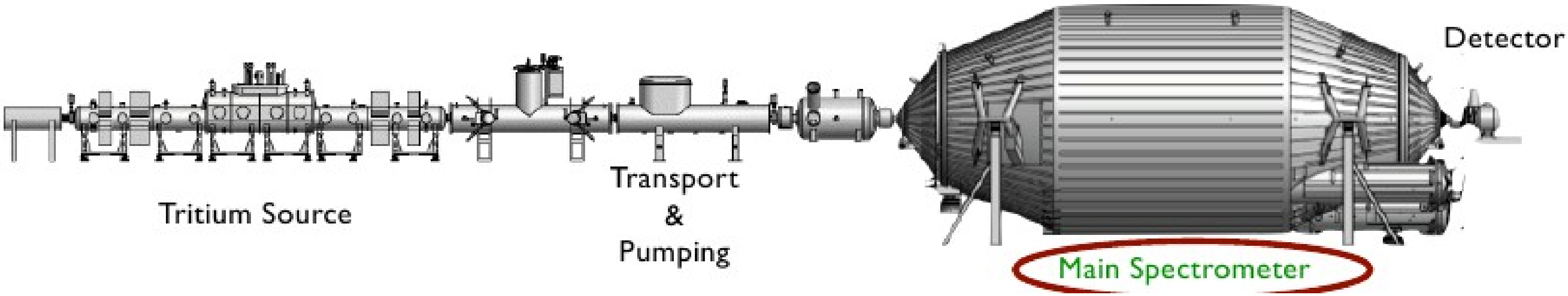
Tritium is a good candidate for mass measurements:

- endpoint energy of 18.6 keV
- Lifetime 12.3 yrs
- Simple structure minimizes systematics



G. Drexlin et al., Adv. High Energy Phys. 2013

KATRIN

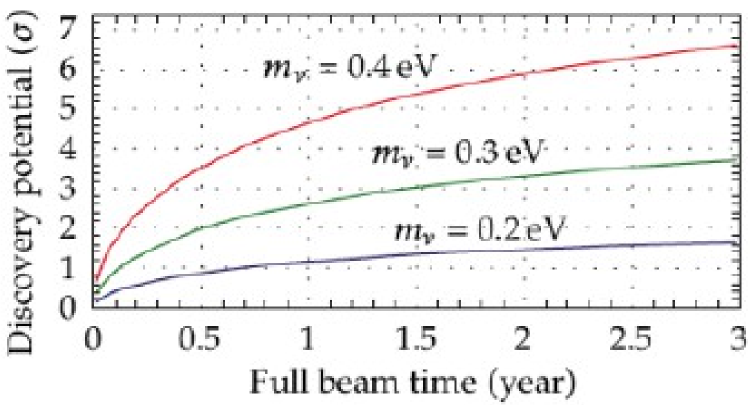

Detector
Tritium Source
Transport
&
Pumping
Main Spectrometer

KATRIN

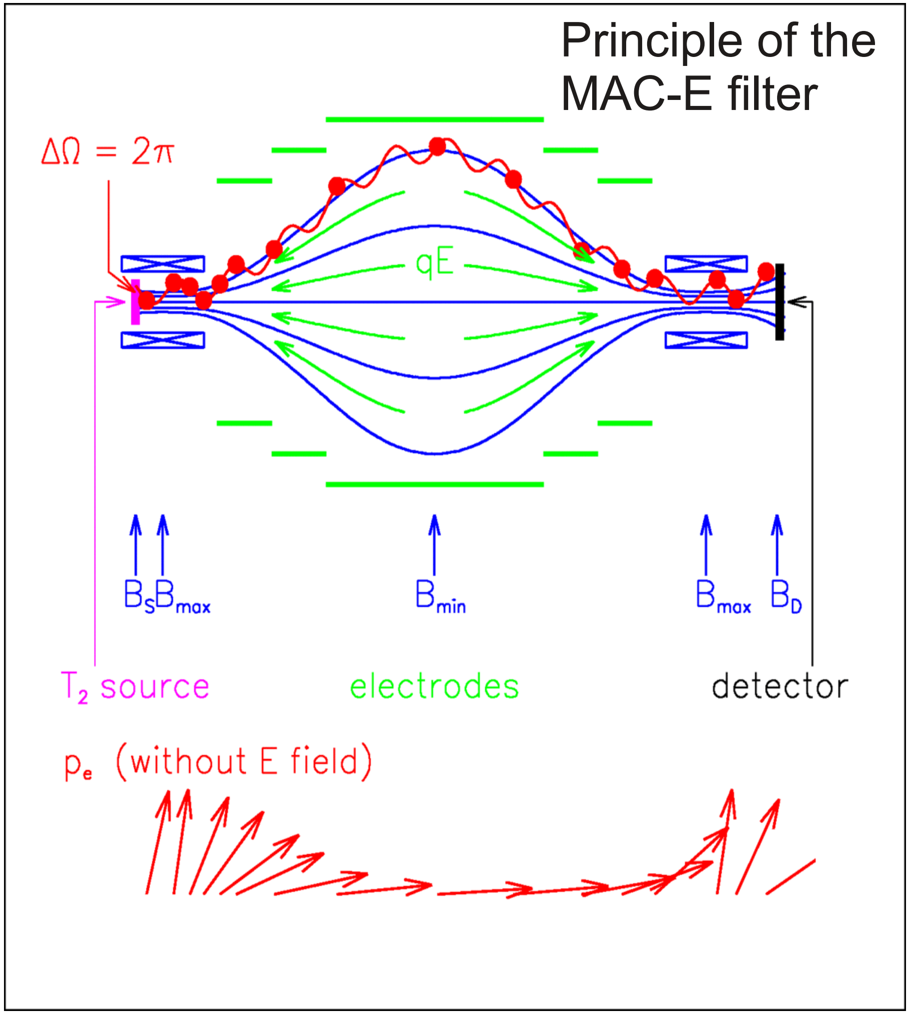
Works using the MAC-E filter (effectively high pass filter)

$$\mu = \frac{p_\perp}{B} = const$$

Start foreseen for 2016.



Cannot really scale up from here.

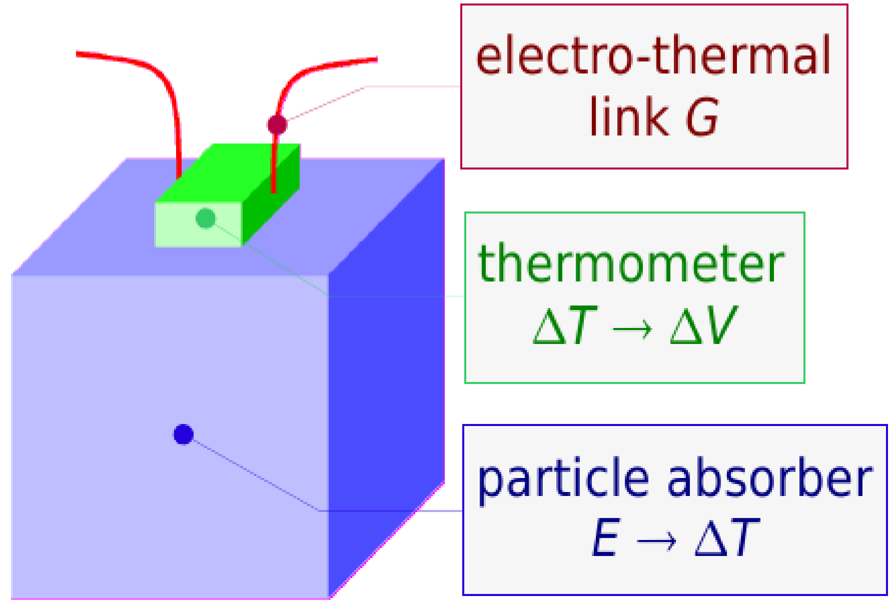


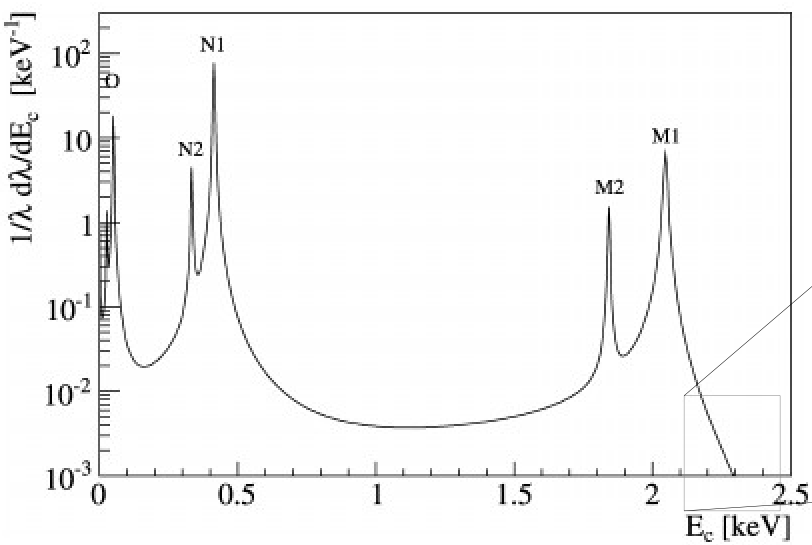
Other ideas: Holmium

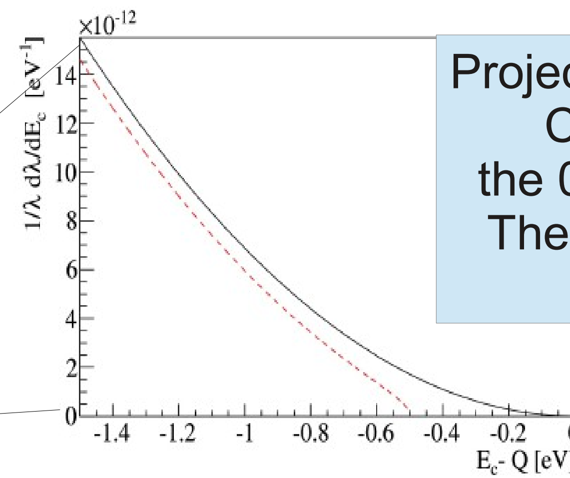
Electron capture on Holmium (HOLMES, ECHO)

$$^{163}\mathrm{Ho}^{+} + e^{-} \rightarrow {}^{163}\,\mathrm{Dy}_i^{*} + \nu_e \rightarrow {}^{163}\,\mathrm{Dy} + E_i + \nu_e\ .$$

Low temperature Bolometric detectors – all energy contained.







Projected sensitivities Could reach the 0.2 eV range in The next “several” years

Other ideas: Frequency

PROJECT 8

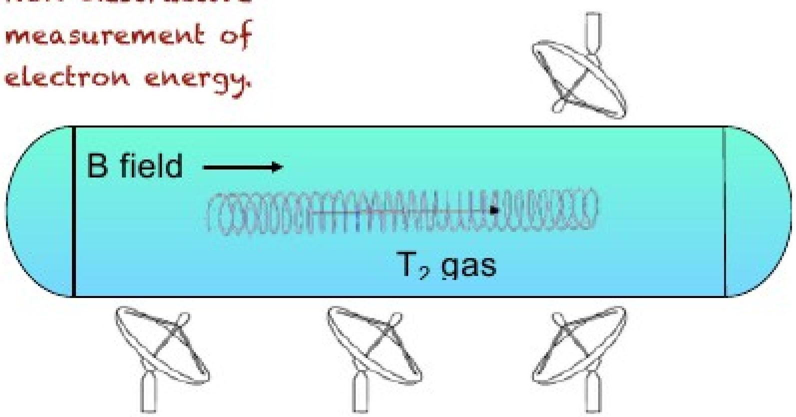
Frequency Approach

$^3H \rightarrow {}^3He^+ + e^- + \bar{\nu}_e$

$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

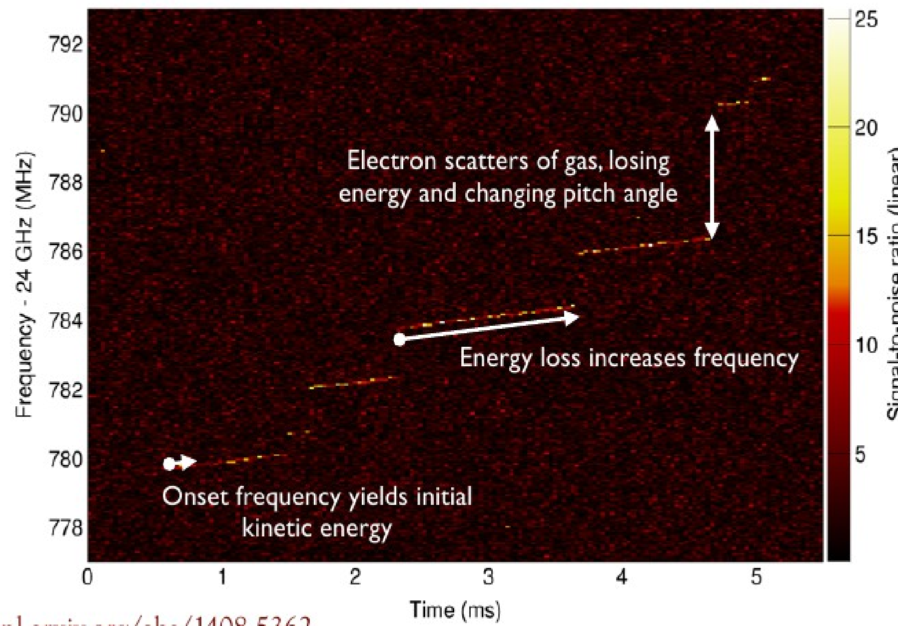
First tests with a ^{83}Kr source

- Non-destructive measurement of electron energy.



B. Monreal and JAF, Phys. Rev D80:051301

Project 8 "Event Zero"



//lanl.arxiv.org/abs/1408.5362

Projected sensitivities
In the 0.2 eV range (2018) and even
In 0.05 eV range (2018+)

Big Questions in ν-physics

- Experimental neutrino physics in the next decade (and beyond) will be driven by the following questions:

- ***how much do neutrinos weigh?***
- ***what is the nature of the ν?***

β decay and 0νββ decay

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long-baseline neutrinos

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short-baseline neutrinos

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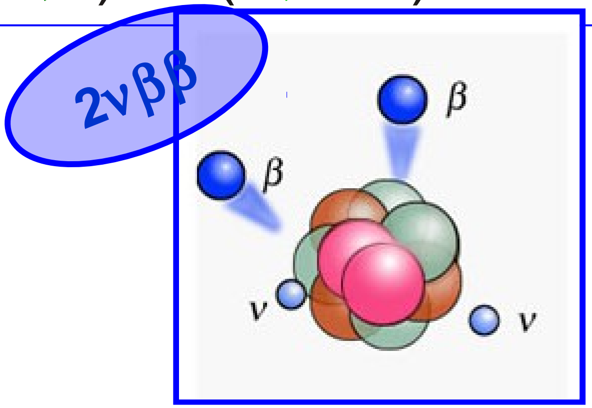
(0.1-10)GeV En. range

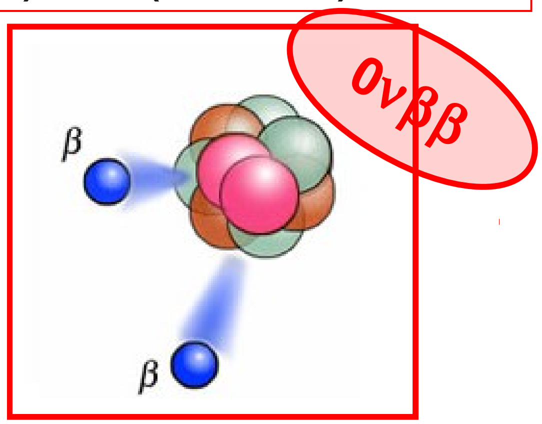
Dirac vs Majorana

- Of the building blocks of matter (quarks, leptons), neutrinos are the only charge-less.
- Thus, they are allowed to have a Majorana mass term.
- In such case, the neutrino is its own anti-particle and we could observe $0\nu\beta\beta$ decay.

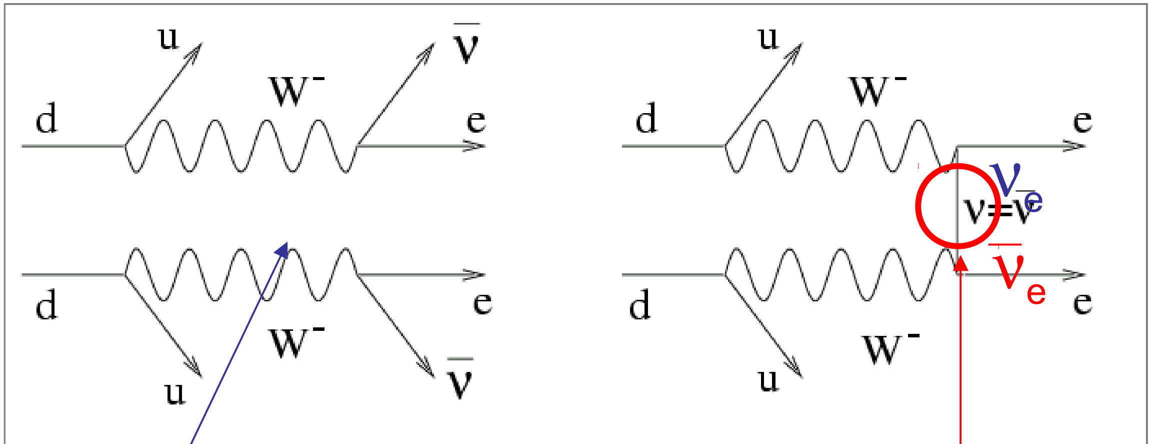
$(A,Z) \rightarrow (A,Z+2) + 2e^{-} + 2\bar{\nu}_e$



$(A,Z) \rightarrow (A,Z+2) + 2e^{-}$



0νββ decay



Only possible for certain isotopes, where the single beta transition is forbidden

Standard process
two "simultaneous" beta decays

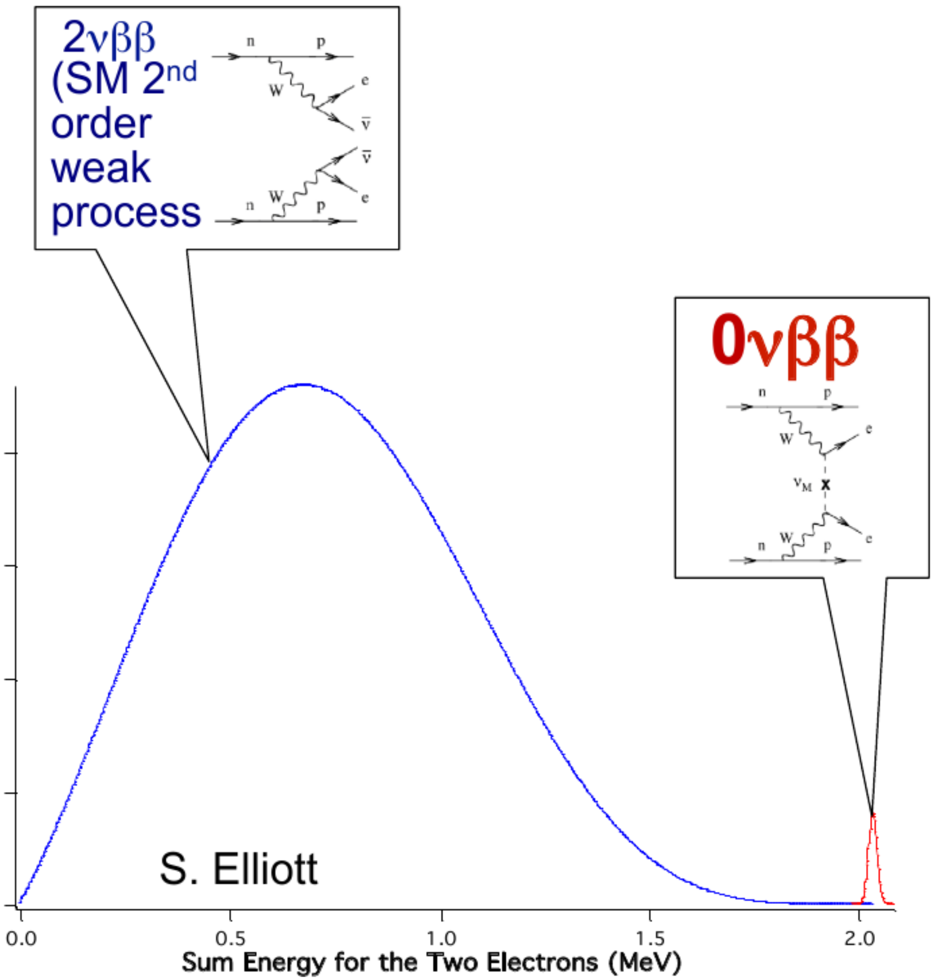
0ν-DBD
a virtual neutrino is exchanged between the two electroweak lepton vertices

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}\ |M^{0\nu}|^2\ |\langle m_\nu\rangle|^2/m_e^2$$

$$\langle m_\nu\rangle^2 = |\sum_i U_{ei}^2 m_{\nu i}|^2$$

never observed
$\tau > 10^{25}$ y
(except a now excluded claim)

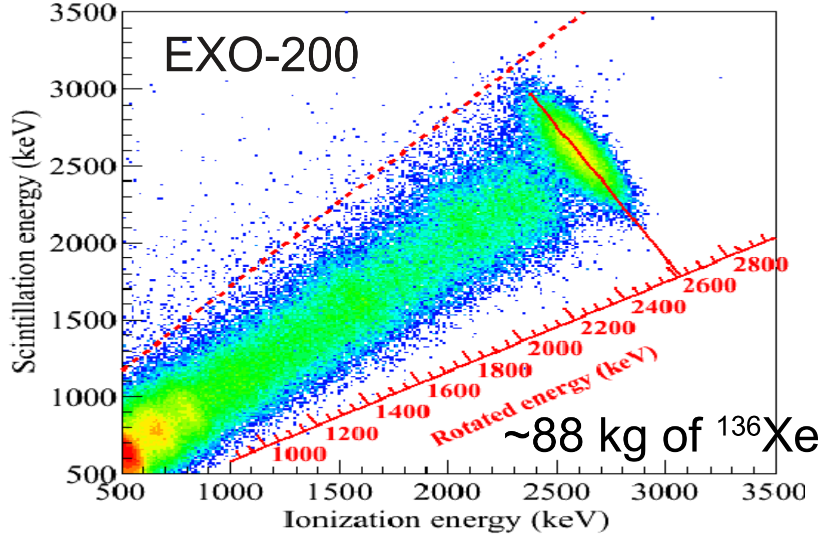
Approaches to measurement



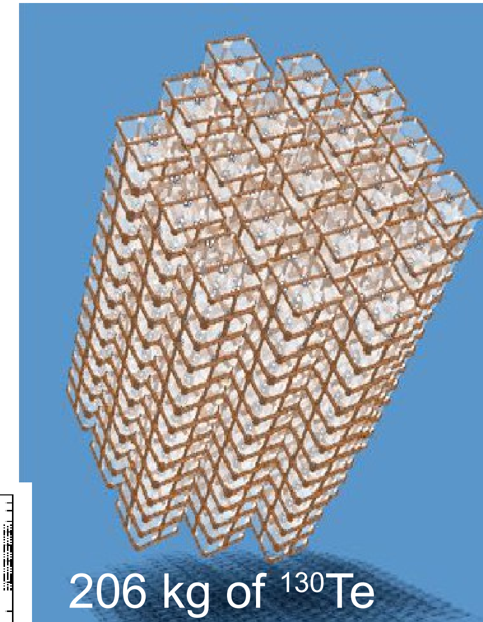
- Large mass to increase statistics.
- Increase energy resolution.
- Reconstruct 2 electron kinematics to reduce background.
- Either way, to cover the IH region need sensitivity 0.1 -1 counts / y ton

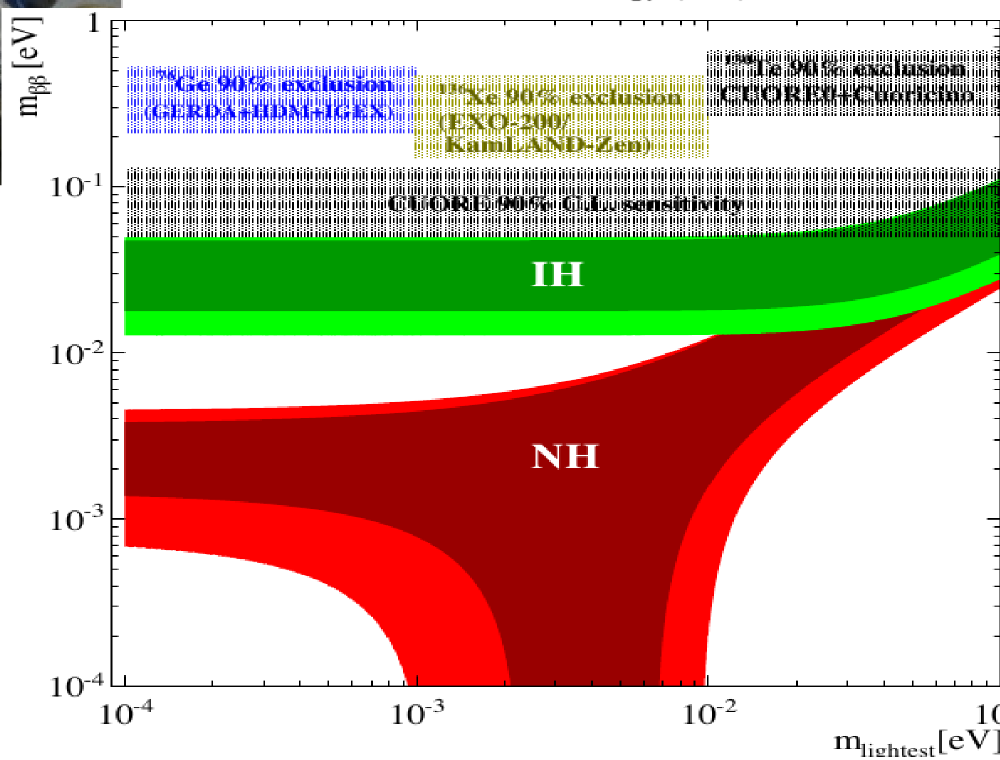
Recent Results

GERDA



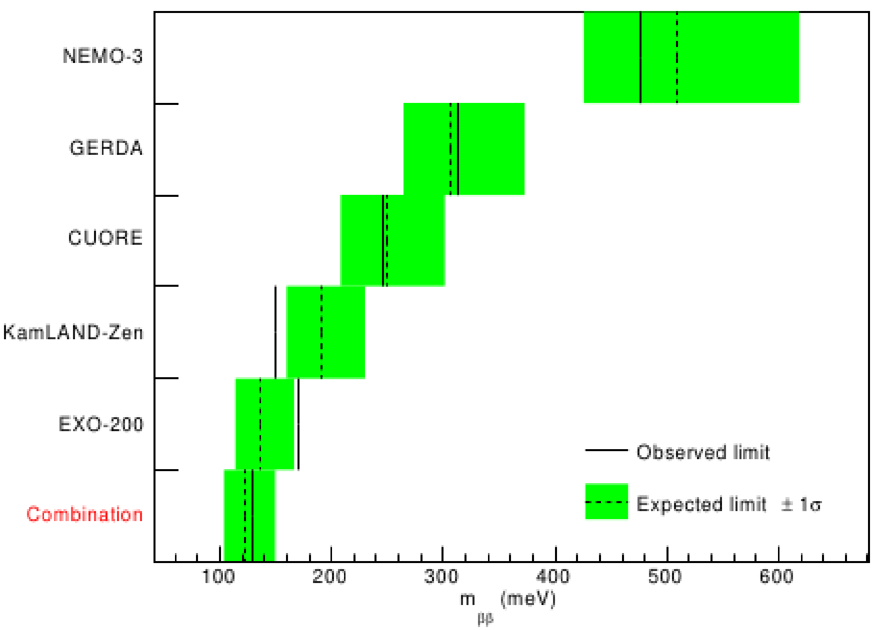
CUORE

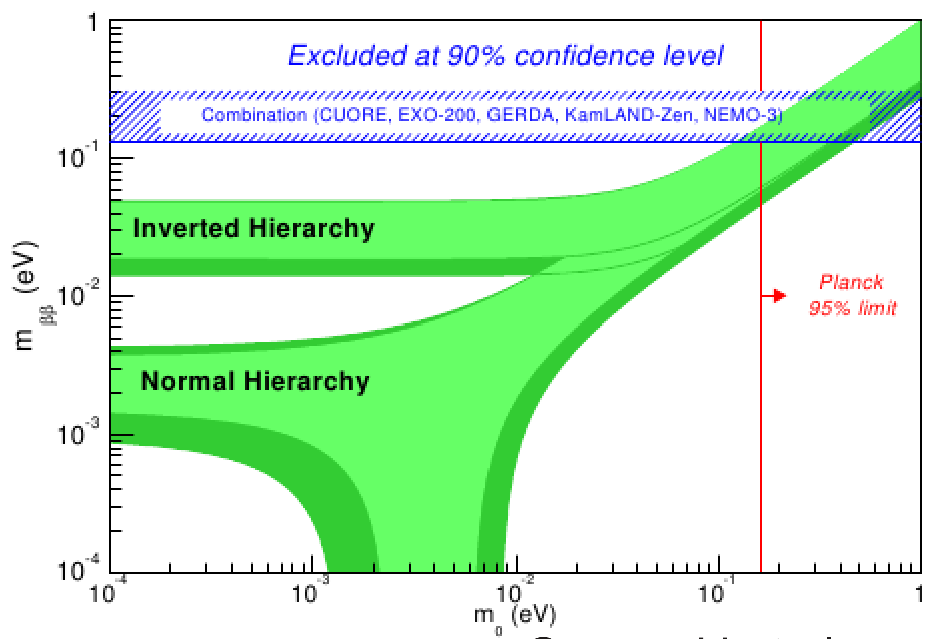




Merging the results

- First attempt to combine different measurements into a single limit.
- Thic combination requires normalizing the isotopes via nuclear matrix elements.





Guzowski et al.

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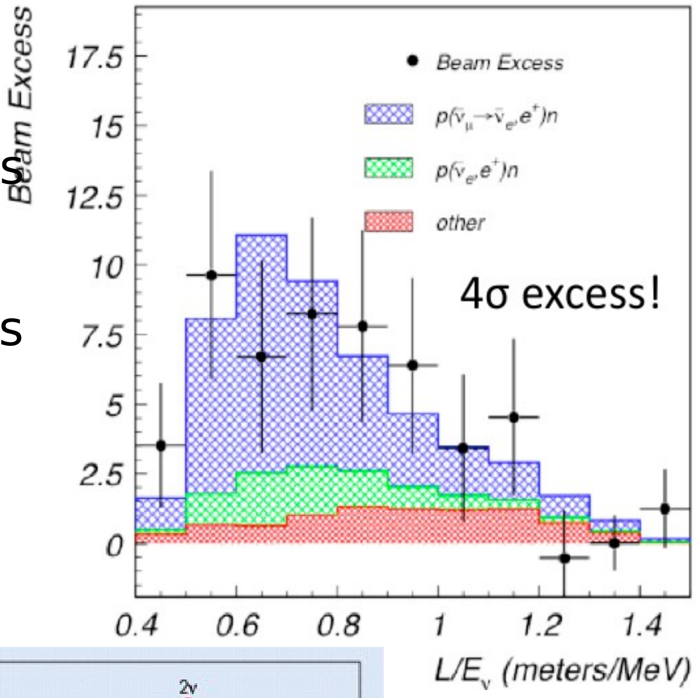
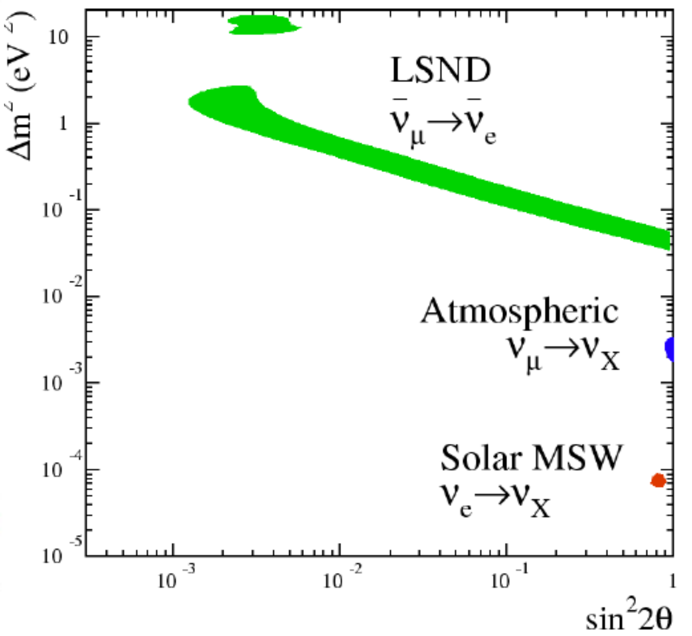
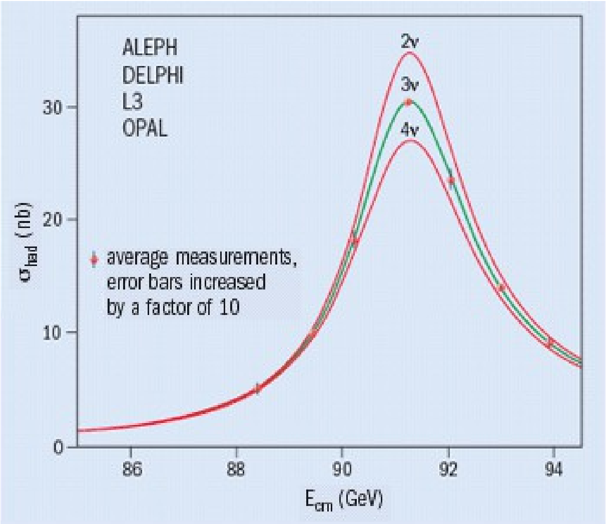
LSND

- LSND, a pion DAR (Decay At Rest) observed an excess of $\bar{\nu}_e$
- The Δm^2 of ~1eV^2 is incompatible with standard neutrino oscillations
- A new neutrino state?

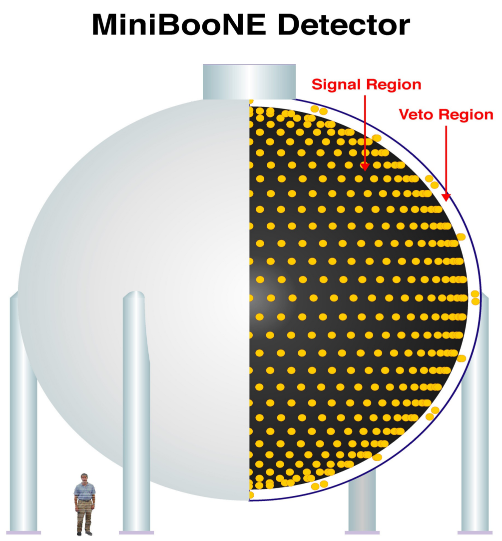




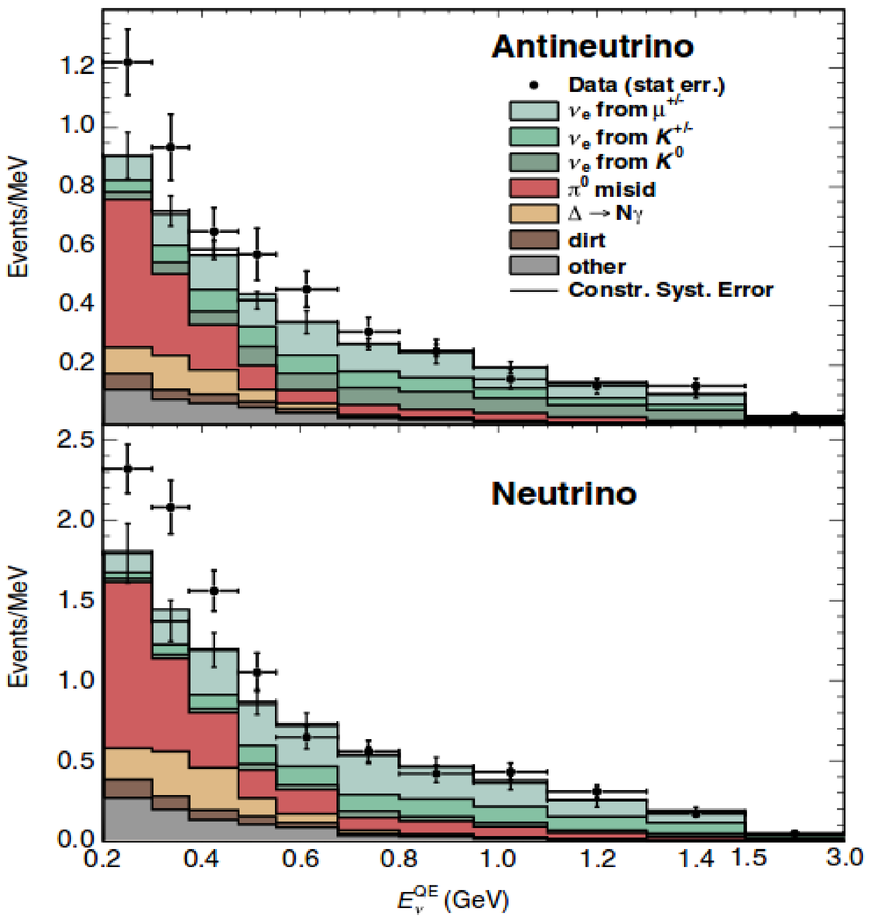


We have v. strong constraints from LEP restricting the number of light neutrino species.
To circumvent new state would have to be **sterile.**

MiniBooNE



Phys. Rev. Lett. 110, 161801 (2013)

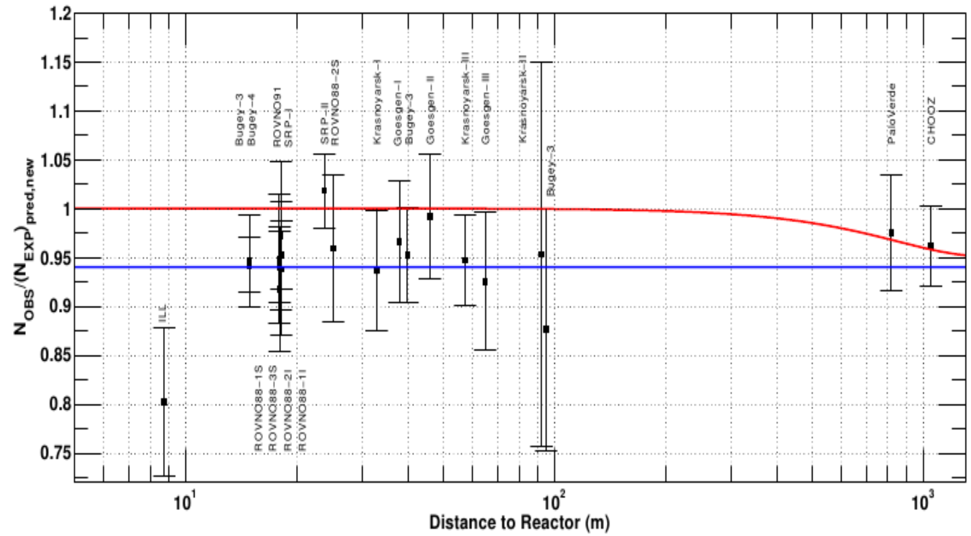


- Set out to confirm/disprove LSND.
  - Same L/E
  - Different detector (Cherenkov)
  - Different source (DIF)
  - Different excess (somewhat)

- Excess is present full data set both in neutrinos and anti-neutrinos.

Reactor Experiments + Gallium (disappearance)

- Recalculation of Reactor neutrino fluxes show a deficit (including Daya Bay)
- Calibration sources for Gallium experiments show a similar behaviour.

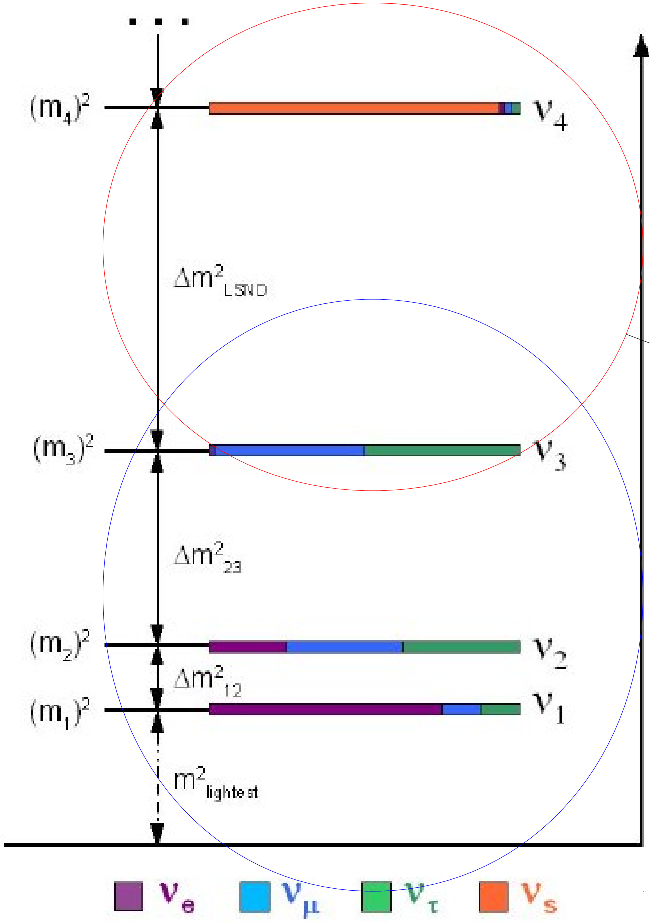


- HINTS: Very different experimental techniques are pointing to short baseline oscillations.

Experiment	Type	Channel	Significance
LSND	DAR	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	3.8σ
MiniBooNE	SBL accelerator	$\nu_\mu \to \nu_e$ CC	3.4σ
MiniBooNE	SBL accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	2.8σ
GALLEX/SAGE	Source - e capture	ν_e disappearance	2.8σ
Reactors	Beta-decay	$\bar{\nu}_e$ disappearance	3.0σ

K. N. Abazajian et al. "Light Sterile Neutrinos: A Whitepaper", arXiv:1204.5379 [hep-ph], (2012)

Has our three neutrino model become 4?



"Unknown" physics

- $\Delta m^2 \sim 1eV^2$ **incompatible with 3 neutrino model**.
- New neutrino has to "sterile".
- If confirmed – Physics Beyond the Standard Model

"Known" physics

How can we further understand this new neutrino?

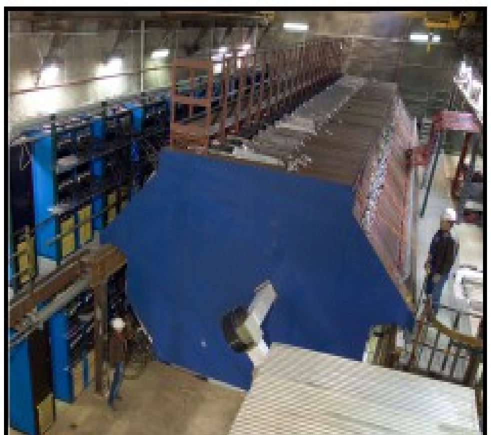
By measuring oscillations!

Many existing experiments sensitive to the effects.

MINOS/MINOS+

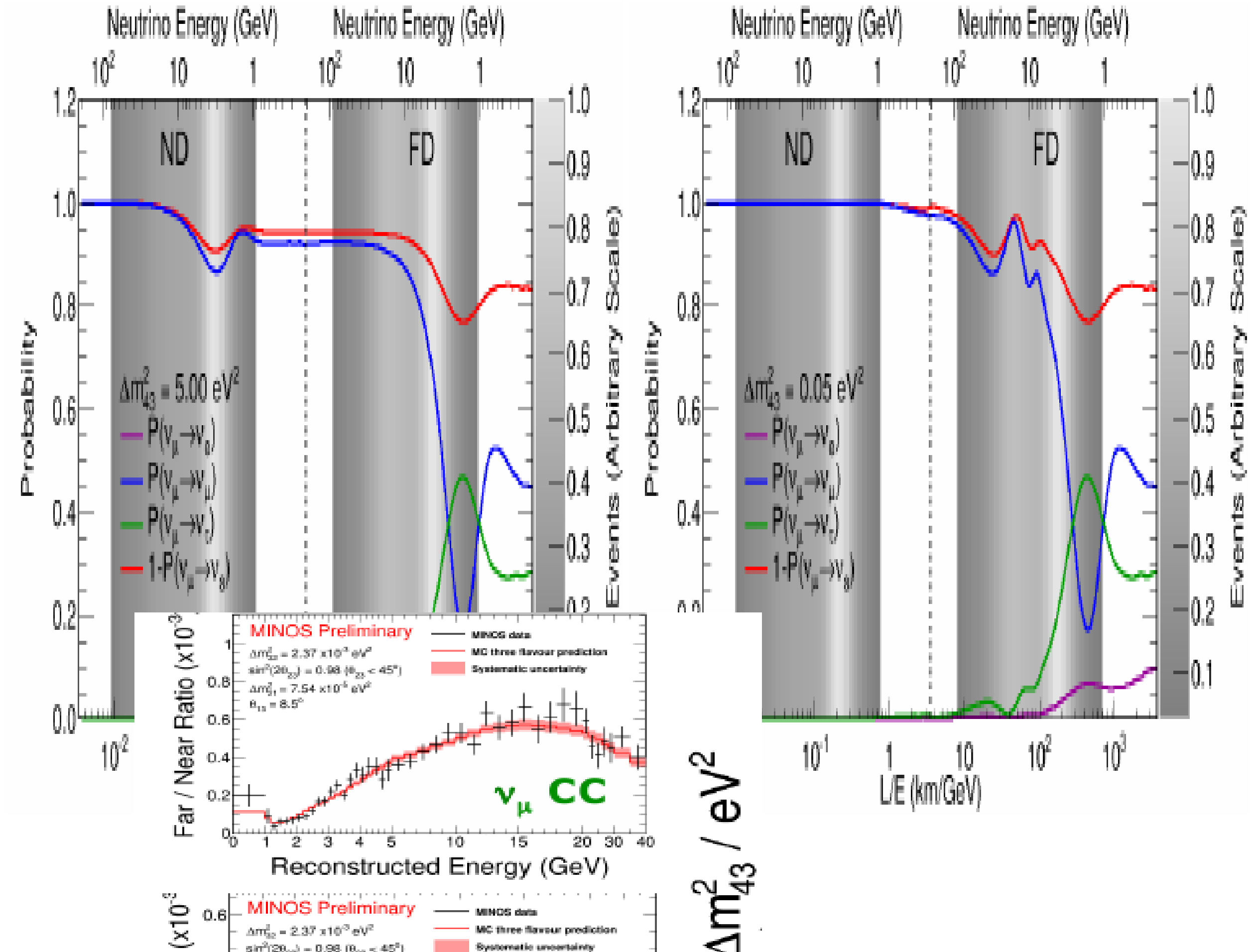
Far Detector (5.4 kton)

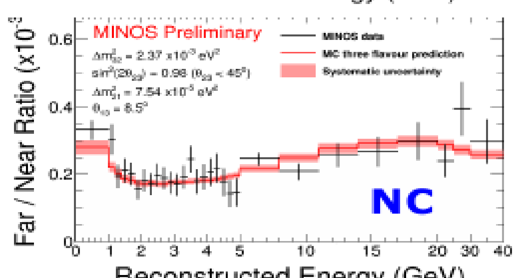
Near Detector (1 kton)



High Δm^2_{43}: Oscillations in Near Detector

Low Δm^2_{43}: Oscillations in Far Detector

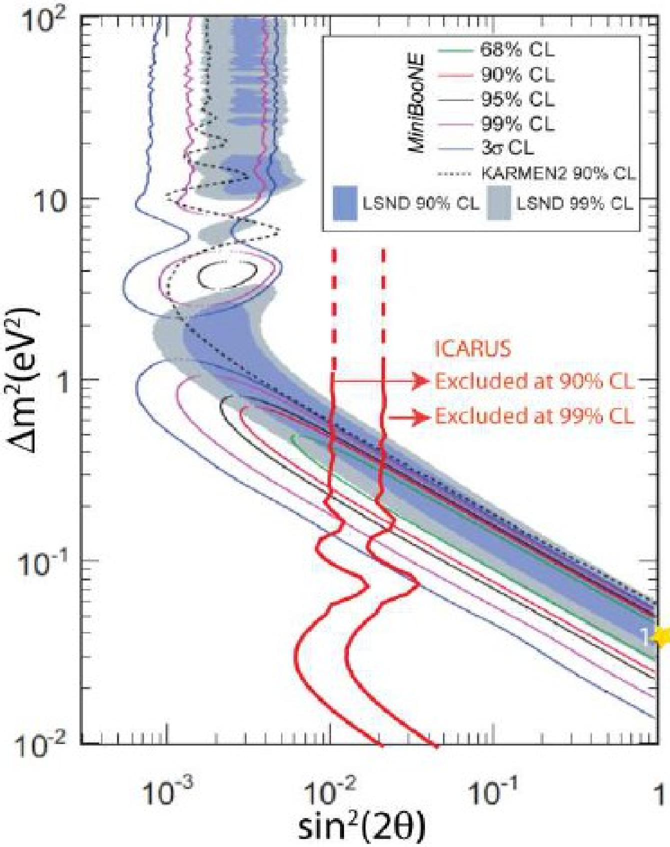




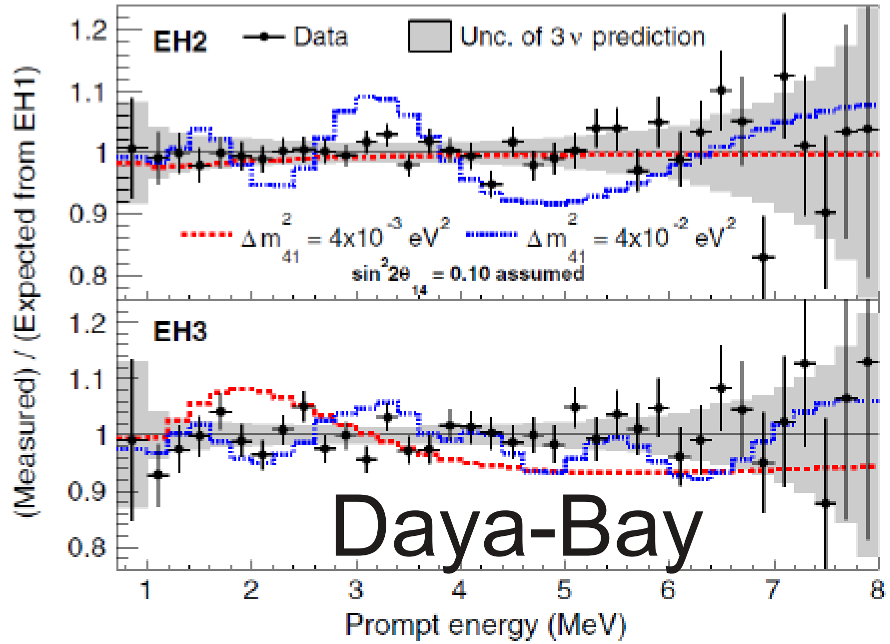
No ν_μ disappearance observed!

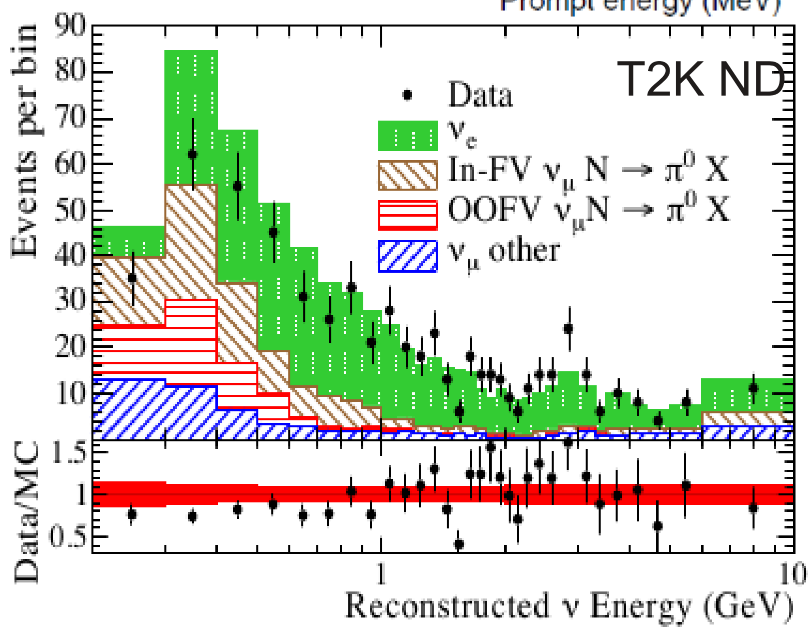
Many New Measurements

So far, disappearance experiments see no further signs of the sterile neutrino.



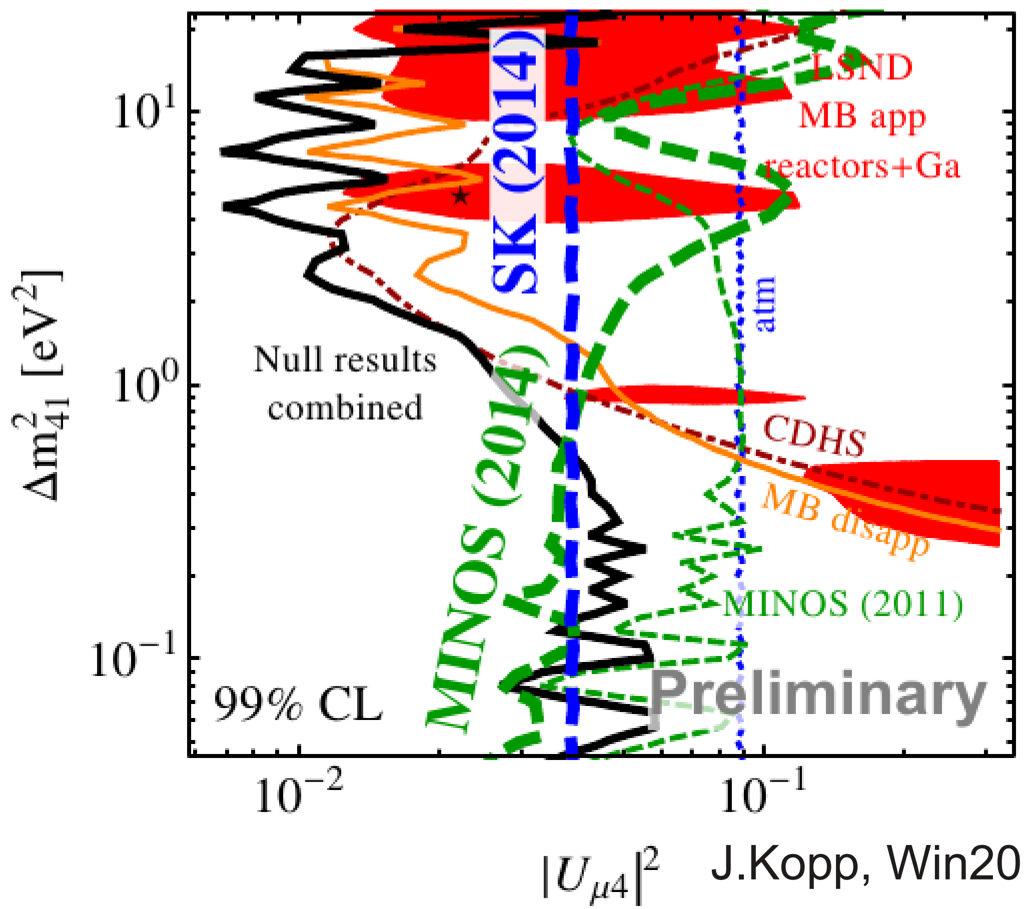
ICARUS





Global fits

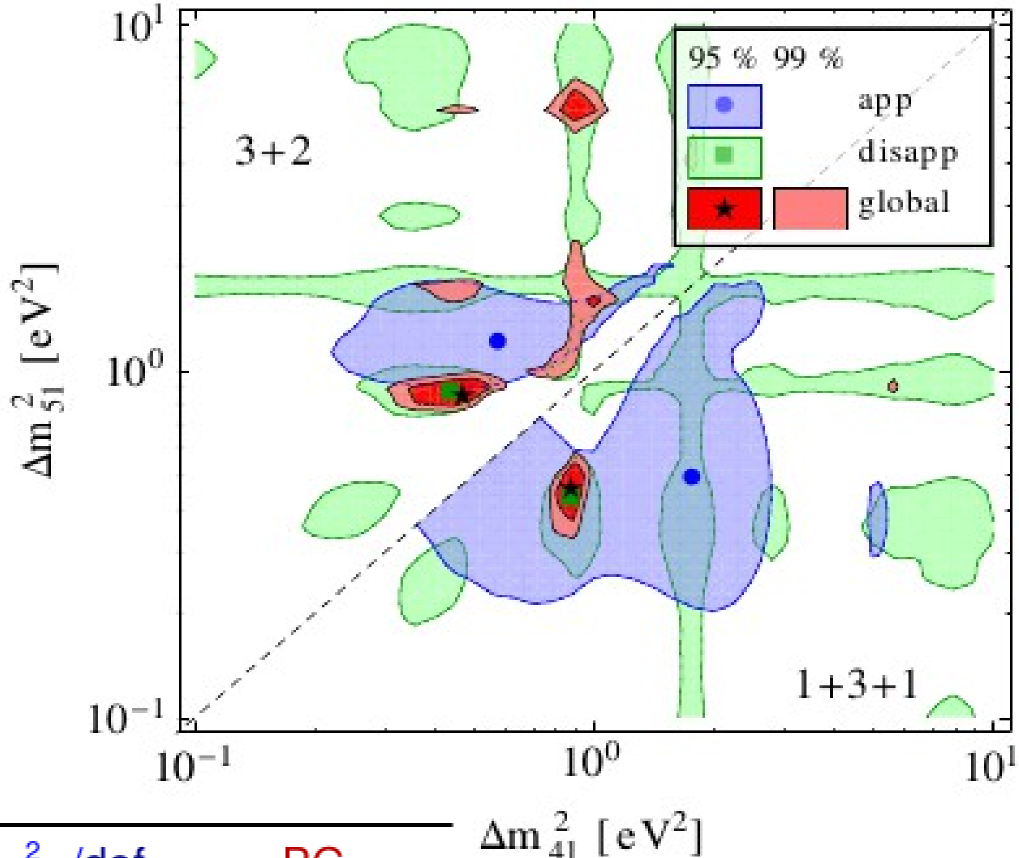
- Appearance/disappearance – significant tension of the 3+1 model.



J.Kopp, Win2015

Global fits

- Appearance/disappearance – significant tension of the 3+1 model.
- The 3+2 model does a little better.



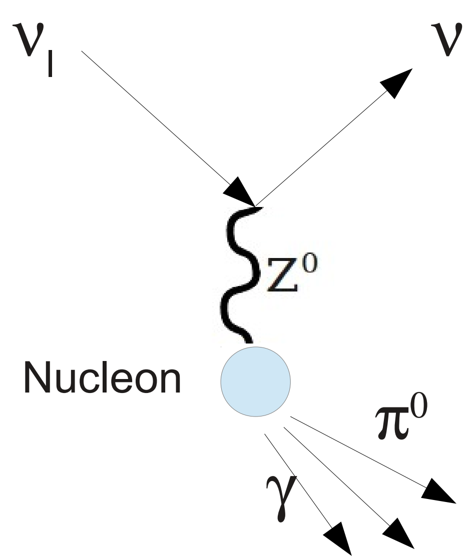
J.Kopp, Win2015

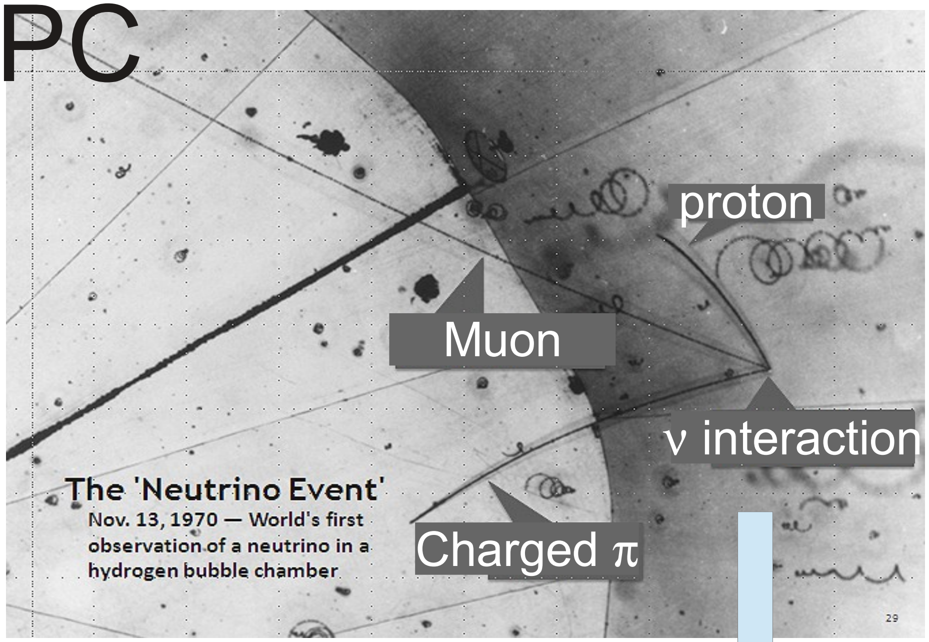
	χ^2_{min}/dof	GOF	χ^2_{PG}/dof	PG
3+1	712/(689 − 9)	19%	18.0/2	1.2×10^{-4}
3+2	701/(689 − 14)	23%	25.8/4	3.4×10^{-5}
1+3+1	694/(689 − 14)	30%	16.8/4	2.1×10^{-3}

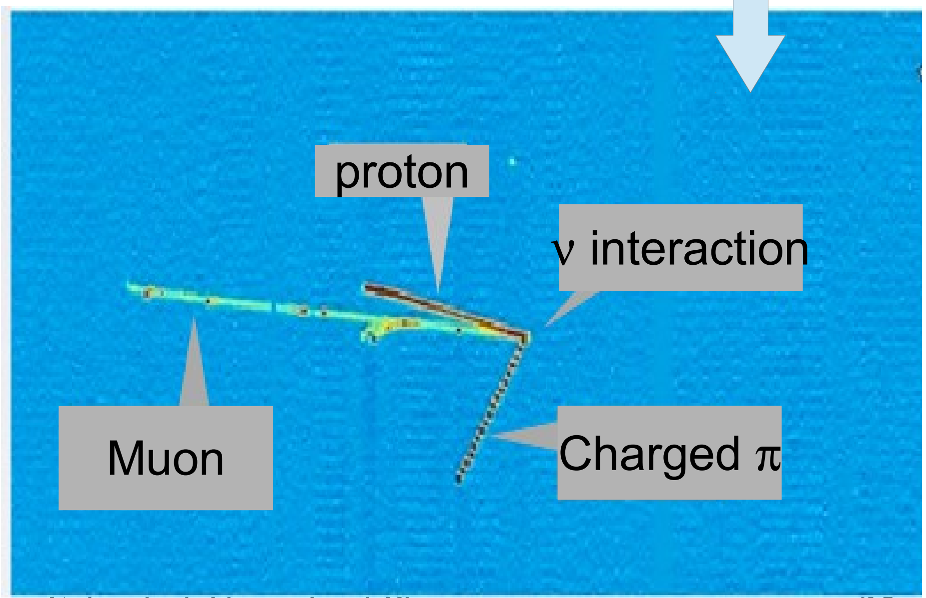
Need definitive test: ν_e appearance?

How to measure ν_e appearance in a LArTPC

- ν_e appearance is even more challenging because EM showers can come from gammas (e.g. originating from π^0 decays).
- The LArTPC and its bubble chamber like-data gives us strong background rejection tools.

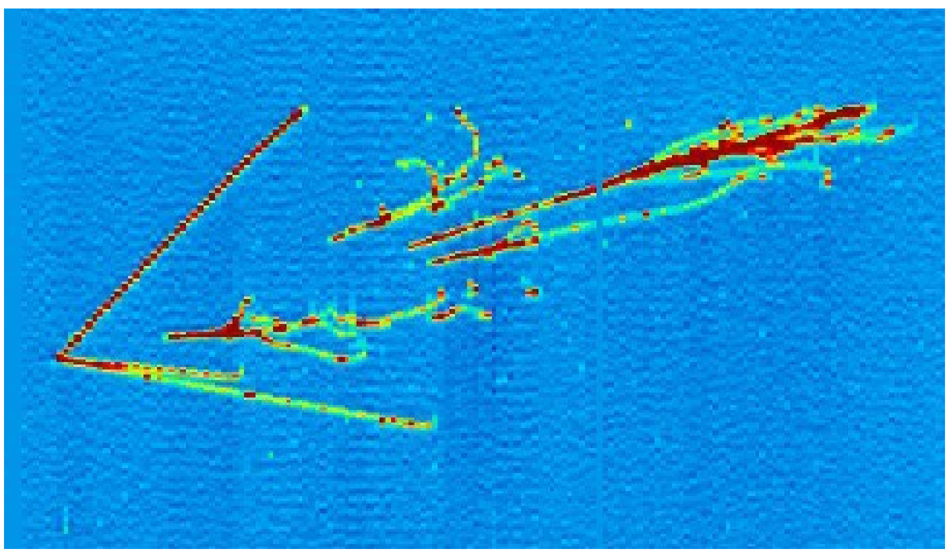


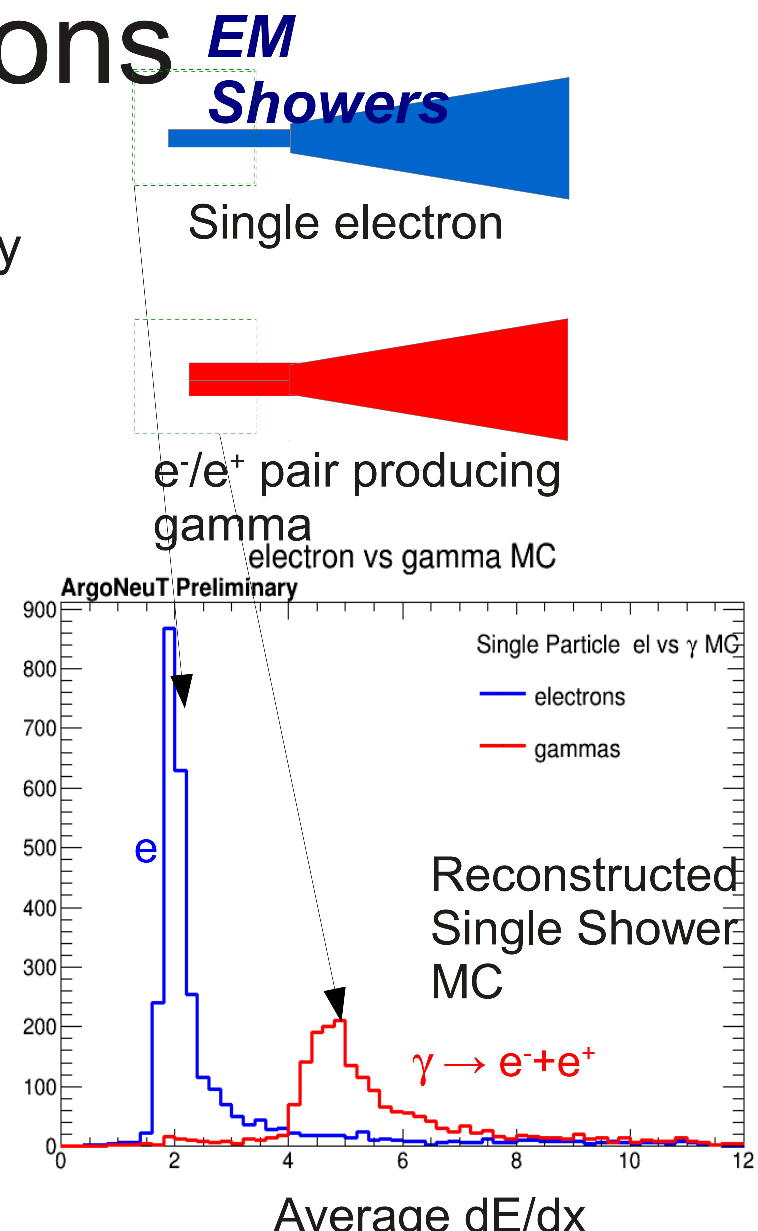




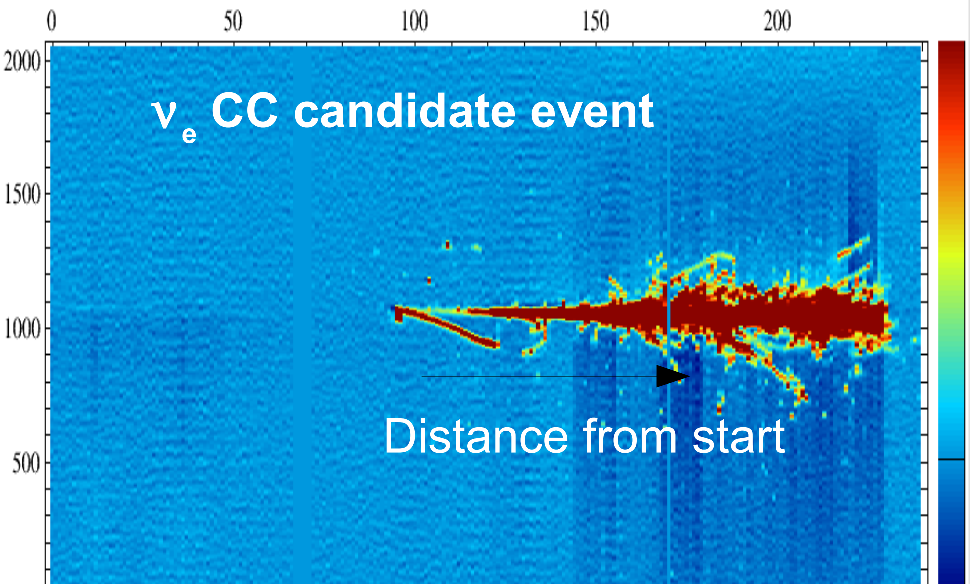
Differentiating photons from electrons

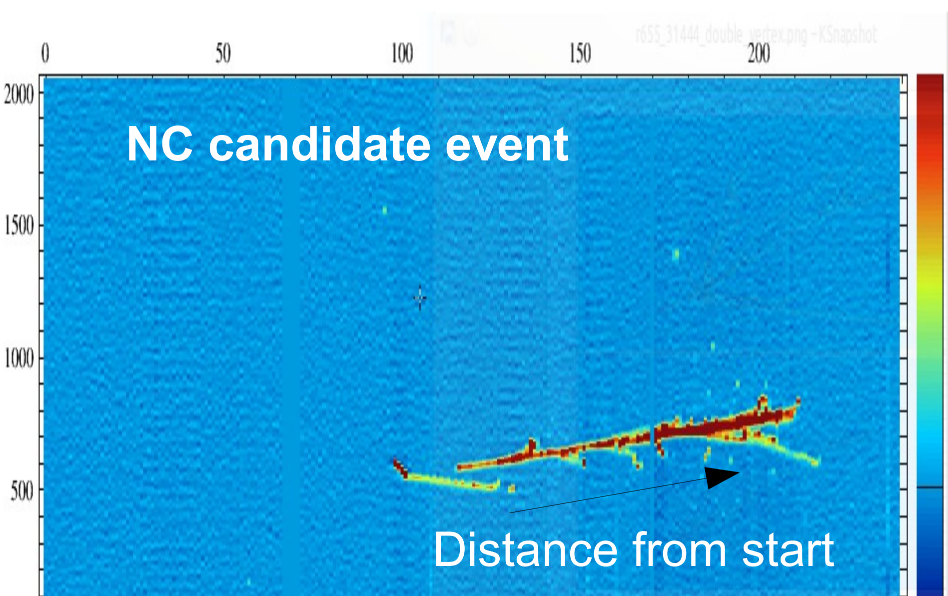
- An EM shower that starts after a gap from the vertex is always background (especially if you can see two of them).
- Even if the gap is very small all is not lost.
  - We can reconstruct the charge at the start of the shower - “dE/dx discrimination”.



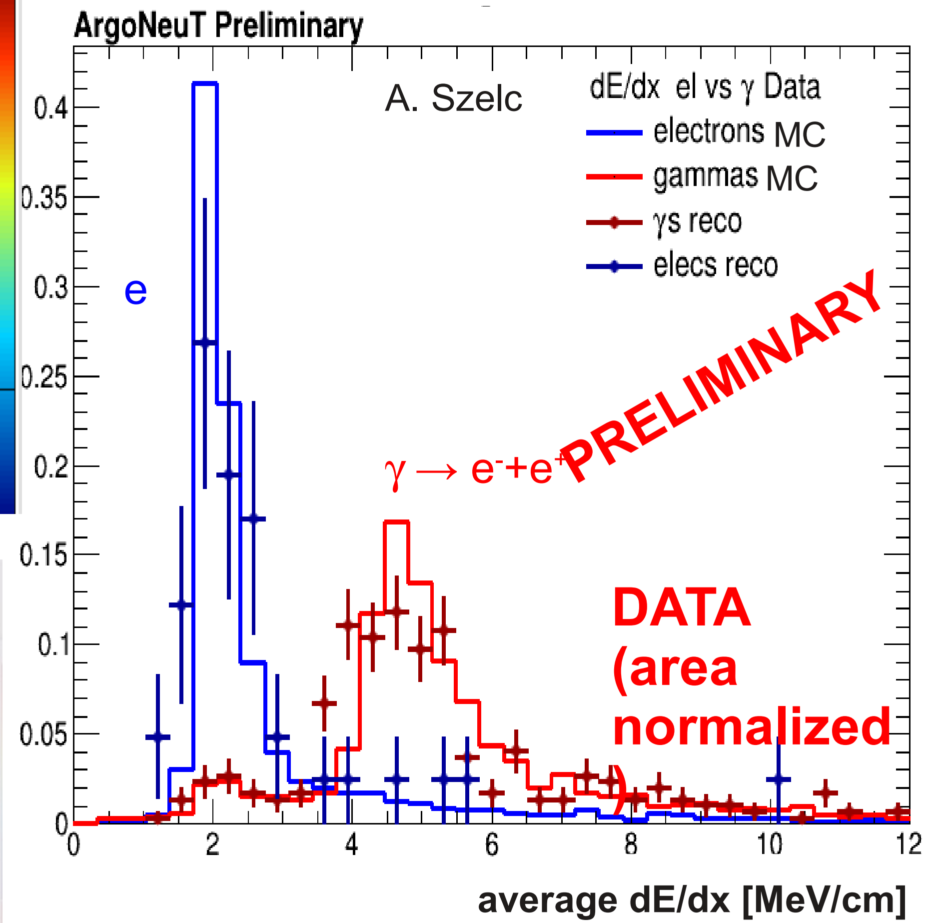


Data-Based dE/dx plot





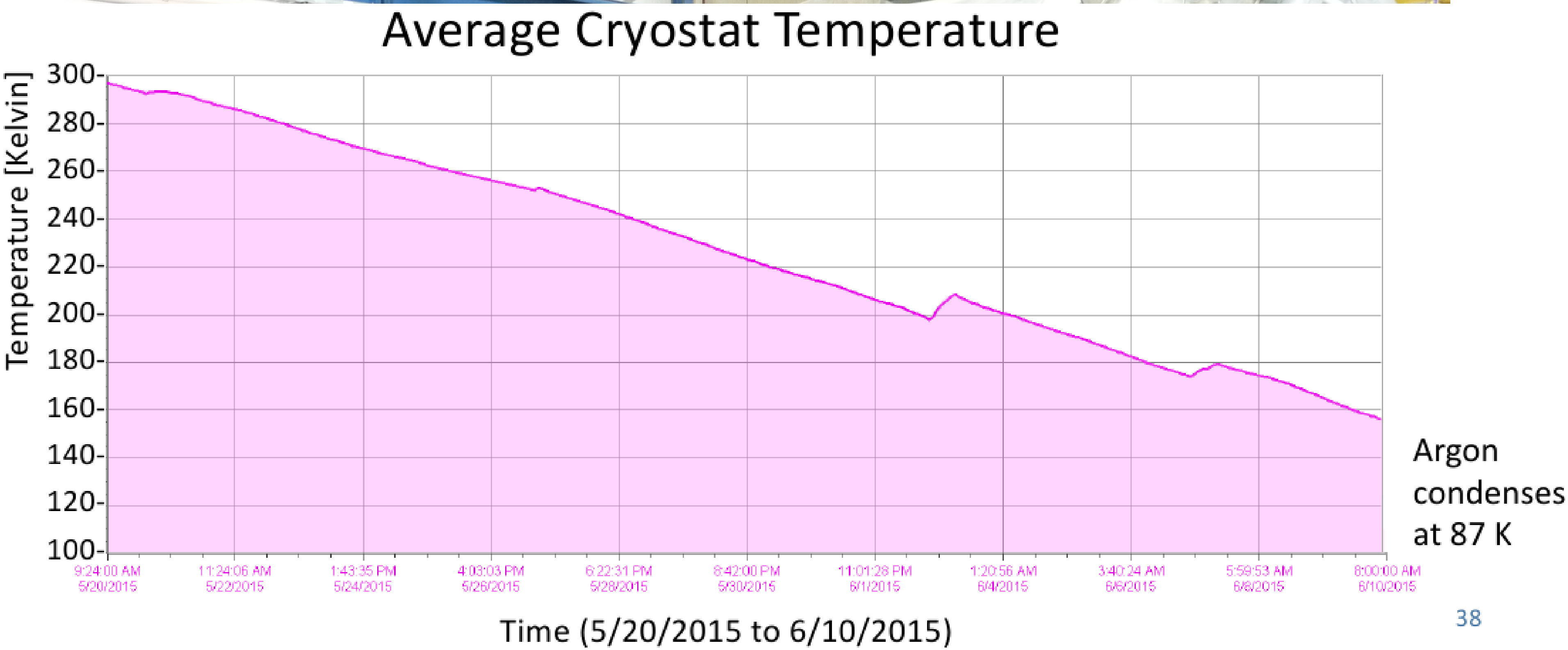
Electron/single gamma separation



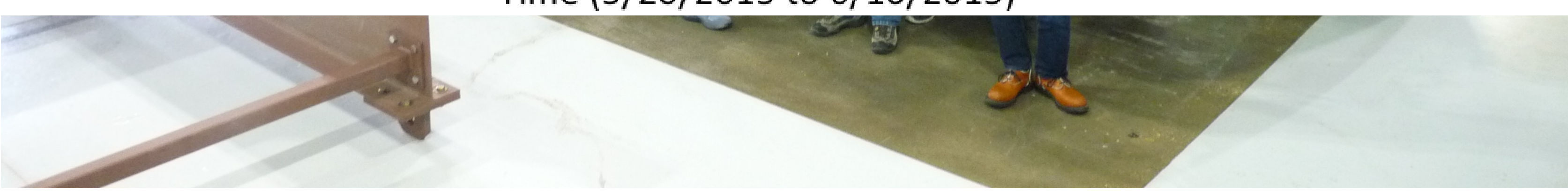
- **Never measured for electron events coming from neutrinos in LAr.**

MicroBooNE

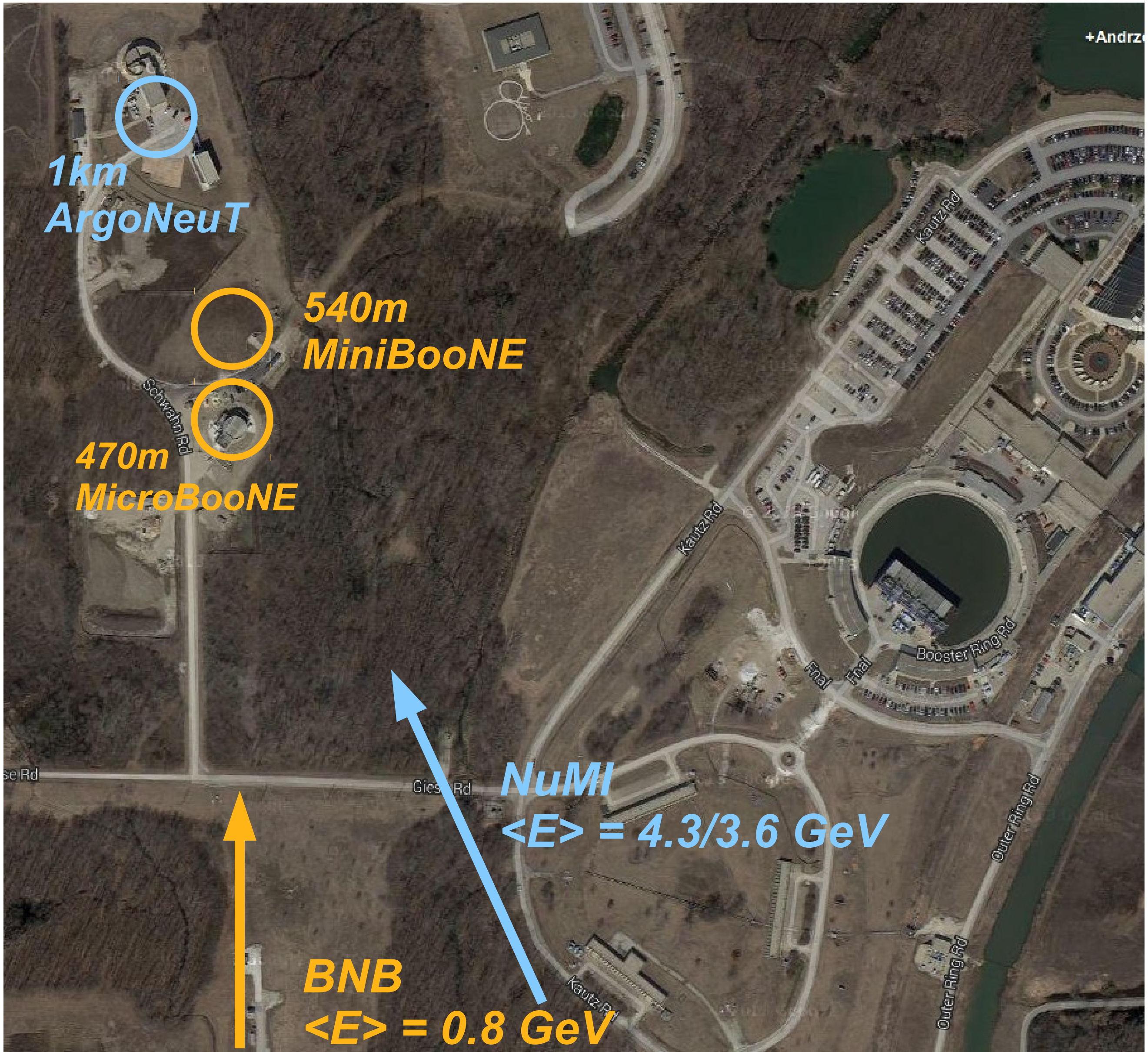
MicroBooNE



Average Cryostat Temperature
Temperature [Kelvin]
300
280
260
240
220
200
180
160
140
120
100
9:24:00 AM 5/20/2015
11:24:06 AM 5/22/2015
1:43:35 PM 5/24/2015
4:03:03 PM 5/26/2015
6:22:31 PM 5/28/2015
8:42:00 PM 5/30/2015
11:01:28 PM 6/1/2015
1:20:56 AM 6/4/2015
3:40:24 AM 6/6/2015
5:59:53 AM 6/8/2015
8:00:00 AM 6/10/2015
Time (5/20/2015 to 6/10/2015)
Argon condenses at 87 K
38



MicroBooNE at Fermilab



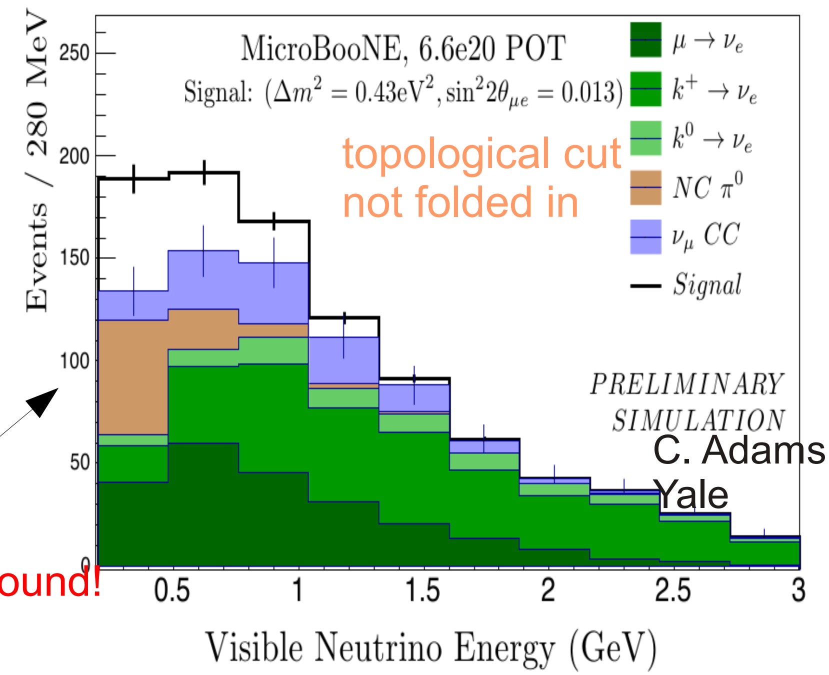
MicroBooNE cooling down now.

Will reside on the same beam as MiniBooNE.

Using the LArTPCs Reconstruction capabilities should resolve the nature of the MiniBooNE excess.

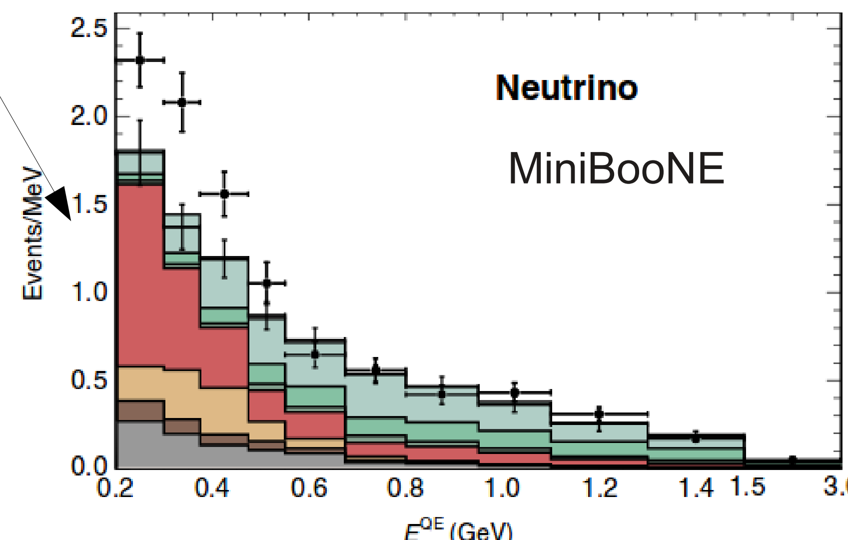
MicroBooNE vs MiniBooNE

- MicroBooNE can resolve the nature of the MiniBooNE excess by performing a ν_e appearance search.

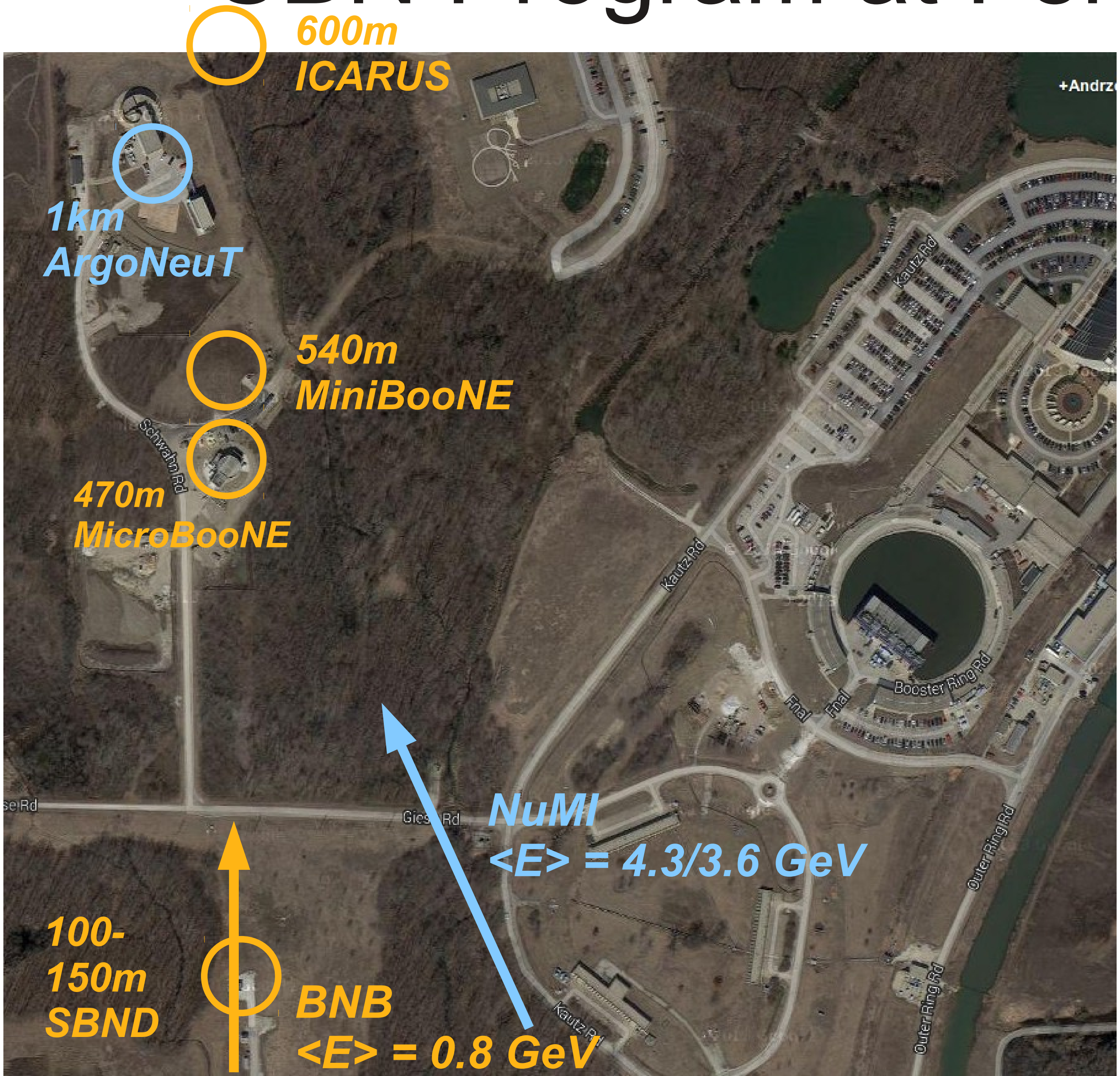


NC π^0 background!

- As a single detector experiment it will not be able to observe the length dependence of an excess signal.

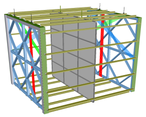


SBN Program at Fermilab

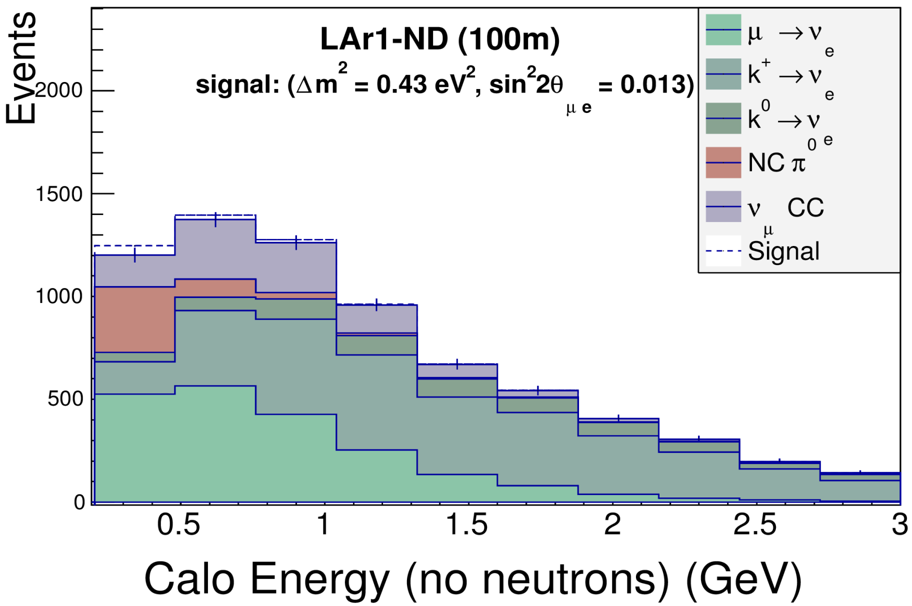


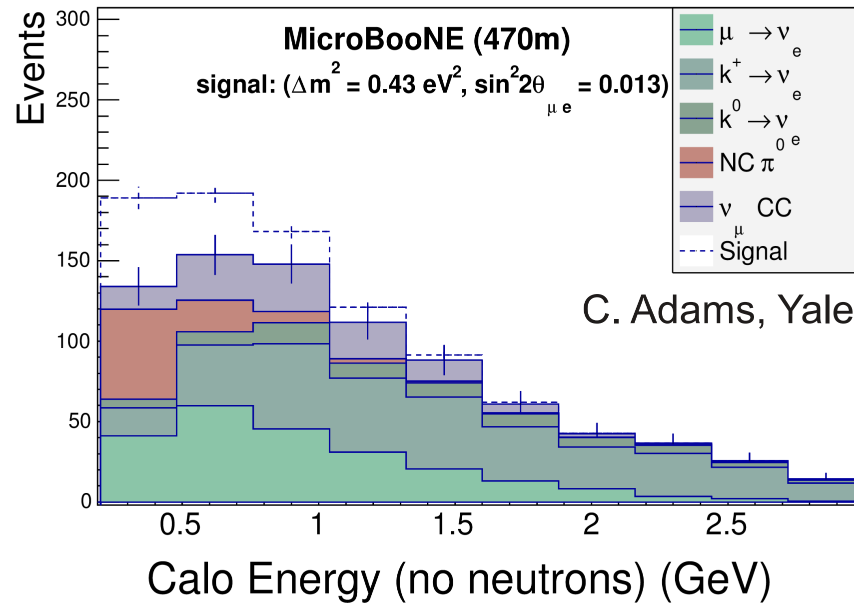
SBND, near detector near the SciBooNE hall should be online in 2018.

ICARUS, far detector – being refurbished at CERN should be online in 2018.



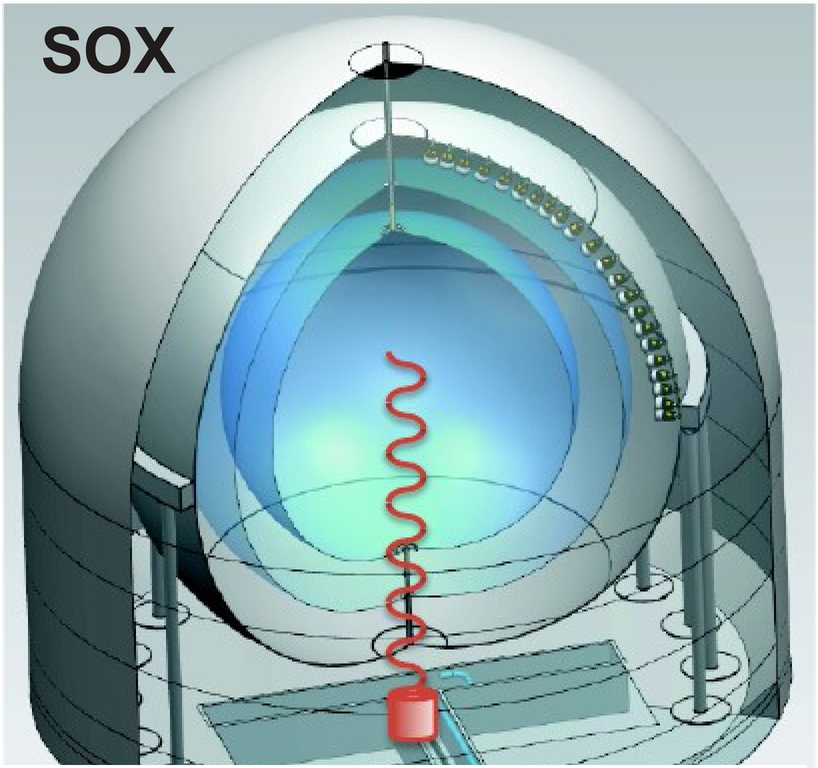
SBND, or MicroBooNE with a Near Detector





- Due to its proximity to the target hall, it is sufficient for it to run for one year to amass higher statistics than MicroBooNE (~1M events).
- This will test the near-far strategy with liquid argon for the first time.

Source and Reactor experiments



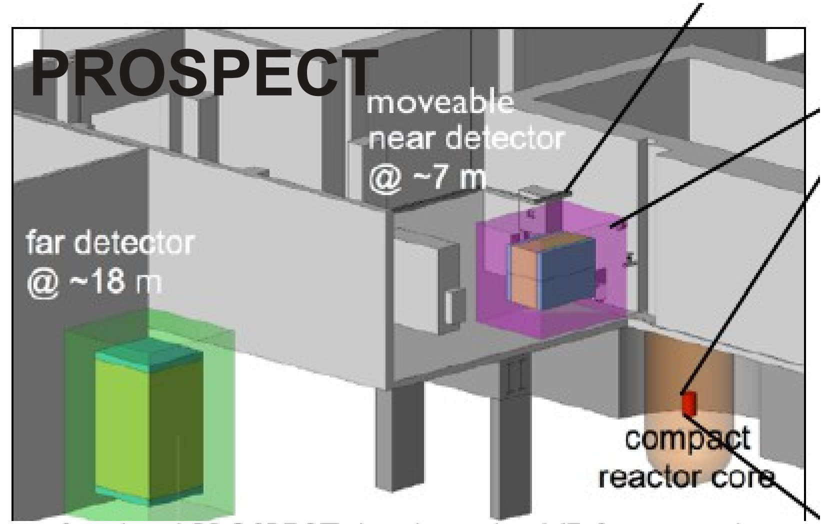
- First phase: **Ce-source** (100 kCi)

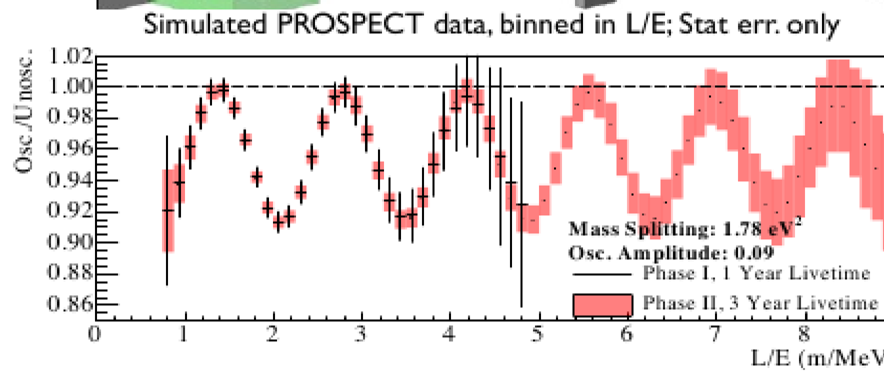
  $^{144}Ce \rightarrow {}^{144}Pr + e^- + \bar{\nu}_e$

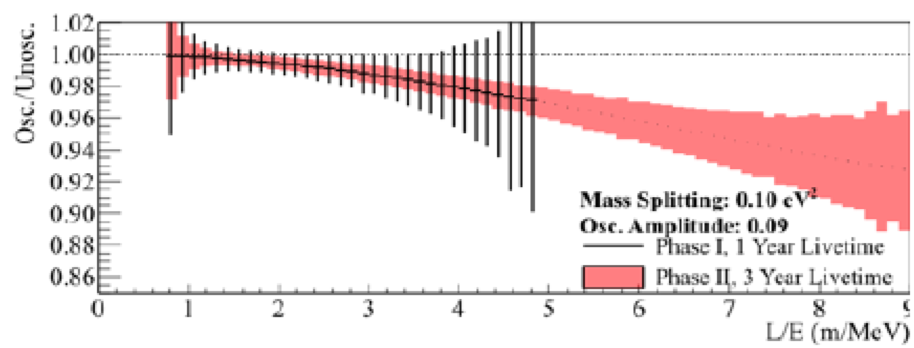
  $^{144}Pr \rightarrow {}^{144}Nd + e^- + \bar{\nu}_e$

  - E_ν<3 MeV, oscillation length ~1m

    → **oscillation pattern within the scintillator volume**

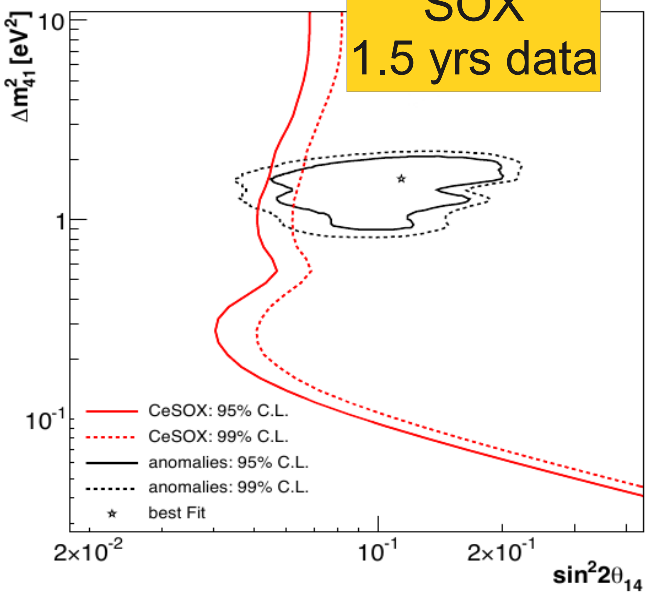


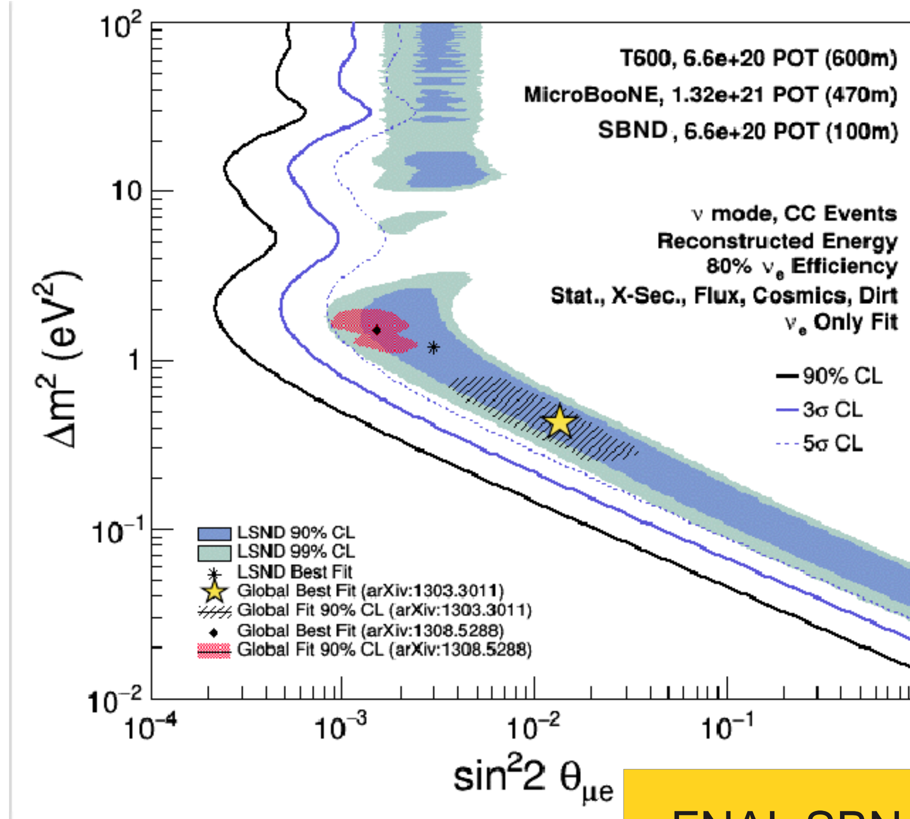




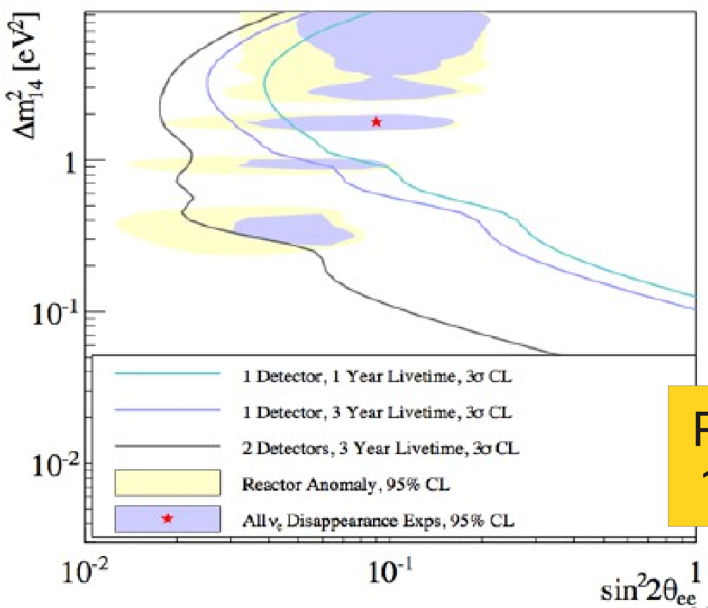
Future Sensitivity

SOX
1.5 yrs data





FNAL SBN
~3yrs



PROSPECT
1-3 yrs data

Big Questions in ν-physics

•Experimental neutrino physics in the next decade (and beyond) will be driven by the following questions:

- ***how much do neutrinos weigh?***
- ***what is the nature of the ν?***

β decay and $0\nu\beta\beta$ decay

- ***which neutrino is the heaviest and which is the lightest (MH)?***
- ***do neutrinos violate CP?***

long-baseline neutrinos

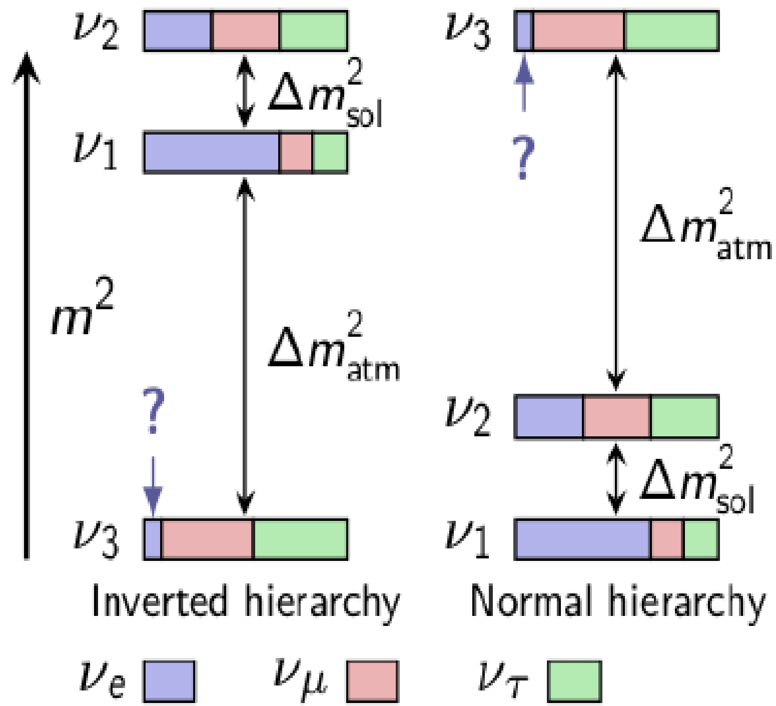
- ***is our picture correct?***
- ***are there more than 3 kinds of neutrinos?***

short-baseline neutrinos

$\nu_\mu \rightarrow \nu_e$ *(0.1-10)GeV En. range*

Mass Hierarchy

- We still don't know what is the ordering of neutrino masses.
- Observing oscillations allows us to measure only mass splittings, i.e. $\Delta m^2_{23} = m_2^2 - m_3^2$
- The way nature has decided to make this ordering will inform GUT theories and determines options for $0\nu\beta\beta$ decays.
- This will affect the $\nu_e(\bar{\nu}_e)$ appearance in a $\nu_\mu(\bar{\nu}_\mu)$ beam due to matter effects.

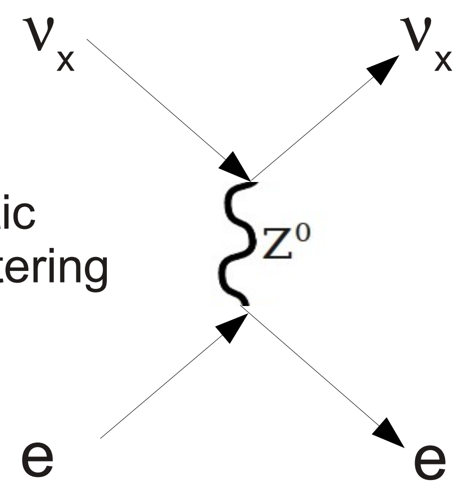


Can be measured
By NOvA and T2K

Matter effects

- Electron neutrinos are preferred, in matter

ES:
Elastic
Scattering



ES:
Elastic
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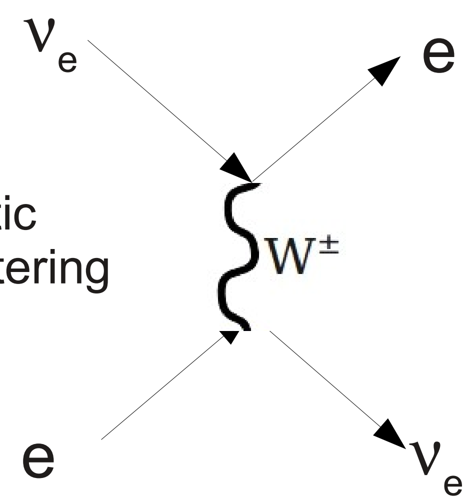
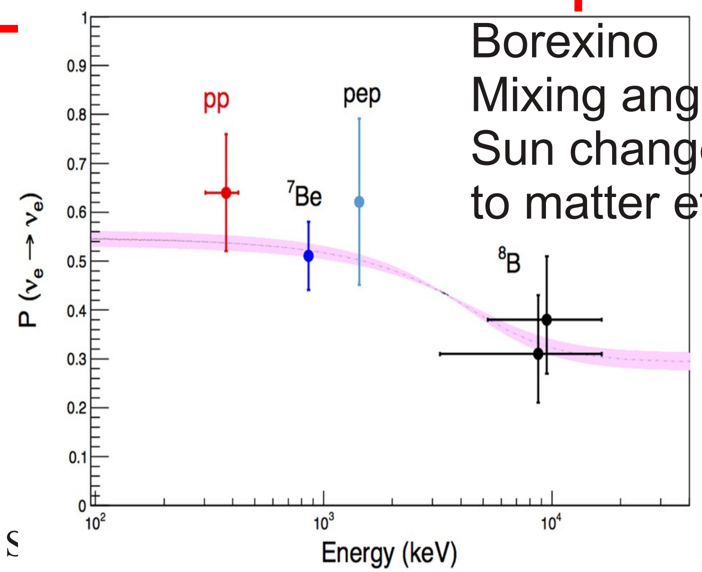


Due to the abundance of electrons in matter electron neutrinos will behave slightly differently.

We've seen hints already:

SNO $ES\,Rate \propto \Phi(\nu_e) + 0.154\,\Phi(\nu_\mu + \nu_\tau)$



Borexino
Mixing angle in Sun changes due to matter effects.

Matter effects

$$P(\nu_e \to \nu_\mu) = P(\nu_\mu \to \nu_e) = \sin^2 2\theta_M \sin^2(\Delta m_M^2 L/4E)$$

Passage through matter changes the effective Δm^2 and mixing angles:

$$\Delta m_M^2 = \Delta m^2 \sqrt{\sin^2 2\theta + (\cos 2\theta - x_\nu)^2}$$

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x_\nu)^2}$$

Effects are Energy and density dependent.

$$x_\nu \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2}$$

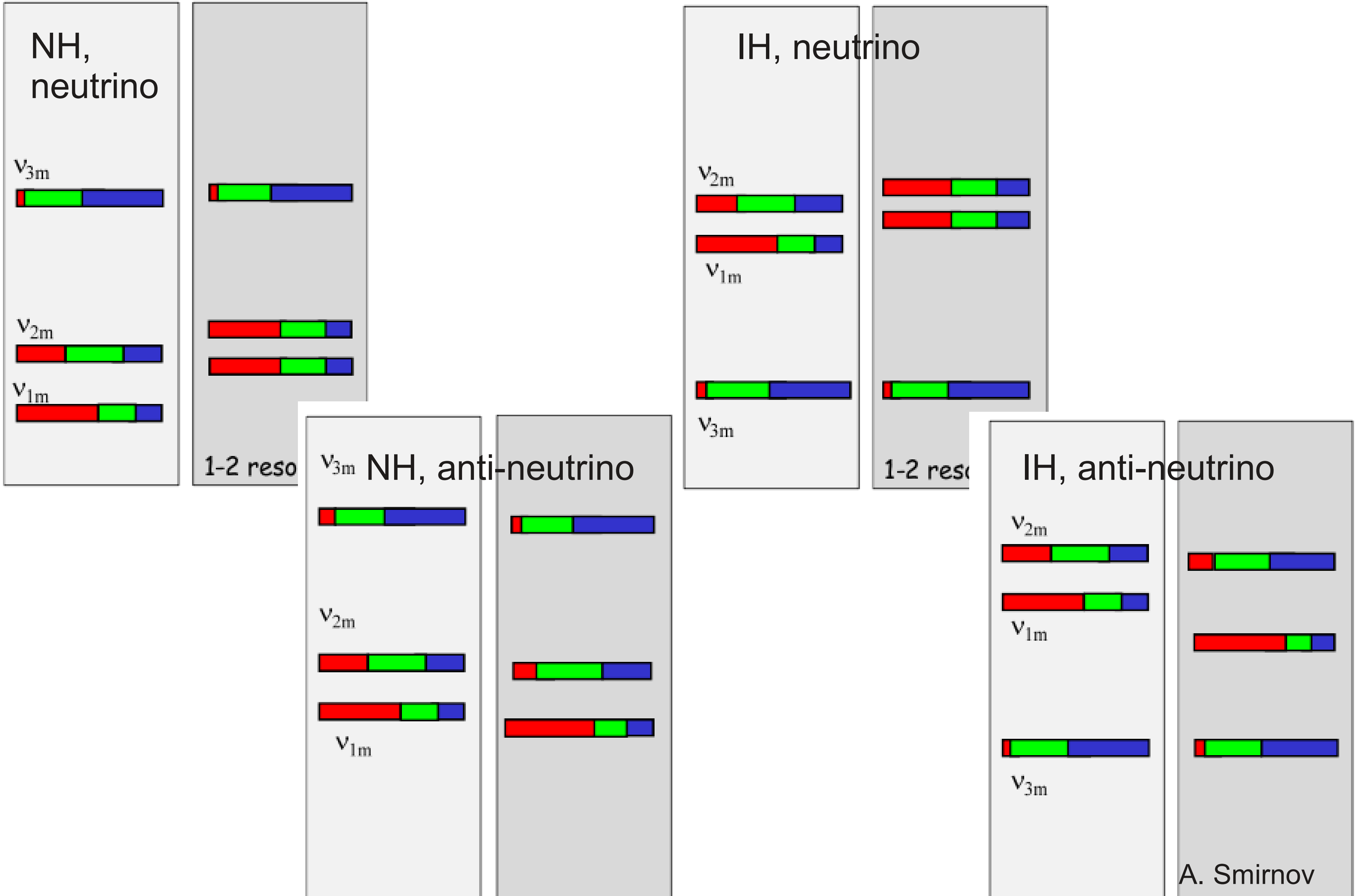
Example: 1000km baseline, through the mantle, $\Delta m_{31}^2 \sim 2.4 \times 10^{-3} eV^2$

$$|x_\nu| \simeq E/12\,\mathrm{GeV}$$

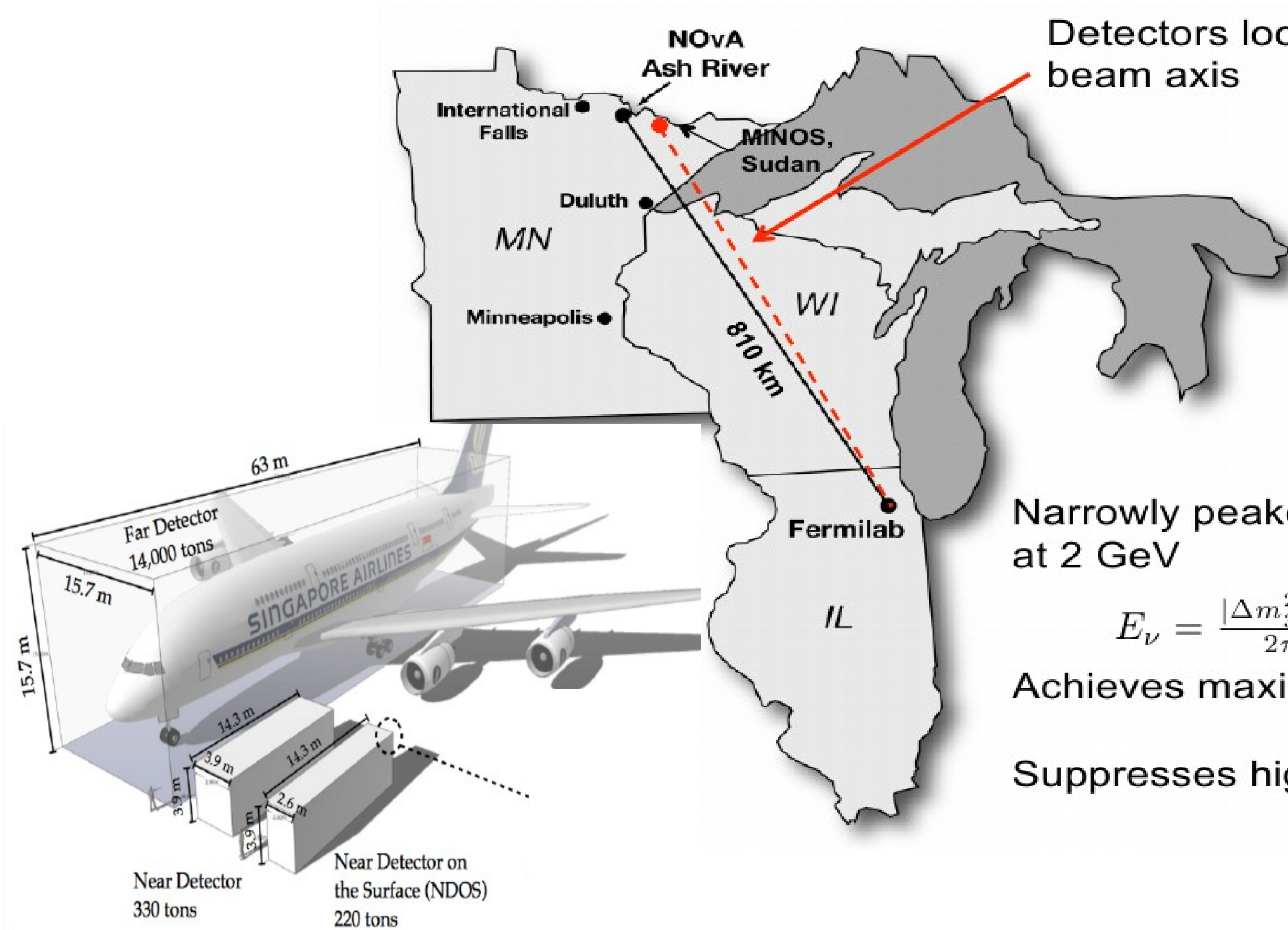
Sign inverted For anti-nu

After B. Kayser

Matter Effects



The NOvA detector



Detectors located 0.8° of NuMI beam axis

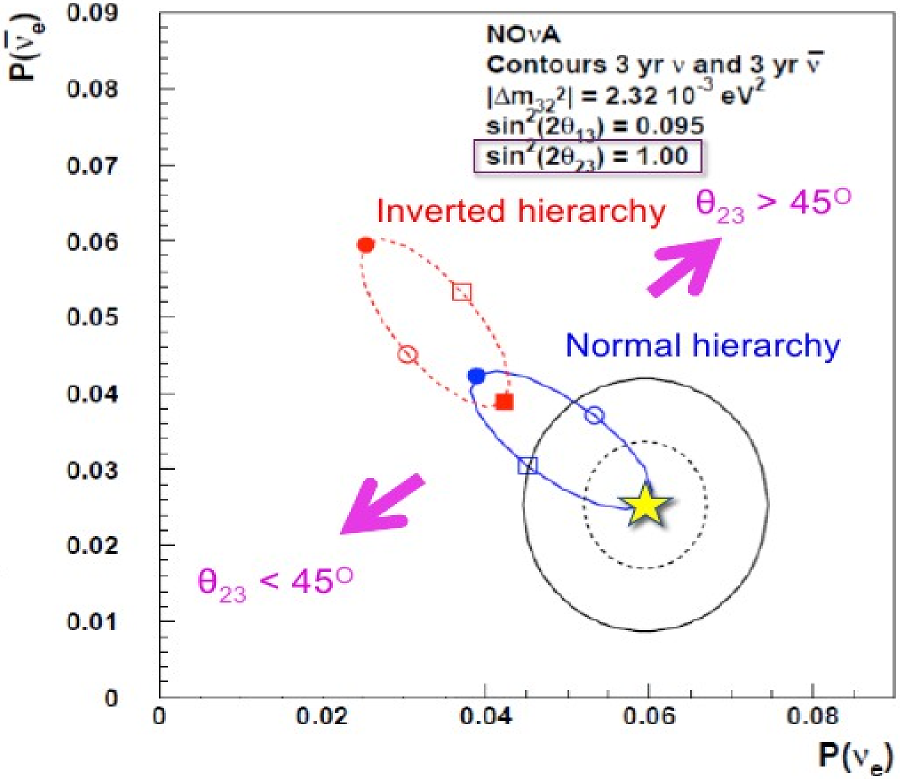
Narrowly peaked ν flux centered at 2 GeV

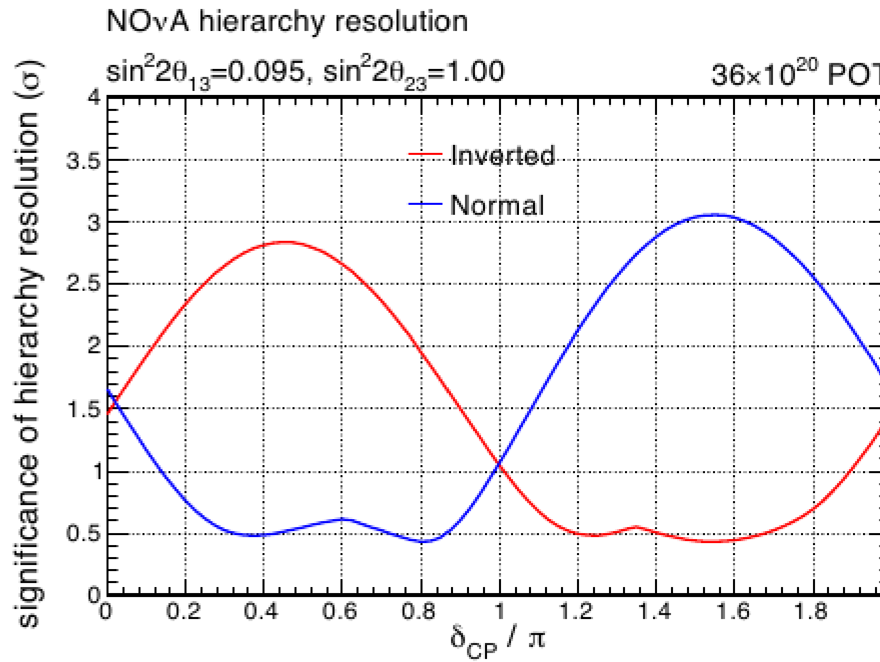
$$E_\nu = \frac{|\Delta m^2_{32}| L}{2\pi} \approx 2 \text{ GeV}$$

Achieves maximum oscillation

Suppresses high energy tail

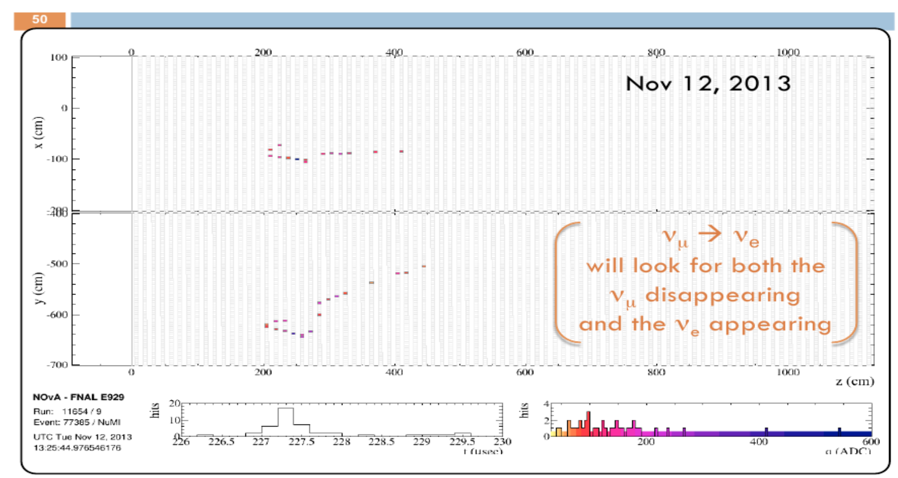
What can NOVA tell us



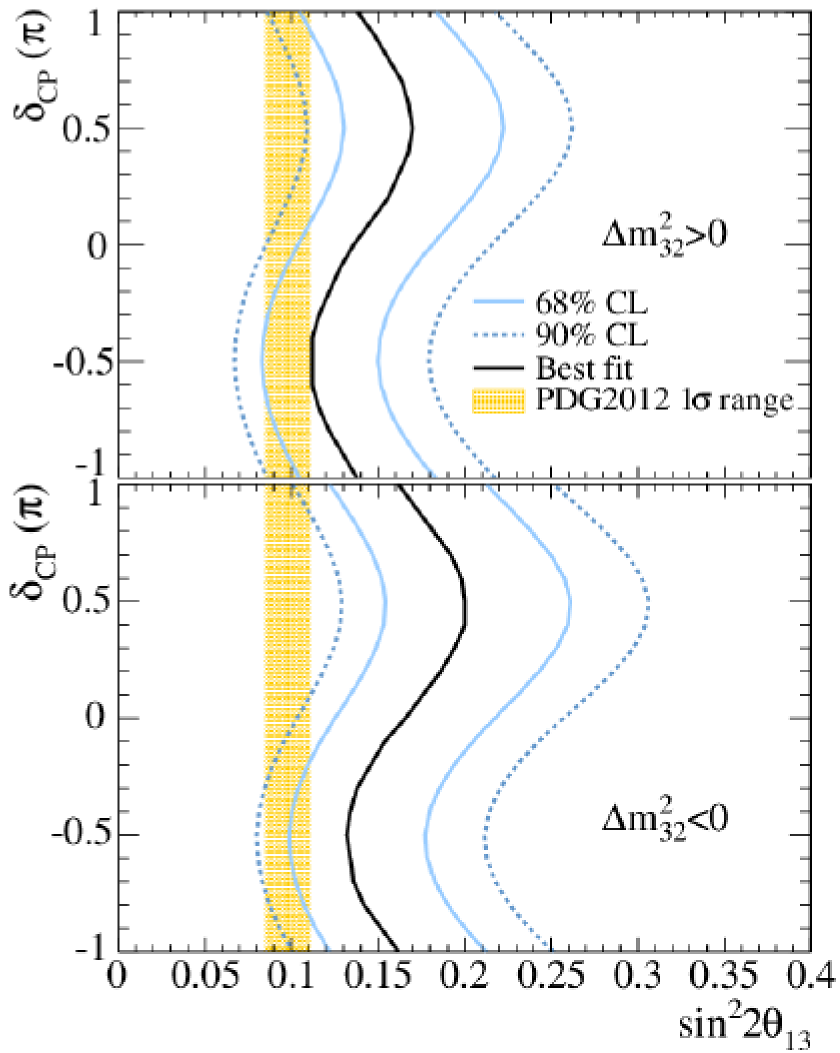


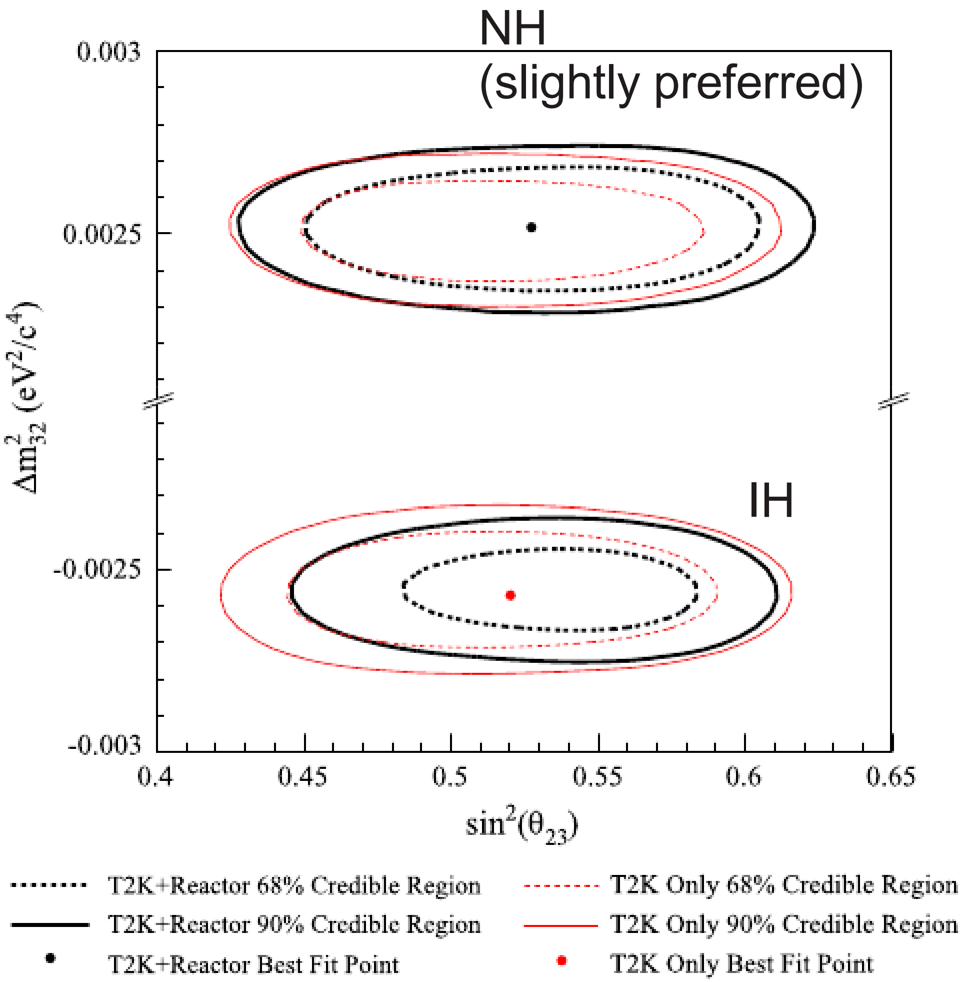
Need 3+3 years of beam.
Full detector just recently assembled.

First Neutrino in NOvA!



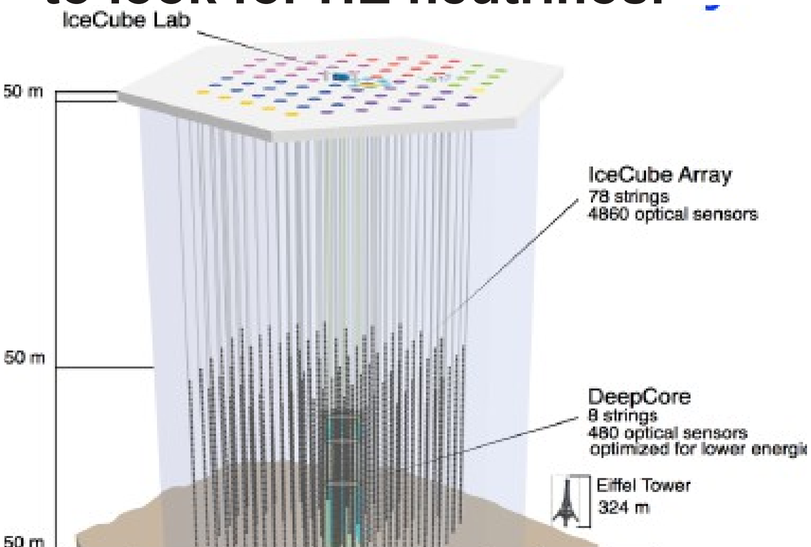
T2K is starting to probe

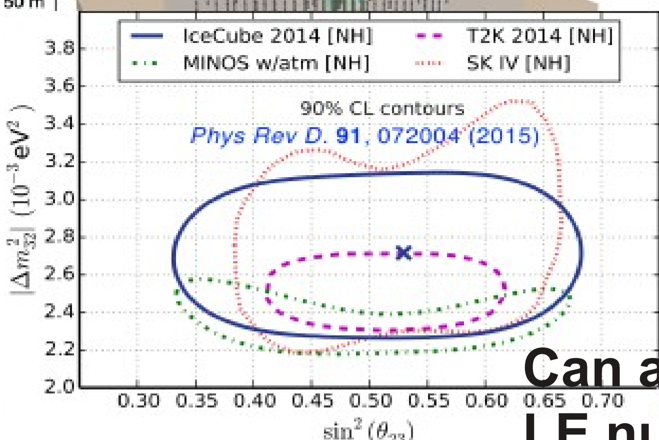




PINGU a very alternative approach

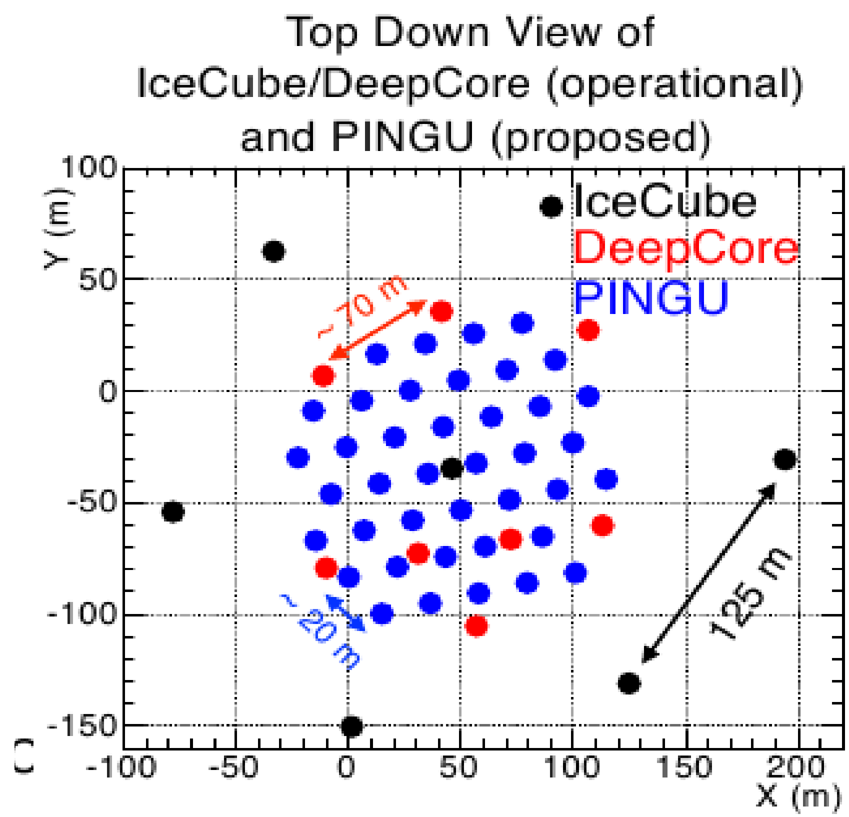
ICECUBE – Ice Cherenkov to look for HE neutrinos.



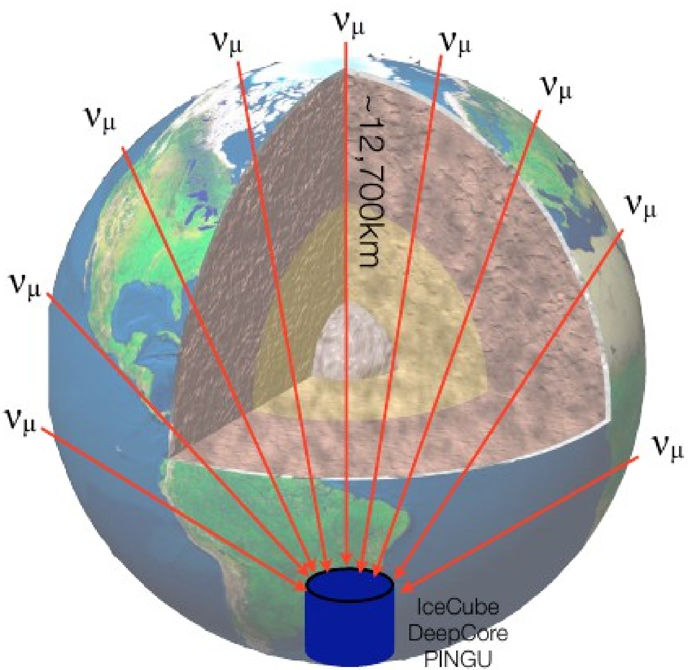


Can also do LE nus: θ_{23}

PINGU: Add strings to center of IceCube to measure MH

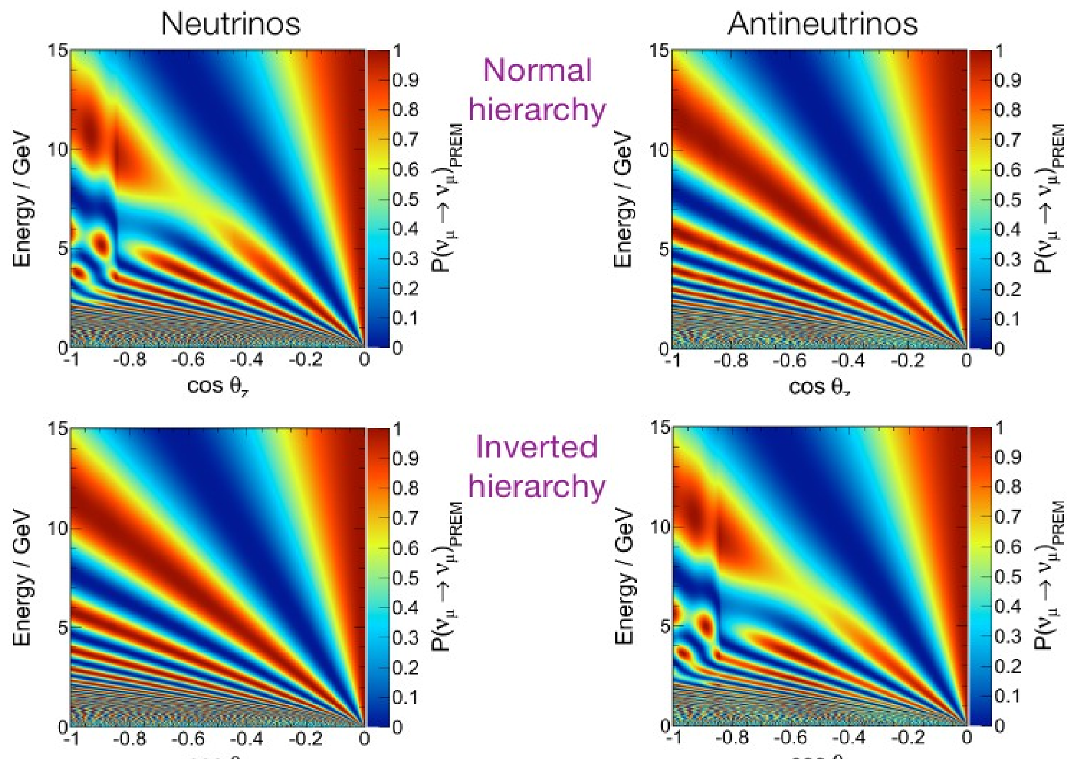


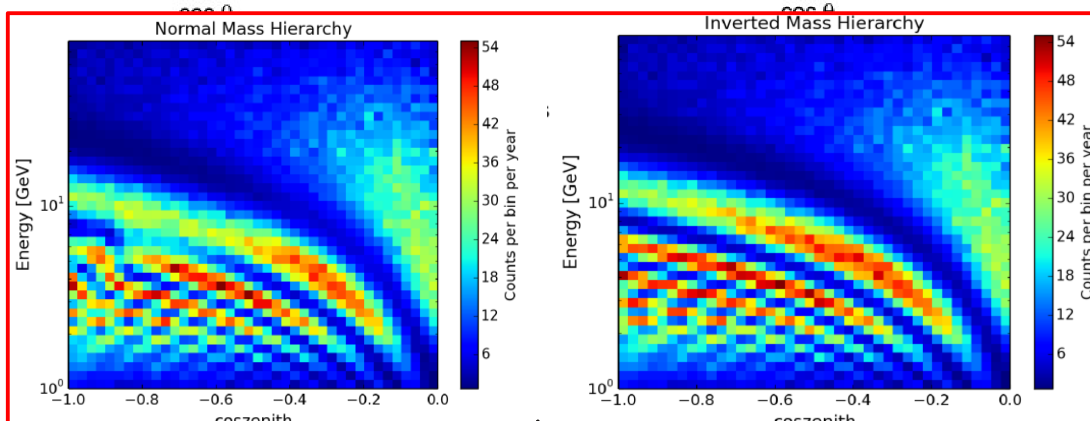
PINGU and Mass Hierarchy



The world is your baseline.

Create oscillograms and the difference will point to the answer.





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- *what is the nature of the ν?*

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long-baseline neutrinos

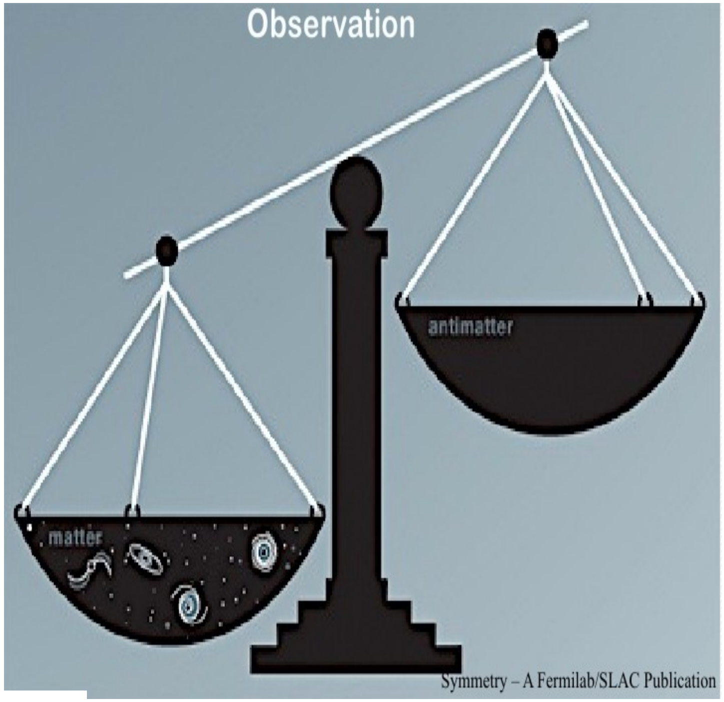
- *is our picture correct?*
- *are there more than 3 kinds of neutrinos?*

short-baseline neutrinos

$\nu_\mu \rightarrow \nu_e$ *(0.1-10)GeV En. range*

CP violation

- The Universe is surprisingly asymmetric – we see “matter” and almost no “anti-matter”.
- For this difference to originate in the Big Bang, we need a much less drastic value 1 in 10^{10} difference.
- This can happen if CP is violated “enough”.
- Neutrinos could provide the needed quantities via leptogenesis - need non-zero δ phase.
- Need to measureme ν_e vs $\bar{\nu}_e$ appearance asymmetry (watch out for MH!).

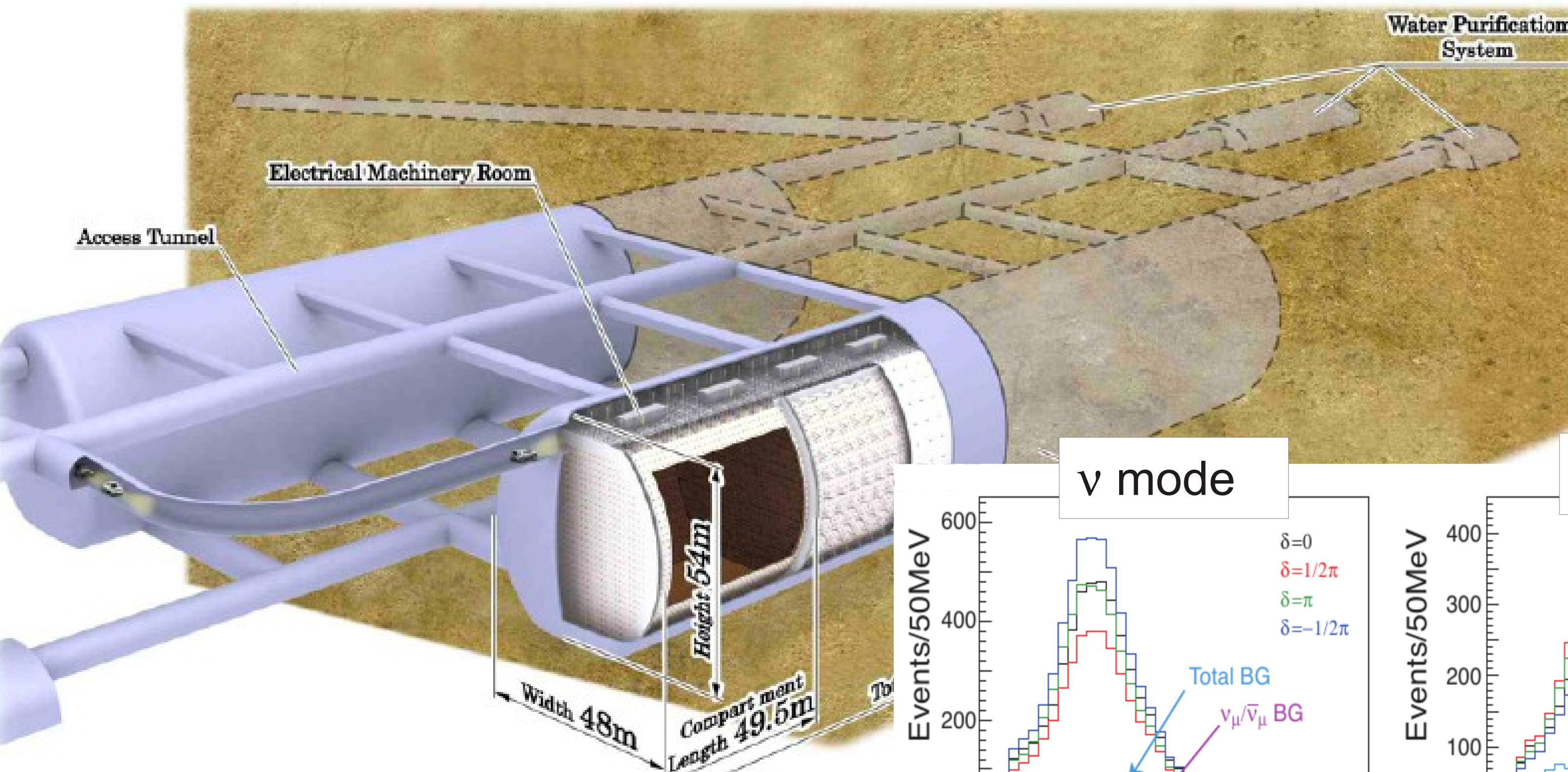


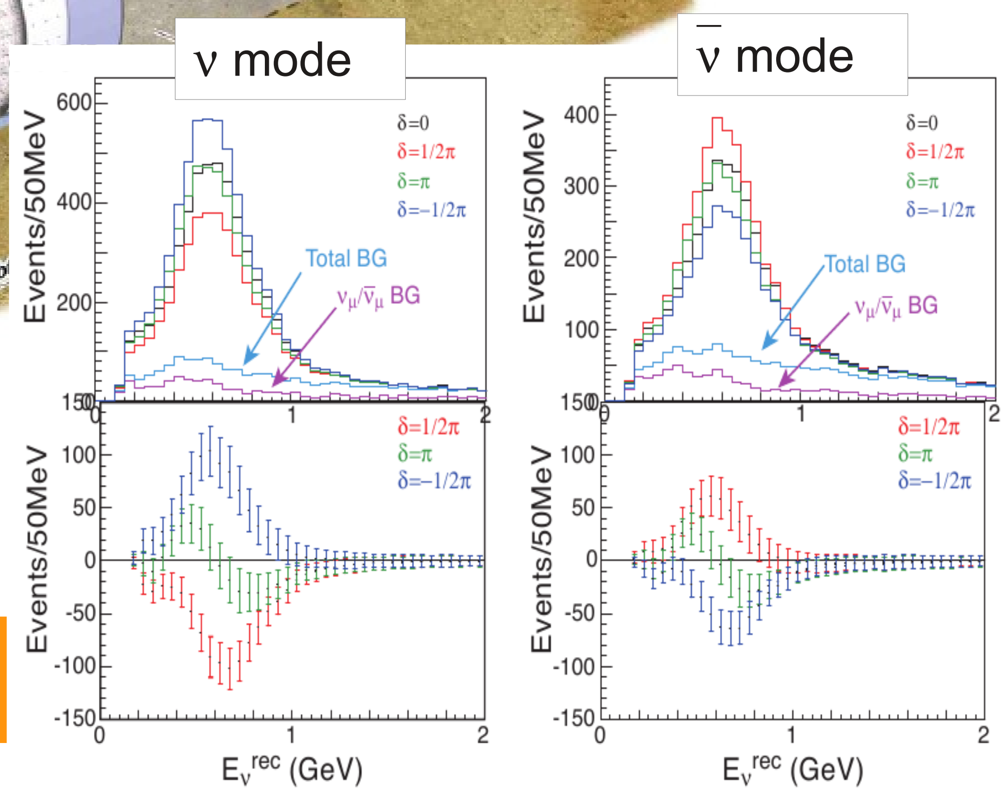
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric — Reactor/Interference — Solar

$\mu \Rightarrow \tau$ — $\mu \Leftrightarrow e$ — $e \Leftrightarrow \mu$

Hyper-K

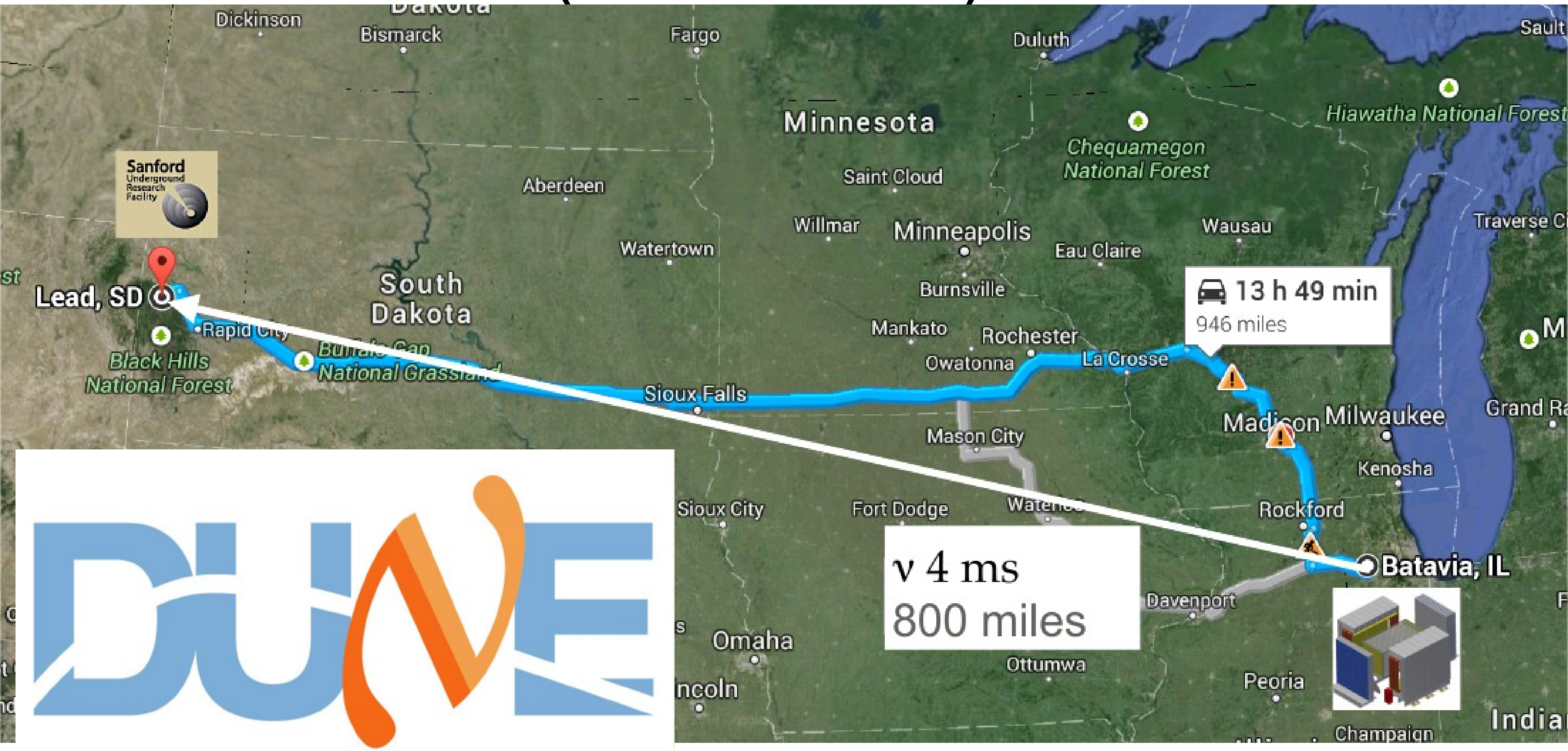




1 Megaton
(~20x larger than SuperK!)
295 km baseline

Needs MH to be determined.

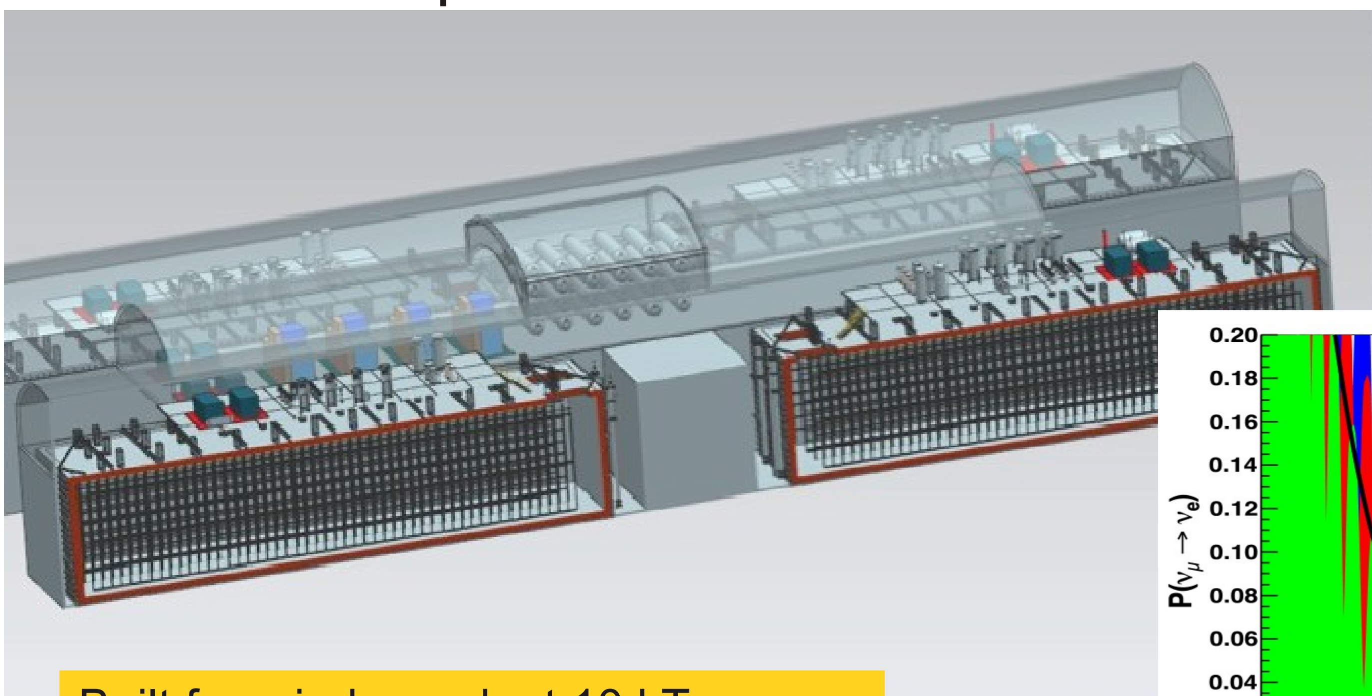
DUNE : ν_e appearance at SURF (Homestake)



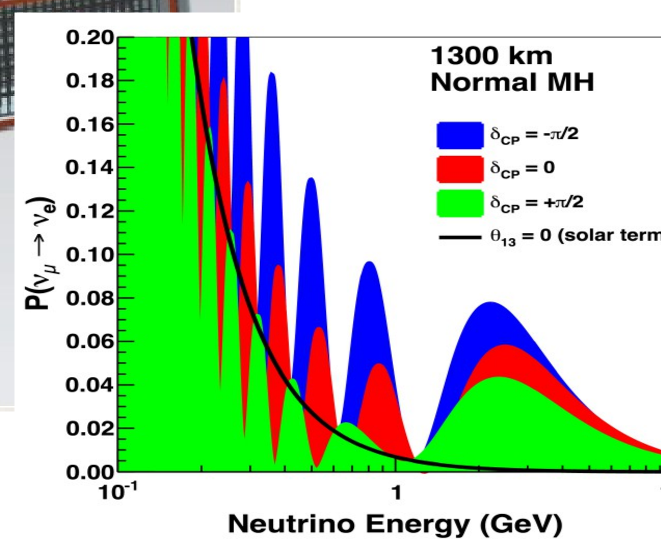
DEEP UNDERGROUND NEUTRINO EXPERIMENT

DUNE = LBNE + LBNO

- The merger of two big Long Baseline Neutrino proposals.
- Largest neutrino collaboration (750 people).
- First module planned ~2024

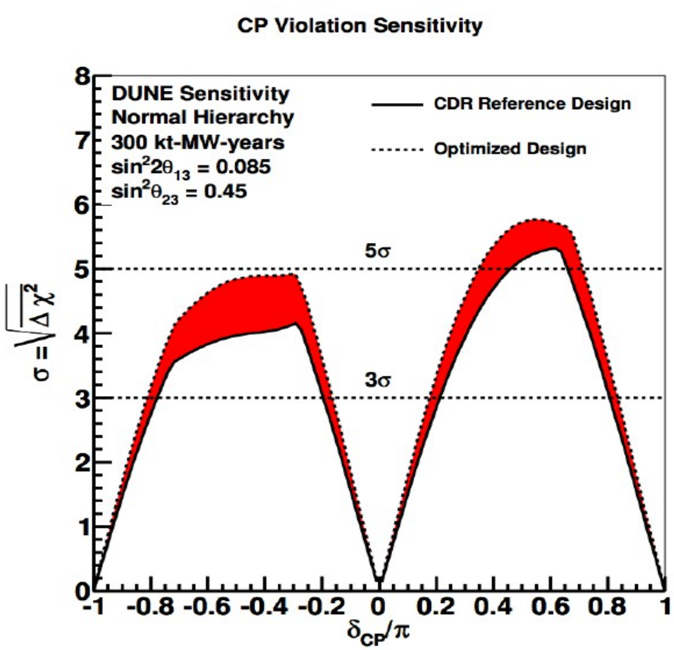


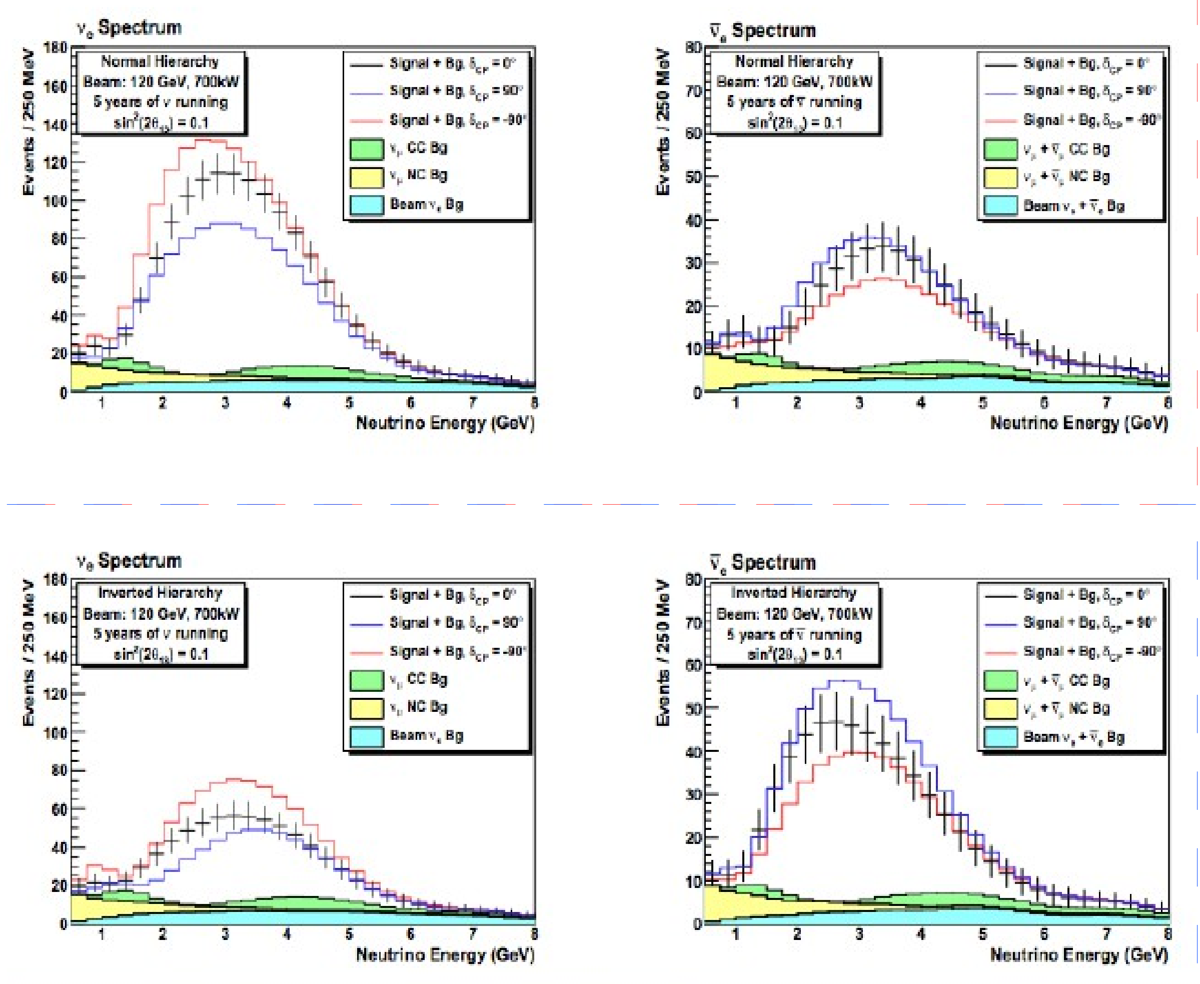
Built from independent 10 kTon LArTPC modules



DUNE δCP measurement

- Need to see subtle differences between neutrinos and anti-neutrinos.





Summary

- There are many exciting experimental measurements in progress.
- And even more coming online in the next couple of years.
- Neutrino Physics is a data-driven (and vibrant) experimental field.

Things I did not talk about

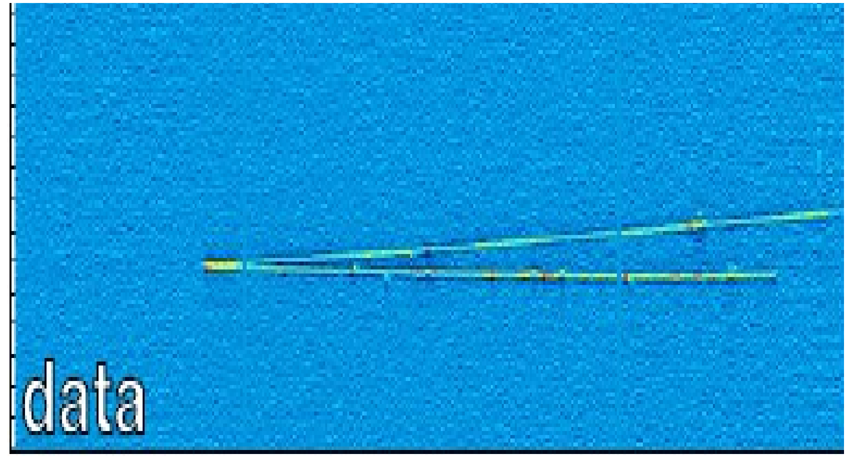
- UHE neutrinos in IceCube
- Cross-section measurements.
- SuperNova Neutrinos.
- Many other cool things.

Thank you for your attention!

Coherent Pion Production

$$\nu_\mu + A_{g.s.} \rightarrow \mu^- + \pi^+ + A_{g.s.}$$

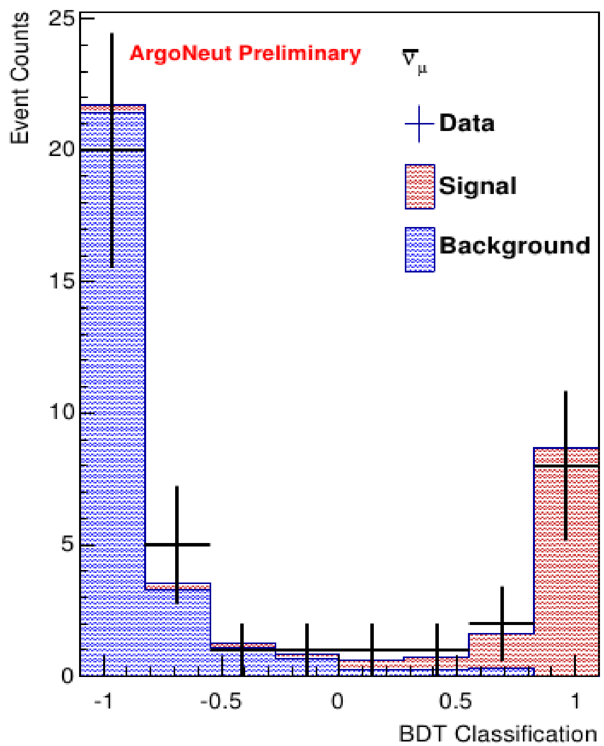
$$\bar{\nu}_\mu + A_{g.s.} \rightarrow \mu^+ + \pi^- + A_{g.s.}$$

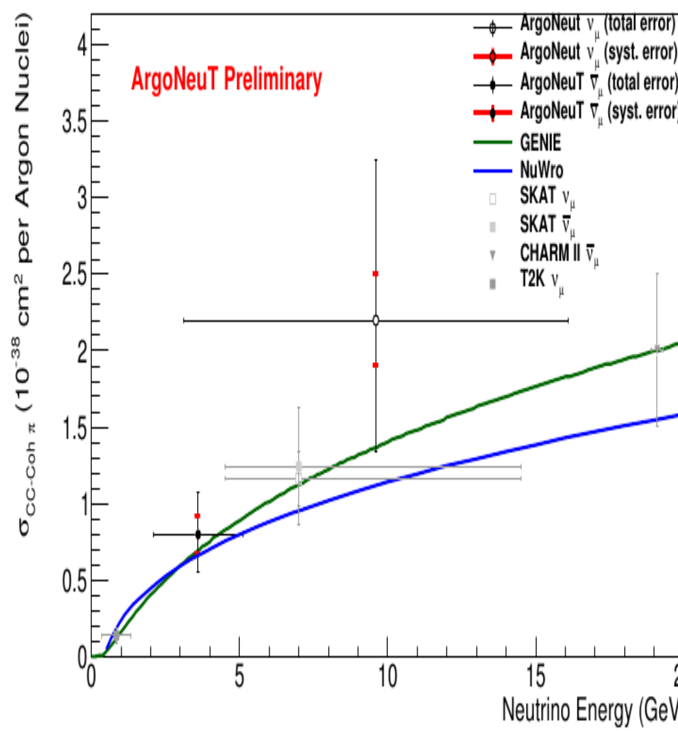


Most pions are not contained so not possible to use Q^2 or t as discrimination.

MC used to build a binned background and signal expectation for a BDT response (based on kinematic variables).

This is then fit to the data.





Also, recent results from Minerva and T2K.