Other Opportunities in Neutrino Experiments

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Imperial College London

PPAP Community Meeting
University of Birmingham
2012 09 18

- Neutrino oscillations lead to rich phenomenology
- Global ν programme has a wide range of future options
- UK physicists are working on many of these ideas
  - In some cases, leadership positions already
  - In others, will be in strong position to assume leadership roles when the time comes
- STFC strategy will group small experiments into broad science areas
  - this talk is a few details on one: **neutrinos**

Outline

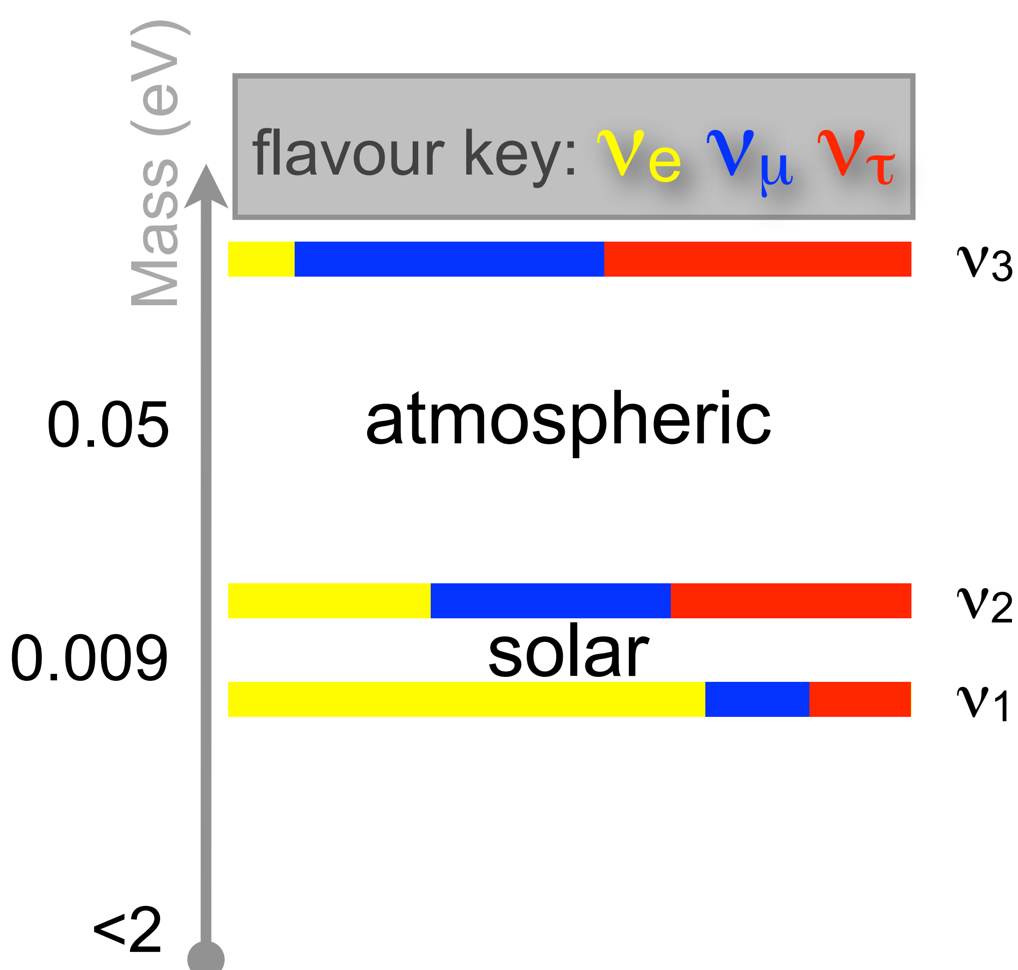
- Reminder of current picture
- Sterile neutrinos
  - Will focus on experiments that are important to the 3-ν paradigm or otherwise add value to global programme
- Reactor neutrinos (θ_{12})
- UHE neutrinos from astrophysical sources

Reminder: neutrino picture

flavour — *atmospheric* — *accelerator* — *solar* — *Majorana* — mass

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\frac{\alpha_1}{2}} & 0 & 0 \\ 0 & e^{i\frac{\alpha_2}{2}} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino physics is making discoveries!
Big results in past year - more discoveries on horizon.



OPEN QUESTIONS:

- Hierarchy?
- CP violation?
- Majorana or Dirac?
- Absolute mass scale?

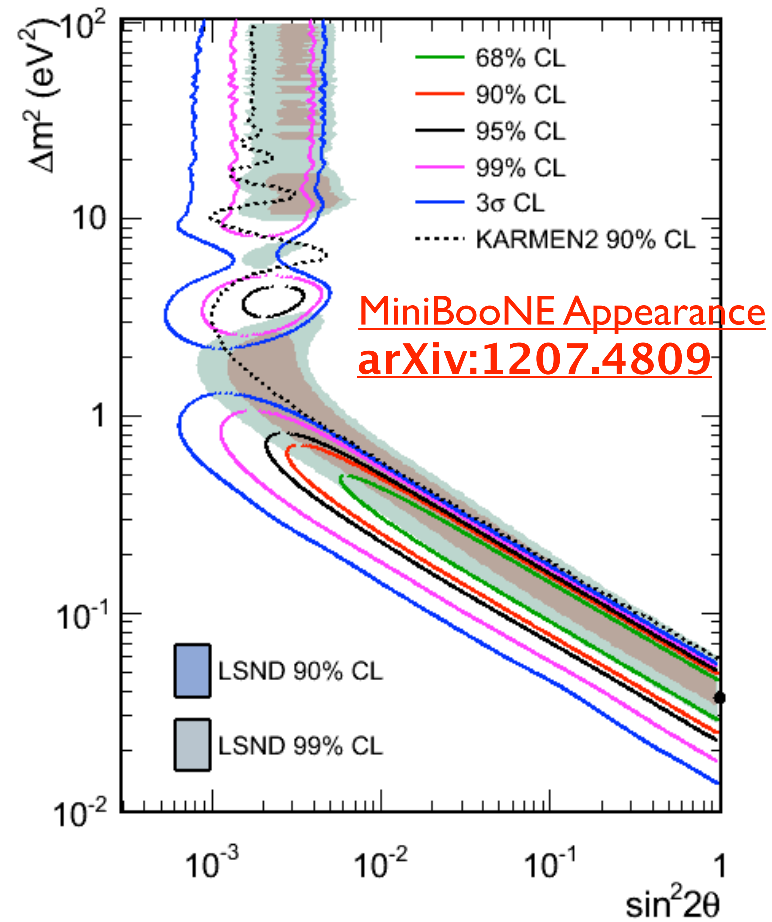
- A nice picture with a clear path forward...

Sterile Neutrinos?

Sterile Neutrinos?

Gallium Anomaly: ν_e Disappearance?

- SAGE and GALLEX gallium solar neutrino experiments used MCi ^{51}Cr and ^{37}Ar sources to calibrate their detectors
  - A recent analysis claims a significant (3σ) deficit (Giunti and Laveder, 1006.3244v3 [hep-ph])
    - Ratio (observation/prediction) = 0.76 ± 0.09
    - An oscillation interpretations gives $\sin^2 2\theta > 0.07, \Delta m^2 > 0.35 eV^2$

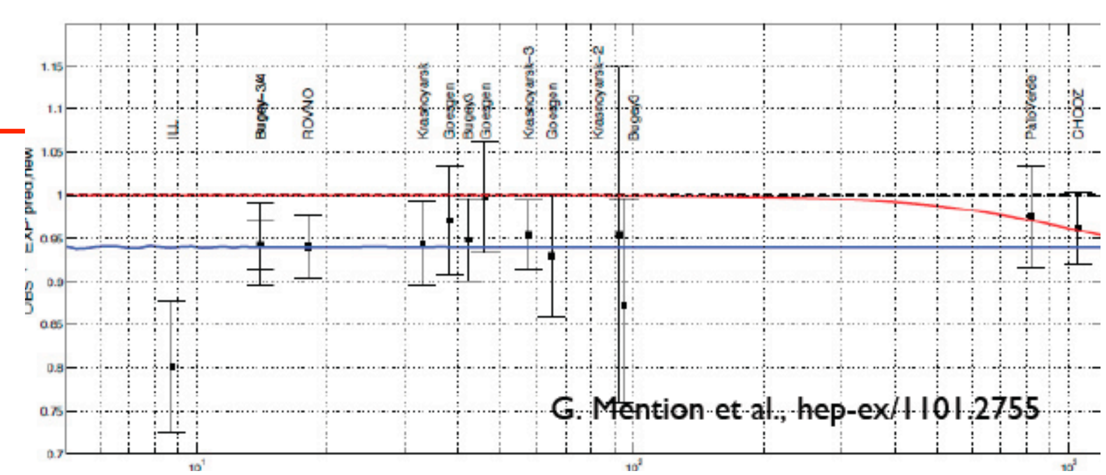


Reactor Antineutrino Anomaly

Re-analysis of predicted reactor fluxes based on a new approach for the conversion of the measured electron spectra to anti-neutrino spectra.

- Reactor flux prediction increases by 3%.
- Re-analysis of reactor experiments show a deficit of electron anti-neutrinos compared to this prediction – at the 2.14σ level
- Could be oscillations to sterile with $\Delta m^2 \sim 1 eV^2$ and $\sin^2 2\theta \sim 0.1$

Red: Oscillations assuming 3 neutrino mixing
Blue: Using a 3+1 (sterile neutrino) model



N.B.: several 2-3 σ results don't constitute compelling evidence...

Active-sterile Neutrino Oscillation

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_{s1} \\ \cdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s_1 1} & U_{s_1 2} & U_{s_1 3} & U_{s_1 4} & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \cdots \end{pmatrix}$$

$\nu_\mu \rightarrow \nu_e$ appearance

$$P(\nu_\mu \rightarrow \nu_e) = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\left[1.27\Delta m^2_{41}\frac{L}{E}\right]$$

ν_e disappearance

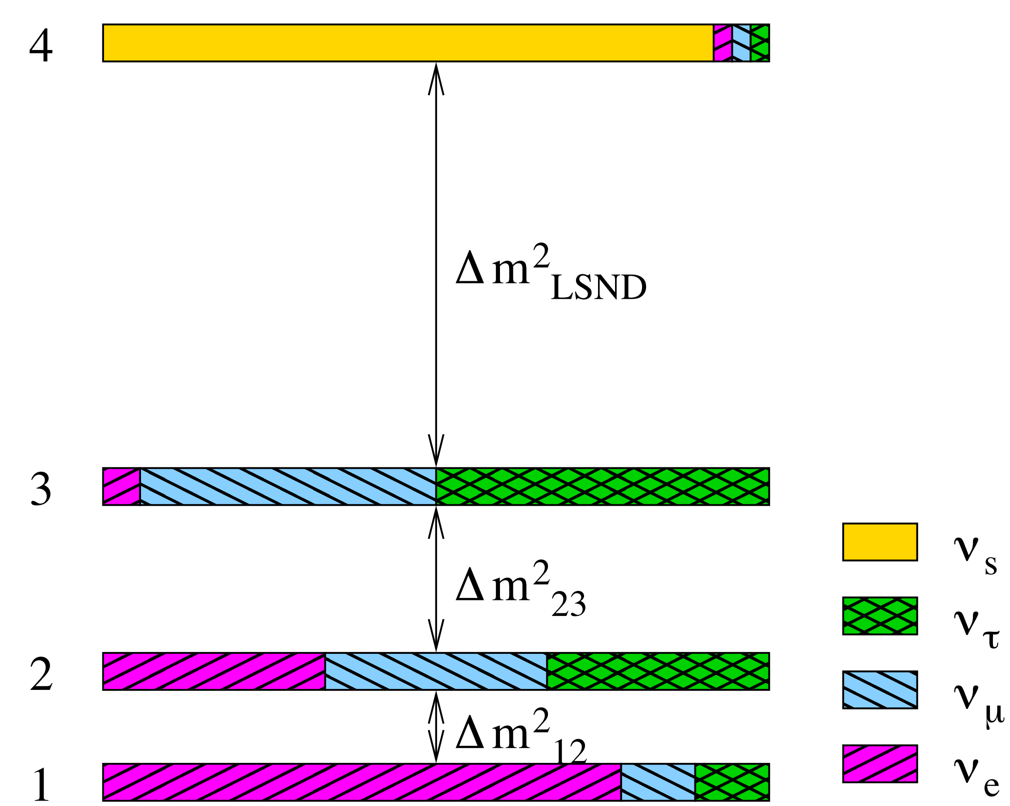
$$P(\nu_e \rightarrow \nu_x) = 1 - 4|U_{e4}|^2(1 - |U_{e4}|^2) \sin^2\left[1.27\Delta m^2_{41}\frac{L}{E}\right]$$

ν_μ disappearance

$$P(\nu_\mu \rightarrow \nu_x) = 1 - 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2) \sin^2\left[1.27\Delta m^2_{41}\frac{L}{E}\right]$$

Close relationships between appearance and disappearance channels

3+1 sterile neutrino scheme



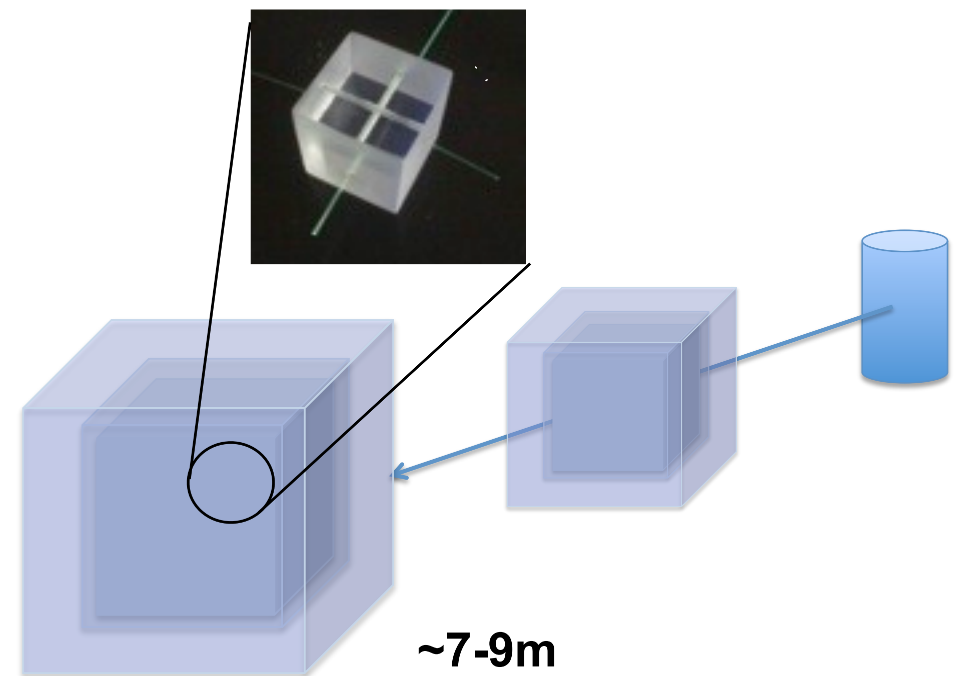
Antonin Vacheret <Antonin.Vacheret@physics.ox.ac.uk>

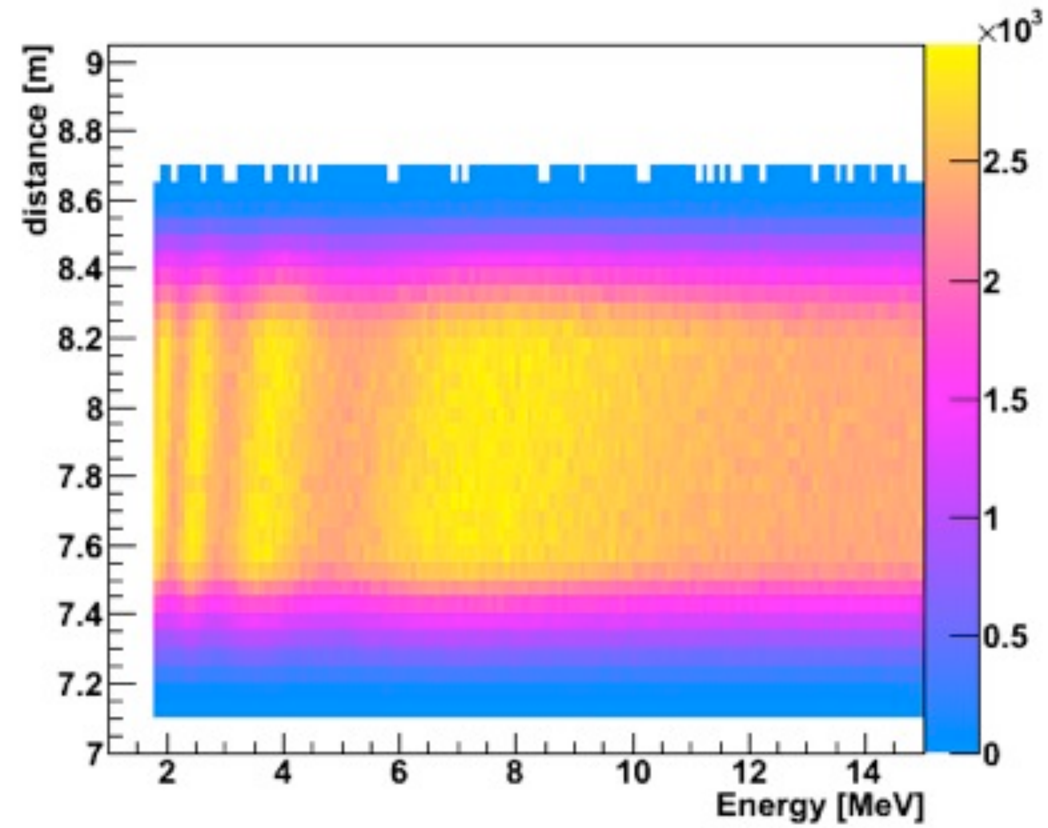
To test reactor flux and Ga anomalies

TWIX

solid segmented plastic scintillator detectors

- Novel approach to detect antineutrinos at reactors
  - composite scintillator cells with Li^6
  - compact system with minimal shielding (1.5m footprint for 1T Fiducial mass)
  - very low sensitivity to gamma background
  - can achieve better signal to background ratio than traditional liquid scintillator system
- Originally developed for reactor monitoring purposes





Δm^2=2.35, $\sin^2 2\theta_{ee}$ = 0.165

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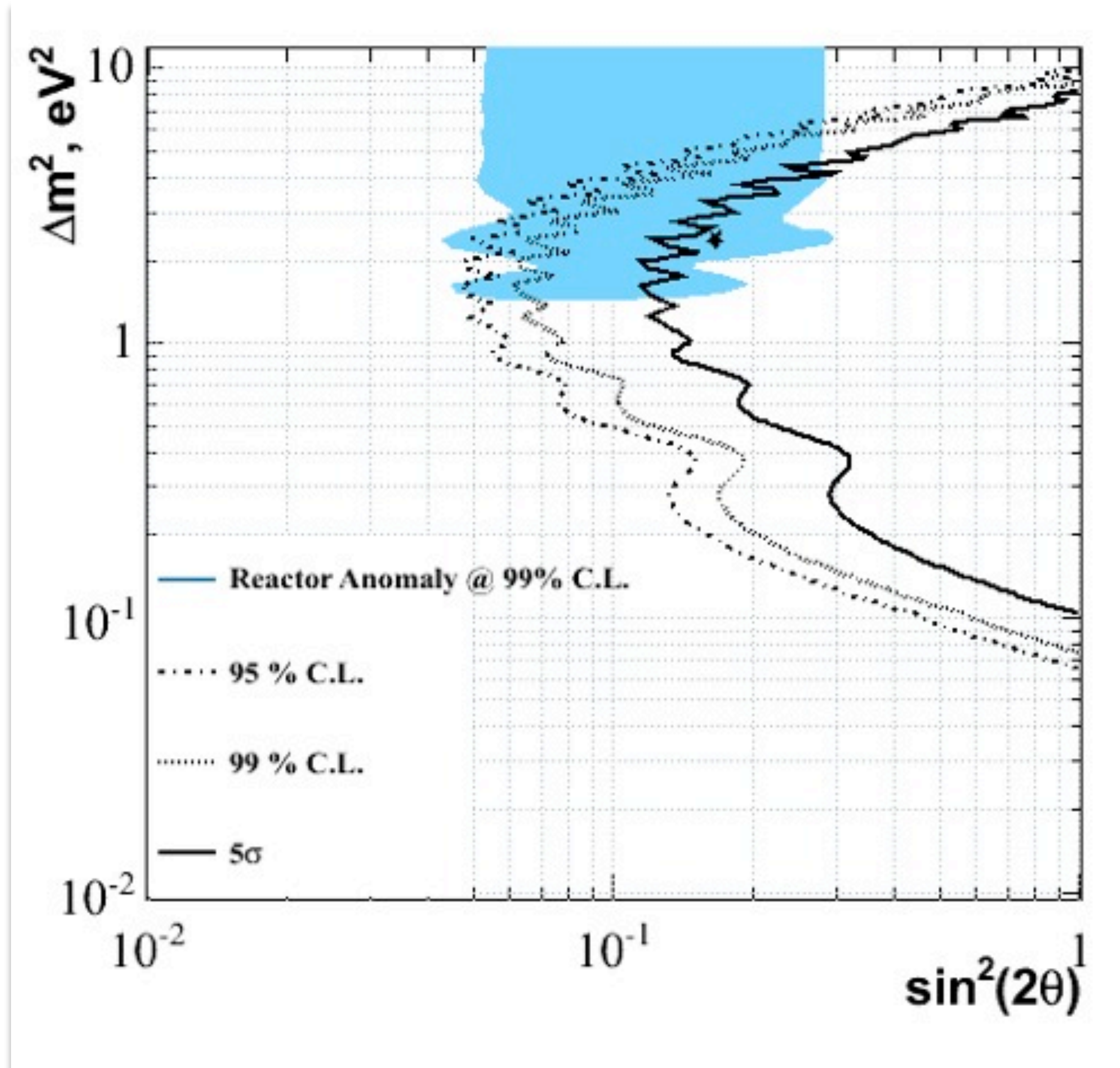
To test reactor flux and Ga anomalies

TWIX

solid segmented plastic scintillator detectors

- Measurement at ILL (2 years) (~50k events)
  - Baselines assumed: 7.5 m near and 9 m far (being optimised)
  - (ILL 0.8m x 0.4m core can provide best resolution on SBL oscillations)
- shape analysis using two detector baseline
  - signal from ratio of spectra
  - 3D vertex reconstruction (< 10 cm resolution)
  - σ_E/E ~ 0.1 MeV



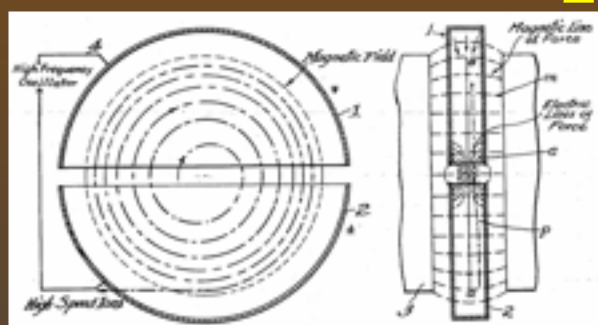
DAEδALUS

arXiv:1006.0260 [physics.ins-det]

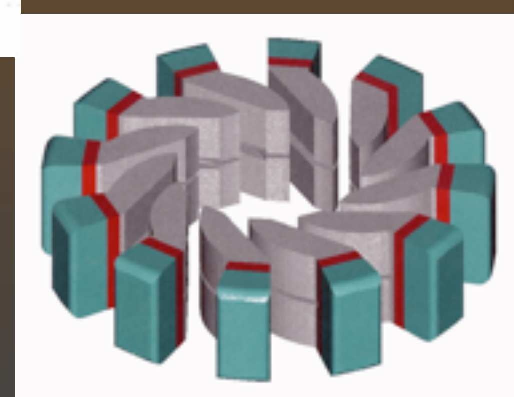
osc max ($\pi/2$) at 40 MeV — 20km

off max ($\pi/4$) at 40 MeV — 8km

Constrains flux — 1.5km

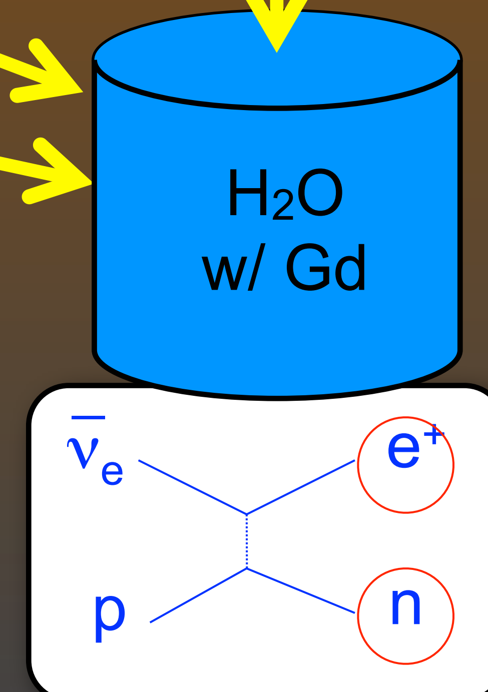


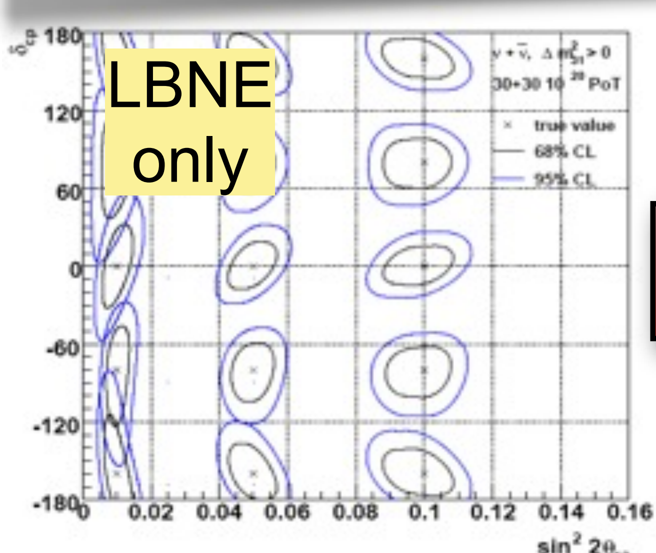
$\pi^+ \rightarrow \nu_\mu \mu^+$
$\rightarrow e^+ \bar{\nu}_\mu \nu_e$



High power cyclotrons create massive $\bar{\nu}_\mu$ flux at multiple baselines

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$





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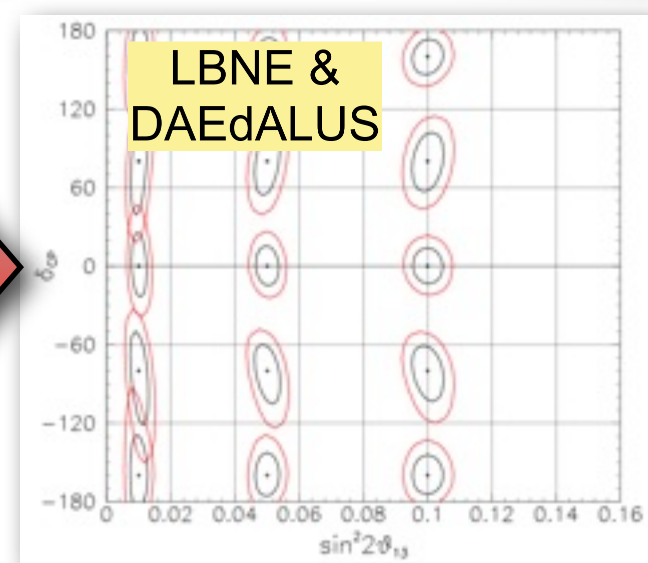

Physics studies done assuming H_2O detector in LBNE, but same performance achievable with Hyper-K or LBNO

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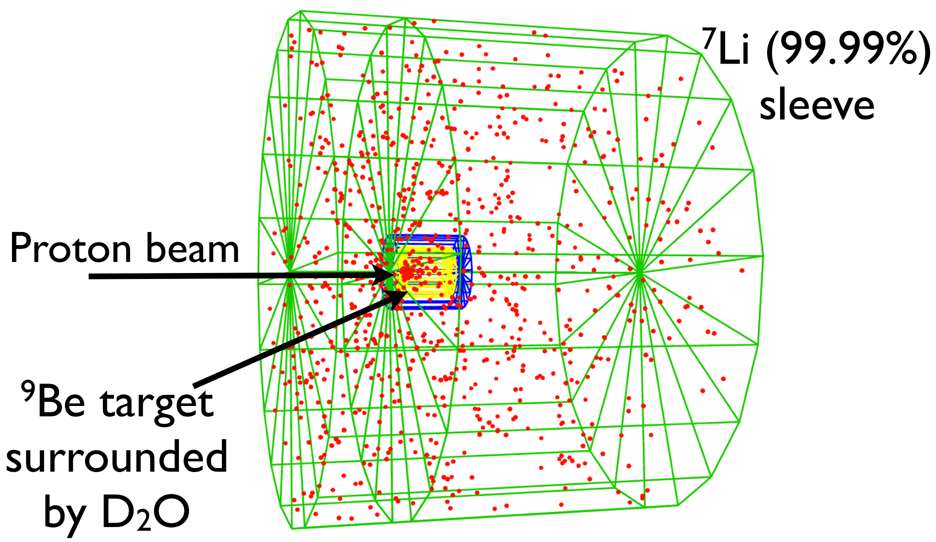
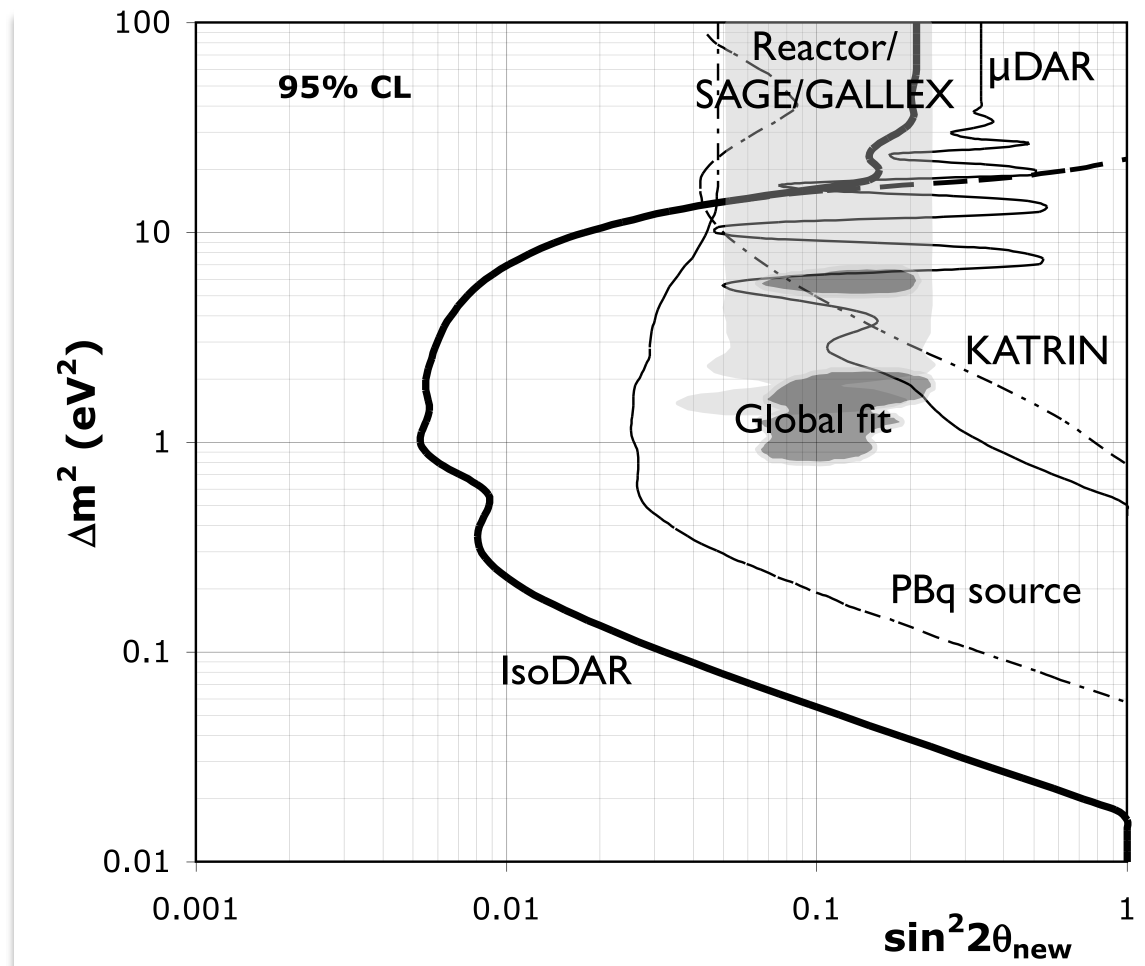
To test reactor flux and Ga anomalies

DAEδALUS

Medium term: IsoDAR

arXiv:1205.4419 [hep-ex]

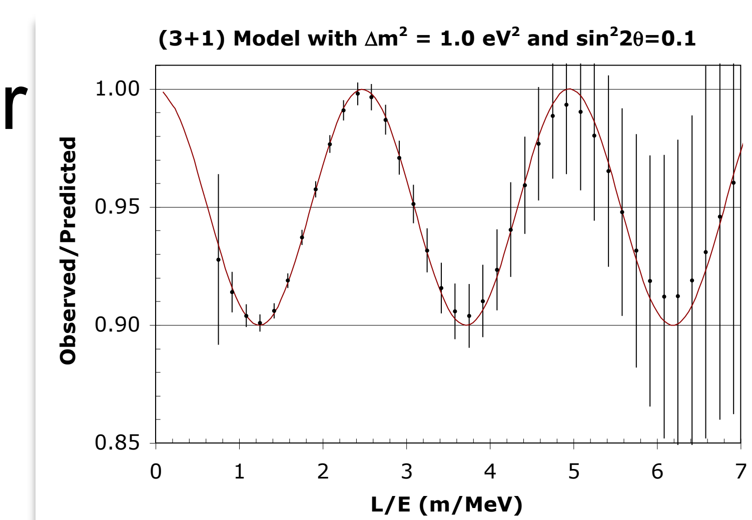


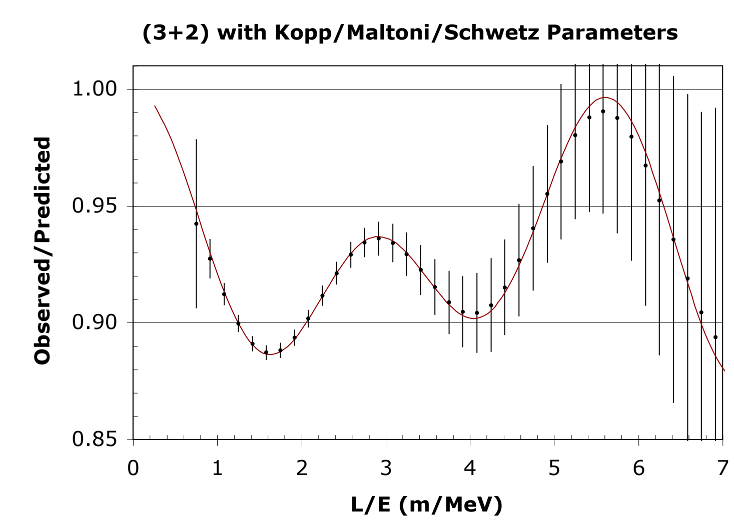


- High power cyclotrons create high $\bar{\nu}_e$ flux
- $n+Li^7 \longrightarrow Li^8$

  ↳ $\bar{\nu}_e$, $<E_\nu>=6.4$MeV

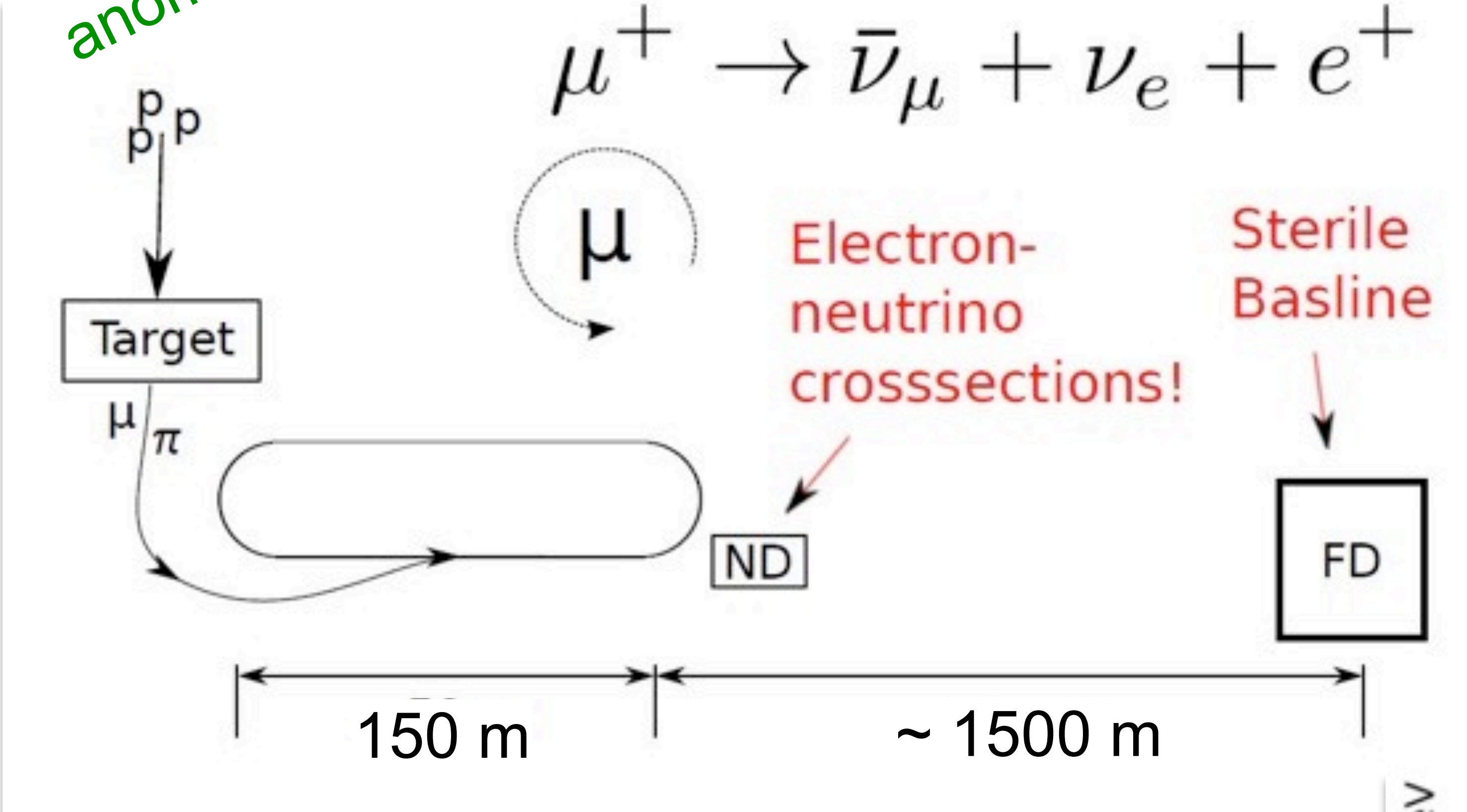
- Placed near a good $\bar{\nu}_e$ detector (e.g. KamLAND) gives excellent sensitivity to sterile oscillation
- UK involved in accelerator and beam dump studies





NuSTORM

To test LSND & MiniBooNE, Ga, and reactor anomalies



[arXiv:1206.0294 [hep-ex]](arXiv:1206.0294)

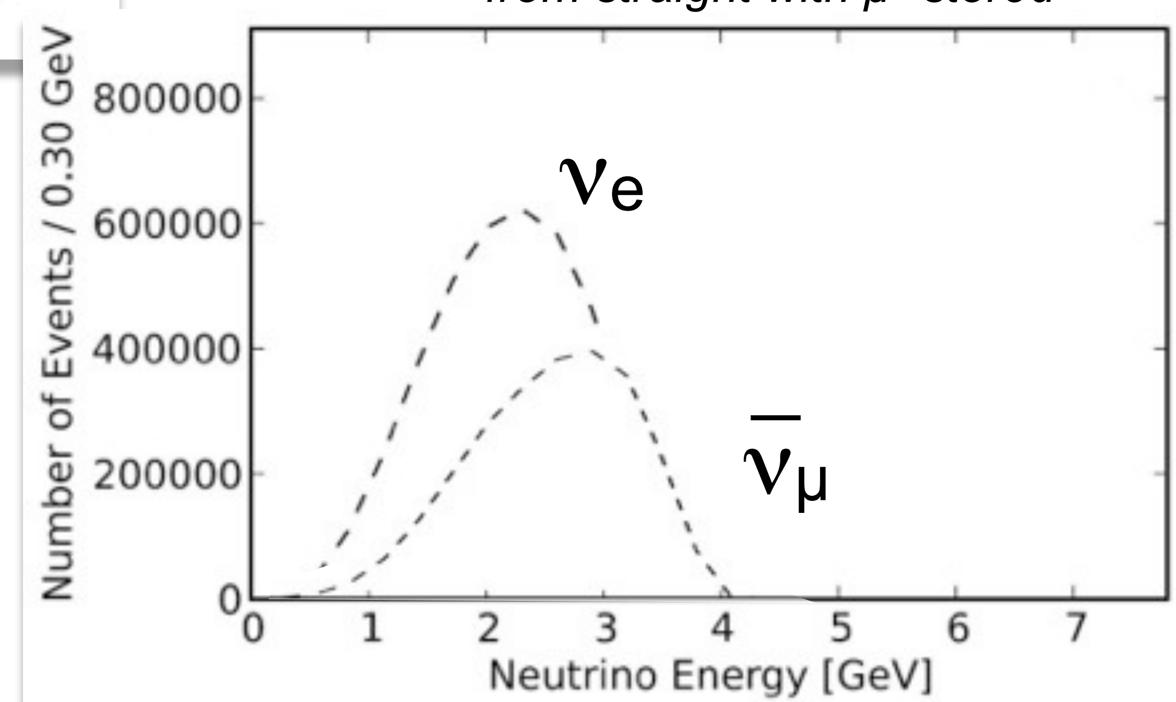
Multiple sterile ν channels

Appearance Channel:

$\nu_e \rightarrow \nu_\mu$

Must reject the wrong sign μ with **high** efficiency

Event rates/100T at Fe ND 50m from straight with μ^+ stored

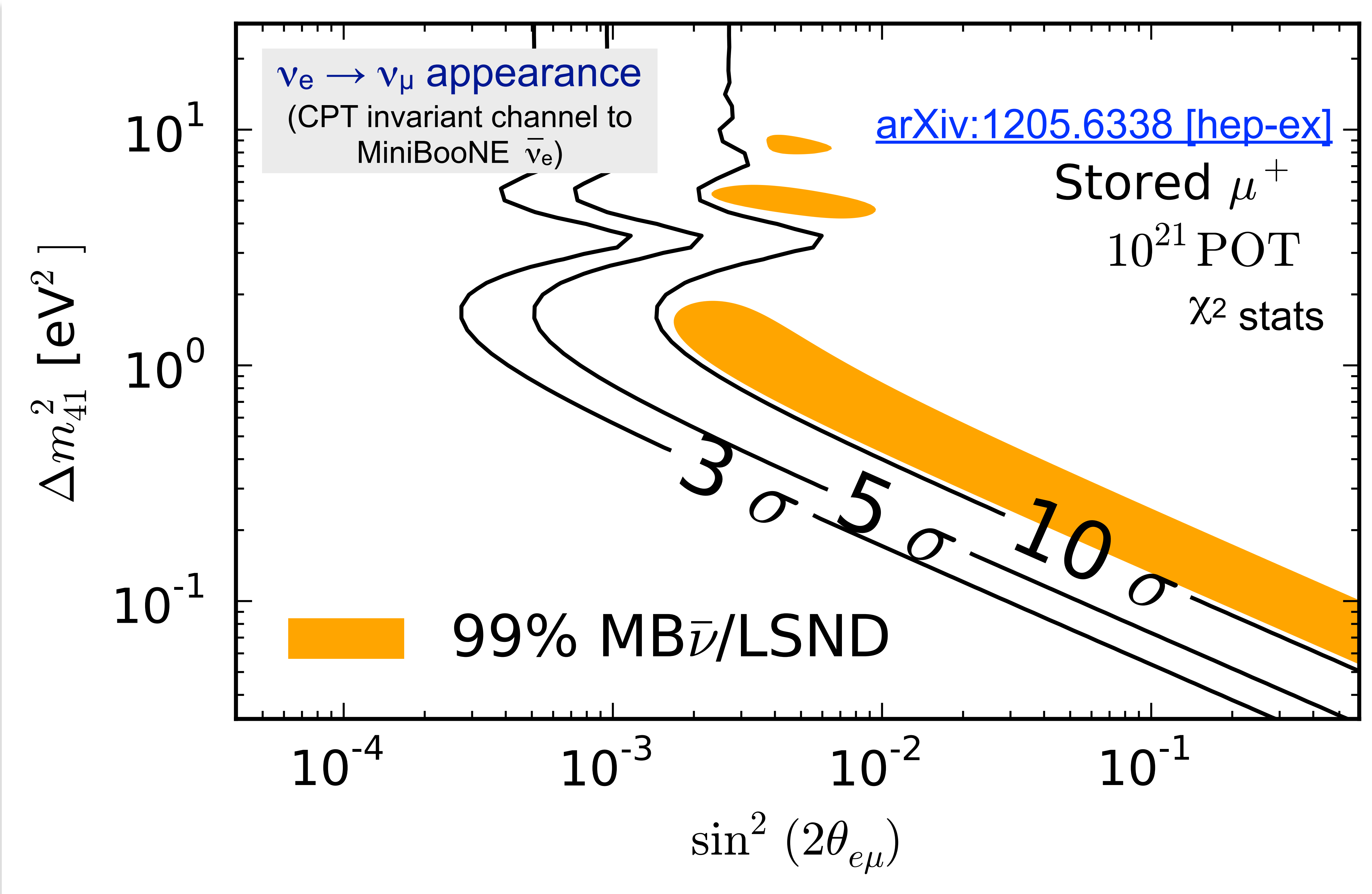


Received positive feedback from Fermilab PAC
http://www.fnal.gov/directorate/program_planning/phys_adv_com/PAC%20Comments%20and%20Recommendations.pdf

http://www.fnal.gov/directorate/program_planning/June2012Public/P-1028_LOI_Final.pdf

Christopher Tunnell <c.tunnell1@physics.ox.ac.uk>

NuSTORM: oscillations



3+1 Assumption

NuSTORM physics programme

- As an experiment, NuSTORM can:
  - ✓ Perform direct tests of the LSND and MiniBooNE anomalies.
  - ✓ Perform direct tests of the Gallium and reactor anomalies.
  - ✓ Test the CP- and T-conjugated channels, constrain with disappearance.
  - ✓ Make precise and **unique** measurements of ν_μ and ν_e cross-sections

Valuable physics input for δ_{CP} searches

- As a facility, NuSTORM:
  - ✓ Provides an accelerator technology test bed
  - ✓ Provides a powerful ν detector test facility

Jaroslaw's talk

- As a programme, NuSTORM:
  - ✓ Provides an important step on the path toward discovery in neutrinos and collider physics

Excellent synergy with superbeams!

NuSTORM ν Cross-sections

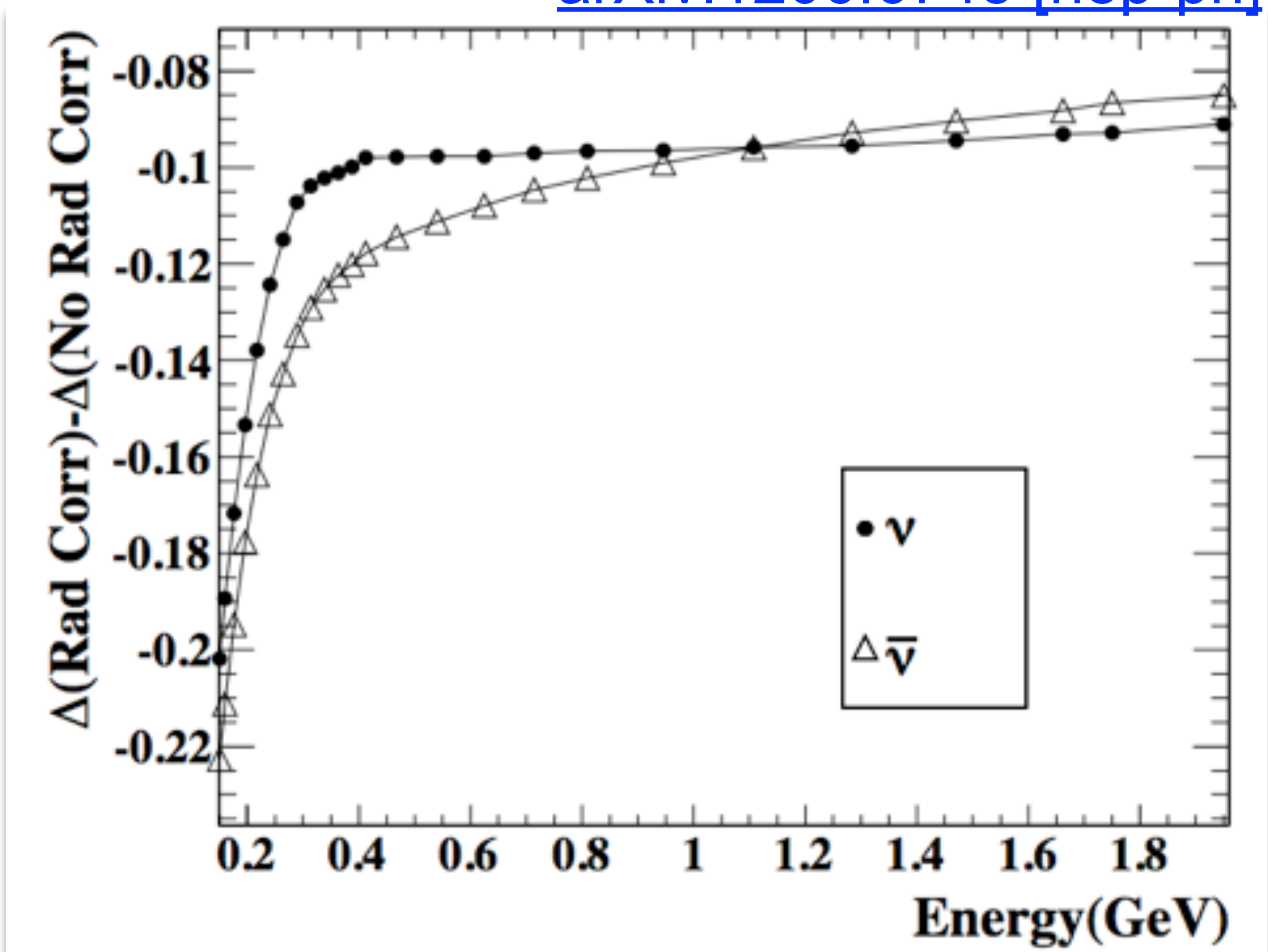
- NuSTORM presents only way to measure ν_e, $\bar{\nu}_\mu$ (& $\bar{\nu}_e, \nu_\mu$) cross-sections in the same detector(s)
  - Supports future long-baseline experiments!
  - E_ν matched well to needs of these experiments

arXiv:1206.6745 [hep-ph]

Recent calculations showing expectations for differences between ν_e and ν_μ cross-sections

We need data!

NuSTORM members have submitted a statement to the PPAP and the CERN Strategy Committee



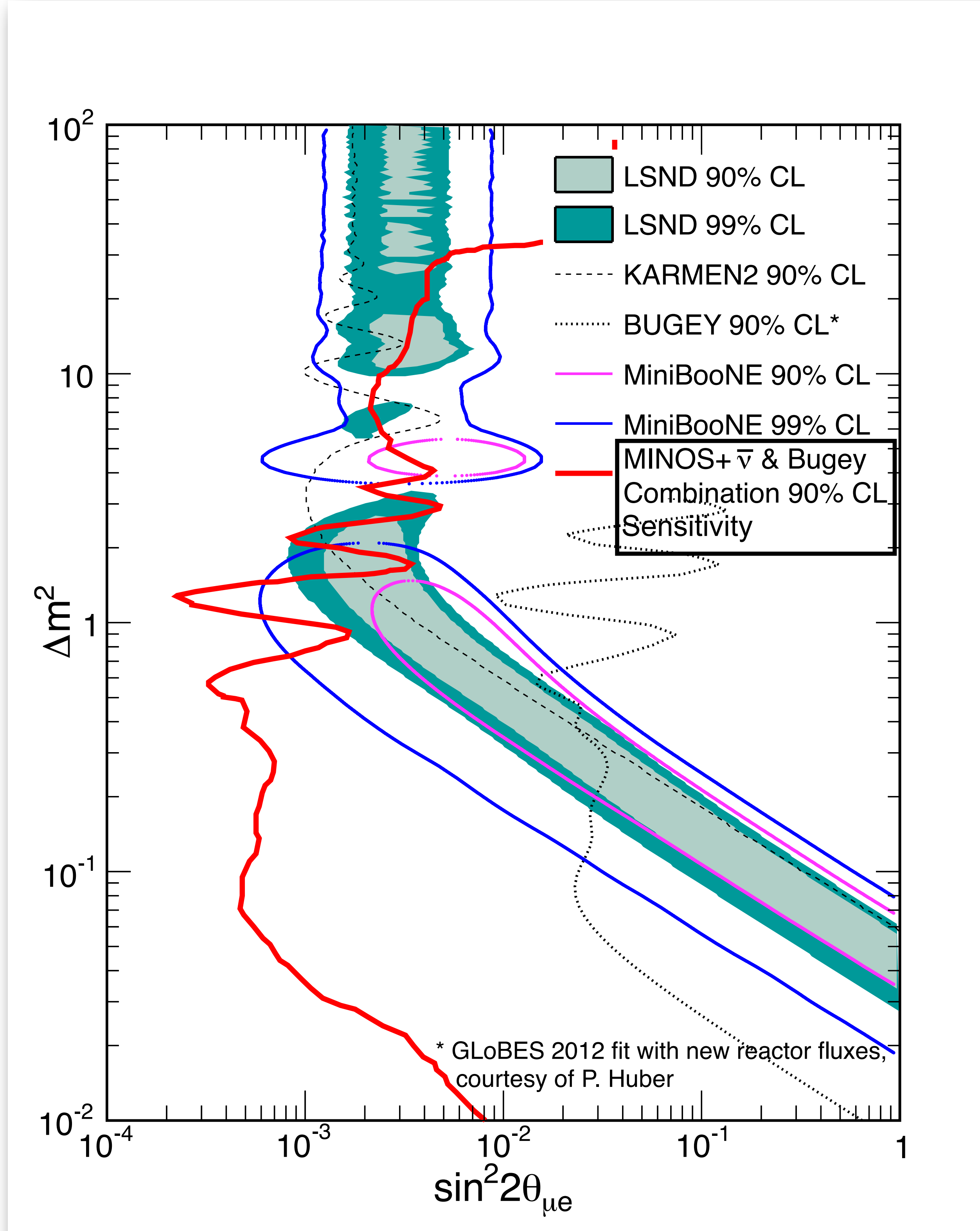
Ryan Nichol <rjn@hep.ucl.ac.uk>

MINOS+

- Extension of MINOS run in the medium-energy NuMI beam
- Runs concurrently with NOvA
- Sterile sensitivity:

$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) < 4P(\bar{\nu}_\mu \rightarrow \bar{\nu}_x)*P(\bar{\nu}_e \rightarrow \bar{\nu}_x)$

Uses reanalysis of Bugey data and assumed sensitivity of MINOS+ with 1.2e21 POT in nubar mode



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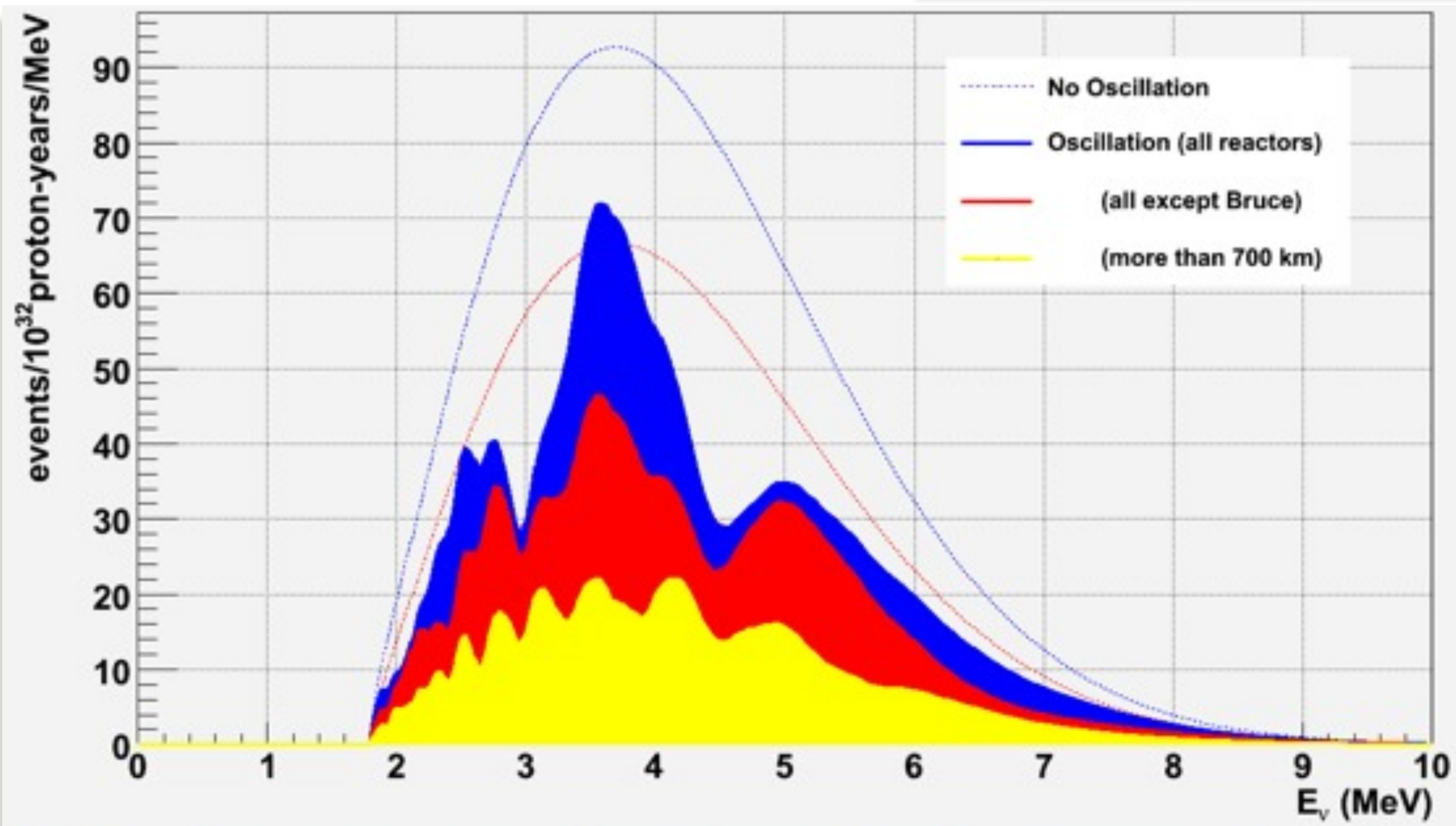
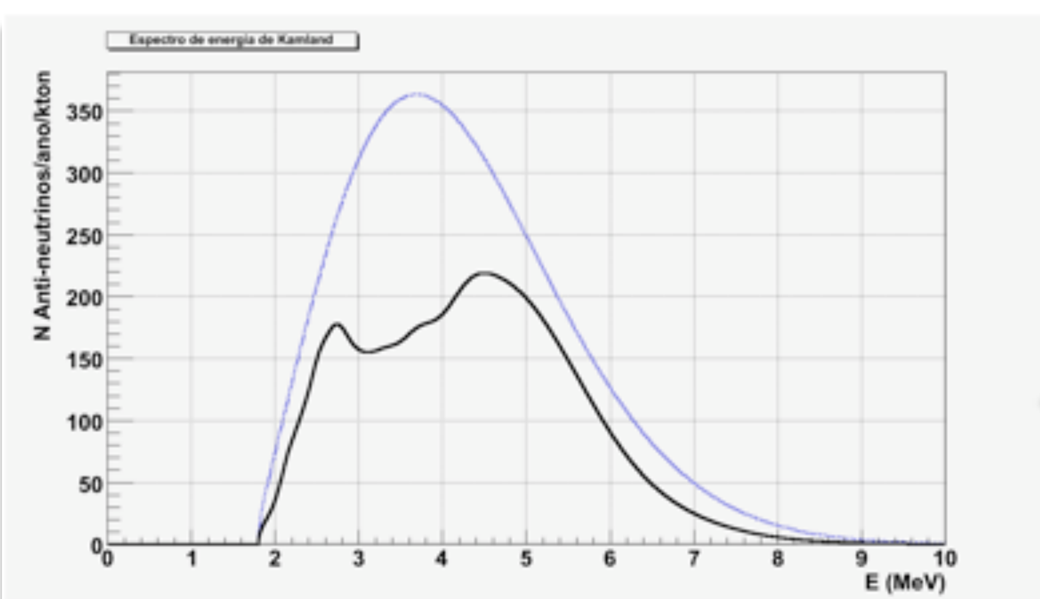
measurement of Δm^2_{12} with precision comparable to or better than KamLAND (despite lower statistics!)



Bruce reactor will contribute mainly to the central peak.



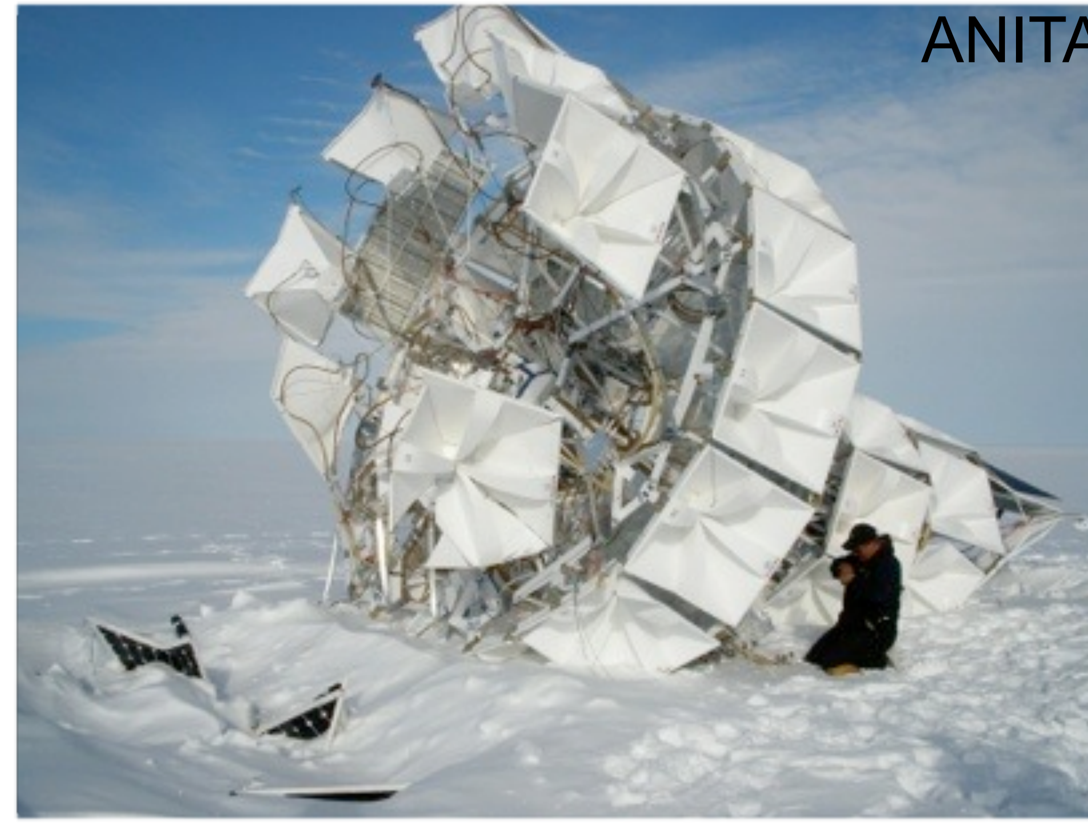
Much better defined peak structure compared to KamLAND

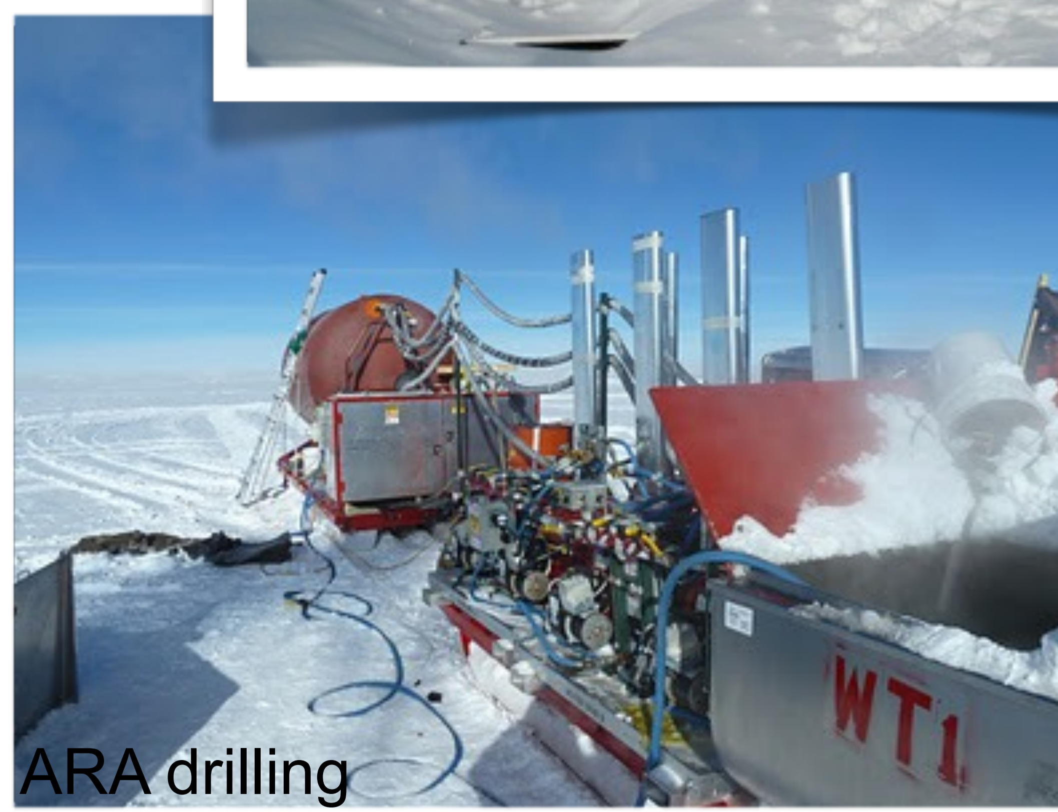
Reactor	d (km)	Th. Power (GW)
Bruce	281	10,32
Pickering	330	6,192
Darlington	340	10,572
R.E. Ginna	455	1,41
James A. Fitzpatrick	488	2,34
Nine Mile Point	488	5,07
Perry	530	3,1615
Enrico Fermi	559	3,255
Kewaunee	568	1,509
Davis-Besse	588	2,531
Point Beach	589	2,91
Palisades	617	2,34
Gentily	648	1,914
Beaver Valley	657	4,929
Donald C. Cook	685	3,06

Ryan Nichol <rjn@hep.ucl.ac.uk>

UHE astrophysical neutrinos

- ANITA
  - Active project that will have new data in the next 18 months.
  - The third ANITA flight is scheduled for the Austral summer 2013/14
  - This flight will be the most sensitive to ultra-high energy neutrinos in the range 10^{19} - 10^{23} eV
- ARA (Askaryan Radio Array)
  - Will deploy the first three full prototype stations Jan 2013
  - One year of data comparable sensitivity to ANITA around 10^{19} eV
  - If the stations prove successful would submit proposal for deploying the full 37 station array
  - Would seek wider UK/STFC support at that point





Conclusions

- UK physicists are already working and assuming leadership roles in many small efforts that will grow in the medium term.
  - Even this list was not exhaustive!
- Several future experiments show good sensitivity to sterile ν oscillation.
  - Expts that constitute steps in the global 3-ν paradigm must have priority.
    - IsoDAR and NuSTORM fit that bill.
  - Experiments that fulfil other important criteria should also be prioritised.
    - Twix grows out of nuclear non-proliferation efforts with significant KE potential. (And it's fast and inexpensive!)
- Lots of good work ongoing, with results and opportunities ahead.

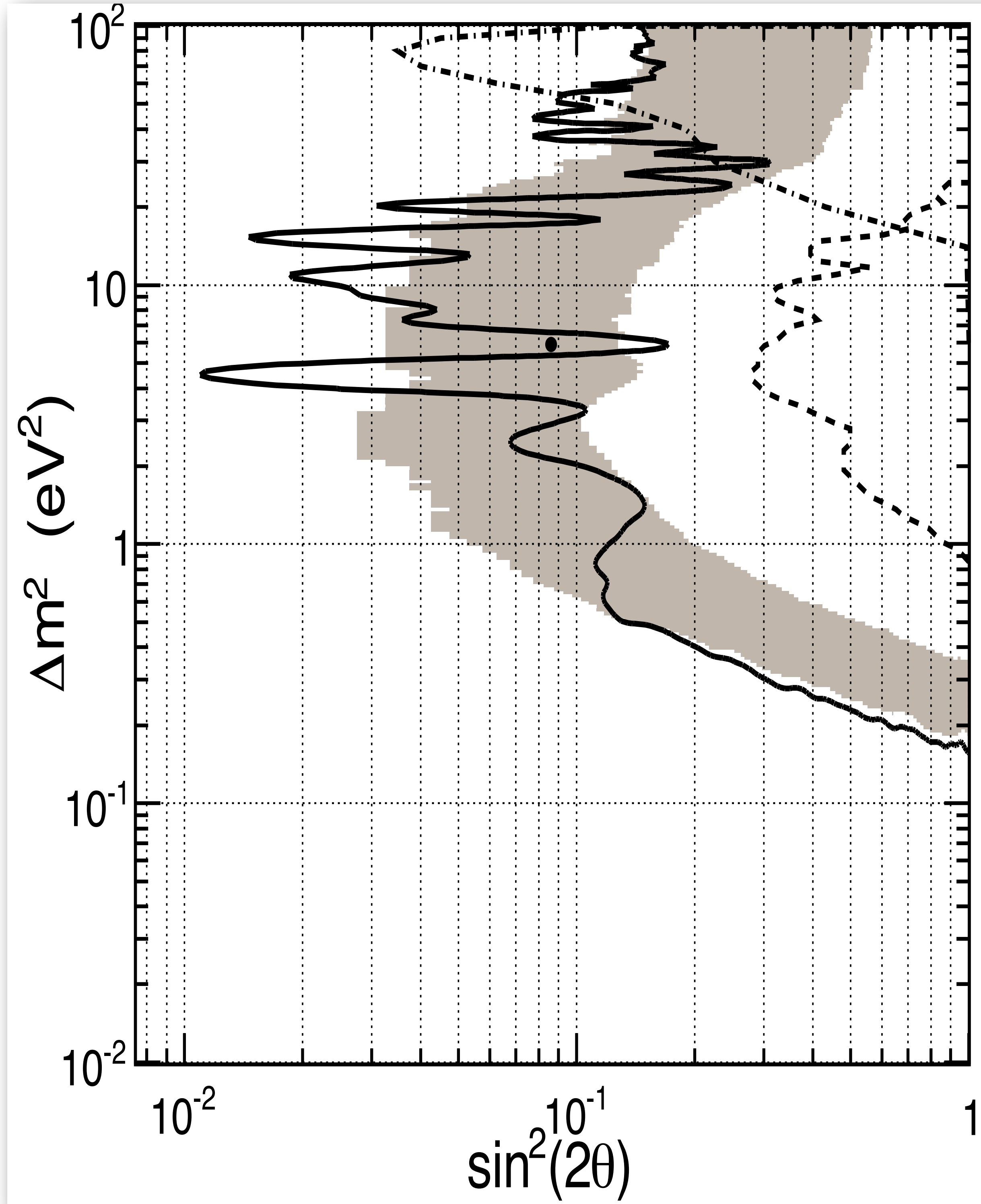
Not pushing an experiment, pushing an experimental programme!

THANK YOU!

SciBooNE/MiniBooNE

arXiv:1208.0322 [hep-ex]

- Muon antineutrino disappearance in MiniBooNE with SciBooNE as near detector
- World's best result over two decades of Δm^2
- Data release available on the web:
- http://www-sciboone.fnal.gov/data_release/joint_numubar_disap/



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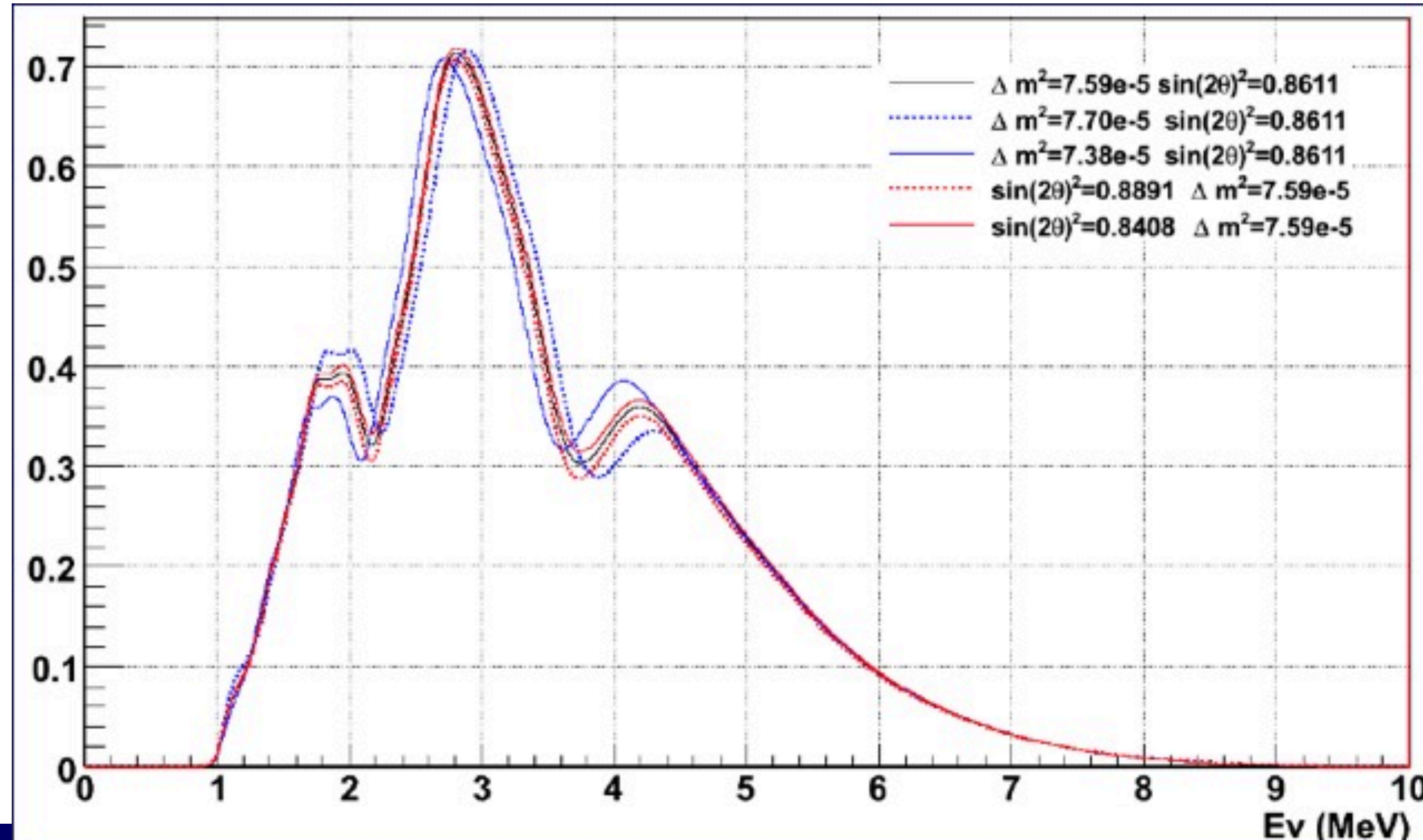
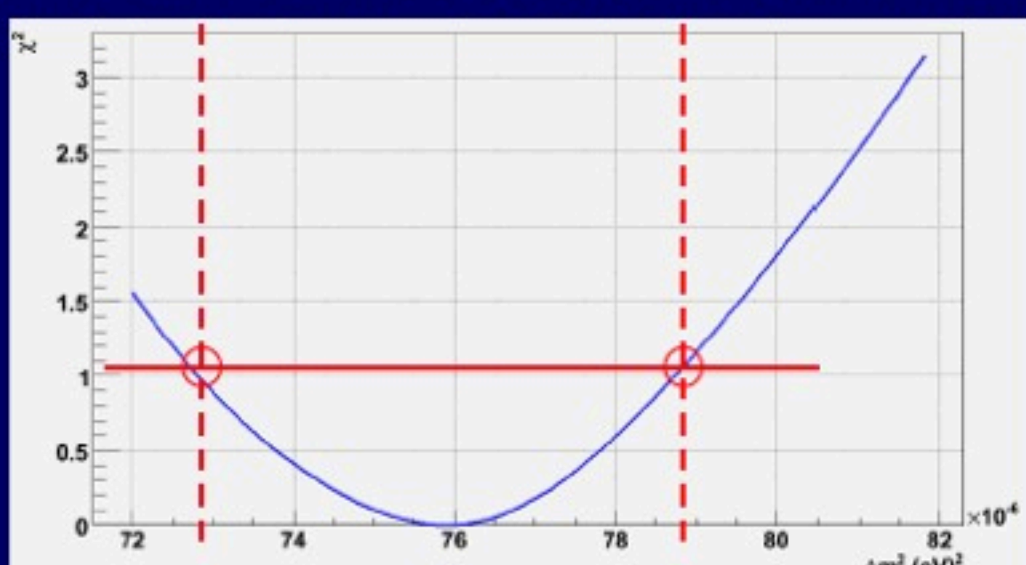


"Straw-man" calculation of statistics-limited precision as a function of assumed resolution

- Study for Δm^2

Chi^2 test applied to the visible energy spectrum with a varying Δm^2 around 7.59e-5 eV² and a fixed value of $\sin(2\Theta)^2$=0.8611 (plot for 6% resolution).



Resolution	-1σ	+1σ
6%	7.27e-5	7.88e-5
3%	7.32e-5	7.82e-5

6% : $\Delta m^2_{12} = 7.59^{+0.29}_{-0.32} \times 10^{-5} (eV)^2$

3% : $\Delta m^2_{12} = 7.59^{+0.23}_{-0.27} \times 10^{-5} (eV)^2$

Relative Diference in errors ~20%

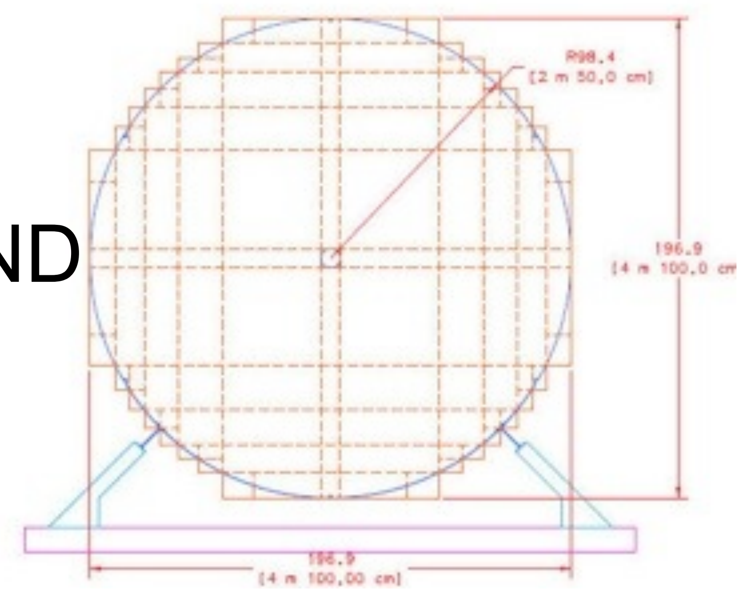
(life-time=1x10³²proton-year, approx 1.8 years for the calculations)

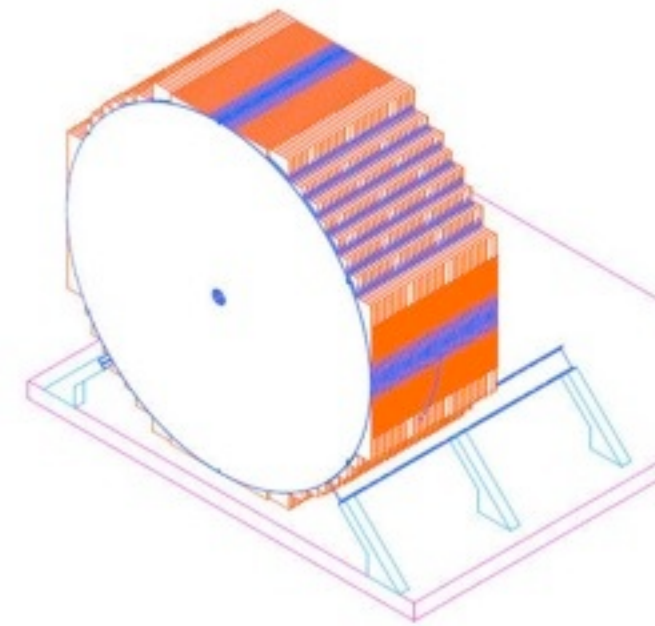
NuSTORM Assumptions

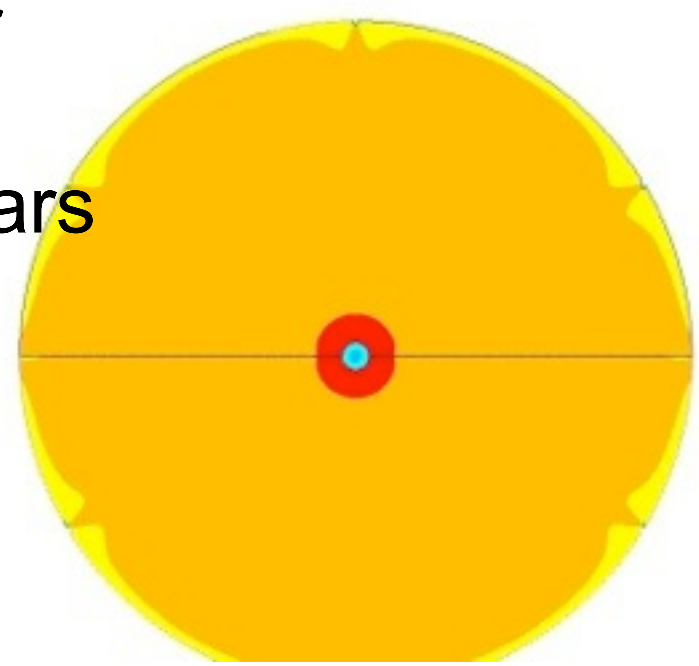
- N_μ = (POT) X (π/POT) X $\varepsilon_{collection}$ X ε_{inj} X (μ/π) X $A_{dynamic}$ X Ω
  - 10^{21} POT in 5 years of running @ 60 GeV in Fermilab PIP era
  - 0.1 π/POT (FODO)
  - $\varepsilon_{collection}$ = 0.8
  - ε_{inj} = 0.8
  - μ/π = 0.08 ($\gamma c\tau$ X μ capture in $\pi \rightarrow \mu$ decay) [π decay in straight]
    - Might do better with a $\pi \rightarrow \mu$ decay channel
  - $A_{dynamic}$ = 0.75 (FODO)
  - Ω = Straight/circumference ratio (0.43) (FODO)
- This yields ≈ 1.7 X 10^{18} useful μ decays

Baseline Detector
Super B Iron Neutrino Detector: SuperBIND

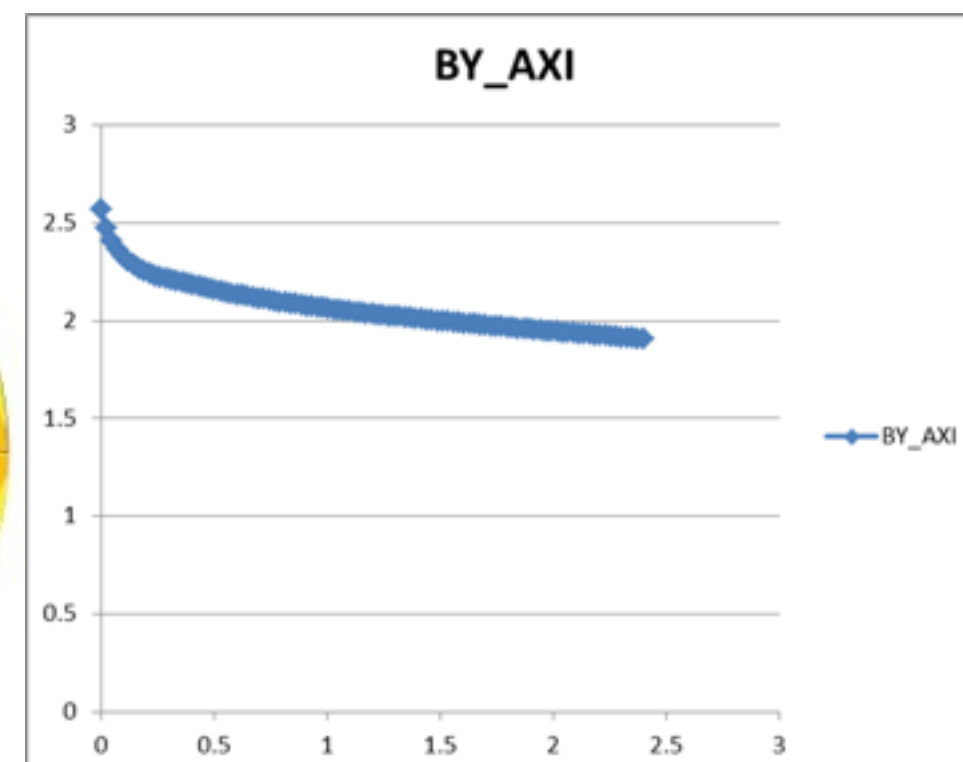
- Magnetized Iron
  - 1.3 kT
    - Following MINOS ND ME design
    - 1-2 cm Fe plate
    - 5 m diameter
  - Utilize superconducting transmission line for excitation
    - Developed 10 years ago for VLHC
  - Extruded scintillator +SiPM





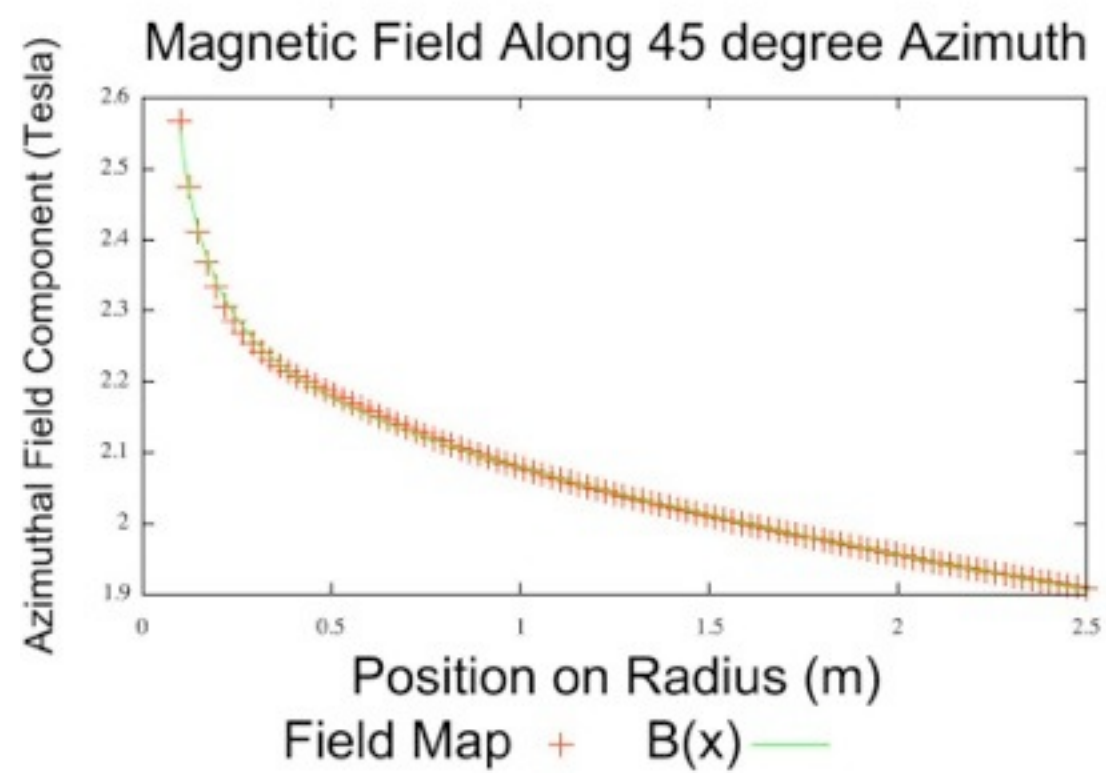


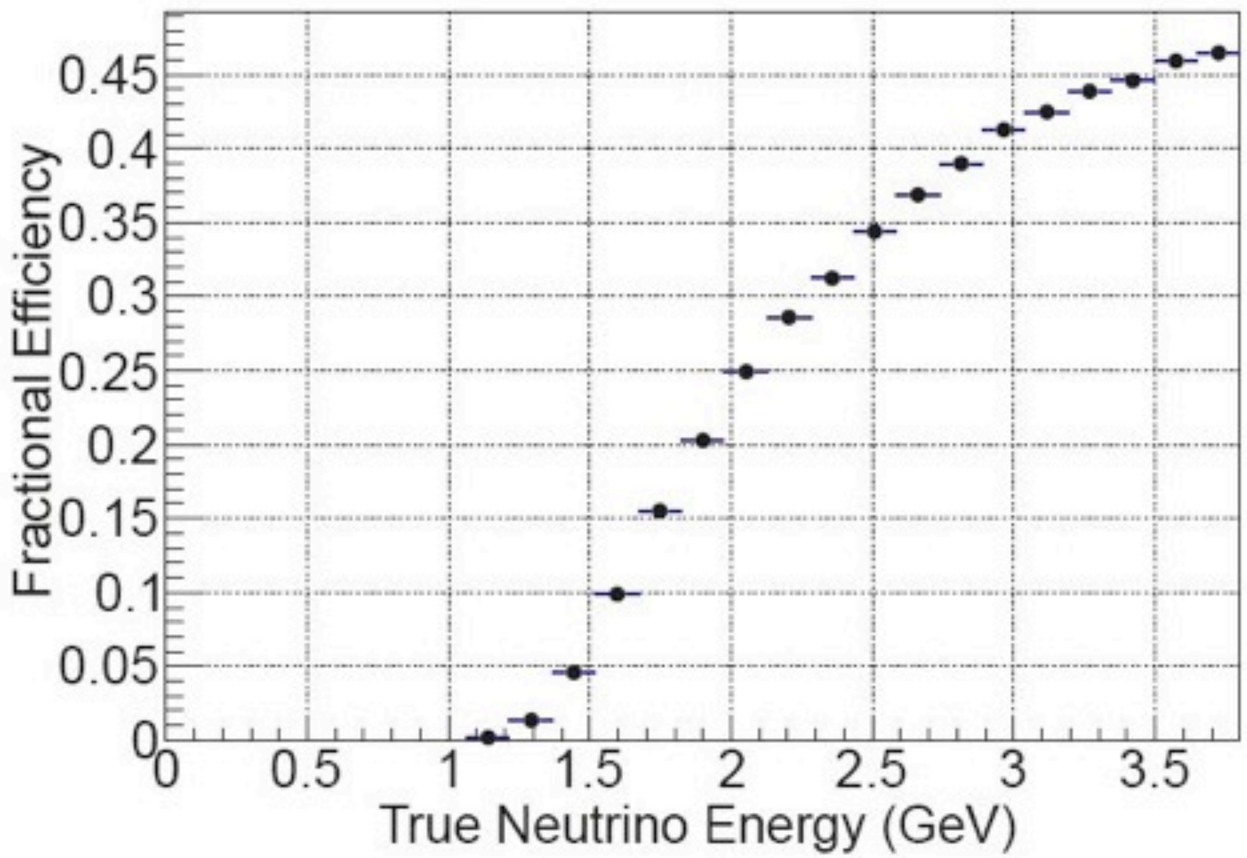
20 cm hole
For 3 turns
of STL

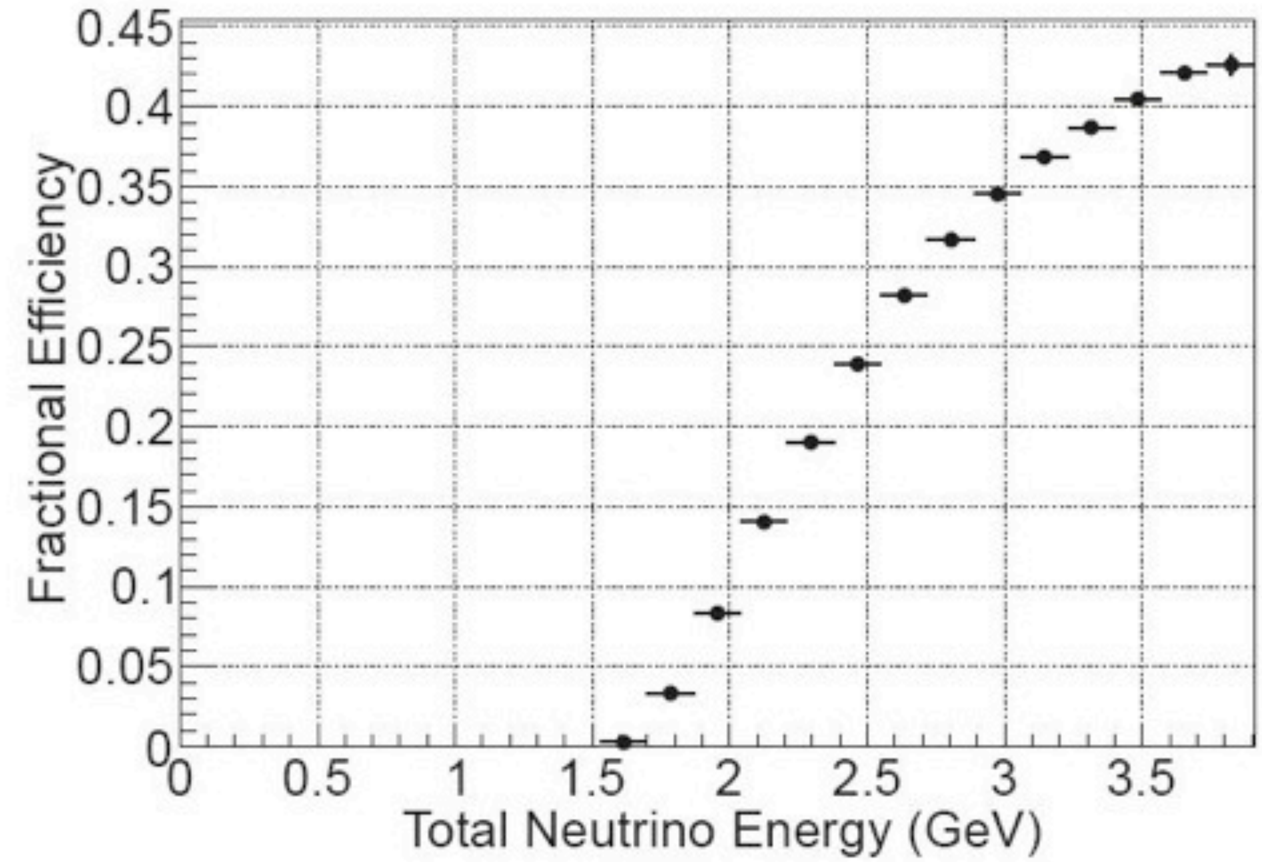


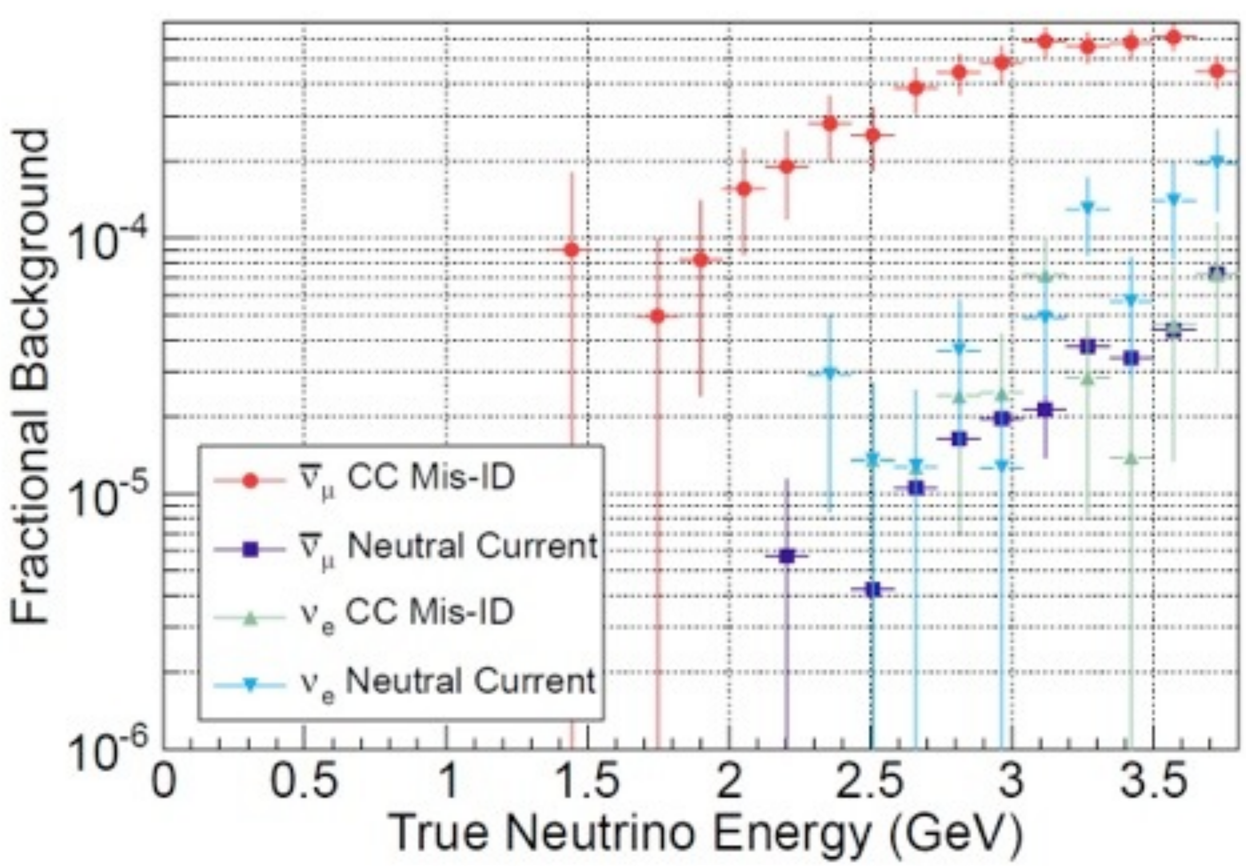
Simulation – ν_μ appearance

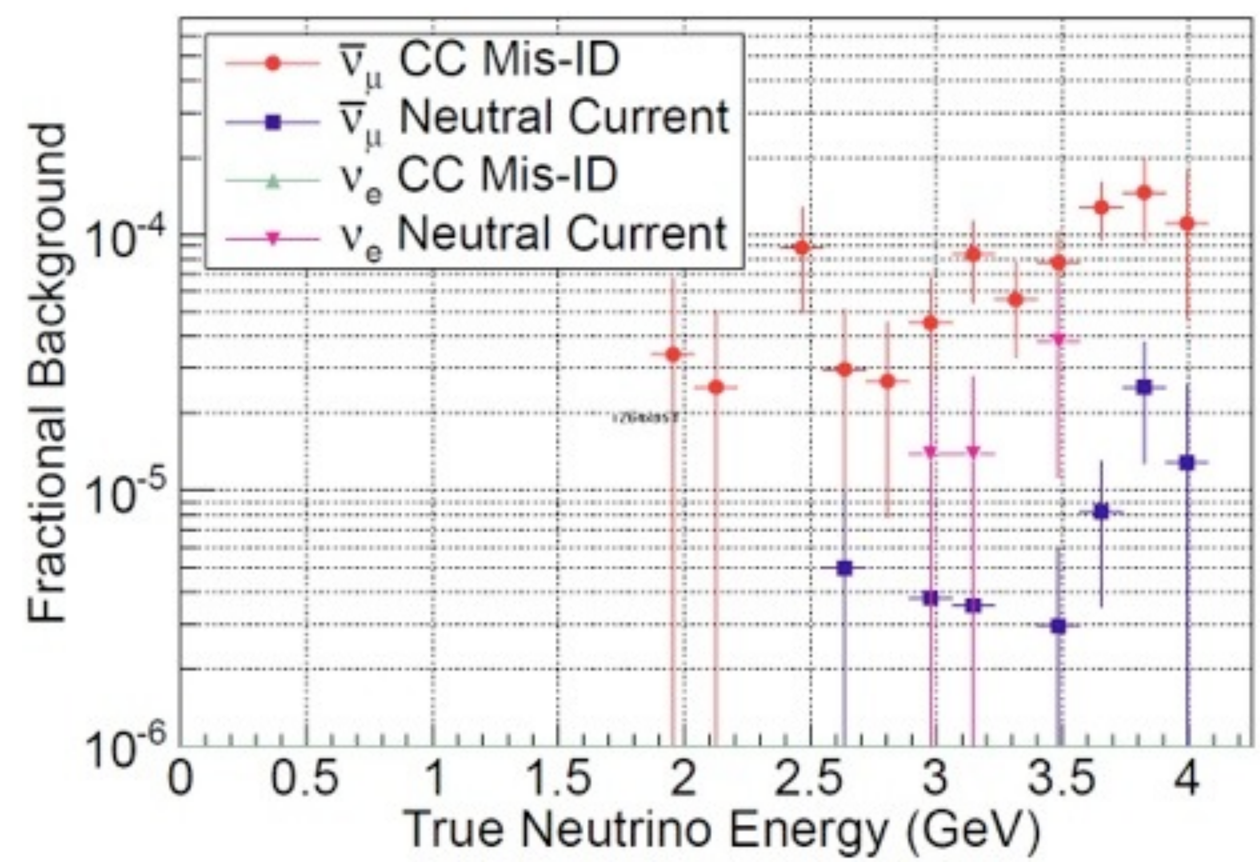
- Full GEANT4 Simulation
  - Extrapolation from ISS and IDS-NF studies for the MIND detector
  - Uses GENIE to generate the neutrino interactions.
  - Involves a flexible geometry that allows the dimensions of the detector to be altered easily (for optimization purposes, for example).
  - Does not yet have the detailed B field, but parameterized fit is very good
  - Event selection/cuts
    - Cuts-based analysis
    - Multivariate to come later







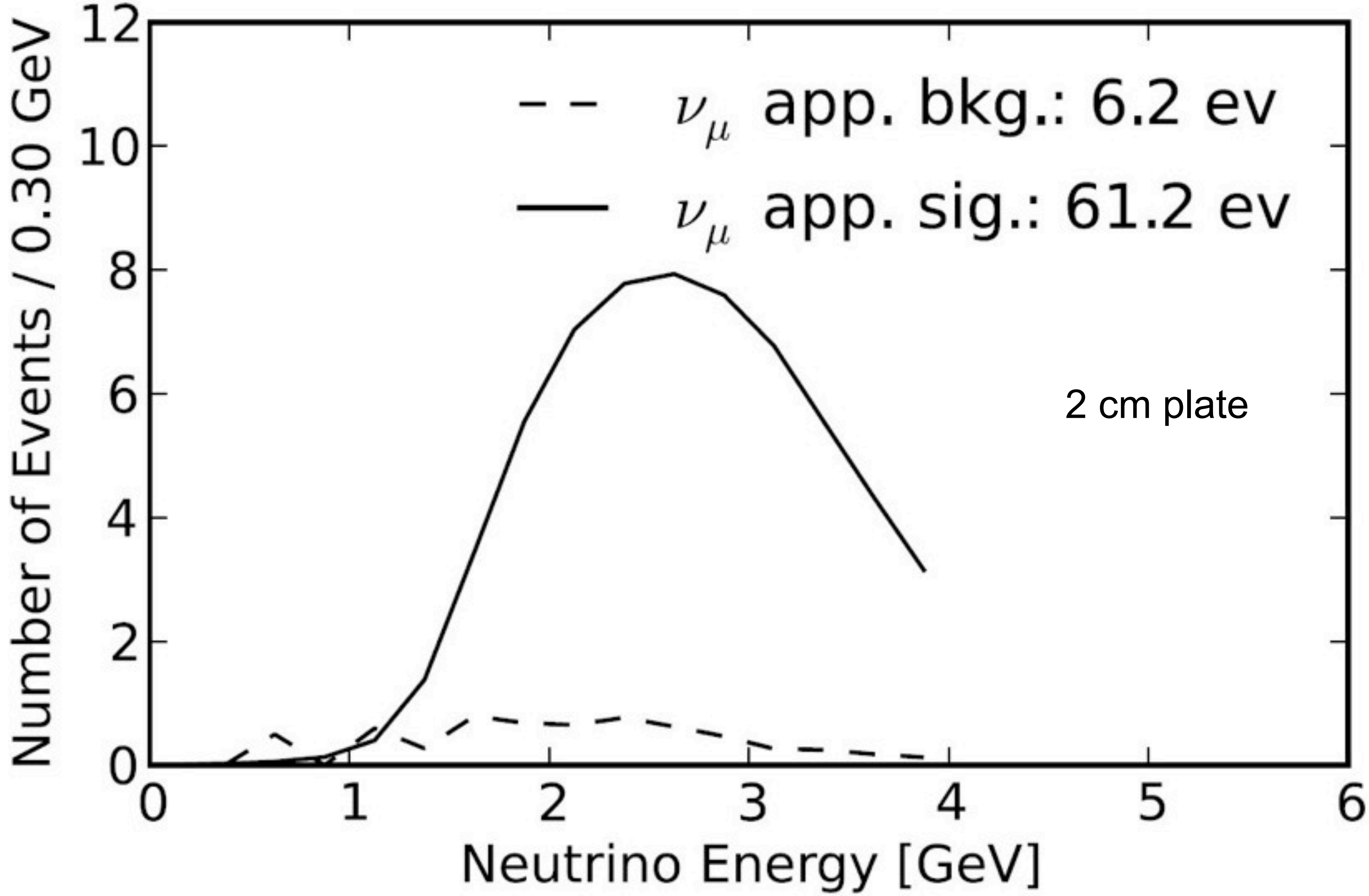




Left: 1 cm plates

Right: 2 cm plates

$\nu_e \rightarrow \nu_\mu$ appearance
CPT invariant channel to MiniBooNE $\bar{\nu}_e$



Raw Event Rates

Neutrino mode with stored μ^+.

Channel	$N_{\text{osc.}}$	N_{null}	Diff.	$(N_{\text{osc.}} - N_{\text{null}})/\sqrt{N_{\text{null}}}$
$\nu_e \to \nu_\mu$ CC	332	0	∞	∞
$\bar{\nu}_\mu \to \bar{\nu}_\mu$ NC	47679	50073	-4.8%	-10.7
$\nu_e \to \nu_e$ NC	73941	78805	-6.2%	-17.3
$\bar{\nu}_\mu \to \bar{\nu}_\mu$ CC	122322	128433	-4.8%	-17.1
$\nu_e \to \nu_e$ CC	216657	230766	-6.1%	-29.4

Anti-neutrino mode with stored μ^-.

Channel	$N_{\text{osc.}}$	N_{null}	Diff.	$(N_{\text{osc.}} - N_{\text{null}})/\sqrt{N_{\text{null}}}$
$\bar{\nu}_e \to \bar{\nu}_\mu$ CC	117	0	∞	∞
$\bar{\nu}_e \to \bar{\nu}_e$ NC	30511	32481	-6.1%	-10.9
$\nu_\mu \to \nu_\mu$ NC	66037	69420	-4.9%	-12.8
$\bar{\nu}_e \to \bar{\nu}_e$ CC	77600	82589	-6.0%	-17.4
$\nu_\mu \to \nu_\mu$ CC	197284	207274	-4.8%	-21.9

3+1
Assumption

Appearance channels

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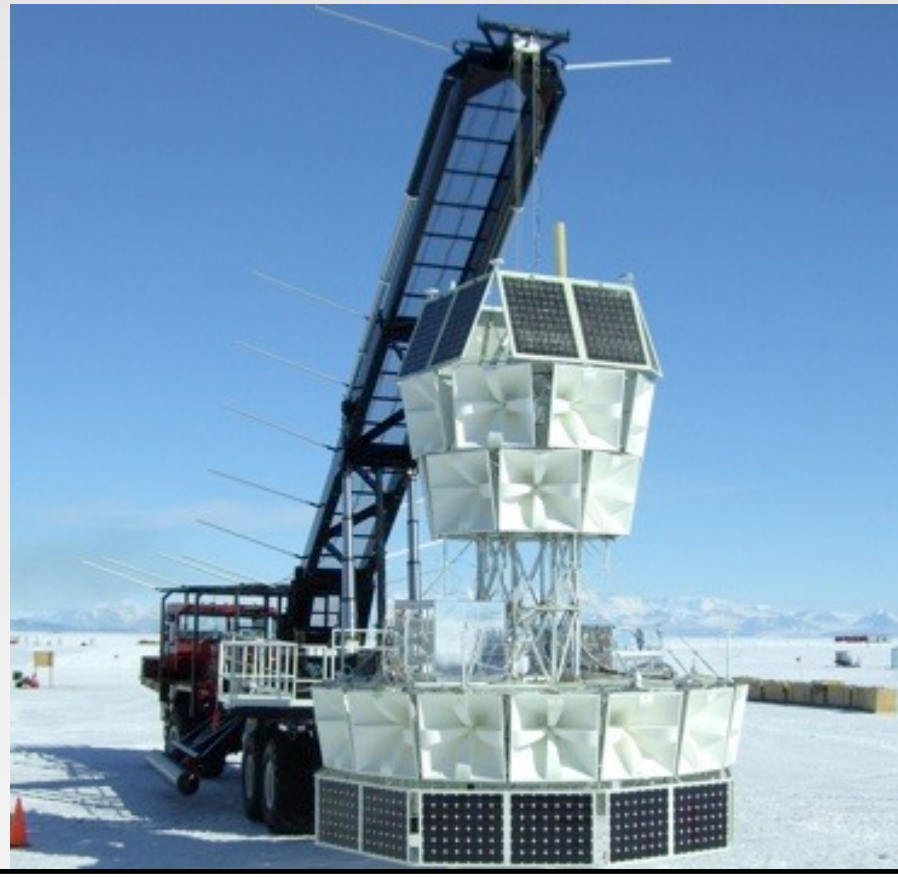
ANITA

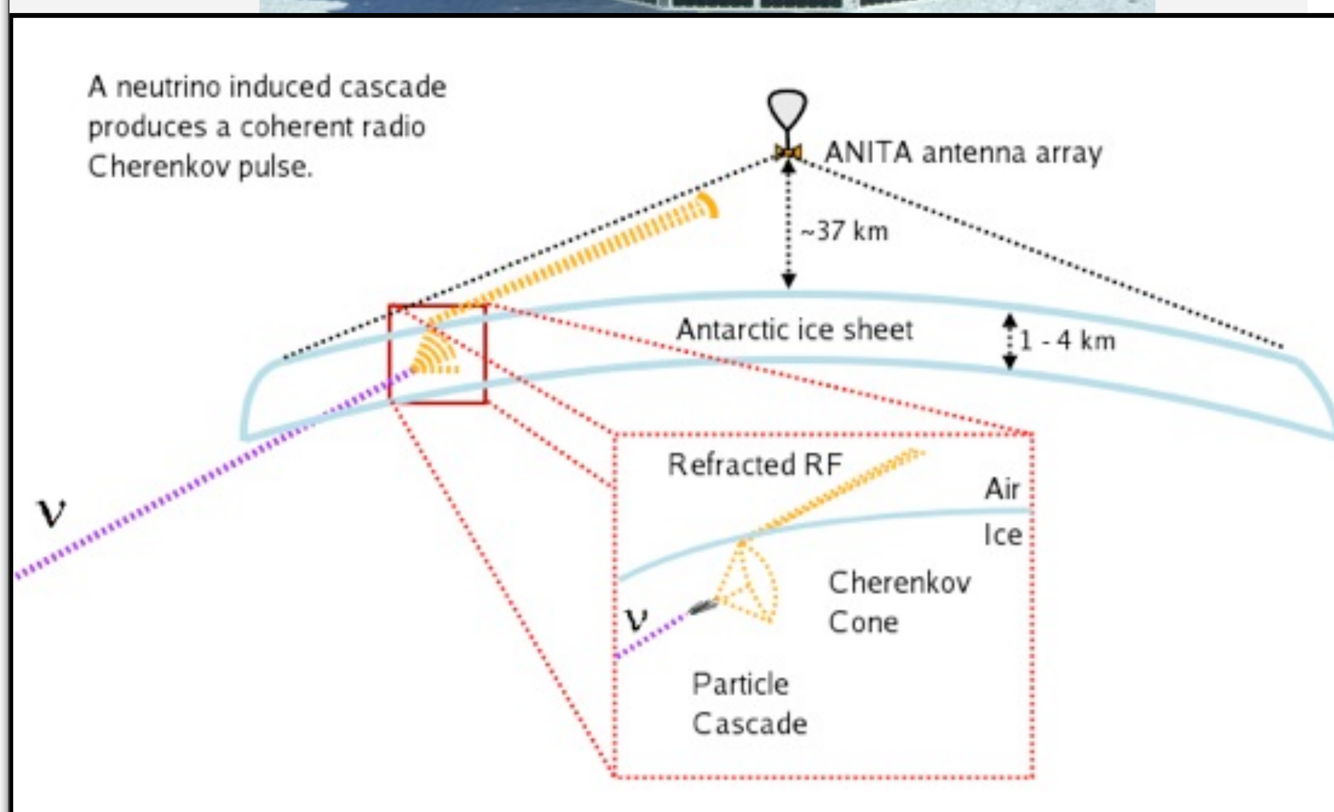
UCL

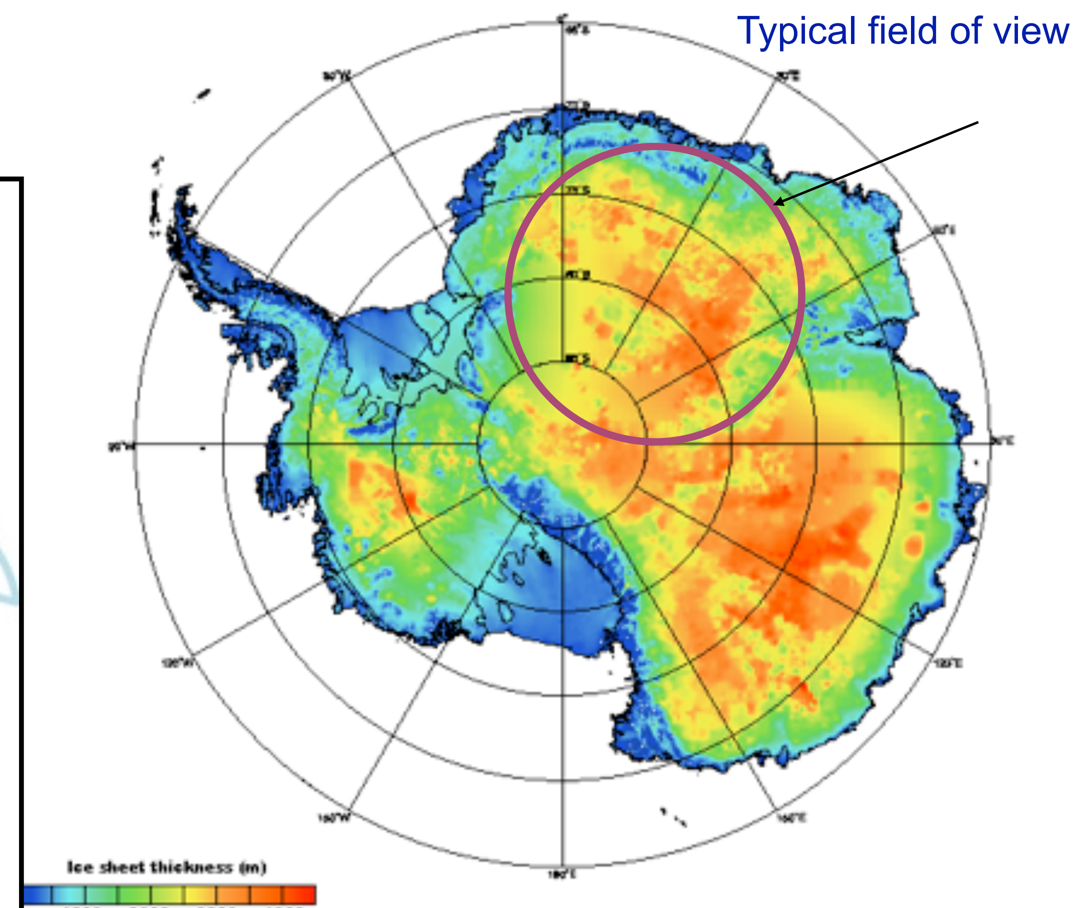


ANITA looks for neutrinos interacting in the antarctic ice, by dangling from a balloon 37km above the continent.

Over a million cubic kilometres of ice visible.

Third flight scheduled for December 2013



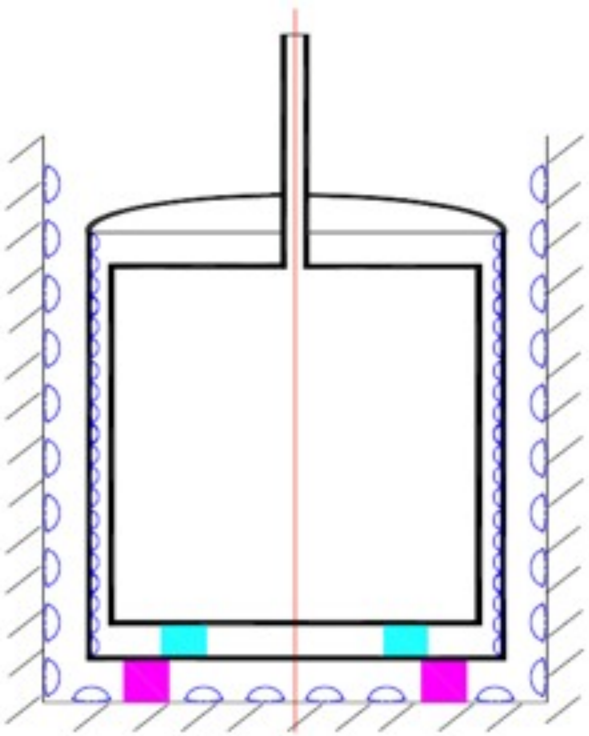


Jenny Thomas <jthomas@hep.ucl.ac.uk>

Daya Bay 60km

>40GW

- Neutrino target: ~20kt LS, LAB based
- 30m(D)×30m(H)
- Oil buffer: 6kt
- Water buffer: 10kt
- PMT: 15000 20”



2012-2014 R&D
2015 proposal to government
2016-2020 construction
2020 start operation

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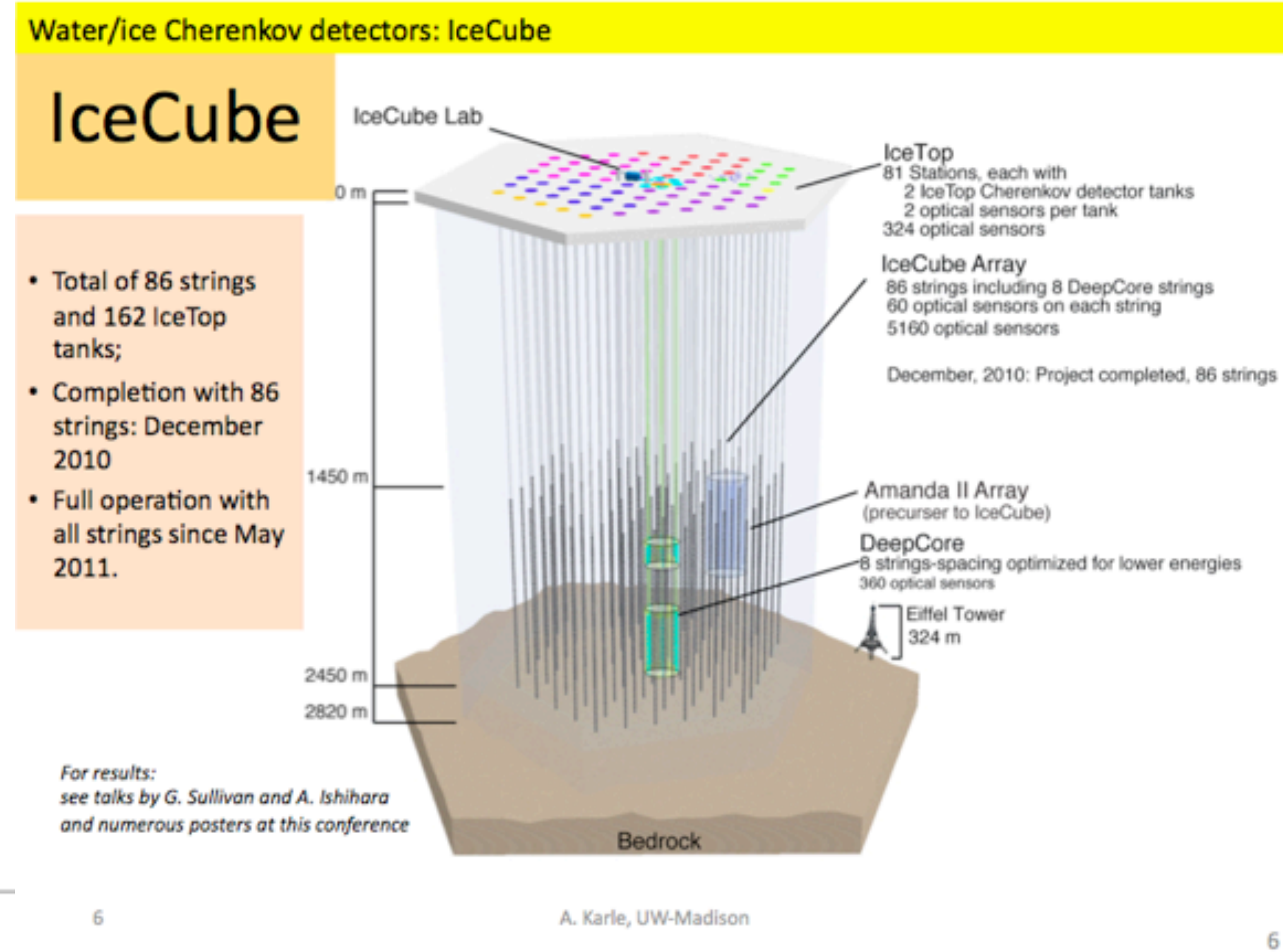
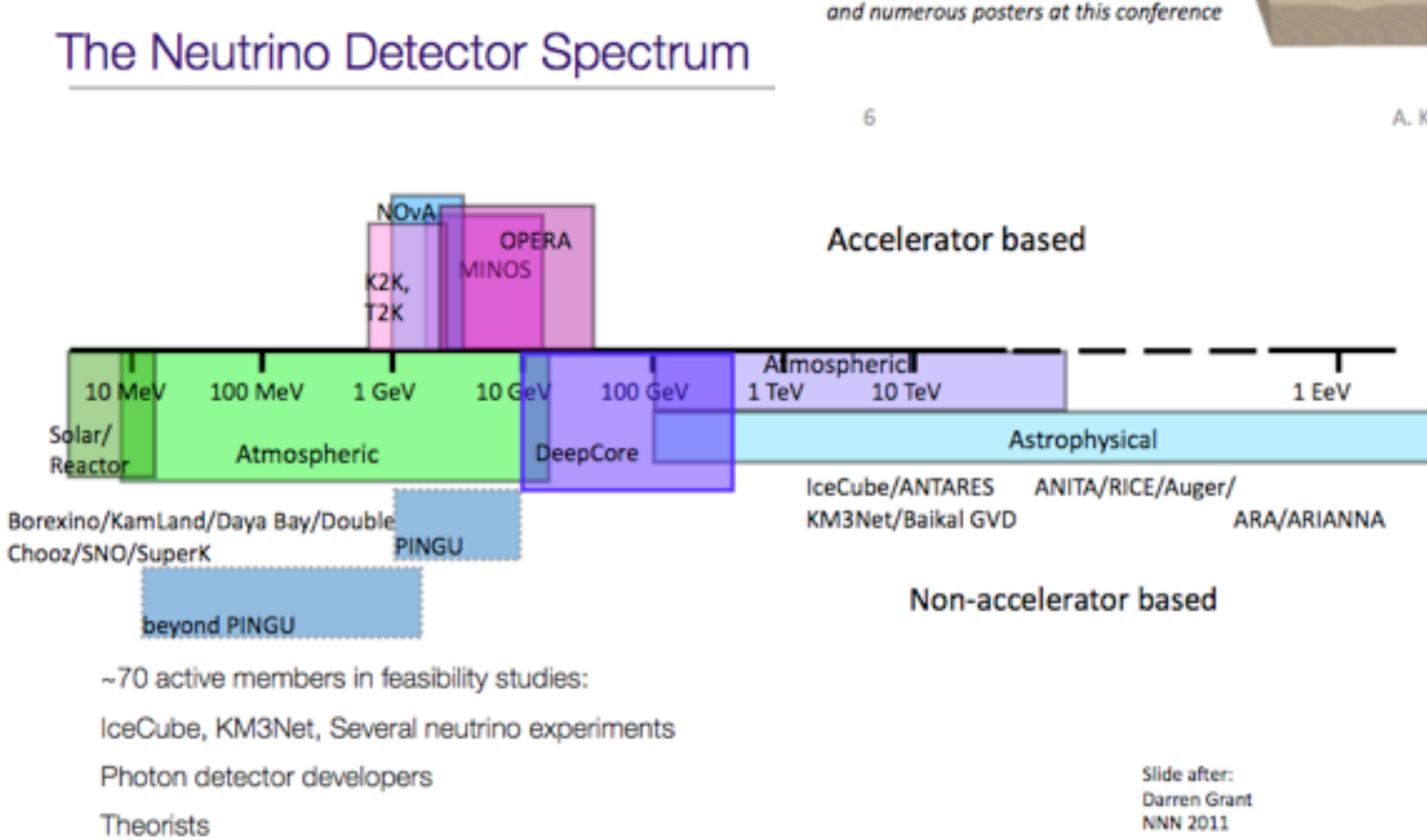
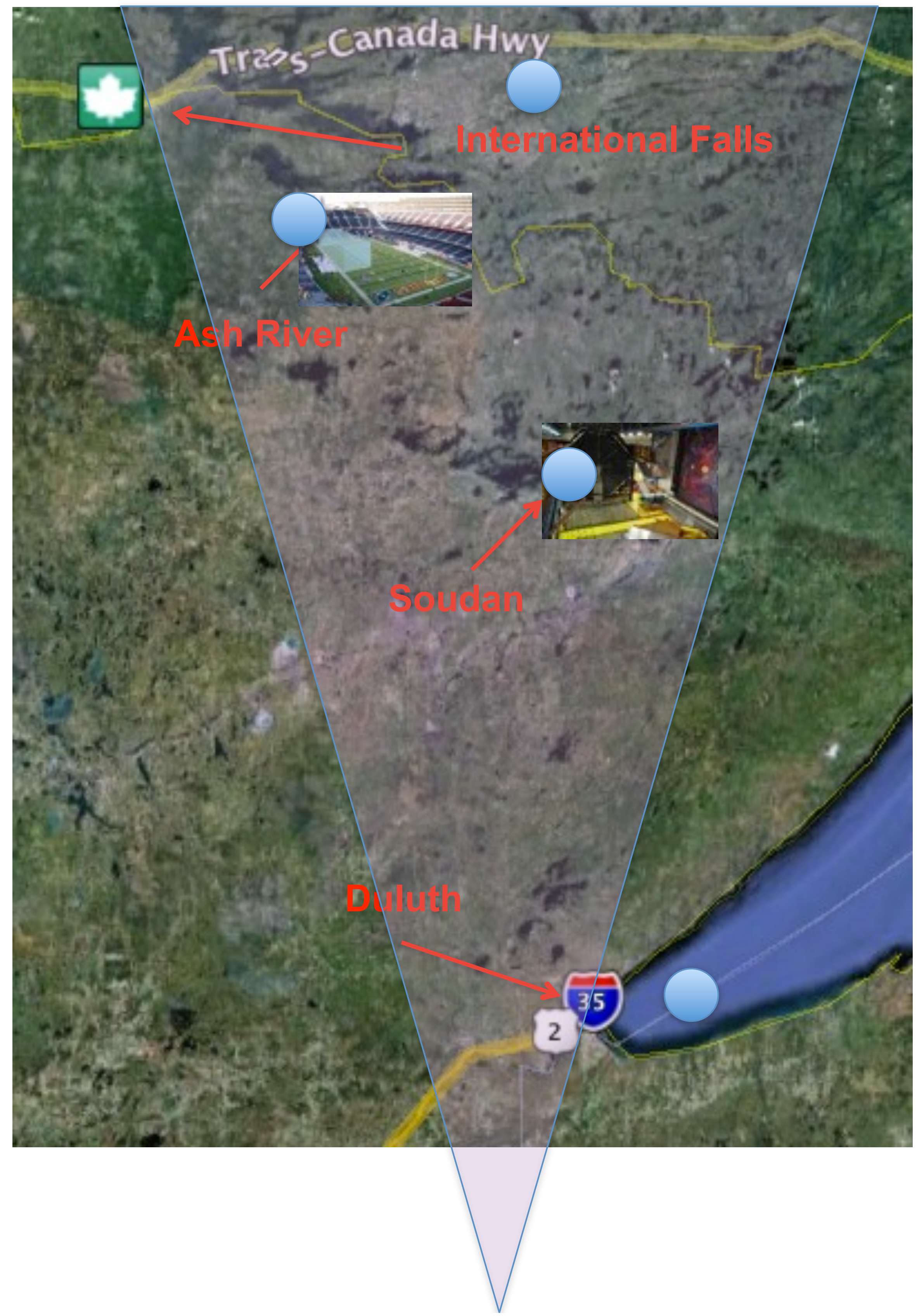


- Deep Core has proved the method of reduction of energy threshold with higher density strings
- Pingu will push it further… and they will still have 1 MegaTon!!!
- 2 years running will measure MH to between 3-11σ



Jenny Thomas <jthomas@hep.ucl.ac.uk>

- Further exploitation of the NuMI beam is a good idea in the short term
  - The beam is the highest intensity beam in the world
  - It exists
- FNAL could consider:
  - Off-axis at Ash River (810km, 14mr)
  - On-axis on surface at Soudan or beyond (735km, LE)
  - On-axis underground at Soudan Laboratory (735km, LE)
  - Cherenkov detector in Lake Superior (655km, 20mr off axis)
- There is room for thinking out of the box, and time to get results
  - NuMI will run for 6-10 years




水戸の梅の花