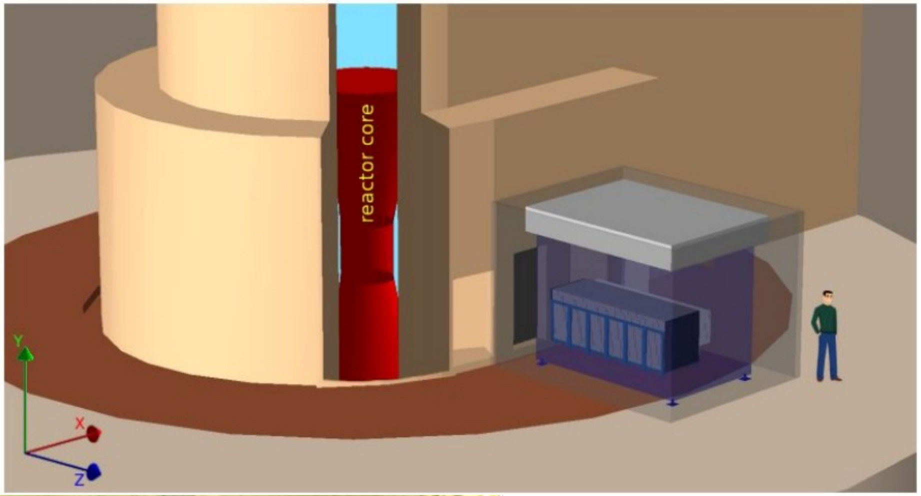
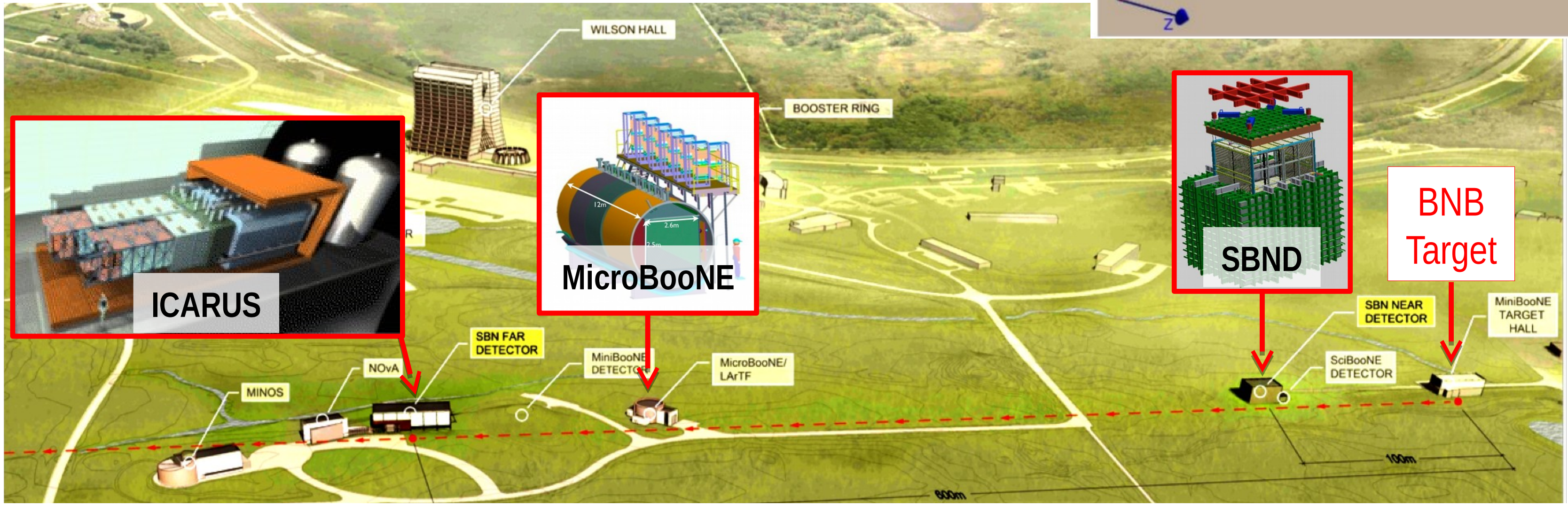
Overview of Short Baseline Oscillations

Andrzej Szelc

(University of Manchester)





Outline

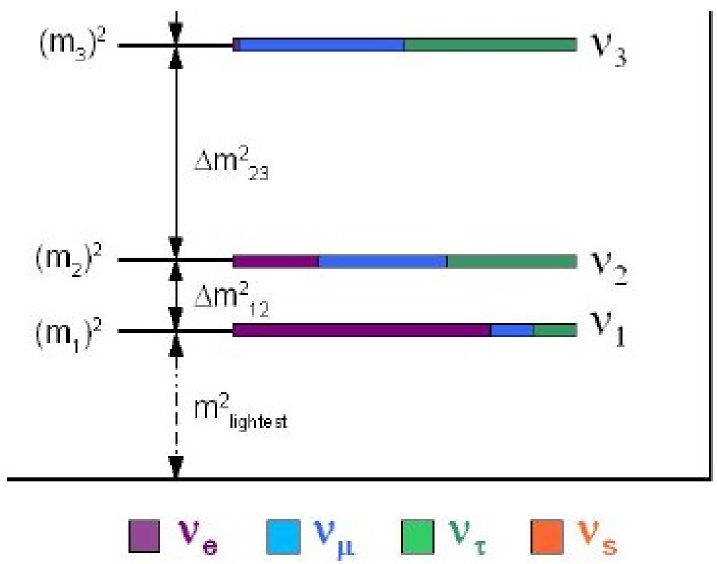
- What we know about neutrinos and oscillations
- Reactor measurements of θ_{13}
- Motivation for sterile neutrinos.
- Reactor searches
- The SBN programme at Fermilab
- Conclusions

The Current State of Neutrino Knowledge

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

Our picture of Neutrinos in the standard model is almost complete.

Last mixing angle θ_{13} was first measured not that long ago (more on that later)

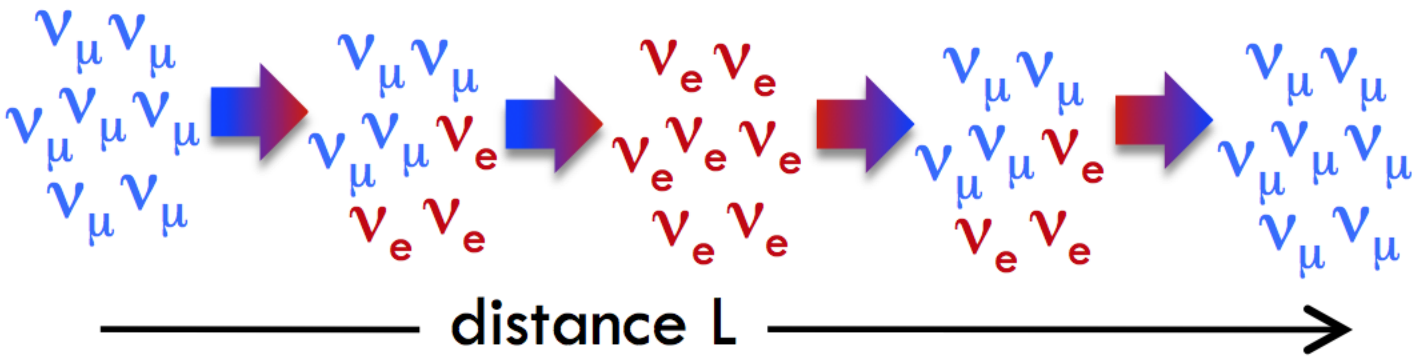


"Known" neutrino physics

Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	7.56 ± 0.19
$\|\Delta m^2_{31}\|$ $[10^{-3}\mathrm{eV}^2]$ (NO)	2.55 ± 0.04
$\|\Delta m^2_{31}\|$ $[10^{-3}\mathrm{eV}^2]$ (IO)	2.49 ± 0.04
$\theta_{12}/^\circ$	$34.5^{+1.1}_{-1.0}$
$\theta_{13}/^\circ$	$8.44^{+0.18}_{-0.15}$
$\delta/^\circ$	252^{+56}_{-36}
$\sin^2\theta_{23}/10^{-1}$ (NO)	$4.30^{+0.20}_{-0.18}$
$\theta_{23}/^\circ$	41.0 ± 1.1
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.96^{+0.17}_{-0.18}$
$\theta_{23}/^\circ$	50.5 ± 1.0

Salas, Forero, Ternes, Tortola, Valle: 2017

Neutrino Oscillations



- We usually start with one type of neutrino and measure how it changes into another.

$$P(\nu_\alpha \to \nu_\beta) = -4[(U_{\alpha 1}U_{\beta 1}U_{\alpha 2}U_{\alpha 2})sin^2(1.27\Delta m^2_{12}\frac{L}{E})$$
$$+ (U_{\alpha 1}U_{\beta 1}U_{\alpha 3}U_{\alpha 3})sin^2(1.27\Delta m^2_{13}\frac{L}{E})$$
$$+ (U_{\alpha 2}U_{\beta 2}U_{\alpha 3}U_{\alpha 3})sin^2(1.27\Delta m^2_{23}\frac{L}{E})]$$

"amplitude" "frequency"

$$P(\nu_x \to \nu_y) = sin^2(2\theta)sin^2(1.27\Delta m^2\frac{L(km)}{E(GeV)})$$

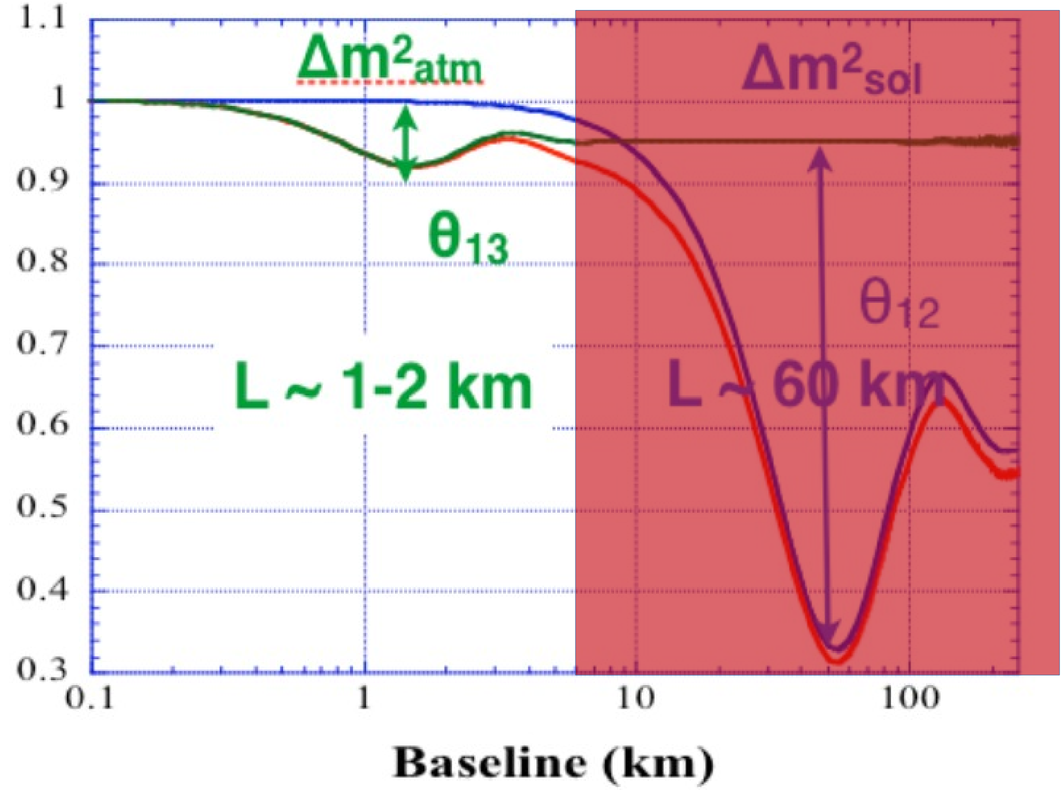
- We can do this by detecting the new neutrinos (appearance) or registering the loss of original (disappearance).
- Need to know how many neutrinos there were originally (flux or near detector).

Two flavour approximation is good enough in most cases.

What do I mean by Short Baselines?

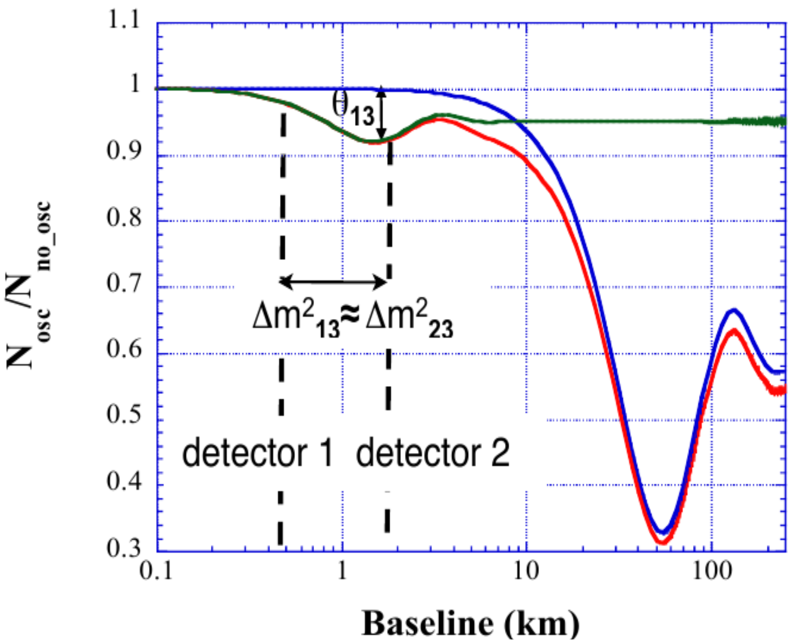
- Oscillations depend on L/E
- Hence, with different energies can probe different oscillation phenomena.
- I will focus on baselines <o(~1km).

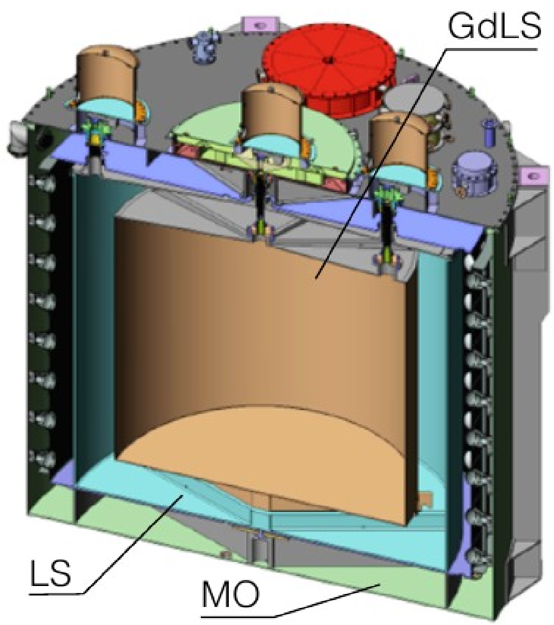
$$P = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{1.267\Delta m^2_{21}L}{E} - \sin^2 2\theta_{13}\sin^2\frac{1.267\Delta m^2_{ee}L}{E}.$$



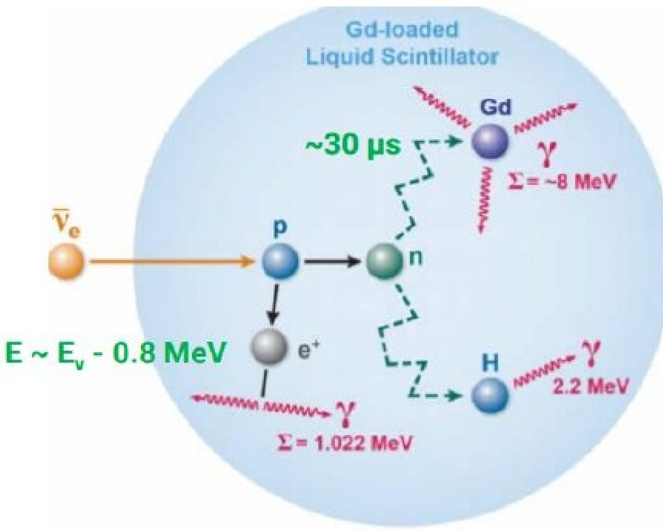
SBL measurements of θ_{13}

- Reactor experiments:
  - Daya Bay
  - Reno
  - Double Chooz
- Use near/far detectors to understand flux.

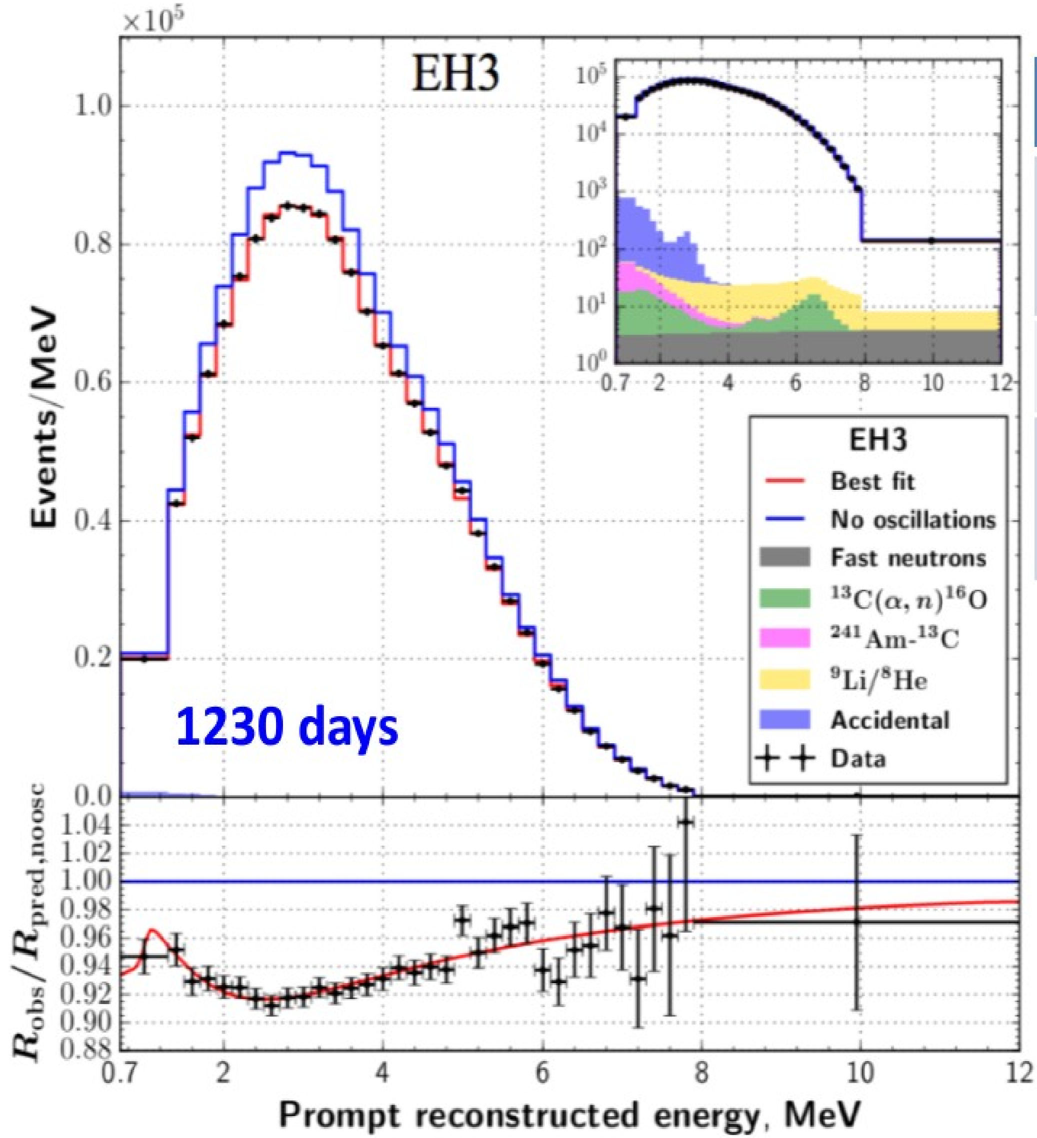




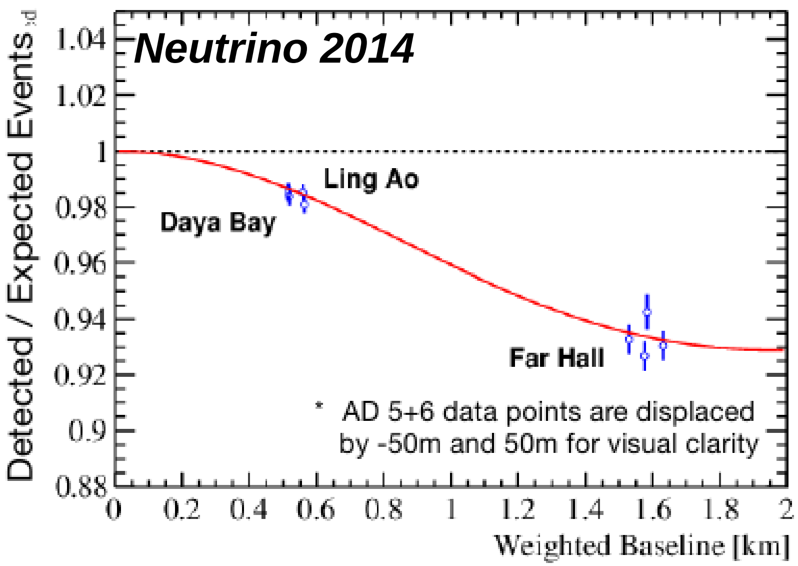
Daya Bay:
8 detectors,
Gd loaded
scintillator



Most recent results



$$\sin^2 2\theta_{13} = 0.0841 \pm 0.0027(stat.) \pm 0.0019(syst.)$$



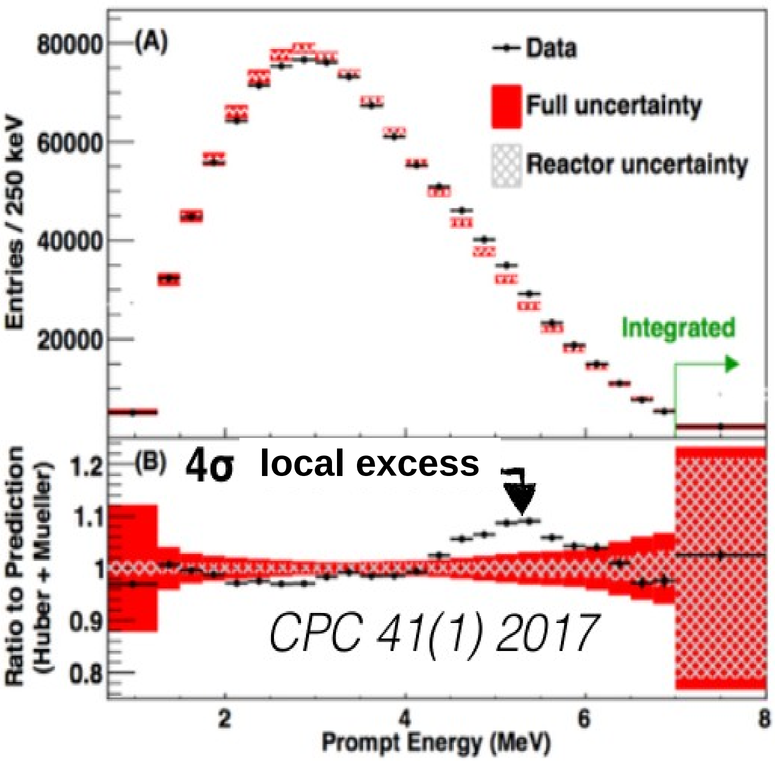
- θ_{13} is now the best measured mixing angle (not clear if zero ~6 years ago)
- Measurements from Daya Bay, Reno and Double Chooz consistent with long baseline measurements.

The University of Manchester

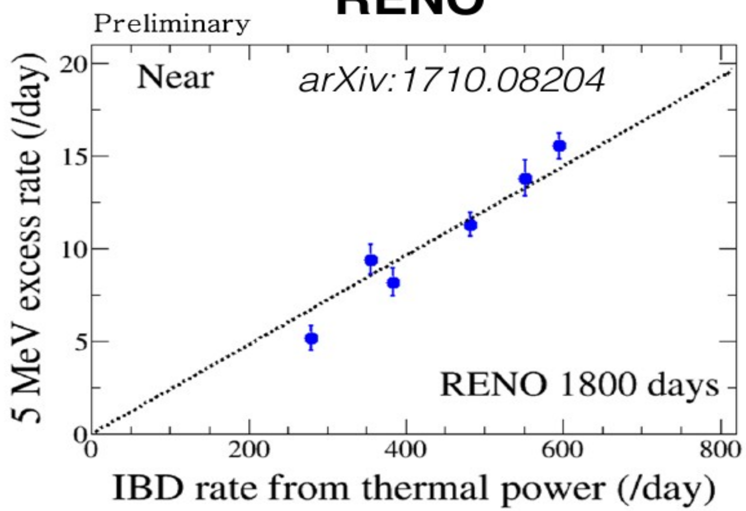
Surprises in Flux

- The 5MeV “bump”. Observed by all reactor neutrino experiments.
- Daya Bay measurement of rate vs fuel composition.

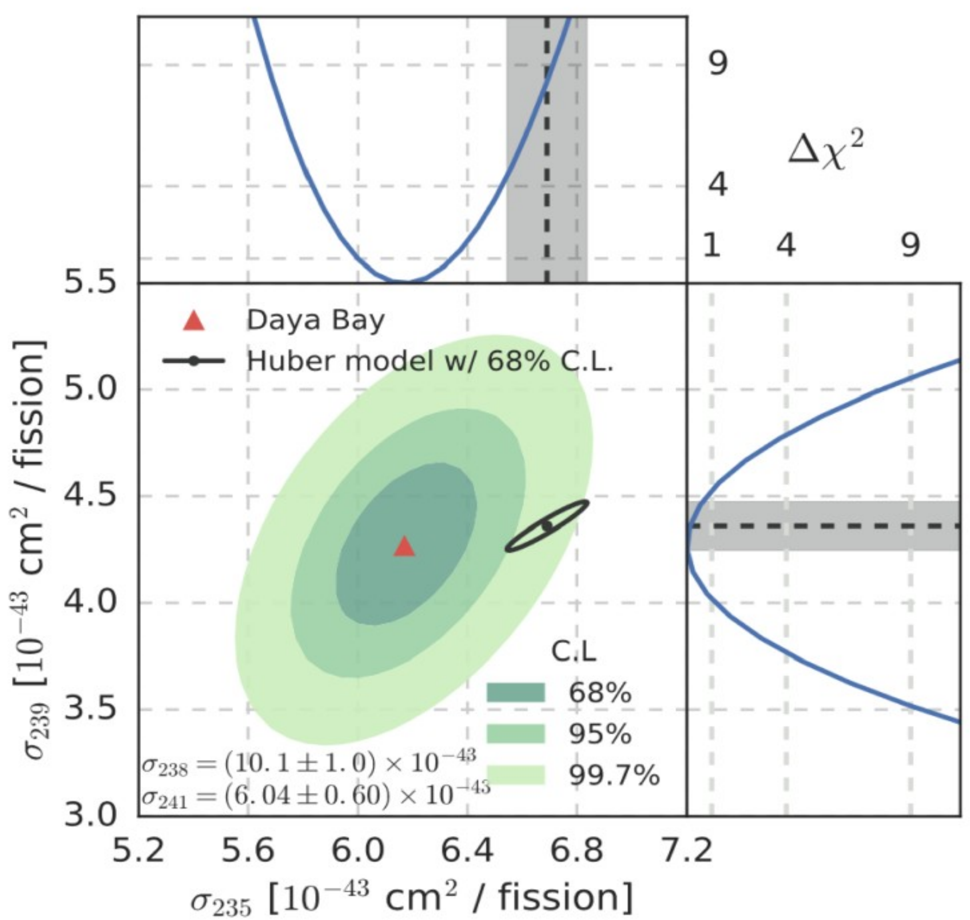
Daya Bay



RENO



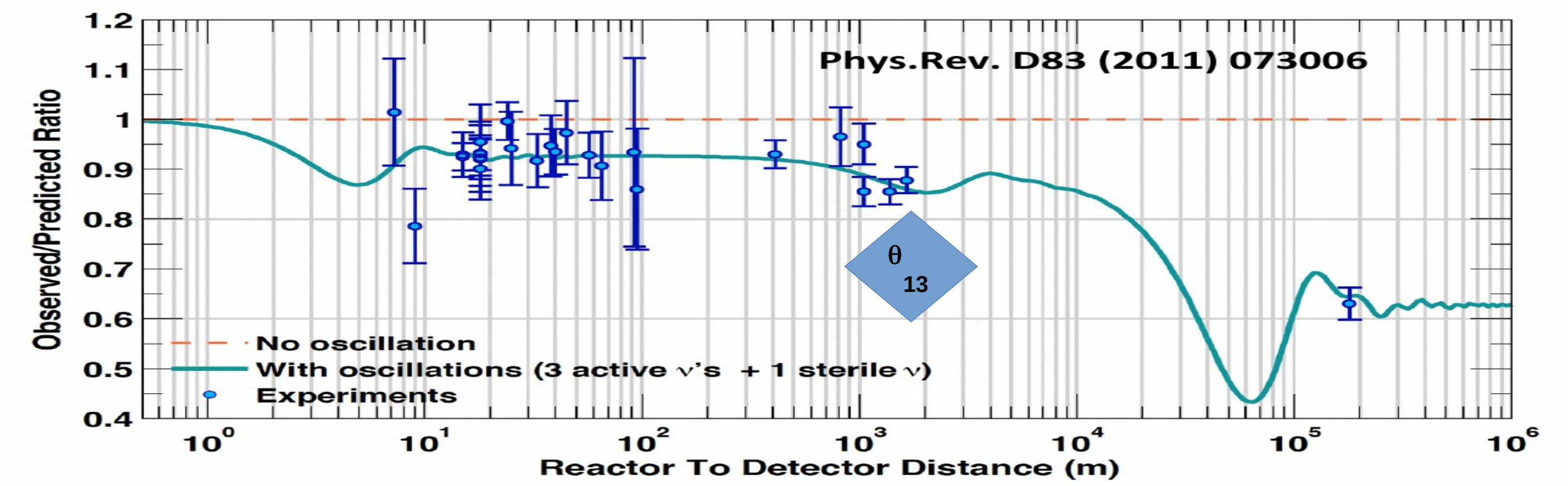
Phys. Rev. Lett. 118, 251801 (2017)

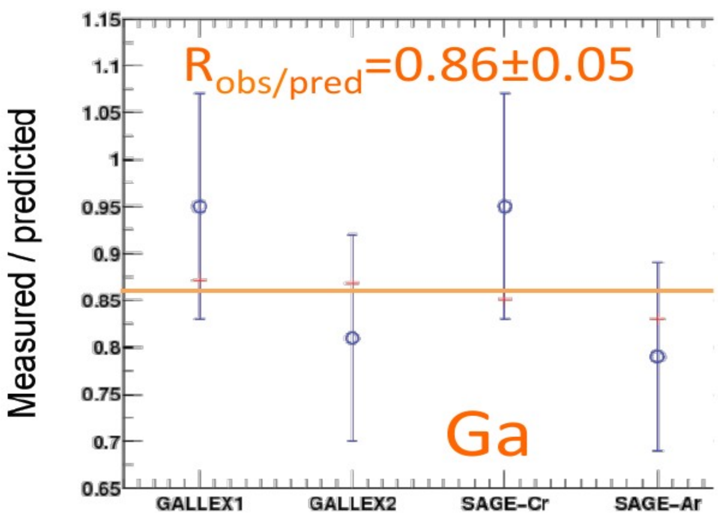


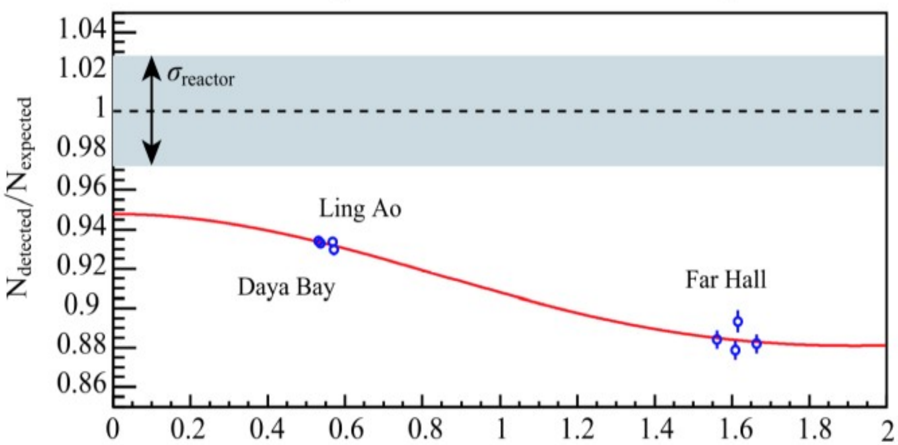
The University of Manchester

Also at short baselines

- Recalculation of reactor neutrino fluxes and analysis of sources in gallium experiments show a deficit.





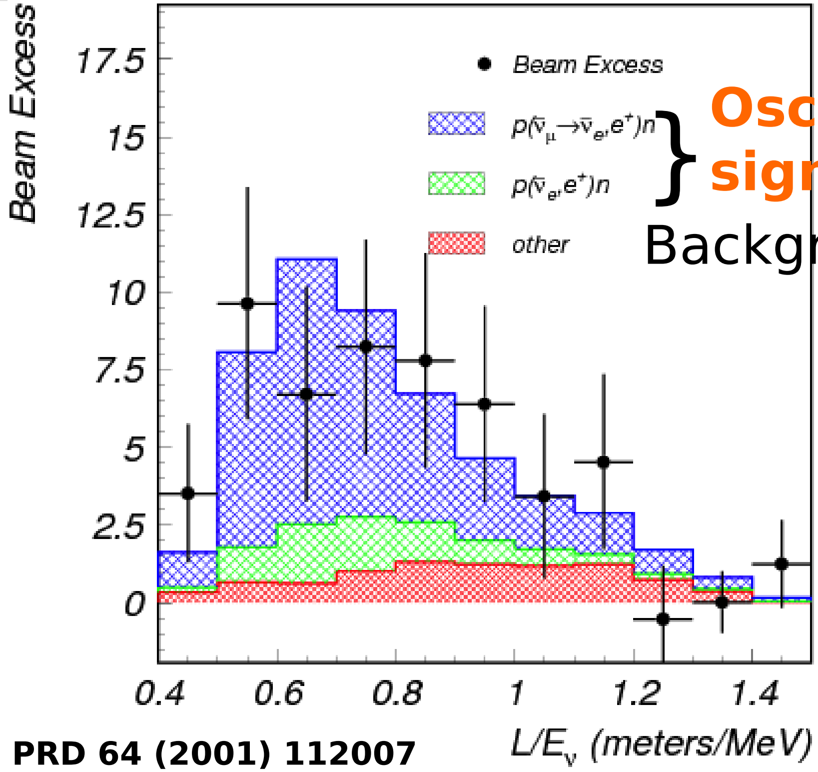


These results need an understanding of the neutrino flux

Accelerator Anomalies

LSND

Baseline 30 m
E= [20 – 50] MeV
L/E ≈ 1 m/MeV
167 tons liquid scintillator



Oscillation signal?

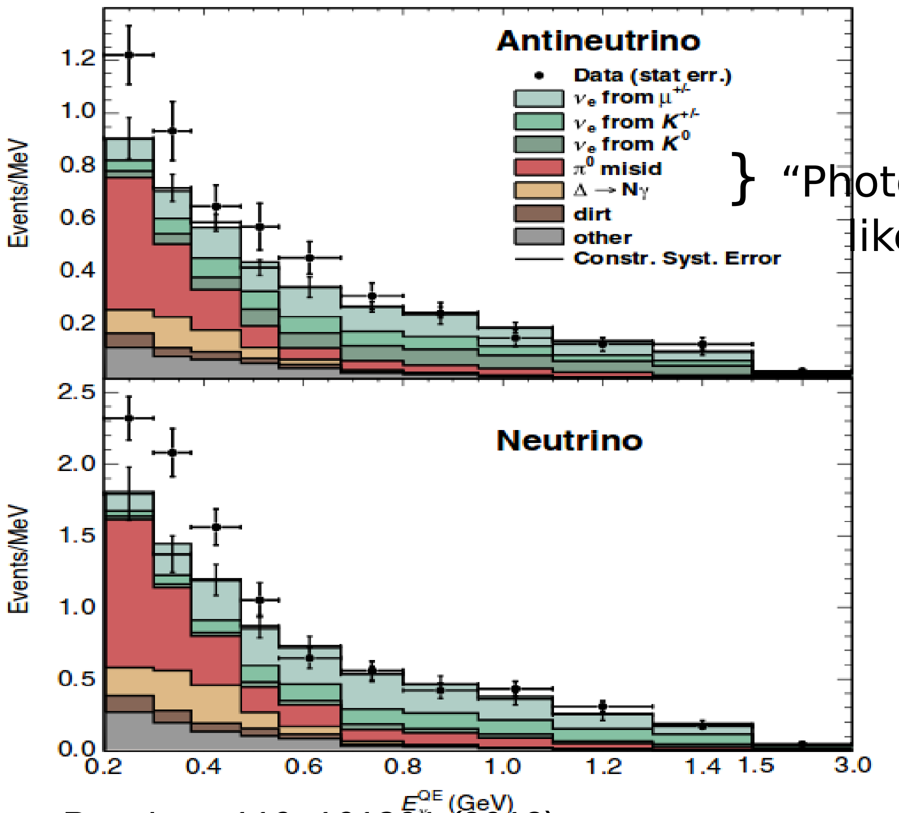
Backgrounds

PRD 64 (2001) 112007

excess appearance of $\bar{\nu}_e$ - evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation at $\Delta m^2 \simeq 1$ eV^2 ?

MiniBooNE

Baseline 540 m
E=[0 - 2] GeV
L/E ≈ 1 m/MeV

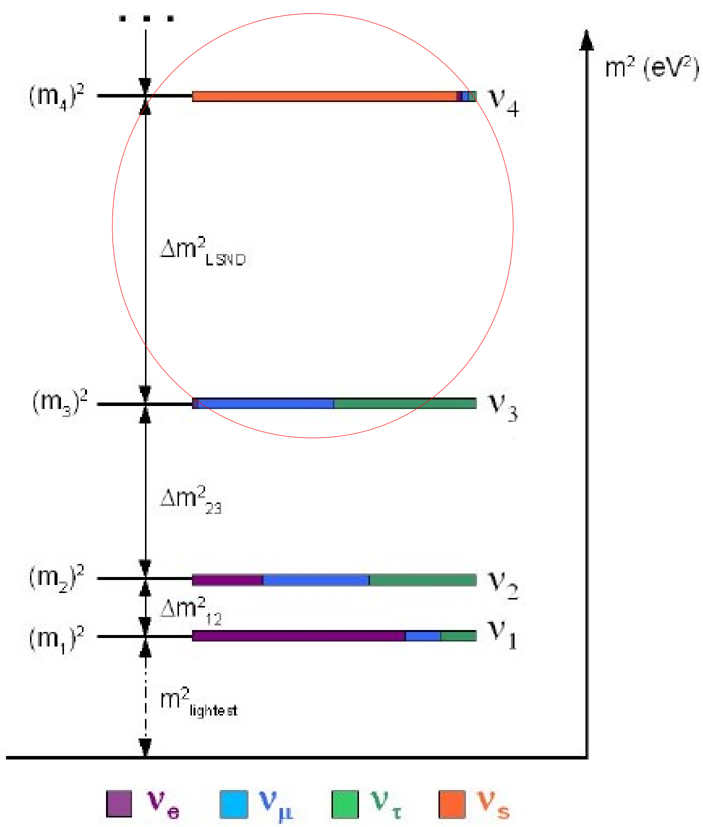


"Photon like"

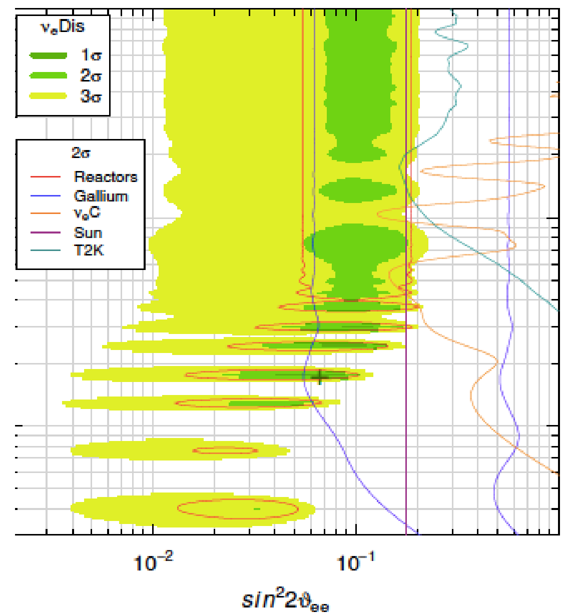
Phys. Rev. Lett. 110, 161801 (2013)

excess appearance of $\bar{\nu}_e$ and ν_e:
So called low energy excess.
Cherenkov detector: e ~ γ

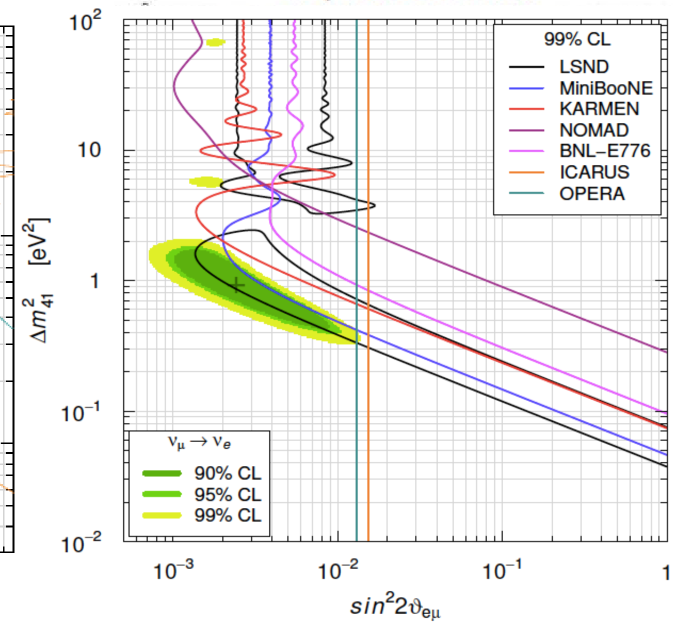
What does this lead to?



$\nu_e \rightarrow \nu_e$ and $\bar{\nu}_e \rightarrow \bar{\nu}_e$
(ν_e disappearance)

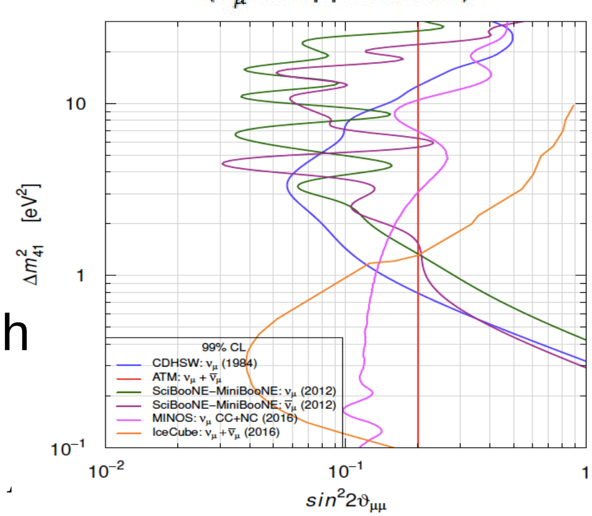


$\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
(ν_e appearance)



S. Gariazzo, C. Giunti, M. Laveder, Y.F. Li, arXiv:1703.00860, JHEP06(2017)135

$\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$
(ν_μ disappearance)



- Very different experimental techniques are hinting at short baseline oscillations.
- Need 4th neutrino state which would have to be sterile.

- Tension with other experiments, e.g. long-baseline muon disappearance.

The rest of this talk will be devoted to efforts to sort this out .

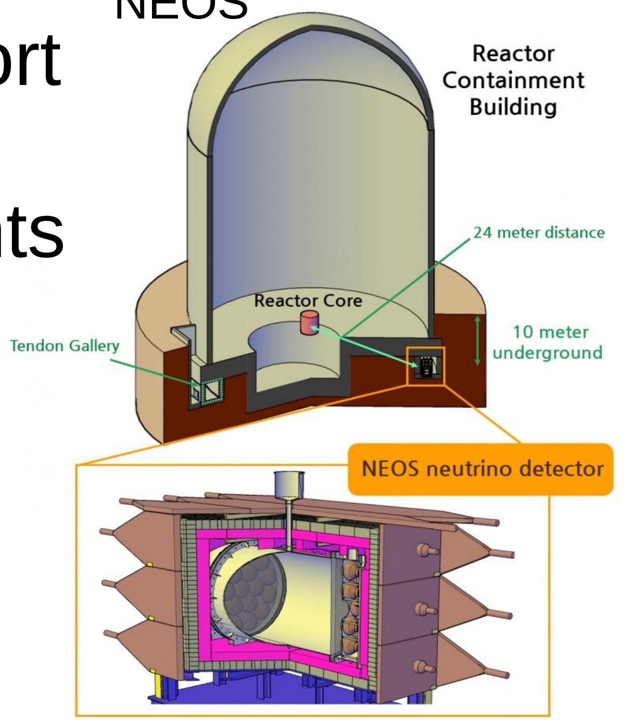
Reactor searches for sterile νs

- We're looking at L/E, so need to get close (few meters)
  - use compact research reactors.
- Need do disambiguate from flux uncertainties.
  - Moveable detector or segmentation.
- Backgrounds (from reactor and cosmics)
  - Fiducialization, shielding, efficient neutron tagging.

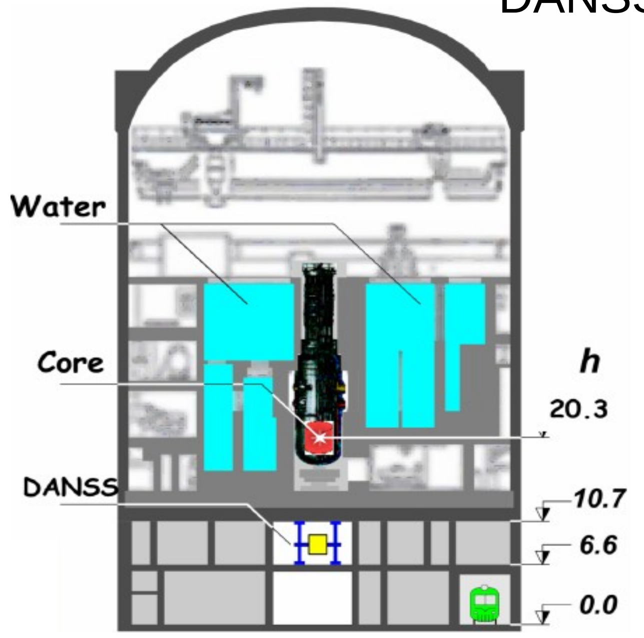
Recent results

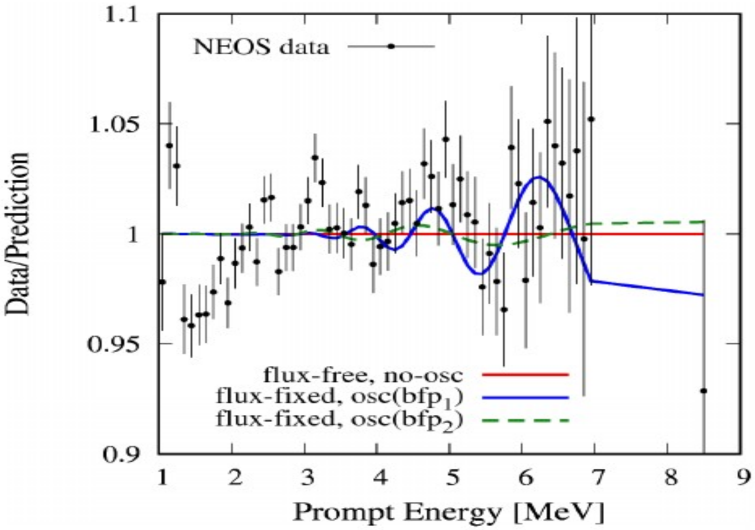
- First new short baseline measurements are here.
- So far, inconclusive.

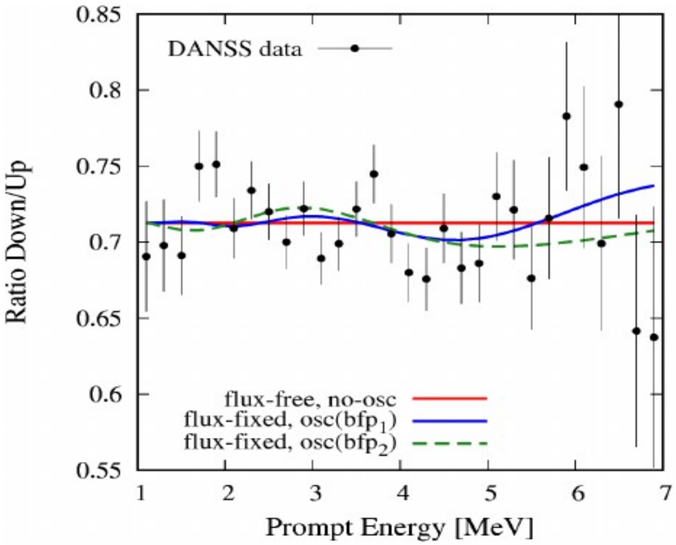
NEOS



DANSS



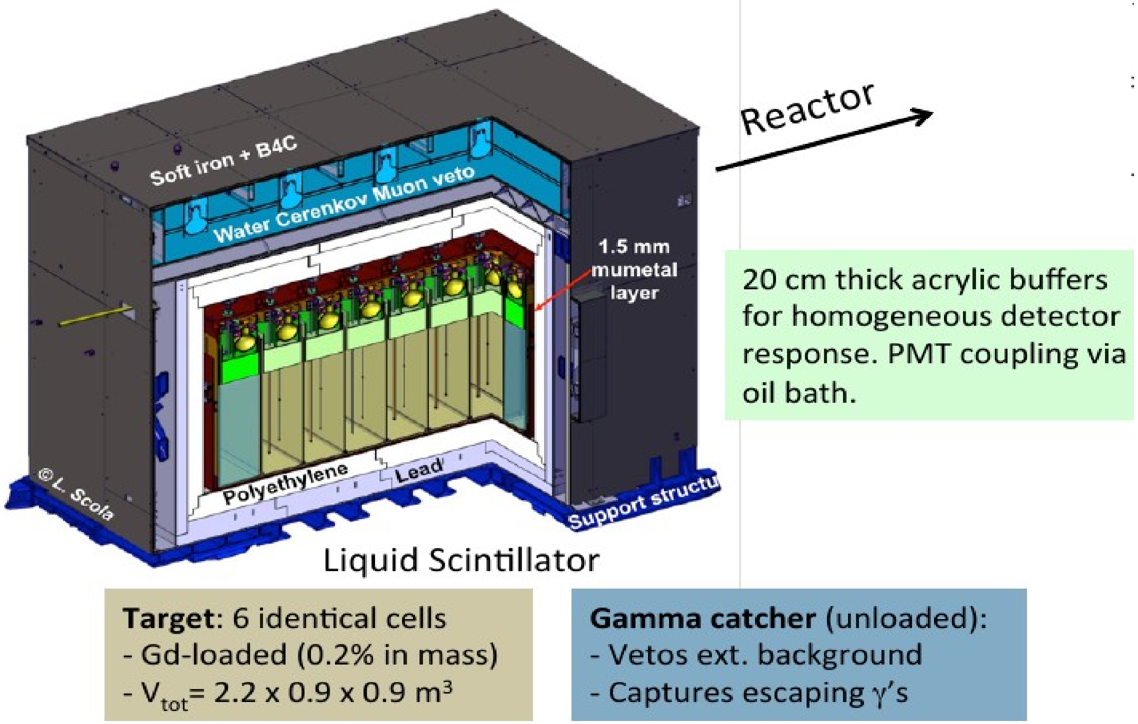




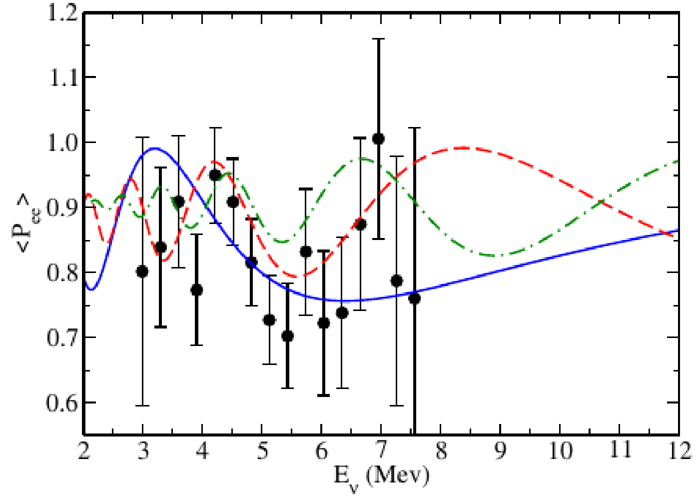
Dentler et al **JHEP 1711 (2017) 099**

Very Recent Results

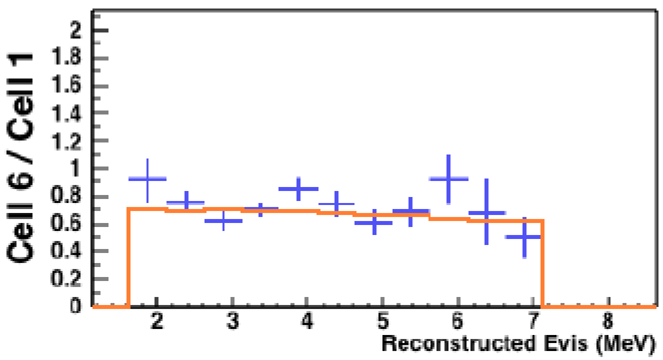
STEREO@ILL Grenoble
First data, will acquire more this year.

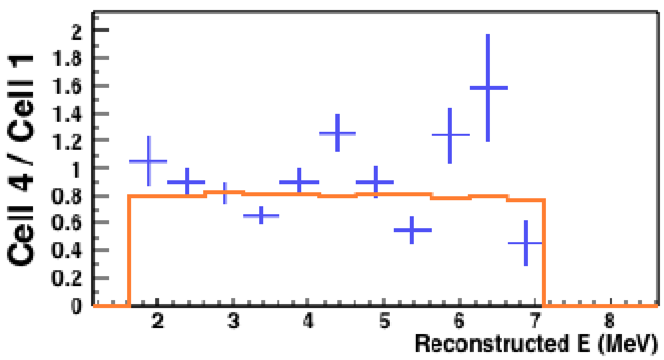


Revisiting old ILL results (v. short baseline) leads to higher significance.



B.K. Cogswell et al., arXiv:1802.07763





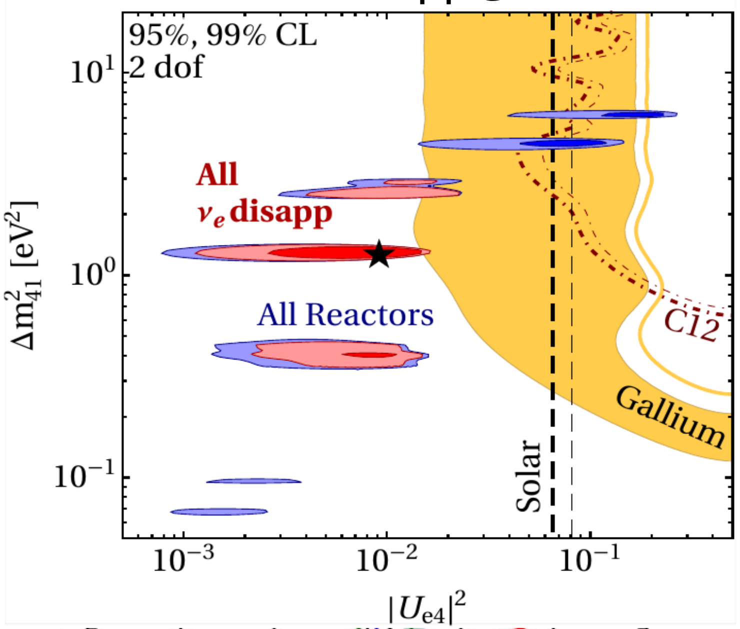
D. Lhuillier - Moriond EW 2018

MANCHESTER 1824

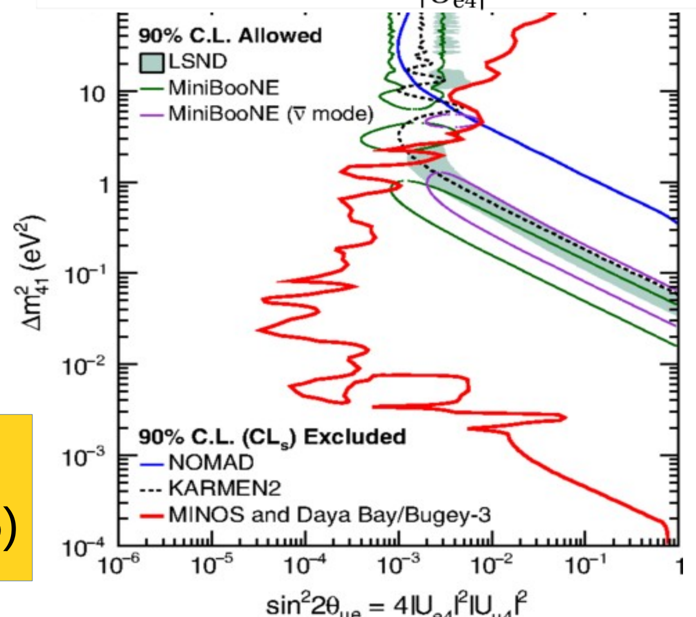
The University of Manchester

So, is the reactor anomaly there or not?

J. Kopp@MoriondEW



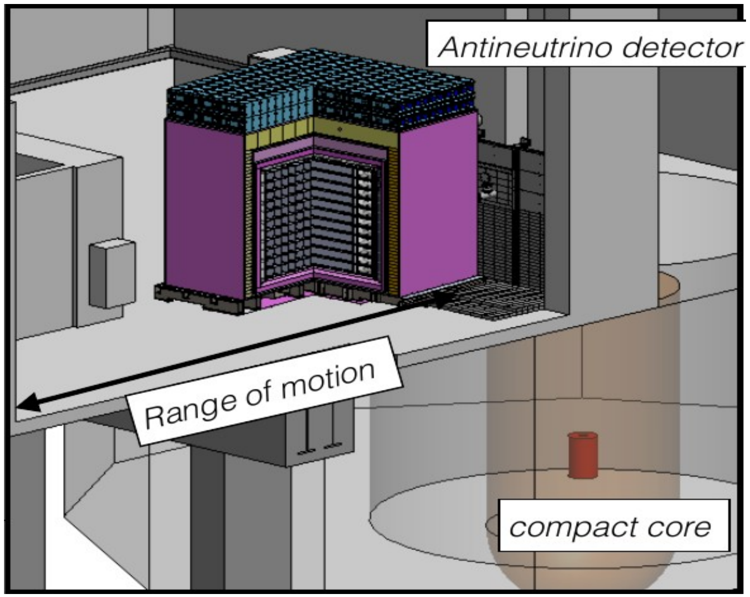
- The groups performing the global fits: Gariazzo et al., **JHEP 1706 (2017) 135**, Giunti et al., **JHEP 1710 (2017) 143**, Dentler et al. **JHEP 1711 (2017) 099,** agree that the sterile neutrino model cannot be ruled out. (before STEREO results and the ILL revisiting).
- This can still work with the accelerator results (more on that later) – but then trouble with muon neutrino disappearance.

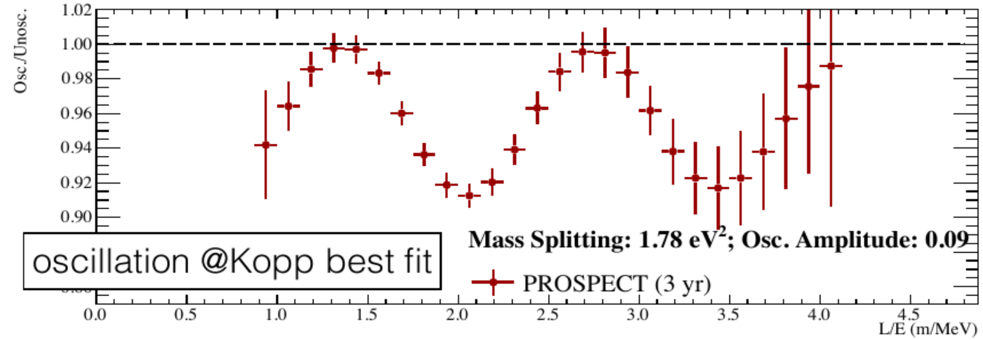


MINOS + Daya Bay + Bugey 3
Phys Rev Lett, 171 151801 (2016)

Need more data

- PROSPECT commissioning at HFIR (Tennessee)





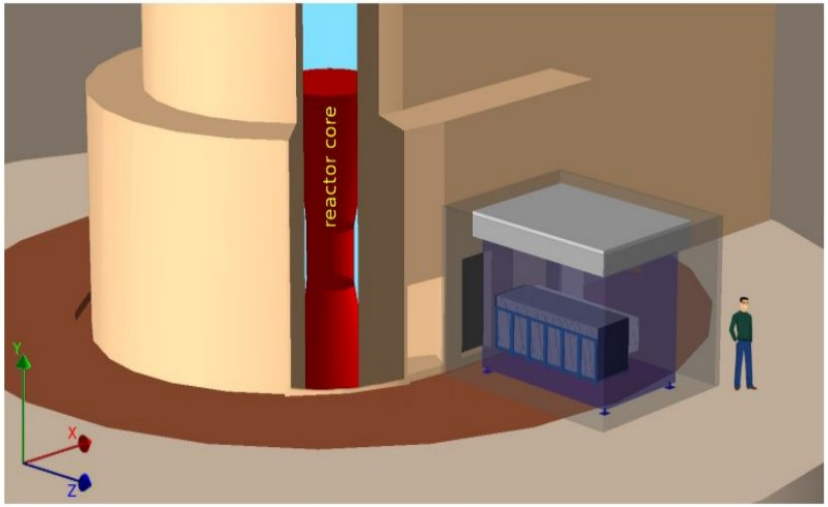
Baseline 7-12 m

Lithium doped Liquid Scintillator

Segmented detector allows a model independent search.

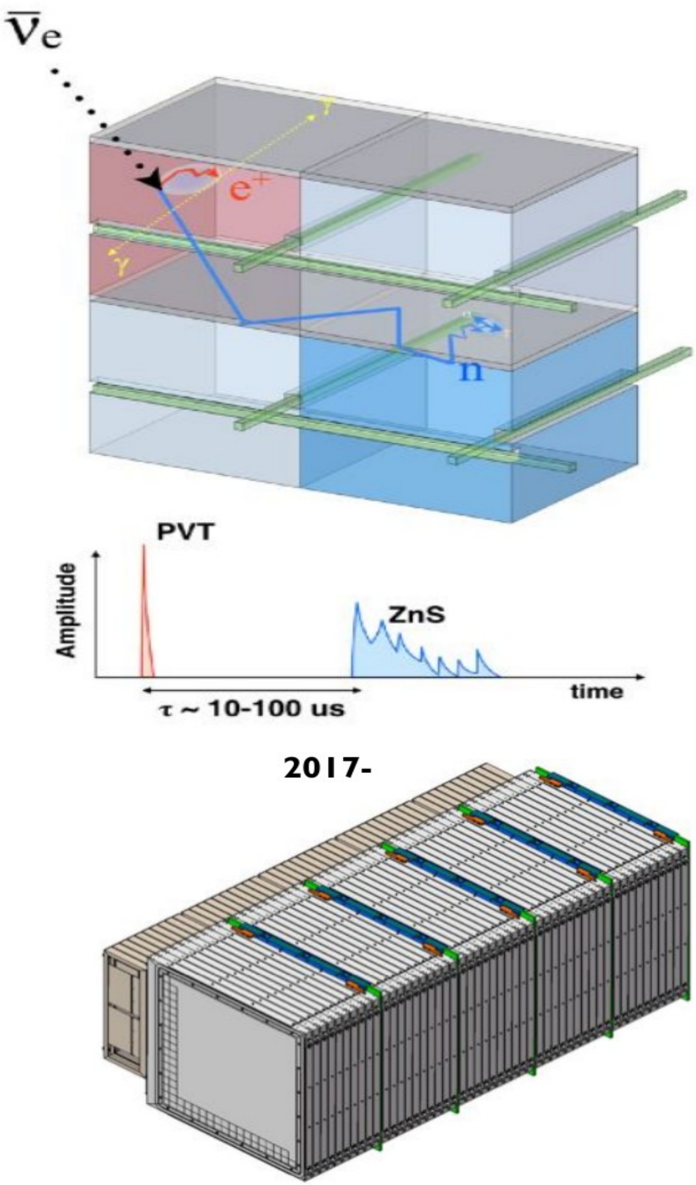
SoLid

- UK Led collaboration
- Detector designed in UK
- Use scintillator (PVT) filled cubes for segmentation.



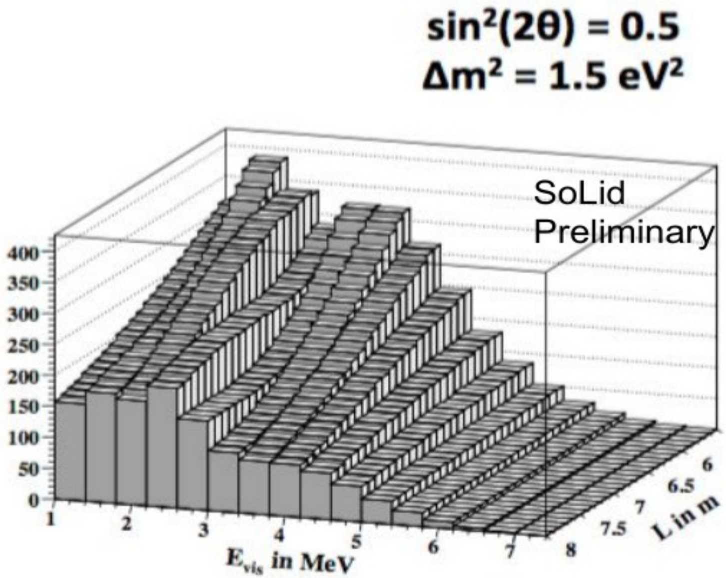
Belgian Reactor 2 (BR2) at SCK-CEN.

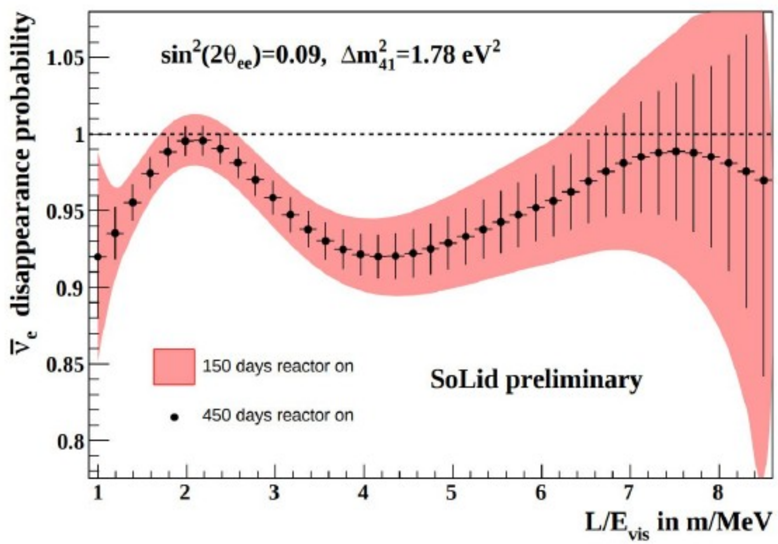
95% Enriched ^{235}U, 60MW.

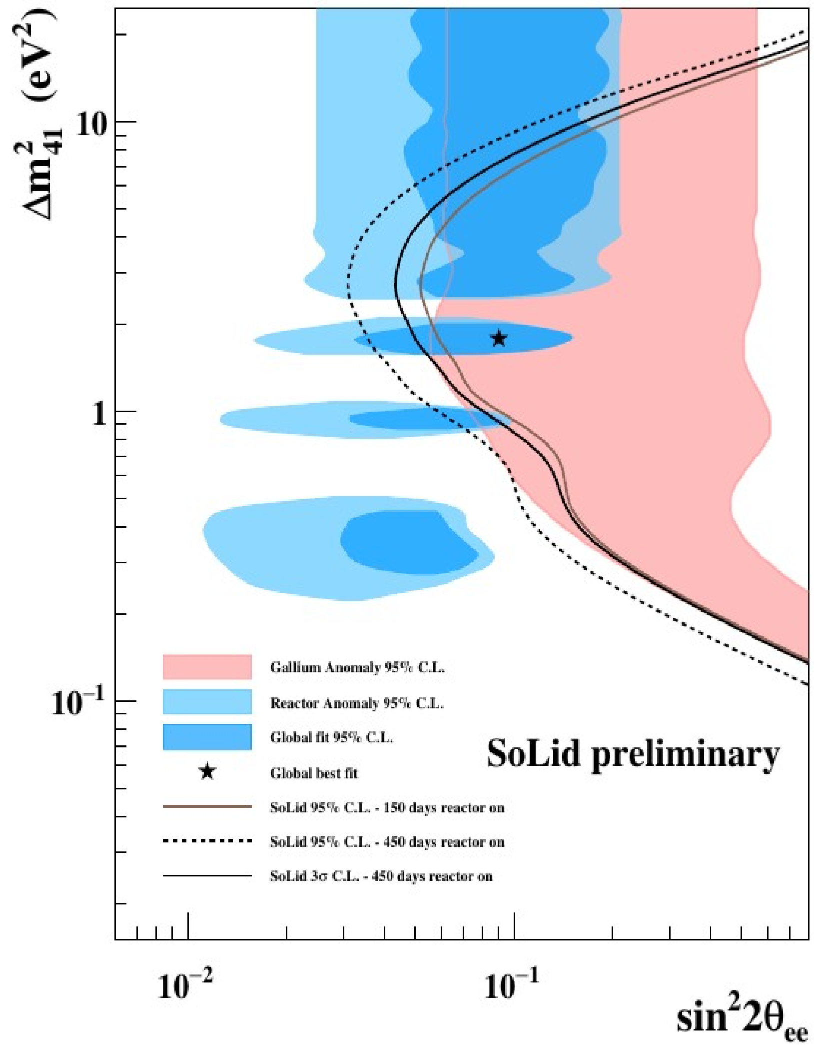


SoLid Phase I (1.6 T)
12k cubes with 3.2k channels,
~300 events/day.
Perform oscillation search.

SoLid sensitivity

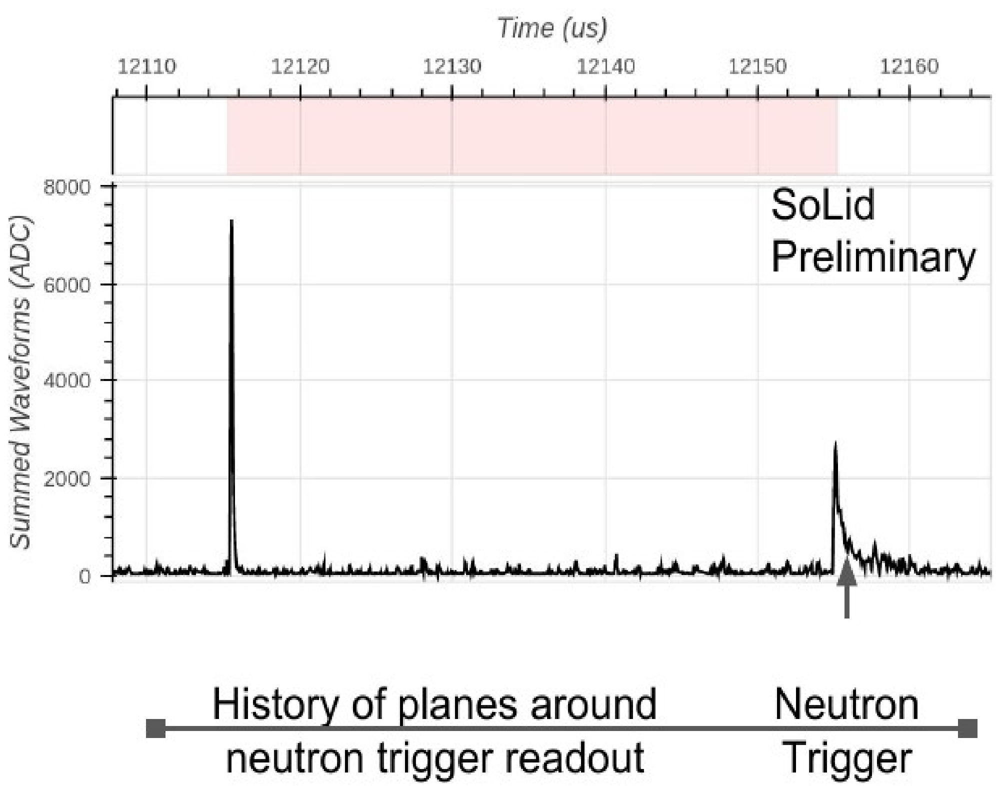


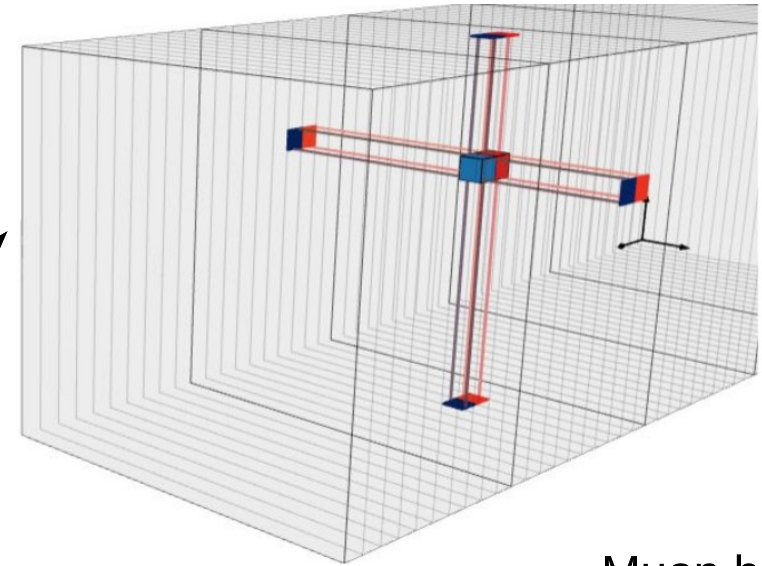




SoLid

Data taking in 2018 continuing stably:
- ~ 150 days reactor on.
- + data in 2019-2020.
- First Physics results expected late 2018.





Muon bckgr

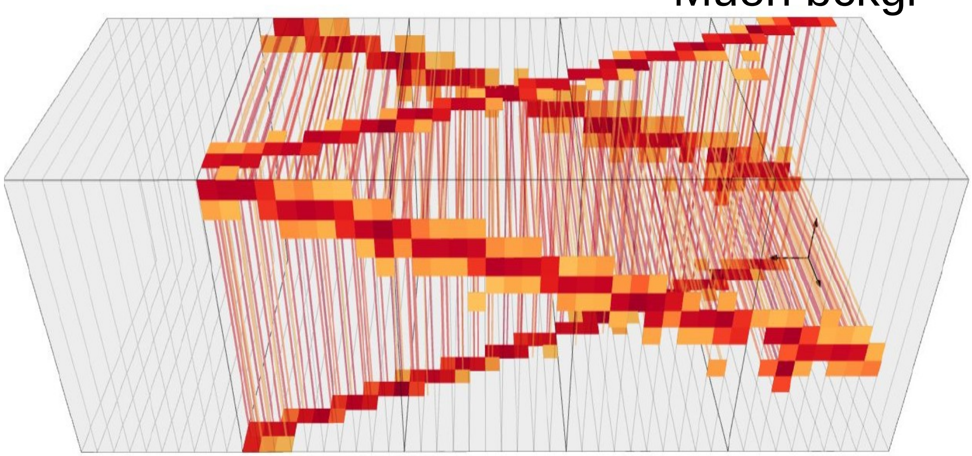


Fig: Example muon candidate, crossing all four modules. 50ns time window.

From: D. Saunders, ICL

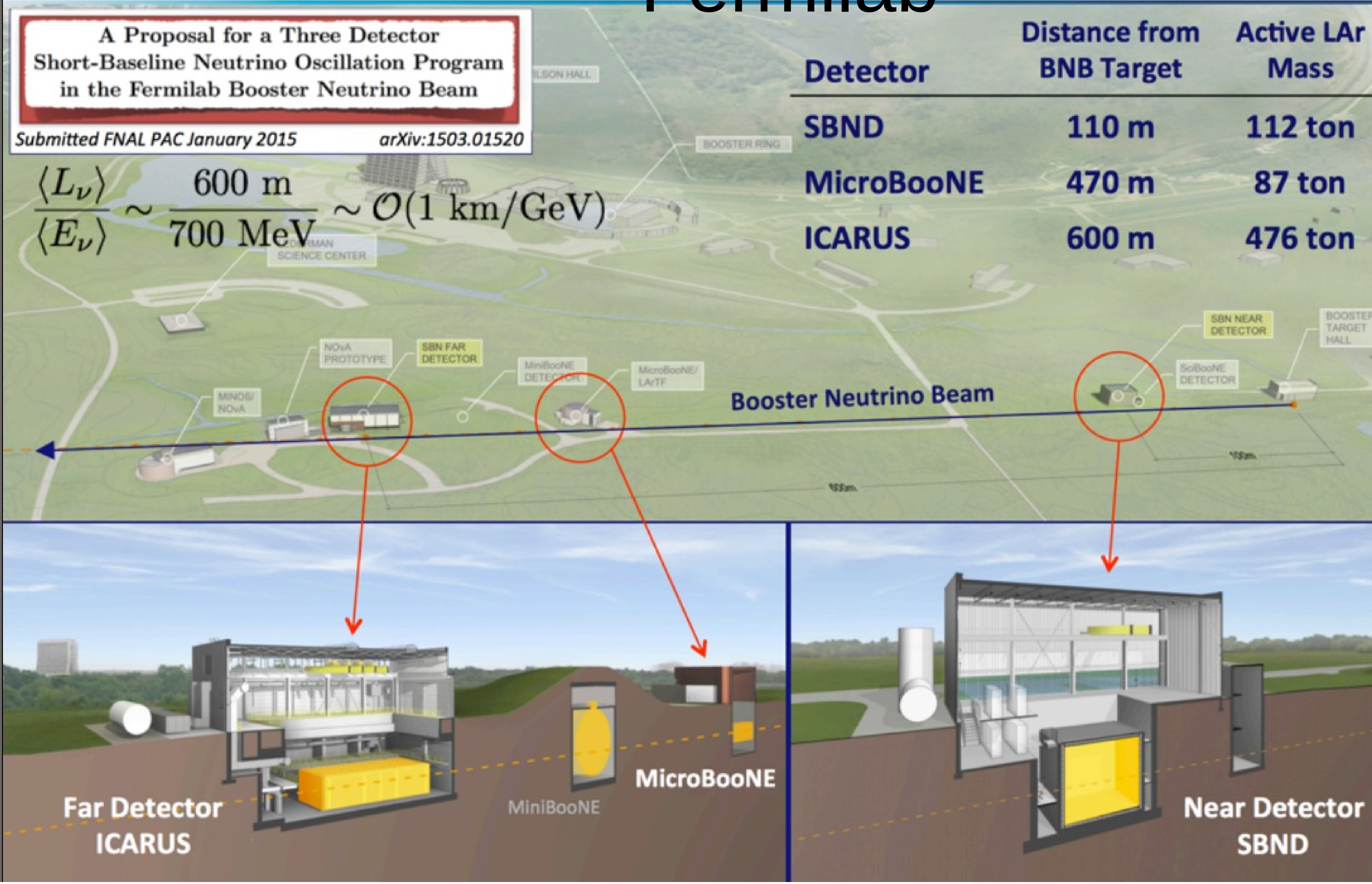
Enter SBN Programme at Fermilab

A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam

Submitted FNAL PAC January 2015 *arXiv:1503.01520*

$$\frac{\langle L_\nu \rangle}{\langle E_\nu \rangle} \sim \frac{600\ \mathrm{m}}{700\ \mathrm{MeV}} \sim \mathcal{O}(1\ \mathrm{km/GeV})$$

Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton



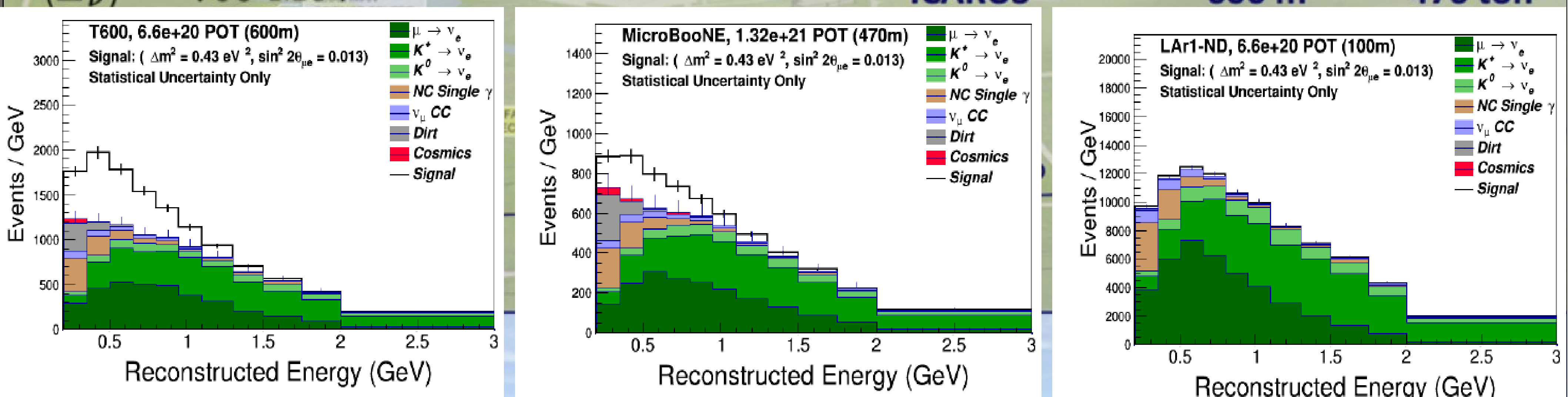
SBL osc in full running

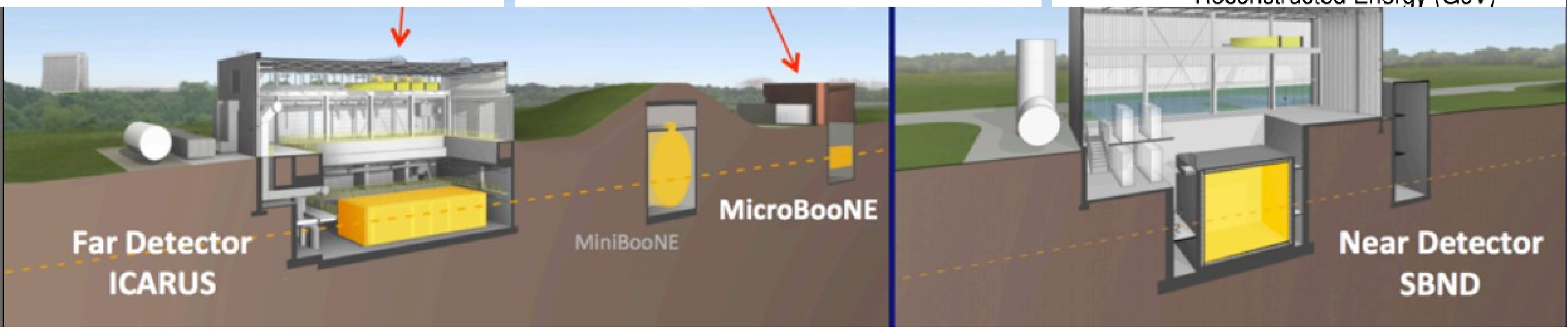
A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam

Submitted FNAL PAC January 2015 *arXiv:1503.01520*

$$\frac{\langle L_\nu \rangle}{\langle E_\nu \rangle} \sim \frac{600\ \text{m}}{700\ \text{MeV}} \sim \mathcal{O}(1\ \text{km/GeV})$$

Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton





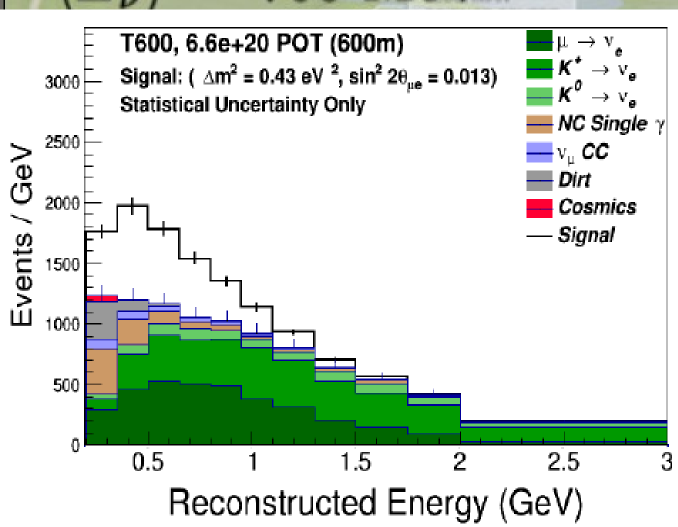
SBL osc in full running

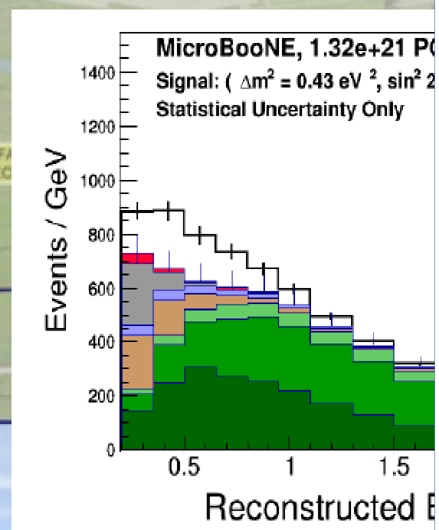
A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam

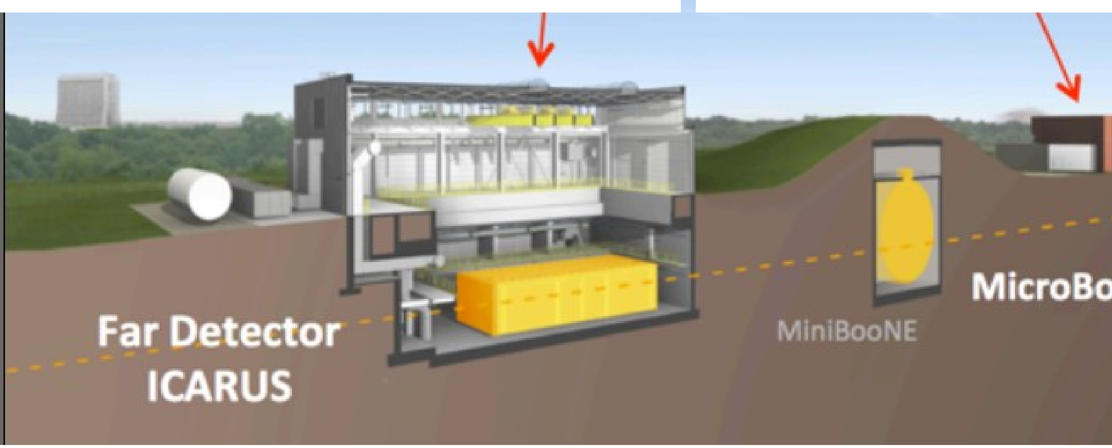
Submitted FNAL PAC January 2015 *arXiv:1503.01520*

Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton

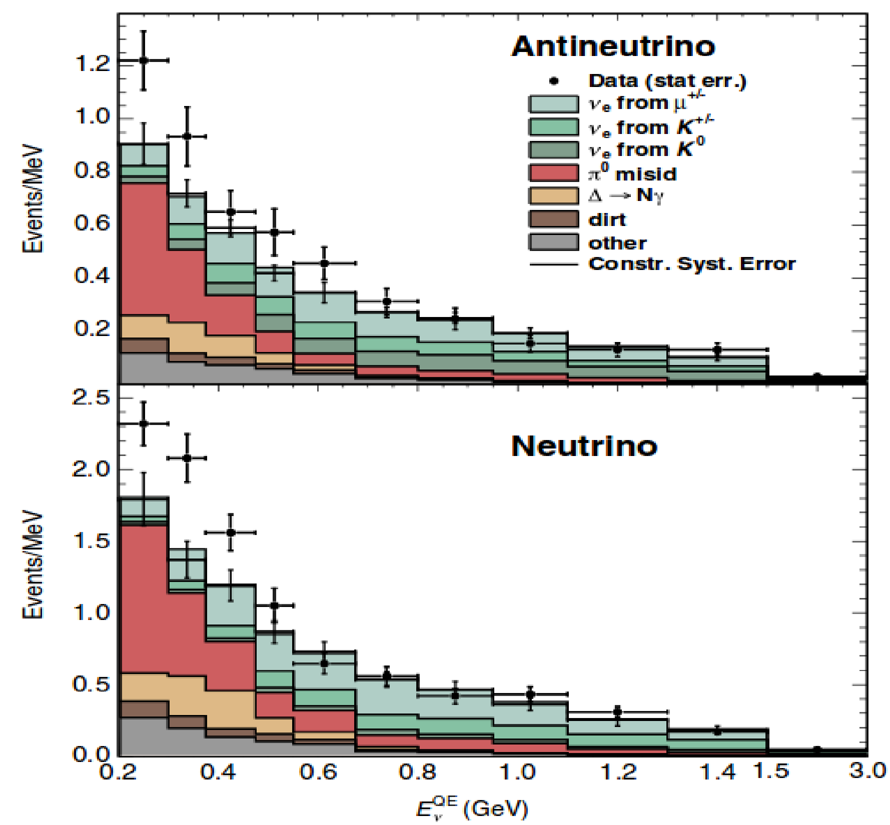
$$\frac{\langle L_\nu \rangle}{\langle E_\nu \rangle} \sim \frac{600\ \text{m}}{700\ \text{MeV}} \sim \mathcal{O}(1\ \text{km/GeV})$$





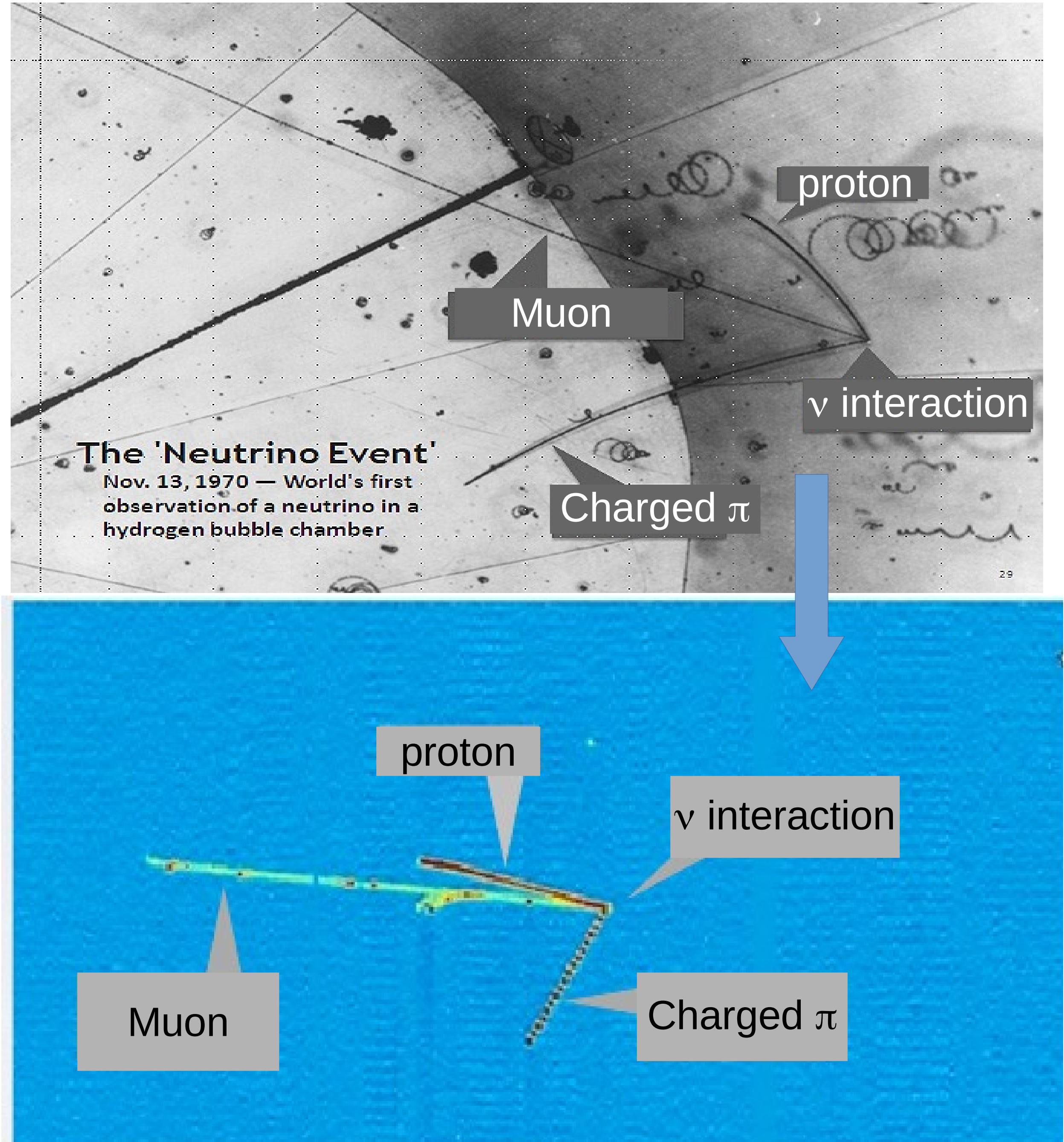


Recall the MiniBooNE Low Energy Excess.

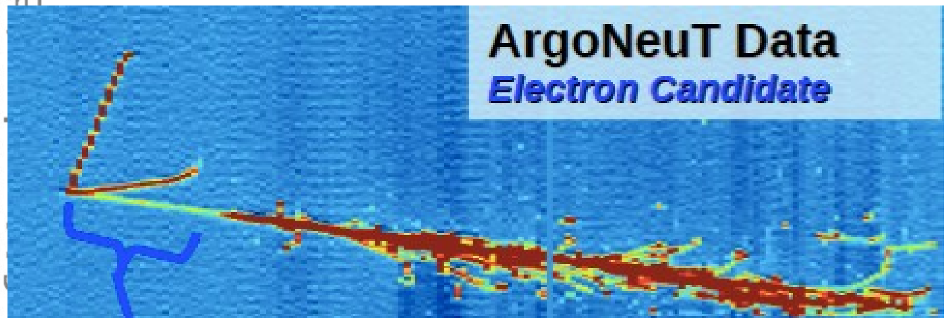


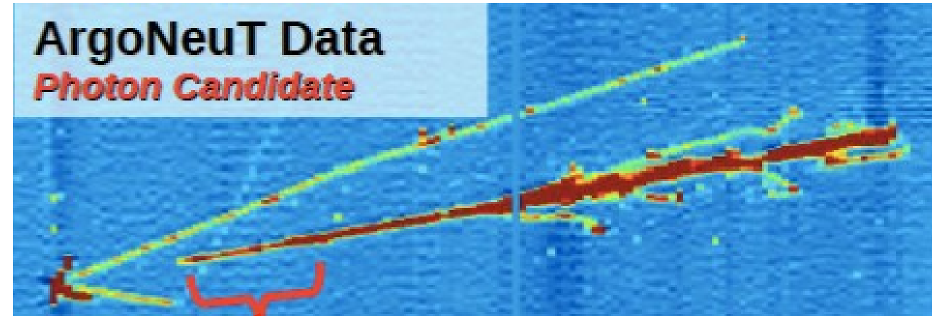
Detecting neutrinos in a LArTPC

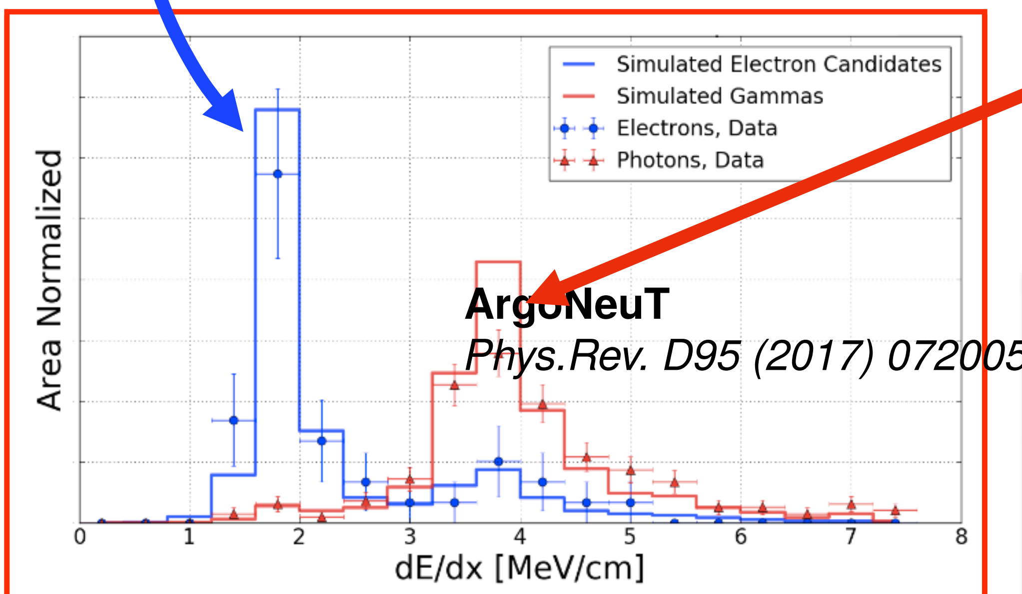
- The golden channel is ν_e appearance ($\nu_\mu \rightarrow \nu_e$) – sterile neutrino possible.
- Alternatively single photons – something new in neutrino interactions (see R. Murrells talk)
- The LArTPC and its bubble chamber-like data gives us excellent tools to tell them apart.



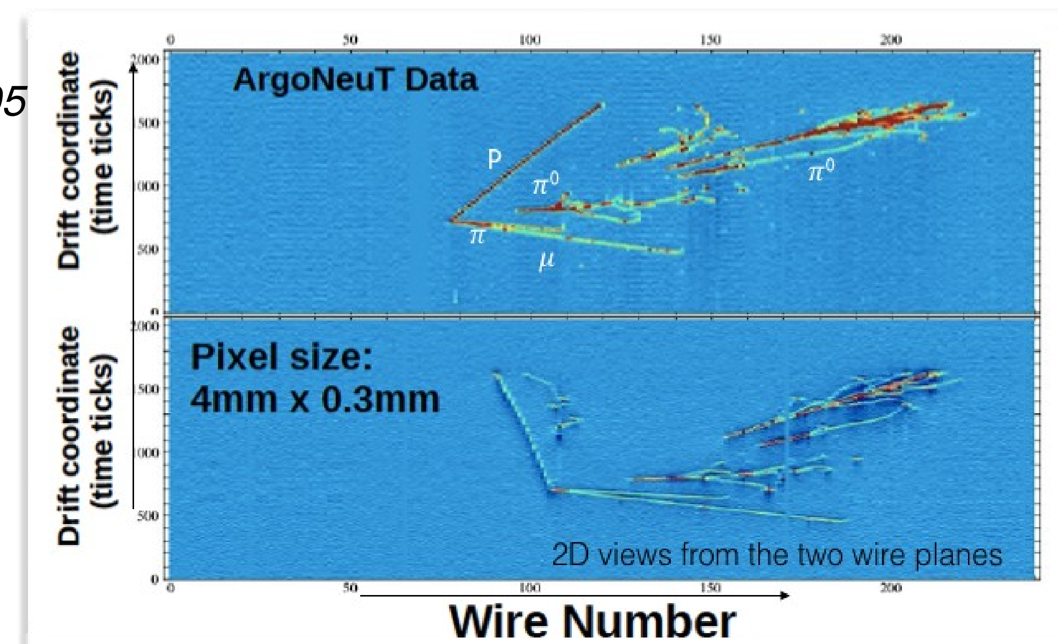
Electron-γ separation in LAr







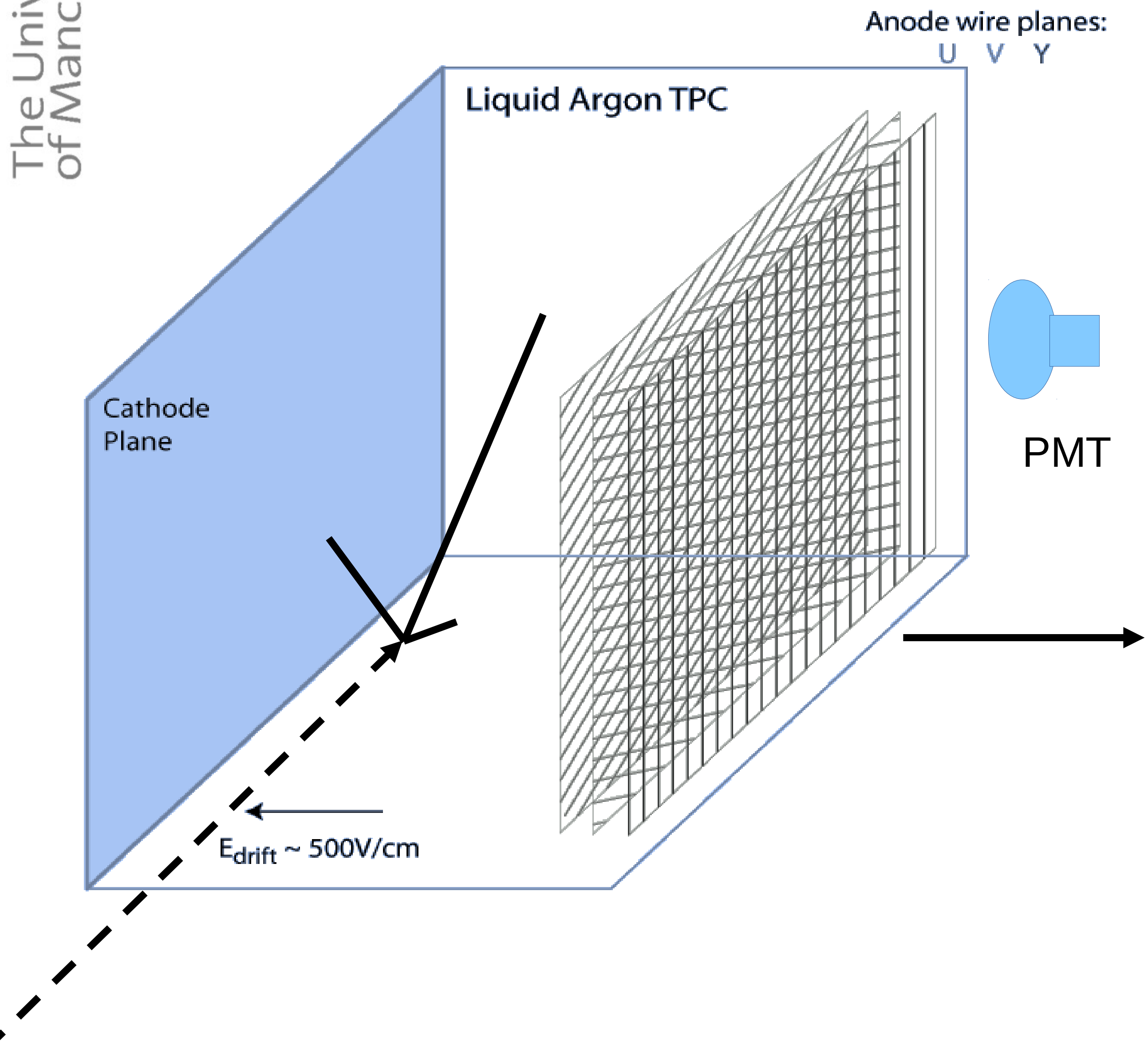
Double handle: topology and dE/dx

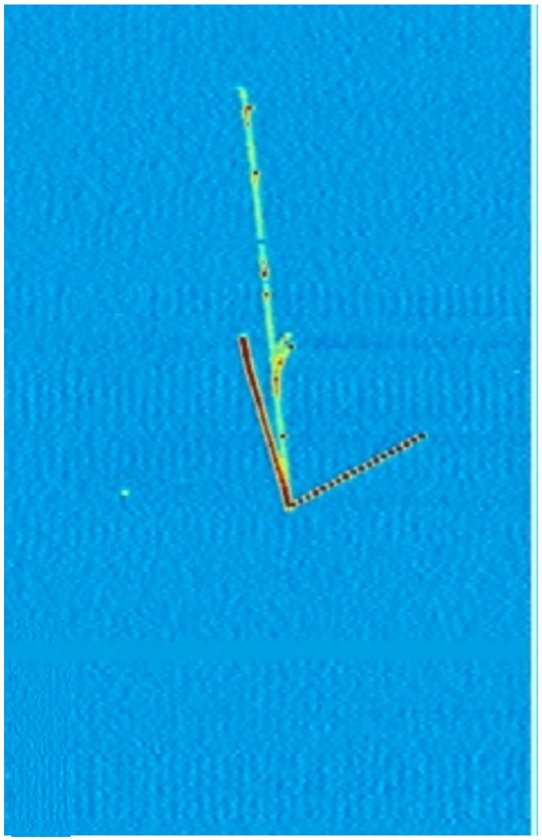


The LArTPC is an excellent tool for electron/photon separation

The University of Manchester

LArTPC Operation





MANCHESTER 1824

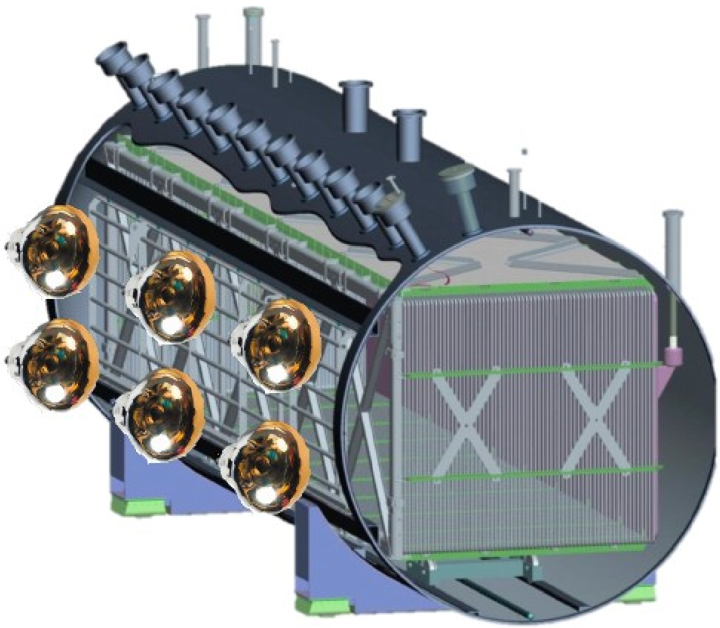
The University of Manchester

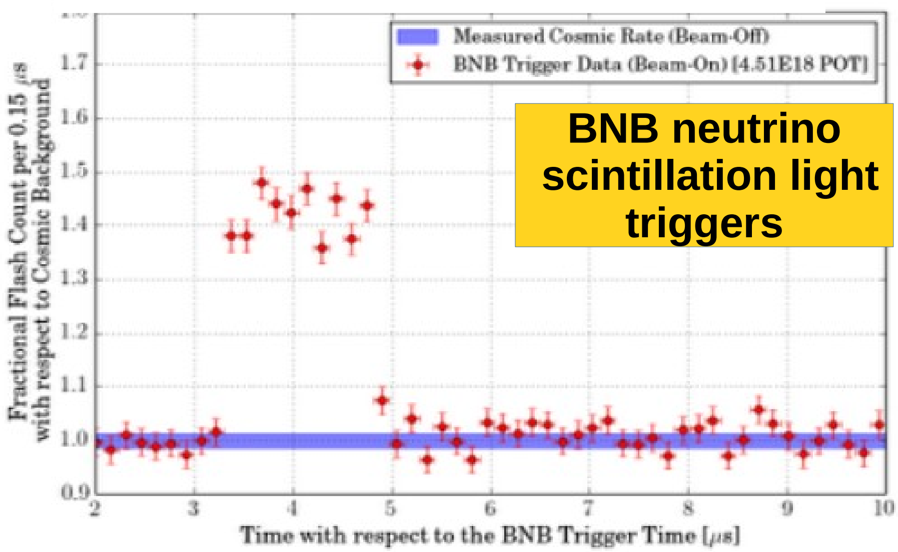
MicroBooNE

MANCHESTER 1824

The University of Manchester

MicroBooNE





Running stably since 2015 (Largest running LArTPC in the World).

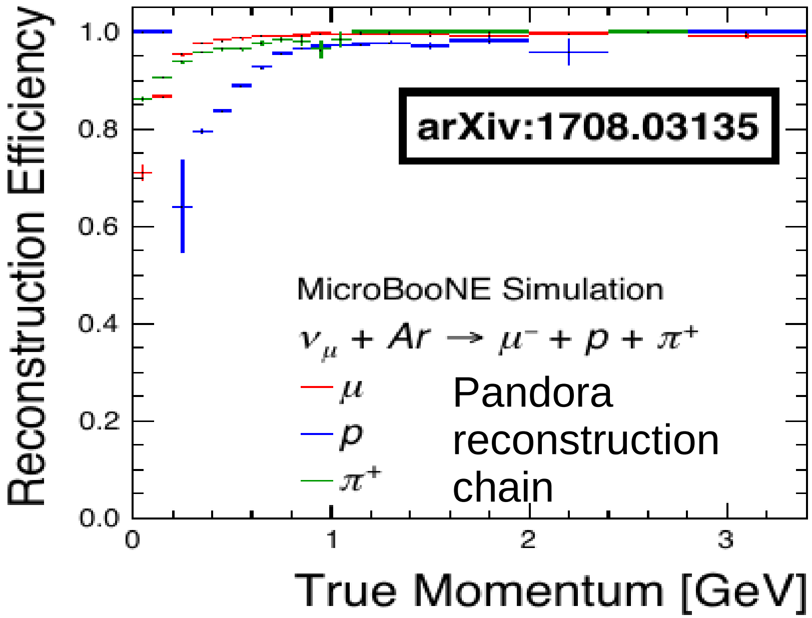
Significant UK involvement.

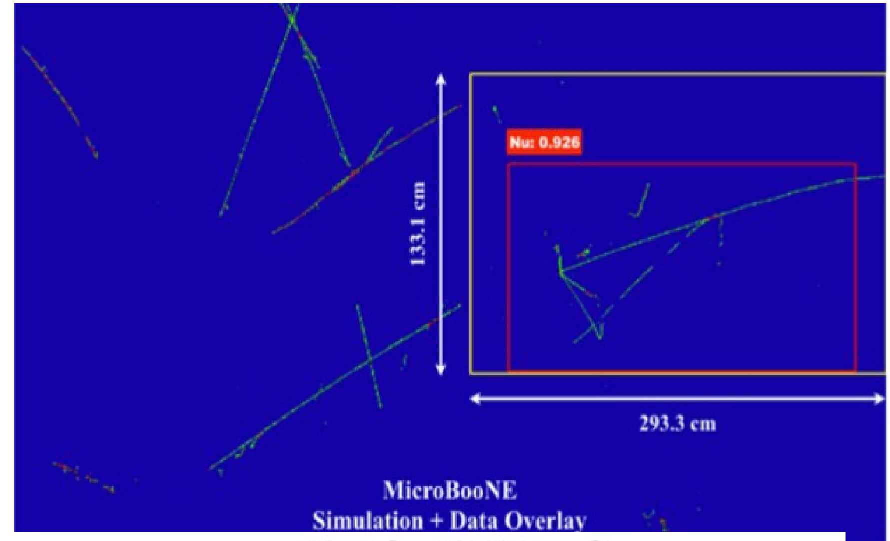
Development and understanding of LArTPC technology for future programme (DUNE) – see talk by A. Lister

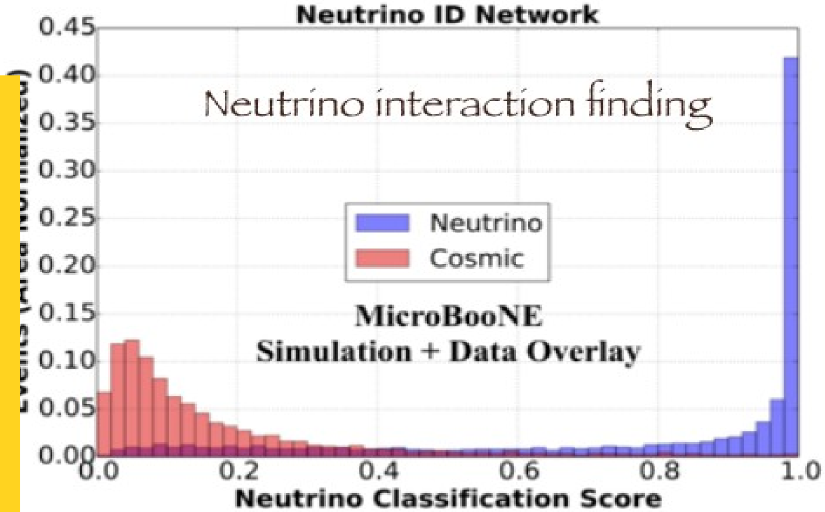
Extremely high argon purity obtained.

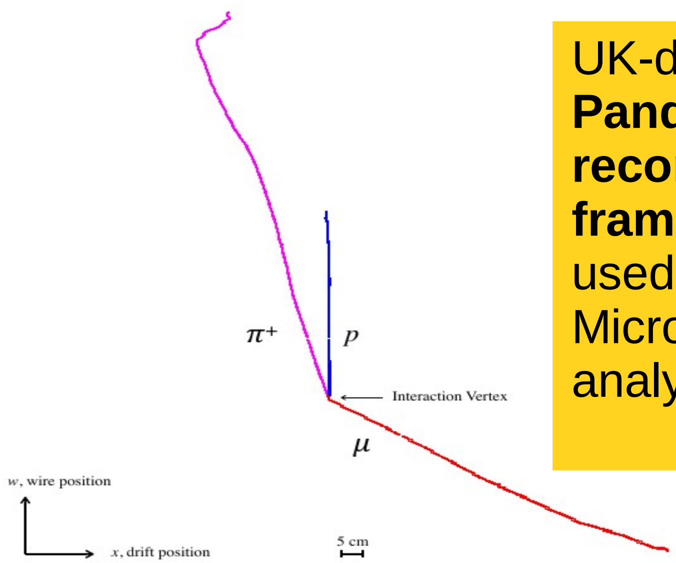
Constructed CRT – important for cosmic backgrounds (and independent efficiencies).

Developing LAr reconstruction







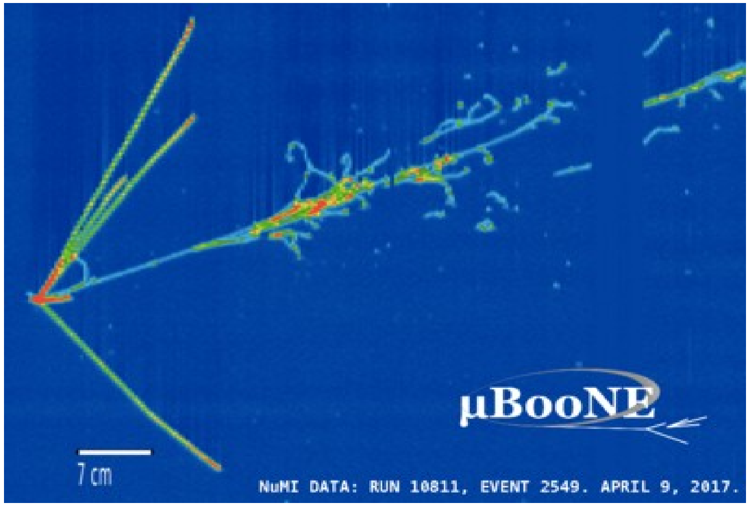


UK-developed **Pandora reconstruction framework** is being used for the first MicroBooNE analyses

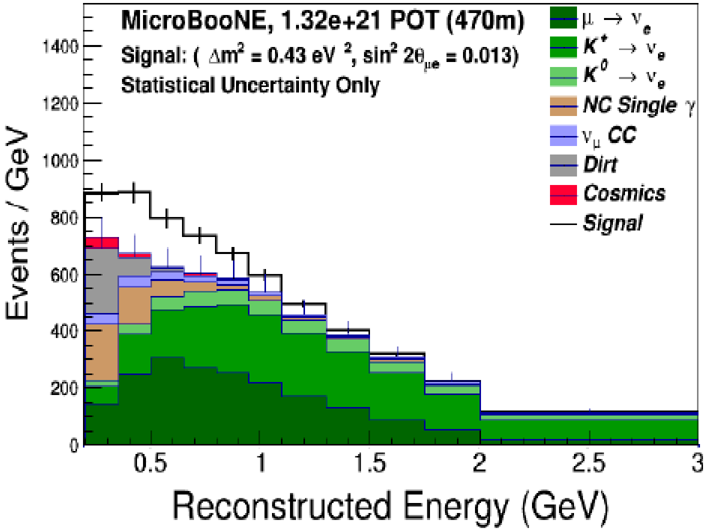
Event selection using Deep Learning
JINST 12, P03011 (2017)

Towards Understanding the Low Energy Excess

- MicroBooNE has demonstrated key “first” steps in automated reconstruction and understanding
  the detector response.
- Coming Soon:
  - First neutrino physics measurements (led by UK students and post-docs)
- This experience feeds into the LEE analysis. (strong UK contribution)



NuMI beam electron-neutrino candidate



SBND – the near detector

The Short-Baseline Near Detector (SBND), will be located closest to the source of neutrinos.

It will characterize the beam before oscillations occur and address one of the dominant systematic uncertainties.

Planned start of operation 2019/2020.

SBND

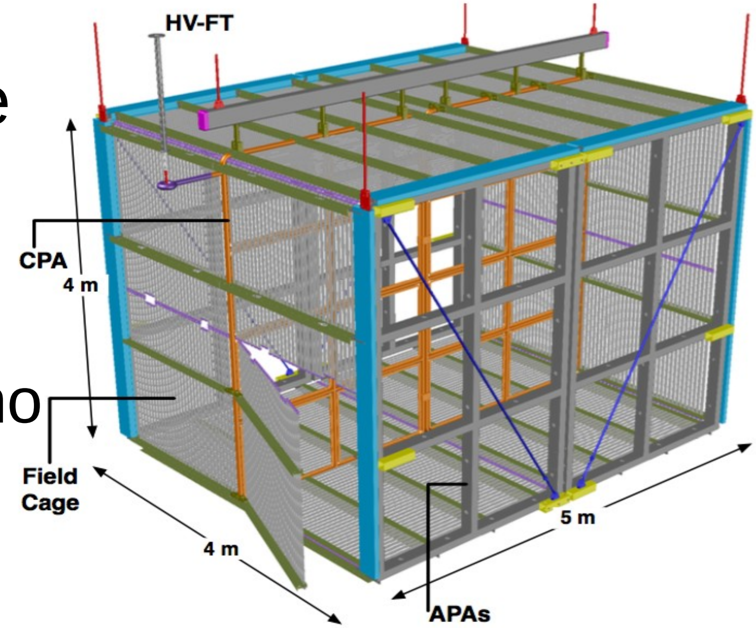
Significant UK contributions to hardware and leadership of physics programme.

SBND will see a huge event rate.

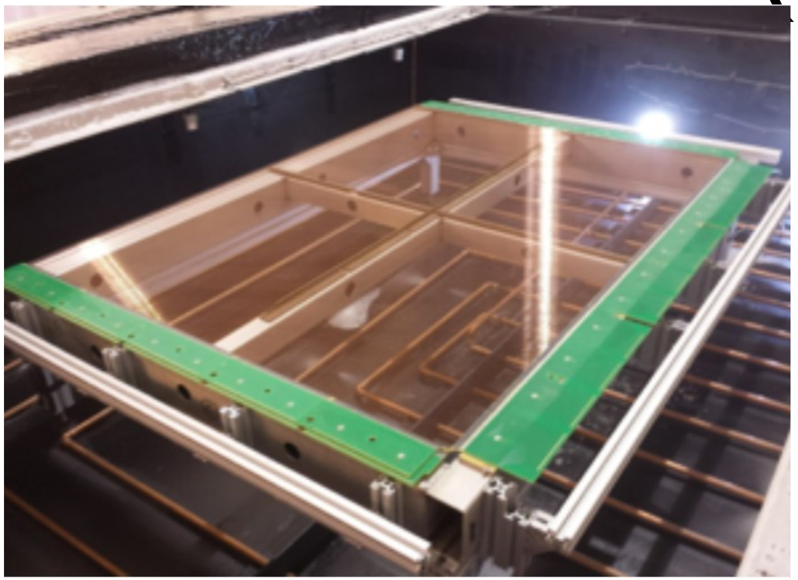
Enables precision measurements of neutrino cross-sections and nuclear effects.

Detector made of two TPCs (Four Anode Plane Assemblies and 2 Cathode Plane Assemblies)

Membrane Cryostat

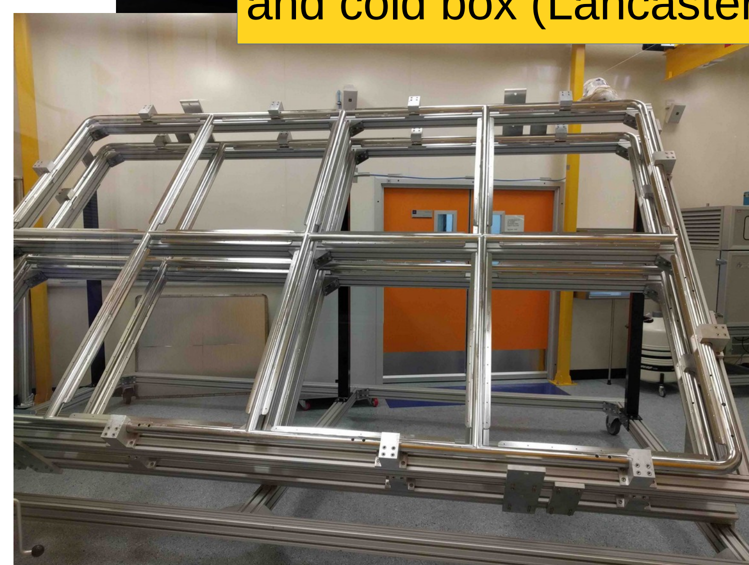


SBND construction (UK-biased)



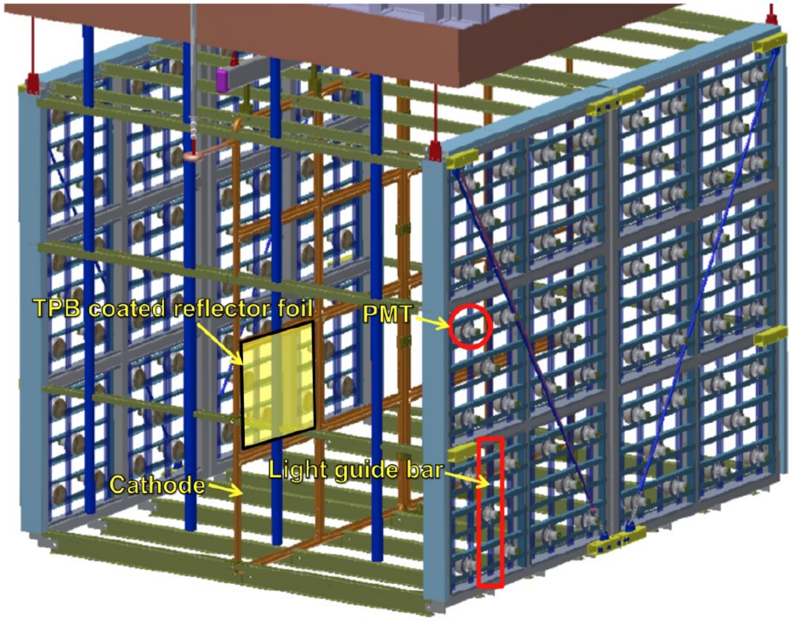
- Construction of field cage elements has started:
  - Cathode planes will be shipped to Fermilab soon (Liverpool).
  - Wire winding has begun in January in Daresbury lab (Manchester) (test frame fully wound) – followed by US winding.
  - HV Feedthrough (UCL)
- Fieldcage assembly at Fermilab planned for August.

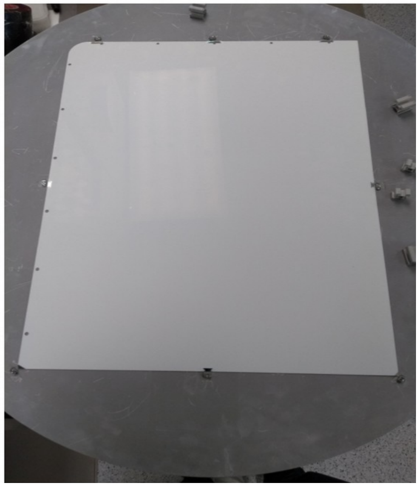
Frames (Sheffield) and cold box (Lancaster)

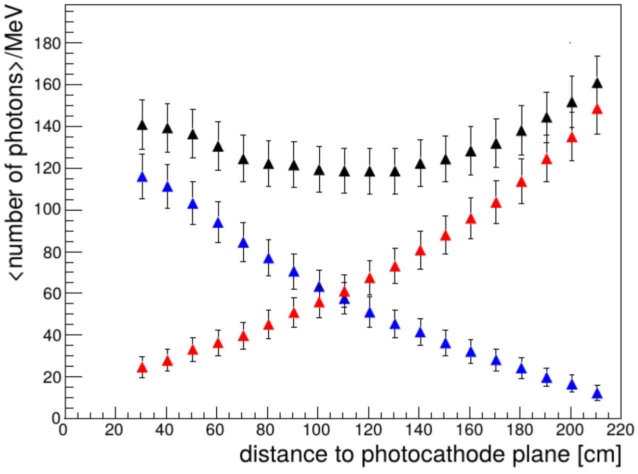


Light Detection in SBND

- Important R&D aspect
- Scintillation light applications:
  – trigger, t_0
  – background rejection
  – calorimetry, particle ID
- Mounted on Cathode:
  – WLS-coated reflector foils to improve collection efficiency and uniformity (UK led).





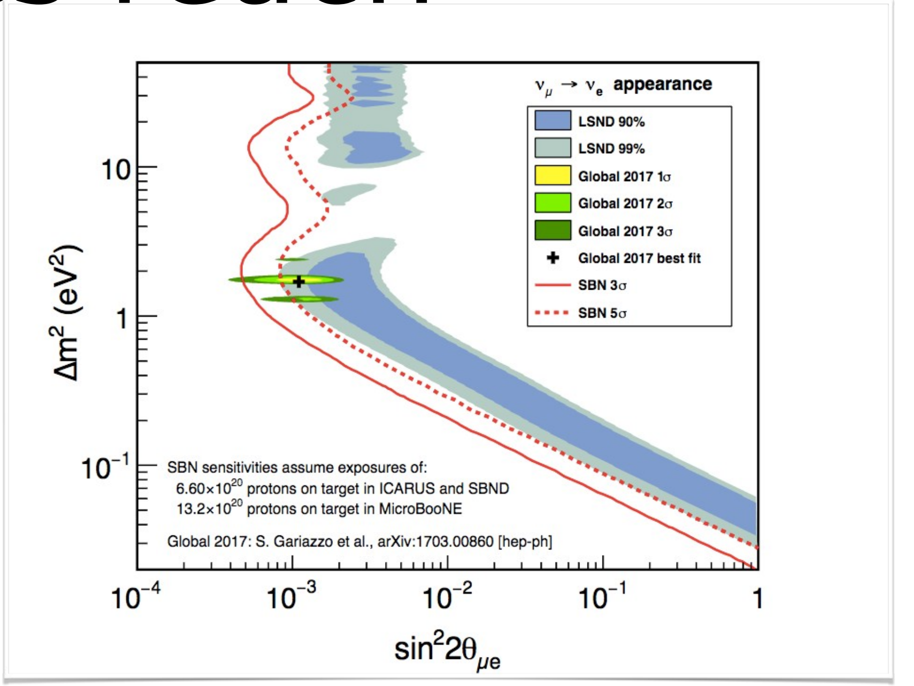


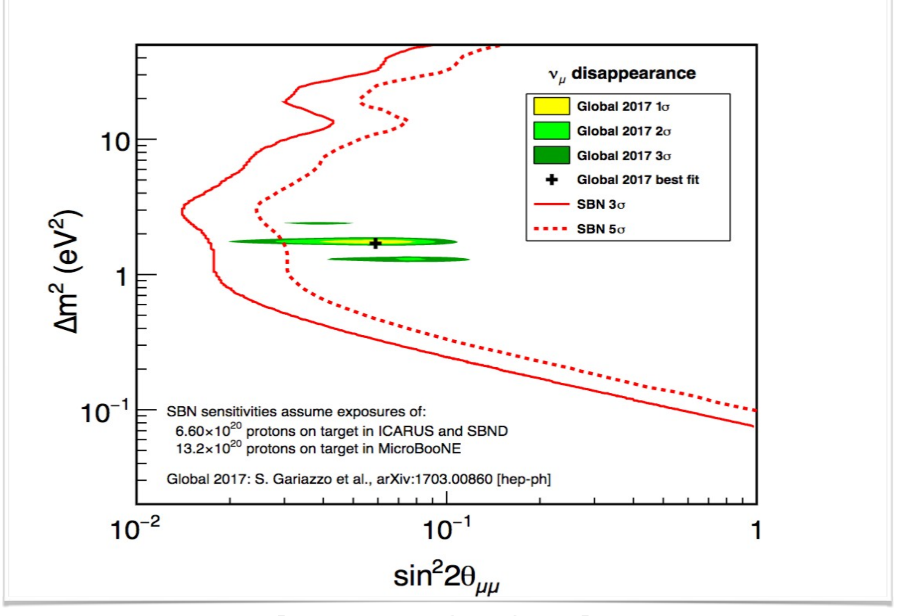
SBN Physics reach

Constraints on the flux and cross-sections from the near detector lead to a powerful combined exclusion region.

LSND parameter space excluded at 5σ.

In addition, SBN can also perform ν_μ disappearance searches. Would confirm an oscillation interpretation of any observed ν_e appearance signal.



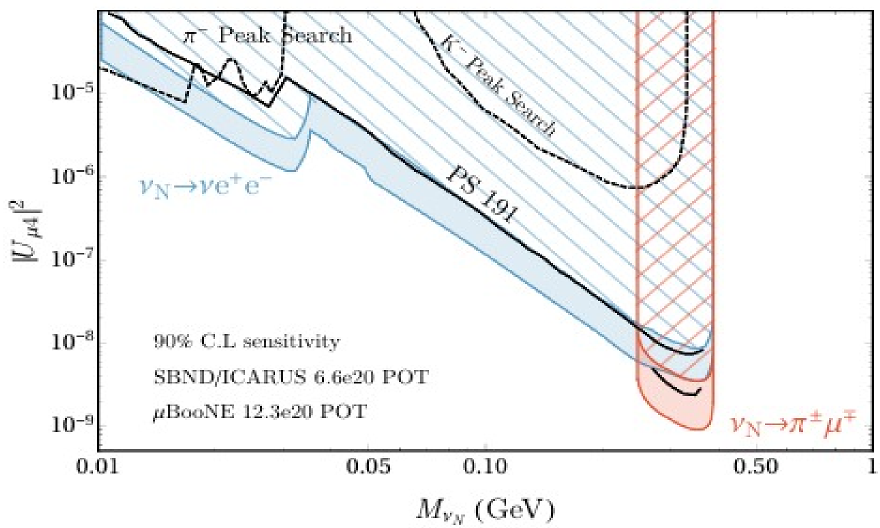


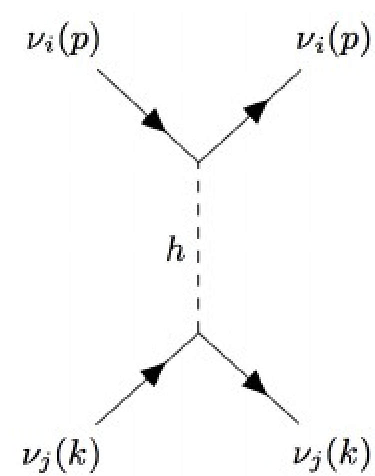
Fit from S. Gariazzo et al., arXiv:1703.00860

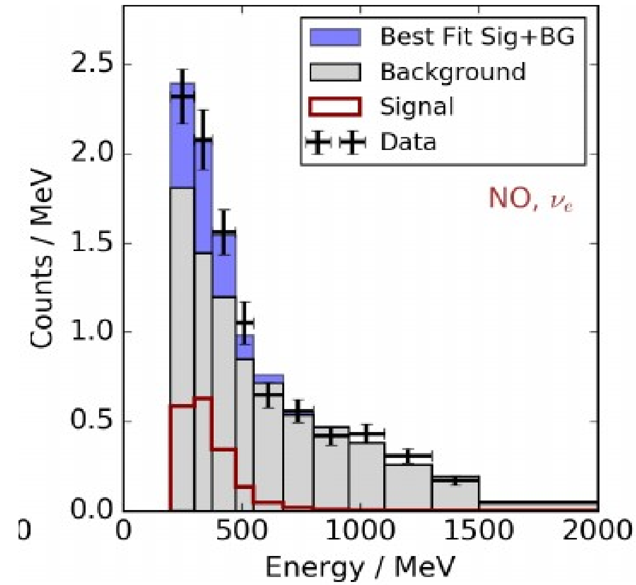
Alternative explanations to LEE signal

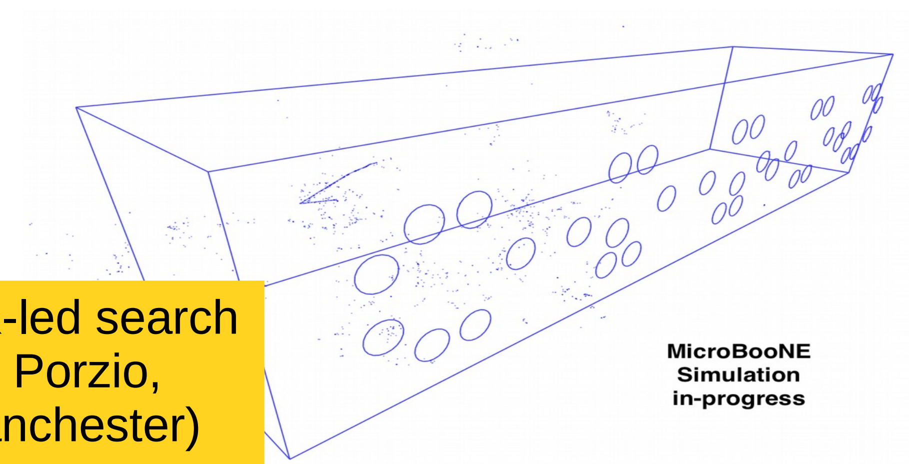
Ballett et al. JHEP04(2017)102

Heavy Sterile neutrino decays as an explanation of MiniBooNE signal.









UK-led search (D. Porzio, Manchester)

Light neutrinophilic higgs exchange with neutrino cosmic background can result in resonance and imitate MiniBooNE signal.

Asaadi, Church, Jones, Guenette & A.S., arXiv:1712.08019 Accepted by PRD

The University of Manchester

MANCHESTER 1824

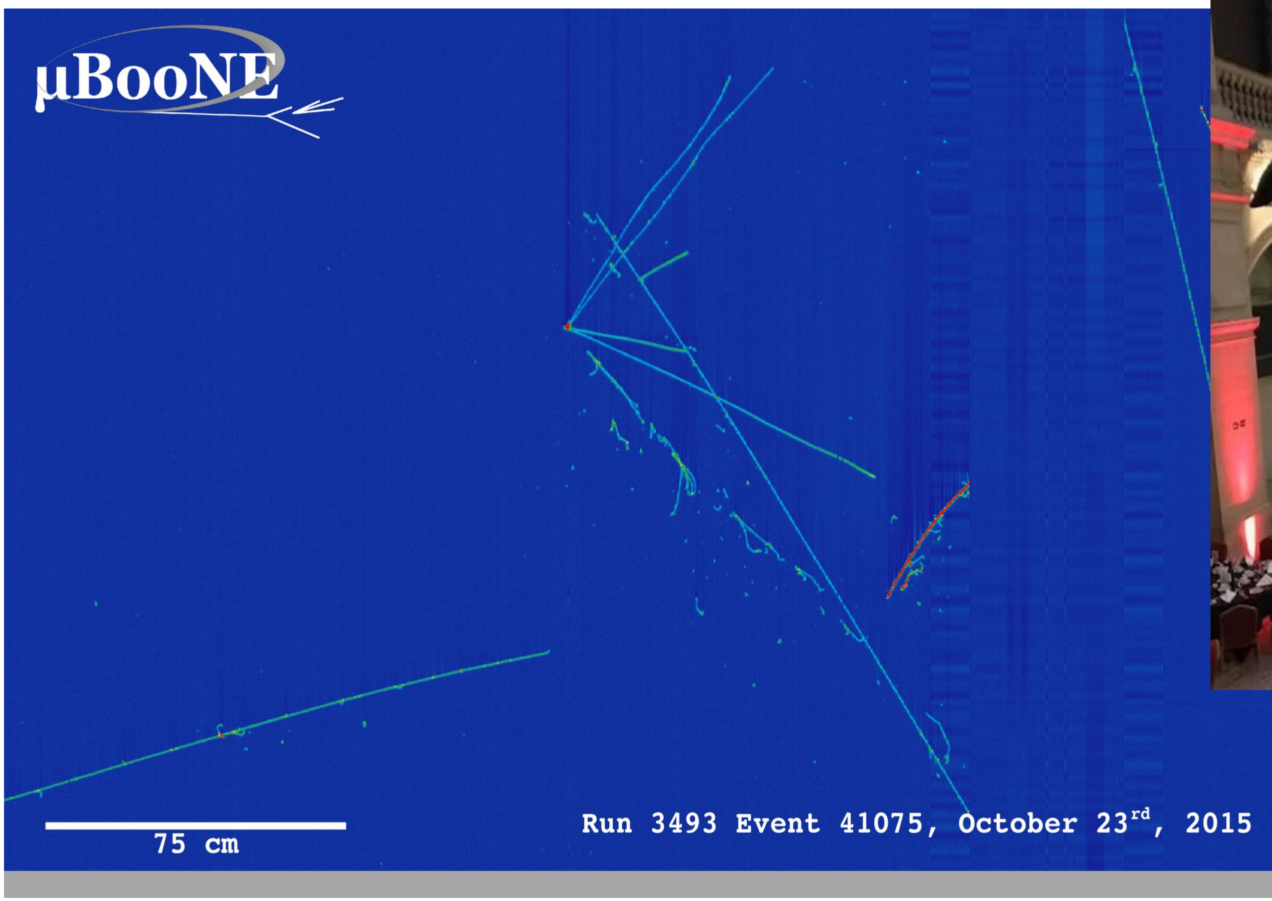
Summary

- Short Baseline Neutrino Oscillations are an exciting, data driven field.
- First measurement of θ_{13} with reactor anti-neutrinos.
- Possible hints of new physics through short baseline oscillations.
- More data needed to clarify the situation.
- UK leading efforts in reactor based and accelerator based experiments.
- Interesting times lie ahead - stay tuned!

MANCHESTER 1824

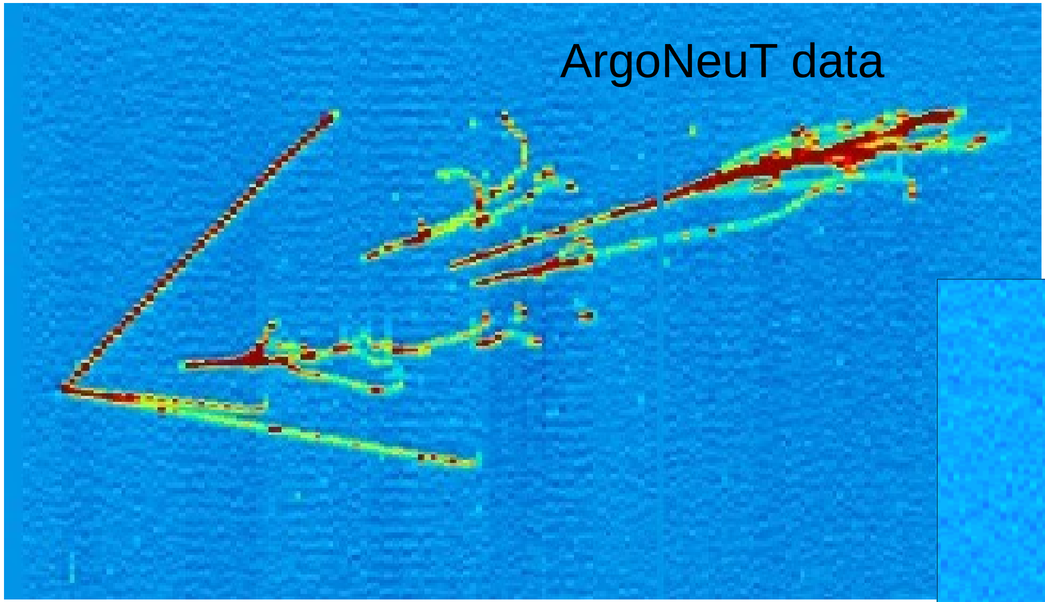
The University of Manchester

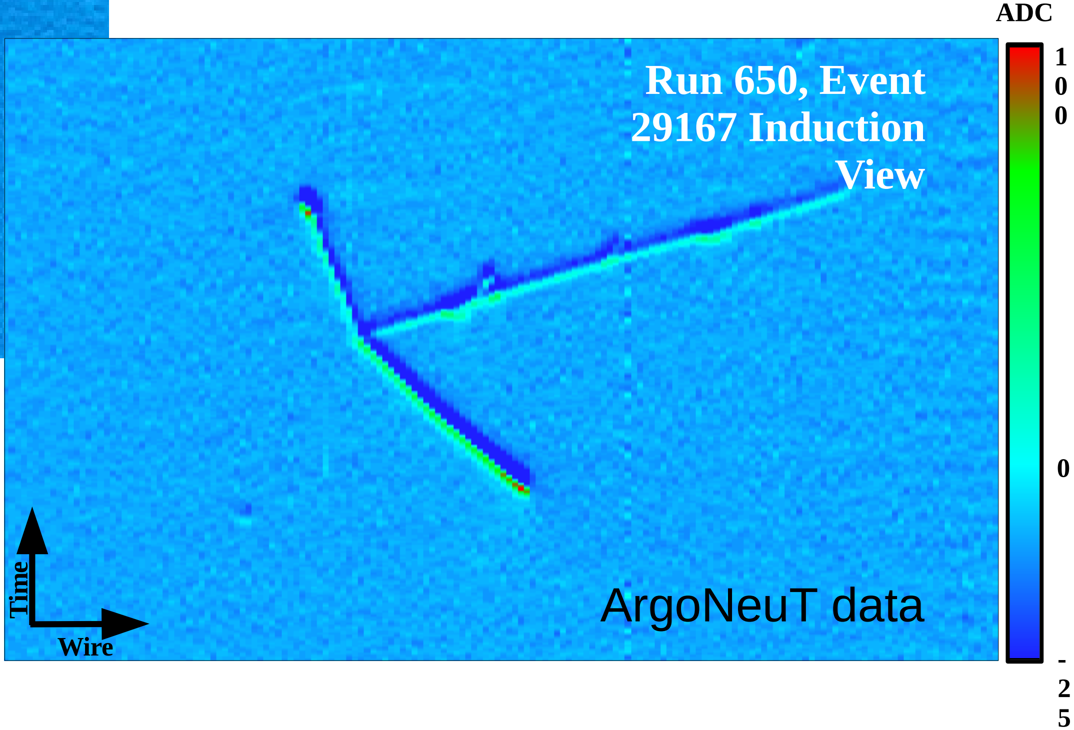
Thank You for your Attention

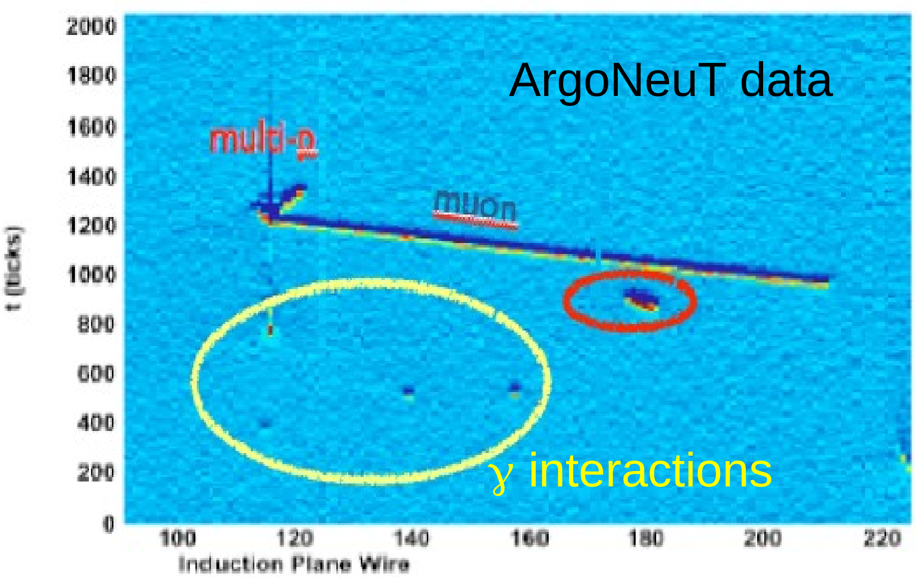


Thanks to A. Vacheret and B. Littlejohn for providing materials.

Neutrino interactions in LArTPCs

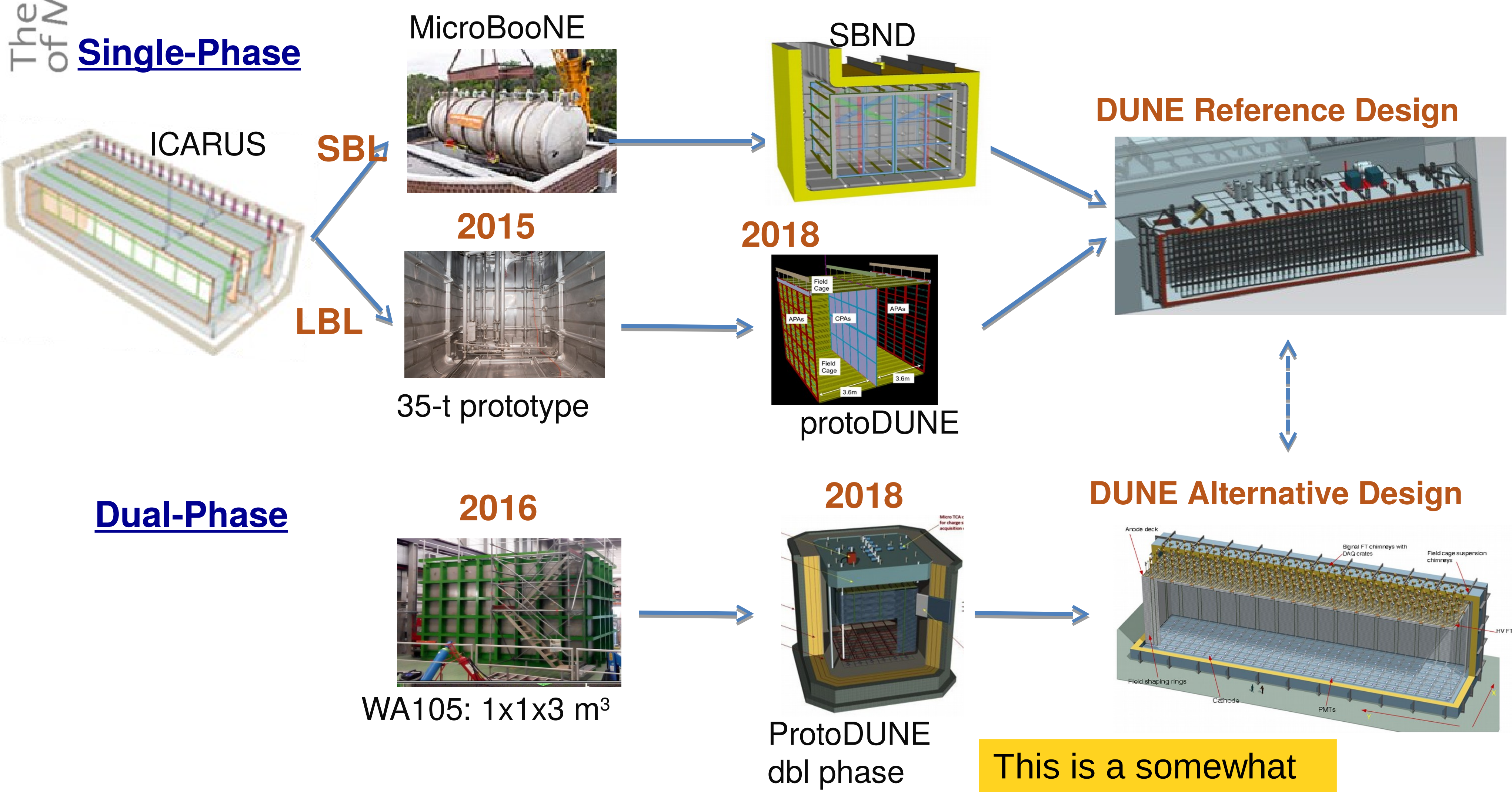






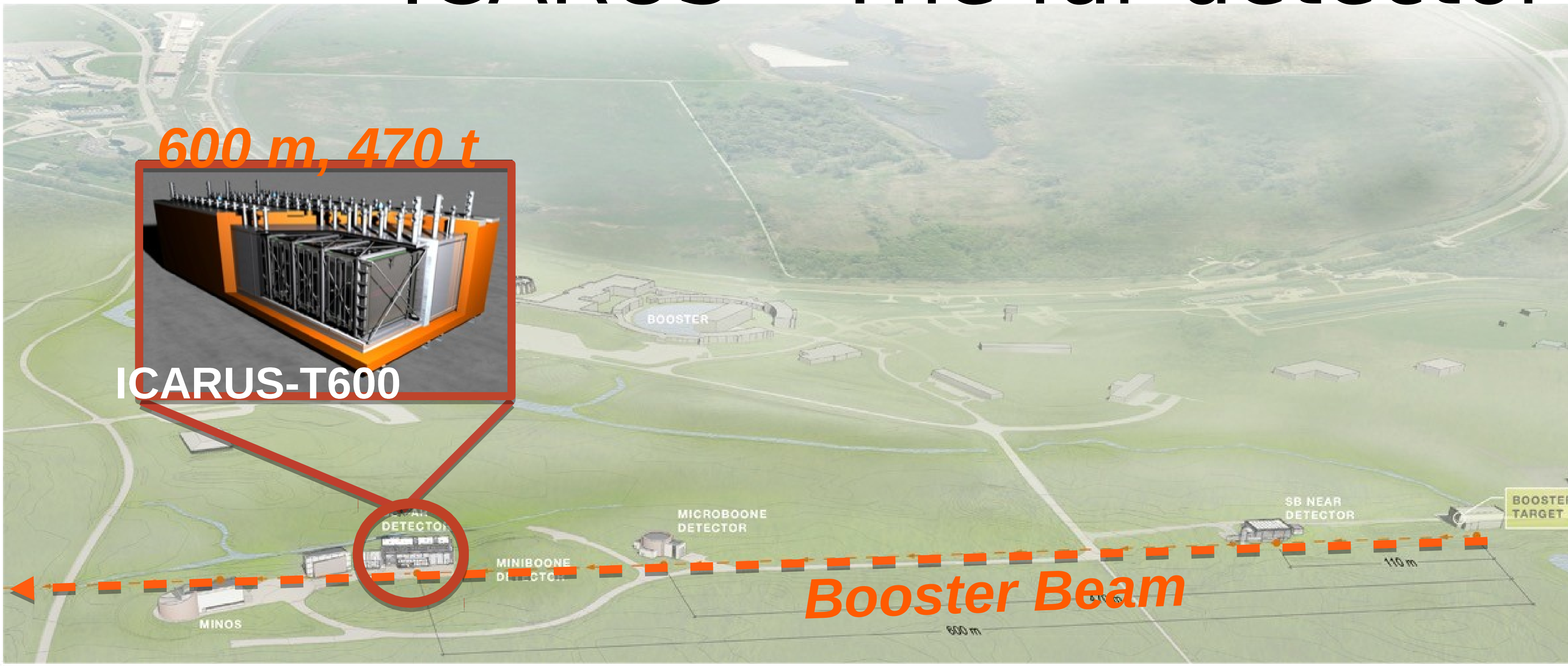
LArTPC development

Development and prototyping through the Fermilab SBN and CERN neutrino platform programmes



This is a somewhat simplified drawing...

ICARUS – The far detector



Given its large mass and relatively large distance from the source the ICARUS-T600 will have high sensitivity to neutrino oscillation effects.

- Planned start of operation 2019.

MANCHESTER 1824

The University of Manchester

ICARUS from Gran Sasso to CERN to Fermilab

The ICARUS T600, after a succesful Run at Gran Sasso on the CNGS beam Was transported to CERN for refurbishment.

It then travelled to Fermilab over the Summer (#IcarusTrip).

Building to hold is ready, the cryostat Is under construction. Commissioning planned for 2018

ICARUS @ FNAL

ICARUS @ CERN

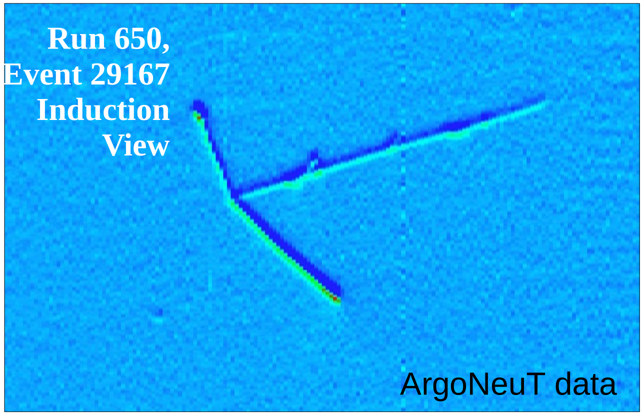
SBND cross-section physics

$\nu_\mu CC$, BNB/FHC, 6.6×10^{20} POT, 112 tonnes active mass

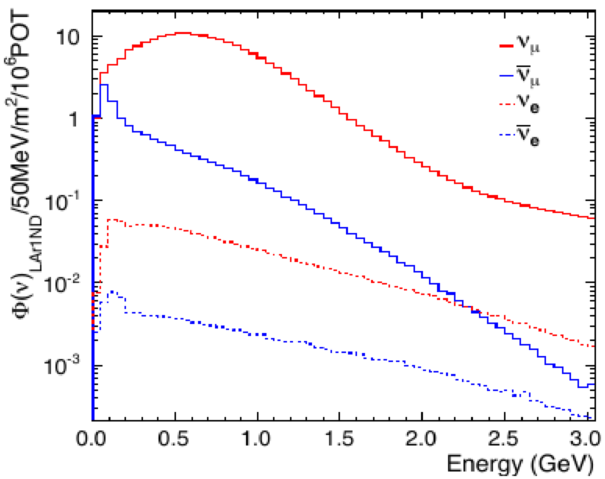
	GENIE Model Configurations	
Hadronic Final State	**G17_01b**	**G17_02a**
Inclusive	5,389,168	5,329,241
$0\ \pi$	3,814,198	3,744,108
$0\ \pi$ + 0p	27,269	34,696
$0\ \pi$ + 1p (> 20 MeV)	1,629,252	2,235,338
$0\ \pi$ + 2p (> 20 MeV)	1,150,368	637,535
$0\ \pi$ + 3p (> 20 MeV)	413,956	229,239
$0\ \pi$ + >3p (> 20 MeV)	396,212	263,727
$1\ \pi^+ + X$	942,555	1,021,212
$1\ \pi^- + X$	38,012	21,242
$1\ \pi^0 + X$	406,555	370,666
$2\ \pi + X$	145,336	131,308
$\geqslant 3\pi + X$	42,510	40,702
Physical Process		
QE	1,569,073	2,827,928
MEC	1,398,773	513,453
RES	1,816,570	1,539,159
DIS	581,905	441,057
Coherent	22,846	7642

C. Andrepoulos, NuINT 17

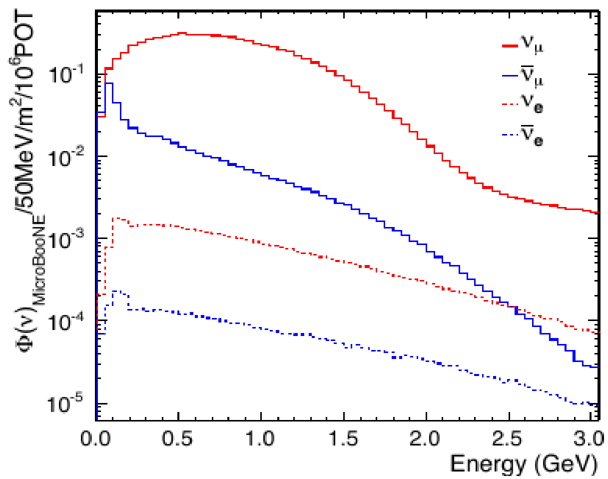
- SBND will see a huge event rate.
- Enables precision measurements of neutrino cross-sections and nuclear effects.
- Crucial for energy reconstruction.



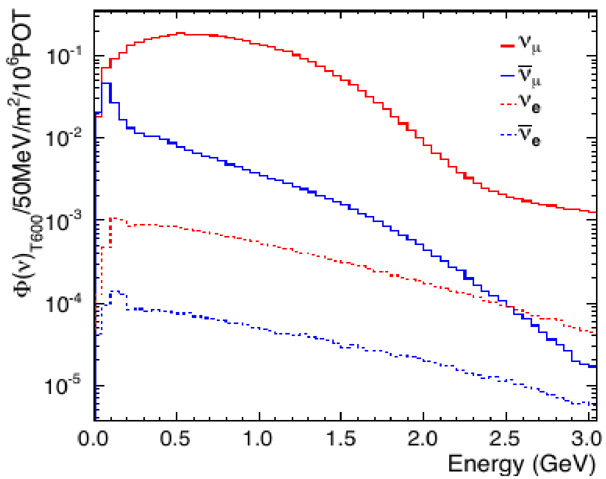
Booster Neutrino Beamline



at SBND

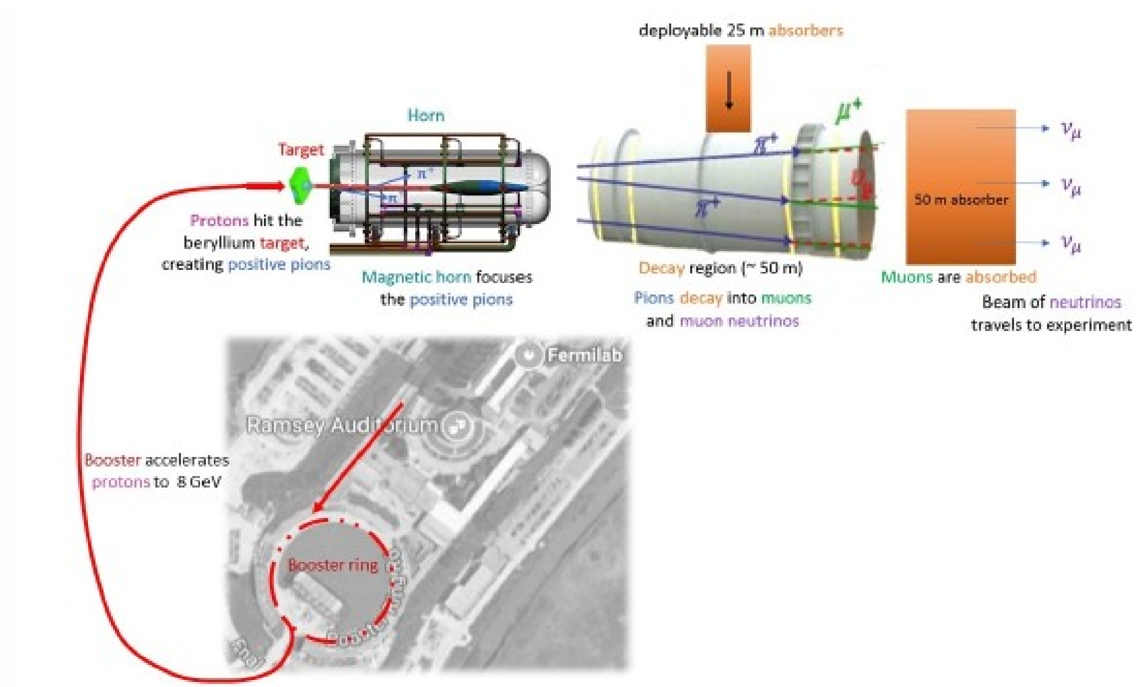


at MicroBooNE



at ICARUS

- Same beamline as MiniBooNE.
- A well known and understood system.



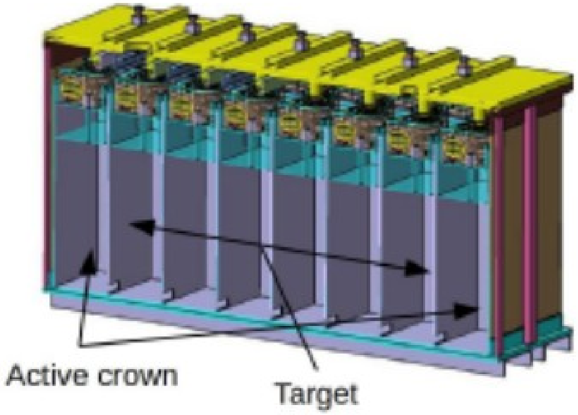
Short-Baseline Reactor Experiments Worldwide

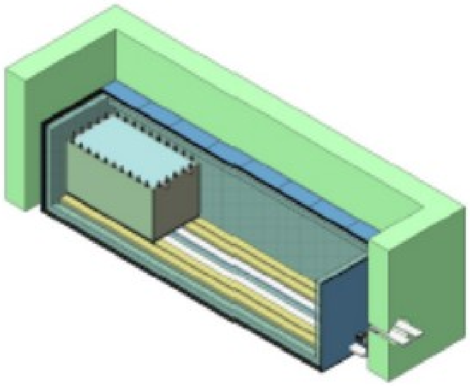
STEREO: Gd-LS detector at 10m from ILL , France

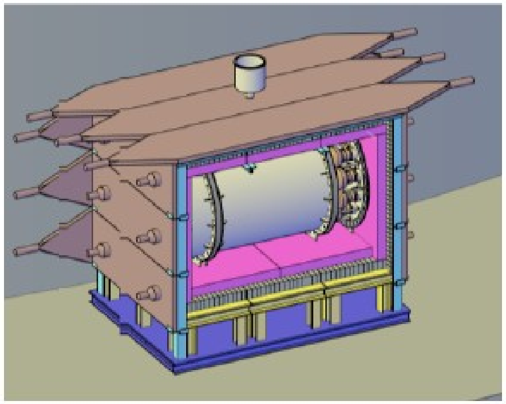
Neutrino-4: Gd-LS detector at 6-12m from SM-3, Russia

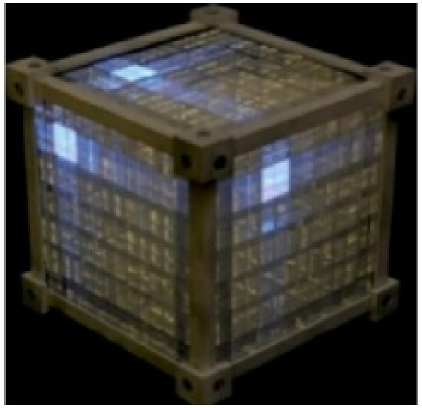
NEOS: Gd-LS detector at ~30m from Hanbit, Korea

NuLAT: Li-loaded plastic scintillator cubes





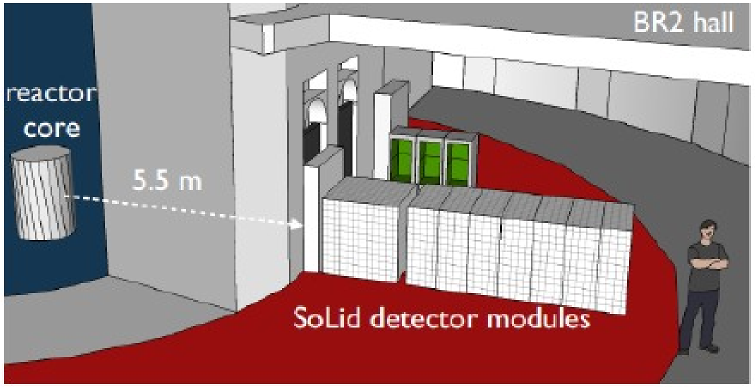


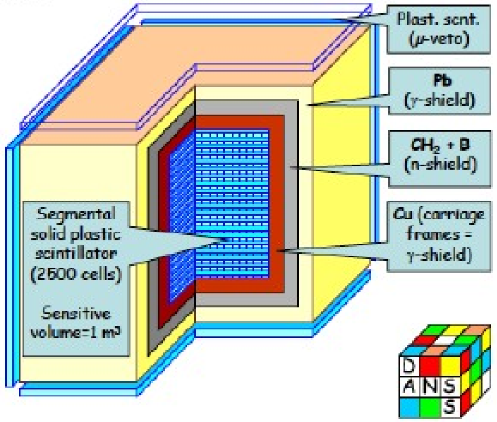


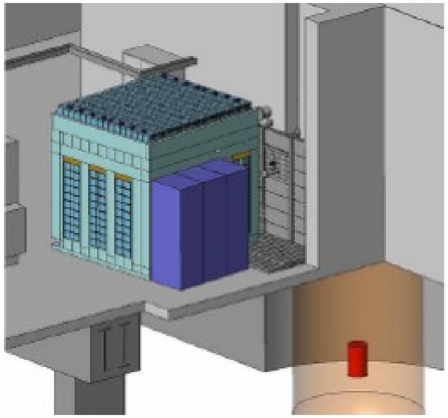
SoLid/CHANDLER: segmented composite scintillator cubes at 5.5m from BR2, Belgium

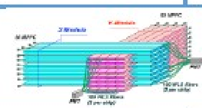
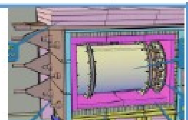
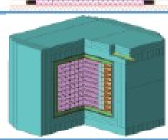
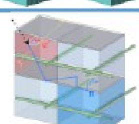
DANSS: Segmented plastic scintillator at ~10m from KNPP, Russia

PROSPECT: Segmented ^{6}Li liquid scintillator at 7-12m from HFIR, US





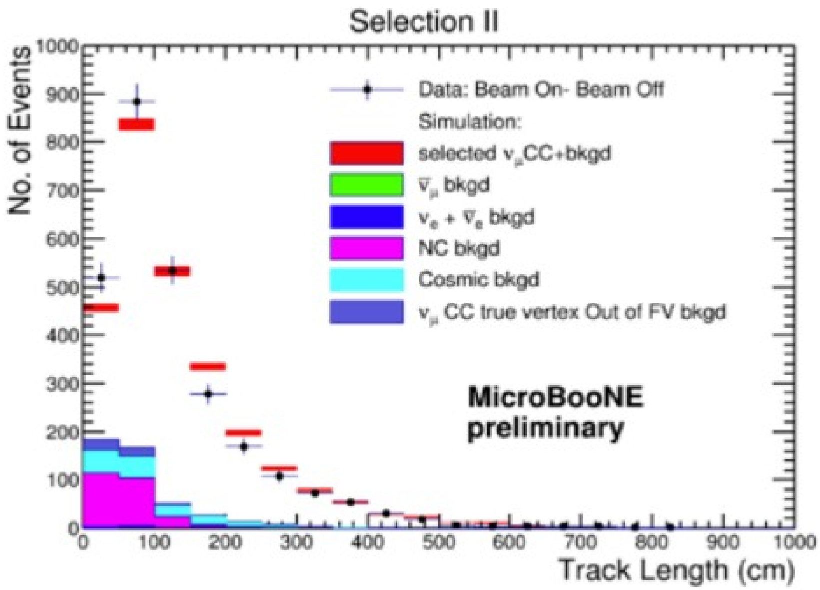


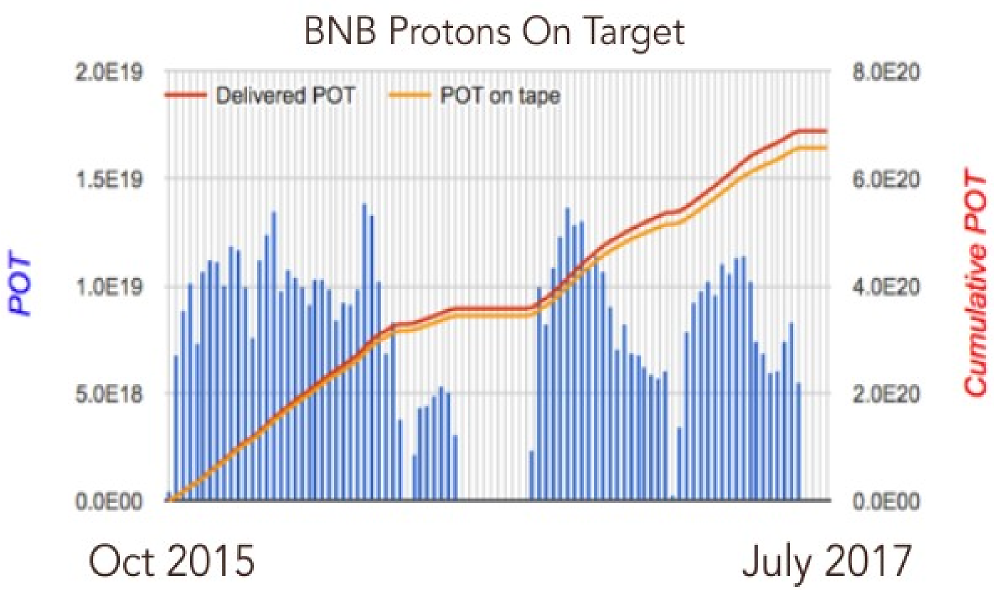
Experiment		Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia)		3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea)		2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA)		40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia)		100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA)		85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US)		72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA)		72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France)		57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

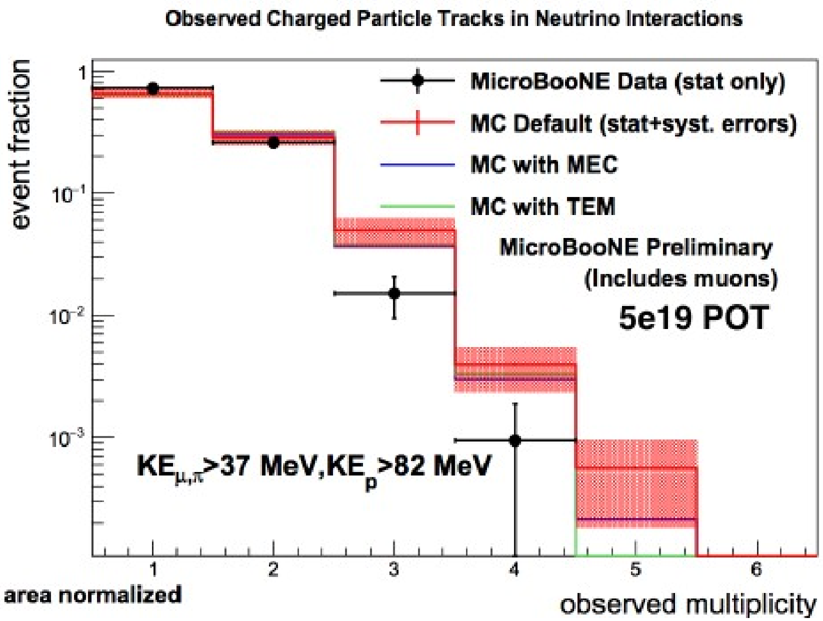
N. Bowden AAP 2016

Physics with tracks

- CC-inclusive measurement close to completion.
- In parallel studying the multiplicity of charged tracks – important for understanding nuclear models and energy reconstruction.

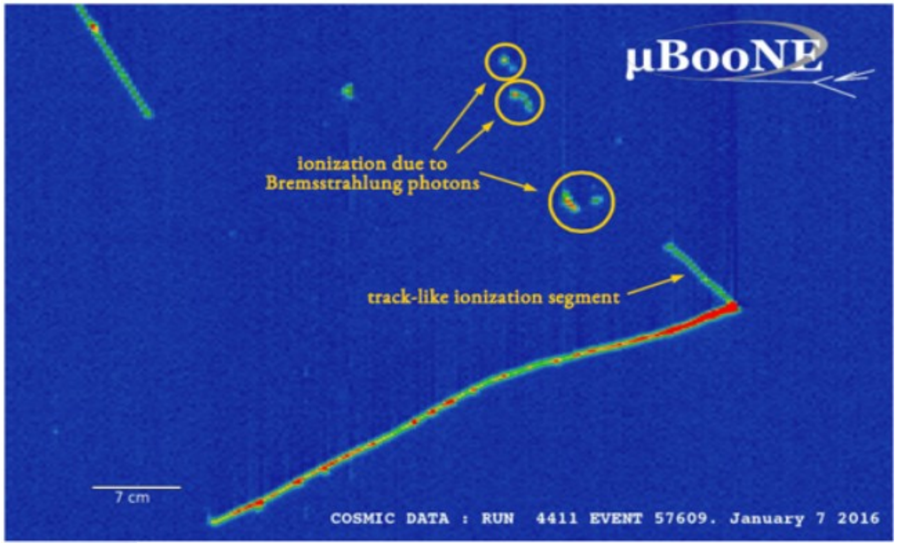


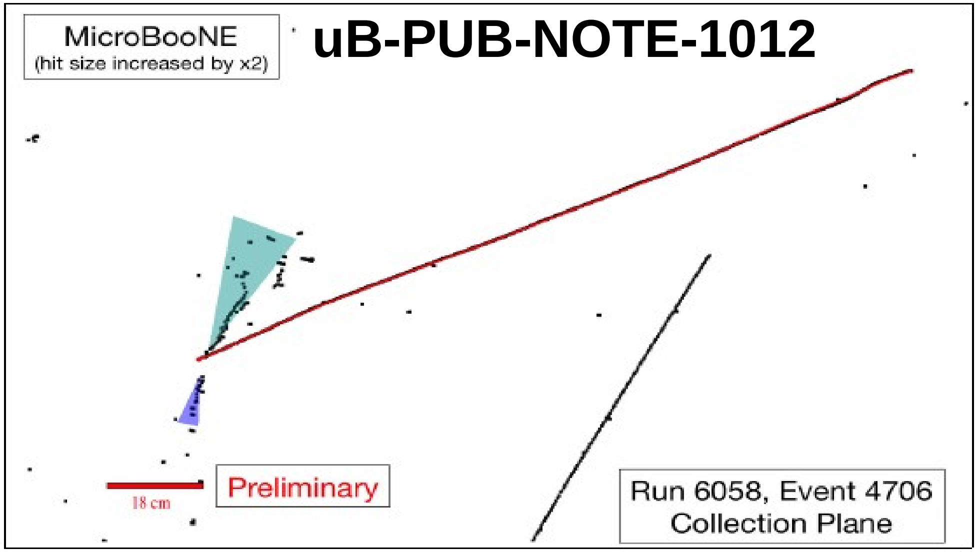


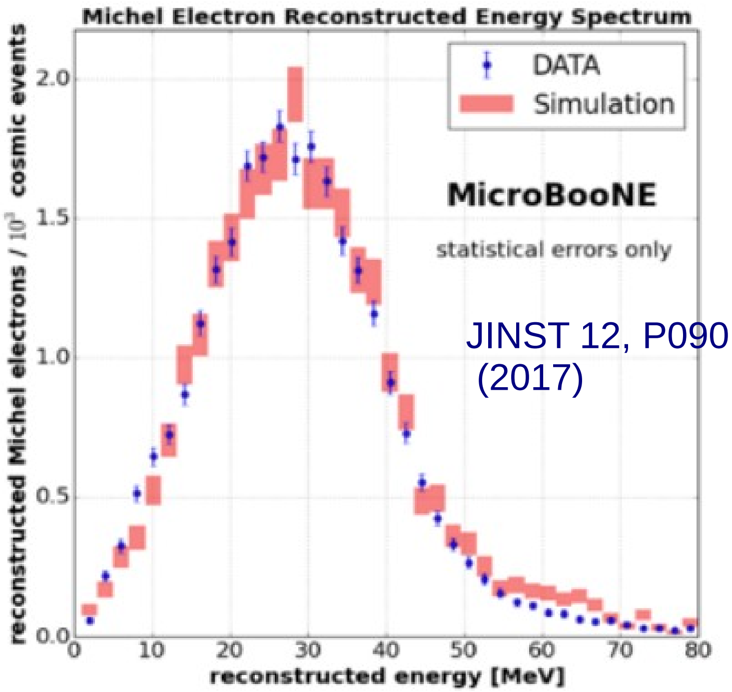


Physics with electrons and showers.

- Michel electrons are an excellent calibration source.
- Allows us to check that our modelling of EM processes is working well.
- Next step – π^o from neutrino interactions.
  - A great sample to understand you EM shower reconstruction in energy, angles etc...



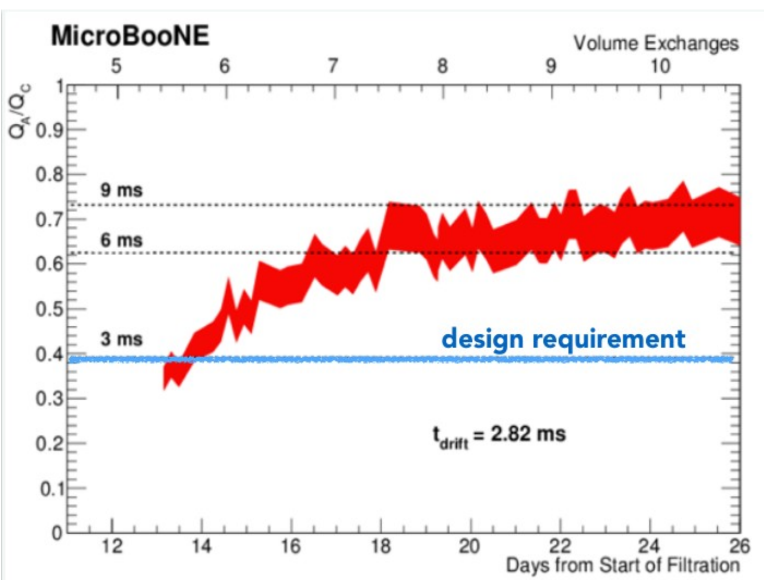


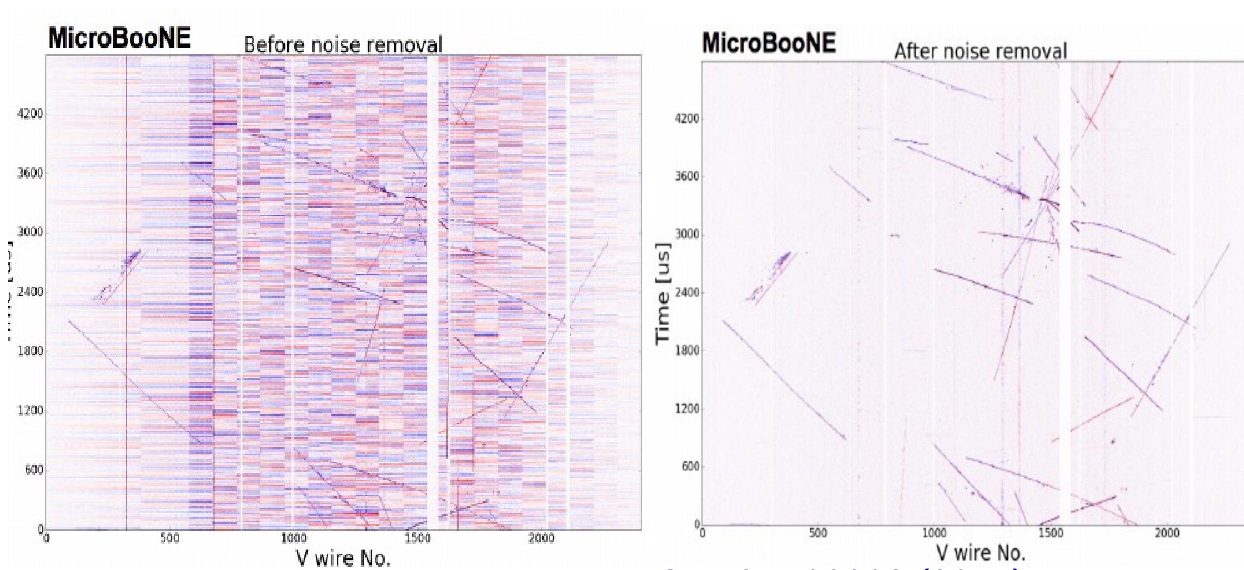


JINST 12, P09014 (2017)

Developing LArTPCs with MicroBooNE

- Extremely high purity obtained.
- Constructed CRT – important for cosmic backgrounds (and independent efficiencies).
- Understanding noise and signal formation in LArTPCs.





JINST 12, P08003 (2017)