EV-SCALE STERILE NEUTRINOS AT LENUSTORM

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ESS neutrino Super Beam plus

ROMA TRE UNIVERSITÀ DEGLI STUDI

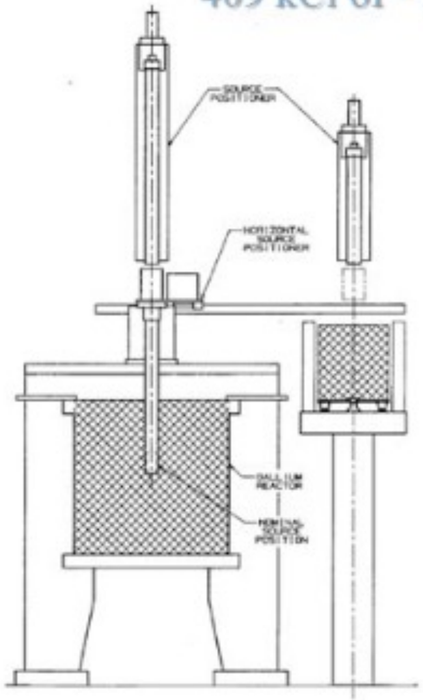
WP5 in-person meeting
18/05/2023

THE GALLIUM ANOMALY

Gallium Experiment at Gran Sasso

GALLEX

INTERNATIONAL
SOLAR NEUTRINO RESEARCH
COLLABORATION



SAGE Sources: 680 kCi of ^{51}Cr
409 kCi of ^{37}Ar

GALLEX and SAGE solar neutrino experiments have measured the solar neutrino flux using the radiochemical reaction

$$\nu_e + {}^{71}\mathrm{Ga} \to e^- + {}^{71}\mathrm{Ge}.$$

THE GALLIUM ANOMALY

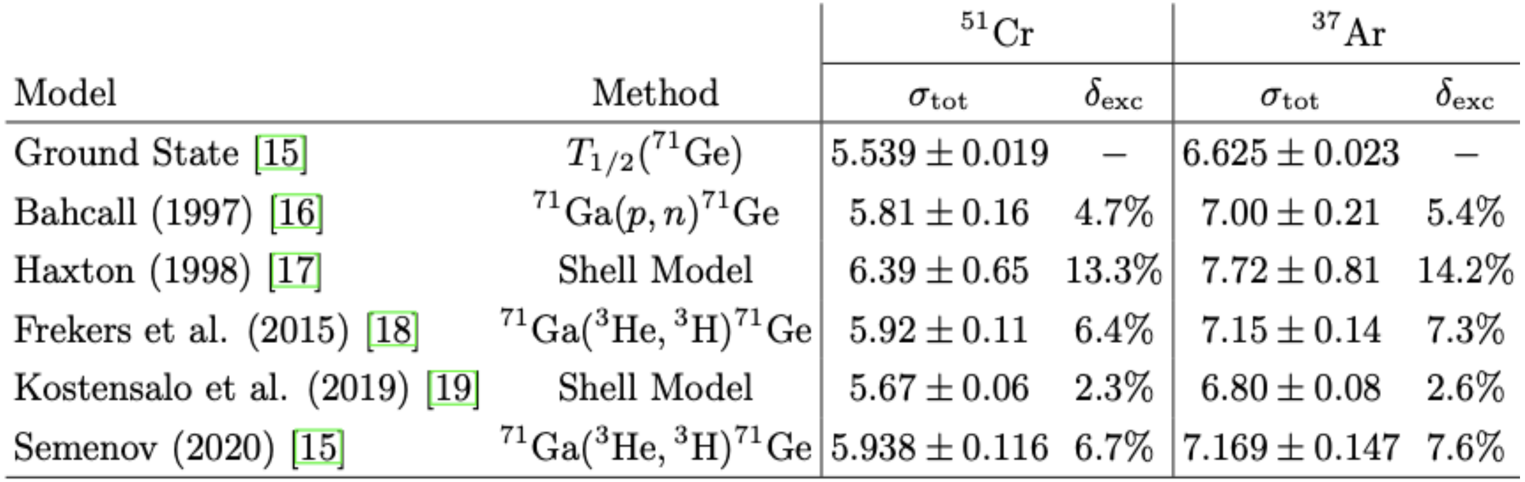
The calibration of these experiments was performed using Cr and Ar radioactive sources which emitted neutrinos through the following electron capture processese

$$e^- + {}^{51}\text{Cr} \rightarrow {}^{51}\text{V} + \nu_e$$

$$e^- + {}^{37}\text{Ar} \rightarrow {}^{37}\text{Cl} + \nu_e$$

(0.4-0.8 MeV)

WELL KNOWN CROSS-SECTIONS!



Model	Method	^{51}Cr		^{37}Ar	
		σ_{tot}	δ_{exc}	σ_{tot}	δ_{exc}
Ground State [15]	$T_{1/2}(^{71}\text{Ge})$	5.539 ± 0.019	–	6.625 ± 0.023	–
Bahcall (1997) [16]	$^{71}\text{Ga}(p,n)^{71}\text{Ge}$	5.81 ± 0.16	4.7%	7.00 ± 0.21	5.4%
Haxton (1998) [17]	Shell Model	6.39 ± 0.65	13.3%	7.72 ± 0.81	14.2%
Frekers et al. (2015) [18]	$^{71}\text{Ga}(^3\text{He}, ^3\text{H})^{71}\text{Ge}$	5.92 ± 0.11	6.4%	7.15 ± 0.14	7.3%
Kostensalo et al. (2019) [19]	Shell Model	5.67 ± 0.06	2.3%	6.80 ± 0.08	2.6%
Semenov (2020) [15]	$^{71}\text{Ga}(^3\text{He}, ^3\text{H})^{71}\text{Ge}$	5.938 ± 0.116	6.7%	7.169 ± 0.147	7.6%

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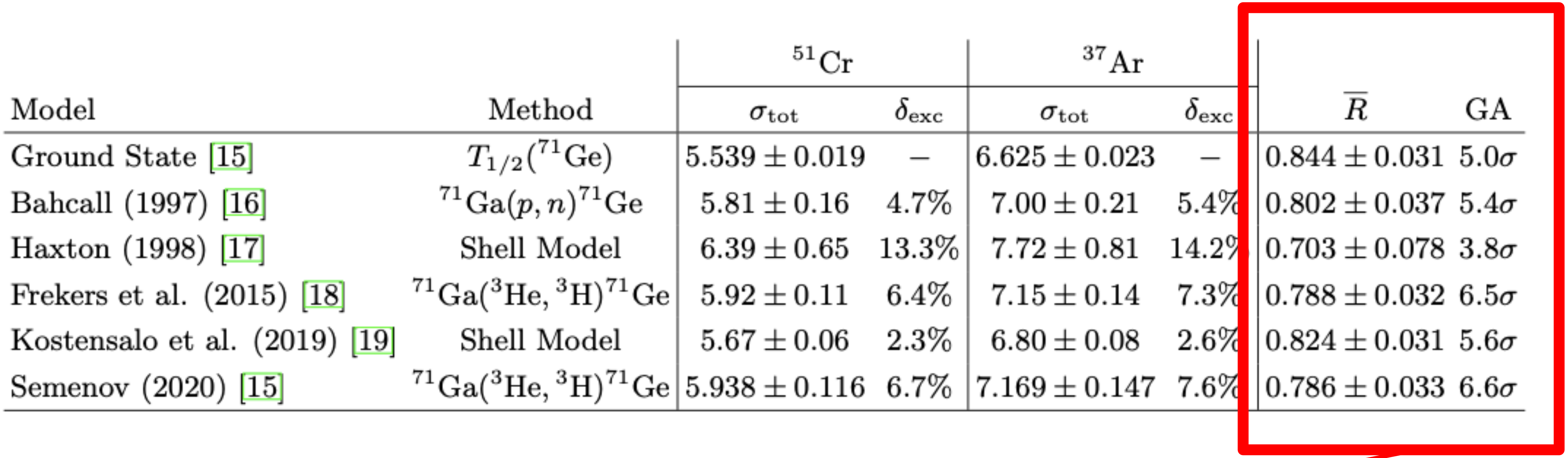
THE GALLIUM ANOMALY

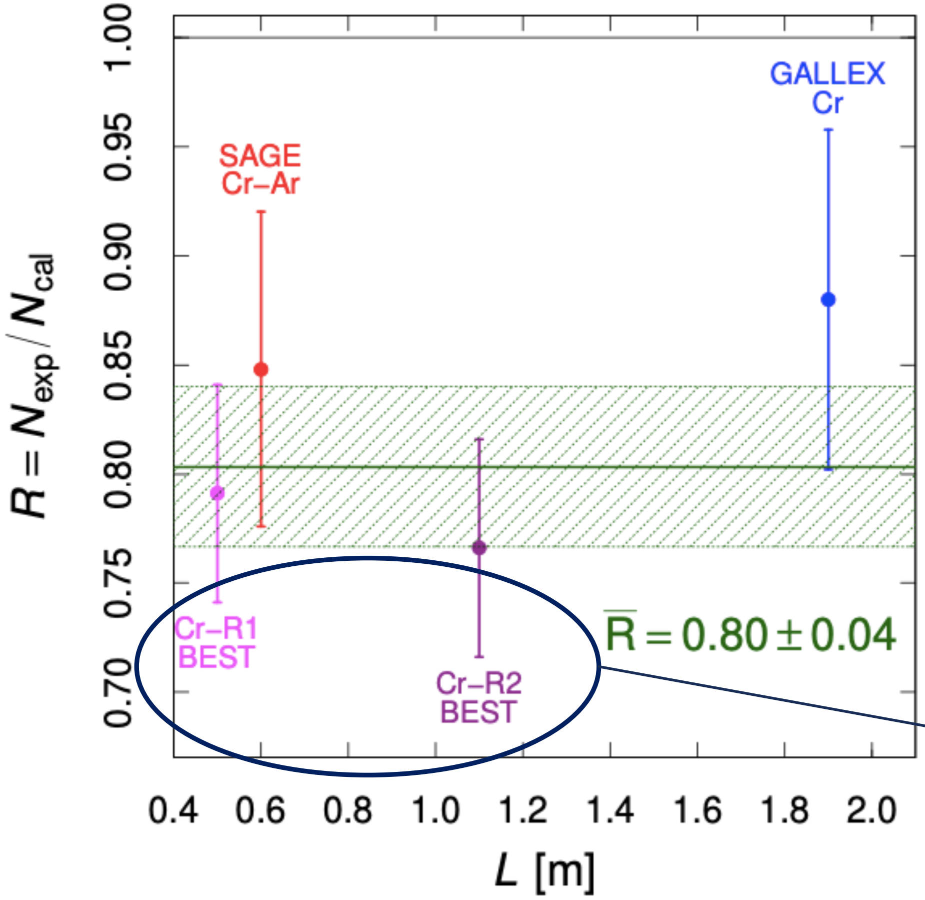


Model	Method	^{51}Cr		^{37}Ar			
		σ_{tot}	δ_{exc}	σ_{tot}	δ_{exc}	$\overline{R}$	GA
Ground State [15]	$T_{1/2}(^{71}\text{Ge})$	5.539 ± 0.019	–	6.625 ± 0.023	–	0.844 ± 0.031	5.0σ
Bahcall (1997) [16]	$^{71}\text{Ga}(p,n)^{71}\text{Ge}$	5.81 ± 0.16	4.7%	7.00 ± 0.21	5.4%	0.802 ± 0.037	5.4σ
Haxton (1998) [17]	Shell Model	6.39 ± 0.65	13.3%	7.72 ± 0.81	14.2%	0.703 ± 0.078	3.8σ
Frekers et al. (2015) [18]	$^{71}\text{Ga}(^{3}\text{He},{}^{3}\text{H})^{71}\text{Ge}$	5.92 ± 0.11	6.4%	7.15 ± 0.14	7.3%	0.788 ± 0.032	6.5σ
Kostensalo et al. (2019) [19]	Shell Model	5.67 ± 0.06	2.3%	6.80 ± 0.08	2.6%	0.824 ± 0.031	5.6σ
Semenov (2020) [15]	$^{71}\text{Ga}(^{3}\text{He},{}^{3}\text{H})^{71}\text{Ge}$	5.938 ± 0.116	6.7%	7.169 ± 0.147	7.6%	0.786 ± 0.033	6.6σ

$$R = \frac{N_{obs}}{N_{th}}$$

DEFICIT OF OBSERVED EVENTS DURING GALLIUM EXPERIMENTS CALIBRATION!

THE GALLIUM ANOMALY

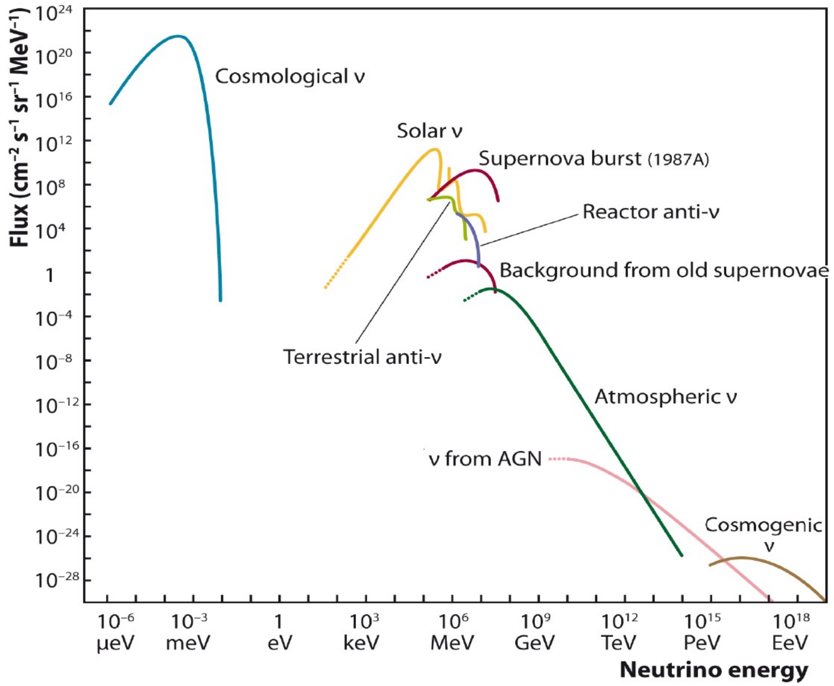


OSCILLATIONS AT VERY SHORT BASELINE?

More recent observations at the BEST experiment (2019)

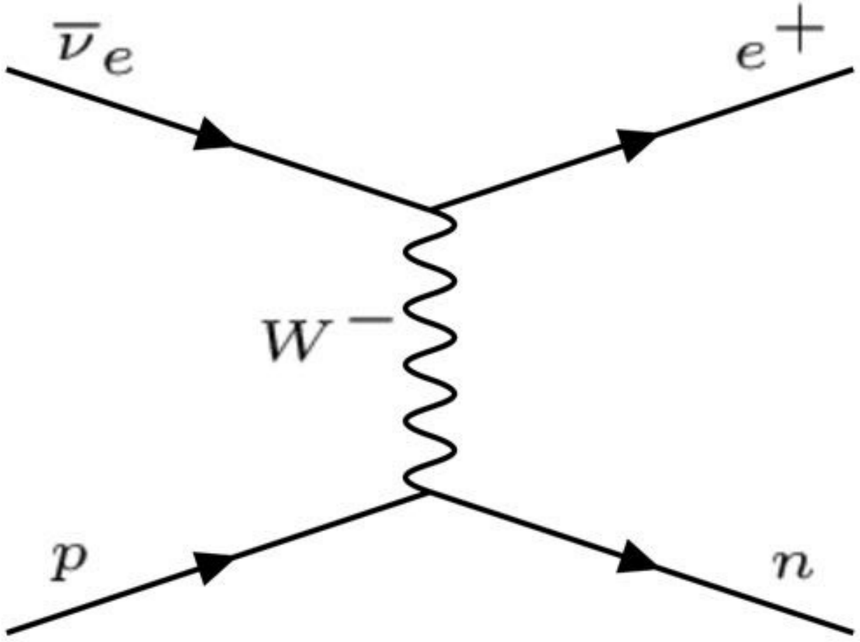
THE REACTOR ANOMALY

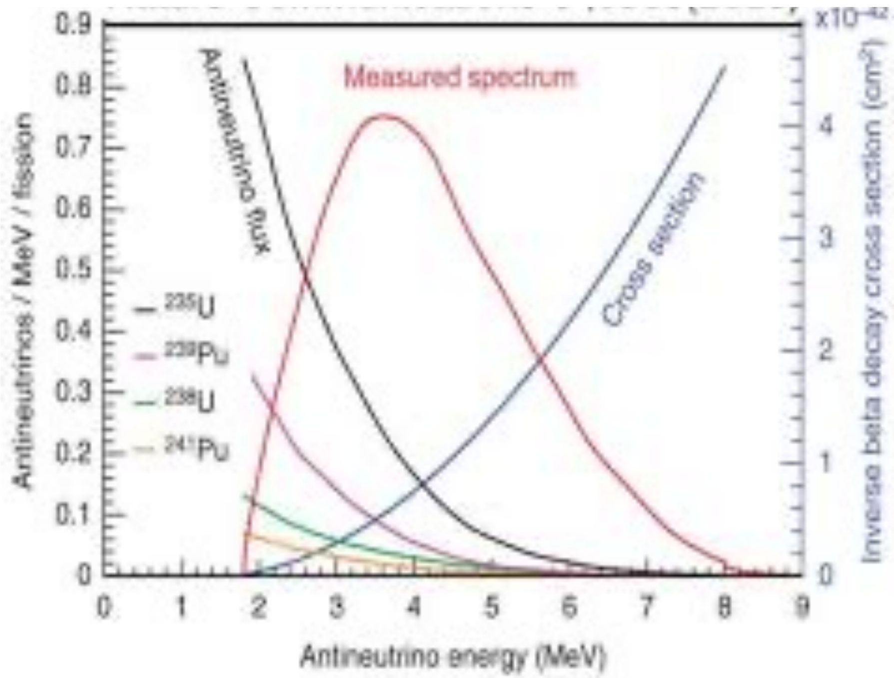
Reactor experiments look at electron antienutrinos produced at reactors. Such experiments have been builts since 1980s due to the high flux of reactor neutrinos which can be observed



THE REACTOR ANOMALY

Reactor neutrinos are usually observed through an inverse beta decay reaction in water detectors





THE REACTOR ANOMALY

Reactor flux predictions and total cross sections are complicated to compute!

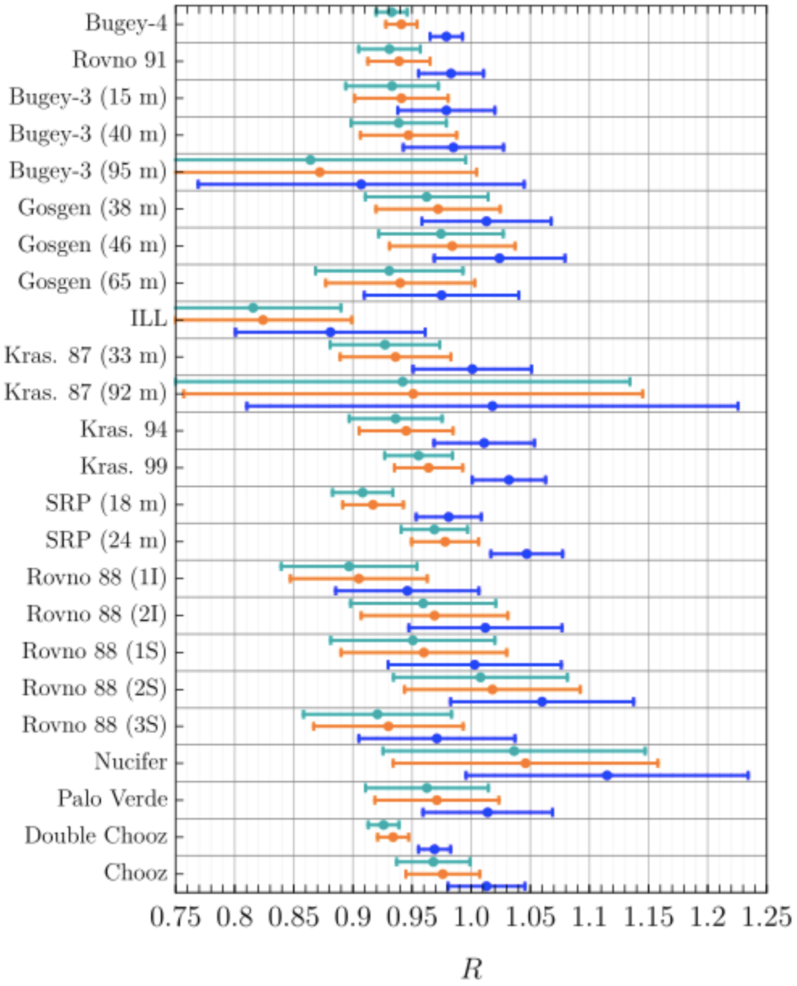
$$\sigma_{\mathrm{AI}}^{235} = (6.17 \pm 0.13) \times 10^{-43}\ \mathrm{cm}^2/\mathrm{fission}$$
$$\sigma_{\mathrm{AI}}^{238} = (9.94 \pm 1.09) \times 10^{-43}\ \mathrm{cm}^2/\mathrm{fission}$$
$$\sigma_{\mathrm{AI}}^{239} = (4.32 \pm 0.11) \times 10^{-43}\ \mathrm{cm}^2/\mathrm{fission}$$
$$\sigma_{\mathrm{AI}}^{241} = (6.10 \pm 0.13) \times 10^{-43}\ \mathrm{cm}^2/\mathrm{fission}$$

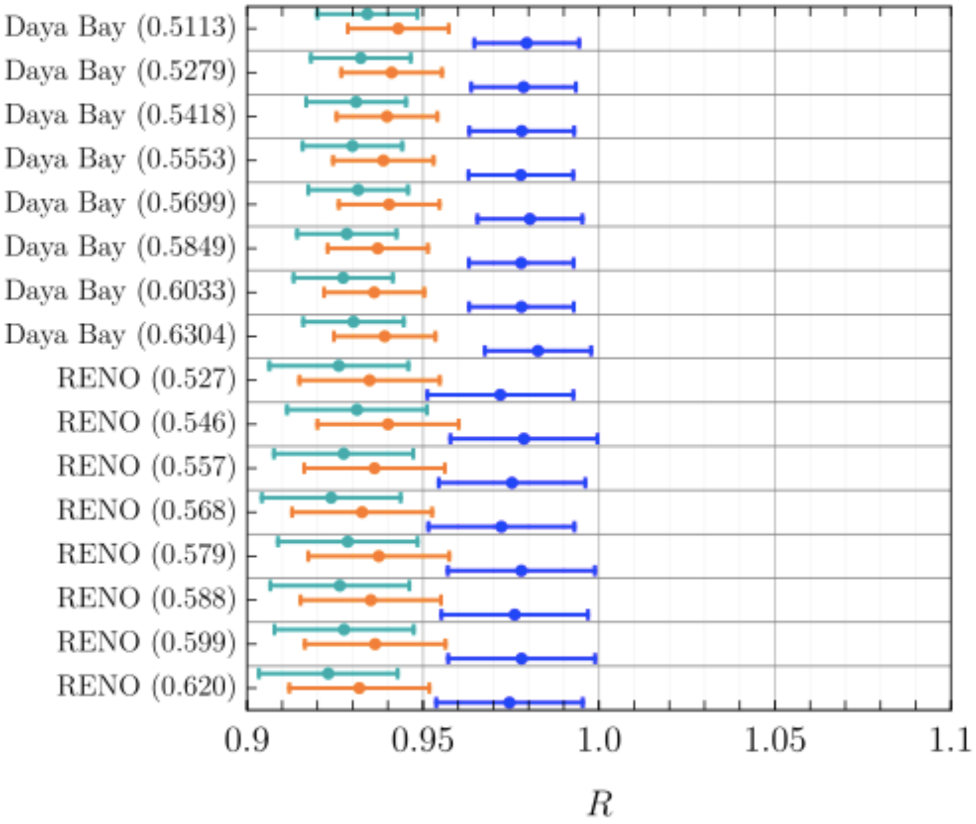
$$\sigma_{\mathrm{HM}}^{235} = (6.60 \pm 0.14) \times 10^{-43}\ \mathrm{cm}^2/\mathrm{fission}$$
$$\sigma_{\mathrm{HM}}^{238} = (10.00 \pm 1.12) \times 10^{-43}\ \mathrm{cm}^2/\mathrm{fission}$$
$$\sigma_{\mathrm{HM}}^{239} = (4.33 \pm 0.11) \times 10^{-43}\ \mathrm{cm}^2/\mathrm{fission}$$
$$\sigma_{\mathrm{HM}}^{241} = (6.01 \pm 0.13) \times 10^{-43}\ \mathrm{cm}^2/\mathrm{fission}$$

$$\sigma_{\mathrm{HKSS}}^{235} = (6.67 \pm 0.15) \times 10^{-43}\ \mathrm{cm}^2/\mathrm{fission}$$
$$\sigma_{\mathrm{HKSS}}^{238} = (10.08 \pm 1.14) \times 10^{-43}\ \mathrm{cm}^2/\mathrm{fission}$$
$$\sigma_{\mathrm{HKSS}}^{239} = (4.37 \pm 0.12) \times 10^{-43}\ \mathrm{cm}^2/\mathrm{fission}$$
$$\sigma_{\mathrm{HKSS}}^{241} = (6.06 \pm 0.14) \times 10^{-43}\ \mathrm{cm}^2/\mathrm{fission}$$

Biggest discrepancy

THE REACTOR ANOMALY





Deficit of events in antineutrino disappearance in most of reactor experiments!

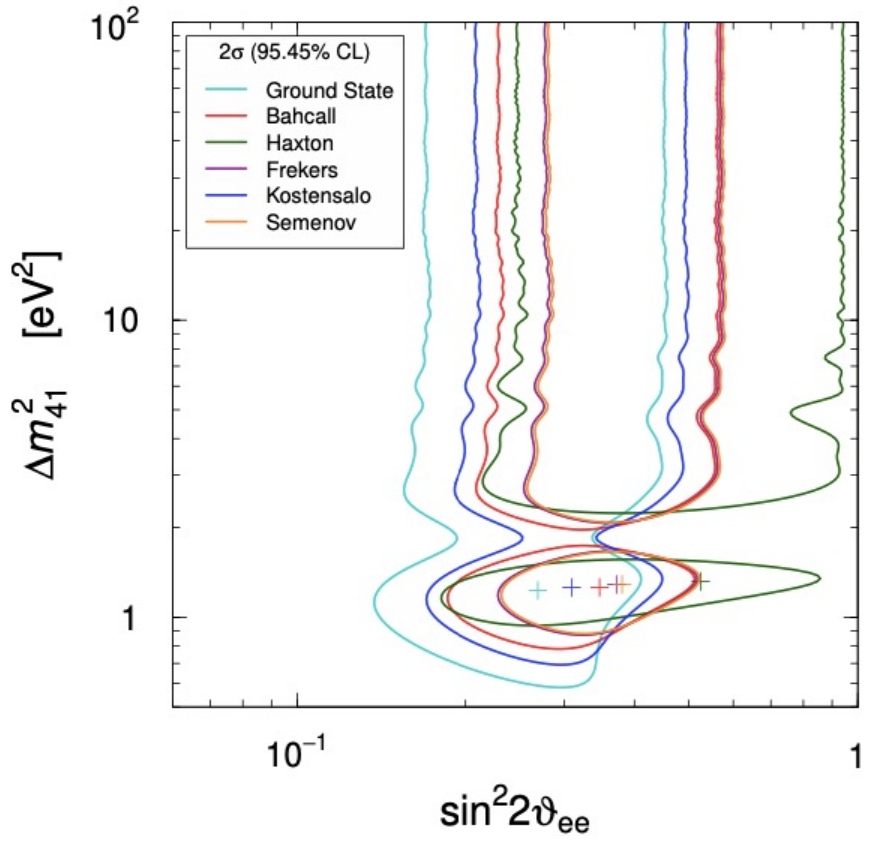
THE STERILE NEUTRINO HYPOTHESIS

Short baselines with a smaller number of events → *Fast oscillations?*

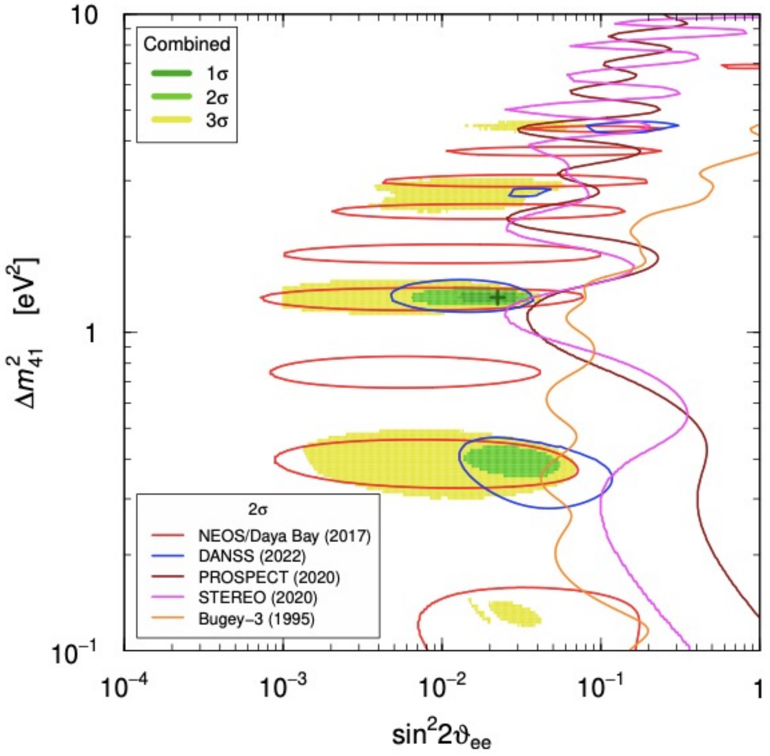
$$P_{ee} \simeq 1 - \sin^2 2\vartheta_{ee} \, \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2(1 - |U_{e4}|^2)$$

THE STERILE NEUTRINO HYPOTHESIS



Gallium



Reactors

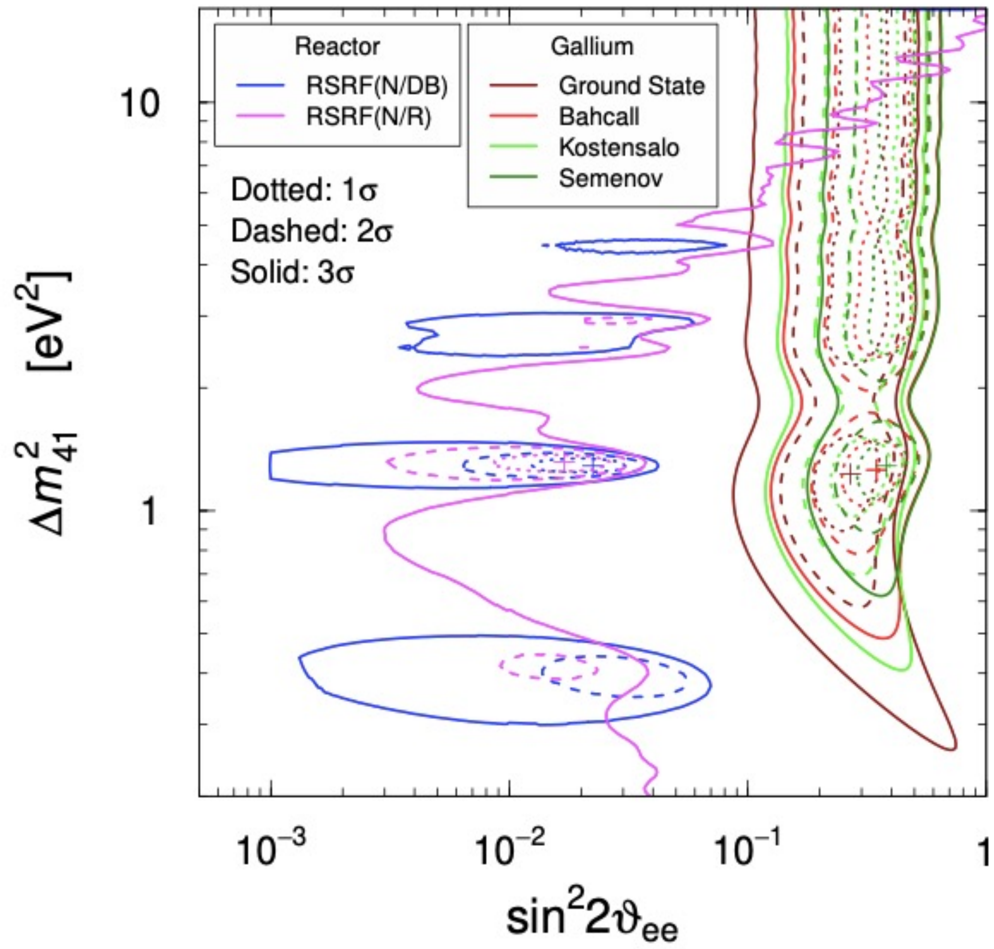
THE STERILE NEUTRINO HYPOTHESIS

Fast oscillations driven by a sterile neutrino ($\Delta m^2_{41} \sim 1\ \mathrm{e}V^2$)

However….

Gallium prefers large mixing angles

Reactor prefer very small mixing angle



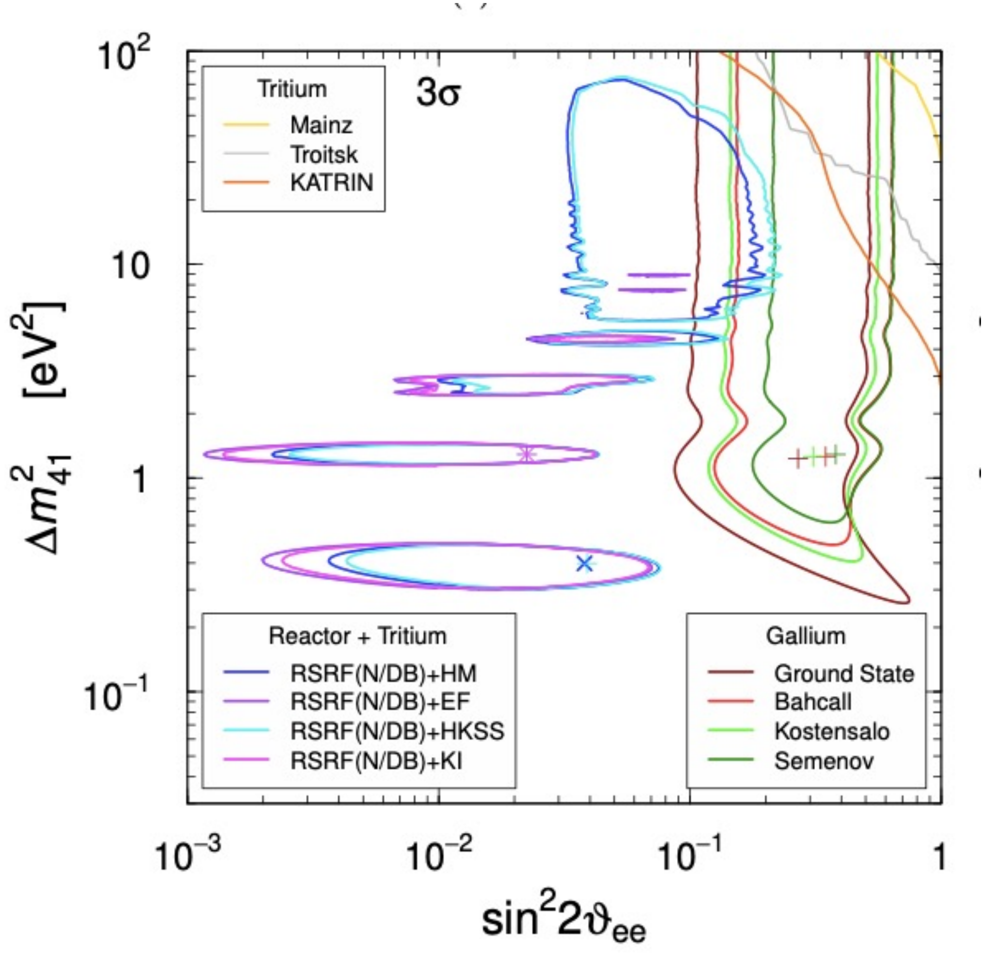
THE STERILE NEUTRINO HYPOTHESIS

First tension!

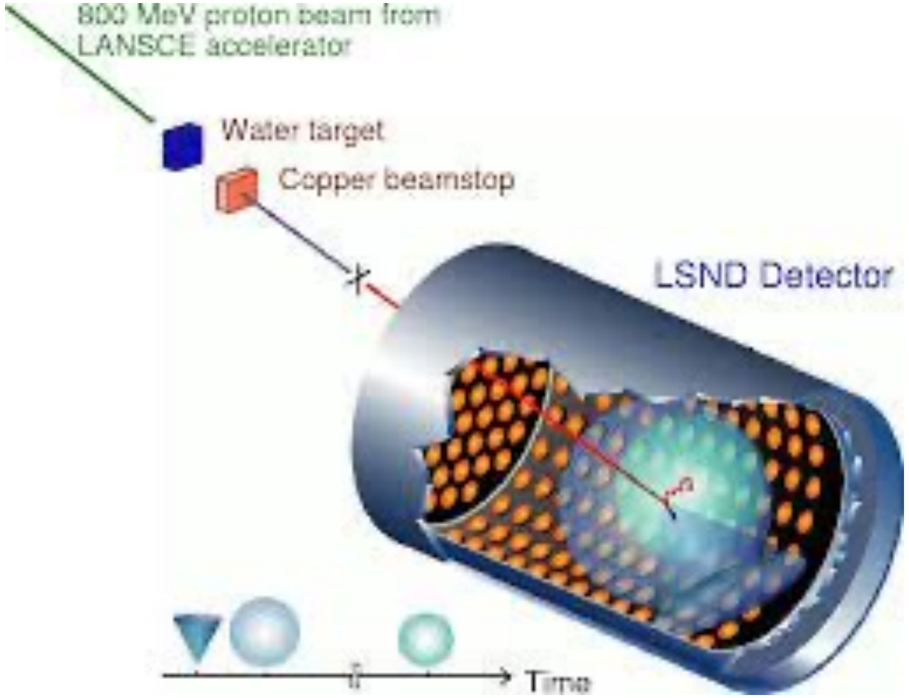
+ Tritium decay spectrum limits (KATRIN)!

$$m_\beta^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2 .$$

$$R_{\rm pred}(E, m_\beta^2, m_4^2, |U_{e4}|^2) = (1 - |U_{e4}|^2)\, R_\beta(E, m_\beta^2) + |U_{e4}|^2\, R_\beta(E, m_4^2) .$$



THE SHORT BASELINE ANOMALY



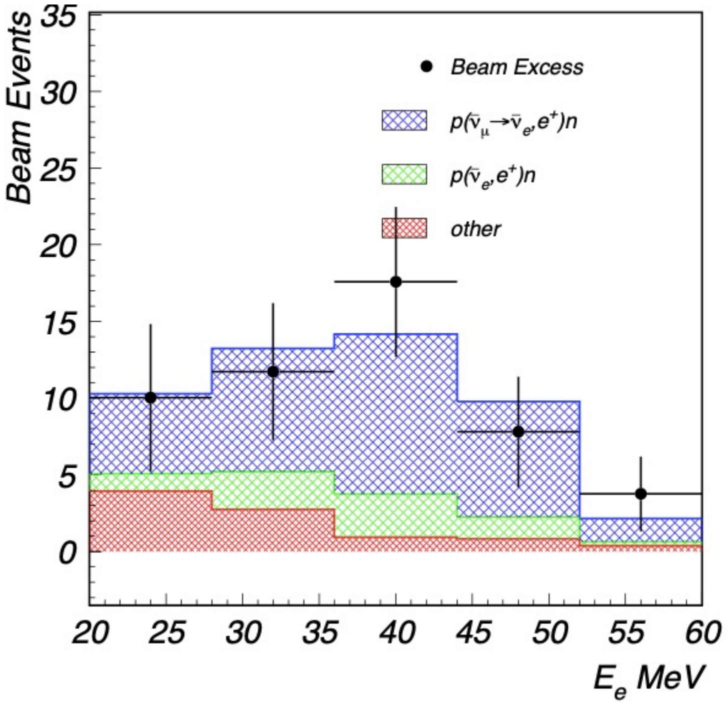
LSND was an experiment looking at 30 MeV neutrinos at 30 meters from the source.

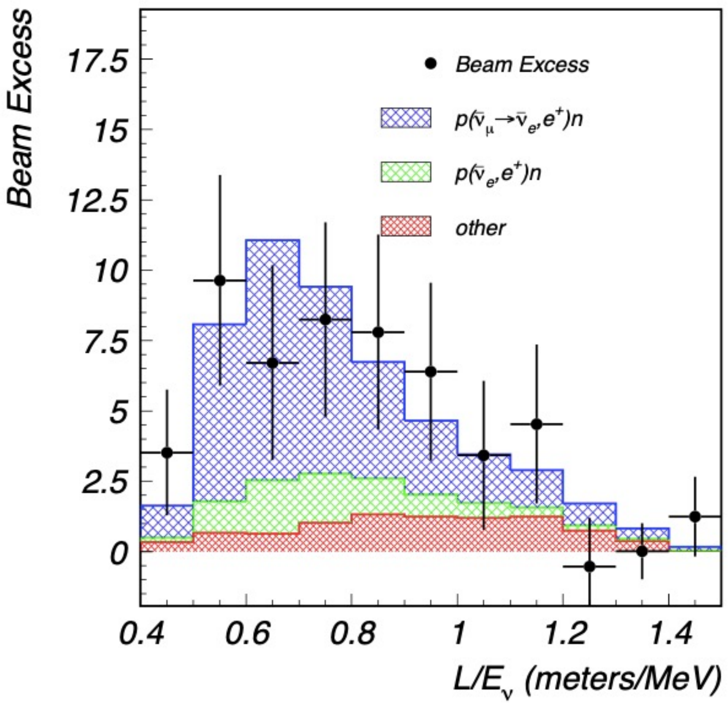
Neutrinos we are interested in are muon antineutrinos from muons at rest

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$

THE SHORT BASELINE ANOMALY





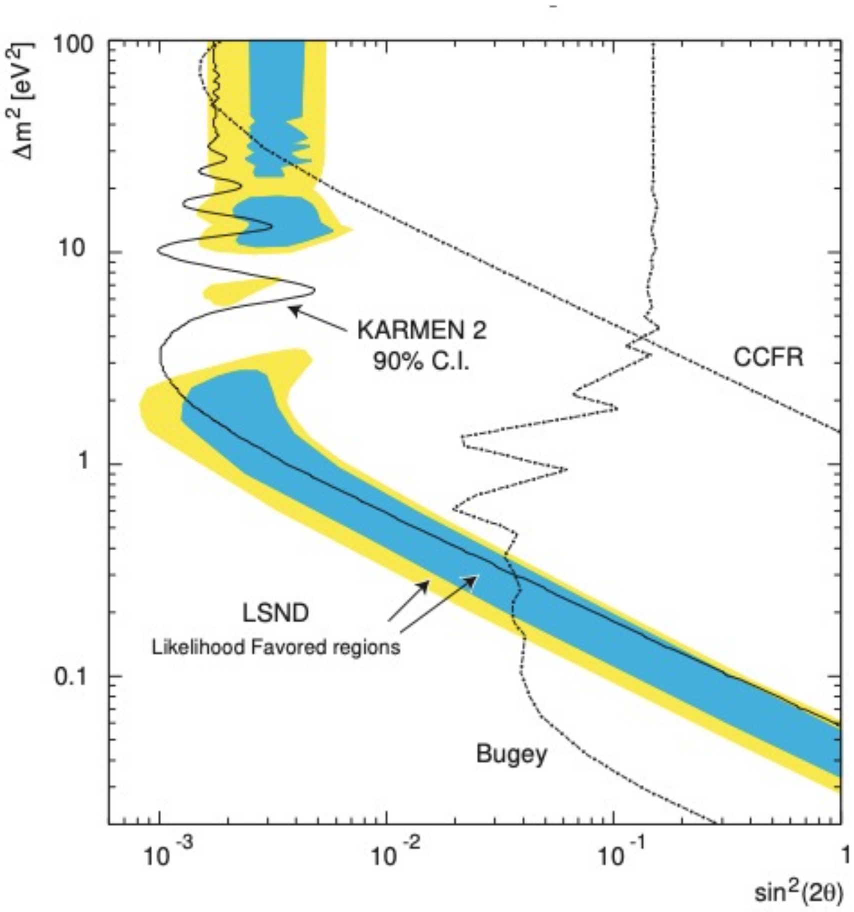
Saw an excess of:
87.9 ± 22.4 ± 6.0 events.

With an oscillation probability of (0.264 ± 0.067 ± 0.045)%.

But….We expect no oscillation!

$$\frac{\Delta m^2_{21}}{4E_\nu} L \ll \frac{\Delta m^2_{31}}{4E_\nu} L \ll 1$$

THE SHORT BASELINE ANOMALY



Again, may be explained with fast oscillation!

$$P_{\alpha\beta}^{\mathrm{SBL}} \approx \sin^2(2\theta_{\alpha\beta})\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

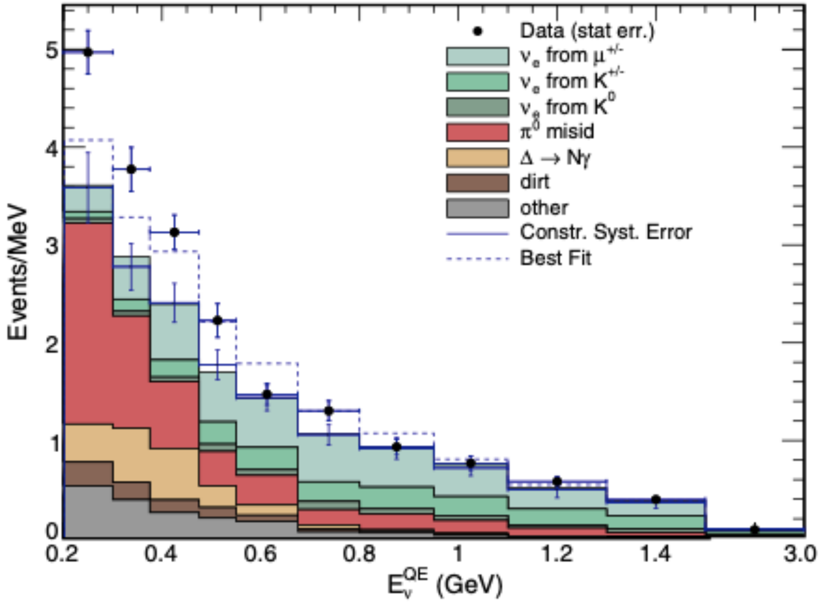
$$\sin^2(2\theta_{\alpha\beta}) = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2$$

Also, KARMEN expriment (L~17m) did not osbserve excess but could not fully exclude LSND allowed regions

THE SHORT BASELINE ANOMALY

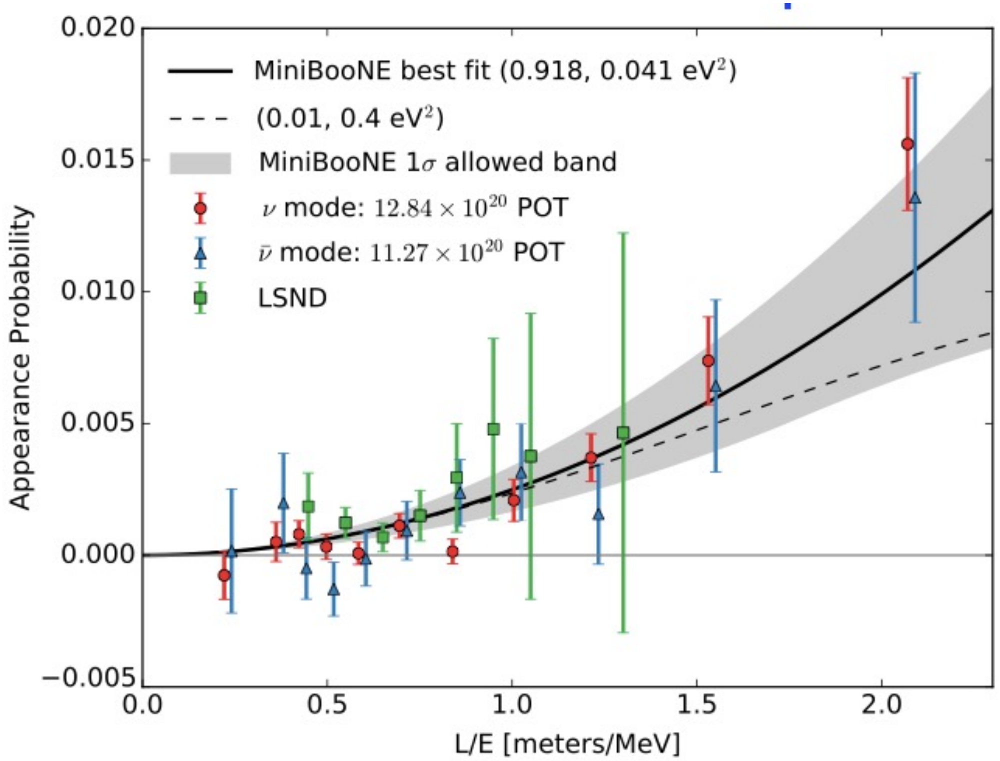
Years later, with a water Cherenkov detector looking at muon neutrinos from accelerator….

MiniBooNE, neutrinos of energy above 500 MeV, at 500 meters

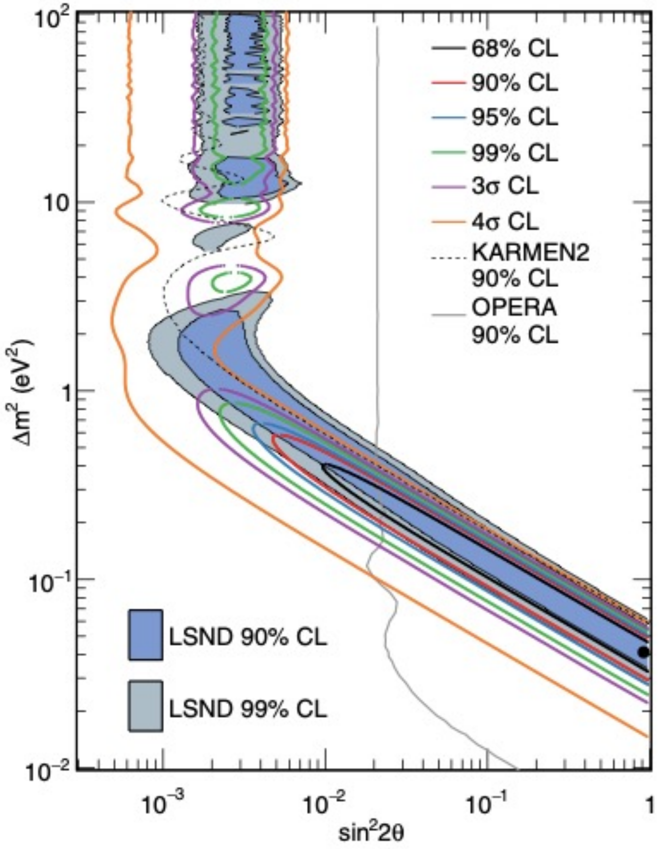


Again, low energy excess!
Fast oscillations here, too?

THE SHORT BASELINE ANOMALY



$\nu_\mu \to \nu_e + \bar{\nu}_\mu \to \bar{\nu}_e$



Compatible!

Up to 6σ anomaly!

End of the story?

1805.12028

THE SHORT BASELINE ANOMALY

LBL experiments observe also the muon neutrino disappearance…

$$P_{\alpha\beta}^{\mathrm{SBL}} \approx \sin^2(2\theta_{\alpha\beta}) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

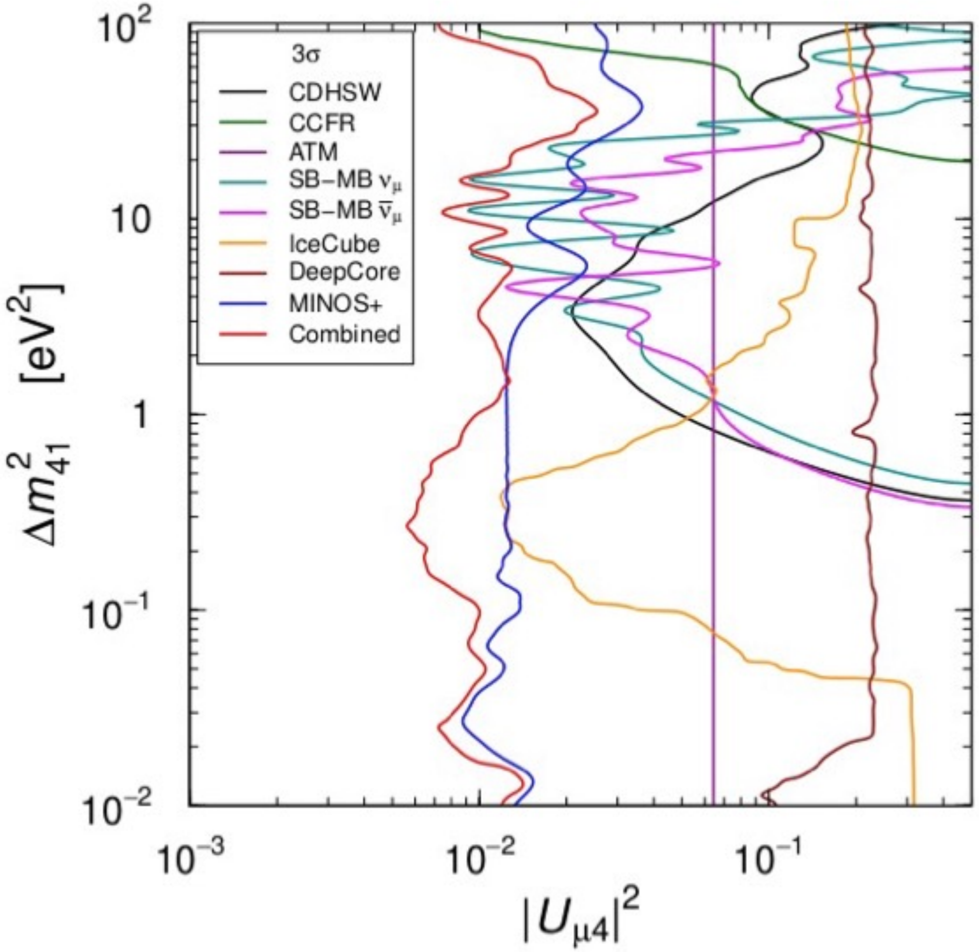
$$\sin^2(2\theta_{\alpha\beta}) = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2$$

$$P_{\alpha\alpha}^{\mathrm{SBL}} \approx 1 - \sin^2(2\theta_{\alpha\alpha}) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

$$\sin^2(2\theta_{\alpha\alpha}) = 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)$$

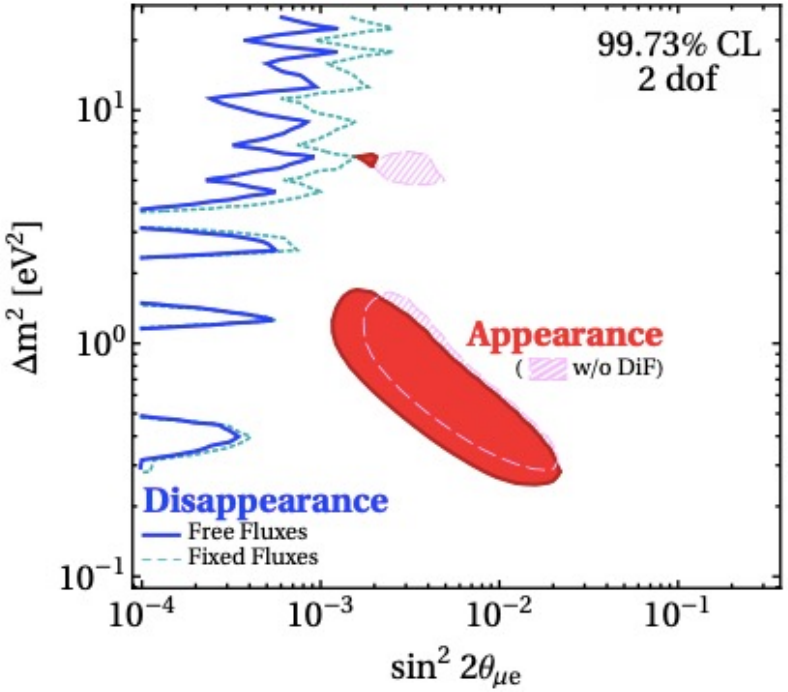
If we observe anomalies in electron appearance, it is mandatory to observe also anomalies in muon disappearance!

THE SHORT BASELINE ANOMALY



2005.12942

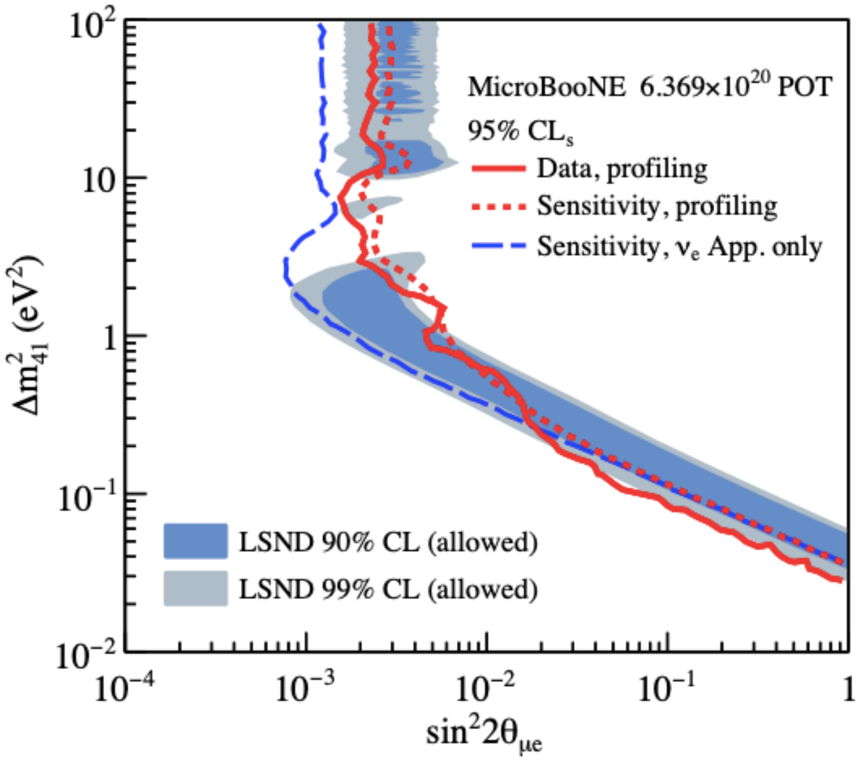
1803.10661

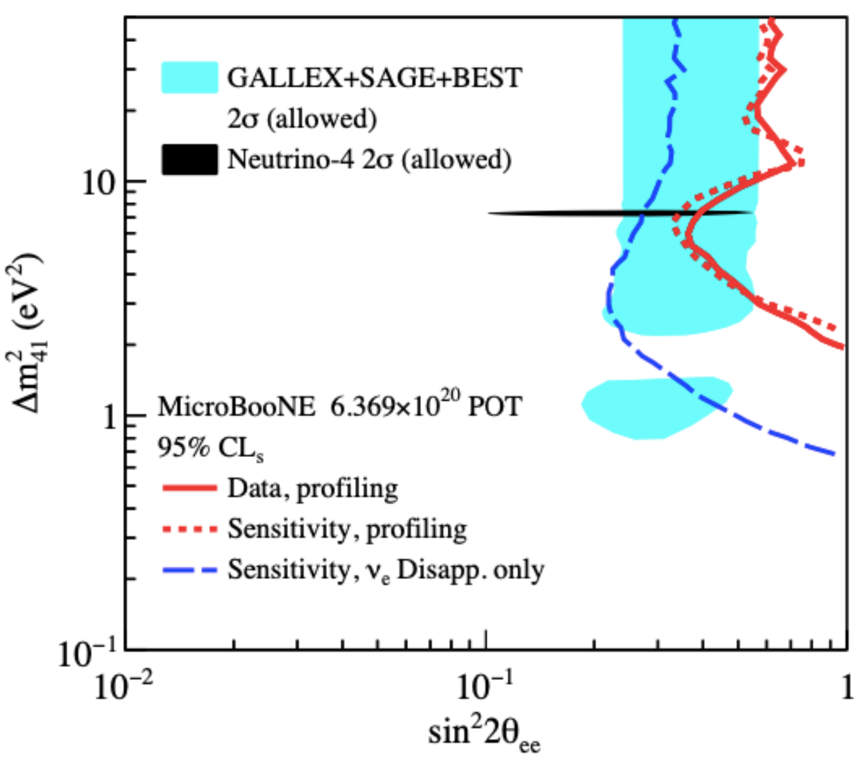


COMBINED!

Second tension!

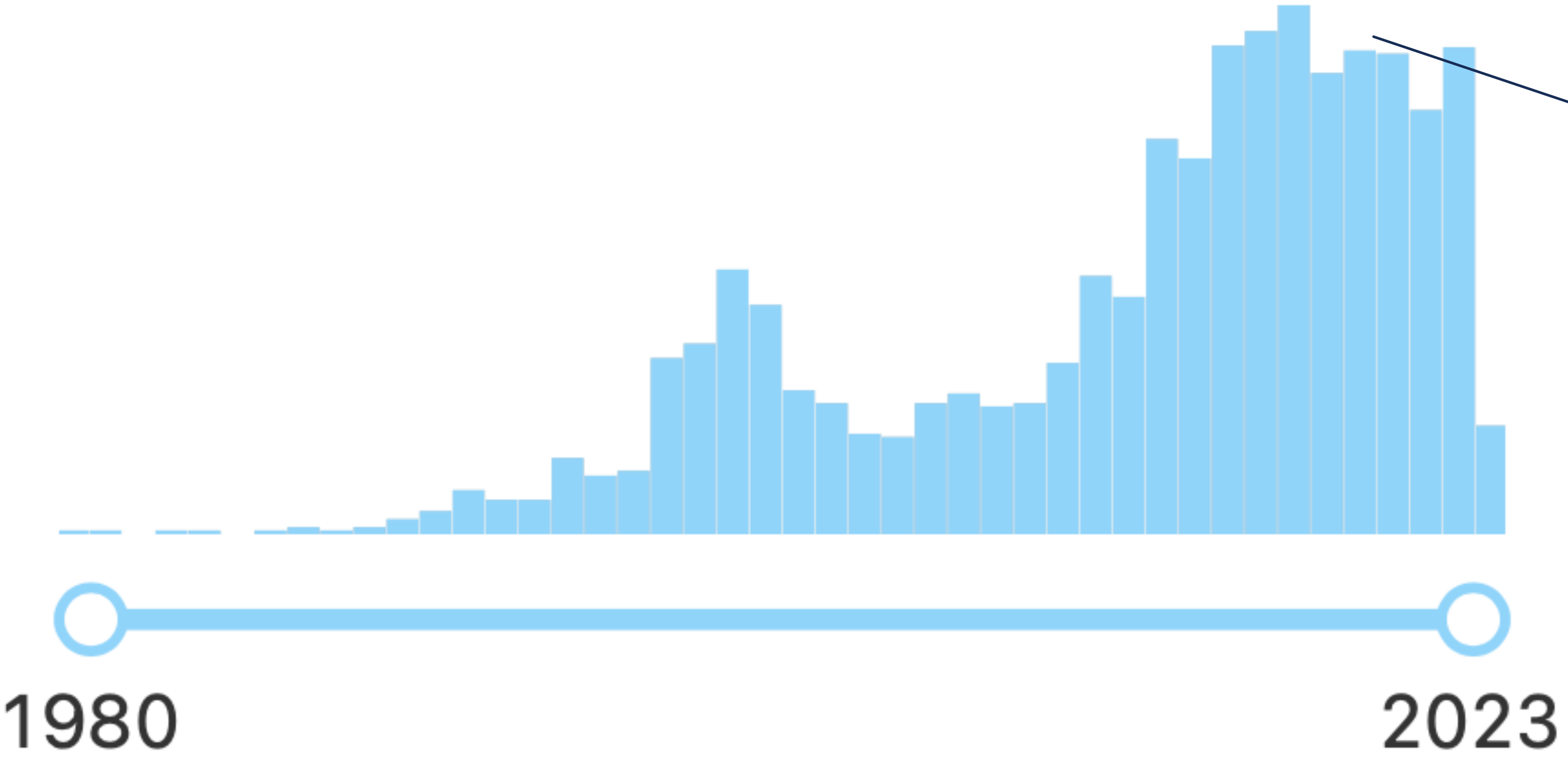
THE SHORT BASELINE ANOMALY





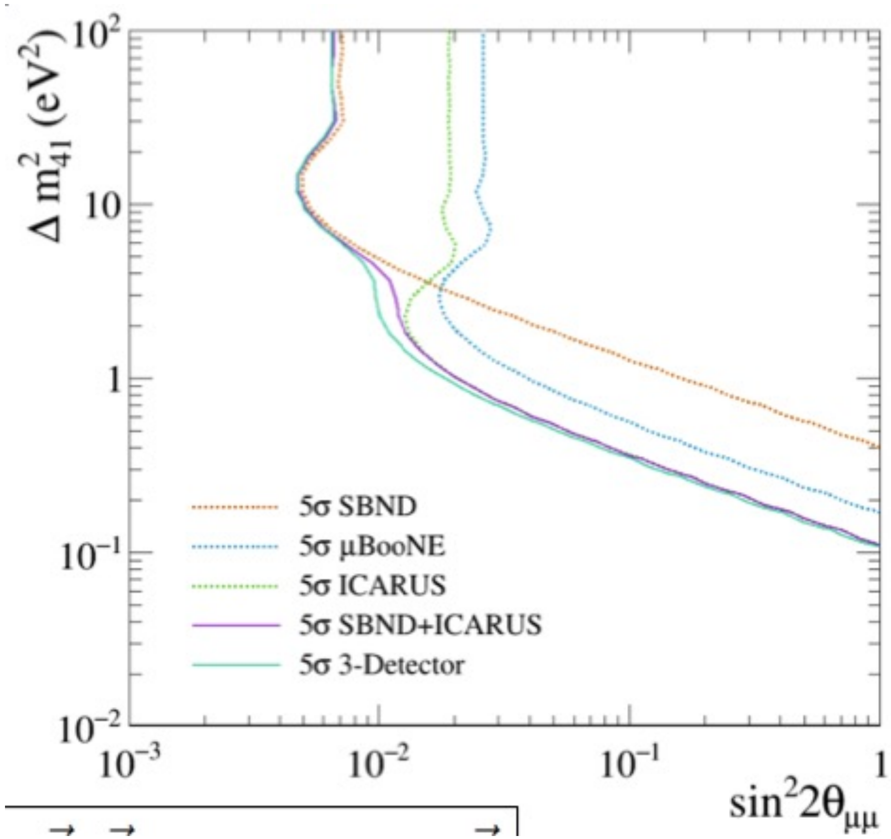
Also, new results from MicroBooNE further reduce the allowed parameter space!

STILL AN HOT TOPIC!



300 papers per year!

FUTURE OF SBL EXPERIMENTS: SBN

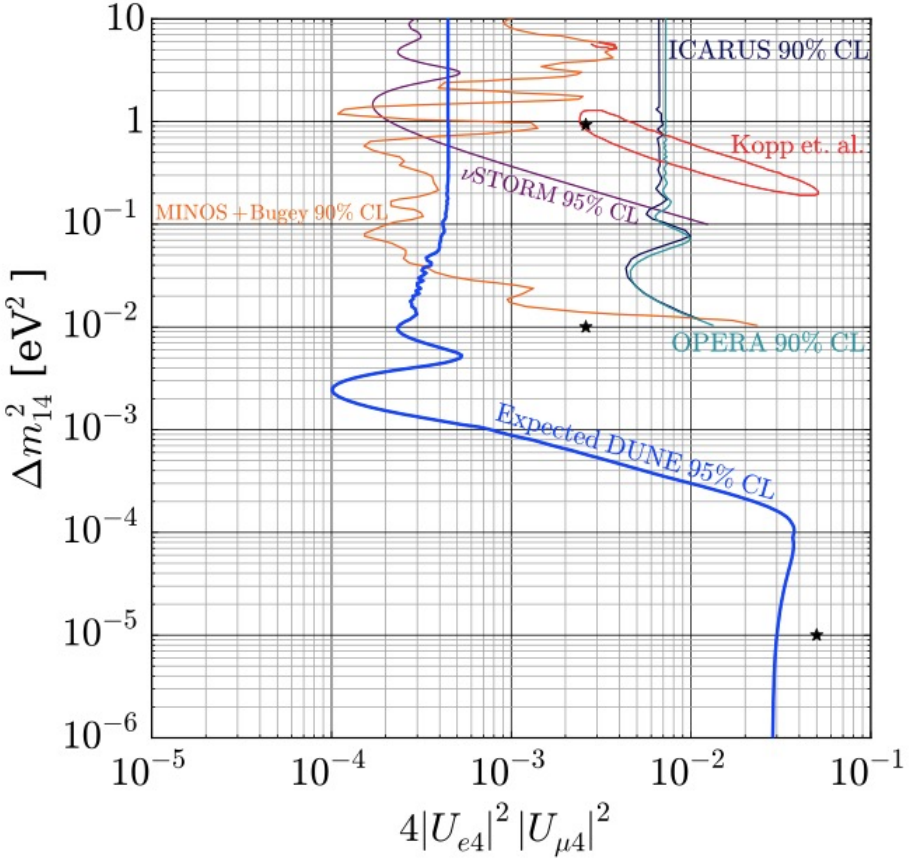


SBN program at Fermilab aims to look at sterile Neutrinos with also muon disappearance with 3 Detectors:

-SBND (Near Detector)
-MicroBooNE (Middle Detector)
-ICARUS (Far Detector)

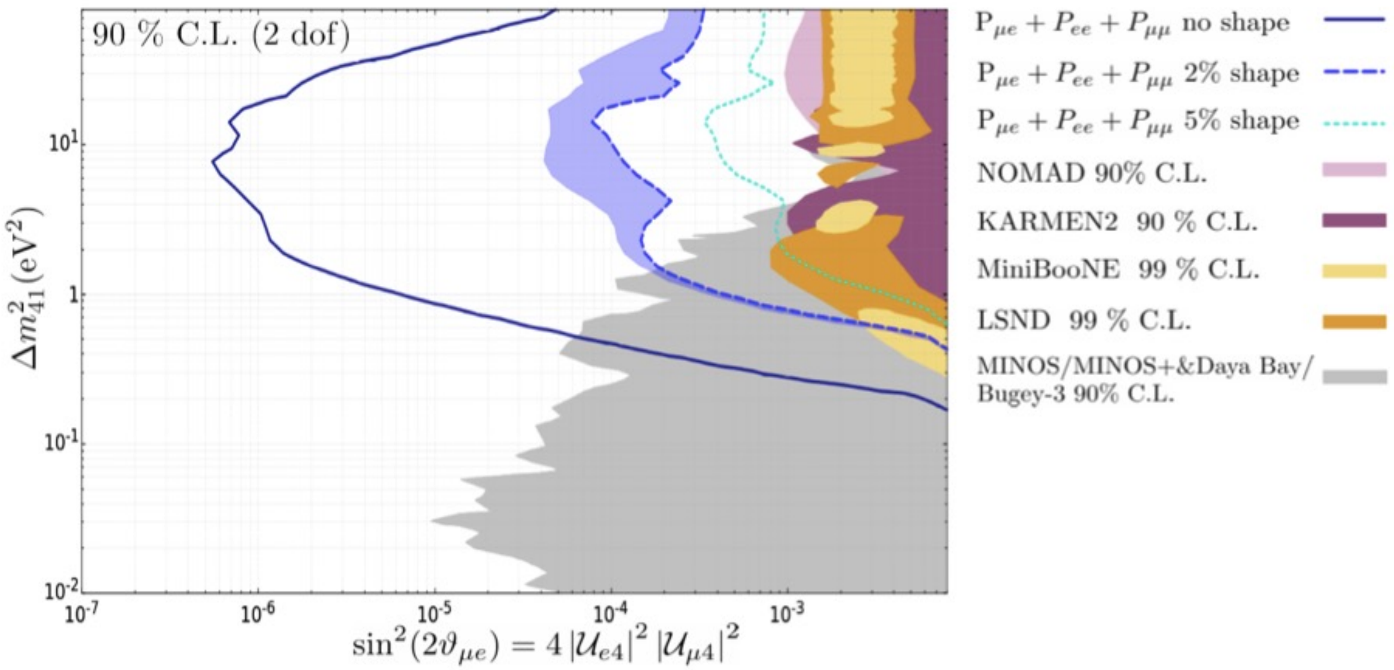
DUNE EXPECTED BOUNDS

1507.03986



Far Detector

2111.05470

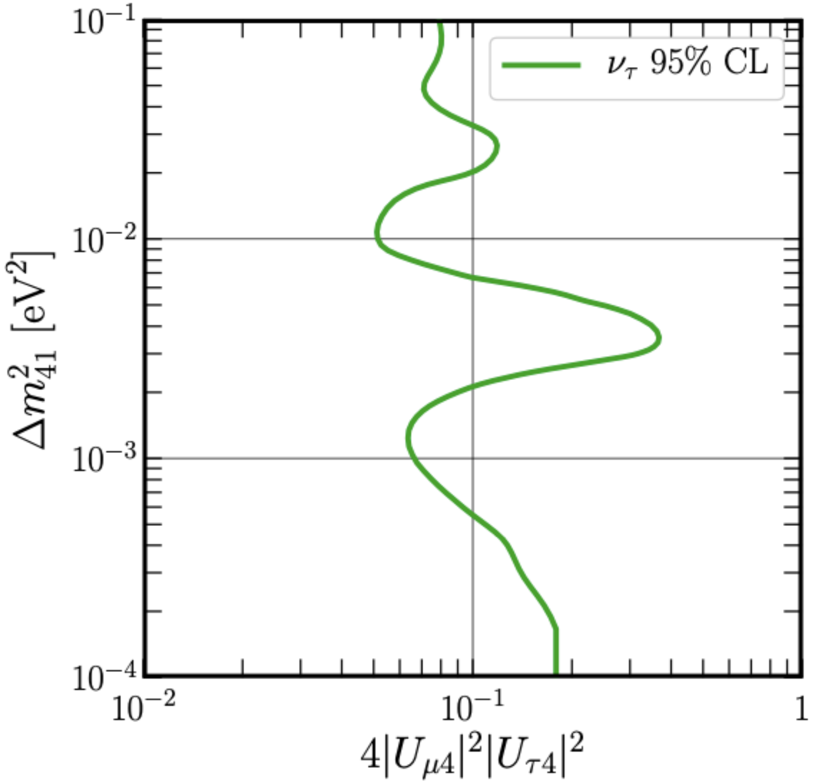


Near Detector

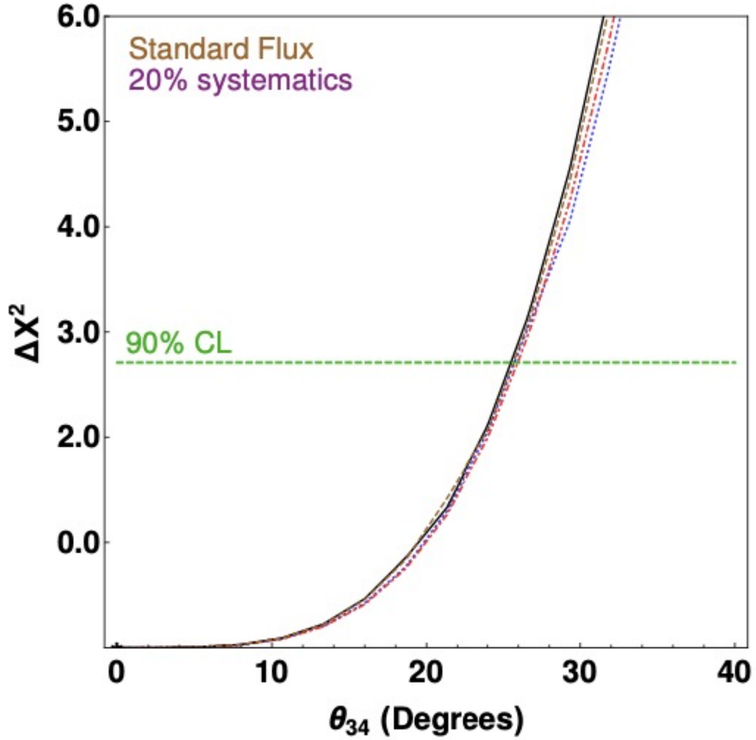
DUNE TAU SEARCHES

With the small tau neutrino sample DUNE should be able to further reduce the parameter space

$$U_{PMNS} = R(\theta_{34})\,R(\theta_{24})\,R(\theta_{23},\delta_2)\,R(\theta_{14})\,R(\theta_{13},\delta_3)\,R(\theta_{12},\delta_1)$$

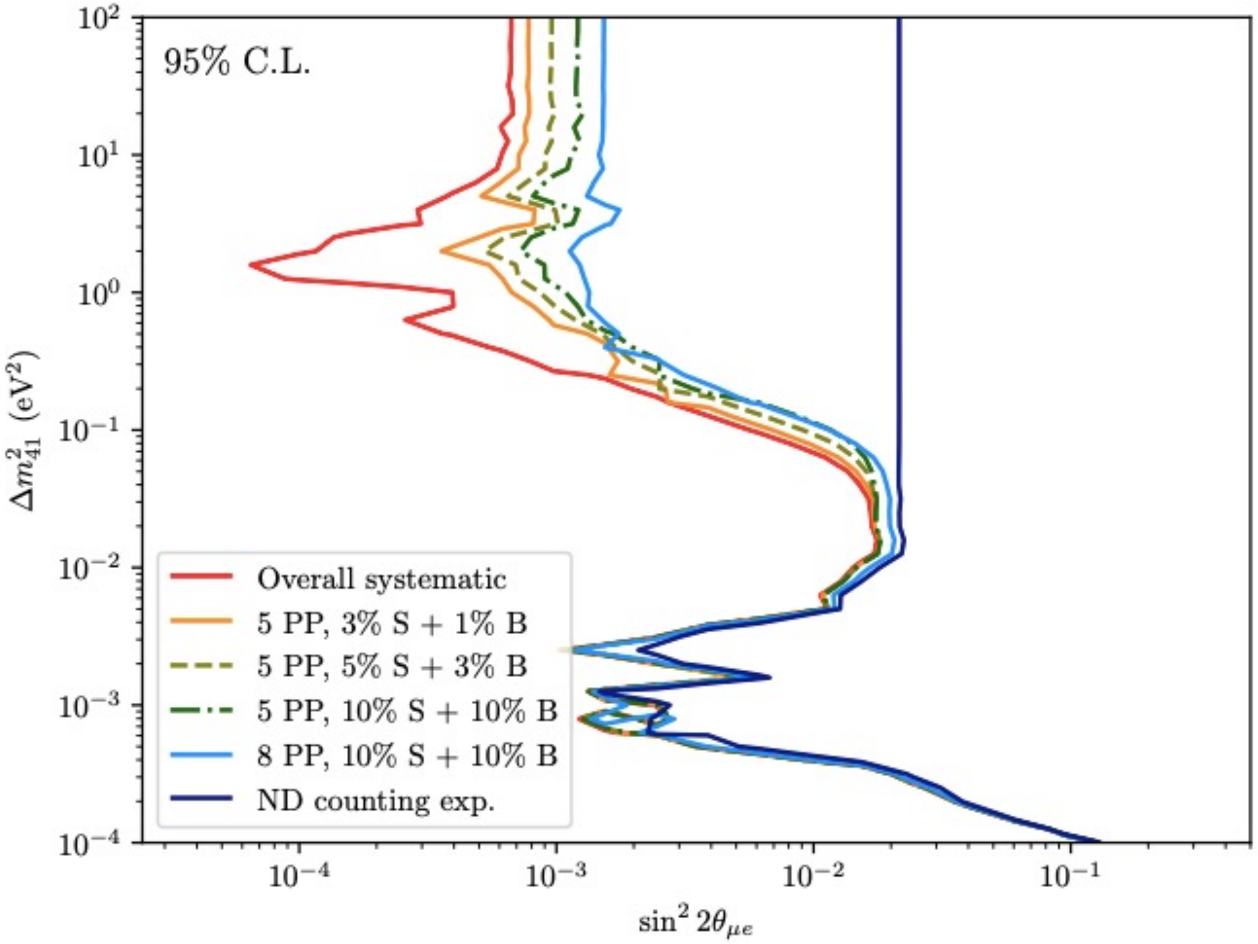


1904.07265



1906.06212

ESSNUSB EXPECTED SENSITIVITY



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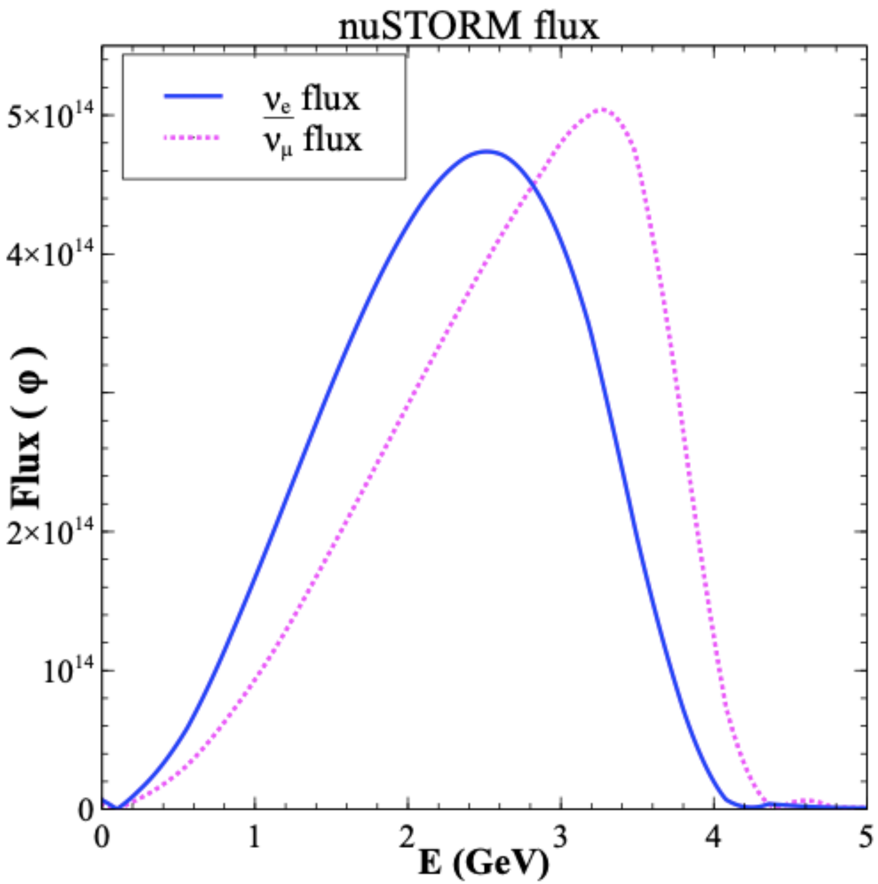
NUSTORM AND LENUSTORM

STERILES AT NUSTORM

Neutrinos from muon decays



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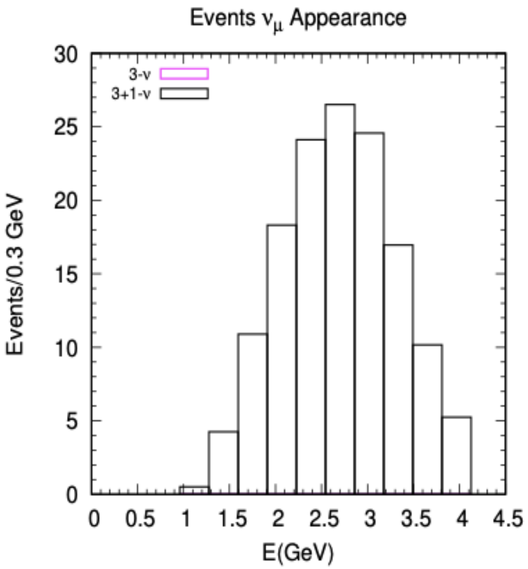
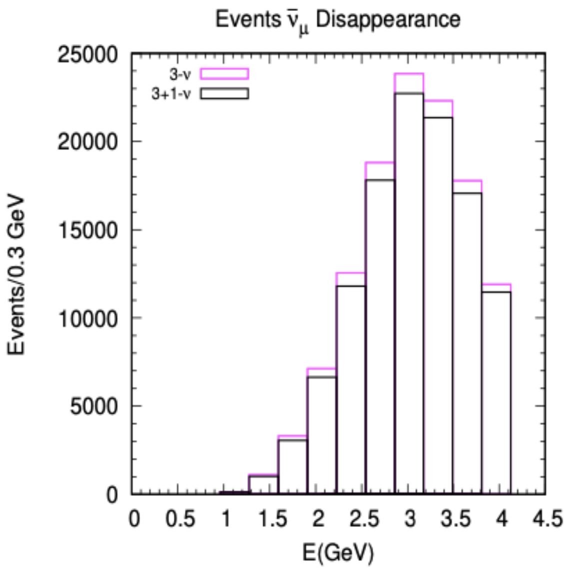
GeV neutrinos at 2km baseline, in presence of steriles, we observe appearance events and a depletion of disappearance!





STERILES AT NUSTORM

With the convention for the mixing matrix $U = R_{34}\tilde{R}_{24}\tilde{R}_{14}R_{23}\tilde{R}_{13}R_{12}$

The fourth column of the PMNS is very simple

$$U_{e4} = \sin\theta_{14}$$

$$U_{\mu4} = \cos\theta_{14}\sin\theta_{24}$$

$$U_{\tau4} = \cos\theta_{14}\sin\theta_{24}$$

$$U_{s4} = \cos\theta_{14}\cos\theta_{24}\cos$$

$$P_{\alpha,\beta} = 4|U_{\alpha4}|^2|U_{\beta4}|^2\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

$$P_{\alpha\alpha} = 1 - 4|U_{\alpha4}|^2(1-|U_{\alpha4}|^2)\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

STERILES AT NUSTORM

$$P_{e\mu} = 4\cos^2\theta_{14}\sin^2\theta_{14}\sin^2\theta_{24}\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

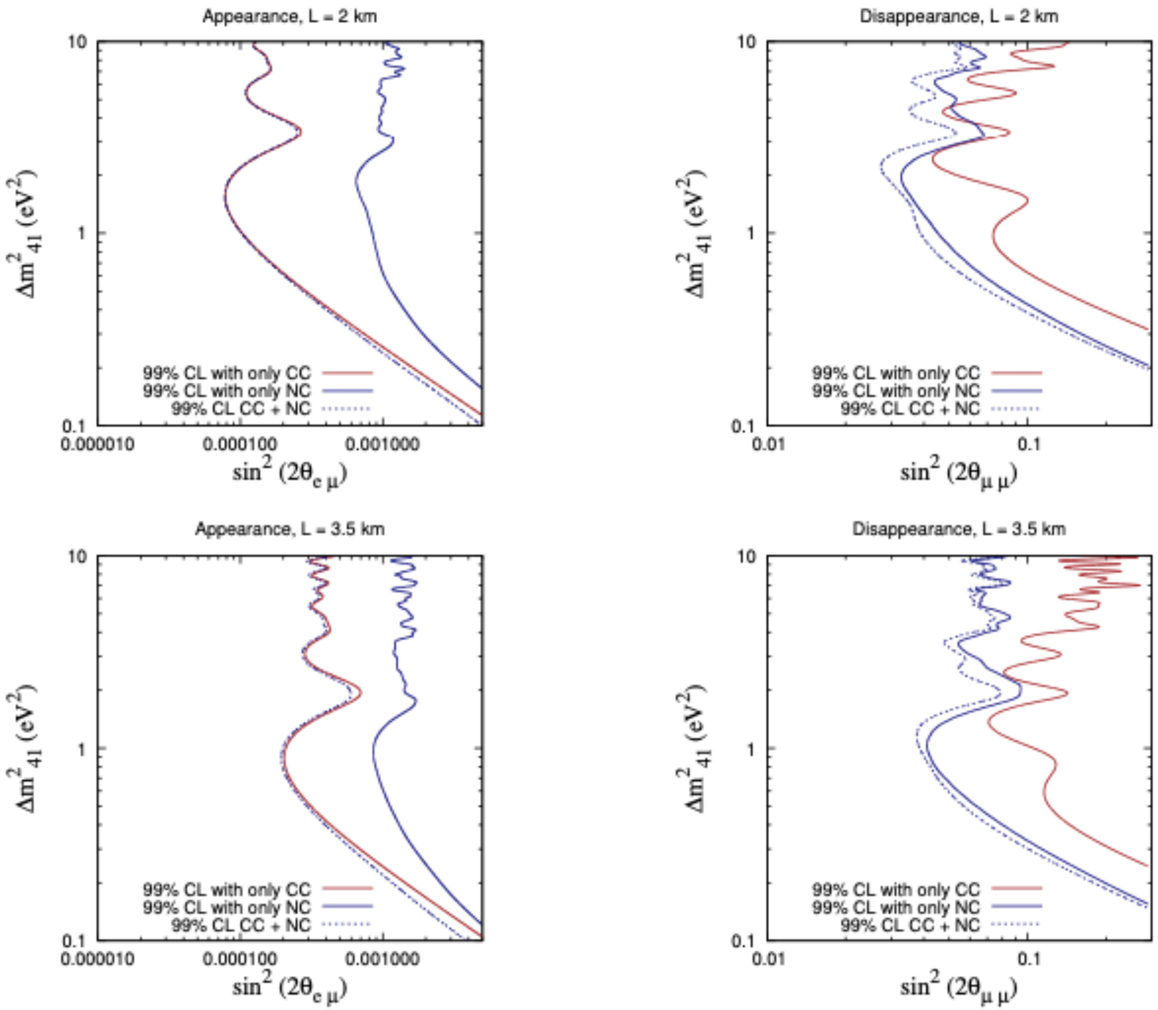
$$P_{\mu\mu} = 1 - 4\sin^2\theta_{24}\cos^2\theta_{14}(1 - \sin^2\theta_{24}\cos^2\theta_{14})\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

$$P_{\mu s} = 4\cos^4\theta_{14}\cos^2\theta_{24}\cos^2\theta_{34}\sin^2\theta_{24}\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

$$P_{es} = 4\cos^2\theta_{14}\sin^2\theta_{14}\cos^2\theta_{24}\cos^2\theta_{34}\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

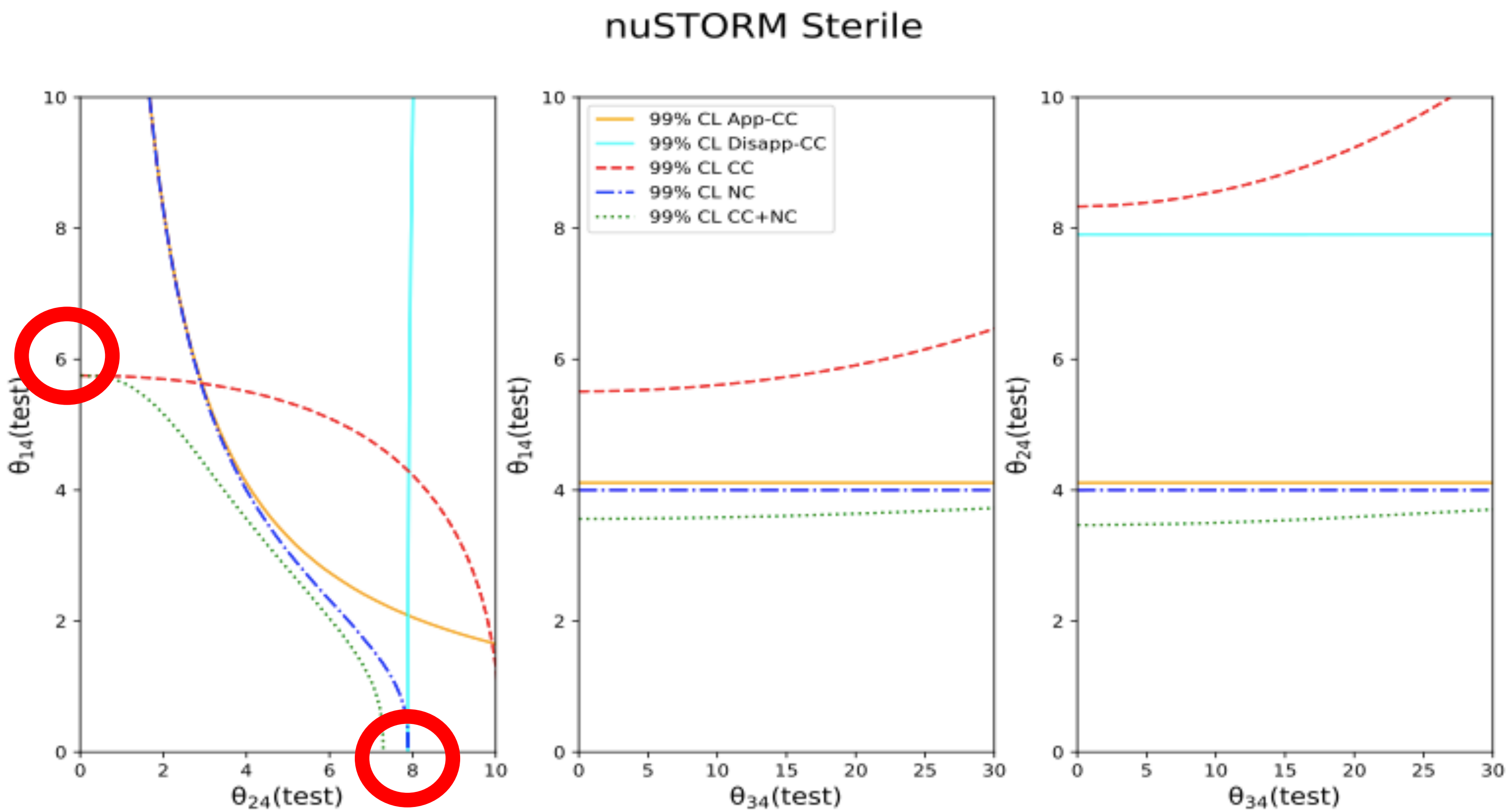
It is possible to bound the first two sterile mixing angle, no sensitivity (very poor) to the third one!

STERILES AT NUSTORM

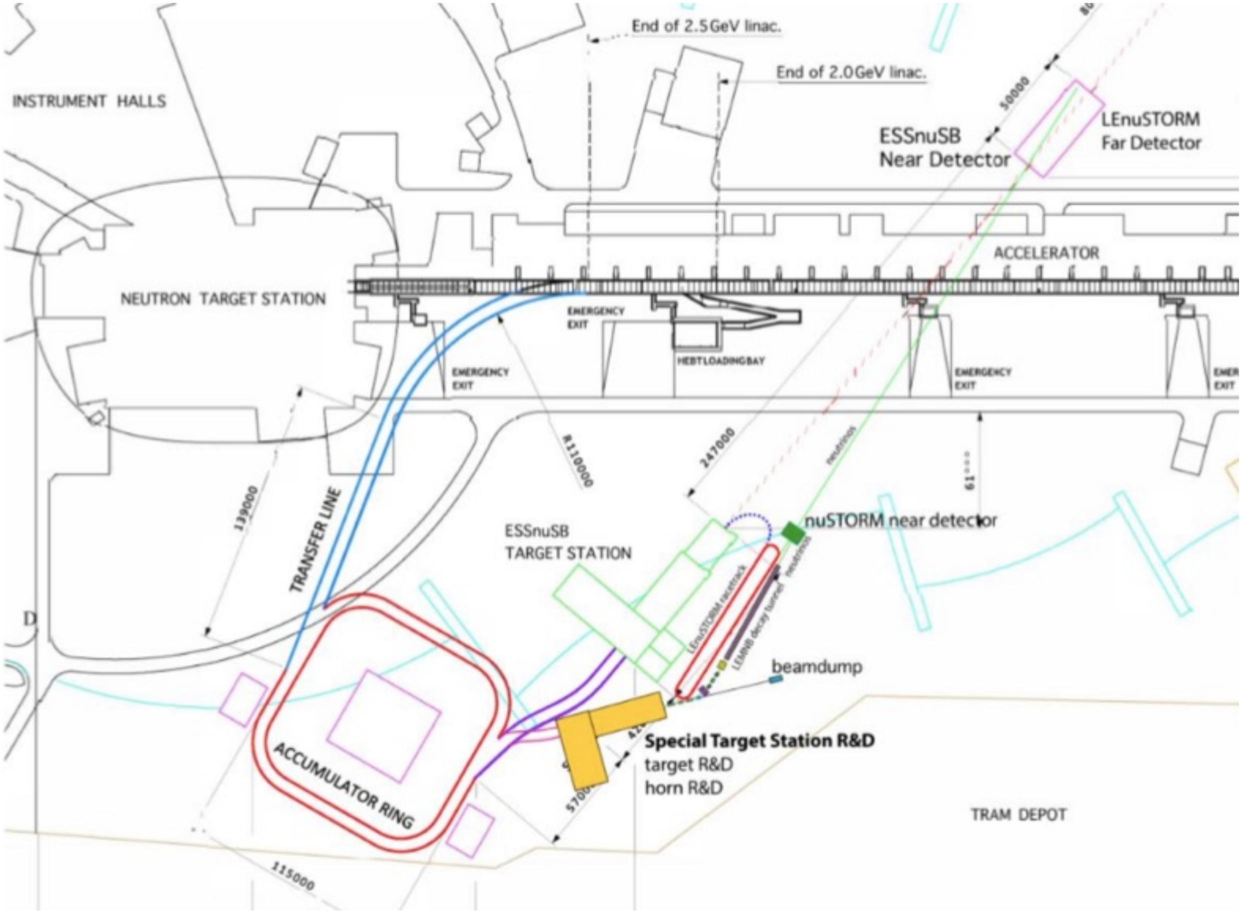


What to expect? Great limits from appearance! But also interesting limits from disappearance

STERILES AT NUSTORM



WHAT TO EXPECT AT LENUSTORM?



-Low energy neutrinos from muon decays, with an energy between 200 and 600 MeV.

-Near detector at 50 meters

-Far Detector at 250 meters

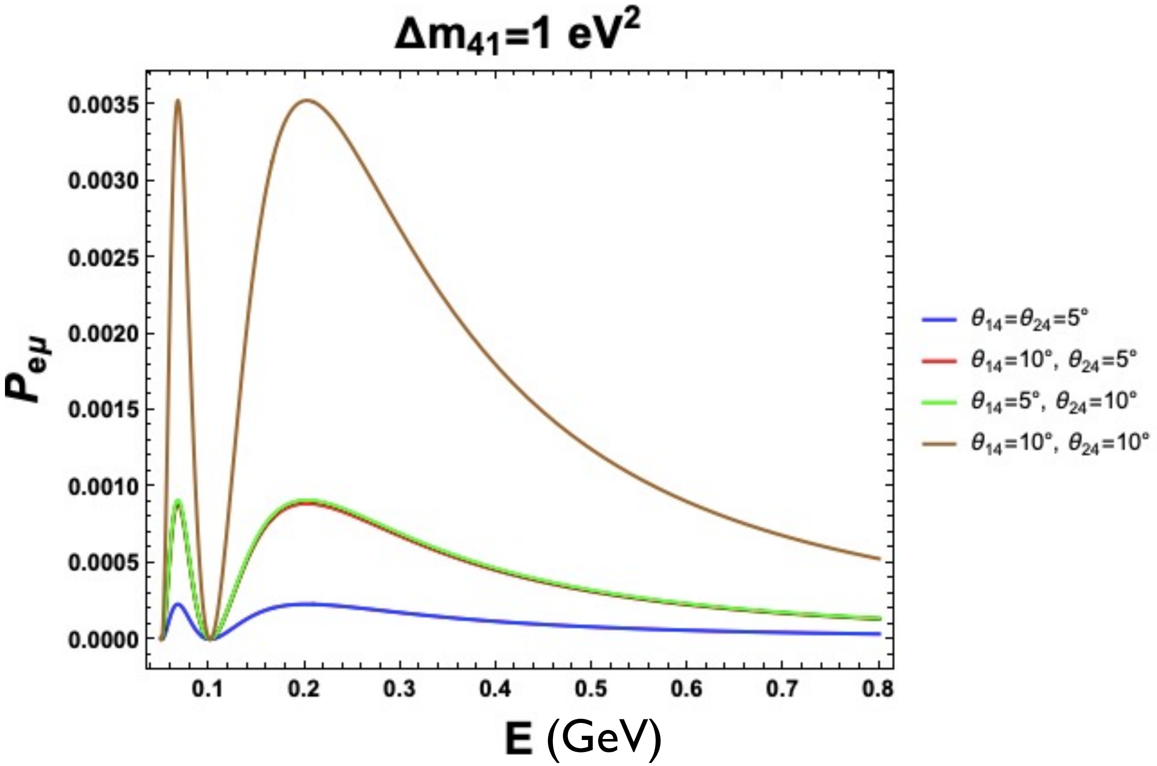
WHAT TO EXPECT AT LENUSTORM?

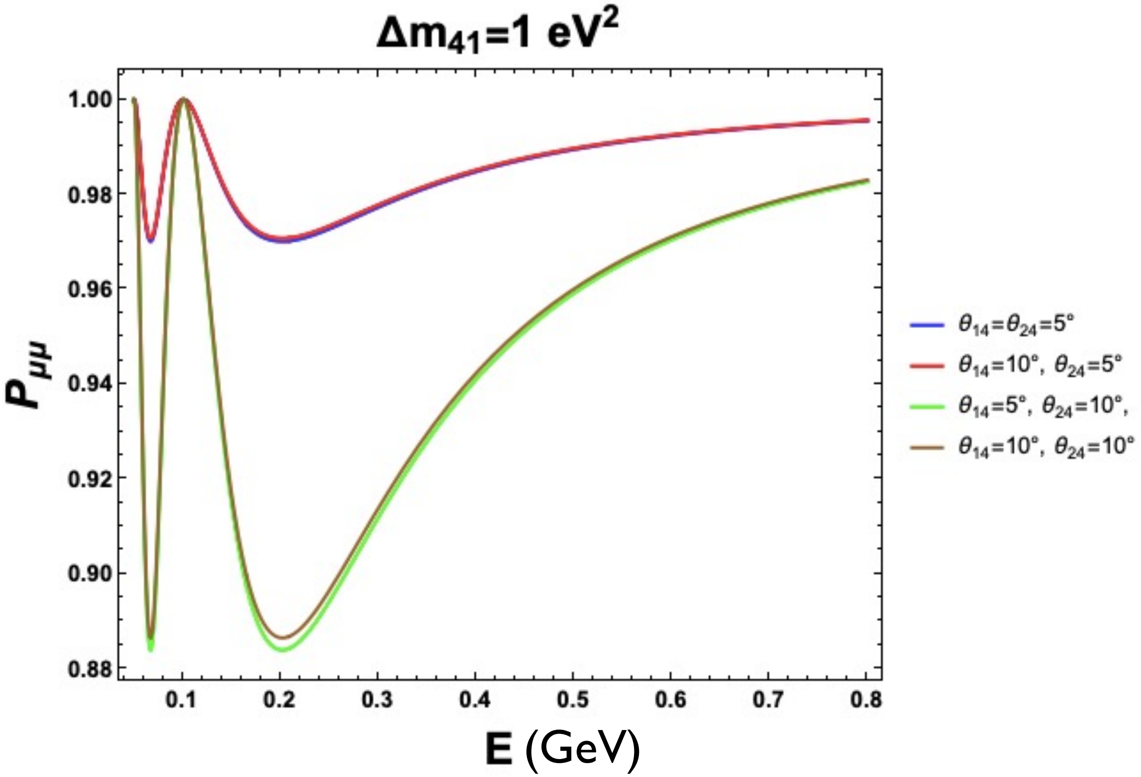
Regardless of the expected performances of the detectors, let us compute the L/E ratio for LEnuSTORM far detector

$$\frac{L}{E} \sim 0.3 - 1.2\ km/GeV \Longrightarrow \Delta m_{41}^{2} \sim \frac{2\ E\ \pi}{L} \sim 1 - 3\ eV^{2}$$

Expected good sensitivity to sterile neutrinos!

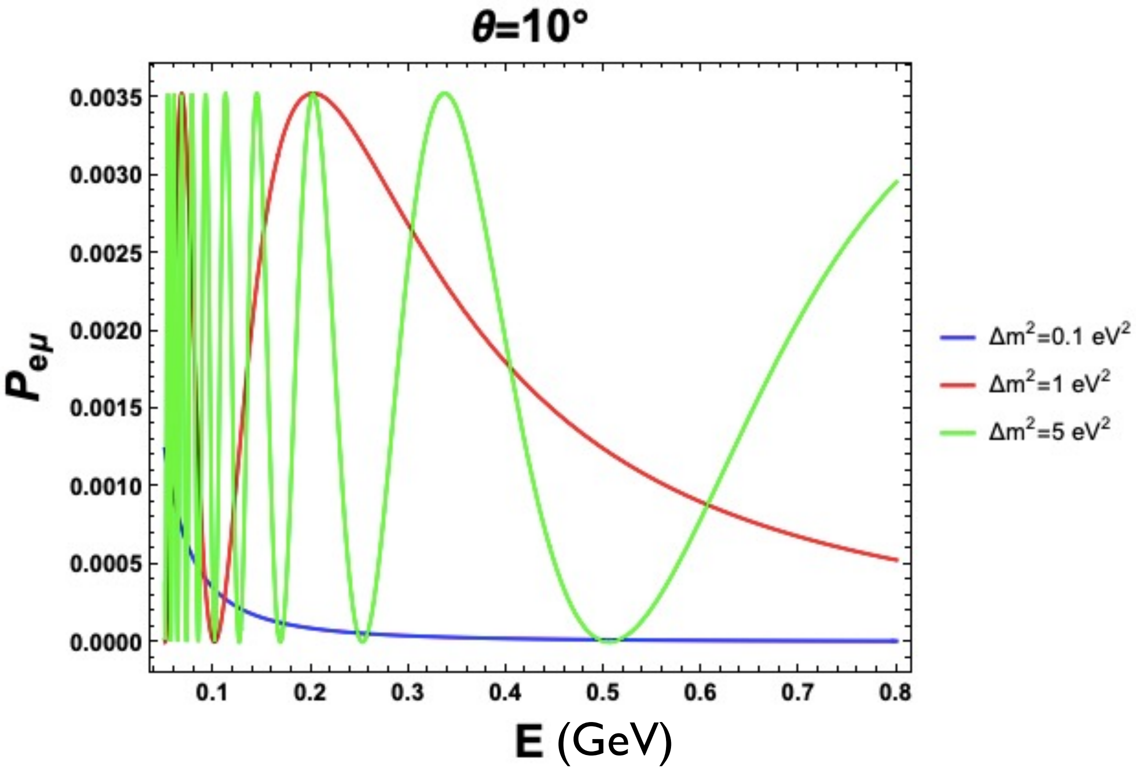
WHAT TO EXPECT AT LENUSTORM?

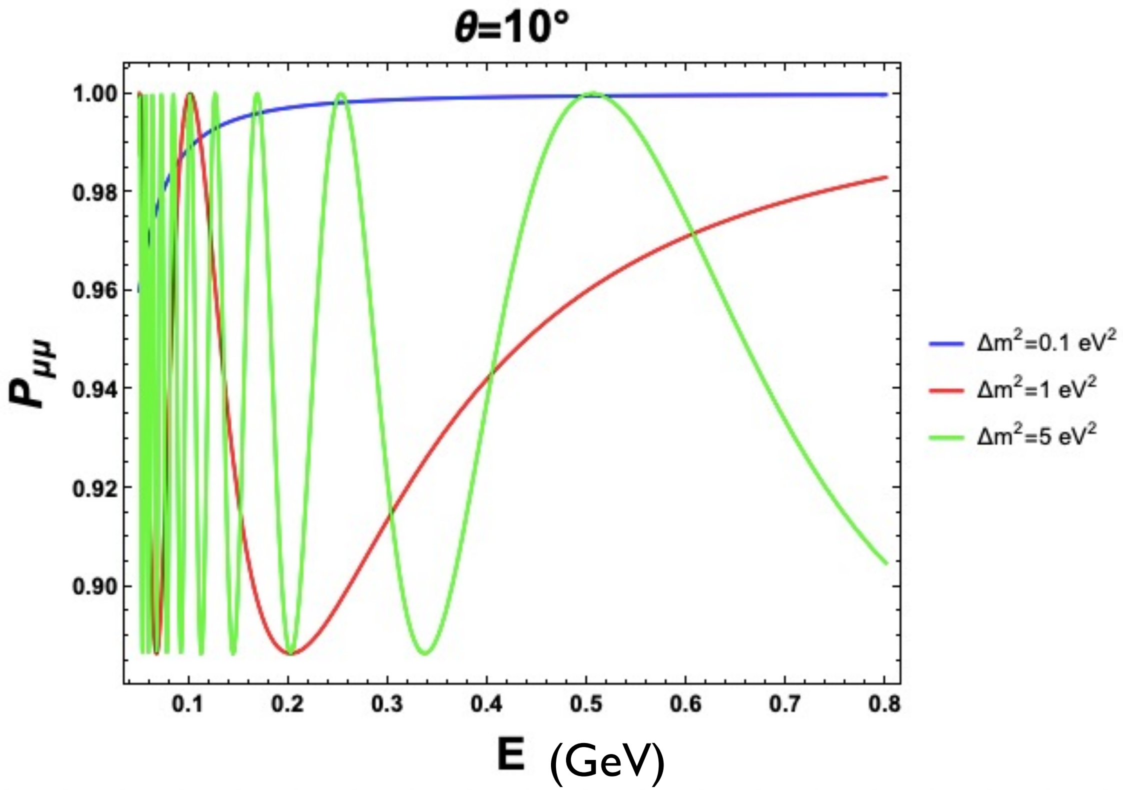




$(\sin 5°)^2 \sim 0.007$ $\quad$ $(\sin 10°)^2 \sim 0.03$

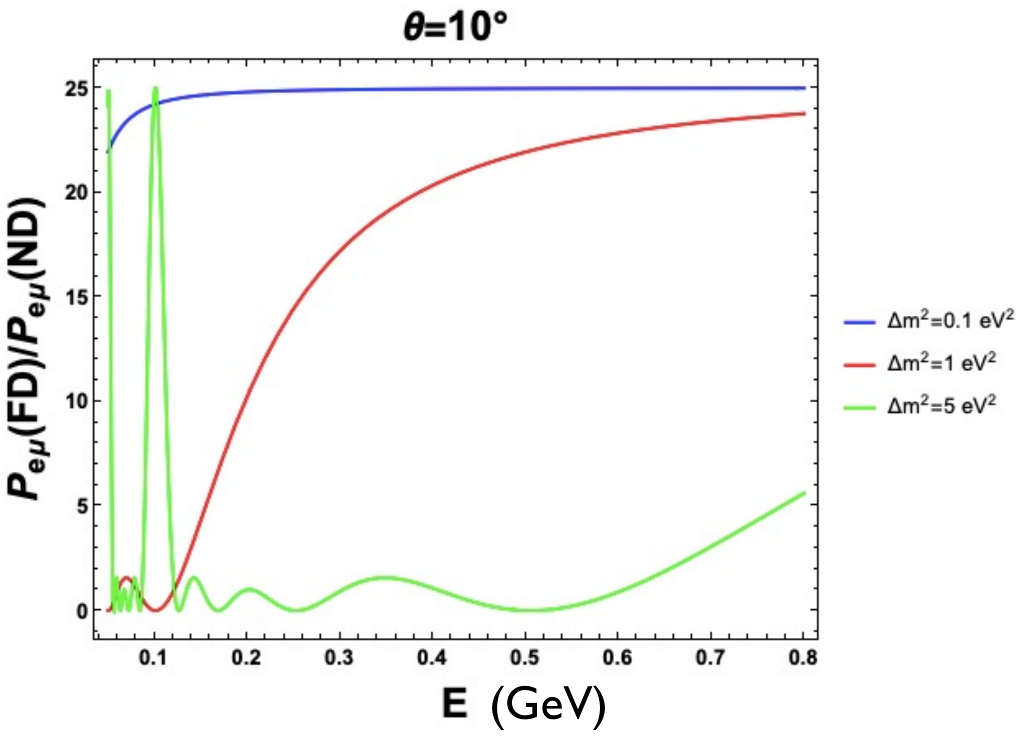
WHAT TO EXPECT AT LENUSTORM?

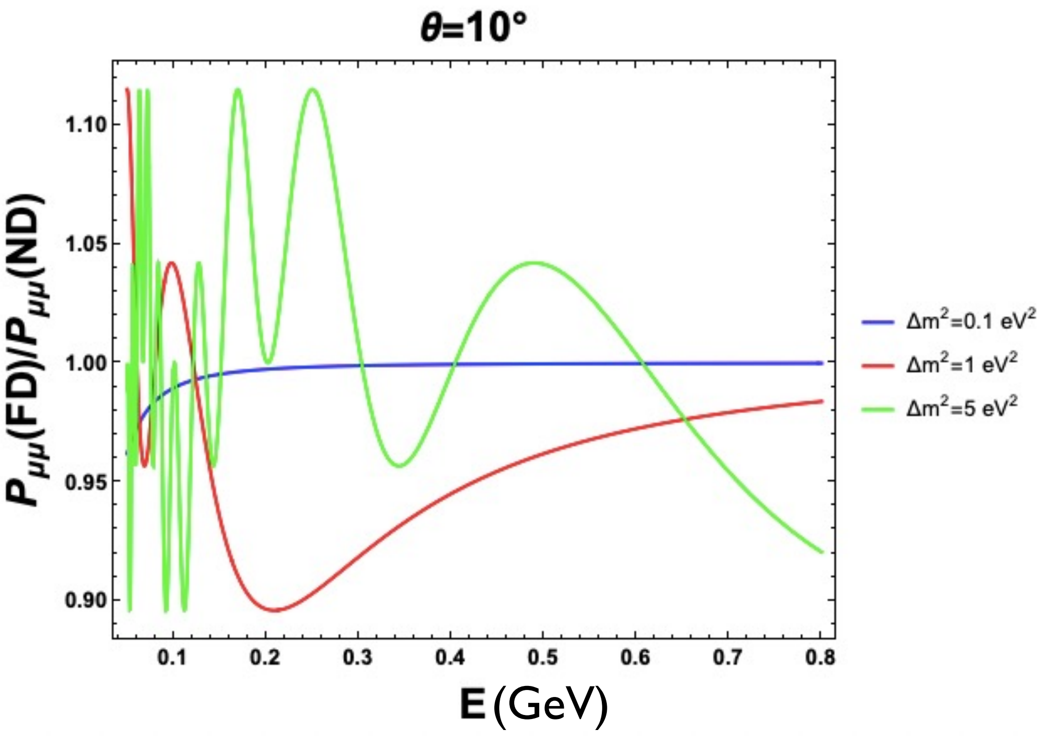




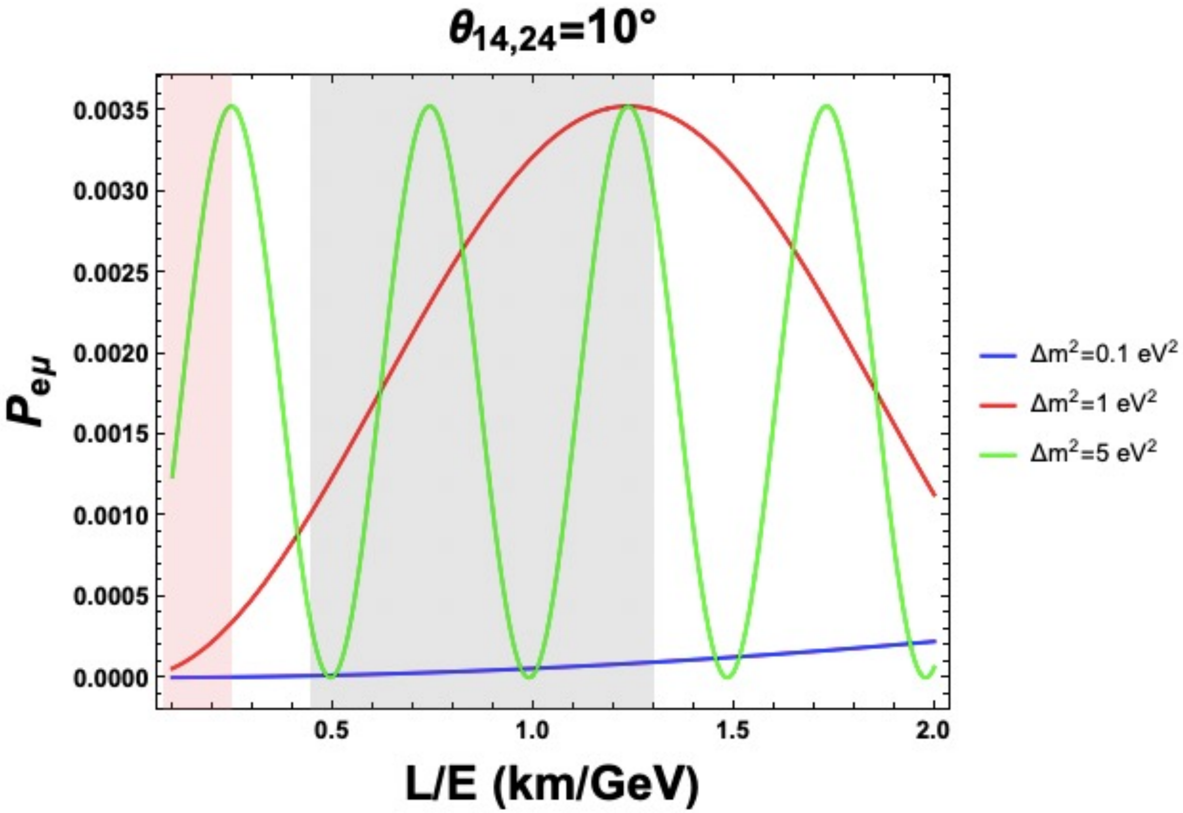
WHAT TO EXPECT AT LENUSTORM?

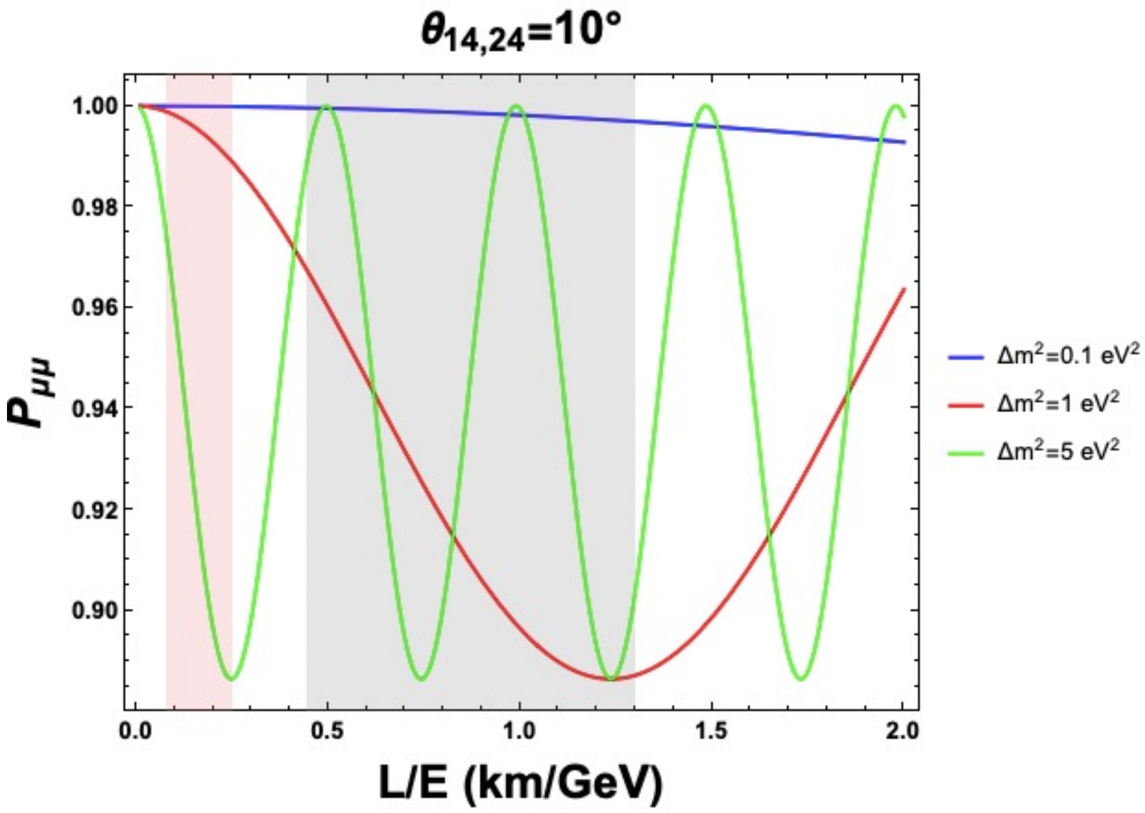
With a Near Detector at 50 m one may resolve fast oscillation





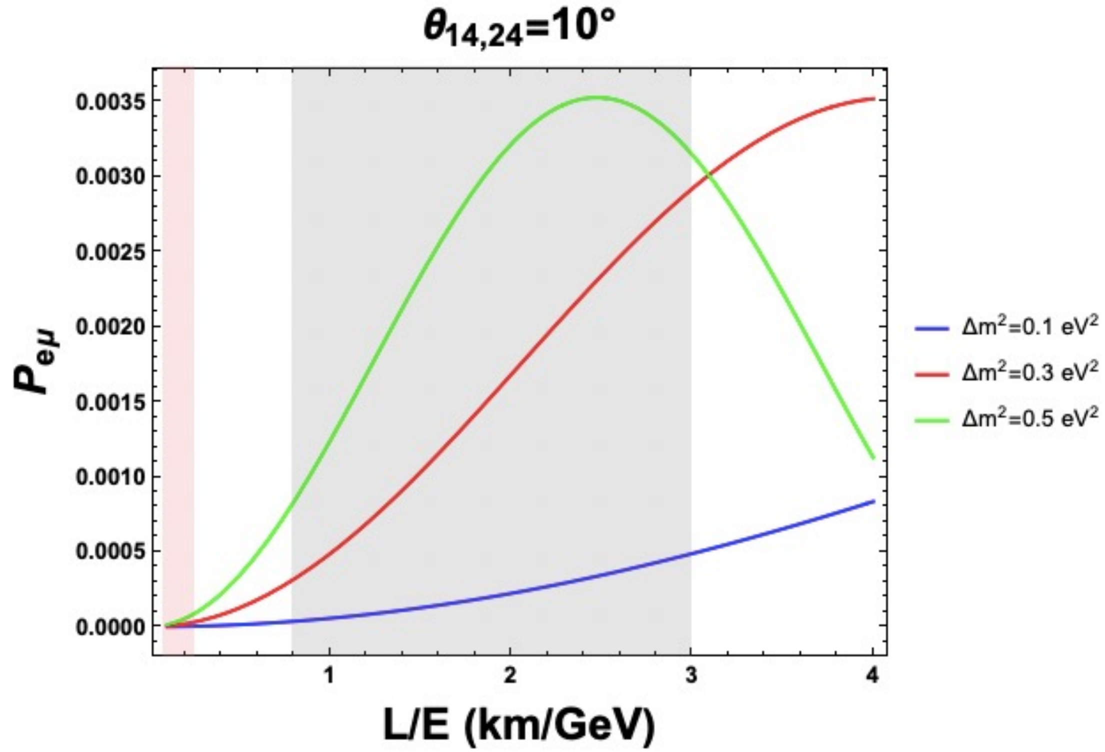
WHAT TO EXPECT AT LENUSTORM?

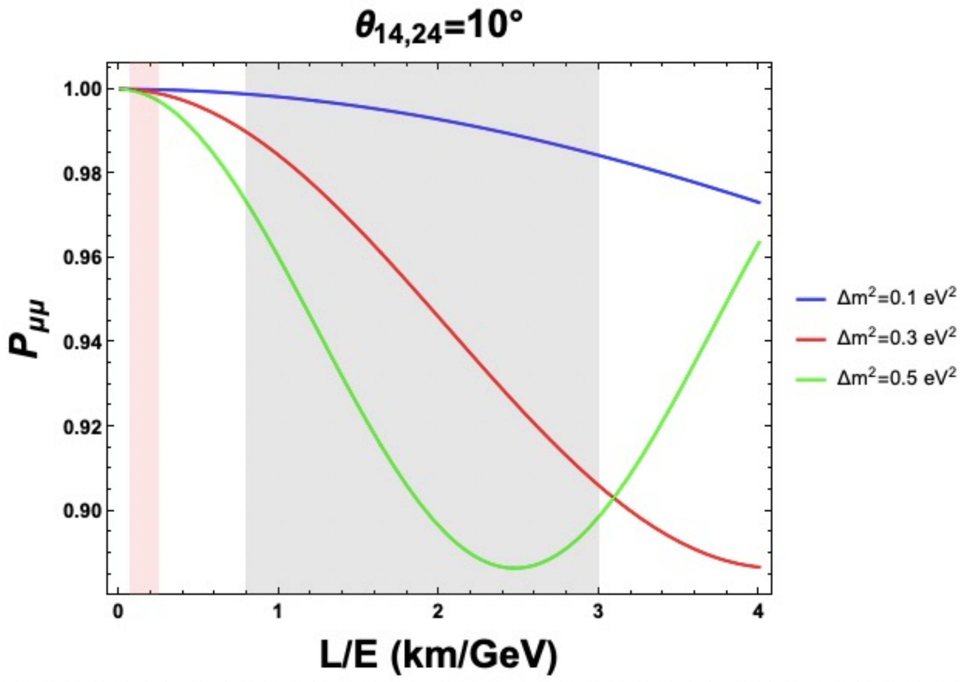




WHAT TO EXPECT AT LENUSTORM?

Can we go with larger baseline and resolve slower oscillation?





WHAT TO EXPECT AT LENUSTORM?

Following the strategy used for NuSTORM, one may also look at the NC events *(performances of the detectors need to be studied)*

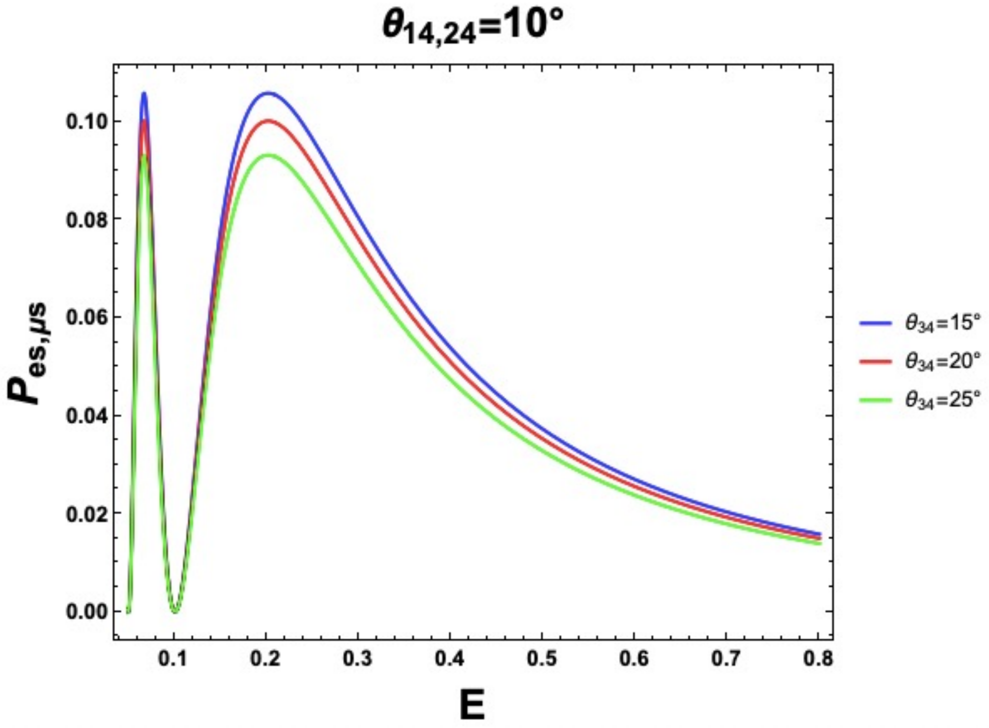
$$N_{\mu}^{CC} = \Phi(\nu_e) P_{e\mu} \sigma_{CC}$$

$$N_{\bar{\mu}}^{CC} = \Phi(\bar{\nu_{\mu}}) P_{\bar{\mu}\bar{\mu}} \sigma_{CC}$$

$$\underline{N_{total}^{NC} = \Phi(\bar{\nu_{\mu}})(1 - P_{\mu s})\sigma_{NC} + \Phi(\nu_e)(1 - P_{es})\sigma_{NC})}$$

Little sensitivity to the third sterile mixing angle!

$$P_{es} = 4\cos^2\theta_{14}\sin^2\theta_{14}\cos^2\theta_{24}\cos^2\theta_{34}\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$



THANKS FOR YOUR ATTENTION