Review of sterile-ν experiments

15 Jun @ PPC 2023, Daejeon

Yoomin Oh

ibs CENTER FOR UNDERGROUND PHYSICS

In this talk,

- ~~Theoretical meaning of sterile neutrino,~~
- ~~Relation with cosmology,~~
- ~~Interpretations more complicated than 3+1ν~~,
- ~~Criticism on the experimental data analysis,~~

- List of experiments of personal, but hopefully general choice.
  - Main focus on eV-mass scale.
  - In order of time.

Search for neutrino oscillations at a fission reactor

H. Kwon,* F. Boehm, A. A. Hahn,* H. E. Henrikson, and J.-L. Vuilleumier*
California Institute of Technology, Pasadena, California 91125

J.-F. Cavaignac, D. H. Koang, and B. Vignon
Institut des Sciences Nucleáires de Grenoble, IN2P3, 38026 Grenoble Cedex, France

F. v. Feilitzsch* and R. L. Mössbauer
Physik-Department, Technische Universität München, 8046, Garching, Federal Republic of Germany

(Received 7 April 1981)

8.76 m from 57 MWt ILL reactor

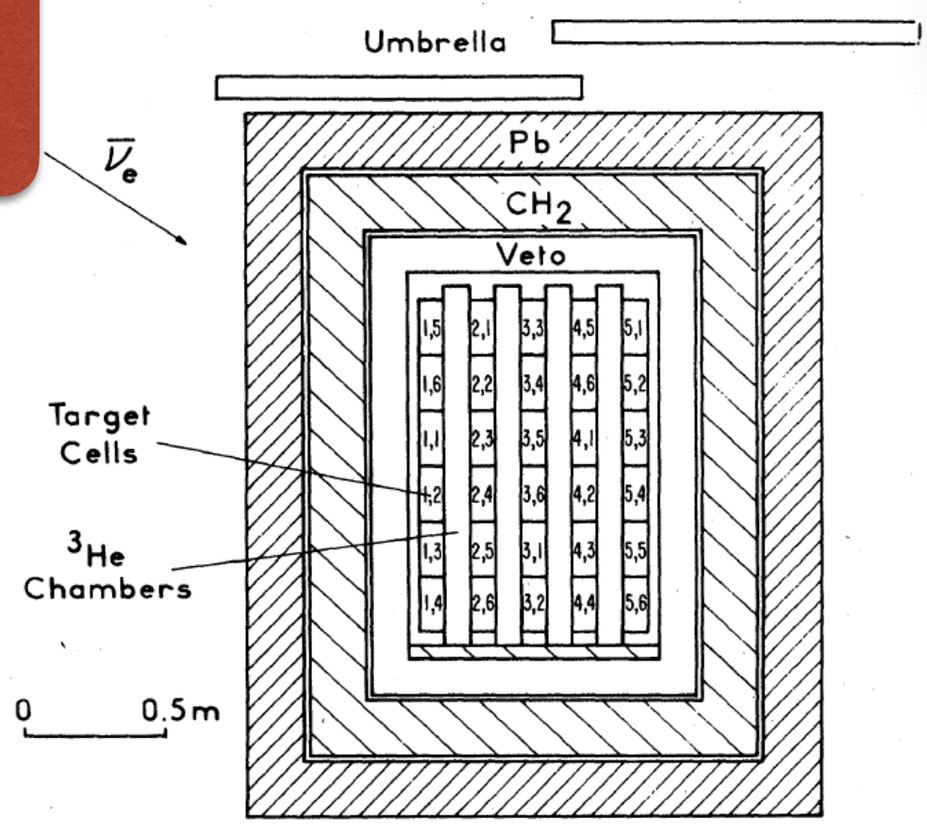
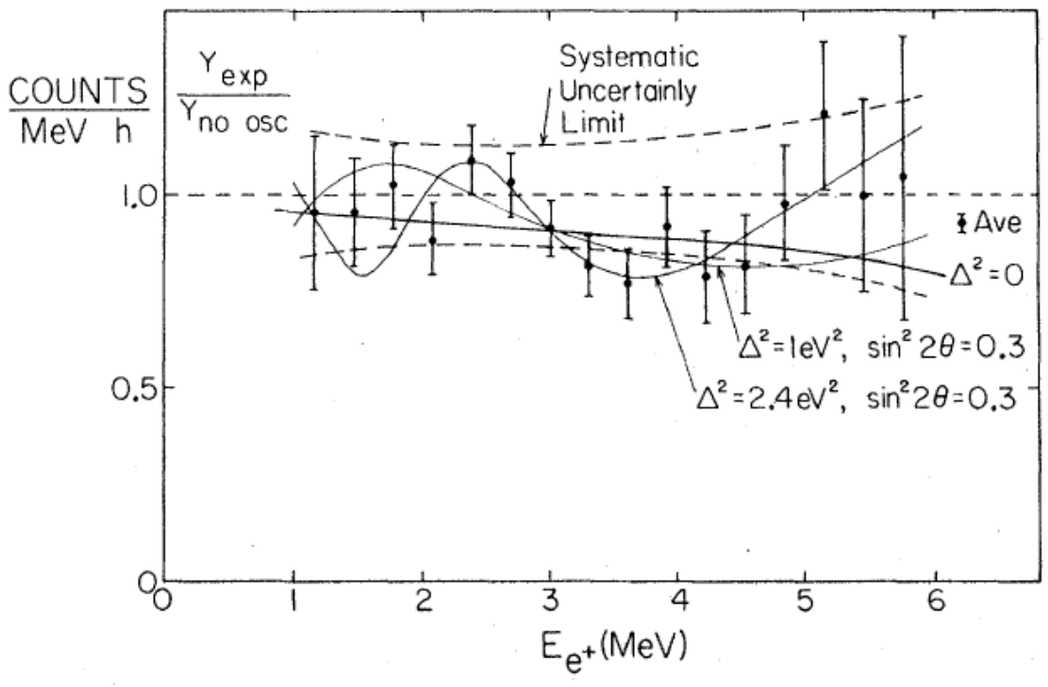


FIG. 1. Experimental arrangement of the detector system and shielding.

The present experimental limits on the masses of ν_e, ν_μ, and ν_τ are 35 eV,[9] 570 keV,[10] and 250 MeV,[11] respectively, which leaves ample room for



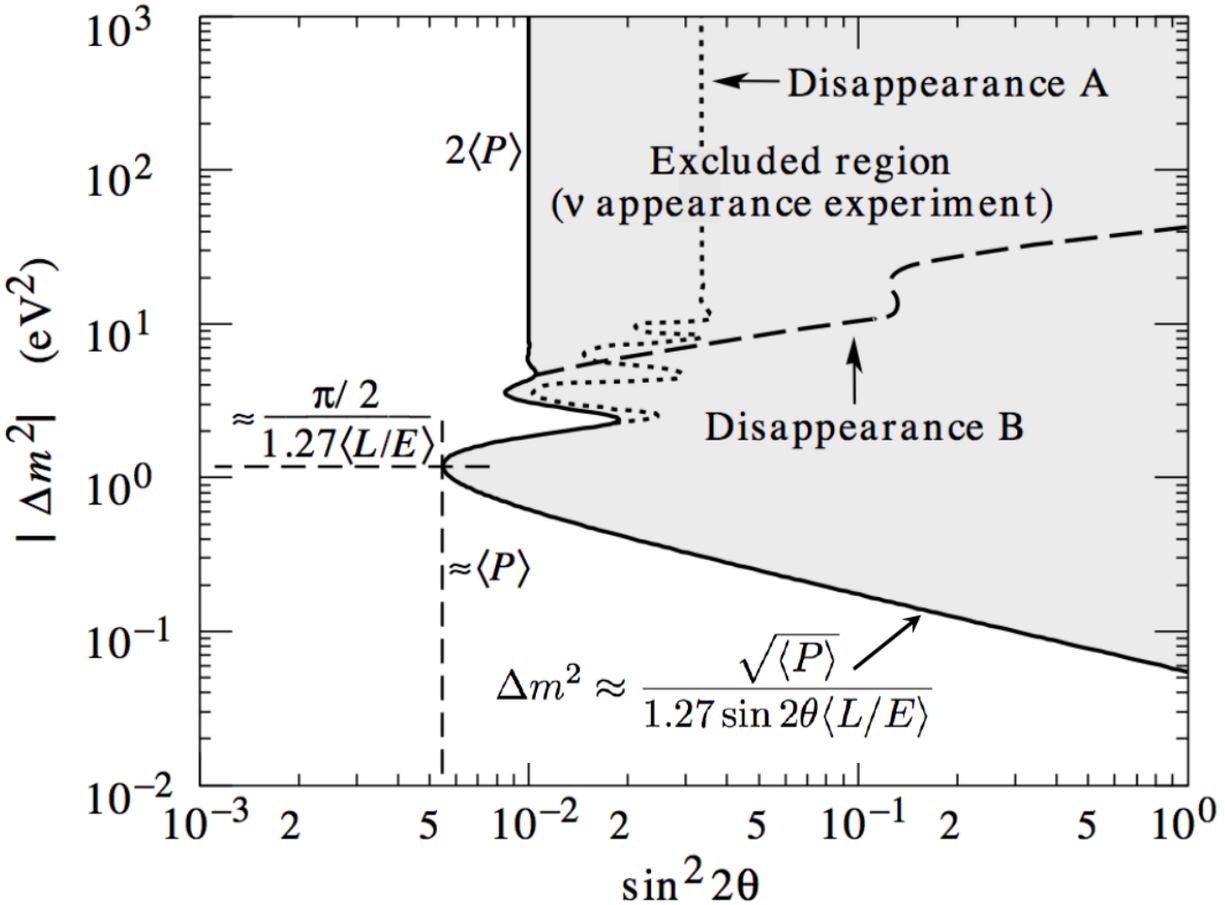
Starting line

$$P(E_{\bar{\nu}}, \Delta^2 d, \theta) = 1 - \tfrac{1}{2}\sin^2 2\theta[1 - \cos(2.53\ \Delta^2 d/E_{\bar{\nu}})] \quad (2)$$

$$P_{\alpha\to\beta} \sim \sin^2 2\theta\ \sin^2\left(1.27\Delta m^2\,[\mathrm{eV}^2]\frac{L\,[\mathrm{m/km/Mm}]}{E_\nu\,[\mathrm{MeV/GeV/TeV}]}\right)$$

size of mixing

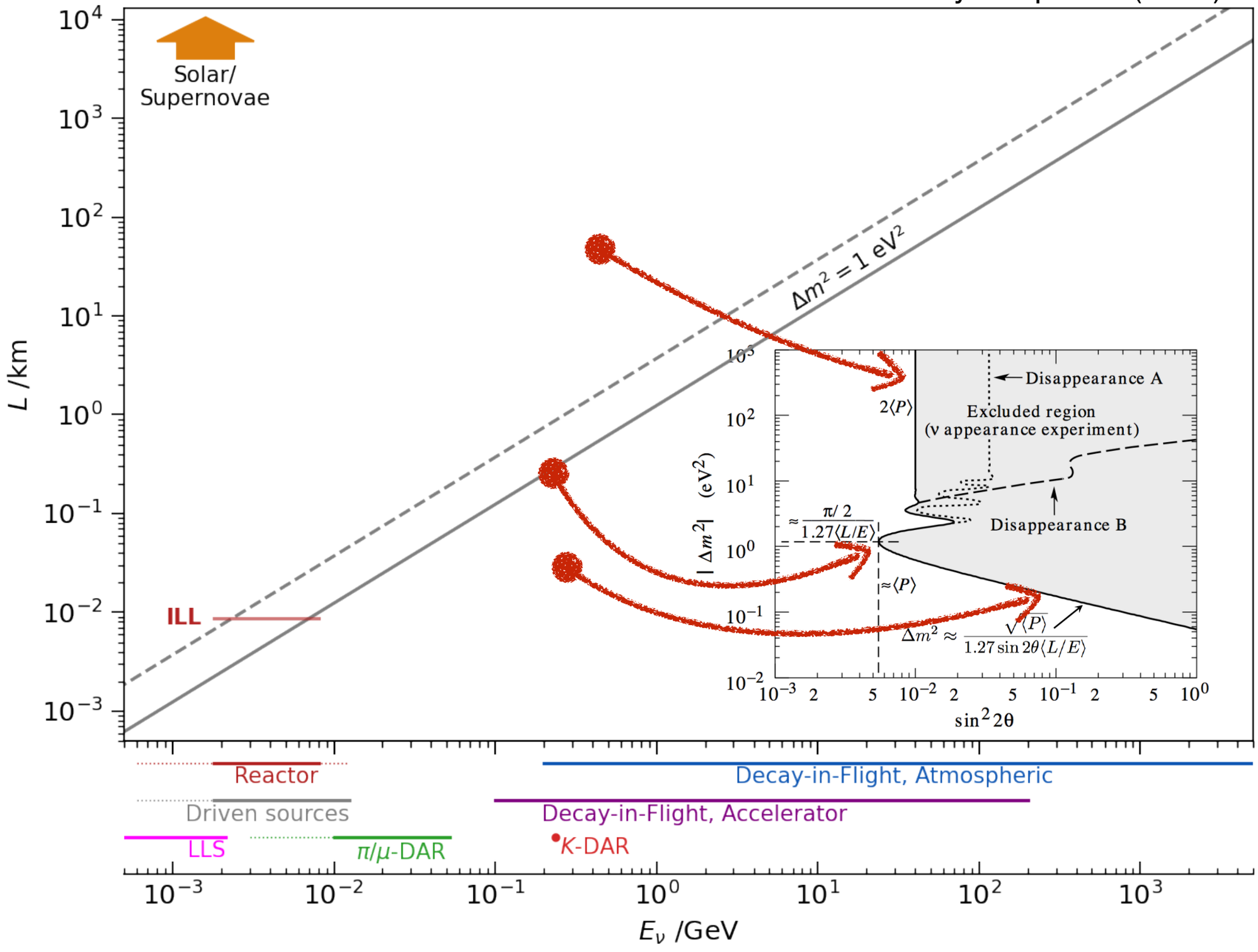
shape of oscillation



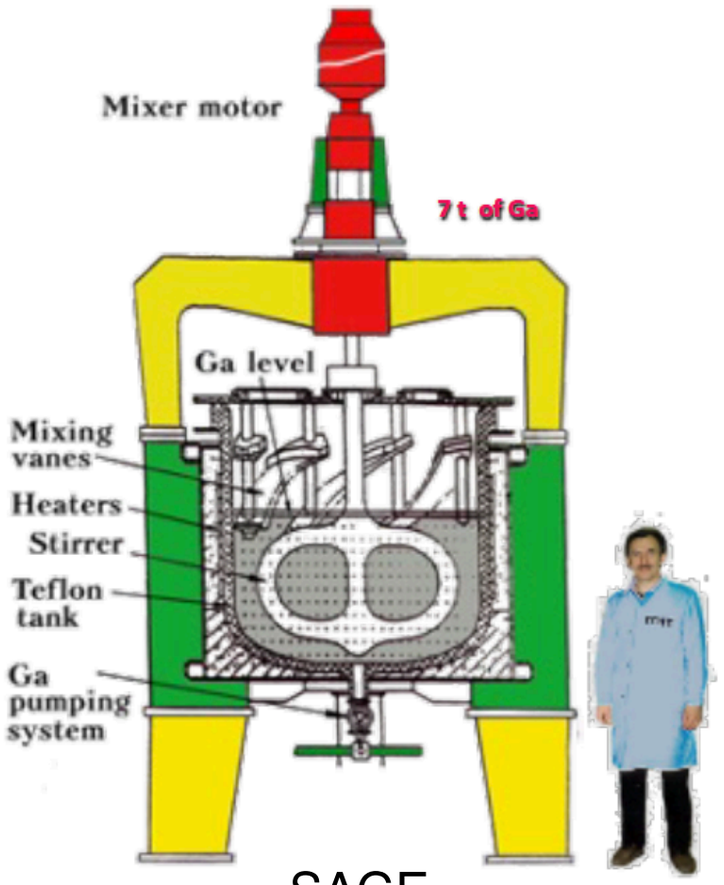
PDG 1996

Where to put the detector?

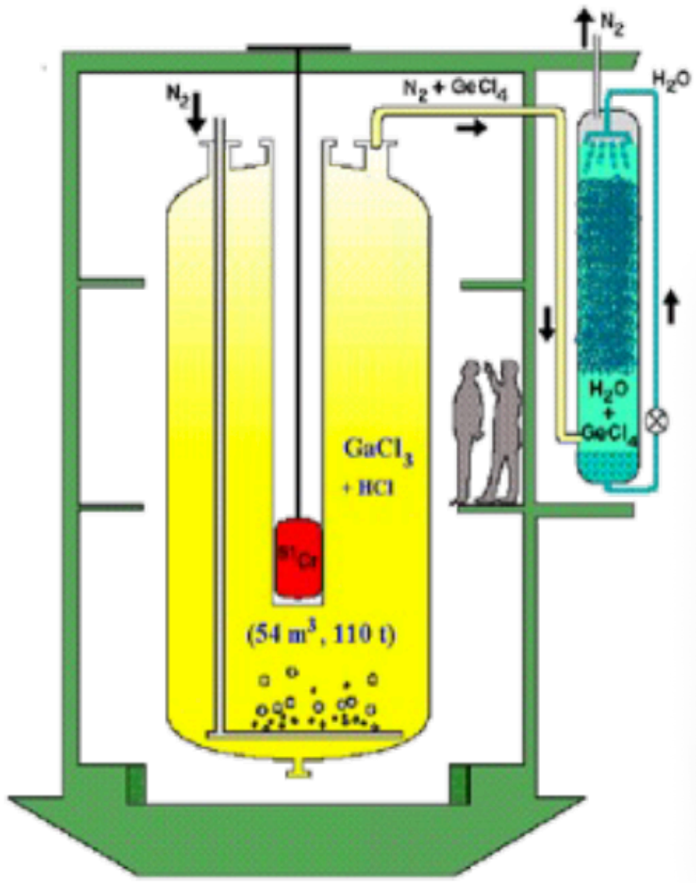
Redrawn from Diaz et al,
Phys.Rep. 884 (2020) 1



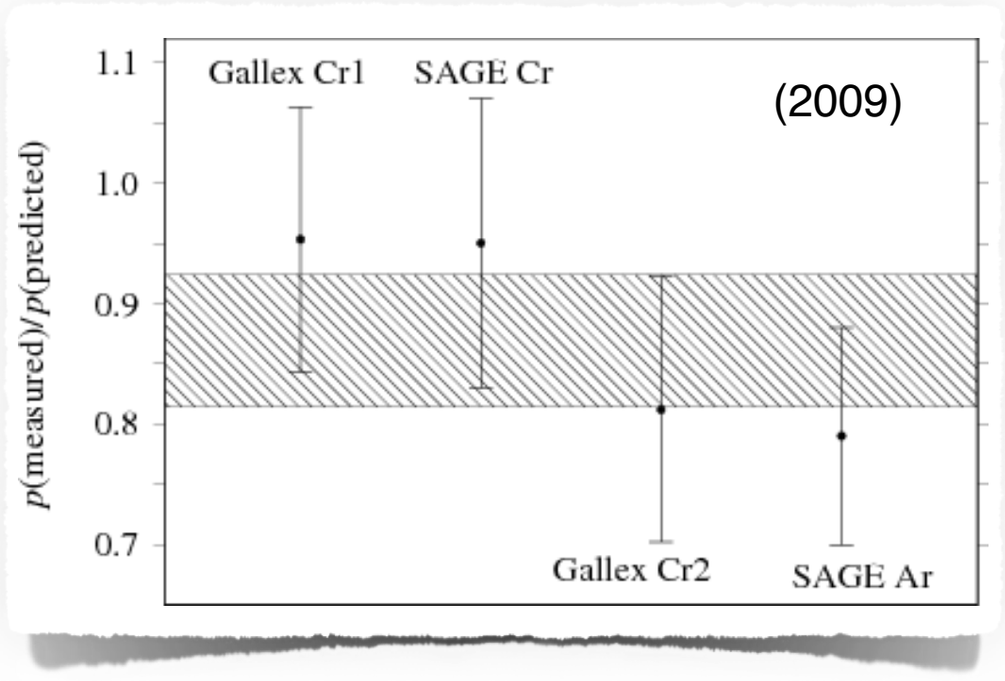
GALLEX, SAGE (1990's)



SAGE



GALLEX



- To solve solar-ν puzzle.
  $\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$
- Tested with ^{51}Cr and ^{37}Ar→measured deficit (Ga Anomaly)
  $e^- + {}^{51}\mathrm{Cr} \rightarrow {}^{51}\mathrm{V} + \nu_e$, $e^- + {}^{37}\mathrm{Ar} \rightarrow {}^{37}\mathrm{Cl} + \nu_e$

LSND

800 MeV proton beam

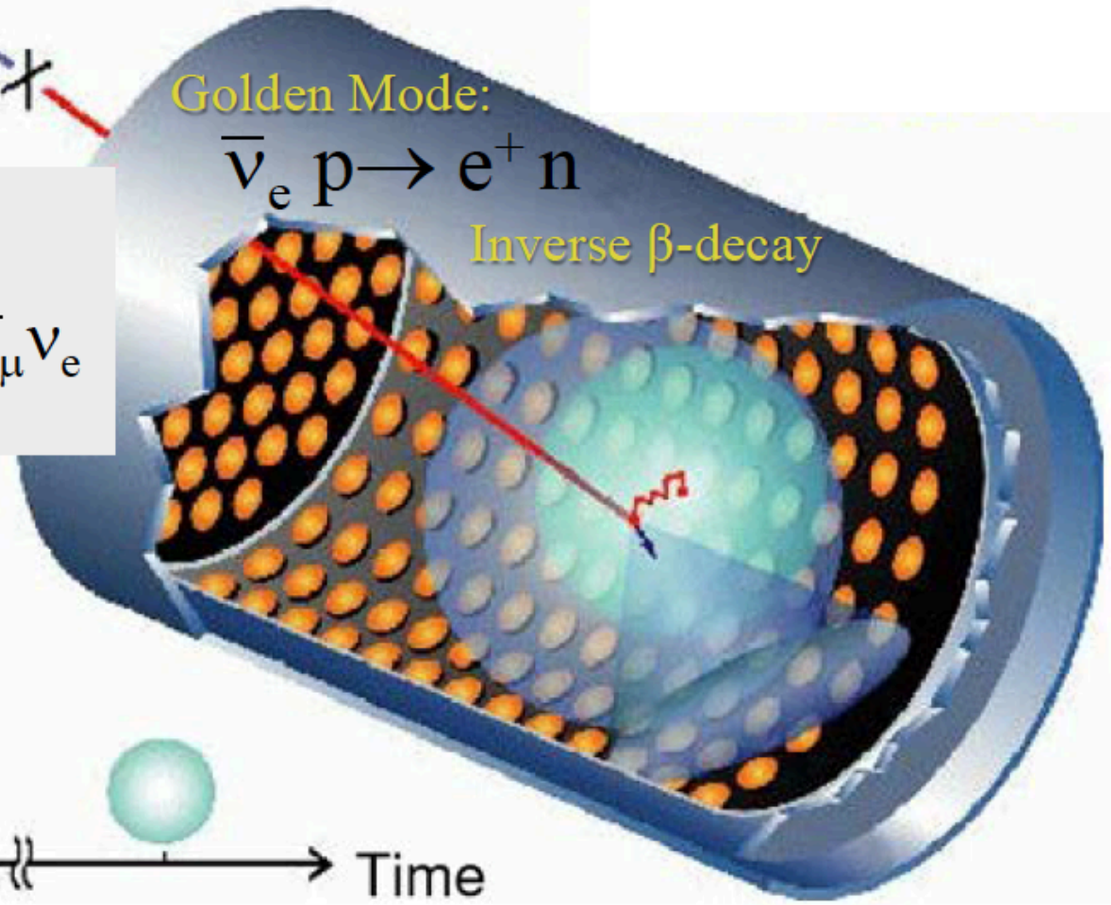
Water target

Copper beamstop

Energy range: 20 to 55 MeV

Baseline: 30 m

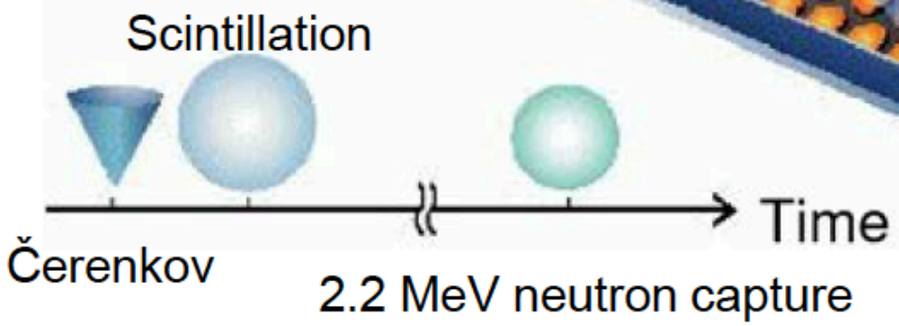
L/E ~ 1 m/MeV



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

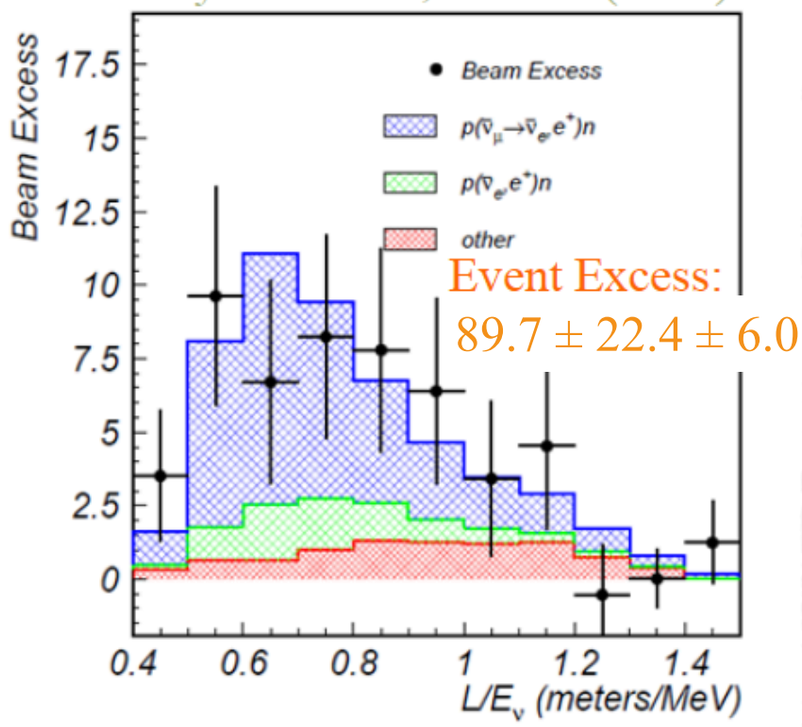
Stopped Pion Beam $\hookrightarrow e^+ \bar{\nu}_\mu \nu_e$

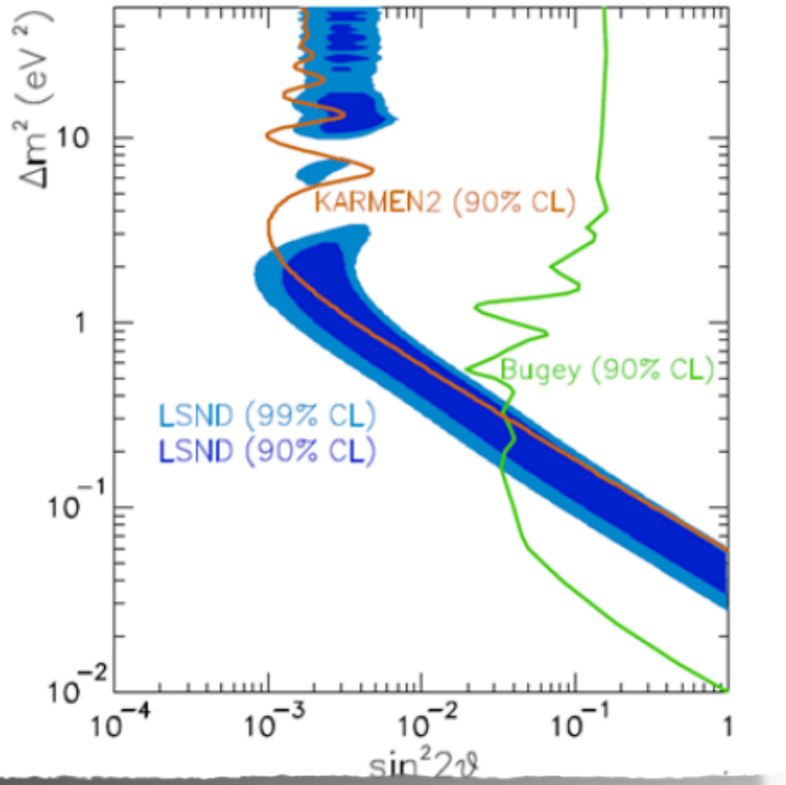
Signature



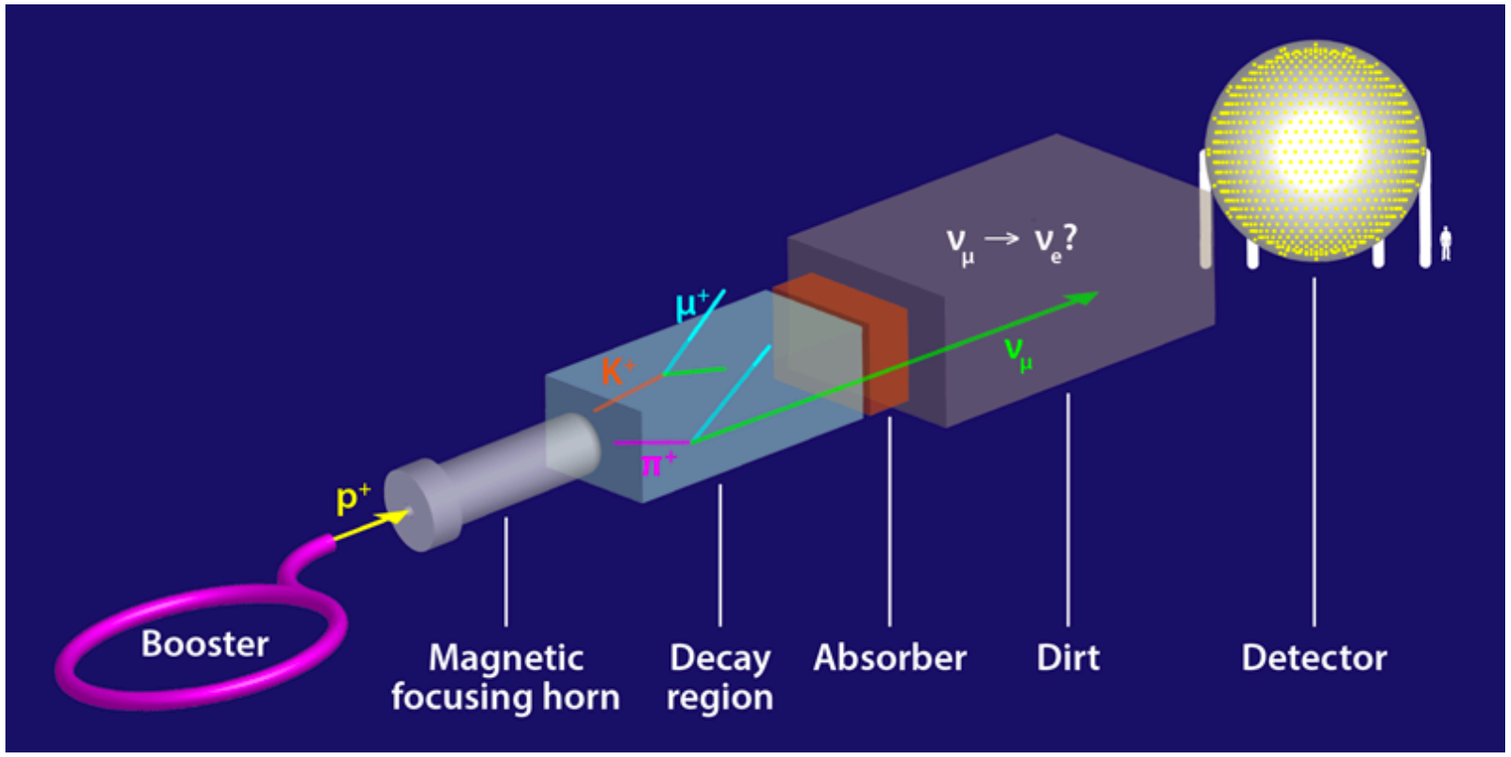
Courtesy of Jonathan Link

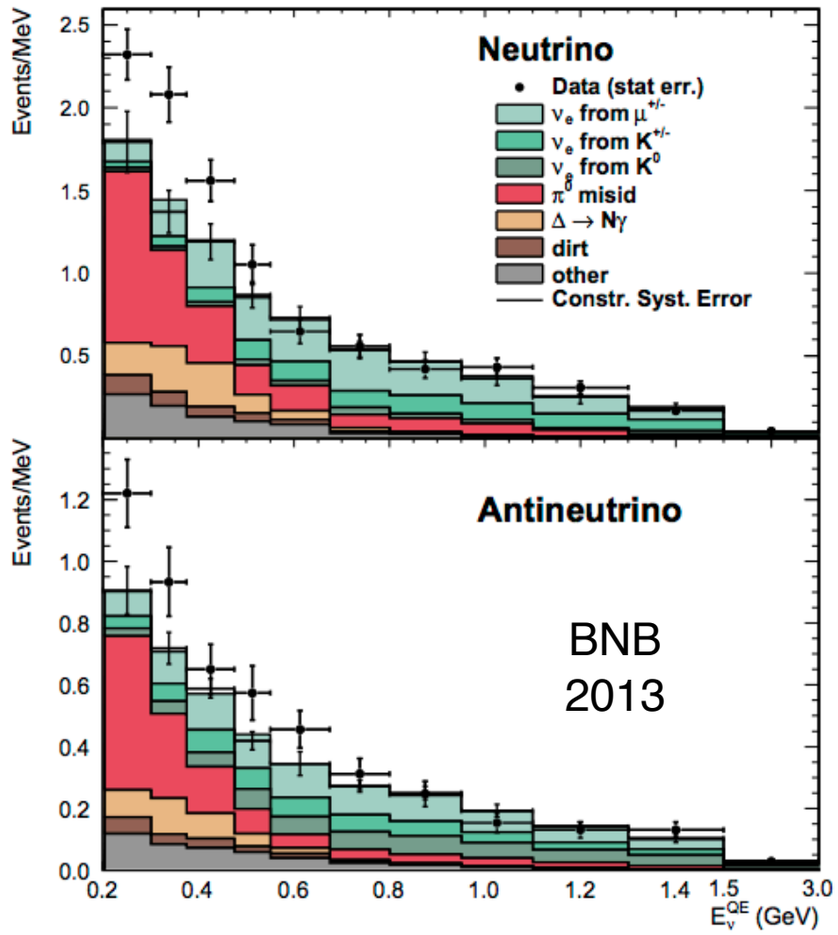
Phys.Rev.D64, 112007 (2001)

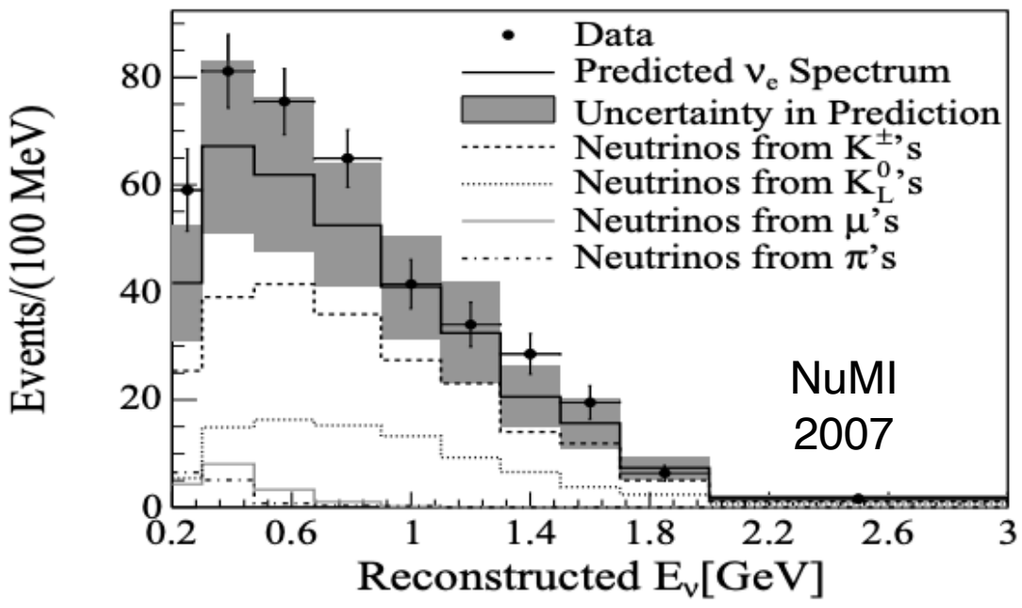




MiniBooNE

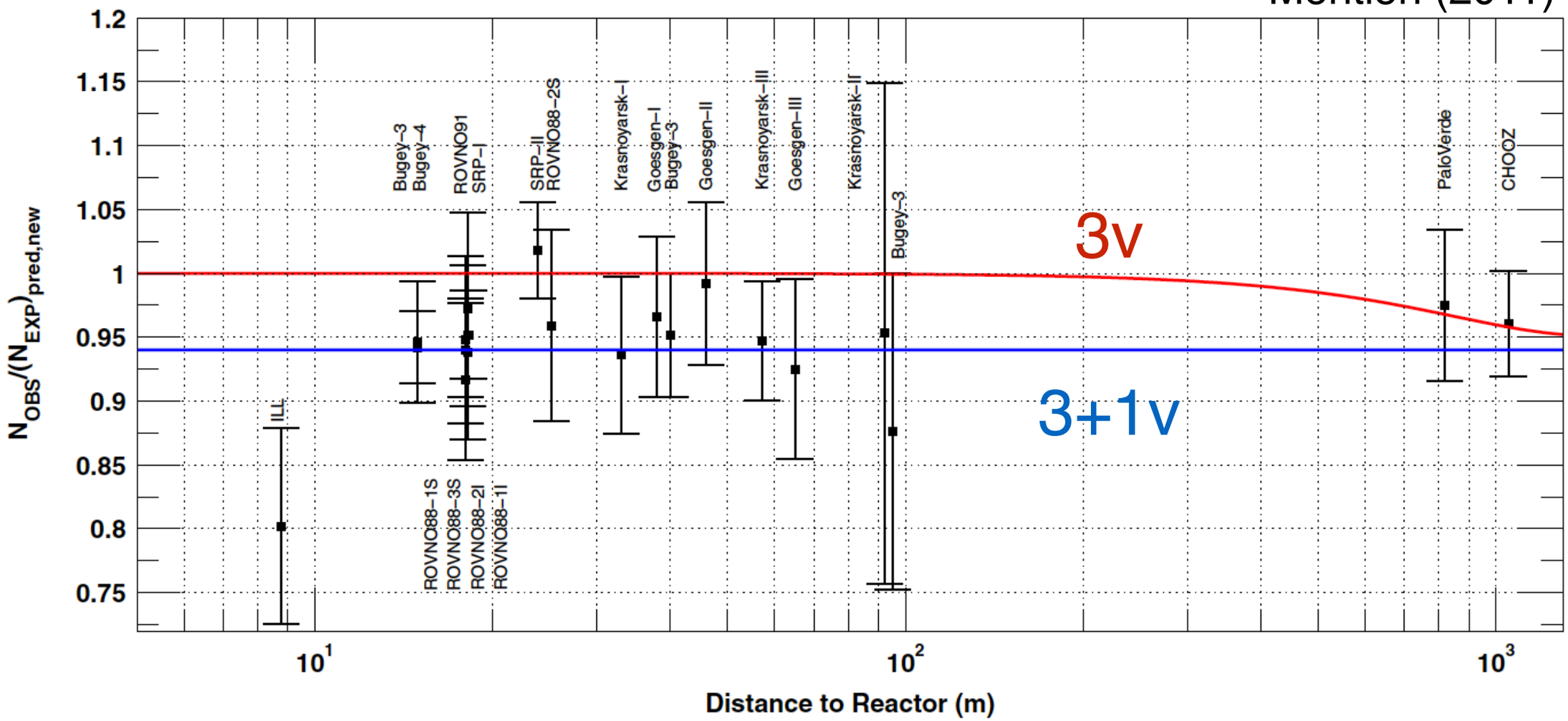

Booster
p+
μ+
K+
π+
νμ → νe?
νμ
Magnetic focusing horn
Decay region
Absorber
Dirt
Detector


Neutrino
Data (stat err.)
νe from μ+/-
νe from K+/-
νe from K0
π0 misid
Δ → Nγ
dirt
other
Constr. Syst. Error
Events/MeV
Antineutrino
BNB
2013
EνQE (GeV)


Data
Predicted νe Spectrum
Uncertainty in Prediction
Neutrinos from K±'s
Neutrinos from K0L's
Neutrinos from μ's
Neutrinos from π's
Events/(100 MeV)
NuMI
2007
Reconstructed Eν[GeV]

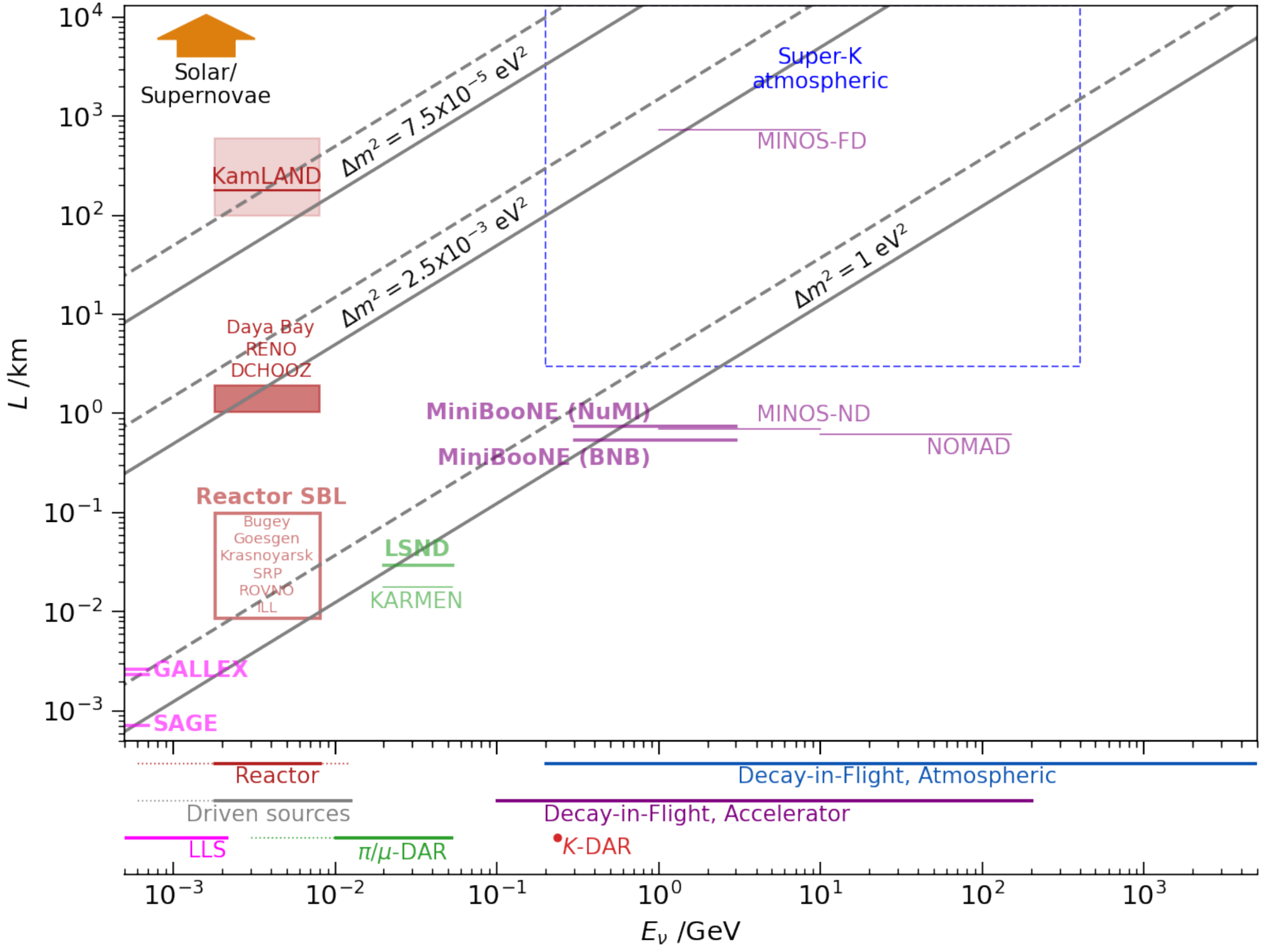
Reactor SBL re-analyzed in 2011

Mention (2011)



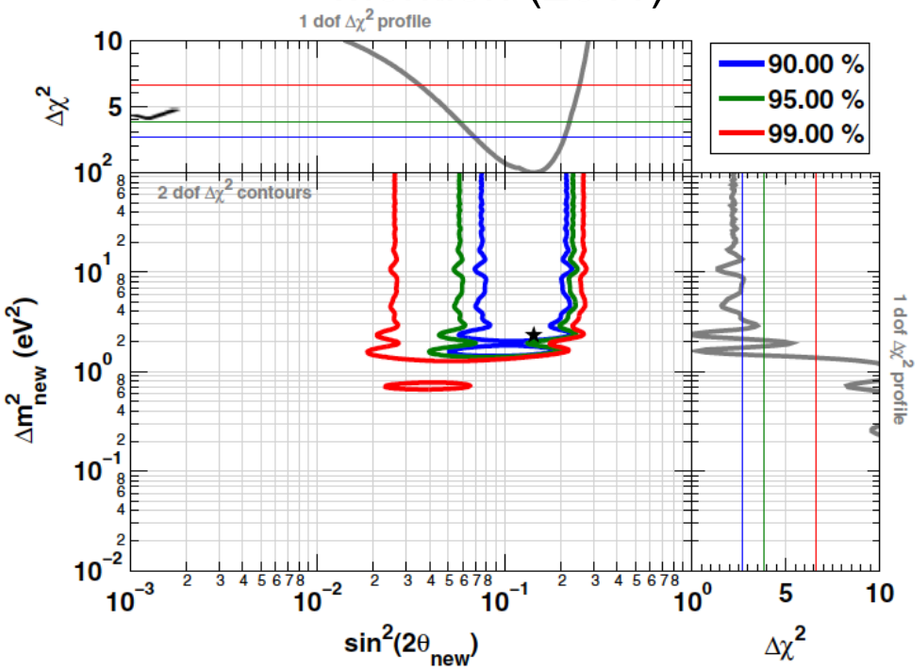
- Updated calculation of reactor $\bar{\nu}$ spectrum (Huber and Mueller).
- Decreased neutron lifetime.
- 6% deficit of the measured yield in average from expected value.

By 2013,

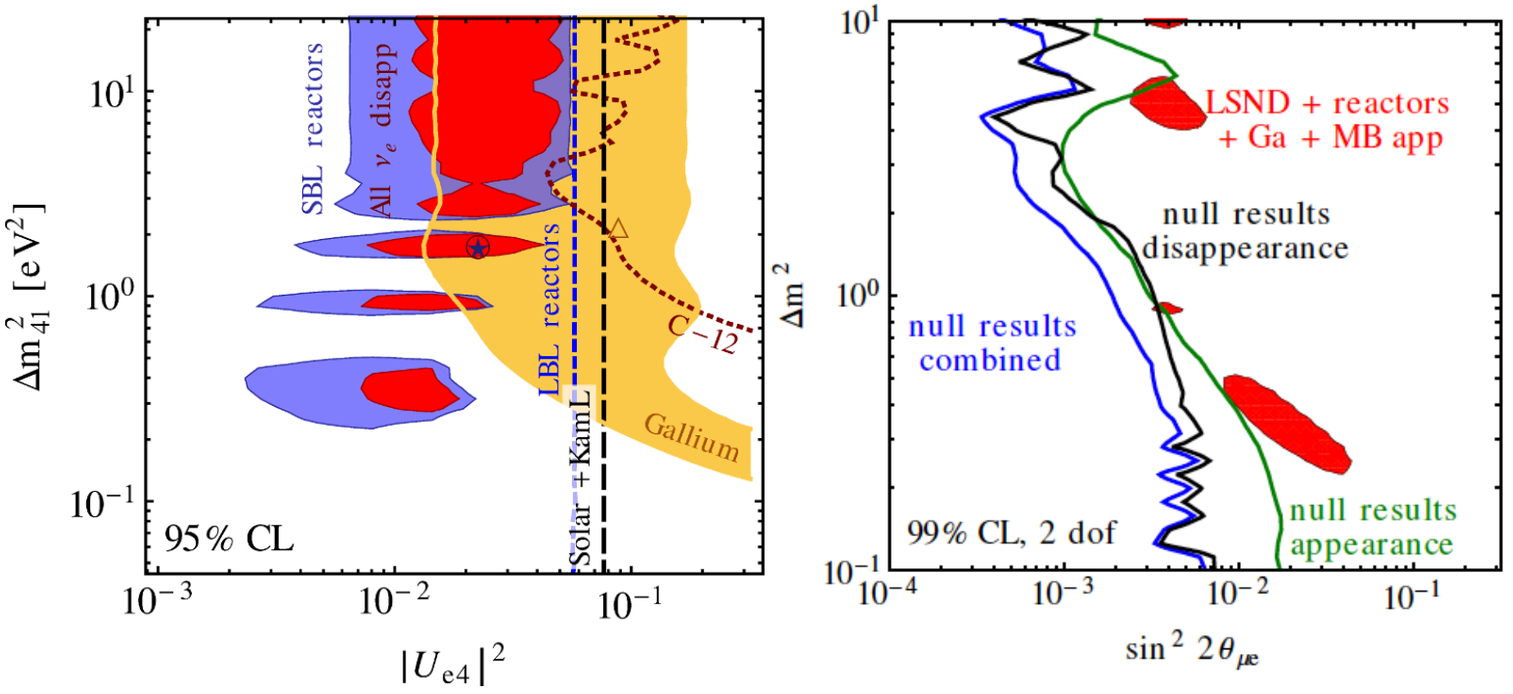

Solar/
Supernovae
KamLAND
Daya Bay
RENO
DCHOOZ
Reactor SBL
Bugey
Goesgen
Krasnoyarsk
SRP
ROVNO
ILL
GALLEX
SAGE
LSND
KARMEN
Super-K
atmospheric
MINOS-FD
MiniBooNE (NuMI)
MiniBooNE (BNB)
MINOS-ND
NOMAD
$\Delta m^2 = 7.5\text{x}10^{-5}$ eV^2
$\Delta m^2 = 2.5\text{x}10^{-3}$ eV^2
$\Delta m^2 = 1$ eV^2
L /km
E_ν /GeV
Reactor
Driven sources
LLS
π/μ-DAR
Decay-in-Flight, Atmospheric
Decay-in-Flight, Accelerator
K-DAR

Global analysis, 3+1 framework

Mention (2011)



Kopp (2013)



Diaz (2020)

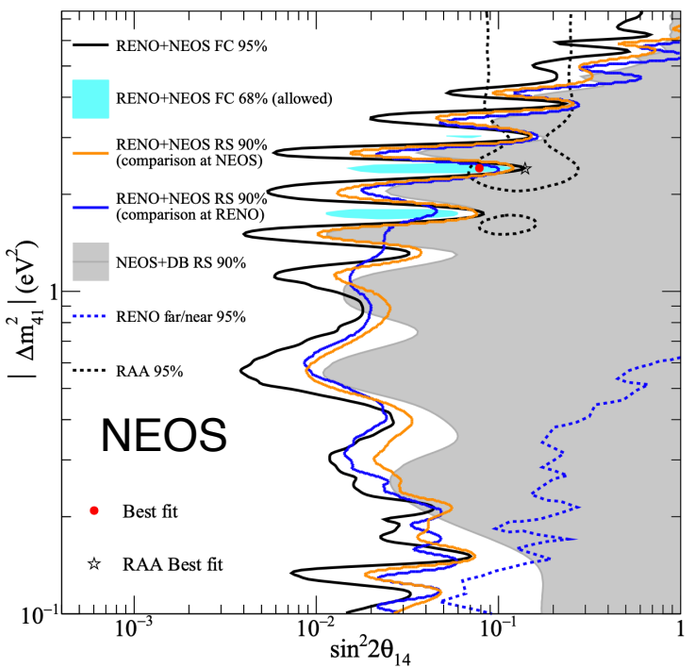
$\sin^2 2\theta_{ee}$	$= \sin^2 2\theta_{14}$	$= 4(1-\lvert U_{e4}\rvert^2)\lvert U_{e4}\rvert^2$
$\sin^2 2\theta_{\mu\mu}$	$= 4\cos^2\theta_{14}\sin^2\theta_{24}(1-\cos^2\theta_{14}\sin^2\theta_{24})$	$= 4(1-\lvert U_{\mu4}\rvert^2)\lvert U_{\mu4}\rvert^2$
$\sin^2 2\theta_{\tau\tau}$	$= 4\cos^2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34}(1-\cos^2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34})$	$= 4(1-\lvert U_{\tau4}\rvert^2)\lvert U_{\tau4}\rvert^2$
$\sin^2 2\theta_{\mu e}$	$= \sin^2 2\theta_{14}\sin^2\theta_{24}$	$= 4\lvert U_{\mu4}\rvert^2\lvert U_{e4}\rvert^2$
$\sin^2 2\theta_{e\tau}$	$= \sin^2 2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34}$	$= 4\lvert U_{e4}\rvert^2\lvert U_{\tau4}\rvert^2$
$\sin^2 2\theta_{\mu\tau}$	$= \sin^2 2\theta_{24}\cos^4\theta_{14}\sin^2\theta_{34}$	$= 4\lvert U_{\mu4}\rvert^2\lvert U_{\tau4}\rvert^2$

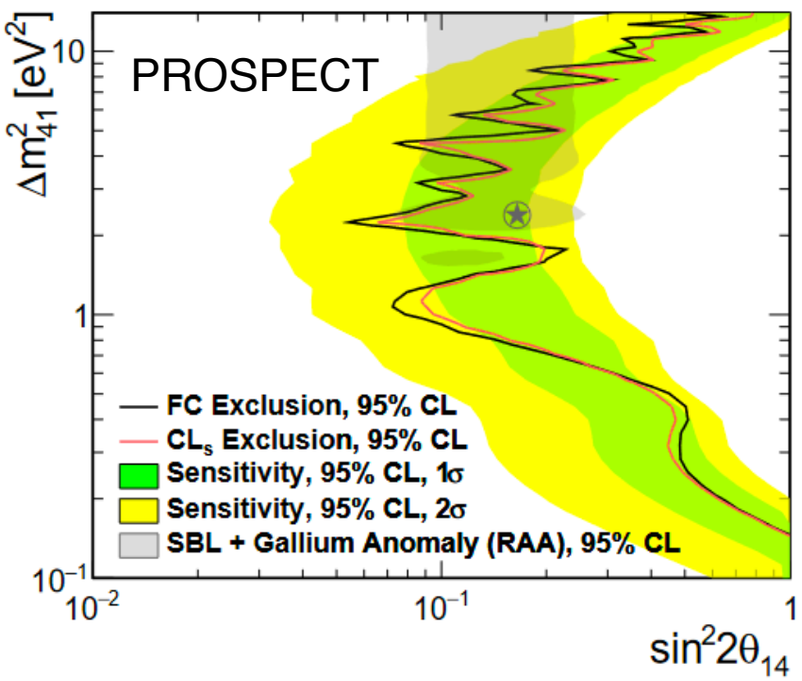
TABLE III: 3+1 Sterile Neutrino Mixing Parameter Cheatsheet

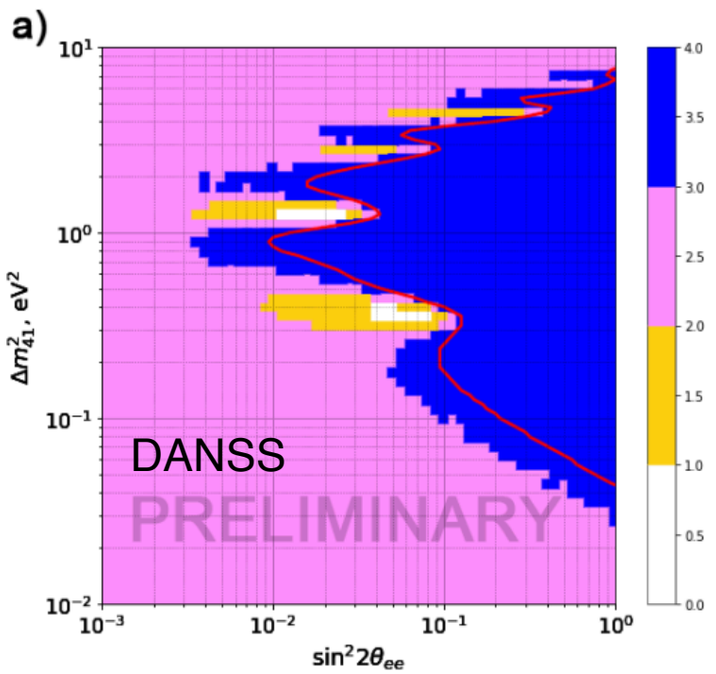
In the last decade,

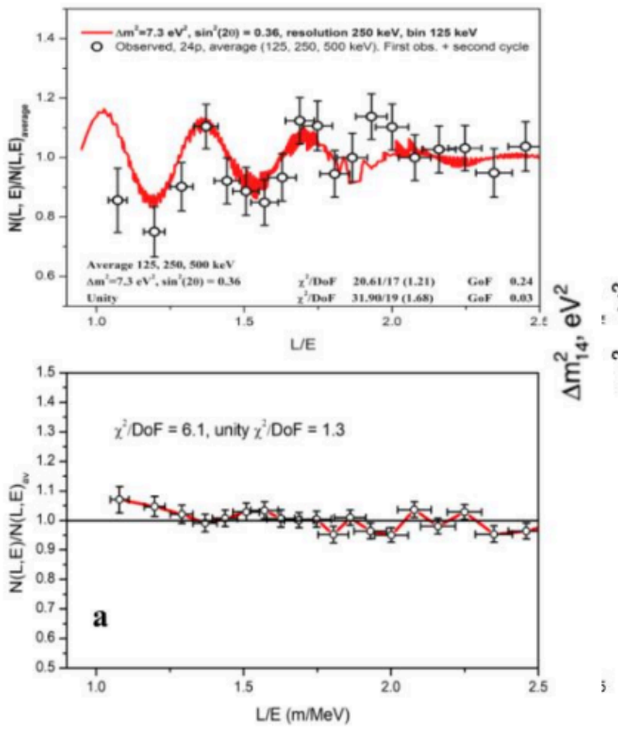
- Reactor:
  - Precision results from Daya Bay, Double Chooz, RENO.
  - New SBL experiments: DANSS, NEOS, Neutrino-4, PROSPECT, STEREO, Solid, …
- Accelerator:
  - More statistics from MiniBooNE, more significant LEE,
  - MINOS/MINOS+,
  - MicroBooNE launched (LArTPC),
  - JSNS^2 launched.
- Source: BEST to check Ga anomaly
- Others: IceCube, …

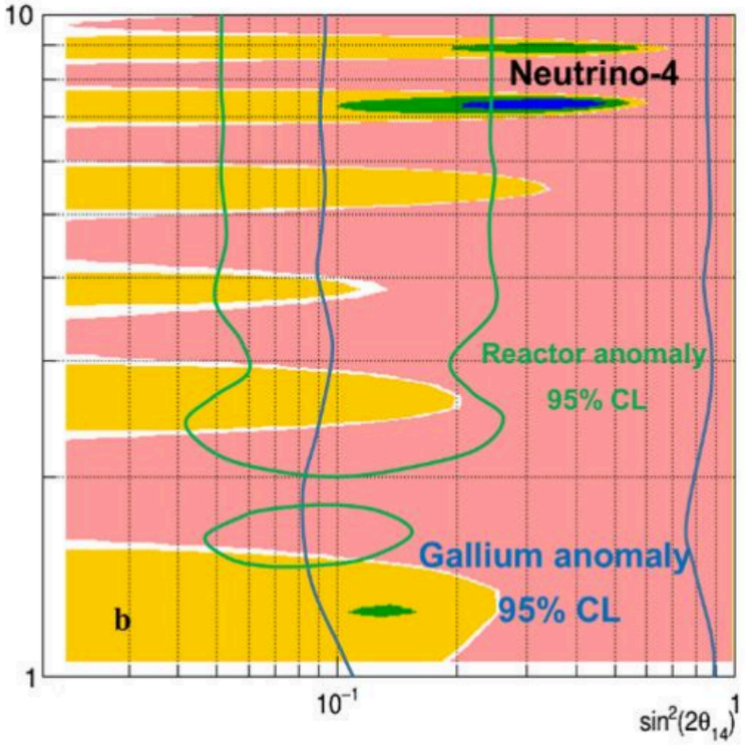
Reactor SBL

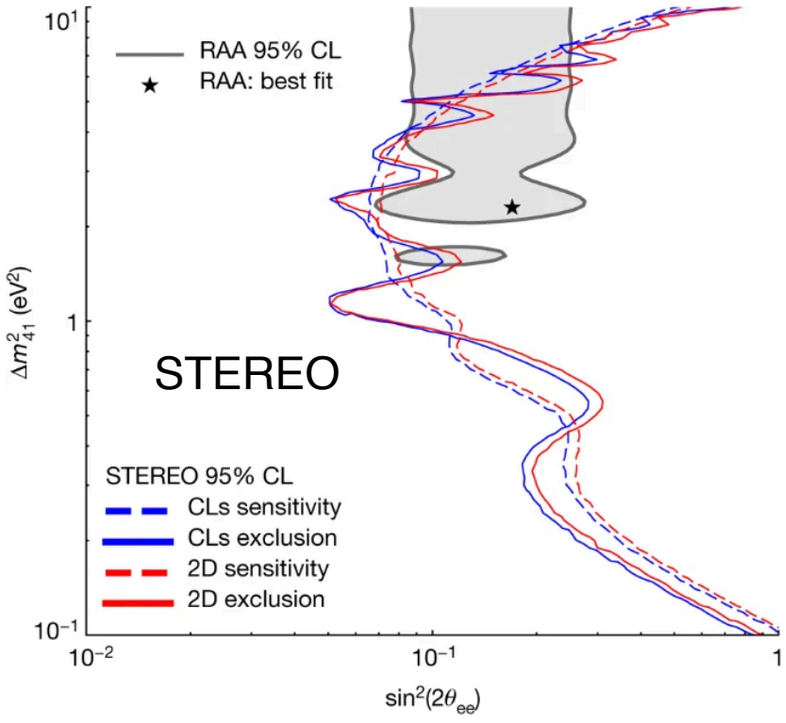

RENO+NEOS FC 95%
RENO+NEOS FC 68% (allowed)
RENO+NEOS RS 90% (comparison at NEOS)
RENO+NEOS RS 90% (comparison at RENO)
NEOS+DB RS 90%
RENO far/near 95%
RAA 95%
NEOS
Best fit
RAA Best fit
$|\Delta m^2_{41}|$ (eV^2)
$\sin^2 2\theta_{14}$


PROSPECT
FC Exclusion, 95% CL
CL$_s$ Exclusion, 95% CL
Sensitivity, 95% CL, 1σ
Sensitivity, 95% CL, 2σ
SBL + Gallium Anomaly (RAA), 95% CL
Δm^2_{41} [eV^2]
$\sin^2 2\theta_{14}$


a)
DANSS
PRELIMINARY
Δm^2_{41}, eV^2
$\sin^2 2\theta_{ee}$


Δm^2=7.3 eV^2, sin^2(2θ) = 0.36, resolution 250 keV, bin 125 keV
Observed, 24p, average (125, 250, 500 keV). First obs. + second cycle
N(L, E)/N(L,E)$_{average}$
L/E
χ^2/DoF = 6.1, unity χ^2/DoF = 1.3
N(L,E)/N(L,E)$_{fit}$
a
L/E (m/MeV)

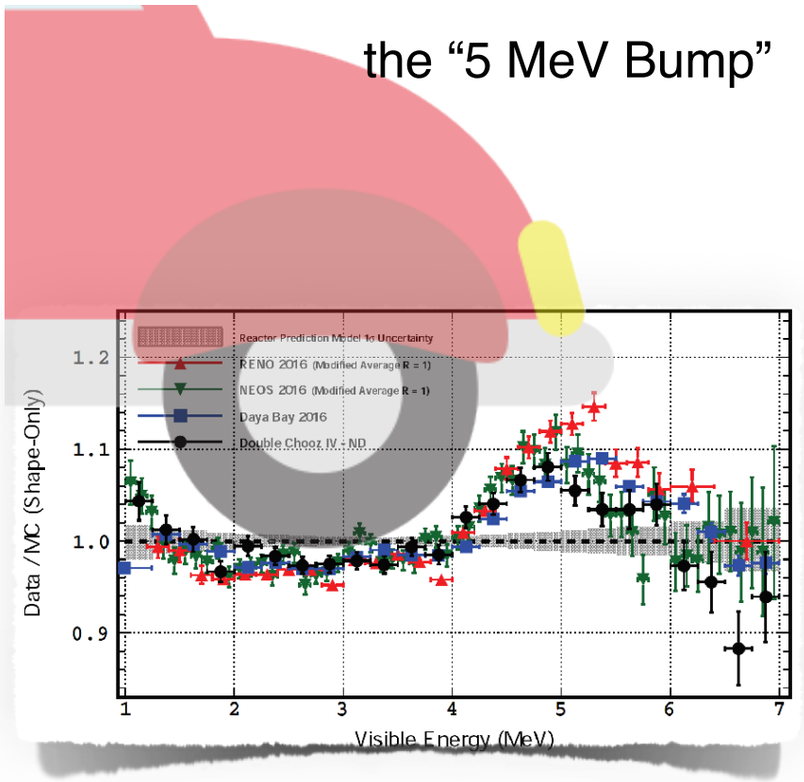

Neutrino-4
Reactor anomaly
95% CL
Gallium anomaly
95% CL
b
Δm^2_{14}, eV^2
$\sin^2(2\theta_{14})$

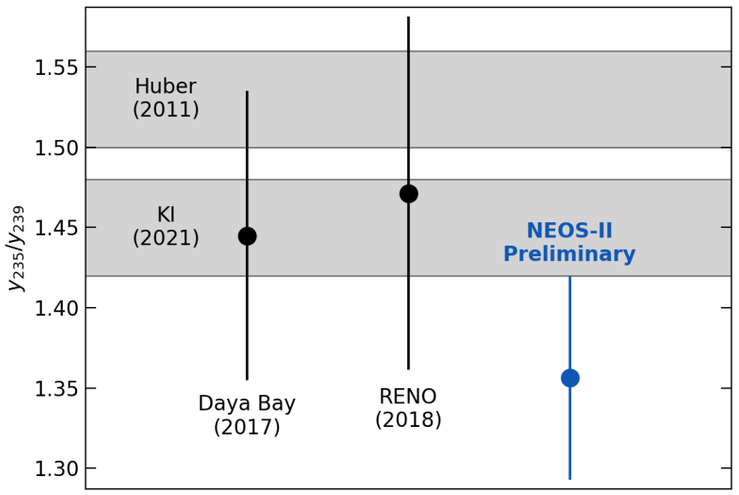

RAA 95% CL
RAA: best fit
STEREO
STEREO 95% CL
CLs sensitivity
CLs exclusion
2D sensitivity
2D exclusion
Δm^2_{41} (eV^2)
$\sin^2(2\theta_{ee})$

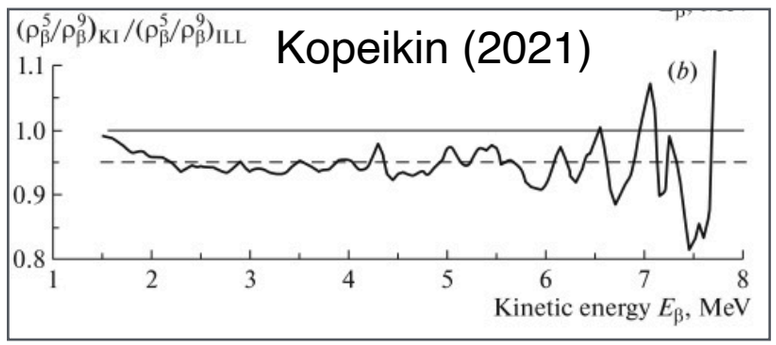
Reactor-ν

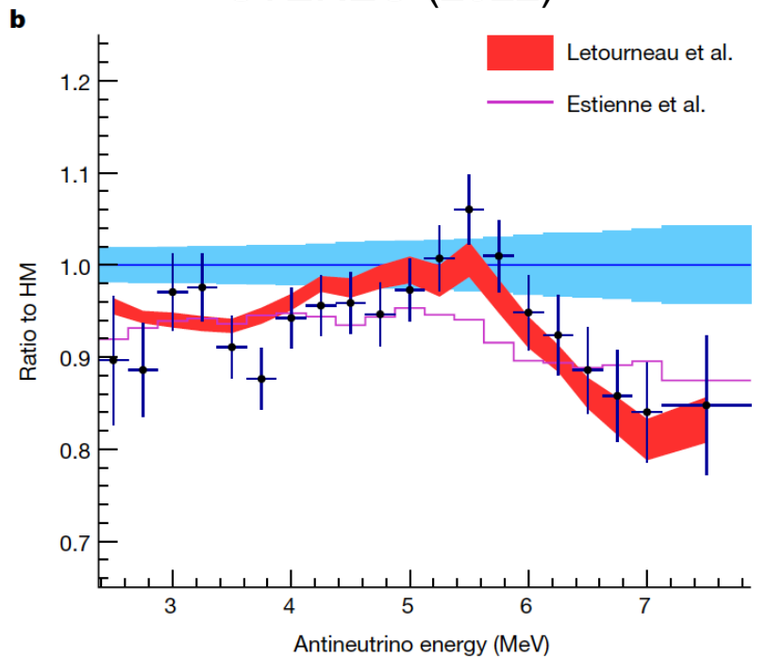
Shape anomaly and expected flux

the “5 MeV Bump”





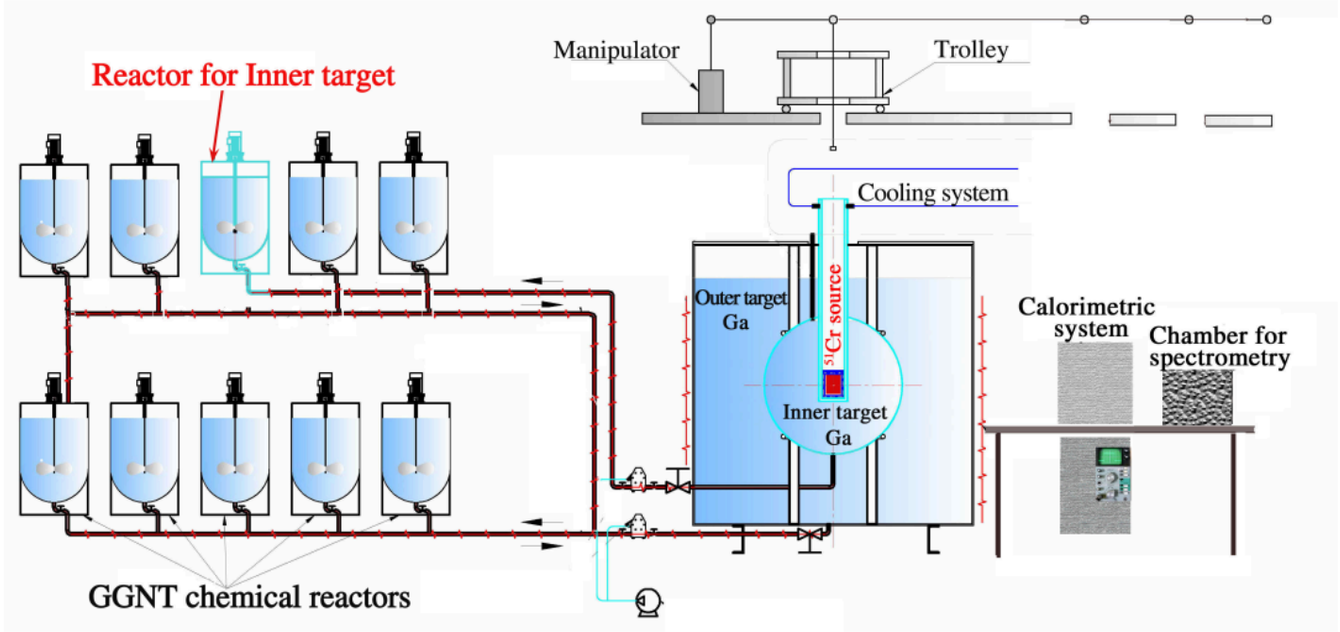




- Problem in the flux estimation in 2011 by conversion method.
- β spectrum ratio ϕ_{235}/ϕ_{239} was overestimated in ILL experiment.
- Some updated summation methods reproduce measured spectrum better.

BEST (2022)

The Baksan Experiment for Sterile Transitions



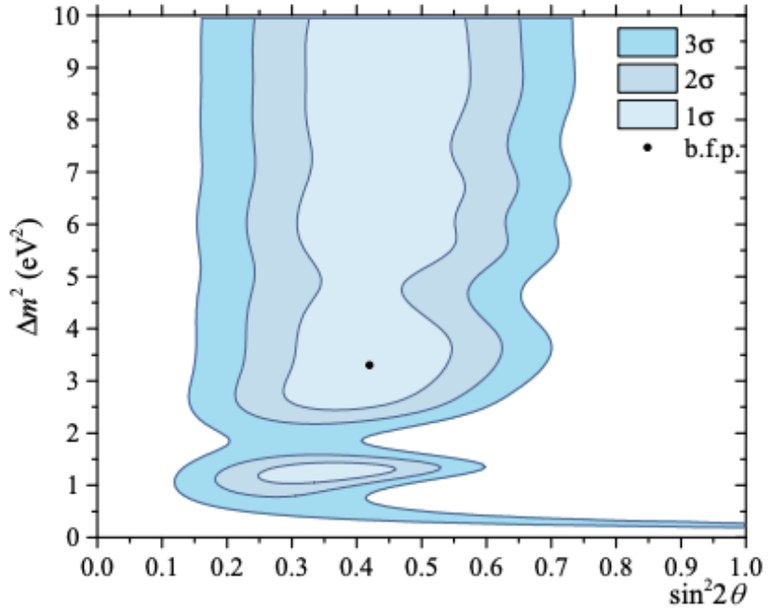
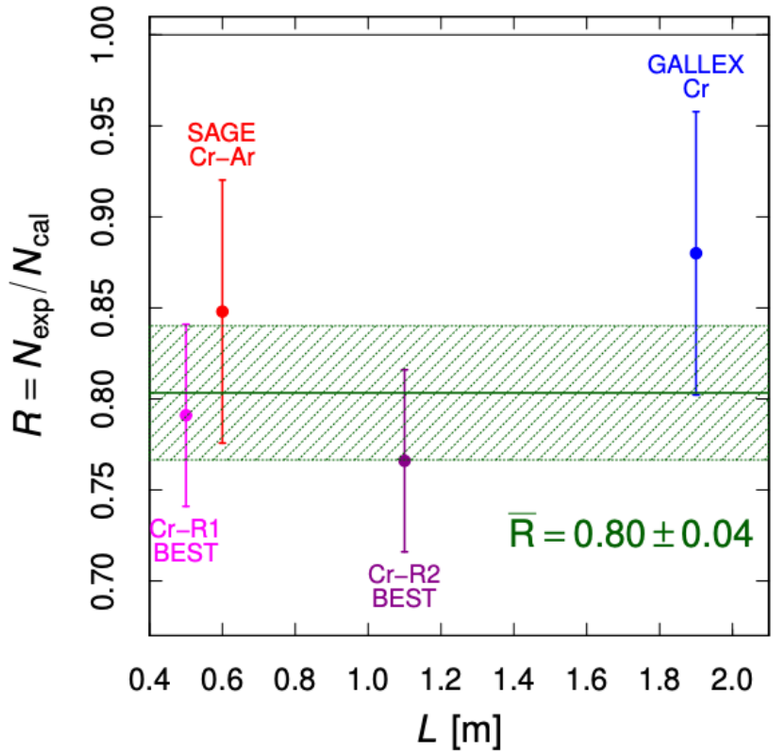
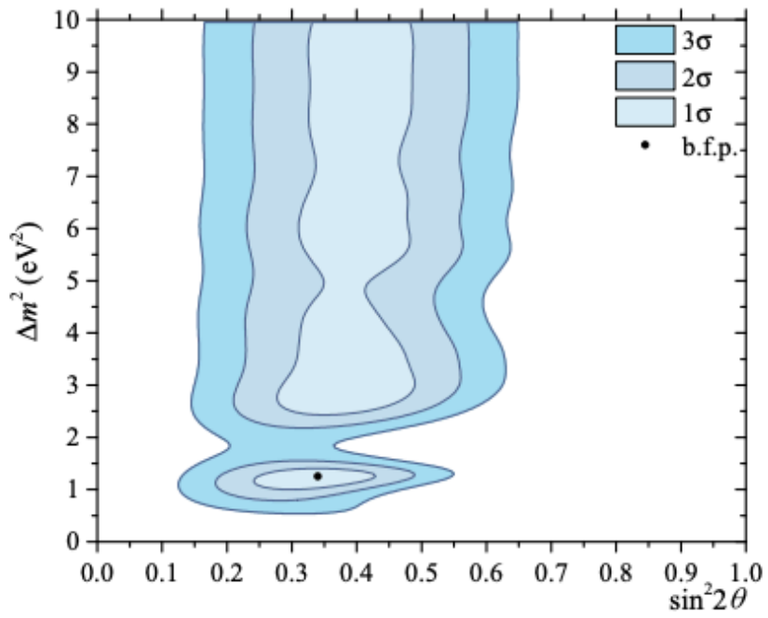


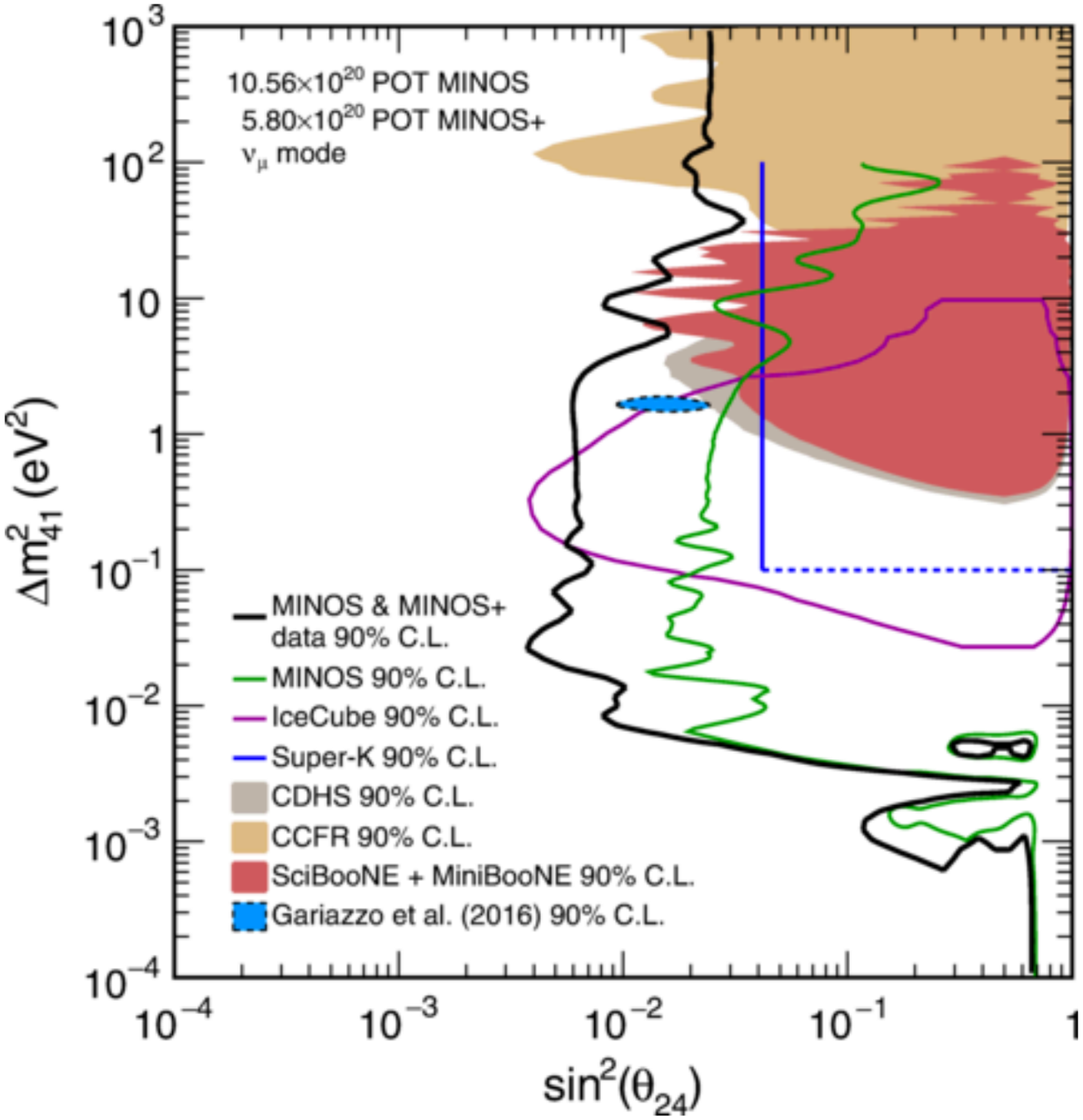
FIG. 10. Allowed regions for two BEST results. The best-fit point is $\sin^2 2\theta = 0.42^{+0.15}_{-0.17}$, $\Delta m^2 = 3.3^{+\infty}_{-2.3}$ eV^2 and is indicated by a point.

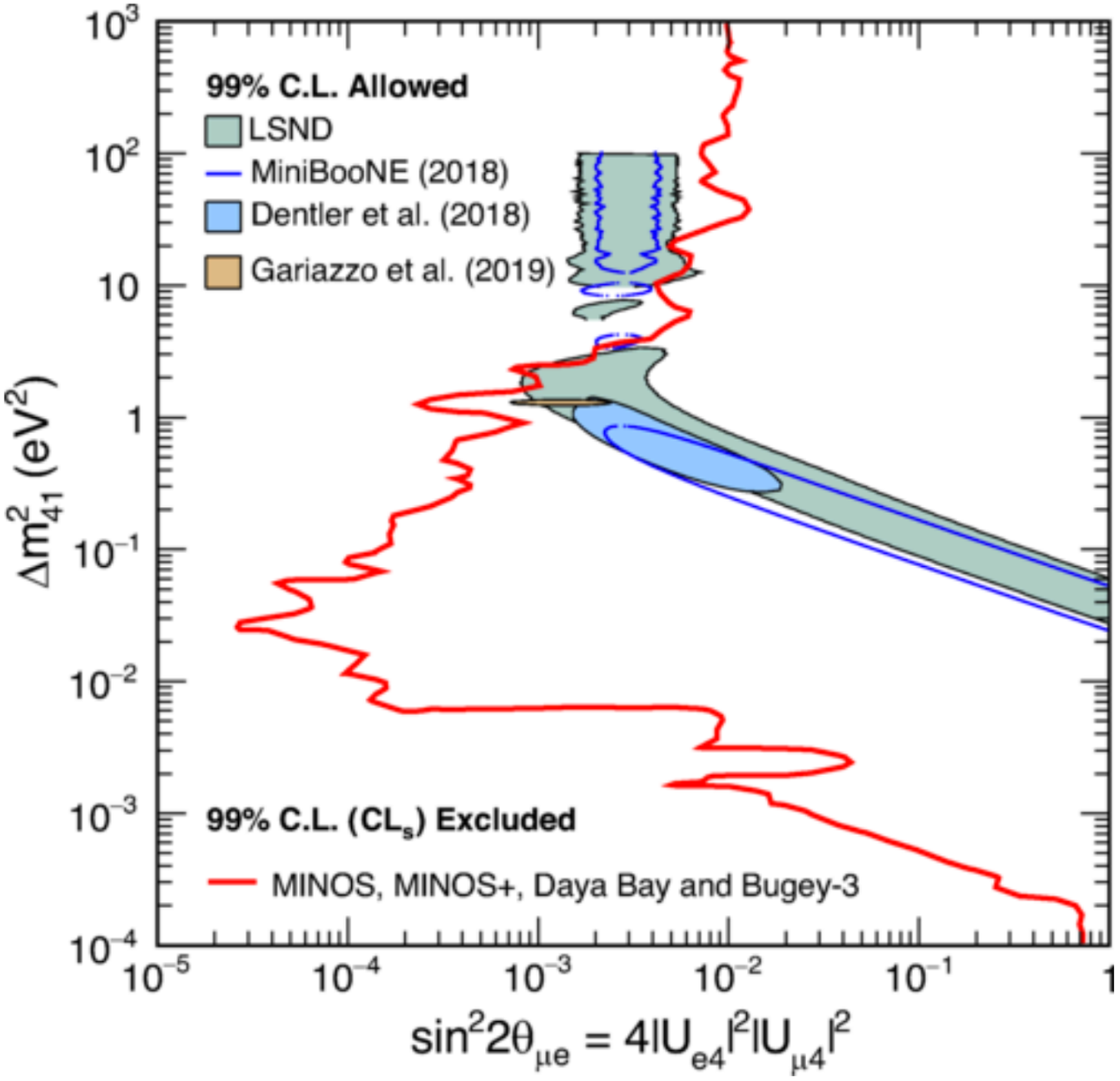




MINOS/MINOS+

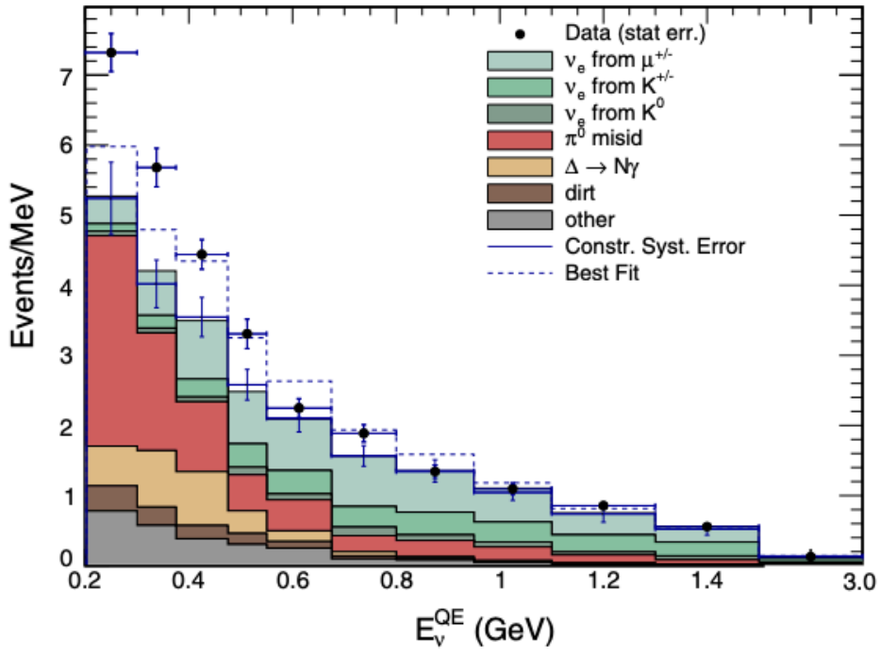
and combined with reactor data (2020)

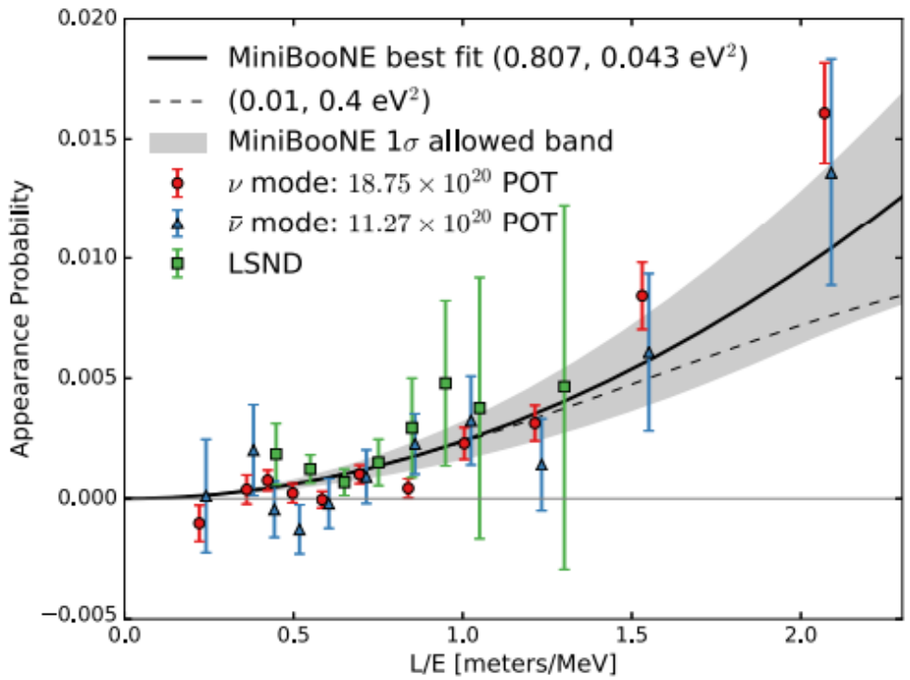


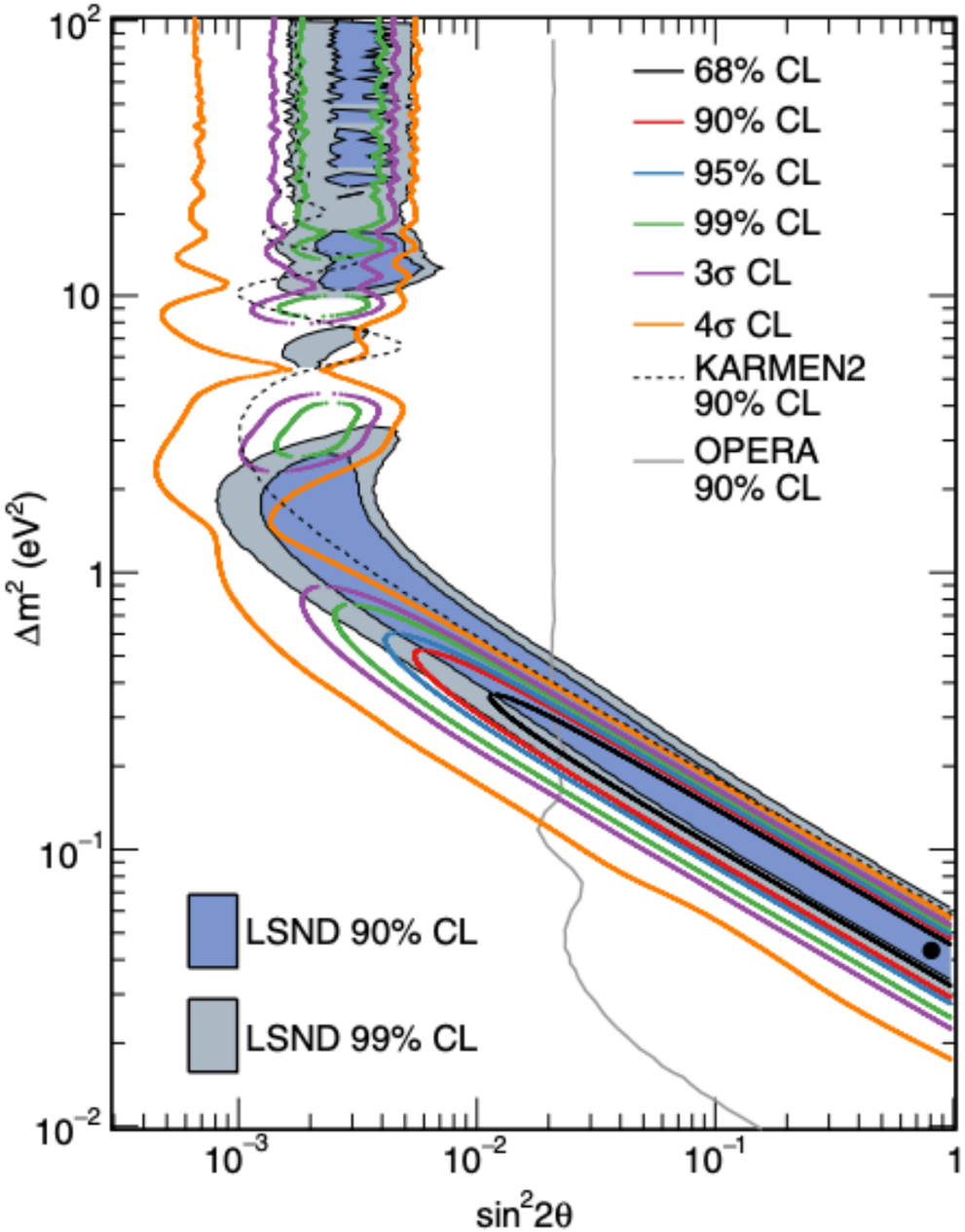


MiniBooNE update in 2021

LEE more significant (4.8σ)

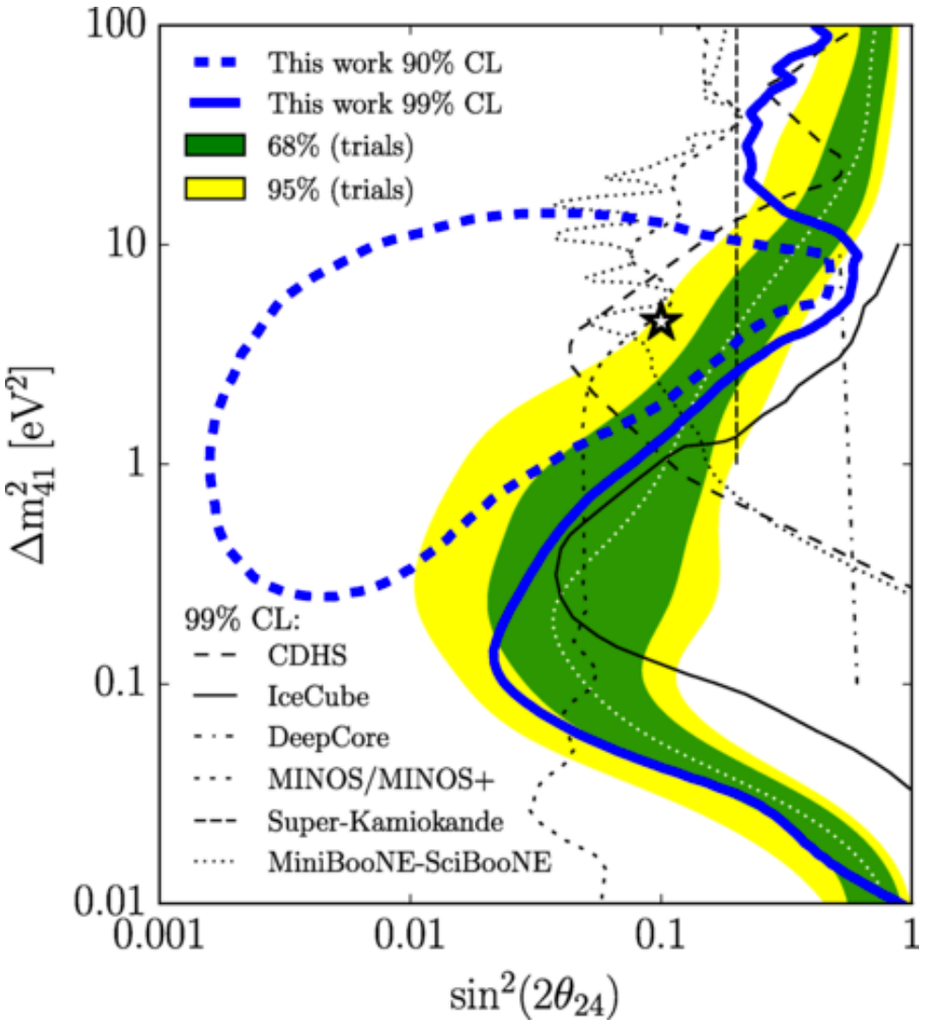




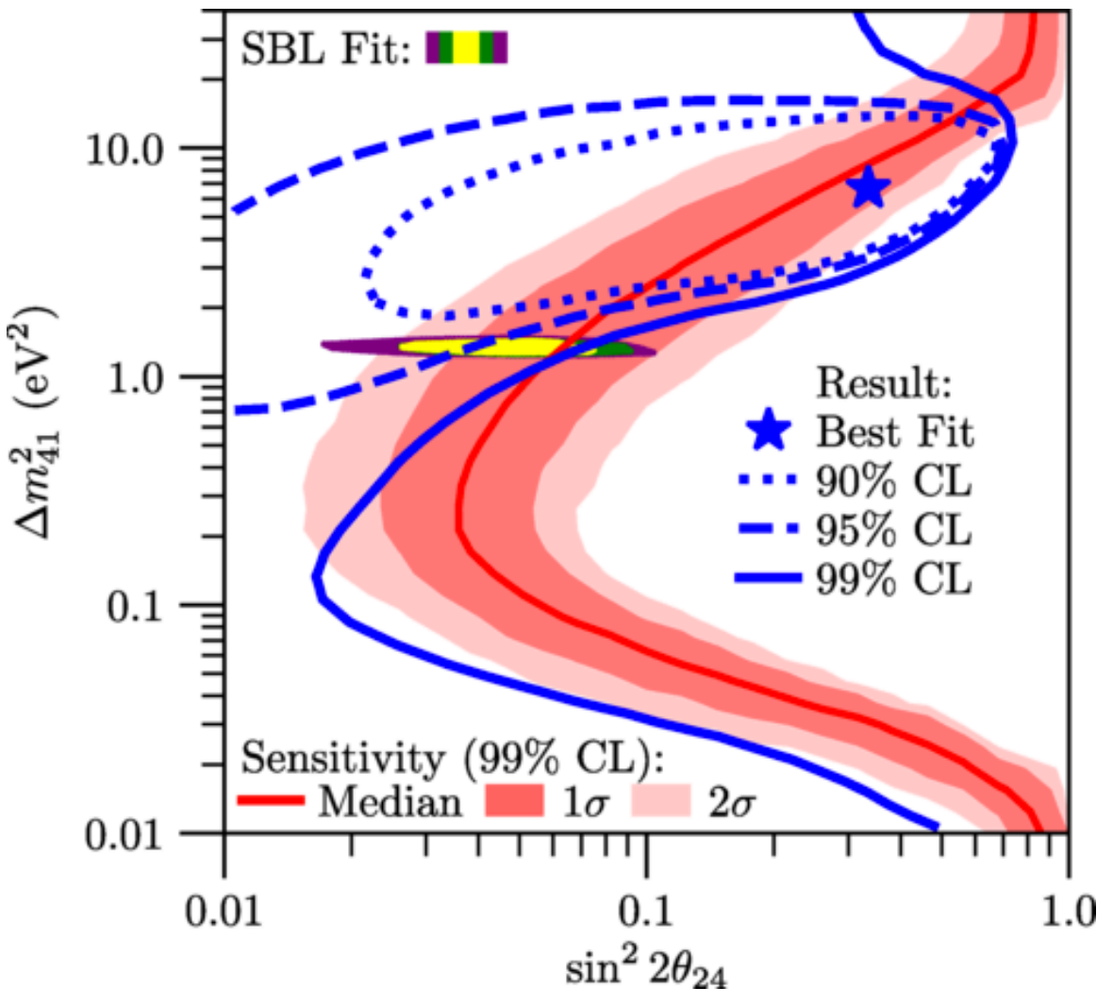


IceCube

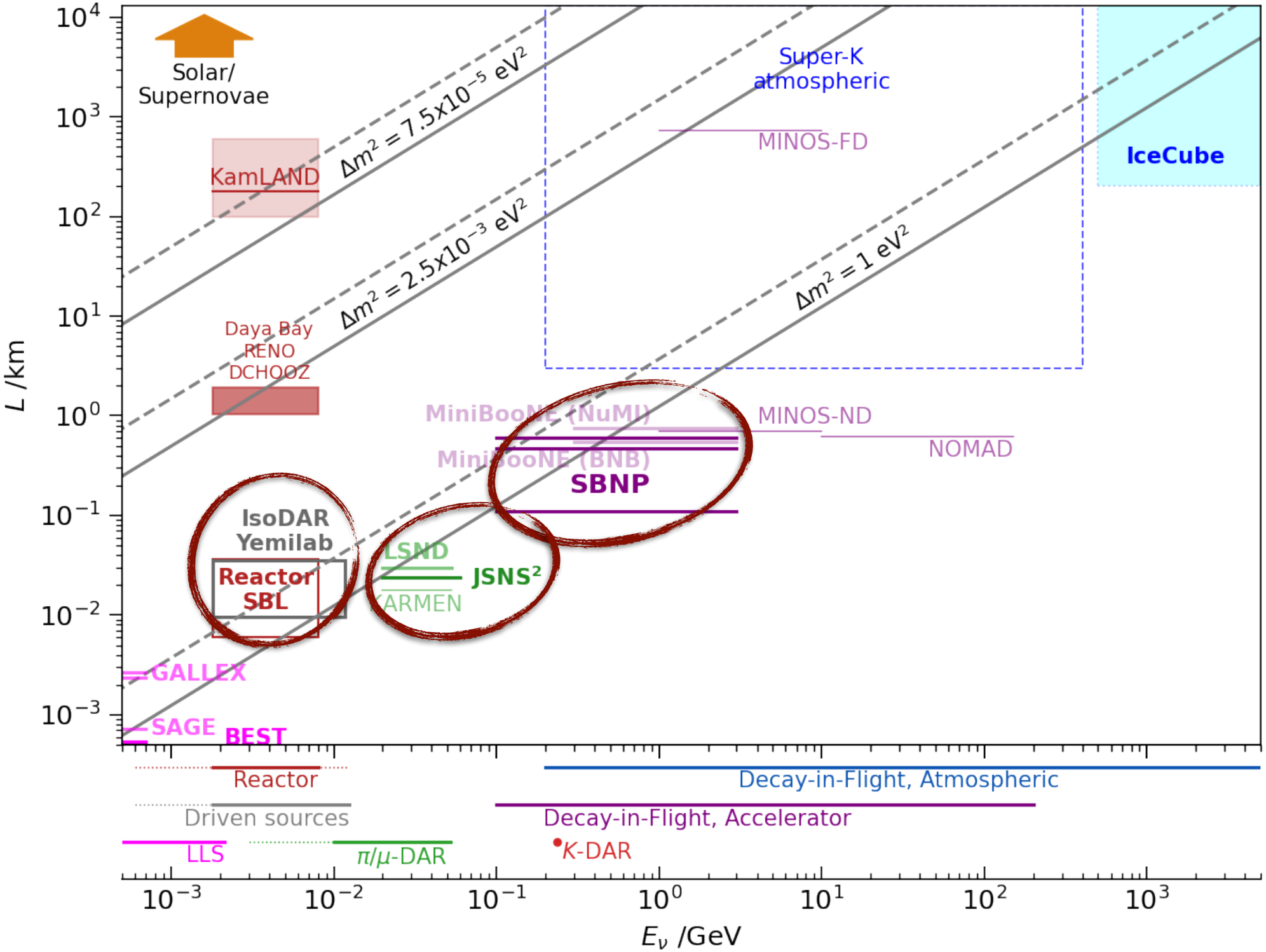
3+1 analysis (2020)



3+1+decay analysis (2022)

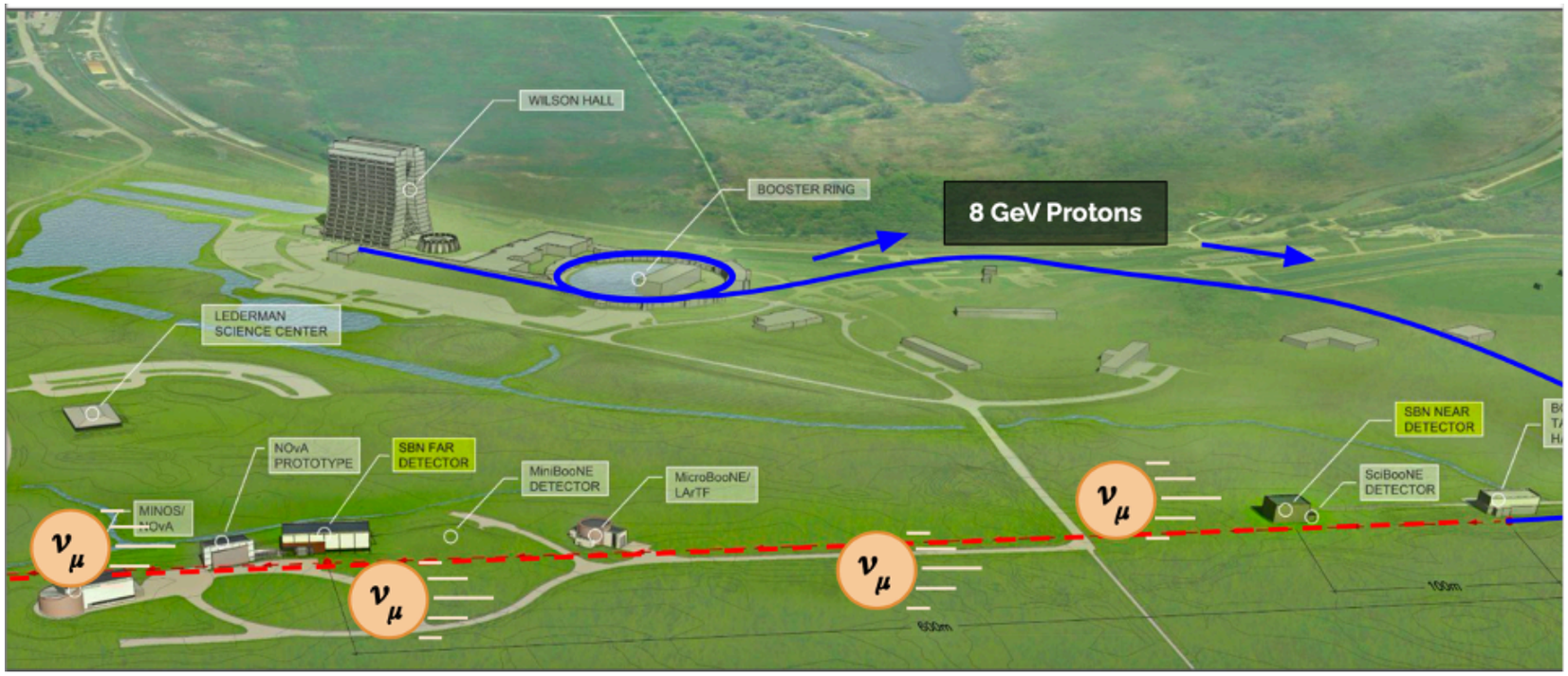


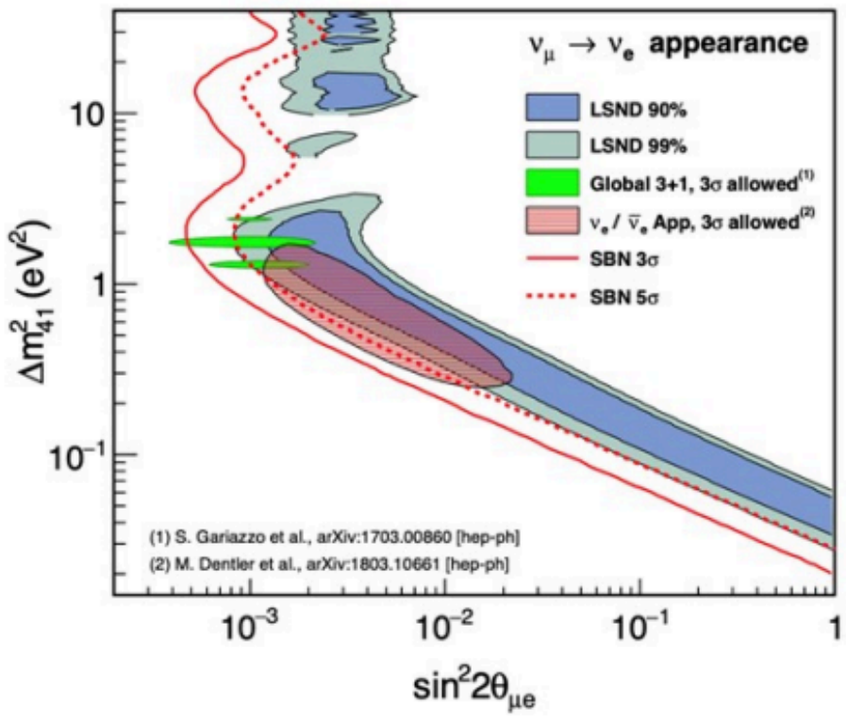
Active / future experiments

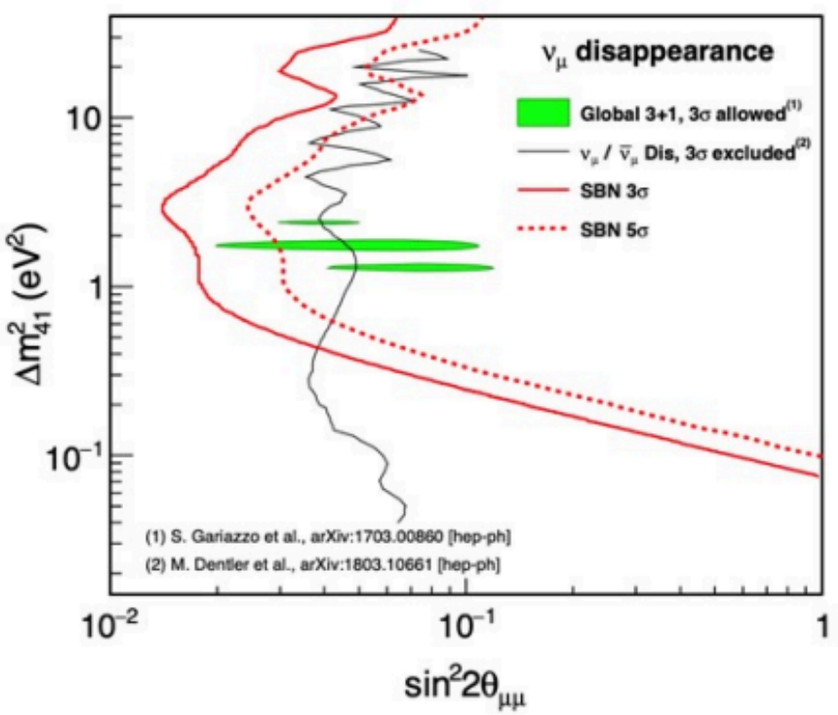


SBN program @ Fermilab

+ ICARUS as far detector of SBND in Phase-II

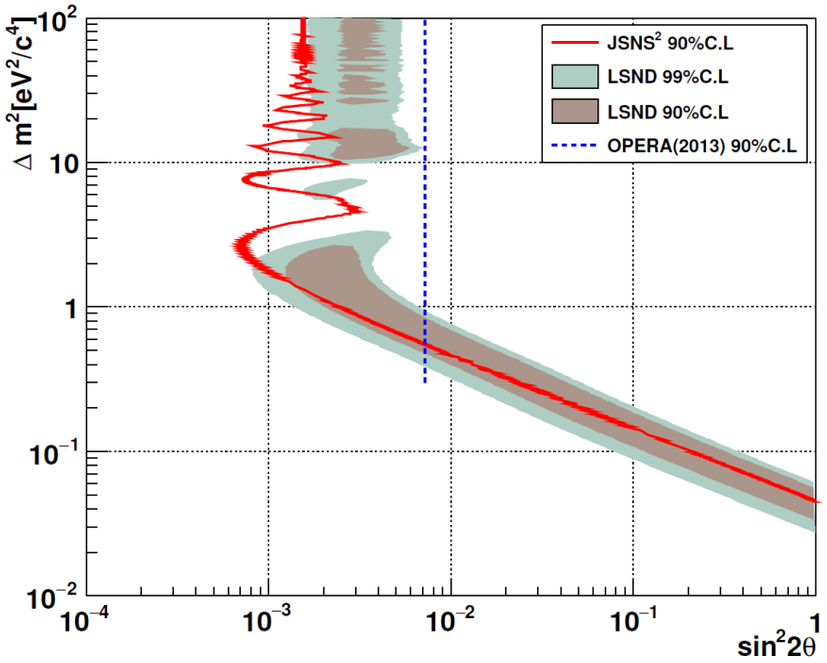


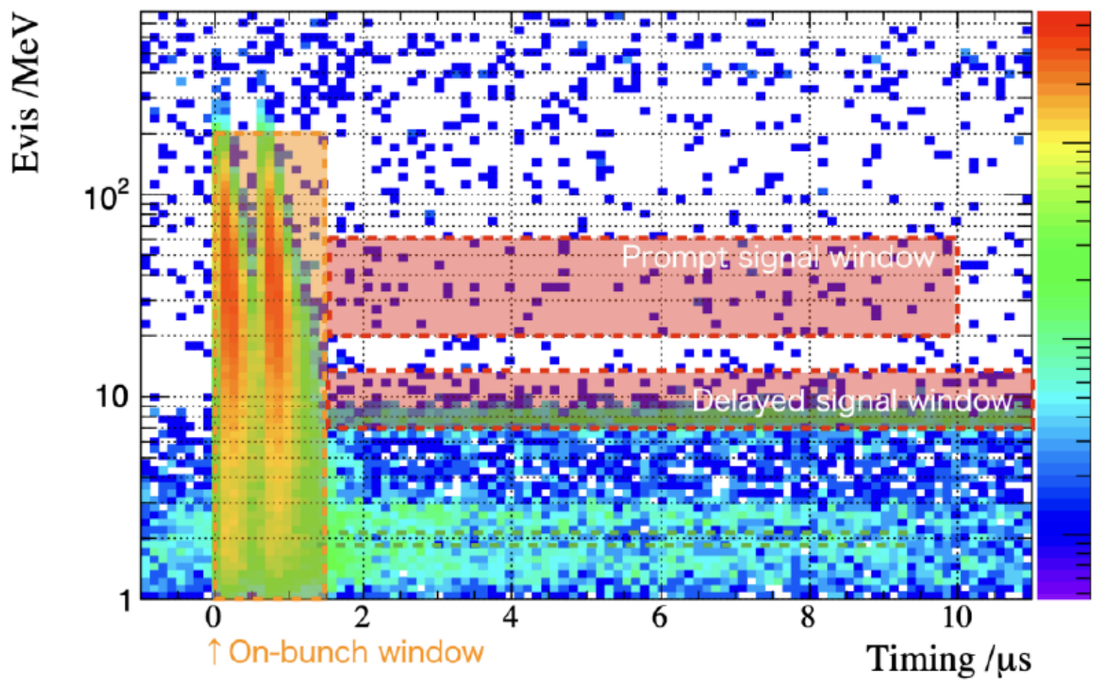




JSNS²

verification of LSND anomaly

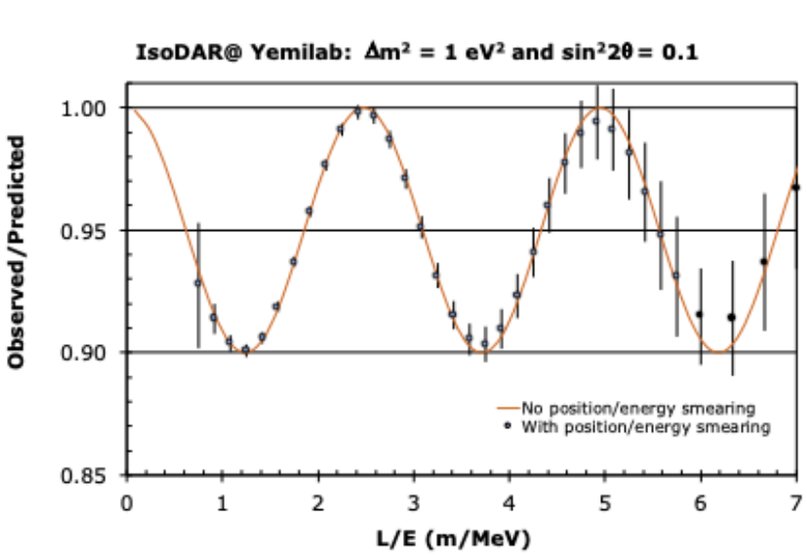


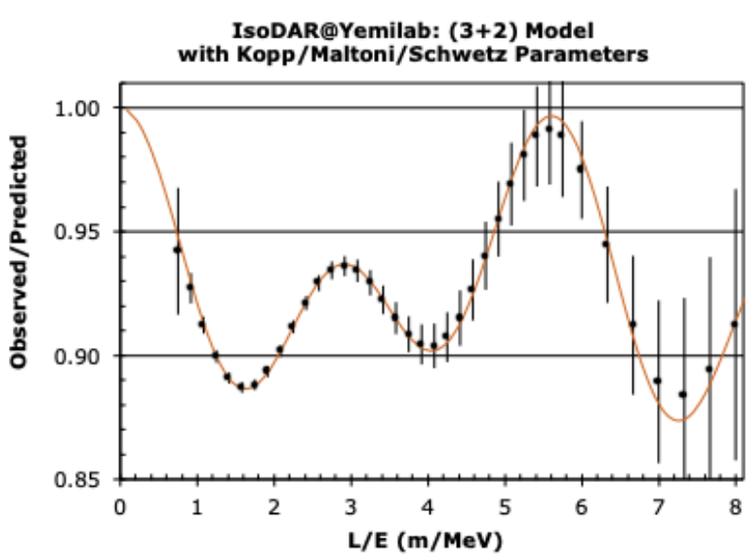


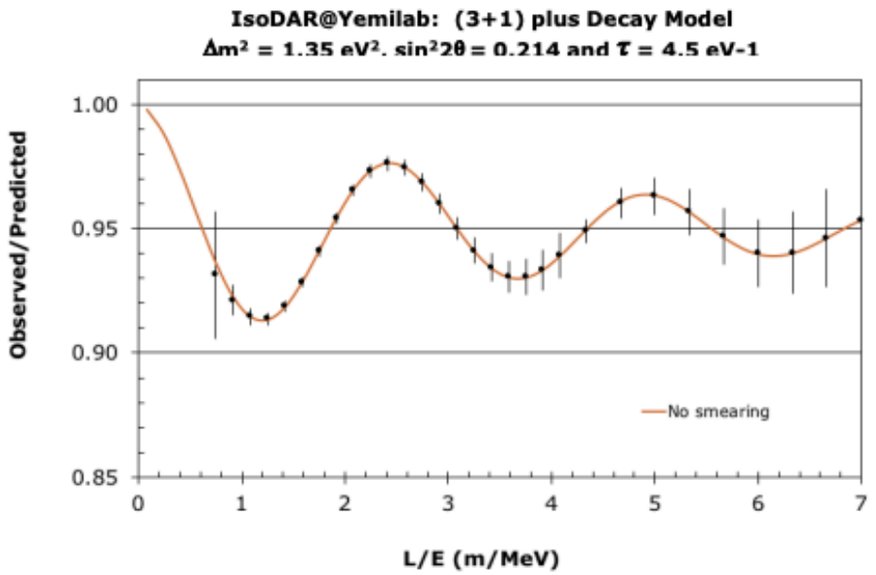
- Same source (π/μ-DAR) and detection channel (IBD), but
- Improved in IBD-n-capture identification (Gd-LS), PSD, fine pulsed beam.
- Struggling with cosmic-induced fast-n.
- Details in Dr. Ryeonggyoon Park's talk, yesterday.

Reactor, driven source

- Reactor:
  - Solid is running at BR-2 reactor.
  - JUNO-TAO: extreme energy resolution~2% at 1 MeV.
  - PROSPECT, Neutrino-4, DANSS have upgrade plans.
- IsoDAR @ Yemilab:
  - ^{8}Li-DAR produced with ^{9}Be target hit by H_2^+ from high power cyclotron.
  - Measured using 2.5 kt LS counter.

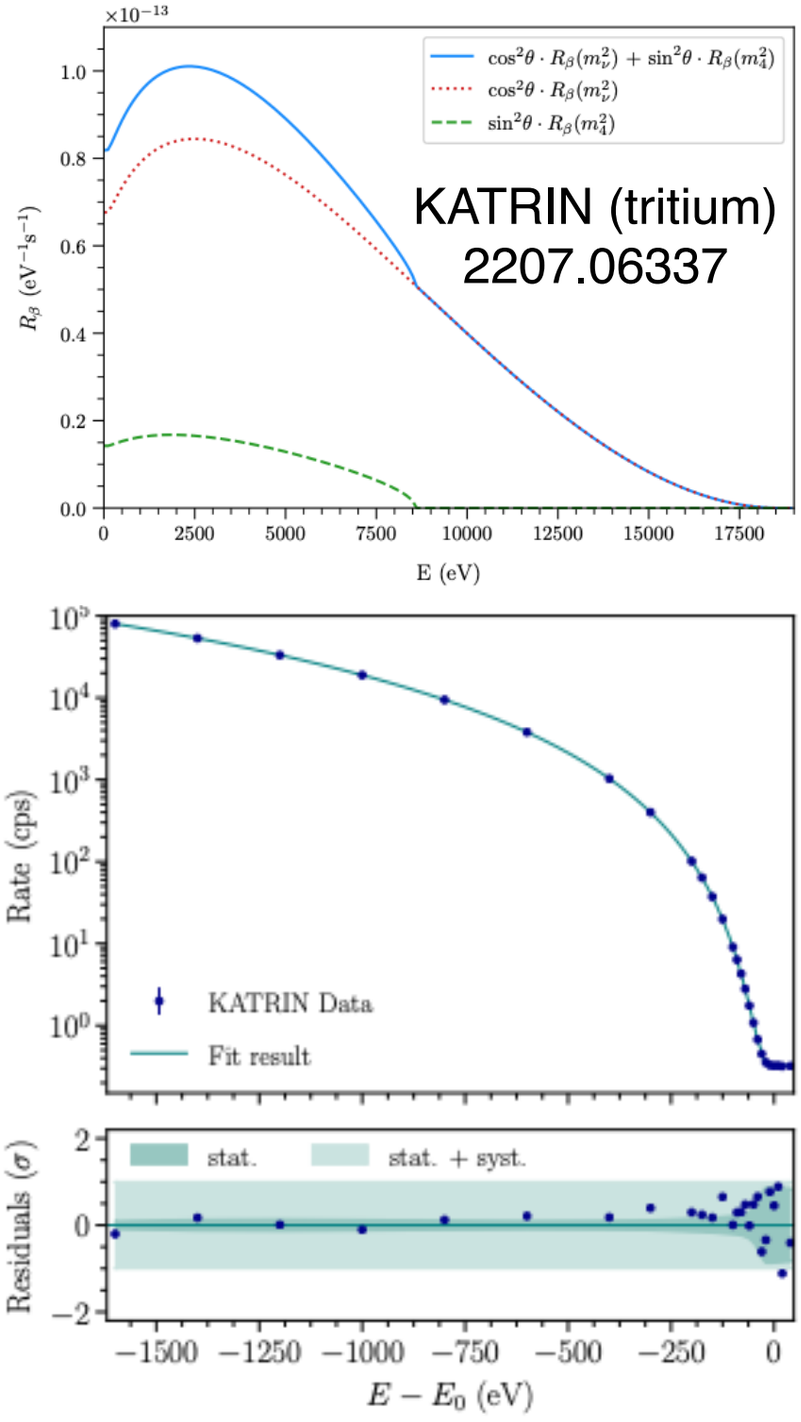


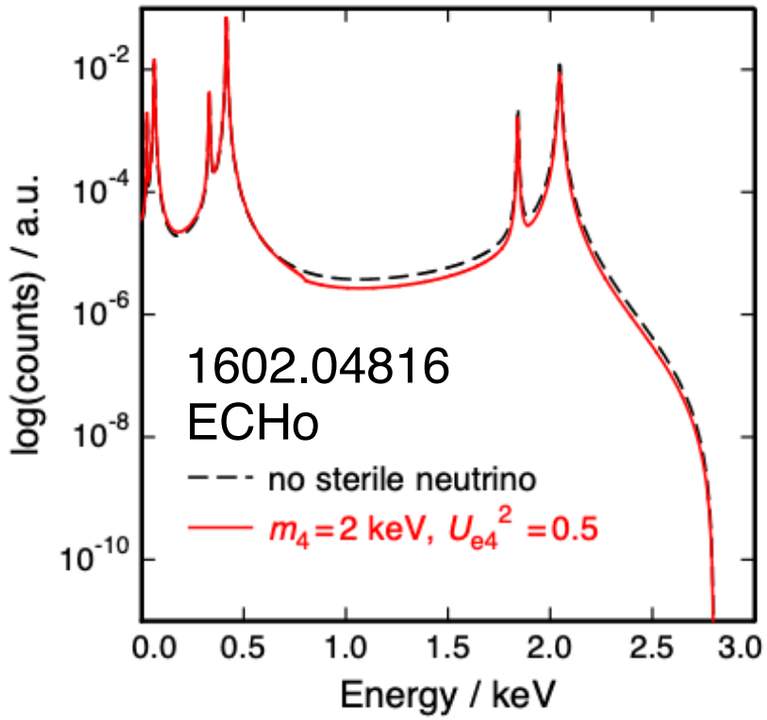


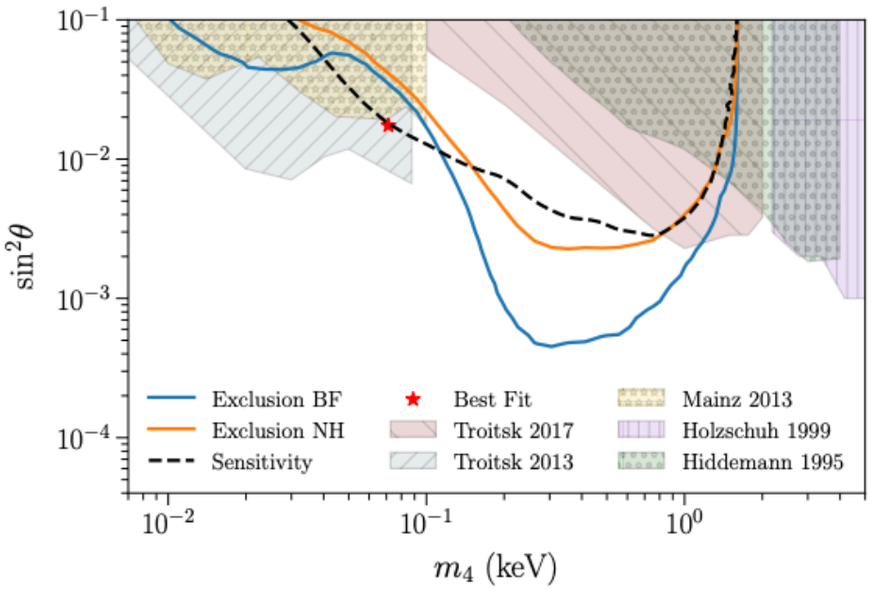


Glimpse on higher mass range

Probing keV scale at laboratory







Closing

- Experiments mainly sensitive to Δm^2 [eV^2]~E [MeV/GeV]/L [m/km] have been reviewed in the 3+1ν framework.
  - Reactor: no strong oscillation signature found, except for neutrino-4.
  - But minima at Δm^2~1-2 eV^2 found in most experiments.
- Source: Ga anomaly persists.
- Accelerator: strong disagreement between app. and disapp. channels.

- To be verified by active/future experiments.
- Theoretical explanation better than 3+α ν???

Thank you

Remark on ν-osc study

Qian et al, NIM 827A, 63 (2016)

$\Delta\chi^2$ and confidence level

- Best fit always found at along the edge of the experimental sensitivity, even there is no true signal ($\sin^2 2\theta=0$).
- $\Delta\chi^2 = \chi^2_{4\nu,\text{best}} - \chi^2_{3\nu} > 0$.
- $\Delta\chi^2$ distribution does not follow the χ^2 distribution of 2-DOF.
- $\Delta\chi^2$ distribution of individual experiment is determined by its own sizes of systematic uncertainties.
- Combination of the experimental results by addition of their χ^2 and looking-up the χ^2 table does not tell the correct confidence level.