中微子振荡的实验证据

Solar neutrinos

Reactions

pp chain:

$$p + p \to d + e^+ + \nu_e$$

$$p + e^- + p \to d + \nu_e$$

$$^3\mathrm{He} + p \to {}^4\mathrm{He} + e^+ + \nu_e$$

$$^7\mathrm{Be} + e^- \to {}^7\mathrm{Li} + \nu_e(+\gamma)$$

$$^8\mathrm{B} \to {}^8\mathrm{Be}^* + e^+ + \nu_e$$

CNO cycle:

$$^{13}\mathrm{N} \to {}^{13}\mathrm{C} + e^+ + \nu_e$$

$$^{15}\mathrm{O} \to {}^{15}\mathrm{N} + e^+ + \nu_e$$

$$^{17}\mathrm{F} \to {}^{17}\mathrm{O} + e^+ + \nu_e$$

overall fusion of protons: $4p \to {}^4\mathrm{He} + 2e^+ + 2\nu_e$

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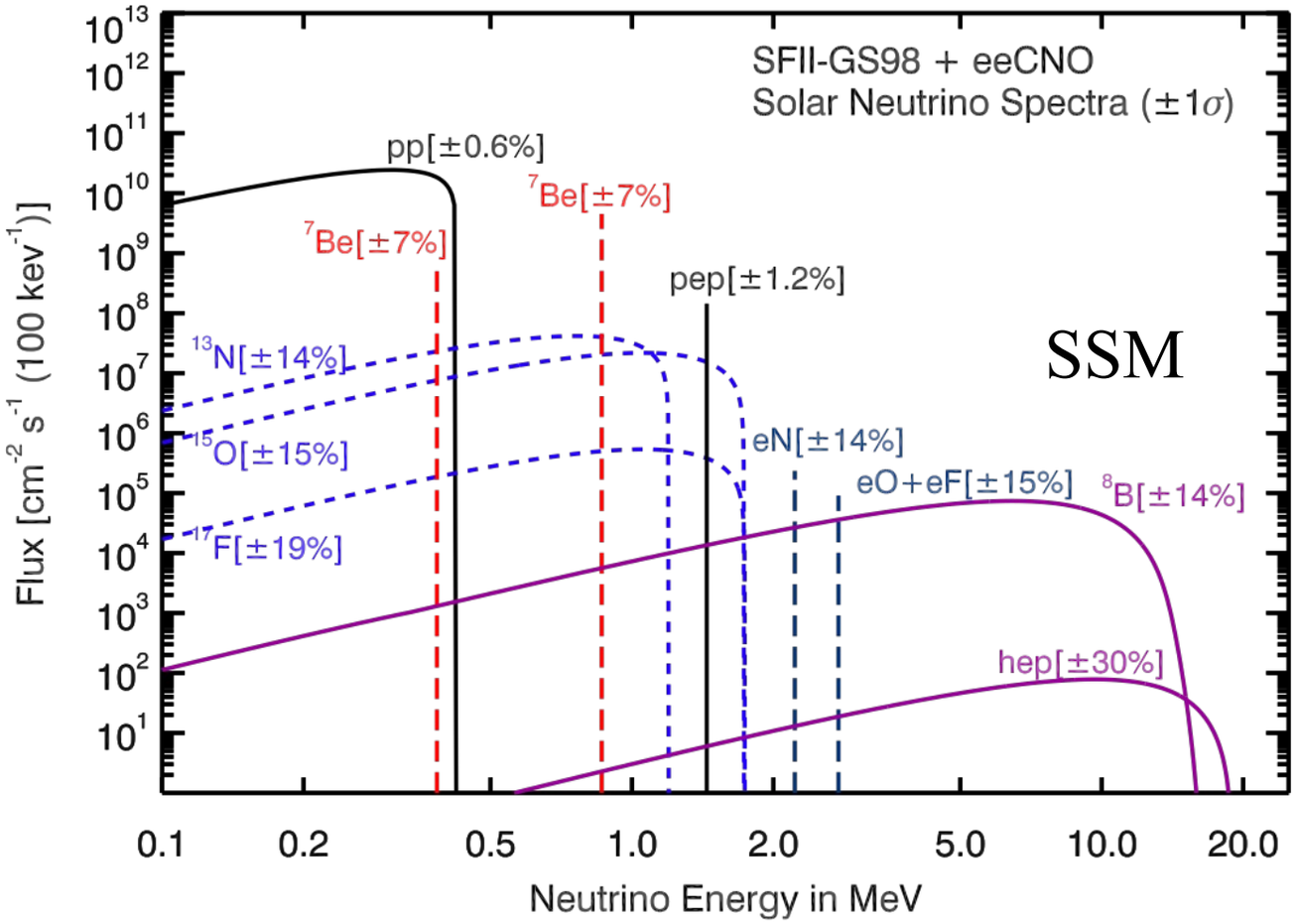
Solar neutrino problem

Name	Target material	Energy threshold (MeV)
Homestake	C_2Cl_4	0.814
SAGE	Ga	0.233
GALLEX	$GaCl_3$	0.233
GNO	$GaCl_3$	0.233
Kamiokande	H_2O	6.5
Super-Kamiokande	H_2O	3.5
SNO	D_2O	3.5
KamLAND	Liquid scintillator	0.5/5.5
Borexino	Liquid scintillator	0.19



$$\nu_e + {}^{37}\mathrm{Cl} \to e^- + {}^{37}\mathrm{Ar}$$

Homestake: $2.56 \pm 0.16 \pm 0.16\,\mathrm{SNU}$ SSM: $8.46^{+0.87}_{-0.88}\,\mathrm{SNU}$

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

GALLEX+GNO: $69.3 \pm 4.1 \pm 3.6\,\mathrm{SNU}$

SAGE: $65.4^{+3.1+2.6}_{-3.0-2.8}\,\mathrm{SNU}$ SSM: $127.9^{+8.1}_{-8.2}\,\mathrm{SNU}$

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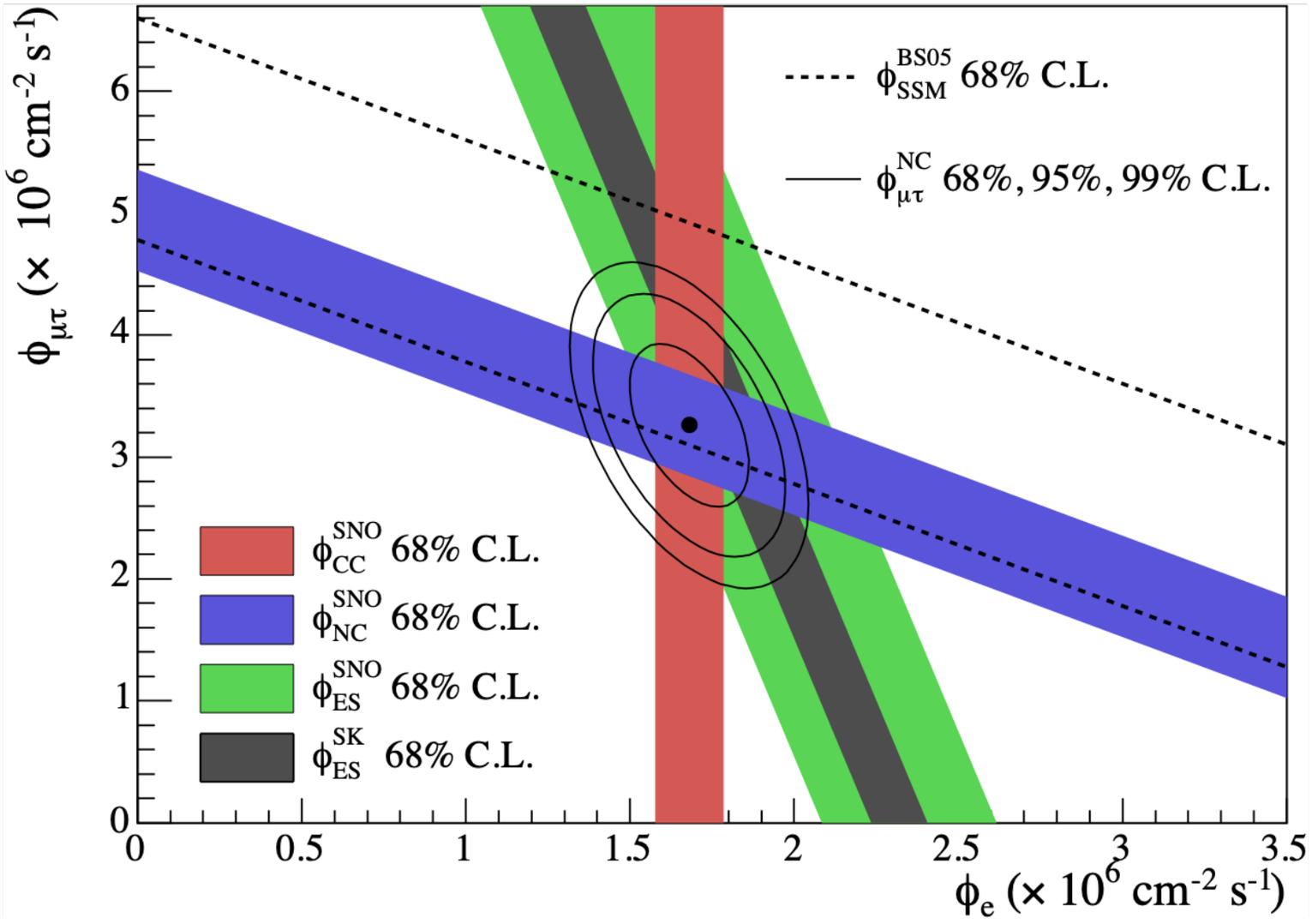
Solution



CC: $\nu_e + d \to e^- + p + p$ ES: $\nu_x + e^- \to \nu_x + e^-$

NC: $\nu_x + d \to \nu_x + p + n$

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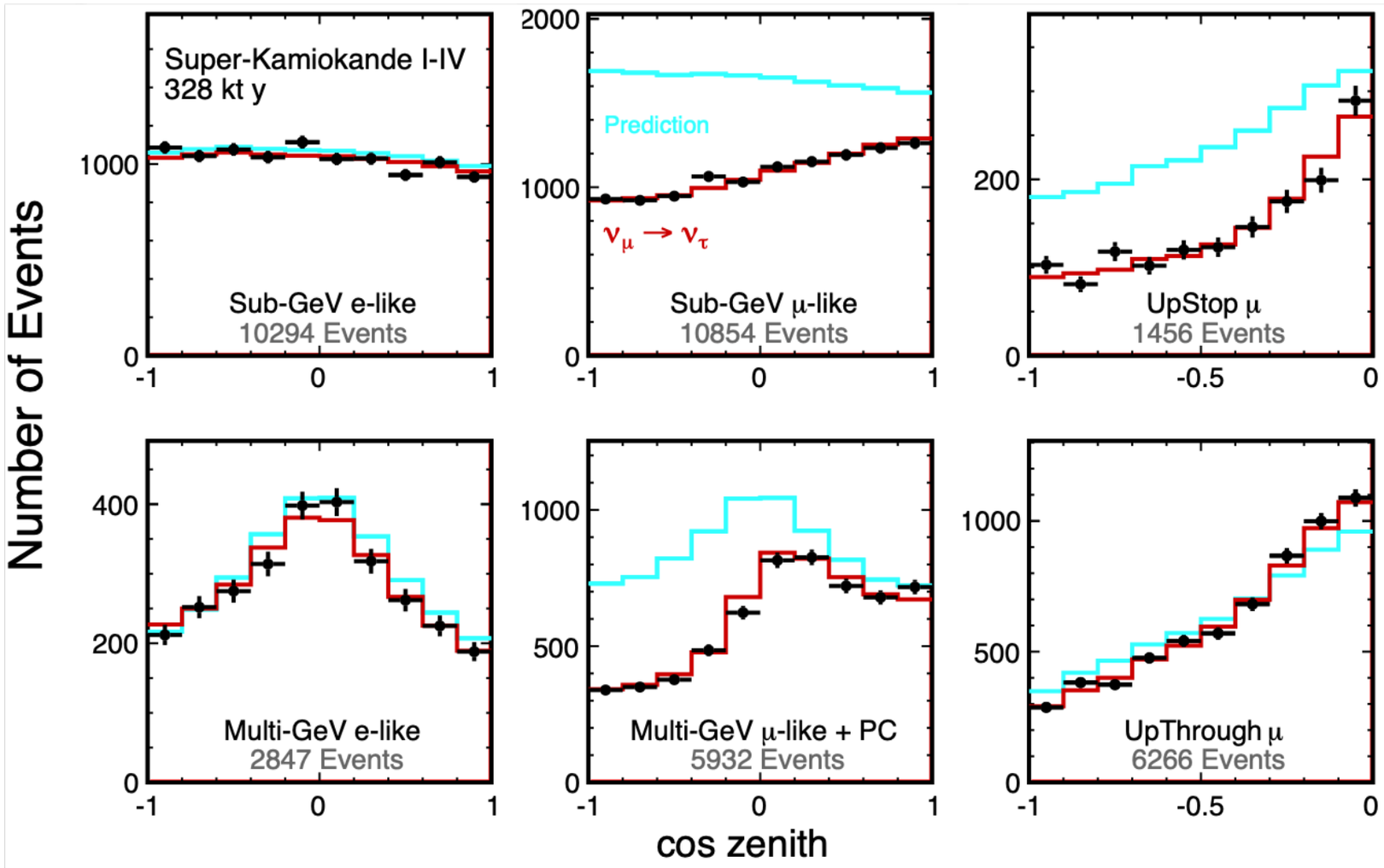
Atmospheric neutrinos

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

theory: $\dfrac{N(\nu_\mu + \bar{\nu}_\mu)}{N(\nu_e + \bar{\nu}_e)} = 2$



Super-Kamiokande

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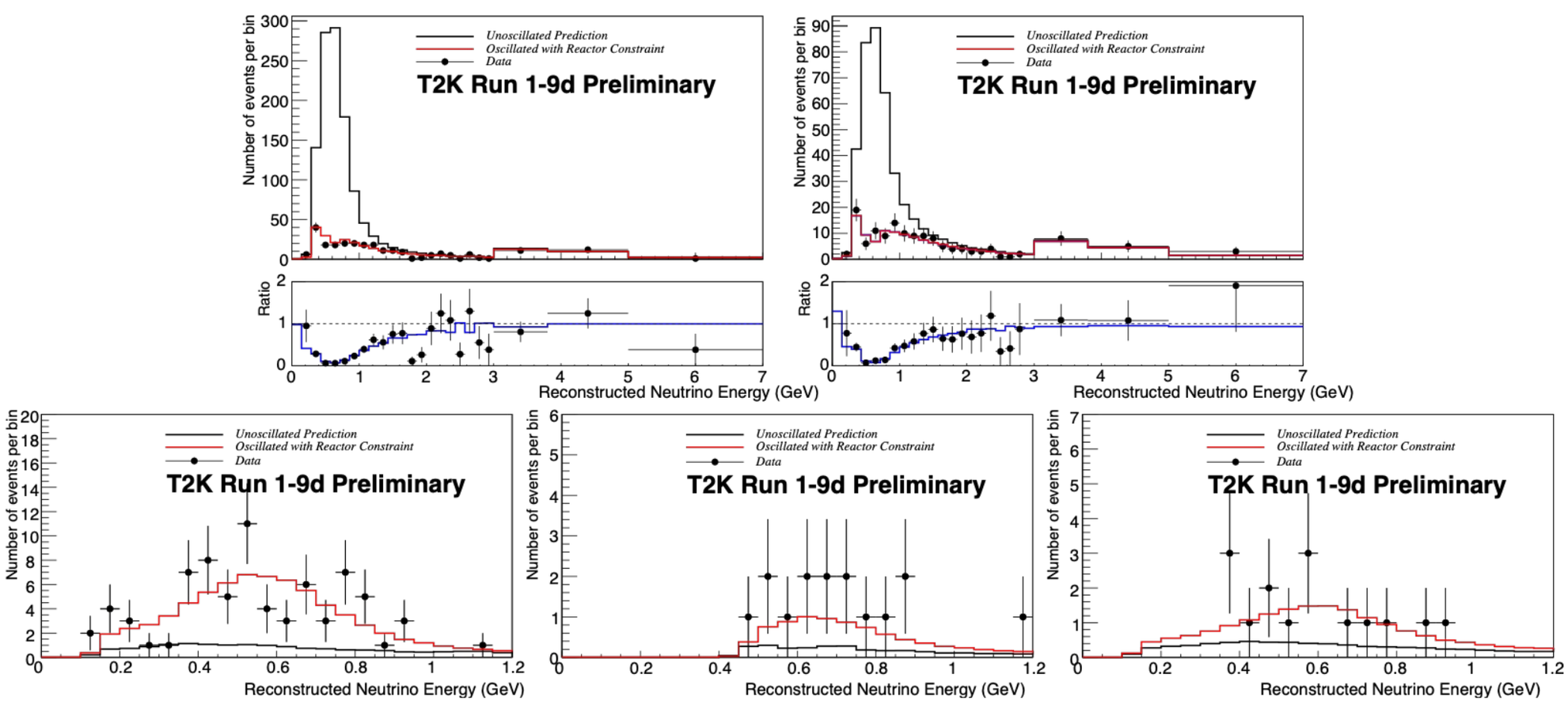
Accelerator neutrinos

Name	Beamline	Far Detector	L (km)	E_ν (GeV)	Year
K2K	KEK-PS	Water Cherenkov	250	1.3	1999–2004
MINOS	NuMI	Iron-scintillator	735	3	2005–2013
MINOS+	NuMI	Iron-scintillator	735	7	2013–2016
OPERA	CNGS	Emulsion	730	17	2008–2012
ICARUS	CNGS	Liquid argon TPC	730	17	2010–2012
T2K	J-PARC	Water Cherenkov	295	0.6	2010–
NOvA	NuMI	Liquid scint. tracking calorimeter	810	2	2014–



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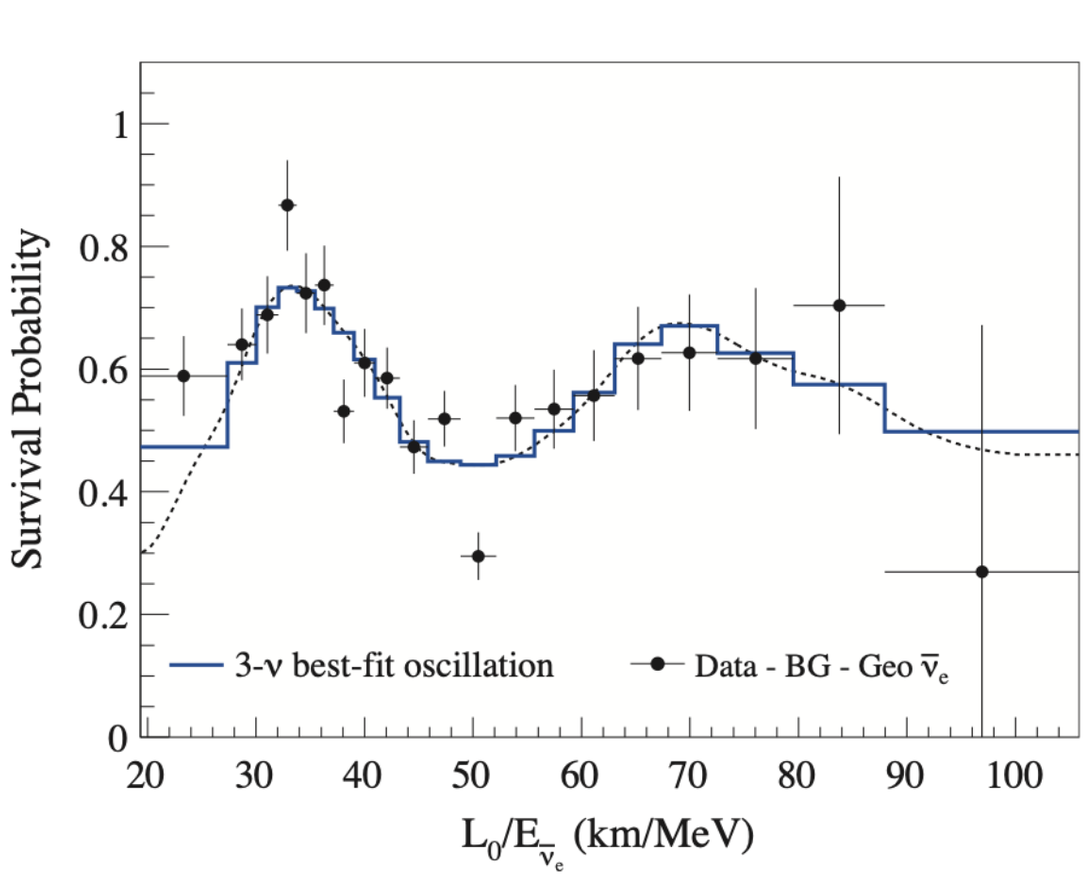
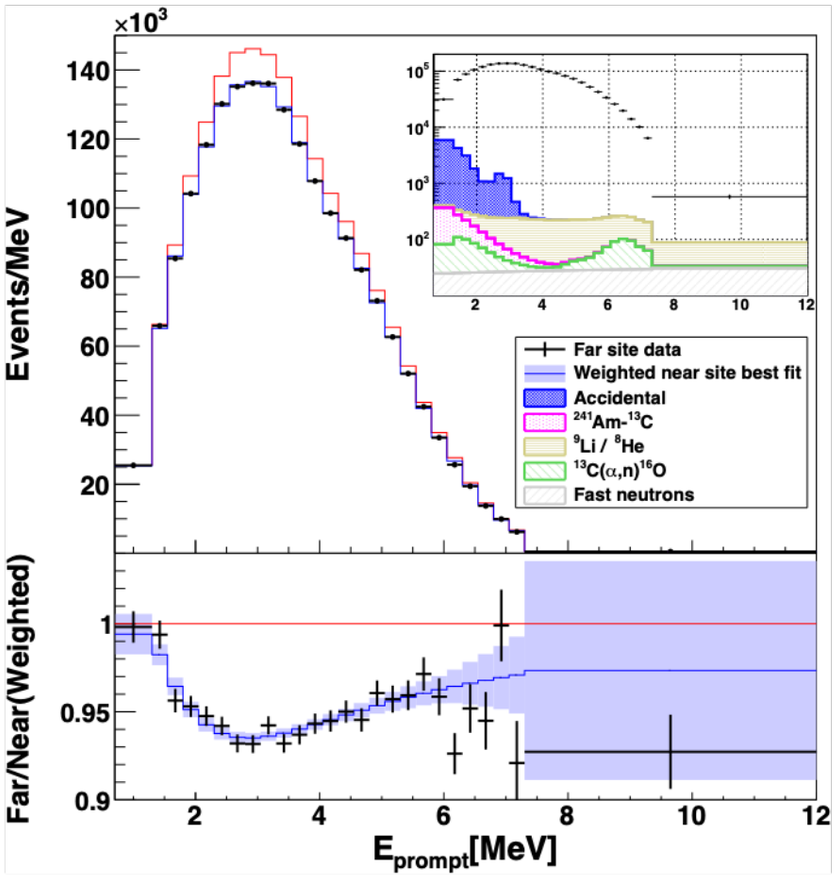
Reactor antineutrinos

Name	Reactor power (GW_{th})	Baseline (km)	Detector mass (t)	Year
KamLAND	various	180 (ave.)	1,000	2001–
Double Chooz	4.25×2	1.05	8.3	2011–2018
Daya Bay	2.9×6	1.65	20×4	2011–
RENO	2.8×6	1.38	16	2011–
JUNO	26.6 (total)	53	20,000	



KamLAND



Daya Bay