8.701

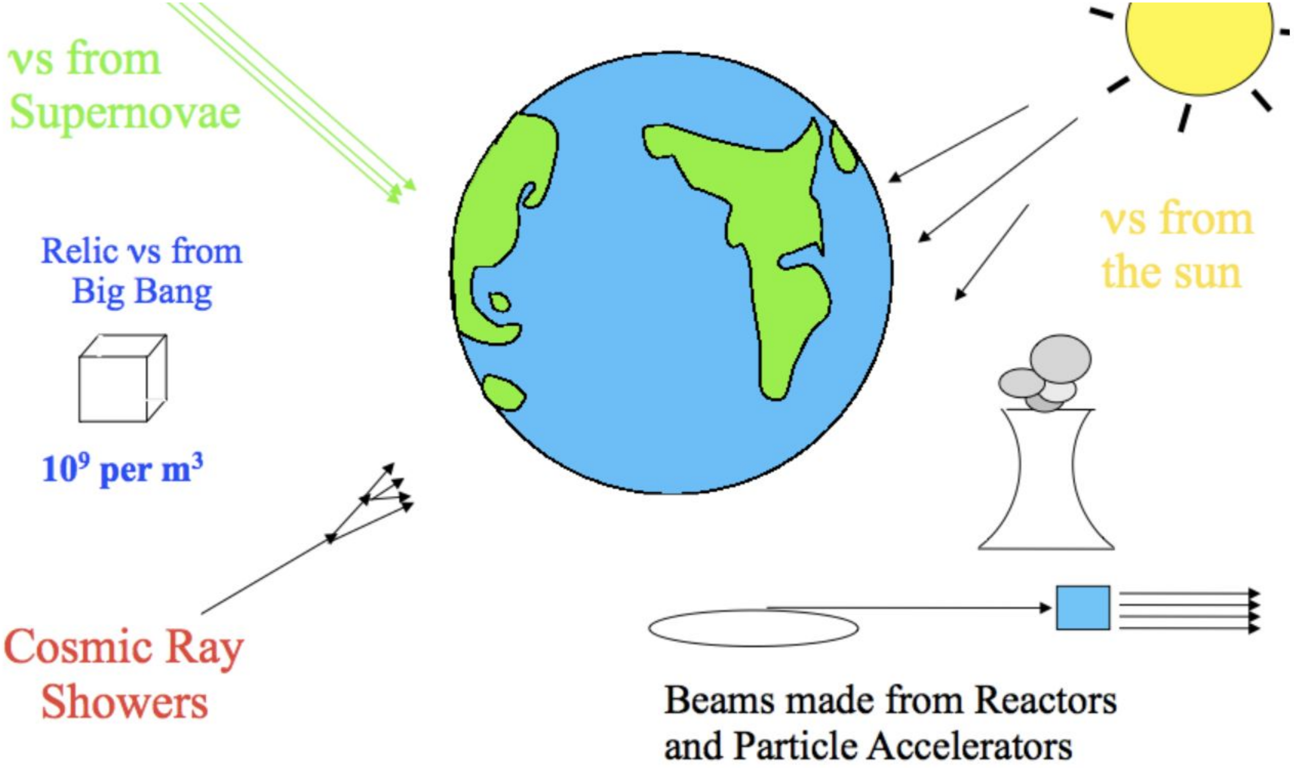
Introduction to Nuclear and Particle Physics

Markus Klute - MIT

8. Neutrinos

8.4 Experimental Study

Neutrino Production



νs from Supernovae

Relic νs from Big Bang

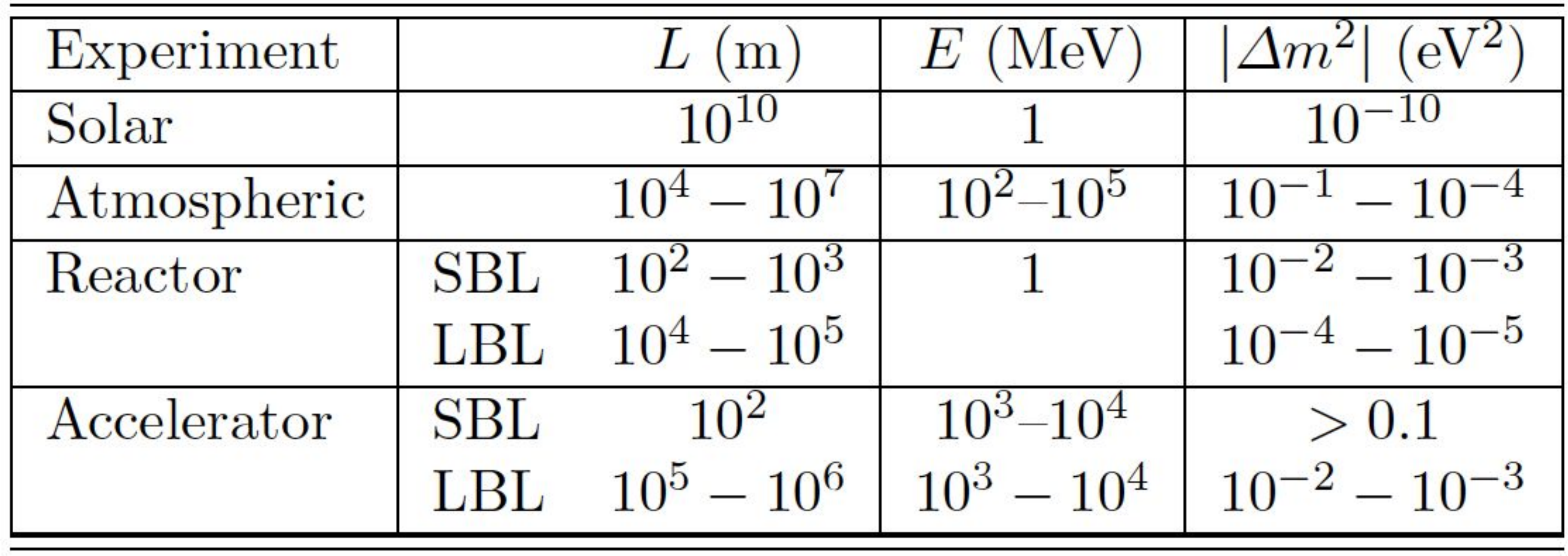
10^9 per m^3

Cosmic Ray Showers

νs from the sun

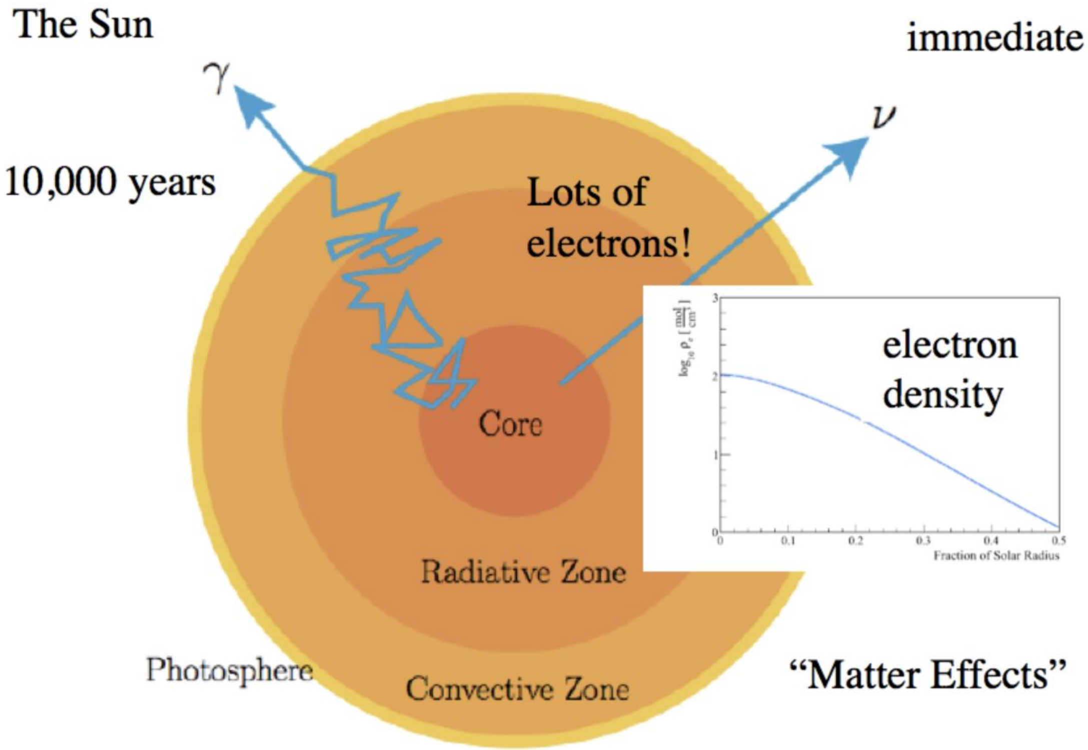
Beams made from Reactors and Particle Accelerators

Experimental Studies of Neutrino Oscillations

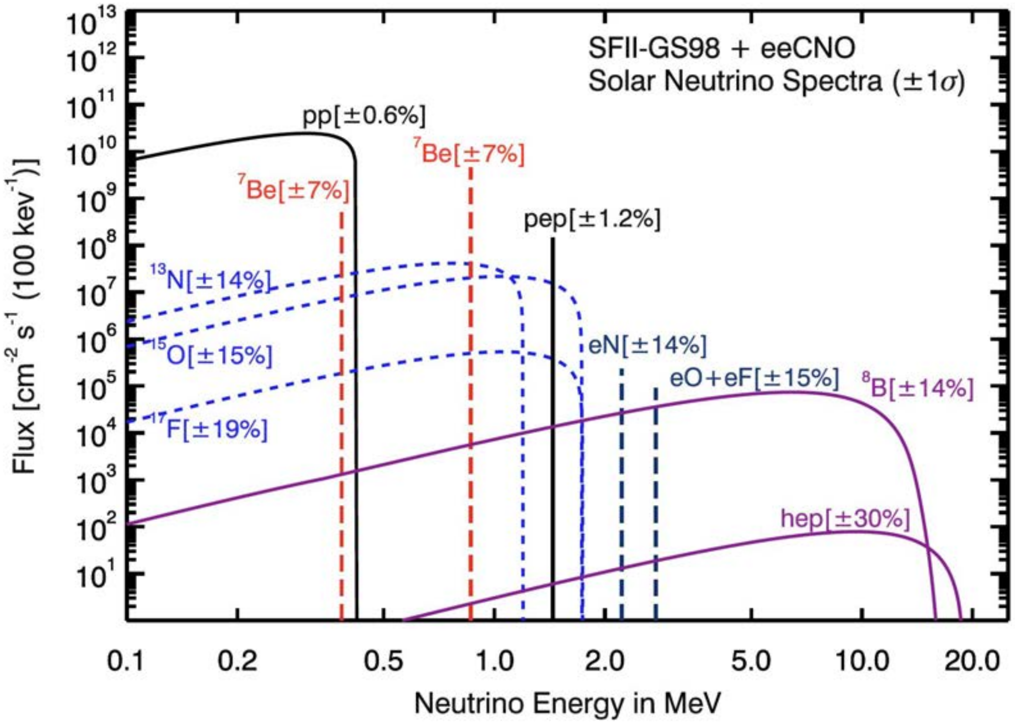


Experiment		L (m)	E (MeV)	$\lvert\Delta m^2\rvert$ (eV^2)
Solar		10^{10}	1	10^{-10}
Atmospheric		$10^4 - 10^7$	10^2–10^5	$10^{-1} - 10^{-4}$
Reactor	SBL	$10^2 - 10^3$	1	$10^{-2} - 10^{-3}$
	LBL	$10^4 - 10^5$		$10^{-4} - 10^{-5}$
Accelerator	SBL	10^2	10^3–10^4	> 0.1
	LBL	$10^5 - 10^6$	$10^3 - 10^4$	$10^{-2} - 10^{-3}$

Solar Neutrinos



Solar Neutrinos

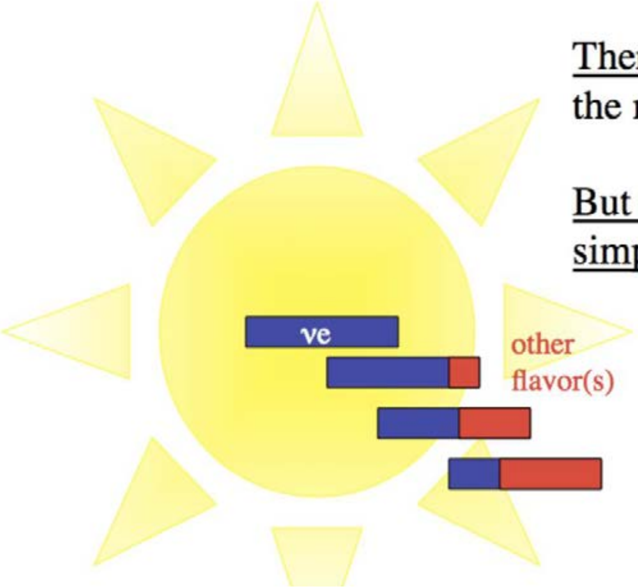


Solar Neutrinos

In the electron "soup"

The ν_e sees a CC and NC potential

The ν_μ and ν_τ see only the NC potential



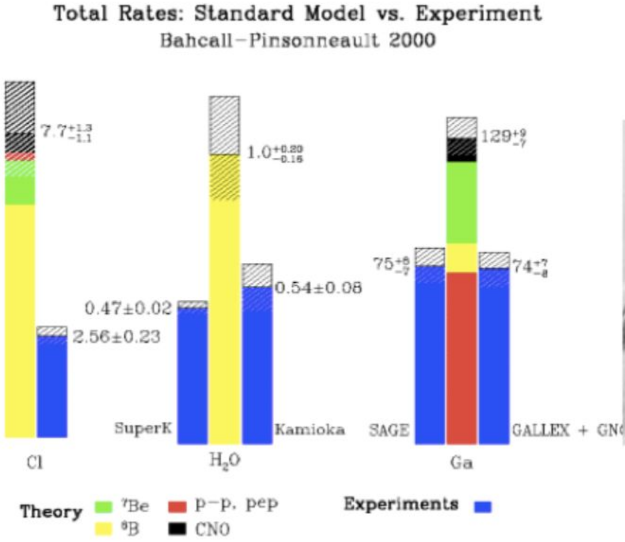
There is flavor evolution as the neutrinos traverse the sun.

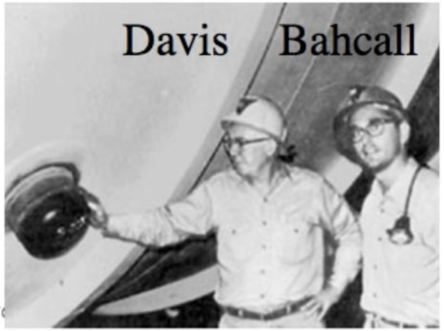
But the equations do not simplify to oscillations

The result looks like disappearance in detectors sensitive to only ν_e flavors...

Solar Neutrinos

The famous “Solar Neutrino Deficit”

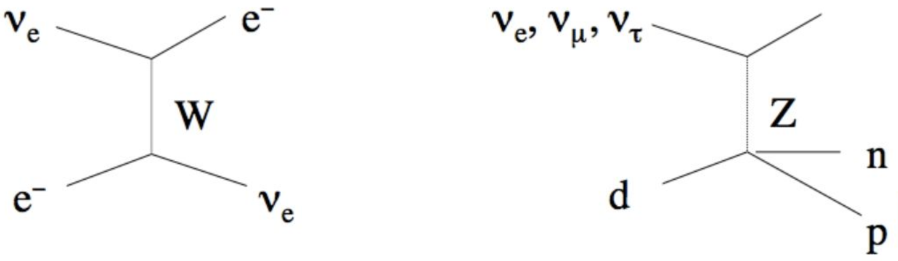




The rate of morphing with energy depends on Δm^2 and the mixing angle

Solar Neutrinos

Of course it is only a deficit if you can only see ν_e CC scatters!



most solar experiments

SNO

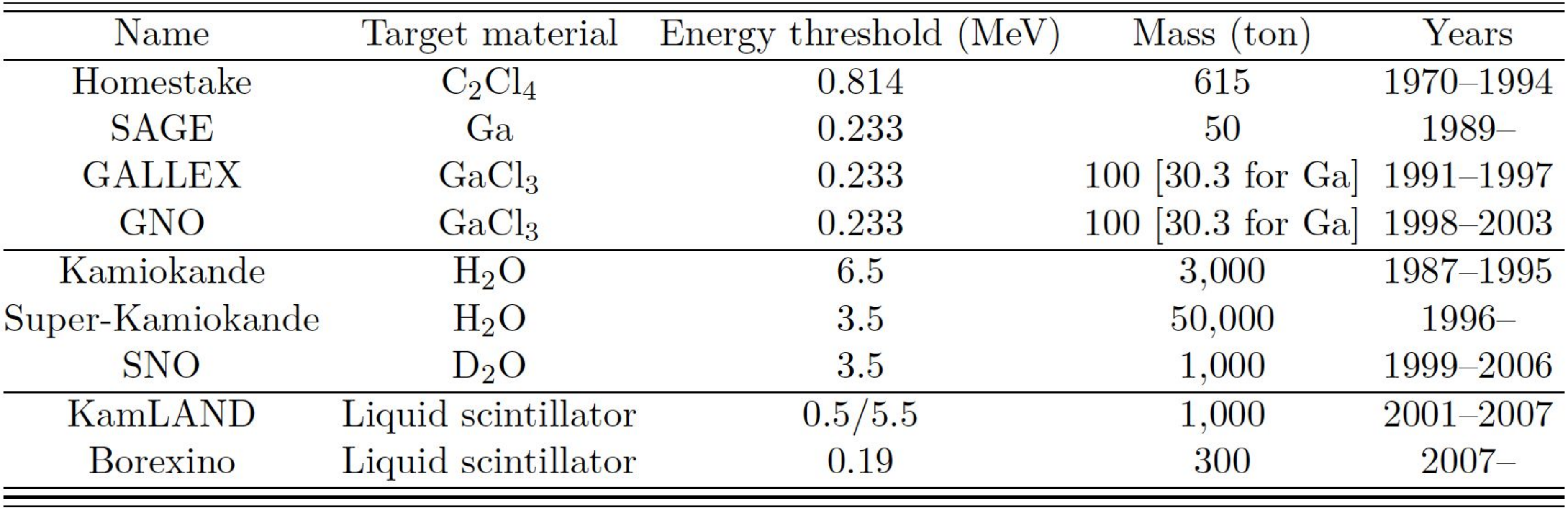
SNO: $\phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau} = (4.94 \pm 0.21 \pm 0.36) \times 10^6/\text{cm}^2\text{sec}$

Theory: $\phi_{\text{total}} = (5.69 \pm 0.91) \times 10^6/\text{cm}^2\text{sec}$

Bahcall, Basu, Serenelli

The NC interaction shows the neutrinos are still there!

Solar Neutrino Experiments



Name	Target material	Energy threshold (MeV)	Mass (ton)	Years
Homestake	C_2Cl_4	0.814	615	1970–1994
SAGE	Ga	0.233	50	1989–
GALLEX	$GaCl_3$	0.233	100 [30.3 for Ga]	1991–1997
GNO	$GaCl_3$	0.233	100 [30.3 for Ga]	1998–2003
Kamiokande	H_2O	6.5	3,000	1987–1995
Super-Kamiokande	H_2O	3.5	50,000	1996–
SNO	D_2O	3.5	1,000	1999–2006
KamLAND	Liquid scintillator	0.5/5.5	1,000	2001–2007
Borexino	Liquid scintillator	0.19	300	2007–

Atmospheric Neutrinos

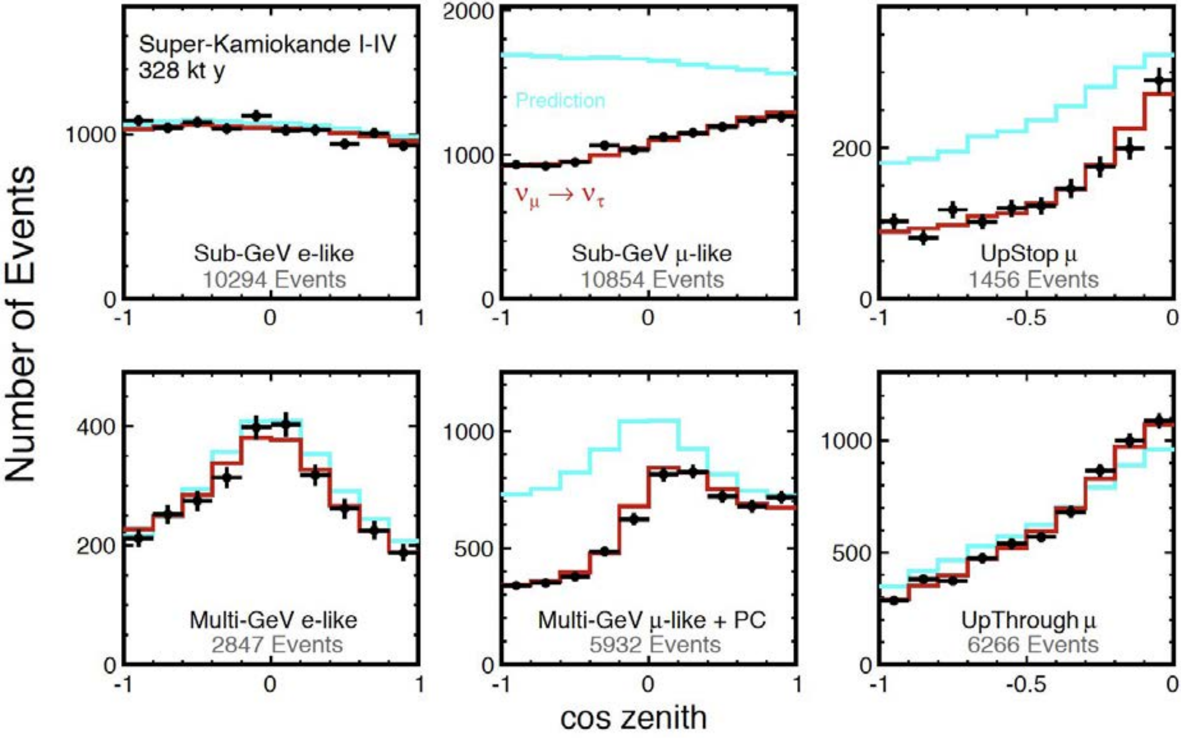
Neutrinos produced by decays of pions and kaons generated in the interaction of cosmic rays and nucleons in the Earth’s atmosphere.

$$\pi^+ \to \mu^+ \nu_\mu$$

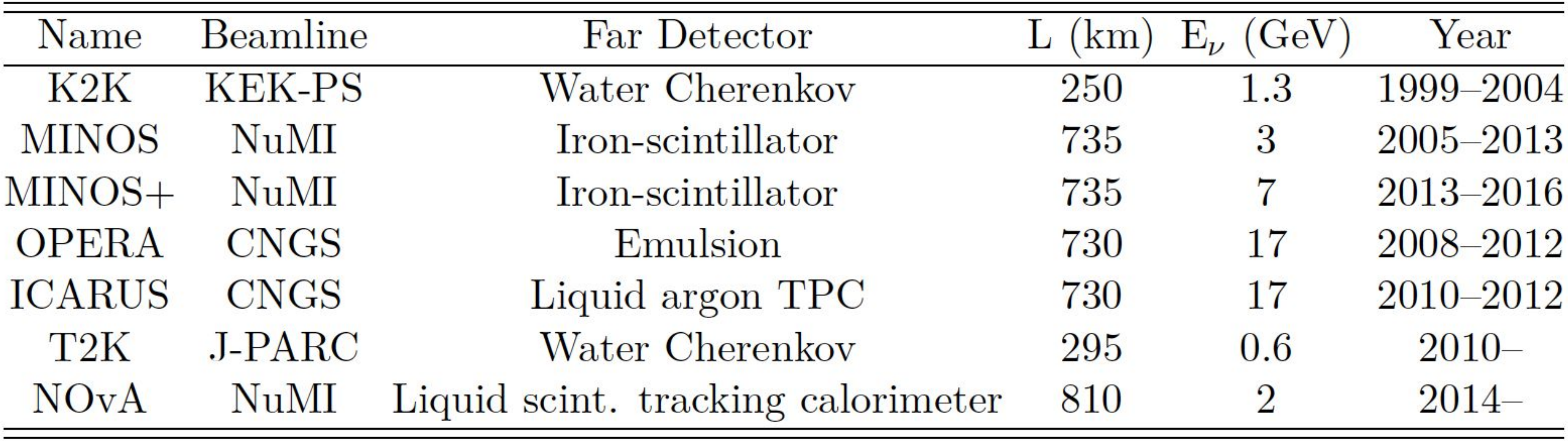
$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$

$$(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$$

Atmospheric Neutrinos

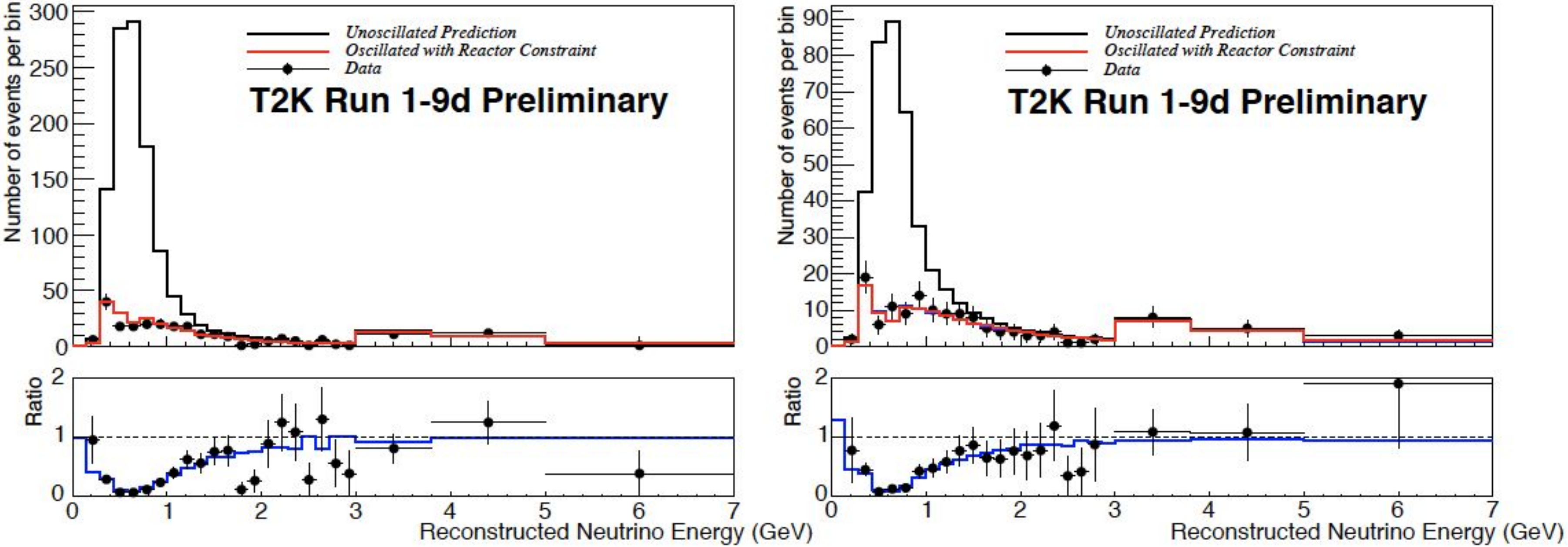


Accelerator Neutrinos

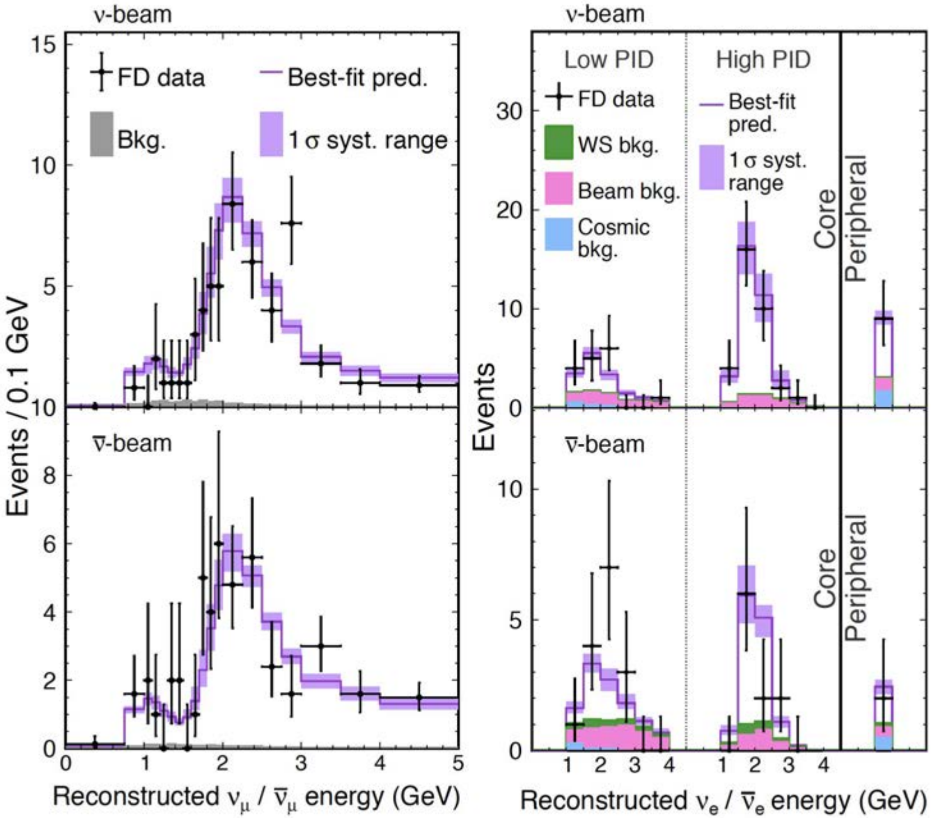


Name	Beamline	Far Detector	L (km)	E_ν (GeV)	Year
K2K	KEK-PS	Water Cherenkov	250	1.3	1999–2004
MINOS	NuMI	Iron-scintillator	735	3	2005–2013
MINOS+	NuMI	Iron-scintillator	735	7	2013–2016
OPERA	CNGS	Emulsion	730	17	2008–2012
ICARUS	CNGS	Liquid argon TPC	730	17	2010–2012
T2K	J-PARC	Water Cherenkov	295	0.6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

Accelerator Neutrinos



Accelerator Neutrinos

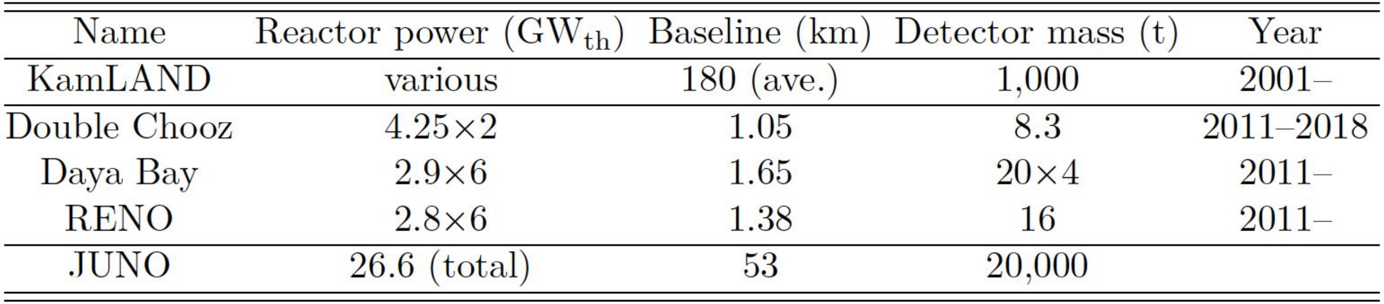


Reactor Neutrinos

Using neutrinos from nuclear fission of heavy isotopes, mainly ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu.

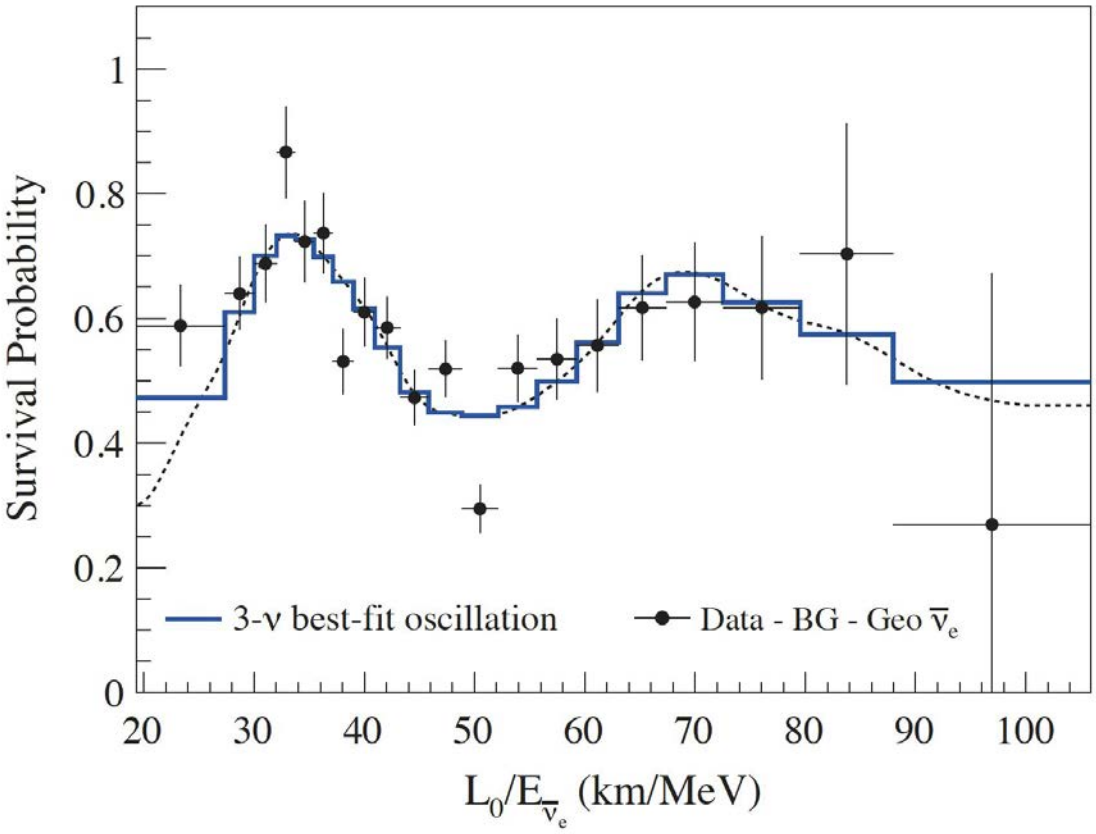
Flux can be calculated from thermal power output and fuel consumption

Study anti-electron-neutrino disappearance with $\bar{\nu}_e + p \rightarrow e^+ + n$



Name	Reactor power ($\mathrm{GW_{th}}$)	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	

Reactor Neutrinos



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