NEWS seminar,
August 23rd, 2019, RCNP

Review on Sterile Neutrino Experiments

Tatsushi Shima

Research Center for Nuclear Physics, Osaka University, Japan

1. Property of Sterile Neutrino (ν_s)
2. Experimental evidences of ν_s
   Accelerator experiment, Source experiment, Reactor experiment
3. Cosmological constraint
4. Summary

1. Property of Sterile Neutrino

$$Q = T_3 + \frac{1}{2} Y_W$$

Active neutrino; Q=0, T_3=-1/2, Y_W=+1

$SU(2) \times U(1)_Y$ doublet with charged leptons

→ normal weak interaction

$\nu_L \leftrightarrow \nu_R^C$ by CP transform

Sterile neutrino; Q=0, T_3=0, Y_W=0

$SU(2) \times U(1)_Y$ singlet

→ no coupling with W, Z, couple with Higgs only

$\nu_R \leftrightarrow \nu_L^C$ by CP transform

Mass term

Standard model;

$$\psi_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad \psi_R = e_R$$

$$L_m = g\left(\overline{\psi}_L \phi \psi_R + \overline{\psi}_R \phi^\dagger \psi_L\right) = \frac{g}{\sqrt{2}}\left(v\overline{e}e + H\overline{ee}\right)$$, where ϕ is a Higgs field.

Dirac mass with right-handed neutrino;

$$L_D = \frac{1}{2} m_D g\left(\overline{\nu}_R \nu_L + \overline{\nu}_L \nu_R\right) = \frac{1}{\sqrt{2}} h_\nu \langle \phi_0 \rangle \overline{\nu}_D \nu_D \ , \quad \nu_D \equiv \nu_L + \nu_R$$

Majorana mass;

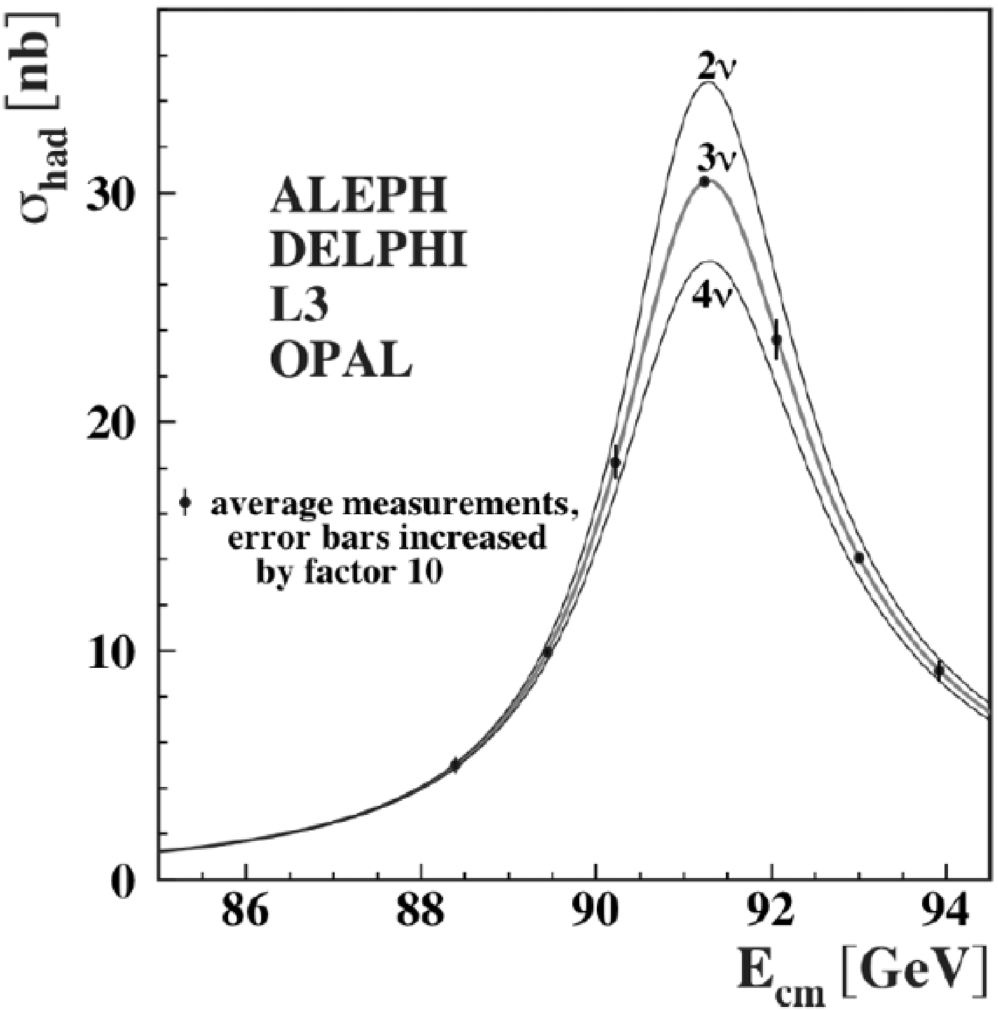
$$L_M = \frac{1}{2} m_M \left(\overline{\nu}_L^C \nu_L + \overline{\nu}_L \nu_R^C\right) = \frac{1}{2} m_M \overline{\nu}_M \nu_M$$

$$\nu_L^C = \nu_R \ , \quad \nu_R^C = \nu_L \ , \quad \nu_M \equiv \nu_L + \nu_R^C = \nu_M^C$$

Sterile neutrino

- introduced to solve anomalies in short baseline ν-oscillation experiments
- singlet fermion of gauge interactions → right-handed ν
- beyond SM, beyond minimal GUT like SU(5)
- sensitive to only gravity, but affects ν-oscillations
- possible candidate of cold or warm dark matter

Z-boson decay width@LEP



S. Schael et al., Phys. Rept. 427, 257 (2006)

$N_\nu(Z)=2.9840\pm0.0082$

2. Experimental evidences of ν_s

Exp.	ν source	Signal	Significance	E_ν [MeV]	L [m]
LSND	μ Decay-At-Rest	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	3.8σ	40	30
MiniBooNE	π Decay-In-Flight	$\nu_\mu \rightarrow \nu_e$	3.4σ	800	600
		$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	2.8σ		
		Combined	3.8σ		
Ga	e capture	$\nu_e \rightarrow \nu_x$	2.7σ	<3	10
Reactors	Beta decay	$\bar{\nu}_e \rightarrow \bar{\nu}_x$	3.0σ	3	10^{1-2}

Neutrino oscillation (short-baseline limit) $\frac{L[m]}{E_\nu[MeV]} \sim 1$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_S \\ \bullet \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \bullet \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \bullet \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \bullet \\ U_{S1} & U_{S2} & U_{S3} & U_{S4} & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \bullet \end{pmatrix}$$

Flavor eigenstate Mass eigenstate

$$m_4 >> m_{1,2,3} \;, \quad U_{S4} \sim 1 >> U_{e\mu\tau,4}$$

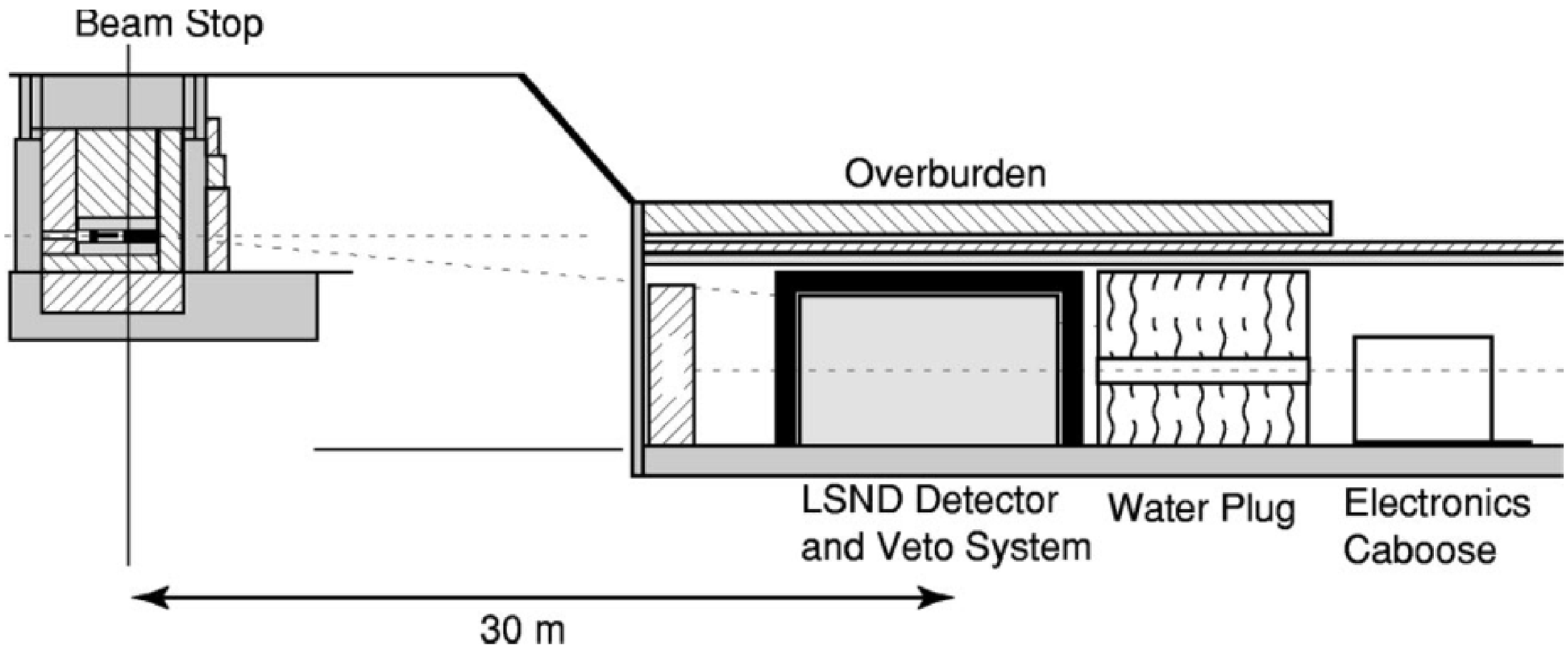
$$P\left(\nu_e \to \nu_\mu\right) = -4 \sum_{i=1,2,3} \left(U_{e4}^* U_{\mu 4} U_{ei} U_{\mu i}^*\right) \sin^2 \frac{\left(m_4^2 - m_i^2\right) L}{4E_\nu} \sim 4\left|U_{e4}\right|^2 \left|U_{\mu 4}\right|^2 \sin^2 \frac{\Delta m_4^2 L}{4E_\nu}$$

LSND (Liquid Scintillator Neutrino Detector)

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

A. Aguilar et al., Phys. Rev. D64, 112007 (2001).

Proton@LANSCE
798MeV, 1mA

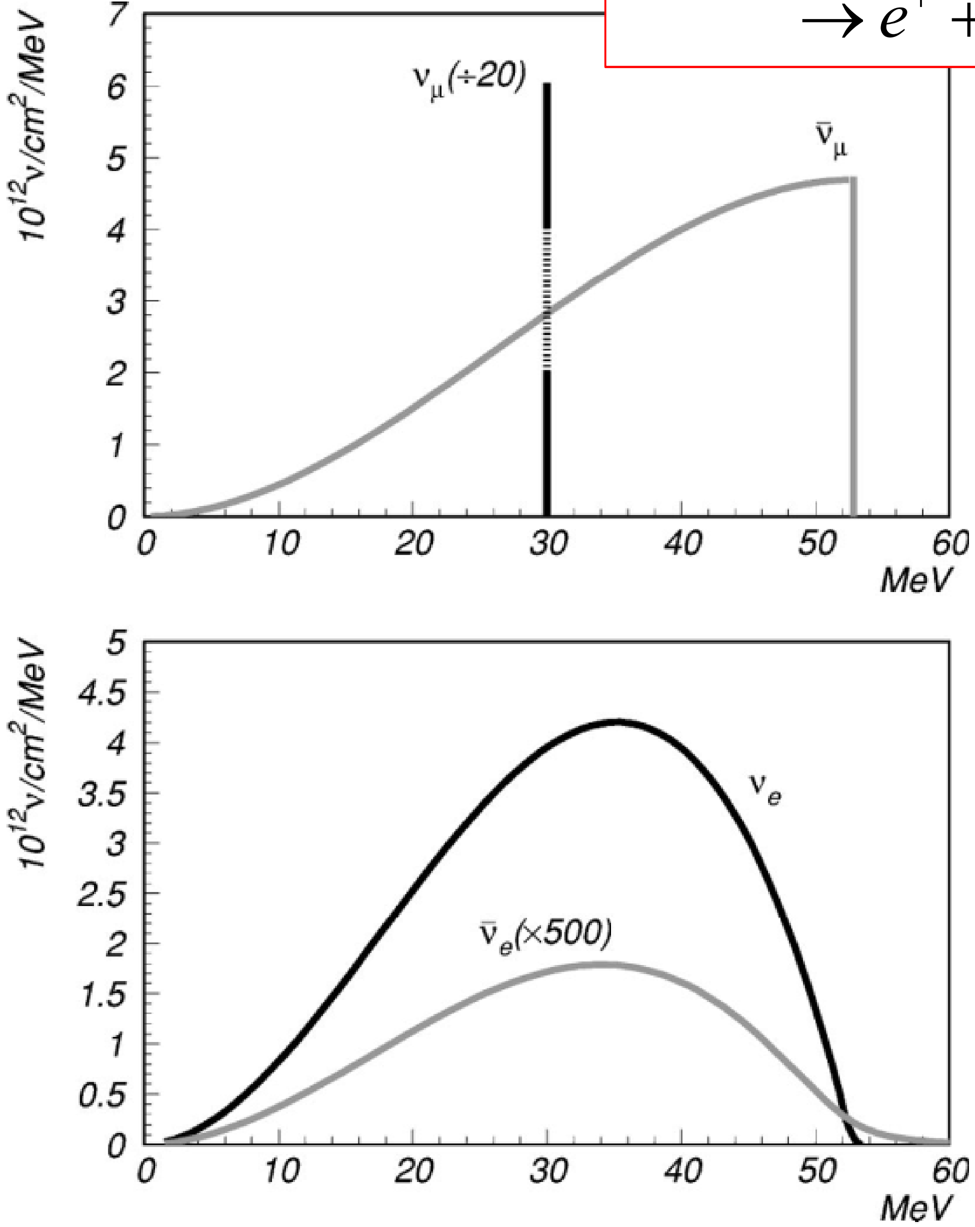


Mineral oil; 167 tons

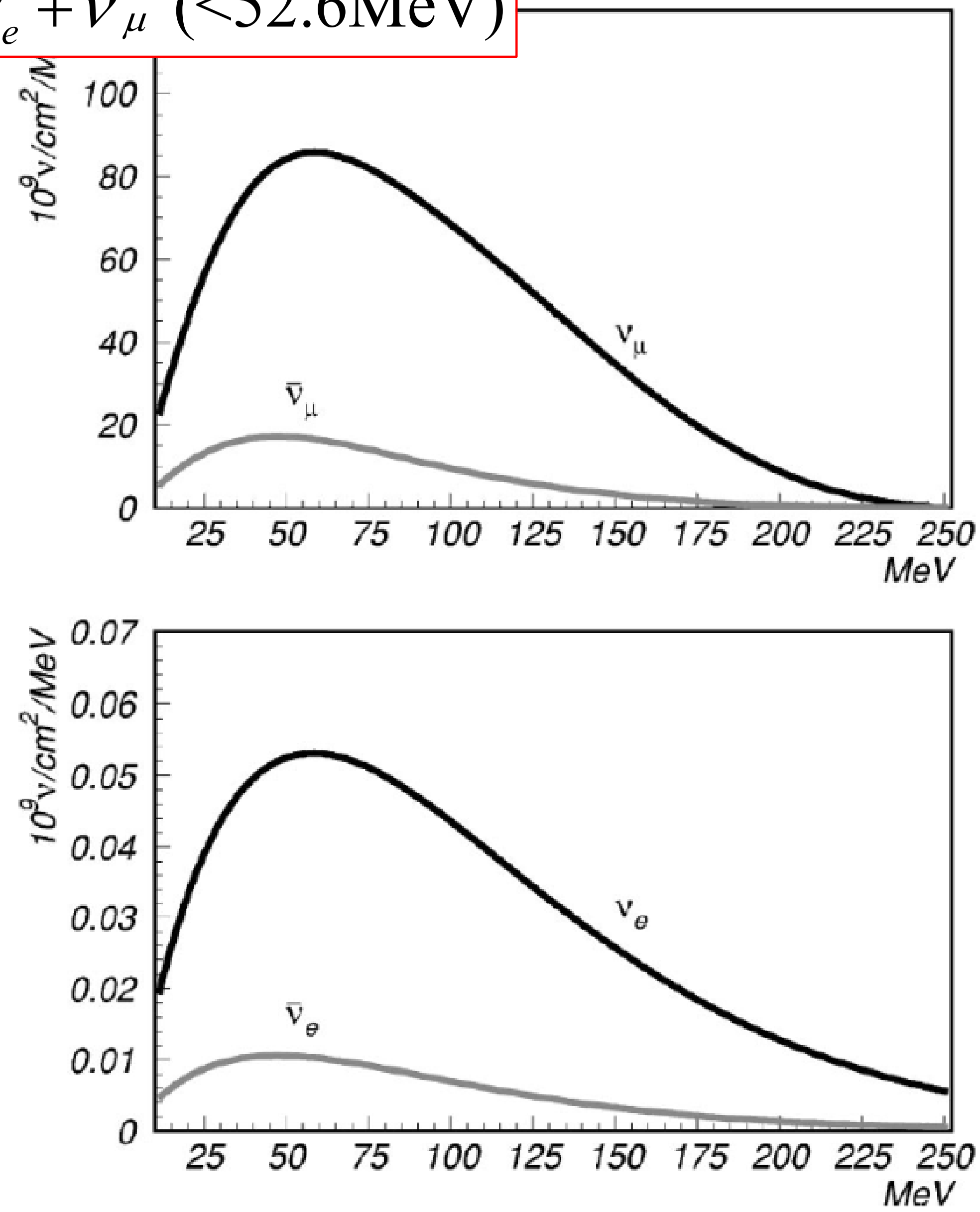
DAR ν_e; 10.58×10^{13} /cm^2

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu} \ (30\text{MeV})$$

$$\rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu} \ (<52.6\text{MeV})$$



Decay-at-rest (DAR)

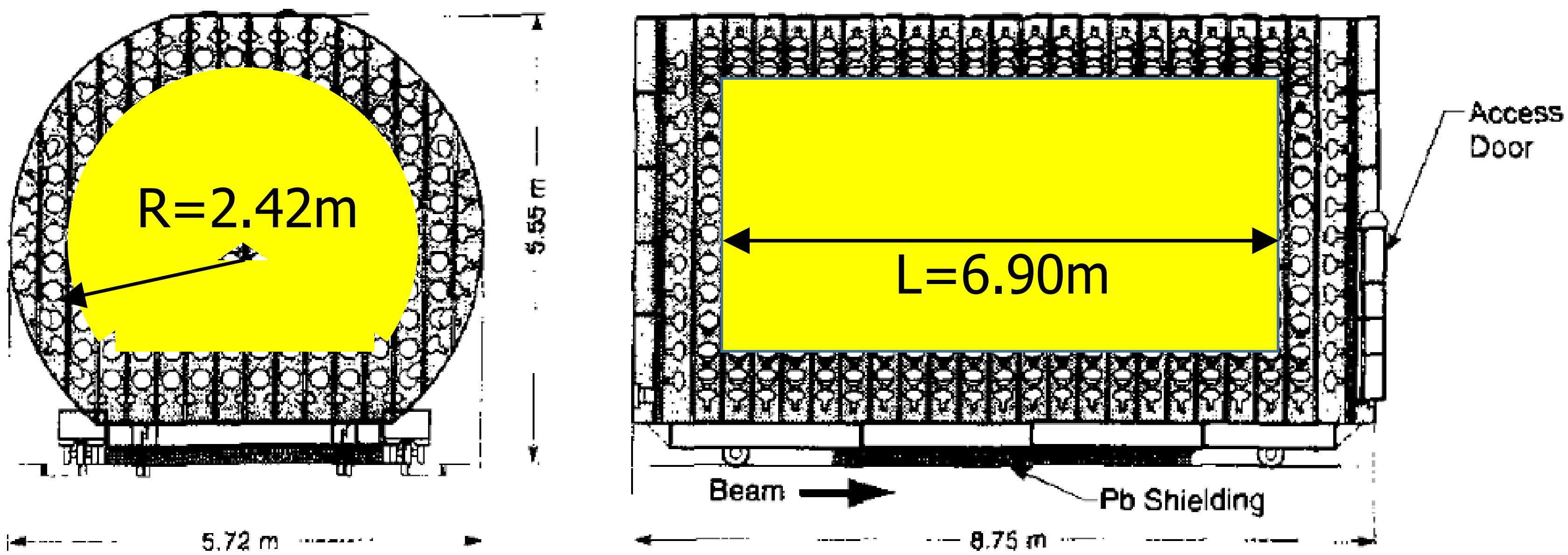


Decay-in-flight (DIF)

Liquid Scintillation Detector

Spatial resolution; Δ=20cm (rms)

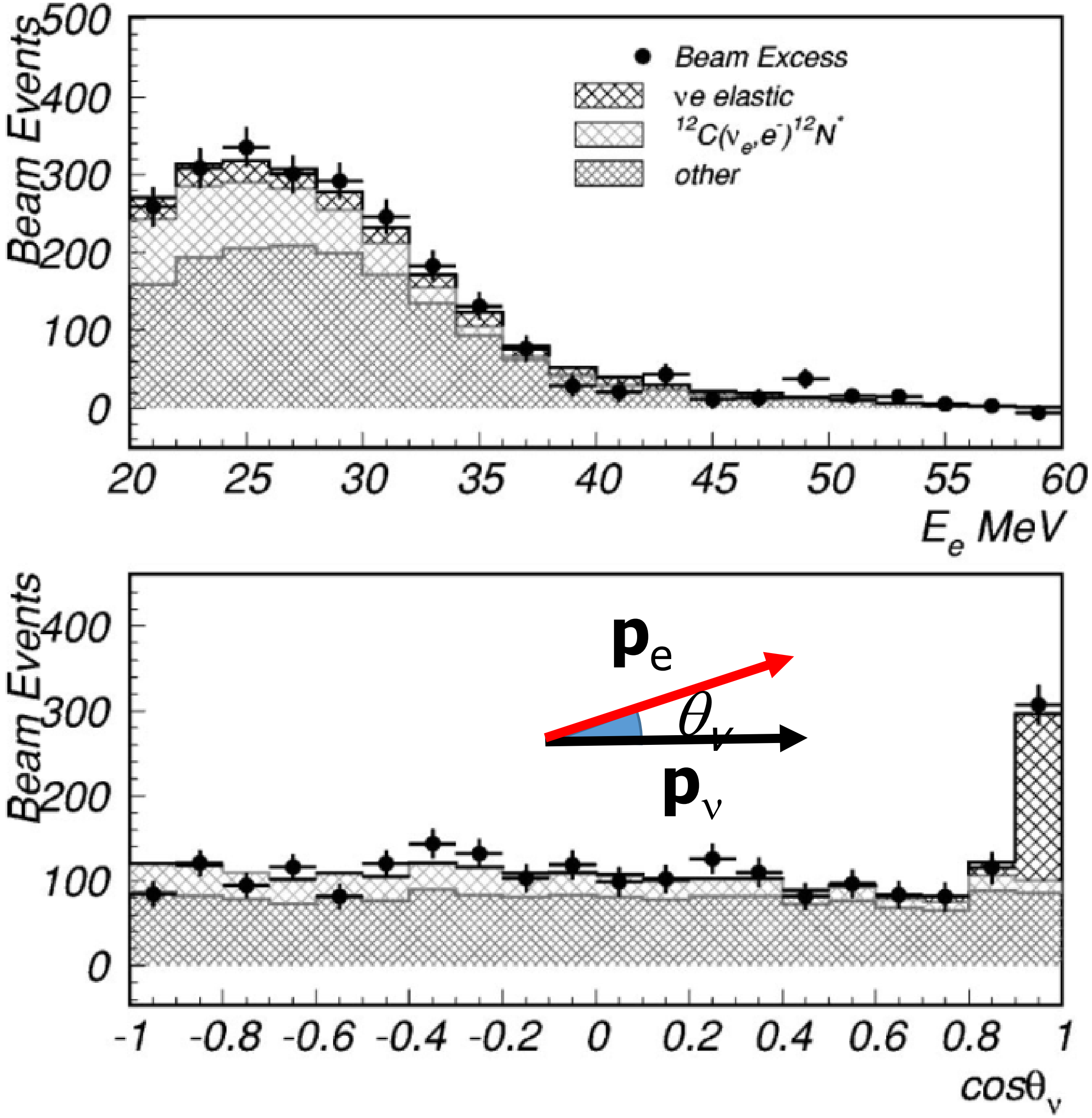
Fiducial volume; $S=14.8m^2$, $L=6.90m \rightarrow V=102m^3$

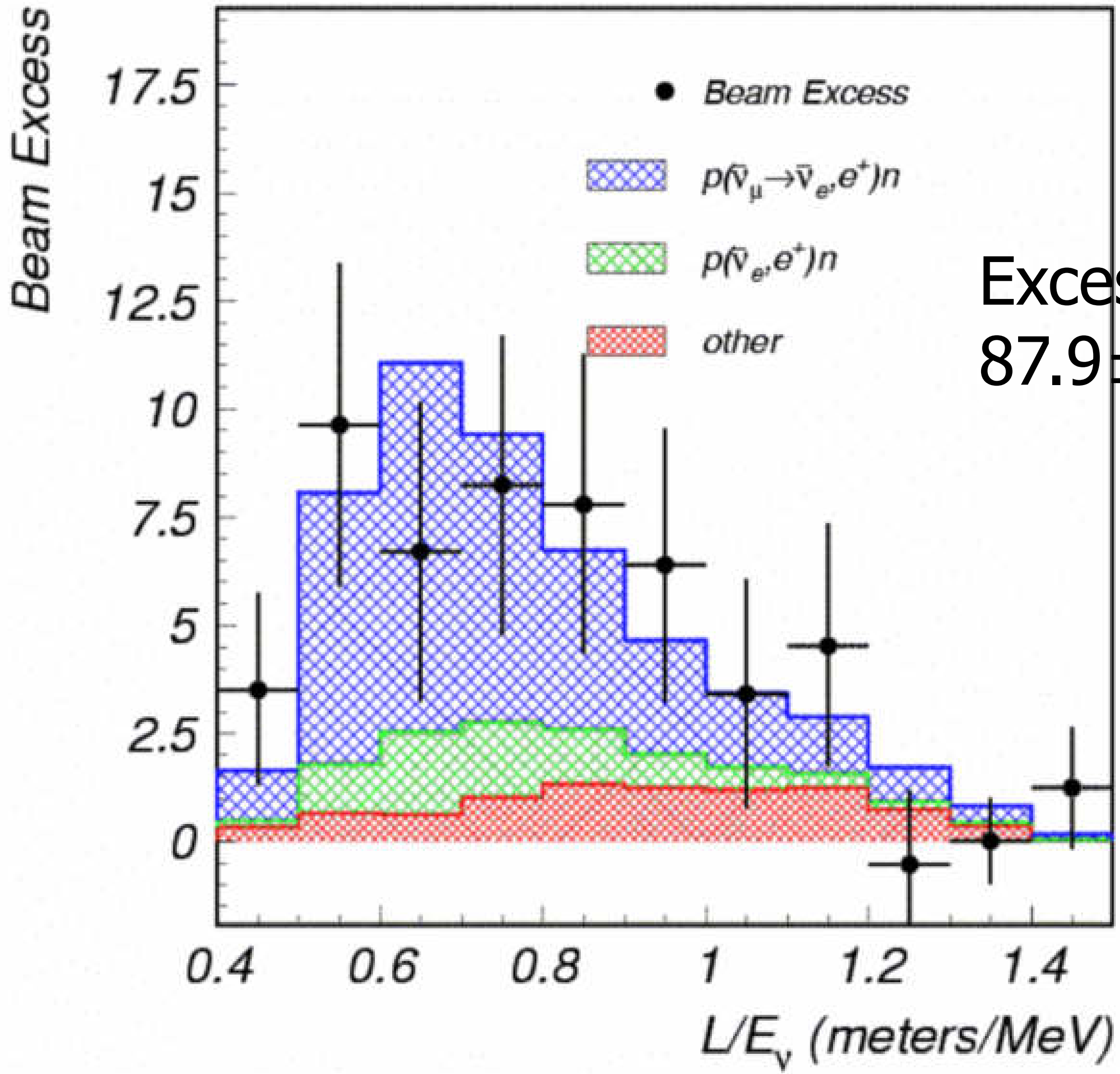


$$\bar{\nu}_\mu \rightarrow\rightarrow\rightarrow \bar{\nu}_e + p \rightarrow e^+ + n$$ $E_{e^+} \leq 52.6$MeV

$$+ p \rightarrow d + \gamma$$ $E_\gamma = 2.22$MeV

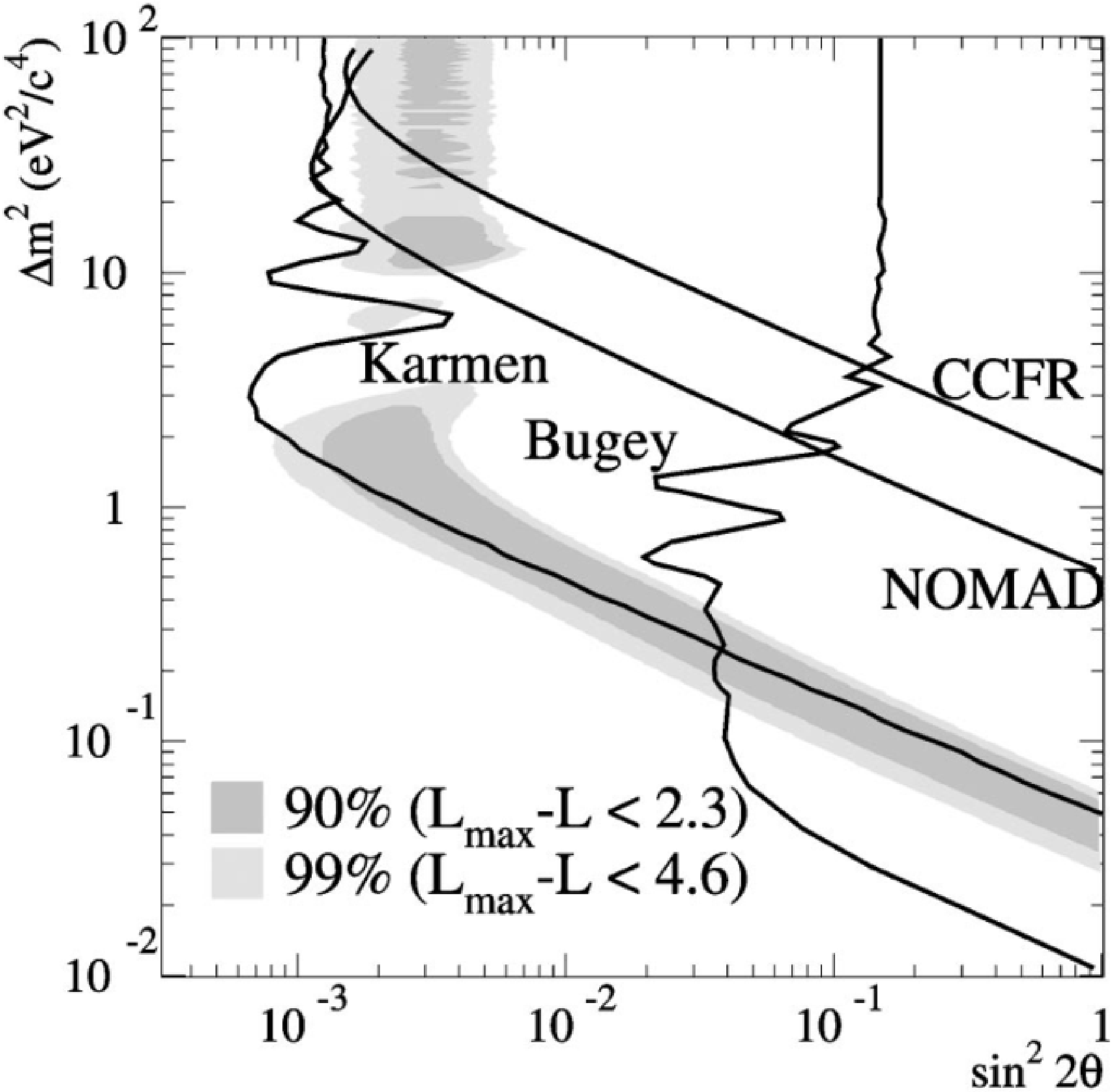
Electron-like events; energy/angular distributions





Excess;
87.9±22.4±6.0 events

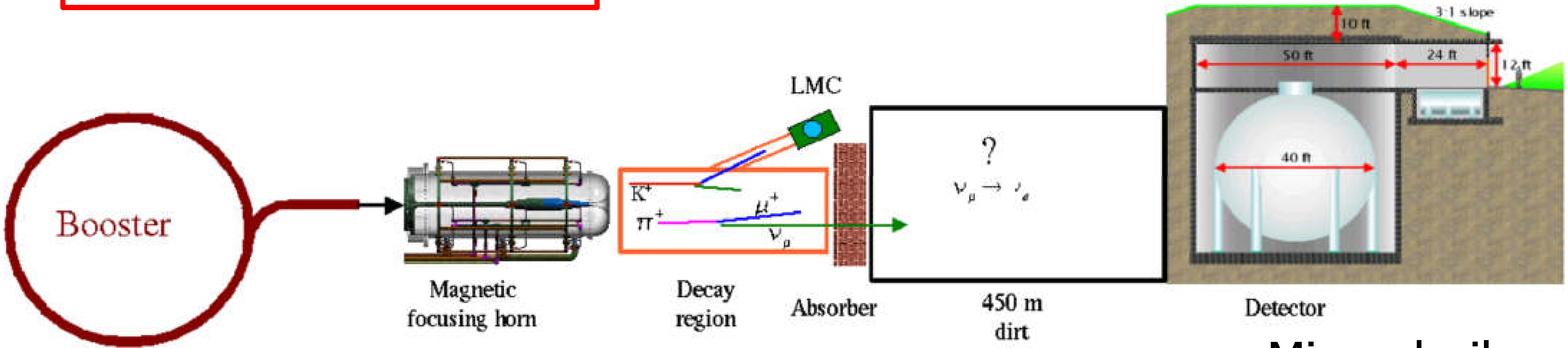
Oscillation parameter (as of 2001)



MiniBooNE (Mini Booster Neutrino Exp. @FNAL)

A.A. Aguilar-Arevalo et al., PRL110, 161801 (2013)

$$\nu_\mu \rightarrow \nu_e \ , \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_e$$



8GeV proton

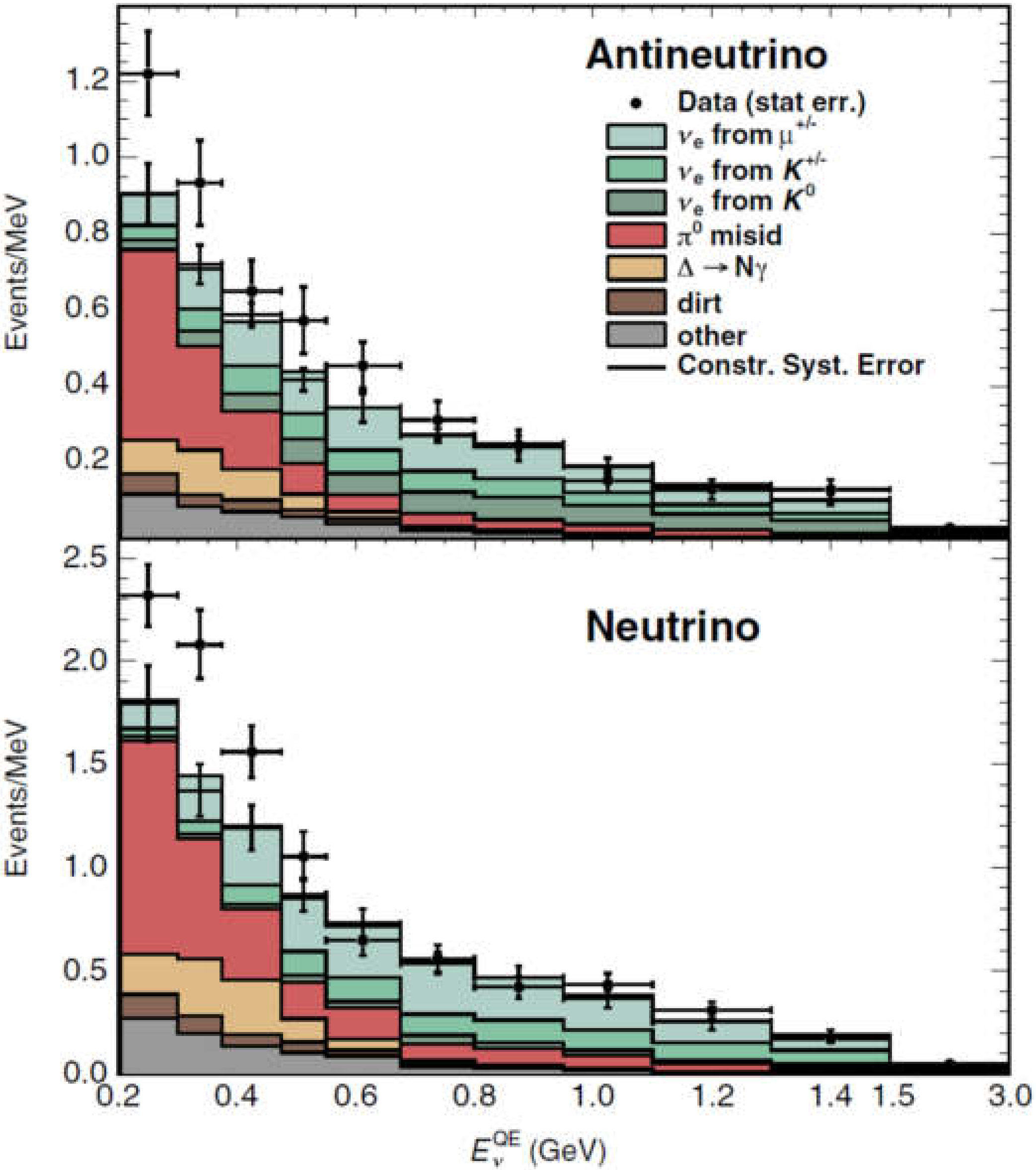
π^+, K^+

DIF ν

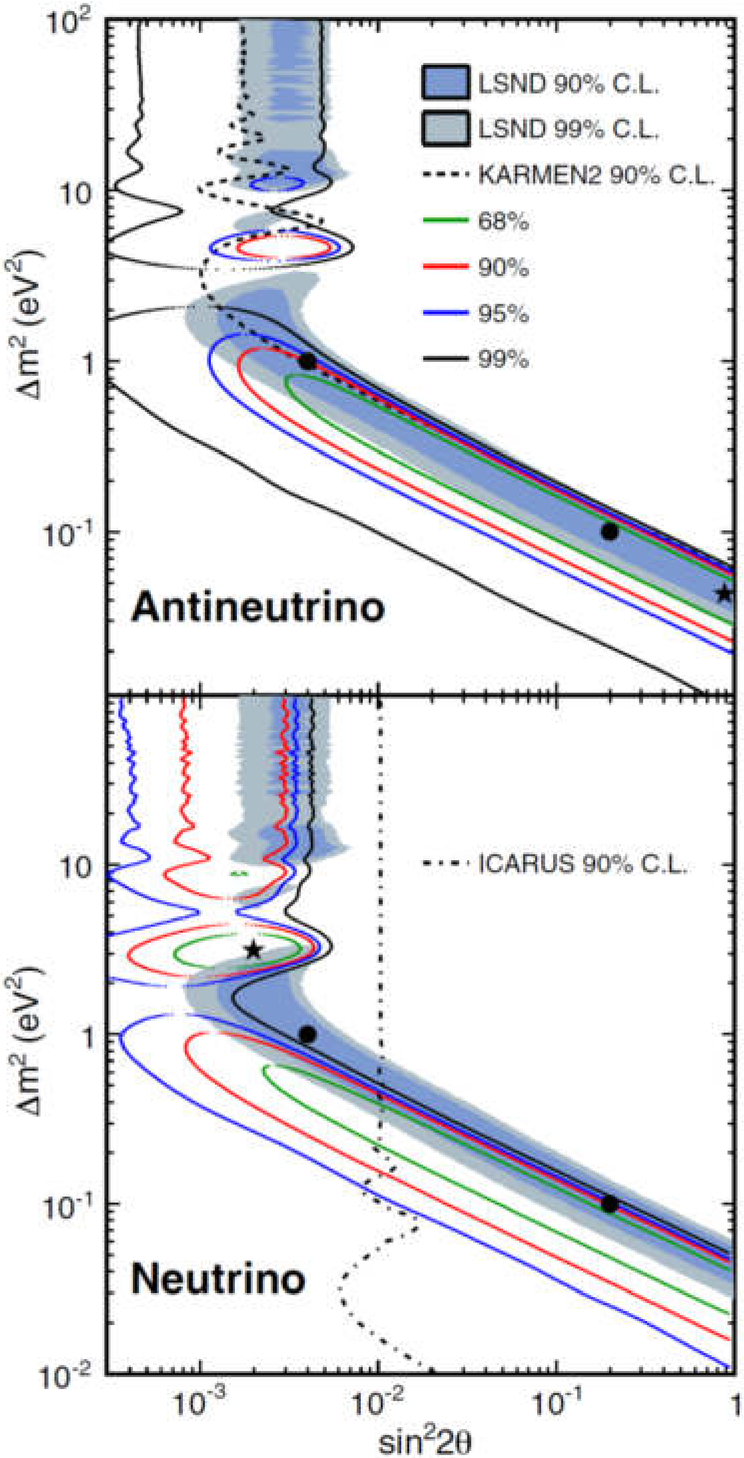
$\nu_\mu \rightarrow \nu_e$?

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$?

Mineral-oil Cherenkov Detector



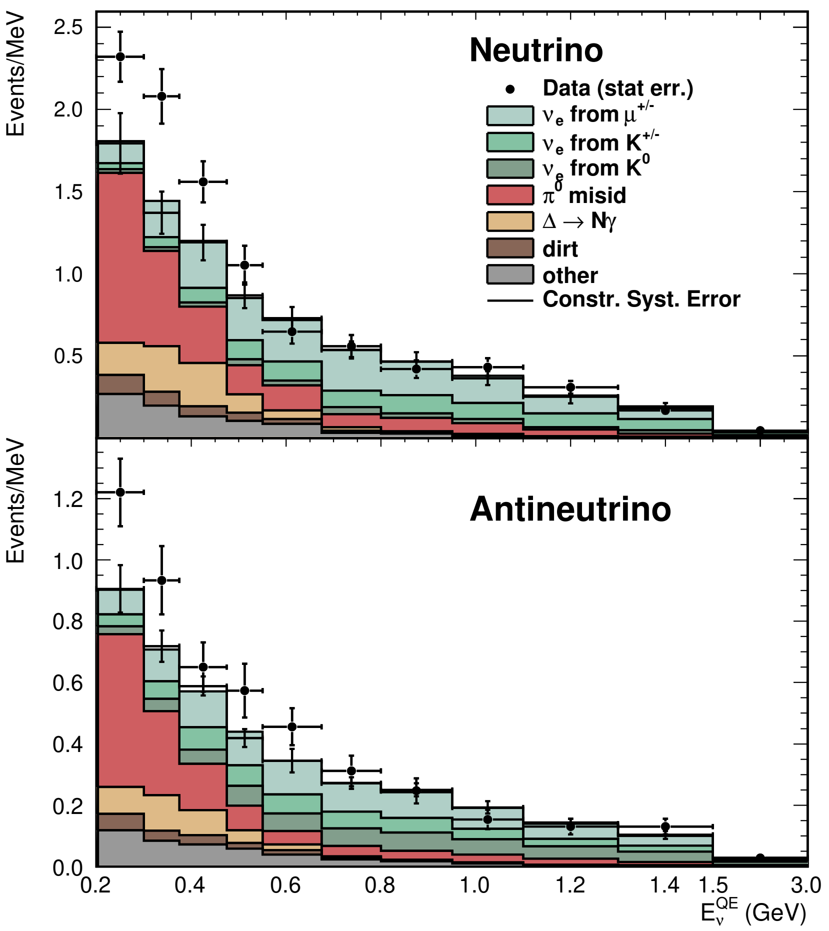
Antineutrino
Data (stat err.)
ν_e from $\mu^{+/-}$
ν_e from $K^{+/-}$
ν_e from K^0
π^0 misid
$\Delta \rightarrow N\gamma$
dirt
other
Constr. Syst. Error
Neutrino
Events/MeV
E_ν^{QE} (GeV)

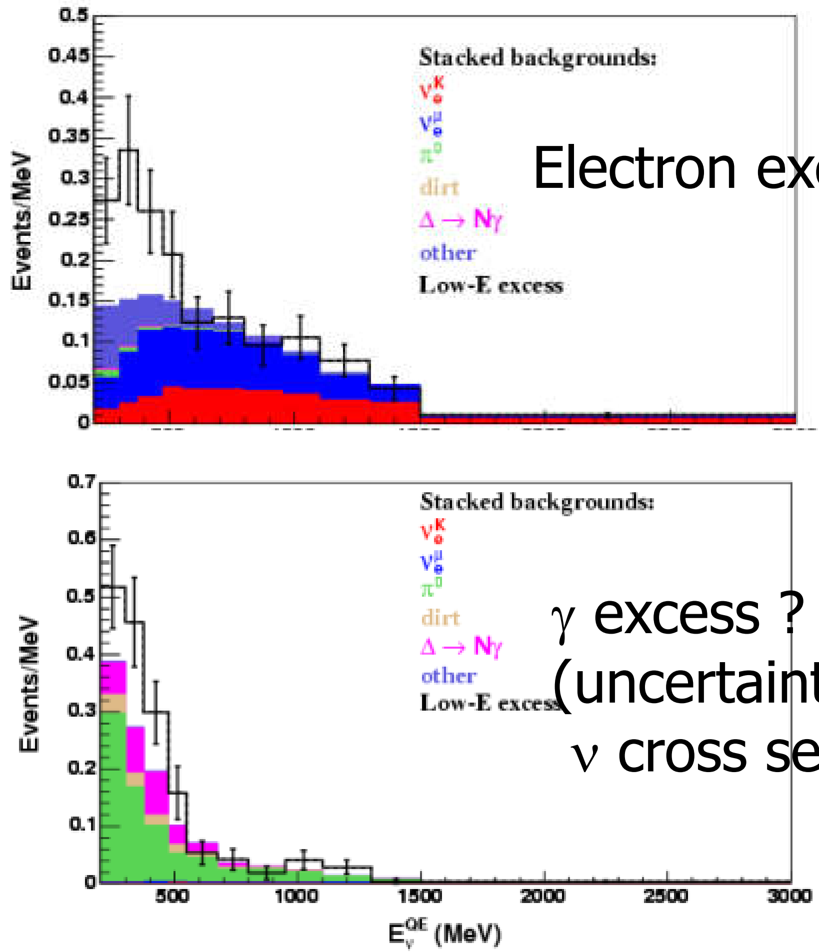


LSND 90% C.L.
LSND 99% C.L.
KARMEN2 90% C.L.
68%
90%
95%
99%
Antineutrino
ICARUS 90% C.L.
Neutrino
Δm^2 (eV^2)
$\sin^2 2\theta$

New Experiment@FNAL

ICARUS + MicroBooNE + LAr1
→ Better discrimination of e^-, π^0 and single γ

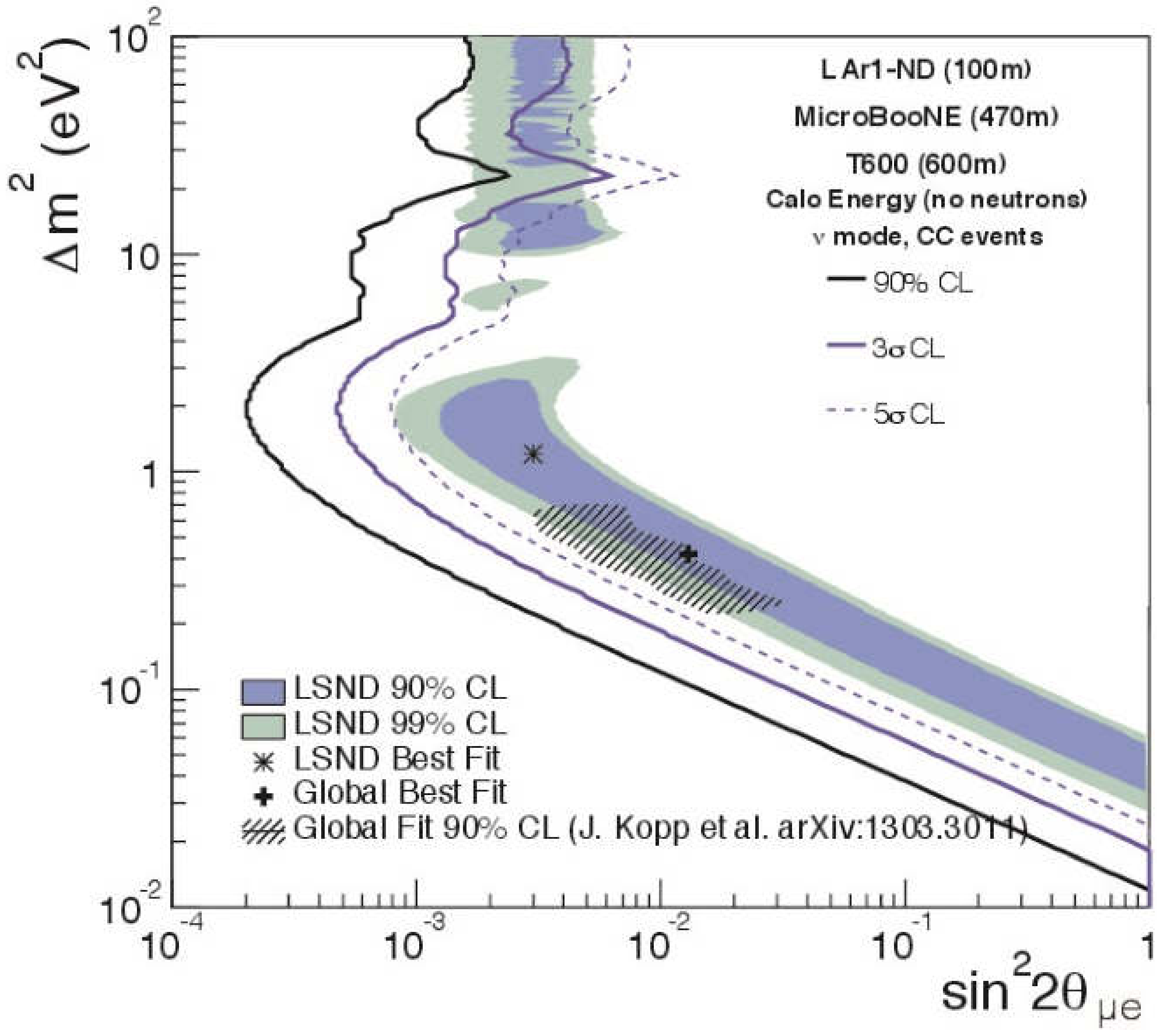


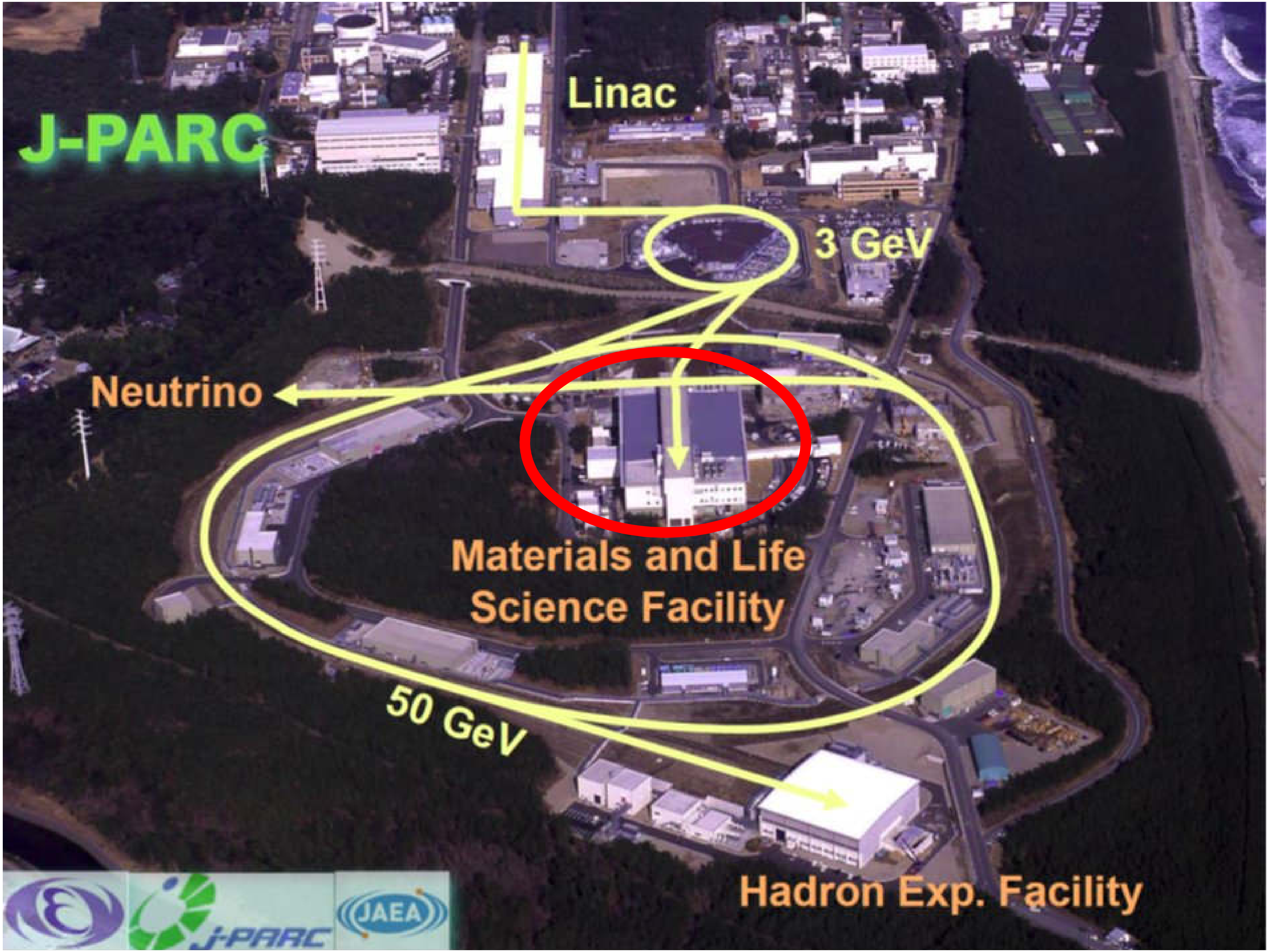


Electron excess ?

γ excess ?
(uncertainty of
ν cross section)

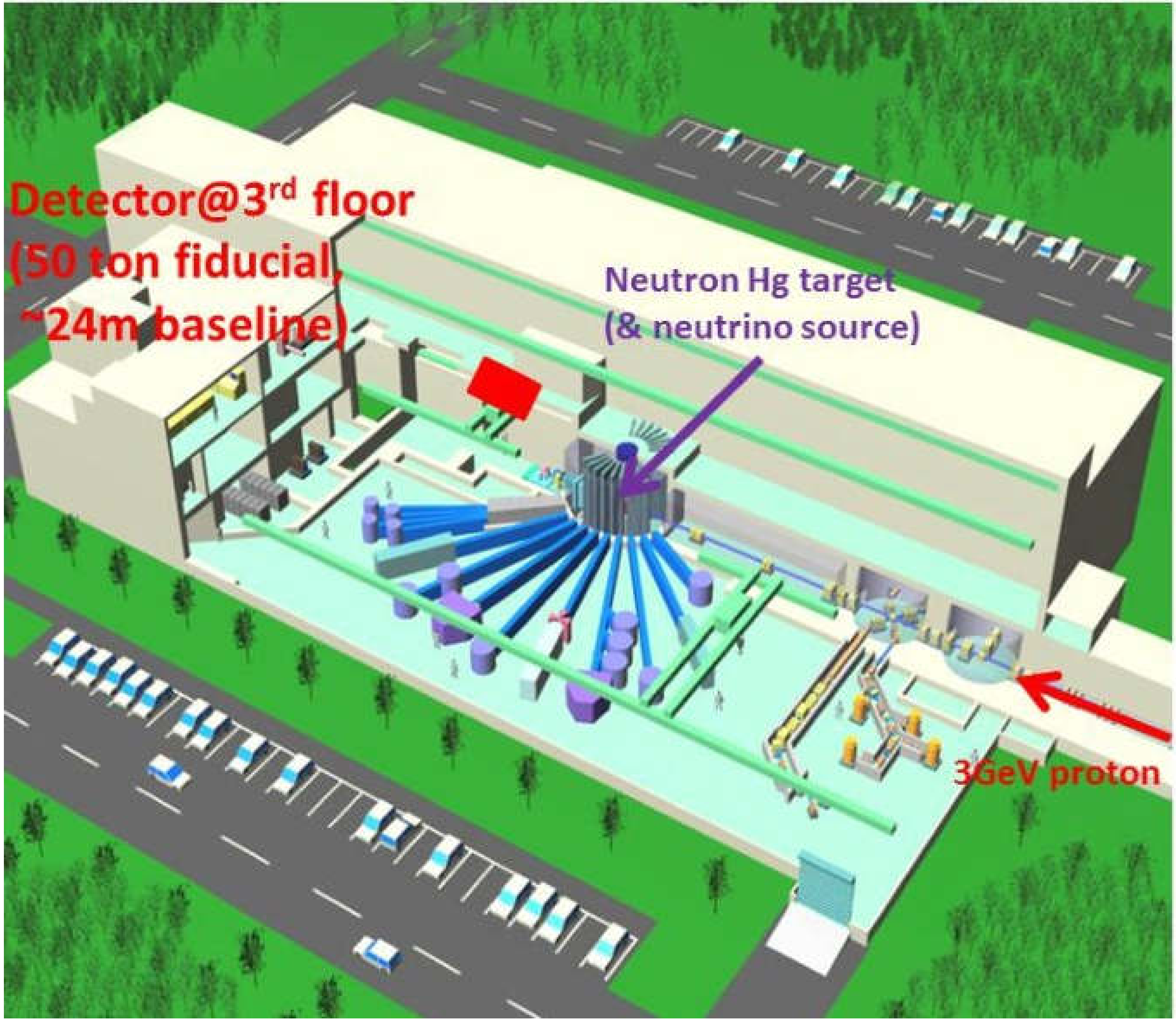
Triple LAr @ FNAL goal





J-PARC
Linac
3 GeV
Neutrino
Materials and Life
Science Facility
50 GeV
Hadron Exp. Facility
JAEA
J-PARC

J-PARC Sterile Neutrino Search using νs
from J-PARC Spallation Neutron Source (E56)



JSNS^2 collaboration

Spokesperson; T. Maruyama (KEK)

S. Ajimura[1], M. K. Cheoun[2], J. H. Choi[3], H. Furuta[4], M. Harada[5], S. Hasegawa[5], Y. Hino[4], T. Hiraiwa[1], E. Iwai[6], S. Iwata[7], J. S. Jang[8], H. I. Jang[9], K. K. Joo[10], J. Jordan[6], S. K. Kang[11], T. Kawasaki[7], Y. Kasugai[5], E. J. Kim[12], J. Y. Kim[10], S. B. Kim[13], W. Kim[14], K. Kuwata[4], E. Kwon[13], I. T. Lim[10], T. Maruyama[*15], S. Meigo[5], S. Monjushiro[15], D. H. Moon[10], T. Nakano[1], M. Niiyama[16], K. Nishikawa[15], M. Nomachi[1], M. Y. Pac[3], J. S. Park[15], S.J.M. Peeters[17], H. Ray[18], C. Rott[19], K. Sakai[5], S. Sakamoto[5], H. Seo[13], S. H. Seo[13], A. Shibata[7], T. Shima[1], J. Spitz[6], I. Stancu[20], F. Suekane[4], Y. Sugaya[1], K. Suzuya[5], M. Taira[15], T. Torizawa[7], J. Waterfield[17], R. White[17], M. Yeh[21], and I. Yu[18]

[1] *Research Center for Nuclear Physics, Osaka University, Osaka, JAPAN*
[2] *Department of Physics, Soongsil University, Seoul 06978, KOREA*
[3] *Department of Radiology, Dongshin University, Chonnam 58245, KOREA*
[4] *Research Center for Neutrino Science, Tohoku University, Sendai, Miyagi, JAPAN*
[5] *J-PARC Center, JAEA, Tokai, Ibaraki JAPAN*
[6] *University of Michigan, Ann Arbor, MI, 48109, USA*
[7] *Department of Physics, Kitasato University, Sagamihara 252-0373, Kanagawa, JAPAN*
[8] *Gwangju Institute of Science and Technology, Gwangju, 61005, KOREA*
[9] *Department of Fire Safety, Seoyeong University, Gwangju 61268, KOREA*
[10] *Department of Physics, Chonnam National University, Gwangju, 61186, KOREA*
[11] *School of Liberal Arts, Seoul National University of Science and Technology, Seoul, 139-743, KOREA*
[12] *Division of Science Education, Physics major, Chonbuk National University, Jeonju, 54896, KOREA*
[13] *Department of Physics and Astronomy, Seoul National University, Seoul 08826, KOREA*
[14] *Department of Physics, Kyungpook National University, Daegu 41566, KOREA*
[15] *High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, JAPAN*
[16] *Department of Physics, Kyoto University, Kyoto, JAPAN*
[17] *Department of Physics and Astronomy, University of Sussex, Brighton, UK*
[18] *University of Florida, Gainesville, FL, 32611, USA*
[19] *Department of Physics, Sungkyunkwan University, Gyeong Gi-do, KOREA*
[20] *University of Alabama, Tuscaloosa, AL, 35487, USA*
[21] *Brookhaven National Laboratory, Upton, NY, 11973-5000, USA*

57 collaborators from Japan, Korea, US, UK

J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source

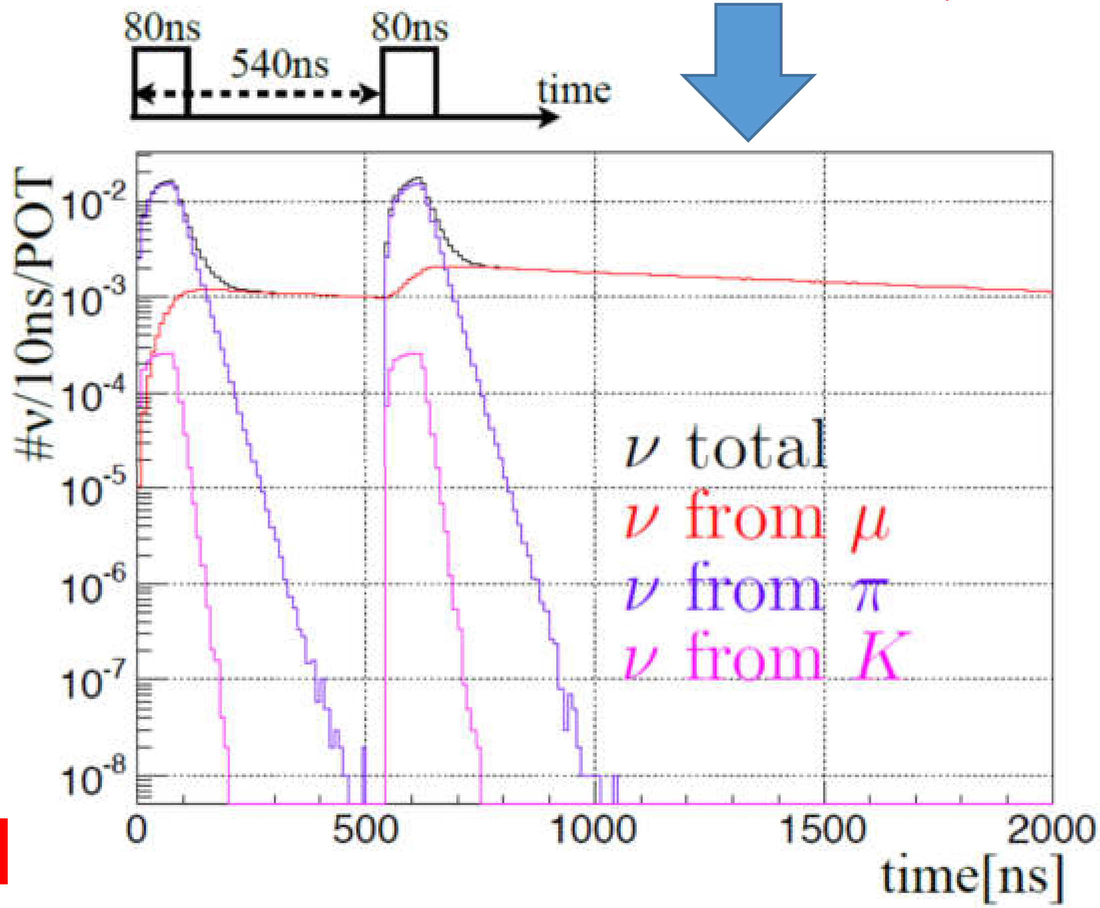
http://research.kek.jp/group/mlfnu/

Time profile of neutrino beam

Pure $\nu_e + \overline{\nu_\mu}$!

- Pulse width; 80ns ×2
  (double pulses,
  540ns interval)
- Repetition rate; 25Hz
- ν from decay-at-rest μ ;
  well separated from
  beam pulse

→ low background



J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source

Detector

Gd-loaded liq. scintillator or/and Cherenkov, 25 ton × 2, detecting

$$\overline{\nu_e} + p \rightarrow n + e^+ \quad \text{(prompt)}$$

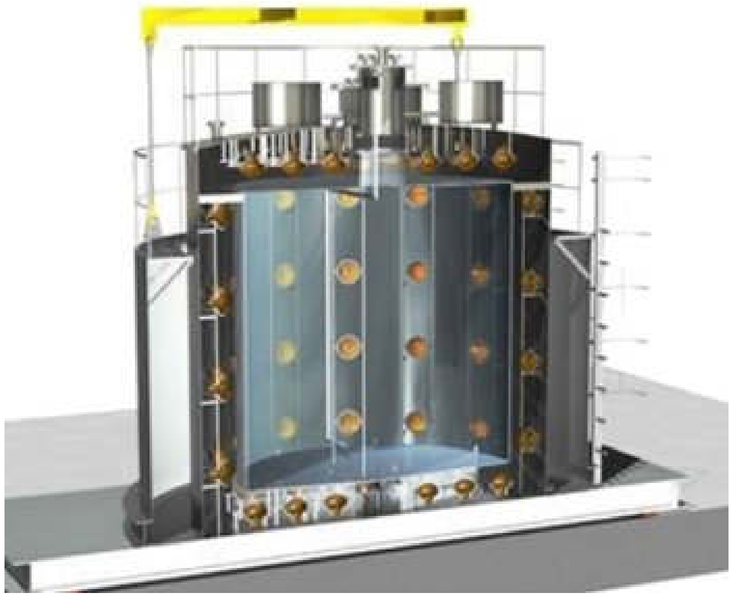
$$n + {}^{157}Gd \rightarrow {}^{158}Gd + \gamma \quad \text{(delayed; Q\sim8MeV, } \tau_{cap}\text{\sim30}\mu\text{s)}$$

(253000b@thermal)

Prompt; t_e=1~10μs, E_e=20~60MeV

Delayed; t_γ=1~100μs, E_γ=7~12MeV

→ Delayed coincidence



J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source

Merits of JSNS^2

- Neutrino beam

	Facility	Beam Pow. [MW]	Rep. Rate [Hz]	Pulse Width [ns]	Duty Factor
JSNS^2	**J-PARC/MLF**	**1**	**25**	**620**	**1.55e-5**
LSND	LANL/LAMPF	0.8	120	6e+5	0.072
KARMEN	RAL/ISIS	0.16	50	430	2.15e-5

--- Φ_ν ~10×KARMEN S/N > 1000×LSND

- Detector

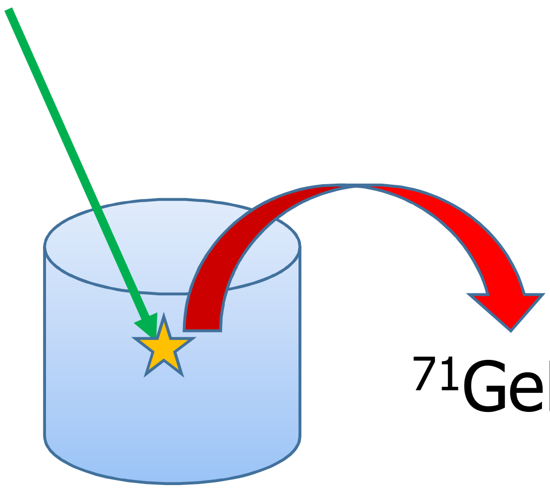
	Type	Mass [t]	L [m]
JSNS^2	**Gd-LS PSD**	**50**	**24**
LSND	LS	167	30
KARMEN	LS + Gd coating	56	17.7

SAGE (Russian-American collab. on solar ν measurement)

GALLEX (Gallium Experiment for solar ν)

$$\nu_e \rightarrow \nu_S$$

Solar ν



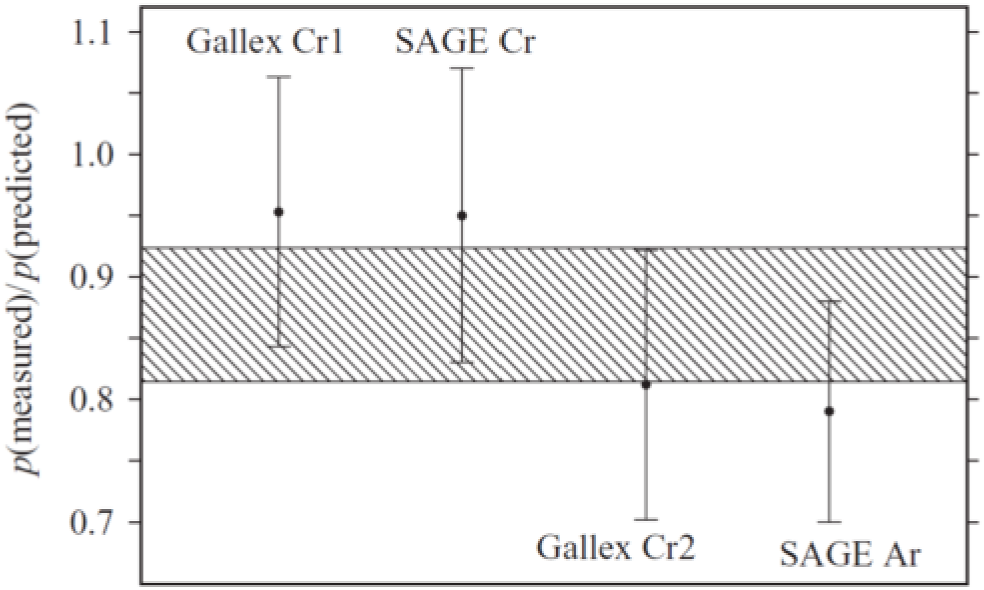
$^{71}GeH_4$ + Xe

Proportional Counter

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

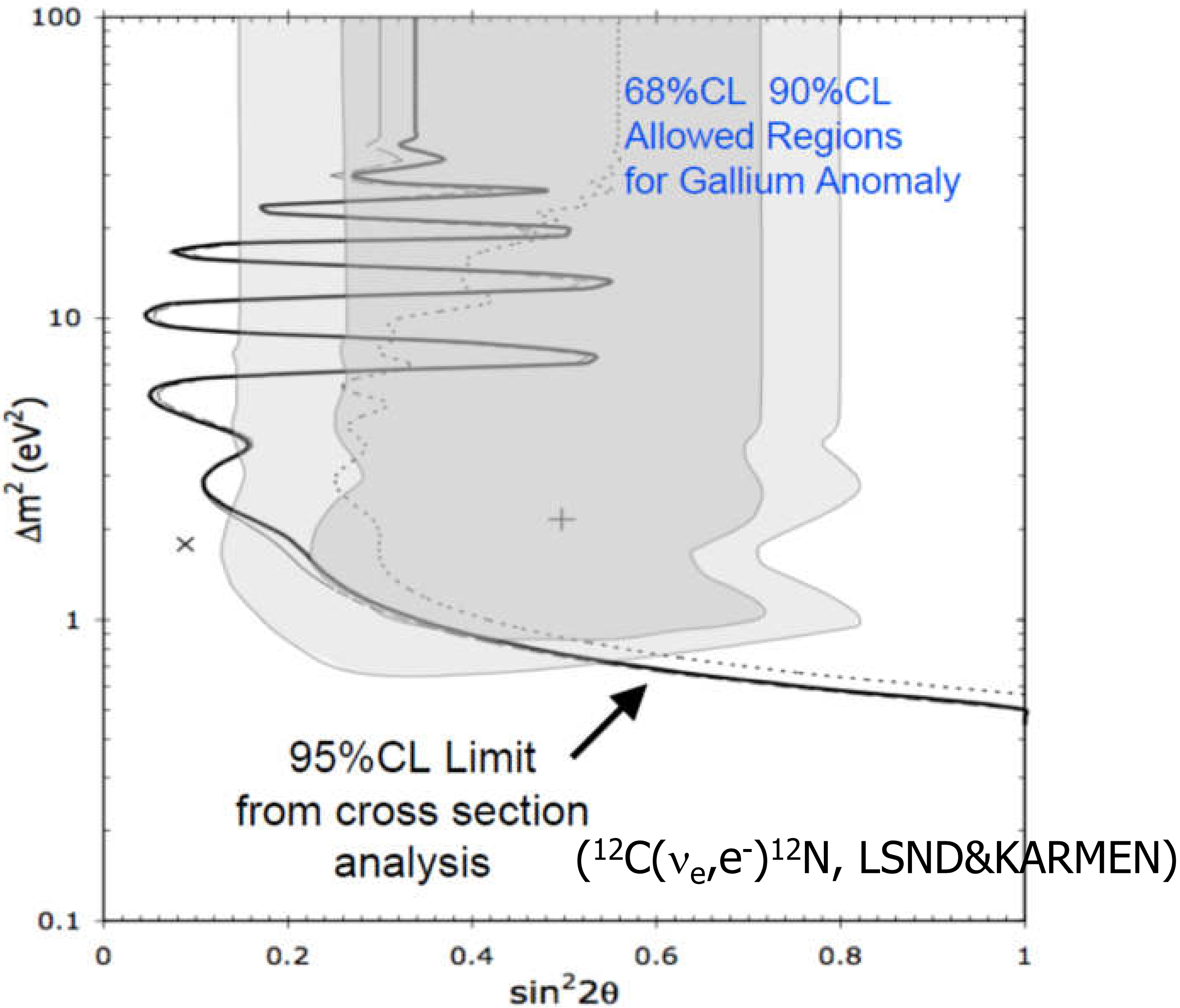
$T_{1/2}(EC)$=11.4d
X-ray, Auger ~10keV

Calibration with sources;
^{51}Cr (Q_{EC} =752keV)
^{37}Ar (Q_{EC} =814keV)

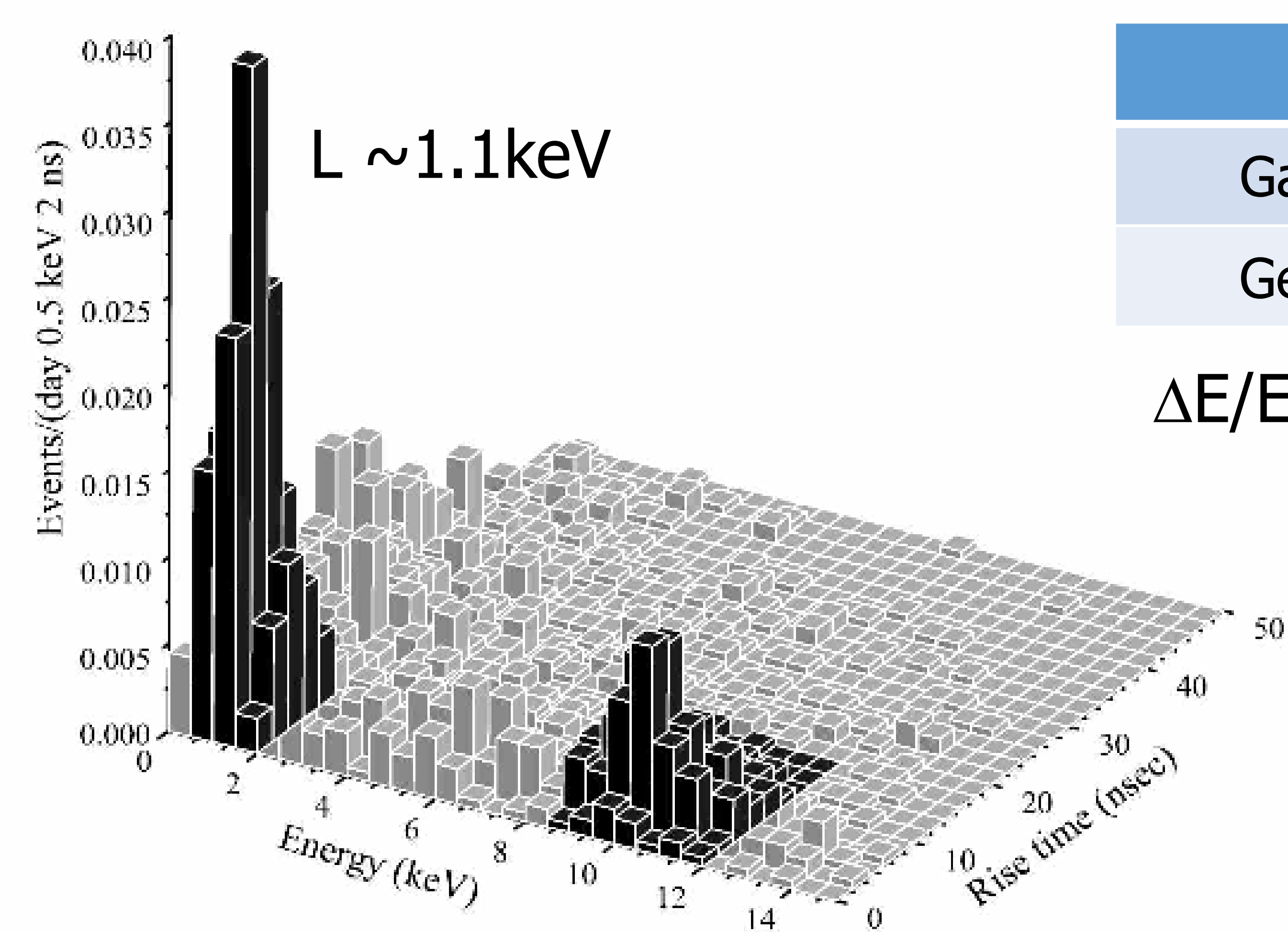


L ~ a few m

→ Prof. Ejiri's talk


68%CL 90%CL
Allowed Regions
for Gallium Anomaly
95%CL Limit
from cross section
analysis
($^{12}C(\nu_e,e^-)^{12}N$, LSND&KARMEN)
Δm^2 (eV^2)
$\sin^2 2\theta$
100
10
1
0.1
0
0.2
0.4
0.6
0.8
1

Energy deposit vs Rise time



Kα ~9.3keV

	$K\alpha_1$ [keV]	L [keV]
Ga	9.252	1.1
Ge	9.886	1.19

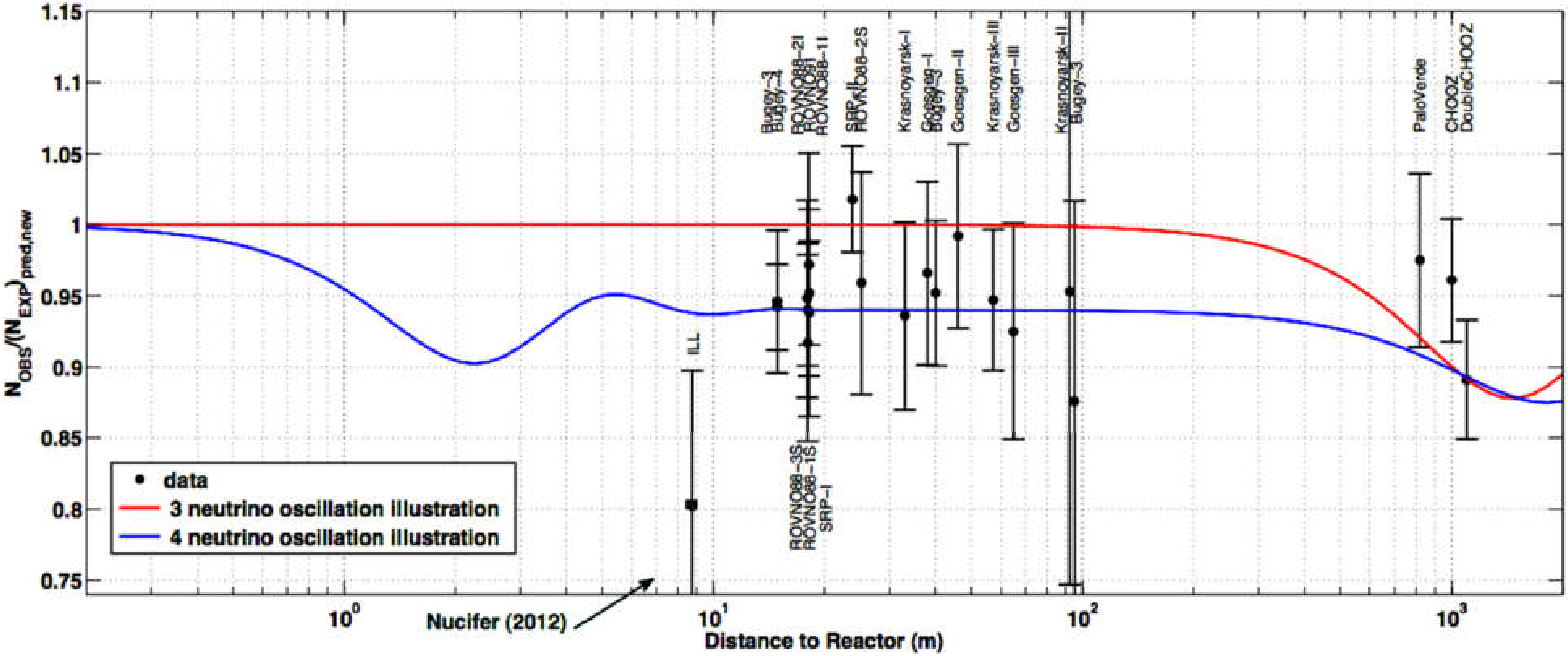
$\Delta E/E$(FWHM)~10%@10keV...

Direct signals of more energetic electrons can be distinguished with rise times.

However, it is difficult to distinguish signals from the excited Ge atoms …

Reactor experiments

$$\overline{\nu}_e \rightarrow \overline{\nu}_S$$



10m 100m 1000m

3. Cosmological constraint

- Scale factor; $a(t)$ → DOF of fermion gas → N_{eff}
- Dark matter density; $\Omega_\nu \rightarrow \sum_i m_i$

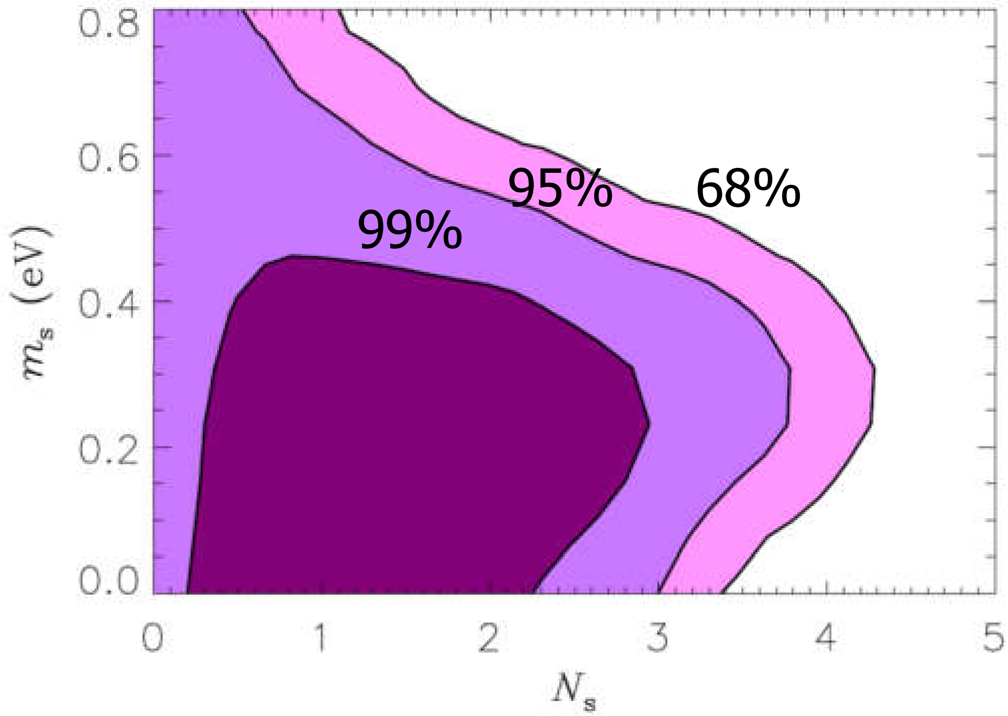
Observables

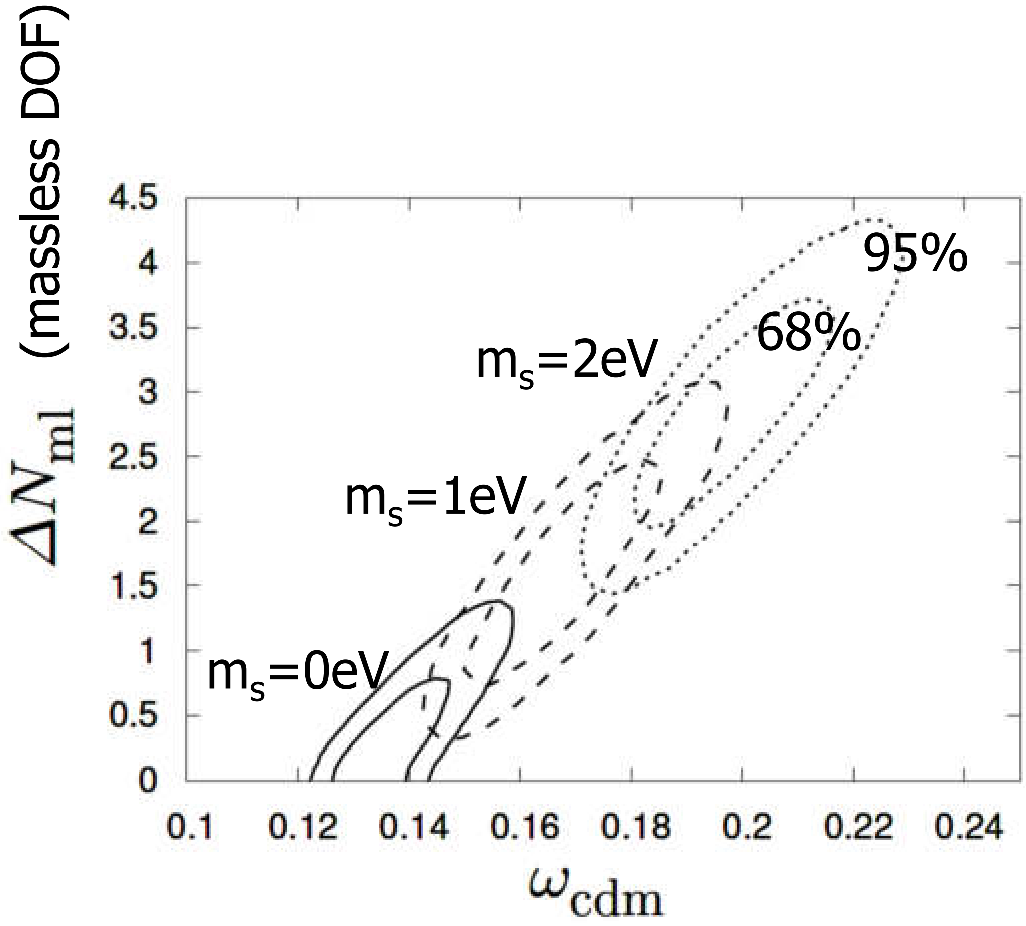
- Unisotropy of Cosmic Microwave Background (CMB)
- Large-scale structure (LSS), galaxy formation
- Big-bang nucleosynthesis (BBN)

J. Hamann et al., J. Physics: Conf. Ser. 375 (2012) 032003

CMB+LSS (combined dta; WMAP, ACBAR, BICEP, QuAD, SDSS, Union-2, HST)

ΛCDM + sterile

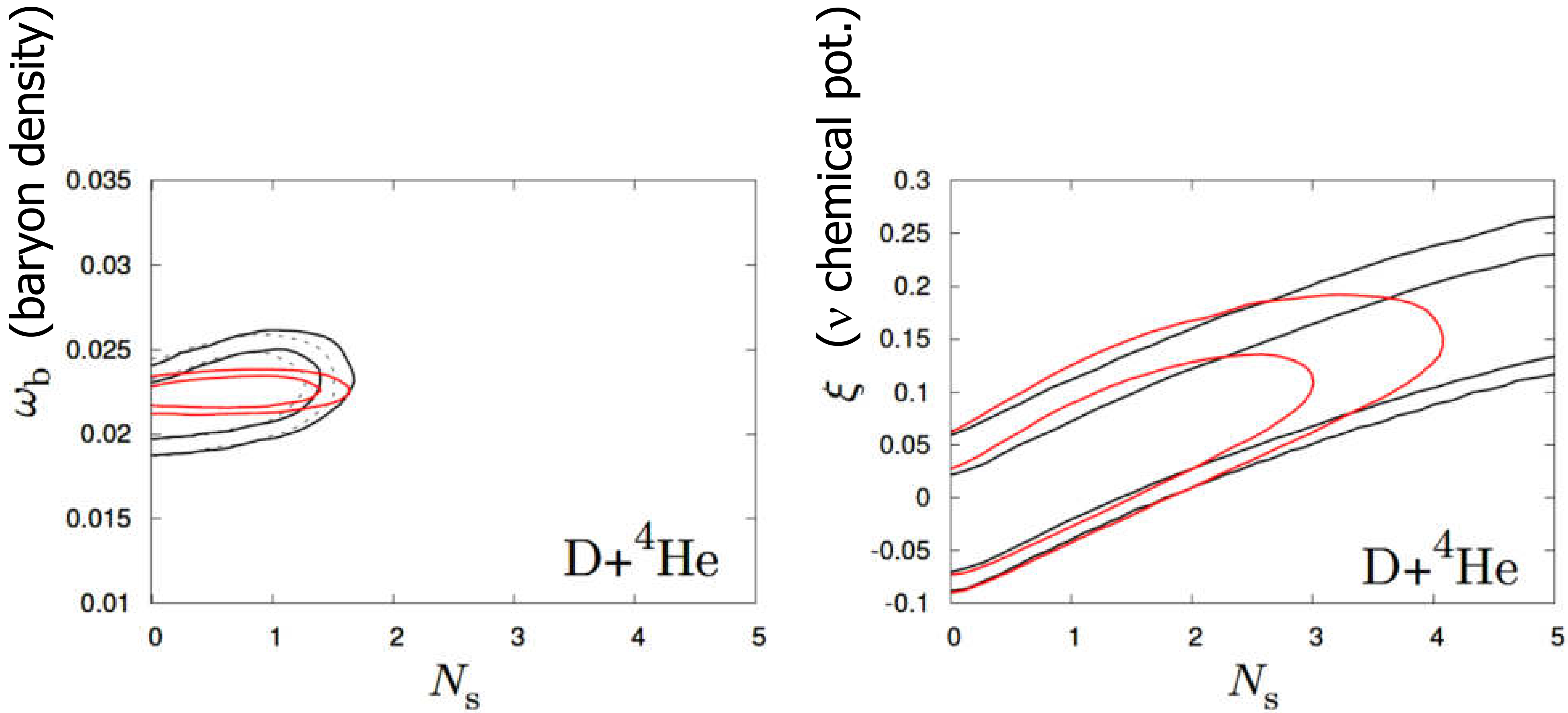




(EOS parameter of Λ)

J. Hamann et al., J. Physics: Conf. Ser. 375 (2012) 032003

BBN; D+^{4}He



Solid; τ_n =878.5s　Dashed; τ_n =885.7s

Black; BBN only　Red; with CMB+LSS

4. Summary

- Sterile neutrino can be naturally introduced in GUTs beyond minimal SU(5).
- It can be Majorana type → $0\nu\beta\beta$
- Short-baseline experiments suggest $\Delta m^2 \sim 1\mathrm{eV}^2$ and $\sin^2 2\theta = 10^{-3}$-10^{-2} (but not all).
- Many new experiments with accelerator neutrinos are planned or on-going.
- Cosmological constraint is important as complementary one.
  → PLANCK data   A.M. Knee, D. Contreras, D. Scott, J. Cosm. Astr. Phys., July2019