An Update on KamLAND

Brian Kurt Fujikawa for the KamLAND Collaboration

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KamLAND Phase I

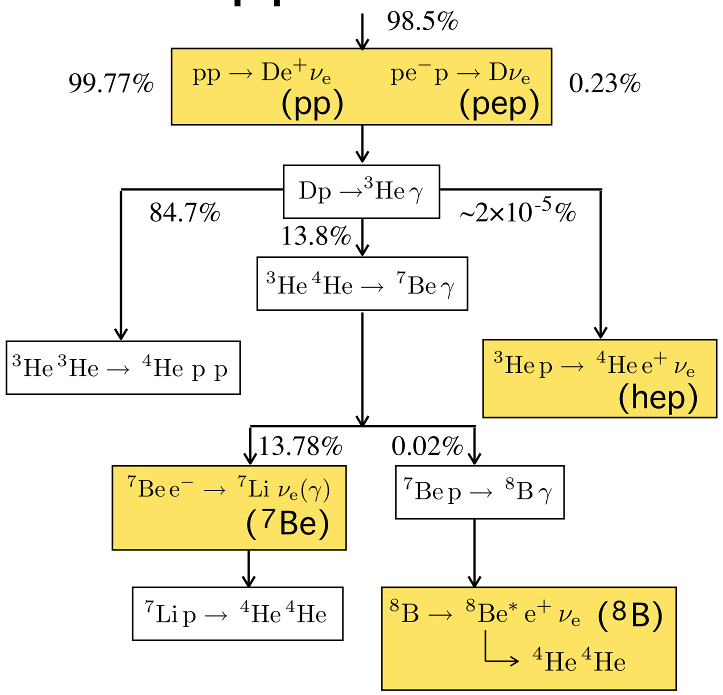
(January 21, 2002 to May 12, 2007)

- Reactor Anti-Neutrino Disappearance
- Geo-Neutrinos
- Neutron Disappearance
- Solar Electron Anti-Neutrino Search
- Supernova Watch
- Cosmic Ray Muon Spallation (work in progress)

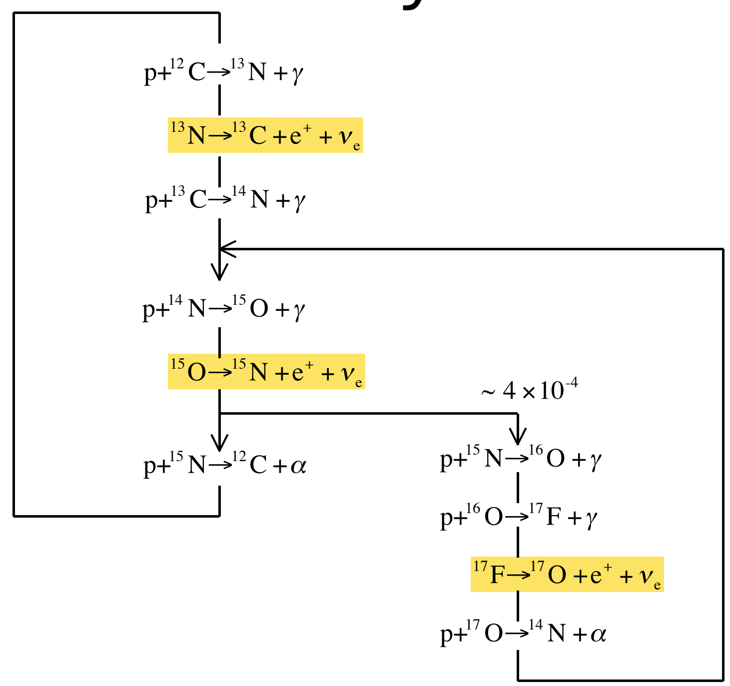
Reactor Anti-Neutrino Disappearance

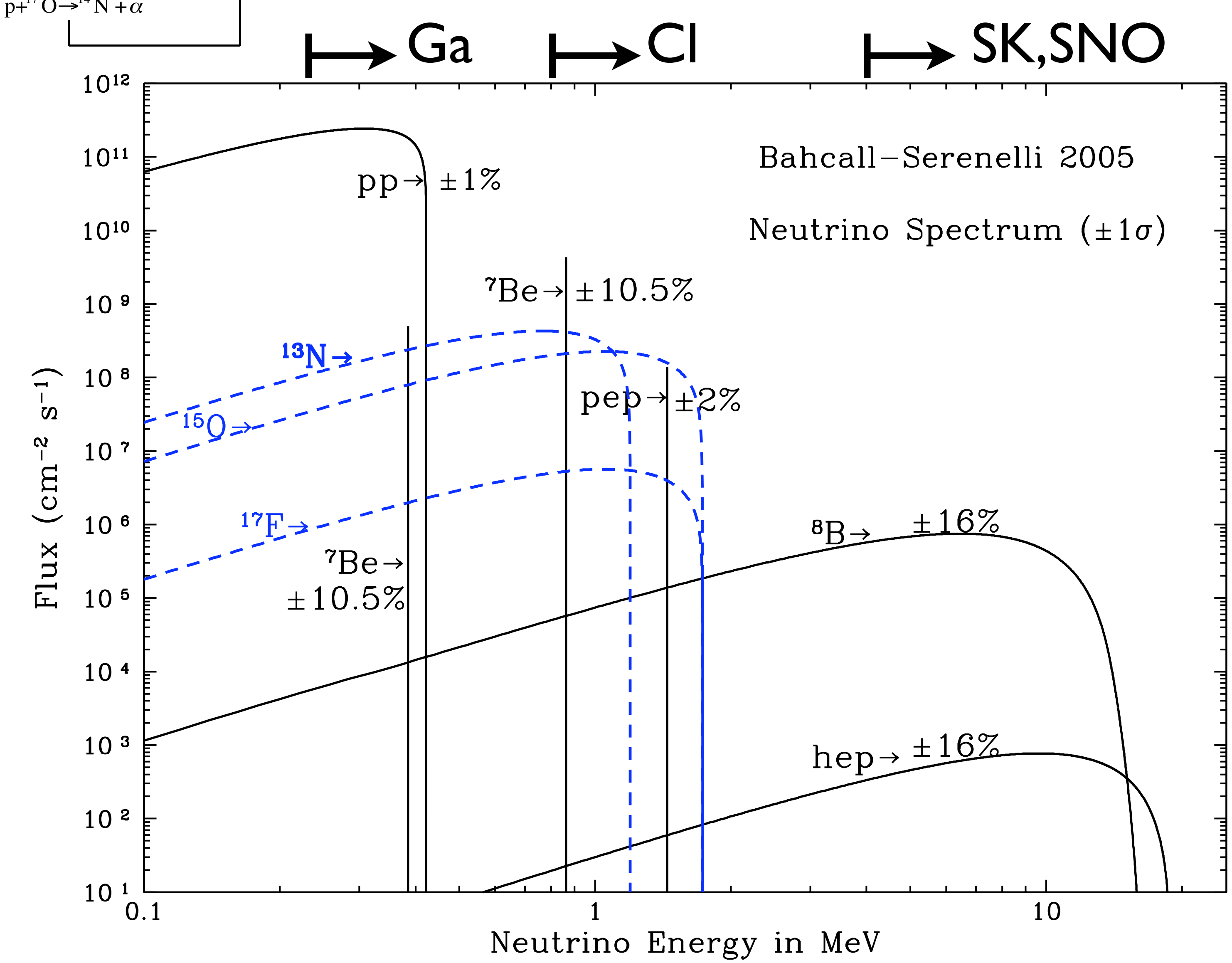
The Standard Solar Model

pp chain

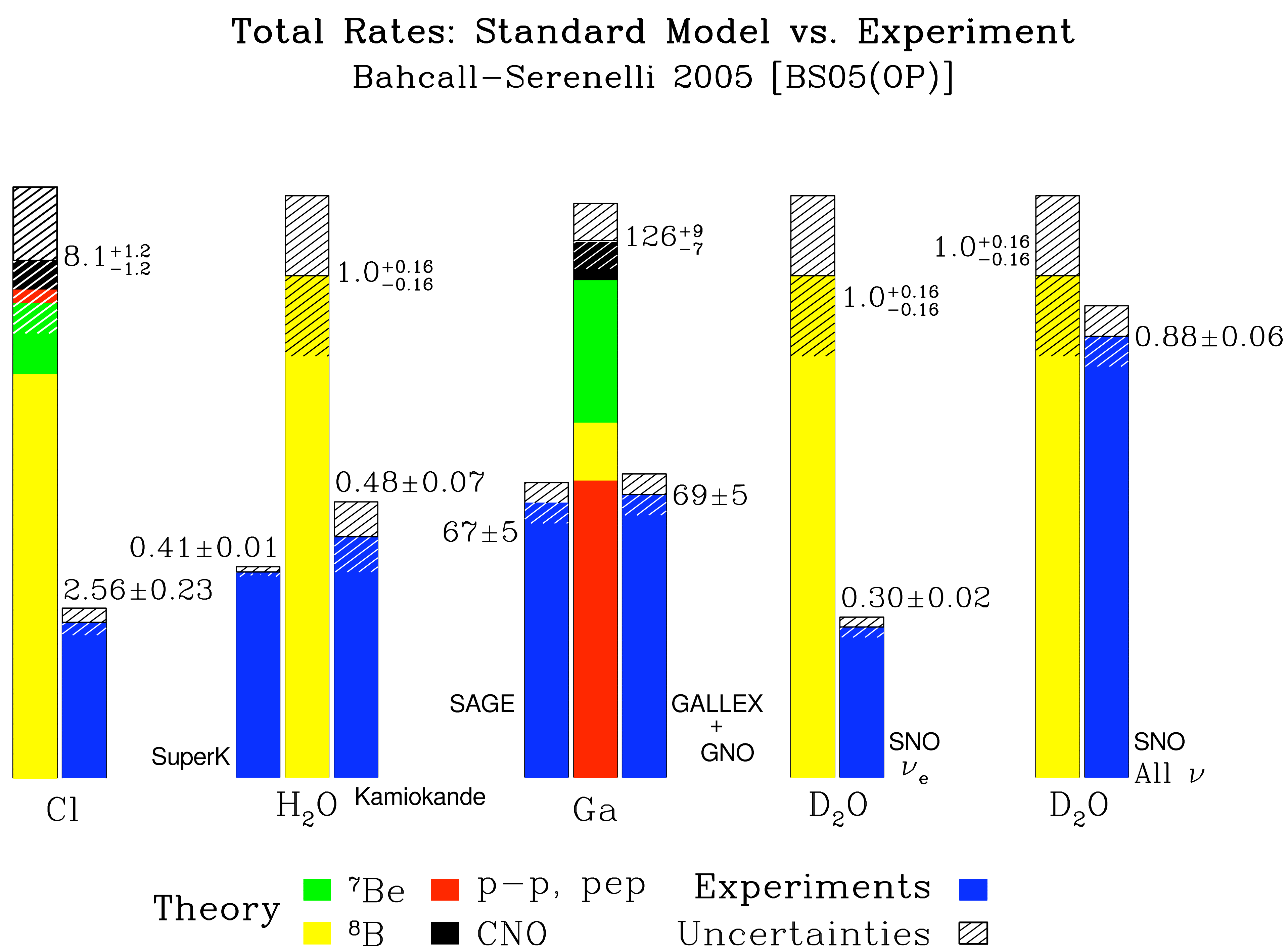


CNO cycle





The Solar Neutrino Problem



Neutrino Oscillations

$$|\nu_l\rangle = \sum_{i=1}^{3} U_{li}|\nu_i\rangle; \quad l = e, \mu, \tau$$

$$U_{MNSP} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric/accelerator } \nu} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_D} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_D} & 0 & c_{13} \end{pmatrix}}_{\text{reactor/accelerator } \nu} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar/reactor } \nu}$$

$$|\nu_i\rangle = e^{-i\frac{m_i^2 L}{2E}} |\nu_i(L=0)\rangle$$

Neutrino Oscillations

$$|\nu_l\rangle = \sum_{i=1}^{3} U_{li}|\nu_i\rangle; \quad l = e, \mu, \tau$$

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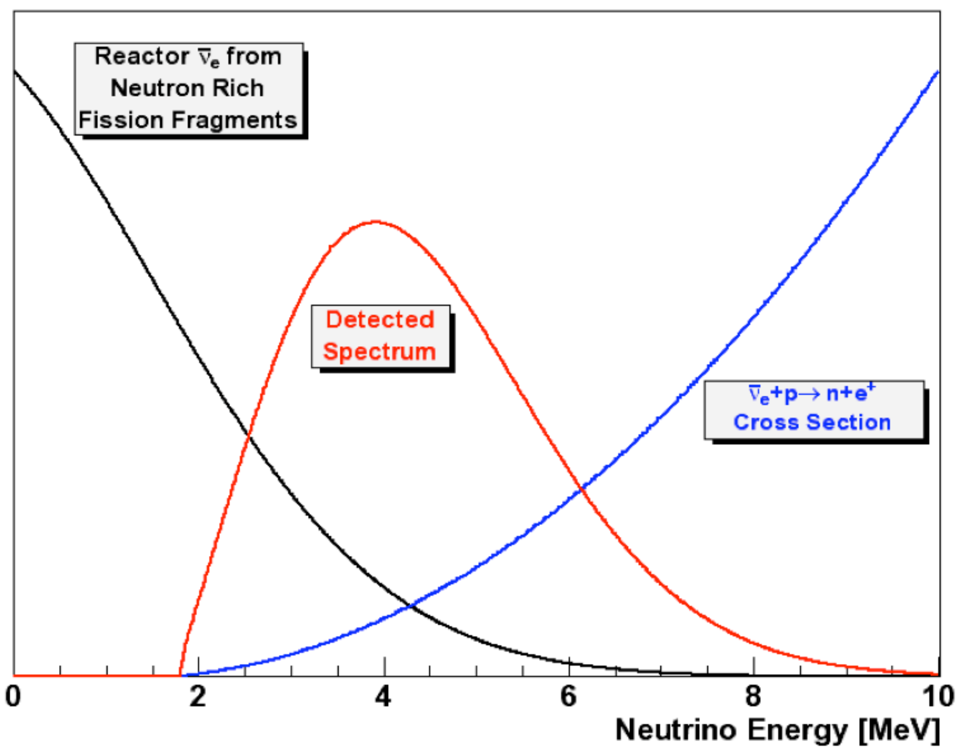
$$|\nu_i\rangle = e^{-i\frac{m_i^2 L}{2E}}|\nu_i(L=0)\rangle$$

consider only two neutrino oscillations:

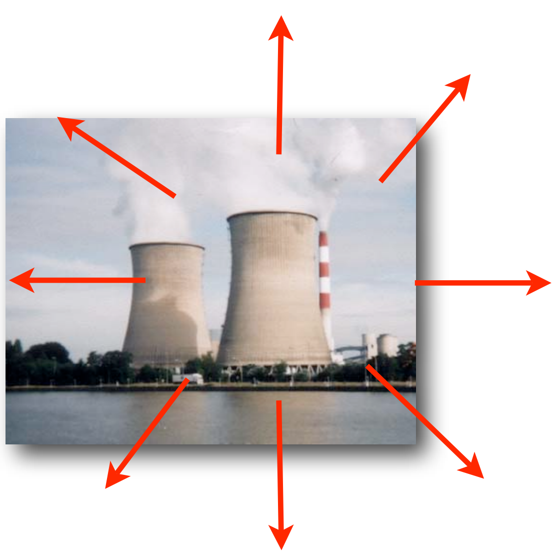
$$P(\overline{\nu}_e \to \overline{\nu}_\mu) \approx \sin^2 2\theta_{12} \sin^2 \frac{4\Delta m_{12}^2 L}{E} = \sin^2 2\theta \sin^2 \frac{1.27\Delta m^2 L}{E}$$

Reactor Anti-Neutrino Disappearance Experiments



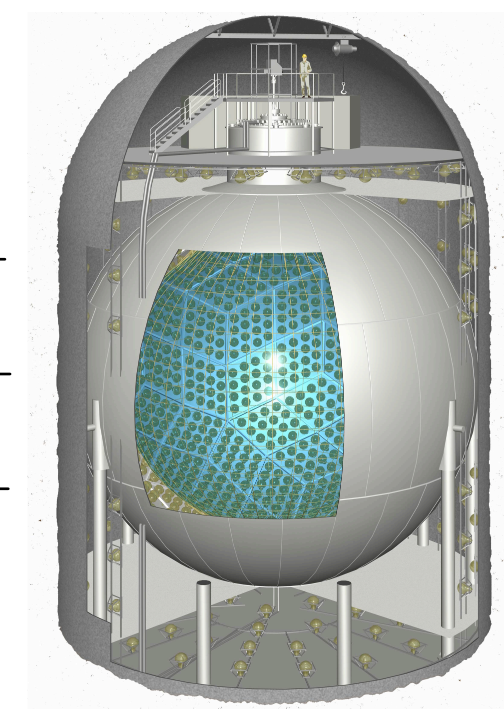
Beta Decay of Neuron Rich Fission Fragments

$$(A,Z) \rightarrow (A,Z+1) + e^- + \overline{\nu}_e \rightarrow \quad \begin{aligned} &\rightarrow \overline{\nu}_e + p \rightarrow n + e^+ \\ &\rightarrow \overline{\nu}_\mu + p \rightarrow n + \mu^+ \\ &\rightarrow \overline{\nu}_\tau + p \rightarrow n + \tau^+ \end{aligned}$$

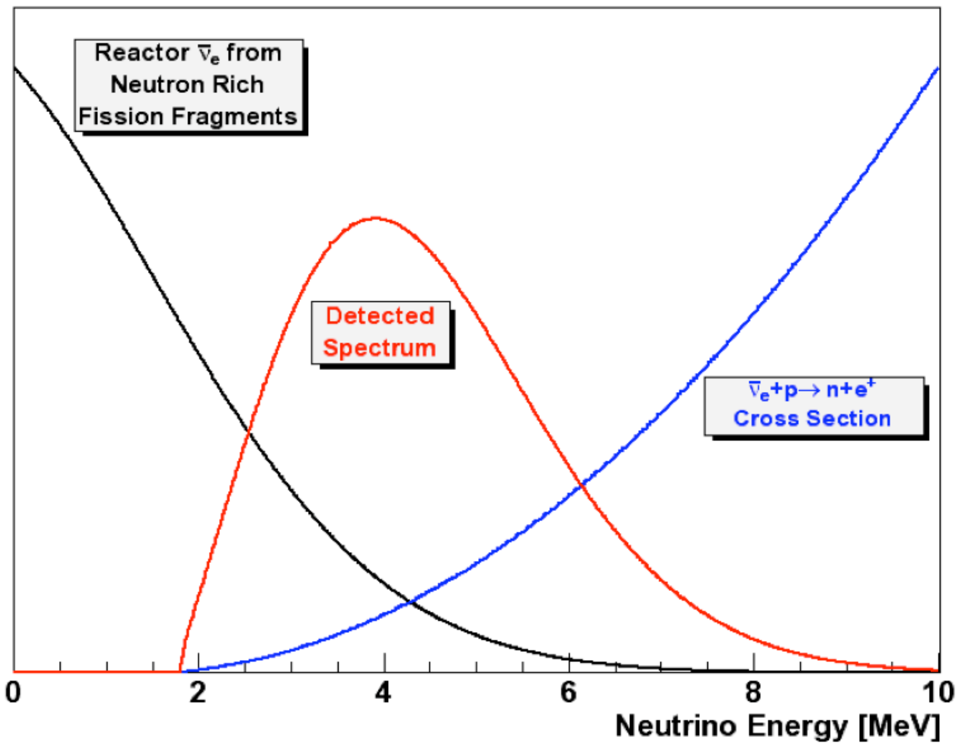


$\overline{\nu}_e$

N_{e^+}
N_{μ^+}
N_{τ^+}



Reactor Anti-Neutrino Disappearance Experiments

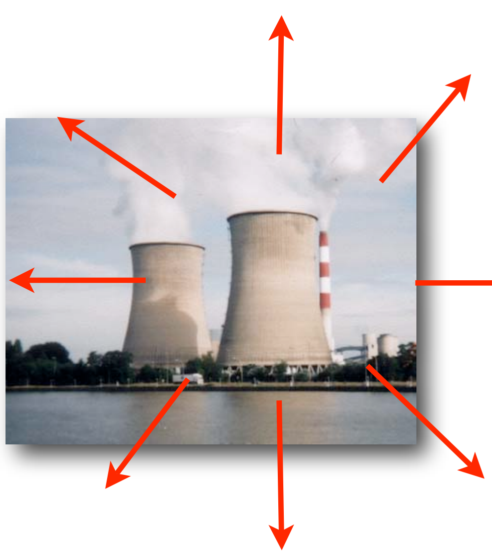


Beta Decay of Neuron Rich Fission Fragments

$$(A,Z) \rightarrow (A,Z+1) + e^- + \overline{\nu}_e \rightarrow \quad \rightarrow \overline{\nu}_e + p \rightarrow n + e^+$$

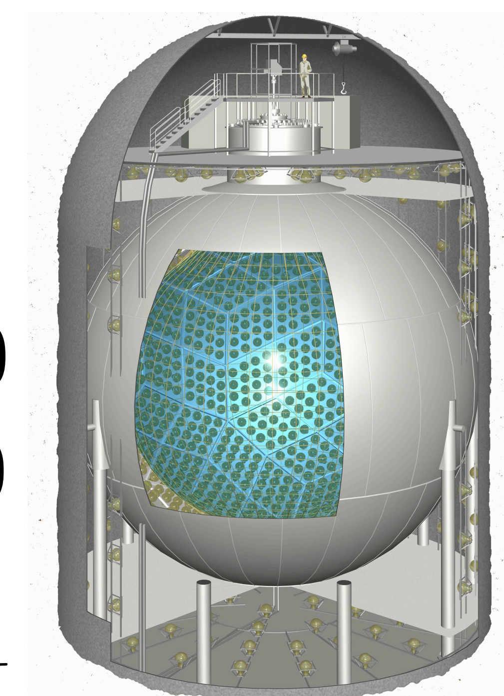
~~$\rightarrow \overline{\nu}_\mu + p \rightarrow n + \mu^+$~~

~~$\rightarrow \overline{\nu}_\tau + p \rightarrow n + \tau^+$~~



$\overline{\nu}_e$

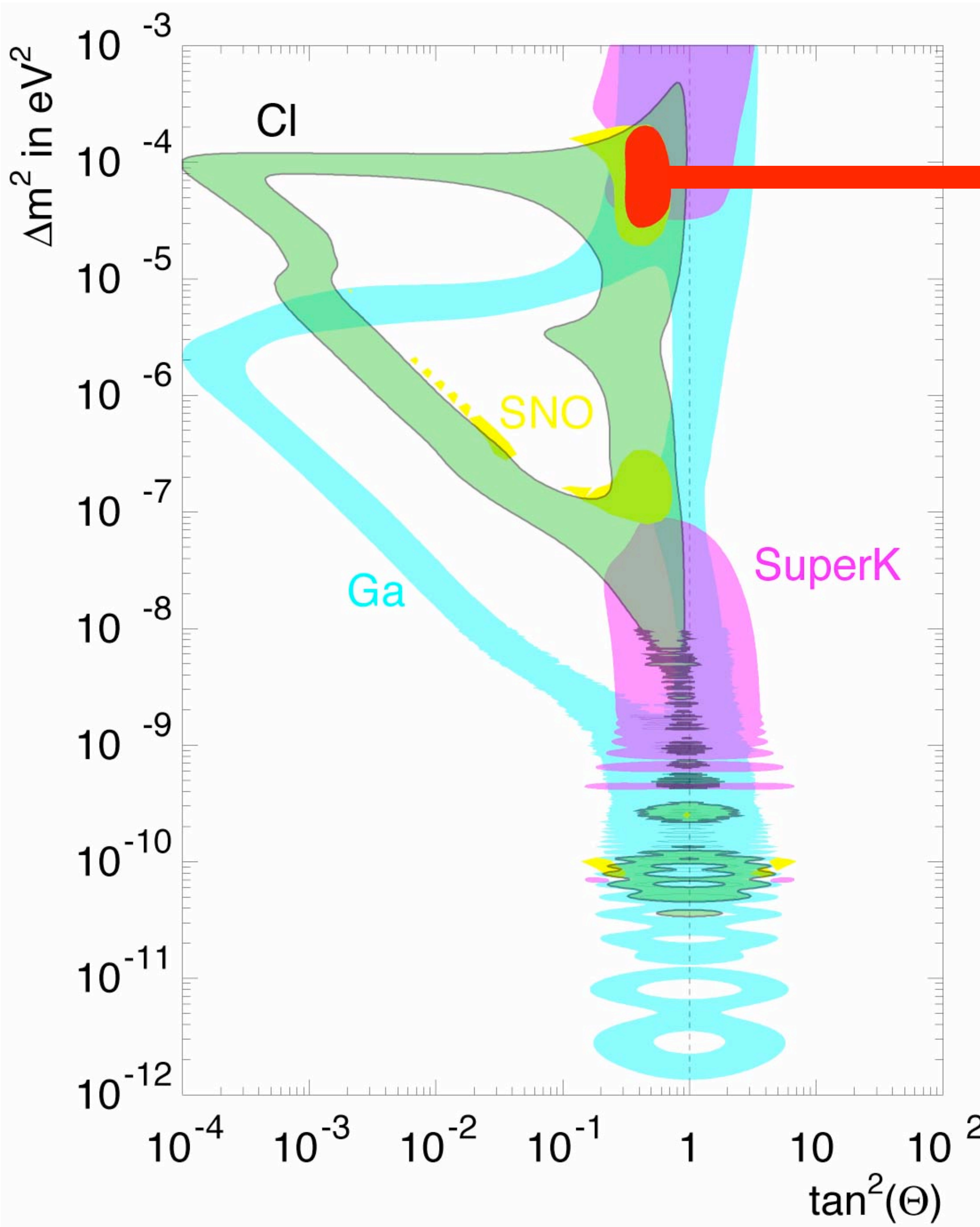
$$N_{e^+}$$
$$N_{\mu^+} = 0$$
$$N_{\tau^+} = 0$$

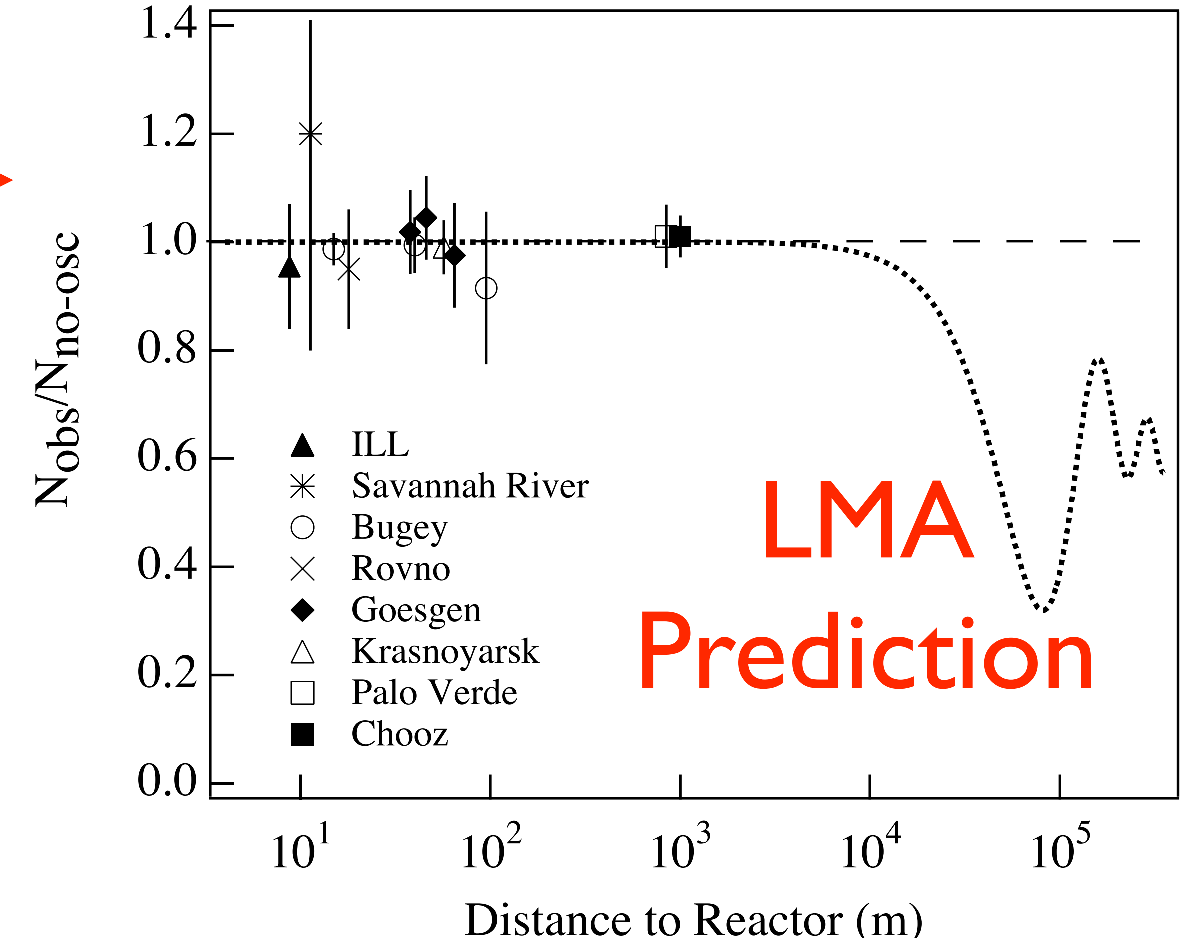


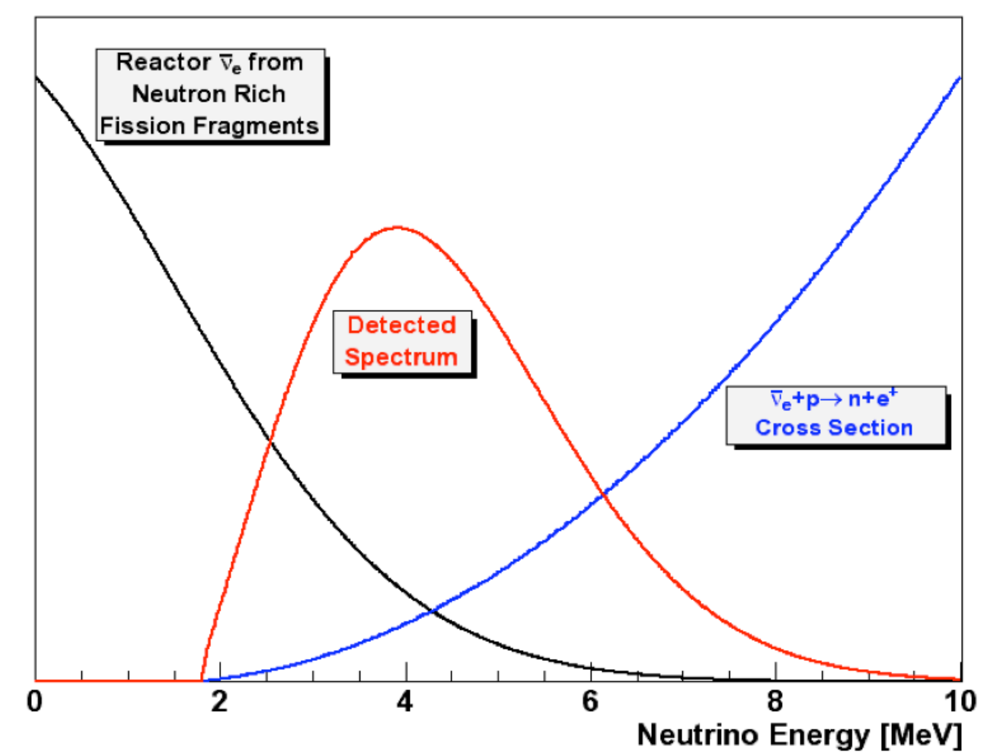
$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2 2\theta \, \sin^2 \frac{1.27 \Delta m^2 L}{E}$$

L

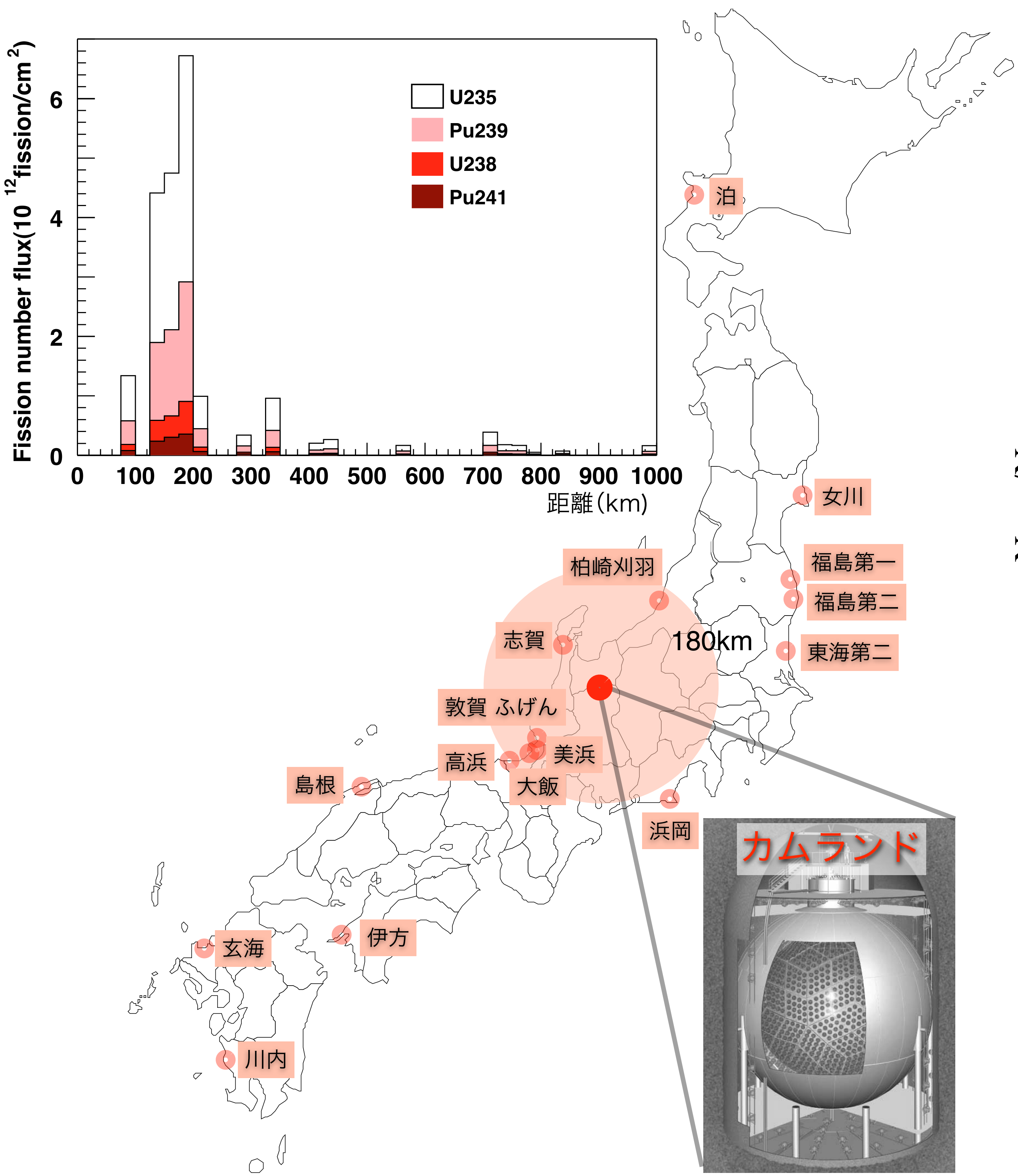
Large Mixing Angle (LMA) Solution to the Solar Neutrino Problem

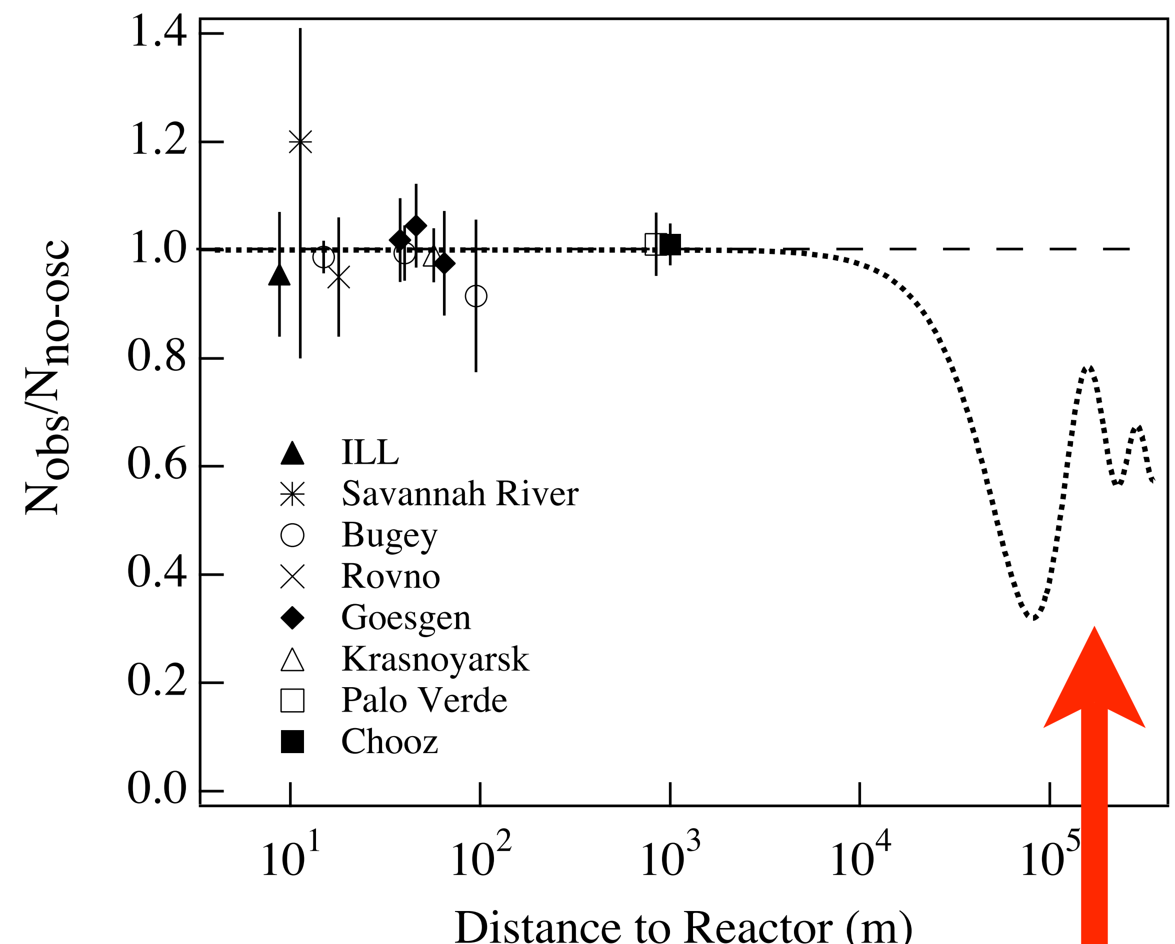






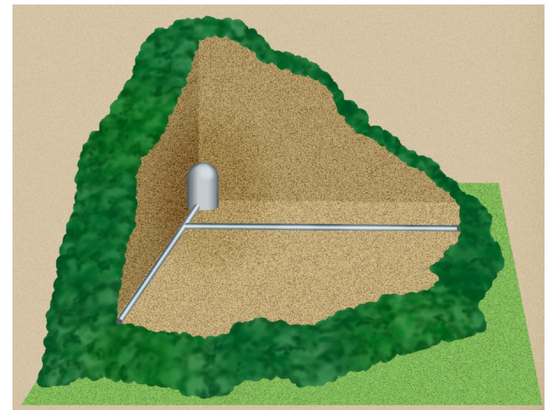
LMA and KamLAND





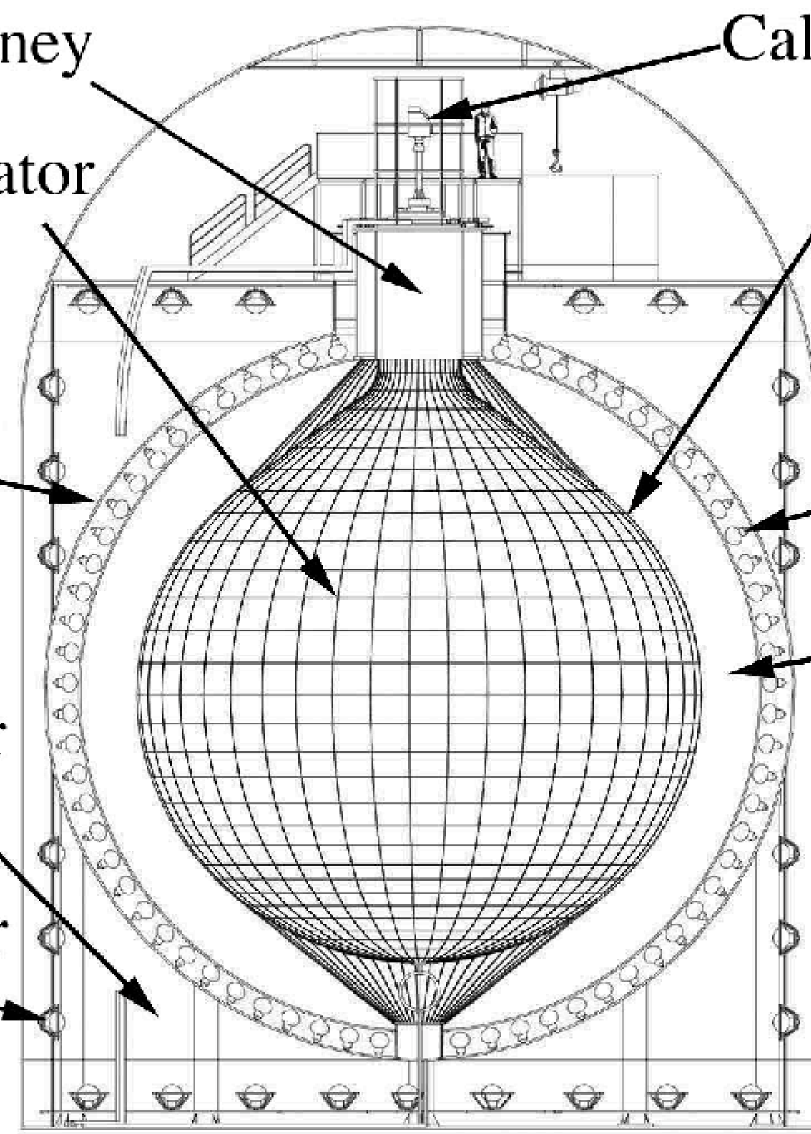
180 km

The KamLAND Detector

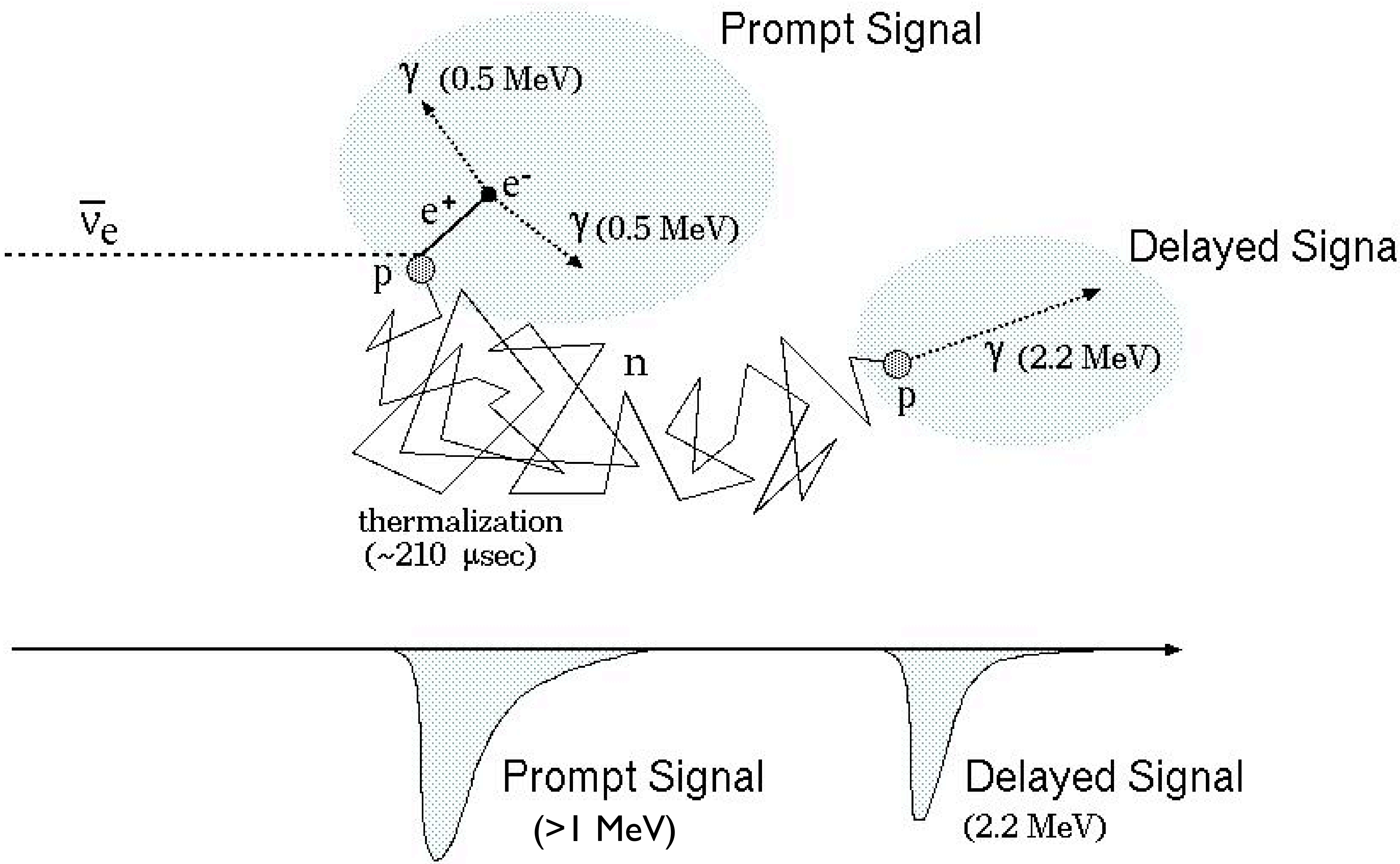


1000m rock
= 2700 mwe

long. 137°18′43.495″
lat. 36°25′35.562″
alt. 358 m



Detection of Electron Anti-Neutrinos



$$E_{\overline{\nu}_e} \approx E_{prompt} + 0.8\,\mathrm{MeV}$$

KamLAND Reactor Anti-Neutrino Disappearance Studies

- 1st Result (162 ton·year exposure)
- 2nd Result (766 ton·year exposure)
- 3rd Result (2880 ton·year exposure)

1st KamLAND Reactor Result

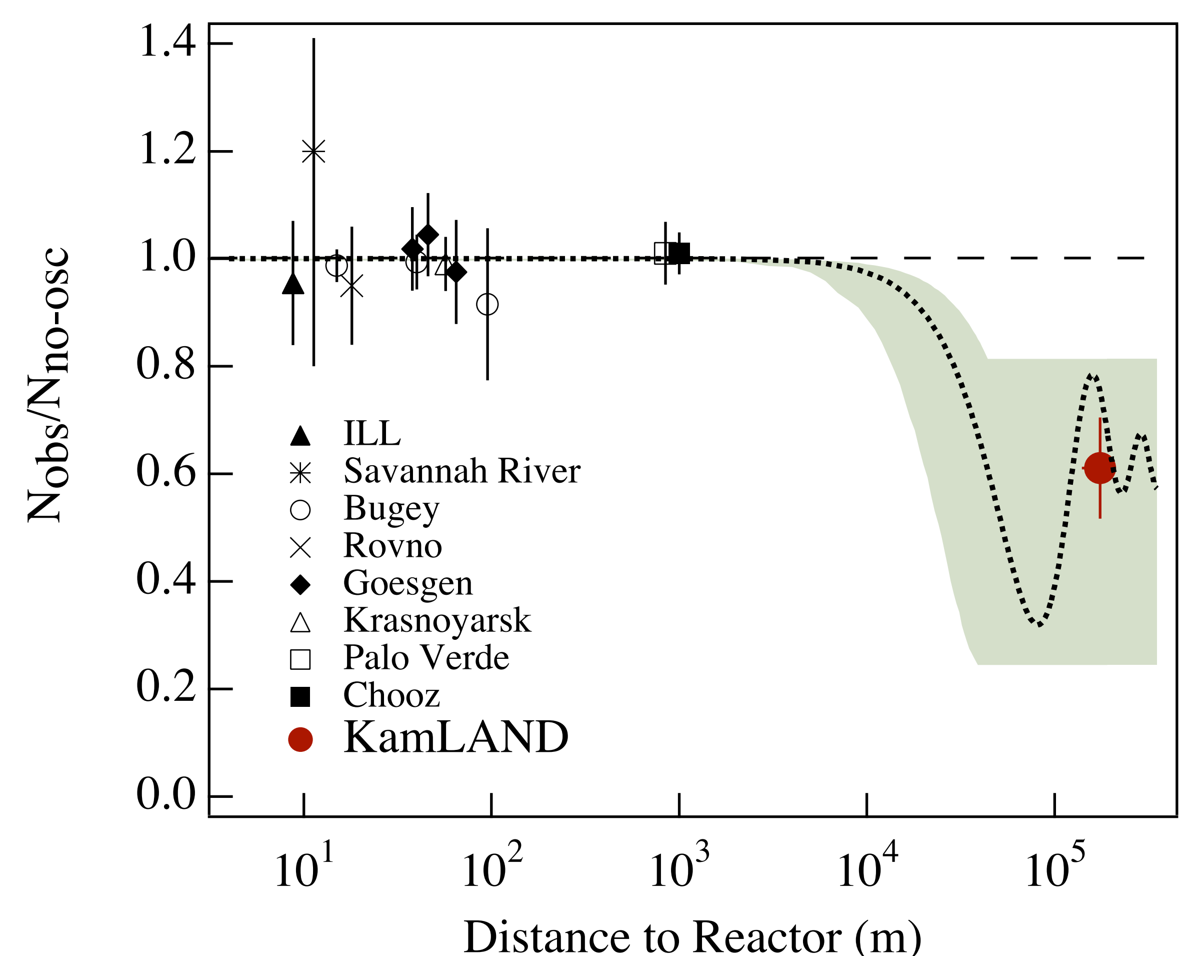
VOLUME 90, NUMBER 2 PHYSICAL REVIEW LETTERS week ending 17 JANUARY 2003

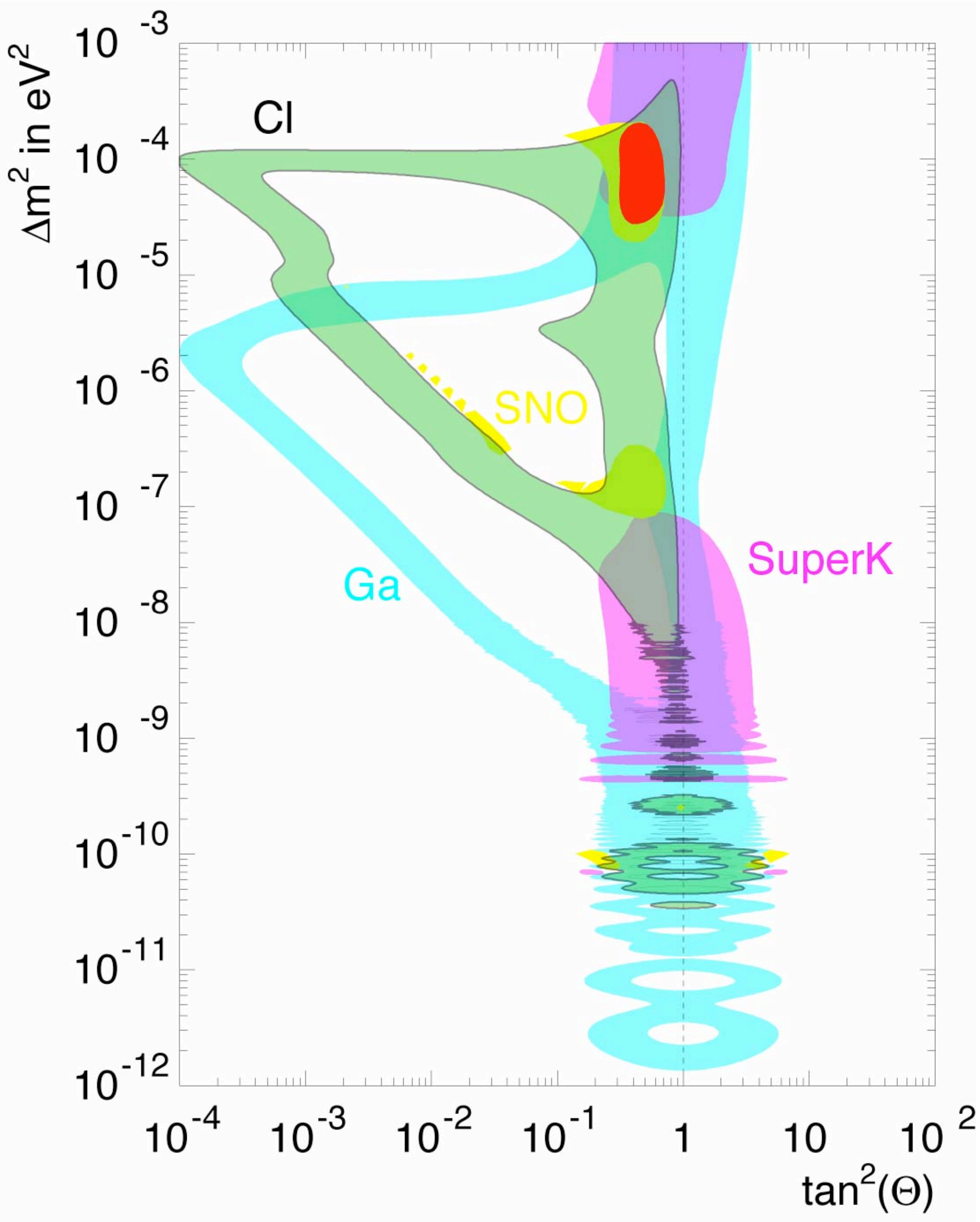
First Results from KamLAND: Evidence for Reactor Antineutrino Disappearance

K. Eguchi,[1] S. Enomoto,[1] K. Furuno,[1] J. Goldman,[1] H. Hanada,[1] H. Ikeda,[1] K. Ikeda,[1] K. Inoue,[1] K. Ishihara,[1] W. Itoh,[1] T. Iwamoto,[1] T. Kawaguchi,[1] T. Kawashima,[1] H. Kinoshita,[1] Y. Kishimoto,[1] M. Koga,[1] Y. Koseki,[1] T. Maeda,[1] T. Mitsui,[1] M. Motoki,[1] K. Nakajima,[1] M. Nakajima,[1] T. Nakajima,[1] H. Ogawa,[1] K. Owada,[1] T. Sakabe,[1] I. Shimizu,[1] J. Shirai,[1] F. Suekane,[1] A. Suzuki,[1] K. Tada,[1] O. Tajima,[1] T. Takayama,[1] K. Tamae,[1] H. Watanabe,[1] J. Busenitz,[2] Z. Djurcic,[2] K. McKinny,[2] D.-M. Mei,[2] A. Piepke,[2] E. Yakushev,[2] B. E. Berger,[3] Y. D. Chan,[3] M. P. Decowski,[3] D. A. Dwyer,[3] S. J. Freedman,[3] Y. Fu,[3] B. K. Fujikawa,[3] K. M. Heeger,[3] K. T. Lesko,[3] K.-B. Luk,[3] H. Murayama,[3] D. R. Nygren,[3] C. E. Okada,[3] A. W. P. Poon,[3] H. M. Steiner,[3] L. A. Winslow,[3] G. A. Horton-Smith,[4] R. D. McKeown,[4] J. Ritter,[4] B. Tipton,[4] P. Vogel,[4] C. E. Lane,[5] T. Miletic,[5] P. W. Gorham,[6] G. Guillian,[6] J. G. Learned,[6] J. Maricic,[6] S. Matsuno,[6] S. Pakvasa,[6] S. Dazeley,[7] S. Hatakeyama,[7] M. Murakami,[7] R. C. Svoboda,[7] B. D. Dieterle,[8] M. DiMauro,[8] J. Detwiler,[9] G. Gratta,[9] K. Ishii,[9] N. Tolich,[9] Y. Uchida,[9] M. Batygov,[10] W. Bugg,[10] H. Cohn,[10] Y. Efremenko,[10] Y. Kamyshkov,[10] A. Kozlov,[10] Y. Nakamura,[10] L. De Braeckeleer,[11] C. R. Gould,[11] H. J. Karwowski,[11] D. M. Markoff,[11] J. A. Messimore,[11] K. Nakamura,[11] R. M. Rohm,[11] W. Tornow,[11] A. R. Young,[11] and Y.-F. Wang[12]

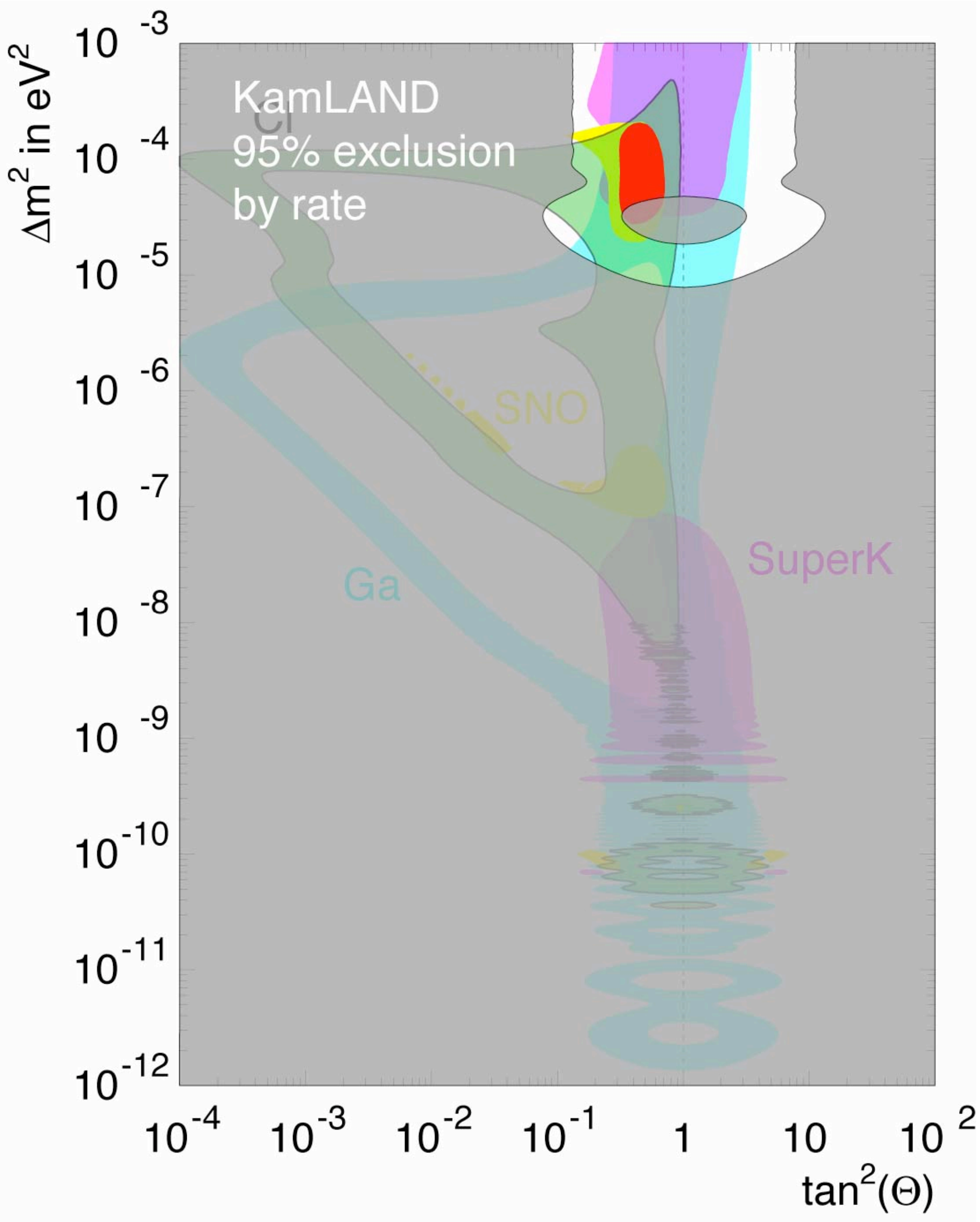
(KamLAND Collaboration)

$$\frac{N_{obs} - N_{bkgd}}{N_{no-osc}} = 0.611 \pm 0.085_{stat} \pm 0.041_{syst}$$

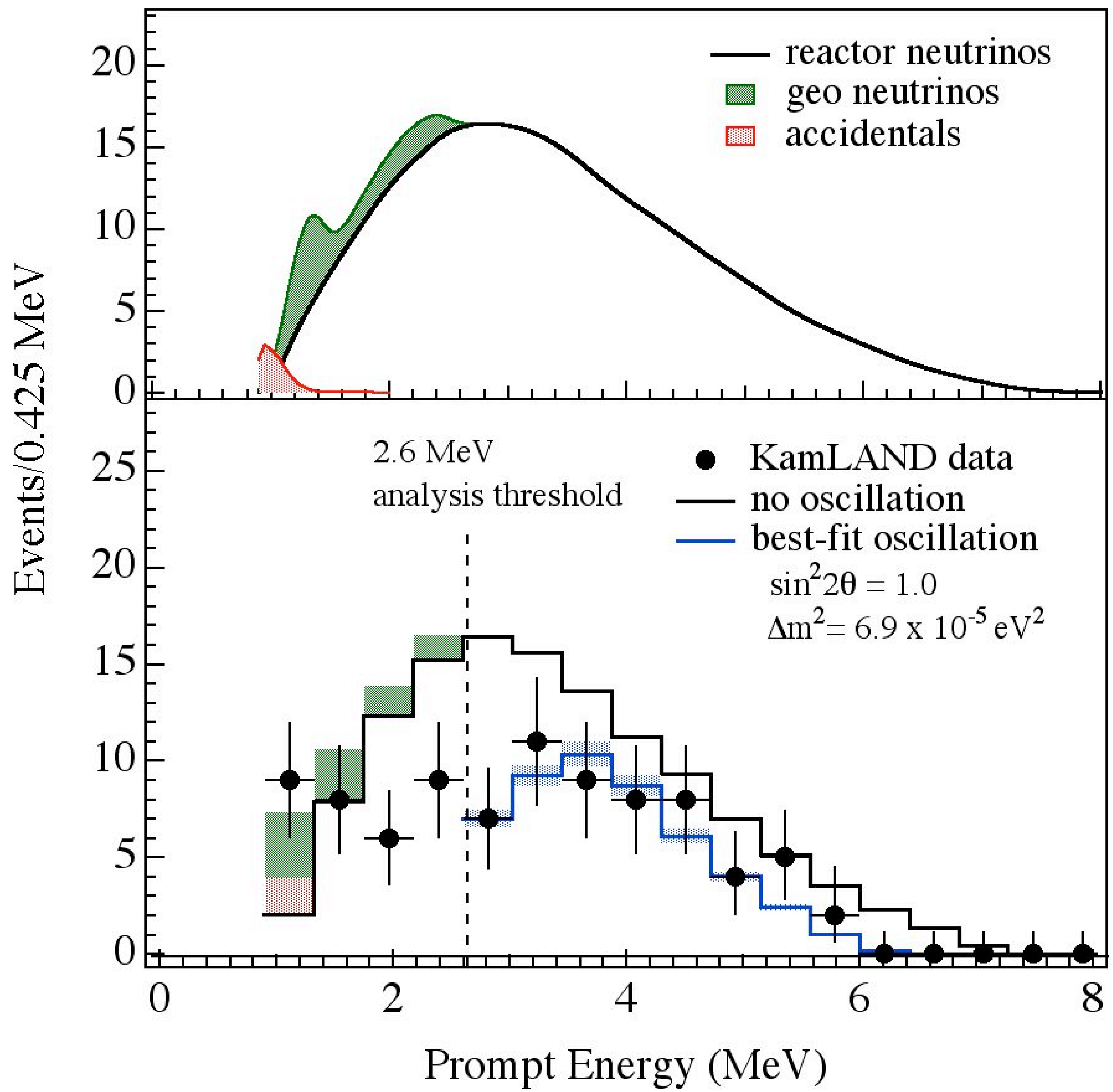




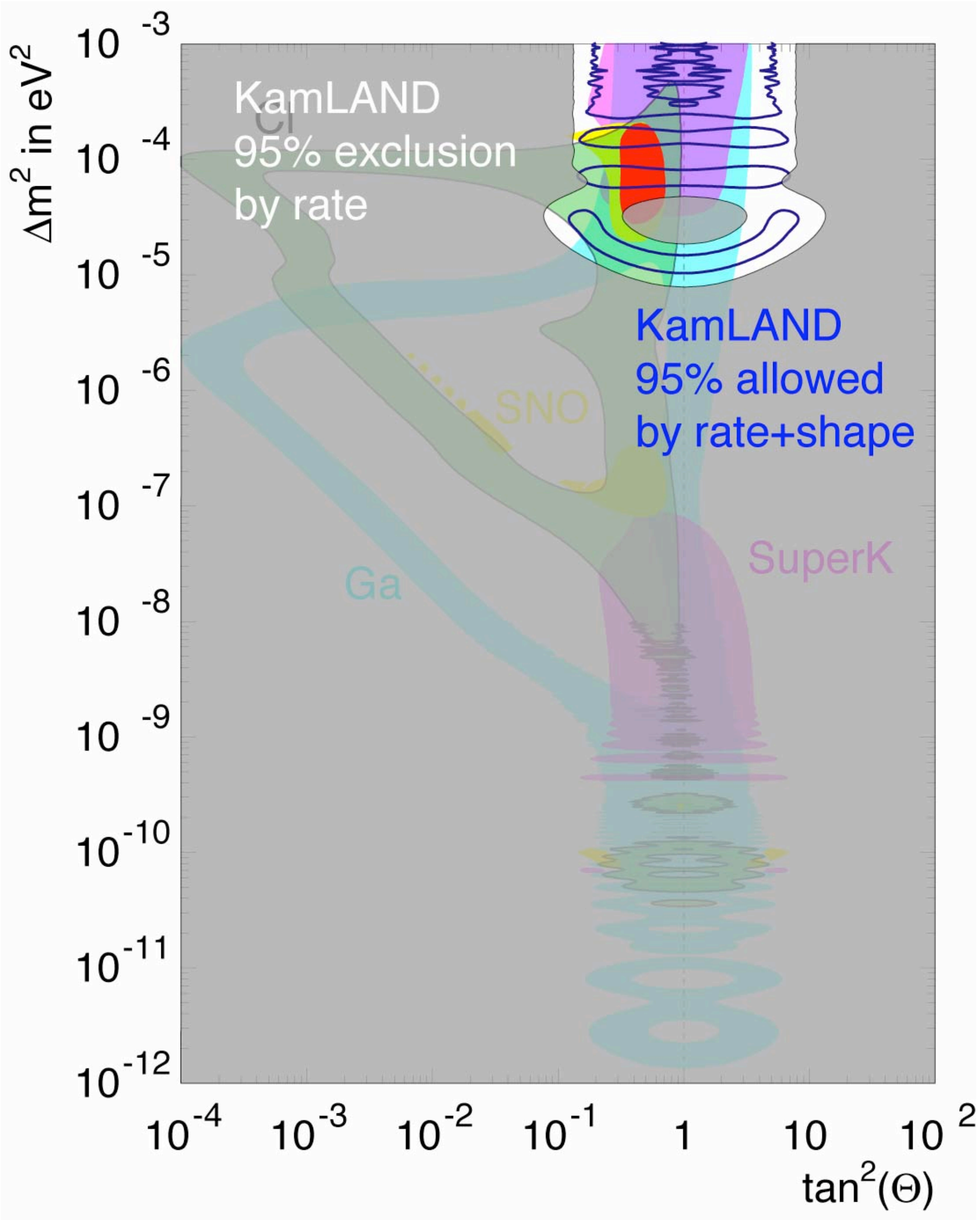
Δm^2 in eV^2
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
Cl
SNO
SuperK
Ga
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\Theta)$



KamLAND
95% exclusion
by rate
Cl
SNO
SuperK
Ga
Δm^2 in eV^2
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\Theta)$



reactor neutrinos
geo neutrinos
accidentals
Events/0.425 MeV
2.6 MeV
analysis threshold
KamLAND data
no oscillation
best-fit oscillation
sin²2θ = 1.0
Δm² = 6.9 x 10⁻⁵ eV²
Prompt Energy (MeV)



Δm^2 in eV^2
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
KamLAND
95% exclusion
by rate
Cl
SNO
KamLAND
95% allowed
by rate+shape
SuperK
Ga
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$tan^2(\Theta)$

Discovery ⇨ Measurement

2nd KamLAND Reactor Result

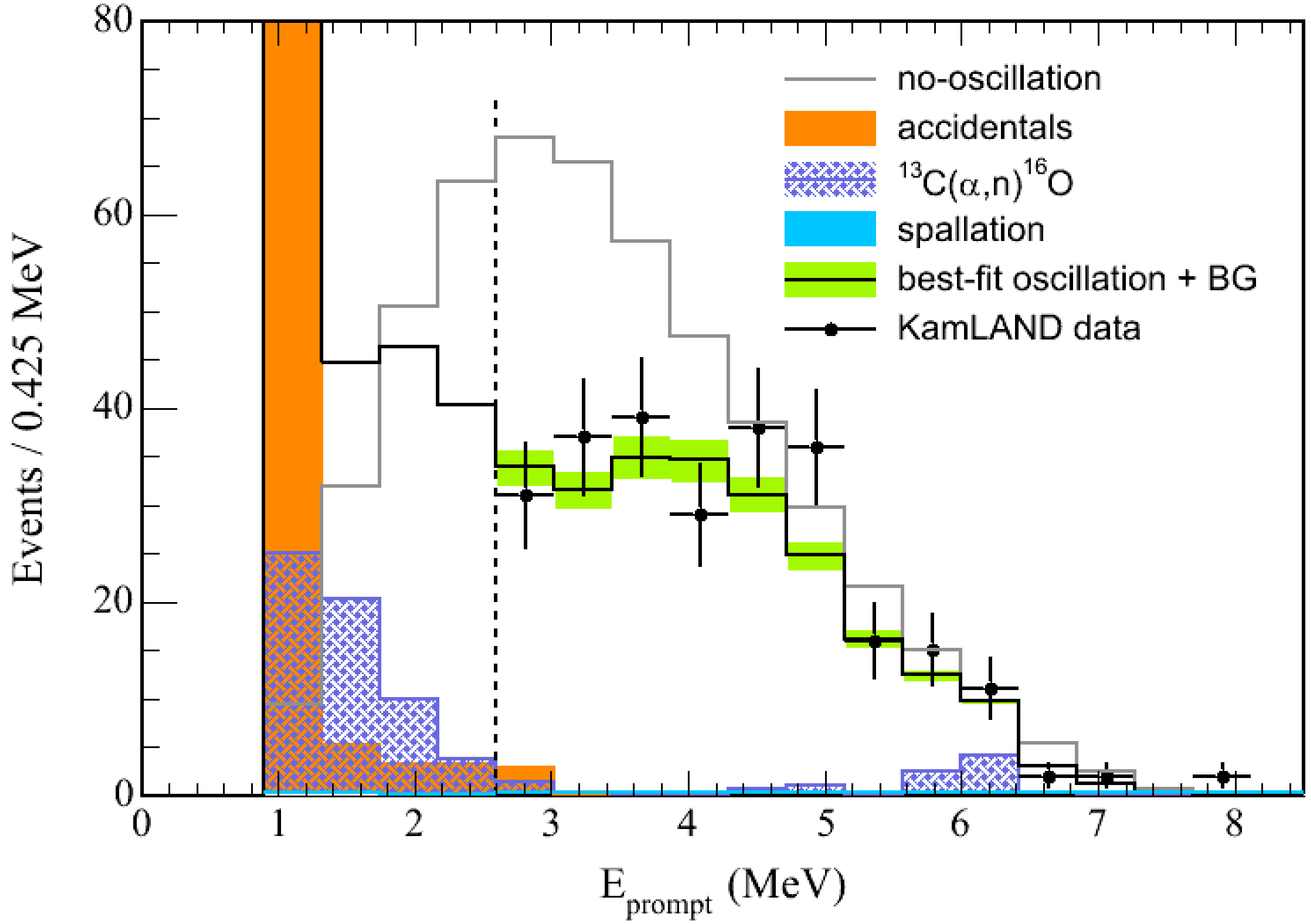
PRL 94, 081801 (2005) PHYSICAL REVIEW LETTERS week ending 4 MARCH 2005

Measurement of Neutrino Oscillation with KamLAND: Evidence of Spectral Distortion

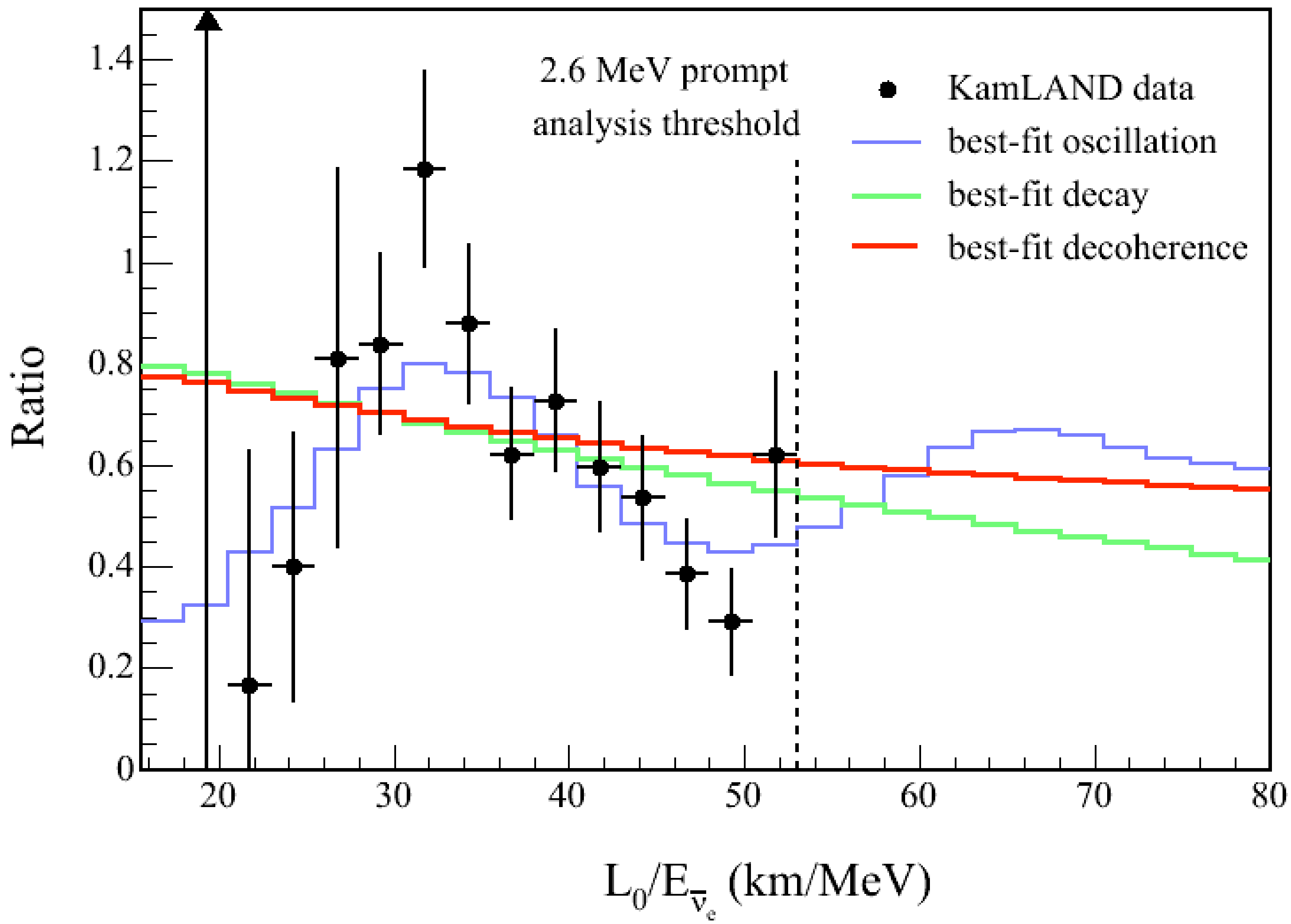
T. Araki,[1] K. Eguchi,[1] S. Enomoto,[1] K. Furuno,[1] K. Ichimura,[1] H. Ikeda,[1] K. Inoue,[1] K. Ishihara,[1,*] T. Iwamoto,[1,†] T. Kawashima,[1] Y. Kishimoto,[1] M. Koga,[1] Y. Koseki,[1] T. Maeda,[1] T. Mitsui,[1] M. Motoki,[1] K. Nakajima,[1] H. Ogawa,[1] K. Owada,[1] J.-S. Ricol,[1] I. Shimizu,[1] J. Shirai,[1] F. Suekane,[1] A. Suzuki,[1] K. Tada,[1] O. Tajima,[1] K. Tamae,[1] Y. Tsuda,[1] H. Watanabe,[1] J. Busenitz,[2] T. Classen,[2] Z. Djurcic,[2] G. Keefer,[2] K. McKinny,[2] D.-M. Mei,[2,‡] A. Piepke,[2] E. Yakushev,[2] B. E. Berger,[3] Y. D. Chan,[3] M. P. Decowski,[3] D. A. Dwyer,[3] S. J. Freedman,[3] Y. Fu,[3] B. K. Fujikawa,[3] J. Goldman,[3] F. Gray,[3] K. M. Heeger,[3] K. T. Lesko,[3] K.-B. Luk,[3] H. Murayama,[3,§] A. W. P. Poon,[3] H. M. Steiner,[3] L. A. Winslow,[3] G. A. Horton-Smith,[4,‖] C. Mauger,[4] R. D. McKeown,[4] P. Vogel,[4] C. E. Lane,[5] T. Miletic,[5] P. W. Gorham,[6] G. Guillian,[6] J. G. Learned,[6] J. Maricic,[6] S. Matsuno,[6] S. Pakvasa,[6] S. Dazeley,[7] S. Hatakeyama,[7] A. Rojas,[7] R. Svoboda,[7] B. D. Dieterle,[8] J. Detwiler,[9] G. Gratta,[9] K. Ishii,[9] N. Tolich,[9] Y. Uchida,[9,¶] M. Batygov,[10] W. Bugg,[10] Y. Efremenko,[10] Y. Kamyshkov,[10] A. Kozlov,[10] Y. Nakamura,[10] C. R. Gould,[11] H. J. Karwowski,[11] D. M. Markoff,[11] J. A. Messimore,[11] K. Nakamura,[11] R. M. Rohm,[11] W. Tornow,[11] R. Wendell,[11] A. R. Young,[11] M.-J. Chen,[12] Y.-F. Wang,[12] and F. Piquemal[13]

(KamLAND Collaboration)

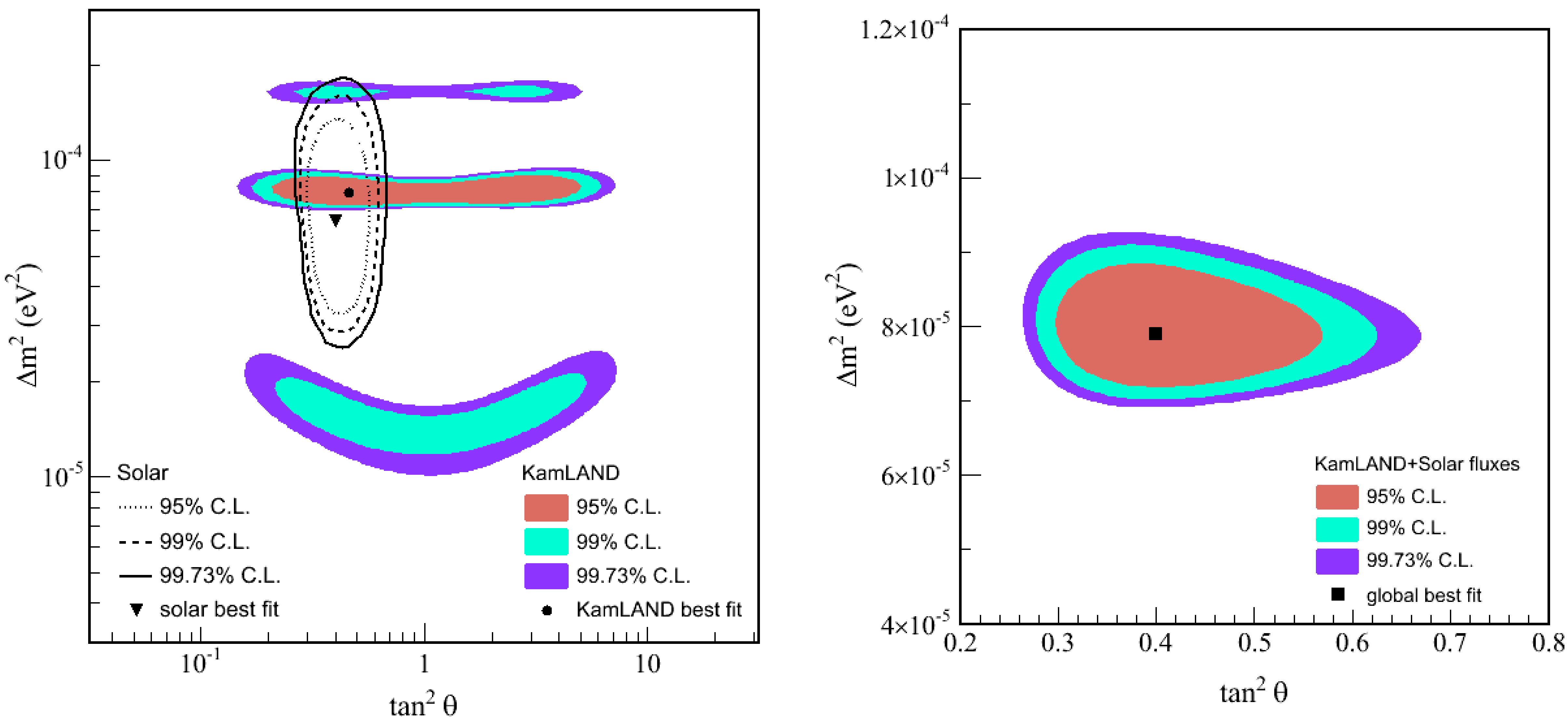
- Increased fiducial volume: 5 m → 5.5 m radius
- Increased live time
- Exposure: 162 ton·year → 766 ton·year



- $\chi_p^2/\mathrm{dof} = 24.2/17$ (11% CL)
- $\chi_p^2/\mathrm{dof} = 37.8/18$ (0.4% CL) for an undistorted shape



2.6 MeV prompt
analysis threshold
KamLAND data
best-fit oscillation
best-fit decay
best-fit decoherence
Ratio
0
0.2
0.4
0.6
0.8
1
1.2
1.4
20
30
40
50
60
70
80
$L_0/E_{\bar{\nu}_e}$ (km/MeV)



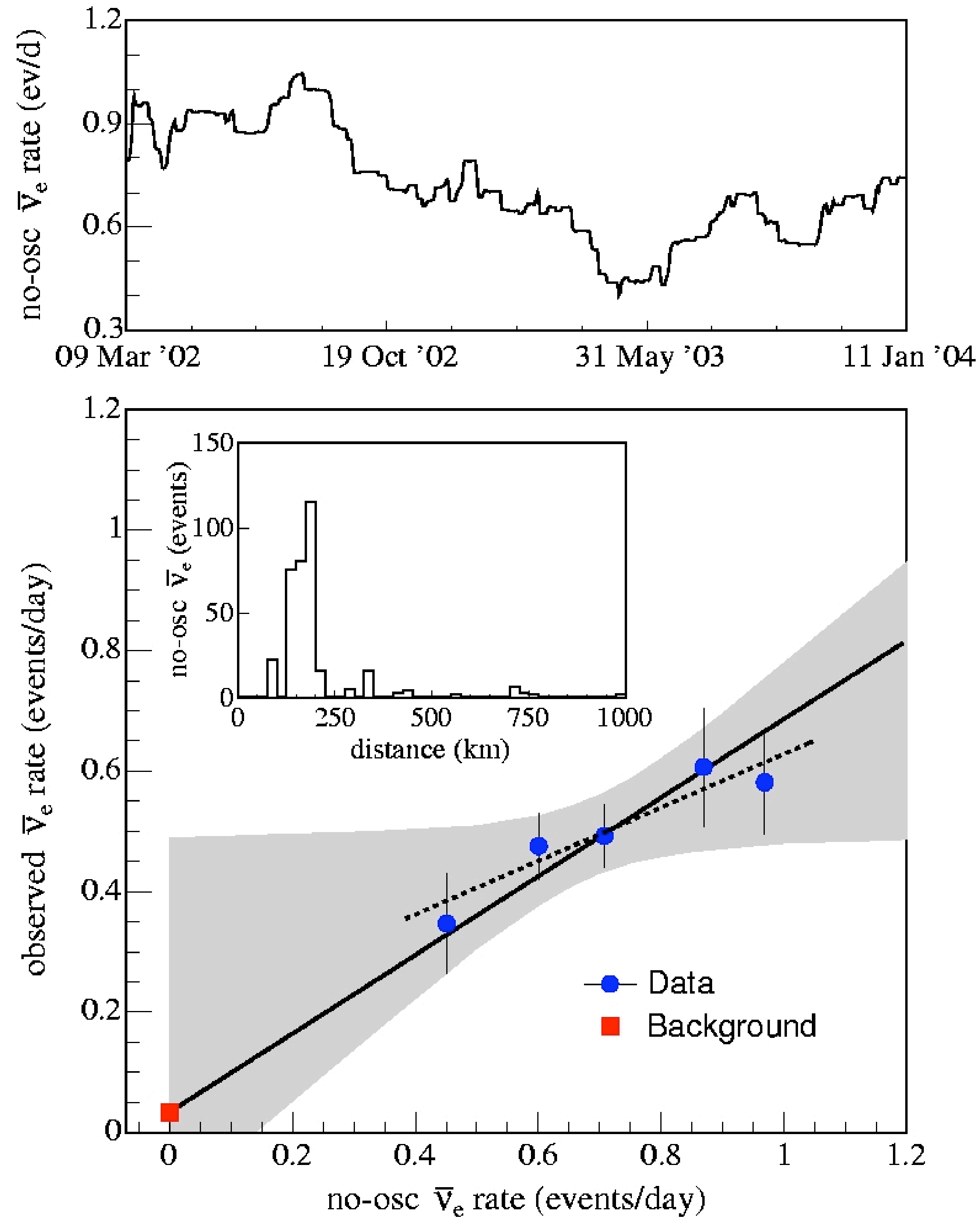
10^{-4}
10^{-5}
Δm^2 (eV^2)
10^{-1}
1
10
$\tan^2\theta$
Solar
95% C.L.
99% C.L.
99.73% C.L.
solar best fit
KamLAND
95% C.L.
99% C.L.
99.73% C.L.
KamLAND best fit
1.2×10^{-4}
1×10^{-4}
8×10^{-5}
6×10^{-5}
4×10^{-5}
Δm^2 (eV^2)
0.2
0.3
0.4
0.5
0.6
0.7
0.8
$\tan^2\theta$
KamLAND+Solar fluxes
95% C.L.
99% C.L.
99.73% C.L.
global best fit

3rd KamLAND Reactor Result

(1) Increased exposure: 766 ton·year → 2880 ton·year

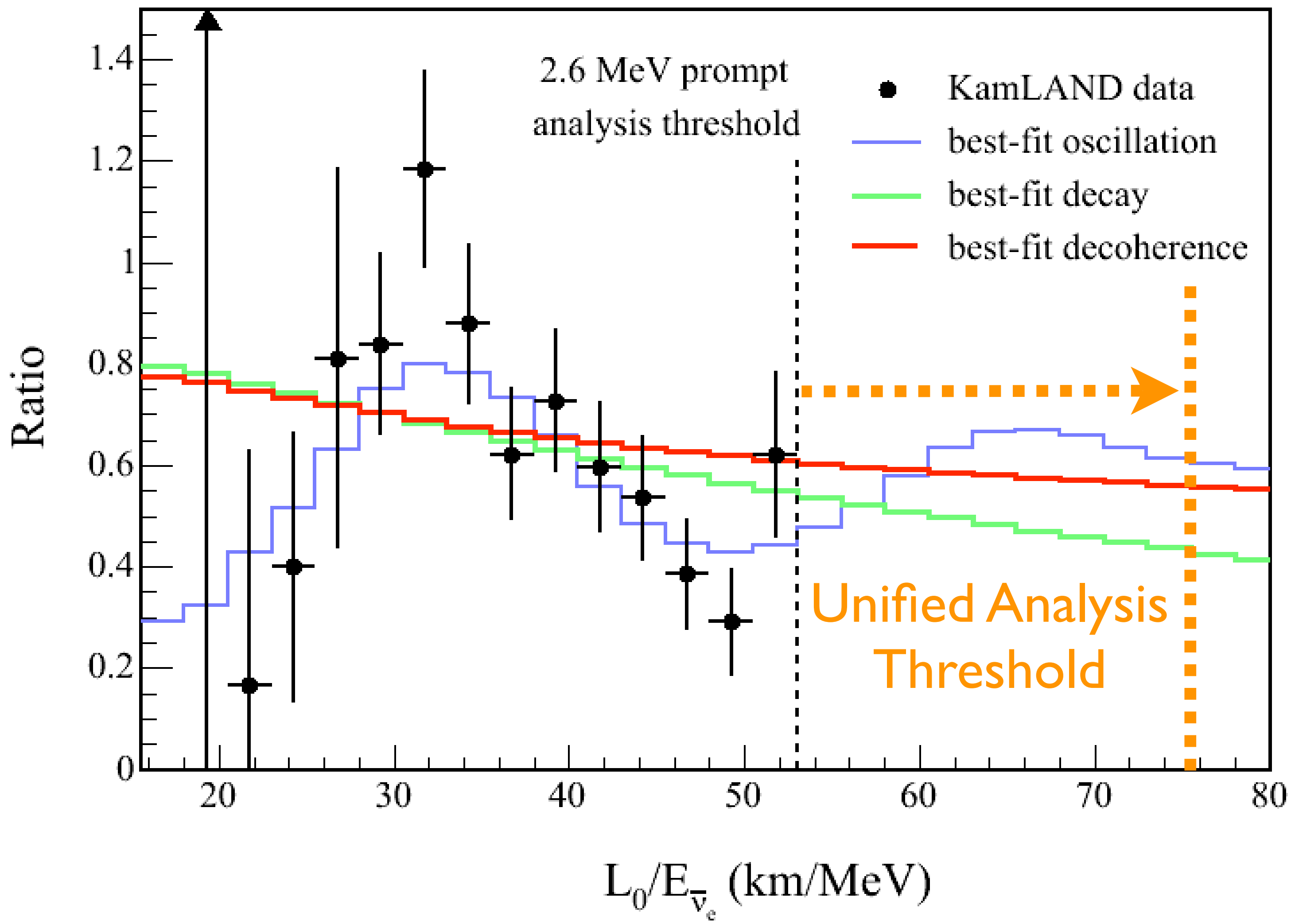
- Increased fiducial volume: 5.5 m → 6 m radius.
- Increased live time.
- Improved statistical precision.
- Improved history of signal to background variations and small baseline perturbations due to the power fluctuations of the nuclear power reactors.

KamLAND PRL 2005

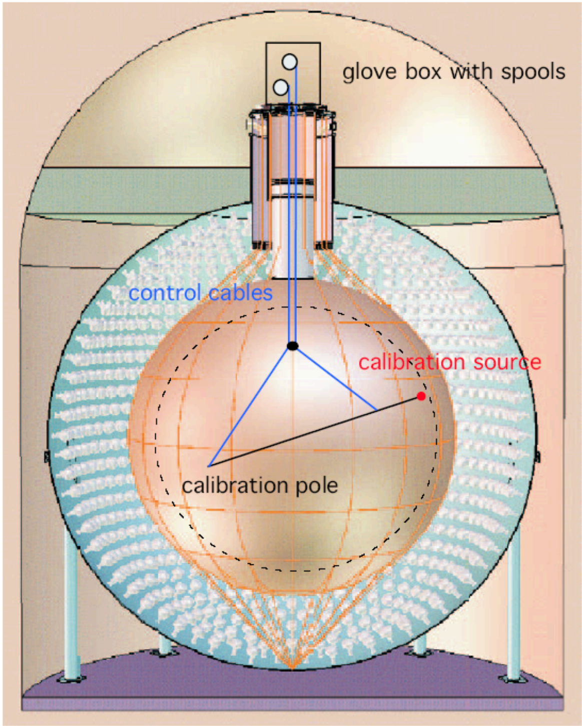


(2) Lower analysis threshold: 2.6 MeV → 0.9 MeV

(unified reactor neutrino and geo-neutrino analysis)

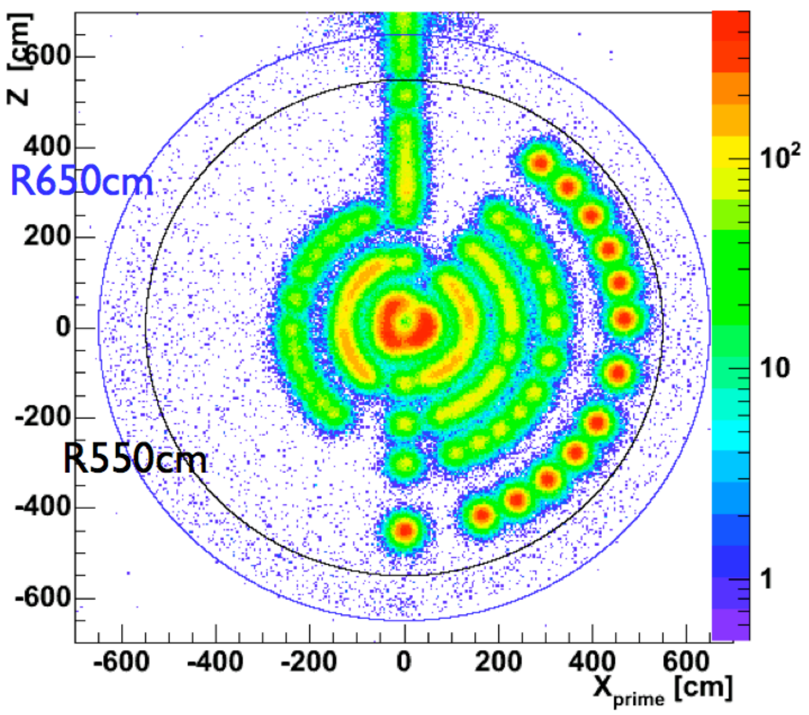


(3) Reduced Systematic Errors



Off-axis Calibration Campaign

Recent Full Volume Calibration



Uncertainty	%
Fiducial volume	4.7
Energy threshold	2.3
Cuts efficiency	1.6
Live time	0.1
Reactor thermal power	2.1
Fuel composition	1.0
Anti-neutrino spectra	2.5
Cross section	0.2
Total uncertainty	6.5

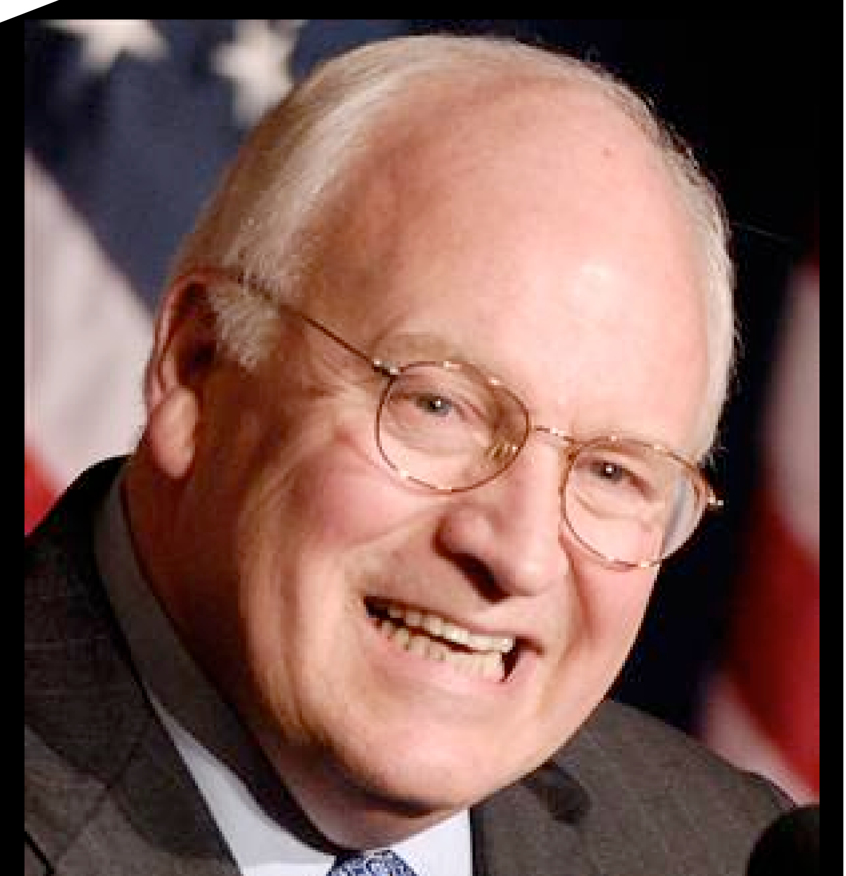
} Future improvements

The 3rd KamLAND Reactor Result is...

Treated as SECRET/SCI

The 3rd KamLAND Reactor Result is...

Treated as SECRET/SCI



Please wait one month.

Geoneutrino Results

Experimental investigation of geologically produced antineutrinos with KamLAND

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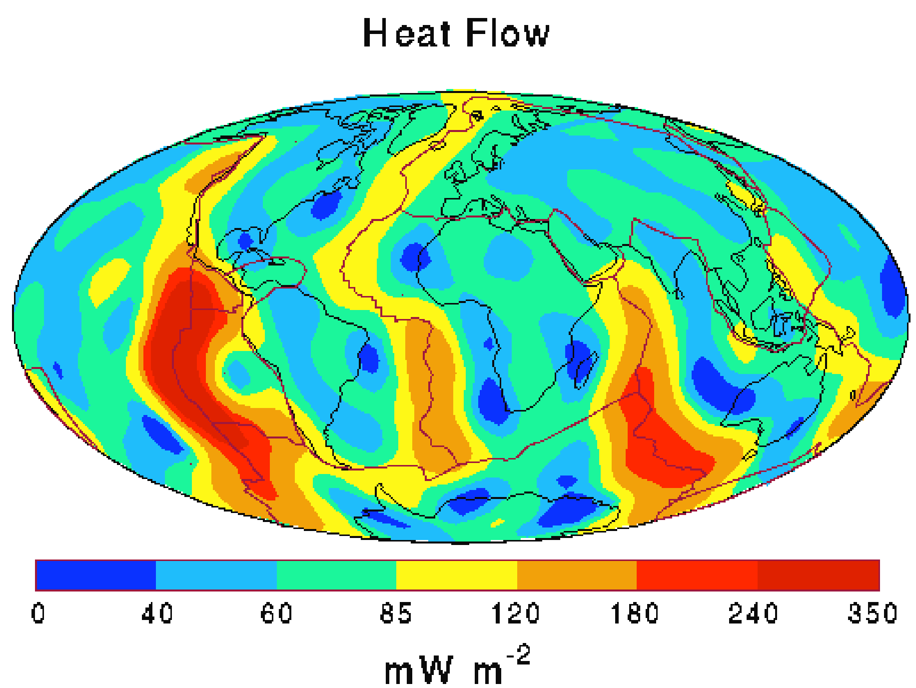
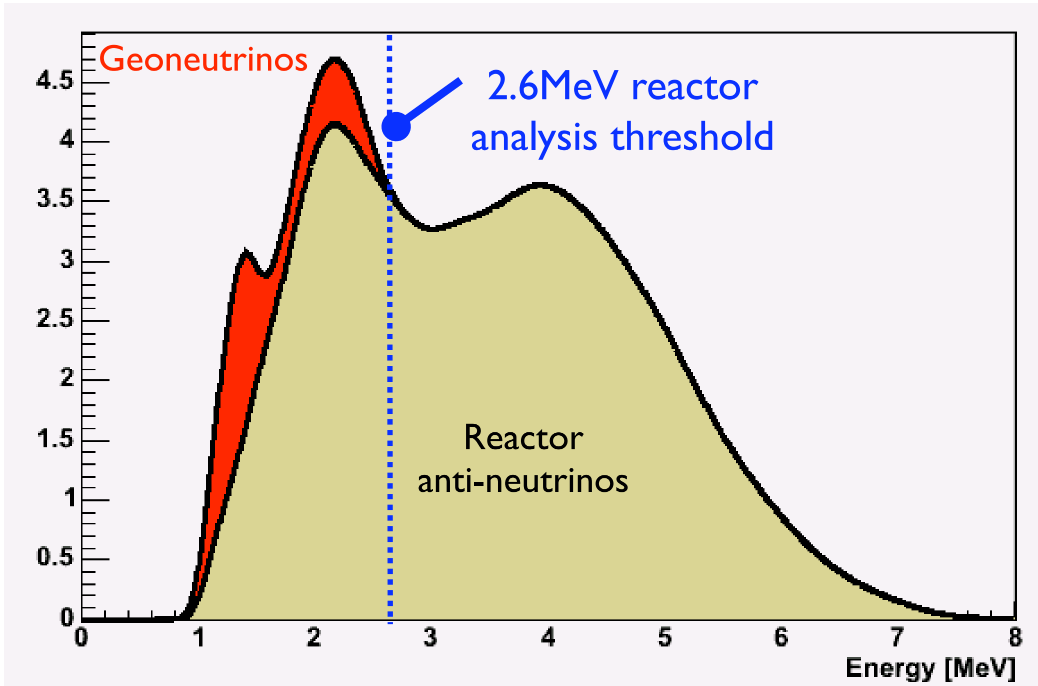
The detection of electron antineutrinos produced by natural radioactivity in the Earth could yield important geophysical information. The Kamioka liquid scintillator antineutrino detector (KamLAND) has the sensitivity to detect electron antineutrinos produced by the decay of ^{238}U and ^{232}Th within the Earth. Earth composition models suggest that the radiogenic power from these isotope decays is 16 TW, approximately half of the total measured heat dissipation rate from the Earth. Here we present results from a search for geoneutrinos with KamLAND. Assuming a Th/U mass concentration ratio of 3.9, the 90 per cent confidence interval for the total number of geoneutrinos detected is 4.5 to 54.2. This result is consistent with the central value of 19 predicted by geophysical models. Although our present data have limited statistical power, they nevertheless provide by direct means an upper limit (60 TW) for the radiogenic power of U and Th in the Earth, a quantity that is currently poorly constrained.

Geoneutrinos



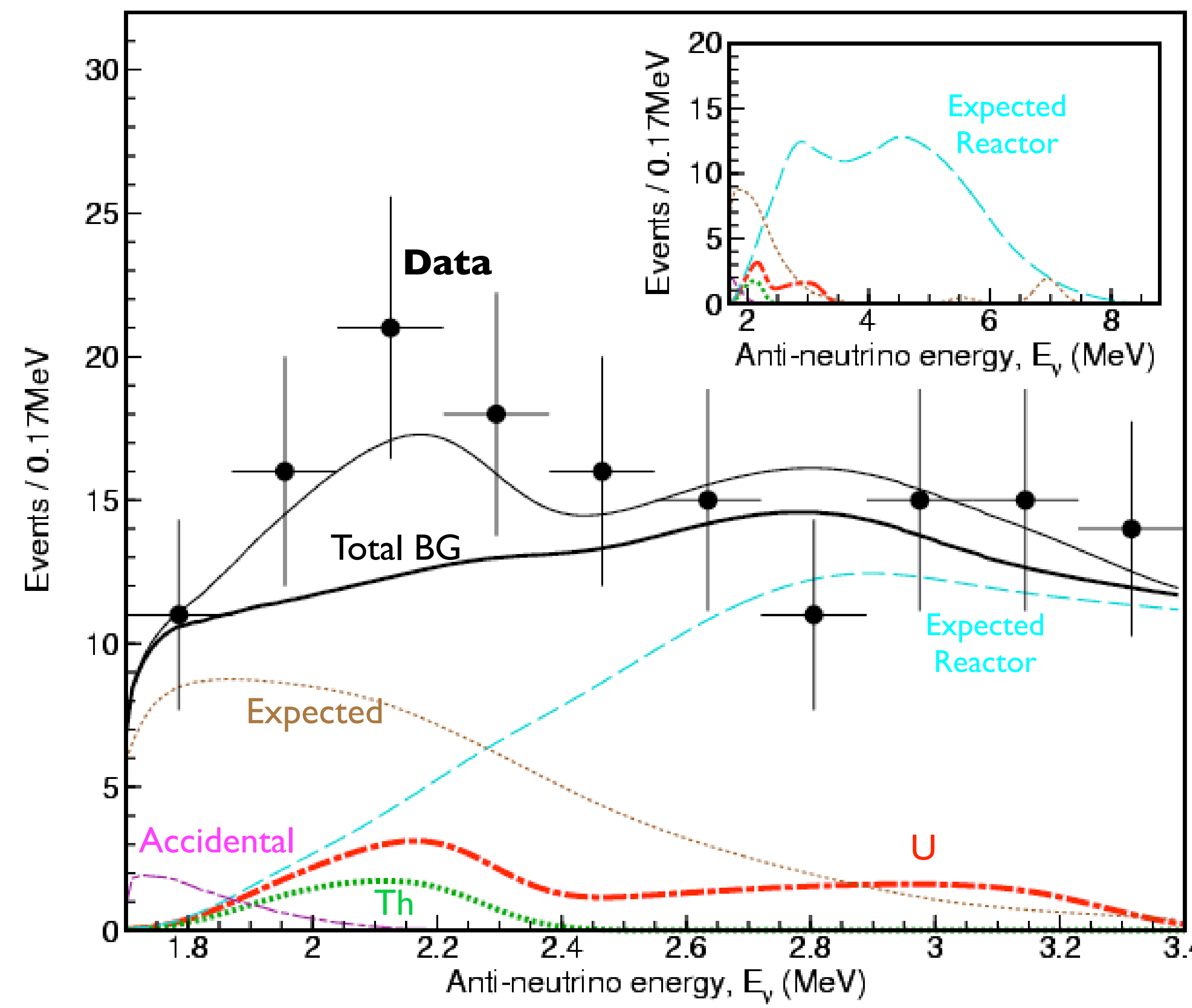
Total Earth heat-flow: 30-40TW
Where does the heat come from?

- Radioactive decays: ^{40}K, ^{232}Th, ^{238}U must contribute a significant fraction
- Anti-neutrinos from ^{232}Th and ^{238}U decays visible in KamLAND
- Reactor neutrinos main background
- Use KamLAND to measure radiogenic heat contribution



Geoneutrino Results

- For 749 days of livetime
- "Rate" result
  - Observed: 152 events
  - Background: 127 ± 13 events
  - Geoneutrinos: 25^{+19}_{-18}
- "Shape" result
  - Central value: 28
  - ~2 sigma effect



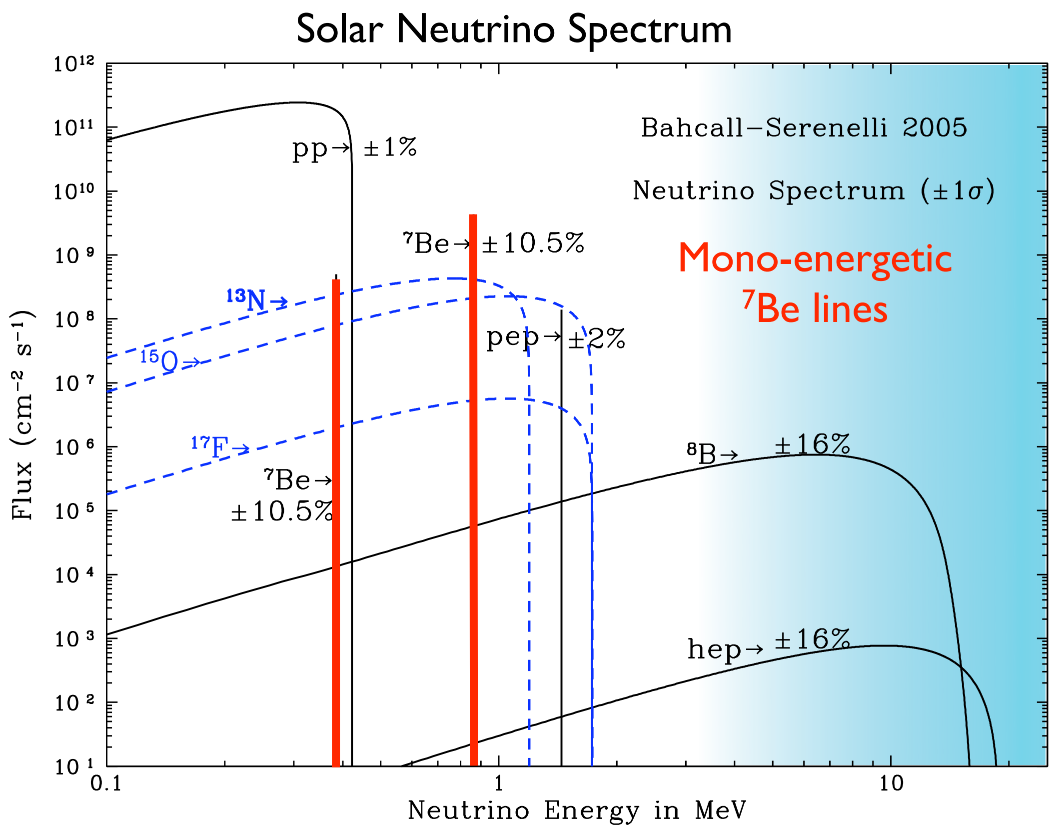
Current data limit radiogenic heat to < 160TW

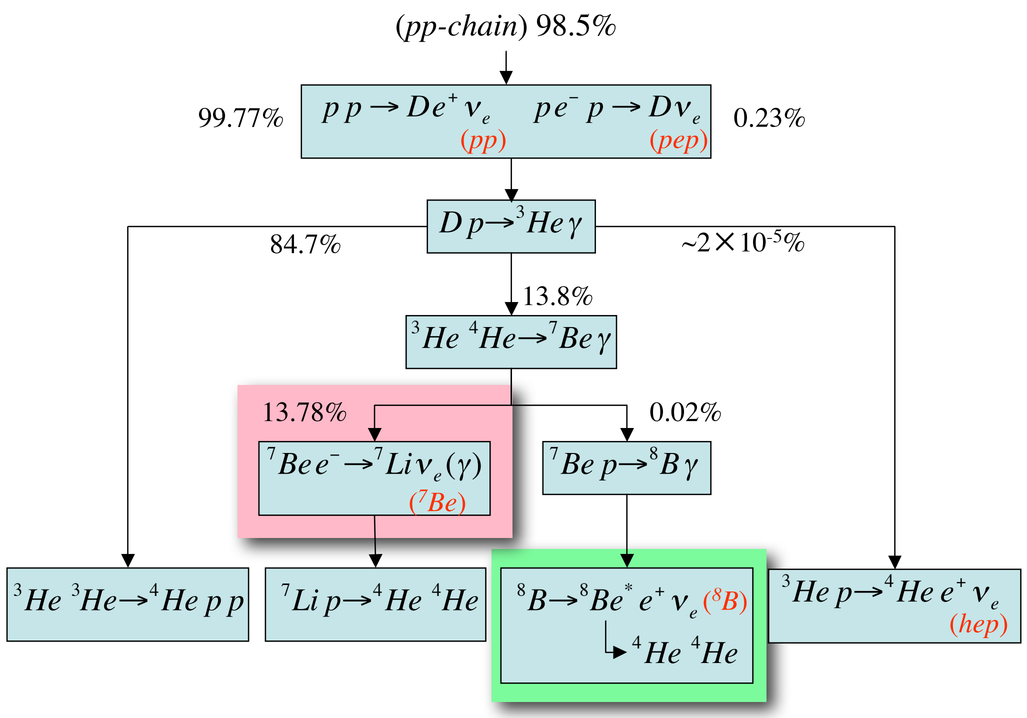
KamLAND Phase II
The Low Background Phase

(May 12, 2007 to present)

- Measurement of the ^{7}Be Solar Neutrino Flux
- Improved Geo-Neutrino Measurement
- Supernova Watch

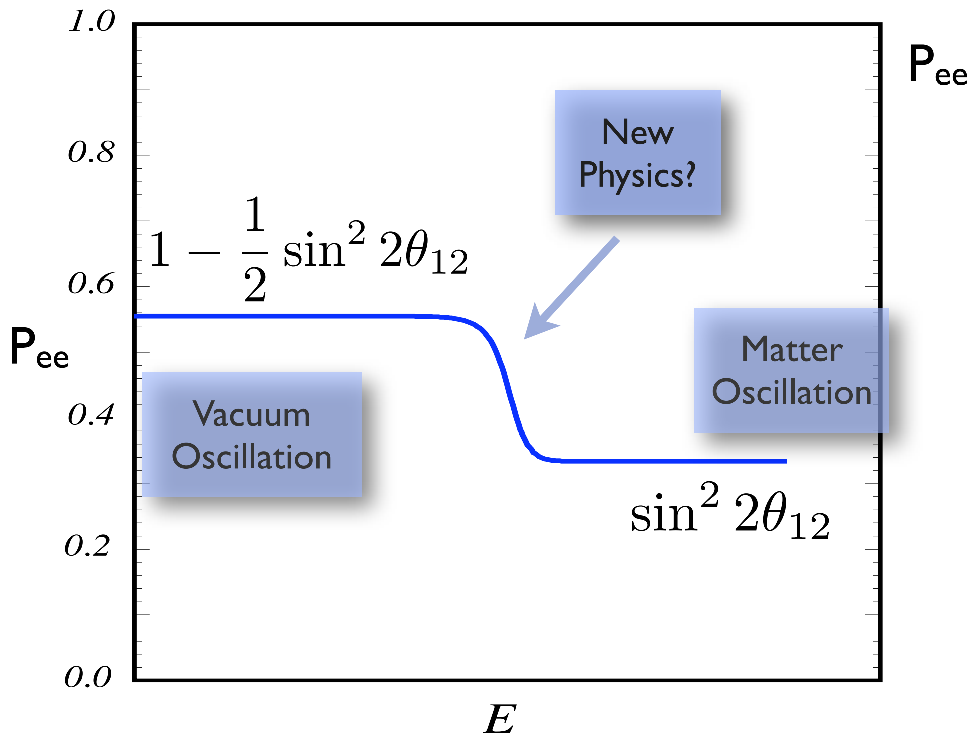
Solar ^{7}Be Neutrino Flux Measurement

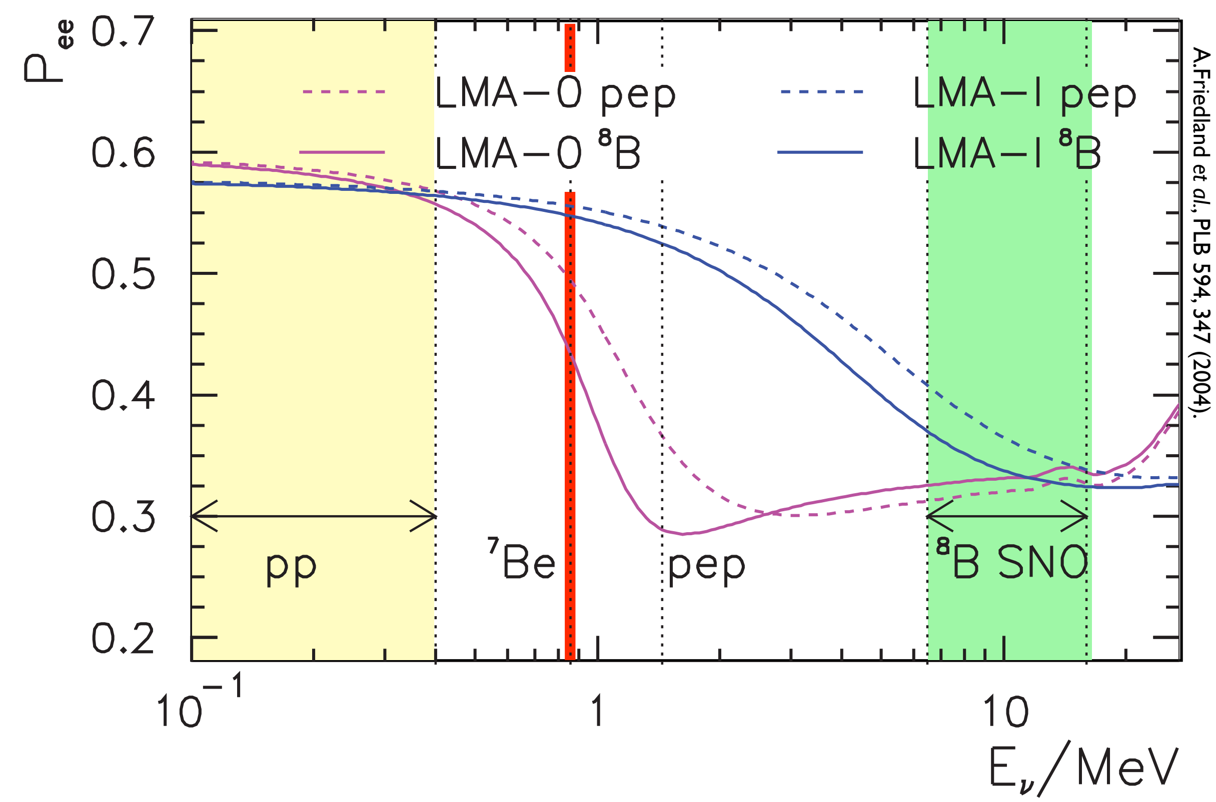




^{7}Be ~14% ^{8}B ~0.02%

Testing the SSM and the LMA MSW

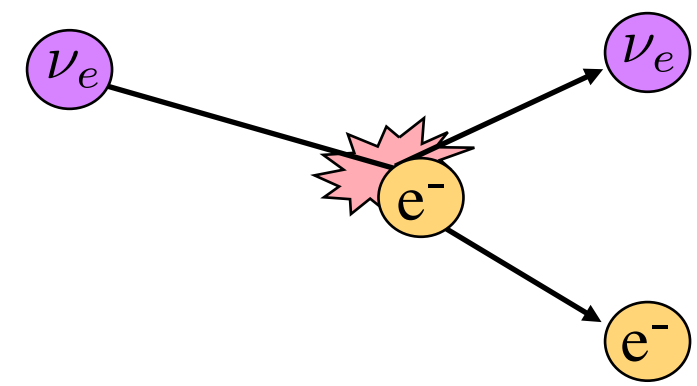


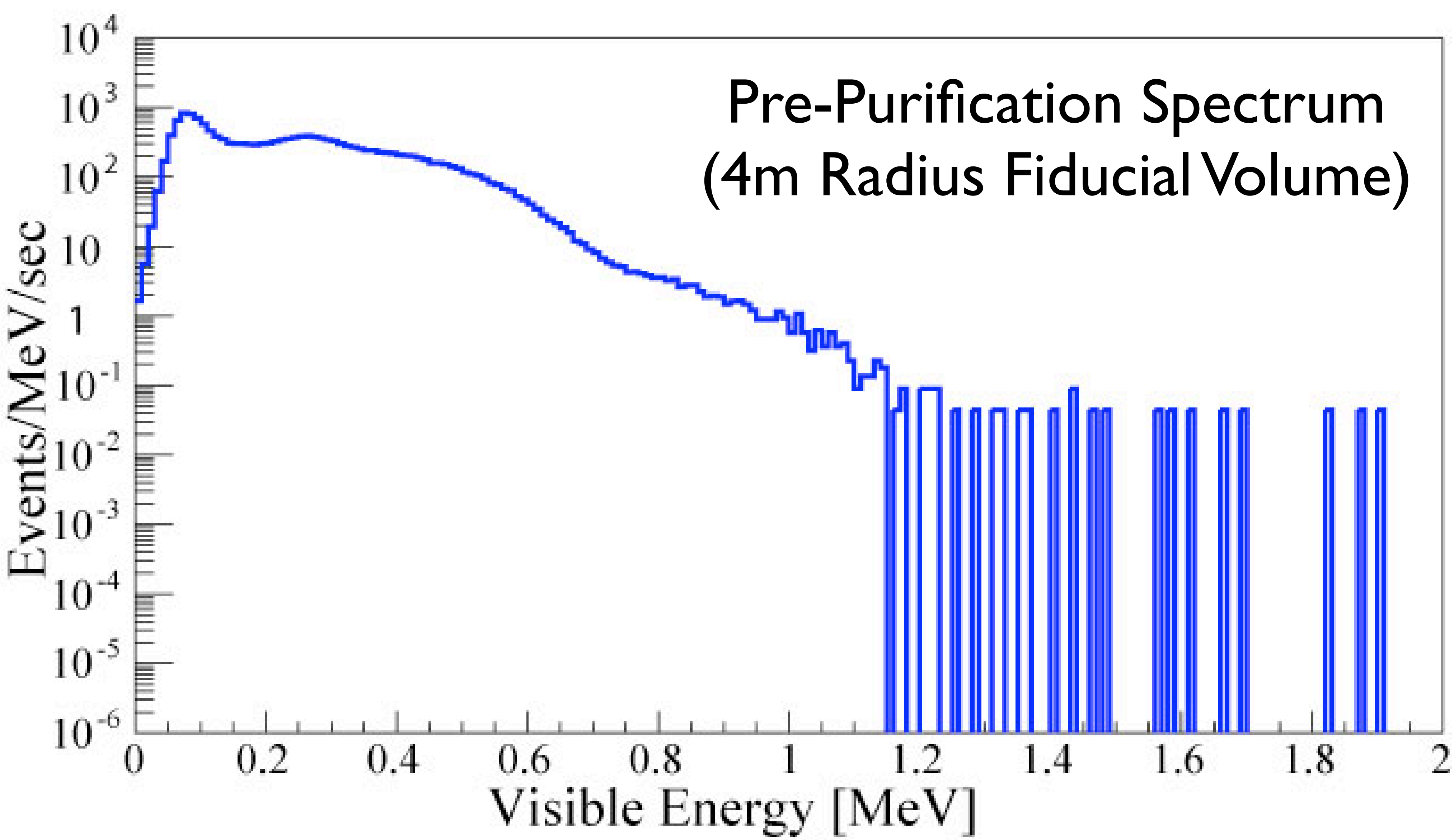


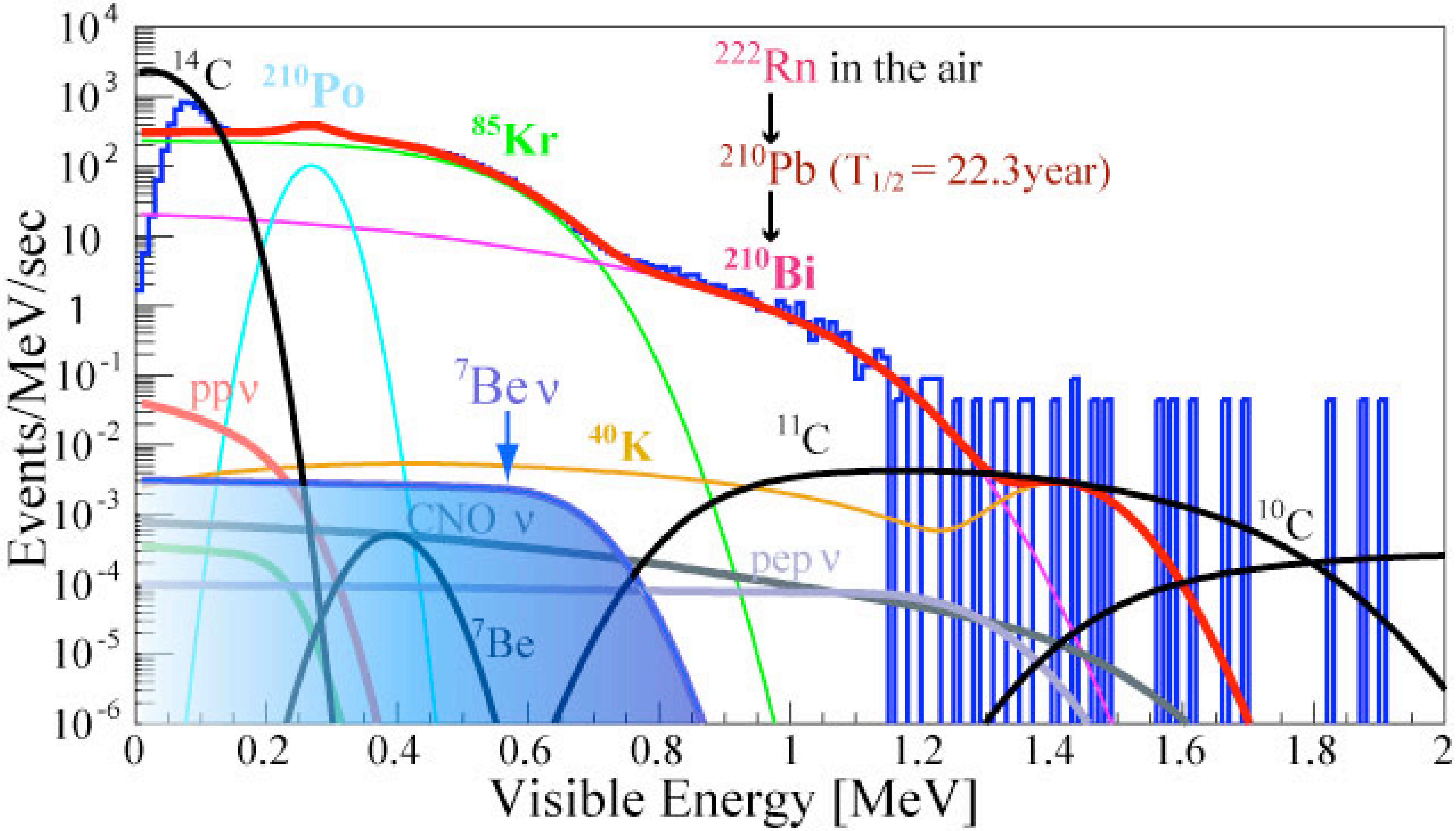
- Observation the transition from Matter → Vacuum Oscillations.
- Contribute to an improved measurement of the Solar pp Neutrino Flux.
- Need a 5% Measurement.

Detection of 7Be Solar Neutrinos

Detect through neutrino-electron elastic scattering:
(no delayed coincidence to suppress backgrounds)

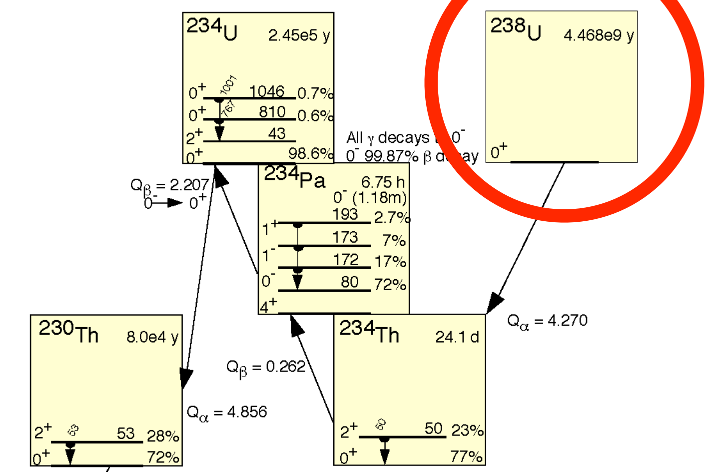


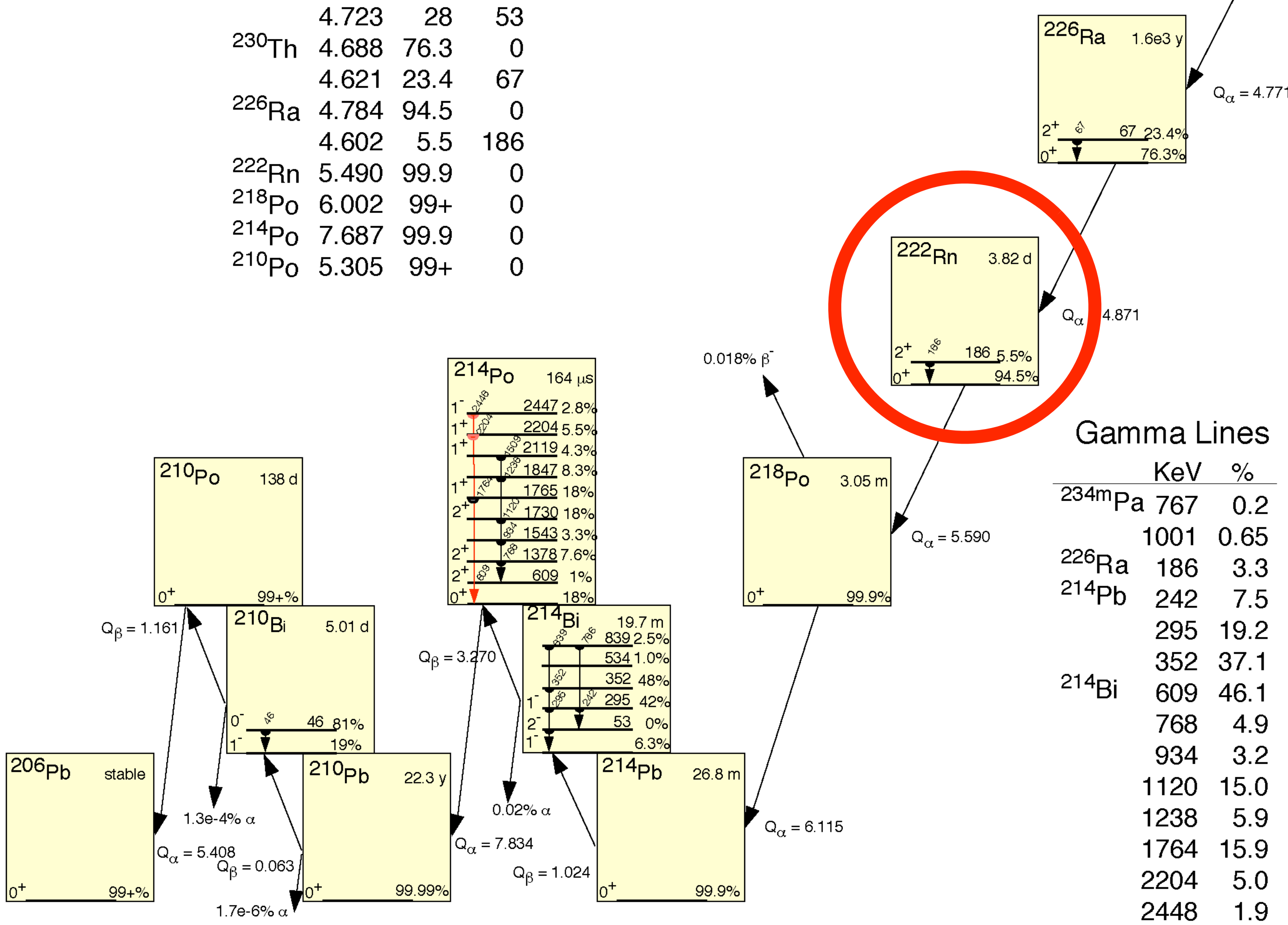




^{14}C
^{210}Po
^{85}Kr
^{222}Rn in the air
^{210}Pb ($T_{1/2}$ = 22.3year)
^{210}Bi
pp ν
^{7}Be ν
^{40}K
^{11}C
CNO ν
^{10}C
pep ν
^{7}Be
Events/MeV/sec
Visible Energy [MeV]

Decay of ^{238}U to ^{206}Pb





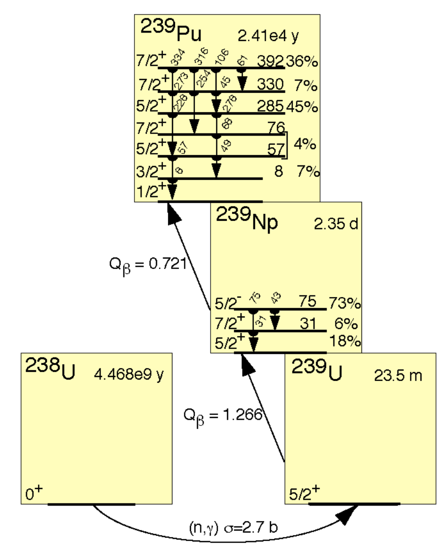
Alpha Lines

	KeV	%	Level
^{238}U	4.196	77	0
	4.149	23	50
^{234}U	4.777	72	0
	4.723	28	53
^{230}Th	4.688	76.3	0
	4.621	23.4	67
^{226}Ra	4.784	94.5	0
	4.602	5.5	186
^{222}Rn	5.490	99.9	0
^{218}Po	6.002	99+	0
^{214}Po	7.687	99.9	0
^{210}Po	5.305	99+	0

Gamma Lines

	KeV	%
^{234m}Pa	767	0.2
	1001	0.65
^{226}Ra	186	3.3
^{214}Pb	242	7.5
	295	19.2
	352	37.1
^{214}Bi	609	46.1
	768	4.9
	934	3.2
	1120	15.0
	1238	5.9
	1764	15.9
	2204	5.0
	2448	1.9

Neutron Activation of - ^{238}U

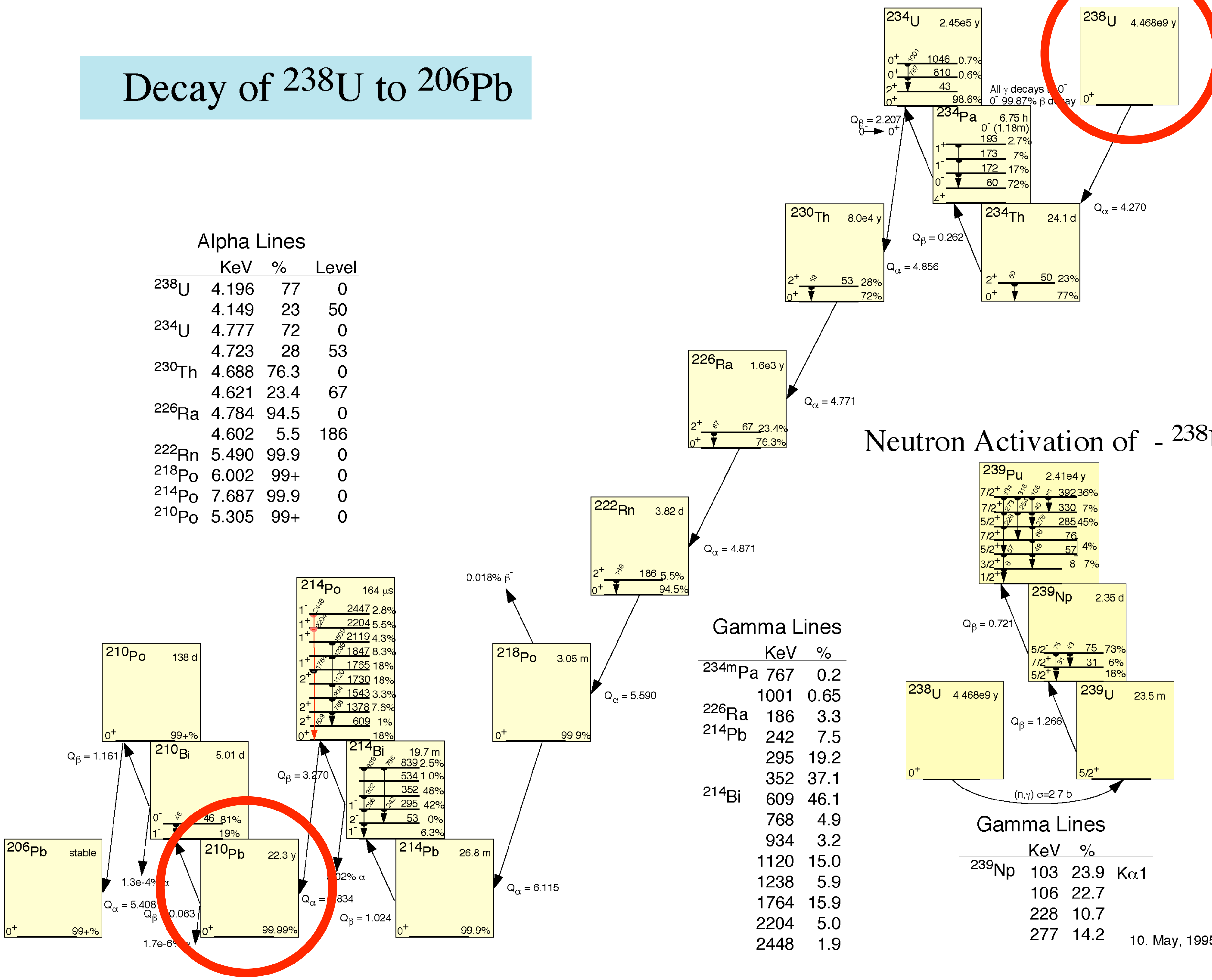


Gamma Lines

	KeV	%	
^{239}Np	103	23.9	Kα1
	106	22.7	
	228	10.7	
	277	14.2	

10. May, 1995 jmw

Decay of ^{238}U to ^{206}Pb



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Neutron Activation of - ^{238}U

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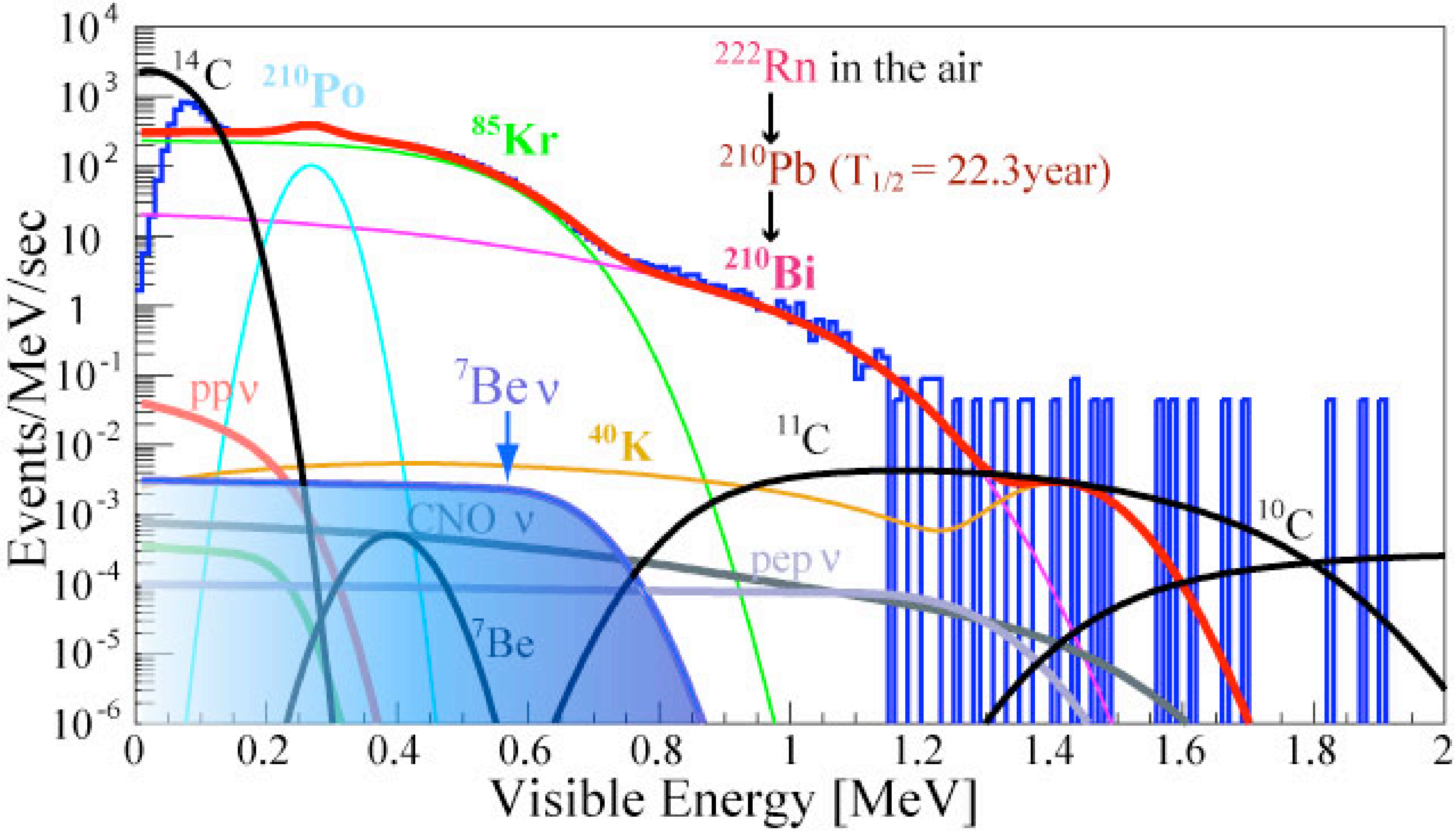
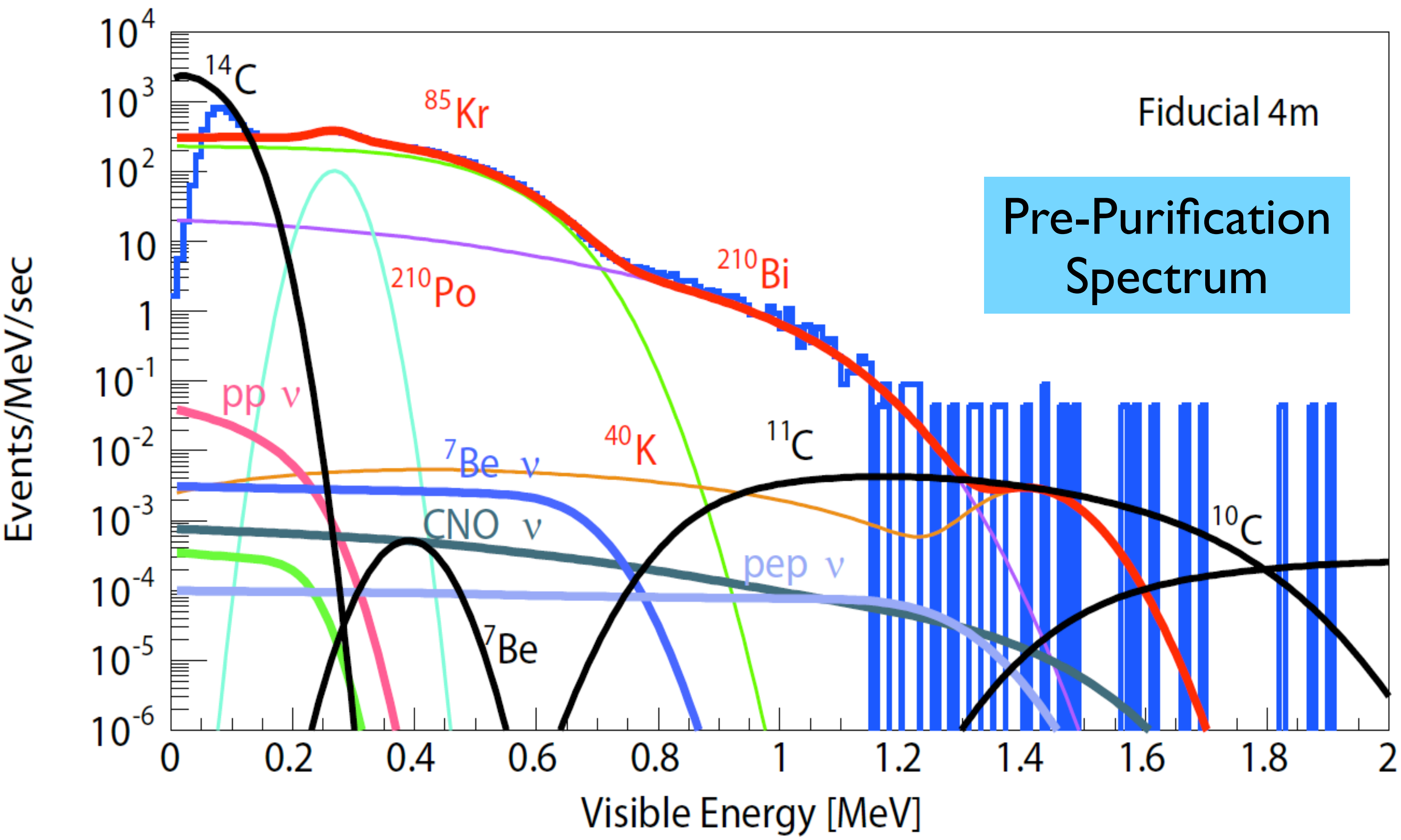
10. May, 1995 jmw



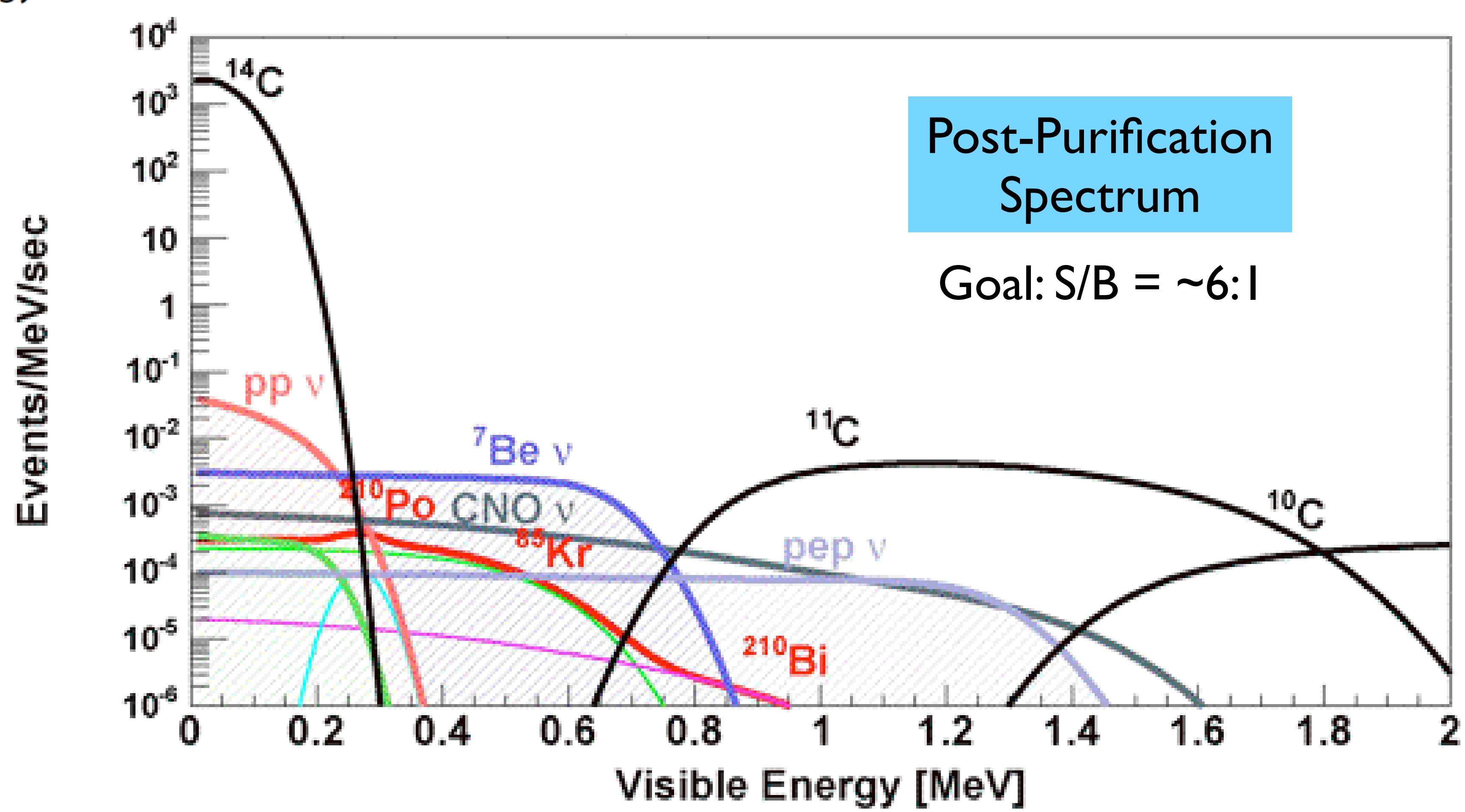
14C
210Po
85Kr
222Rn in the air
210Pb (T1/2 = 22.3year)
210Bi
pp ν
7Be ν
40K
11C
CNO ν
pep ν
7Be
10C
Events/MeV/sec
Visible Energy [MeV]

Isotope	$T_{1/2}$	Current Concentration	Goal	Purification Level	Method
^{210}Pb	22.5 yr	10^{-20} g/g	10^{-25} g/g	10^{-5}	Distillation
^{40}K	10^{9} yr	1.9×10^{-16} g/g	10^{-18} g/g	10^{-2}	Distillation
^{85}Kr	11 yr	700 mBq/m^3	1 μBq/m^3	10^{-6}	N_2 purging
^{238}U	10^{9} yr	3.5×10^{-18} g/g	10^{-18} g/g		
^{232}Th	10^{10} yr	5.2×10^{-17} g/g	10^{-16} g/g		
^{222}Rn	3.8 days		<1mBq/m^3		[Produces ^{210}Pb]

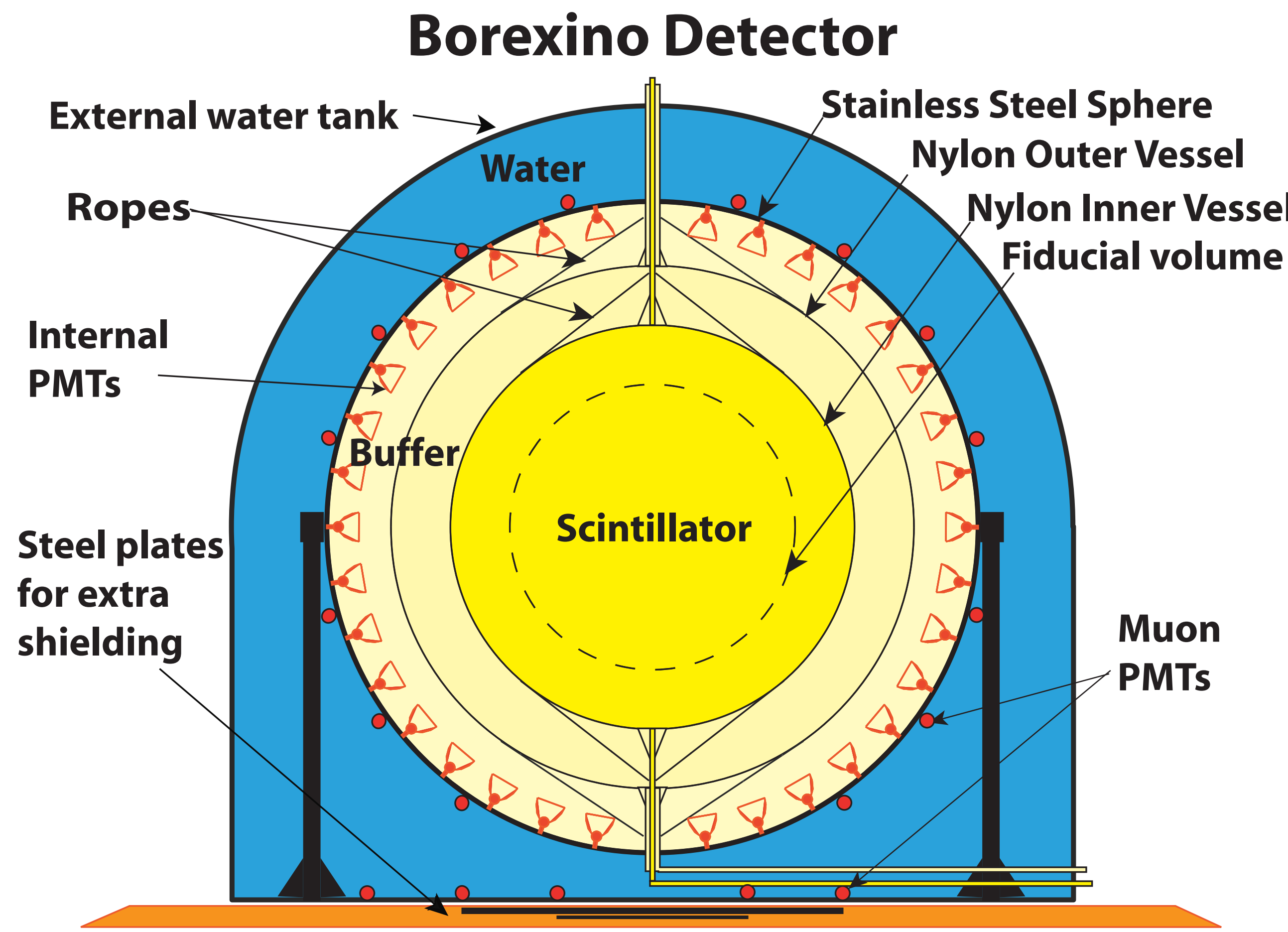


^{7}Be ν 79.9 event / day
pep ν 3.8 event / day
CNO ν 16.3 event / day

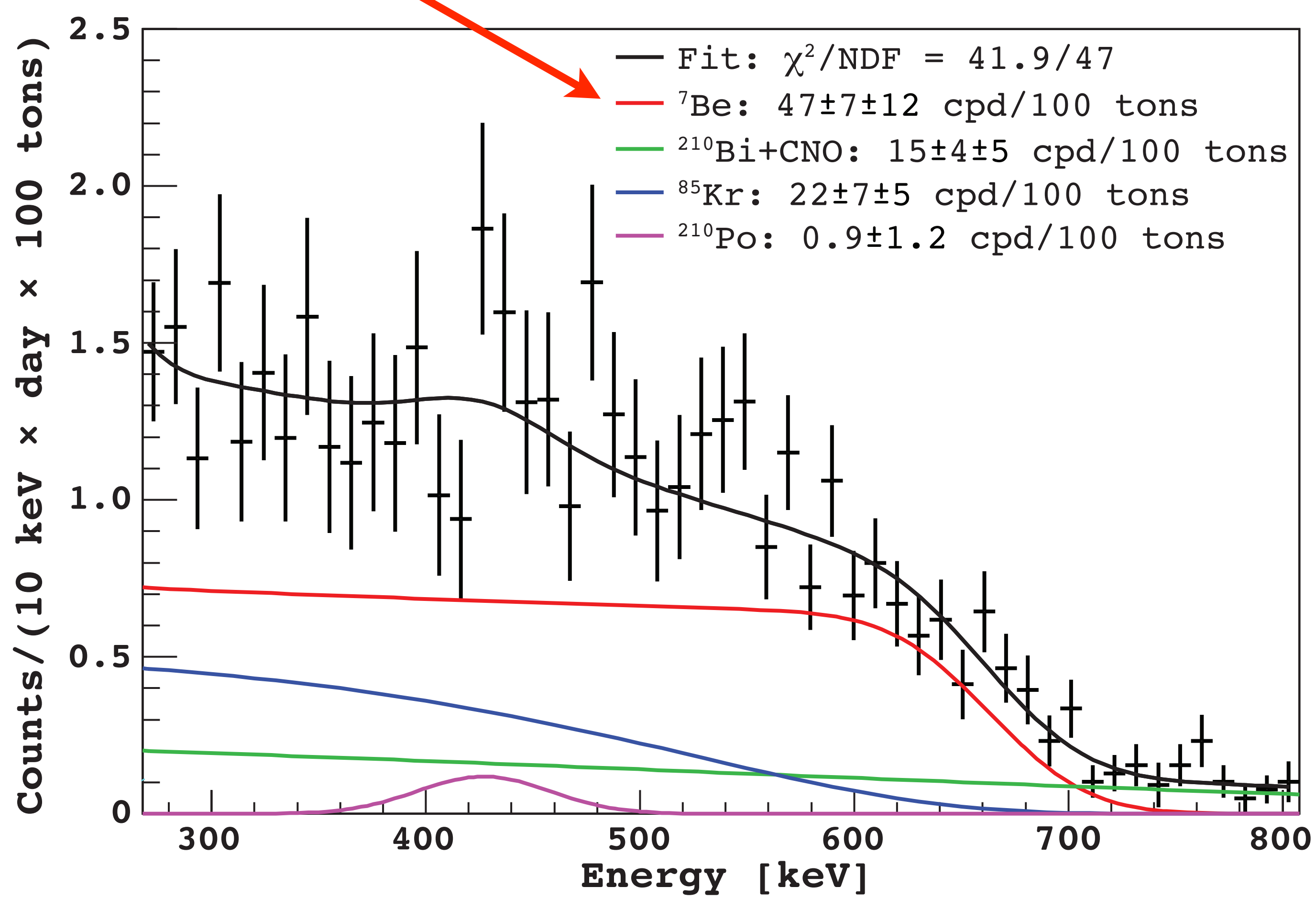
After 10^{-6} reduction in ^{210}Pb and ^{85}Kr



Borexino

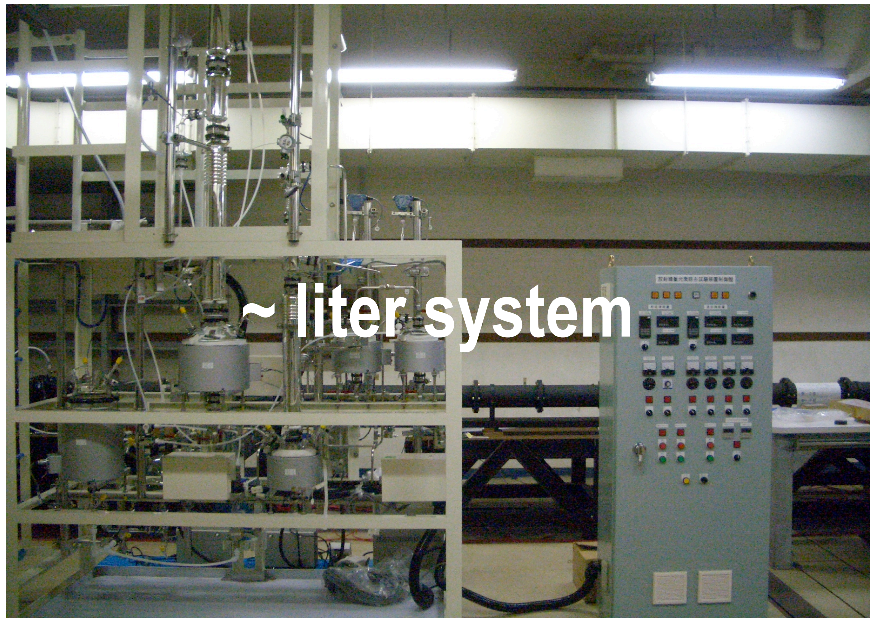


~30% Measurement

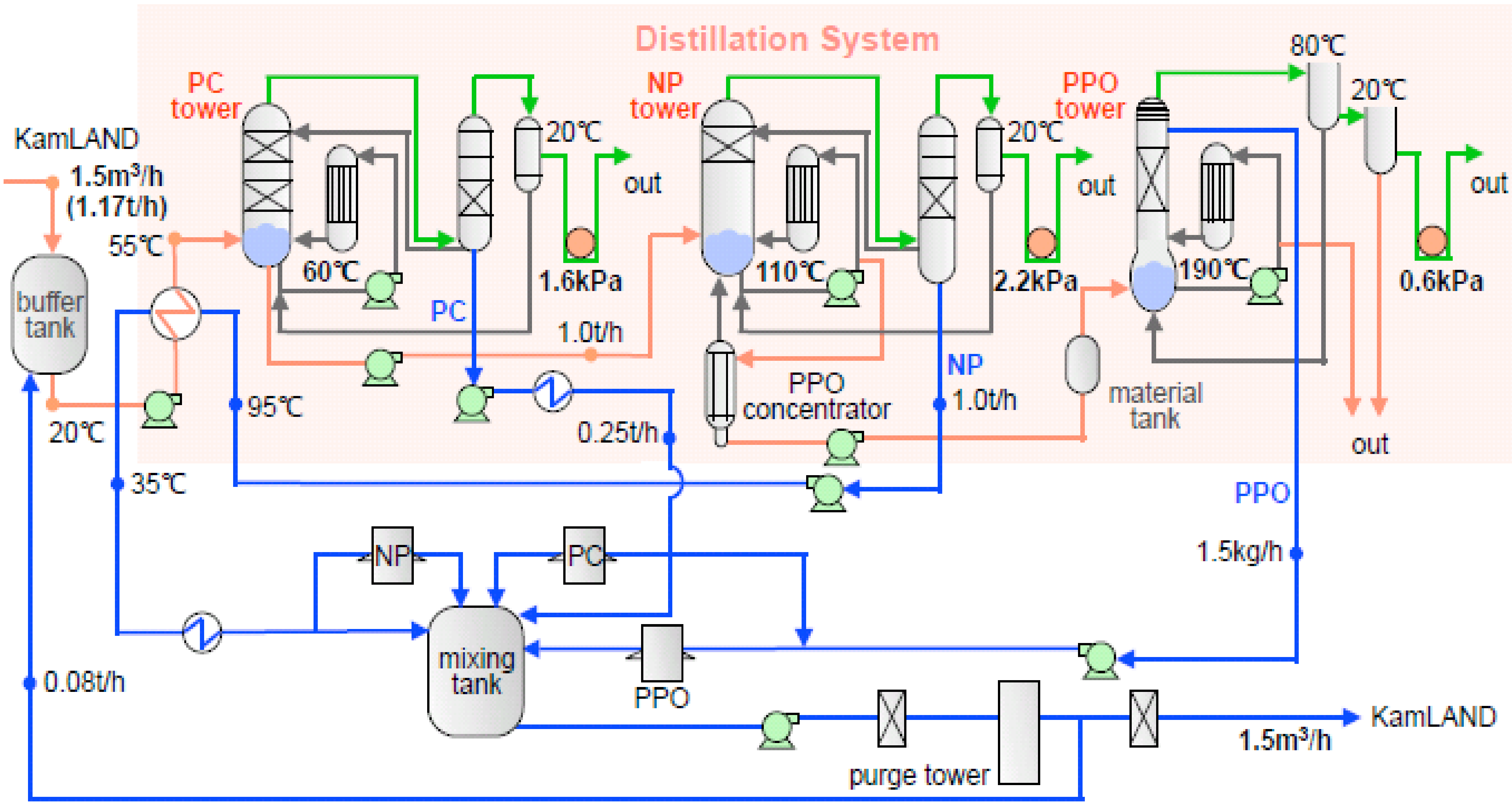


arXiv:0708.2251v1 [astro-ph]

KamLAND Liquid Scintillator Purification Development

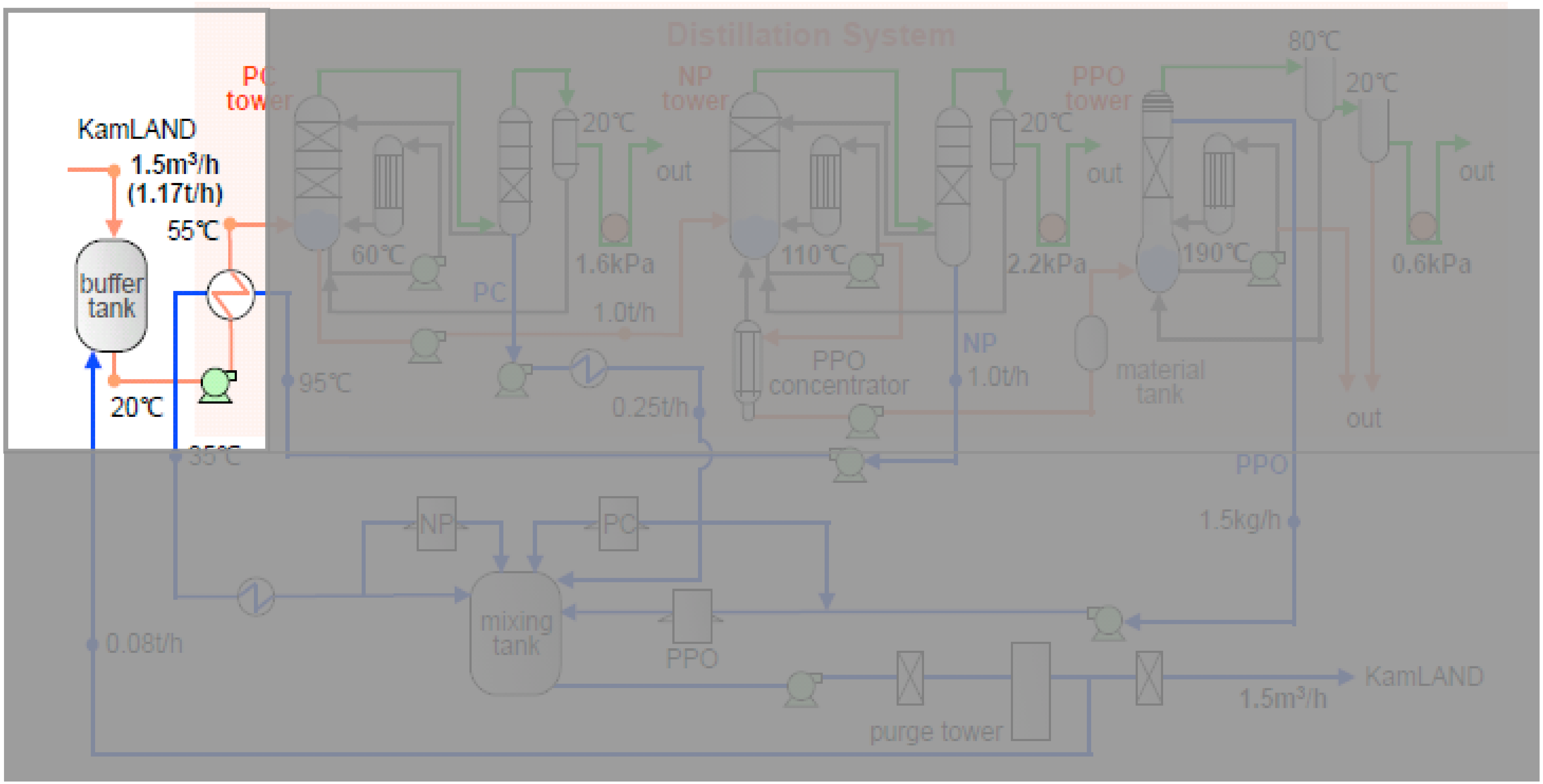


KamLAND Purification System



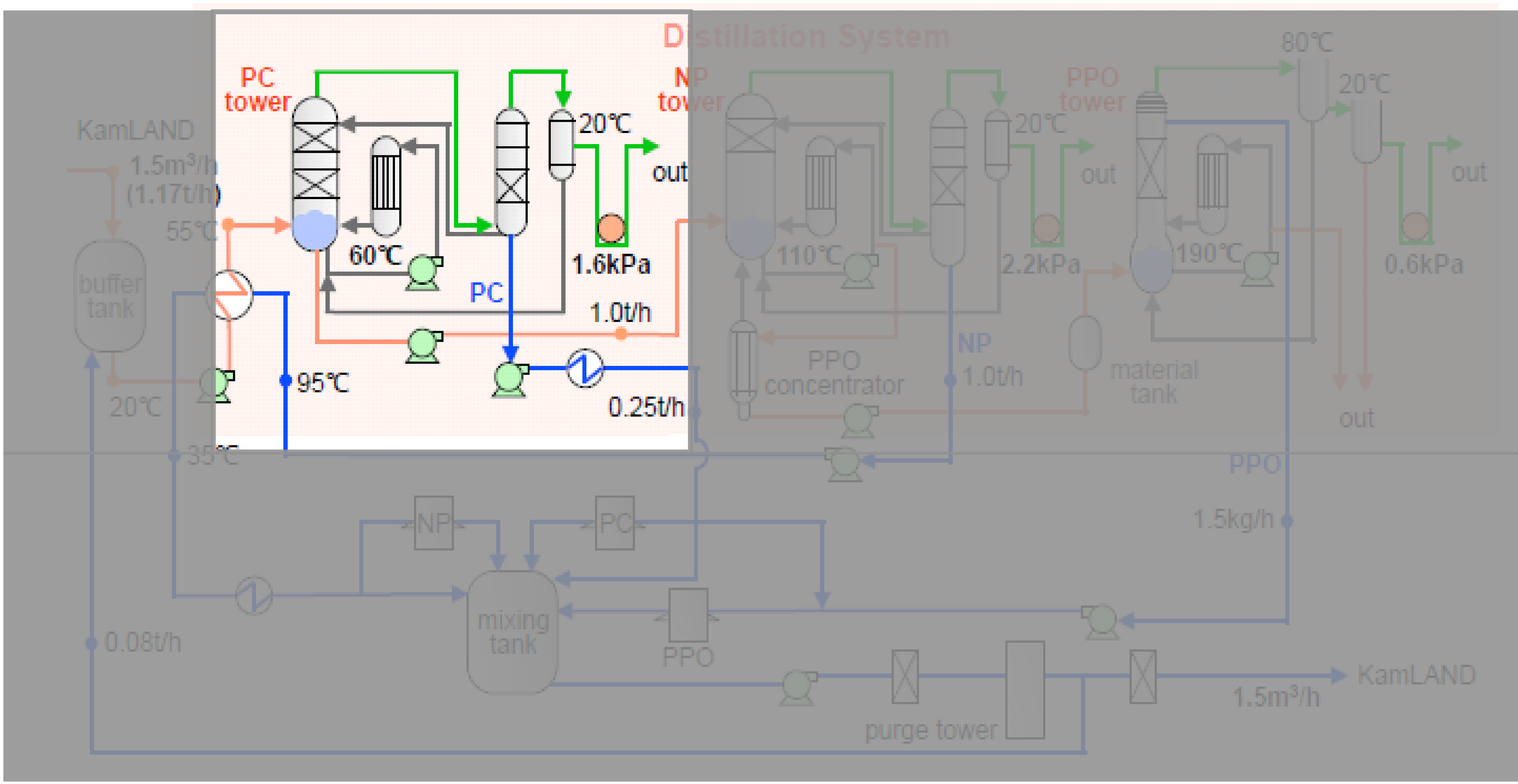
- Distillation into separate components: Pseudocumene (PC), Dodecane (NP) & PPO

LS is taken from KamLAND



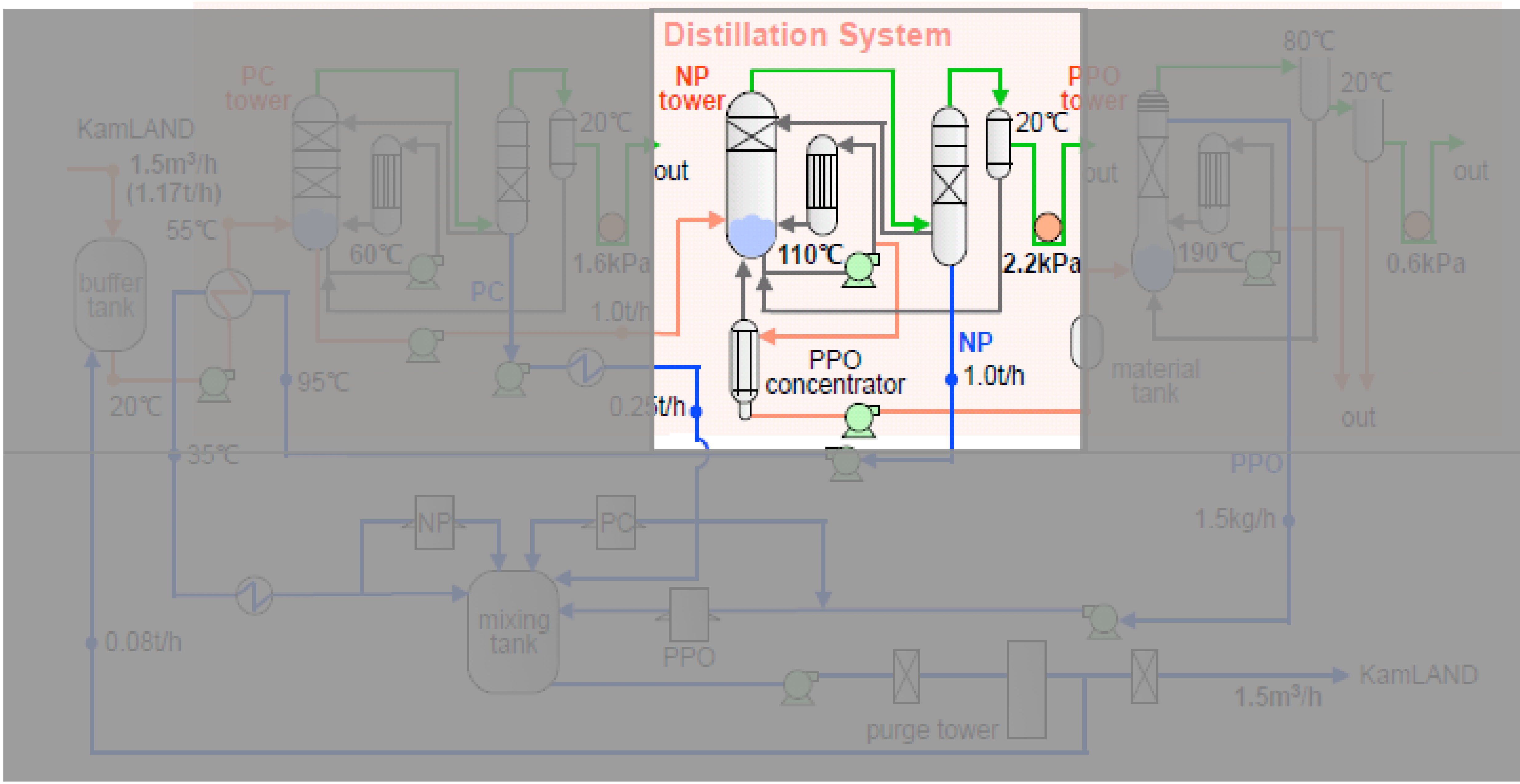
- Liquid Scintillator (LS) is fed from KamLAND into a small ($2m^3$) holding tank

Pseudocumene Distillation



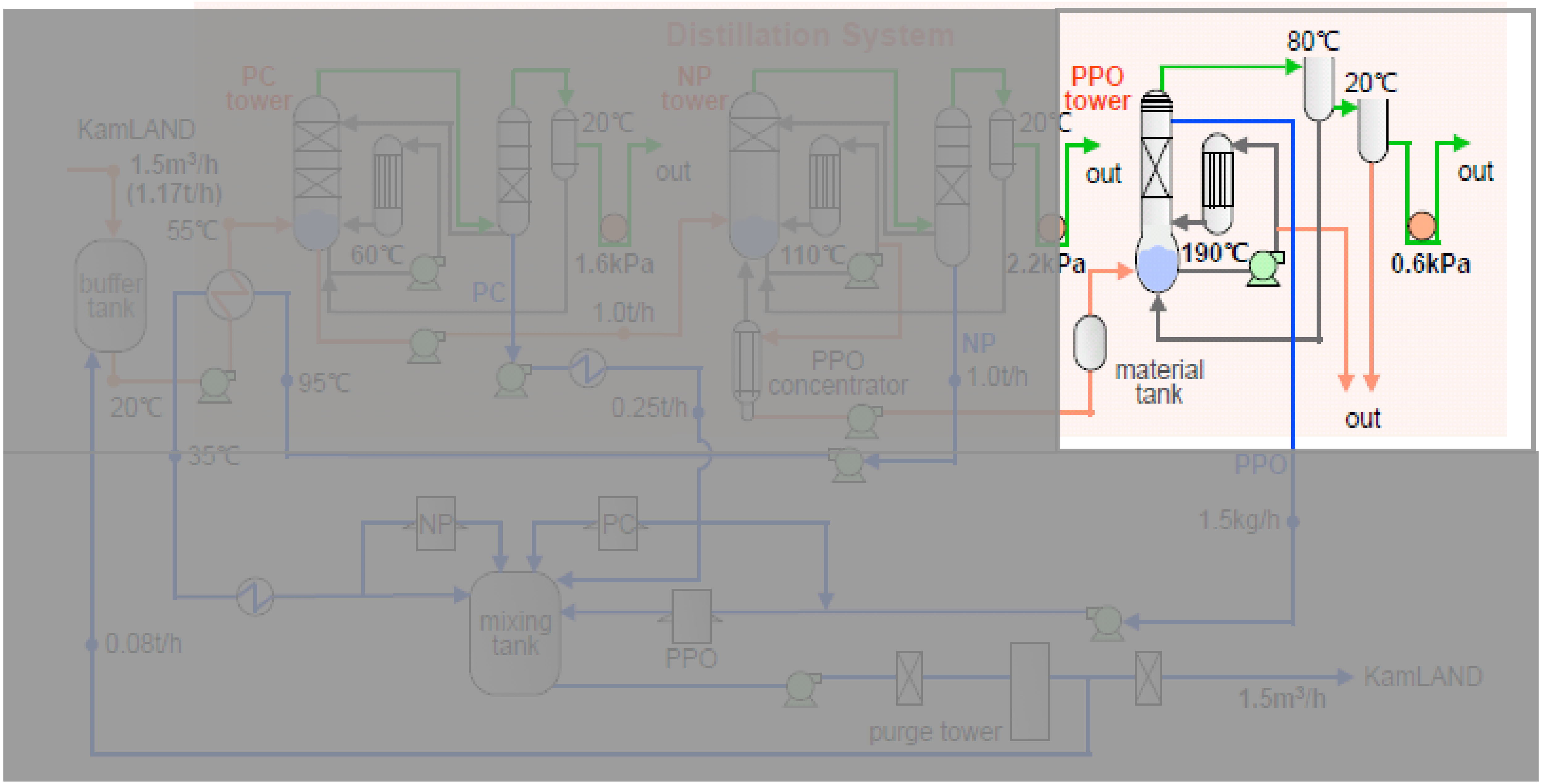
- Pseudocumene distillation in first tower
- Remainder sent to next tower

Dodecane Distillation



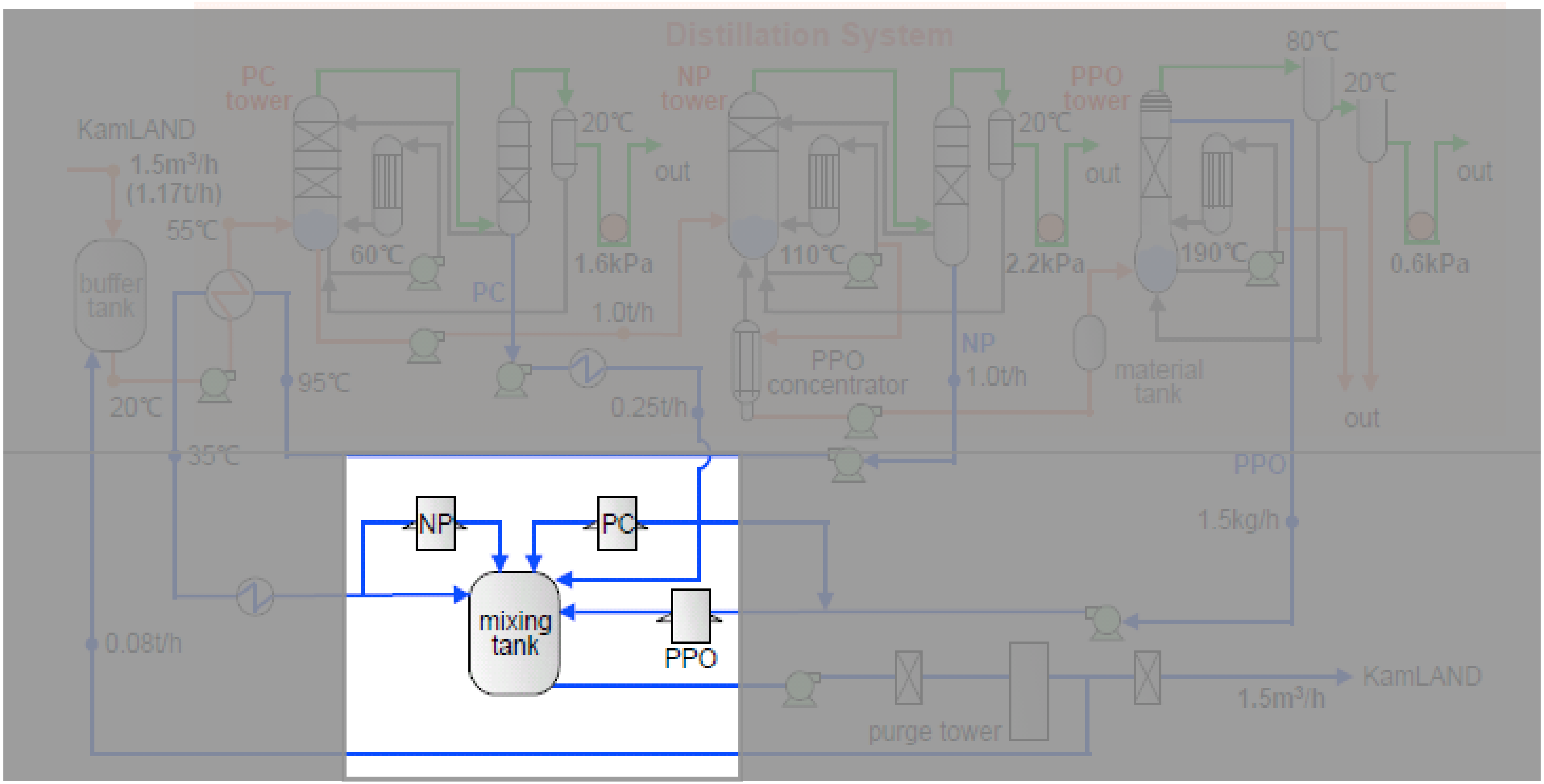
- Dodecane is distilled in the 2nd tower
- Remainder in the distillation tower is further concentrated and sent to PPO tower

PPO Distillation



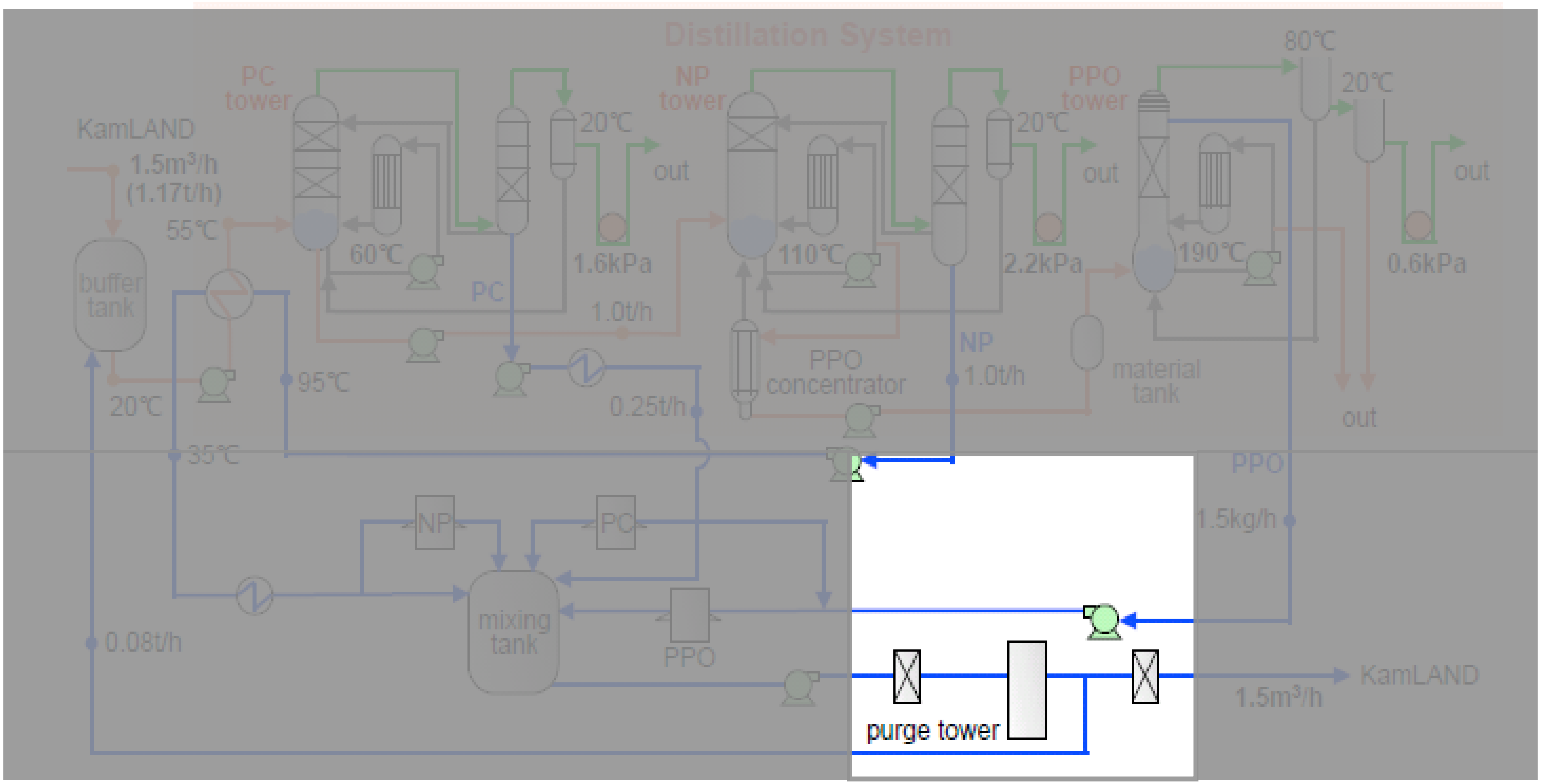
- PPO is the final step in distillation
- Remainder is discarded

PC, NP, and PPO Mixing



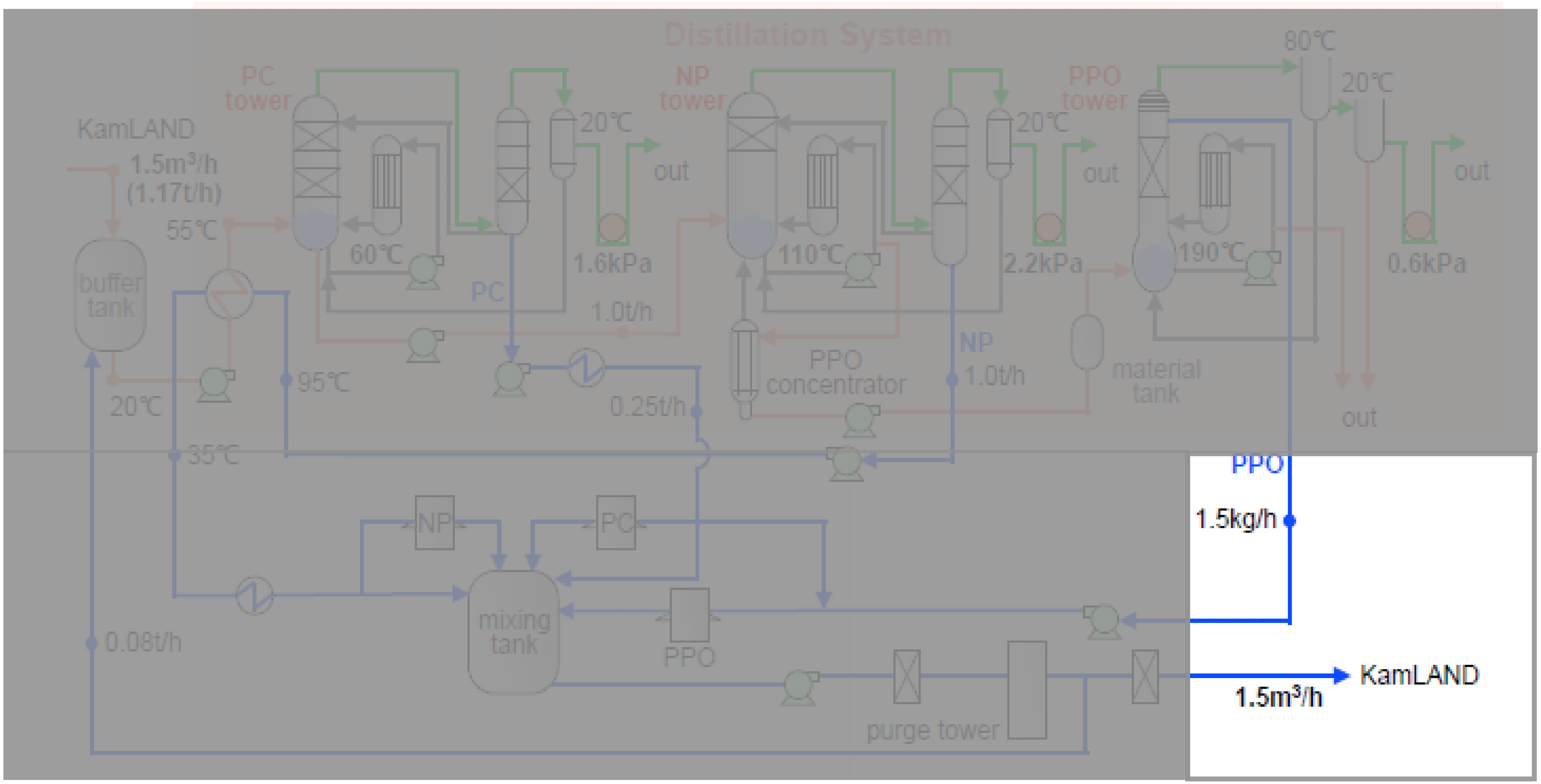
- Distilled PC, NP and PPO are blended to remake the liquid scintillator

Distillation of Pseudocumene



- Final step is N2 purging of the Liquid Scintillator
- Radon and Krypton Removal

Purified LS is Returned to KamLAND



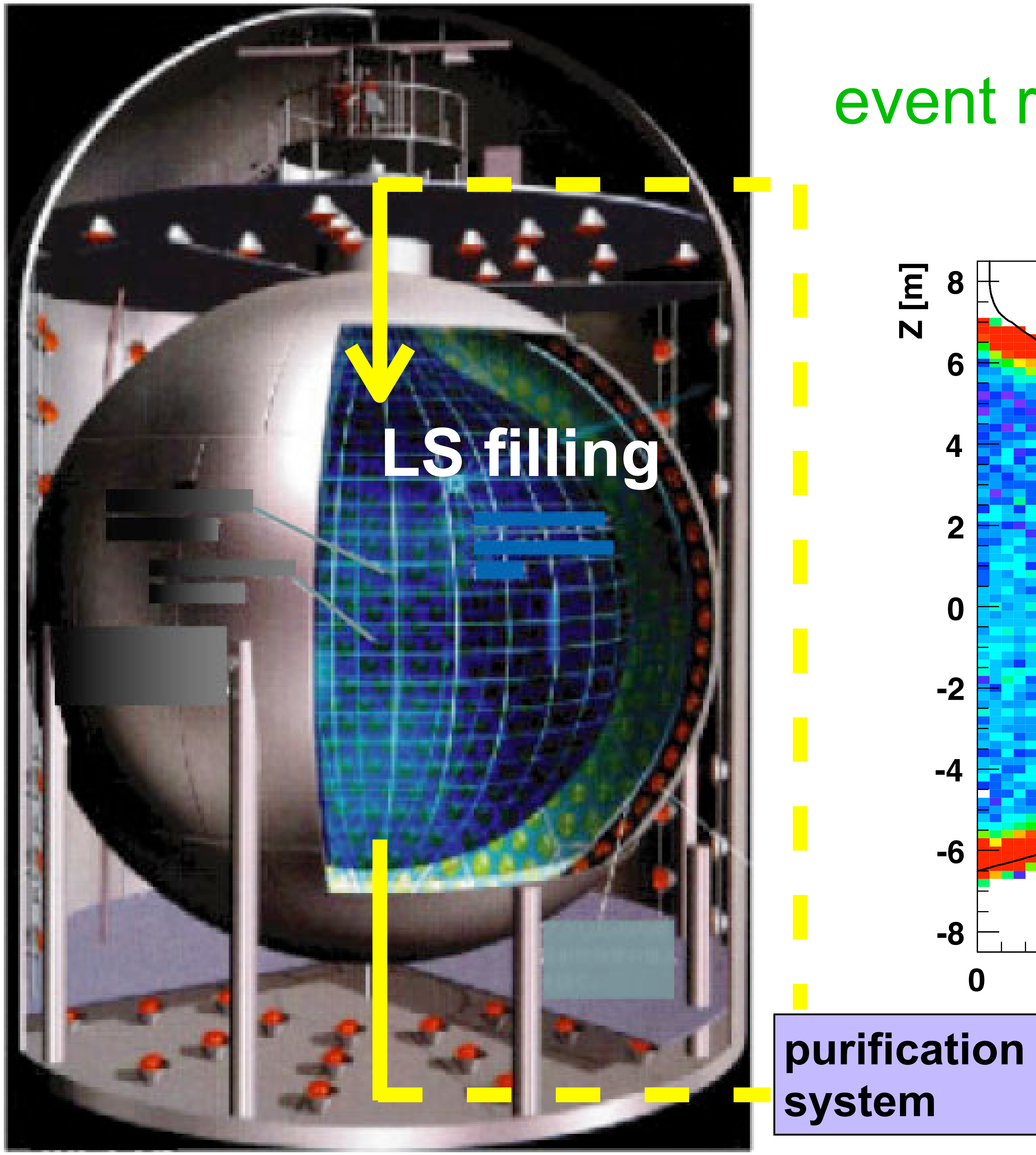
Purified LS Monitoring

- Radon content measured with miniLAND
- Krypton monitored with RGA
- Attenuation Length and Light Yield Measurements

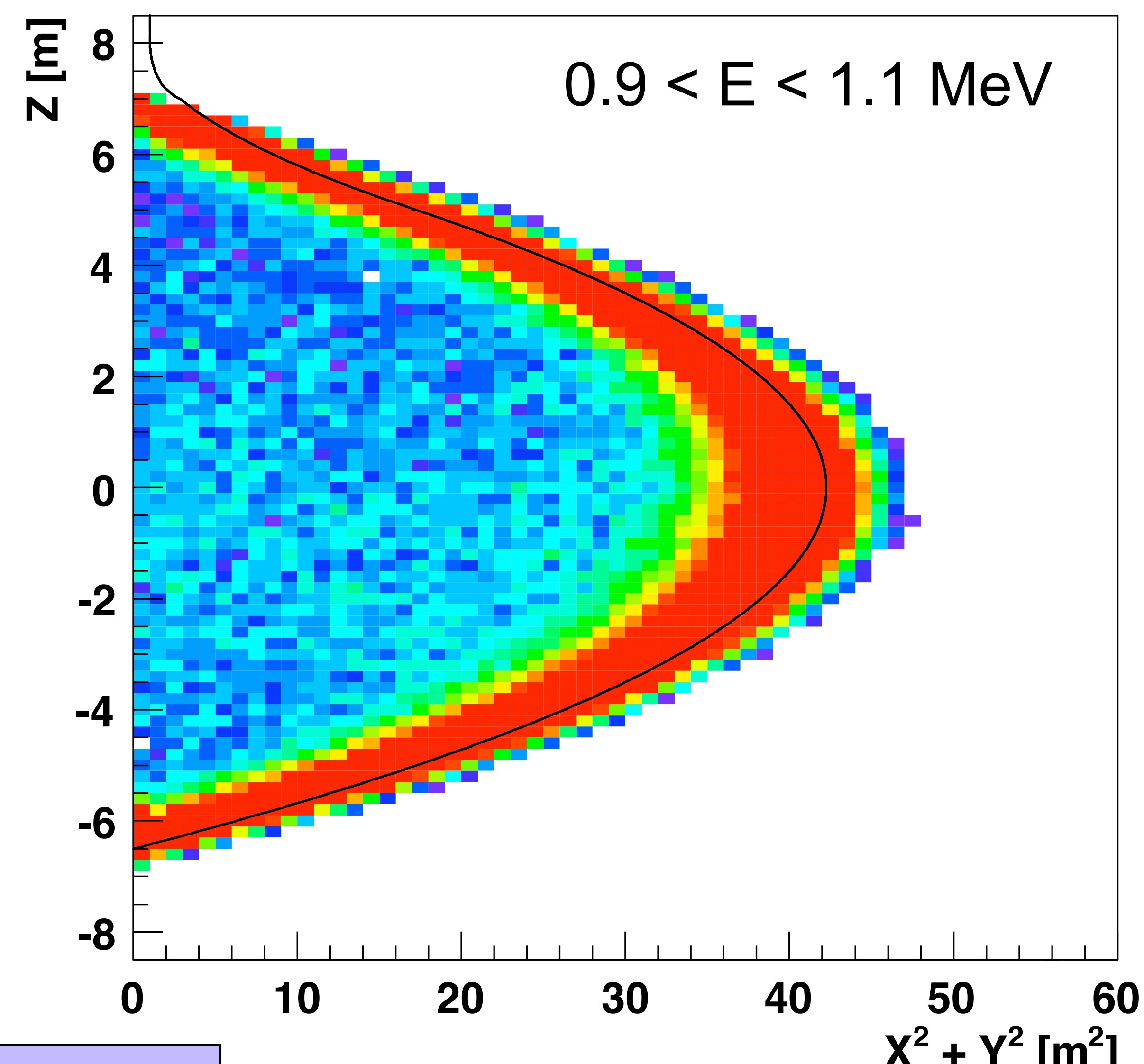
KamLAND Purification Status

- December 2006 - begin testing complete purification system in a closed circulation loop
- May 12, 2007 - first transfer of purified liquid scintillator into KamLAND

Purification Status in Real System



event rate map before purification (arbitrary unit)



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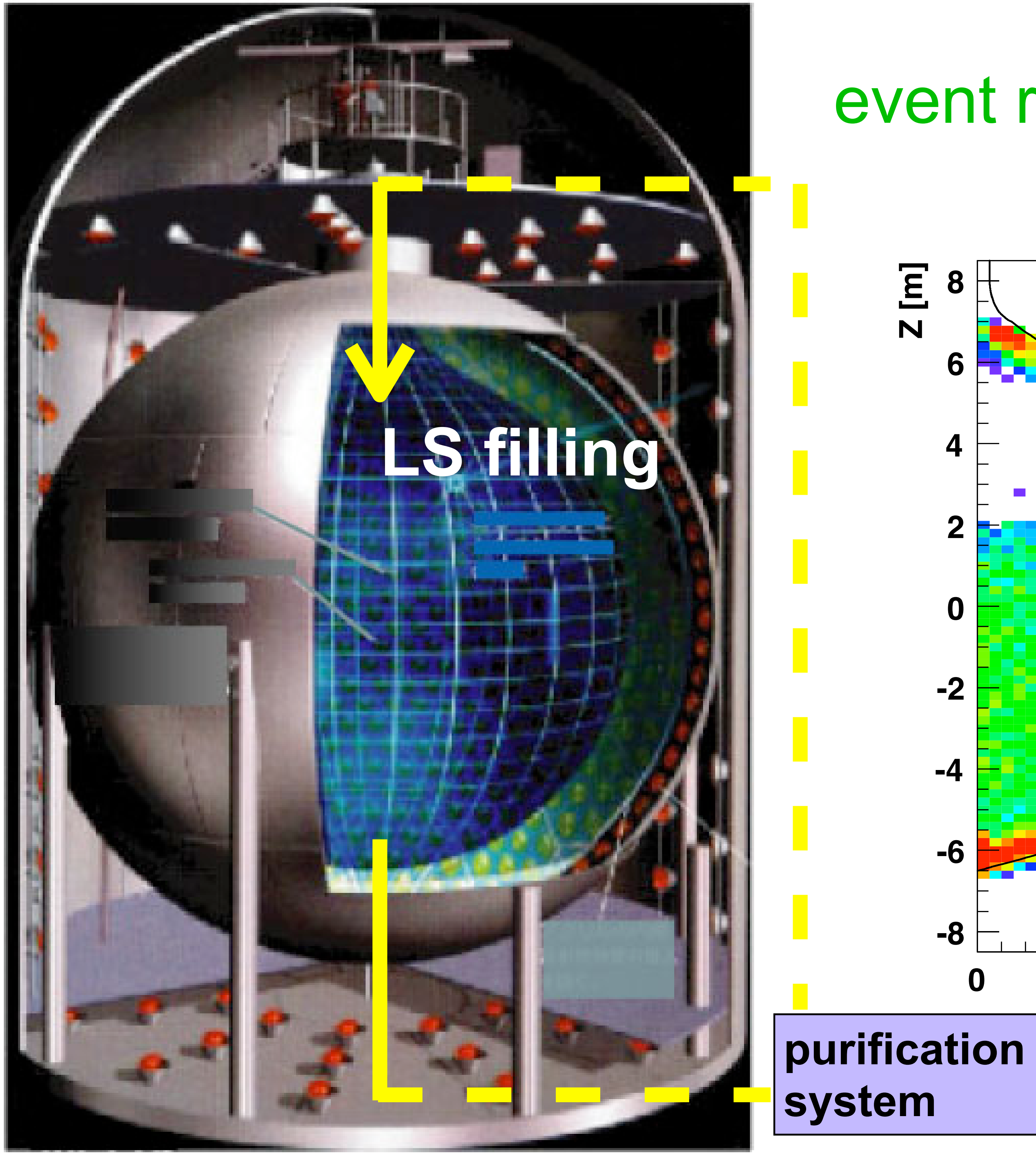

event rate map after purification
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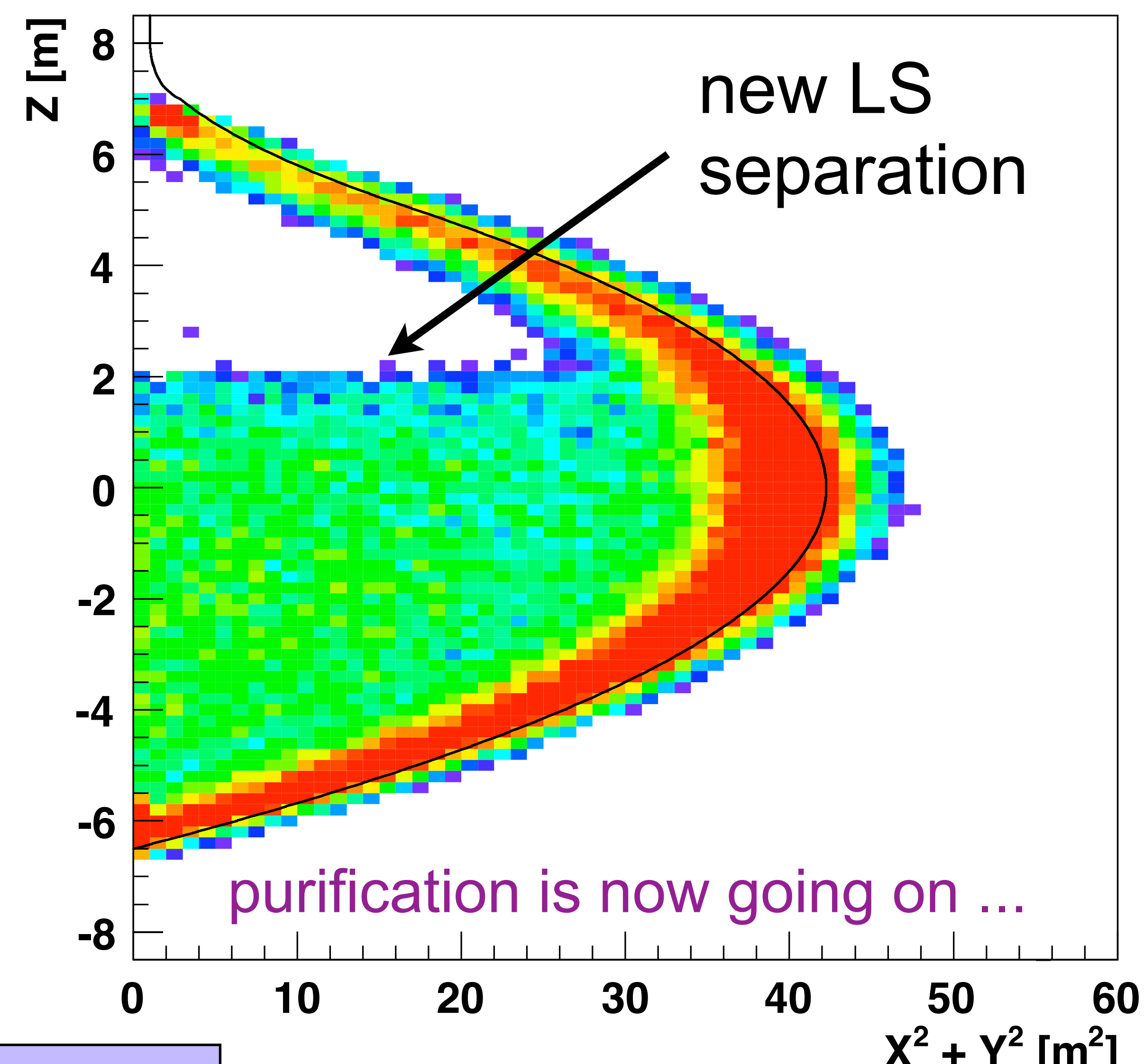

~ 300 m^3 after 10 day operation

KamLAND Purification Status

- December 2006 - begin testing complete purification system in a closed circulation loop
- May 12, 2007 - first transfer of purified liquid scintillator into KamLAND
- August 1, 2007 - scheduled purification stop (due to blasting for XMass experiment)
- Restart purification after blasting is complete (Fall 2007/Winter 2008)

Summary

- KamLAND Phase 1 (January 21, 2002 to May 12, 2007)
  - KamLAND results strengthen support for "neutrino disappearance" and LMA-MSW as the solution to the Solar Neutrino Problem
  - Precision measurements: best-fit KamLAND+Solar oscillation parameters are: $\Delta m^2 = 8.0^{+0.6}_{-0.4} \times 10^{-5} eV^2 \quad \tan^2\theta = 0.45^{+0.09}_{-0.07}$
  - New results soon!
  - First indication of Geoneutrino detection: new tool to investigate the Earth
- KamLAND Phase 2 (Low Background Phase, May 12, 2007 to present)
  - Measurement of solar ^{7}Be neutrinos: is solar oscillation only LMA-MSW? Investigating SSM
  - Geoneutrino measurements will continue with significantly lower backgrounds
  - Lower supernova threshold to ~0.2MeV

Thank you!

KamLAND Collaboration Meeting
September 2006, Toyama, Japan