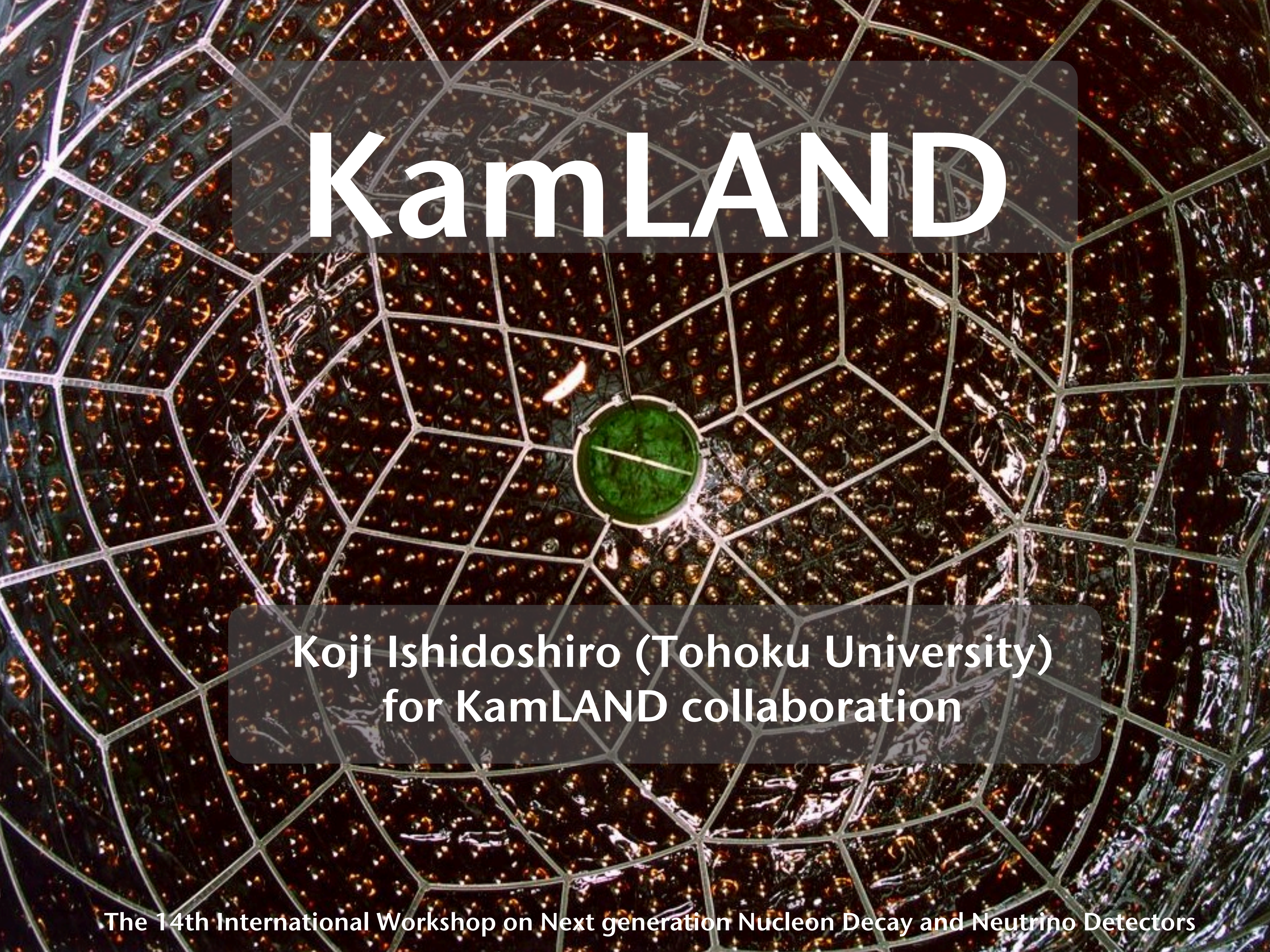


KamLAND

Koji Ishidoshiro (Tohoku University)
for KamLAND collaboration

The 14th International Workshop on Next generation Nucleon Decay and Neutrino Detectors

KamLAND collaboration

University of Washington

University of Tennessee

NIKEF

Tohoku university

Berkeley

University of Tokyo

Hawaii University

North Carolina Central University

Osaka university

Colorado State University

University of Alabama

11 institutes,
46 scientists

Hida, Japan
March 2013

Contents

- KamLAND detector
- Latest results
- Next challenges
- Summary

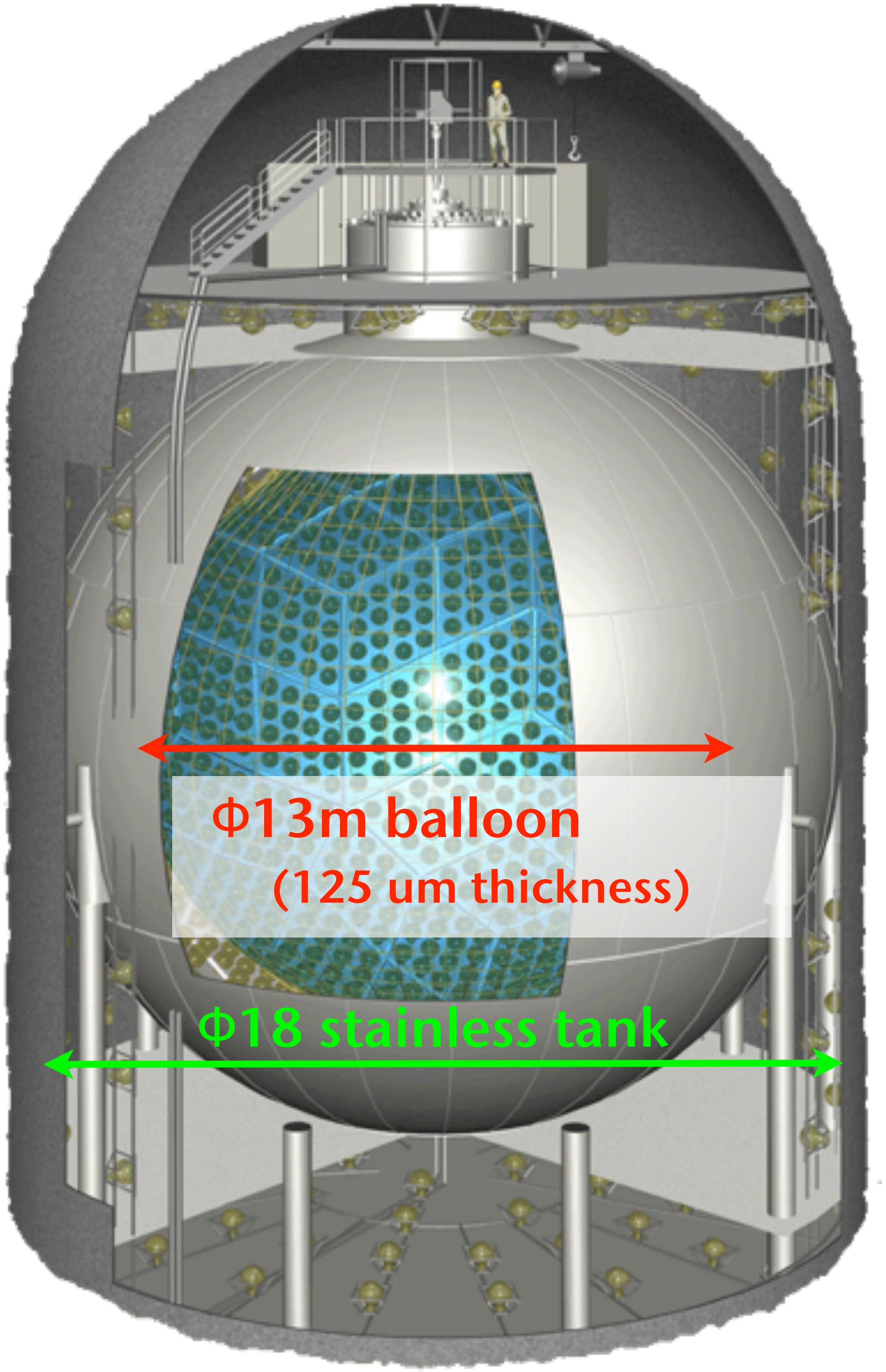
Note: KamLAND-Zen will be presented in after noon session and poser session.

KamLAND detector

KamLAND

Kamioka Liquied scintillator
Anti-Neutrino Detector (since 2002)

- 1,000 m depth (Kamioka mine)
- 1,000 t liquid scintillator
  Dodecan (80%), Psedocumene (20%), PPO (1.36g/l)
- 1,325 17inch + 554 20inch PMTs

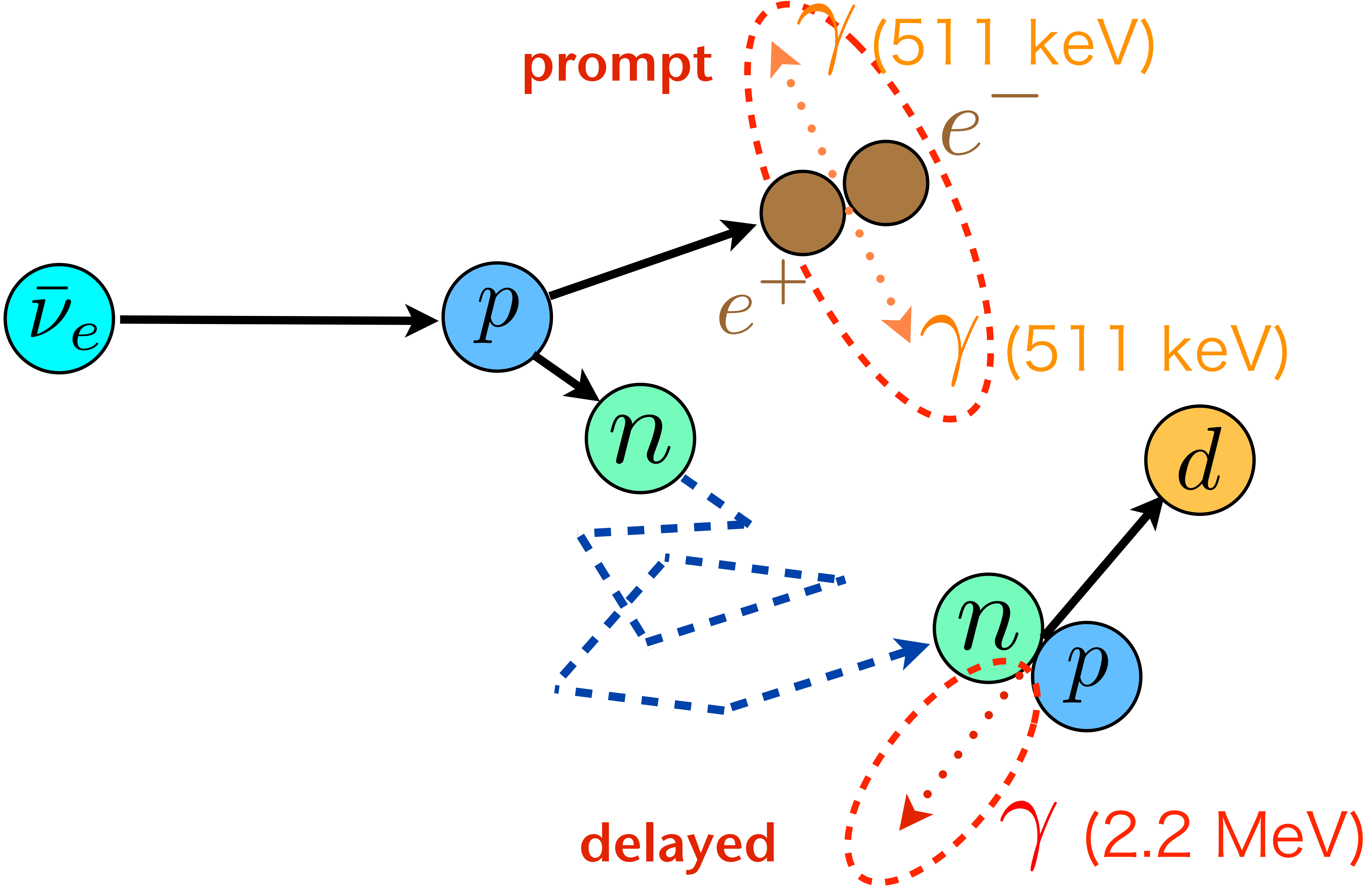


Outer detector (for muon veto)
- 3.2kton water cherenkov detector
- ~100 20inch PMTs

KamLAND

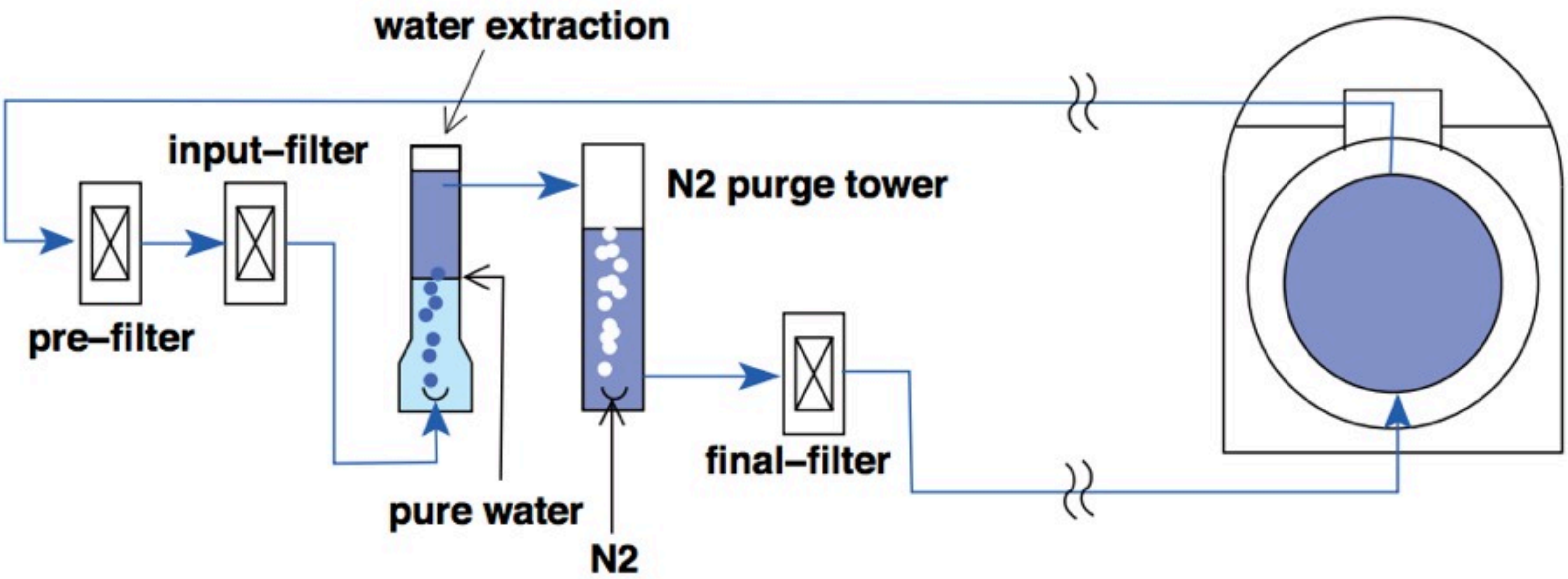
Anti-neutrino detection: delayed coincidence measurement

- time-spatial correlated events
- Reduction of background events

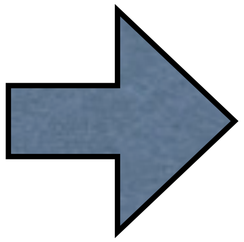


KamLAND

The world cleanest detector



Ions are billion time more solvable to water.
Wash scintillator with pure water.



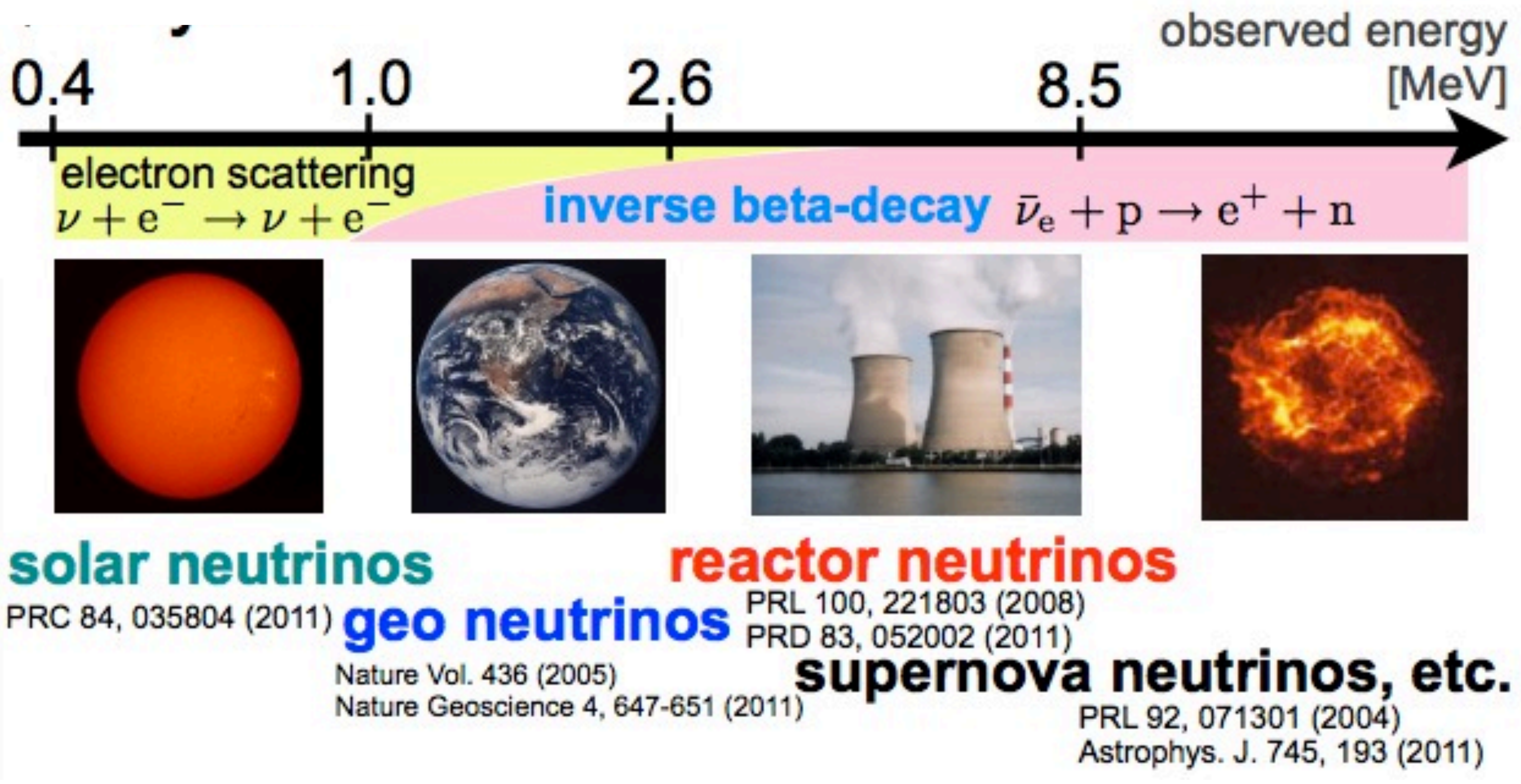
^{238}U 3.5x10^{-18}g/g
^{232}Th 5.2x10^{-17}g/g

It is trillion times cleaner than ordinary material
or 100 times cleaner than Super-Kamiokande.

Targets of KamLAND

Largest anti-neutrino detector
with ultimate low background.

Different neutrino physics in a wide energy range



solar neutrinos
PRC 84, 035804 (2011)

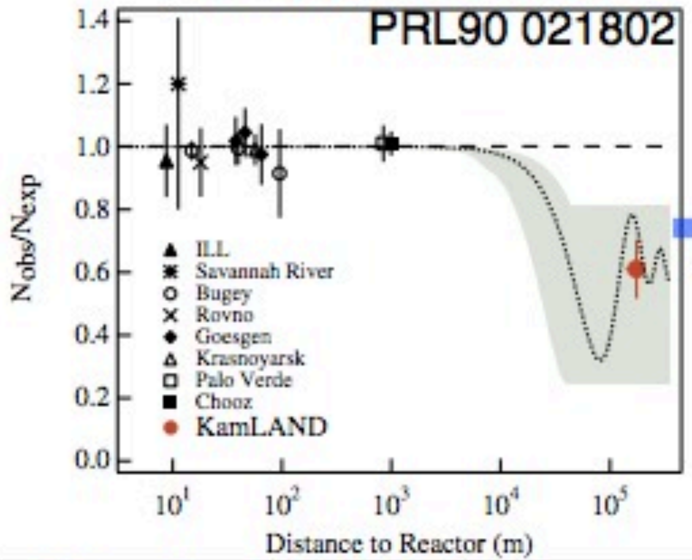
geo neutrinos
Nature Vol. 436 (2005)
Nature Geoscience 4, 647-651 (2011)

reactor neutrinos
PRL 100, 221803 (2008)
PRD 83, 052002 (2011)

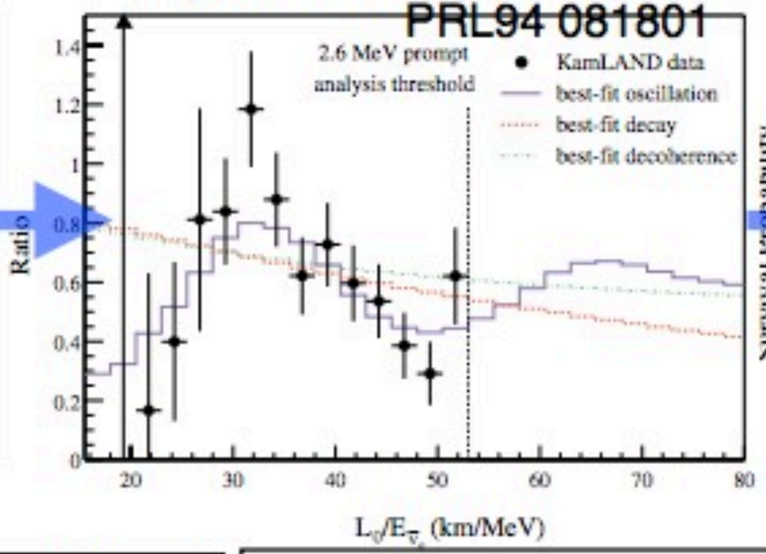
supernova neutrinos, etc.
PRL 92, 071301 (2004)
Astrophys. J. 745, 193 (2011)

History of KamLAND

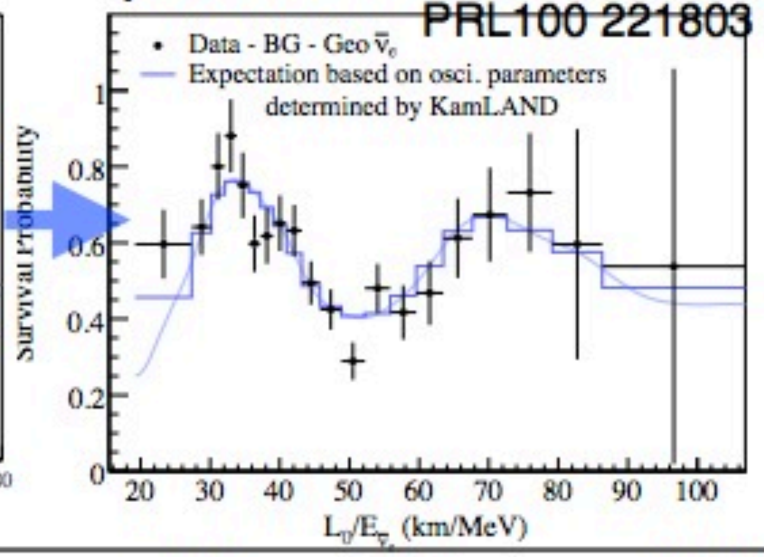
disappearance

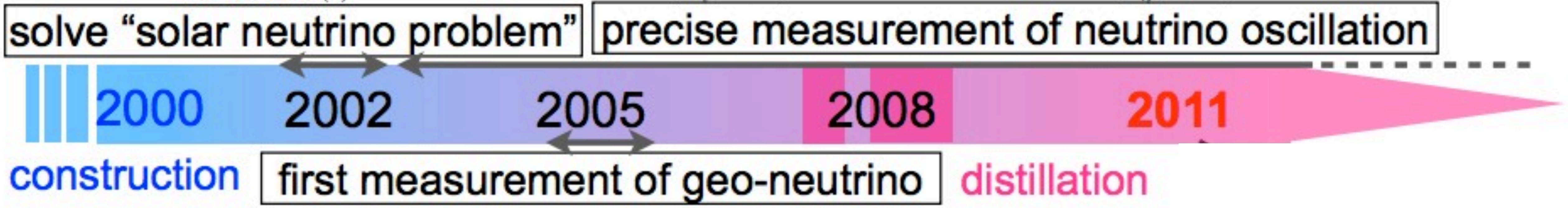


spectral distortion



precise measurement





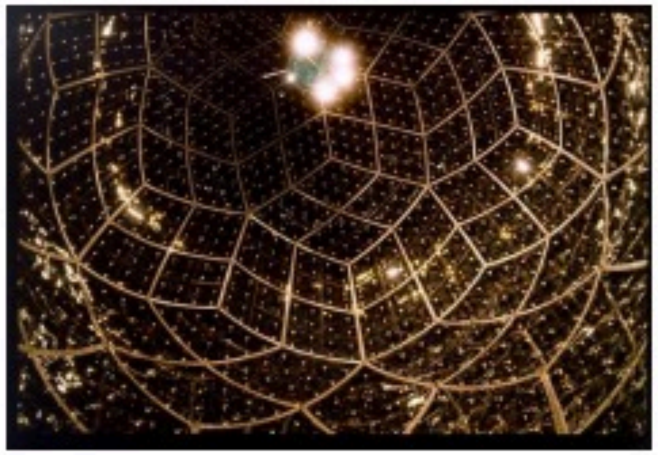
solve “solar neutrino problem”

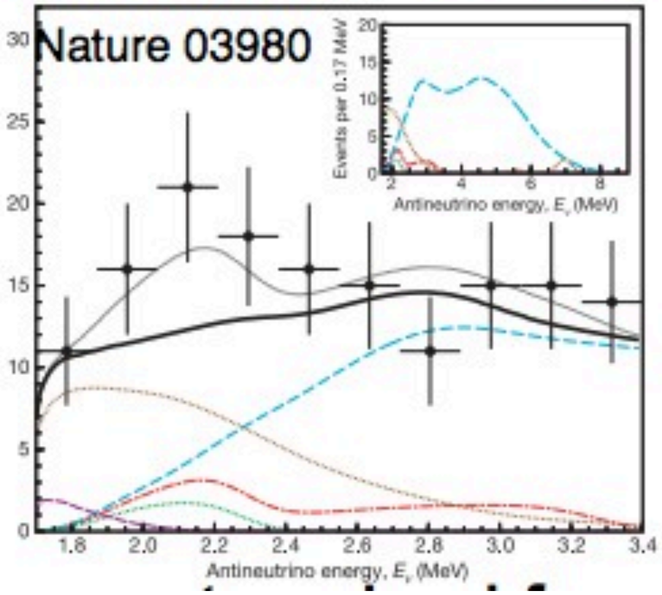
precise measurement of neutrino oscillation

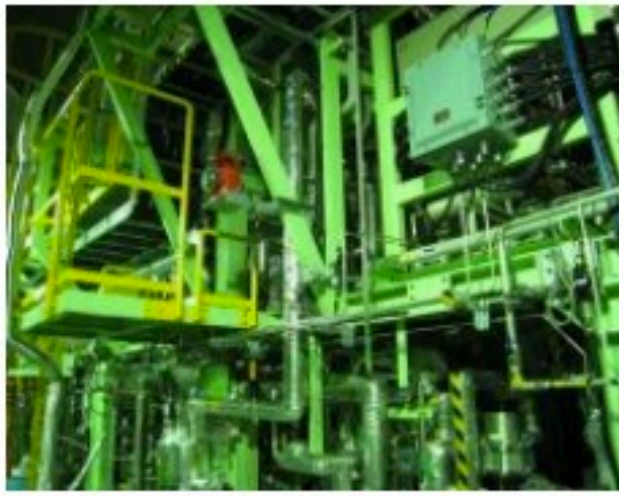
construction

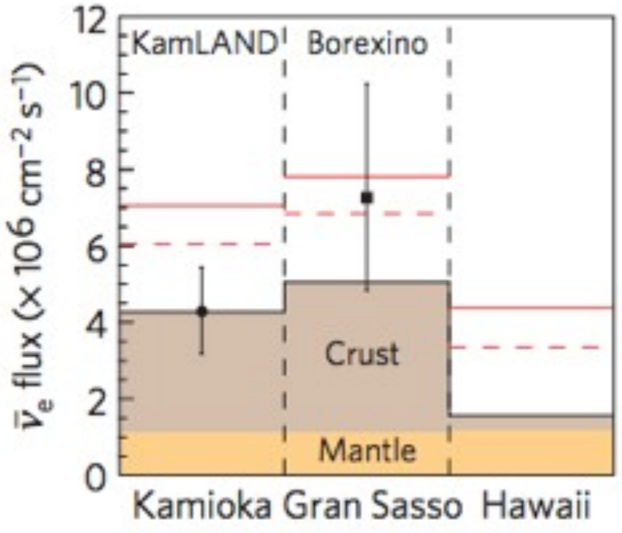
first measurement of geo-neutrino

distillation







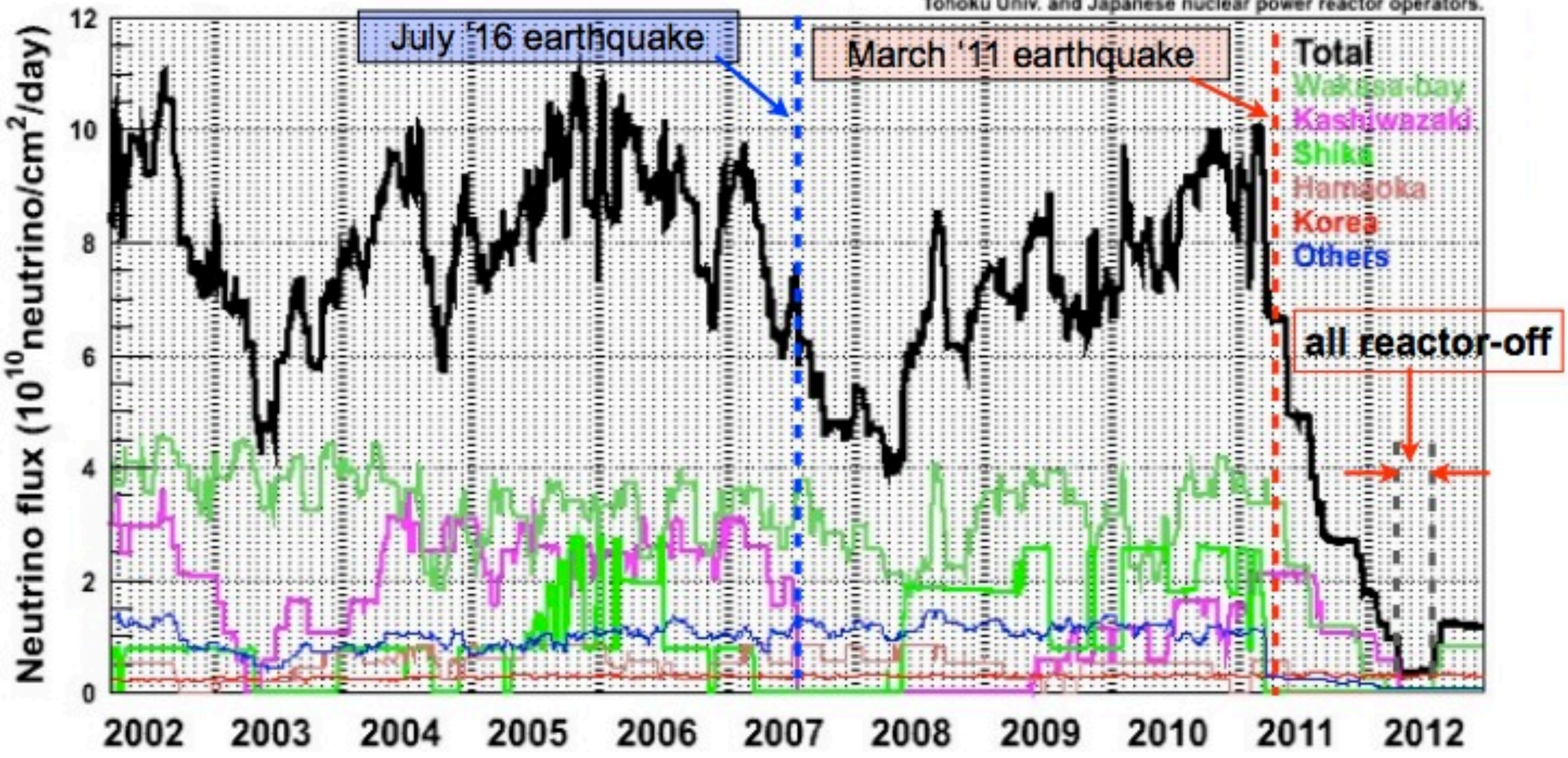


Latest results

- ◆ Reactor neutrino
- ◆ Geo-neutrino

Anti-neutrino flux in Kamioka

time variation of neutrino flux



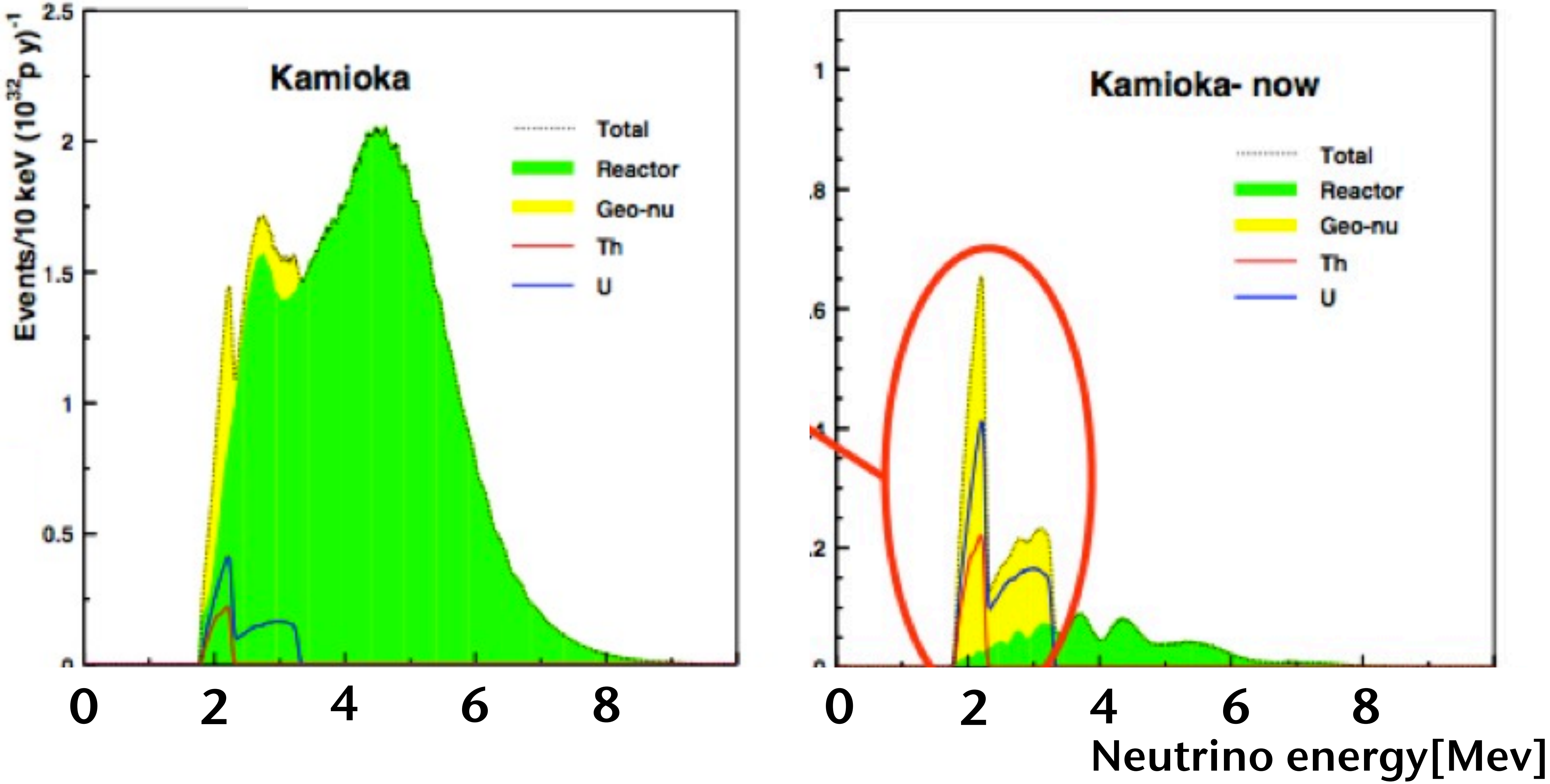
Data provided according to the special agreements between Tohoku Univ. and Japanese nuclear power reactor operators.

significant reduction of anti-neutrino flux
from reactors after Fukushima-I accident

Expected spectrum

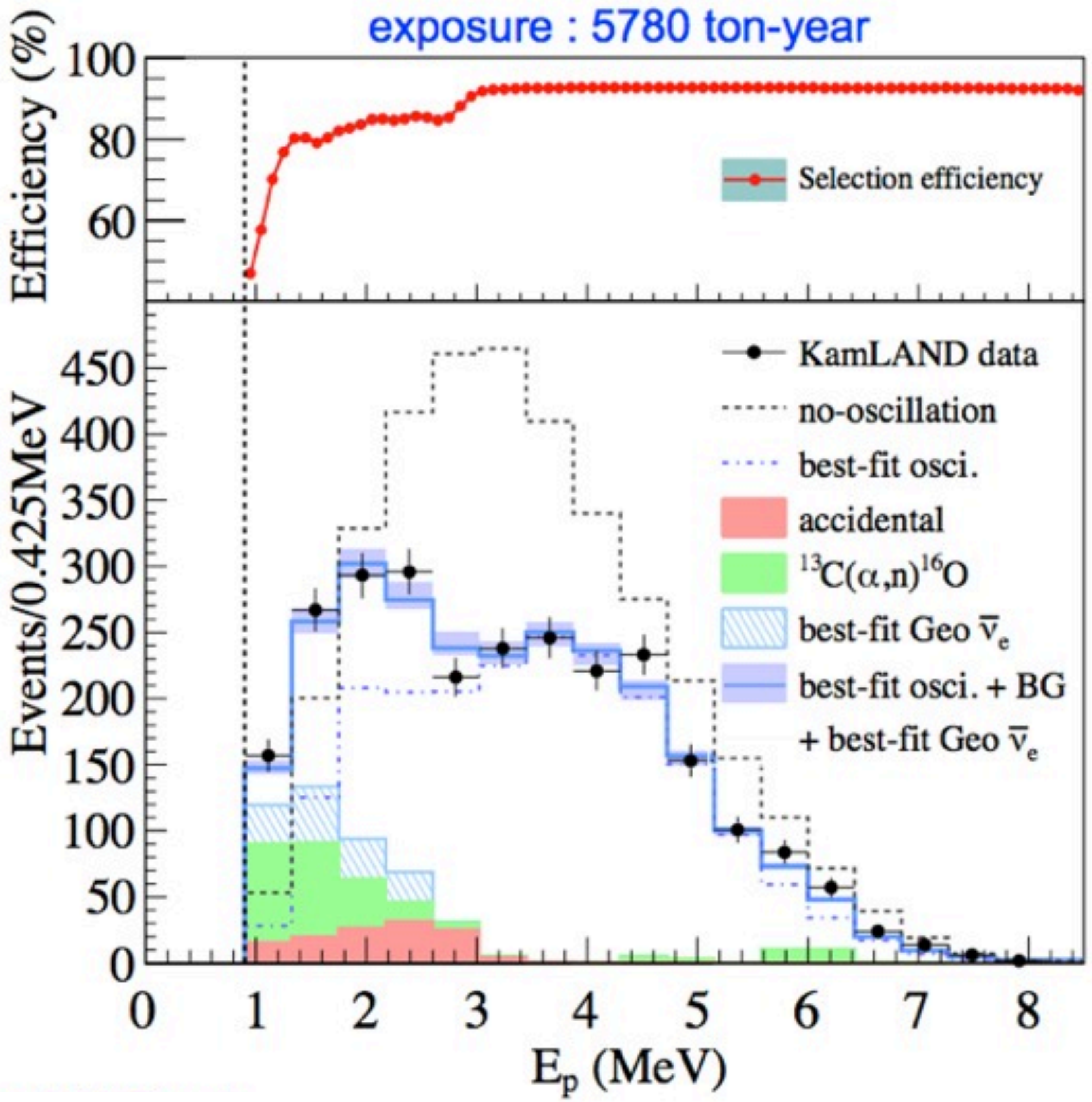
Normal-reactor phase

Low-reactor phase



"Reactor on-off" study for neutrino oscillation and geo-neutrino analysis

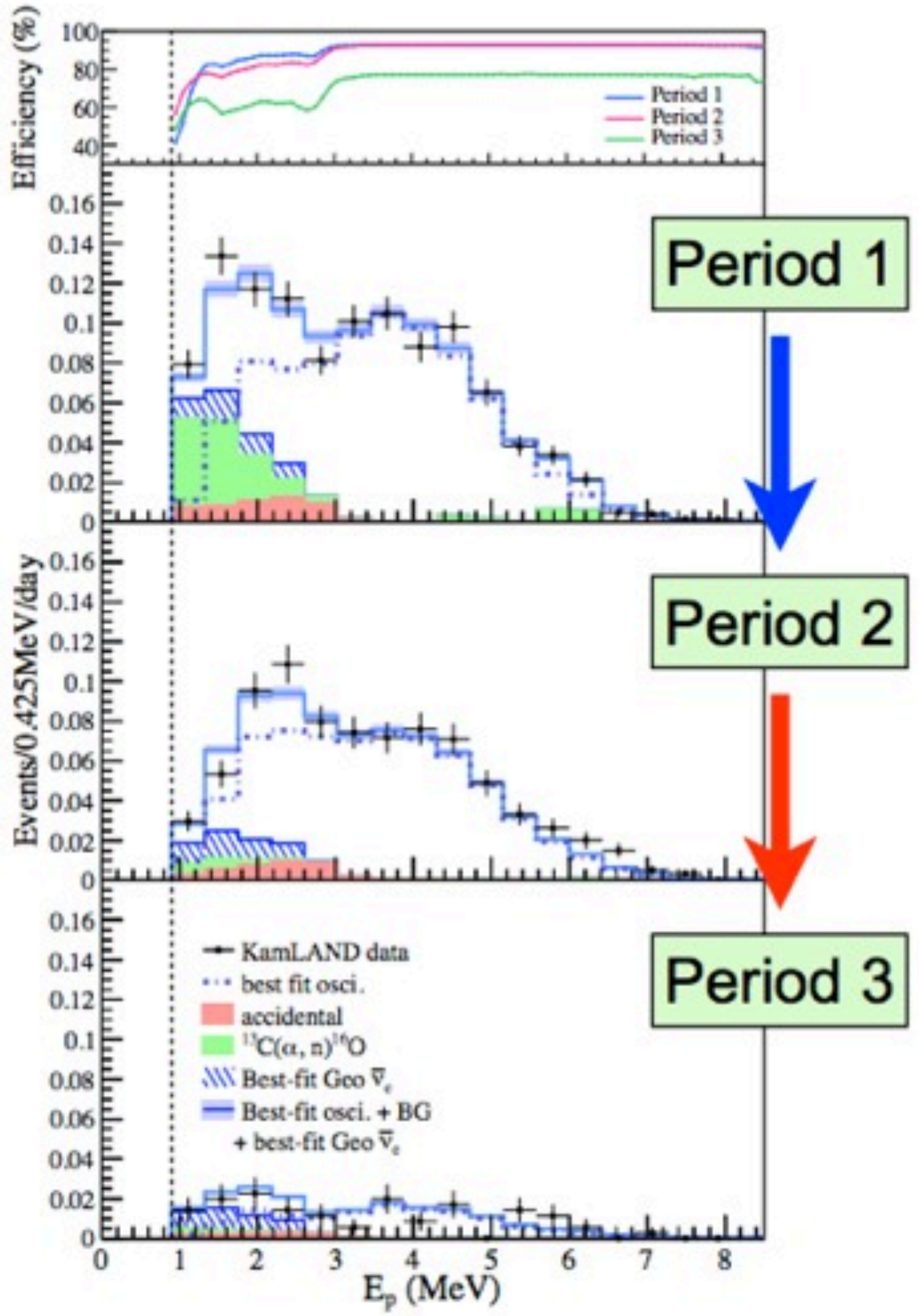
Observed spectrum



No osci. expected	3564 ± 145
Background (w/o geo neutrino)	364 ± 31
Observed events	2611

purification **(α,n) ↓**

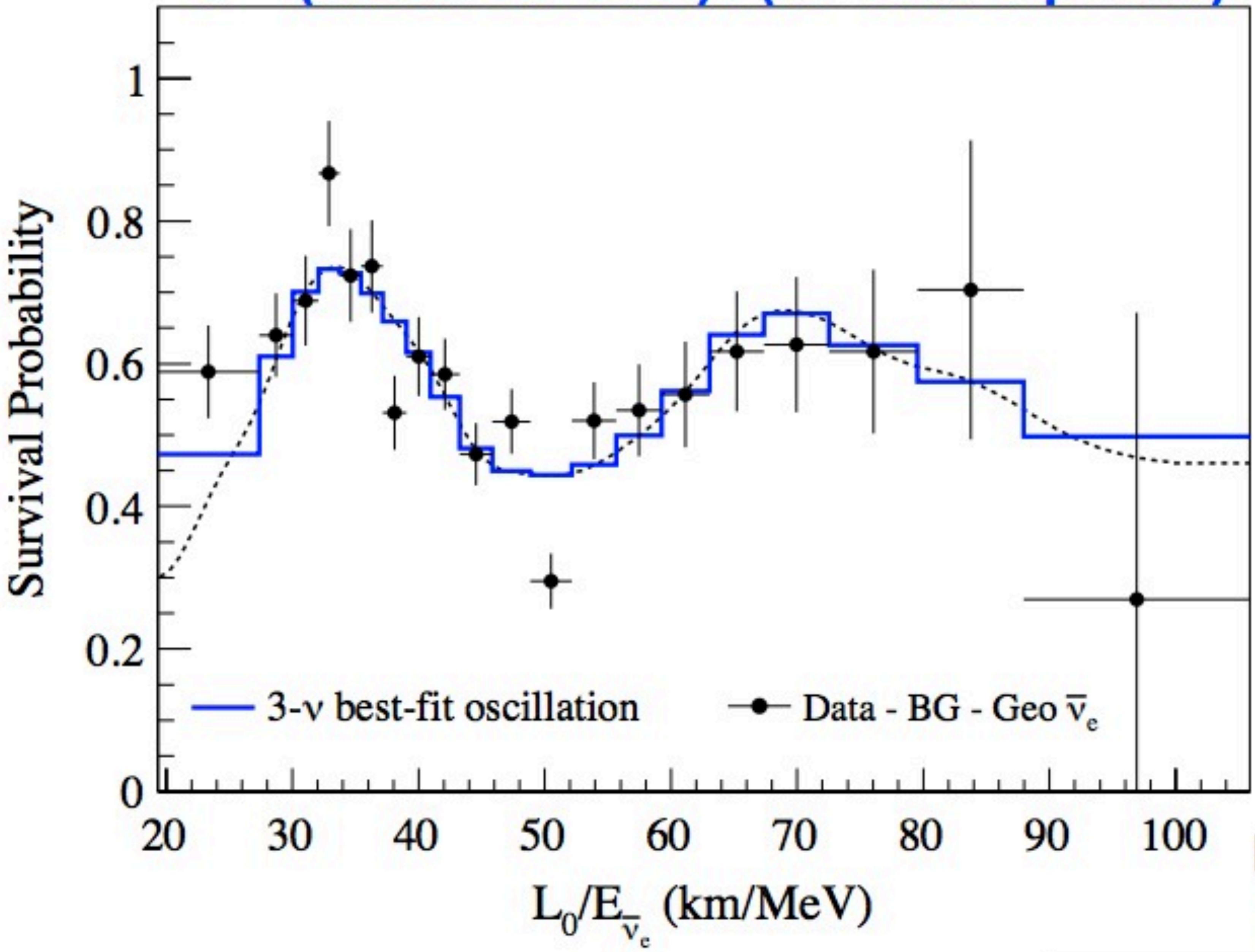
earthquake **reactor ↓**



significant reduction

L/E plot

P = (observed - B.G.) / (no osci. expected)



※L_0=180km fixed

best-fit parameters
(KamLAND only)

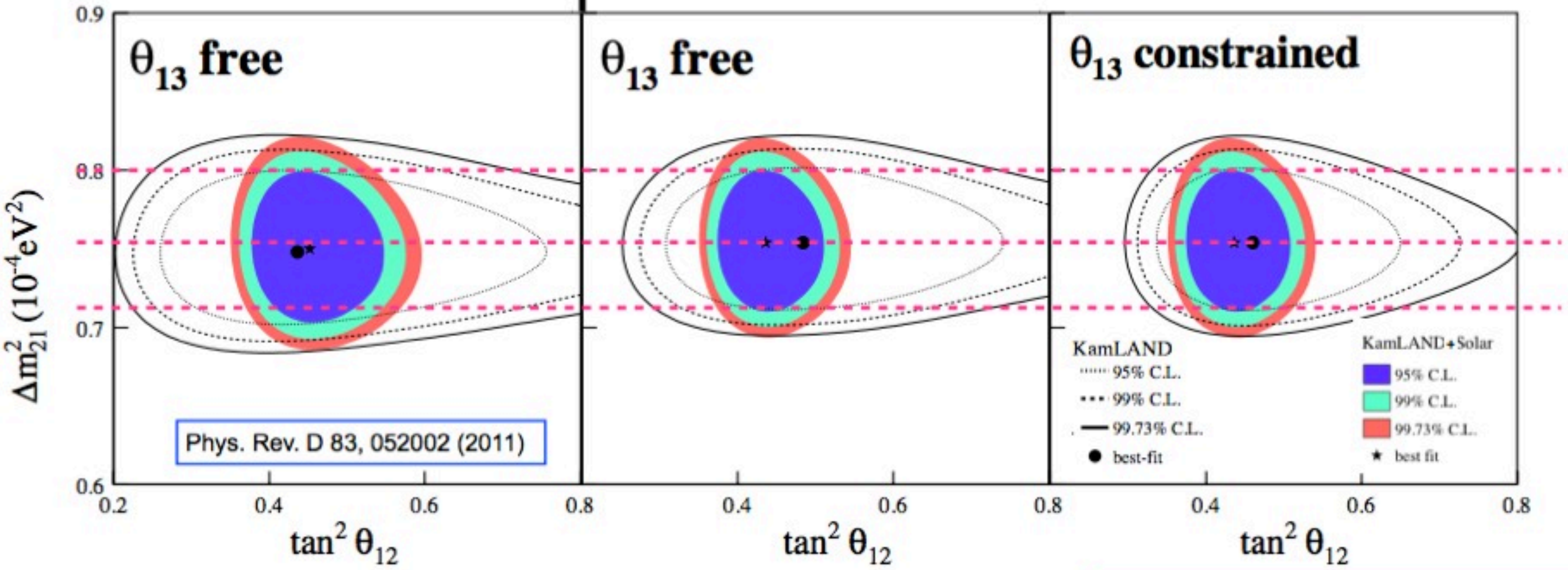
$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18} \times 10^{-5} \mathrm{eV}^2$$
$$\tan^2\theta_{12} = 0.481^{+0.092}_{-0.080}$$
$$\sin^2\theta_{13} = 0.010^{+0.033}_{-0.034}$$

~2 cycles of oscillation
measured precisely

Oscillation analysis

Δm^2: systematic uncertainty 1.9%
(dominated by linear energy scale uncertainty)

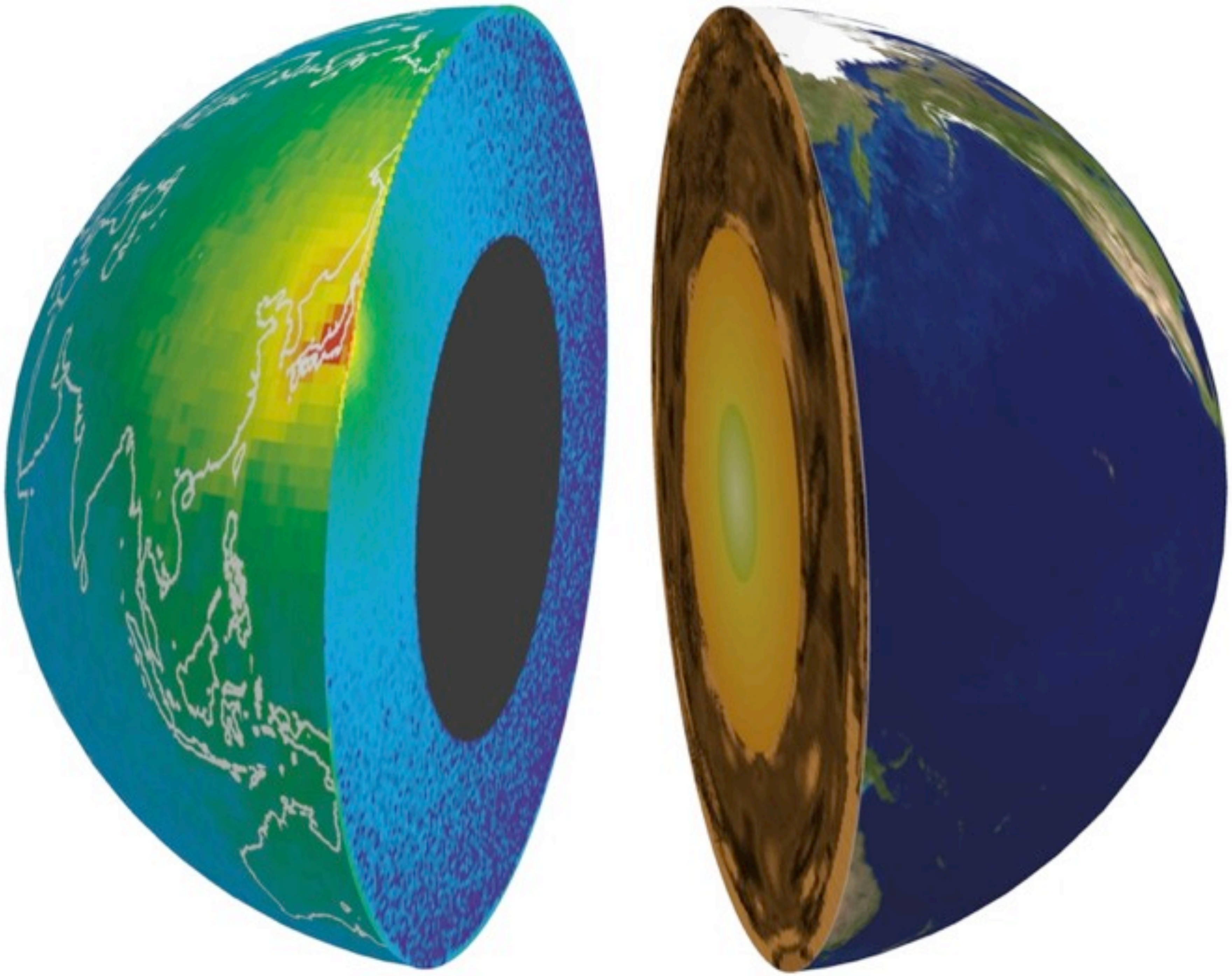
2011 result | This result



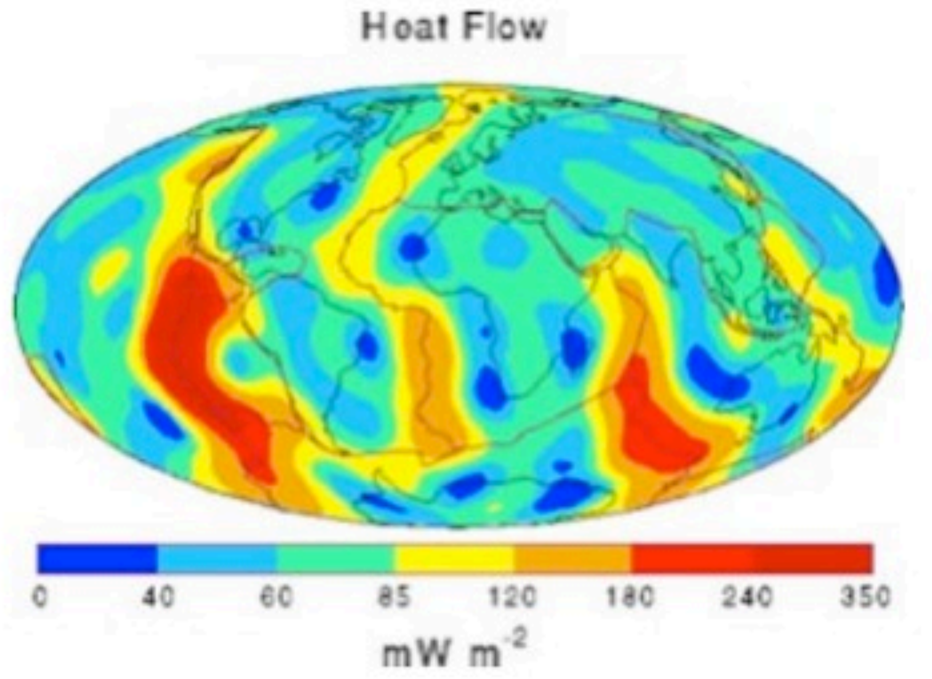
KamLAND+Solar	KamLAND+Solar	KamLAND+Solar+Theta13
$\Delta m^2_{21} = 7.50^{+0.19}_{-0.20} \times 10^{-5}\mathrm{eV}^2$	$\Delta m^2_{21} = 7.53^{+0.19}_{-0.18} \times 10^{-5}\mathrm{eV}^2$	$\Delta m^2_{21} = 7.53^{+0.18}_{-0.18} \times 10^{-5}\mathrm{eV}^2$
$\tan^2\theta_{12} = 0.450^{+0.037}_{-0.031}$	$\tan^2\theta_{12} = 0.437^{+0.029}_{-0.026}$	$\tan^2\theta_{12} = 0.436^{+0.029}_{-0.025}$
$\sin^2\theta_{13} = 0.020^{+0.016}_{-0.016}$	$\sin^2\theta_{13} = 0.023^{+0.015}_{-0.015}$	$\sin^2\theta_{13} = 0.023^{+0.002}_{-0.002}$

- Δm^2 is measured at 2.3% precision
- $\tan^2\theta_{12}$ uncertainty is improved by a factor 1.2

Geo-neutrino



Motivation of geo-neutrino



Bulk Silicate Earth (BSE) model

componential analysis of chondrite meteorite

U : 8 TW

Th : 8 TW

K : 4 TW

Surface heat flow
44 TW

\>

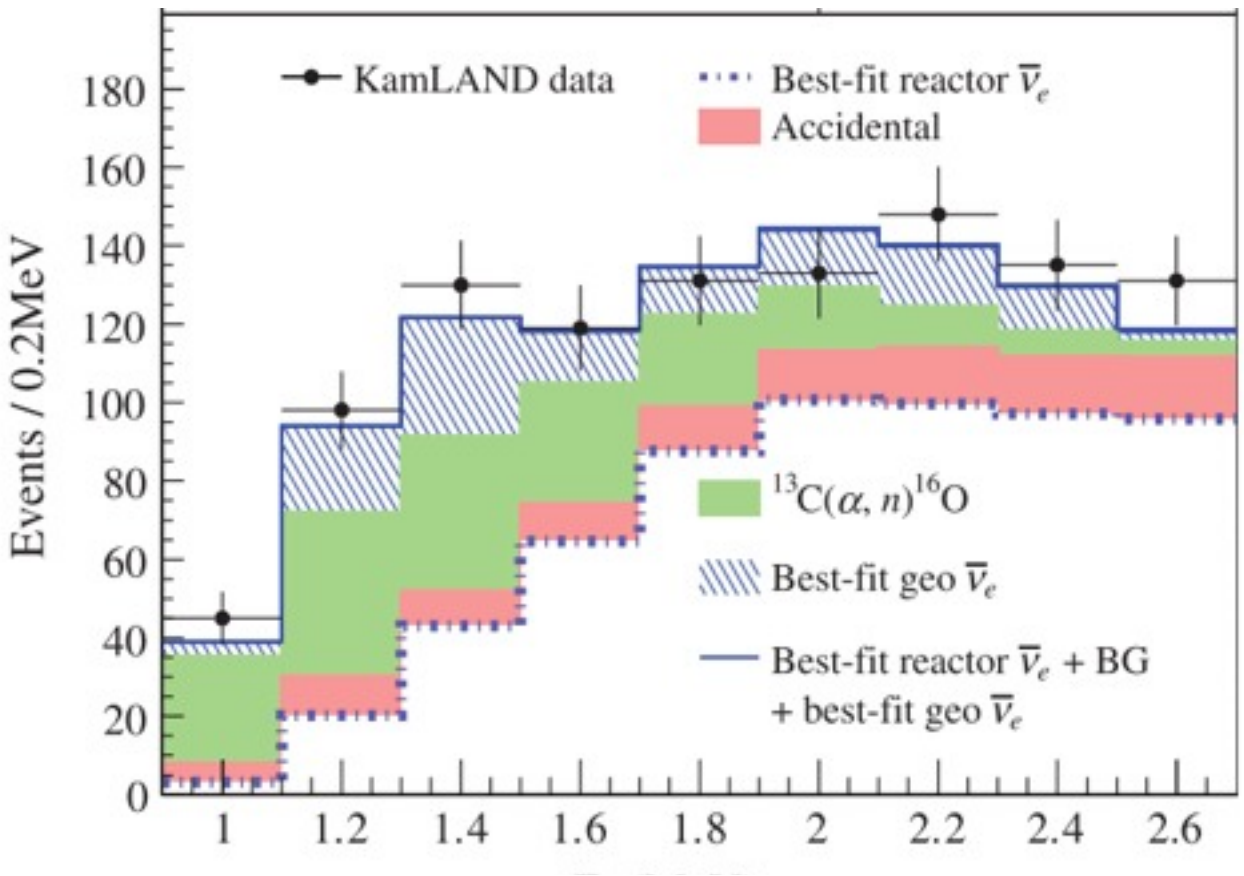
Radiogenic heat
19 TW

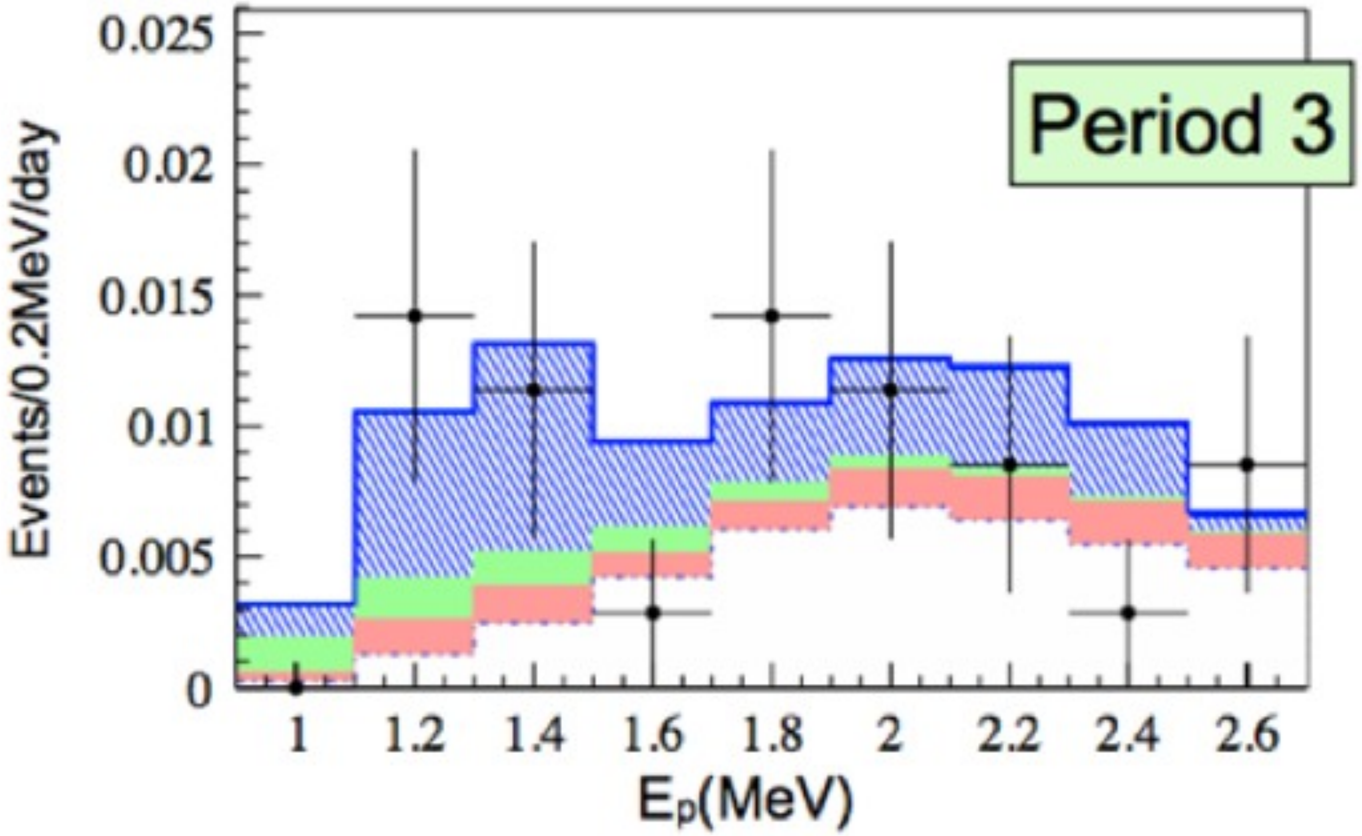
(Indirect measurement)

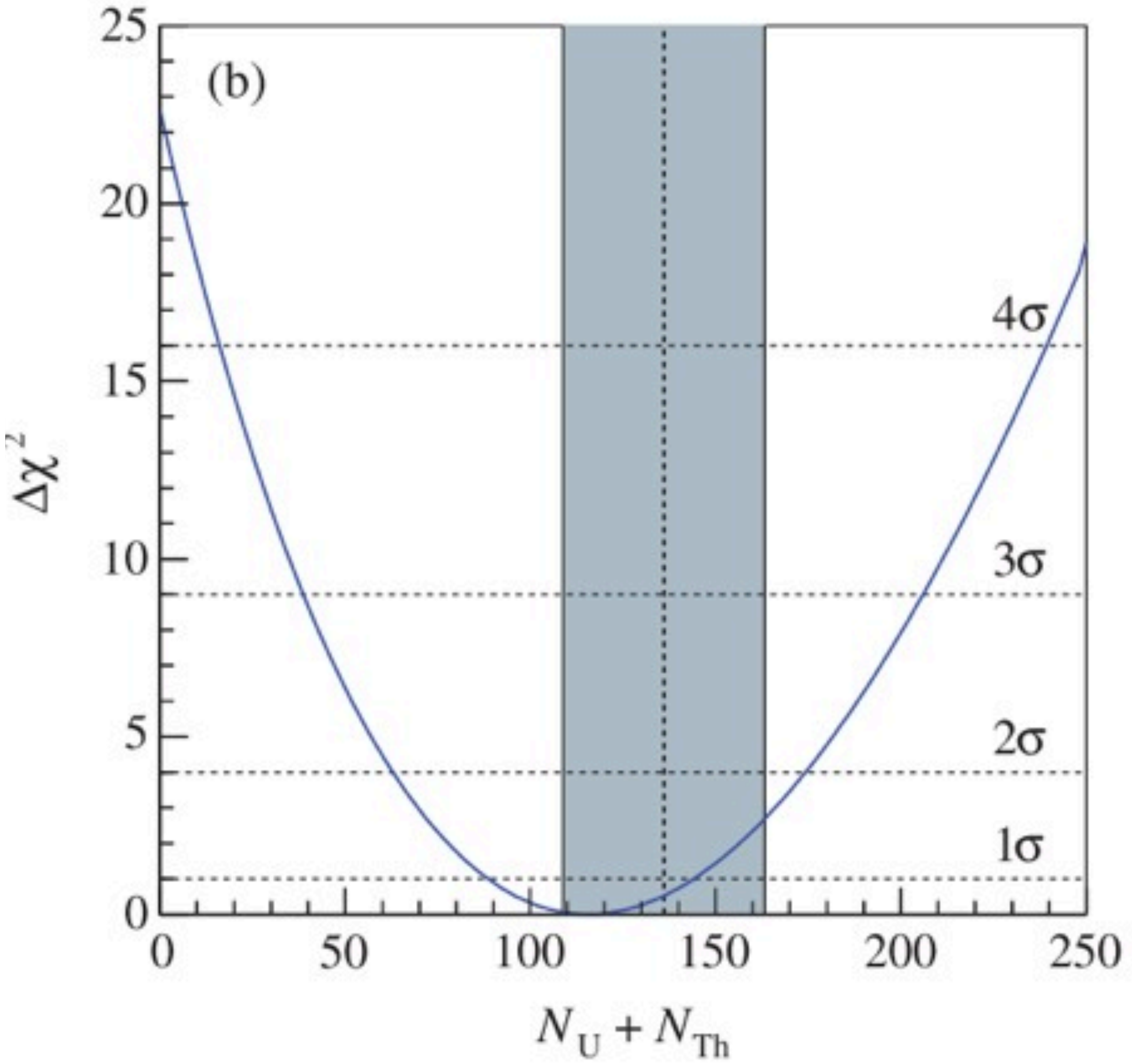
Why ?

Geo-neutrino can directly test radiogenic heat production and the BSE model(s).

Results of geo-neutrino



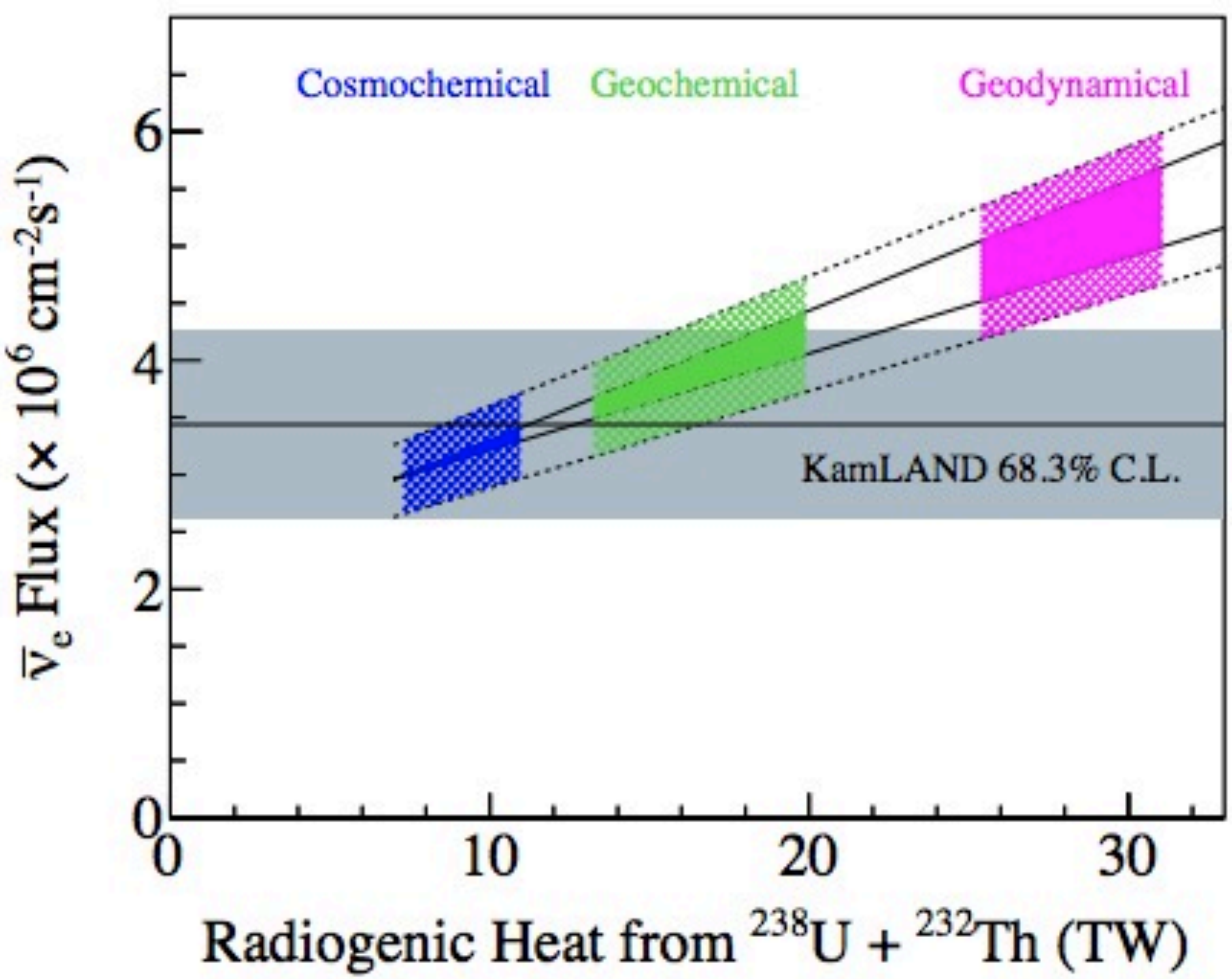




$N_{geo} = 116^{+28}_{-27}$ events

$F_{geo} = 3.4^{+0.8}_{-0.8} \times 10^6$ /cm²/sec

Comparison with Models



- The measured KamLAND geo-neutrino flux translates to a total radiogenic heat production : $11.2^{+7.9}_{-5.1}$ TW
- The geodynamical prediction with the homogeneous hypothesis is disfavored at 89% C.L.
- The BSE composition models are still consistent within ~2 σ.

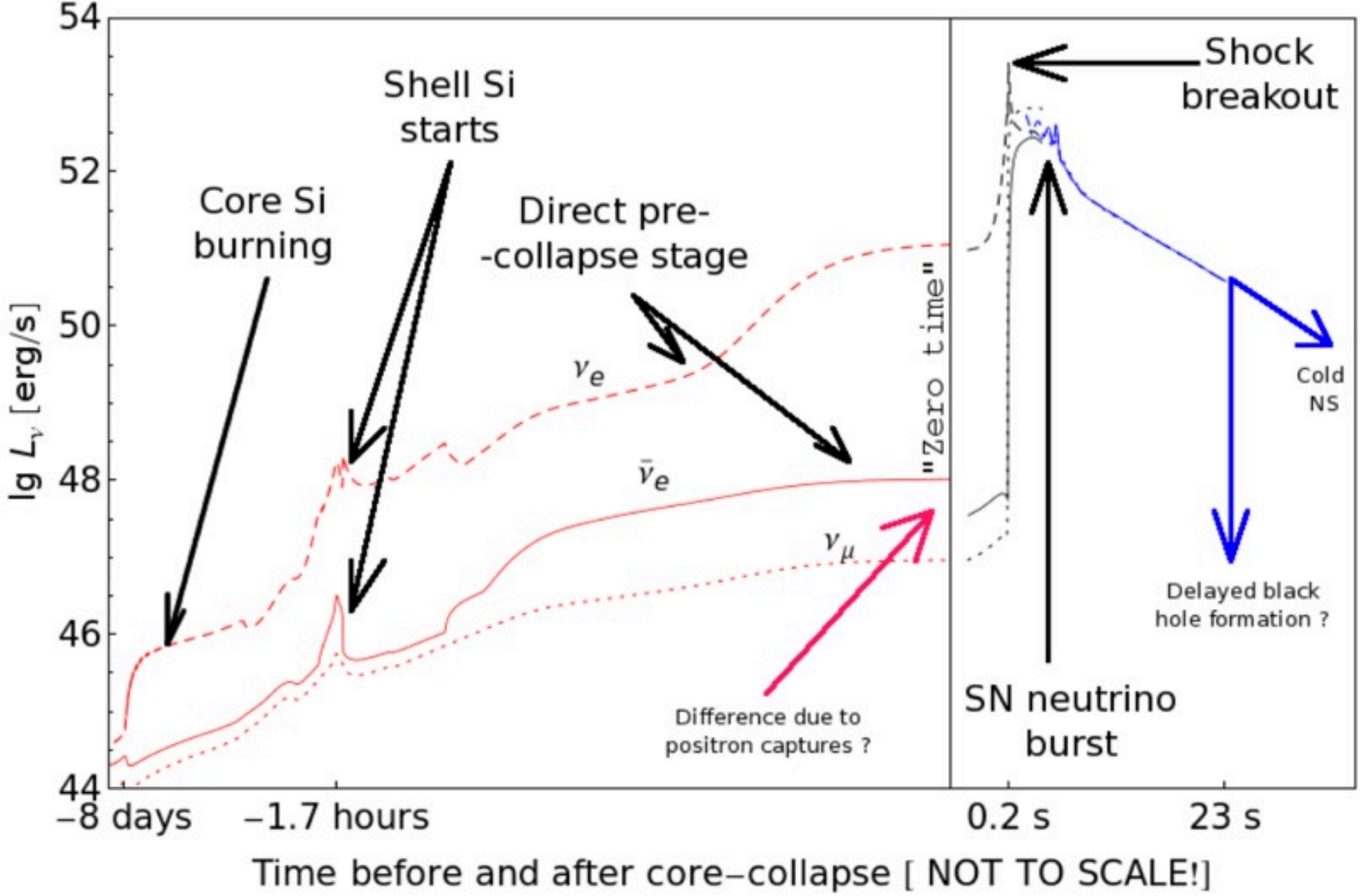
Next challenges

- PreSN neutrino
- Proton decay
- Future projects

PreSN neutrino

PreSN neutrino

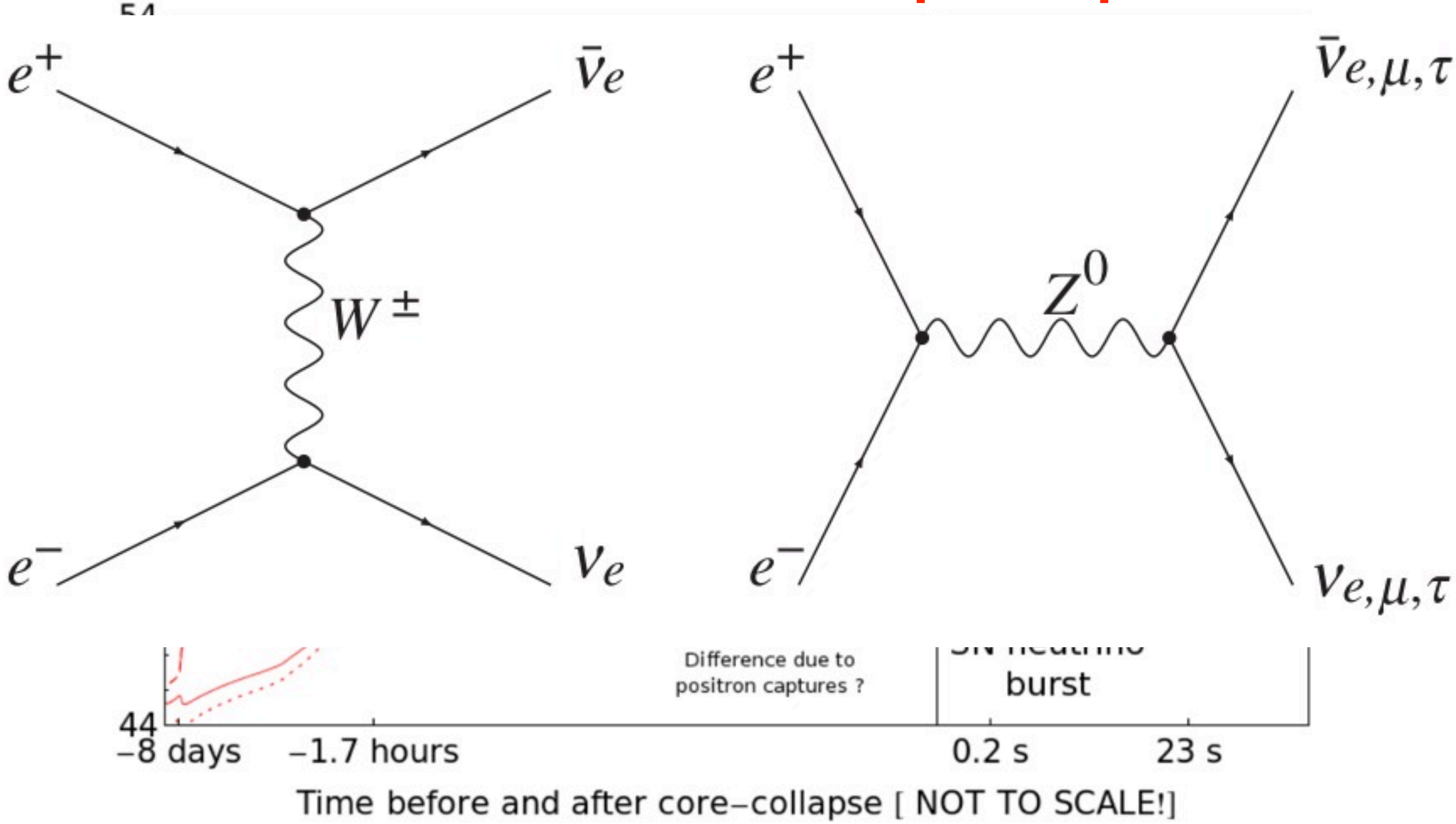
Emitted neutrinos in Si burning phase before core-collapse supernova



ACTA PHYSICA POLONOCA B 40, 3063 (2009)

PreSN neutrino

Emitted neutrinos in Si burning phase before core-collapse supernova



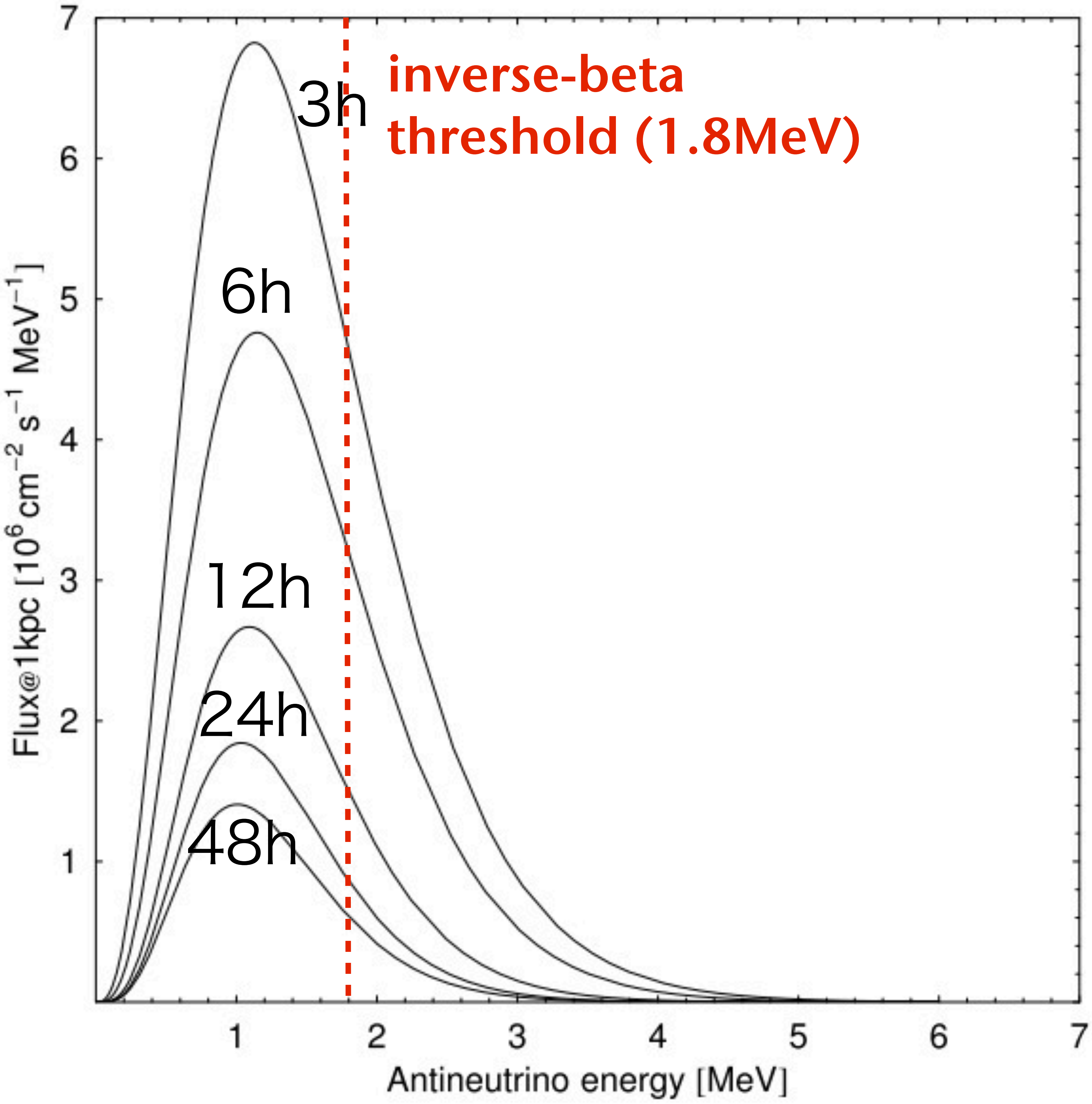
ACTA PHYSICA POLONOCA B 40, 3063 (2009)

Flux of PreSN neutrino

Energy is low !!

Only high energy tail (>1.8MeV) is detectable

Nearby events

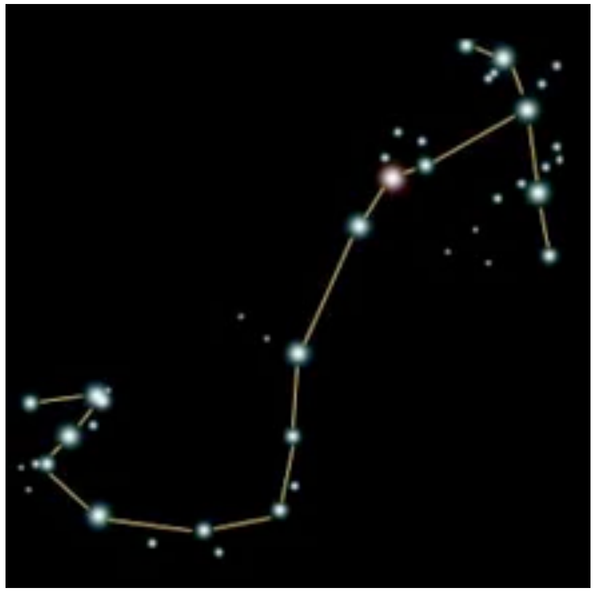


AIP Conference Proceedings 944, 109 (2007

Candidates

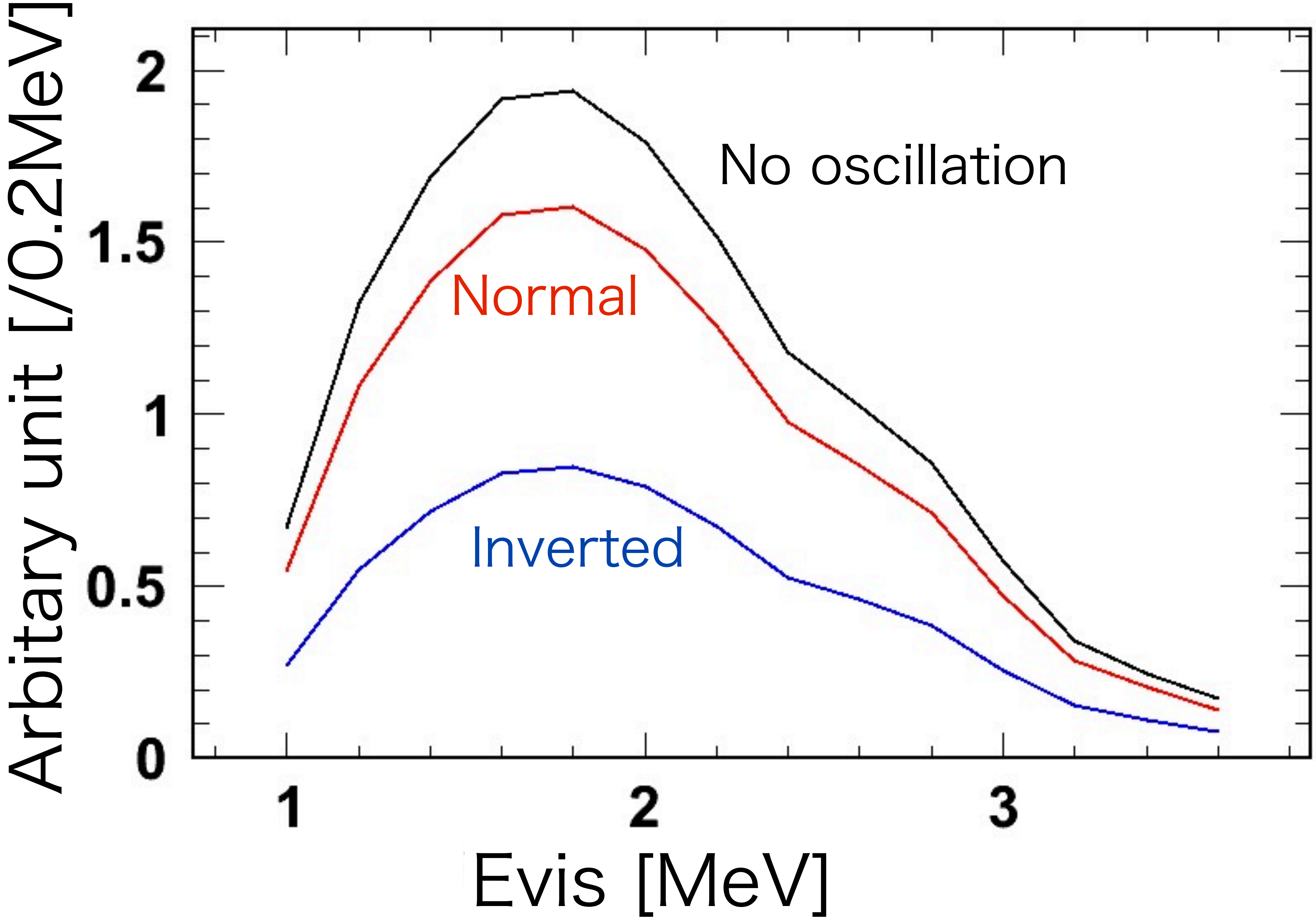
Nearby supergiants

Red supergiants
- Antares (170pc)
- Betelgeuse (200pc)



Wolf-Rayer star
- Gamma Velorum (340pc)

Expected spectrum



Expected values

Model: Betelgeuse like star with d=200pc

Number of events

48-24h	24-3h	3-0h	Time
1.6	6.1	9.2	Normal
0.7	2.9	4.4	Inverted

Expected values

Model: Betelgeuse like star with d=200pc

Number of events

48-24h	24-3h	3-0h	Time
1.6	6.1	9.2	Normal
0.7	2.9	4.4	Inverted

Detection efficiency (with present background level)

	48-24h	24-3h	3-0h	
Efficiency	50%	**98%**	**99.6%**	Normal
Efficiency	19%	**80%**	**93%**	Inverted
False rate/yr	1.7	1.3	0.032	

Expected values

Model: Betelgeuse like star with d=200pc

Number of events

48-24h	24-3h	3-0h	Time
1.6	6.1	9.2	Normal
0.7	2.9	4.4	Inverted

Detection efficiency (reactor on)

	48-24h	24-3h	3-0h	
Efficiency	31%	**95%**	**99.9%**	Normal
Efficiency	9.4%	**62%**	**94%**	Inverted
False rate/yr	2.4	1.6	0.38	

Very early alarm

KamLAND will detect PreSN neutrinos.

Large uncertainty of detection efficiency:

- reactor status
- neutrino mass hierarchy
- uncertainty of distance
- models of the stellar evolution

Betelgeuse: 200±50pc

Targets: Antares, Betelgeuse, and Gamma Velorum

Very early alarm (before SN neutrino)

Useful for astro committee and neutrino/GW detectors

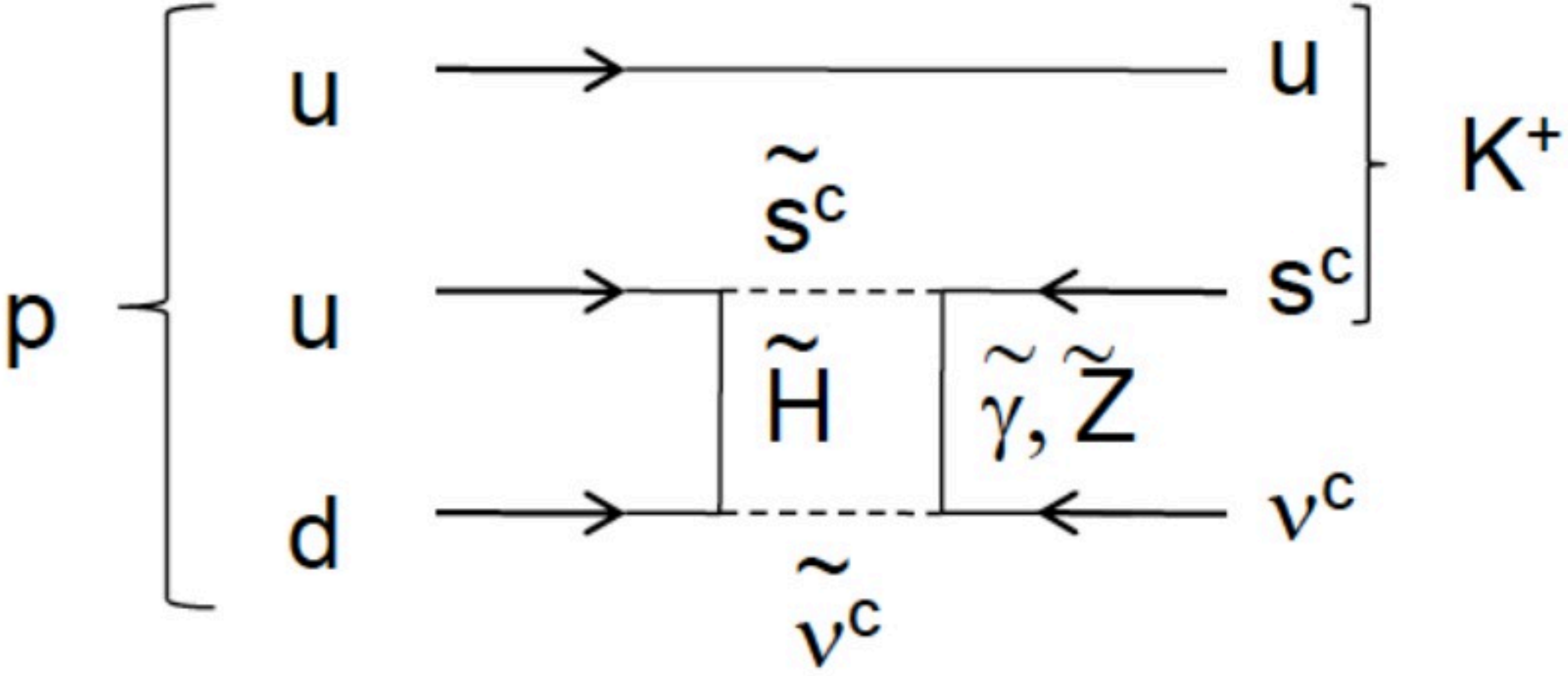
Not miss neutrino/GW from SN

Excellent chance:

- Measurement of optical shock wave
- Study on the final stage of the stellar evolution

We are developing the alarm system.

Proton decay



Proton decay

KamLAND (and scintillator experiment): sensitive to K^+

SUSY SO(10): $p \to K^+ \bar{\nu}$ **with** $\tau \sim 10^{32} - 10^{34}$ **yr**

- Water Cherenkov detector

  K^+ : below the Cherenkov threshold (253MeV)

  Indirect measurement (efficiency ~5%): 5.9×10^{33}yr

- KamLAND is searching for $p \to K^+ \bar{\nu}$ with higher efficiency.

K^+ decay channel

$$K^+ \to \mu^+ \nu_\mu \quad (63.54\%)$$

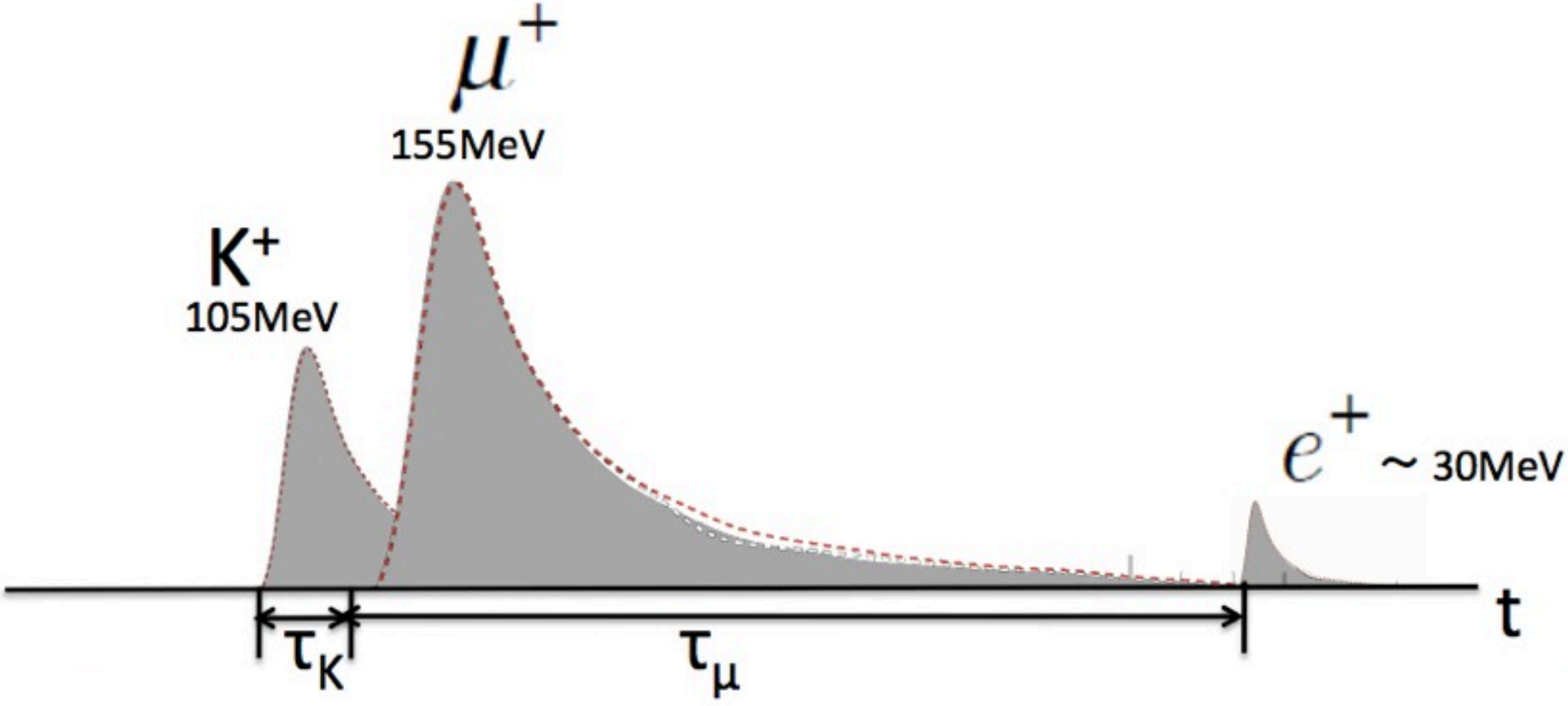
$$K^+ \to \pi^0 \pi^+ \quad (20.68\%)$$

Features of signal

$P \rightarrow K^+ \nu$

$K^+ \rightarrow \mu^+ \nu$ $\tau_K = 12.3\text{ns}$

$\mu^+ \rightarrow e^+ \nu \nu$ $\tau_\mu = 2200\text{ns}$



Features of signal

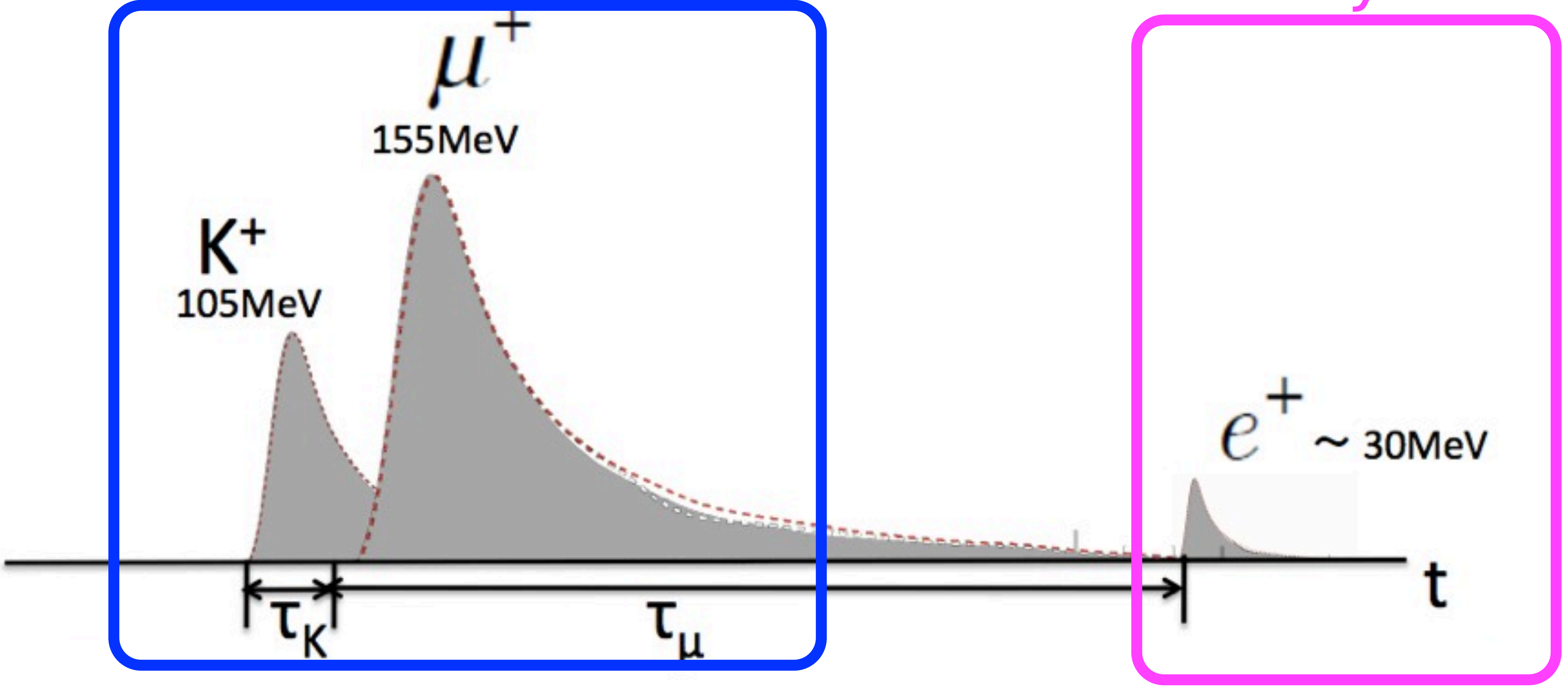
$P \rightarrow K^+ \nu$

$K^+ \rightarrow \mu^+ \nu$ $\tau_K = 12.3\text{ns}$

$\mu^+ \rightarrow e^+ \nu\ \nu$ $\tau_\mu = 2200\text{ns}$

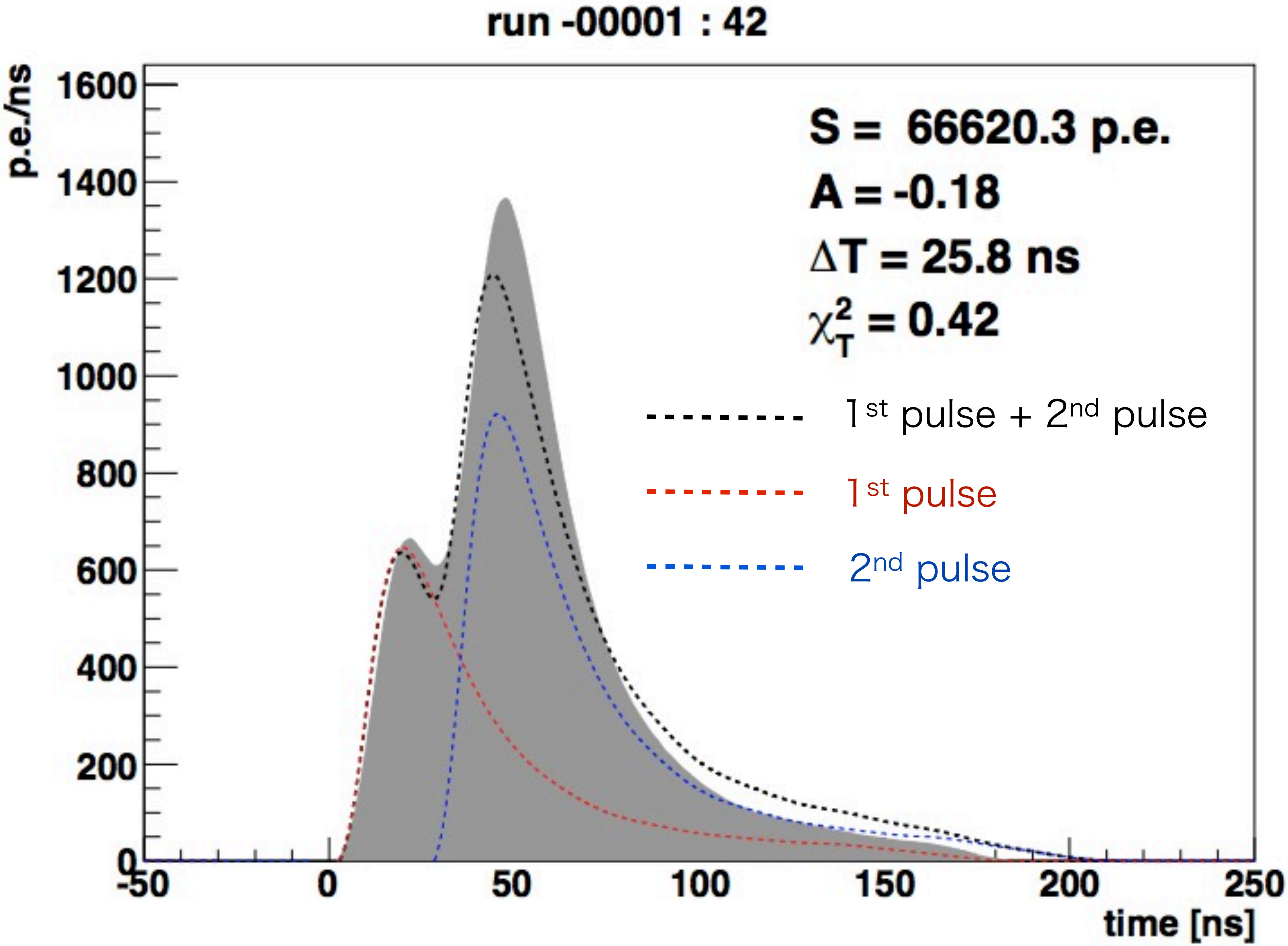
Prompt (double pulse) event

Delayed event

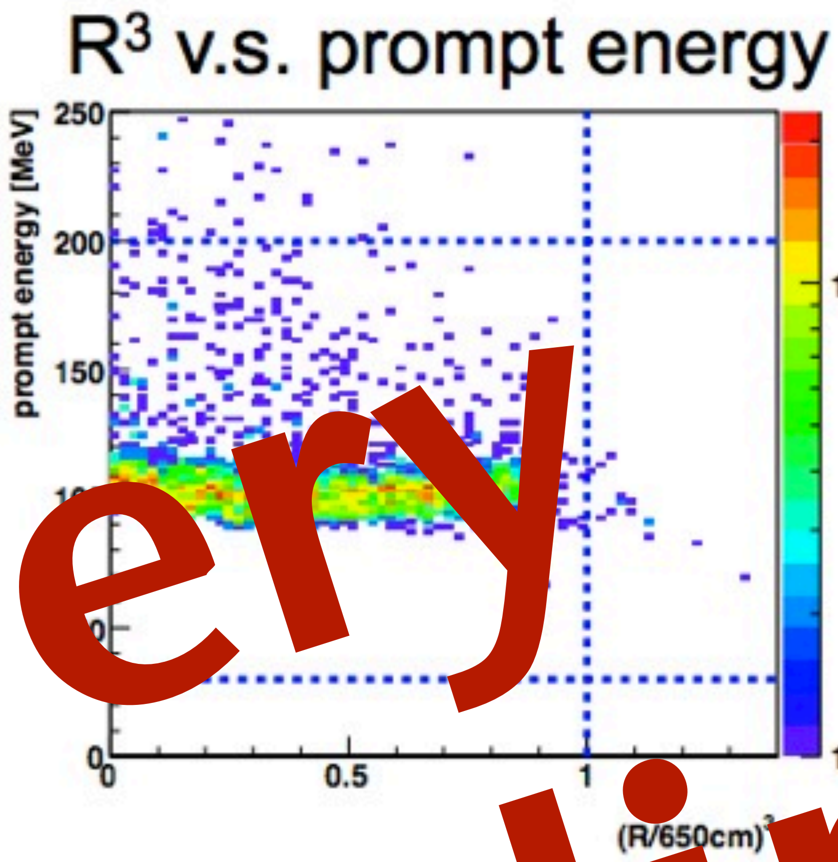


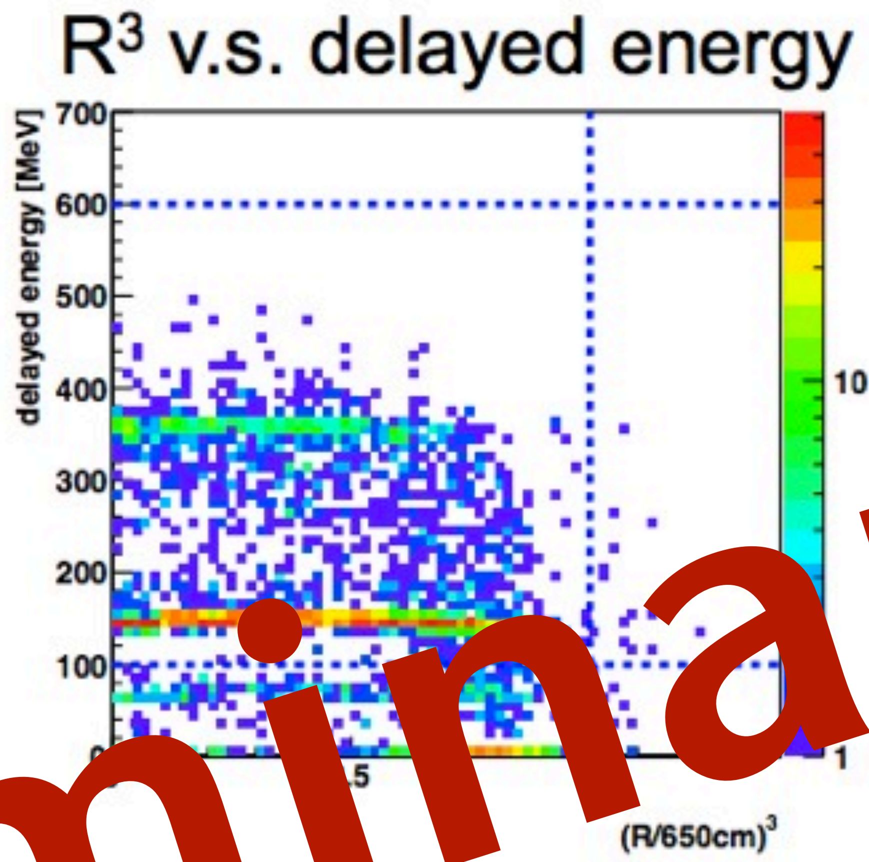
Asymmetry of 1st and 2nd peak

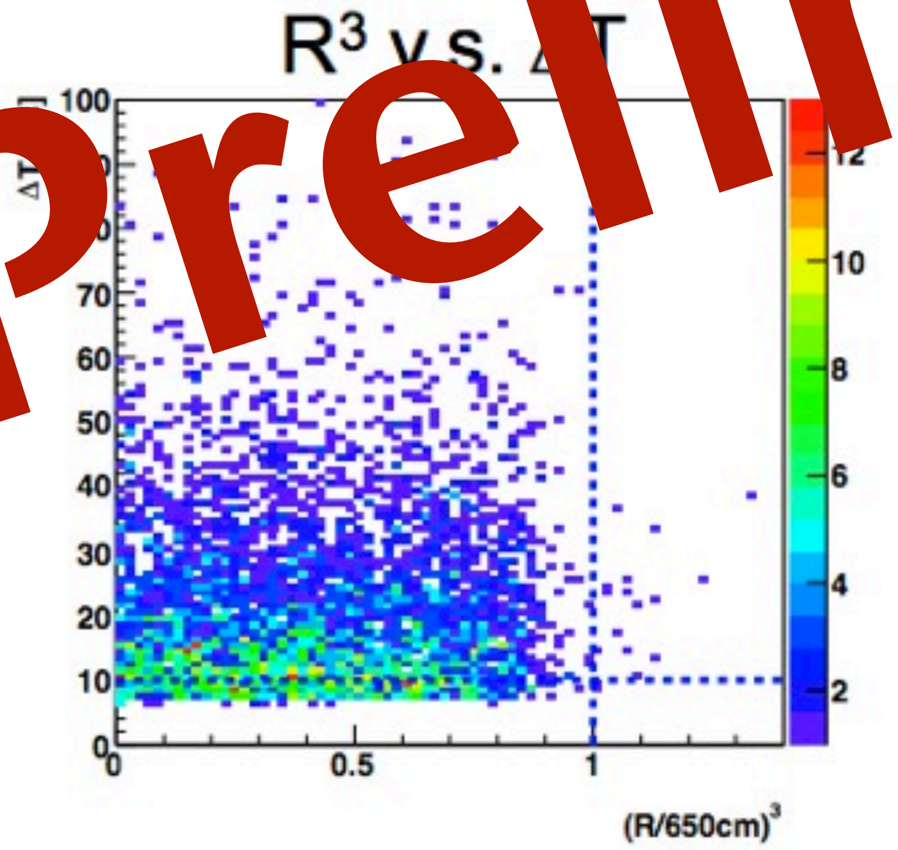
Simulation of double pulse fitting

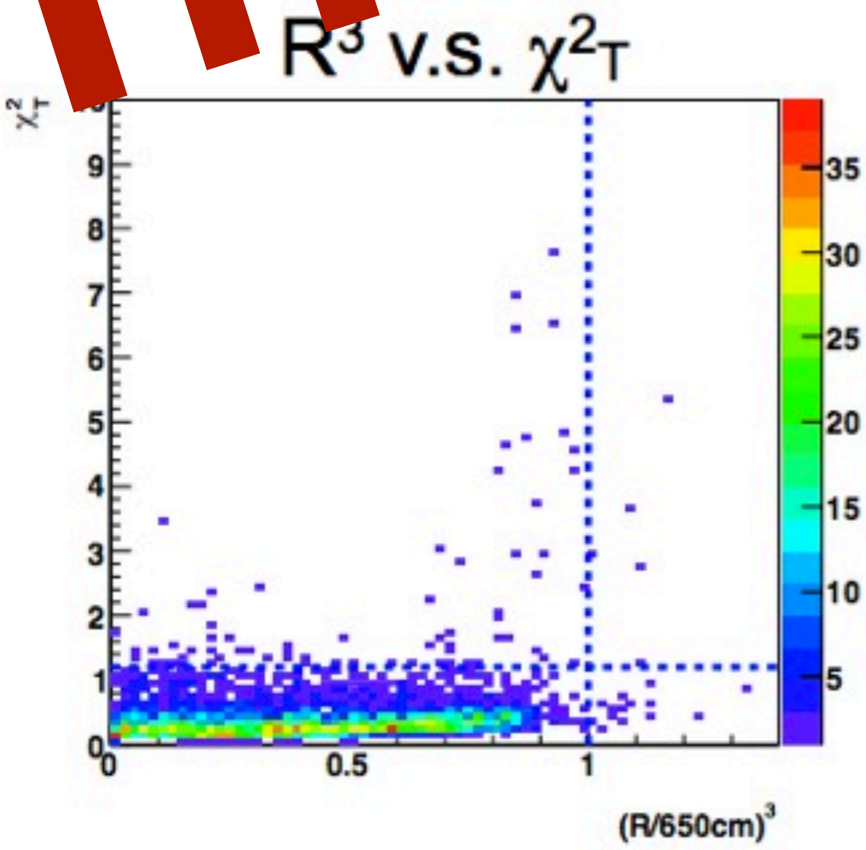


MC simulation (efficiency)





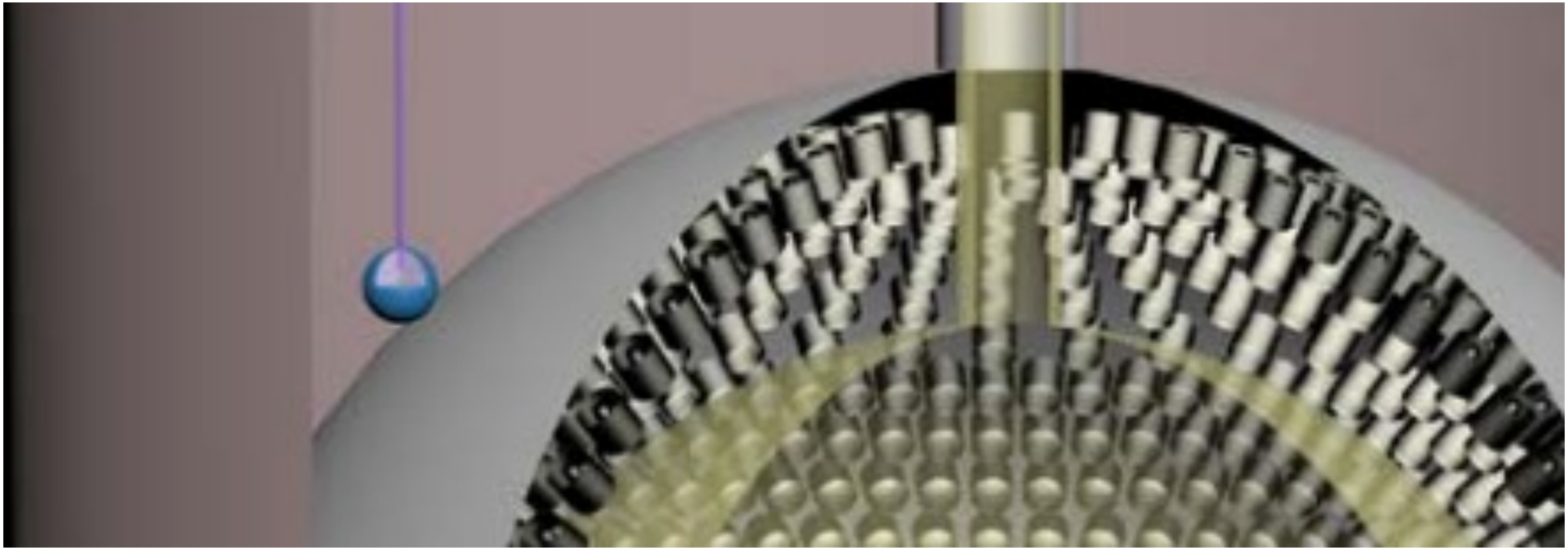




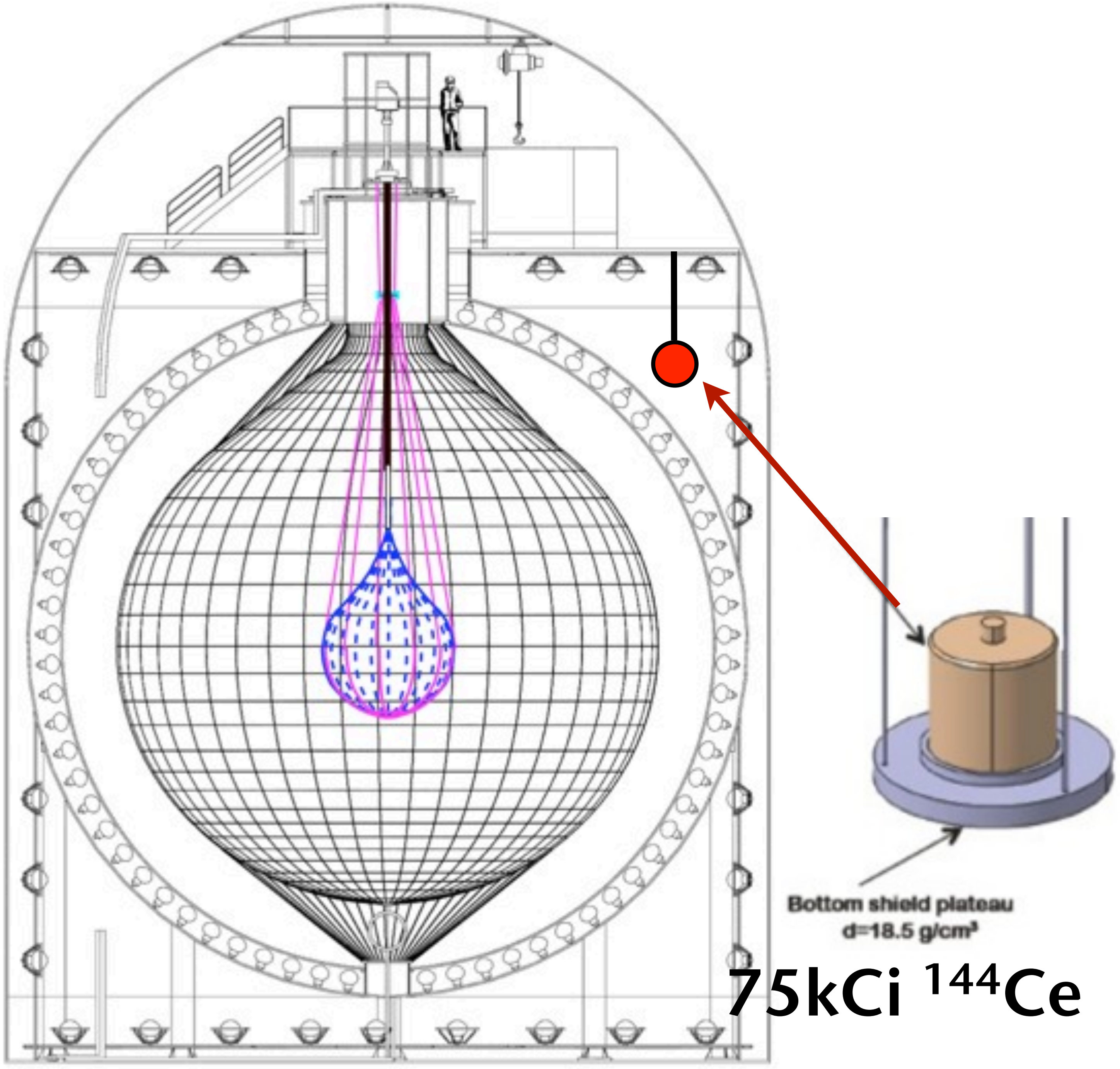
Life time

Coming soon !!

Future projects



Future projects



75kCi ^{144}Ce

CeLAND

4th neutrino search

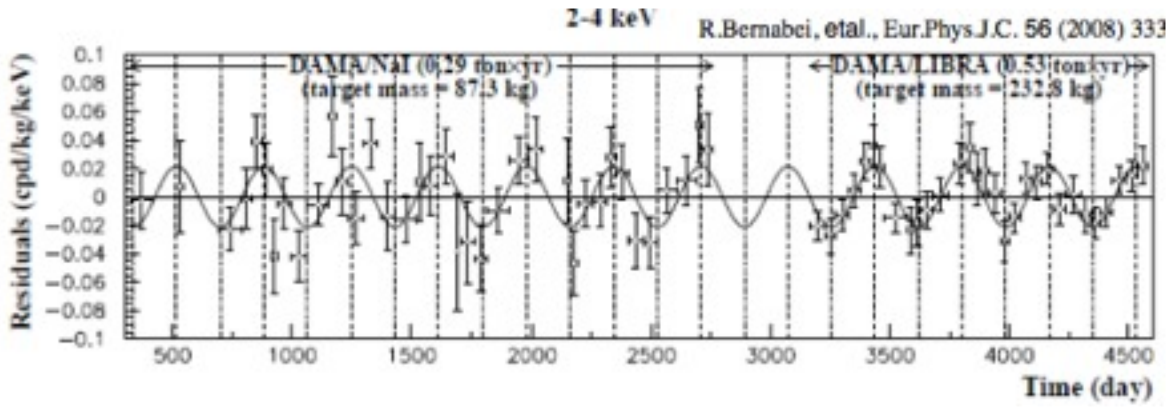
Ce source in KamLAND

KamLAND-Pico

Dark matter search

NaI in KamLAND

Check DAMA result



R.Bernabei, etal., Eur.Phys.J.C. 56 (2008) 333

Summary

KamLAND: the largest anti-neutrino detector

Latest results

Including reactor-off period

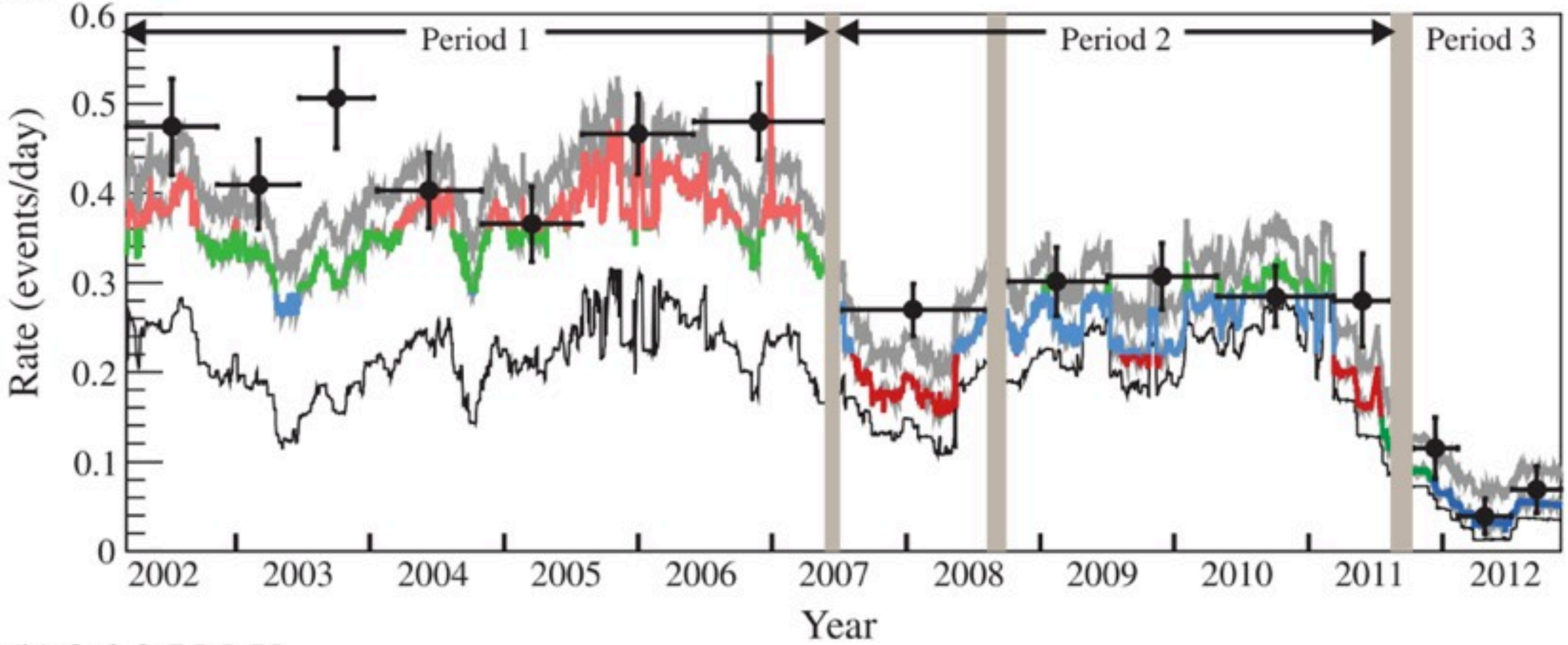
- Improvements of oscillation parameter
- Geo-neutrino measurement with low background

Next challenges

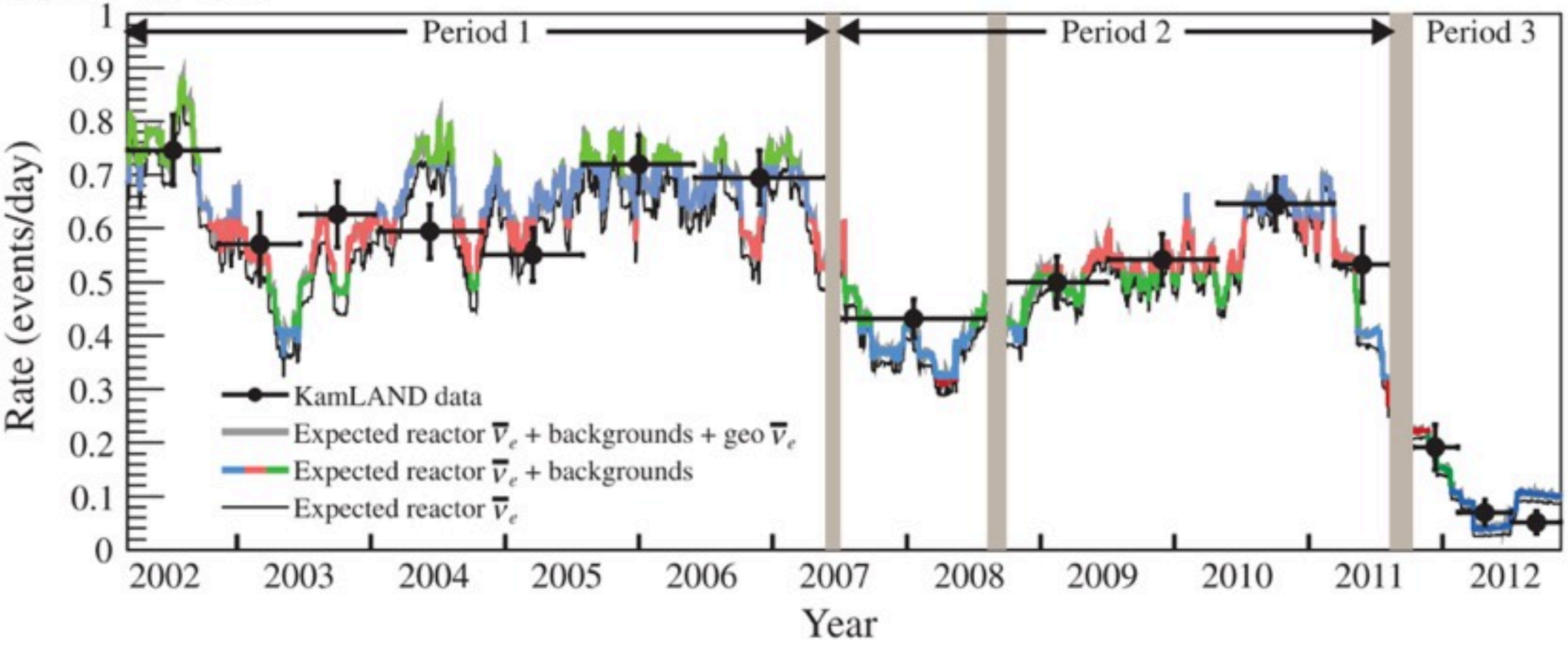
- PreSN monitor system
- Proton decay ($K^+\nu$)
- CeLAND (4th neutrino)
- KamLAND-Pico (dark matter)

categorizes the models into three groups: geochemical, cosmochemical, and geodynamical. Geochemical models [11], such as the reference Earth model of Ref. [18], use primordial compositions equal to those found in CI carbonaceous chondrites, but allow for elemental enrichment by differentiation, as deduced from terrestrial samples. Cosmochemical models [37] assume a mantle composition similar to that of enstatite chondrites, and yield a lower radiogenic abundance. Geodynamical models [38], on the other hand, require higher radiogenic abundances in order to drive realistic mantle convection.

(a) 0.9-2.6 MeV



(b) 2.6-8.5 MeV



Geo-neutrino detection

Beta-decay of radioactivities (U, Th, K) in the Earth

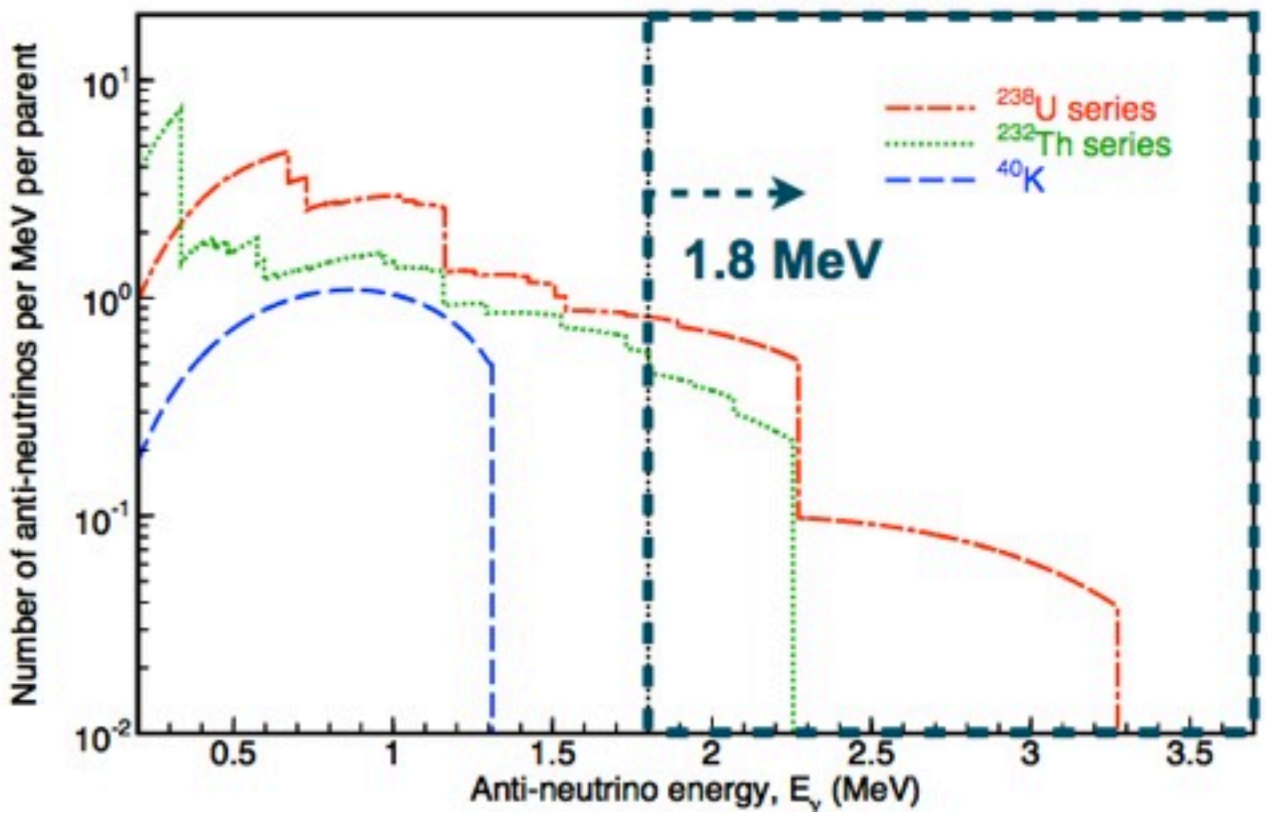
$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\,^{4}\mathrm{He} + 6e^{-} + 6\bar{\nu}_e + 51.7\ \mathrm{MeV}\ \ (100\%)$$

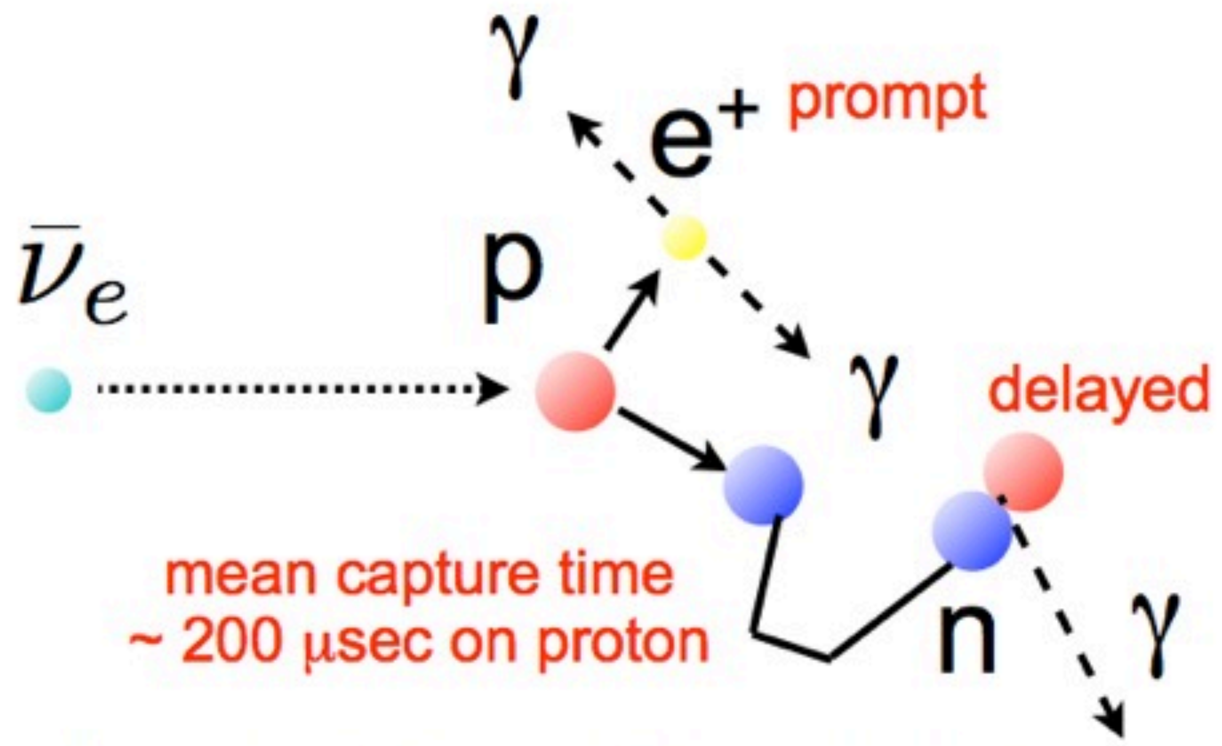
$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\,^{4}\mathrm{He} + 4e^{-} + 4\bar{\nu}_e + 42.7\ \mathrm{MeV}\ \ (100\%)$$

$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e^{-} + \bar{\nu}_e + 1.31\ \mathrm{MeV}\ \ (89.28\%)$$

$$^{40}\mathrm{K} + e^{-} \rightarrow {}^{40}\mathrm{Ar} + \nu_e + 1.51\mathrm{MeV}(10.72\%)$$

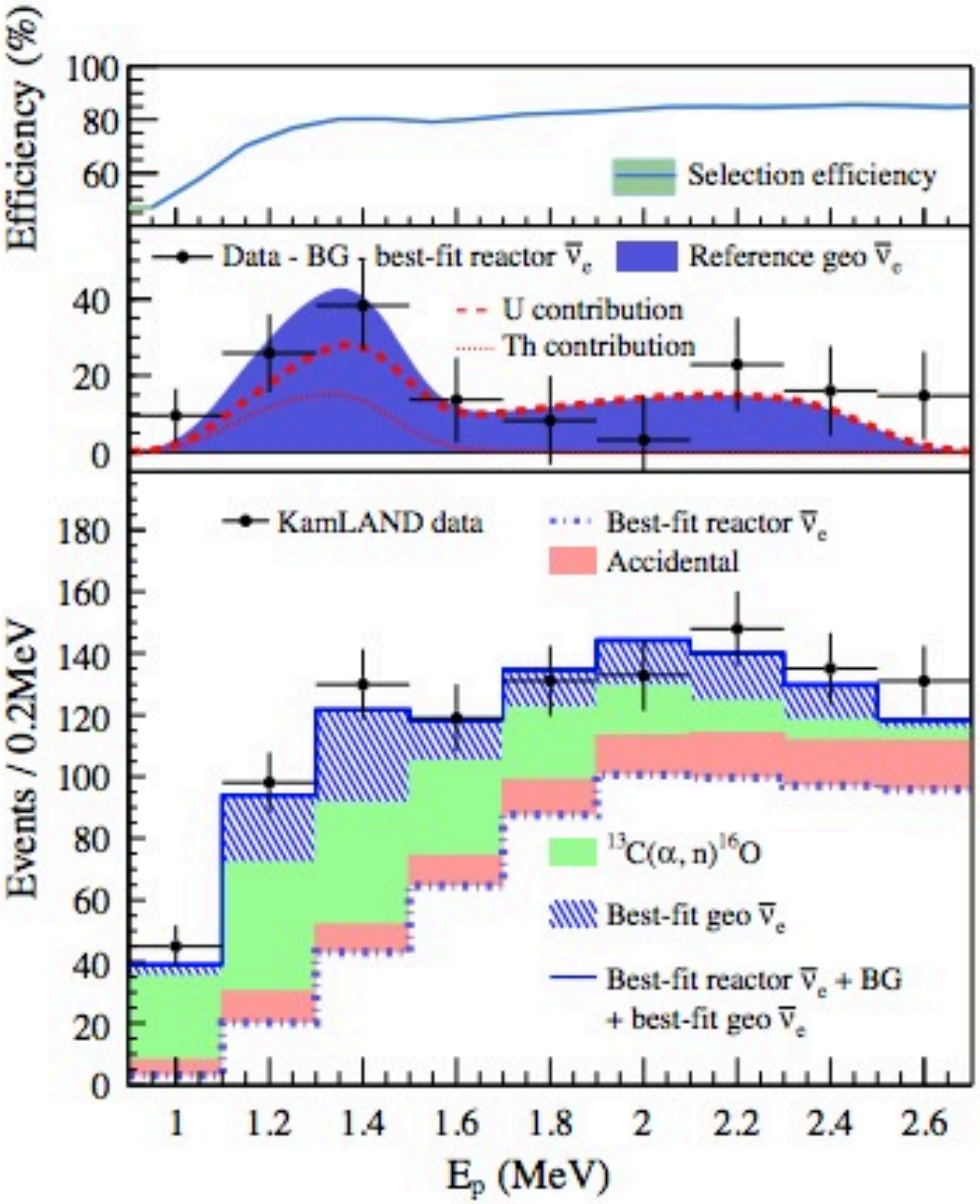
anti-neutrino energy spectrum

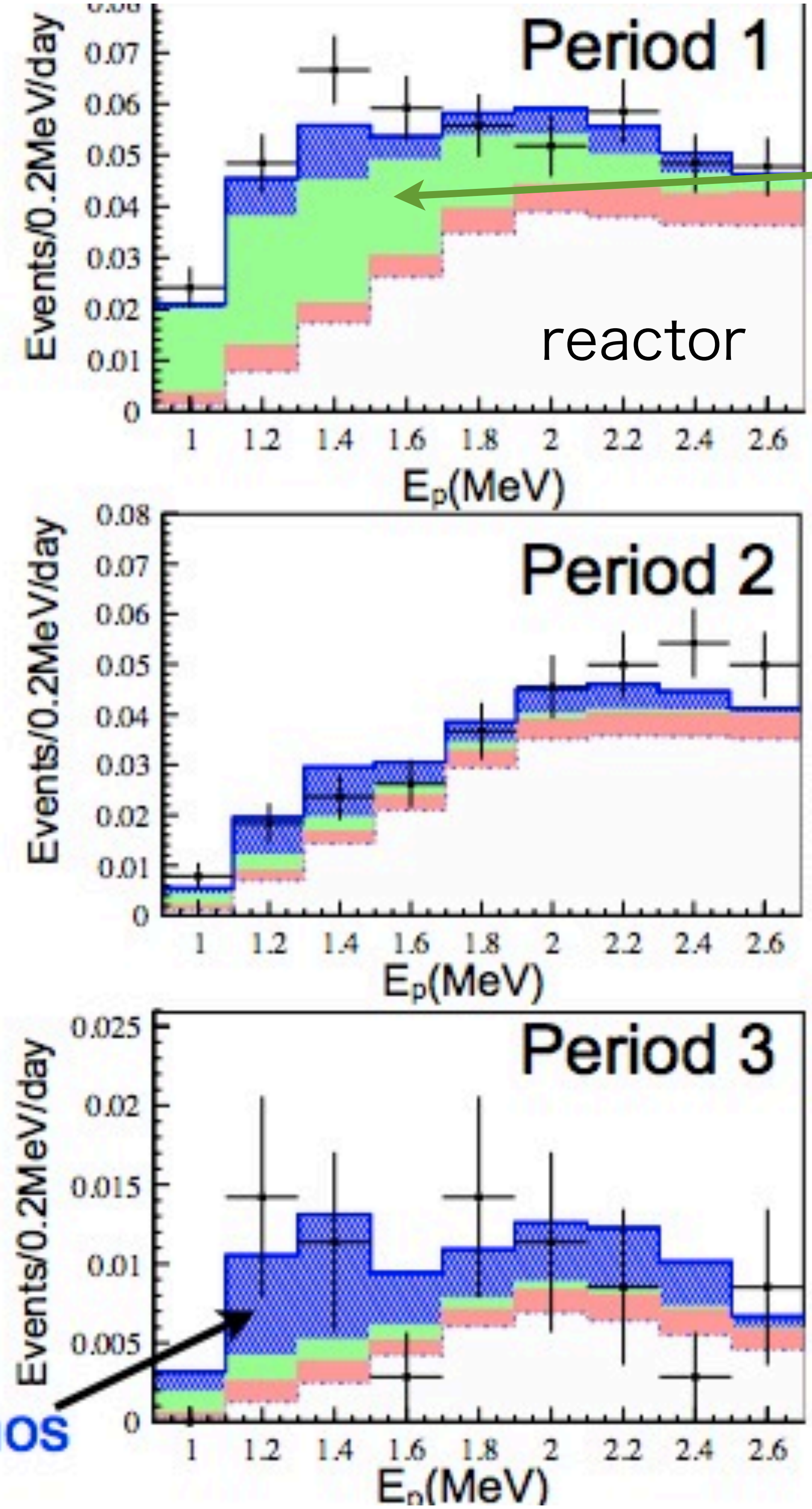




anti-neutrino detection by inverse beta-decay

Energy spectrum





(α, n)

reactor

$^{13}C\ (\alpha, n)^{16}O$

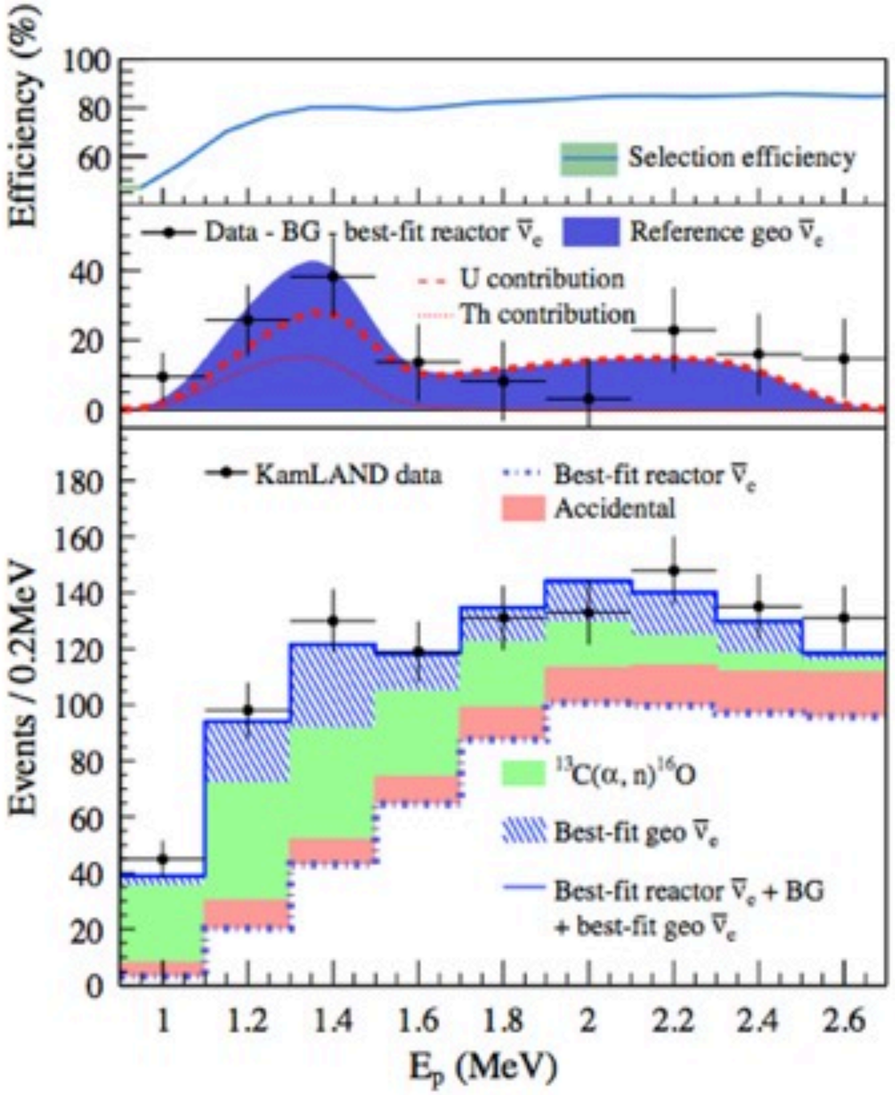
decreased

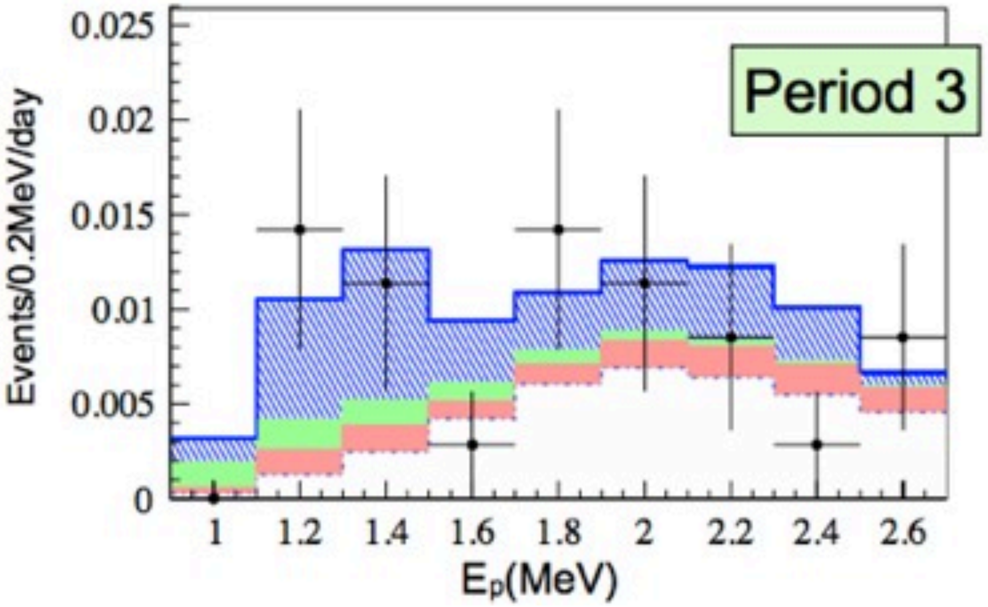
Reactor-ν

decreased

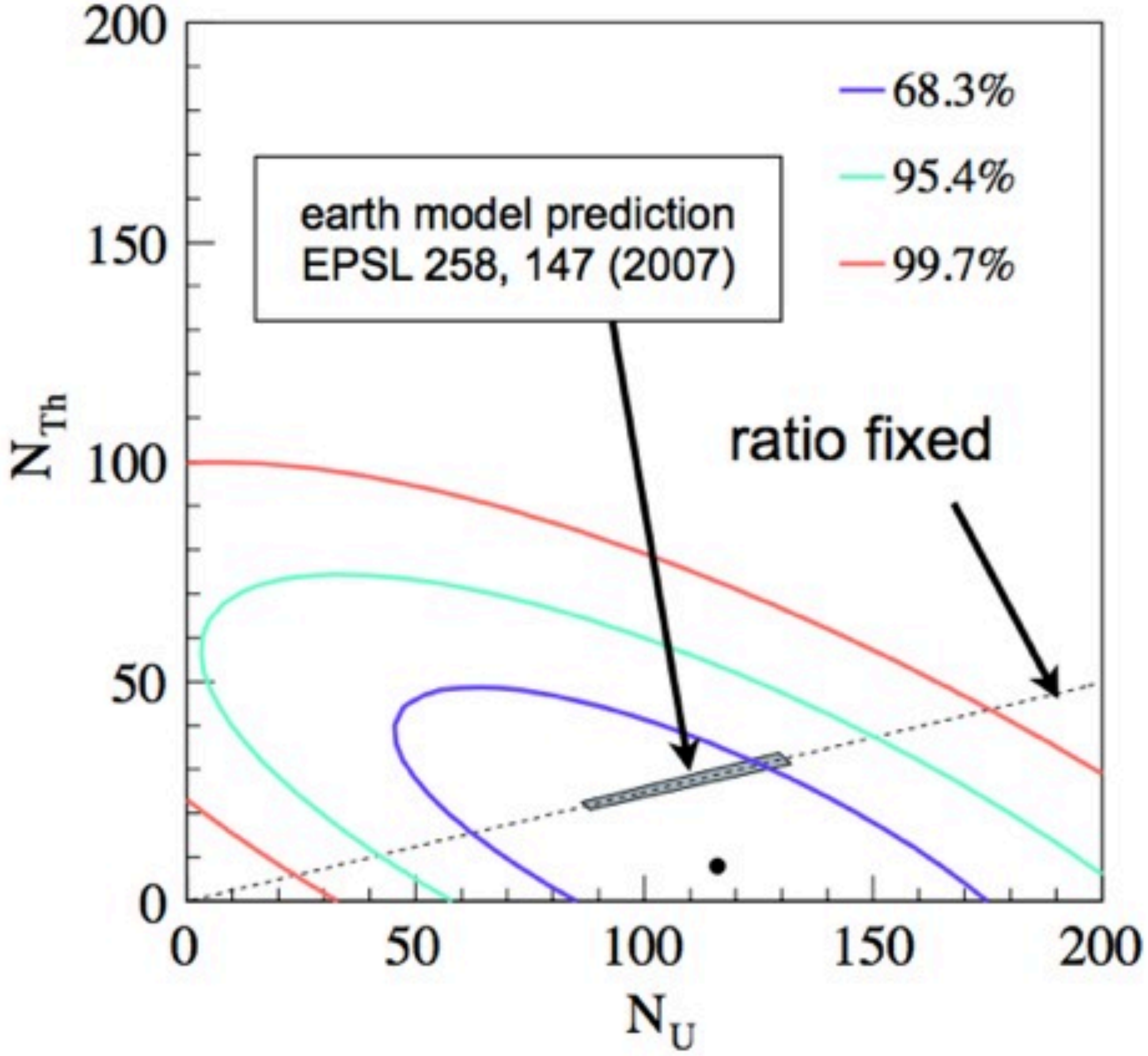
geo-neutrinos

Results of geo-neutrino





best-fit $(N_U, N_{Th}) = (116,8)$



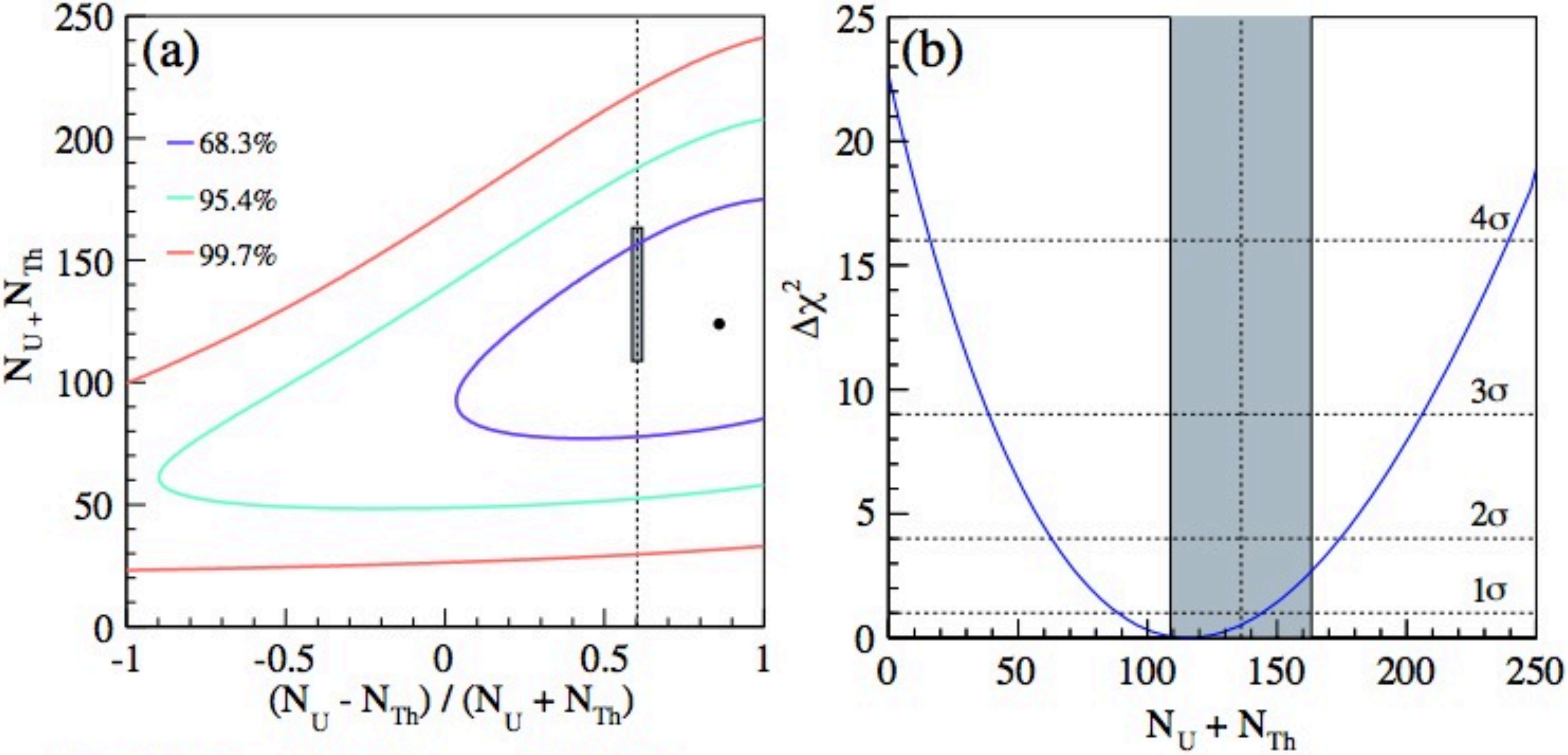
$$N_{geo} = 116^{+28}_{-27} \text{ events}$$

$$F_{geo} = 3.4^{+0.8}_{-0.8} \times 10^6 \text{ /cm}^2\text{/sec}$$

$$(30.7^{+7.5}_{-7.3} \text{ TNU})$$

Rate + shape + time analysis

$N_U + N_{Th}$

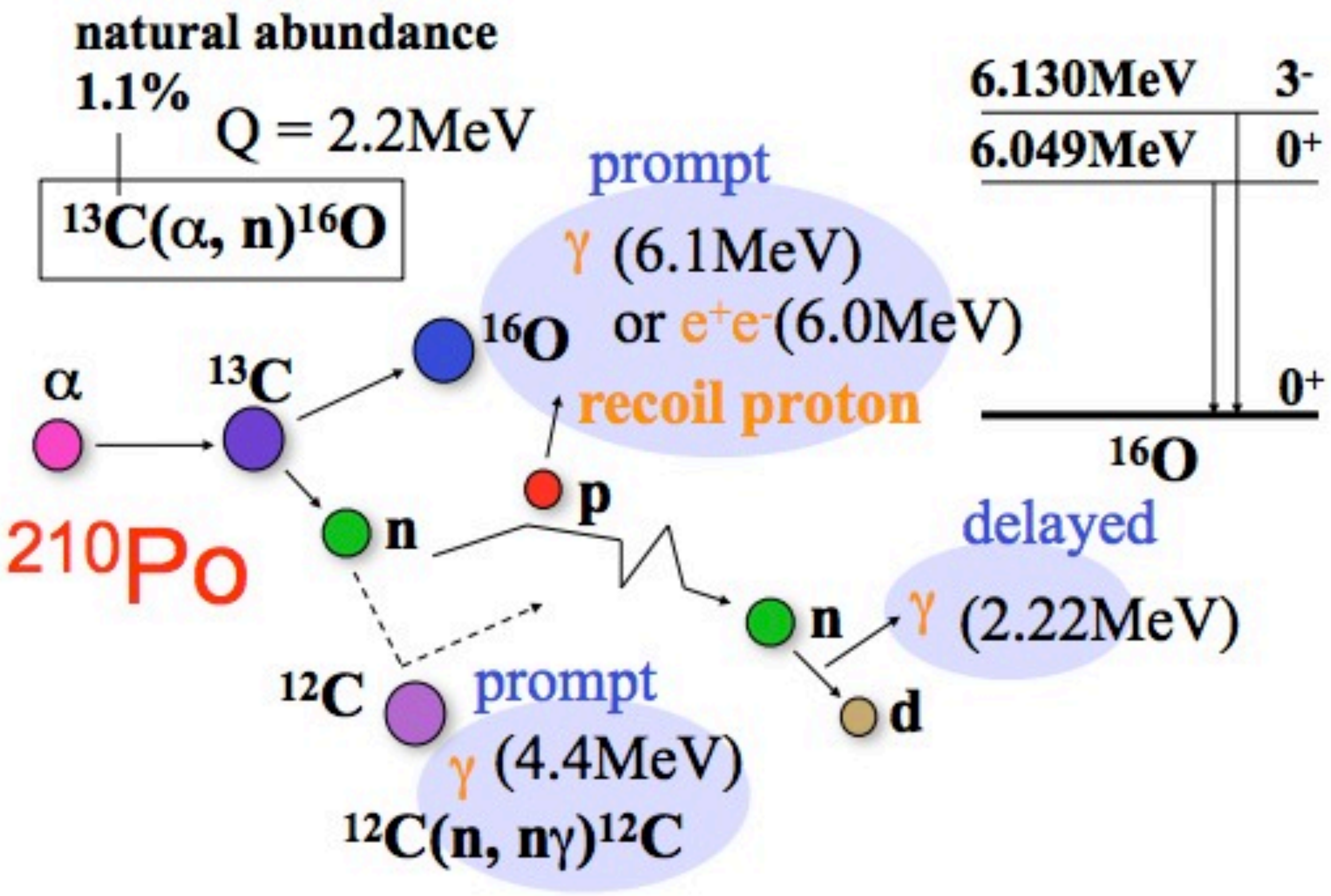


best-fit $N_U+N_{Th} = 116^{+28}_{-27}$

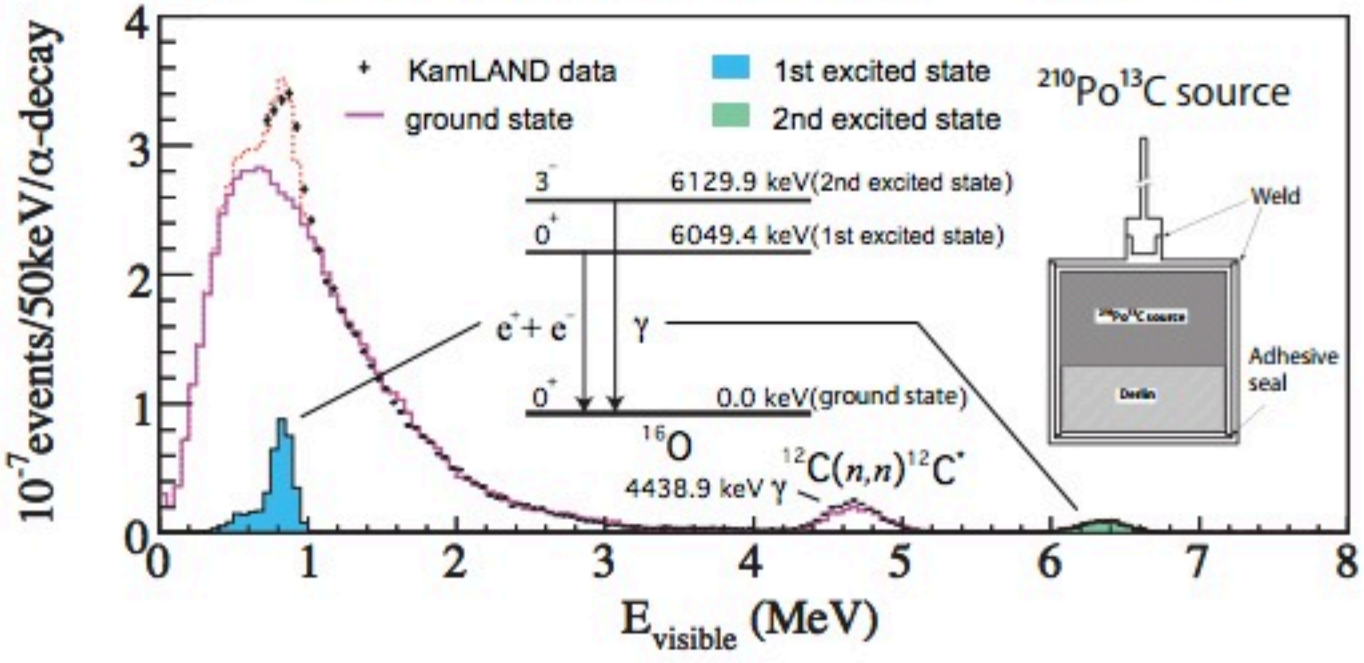
Flux : $3.4^{+0.8}_{-0.8} \times 10^6$ $cm^{-2}s^{-1}$

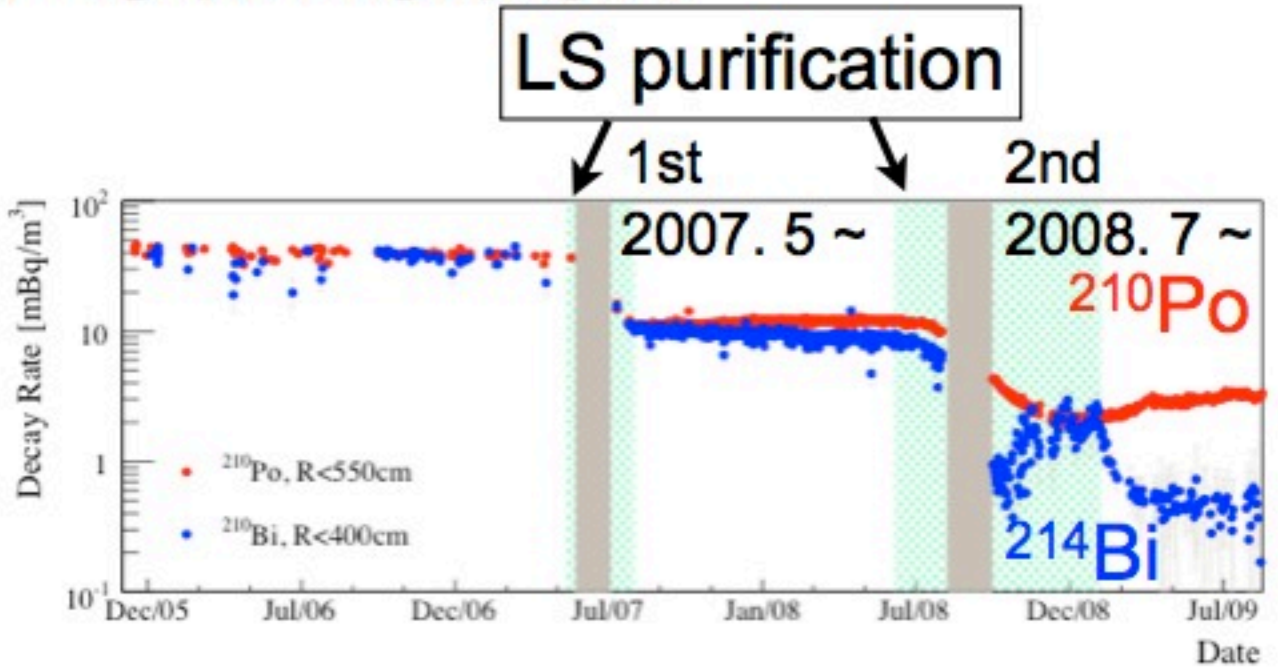
0 signal rejected at 99.9998% C.L. (2×10^{-6})

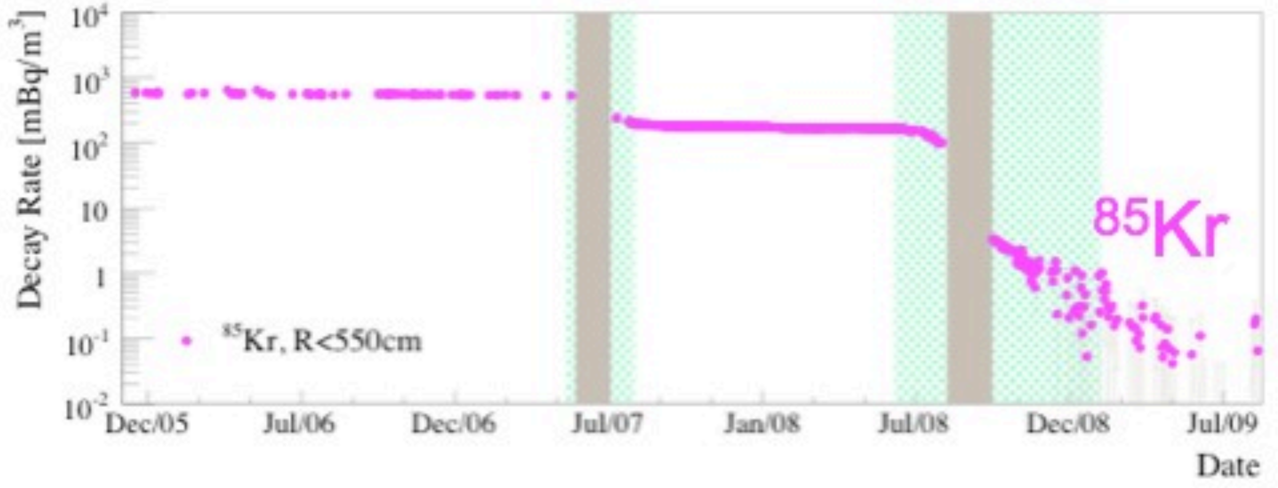
Background Estimation



in-situ calibration with $^{210}Po^{13}C$





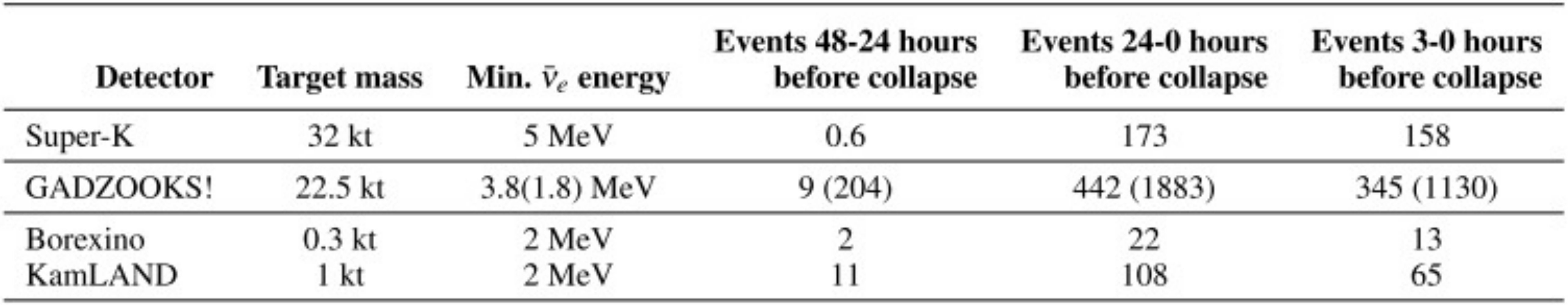


(1) dominant BG source (α, n) has been reduced by down to ~ 1 / 20

(2) determination of the cross section is improved by in-situ calibration

uncertainty: 11% for ground state

Expected events



Detector	Target mass	Min. $\bar{\nu}_e$ energy	Events 48-24 hours before collapse	Events 24-0 hours before collapse	Events 3-0 hours before collapse
Super-K	32 kt	5 MeV	0.6	173	158
GADZOOKS!	22.5 kt	3.8(1.8) MeV	9 (204)	442 (1883)	345 (1130)
Borexino	0.3 kt	2 MeV	2	22	13
KamLAND	1 kt	2 MeV	11	108	65

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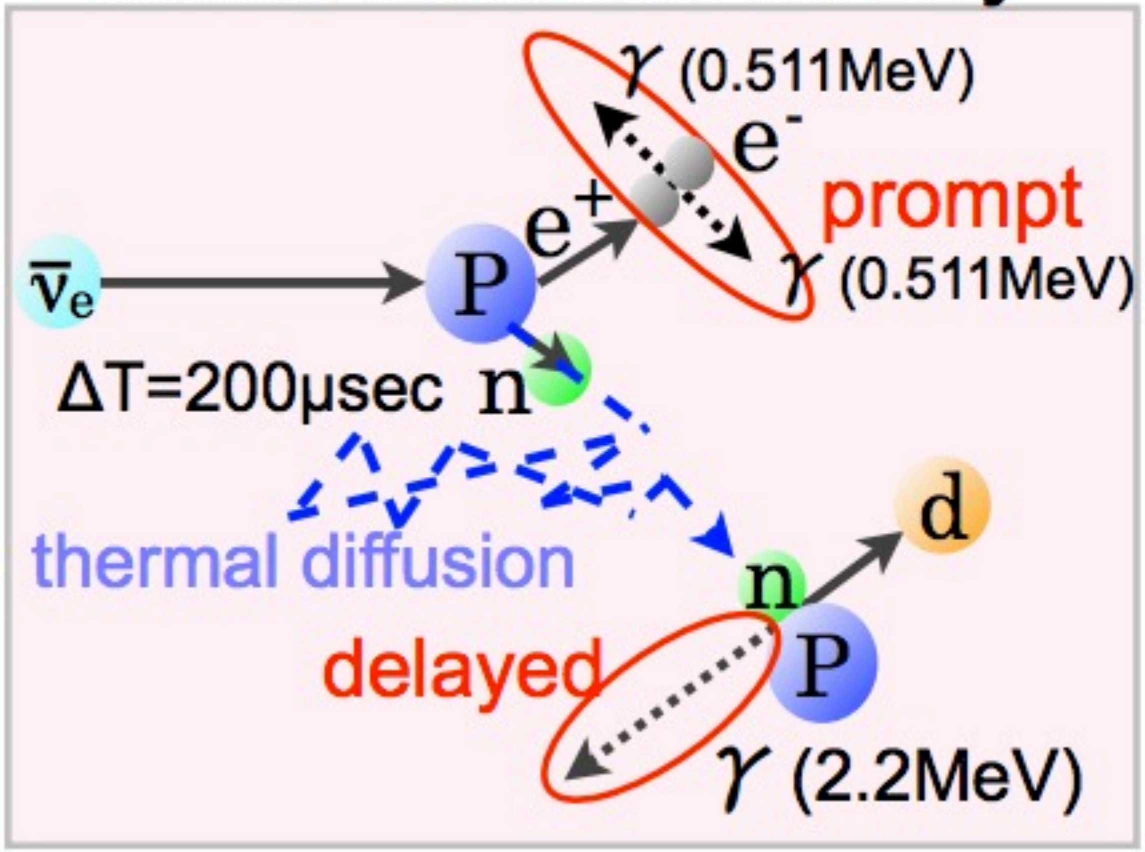
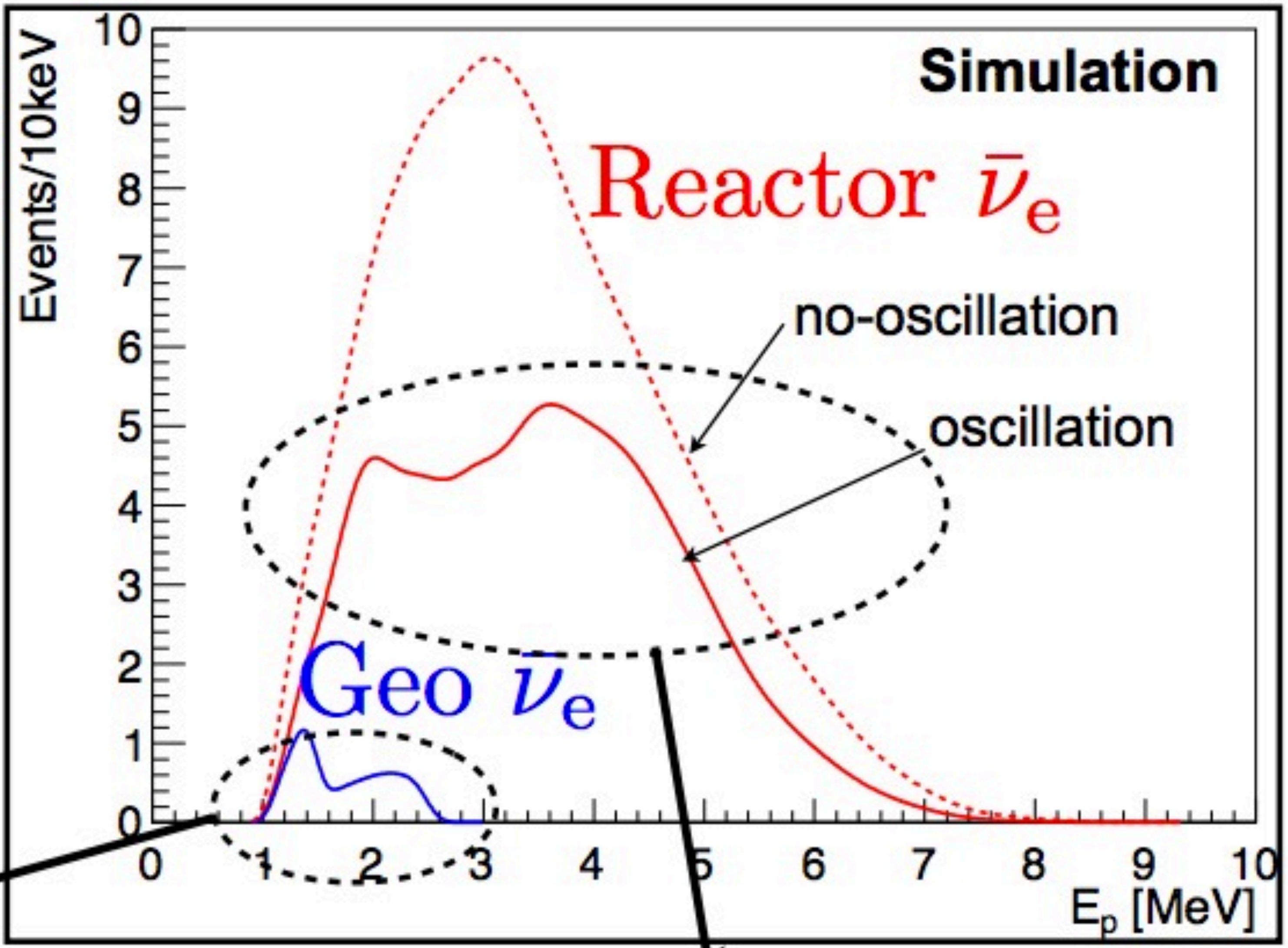
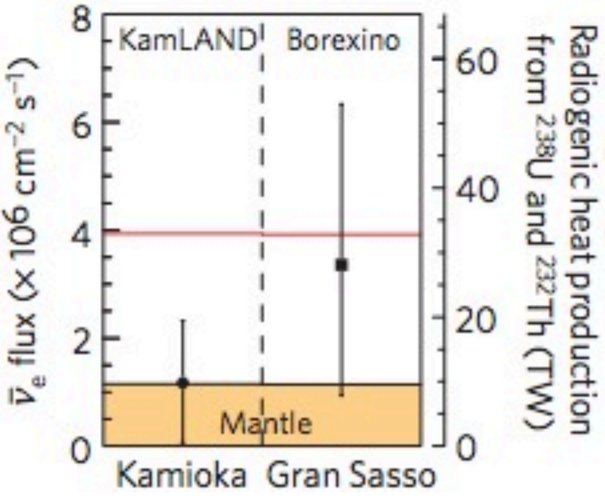
inverse-beta decay



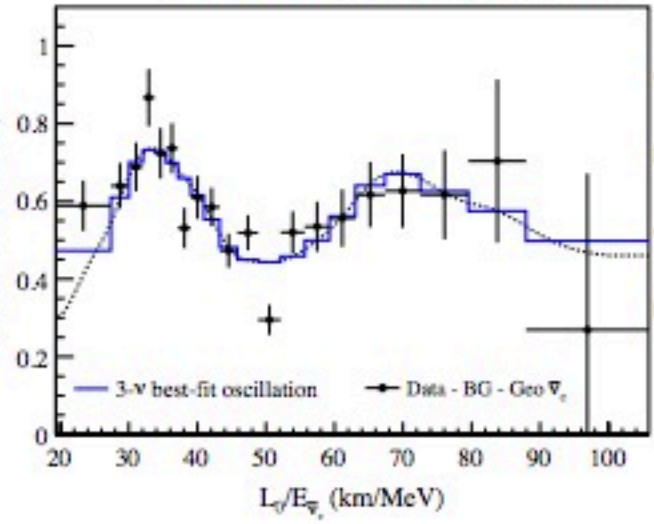


Geoneutrinos
: Neutrino Application



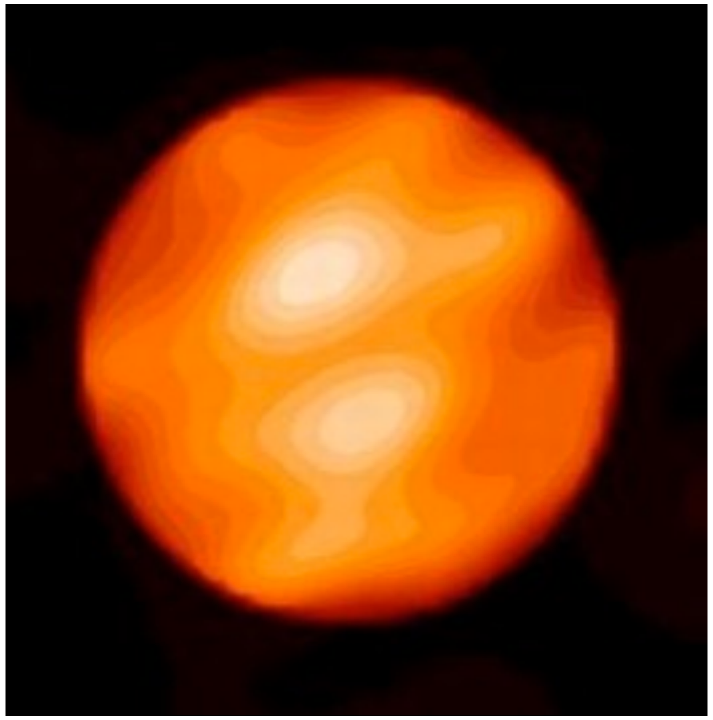
- Direct measurement of radiogenic heat contribution

Neutrino Property Study



- Signature of neutrino oscillation
- Precise measurement of oscillation parameters

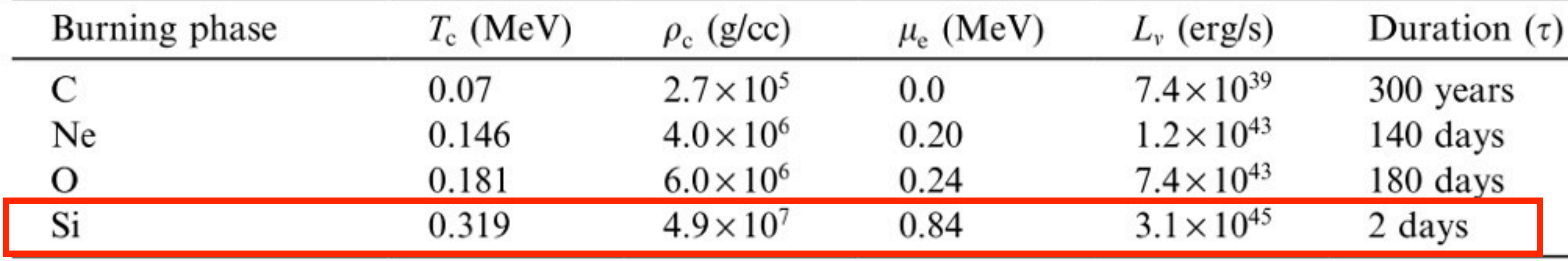
Model



Betelgeuse like star

- Mass: 20M
- Distance: 200pc

Stellar evolution



Burning phase	T_c (MeV)	ρ_c (g/cc)	μ_e (MeV)	L_ν (erg/s)	Duration (τ)
C	0.07	2.7×10^5	0.0	7.4×10^{39}	300 years
Ne	0.146	4.0×10^6	0.20	1.2×10^{43}	140 days
O	0.181	6.0×10^6	0.24	7.4×10^{43}	180 days
Si	0.319	4.9×10^7	0.84	3.1×10^{45}	2 days

Oscillation

$$F = pF_{\bar{\nu}_e} + (1-p)F_{\bar{\nu}_x}$$

p : survival probability

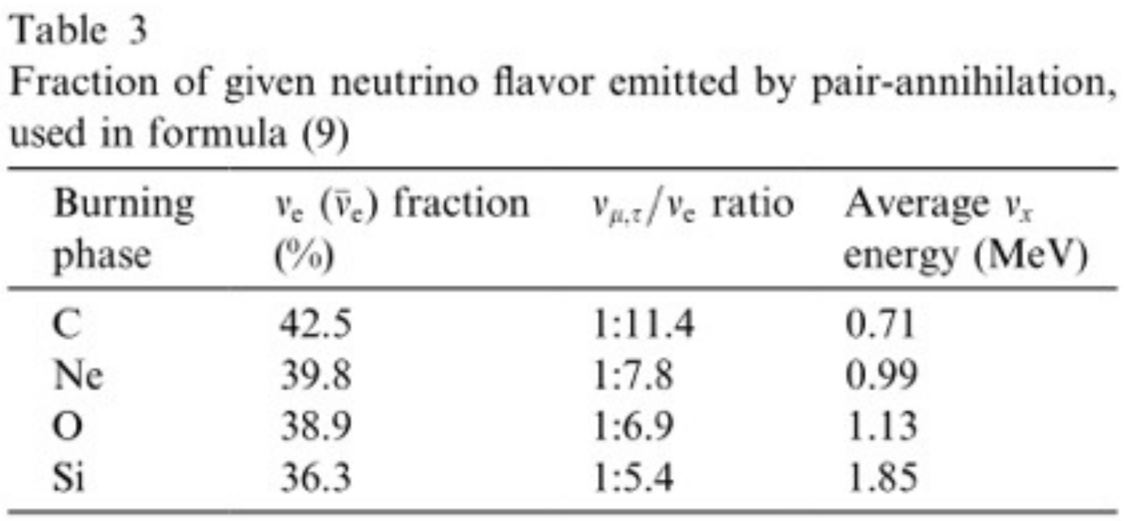


Table 3
Fraction of given neutrino flavor emitted by pair-annihilation, used in formula (9)

Burning phase	ν_e ($\bar{\nu}_e$) fraction (%)	$\nu_{\mu,\tau}/\nu_e$ ratio	Average ν_x energy (MeV)
C	42.5	1:11.4	0.71
Ne	39.8	1:7.8	0.99
O	38.9	1:6.9	1.13
Si	36.3	1:5.4	1.85

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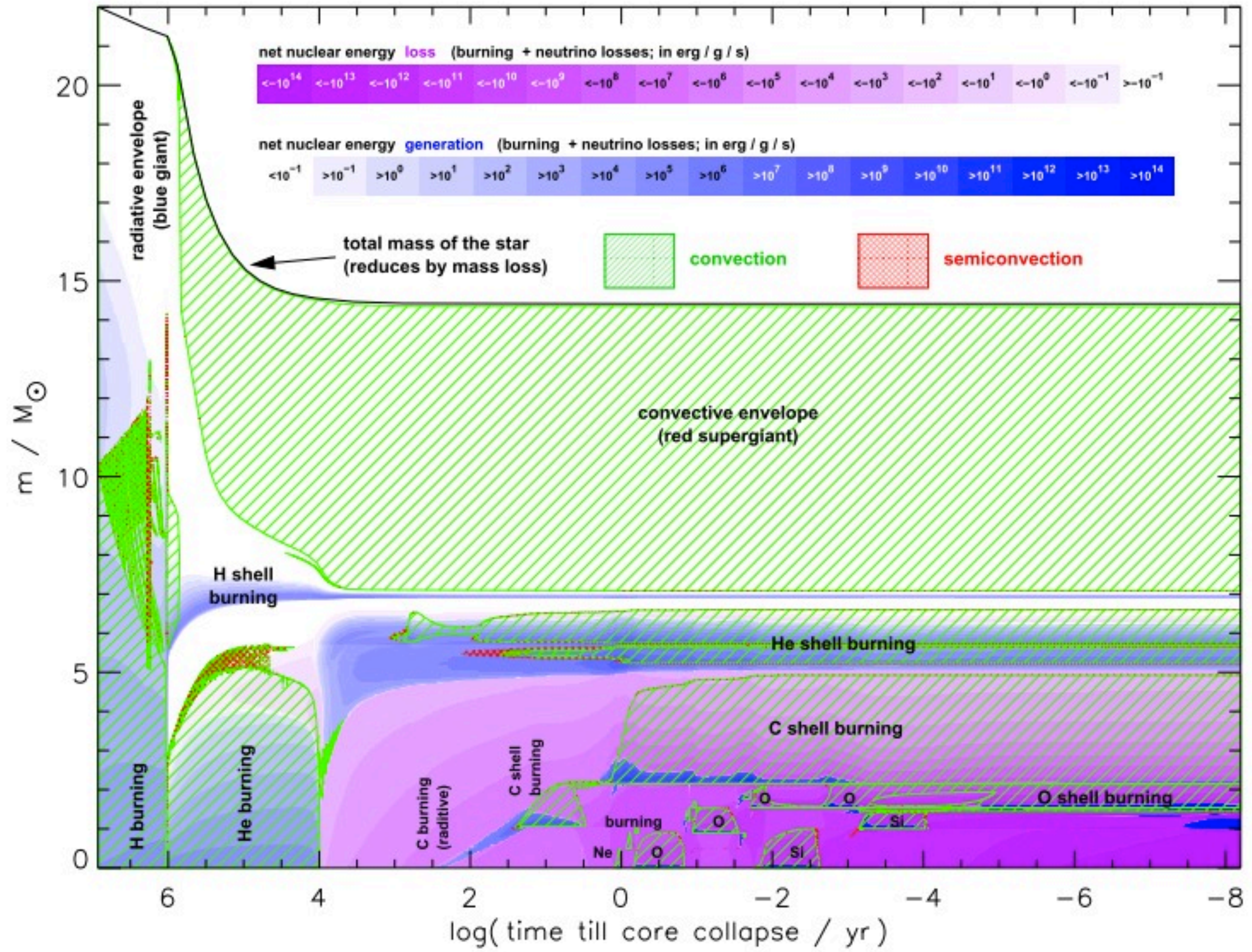
Stellar evolution



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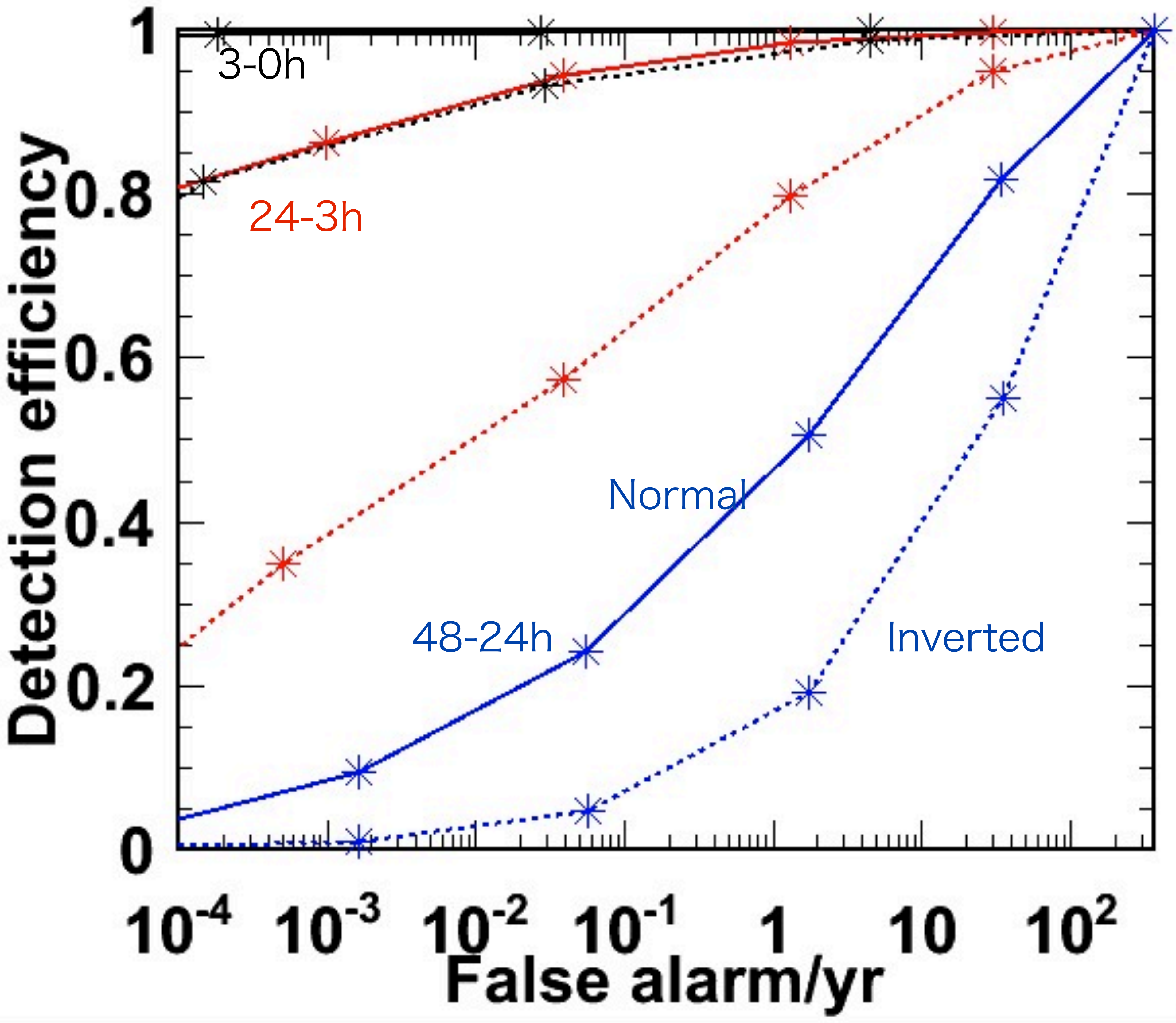
Statistics

200pc and low-reactor status (0.1 event/day)



Detection efficiency

150pc and low-reactor status

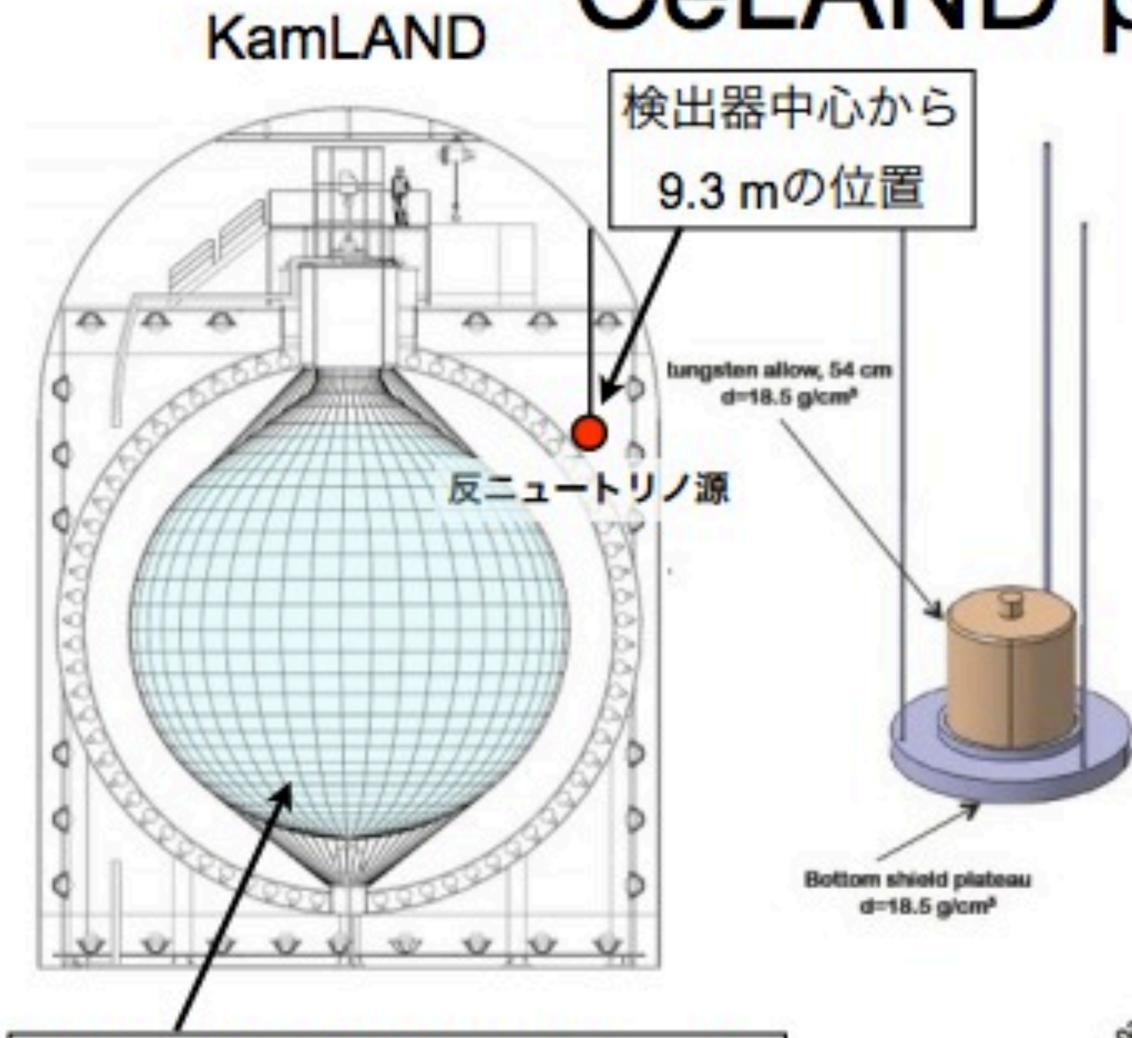
	48-24h	24-3h	3-0h	
Efficiency	78%/55%	>99%	>99%	Normal
Efficiency	41%/17%	96%/89%	>99%	Inverted
False rate/yr	1.7/0.06	1.3/0.034	0.032	

150pc and normal status

	48-24h	24-3h	3-0h	
Efficiency	42%	>99%	>99%	Normal
Efficiency	10%	81%	>99%	Inverted
False rate/yr	0.6	0.4	0.68	

- **Final stage is OK !!**
- **Early alarm is possible (efficiency > 80%)**

CeLAND phase 1

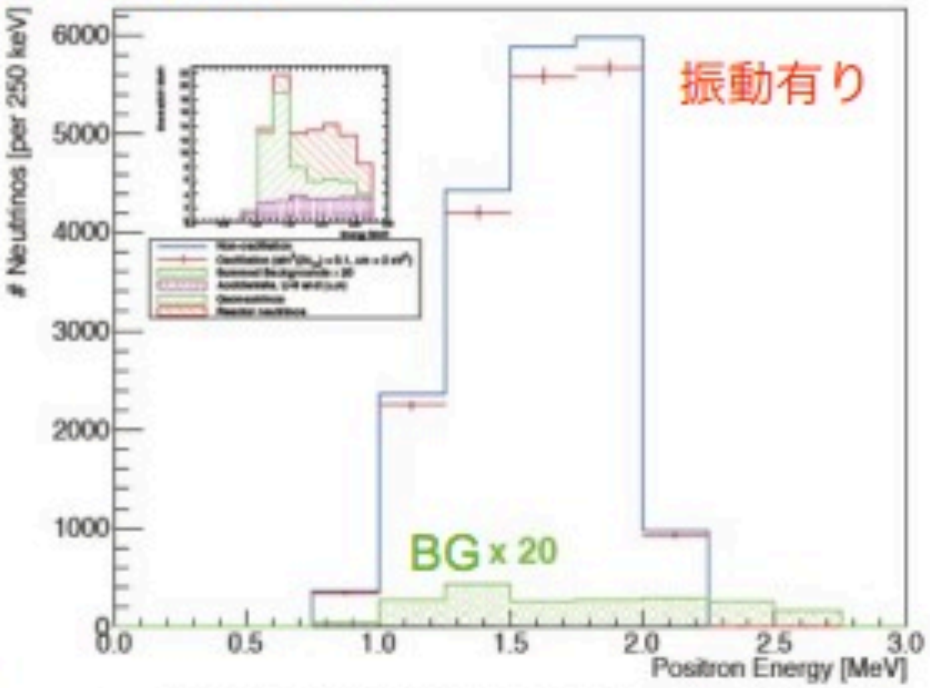


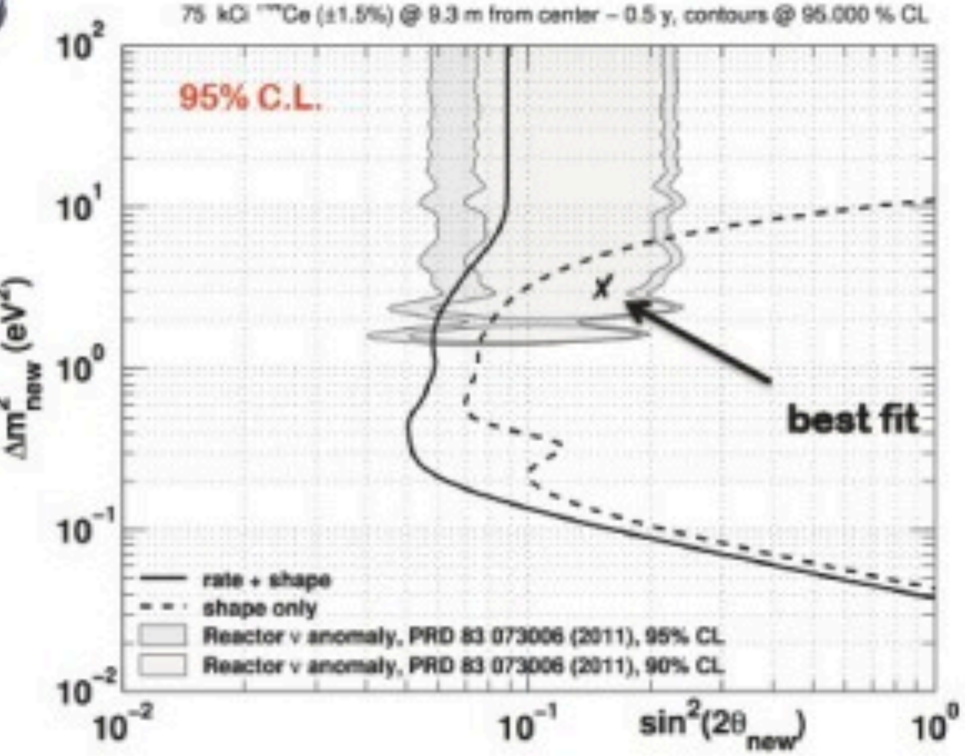
1000トン液体シンチレータ

エネルギー分解能　$6.4\%/\sqrt{E(\mathrm{MeV})}$

位置分解能　$12\,\mathrm{cm}/\sqrt{E(\mathrm{MeV})}$

~1 eV² 振動探索が可能

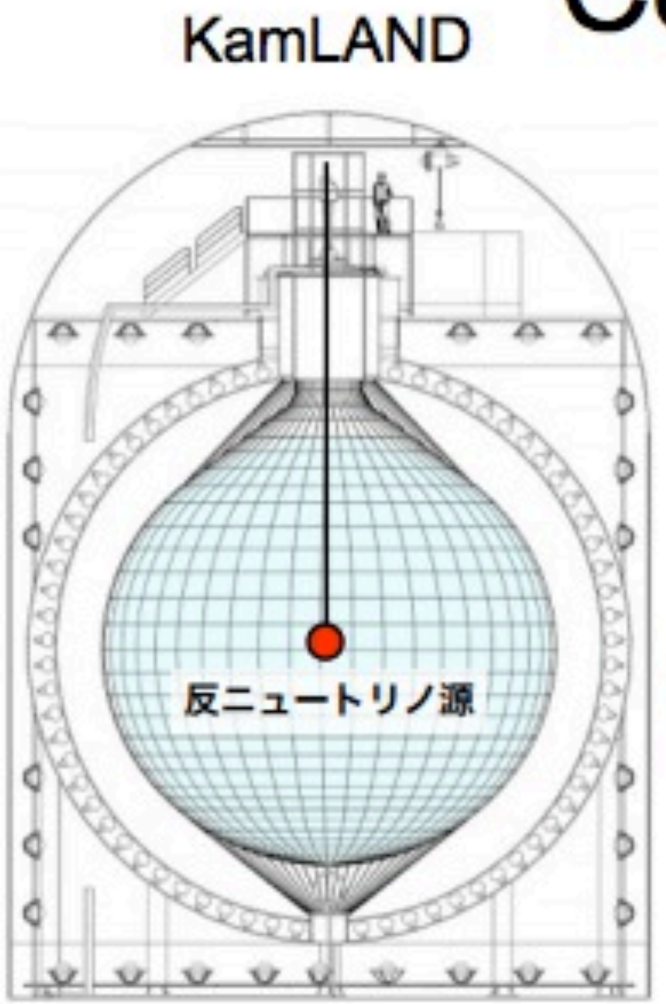


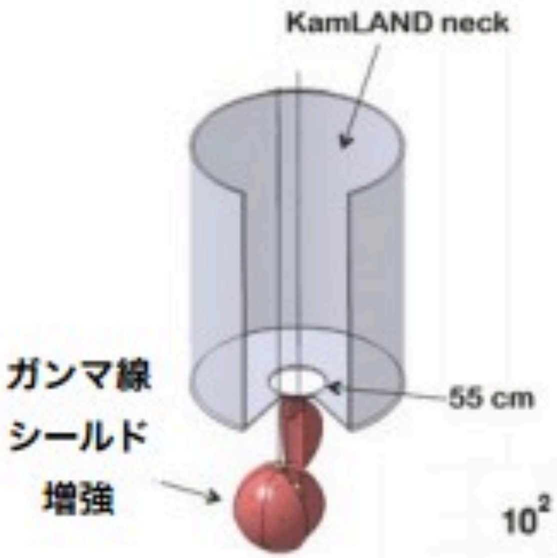


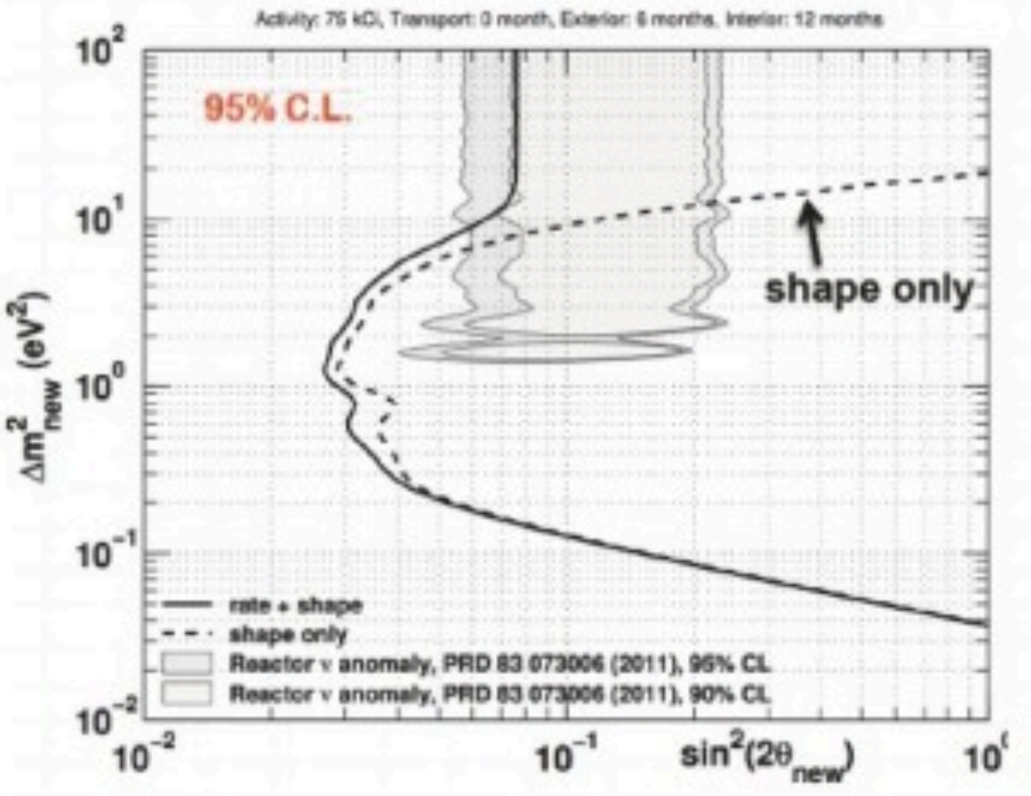
CeLAND phase 2

改善点

- phase 1 の約 5 倍の統計量での観測
- スペクトルのみでもグローバル解析の95% C.L.領域をカバー







線源強度の減衰	観測時間
75kCi ^{144}Ce (phase1)	0.5年
↓ 6ヶ月後	
50kCi ^{144}Ce (phase2)	1.0年

	Detector-related (%)		Reactor-related (%)	
Δm^2_{21}	Energy scale	1.8/1.8	$\bar{\nu}_e$-spectra [27]	0.6/0.6
Rate	Fiducial volume	1.8/2.5	$\bar{\nu}_e$-spectra [24]	1.4/1.4
	Energy scale	1.1/1.3	Reactor power	2.1/2.1
	$L_{\mathrm{cut}}(E_{\mathrm{p}})$ efficiency	0.7/0.8	Fuel composition	1.0/1.0
	Cross section	0.2/0.2	Long-lived nuclei	0.3/0.4
	Total	2.3/3.0	Total	2.7/2.8