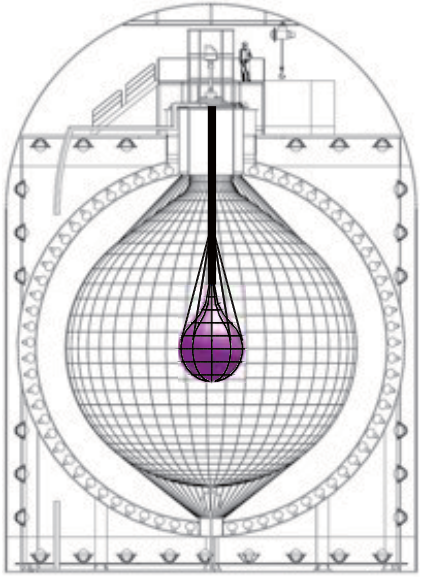
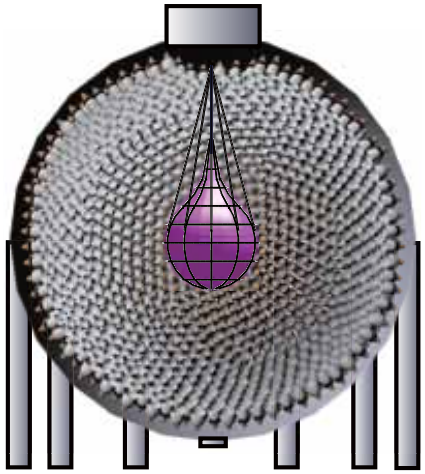
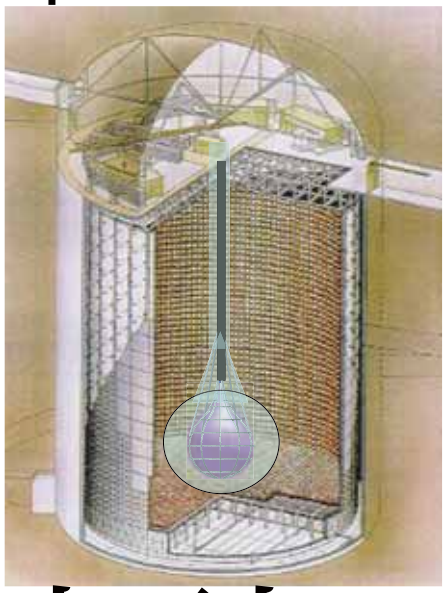
KamLAND-Zen



KamLAND2-Zen



Super-KamLAND-Zen



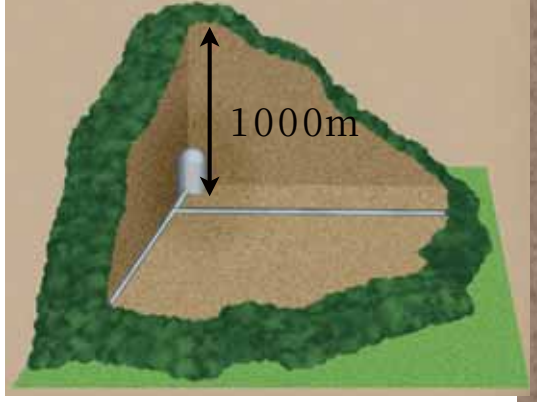
カムランドの将来計画

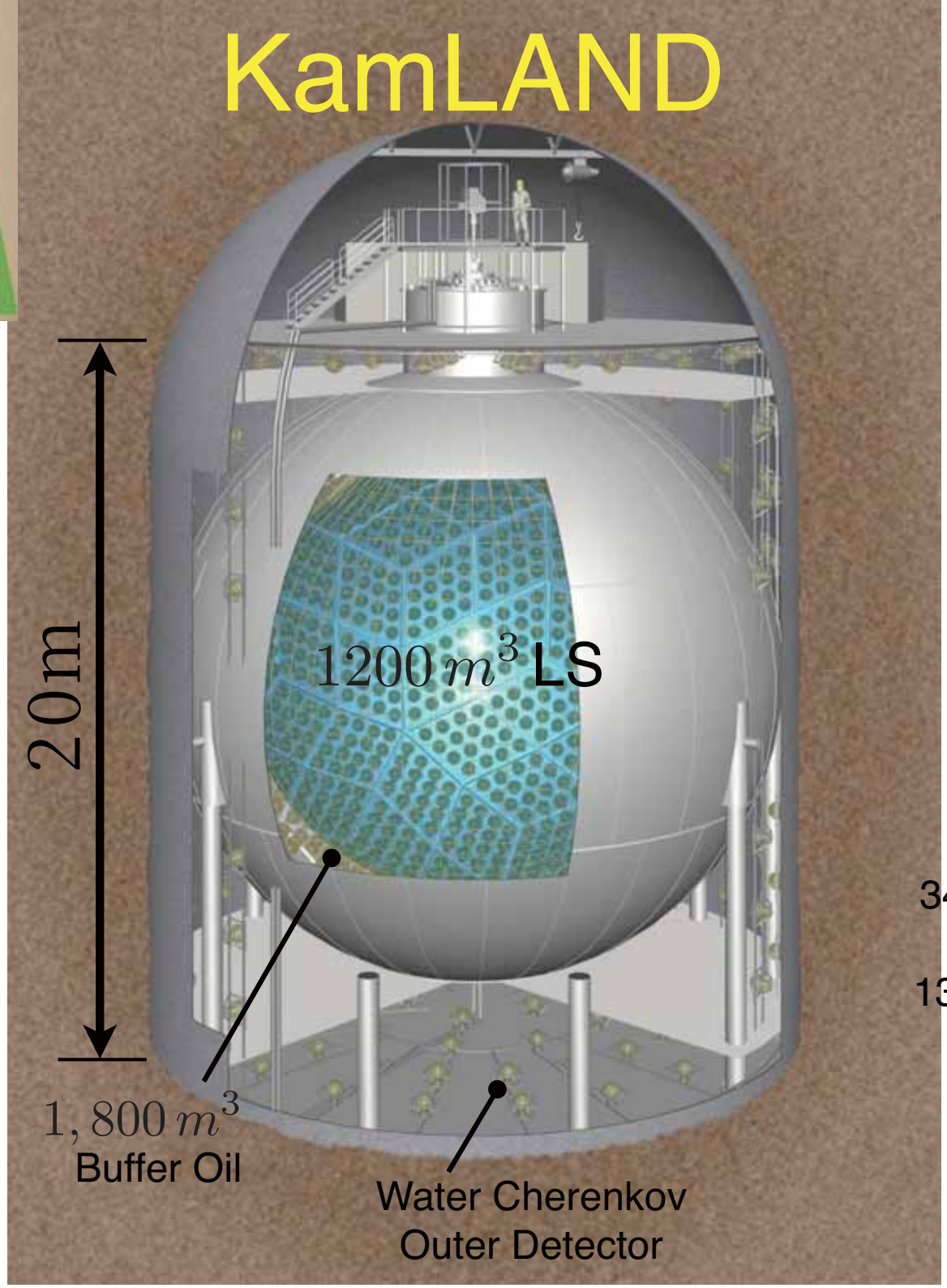
2010年９月１６日 CRC将来計画シンポジウム

井上邦雄
東北大学ニュートリノ科学研究センター

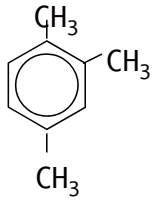
目次

KamLAND



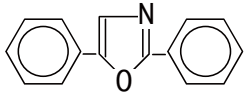


LS



20%

80%



1.5g/l

$\rho = 0.78 g/cm^3$

$8,000 photons/MeV$

$\lambda \sim 10\,m$

BO

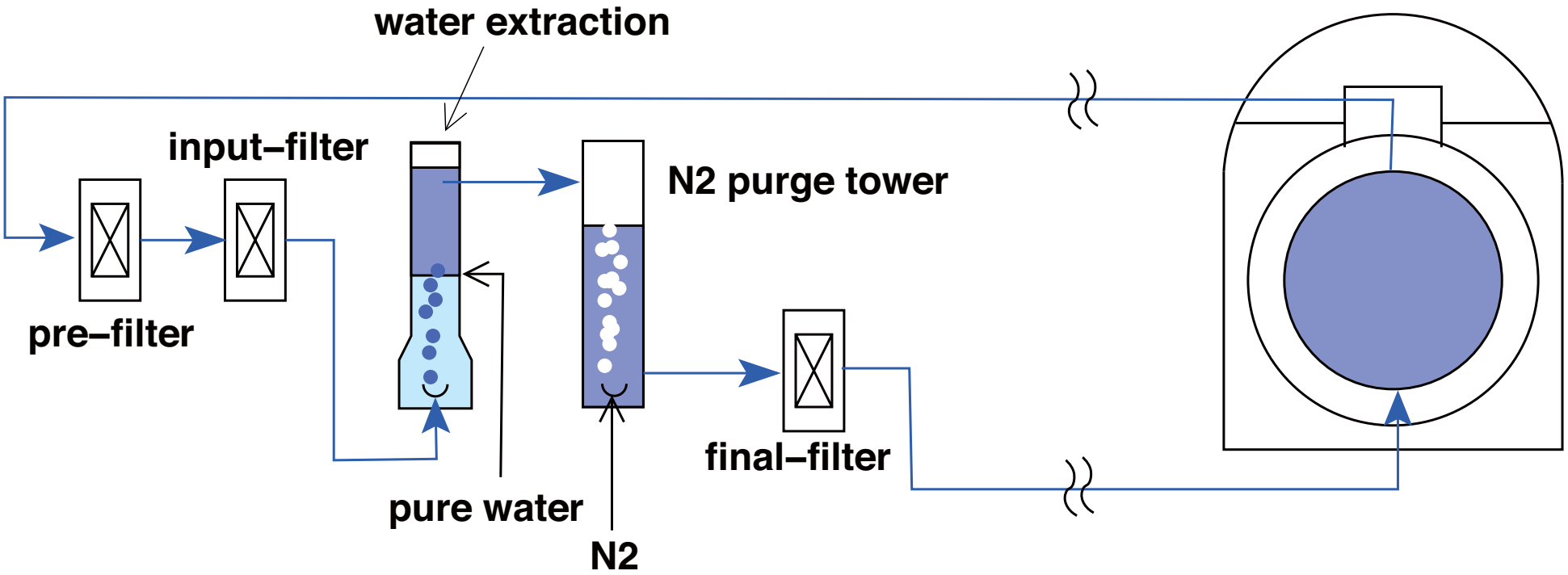
50% dodecane
50% isoparaffin

$$\frac{\rho_{LS}}{\rho_{BO}} = 1.0004$$

34% photo-coverage
with
1325 17” and 554 20”
photo-tubes

~500p.e./MeV

The world cleanest detector



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

Achievement is ^{238}U 3.5×10^{-18} g/g
^{232}Th 5.2×10^{-17} g/g

It is trillion times cleaner than ordinary material (~1 ppm) or 100 times cleaner than Super-Kamiokande.

Super-Kamiokande

50,000 ton pure water

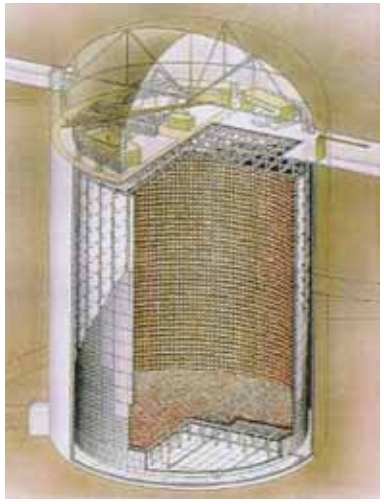
Cherenkov detector

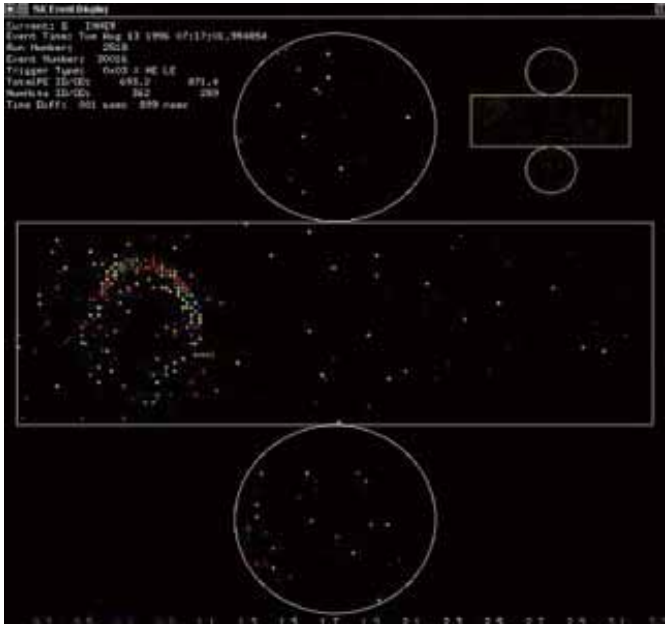
photon yield 6 p.e./MeV

Energy threshold ～5 MeV

Physics target

- Solar neutrino
- Atmospheric neutrino
- Supernova neutrino
- proton decay
- etc.





KamLAND

1,000 ton ultra pure oil

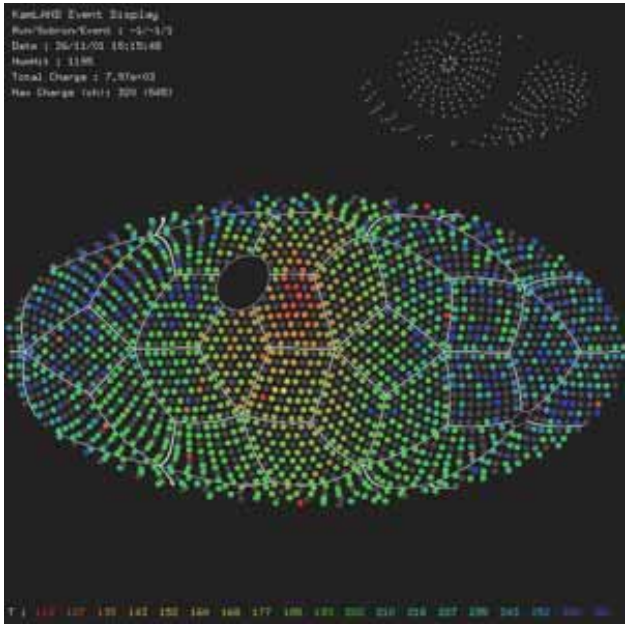
Scintillation detector

photon yield 500 p.e./MeV

Energy threshold 0.25～0.4 MeV

Physics target

- reactor neutrino
- geo-neutrino
- low energy solar neutrino
- nucleon decay
- etc.



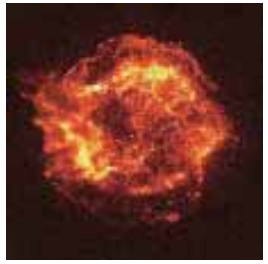
Various Physics Targets with wide energy range

0.4 | 1.0 | 2.6 | 8.5 | Visible energy [MeV]

neutrino electron elastic scattering

$\nu + \mathrm{e}^- \rightarrow \nu + \mathrm{e}^-$

inverse beta decay $\bar{\nu}_\mathrm{e} + \mathrm{p} \rightarrow \mathrm{e}^+ + \mathrm{n}$

^{7}Be solar neutrino	geo-neutrino	reactor neutrino	supernova relic neutrino etc.
			
Neutrino Astrophysics	Neutrino Geophysics	Neutrino Physics	Neutrino Astrophysics/Cosmology
coming 2nd phase	Nature Vol. 436 #7050 499-503	PRL 90, 021802 (2003) PRL 94, 081801 (2005)	Solar $\bar{\nu}_\mathrm{e}$ PRL 92, 071301 (2004)

$$\nu + e^- \rightarrow \nu + e^-$$

single event

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$+e^- \rightarrow 2\gamma$$

$\tau \sim 200\ \mu\mathrm{sec}$

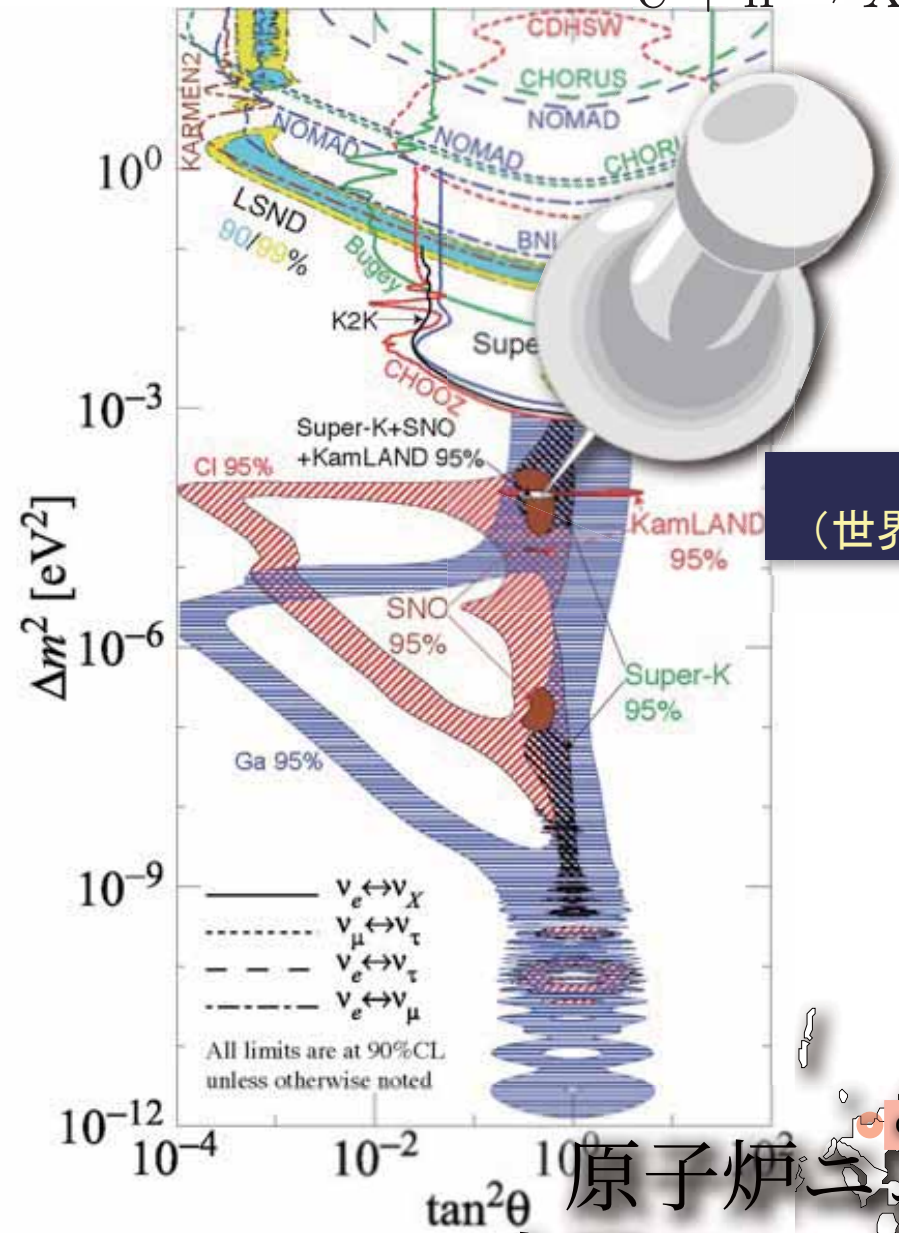
$$+p \rightarrow D + \gamma$$

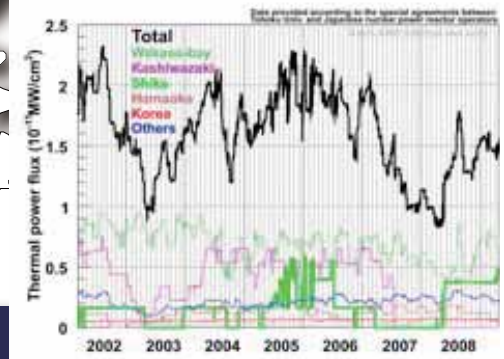
two-fold delayed coincidence signal

1．原子炉起源反電子ニュートリノの高精度精密測定

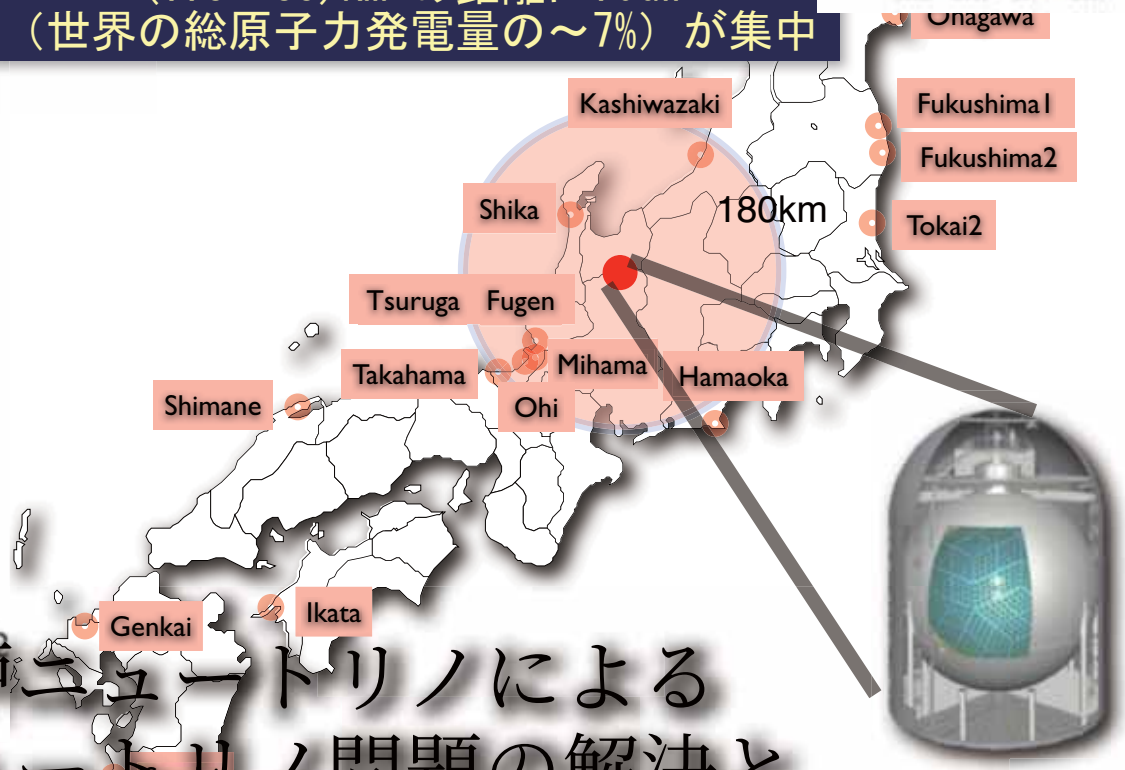
$$^{235}\mathrm{U} + \mathrm{n} \rightarrow \mathrm{X} + \mathrm{Y} + 6.1\mathrm{e}^- + 6.1\bar{\nu}_\mathrm{e} + 2.5\mathrm{n} + 202\,\mathrm{MeV}$$

その他　$^{239}\mathrm{Pu}$, $^{238}\mathrm{U}$, $^{241}\mathrm{Pu}$





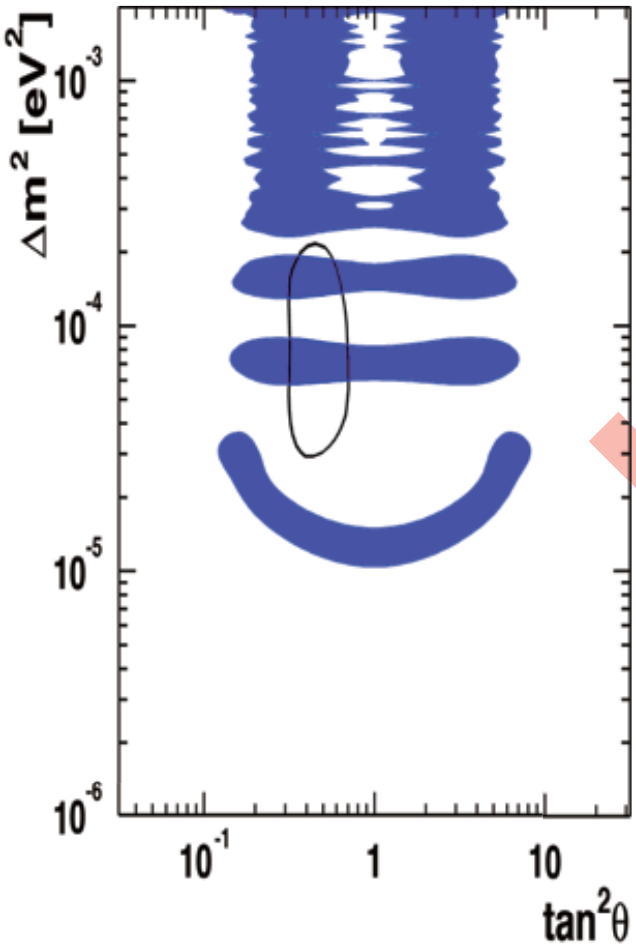
(175±35) km の距離に70GW
（世界の総原子力発電量の～7%）が集中

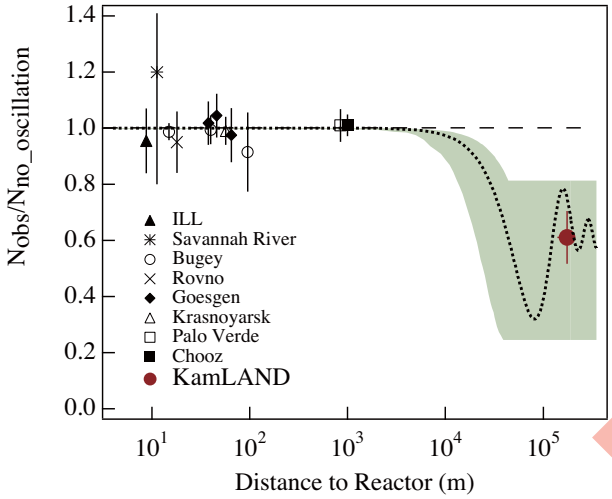


原子炉ニュートリノによる
太陽ニュートリノ問題の解決と
ニュートリノ振動パラメータの精密測定

achievement 1

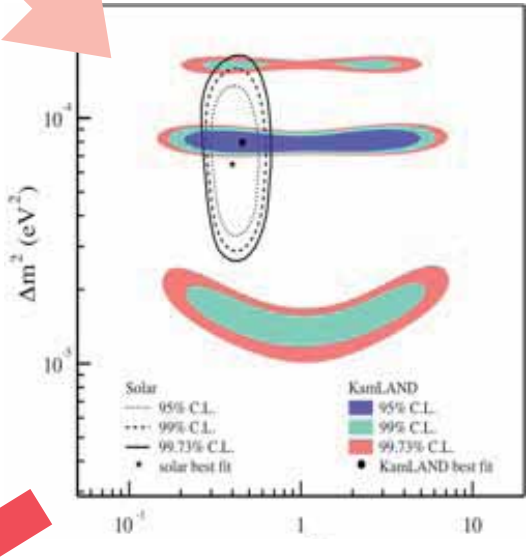
reactor anti-neutrino observation



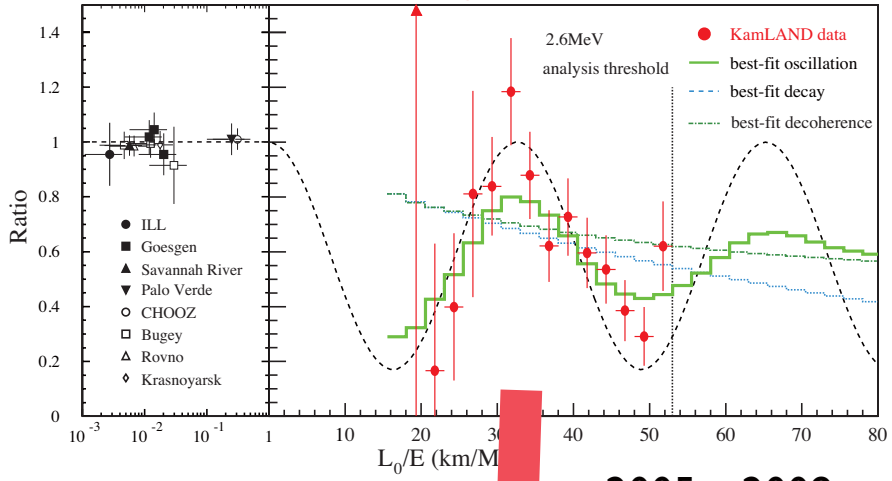


#1 citation（ISI 2004, 2005）

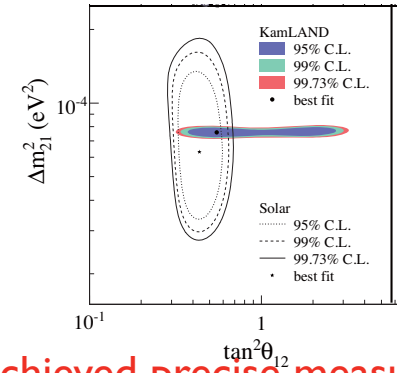
2003→2005



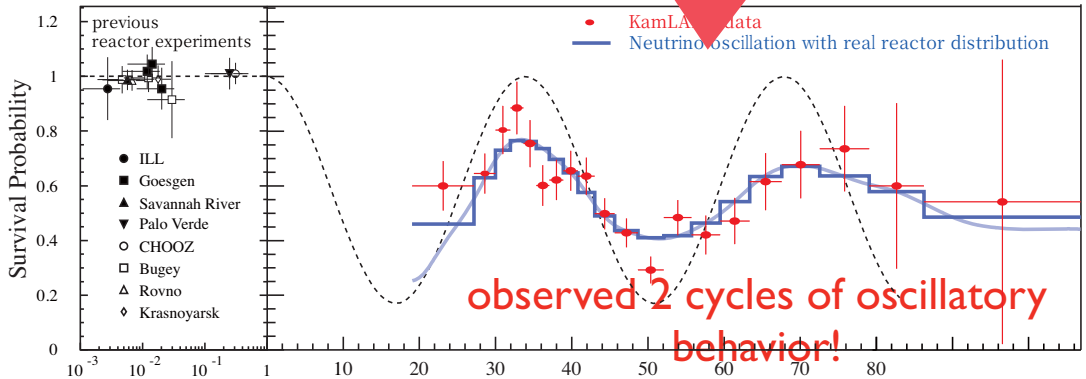
2003→2005



2005→2008



2005→2008



achieved precise measurement of oscillation parameters!

observed 2 cycles of oscillatory behavior!

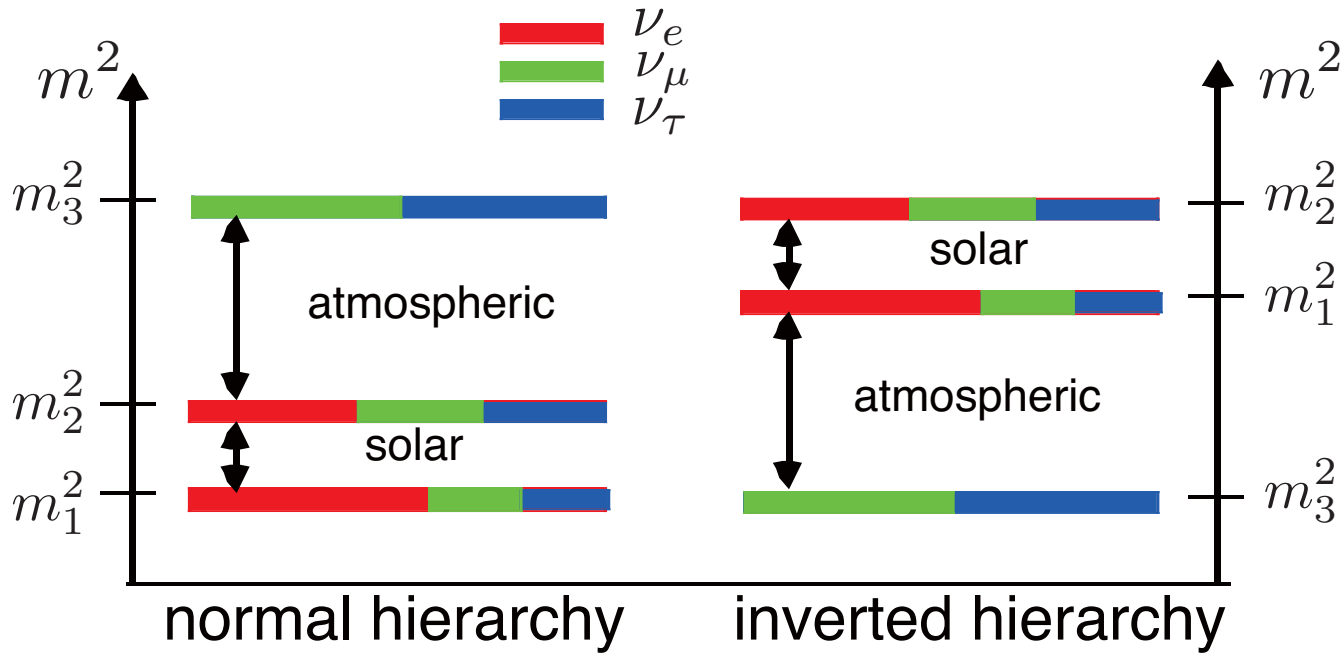
$$\Delta m^2_{atm} = (2.6 \pm 0.4) \times 10^{-3}\ \mathrm{eV}^2$$

SK, K2K, MINOS

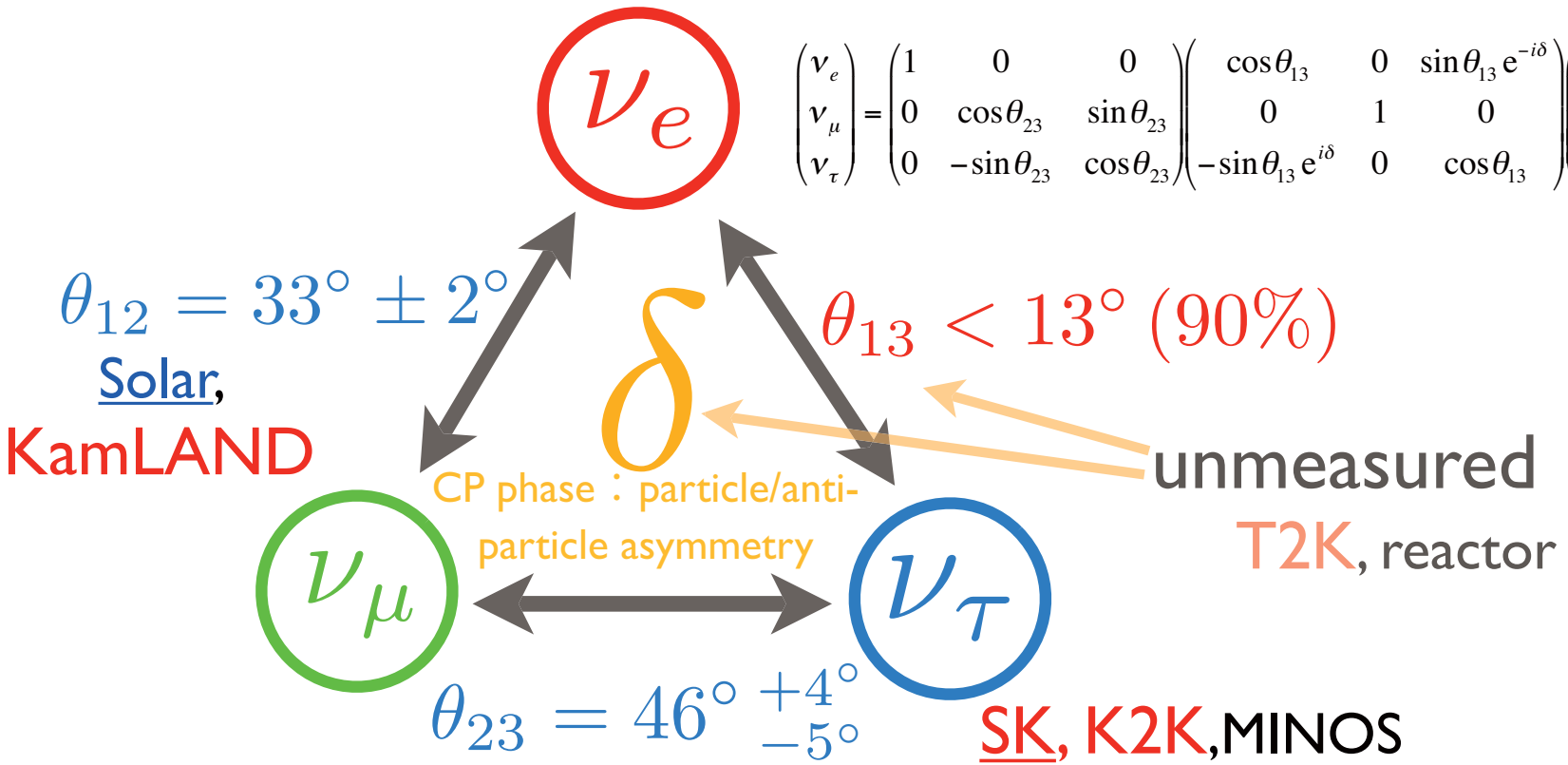
$$\Delta m^2_{sol} = (7.6 \pm 0.2) \times 10^{-5}\ \mathrm{eV}^2$$

KamLAND,

Solar



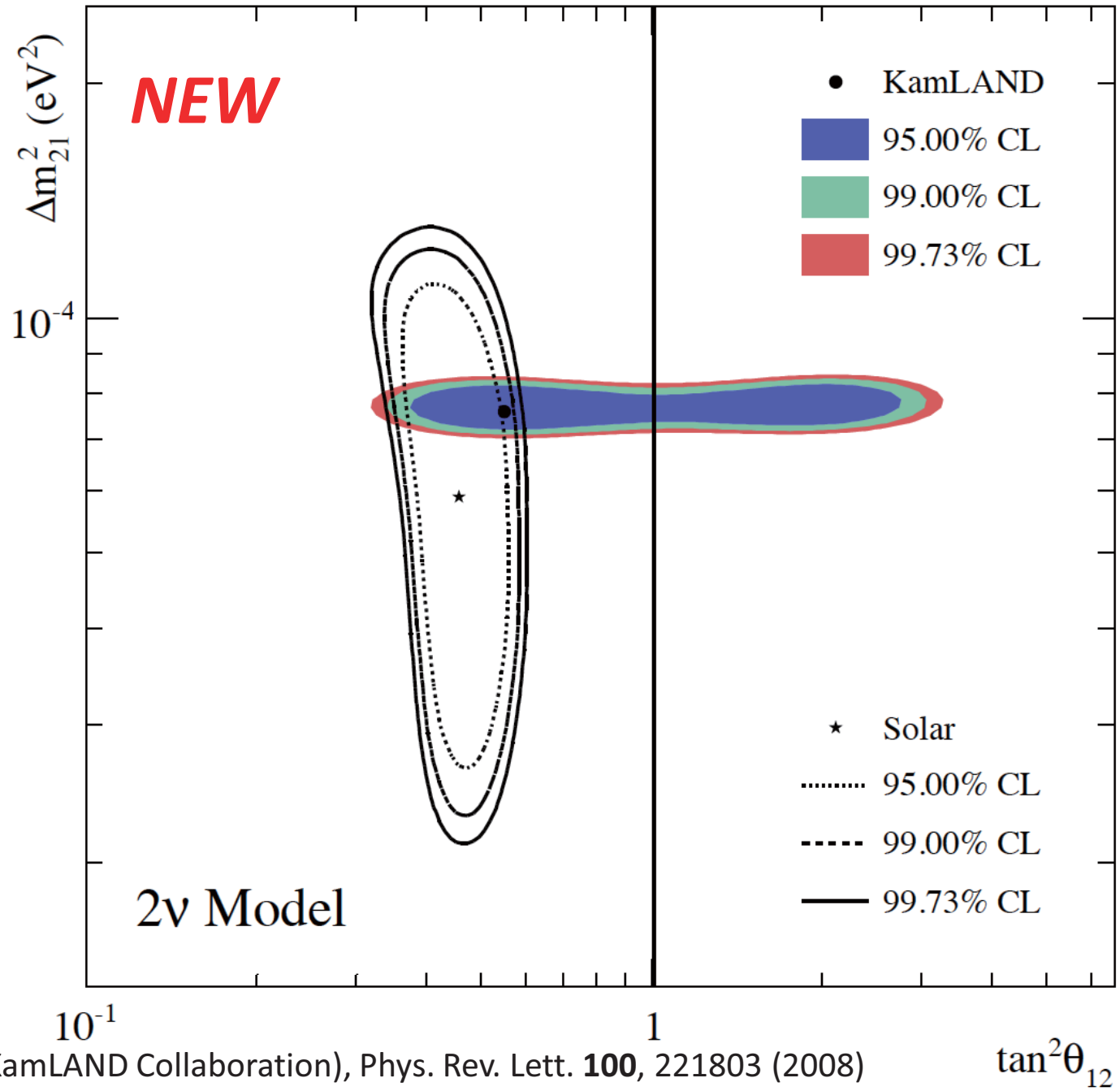
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}\, e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Solar + KamLAND 2-flavor Overlay

LETA paper 2009:
LETA joint-phase fit
+ Phase III
+ all solar expts
+ KamLAND

2-flavor overlay:

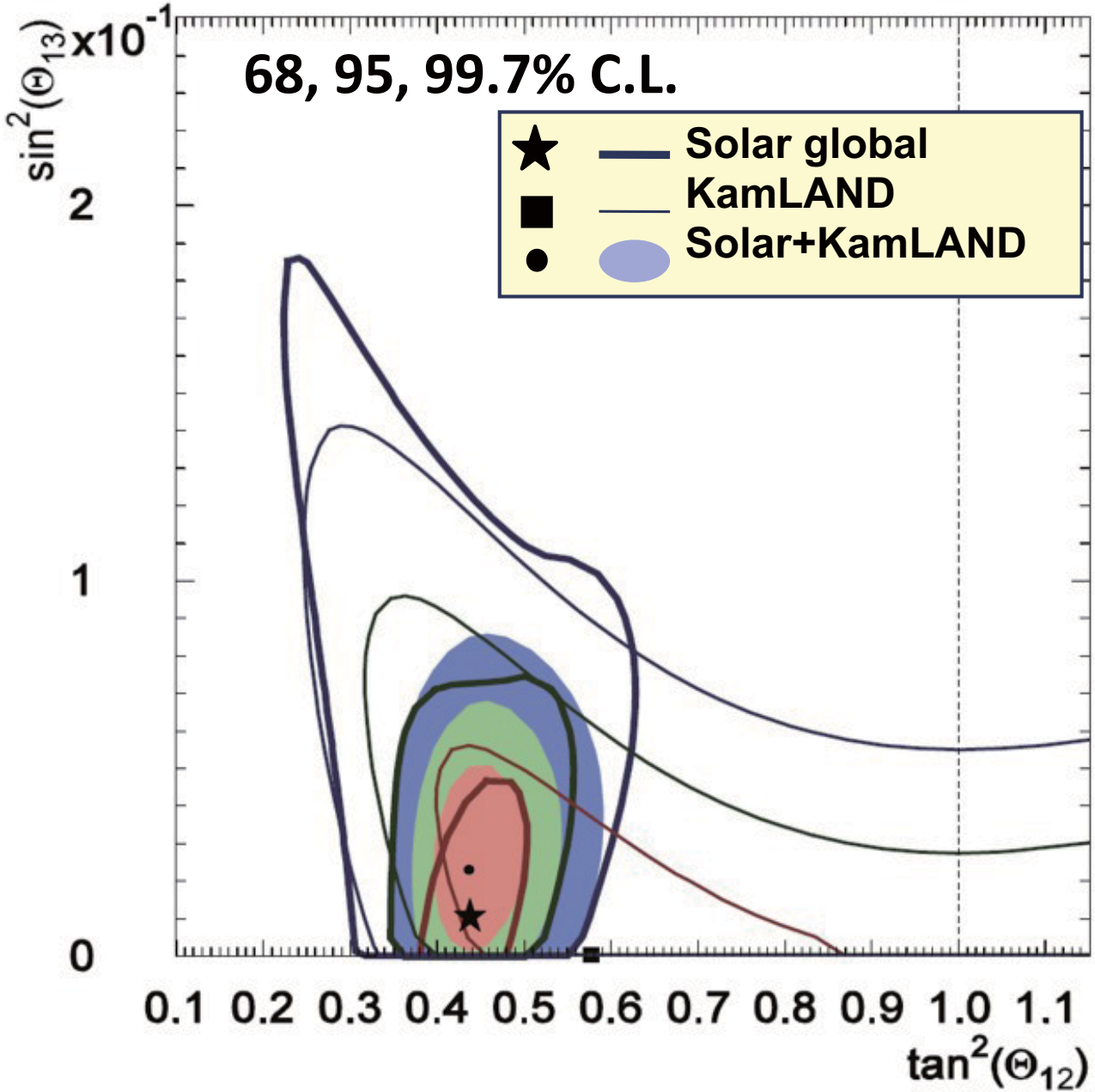


S. Abe *et al.* (KamLAND Collaboration), Phys. Rev. Lett. **100**, 221803 (2008)

3-flavor analysis: θ_{12} - θ_{13}

Preliminary

May 2010



Solar global:

$\sin^2\theta_{13}$<0.060 @95%C.L.

Solar global + KamLAND:

$\sin^2\theta_{13}$=0.025 $^{+0.018}_{-0.016}$ (<0.059 @95%C.L.)

Cf. PRC81, 055504 (2010)
$\sin^2\theta_{13}$=0.020+0.021-0.016
(<0.057 @95%C.L.)

Takeuchi @ neutrino2010

さらなる高精度化　　混合角の誤差は小さくできるか？

TABLE I. Estimated systematic uncertainties relevant for the neutrino oscillation parameters Δm^2_{21} and θ_{12}.

	Detector-related (%)		Reactor-related (%)	
Δm^2_{21}	Energy scale	1.9	$\bar{\nu}_e$-spectra [7]	0.6
Event rate	Fiducial volume	1.8	$\bar{\nu}_e$-spectra	2.4
	Energy threshold	1.5	Reactor power	2.1
	Efficiency	0.6	Fuel composition	1.0
	Cross section	0.2	Long-lived nuclei	0.3

原子炉θ13実験に期待
新炉の横での測定も可能か？

1%?

0.8%?

4.1%→<3%?

炉出力の誤差を統計的に扱えるか検討中　J.Phys.G36:045002,2009

最大誤差要因の熱水流量測定（ベンチュリ式→超音波式）

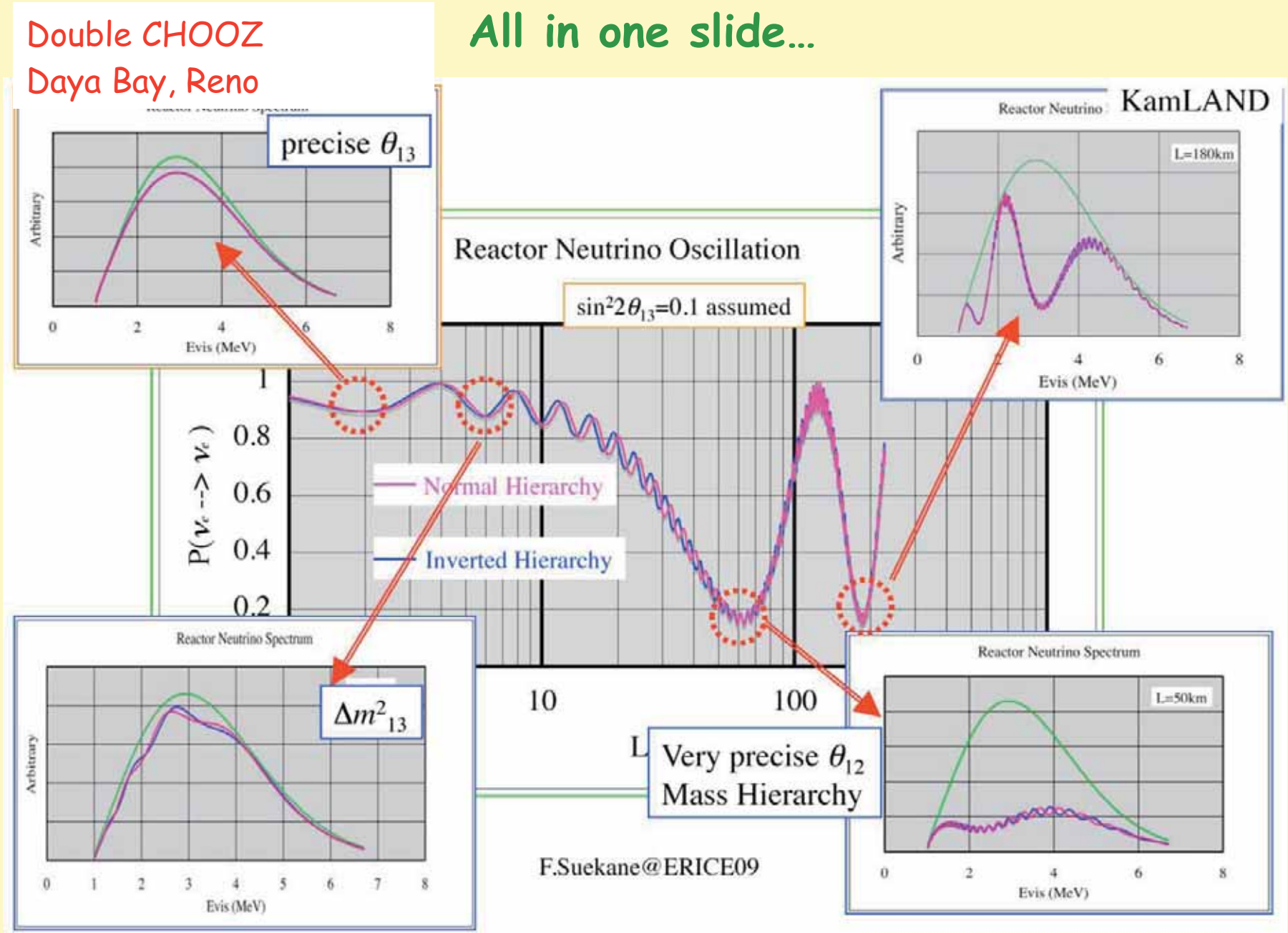
スケールで誤差が蓄積　　東電は全炉に装備

TABLE II. Estimated backgrounds after selection efficiencies.

Background	Contribution
Accidentals	80.5 ± 0.1
^{9}Li/^{8}He	13.6 ± 1.0
Fast neutron & Atmospheric ν	<9.0
^{13}C$(\alpha, n)^{16}$O$_{gs}$, $np \to np$	157.2 ± 17.3
^{13}C$(\alpha, n)^{16}$O$_{gs}$, ^{12}C$(n, n')^{12}$C* (4.4 MeV γ)	6.1 ± 0.7
^{13}C$(\alpha, n)^{16}$O 1st exc. state (6.05 MeV e^+e^-)	15.2 ± 3.5
^{13}C$(\alpha, n)^{16}$O 2nd exc. state (6.13 MeV γ)	3.5 ± 0.2
Total	276.1 ± 23.5

純化によりほぼ無視できる。

All in one slide…



●志賀(~80km)のパワーが上がっているので大型装置ならON/OFFさっ引きで精密測定が可能か？

●θ13、ヒエラルキーも可能？

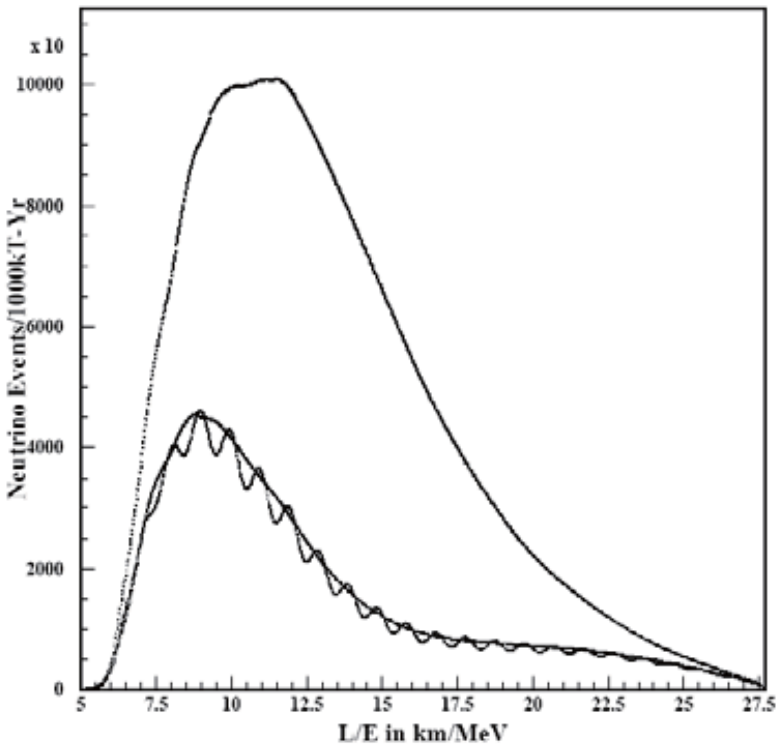
J.Learned et al. hep-ex/0612022

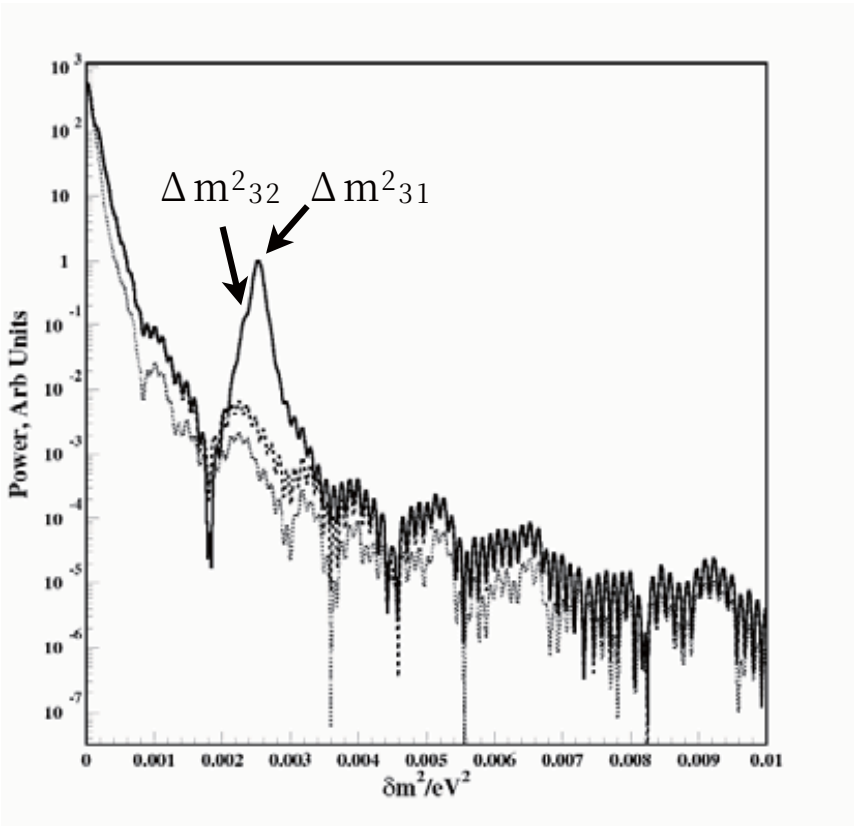
H.Minakata et al. PR D74, 053008 (2006)

$$P_{ee}=1-\{\cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) + \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) + \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})\}$$

← 強

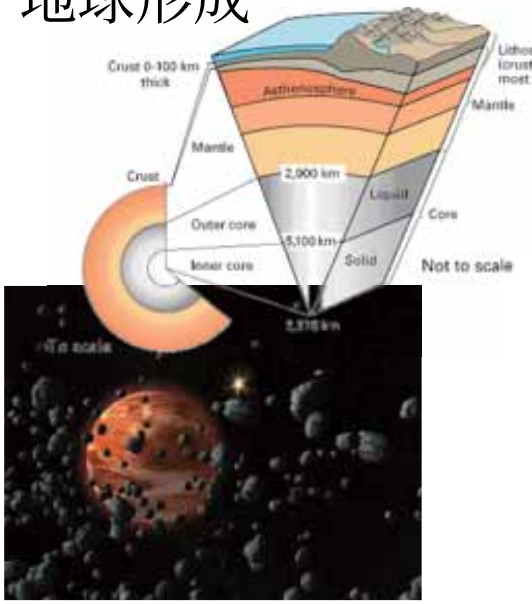
← 弱



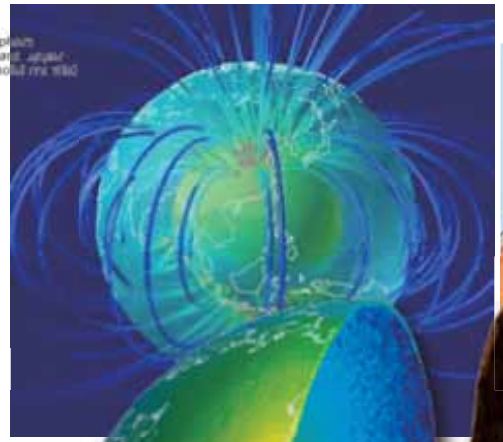


2．地球起源反電子ニュートリノの高精度精密測定

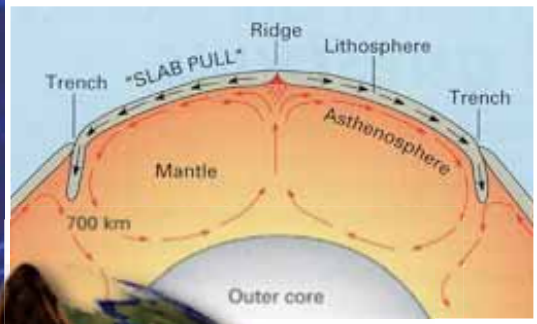
地球形成



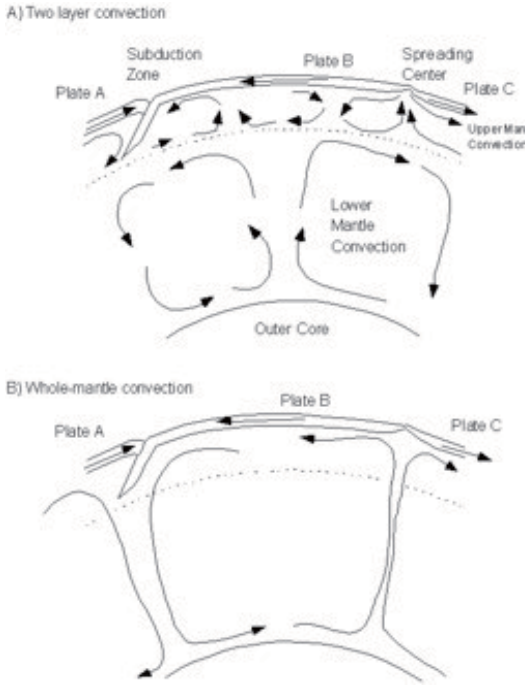
地磁気生成機構



地球ダイナミクス



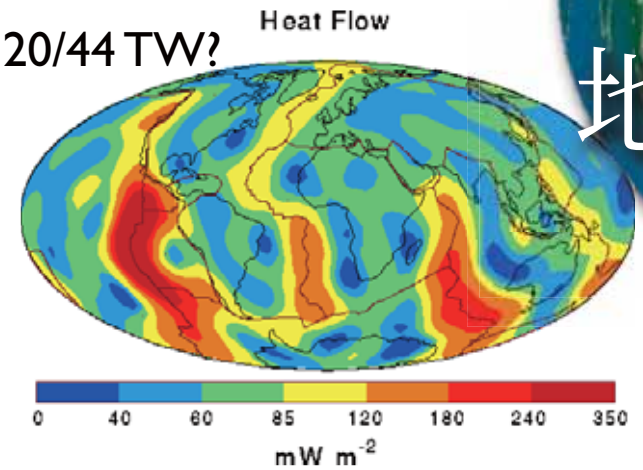
長年の謎へ



ニュートリノ

地球物理の推進

20/44 TW?



$$^{238}\mathrm{U} \rightarrow ^{206}\mathrm{Pb} + 8\,^{4}\mathrm{He} + 6\mathrm{e}^{-} + 6\bar{\nu}_{\mathrm{e}} + 51.7\,\mathrm{MeV}$$

$$^{232}\mathrm{Th} \rightarrow ^{208}\mathrm{Pb} + 6\,^{4}\mathrm{He} + 4\mathrm{e}^{-} + 4\bar{\nu}_{\mathrm{e}} + 42.7\,\mathrm{MeV}$$

$$^{40}\mathrm{K} \rightarrow ^{40}\mathrm{Ca} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}} + 1.31\,\mathrm{MeV}$$

total 19TW?

地球科学の５大問題に関連

5 Big Questions:

McDonough in neutrino 2008

△ - What is the Planetary K/U ratio?
Potassium neutrino detection! *planetary volatility curve*

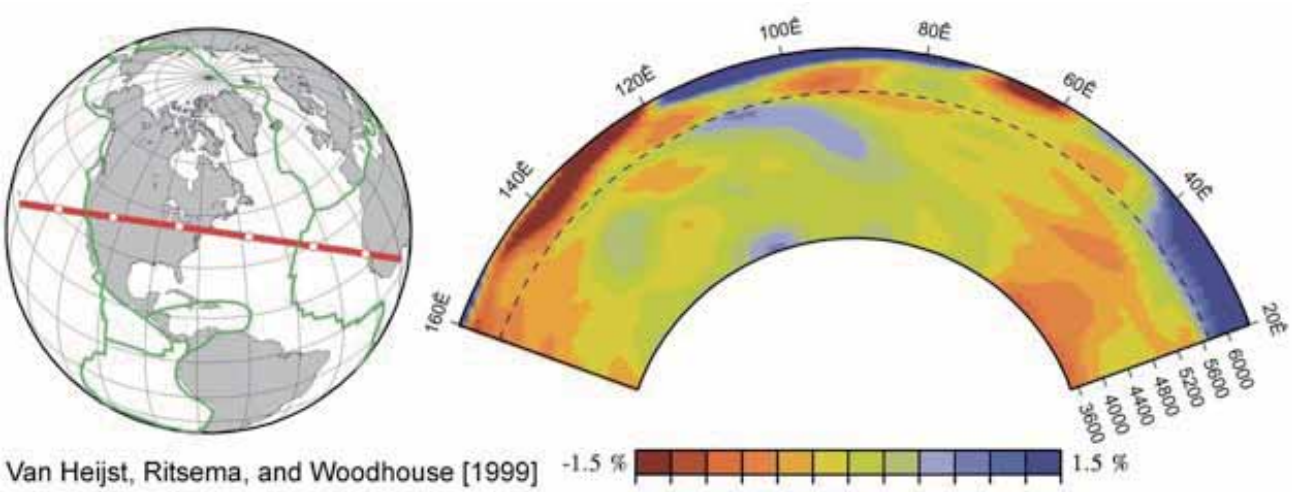
○ Radiogenic contribution to heat flow?
secular cooling

○ Distribution of reservoirs in mantle?
whole vs layered convection

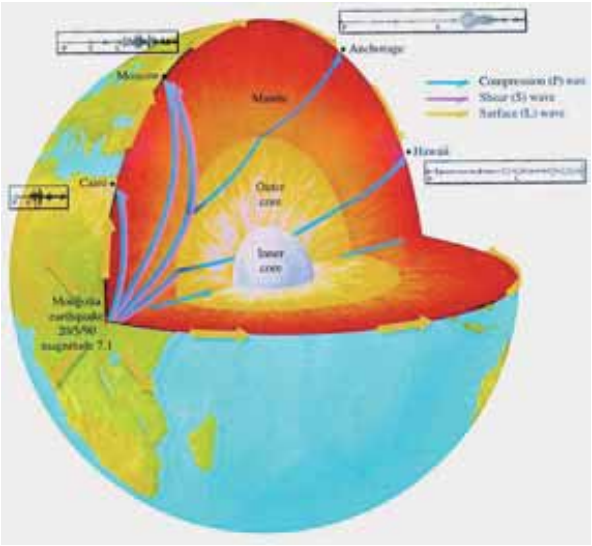
△ - Radiogenic elements in the core??
directional measurement? *Earth energy budget*

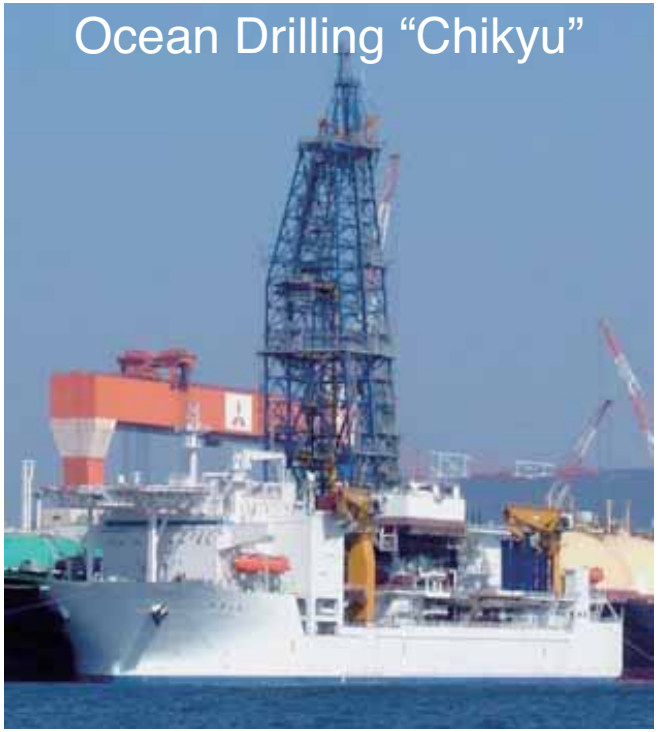
○ Nature of the Core-Mantle Boundary?
geo-reactor *hidden reservoirs*

Possible windows to the interior of the earth



Van Heijst, Ritsema, and Woodhouse [1999]





4000m(sea depth)+7000m (boring)

Detailed seismic analysis gives precise "velocity" distribution. density/viscosity

However, it doesn't tell chemical composition.

Very deep boring may reach the upper mantle.

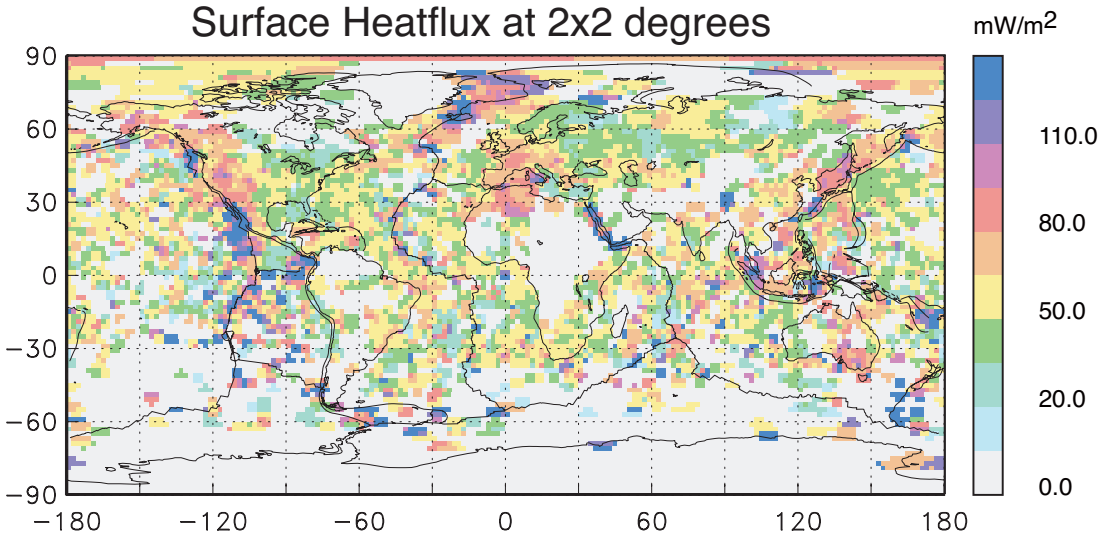
However, it's only up to 7 km.

Phase studies at high pressure and temperature, solubility studies are all in "Laboratory".

Analyses of eruptions,
magnetic field measurement provide imformation.

However, it's not very conclusive for the global structure.

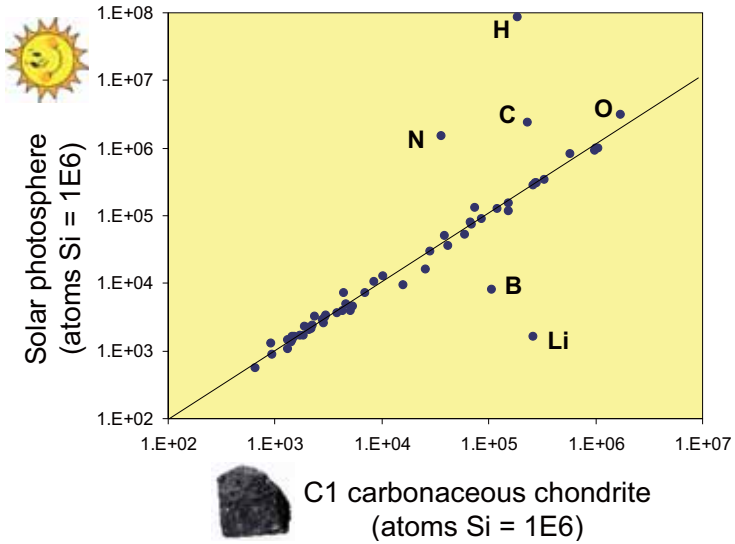
surface heat flow measurement

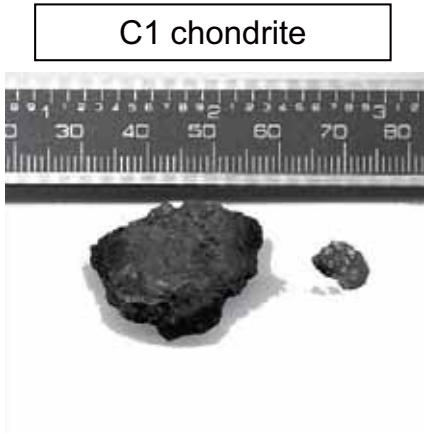


reference : 44 TW

Despite its high importance for geophysics, heat flow is not understood very well.

BSE model



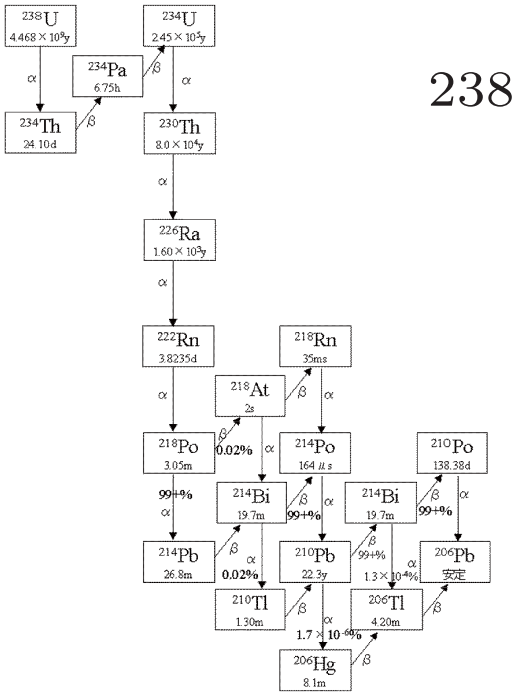


Meteorite analysis provides estimation for radioactive heat production. (total 19TW, U : 8TW, Th : 8TW, K : 3TW)

The other sources are thought to be initial heat/ latent heat/ gravitational energy.

Direct measurement is desired. How??

^{238}U series



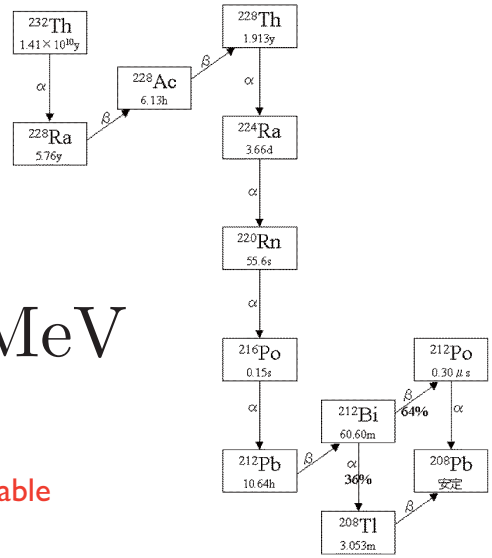
$$^{238}\mathrm{U} \rightarrow ^{206}\mathrm{Pb} + 8\,^{4}\mathrm{He} + 6\mathrm{e}^{-} + 6\bar{\nu}_{\mathrm{e}} + 51.7\,\mathrm{MeV}$$

endpoint energy 3.27 MeV

observable

anti-electron-neutrinos are emitted.

^{232}Th series

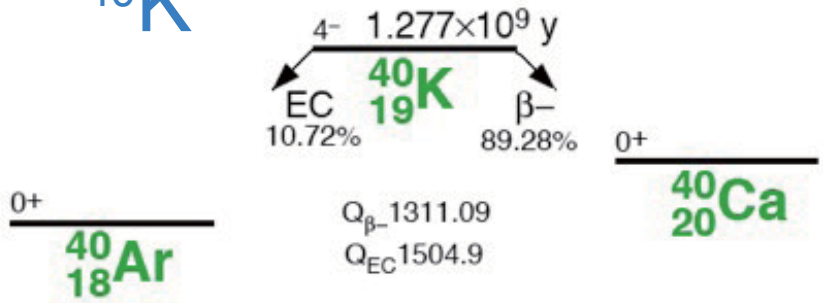


$$^{232}\mathrm{Th} \rightarrow ^{208}\mathrm{Pb} + 6\,^{4}\mathrm{He} + 4\mathrm{e}^{-} + 4\bar{\nu}_{\mathrm{e}} + 42.7\,\mathrm{MeV}$$

endpoint 2.25 MeV

observable

^{40}K



$$^{40}\mathrm{K} \rightarrow ^{40}\mathrm{Ca} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}}$$

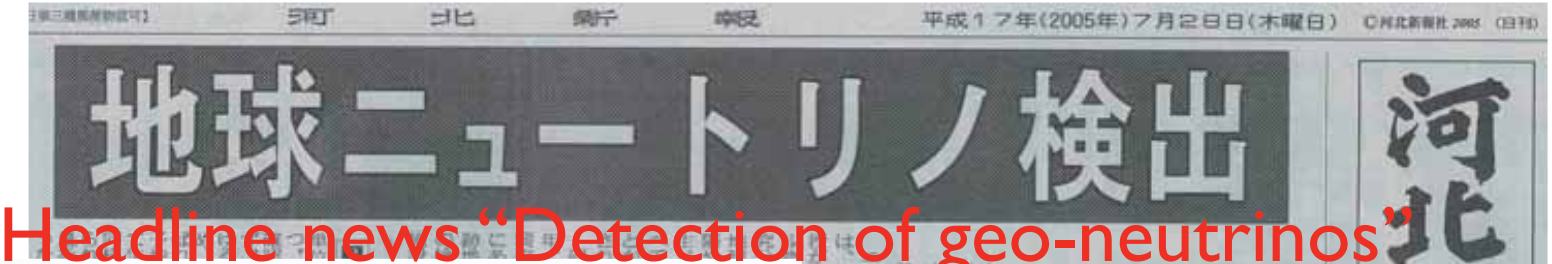
endpoint 1.31 MeV

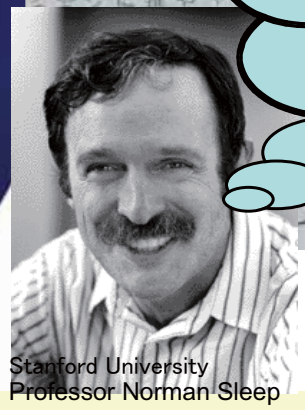
so far not observable

$$^{40}\mathrm{K} + \mathrm{e}^{-} \rightarrow ^{40}\mathrm{Ar} + \nu_{\mathrm{e}}$$

future interest

Headline news "Detection of geo-neutrinos"





Stanford University
Professor Norman Sleep

This is not an evolution but a revolution!

KamLAND established new method to investigate the deep interior of the earth and opened new science field "Neutrino Geophysics."

5 Big Questions: Prof. McDonough in Neutrino 2008

△ - What is the Planetary K/U ratio?

planetary volatility curve

neutrinos from Potassium? (need development)

○ - Radiogenic contribution to heat flow?

secular cooling

○ - Distribution of reservoirs in mantle?

whole vs layered convection

△ - Radiogenic elements in the core??

Earth energy budget

directional measurement? (under development)

○ - Nature of the Core-Mantle Boundary?

hidden reservoirs

geo-reactor?

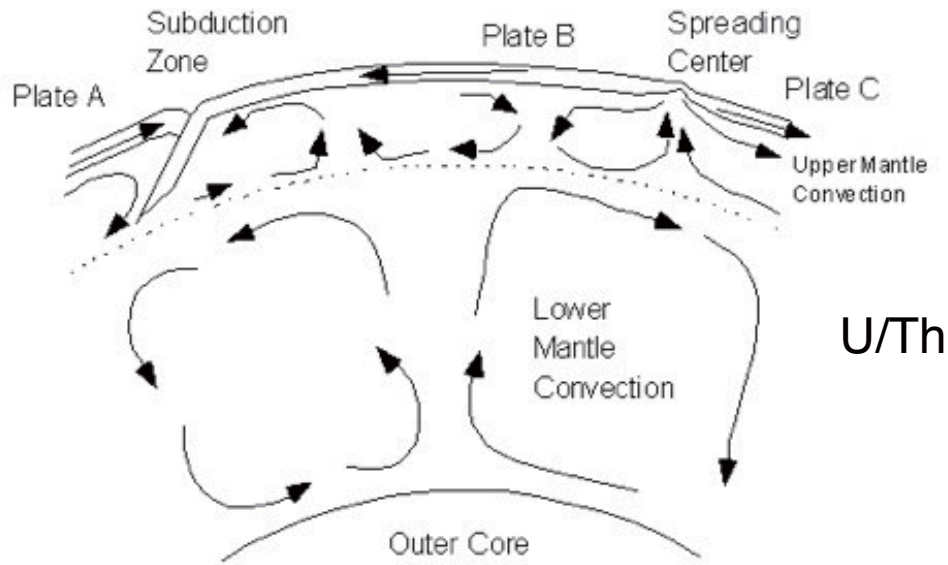
Neutrinos can play key roles on all these questions.

Only KamLAND is observing geo-neutrinos, now.

Two layer or whole mantle convection is still a long-standing argument.

A) Two layer convection

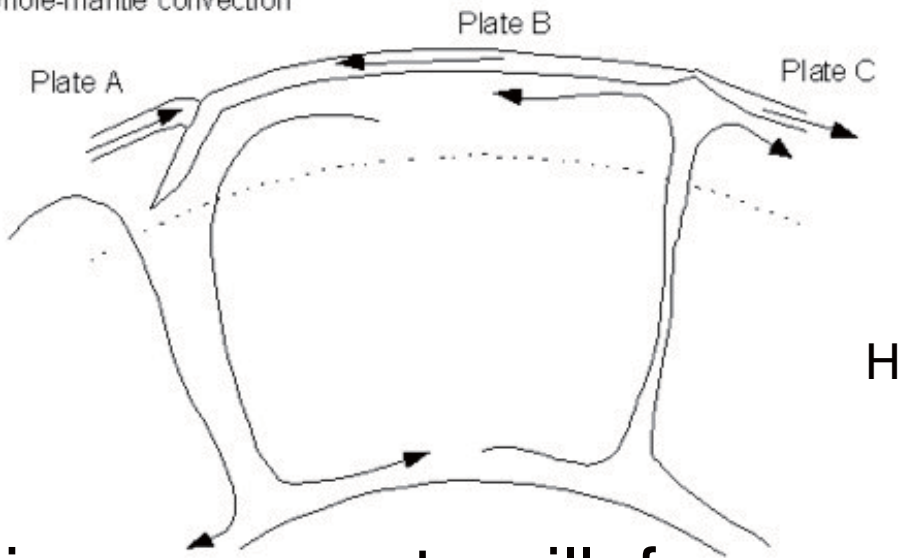
Geo-chemist



U/Th rich lower mantle

Geo-physicist

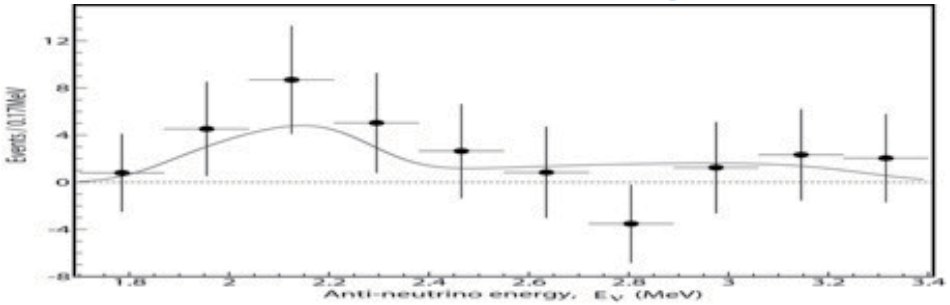
B) Whole-mantle convection

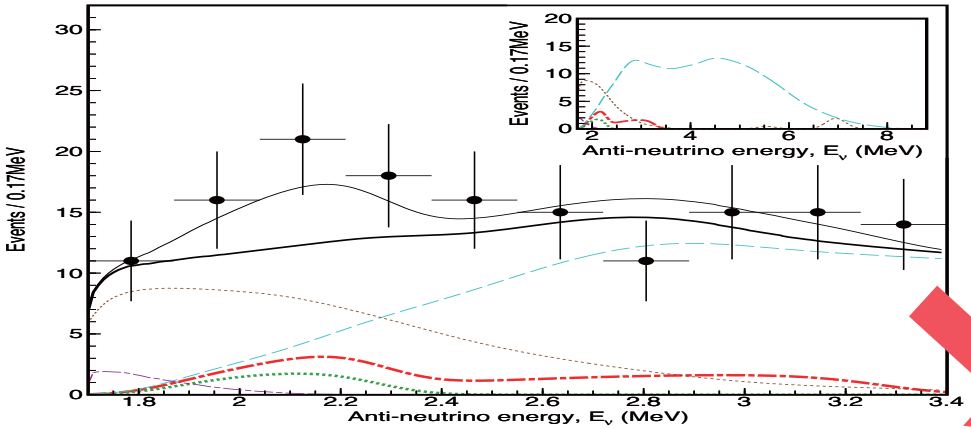


Homogeneous mantle

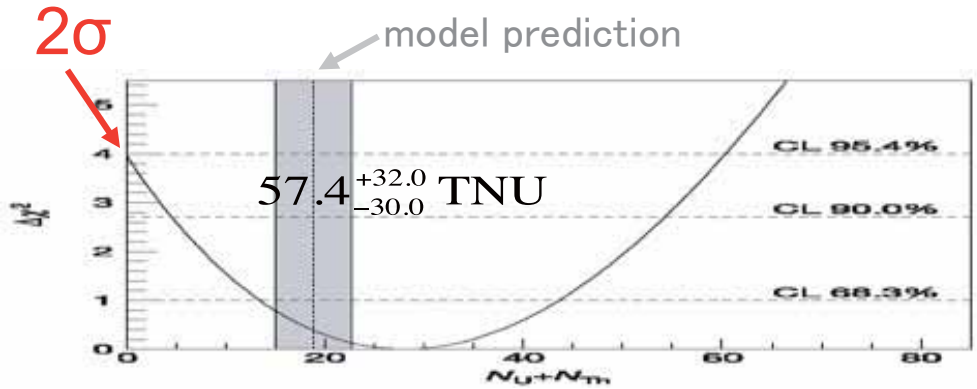
Future improvements will, for example, settle the discussion.

achievement 2 geo-neutrino observation

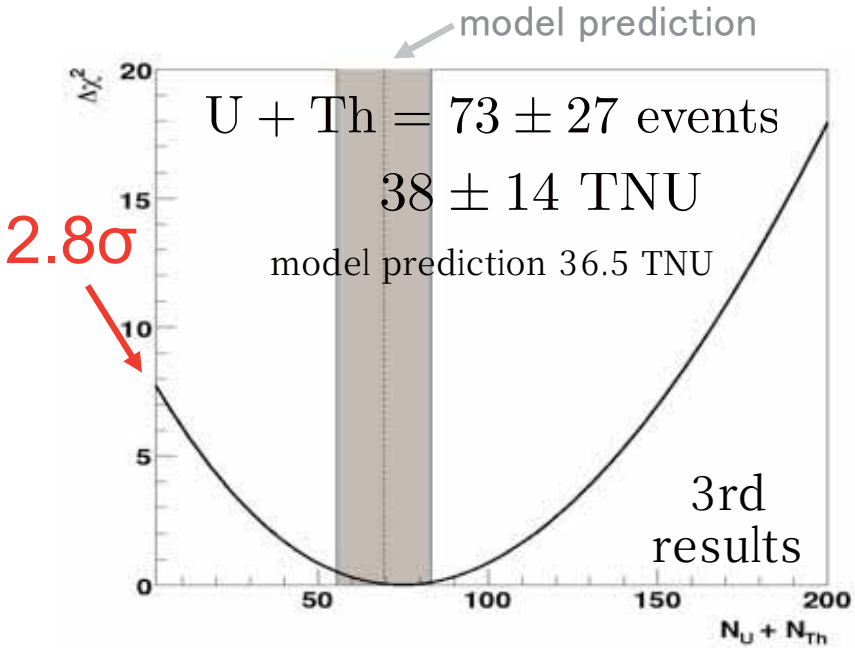


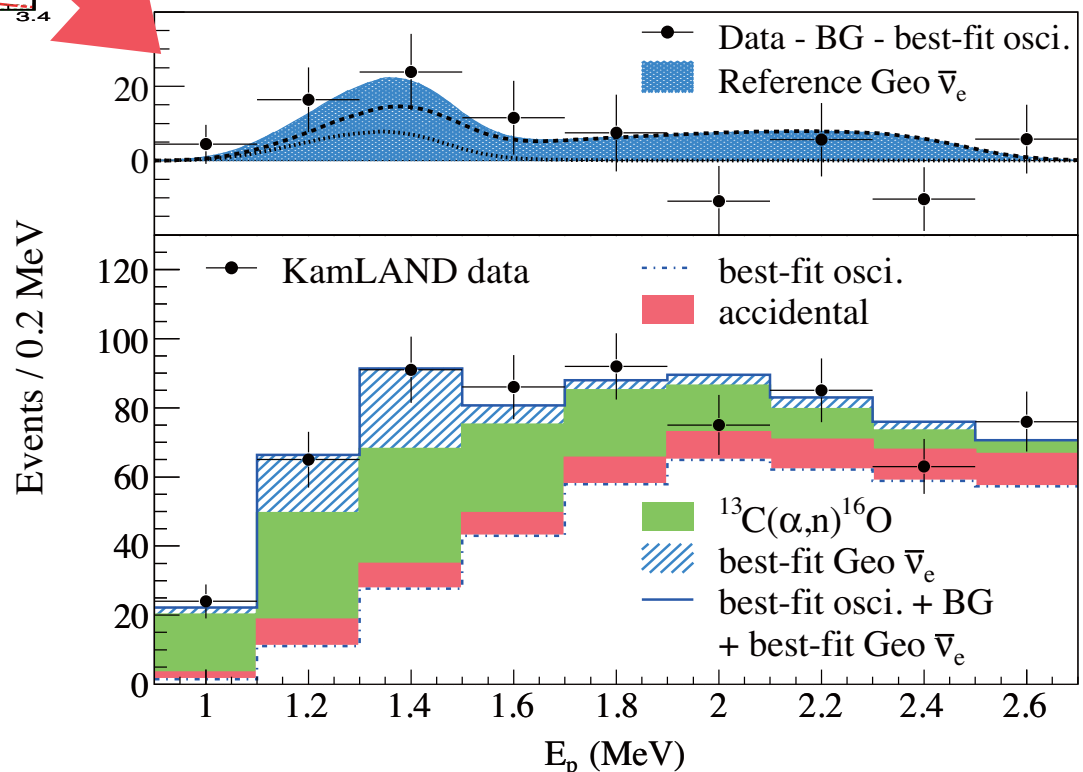


result on Nature



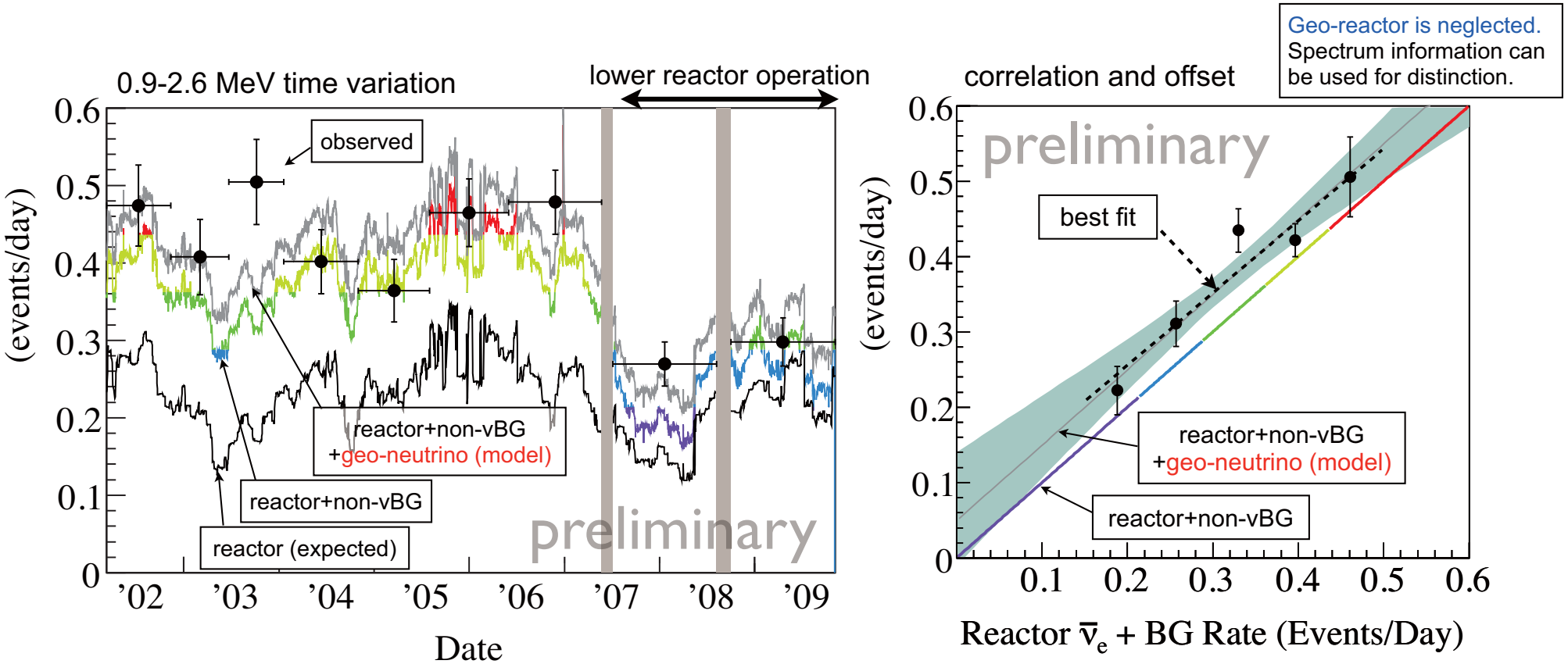
2005→2008





Background-continued

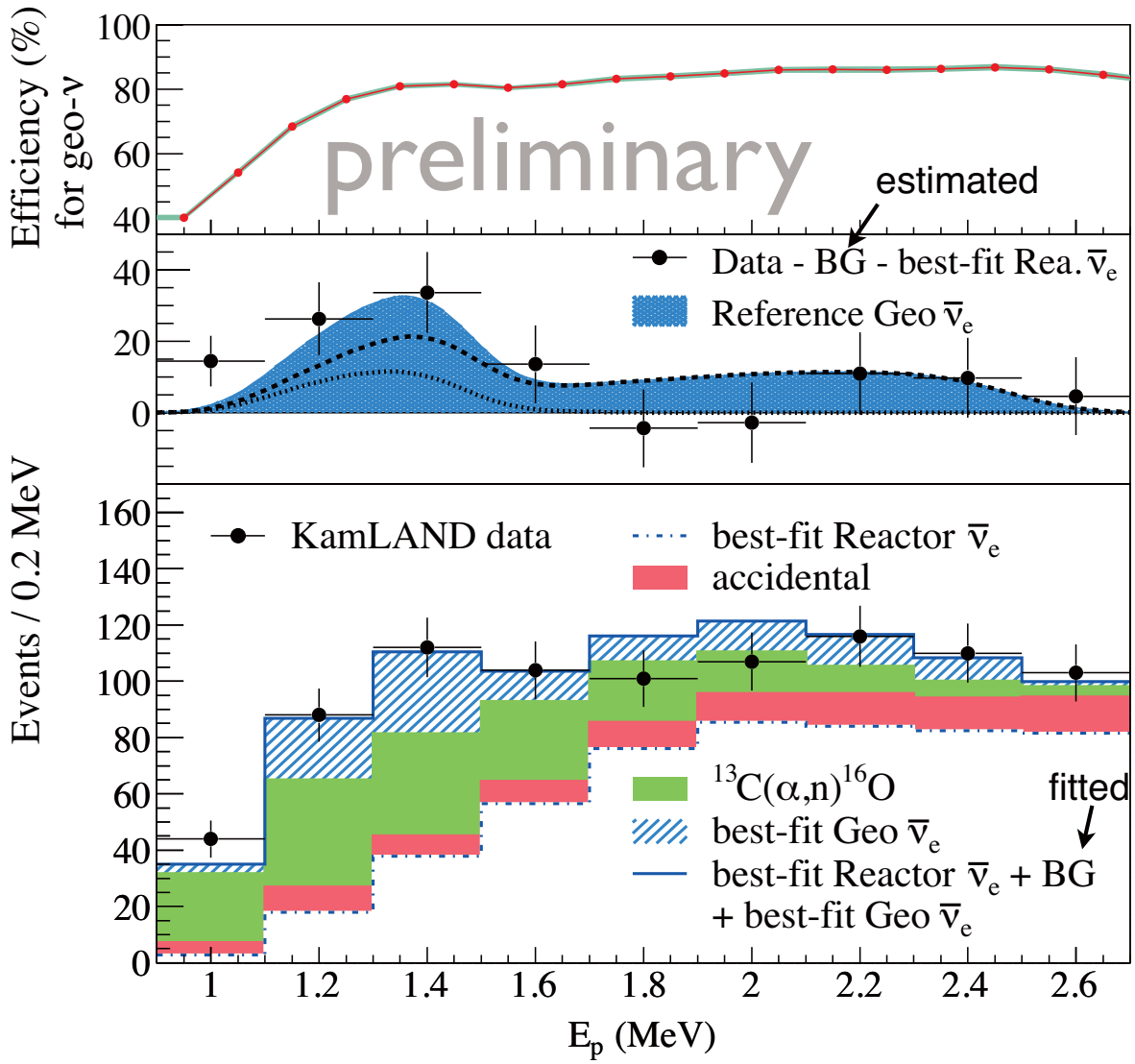
Operational issues at the power reactor and a serious earthquake reduced the reactor neutrino flux. KamLAND has experienced a large (but known) time variation of the background. The geo-neutrino background rate is about half of what it was before 2007.



Constant contribution from geo-neutrinos is seen above the estimated reactor neutrino + non-neutrino background in the energy range 0.9 - 2.6 MeV.
Time information is effective to improve geo-neutrino discrimination.

Observed energy spectrum and estimated backgrounds

Period: March 9, 2002 ~ November 4, 2009
Total exposure: 3.49 x 10^{32} target-proton-years



841 candidates in 0.9-2.6 MeV

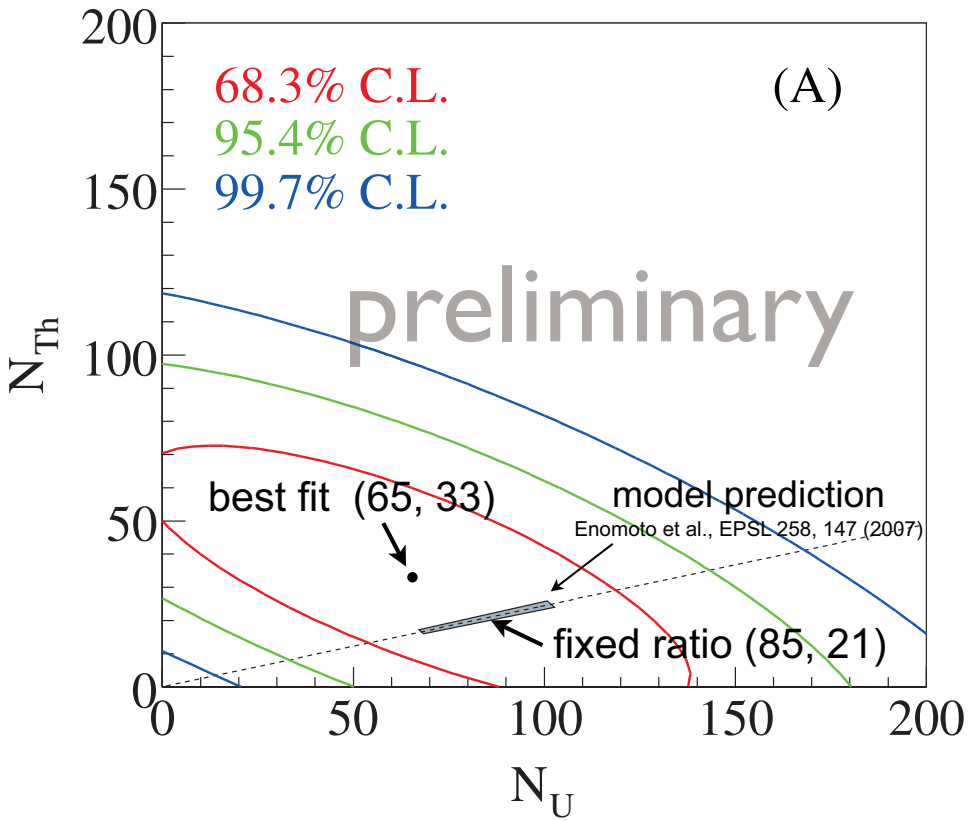
BG summary

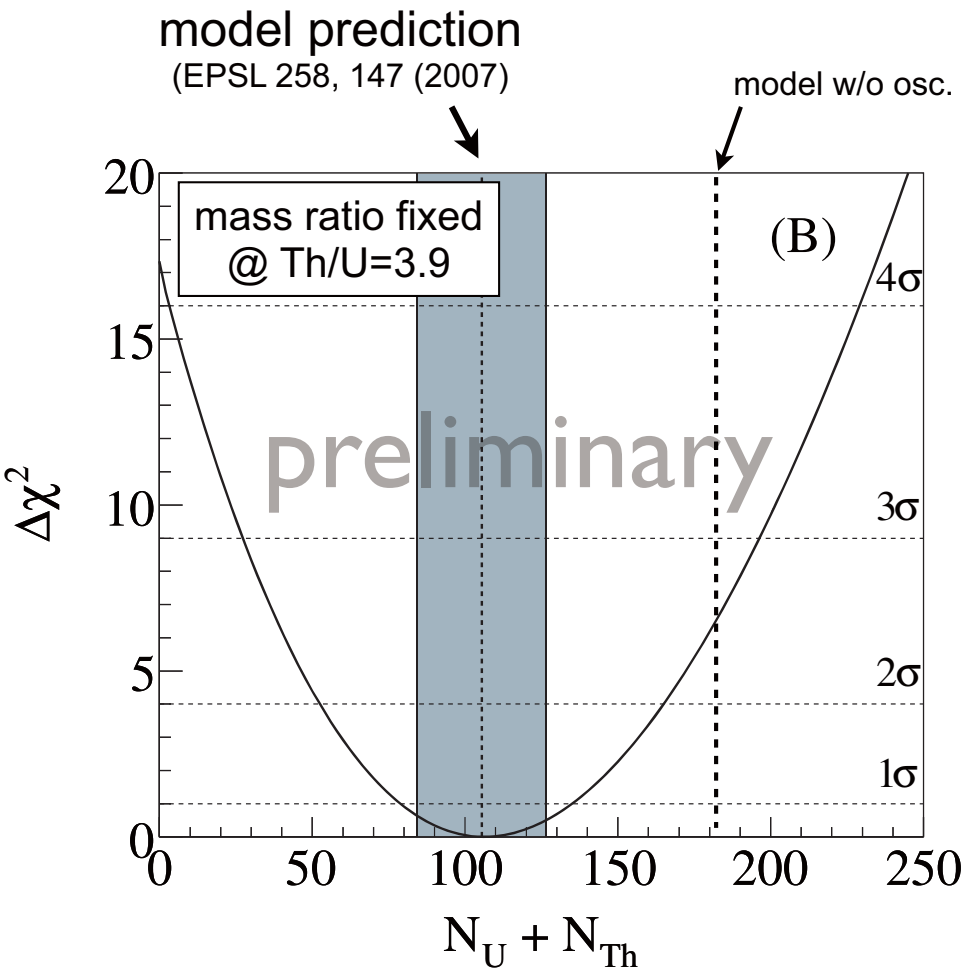
reactor $\bar{\nu}_e$	484.7±26.5
$^{13}C(\alpha,n)^{16}O$	165.3±18.2
accidental	77.4±0.1
^{9}Li	2.0±0.1
atm.ν+fast n	<2.8
Total	729.4±32.3

rate-only analysis 111^{+45}_{-43} events

Null signal exclusion 99.55% CL.
(rate-only hypothesis test)

Rate-shape-time analysis





0 signal is rejected at 99.997% CL. (>4σ)
(rate-shape-time $\Delta\chi^2$)

# of geo-ν events 106^{+29}_{-28}

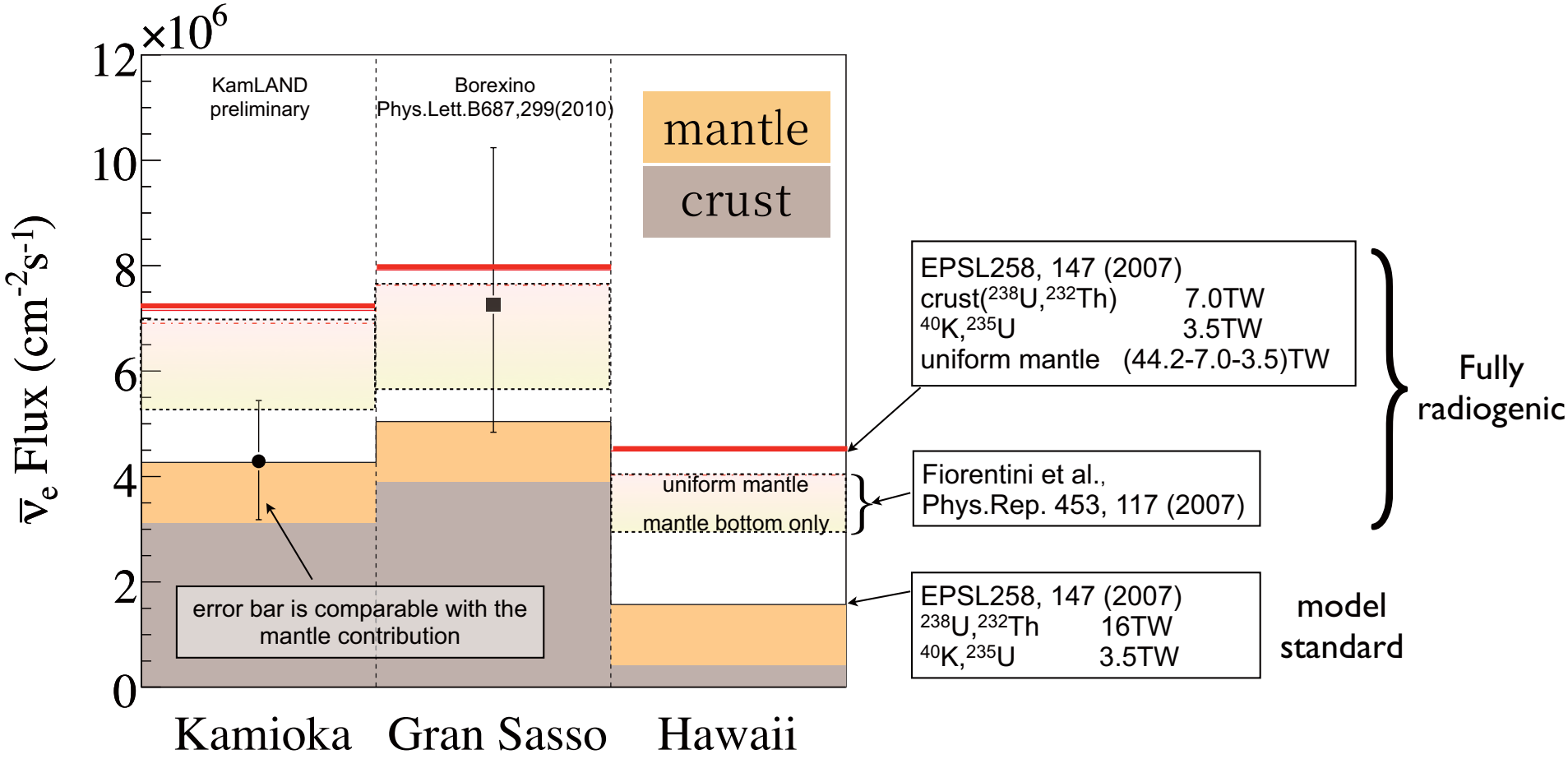
integrated $\bar{\nu}_e$ flux from 0 MeV for ^{238}U, ^{232}Th

$$4.3^{+1.2}_{-1.1} \times 10^6 \ /\mathrm{cm}^2/\mathrm{sec}$$

$$(38.3^{+10.3}_{-9.9}\ \mathrm{TNU})$$

corresponds to ~16TW (U,Th)

Comparison with models



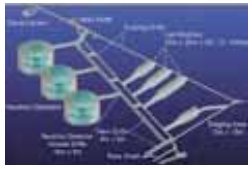
The observed geo-neutrino flux is consistent with the model prediction.
For the first time, fully radiogenic models start to be disfavored. (KL only 2.4σ, KL+Borexino 2.3σ)

From a geophysical point of view, extracting the mantle contribution is very important.
In the future, the combination of data from multiple sites and possible data from an oceanic experiment (where the crust is much thinner and so its contribution much smaller) will provide stronger constraints.

将来の地球ニュートリノ観測計画

Locations for Possible Geonu Experiments

Color indicates U/Th neutrino flux, mostly from crust



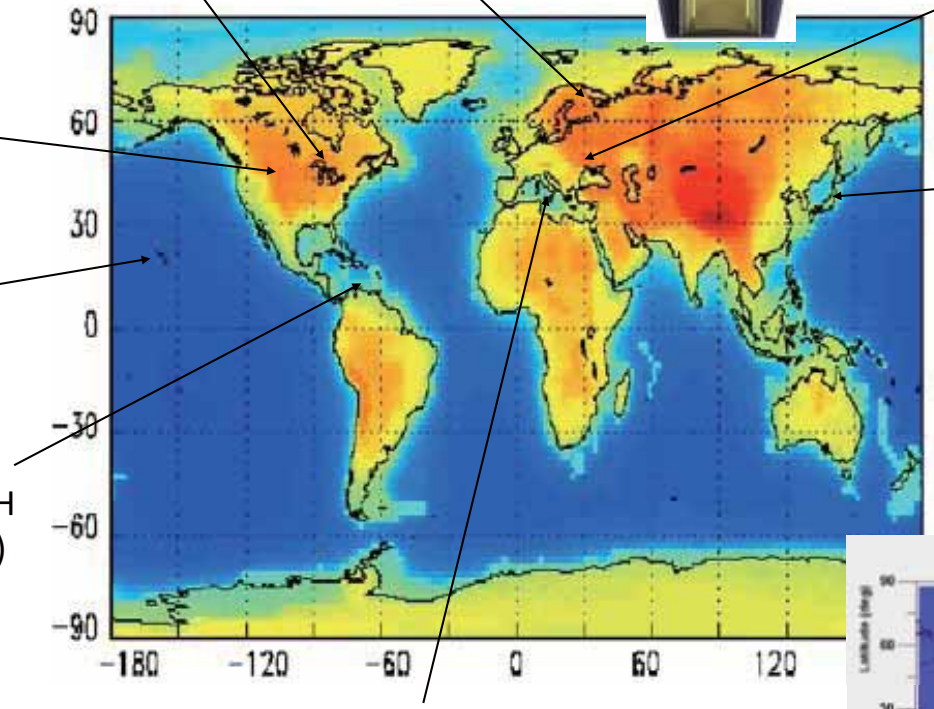
DUSEL
(R&D – 300 kton)
4200 mwe

SNO+ (soon – 1 kton)
5400 mwe

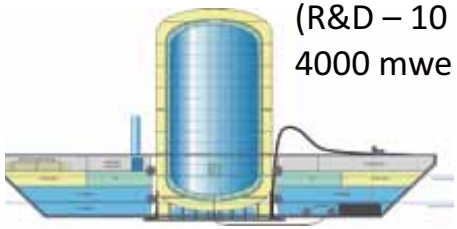
LENA(R&D – 50 kton)

Baksan(R&D)

KamLAND
(running – 1kton)
2700 mwe

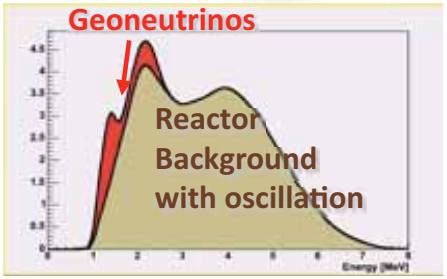


Hanohano
(R&D – 10 kton)
4000 mwe

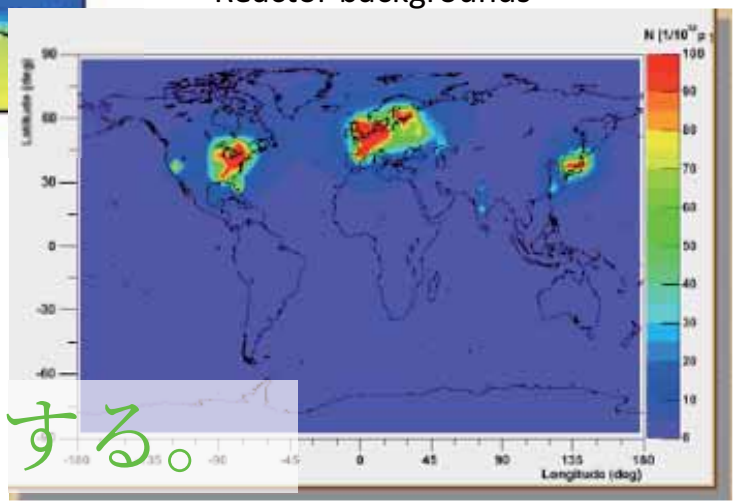


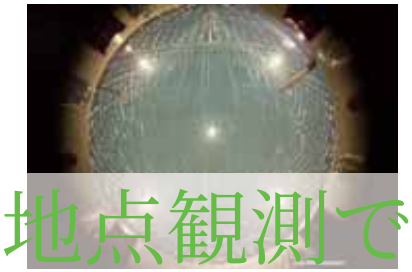
マントルの寄与が７５％
移動可能

EARTH
(R&D)



Reactor backgrounds

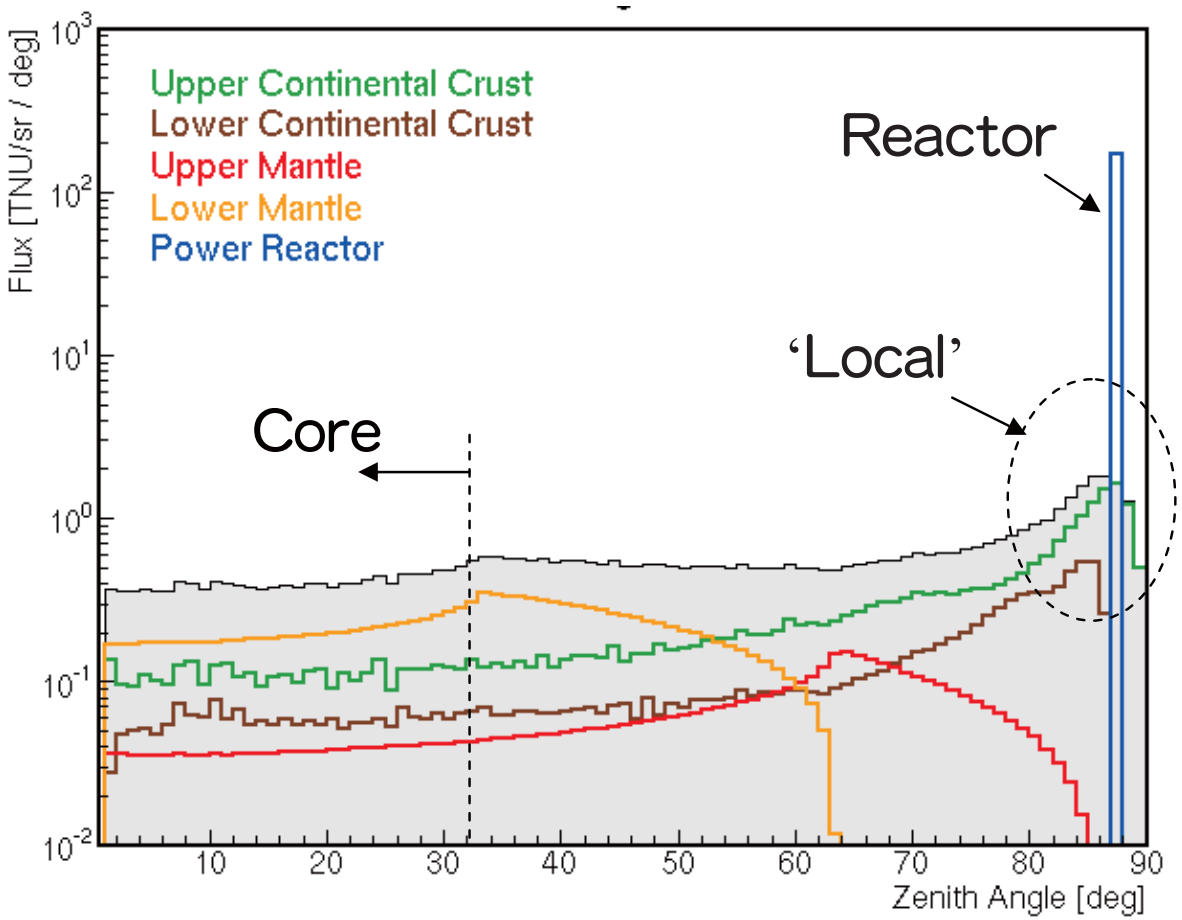




Borexino
(running – 300 ton, 3700 mwe)

多地点観測で地球を立体視する。

もっと直接的には、方向が測定できれば．．．．



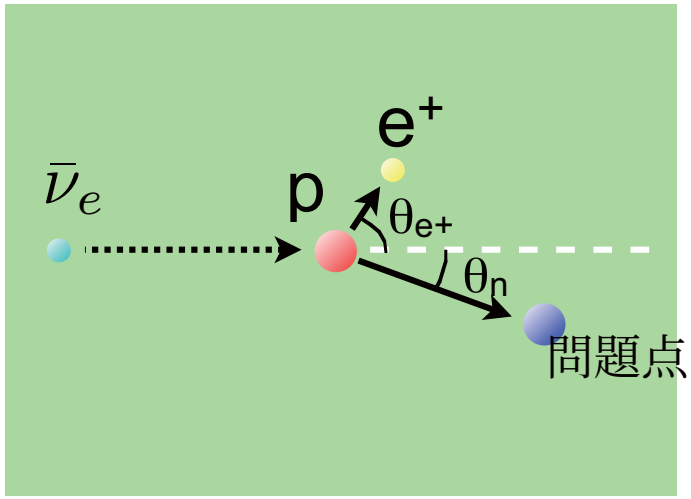
原子炉ニュートリノを区別できる。

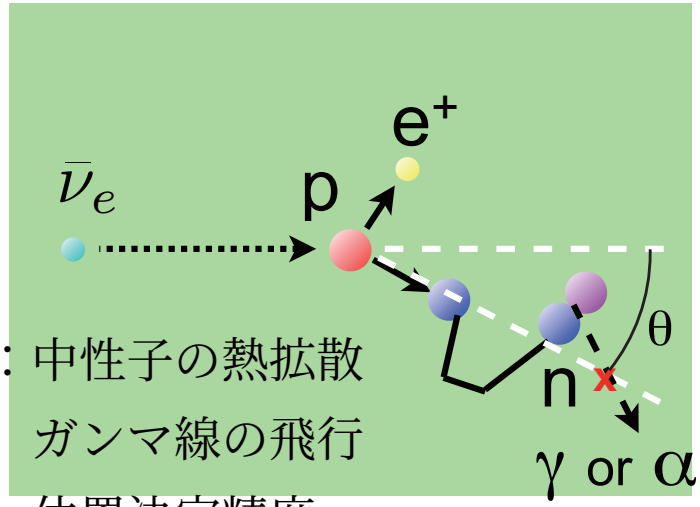
核/マントル/地殻を効率的に区別

等方向に発光するシンチレーションは方向情報を失っている！？

何か手はないか?

方向測定

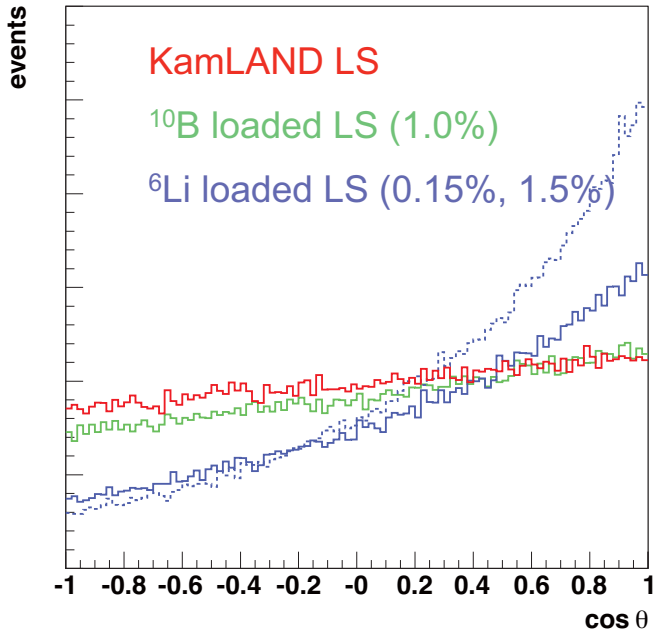




問題点：中性子の熱拡散

ガンマ線の飛行

位置決定精度



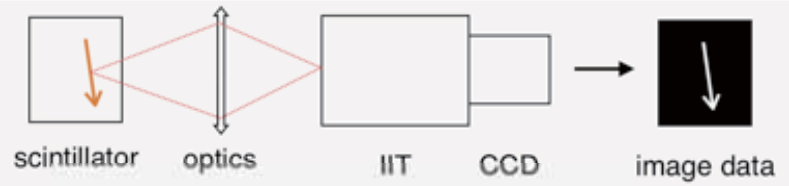
先発　　遅延

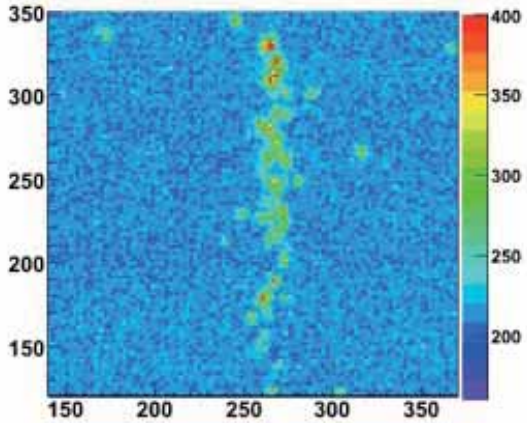
$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$n + {}^6\mathrm{Li} \rightarrow \alpha + {}^3\mathrm{H}$$

σ(n+Li6)~940 barn　σ(n+p)~0.3 barn

リチウム含有液体シンチレータの開発に成功

PC + PPO + POE(surfactant)
+ LiBr water solution

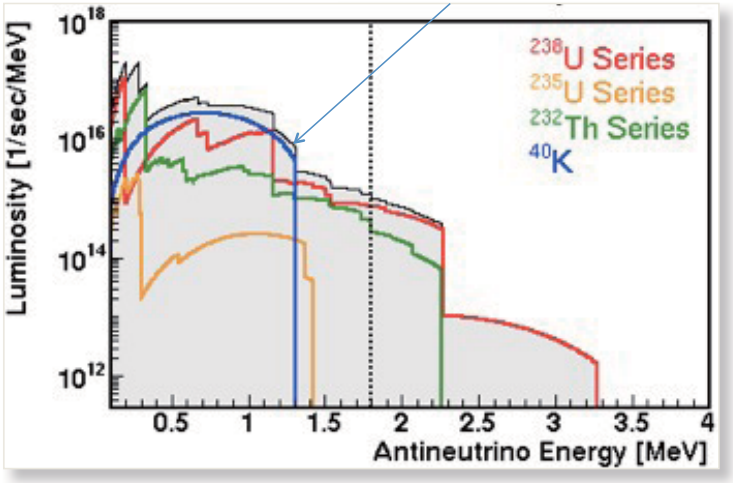




ミュー粒子の軌跡の撮影に成功

Measuring Potassium 40 Content

$$^{40}K \rightarrow {}^{40}Ca + e^- + \bar{\nu}_e$$



- Energy source for geo-dynamo is not understood well.
- Potassium seems to be under-abundant.
- Is potassium accumulated in the core?
- Reference earth model predicts 3 TW from potassium.
- Potassium is below inverse beta threshold.

  Any other nuclei?

	Natural Abundance	Ethresh [MeV]	Amount for ~100 ev/yr
^{187}Os	1.6%	1.025	16 Gton
^{3}He	<0.01%	1.041	7.4 ton
^{107}Ag	51.8%	1.055	1.7 Gton
^{151}Eu	47.8%	1.098	680 kton
^{93}Nb	100%	1.114	6.8 Gton
^{171}Yb	14.3%	1.119	98 kton
^{14}N	99.6%	1.179	98 Mton
^{79}Br	50.7%	1.181	2.1 Gton
^{35}Cl	75.8%	1.190	4.9 Mton
^{135}Ba	6.6%	1.227	470 Gton
^{155}Gd	14.8%	1.268	550 Mton
^{33}S	0.76%	1.271	14 kton
^{106}Cd	1.2%	1.216	~10 kton

Potassium geo-neutrino flux

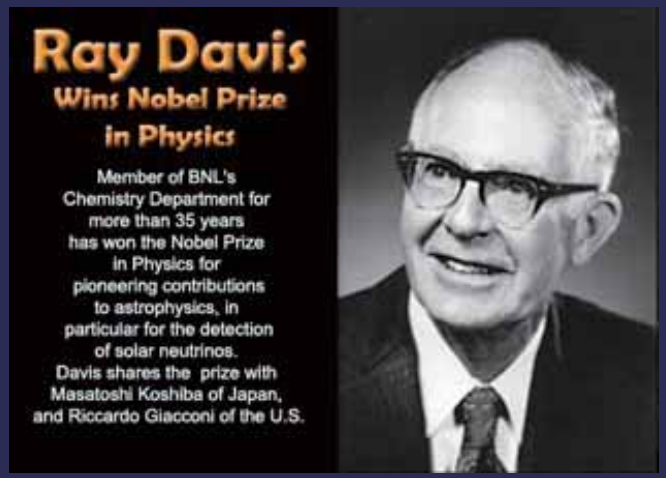
- (5-15) × 10^6 cm^{-2} s^{-1} for the antineutrinos (<1.311 MeV)
- (5-15) × 10^5 cm^{-2} s^{-1} for the 44 keV ν_e
- (2-6) × 10^3 cm^{-2} s^{-1} for the 1.5 MeV ν_e
- compare to 1.44 MeV pep solar neutrinos 1.42× 10^8 cm^{-2} s^{-1}

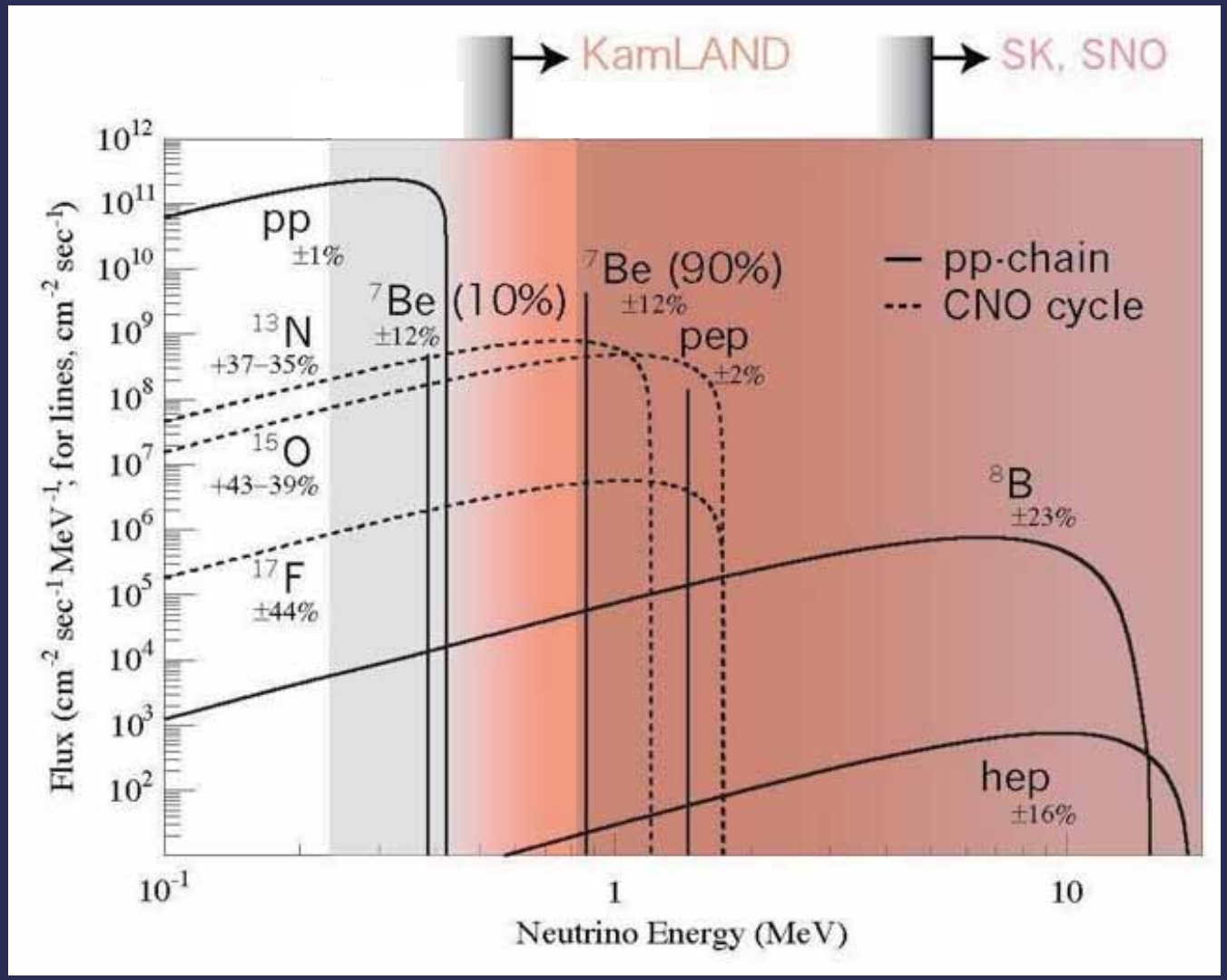
So far, no feasible implementation is proposed.

3．太陽起源電子ニュートリノの高精度精密測定

太陽ニュートリノ欠損現象の発見

R.デービス
実験開始
(1968～)

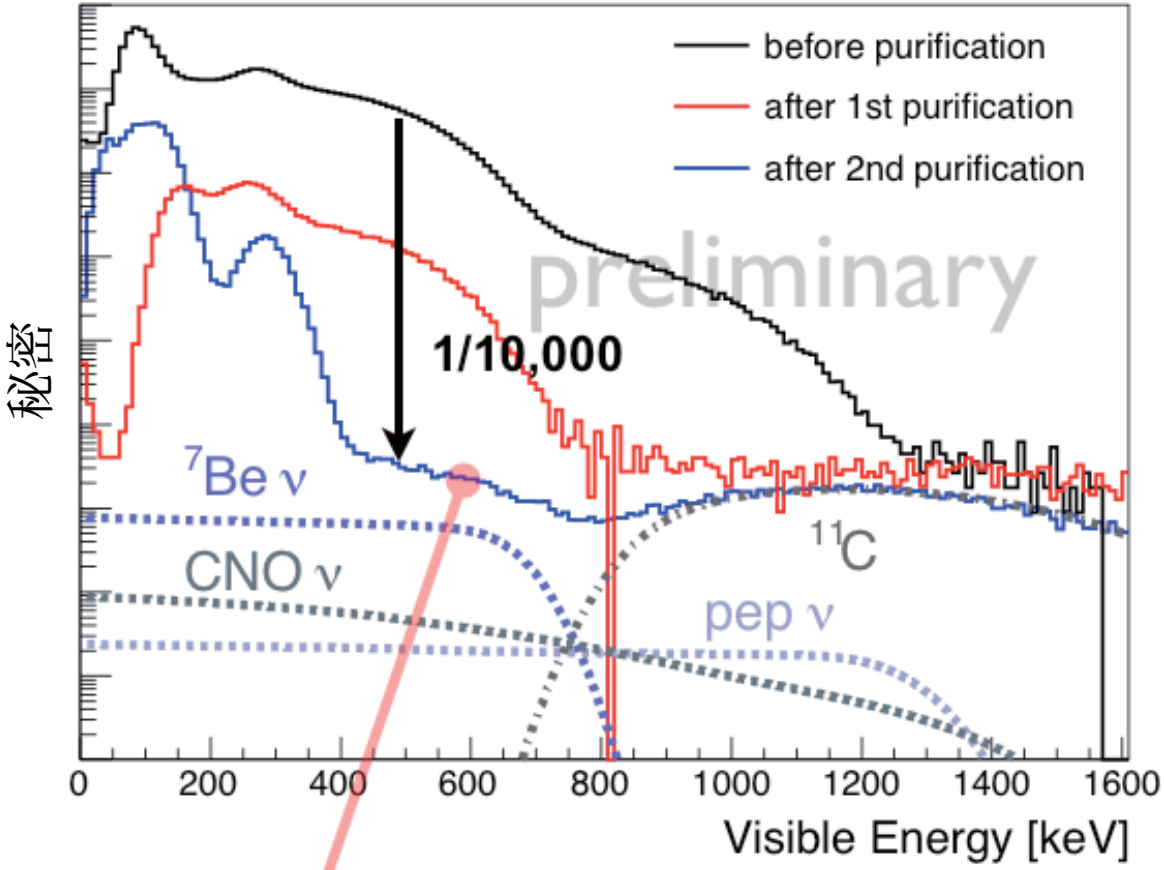


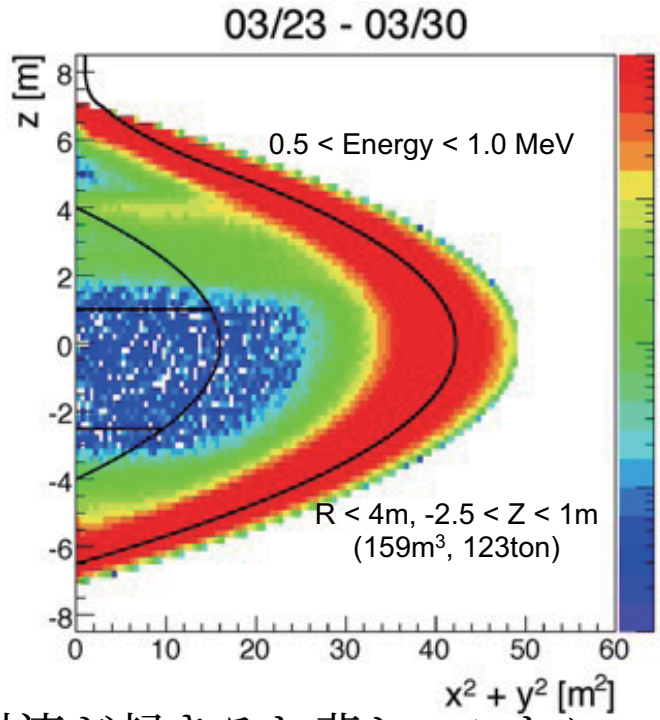


- ^{7}Beニュートリノの初検出
- 星の進化の過程の実験的検証

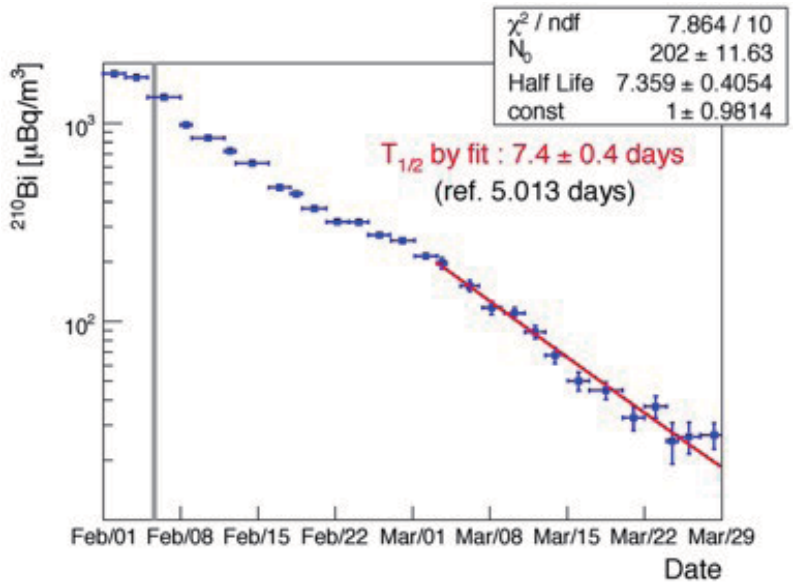
- 原子炉反電子ニュートリノ振動との比較：CPT対称性の検証

再純化の成果２





対流が起きると悲しいことに。。



再純化により、^{7}Be太陽ニュートリノが観測できるレベルにバックグランドを低減できた。

^{238}U: 3.5×10^{-18}	→ 7.3×10^{-19} g/g	OK
^{232}Th: 5.2×10^{-17}	→ 1.5×10^{-17} g/g	OK
^{40}K: 40 μBq/m^3	→ <1.5 μBq/m^3	OK
^{85}Kr: 574000 μBq/m^3	→ 9 μBq/m^3	我慢できる
^{210}Bi: 52,000 μBq/m^3	→ 23 μBq/m^3	何とか我慢できる（バルーン表面や配管から供給している可能性）

やり残したこと

^{8}B spectrum upturn MSWの証拠　**KamLAND+MoGURA, KamLANDi**

^{10}C, ^{11}C をタギングで低減できれば2MeV程度までつながる

^{11}C のマルチバーテックス識別で1.5MeV程度までつながる

^{7}Be の精密測定　**KamLAND2**

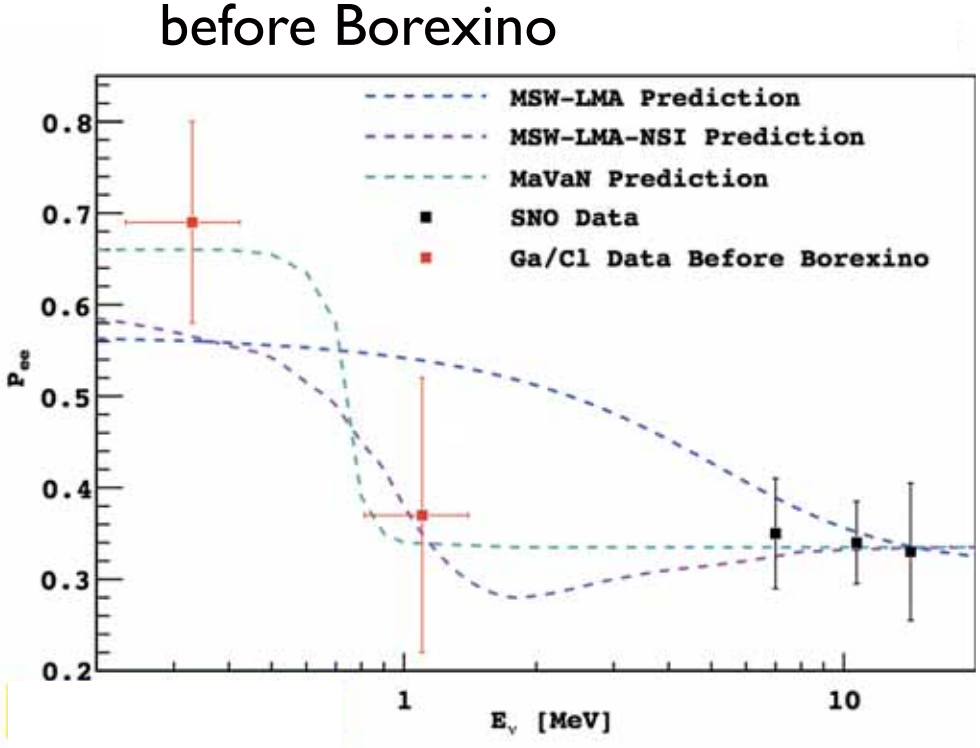
^{210}Bi (^{210}Pb) , ^{85}Krの更なる低減と対流の制御、清浄なバルーンの製作が必要

pep/CNOの測定　**KamLAND2/KamLANDi**

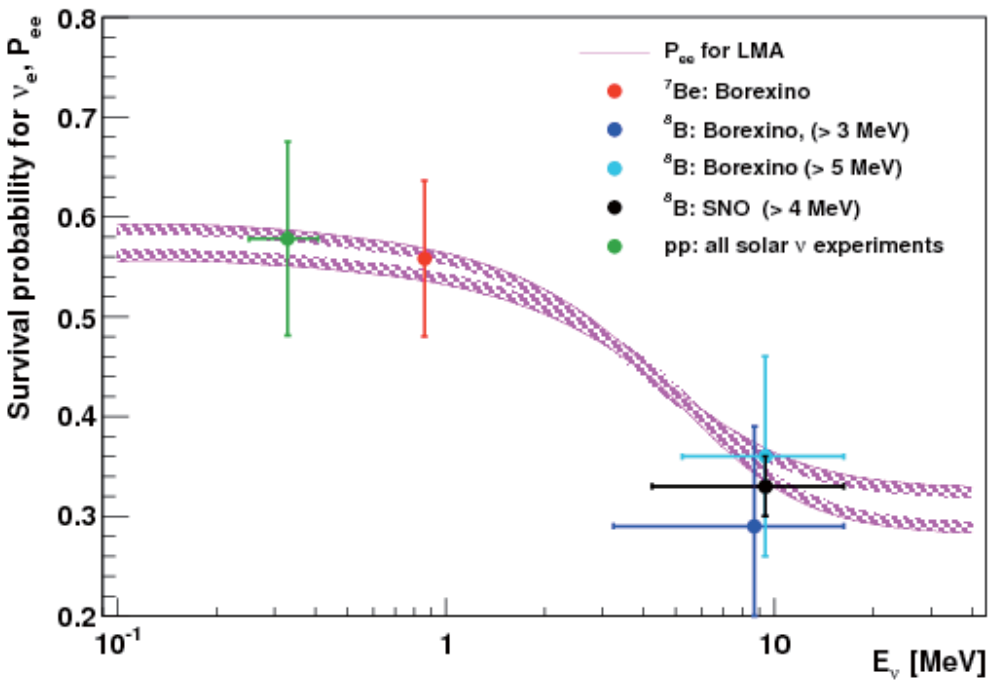
^{11}C のタギング向上が必要、マルチバーテックス識別でより強力

^{210}Bi (^{210}Pb) の更なる低減と対流の制御、清浄なバルーンの製作が必要

before Borexino



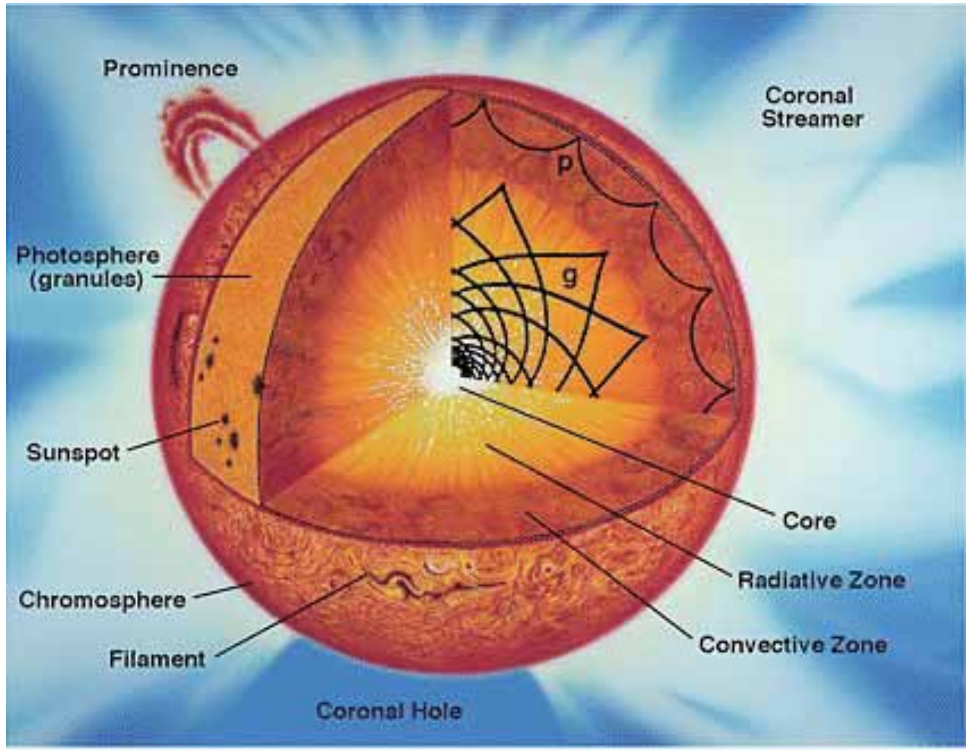
after Borexino

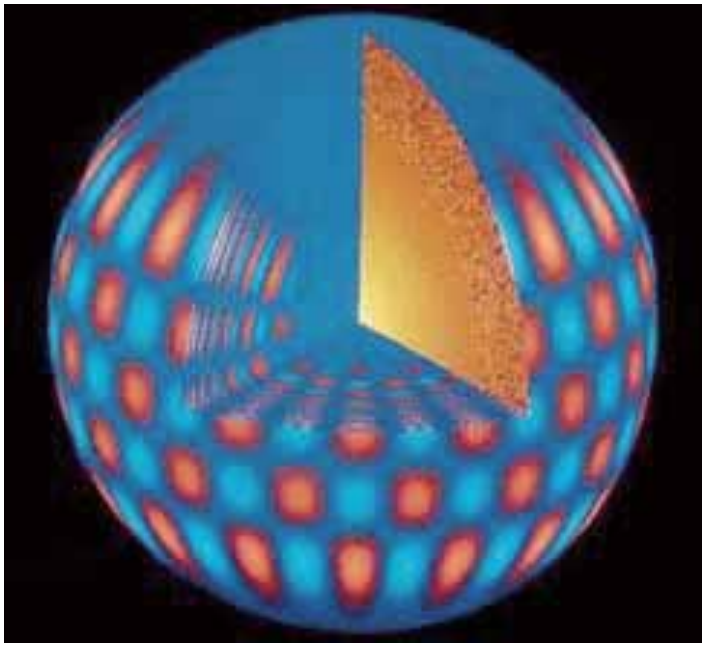


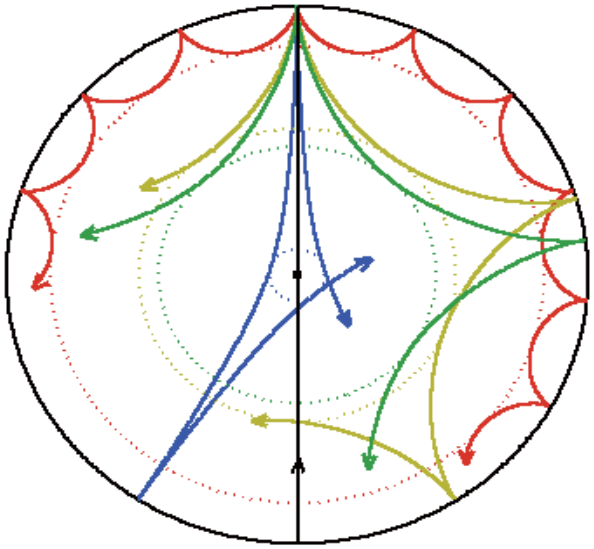
現在~3MeVまで

太陽中心を調べるには？

表面振動も使える（陽震学）







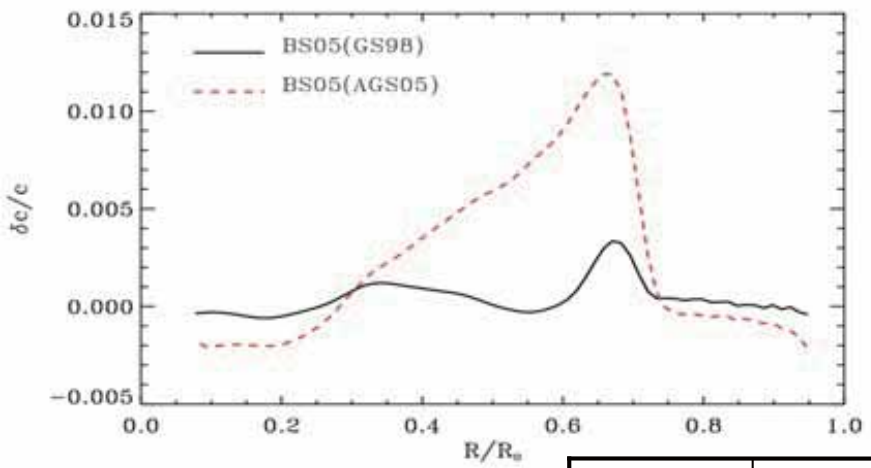
表面振動の測定も太陽中心に迫っている。

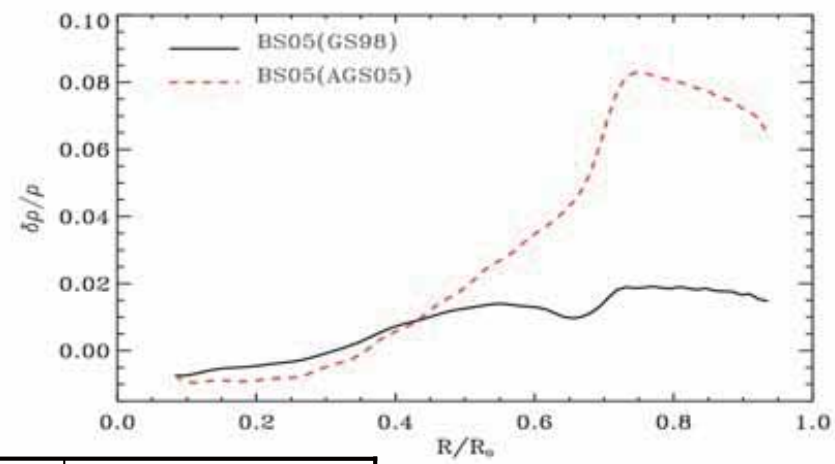
Success of the standard solar model has been highlighted by an agreement with helioseismology. BUT!

Results from the "Asplund group" summarized in Asplund, Grevesse & Sauval (2005; AGS05): improved modeling of solar atmosphere ⇒ large reduction in volatile elements: C, N, O, Ne, Ar

$(Z/X)_{\odot,\mathrm{today}} = 0.0165$ (old 0.0229)

Sound speed and density profiles are degraded, particularly outer half





	GS98	ASG05	Helioseism.
R_{CZ}	0.713	0.728	0.713±0.001
Y_{SURF}	0.243	0.229	0.2485 ±0.004
$\langle\delta c\rangle$	0.001	0.005	---
$\langle\delta\rho\rangle$	0.012	0.044	---

SSM – BS05(OP,AGS): Neutrino fluxes

- Central temperature lower by ~ 1%
- Lower CNO abundances directly affect CNO fluxes

	GS98	AGS05	
pp	5.99×10^{10}	6.06×10^{10}	↑ 1%
pep	1.42×10^{8}	1.45×10^{8}	↑ 2%
hep	7.93×10^{3}	8.25×10^{3}	↑ 4%
^{7}Be	4.84×10^{9}	4.34×10^{9}	↓ 10%
^{8}B	5.69×10^{6}	4.51×10^{6}	↓ 20%
^{13}N	3.05×10^{8}	2.00×10^{8}	↓ 33%
^{15}O	2.31×10^{8}	1.44×10^{8}	↓ 38%
^{17}F	5.84×10^{6}	3.25×10^{6}	↓ 44%

$$\phi_{\rm SNO}(^{8}{\rm B}) = 4.94 \pm 0.21^{+0.38}_{-0.34}$$

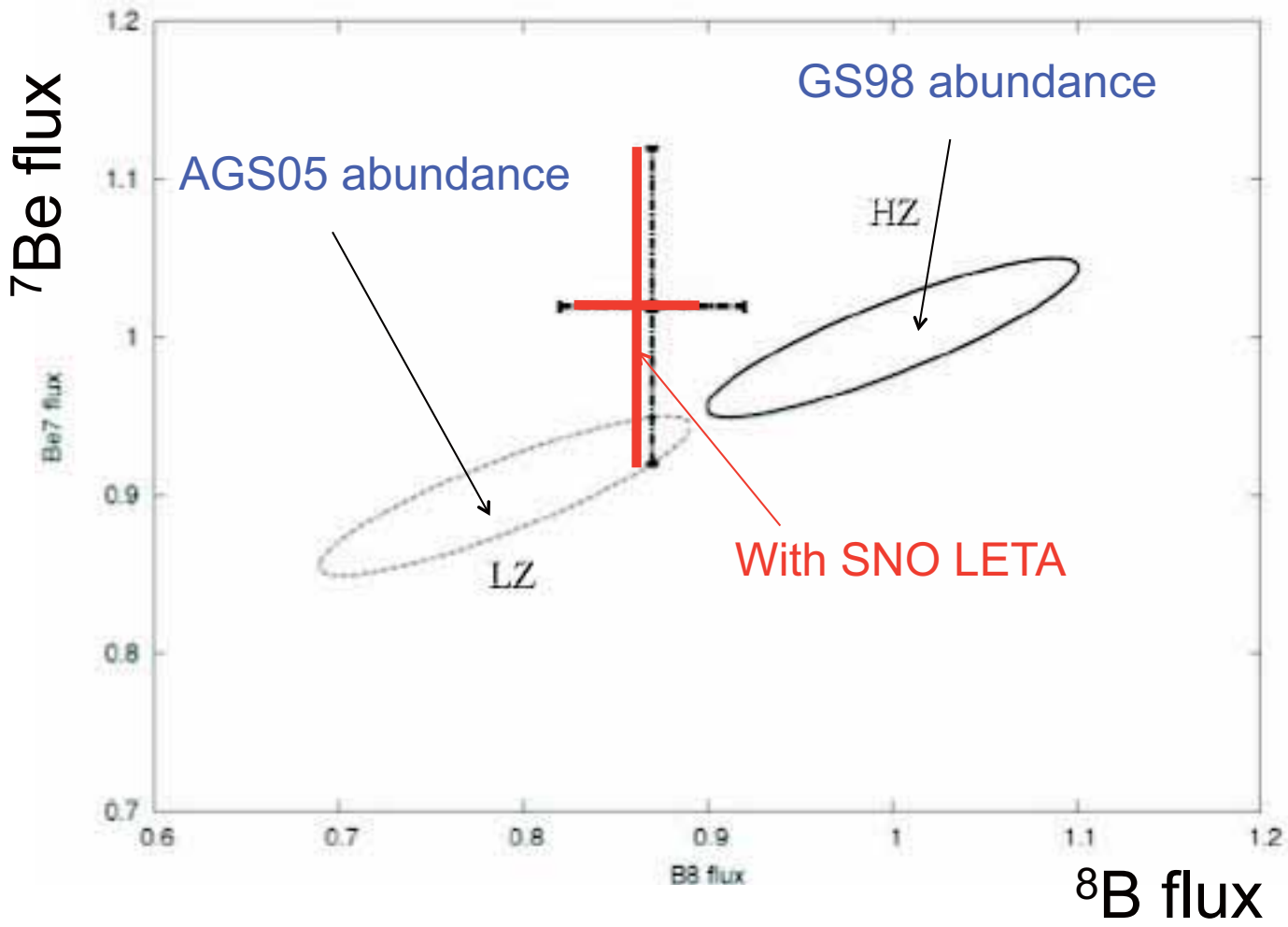
	GS98-Cons		AGS05-Opt	
Flux	σ[%]		σ[%]	
pp	0.9		0.7	
pep	1.5		1.1	
hep	15.5		15.5	
^{7}Be	10.5		9.3	
Flux	σ_+[%]	σ_-[%]	σ_+[%]	σ_-[%]
^{8}B	17.3	14.7	12.7	11.3
^{13}N	36.6	26.8	14.5	12.7
^{15}O	37.4	27.2	16.5	14.2
^{17}F	72.4	42.0	16.6	14.2

^{7}Be, CNO neutrino measurements may well discriminate these.

Improvement on S_{34} uncertainty (9.4%) is important.

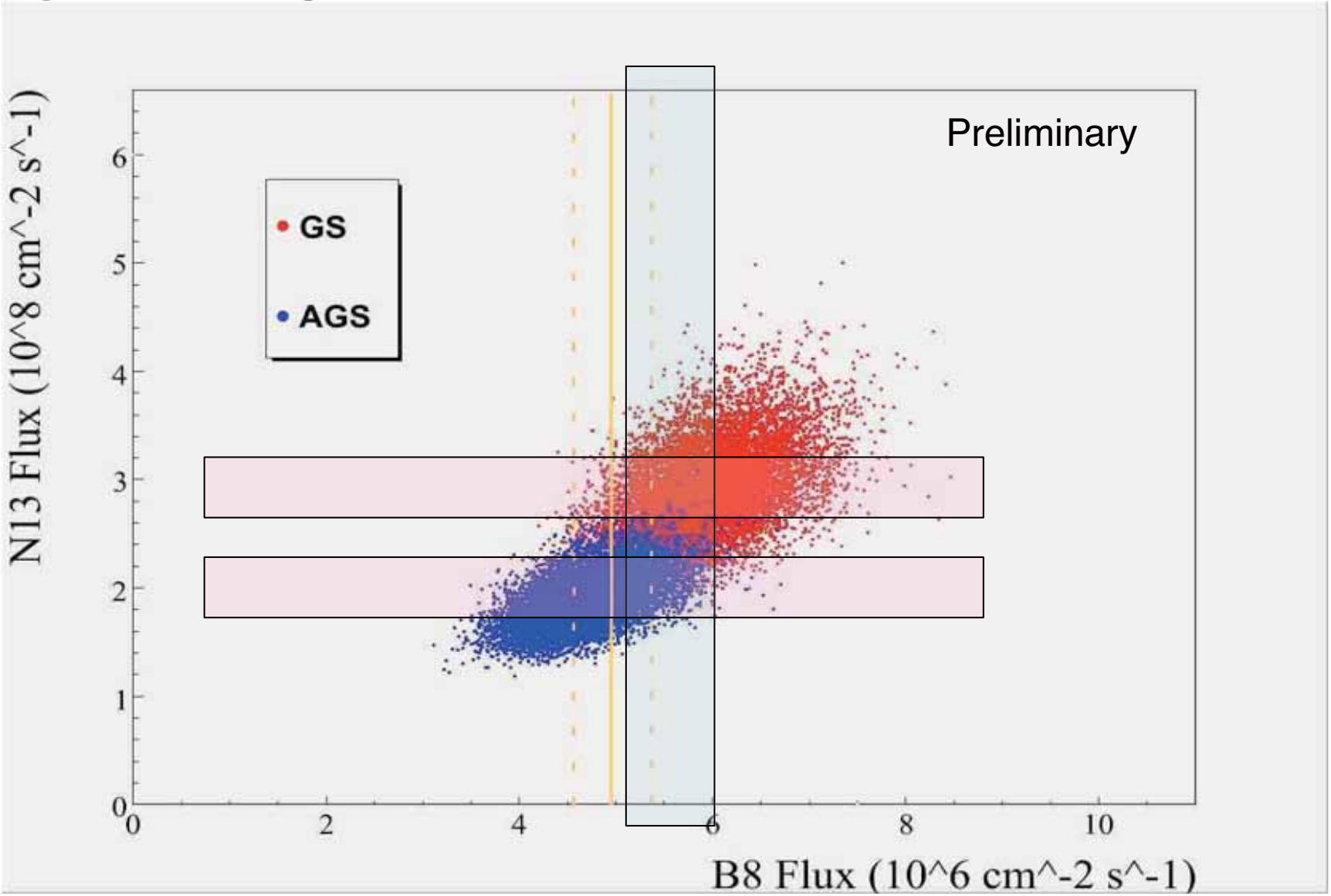
太陽組成問題に対する観測状況

^{8}B – ^{7}Be flux correlation



^{7}Beの精密測定も欲しいが、

N13 flux vs. ^{8}B



Measure CNO flux (to ±10%) and compare with solar models to differentiate high-Z / low-Z core metallicity

CNOはいっそう感度が高い。

utilizing ultra-low background environment

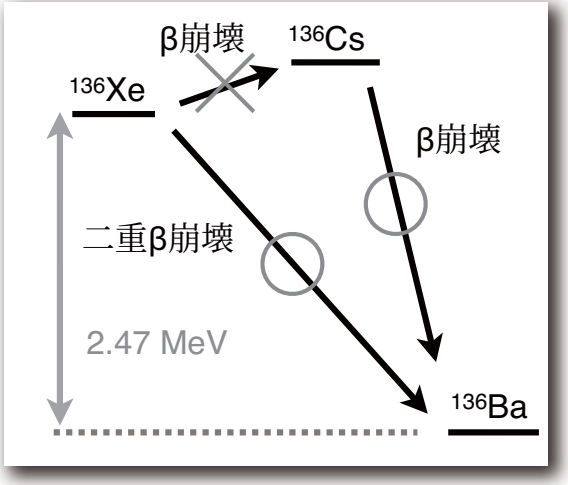
for Rare Phenomena Study

4．ニュートリノレス二重β崩壊の研究

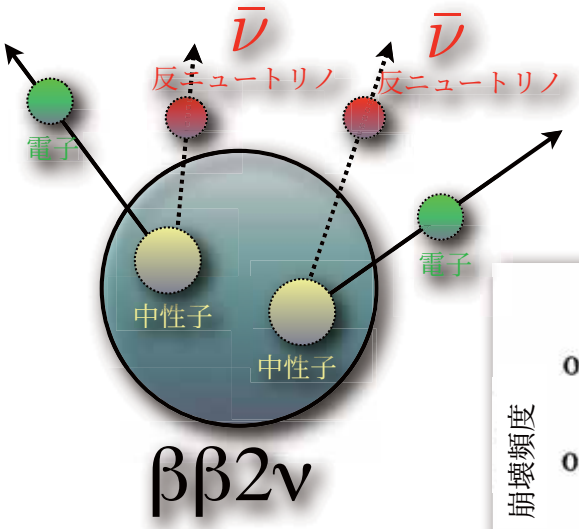
ニュートリノの質量起源を説明し大統一理論と密接に関係するシーソー模型や宇宙の物質優勢を説明するレプトジェネシス理論の基礎となるニュートリノのマヨラナ性を実証する唯一の手法である。
ニュートリノ質量構造の決定にも最も感度が高い。

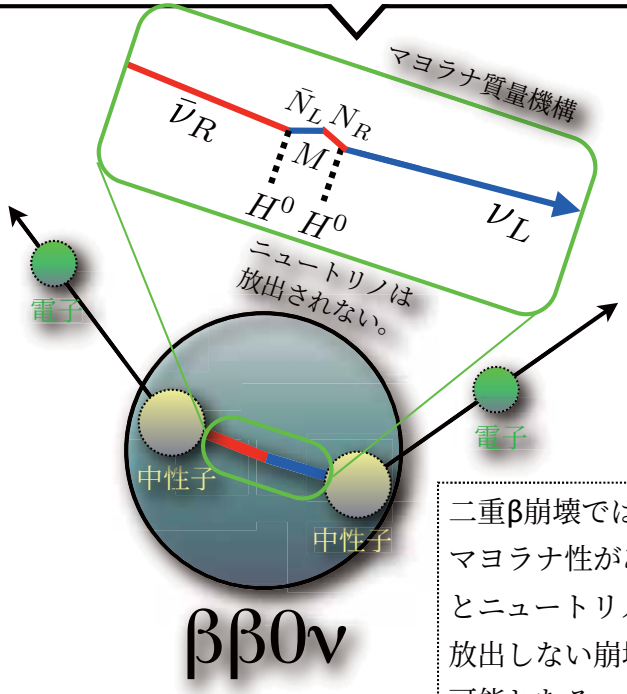
二重ベータ崩壊

特別な準位の原子核は２つのβ崩壊が同時に起き、２つの反ニュートリノを同時に放出する。

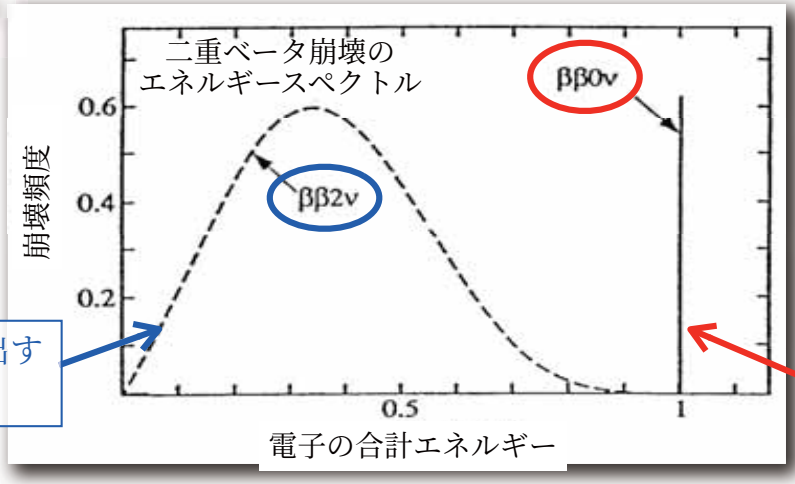


マヨラナ性は、質量がある反ニュートリノをニュートリノに変身させる。重いほど変身しやすいので、質量を測定できる。





二重β崩壊では、マヨラナ性があるとニュートリノを放出しない崩壊が可能となる。



ニュートリノがエネルギーを持ち出すため連続スペクトルとなる。

ニュートリノを放出しないため電子の合計エネルギーが大きい。

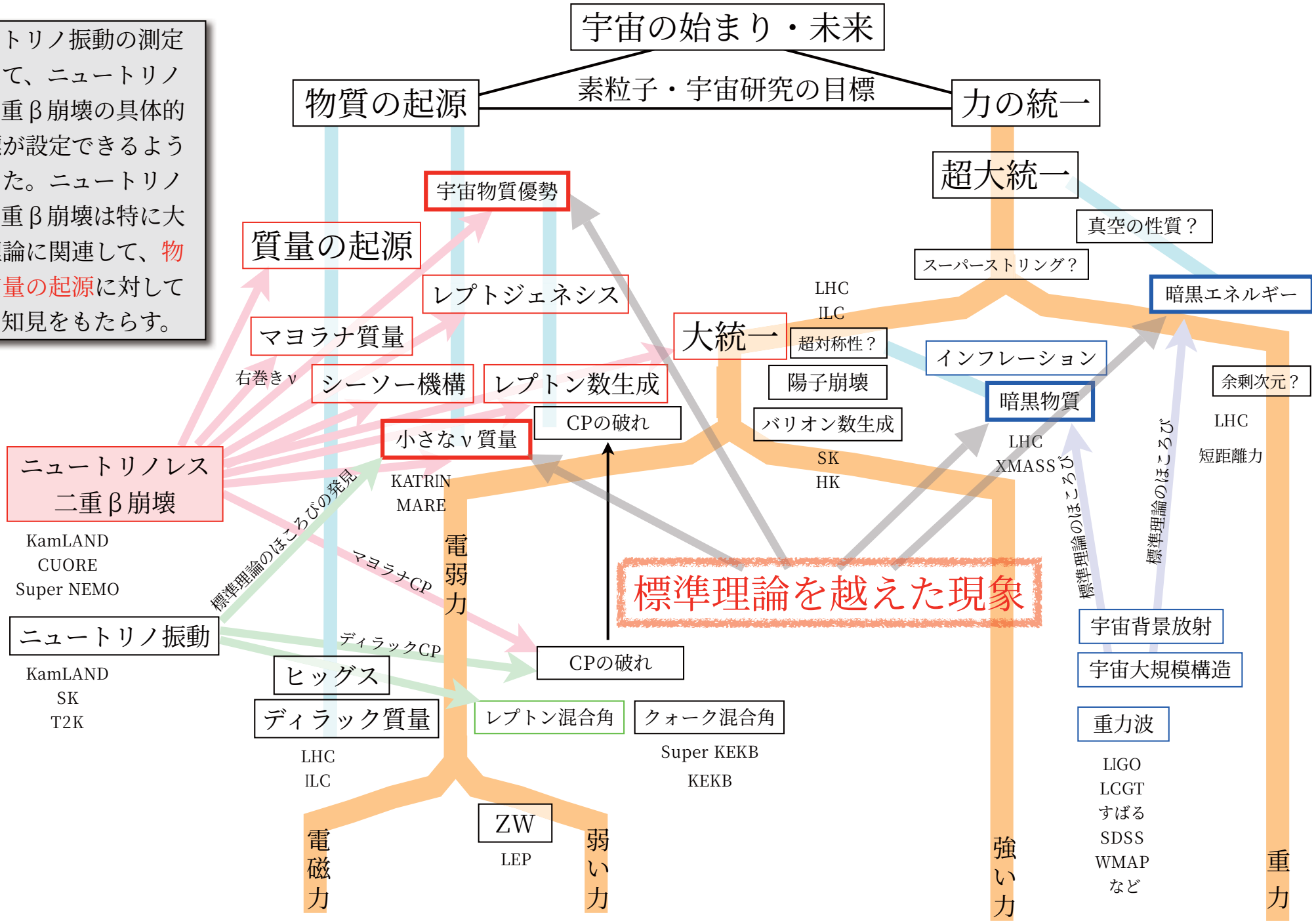
これを探索する。

発見されなくても、大統一理論のもとニュートリノ質量構造を究明できる。

ニュートリノレス二重β崩壊の発見 ⇒ マヨラナニュートリノの証拠 ニュートリノ質量の絶対値決定 ⇒ ニュートリノ質量機構の解明 大統一理論の選別 宇宙物質優勢の解明への指針

二重β崩壊研究の位置づけ

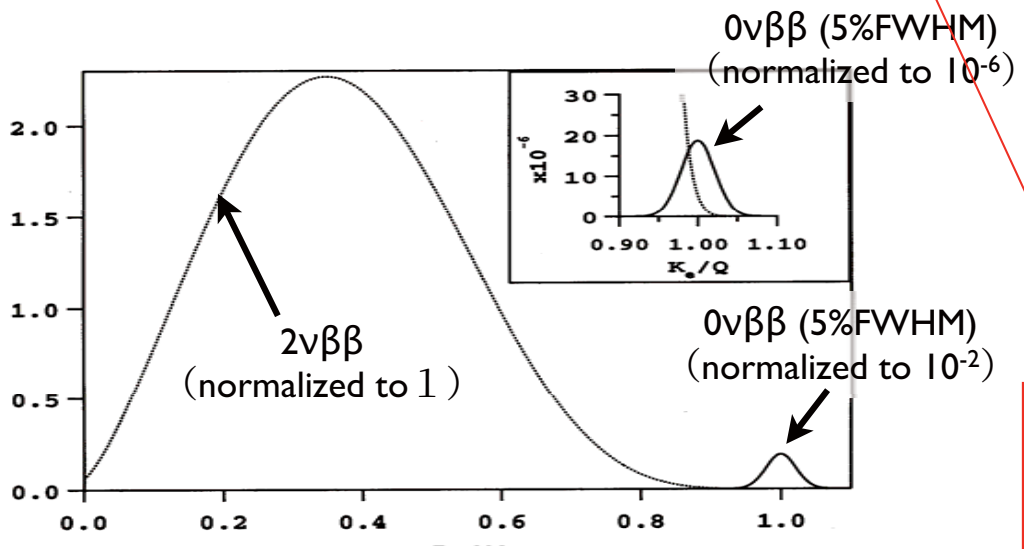
ニュートリノ振動の測定によって、ニュートリノレス二重β崩壊の具体的な目標が設定できるようになった。ニュートリノレス二重β崩壊は特に大統一理論に関連して、物質・質量の起源に対して多くの知見をもたらす。



comparison of double beta decay nuclei

Rodin et al., Nucl. Phys. A793 (2007)213-215

Nucleas	$T^{0\nu}_{1/2}(50\,\mathrm{meV})$	$T^{2\nu}_{1/2}$ measured (year)	Nat. Abundance (%)	Q-value (keV)	
$^{48}Ca \rightarrow ^{48}Ti$		$(4.2^{+2.1}_{-1.0}) \times 10^{19}$	0.19	4271	max. Q、 fast 2ν
$^{76}Ge \rightarrow ^{76}Se$	0.86×10^{27}	$(1.5 \pm 0.1) \times 10^{21}$	7.8	2039	semiconductor
$^{82}Se \rightarrow ^{82}Kr$	2.44×10^{26}	$(0.92 \pm 0.07) \times 10^{20}$	9.2	2995	
$^{96}Zr \rightarrow ^{96}Mo$	0.98×10^{27}	$(2.0 \pm 0.3) \times 10^{19}$	2.8	3351	
$^{100}Mo \rightarrow ^{100}Ru$	2.37×10^{26}	$(7.1 \pm 0.4) \times 10^{18}$	9.6	3034	fast 2ν
$^{116}Cd \rightarrow ^{116}Sn$	2.86×10^{26}	$(3.0 \pm 0.2) \times 10^{19}$	7.5	2805	
$^{128}Te \rightarrow ^{128}Xe$	4.53×10^{27}	$(2.5 \pm 0.3) \times 10^{24}$	31.7	867	
$^{130}Te \rightarrow ^{130}Xe$	2.16×10^{26}	$(0.9 \pm 0.1) \times 10^{21}$	34.5	2529	large nat. abundance
$^{136}Xe \rightarrow ^{136}Ba$	4.55×10^{26}	$>10^{22}$	8.9	2476	slow 2ν, rare gas
$^{150}Nd \rightarrow ^{150}Sm$	2.23×10^{25}	$(7.8 \pm 0.6) \times 10^{18}$	5.6	3367	0ν, fast 2ν

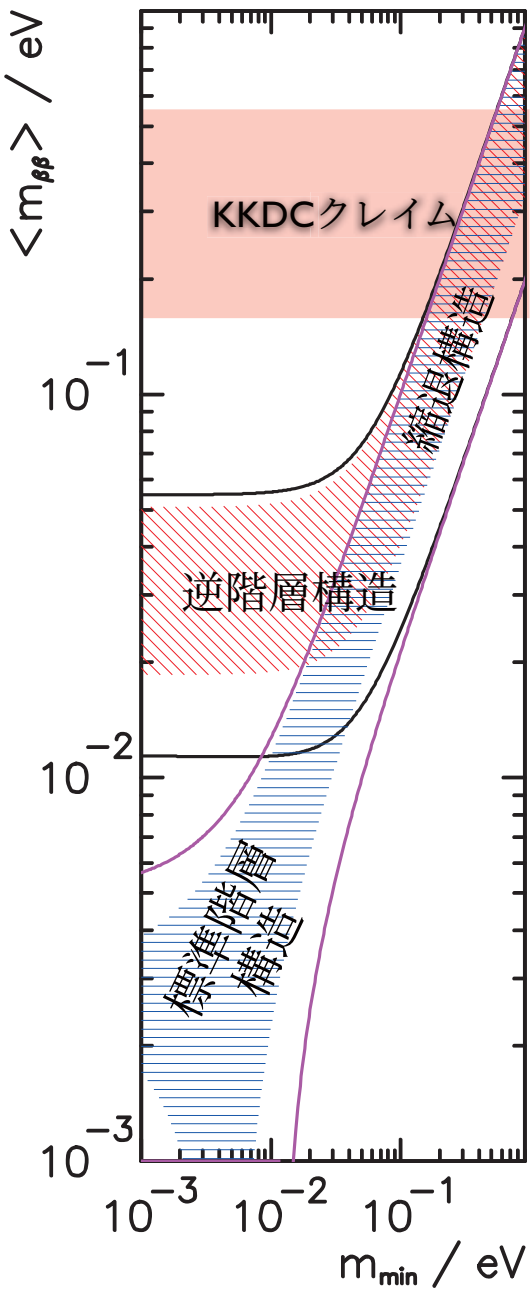


High resolution is necessary if 2ν is fast.

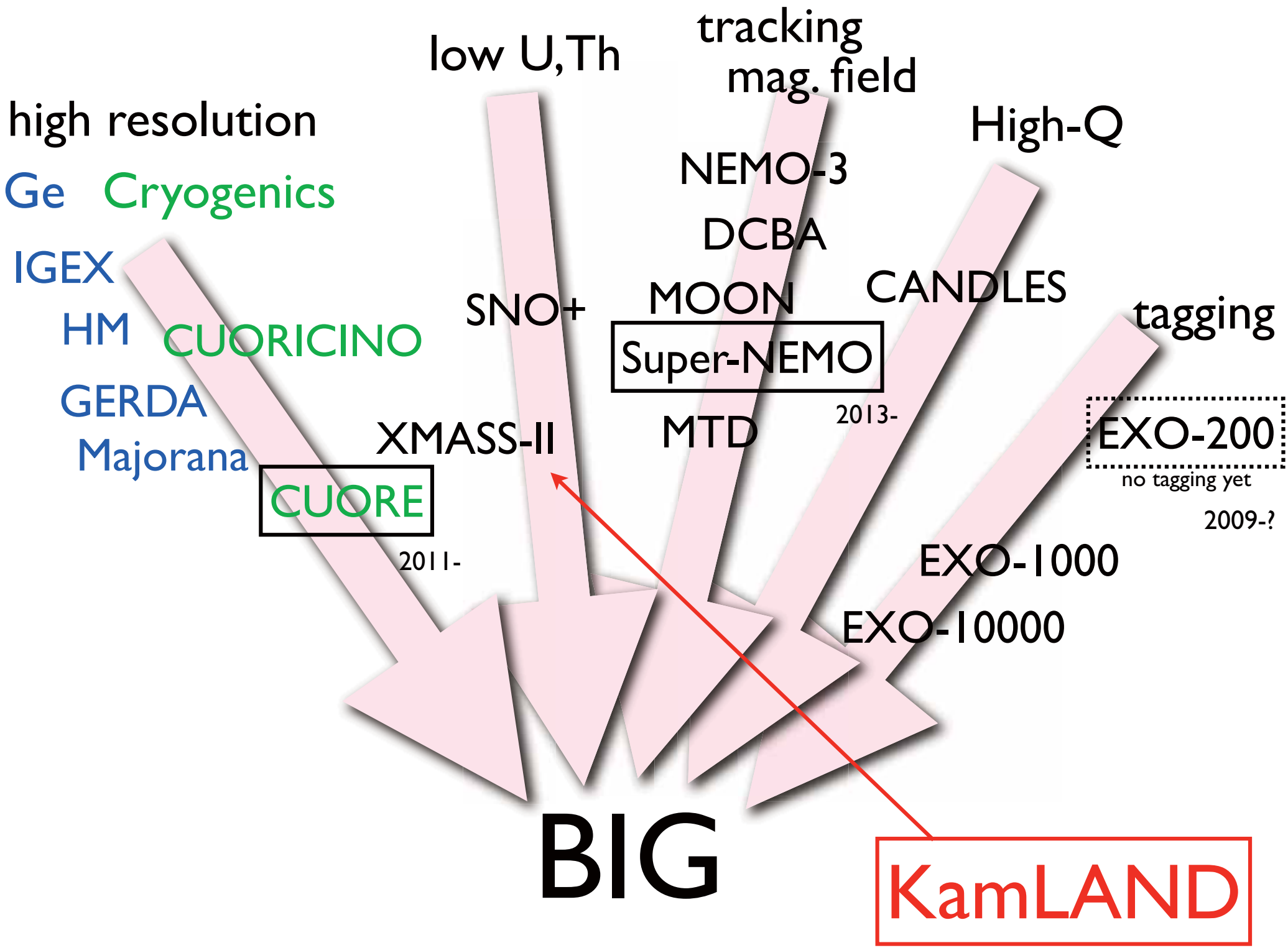
2ν BG is proportional to ~5.8th powers of the energy resolution.

Small $T^{0\nu}/T^{2\nu}$ requires modest energy resolution.

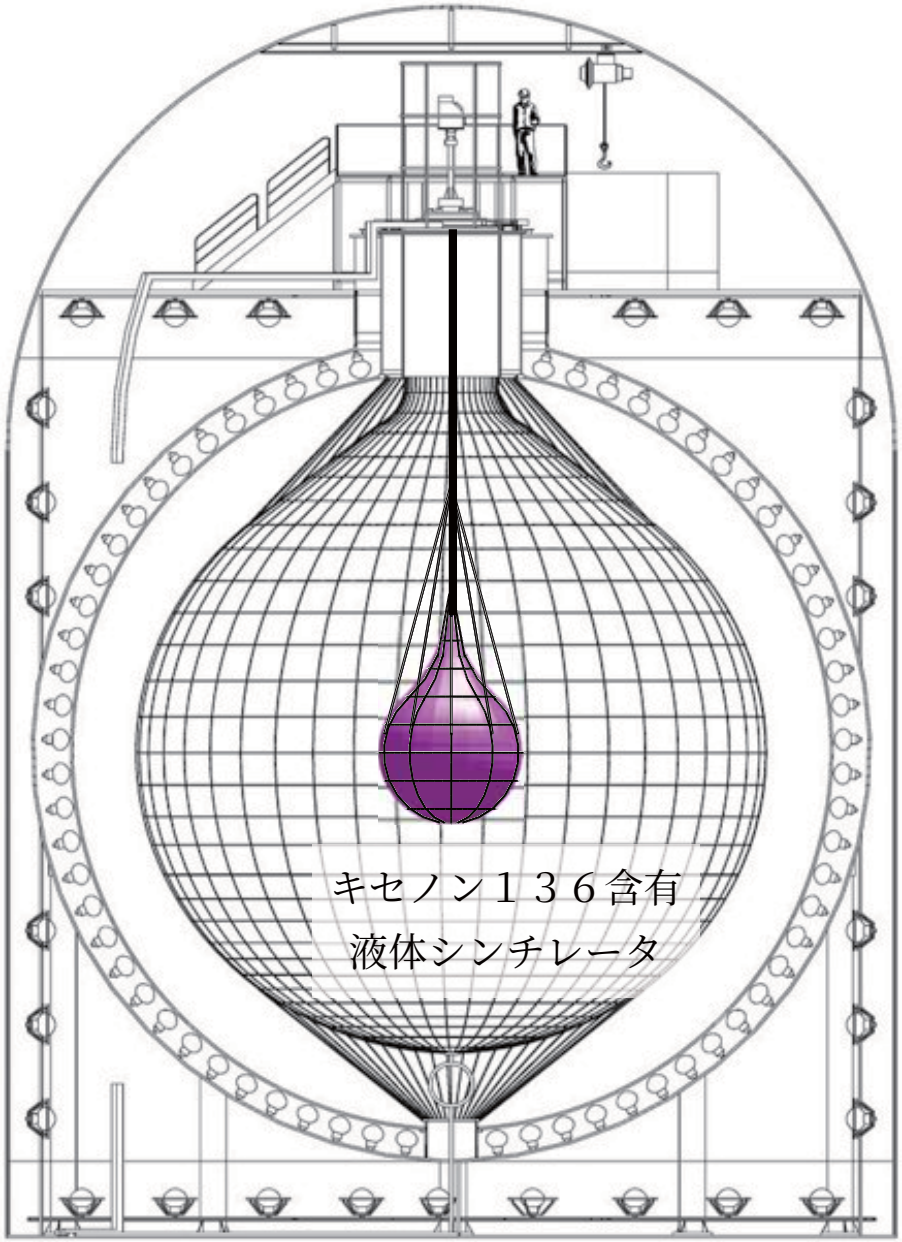
Milestone



	half lives	mass
~100meV KKDC クレイム →	10^{25}~10^{26}y	10~100kg
~60meV 縮退構造 →	10^{26}~10^{27}y	100~1000kg
~20meV 逆階層構造 →	10^{27}~10^{28}y	1000~ kg


high resolution
Ge
Cryogenics
IGEX
HM
CUORICINO
GERDA
Majorana
CUORE
2011-
low U,Th
SNO+
XMASS-II
tracking
mag. field
NEMO-3
DCBA
MOON
Super-NEMO
2013-
MTD
High-Q
CANDLES
tagging
EXO-200
no tagging yet
2009-?
EXO-1000
EXO-10000
BIG
KamLAND

KamLAND-Zen



キセノンを使うメリット

- 同位体濃縮、純化手法が確立している。
- シンチレータに3%以上可溶で回収も容易。
- 2ν2βの半減期が長く ($T_{1/2}>10^{22}$ 年) 、分解能への要求が緩い。

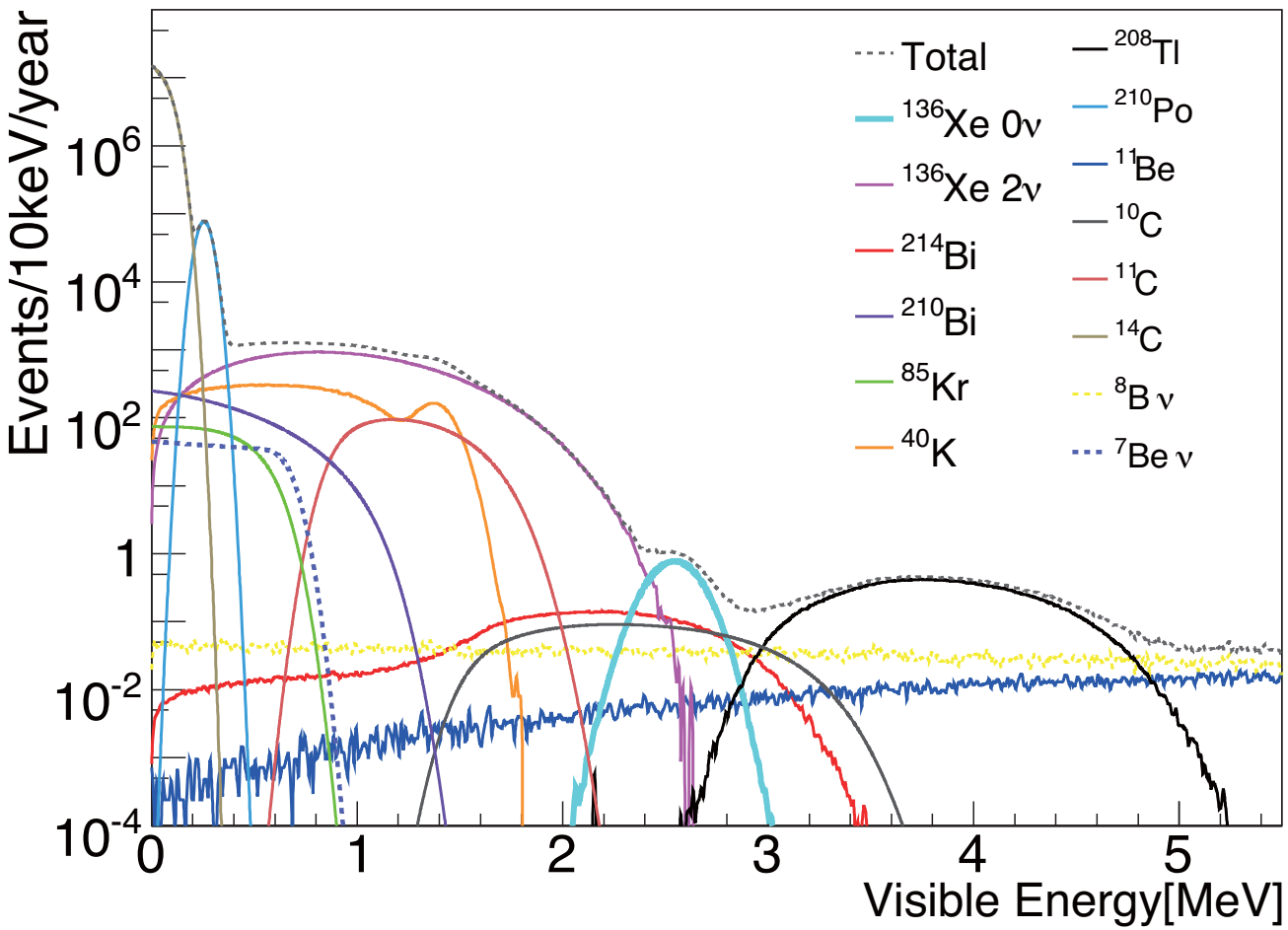
カムランドを使うメリット

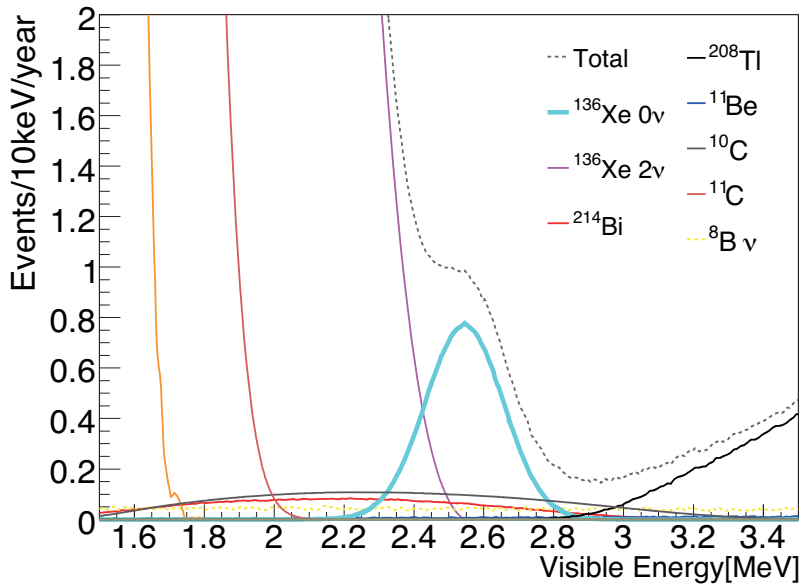
- 超純液体シンチレータと半径９mにおよぶアクティブシールドで極低放射能環境を実現済み。

U: $<3.5\times10^{-18}$ g/g
Th: $<5.2\times10^{-17}$ g/g

- ほぼ無改造で二重ベータ崩壊核を導入できるため低コスト。
- 巨大であるため、予算に応じた大量の二重ベータ崩壊核導入で高感度をめざせる。 10トンも可。
- 集光ミラーや高性能シンチレータで高分解能化も可能。
- 原子炉・地球ニュートリノ研究も継続できる。

▸expected energy spectrum





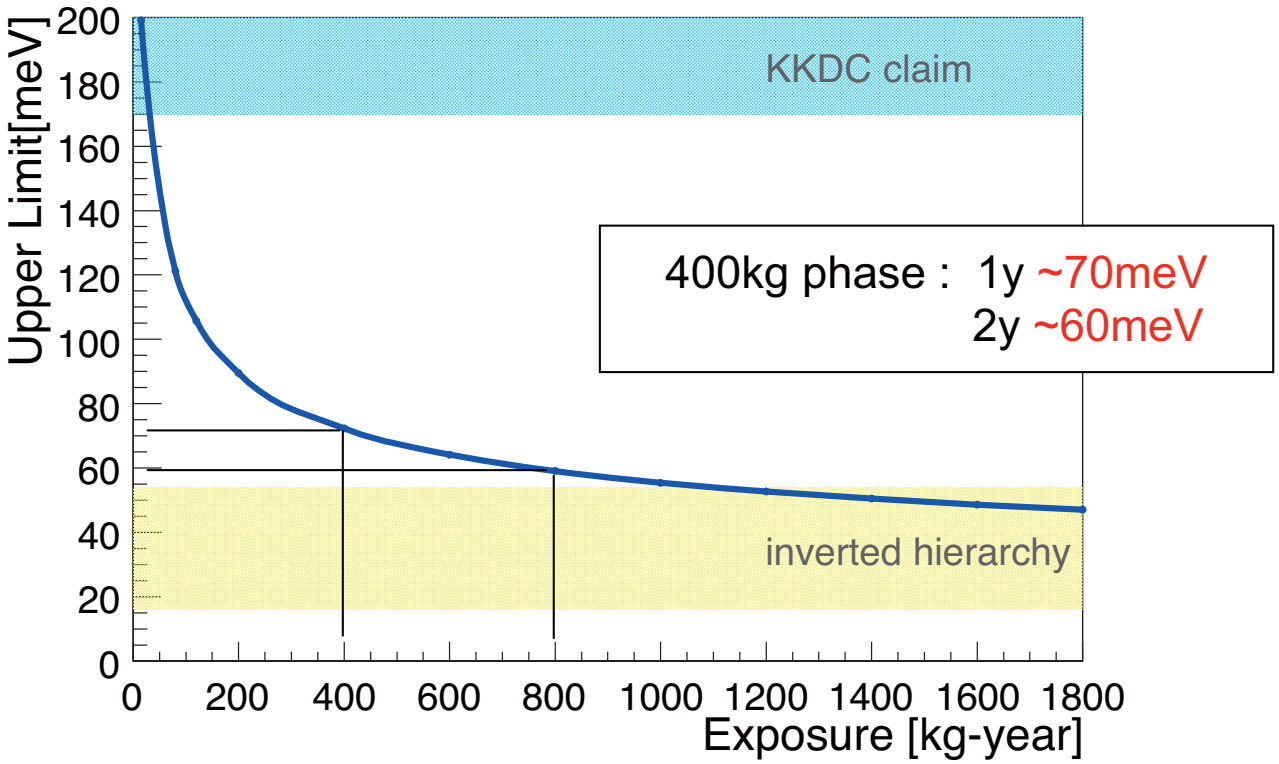
Conditions

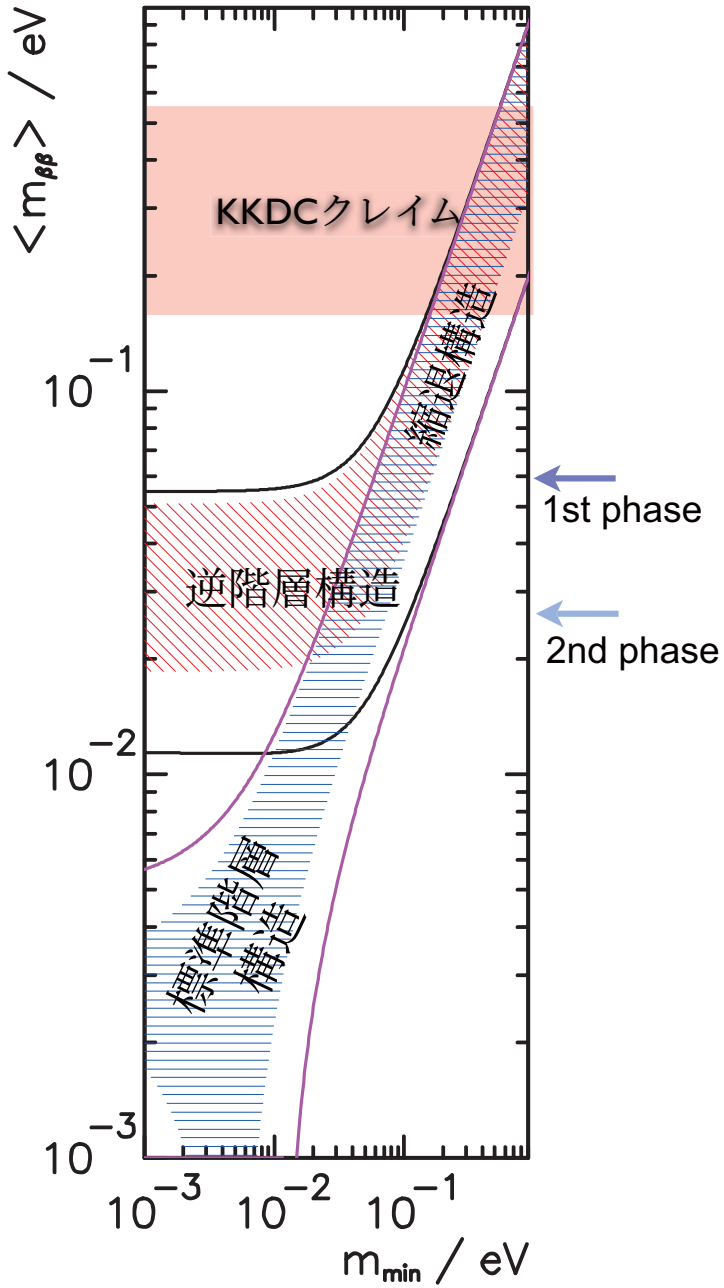
- mini balloon : 放射性不純物 (^{238}U, ^{232}Th, ^{40}K) = (10^{-12}, 10^{-12}, 10^{-11})[g/g]
- neutrino effective mass $\langle m_\nu \rangle$ = 150meV
- ^{10}C 90% tag
- $T_{1/2}(2\nu\beta\beta) > 10^{22}$y, $T_{1/2}(0\nu\beta\beta) = 1.14\times10^{24}\text{y} \cdot (1\text{meV}/\langle m_\nu \rangle[\text{meV}])^2$

QRPA

最初の目標 → KKDC クレイム, ニュートリノ質量の縮退構造

2年弱で~60 meV





▸バックグラウンドの詳細

1年間の観測で期待されるイベント数　　$<m_\nu>$ = 150meV, QRPAモデル

^{136}Xe 2ν	^{208}Tl	^{214}Bi	^{10}C	^{11}Be	^{8}B	Total	^{136}Xe 0ν
1.93 ±0.15	1.18×10^{-2} $\pm0.12\times10^{-2}$	3.15 ±0.01	2.44 ±0.01	0.20 ±0.01	1.18 ±0.02	8.93 ±0.21	17.79 ±0.02

20.6 ev　　24.4ev

^{10}C : 新開発デットタイムフリー回路(MoGURA)を用いて90%除去出来る

３事象の同時遅延計測タギング

① ミューオン(> 100meV)
↓ 210μsec
② 中性子捕獲イベント (~ 2.2MeV)
↓ 28sec
③ ^{10}C崩壊イベント (1.5 ~ 3.5MeV)

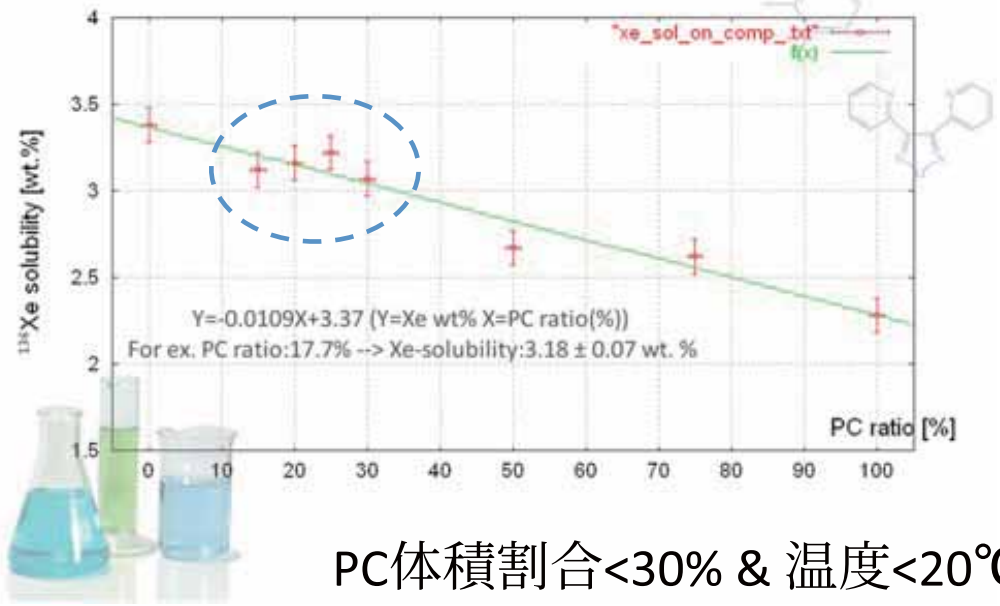
^{214}Bi : 最も寄与の大きなバックグラウンド。mini balloon中の^{238}U起源。

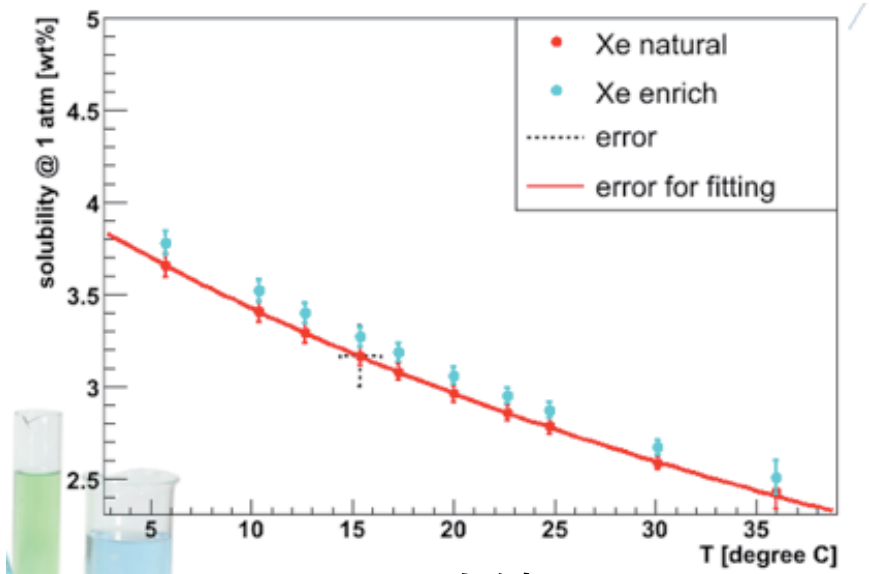
- mini balloonへの要求 : 極低放射性不純物

目標purity : (^{238}U, ^{232}Th, ^{40}K) = (10^{-12}, 10^{-12}, 10^{-11})[g/g]

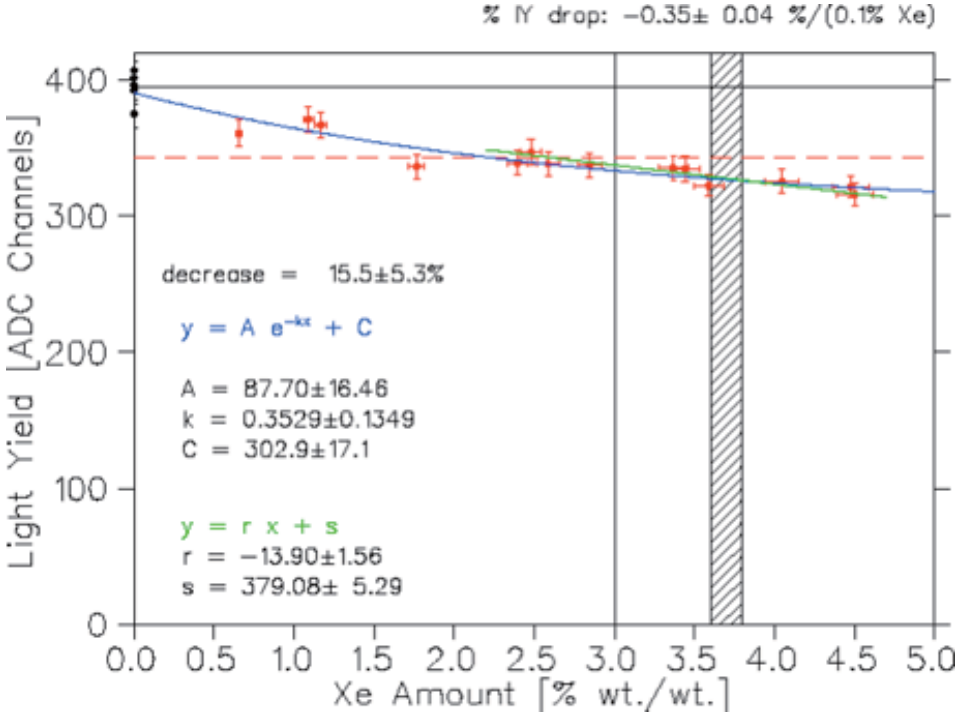
有効体積を300kg にするとほぼ問題なくなる。

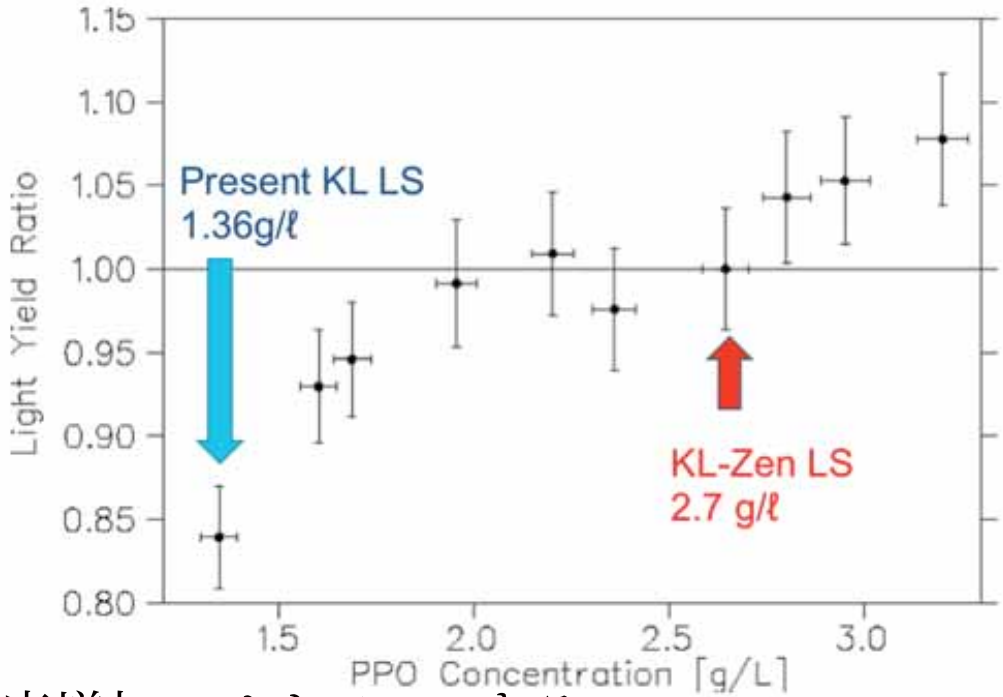
Xe loaded LS properties





PC体積割合<30% & 温度<20℃ で **Xe** は**3.0 wt.%**以上溶ける。





Xe溶解での光量減少はPPO濃度増加でリカバーできる。

バルーンの試作、導入テスト

空気中での膨張テスト

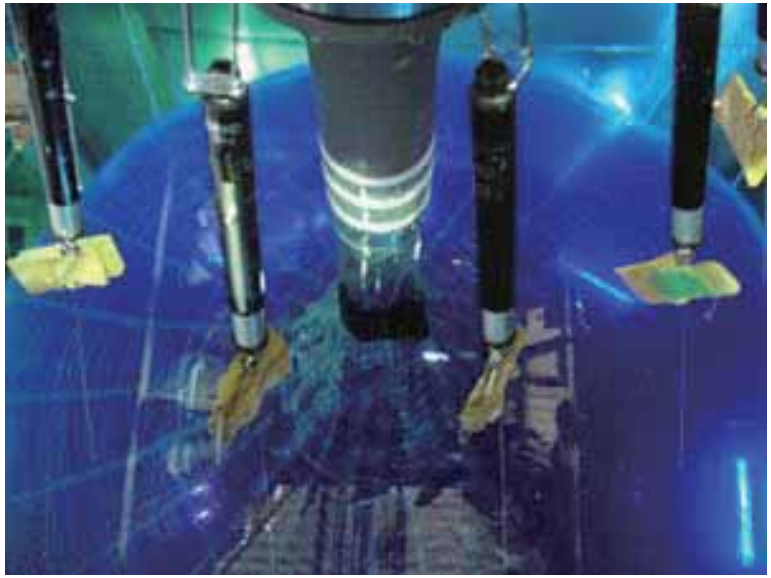
水中での導入・膨張テスト

畳んだ状態で長さ約１０ｍ

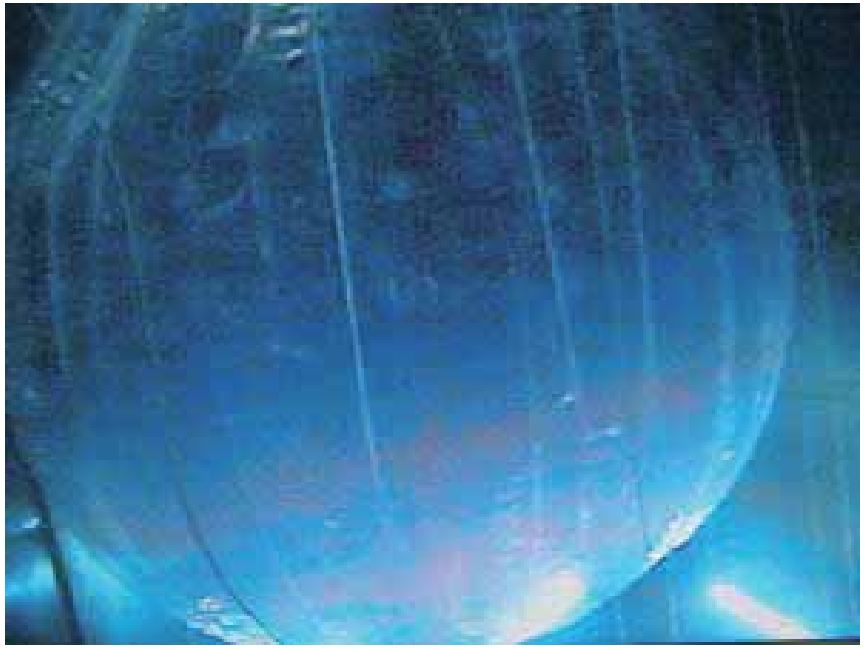
導入口を30cmX30cm
に制限

水中カメラ、ファイバースコープで監視しながら密度差０．０４％の着色砂糖水を送液

１２本の糸で支える



バルーン膨張に成功



Nylon6 contamination level

	U (g/g)	Th (g/g)	K (^{40}K) (g/g)
• Syuusei (Taiwang)	$< 5\times10^{-12}$	$< 5\times10^{-12}$	$< 1\times10^{-7}$ ($<1.2\times10^{-11}$)
• BASF (Germany)	$< 5\times10^{-12}$	$< 5\times10^{-12}$	$< 1\times10^{-7}$ ($<1.2\times10^{-11}$)
• DSM (Netherlands)	$< 5\times10^{-12}$	$< 5\times10^{-12}$	$< 1\times10^{-7}$ ($<1.2\times10^{-11}$)
• Ube industries(Japan)	$< 5\times10^{-12}$	$< 5\times10^{-12}$	$< 1\times10^{-7}$ ($<1.2\times10^{-11}$)
• Mitsubishi plastic (Japan)	$< 5\times10^{-12}$	$< 5\times10^{-12}$	$< 1\times10^{-7}$ ($<1.2\times10^{-11}$)

10^{-13}g/g感度での測定実施中

Neutron activation analysis 依頼済

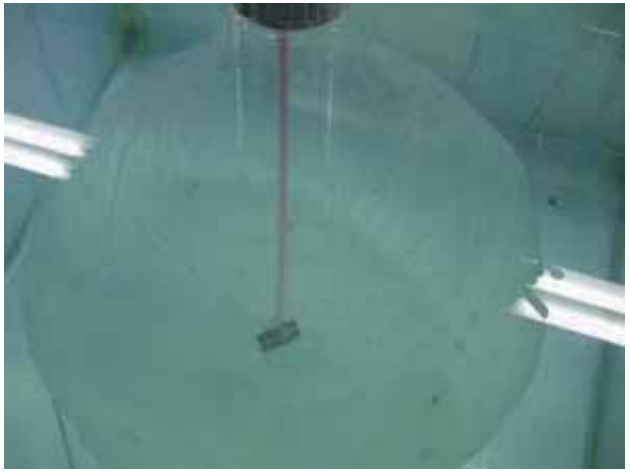
Radon emanation analysis 順番待ち

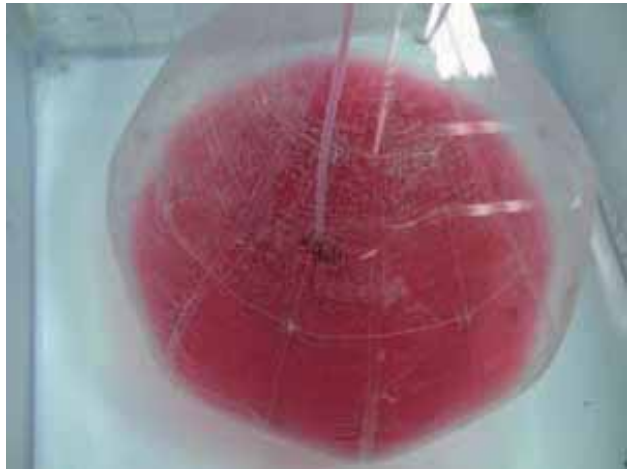
fillerなしでのフィルム作成進行中

最終素材バルーンでのリハーサル１２～１月に計画

実際の導入計画

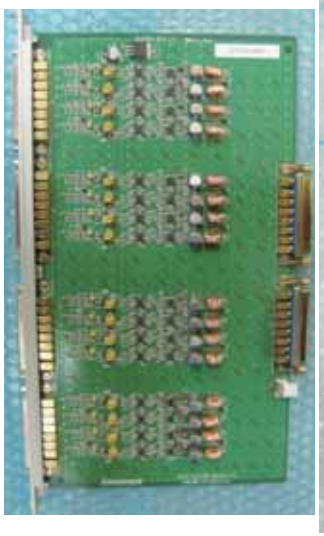
１．キセノン無しシンチレータで膨張（数日）
２．破れがないか確認
３．キセノン入りシンチレータで置換（約１週間）

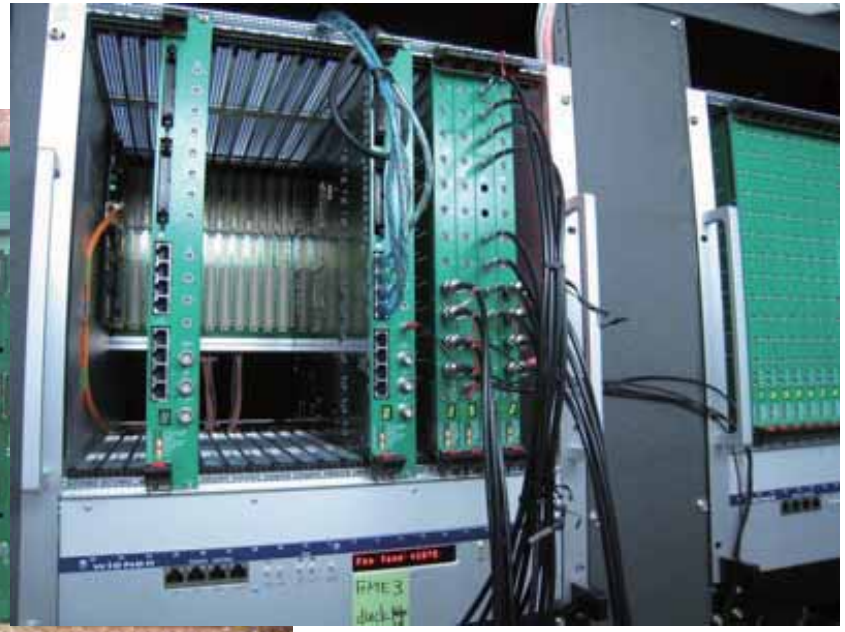




４分の１スケールでテスト、１週間でも界面を維持

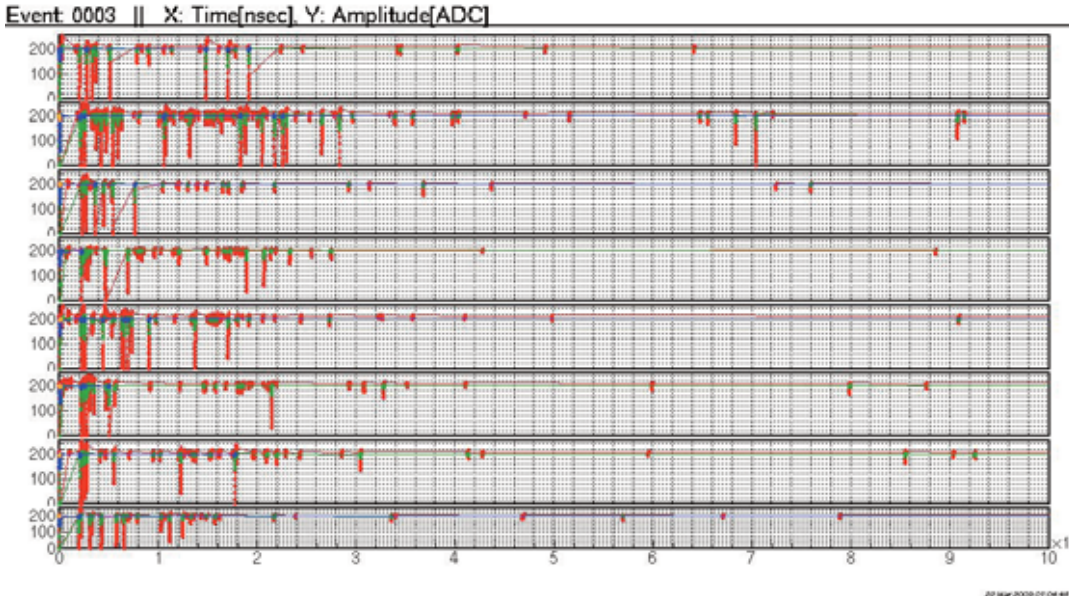
新開発デッドタイムフリー電子回路　宇宙線起源バックグラウンドを1/20に低減する。



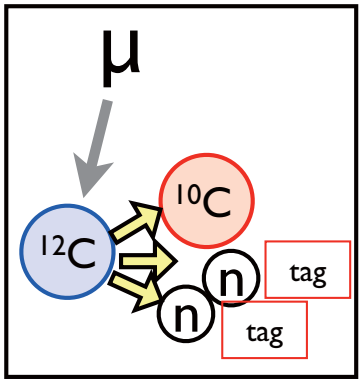


ベースライン安定化回路　　波形デジタイザ　　トリガー回路

Muon events with BLR 0-100usec

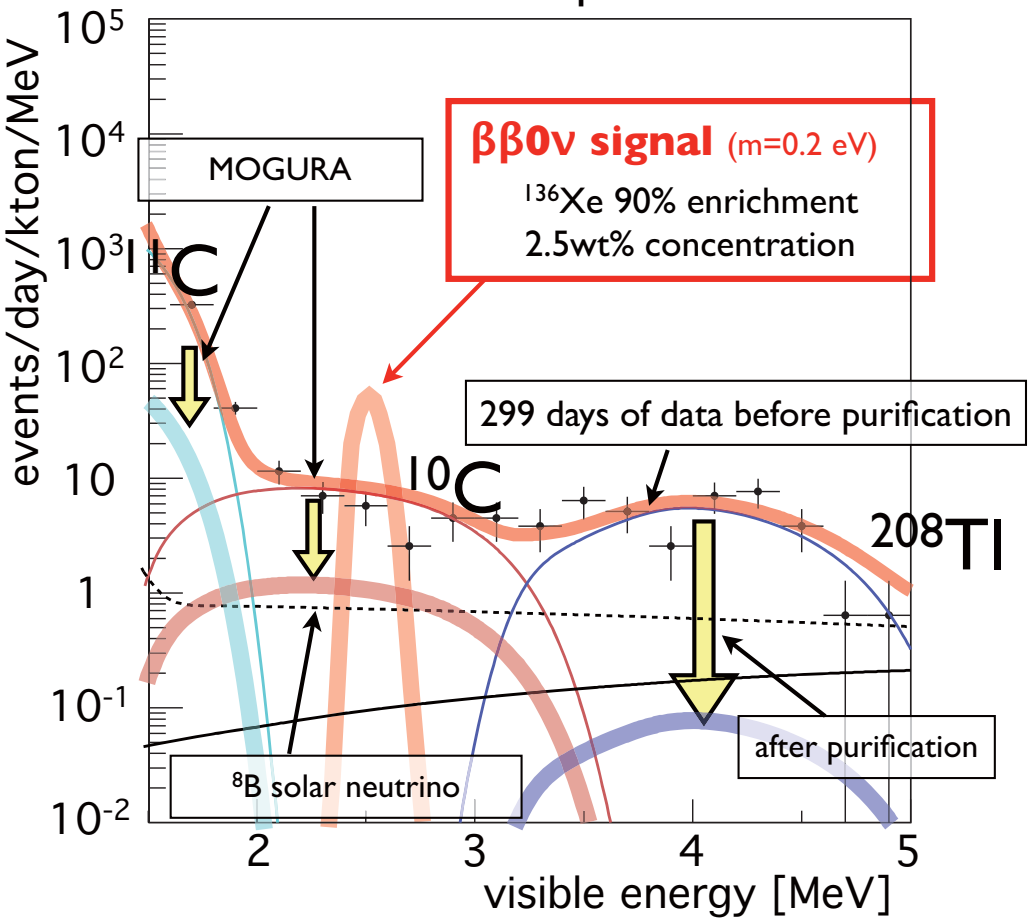


^{11}C ^{10}C reduction

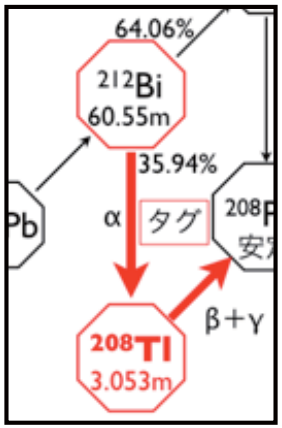


MOGURA

BG level before purification



^{208}Tl reduction



LS with water extraction is already clean enough.

調達状況

○キセノン含有液体シンチレータ用オイルタンク設置空洞の掘削

タンクは特別推進で今年度導入

○キセノン回収保管装置、溶解・回収装置用空洞の整備

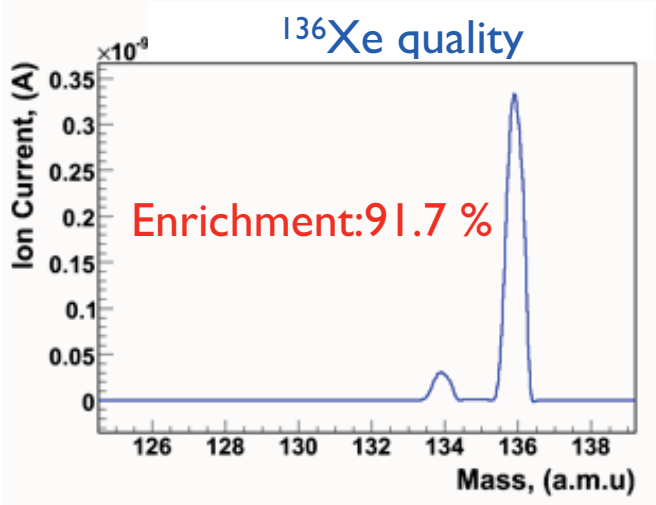
キセノン貯蔵装置は平成２１年度特別推進で導入

○キセノン溶解・回収装置の導入　１２月納入予定

○残留ガス分析装置の導入

納入済みキセノンガスを順次分析

真空一定装置は平成21年度特別推進で導入

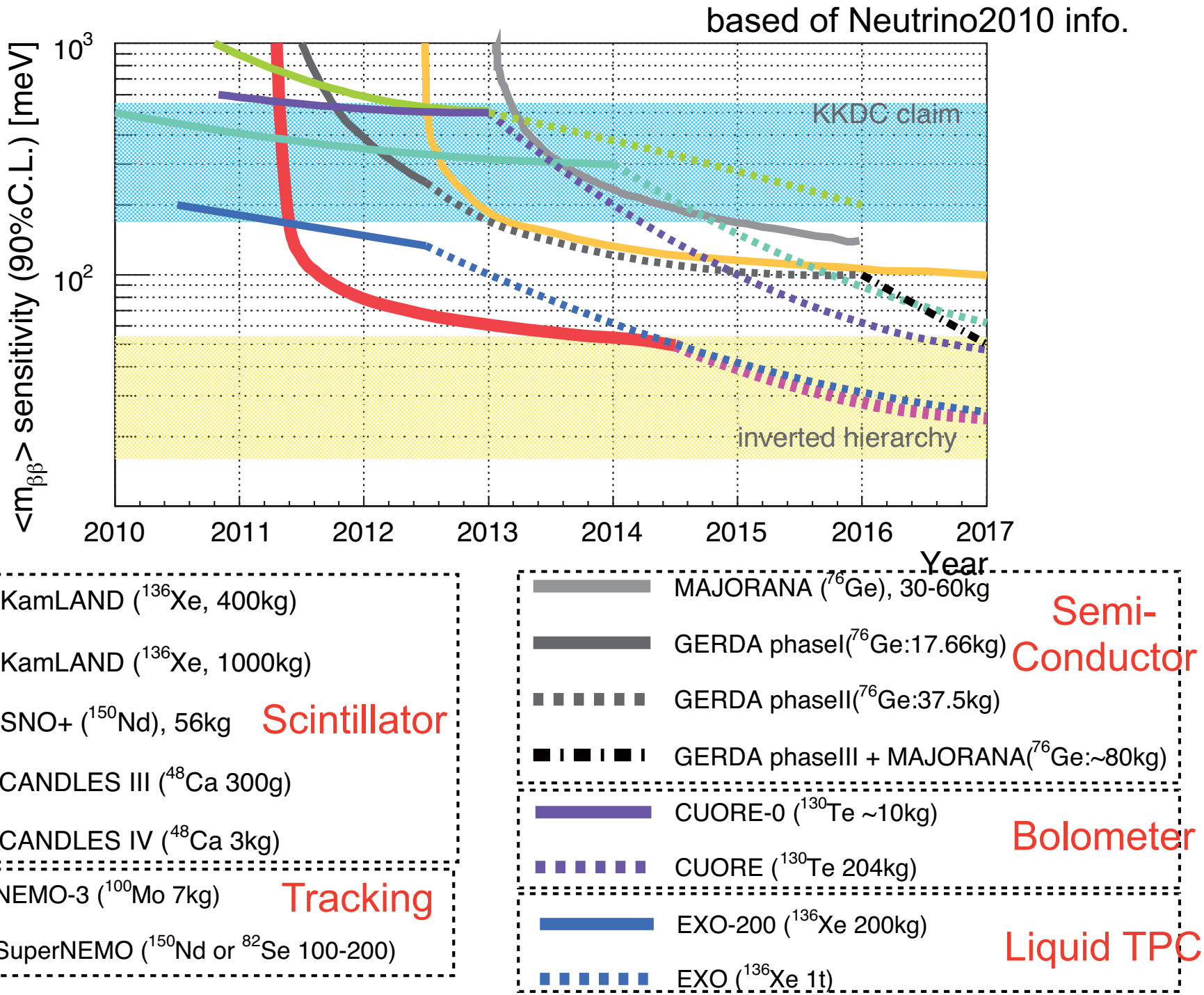


○キセノン調達

現在190kgを地下に貯蔵

今年度中に420kg 調達予定

KamLAND-Zen開始予定2011年5月！！



KamLAND-Zen の強化の可能性

^{136}Xe 2ν	^{208}Tl	^{214}Bi	^{10}C	^{11}Be	^{8}B	Total	^{136}Xe 0ν
1.93 ±0.15	1.18×10^{-2} $\pm0.12\times10^{-2}$	3.15 ±0.01	2.44 ±0.01	0.20 ±0.01	1.18 ±0.02	8.93 ±0.21	17.79 ±0.02

1．Massの向上

10トンでも内包可能。

2．有効体積の設定

75%（300kg）で^{214}Bi は問題なし。

3．エネルギー分解能の向上 →KamLAND2

2ν は問題無くなる。

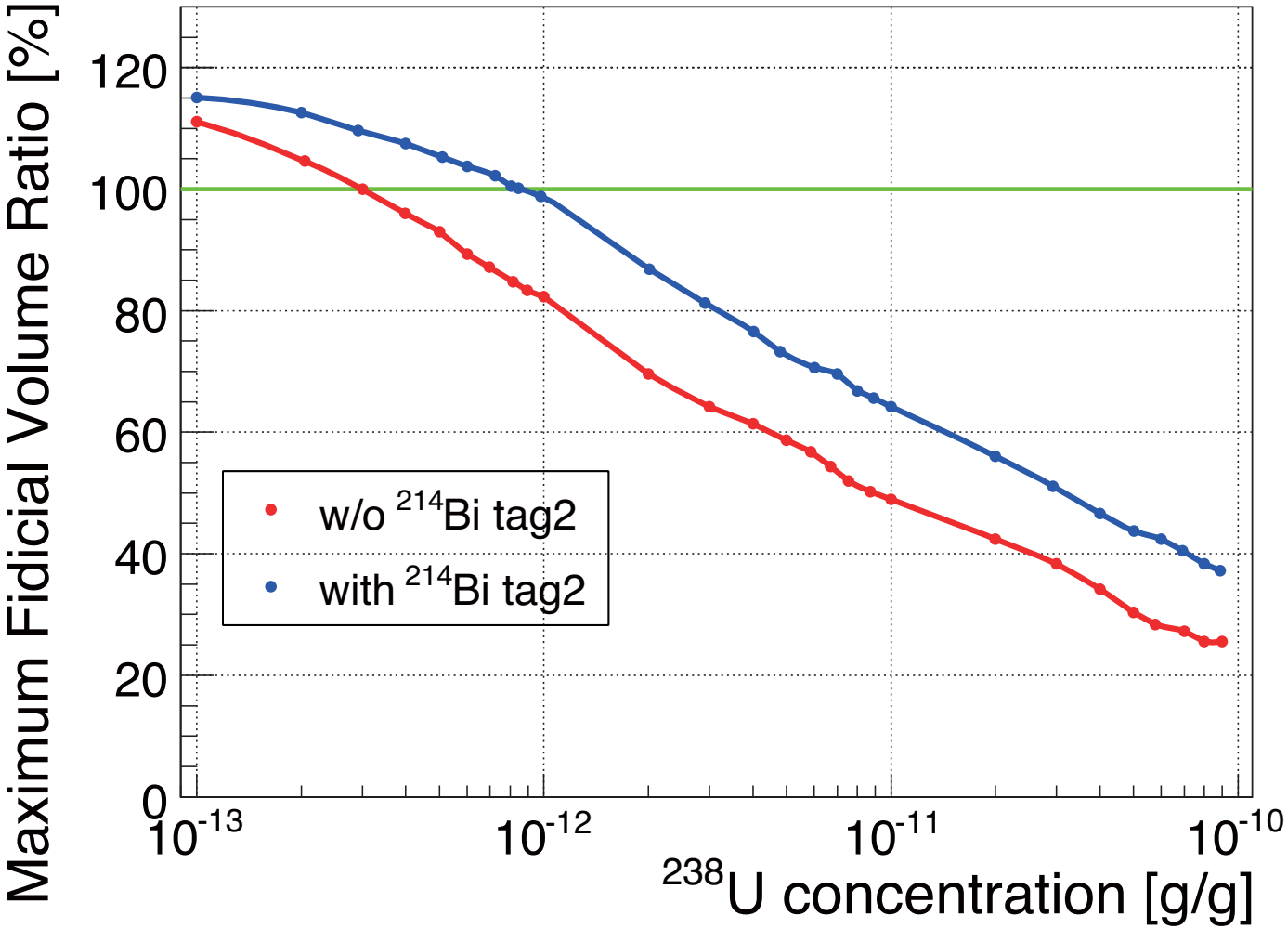
4．キセノン昇厚

^{10}C、^{8}B ν の低減

5．イメージング装置の設置 →KamLANDi

マルチバーテックス ^{10}Cの低減

•mini balloon 中の^{238}U 濃度とfiducial volume



target revel : ^{238}U < 10^{-12} g/g

※ナイロンサンプルを分析中

フィルム作成時に使われている添加物が放射性物質の原因の大半

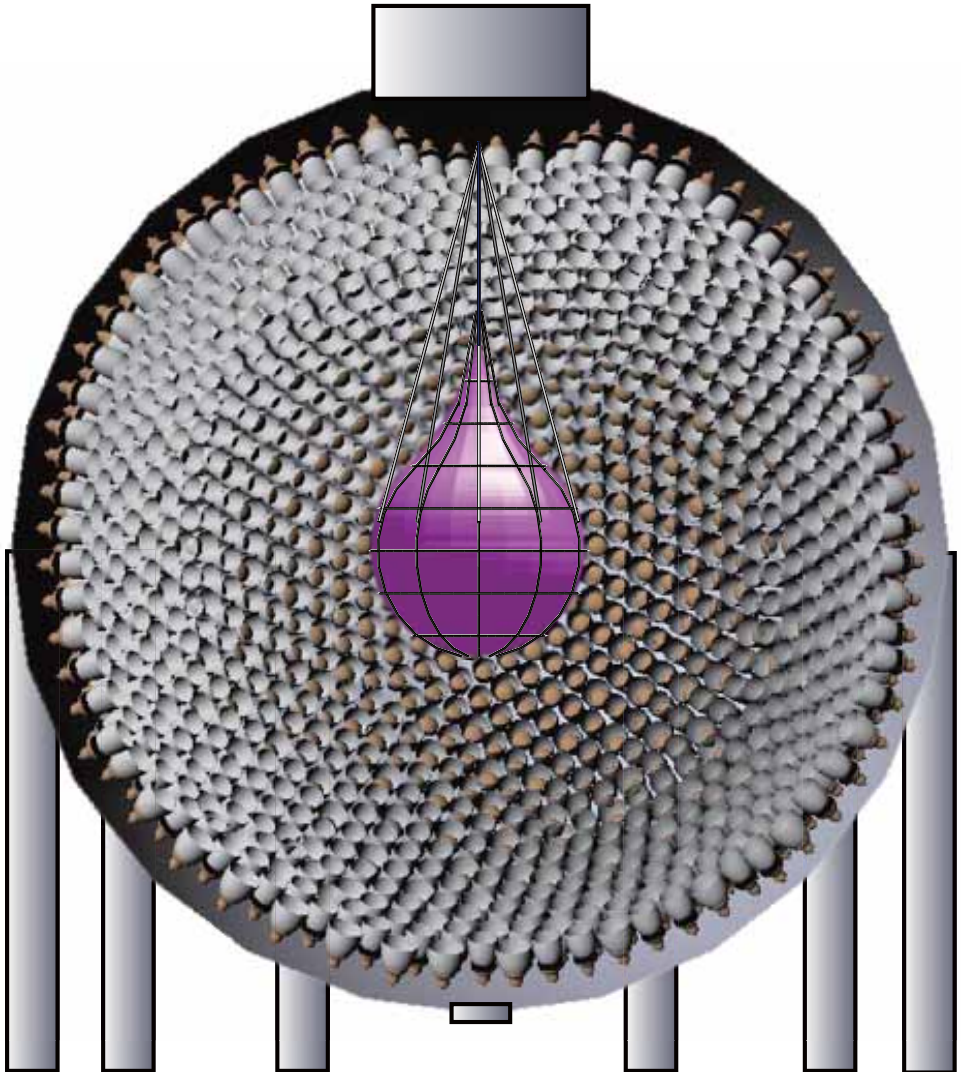
添加剤無しのペレット：^{238}U < 5×10^{-12} [g/g] (ICPMS検出限界)

高感度分析器で分析中

KamLAND2-Zen

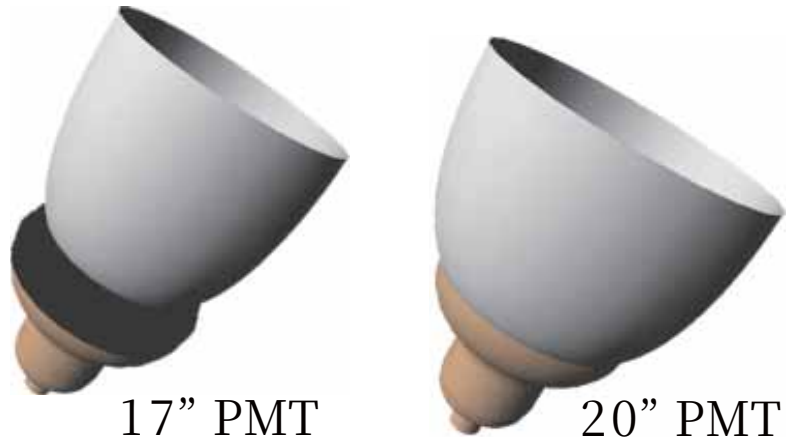
chimney enlargement

capability to accommodate
CANDLES, $CdWO_4$, NaI and others



Winston cone

photo-coverage > x2
photon collection > x1.8



LS renewal

KL LS 8,000 photons/MeV
standard LS 12,000 photons/MeV

x1.4

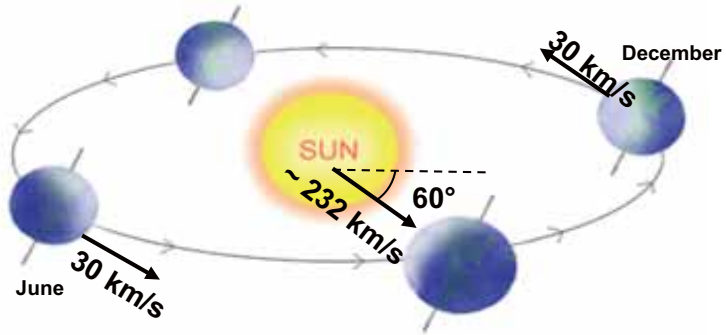
1000kg enriched Xenon

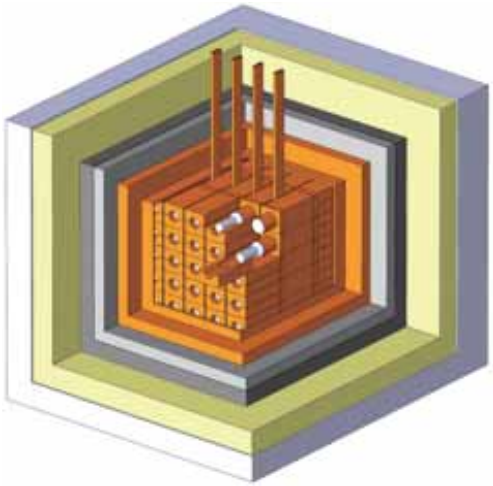
more?値段 pressurized?コツがいる

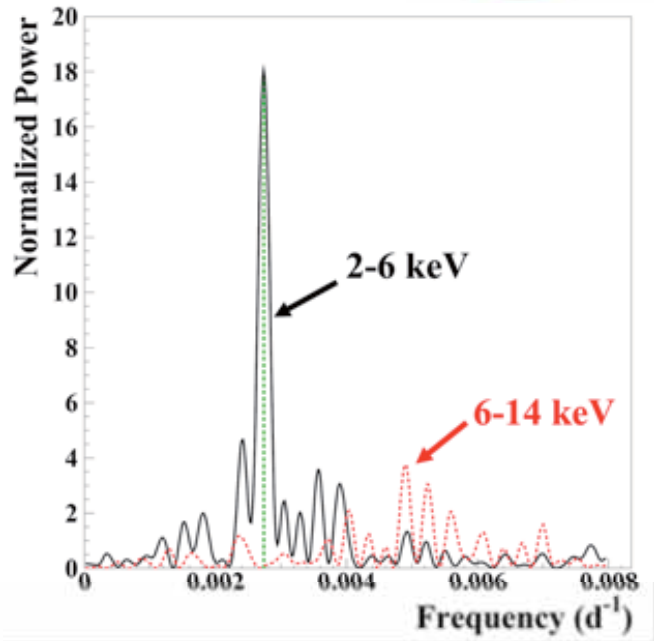
目標感度 ~20meV/5年

素粒子物理でのもう一つの大きな論争

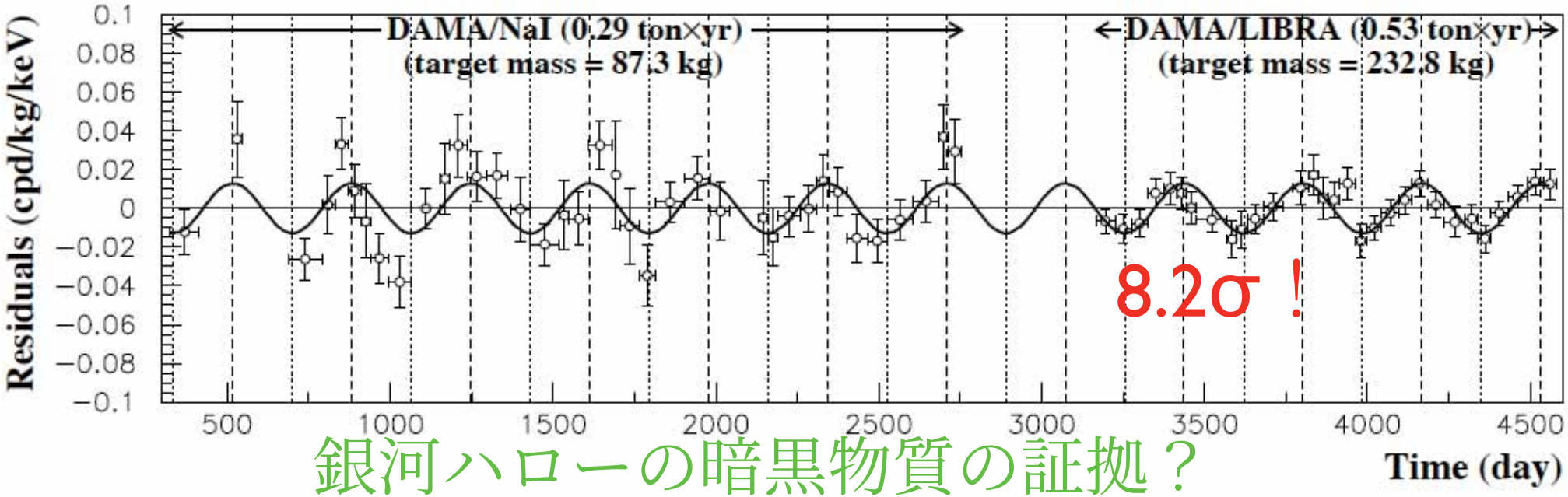
DAMA/NaI+LIBRA







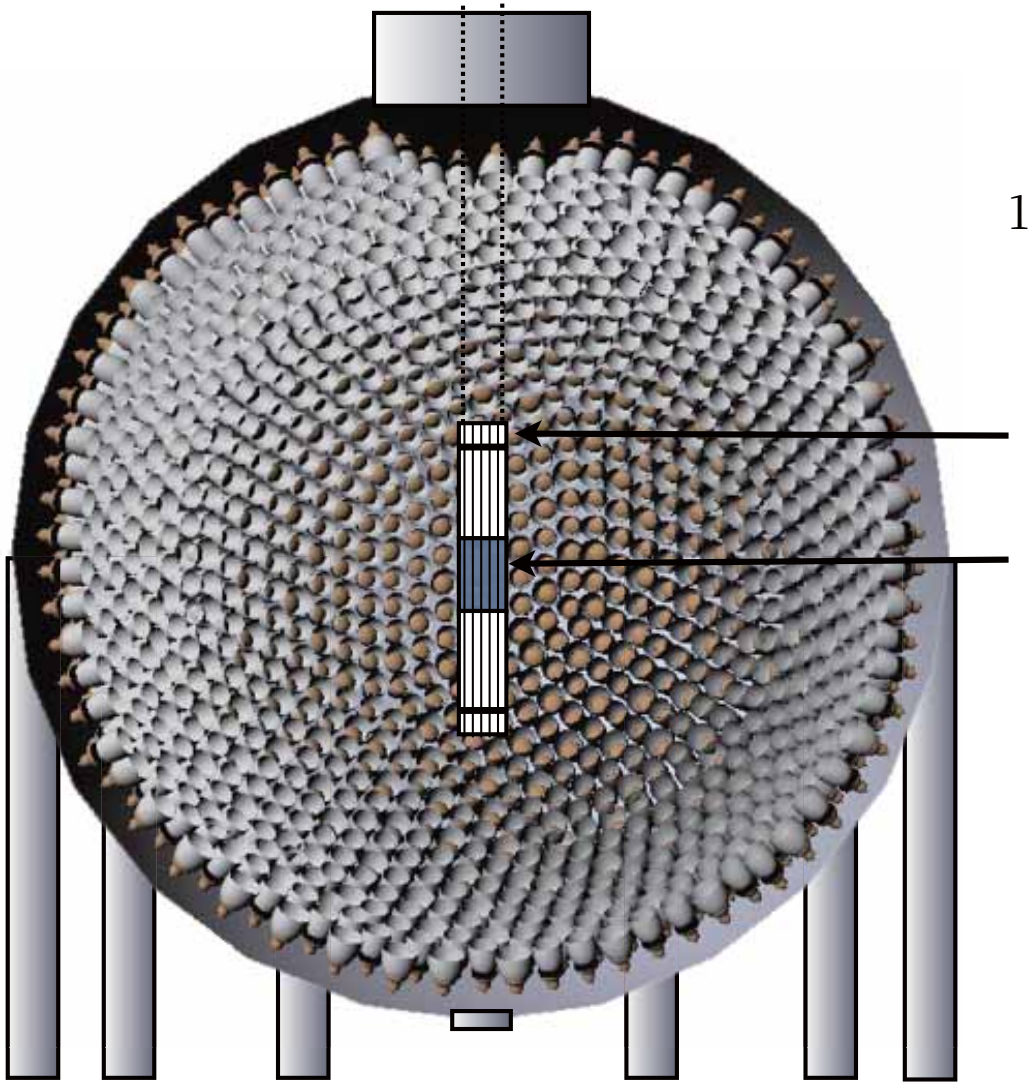
2-6 keV



銀河ハローの暗黒物質の証拠？

KamLAND2-NaI, CANDLES, $^{116}CdWO_4$

拡張した導入口でいろいろなものをつり下げることが出来る。



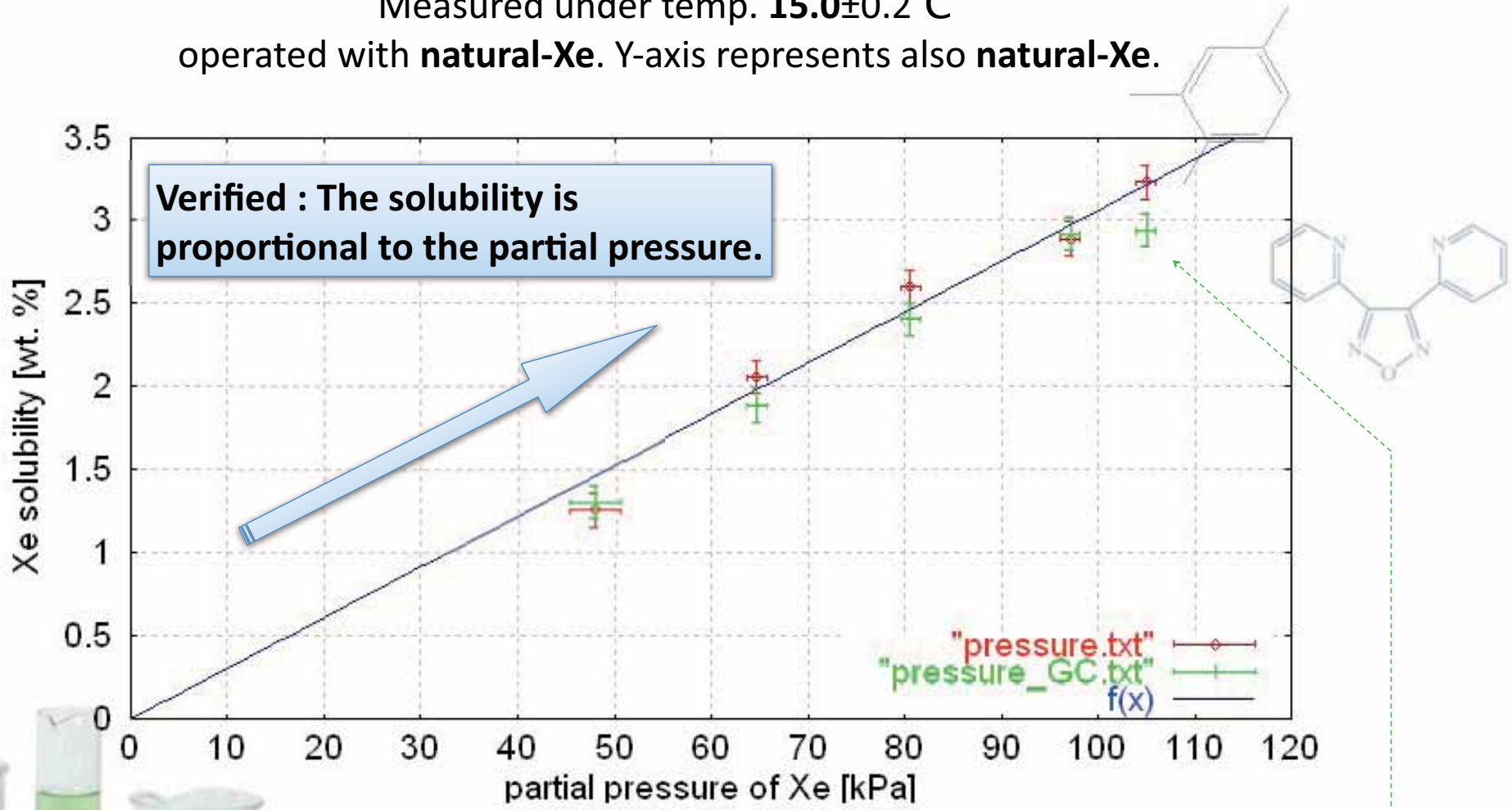
ロシア（Barabash）が提供

100kgで30~60meVの感度

こんな感じ？

Pressure dependence of Xe-solubility

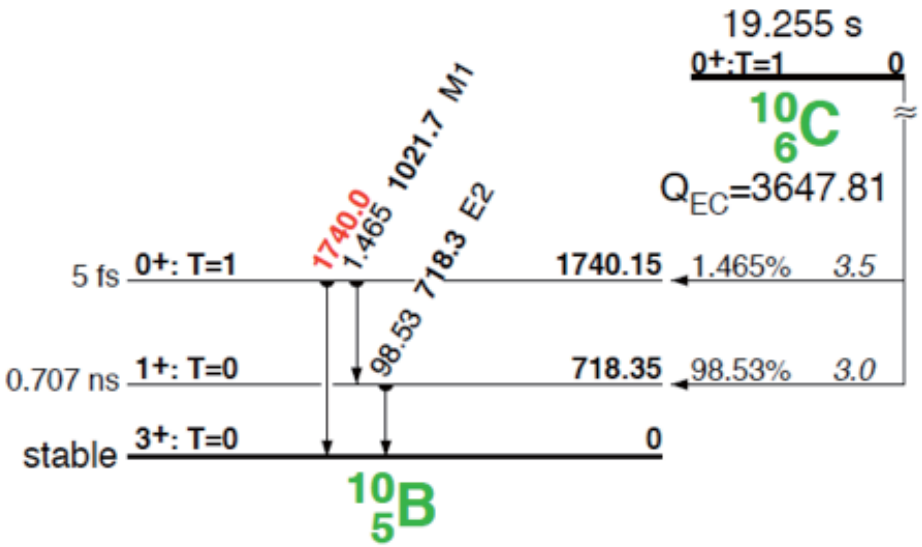
Measured under temp. **15.0**±0.2℃
operated with **natural-Xe**. Y-axis represents also **natural-Xe**.



Points colored red are measured by mass-flowmeter. Greens are by Gas-Chromatograph.
In high solubility region, the value measured by G.C. tends to decline because of sampling-loss.

昇厚すればキセノン濃度を向上できる。10mで２倍、**30m**で４倍！！

~15wt%



^{10}C はβ^{+}＋γ ： 4 vertices

1% photo coverage / 5cm 分解能なら可能か？

KamLANDi

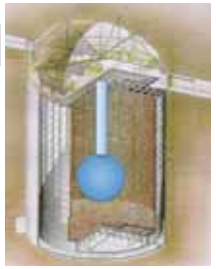
４端子読み出しアバランシフォトダイオード？

GEM+何か？

キヤノン製 20cm角のCMOS光センサー！

Improvement of the sensitivity
--each group has their own story--

Example: KamLAND-ZEN ➔ Super-KamLAND-ZEN



Improvement of Resolution x BG

- KL-ZEN
  - FWHM(@2.5MeV) ~10.3%
  - ^{8}B : 3.9x10^{-3} /kg/yr
  - 2ν : 4.8x10^{-3} /kg/yr
  - ^{10}C : 2.4x10^{-3} /kg/yr

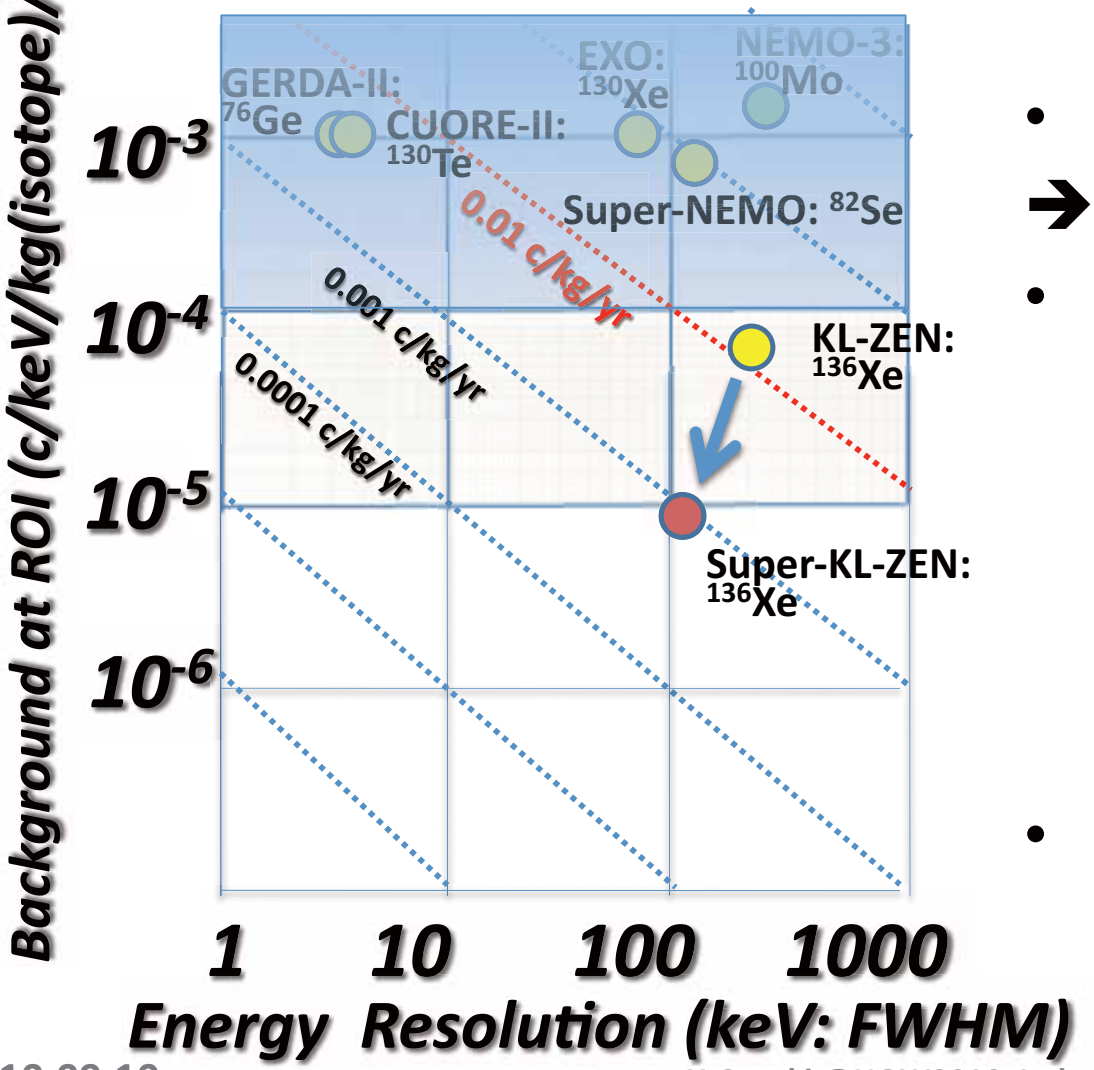
Increase number of photo electrons:
New scintillator: linear
➔ Alkylbenzene x1.4
Photo-coverage
➔ SK: (40% + 40%) x2.4
Total: 3.3 times increase

Reduce ^{10}C further:
multiple vertex identification
➔ > 1/10 reduction

Increase the Pressure of Xe: x4 at 30m depth
➔ Xe density x4 ➔ Effective BG reduction: ¼

- Super-KL-ZEN
  - FWHM(@2.5MeV) ~ 5.7%
  - ^{8}B : 6.5x10^{-4} /kg/yr
  - 2ν : << ^{8}B
  - ^{10}C : 2.4x10^{-4} /kg/yr

Super-KamLAND-ZEN



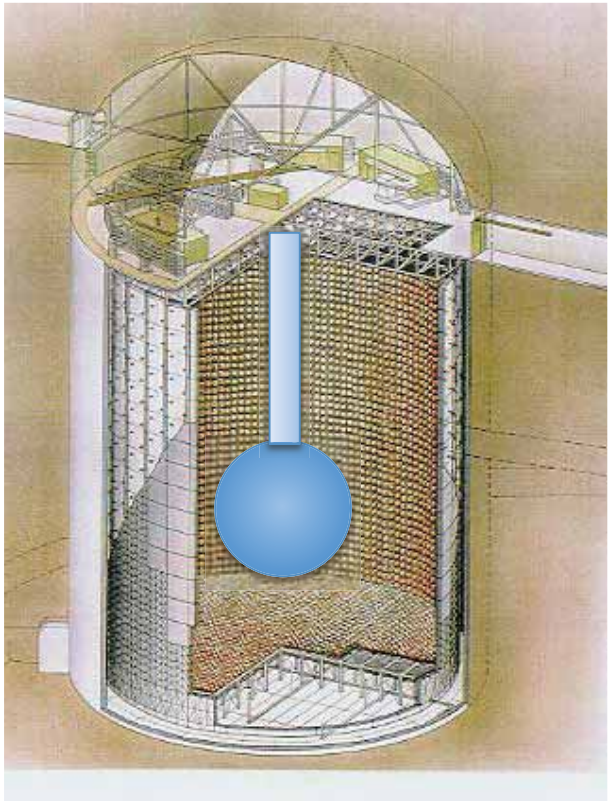
- Resolution x BG

➔x ~12 improvement

- Further improvements need

- Mass 400kg ➔ 40tons x 100

Super-KamLAND-ZEN



- Improve 1,200 times from KL-ZEN, but not 10,000
- Sensitivity

  ➔ Down to 7.6 meV

  ➔ Just step on the NMH region

  → may need further improvement

Cost estimate

SK improvement	$ 30M
Scintillator	$ 20M
Xenon	$200M

KamLAND-Zen の外的要因による日程

2013 外水槽からのタンクの点検（消防法）

可能性	効果
OD用PMTの死球交換	VETO効率の向上
ミューオントラッカーの設置	トラッキングのキャリブレーション spallation cut 効率の改善
水漏れの補修	維持費軽減
対流対策（温度制御）の追加	Be7,CNO/pep のBG(^{210}Bi)低減
集光ミラーの設置？？	光量 1.8倍 } 2015点検の前倒し ７億円？
液シンの改良？？　（金が厳しい）	光量 1.4倍 } 2015点検の前倒し ７億円？
加圧キセノン	キセノン２倍？、ＢＧ２分の１？ ６億円？

2015 内側からのタンクの点検（消防法）

可能性	効果
集光ミラー・高性能液シン	光量 2.5倍
上部入口拡大	低バックグランド実験施設

Comparison of hierarchies

May 2010

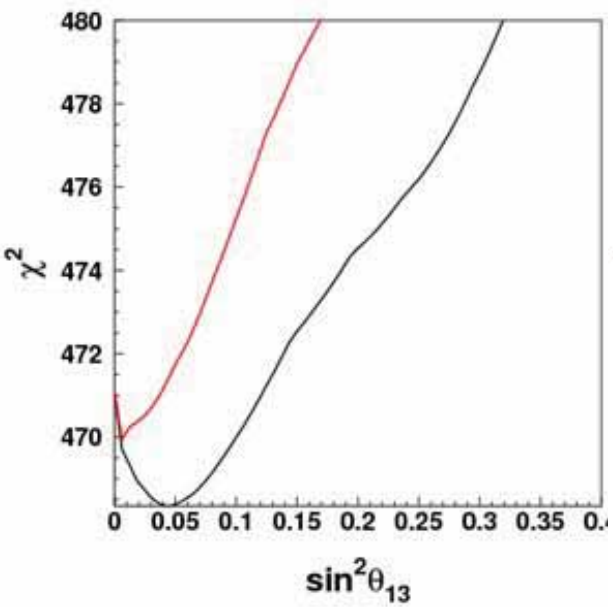
Best fit is in the inverted hierarchy case

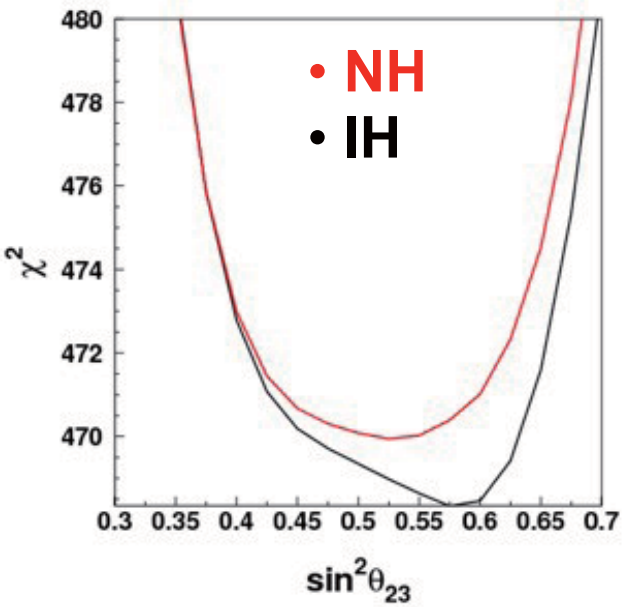
Normal hierarchy (NH):χ^2_{min}= 469.94/416dof

Inverted hierarchy (IH):χ^2_{min}= 468.34/416dof

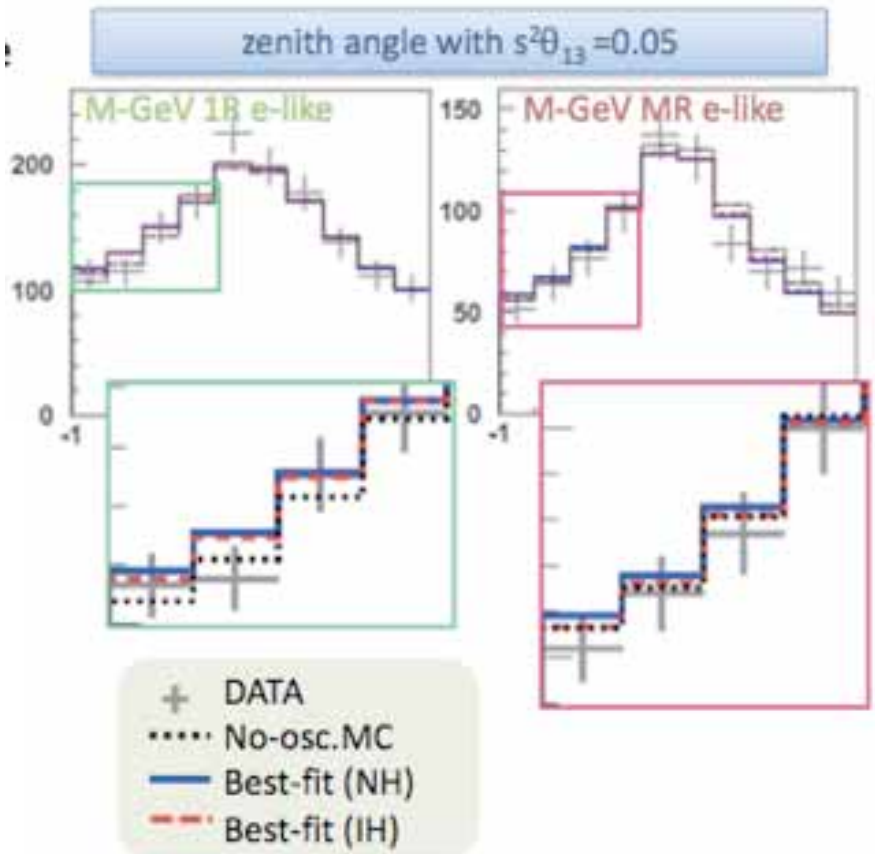
→ $\Delta\chi^2$ = 1.6

No significant difference





Multi-GeV samples tend to favor inverted hierarchy.



There are also some contributions from Multi-GeV μ-like samples favoring IH to NH.

Takeuchi @ neutrino2010

超新星ニュートリノ

World $\bar{\nu}_e$ observatories (examples)

	Detector	E_{th} (MeV)	(a_E, b_E)	Fiducial mass (kton)	$N^{det}_{\bar{\nu}_e}$ ($D = 10$ kpc)
Čerenkov	SK[48, 49] (H_2O)	5	(0.47, 0)	32	5,900 - 9,990
	SNO[50, 51]	4	(0.35,0)		
	H_2O			1.4	260 - 440
	D_2O			1.0	80 - 160
Scintillator	KamLAND [52] (N12+PC+PPO)	2.6	(0,0.075)	1.0	240 - 400
Čerenkov	HK[33] (H_2O)	5	(0.5,0)	540	100,000 - 170,000
	UNO [55] (H_2O)	5	(0.5,0)	650	120,000 - 203,000
Scintillator	LENA [35] (PXE)	2.6	(0.1,0)	30	7,500 - 12,600

TABLE I: The relevant $\bar{\nu}_e$ detection parameters for some of the present and proposed detectors. In the last column we give the expected range for the number of charged current $\bar{\nu}_e$ events from a Galactic SN at 10 kpc, assuming the neutrino oscillation pattern discussed in sect 3B. The larger (smaller) numbers correspond to SN model 1 (model 2).

E. Nardi and J.L. Zuluaga, hep-ph/0412104

10kpc
Possible detection of supernova neutrinos with KamLAND

CC $\bar{\nu}_e + p \rightarrow e^+ + n$ ~300 events

CC/NC $\nu(\bar{\nu}) + {}^{12}\mathrm{C} \rightarrow \underbrace{{}^{12}\mathrm{N},\ {}^{12}\mathrm{B}}_{\text{a handful of events}},\ {}^{12}\mathrm{C}^*$ ~60 events

CC+NC $\nu + e^- \rightarrow \nu + e^-$ ~20 events

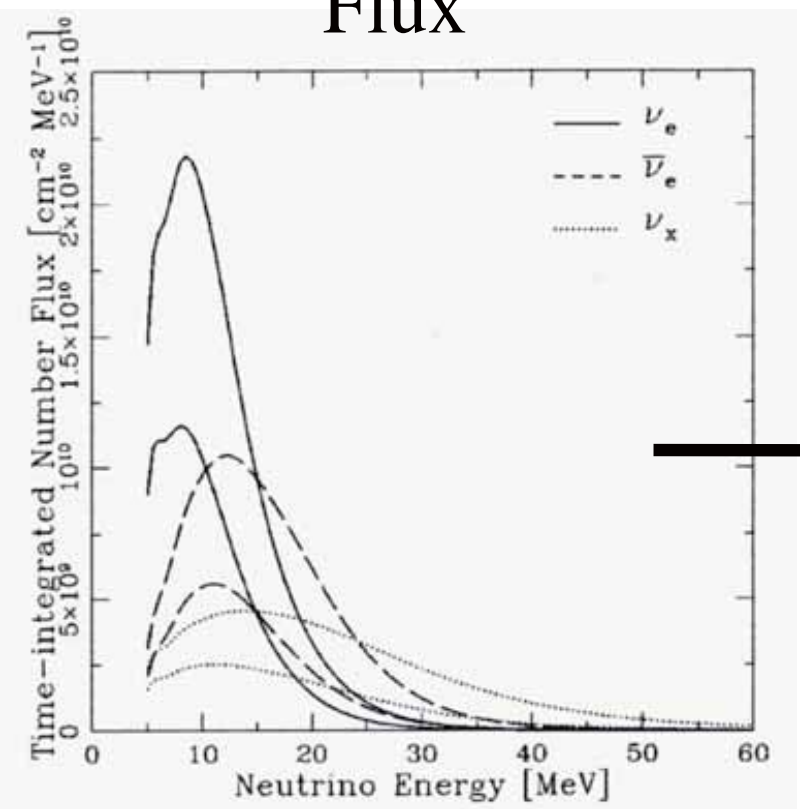
NC $\nu + p \rightarrow \nu + p$ ~300 events

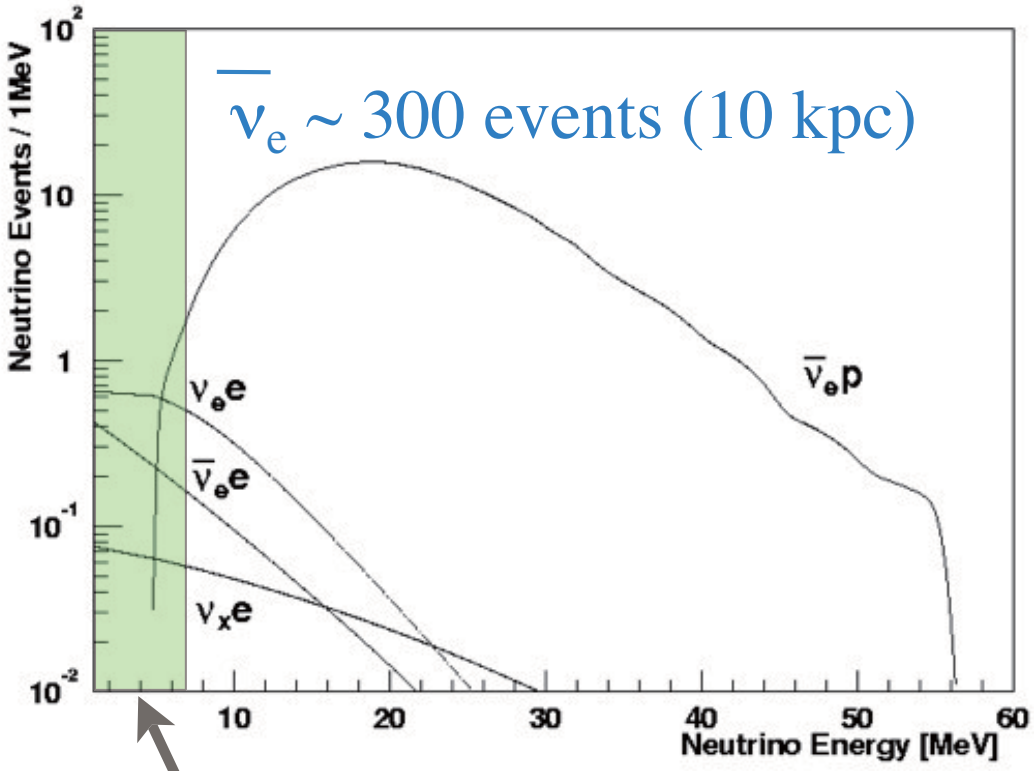
Supernova observation with KamLAND

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

KamLAND expected:
6.5-m fiducial, 100% efficiency,
Resolution 7.25%/√(E/[MeV])

Flux





unique for KamLAND

S. Ando and K. Sato, PRD **67**, 023004,
68, 023003 (2003)

Differential cross section

- proton recoil favors the maximum energy ($2E_\nu^2/M_p$). (good for E_ν measurement)

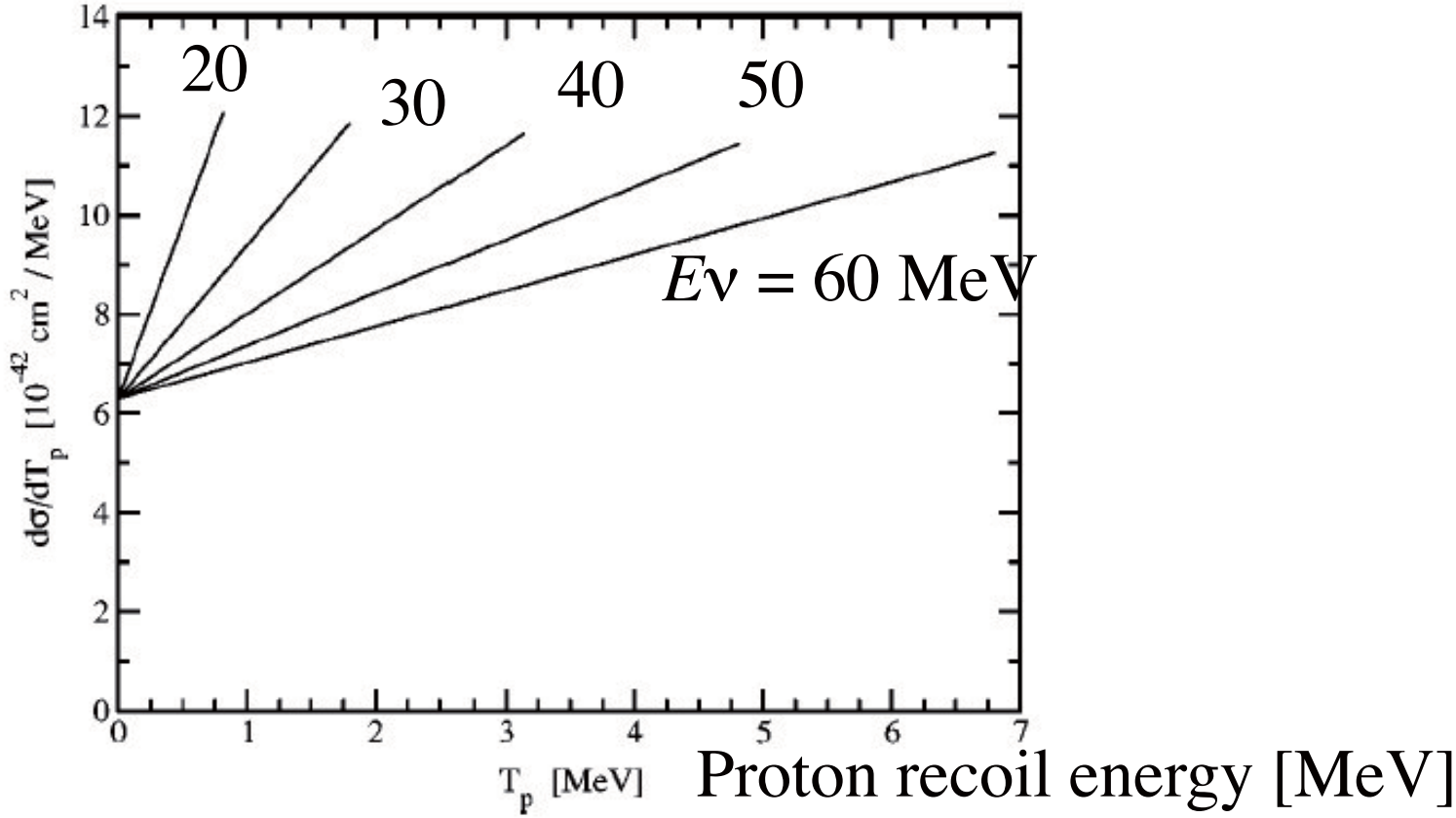
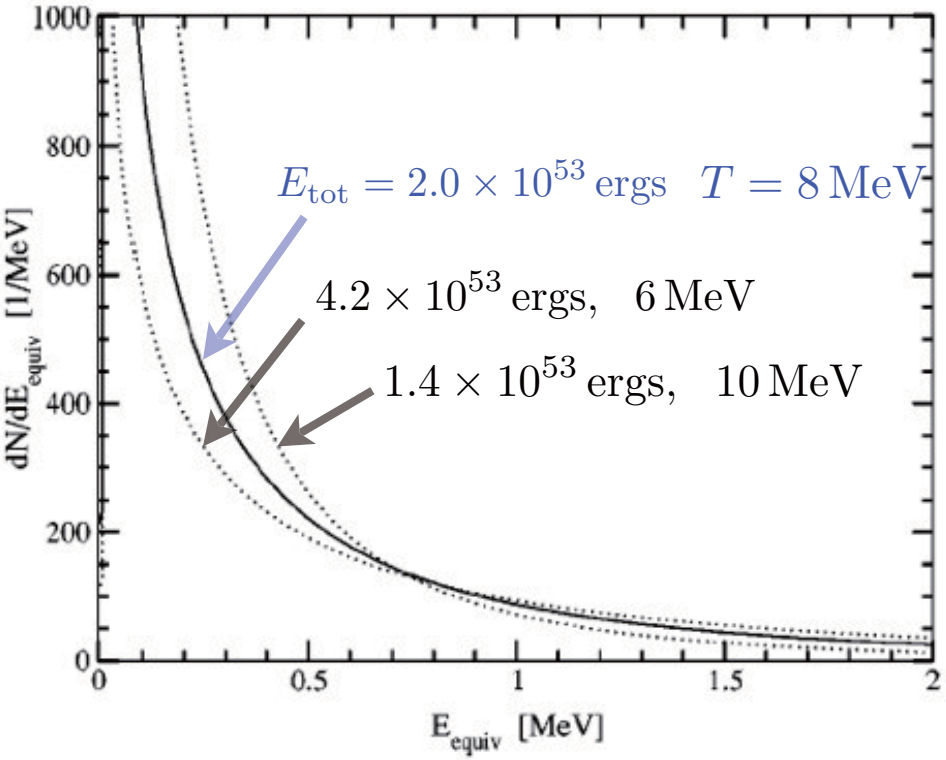
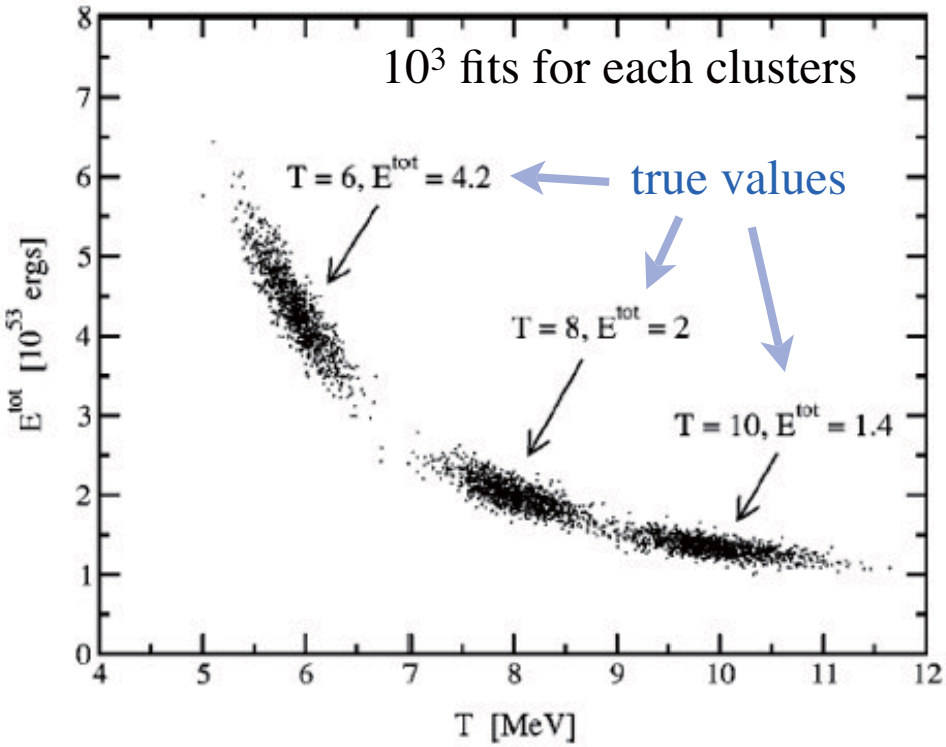


FIG. 1. The differential cross section as a function of T_p for fixed E_ν. Note the rise at large T_p, indicating that large kinetic energies are preferred. From left to right, the lines are for $E_\nu = 20$, 30, 40, 50, and 60 MeV.

超新星観測でのカムランドの特徴





Visible energy [MeV]

$$\nu + p \longrightarrow \nu + p$$

スペクトルの違いから、全放出エネルギーと温度が同時に測定できる。

核子崩壞

得意なのは。。。

$$n \longrightarrow \text{invisible}$$

(KL: $\tau > 5.8\times10^{29}$ yr)

PRL 96,101802 (2006)

$^{12}C \rightarrow$ invisible $+ {}^{10}C + n\ (+\gamma)$

$T_{1/2}$=19.3s

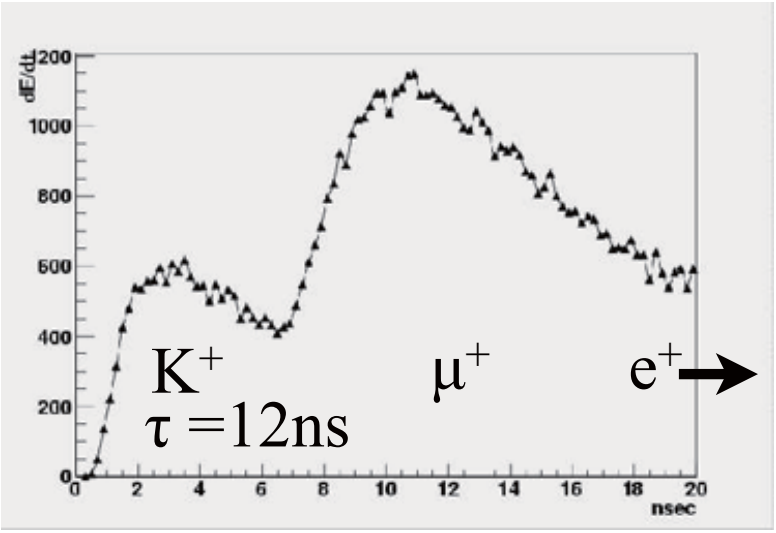
分岐比　5.8%

第一信号	n recoil + (γ)
第二信号	n capture
第三信号	^{10}C decay

$$p \longrightarrow K^+ \bar{\nu}$$

(SK: $\tau > 2.3\times10^{33}$ yr)

	Decay mode	Branching Ratio	peak MeV	number of the events	pulse	delayed coincidence ?
P-1	$K^+ \to \mu^+ \ \nu_\mu$	0.6354	255	10979	double	yes
P-2	$K^+ \to \pi^+ \pi^0$	0.2068	465	8585	triple	yes
P-3	$K^+ \to \pi^+ \ \pi^+ \ \pi^-$	0.0559	195	2268	triple	yes
P-4	$K^+ \to \pi^+ \pi^0 \pi^0$	0.0176	465	1757	triple	yes
P-5	$K^+ \to \pi^0 e^+ \nu$	0.0508	425	302	double	no
P-6	$K^+ \to \pi^0 \mu^+ \nu$	0.0335	245	172	double	yes



5 ns 程度の時間差なら分離可能

識別効率　60%以上

KamLANDで10^{33}程度の感度

Super-Kam LANDで10^{34}程度の感度?

カムランドの将来展望まとめ

進行中 **KamLAND-Zen**

縮退構造

↓

予算要求中 **KamLAND2-Zen** pep/CNO, precise ^{7}Be, ^{8}B upturn

2014~開始 25億円 逆階層 NaI, CANDLES, $CdWO_4$

<5億円

↓?

KamLANDi-Zen precise pep/CNO

100億円？ 標準階層? geo-neutrino direction?

↓?

Super-KamLAND-Zen $p \to K\nu$, precise θ_{12}, θ_{13}, hierarchy, precise geo-neutrino, relic SN

250億円？ 標準階層?