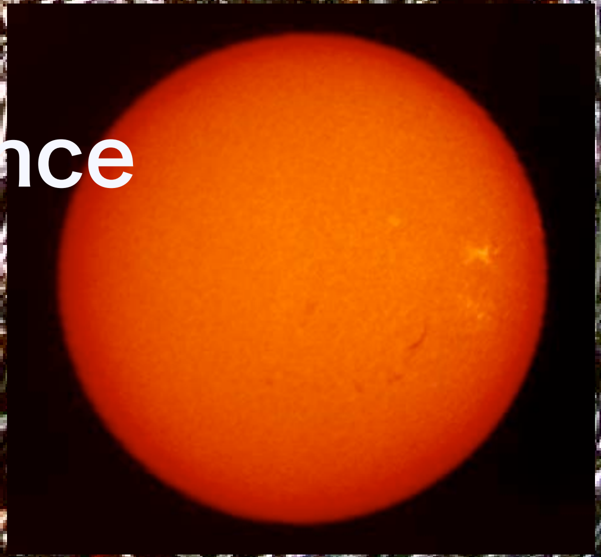
Exploring the earth and the sun with neutrinos



Research Center for Neutrino Science

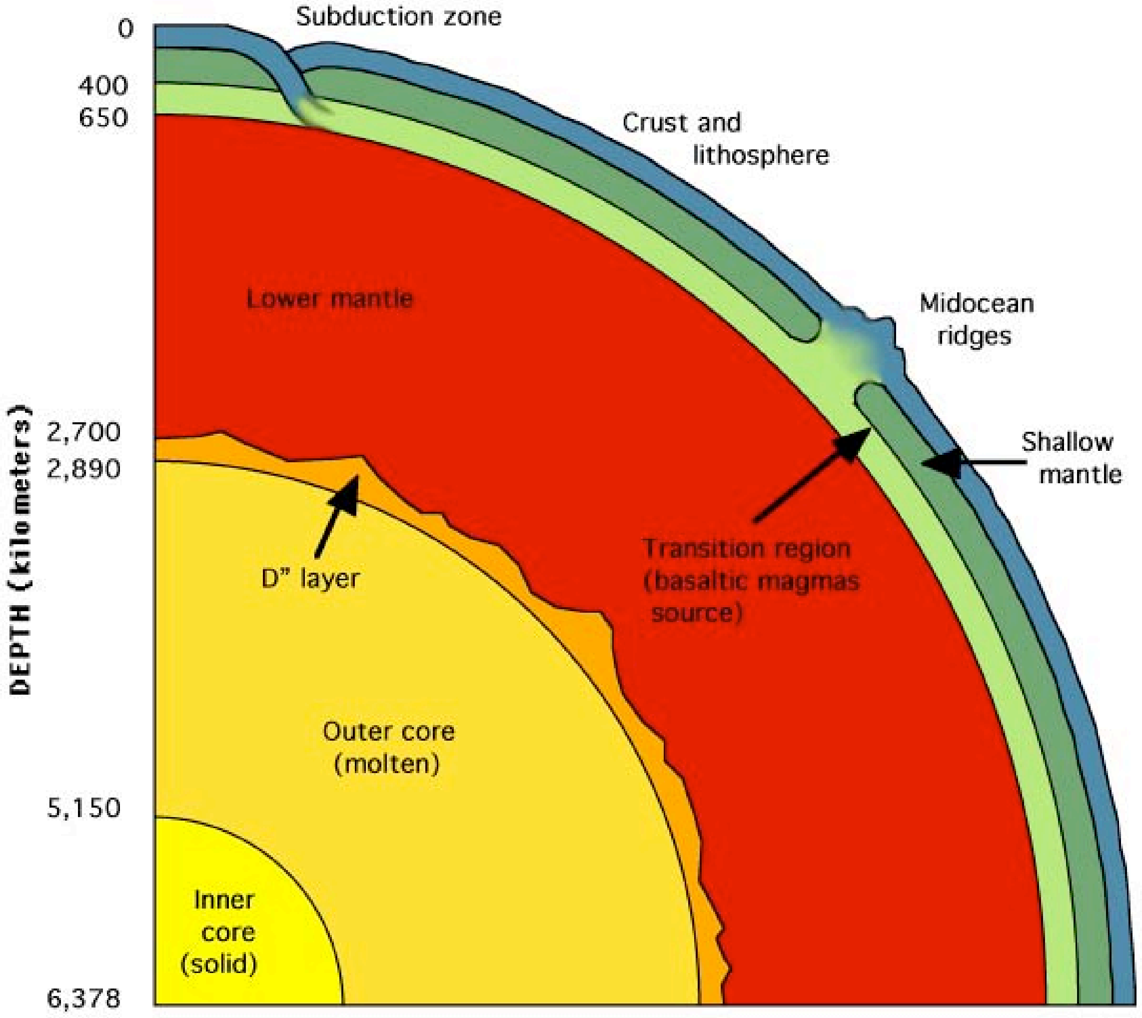
Kunio Inoue

Motivations

with my amateur knowledge

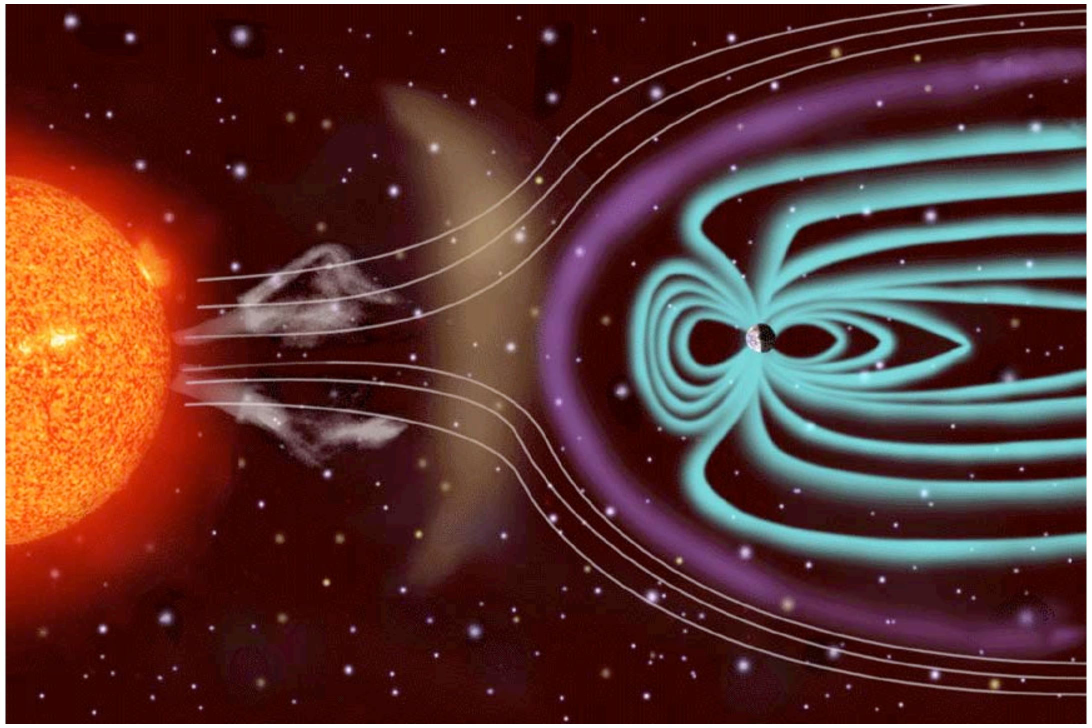
The Earth

The earth has formed by acretion of small astronomical objects such as grain or meteorite.



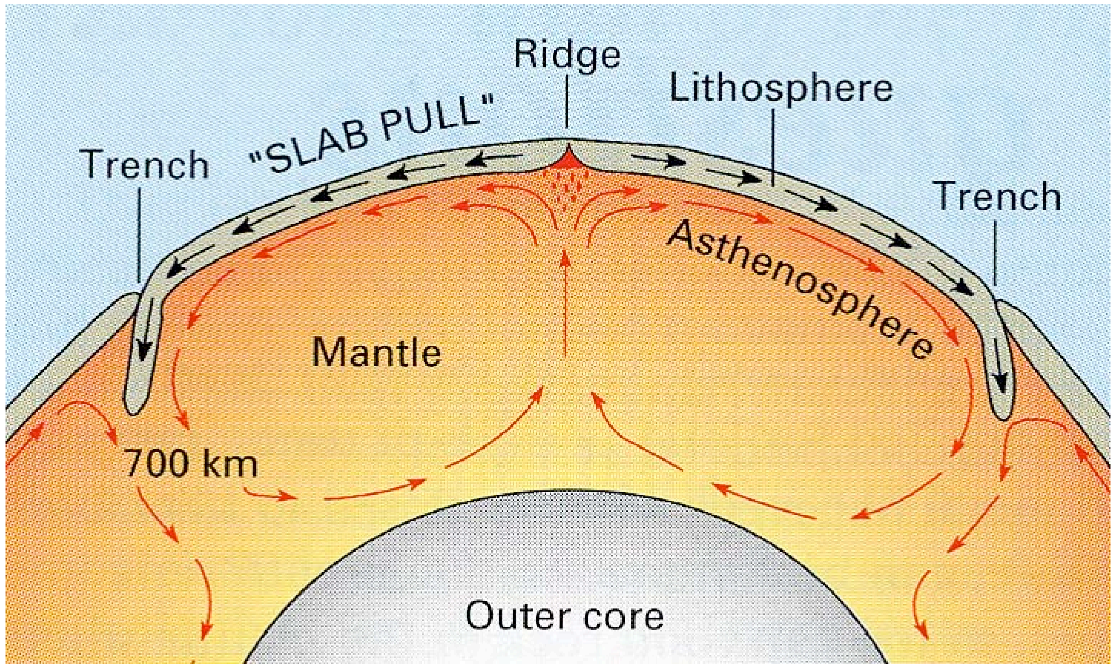
Heavy nickel and iron sank and light silicon went up in the molten protoearth and the layer structure was formed.

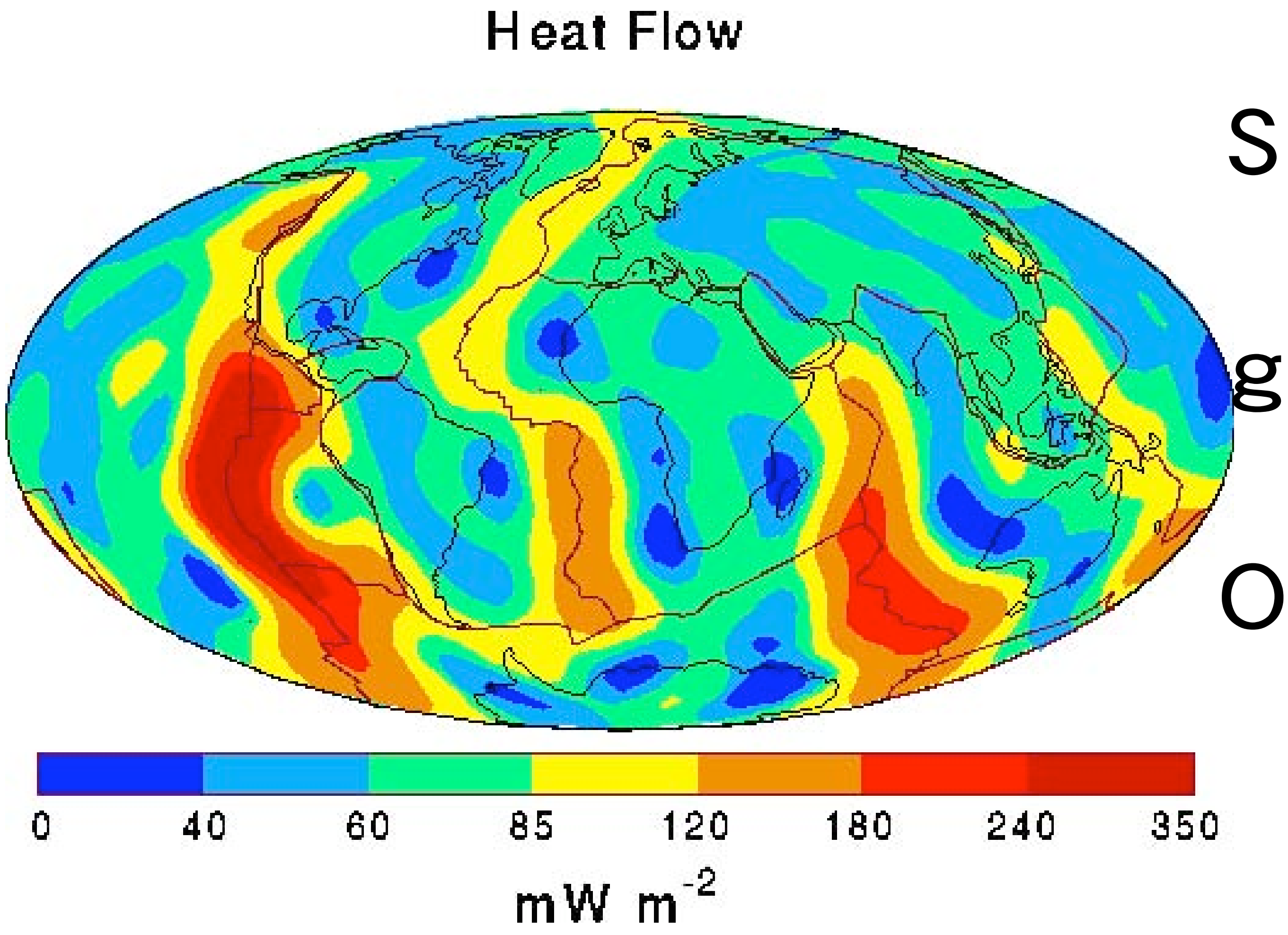
Heat account is important to understand the bulk silicate earth formation.



Terrestrial magnetic field,
protecting lives from solar wind,
is caused by a core movement.
It requires some heat source.

Terrible earthquakes,
eruptions etc. are originally
caused by mantle
convection driven by heat.





Surface heat flow is estimated by extrapolating local heat gradient measurements to the entire surface.

One popular estimation: 44 TW

Recent estimation : 34 TW

This important geophysical parameter is not quite well understood.

More uncertain estimation from CI Chondrite

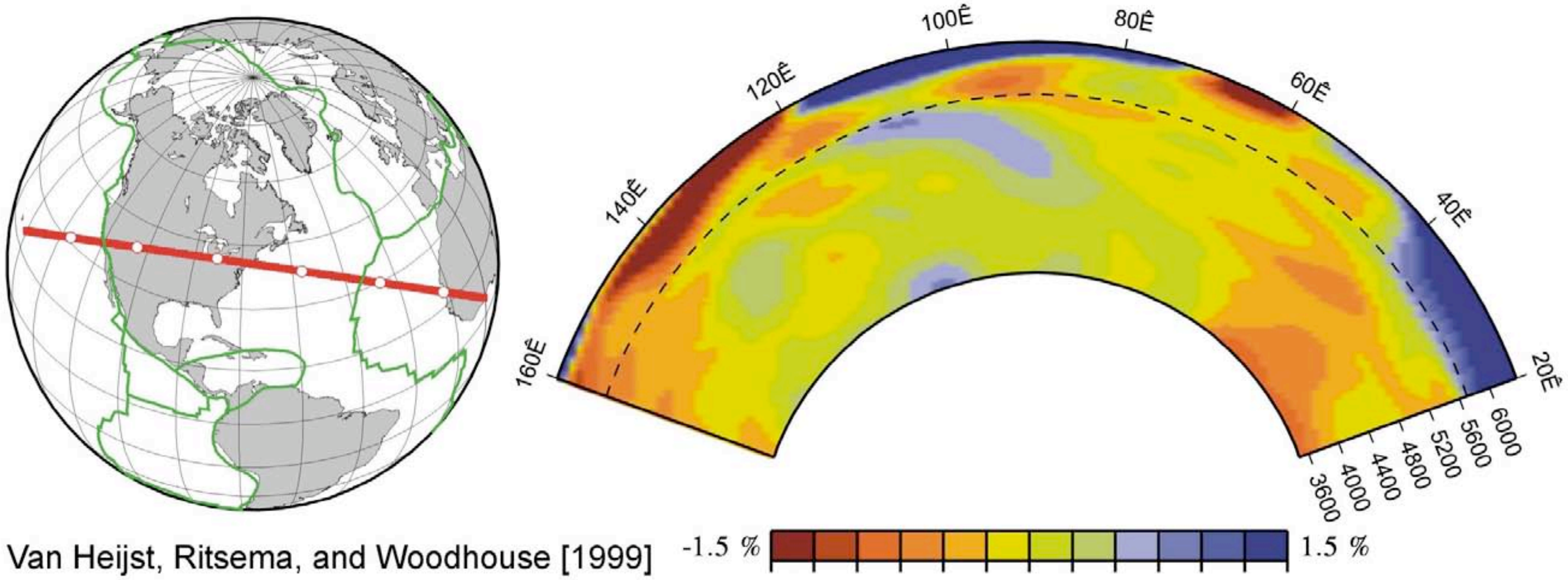
(chemical composition is close to the original grains)

tells 20 TW comes from radioactivity in the earth.

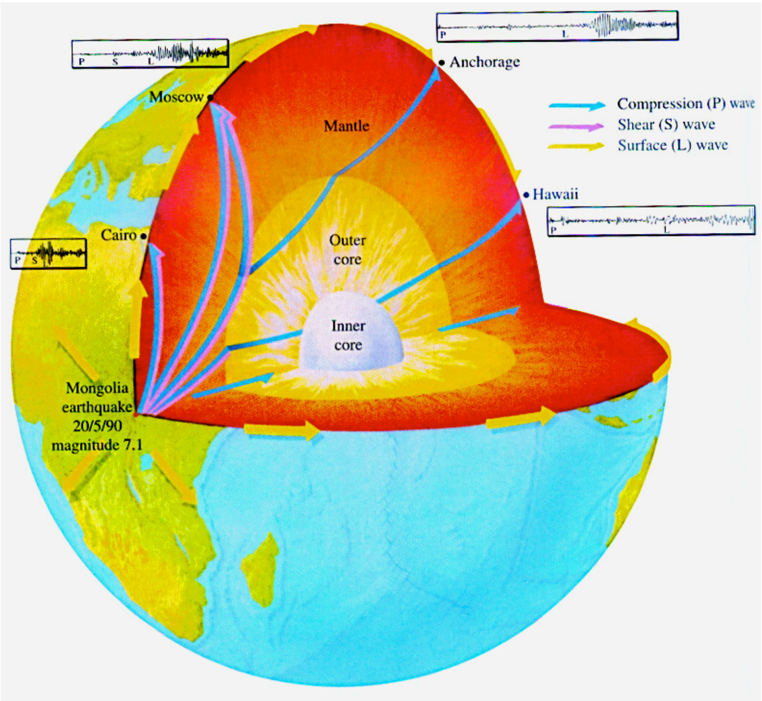
Uranium : 8TW, Thorium : 8TW, Potassium : 4TW

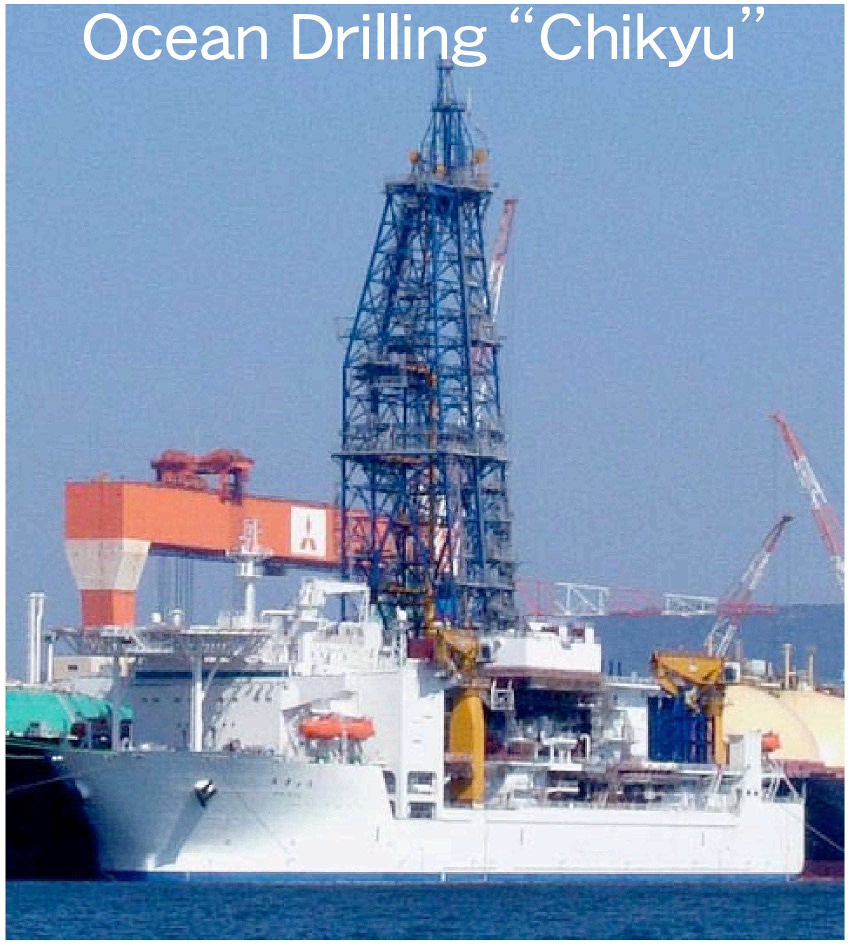
Direct measurement is desired!! HOW??

Possible windows to the interior of the earth



Van Heijst, Ritsema, and Woodhouse [1999]





Ocean Drilling “Chikyu”

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.

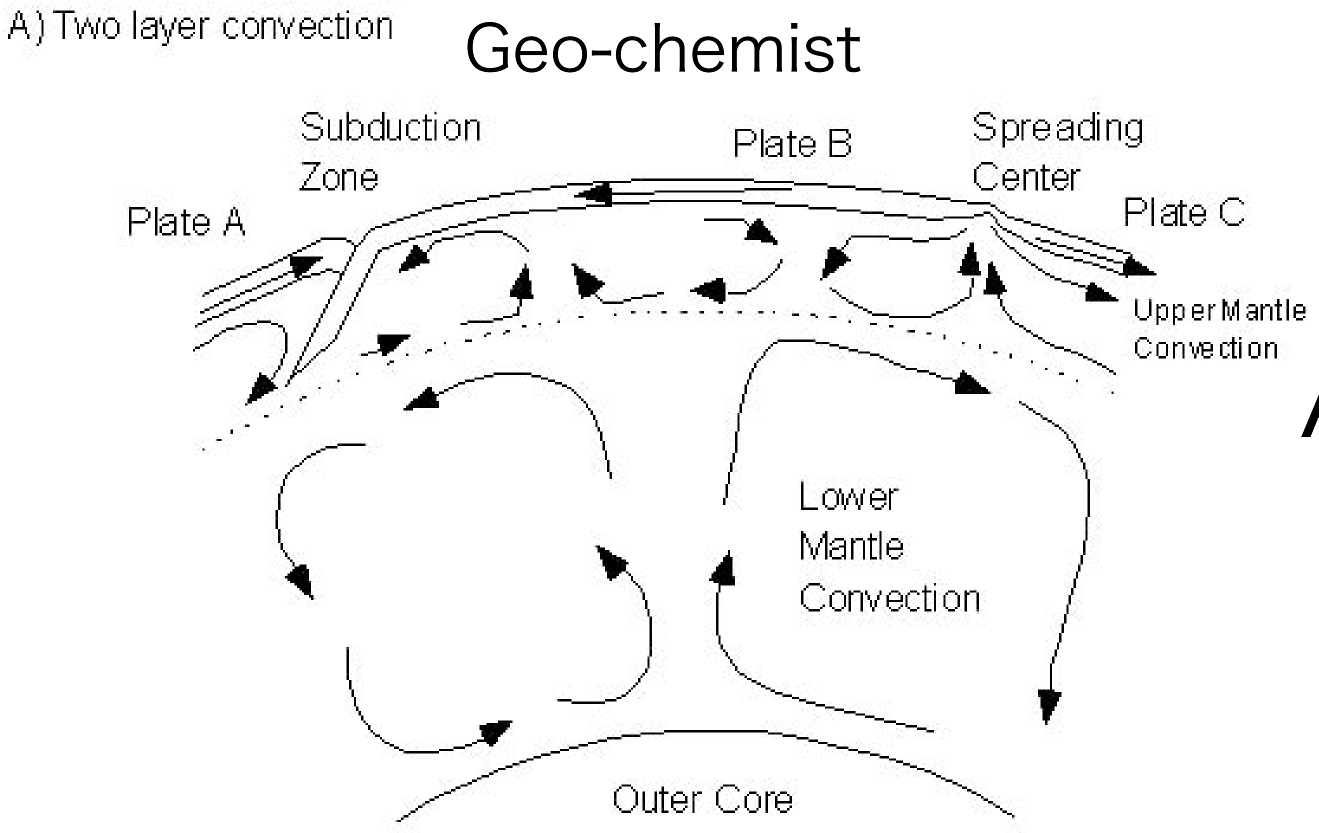
However, it’s only up to 7 km.

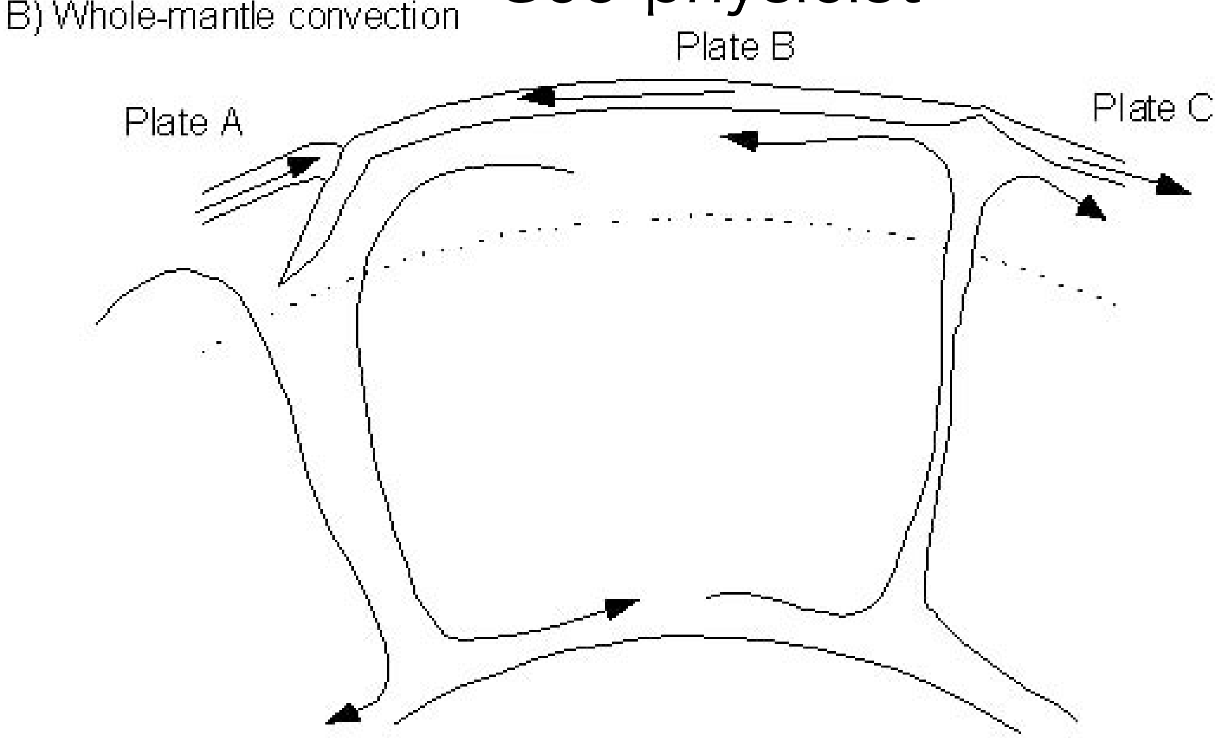
Phase studies at high pressure and temperature, solubility studies are all in “Laboratory”.

Analyses of eruptions,
magnetic field measurement provide imformation.

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

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

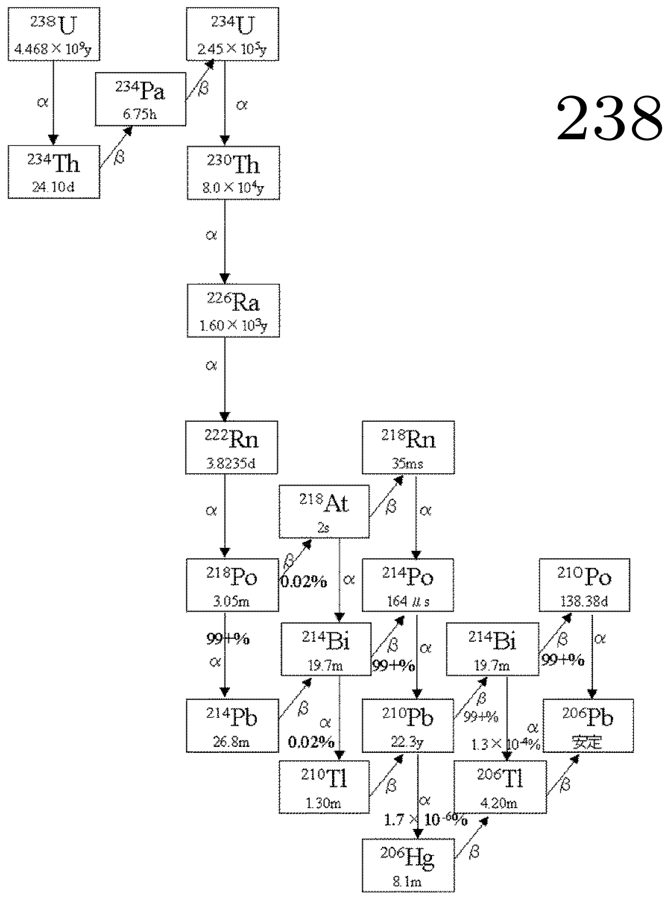

Geo-chemist


Geo-physicist

A model assumes driving heat is 75% from radioactivity and 25% from outer core.

Do upper and lower mantle have homogeneous chemical composition?

^{238}U series

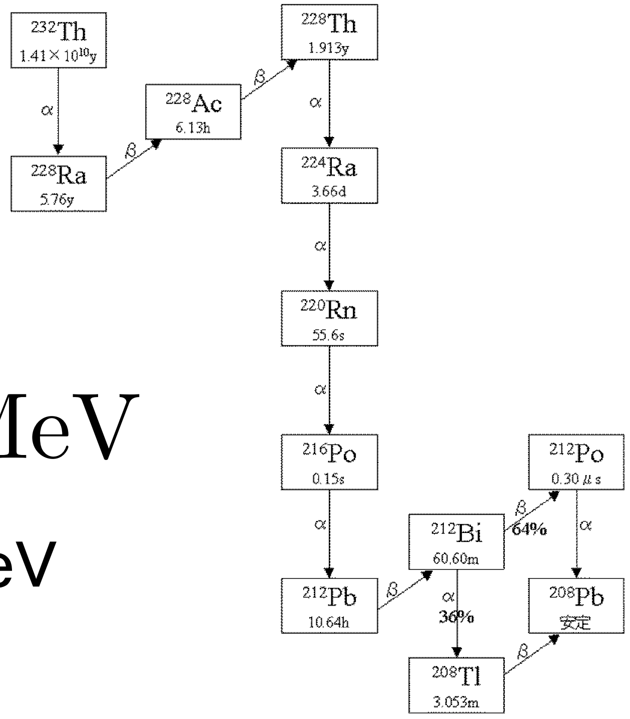


$$^{238}\mathrm{U} \rightarrow ^{206}\mathrm{Pb} + 8\,^4\mathrm{He} + 6\mathrm{e}^- + 6\bar{\nu}_\mathrm{e} + 51.7\,\mathrm{MeV}$$

endpoint 3.27 MeV

Anti-electron-neutrinos are emitted.

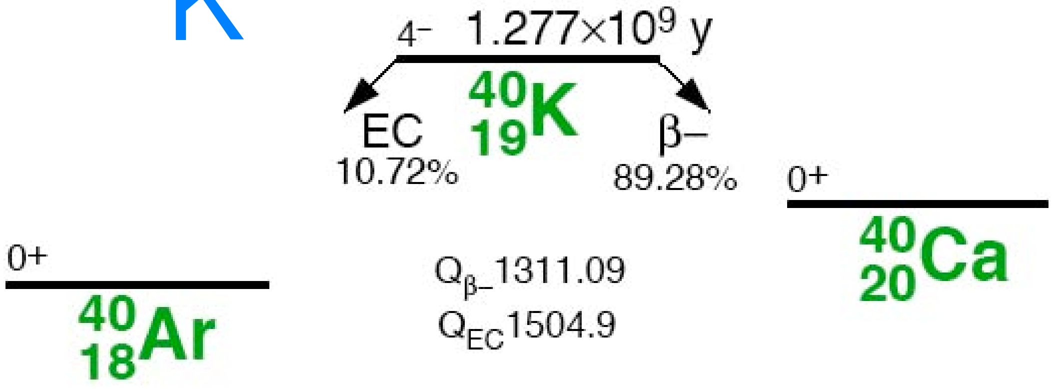
^{232}Th series



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

endpoint 2.25 MeV

^{40}K



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

endpoint 1.31 MeV

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

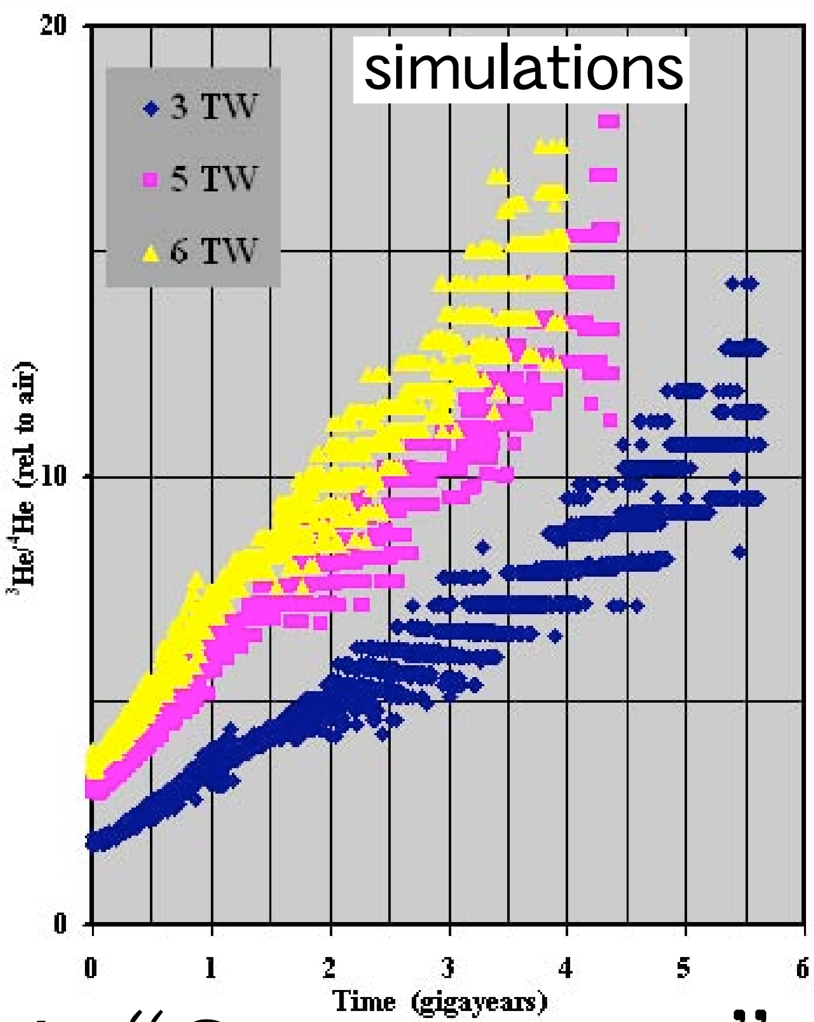
future interest

Geo-reactor?

Why does terrestrial magnetic field flip every million years?

$^3\mathrm{He}/^4\mathrm{He}$ relative to air (95% CL)

Propagating Lithospheric Tears	11.75 ± 5.13 R_A
Manus Basin	10.67 ± 3.36 R_A
New Rifts	10.01 ± 4.67 R_A
Continental Rifts or Narrow Oceans	9.93 ± 5.18 R_A
South Atlantic Seamounts	9.77 ± 1.40 R_A
MORB	8.58 ± 1.81 R_A
EM Islands	7.89 ± 3.63 R_A
North Chile Rise	7.78 ± 0.24 R_A
Ridge Abandoned Islands	7.10 ± 2.44 R_A
South Chile Rise	6.88 ± 1.72 R_A
Central Atlantic Islands	6.65 ± 1.28 R_A
HIMU Islands	6.38 ± 0.94 R_A
Abandoned Ridges	6.08 ± 1.80 R_A

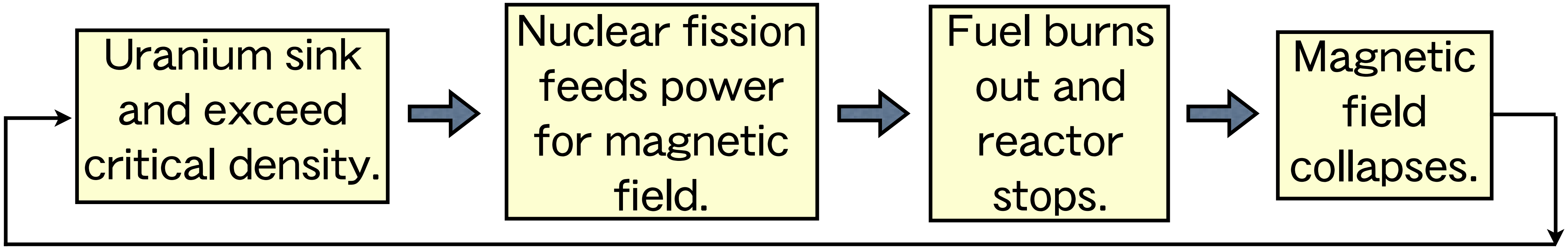


Why do volcanic lava and basalt of Hawaii and Iceland contain ^{3}He?

玄武岩

What is the mechanism?

New exotic hypothesis “Geo-reactor” may explain those.



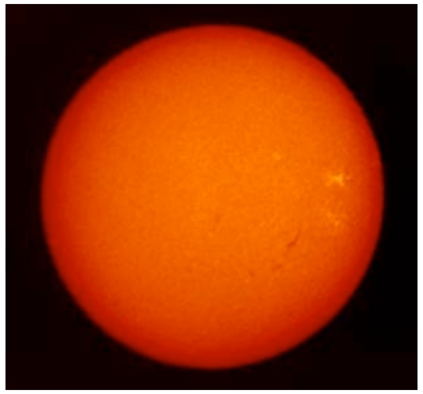
Uranium sink and exceed critical density.

Nuclear fission feeds power for magnetic field.

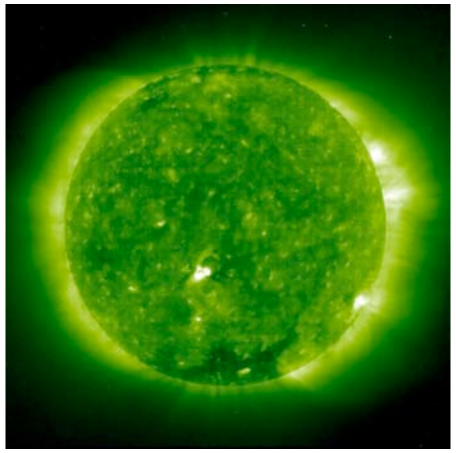
Fuel burns out and reactor stops.

Magnetic field collapses.

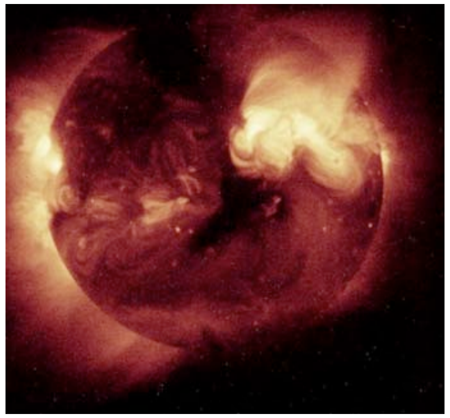
The Sun



visible



UV



X-ray

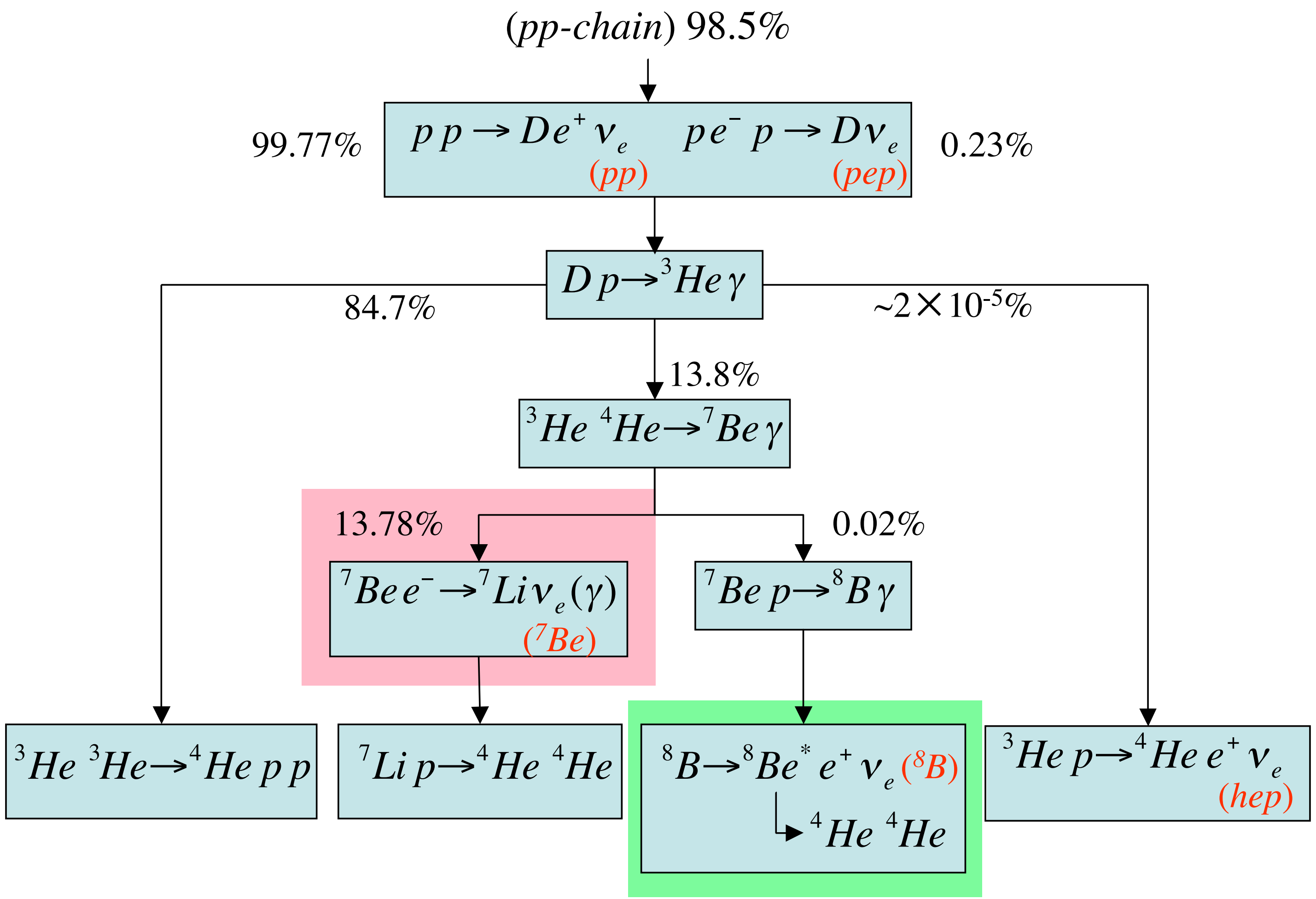
The sun is shining with fusion reaction at the very center.
Optical observation doesn’t provide direct information of it.
Photons spend ~one million years to emerge while neutrinos take only 2.3 sec.

$$4\mathrm{p} \to \alpha + 2\mathrm{e}^{+} + 2\nu_{\mathrm{e}} + 26.73\,\mathrm{MeV}$$

This conclusion is an outcome of great success of nuclear physics. (nuclear cross section, opacity etc.)

Originally, two possibilities were considered.

pp chain



(*pp-chain*) 98.5%

99.77%

$p\,p \to D e^+ \nu_e$ (*pp*)

$p e^- p \to D \nu_e$ (*pep*)

0.23%

$D\,p \to {}^3He\,\gamma$

84.7%

~2×10

$\sim 2\times 10^{-5}\%$

13.8%

${}^3He\,{}^4He \to {}^7Be\,\gamma$

13.78%

0.02%

${}^7Be\,e^- \to {}^7Li\,\nu_e(\gamma)$ (${}^7Be$)

${}^7Be\,p \to {}^8B\,\gamma$

${}^3He\,{}^3He \to {}^4He\,p\,p$

${}^7Li\,p \to {}^4He\,{}^4He$

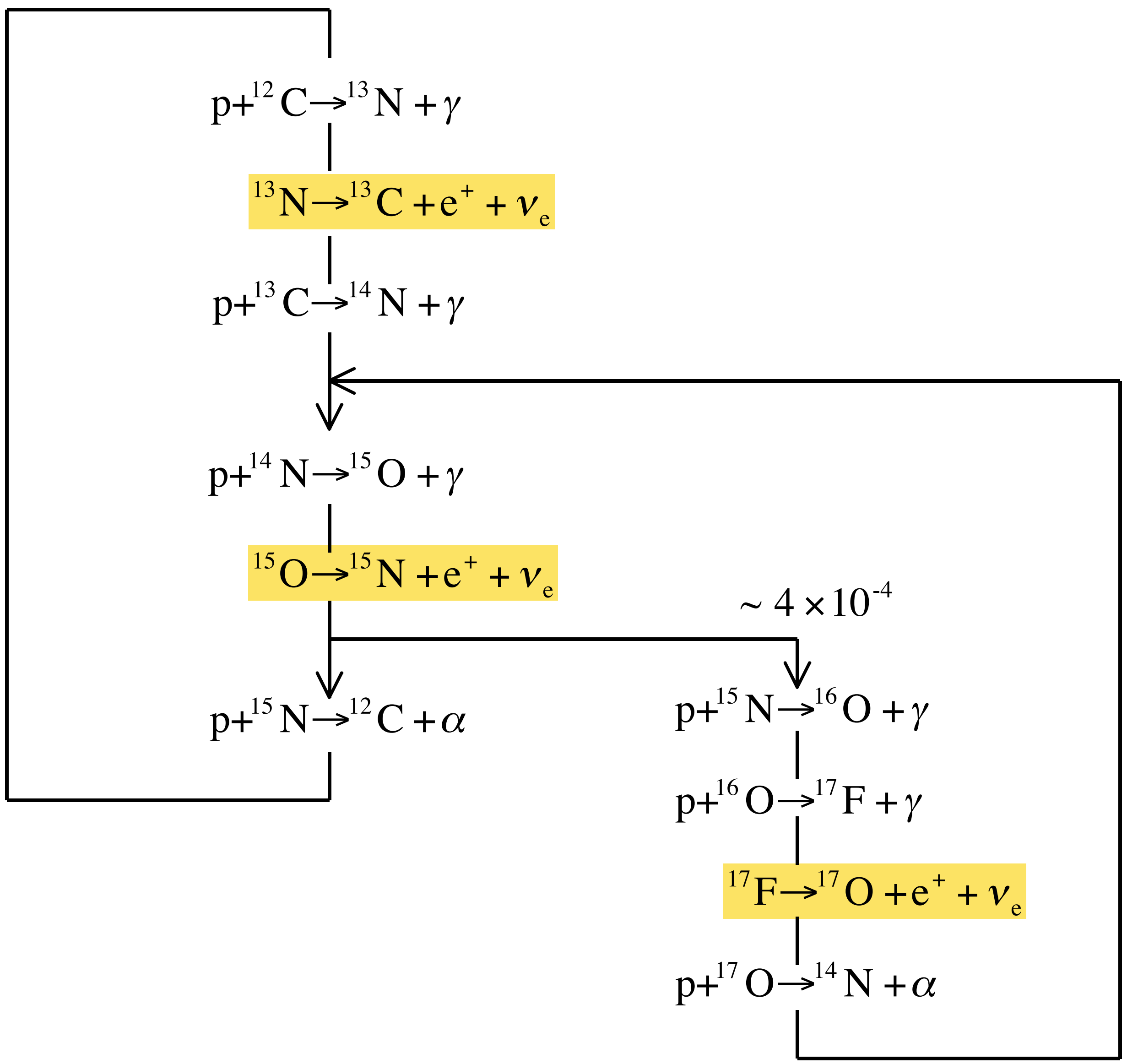
${}^8B \to {}^8Be^*\,e^+\,\nu_e$ (${}^8B$)

$\to {}^4He\,{}^4He$

${}^3He\,p \to {}^4He\,e^+\,\nu_e$ (*hep*)

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

The CNO cycle



$p + {}^{12}C \to {}^{13}N + \gamma$

${}^{13}N \to {}^{13}C + e^+ + \nu_e$

$p + {}^{13}C \to {}^{14}N + \gamma$

$p + {}^{14}N \to {}^{15}O + \gamma$

${}^{15}O \to {}^{15}N + e^+ + \nu_e$

$\sim 4 \times 10^{-4}$

$p + {}^{15}N \to {}^{12}C + \alpha$

$p + {}^{15}N \to {}^{16}O + \gamma$

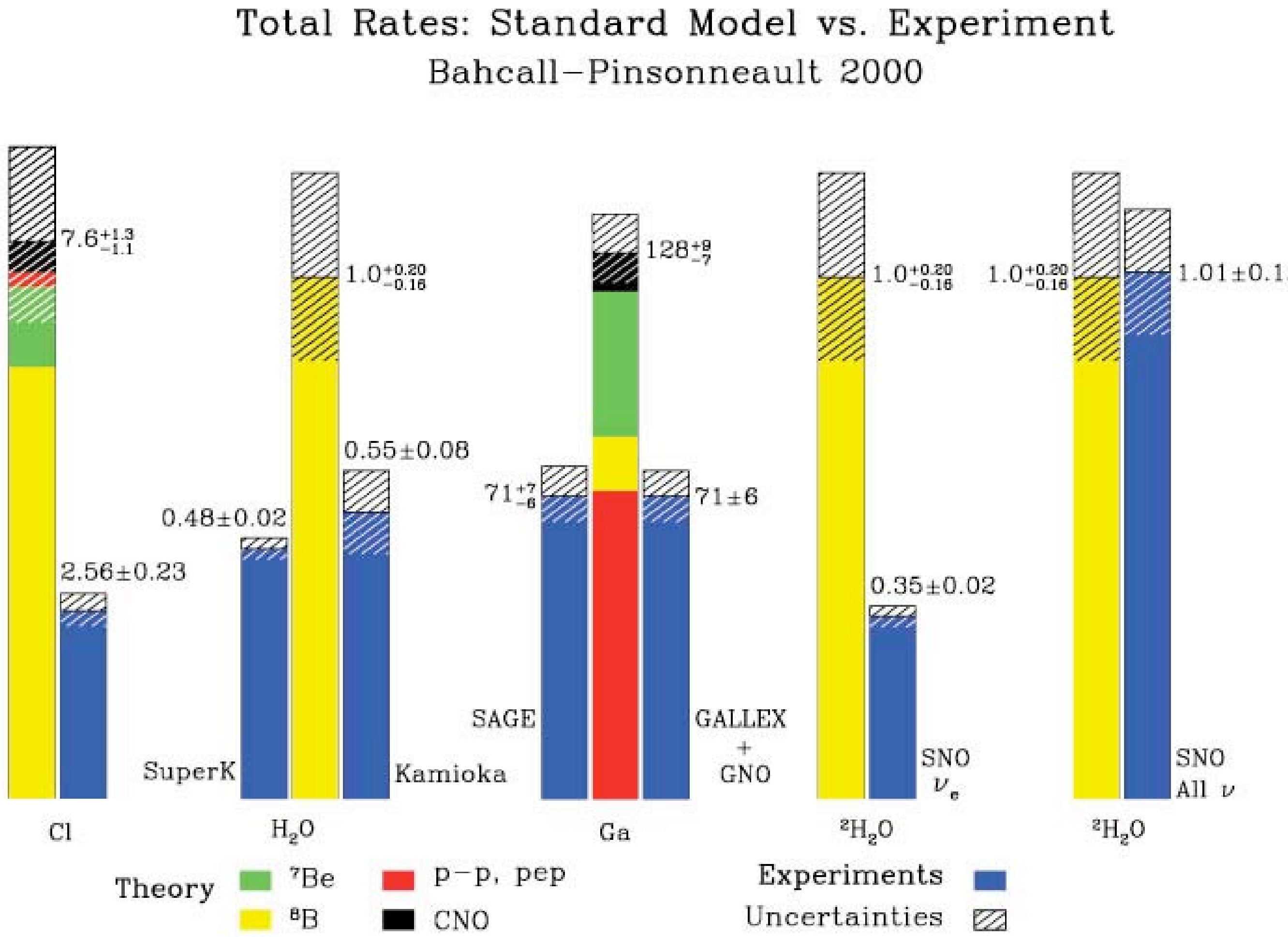
$p + {}^{16}O \to {}^{17}F + \gamma$

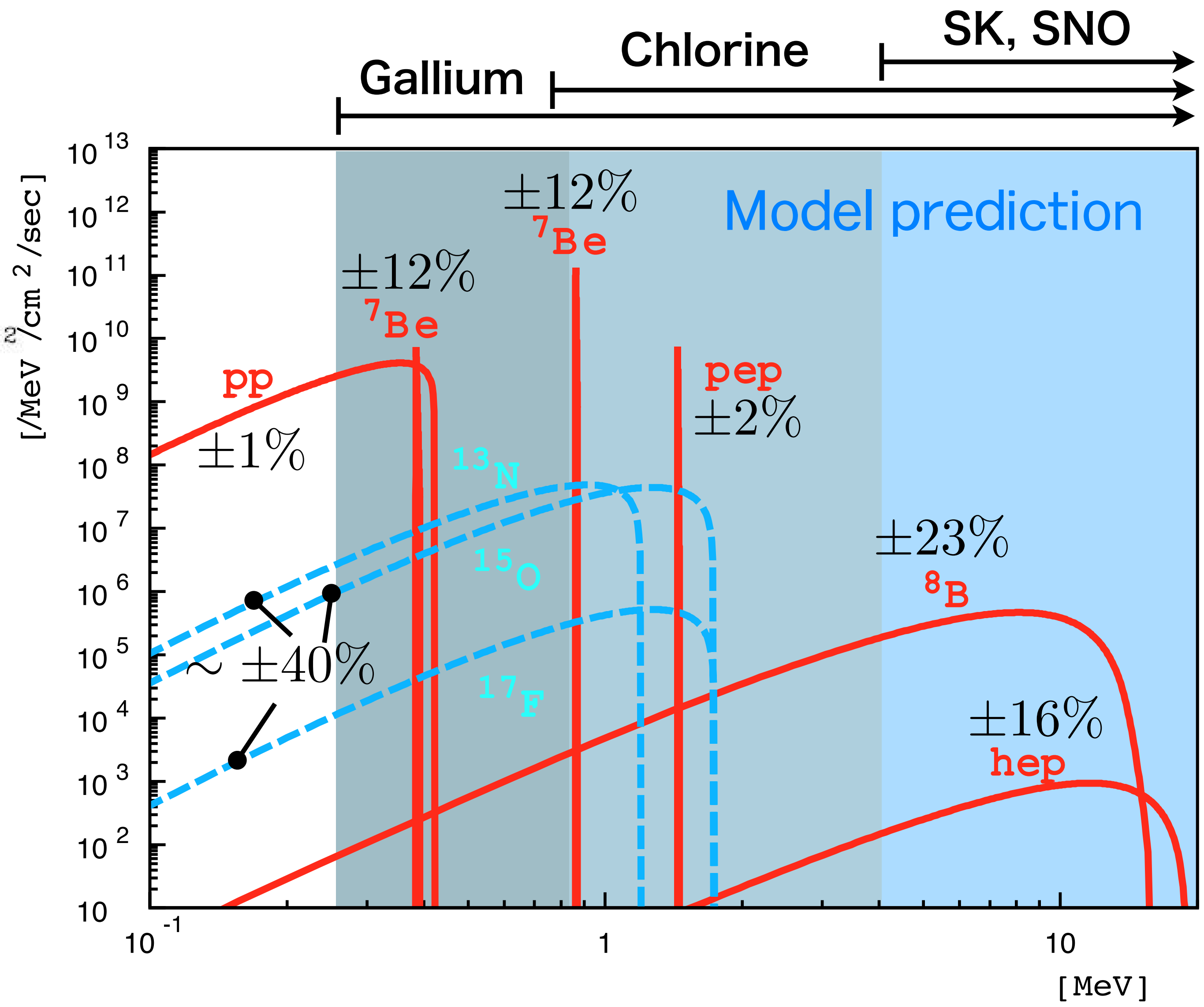
${}^{17}F \to {}^{17}O + e^+ + \nu_e$

$p + {}^{17}O \to {}^{14}N + \alpha$

Pioneering Davis (Novel laureate with Koshiba) experiment was aiming at discriminating these.

However, it was a start of “the solar neutrino problem”.





The problem has lasted more than 30 years until KamLAND.

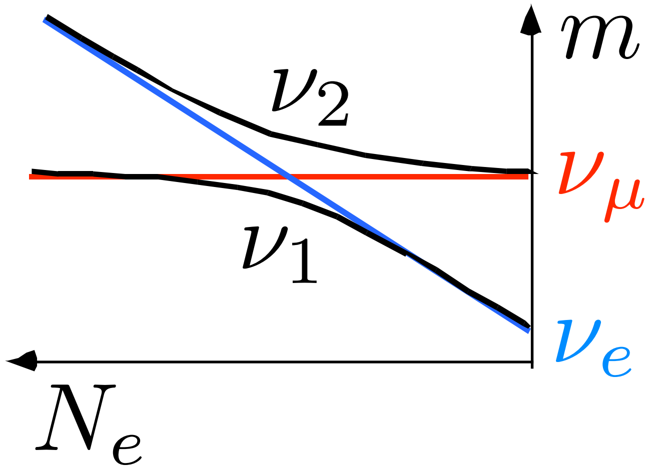
Correct knowledge of neutrino propagation is indispensable for “the Neutrino Astrophysics”!

Low energy neutrino observation is desired for cross check of the standard solar model.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$m_1 \neq m_2$$

In matter (in the sun)

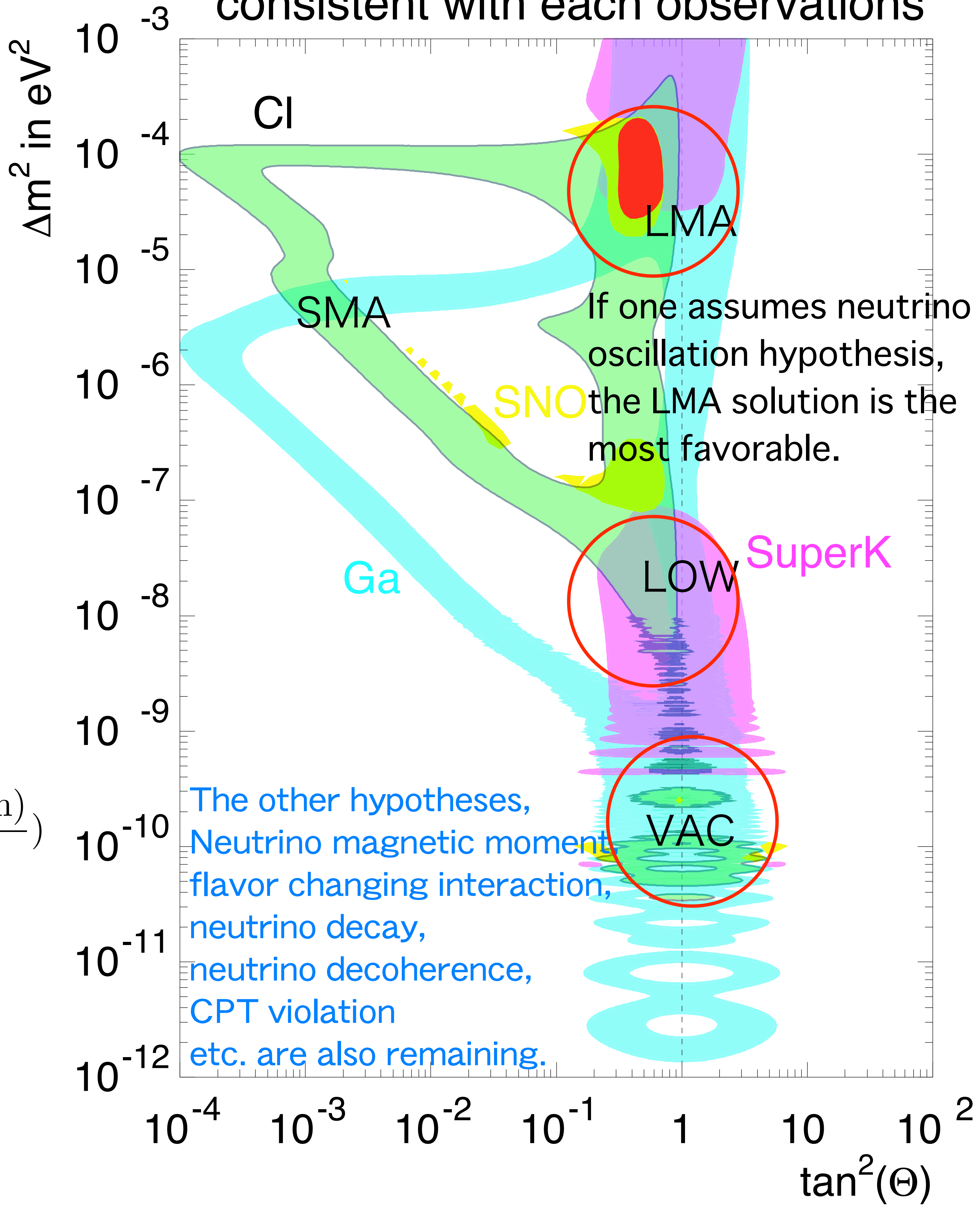


In vacuum

$$P(\nu_e \to \nu_\mu) \simeq \sin^2 2\theta \sin^2(\frac{\Delta m^2 t}{4E})$$
$$\simeq \sin^2 2\theta \sin^2(1.27\frac{\Delta m^2(\mathrm{eV}^2)L(\mathrm{m})}{E(\mathrm{MeV})})$$

Further investigation with well-understood man-made neutrinos is desired.

Neutrino oscillation parameters consistent with each observations



If one assumes neutrino oscillation hypothesis, the LMA solution is the most favorable.

The other hypotheses,
Neutrino magnetic moment,
flavor changing interaction,
neutrino decay,
neutrino decoherence,
CPT violation
etc. are also remaining.

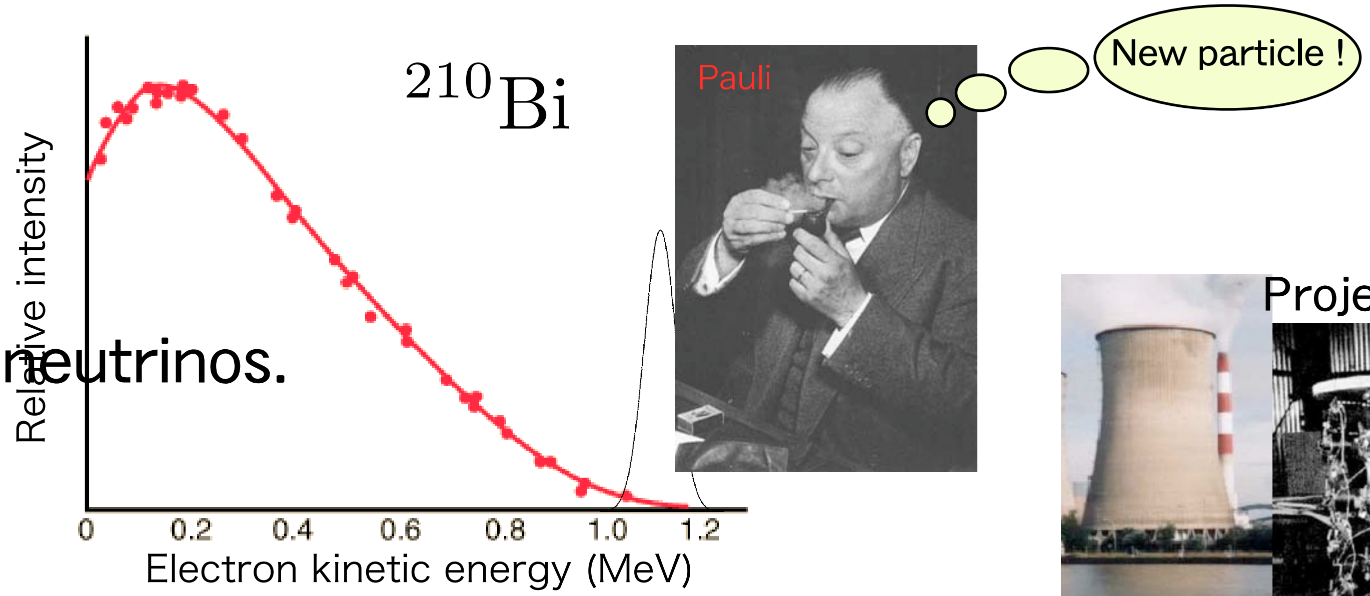
Neutrinos

Neutrino?

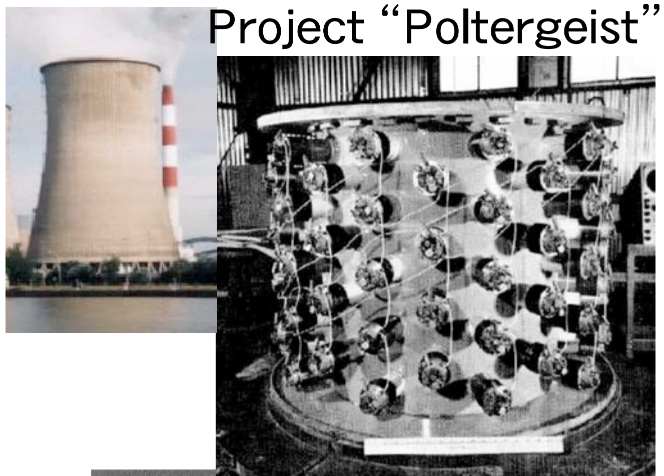
1930 Theoretical prediction

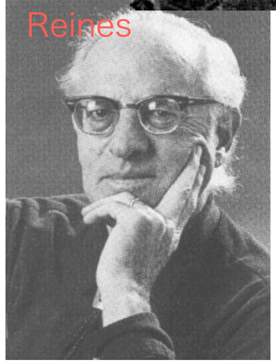
1956 First discovery with reactor neutrinos.

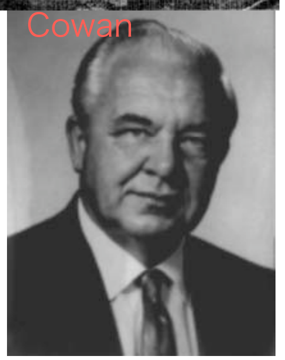
Why did it take so much time?



Project “Poltergeist”







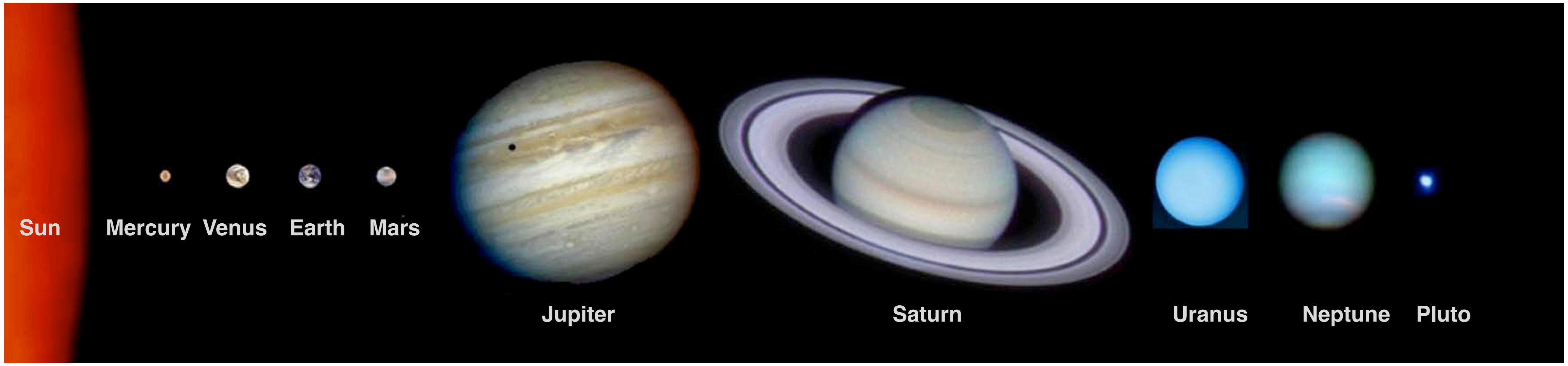
Neutrinos rarely interact with matter.

Typical reactor neutrino energy is ~4MeV.

Cross section at the energy is $\sim 7 \times 10^{-43}\,\mathrm{cm}^2$

$$\bar{\nu}_\mathrm{e} + \mathrm{p} \to \mathrm{e}^+ + \mathrm{n}$$

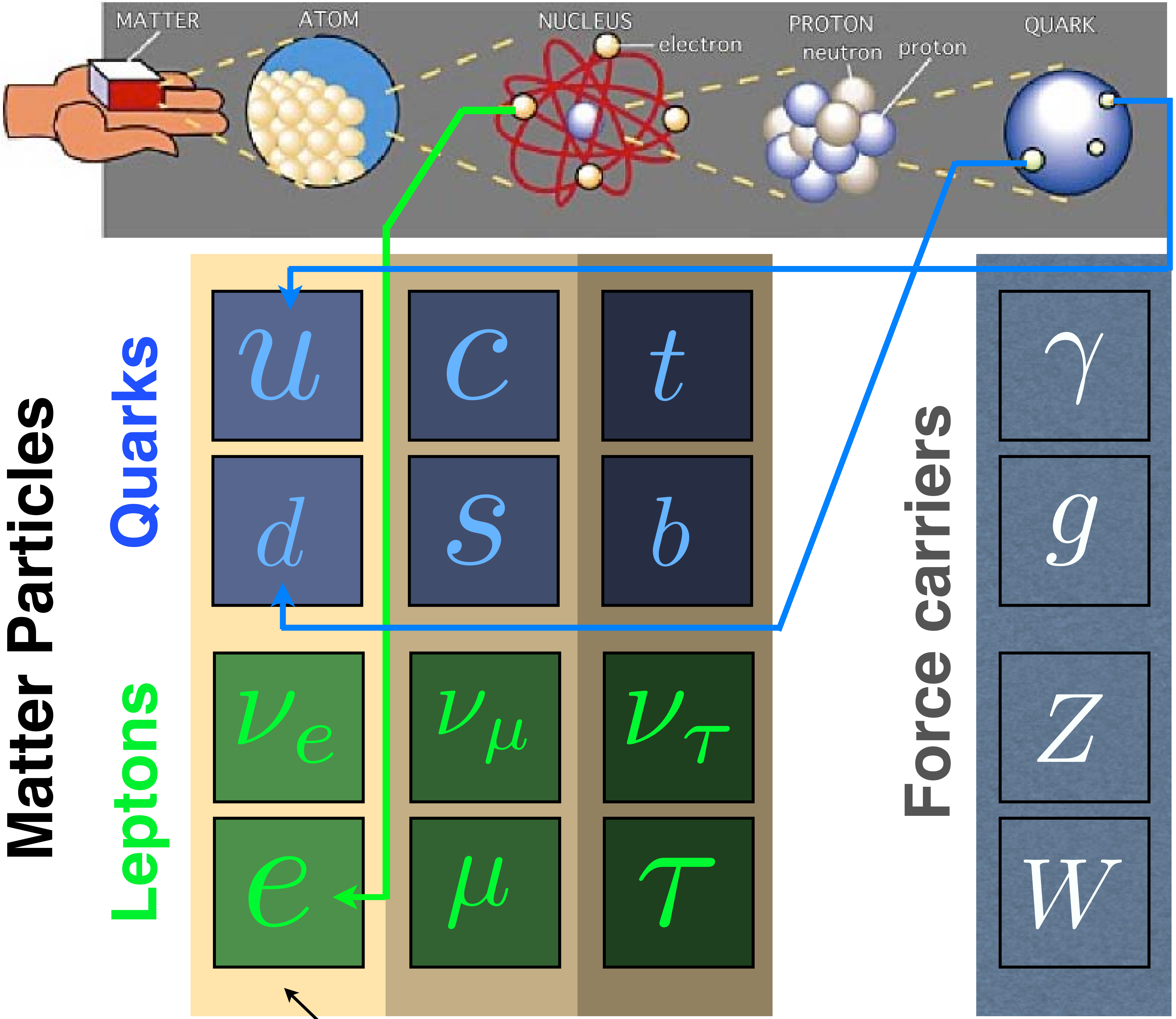
In case of water target, interaction length is ~20 light years.



$\times \sim 1000$

Probability that the reaction takes place in “Poltergeist” was only $\sim \dfrac{1}{10^{17}}$.

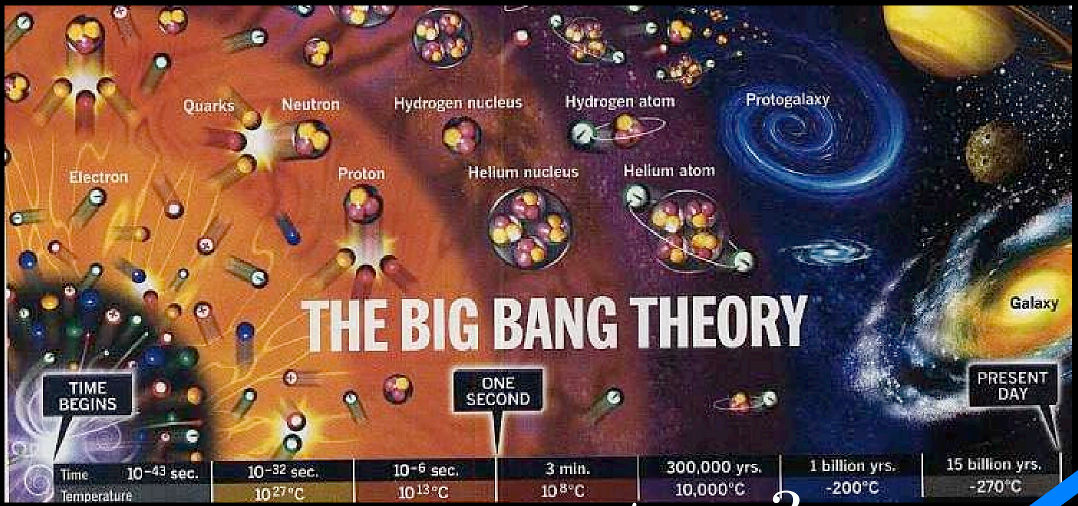
Strong neutrino source and huge detector are indispensable.



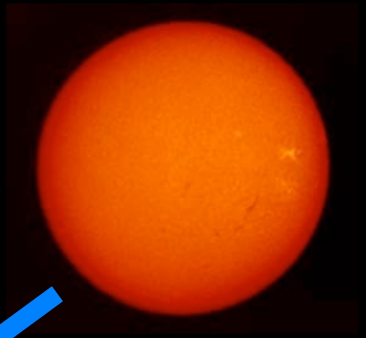
All ordinary matter belongs to this generation.

Where do neutrinos come from?

Big bang



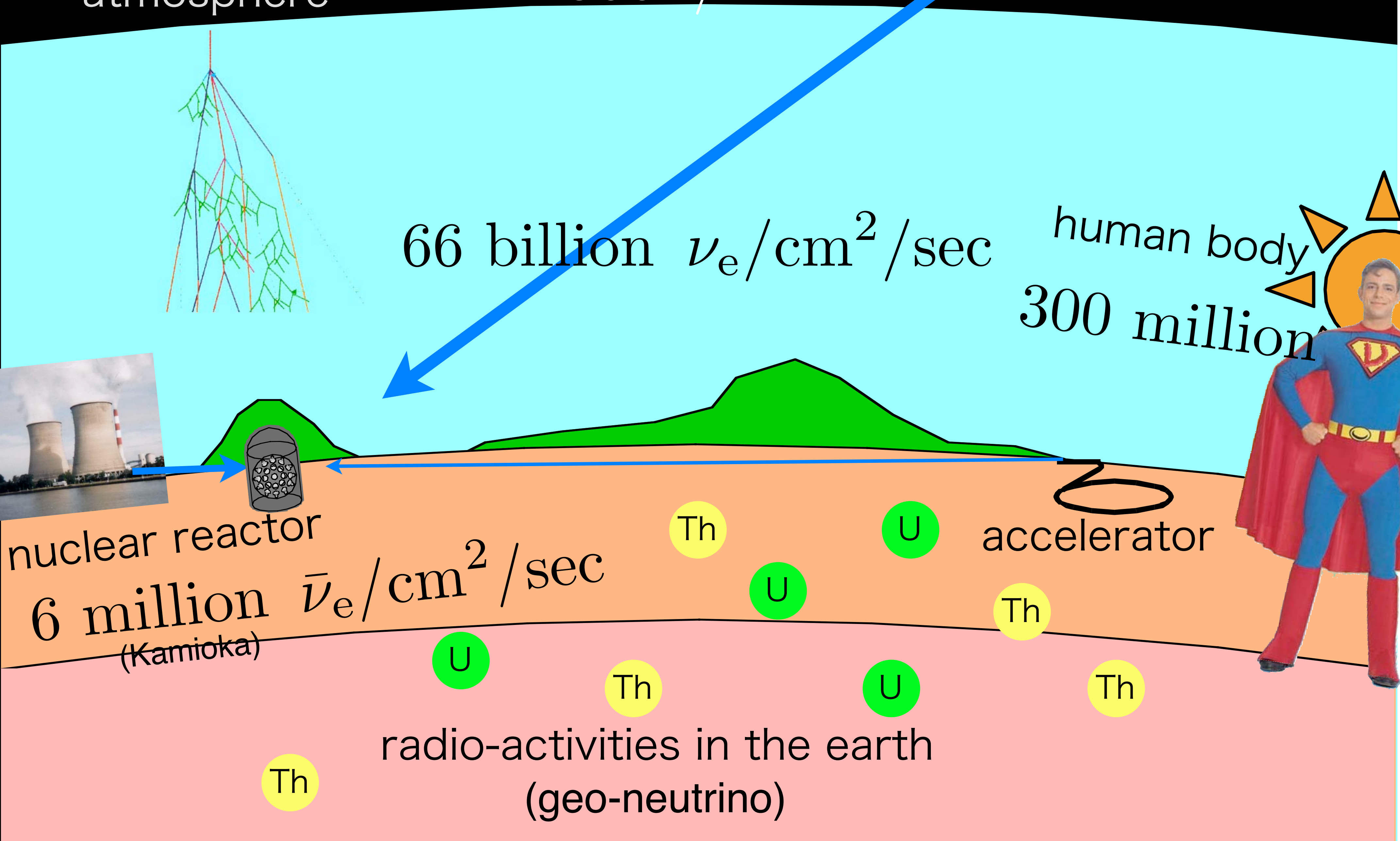
The sun



supernova

$300\nu/cm^3$

atmosphere



$$66\ \text{billion}\ \ \nu_e/\text{cm}^2/\text{sec}$$

human body

300 million/day

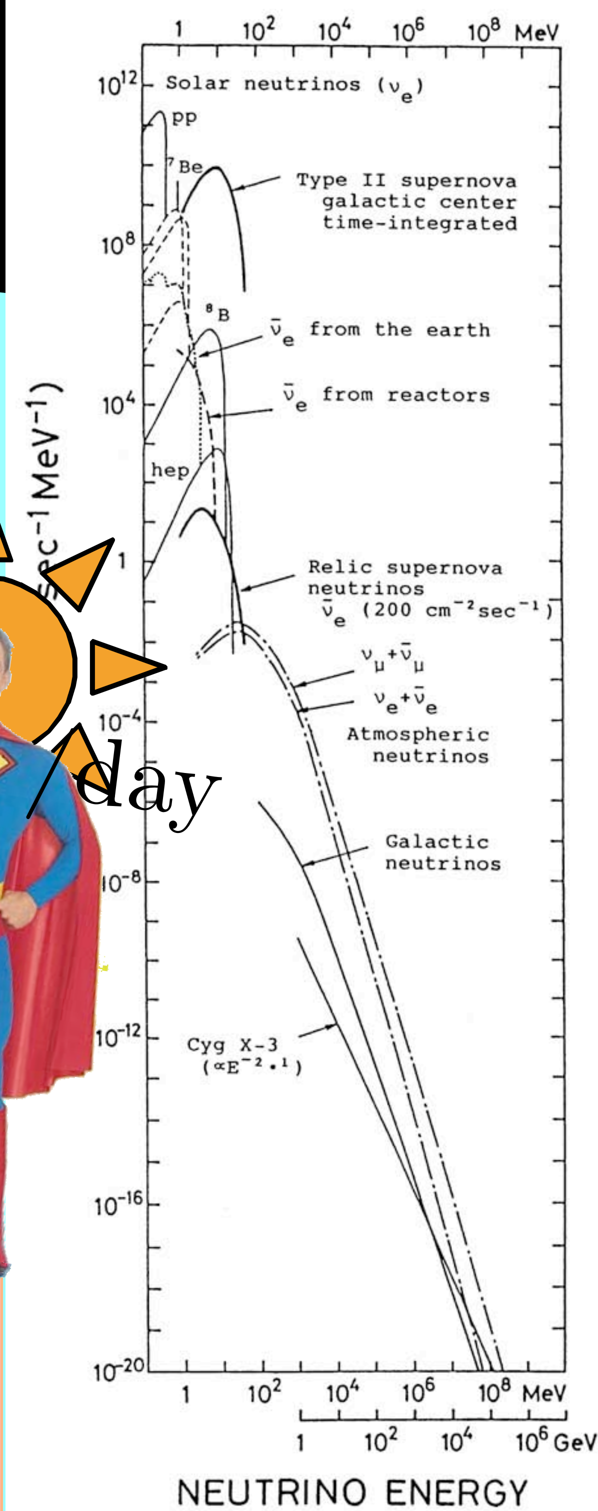
accelerator

nuclear reactor

$$6\ \text{million}\ \ \bar{\nu}_e/\text{cm}^2/\text{sec}$$

(Kamioka)

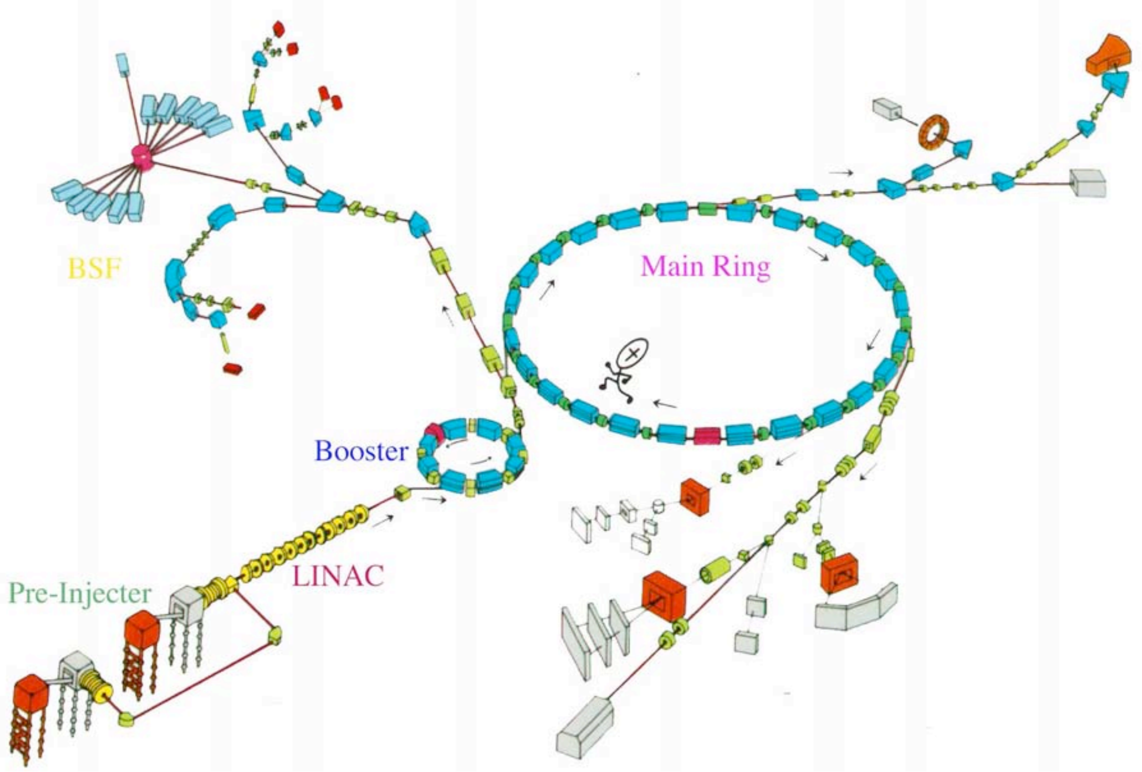
radio-activities in the earth
(geo-neutrino)



First of all, we have to understand neutrino propagation for the exploration of the earth and the sun.

Man-made neutrinos are good choice.

accelerator



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

etc.

expensive

commercial reactor

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

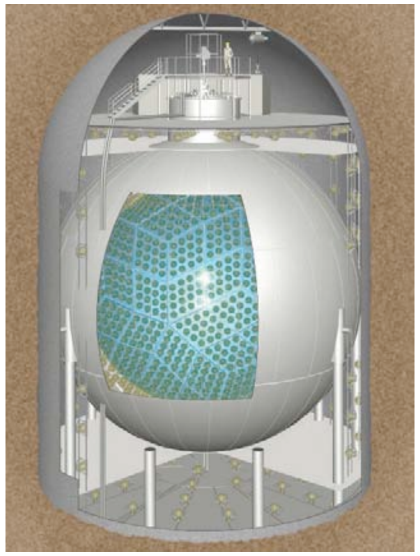
also $^{239}\mathrm{Pu}$, $^{238}\mathrm{U}$, $^{241}\mathrm{Pu}$

No charge

Reactor neutrino detection

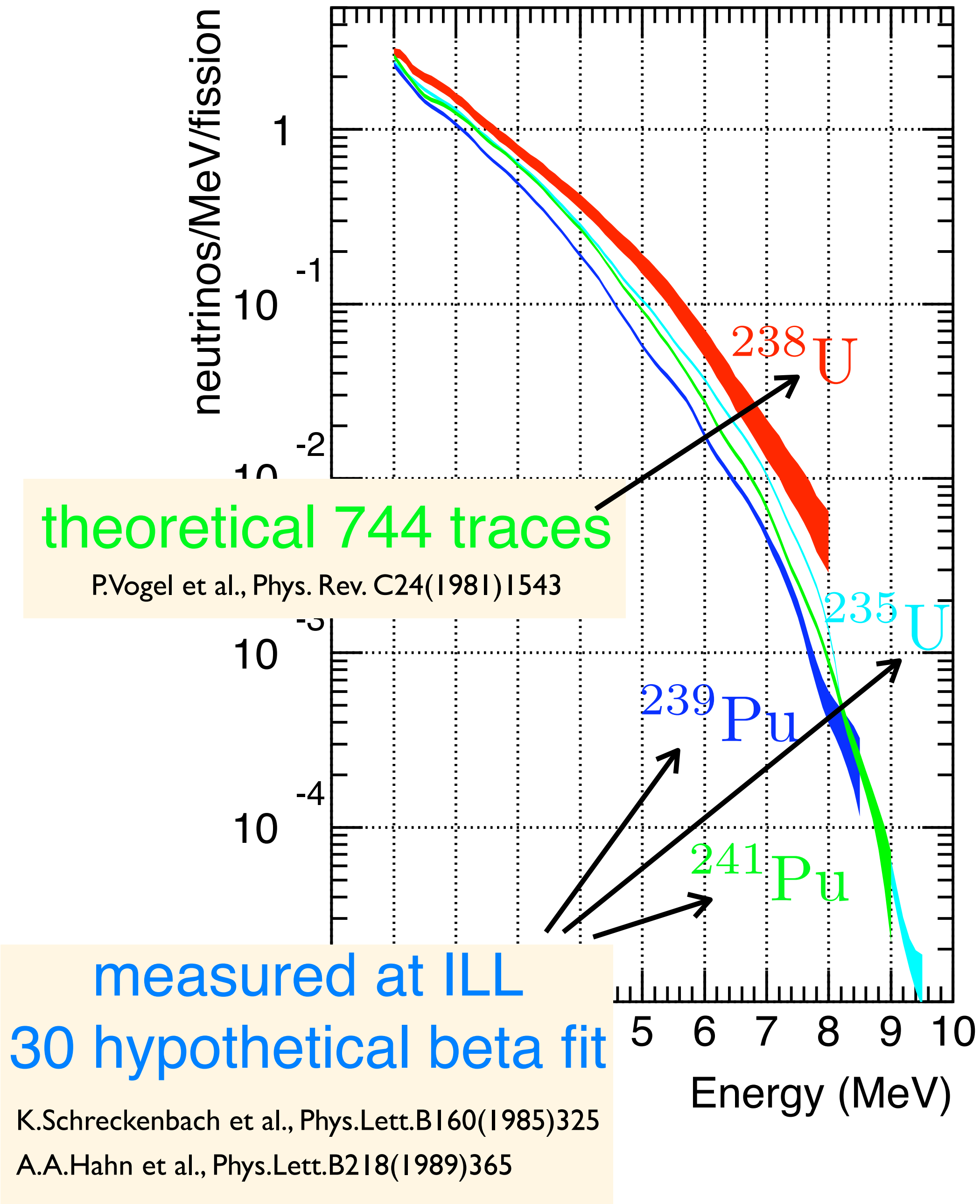
$\sim 2 \times 10^{20}\ \bar{\nu}_{\mathrm{e}}/\mathrm{GW}_{\mathrm{th}}/\mathrm{sec}$

$\bar{\nu}_{\mathrm{e}}$ ~99.999% $(E > 1.8\,\mathrm{MeV})$



$^{235}\mathrm{U} : 201.7,\ ^{238}\mathrm{U} : 205.0,\ ^{239}\mathrm{Pu} : 210.0,\ ^{241}\mathrm{Pu} : 212.4\,\mathrm{MeV}$

M.F.James, J.Nucl.Energy 23(1969)517



theoretical 744 traces

P.Vogel et al., Phys. Rev. C24(1981)1543

measured at ILL

30 hypothetical beta fit

K.Schreckenbach et al., Phys.Lett.B160(1985)325

A.A.Hahn et al., Phys.Lett.B218(1989)365

$$E_{\mathrm{th}} = \frac{(M_{\mathrm{n}} + m_{\mathrm{e}})^2 - M_{\mathrm{p}}^2}{2M_{\mathrm{p}}} = 1.806\,\mathrm{MeV}$$

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

prompt signal

$$\mathrm{e}^{+} + \mathrm{e}^{-} \rightarrow 2\gamma \quad E_{\mathrm{vis}} \sim E_{\nu} - 0.78\,\mathrm{MeV}$$
$$> 1.022\,\mathrm{MeV}$$

$\tau \sim 210\,\mu\mathrm{sec}$

$$\mathrm{n} + \mathrm{p} \rightarrow \mathrm{d} + \gamma(2.2\,\mathrm{MeV})$$

delayed signal

$\sigma(\bar{\nu}_{\mathrm{e}}\mathrm{p})$ is calculable at 0.2% accuracy.

P.Vogel and J.F.Beacom, Phys.Rev.D60(1999)053003

A.Kurylov et al., Phys.Rev.C67(2003)035502

with a help of inverse reaction

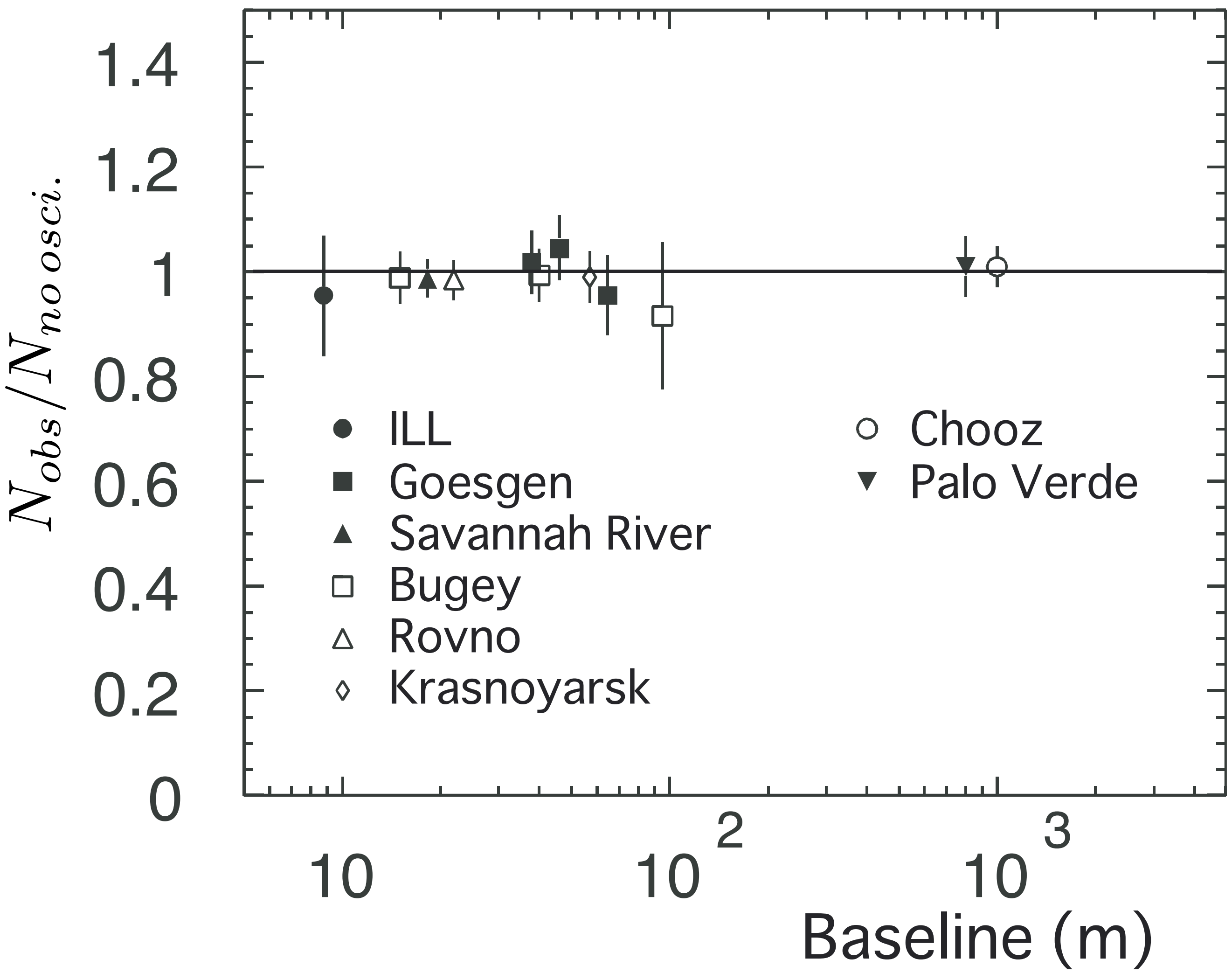
$$\mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}}$$

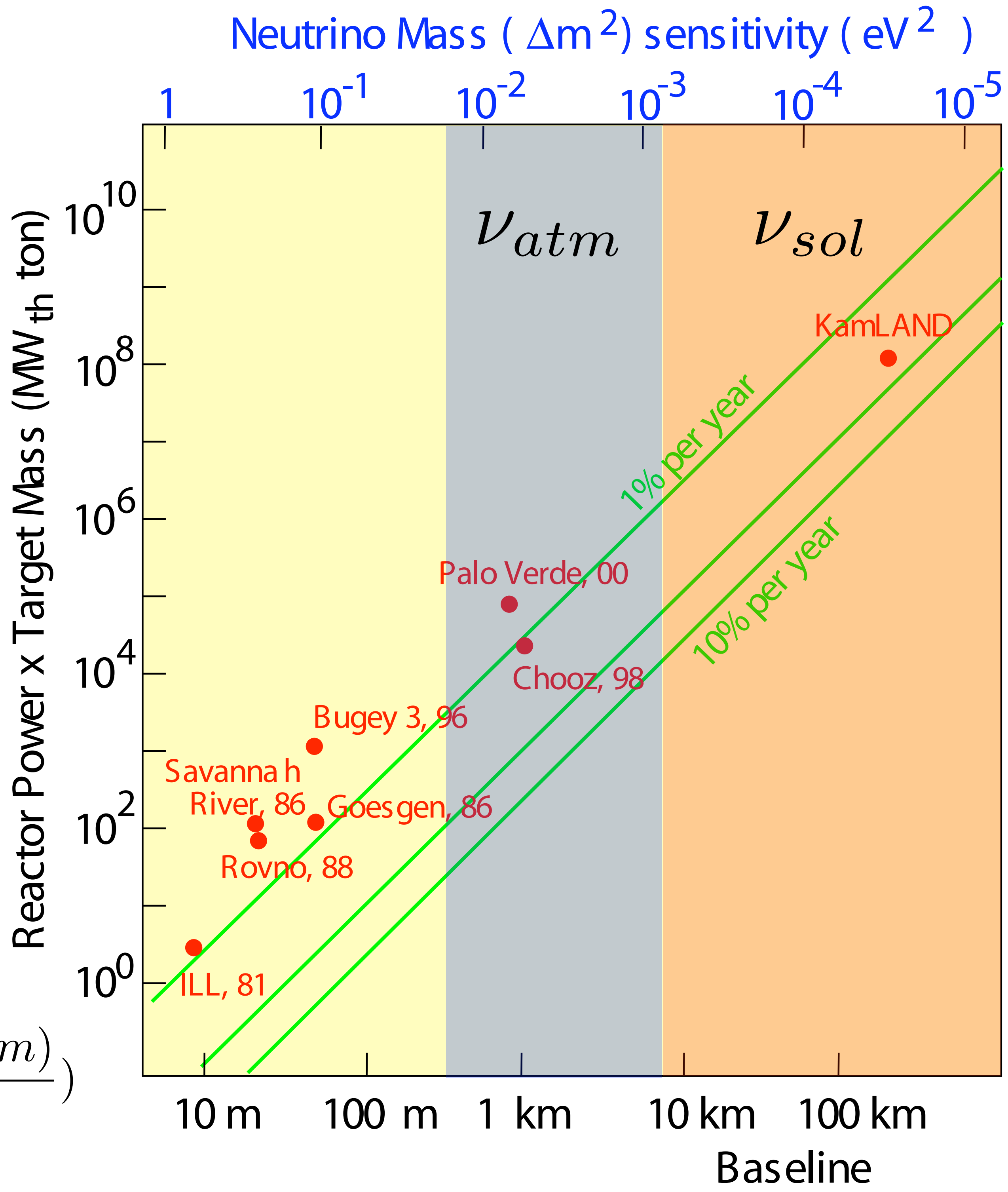
$$\sigma_{\mathrm{tot}}^{(0)} = \frac{2\pi^2/m_{\mathrm{e}}^5}{f_{\mathrm{p.s.}}^{\mathrm{R}}\tau_{\mathrm{n}}} E_{\mathrm{e}}^{(0)} p_{\mathrm{e}}^{(0)}$$

$$\tau_{\mathrm{n}} = 885.7 \pm 0.8\,\mathrm{sec}$$

Status before KamLAND

Oscillation Search up to 1 km baseline





$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta \sin^2 (1.27 \times \frac{\Delta m^2 (eV^2) L(m)}{E(MeV)})$$

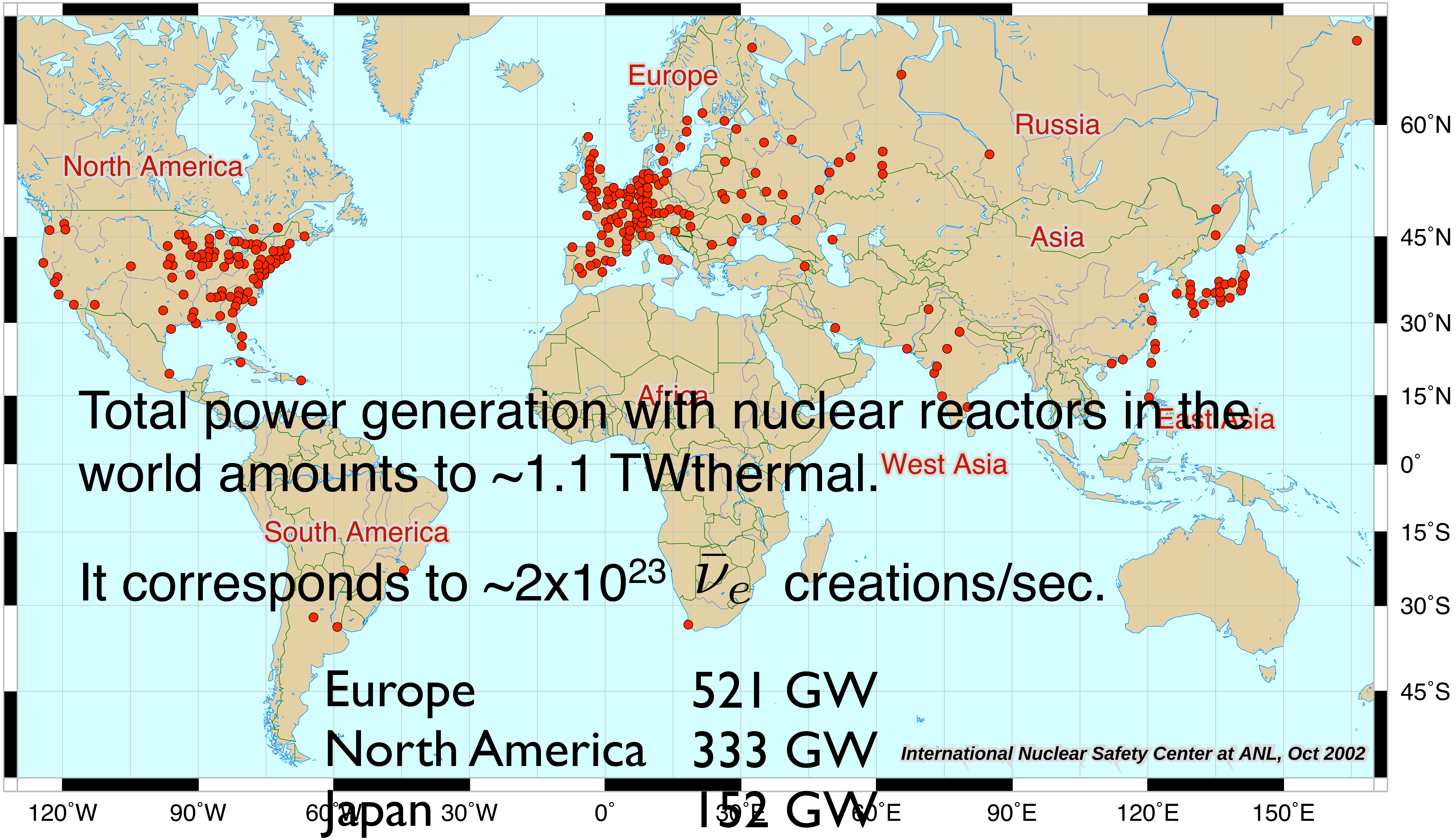
$$E_{reactor} \sim 5MeV$$

More than 100km baselines is necessary to explore the LMA solution.

⬇

Powerful reactor, Big detector, Deep underground

Where is a powerful reactor?



International Nuclear Safety Center at ANL, Oct 2002

Total power generation with nuclear reactors in the world amounts to ~1.1 TWthermal.

It corresponds to ~2x10^{23} $\bar{\nu}_e$ creations/sec.

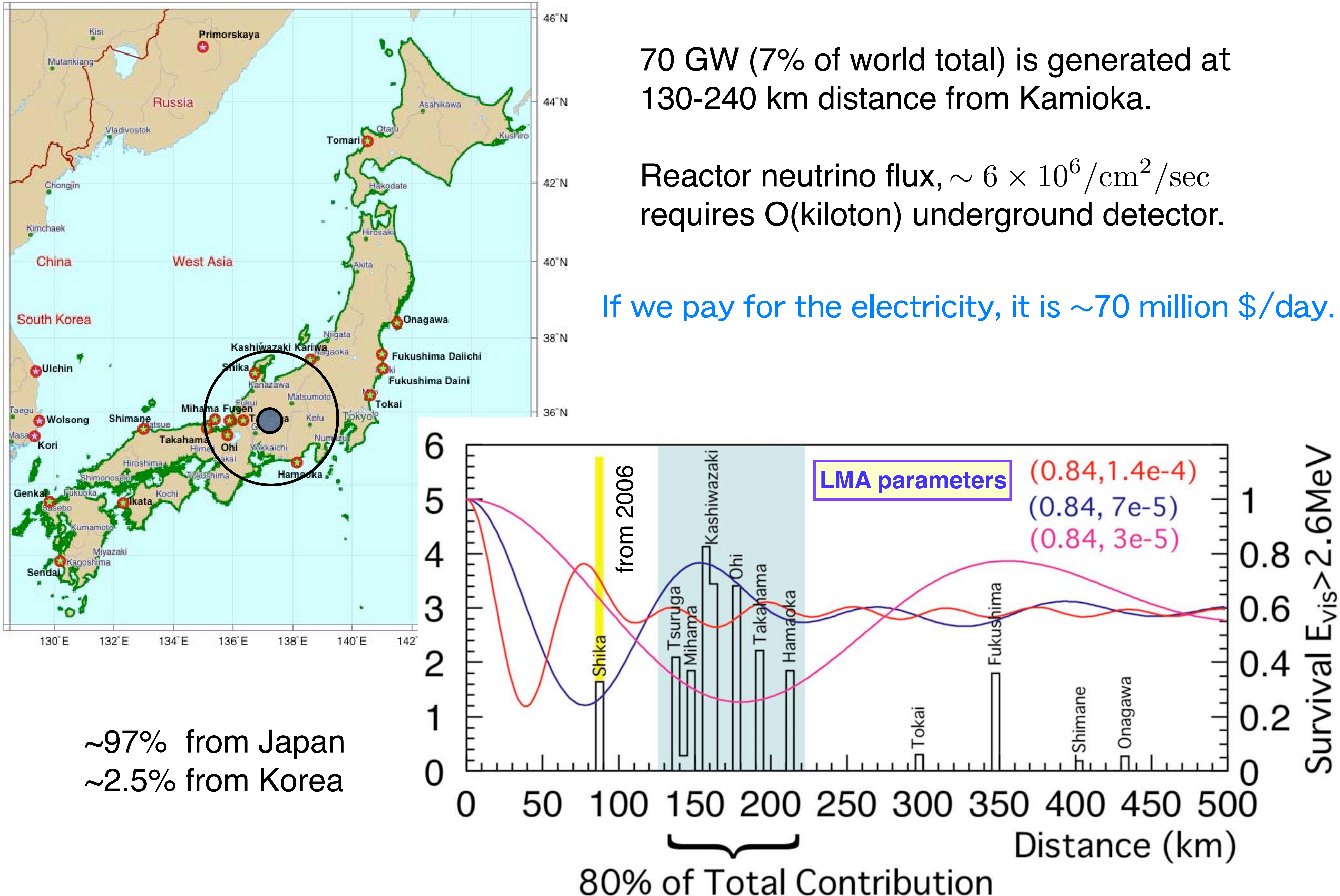
Europe	521 GW
North America	333 GW
Japan	152 GW
Asia w/o Japan	60 GW
Others	11 GW

It is Kamioka!

70 GW (7% of world total) is generated at 130-240 km distance from Kamioka.

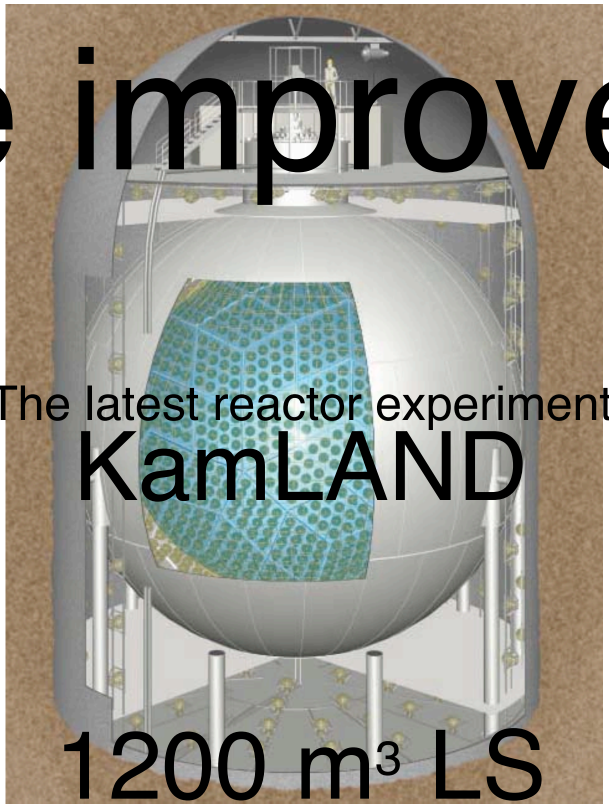
Reactor neutrino flux, $\sim 6 \times 10^6/\mathrm{cm}^2/\mathrm{sec}$ requires O(kiloton) underground detector.

If we pay for the electricity, it is ~70 million $/day.



~97% from Japan
~2.5% from Korea

Orders of magnitude improvements

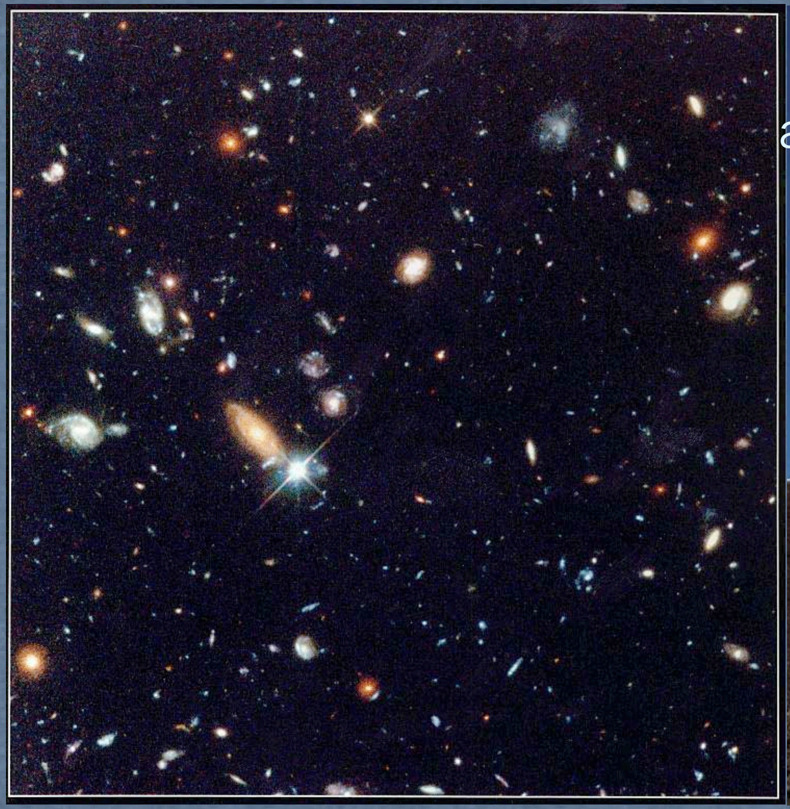


	The 1st neutrino experiment in 1956 Poltergeist	The latest reactor experiment KamLAND	
Detector Size	1400 litter LS	1200 m^3 LS	×1000
Reactor Power	700 MW	70 GW	×100
Depth	12 m	1000 m	×100
 Distance	11 m 3 sec jog	~180 km 3 hour drive	×10000

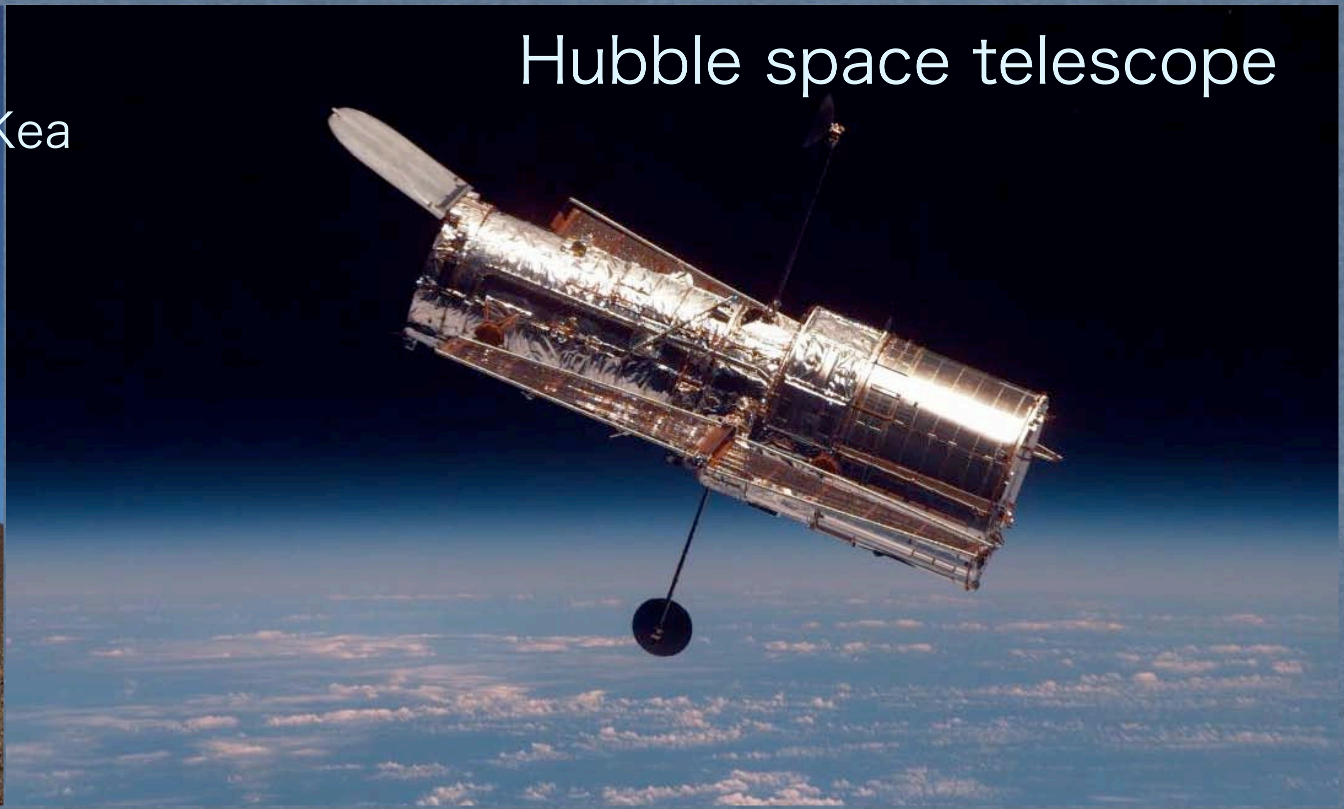
This is the right distance to explore the LMA solution.

This extension becomes possible by many important improvements on knowledge of reactor neutrinos by previous experiments.

Where to go?



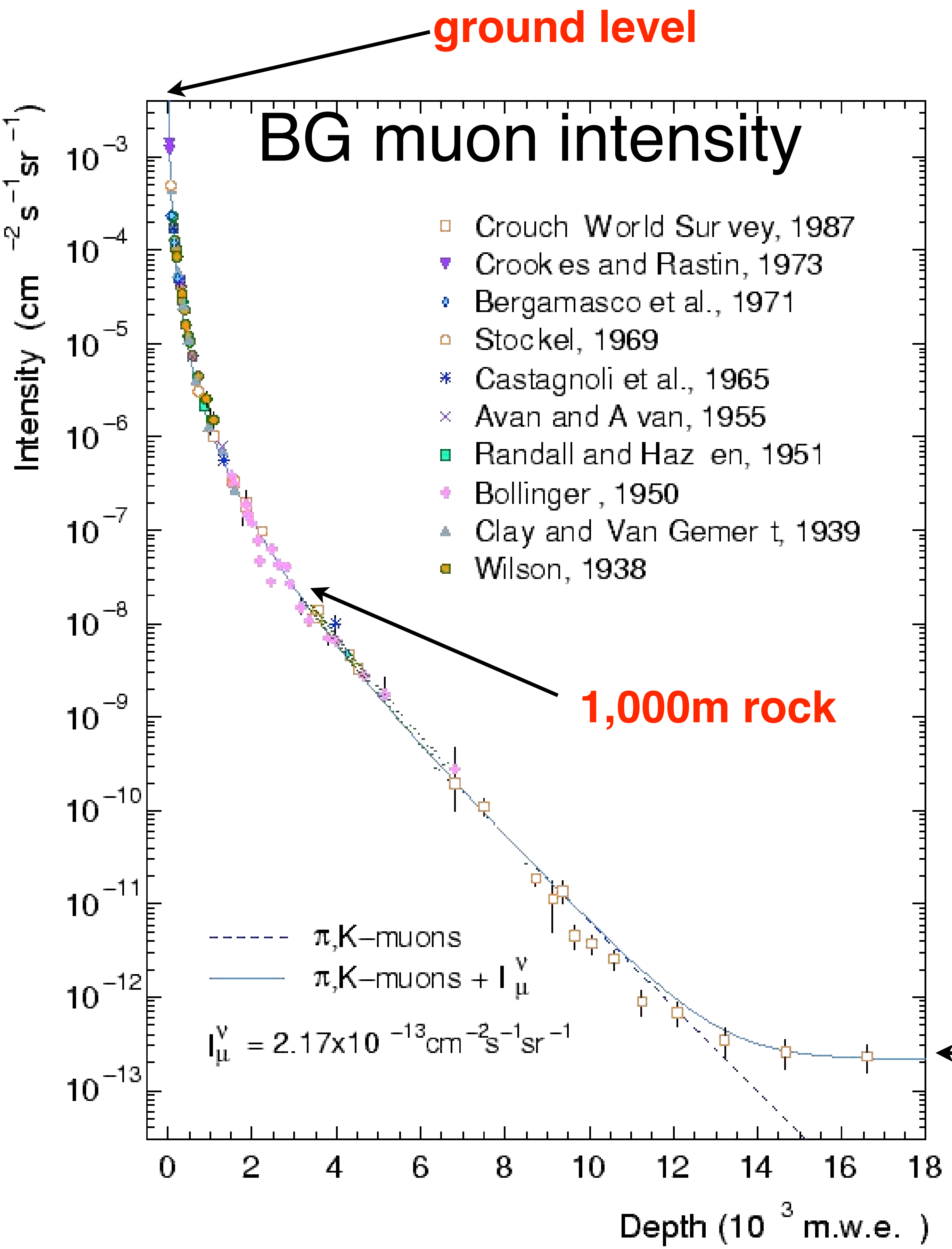
Subaru telescope
at the summit of Mauna Kea



Hubble space telescope

Going higher?

No! Digging underground.



On the ground,

interaction rate of muons with one’s body is ~100 /s

and of neutrinos is ~1/week.

mainly low energy solar neutrinos

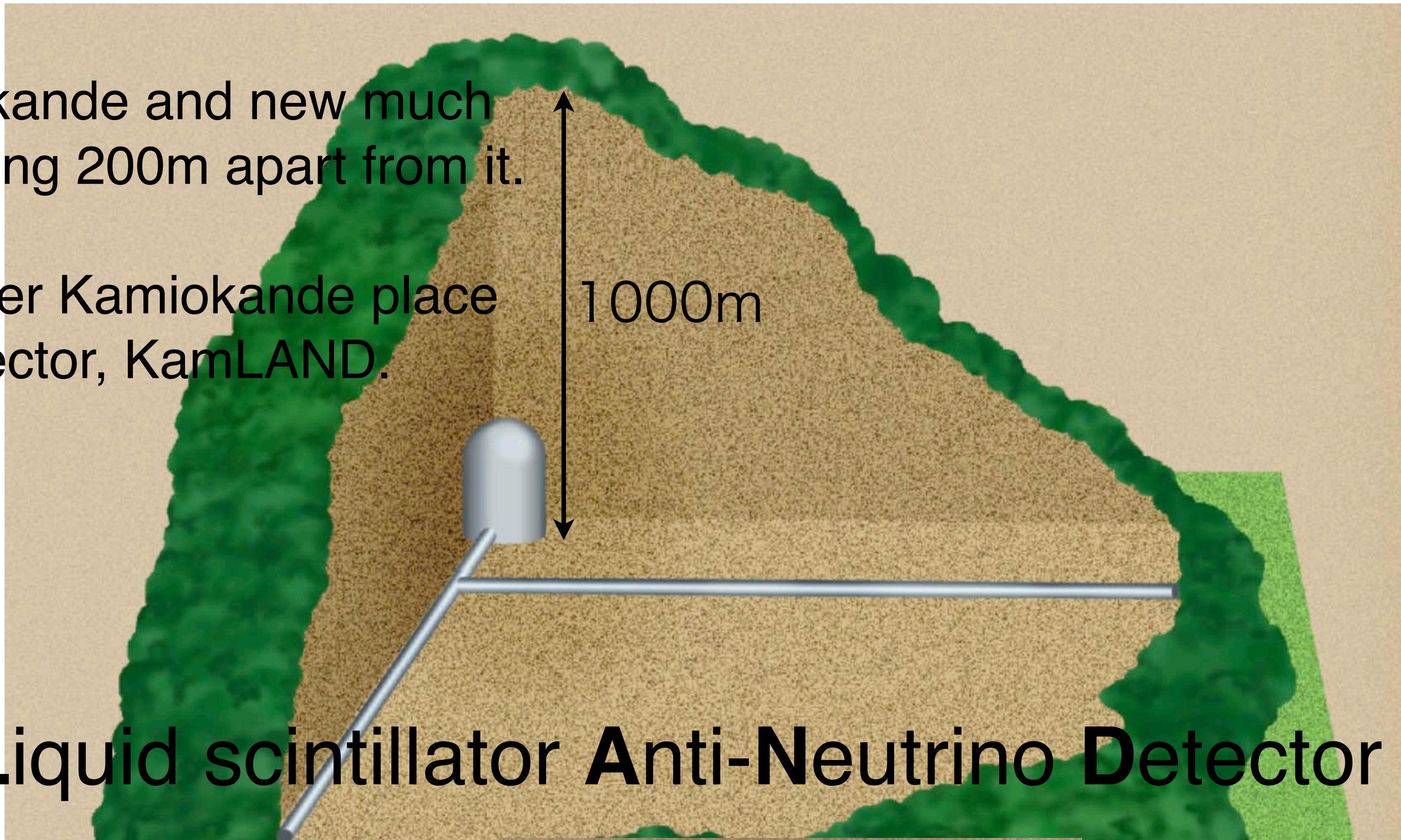
1,000m rock reduces muon rate by factor 100,000 but no reduction for neutrinos.

Does a mole here sees neutrinos?

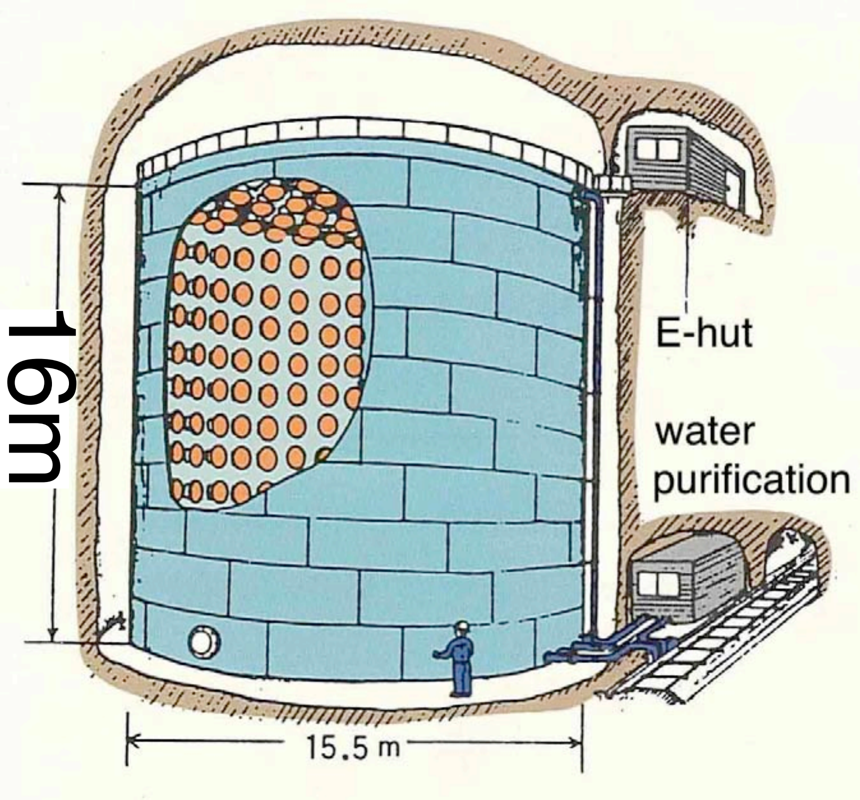
He has to overcome radioactive impurities and target mass.

There was a retired detector, Kamiokande and new much bigger Super-Kamiokande was running 200m apart from it.

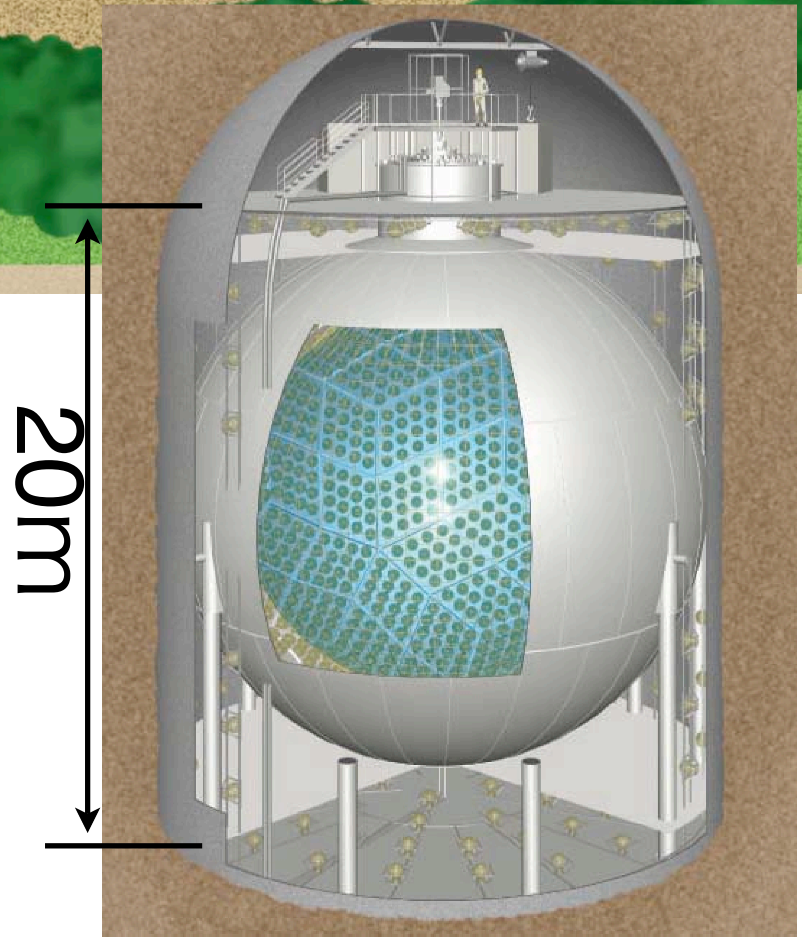
Tohoku university took over the former Kamiokande place and built a new liquid scintillator detector, KamLAND.



KamLAND = **Kamioka L**iquid scintillator **A**nti-**N**eutrino **D**etector



Kamiokande

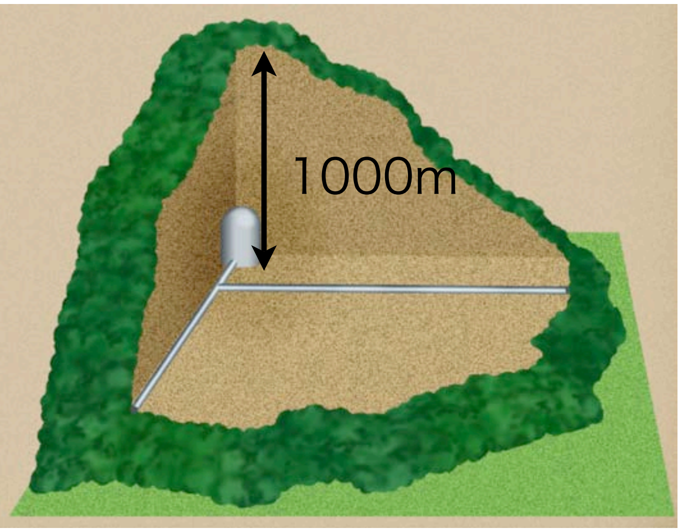


KamLAND

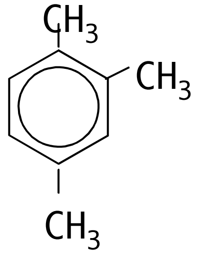
KamLAND

KamLAND 18mϕ stainless tank

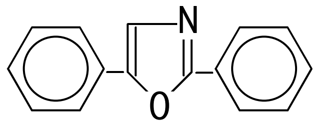
KamLAND



LS


20%

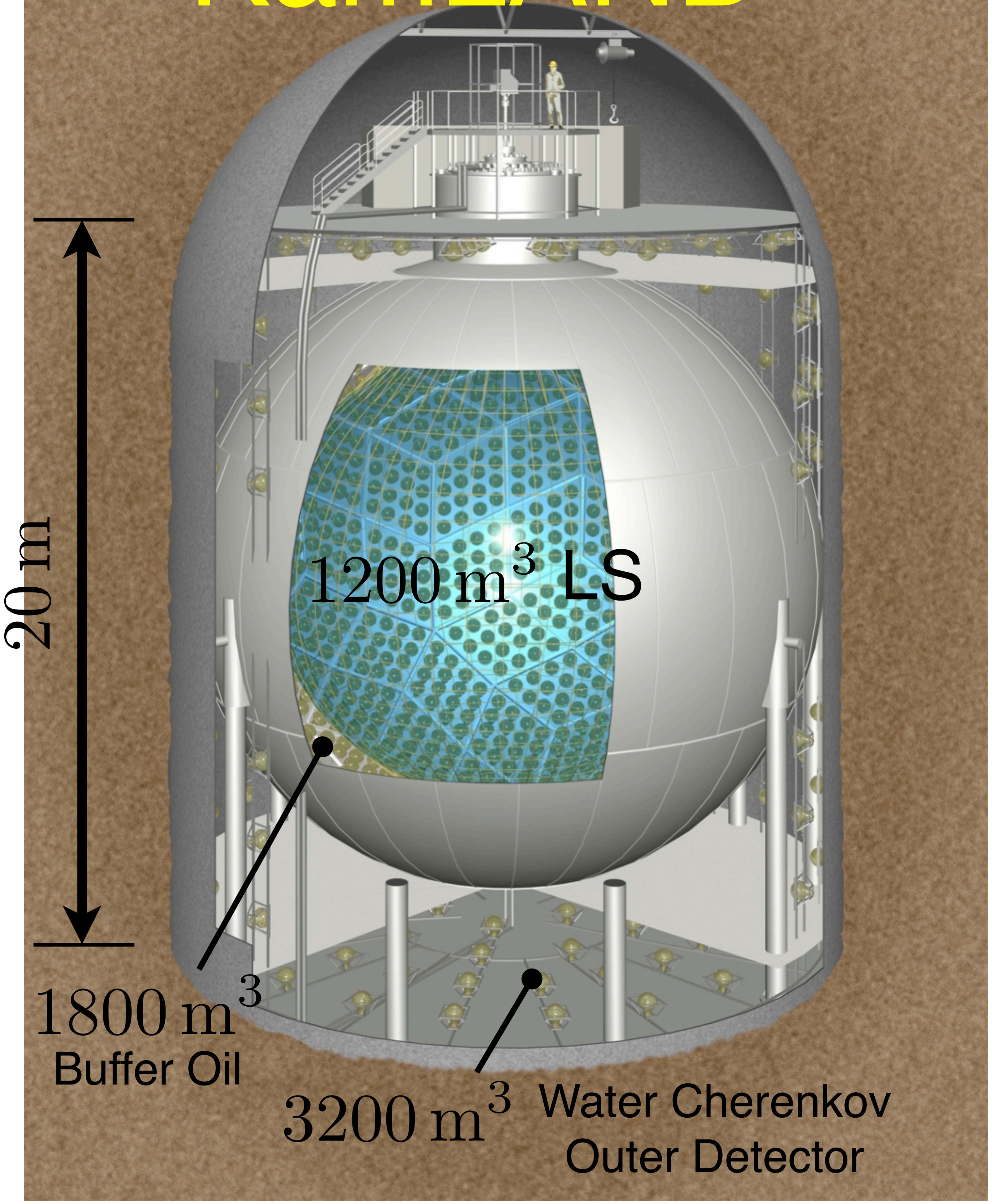

80%


1.5g/l

$\rho = 0.78\,\mathrm{g/cm^3}$

$8000\,\mathrm{photons/MeV}$

$\lambda \sim 10\,\mathrm{m}$



BO

50% dodecane
50% isoparaffin

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

1325 17”-PMTs
+
554 20”-PMTs
(since Feb 2003)

photo-coverage
22% --> 34%

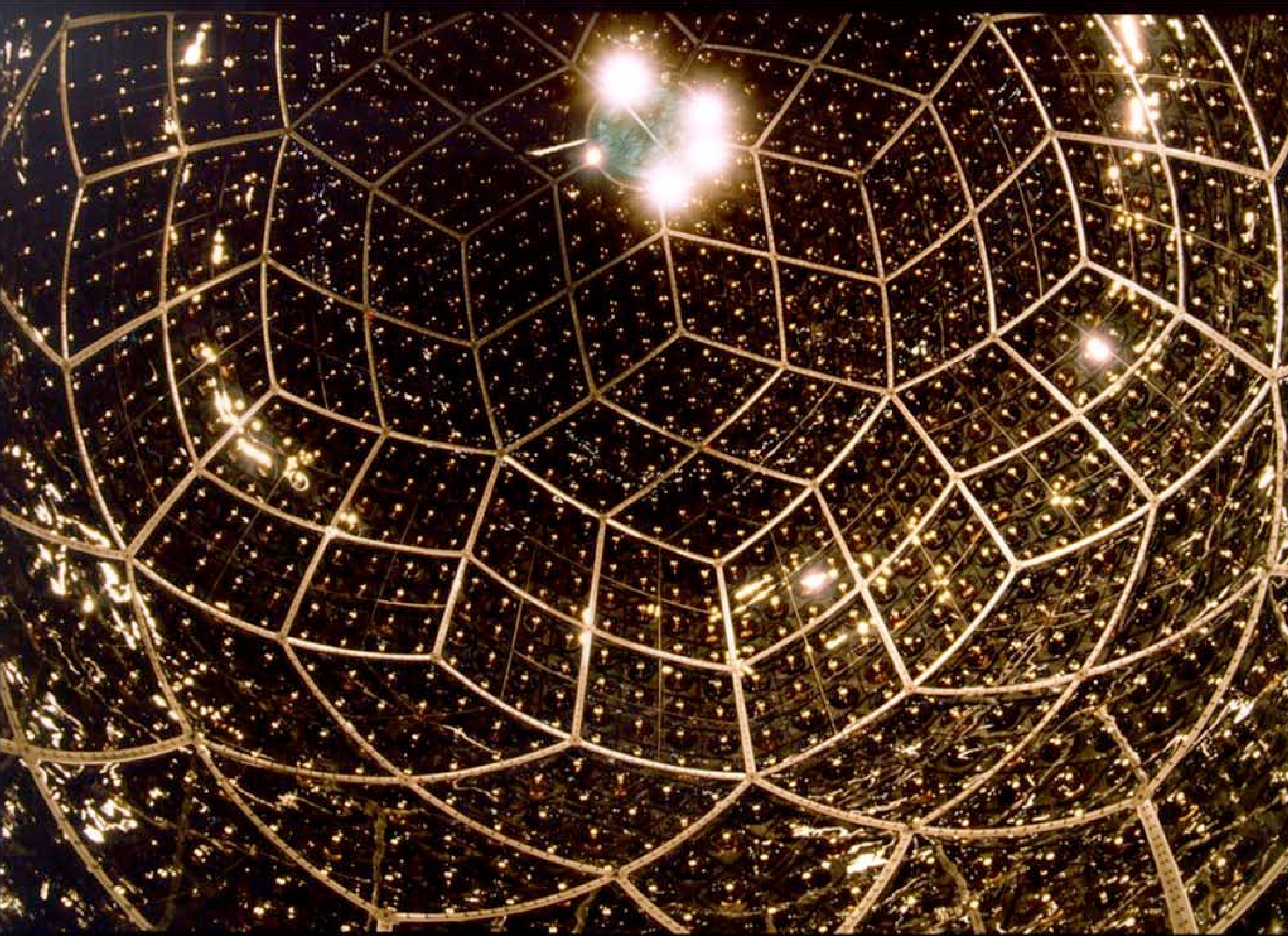
$\sim 500\,\mathrm{p.e./MeV}$

A fortran program loaded on us

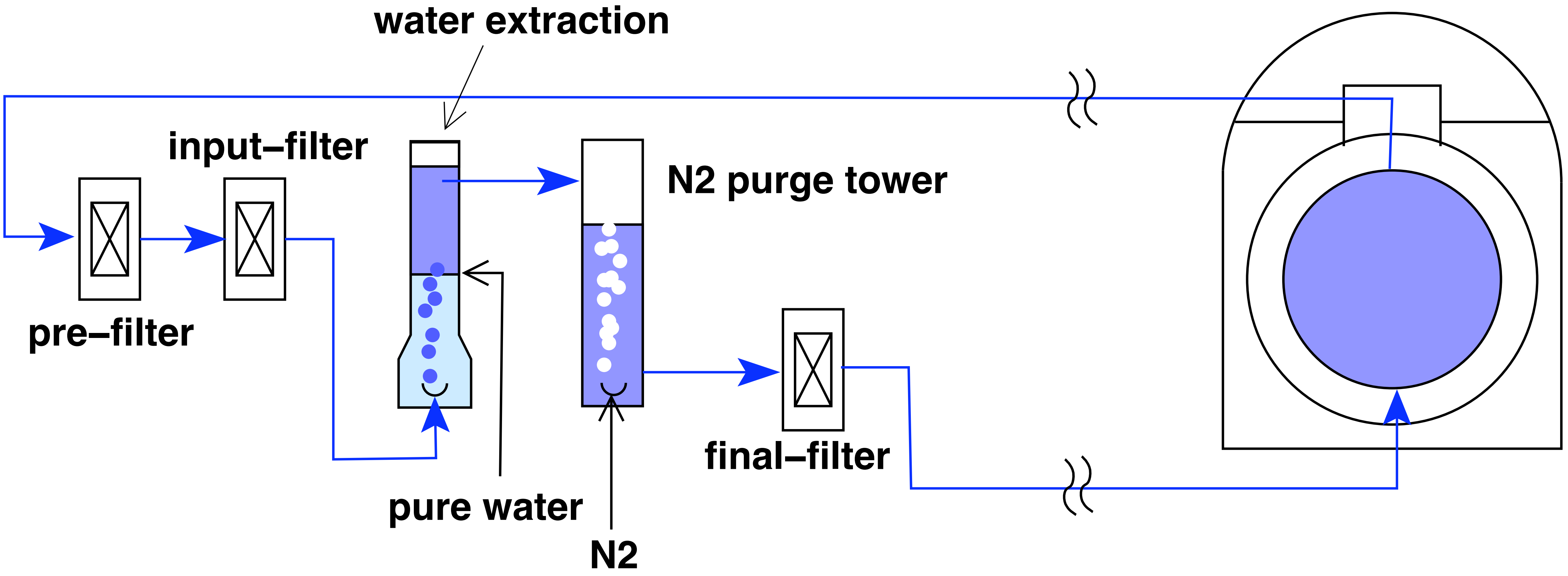
```
1  wash by detergent
   rinse with pure water
   polish with alcohol
   goto 1
   stop
   end
```

The best cleaning tools we've found are a kitchen sponge and a kitchen detergent (Magiclean^{TM}).

Total hand movement
during the scrub is
~1000km!



The world cleanest detector

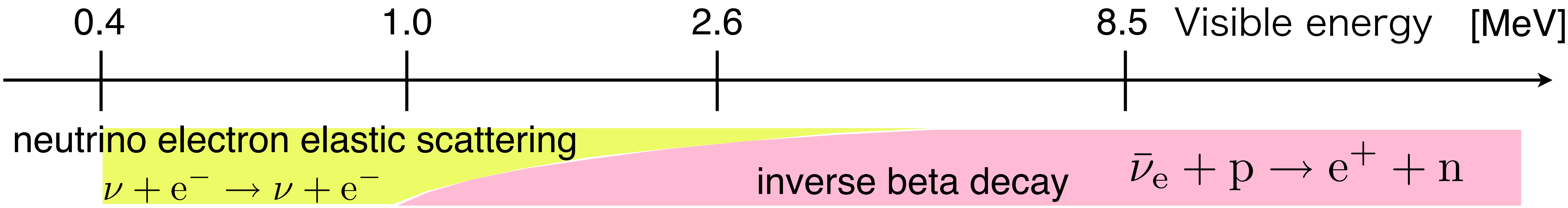


Ions are billion times more solvable to water.
Wash scintillator with pure water.

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

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

Various Physics Targets with wide energy range

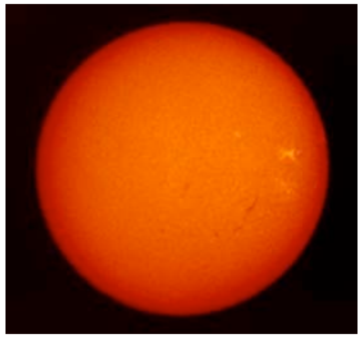


neutrino electron elastic scattering

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

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

^{7}Be solar neutrino



Neutrino Astrophysics

verification of SSM

future
2nd phase

geo-neutrino

Neutrino Geophysics

verification of earth evolution model

forthcoming

reactor neutrino

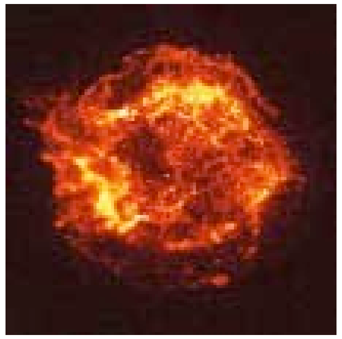
Neutrino Physics

Precision measurement of oscillation parameters

1st results
PRL 90, 021802 (2003)

2nd results
PRL 94, 081801(2005)

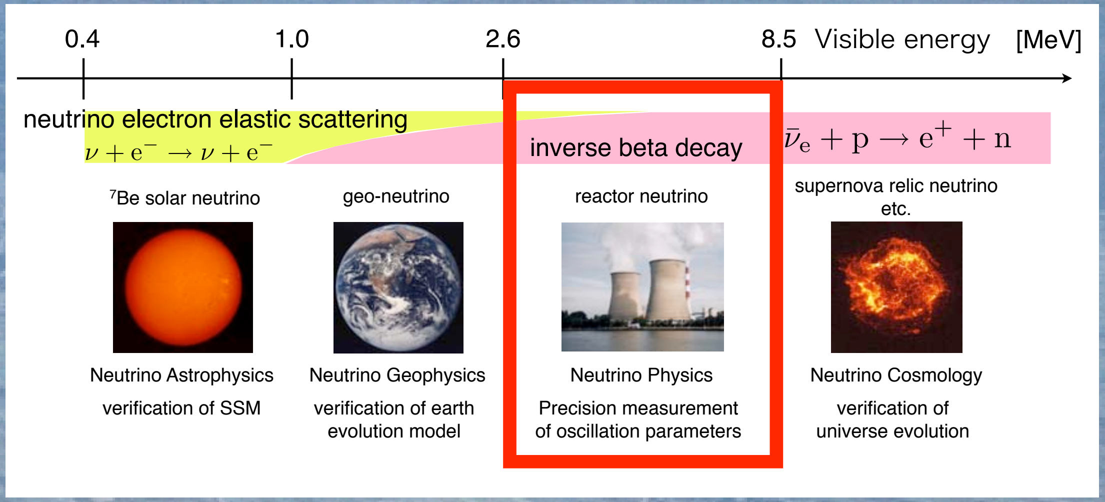
supernova relic neutrino etc.



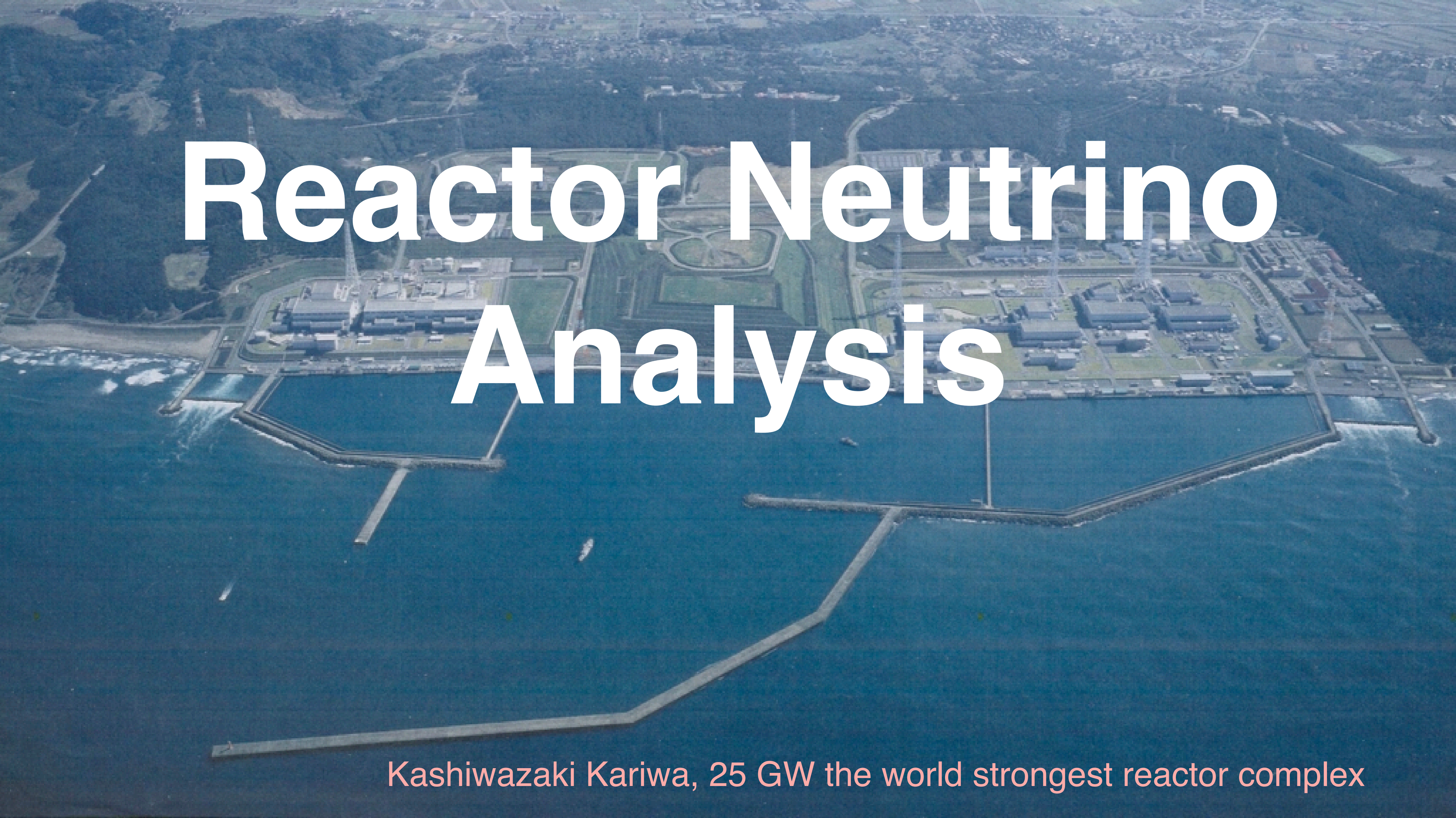
Neutrino Cosmology

verification of universe evolution

Solar $\bar{\nu}_\mathrm{e}$
PRL 92, 071301 (2004)



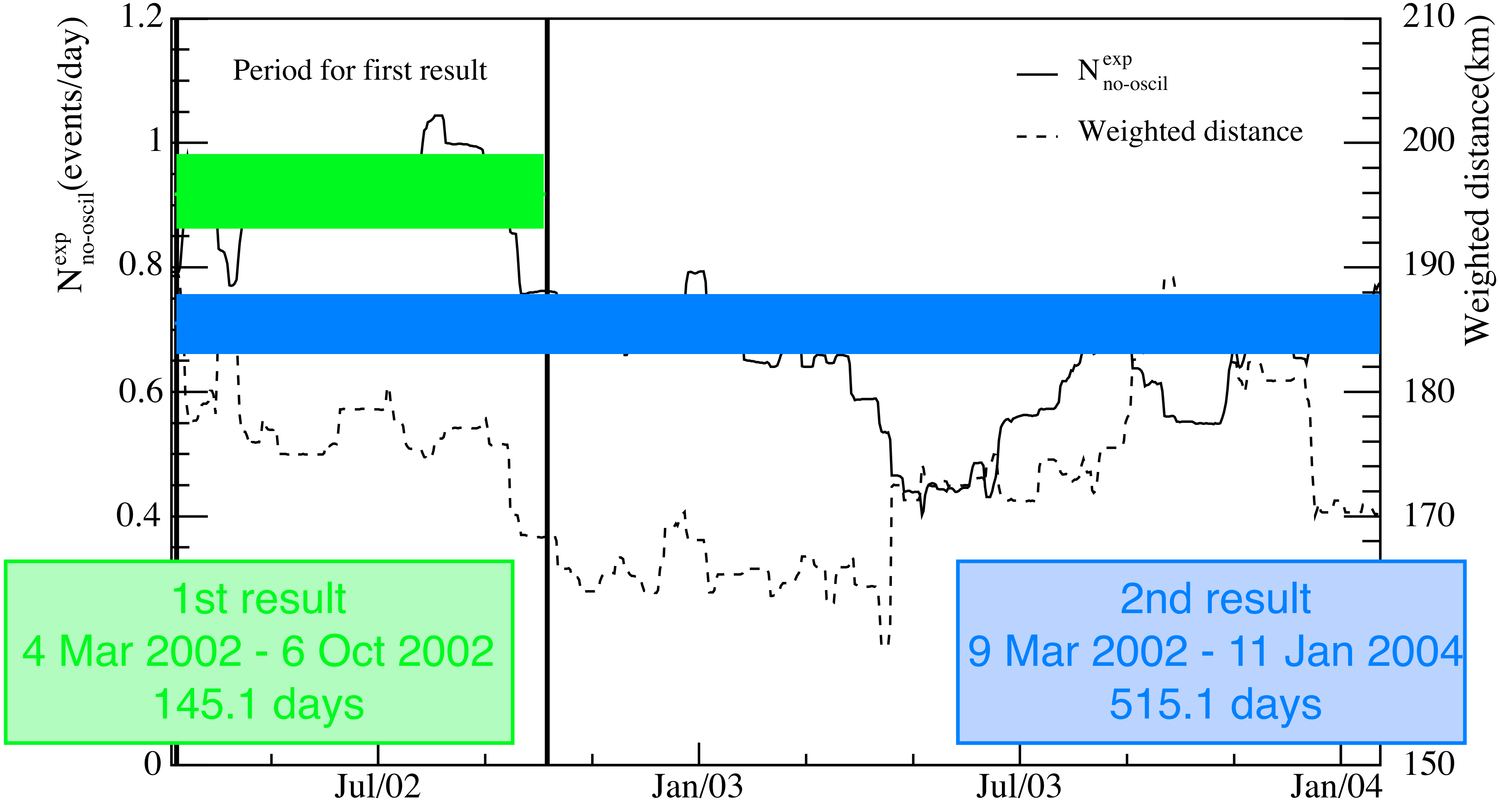
Reactor Neutrino Analysis



Kashiwazaki Kariwa, 25 GW the world strongest reactor complex

Reactor data

Available information	Contribution
Detailed information from Japanese reactors	95.5%
History of electric power output from Korean reactors	3.4%
Nominal power from the other reactors	1.1%



1st result
4 Mar 2002 - 6 Oct 2002
145.1 days

2nd result
9 Mar 2002 - 11 Jan 2004
515.1 days

1st result

Data Summary

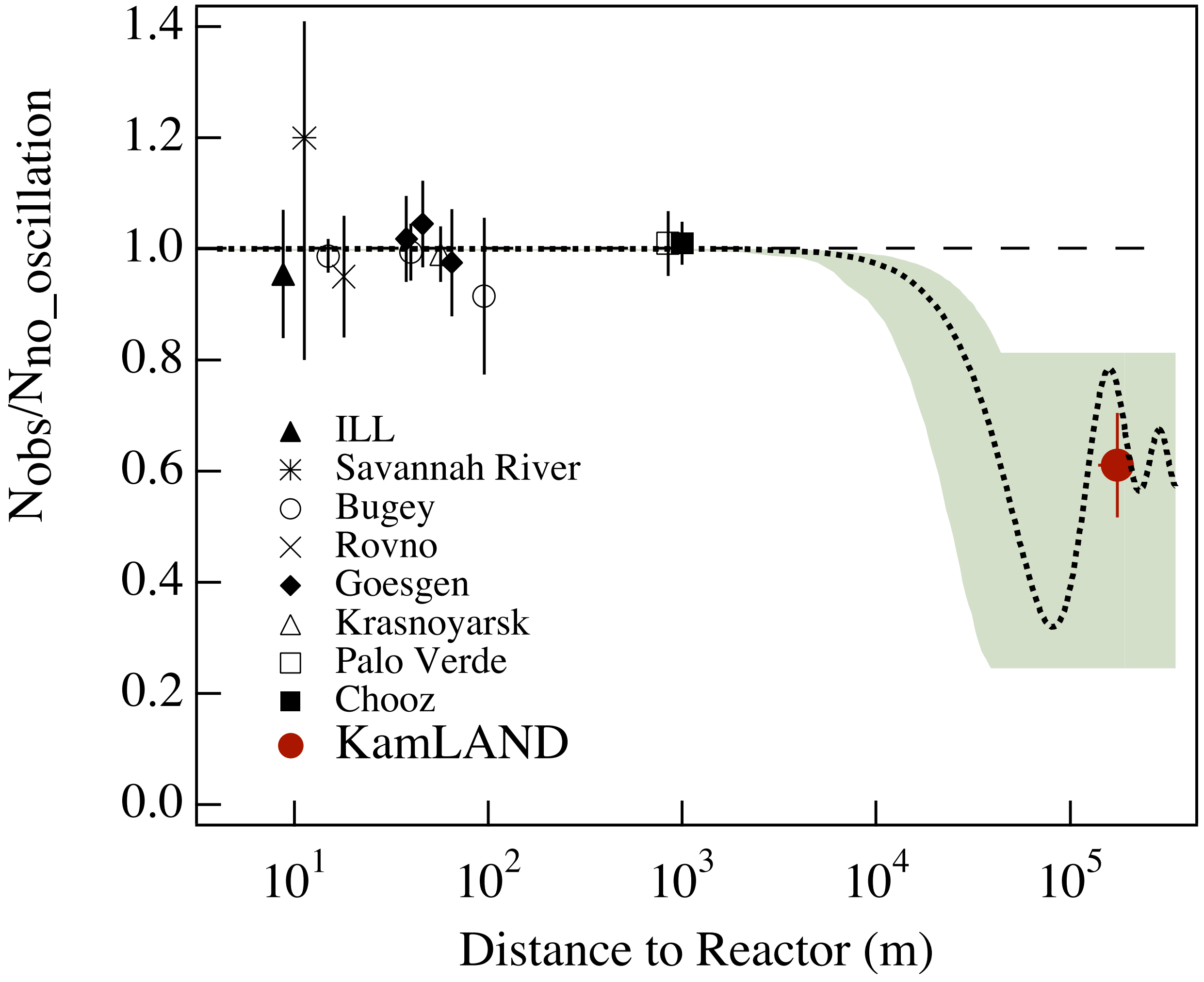
from March 4 to October 6, 2002
145.1 live days, 162 ton-year exposure

Analysis threshold 2.6 MeV

expected signal	86.8 ± 5.6
BG	1 ± 1
observed	54

Neutrino disappearance at 99.95% CL.

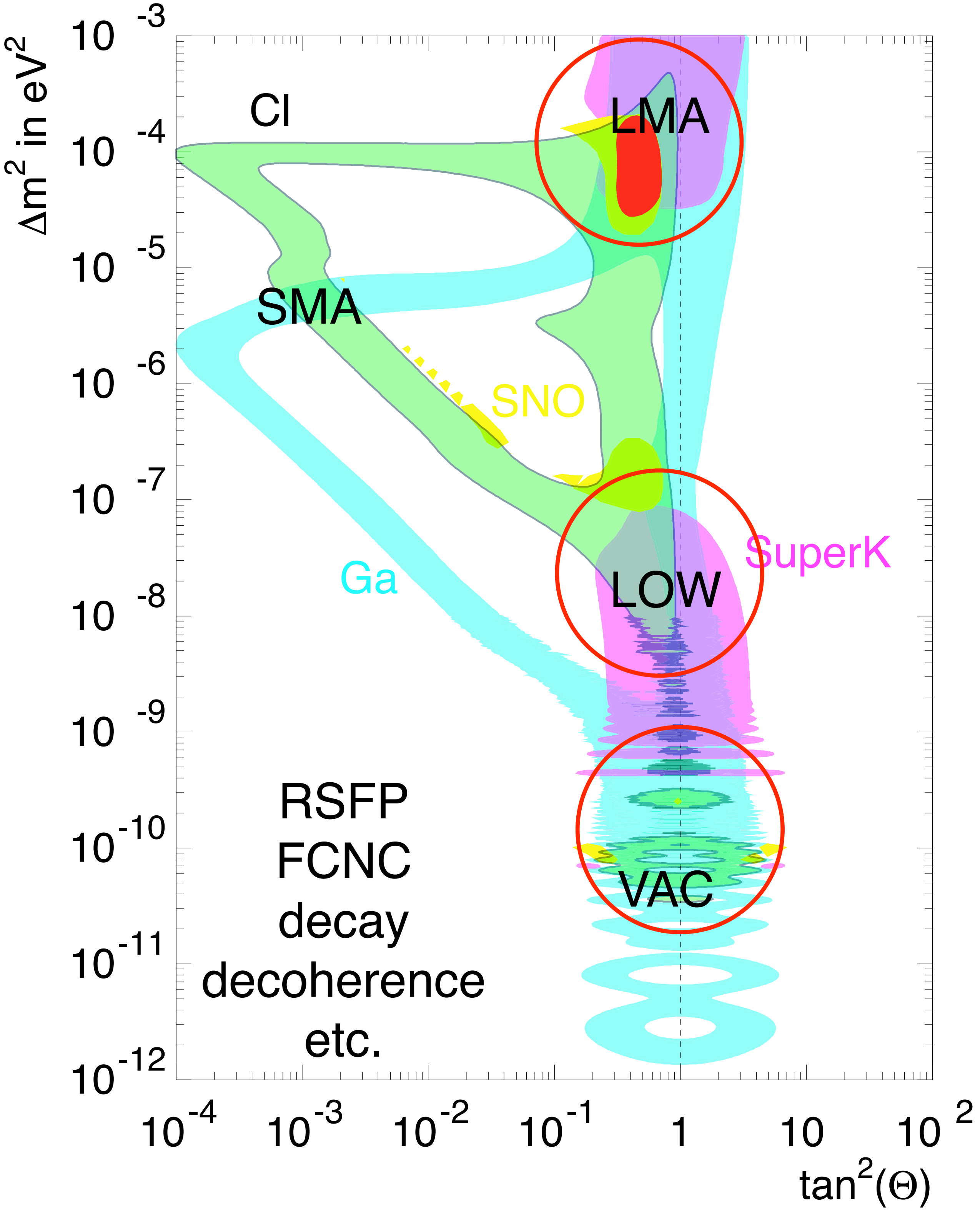
$$R = 0.611 \pm 0.085(\mathrm{stat}) \pm 0.041(\mathrm{syst})$$



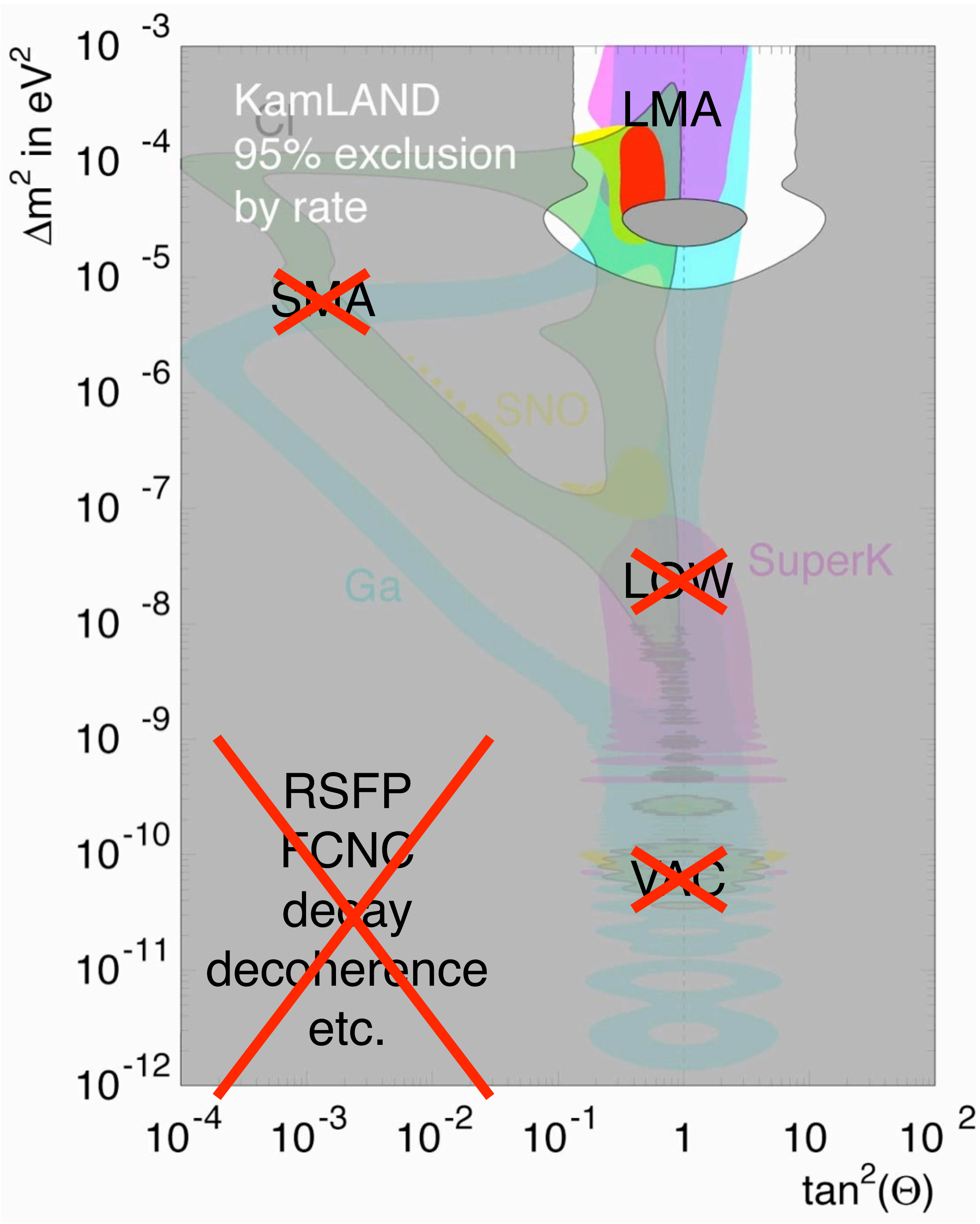
KamLAND collaboration, Phys.Rev.Lett.90(2003)021802

Evidence for reactor neutrino disappearance

2 gen. Neutrino oscillation parameters consistent with each solar results



with KamLAND rate



Reactor neutrino disappearance excluded all but LMA from leading phenomena.

2nd result

Data Summary

from 9 Mar 2002 to 11 Jan 2004
515.1 live days, 766.3 ton-year exposure
×4.7 exposure (×3.55 live time, ×1.33 fiducial)

expected signal	365.2 ± 23.7
BG	17.8 ± 7.3
observed	258

Neutrino disappearance at 99.998% CL.

$$R = 0.658 \pm 0.044(\mathrm{stat}) \pm 0.047(\mathrm{syst})$$

$$R = 0.601 \pm 0.069 \pm 0.042$$

for Mar to Oct 2002

is consistent with first results

KamLAND collaboration, hep-ex/0406035

1st result

Data Summary

from March 4 to October 6, 2002
145.1 live days, 162 ton-year exposure

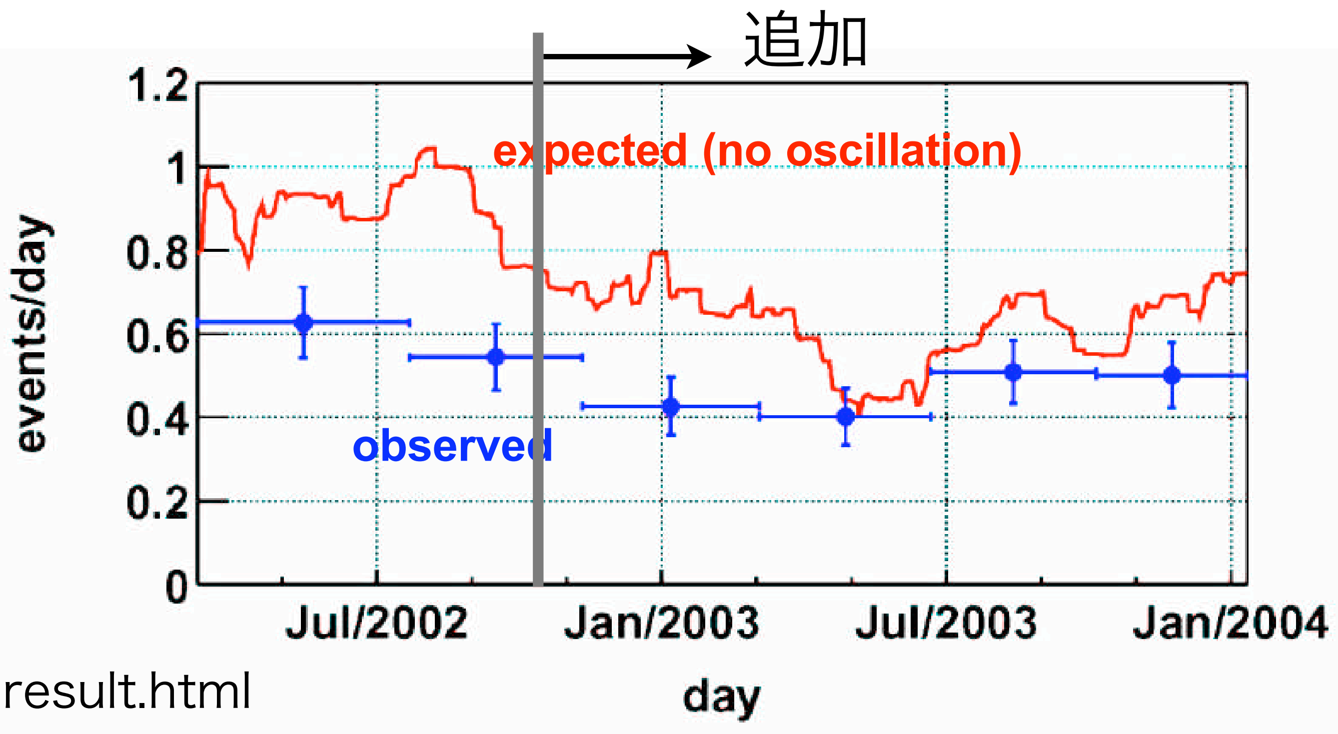
expected signal	86.8 ± 5.6
BG	2.8 ± 1.7
observed	54

Neutrino disappearance at 99.95% CL.

$$R = 0.589 \pm 0.085(\mathrm{stat}) \pm 0.042(\mathrm{syst})$$

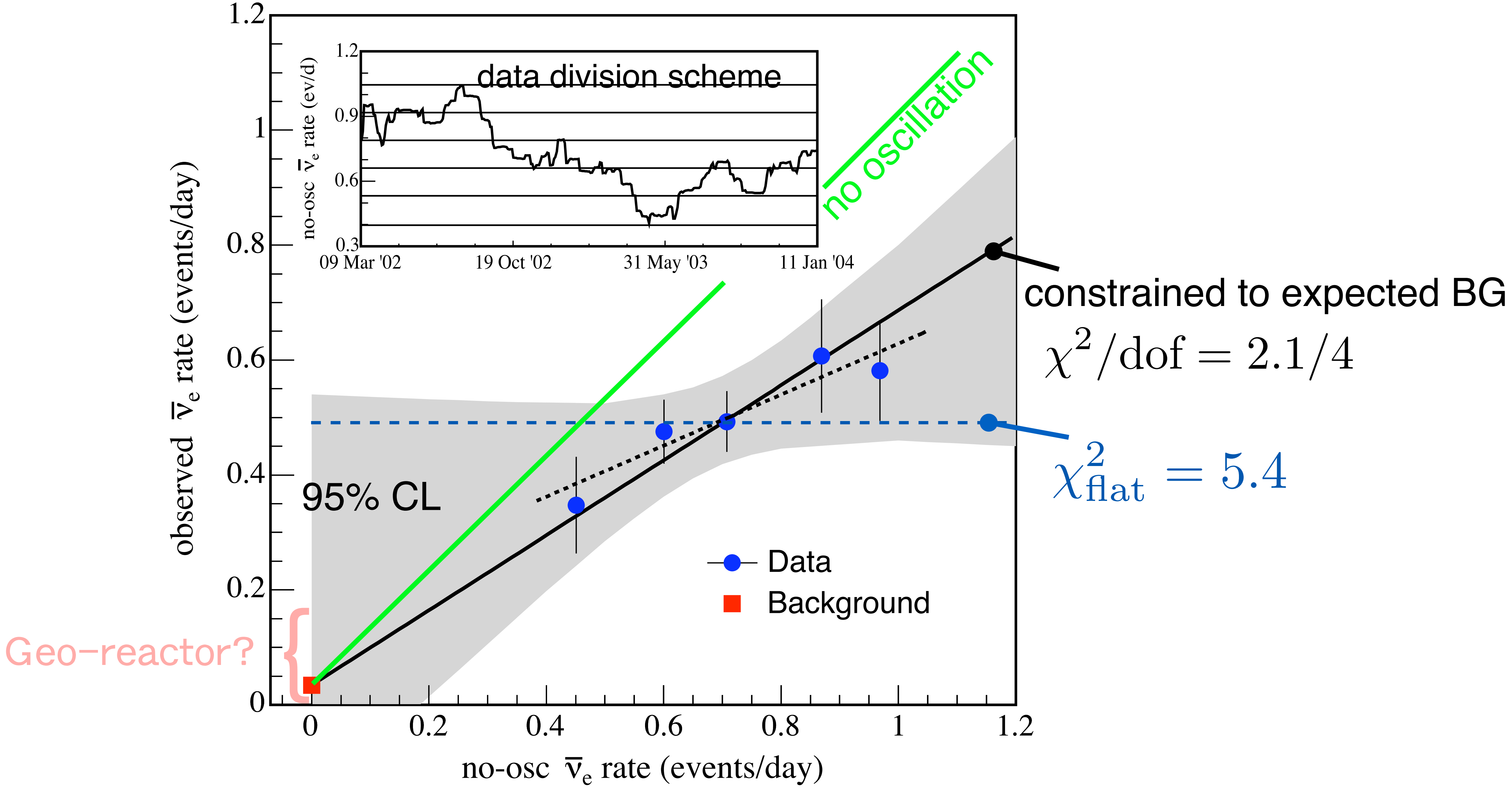
with new background correction

KamLAND collaboration, Phys.Rev.Lett.90(2003)021802



Event list and relevant numbers are available at
http://www.awa.tohoku.ac.jp/KamLAND/datarelease/2ndresult.html

Correlation with reactor power



constrained to expected BG

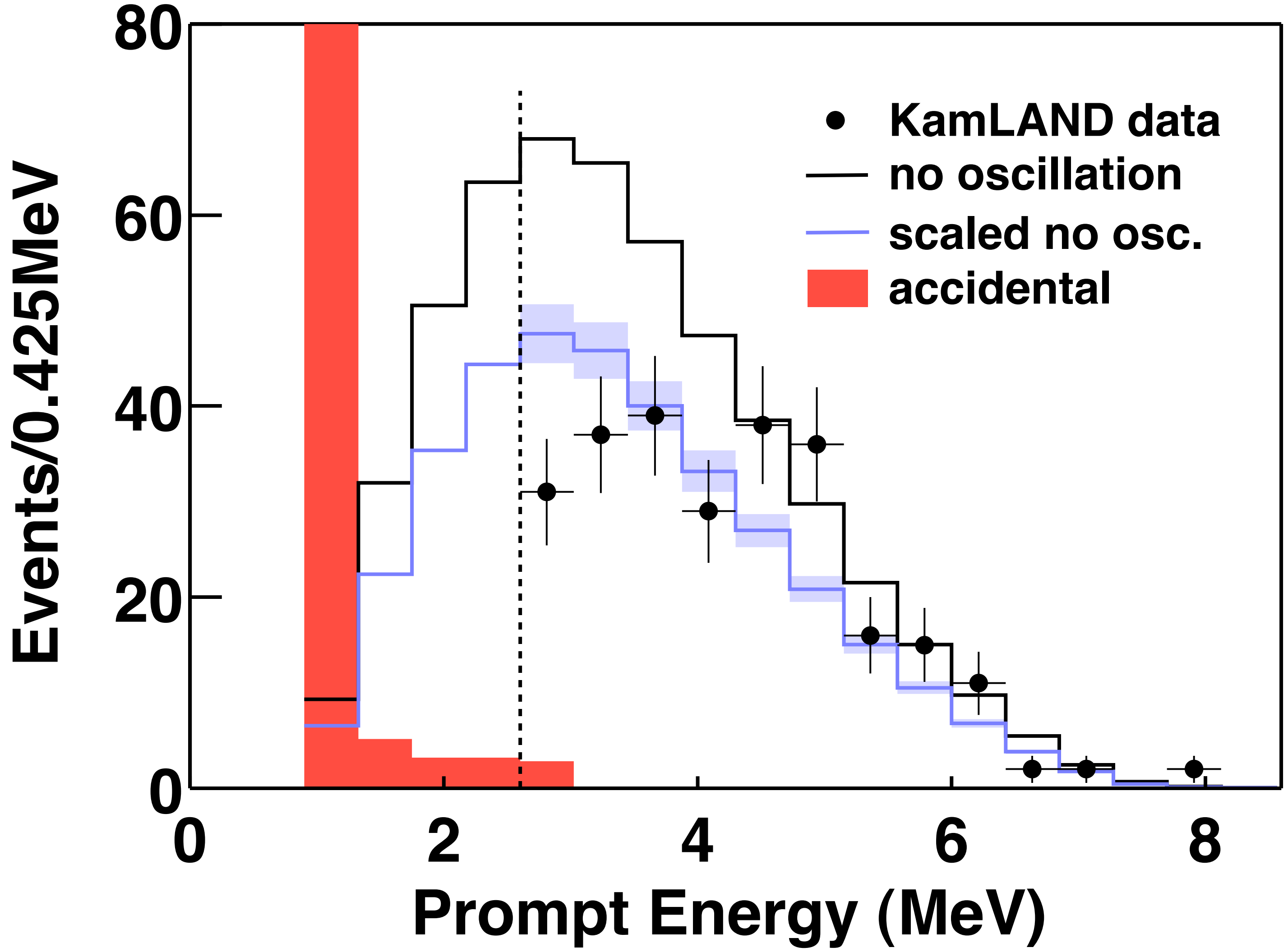
$$\chi^2/\mathrm{dof} = 2.1/4$$

$$\chi^2_{\mathrm{flat}} = 5.4$$

Geo-reactor?

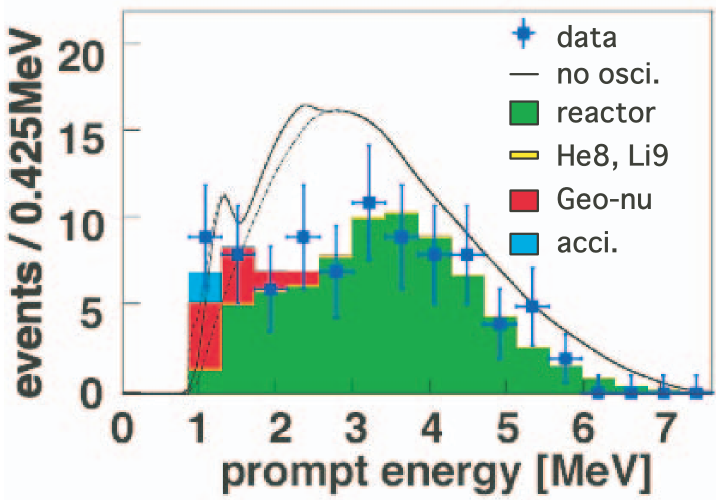
Current statistics is not enough to say definite thing.

Energy Spectrum



spectral distortion at >99.6% CL

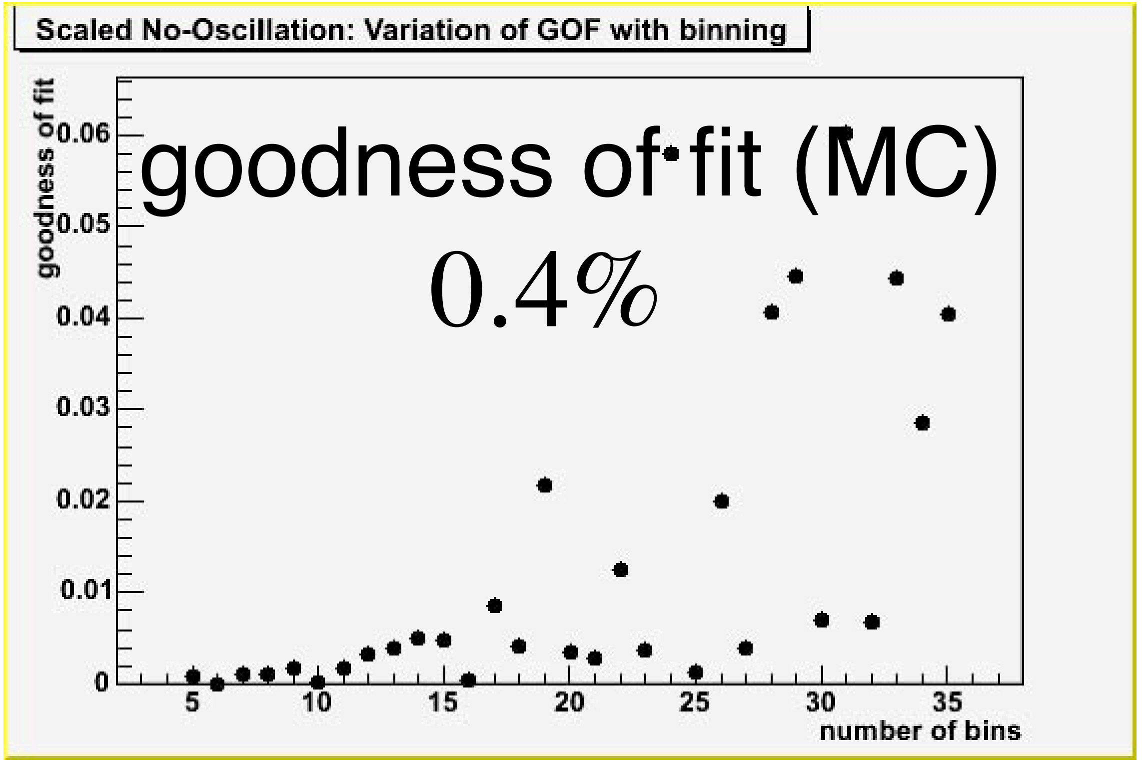
rate + shape 99.999995% CL



hypothesis test of scaled no oscillation

$$\chi^2/\mathrm{dof} = 37.3/19$$

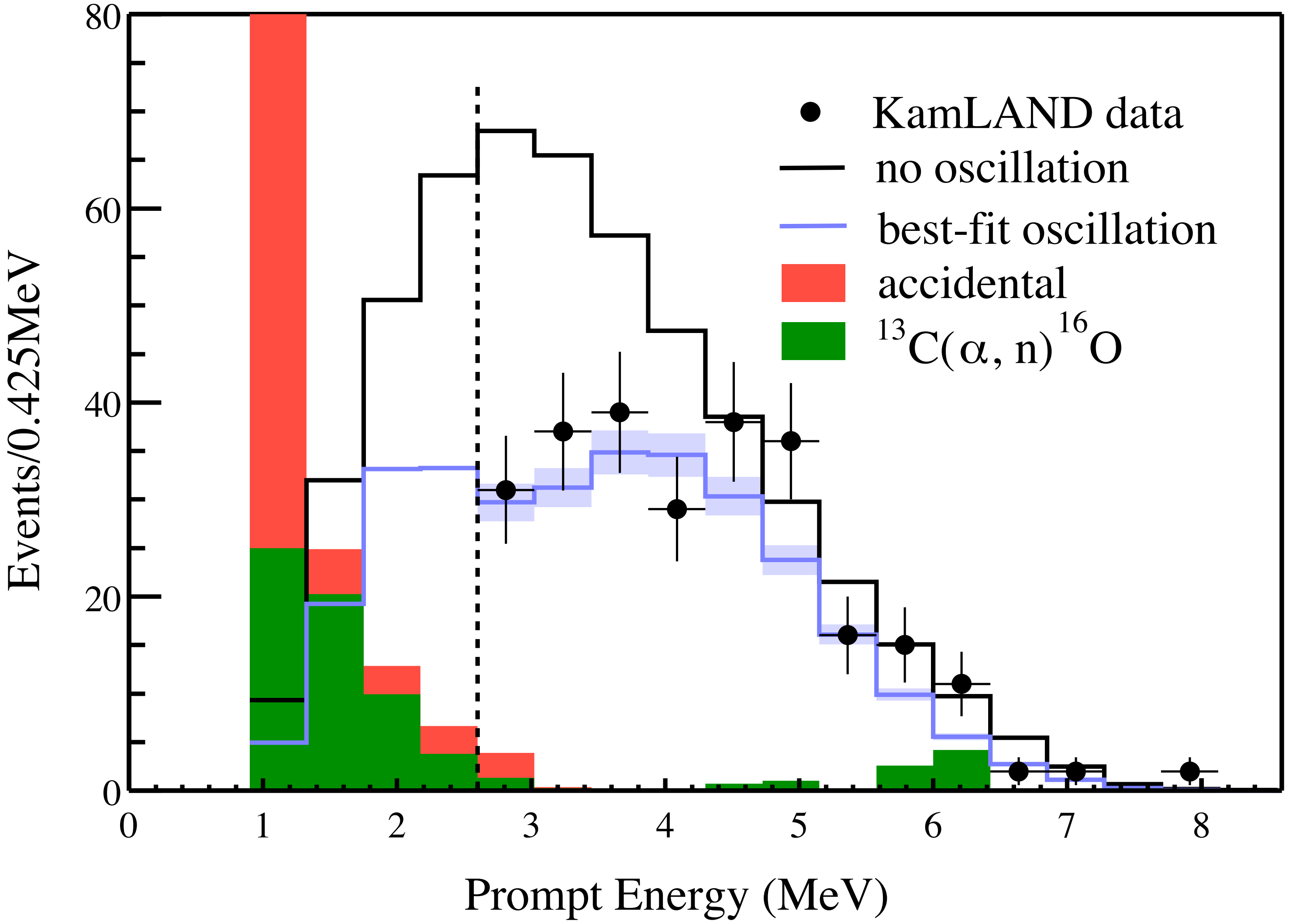
for 20 equal probability bins



goodness of fit (MC)

0.4%

	by unbin-likelihood method	equal probability 20 bins	MC based
Model	Best fit parameters	χ^2/dof	GOF
oscillation	$(\sin^2 2\theta, \Delta m^2) = (0.86, 7.9 \times 10^{-5}\,\mathrm{eV}^2)$	$24.2/17$	11.1%
decay	$(\sin^2\theta, m_2/c\tau) = (1.0,\ 0.011\,\mathrm{MeV/km})$	$35.8/17$	0.7%
decoherence	$(\sin^2 2\theta, \gamma) = (1.0,\ 0.030\,\mathrm{MeV/km})$	$32.2/17$	1.8%



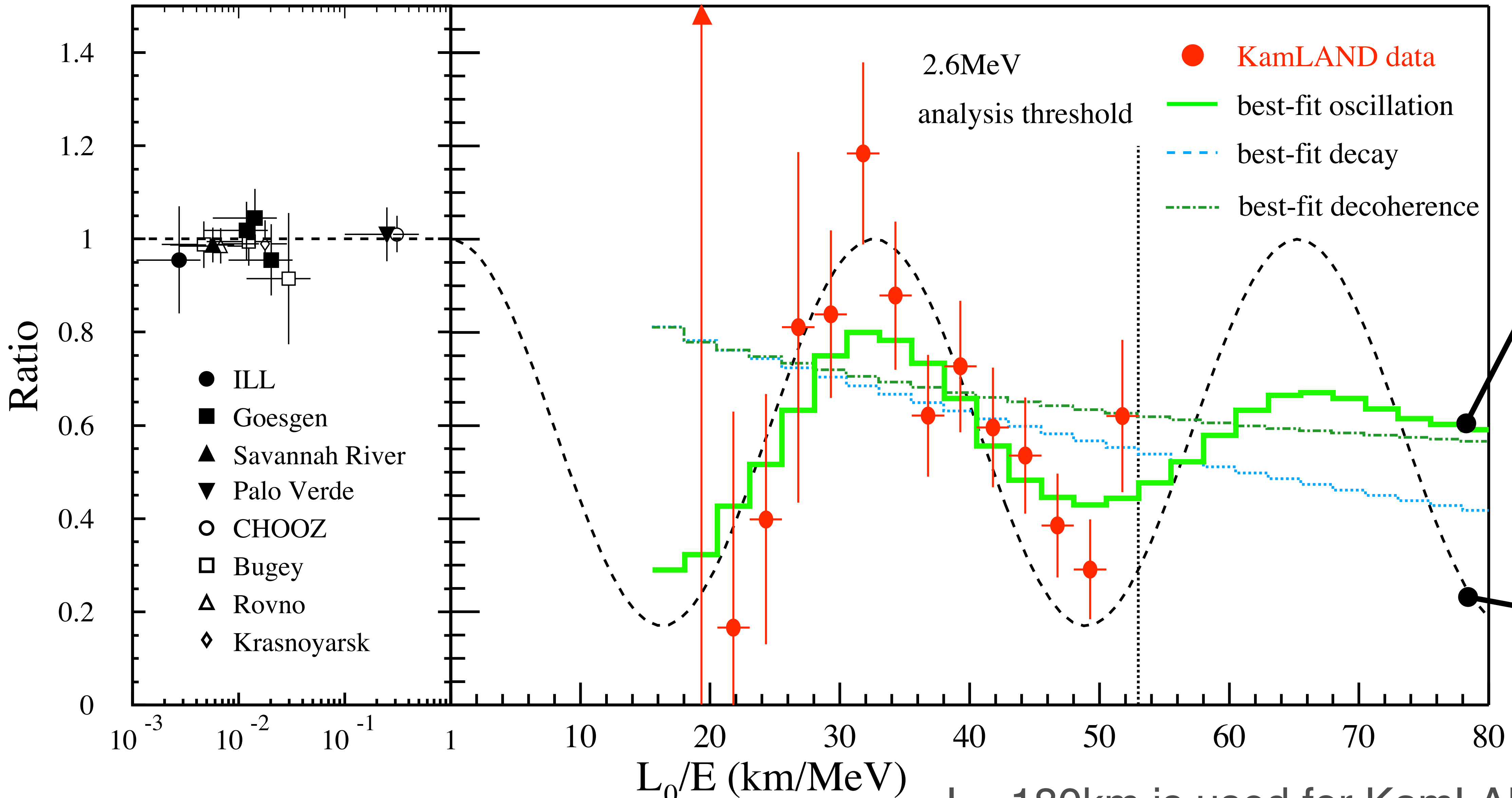
Significant spectral distortion supports neutrino oscillation.

Clear oscillation pattern has been seen.

oscillation $P_{\rm ee} = 1 - \sin^2 2\theta \sin^2(\frac{\Delta m^2}{4} \frac{L}{E})$

decay $P_{\rm ee} = (\cos^2\theta + \sin^2\theta \exp(-\frac{m_2}{2\tau}\frac{L}{E}))^2$

decoherence $P_{\rm ee} = 1 - \frac{1}{2}\sin^2 2\theta(1 - \exp(-\gamma\frac{L}{E}))$



with real reactor distribution

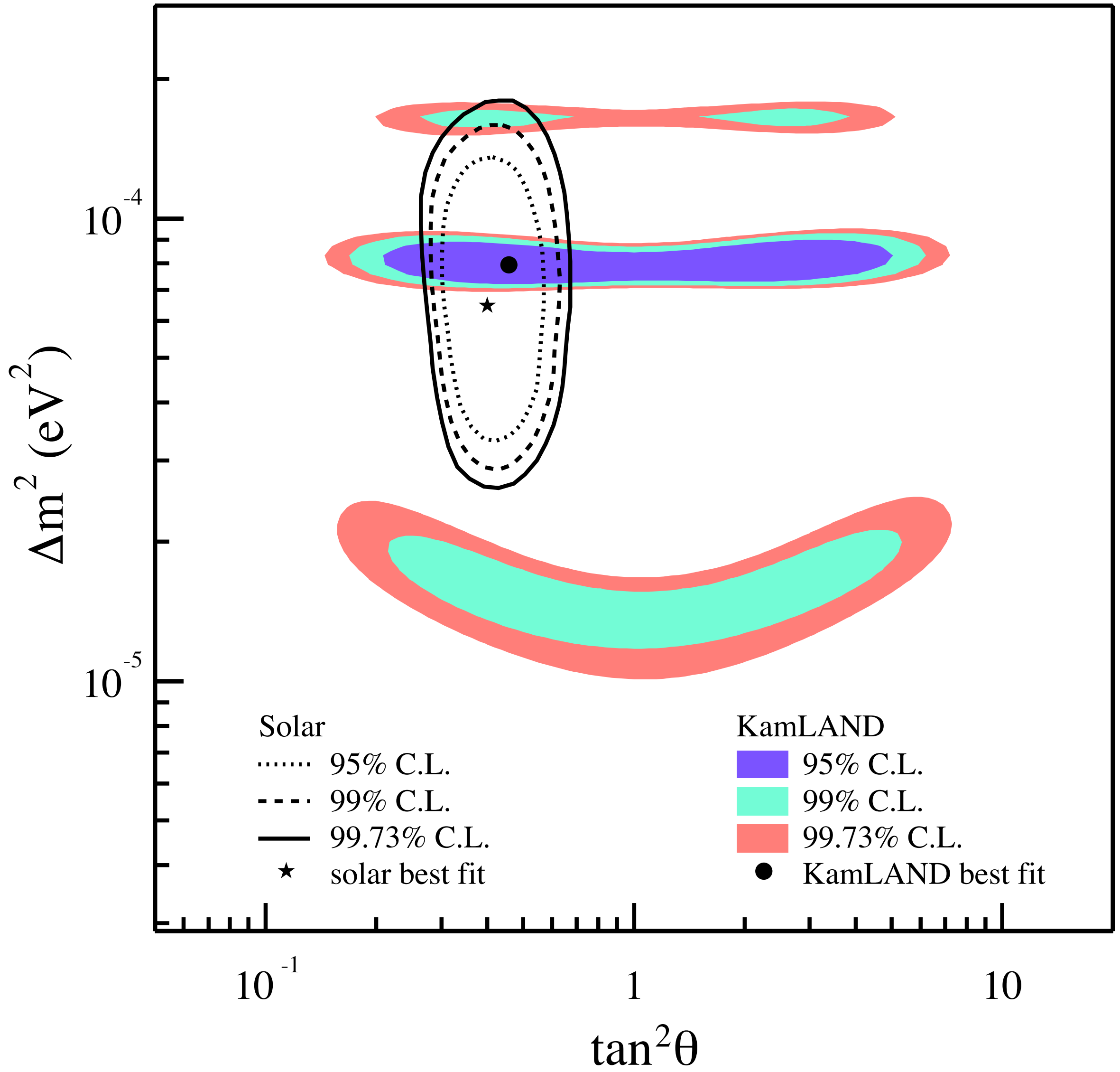
ideal oscillation pattern

L_0=180km is used for KamLAND

Measurement of neutrino oscillation parameters

matter effect makes small difference

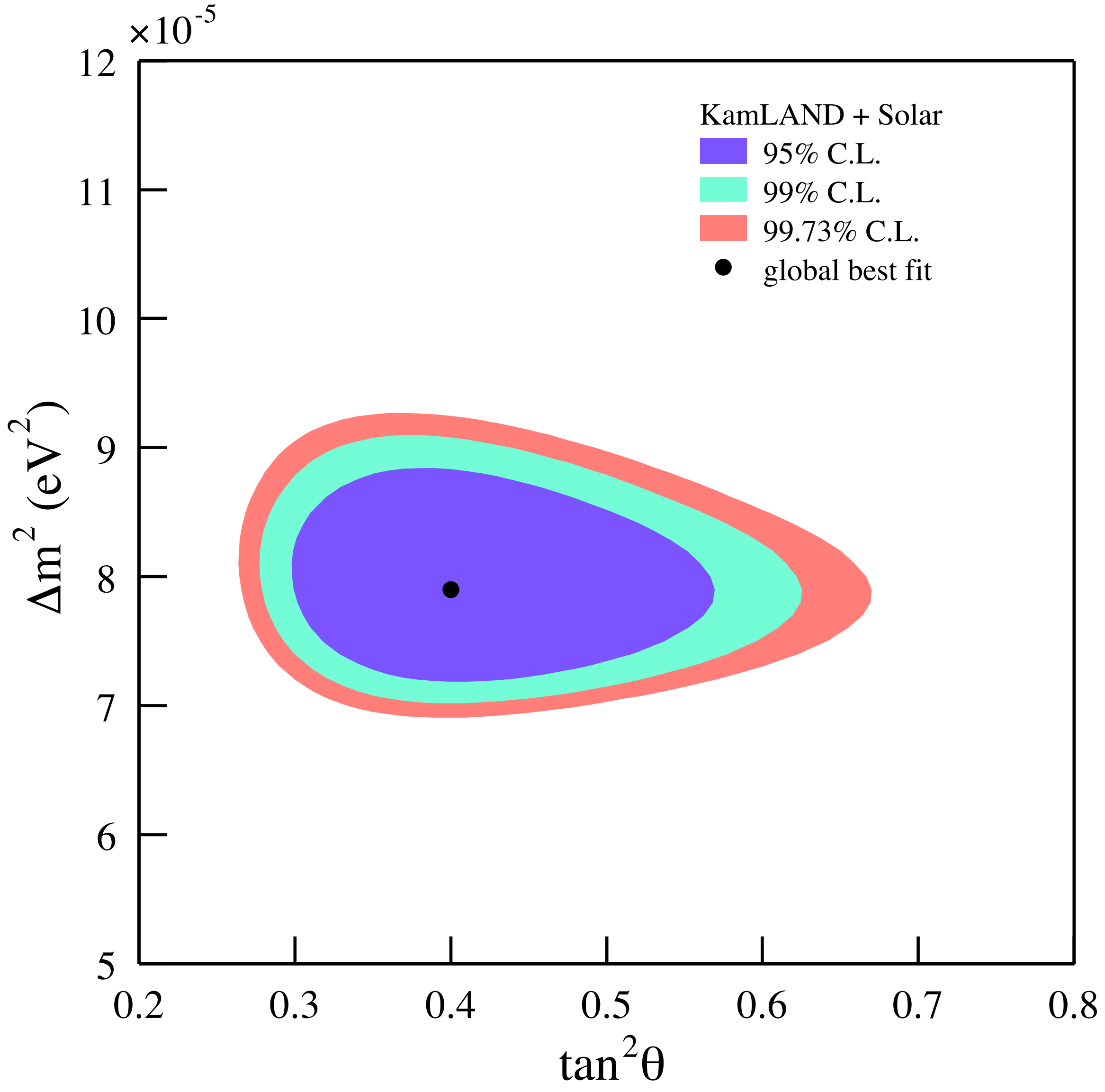
$\langle m_{\nu_e} \rangle < \langle m_{\nu_\mu} \rangle$ $\langle m_{\nu_e} \rangle > \langle m_{\nu_\mu} \rangle$



best fit rate+shape

$$(\tan^2\theta, \Delta m^2) = (0.46,\ 7.9 \times 10^{-5}\,\mathrm{eV}^2)$$

Assuming CPT invariance



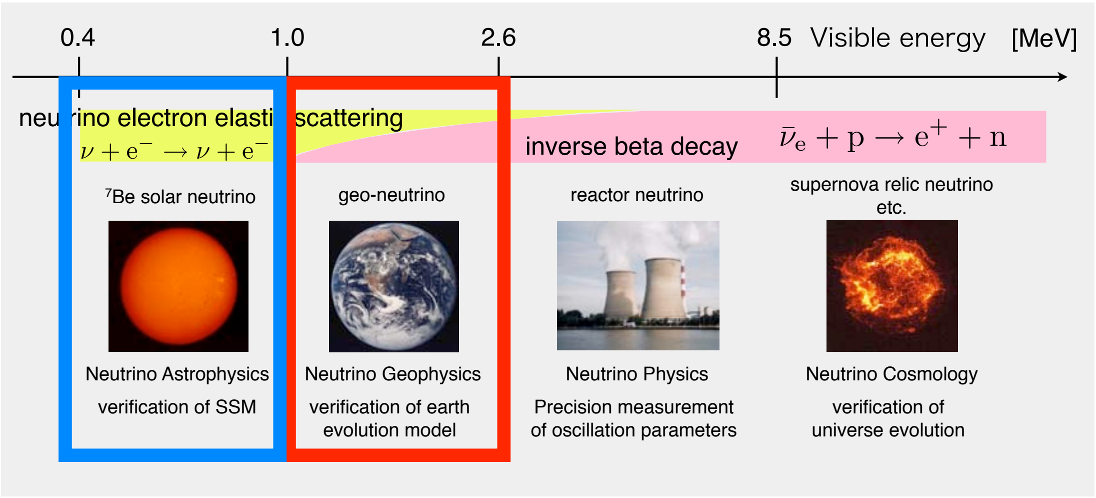
$$\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5}\,\mathrm{eV}^2$$

several orders -> less than 10%

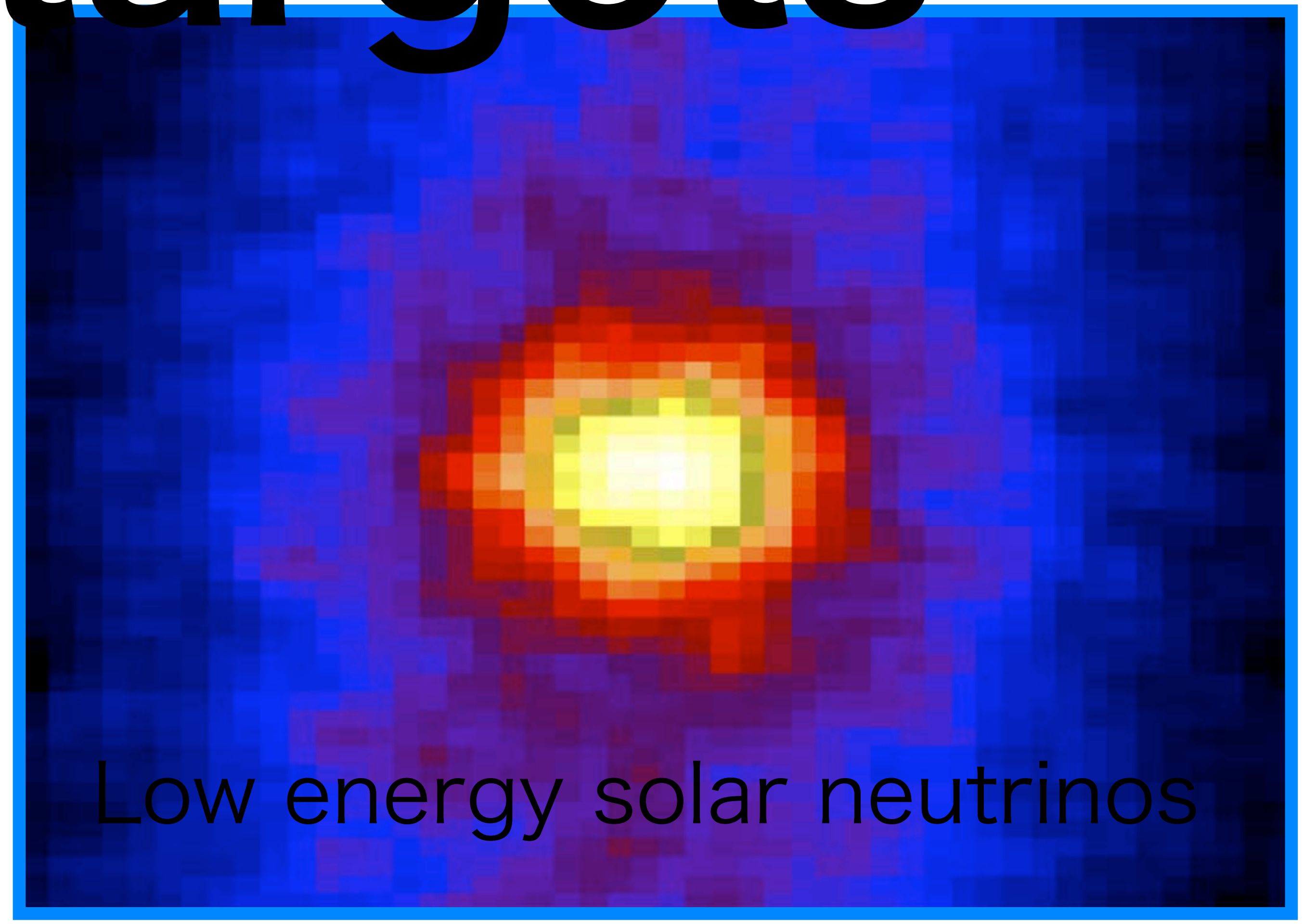
$$\tan^2\theta = 0.40^{+0.10}_{-0.07}$$

Precise determination of oscillation parameters made possible to use neutrinos as a new probe.

Nex targets



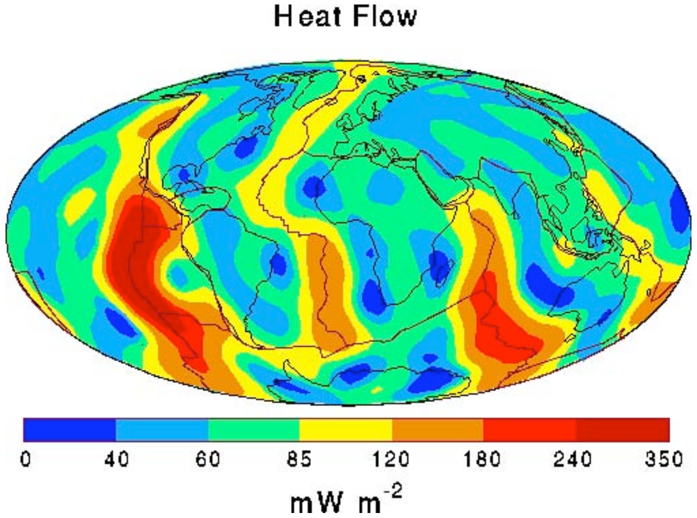
neutri



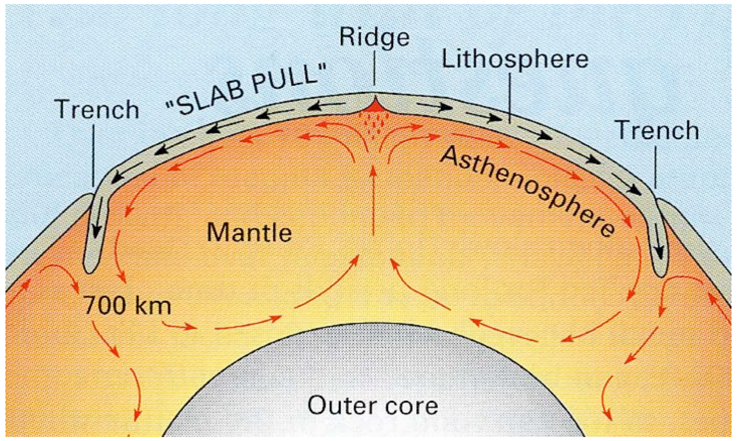
Low energy solar neutrinos

“Neutrino geophysics”

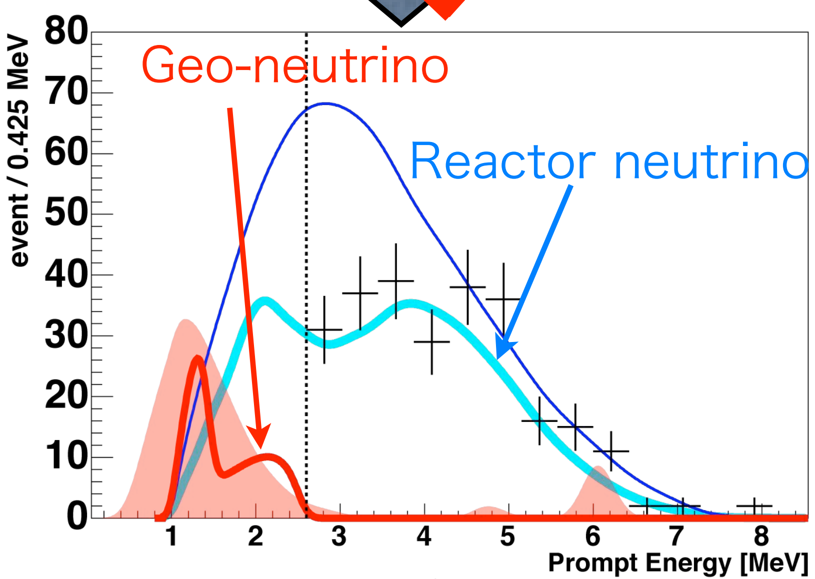
Precise measurement of oscillation parameters



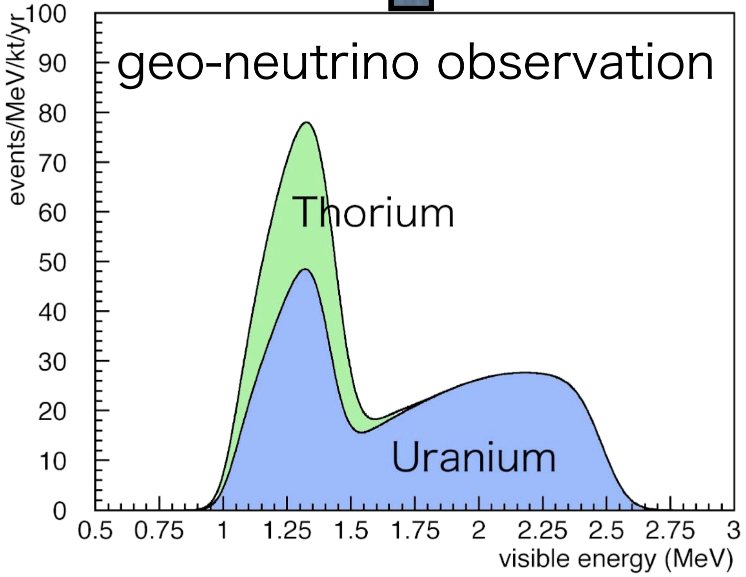
investigation of heat source



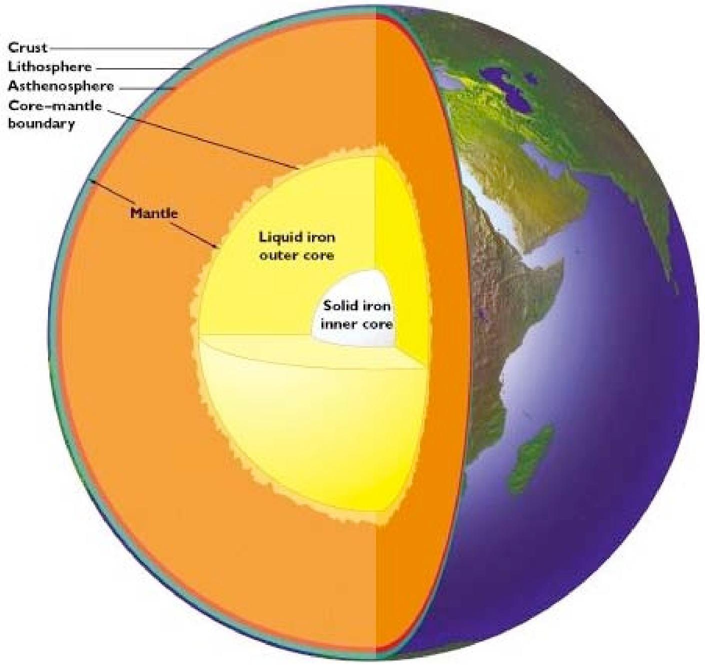
Study of earth dynamics



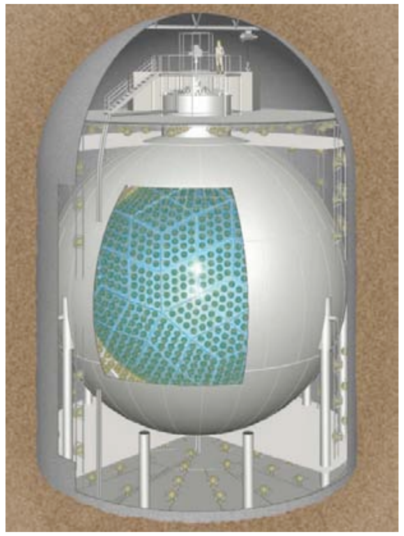
KamLAND data



geo-neutrino observation

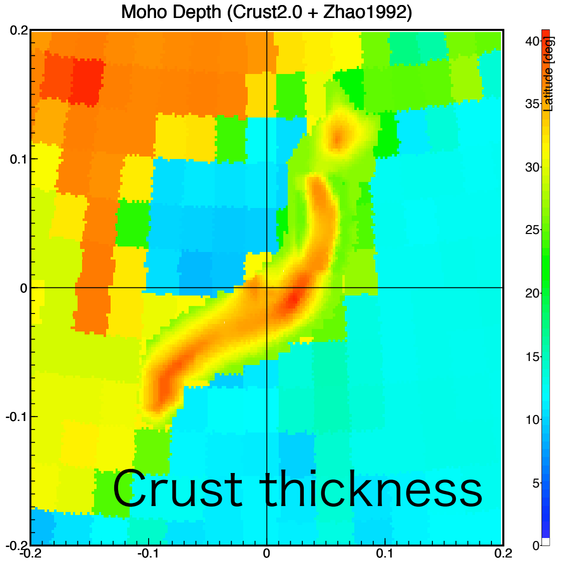


Study of earth structure

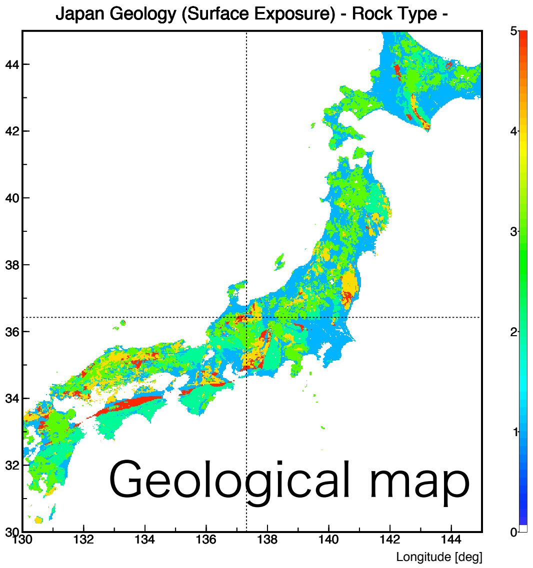


KamLAND detector

feed back from geophysics information

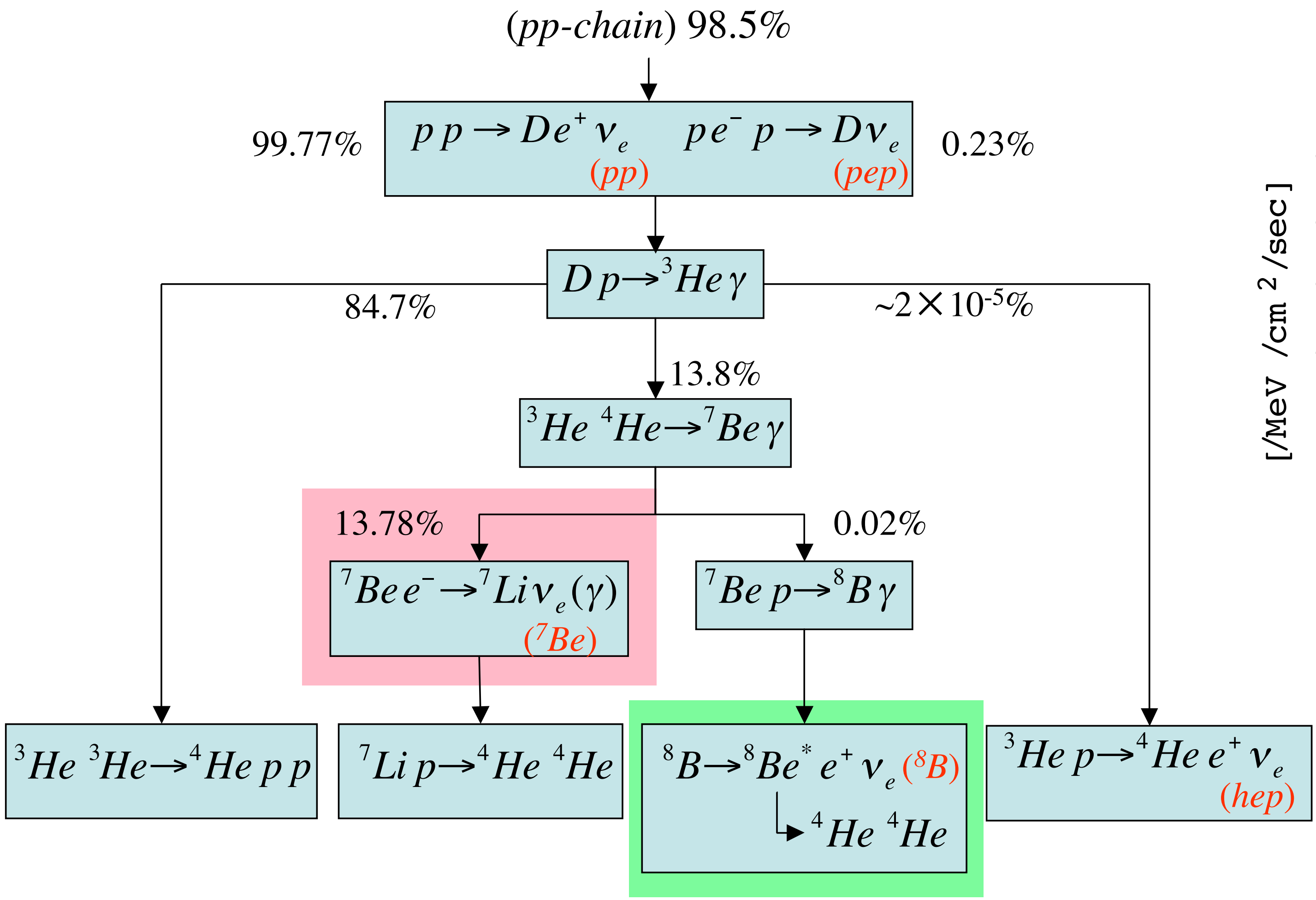


Crust thickness



Geological map

Solar neutrino observation



(pp-chain) 98.5%

99.77% $p\,p \rightarrow D e^+ \nu_e$ (pp)

$p e^- p \rightarrow D \nu_e$ (pep) 0.23%

$D\,p \rightarrow {}^3He\,\gamma$

84.7%

~2×10-5%

13.8%

${}^3He\,{}^4He \rightarrow {}^7Be\,\gamma$

13.78%

${}^7Be\,e^- \rightarrow {}^7Li\,\nu_e(\gamma)$ (${}^7Be$)

0.02%

${}^7Be\,p \rightarrow {}^8B\,\gamma$

${}^3He\,{}^3He \rightarrow {}^4He\,p\,p$

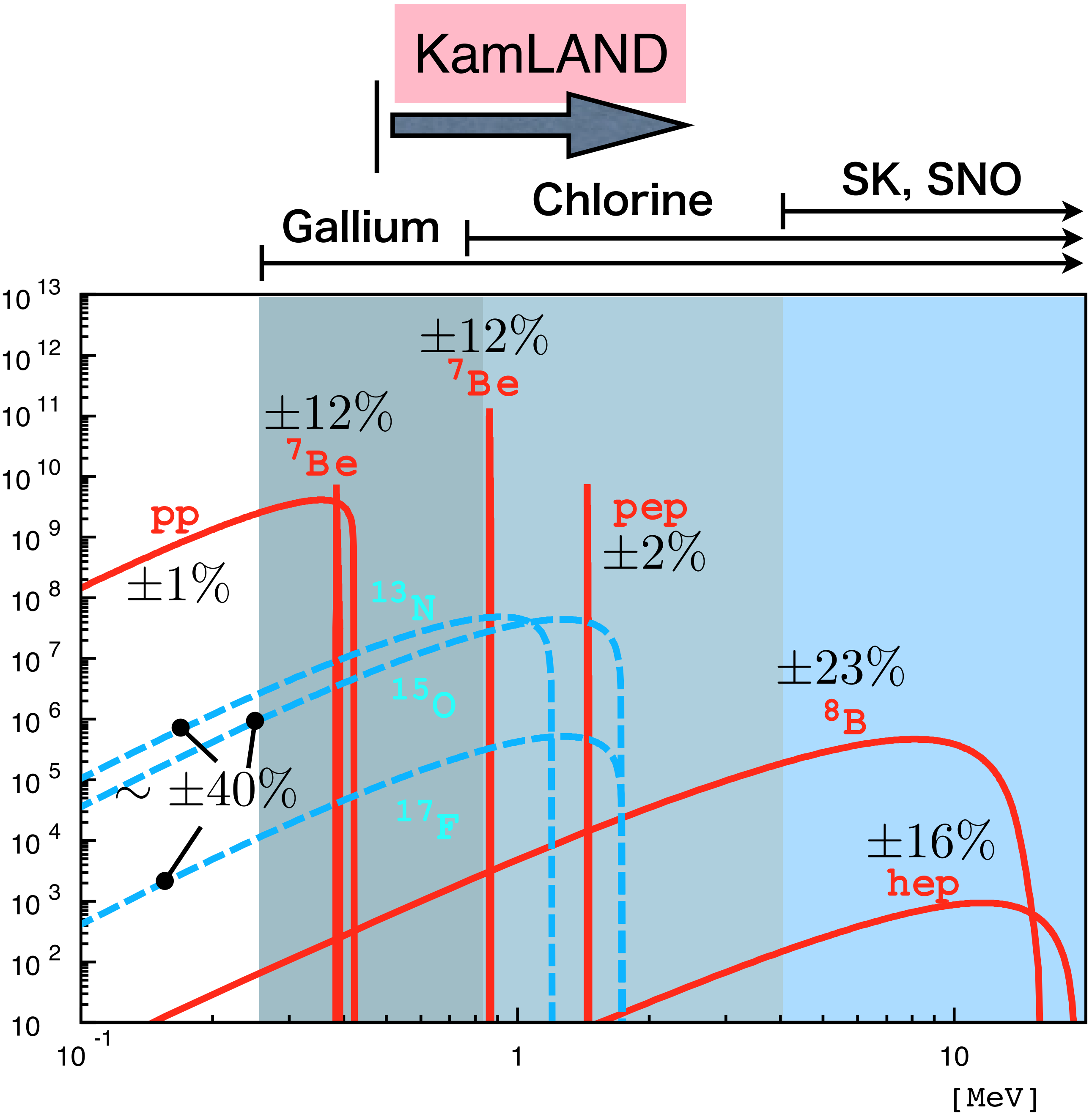
${}^7Li\,p \rightarrow {}^4He\,{}^4He$

${}^8B \rightarrow {}^8Be^*\,e^+\,\nu_e$ (${}^8B$)

↳ ${}^4He\,{}^4He$

${}^3He\,p \rightarrow {}^4He\,e^+\,\nu_e$ (hep)

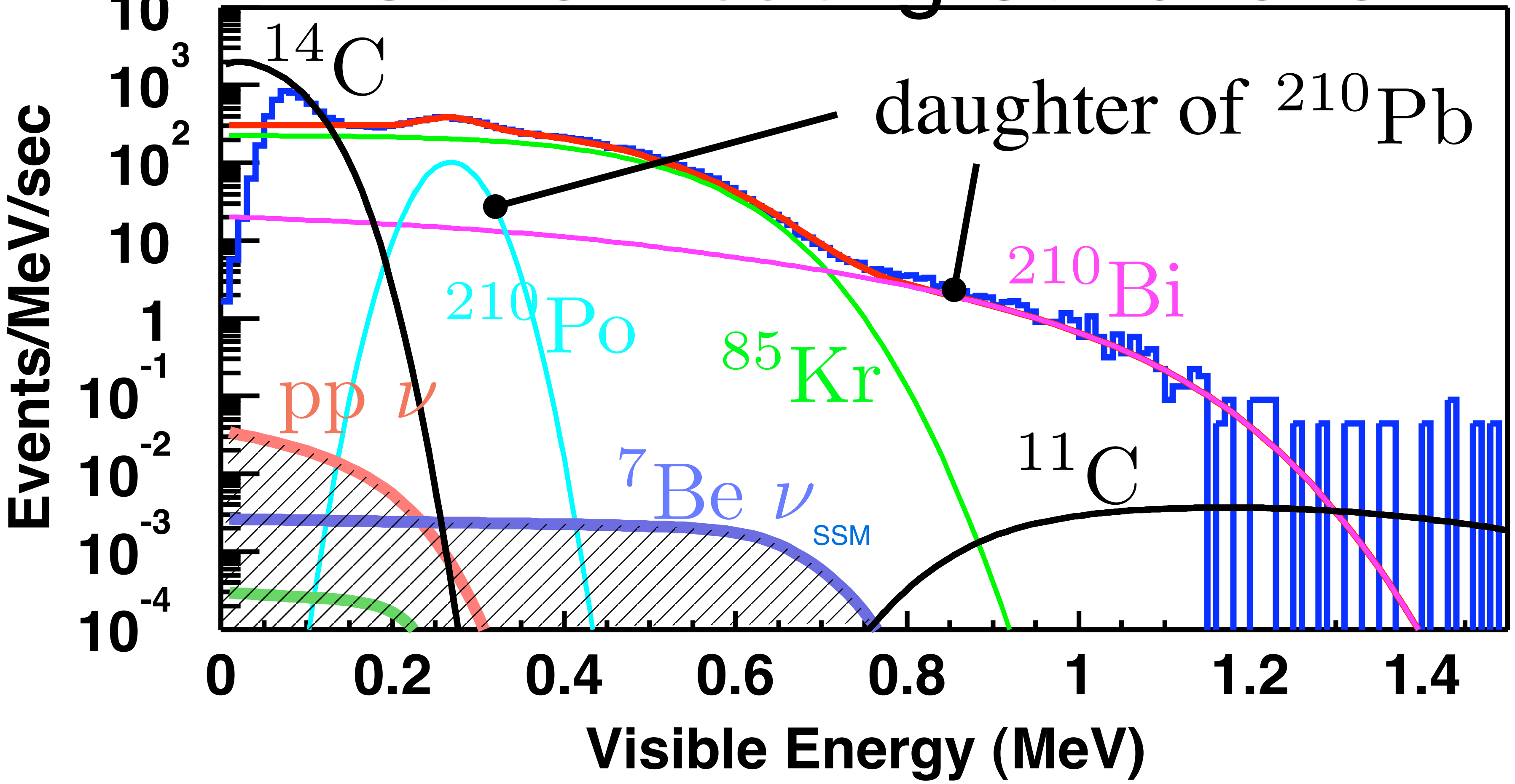
^{7}Be ~14% ^{8}B ~0.02%



Branching ratio to ^{7}Be neutrino is larger and theoretical uncertainty is smaller.

Its flux is so far measured at only 40% level.

Current background level



Background	now	goal
^{238}U(by Bi-Po)	3.5×10^{-18}g/g	**OK!!**
^{238}U(by ^{234}Pa)	$\mathbf{O}(10^{-15}$g/g)(Max.)	10^{-18}g/g
^{232}Th (by Bi-Po)	5.2×10^{-17}g/g	**OK!!**
^{40}K	2.7×10^{-16}g/g(max.)	$< 10^{-18}$g/g
^{210}Pb	$\sim 10^{-20}$g/g	5×10^{-25}g/g $\sim 1\mu$Bq/m^3
^{85}Kr, ^{39}Ar	^{85}Kr $=0.7$Bq/m^3	1μBq/m^3
^{222}Rn (after purification)	^{238}U $= 3.5 \times 10^{-18}$g/g $= 3.3 \times 10^{-8}$Bq/m^3	**OK!!** (1μBq/m^3)
^{222}Rn (during purification)		1mBq/m^3 ^{210}Pb $= 0.5\mu$Bq/m^3 after decay

required further improvement

$$\frac{1}{10^{4\sim5}}$$

$$\frac{1}{10^{\sim6}}$$

Purification achievement

- ○ N_2 gas purge

  N_2/LS=25 ---> ~1/10 Rn, ~1/100 Kr

- ○ Fractional Distillation (164℃, 300 hPa)

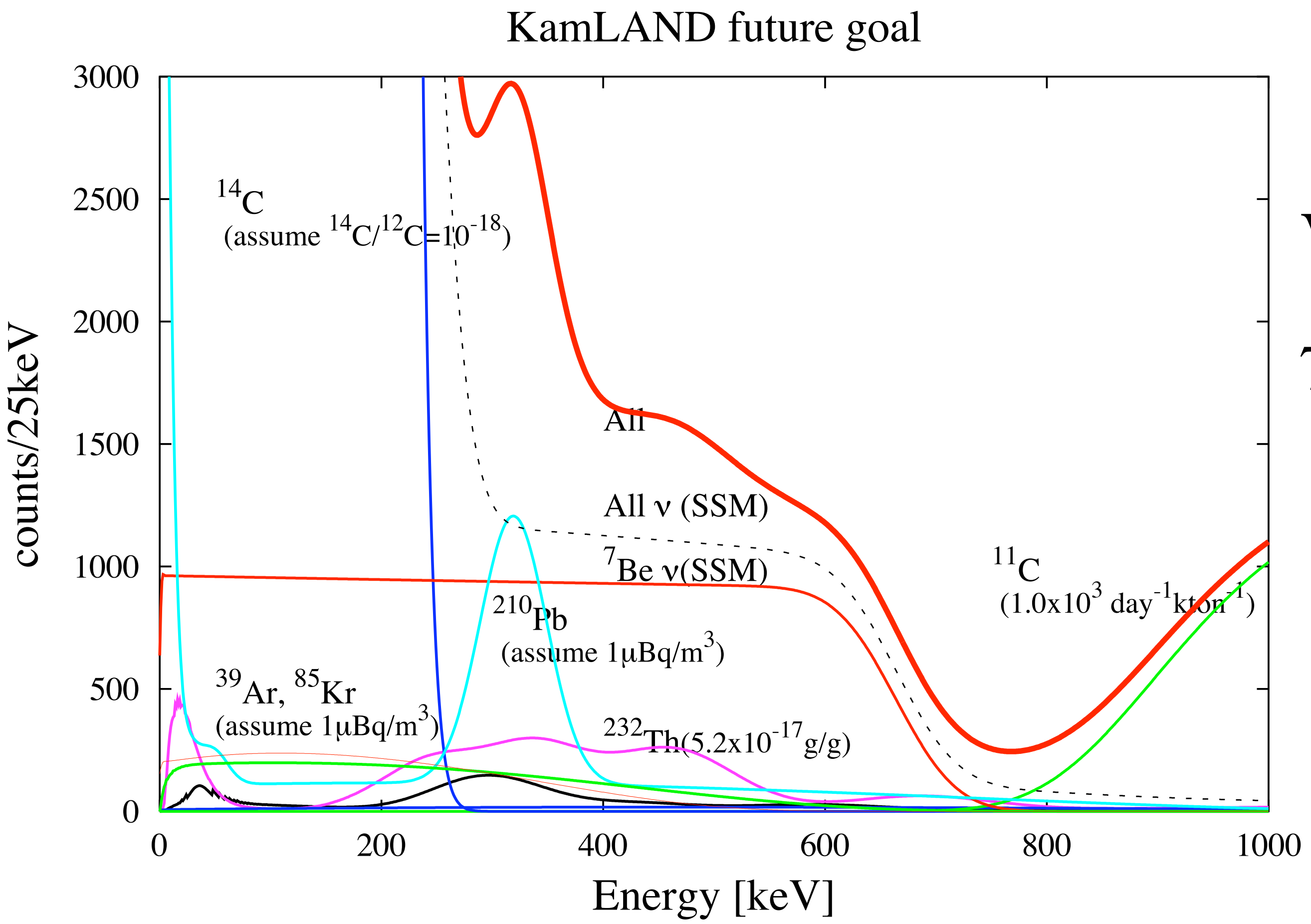
  3×10^{-5} Pb

  1×10^{-5} Rn

  $<2\times10^{-6}$ Kr

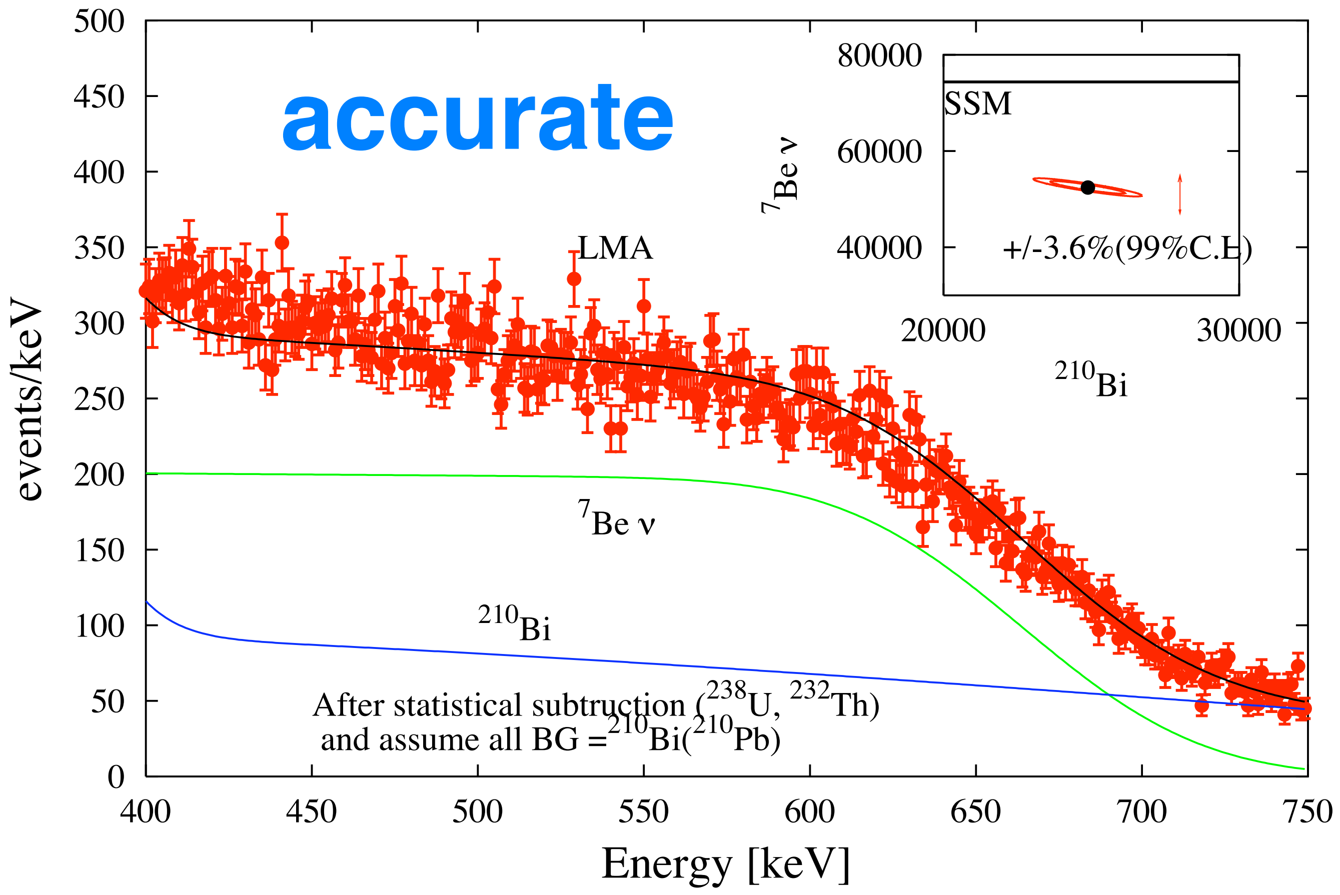
  Residual impurities will be some organic lead (e.g. tetra-ethyl-lead) and they disintegrate at ~200 ℃.

Required performance is almost achieved.

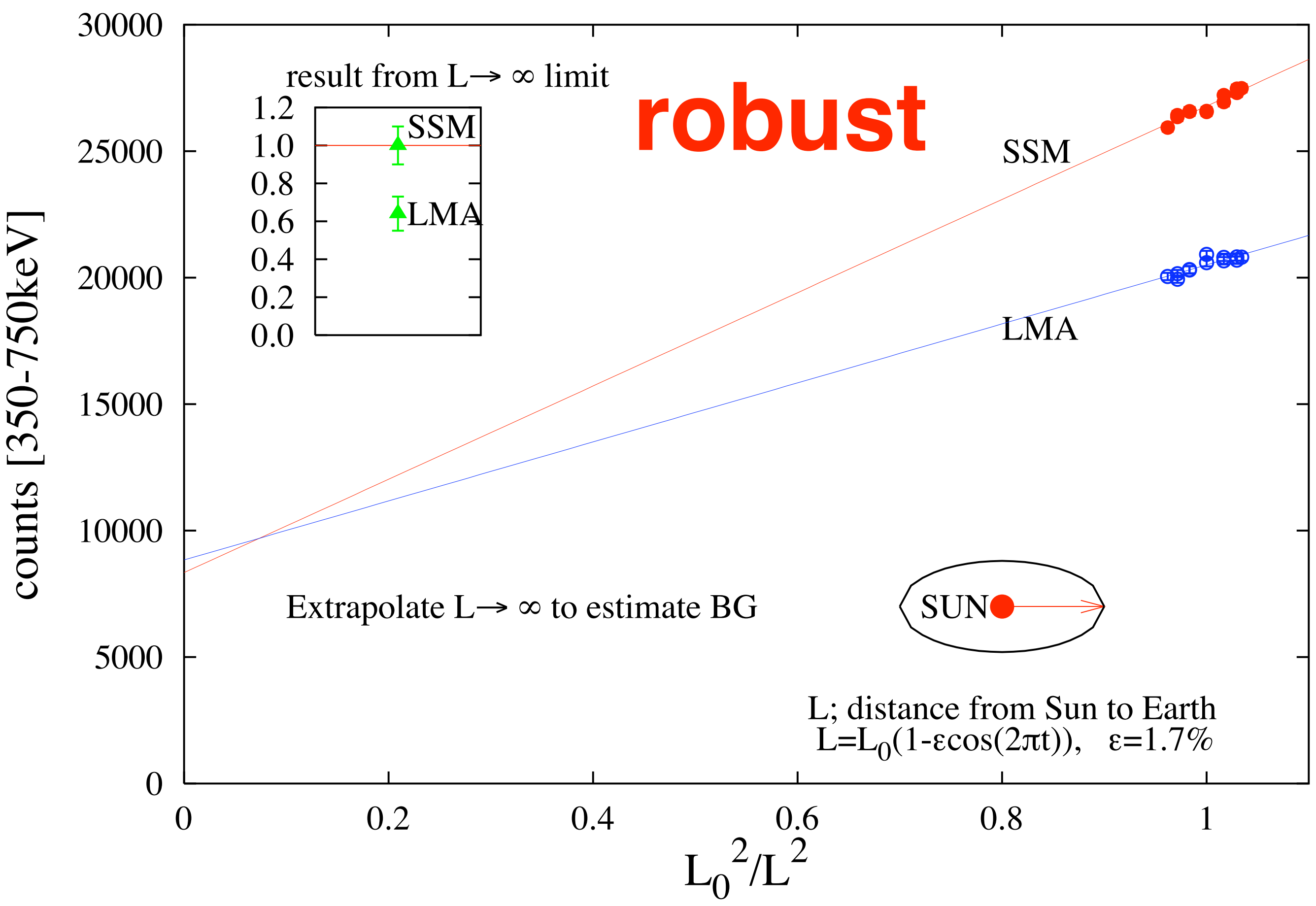

KamLAND future goal

When the required reduction is achieved, ^{7}Be neutrinos will be seen in the window between ^{14}C and ^{11}C background.

BG subtraction with shape fit


KamLAND (expected 3y, R<4m)

BG subtraction with seasonal variation


KamLAND expected (5y, fiducial R<4m)

Thank you!

The KamLAND collaboration

Tohoku + 11 US + 1 Chinese + 1 French institutes