Future Solar Neutrino Experiments

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@Neutrino2004

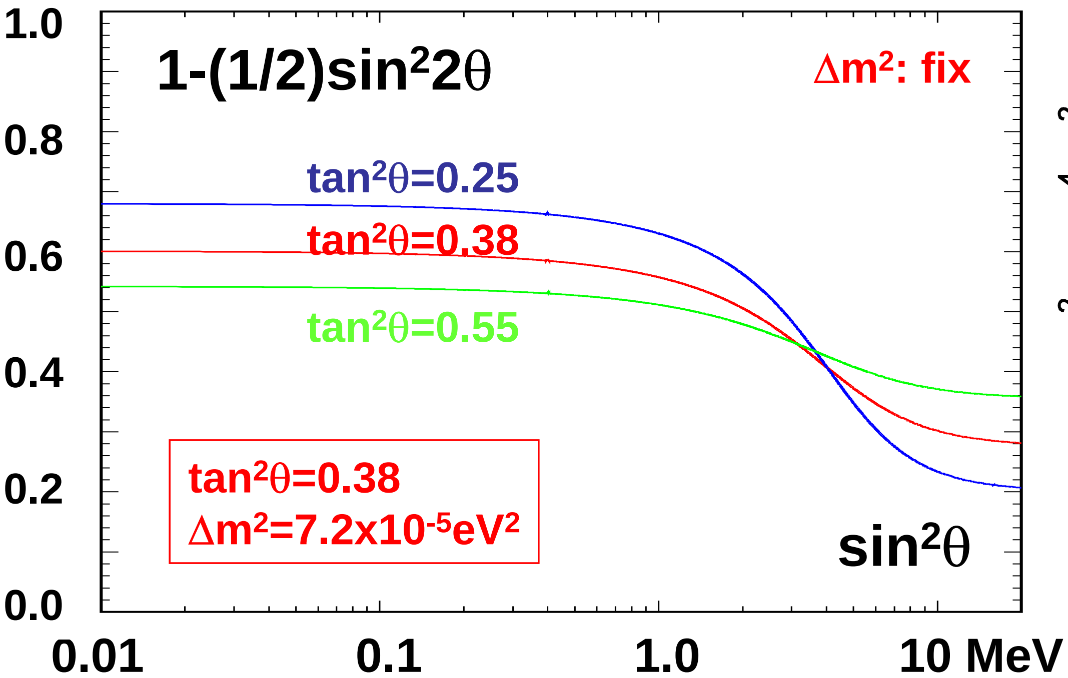
- Purpose of the future
  solar neutrino experiments
- Detector developments
  (especially on new efforts)

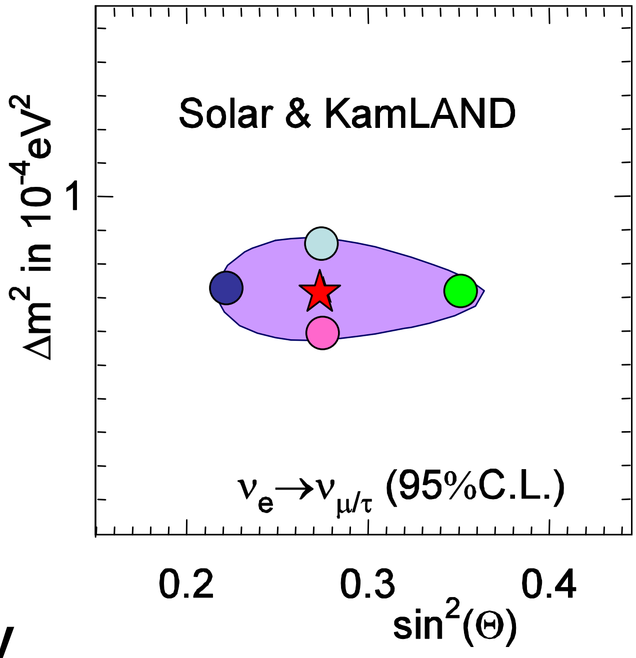
Flux suppression for LMA

E <1 MeV: Vacuum $\theta_m \rightarrow \theta_V$ → ***P=1-(1/2)sin²2θ***

E >a few MeV: Adiabatic $P=\cos^2\theta\cos^2\theta_m+\sin^2\theta\sin^2\theta_m$ → ***P=sin²θ***

$(\theta_m \rightarrow \pi/2)$





pp &⁷Be-neutrinos →

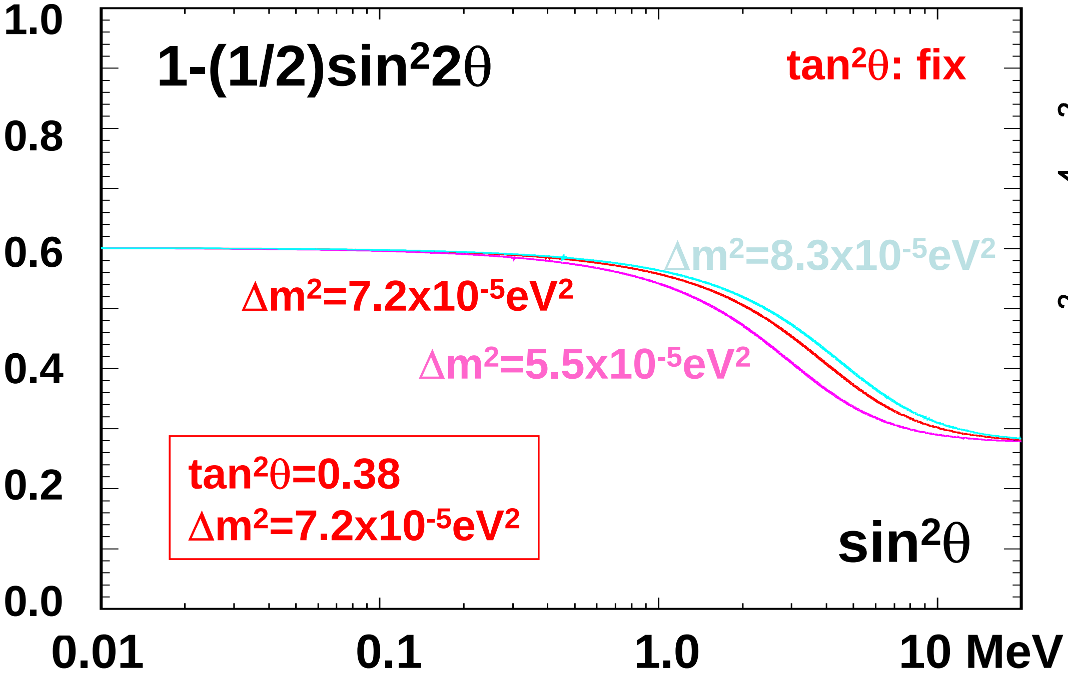
~50~70% suppression

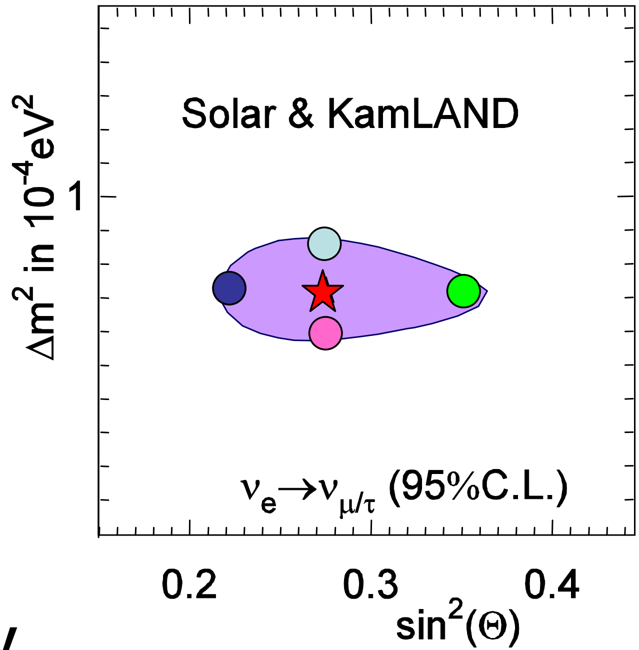
Flux suppression for LMA

E <1 MeV: Vacuum $\theta_m \rightarrow \theta_V$ → ***$P=1-(1/2)\sin^2 2\theta$***

E >a few MeV: Adiabatic $P=\cos^2\theta\cos^2\theta_m+\sin^2\theta\sin^2\theta_m$ → ***$P=\sin^2\theta$***

($\theta_m \rightarrow \pi/2$)



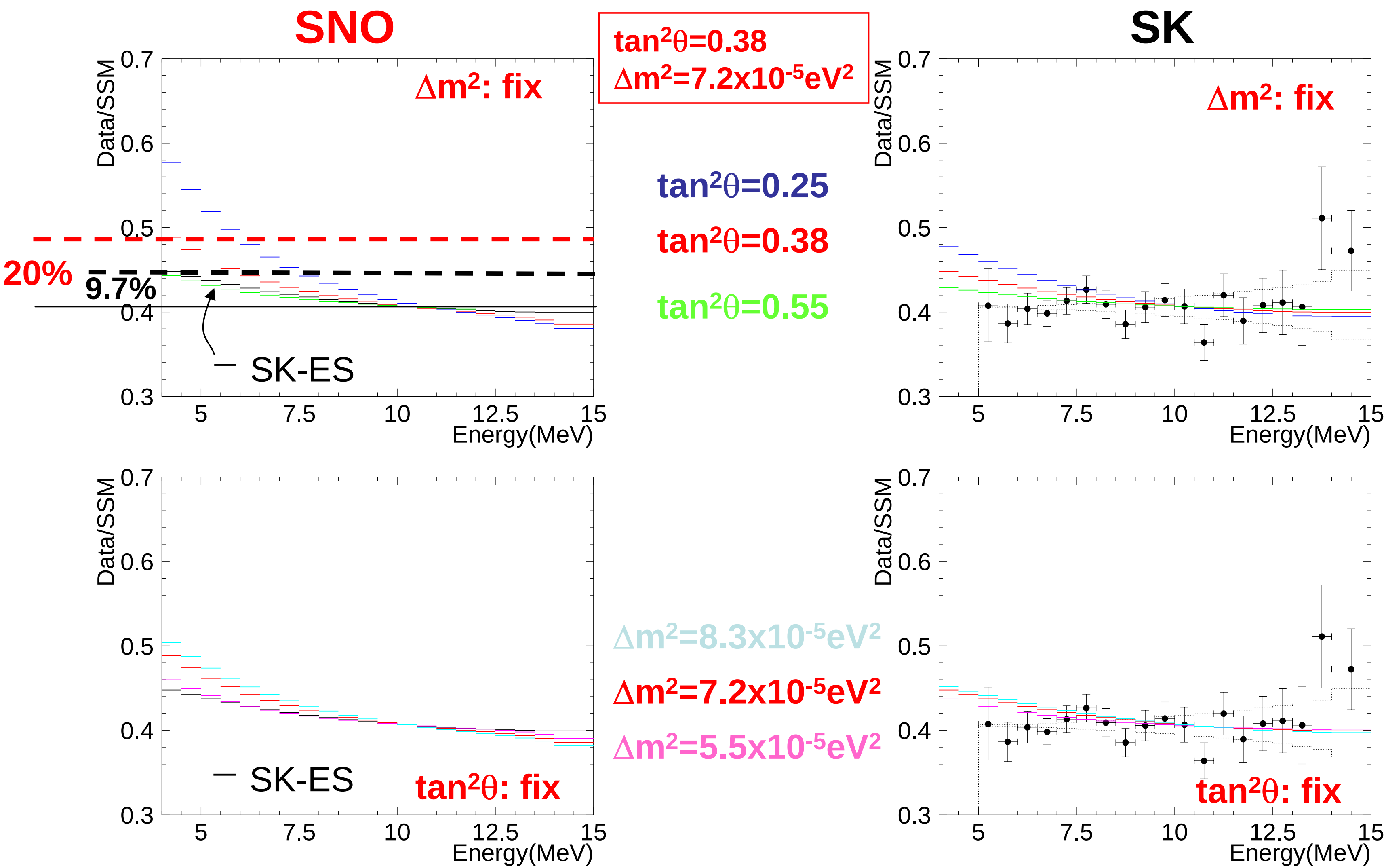


effect of different Δm^2 → small difference in the upturn

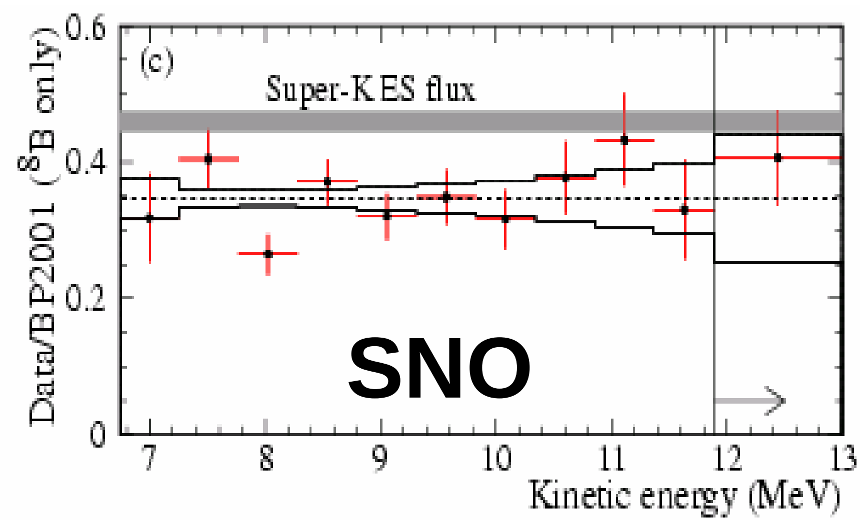
Aim of the future solar neutrino experiments

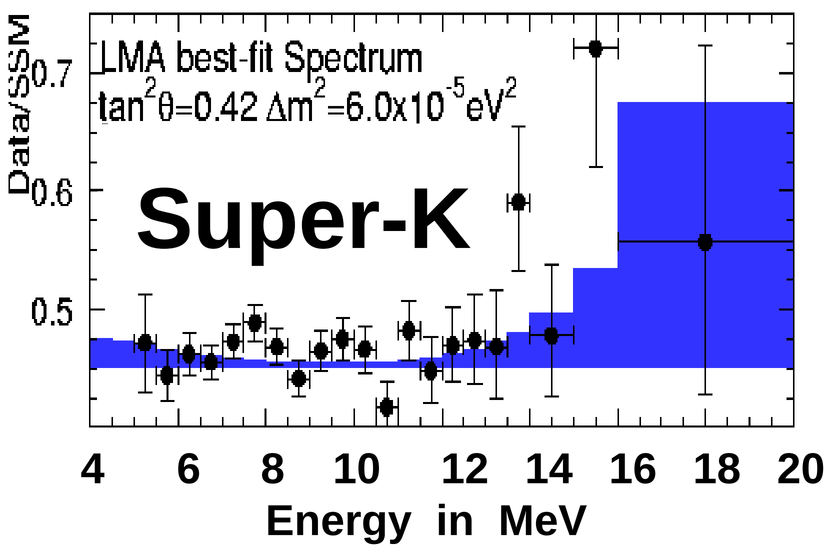
- Confirmation of LMA
  & find small sub-leading effects
  - ^{8}B: low energy upturn & Day/Night effect
  - Matter Vacuum transition
    - Precise spectrum measurements in low energy
      - Cl – problem?
  - Sterile neutrinos?
    - Best by pp neutrinos
  - Other sub-leading effects
    - Test of CPT (Solar + KamLAND), ………..
- Precise determination of θ_{12} and Δm_{12}
    - ^{8}B (large WC)
    - pp-neutrino, ^{7}Be(CC+ES)
- Astrophysics
  - Test of SSM (energy creation, photon luminosity) and….
  - Study the interior of the sun and……

Expected low energy upturn (^{8}B)



Measurement by SNO and SK





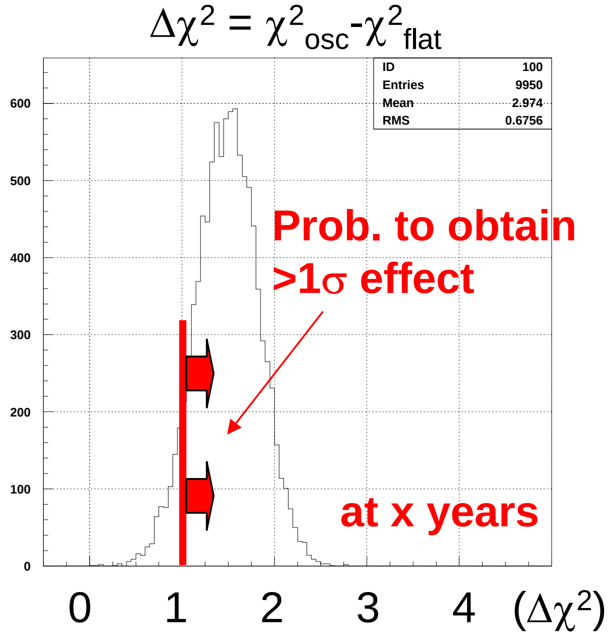
- Not yet seen either in SK and SNO
  - Limited by the data quality?
  - Larger mixing angle?
  - Something wrong?
  - Something unknown happening?
- Spectrum measurement

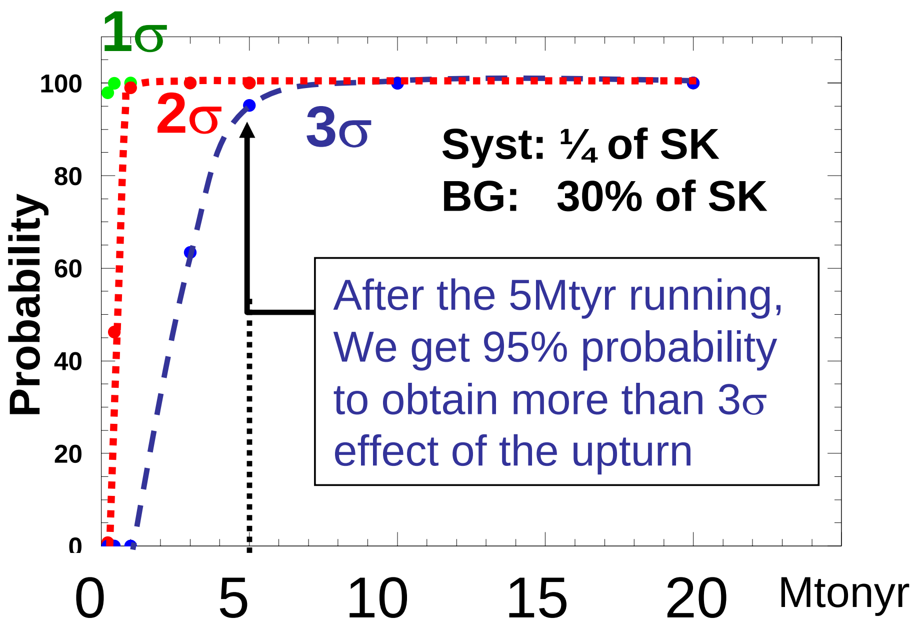
!! Difficult
  - Systematics
    - ～3% (SK;SNO) → may be ok
  - Backgrounds
    - should be reduced (SK)
    - correlation (SNO)
  - Statistically limited
    - Need longer run

➔ A larger detector with lower BG is needed

Future large WC detector

- The Megaton scale detector can be made by the Water Cherenkov technique.
  - (may be the only possibility in practice)
- Test with
  - Syst. → ala SK, ½ of SK, ¼ of SK
  - BG → ala SK, 30% of SK, 15% of SK



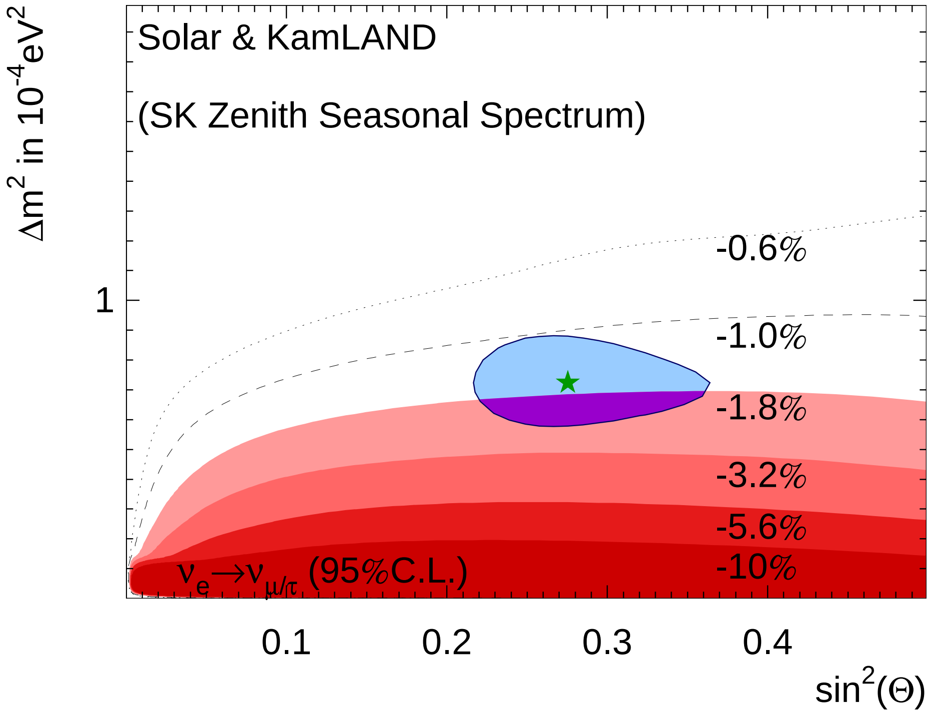


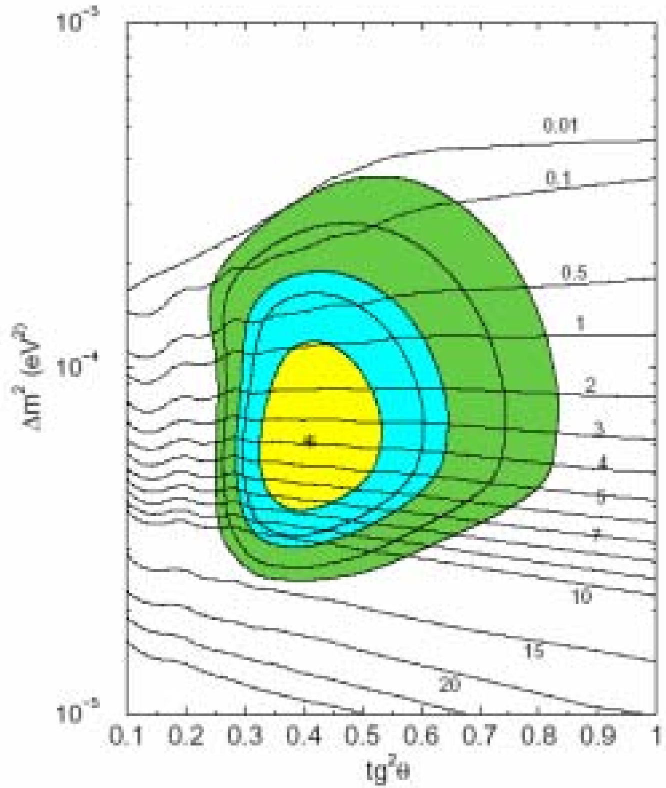
^{8}B -- Day-Night effect

- Not yet convincingly seen either in **SK** nor **SNO**

~1~3% effect

~2~6% effect

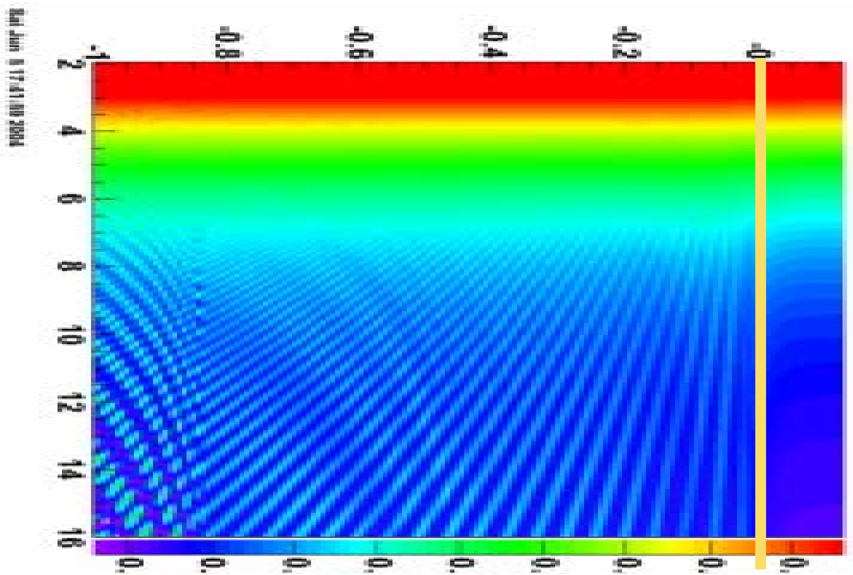


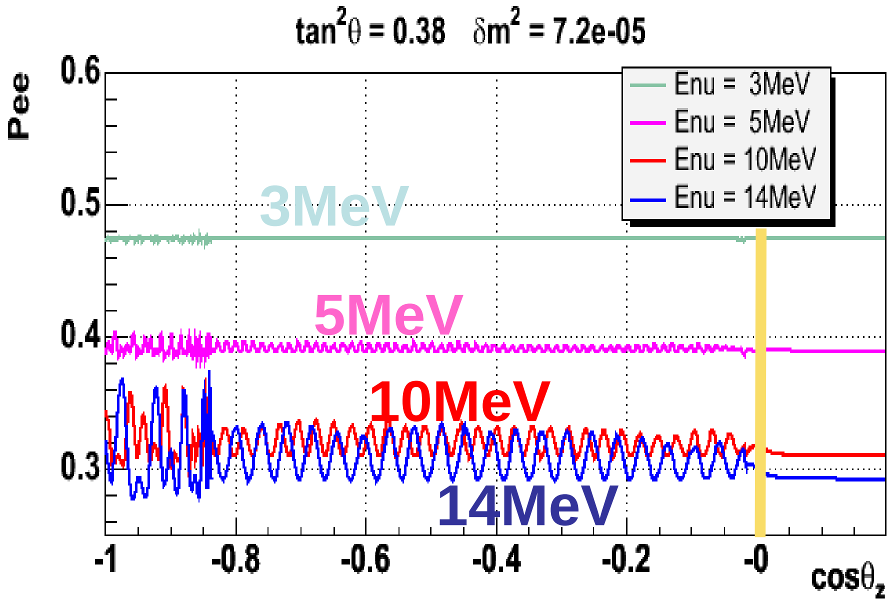


$$-0.018 \pm 0.016^{+0.013}_{-0.012}$$

$$-0.07 \pm 0.049^{+0.013}_{-0.012}$$

Day-Night Sensitivity

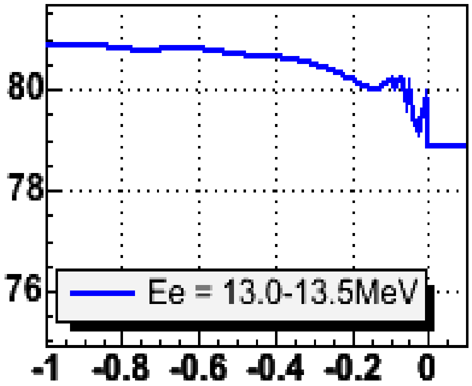




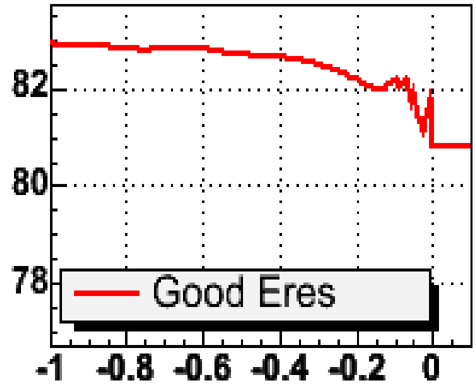
- Prominent at the high energy region and though core
- Possible to measure those structures ?
- ES events smears out the effect by kinematics
- CC events should have better sensitivity

Energy Slice ($E_e^{observed}$ =13-13.5 MeV)

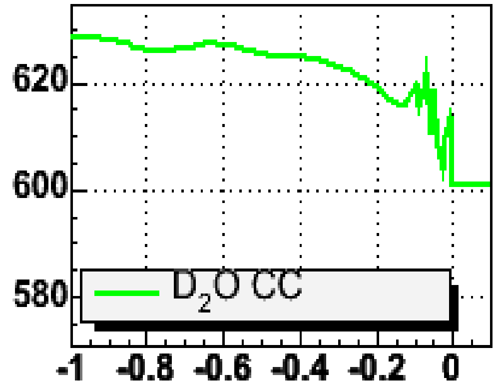
SK-Resolution



SK/ sqrt(2)

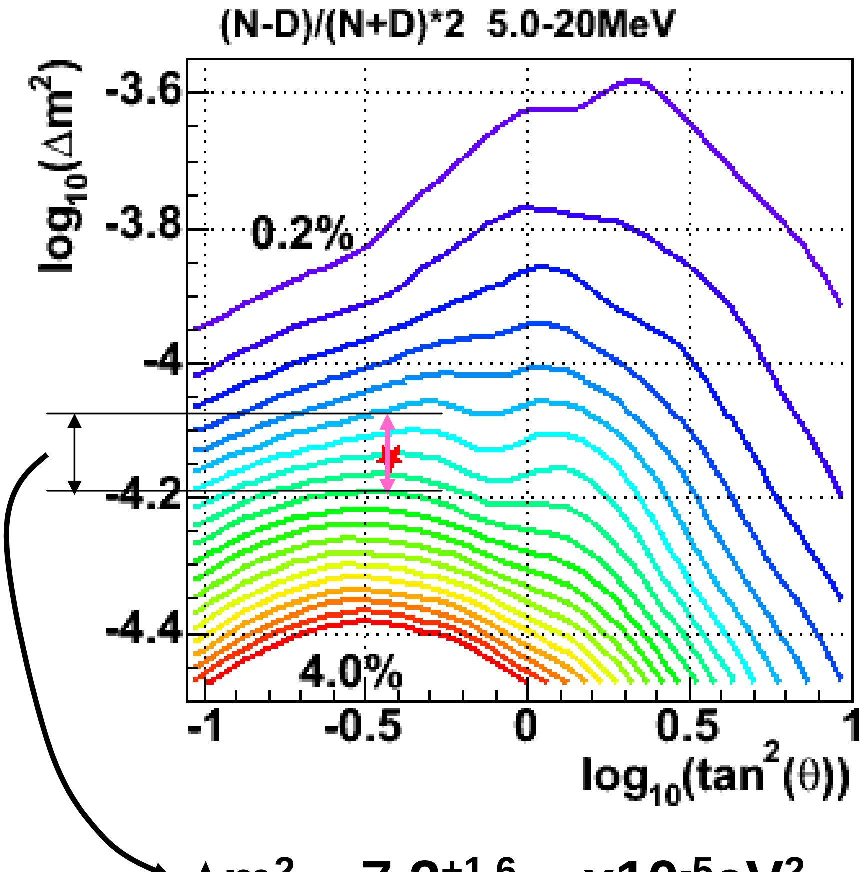


SNO-Resolution



- Further, energy resolution smearing
  - Not only for ES but CC
  - Fine structure around the core washed out
  - Fine structure near the surface partially remains due to a phase matching in a certain energy range
    - Effect → 1-2% for ES and 2-3% for CC
    - But need $\Delta\cos\theta$=0.01 binning to see the effect
    - For example, need 10 – 20 Mtyr (ES) to see this fine structure

Large WC



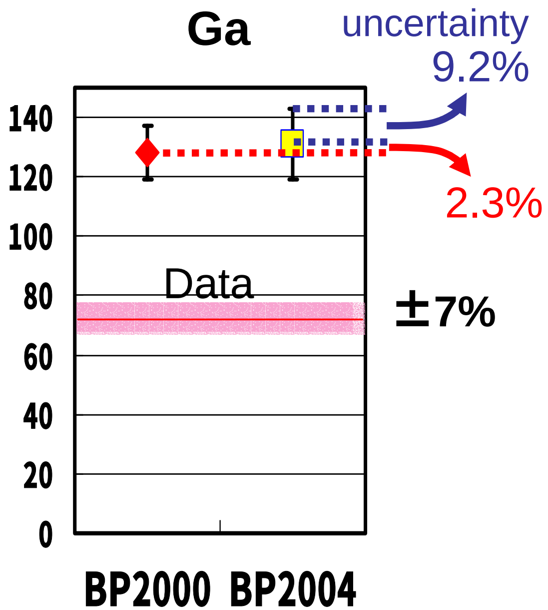
$\Delta m^2 \sim 7.2^{+1.6}_{-0.6} x10^{-5} eV^2$

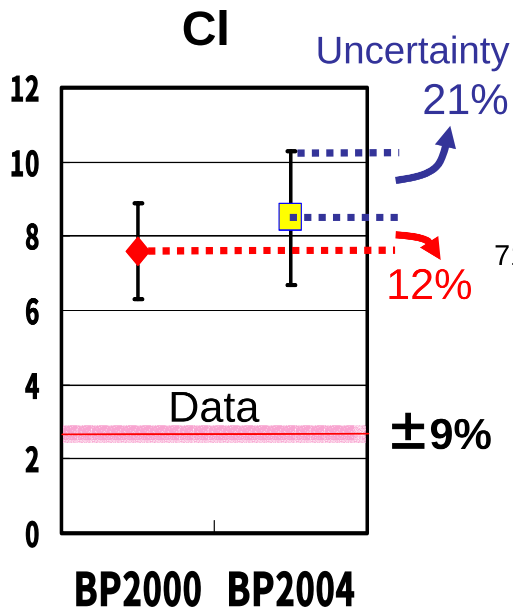
- **Simple D/N ratio is most effective, even for large WC**
- **Ultimate sensitivity**
  ← systematics
- **Large WC ES:**
  suppose ~0.4% (sys)
  → 4~5σ effect
- **Super-SNO(?) can do much better**

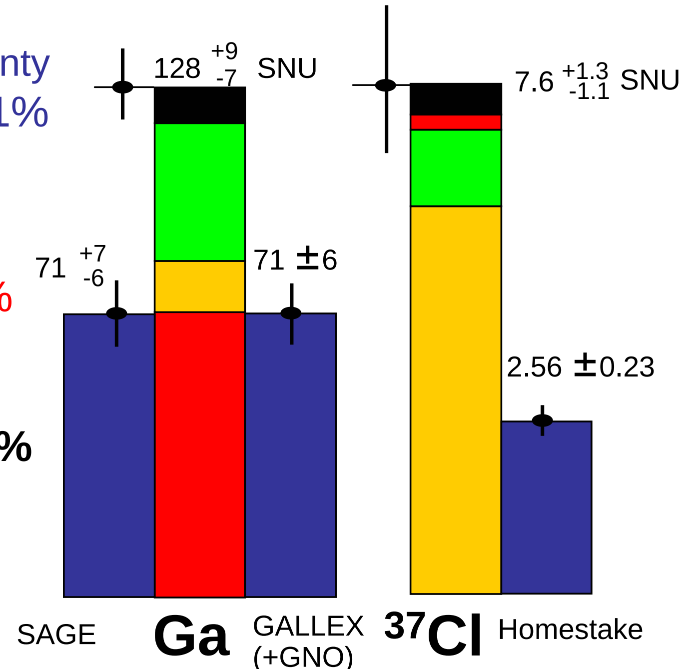
Sub-MeV solar neutrinos

(Vac-Matter transition)

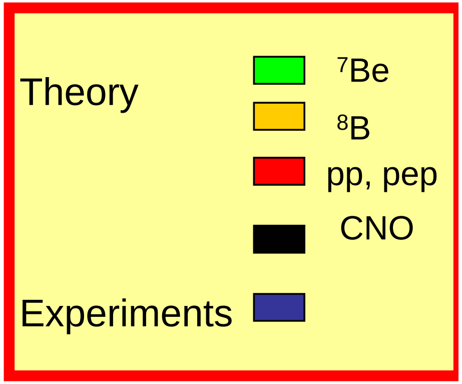
So far measurements are only for the integrated flux







$\Delta\phi$(pp-ν) → 1% uncertainty and robust
pp-ν → a precise (2~3 % level) study
^{7}Be-ν ($\Delta\phi$(^{7}Be)=12%)
→ need both ES and CC

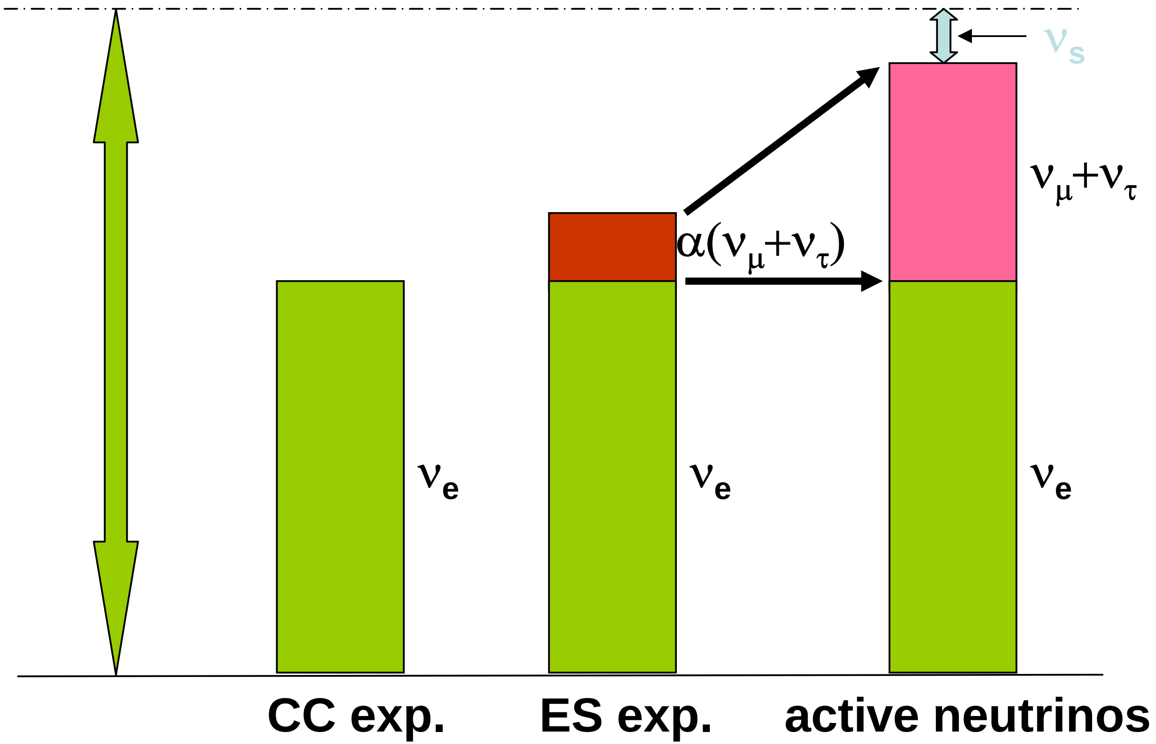


Direct search for sterile neutrinos

Charged Current(CC) ➔ ν_e flux measurement

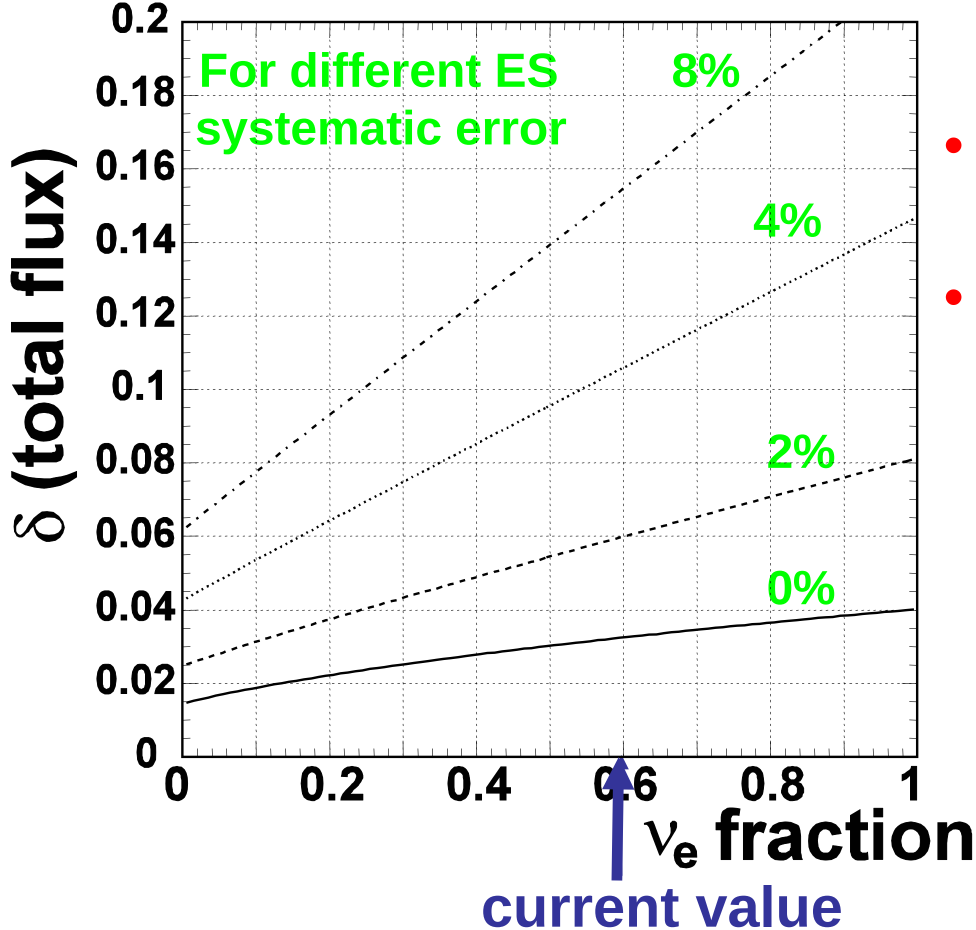
νe scattering(ES) ➔ $\nu_e + \alpha(\nu_\mu + \nu_\tau)$ flux measurement

ϕ(pp ν) ($\delta\phi$ = ±1%) is the best for the search.



Note: Precise NC experiment in Low energy is also valuable

Sensitivity to the sterile neutrinos (5yrs of data: ES & CC)



Example (pp-ν)

- **ES: 10 ton Xe (XMASS?)**
  - 3300 events/year
- **CC: 60 ton In (LENS?)**
  - 1477 events/year

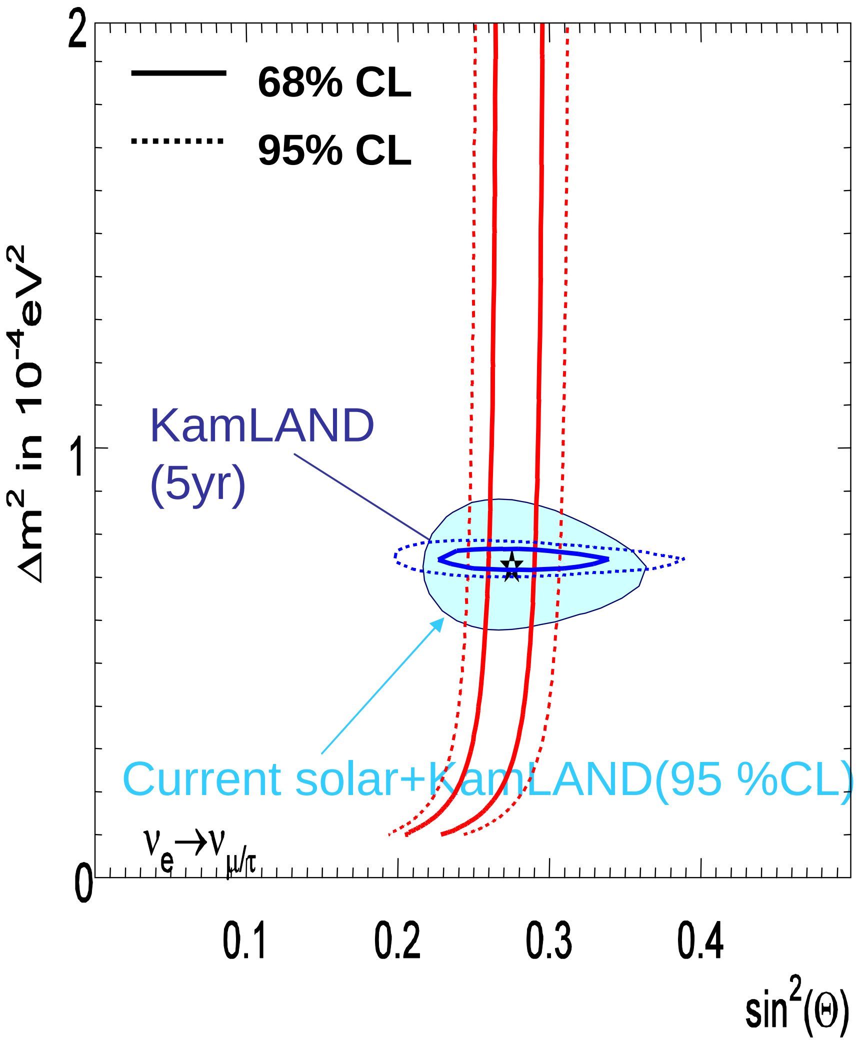
Depending on the experimental errors

< 5~6 % sensitivity for the sterile contribution

Current limit on sterile contribution: < 13% (1σ)

(Bahcall and Pena-Garay, JHEP 0311:004,2003)

Precise determination of θ_{12}



KamLAND contour from K.Inoue

- **pp neutrino flux measurement by :**
  - **10 ton (Xe) detector**
  - **νe scattering experiment**
  - **5 years data**
  - **Statistical error**

    + SSM flux error

Accuracy of mixing angle :

$\sin^2\theta = 0.28 \pm 0.015$ (stat.+SSM)

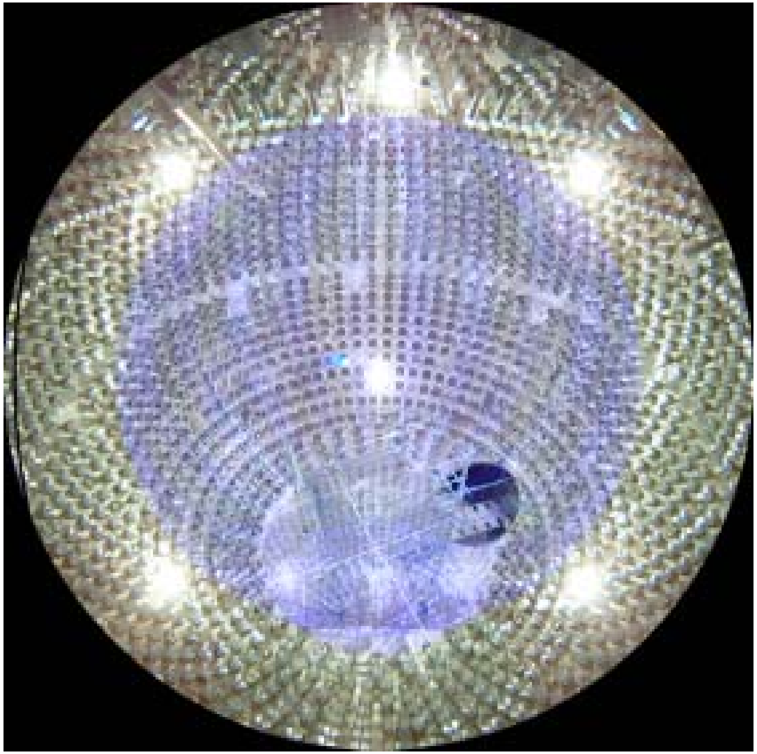
Precise determination of oscillation parameters by KamLAND + pp experiments

Proposed experiments

- ^{7}Be-experiments
  - [ES] Borexino(LS), KamLAND(LS)
  - [CC] LENS-Sol($\nu_e{}^{115}In \rightarrow e^{-115}Sn$, e, γ : **InL-LS**) **(also pep, CNO)**
  - [CC] Lithium($\nu_e{}^{7}Li \rightarrow e^{-}\ {}^{7}Be$: **Radio-Chemical**)**(also pep, CNO)**
- pp-(^{7}Be)-experiments
  - [ES] XMASS(Xe), HERON(He), CLEAN(Ne)
  - [CC] MOON($\nu_e{}^{100}Mo \rightarrow e^{-100}Tc$, β**: Mo-foil+Pl.Sci**)
- pep & CNO
  - [ES] SNO-scintillator

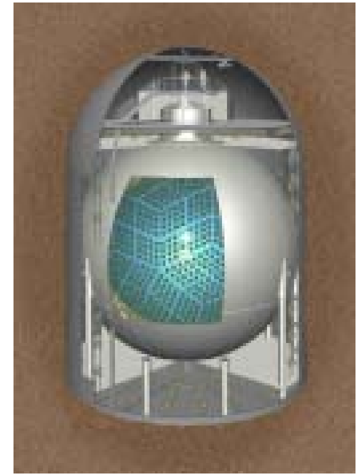
Borexino

The front runner of this race



Previous Speaker

^{7}Be neutrino observation in KamLAND



- Another effort to observe ^{7}Be neutrinos.
- 70 events / day @ 250 keV threshold
- Backgrounds are the key issue
- Most problem:

^{85}Kr: 0.7Bq/m^3

→ 1μBq/m^3

^{210}Pb (^{210}Bi: β):5x10^{-20}g/g

→ 5x10^{-25}g/g

~1μBq/m^3

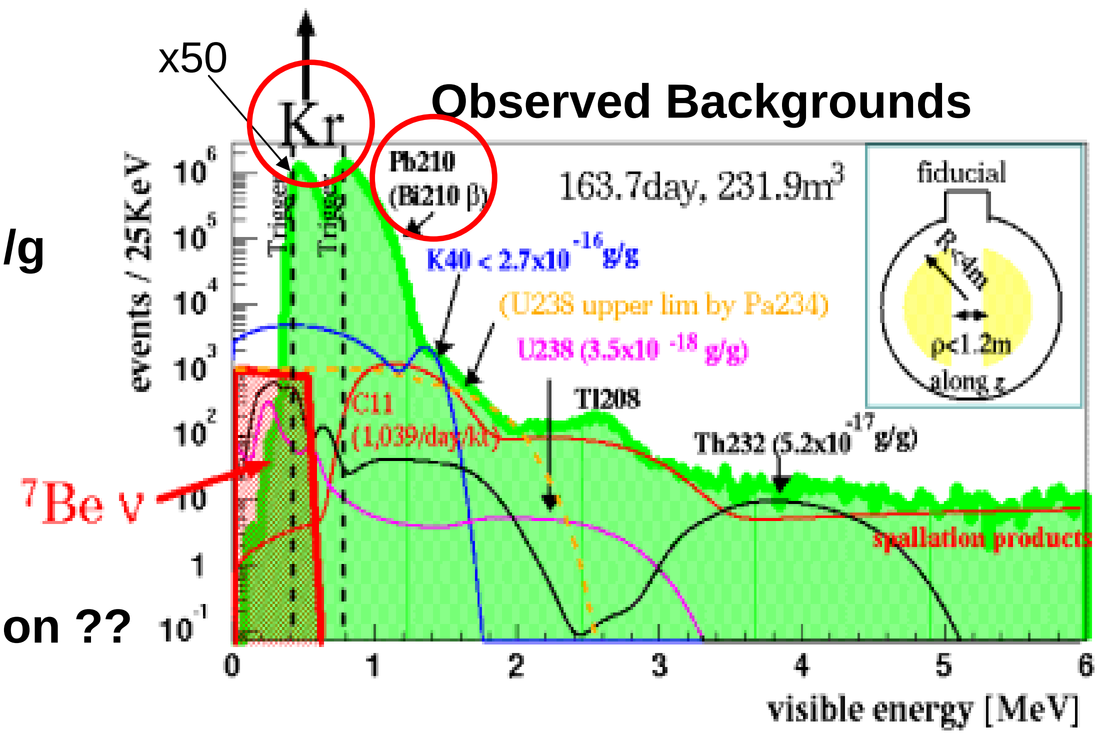
^{40}K: 2.7x10^{-16}g/g (max)

→ < 10^{-18}g/g

^{238}U, ^{232}Th, ^{222}Rn: OK

^{222}Rn: during purification ??

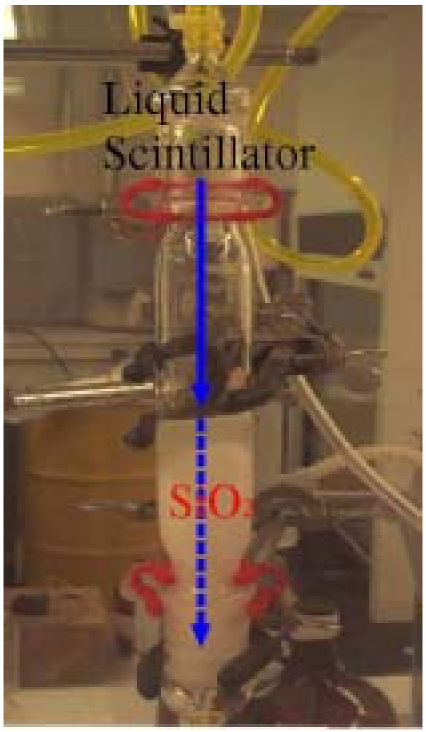
→ 1μBq/m^3



Background removal

1) Removal of Kr can be done with nitrogen purge.
   Optimization of the bubbling tower is going on.
2) Pb removal is tested with adsorption and distillation.

Adsorption with Silica gel



- ^{212}Pb-rich LS
- condition
  - –10g of SiO_2
  - –32-63μm SiO_2
- Results

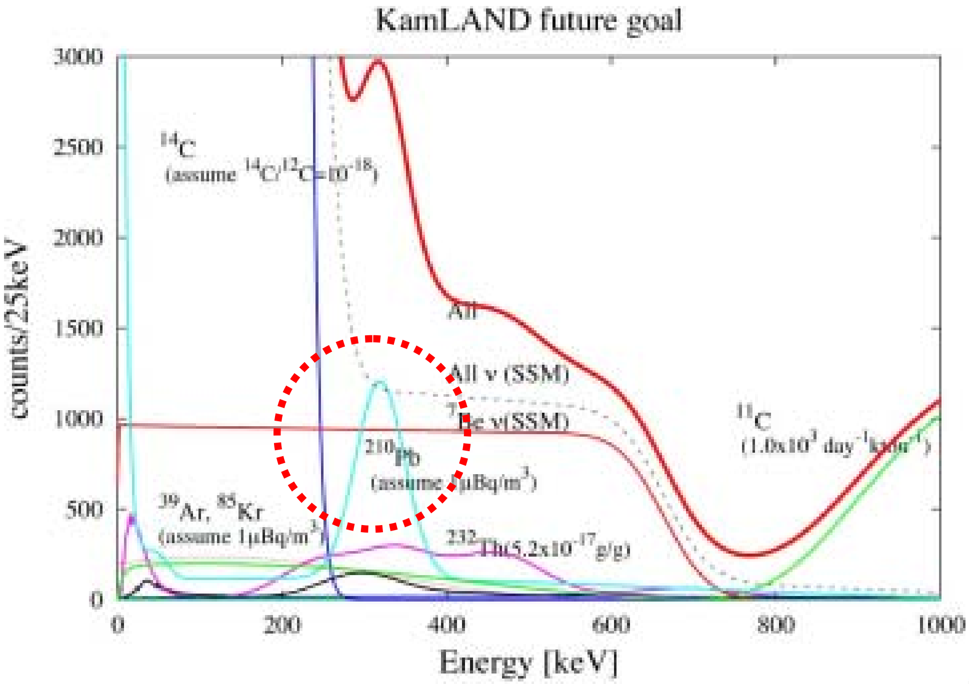
95%

Distillation

- ^{212}Pb-rich dodecane
- condition
  - –T=130C
  - –P=50-55hPa
  - –t=5min for 50g
- Results

99.5%(1 path)

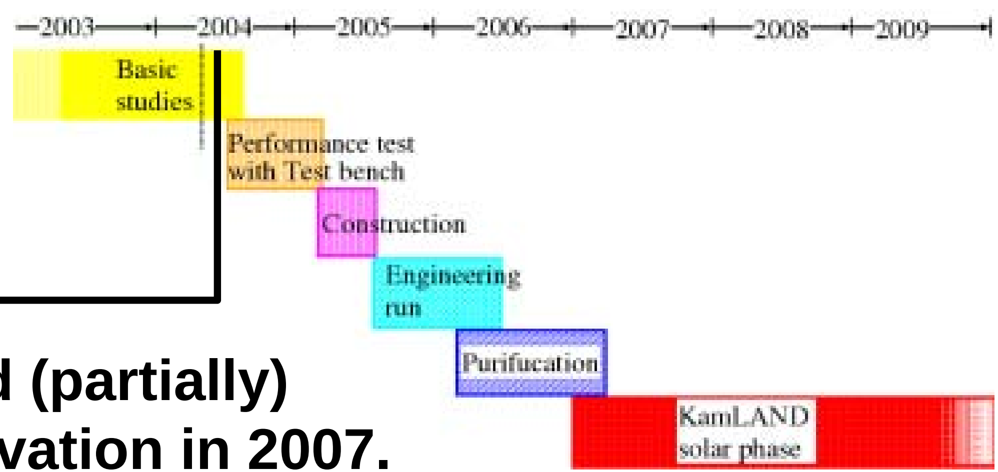
> 99.95% (5 pathes)



- If the required impurity level is achieved:

➔

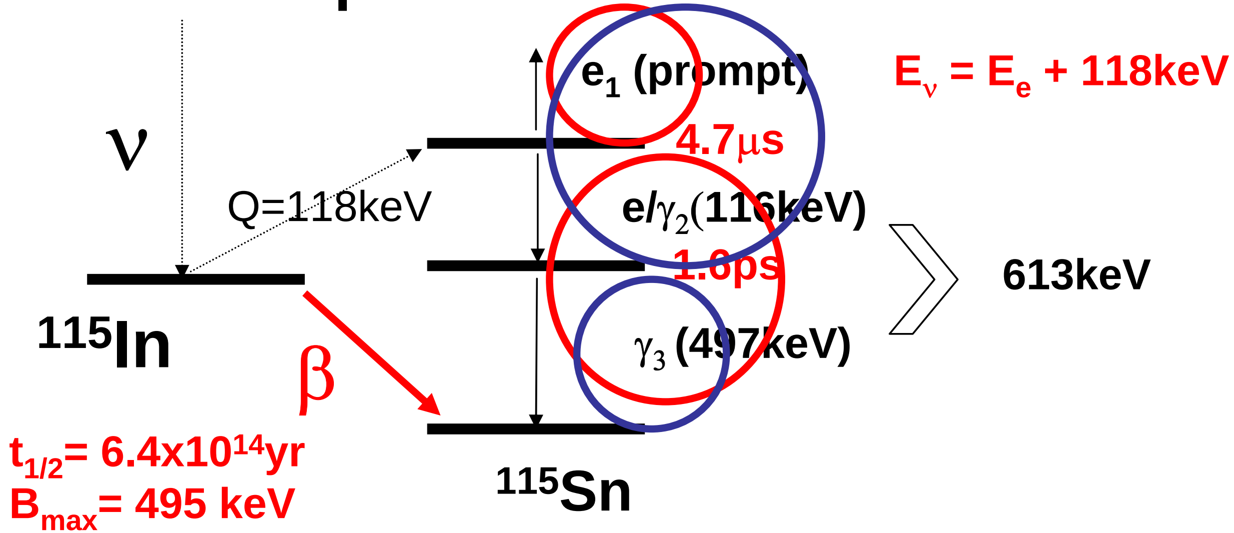
- The remaining BG may be $^{210}Pb(\alpha)$, which determines the level of threshold.
- ^{7}Be flux will be measured at a few %



Good NEWS !

KamLAND(^{7}Be) is funded (partially)
They hope to start observation in 2007.

Indium experiment for ^{7}Be



BUT

→ segmentation of the detector

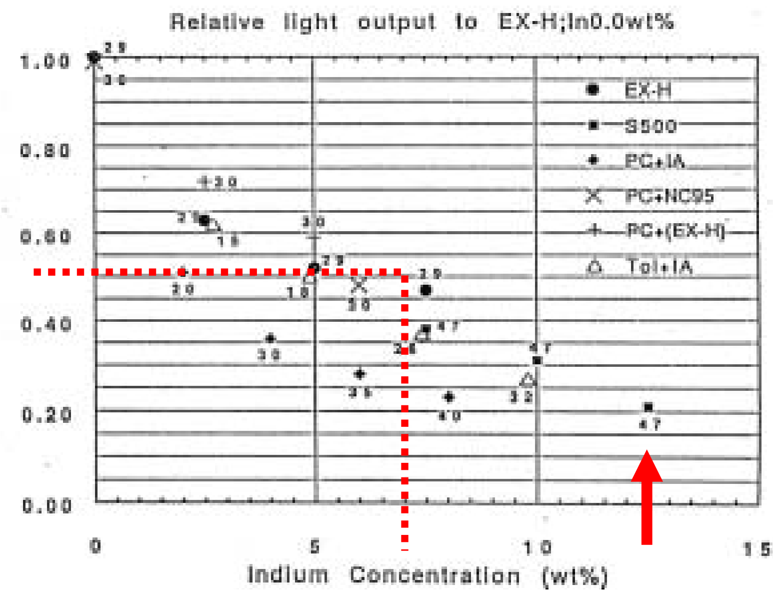
From the past study, there is consensus that ^{7}Be-(pep-) neutrino detection may be feasible, but pp-neutrino detection is very difficult.

Development of the liquid scintillator with good energy resolution is a key for the ^{7}Be measurement

- $\nu + ^{115}In \rightarrow e + e/\gamma + \gamma + ^{115}Sn$
- **Energy measuremet**
- **Two fold timing coincidence**
- **Two fold spatial coincidence**
- **(pp), pep, ^{7}Be and CNO**

Indium loaded liquid scintillator

- Incidentally, we had an Indium meeting at Coll. de France in 1989, 15 years ago.
  - **Participants**：de Bellefon, Booth, Barloutaud, Borg, Cavaignac, Ernwein, von Feilitzsch, Inagaki, Kim, Mann, Mosca, Raghavan, Salmon, Y.Suzuki, Thevenin
- We had presented a new result on the indium loaded liquid scintillator. (Y.Suzuki et al, NIMA239,615(90))



- upto 12% indium concentration
- 50% light output of a standard scintillator (@7% content)
- Long attenuation length: longer than1.5m @7%
- We have demonstrated that we can measure ^{7}Be-ν.

THE INSTITUTE FOR ADVANCED STUDY

PRINCETON, NEW JERSEY 08540

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SCHOOL OF NATURAL SCIENCES   JOHN N. BAHCALL

8 August 1989

Dr. Yoichiro Suzuki
Institute For Cosmic Ray Research
University of Tokyo
Midori-Cho, Tanashi-Shi
Tokyo, 188, Japan

Dear Dr. Suzuki:

Congratulations on making an indium-loaded scintillator with more than 1.5 m attenuation length! I hope very much this leads to a practical 7_{Be} experiment.

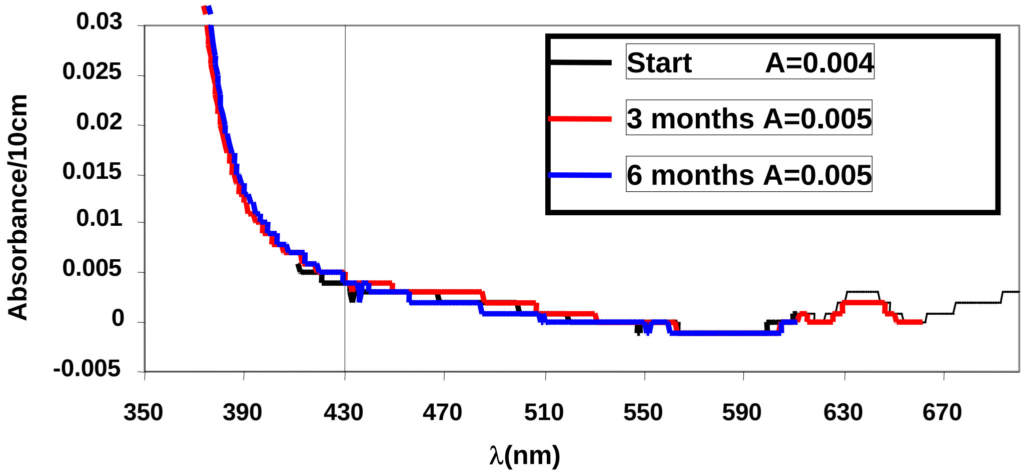
I have also forwarded a copy of your letter to M. Spiro.

Sincerely yours,

John N. Bahcall
Professor of Astrophysics

JNB:ar
cc: M. Spiro

New development at Bell Labs-BNL



Stability: The UV-VIS absorbance (430 nm) with time over six months (BNL#115, In%=6.77)

- **High Indium content (~7 wt%) with new solvent, Phenylcyclohexane**
- **Good light yield (~40% of PC based)**
- **Long attenuation length of ~9 m**
- **Chemically and optically stable for over 6 months**

LENS-Experimental Plan

R.S.Raghavan
@NOON2004

LENS-Sol

Liquid scintillator based

CC Solar Nu Experiment at Kimballton (VA USA)

(60ton In; 750 ton InLS; 3000 ton In-free LS)

CC parameter Known only from (p,n) reactions.

Direct measurement integral part of precision experiment.

LENS-Cal

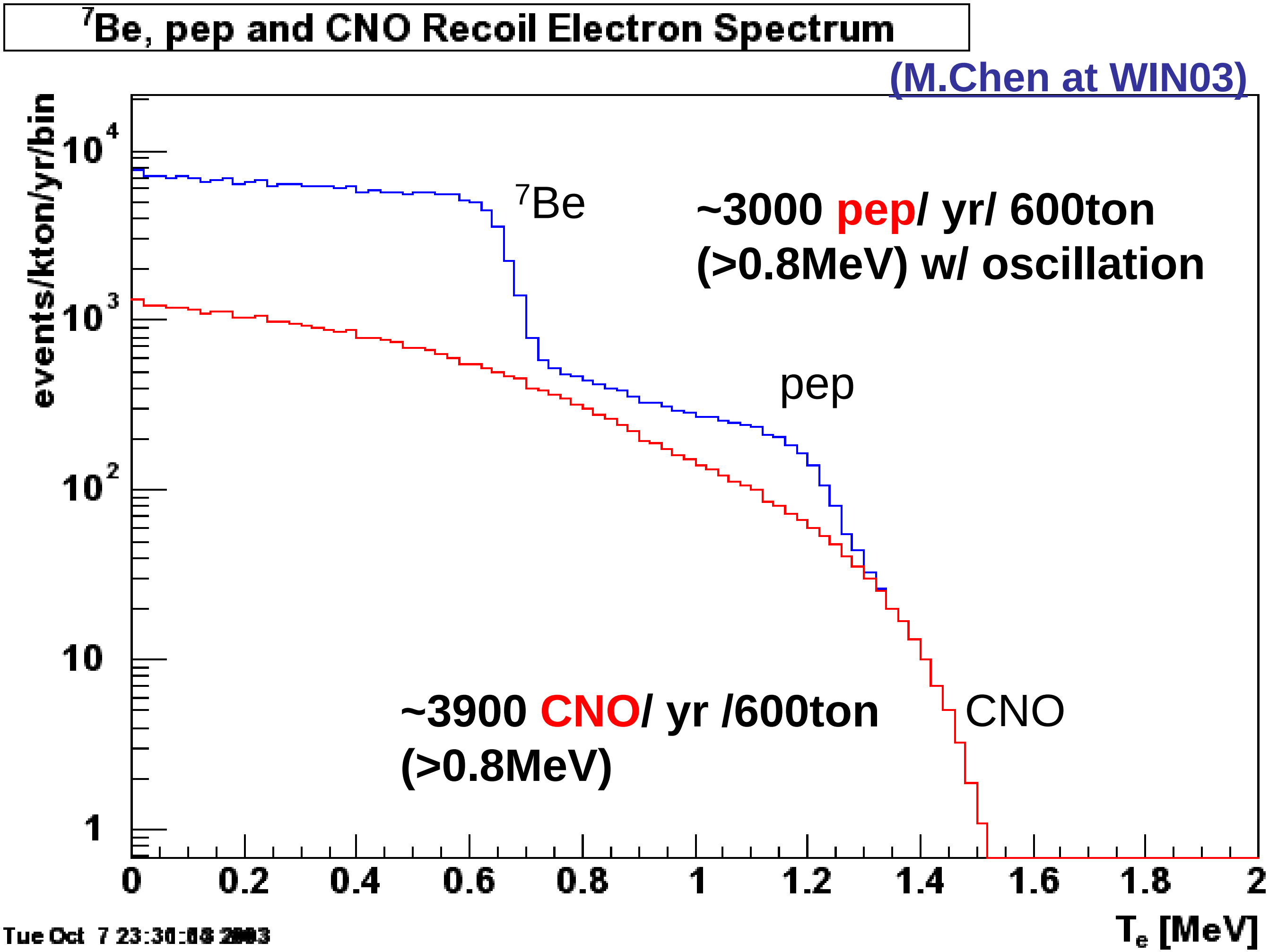
Precision (<3%?) Calibration of In CC (GT) parameter

By MCi υ Source (^{37}Ar ?) -- in BAKSAN, Russia

In metal foil/Plastic or LS Scint. Sandwich Detector

(5 ton In; 15 ton Scint)

SNO with liquid scinitillator for *pep and CNO*



Cosmogenic Background (^{11}C) is important

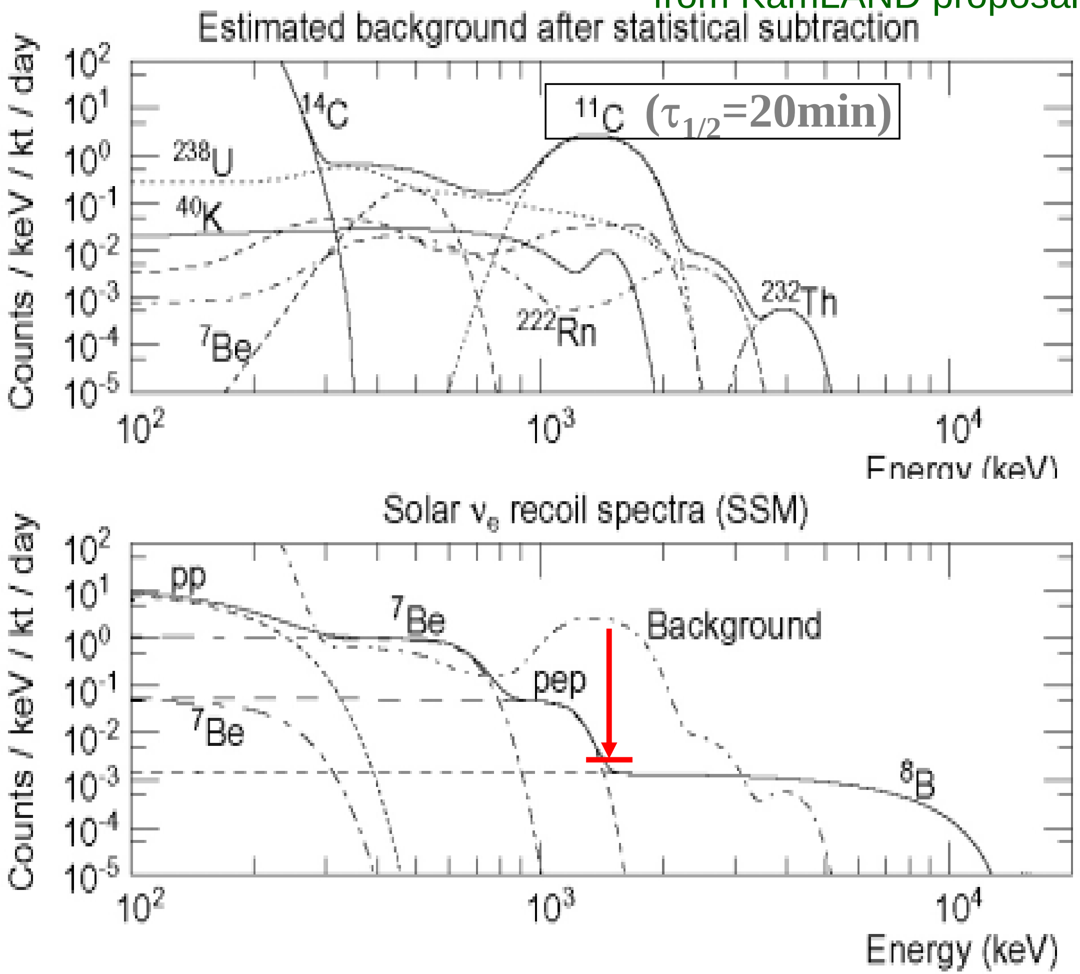
Depth is a crucial key!

Muon rate:
~26000/day @KL

1/ 400

~ 70/day @SNO

from KamLAND proposal

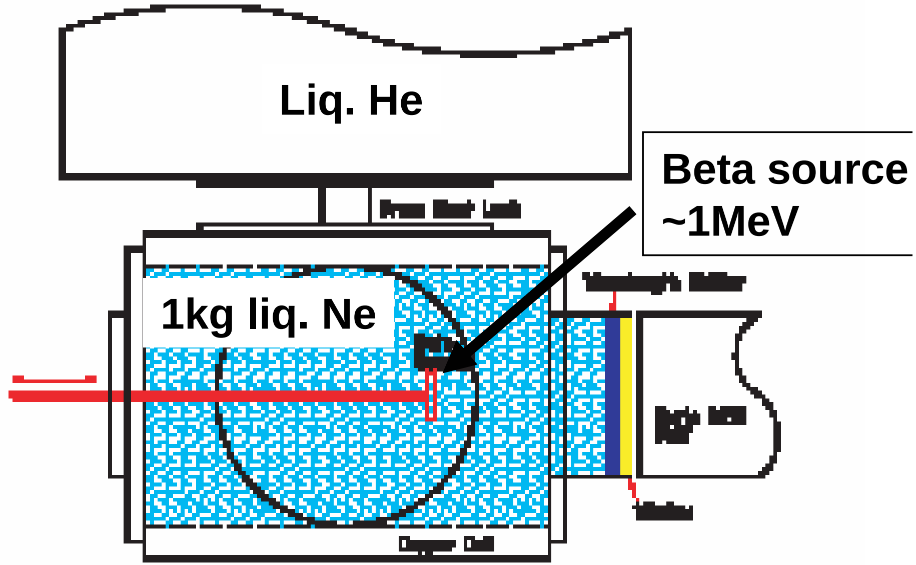


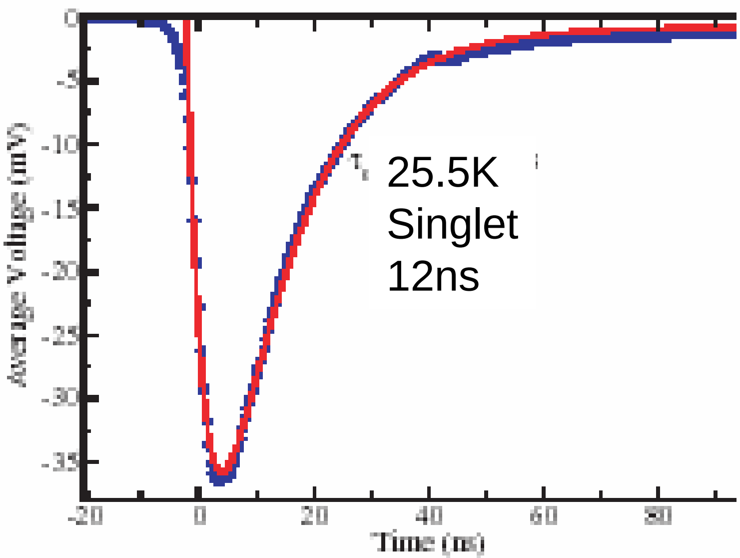
CLEAN

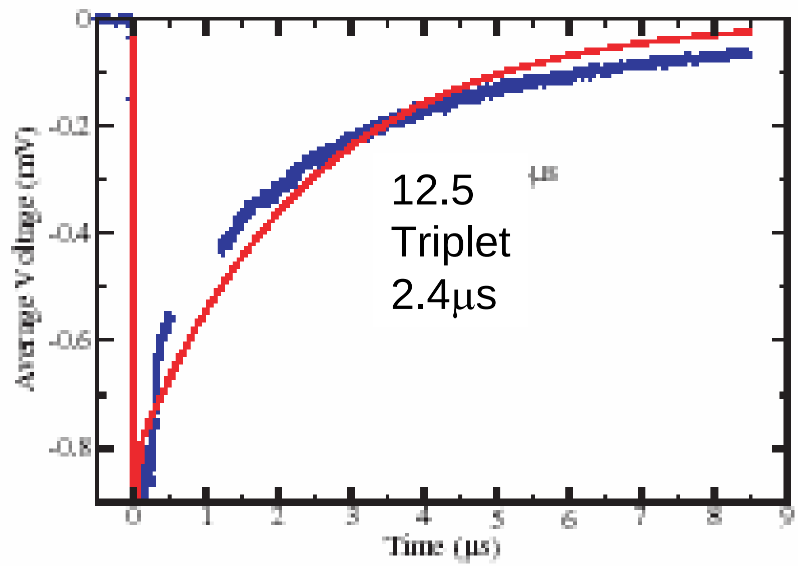
Measurement In Feb. 2004

Liquid Neon Scintillations

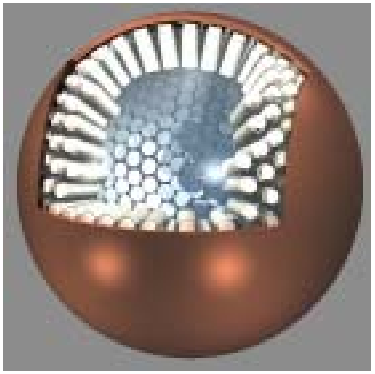
Plan in this summer:
Test PMT in liq. Ne
Purifying Ne
Neutron and alpha response







XMASS



- Liquid Xenon Scintillation detector
  ~160^{o}K; (LNe~27^{o}K; LHe~40^{o}K)
- 10 ton fiducial mass
  for solar ν detection
  Event rate: ~10 pp + ~5 ^{7}Be/day
  (>50keV, w/ oscill.)

Multi-purpose detector

- **Xenon MASSive Detector for Solar Neutrinos (pp/^{7}Be)**
- **Xenon Detector for Weakly Interacting MASSive Particles (Dark Matter Search)**
- **Xenon Neutrino MASS Detector (Double Beta Decay)**

Characteristics of the detector

- High photon yield
  - 42,000 photons /MeV (@173nm)
  - QE~30%; Coll. Eff.~70% for 80% PMT coverage

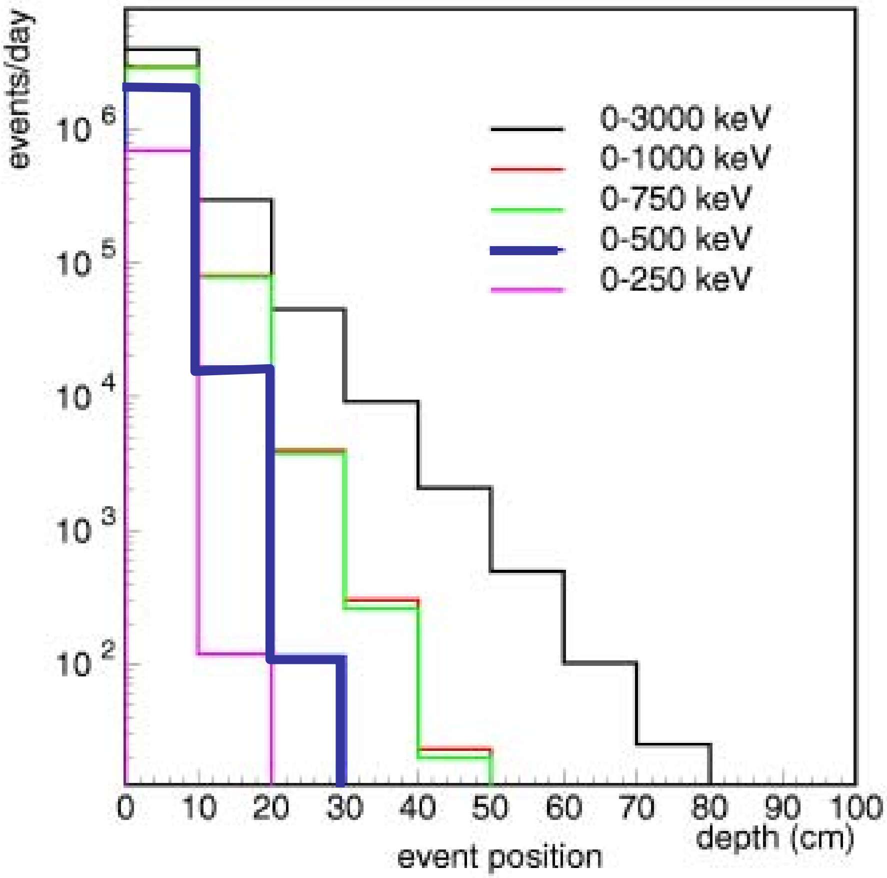
    → 360 p.e. @50keV

    → Low threshold(10~20 keV); Good resolution
- Density ~$3g/cm^3$、Z=56、radiation length～2.4cm

    → Self-shields (against **EXTERNAL incoming BG**)
  - compact (r=1.22m for 23 tons (10ton w/ 30cm self-shields))
- Various purification methods
  - Distillation, circulation during the experiment, bubbling, centrifugal, columnm

    → can reduce **INTERNAL BG**
- No long life isotopes (Longest: ^{127}Xe(36.4days))
- Easy for isotope separation
- Reasonable Price ($1M~1ton: natural)

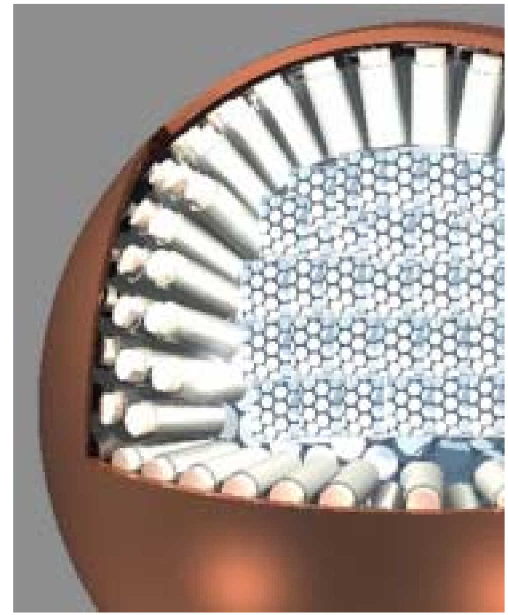
Self-shield



- Quite effective for the events below ~500 keV
  (Solar neutrino and Dark Matter)
- Not effective for double beta decay experiment

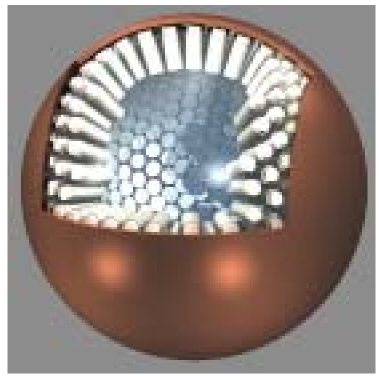
Strategy for XMASS

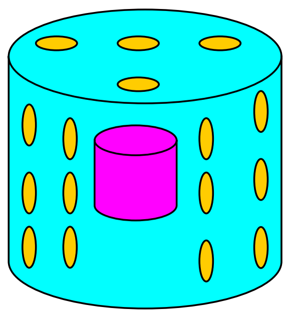
～10ton detector
Solar neutrinos
Dark matter search



Prototype detector
R&D

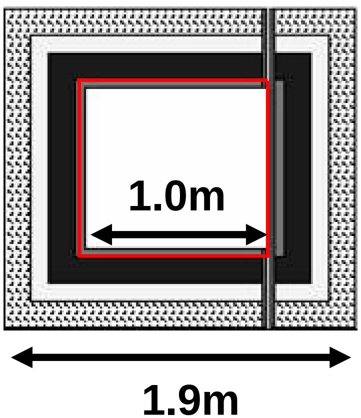
～1ton (800kg) detector
Dark matter search





dedicated detector for
Double beta decay search

R&D by the prototype detector



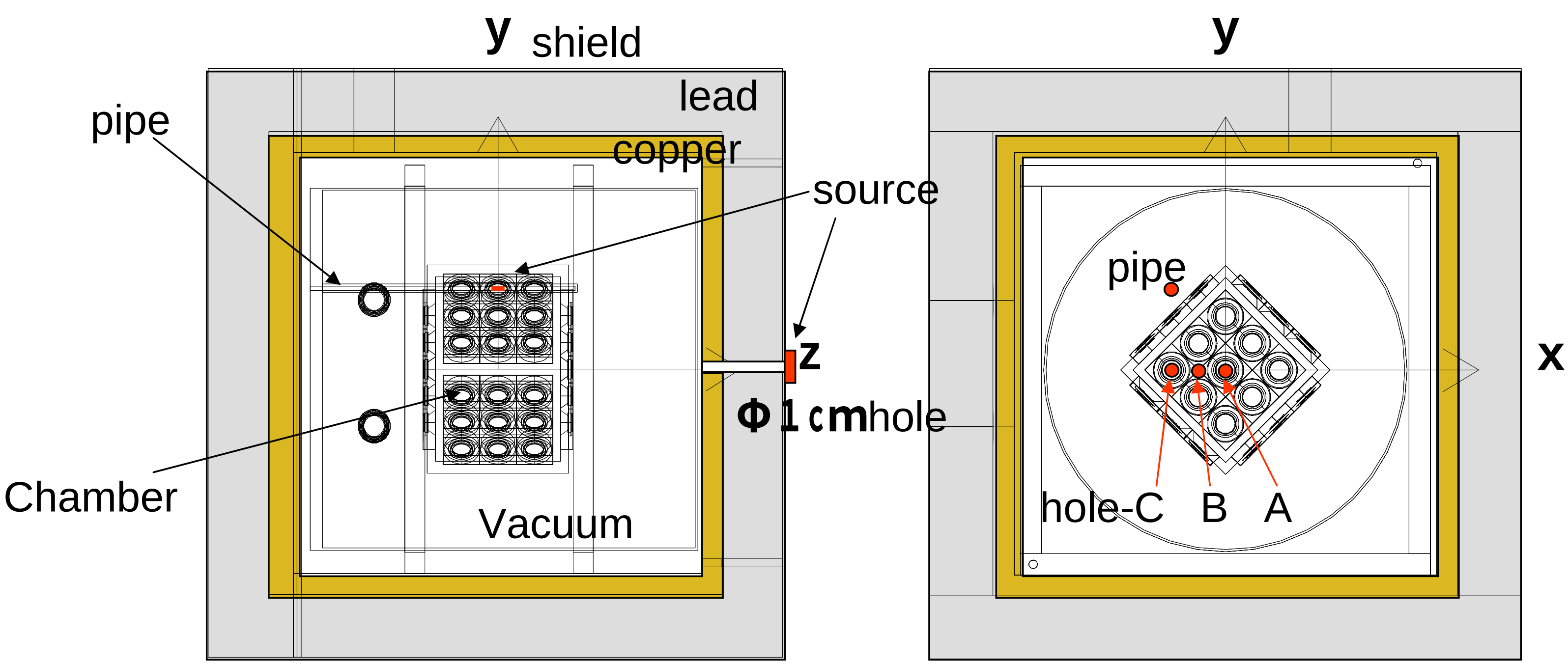
- Polyethylen(15cm)
- Boracic acid(5cm)
- lead(15cm)
- EVOH sheets(30μm)
- OFC(5cm)

Rn free air (~ $3 mBq/m^3$)

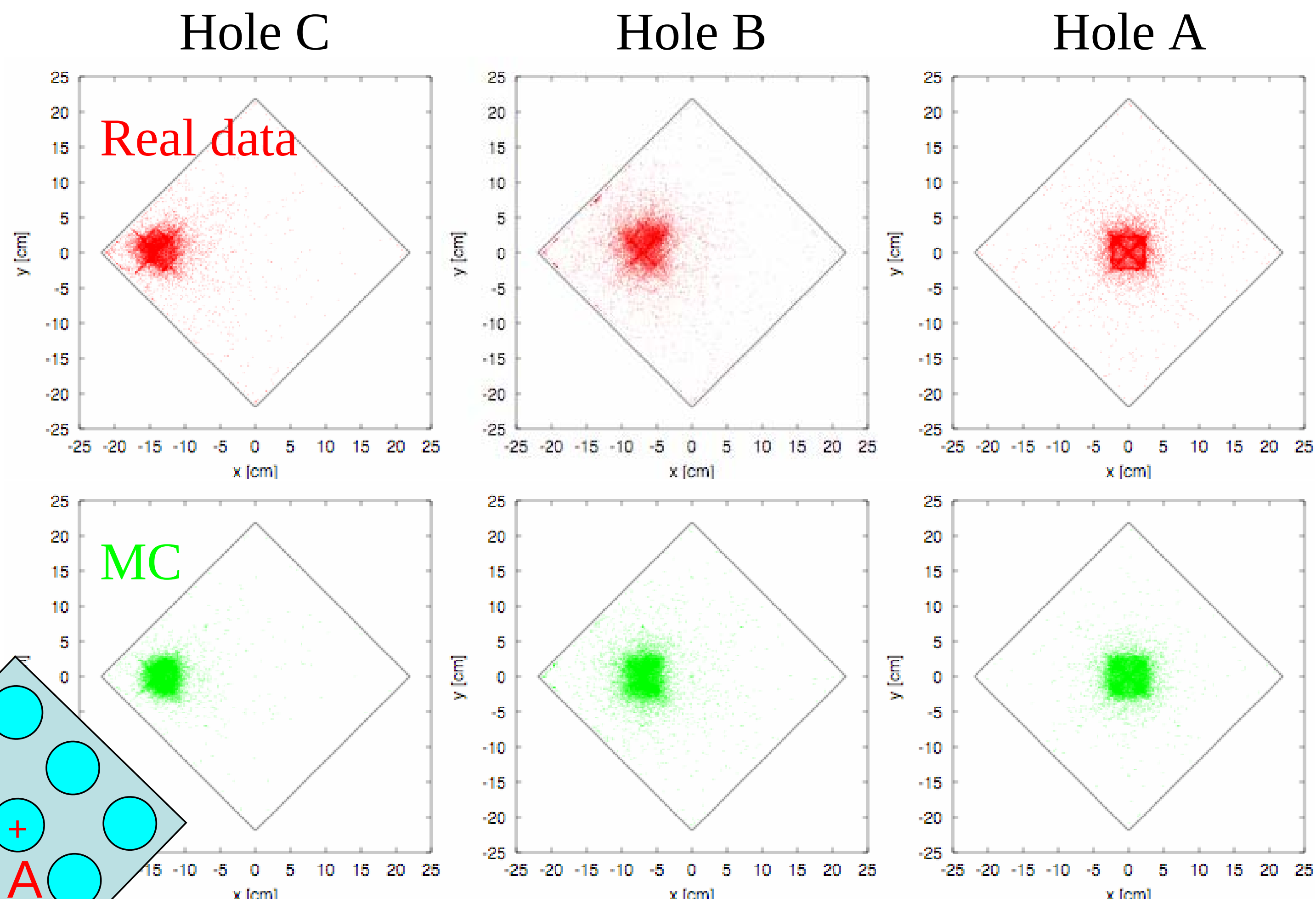
- **Test experiment (Prototype chamber)：**

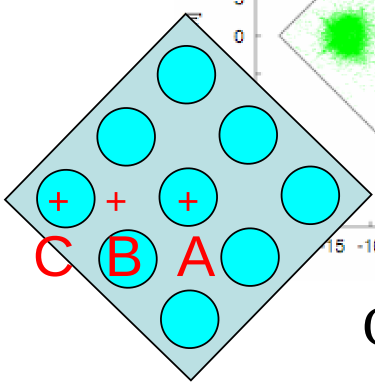
December-2003

- **Data acquisition ～6 days（173°K、1．5atm）**
  - **Normal run for BG measurements**
  - **γ-source run**

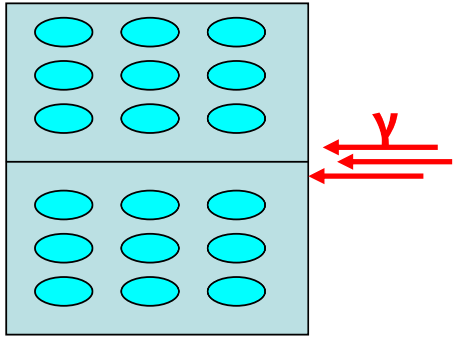


^{137}Cs photo-peak





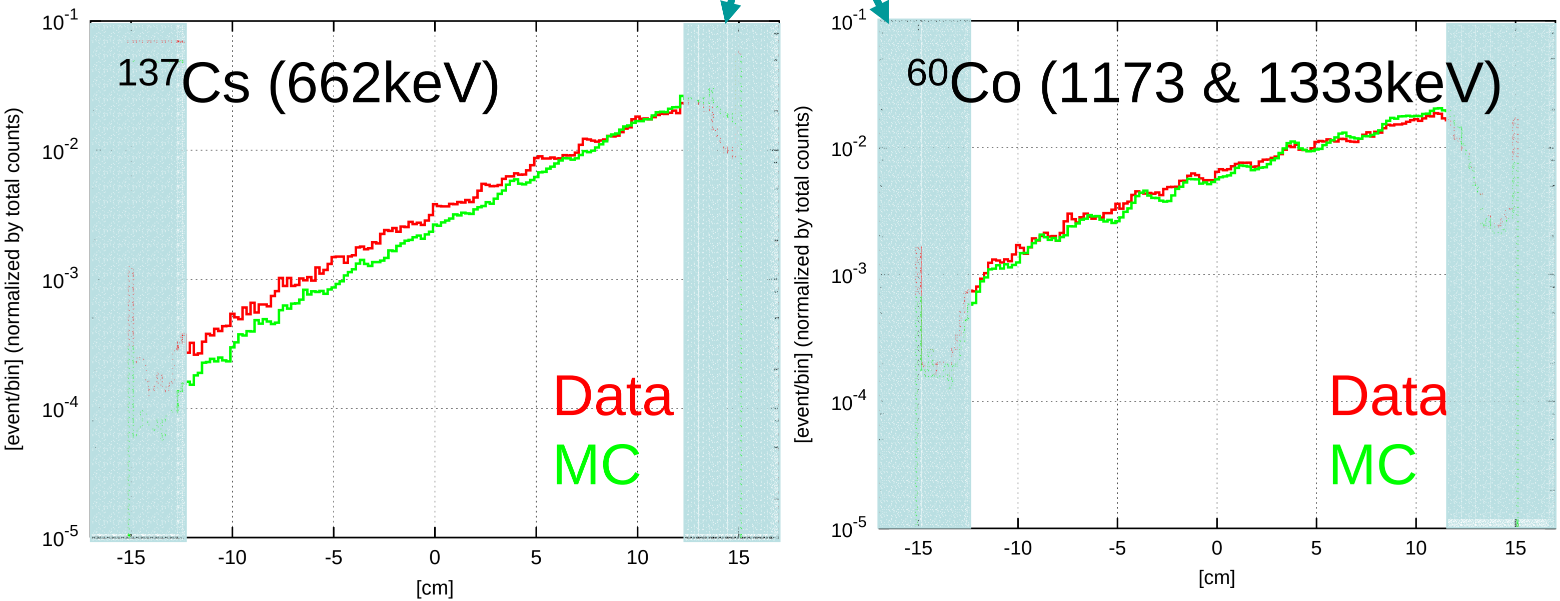
Collimated gamma rays for three different positions



Z= -15 Z= +15

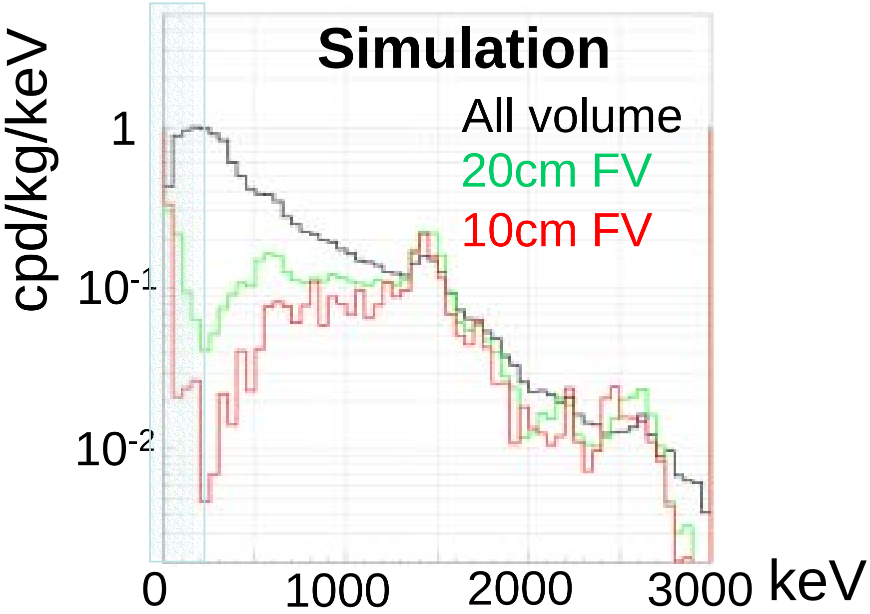
- Proof of the self-shield

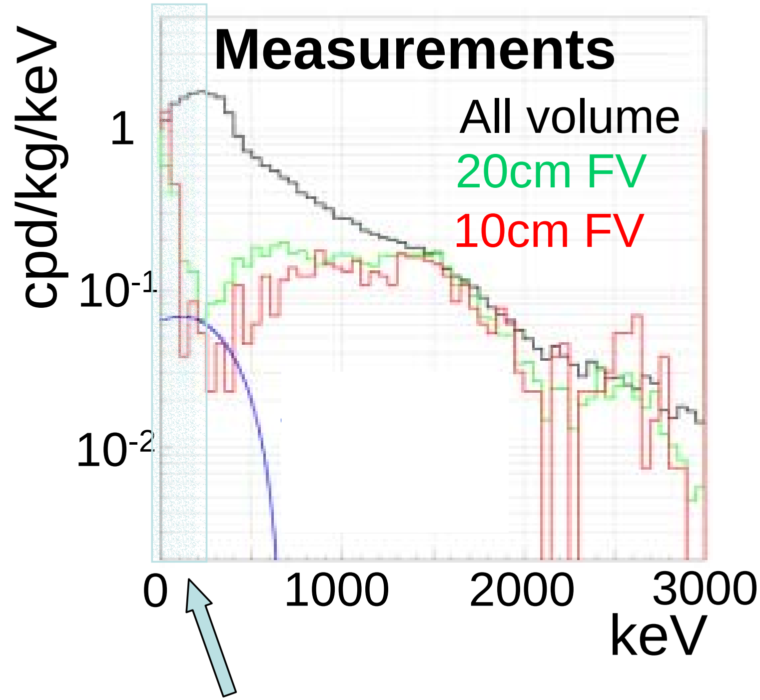
Remove events w/ Saturation

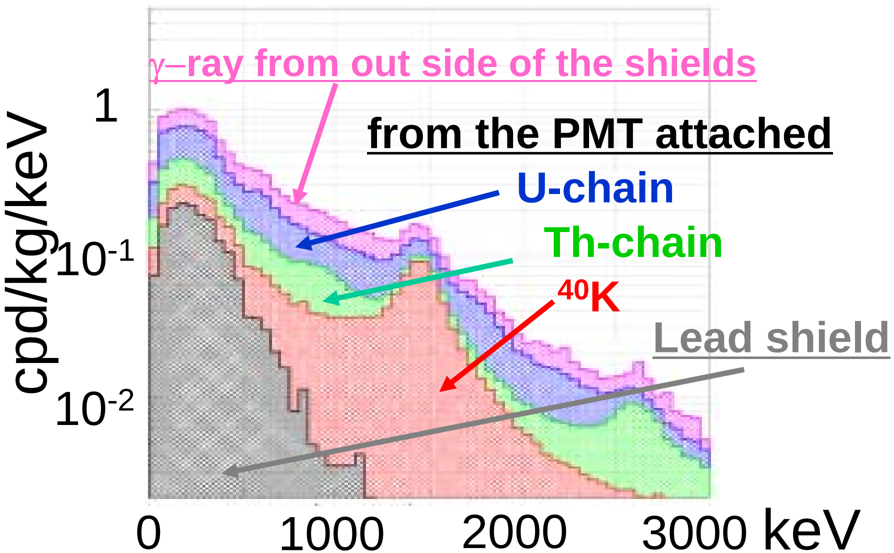


MC reproduces data very well.
We have demonstrated that the self-shield actually works.

Backgrounds measurement







- Please ignore excess
- self-shield works
- excess ~200~400keV
  ← Kr ~3ppb
  $^{85}Kr/Kr \sim 1.2 \times 10^{-11}$

β-γ (0.4%) → 2.2 ppb

Development of the low BG PMT

Q.E. ~ 30% @ 175nm; Collection eff. ~ 90%
Quartz window & Metal tube (Low BG)
Selection of the parts（measured by HPGe）
→ Low BG PMT base ~1/10 of the usual ones

U	$1.5 \pm 0.3 \times 10^{-3}$ Bq
Th	$3.2 \pm 4.6 \times 10^{-4}$ Bq
^{40}K	$1.7 \pm 2.9 \times 10^{-3}$ Bq

Aiming for another order of magnitudes improvement

Hexagonal PMT
to accomplish 70-80% PMT coverage

Summary of the measured internal BG

- Results

Goal for 800kg

(Bi-Po for U/Th)

– ^{238}U: = (48±8)x10^{-14} g/g → 1x10^{-14} g/g

– ^{232}Th: < 63x10^{-14} g/g → 2x10^{-14} g/g

Factor 30~50

– Kr: < 2.2ppb (β+γ)
< 2~3ppb (687keV β) → 1 ppt

Factor ~3000

Distillation

Additional purification (filter, etc.)

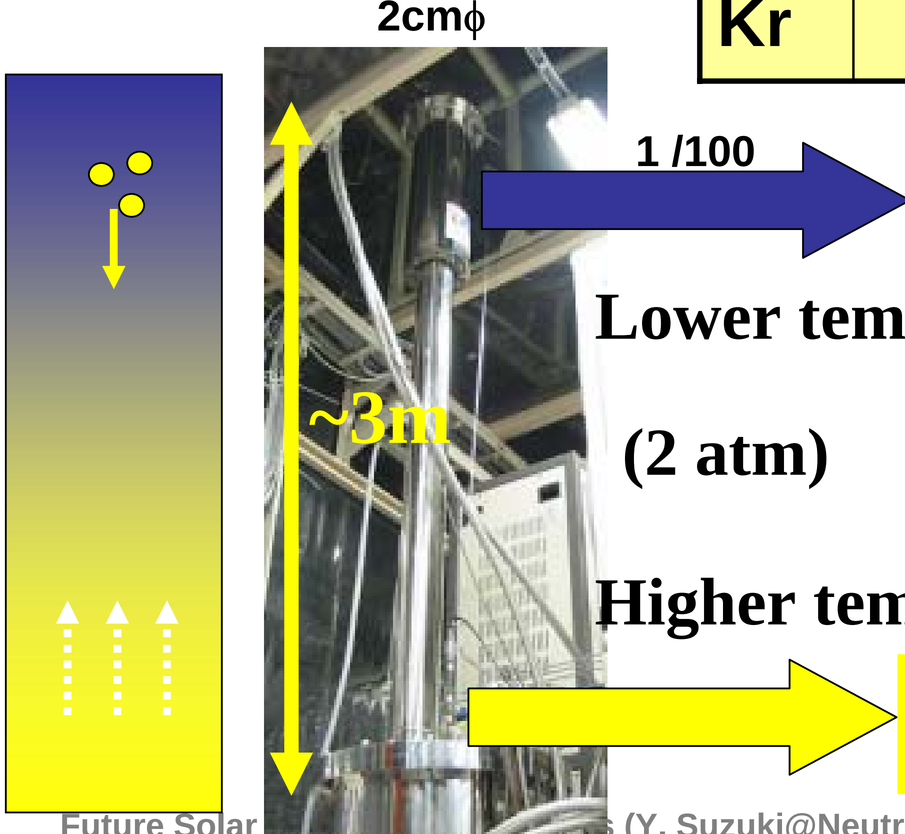
Distillation to remove Kr

Boiling point is different

Processing speed: 0.6kg /hour

	Boiling P. (@1 atm)
Xe	165K
Kr	120K

Raw Xe



Off- gas (Kr rich)

Lower temp.

(2 atm)

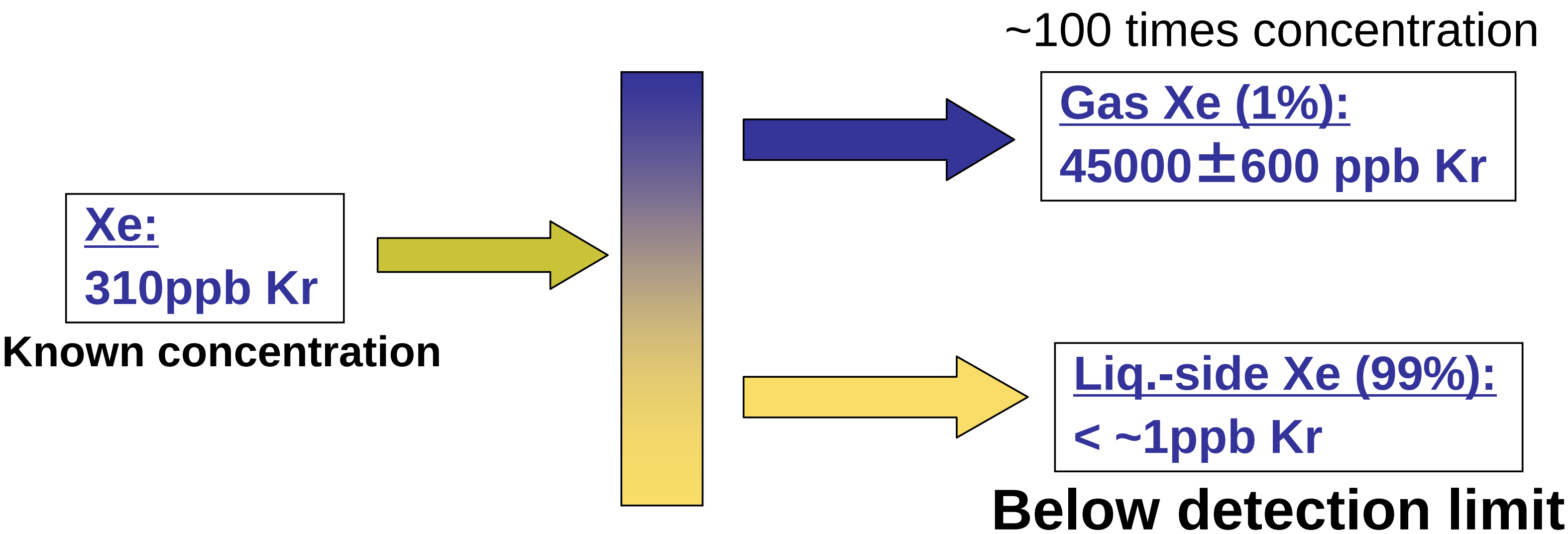
Higher temp.

Purified Xe

13 stage of

Distillation

Test using 1.6kg Xe in Sep. 2003



Performance:
< 1 / 300
(design: 1 / 1000)

Kripton was removed by distillation

Distillation

Processed 100kg Xe in March 2004, used in December `03 run

~100 times concentration

100kg Xe used in the December run

Xe:
? ppb Kr

Gas Xe (1%):
330±100 ppb Kr

~ 3 ppb

Liq.-side Xe (99%):
? ppb Kr

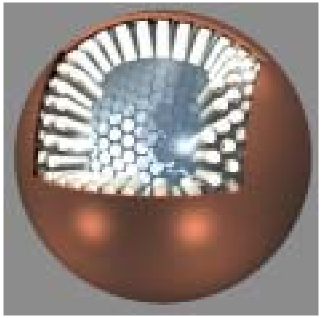
Below detection limit

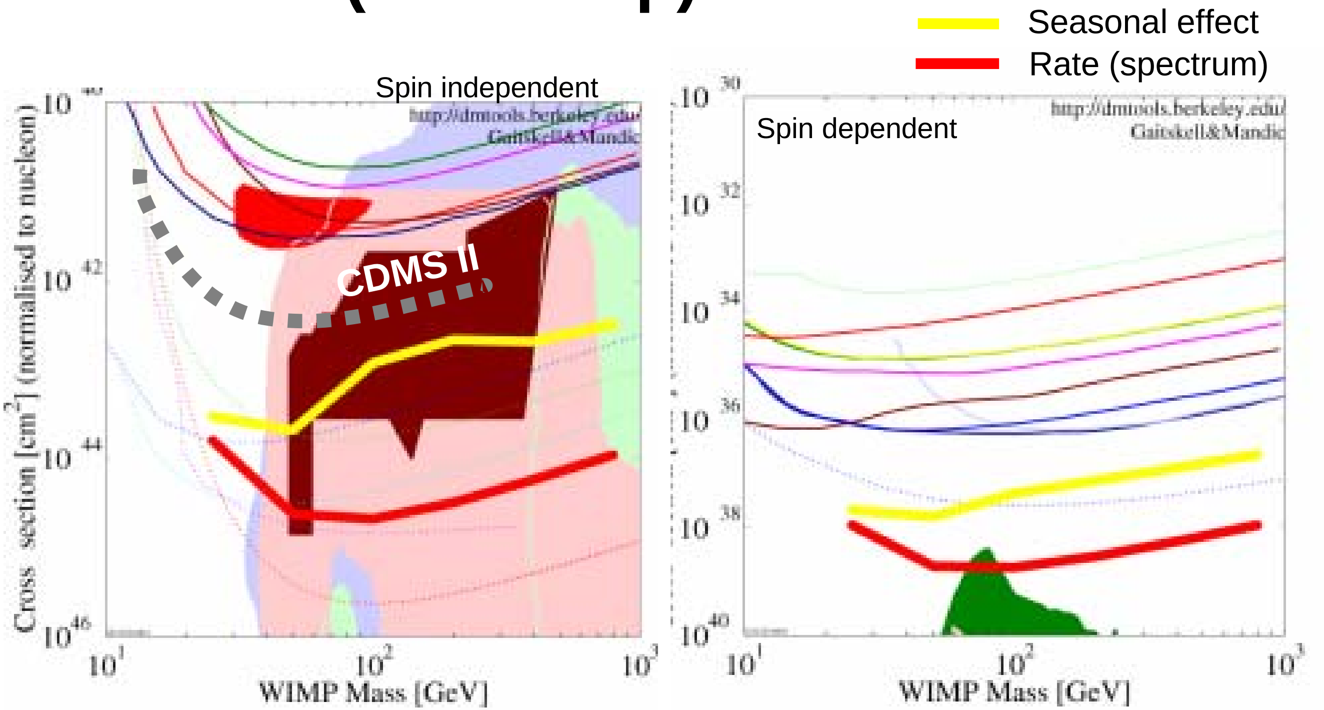
Performance:
< 1 / 300
(design: 1 / 1000)

Agree with the β and β+γ Measuremnt in December run

Hope to get: < 0.01ppb for <1/300 reduction
0.003ppb for 1/1000 (design value)

800kg (100kg w/ 20cm self-shield layer) detector (Next Step)

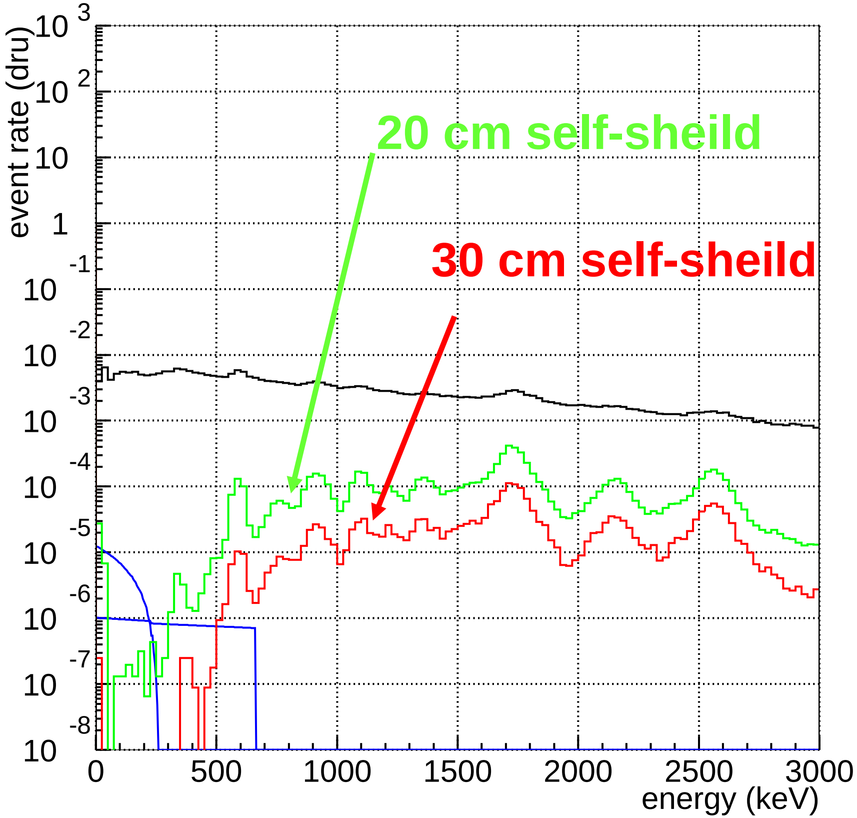




- BG levels required could be achievable
- Mostly for the Dark Matter Search
- Solar neutrinos
  - Mass → 10 ton fiducial
  - Self-Sheild → 30 cm

Towards solar neutrino measurements

- External BG →
- Internal BG
  - ^{85}Kr:
    Kr/Xe< $4x10^{-15}$g/g
    → 1/ 250
  - **U/Th:**
    U.Th/Xe < $1x10^{-16}$g/g
    →1/ 100 ~ 1/ 200
  - **Rn:**
    Rn(in Liq) < 10μBq/m^3
- need isotope separation if $\tau_{1/2}(2\nu\beta\beta) < 8 \times 10^{23}$y



Summary

- Entire spectrum measurements of solar neutrino will be important to test LMA and to determine oscillation parameters, or to find small sub-leading effects.
- ^{7}Be measurement is the immediate goal.

  (Borexino, KamLAND, LENS, …………..)
- pp-neutrino measurements, majority of the solar neutrinos, are important, coupled with the precise flux prediction.

  (Xmass, Heron, Clean, Moon, Li,…….)
- The high precision measurements of spectrum upturn and DN by Large (>Mega ton) WC detectors in high energy region would also be important.