Search for B-L Violation

(as seen by experimentalist)

Yuri Kamyshkov / University of Tennessee

Fundamental Neutron Physics Workshop, INT UW, Seattle, May 1, 2007

This talk should be consolidated with other INT-07-01 talks:

1. W. Mike Snow, Indiana University/IUCF: "Neutron-Antineutron Oscillations: Can the Current Experimental Limits be Improved?" , April 10, 2007
   http://www.int.washington.edu/talks/WorkShops/int_07_1/People/Snow_M/Snow.pdf

2. Rabi Mohapatra, University of Maryland: "Neutron-Anti-Neutron Oscillation as a Probe of B-L Symmetry" , April 30, 2007

3. Brandon Hartfiel, California State University, Dominguez Hills:
   "Search for Neutron-Antineutron Oscillations at Super Kamiokande I"
   May 1, 2007

4. Albert Young, North Carolina State University: "Ultra-Cold Neutrons and NN-bar Oscillations", May 4, 2007

Why we need B, L, and B-L violation ?

Old arguments (remain unproven by experiment):

- ❖ There are no good fundamental reasons for global quantum numbers like B, LF, or L to be conserved. ν *oscillations* → *LFV*

- ❖ Matter-Antimatter asymmetry of the Universe requires BV

  → *3 Sakharov's conditions (1967):*

  (1) Baryon number violation
  (2) Large C and CP symmetry violation
  (3) Departure from thermal equilibrium

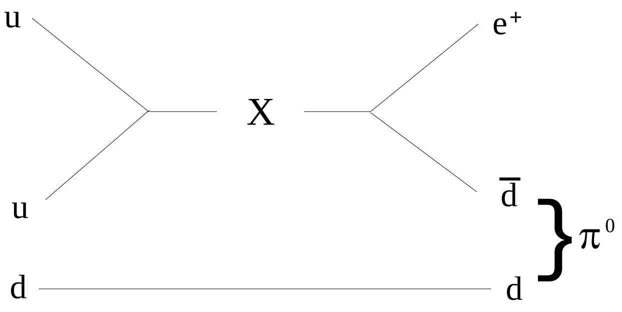
- ❖ Scale of Early Inflation requires BV *(Zeldovich, Dolgov 1981)*

- ❖ GUT (Grand Unification Theory) models require BV:

Pati & Salam (1973) :	quark–lepton unification
Georgi & Glashow (1974) :	SU(5) – unification of forces . . .

Major expectation:

$$proton\ \ decay$$
$$e.g.\ in\ \ SU(5)$$



$$M_{PDK} \sim g\frac{uued}{m_X^2}$$

$$[\,fermion\,] = m^{3/2}$$

$$m_X \sim 10^{15}\,GeV$$

not measured
above this line

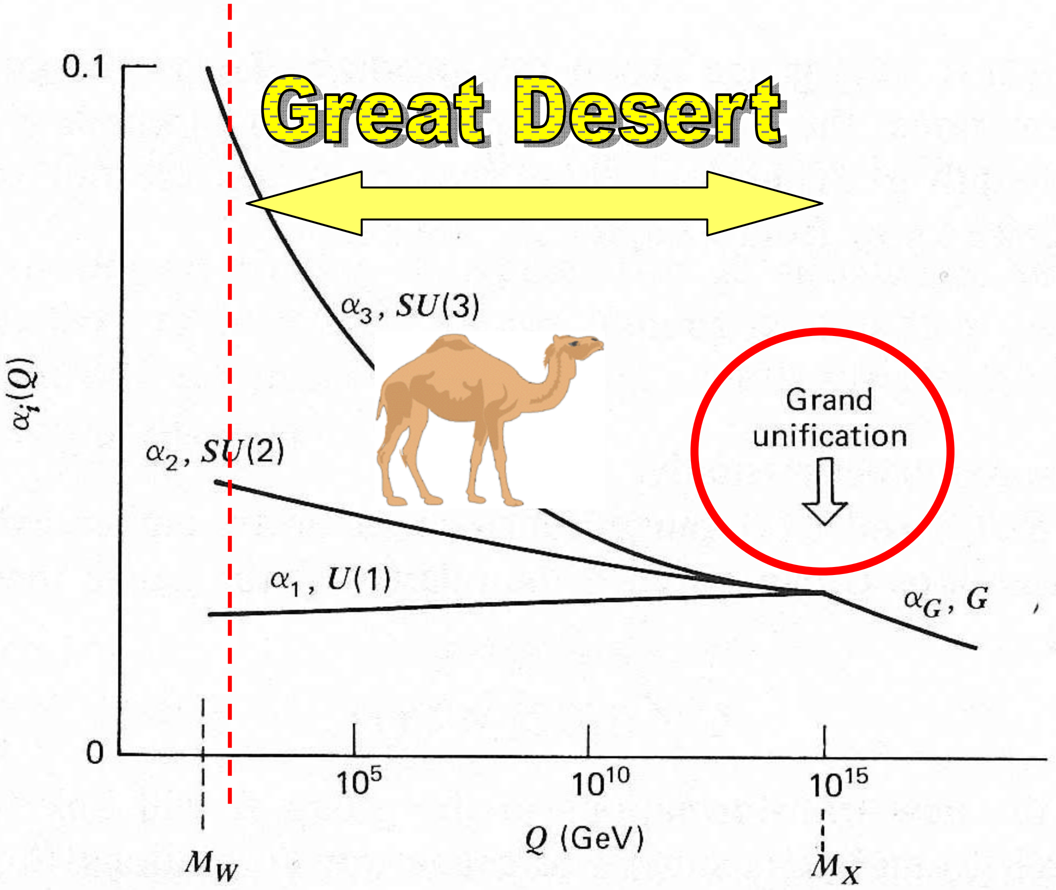
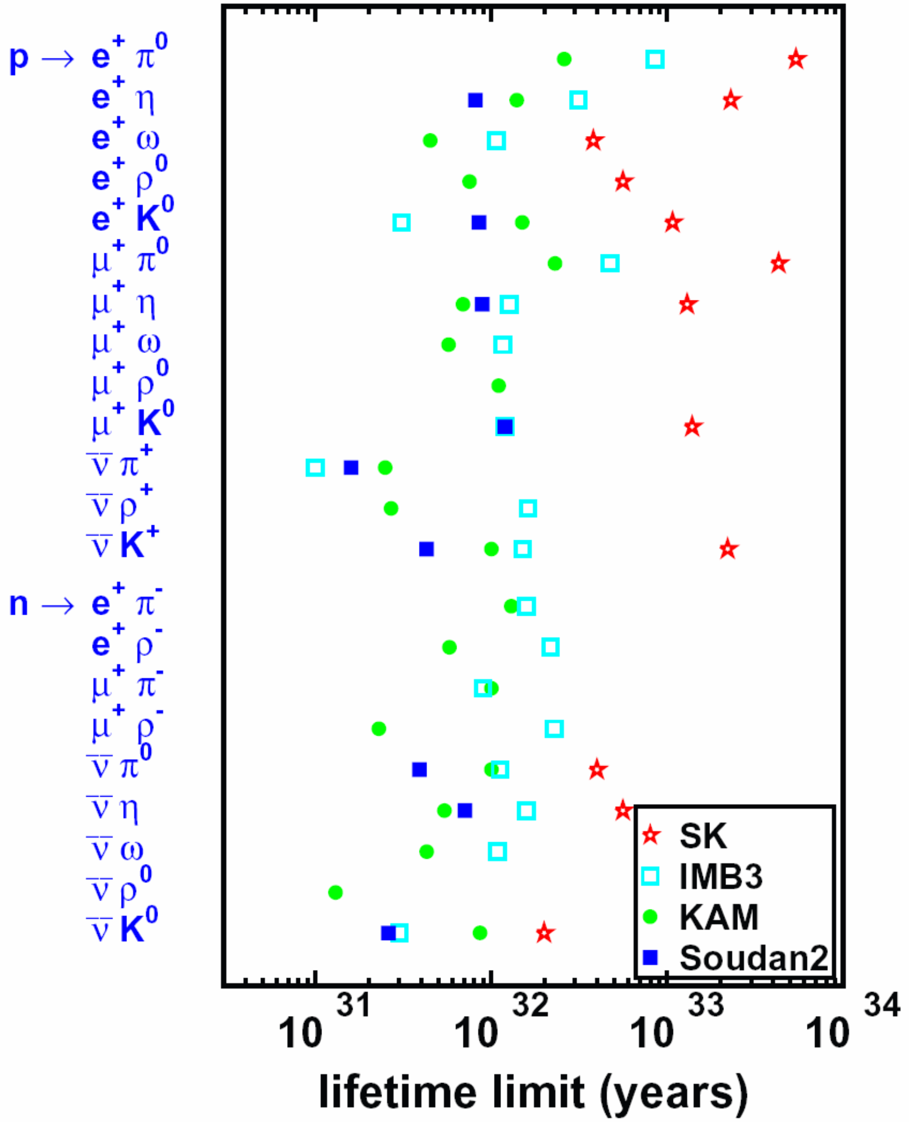


Fig. 15.4 The variation of $\alpha_i \equiv g_i^2/4\pi$ with Q, showing the speculative grand unification of strong [$SU(3)_{\text{color}}$] and electroweak [$SU(2)_L \times U(1)_Y$] interactions at very short distances $1/Q \approx 1/M_X$.

We should prize the work on Nucleon decay search performed by Super-K, Soudan-2, IMB3, Kamiokande, Fréjus experiments

although they found nothing

2003, M. Shiozawa
28th International
Cosmic Ray Conference



Proton Decay
by David Halliday

A proton once said, "I'll fulfill
My long-term belief in free will.
Though theorists (may) say
That I ought to decay
I'm damned if I think that I will."

All modes on this plot are baryon → anti-lepton and therefore are conserving (B–L)

More recent arguments:

- ❖ Before the Grant Unification happens all interactions should become Left-Right symmetric.

General relation in Left-Right symmetric SO(10):

$$Q = T_{3L} + T_{3R} + \frac{B-L}{2}$$

(B–L) is violated by 2 at the same scale where L-R symmetry broken

Non-conservation of (B–L) was discussed theoretically since 1978 by
Davidson, Marshak, Mohapatra, Wilczek, Chang, Ramond ...

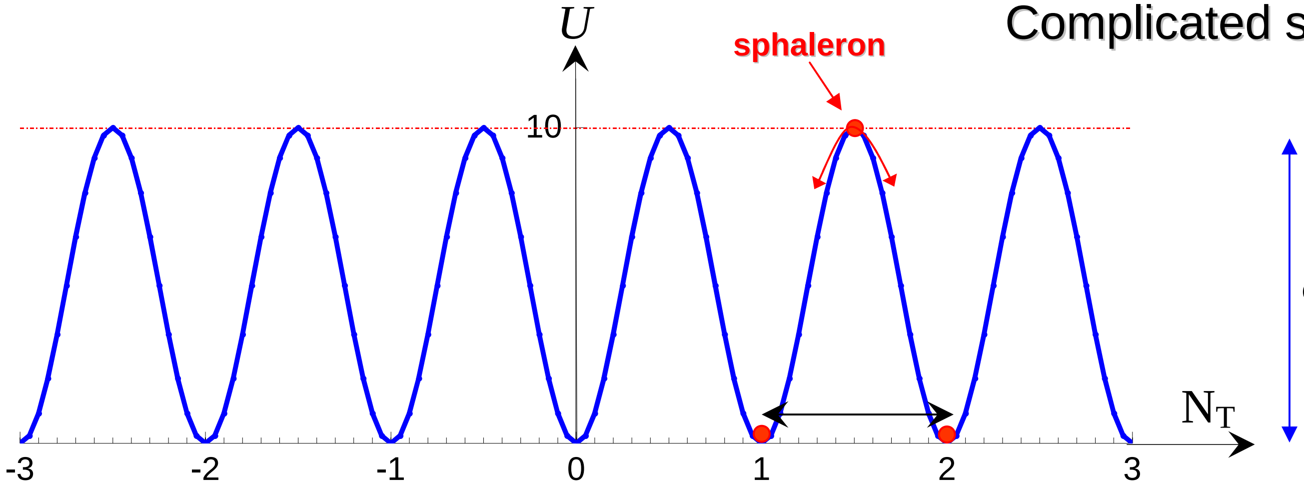
- ❖ Neutrino masses require Seesaw mechanism and heavy Majorana neutrinos violating (B–L) by two units → $2\beta0\nu$ detection efforts

- ❖ Low Quantum Gravity scale models might lower the unification scale down to ~ 100 TeV (No Great Desert !) and can destroy global B,L

- Fast anomalous SM interactions (*sphalerons*) in early Universe at TeV scales require that (B–L) should be violated at > 10 TeV scale

V. Kuzmin, V. Rubakov, M. Shaposhnikov, 1985

Complicated structure of E-W vacuum



$$\propto \left(\frac{4\pi}{g_2^2}\right) M_W \sim 10\,TeV$$

at high temperatures sphaleron transition are very intensive with rate exceeding the rate of inflation → will erase BAU made by Δ(B-L)=0 effects

“Proton decay is not a prediction of baryogenesis!” [Yanagida’02]

→ Leptogenesis or Baryogenesis with (B–L) violation

→ Motivation for Proton Decay with (B–L)=0 is weaker that 20 years ago

Role of (B–L) : two possibilities

For transitions *fermion* → *fermion* the conservation of angular momentum requires that spin ½ of nucleon should be transferred to another fermion (lepton or baryon):

That leads to the selection rule:
$\Delta B = \pm \Delta L$ or $|\Delta(B-L)| = 0, 2$

- <u>In Standard Model, in SU(5), and many SUSY extensions:</u>

  $\Delta(B-L) = 0$ or $\Delta B = + \Delta L$ (e.g. nucleon → antilepton)

- Second possibility of $|\Delta(B-L)| = 2$ allows transitions with

  $\Delta B = - \Delta L$ (nucleon → lepton), or $|\Delta B| = 2$, or $|\Delta L| = 2$

Conservation or violation of (B– L) determines
the mechanism of baryon instability.

Is (B–L) number conserved?

✧ In our laboratory samples (B–L) = # protons + # neutrons – # electrons ≠ 0

(B–L) ≠ 0
Is it smoking gun?

✧ In the Universe most of the leptons exist as, yet undetected, relict neutrino and antineutrino radiation (similar to CMBR) and the conservation of (B–L) on the scale of the whole Universe is still an open question

Possible (B–L)V manifestations following from Δ(B–L)=2

$\Delta B = 0 ; \Delta L = 2 \quad \nu \leftrightarrow \bar{\nu}$ *i.e.* Majorana neutrino, $2\beta 0\nu$ observable

$\Delta L = 0 ; \Delta B = 2 \quad n \leftrightarrow \bar{n}$ oscillations

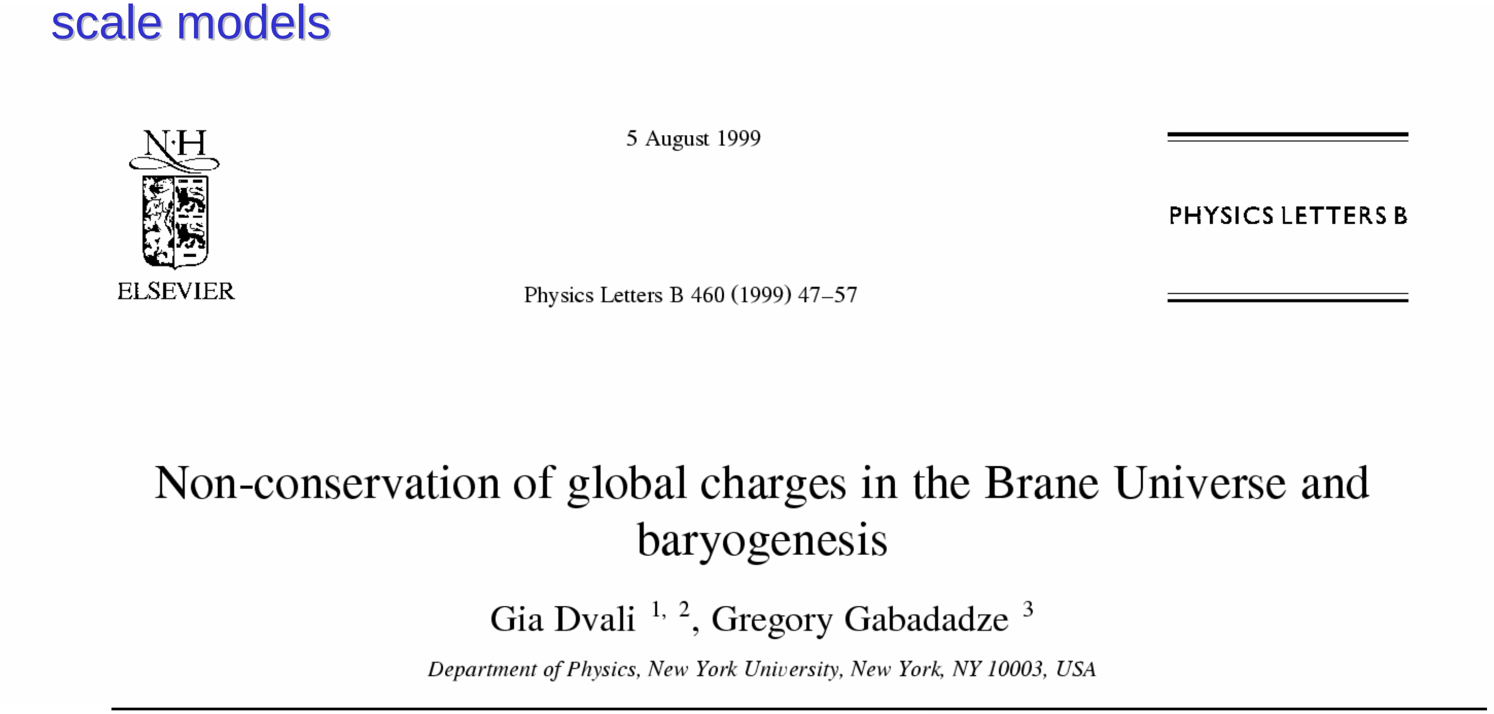
$\Delta B = -\Delta L$ e.g. $n \to \nu\nu\bar{\nu}$ or $p \to \nu\nu e^+$ (nucleon → lepton)

also e.g. $\tau^- \to n + \pi^-$ and $\Lambda^0 \to \mu^- + \pi^+$

Singlet n_R is part of the SM while ν_R might be heavy and difficult to detect

All observable Δ(B–L)=2 processes are topologically similar: operators of dim-9 for non-SUSY amplitude

Low quantum gravity scale models



5 August 1999

ELSEVIER

PHYSICS LETTERS B

Physics Letters B 460 (1999) 47–57

Non-conservation of global charges in the Brane Universe and baryogenesis

Gia Dvali [1, 2], Gregory Gabadadze [3]

Department of Physics, New York University, New York, NY 10003, USA

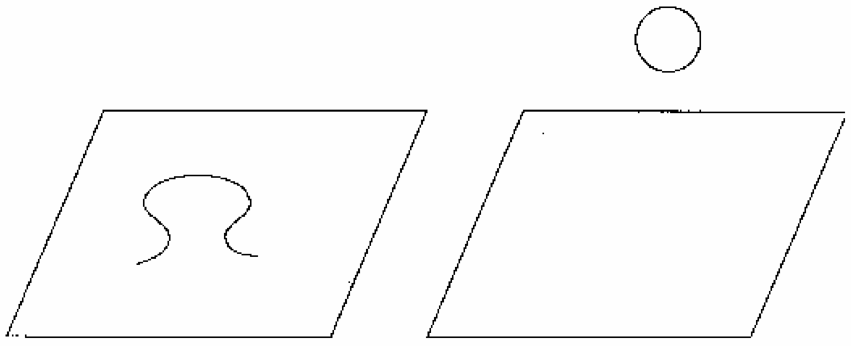


Fig. 1. Creation of baby branes.

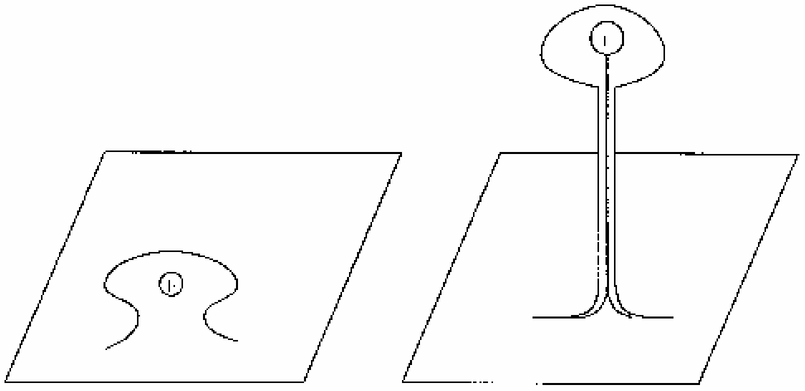


Fig. 2. Flux tube holding the baby brane with a local charge.

Proton decay is strongly suppressed in this model, but n-nbar should occur since n_R has no gauge charges

$n \leftrightarrow \bar{n}$ $|\Delta B|=2$; $|\Delta(B-L)|=2$

❖ There are no laws of nature that would forbid the N ↔ Nbar transitions except the conservation of "*baryon charge (number)*":

M. Gell-Mann and A. Pais, Phys. Rev. 97 (1955) 1387
L. Okun, Weak Interaction of Elementary Particles, Moscow, 1963

❖ N ↔ Nbar was first suggested as a possible mechanism for explanation of Baryon Asymmetry of Universe *by V. Kuzmin, 1970*

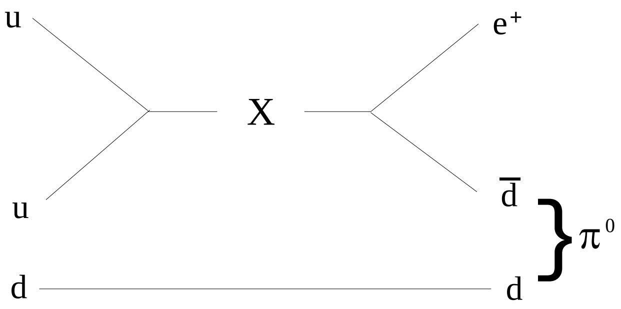
❖ N ↔ Nbar works within GUT + SUSY ideas. First considered and developed within the framework of L/R symmetric Unification models

by R. Mohapatra and R. Marshak, 1979 …

Why N→Nbar was not popular 25 years ago?

$proton\ \ decay$

$e.g.\ \ in\ \ SU(5)$



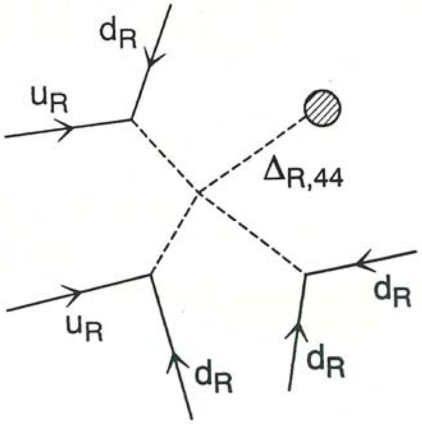
$$M_{PDK} \sim g\,\frac{uued}{m_X^2}$$

$$m_X \sim 10^{15}\,GeV$$

$n \rightarrow \bar{n}\ \ transition$

$e.g.\,\mathrm{in\ SO(10)} \rightarrow$

$\mathrm{SU(2)_L \otimes SU(2)_R \otimes SU(4)_C}$



$$M_{n\bar{n}} \sim \lambda\,\frac{udd\bar{d}\bar{d}\bar{u}}{m_{B-L}^5}$$

$$m_{B-L} \sim 10^5\,GeV$$

Recent $n \leftrightarrow \bar{n}$ theoretical papers $|\Delta B|=2$; $|\Delta(B-L)|=2$

- Connection with neutrino mass physics via seesaw (B–L)V mechanism

K. Babu and R. Mohapatra, PLB 518 (2001) 269
B. Dutta, Y. Mimura, R. Mohapatra, PRL 96 (2006) 061801

- Connection to low quantum gravity scale ideas

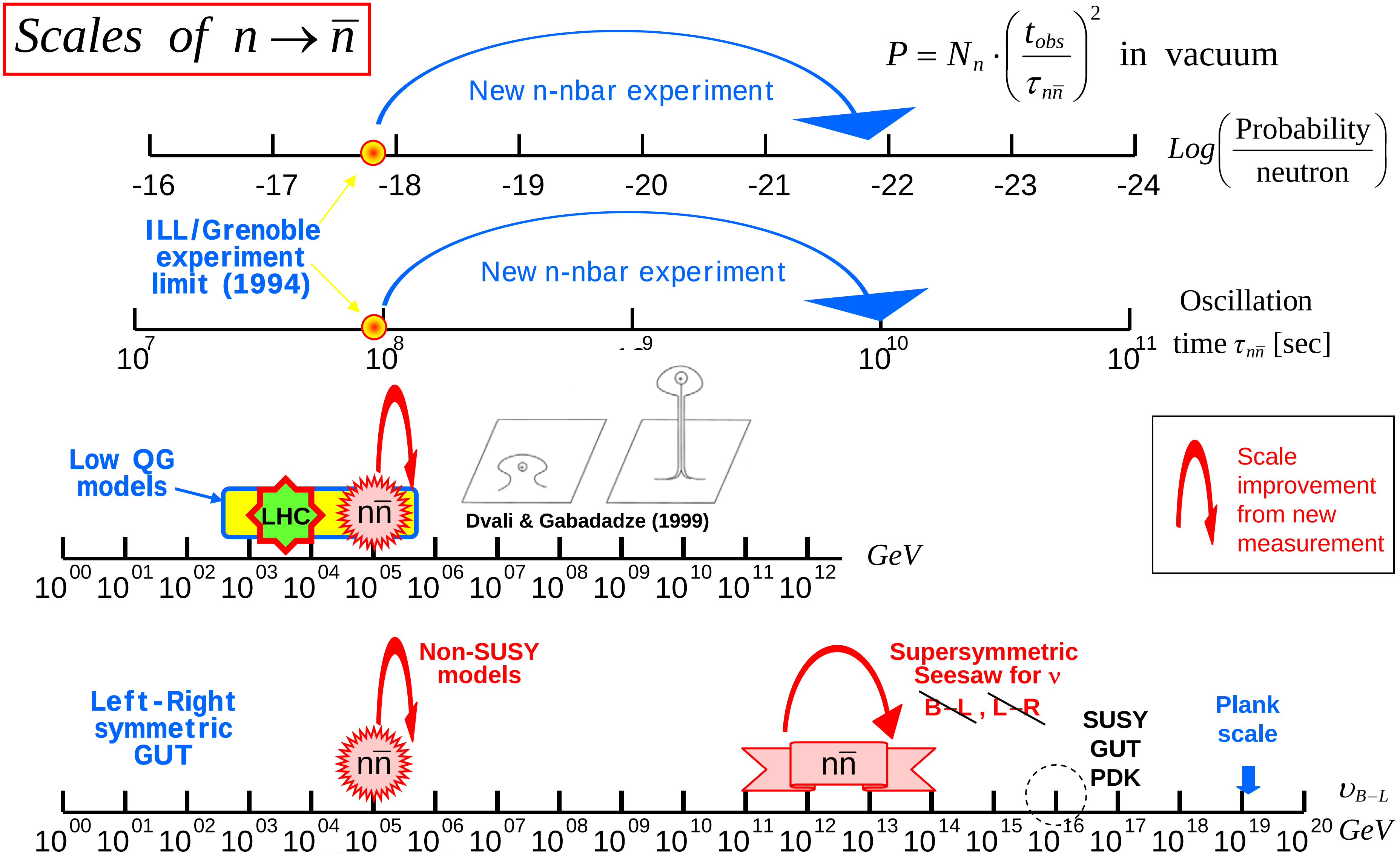
G. Dvali and G. Gabadadze, PLB 460 (1999) 47
S. Nussinov and R. Shrock, PRL 88 (2002) 171601
C. Bambi et al., hep-ph/0606321

- Baryogenesis models at low-energy scale

A. Dolgov et al., NP B752 (2006) 297
K. Babu et al., PRL 97 (2006) 131301

$Scales\ \ of\ \ n \rightarrow \bar{n}$

$$P = N_n \cdot \left(\frac{t_{obs}}{\tau_{n\bar{n}}}\right)^2 \text{ in vacuum}$$



New n-nbar experiment

$Log\left(\frac{\text{Probability}}{\text{neutron}}\right)$

ILL/Grenoble experiment limit (1994)

New n-nbar experiment

Oscillation time $\tau_{n\bar{n}}$ [sec]

Low QG models

Dvali & Gabadadze (1999)

Scale improvement from new measurement

Left-Right symmetric GUT

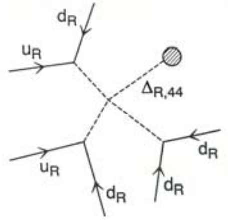
Non-SUSY models

Supersymmetric Seesaw for ν

~~B-L~~ , ~~L-R~~

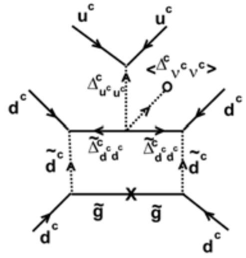
SUSY GUT PDK

Plank scale



$$\propto \upsilon_{B-L}^{-5}$$

Mohapatra & Marshak (1980)



$$\propto \upsilon_{B-L}^{-2} \cdot \upsilon_{WK}^{-3}$$

Dutta-Mimura-Mohapatra (2005)

n→nbar transition probability

All beyond SM physics is here

α-mixing amplitude

$\Psi = \begin{pmatrix} n \\ \bar{n} \end{pmatrix}$ mixed n - nbar QM state

$\mathrm{H} = \begin{pmatrix} E_n & \alpha \\ \alpha & E_{\bar{n}} \end{pmatrix}$ Hamiltonian on the system

where E_n and $E_{\bar{n}}$ are non - relativistic energy operators :

$$E_n = m_n + \frac{p^2}{2m_n} + U_n \;\; ; \;\; E_{\bar{n}} = m_{\bar{n}} + \frac{p^2}{2m_{\bar{n}}} + U_{\bar{n}}$$

Important assumptions :

- $\alpha(n \to \bar{n}) \cong \alpha(\bar{n} \to n) = \alpha$ (i.e. T - invariance is hold)
- there is a reference frame where $p = 0$
- $m_n = m_{\bar{n}}$ (if CPT is not violated)
- gravipotential for n and $\bar{n}$ is the same : $\Delta U = U_n - U_{\bar{n}} = 0$
- magnetic moment $\mu(\bar{n}) = -\mu(n)$ as follows from CPT [BTW $\mu(\bar{n})$ not measured!]
- Earth mag. field can be screened down to accepatable few nT level

n→nbar transition probability (for given α)

For $H = \begin{pmatrix} m_n + V & \alpha \\ \alpha & m_{\bar{n}} - V \end{pmatrix}$

$$\boxed{P_{n\to\bar{n}}(t) = \frac{\alpha^2}{\alpha^2 + (V + \Delta m/2)^2} \times \sin^2\left[\frac{\sqrt{\alpha^2 + (V + \Delta m/2)^2}}{\hbar} t\right]}$$

where V is a potential different for neutron and anti - neutron

(e.g. due to non - compensated Earth mag. field; or part of gravipotential)

t is observation time in an experiment, and $\Delta m = m_n - m_{\bar{n}}$

In an ideal situation of the "vacuum oscillations" $V = 0$ and $\Delta m = 0$

$$\boxed{P_{n\to\bar{n}} = \left(\frac{\alpha}{\hbar} \times t\right)^2 = \left(\frac{t}{\tau_{n\bar{n}}}\right)^2}$$

$\tau_{n\bar{n}} = \dfrac{\hbar}{\alpha}$ is characteristic transition (oscillation) time $[\alpha < 10^{-23} eV]$

$$\boxed{\text{"}Sensitivity\text{"} \propto N_n \bullet < t^2 >}$$

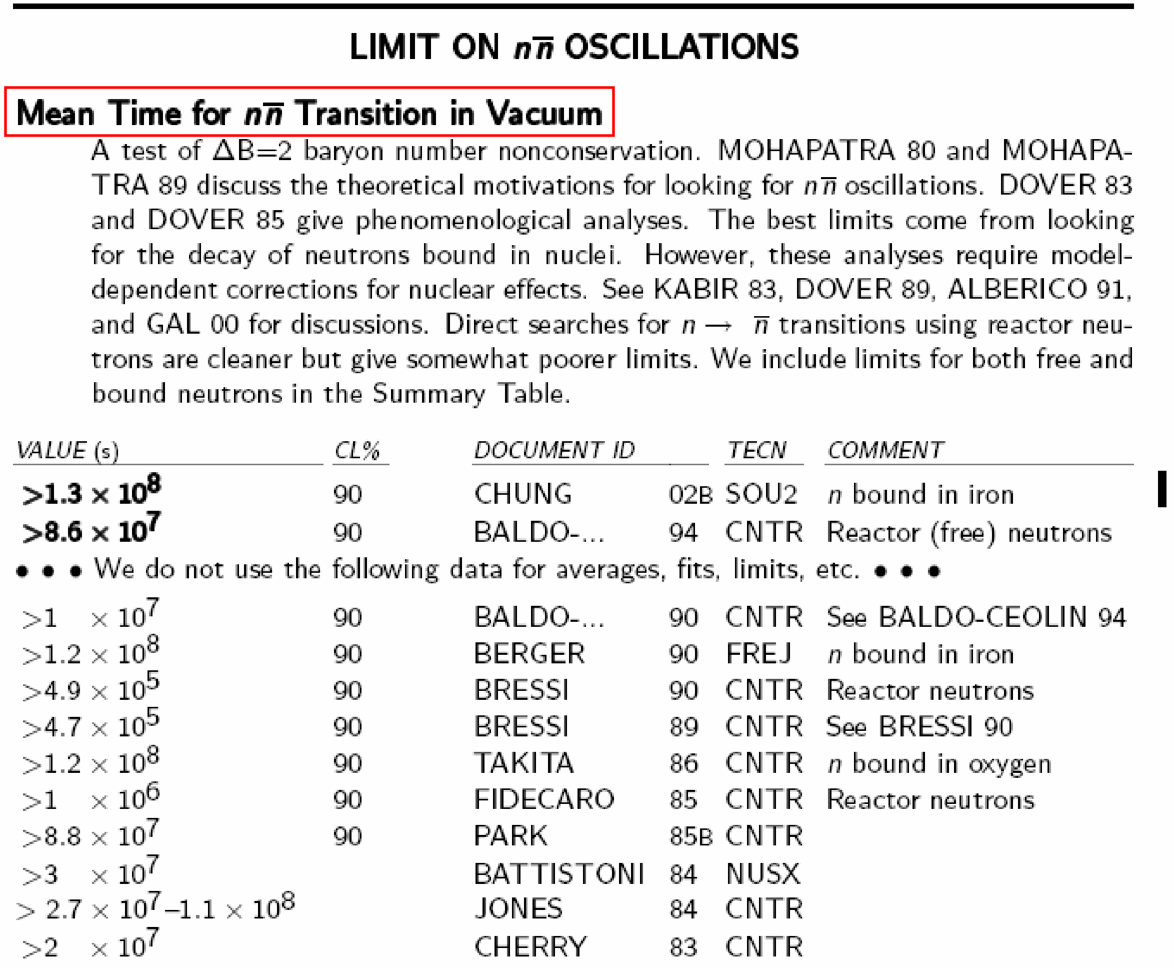
(N_n number of neutrons used per sec, t^2 square of flight time)

PDG 2006:
Limits for both
free reactor neutrons and
neutrons bound inside nucleus

Bound n: J. Chung et al., (Soudan II)
Phys. Rev. D 66 (2002) 032004 $> 7.2\cdot10^{31}$ years

Free n: M. Baldo-Ceolin et al.,
(ILL/Grenoble) *Z. Phys* **C63** (1994) 409
with $P = (t/\tau_{free})^2$

$$\tau_{bound} = R\cdot\tau_{free}^{2}$$
where $R \sim 10^{23}\,s^{-1}$



LIMIT ON $n\bar{n}$ OSCILLATIONS

Mean Time for $n\bar{n}$ Transition in Vacuum

A test of ΔB=2 baryon number nonconservation. MOHAPATRA 80 and MOHAPATRA 89 discuss the theoretical motivations for looking for $n\bar{n}$ oscillations. DOVER 83 and DOVER 85 give phenomenological analyses. The best limits come from looking for the decay of neutrons bound in nuclei. However, these analyses require model-dependent corrections for nuclear effects. See KABIR 83, DOVER 89, ALBERICO 91, and GAL 00 for discussions. Direct searches for $n \to \bar{n}$ transitions using reactor neutrons are cleaner but give somewhat poorer limits. We include limits for both free and bound neutrons in the Summary Table.

VALUE (s)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$>1.3 \times 10^{8}$	90	CHUNG	02B	SOU2	n bound in iron
$>8.6 \times 10^{7}$	90	BALDO-...	94	CNTR	Reactor (free) neutrons
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$>1 \times 10^{7}$	90	BALDO-...	90	CNTR	See BALDO-CEOLIN 94
$>1.2 \times 10^{8}$	90	BERGER	90	FREJ	n bound in iron
$>4.9 \times 10^{5}$	90	BRESSI	90	CNTR	Reactor neutrons
$>4.7 \times 10^{5}$	90	BRESSI	89	CNTR	See BRESSI 90
$>1.2 \times 10^{8}$	90	TAKITA	86	CNTR	n bound in oxygen
$>1 \times 10^{6}$	90	FIDECARO	85	CNTR	Reactor neutrons
$>8.8 \times 10^{7}$	90	PARK	85B	CNTR	
$>3 \times 10^{7}$		BATTISTONI	84	NUSX	
$> 2.7 \times 10^{7}$–1.1×10^{8}		JONES	84	CNTR	
$>2 \times 10^{7}$		CHERRY	83	CNTR	

Search with free neutrons is square more advantageous but in suppressed intra-nuclear transitions larger number of neutrons can be used

Suppression of n→nbar in intranuclear transitions

Neutrons inside nuclei are "free" for the time: $\Delta t \sim \frac{1}{E_{binding}} \sim \frac{1}{10 MeV} \sim 10^{-22}\, s$

each oscillating with free probability $= \left(\frac{\Delta t}{\tau_{n\bar{n}}}\right)^2$

and "experiencing free condition" $N = \frac{1}{\Delta t}$ times per second.

Transition probability per second: $P_A = \frac{1}{\tau_A} = \left(\frac{\Delta t}{\tau_{n\bar{n}}}\right)^2 \times \left(\frac{1}{\Delta t}\right)$

Intranuclear transition (exponential) lifetime: $\boxed{\tau_{\text{A}} = \frac{\tau_{n\bar{n}}^2}{\Delta t} = R \times \tau_{n\bar{n}}^2}$

where R $\sim \frac{1}{\Delta \text{t}} \sim 10^{22}\, s^{-1}$ is "nuclear suppression factor"

Actual nuclear theory calculations for $^{16}O, ^{2}D, ^{56}Fe, ^{40}Ar$ by C. Dover et al; W.Alberico et al; and most recently B.Kopeliovich and J. Hufner are consitent and give an order of maginitude higher suppression factors with uncertainty of $\times 2$

Thus, e.g. Soudan-II limit $\tau_{Fe} > 7.2 \times 10^{31}\, yr$ corresponds to $\tau_{n\bar{n}} > 1.3 \times 10^{8}\, s$

n→nbar search limits with bound neutrons

$$\text{Soudan-2 limit: } \tau_{Fe} > 7.2\times10^{31}\ years$$

$$S/B = 4/4.5$$

Future potential limits expected from SNO and Super-K (guess of 2002 by Tony Mann):

$$\text{SNO:} \qquad \tau_D \sim 4.8\times10^{32}\ years$$

$$\text{Super-K:} \quad \tau_O \sim 7.5\times10^{32}\ years$$

Since sensitivity of SNO, Super-K, and future large underground detectors will be limited by atmospheric neutrino background (as demonstrated by Soudan-2 experiment), it will be possible to set a new limit, but difficult to make a discovery!

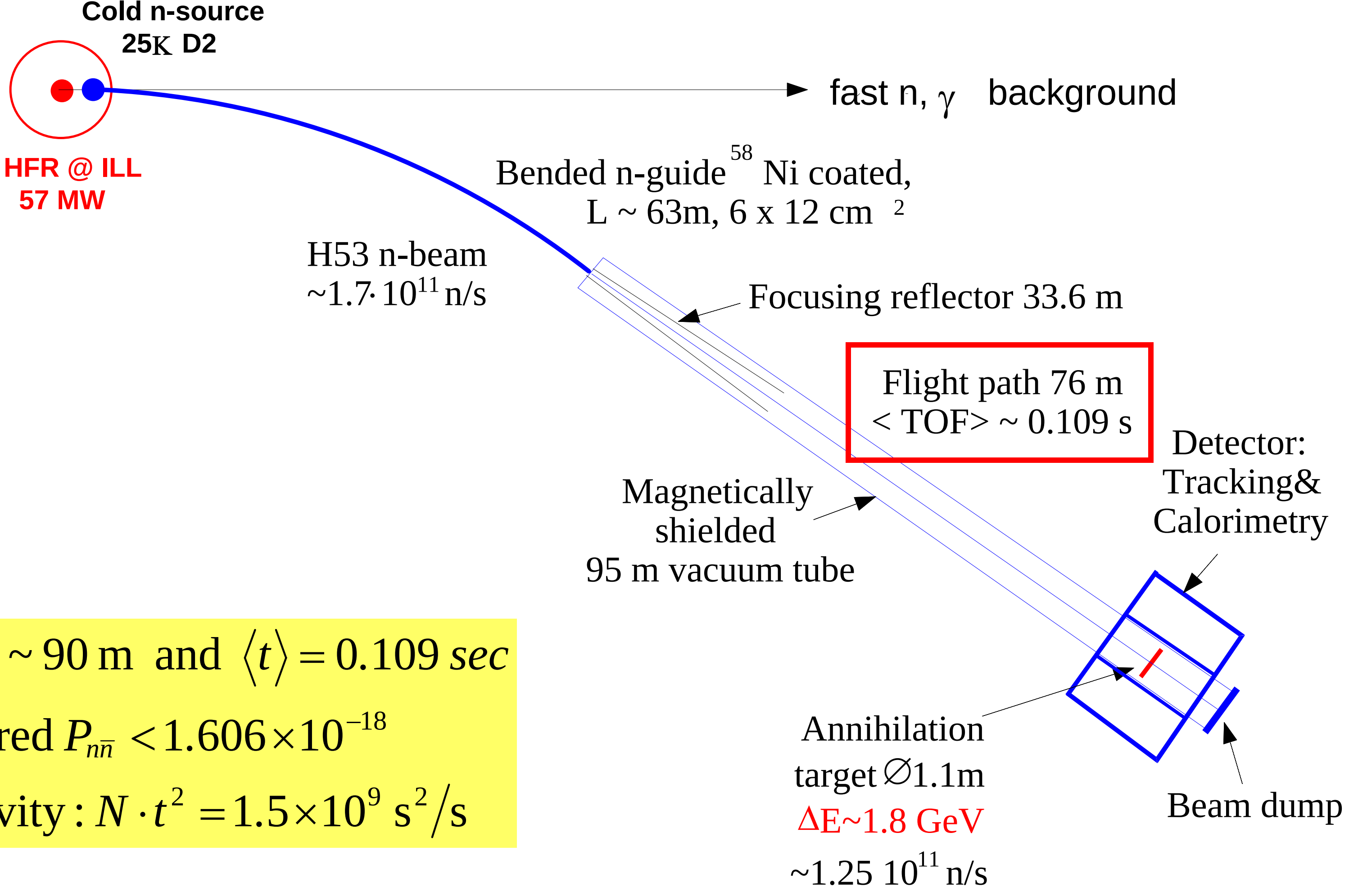
ILL: Institute Max Von Laue-Paul Langevin in Grenoble

Previous n-nbar search experiment with free neutrons

At ILL/Grenoble reactor in 89-91 by Heidelberg-ILL-Padova-Pavia Collaboration

M.Baldo-Ceolin M. et al., Z. Phys., C63 (1994) 409

(not to scale)



Cold n-source
25K D2

HFR @ ILL
57 MW

fast n, γ background

Bended n-guide ^{58}Ni coated,
L ~ 63m, 6 x 12 cm ^{2}

H53 n-beam
$\sim 1.7\cdot 10^{11}$ n/s

Focusing reflector 33.6 m

Flight path 76 m
< TOF> ~ 0.109 s

Detector:
Tracking&
Calorimetry

Magnetically
shielded
95 m vacuum tube

Annihilation
target $\varnothing$1.1m
ΔE~1.8 GeV
$\sim 1.25\ 10^{11}$ n/s

Beam dump

with L ~ 90 m and $\langle t \rangle = 0.109\ sec$

measured $P_{n\bar{n}} < 1.606\times10^{-18}$

sensitivity : $N\cdot t^{2} = 1.5\times10^{9}\ \mathrm{s}^{2}/\mathrm{s}$

Detector of Heidelberg -ILL-Padova-Pavia Experiment @ILL 1991

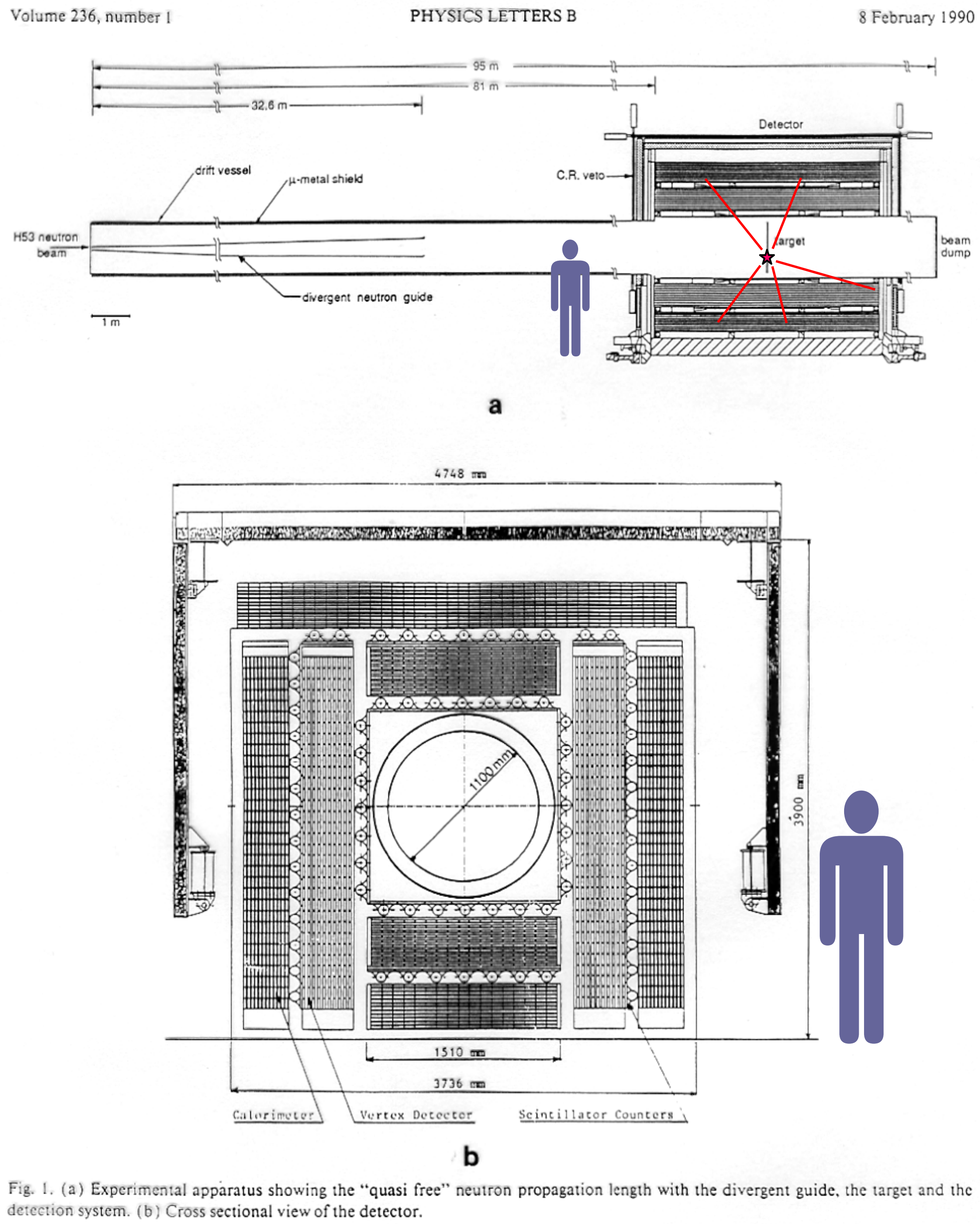
No background!

No candidates observed.

Measured limit for
a year of running:

$\tau_{n\bar{n}} \geq 8.6 \times 10^{7}\ sec$

= 1 unit of sensitivity



Volume 236, number 1 PHYSICS LETTERS B 8 February 1990

Fig. 1. (a) Experimental apparatus showing the "quasi free" neutron propagation length with the divergent guide, the target and the detection system. (b) Cross sectional view of the detector.

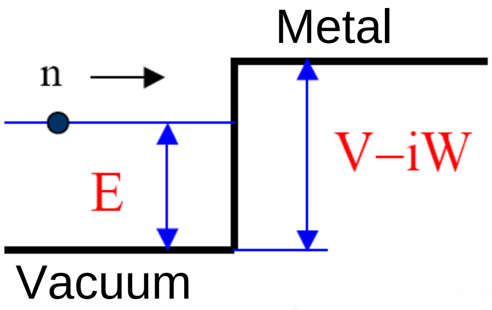
How one can improve on such state-of-the-art experiment and achieve 3-4 orders of magnitude higher sensitivity?

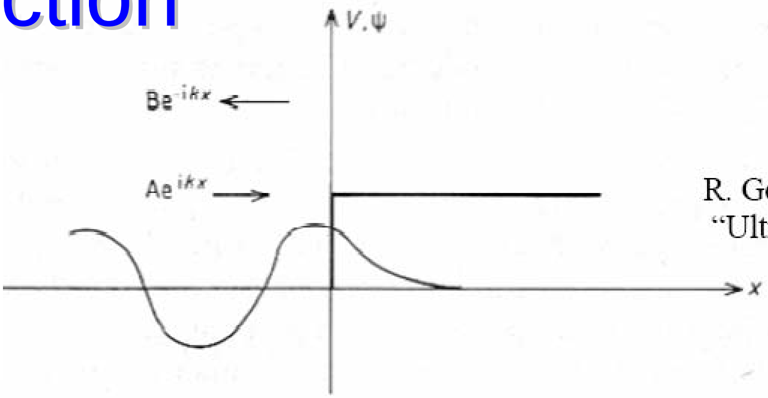
Two major improvements:

1. Focusing of neutrons: use of larger solid angle
   → longer neutron flight path

2. Vertical layout: compensating Earth gravity

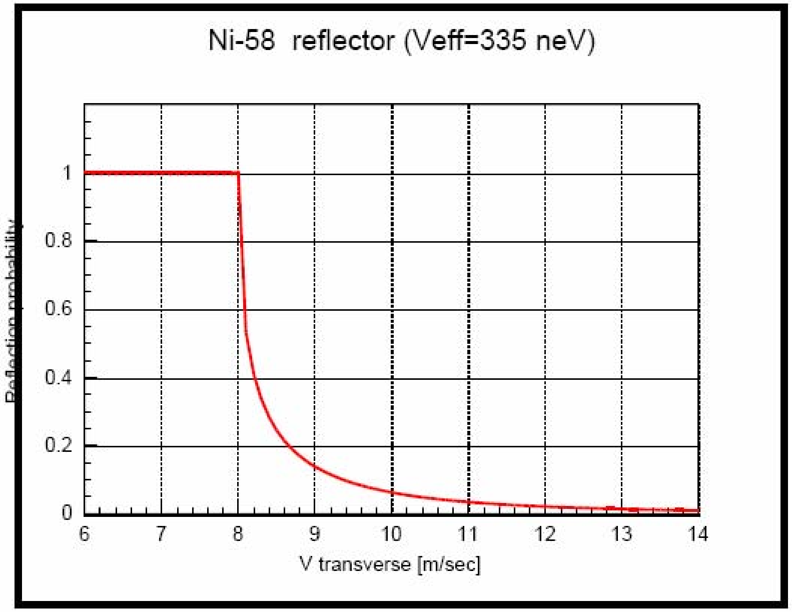
Neutron reflection





R. Golub, D. Richardson, S. Lamoreaux,
"Ultra-Cold Neutrons"

Reflection coefficient: $$R = \left| \frac{1 - \sqrt{1 - \frac{V}{E}(1 - if)}}{1 + \sqrt{1 - \frac{V}{E}(1 - if)}} \right|^2$$ where $U = V - iW$ and $f = \frac{W}{V}$



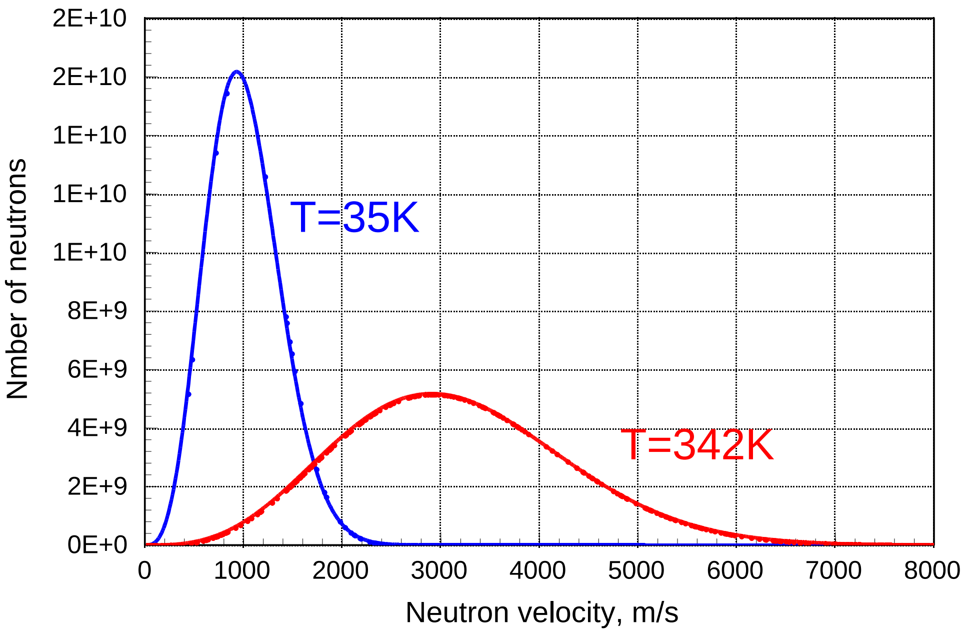
Need max flux and max observation time!

E of reactor fission neutrons ~ 2 MeV

E of thermal (300 K) neutrons ~ 0.025 eV

<V> of thermal neutrons ~ 2200 m/s

<V> of Cold neutrons ~ 1000 m/s



For 1-km initially horizontal flight path the vertical displacement due to gravity acceleration is ~ 5m for V_X=1000 m/s and t=1 sec; vertical velocity component is V_Y=10 m/s

→ Trajectory wiping effect on cold neutrons for horizontal beam layout

→ Vertical beam layout preserves all the cold spectrum and allows max path length

For layout without focusing:

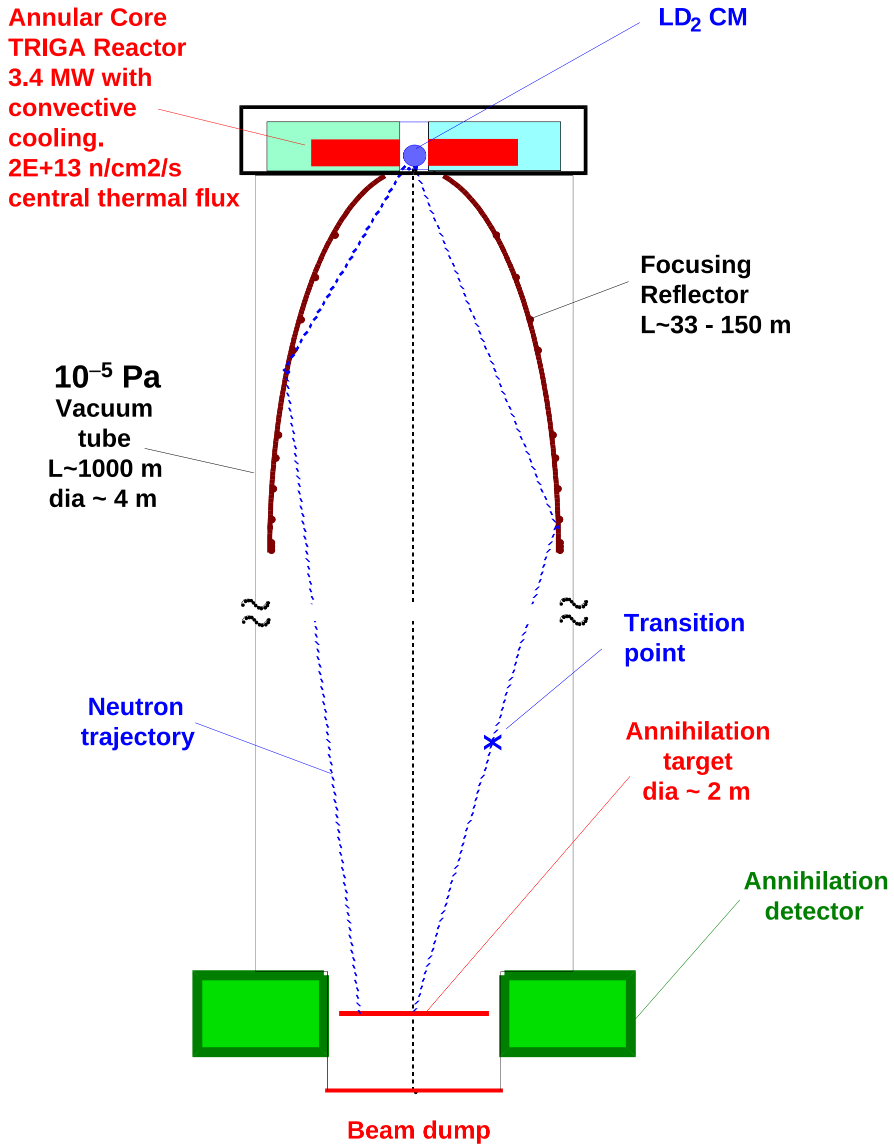
$$Sensitivity \propto \frac{1}{\sqrt{T}}$$

For vertical layout with focusing:

$$Sensitivity \propto \frac{L^2}{\sqrt{T^3}}$$

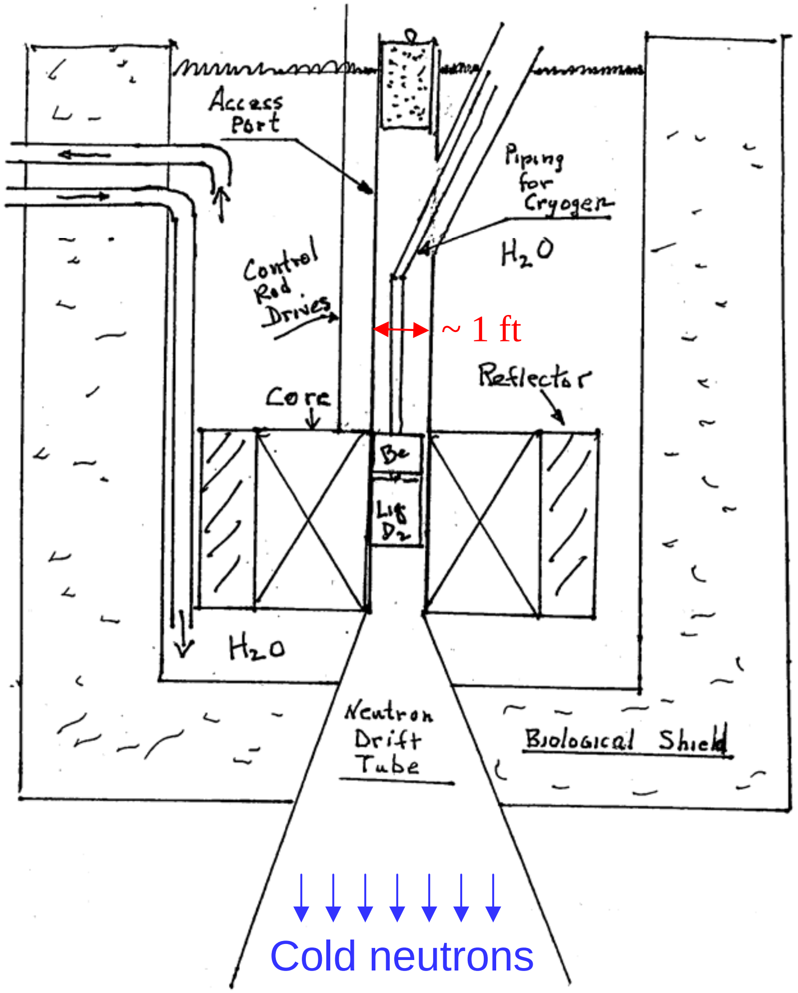
N-Nbar search experiment idea with vertical layout

- Dedicated small-power research reactor with cold neutron moderator → $V_n \lesssim 1000$ m/s
- Vertical shaft $\gtrsim$ 1000 m deep with diameter $\gtrsim$5 m
- Large vacuum tube 10^{-5} Pa, focusing reflector; Earth magnetic field compensation system to ~ nT
- Detector (similar to ILL N-Nbar detector) at the bottom of the shaft (no new technologies)
- No background: one event→ discovery!
- Sensitivity increase factor ~ **1,000** (relative to present limits)



Not to scale

Annular core TRIGA reactor (GA) for N-Nbar search experiment



Courtesy of W. Whittemore
(General Atomics)

- GA built ~ 70 TRIGA reactors 0.01÷14 MW (th)
- 19 TRIGA reactors are presently operating in US (last commissioned in 1992)
- 25 TRIGA reactors operating abroad (last commissioned in 2005)
- some have annular core and vertical channel
- most steady, some can be pulsed up to 22 GW
- safe ~ 20% EU uranium-zirconium hydride fuel

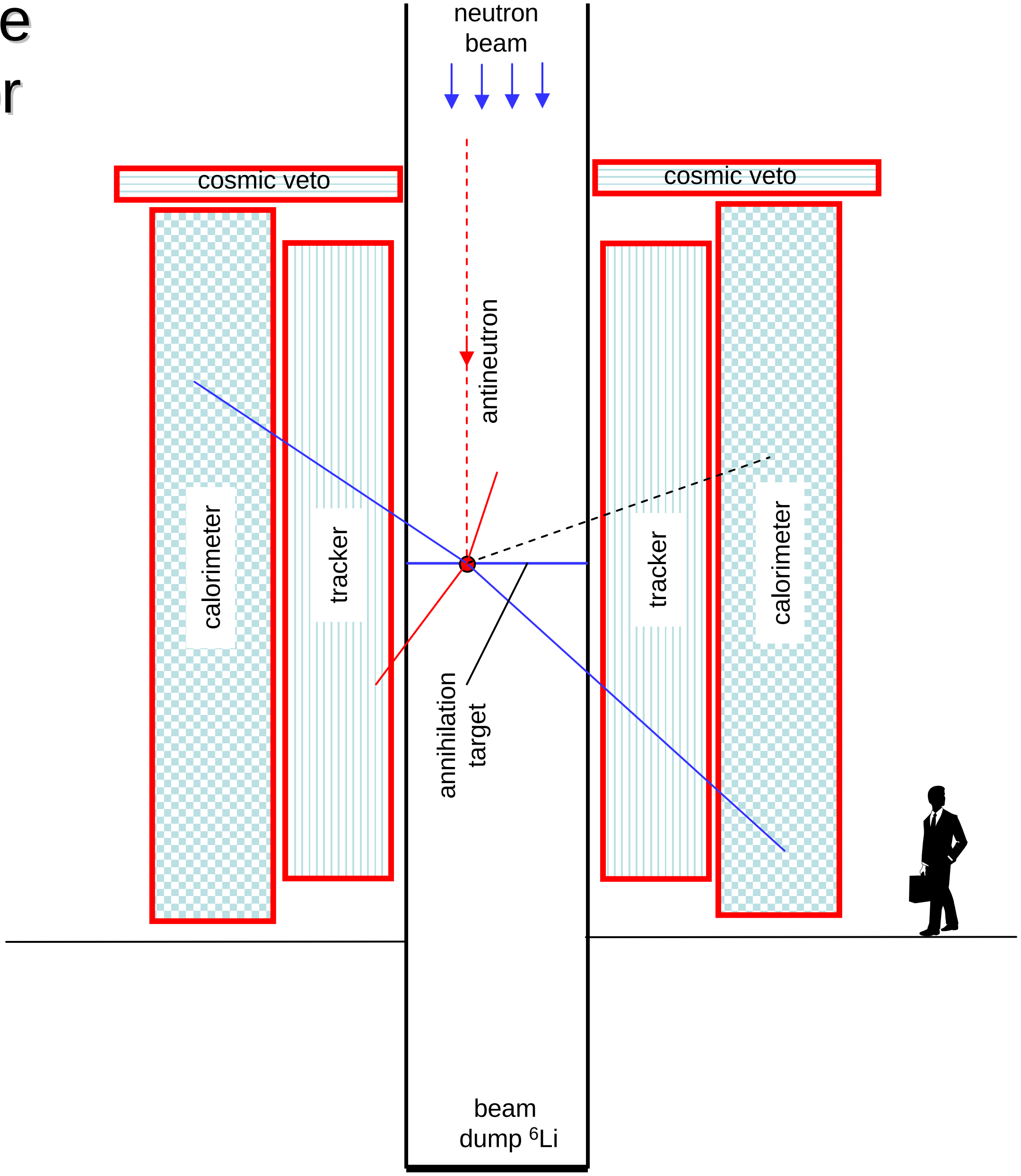
Economic solution for n-nbar:
annular core TRIGA reactor 3.4 MW
with convective cooling, vertical channel,
and large cold LD_2 moderator (T_n ~ 35K).
Unperturbed thermal flux in the vertical
channel ~ 2×10^{13} n/cm^2/s

Neutron source needed: small power 3.4 MW TRIGA reactor

Dry central cavity in annular core

TRIGA Reactor picture courtesy of General Atomics

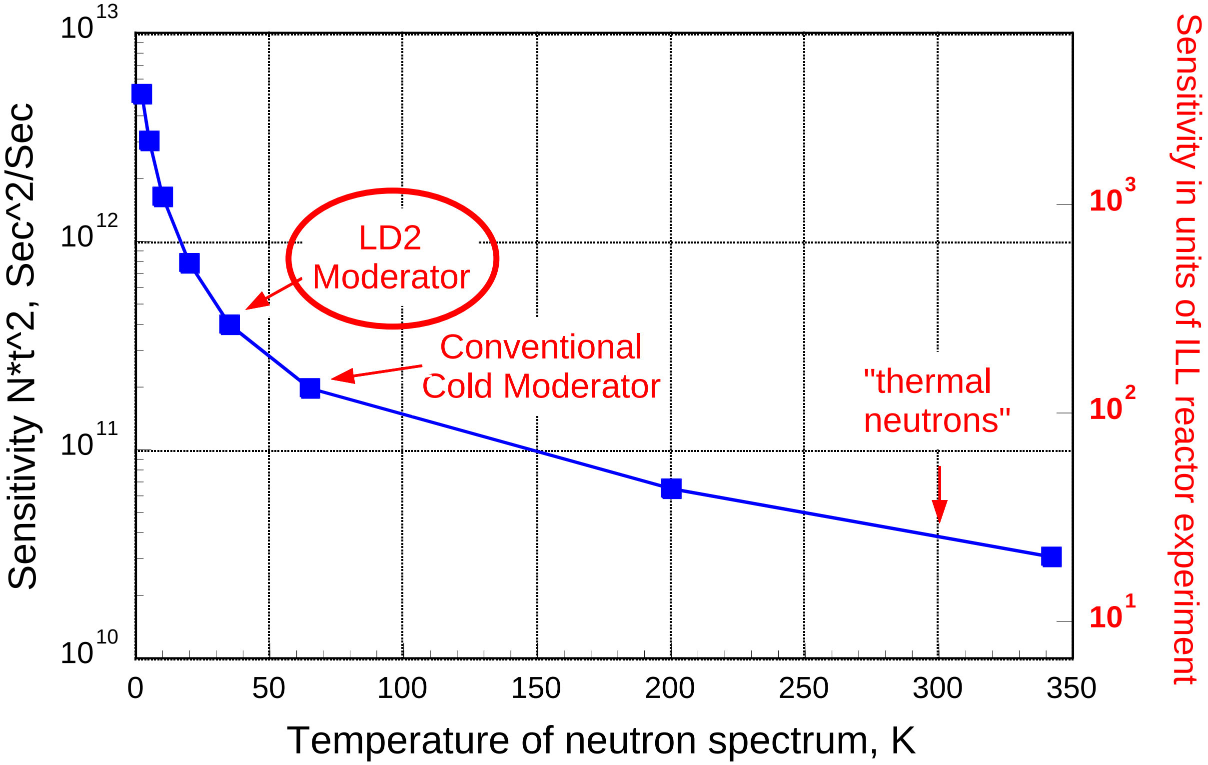
The conceptual scheme of antineutron detector



N-Nbar sensitivity vs neutron temperature

MC simulation: source dia 25 cm, target dia 2m, L(S/T) = 1150 m

$3\theta_C$ reflector starts at z = 2m with dia 1 m; ends at z = 33 m with dia 4 m



Base-line for cold TRIGA source is LD_2 moderator

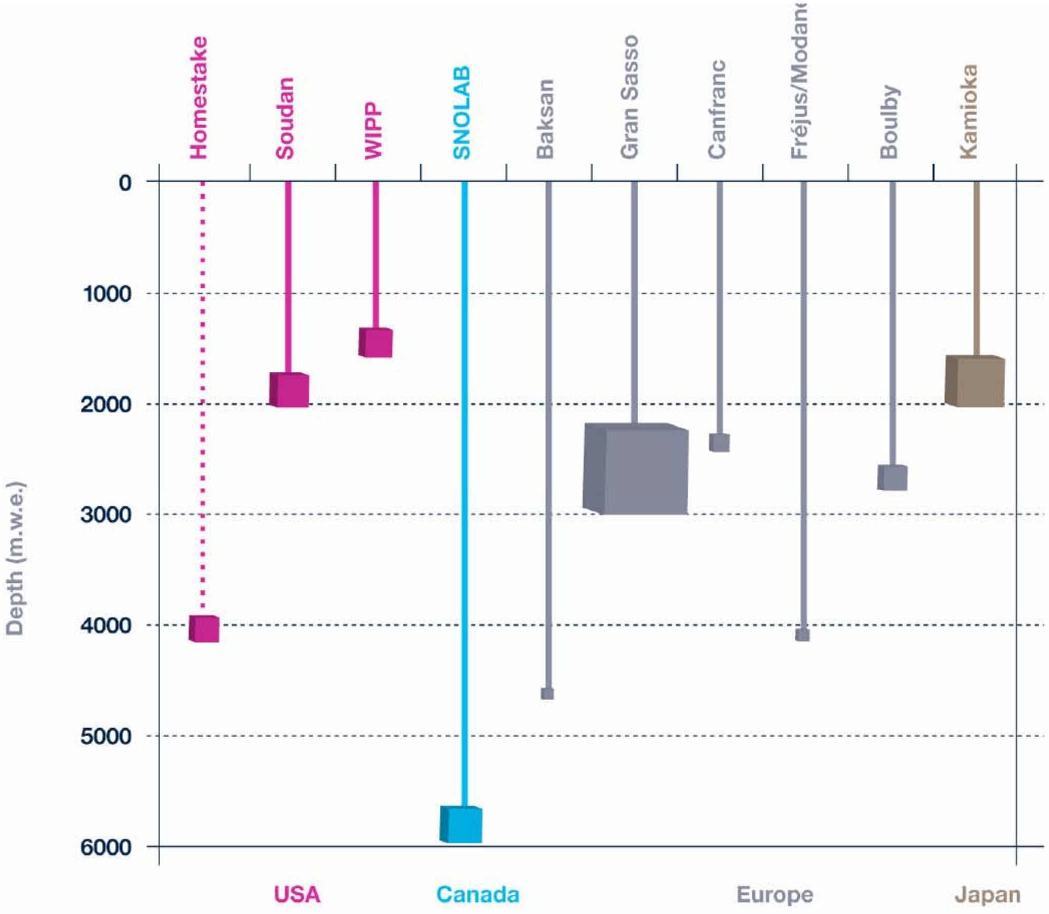
DUSEL

Deep Underground Science and Engineering Laboratory

Initiative in US by National Science Foundation in 2004
(also supported by DOE) motivated by possible broad
scope of the underground science including

- Non-accelerator physics: solar neutrinos, $\beta\beta0\nu$ - decay, Dark Matter, supernovae
- Long-baseline neutrino physics
- Nucleon instability search (proton decay, neutron-antineutron oscillations)
- Geology (formations, conditions closer to earthquakes)
- Mine Engineering (rock mechanics, stresses, stability, hydrology)
- Microbiology (life at large depth and high pressure and temperatures)
- Atmospheric physics (rain/snow formation and growth)

Presently underground experimental facilities in US are not best in the world



8 Candidate sites: Cascades, WA ; Henderson Mine, CO ; Homestake Mine, SD ; Kimballton Mine, VA ; San Jacinto, CA ; Soudan Mine, MN ; SNOLAB, Sudbury, ONT ; WIPP, Carlsbad, NM

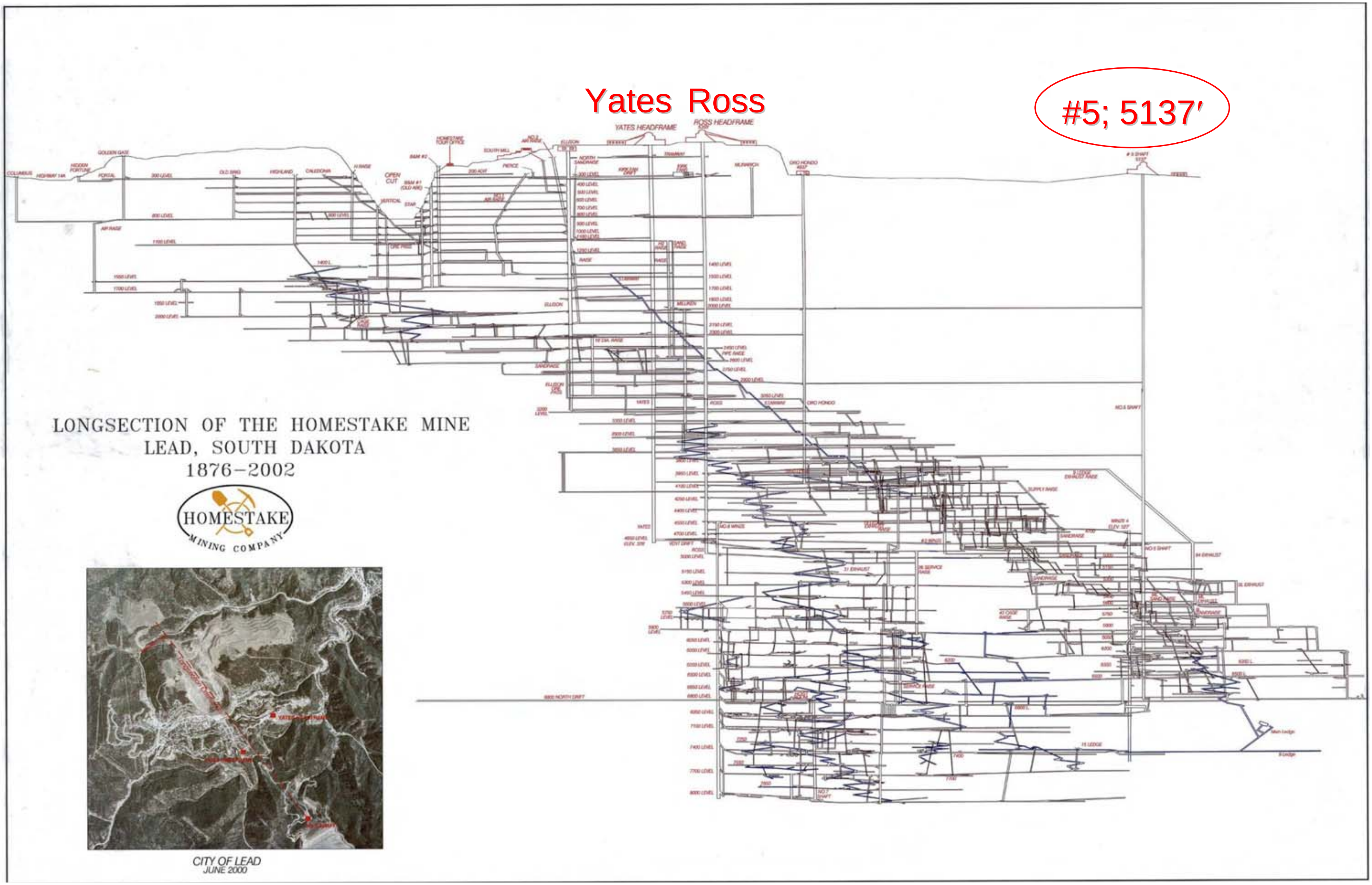
2 Candidate sites (2005): Henderson Mine,CO ; Homestake Mine, Lead, SD

4 Candidate sites (2006): Henderson, Homestake, Cascades, Minnesota*

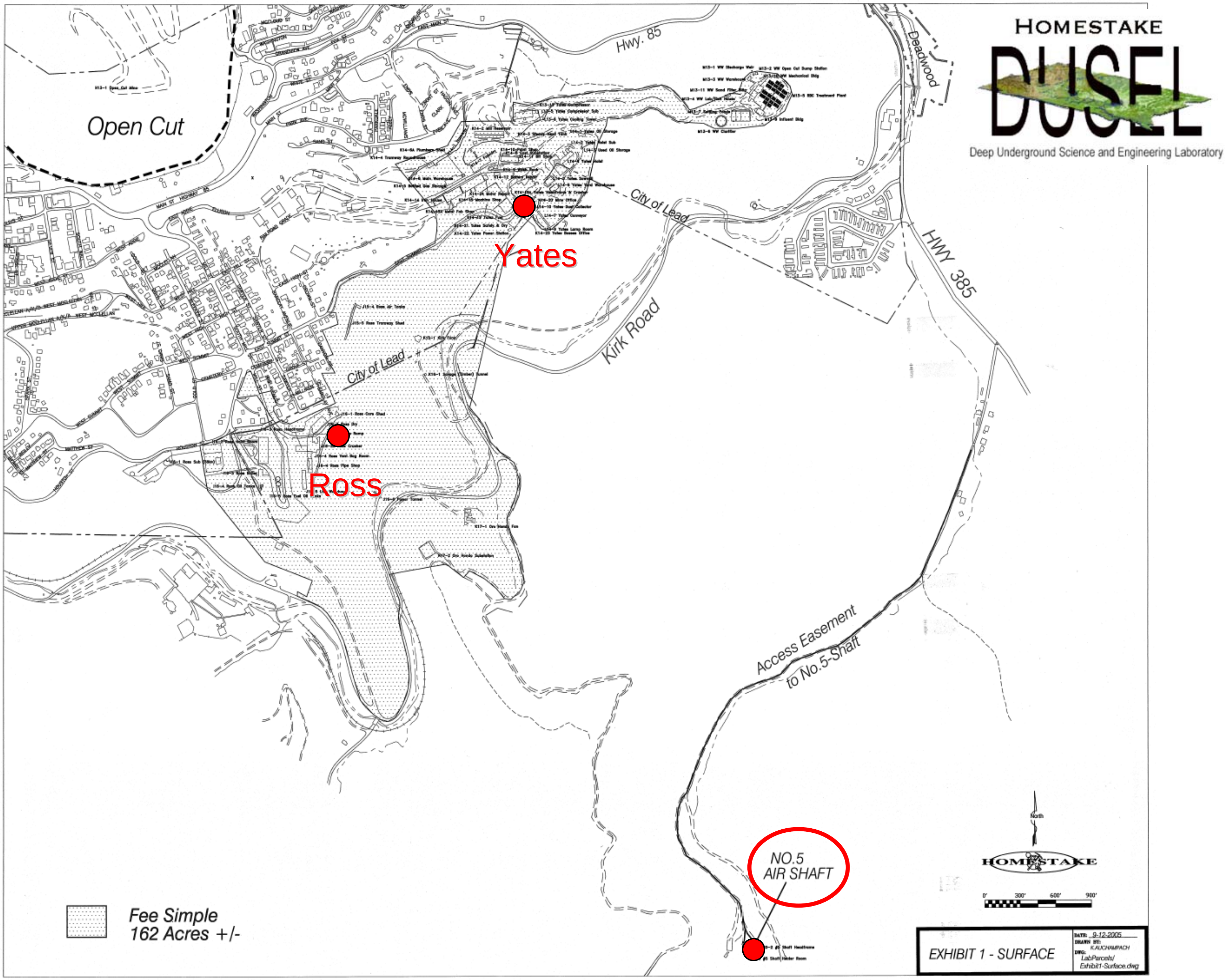
Final decision expected in Spring 2007

Homestake shafts

HOMESTAKE
DUSEL
Deep Underground Science and Engineering Laboratory


Yates Ross

#5; 5137′


HOMESTAKE
DUSEL
Deep Underground Science and Engineering Laboratory
Open Cut
Hwy. 85
Deadwood
City of Lead
Yates
Kirk Road
HWY 385
City of Lead
Ross
Access Easement
to No.5-Shaft
NO.5
AIR SHAFT
Fee Simple
162 Acres +/-
North
HOMESTAKE
0'
300'
600'
900'
EXHIBIT 1 - SURFACE
DATE: 9-12-2005
DRAWN BY:
K.AUCHAMPACH
DWG:
LabParcels/
Exhibit1-Surface.dwg

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Deep Underground Science and Engineering Laboratory

February 9, 2006, Lead, SD (LOI #7)

Search for neutron → antineutron transitions at DUSEL

N-Nbar proto-collaboration

*D. Baxter[2], W. Bugg[8], Y. Efremenko[8], A. Fomin[7], T. Gabriel[8], K. Ganezer[1],
T. Handler[8], T. Ito[3], Y. Kamyshkov[8], A. Kharitonov[7], A. Kozlov[8], M. Leuschner[2],
C-Y. Liu[2], V. Mityukhlyaev[7], R. Mohapatra[4], P. Mumm[6], A. Serebrov[7], G. Shmelev[7],
W. M. Snow[2], S. Spanier[8], A. Young[5], C.West[8], A. Young[5], B. Wehring[5], A. Zakharov[7]*

[1] *California State University, Domingues Hills*
[2] *Indiana University*
[3] *Los Alamos National Laboratory*
[4] *University of Maryland*
[5] *North Carolina State University*
[6] *NRC/NIST*
[7] *St. Petersburg Nuclear Physics Institute, Russia*
[8] *University of Tennessee*

(Contact address: Yuri Kamyshkov <kamyshkov@utk.edu>)

$n \rightarrow \overline{n}$ Search Sensitivity

Soudan II limit ≈ Grenoble limit = 1 unit (1 u) of sensitivity

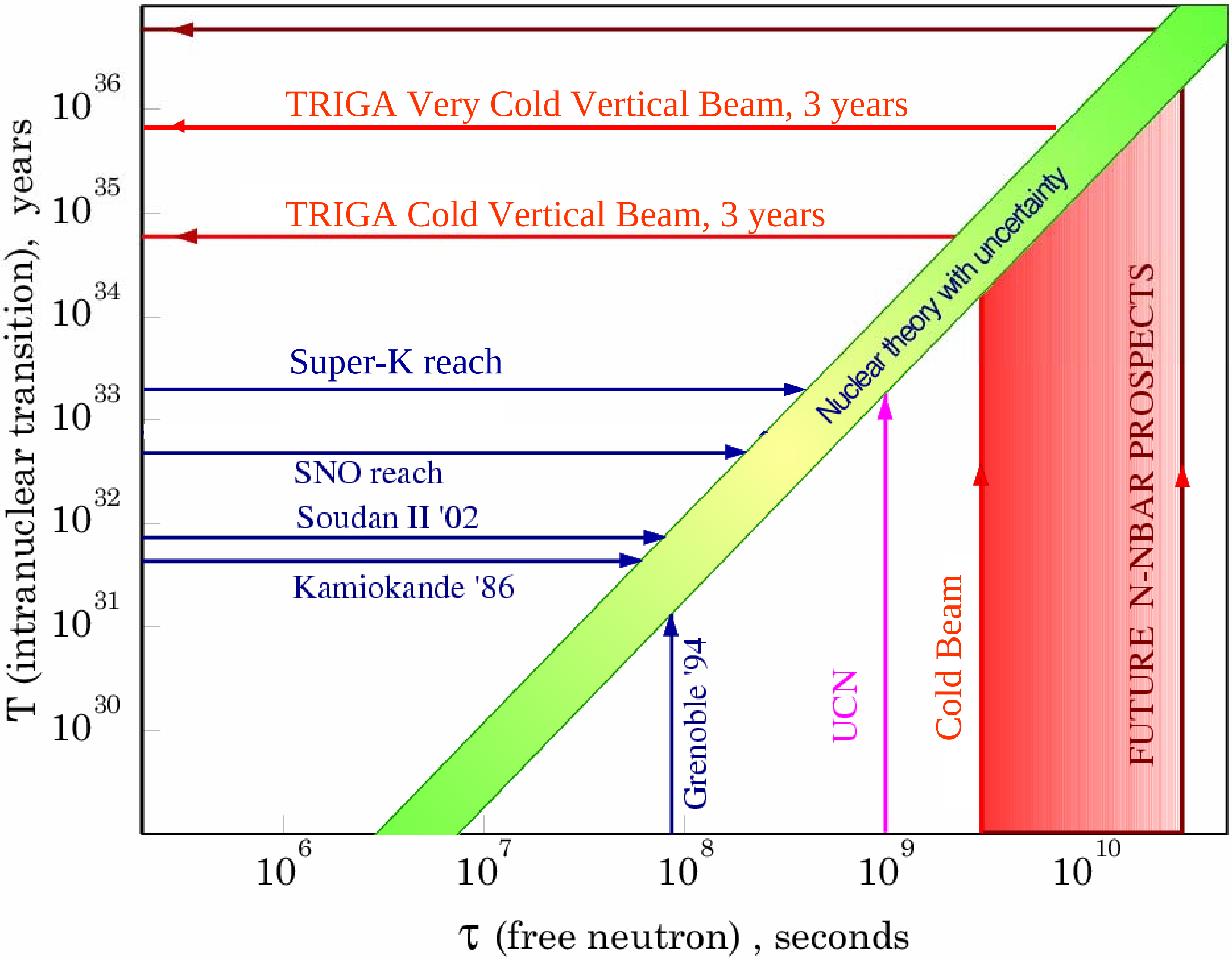
Method	Present limit	Possible future limit	Possible sensitivity increase factor
Intranuclear (in N-decay expts)	$7.2 \cdot 10^{31}$ yr = 1u Soudan II	$7.5 \cdot 10^{32}$ yr (Super-K) $4.8 \cdot 10^{32}$ yr (SNO)	× 16 u (*)
Geo-chemical (ORNL)	none	$4 \cdot 10^{8} \div 1 \cdot 10^{9}$ s (Tc in Sn ore)	× 20÷100 u (*)
UCN trap (6×10^{7} ucn/sec)	none	$\sim 1 \cdot 10^{9}$ s	× 100 u (**)
Cold horizontal beam	$8.6 \cdot 10^{7}$ s = 1u @ILL/Grenoble	$> 3 \cdot 10^{9}$ s (e.g. HFIR@ORNL)	× 1,000 u ~~(***)~~
Cold Vertcal beam	none	$> 3 \cdot 10^{9}$ s (TRIGA 3.4 MW)	> × 1,000 u (***)

DUSEL

There is no competition in the world ↗

Stability of matter from Neutron-Antineutron transition search

$T_A = R * (\tau_{free})^2$, where R is "nuclear suppression factor" in intranuclear transition



NNbar Summary

New physics beyond the SM can be discovered by NNbar search at DUSEL
Expected improvement in N-Nbar search sensitivity is a big factor of >1,000!

If discovered:

- n→nbar will establish a new force of nature and a new phenomenon leading to exploration of the new physics beyond the SM at the energy scale above TeV
- will we relevant for understanding of matter-antimatter asymmetry

If NOT discovered:

- within the reach of improved experimental sensitivity will set a new limit on the stability of matter exceeding the sensitivity of X-large nucleon decay experiments

Status of Baryon → Lepton transition search with (B–L)V

Some |Δ(B–L)|=2 nucleon decay modes (PDG’06+)

(B–L)≠0 modes	Limit at 90% CL	S/B	Experiment’year
$n \rightarrow e^{-}\pi$	>6.5×10³¹ yr	0/1.6	IMB’88
$n \rightarrow \mu^{-}K^{+}$	>5.7×10³¹ yr	0/2.8	Fréjus’91
$p \rightarrow e^{-}\pi^{+}\pi^{+}$	>3.0×10³¹ yr	1/2.5	Fréjus’91
$n \rightarrow \mu^{-}\pi^{+}\pi^{0}$	>3.4×10³¹ yr	0/0.78	Fréjus’91
$p \rightarrow e^{-}\pi^{+}K^{+}$	>7.5×10³¹ yr	81/127	IMB3’99
$p \rightarrow \mu^{-}\pi^{+}K^{+}$	>2.45×10³² yr	3/4	IMB3’99
$n \rightarrow \nu\gamma$	>2.8×10³¹ yr	163/145	IMB3’99
$n \rightarrow \nu\gamma\gamma$	>2.19×10³² yr	5/7.5	IMB3’99
$p \rightarrow \nu\nu e^{+}$	>1.7×10³¹ yr	152/153.7	IMB3’99
$p \rightarrow \nu\nu\mu^{+}$	>2.1×10³¹ yr	7/11.23	Fréjus’91
$n \rightarrow e^{+}e^{-}\nu$	>2.57×10³² yr	5/7.5	IMB3’99
$n \rightarrow \mu^{+}\mu^{-}\nu$	>7.9×10³¹ yr	100/145	IMB3’99
$n \rightarrow \nu\nu\bar{\nu}$	>1.9×10²⁹ yr	686.8/656	SNO’04
$n \rightarrow \nu\nu\bar{\nu}$	>5.8×10²⁹ yr	0/0.82	KamLAND’06

Rest of my talk

- These limits are lower than limits for Δ(B–L) = 0 PDK modes and are determined by background
- In the presence of physics background new limits $\sim \sqrt{kt \times yr}$
- In the presence of background effect discovery can not be made

KamLAND – neutrino experiment

KamLAND Publications:

1) “First results from KamLAND: Evidence for reactor anti-neutrino disappearance”
Phys.Rev.Lett.90:021802,2003

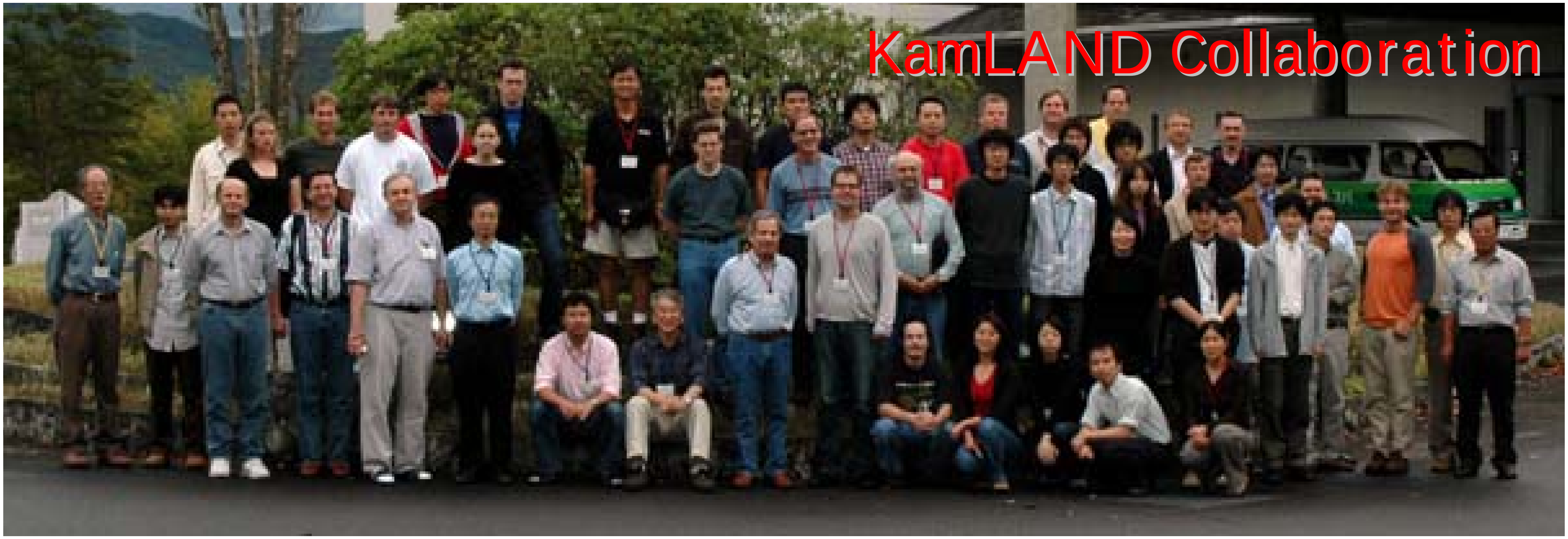
2) “A High sensitivity search for $\bar{\nu}_e$'s from the sun and other sources at KamLAND”
Phys.Rev.Lett.92:071301,2004

3) “Measurement of neutrino oscillation with KamLAND: Evidence of spectral distortion”
Phys.Rev.Lett.94:081801,2005

4) “Experimental investigation of geologically produced antineutrinos with KamLAND”
Nature 436:499-503,2005

5) “Search for the invisible decay of neutrons with KamLAND”
Phys.Rev.Lett.96:101802,2006

KamLAND Collaboration



- Tohoku University: T. Araki, S.Enomoto, K. Furuno, Y. Gando, K. Ichimura, H. Ikeda, **K. Inoue**, Y. Kishimoto, M.Koga, Y. Koseki, T. Maeda, T. Mitsui, M. Motoki, K. Nakajima, K. Nakamura, H.Ogawa, M. Owada, K. Owada, J.-S. Ricol, I. Shimizu, J. Shirai, F. Suekane, A. Suzuki, K. Tada, S. Takeuchi, K. Tamae, Y. Tsuda, H. Watanabe
- University of Alabama: J. Busenitz, T. Classen, Z. Djurcic, G. Keefer, D.S. Leonard, A. Piepke, E. Yakushev
- LBNL/UC Berkeley: B.E. Berger, Y.D.Chan, M.P. Decowski, D.A. Dwyer, S.J. Freedman, B.K. Fujikawa, J. Goldman, F. Gray, K.M. Heeger, L. Hsu, K.T. Lesko, K.-B. Luk, H. Murayama, T. O'Donnell, A.W.P. Poon, H.M. Steiner, L.A. Winslow
- California Institute of Technology: C. Jillings, C. Mauger, R.D. McKeown, P. Vogel, C. Zhang
- Drexel University: C.E. Lane, T. Miletic
- University of Hawaii: G. Guillian, J.G. Learned, J. Maricic, S. Matsuno, S. Pakvasa
- Kansas State University: G.A. Horton-Smith
- Louisiana State University: S. Dazeley, S. Hatakeyama, A. Rojas, R.C. Svoboda
- University of New Mexico: B.D. Dieterle
- Stanford University: J. Detwieler, G.Gratta, K. Ishii, N. Tolich, Y. Uchida
- University of Tennessee: M. Batygov, W. Bugg, Y. Efremenko, Y. Kamyshkov, A. Kozlov
- TUNL/NCSU: H.J. Karwowski, D.M. Markoff, R.M. Rohm, W. Tornow, R. Wendell
- IHEP, Beijing: M.-J. Chen, Y.-F. Wang
- CEN Bordeaux: F. Piquemal

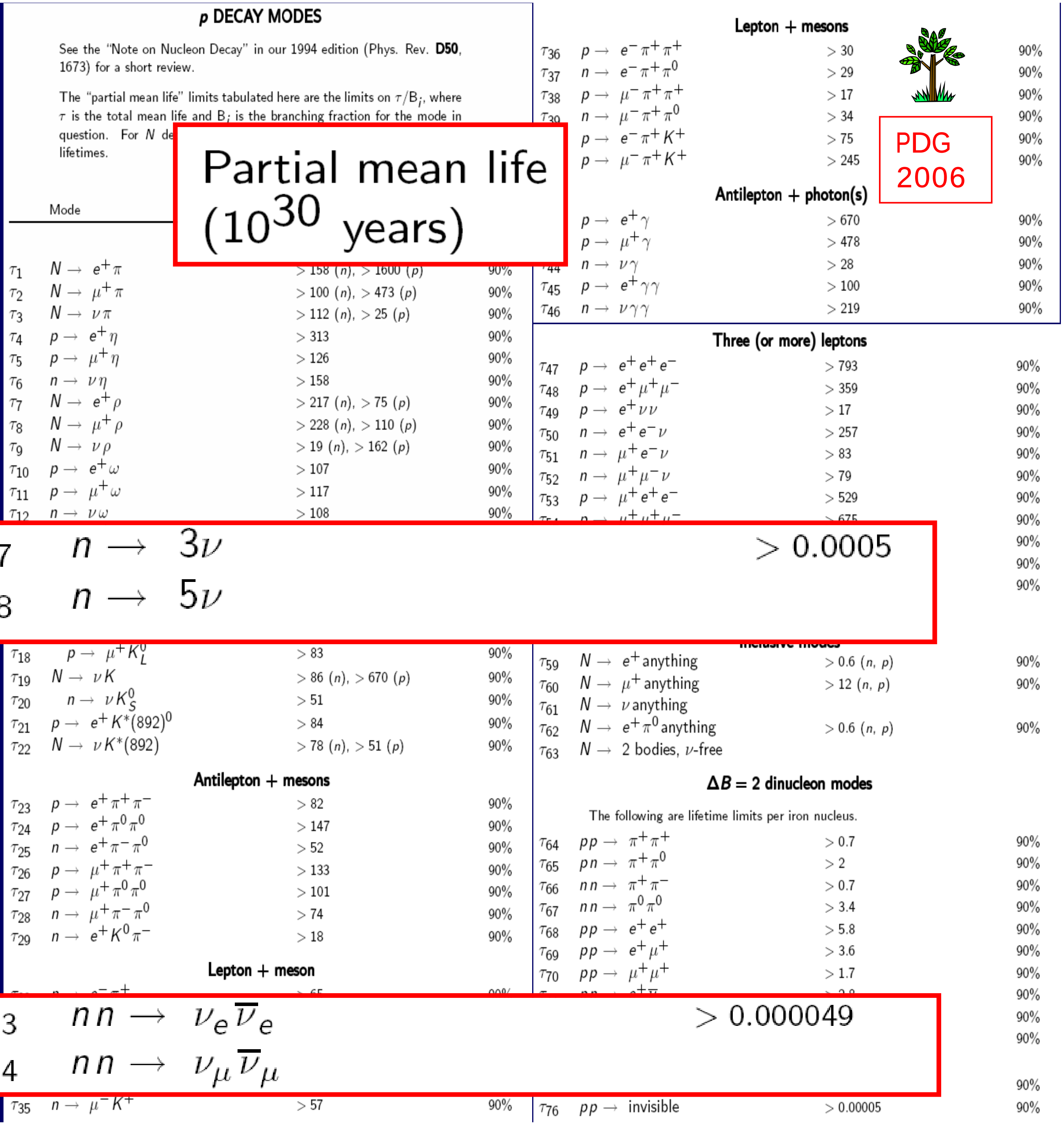
"Search for the invisible decay of neutrons with KamLAND"
T. Araki et al, PRL 96:101802, 2006

- for neutrons inside nuclei
- search for neutron "invisible decay" modes
  ⇒ baryon number violation search
- decays that can not be seen in identifiable modes
- decays in the modes that are least constrained
  by existing experimental limits
- decays in the modes that might violate (B–L) needed
  for explanation of Matter-Antimatter asymmetry
- e.g. n → neutrinos, nn → neutrinos
- or n, nn → anything invisible reasonably allowed
  by the conservation laws which are not in question
  (e.g. electric charge, angular momentum)
- detectability is independent of the specifics of the process
  as long as the rest-energy of n is carried away by the
  undetected particles

Most of measured nucleon decay modes in PDG 2006 have lifetime > (1-100)·10^{30} yr

but few exceptions:

These are neutron disappearance modes



p DECAY MODES

See the "Note on Nucleon Decay" in our 1994 edition (Phys. Rev. **D50**, 1673) for a short review.

The "partial mean life" limits tabulated here are the limits on τ/B_i, where τ is the total mean life and B_i is the branching fraction for the mode in question. For N de

lifetimes.

Partial mean life (10^{30} years)

	Mode		
τ_1	$N \to e^+\pi$	> 158 (n), > 1600 (p)	90%
τ_2	$N \to \mu^+\pi$	> 100 (n), > 473 (p)	90%
τ_3	$N \to \nu\pi$	> 112 (n), > 25 (p)	90%
τ_4	$p \to e^+\eta$	> 313	90%
τ_5	$p \to \mu^+\eta$	> 126	90%
τ_6	$n \to \nu\eta$	> 158	90%
τ_7	$N \to e^+\rho$	> 217 (n), > 75 (p)	90%
τ_8	$N \to \mu^+\rho$	> 228 (n), > 110 (p)	90%
τ_9	$N \to \nu\rho$	> 19 (n), > 162 (p)	90%
τ_{10}	$p \to e^+\omega$	> 107	90%
τ_{11}	$p \to \mu^+\omega$	> 117	90%
τ_{12}	$n \to \nu\omega$	> 108	90%

τ_{57}	$n \to 3\nu$	> 0.0005
τ_{58}	$n \to 5\nu$	

τ_{18}	$p \to \mu^+K^0_L$	> 83	90%
τ_{19}	$N \to \nu K$	> 86 (n), > 670 (p)	90%
τ_{20}	$n \to \nu K^0_S$	> 51	90%
τ_{21}	$p \to e^+K^*(892)^0$	> 84	90%
τ_{22}	$N \to \nu K^*(892)$	> 78 (n), > 51 (p)	90%

Antilepton + mesons

τ_{23}	$p \to e^+\pi^+\pi^-$	> 82	90%
τ_{24}	$p \to e^+\pi^0\pi^0$	> 147	90%
τ_{25}	$n \to e^+\pi^-\pi^0$	> 52	90%
τ_{26}	$p \to \mu^+\pi^+\pi^-$	> 133	90%
τ_{27}	$p \to \mu^+\pi^0\pi^0$	> 101	90%
τ_{28}	$n \to \mu^+\pi^-\pi^0$	> 74	90%
τ_{29}	$n \to e^+K^0\pi^-$	> 18	90%

Lepton + meson

τ_{73}	$nn \to \nu_e\overline{\nu}_e$	> 0.000049
τ_{74}	$nn \to \nu_\mu\overline{\nu}_\mu$	

τ_{35}	$n \to \mu^-K^+$	> 57	90%

Lepton + mesons

PDG 2006

τ_{36}	$p \to e^-\pi^+\pi^+$	> 30	90%
τ_{37}	$n \to e^-\pi^+\pi^0$	> 29	90%
τ_{38}	$p \to \mu^-\pi^+\pi^+$	> 17	90%
τ_{39}	$n \to \mu^-\pi^+\pi^0$	> 34	90%
	$p \to e^-\pi^+K^+$	> 75	90%
	$p \to \mu^-\pi^+K^+$	> 245	90%

Antilepton + photon(s)

	$p \to e^+\gamma$	> 670	90%
	$p \to \mu^+\gamma$	> 478	90%
	$n \to \nu\gamma$	> 28	90%
τ_{45}	$p \to e^+\gamma\gamma$	> 100	90%
τ_{46}	$n \to \nu\gamma\gamma$	> 219	90%

Three (or more) leptons

τ_{47}	$p \to e^+e^+e^-$	> 793	90%
τ_{48}	$p \to e^+\mu^+\mu^-$	> 359	90%
τ_{49}	$p \to e^+\nu\nu$	> 17	90%
τ_{50}	$n \to e^+e^-\nu$	> 257	90%
τ_{51}	$n \to \mu^+e^-\nu$	> 83	90%
τ_{52}	$n \to \mu^+\mu^-\nu$	> 79	90%
τ_{53}	$p \to \mu^+e^+e^-$	> 529	90%

Inclusive modes

τ_{59}	$N \to e^+$ anything	> 0.6 (n, p)	90%
τ_{60}	$N \to \mu^+$ anything	> 12 (n, p)	90%
τ_{61}	$N \to \nu$ anything		
τ_{62}	$N \to e^+\pi^0$ anything	> 0.6 (n, p)	90%
τ_{63}	$N \to$ 2 bodies, ν-free		

$\Delta B = 2$ dinucleon modes

The following are lifetime limits per iron nucleus.

τ_{64}	$pp \to \pi^+\pi^+$	> 0.7	90%
τ_{65}	$pn \to \pi^+\pi^0$	> 2	90%
τ_{66}	$nn \to \pi^+\pi^-$	> 0.7	90%
τ_{67}	$nn \to \pi^0\pi^0$	> 3.4	90%
τ_{68}	$pp \to e^+e^+$	> 5.8	90%
τ_{69}	$pp \to e^+\mu^+$	> 3.6	90%
τ_{70}	$pp \to \mu^+\mu^+$	> 1.7	90%
τ_{76}	$pp \to$ invisible	> 0.00005	90%

Previous disappearance limits

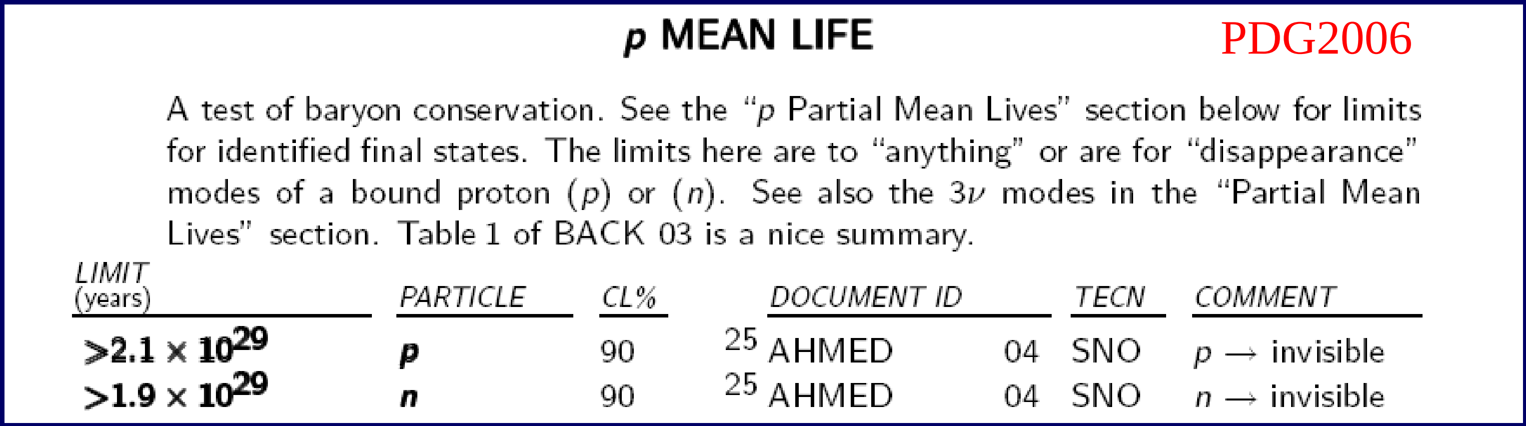
J. Learned, F. Reines, A. Soni, PRL**43** (1979) 907

$$n \to 3\nu_\mu \qquad \tau > 5\times10^{26}\ years$$

Y. Suzuki, et al (Kamiokande II), " … $n\to\nu\nu\bar{\nu}$ …"
Phys. Lett. B311 (1993) 357

$$n \to 3\nu \qquad \tau > 4.9\times10^{26}\ years$$

Recently: S. N. Ahmed *et al.* (SNO Collaboration), PRL**92**, 102004 (2004).



***p* MEAN LIFE**

PDG2006

A test of baryon conservation. See the "*p* Partial Mean Lives" section below for limits for identified final states. The limits here are to "anything" or are for "disappearance" modes of a bound proton (*p*) or (*n*). See also the 3ν modes in the "Partial Mean Lives" section. Table 1 of BACK 03 is a nice summary.

LIMIT (years)	*PARTICLE*	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>2.1 × 10^{29}	***p***	90	[25] AHMED	04	SNO	$p \to$ invisible
>1.9 × 10^{29}	***n***	90	[25] AHMED	04	SNO	$n \to$ invisible

de-excitation of γ-rays following *n*-dis in ^{16}O

H.O. Back et al (Borexino)
Phys. Lett. B563(2003) 23

$$nn \to inv \qquad \tau > 4.9\times10^{25}\ years$$

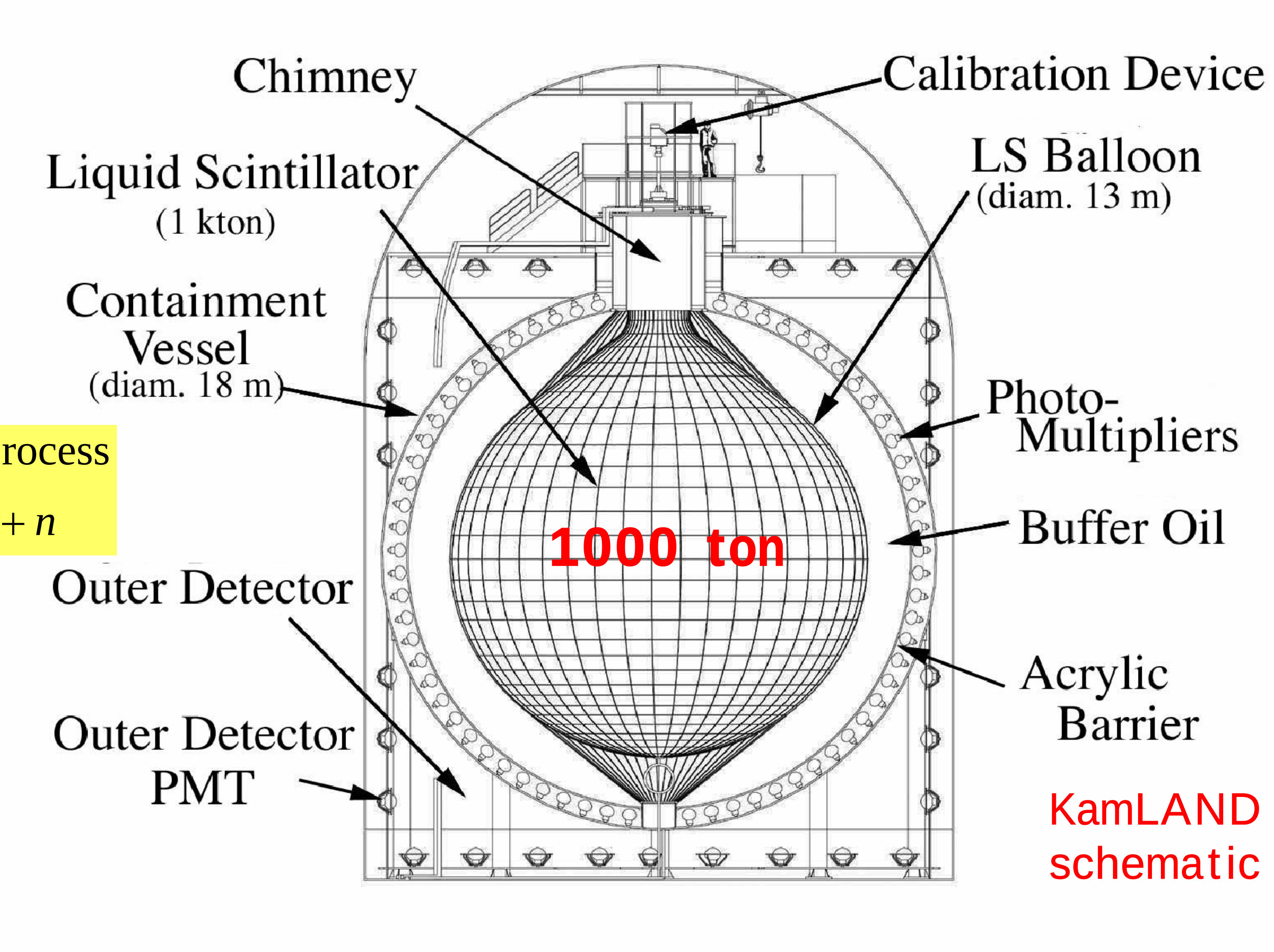
Decays of unstable nuclides resulting from *nn*-dis in ^{12}C, ^{13}C and ^{16}O

KamLAND Detector

data collected since early 2002

$\bar{\nu}$ detection process

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



KamLAND schematic

Special features of KamLAND detector:

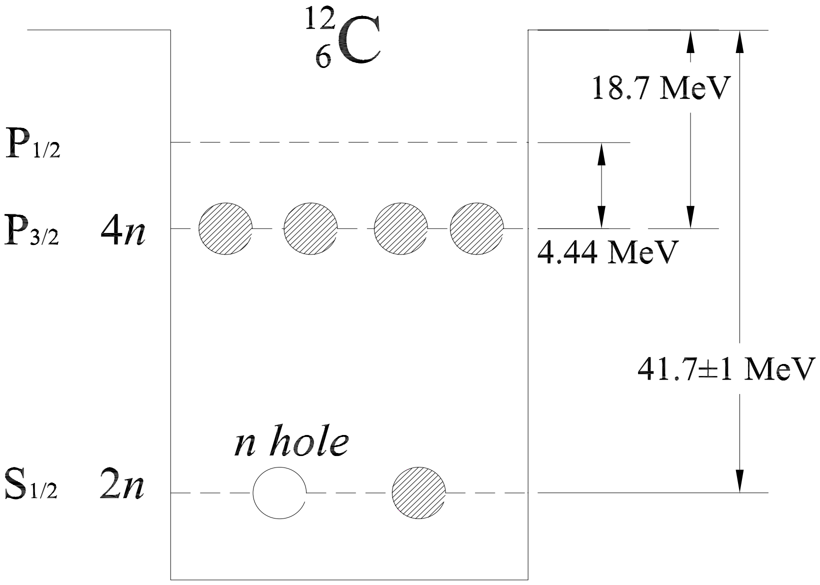
- Large mass: 1,000 ton of Liquid Scintillator (~ CH_2)
- Low detection threshold: < 1 MeV
- Good energy resolution: $\sim 6.2\% / \sqrt{E(MeV)}$
- Position reconstruction accuracy in x,y,z: ~ 20 cm
- neutron detection efficiency close to 100%
- Low background: 2700 mwe; buffer shield; veto-shield; Rn shield; pure LS: U, Th < 10^{-16} g/g

These features allow observation of the sequence of nuclear de-excitation events correlated in space and time produces by disappearance of neutron from ^{12}C

How it happens:

SIGNATURES OF NUCLEON DISAPPEARANCE IN LARGE UNDERGROUND DETECTORS. *Edwin Kolbe and YK*
Phys.Rev.D67:076007, 2003

$${}^{12}C \to n\left(in\ \ s_{1/2}\ \ state\ \ disappeared\right) + {}^{11}C^{*}\left(excited\right)$$



$${}^{11}C^{*} \to deexcitation\ \ particles$$

$$+\beta - decay\ \ of\ \ daughter\ \ nucleus$$

2 neutrons out of 6 in ${}^{12}C$ are is $s_{1/2}$ state

Modes favorable for detection in KL

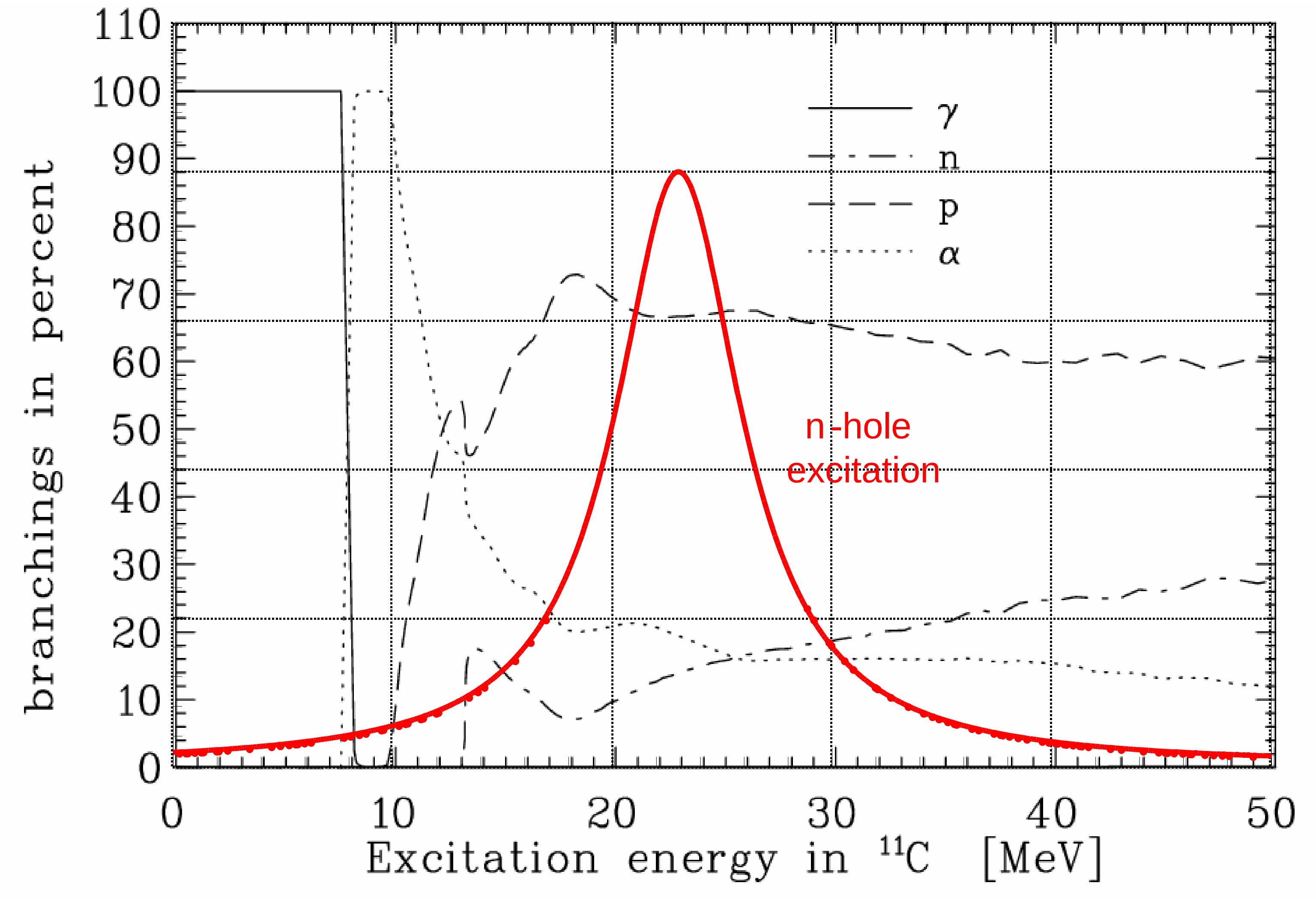
n dis.$^{11}C^* \to$	Br %	Hits	3-rd hit $T_{1/2}$, Q_{EC}
$n + {}^{10}C_{gs}\,(\beta^+)$	3.0	3	19.3 s, 3.65 MeV
$n + \gamma + {}^{10}C_{gs}\,(\beta^+)$	2.8	3	19.3 s, 3.65 MeV
nn dis.$^{10}C^* \to$			
$n + {}^{9}C_{gs}\,(\beta^+)$	6.2	3	0.127 s, 16.5 MeV
$n + p + {}^{8}B_{gs}\,(\beta^+,\alpha)$	6.0	3	0.77 s , 18 MeV

↑ fast *n*

↑ ± 30% uncertainty

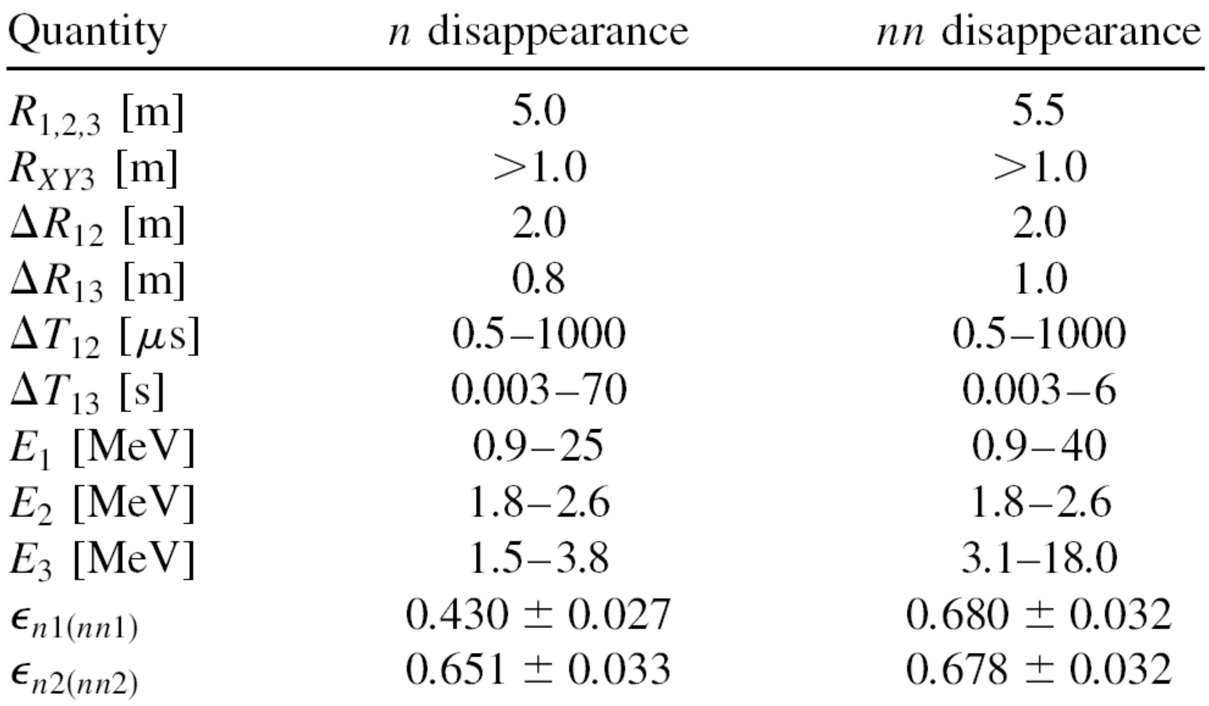
De-excitation branching of $J^{\pi}=½^{+}$ $^{11}C^{*}$ state vs excitation energy

in statistical code SMOKER: J.J. Cowan, F.-K. Thielemann, J.W. Truran, Phys. Rep. 208 (1991) 267



Selection criteria and efficiency

Hit 1 → Hit 2 → Hit 3



Quantity	n disappearance	nn disappearance
$R_{1,2,3}$ [m]	5.0	5.5
R_{XY3} [m]	>1.0	>1.0
ΔR_{12} [m]	2.0	2.0
ΔR_{13} [m]	0.8	1.0
ΔT_{12} [μs]	0.5–1000	0.5–1000
ΔT_{13} [s]	0.003–70	0.003–6
E_1 [MeV]	0.9–25	0.9–40
E_2 [MeV]	1.8–2.6	1.8–2.6
E_3 [MeV]	1.5–3.8	3.1–18.0
$\epsilon_{n1(nn1)}$	0.430 ± 0.027	0.680 ± 0.032
$\epsilon_{n2(nn2)}$	0.651 ± 0.033	0.678 ± 0.032

+ muon veto

MC

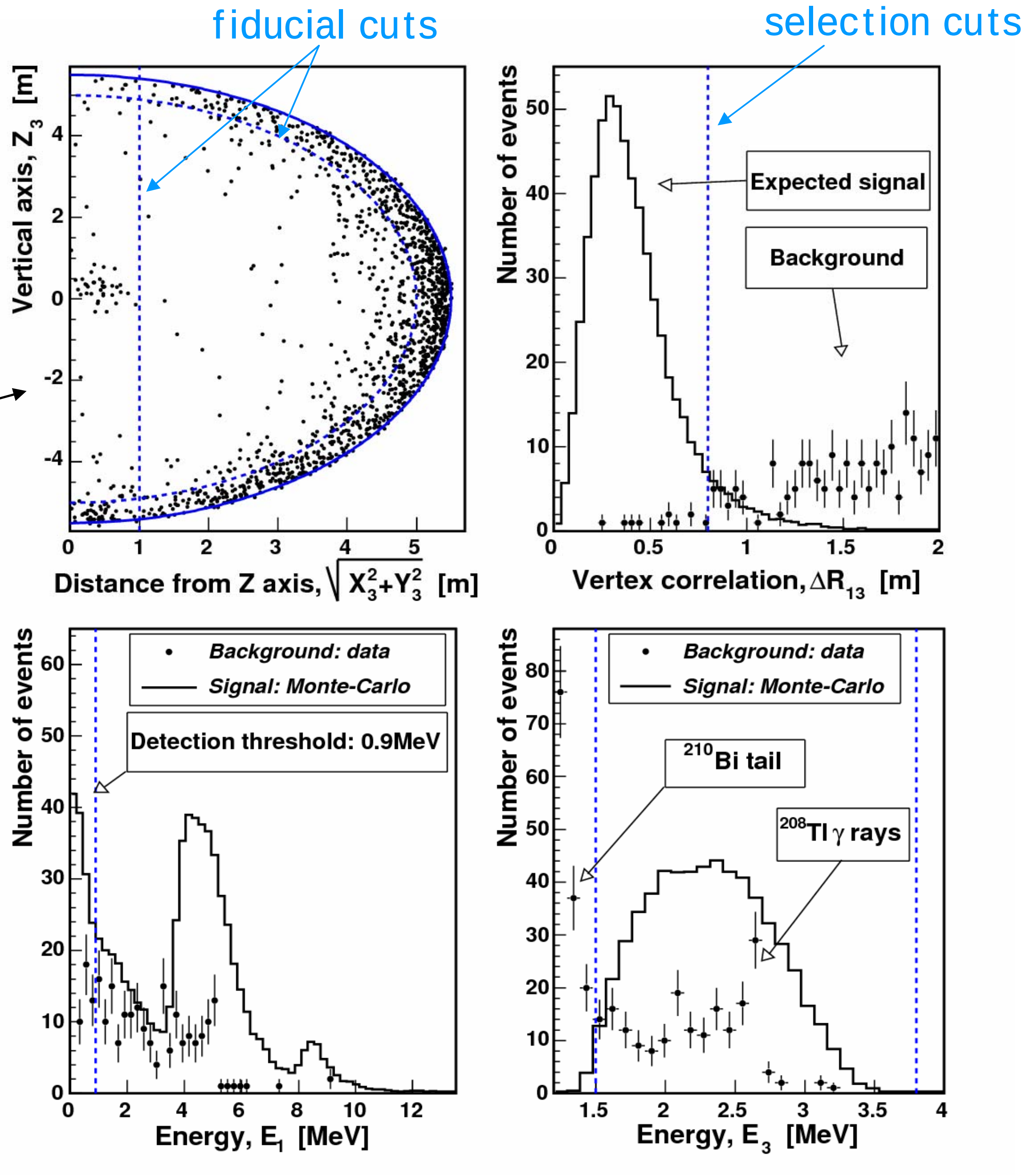
Note: due to emission of *n* first two hits are similar to antineutrino signature in KL

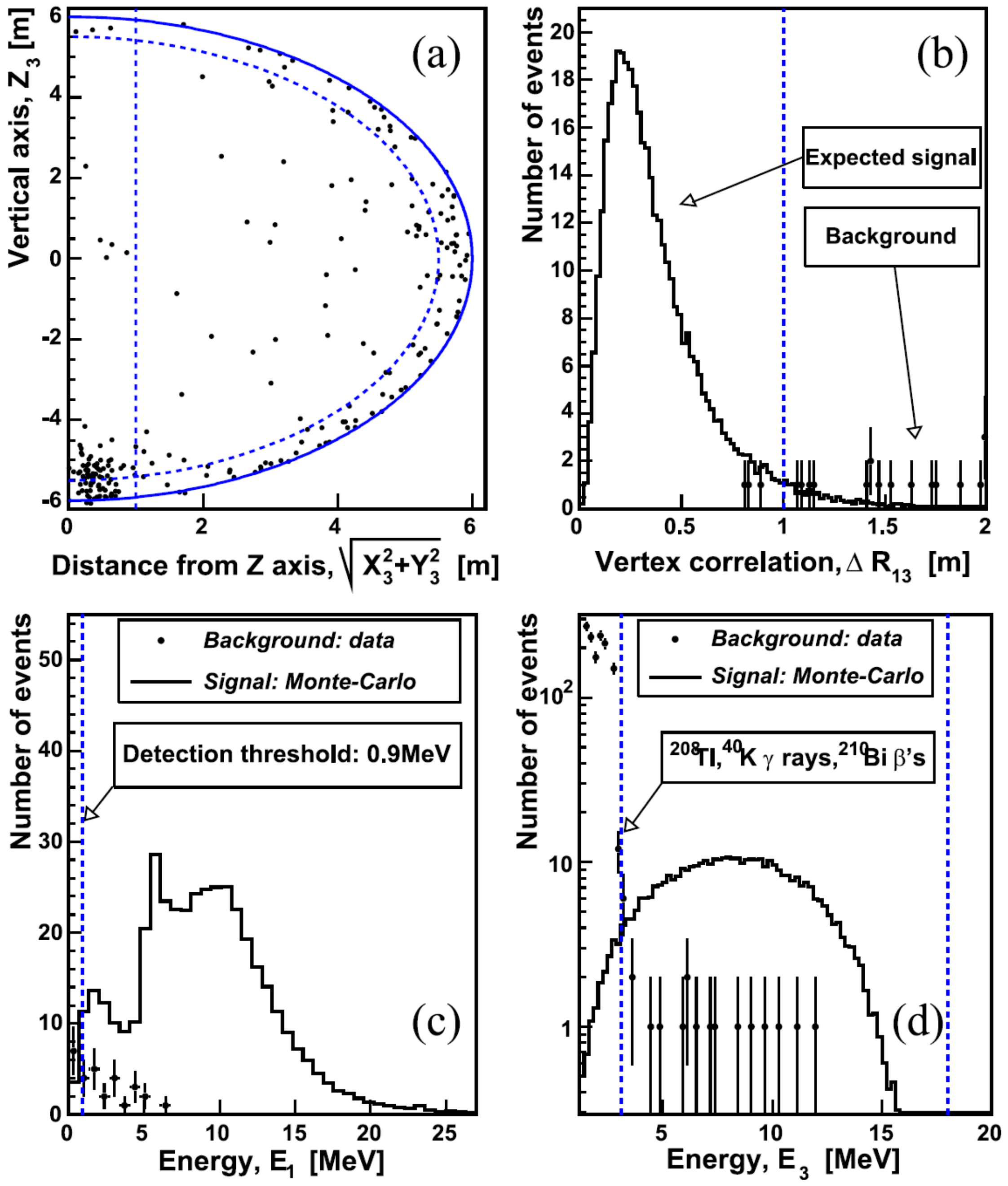
For ~ 1.5 year data analyzed:

mode	data sample	events observed	meas. accidental background
n-dis	838 ton·yr	1	0.82±0.26
nn-dis	1119 ton·yr	0	0.018±0.010

Search for one n disappearance

Enhanced correlated background in 150 – 1000 s off-time window for 3-rd hit, R<5.5 m, and ΔR_{13} < 2m



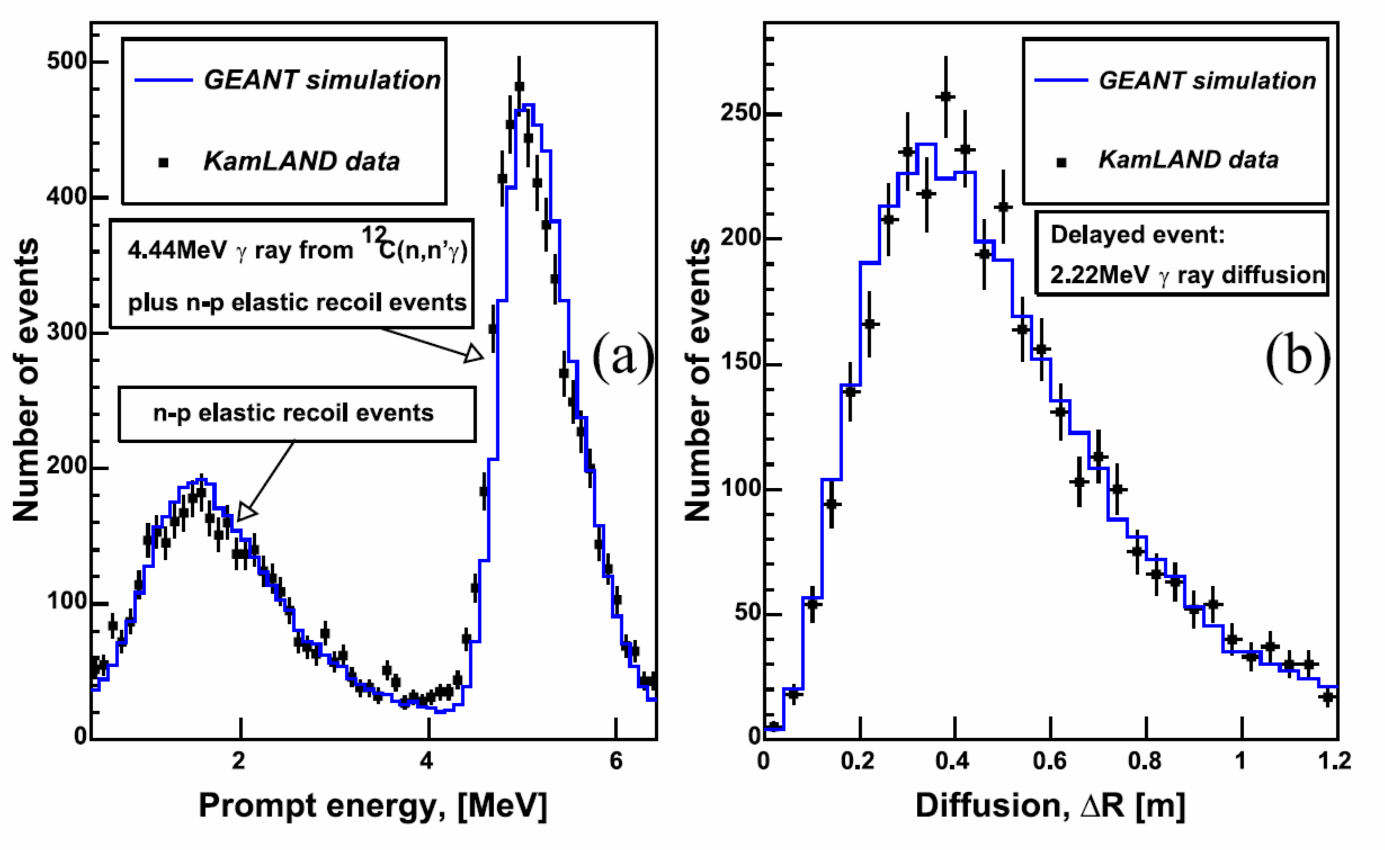


Search for nn disappearance

Enhanced correlated background
in 10 – 1000 s
off-time window for
3-rd hit, R<6 m,
and $\Delta R_{13} < 2$m

Efficiencies of position and energy cuts are based on MC simulations of de-excitation events, where fast neutron detection in LS is the most critical part.
→ GEANT vs SCINFUL (ORNL code) comparison and tuning.

Am-Be neutron source in KamLAND: data vs GEANT Monte Carlo



Results

Major systematic uncertainty ±30%
from the model predictions of de-excitation branchings

$$\tau(n \to inv) > 5.8 \times 10^{29}\, yr \quad \text{at} \quad 90\%\text{CL}$$

factor of 3 better than previous SNO result

$$\tau(nn \to inv) > 1.4 \times 10^{30}\, yr \quad \text{at} \quad 90\%\text{CL}$$

improvement of factor 10,000 to previous Borexino limit

In the future:

- more statistics ×3 in hands
- improved analysis tools
- liquid scintillator purification in KL-II should reduce accidental background

International Workshop: "Search for Baryon and Lepton number violation"

September 20-22, 2007 at LBL, Berkley, CA

- E-W SM sphaleron transition and violation of (B–L)
- role (B – L) in baryogenesis and cosmology
- status of leptogenesis
- relation of (B-L) violation with Left-Right Symmetry
- status of proton decay search and corresponding models
- review of proposed PDK search experiments
- n-nbar oscillations models and expectations for osc. time
- n-nbar future experimental plans
- Majorana neutrino and $2\beta0\nu$ search
- sterile neutrinos and mirror matter search
- (B – L) violating nucleon decays (like $n\to3\nu$ and others)
- τ decays with (B – L) violation
- (B – L) violation search in hyperon decays
- searches of B, L, and B–L violation at LHC and ILC

Workshop website: http://inpa.lbl.gov/blnv/blnv.htm