P5 Meeting • Brookhaven • December 16, 2013

Search for Neutron to Antineutron Oscillations

On behalf of

NNbarX Collaboration

(see backup slides)

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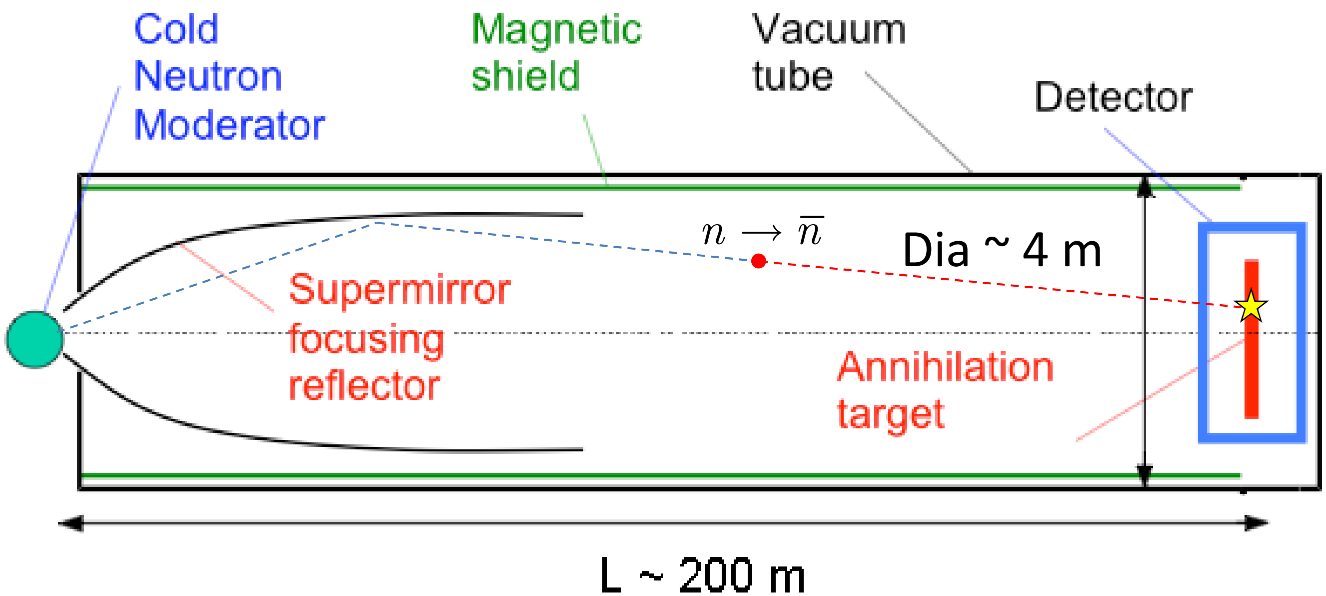
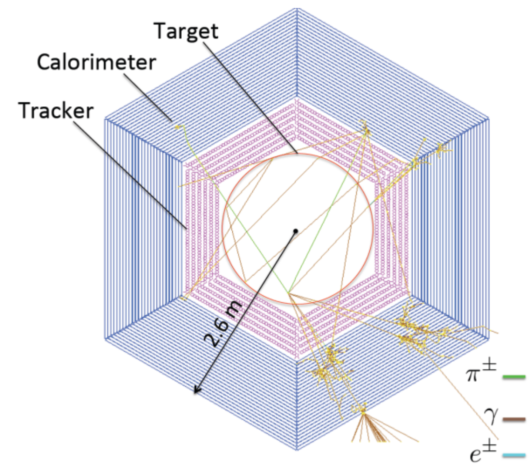
What makes n-nbar search unique?

- New window of exploration of $\Delta B=2$ and (B – L) violation on a different scale than $\Delta B=1$ proton decay: above LHC up to $\sim 10^{12}$ GeV
- Possibility of significant increase of discovery sensitivity $\sim \times$ 1,000 (compared to 20-years old result from ILL reactor)
- Possibility of building backgroundless detector with 1 event = discovery;
- Possibility of controlling a (non-zero) n-nbar effect by weak magnetic field;
- In case of null discovery: test Post-Sphaleron Baryogenesis (PSB) models;
- NO direct competition, although world interest in n-nbar is converging to one collaboration
- NNbarX is an example of a strong collaboration between HEP and NP communities

K. Babu et. al (NNbarX Collaboration), Neutron-Antineutron Oscillations: A Snowmass 2013 White Paper http://arxiv.org/abs/arXiv:1310.8593

Scheme of Horizontal N-Nbar experiment Conceived for Project X or ESS Neutron Targets

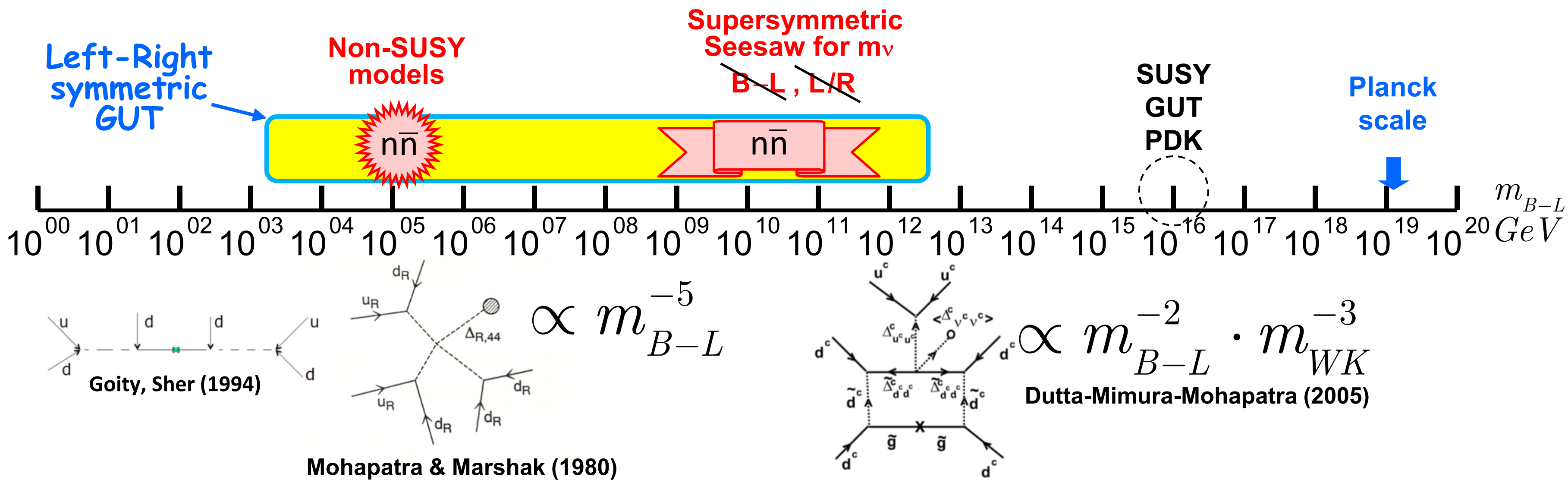




Notional timeline: (parallel to n-source development & construction)
3 years: for R&D, design, and optimization of performance/cost;
4 years: for experiment construction after n-source is identified;
3 years: of measurements at nominal intensity for possibility of obtaining sensitivity increase of ~ × 500 compared to the previous ILL reactor-based experiment (see backup slides for sensitivity definition and ILL experiment). Oscillation time τ > 2.0 E+9 sec will be reached.

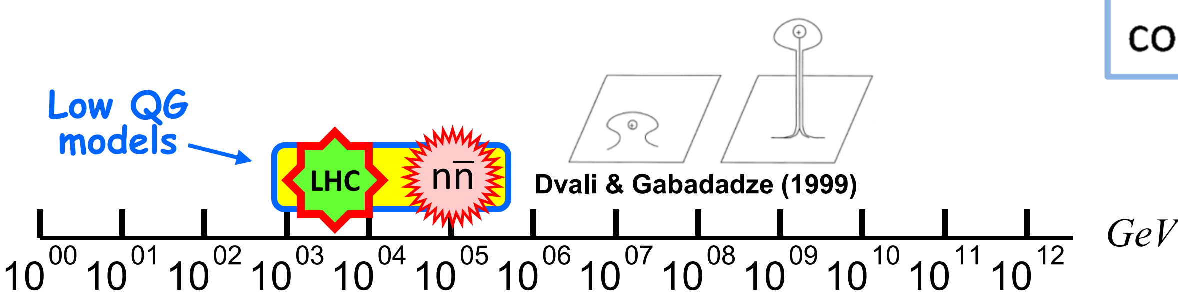
For further sensitivity reach more R&D is required for colder neutron sources and vertical experiment layout. For more details see Snowmass n-nbar white paper http://arxiv.org/abs/arXiv:1310.8593 and backup slides.

$\Lambda - scales\ \ of\ \ n \rightarrow \bar{n}$ and $(B-L)V$



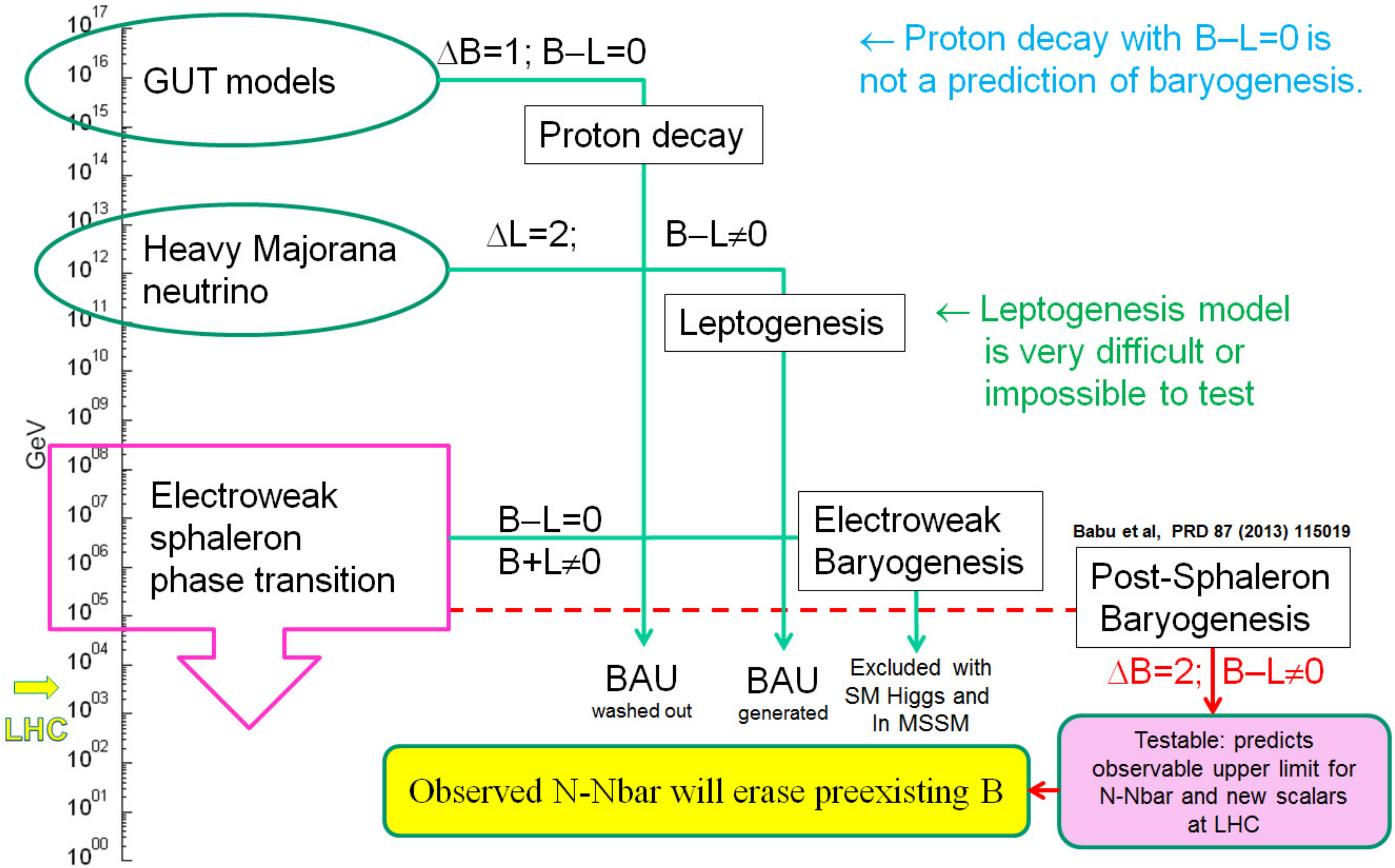
Baryogenesis at TeV scale
or PSB Babu et al.,
PRD 87, 115019 (2013),
connected to LHC observables

Experimental motivation!
large increase of sensitivity:
factor of ×1,000 is possible
compared to existing limit



Shrock & Nussinov (2002)
Dolgov (2011)

Baryogenesis Models



Positive $n\bar{n}$ result will probe different energy scales.
Null $n\bar{n}$ result can rule out PSB, a testable model of baryogenesis.

Scenarios

for free neutron experiment siting

1. Baseline horizontal option was developed for spallation target in Project X program http://arxiv.org/abs/1306.5009 and discussed at Snowmass.
2. It is under consideration at European Spallation Source (ESS) to include n-nbar search in ESS Fundamental Physics program (see backup slides; sensitivity is the same or better than with Project X; background is better due to pulsed mode).
3. LANSCE at Los Alamos (siting is possible in existing area A, with vertical layout)
4. Indian Spallation Neutron Source (ISNS) 1 MW is considering possibility of n-nbar search experiment (possibly with same sensitivity as with Project X).
5. Second Target Station at SNS in Oak Ridge (it is BES not HEP facility; same or slightly smaller sensitivity than with Project X).
6. High Flux Isotope Reactor at Oak Ridge (it is BES not HEP facility; same sensitivity as with Project X)
7. NCNR Reactor at NIST (smaller sensitivity)

Sharing existing national facilities between BES, HEP, NP at DOE and Dept. of Commerce could make some scenarios more viable.

Top Level Cost Estimate in FY2014 US M$

(including 35% contingency)

Was developed in scenario of horizontal n-nbar experiment for Project X:

	#	WBS Item	Basis of estimate	M$
source	1	Spallation target system and cryogenic moderator	Based on experience of SNS spallation target construction	218
experiment	2	Large vacuum tube with focusing reflector and magnetic shield	Based on experience of NP community with neutron beam elements construction	77
	3	Antineutron target and annihilation detector	Based on experience of FNAL in detector construction	63

Higher level of WBS is available on request

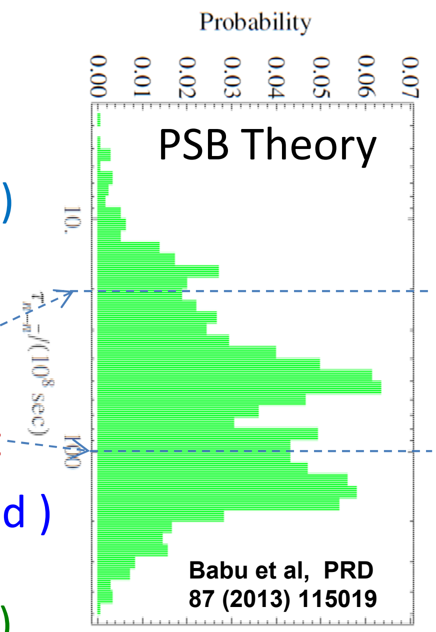
In other scenarios when cold neutron source can be made ready available, like ESS, LANSCE, ISNS, SNS-II, HFIR, item 1 would be eliminated or greatly reduced.

Limits of NNbar search and R&D

$$1 \text{ ILL unit "u" of sensitivity} = N \times \overline{t^2} = 1.5 \times 10^9 \ \frac{n}{s} \cdot s^2$$

#	τ (free nnbar) oscillation parameter	in ILL units of appearance probability
1	0.86×10^8 s	1u
2	3.45×10^8 s	16u
3	7.5×10^8 s	76u
4	2×10^9 s	500u
5	1×10^{10} s	13,500u
6	1×10^{10} s	13,500u

←Free neutrons at ILL (1994)
←Super-K (2011), 22.5kt, 4 years (bkgr)
←Hyper-K 500kt, 10 years
←Horizontal beam (Project X, ESS)
←VCN-UCN source with vertical layout
←LBNE, 35 kt, 10 yr ? (if no background)



Searches with free and bound neutrons are complementary (see backup)

4. Known technologies. R&D required for optimization performance/cost
5. New R&D is required on “4π” enhanced VCN, UCN sources, and vertical layout
6. R&D is required for demonstration of atm. ν vs nnbar suppression in LAr detectors

2,3,6. Theory R&D is required for Lattice calculations of QCD suppression factor

NNbarX R&D program for design of n-nbar experiment with optimized performance/cost for an available siting opportunity

1. Super-mirror cost reduction, shape, radiation damage
2. Active/passive magnetic shielding down to 1 nT
3. Vacuum system design
4. Economic annihilation detector design
5. Measurement at LANSCE of detectors response to fast neutrons
6. Management of cold neutron (n,γ) background
7. More brighter and colder neutron moderators
8. Optimization of sensitivity vs parameters including cost
9. Simulations of annihilation events with detector performance
10. Participation in LBNE effort for exploring n-nbar potentials in LAr

(Physics Report paper is in preparation to reflect R&D work done so far)

Required for 3-years R&D phase: research time of US experimental faculty + 3 postdocs + support for 3 graduate students + travel with total $520K per year spread to the University's grants.

Endorsement by P5 to:

1. Explore possibilities of facilities in the US
   (PIP-II; LANL, SNS, HFIR, NIST) and elsewhere
2. Explore possibilities of participation in a European ESS n-nbar effort
3. Pursue a 3-years R&D program for the development of the conceptual horizontal n-nbar experiment with optimized sensitivity/cost and new techniques
4. Pursue collaboration with US National Laboratories
   ANL, BNL, FNAL, LANL, NIST, ORNL in n-nbar research
5. Development of International Collaboration.
   We collaborating now with Japan, India, France and Russia;
   will grow collaboration in Europe: ESS and possibly CERN

Backup slides

- NNbarX Collaboration
- ESS interest/intention
- Siting and possible cost-sharing
- NNbar theory, Probability, Sensitivity
- Previous ILL-based experiment with free n
- Sensitivity gains and improvement factors
- Vertical version
- Annihilation Detector
- Feasibility assessment
- N-Nbar inside nuclei; comparison with free n
- CPT test if n-nbar will be observed

Neutron-Antineutron Oscillations
NNbarX Collaboration (2013)

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ESS opportunity

European community is exploring possibility of performing n-nbar search at new European Spallation Source (ESS) that is in CD2 equivalent status and will start operation in ~ 2019. This possibility appeared and being discussed for only few weeks.

Today (Dec 16) STAP Panel is considering n-nbar possibility for ESS. It is presented by Gustaaf Brooijmans (Columbia University). Following couple of slides were endorsed by ESS.

This possibility is very cost-effective since the construction of the cold neutron source can be provided "free" by ESS; a new collaboration centered in Europe should be formed providing the funding for an experiment. ESS can go through the process of consideration, discussion, and approval of the idea of n-nbar experiment on a scale of ~ 0.5 years.

Why NNbar at ESS?

- Availability of the world most intense neutron source
- Dedicated beam line with large cold moderator possible
- Large acceptance using super mirrors close to the moderator possible
- Long shielded flight path with efficient neutron guides possible
- Background free detection possible
- Improvement in τ of two orders of magnitude compared to previous experiment feasible

ESS position regarding NNbar

- The ESS baseline includes at least one beam line dedicated to fundamental physics
- The ESS construction budget includes contributions to beamlines. For an NNbar experiment additional significant contributions would be required.
- ESS Scientific and Technical Advisory Panel for the fundamental physics beam line will discuss different experiments including NNbar in its next meeting 16 December 2013
- The ESS neutron extraction for the fundamental physics beam line is under design and could be designed to accommodate a large acceptance super mirror close to the moderator
- The proposal for a “pancake” moderator for the neutron scattering instruments open the possibility for a larger moderator on the opposite side of the target for high flux and large acceptance experiments such as NNbar.
- Discussions on-going with Geoff Greene, NNbarX collaboration and Gustaaf Brooijmans to set up an ESS NNbar collaboration. ESS supported workshop planned for spring 2014.

Hosting HEP experiment

- Most favorable option will be to perform n-nbar search in US.
- Several powerful neutron sources exist in US where n-nbar would be feasible (e.g. HFIR reactor or planned SNS second target station at Oak Ridge). These facilities "belong" to BES/DOE who has a different research mission than HEP and therefore projects like n-nbar can not be hosted at these facilities.
- P5 possibly can make recommendations to DOE-at-large through HEP for considering all national facilities as common experimental assets to all US research communities. This would allow us to study other versions of n-nbar and develop new techniques enhancing n-nbar sensitivity; it might also go together well with pursuing the improvements for neutron and nuclear EDM search and having UCN production facility in the country.

On possible cost sharing

- It will depend on the siting/hosting of experiment
- In Project X scenario we assumed (though no solid commitments) that Japan and India will participate and contribute in-kind.
- In ESS scenario (which is very recent) we assume now that US groups will contribute to the detector construction and neutron focusing system as part of a broader ESS-based collaboration. Cold neutron beam will be provided by ESS.
- <u>About NP co-sharing</u>

  US part of NNbarX Collaboration includes people and groups traditionally funded by HEP and NP (either from DOE or NSF). So far support from all agencies for n-nbar development was zero. Previous discussions with DOE-NP so far indicated that n-nbar will not be considered as part of portfolio of NP.

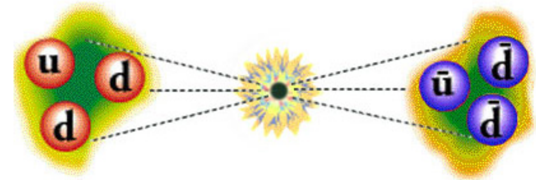
Scope of n-nbar theory

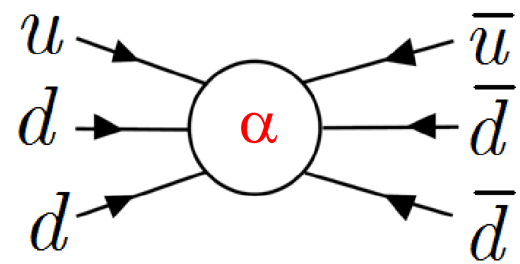
- Baryon number violation with $\Delta B = 2$ as complementary to the proton decay with $\Delta B = 1$ and with different energy scale
- Physics with $(B-L)V$ at scales 10^5-$10^{12} GeV$
- in possible connection with L/R symmetry restoration
- connection with origin of neutrino masses in GUT and SUSY/GUT models
- Tests Post-Sphaleron-Baryogenesis (PSB) models
- Tests low-scale QG models

K. Babu et. al (NNbarX Collaboration), Neutron-Antineutron Oscillations: A Snowmass 2013 White Paper http://arxiv.org/abs/arXiv:1310.8593

n→nbar transition probability

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





α-mixing amplitude (δm)

All beyond SM physics is here

$$H = \begin{pmatrix} E_n & \alpha \\ \alpha & E_{\bar{n}} \end{pmatrix}$$

$$E_n = m_n + U_n \quad ; \quad E_{\bar{n}} = m_{\bar{n}} + U_{\bar{n}}$$

$$U_{n,\bar{n}} = U_0 \pm V \quad \leftarrow \quad V = \text{part different for } n \text{ and } \bar{n}$$

$$P_{n\rightarrow\bar{n}}(t) = \frac{\alpha^2}{\alpha^2+V^2}\cdot\sin^2\left(\frac{\sqrt{\alpha^2+V^2}}{\hbar}\cdot t\right)$$

where V is a potential symmetrically different for n and $\bar{n}$
(e.g. due to non-compensated Earth mag. field, or nuclear potential);
t is observation time in an experiment.

In ideal situation of no suppression i.e.
"vacuum oscillations" : $V = 0$
and experimentally t ~ 0.1 s to 10 s

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

$\tau_{n\bar{n}} = \frac{\hbar}{\alpha}$ is characteristic "oscillation" time [$\alpha < 2\cdot 10^{-24}\,eV$, as presently known]

Existing exp. limits are set by at ILL (free n) and by Super-K (bound n)

Predictions of theoretical models: observable effect around $\alpha \sim 10^{-25} - 10^{-26}\,eV$

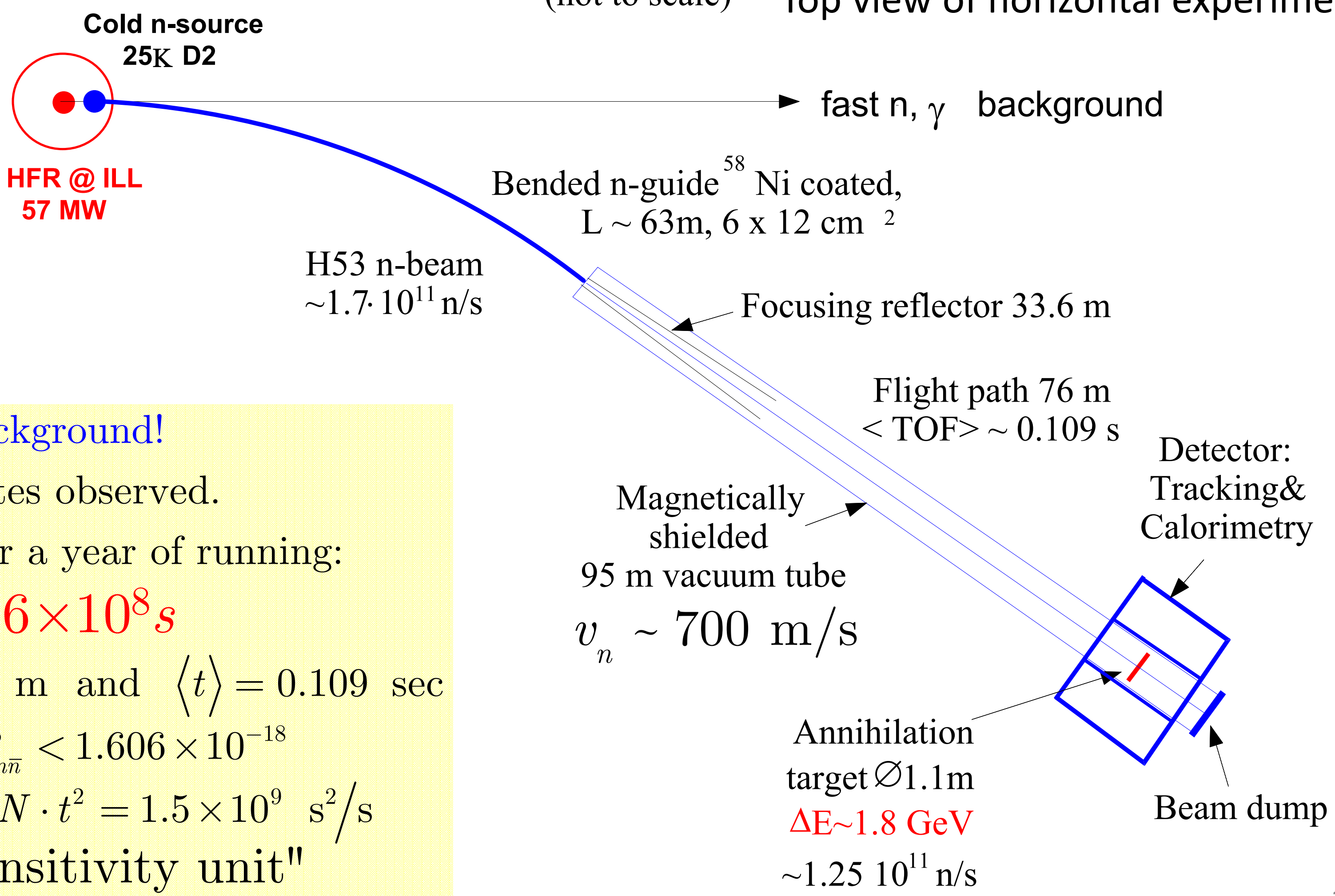
Sensitivity (or figure of merit) is $\rightarrow$ $N_n \times \overline{t}^2$

Previous n-nbar search experiment with free neutrons

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

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

(not to scale) Top view of horizontal experiment



No GeV background!

No candidates observed.

Limit set for a year of running:

$$\tau_{n\bar{n}} > 0.86 \times 10^8 s$$

with L ~ 76 m and $\langle t \rangle = 0.109$ sec

measured $P_{n\bar{n}} < 1.606 \times 10^{-18}$

sensitivity: $N \cdot t^2 = 1.5 \times 10^9 \;\; s^2/s$

$\doteq$ "ILL sensitivity unit"

Sensitivity $N_n \cdot t^2$ improvement factors

- Use many neutrons → optimized spallation source
- Neutron manipulation by mirror and diffuse reflectors

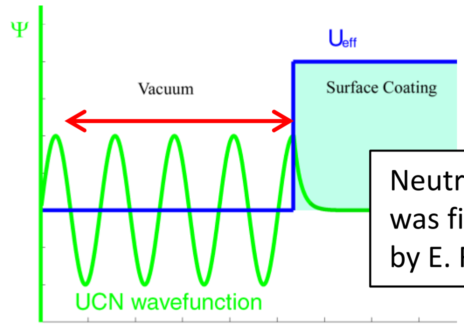
Horizontal layout

- Use solid angle 4π in the source
- Use slow neutrons → cold → VCN → UCN
- Neutron manipulation by gravity → vertical

Vertical layout

Neutron mirrors and Super-mirrors Technique

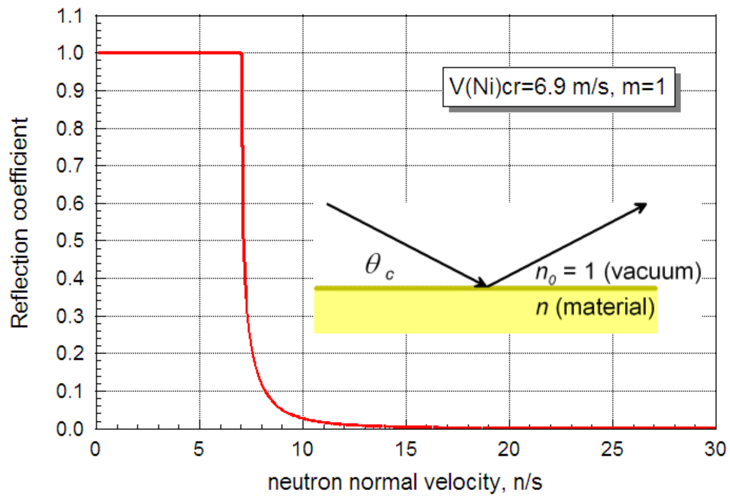
Neutron reflection



Case where $E < U_{eff}$

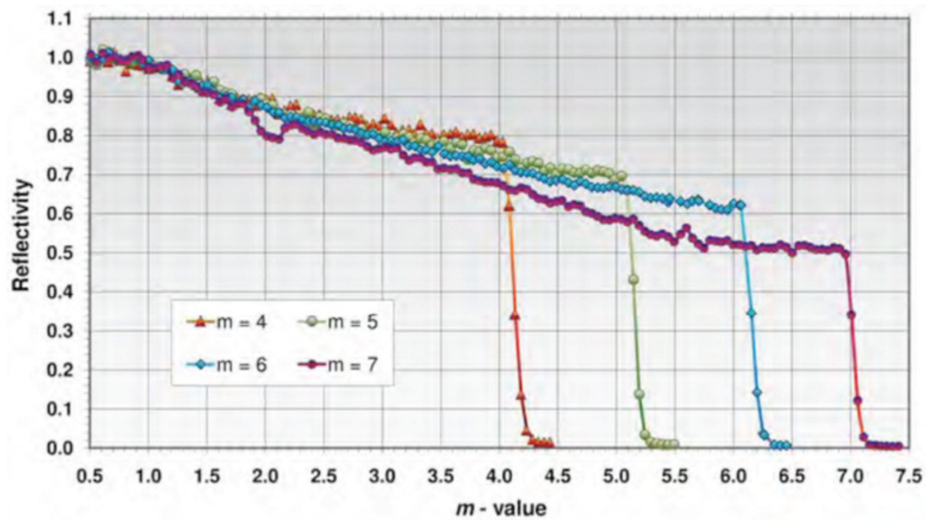
Neutron reflection was first explained by E. Fermi

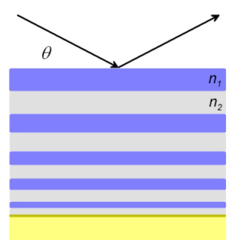
m=1 reflector value – QM effect



Progress in neutron super-mirrors

High-m neutron super-mirrors are commercial products, e.g. produced by Swiss Neutronics
http://www.swissneutronics.ch/index.php?id=24





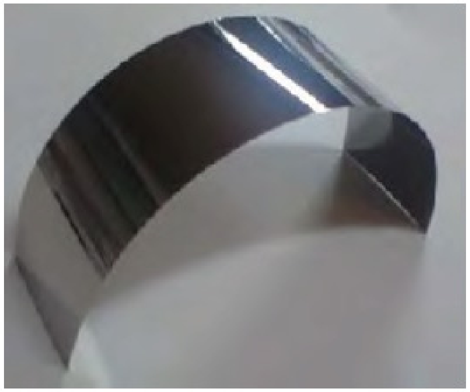
m > 1 reflector
Bragg scattering

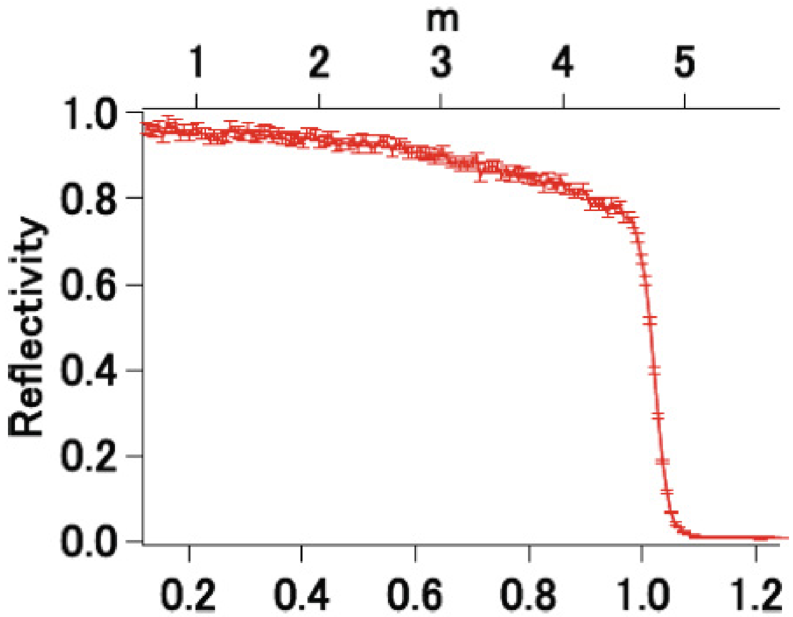
m=7 can reflect neutrons with
$v_\perp \lesssim 50$ m/s

How to make high-m cheaper ?
Hiro Shimizu/
Nagoya U. R&D

Substrateless Supermirror

On-going development in Japan by NNbarX collaborators





no substrate (radiation hardness expected)

DLC Supermirror?

Nuclear Instruments and Methods in Physics Research A 595 (2008) 631–636

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Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

The reflection of very cold neutrons from diamond powder nanoparticles

V.V. Nesvizhevsky [a,*], E.V. Lychagin [b], A.Yu. Muzychka [b], A.V. Strelkov [b], G. Pignol [c], K.V. Protasov [c]

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New reflection technology to be explored by R&D

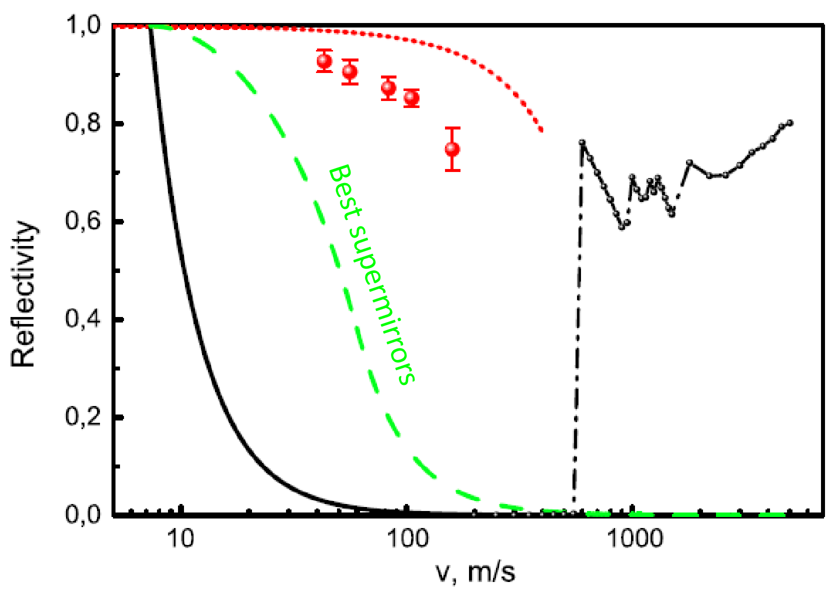
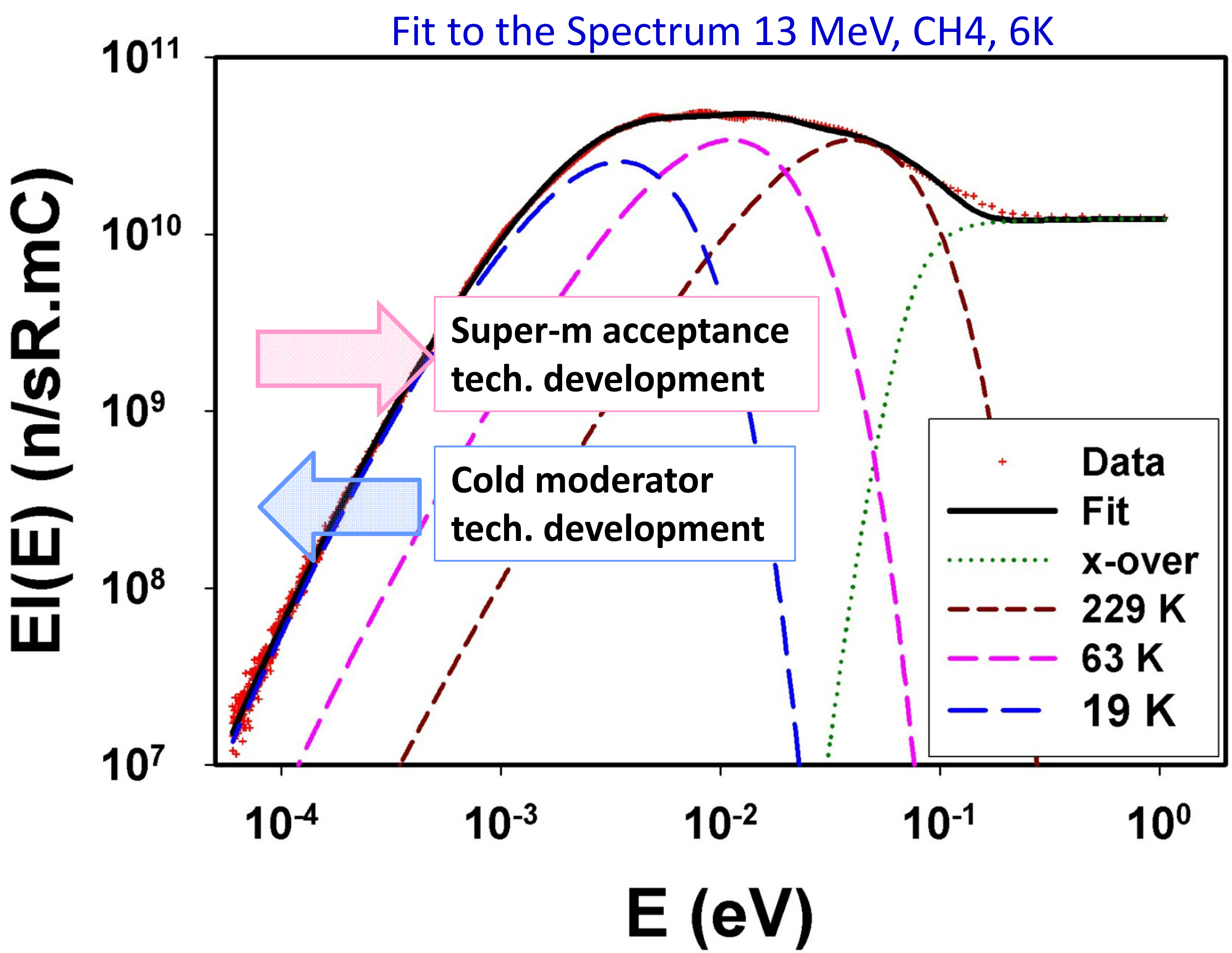


Fig. 9. The elastic reflection probability for isotropic neutron flux is shown as a function of the neutron velocity for various carbon-based reflectors: (1) Diamond-like coating (DLC) (thin solid line), (2) The best supermirror [16] (dashed line), (3) Hydrogen-free ultradiamond [15] powder with the infinite thickness (dotted line). Calculation. (4) VCN reflection from 3 cm thick diamond nanopowder at ambient temperature (points), with significant hydrogen contamination [this Letter]. Experiment. (5) MCNP calculation for reactor graphite reflector [2] with the infinite thickness at ambient temperature.

Fig. 4. The VCN trap. The cover is open.

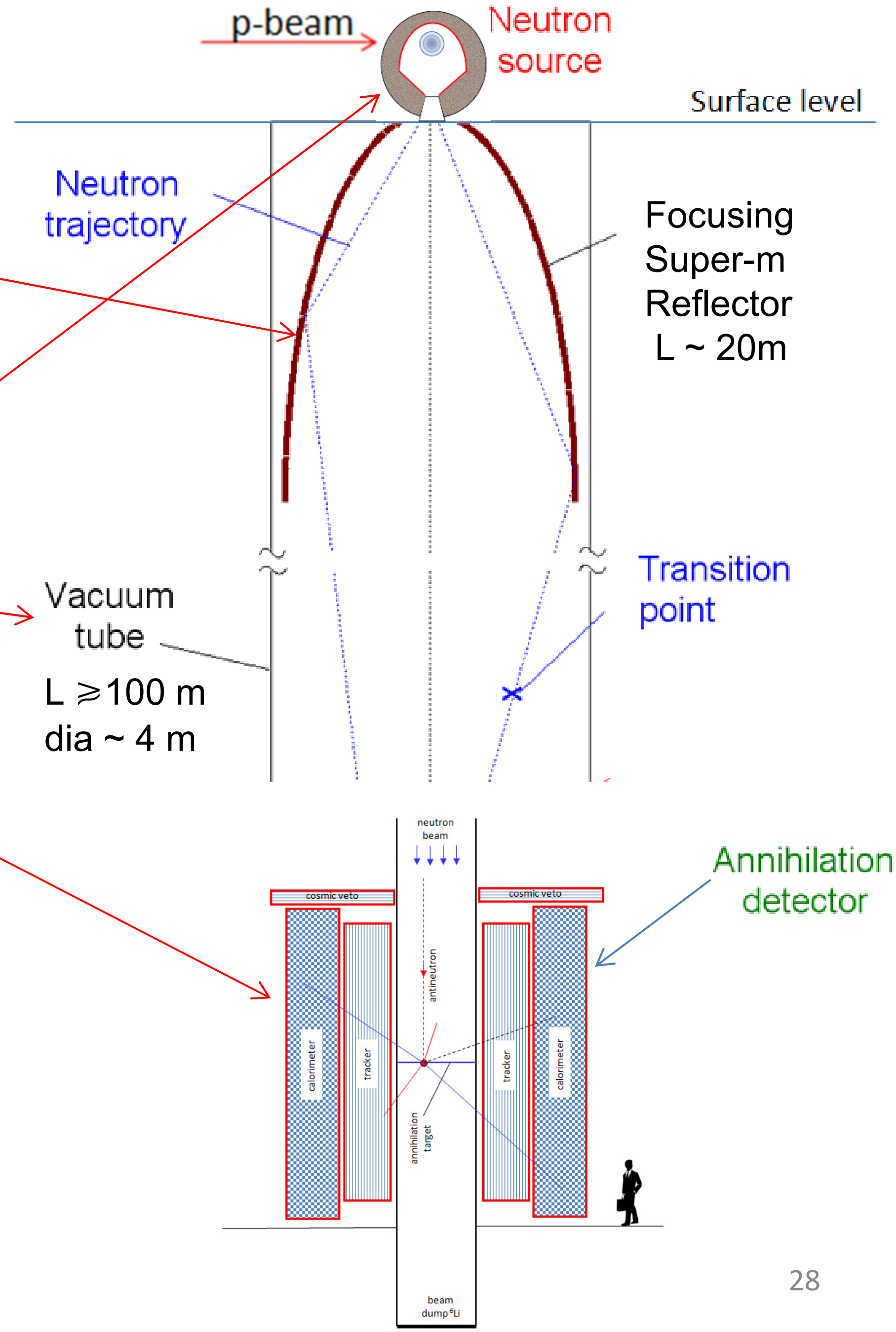
Colder moderator R&D at Indiana University / CEEM



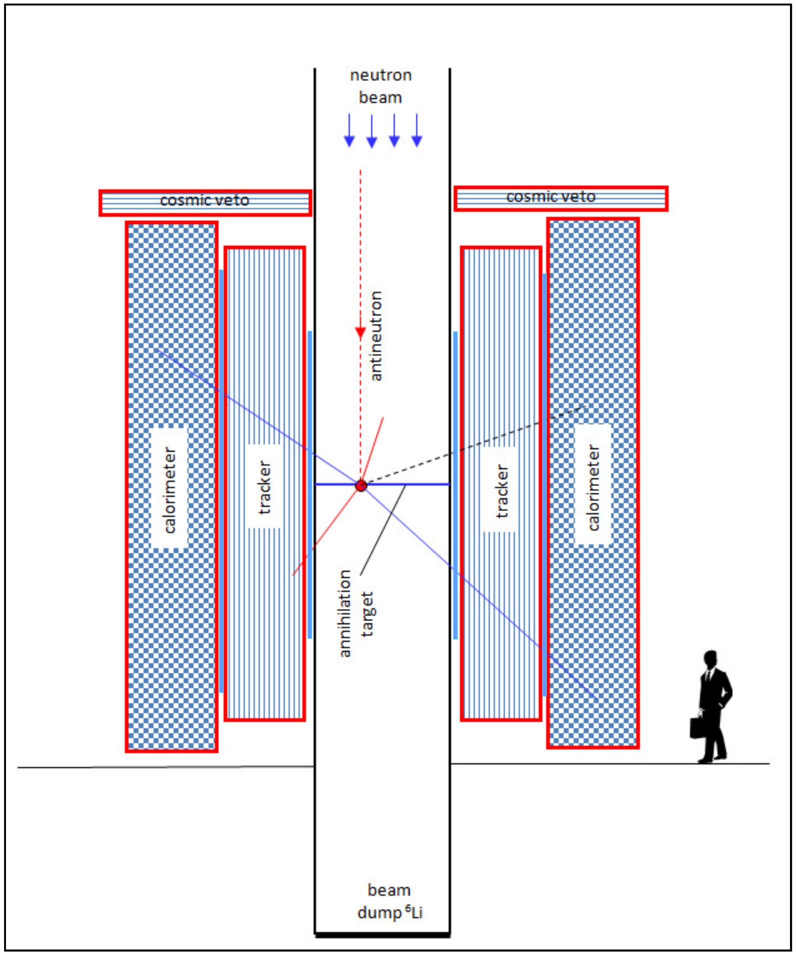
Dave Baxter, Chen-Yu Liu / Indiana U.

N-Nbar vertical scheme

- New concept of large focusing neutron reflector using super-mirror. Sensitivity increases as ~ L^2
- <u>Dedicated spallation target optimized for cold neutron production</u>
- Magnetic shielding $\leq$ 1 nT and vacuum $\leq 10^{-5}$ Pa
- “Background free” detector: one event = discovery ! Effect can be OFF by mag. field.
- Expected sensitivity > 2,000 ILL units
- Cost model to be developed together with configuration optimization in pre-conceptual source design R&D



Annihilation Detector



Annihilation features: $\bar{n} + C \rightarrow \langle 5\pi \rangle$

- Use concepts of backgroundless ILL detector;
- Can be Vertical and Horizontal;
- Carbon-film annihilation target;
- Tracker for finding vertex in thin carbon target;
- Calorimeter for trigger and energy reconstruction;
- TOF before and after tracker to remove vertices of particles coming from outside;
- Cosmic veto;
- Intelligent shielding and beam dump to minimize (n,γ) emission.
- R&D on detector configuration and cost optimization by NCSU, IU, UT, and India together with FNAL

Feasibility conclusion of Dirk Dubbers/Heidelberg

(one of the leaders of ILL experiment in 1991)

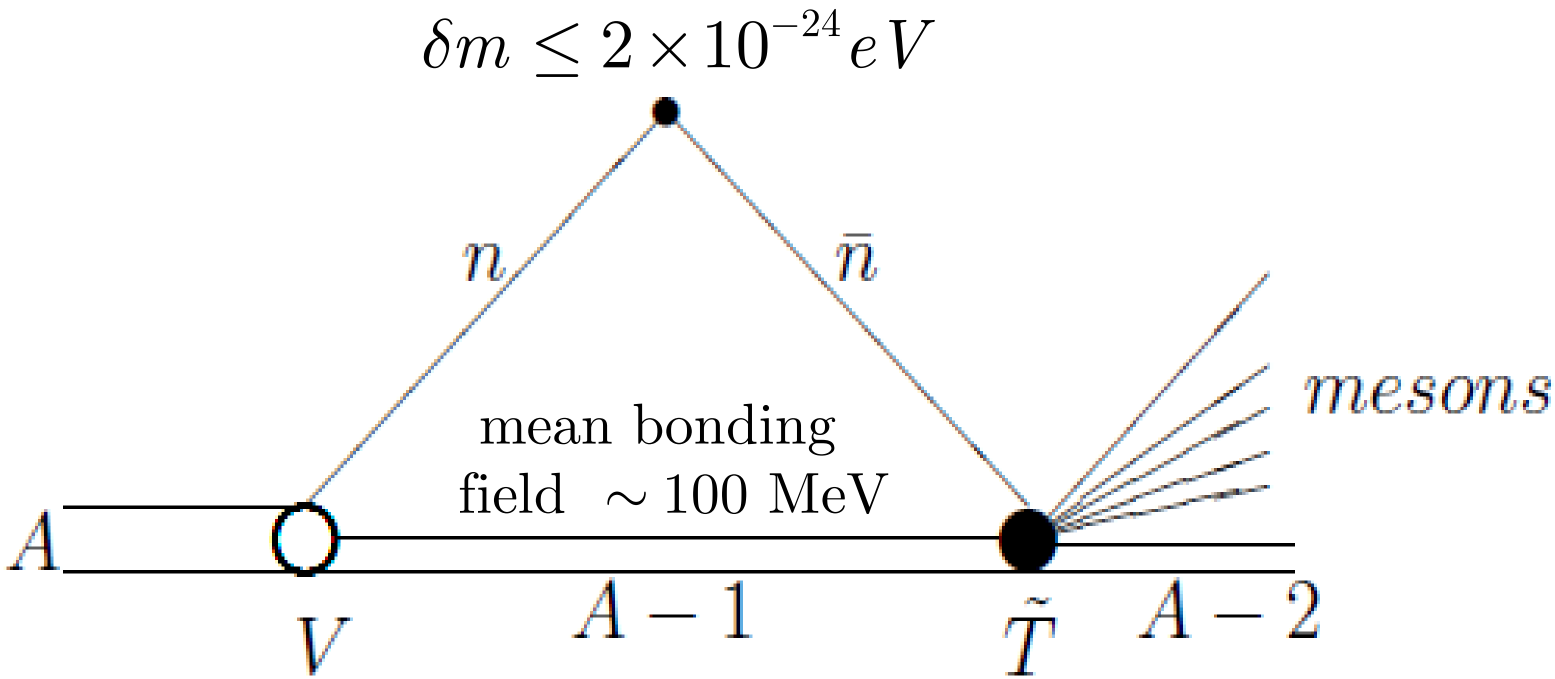
In upscaled n-nbar experiment:

1. Magnetic shielding on 1 nT scale is feasible with state-of-the-art techniques.

2. Radiation background, beam related, should be improved by using thinner and cleaner target and tighter ^{6}LiF shield.

3. Annihilation detector with higher track resolution is desirable.

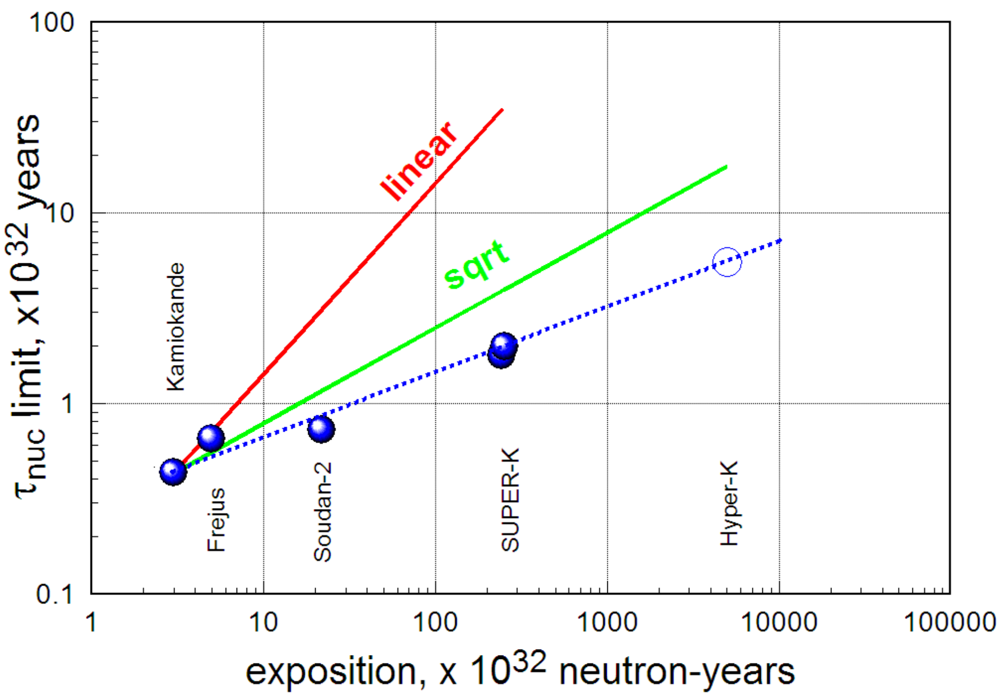
N-Nbar inside nuclei



Nuclear suppression factor for intranuclear n-nbar transformation is computable with nuclear phenomenological theory. This kind of suppression is not common for other nuclear processes where nuclear theory is successfully used and needs additional viability demonstration. Such alternative confirmation of the size of suppression factor can be provided by nuclear lattice calculations (in development). = Lattice R&D topic.

Bound neutron N-Nbar search experiments

Experiment	Year	A	n·year (10^{32})	Det. eff.	Candid.	Bkgr.	τ_{nucl}, yr (90% CL)
Kamiokande	1986	O	3.0	33%	0	0.9/yr	$>0.43\times10^{32}$
Frejus	1990	Fe	5.0	30%	0	4	$>0.65\times10^{32}$
Soudan-2	2002	Fe	21.9	18%	5	4.5	$>0.72\times10^{32}$
Super-K	2007	O	245.4	10.4%	20	21.3	$>1.8\times10^{32}$
Super-K	2009	O	254.5	12%	23	24	$>1.97\times10^{32}$
SNO *	2010	D	0.54	41%	2	4.75	$>0.301\times10^{32}$
Super-K *	2011	O	245	12.1%	24	24.1	$>1.89\times10^{32}$



* Not yet published

Observed improvement is weaker than SQRT due to irreducible background of atmospheric ν's.

Still possible to improve a limit (though slowly) but impossible to claim a discovery.

Conversion of Bound Limit to free Oscillation Limit

Experiment	Year	A	τ_{nucl}, yr (90% CL)	R(old), s^{-1}	R(new), s^{-1}	τ(old), s	τ(new), s
Kamiokande	1986	O	$>0.43\times10^{32}$	10×10^{22}	5×10^{22}	$>1.2\times10^{8}$	$>1.65\times10^{8}$
Frejus	1990	Fe	$>0.65\times10^{32}$	14×10^{22}	?	$>1.2\times10^{8}$	?
Soudan-2	2002	Fe	$>0.72\times10^{32}$	14×10^{22}	?	$>1.3\times10^{8}$	?
SNO * (0.002 × SK)	2010	D	$>0.301\times10^{32}$	2.48×10^{22}	2.94×10^{22}	$>1.96\times10^{8}$	$>1.8\times10^{8}$
Super-K *	2011	O	$>1.89\times10^{32}$	10×10^{22}	5×10^{22}	$>2.44\times10^{8}$	$>3.45\times10^{8}$

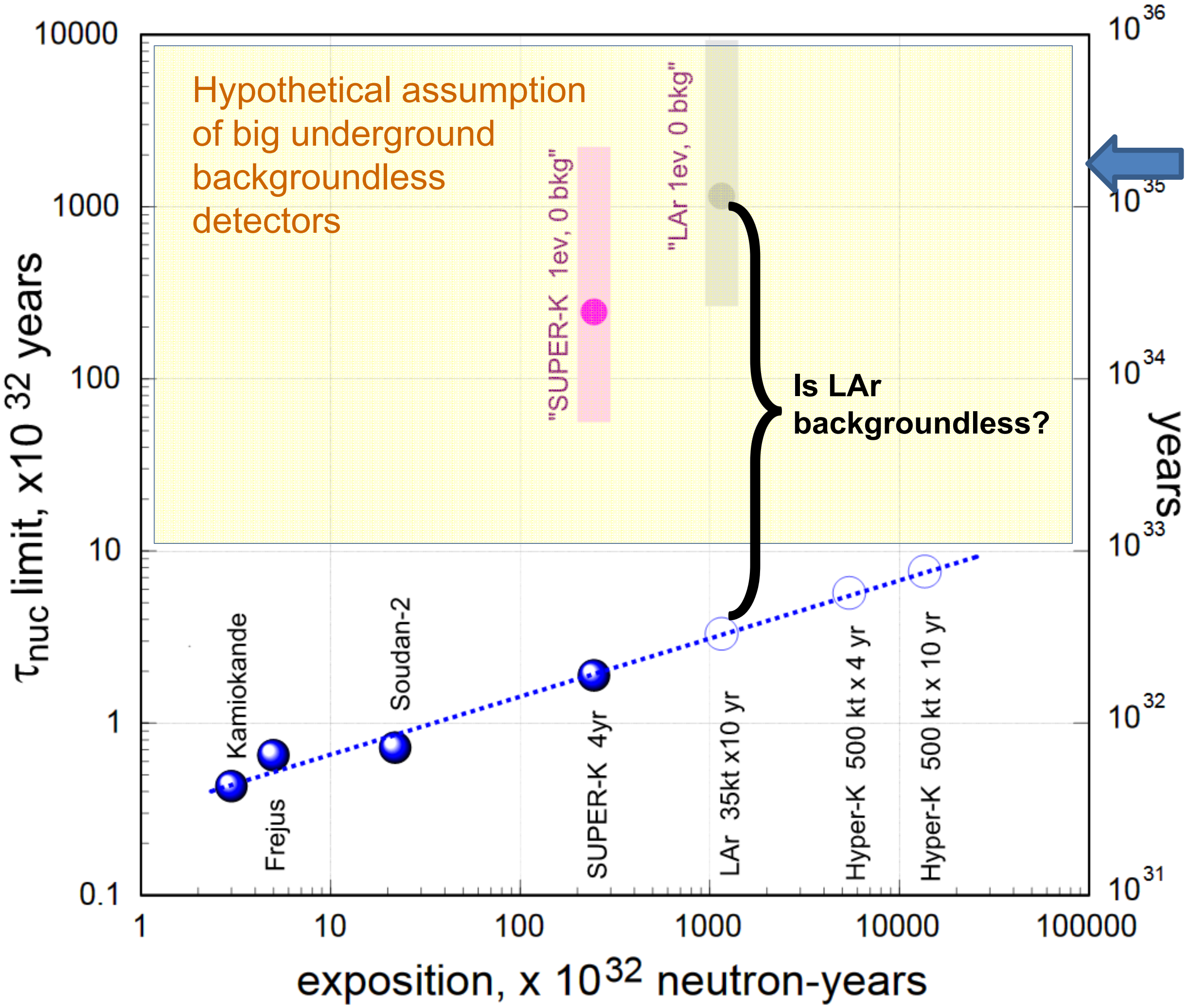
Dover, Gal et. al, old

V. Kopeliovich 2011, Deuterium

Friedman and Gal 2008, Oxygen

$$\Rightarrow \tau_{n\bar{n}}(\text{from bound}) > 3.5\times10^{8}s \quad \text{or} \quad \alpha < 2\times10^{-24}eV$$

Comparison with intranuclear n-nbar search



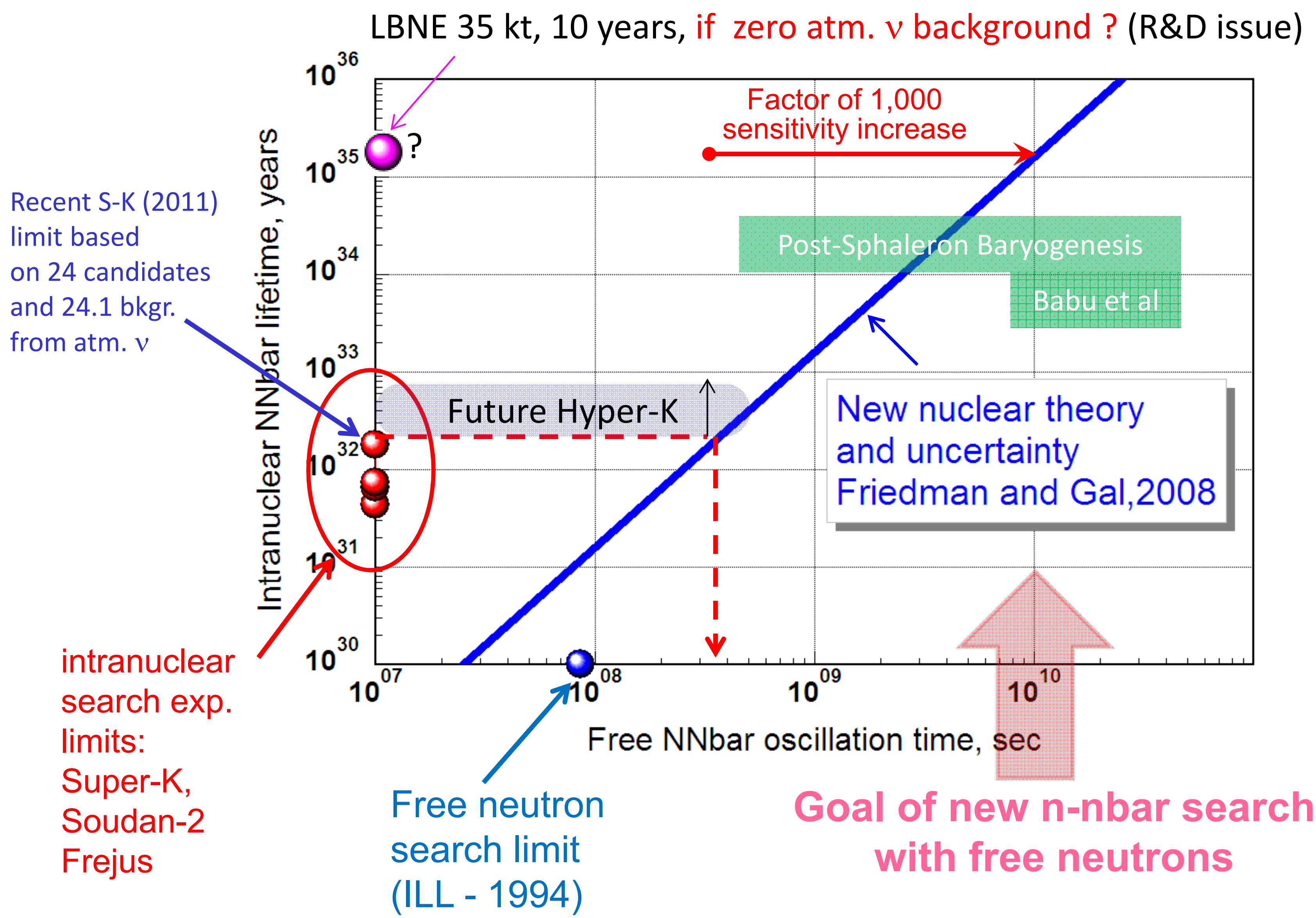
Ultimate goal of NNbarX sensitivity. Absence of background is critically important

24 candidate events in Super-K might contain several genuine n-nbar events. Backgroundless PDK detectors are needed to explore nnbar > 10^{33} years. Whether atmospheric neutrinos and nnbar signals can be separated in LAr detectors is an R&D issue for LBNE.

$$\tau_{bound} = R \times \tau_{free}^2$$

Free Neutron vs Bound Neutrons NNbar Search Sensitivity Comparison

(see backup slides on complementarity of free and bound neutron search)



Observations of n-nbar with both free and bound neutrons are important

Theory expectation

1. If CPT is violated with $\Delta m = \left| m_n - m_{\bar{n}} \right| < 10^{-19} m_n \simeq \left(\frac{m_n}{m_{Planck}} \right) m_n$

then transformation of free $n \rightarrow \bar{n}$ will be suppressed by Δm.
But it will NOT be additionally suppressed inside the nuclei where suppression factor is present due to $\Delta E \sim 30 MeV$ (Abov, Djeparov, Okun - 1984).

2. If n-nbar will be observed inside nuclei but due to Δm will *not* appear with free neutron, it will be possible to "unlock" it for free neutrons by tuning the magnetic field.

3. If n-nbar will be observed both with free neutrons and inside nuclei, it will be possible to set a new more tight limit on $\Delta m / m$ as a test of CPT.

How CPT violation works in n→nbar transitions?

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

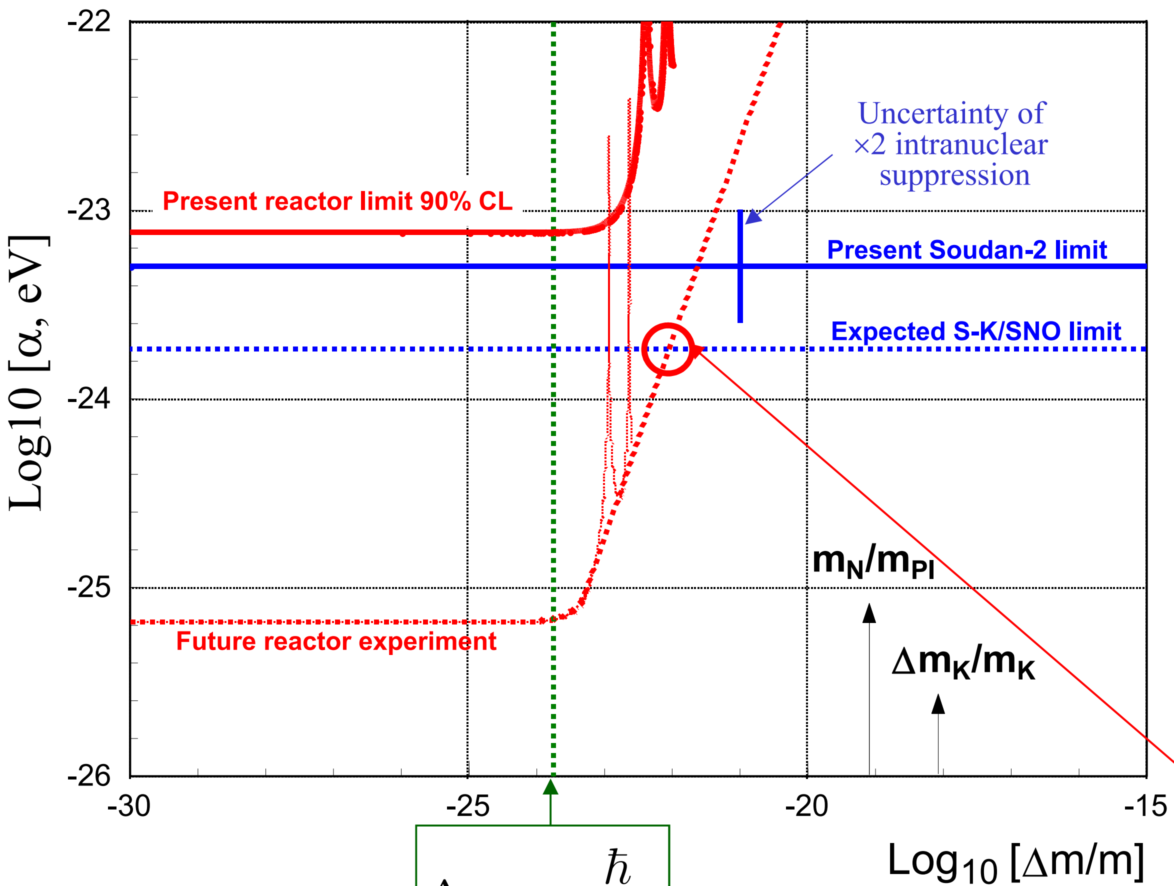
Following Yu.Abov, F.Djeparov, and L.Okun, Pisma ZhETF 39 (1984) 493

- Transformations for free neutrons V=0 are suppressed when $\Delta m > \dfrac{\hbar}{t_{free}}$
- Suppression when $\Delta m > \alpha$

E.g. for $\alpha = 10^{-24} eV$ suppression by factor of 2 at $\Delta m \sim 10^{-13} eV$

- Intranuclear transformation is suppressed by huge factor due to V~30 MeV; then small $\Delta m \sim 10^{-13} eV$ will provide no additional suppression. Intranuclear transitions are not sensitive to small Δm !

Δm vs α in n→nbar search (if α≠0)



$$\Delta m = \frac{\hbar}{t_{free}}$$

PDG experimental limits on mass difference

$$\left|m_{K^0} - m_{\bar{K}^0}\right| / m_K < 6.\times 10^{-19}$$

$$\left|m_p - m_{\bar{p}}\right| / m_p < 2\times 10^{-9}$$

$$\left|m_{e^+} - m_{e^-}\right| / m_e < 8\times 10^{-9}$$

$$\left(m_n - m_{\bar{n}}\right) / m_n = \left(9\pm 6\right)\times 10^{-5}$$

If n→nbar transition would be observed here with free and bound n's this will be a new limit on CPT Δm/m test