

PAC Meeting • Fermilab • October 15, 2012

NNbarX

Expression of Interest

On behalf of NNbarX Collaboration
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Expression of Interest

Search for Neutron-Antineutron Transformation at Fermilab

The NNbarX Collaboration

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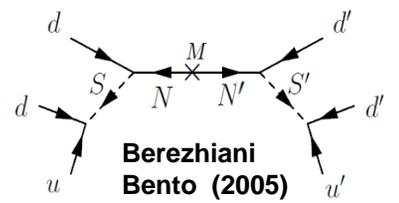
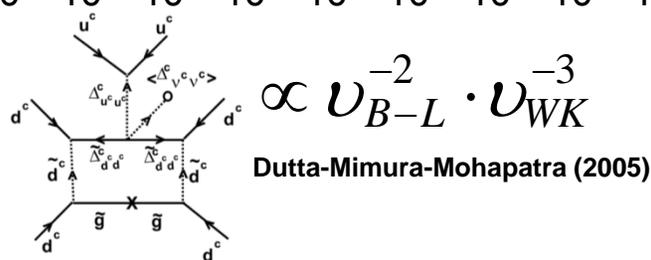
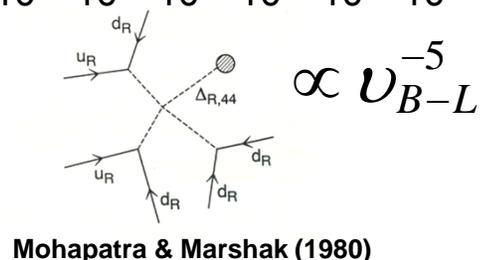
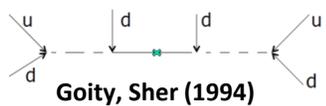
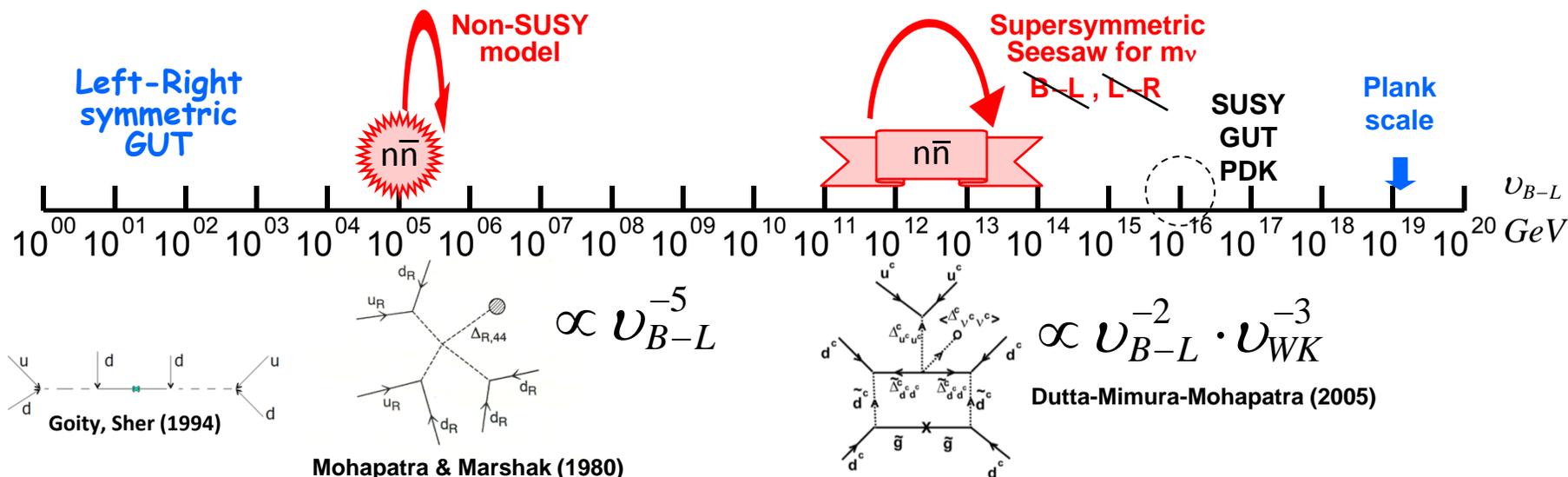
Variable Energy Cyclotron Centre, Kolkata, India

- HEP and NP groups from US Universities are involved together with Fermilab
- National Labs neutron and spallation target experts are engaged
- International groups and experts participate
- Strong Theory Support group:
K. Babu, Z. Berezhiani,
M-C. Chen, R. Cowsik,
A. Dolgov, A. Gal, B. Kerbikov,
B. Kopeliovich, V. Kopeliovich,
R. Mohapatra, L. Okun, C. Quigg,
U. Sarkar, R. Shrock, A. Vainshtein

Vision of physics importance

- ❖ Observation of violation of Baryon number is one of the pillars of the modern Cosmology and Particle Physics
 - it is required for explanation of Matter-Antimatter asymmetry or BAU (Sakharov)
 - it follows from the inflation (Dolgov, Zeldovich)
 - it is motivated by GUT models (Giorgi, Glashow, Pati, Salam, ...)Proton decay $\Delta B = 1$ (underground) and $n \rightarrow \bar{n}$ $\Delta B = 2$ (n-sources) are complementary
- ❖ $(B - L)$ must be violated (Kuzmin, Rubakov, Shaposhnikov)
 - idea of Leptogenesis with $\Delta L = 2$ (Fukugita, Yanagida ...)Majorana nature of ν 's can experimentally demonstrate $\Delta L = 2$, i.e. $(B - L)V$, however, experimental prove of Leptogenesis mechanism will not be likely possible.
- ❖ Most of the Proton decay searches with $\Delta B = 1$ motivated by GUT or SUSY-GUT models are conserving $(B - L)$. → “Proton decay with $\Delta(B-L)=0$ is not a prediction of baryogenesis” (Yanagida, 2002).
- ❖ Alternative search for $n \rightarrow \bar{n}$ transformation with $\Delta B = 2$ and $(B - L)V$ (Mohapatra ...)
- ❖ All theoretical models with $\Delta B = 1$ and $\Delta B = 2$ at high-energy scale have difficulties when passing through the electroweak period due to sphaleron mechanism.
 - Interesting class of models with baryogenesis below EW scale (Babu ...)These models explain small neutrino masses, predict new color scalars at LHC and observable $n \rightarrow \bar{n}$.

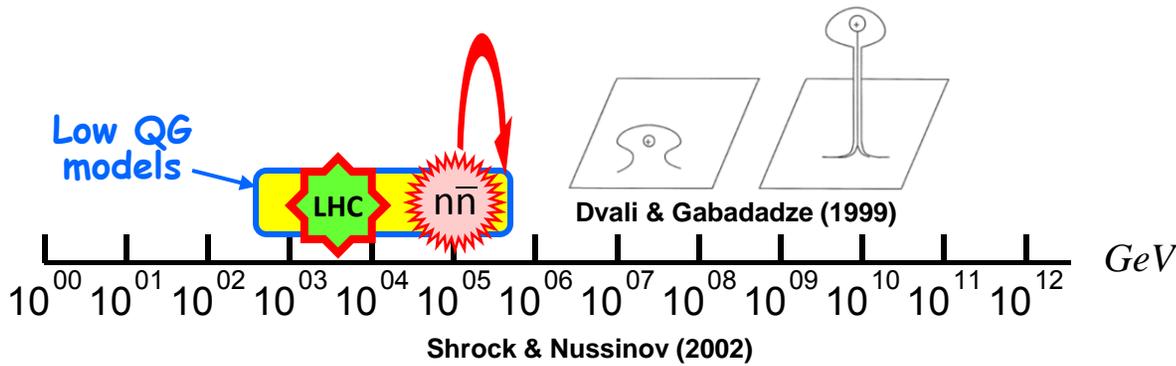
Scales of $n \rightarrow \bar{n}$ $(B-L)V$ in theory



Connected with observable effects at LHC

Baryogenesis at TeV scale

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



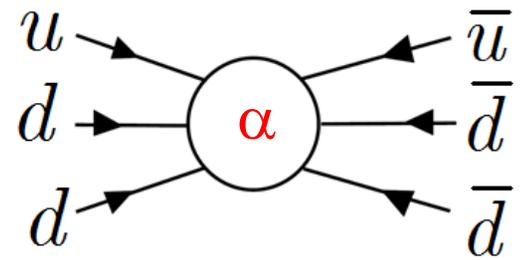
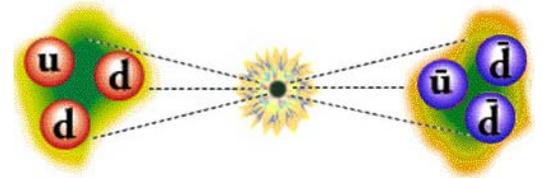
n → n̄ transition probability

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

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

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

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



α -mixing amplitude

All beyond SM physics is here

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

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 $t \sim 0.1$ 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)

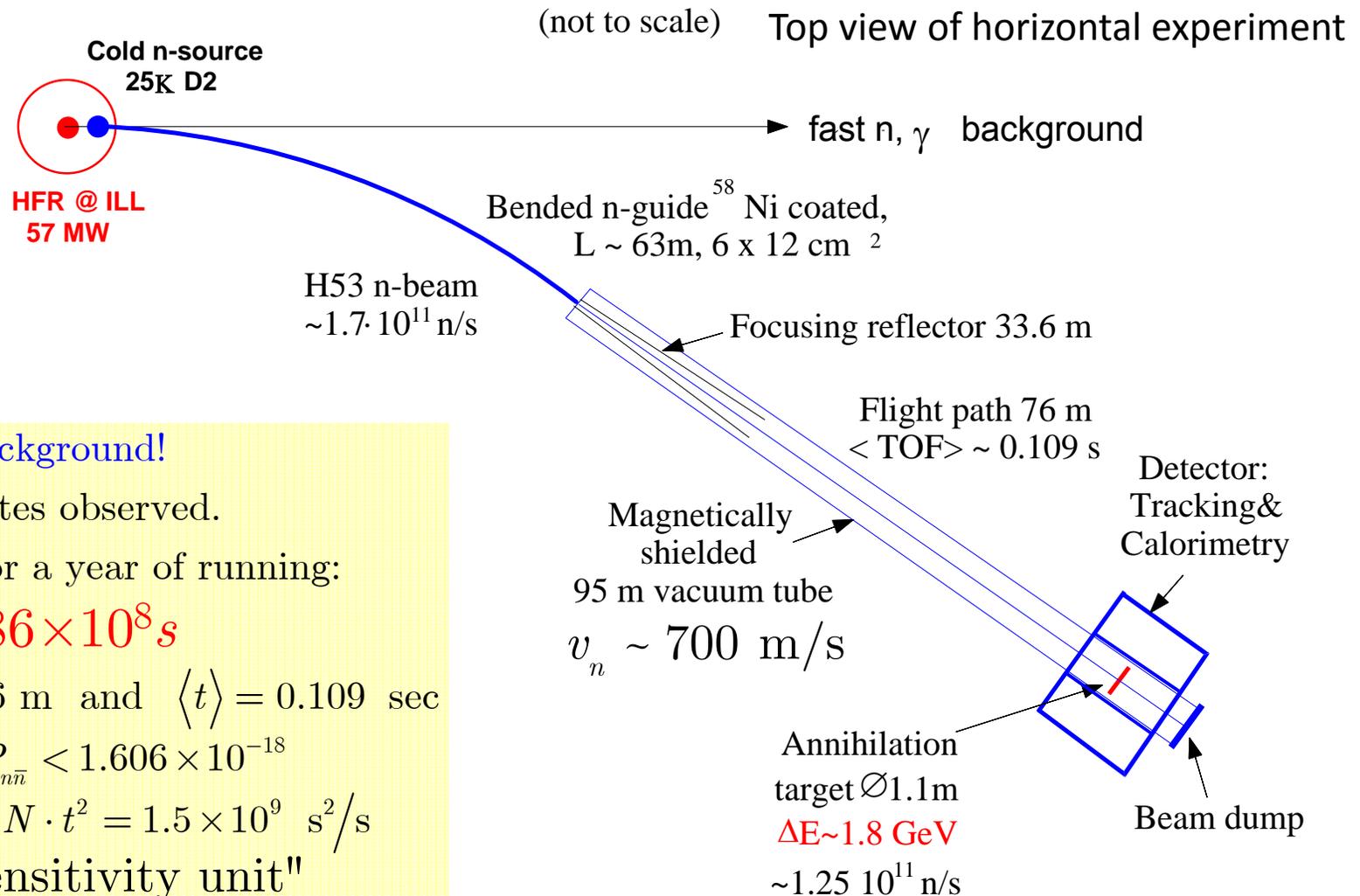
Predictions of theoretical models: observable effect around $\alpha \sim 10^{-25} - 10^{-26} eV$

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

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



No GeV background!

No candidates observed.

Limit set for a year of running:

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

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

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

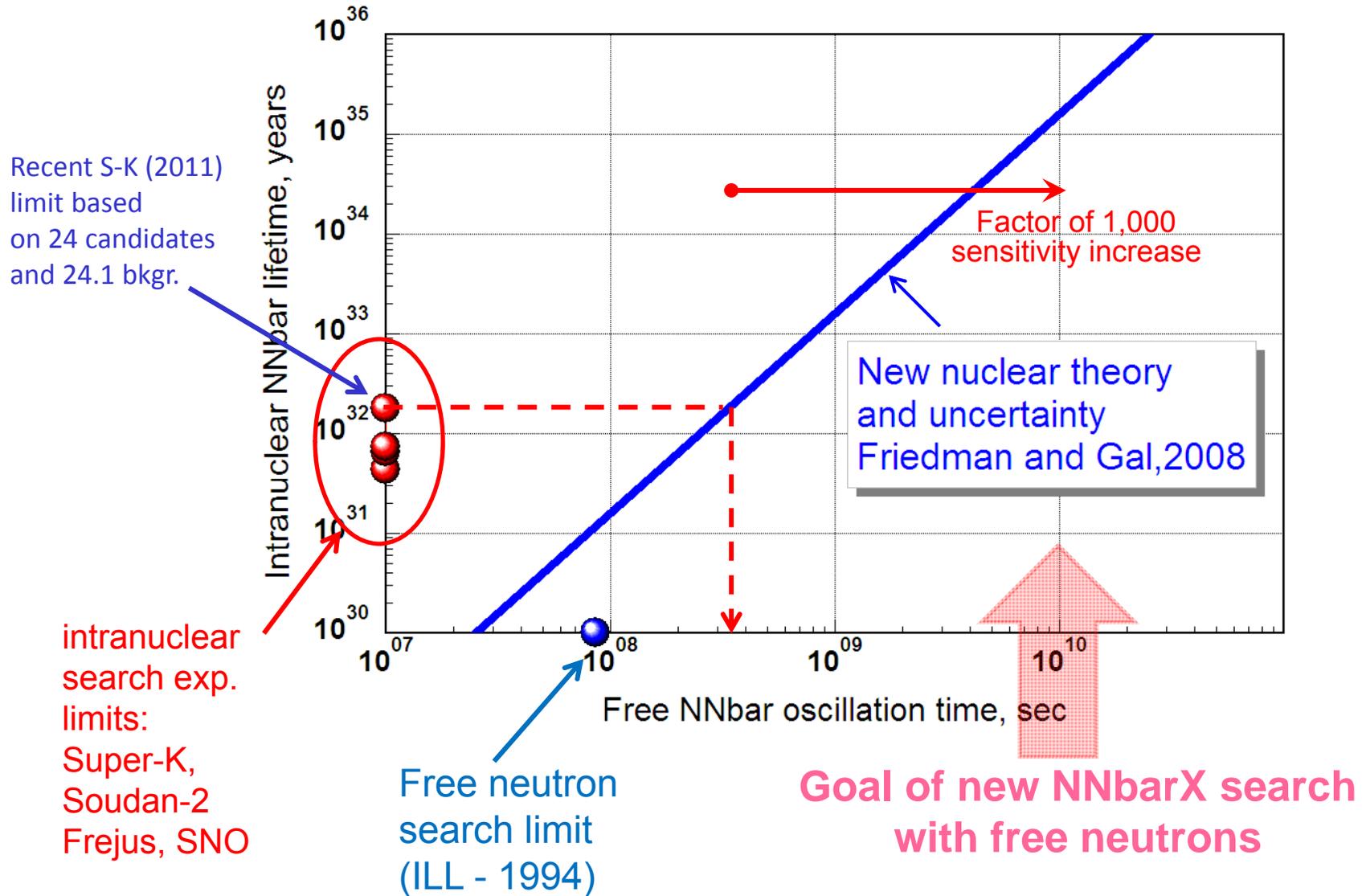
sensitivity: $N \cdot t^2 = 1.5 \times 10^9 \text{ s}^2/\text{s}$

\doteq "ILL sensitivity unit"

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

Free Neutron and Bound Neutrons NNbar Search Limits Comparison

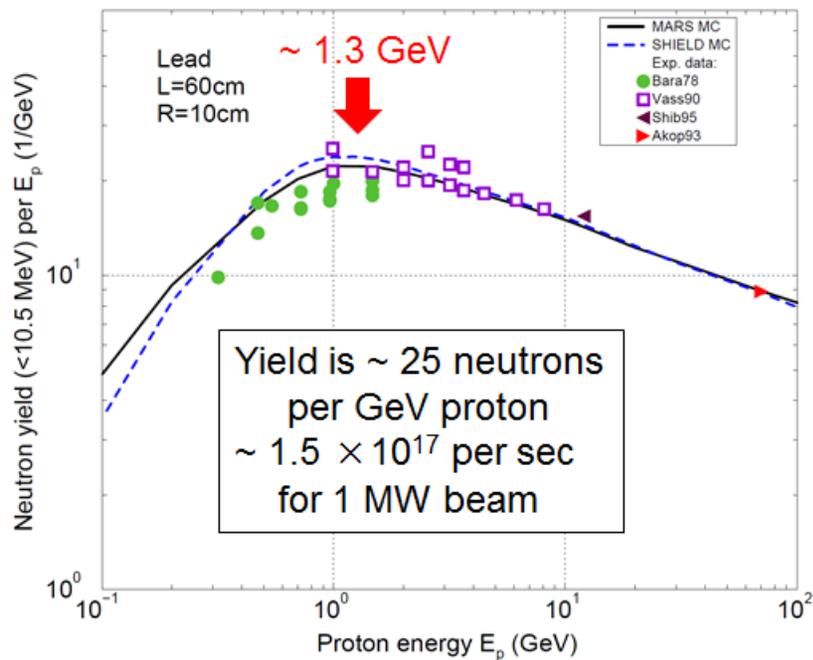
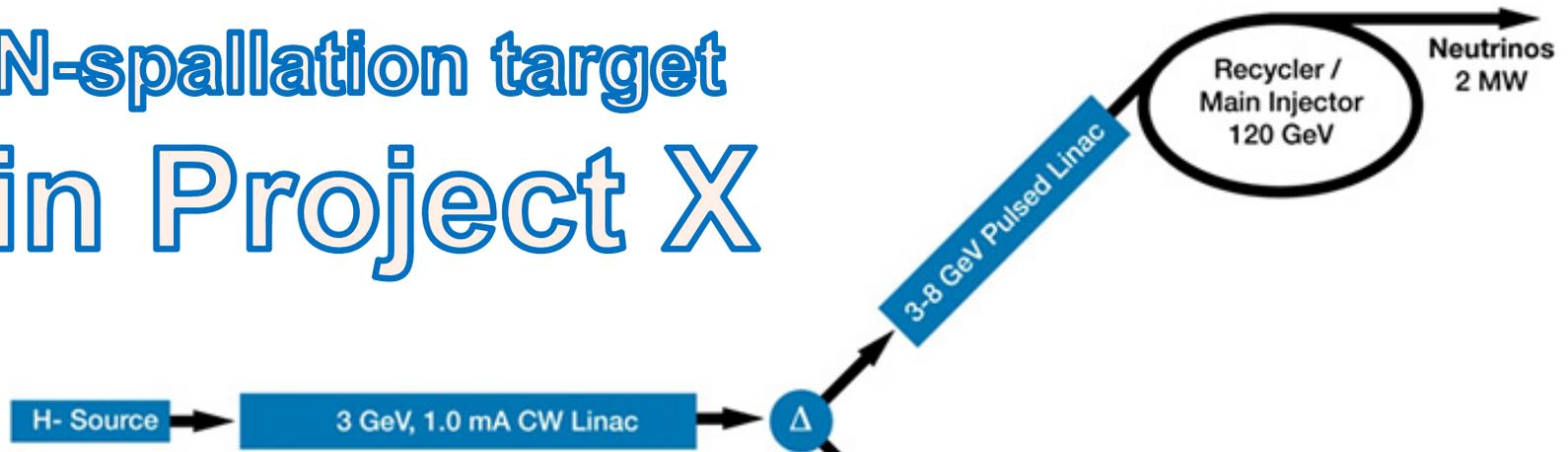
Large improvement with free-neutron experiments is possible



Sensitivity $N_n \cdot t^2$ improvement factors

- Use many neutrons \rightarrow optimized spallation source
- Use solid angle 4π in the source
- Use slow neutrons \rightarrow cold \rightarrow VCN \rightarrow UCN
- Neutron manipulation by mirror and diffuse reflectors
- Neutron manipulation by gravity \rightarrow vertical

N-spallation target in Project X



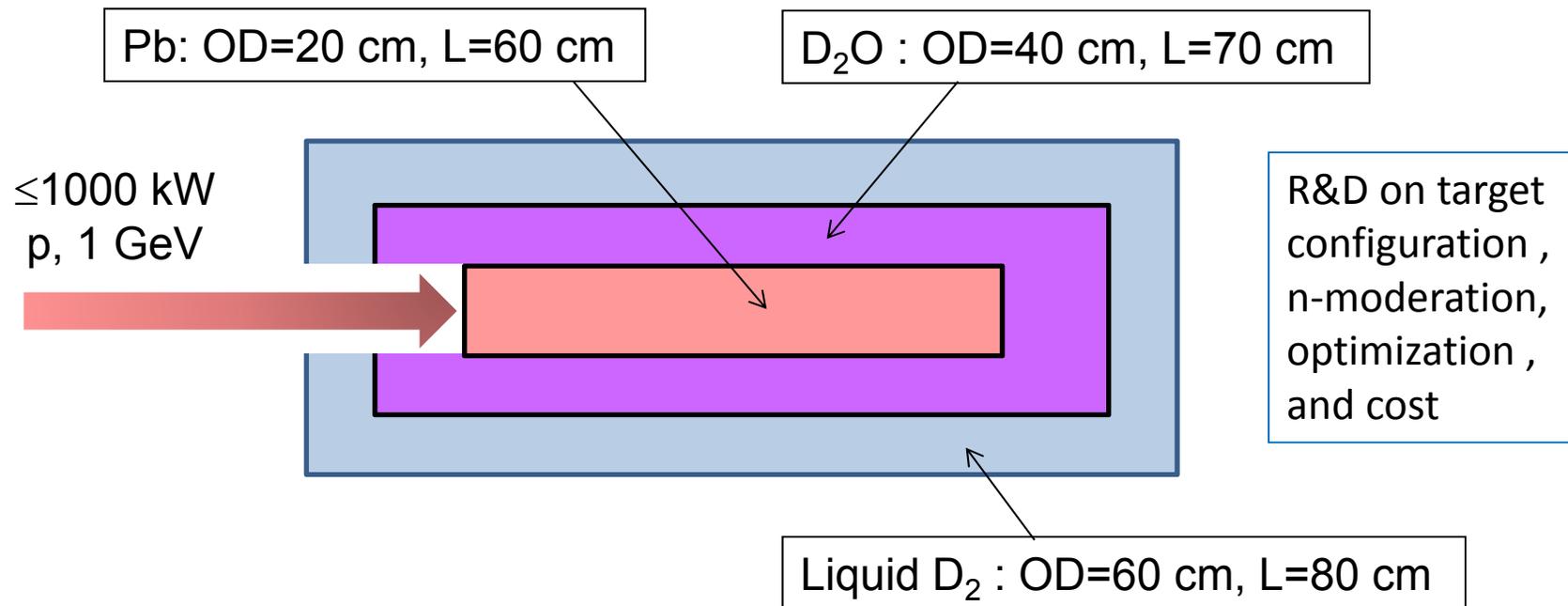
N. Mokhov, MARS simulations, FNAL, 2011

First stage of Project X with 1 GeV p-beam is optimal for neutron production

Generic View of Cold Spallation Target

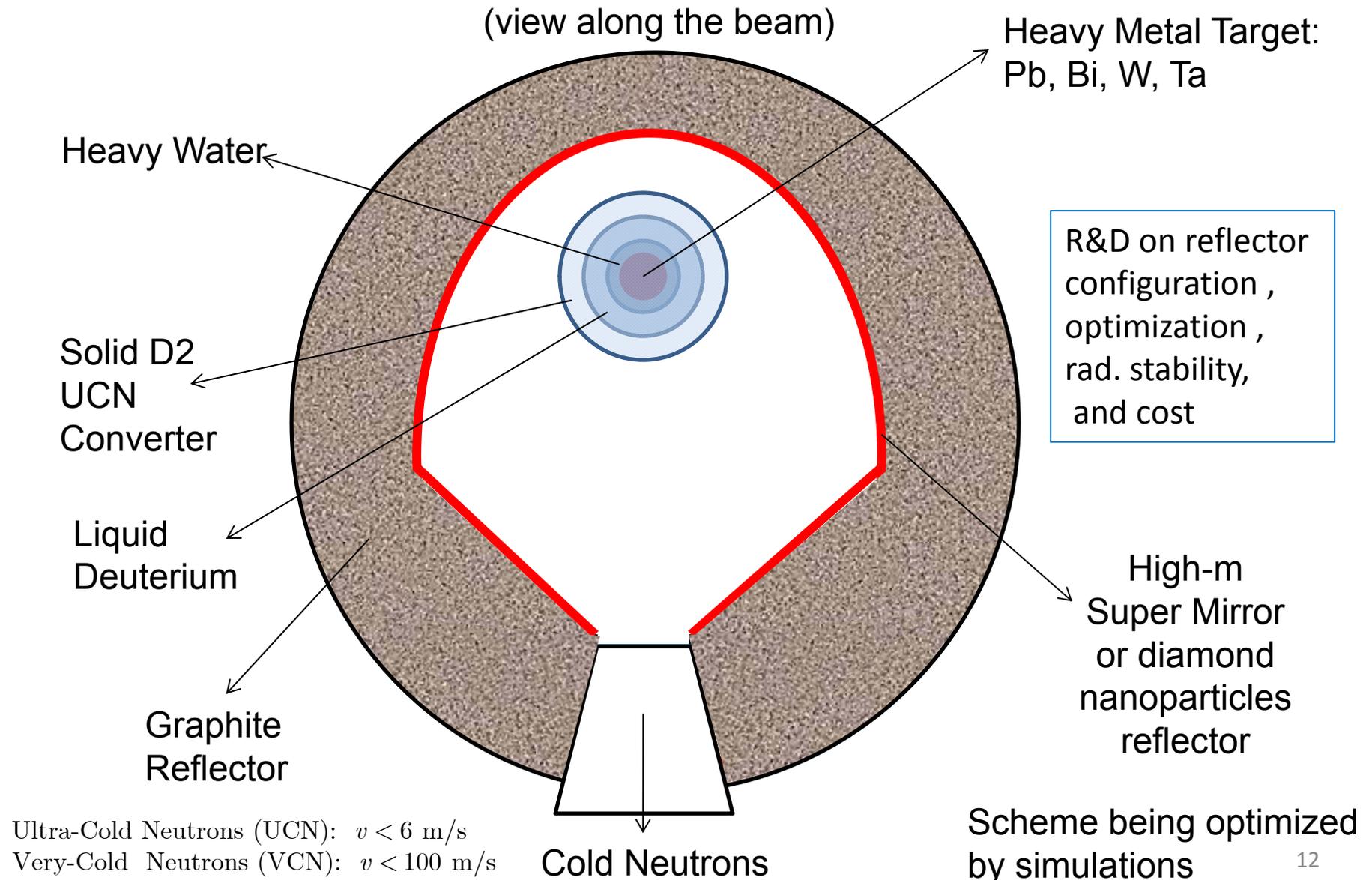
For NNbarX and n-EDM experiments

- Should try to use neutrons produced within 4π rather than in few % of 4π for most n-beam lines



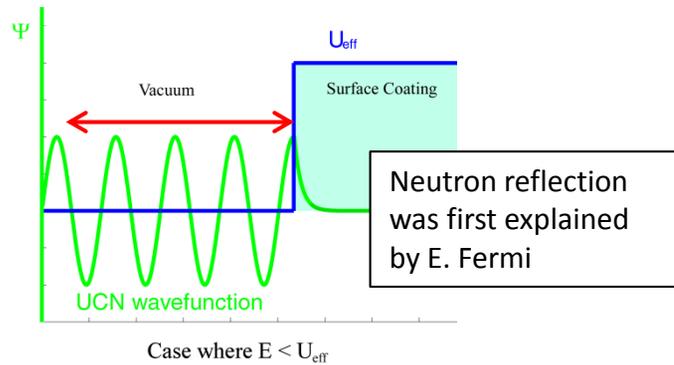
Spallation neutrons produced with kinetic energy ~ 2 MeV; moderated down to thermal $T \sim 300$ K velocities ~ 2 km/s and then to the cryogenic velocities ~ 600 m/s. Some fraction of Maxwellian spectrum will have velocities $\lesssim 100$ m/s

Conceptual dedicated spallation target with VCN-UCN converter

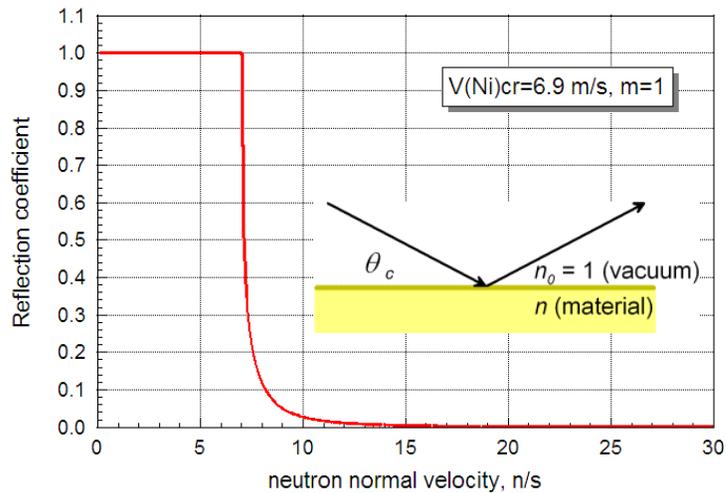


Neutron mirrors and Super-mirrors

Neutron reflection

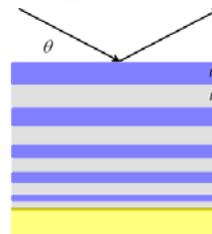
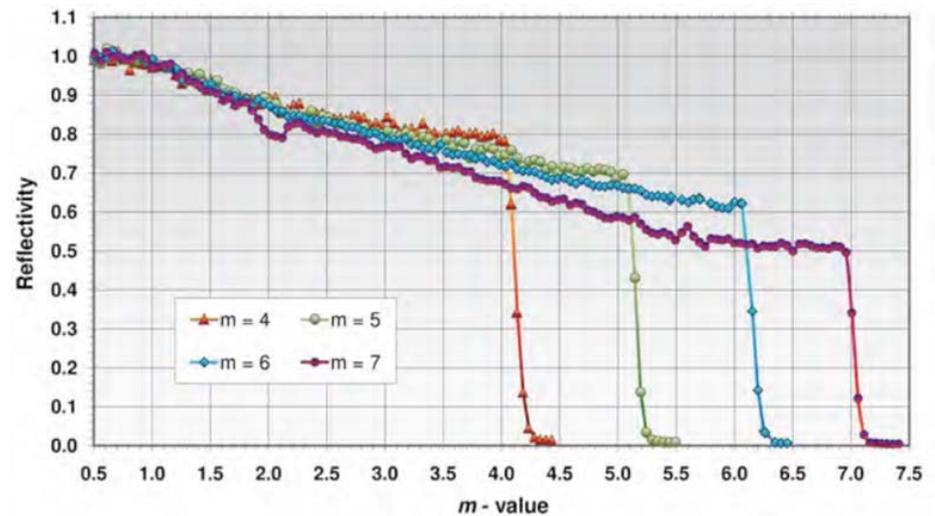


m=1 reflector value – QM effect



Progress in neutron super-mirrors

Commercial products of Swiss Neutronics



$m > 1$ reflector
Bragg scattering

Can reflect
neutrons with
 $v_{\perp} \lesssim 50 \text{ m/s}$

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



Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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



New reflection technology to be explored by R&D

The reflection of very cold neutrons from diamond powder nanoparticles

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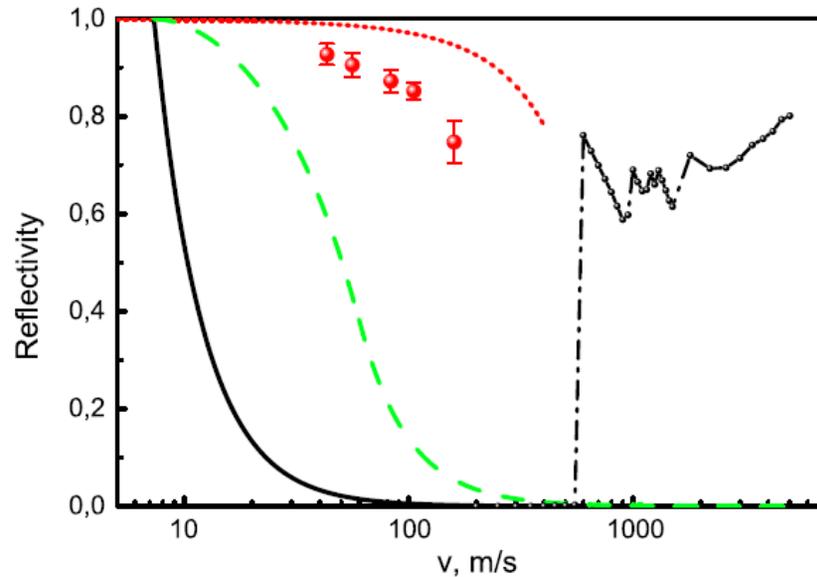


Fig. 9. The elastic reflection probability for isotropic neutron flux is shown as a function of the neutron velocity for various carbon-based reflectors: (1) Diamond-like coating (DLC) (thin solid line), (2) The best supermirror [16] (dashed line), (3) Hydrogen-free ultradiamond [15] powder with the 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.

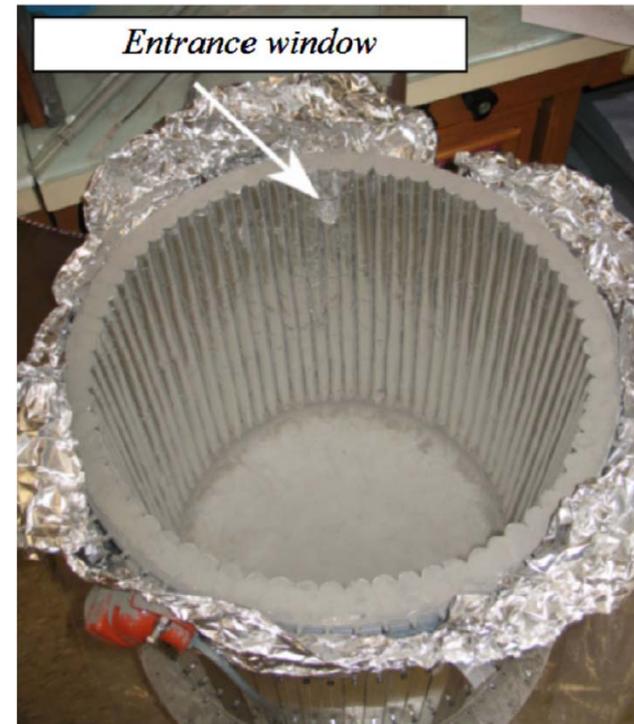
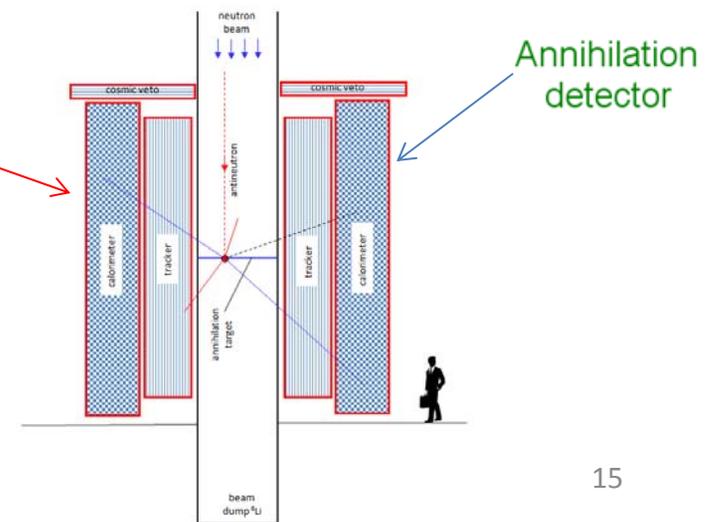
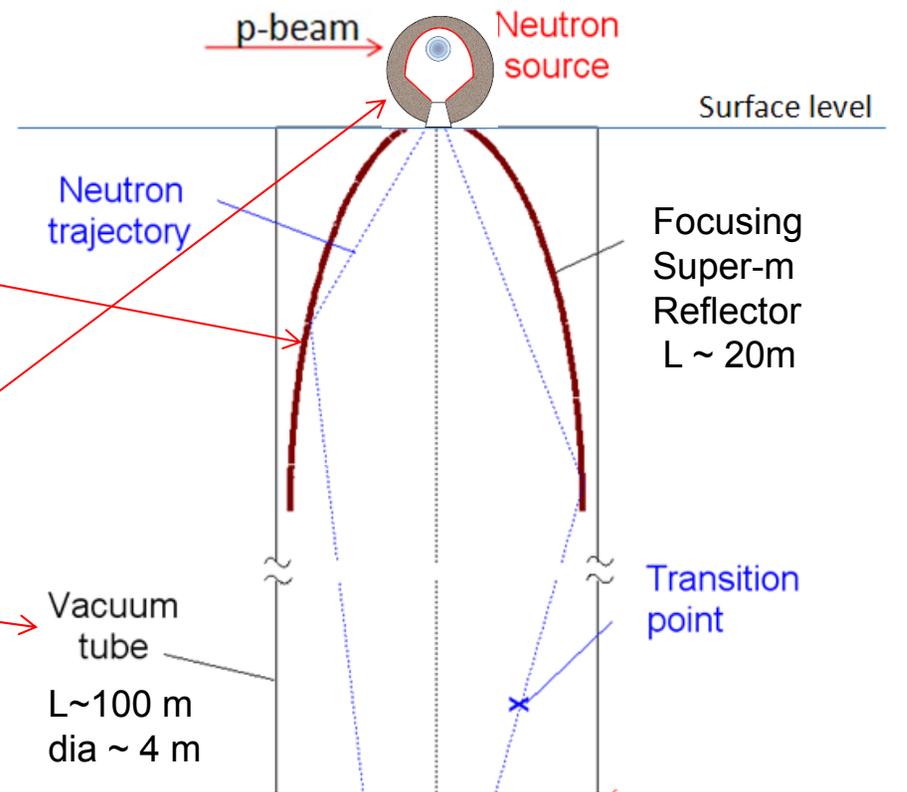


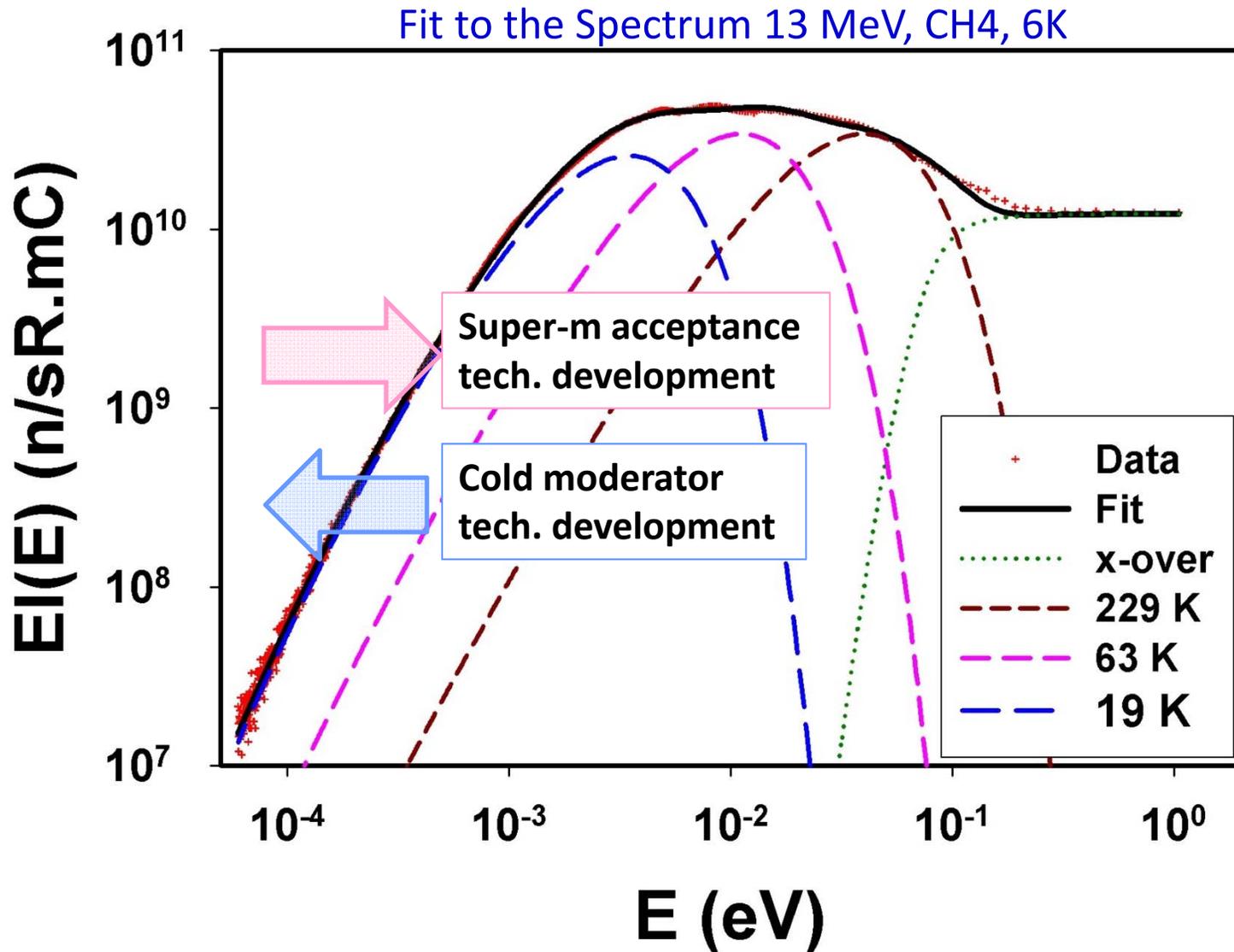
Fig. 4. The VCN trap. The cover is open.

N-Nbar vertical scheme

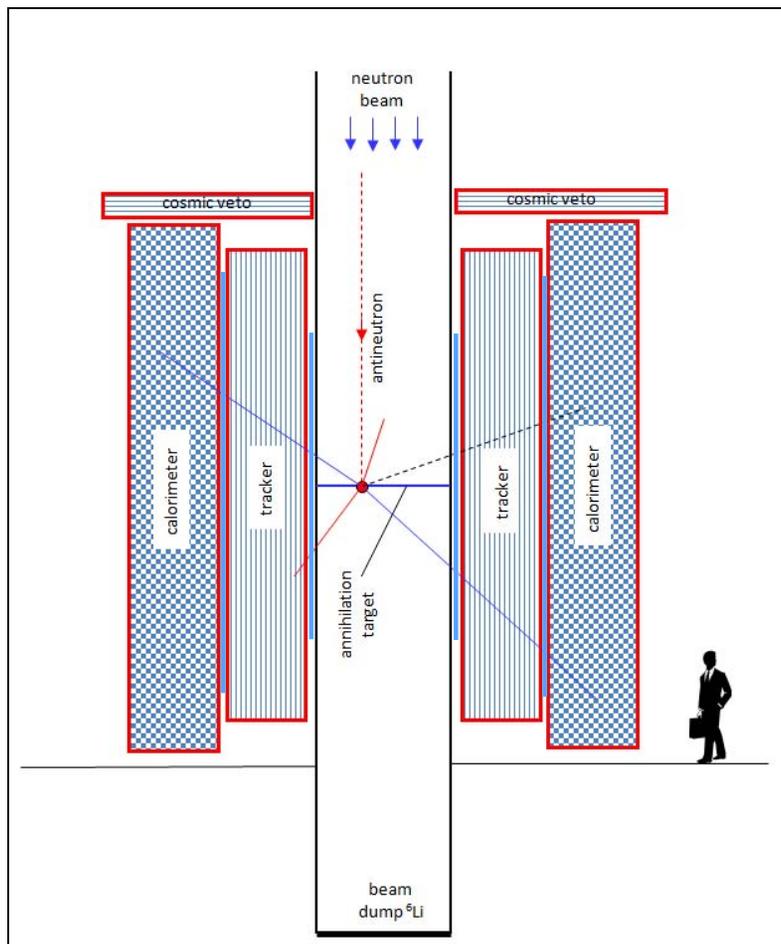
- New concept of large focusing neutron reflector using super-mirror. Sensitivity increases as $\sim L^2$
- Dedicated spallation target optimized for cold neutron production
- Magnetic shielding ≤ 1 nT and vacuum $\leq 10^{-5}$ Pa
Indiana U. R&D
- “Background free” detector:
one event = discovery!
Effect 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 by U. of Tennessee + all NNbarX



Colder moderator R&D at Indiana University / CEEM



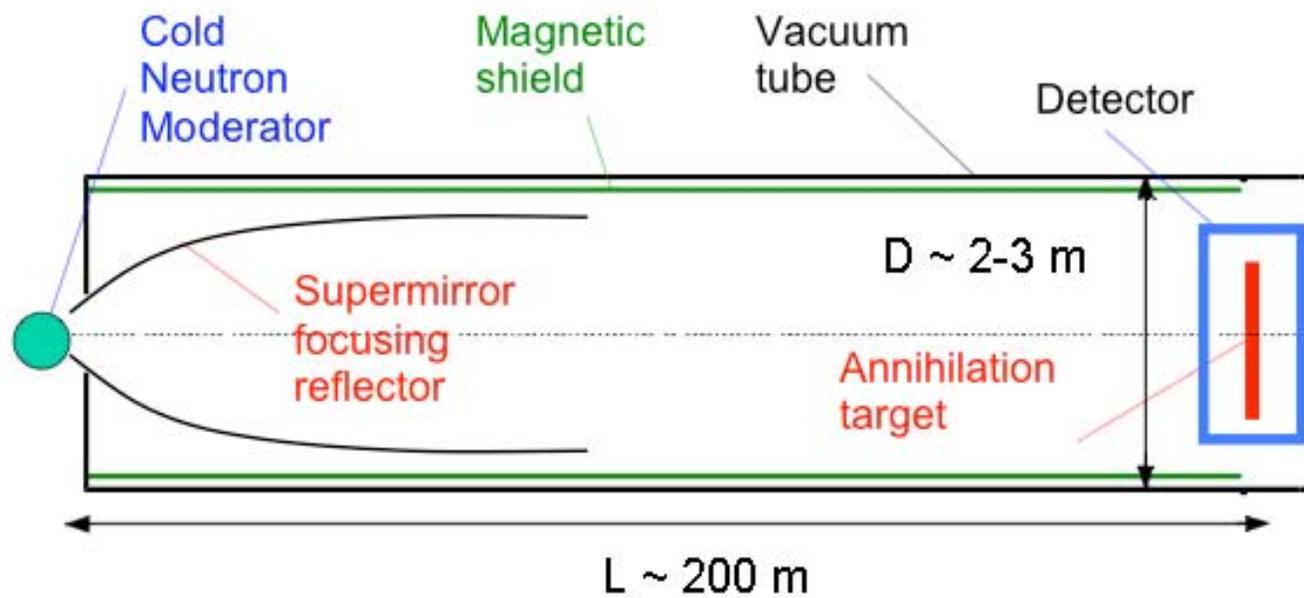
Annihilation Detector



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

- Use concepts of backgroundless ILL detector;
- Can be Vertical and Horizontal;
- Carbon-film annihilation target;
- Tracker for vertex to 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, and India together with FNAL

Less Expensive Conceptual Horizontal version
(Stage 1) with Free Neutrons for Project X



Summary of R&D topics (submitted as DOE R&D proposals)

We ask PAC to support the appropriateness of these:

Indiana U: “ Neutronic, magnetic and tracking detector research and development relevant to experimental investigation of n-nbar oscillations and other phenomena with cold neutrons at Project-X “

NCSU: “A Neutron-Antineutron Oscillation Experiment at Fermilab: Detector and Target Research and Development towards a Pre-conceptual Proposal for Project-X”

U Tennessee: “Development of a Pre-Conceptual Design for a Spallation Target and Support System for N-Nbar Oscillation Search and Other Potential Experiments with Cold Neutrons in Project X” (including optimization for n-EDM)

Working NNbarX Collaboration:

- Common planning of R&D work
- Internet resources: DocDB, Wiki; conference calls
- Collaboration meeting November 16-17, 2012 in TN
- Will evolve into more elaborate structure upon PAC encouragement

Connection with n-EDM community:

Liaison: W. Korsch (U. of Kentucky)

Also G. Greene (UT), R. Golub (NCSU), A. Serebrov (PNPI)

Exploring other possible sources of funding and support, that also can be influenced by PAC recommendations:

- Discussions with M&P NSF
- Seed money \$90K from University of Tennessee support activity of the group including SNS experts (Tony Gabriel and others), HEP and NP physicists, Nuclear engineers and grad. students working on MNCPX neutron production and transport code, experiment sensitivity configuration code, and spallation target thermal analysis
- Enabling neutron target experts and engineers from National Labs (SNS/ORNL, LANL, NIST) to participate in the Project X spallation target design + NNbarX and n-EDM experiment configuration
- Attracting international participation of groups and experts:
India Institutions: contribution to magnetic shieling, nano-powder reflectors, and detector R&D;
Nagoya U./Japan: super-mirror reflectors production R&D;
ILL/Grenoble, PNPI/Russia: expertise in neutron technologies and experiments
- NNbarX is open to new US and international collaborators.

Collaboration with FNAL

- Very essential
- The organizing interaction with Fermilab is in place
- We would like to see larger FNAL group involved in NNbarX
- University groups so far are not funded for NNbarX developments → a postdoc position would greatly move our progress towards Snowmass

Fermilab Colleagues involvement:

S. Brice – helping with organizing an NNbarX research group at FNAL.

Since there are no unengaged physicists, new position slot would be very desirable.

N. Mokhov – working together on the neutron yield simulations, modification of MARS code to include transport in gravity field, cold and ultra-cold moderation; super-mirror and diffuse neutron reflectors. Providing candidate graduate student for Fermilab PhD program

E. Ramberg – liaison for detector configuration ;

A. Soha – liaison for siting and cost estimate of horizontal and vertical options;

R. Tschirhart – liaison for Project X and schedule;

C. Quigg – coordination of theoretical n-nbar developments.

We ask PAC to support formation of NNbarX group at Fermilab

END

Spare slides

Physics goals of staged NNbarX

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

τ	ILL units
0.86×10^8 s	1u
3.45×10^8 s	16u
5.5×10^8 s	50u
7.5×10^8 s	76u
1×10^{10} s	13,500u
1×10^{11} s	1,350,000u

←Free neutrons at ILL (1994)

←Super-K (2011), 22.5kt, 4 years

←Goal of horizontal NNbarX

←Hyper-K 500kt, 10 years

←Goal of vertical NNbarX

←Theory wish (R&D)

Optimization of performance of various configurations vs cost is a goal of our studies towards Snowmass 2013

$n \rightarrow \bar{n}$ for bound n inside nuclei is strongly suppressed

Neutrons inside nuclei are "free" for the time: $\Delta t \sim \frac{\hbar}{E_{well}} \sim \frac{\hbar}{30 MeV} \sim 2.2 \times 10^{-23} s$

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.

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

Intranuclear (exponential) lifetime:

$$\tau_A = \frac{\tau_{n\bar{n}}^2}{\Delta t} = R \times \tau_{n\bar{n}}^2$$

where $R \sim \frac{1}{\Delta t} \sim 4.5 \times 10^{22} s^{-1}$ is "nuclear suppression factor"

Actual nuclear theory suppression calculations for $^{16}O, ^2D, ^{56}Fe, ^{40}Ar$ by C. Dover et al; W.Alberico et al; B.Kopeliovich and J. Hufner, and most recently by Friedman and Gal (2008) for ^{16}O with correction of factor of $\times 2$ to the previous

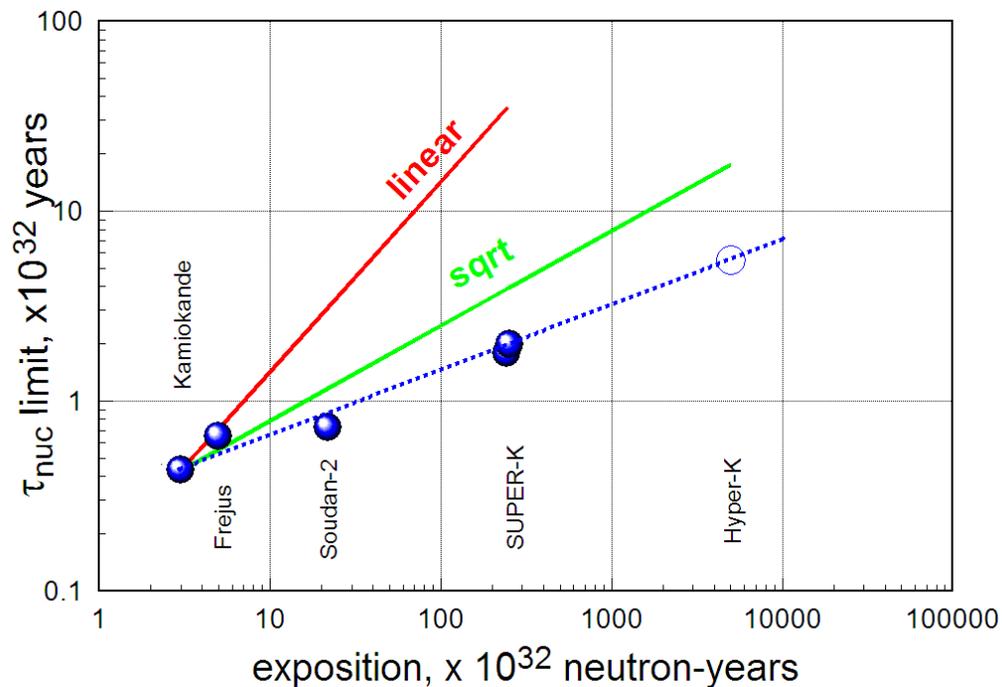
$$R(\text{Oxygen}) \approx 5 \times 10^{22} s^{-1} (\pm 15\%)$$

(Friedman and Gal, 2008)

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	$>0.43 \times 10^{32}$
Frejus	1990	Fe	5.0	30%	0	4	$>0.65 \times 10^{32}$
Soudan-2	2002	Fe	21.9	18%	5	4.5	$>0.72 \times 10^{32}$
Super-K	2007	O	245.4	10.4%	20	21.3	$>1.8 \times 10^{32}$
Super-K	2009	O	254.5	12%	23	24	$>1.97 \times 10^{32}$
SNO *	2010	D	0.54	41%	2	4.75	$>0.301 \times 10^{32}$
Super-K	2011	O	245	12.1%	24	24.1	$>1.89 \times 10^{32}$

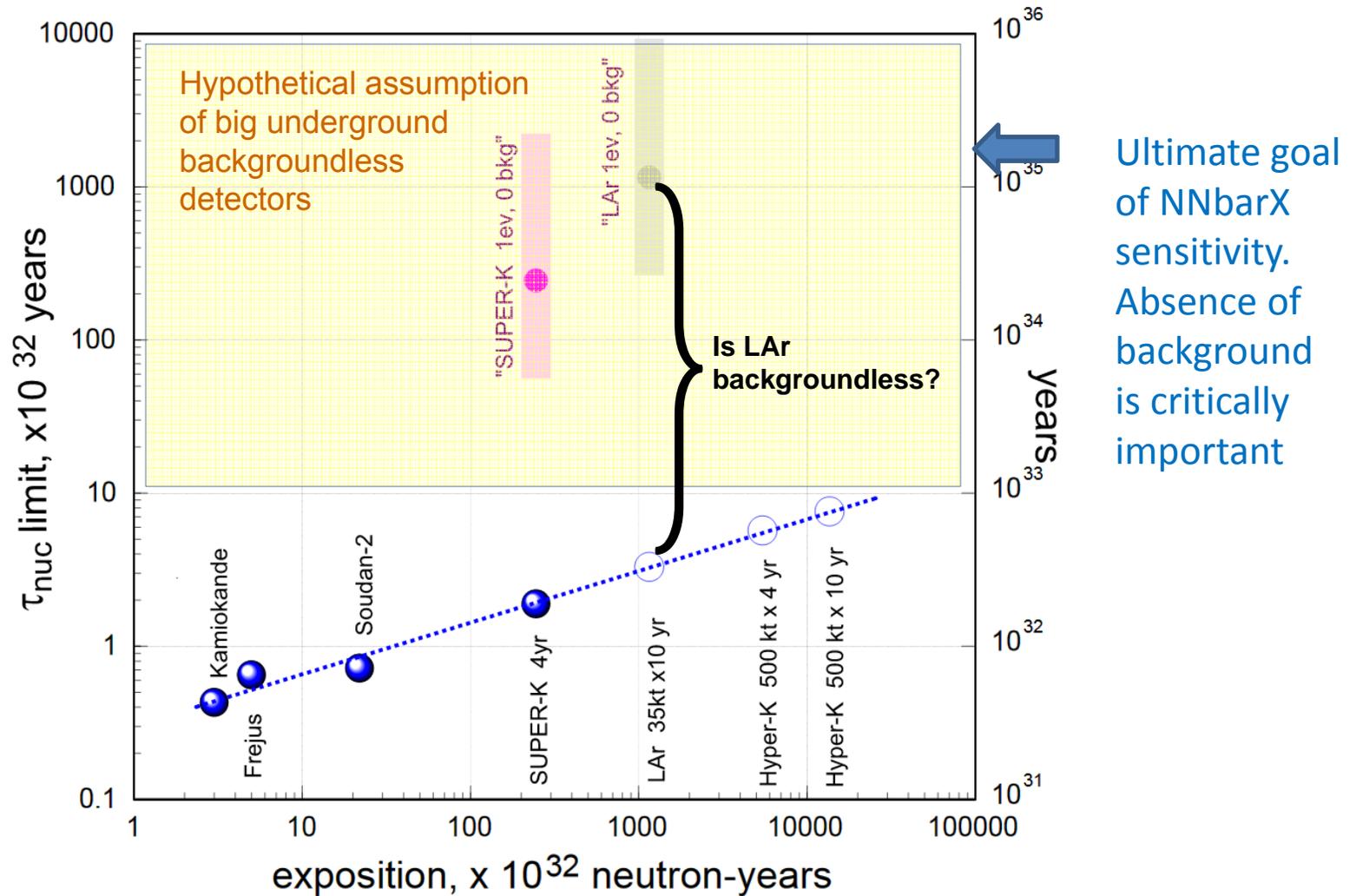
* Not yet published



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.

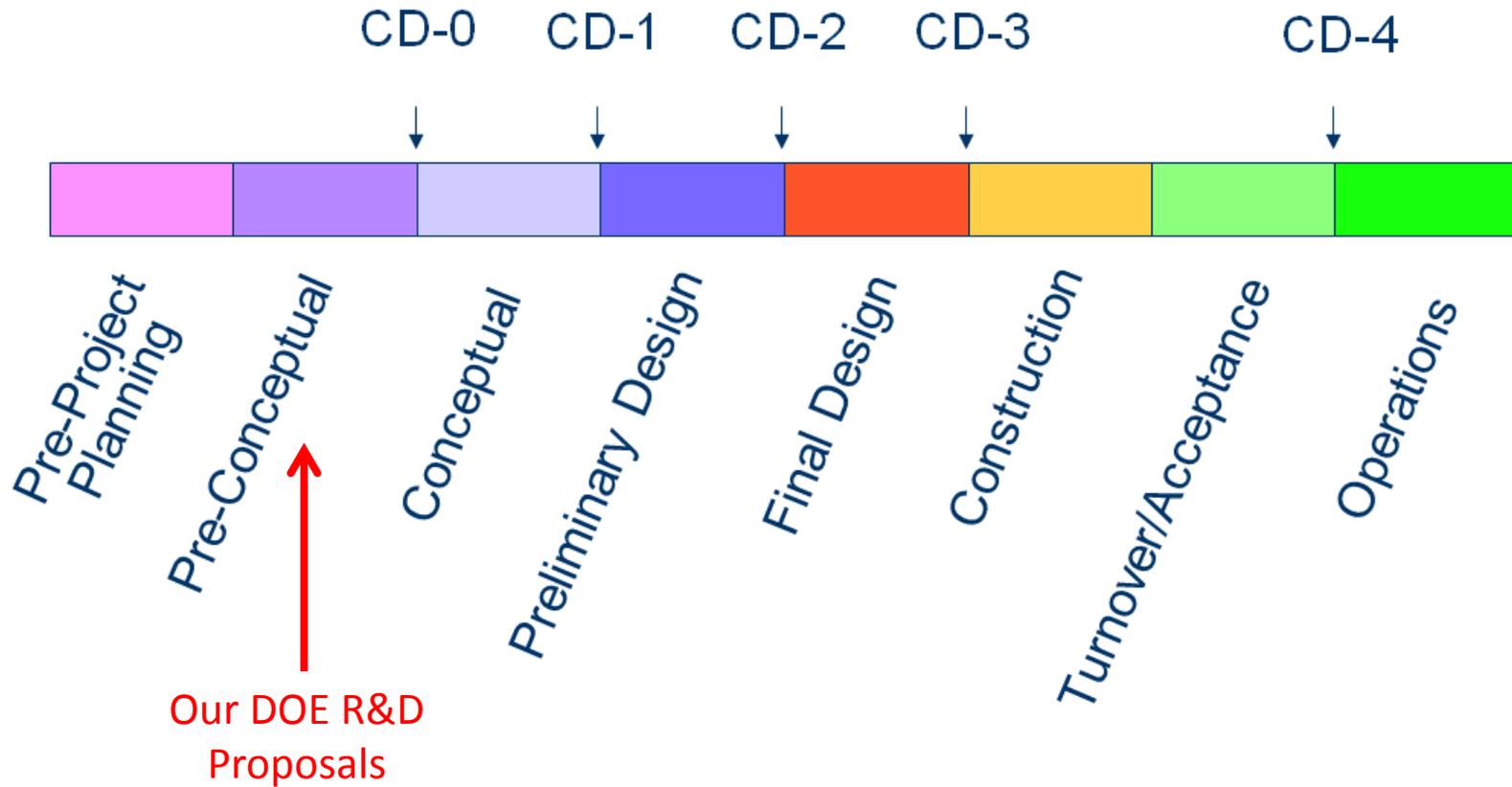
Comparison with intranuclear n-nbar search



24 candidate events in Super-K might contain several genuine n-nbar events. Backgroundless PDK detectors are needed to explore nbar > 10³³ years. Can atmospheric neutrinos and nbar signals be separated in LAr detectors???



PROJECT LIFECYCLE



R&D Proposal sent to DOE (Detector R&D area) on September 10, 2012



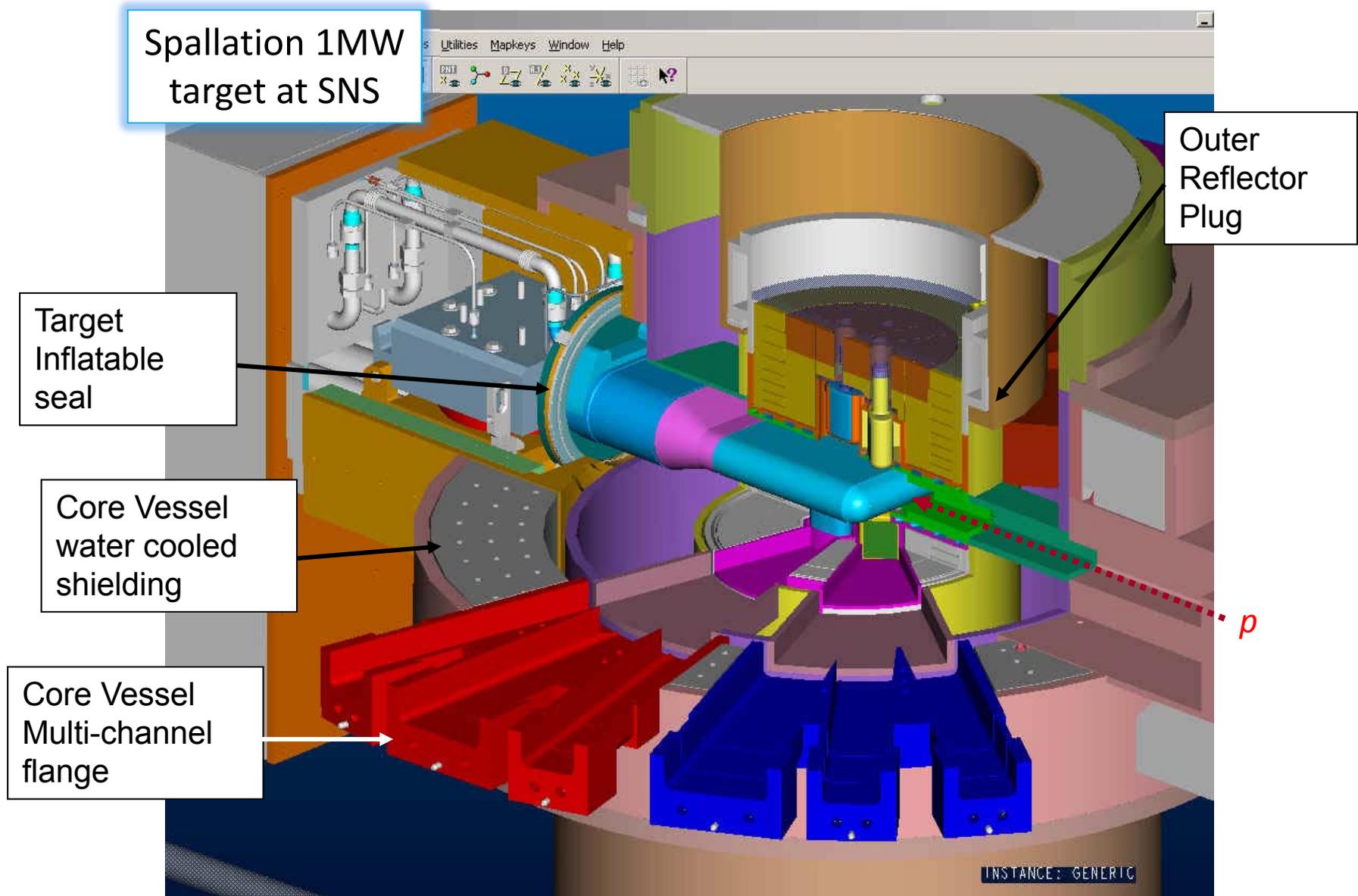
New proposal to DOE/HEP in the area of “Particle Detector Research and Development”

Development of a Pre-Conceptual Design for a Spallation Target and Support System for N-Nbar Oscillation Search and Other Potential Experiments with Cold Neutrons in Project X

From research group: Senior Investigators: University of Tennessee, Physics Department: T. Gabriel (co-PI), G. Greene (co-PI), T. Handler (co-PI), Y. Kamyshkov (PI); *University of Tennessee, Nuclear Engineering Department:* L. Heilbronn (co-PI), A. Ruggles (co-PI), L. Townsend (co-PI); *Senior Key Personnel:* D. Lousteau (*Scientific Investigation and Development*);

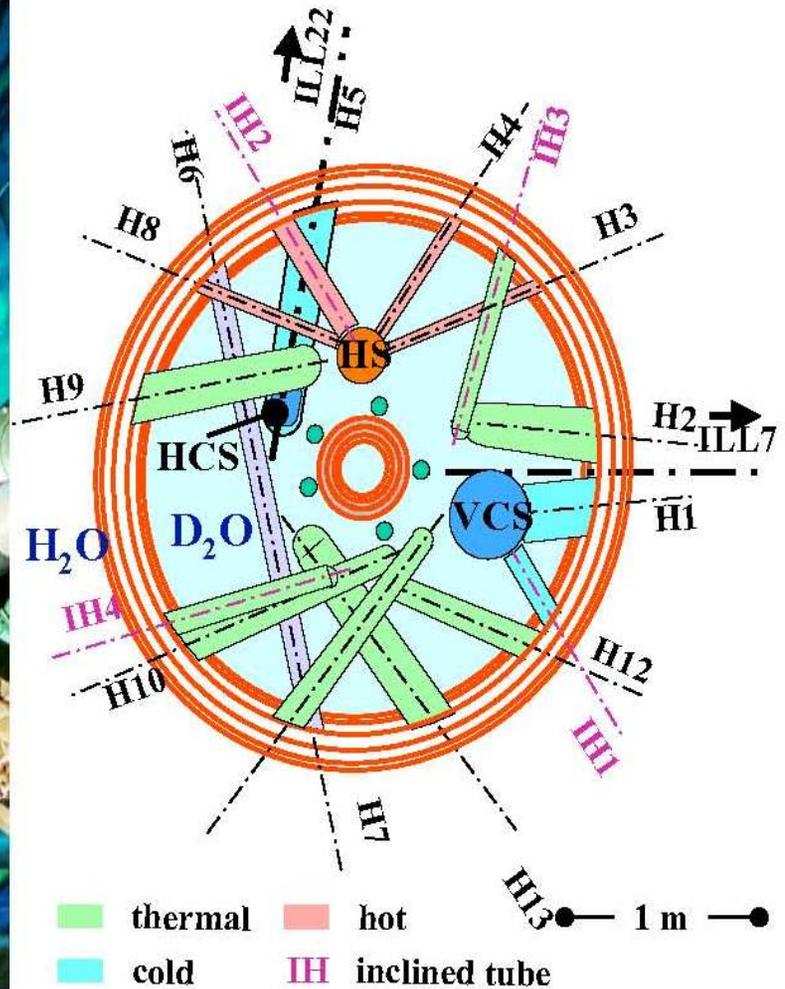
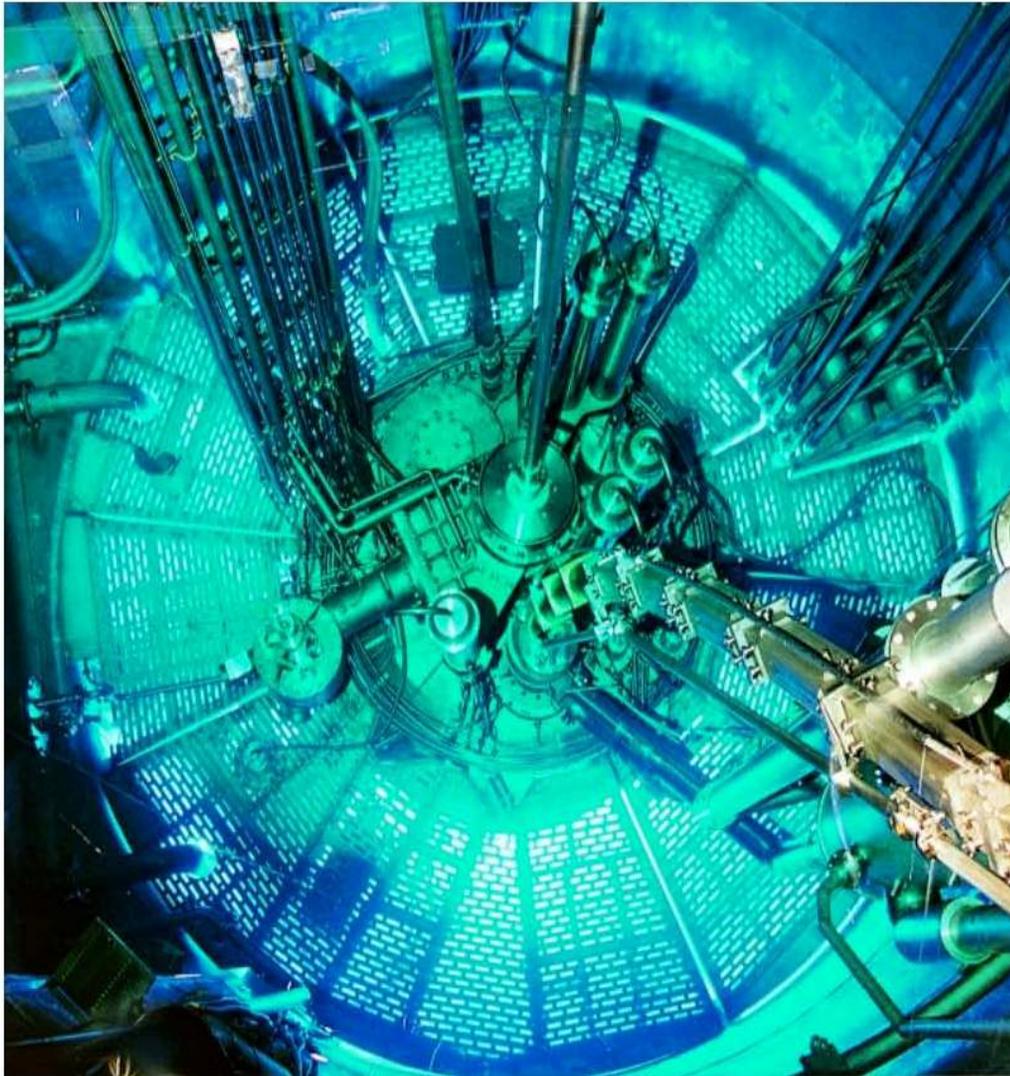
Program manager for this proposal is Glen Crawford

Existing multiple n-beam lines ar SNS are using small faction of 4π



Tony Gabriel/UT/SNS

The Institut Laue Langevin High Flux Reactor is optimized to serve many neutron beamlines



The High Flux neutron Source at the ILL

Geoff Greene/UT

NNbar Summary

New physics beyond the SM can be discovered by new NNbarX search experiment

New direction within US Intensity Frontier initiative

Requires R&D on design of dedicated optimized spallation UCN-VCN source

Expected improvement in N-Nbar search sensitivity is a big factor of >1,000 that is within the predicted range of several models

Without a background one event can be a discovery !

Effect can be uniquely checked/controlled by weak magnetic field

If discovered:

- $N \rightarrow \bar{N}$ will establish a new force of nature and a new phenomenon of (B-L)V leading to the exploration of the new physics beyond the SM at the energy scale above TeV. Can be also an interesting CPT laboratory measuring $\Delta m_{n-\bar{n}}$

If NOT discovered:

- within the reach of improved experimental sensitivity will set a new limit on the stability of matter exceeding the sensitivity of XL nucleon decay experiments. Will test/constraint models of low scale baryogenesis.

Vacuum N-Nbar transformation from bound neutrons:

Best result so far from Super-K in Oxygen-16

$$\tau_{16O} > 1.89 \times 10^{32} \text{ yr} \quad (90\% \text{ CL})$$

← { 24 observed candidates;
24.1 exp. background

$$\tau_{nucl} = R \times \tau_{n\bar{n} \text{ free}}^2$$

if $R_{16O} = 5 \cdot 10^{22} \text{ s}^{-1}$ from Friedman and Gal (2008)

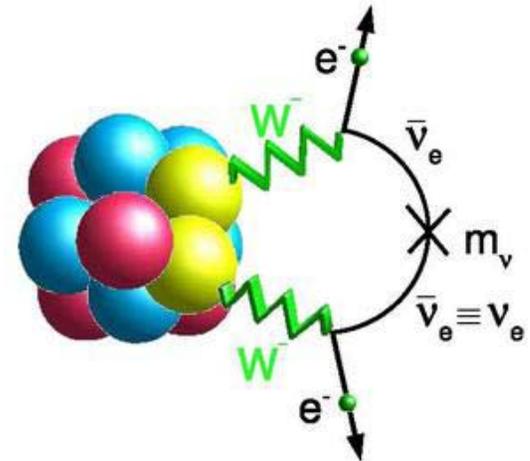
$$\Rightarrow \tau(\text{from bound}) > 3.5 \times 10^8 \text{ s} \quad \text{or} \quad \alpha < 2 \times 10^{-24} \text{ eV}$$

× 16 times higher than
sensitivity of ILL expt.

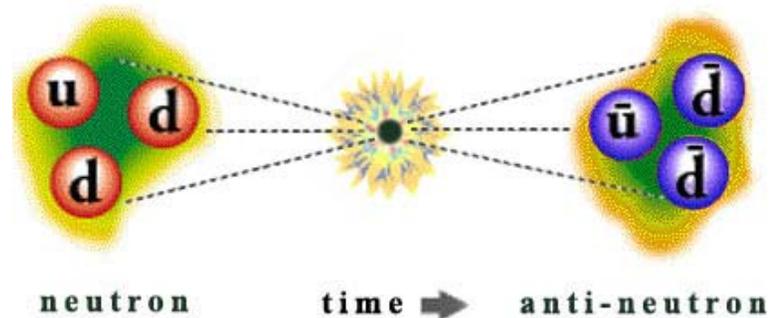
ILL limit (1994) for free neutrons: $\tau_{n\bar{n}} > 0.86 \times 10^8 \text{ s}$

Alternative searches for B, L, B – L violation

- ❖ Several experiments are currently searching for Majorana neutrino in “neutrinoless double beta decay”. Majorana neutrinos means $\nu \leftrightarrow \bar{\nu}$ and $\Delta L = 2$, thus violating (B – L) by 2.



- ❖ If (B – L) is violated by 2 that also means that $\Delta B=2$ should exist and thus $n \leftrightarrow \bar{n}$ is possible



B, L, and B – L

- ❖ e.g. $n \rightarrow p + e^- + \bar{\nu}_e$ conserves B and L: $\Delta B=0$ and $\Delta L=0$
- ❖ B and L are “accidental symmetries” \rightarrow might be violated: $\Delta B, \Delta L \geq 1$
- ❖ ΔB and ΔL are connected via conservation of angular momentum.
 $\Delta L = \pm \Delta B \rightarrow \Delta(B-L) = 0$ or $\Delta(B-L) = 2$. Is (B – L) conserved ?
- ❖ Naively (B – L) is strongly violated in regular matter: $\#n + \#p - \#e \neq 0$
However, on the scale of the universe it might be compensated by the unknown number of relic neutrinos and antineutrinos ...
- ❖ Standard Model conserves (B – L) but violates B, L and (B+L) at tiny unobservable level at present temperature [G. ‘t Hooft, 1976];
at electroweak scale fast (B+L) violation would wipe out matter-antimatter asymmetry if the latter is due to (B – L) conservation processes at GUT scale.
[V. Kuzmin, A. Rubakov, M. Shaposhnikov, 1985]
- ❖ V(B–L) is starting point for “Leptogenesis” [Fukugita, Yanagida, 1986]

Some history of $n \leftrightarrow \bar{n}$ ideas

- ❖ There are no laws of nature that would forbid the $N \leftrightarrow Nbar$ 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

- ❖ $N \leftrightarrow Nbar$ -like process was suggested as a possible mechanism for explanation of Baryon Asymmetry of Universe

V. Kuzmin, 1970

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

R. Mohapatra and R. Marshak, 1979 ...

- ❖ Recent models explaining neutrino masses, low-scale baryogenesis, connecting with dark matter, involving gravity, extra-Ds, predicting new particles at LHC...include $N \leftrightarrow Nbar$

K. Babu, R. Mohapatra et al; Z. Berezhiani et al;

A. Dolgov et al; G. Dvali and G. Gabadadze, ...

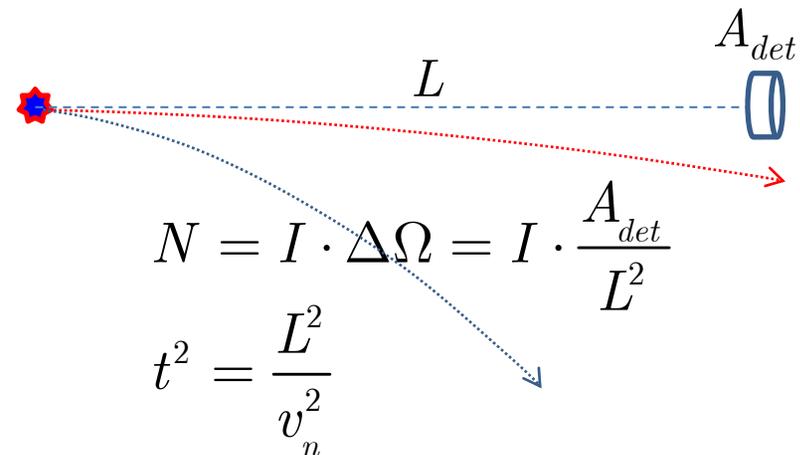
$$P \propto N \cdot \left(\frac{t}{\tau}\right)^2$$

Let's try to design such an experiment

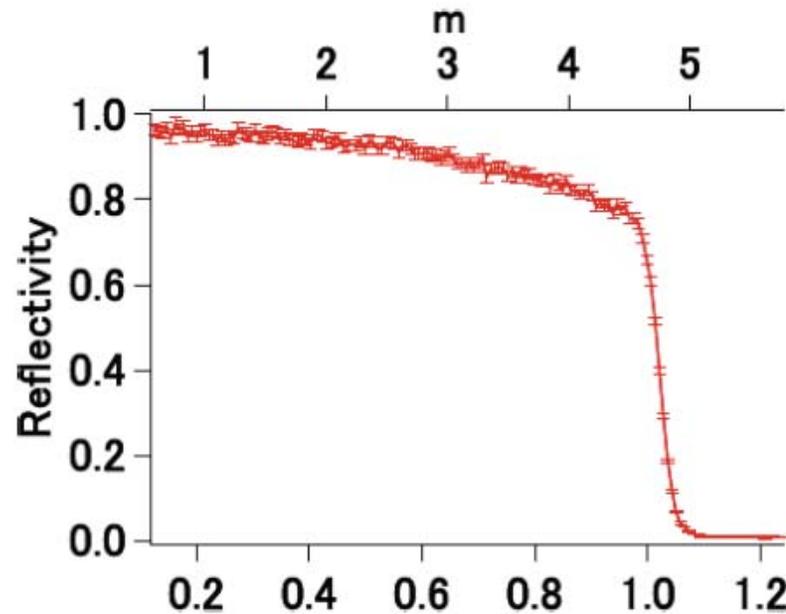
- Concept: after time t some of the neutrons might be spontaneously converted to antineutrons and will annihilate with a target producing a star of pions.
- Need many neutrons: \rightarrow reactor or spallation source ← Produced as ~ 2 MeV
- Slowest possible neutrons with maximum observation time ← Even moderated to 300K $v_n \sim 2,200$ m/s with broad Maxwell-Boltzmann spectrum
- Earth magnetic field shielding: $(2\mu B) \cdot t < \hbar \rightarrow B < 1 - 10$ nT
- Vacuum $< 10^{-5}$ Pa

Distance ? Doesn't matter here \rightarrow

Gravity effect on horizontal beam



Substrateless Supermirror



no substrate (radiation hardness expected)

DLC Supermirror?



Date(2012/06/18) by(H.M.Shimizu)
Title(Supermirrors)
Conf(Project X Physics Meeting) At(Batavia, IL)

Hiro Shimizu



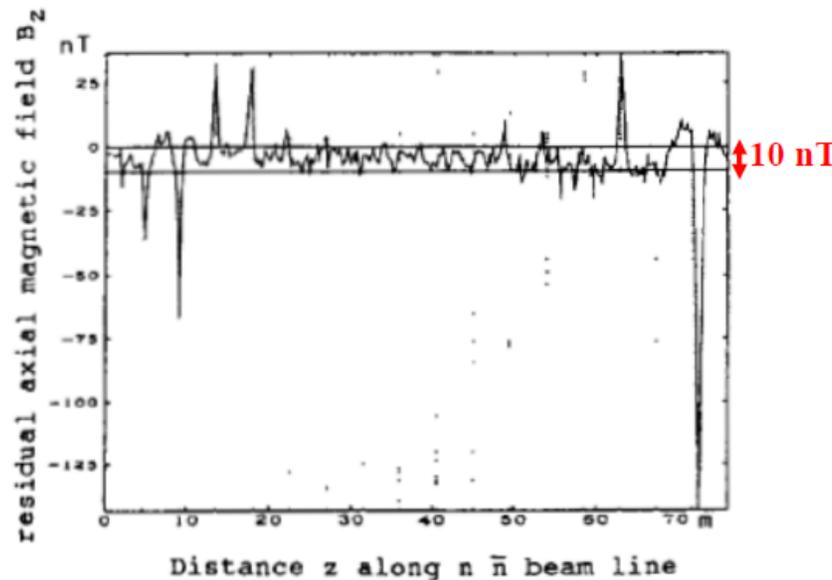
Magnetic Shielding in ILL (1991) experiment

$B(z)$ with mumetal $\varnothing 1.1$ m

+ active compensation (changing environmental field)

+ demagnetization

50 Hz axial plus
1 Hz radial



$$\mu_{\text{eff}} = 2 \times 10^6$$

Measured twice daily

Restriction on μ metal diameter
due to the size of annealing oven

0.984 ± 0.003 quasifree efficiency

T. Bitter et al.,
NIM A **309**, 521 (1991)
U. Kinkel,
Z. Ph. C **54**, 573 (1992)

Alternative idea of sub-nT magnetic shielding

Magnetic Shielding At Petersburg Nuclear Physics Institute



Pre-bended, pre-annealed μ metal tiles arranged in multilayer shield

Separated panel construction for segmented shield developed for Neutron EDM experiment

Mike Snow

Photo courtesy A. Serebrov

Shielding in Target region

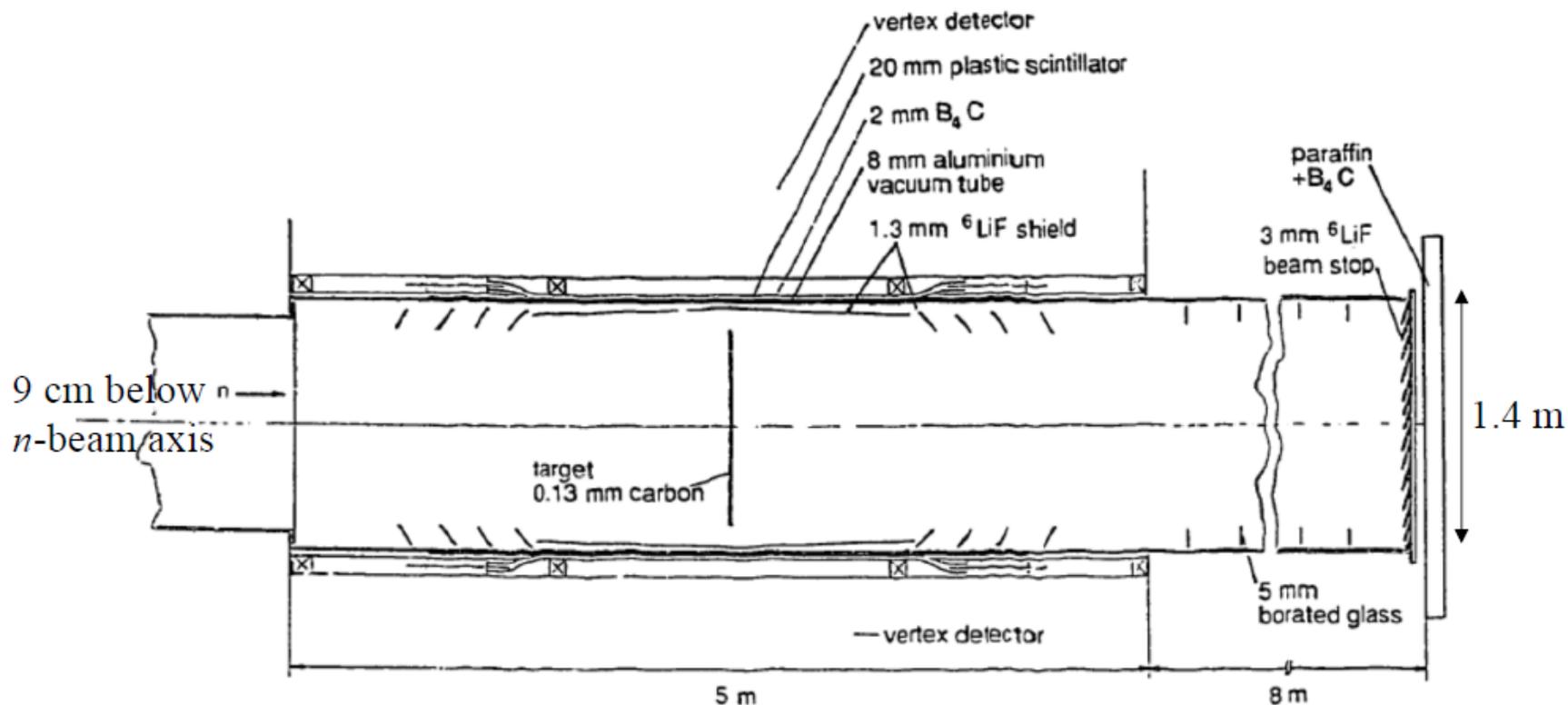


Fig. 1. The target region of the $n\bar{n}$ experiment and its surroundings.

Fermilab 18.06.2012

Dirk Dubbers/Heidelberg

$$10^7 \gamma/\text{s ILL} \Rightarrow 10^8 \gamma/\text{s at PX ST}$$

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 ${}^6\text{LiF}$ shield.
3. Annihilation detector with higher track resolution is desirable.

Maxwellian spectra of thermalized neutrons at temperature T

