Seminar at LNGS • May 17, 2012

Matter-Antimatter Transformation via Neutron-Antineutron Oscillations

Status Review and New Searches of $n \rightarrow \overline{n}$ *with Cold Neutrons*

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Overview

- ❖ Observation of violation of Baryon number is one of the pillars of modern Cosmology and Particle Physics
  - it is required for explanation of Matter-Antimatter asymmetry BAU (Sakharov)
  - it follows from the inflation (Dolgov, Zeldovich)
  - it is motivated by GUT models

- ❖ Proton decay with $\Delta B = 1$ so far has failed to demonstrate existence of BV

- ❖ (B – L) must be violated $\rightarrow$ idea of Leptogenesis with $\Delta L = 2$.
  Majorana nature of ν's should experimentally demonstrate $\Delta L = 2$, however experimental prove of Leptogenesis will be hardly possible.

- ❖ Alternative search is $n \longrightarrow \overline{n}$ transformation with $\Delta B = 2$ and (B – L)V

- ❖ New developments in NNbar search in US within the "Project X"

Is Neutron a Majorana Particle?

In the famous E. Majorana 1937 paper
“Teoria simmetrica dell’elettrone e del positrone”,
Il Nuovo Cimento, v.14, 1937, pp. 171-184:

“ ... this method ... allows not only to cast the electron-positron theory into a symmetric form, but also to construct an essentially new theory for particles not endowed with an electric charge (neutrons and the hypothetical neutrinos).”

(translated by L. Maiani)

But antineutron discovered in 1956 by B. Cork et al. @ LBL was turned out to be a particle different from neutron.

However, the presence of some small fraction of the antineutron component in the neutron wave function can not be excluded, and the question whether neutron is Majorana particle should remain.

This mixing fraction must be small (otherwise it would be already observed) unless there are some suppression conditions or mechanisms present.

Mixing of neutral components is a general feature observed in Nature:

❖ Such mixing occurs when some symmetry is broken

- Gauge symmetry $\rightarrow$ mixing of U(1) x SU(2) in SM Z^0 and γ
- Strangeness, beauty $\rightarrow$ in $K^0 \longrightarrow \overline{K^0},\ B^0 \longrightarrow \overline{B^0}$
- Flavor number $\rightarrow$ in neutrino flavor oscillation $\nu_\mu \longrightarrow \nu_e$
- Lepton number $\rightarrow$ in Majorana neutrinos $\nu_e \longrightarrow \overline{\nu}_e$
- Baryon number $\rightarrow$ $n \longrightarrow \overline{n}$

B, L, and B – L

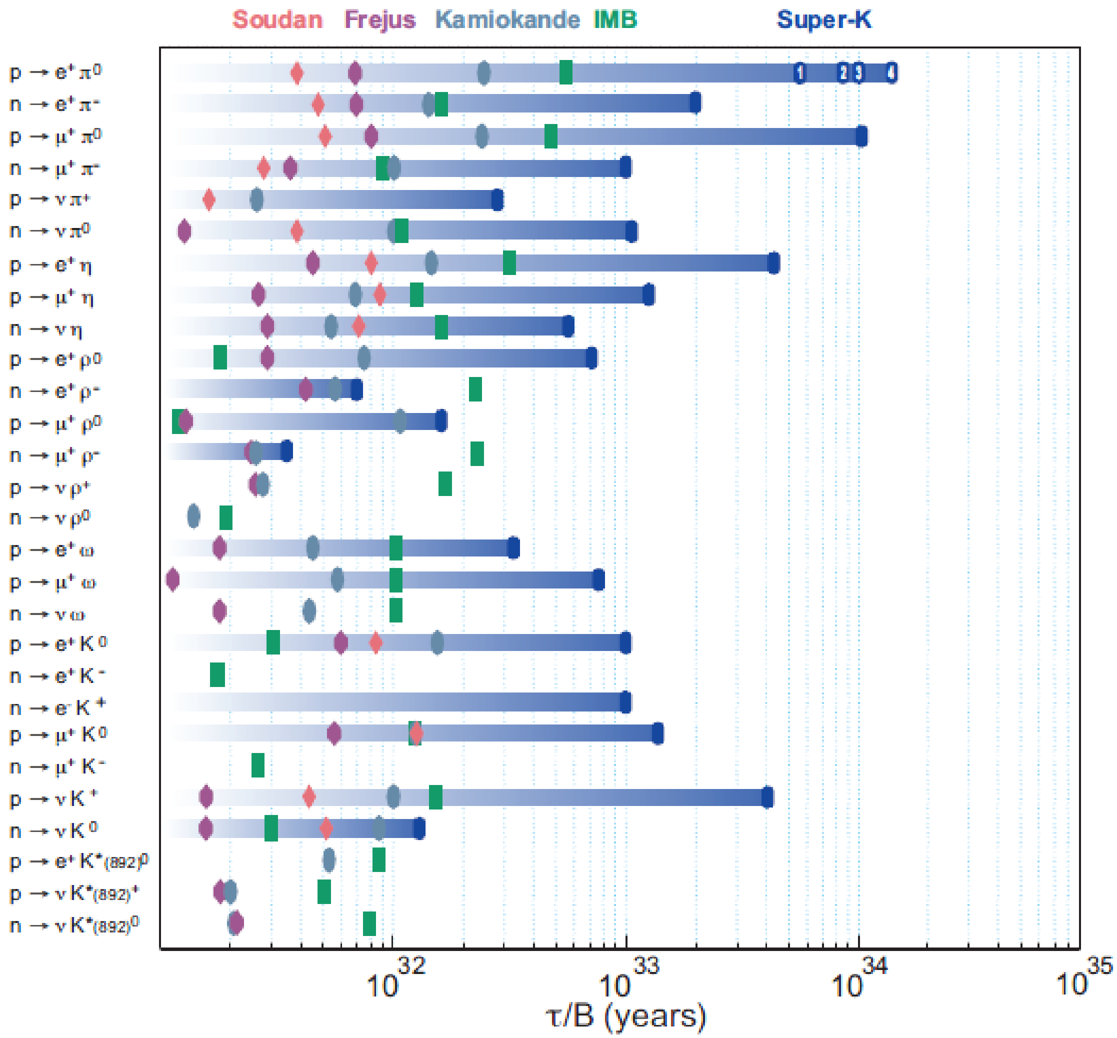
- e.g. $n \longrightarrow p + e^{-} + \overline{\nu}_e$ conserves B and L: ΔB=0 and ΔL=0
- B and L are "accidental symmetries" → might be violated: ΔB, ΔL ≥ 1
- ΔB and ΔL are connected via conservation of angular momentum.
  ΔL = ± ΔB . → Δ(B–L) = 0 or Δ(B–L) = 2. Is (B – L) conserved ?
- Naively (B – L) is strongly violated in regular matter: #n + #p – #e ≠ 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 level at present temperature [G. 't Hooft, 1976];

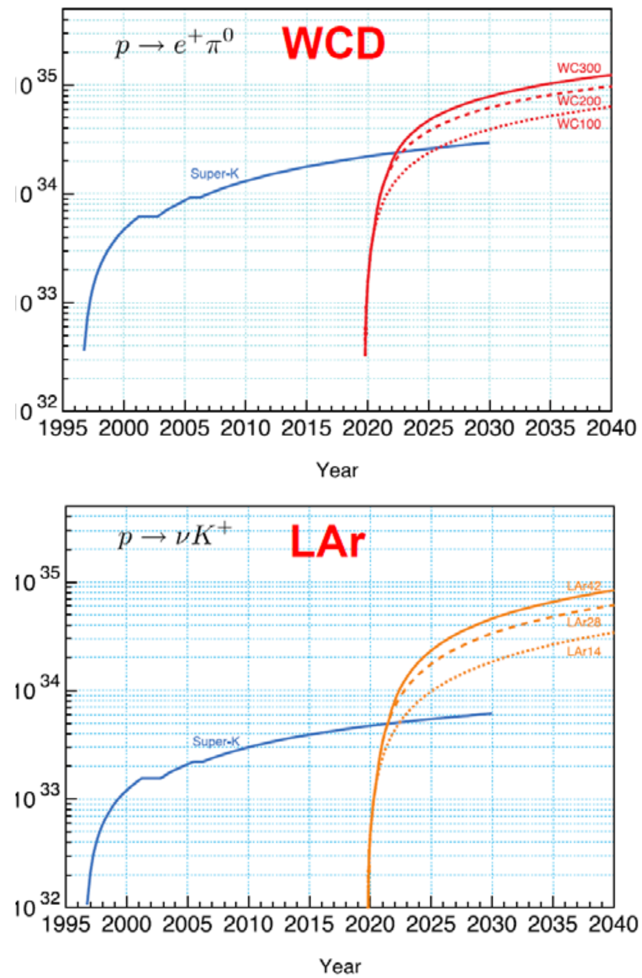
  at electroweak scale fast (B+L) violation would wipe out BAU if the latter is due to (B – L) conservation processes at GUT scale [V. Kuzmin, A. Rubakov, M. Shaposhnikov, 1985].
- Starting point for Leptogenesis [Fukugita, Yanagida, 1986]

Proton Decay Searches

are motivated by (B-L) conserving models



J. L. Raaf @ IF-2011

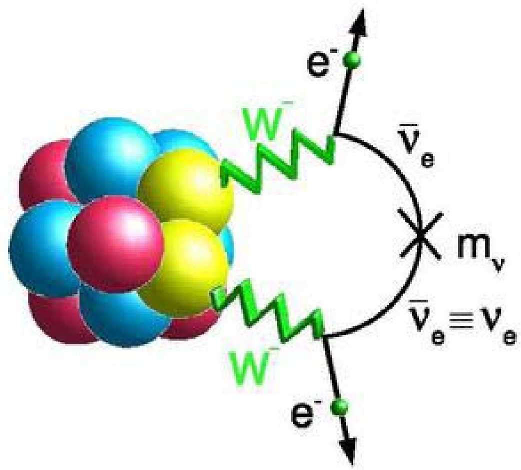


LBNE Physics Working Group Report
arXiv:1110.6249v1 [hep-ex]

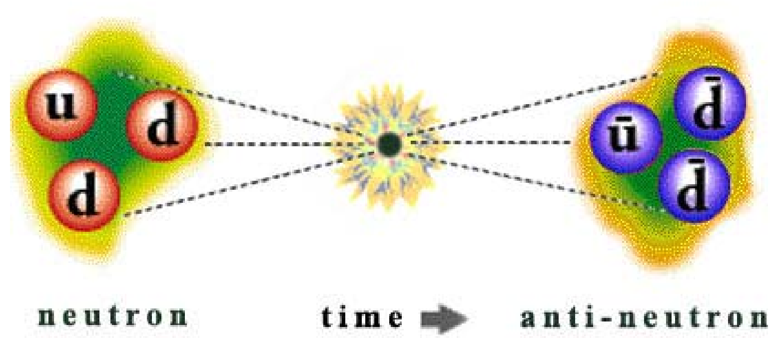
"Proton decay is not a prediction of baryogenesis." [Yanagida, 2002]

Alternative searches for B, L, B – L violation

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



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



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

❖ 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 -like process was suggested as a possible mechanism for explanation of Baryon Asymmetry of Universe *V. Kuzmin, 1970*

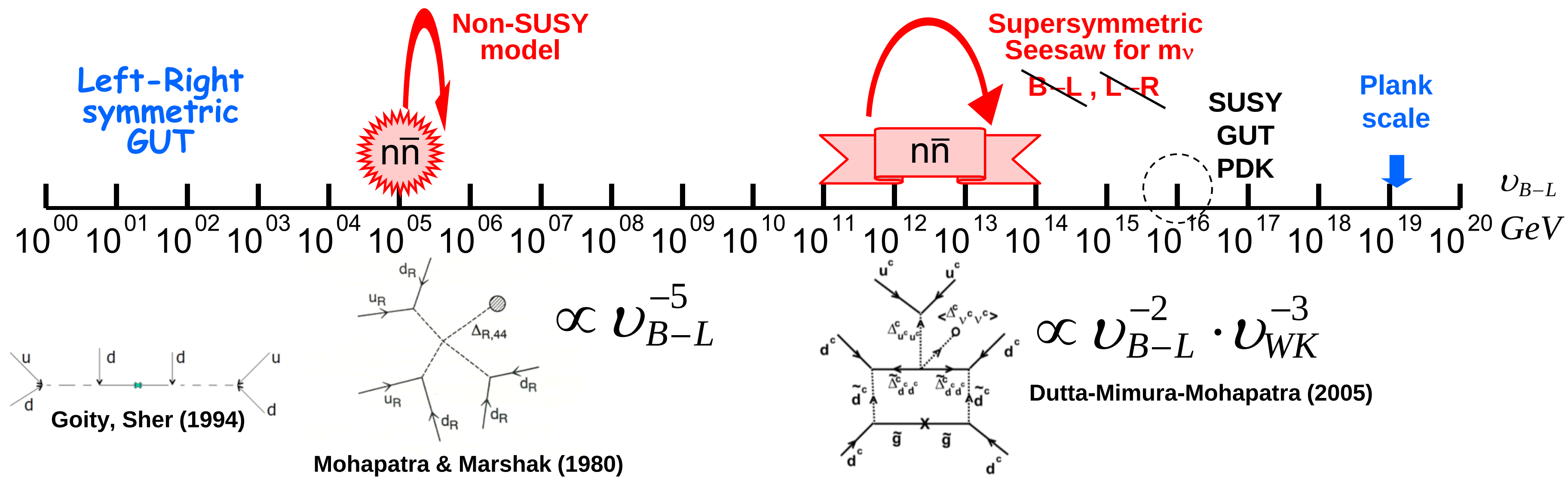
❖ N ↔ Nbar works within GUT + SUSY ideas. First considered and developed within the framework of L/R symmetric Unification models

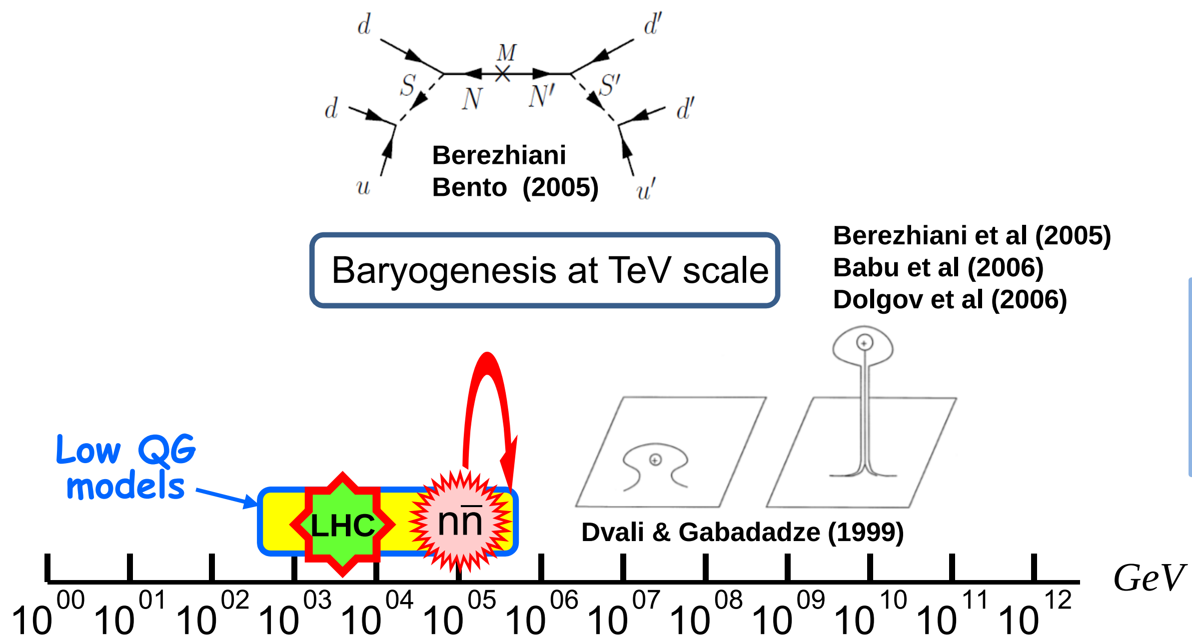
R. Mohapatra and R. Marshak, 1979 …

❖ Recent models explaining neutrino masses, low-scale baryogenesis, connecting with dark matter, involving gravity, extra-Ds, predicting new particles at LHC…

K. Babu, R. Mohapatra et al; Z. Berezhiani et al;
A. Dolgov et al; G. Dvali and G. Gabadadze, …

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

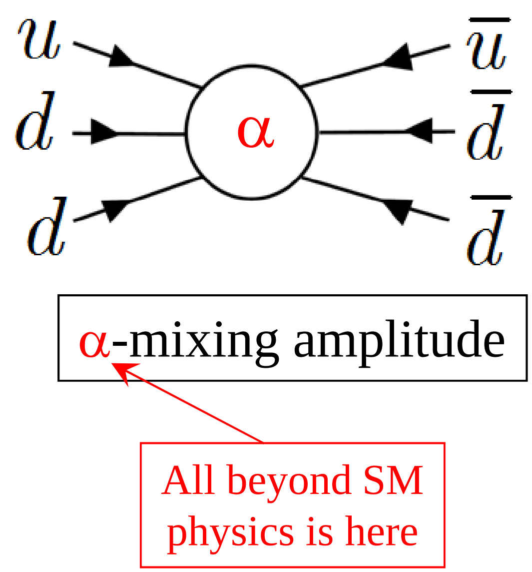




Experimental motivation!
large increase of sensitivity:
factor of ×1,000 is possible

n→nbar transition probability

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



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

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

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

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

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

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

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

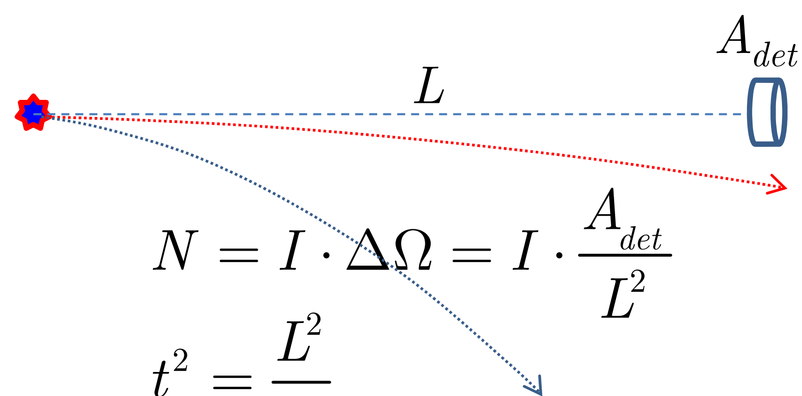
Predictions of theoretical models: observable effect around $\alpha \sim 10^{-25} - 10^{-26}\,eV$

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

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

Let's try to configure such an experiment

- Concept: after time t some of the neutrons might be spontaneously converted to antineutrons and will annihilate with target producing a star of pions.
- Need many neutrons: reactor or spallation source ← Produced as ~ 2 MeV
- Slowest possible neutrons with maximum observation time ← Even moderated to 300K v_n ~ 2,200 m/s with broad Maxwell-Boltzmann spectrum
- Earth magnetic field shielding: $2\mu B < \frac{\hbar}{t} \quad \rightarrow \quad B < 1 - 10 \;\; nT$
- Vacuum < 10^{-5} Pa
- Distance ? Doesn't matter here →
- Gravity effect on horizontal beam



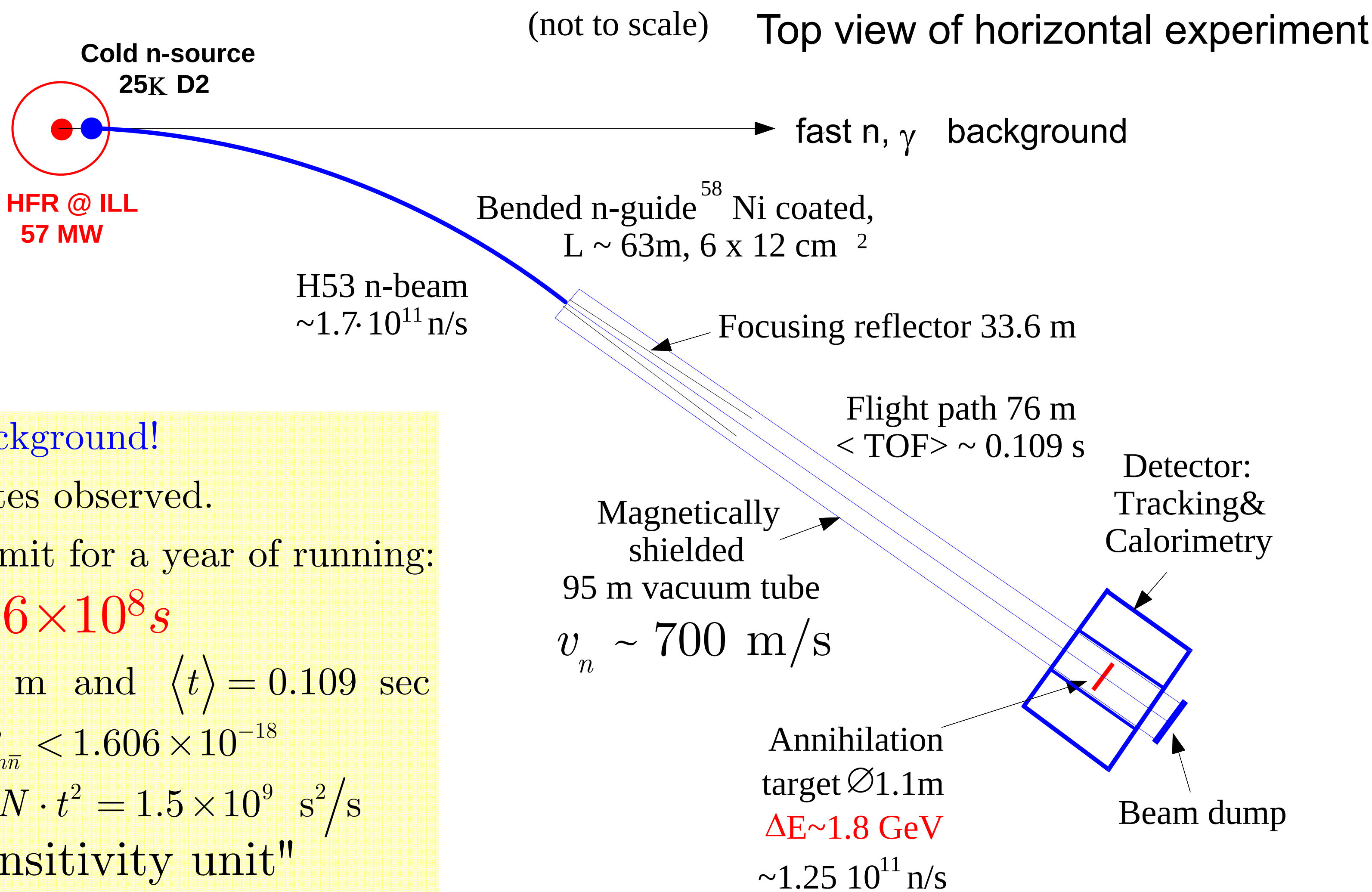
$$N = I \cdot \Delta\Omega = I \cdot \frac{A_{det}}{L^2}$$

$$t^2 = \frac{L^2}{v_n^2}$$

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.

Measured limit 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: $N \cdot t^2 = 1.5 \times 10^9 \ \mathrm{s^2/s}$

$\doteq$ "ILL sensitivity unit"

$n \to n$bar 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: $$\tau_{\text{A}} = \frac{\tau_{n\bar{n}}^2}{\Delta t} = R \times \tau_{n\bar{n}}^2$$

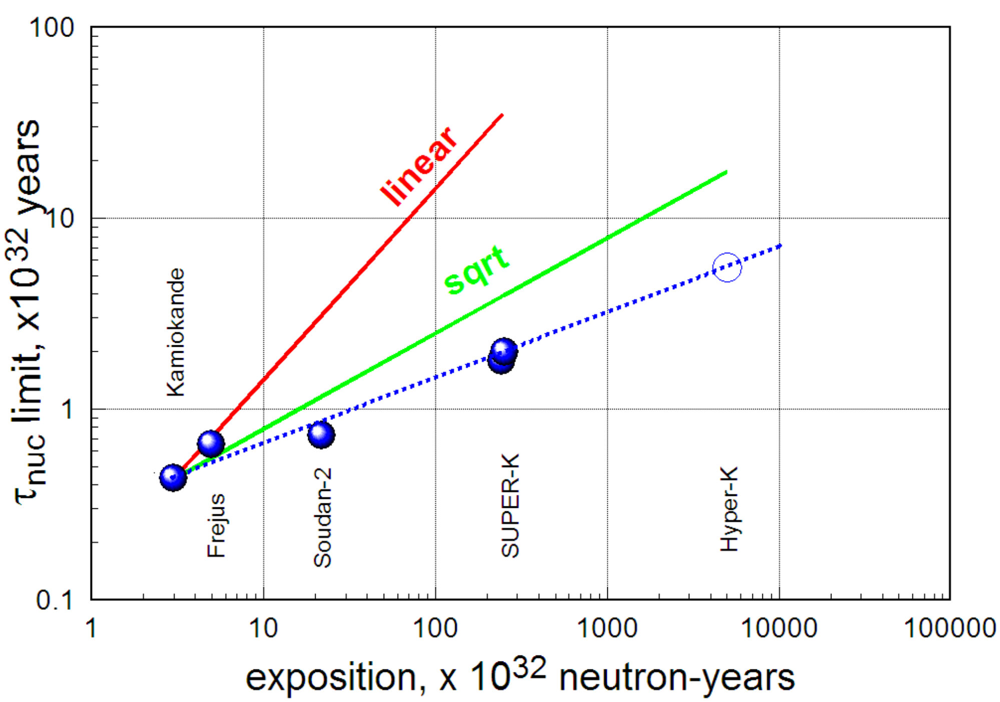
where $R \sim \frac{1}{\Delta t} \sim 4.5 \times 10^{22} s^{-1}$ is "nuclear suppression factor"

Actual nuclear theory suppression calculations for $^{16}O, ^{2}D, ^{56}Fe, ^{40}Ar$ 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

$R(\text{Oxygen}) \approx 5 \times 10^{22} \text{s}^{-1}$ $(\pm 15\%)$ (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	$>0.43\times10^{32}$
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.

Vacuum N-Nbar transformation from bound neutrons:

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

$$\tau_{^{16}O} > 1.89 \times 10^{32} yr \quad (90\%\ \text{CL})$$ $\leftarrow$ 24 observed candidates; 24.1 exp. background

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

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

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

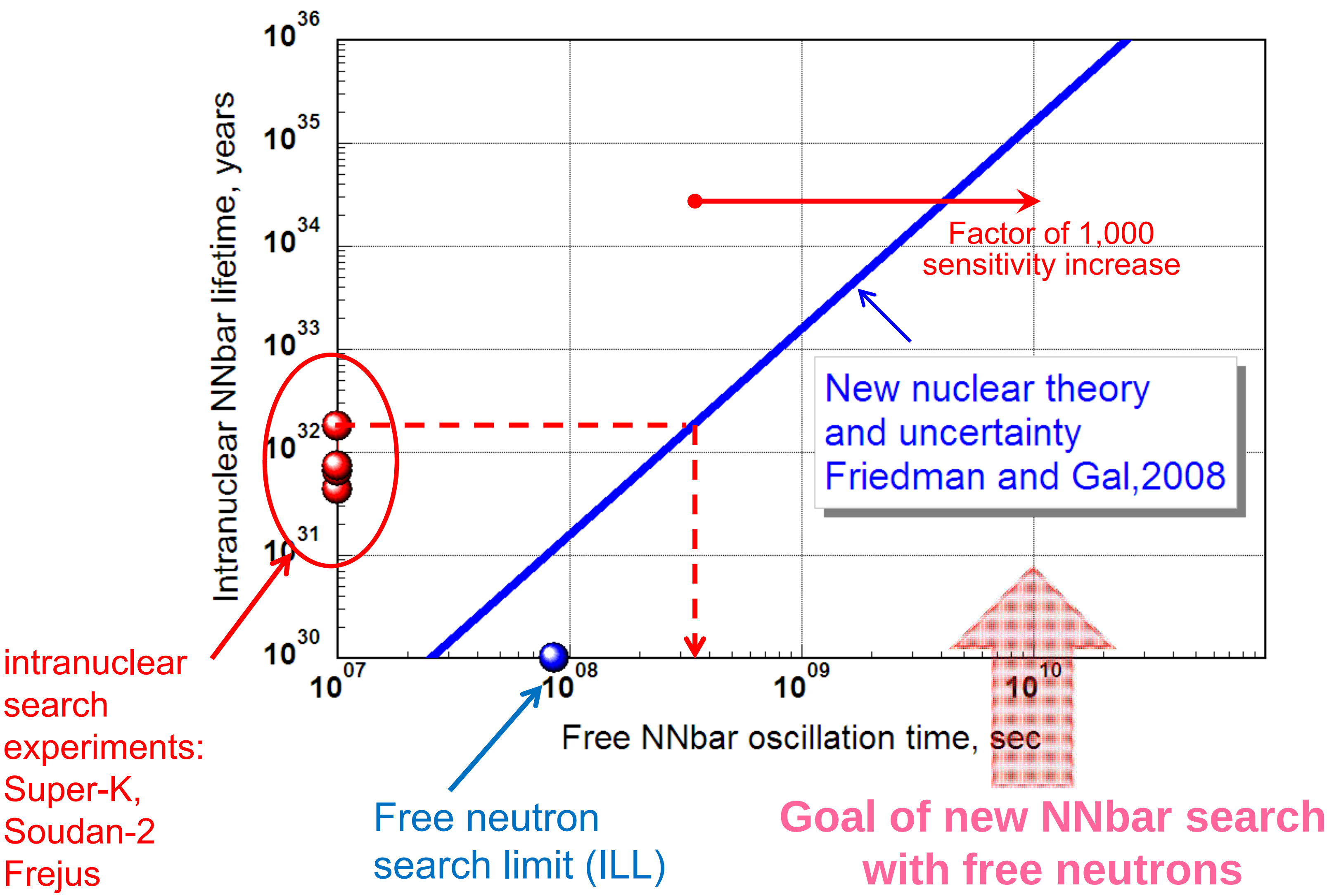
$\times 16$ times higher than sensitivity of ILL expt.

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

$$\tau_{nucl} = R \times \tau^2_{n\bar{n}}$$

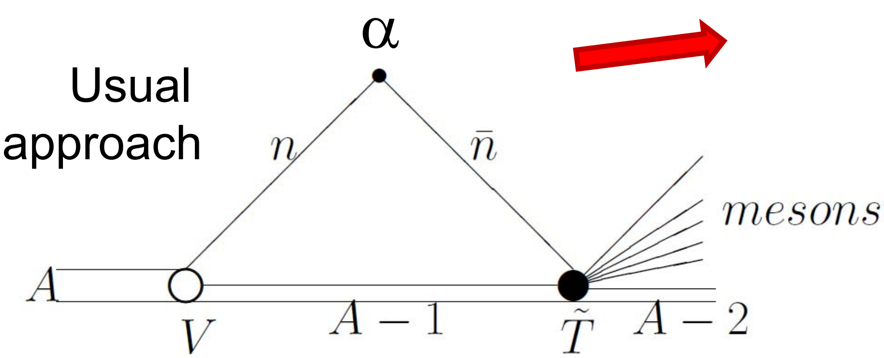
Free Neutron and Intranuclear NNbar Limits Comparison

Large improvement with free-neutron experiments is possible



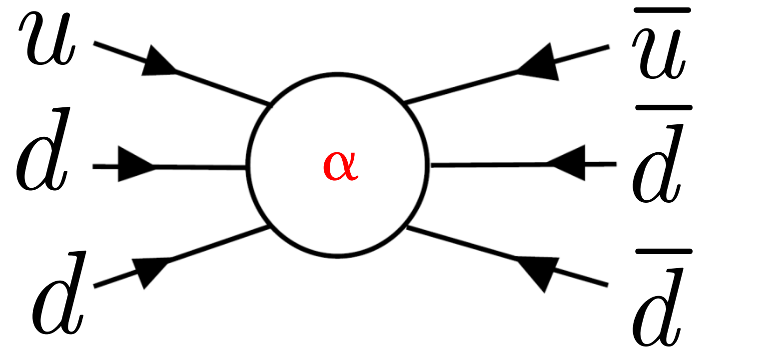
Theoretical nuclear NNbar suppression model is incomplete

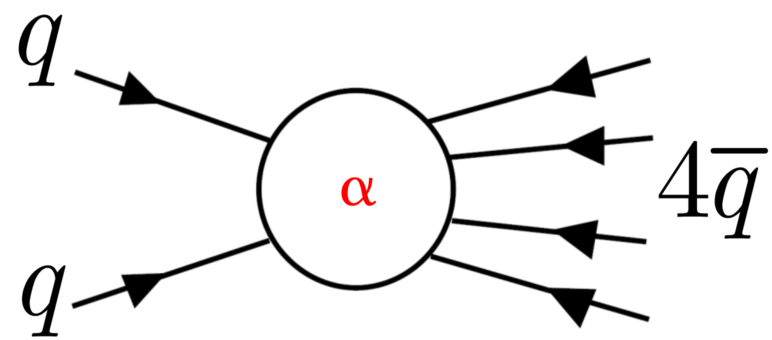
Usual approach



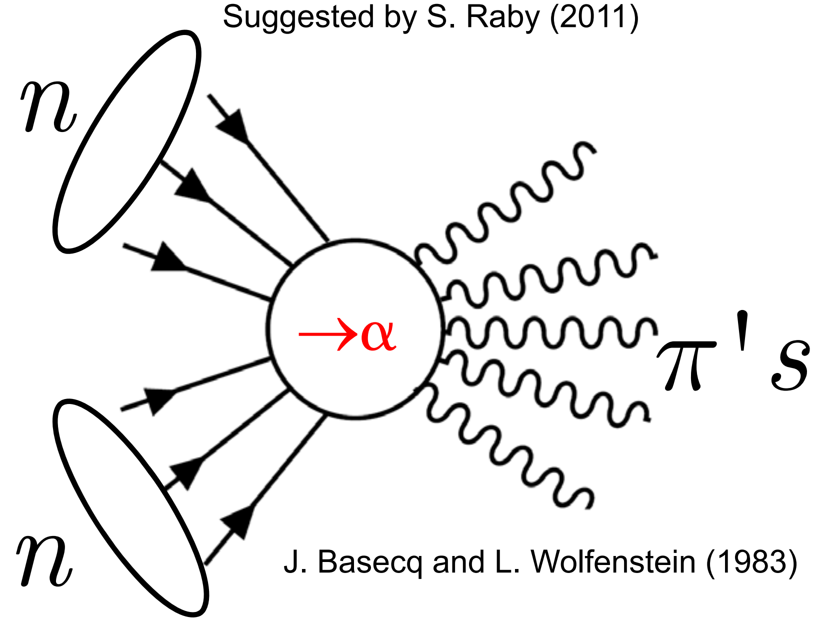
All these processes →
include the same amplitude α
and result in the same
indistinguishable final state
(of ~ 5 πs)

Existing intranuclear NNbar limits need to be re-evaluated





Suggested by S. Raby (2011)



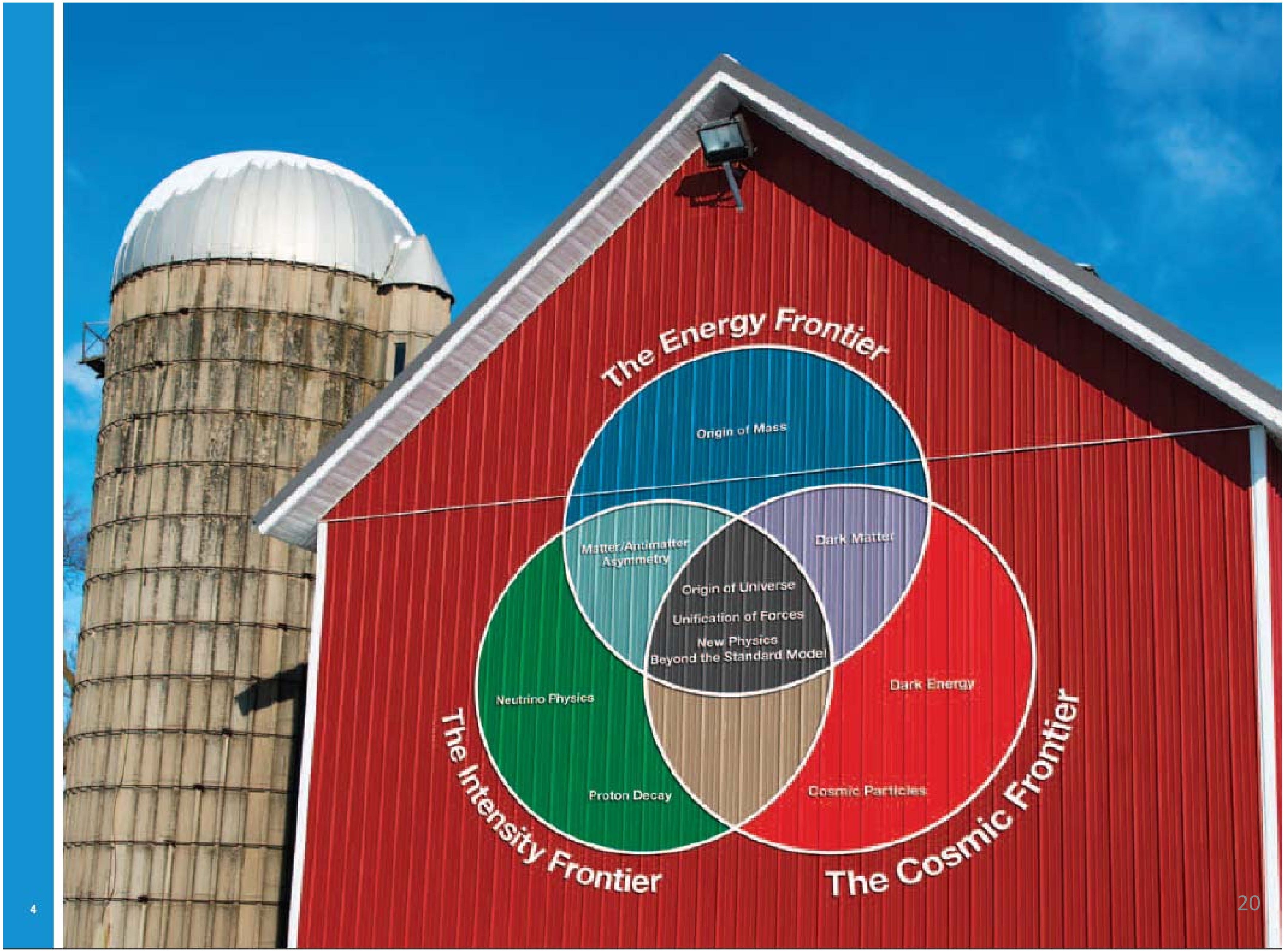
J. Basecq and L. Wolfenstein (1983)

How the major improvement in sensitivity can be made?

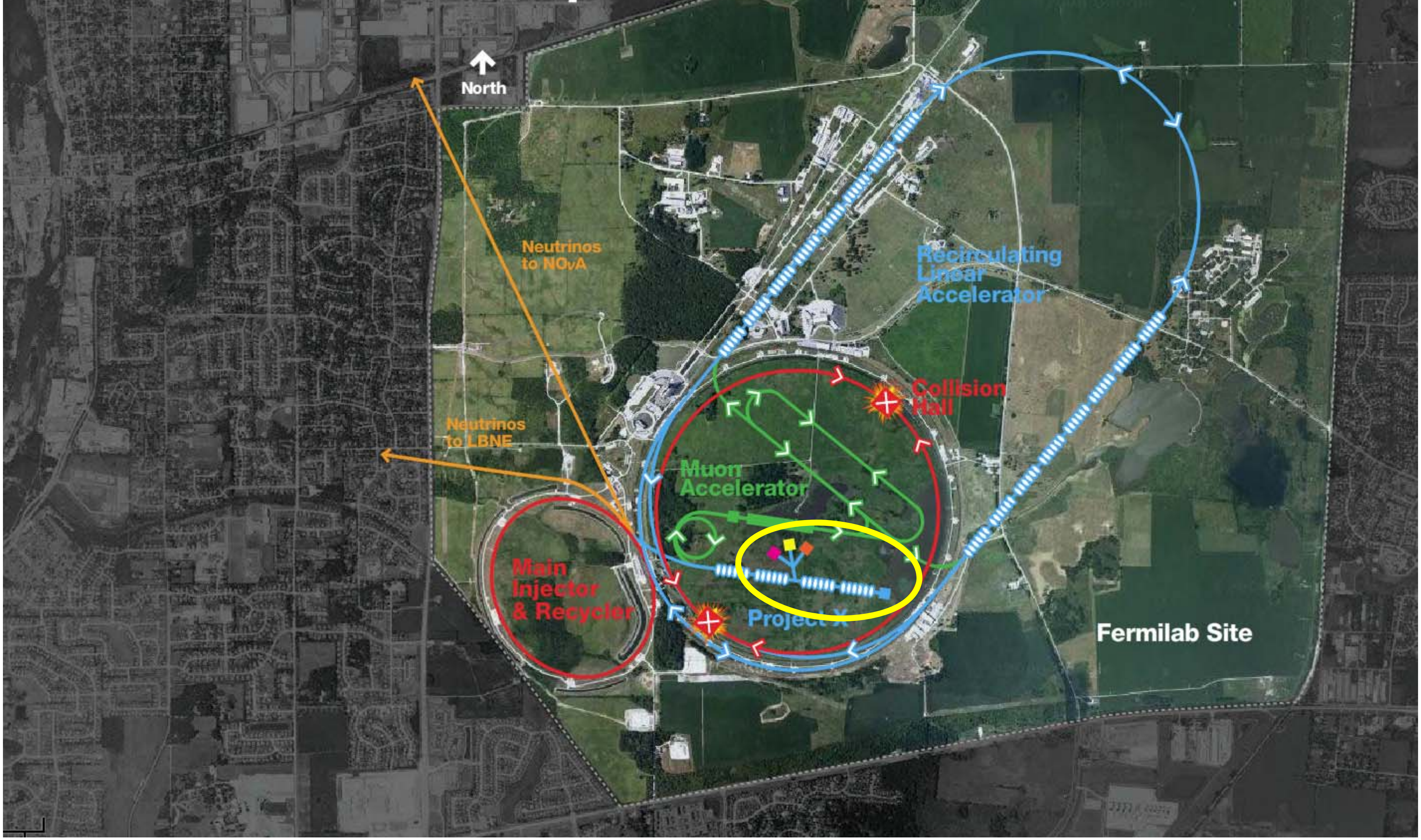
Sensitivity improvement factors for $N \cdot t^2$

- Use many neutrons (spallation source or reactor)
- Use slow neutrons: cold, VCN, UCN
- Neutron manipulation by mirror reflections
- Neutron manipulation by gravity

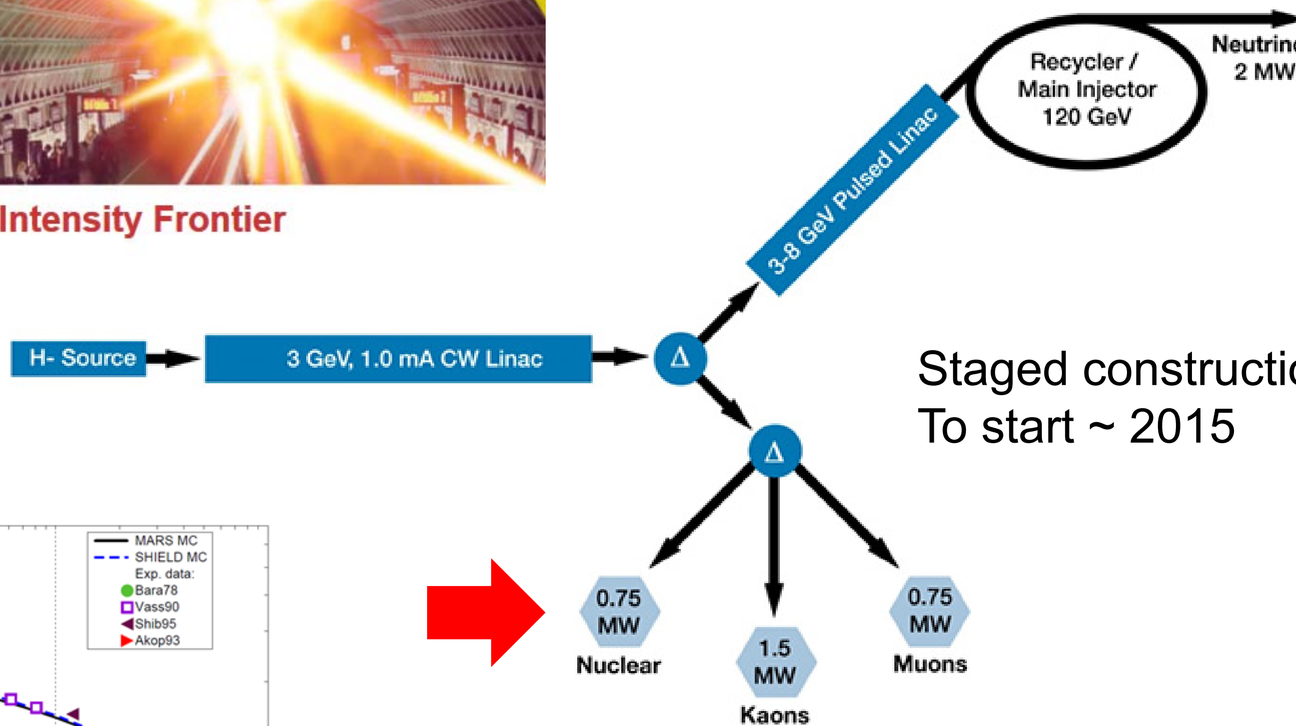
High-Intensity at Fermilab – Intensity Frontier



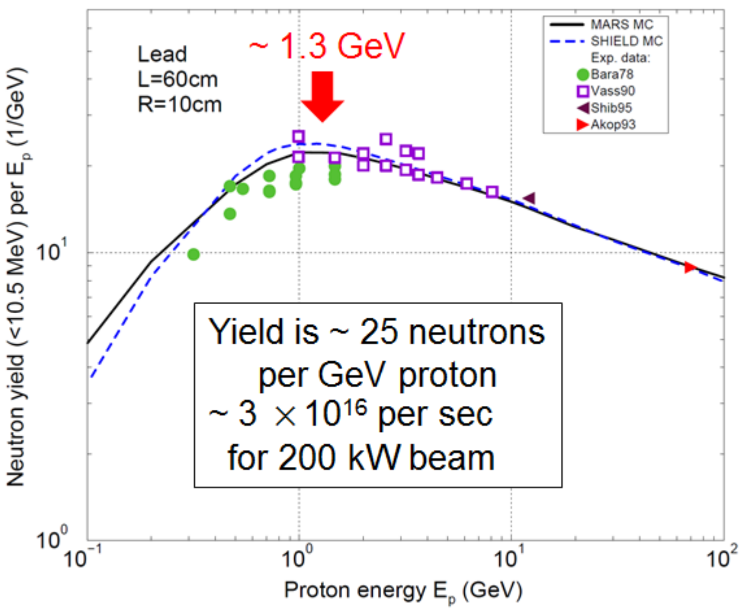
Expansion of the Fermilab Accelerator Complex



Fundamental Physics at the Intensity Frontier
November 30 - December 2, 2011
Rockville, MD



Staged construction
To start ~ 2015

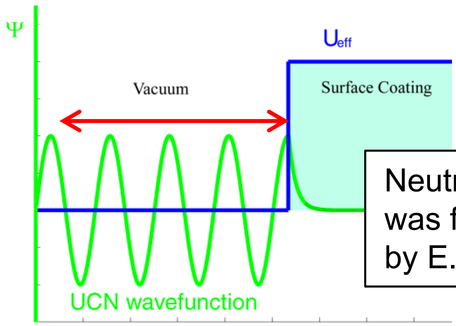


N. Mokhov, FNAL, 2011

N-spallation target in Project X

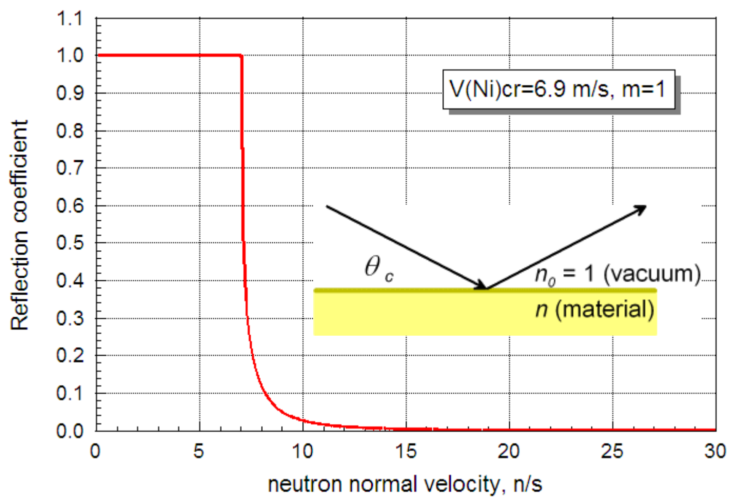
HEP Intensity Frontier

Neutron reflection



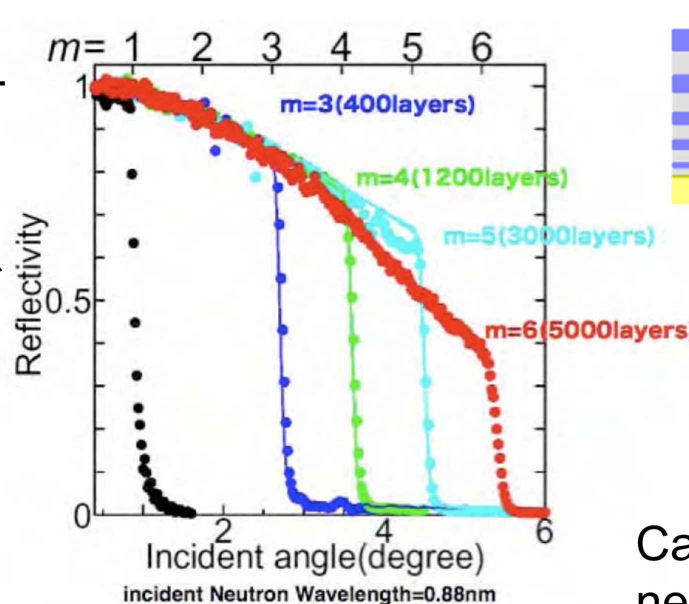
Neutron reflection was first explained by E. Fermi

Case where E < U_{eff}

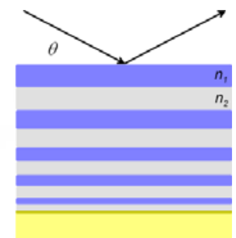


Progress in neutron super-mirrors

H. Shimizu, KEK/Japan



M.Hino et al., Nucl. Instrum. Methods A529 (2004) 54

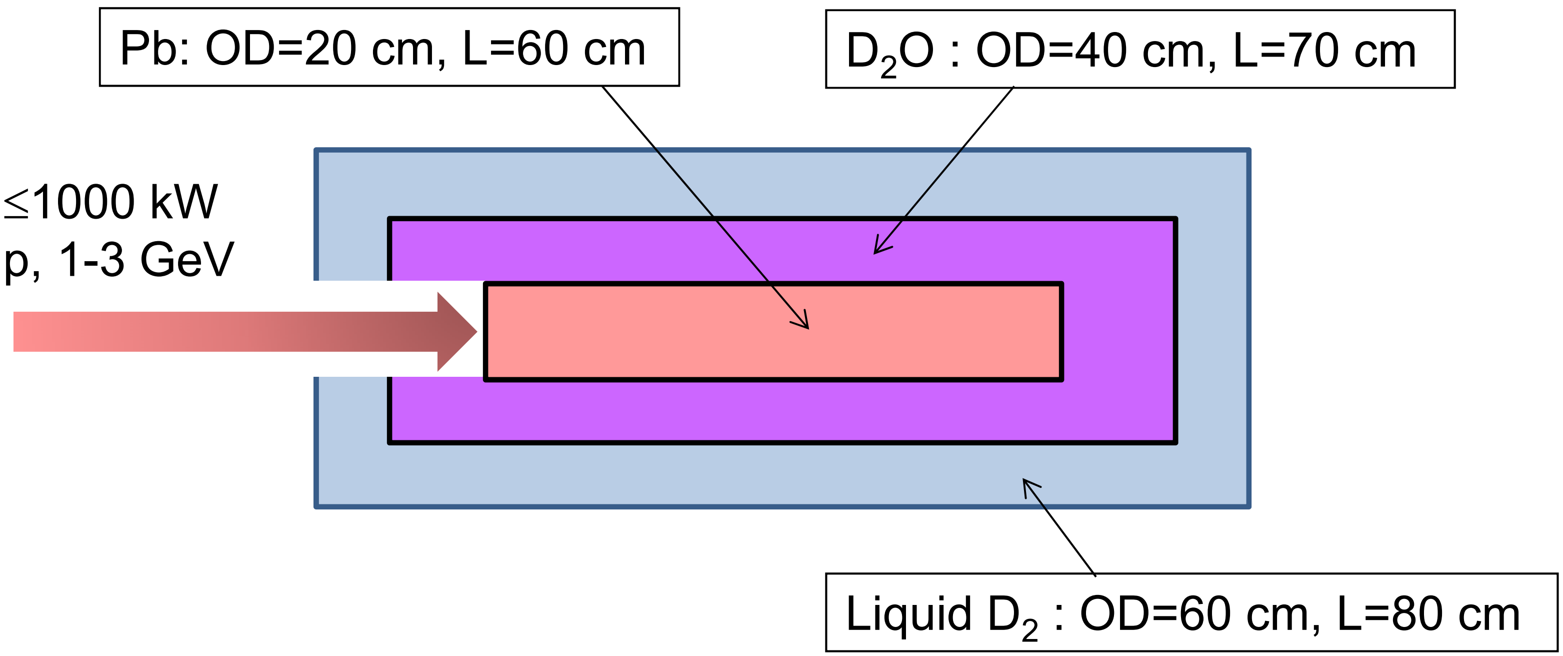


3/2011 status R=50% at m=10

Can reflect neutrons with $v_T \lesssim 70$ m/s

Generic View
Of Cold Spallation Target

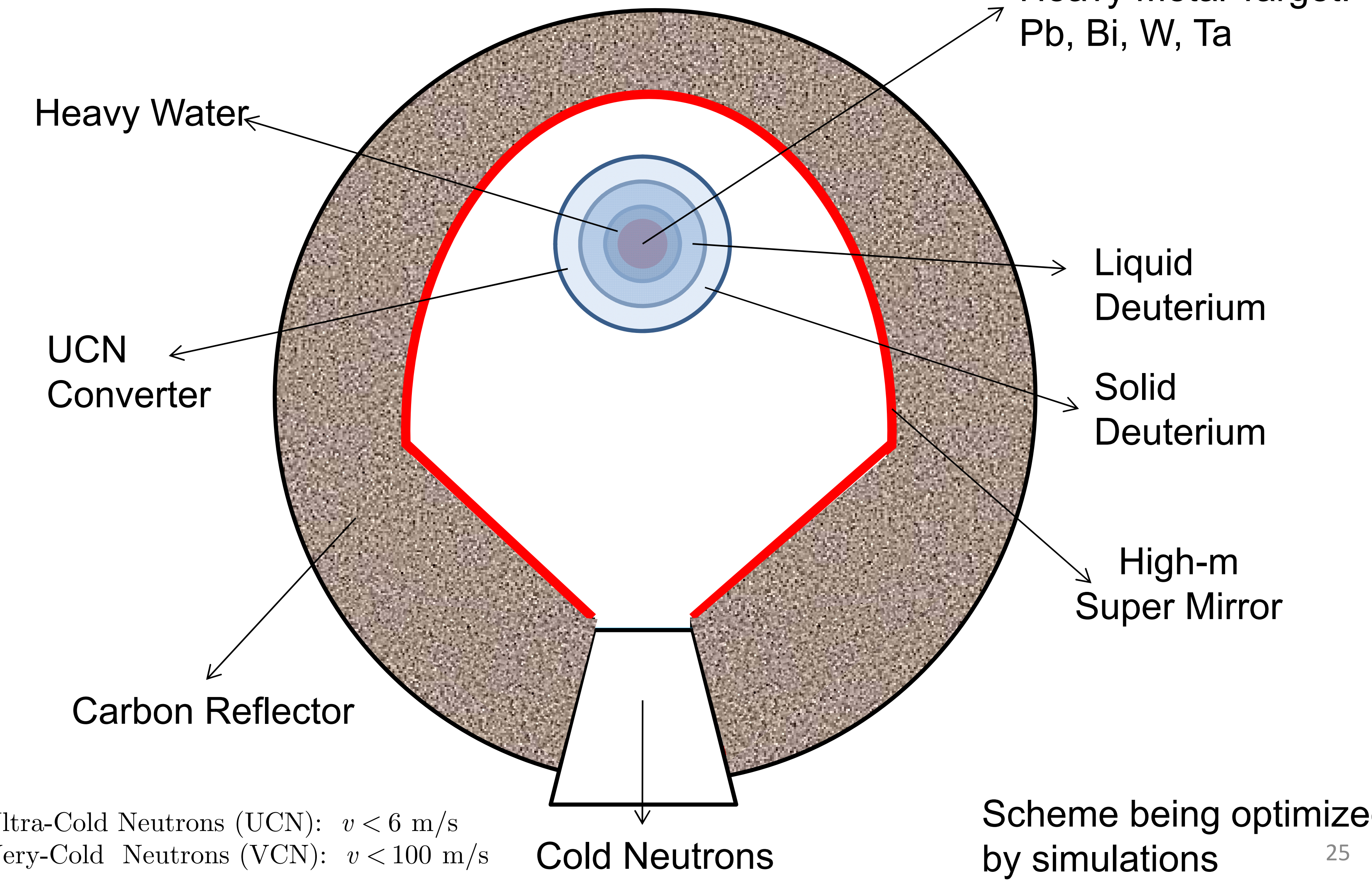
- Should try to use neutrons produced within 4π rather than few % of 4π for most n-beam lines



Spallation neutrons produced with kinetic energy ~ 2 MeV should be moderated down to thermal T~300K 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

Dedicated spallation target with VCN-UCN converter

(view along the beam)

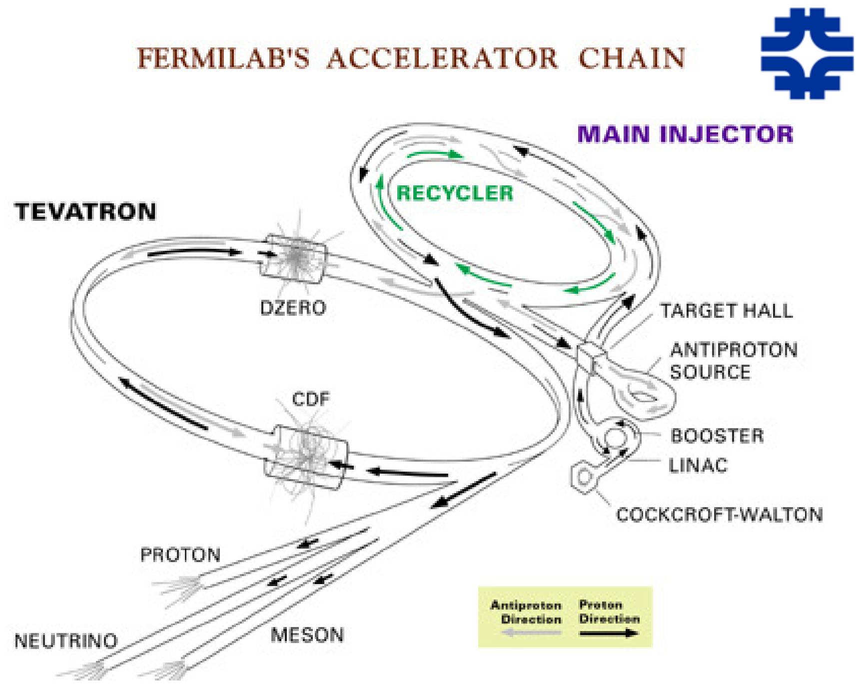


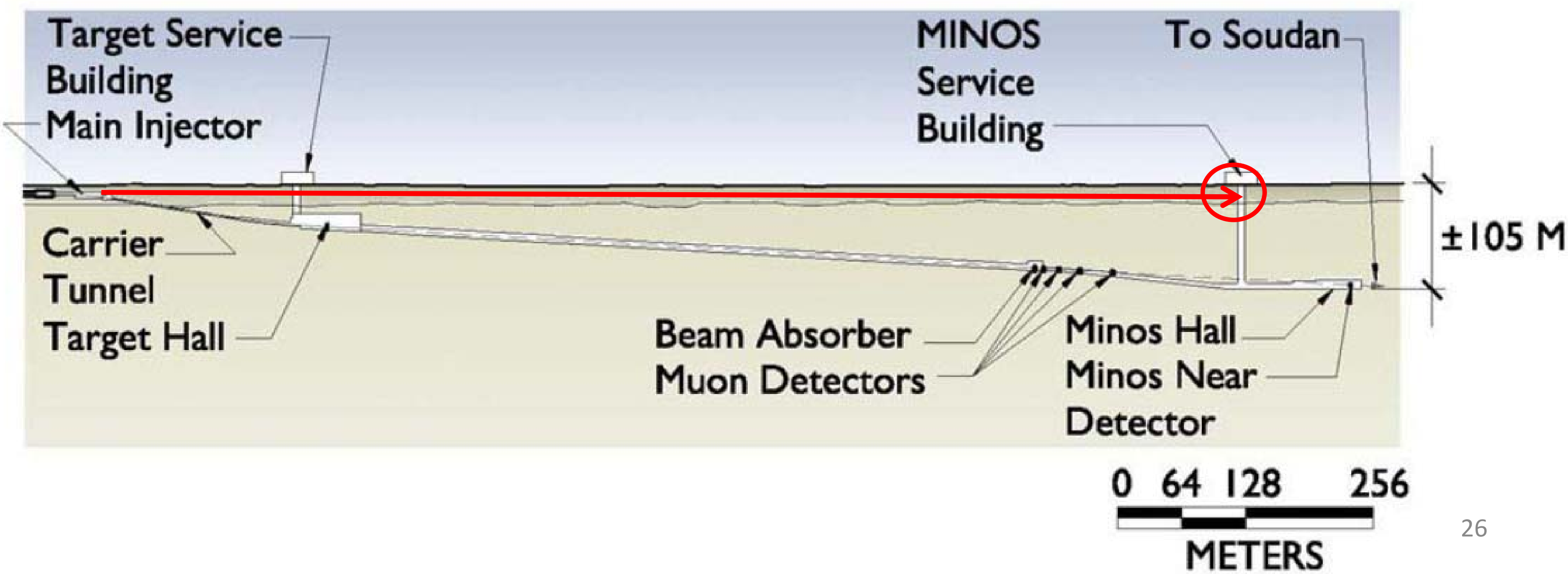
Ultra-Cold Neutrons (UCN): $v < 6$ m/s
Very-Cold Neutrons (VCN): $v < 100$ m/s

Scheme being optimized by simulations

NNbar search with spallation source at Fermilab with cold free neutron

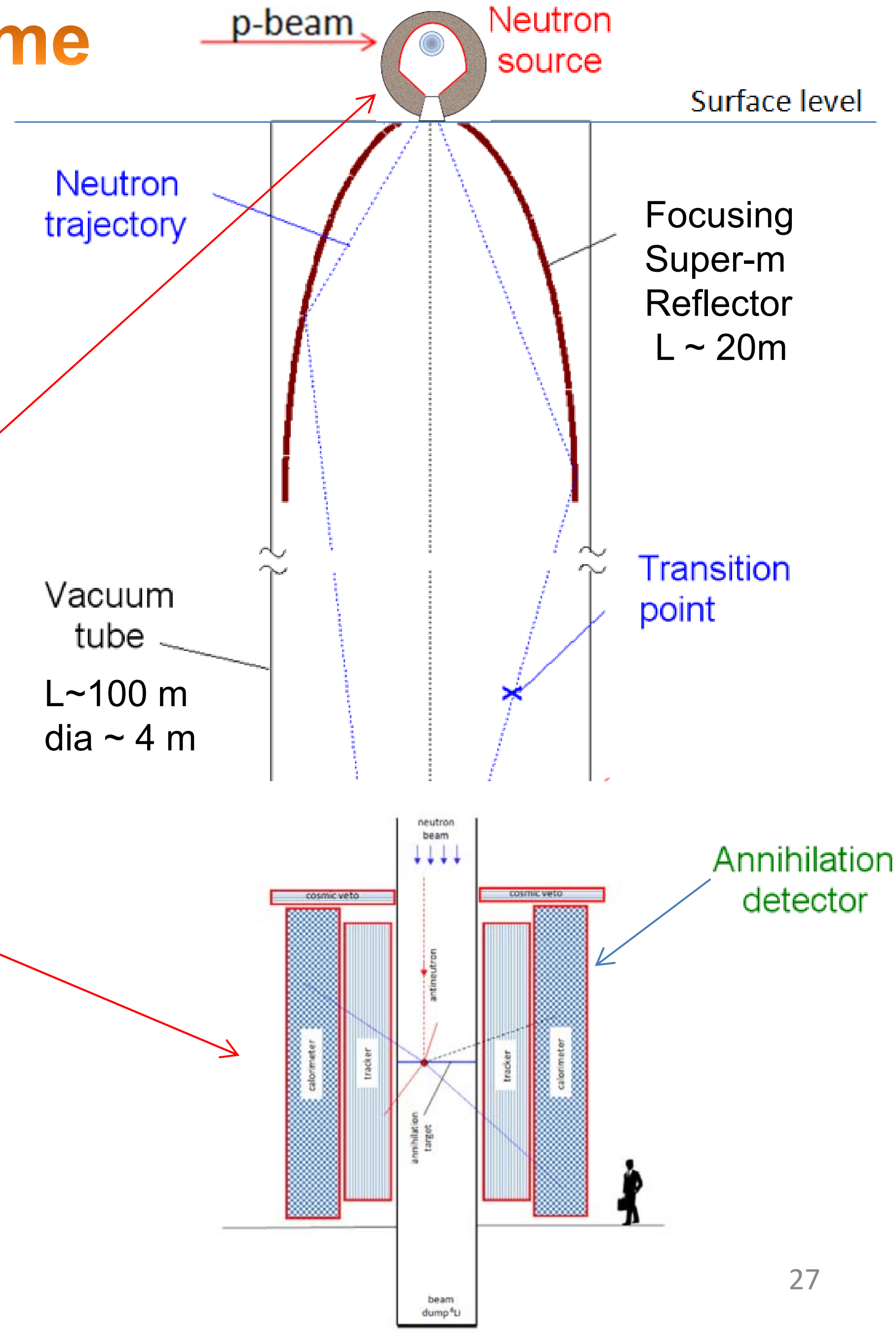
E.g. using existing MINOS vertical shaft for housing the experiment.





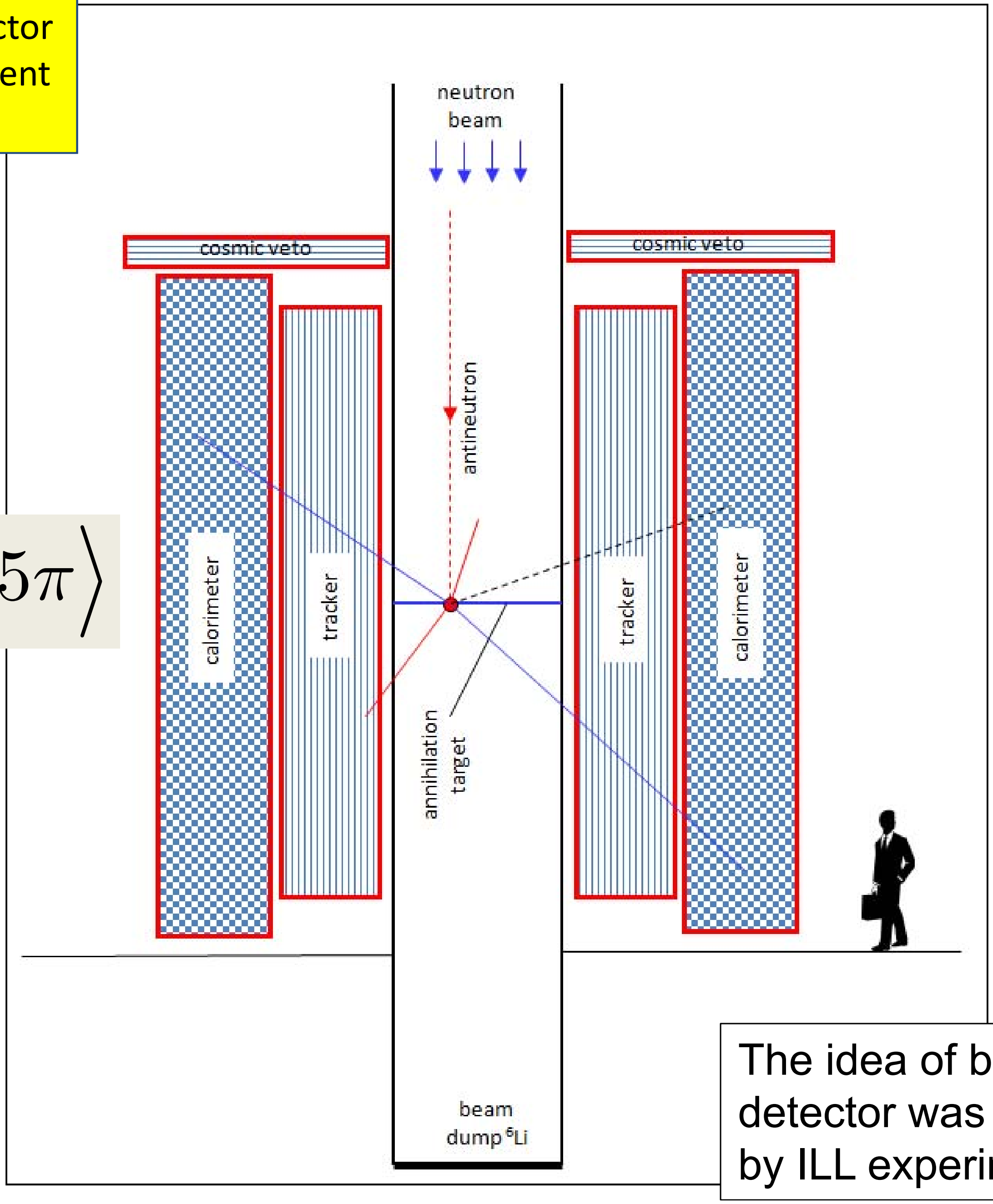
New N-Nbar vertical scheme

- New concept of large focusing neutron reflector using super-mirror. Sensitivity increases as ~ L^2
- Proton beam from MI or Project X; with power > 200 kW
- <u>Dedicated spallation target optimized for cold neutron production</u>
- "Background free" detector: one event = discovery !
- Expected sensitivity > 2,000 ILL units



The conceptual scheme of antineutron detector for NNbarX experiment planned at Fermilab

$$\overline{n} + C \rightarrow \langle 5\pi \rangle$$



The idea of backgroundless detector was demonstrated by ILL experiment

Vertical N-Nbar Experiment

can be unique for $n \rightarrow n'$ disappearance search
if indications of ILL-based experiment will be confirmed

http://arxiv.org/abs/1203.1035
Eur. Phys. J. C (2012) 72:1974

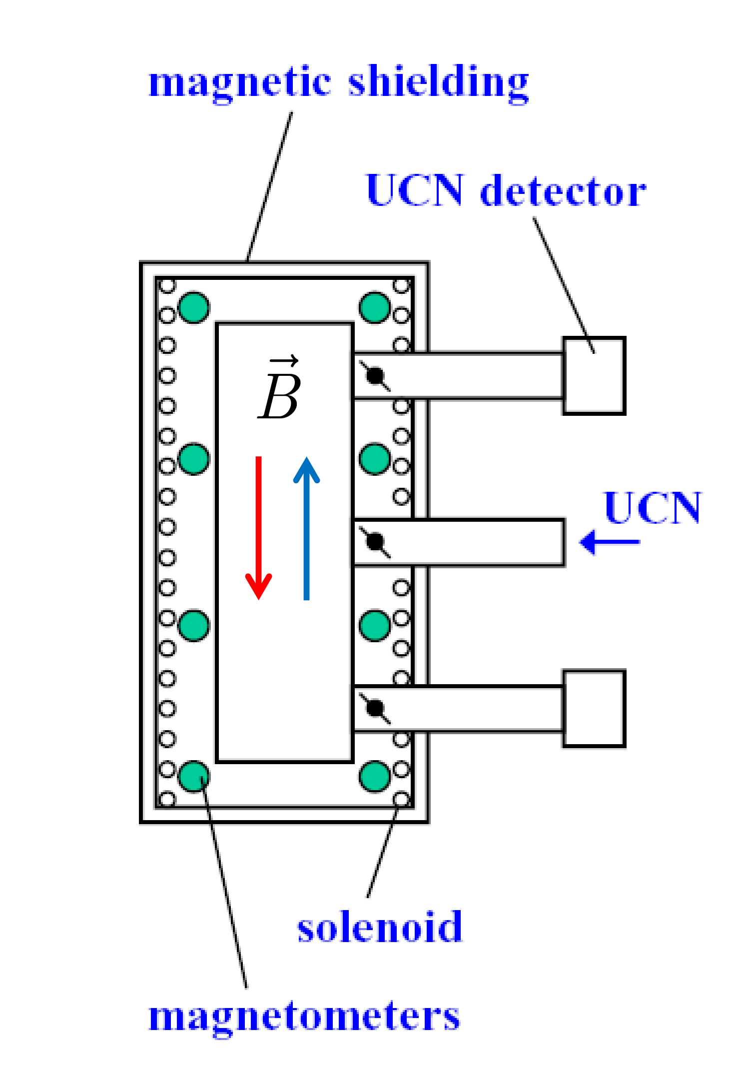
Magnetic anomaly in UCN trapping: signal for neutron oscillations to parallel world?

Z. Berezhiani[1,2] and F. Nesti[1]
[1] *Dipartimento di Fisica, Università dell'Aquila, Via Vetoio, 67100 Coppito, L'Aquila, Italy*
[2] *INFN, Laboratori Nazionali Gran Sasso, 67100 Assergi, L'Aquila, Italy*
(Dated: March 7, 2012)

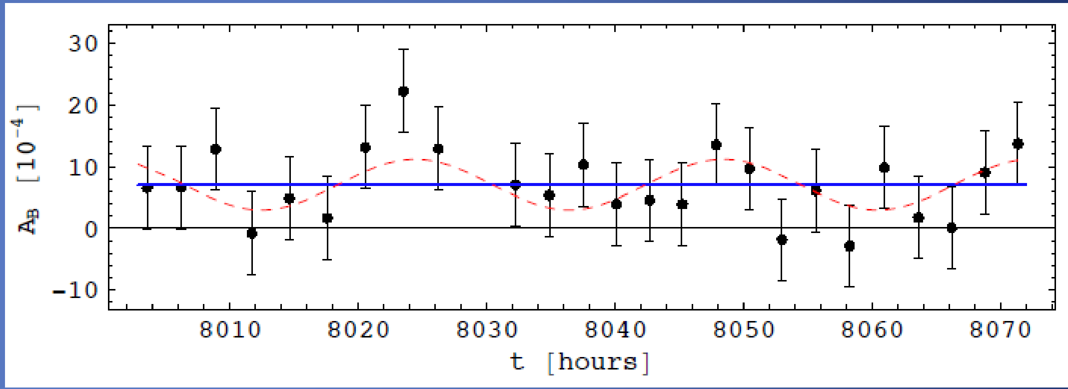
Present experiments do not exclude that the neutron transforms into some invisible degenerate twin, so called mirror neutron, with an appreciable probability. These transitions are actively studied by monitoring neutron losses in ultra-cold neutron traps, where they can be revealed by their magnetic field dependence. In this work we reanalyze the experimental data acquired by the group of A.P. Serebrov at Institute Laue-Langevin, and find a dependence at more than 5σ away from the null hypothesis. This anomaly can be interpreted as oscillation to mirror neutrons with a timescale of few seconds, in the presence of a mirror magnetic field $B' \sim 0.1\,\mathrm{G}$ at the Earth. If confirmed by future experiments, this will have a number of deepest consequences in particle physics and astrophysics.

PNPI Experiment to search for $n \to n'$ disappearance at ILL/Grenoble reactor, A. Serebrov et al (2009)

NIM A611 (2009) 137-140



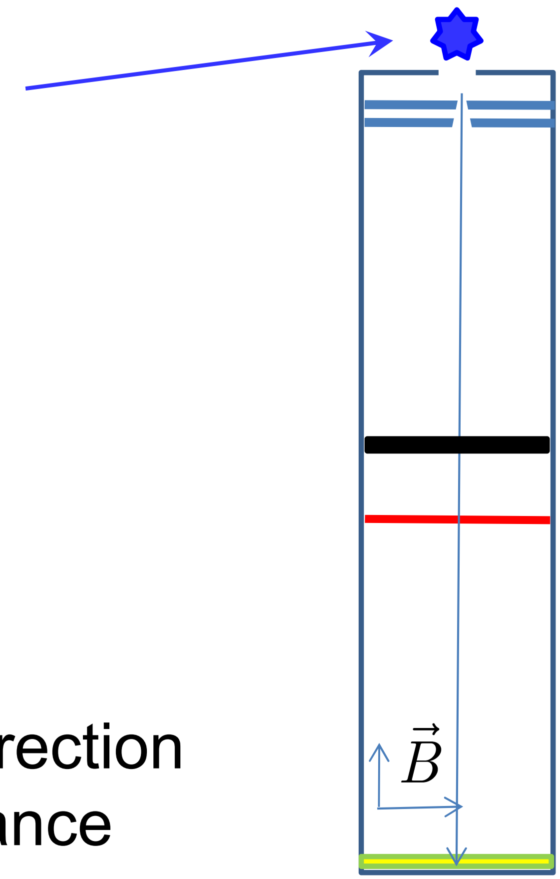
Measurements of UCN life-time asymmetry under alternation of vertical magnetic field



$$A_B^{\det}(t) = \frac{N_{-B}(t) - N_B(t)}{N_{-B}(t) + N_B(t)}$$

Measured asymmetry →
~ (7±1.4)×10^{-4} (~5σ)
$n \to n'$ oscillation time ~ 2-5 sec;
resonance mag. field ~ 0.1 G

Possible future n disappearance with spallation source



- Let's assume that ~ 175 m long vertical shaft can be used
- 10 m/s neutron falls 175 m for ~ 5 s.
- Pulsed target operation would explores different velocities
- Controlled variation of lab field B and its direction should detect resonance in the disappearance
- If one absorbs all neutrons in the max of disappearance it will be possible to observe the regeneration effect (appearance on neutrons)

NNbar Summary

New physics beyond the SM can be discovered by new NNbar 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→Nbar 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.