Spontaneous Workshop VI, Cargèse • May 11, 2012

Search for Matter-Antimatter Transformation with Cold Neutrons

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Overview

❖ Observation of violation of Baryon number is one of the pillars of Cosmology:

  - it is required for Matter-Antimatter asymmetry explanation 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 $n \rightarrow \bar{n}$ transformation with $\Delta B = 2$ and $(B - L)$V

❖ New developments in NNbar search within "Project X"

Can Neutron be 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.

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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 $K^0 \rightarrow \overline{K^0}, \ B^0 \rightarrow \overline{B^0}$

- Flavor number $\rightarrow$ in neutrino flavor oscillation $\nu_\mu \rightarrow \nu_e$

- Lepton number $\rightarrow$ in Majorana neutrinos $\nu_e \rightarrow \overline{\nu}_e$

- Baryon number $\rightarrow$ $n \rightarrow \overline{n}$

B, L, and B−L

❖ e.g. $n \rightarrow p + e^- + \overline{\nu}_e$ 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 . 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 [G. 't Hooft, Nobel Prize, 1999];

   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].

❖ That was a starting point for the models of Leptogenesis.

Proton Decay Searches

## are motivated by (B-L) conserving models
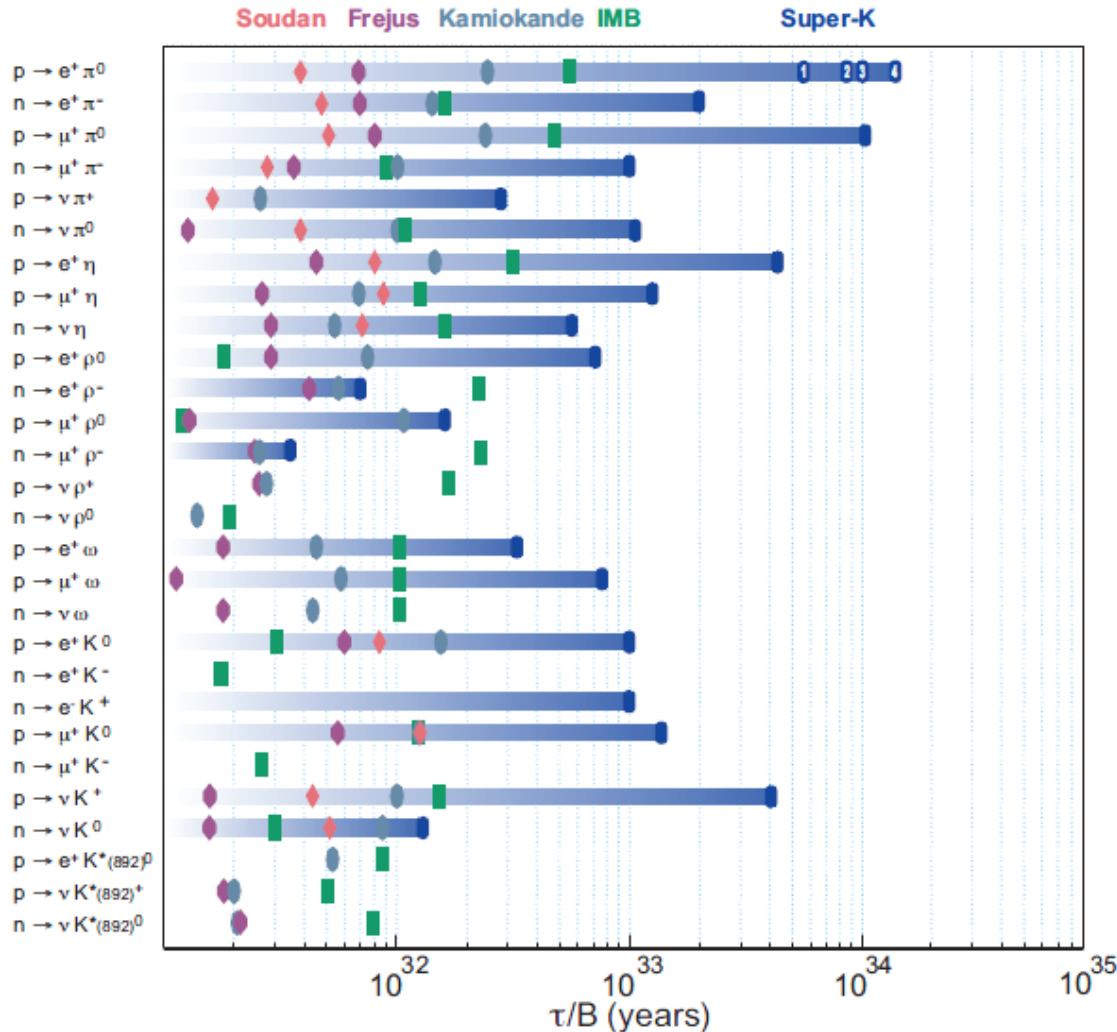
J. L. Raaf @ IF-2011
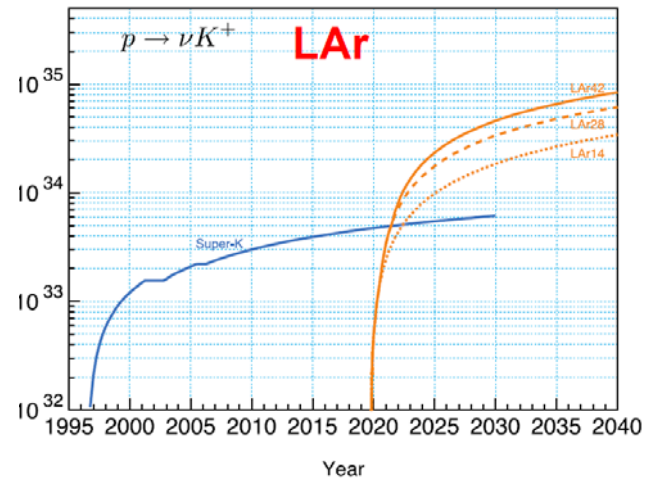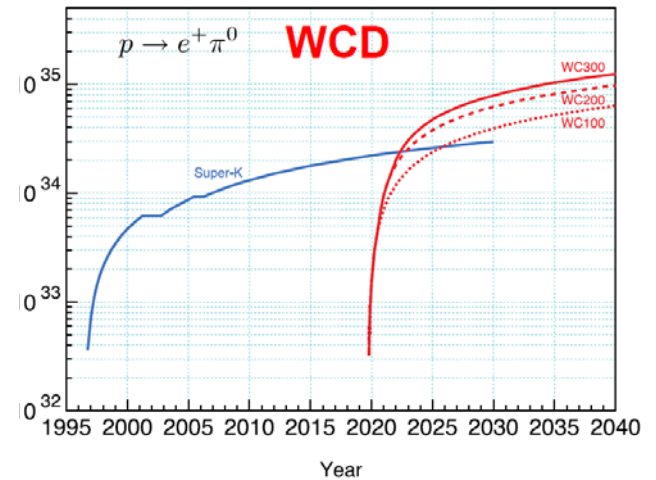
LBNE Physics Working Group Report
arXiv:1110.6249v1 [hep-ex]

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

New 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 $\Delta L = 2$, thus violating (B − L) by 2.
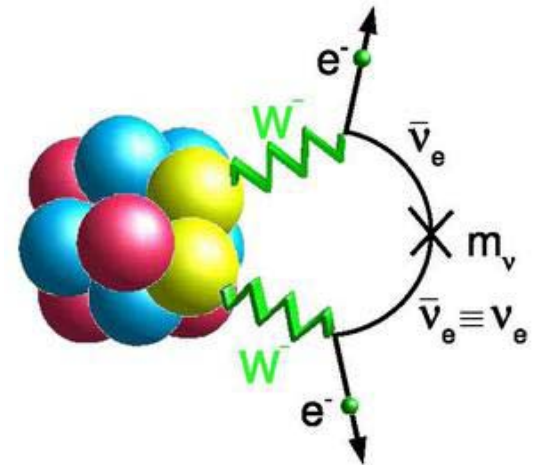
❖ If (B − L) is violated by 2 that also means that $\Delta B = 2$ should exist and thus $n \leftrightarrow \overline{n}$ is possible

neutron   time   anti-neutron
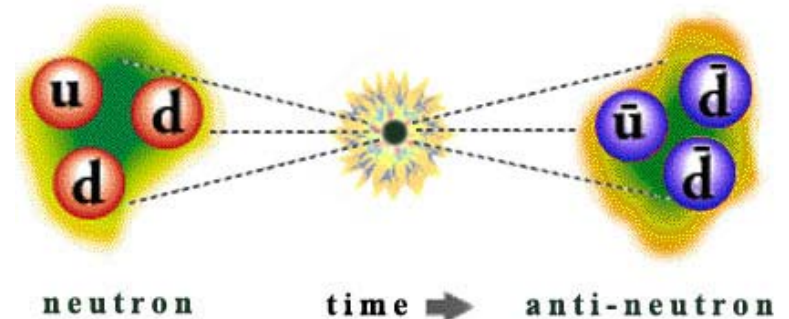
Some history of $n \leftrightarrow \bar{n}$ ideas

❖ 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 ...

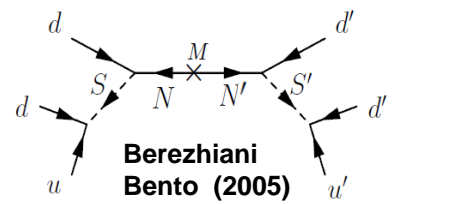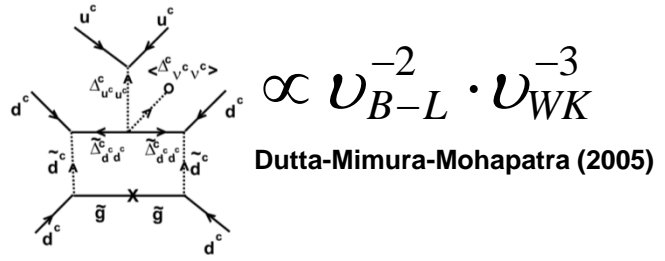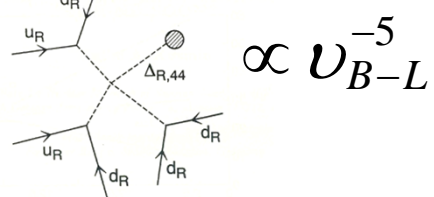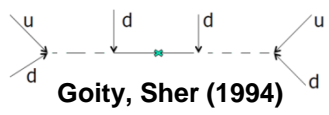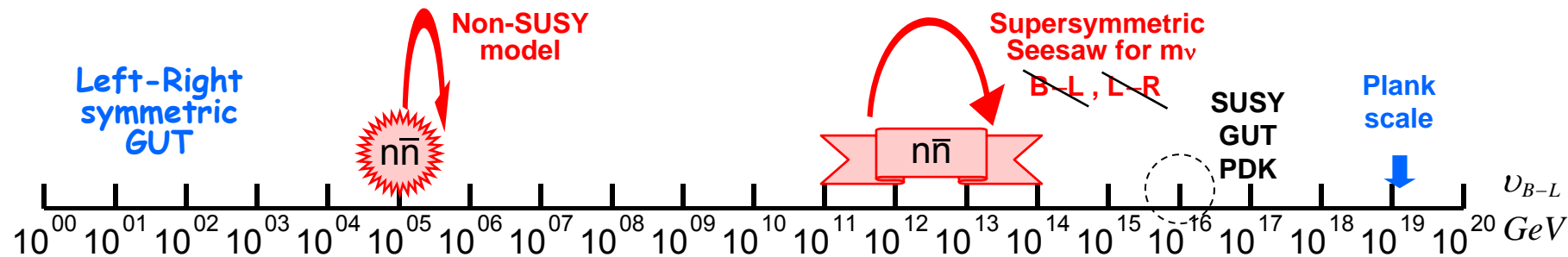❖ Recent models explaining neutrino masses, low-scale baryogenesis, connecting with dark matter, involving gravity, extra-Ds, predicting new particles at LHC…

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

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

Non-SUSY model

Left-Right symmetric GUT

Supersymmetric Seesaw for m_ν

~~B-L, L-R~~

SUSY GUT PDK

Plank scale

n̄n

n̄n

v_{B-L}

10^{00} 10^{01} 10^{02} 10^{03} 10^{04} 10^{05} 10^{06} 10^{07} 10^{08} 10^{09} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20} GeV

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

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

Goity, Sher (1994)

Mohapatra & Marshak (1980)

Dutta-Mimura-Mohapatra (2005)

Berezhiani Bento (2005)

Baryogenesis at TeV scale

Berezhiani et al (2005)
Babu et al (2006)
Dolgov et al (2006)

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

Low QG models

LHC

n̄n

Dvali & Gabadadze (1999)

GeV

10^{00} 10^{01} 10^{02} 10^{03} 10^{04} 10^{05} 10^{06} 10^{07} 10^{08} 10^{09} 10^{10} 10^{11} 10^{12}
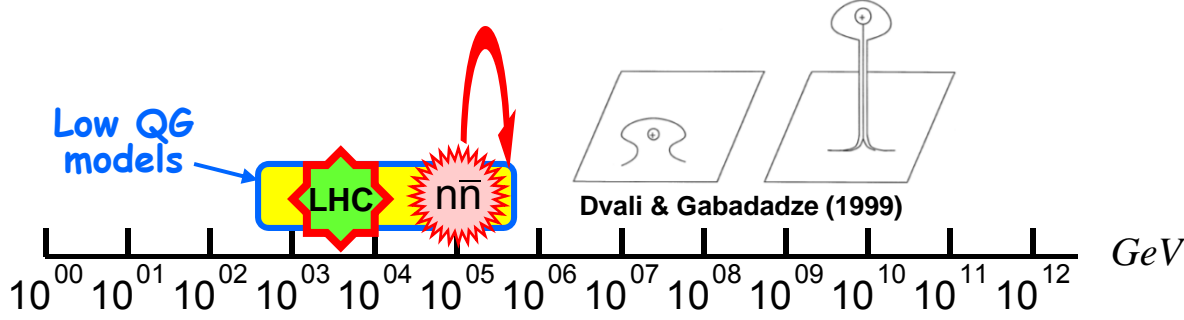
n→nbar transition probability
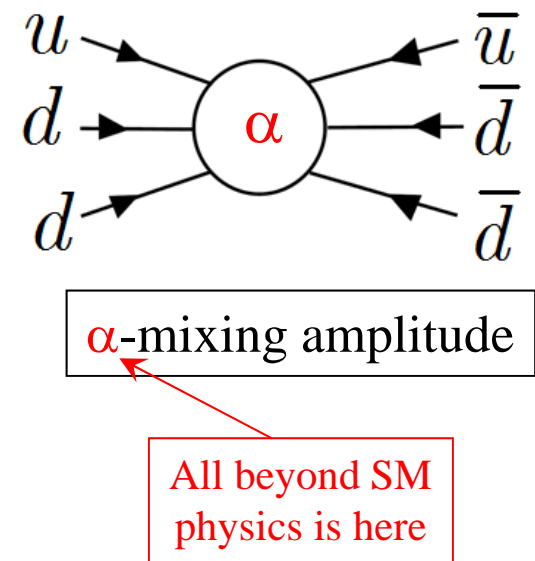
$$\Psi = \begin{pmatrix} n \\ \bar{n} \end{pmatrix} \quad \text{mixed n-nbar QM state}$$

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

α-mixing amplitude

All beyond SM physics is here

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

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

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

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 $t \sim 0.1$ s to 10 s

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

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

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

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

$$P \propto N \cdot \left(\frac{t}{\tau}\right)^2$$
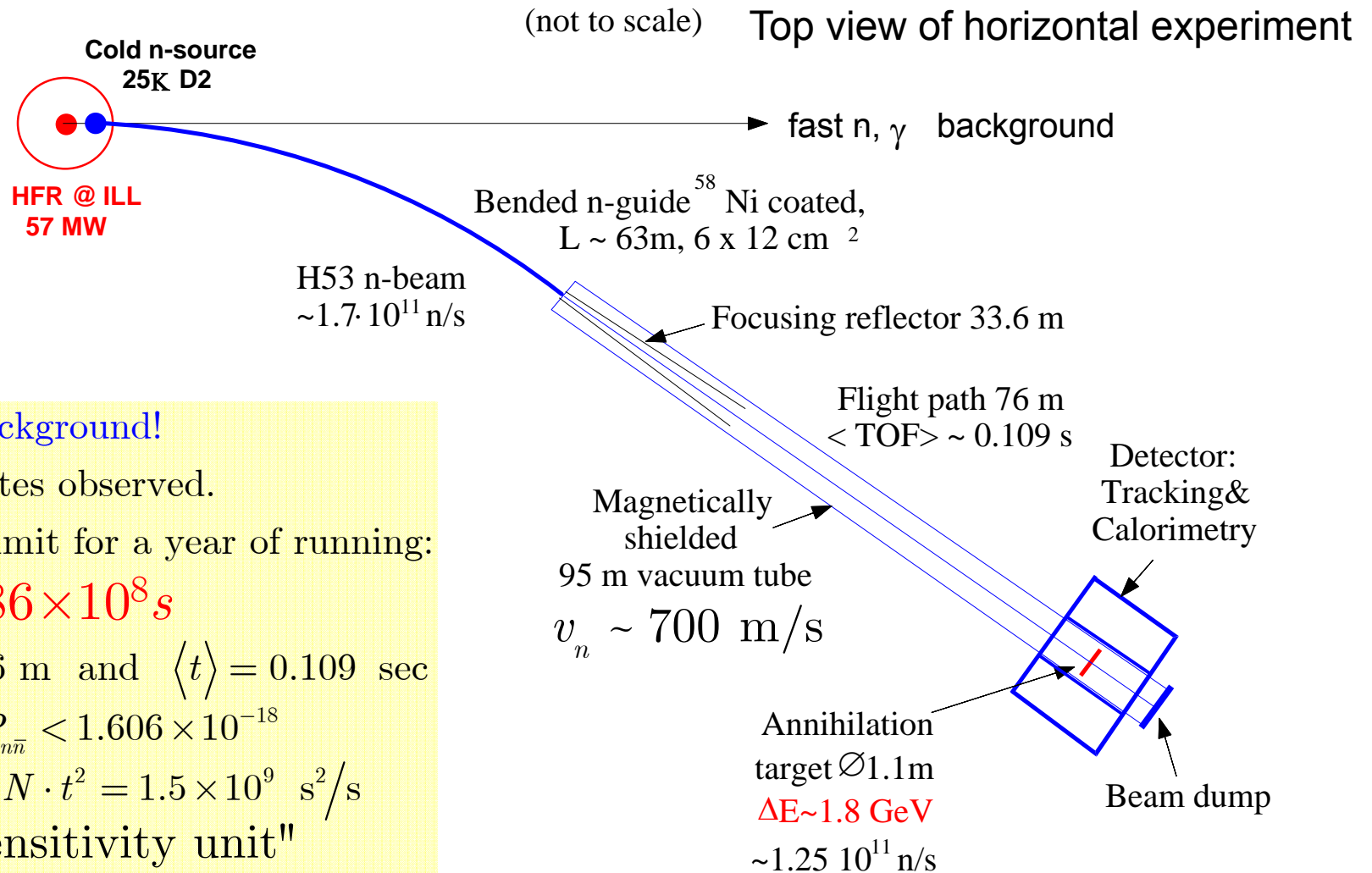
Let's try to configure such an experiment

- Concept: after time t some of the neutrons might be spontaneously converted to antineutrons and will annihilate with the matter producing a star of pions.

- Need many neutrons: reactor or spallation source   ← Produced as ~ 2 MeV

- Slowest possible neutrons   ← Even moderated to 300K v_n ~ 2,200 m/s
  with maximum observation time   with broad Maxwell-Boltzmann spectrum

- Earth magnetic field shielding: $2\mu B < \dfrac{\hbar}{t}$ → $B < 1 - 10 \ nT$

- Vacuum $< 10^{-5}$ Pa

- Distance ? Doesn't matter here →

- Gravity effect on horizontal beam

A_{det}

L

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

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

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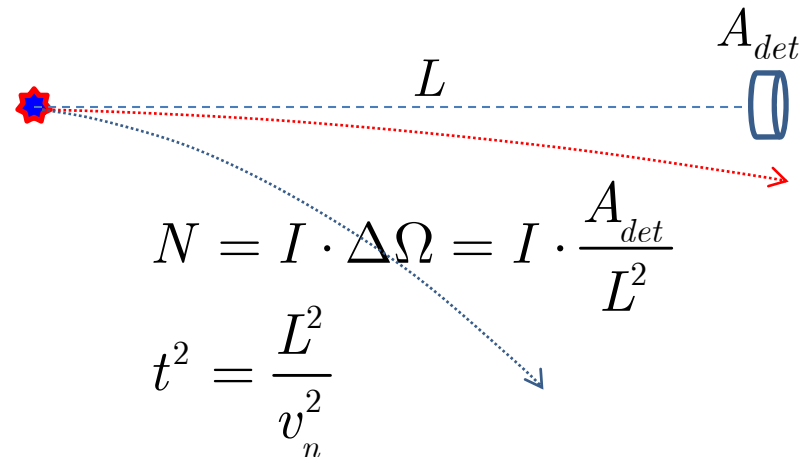
Previous n-nbar search experiment with free neutrons

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**

Cold n-source
25K D2

fast n, γ background

HFR @ ILL
57 MW

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

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

Focusing reflector 33.6 m

Flight path 76 m
< TOF> ~ 0.109 s

Detector:
Tracking&
Calorimetry

Magnetically
shielded
95 m vacuum tube

$v_n \sim 700$ m/s

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

Beam dump

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: $N \cdot t^2 = 1.5 \times 10^9$ 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: $\Delta t \sim \dfrac{\hbar}{E_{well}} \sim \dfrac{\hbar}{30 MeV} \sim 2.2 \times 10^{-23} s$

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

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

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

Intranuclear (exponential) lifetime:

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

where $R \sim \dfrac{1}{\Delta t} \sim 4.5 \times 10^{22} s^{-1}$ 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	$>0.43\times10^{32}$
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
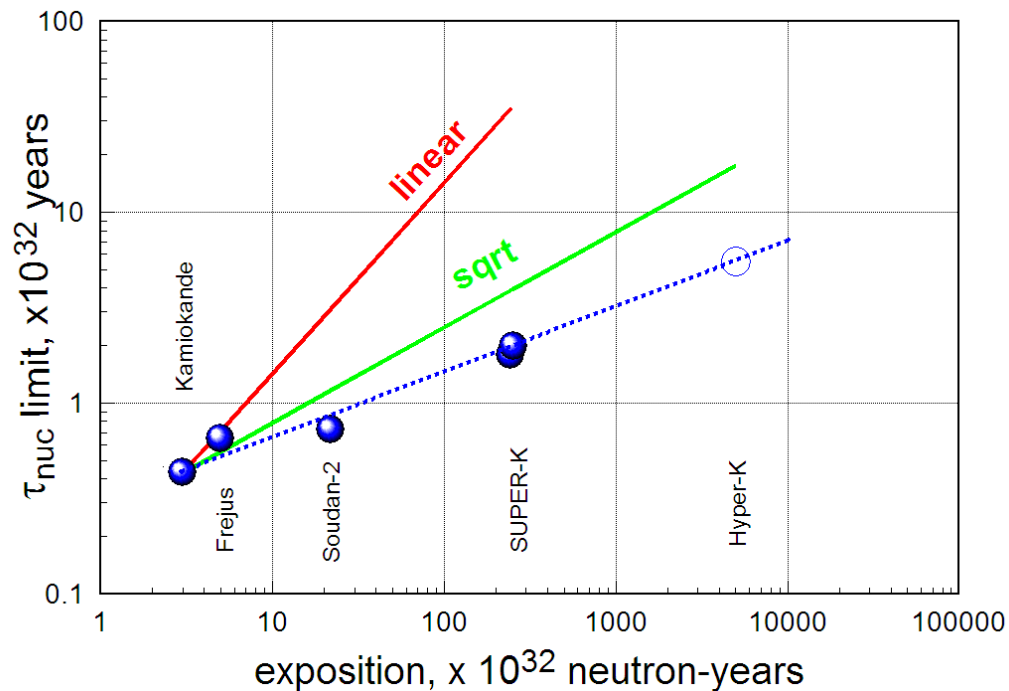
Observed improvement is weaker than SQRT due to irreducible background of atmospheric ν's.

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

N-Nbar transformation search with bound neutrons:

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

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

$\leftarrow \begin{cases} 24 \text{ observed candidates;} \\ 24.1 \text{ exp. background} \end{cases}$

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

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

$$\Rightarrow \tau(\text{from bound}) > 3.5 \times 10^8 s \quad \text{or} \quad \alpha < 2 \times 10^{-24} eV$$
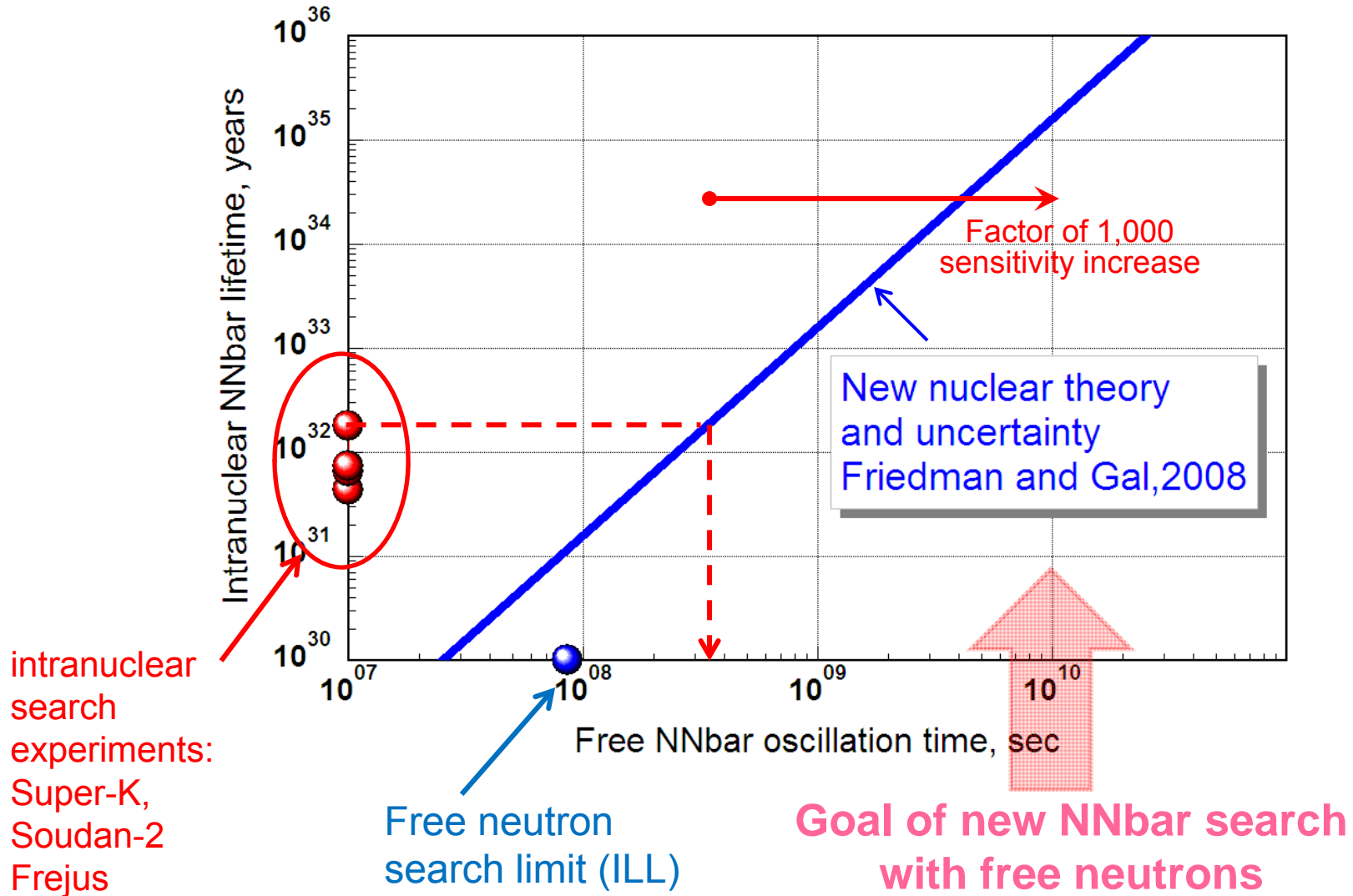
$\times 16$ times higher than
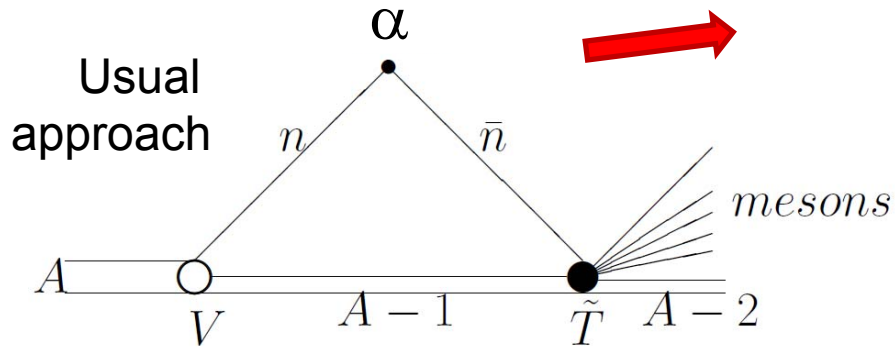sensitivity of ILL expt.

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

Free Neutron and Intranuclear NNbar Limits Comparison

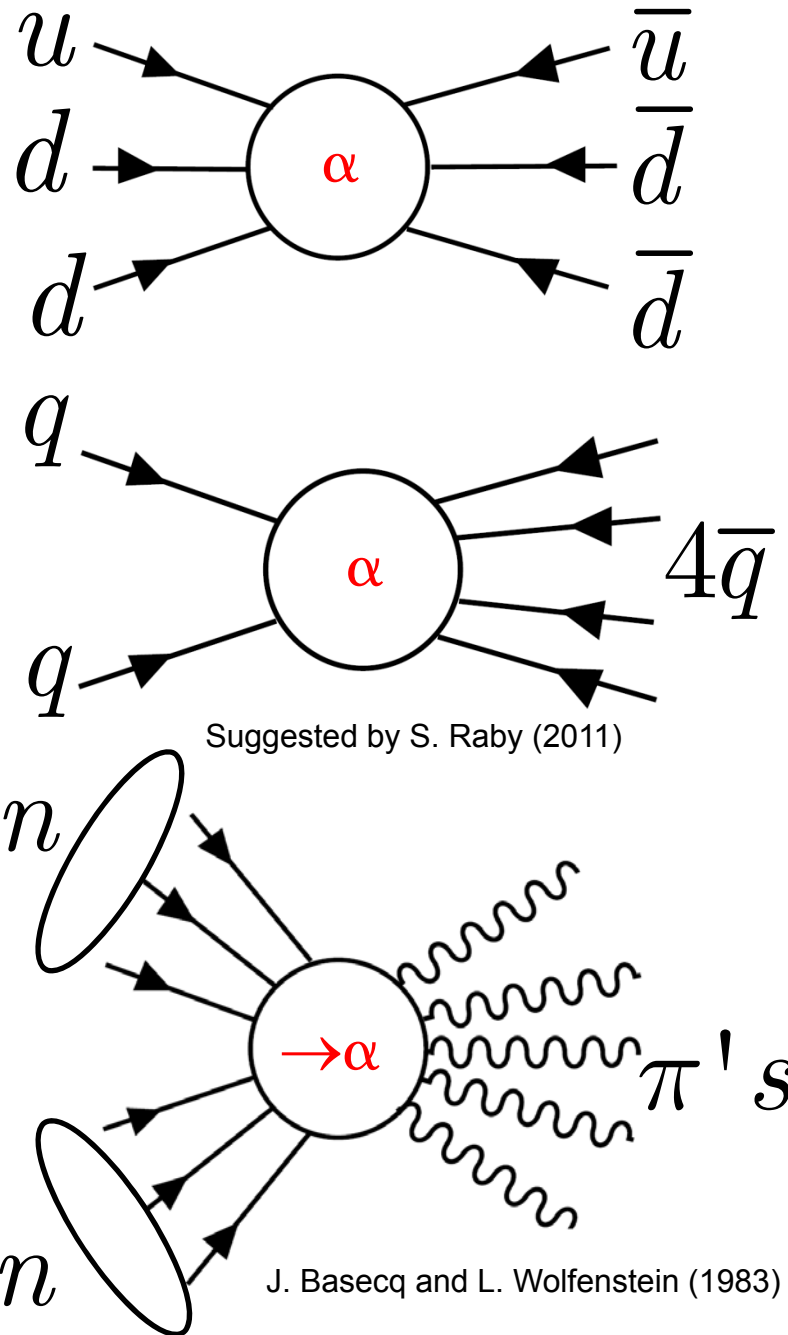## Large improvement with free-neutron experiments is possible

Factor of 1,000 sensitivity increase

New nuclear theory and uncertainty Friedman and Gal,2008

intranuclear search experiments: Super-K, Soudan-2 Frejus

Free neutron search limit (ILL)

Goal of new NNbar search with free neutrons

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)

Suggested by S. Raby (2011)

J. Basecq and L. Wolfenstein (1983)

Existing intranuclear NNbar limits need to be re-evaluated

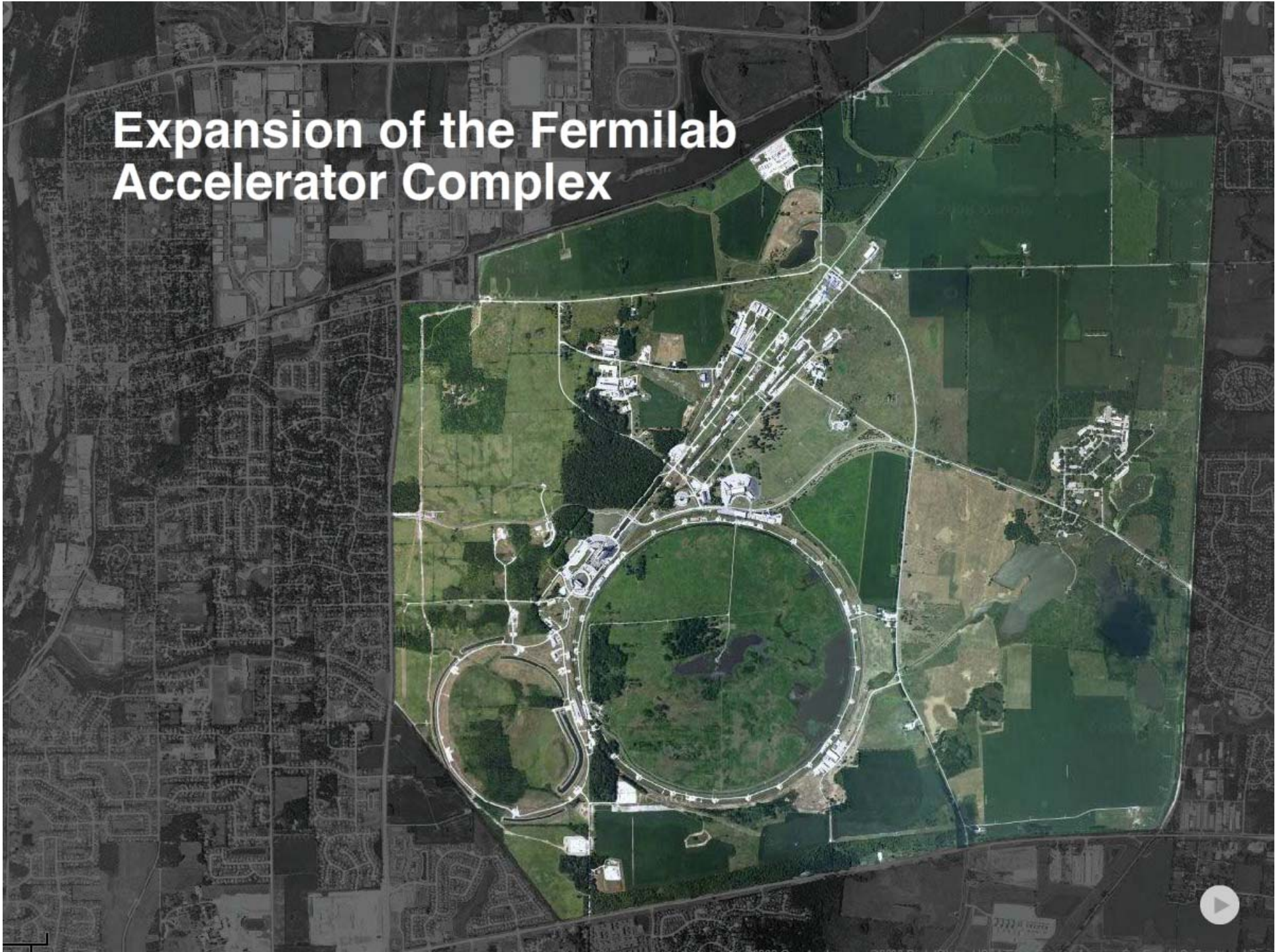# Sensitivity improvement factors for $N \cdot t^2$

- Use many neutrons (spallation source or reactor)

- Use slow neutrons: cold, VCN, UCN

- Neutron manipulation by mirror reflections

- Neutron manipulation by gravity

New NNbar Search Proposed for Fermilab
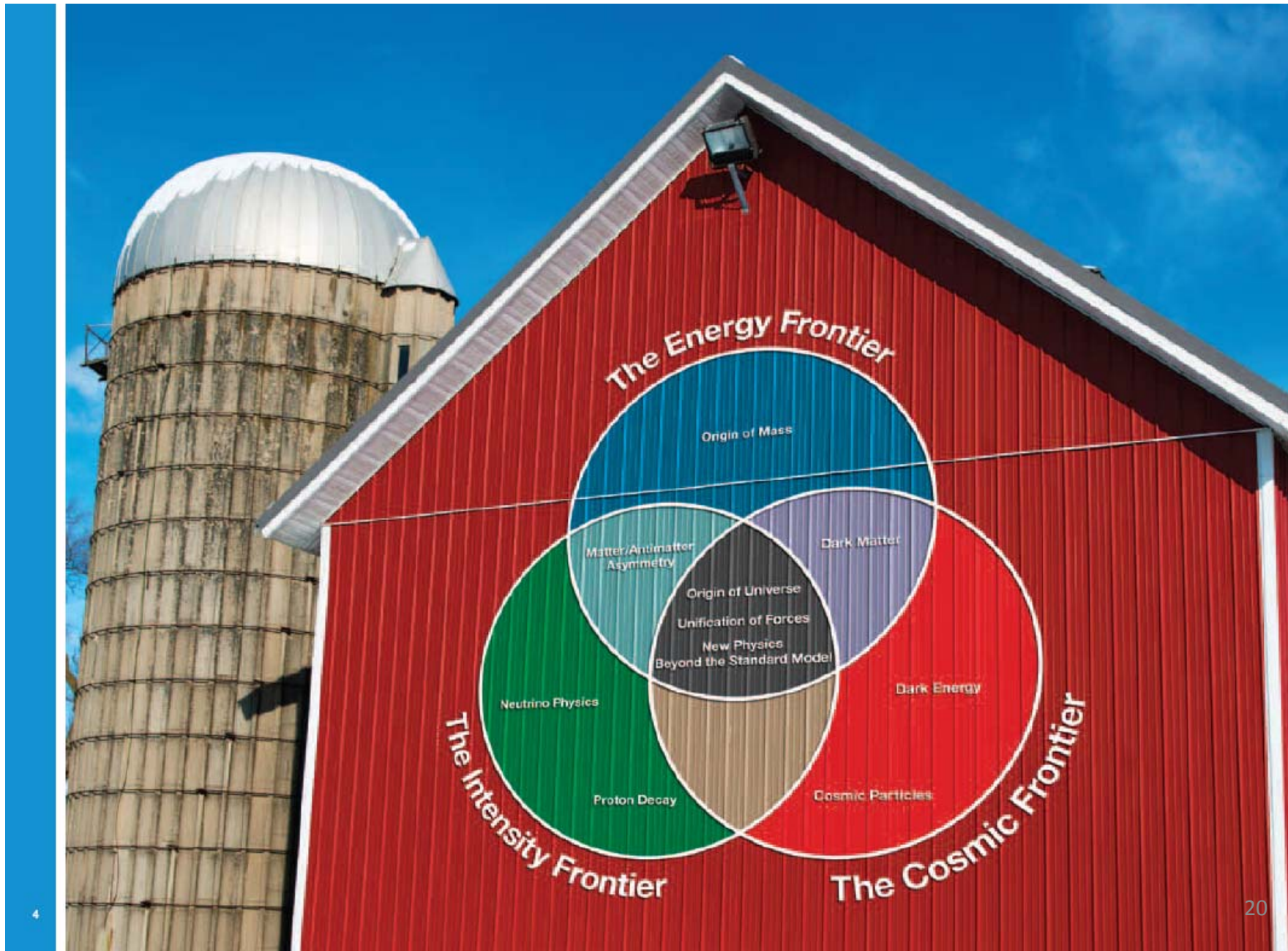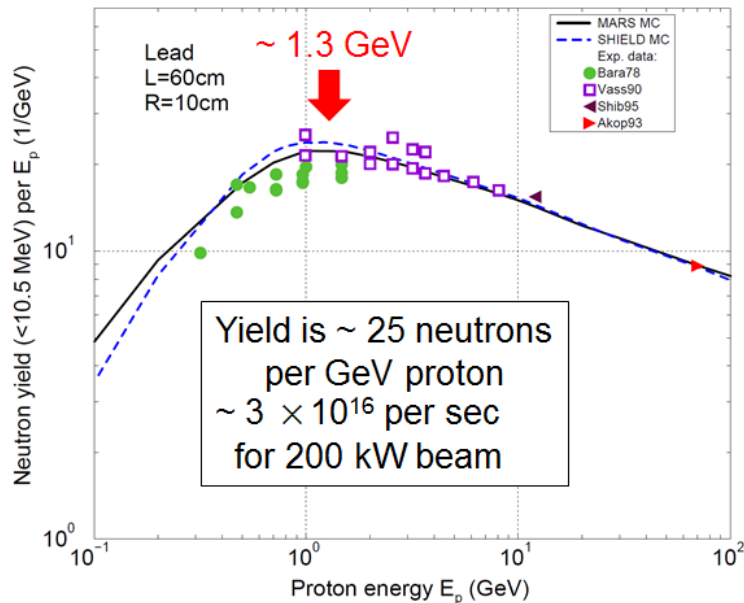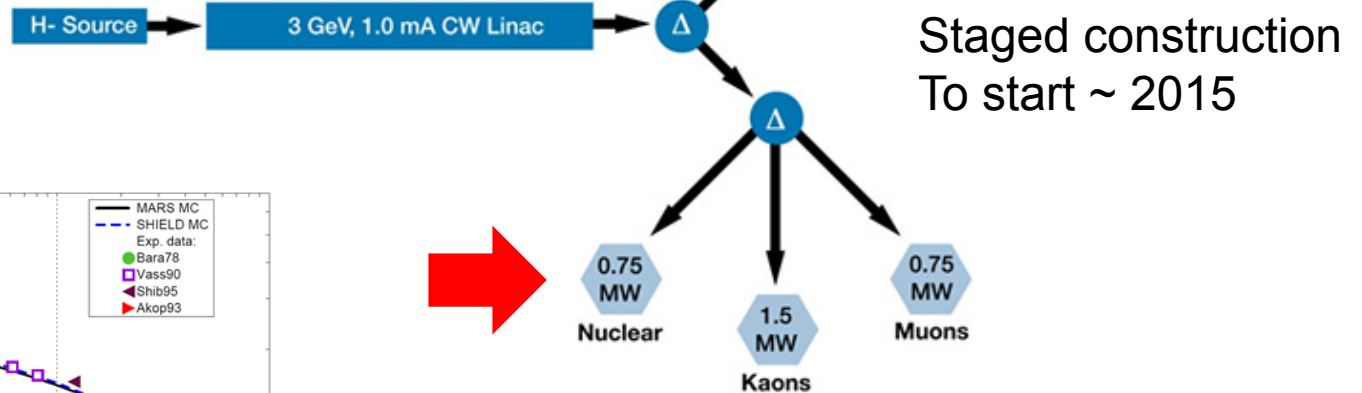
Expansion of the Fermilab Accelerator Complex

www.intensityfrontier.org

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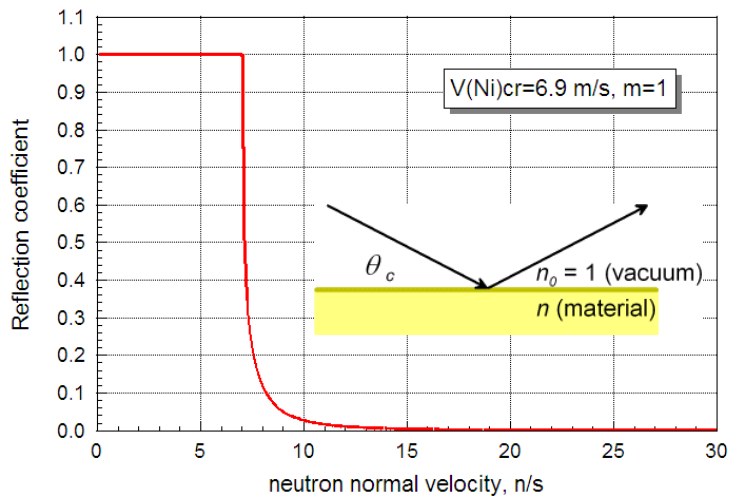November 30 - December 2, 2011
Rockville, MD

Recycler / Main Injector 120 GeV → Neutrinos 2 MW

3-8 GeV Pulsed Linac

H- Source → 3 GeV, 1.0 mA CW Linac → Δ

Δ

Staged construction
To start ~ 2015

0.75 MW — Nuclear

1.5 MW — Kaons

0.75 MW — Muons

~ 1.3 GeV

Lead
L=60cm
R=10cm

MARS MC
SHIELD MC
Exp. data:
Bara78
Vass90
Shib95
Akop93

Yield is ~ 25 neutrons
per GeV proton
~ 3×10^{16} per sec
for 200 kW beam

Neutron yield (<10.5 MeV) per E_p (1/GeV)
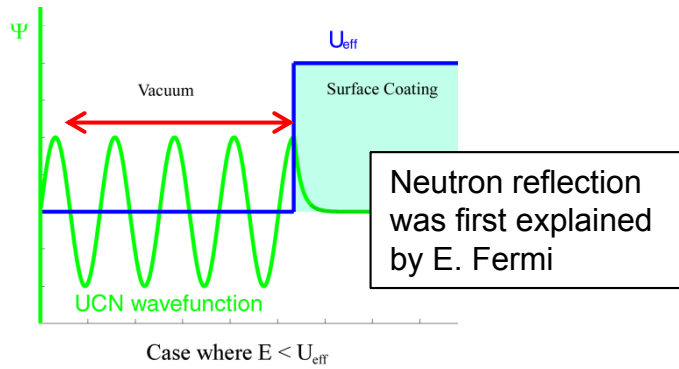
Proton energy E_p (GeV)

N. Mokhov, FNAL, 2011

N-spallation target
in Project X
HEP Intensity Frontier

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Neutron reflection

Progress in neutron super-mirrors

Ψ

U_eff

Vacuum   Surface Coating

Neutron reflection was first explained by E. Fermi

UCN wavefunction

Case where E < U_eff

V(Ni)cr=6.9 m/s, m=1

θ_c $n_0 = 1$ (vacuum)
n (material)

Reflection coefficient

neutron normal velocity, n/s

H. Shimizu, KEK/Japan

m= 1   2   3   4   5   6

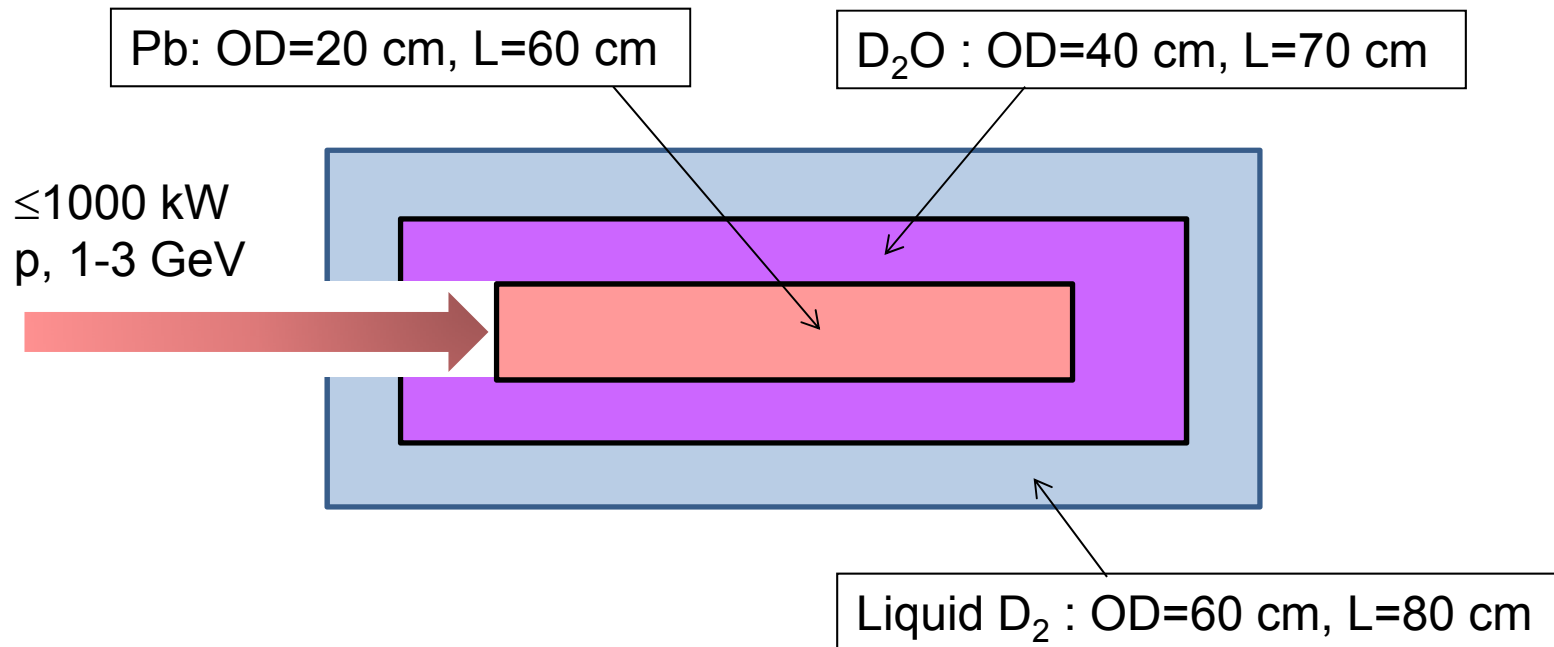m=3(400layers)

m=4(1200layers)

m=5(3000layers)

m=6(5000layers)

Reflectivity

Incident angle(degree)

incident Neutron Wavelength=0.88nm
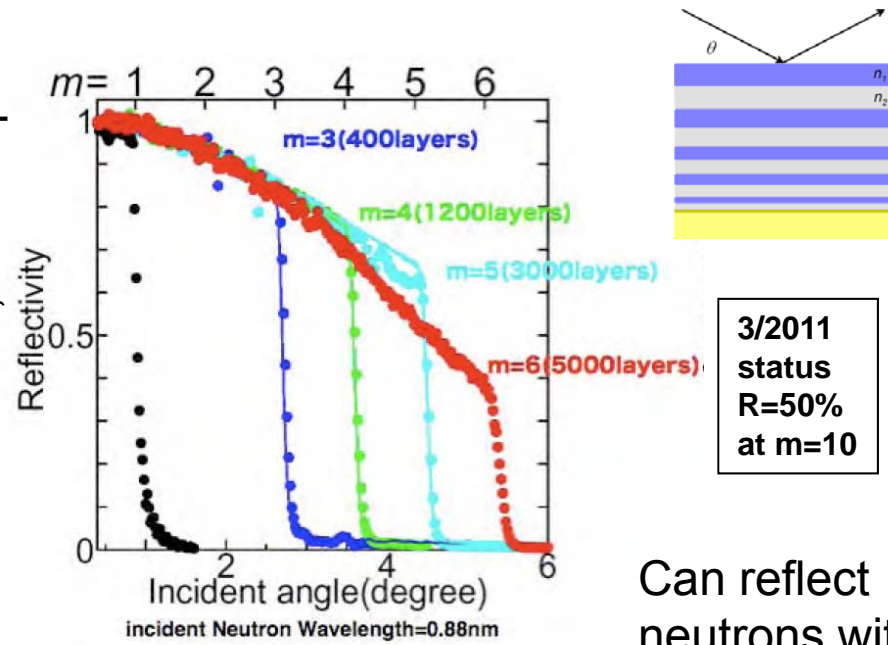
M.Hino et al., Nucl. Instrum. Methods A529 (2004) 54

θ n_1 n_2

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

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

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Generic View Of Cold Spallation Target

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

Pb: OD=20 cm, L=60 cm

D_2O : OD=40 cm, L=70 cm

$\leq$1000 kW
p, 1-3 GeV

Liquid D_2 : OD=60 cm, L=80 cm

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
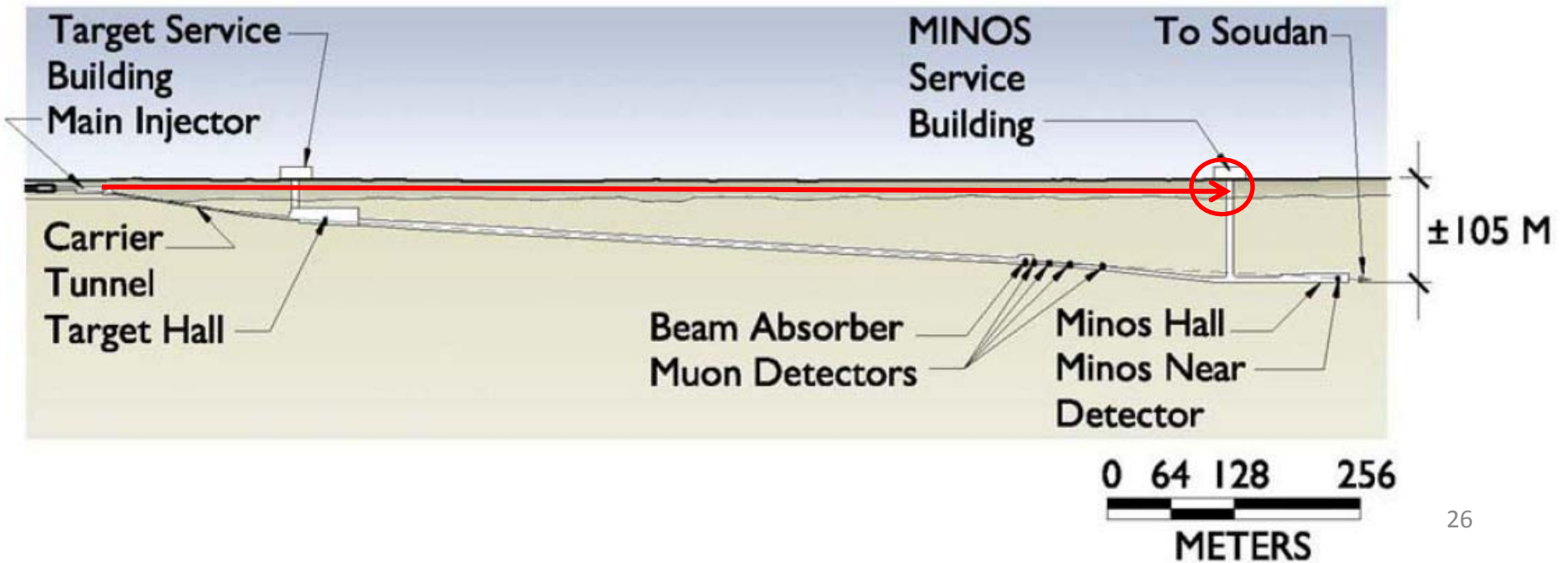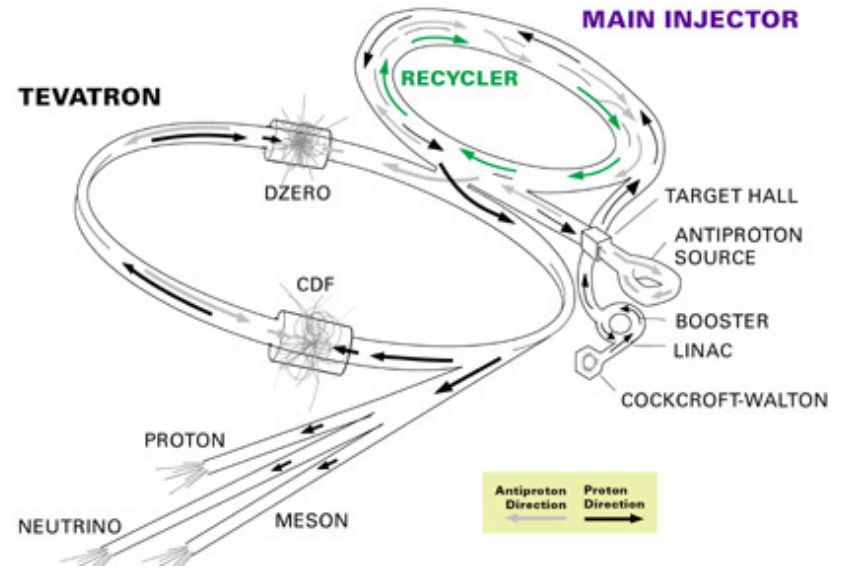
Dedicated spallation target
with VCN-UCN converter

(view along the beam)

Heavy Metal Target:
Pb, Bi, W, Ta

Heavy Water

Liquid
Deuterium

UCN
Converter

Solid
Deuterium

High-m
Super Mirror

Carbon Reflector

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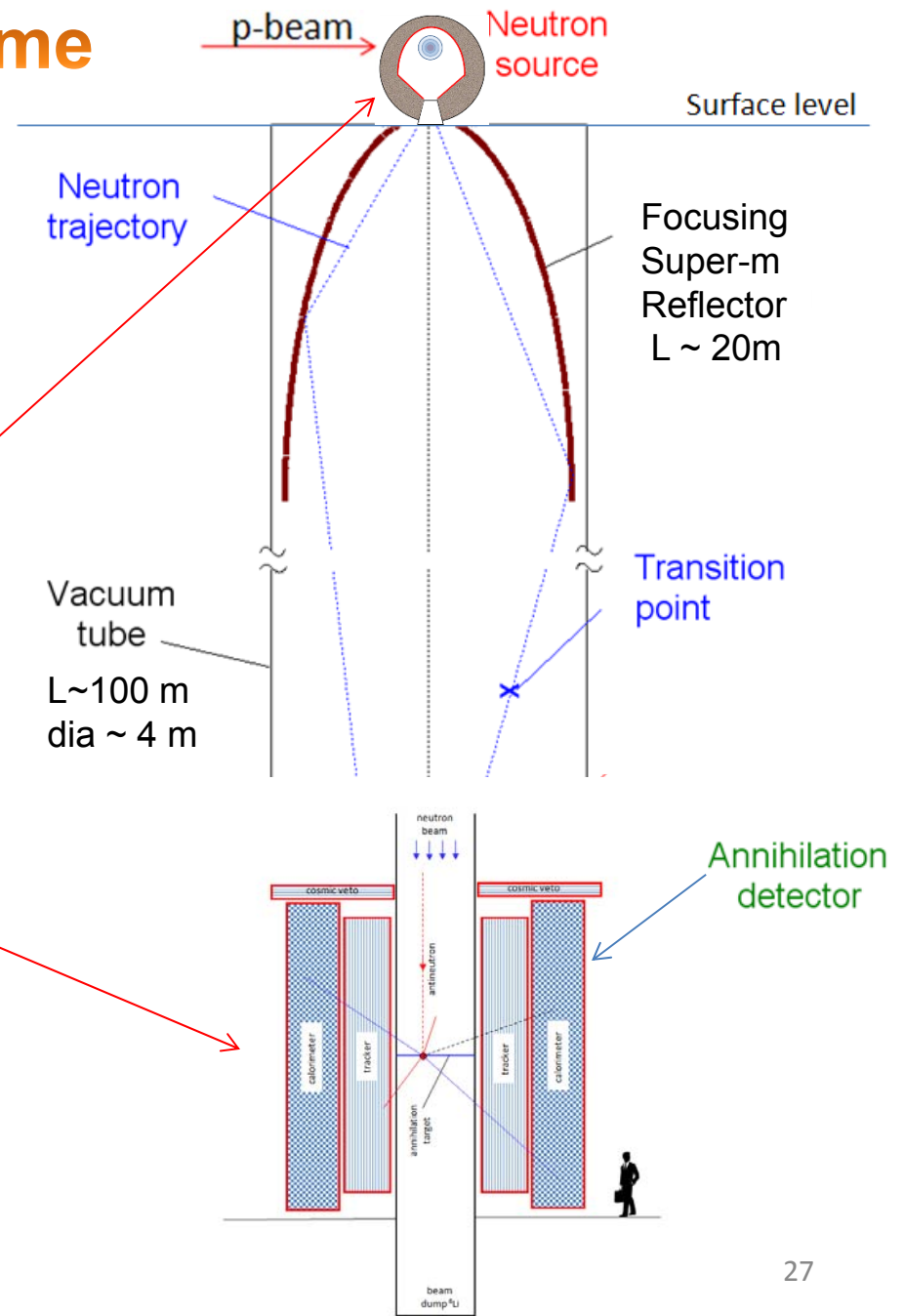
Cold Neutrons

Scheme being optimized
by simulations

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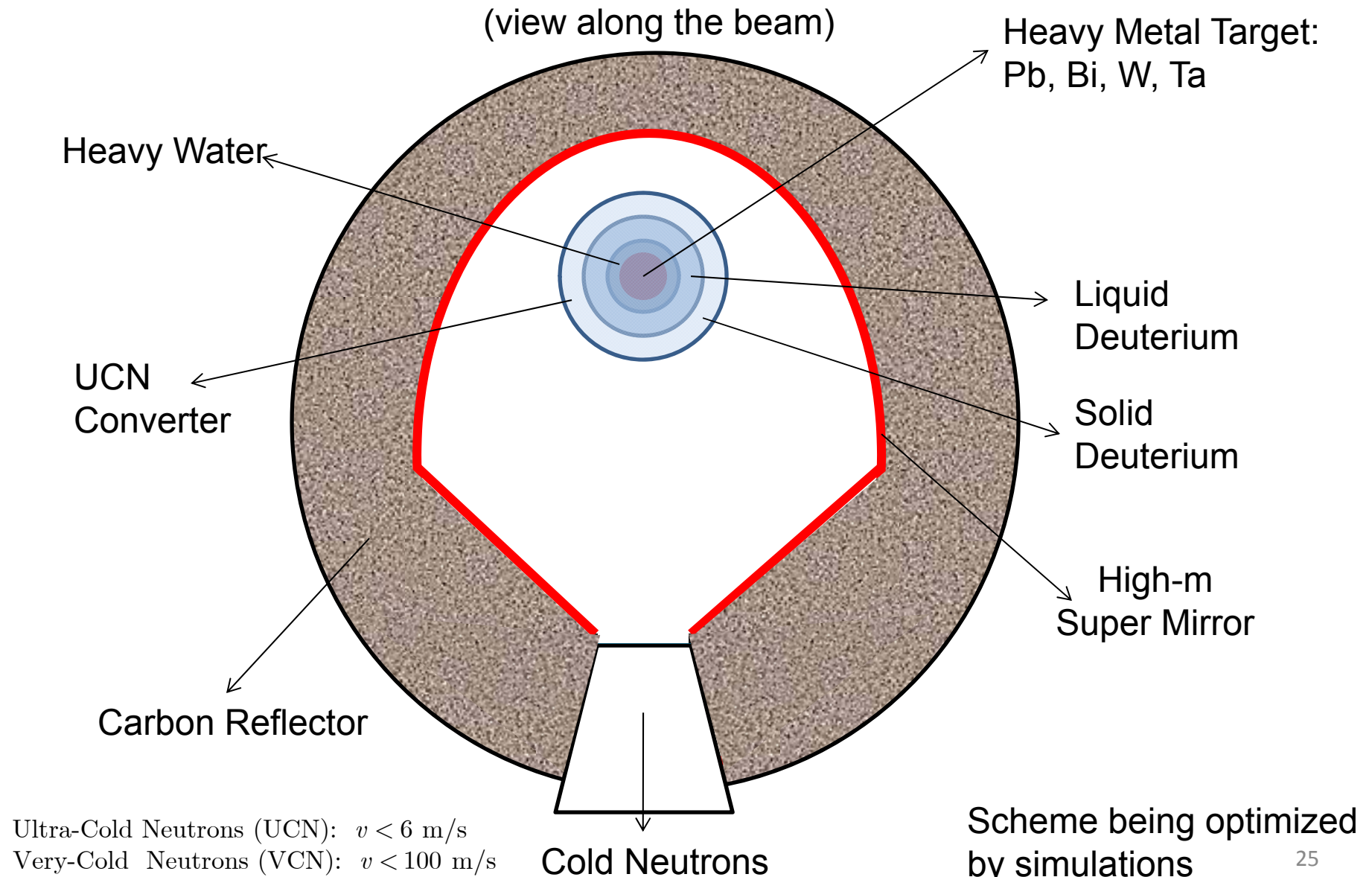
NNbar search with spallation source at Fermilab with cold free neutron

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

FERMILAB'S ACCELERATOR CHAIN

MAIN INJECTOR

RECYCLER

TEVATRON

DZERO

TARGET HALL

ANTIPROTON SOURCE

CDF

BOOSTER

LINAC

COCKCROFT-WALTON

PROTON

NEUTRINO

MESON

Antiproton Direction   Proton Direction

Target Service Building Main Injector

MINOS Service Building

To Soudan

Carrier Tunnel Target Hall

Beam Absorber Muon Detectors

Minos Hall Minos Near Detector

±105 M

0   64 128   256

METERS

New N-Nbar vertical scheme

o New concept of large focusing
  neutron reflector using super-mirror.
  Sensitivity increases as ~ L^2

o Proton beam from MI or Project X;
  with power > 200 kW

o Dedicated spallation target
  optimized for cold neutron production

o "Background free" detector:
  one event = discovery !

o Expected sensitivity > 2,000 ILL units

p-beam

Neutron source

Surface level

Neutron trajectory

Focusing Super-m Reflector
L ~ 20m

Vacuum tube

Transition point

L~100 m
dia ~ 4 m

neutron beam

Annihilation detector

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

$$\overline{n} + C \rightarrow \langle 5\pi \rangle$$
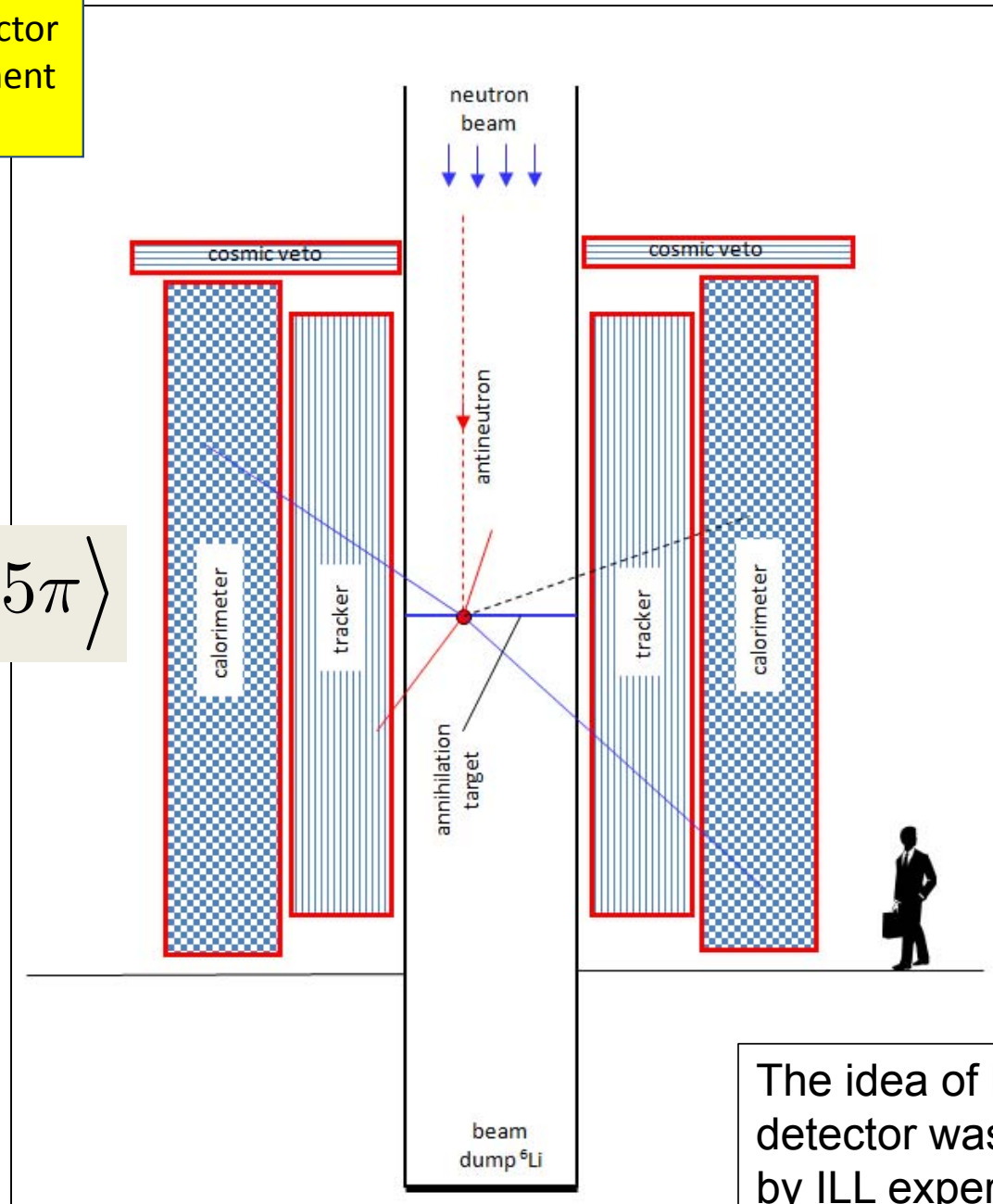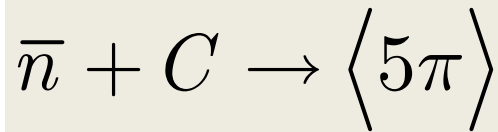
The idea of backgroundless detector was demonstrated by ILL experiment

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

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

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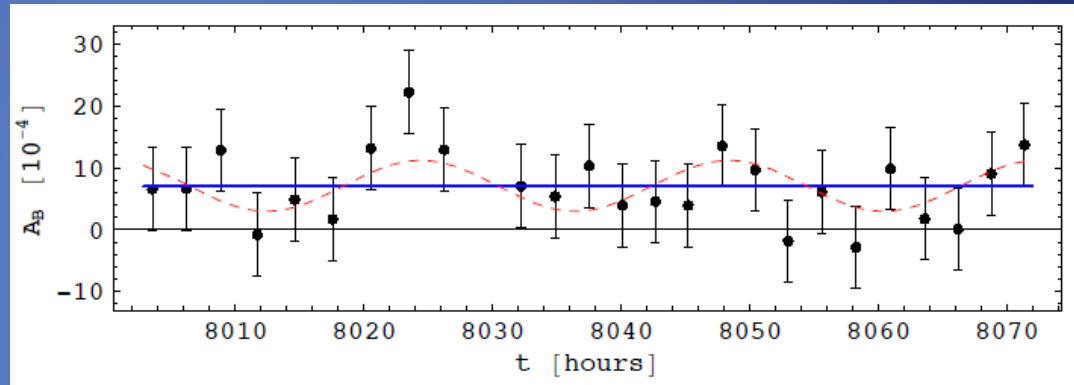
PNPI Experiment to search for $n \to n'$ disappearance at ILL/Grenoble reactor, A. Serebrov et al (2009)

NIM A611 (2009) 137-140
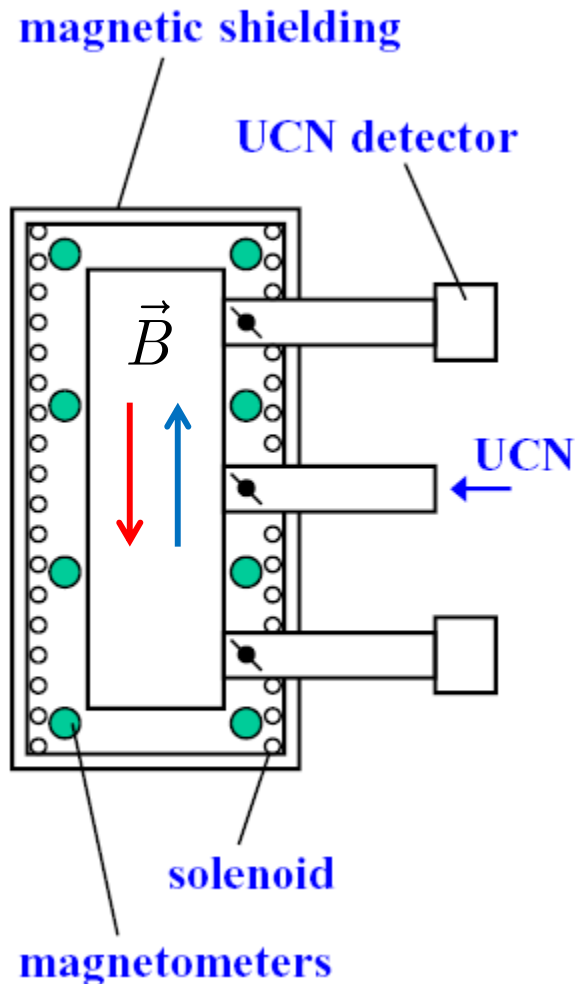
Measurements of UCN life-time asymmetry under alternation of vertical magnetic field

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

Measured asymmetry →
~ $(7 \pm 1.4) \times 10^{-4}$ (~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)

$\vec{B}$
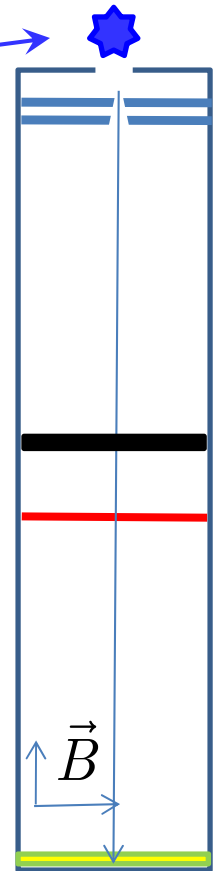
NNbar Summary

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 <u>one event</u> can be a discovery !

Effect can be uniquely checked/controlled by weak magnetic field

If discovered:

- N$\rightarrow$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.