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Requirements for Neutron → Antineutron Search

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Physics Overview

- Strong theoretical motivations: ideas of GUT+SUSY, neutrino mass, low-scale quantum gravity and hidden sector, low-scale baryogenesis models + new particles for LHC accomodate $n \to \bar{n}$ with probabilities testable by new experiment.
- Search for baryon number violation with $\Delta B = 2$ and $\Delta(B-L) = 2$ – more relevant for understanding of matter-antimatter asymmetry – is complementary to proton decay with $\Delta B = 1$ and $\Delta(B-L) = 0$.
- Strong experimental motivation: there is a possibility of increasing detection probability by a big factor of $\geq$ 1,000 and while keeping zero background $\Rightarrow$ one event can be a discovery.
- New physics unique for Project X. So far, no competition.

$$\mathrm{H} = \begin{pmatrix} E_n & \alpha \\ \alpha & E_{\bar{n}} \end{pmatrix} \Rightarrow P_{n\to\bar{n}}(t) = \frac{\alpha^2}{\alpha^2 + (V + \Delta m/2)^2} \times \sin^2\left[\frac{\sqrt{\alpha^2 + (V + \Delta m/2)^2}}{\hbar} \cdot t\right]$$

,where α – mixing parameter; V is a part of potential different for neutron and anti-neutron; t is neutron observation time; $\Delta m = m_{\bar{n}} - m_n = 0$

In case of "quasi-free conditions" : $V = 0$
(i.e. vacuum and shielded Earth magnetic field)
t experimentally can be large ~ 0.1 s – 10 s
(neutron lifetime ~ 900 s can be neglected)

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

$\tau_{n\bar{n}} = \frac{\hbar}{\alpha}$ is characteristic "oscillation" time

$\alpha < 2 \cdot 10^{-24} eV$ or $\tau_{n\bar{n}} > 3.45 \cdot 10^8$s from present Super-K limits for bound neutrons;

$\tau_{n\bar{n}} > 0.86 \cdot 10^8$s from free neutron experiment at ILL (1994)

<u>Predictions of theoretical models:</u>

observable effect around $\alpha \sim 10^{-25} - 10^{-26} eV$

or for $\tau_{n\bar{n}} \sim 10^{10\pm1} s$

Detection idea is very simple

- Observe a neutron in vacuum in the absence of magnetic field for as long as possible.
- Observe as many neutrons as possible.
- If one will be transformed into antineutron detect the latter by annihilation interaction into $\langle 5 \rangle$ pions.
- Measure probability of appearance or set a limit.

Positive NNbar observation means: $\alpha \neq 0$ or $\tau - known$

Probability of appearance per neutron: $P = (t/\tau)^2$

Sensitivity (= figure of merit) is $N_n \times \overline{t}^{\,2}$ to be maximized,
where N_n – number of neutrons used in experiment;
$\overline{t}$ – average time of flight in "quasi-free" condition
(no collisions, no magnetic field, no average Fermi potential)

Unit of sensitivity (from previous ILL-based experiment)
with free neutrons: $N\overline{t}^{\,2} = 1.5 \cdot 10^9 \; s^2/s = 1u$

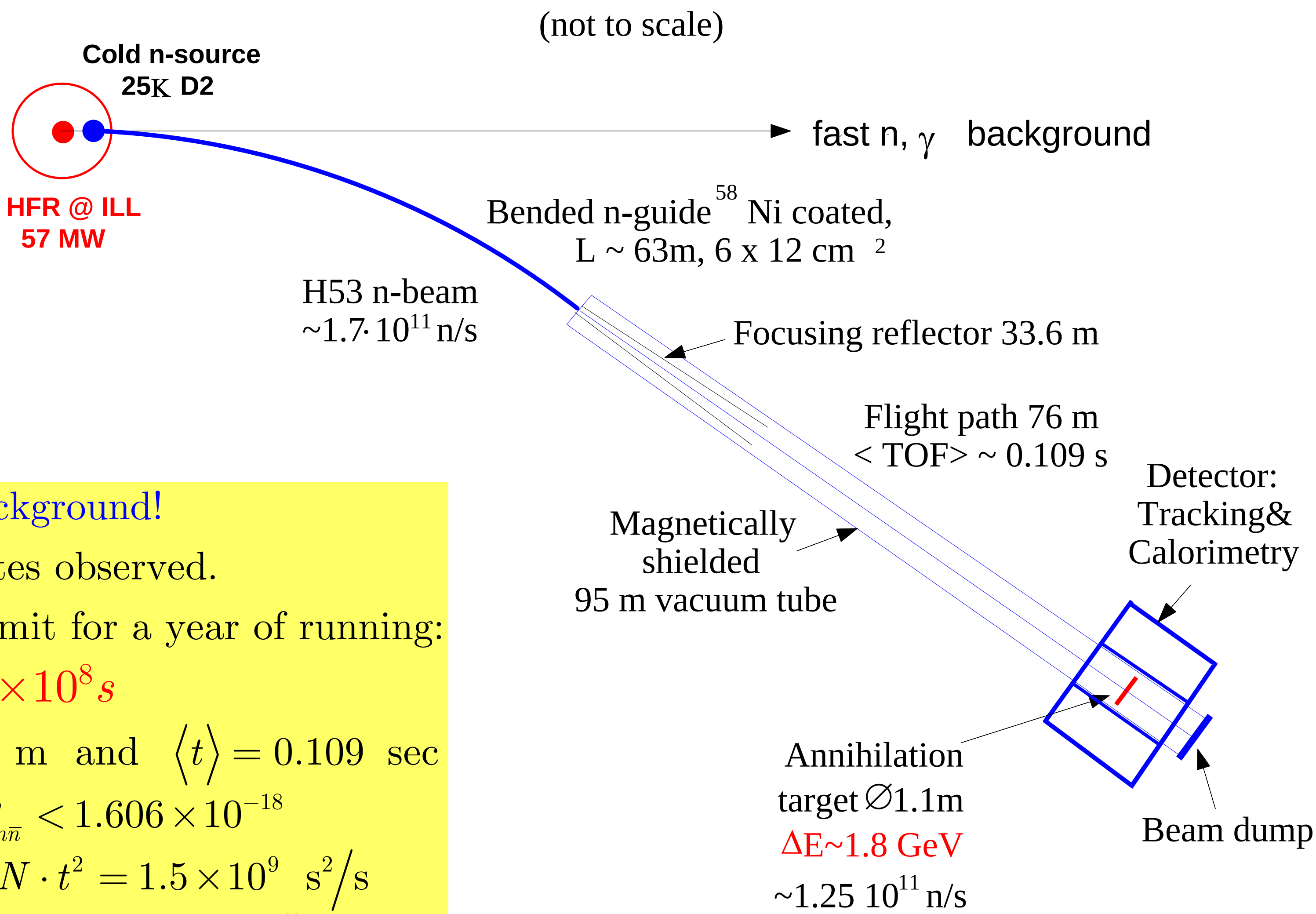
If theoretical intranuclear suppression calculations are OK,
then Super-K $n \to \overline{n}$ limit corresponds to $16u$

Sensitivity $\simeq$ appearance probability; the oscillation time τ
~ $\sqrt{\text{sensitivity}}$. It is a "parameter of theory".

Previous n-nbar search experiment with free neutrons (1u of sensitivity)

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

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

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

$\doteq$ "ILL sensitivity unit"

$$1 \text{ ILL unit of sensitivity} = 1.5 \times 10^9 s$$

τ	ILL units	
0.86×10^8 s	1u	←Free neutrons at ILL (1994)
3.45×10^8 s	16u	←Super-K now, 22kt, 10 years
6.3×10^8 s	54u	←Hyper-K 500kt, 10 years
1×10^9 s	135u	
1×10^{10} s	13,500u	←Can be ultimate goal of NNbarX
1×10^{11} s	1,350,000u	

↑

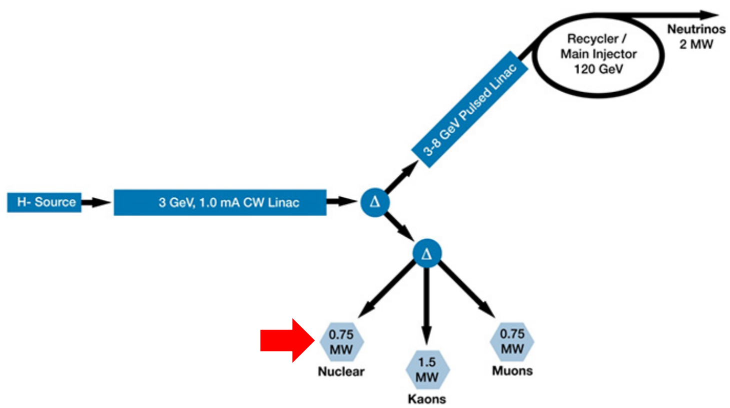
Is it possible to reach with optimization of performance vs cost ? It is the question of our on-going study.

Methods of increasing Nt^2

- Larger number of neutrons N : more power from target or reactor
- Lower neutron velocities; larger t $\rightarrow$ cold neutrons, VCN, UCN
- Larger flight distance L ?
- Use as much as possible 4π geometry
- Use diffusive reflection for fast neutrons
- Use super-mirror reflectors (transversal velocity $< m \times 7\,\frac{m}{s}$)
- Use neutron focusing (ellipsoidal mirrors)
- Use gravity for neutron manipulation
- Use all in combination!

Spallation target in ProjectX is a *unique possibility to optimize the performance* of the target for the sensitivity needed by single experiment. It was not possible before: due to constructional and regulational constraints (e.g. at the reactors) or due to having multi-user facilities (e.g. at SNS, PSI...)

Optimal Production Energy



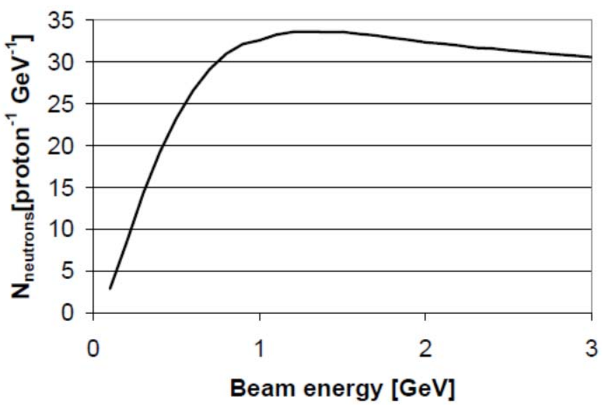
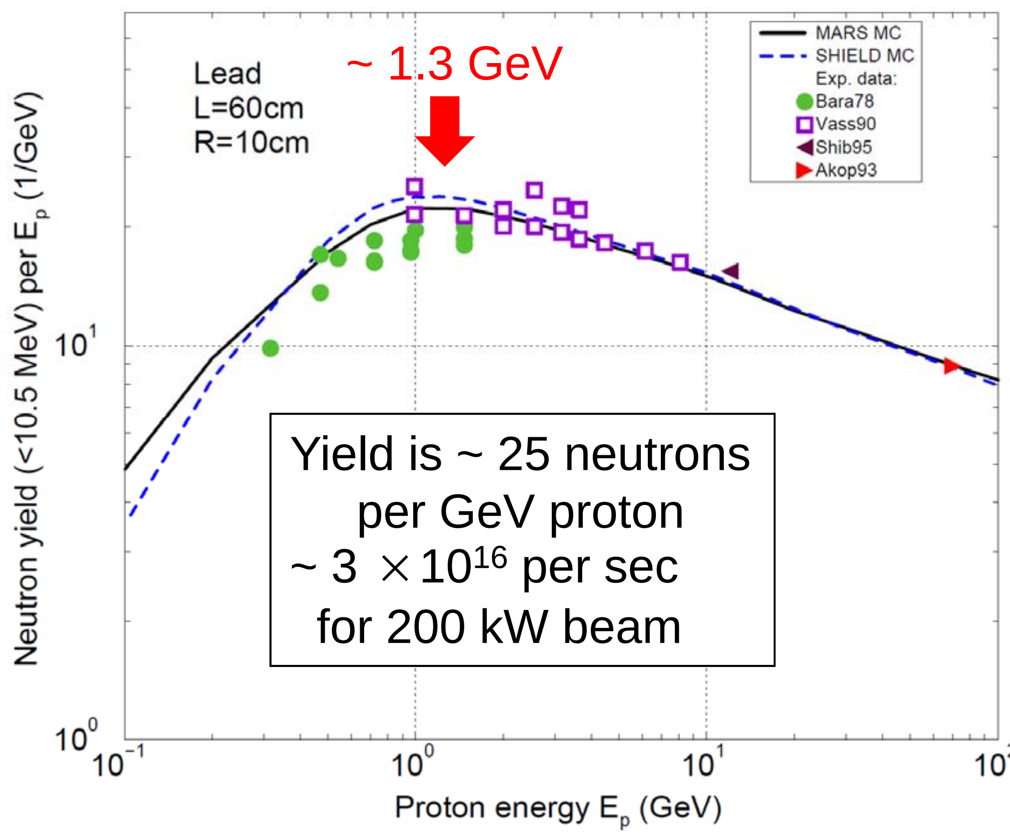


Figure 4.8: Dependency of the number of produced neutrons in the whole setup on the energy of the protons, normalized to one proton and to one GeV (MCNPX simulation).



N. Mokhov, MARS simulations, FNAL, 2011

Mitja Majerle (2009)
Czech Technical University in Prague

For target made of fissionable materials (e.g. Th, DU) neutron yield can be factor ~ 2 higher (geometry dependent)

Slow neutrons

- Primary Spallation neutron spectrum is ~ similar to that of fission $\rightarrow$

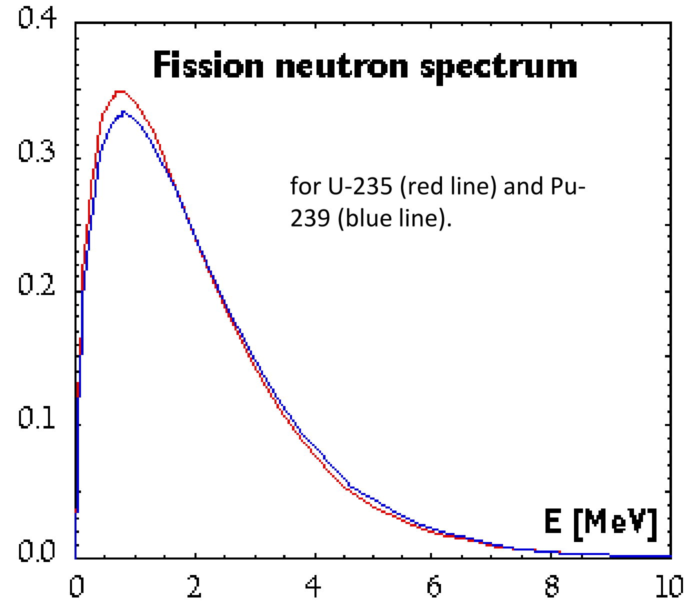
- ~ 2 MeV neutrons with velocities ~ 20,000 km/s are too fast to be useful for NNbar search
$\rightarrow$ moderation to thermal (heavy water)
$\rightarrow$ cryogenic (liquid deuterium)
$\rightarrow$ VCN $\rightarrow$UCN

- Optimal cryogenic moderation – compromise between thickness and capture, since capture cross section is ~ $1/v$.

- Radiative heating of moderator (n, γ) and heat removal are design challengers.

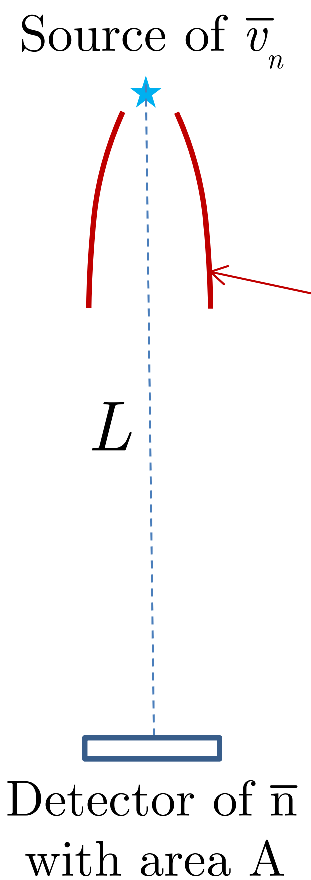
- Important question for simulation is optimization of moderator configuration giving maximum yield of cold neutrons (more precisely $Nt^2 \sim N/v^2 \sim N/\langle E \rangle$)
What fraction of initial number of neutrons is thermalized to Maxwellian distribution with temp. T ?

- R&D on VCN thermalization down to lower neutron temperatures is a great reserve (ANL)



- Neutrons thermalized to T $\sim$ 300K have average Maxwellian velocity 2.2 km/s.
- Thermalization "record" @ILL: significant part of spectrum is fitted by Maxwellian with T=35K $\langle v \rangle \sim$ 700 m/s
- UCN with v <7 m/s are small part of Maxw. spectrum

Distance L (source-target) in simple-minded approach



$$N \times \overline{t}^{\,2} = I_n \cdot \Delta\Omega \times \left(\frac{L}{\overline{v}_n}\right)^2 = I_n \cdot \frac{A}{L^2} \times \frac{L^2}{v_n^2}$$

$\Rightarrow$ sensitivity doesn't depend on L !

Addition of elliptical focusing reflector directing neutrons to the detector fixes $\Delta\Omega'$

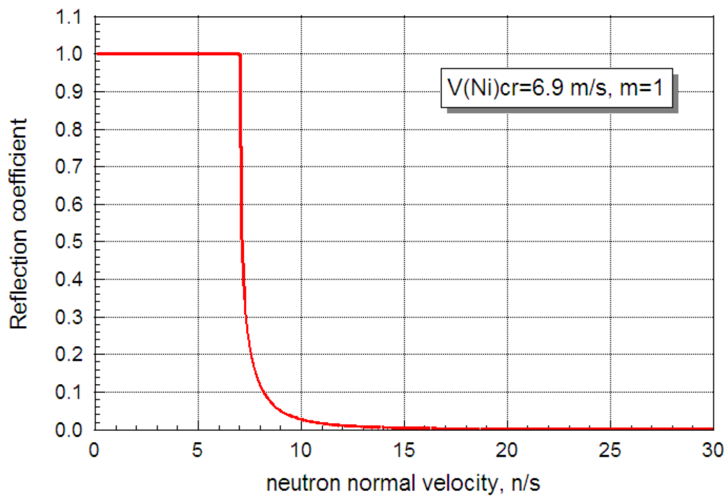
$$N \times \overline{t}^{\,2} = I_n \cdot \Delta\Omega' \times \frac{L^2}{v_n^2} \quad \Rightarrow \quad L^2 \text{ dependence}$$

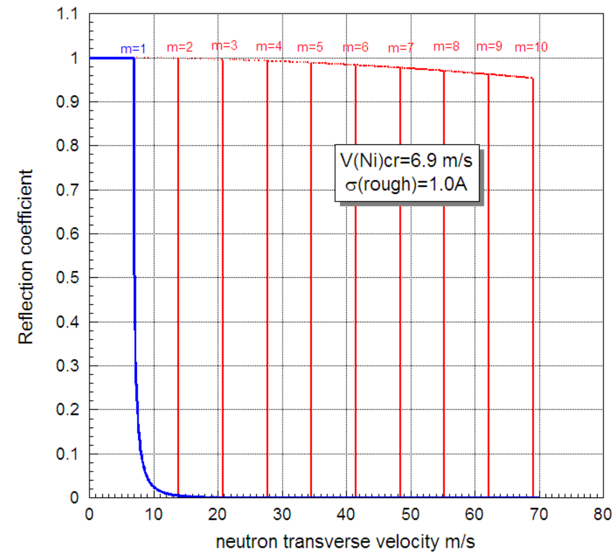
In fact, this approximate qualitative picture is a bit more complicated:

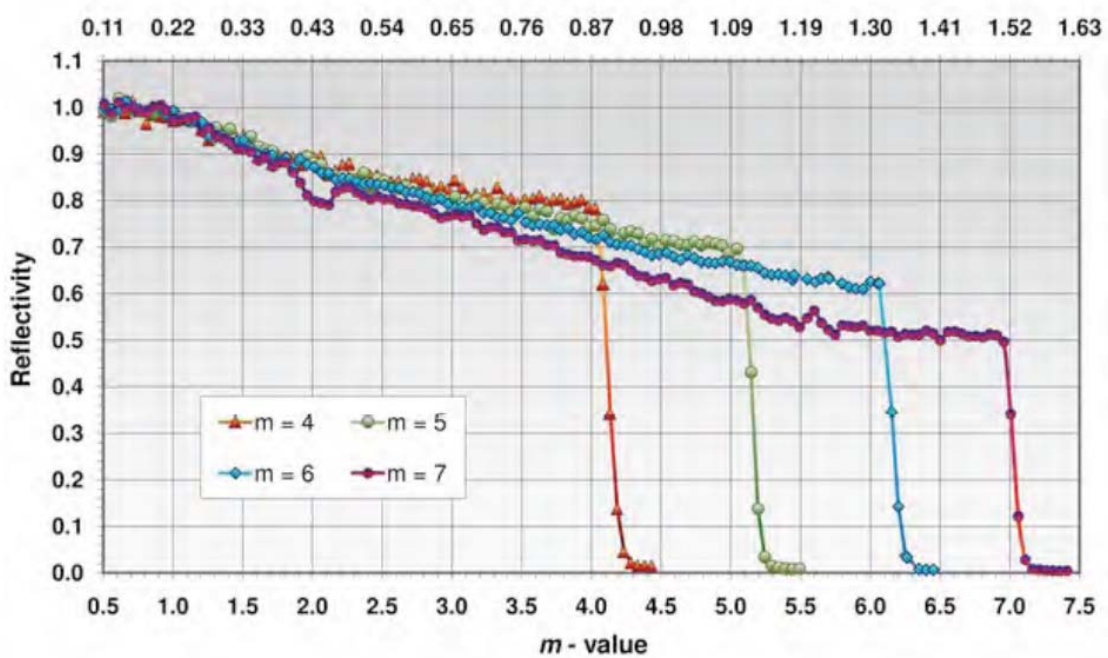
$$I_n \sim F_n \sim v_n; \quad \Delta\Omega' \sim \frac{1}{v_n^2}; \quad N\overline{t}^{\,2} \sim \frac{L^2}{v_n^3}$$

With focusing reflector the L^2 works and cold source is becoming even more efficient

Development of high-m neutron reflectors







Can be economically possible in the future

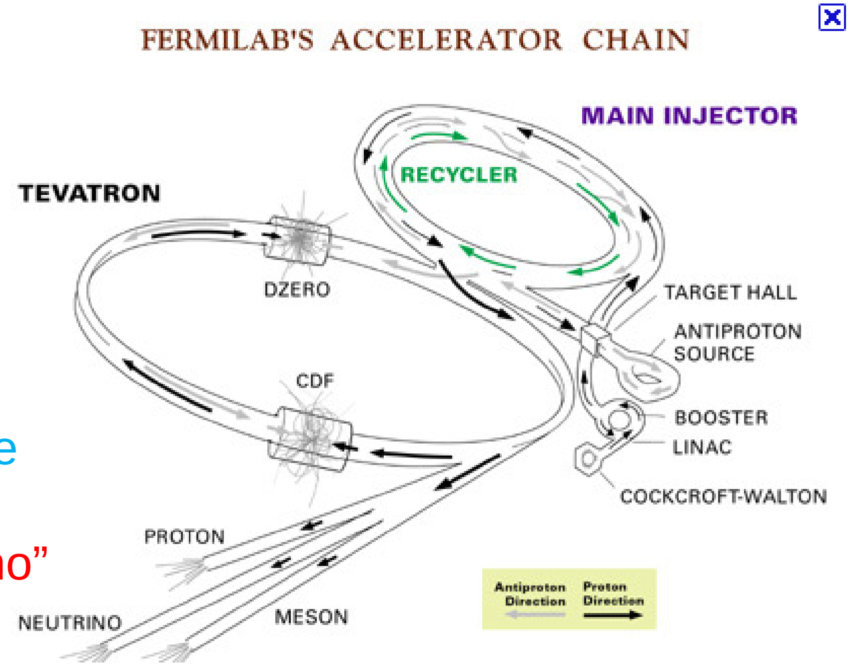
← Commercially available up to m=7 $(v_{\perp} \cong 50\ m/s)$

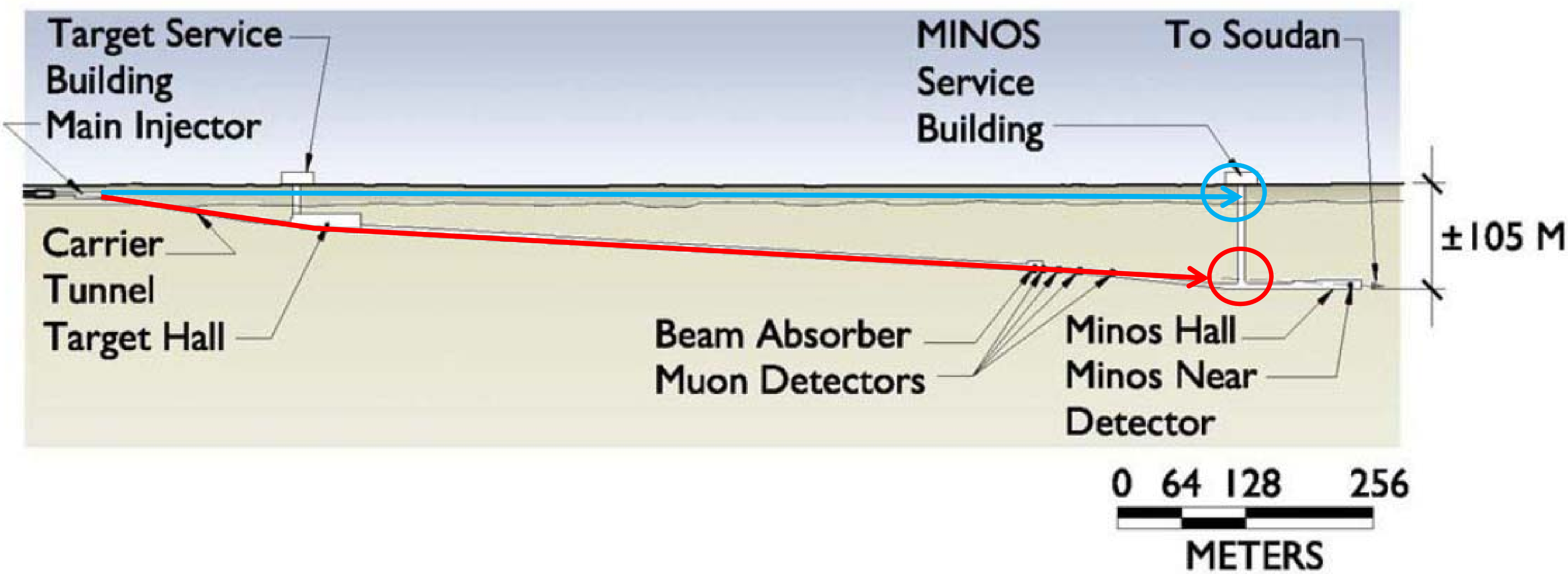
New options for NNbar search with Fermilab spallation target

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

Option 1: "TOP – DOWN" if km-long beam line from MI can be available

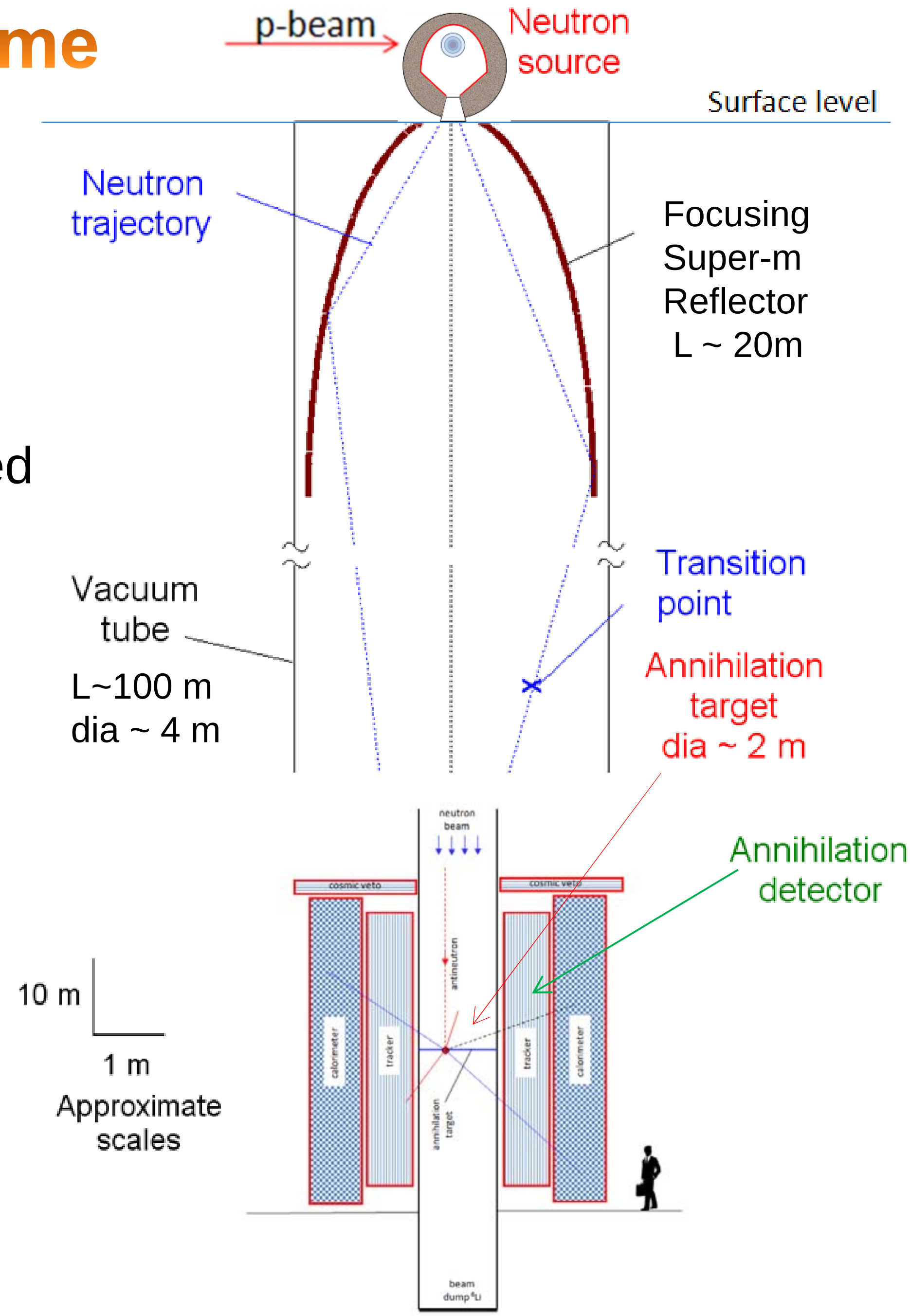
Option 2: "BOTTOM – UP" if modified "neutrino" beam line can be available





Top-Down vertical scheme

- 400 KW or 700 KW MI beam can be used, or ~ 1 MW Project X spallation target; CW or pulsed
- Dedicated spallation target optimized for the cold neutron production and enhanced for VCN and UCN
- “Background free” detector; prototyped by ILL experiment; one event = discovery
- Expected sensitivity > 2,000 ILL units (simulations are in progress)



Schematic of spallation target with VCN-UCN converter for Top-Down configuration