Intensity Frontier Workshop • ANL • April 25-27, 2013

# NNbarX
# Baseline Configuration Sensitivity and Future Developments

On behalf of NNbarX Collaboration

Yuri Kamyshkov/ University of Tennessee
email: kamyshkov@utk.edu

# Importance of Observation of Baryon Violation

- Observation of violation of Baryon number is one of the pillars needed for modern Cosmology and Particle Physics:

  - it follows from the inflation (Dolgov & Zeldovich);
  - required for explanation of BAU (Sakharov);
  - present within SM, although at non-observable level (‘t Hooft);
  - motivated by BSM models (Georgi & Glashow, Pati &Salam, ...)

- Proton decay $\Delta B = 1$ and $n \rightarrow \overline{n}$ $\Delta B = 2$ are complementary.

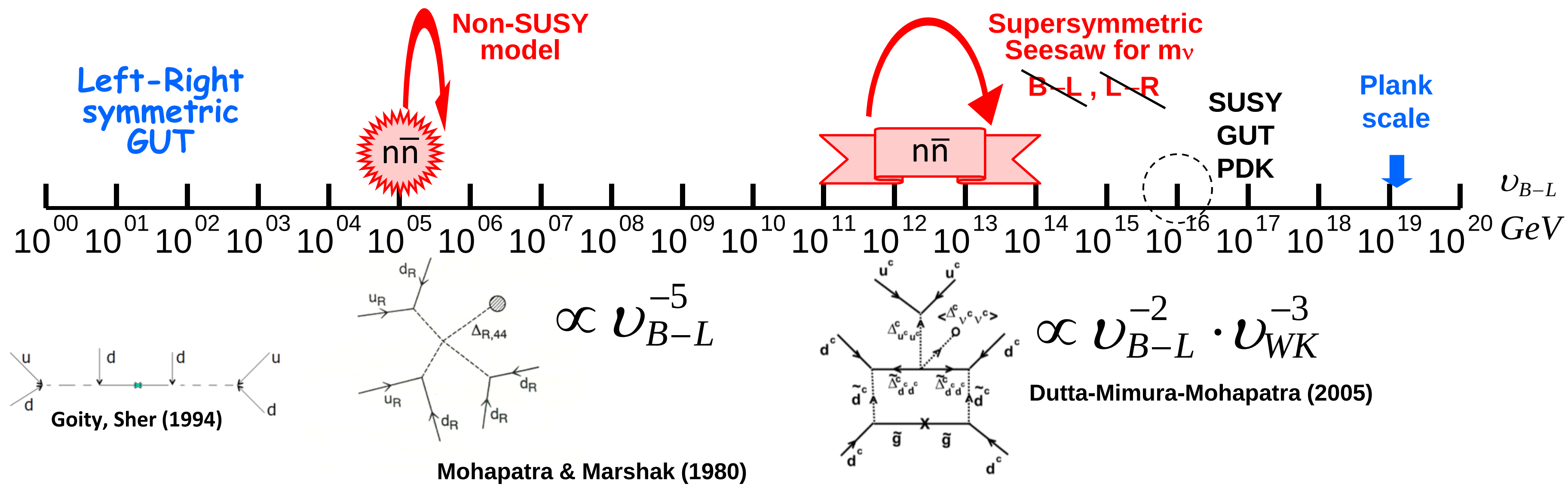
# Neutron-Antineutron Transformations ΔB=2

- Neutron-antineutron transformation is natural in L-R symmetric models with V(B−L) at the scales below $10^{16}$ GeV scale where neutrino masses are also explained (Mohapatra & Marshak); Observable $n \rightarrow \overline{n}$ together with new TeV-scale color-sextet scalars at LHC are predicted in the new scheme of Post-Sphaleron Baryogenesis (Babu, Mohapatra).

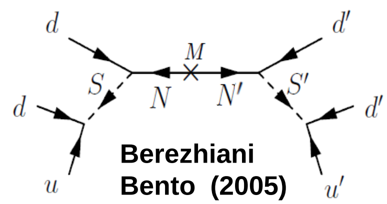
- Interesting theoretical discussions on $n \rightarrow \overline{n}$

R. Schrock and S. Nussinov (2002)
K. Babu and R. Mohapatra et al. (> 2001)
G. Dvali and G. Gabadadze (1999)
J. Arnold et al. (2012)
G. Durieux et al. (BLV-2013) http://www.mpi-hd.mpg.de/BLV2013/
Z. Berezhiani (BLV-2013)

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



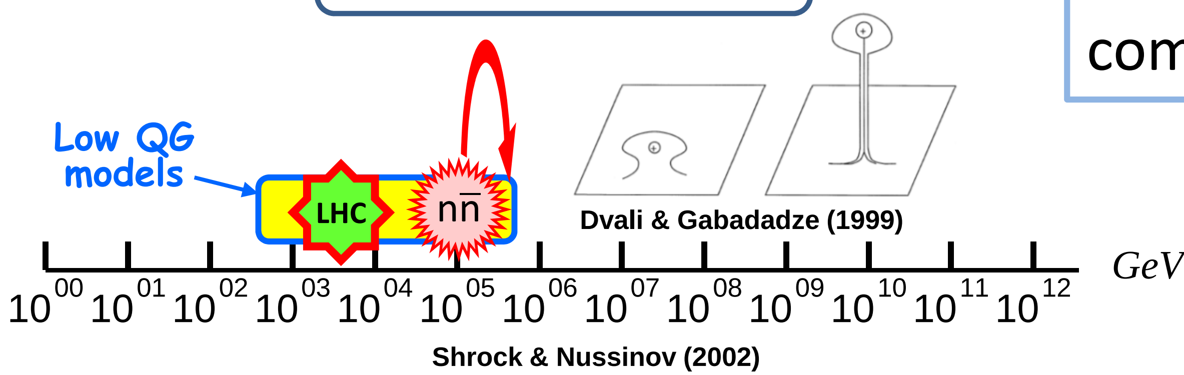

Observable effects at LHC
Berezhiani; Babu et al. (2013)




Post-Sphaleron Baryogenesis
Babu, Mohapatra, et al.(2013)

**<u>Experimental motivation!</u>**

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



# Sensitivity or figure of merit

For experimental "quasifree conditions"
when external fields are approx. 0
and $n$ "observation" time $t$ ~ 0.1 s to 10 s

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

$N \cdot \overline{t}^{\,2} \doteq$ sensitivity for free neutrons $\sim P$

$$\tau_{n\bar{n}} = \tau_{free} \sim \sqrt{N \cdot \overline{t}^{\,2}}$$

$\tau_{n\bar{n}} = \frac{\hbar}{\alpha}$ 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 $n$)

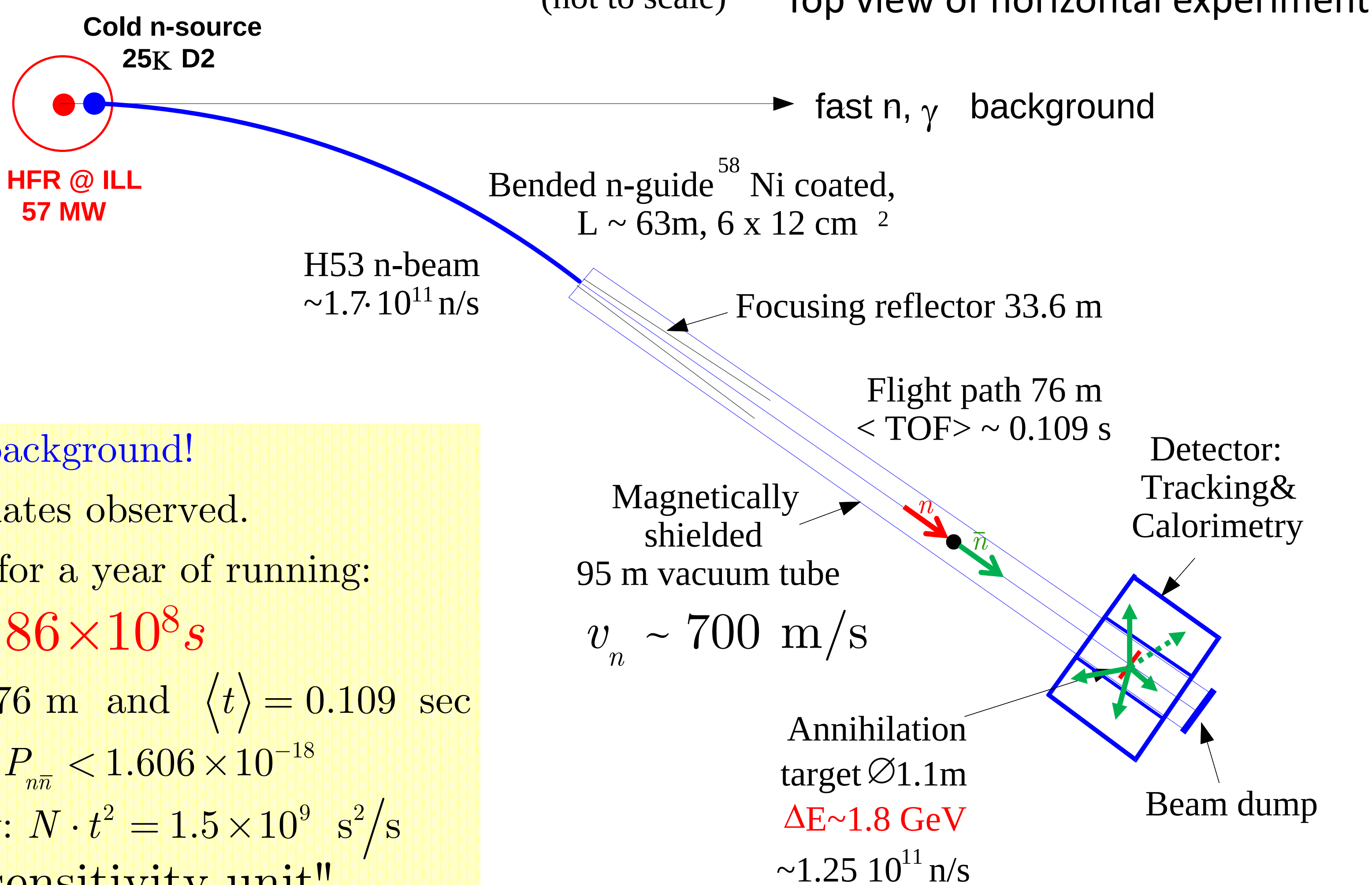
Predictions of theoretical models: observable effect around $\alpha \sim 10^{-25} - 10^{-26} eV$

# Previous state-of-the-art 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: $N \cdot t^2 = 1.5\times 10^{9}\ \ s^2/s$

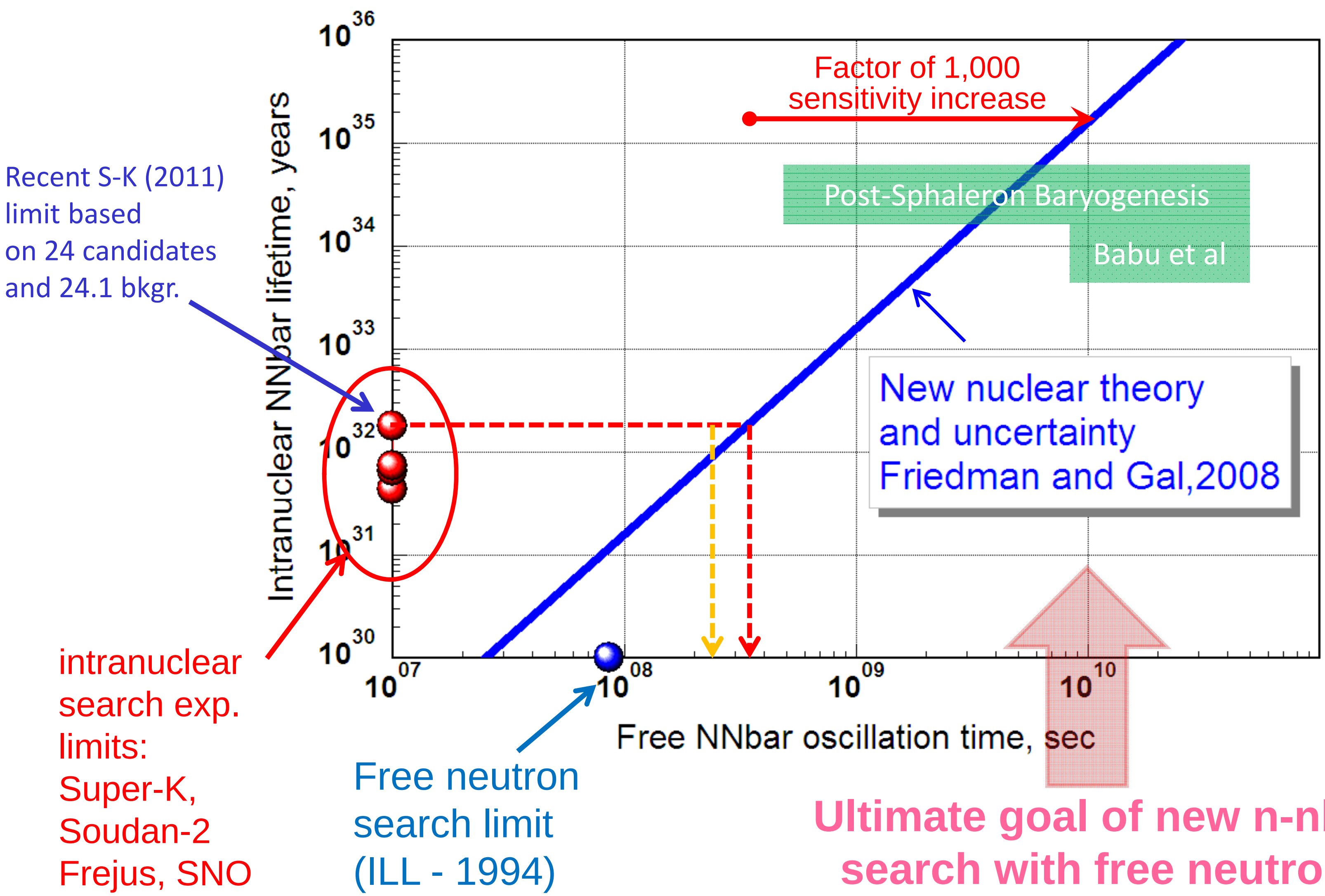
$\doteq$ "ILL sensitivity unit"

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

$R$ was discussed by Ed Kearns

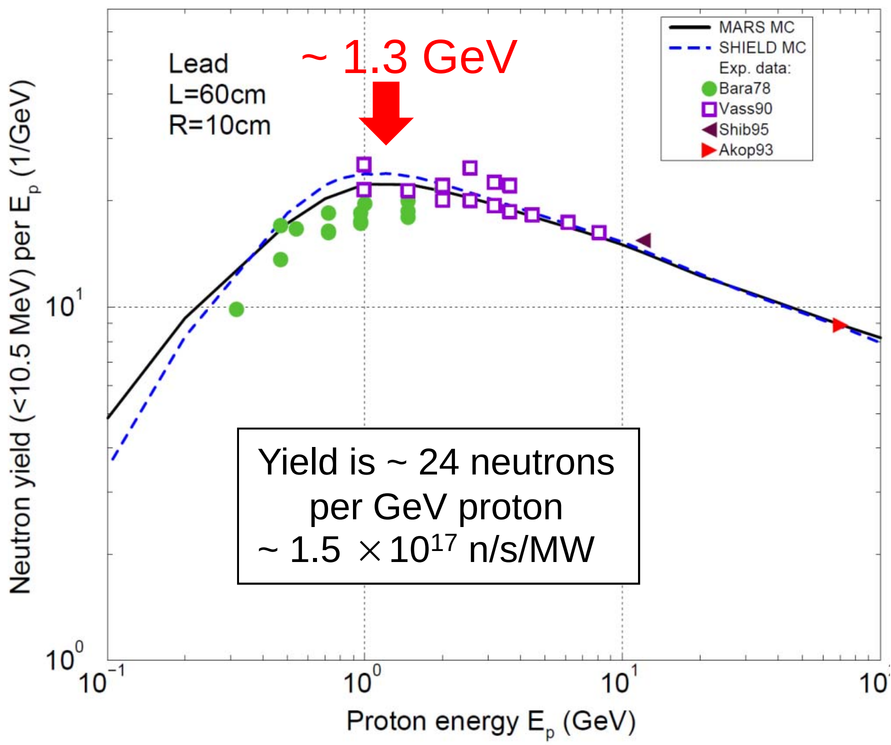
# Free Neutron and Bound Neutrons NNbar Search Limits Comparison

Large improvement with free-neutron experiments is possible




**Ultimate goal of new n-nbar search with free neutrons**

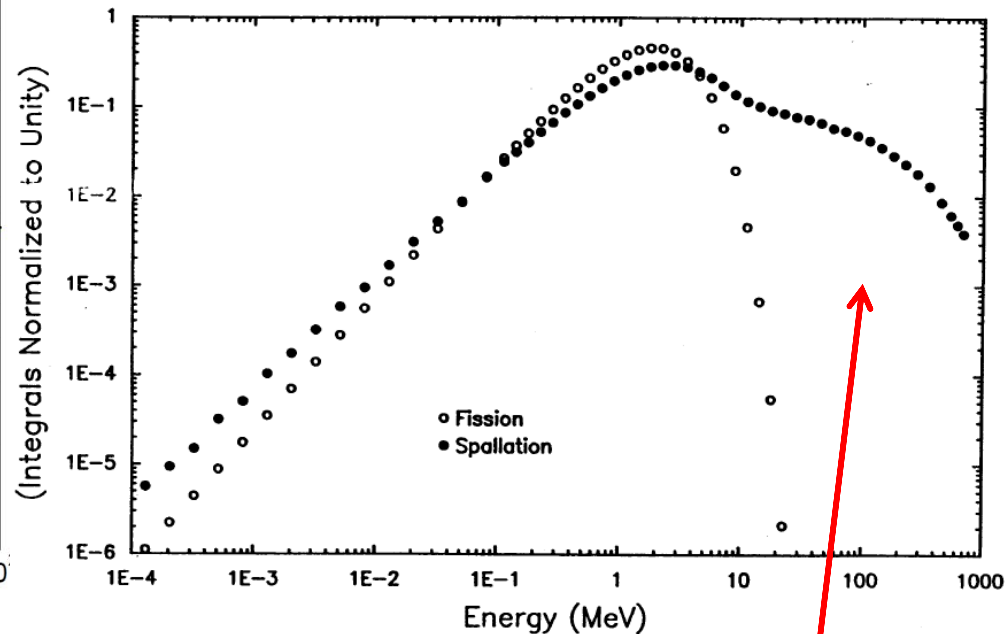
# Optimal Neutron Production Energy




N. Mokhov, MARS simulations, FNAL, 2011

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

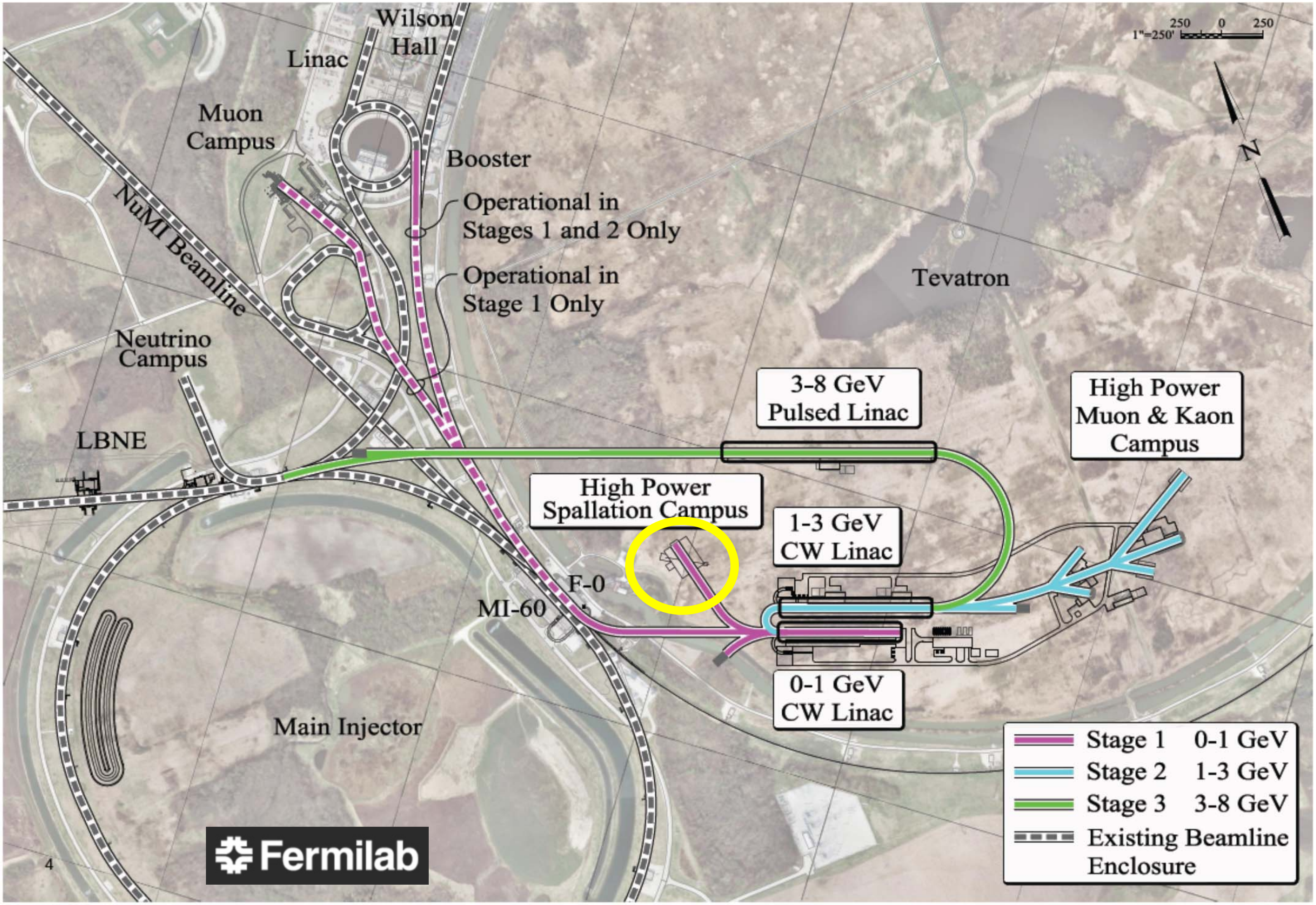
# Spectrum of Primary Neutrons



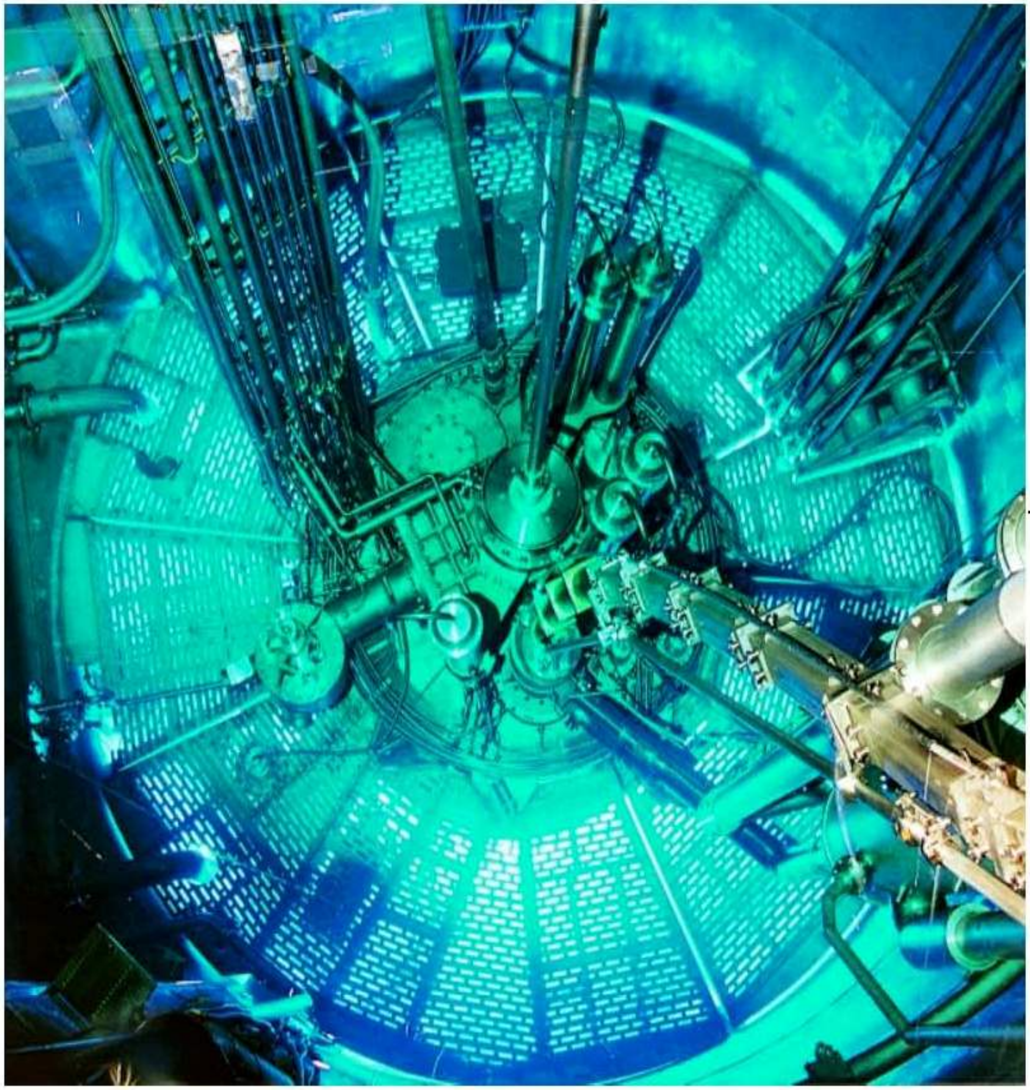

Spectrum of primary fast n from spallation target and from fission (Courtesy of Gary Russel).

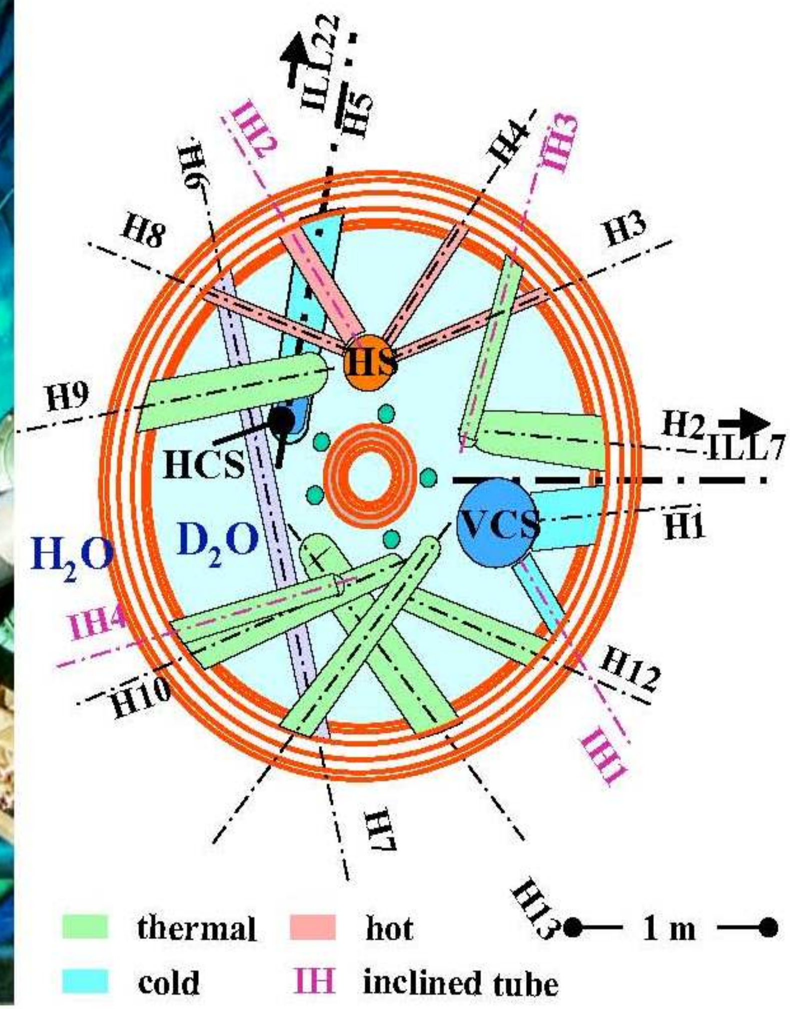
Potential source of the "fast " background for n-nbar that was non-existent in the previous ILL experiment

# Spallation Target in Project X

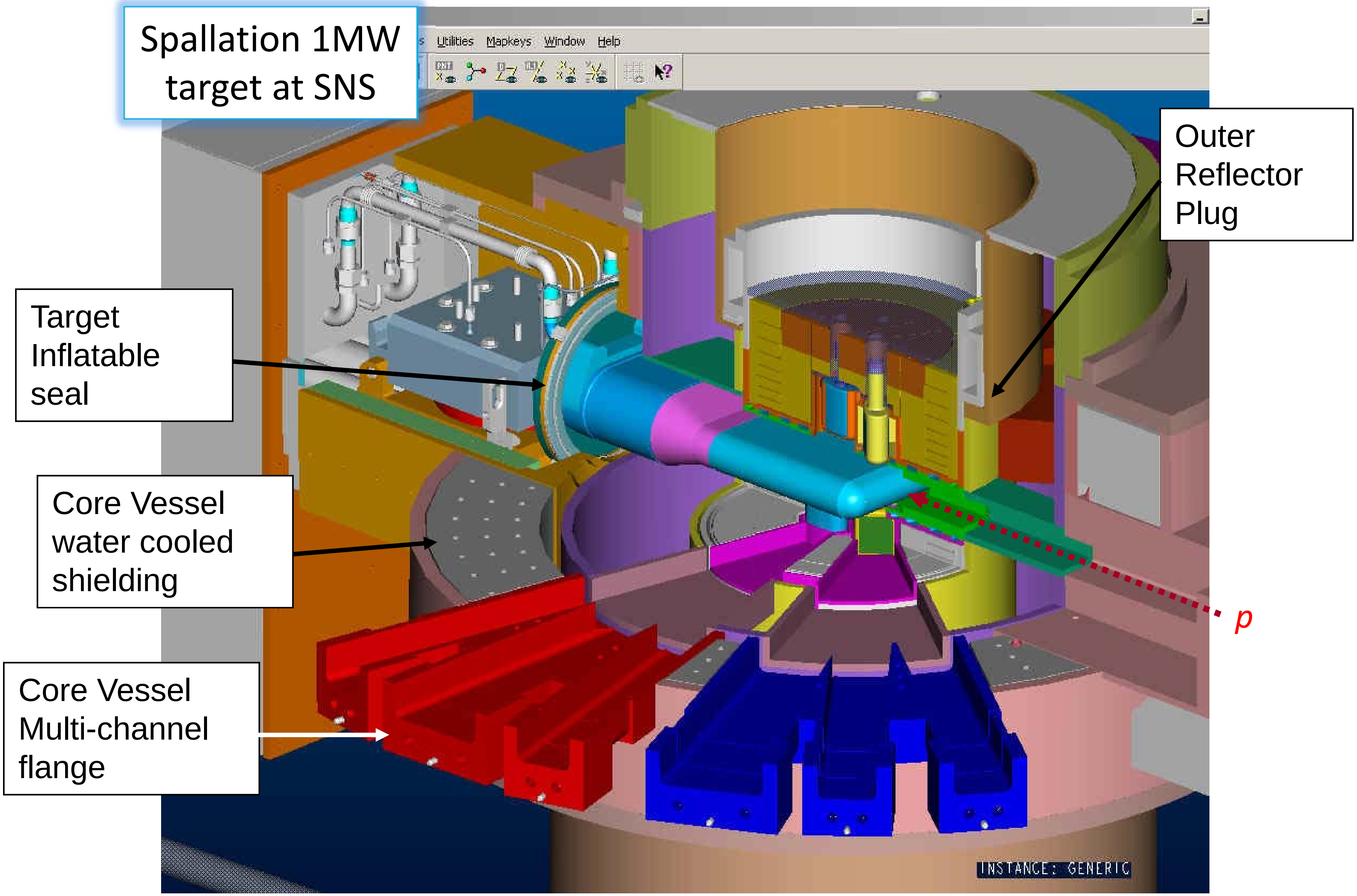


# The Institut Laue Langevin 58 MW High Flux Reactor is optimized to serve many neutron beamlines



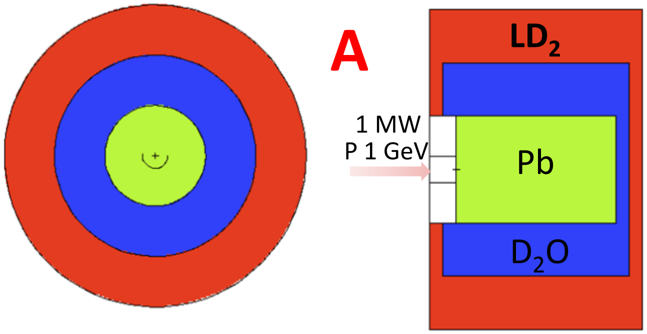


# Existing multiple n-beam lines at SNS are using small faction of $4\pi$




Tony Gabriel/UT/SNS

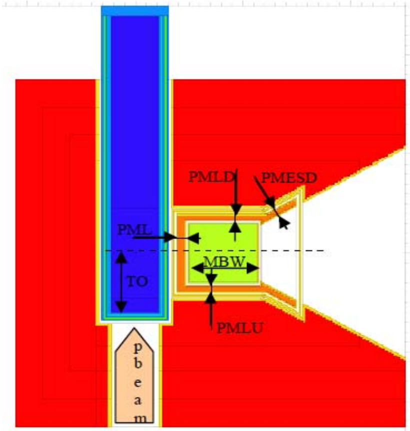
# Target Models in MCNPX (NNbarX studies for Project X)

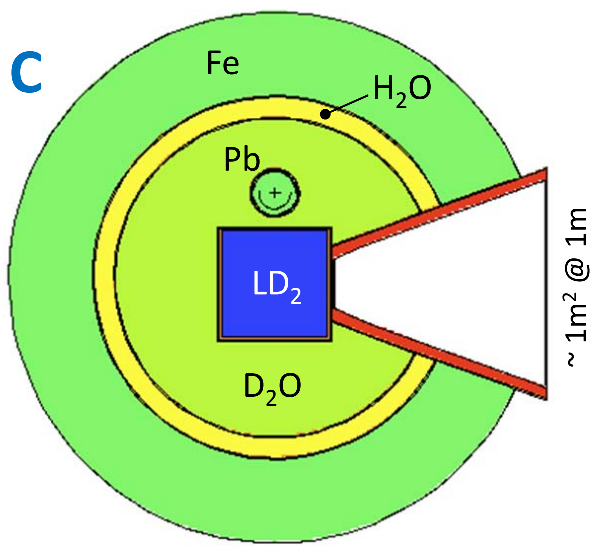



Configuration (A) G. Muhrer/LANL

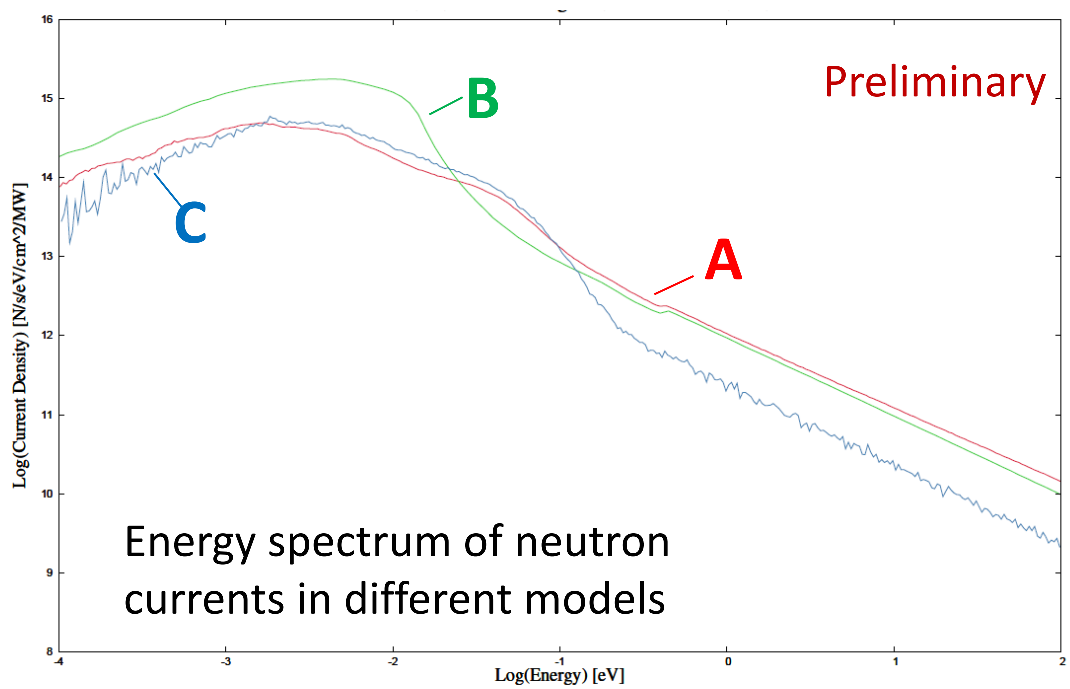
Configuration (B)
F. Gallmeier/SNS
with $LH_2$

B





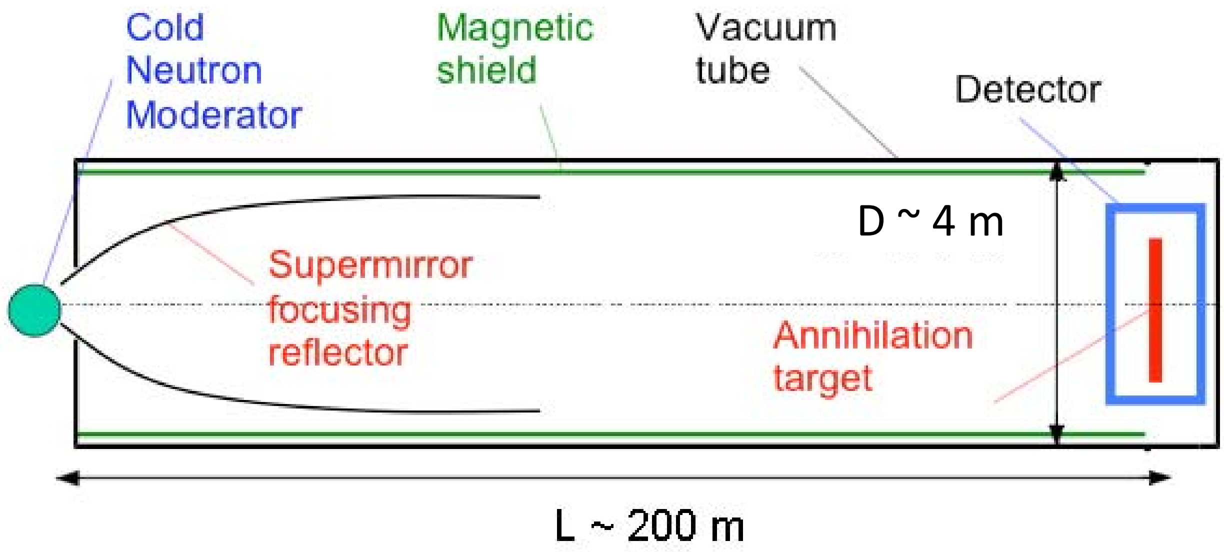

Initial UT model (C) L. Castellanos/UT




Energy spectrum of neutron currents in different models

# Conceptual Horizontal Baseline Configuration

with elliptical focusing reflector (method proposed by us in 1995)




| Typical initial baseline parameters: | |
|---|---|
| Cold source configuration | C |
| Luminous source area, dia | 30 cm |
| Annihilation target, dia | 200 cm |
| Reflector starts at | 2 m |
| Reflector ends at | 50 m |
| Reflector semi-minor axis | 2.4 m |
| Distance to target | 200 m |
| Super-mirror | m=7 |
| Vacuum | $< 10^{-5}$ Pa |
| Residual magnetic field | < 1 nT |

MC Simulated sensitivity $Nt^2$:

150 "ILL units" x years

Sensitivity and parameters are subject of optimization by Monte-Carlo including overall cost

N-nbar effect can be suppressed by weak magnetic field.

## Independent sensitivity estimate by scaling from ILL experiment (Dave Baxter)

Starting from Fundamental Physics beam line at SNS
that is about similar to the cold beam in ILL experiment:

| | | |
|---|---|---|
| × | 3 | due to acceptance solid angle increase from m=3.5 to m=6 |
| × | 3 | larger emission area of cold moderator |
| × | 1.2 | replacement target from Hg to Pb/Bi |
| × | 2 | more efficient moderator |
| × | 6.9 | flight path increase from 76m to 200m |
| | | (some improvement factors are not included) |
| × | 150 | sensitivity increase factor × number of years |

For 3 years of running sensitivity can be ~ 450 of ILL units
or $\tau_{free} = 1.8 \times 10^9$ s

Sensitivity $Nt^2$ is a function of the performance of the source and several parameters of experiment which also can be defined and constrained by the cost factors. It is possible to envisage a configuration with larger sensitivity. The goal of our study is relate the configuration(s) with the cost by a parametric cost model.

# Fermilab Physics Advisory Committee Meeting
# 2012 October 15-17

## Comments and Recommendations

The previous state-of-the-art experiment (at ILL, Grenoble) provided the current lower limit on the $n$-$\bar{n}$ oscillation time of about $10^8$ s. An interesting increase of sensitivity is projected for NNbarX, by a factor of 20–30 for a first proposed phase with a horizontal detector layout. A second stage with a vertical layout could give a further factor of 100, corresponding to probing the oscillation time up to $10^{10}$ s. The vertical layout would be more challenging to construct, but would allow the use of very slow neutrons (which would suffer excessive gravitational deflection in a horizontal layout). The main improvements in sensitivity reportedly come from increase of the neutron flux delivered to the annihilation target, optimized with super-mirrors or diamond nanoparticle reflectors, and from extending the observation time through increased length of the vacuum vessel or the use of slower neutrons. A dedicated spallation source would be required at Project X, a challenging design with cryogenic moderator surrounding the solid metal target.

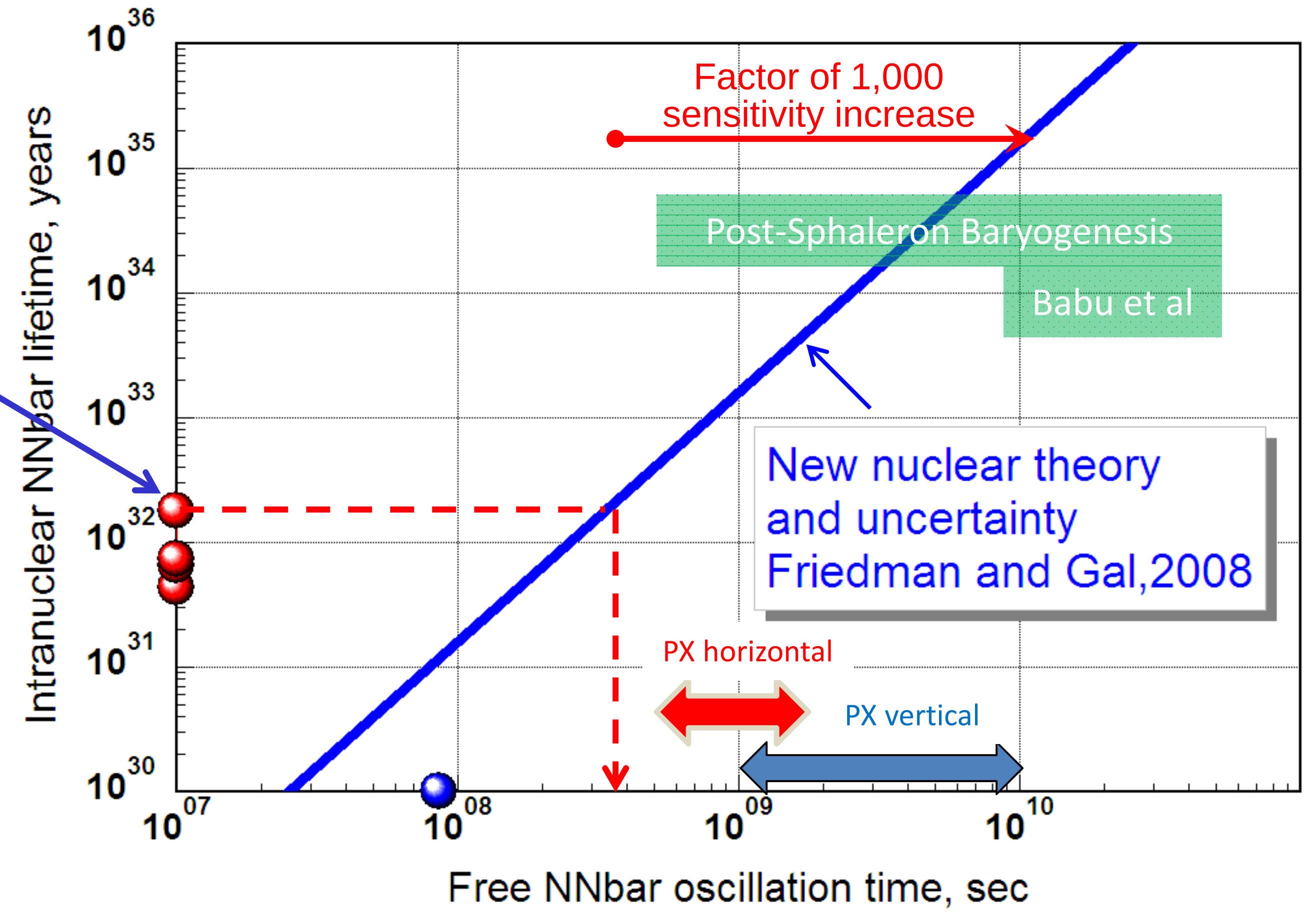
Fermilab PAC recommendation sets for horizontal option a “minimal sensitivity goal” of ~ 30 or $\tau_{free} = 5 \times 10^8$ s

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

# Free Neutron and Bound Neutrons NNbar Search Limits Comparison

Large improvement with free-neutron experiments is possible

Recent S-K (2011) limit based on 24 candidates and 24.1 bkgr.



# Sensitivity improvement factors

As compared to previous ILL/Grenoble experiment

Existing ready-to-use technologies (within economical feasibility range)

1. Use super-mirror reflector to intercept larger solid angle n's from the source
2. Use advantages of the Project X for optimal design of the source/positioning
3. Parameters vs cost optimization

Possible sensitivity improvement factor 450 or $\tau_{free} \sim 1.8 \times 10^9$ sec

New technologies (R&D and cost-impact studies are required)

1. Use vertical layout of experiment with flight path ~ 200 m
2. Use "4$\pi$ reflection source" with nano-particle diamond reflectors
3. Use commercially improved high-m reflecting mirrors
4. Use advanced colder cryogenic moderators
5. Understand possible limitations from radiation damage

Additional sensitivity improvement factor $\gtrsim 100$ with $\tau_{free}$ up to $1 \times 10^{10}$ sec.

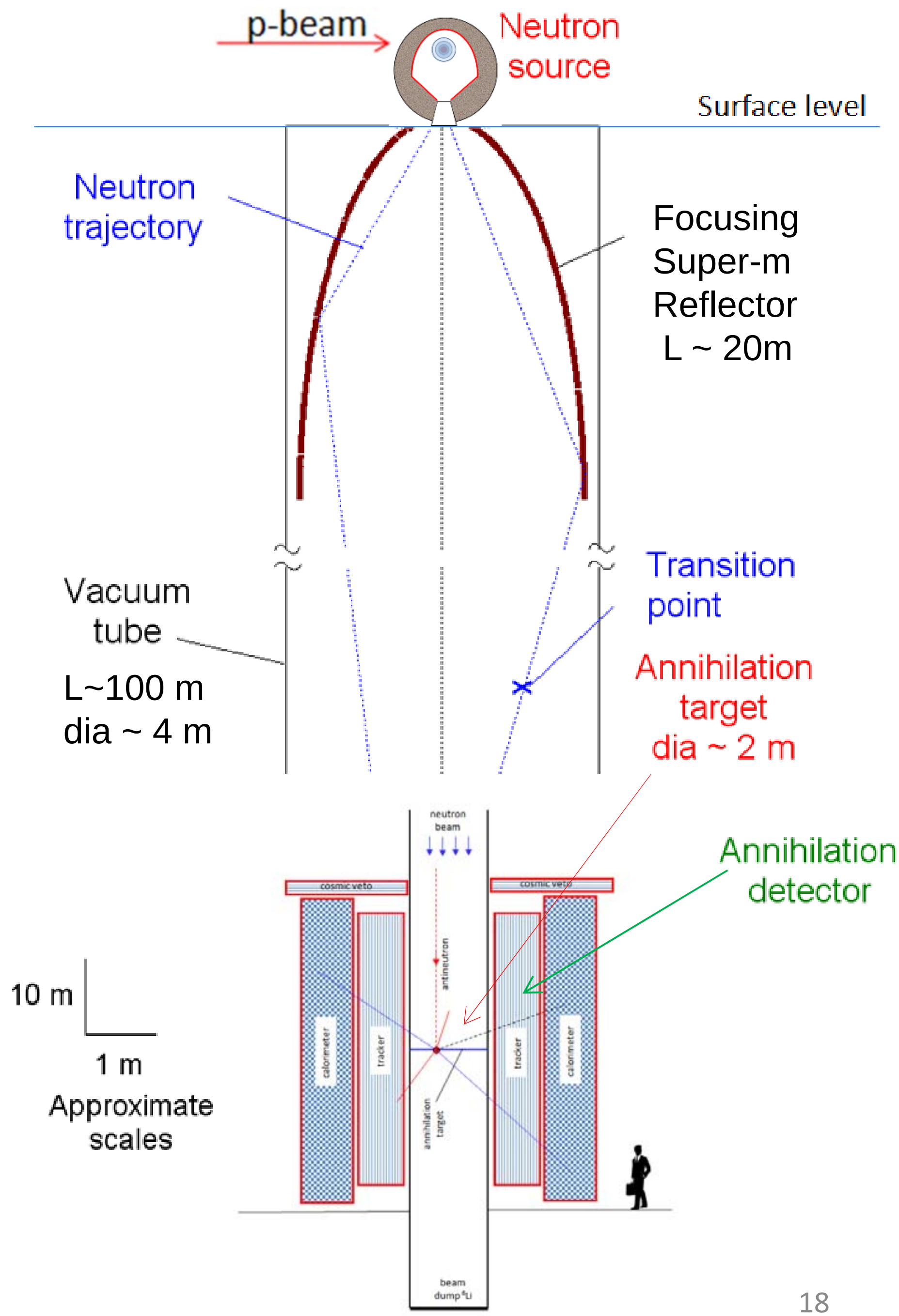
# Example of Vertical layout

Vertical layout enables use of the whole cold spectrum incl.UCN

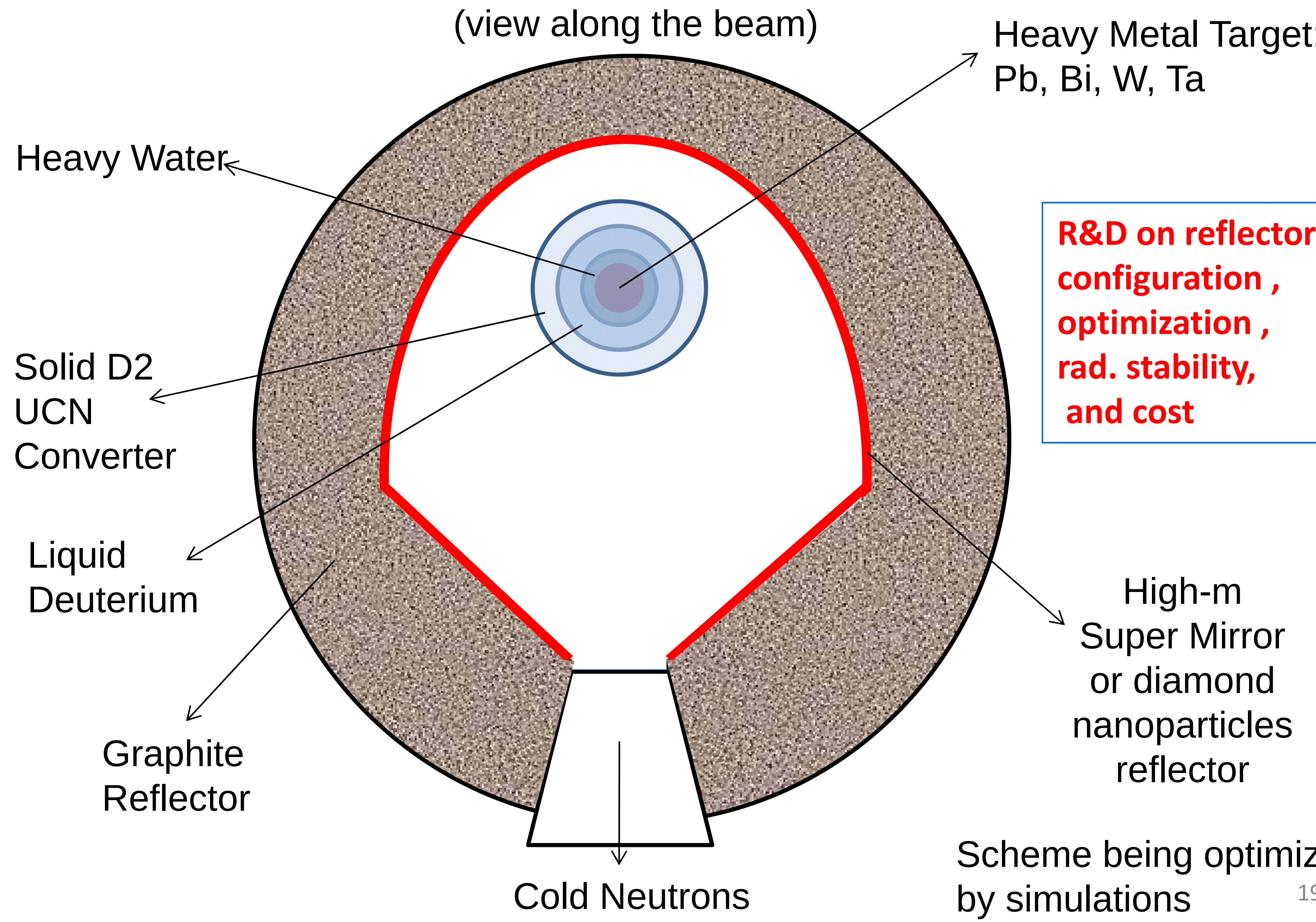
$$h = v_0 t + \frac{1}{2} g t^2$$

$$105\ \mathrm{m} = 100\ \mathrm{m/s} \cdot 1\ \mathrm{s} + 4.9\ \mathrm{m/s^2} \cdot 1^2 \mathrm{s^2}$$

$$105\ \mathrm{m} = 10\ \mathrm{m/s} \cdot 3.7\ \mathrm{s} + 4.9\ \mathrm{m/s^2} \cdot 3.7^2 \mathrm{s^2}$$



# Further sensitivity improvement concept: dedicated spallation target with VCN-UCN converter (4π emission)




**R&D on reflector configuration , optimization , rad. stability, and cost**

Scheme being optimized by simulations

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

Contents lists available at ScienceDirect

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]

[a] Institute Laue-Langevin, 6 rue Jules Horowitz, F-38042 Grenoble, France
[b] Joint Institute for Nuclear Research, 141980 Dubna, Russia
[c] LPSC, UJF-CNRS/IN2P3-INPG, 53 rue des Martyrs, F-38026 Grenoble, France

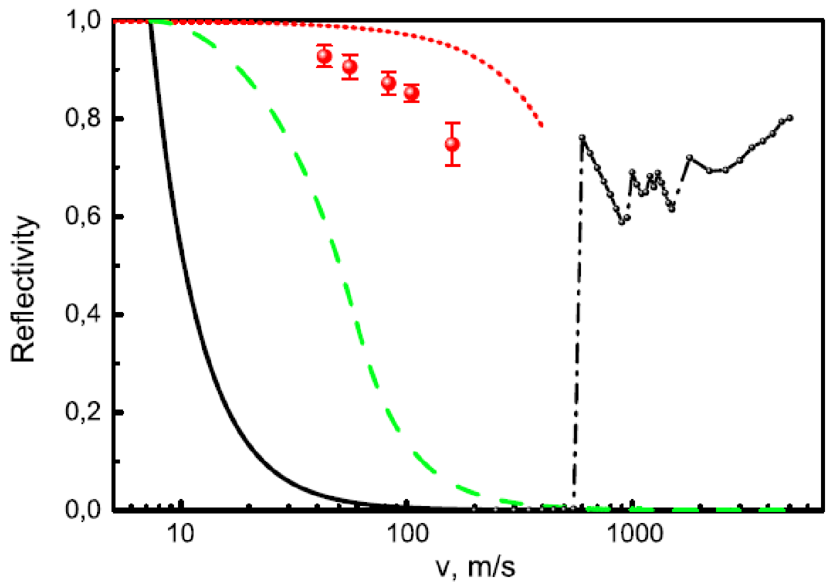
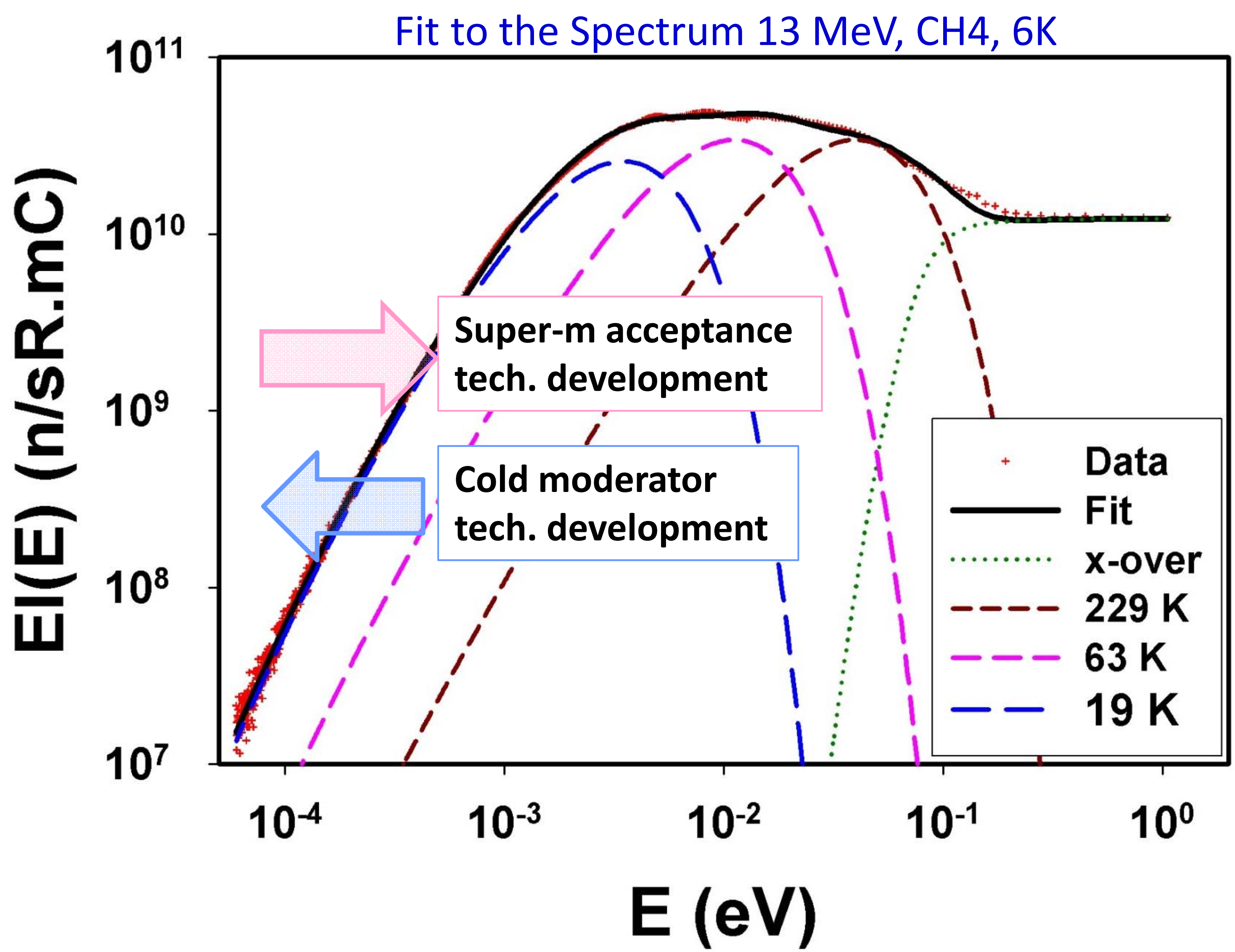



**Fig. 9.** The elastic reflection probability for isotropic neutron flux is shown as a function of the neutron velocity for various carbon-based reflectors: (1) Diamond-like coating (DLC) (thin solid line), (2) The best supermirror [16] (dashed line), (3) Hydrogen-free ultradiamond [15] powder with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

# Comparison with other Sources for N-Nbar Search

- Research reactors (HFIR/ORNL 85 MW; ILL/France 58 MW; NIST 20 MW, etc.) are generally not available for HEP experiments. If would be available the advantage of high flux will be depreciated by inability of allowed source modifications (NRC etc.) Possible sensitivity ~ 300 "ILL units" $\times$ years.

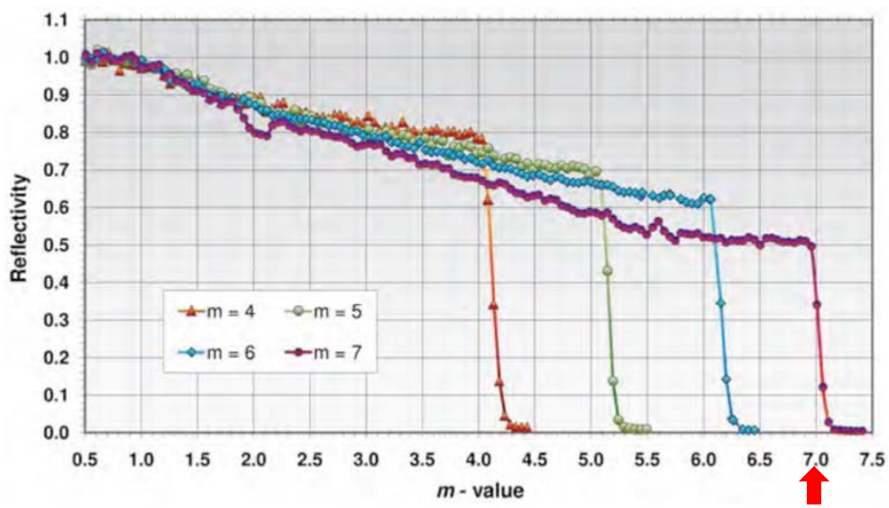
- Spallation sources: SNS 1 MW, ESS 5 MW are multi-user facility with small fraction of total flux, real estate, and time. Spallation process produce factor of ~ 5 more neutrons per MW. Possible sensitivity ~ 50 "ILL units" $\times$ years.

- Dedicated facility like Spallation Target in Project X ~ 1 MW allows optimization of the source configuration, large acceptance due to close location of experiment, $4\pi$ cold neutron concentration, vertical layout of experiment. These features are unique for cold neutron sources and might be advantageous for other future cold and ultra-cold neutron experiments. E.g. n-EDM search can benefit from high cold neutron flux optimized for N-Nbar search. Possible horizontal baseline NNbarX sensitivity ~ 450 "ILL units"

# End

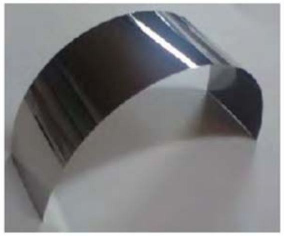
# Super-mirrors material for large elliptical focusing reflector

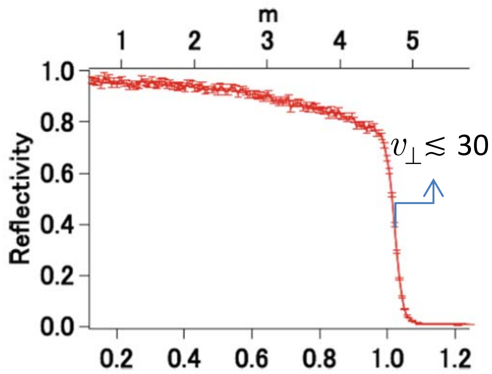
Commercial products of Swiss Neutronics




$v_\perp \lesssim$ 50 m/s

Progress in neutron super-mirrors



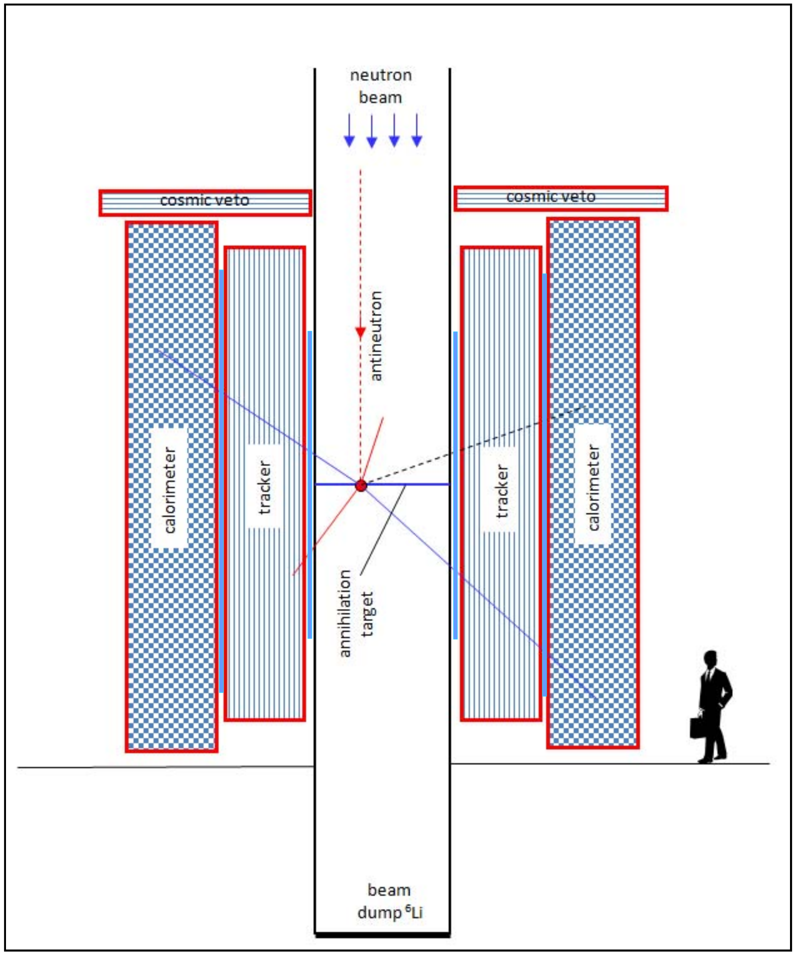



$v_\perp \lesssim$ 30 m/s

**no substrate (radiation hardness expected)**

(H. Shimizu, 2012)

# Annihilation Detector




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

- Use concepts of backgroundless ILL detector;
- Can be Horizontal or Vertical;
- 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,$\gamma$) emission.
- R&D on detector configuration and cost optimization by NCSU, IU, and India together with FNAL