Neutron-Antineutron Oscillations and Small Neutron Sources

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what are neutron-antineutron oscillations?
why are they interesting? (B violation for cosmology)
Possible experimental arrangements (cold n, UCN,…)

Any experiment will require an especially close coupling of the beam to the source with nonstandard moderator or optics. A candidate development project for a “small” neutron source

Thanks for slides/calculations to: Rabi Mohapathra,
Yuri Kamyshkov, Geoff Greene, Hiro Shimizu, Ed Kearns, Albert Young

Cold neutron source “proto-collaboration” for nnbar

UT Physics: Geoff Greene, Tom Handler, Yuri Kamyshkov;
UT NE: Larry Townsend, Larry Heilbronn, Art Ruggles;
ORNL/SNS: Tony Gabriel, Phil Ferguson;
Students: Chris Tate, Davis Cooper

+ A. Young (NCSU), M. Snow, D. Baxter (Indiana), H. Shimizu (KEK), VECC and PRL (India)

VECC = Variable Energy Cyclotron Centre in Kolkata, India
PRL = Physics Research Laboratory in Ahmedabad, India

Plan: to collaborate with interested parties (FNAL for Project X, VECC/PRL(India), …) to produce a conceptual design of a slow neutron source for nnbar

Project X

DAEδALUS

NANO

HOMESTAKE DUSEL

nnbar

$n \leftrightarrow \bar{n}$ transitions — “too crazy”?

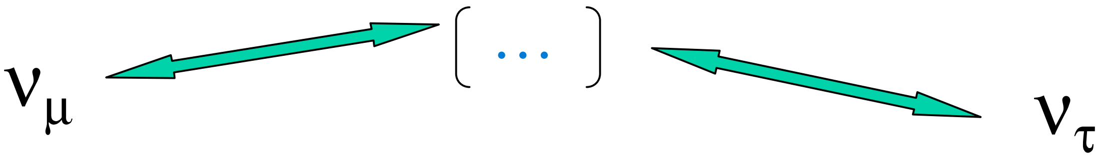
But neutral meson $|q\bar{q}\rangle$ states oscillate -

K^0, B^0

2nd order weak

$\bar{K}^0, \bar{B}^0$

And neutral fermions can oscillate too -

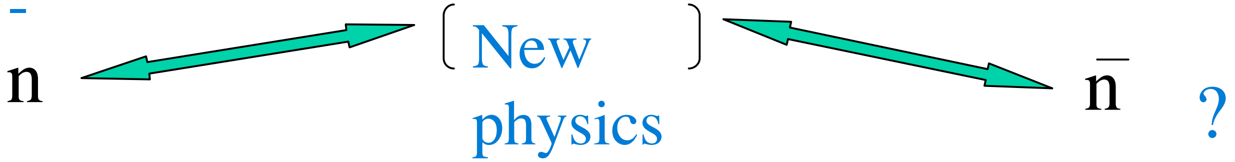


ν_μ

…

ν_τ

So why not -



n

New physics

$\bar{n}$

?

Neutron is a long-lived neutral particle ($q_n < 10^{-21}e$) and can oscillate into an antineutron. No oscillations have been seen yet.

Need interaction beyond the Standard Model that violates Baryon number (B) by 2 units. No direct observation of B violation yet anywhere. Should we expect B violation?

B,L are Probably Not Conserved

No evidence that either B or L is locally conserved like Q: where is the macroscopic B/L force? (not seen in equivalence principle tests).

Baryon Asymmetry of Universe (BAU) is not zero. If B(t=after inflation)<<BAU (otherwise inflation is destroyed, Dolgov/Zeldovich), we need B violation.

Both B and L conservation are “accidental” global symmetries: given $SU(3)\otimes SU(2)\otimes U(1)$ gauge theory and matter content, no dimension-4 term in Standard Model Lagrangian violates B or L in perturbation theory.

Nonperturbative EW gauge field fluctuations (sphalerons) present in SM VIOLATE B, L, B+L, but conserve B-L. Active at electroweak phase transition (E~1000 TeV , ~x100 LHC scale). Erases earlier B, but can convert L into B (“leptogenesis”)

Could B violation happen below EW phase transition? Yes (“post-sphaeleron baryogenesis”, Babu/Mohapathra). nnbar limit improvement in combination with LHC data can rule this out!

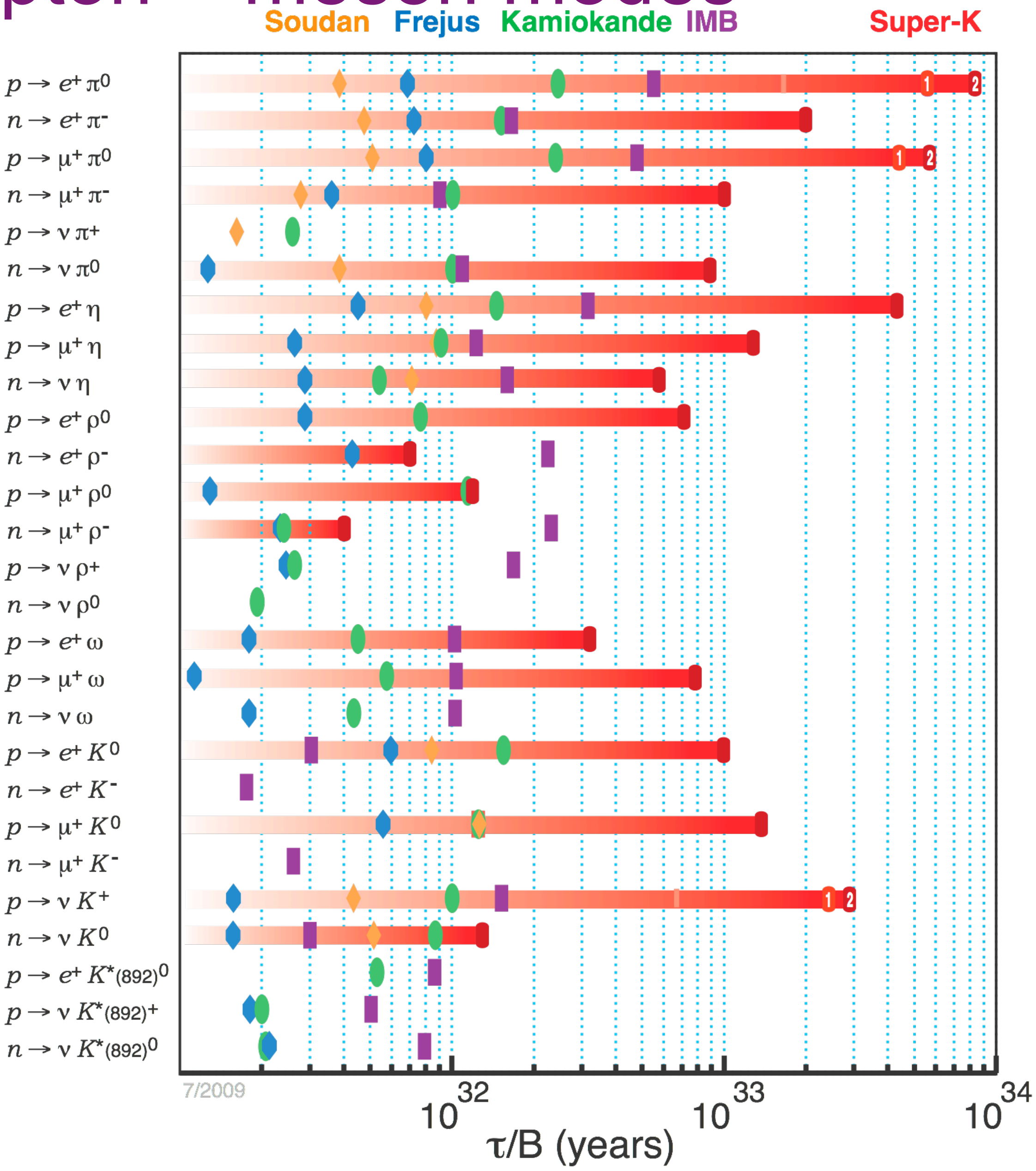
How to search for B violation experimentally? Two main methods are (a) proton decay, (b) neutron-antineutron oscillations

Proton Decay: Antilepton + meson modes

over last 3 decades the experimental sensitivity was increased by many orders of magnitude

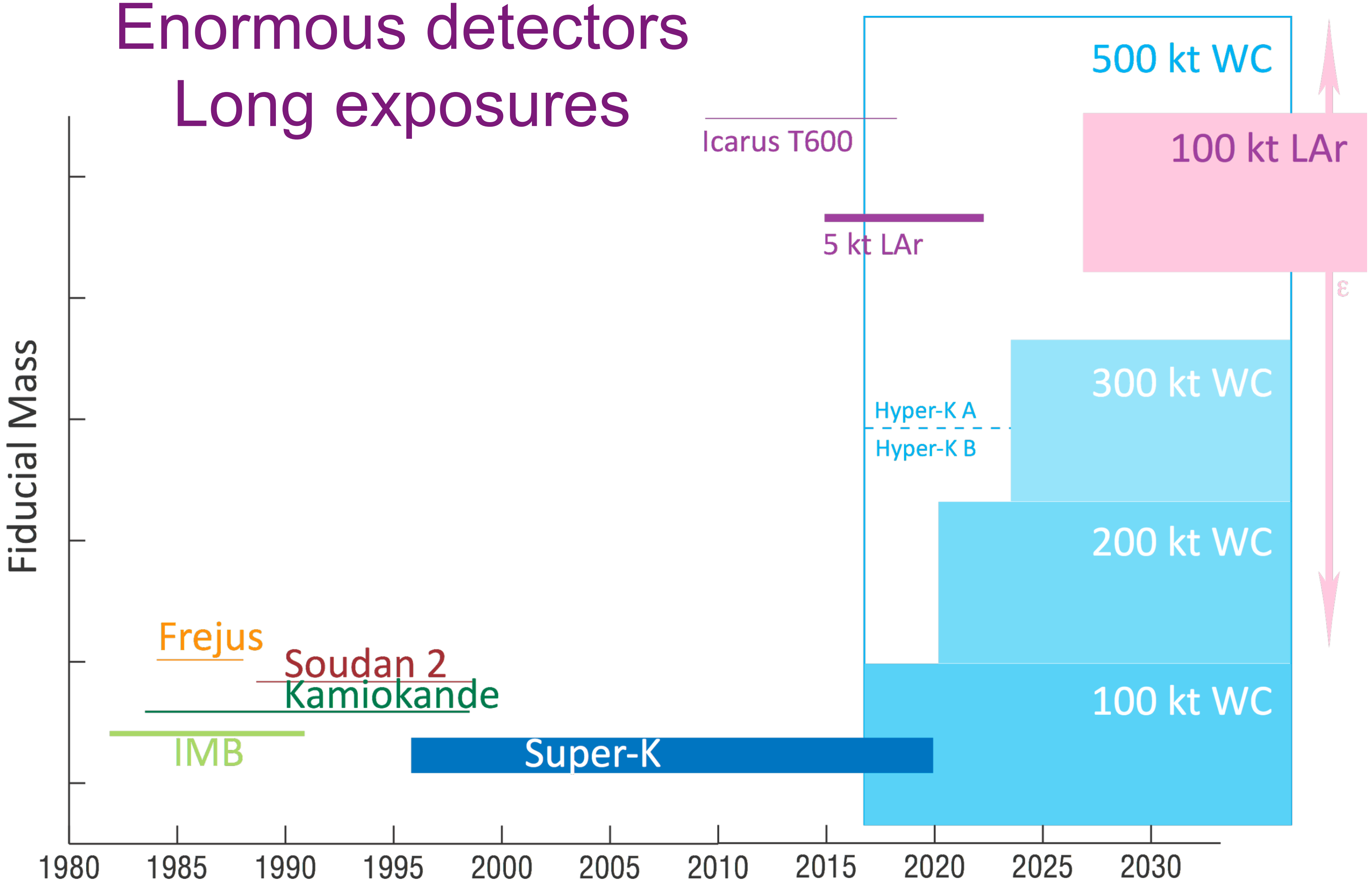
Decay modes with conservation of (B–L) were a major focus: more difficult (B–L) violating modes contaminated with background were studied by Fréjus and IMB3

For background dominated modes the lifetime limits can be statistically improved with longer running time/larger detectors



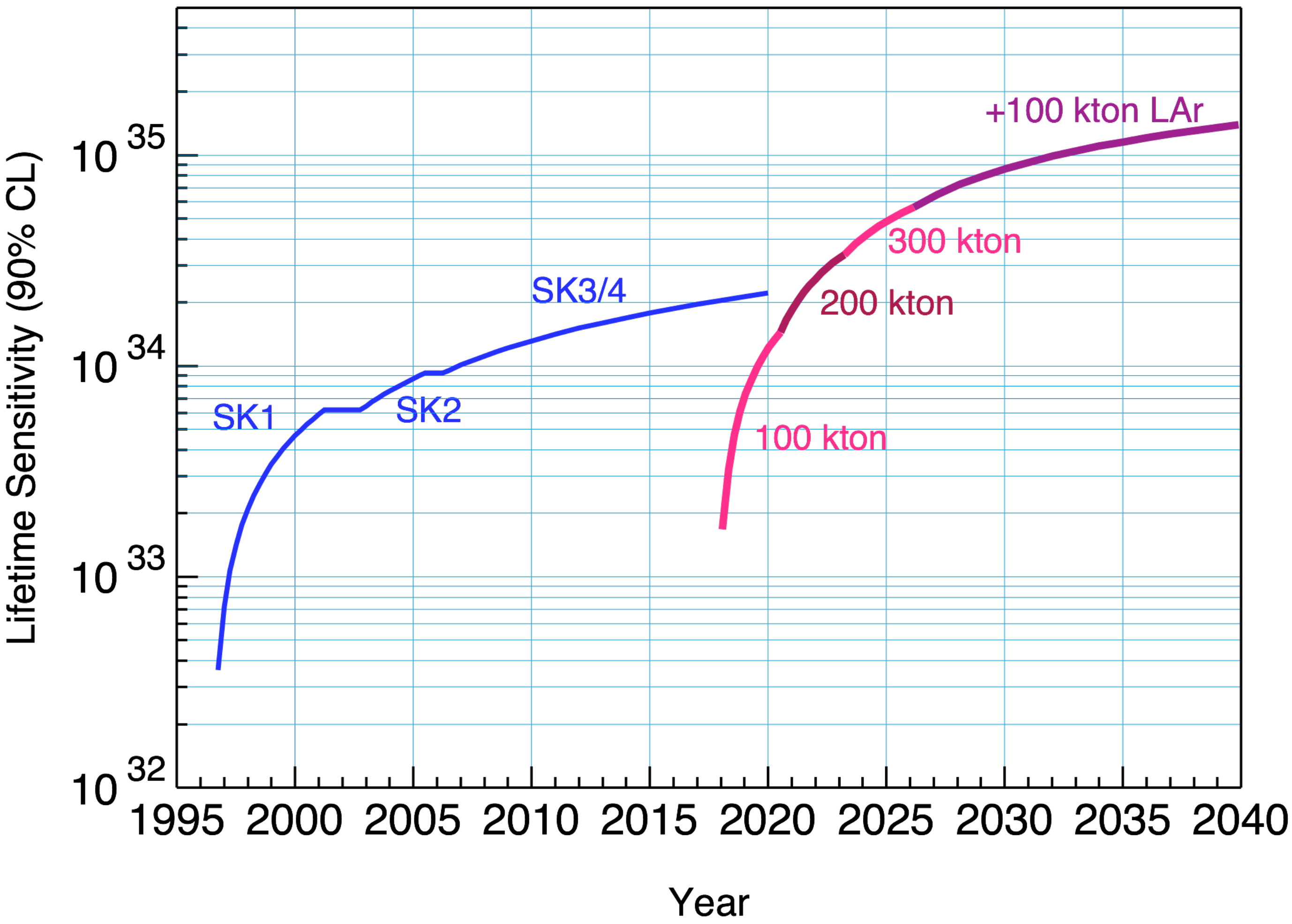
Ph.D. thesis H. Nishino, U. Tokyo (2009)

Enormous detectors
Long exposures



E. Kearns

$p \rightarrow e^+\pi^0$



Efficiency = 0.45
BG = 0.2 evts/100 kty
Nobs = Nbg

E. Kearns

Neutron-Antineutron Oscillations: Formalism

α≠0 allows oscillations

$$\Psi = \begin{pmatrix} n \\ \bar{n} \end{pmatrix}$$ n-nbar state vector

$$\mathrm{H} = \begin{pmatrix} E_n & \alpha \\ \alpha & E_{\bar{n}} \end{pmatrix}$$ Hamiltonian of n-nbar system

$$E_n = m_n + \frac{p^2}{2m_n} + U_n \quad ; \quad E_{\bar{n}} = m_{\bar{n}} + \frac{p^2}{2m_{\bar{n}}} + U_{\bar{n}}$$

Note :

- α real (assuming T)
- $m_n = m_{\bar{n}}$ (assuming CPT)
- $U_n \neq U_{\bar{n}}$ in matter and in external B [$\mu(\bar{n}) = -\mu(n)$ from CPT]

Neutron-Antineutron transition probability

For $H = \begin{pmatrix} E+V & \alpha \\ \alpha & E-V \end{pmatrix}$ $\quad P_{n\to\bar{n}}(t) = \frac{\alpha^2}{\alpha^2+V^2} \times \sin^2\left[\frac{\sqrt{\alpha^2+V^2}}{\hbar} t\right]$

where V is the potential difference for neutron and anti-neutron.

Present limit on $\alpha \le 10^{-23} eV$

Contributions to V:

<Vmatter>~100 neV, proportional to density

<Vmag>=μB, ~60 neV/Tesla; B~10nT-> Vmag~10^{-15} eV

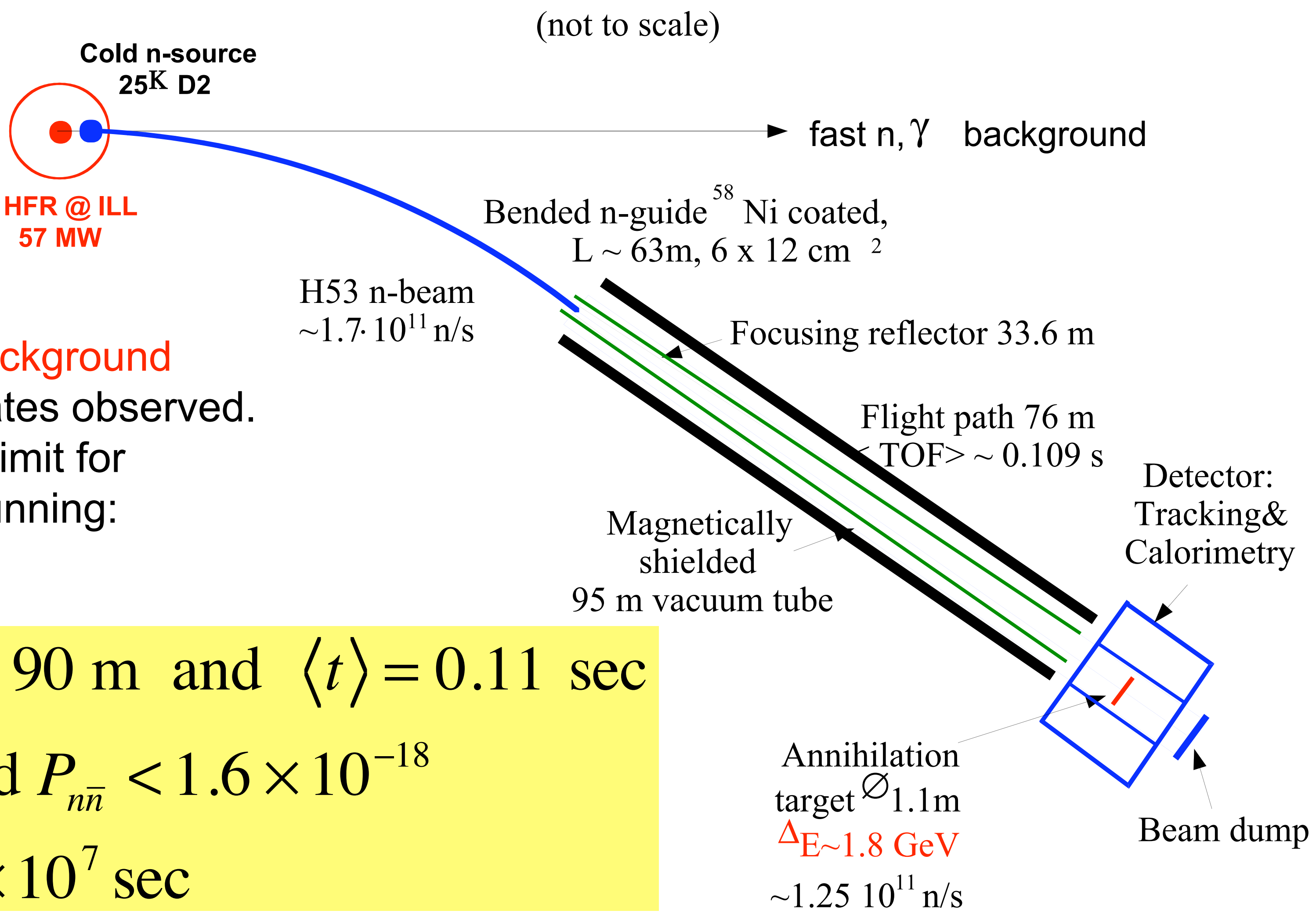
<Vmatter> , <Vmag> both >>α

For $\left[\frac{\sqrt{\alpha^2+V^2}}{\hbar} t\right] << 1$ ("quasifree condition") $\quad P_{n\to\bar{n}} = \left(\frac{\alpha}{\hbar} \times t\right)^2 = \left(\frac{t}{\tau_{n\bar{n}}}\right)^2$

Figure of merit= NT^2 N=#neutrons, T="quasifree" observation time

Experiment developed at small source (Pavia), then later to ILL

Heidelberg - ILL - Padova - Pavia $n\bar{n}$ search experiment at Grenoble 89-91



No GeV background

No candidates observed.
Measured limit for
a year of running:

$$\text{with L} \sim 90 \text{ m and } \langle t \rangle = 0.11 \text{ sec}$$

$$\text{measured } P_{n\bar{n}} < 1.6 \times 10^{-18}$$

$$\tau > 8.6 \times 10^{7} \text{ sec}$$

Baldo-Ceolin M. et al., Z. Phys. C63,409 (1994).

Quasifree Condition: B Shielding and Vacuum

$\mu Bt<<\hbar$ ILL achieved |B|<10 nT over 1m diameter, 80 m beam,one layer 1mm shield in SS vacuum tank, 1% reduction in oscillation efficiency (Bitter et al, NIM A309, 521 (1991). For new experiment need |B|<~1 nT

If nnbar candidate signal seen, easy to "turn it off" by increasing B

$V_{opt}t<<\hbar$:

Need vacuum to eliminate neutron-antineutron optical potential difference.

$P<10^{-5}$ Pa is good enough, much less stringent than LIGO

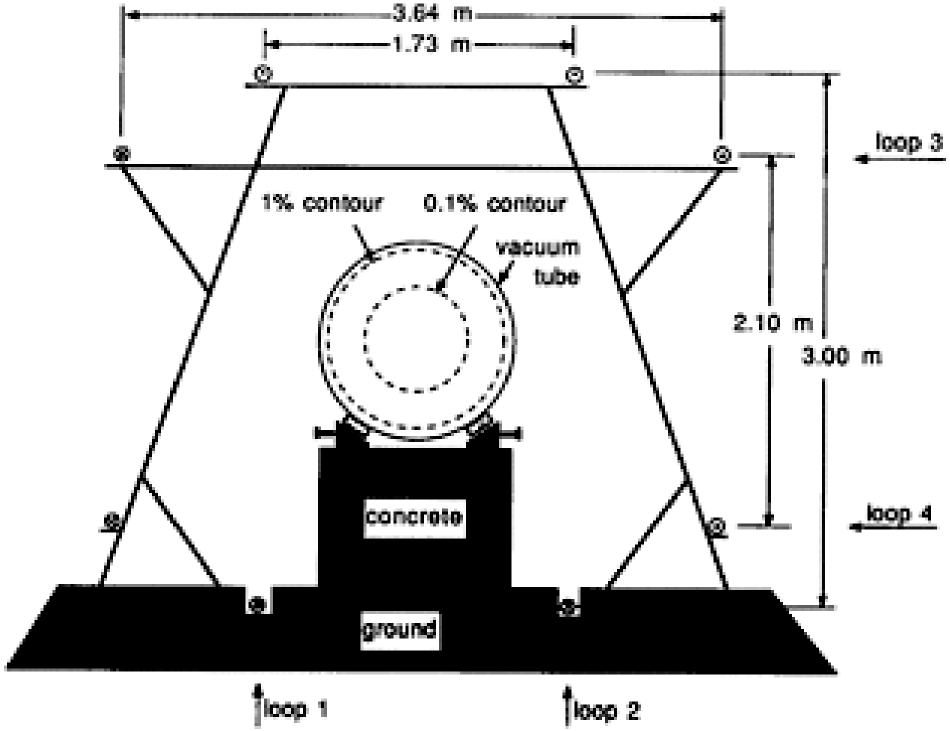
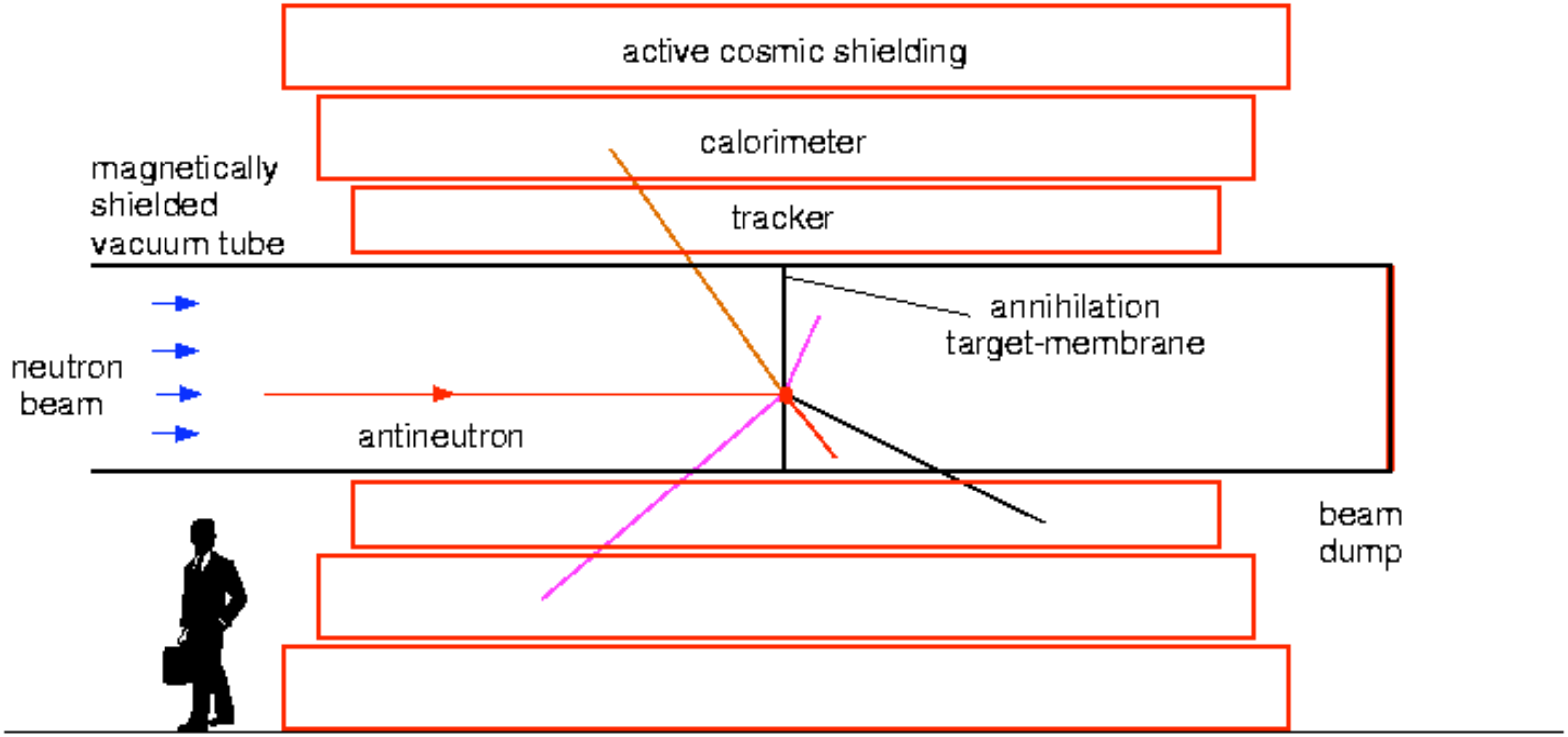


Fig. 10. The transverse field compensation system. Loops 1 and 2 are under 49 A current and compensate the horizontal field component; loops 3 and 4 are under 120 A current and compensate the vertical field component.

The conceptual scheme of antineutron detector



$$\boxed{\bar{n} + A \rightarrow \langle 5 \rangle \; pions \quad (1.8\ \text{GeV})}$$

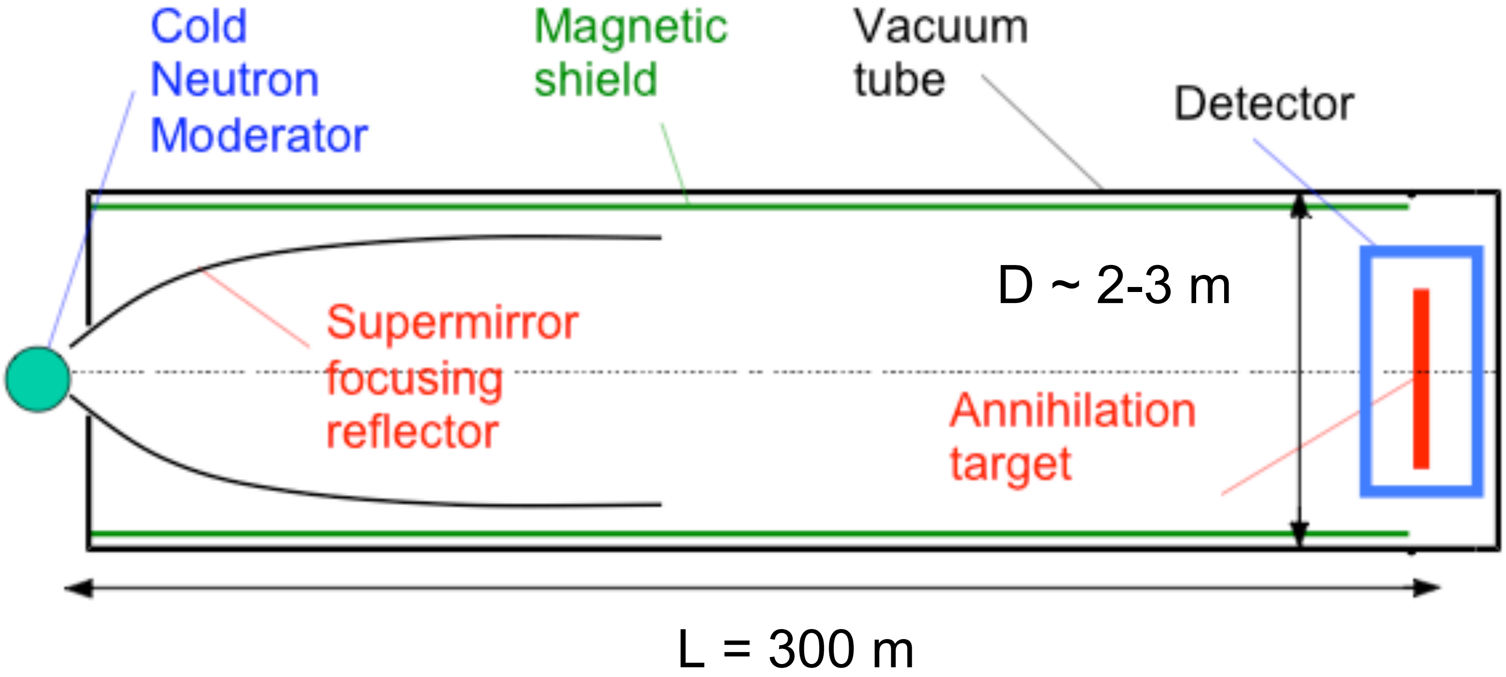
Annihilation target: ~100μ thick Carbon film

$\sigma_{\text{annihilation}} \sim 4$ Kb $\qquad \sigma_{\text{nC capture}} \sim 4$ mb

Better Cold Neutron Experiment (Horizontal beam

- need cold neutrons from high flux source, access of neutron focusing reflector to cold source, free flight path of ~200-300m

Improvement on ILL experiment by factor of ~1000 in transition probability is possible (but expensive) with existing n optics technology and sources



Supermirror Neutron Optics: Elliptical Focusing Guides

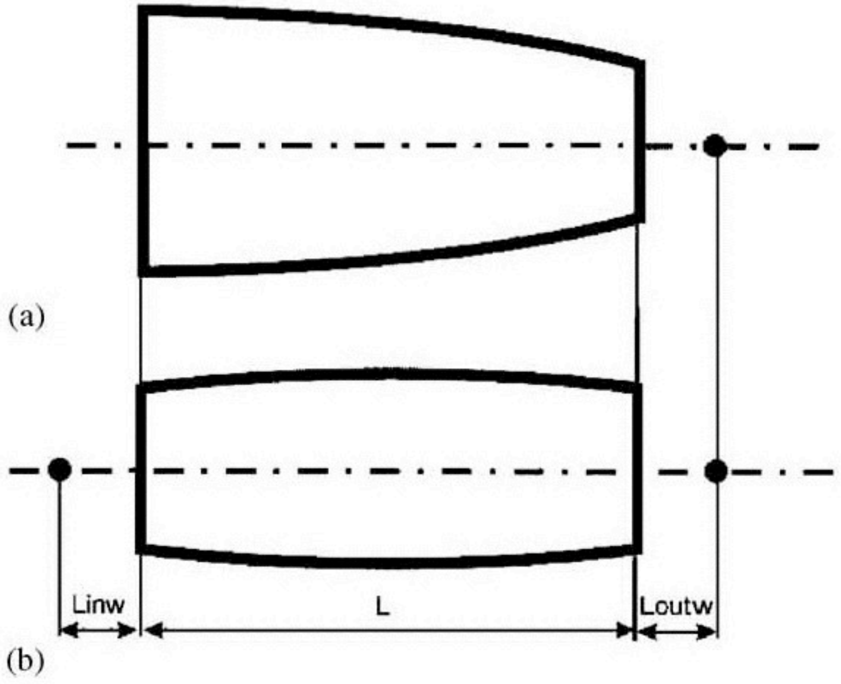


Fig. 1. Parameters for the (a) parabolic and (b) elliptic focusing guide in the x-plane.

Muhlbauer et. al., Physica B 385, 1247 (2006).

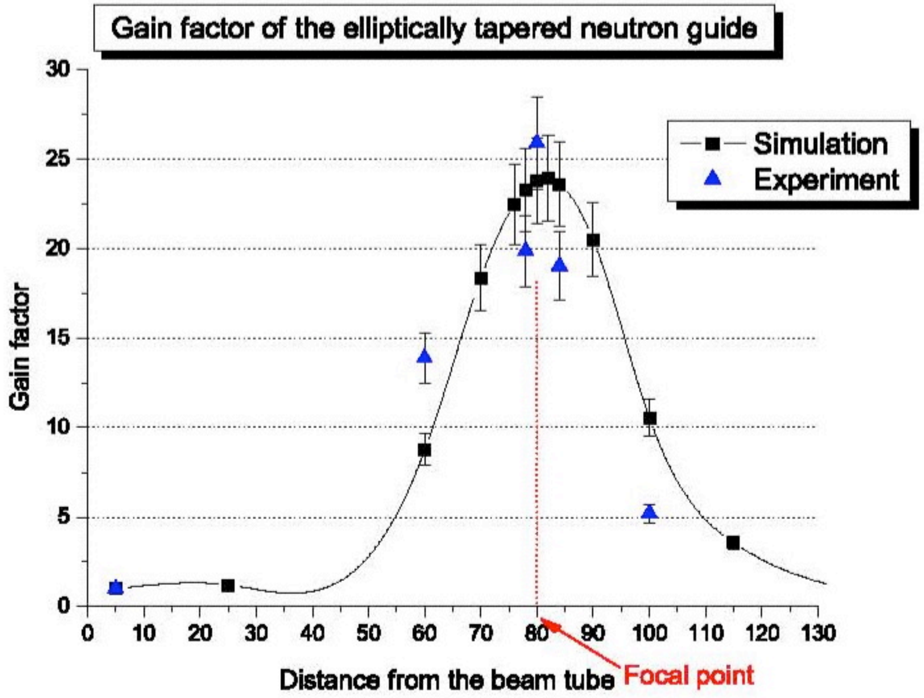
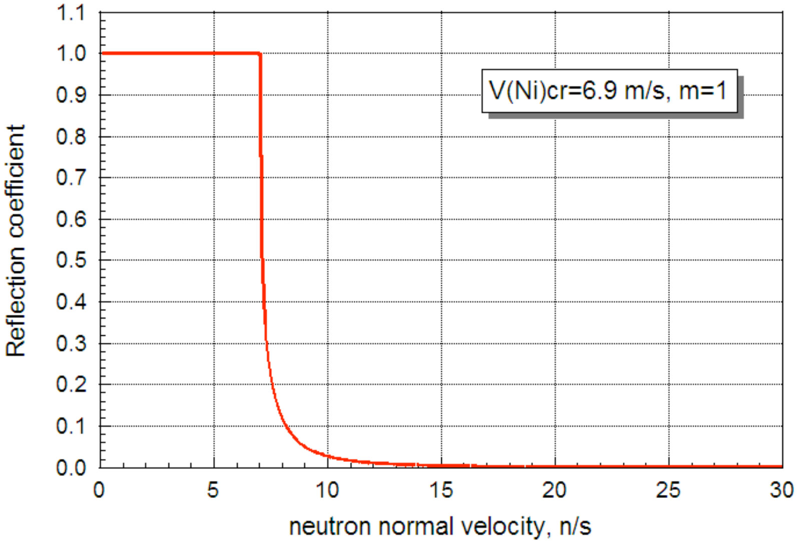


Fig. 3. Neutron intensity as measured and calculated versus distance from the exit of the guide. Clearly seen is the point of maximum intensity near $F_2 = 80\,\text{mm}$.

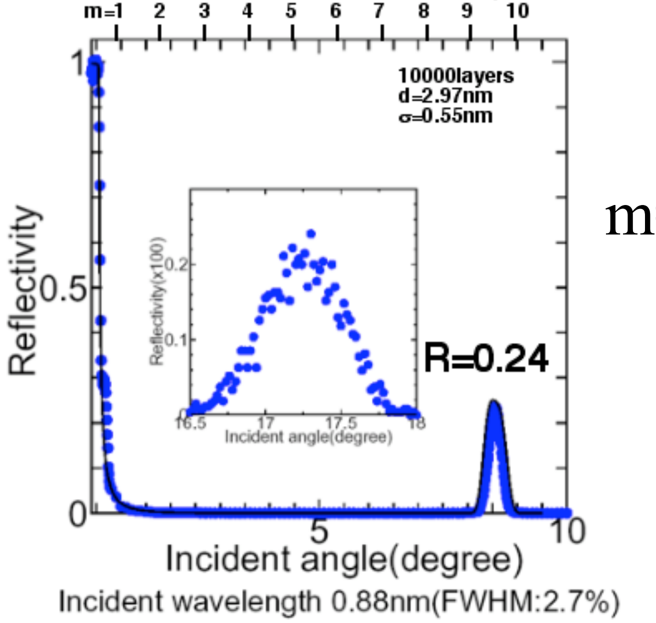
Under development for neutron scattering spectrometers

Can be used to increase fraction of neutrons delivered from cold source (cold source at one focus, nbar detector at other focus)

Supermirror Neutron Optics: Higher m and reflectivity

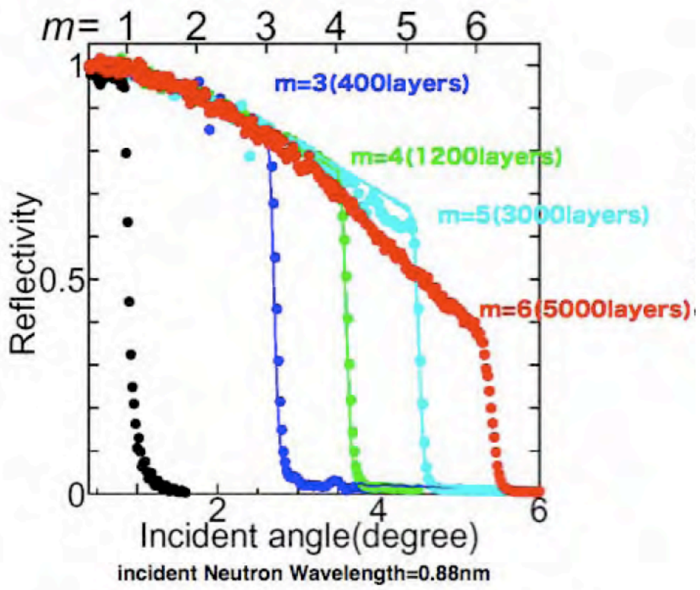


M.Hino, HAMON Vol.15 No.1 (2005) 31. (Japanese)



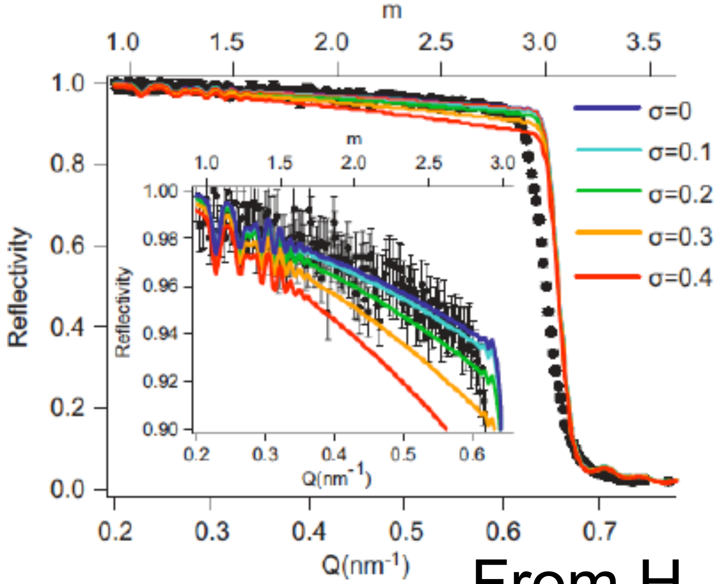
m=10!

H. Shimizu, KEK/Japan



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

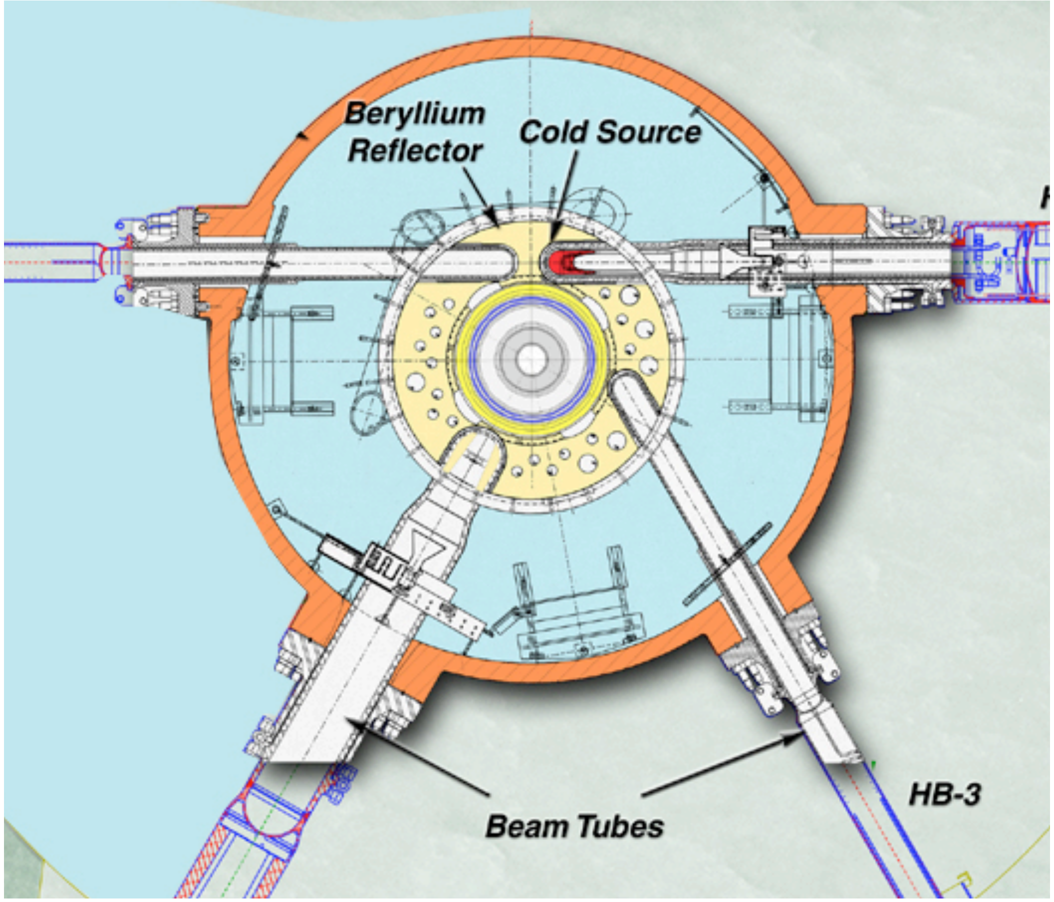
M.Hino, Nucl. Instrum. Methods A600 (2009) 207.



From H. Shimizu

New Experiment at Existing Research Reactor?

- need close access to cold source to fully illuminate elliptical reflector
- Requests to all >20 MW research reactors with cold neutron sources
- Can a reactor be found? Not yet…



Cutaway view HFIR reactor at ORNL

Supermirror Neutron Optics: Future Possibilities

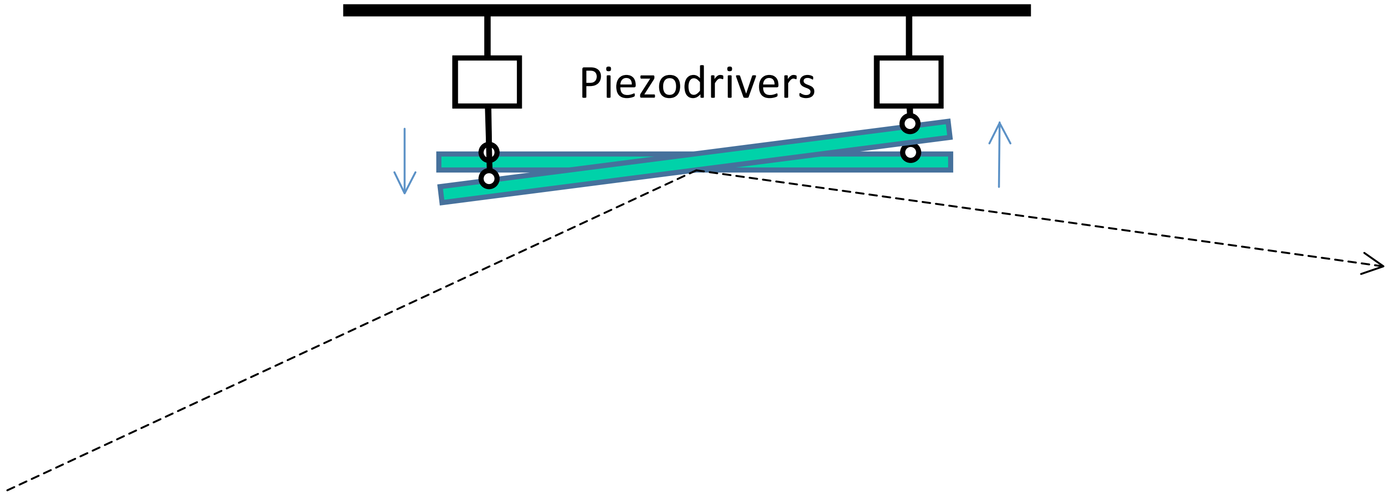
"In the future one may consider varying the shape of the guides actively by means of piezo actuators. If used at pulsed sources, beam size and therefore the divergence for each wavelength during a neutron pulse can be optimized. This corresponds to a kind of active phase space transformation that will allow the circumvention of Liouville's theorem. The combination of fast mechanical actuators with supermirror technology may become useful for active phase space transformation."

P.Boni, NIM A586, 1 (2008).

One could design the experiment to be able to take advantage of such advances in active neutron optics technology through modification of the focusing mirror

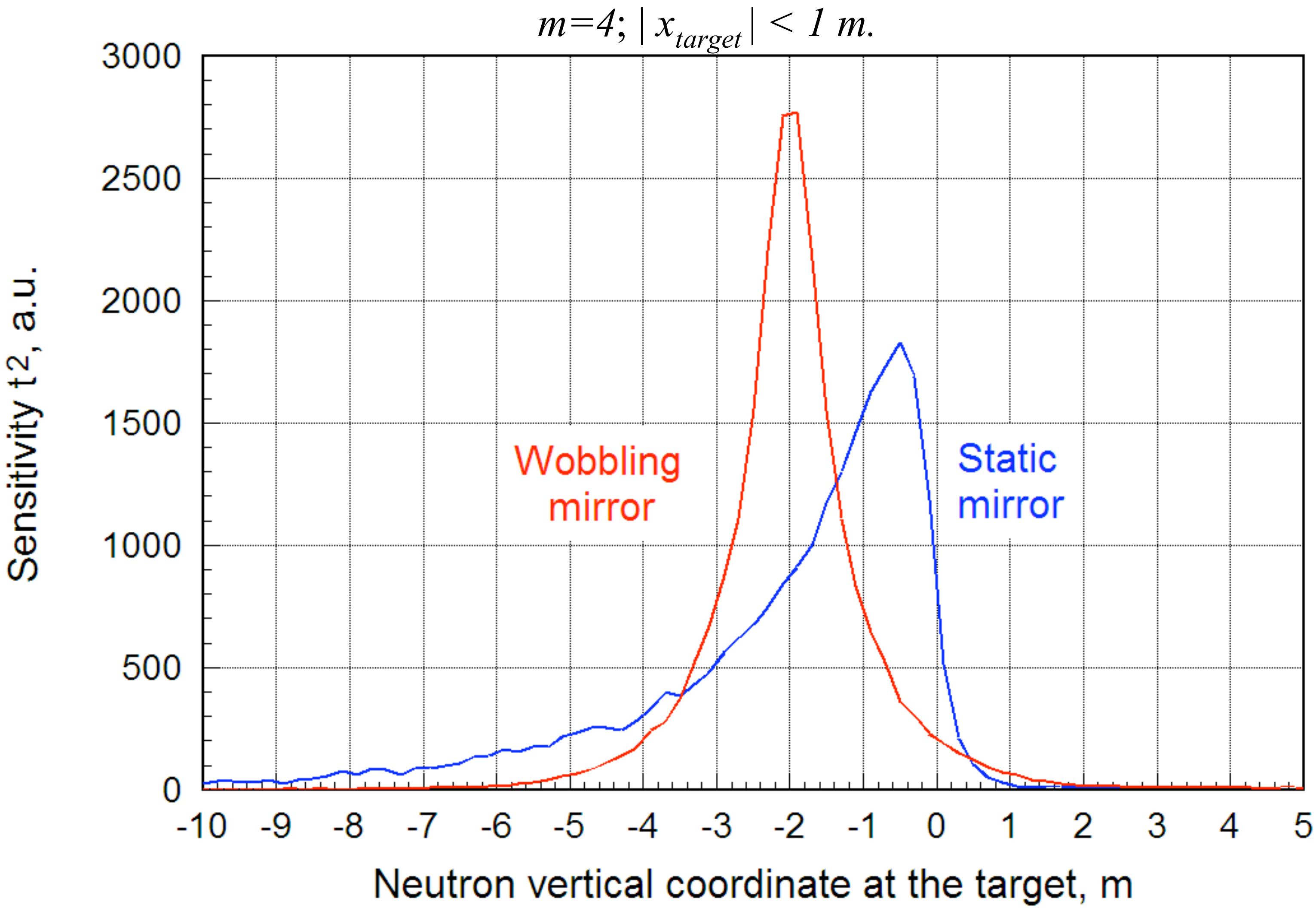
Wobbling supermirrors

At a pulsed neutron source, neutrons of a given speed reach the mirror at a known time. We can therefore imagine an array of mirrors tiling an ellipse and phased to the source to condition the beam



This tilting can be used to counteract the defocusing of the beam from gravity, thereby reducing the beam/detector size and therefore reduce the cost of the experiment.

N·T^2 distribution vs height in the target plane 200m from source



Radius of beam is smaller by ~factor of 2

->cost of experiment is smaller (scales generically as the area)

Possible for ~MW-class sources (ESS?)

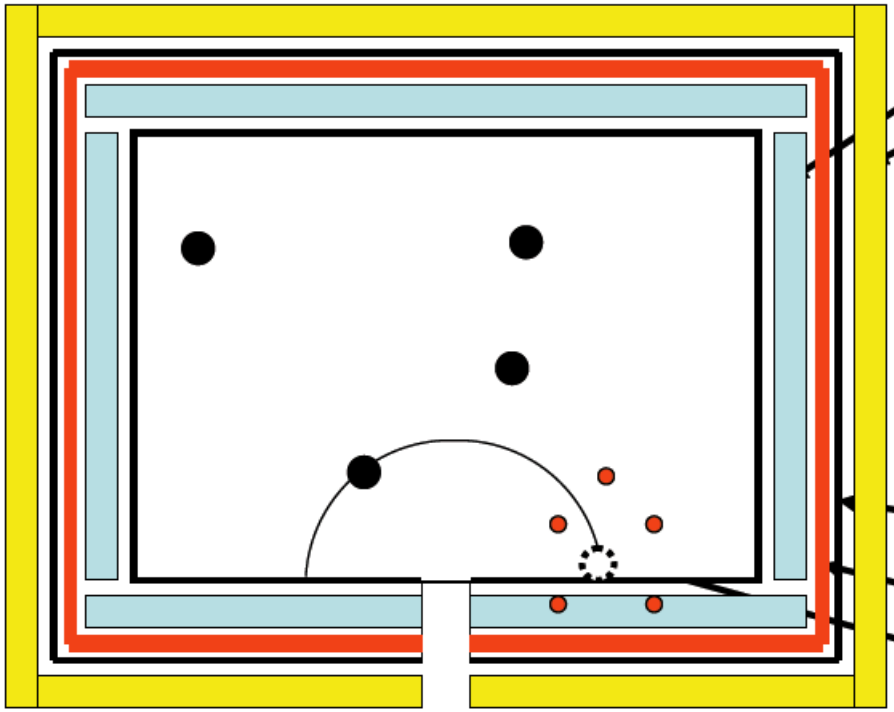
Possible UCN sources

- ILL: $3x10^6$ UCN/s available now

- **Potentially competitive SD_2 sources**:
  - PULSTAR reactor w/ 3.5 MW upgrade: $1.2x10^7$ UCN/s
  - PSI (10-20 kW spallation target– 1 MW peak): $5x10^9$ in close-coupled storage volume, every 4 to 8 minutes; operation in 2011
  - FRM II reactor (24 MW): perhaps 4×10^7 UCN/s; begin operation roughly 2012 (project funded 2007)

- **LHe superthermal sources**
  - TRIUMF (5-10 kW spallation target; 50 kW peak): $5x10^7$ UCN/s
  - Dedicated 1.9K source (200 kW): $3.3x10^8$ UCN/s

NNbar with UCN



hadron tracking and calorimeter

outer detector and muon veto

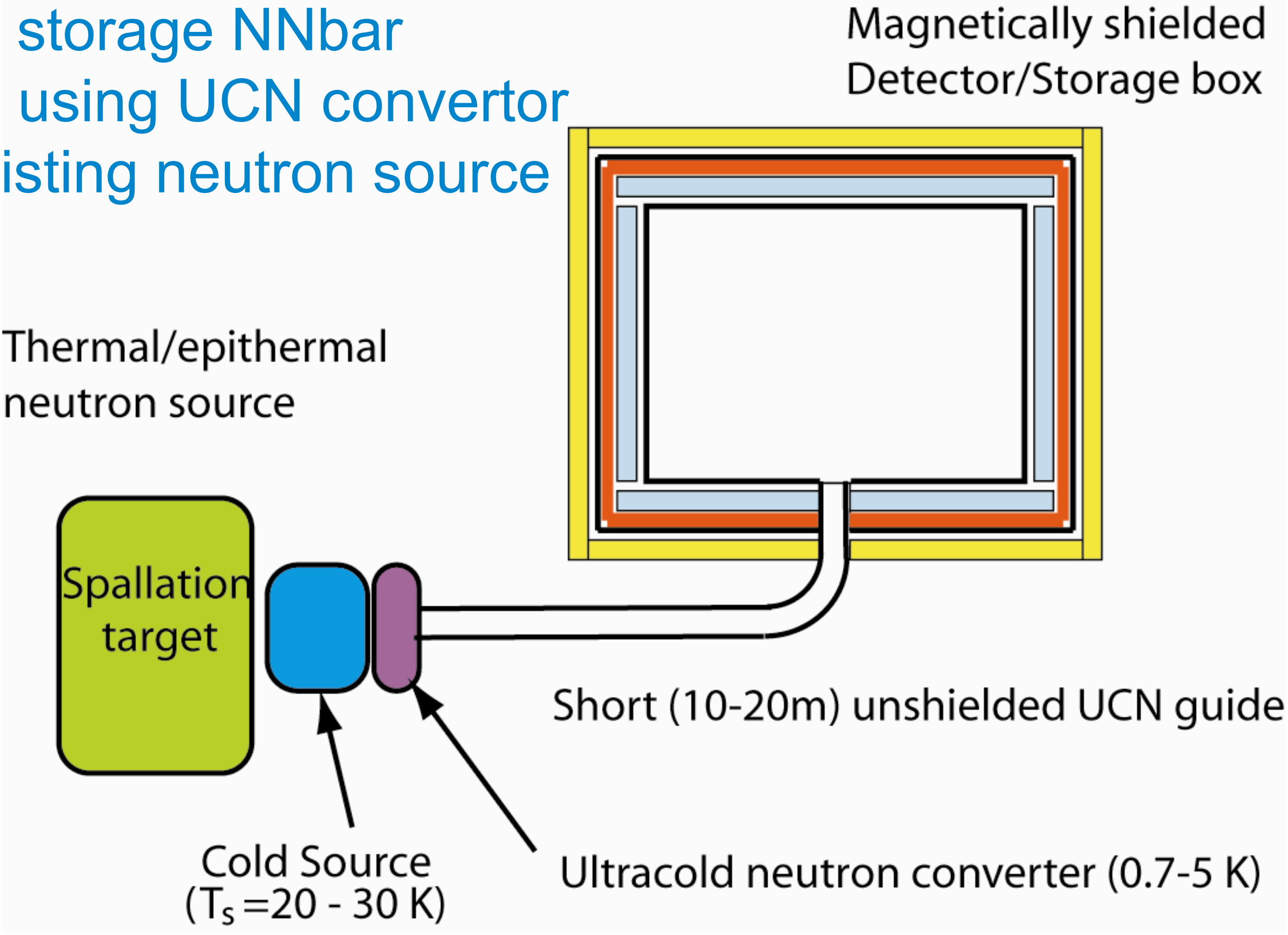
vacuum vessel

magnetic shielding

$\bar{n}$ amplitude sampled when UCN hits surface

Box filled with UCN gas…many samples/neutron
longer average flight times (~1/3 sec)
large neutron current required

UCN storage NNbar expt. using UCN convertor at existing neutron source



Magnetically shielded
Detector/Storage box

Thermal/epithermal
neutron source

Spallation
target

Short (10-20m) unshielded UCN guide

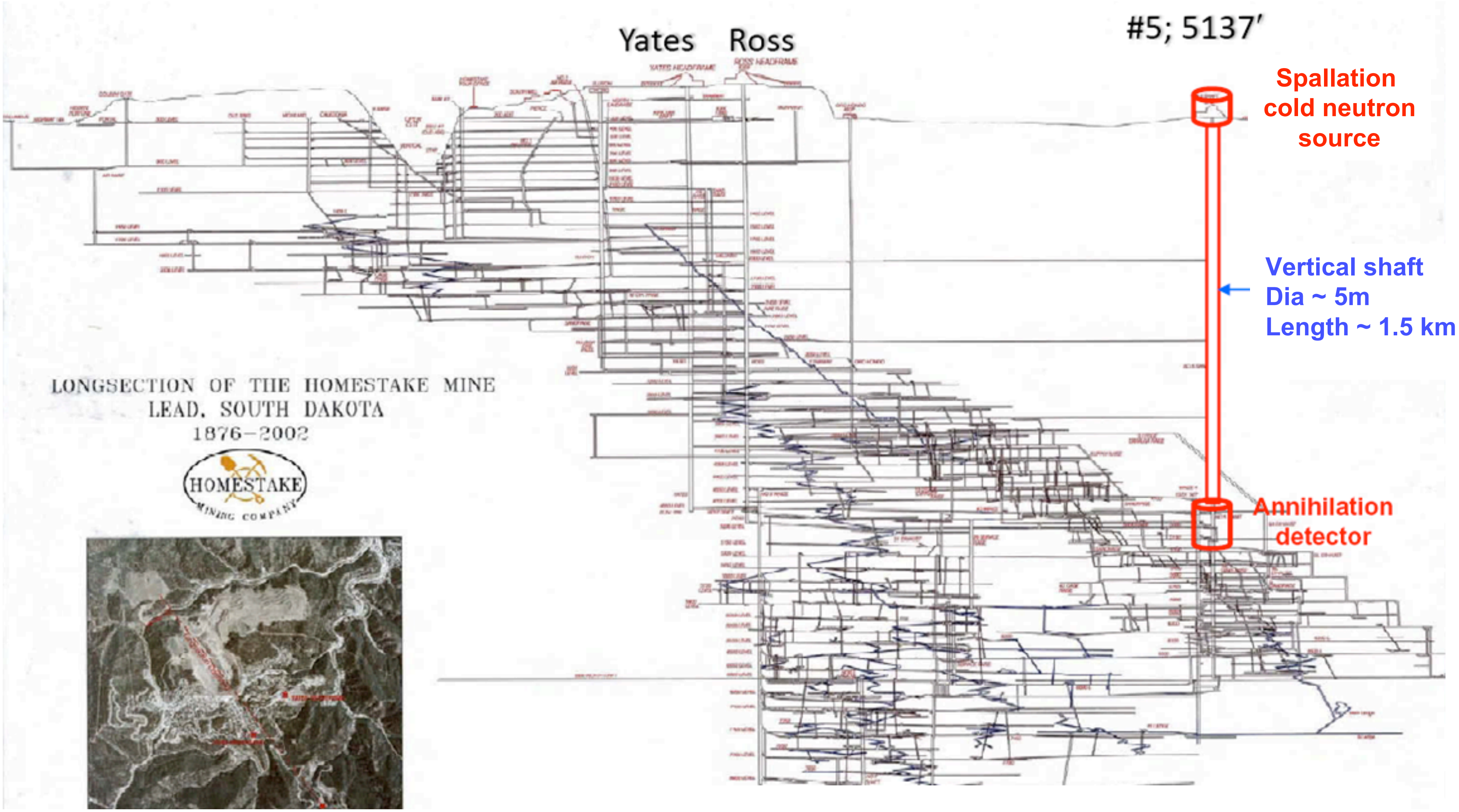
Cold Source
(T_S =20 - 30 K)

Ultracold neutron converter (0.7-5 K)

Spallation neutrons are produced in 4π but used for UCN conversion only in a small fraction of a solid angle.
In best A. Young’s (NCSU) scenario with a dedicated 1.9K, 200 kW source: 3.3310^{8} ucn/s can be made available in the transport tube.

Albert Young/NCSU

Our NNbar proposal for DUSEL with vertical layout



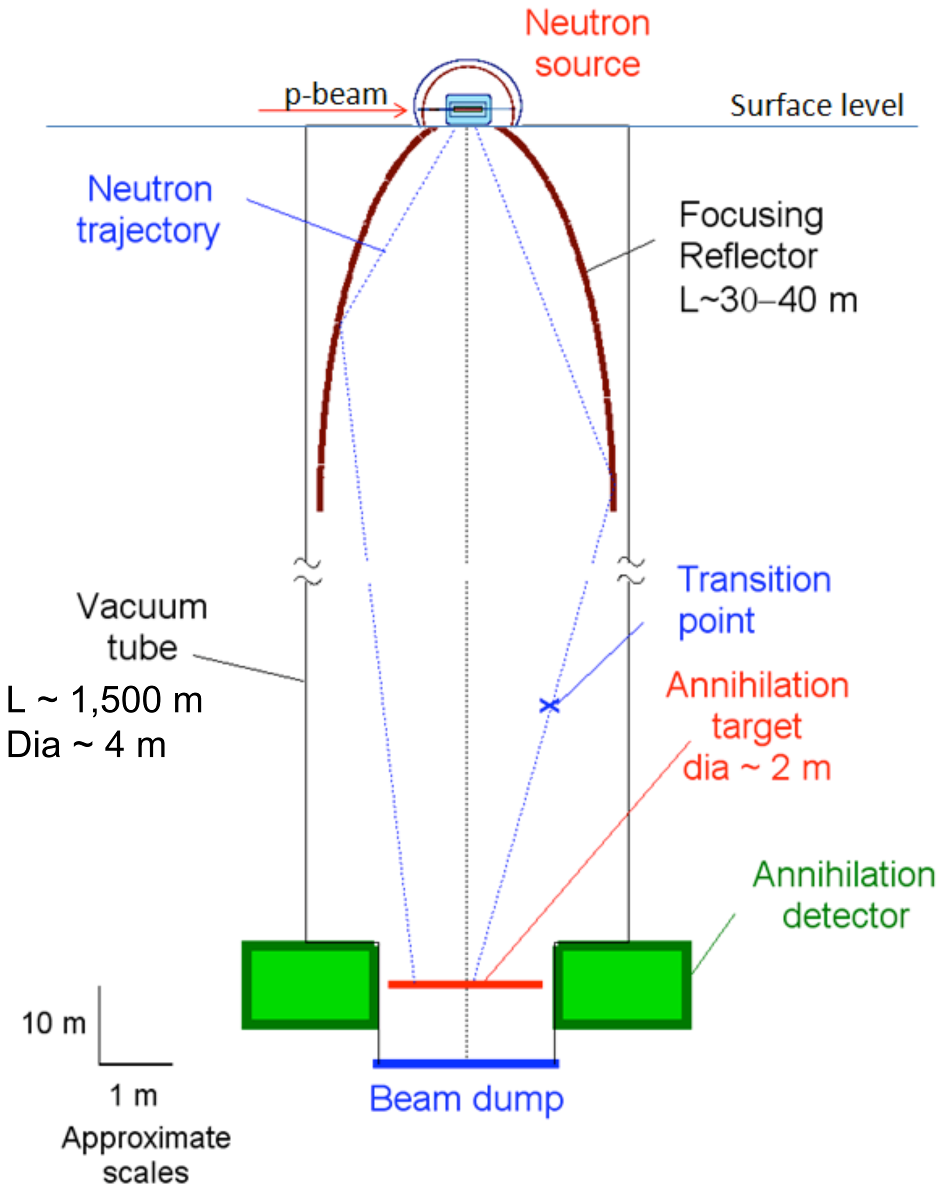
Spallation
cold neutron
source

Vertical shaft
Dia ~ 5m
Length ~ 1.5 km

Annihilation
detector

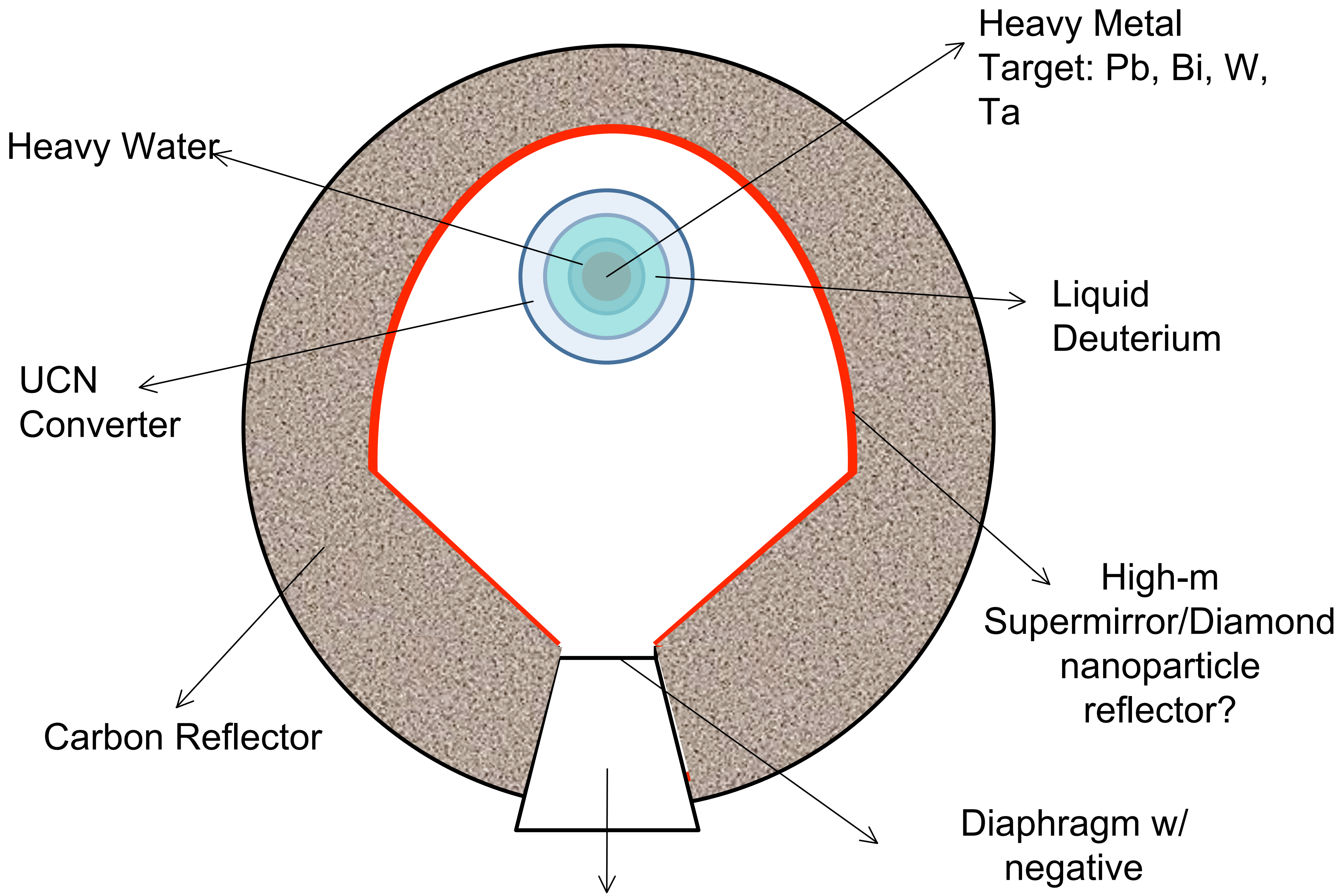
Shooting slow neutrons down a mine shaft

Schematic view of the vertical NNbar experiment with cold neutrons from a spallation neutron source provided by dedicated high-current accelerator. e.g. by a CW cyclotron 0.2 – 1 MW advocated by DAEδALUS Collaboration



Target schematic with cold/VCN/UCN converter for NNbar

(view along the beam)



Heavy Metal Target: Pb, Bi, W, Ta

Heavy Water

Liquid Deuterium

UCN Converter

High-m Supermirror/Diamond nanoparticle reflector?

Carbon Reflector

Diaphragm w/ negative nuclear potential

Estimated N-Nbar sensitivity improvements for different sources/moderator/reflectors relative to ILL experiment

	HFIR	DUSEL	FNAL/UCN	NANO/UCN
P, MW	85	3.5	0.2	0.2
Layout	horizontal	vertical	vertical	vertical
Distance, m	300	1,000	100	1,000
N [n/s]	8.5×10^{12}	3×10^{11}	3×10^{10}	3×10^{10}
t^2 [s^2]	0.073	2	~10	~182
Nt^2	6.2×10^{11}	6×10^{11}	3×10^{11}	5.5×10^{12}
In ILL units	×400	×400	×200	×4000

How reliable are these estimates one can find only with R&D

We can approach the ~factor of 1000 improvement needed to rule out B violation below the electroweak phase transition

Summary

New physics beyond the SM can be discovered by NNbar search

Improvement in N-Nbar transition probability is a factor of ~1,000 is possible

If discovered:

- n→nbar observation would violate B-L by 2 units, establish a new force of nature, illuminate beyond SM physics, and may help to understand matter-antimatter asymmetry of universe

If NOT discovered:

- will set a new limit on the stability of "normal" matter via antimatter transformation channel corresponding to a lifetime of 10^{35} years
- in combination with LHC results, may eliminate all possibilities for B violation below the electroweak phase transition

Sensitivity of cold neutron experiment for n-nbar transition rate can be improved by factor of ~1000 using existing sources and technology [Combination of improvements in neutron optics technology, longer observation time, and larger-scale experiment]. However any experiment requires a nonstandard coupling to the source. A test of the eventual concept at a small neutron source is highly desirable.