The HIBEAM/NNBAR experiment for the European Spallation Source

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Neutron conversions and B, L violation

- BN, LN accidental SM symmetries at perturbative level
  - B-L is conserved, not B, L separately (sphalerons).
- BNV needed for baryogenesis, $(B\text{-}L)V$ baryogenesis above the electroweak scale.
- $BNV, LNV, (B\text{-}L)V$ generic features of SM extensions
- Need to explore the possible selection rules to high precision:

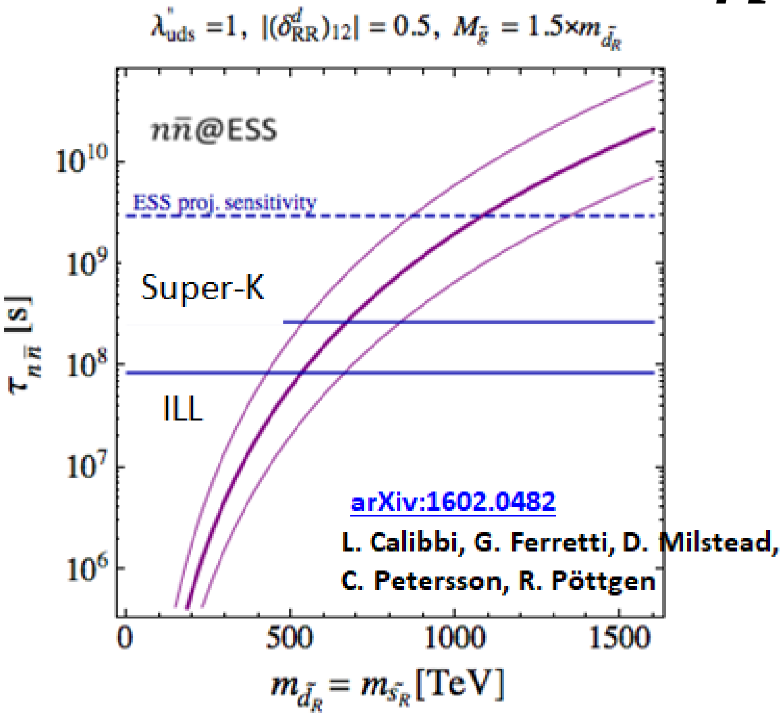
$$\Delta B \neq 0 \ , \ \Delta L = 0, \ \Delta[B - L] \neq 0 \quad (n \to \bar{n}, n')$$

$$\Delta B = 0 \ , \ \Delta L \neq 0, \ \Delta[B - L] \neq 0 \quad (02\nu\beta \text{ decay})$$

$$\Delta L \neq 0 \ , \ \Delta B \neq 0, \ \Delta[B - L] = 0 \quad (p \text{ decay})$$

.....

$n \rightarrow \bar{n}$



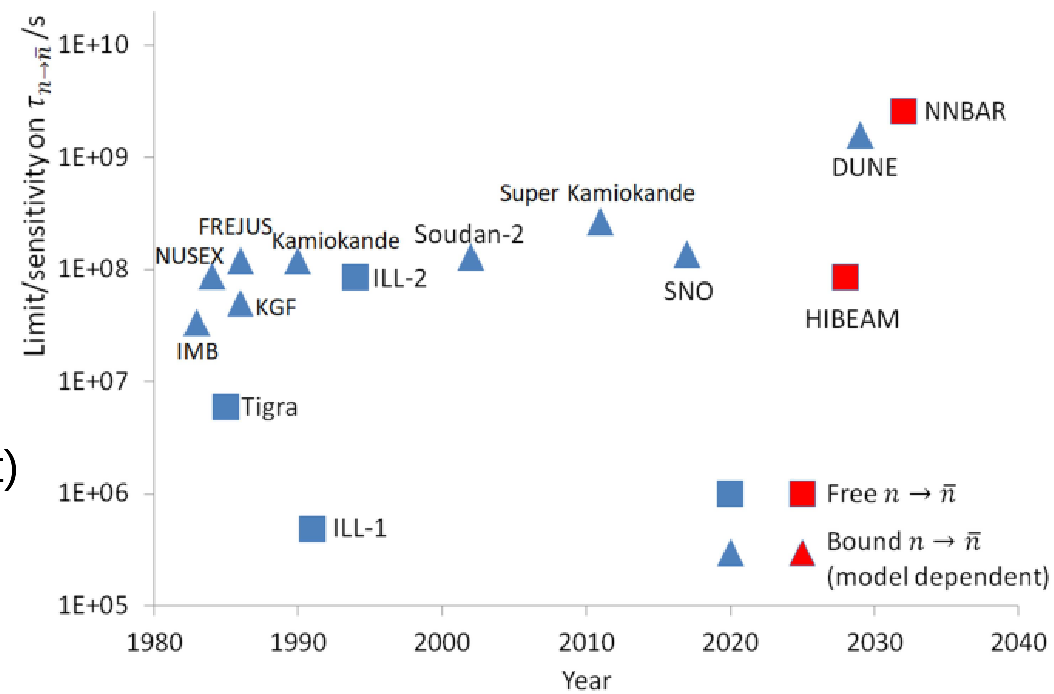
R-parity violating supersymmetry (PeV)

Unification models: $M \sim 10^{15}$ GeV

L-R symmetric models ($n\bar{n}$ and $0\nu 2\beta$)

Extra dimensions models

Post-sphaleron baryogenesis



$$P_{n\to\bar{n}} = \left(\frac{\varepsilon_{n\bar{n}}}{\Delta E}\right)^2 \sin^2(\Delta E \times t) \quad ; \Delta E = E_n - E_{\bar{n}}$$

Bound neutrons $\Rightarrow 10^{-61}$ suppression:

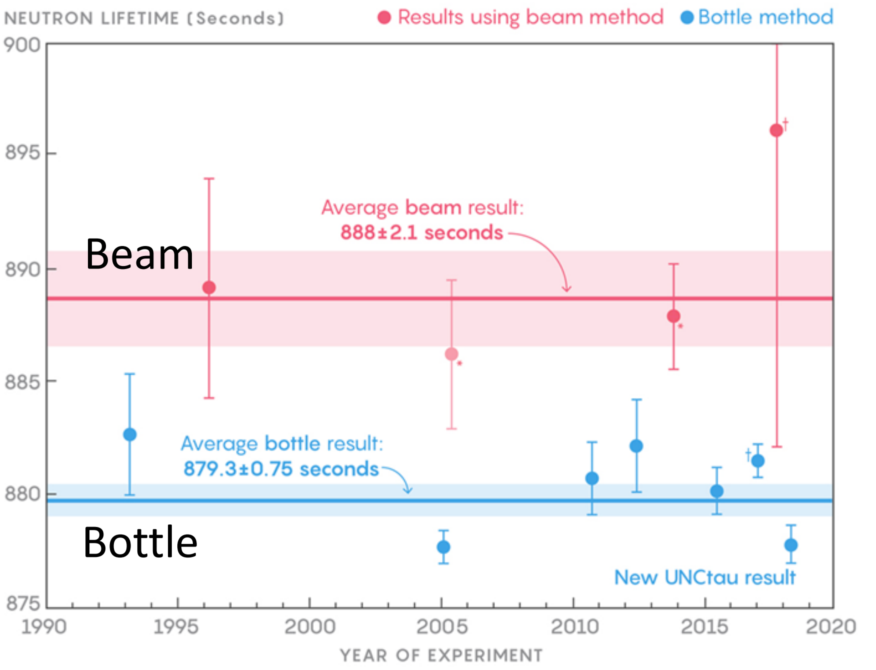
$\tau_{n\bar{n}} > 2.7\times10^8$s (Super-K, mod.-dependent)

Free neutrons $\tau_{n\bar{n}} > 8.6\times10^7$s (ILL)

$n \rightarrow n'$

As a meta-stable neutral particle, the neutron is one of the few possible portals to a hidden/dark sector.
Eg mirror matter, dark matter.
(eg PRD96 (2017) 3, 035039)

Could explain neutron lifetime discrepancy seen in bottle and beam experiments
(eg EPJC79 (2019),6, 484)



$$P_{n\rightarrow n'} = \left(\frac{\varepsilon_{nn'}}{\Delta E}\right)^2 \sin^2\left(\Delta E \times t\right) \quad ; \qquad \Delta E = \mu_n \bullet B - \mu_{n'} \bullet B' \;\; ; \; \varepsilon_{nn'} = \delta m_{nn'} + \kappa' \mu_{n'} \bullet B' + \kappa \mu_n \bullet B$$

Consider "mirror" magnetic field, transition magnetic moment.

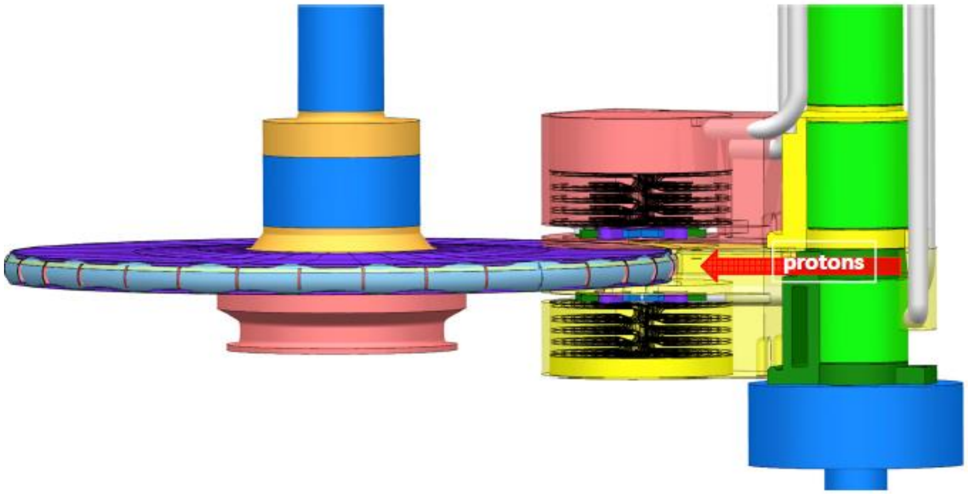
$\Rightarrow$ Search for $n \rightarrow n'$ as a function of $B, \dfrac{dB}{dt}$

The European Spallation Source

High intensity spallation neutron source

Multidisciplinary research centre with 17 European nations participating.

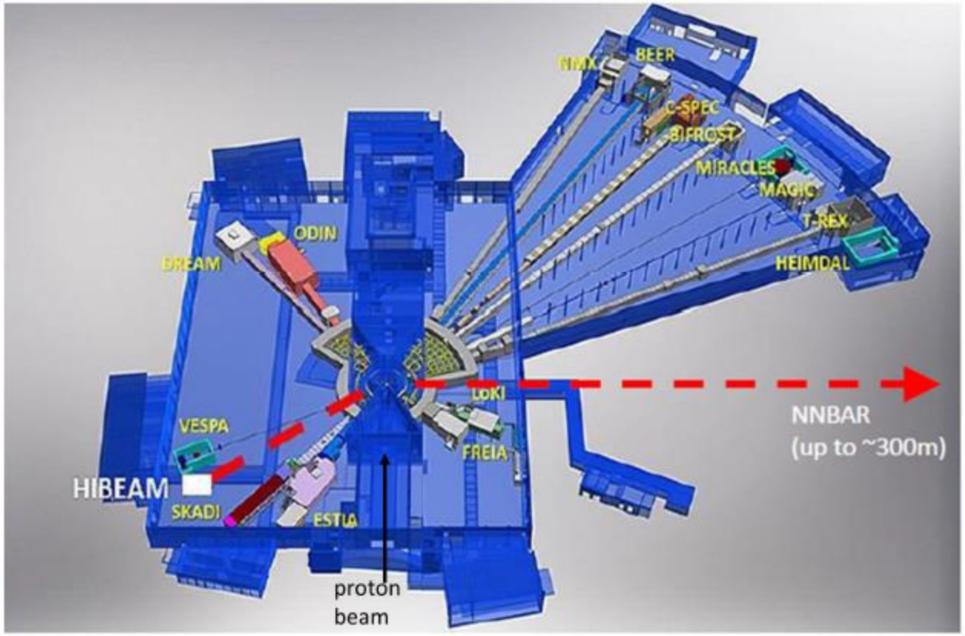
2 GeV protons (3ms long pulse, 14 Hz) hit rotating tungsten target.



~Start operations in ~2024.

	Jan. 2024	Jan. 2025	Jan. 2026	Jan. 2027
Source operator power (MW)	> 0.57	1.25	2	2
Source availability	80%	85%	90%	95%
Source installed capacity (MW)	1	2	3	3
Instruments in operation	3	8	12	15
Days of neutron production	200 minus long shutdown days	200 minus long shutdown days	200	200

HIBEAM and NNbar



Staged experiment:

1. HIBEAM

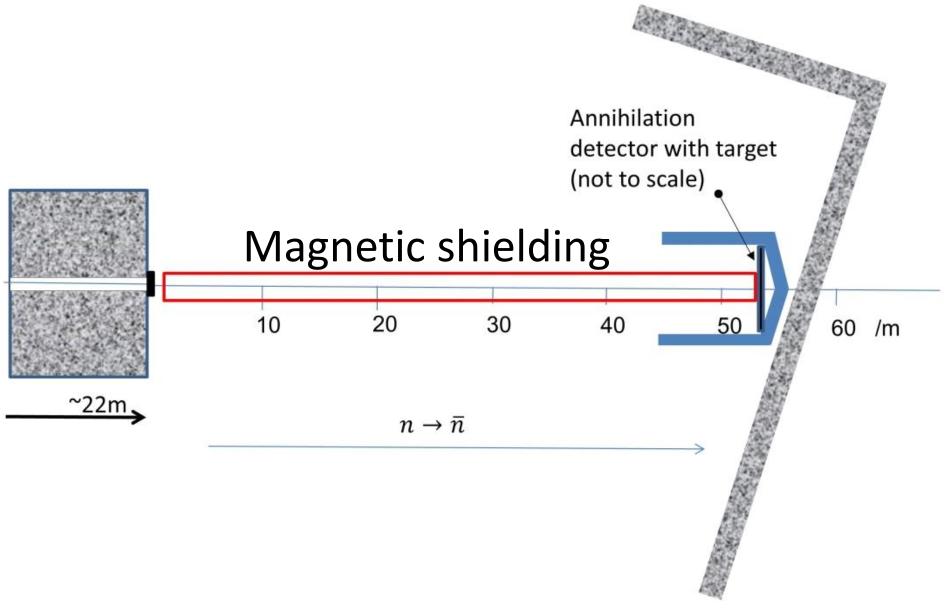
(high intensity baryon extraction and measurement)

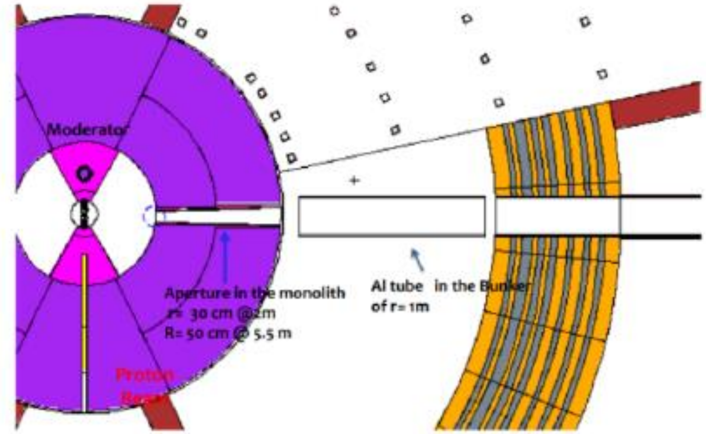
- mid to late 2020's
- world leading searches for $n \rightarrow n'$
- search for $n \rightarrow \bar{n}$ (with lower sensitivity)
- R&D for full experiment.

2. NNBAR

- Extremely high precision searches $n \rightarrow \bar{n}$, $n \rightarrow n'$
- Improve sensitivity to oscillation probability by a factor $\sim 10^3$
- Late 2020's

Search for $n \rightarrow \bar{n}$

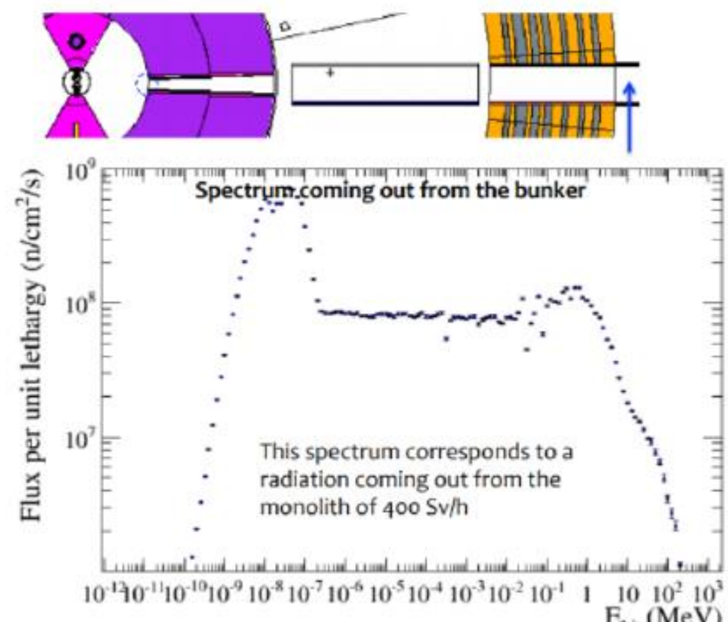




Sensitivity $\propto N_n t^2$

- Cold neutrons ($\bar{v}$<1000ms^{-1})
- Long propagation distance (50m)
- Magnetic shielding

HIBEAM - match ILL sensitivity



MCNP simulation

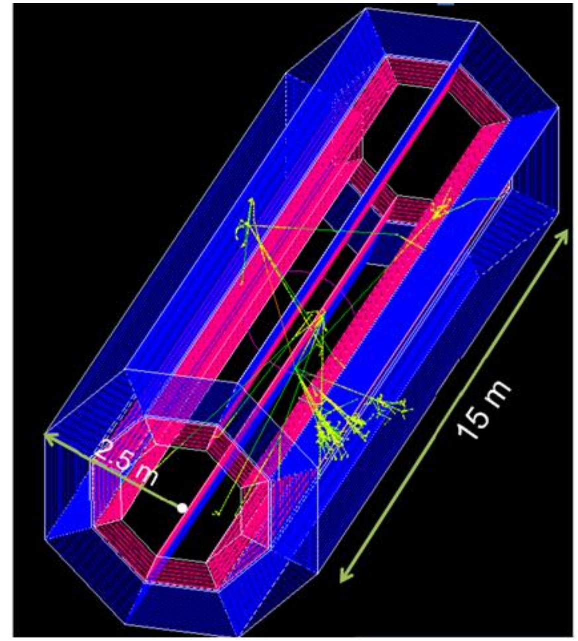
Annihilation detector

Expect $\bar{n} + N \rightarrow \sim 5\pi$ at $\sqrt{s} \sim 2$ GeV

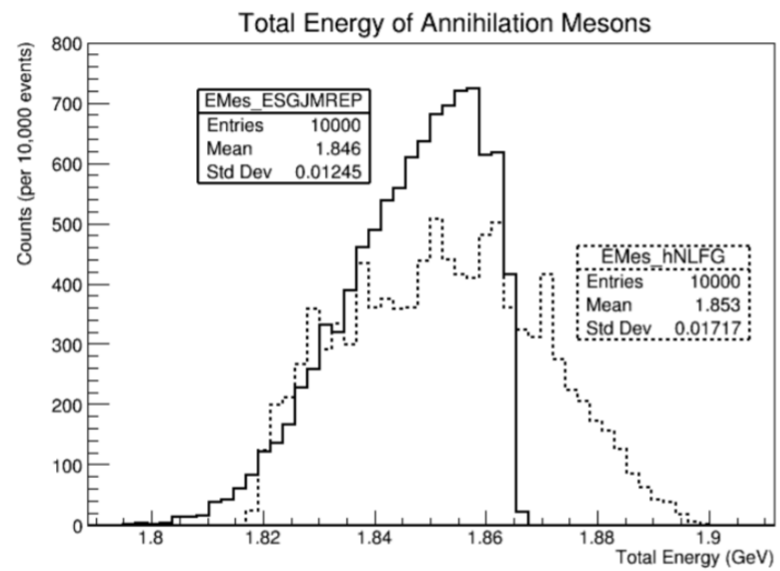
(arxiv:1804.10270 - hep/ex)

Detector design for high efficiency $(\varepsilon > 0.5)$

Aim for <1 event per year (ILL)



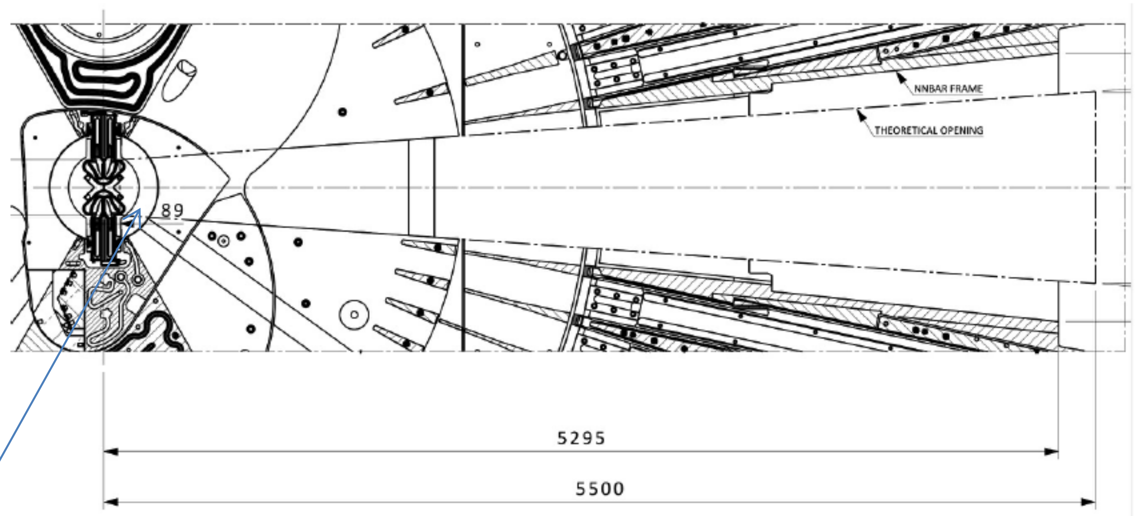
- Annihilation target - carbon sheet
- Tracker TPC ID/vertex reconstruction
- Time-of-flight system
  - scintillators around tracker.
- Calorimeter
  - lead + scintillating and clear fibre.
- Cosmic veto - plastic scintillator pads
- Trigger - Track and cluster algorithms



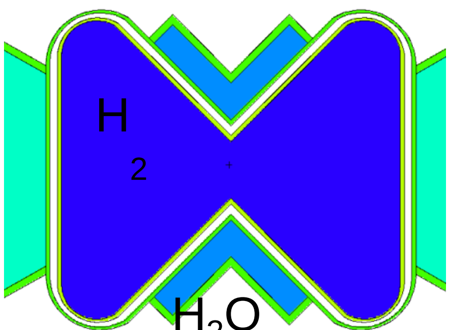
Arxiv:1906.02833

Neutronics - NNBAR

Top view



Large Beam Port



H_2O
ambient

Butterfly upper moderator.

No lower moderator at the start.

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Opportunity for LD_2 lower moderator for NNBAR, source of cold neutrons.

Neutron supermirror configuration ($m \sim 5 - 7$) to reflect neutrons from cold regions towards annihilation target+detector.

Capability of NNBAR

Factor	Gain wrt ILL
Brightness	≥ 1
Moderator temperature	~ 1
Target area	2
Angular acceptance/neutron transmission	40
Length	5
Run time	3
Total	≥ 1000

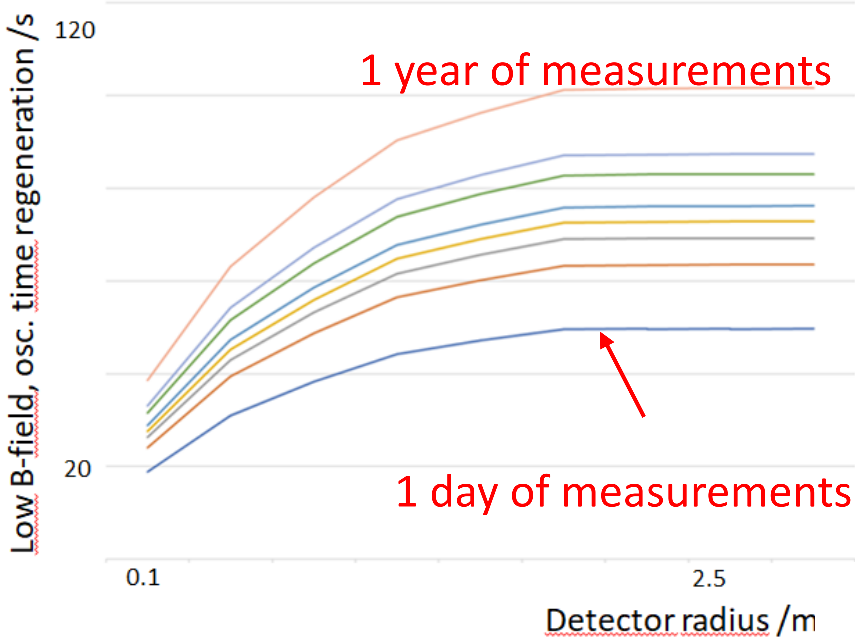
Increase in sensitivity for $P_{n\bar{n}}$ $\sim$ 10^3 compared to previous experiment (ILL)

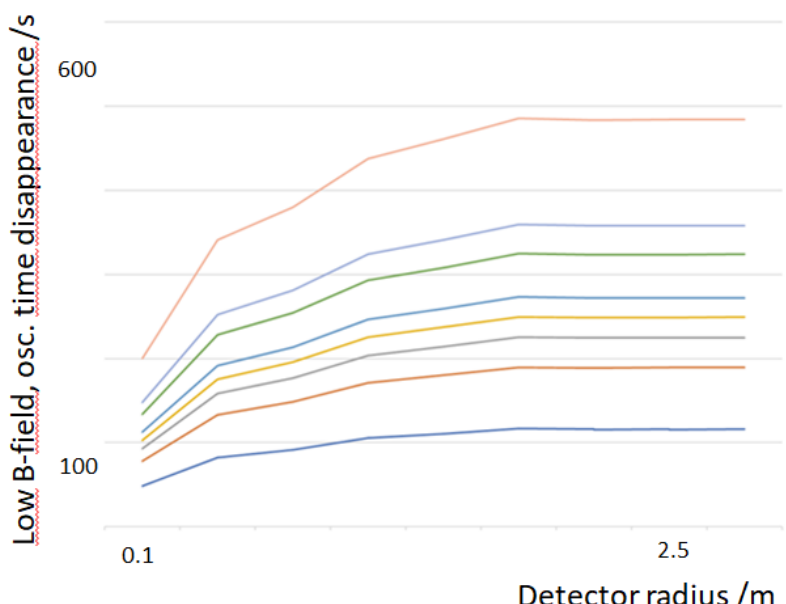
Possible $\sim 10^4$ increase (V. Nesvizhevsky et al., PRL122 (2019) 22,221802

Stability of matter (τ_{life}) sensitivity $\sim 10^{35}$ yrs .

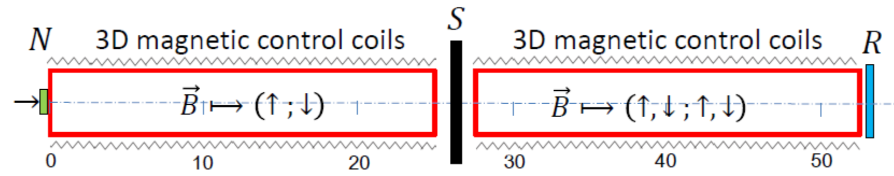
HIBEAM: $n \to n'$

J. Barrow



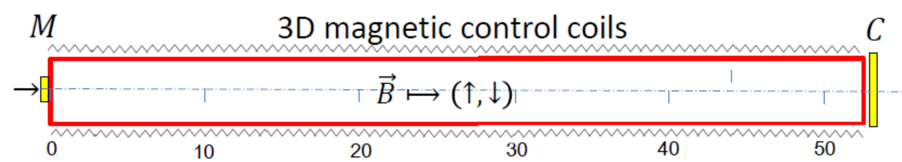


Regeneration



$n \to n'$ $\quad$ $n' \to n$

Disappearance



$n \to n'$

Current limits ~30s (bottle neutrons, wall-collision uncertainties)
Also TMM with B-field gradients.

HIBEAM, NNBAR and the ESS

HIBEAM/NNBAR
Expression of Interest 2015 (NNBAR)
26 institutes, 8 countries
Eight workshops (CERN, Lund, Gothenburg, Copenhagen, Grenoble)
Co-spokespersons: G. Brooijmans, D. Milstead
Lead scientist: Y. Kamyshkov
Sweden: PP+NU: SU, LU, UU, CTU, ESS,

ESS
No fundamental physics instrument from first call

Particle physics beam port now a high priority for ESS HIBEAM can run off this.

ESS has made a substantial investment in Large Beam Port , with NNBAR in mind.

Summary

Observation of baryon number violation would be of fundamental significance with implications for baryogenesis, dark matter and the nature of physics beyond the Standard Model.

BNV-only searches form part of the global effort for BNV,LNV searches.

Nature makes BNV-only processes hard to observe.

Last free $n \rightarrow \bar{n}$ search at ILL (1994).

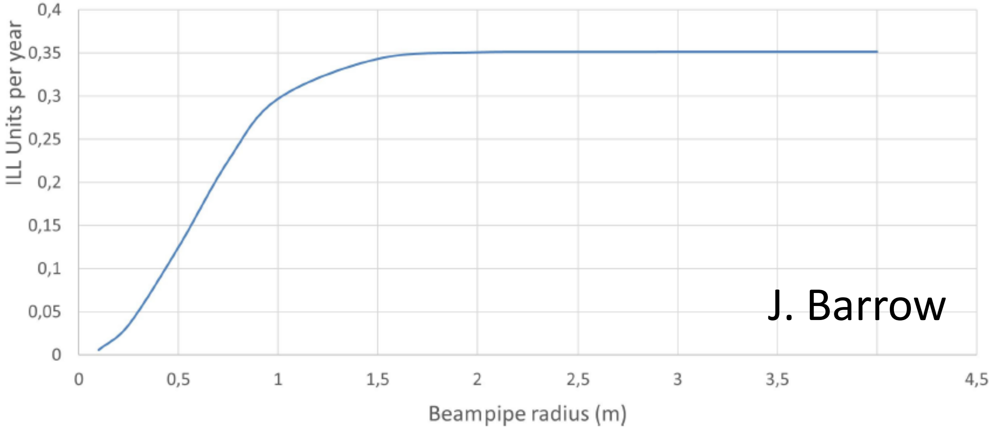
ESS provides possibility to improve sensitivity to $P\left(n \rightarrow \bar{n}\right)$ by 10^3

Two stage experiment (HIBEAM $\rightarrow$ NNBAR) is planned.

Opportunities for a large leap in sensitivity in the test of a global symmetry are rare.

HIBEAM: $n \rightarrow \bar{n}$

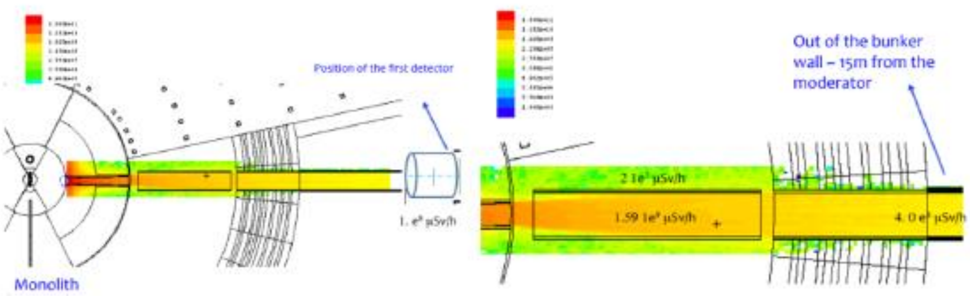
Free $n \rightarrow \bar{n}$



Sensitivity depends on ESS power during ramp up.

ILL sensitivity achievable after several years with appropriate conditions.

Can also search for (unconstrained) $n \rightarrow n' \rightarrow \bar{n}$



Principal aim - R&D for NNBAR experiment + background estimations (cold neutrons, cosmics, high energy spallation products).

Aim for ~0 bg events as at ILL.