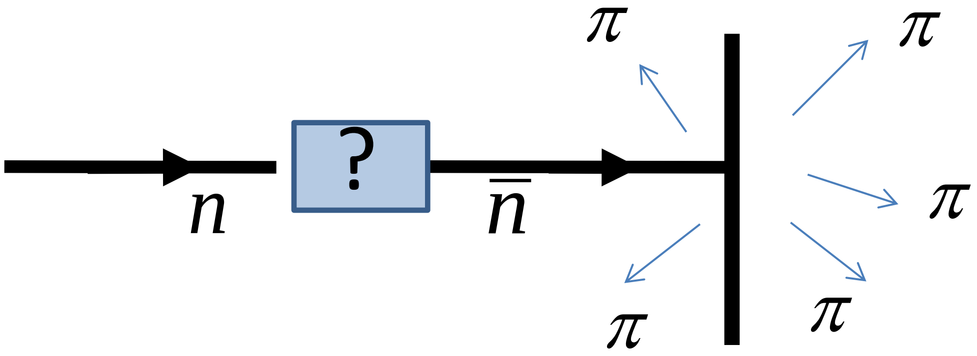
Searching for neutron conversions with the HIBEAM/NNBAR experiment



D. Milstead
Stockholm University

Towards a CDR

Arxiv:2006.04907 [physics. Ins-det]

New high-sensitivity searches for neutrons converting into antineutrons and/or sterile neutrons at the European Spallation Source

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Two-stage experiment – HIBEAM + NNBAR

Broad international base and support.
~ 100 authors from 50 institutes in 8 countries
Combines experts in neutronics, magnetics, nuclear and particle physics.

Co-spokespersons: G. Brooijmans (Columbia), D. Milstead (Stockholm Uni.)
Lead scientist: Y. Kamyshkov (Tennessee Uni.)
Technical coordinator: V. Santoro (ESS)

HORIZON 2020

Development of High Intensity Neutron Source at the European Spallation Source

Fact Sheet

Objective

The European Spallation Source being constructed in Lund, Sweden will provide the user community with a neutron source of unprecedented brightness. By 2025, a suite of 15 instruments will be served by a high-brightness

Project Information

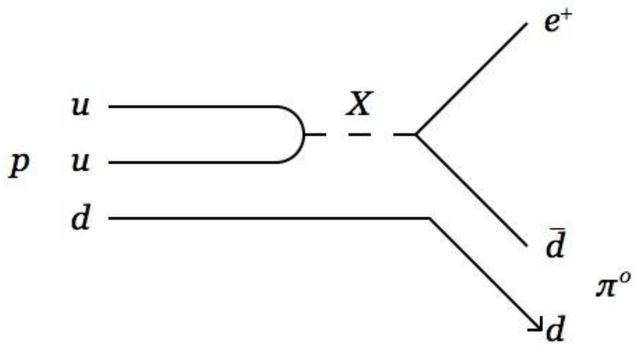
HighNESS
Grant agreement ID: 951782
Status

Horizon 2020 (3MEuro) Infrastucture Design Grant for CDR for cold lower moderator, beam extraction and experiments (including NNBAR) - P.I. V. Santoro
Also Vetenskapsrådet (3MSEK) for HIBEAM design P.I. D. Milstead

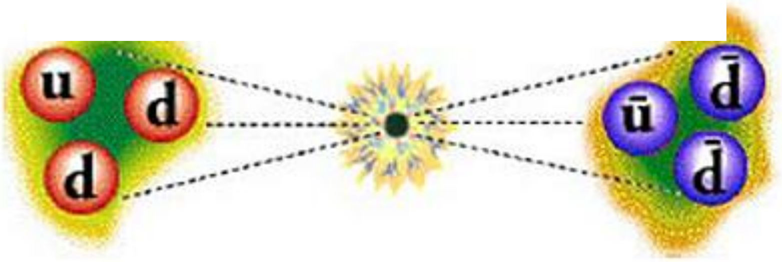
Baryon number violation

- BN, LN "accidental" SM symmetries at perturbative level
  - BNV, LNV in SM non-perturbatively (eg instantons)
  - B-L is conserved, not B, L separately.
- BNV needed for baryogenesis
- BNV is a generic feature of SM extensions (eg SUSY)
- Neutron conversions: $n \to \bar{n}$ and $n \to n'$ (sterile neutron) offer a unique discovery window for BNV.

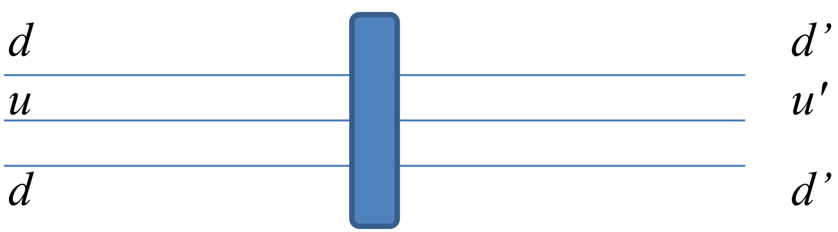
BNV Candles



Single nucleon decay.
Eg $p \to e^+ + \pi^0$, $|\Delta B| = |\Delta L| = 1$



$n \to \bar{n}$ and dinucleon decay
$|\Delta B| = 2, |\Delta L| = 0$



Neutron-sterile neutron conversion, $n \to n'$
$|\Delta B| = 1, |\Delta L| = 0$

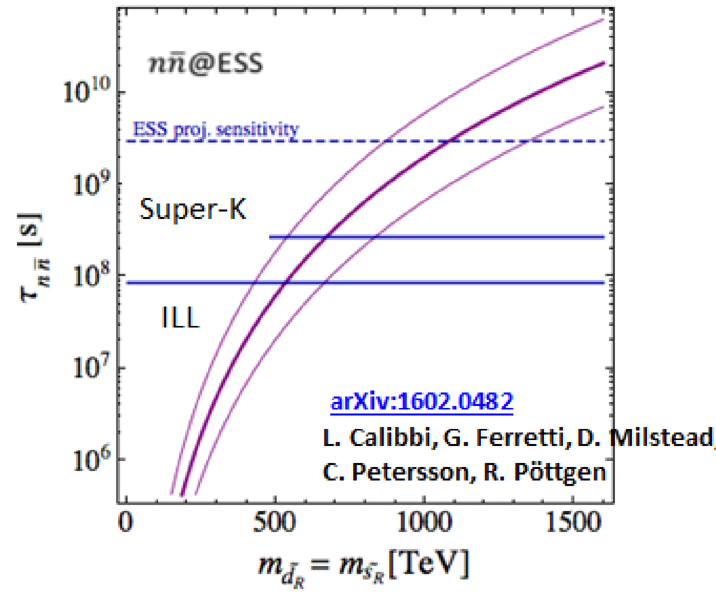
Neutron conversions $n \to \bar{n}$ and $n \to n'$
- under-explored
- open a unique window in BNV hunting
- do not rely on the violation of other quantities.

Theoretical motivation

$n \rightarrow \bar{n}$

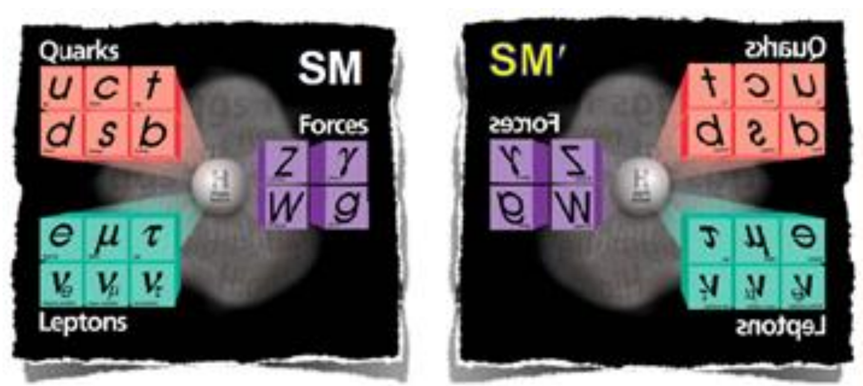
- Baryogenesis (eg post-sphaleron baryogenesis)
- R-parity violating supersymmetry
- Extra dimensions
- Left-right symmetric unification models
- Symbiosis with p-decay and $0\nu2\beta$

$$\text{Sphaleron} \equiv [\ \underbrace{QQQQQQ}_{n \rightarrow \bar{n}}\ \ \underbrace{QQQL}_{p \rightarrow e^+ + \pi^0}\ \ \underbrace{LL}_{0\nu2\beta}\ ]$$



$n \rightarrow \bar{n}', n'$

- Co-genesis (baryogenesis and dark matter)
- Generic dark sector
- Mirror matter
- Can potentially solve "beam" vs "bottle" neutron lifetime anomaly



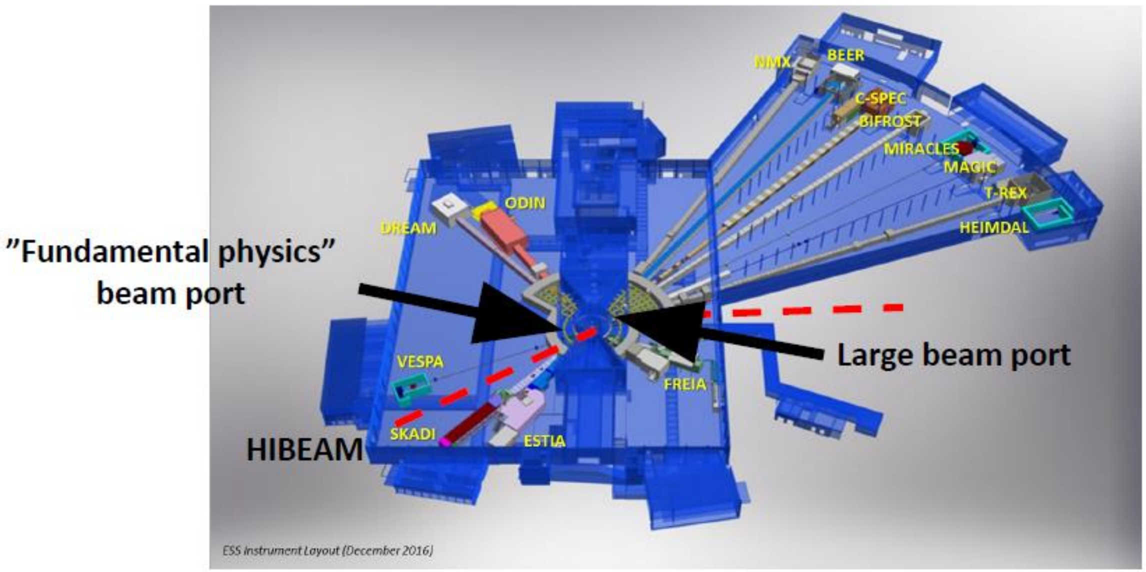
Converting neutrons

$$\hat{\mathscr{H}} = \begin{pmatrix} m_n + \vec{\mu}_n \vec{B} & \varepsilon_{n\bar{n}} & \alpha_{nn'} & \alpha_{n\bar{n}'} \\ \varepsilon_{n\bar{n}} & m_n - \vec{\mu}_n \vec{B} & \alpha_{n\bar{n}'} & \alpha_{nn'} \\ \alpha_{nn'} & \alpha_{n\bar{n}'} & m_{n'} + \vec{\mu}_{n'} \vec{B}' & \varepsilon_{n\bar{n}} \\ \alpha_{n\bar{n}'} & \alpha_{nn'} & \varepsilon_{n\bar{n}} & m_{n'} - \vec{\mu}_{n'} \vec{B}' \end{pmatrix}$$ + TMM terms

Channel		Mixing terms	Experimental conditions
$n \to \bar{n}$	”Classic” nnbar	$\varepsilon_{n\bar{n}}$	Field-free
$n \to [\bar{n}', n'] \to \bar{n}$	Nnbar via sterile neutrons	$\alpha_{nn'}\alpha_{n\bar{n}'}$	Scan B-field
$n \to \bar{n}', n'$	Disappearance	$\alpha_{nn'}\alpha_{n\bar{n}'}$	Scan B-field
$n \to n', \bar{n}' \to n$	Regeneration	$\alpha_{nn'}\alpha_{nn'} + \alpha_{n\bar{n}'}\alpha_{n\bar{n}'}$	Scan B-field

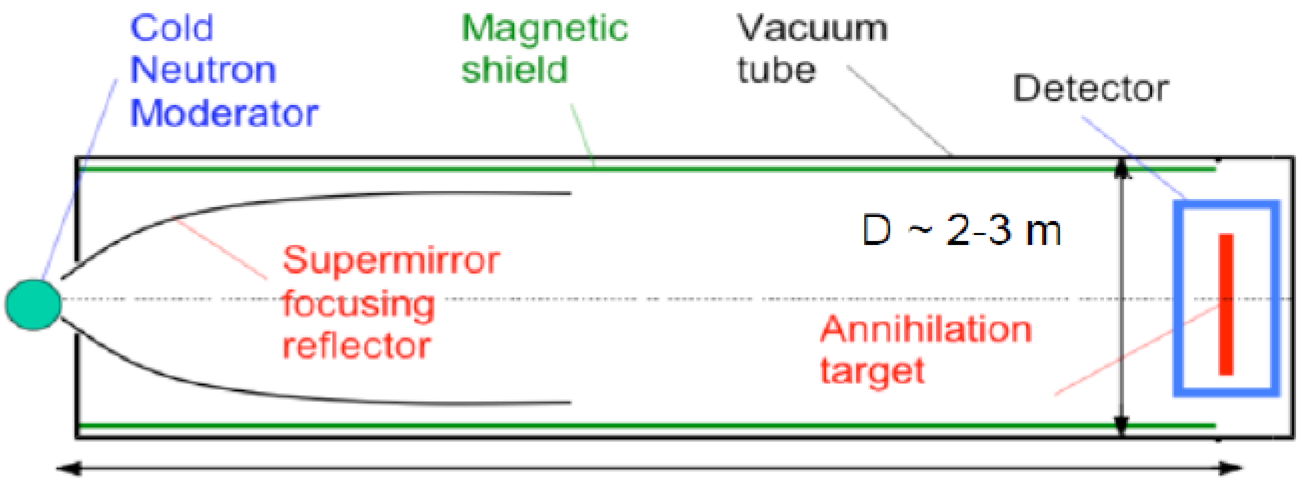
Complete set of searches in one experiment to observe and characterise any new physics.

HIBEAM/NNBAR



- Two stage experiment
- HIBEAM (>2025)
  - High precision (x10 improvement): $n \rightarrow \bar{n}', n'$; $n \rightarrow [\bar{n}', n'] \rightarrow n$; $n \rightarrow [\bar{n}', n'] \rightarrow \bar{n}$
  - Possibility to match earlier sensitivity from 1990's ILL experiment: $n \rightarrow \bar{n}$
  - ANNI beamline
- NNBAR (>2030)
  - $\sim 10^3$ improvement in sensitivity: $n \rightarrow \bar{n}$
  - Large Beam Port

NNBAR: searching for $n \rightarrow \bar{n}$

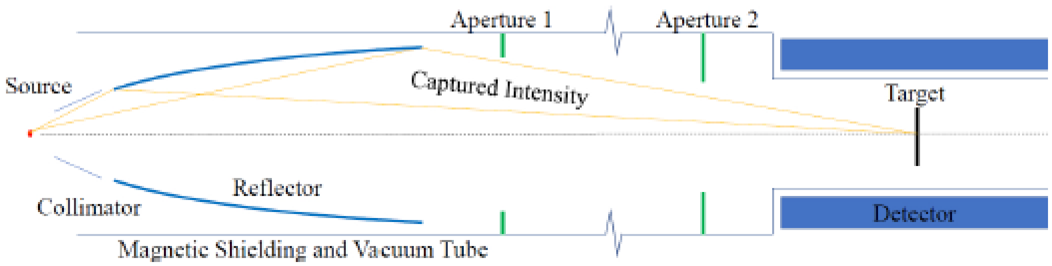


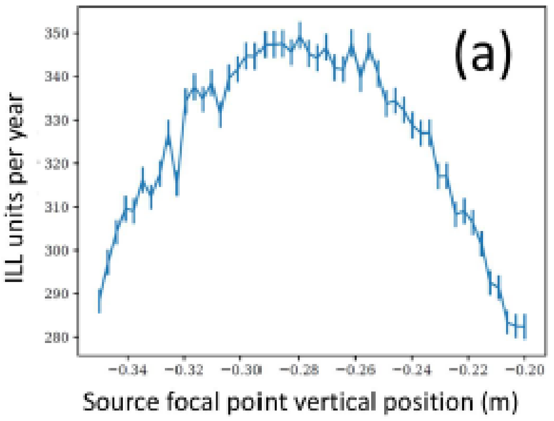
$$\text{Sensitivity} = (\text{free neutron flux at target}) \times P(n \rightarrow \bar{n}) \propto N_n t^2$$

(for low magnetic field <10nT for quasi-free neutrons)

- Cold neutrons (E<5 meV, v<1000ms^{-1})
- Low neutron emission temperature (50-60 K)
- Supermirror transmission and transit time
- Large beam port option, large solid angle to cold moderator.

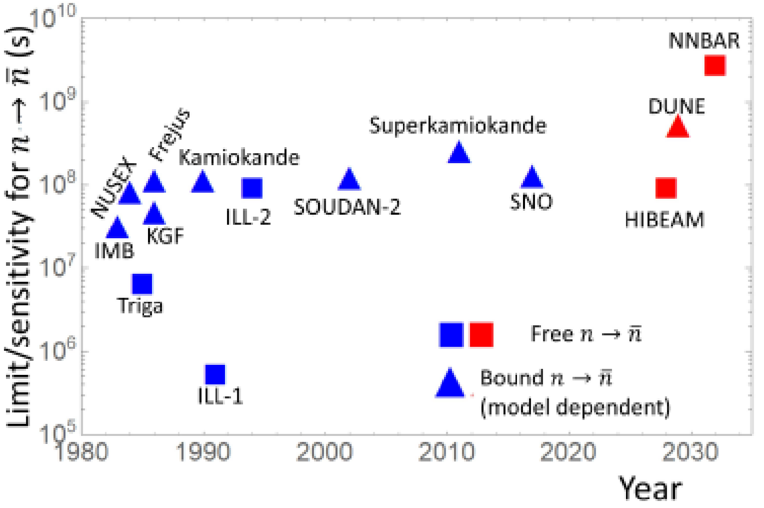
Optimisation of baseline NNBAR



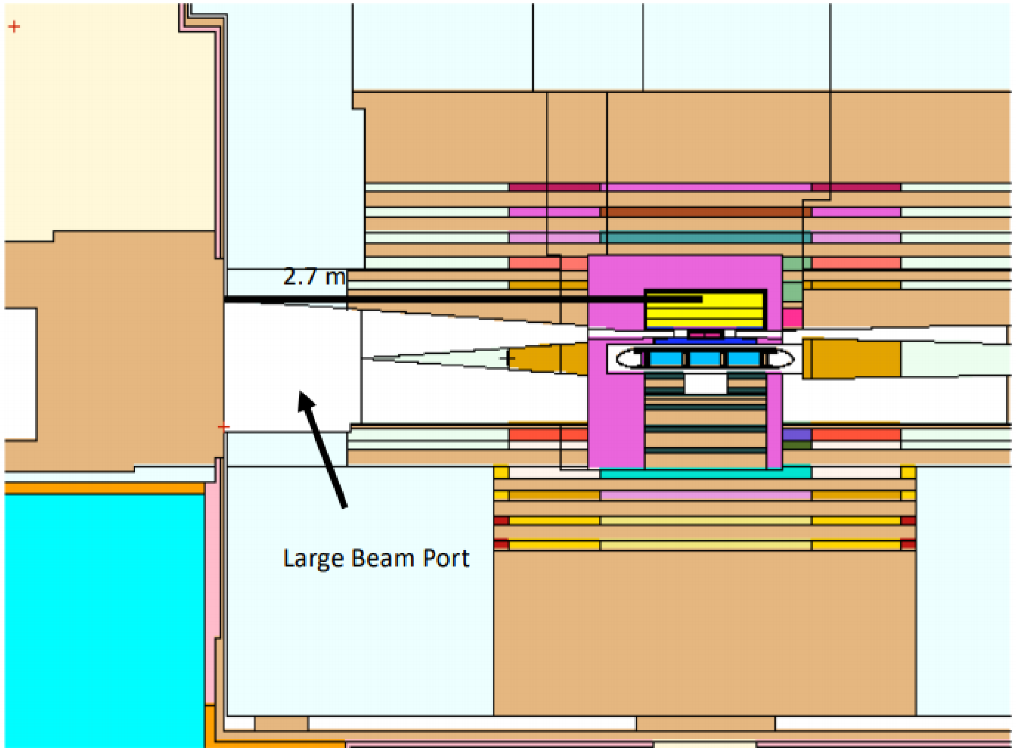


M. Frost – PhD thesis (Tennessee, 2019)
Ellipsoid-like reflector
>1000 ILL units in sensitivity for three years
1 ILL unit = equivalent sensitivity to ILL experiment

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



HighNESS (1)



Complete design of a cold moderator, beam extraction system (A. Takibayev, L. Zanini) and focusing with Wolter optics (O. Zimmer).

Full optimisation

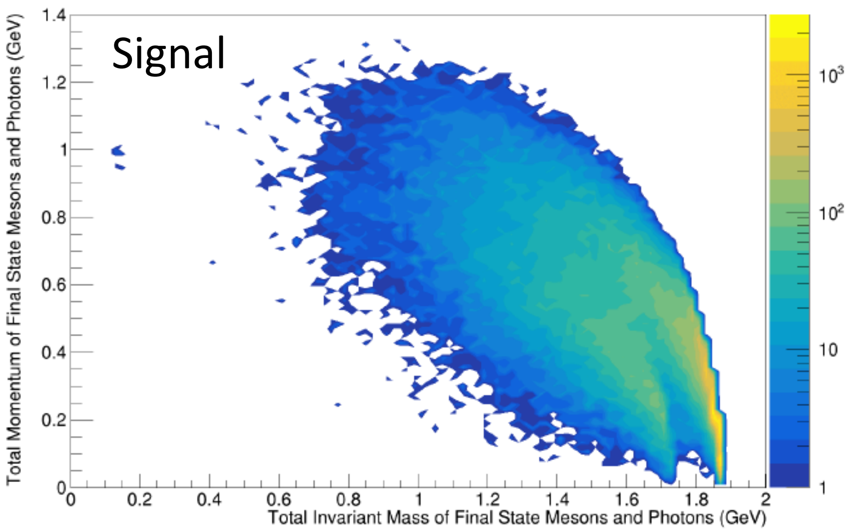
Not considered but potentially very useful – reflections without "resetting the clock" (M. Snow's talk and arxiv:1912.06730 (hep-ph))

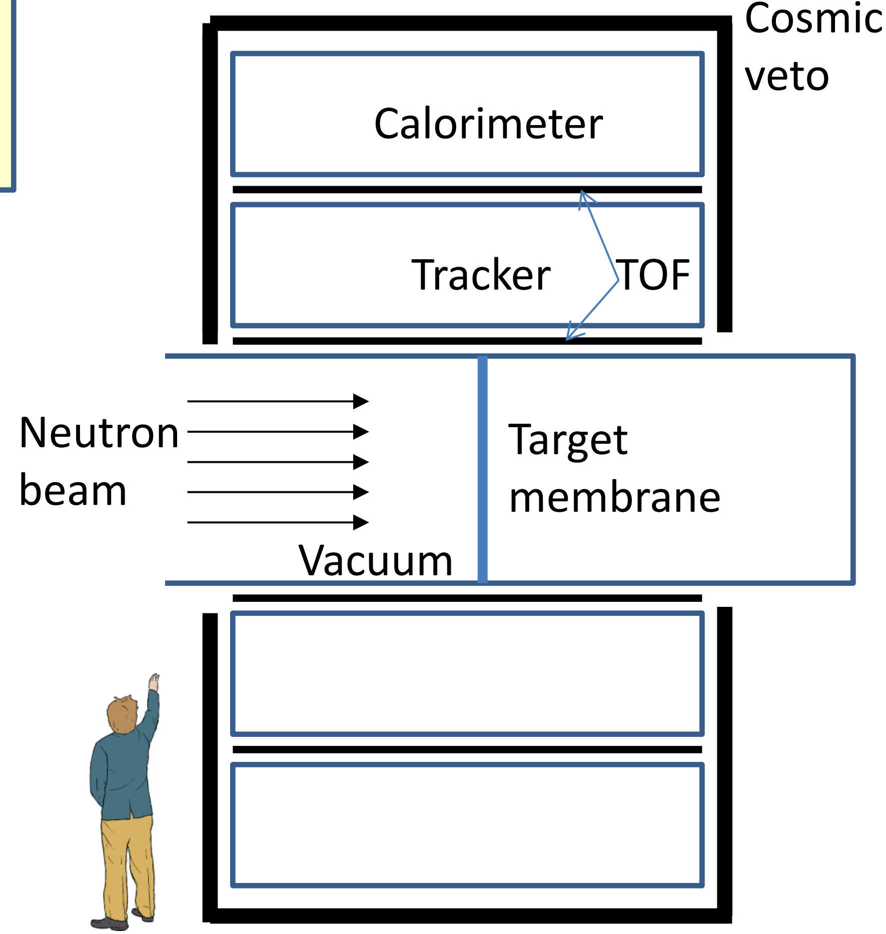
HighNESS (2) - detector

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

Detector design for high efficiency $(\varepsilon > 0.5)$ and low bg (~ 0).

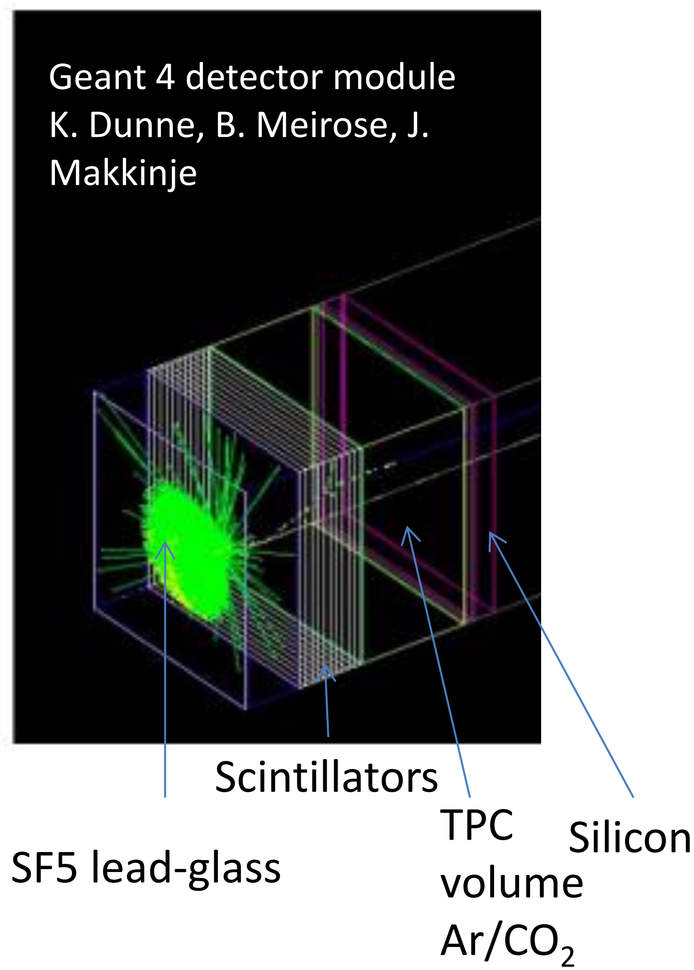
(J. Barrow/E. Golubeva)

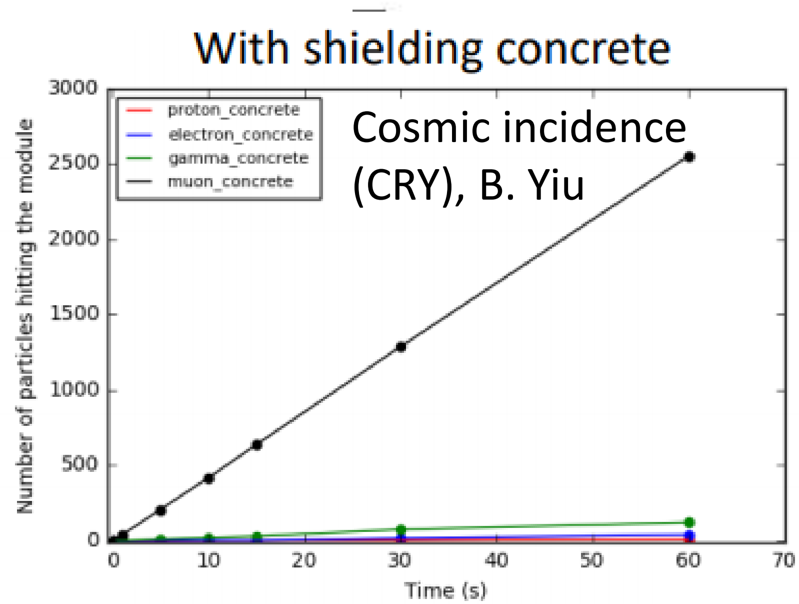


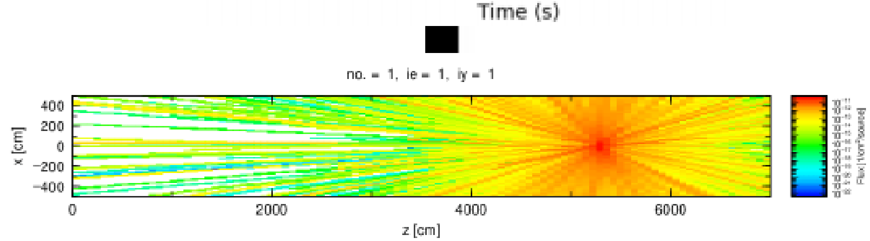


HighNESS (2) – detector and background studies

Modular software development for Geant4 detector with interface of annihilation signal (J. Barrow/E. Golubeva) and background models.



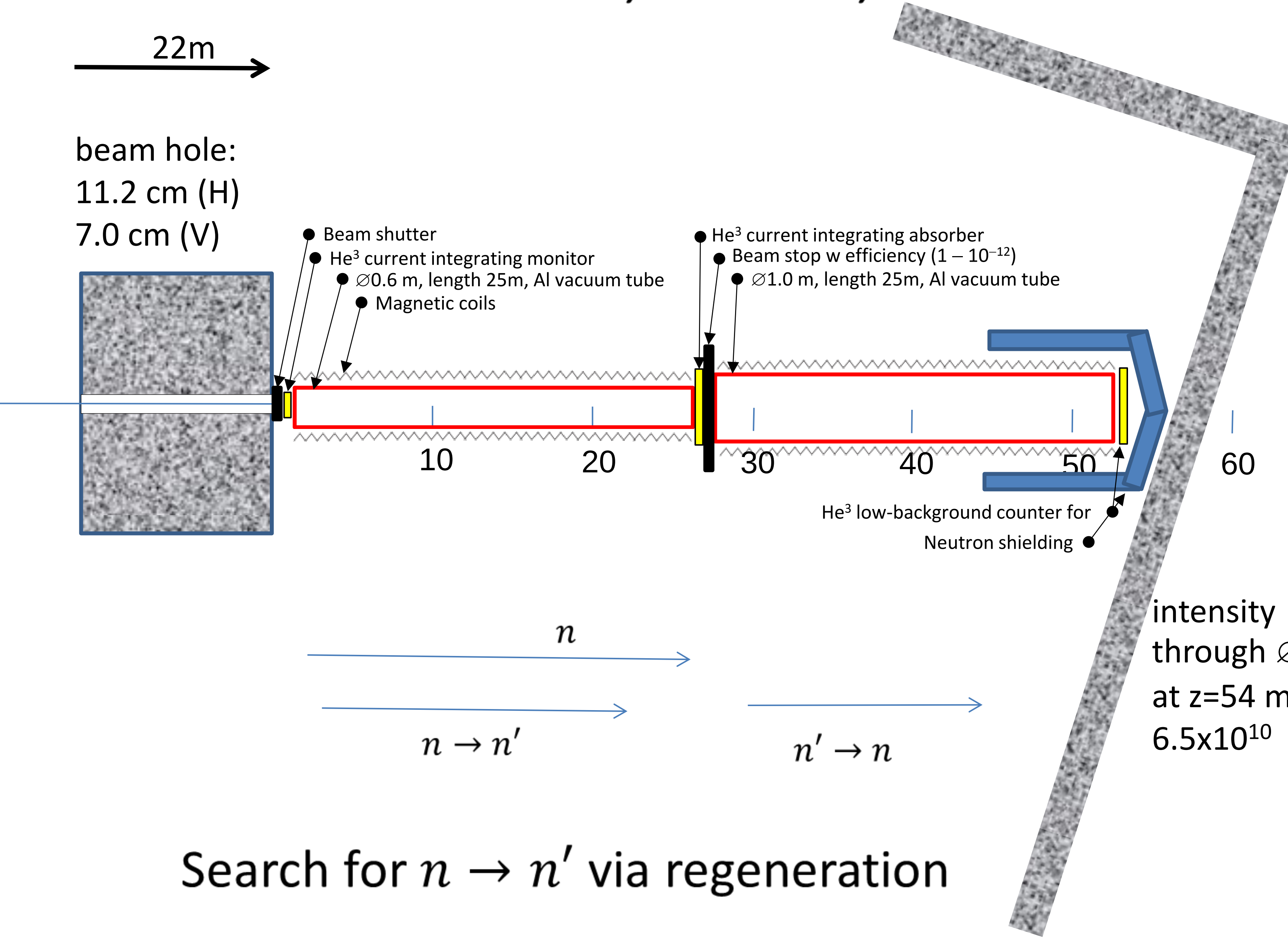




Gamma from neutron capture (B. Meirose)

HIBEAM, $n \rightarrow n'$, at ANNI

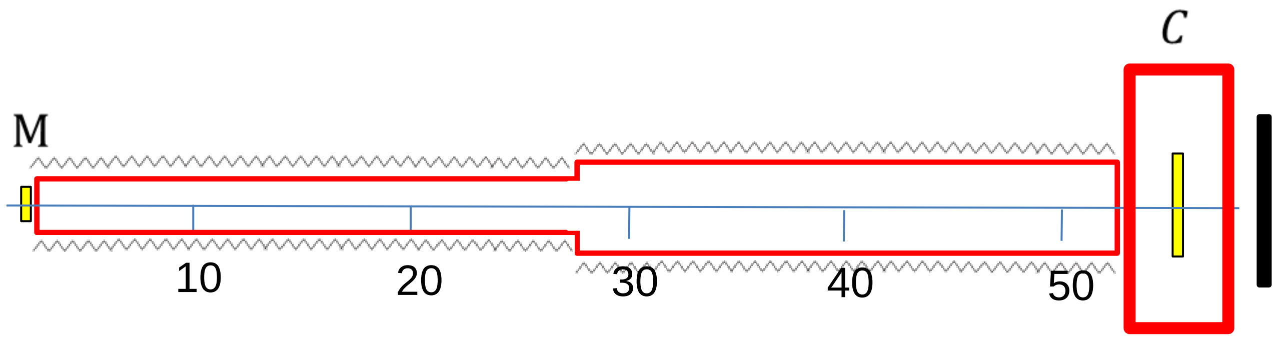
beam hole:
11.2 cm (H)
7.0 cm (V)



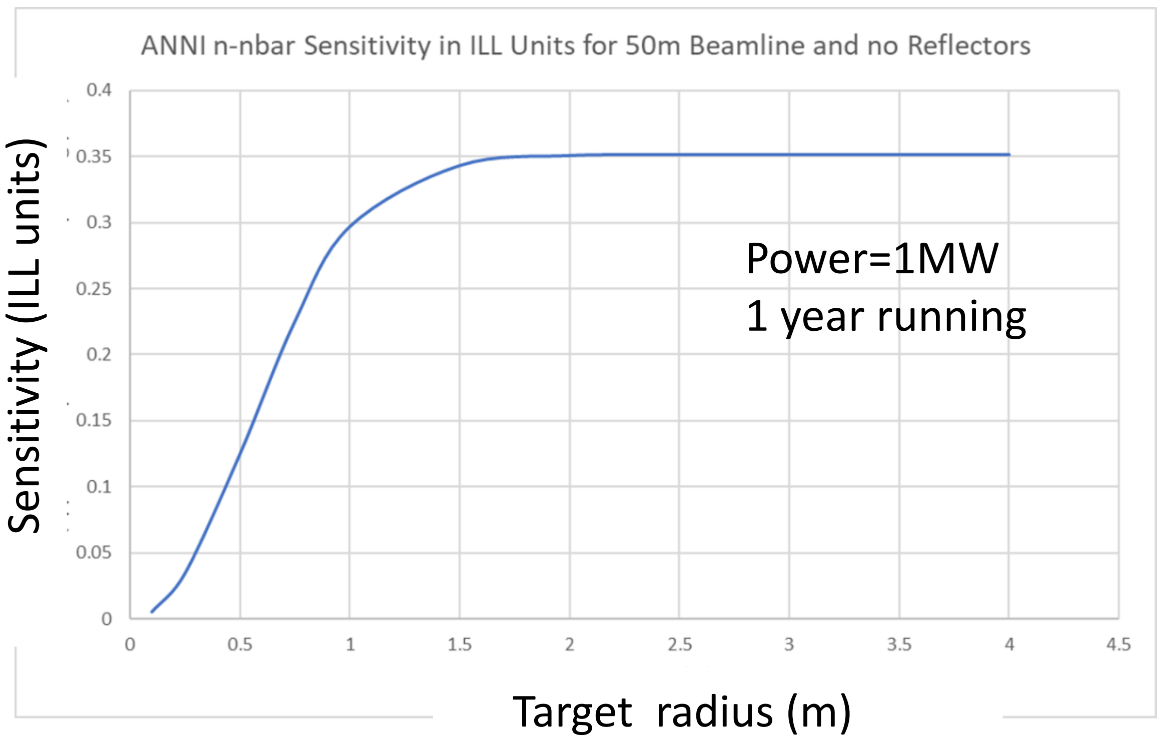
intensity
through ∅1m
at z=54 m
6.5×10^{10} n $s^{-1}W^{-1}$

Search for $n \rightarrow n'$ via regeneration

HIBEAM, $n \to \bar{n}$, at ANNI



J. Barrow

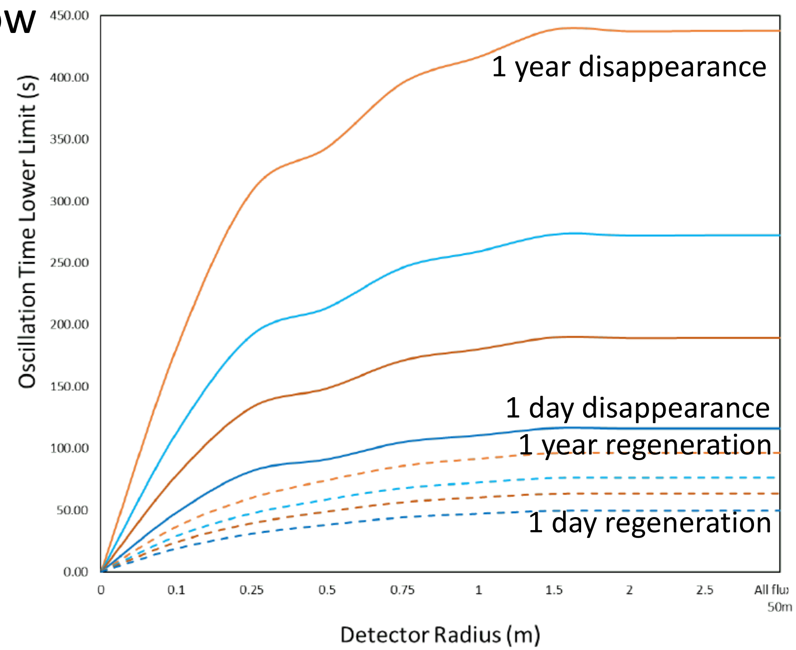


Expect power=2 MW
Possibility to match ILL sensitivity.
R&D experiment

+ competitive search for $n \to [\bar{n}', n'] \to \bar{n}$

HIBEAM sensitivity for $n \rightarrow n'$

J. Barrow



Low field resonant regeneration, assuming 50m
Regeneration and disappearance mode.
Also transition magnetic moment.
Assume 1MW

Extend sensitivity from earlier UCN experiments.

Collaborate with ORNL sterile neutron searches (L. Broussard's talk).
Phased multi-lab program.

Summary

- Baryon number is violated in nature; no BNV process observed in the lab (yet)
- Neutron conversions are a unique BNV tool and can probe dark matter, baryogenesis and generic physics beyond the Standard Model
- Discovery and characterisation of different neutron conversions in one experiment
- Two stage experiment : HIBEAM + NNBAR
- HighNESS driving NNBAR CDR
- Rare opportunity to make a 3 orders of magnitude improvement in tests of a global symmetry.