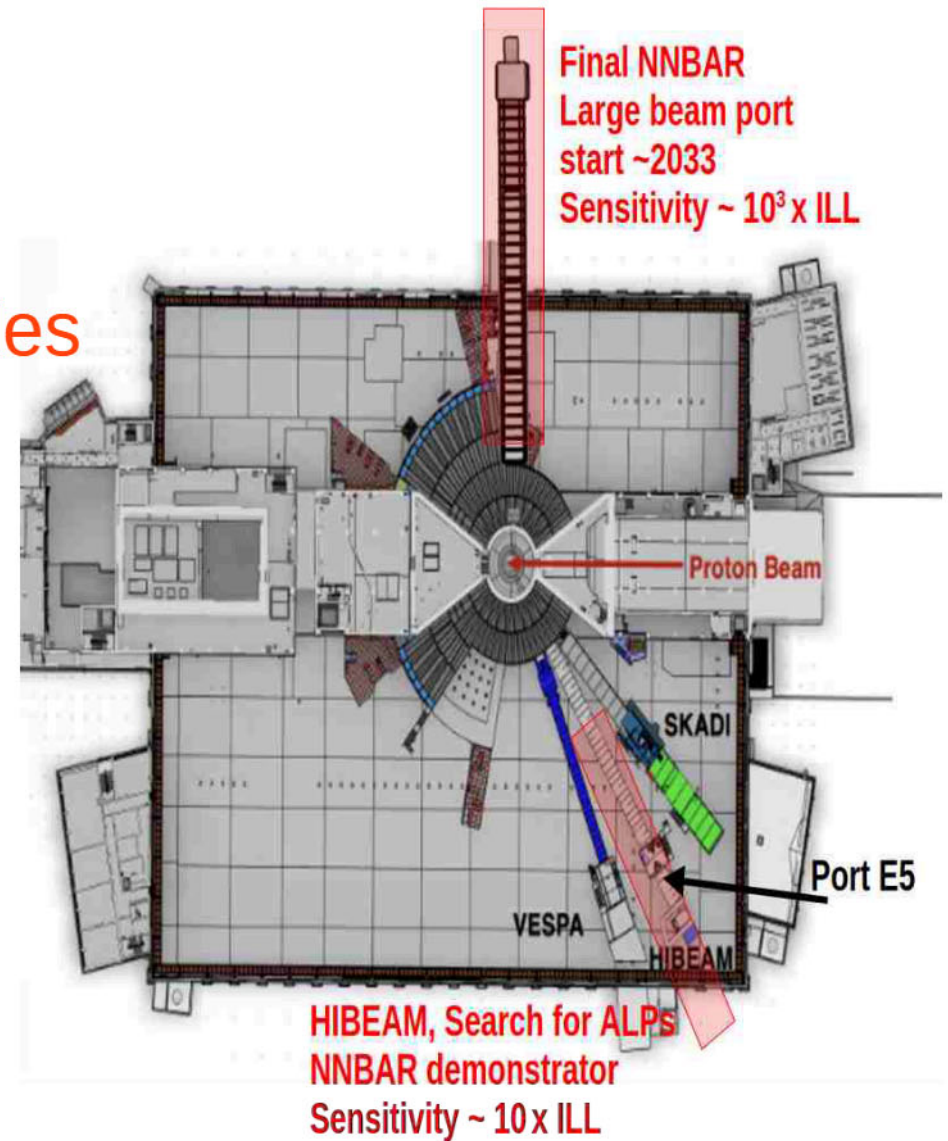


Search for Physics Beyond Standard Model at European Spallation Source in Lund



Physics case

- 1) Search for Axion-Like Particles
- 2) Search for $n\bar{n}$ oscillations
- 3) Portal to dark sector
- 4)



Physics case

1) Search for Axion-Like Particles

Pseudoscalar bosons

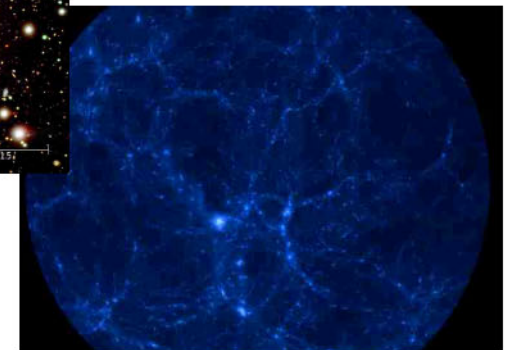
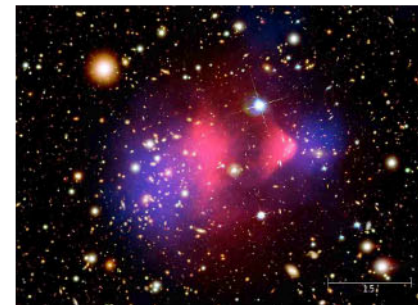
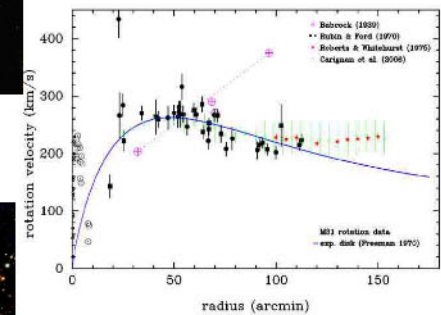
Canonical axion proposed in 1978 by Peccei, Quin to solve
Strong CP Problem

as not observed in high energy collisions abandoned

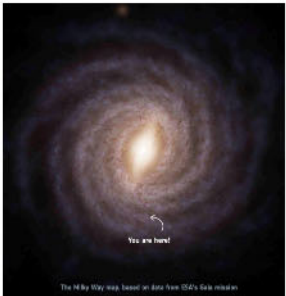
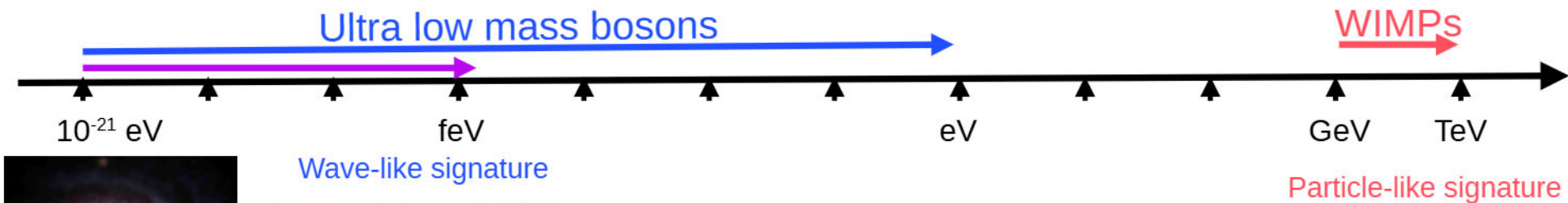
returned as Axion-Like Particle to solve Dark Matter Problem

Dark Matter problem

- Coma cluster (Zwicky, Smith; ~1933)
- Flat galactic rotation curves (Bosma, Rubin; 1978)
- Gravitational lensing (Buleet cluster)
- Large-scale structure formation



HIBEAM and axions or ALPs



Inspired by Evgeny Stadnik talk Lund 2025 & Stadnik, Flambaum, PRD **89**, 043522 (2014)

$$\langle v_{rel} \rangle \approx 240 \frac{km}{s}$$

Axion-nucleon coupling:

$$\mathcal{L}_N = \frac{C_N}{2f_a} \delta_\mu a \tilde{N} \gamma^\mu \gamma^5 N$$

$$H_a(t) = \frac{C_N a_0}{2f_a} \sin(m_a t) \sigma_N \cdot p_a$$

Kraków, 01.12.2025

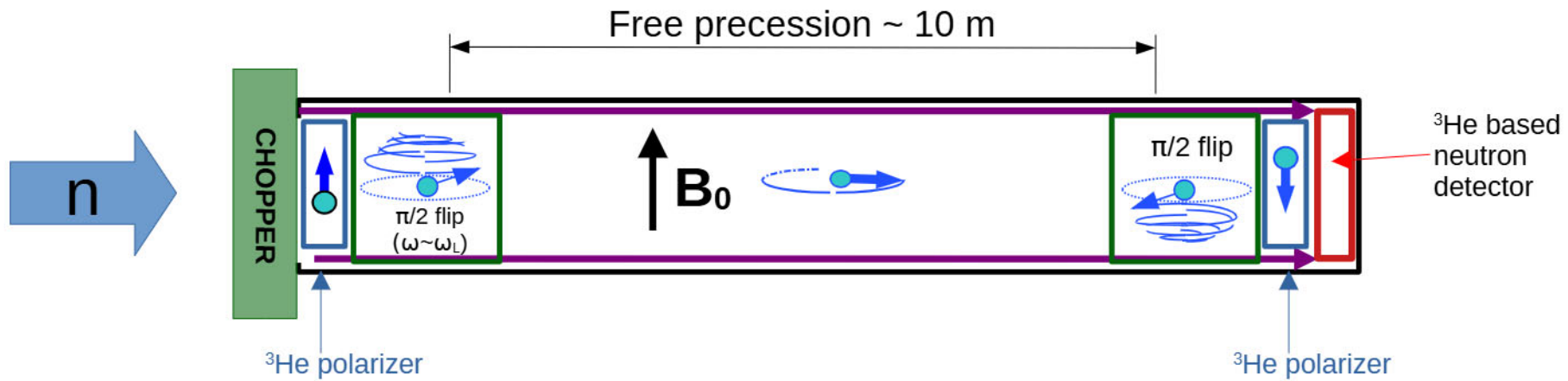
Precession of σ_N around direction of ALP "wind" p_a

Indistinguishable from Larmor precession around magnetic field lines:

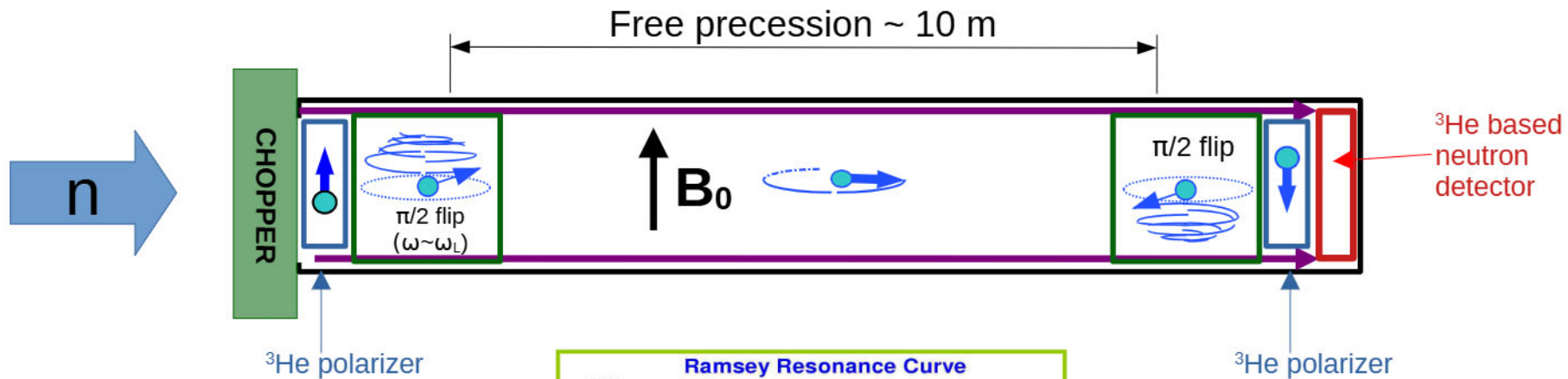
$$H_m(t) = -\gamma \sigma_N \cdot B$$

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HIBEAM and axions or ALPs



HIBEAM and axions or ALP



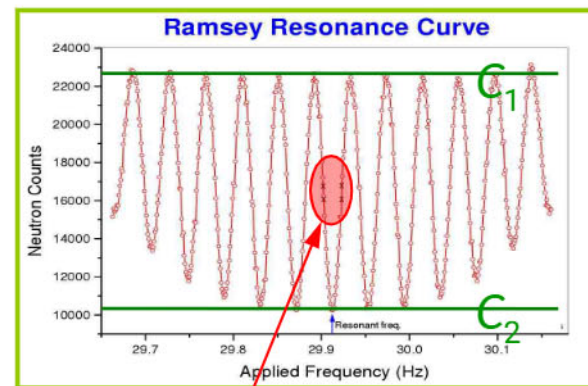
Experimental precision:

$$\Delta f \propto (\alpha T \sqrt{N})^{-1}$$

where T is free precession time, N number of neutrons and α is the resonance visibility:

$$\alpha = \frac{(C_1 - C_2)}{(C_1 + C_2)}$$

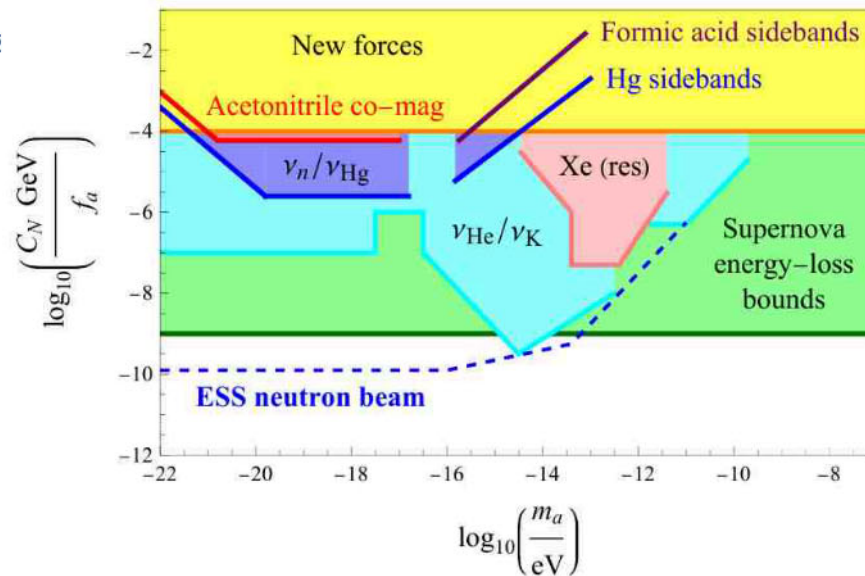
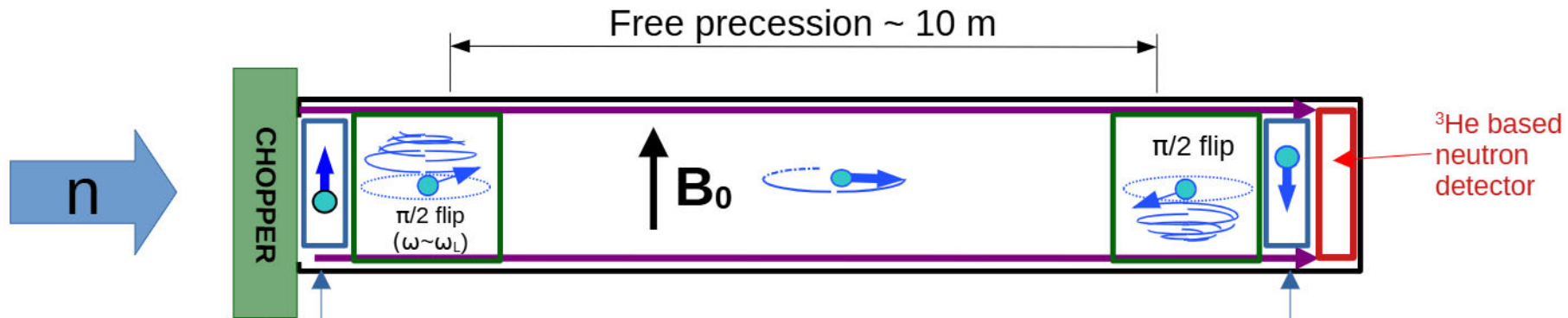
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4 working points
 ω close to Larmor freq.

Kraków, 01.12.2025

HIBEAM and axions or ALP



Up to 3 orders of magnitude
Improvement of current limits

P. Fierlinger, et al., Phys. Lett. 133 (2024) 181001

Neutron-antineutron oscillations

- Would violate conservation of baryon number ($\Delta B=2$, $\Delta L=0$)
- Beyond Standard Model
- Oscillations of neutral mesons: K, B, D (composed particles)
- Neutrino oscillations violate family lepton number conservation
- Baryon number violation never observed, but badly needed as necessary condition to explain another great problem of physics:
matter antimatter asymmetry of universe
- $n\bar{n}$ oscillations and stability of nuclei? 10^{60} suppression factor...

NNBAR: $n \rightarrow \bar{n}$ oscillations

Two types of experimental approaches

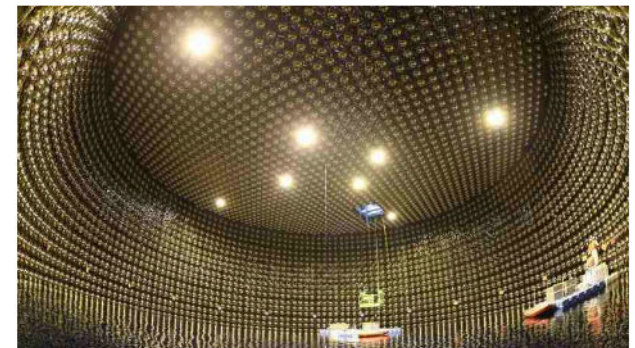
Best experimental limits for $n \rightarrow \bar{n}$ oscillation :

- Super-Kamiokande, K.Abe *et al.* Phys. Rev. D91 (2015) 012008: $\tau_{n\bar{n}} > 2.7 \cdot 10^8 \text{ s}$,
- Super-Kamiokande, K.Abe *et al.* Phys. Rev. D103 (2021) 072006: $\tau_{n\bar{n}} > 4 \cdot 10^8 \text{ s}$,

but: Suppression factor must be accounted for $\rightarrow$ theoretical uncertainties

irreducible background from high energy cosmic neutrinos:

found 11 candidate events when expected $\sim 9 \pm 3$



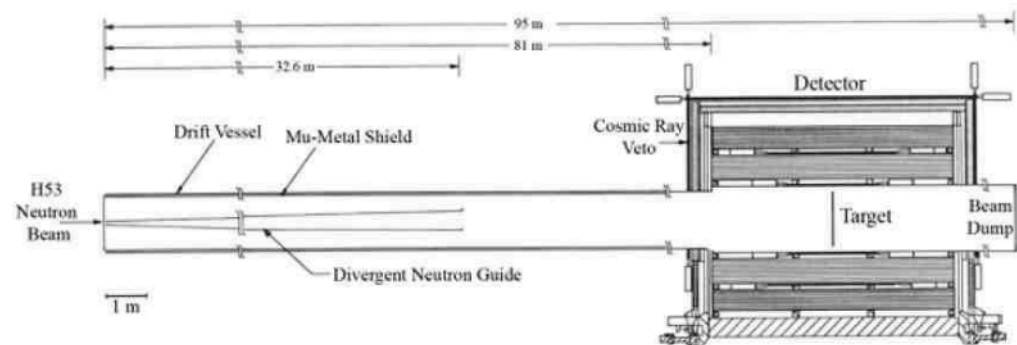
NNBAR: $n \rightarrow \bar{n}$ oscillations

Two types of experimental approaches

Best experimental limits for $n \rightarrow \bar{n}$ oscillation :

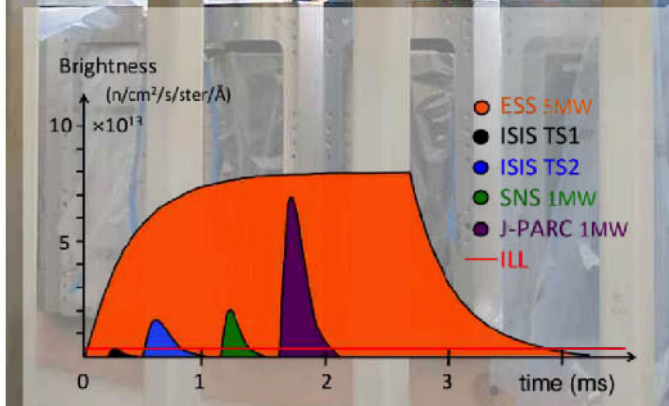
- Super-Kamiokande, K.Abe *et al.* Phys. Rev. D91 (2015) 012008: $\tau_{n\bar{n}} > 2.7 \cdot 10^8 \text{ s}$,
- Super-Kamiokande, K.Abe *et al.* Phys. Rev. D103 (2021) 072006: $\tau_{n\bar{n}} > 4 \cdot 10^8 \text{ s}$,
- ILL, Grenoble, M.Balbo-Ceolin *et al.* Z. Phys. C63 (1994) 409: $\tau_{n\bar{n}} > 0.86 \cdot 10^8 \text{ s}$,

- $3 \cdot 10^{18}$ neutrons within ~ 1 year
- of average velocity $\sim 600 \text{ m/s}$
- Free flight $\sim 60 \text{ m}$
- Vacuum $< 2 \cdot 10^{-4} \text{ Pa}$, $B < 10 \text{ nT}$
- Detection efficiency ~ 0.50
- Found 0, expected 0 events



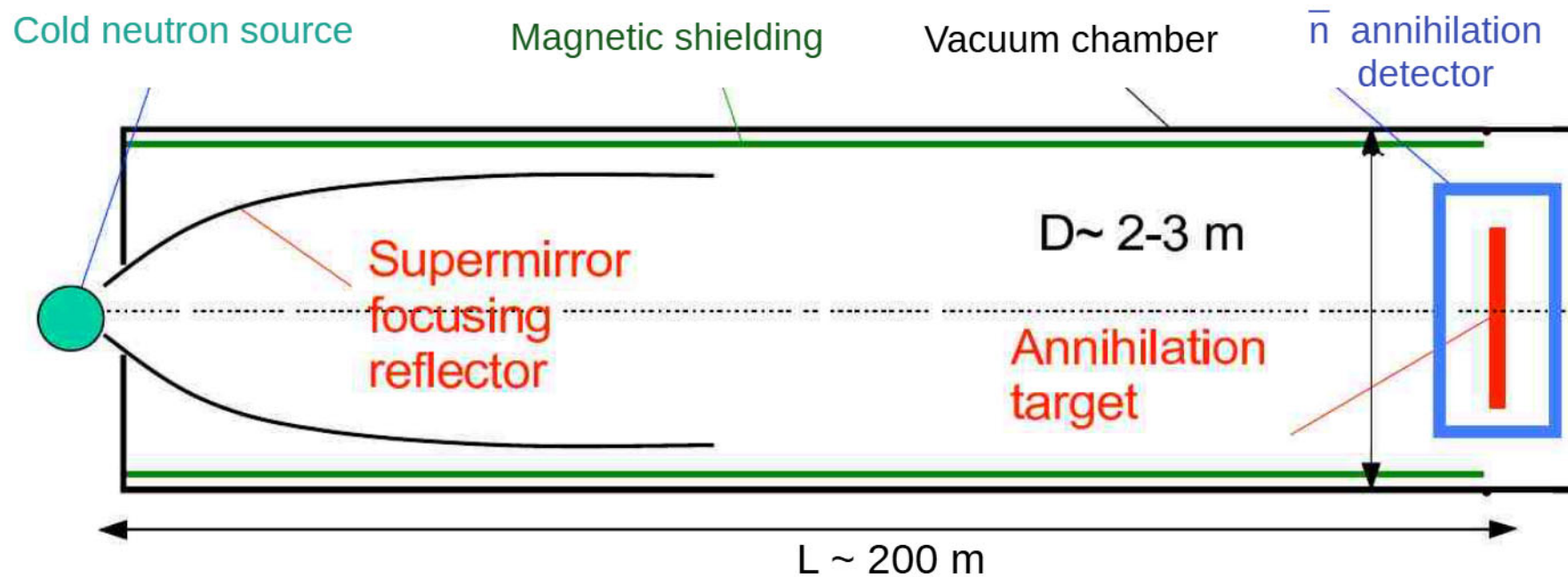
Neutron-antineutron oscillations

Large Beam Port of ESS



NNBAR Large Beam Port has been constructed to provide sufficient intensity of 1.5×10^{15} n/s there is no beamline currently available or planned at any other facility that could reach a flux even close to this number

HIBEAM-NNBAR @ ESS measurement principle



$$FoM \propto n \cdot t^2 \leftarrow \text{free flight time}$$

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

A Addazi¹, J L Barro², Z Berezhn³, G Brooijmans¹⁷, L J Broussard⁷, J Cedercall¹⁸, C Crawford¹⁹, P S B Dev²⁰, D D DiJulio¹⁴, A D Dolp¹, K Dunne¹⁷, P Fierlinger³, M R Fitzsimmons¹⁰, A F M J Frost¹, S Gardiner³, S Gardner¹⁰, A Galindez¹, P Geltenbort¹⁴, S Girmohanta¹, P Golubev¹⁰, E Golubeva²⁰, G L Greene¹⁰, T Greenshaw¹⁰, R Hall-Wilton¹⁴, L Heilbronn¹, J Herrero-Garcia¹, A Holley²⁰, G Ichikawa²⁰, T M Ho¹¹, E Iverr¹, T Johansson²², L Jönsson²², Y-J Jwa²³, K Kanaki¹⁴, E Kearns³², Z Kokal¹⁴, B K M Kitaguchi²⁷, T Kittelmann¹⁴, E Kilin¹, L W Koerner¹⁰, B Kopeliovich²⁵, A V Kudryavtsev⁴², A Kupsc²¹, Y T

NNBAR CDR

A Computing and Detector Simulation Framework for the HIBEAM/NNBAR Experimental Program at the ESS

Software framework

International Conference on Technology and Instrumentation in Particle Physics
Journal of Physics: Conference Series
2374 (2022) 012001

HIBEAM/NNBAR Calorimetry

B Meirose^{1,2,3}, D Milstead¹, S Silverstein¹ and S-C Yin¹
Physics, Stockholm University, 106 38 Stockholm, Sweden
European Spallation Source ERIC, 225 92 Lund, Sweden
Lunds universitet, 221 00 Lund, Sweden
E-mail: damme@fysik.su.se

Axions

Prototype construction

Status of the Design of an Annihilation Detector to Observe Neutron-Antineutron Conversions at the European Spallation Source

Sze-Chun Yiu^{1,*}, Bernhard Meirose^{1,2,3}, Joshua Barrow^{1,4,5}, Christian Böhm¹, Gustaf Brooijmans^{1,6}, Katherine Dunne^{1,7}, Elena S. Golubeva^{1,8}, David Milstead¹, Andre Nepomuceno^{1,9}, Valentina Santos^{1,10} and Samuel Silverstein^{1,10}

Detector design

¹ Physics Department, University of Cambridge, Cavendish Laboratory, Cambridge CB3 0EX, UK; ² Physics Department, University of Oxford, Oxford OX1 3RH, UK; ³ Physics Department, University of Manchester, Oxford Road, Manchester M13 9PL, UK; ⁴ Physics Department, University of Liverpool, Liverpool L69 3GB, UK; ⁵ Physics Department, University of Durham, Durham DH1 1TA, UK; ⁶ Physics Department, University of Edinburgh, Edinburgh EH9 1JQ, UK; ⁷ Physics Department, University of Glasgow, Glasgow G12 8QQ, UK; ⁸ Physics Department, University of London, London WC1E 7BT, UK; ⁹ Physics Department, University of Liverpool, Liverpool L69 3GB, UK; ¹⁰ Physics Department, University of Manchester, Oxford Road, Manchester M13 9PL, UK

lists available at ScienceDirect

ysics Reports

www.elsevier.com/locate/physrep

Spallation Source

ESS particle physics community review paper (initiated and driven by DM/VS)

L. Eklund¹, M. Estrada², M. J. Ferreira³, M. J. Ferreira⁴, A. Farrick⁵, E. Fernandez-Martinez⁶, M. J. Ferreira⁷, M. J. Ferreira⁸, P. Fierlinger⁹, B. Folsom¹⁰, A. Frank¹¹, A. Fratangelo¹², U. Friman-Gayer¹³, T. Fukuda¹⁴, H.O.U. Pynbo¹⁵, A. Garcia Sosa¹⁶, N. Gazis¹⁷, B. Gálnder¹⁸, Th. Gerasis¹⁹, M. Ghosh²⁰, G. Gokbulut²¹, J.J. Gomez-Cadenas²², M. Gonzalez-Alonso²³, F. Gonzalez²⁴, L. Hall²⁵, C. Happe²⁶, P. Heil²⁷, A. Heinz²⁸, H. Herde²⁹, M. Holl³⁰, T. Jenke³¹, M. Jernssen³², E. Jericha³³, H.T. Johansson³⁴, R. Johansson³⁵, T. Johansson³⁶, Y. Kamyshkov³⁷, A. Kayis Topaksu³⁸, B. Kildetoft³⁹, K. Kirch⁴⁰, B. Klitček⁴¹, E. Klinkby⁴², R. Kolevatos⁴³, G. Konrad⁴⁴, M. Koziol⁴⁵, K. Kirhac⁴⁶, A. Kupsc⁴⁷, L. Lacy⁴⁸, L. Larizgoitia⁴⁹, C.M. Lewis⁵⁰, M. Lindroos⁵¹, F. Luchezin⁵², F. Luchezin⁵³, C. Maiano⁵⁴, P. Marinovic⁵⁵, C. Markai⁵⁶

+related JINST 17 (2022) 10, P10046 (Arxiv: 2209.09011, [physics.ins-det])

+ Proc AccApp 21 (arXiv: 2204.04051 [physics.ins-det])

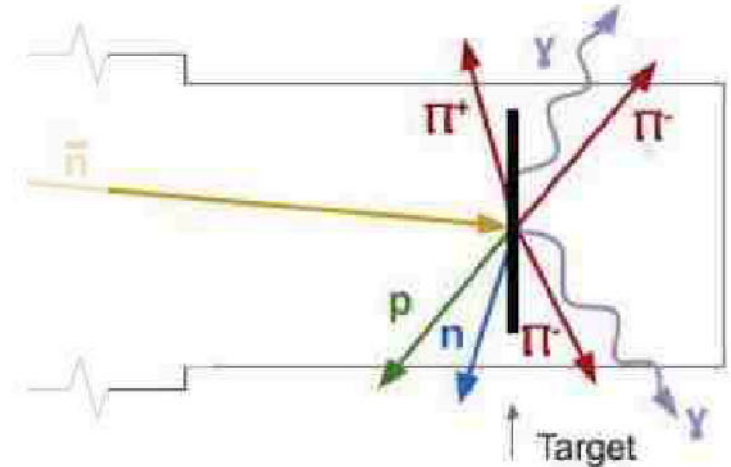


Kraków, 01.12.2025

Taken from Valentina Santoro's talk

Annihilation event signature - extremely strong

- Huge energy release ~ 1800 MeV
- On average 4-5 pions (neutral or charged)
- Light fragments from carbon nuclei
- All tracks from common vertex
- Gammas from π^0 decay
- Process at rest (well isotropic)
- Can not be mimicked by cold neutron capture events (however they must be considered as load in detectors)
- **Cosmic background must be suppressed**



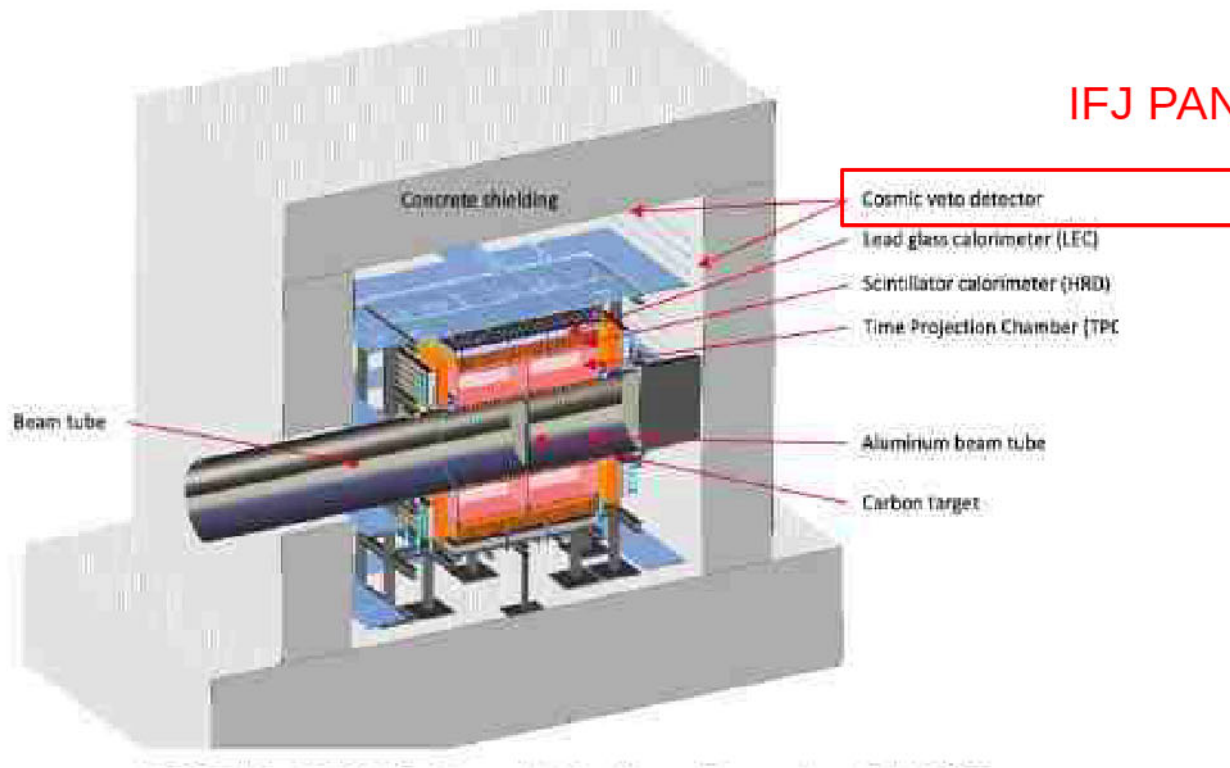
~ 0.1 mm Carbon foil

$$\sigma_{\bar{n}C} \approx 4 \text{ kb}$$

$$\sigma_{nC} \approx 4 \text{ mb}$$

Annihilation detector components

IFJ PAN

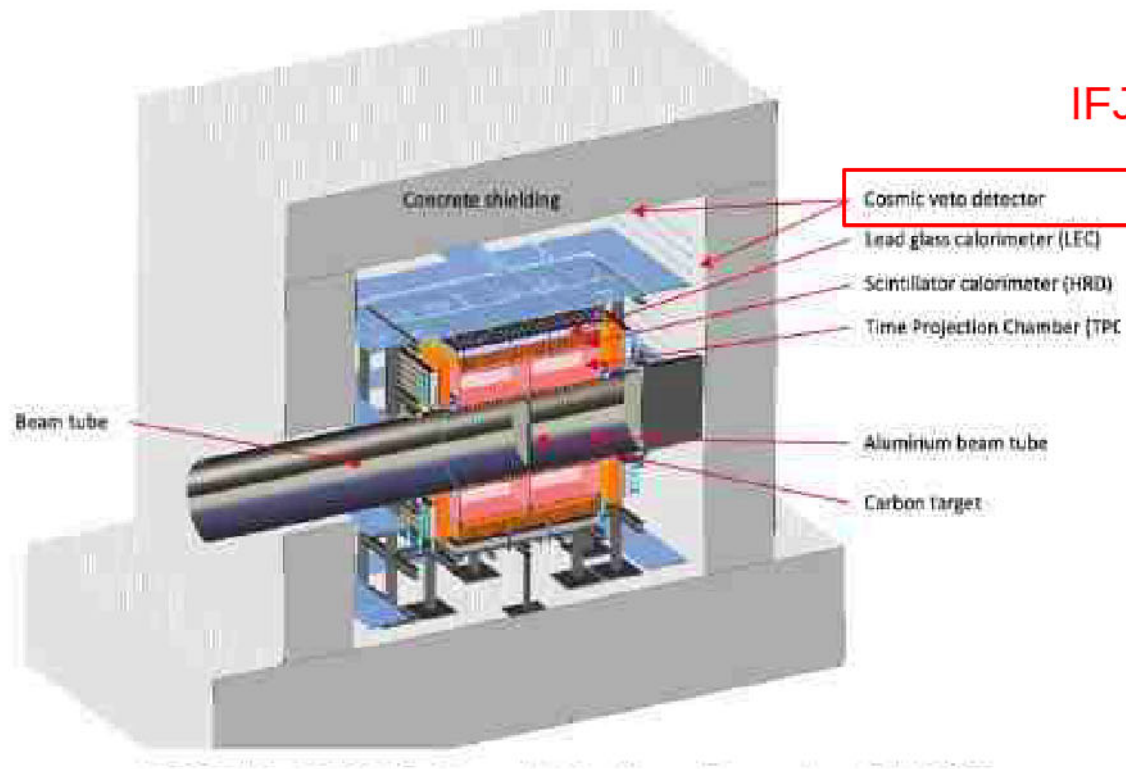


Final version

Adam Kozela

Kraków, 01.12.2025

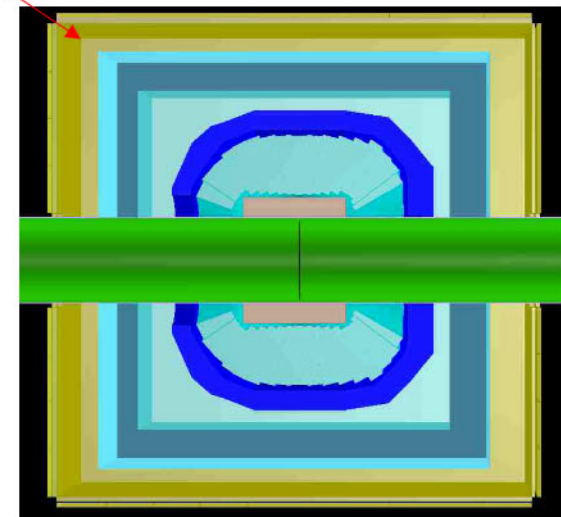
Annihilation detector components



Final version

Adam Kozela

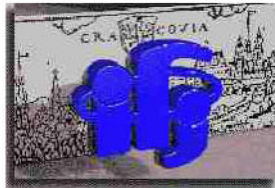
IFJ PAN



HIBEAM version

Kraków, 01.12.2025

HIBEAM-NNBAR-PL



Adam Kozela
Krzysztof Pysz
Hritik Gogoi

...



Tadeusz Pałasz
Michał Silarski

...

Contribution to tasks:

- Cosmic VETO detector
- Neutron ^3H polarizer
- Test of TPC
- ...

THANK YOU !