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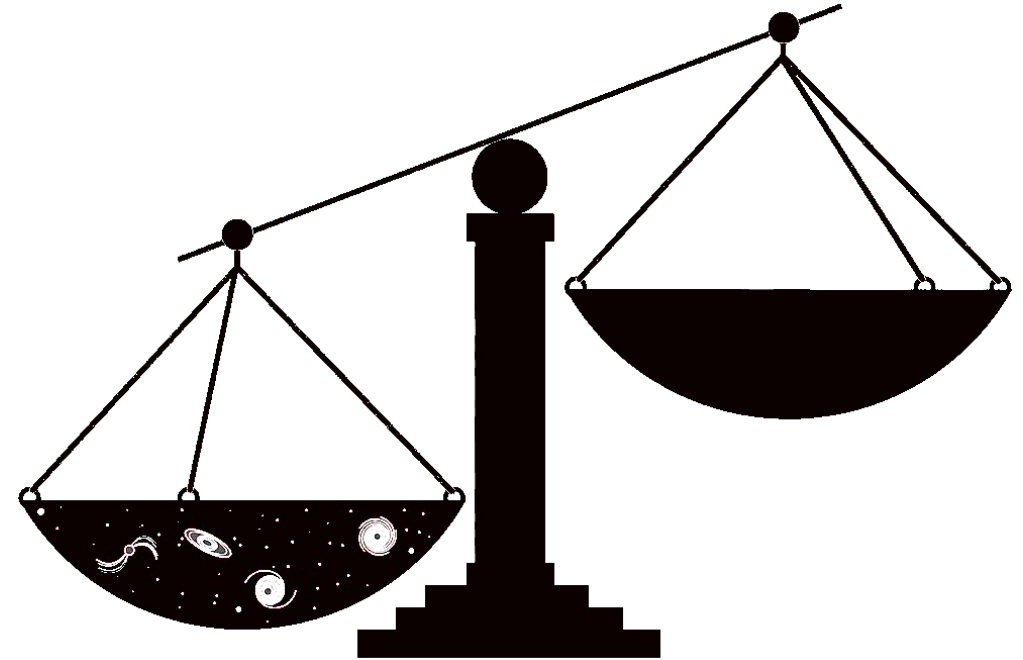
# High-Precision Searches for Baryon Number Violation Using HIBEAM

MATTHIAS HOLL FOR THE HIBEAM COLLABORATION



# Neutron-Antineutron Oscillations

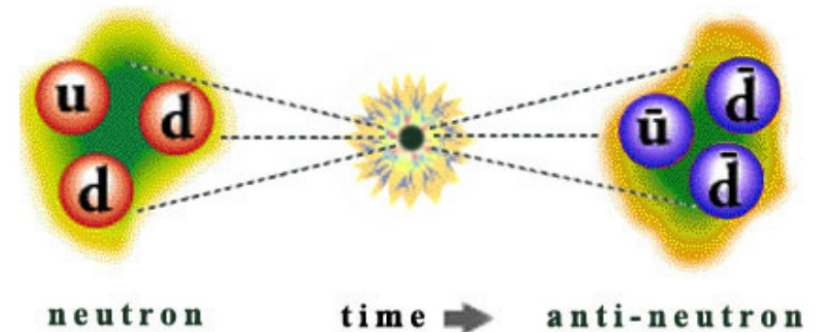
- The reason for the matter-antimatter asymmetry in the universe remains not understood.
- Sakharov conditions
  - Departure from thermodynamic equilibrium
  - C and CP Violation
  - **Baryon Number Violation**
- Neutron oscillations are possible candidates for processes with  $\Delta B \neq 0$



Credit: Symmetry Magazine / Sandbox Studio, Chicago

# Neutron-Antineutron Oscillations

- Neutral particle oscillations have played large role in particle physics
  - Neutrino Oscillations
  - Kaons and B-mesons: CP violation
- In neutron oscillations baryon number would be violated independently of other quantities
  - $n \rightarrow \bar{n}$  ( $\Delta B=2, \Delta L=0$ )
  - $n \rightarrow n'$  ( $\Delta B=1, \Delta L=0$ )
- Features generically in many extensions of the Standard Model
- Searches for free neutron-antineutron conversions are experimentally extremely challenging



# Experimental Sensitivity

$$\hat{H} \leftrightarrow \begin{bmatrix} E_n & \varepsilon \\ \varepsilon & E_{\bar{n}} \end{bmatrix}$$



$$P_{n\bar{n}}(t) = \frac{\varepsilon^2}{(\Delta E/2)^2 + \varepsilon^2} \sin^2(\sqrt{(\Delta E/2)^2 + \varepsilon^2} \cdot t)$$

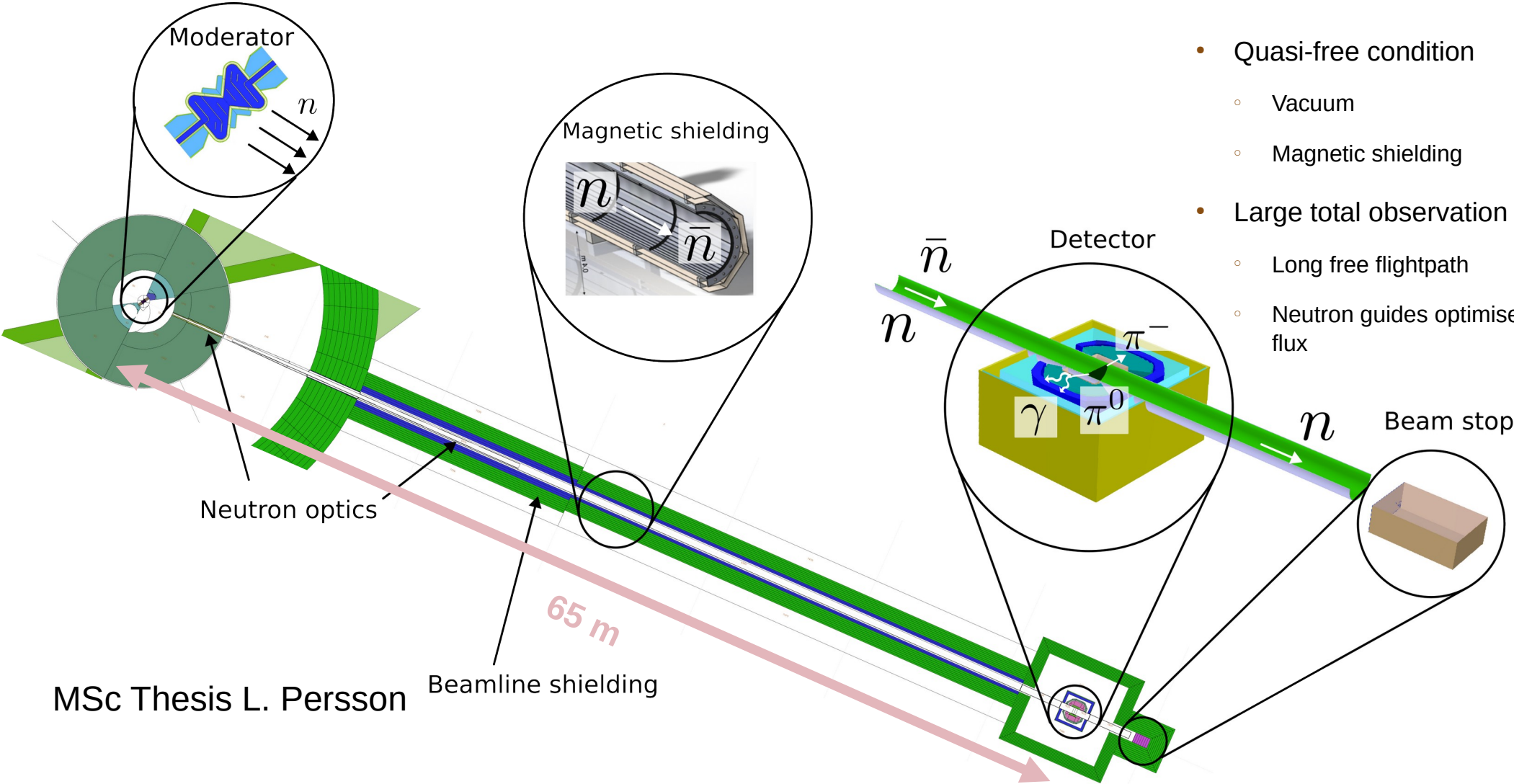


$\Delta E$  small

$$P_{n\bar{n}}(t) = \varepsilon^2 \cdot t^2$$

- Requirement: Quasi-free condition
  - Vacuum
  - Magnetic shielding
- Large total observation time
  - High neutron intensity
  - Long beamline
  - Low average neutron energy
- Small oscillation probability
  - High detection efficiency
  - Background-free measurement
- Most stringent limit obtained 30 years ago at ILL:  
 $\tau_{n\bar{n}} = 8.6 \cdot 10^7$  s
  - Bound  $n$ :  $\tau_{n\bar{n}} = 4.6 \cdot 10^8$  s (Super-Kamiokande, 2022)

# The HIBEAM Beamline



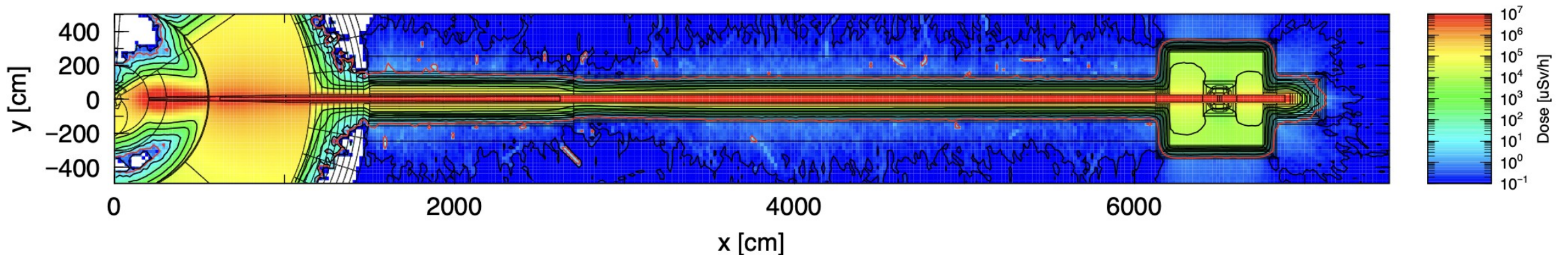
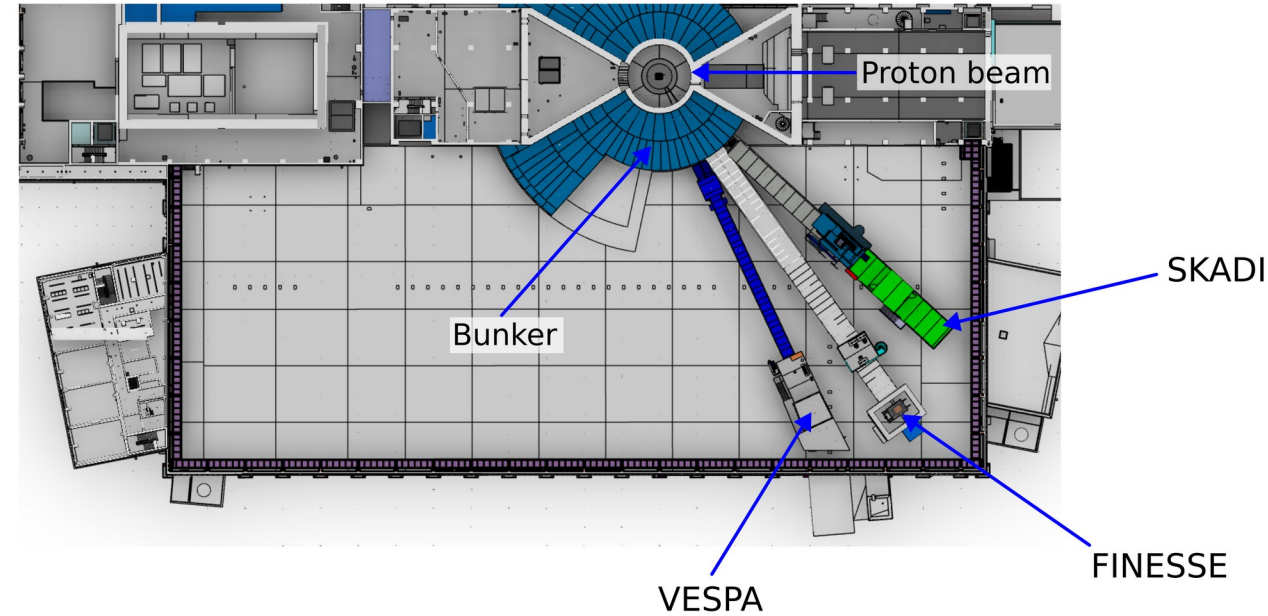
- Quasi-free condition
  - Vacuum
  - Magnetic shielding
- Large total observation time
  - Long free flightpath
  - Neutron guides optimised for cold neutron flux

MSc Thesis L. Persson



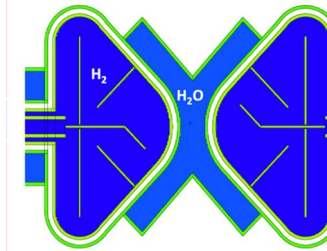
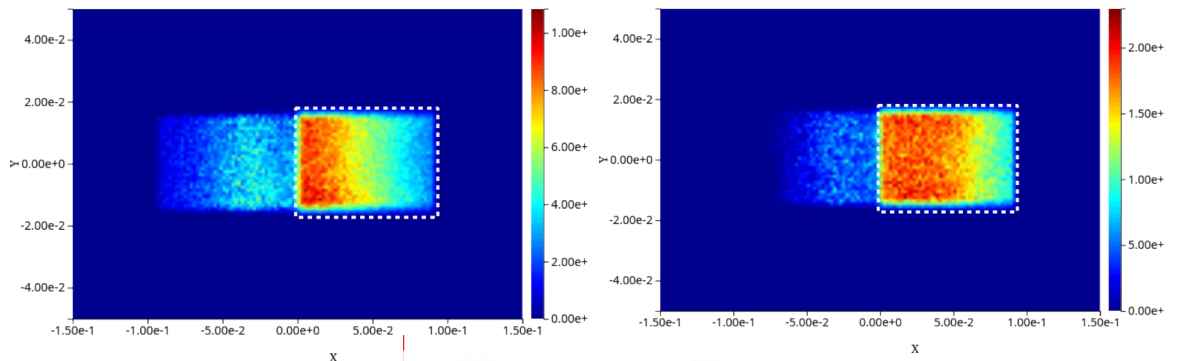
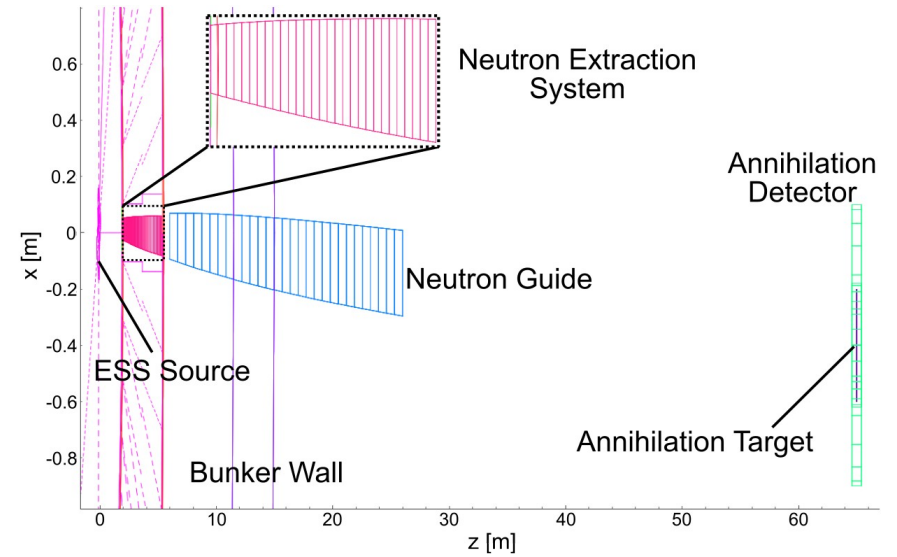
# Beamline Status

- A suitable location could be in the east sector of the ESS experimental hall
- Part of the FINESSE proposal to the "Call for Input to the ESS Instrument Roadmap"
- The radiation shielding of the beamline has been fully designed



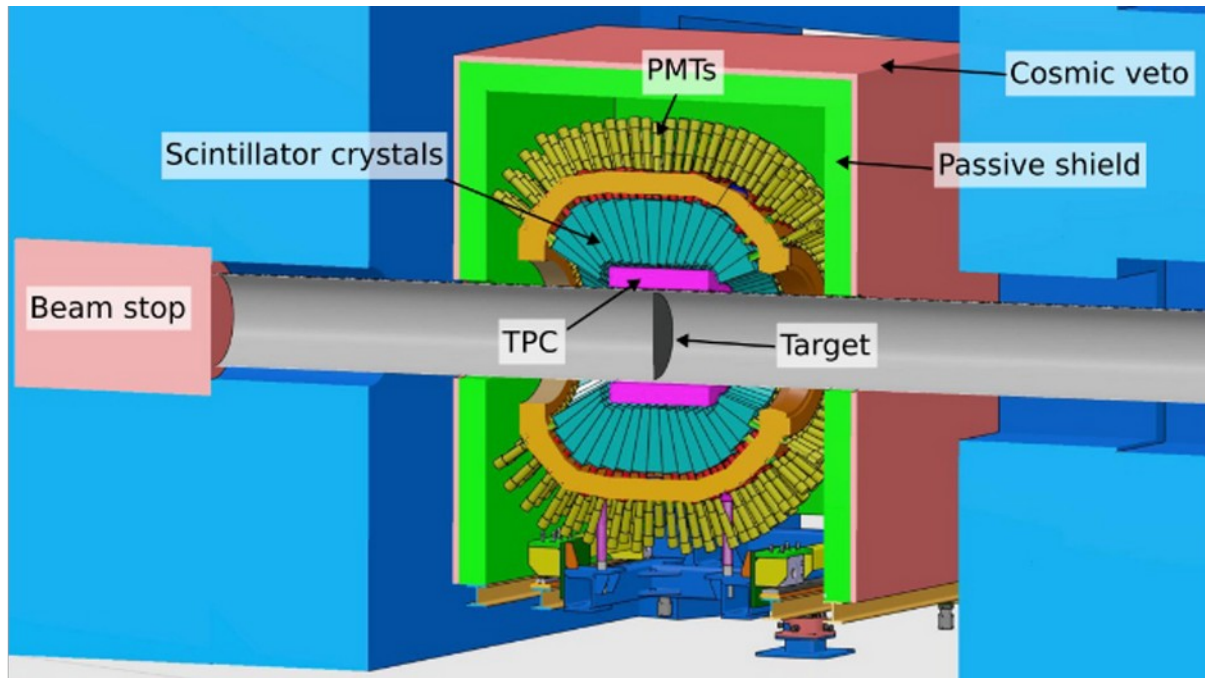
# Beamline Optics

- Neutrons produced at ESS by proton beam hitting tungsten target wheel
- Slowed down in liquid H<sub>2</sub> neutron moderator above the target wheel
- Distributed to experiments via beamports with dedicated guide systems
- HIBEAM: Guides optimized for cold neutron flux
  - asymmetric design
  - guide accepts neutron from entire cold wing of butterfly moderator
- Expected sensitivity from McStas simulations
  - 10<sup>12</sup> neutrons,  $\langle E \rangle = 5.7$  meV ( $\sim 1000$  m/s)
  - $t^2 \sim 2.5 \times \text{ILL/year}$



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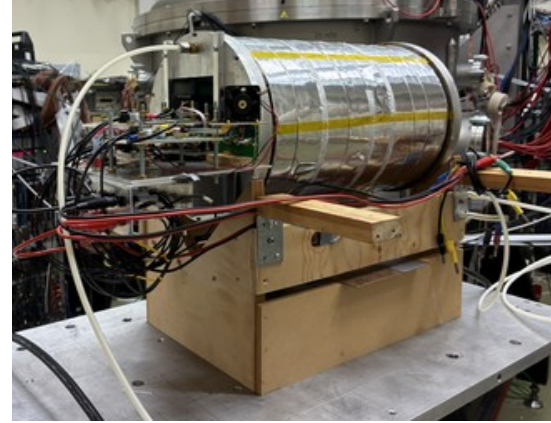
# The Annihilation Detector



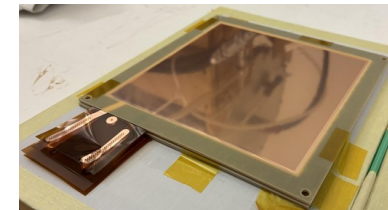
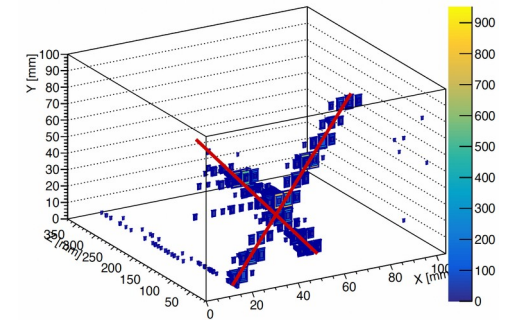
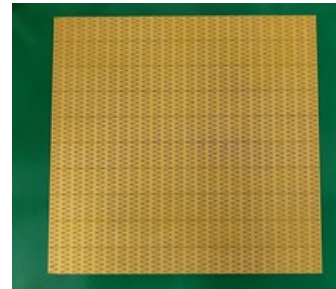
- Task: Distinguish signature of an  $\bar{n}$  interacting with target from spallation and cosmic background
  - 3-5 charged pions and photons from  $\pi^0$  decay
- background-free measurement in high radiation environment
- No magnetic field
- Current design
  - TPC
  - WASA electromagnetic calorimeter
    - Alternative: Plastic scintillators + Lead glass
  - Cosmic Veto (plastic scintillators)

# TPC Prototype

- Cylindrical prototype
  - Ar/CO<sub>2</sub> mix
  - projected track length 10cm
  - Longest drift 23cm (HIBEAM ~25 cm)
- Readout:
  - Triple GEM
  - Zigzag pad plane
  - SALTRO + MCM + SRU
- Developed new tracking algorithm
- Next TPC prototype in development
  - Close to final dimensions



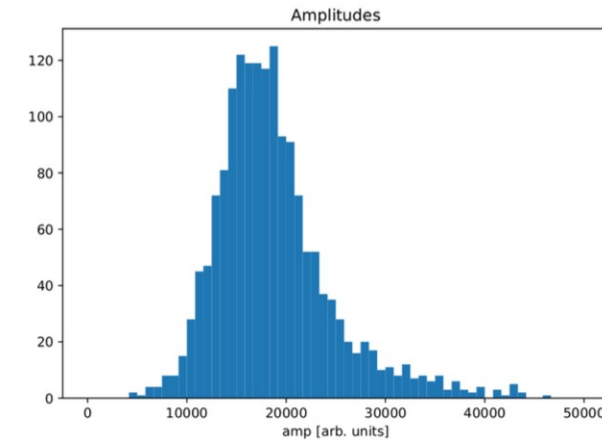
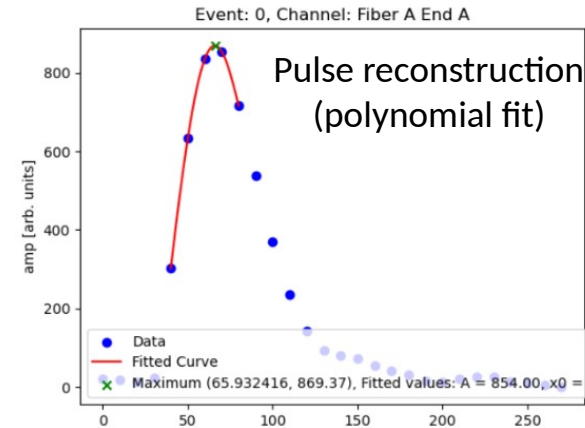
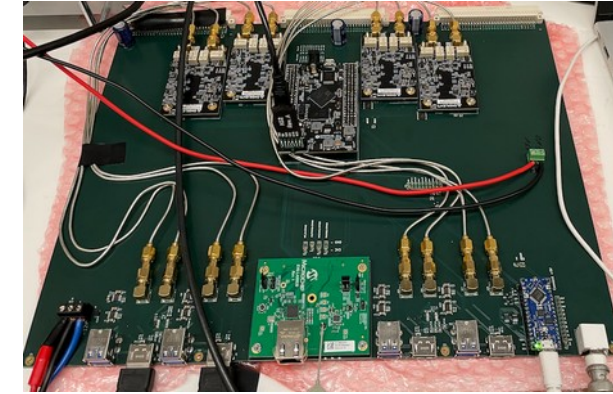
B. Rataj,  
A. Oskarsson



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# Plastic Scintillators

- Prototype staves
  - 50 cm x 5 cm x 2 cm
  - 2 WLS fibers per stove
  - Readout via SiPMs
- Prototype 8-channel readout board for HRD and LEC
  - Based on commercial FPGA, ADC, Ethernet and microcontroller modules
- Cosmic pulse reconstruction studies
  - Time & amplitude reconstruction with a polynomial fit to shaper outputs
  - Initial timing resolutions of 1-1.2ns achieved (mean of 2 stove-end fibers)

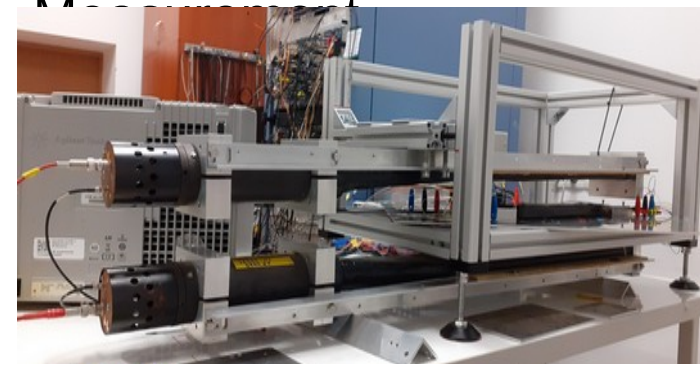
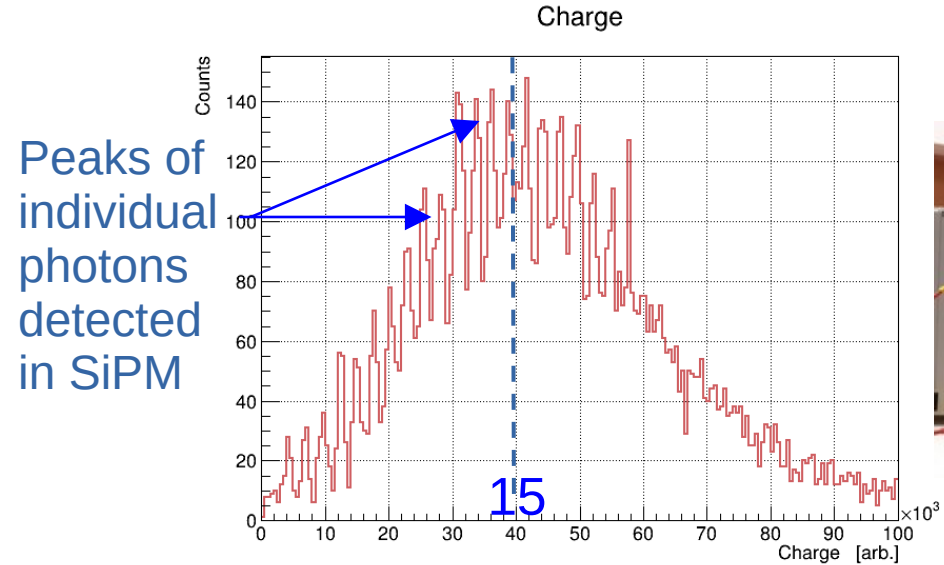
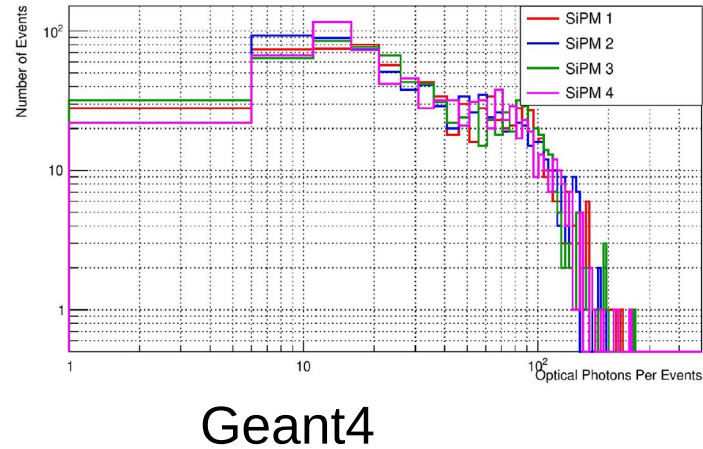


Sam Silverstein, Nina Ewest



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# Cosmic Veto



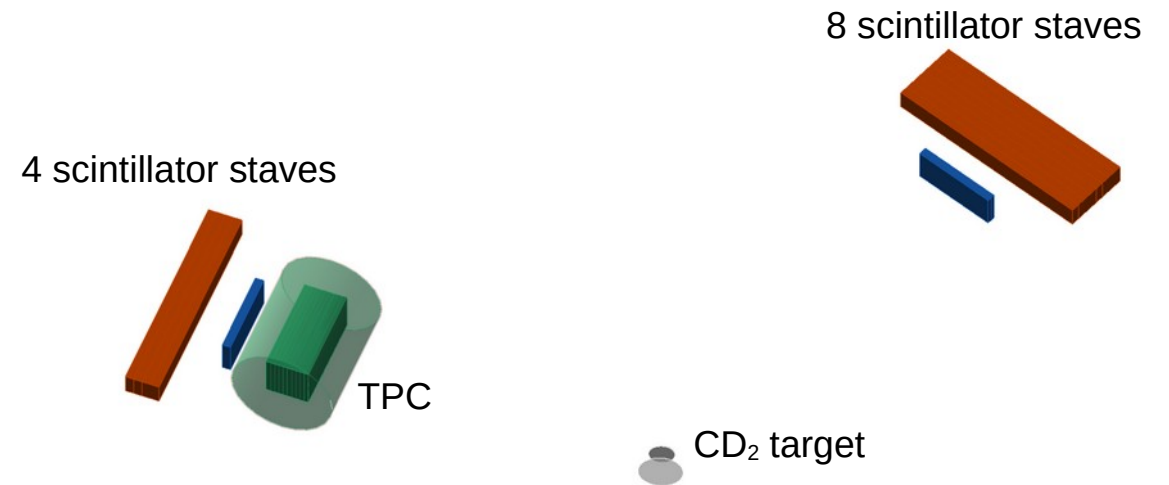
- The detected amount of photons in the light sensors will be small ~a few tens only.
- Confirmed independently by simulations and in measurement
- WLS fiber readout suitable for position sensitive detector?

K. Pysz

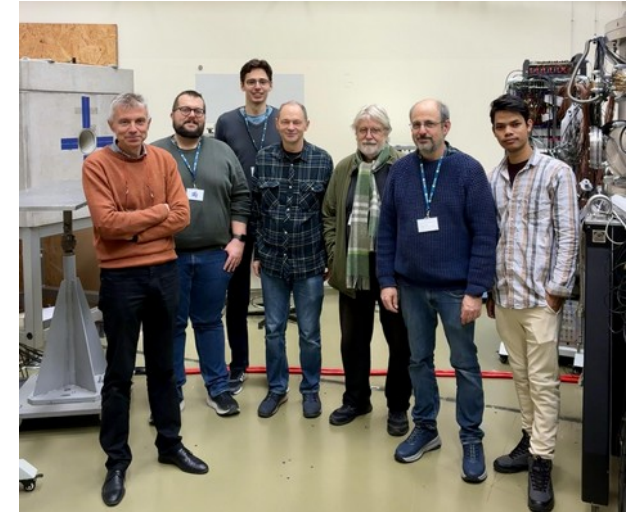
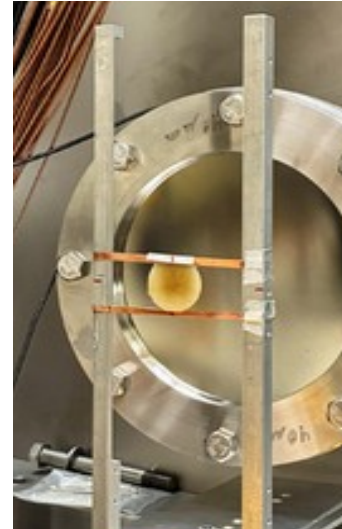
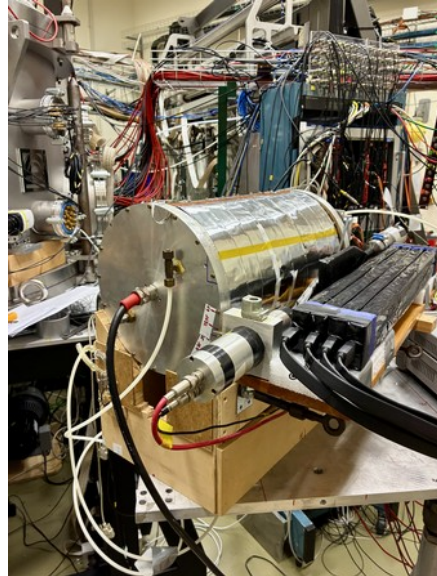


# Test Experiment in December 2025

- Performed at the Cyclotron Centre Bronowice at the Institute of Nuclear Physics PAN in Krakow
  - Beam energy: 190 MeV
  - Intensities up to 20 nA
  - 6 shifts
- Measuring elastic scattering of proton beam on a  $\text{CD}_2$  target
- Experimental goals
  - investigate capability of TPC and scintillators to provide particle identification
  - investigate TPC performance at high track density
  - Test scintillator electronics
  - Validation of Geant4 simulations and tracking algorithm

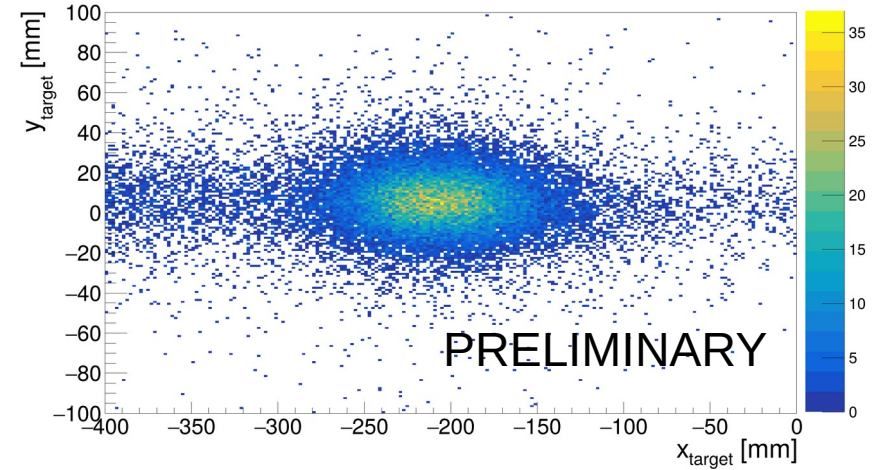
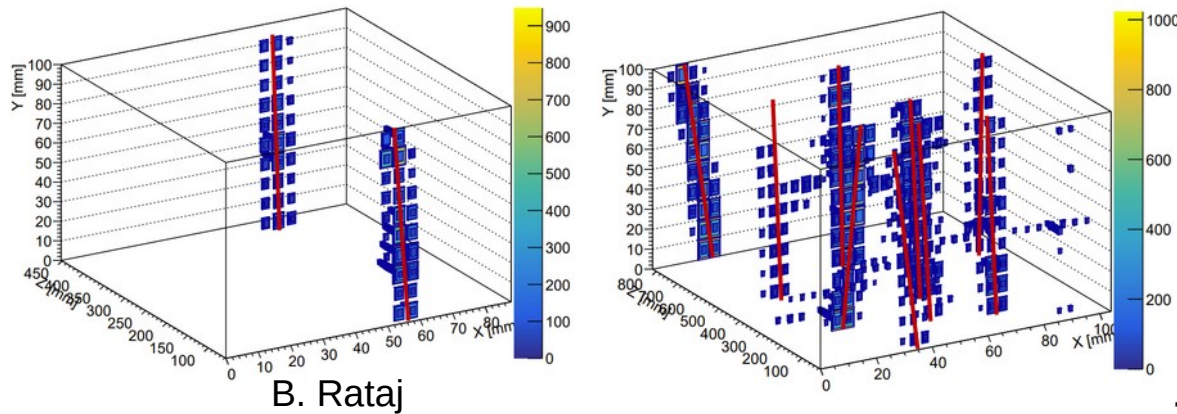


# Test Experiment at CCB

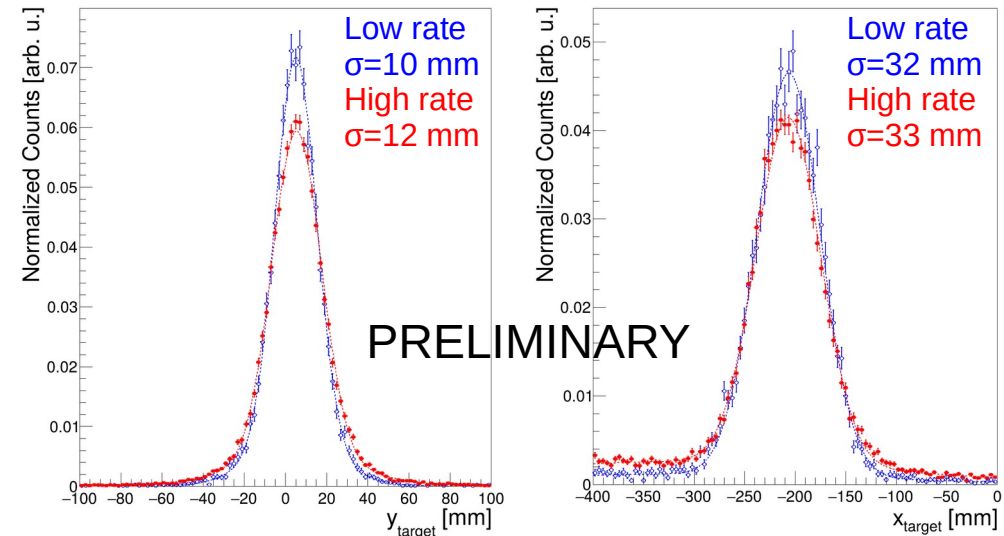


B. Rataj

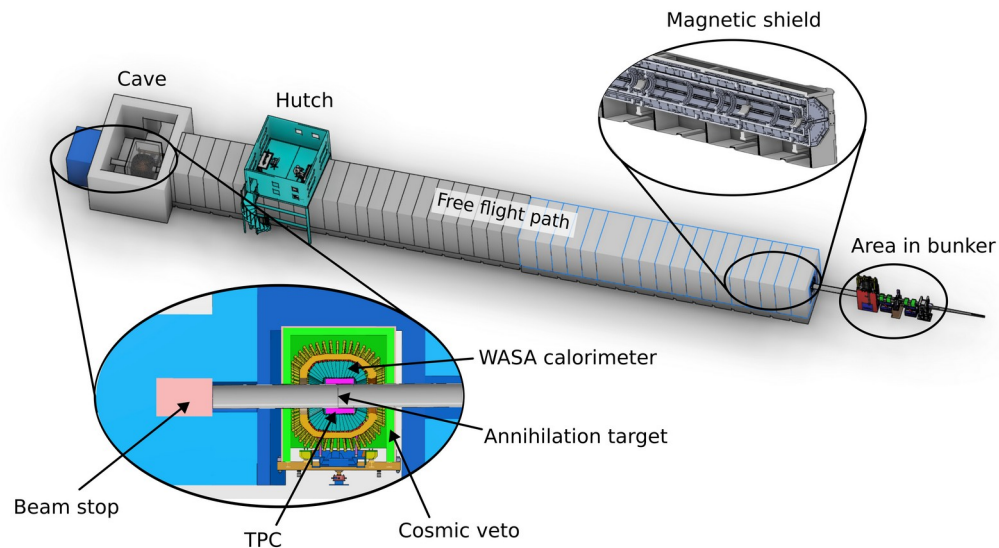
# Test Experiment at CCB



- Reconstructed beamspot on target from TPC tracks
- Compared low ( $<10^4$  pps) and high rate ( $\sim 10^5$  pps) runs
- Spatial resolution of TPC deteriorates for higher rate, but within acceptable margin
- Scintillator analysis and Particle ID ongoing



# The FINESSE Beamline



- FINESSE is a proposed beamline allowing for a wide range of particle physics experiments at the ESS
- Wide range of physics enabled by dual guide
  - Neutron-antineutron oscillations
  - Dark matter searches
    - Sterile neutrons
    - Axion-like particles (talk by Linus Persson on Thursday)
    - Neutron capture
  - Neutron electric dipole moment
  - Neutron decay
  - Non-zero neutron charge
  - Hadronic parity violation

# NNBAR



# Summary

- ESS provides unique opportunities for particle physics with intense cold neutron beams
- HIBEAM proposes to measure neutron oscillations with high precision
- A full design of the beamline, including radiation shielding and neutron optics, has been developed
- The development of the annihilation detector is ongoing
  - First in-beam test of detector prototypes in December 2025

# Funding

- Part of a 3 M€ INFRADEV Study for the ESS upgrade (HighNESS).
- Ongoing support from a VR RFI grant (10 MSEK + 4 MSEK).
- Stiftelsen för Strategisk Forskning (SSF) grant (15 MSEK).
- Funding from Olle Engkvists Stiftelse (4 MSEK).
- VR grant for collaboration with Italy and a VR project grant (0.75 MSEK).
- Support from the Crafoord Foundation (1.2 MSEK).

# The HIBEAM/NNBAR Collaboration



Thank you for your attention!