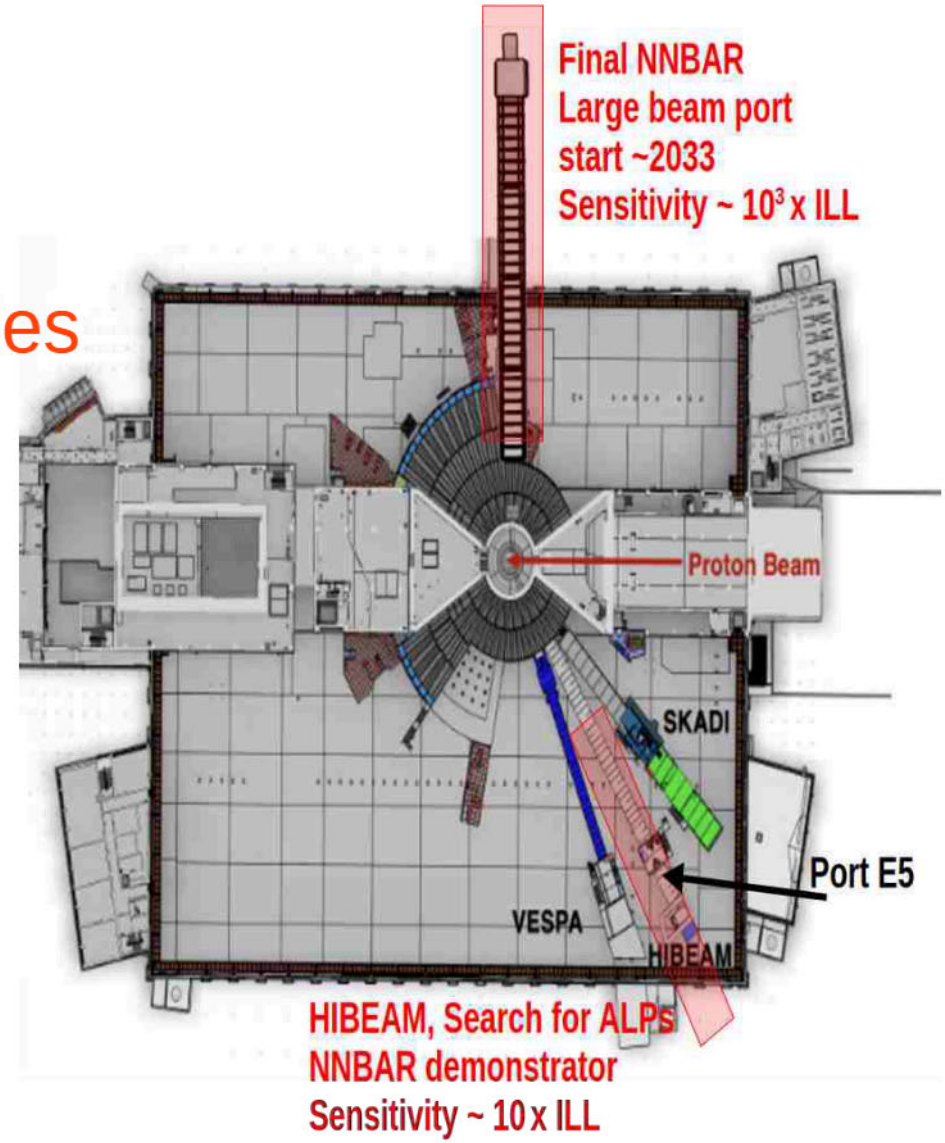
Search for Physics Beyond Standard Model at European Spallation Source in Lund

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

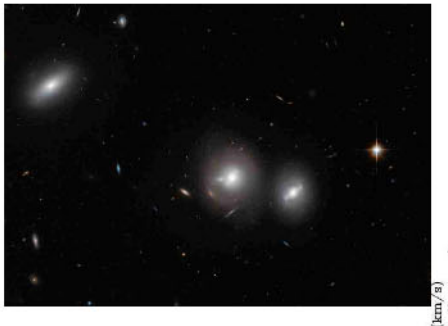
Canonical axion proposed in 1978 by Peccei, Quin to solve
Strong CP Problem

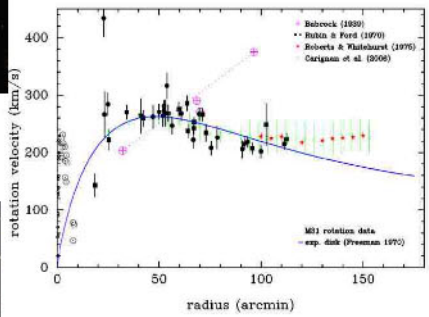
as not observed in high energy collisions abandoned

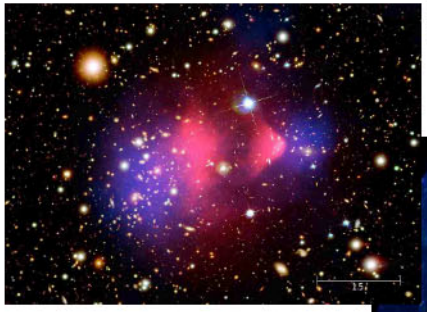
returned as Axion-Like Particle to solve Dark Matter Problem

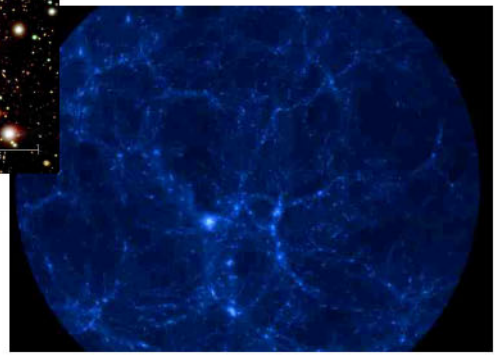
Dark Matter problem

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









HIBEAM and axions or ALPs

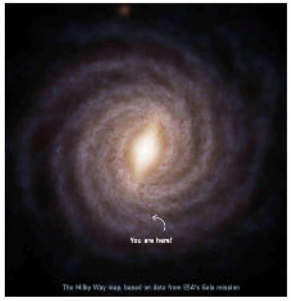
Ultra low mass bosons

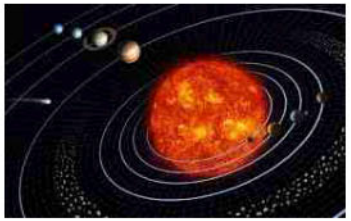
WIMPs

10^{-21} eV — feV — eV — GeV — TeV

Wave-like signature

Particle-like signature





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

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

Axion-nucleon coupling:

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

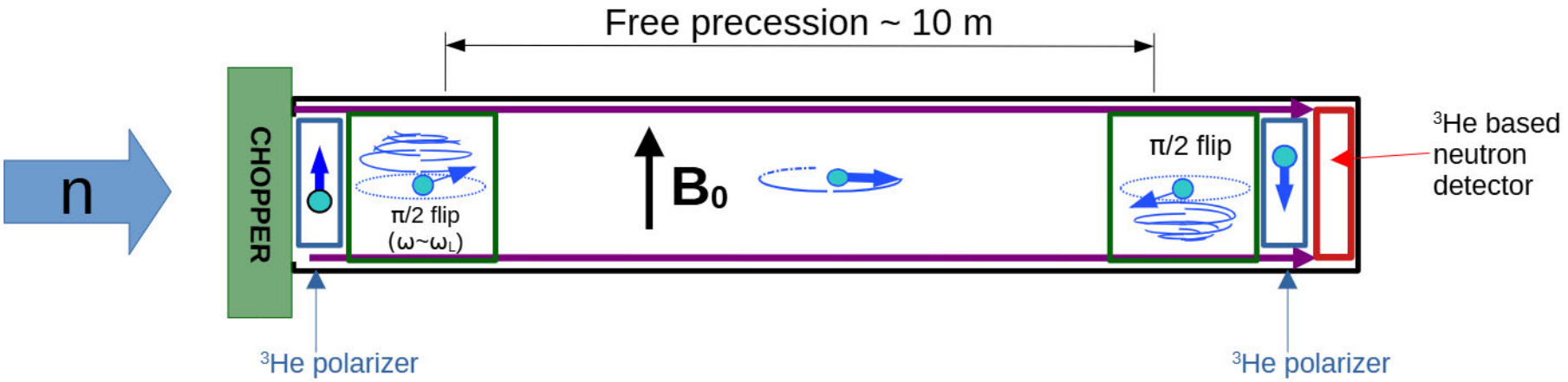
$$H_a(t) = \frac{C_N \, a_0}{2 f_a} \sin(m_a t) \boldsymbol{\sigma}_N \cdot \boldsymbol{p}_a$$

Precession of $\boldsymbol{\sigma}_N$ around direction of ALP "wind" $\boldsymbol{p}_a$

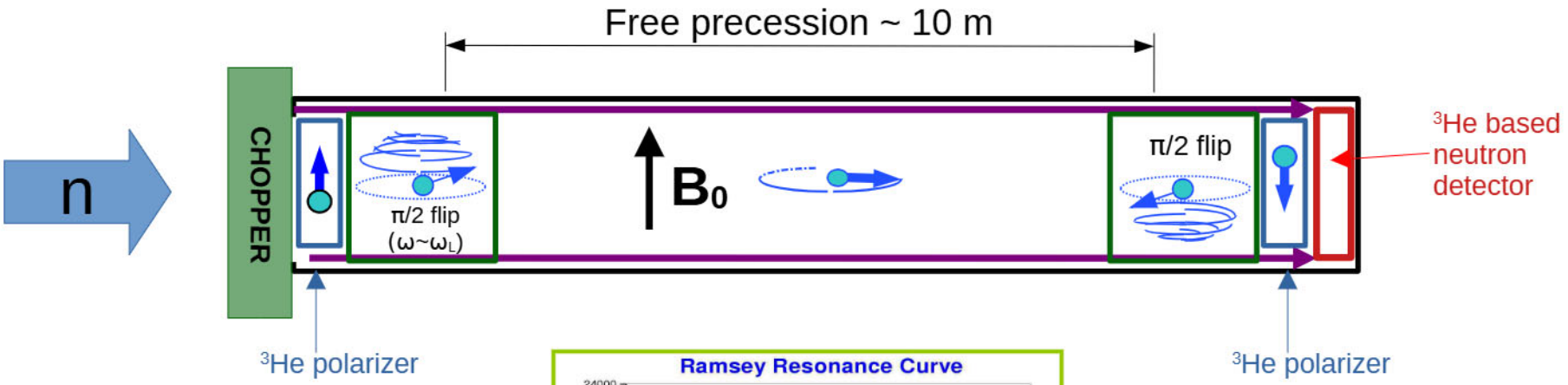
Indistinguishable from Larmor precession around magnetic field lines:

$$H_m(t) = -\gamma \, \boldsymbol{\sigma}_N \cdot \boldsymbol{B}$$

HIBEAM and axions or ALPs



HIBEAM and axions or ALP

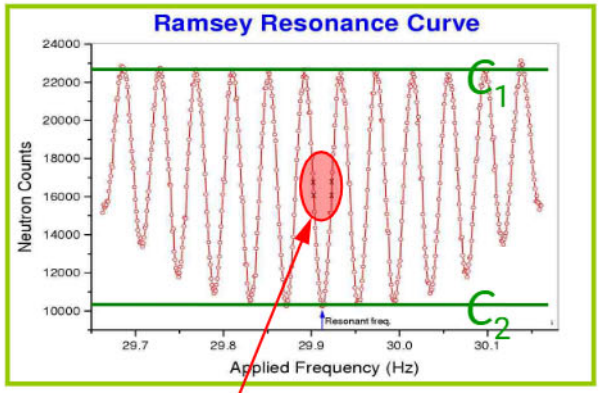


Experimental precision:

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

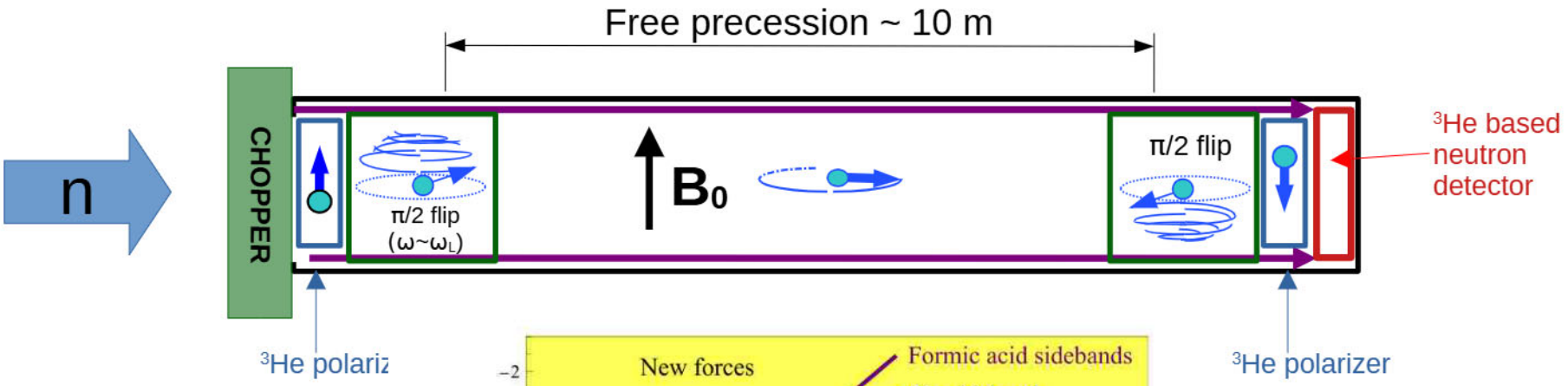
where *T* is free precession time, *N* number of neutrons and α is the resonance visibility:

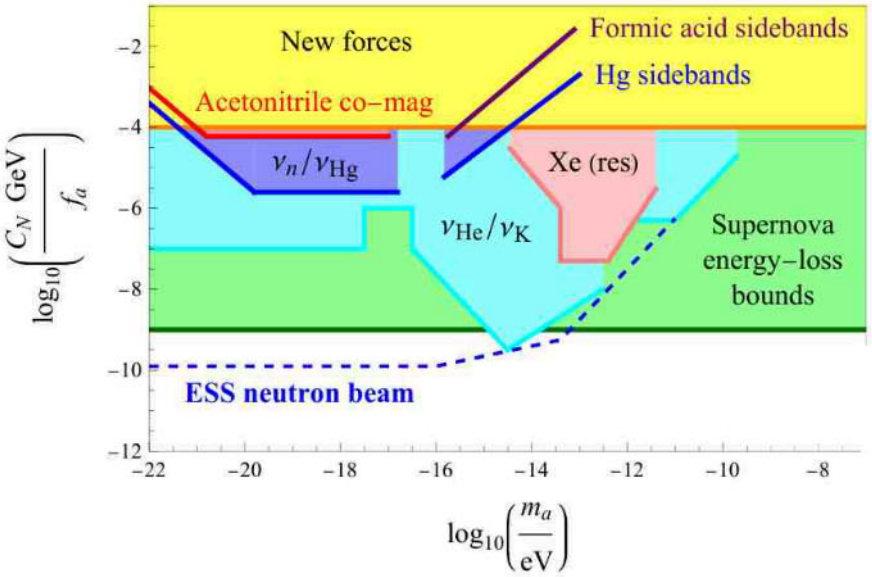
$$\alpha = \frac{(C_1 - C_2)}{(C_1 + C_2)}$$



4 working points
ω close to Larmor freq.

HIBEAM and axions or ALP





Up to 3 orders of magnitude
Improvement of current limits

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

Neutron-antyneutron 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

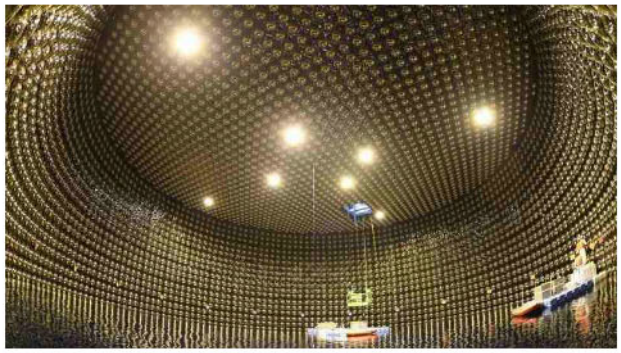
Best experimental limits for $n\,\bar{n}$ oscillation :

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

but: Suppression factor must be accounted for → theoretical uncertainties

irreducible background from high energy cosmic neutrinos:

found 11 candidate events when expected ~ 9±3



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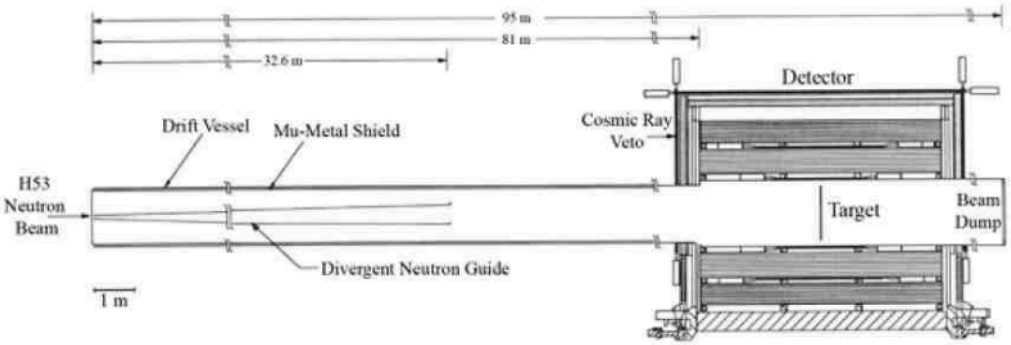
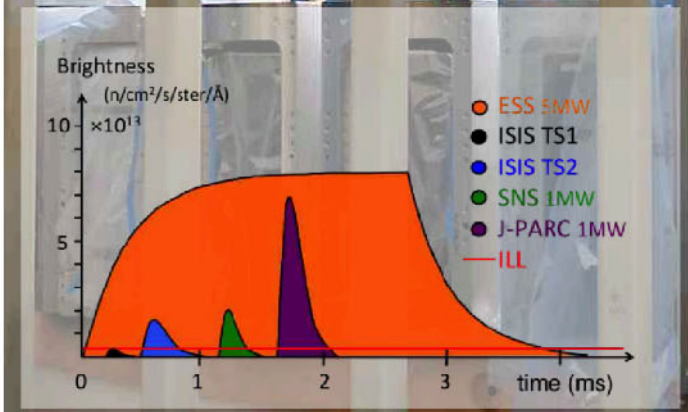
- ILL, Grenoble, *M.Balbo-Ceolin at al.* Z. Phys. C63 (1994) 409: $\tau_{n\bar{n}} > 0.86 \cdot 10^8\,s$,

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

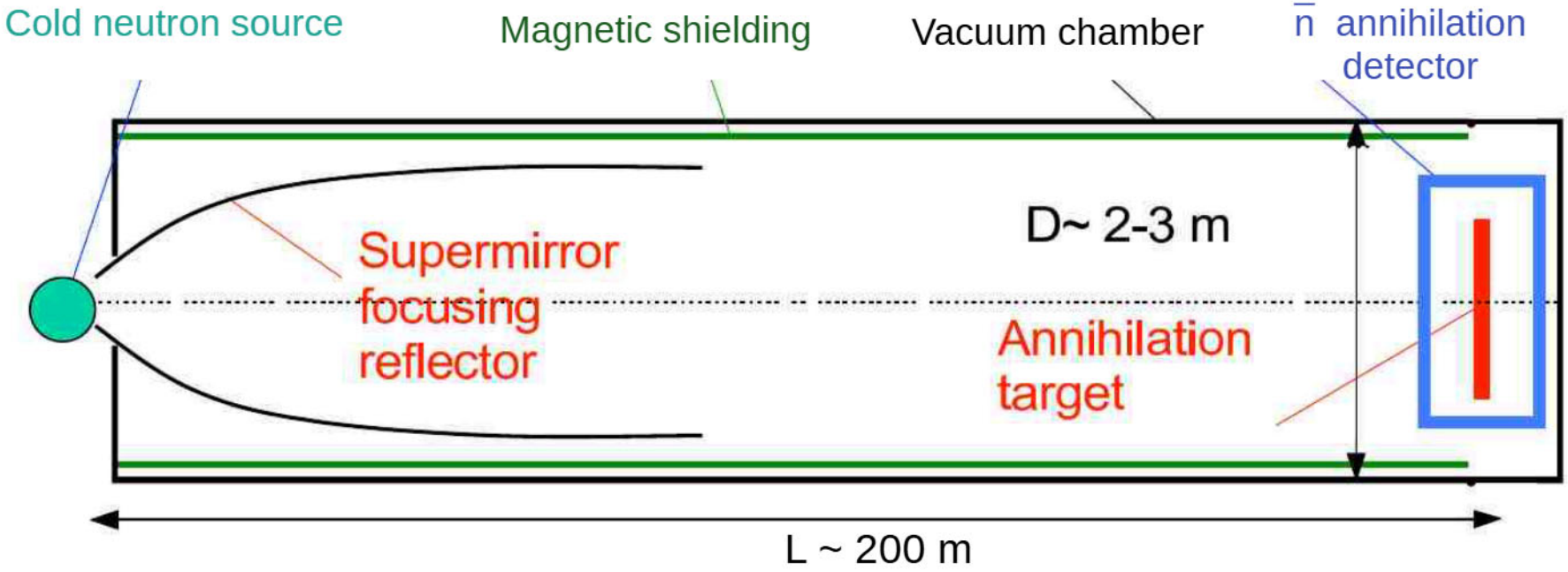


Neutron-antyneutron oscillations
Large Beam Port of ESS

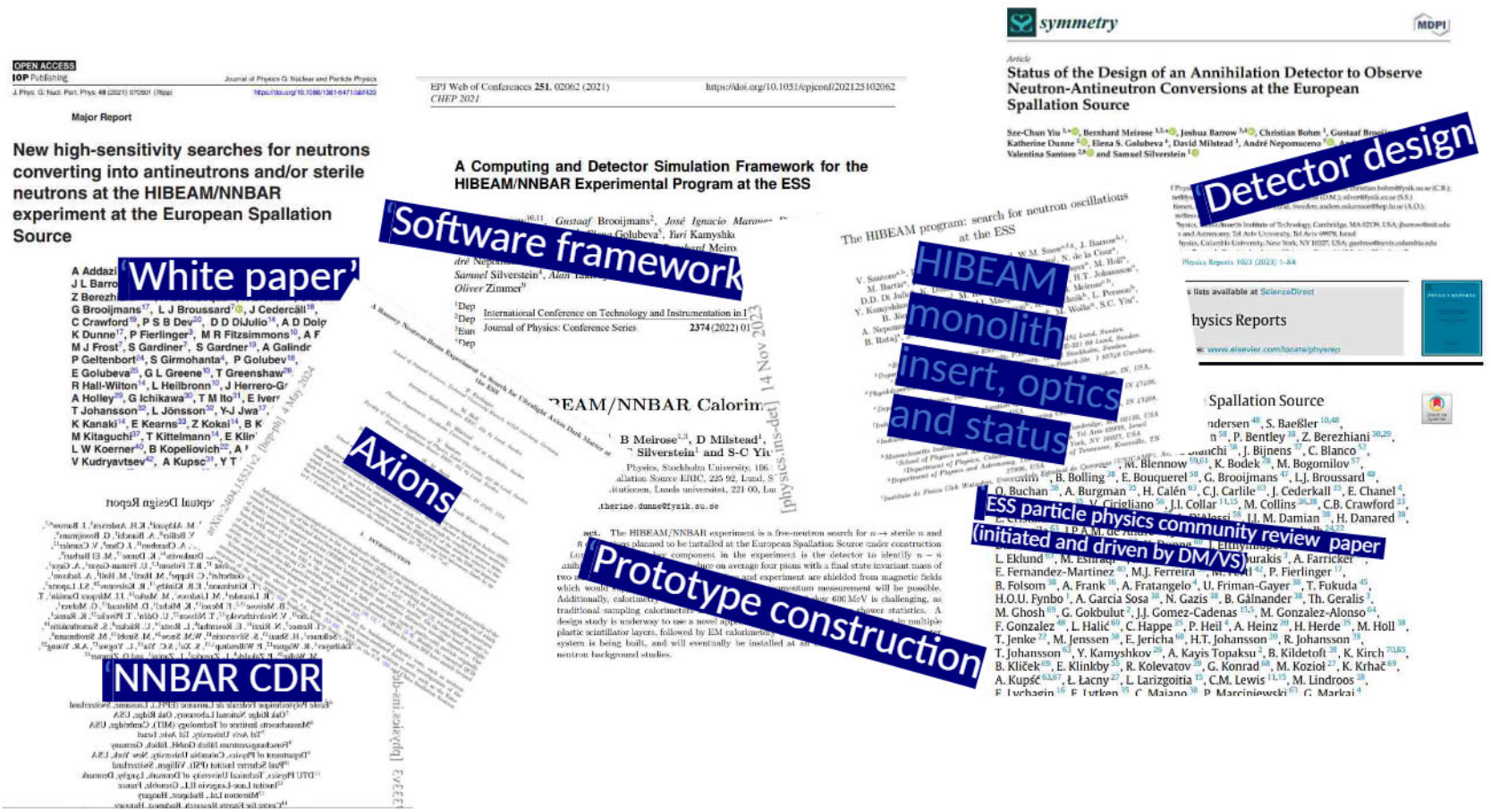


NNBAR Large Beam Port has been constructed to provide sufficient intensity of **1.5×10^{15} n/s**
there is no beamline **currently available or planned at any other facility that could reach a flux even close to this number**

HIBEAM-NNBAR @ ESS measurement principle



$$FoM \propto n \cdot t^2$$ ← free flight time



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

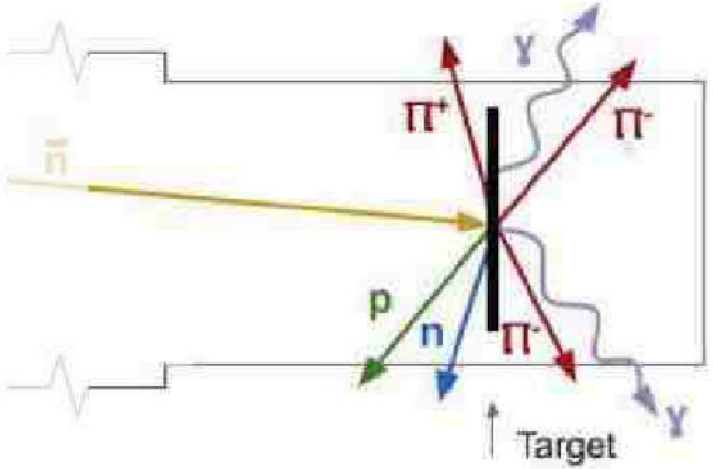
+ Proc AccApp 21 (arXiv: 2204.04051 [physics.ins-det])

+

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



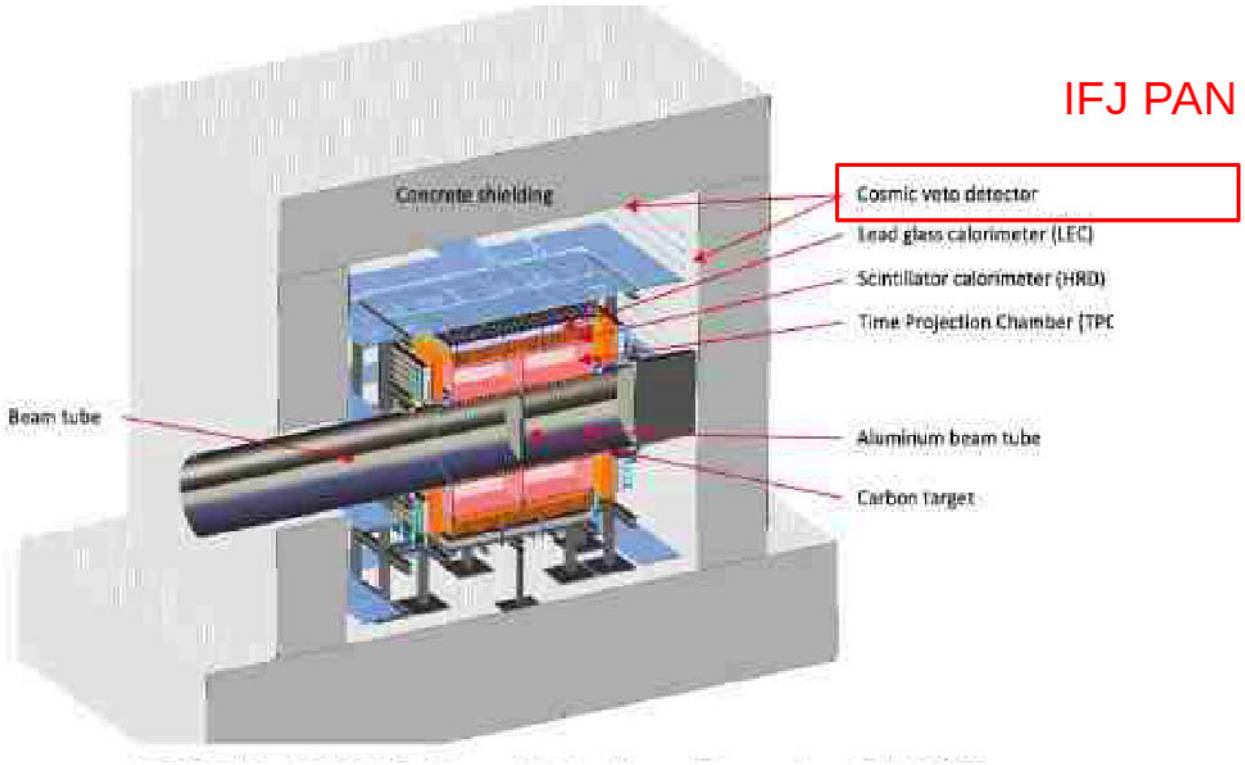
~ 0.1 mm Carbon foil

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

$\sigma_{nC} \approx 4$ mb

Annihilation detector components

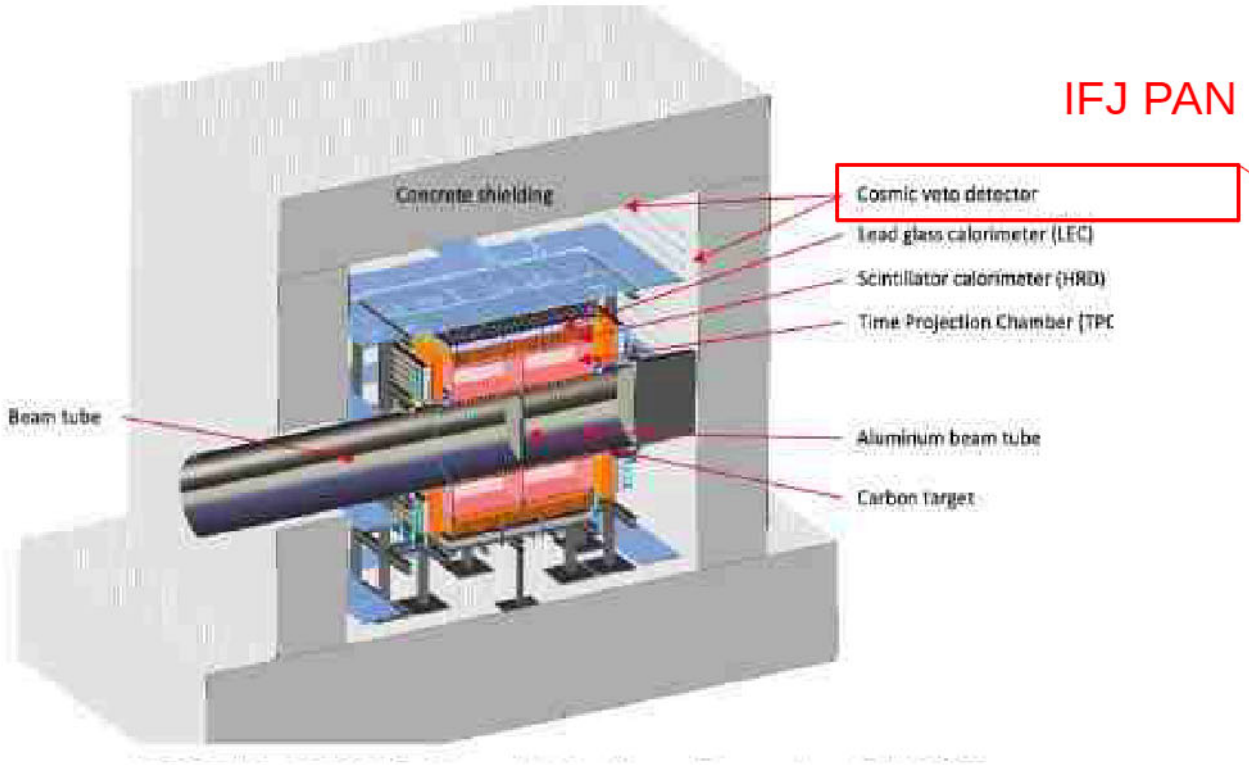
IFJ PAN

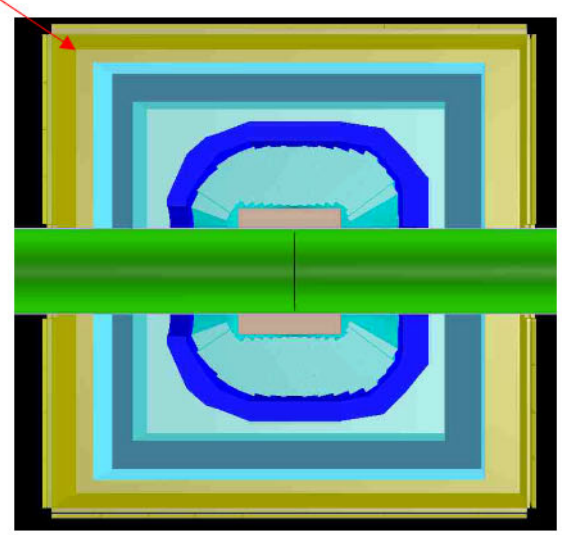


Final version

Annihilation detector components

IFJ PAN





Final version

HIBEAM version

HIBEAM-NNBAR-PL

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Tadeusz Pałasz
Michał Silarski
...

Contribution to tasks:

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

THANK YOU !

Adam Kozela

Kraków, 01.12.2025