Progress towards a program of searches for neutron conversions at the European Spallation Source with the HIBEAM/NNBAR experiment

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NNBAR

https://nnbar.eu/

Motivation in one minute

- Baryon number violation essential condition for baryogenesis
- Baryon number an accidental SM symmetry and is broken in extensions
- Neutron oscillations to antineutrons or sterile neutrons unique probe of BNV processes in which only BN is violated.
- Neutron oscillations in SUSY, dark matter (hidden sector), baryogenesis, extra dimensions
- An opportunity to test a global symmetry with three orders of magnitude better precision than previously done is rare. Even rarer to do it in Sweden.

NNBAR

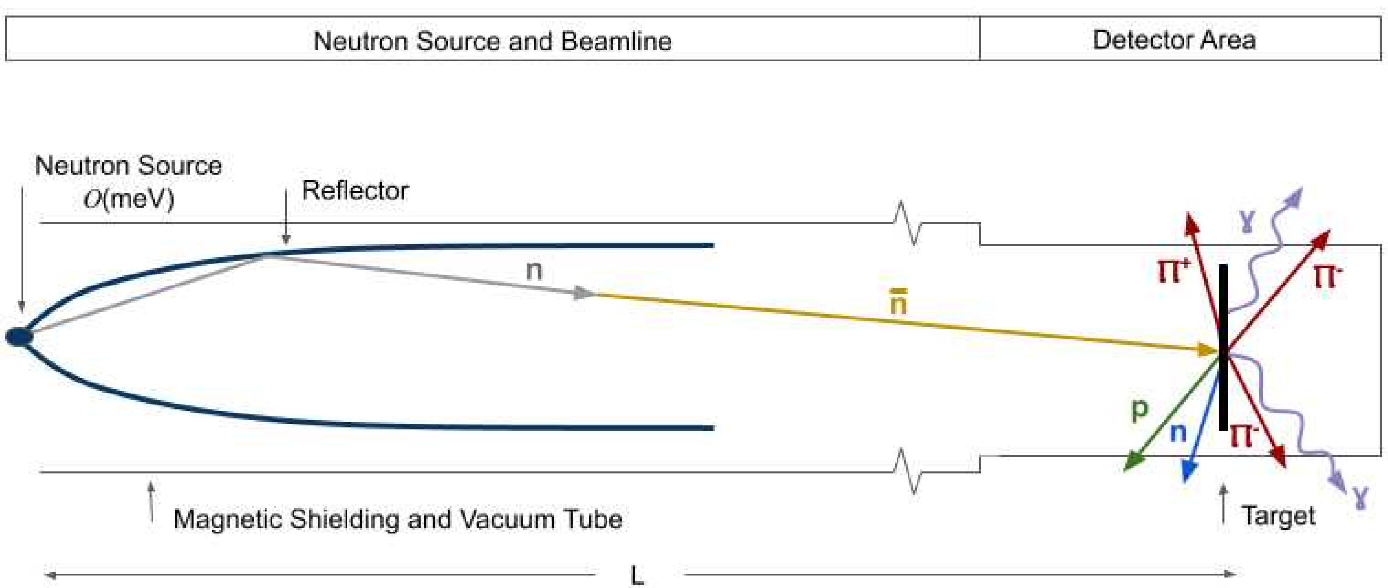
Free NNBAR search in 1 minute

- Goal: observe neutron → antineutron
- Sensitivity 3 orders of magnitude greater than previous experiment
- Strategy: let as many cold neutrons "fly" for as long as possible
- Probability of free neutron transformation into an antineutron:

$$P(\bar{n},t)=(t/\tau)^2 \qquad \text{FOM}= Nt^2$$

- t → neutron flight time; τ → "oscillation time" (BSM predicted, model dependent)

$\tau > 8.7\ 10^7$s (ILL)



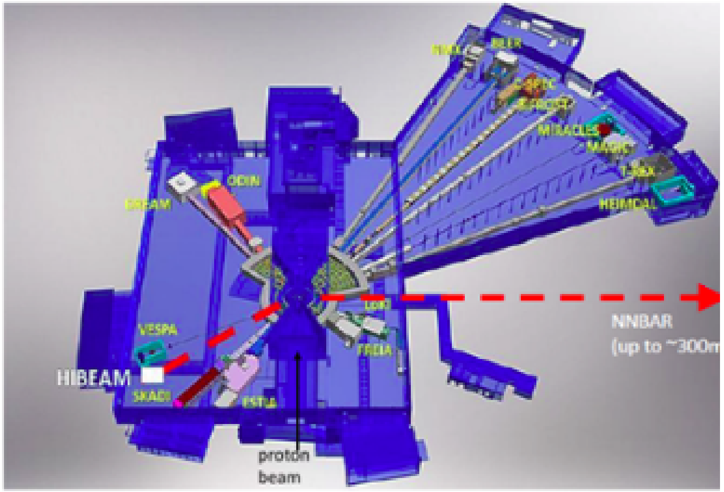
European Spallation Source (ESS)

- Most powerful neutron source
- Place: Lund, Sweden
- Under construction (user program starts 2023)

EUROPEAN SPALLATION SOURCE

HIBEAM and NNBAR

- Staged experiment
- 1. HIBEAM (high intensity baryon extraction and measurement)
  - mid to late 2020's
  - world leading searches n → n'
  - search for n → nbar (with lower sensitivity)
  - also search for n → nbar via sterile neutrons. *First such search*.
  - R&D for full experiment.

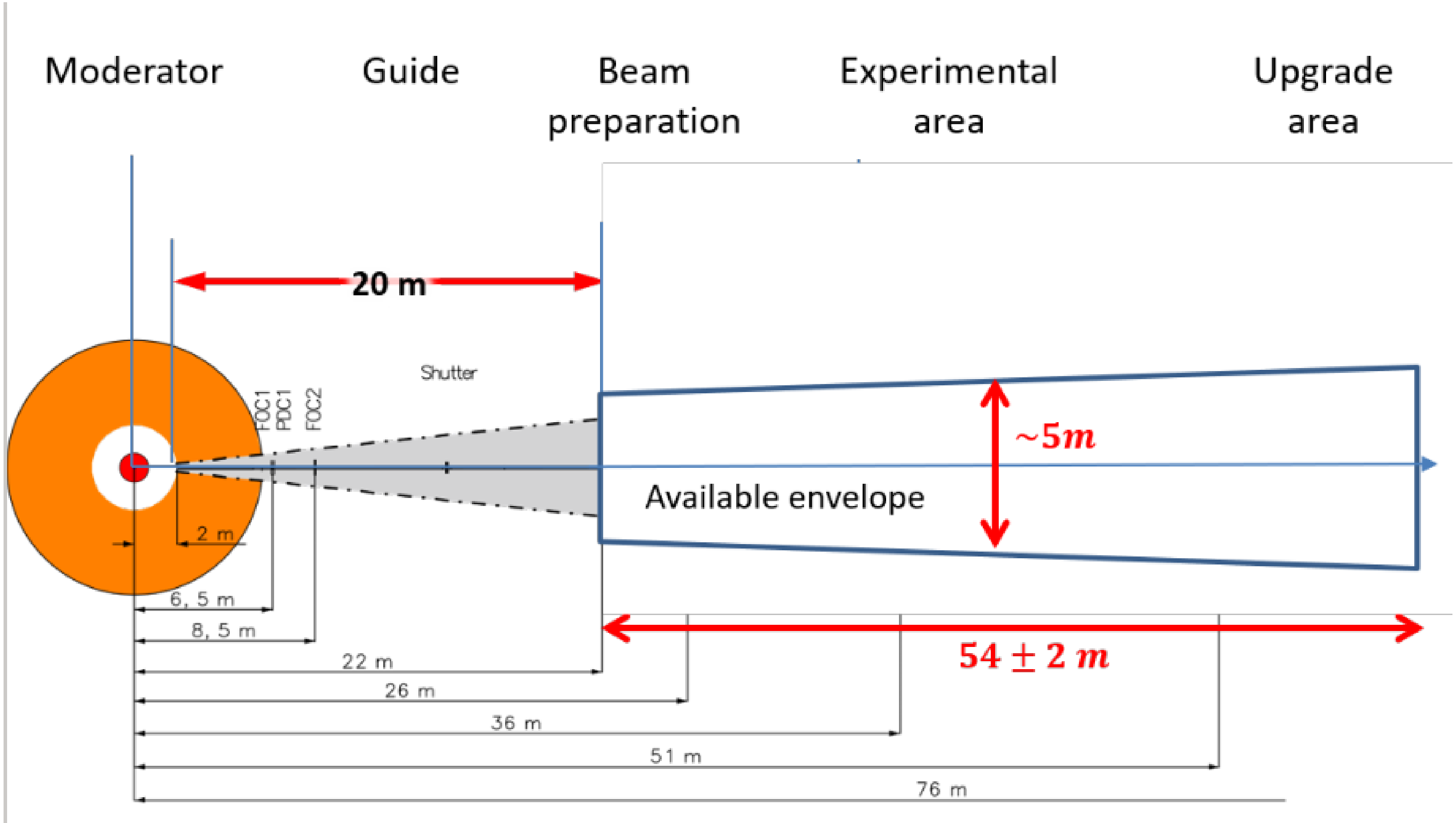


- 2. NNBAR
  - extremely high precision searches n → nbar, n→ n'
  - improve sensitivity to oscillation probability by ~ 10^3
  - Late 2020's

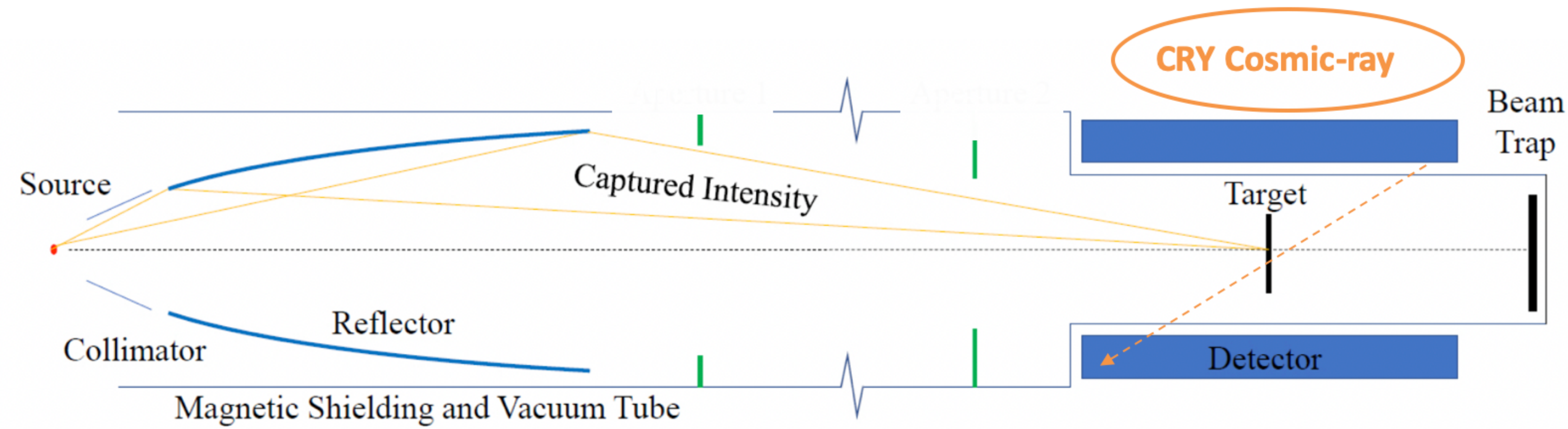
- Test beam prototype/bg tests
  Stay tuned for Katie Dunne's talk about the prototype!

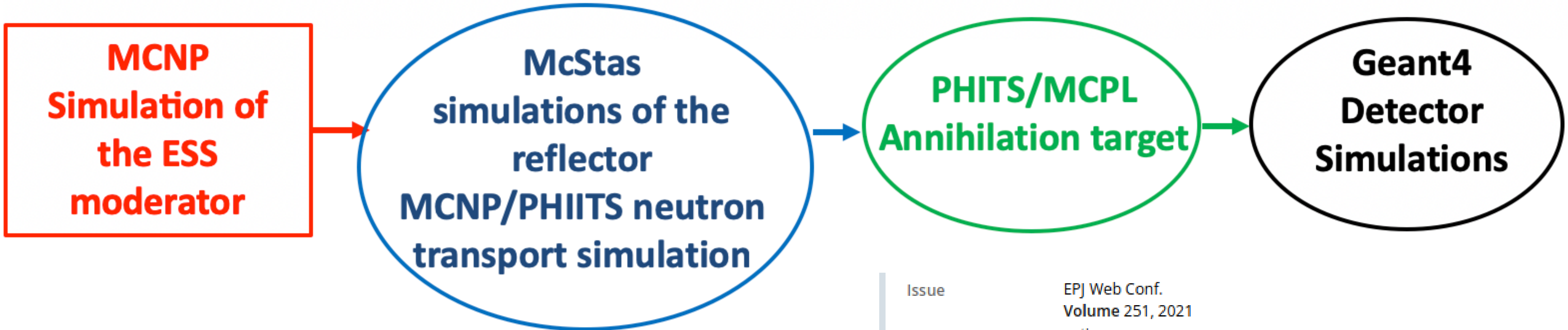
HIBEAM@ANNI

- ANNI: possible fundamental physics beamline (FPB) at ESS
- Uses curved guide: only cold (slow/meV) neutrons get trough



Software Framework





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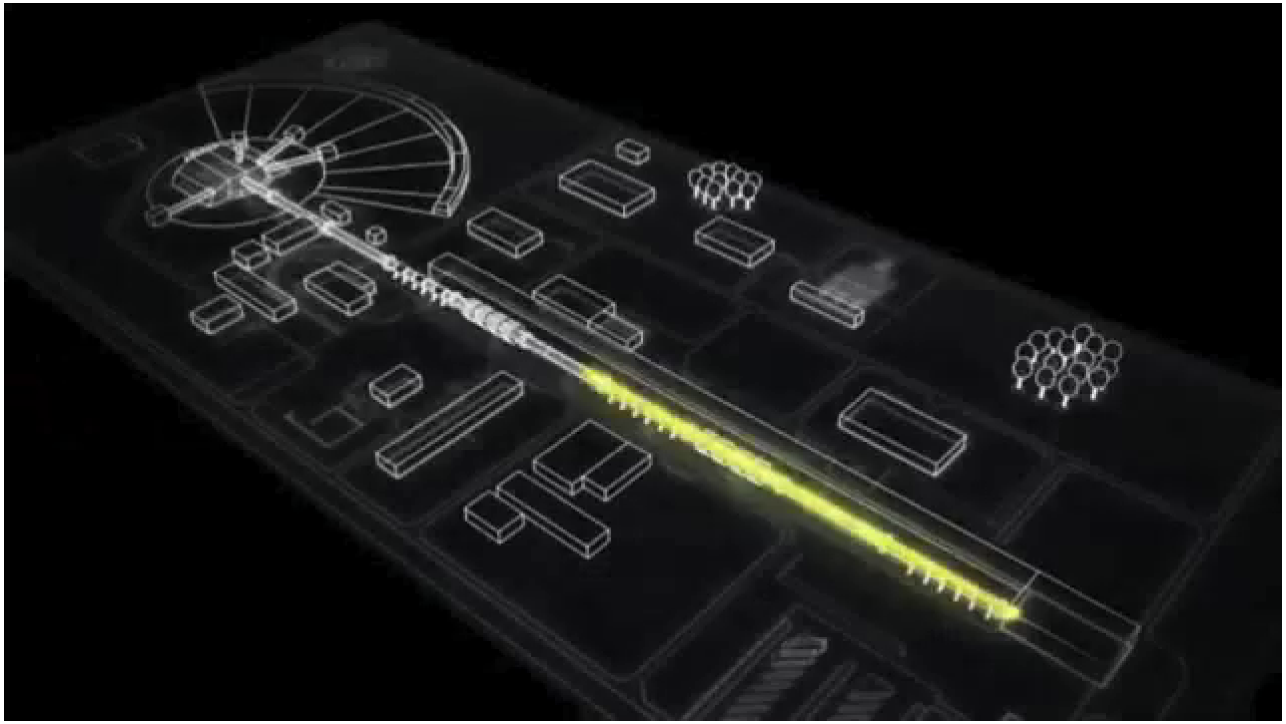
Computing and Detector Simulation Framework for the HIBEAM/NNBAR Experimental Program at the ESS

Moderator source

NNBAR

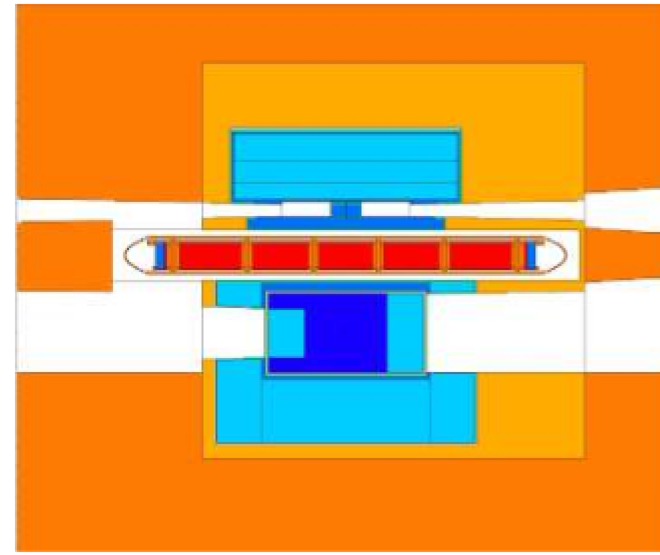
HighNess



Courtesy of Marcos Dracos

Moderator design (courtesy of L. Zanini (ESS))

- We chose a box shape geometry rather than a cylindrical shape.
  - Better fit with 2-opening extraction
  - better neutronic performance



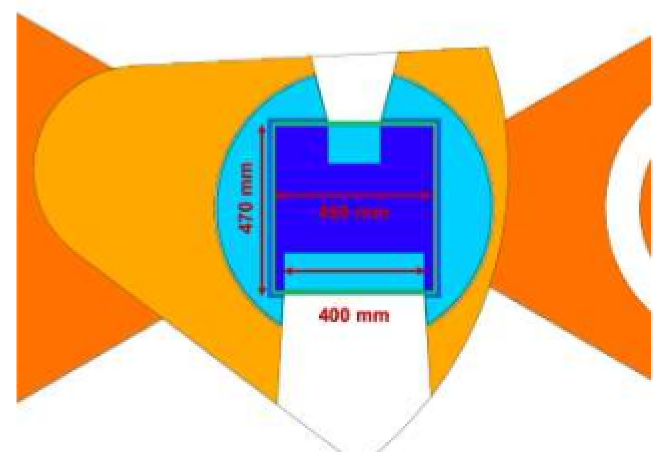
PERFORMANCE

- Integrated intensity for λ > 4 Å : 6.9 × 10^{15} n/s/sr
- Typical values from cylindrical geometry: 3.5 × 10^{15} n/s/sr (24X24 cm^2 opening)
- Original value from 2014 paper arXiv:1401.6003 :

  2.85 × 10^{15} n/s/sr (25X21 cm2 opening)

- The increase is due to:
  - Larger extraction opening: 24X40 cm2
  - Use of box geometry instead of cylindrical
  - Use of Be filter.

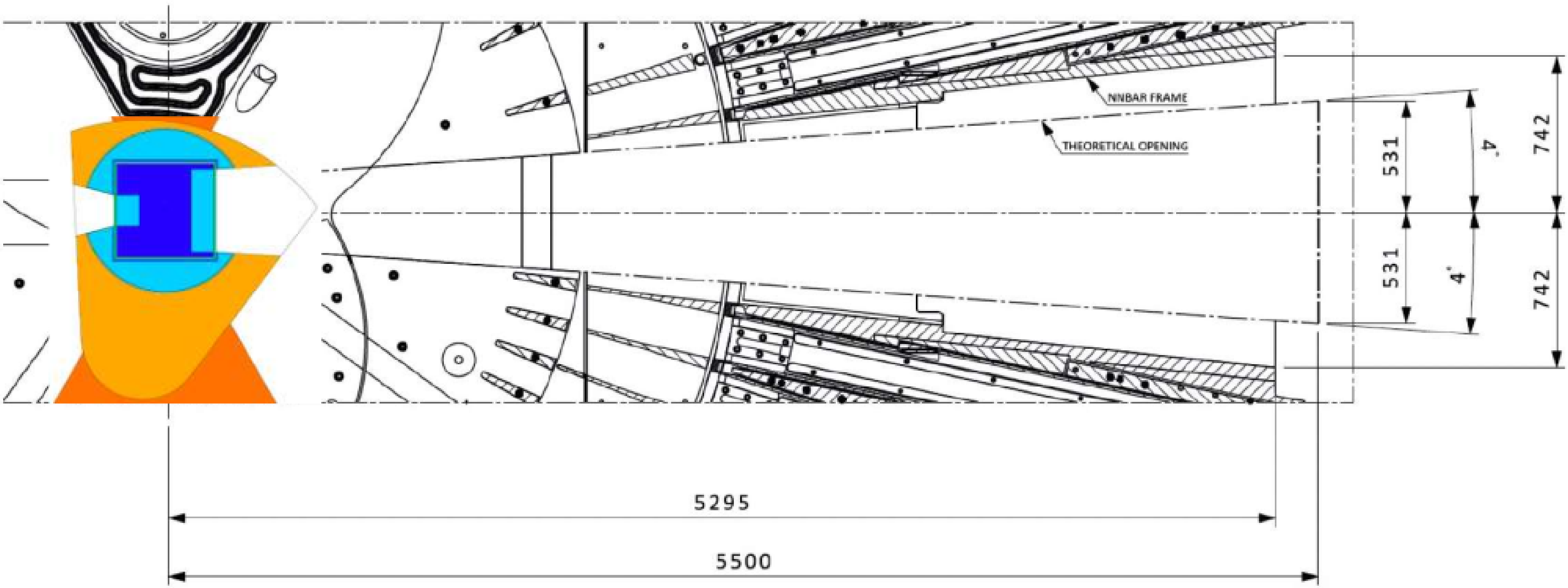
- NB all these values are for physics models, the performance will decrease adding engineering details



HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

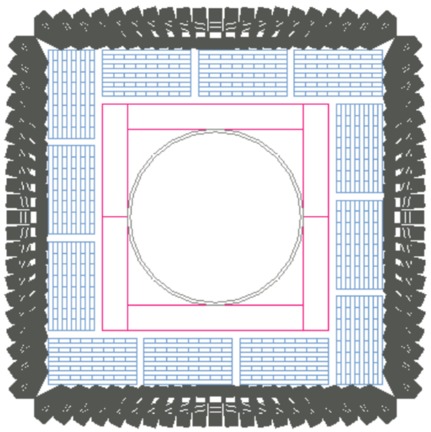
Moderator design (courtesy of L. Zanini (ESS))

A viewed surface of 40 X 24 cm2 provides high intensity neutrons to the NNBAR large beamport



Detector

HIBEAM (top) and NNBAR (bottom) detectors



Aluminum tube

0.55 m inner radius
2 cm thick
6 m long (z direction)

Time Projection Chamber

Two different dimensions
- 0.16 m x 0.73 m
- 1.14 m x 0.16 m

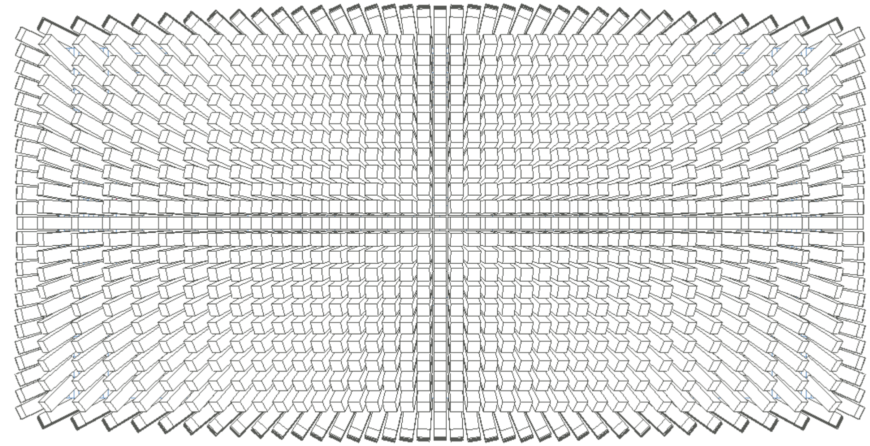
2m long (z direction)
80% Ar + 20% CO_2

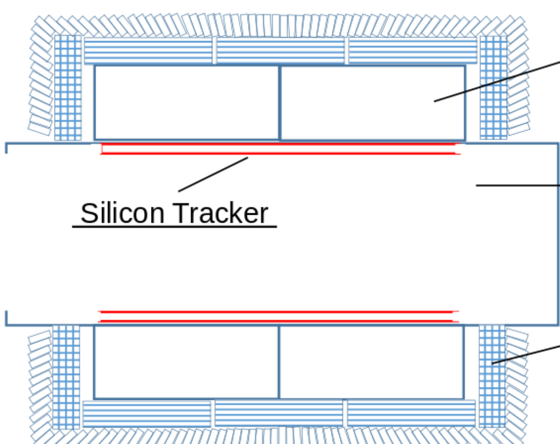
Scintillator Modules

10 layers of plastic scintillator
3 cm thick for each layer

Lead Glass Blocks

Base: 8 cm x 8 cm
Height: 25 cm
Pointing towards the **center of the detector**





Time Projection Chamber

Two different dimensions
- 0.85 m x 1.87 m
- 2.04 m x 0.85 m

2m long (z direction)
80% Ar + 20% CO_2

Aluminum tube

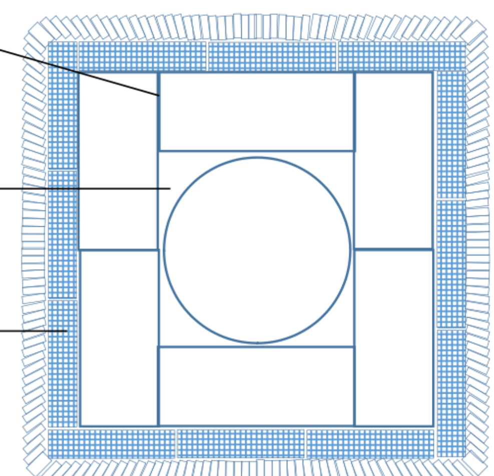
1 m inner radius
2 cm thick
6 m long (z direction)

Scintillator Modules

10 layers of plastic scintillator
3 cm thick for each layer

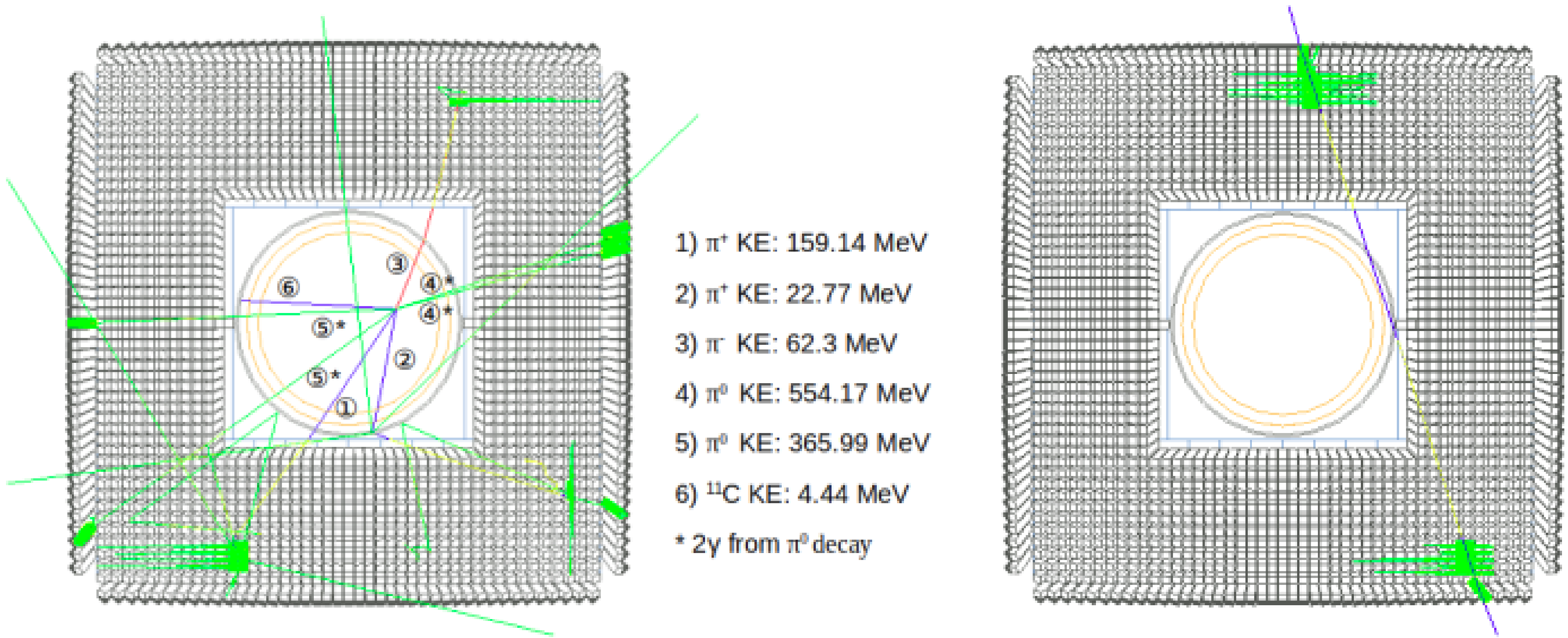
Lead Glass Blocks

Base: 8 cm x 8 cm
Height: 25 cm
Pointing towards the **center of the detector**



Stay tuned for Billy Yiu's talk with all details on detector results!

Event displays in Geant4



(a) (b)

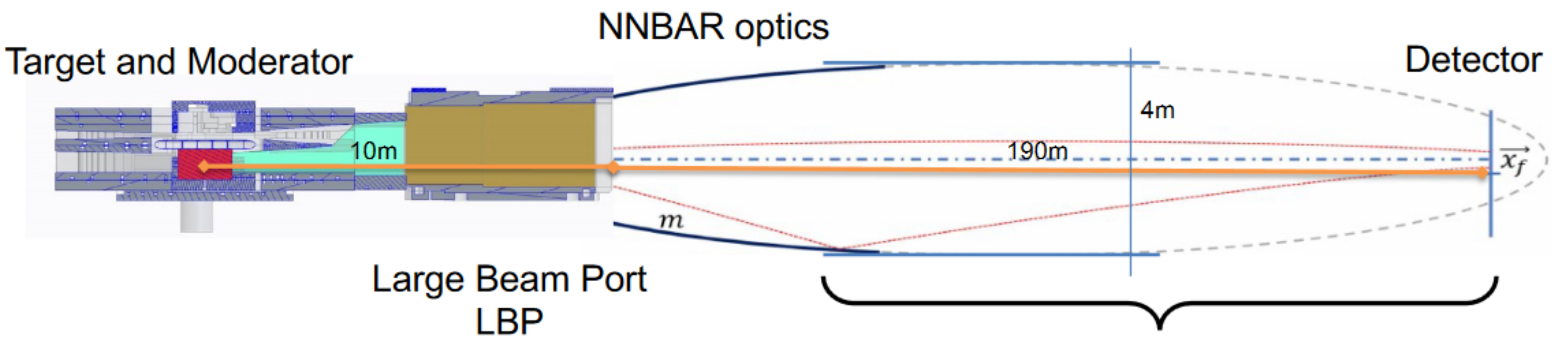
Figure 4. Event displays with the NNBAR detector showing (a) a signal event with five pions (b) a cosmic muon.

Stay tuned for Billy Yiu's talk with all details on detector results!

Sensitivity

NNBAR Optics (courtesy of R. Wagner (ILL))

(not in scale)



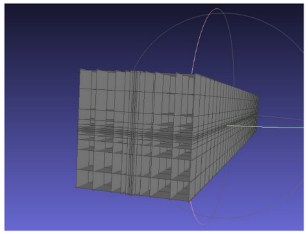
ballistic motion of neutrons that is free from perturbing magnetic stray fields, interaction with walls and ambient gas particles

Figure of Merit (FOM)

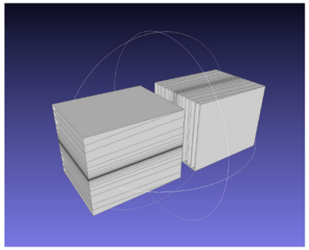
Different optics are compared using this quantity

$$FOM = \sum_i \overbrace{N_i}^{\text{neutrons}} * \overbrace{t_i^2}^{\text{(uninterrupted) flight time}} / \underbrace{4 \times 10^9}$$

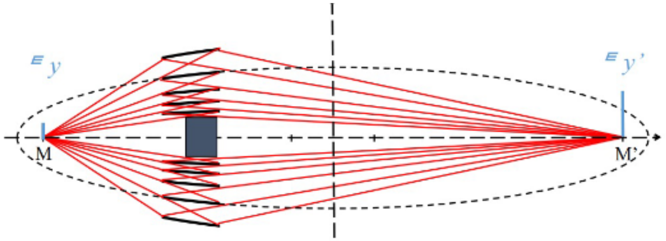
$$\underbrace{(1.5 \times 10^9)}_{\text{FOM ILL experiment}} \times \underbrace{\frac{6600}{5000}}_{\text{Ratio operating hours per year ILL/ESS}} \times \overbrace{2}^{\text{Detector efficiency (50\%)}}$$

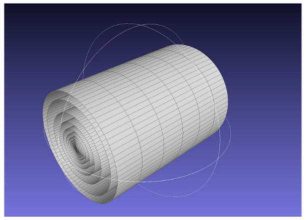


Nested mirrors



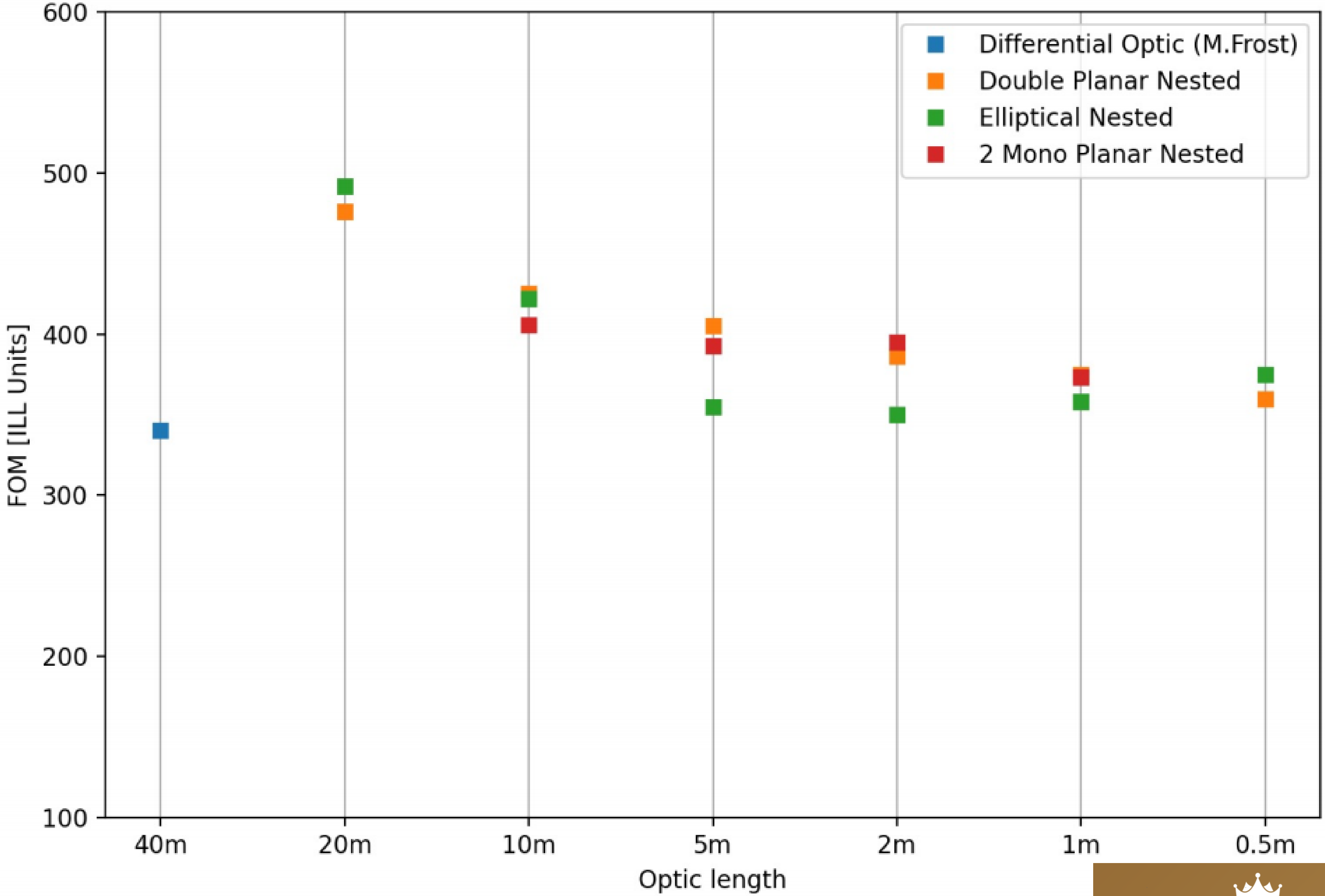
Two Mono Planar Reflectors





Elliptical Reflectors

NNBAR Optics results (courtesy of R. Wagner (ILL))



Recent Papers

- Status of the design of an annihilation detector to observe neutron-antineutron conversions at the European Spallation Source, accepted for publication in *Symmetry*

- The HIBEAM/NNBAR Calorimeter Prototype, TIPP, arXiv:2107.02147

- A Computing and Detector Simulation Framework for the HIBEAM/NNBAR Experimental Program at the ESS, CHEP2021, arXiv:2106.15898

- New high-sensitivity searches for neutrons converting into antineutrons and/or sterile neutrons at the European Spallation Source, J. Phys. G: Nucl. Part. Phys. 48 070501, arXiv:2006.04907

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

A Addazi[1,2], K Anderson[7], S Ansell[8], K S Babu[9], J L Barrow[10], D V Baxter[11,12,13], P M Bentley[14], Z Berezhiani[15,16], R Bevilacqua[14], R Biondi[15], C Bohm[17], G Brooijmans[17], L J Broussard[7], J Cedercäll[18], C Crawford[19], P S B Dev[20], D D DiJulio[14], A D Dolgov[21,22], K Dunne[17], P Fierlinger[3], M R Fitzsimmons[10], A Fomin[23], M J Frost[7], S Gardiner[7], S Gardner[19], A Galindo-Uribarri[7], P Geltenbort[24], S Girmohanta[4], P Golubev[18], E Golubeva[25], G L Greene[10], T Greenshaw[26], V Gudkov[27], R Hall-Wilton[14], L Heilbronn[10], J Herrero-Garcia[28], A Holley[29], G Ichikawa[30], T M Ito[31], E Iverson[7], T Johansson[32], L Jönsson[32], Y-J Jwa[17], Y Kamyshkov[10], K Kanaki[14], E Kearns[33], Z Kokai[14], B Kerbikov[34,35,36], M Kitaguchi[37], T Kittelmann[14], E Klinkby[38], A Kobakhidze[39], L W Koerner[40], B Kopeliovich[22], A Kozela[41], V Kudryavtsev[42], A Kupsc[31], Y T Lee[14], M Lindroos[14], J Makkinje[43], J I Marquez[14], B Meirose[17,18], T M Miller[14], D Milstead[17,*] R N Mohapatra[44], T Morishima[36], G Muhrer[14], H P Mumm[45], K Nagamoto[36], A Nepomuceno[46], F Nesti[16], V V Nesvizhevsky[24], T Nilsson[47], A Oskarsson[18], E Paryev[25], R W Pattie Jr[48], S Penttil[7], H Perrey[18], Y N Pokotilovski[18], I Potashnikovav[40], K Ramic[14], C Redding[49], J-M Richard[50], D Ries[51], E Rinaldi[52,53], N Rizzi[37], N Rossi[15], A Ruggles[49], B Rybolt[54], V Santoro[14], U Sarkar[55], A Saunders[14], G Senjanovic[56,57], A P Serebrov[23], H M Shimizu[36], R Shrock[4], S Silverstein[17], D Silvermyr[18], W M Snow[11,12,13],

A Takibayev[14], I Tkachev[25], L Townsend[58], A Tureanu[59], L Varriano[60], A Vainshtein[61,62], J de Vries[63,64], R Wagner[24], R Woracek[14], Y Yamagata[65], S Yiu[17], A R Young[66], L Zanini[14], Z Zhang[67] and O Zimmer[24]

Summary and outlook

- HIBEAM-NNBAR two stage program at ESS
- HIBEAM – world leading sterile neutron searches + pilot free nnbar search
- NNBAR – world leading neutron-antineutron oscillation searches
- Progress in all main areas of the program:
  moderator, detector, optics
- HIBEAM HIBEAM pre-studies - research needed ahead of a formal beamline proposal:
  - (1) TPC design and prototype construction (LU)
  - (2) Integrated read-out (CTU, UU)
  - (3) Study of WASA detector exploitation (UU)
  - (4) Beamline design (ESS)
  - (5) Prototype tests - see K. Dunne's talk.
- NNBAR CDR planned to be completed in 2023