Stockholm
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The NNbar Experiment

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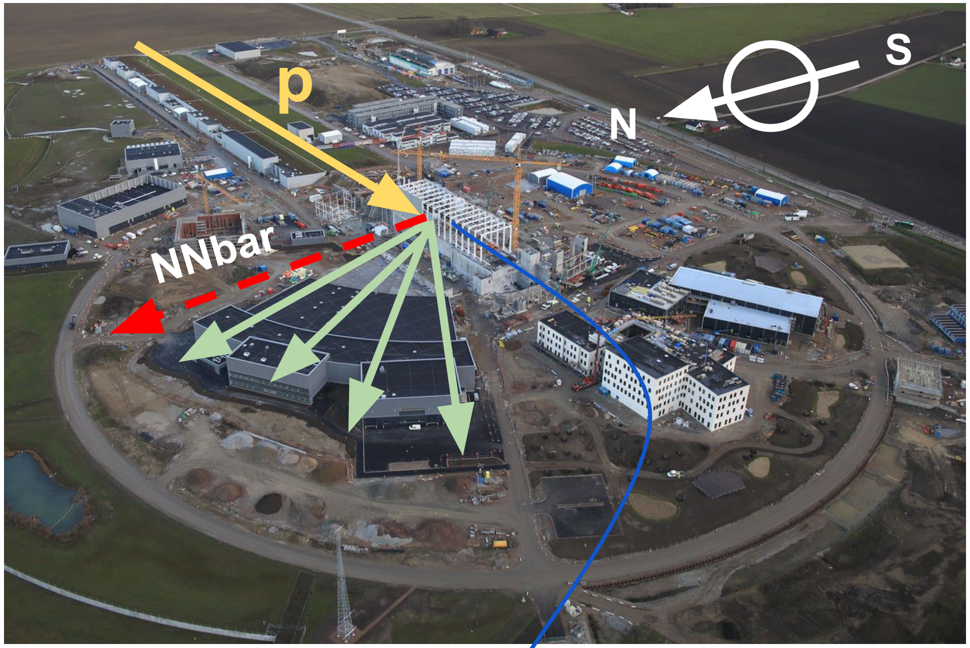
Spåtiand 2020

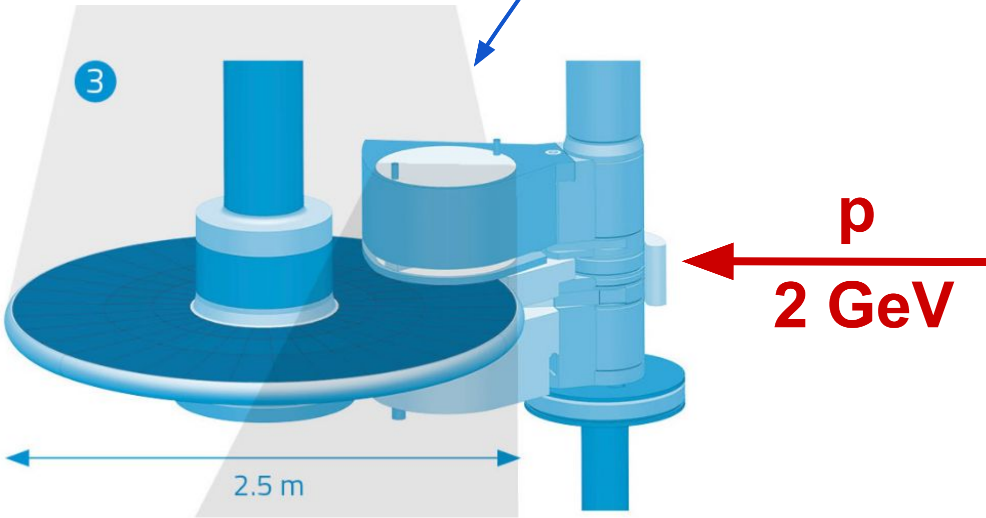
Baryon Number Violation

- BNV necessary for matter-antimatter asymmetry (Sakharov condition)
- *B*, *L* conservation accidental global symmetry
  - (B-L) conserved in SM
  - B, L separately violated non-perturbatively
- Feature in many BSM theories
  - RPV in SUSY
  - Mirror sector (mirror neutron) can explain dark matter
- n->nbar, n->n’ cleanest high precision way of looking for BNV only.
- Complementary to nucleon decay searches (Super-K, DUNE)
  - Intra nuclear osc highly suppressed
  - Conversion to free neutron osc highly model dependent
- Current free neutron limit 8.6×10^7 s
  - ILL reactor experiment 1994
    - M. Baldo-Ceolin et al., Z. Phys., C63 (1994) 409
- ESS opportunity to exploit cold neutron beam for next gen neutron oscillation experiment

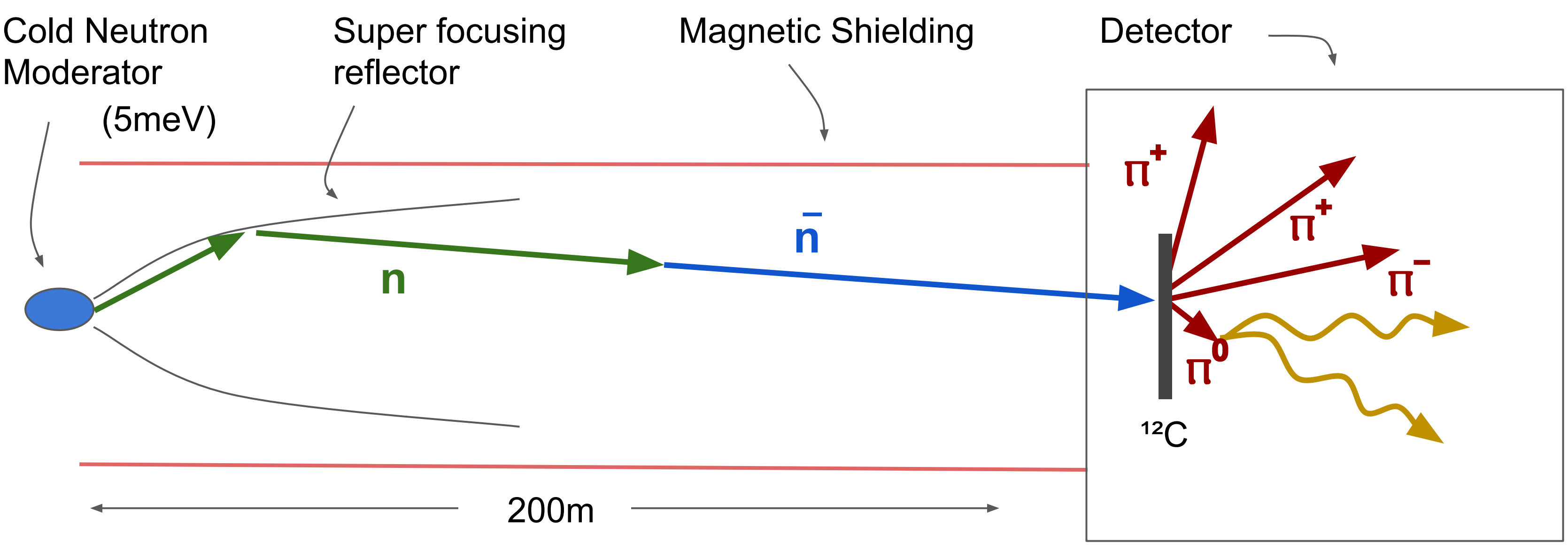
The European Spallation Source

- Under construction in Lund, Sweden
- High intensity
- Pulsed neutron spallation source
    - 2 GeV protons
    - Tungsten target
    - 14 Hz
- Fundamental physics beamline

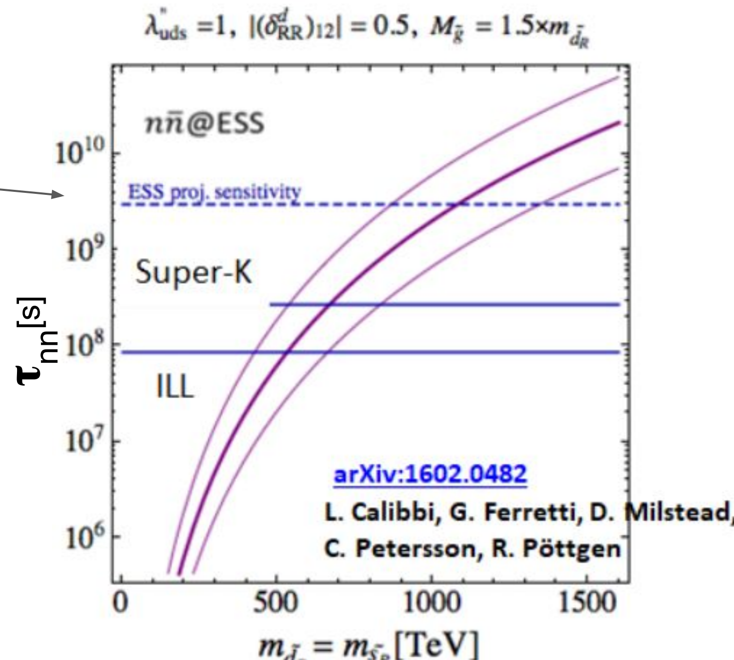




NNbar Experiment



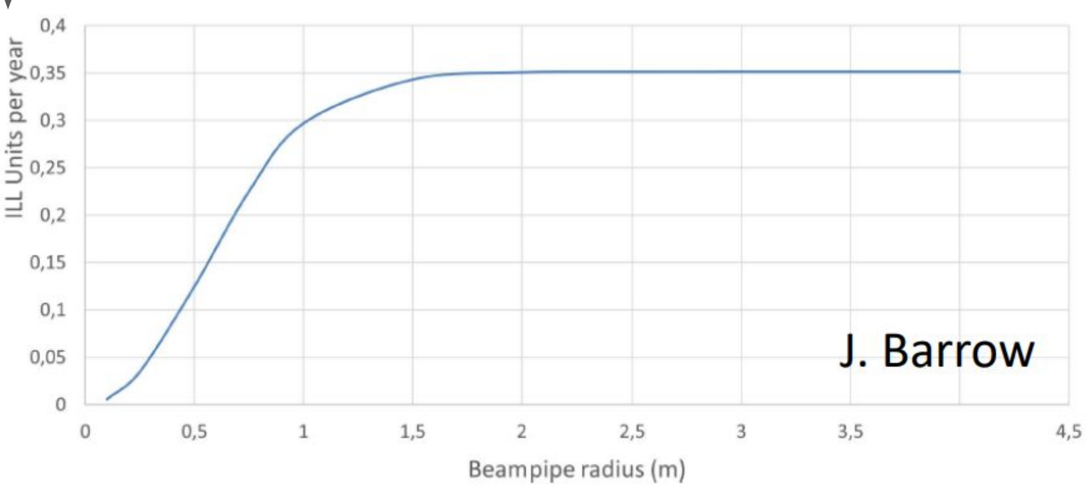
- Free neutron-antineutron conversion search at ESS
- Projected sensitivity x1000 compared to ILL
- Signal Events:
  - Charged pions + photons same vertex
  - Invariant mass final state 1.4--1.9 GeV
- Background Events:
  - Spallation Sources
    - Fast neutrons,protons synchronous w/ accelerator
    - Low energy photons from neutron activation in target, beam tube
  - Cosmic rays (charged and neutral)
    - Dominant source of triggers at ILL

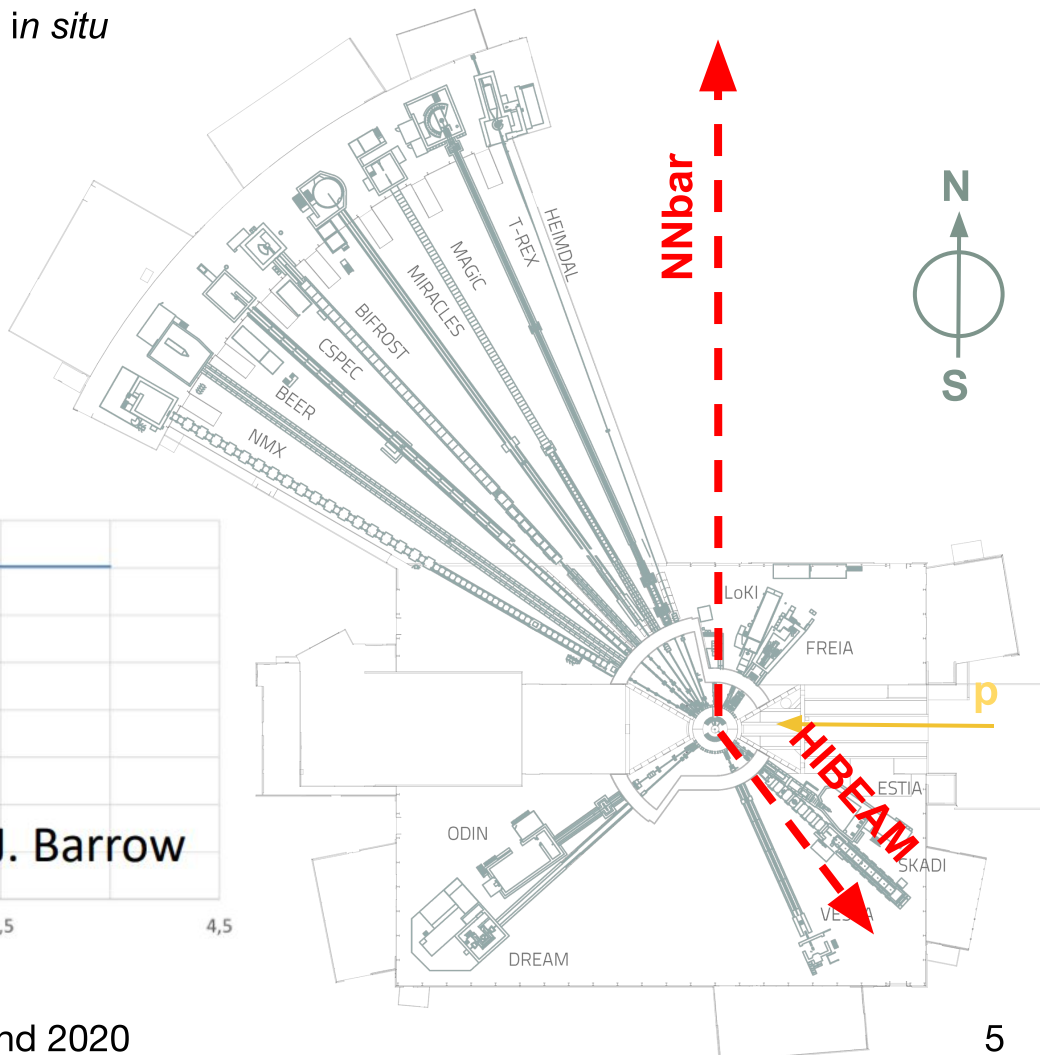


HIBEAM: n->nbar

- Phase I at shorter beamline
- Pilot experiment - reach ILL sensitivity
- Validate
  - Neutronics
  - Simulations -> especially backgrounds *in situ*
  - Detector
- Aim for 0 background events as at ILL

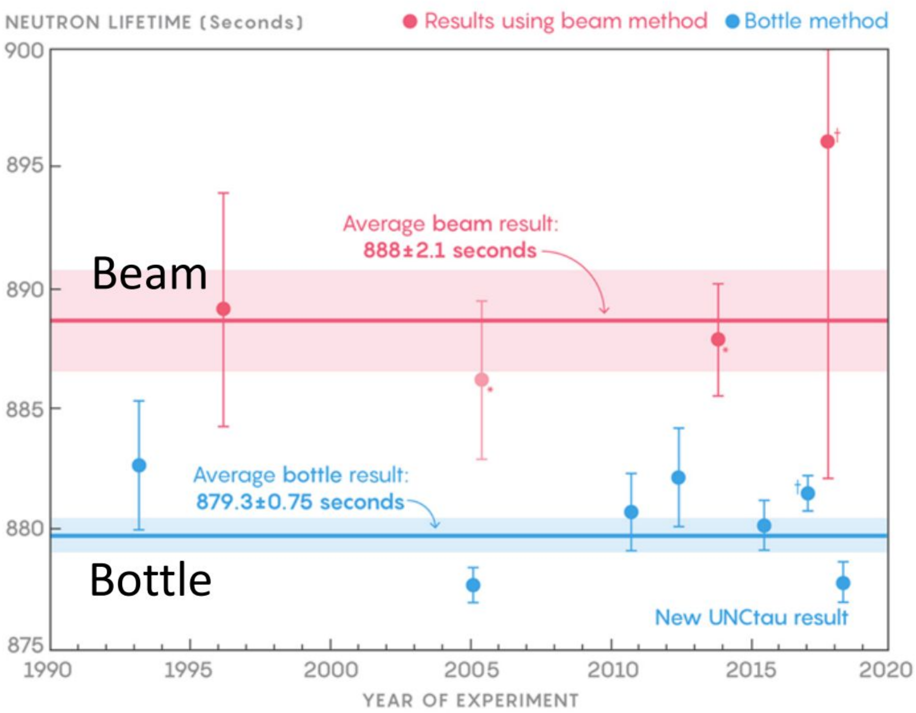
ILL Unit = current limit
3 years HIBEAM > sensitivity of ILL





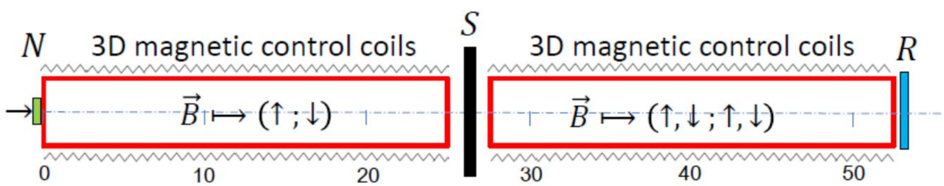
HIBEAM: n->n’

- Mirror Matter as portal to hidden/dark sector
- Experimental anomalies:
  - Bottle/Beam neutron lifetime experiments
- Infrastructure for HIBEAM allows search for n->n’



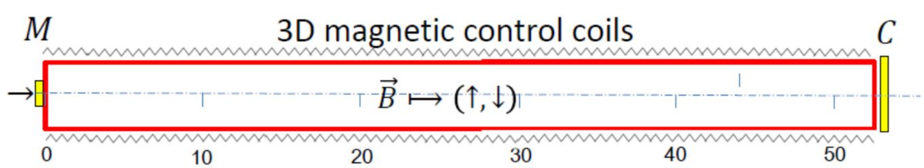
HIBEAM: n->n’

Regeneration



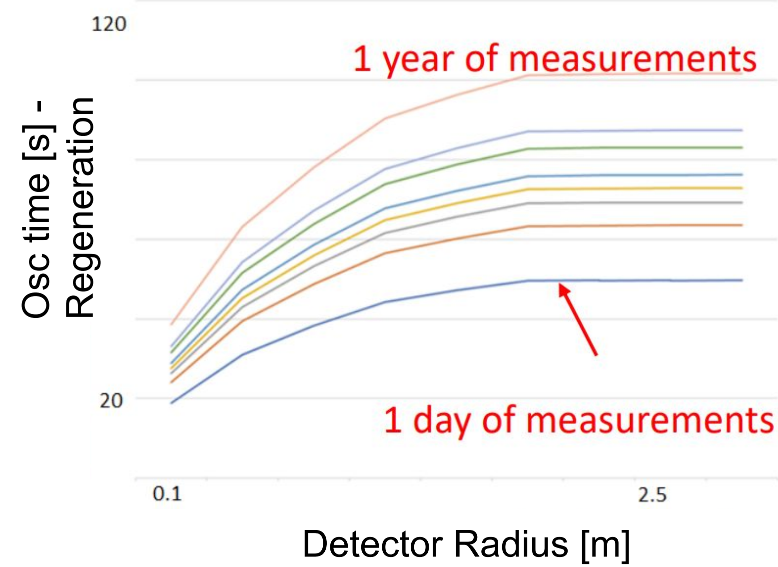
n->n’ n’->n

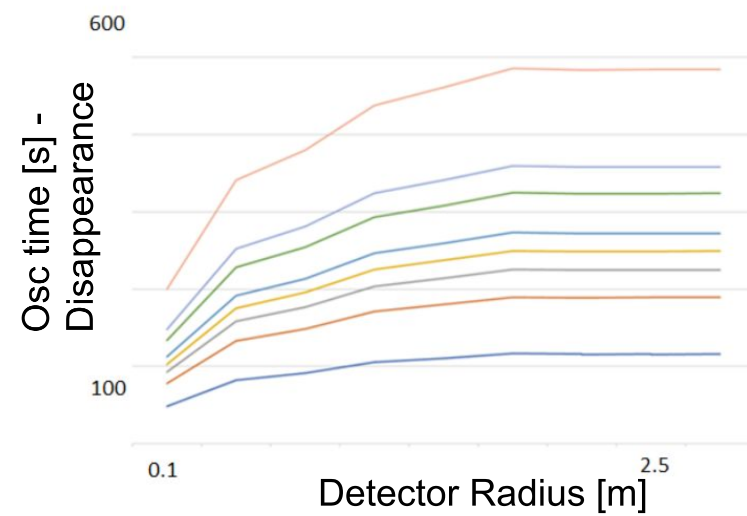
Disappearance



n->n’

J. Barrow

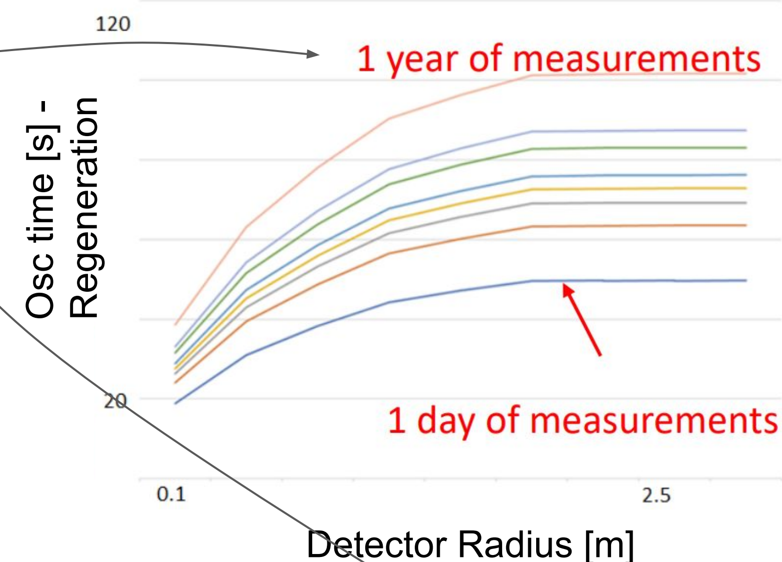




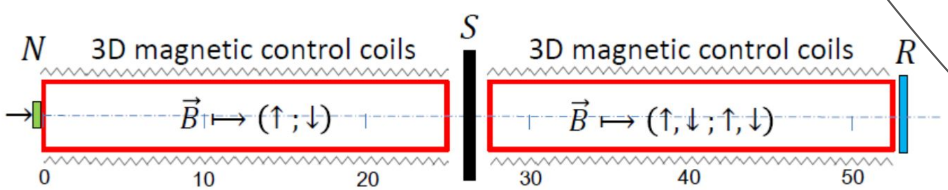
HIBEAM: n->n’

- Current n->n’ osc limits ~30s
- Longer beamline, more neutrons, longer runtime
  - -> HIBEAM way beyond this for regeneration / disappearance experiments

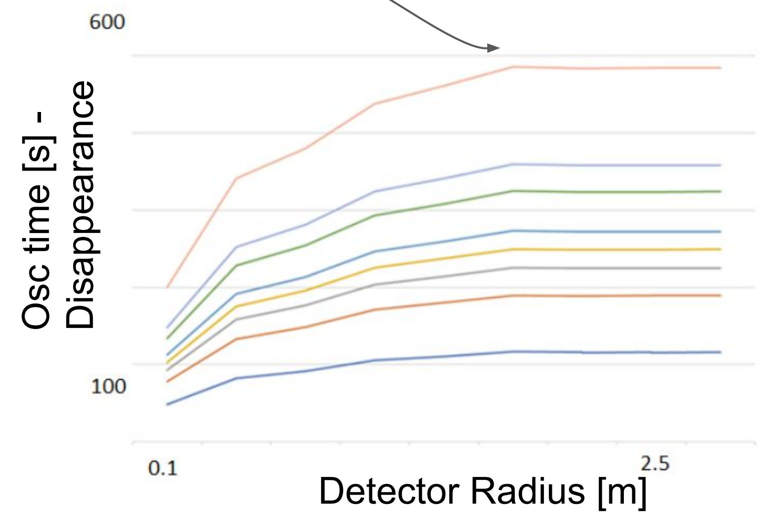
J. Barrow



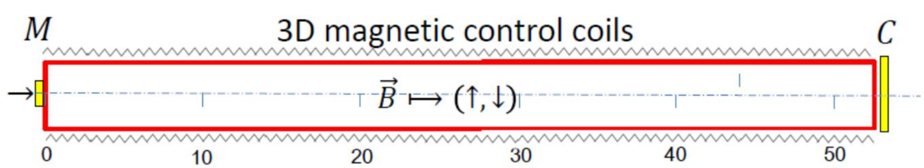
Regeneration



n->n’ n’->n



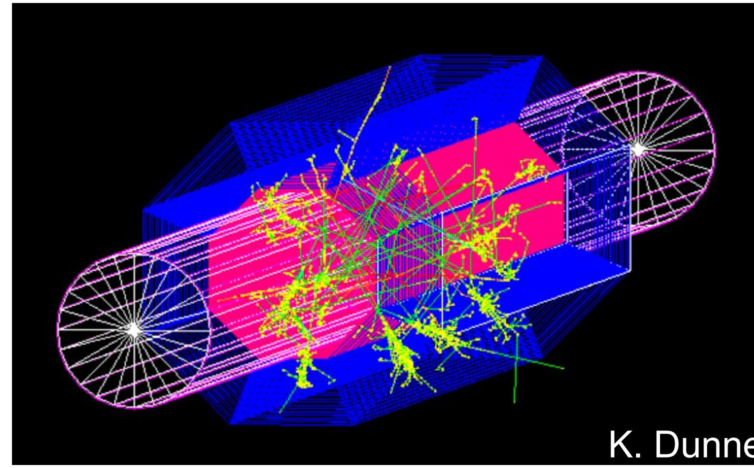
Disappearance



n->n’

Simulation Work

- Detector simulation package NNBarX developed previously using GENIE annihilation event generator (A. Reid, R. Pattie, A. Young, M. Beckard)
  - Straw tube tracker
  - plastic/lead sampling calorimeter



- New annihilation event generator benchmarked with ppbar data (J. Barrow, E. Golubeva, C. Ladd) arXiv:1804.10270
  - Implements annihilation in C nucleus
    - very diff final state compared to a free n-nbar annihilation

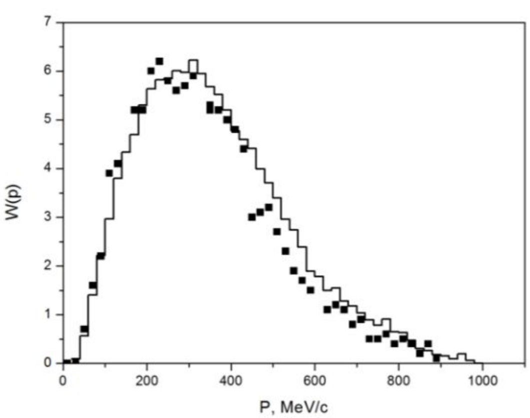
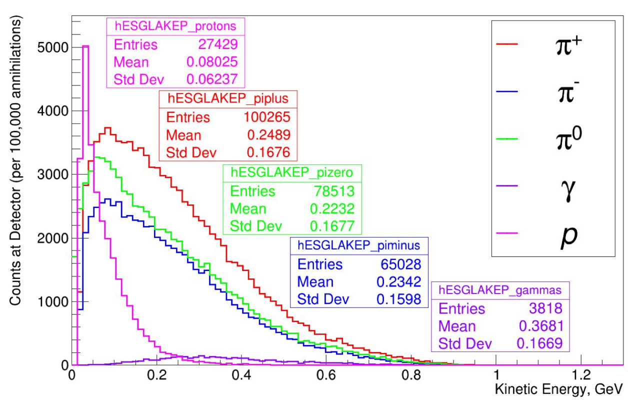
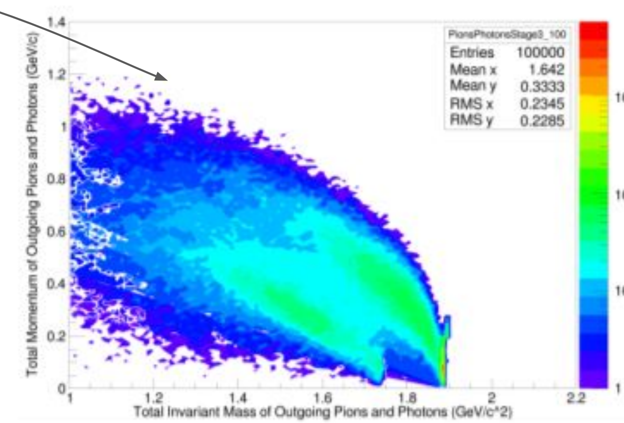


FIG. 5. The momentum distribution of charged pions produced in $\bar{p}p$ annihilation at rest (taking into account the decay of meson resonances). The solid histogram shows the model, with the points showing experimental data [41].



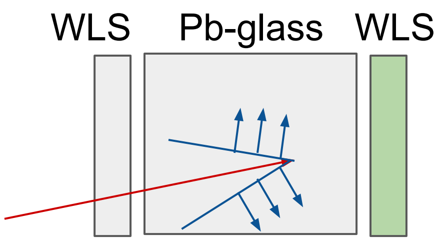


Detector R&D at Stockholm

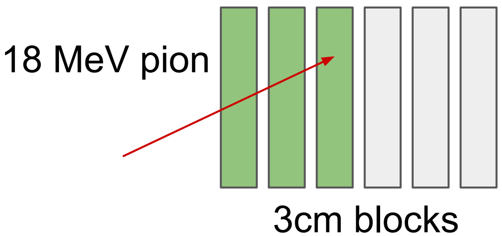
- Building prototype calorimeter at Stockholm University
- Construction to begin in the next year
- Design studies underway
    - Simulations of geometries / materials
    - Simulations of backgrounds / pile up
        - Rate / cm^2 ?
        - Granularity needed?

Detector R&D at Stockholm

- Many geometries / technologies to consider
  - Sampling EM calorimeter ?
    - Approaching low energies where sampling calorimeters are inefficient
      - Poor showering statistics, large fluctuations
  - Full absorption (Lead glass) ?
    - Blind to nuclear fragments
    - Fast, reduce pileup
    - Direction sensitive w/ WLS fibers (light cone has a direction)

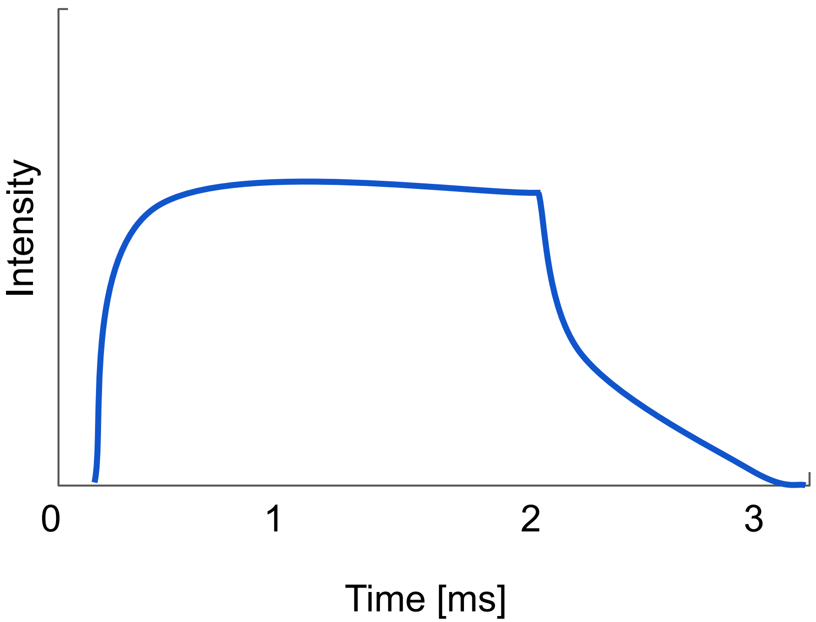


  - Sampling calorimeter with lead glass active absorber ?
    - Dual readout calorimetry: Cherenkov and scintillation light
      - Use ratio to increase energy resolution + PID
  - Range measurement with scintillators ?
    - 6 MeV per 3cm scintillator
    - Threshold to disc low energy nuclear photon background
    - 10 segments, 30cm total
    - Binary readout->energy bins for range



Detector R&D at Stockholm

- Building TDAQ prototype
  - 3ms long neutron pulses
    - not event based like at LHC (i.e. every 25 ns)
    - Signal and background come at random times
  - Triggerless Readout
    - i.e. individual time stamped hits



HIBEAM, NNbar, and the ESS

- The collaboration
  - 26 institutions in 8 countries
  - Co-spokespersons: G. Brooijmans (Columbia), D. Milstead (Stockholm)
  - Lead scientist: Y. Kamyshkov (Univ. Tennessee)
- Several workshops hosted
- Expression of Interest submitted to ESS by NNbar Collaboration
- Particle physics beamline high priority for ESS
  - Substantial investment in beamport with NNbar in mind

EUROPEAN SPALLATION SOURCE

2014/2015 Round	Instrument Construction Proposal
Revision Date	25/04/2019

Expression of Interest for
A New Search for Neutron-Anti-Neutron Oscillations at ESS

	Name	Affiliation
Main proposer	Gustaaf Brooijmans	Columbia University
Co-proposers	David Baxter	Indiana University
	Lorenzo Calibbi	Université Libre de Bruxelles
	Luis Castellanos	University of Tennessee
	Joakim Cederkäll	Lund University
	Brian Cole	Columbia University
	Gabriele Ferretti	Chalmers University of Technology
	Peter Fierlinger	TU Munich
	Matthew Frost	University of Tennessee
	Franz Gallmeier	University of Tennessee, Oak Ridge National Laboratory
	Kenneth Ganezer	California State University Dominguez Hills
	Richard Hall-Wilton	ESS
	Lawrence Heilbronn	University of Tennessee
	Go Ishikawa	Nagoya University
	Tord Johansson	Uppsala University
	Leif Jönsson	Lund University
	Yuri Kamyshkov	University of Tennessee
	Masaaki Kitaguchi	Nagoya University
	Esben Klinkby	ESS
	Mats Lindroos	ESS
	Bernhard Meirose	University of Texas Dallas
	David Milstead	Stockholm University
	Rabindra Mohapatra	University of Maryland
	Thomas Nilsson	Chalmers University of Technology
	Anders Oskarsson	Lund University
	Robert Pattie	Los Alamos National Laboratory
	Christoffer Petersson	Chalmers University of Technology
	David Phillips	North Carolina State University
	Amlan Ray	VECC, Kolkata, India
	Filippo Resnati	CERN
	Arthur Ruggles	University of Tennessee
	Utpal Sarkar	Physical Research Laboratory, Ahmedabad, India
	Alexander Saunders	Los Alamos National Laboratory
	Hirohiko M. Shimizu	Nagoya University
	Robert Shrock	Stony Brook University
	Samuel Silverstein	Stockholm University
	Camille Theroine	ESS
	Lawrence Townsend	University of Tennessee
	Rick Van Kooten	Indiana University
	Albert Young	North Carolina State University
ESS coordinator	Camille Theroine	ESS

Summary

- ESS new source of high intensity cold neutrons w/ physics beamline
- Unprecedented sensitivity in n->nbar, n->n’ oscillation times
- Phase I: HIBEAM
  - Pilot experiments for n->n’ , n->nbar
  - Can probe hidden sectors + physics beyond the Standard Model
- Phase II: Full scale NNbar experiment afterwards

Rare opportunity for 10^3 gain in sensitivity for test of a global symmetry!

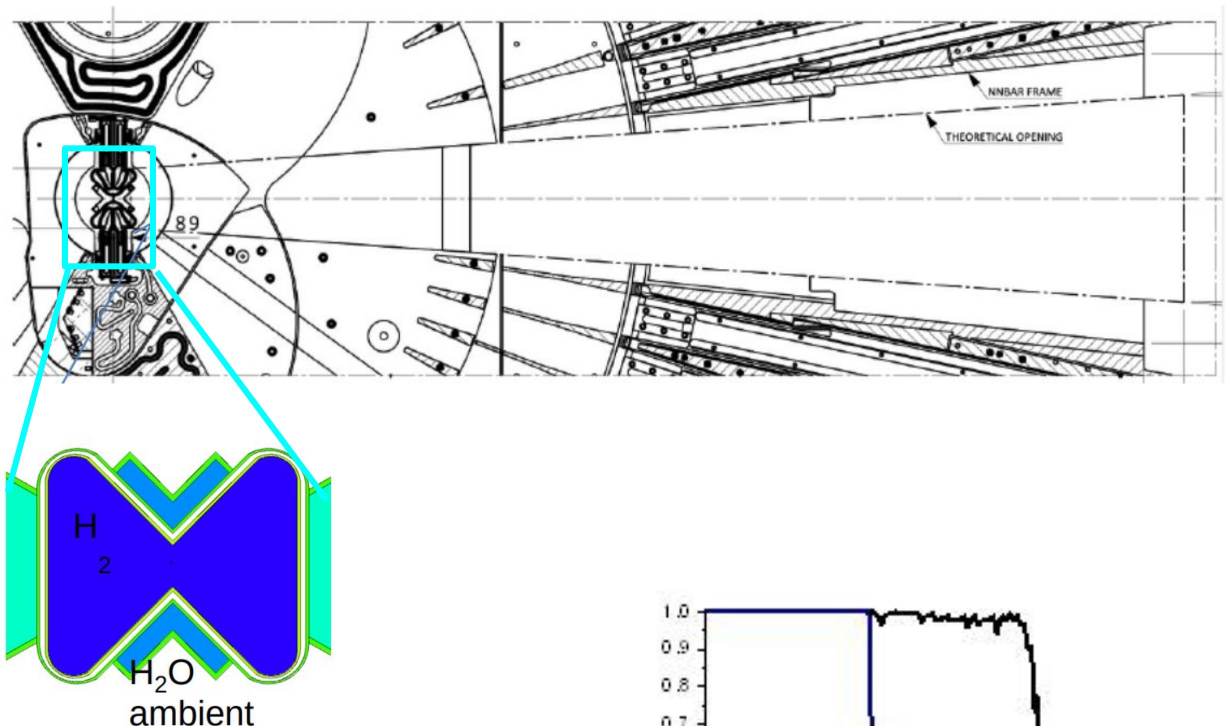
Thank You!

Sensitivity ~> $\Phi\langle t^2\rangle$

t = Neutron Path / Neutron Velocity

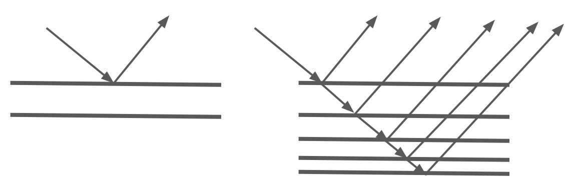
Φ - Free Neutron Flux $\langle t^2\rangle$ - Neutron Observation Time

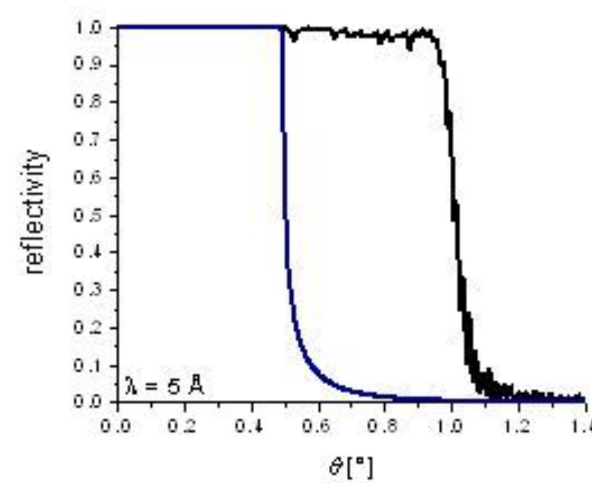
- Large Beam port
  - Maximize solid angle
    -> higher lumi
  - Access 2 moderators
    -> stronger source



- Moderator
  - Lower neutron velocities
  - Cold neutrons (5 meV , v < 1000 m/s)

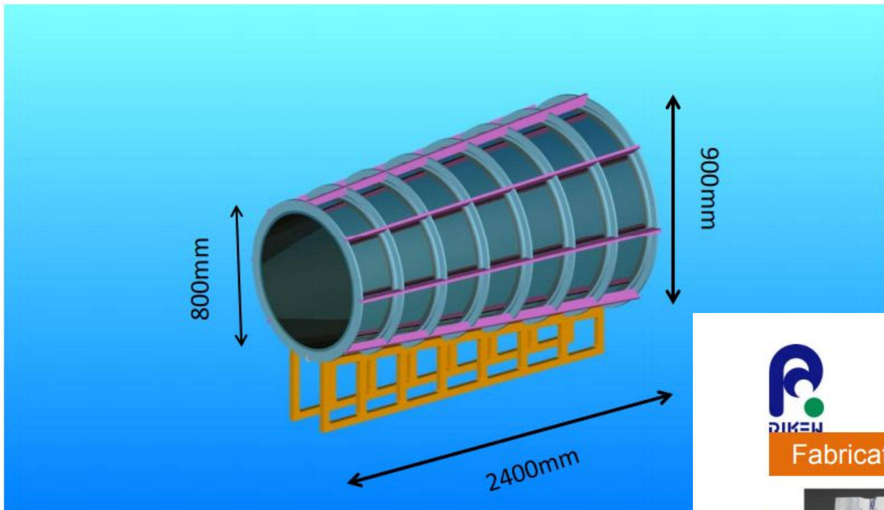
- Reflector
  - Large, elliptical focusing supermirror





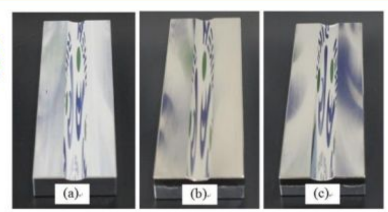
Super Mirror

A realistic drawing of optics
-Additional Optics 2-



Manufacturing result

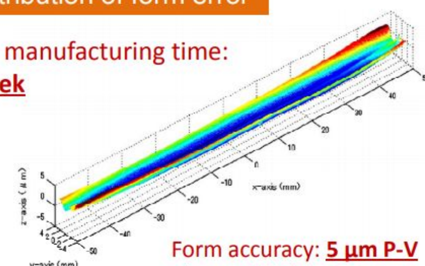
Fabricated test piece (100 mm)



(a) Aluminium substrate processed by precision cutting and Neutron mirror processed by (b) eletroless nickel plating and (c) ultraprecision cutting and polishing

Distribution of form error

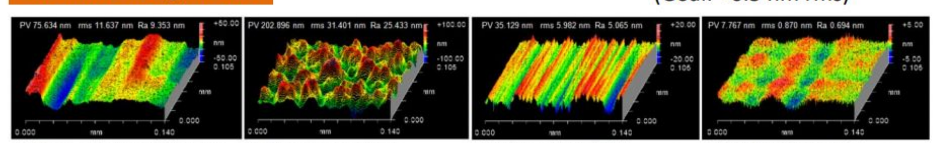
Total manufacturing time: **1 week**



Form accuracy: **5 µm P-V**
(Be available)

Surface roughness

Surface rougness: **0.8 nm rms**
(Goal: <0.5 nm rms)



(a) Aluminum substrate after precision cutting (b) After electroless nickel plating (c) After ultraprecision cutting (d) After 1st polishing process

After eletroless nickel plating process, the surface rougness get worse, while after the 1st polishing process, the surface rougness is reduced to 0.7 nm Ra.