A New Search for Neutron-Anti-Neutron Oscillations

A. R. Young

NCSU

Thanks to G. Brooijmans for slides

PSI 2016

PSI, October 17, 2016

Outline

- Oscillations in Neutral Systems and B Violation
- Current Limits
- European Spallation Source
- Beamline & Detector Concepts
- Collaboration

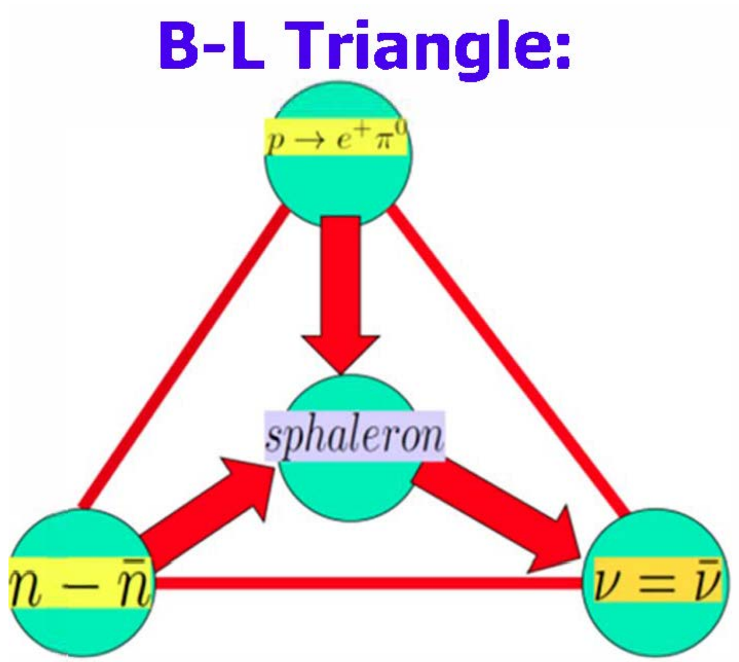
Central Questions for the Standard Model

Origin of neutrino mass

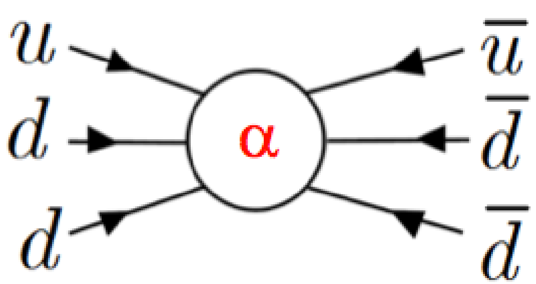
The cosmological baryon asymmetry

Pattern of charges and masses for the SM Fermions

Sources of Baryon Number Violation



All potentially connected by physics at or above EW scale



Observable N-$\bar{\text{N}}$ oscillations in a next generation experiment!

For example…

Gaps in the Standard Model

Many cosmological issues

- Dark matter and dark energy
- Not enough CP violation in the quark sector for baryogenesis
- Baryon number violation required for the baryon asym but where does it come from?
  - Present in the SM through B-L (sphalerons)

$\rightarrow$ Baryogenesis through leptogenesis and B-L?

Also find B violation in GUTs

$\Delta B=1$: proton decay $\rightarrow \Lambda > 10^{13}$ TeV

strong exptl limits…

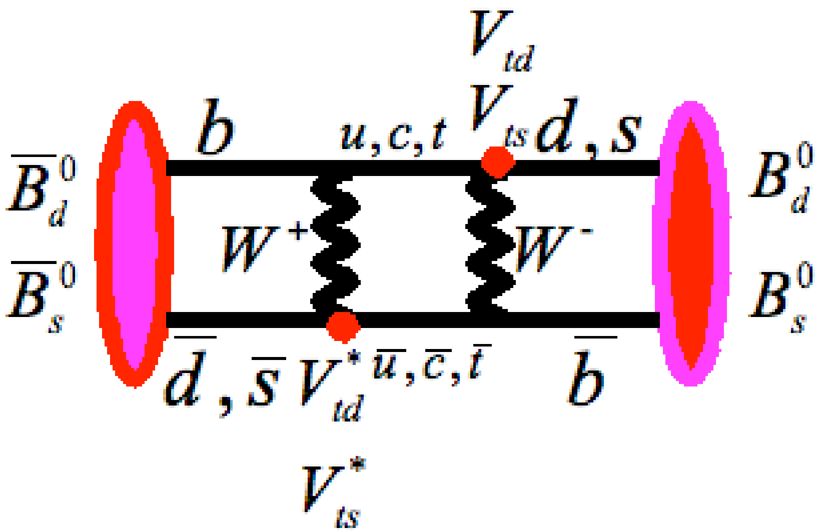
$\Delta B=2$: not constrained by p decay

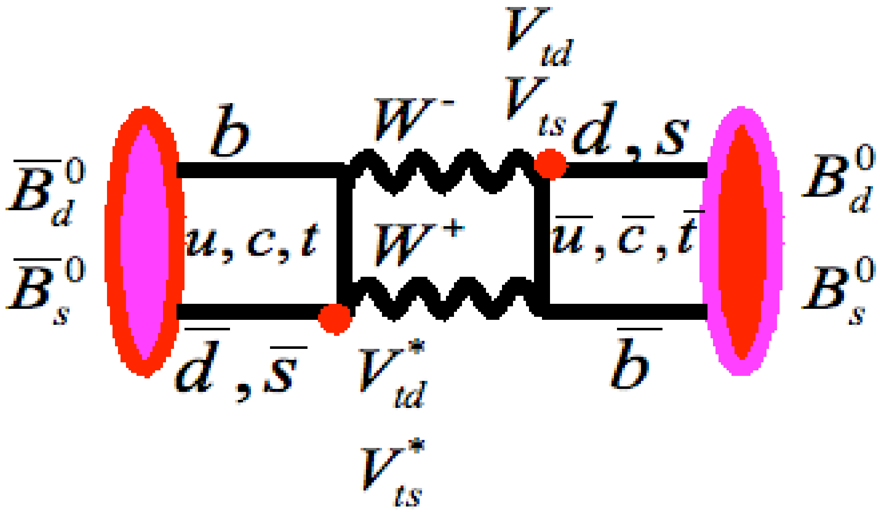
(wide range of scales for new physics…)

produces oscillations!

The Power of Oscillations

- Neutral particle oscillations have played large role in particle physics
  - K^0-$\overline{K^0}$ oscillations (**ΔS = 2**) at the core of our initial understanding of CP-violation
  - B meson oscillations (**ΔBeauty = 2**):
    - Sensitive to CKM elements
    - CP-violation "workhorse"
    - Probe m_t^2/m_W^2
    - → First indication of large top mass! (1987)
- Sensitive probes of high mass

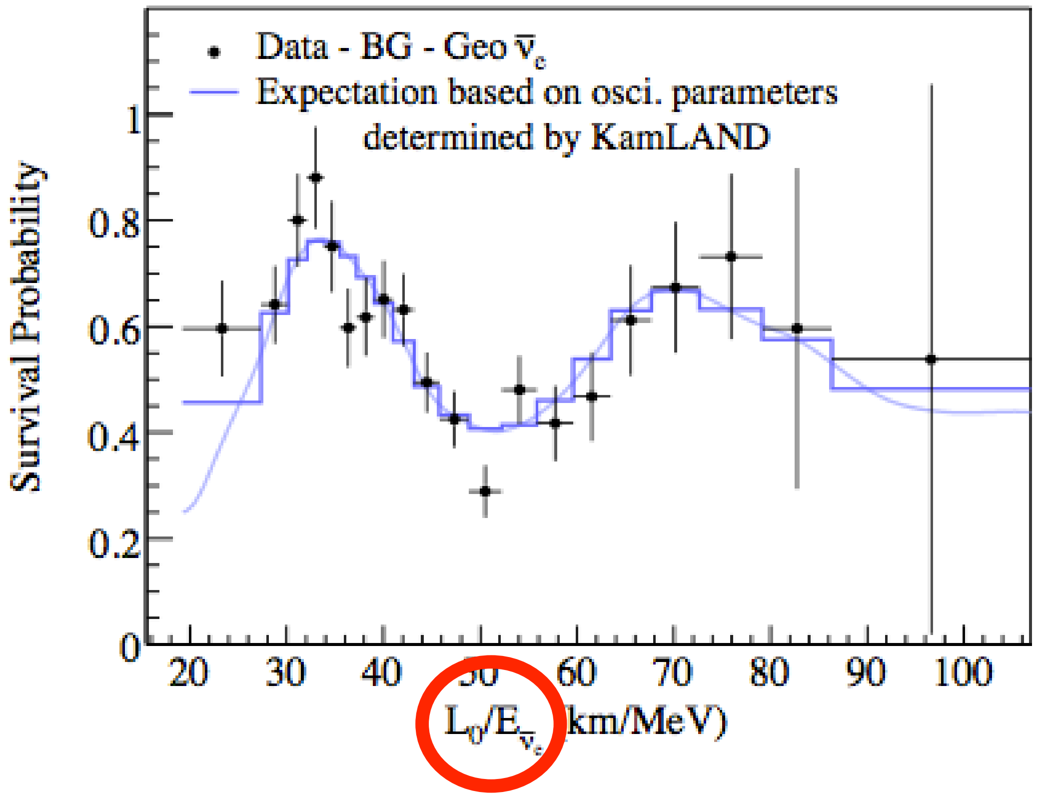




Neutrino Oscillations

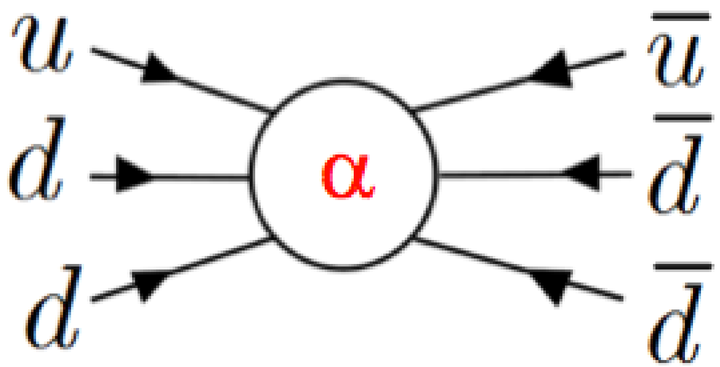
Neutrino oscillations unambiguously establish neutrinos are massive

- Since neutral, **Majorana** mass term allowed
  - If exists, **ΔL = 2**!
- If both Dirac and Majorana mass terms, mixing induces see-saw effect, *explaining* small neutrino masses
  - Two scales: Dirac and Majorana mass terms
    - Lead to observed scales $m_\nu \sim m_D^2/M$ and $m_N \sim M$
  - Dirac scale could be close to other fermions
    - Suggests a Majorana (ΔL=2) scale 10^6 - 10^{10} GeV
- **ΔB = 2** at a similar energy scale?



Experimental Aspects

Process, Critical Parameters



$$P_{n\to\bar{n}}(t) = \frac{\alpha^2}{\alpha^2+V^2}\cdot\sin^2\left(\frac{\sqrt{\alpha^2+V^2}}{\hbar}\cdot t\right)$$

- Potential V (if different for n vs $\bar{n}$)
  - Nuclear potential ~100 MeV
  - $\mu_n.B_{Earth}$ ~ 10^{-18} MeV
  - Current limit: α < ~ 10^{-29} MeV (same order as nEDM)

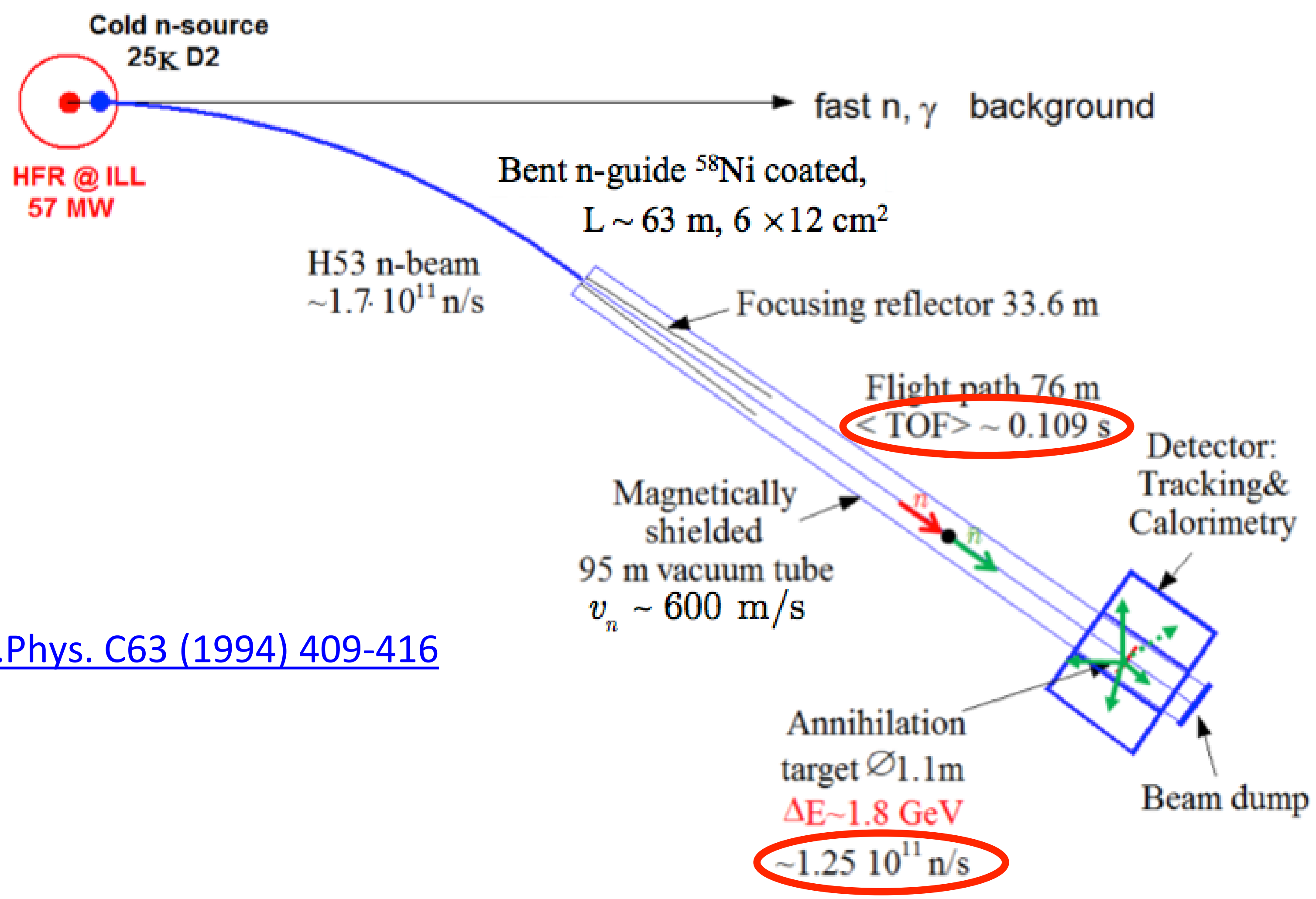
$$P_{n\to\bar{n}} = \left(\frac{\alpha}{\hbar}\times t\right)^2 = \left(\frac{t}{\tau_{n\bar{n}}}\right)^2$$

FOM: Nt^2

- Strongly suppressed unless quasi-free condition holds ($Vt/\hbar \ll 1$)
  - Free neutron experiment requires substantial cancellation of Earth magnetic field, then:
  - For free neutron experiment, magnetic field can be used to check result if signal is seen
    - A few operators identified that allow oscillation with B, but not present in usual BSM physics

arXiv:1504.01176

Current Limits



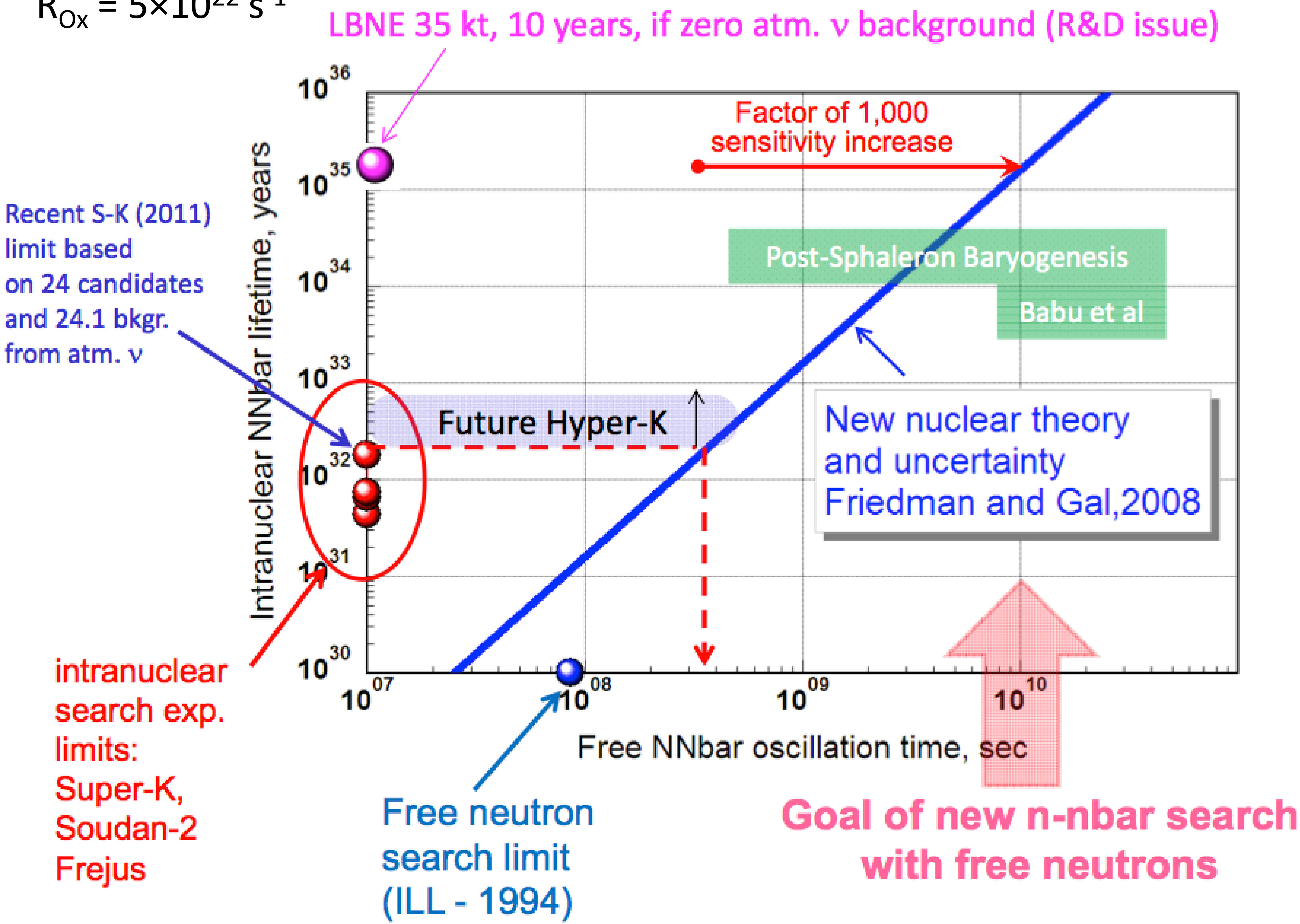
Baldo-Ceolin et al, Z.Phys. C63 (1994) 409-416

- $Nt^2 = 1.5\ 10^9$s, $P < 1.6\ 10^{-18}$ (run lasted ~1 year) and $\tau > 0.86\ 10^8$s
  - Many subtle optimizations to minimize losses and backgrounds
  - Experiment was background-free
- Bound neutron limits ~3 times better
  - But model-dependent, and now limited by atmospheric ν background

$$\tau_{bound} = R \times \tau_{free}^2$$

$R_{Ox} = 5\times10^{22}\ s^{-1}$

Free Neutron vs Bound Neutrons NNbar Search Sensitivity Comparison



New physics could be enhanced *or* suppressed for bound neutrons

Next Generation Free Neutron Experiment

- Increase number of neutrons
  - Flux
    - Moderator brightness and area
  - Angular acceptance
  - Longer run
- Increase time-of-flight
  - Colder neutrons
  - Longer beamline
- Keep (or even increase) detection efficiency (~50%), keep background at ~0
  - Exploit current, established hardware and software technologies
- Better B_{Earth} suppression
  - Improved passive (+ active?) shield

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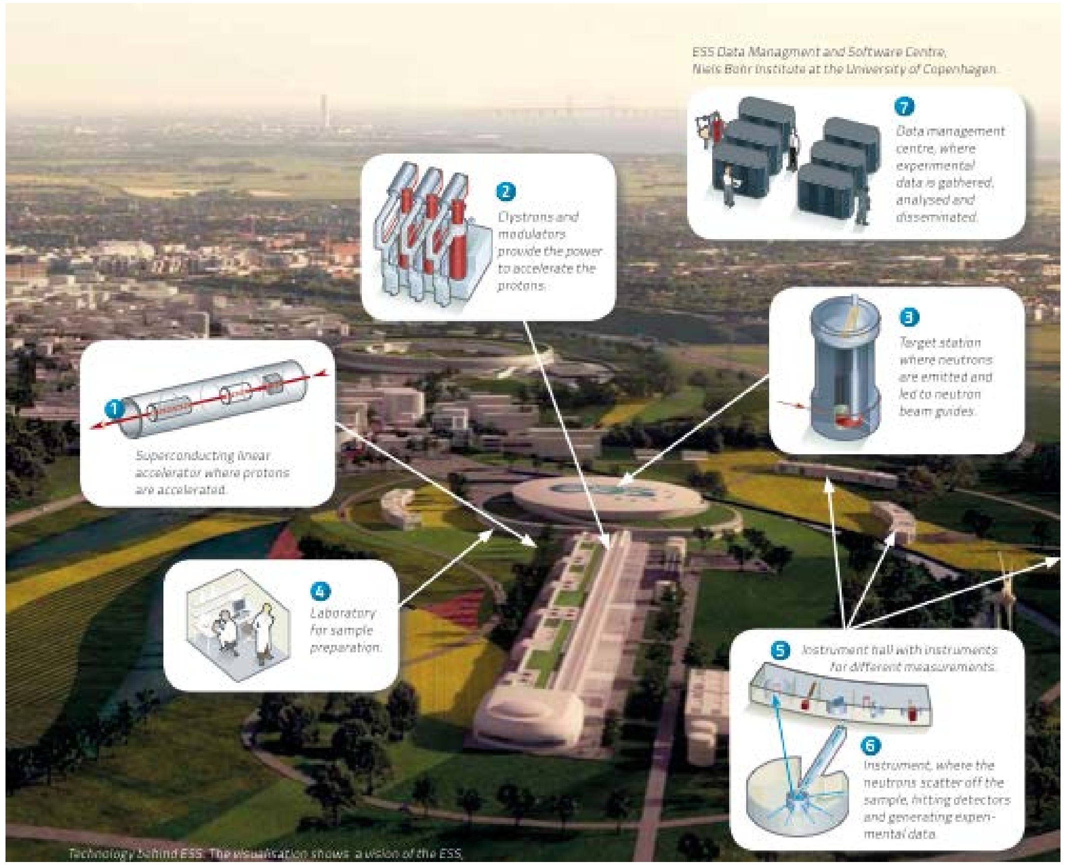
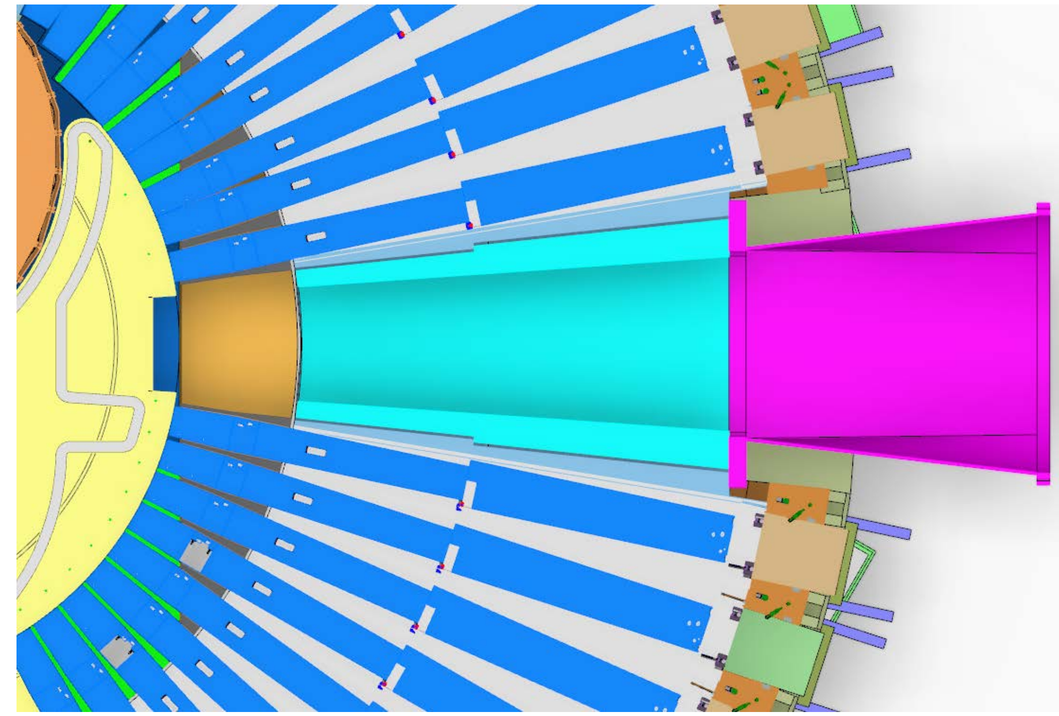
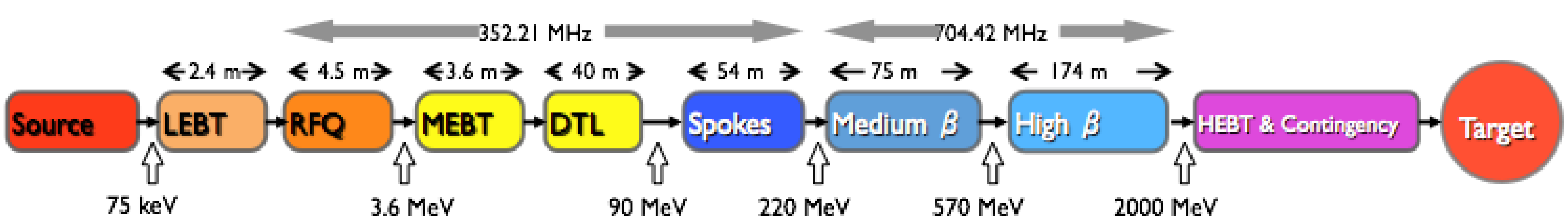
European Spallation Source





Large beam port still in baseline!
(details under discussion)

2.0 GeV superconducting linac, 14 Hz, 5 MW



ESS Timeline

- 2014: ESS construction start
- 2019-2022: Initial phase: commissioning, intensity ramp, experiments by friendly users
  - **Experiment construction begins (first source recycle?)**
- 2023-2025: Initial user program operations: reliable operations with public users; establish basis for future cost sharing
  - **Experiment construction completion, commissioning, physics start**
- 2026+: routine operations, completion of final public instruments
  - **Physics run**

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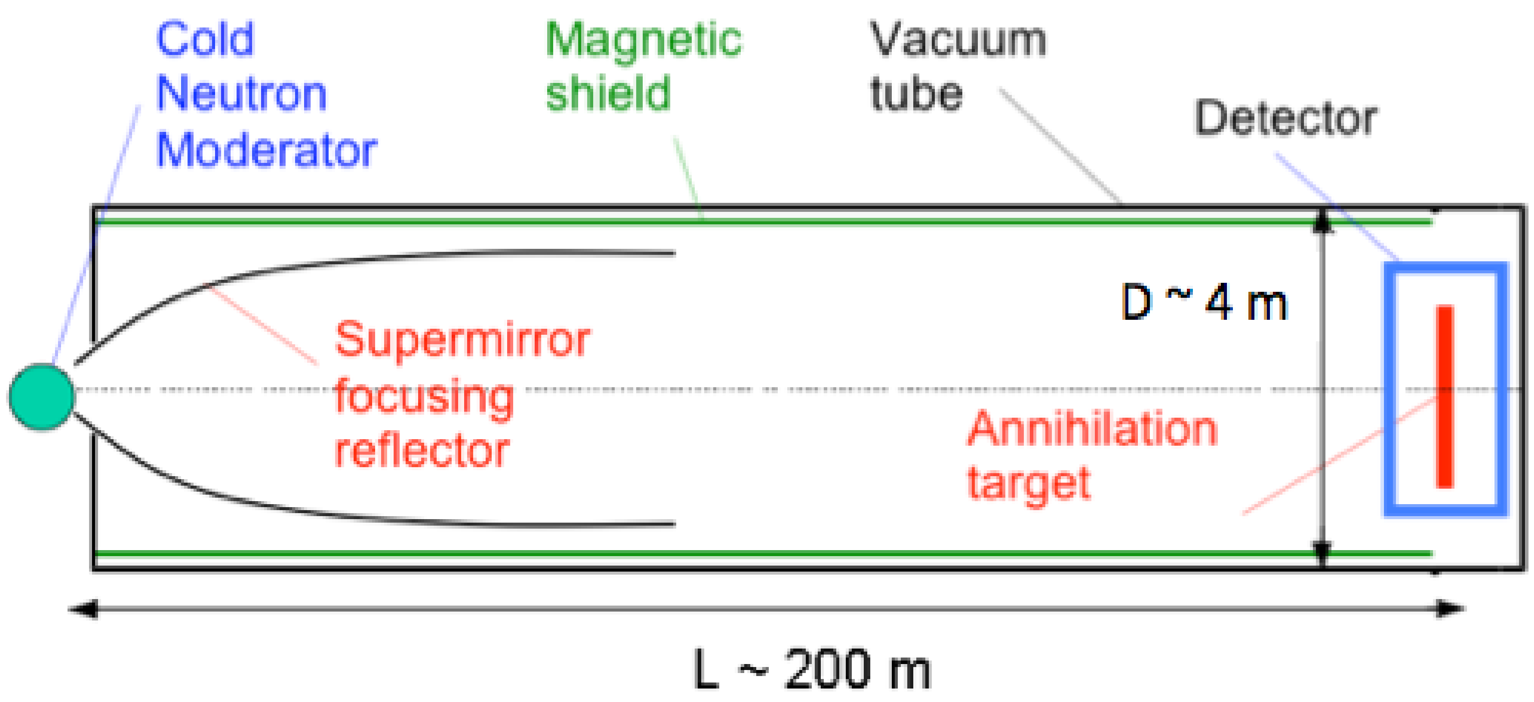
The Experiment

Conceptual Design



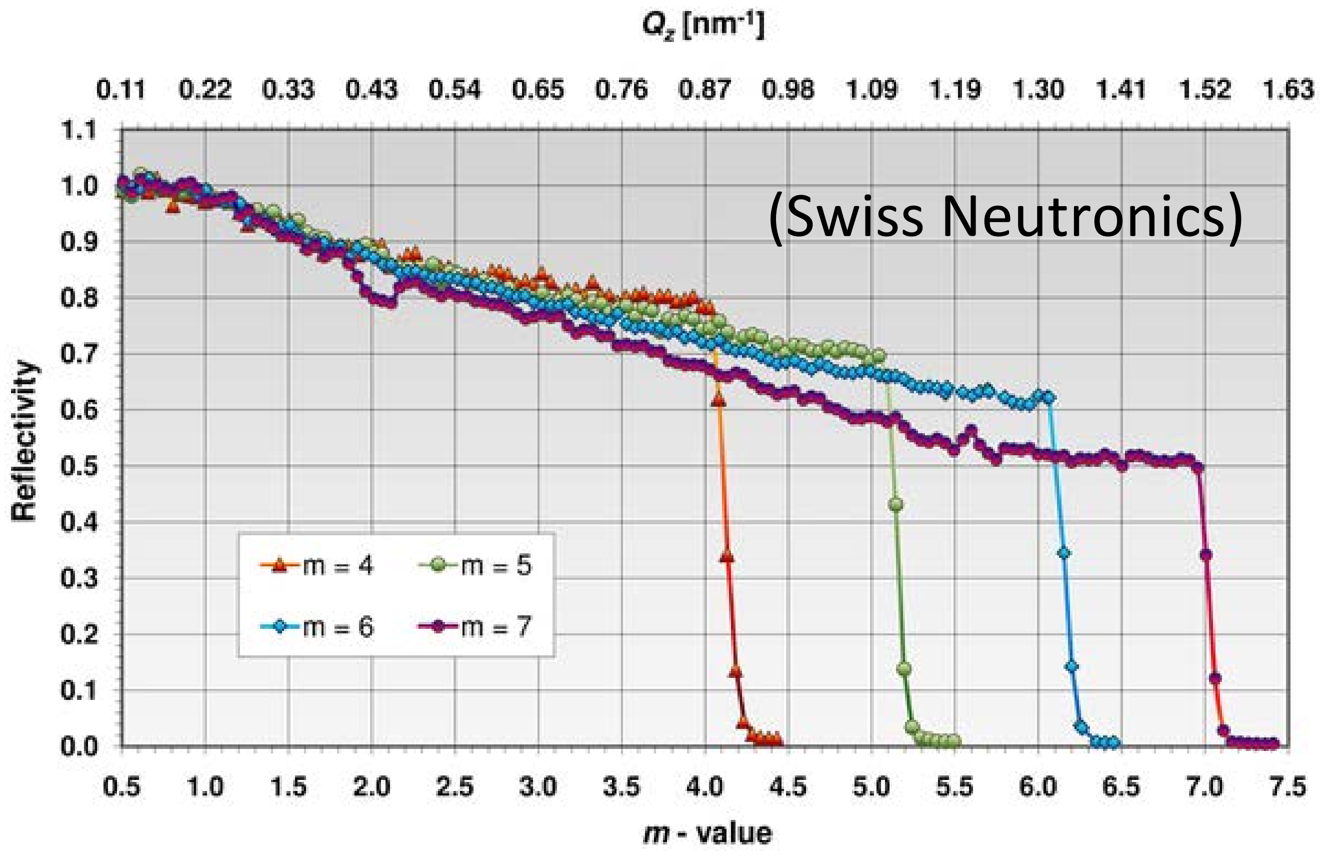
See e.g. NNbarX (Babu et al.), http://arxiv.org/abs/arXiv:1310.8593

- High-m super-mirror
- Residual B field < 5 nT
- Good vacuum < 10^{-5} Pa

MC optimization of parameters ongoing!

Supermirror Reflector

- Crucial in acceptance gain
  - 2D, so acceptance scales quadratically
  - Modern multi-layer supermirrors have good reflectivity at increasingly large momentum transfers



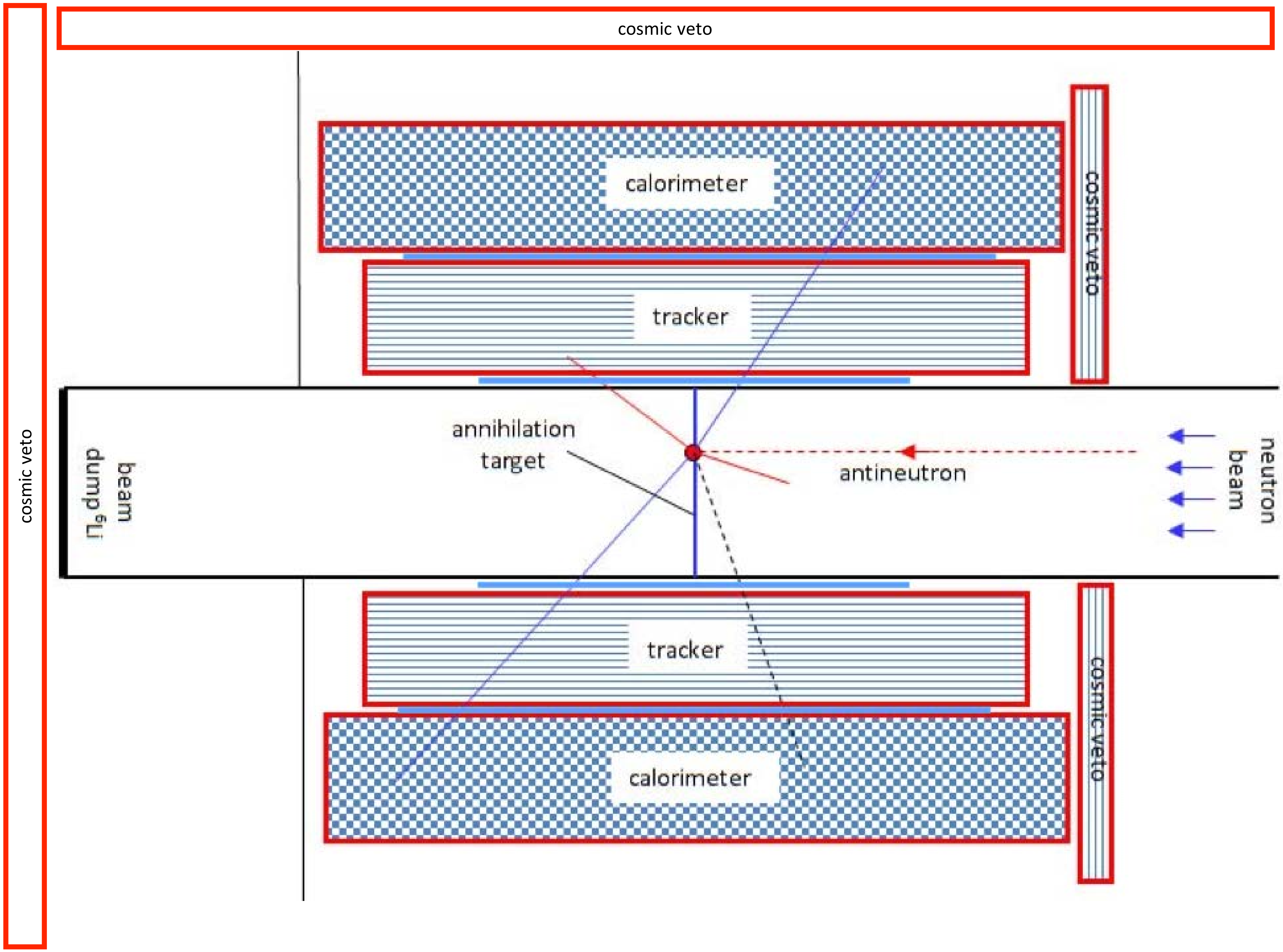
Active R&D at Nagoya University, with devices used at JPARC

Ni reflectivity → 0 defines m=1

Detector

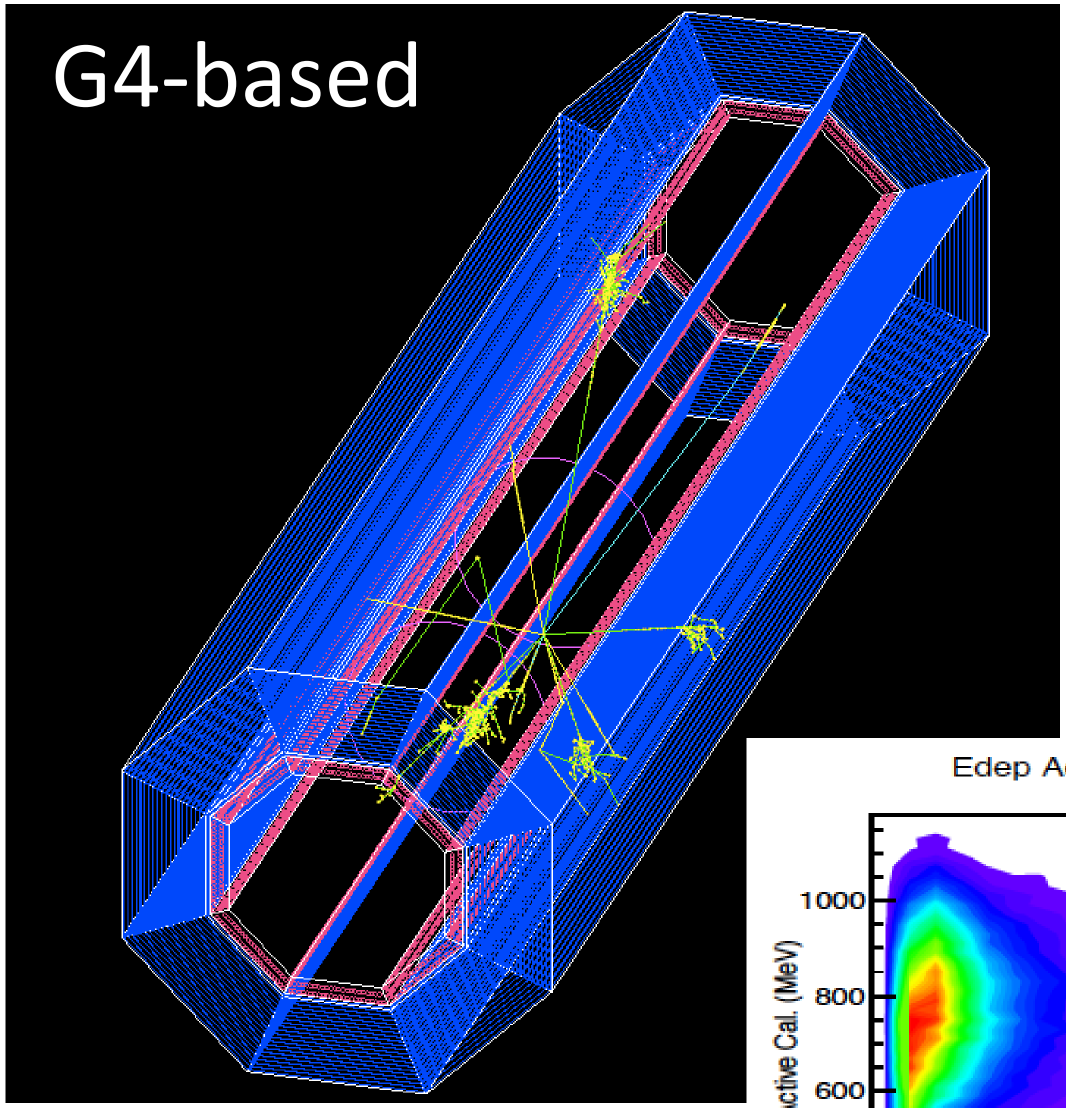
- Anti-neutron annihilation target
  - High annihilation probability, low Z, high transparency to neutrons
    - ILL experiment used a carbon foil, 130 μm thick
- Annihilation produces pions, <n> ~ 5
- Background suppression:
  - Precise annihilation vertex identification of multitrack events
  - Good mass and position resolution
  - Beam time structure? (Mainly for background control samples)

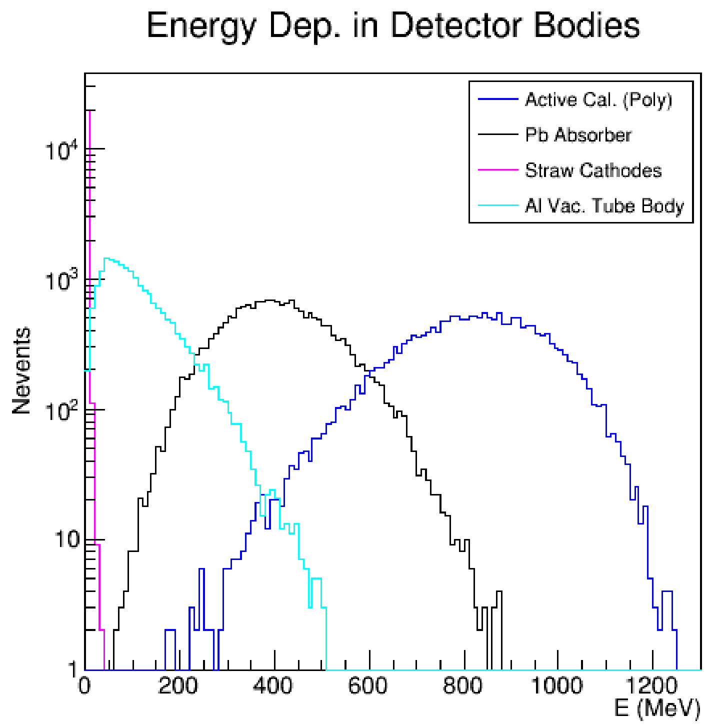
Detector

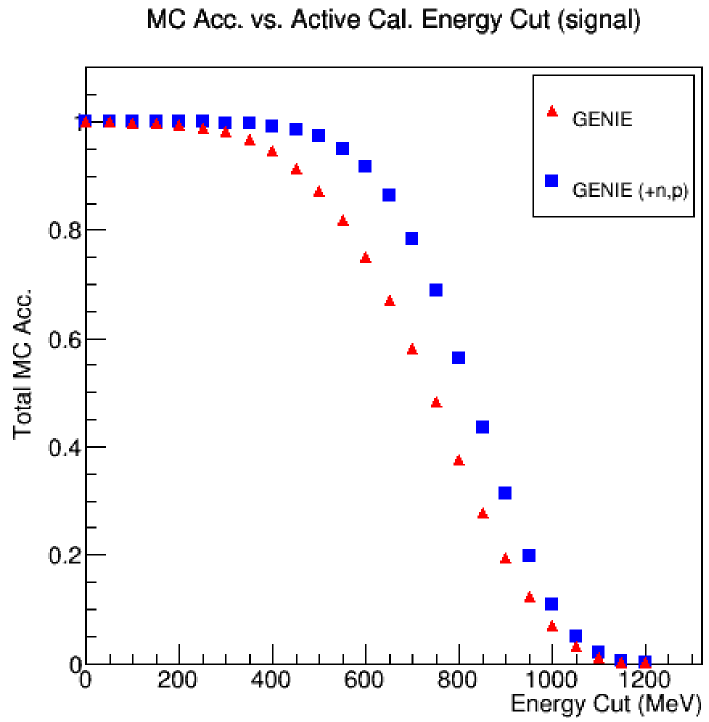


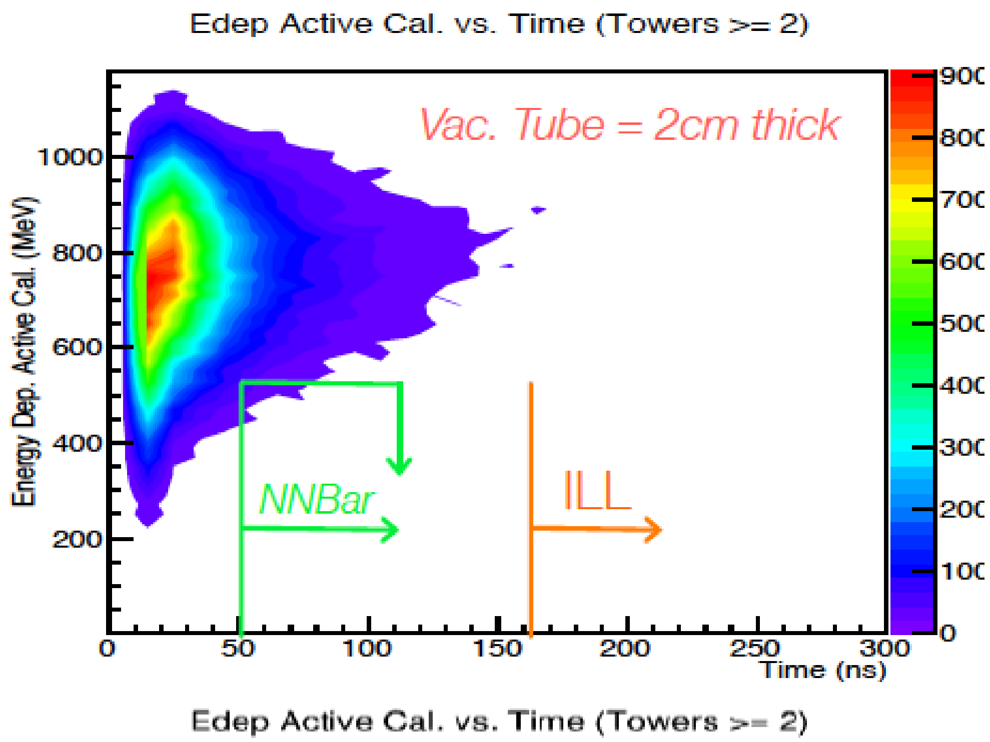
cosmic veto
cosmic veto
calorimeter
tracker
cosmic veto
beam
dump ^{6}Li
annihilation
target
antineutron
neutron
beam
tracker
calorimeter
cosmic veto

Early Simulations: Detector









Identify Target Improvements over ILL

acceptance ~90% (x1.8)

X3 red. in timing window (50 ns)

Lots of possibilities for detector development!

Expected Sensitivity

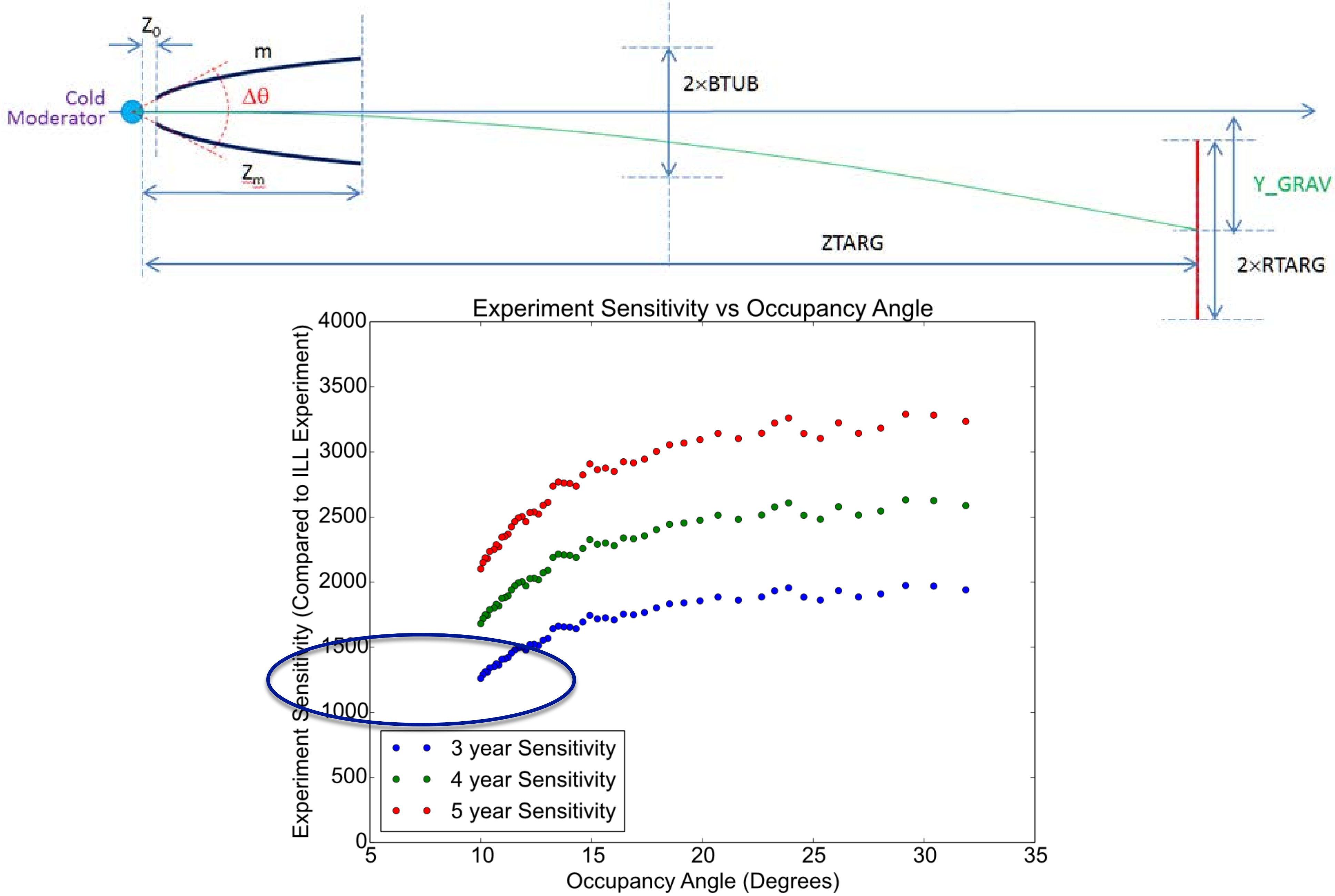
Potential Gains wrt ILL

Brightness		≥ 1
Moderator Area	Needs large aperture	2
Angular Acceptance	2D, so quadratic sensitivity	40
Length	Scale with t^2, so L^2	5
Run Time	ILL run was 1 year	3
Total		≥ 1000

x 1000 in probability, reach $\tau \sim 2\text{-}3 \times 10^9$ s

Early Simulations: Sensitivity

- Neutron spectrum files from ESS
- 50% detection efficiency (as for ILL)



Collaboration

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

	Name	Affiliation
Main proposer	Gustaaf Brooijmans	Columbia University
Co-proposers	Torsten Åkesson	Lund University
	David Baxter	Indiana University
	Hans Calen	Uppsala University
	Lorenzo Calibbi	Université Libre de Bruxelles
	Luis Castellanos	University of Tennessee
	Joakim Cederkäll	Lund University
	Peter Christiansen	Lund University
	Christophe Clément	Stockholm University
	Brian Cole	Columbia University
	Caterina Doglioni	Lund University
	Claes Fahlander	Lund 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
	Vincent Hedberg	Lund University
	Lawrence Heilbronn	University of Tennessee
	Andreas Heinz	Chalmers University of Technology
	Go Ishikawa	Nagoya University
	Håkan Johansson	Chalmers University of Technology
	Tord Johansson	Uppsala University
	Leif Jönsson	Lund University
	Yuri Kamyshkov	University of Tennessee
	Masaaki Kitaguchi	Nagoya University
	Esben Klinkby	ESS, Technical University of Denmark
	Balasz Konya	Lund University
	Andrzej Kupsc	Uppsala University
	Mats Lindroos	ESS
	Else Lytken	Lund University
	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
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	Robert Shrock	Stony Brook University
	David Silvermyr	Lund University
	Samuel Silverstein	Stockholm University
	Oxana Smirnova	Lund University
	Per Erik Tegner	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

- Collaboration growing
  - ESS very supportive
    - Agreed to target area modifications needed
  - Revisiting sensitivity studies now that ESS has frozen moderator configuration
- Regular collaboration meetings

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Neutron-antineutron oscillations: Theoretical status and experimental prospects

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Ongoing work modeling aspects of the oscillation coherence, magnetic field sensitivity, and detailed models of the ESS target and moderator geometry

Conclusion

- Search for n-$\bar{n}$ oscillation strongly motivated:
  - ΔB=2 baryon number violation appears in many models
  - Probe scales from 10^5 - 10^{12} GeV
  - Connection with baryogenesis, neutrino masses, …
- Experiment well within current capabilities
  - Very low technical risk – plenty of opportunities to optimize the approach and improve the project!
- Substantial community exists
  - Bridges particle and nuclear physics communities
  - Synergies with ESS neutron scattering community
- Complementary to planned science at LHC (observable particle production…) and the Underground Physics program
- Exploration of test beam program and n-n' measurements by collaboration is underway
- Opportunities to gain a factor 1000 in sensitivity to processes at core of our existence and understanding of universe are rare

Should **not** be squandered

http://www.nnbar-at-ess.org