Searches for Baryon Number Violation in Neutron-Antineutron Oscillations

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Why do we think that baryon number is not conserved?

Old results, new results, future prospects using underground detectors

Old results, future prospects using free neutrons

Slides from: S. Slamminger, Y. Kamyshkov, R. Mohapathra, S. Nakayama, E. Kearns, J. Barrow, K. Babu, X. Yan,…

Is B the Source of a Field Like Q?

Conservation of electric charge is closely connected with gauge symmetry/ masslessness of photon and 1/r form of EM potential.

$$V_{EM} = Q / r$$

If same idea worked for B, we expect conservation of "baryonic" charge to be associated with new long-range force coupled to B.

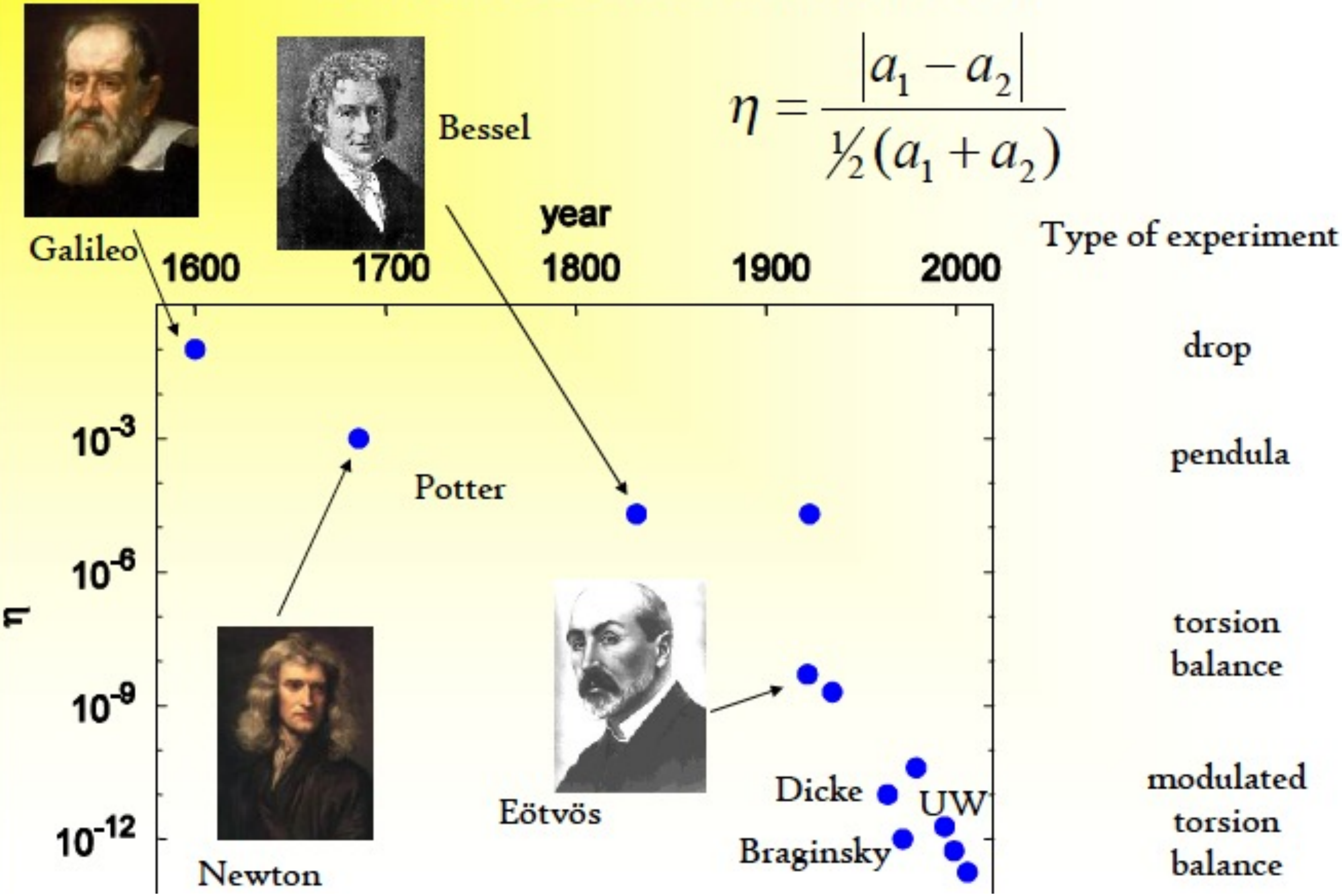
$$V_B = B / r$$

So where is the new long-range force coupled to B?

Experimental tests of equivalence principle for gravity use masses with different B/M ratios, see no effects.

Historical overview

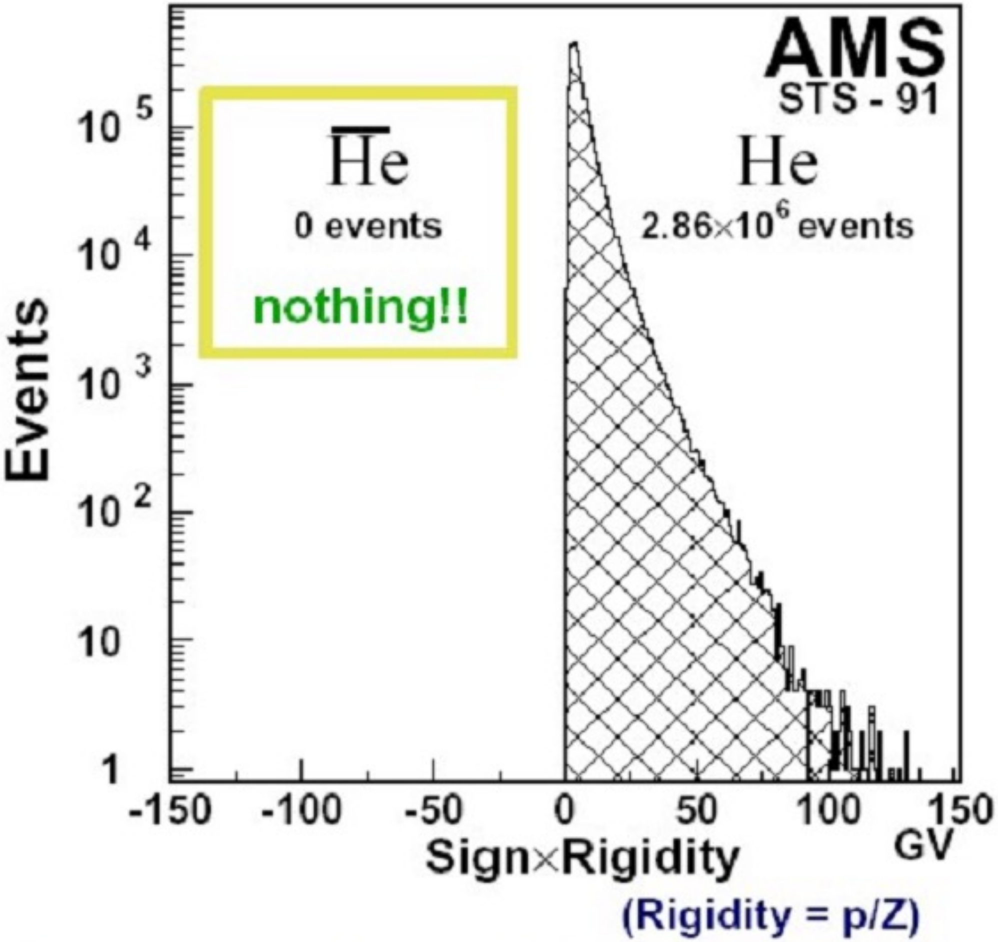
$$\eta = \frac{|a_1 - a_2|}{\frac{1}{2}(a_1 + a_2)}$$



No experimental evidence for long-range force coupled to B

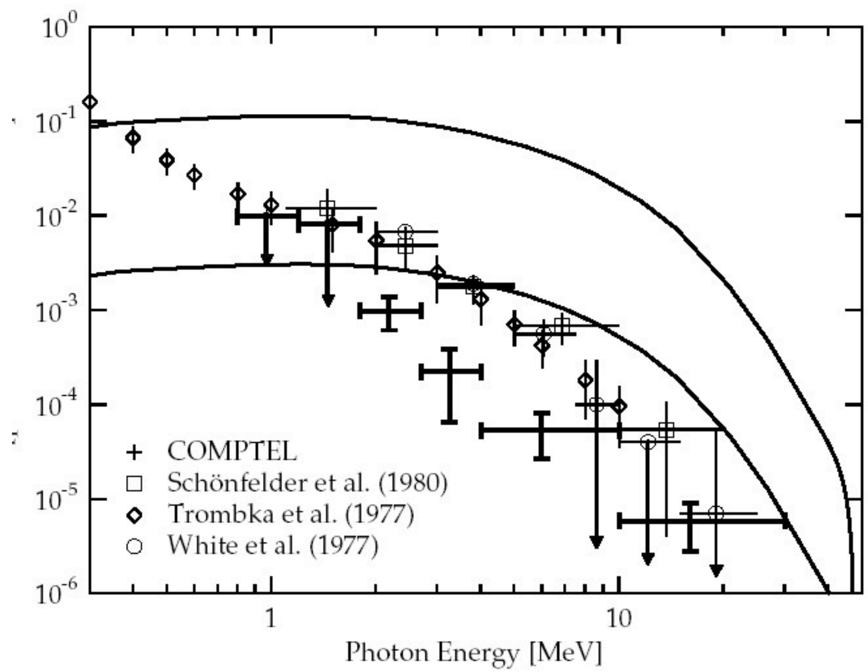
S. Slamminger

Universe looks B Asymmetric



"Search for antihelium in cosmic rays"
Phys. Lett. B461 (1999) 387.

Diffuse γ-ray flux
expected from annihilation



Cohen, De Rujula, Glashow;
astro-ph/9707087

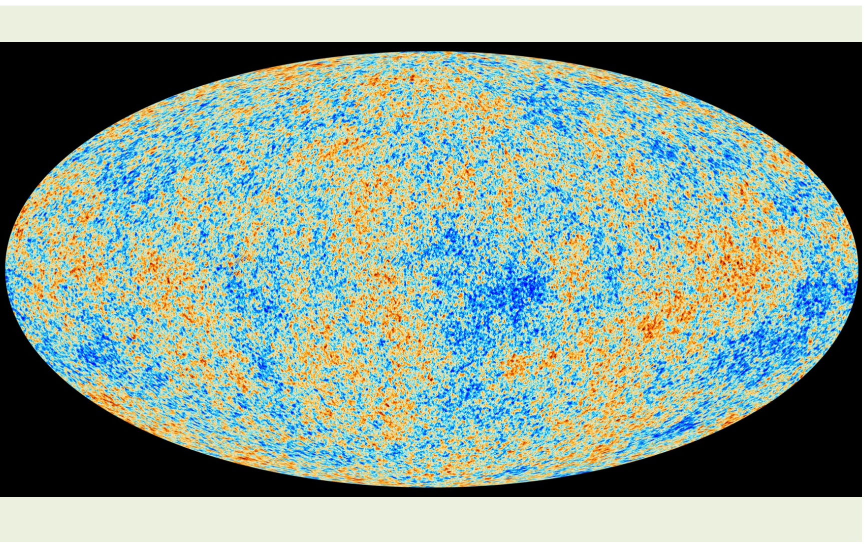
Later observations/estimates: still no evidence
for large hunks of antimatter. B of universe nonzero?

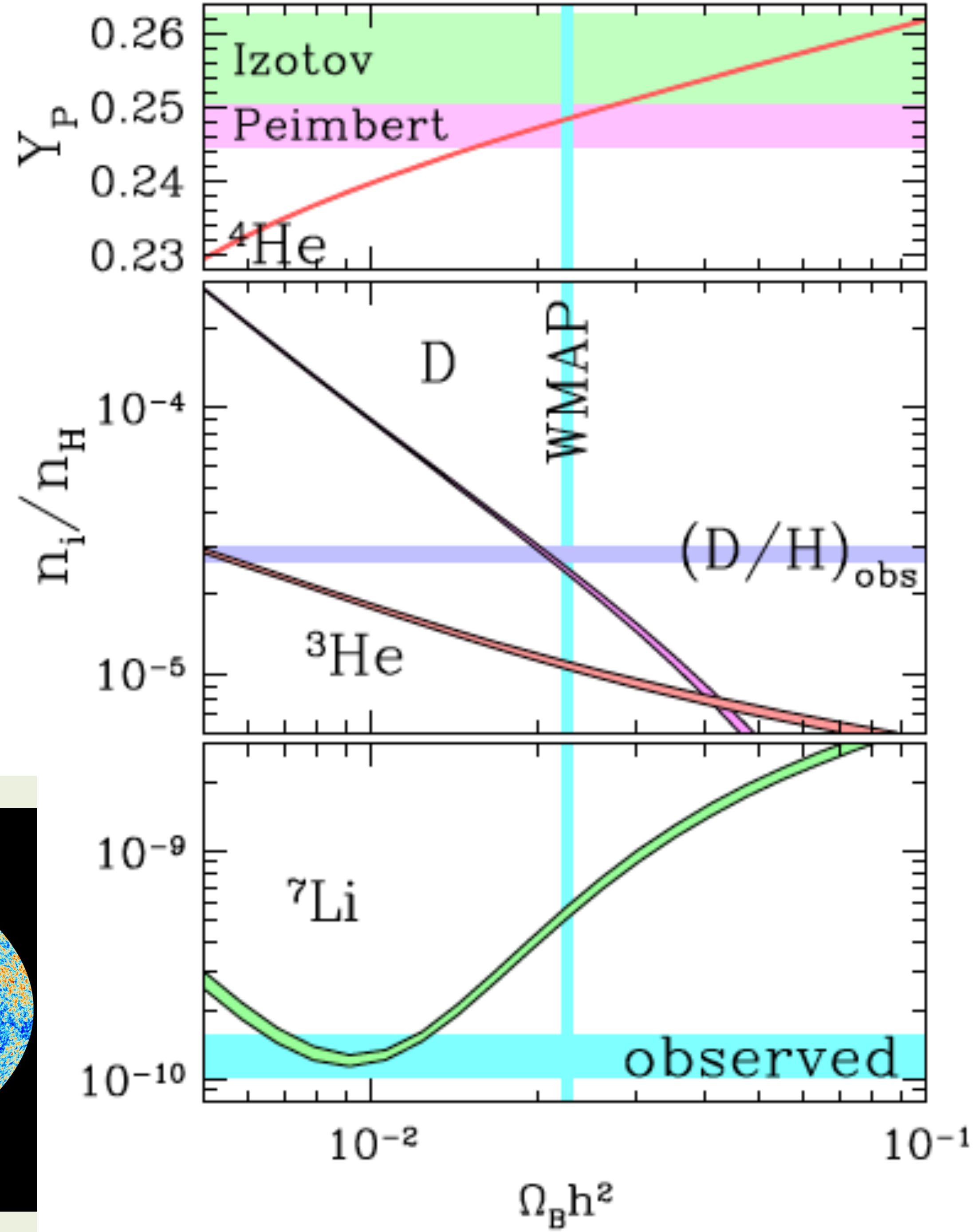
Big Bang nucleosynthesis: theory and observation (+WMAP)

Proportions in agreement with astro observations! (except 7Li…)

Universe B asymmetry:

$\eta = (N_B - N_{antiB}) / N_\gamma \sim 10^{-10}$





B conservation+ $\eta(t=0)=10^{-10}$ as initial condition: why not?

Inflationary period in early universe (needed to solve horizon, flatness, etc. problems in cosmology) asserts that the "size" of the universe increased exponentially at constant energy density:

$$R(t) \propto \exp(3Ht)$$

for ~70 Hubble times with universe at ~constant energy density

But if B is conserved AND B(t=after inflation)~10^{-10}, at earlier times B makes a large, time-dependent contribution to energy density.

B conservation + $\eta=10^{-10}$ destroys inflation.

[A. D. Dolgov, Physics Reports 222, 309 (1992).]

Matter/Antimatter Asymmetry in the Universe in Big Bang, starting from zero

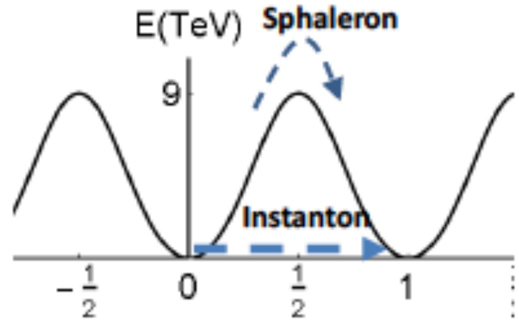
Sakharov Criteria to generate matter/antimatter asymmetry from the laws of physics

- Baryon Number Violation (not yet seen)
- C and CP Violation (seen, but is it enough?)
- Departure from Thermal Equilibrium (happens in Big Bang)

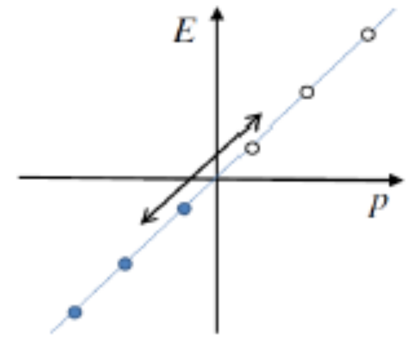
A.D. Sakharov, JETP Lett. 5, 24-27, 1967

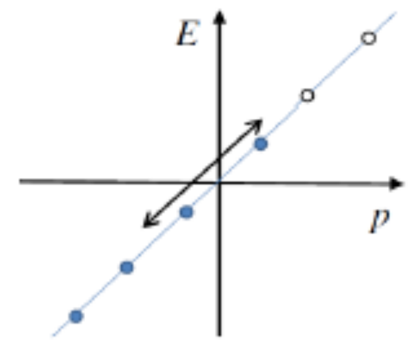
Perturbative B conservation in SM is an “Accident”

Both B and L conservation are “accidental” global symmetries: given SU(3)⊗SU(2)⊗U(1) gauge theory and SM matter content, no dimension-4 term in Lagrangian violates B or L.



B violating operator of dimension D+4 from BSM theory should be suppressed by mass scale M^D from effective field theory point of view.





Nonperturbative EW gauge field fluctuations (sphaelerons) present in SM
VIOLATE B, L, B+L, but CONSERVE B-L.

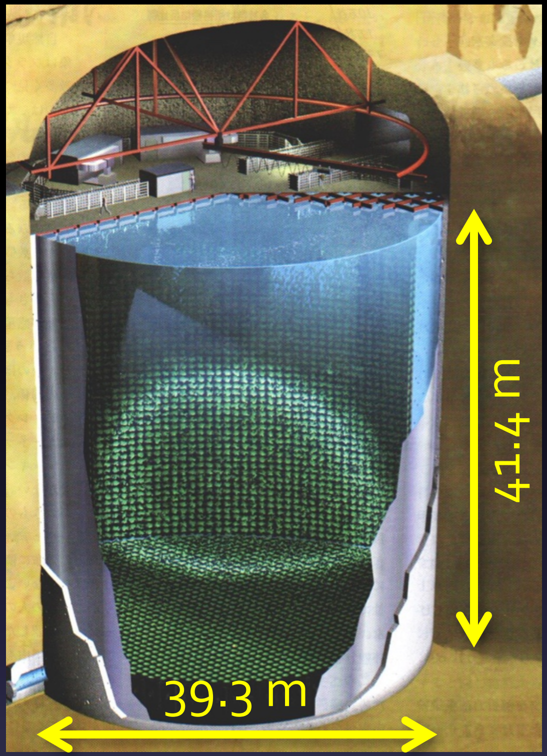
Selection rules for B violation are very important

Nucleon Decay and Neutron-Antineutron Oscillation Probe Different Physics

Mode	Nucleon decay	N-Nbar oscillations
effect on B and L	$\Delta B=1$, $\Delta L=1$, others <u>$\Delta(B-L)=0,2,\ldots$</u>	$\Delta B=2$, $\Delta L=0$, <u>$\Delta(B-L)=2$</u>
Effective operator	$L=\frac{g}{M^2}QQQL$	$L=\frac{g}{M^5}QQQ\bar{Q}\bar{Q}\bar{Q}$
Mass scale probed	Grand Unified (GUT) scale	>electroweak scale (<<GUT)

Neutron-antineutron oscillations generically access scales not far above the electroweak scale: physics is completely different from the GUT scales accessed in proton decay

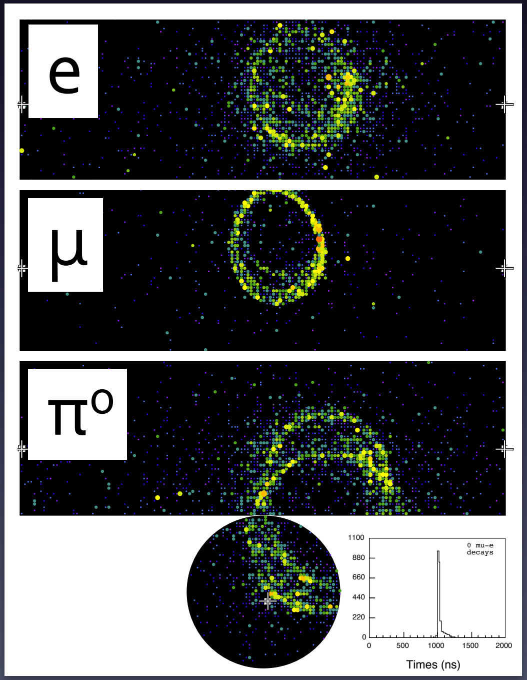
Super-Kamiokande



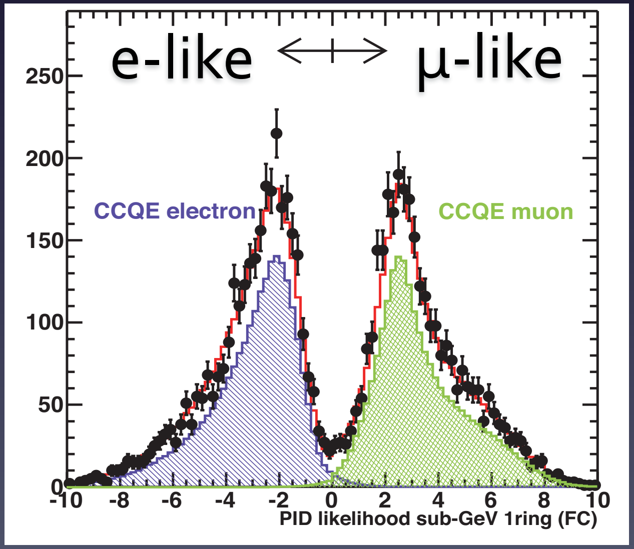
©Scientific American

- World largest "ν & proton decay" detector
- 4π acceptance, uniform response
- Cherenkov ring pattern on detector wall
- Excellent event reconstruction
  - μ/e mis-identification < 1% @~1 GeV

- 1000 m underground
- 50 kton ultrapure water
  - 22.5 kton fiducial
- Inner volume viewed by 11,000 50-cm PMTs

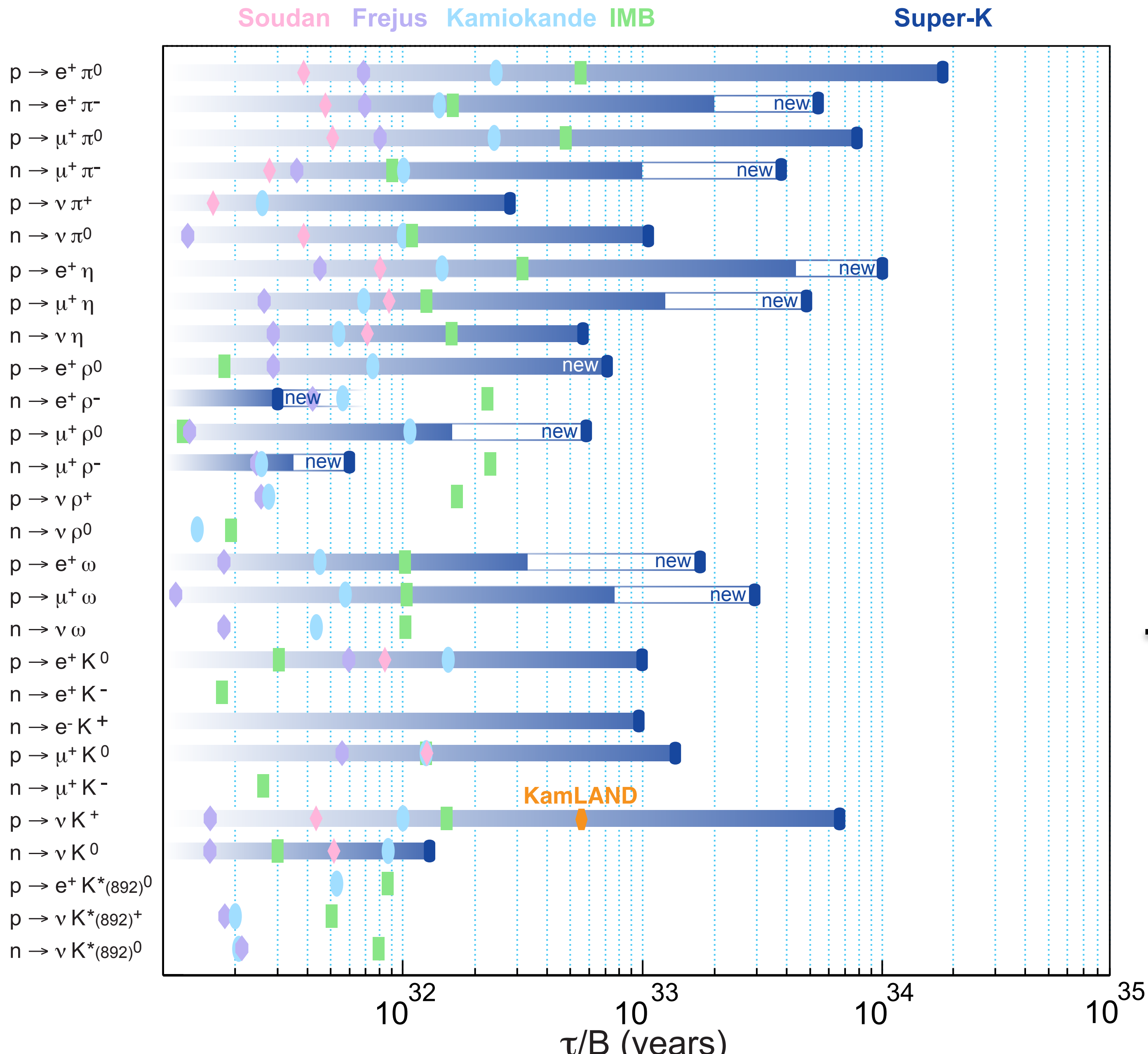


PID parameter
(Atmospheric ν Data/MC)



S. Nakayama

Nucleon decay limits in different decay channels



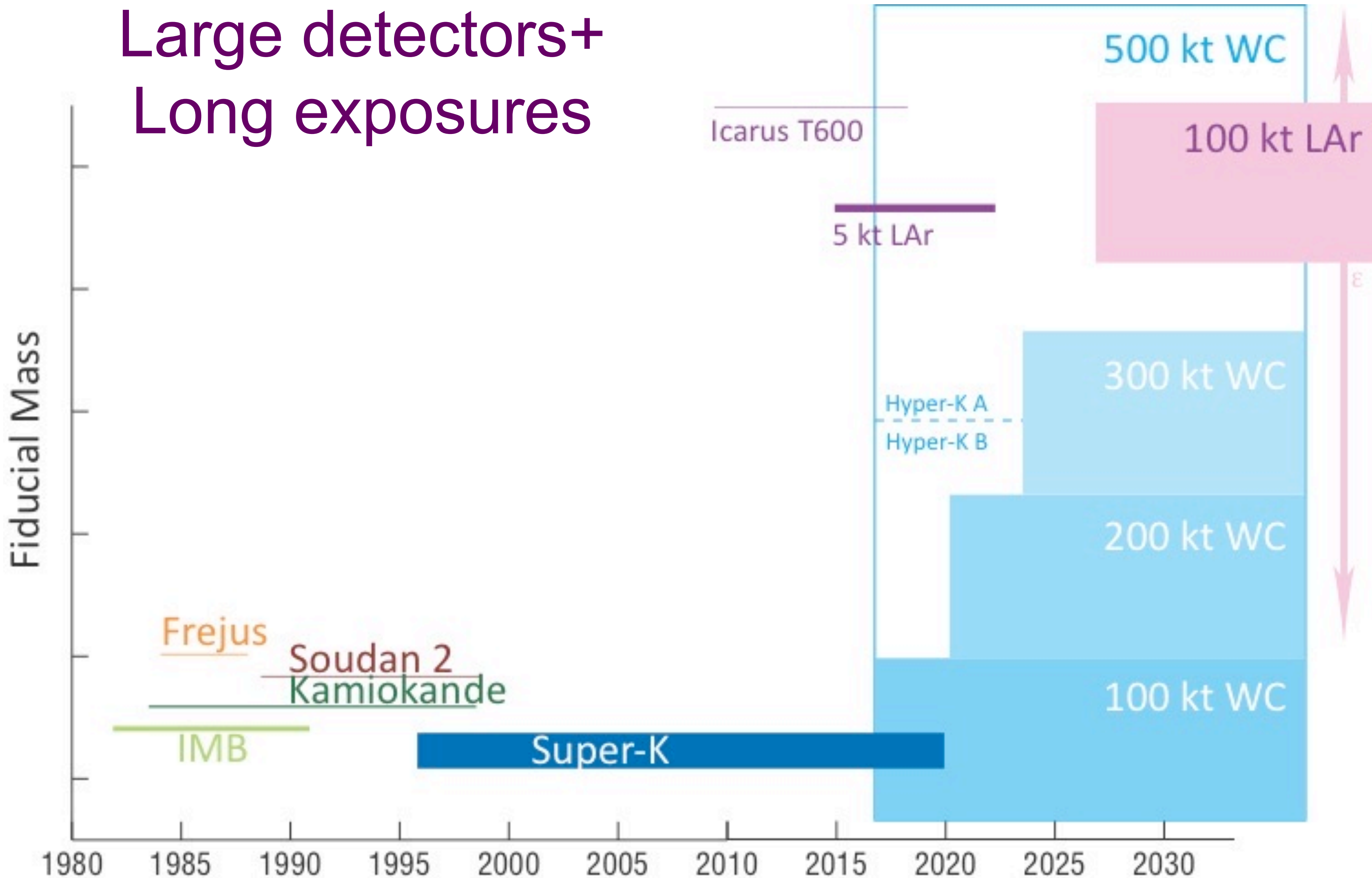
antilepton plus meson

conserves (B-L)

non-strange mesons

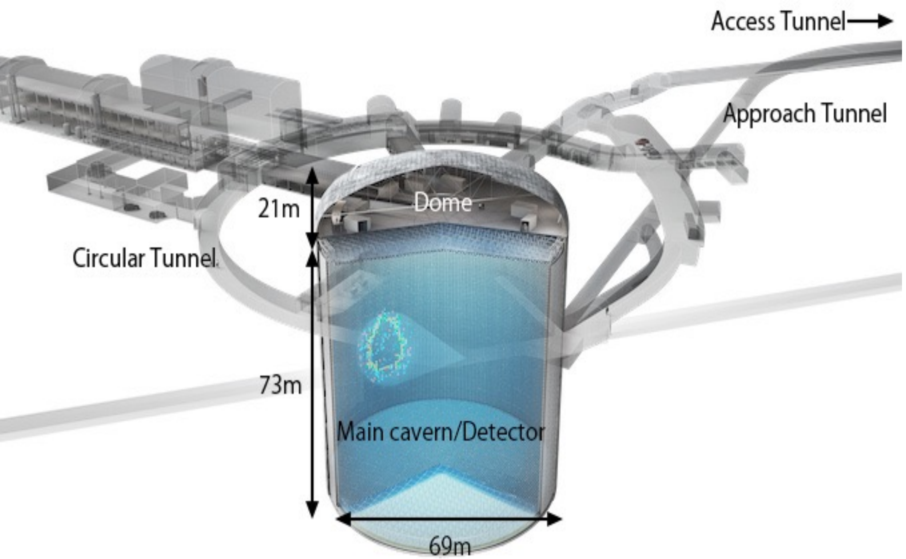
strange mesons

To Improve: need Very Large detectors+ Long exposures



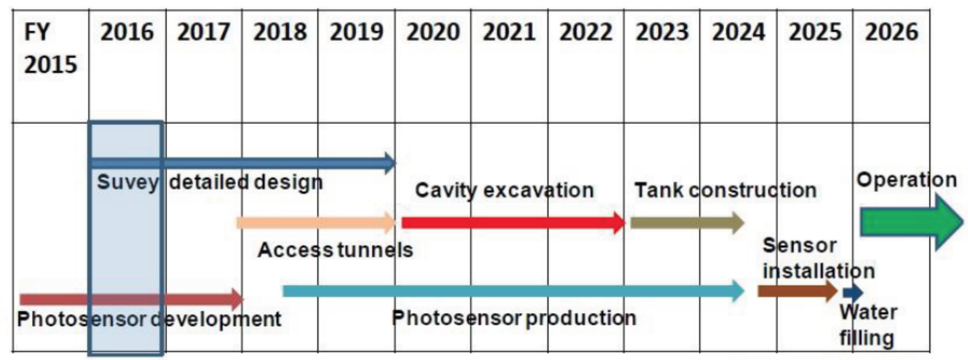
From E. Kearns

Hyper-Kamiokande



Two tank – staging strategy
Each tank:

- 260 kton total, 188 kton fiducial mass
- 40000 50-cm high QE PMTs
- 74 m ⌀ x 60 m high
- 1800 mwe oveburden

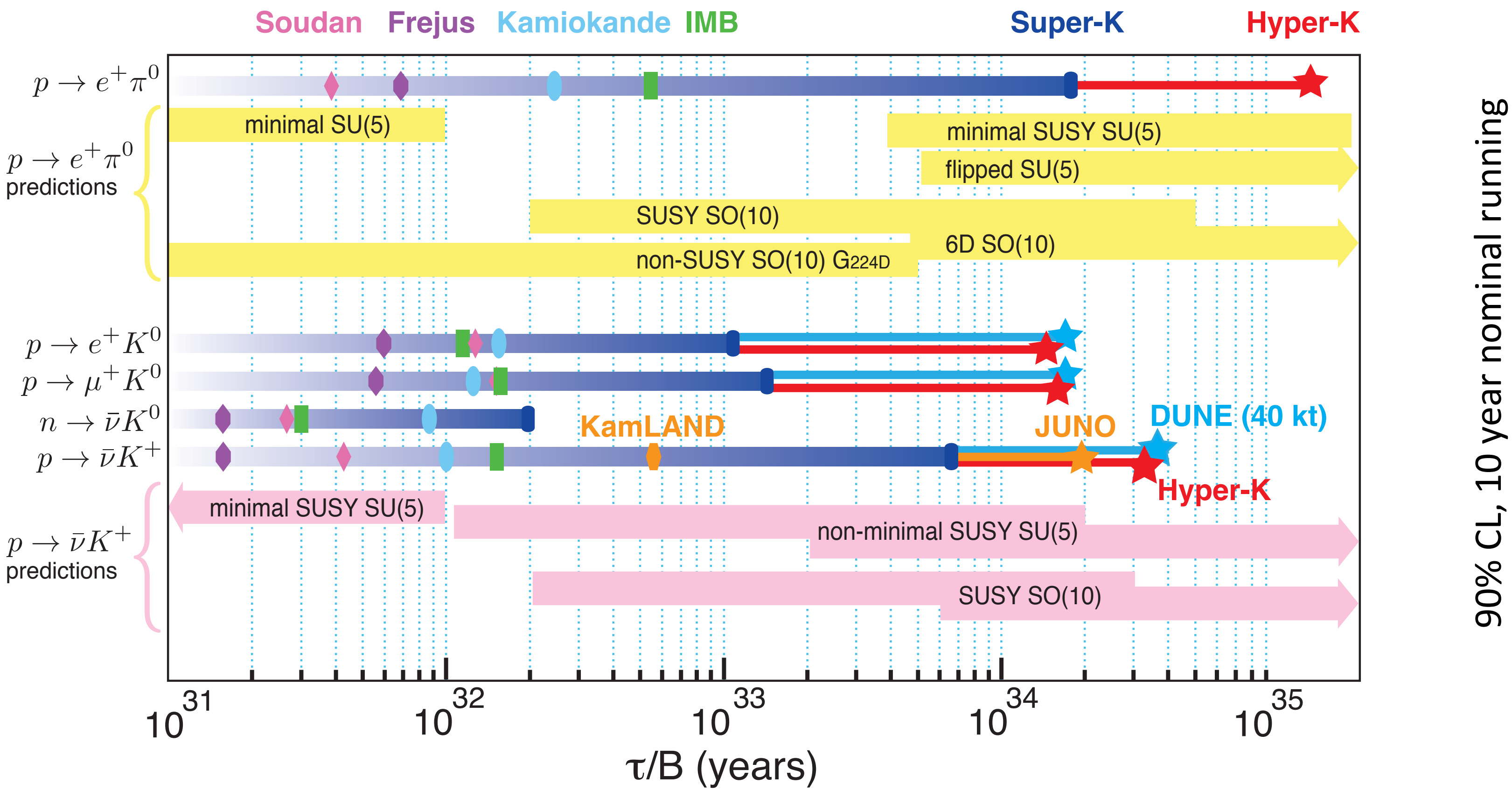


Maximize detector performance – less mass than originally discussed

Cavity excavation started in ~mid-2023

E. Kearns

The decade ahead almost a decade from now



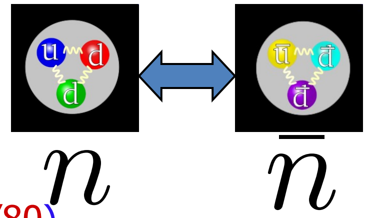
~one order of magnitude improvement

HyperK leading experiment for p -> eπ mode, competitive with DUNE in kaon modes

E. Kearns

What is N-Nbar oscillation ?

- Neutrons in vacuum or low magnetic field spontaneously converting to anti-neutrons.



(Baryogenesis: Kuzmin'70; SU(5): Glashow'79; neutrino mass: Mohapatra and Marshak'80)

- $\delta m_{n\bar{n}}$ is the mixing strength between n and $\bar{n}$
- $\delta m_{n\bar{n}} = 0$ in the standard model.
- **Hence it is a probe of new physics !!**

NNbar oscillations → ~TeV scale physics

- Operator responsible for NNbar:

$$O_{\Delta B=2} = \frac{1}{M_{eff}^5} udd\overline{u}\overline{d}\overline{d}$$

Note M^5 suppression

$$\delta m_{n\bar{n}} = G_{\Delta B=2} < n|O_{\Delta B=2}|\bar{n} > \sim G_{\Delta B=2}\Lambda^6$$

(Rao/Shrock, Bag model, Buchoff/Wagman, Phys. Rev. D 93, 016005 (2016), **arXiv:1506.00647**)

$$\tau_{n-\bar{n}} = \hbar / \delta m_{n-\bar{n}} \sim M^5 / \Lambda^6$$

$$\tau_{n\bar{n}} \sim 10^8 s.$$ M~100 TeV

Observation of NNbar would open a totally new landscape of physics above ~ 100TeV scale

Impact of observable NNbar on pre-existing baryons

- Observation of NNbar would completely alter our thinking about the origin of matter.

- If NNbar transition is observable and a purely low scale phenomenon, $\Delta B = 2$ will (generically) be in equilibrium till T~ 130 GeV

  ⇒ Will erase any pre-existing matter asymmetry

- Would need new models for Baryogenesis

Neutron-Antineutron Oscillations: (simple) 2x2 Formalism

$\alpha \neq 0$ allows oscillations

$$\Psi = \begin{pmatrix} n \\ \bar{n} \end{pmatrix}$$ n-nbar state vector

$$H = \begin{pmatrix} E_n & \alpha \\ \alpha & E_{\bar{n}} \end{pmatrix}$$ Hamiltonian of n-nbar system

$$E_n = m_n + \frac{p^2}{2m_n} + U_n \quad ; \quad E_{\bar{n}} = m_{\bar{n}} + \frac{p^2}{2m_{\bar{n}}} + U_{\bar{n}}$$

Note :

- α real (assuming T)
- $m_n = m_{\bar{n}}$ (assuming CPT)
- $U_n \neq U_{\bar{n}}$ in matter and in external B [$\mu(\bar{n}) = -\mu(n)$ from CPT]

Neutron-Antineutron Oscillations: the experimental figure-of-merit

$$\text{For } H = \begin{pmatrix} E+V & \alpha \\ \alpha & E-V \end{pmatrix} \qquad P_{n\to\bar{n}}(t) = \frac{\alpha^2}{\alpha^2+V^2} \times \sin^2\left[\frac{\sqrt{\alpha^2+V^2}}{\hbar} t\right]$$

where V is the potential difference for neutron and anti-neutron.

Present limit on $\alpha \leq 10^{-23} eV$

Contributions to V:

<Vmatter> ~100 neV, proportional to matter density

<Vmag>=μB, ~60 neV/Tesla; B~10nT-> Vmag~10^{-15} eV

<Vmatter> , <Vmag> both >>α

$$\text{For } \left[\frac{\sqrt{\alpha^2+V^2}}{\hbar} t\right] << 1 \text{ ("quasifree condition")} \qquad P_{n\to\bar{n}} = \left(\frac{\alpha}{\hbar} \times t\right)^2 = \left(\frac{t}{\tau_{n\bar{n}}}\right)^2$$

Figure of merit (with no background)= NT^2 N=#neutrons, T="quasifree" observation time

How to Search for N-Nbar Oscillations

Figure of merit for probability: $$NT^2$$

N=total # of free neutrons observed

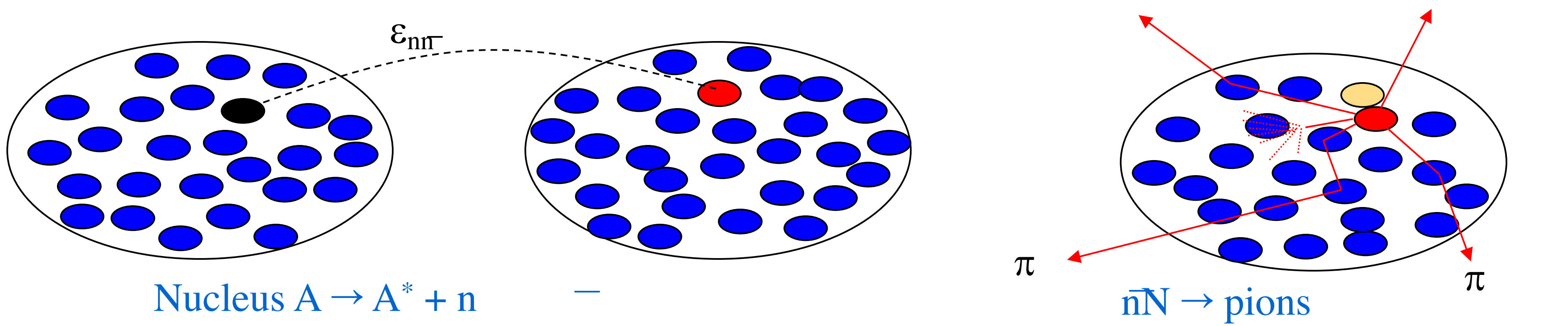
T= observation time per neutron while in “quasifree” condition

When neutrons are in matter or in nucleus, n-nbar potential difference is large->quasifree observation time is short

B field can suppress nnbar oscillations due to opposite magnetic moments for neutron and antineutron

(1) n-nbar transitions in nuclei in underground detectors

(2) Cold and Ultracold neutrons



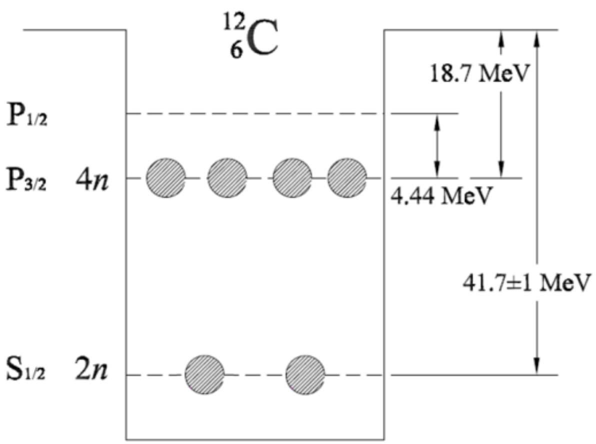
Suppression of n→nbar in intranuclear transitions

Neutrons inside nuclei are "free" for a time: $\Delta t \sim \frac{\hbar}{E_{binding}} \sim \frac{\hbar}{30 MeV} \sim 4.5 \times 10^{-22} s$

oscillate with "free" probability $= \left(\frac{\Delta t}{\tau_{n\bar{n}}} \right)^2$

and do this $N = \frac{1}{\Delta t}$ times per second.

Transition probability per second: $P_A \doteq \frac{1}{\tau_A} = \left(\frac{\Delta t}{\tau_{n\bar{n}}} \right)^2 \times \left(\frac{1}{\Delta t} \right)$



Intranuclear transition lifetime: $\tau_A = \frac{\tau^2_{n\bar{n}}}{\Delta t} = R \times \tau^2_{n\bar{n}}$

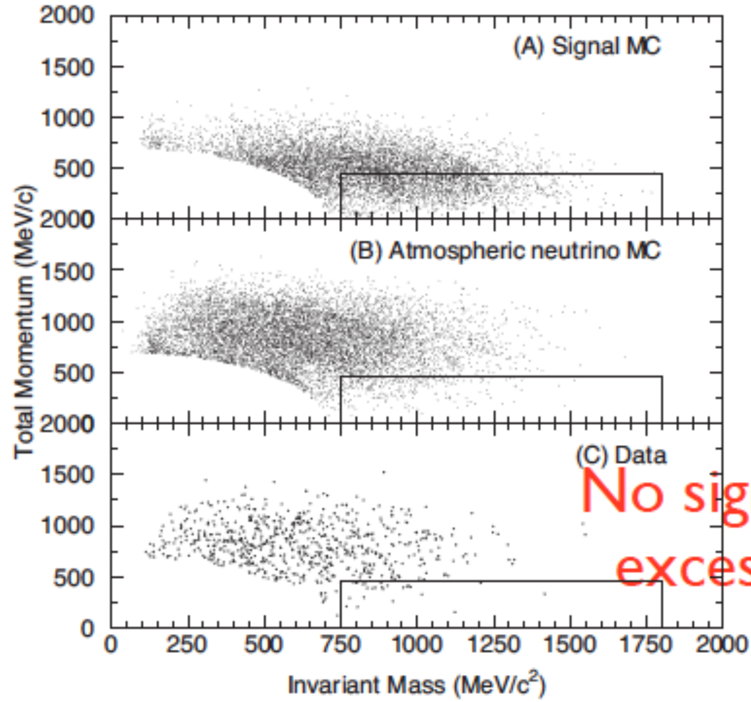
where R~ $\frac{1}{\Delta t} \sim 4.5 \times 10^{22} s^{-1}$ is a nuclear suppression factor

E. Friedman and A. Gal, Phys. Rev. D78, 016002 (2008)

ΔB=2: n-n̄ oscillation

PRD91,072006(2015)

- ΔB=Δ(B-L)=2, might be relevant for the matter asymmetry in the Universe
- look for multiple pions from nbar+nucleon annihilation



- •≧2 Cherenkov rings
- •700<Visible Energy<1300 MeV
- •750<M_{tot}<1800 MeV/c^2
  P_{tot}<450 MeV/c

n-nbar oscillation in ^{16}O

- detection efficiency = 12.1%
- atmospheric ν BG = 24.1 events in 92kton×years (Super-K-I)
- observed signal = 24 events
- $T_{n\text{-}nbar}(^{16}O) > 1.9 \times 10^{32}$ years @ 90%C.L.
  → $T_{n\text{-}nbar}(\text{free}) > 2.7 \times 10^{8}$ sec

Improved analysis w/ more data will be released soon

Gustafson@This workshop

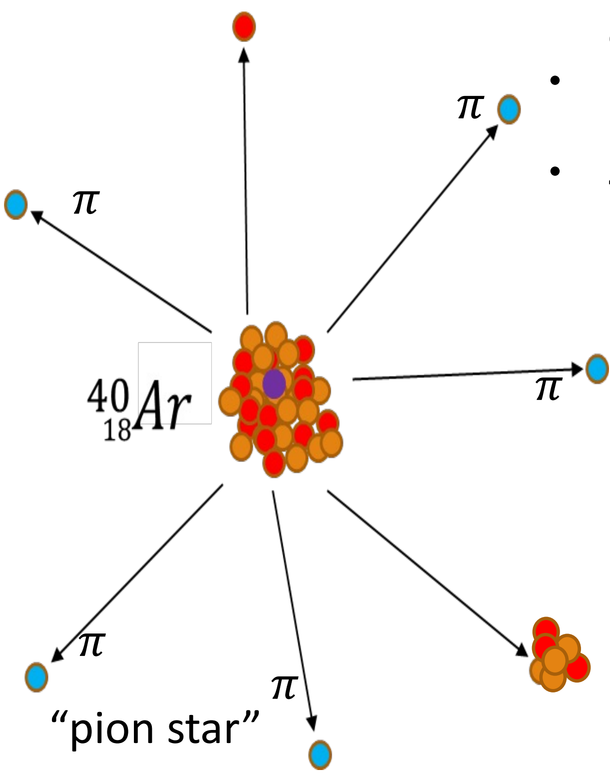
M. Shiozawa

Signal Comparison in Dune

$\boldsymbol{n-\bar{n}}$ vs. Atmospheric Neutrino

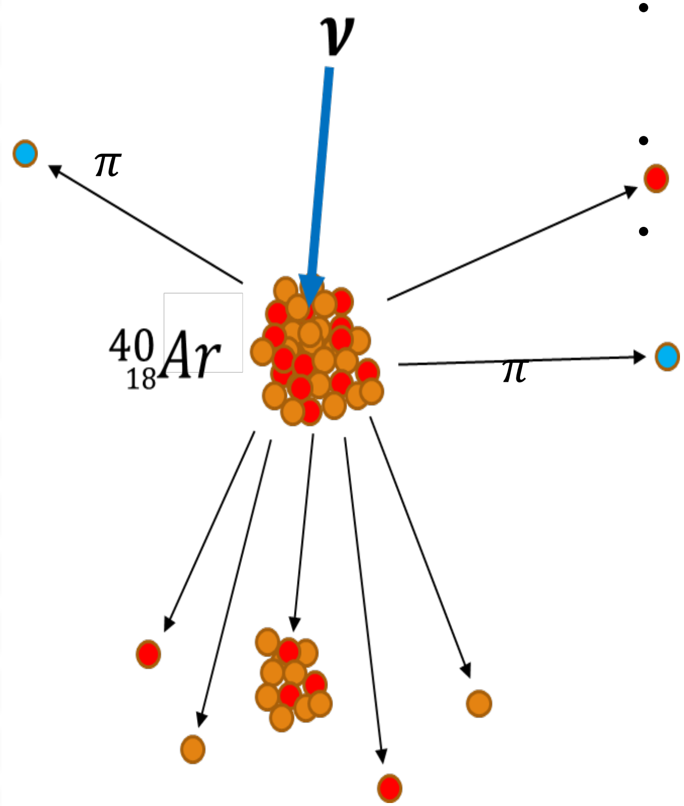
Annihilation and Knockouts

- Noncontinuous energy spectrum
- δ-like function in invariant mass
- Zero total momentum



Neutral Current Atmospheric ν

- Continuous energy spectrum
- Variable invariant mass
- Range of total momentum



DEEP UNDERGROUND NEUTRINO EXPERIMENT

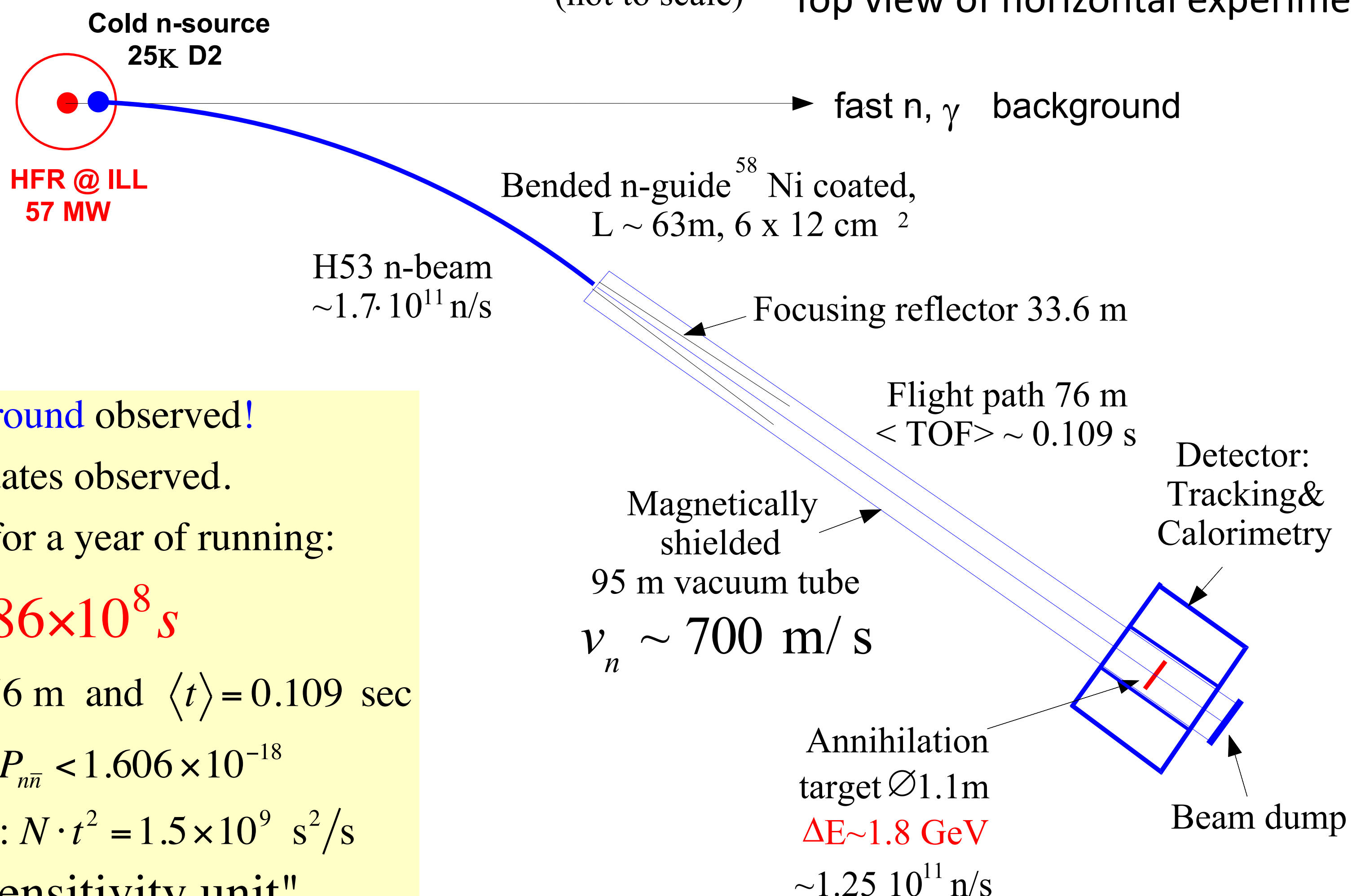
From Josh Barrow

Previous n-nbar search experiment with free neutrons

At ILL/Grenoble reactor in 89-91 by Heidelberg-ILL-Padova-Pavia Collaboration

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

(not to scale) Top view of horizontal experiment



No background observed!

No candidates observed.

Limit set for a year of running:

$$\tau_{n\bar{n}} > 0.86\times10^{8}\, s$$

with L ~ 76 m and $\langle t \rangle = 0.109$ sec

measured $P_{n\bar{n}} < 1.606\times10^{-18}$

sensitivity: $N \cdot t^2 = 1.5\times10^{9}\ \ s^2/s$

$\doteq$ "ILL sensitivity unit"

Better Slow Neutron NNbar Experiment: What do we want? (HOW DIFFICULT IS IT?)

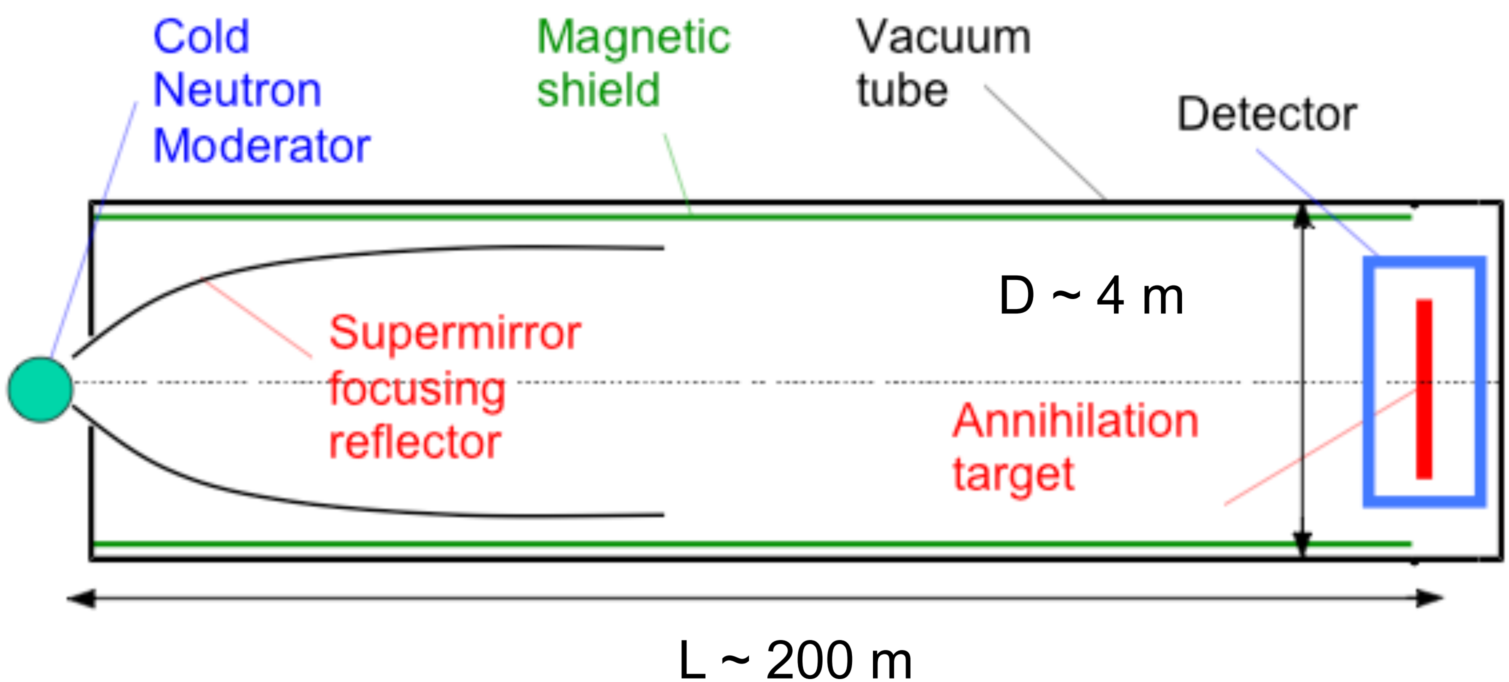
While still keeping quasifree condition, one wants more NT^2 with nbar detector watching the annihilation surface

- higher cold neutron brightness from moderator? POSSIBLE
- slower cold neutron energy spectrum? DIFFICULT
- more efficient extraction of cold neutrons with optics to quasifree flight/detector? YES: GREAT PROGRESS SINCE ILL NNBAR
- longer "quasifree" flight time? YES
- longer experiment operation time? YES (ILL only ran 1 year)

Better Free Neutron Experiment (Horizontal geometry, Kamyshkov '96)

need slow neutrons from high flux source, illuminate phase space acceptance of neutron focusing reflector, free flight path of ~200m

Improvement on ILL experiment by factor of >~500 in transition probability is possible at ESS with existing n optics technology, sources, and moderators for a reasonable running time.

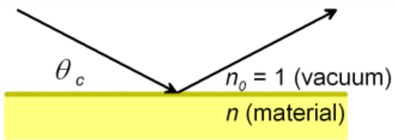


D. G. Phillips, W. M. Snow et al, Phys. Rep. 612, 1 (2016), arXiv:1410.1100

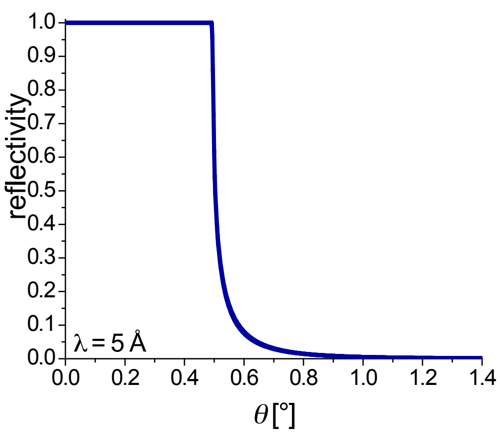
concept of neutron supermirrors: Swiss Neutronics

neutron reflection at grazing incidence (< ≈2°)

@ smooth surfaces

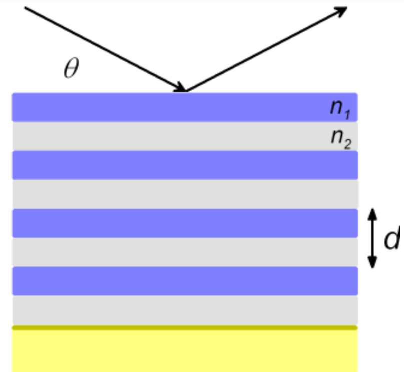


- refractive index n < 1
- total external reflection
  e.g. Ni $\theta_c = 0.1\,°$ /Å

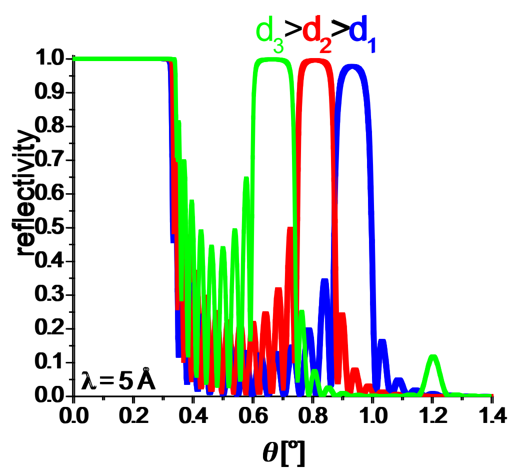


m=1

@ multilayer

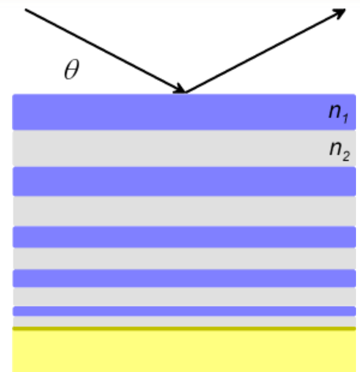


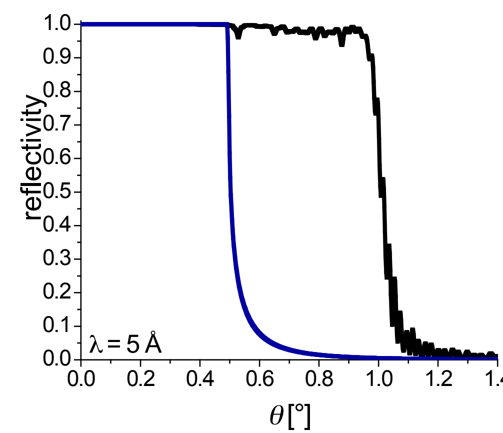
$$\lambda = 2d\sin\theta$$



$\theta_{critical} \rightarrow m\theta_{critical}$

@ supermirror

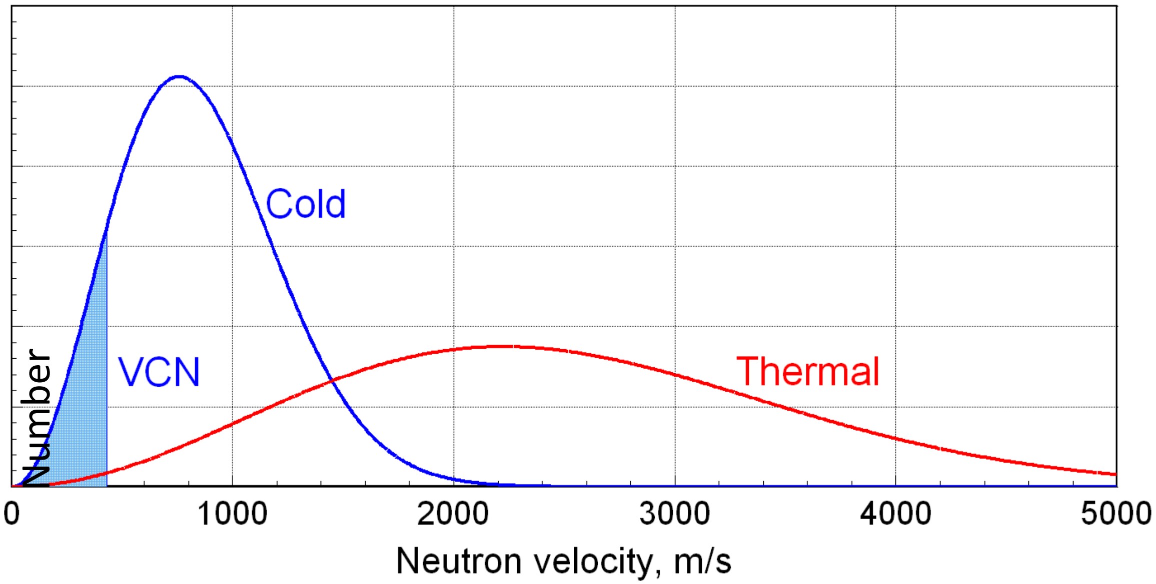




m=2

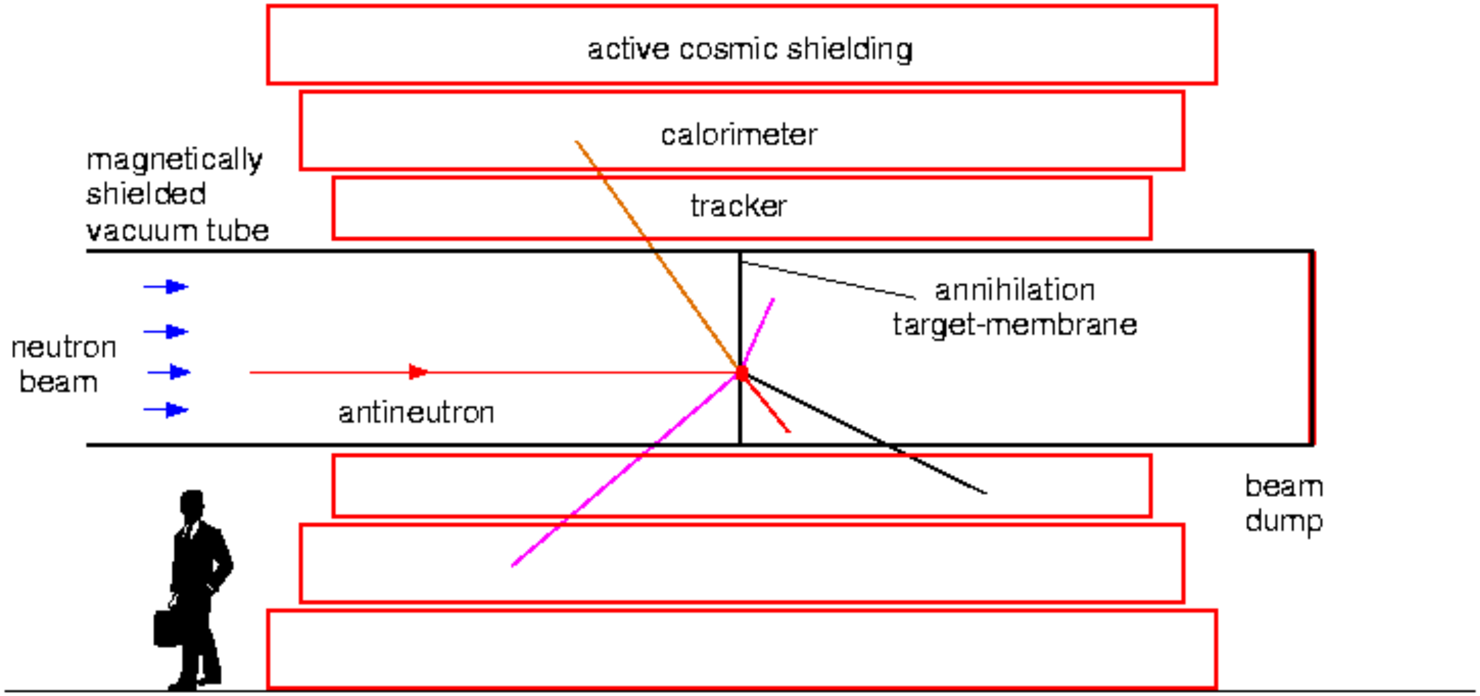
Neutron-Antineutron Oscillations with Free Neutrons: Max. Figure of Merit is for low energy ("cold") neutrons

Neutrons	E kin	T,K	Velocity	Wavelength
Fast	~ 1 MeV	~ 10^{10}	~ 0.046 *c*	~ 0.0003 Å
Thermal	~ 25 meV	~ 300	~ 2.2 km/s	~ 1.8 Å
Cold	~ 3 meV	~ 35	~ 760 m/s	~ 5 Å
Very Cold (VCN)	~ 1 meV	~ 10	~ 430 m/s	~ 9 Å
Ultra Cold (UCN)	~ 250 neV	~ 0.003	~ 8 m/s	~ 600 Å



Achievable at ESS? YES: it is already being optimized for slow neutron production for neutron scattering

Antineutron detector for "zero background" condition



$$\bar{n} + A \rightarrow \langle 5 \rangle \; pions \quad (1.8 \text{ GeV})$$

Annihilation target: ~100μ thick Carbon film

$\sigma_{annihilation} \sim 4$ Kb $\qquad \sigma_{nC\ capture} \sim 4$ mb

vertex precisely defined. No background was observed at ILL

Achievable at ESS? YES (higher energy neutron background, but source is off when slow neutrons arrive at annihilation detector)

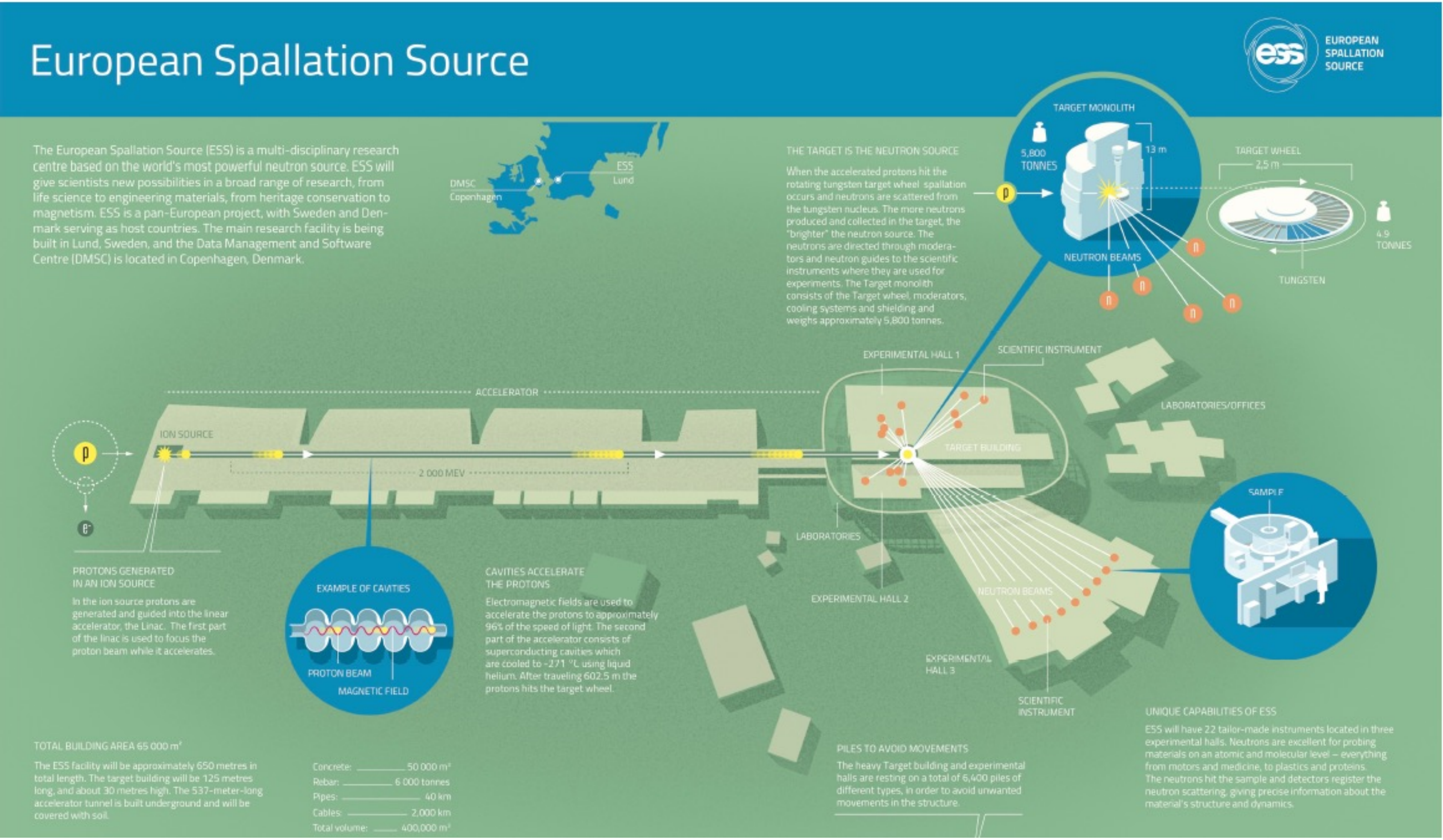
2014/2015 Round Instrument Construction Proposal
Revision Date 15/04/2015

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

57 (senior) authors from:

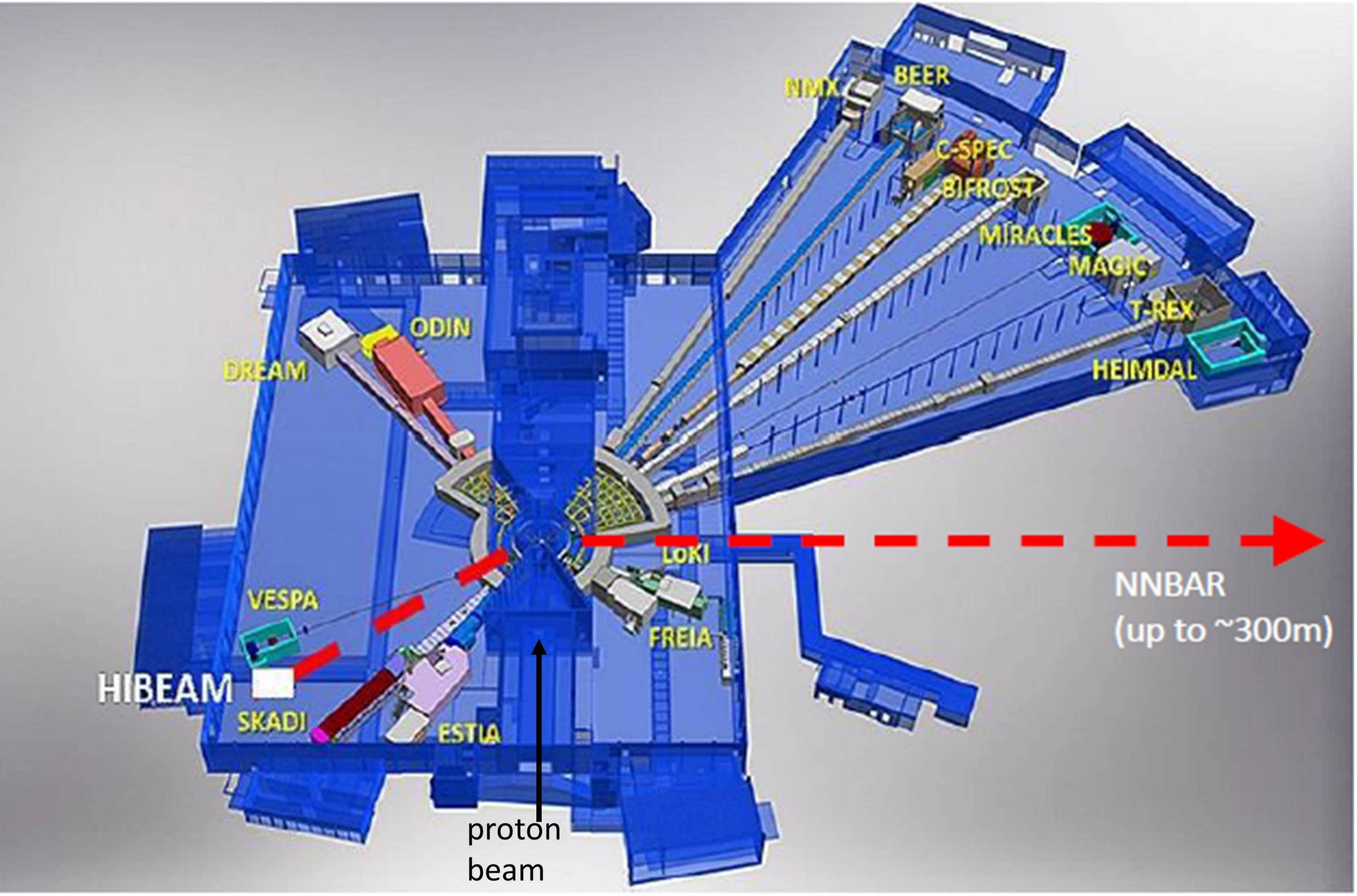
Belgium: (Brussels)
Denmark: (DTU)
Germany: (TU Munich)
India: (PRL, VECC)
Japan: (Nagoya)
Poland (Jagiellonian)
Sweden: (Chalmers, ESS, Lund, Stockholm, Uppsala)
United Kingdom (Glasgow)
United States: (CSU/Dominguez Hills, Columbia, Indiana, LANL, Maryland, NCSU, ORNL, Stony Brook, Tennessee, UT/Dallas)

Updated technical report 3/2016

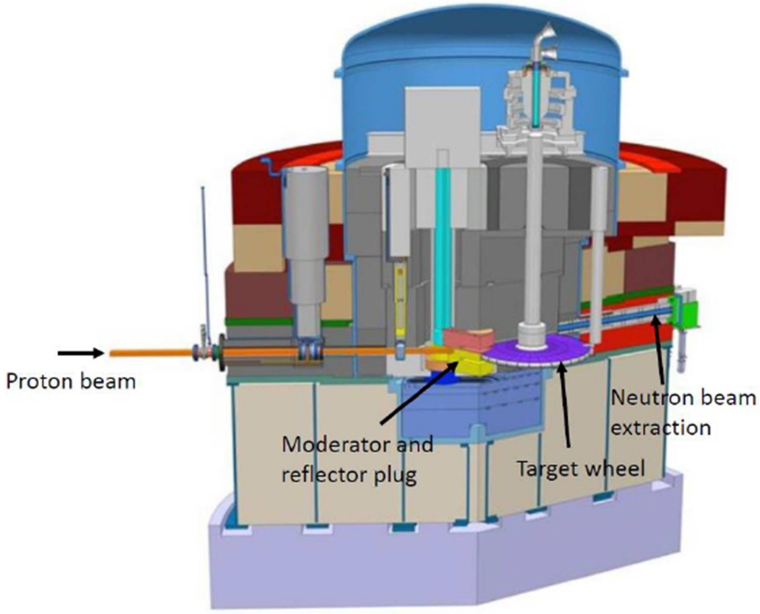


5MW long-pulsed spallation neutron source
Rotating W spallation target
~3 msec pulses, 2 GeV proton linac, 14 Hz rep rate
Lund, Sweden

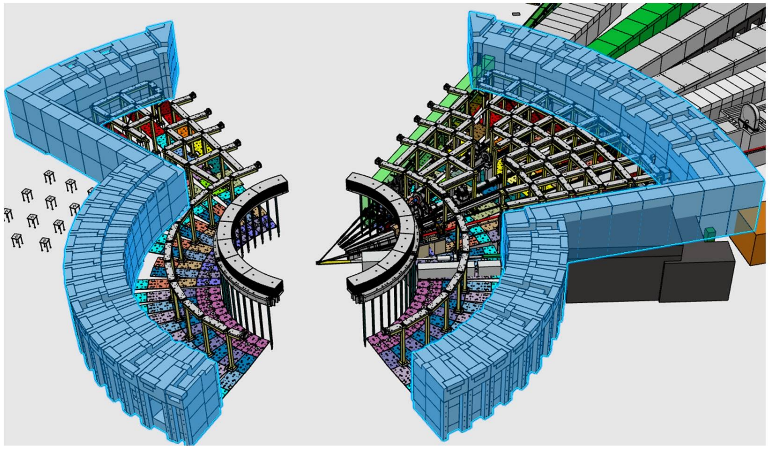
ESS Neutron Scattering Instruments



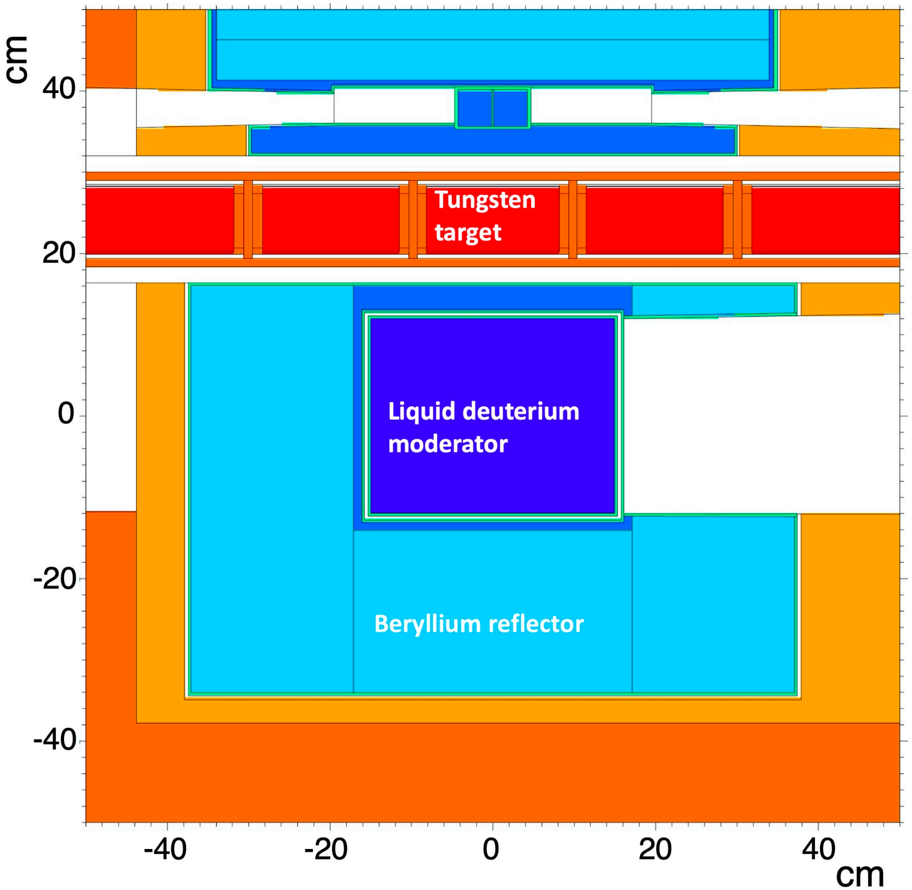
ESS Target Monolith and Bunker



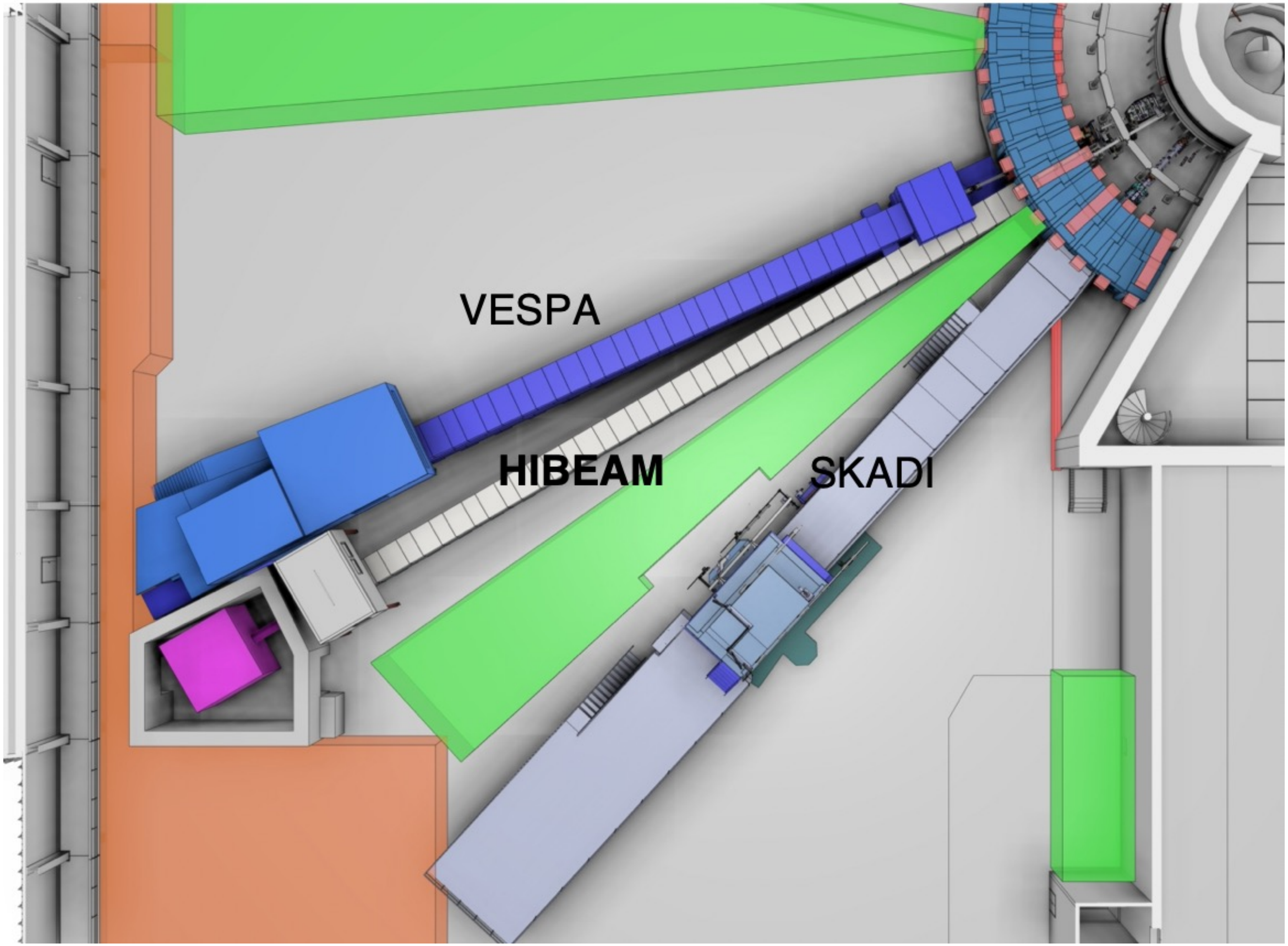
Target monolith



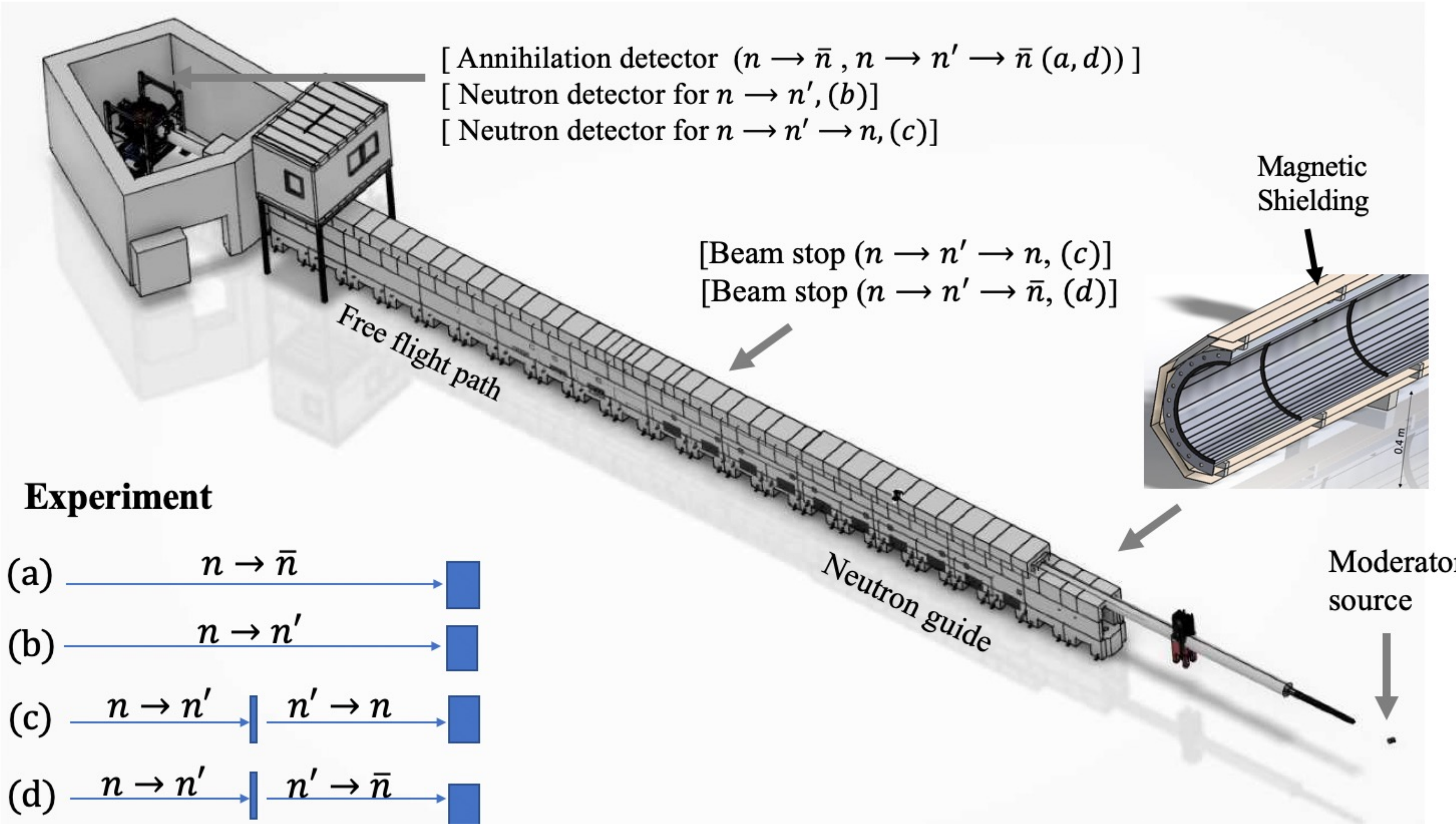
Target monolith and bunker



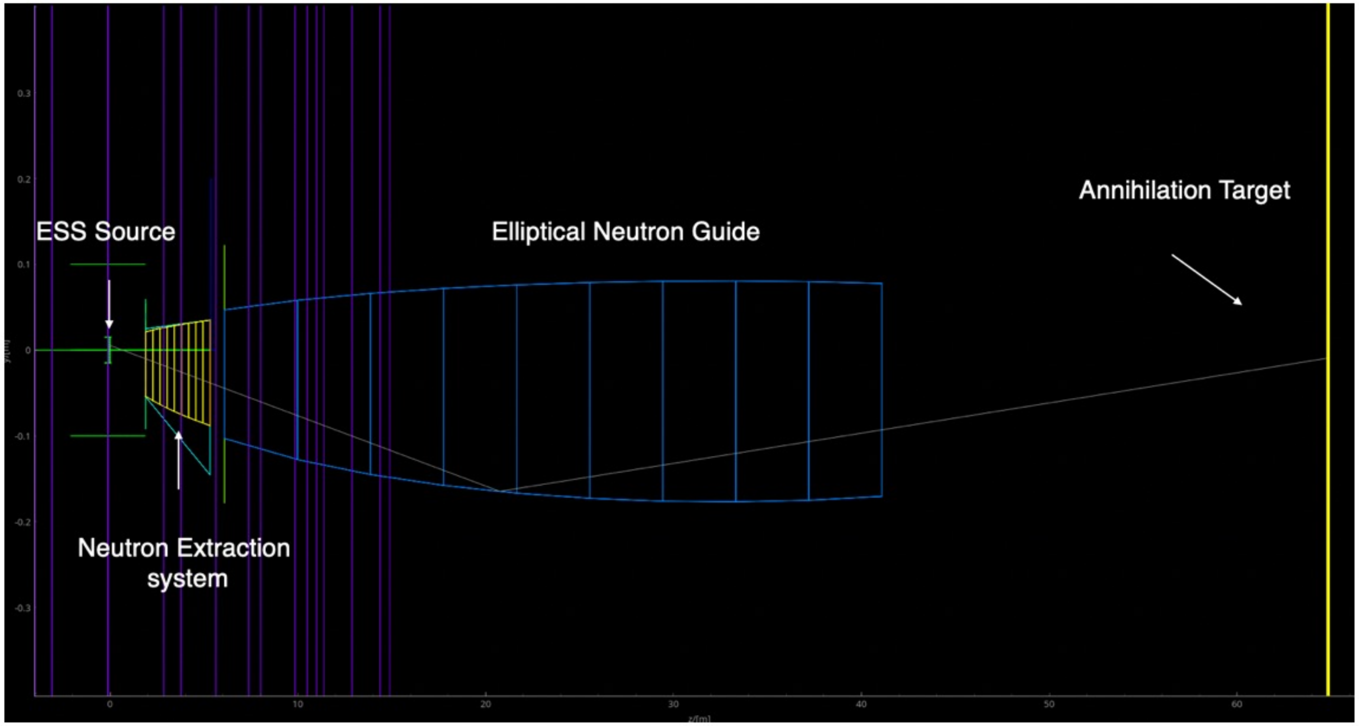
HIBEAM at ESS

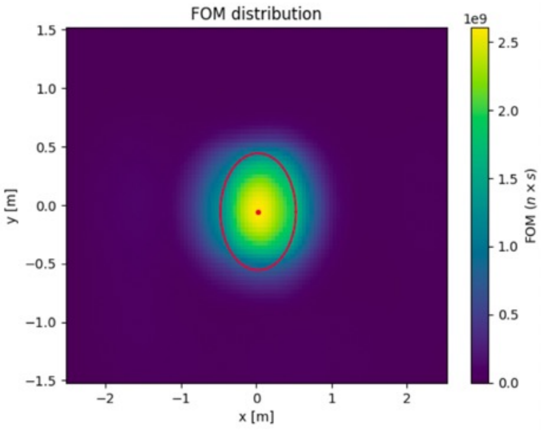


HIBEAM Design

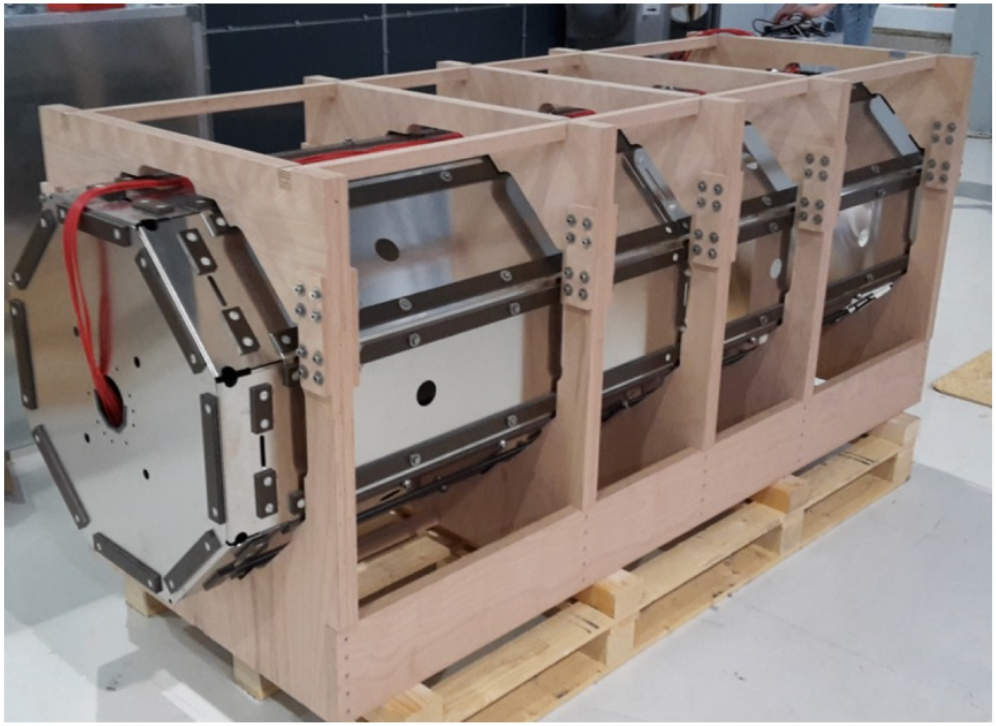


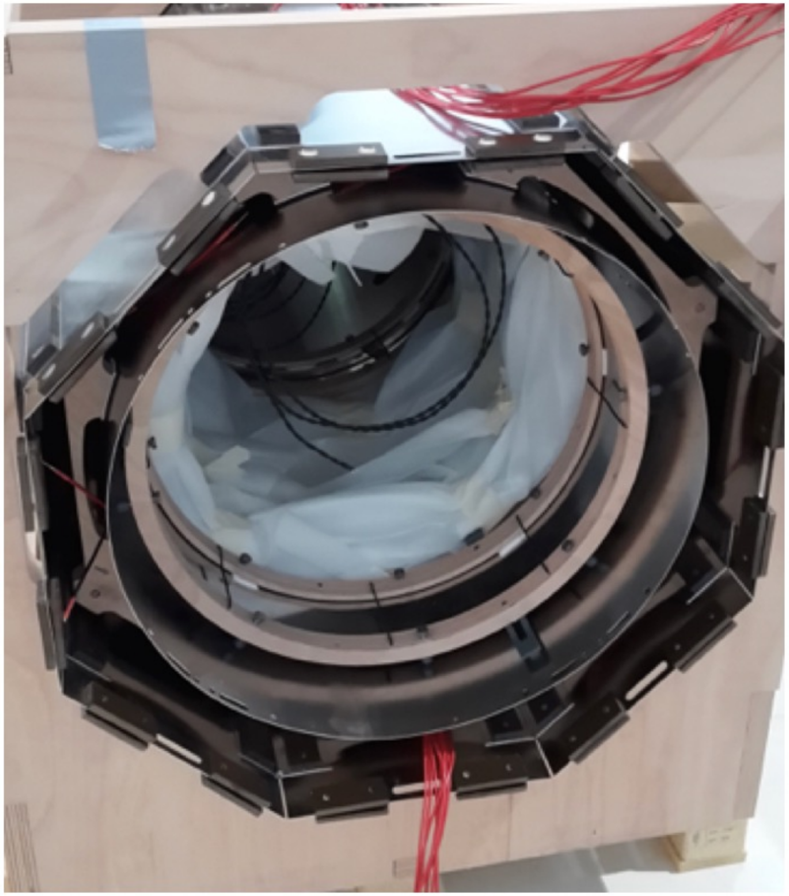
Neutron Beam Extraction





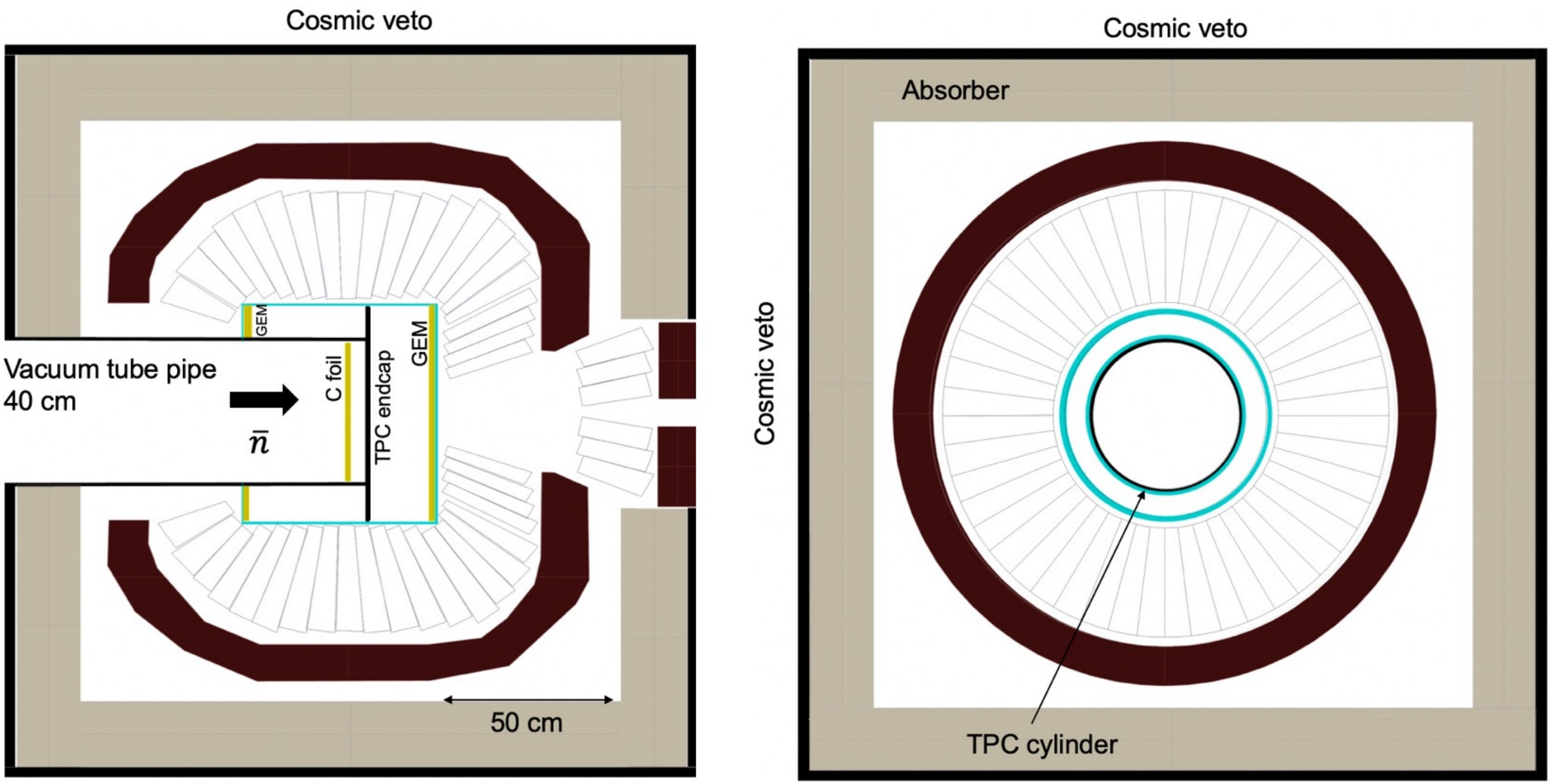
Magnetic Shielding





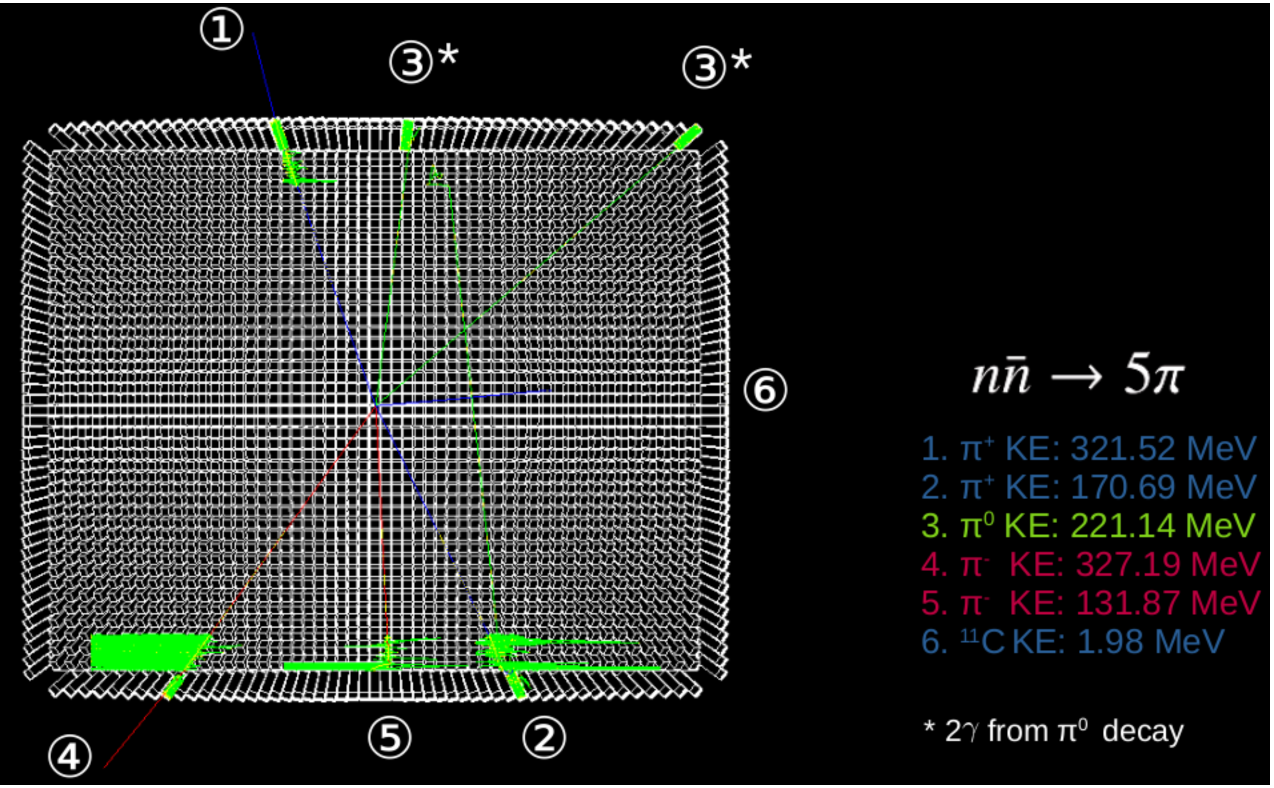
Modular design based on experience in neutron EDM and atom interferometry experiments (P. Fierlinger. TU Munich)

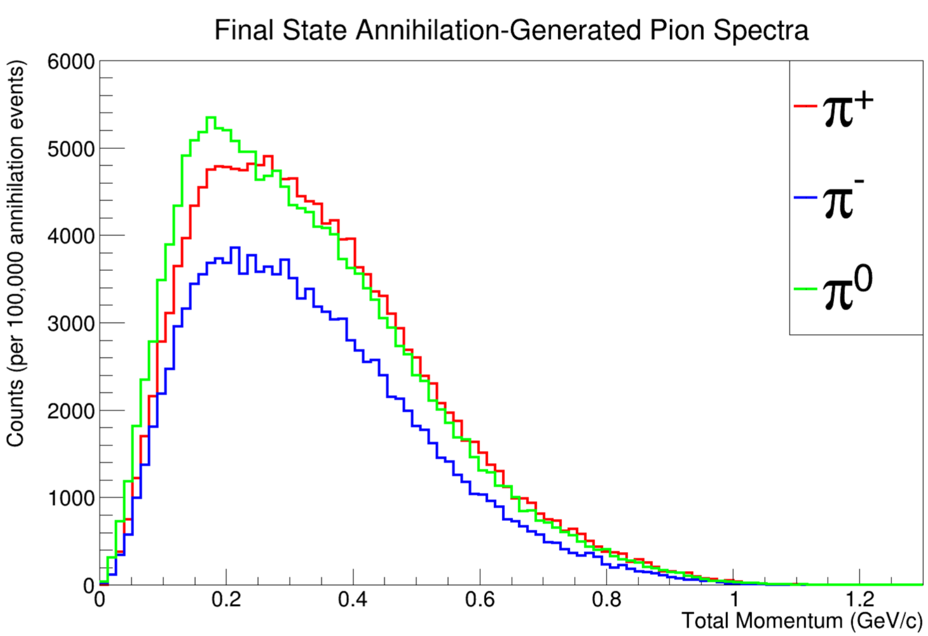
HIBEAM Concept for nbar step 1

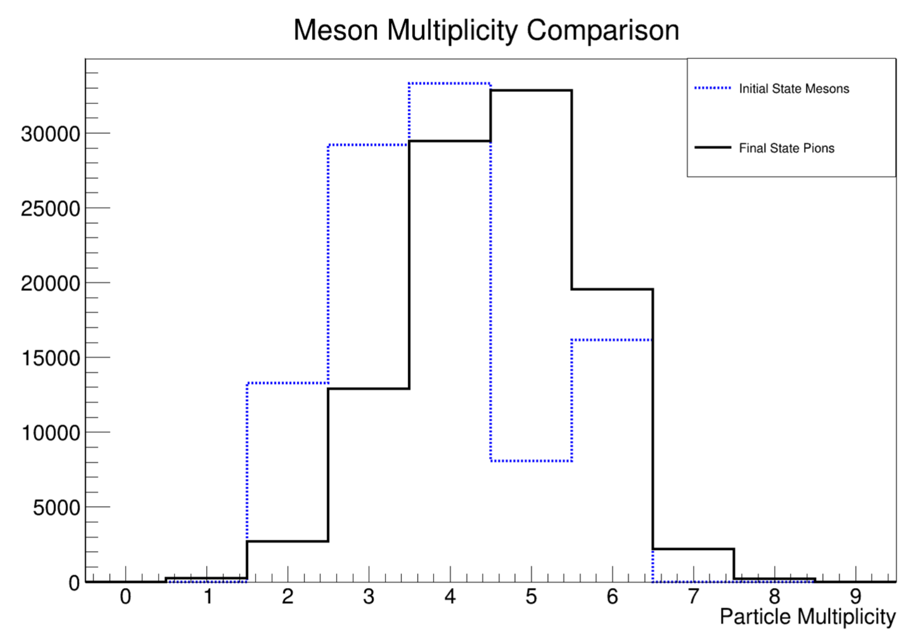


Recycle WASA calorimeter from COSY

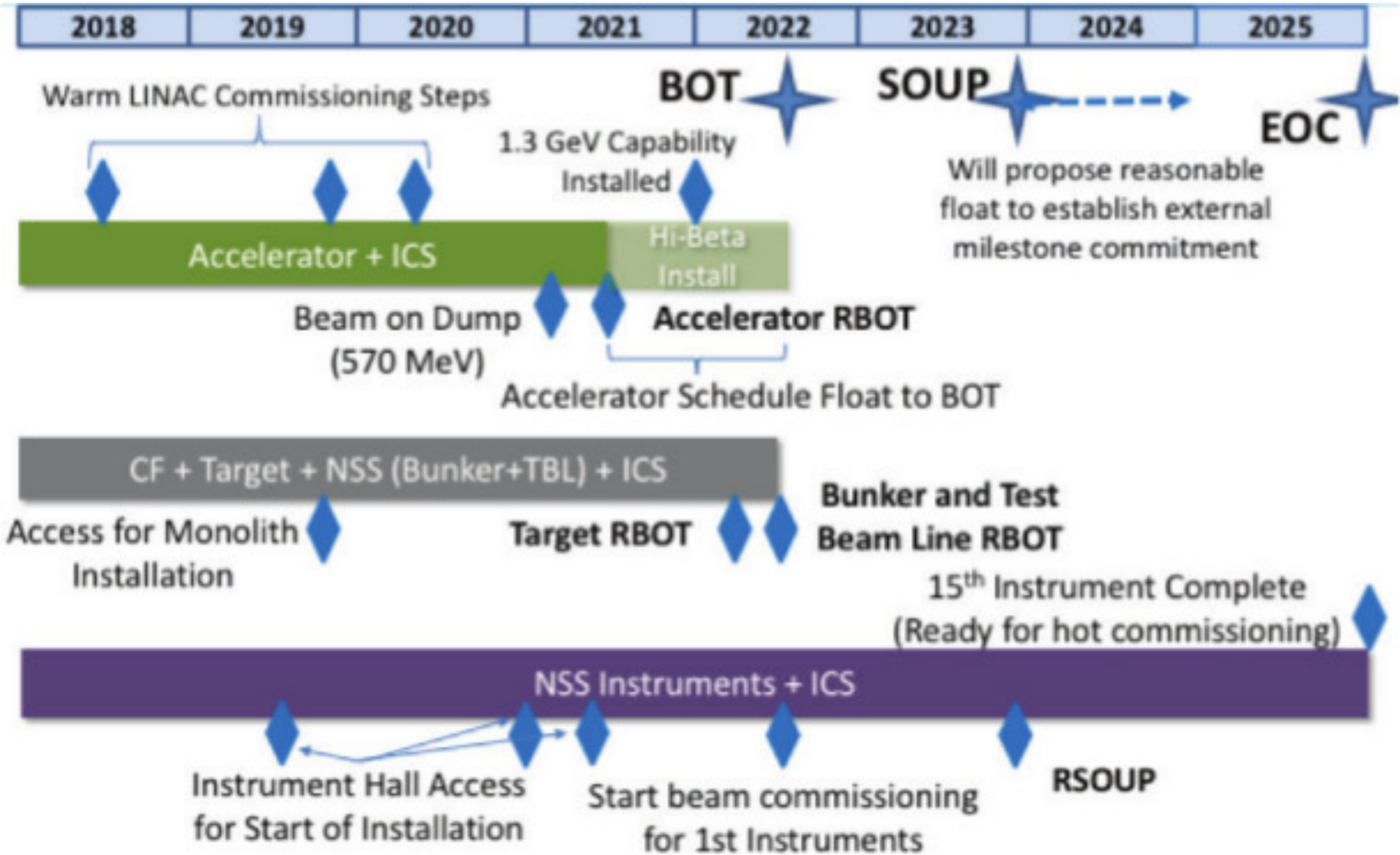
Detector Simulations



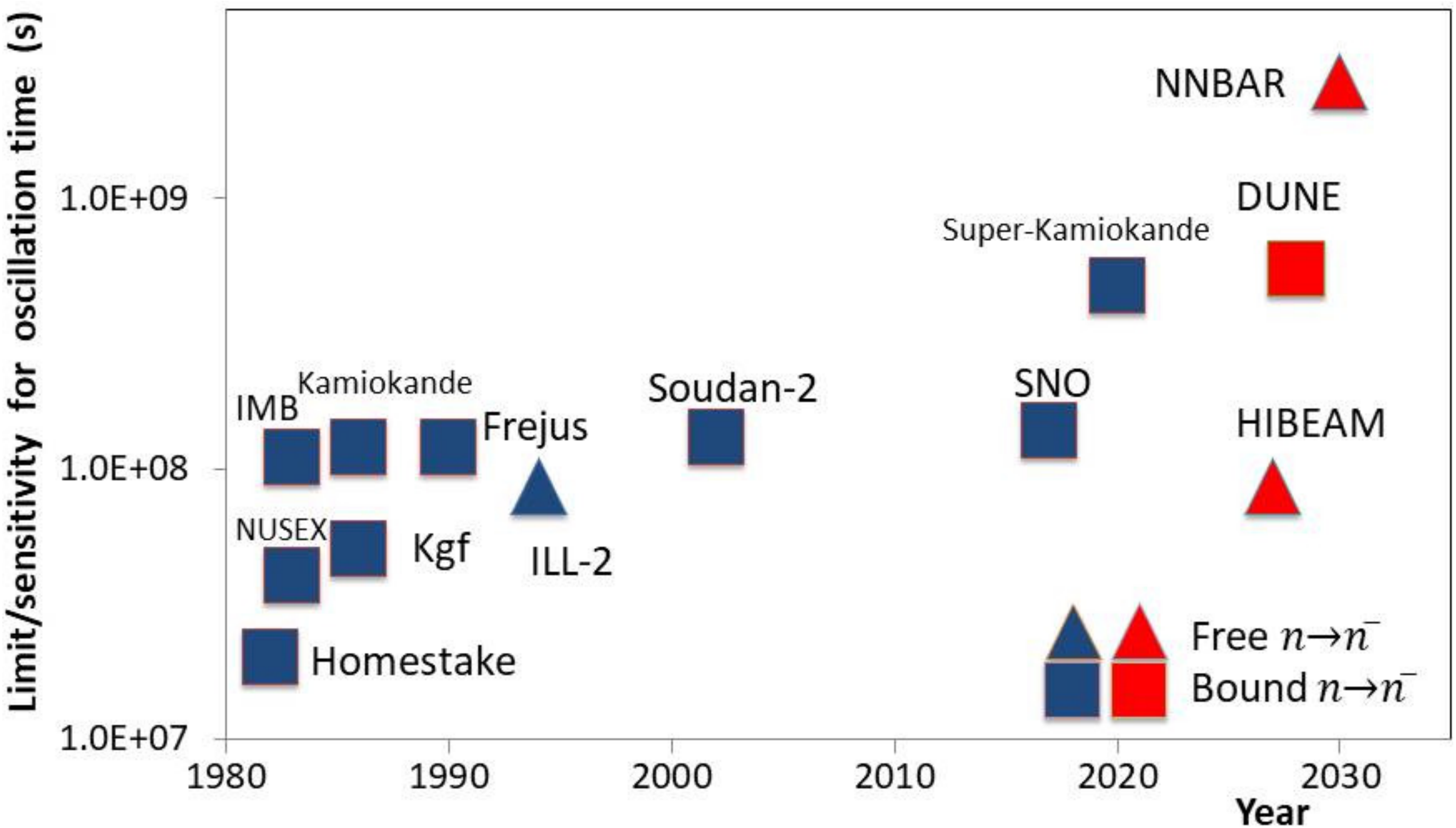




ESS Schedule



Free and Bound nnbar Limits



Summary

New physics beyond the Standard Model can be discovered by NNbar

Better limits/discovery possible from large underground detectors from nnbar annihilation in nuclei.

Experiments with free neutrons can possess very low backgrounds and sharp vertex localization: possibility for a crisp observation. Small magnetic field turns off oscillations.

Sensitivity of free neutron experiment for NNbar transition rate can be improved by factor of >~500-1000 at ESS using existing technology [Combination of improvements in neutron optics technology, longer observation time/larger-scale experiment, and source design optimization at green-field facility].

Beamline at ESS in preparation to get started on this physics.

References

D. G. Phillips, W. M. Snow et al., (NNbarX Collaboration), **Neutron-Antineutron Oscillations: Theoretical Status and Experimental Prospects**, Physics Reports **612**, 1-45 (2016), FERMILAB-PUB-14-263-T, arXiv:1410.1100

A.Addazih et al, **New high-sensitivity searches for neutrons converting into antineutrons and/or sterile neutrons at the HIBEAM/NNBAR experiment at the European Spallation Source,** J. Phys. G Nucl. Part. Phys. **48**, 070501 (2021). arXiv:2006.04907

F. Backman et al, **The Development of the NNBAR Experiment,** JINIST **17**, P10046 (2022). arXiv:2209.09011

V. Santoro et al, **The HIBEAM program: search for neutron oscillations at the ESS,** accepted in J. Phys. G, Nucl. Part. Phys. (2025). arXiv:2311.08326

Post-Sphaleron Baryogenesis

- A scalar (S) or a pseudoscalar (η) decays to baryons, violating B
- $\Delta B = 1$ is strongly constrained by proton decay and cannot lead to successful post-sphaleron baryogenesis
- $\Delta B = 2$ decay of S/η can generate baryon asymmetry below $T = 100$ GeV: $S/\eta \to 6\,q$; $S/\eta \to 6\,\overline{q}$
- Decay violates CP, and occurs out of equilibrium
- Naturally realized in quark-lepton unified models, with S/η identified as the Higgs boson of $B - L$ breaking
- $\Delta B = 2 \Rightarrow$ connection with $n - \overline{n}$ oscillation
- Quantitative relationship exists in quark-lepton unified models based on $SU(2)_L \times SU(2)_R \times SU(4)_C$

Parameter Space Constraints for Post-Sphaeleron Baryogenesis

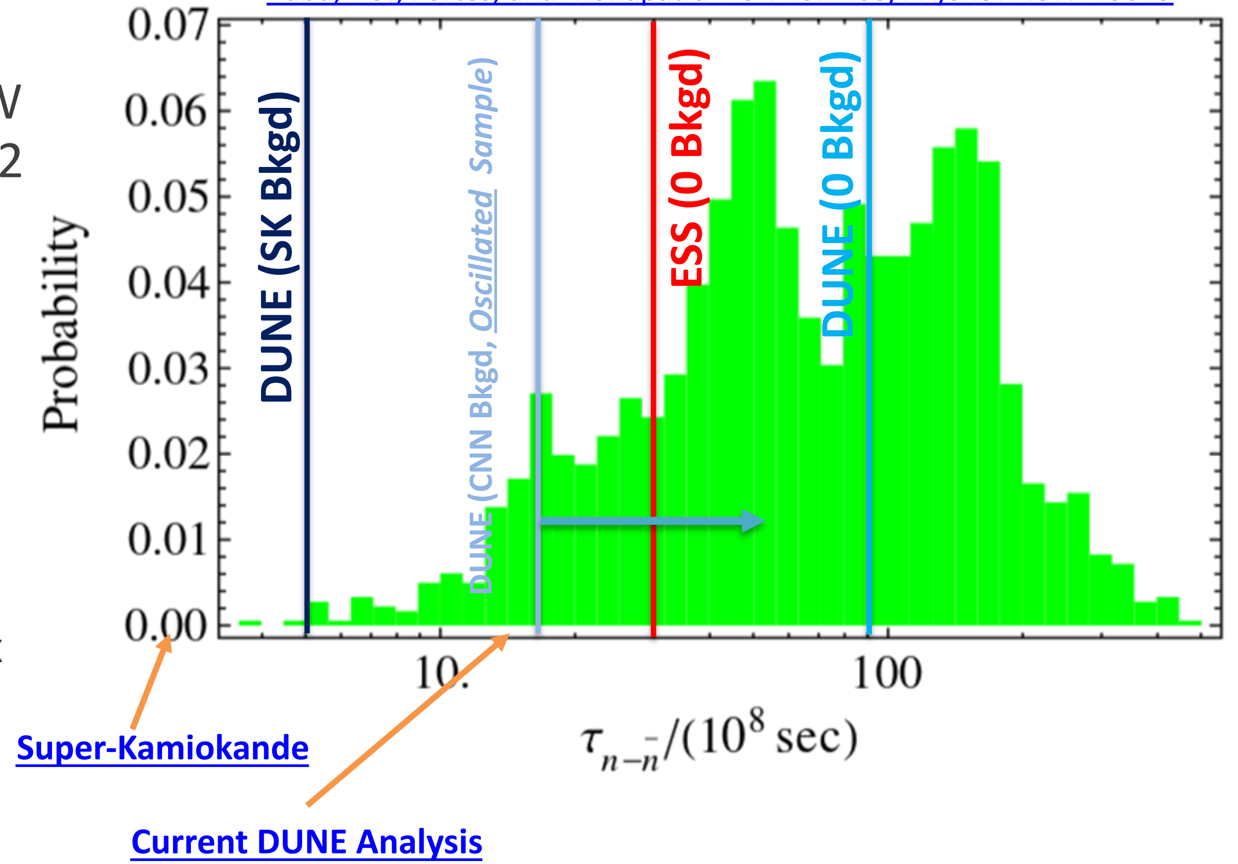
Post-sphaleron baryogenesis: generates B asymmetry BELOW EW phase transition (only ΔB=2 can do this)

Predicts a range of free transformation times

- **Blue** shows intranuclear transformation time
  - DUNE, 10 years, ~13,500x ILL (100% efficiency, no background)

- **Red** line shows free neutron transformation time (ESS 3 yr)

Babu, Dev, Fortes, and Mohapatra-DOI: 10.1103/PhysRevD.87.115019



J. Barrow

Summary

B is almost certainly violated in Nature

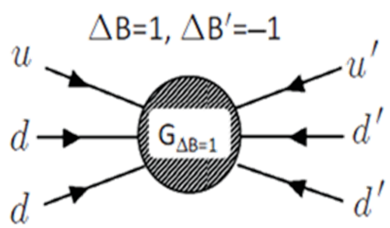
The search for proton decay is as scientifically compelling as ever. New/improved underground detectors will slowly improve the experimental sensitivity. The same detectors can also be used to search for neutron-antineutron oscillations in nuclei and other $\Delta B=2$ modes

Experiments with free neutrons can possess very low backgrounds and sharp vertex localization: possibility for a crisp observation. Sensitivity of free neutron experiment for NNbar transition rate can be improved by factor of >~500-1000 at ESS using existing technology

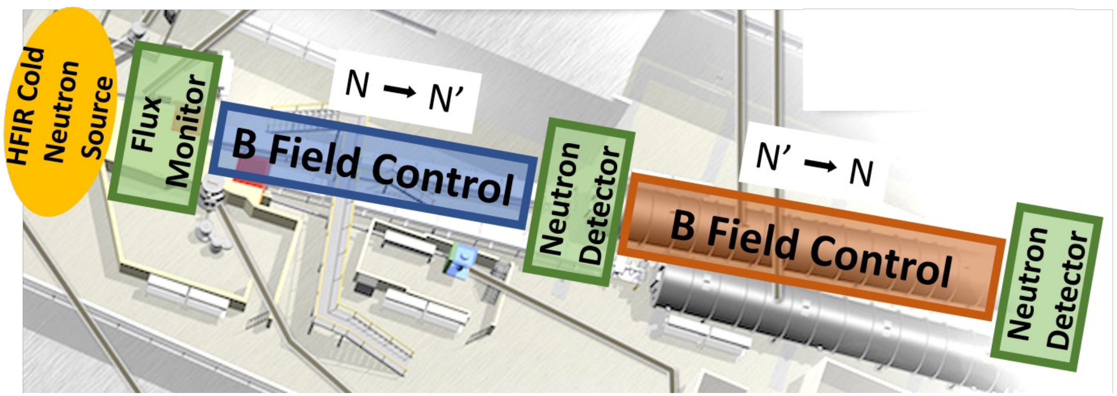
Neutron oscillations to hidden sector

- Fast neutron oscillations (predicted by mirror matter theory[1,2]) not ruled out experimentally[3]
- Strong limits of $\tau > 448$ s for B'=0,[4] but suppressed if off magnetic resonance (B'≠0)
- Controversial results in UCN searches with B'≠0 ($\tau \sim 10$ s)[5,6]
- Proposed CN regeneration experiment at HFIR to resolve controversy

$\mathbf{n \rightarrow n'}$



$$G_{\Delta B=1} = \frac{1}{M_D M_S^4}$$



[1]Z. Berezhiani, Int. J. Mod. Phys. A, 19 3775 (2004)
[2]R. Foot, Int. J. Mod. Phys. A, 29 1430013 (2014)
[3]Z. Berezhiani and L. Bento, Phys. Rev. Lett. 96, 081801 (2006)
[4]A. P. Serebrov *et al*, *NIMA* 611 137 (2009)
[5]Z. Berezhiani and F. Nesti, Eur. Phys. J. C 72 1974 (2012)
[6]I. Altarev *et al.*, Phys. Rev. D 80, 032003 (2009)

L.Broussard

Why $n - \bar{n}$ transitions?

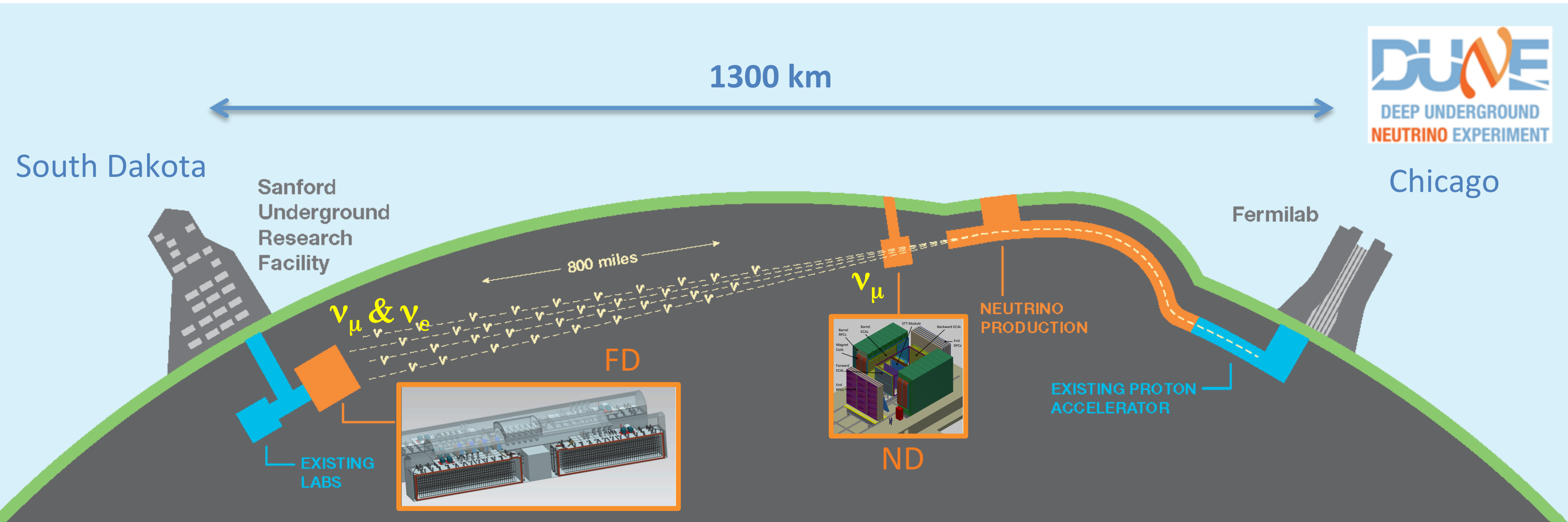
- **Two kinds of $\not{B}$ phenomena:**
  - ✻
    - $|\Delta B| = 1$ (& $|B - L| = 0$): $\Lambda_{p \to e^+ \pi^0} \geq 10^{15}$ GeV; [E. Kearns (2013)]
    - $|\Delta B| = 1$ (& $|B - L| = 2$): $\Lambda_{n \to e^- \pi^+} \geq 10^{10}$ GeV; [S. Seidel et al. (1988)]

    [S. Weinberg (1980), H. A. Weldon and A. Zee (1980).]
  - ✻ $|\Delta B| = 2$: $\Lambda_{n\bar{n}} \geq 10^{5.5}$ GeV. Note $(|\Delta B| = 2) \neq (|\Delta B| = 1)^2$;

    $\Rightarrow$ **a relatively low scale of new physics.**
- **Three possible $n - \bar{n}$ transitions.**
  - ✓ $n - \bar{n}$ **oscillation:** neutrons spontaneously transform into antineutrons. It is sensitive to the energy difference between neutrons and antineutrons. Great efforts to deal with environmental effects, such as magnetic fields and matter.
  - ✓ **Dinucleon decay.** Background induced by atmospheric neutrinos can be a problem.
  - ✻ $n - \bar{n}$ **conversion:** A change of a neutron into an antineutron is realized through the interaction with an external source.

Gardner/Yan, Phys. Rev. D 97, 056008 (2018)

DUNE



Liquid argon TPC
Single and dual phase
4x 17 kton
40 kton fiducial mass

2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
ProtoDUNEs												
	Cavern excavation											
			Cryostat Construction									
					Far Detector Installation							
								Far Detector commissioning				

E. Kearns

Grand Unified Theories

assume the Standard Model, SU(3)⊗SU(2)⊗U(1),
is part of a larger symmetry group, e.g. SU(5):

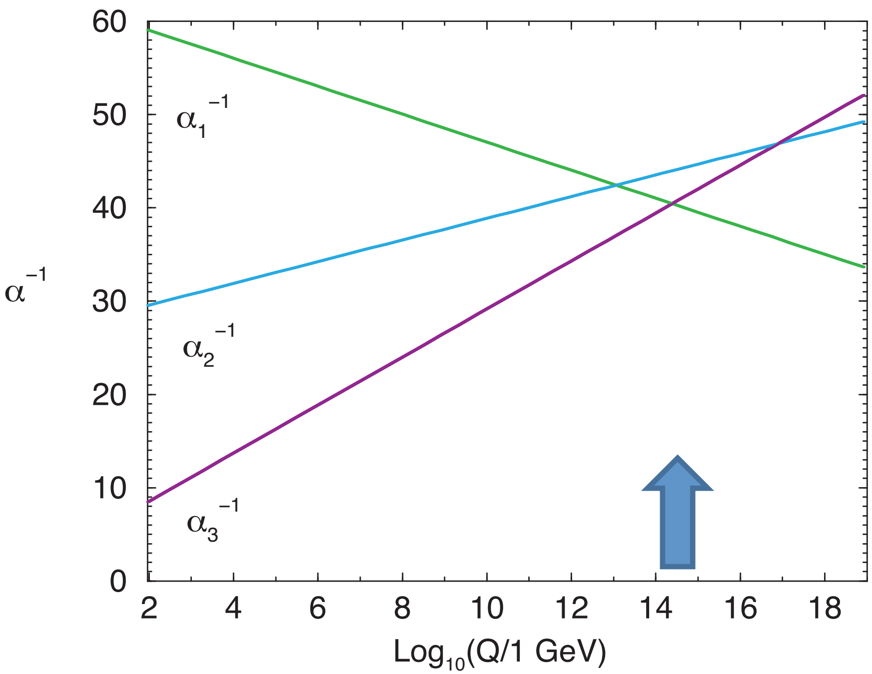
$$\bar{5} = \begin{pmatrix} \bar{d}_g \\ \bar{d}_r \\ \bar{d}_b \\ e^- \\ -\nu_e \end{pmatrix}_L \qquad 10 = \begin{pmatrix} 0 & \bar{u}_b & -\bar{u}_r & -u_g & -d_g \\ & 0 & \bar{u}_g & -u_r & d_r \\ & & 0 & -u_b & -d_b \\ & & & 0 & -e^+ \\ & & & & 0 \end{pmatrix}_L$$

$$24 = \left(\begin{array}{ccc|cc} G_{11} - \frac{2B}{\sqrt{30}} & G_{12} & G_{13} & \bar{X}_1 & \bar{Y}_1 \\ G_{21} & G_{22} - \frac{2B}{\sqrt{30}} & G_{23} & \bar{X}_2 & \bar{Y}_2 \\ G_{31} & G_{32} & G_{33} - \frac{2B}{\sqrt{30}} & \bar{X}_3 & \bar{Y}_3 \\ \hline X_1 & X_2 & X_3 & \frac{W^3}{\sqrt{2}} + \frac{3B}{\sqrt{30}} & W^+ \\ Y_1 & Y_2 & Y_3 & W^- & -\frac{W^3}{\sqrt{2}} + \frac{3B}{\sqrt{30}} \end{array}\right)$$

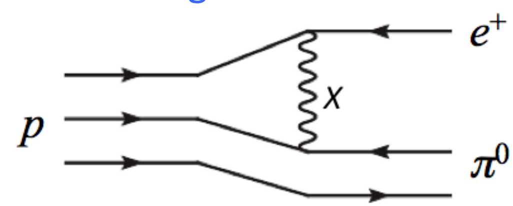
Consequences:

- Single (unified) coupling
- Charge quantization: $Q_d = Q_e/3$, $Q_u = -2Q_d \Rightarrow Q_p = -Q_e$
- New gauge interactions (X, Y bosons) ⇒ proton decay
- Other predictions of SU(5): magnetic monopoles, value of weak mixing angle (poor), massless neutrinos (oops!)
- There are other groups, e.g. SO(10) that accommodate massive neutrinos

Circumstantial Evidence



Gauge mediated

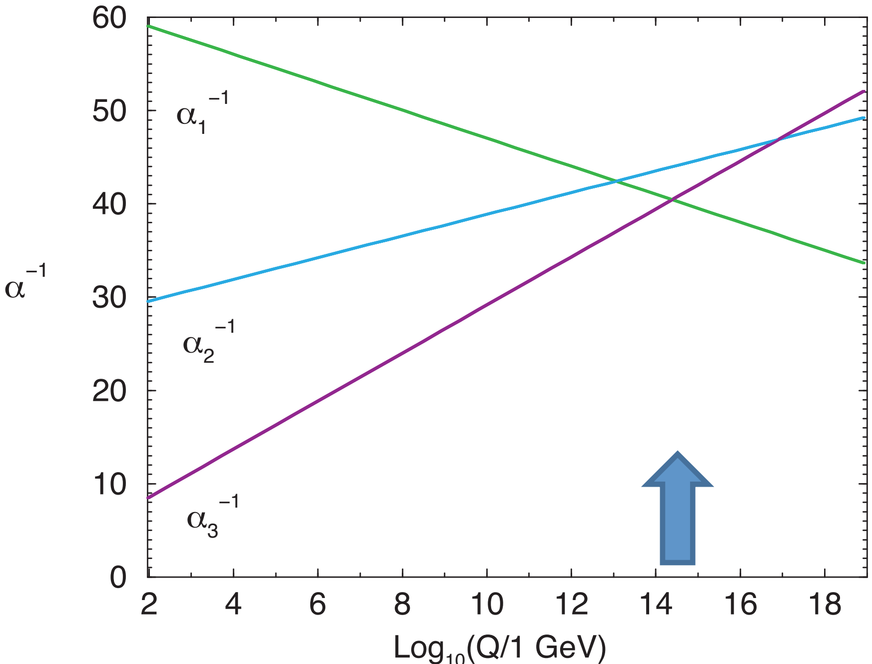


$$\tau = \frac{M_X^4}{\alpha\ m_p^2}$$

$\tau(e^+\pi^0) = 4.5\times 10^{29\pm 1.7}$ *years* (predicted)

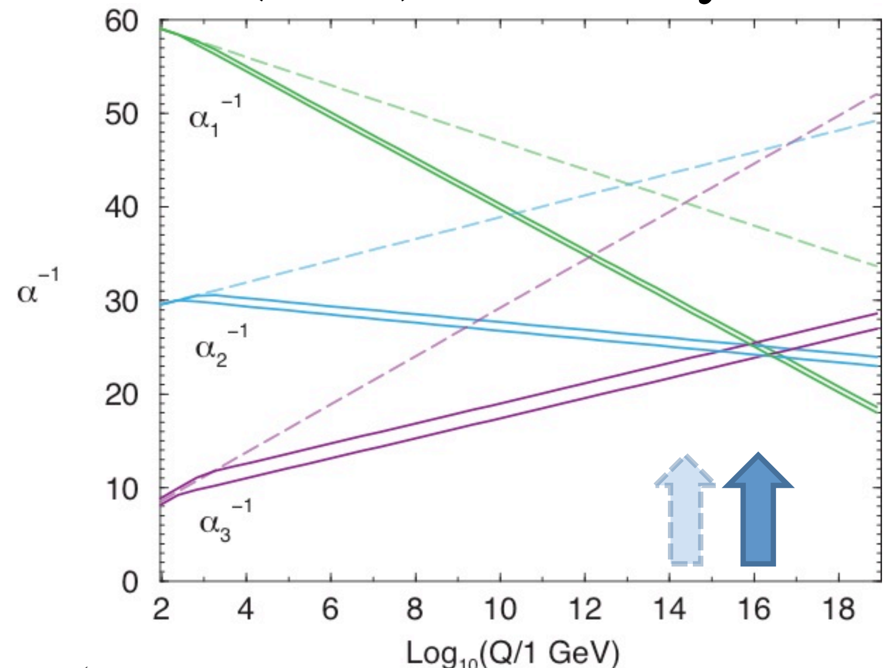
$\tau(e^+\pi^0) > 5.5\times 10^{32}$ *years* (IMB/1990)

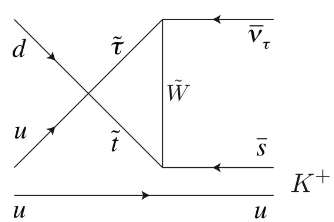
SUSY GUTs ➠



Unification scale pushed up ✔

$$\tau(e^+\pi^0) \approx 10^{35-38} \text{ years}$$

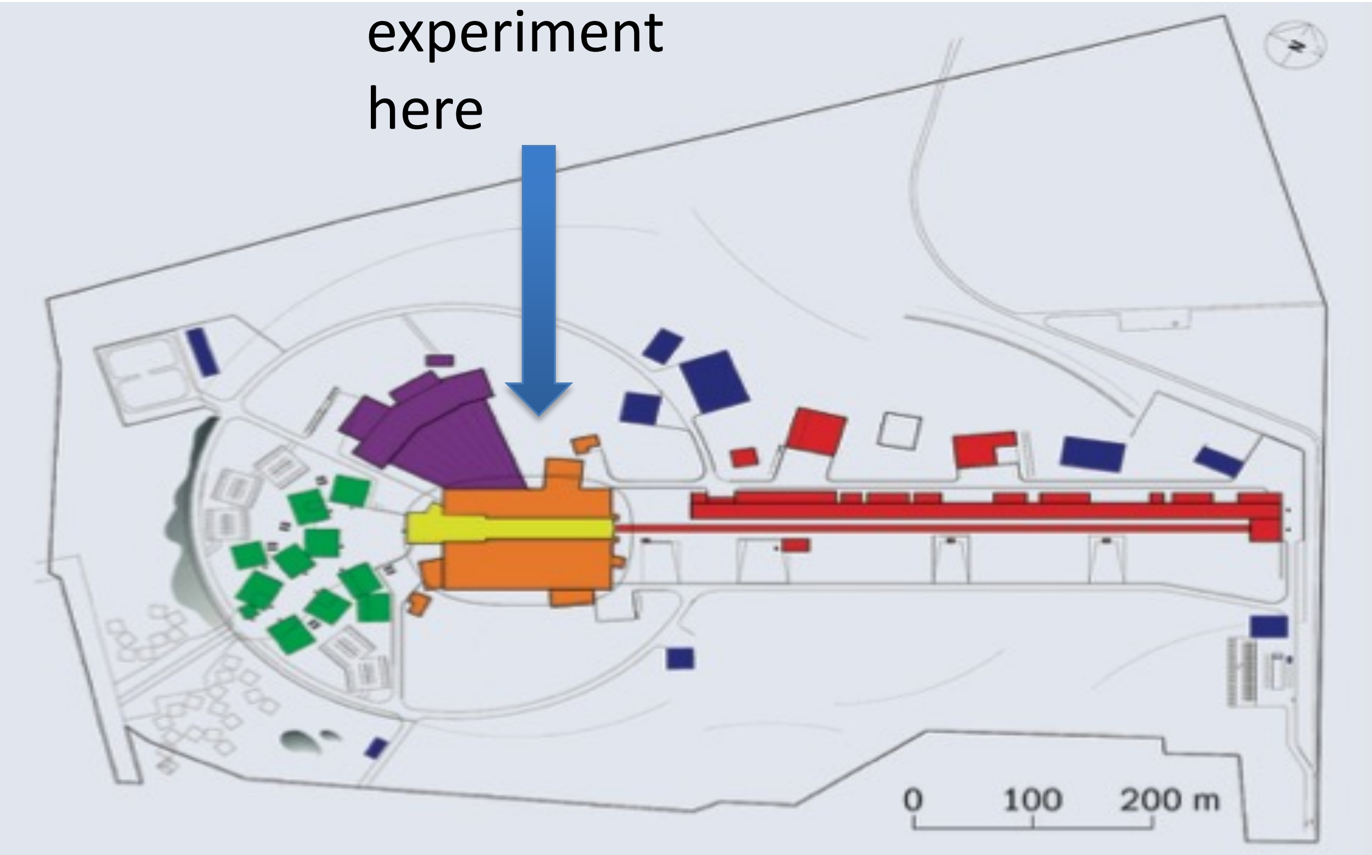




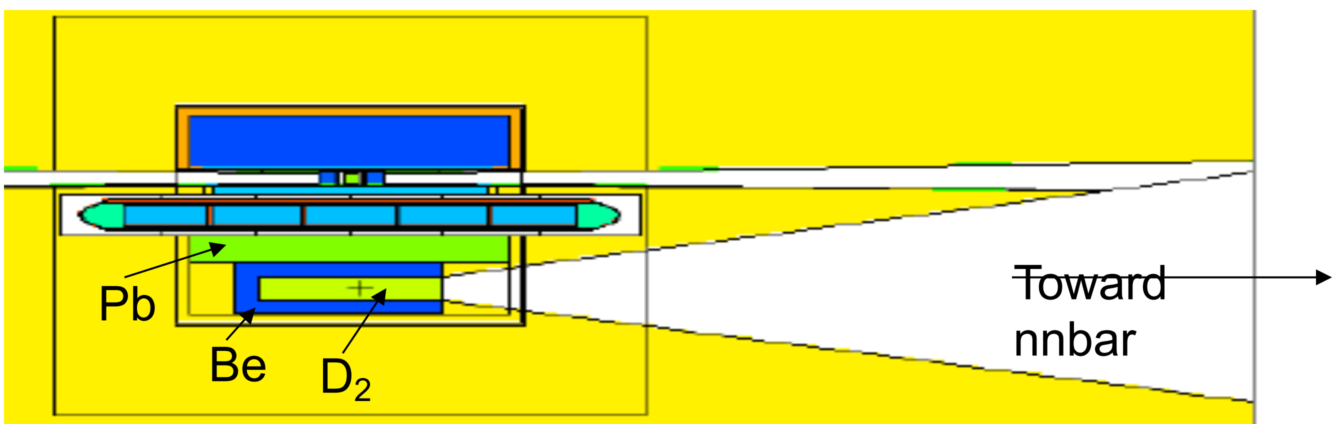
But new modes now present (D=5)

$$\tau(\nu K^+) \approx 10^{29-35} \text{ years}$$

Your nnbar experiment here

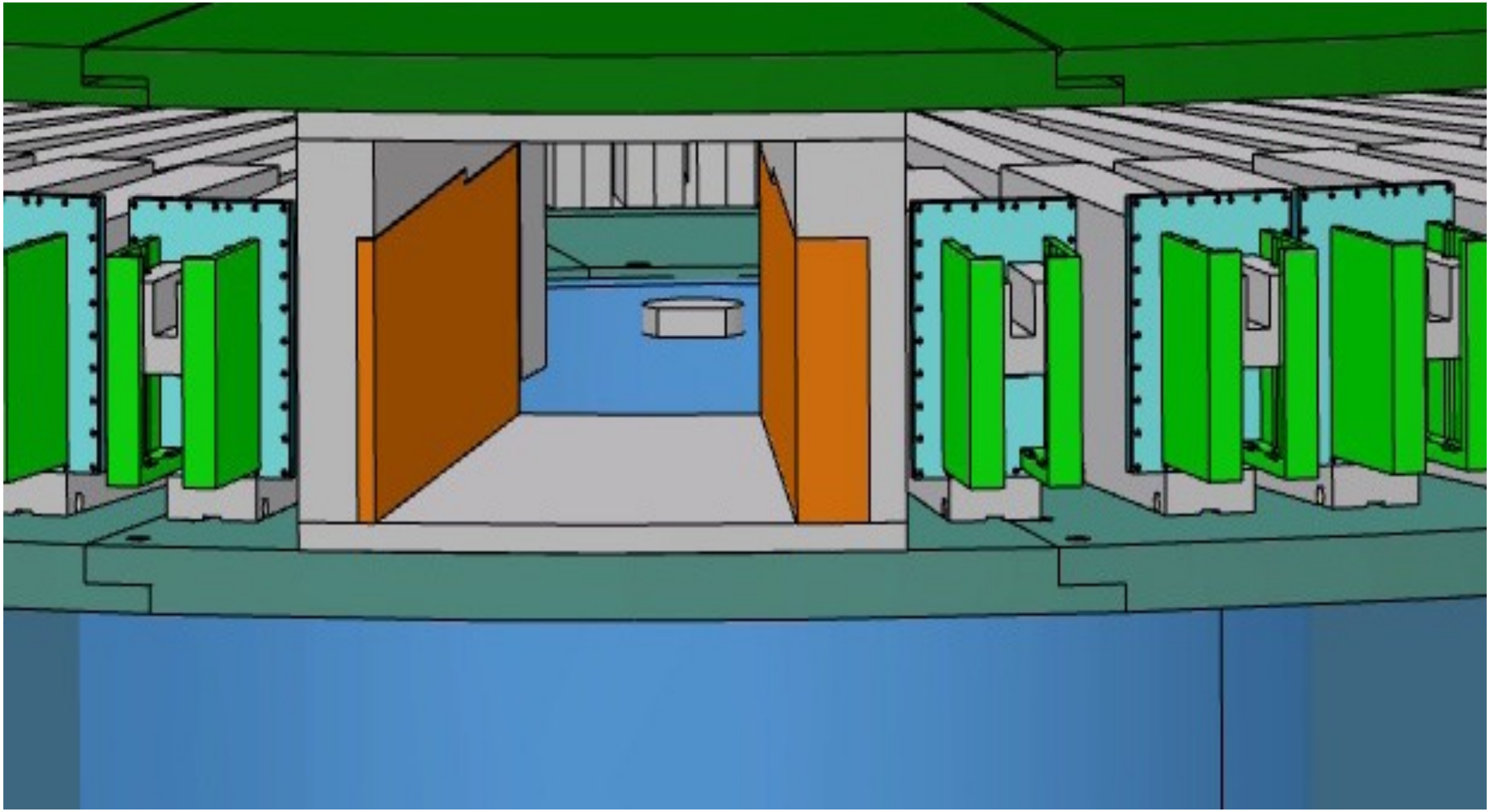


European Spallation Source layout (Lund)



lower tier slow neutron moderator available

ESS Large Beam Extraction Line



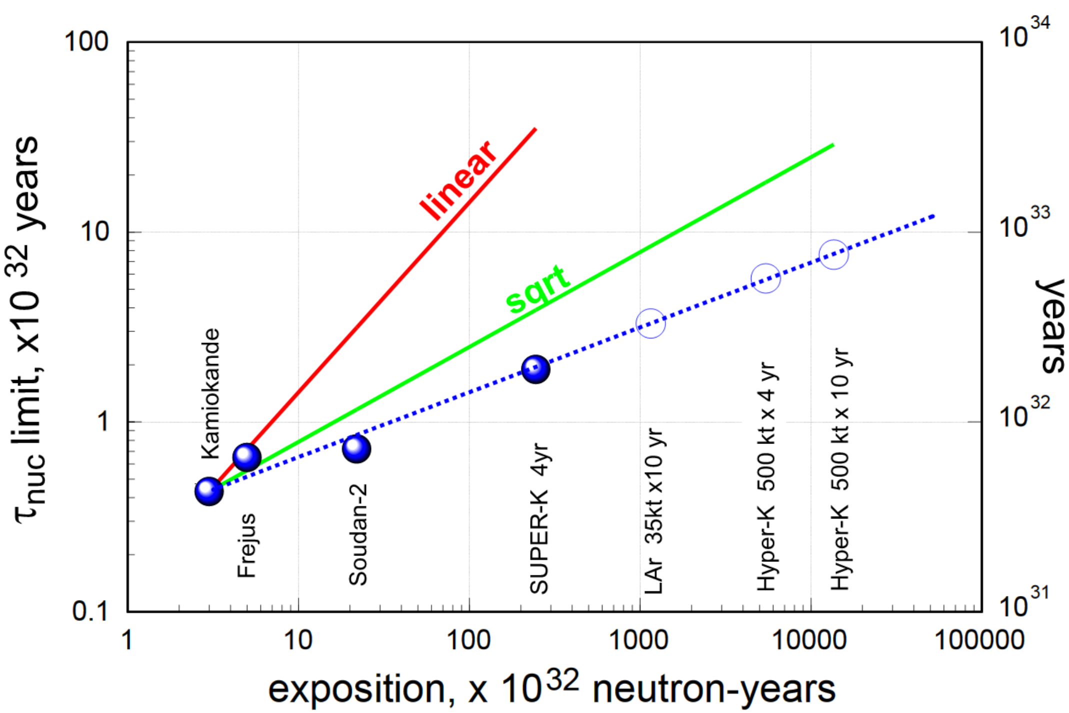
Now designed into the facility

Available for a future nnbar experiment

Bound neutron N-Nbar search experiments

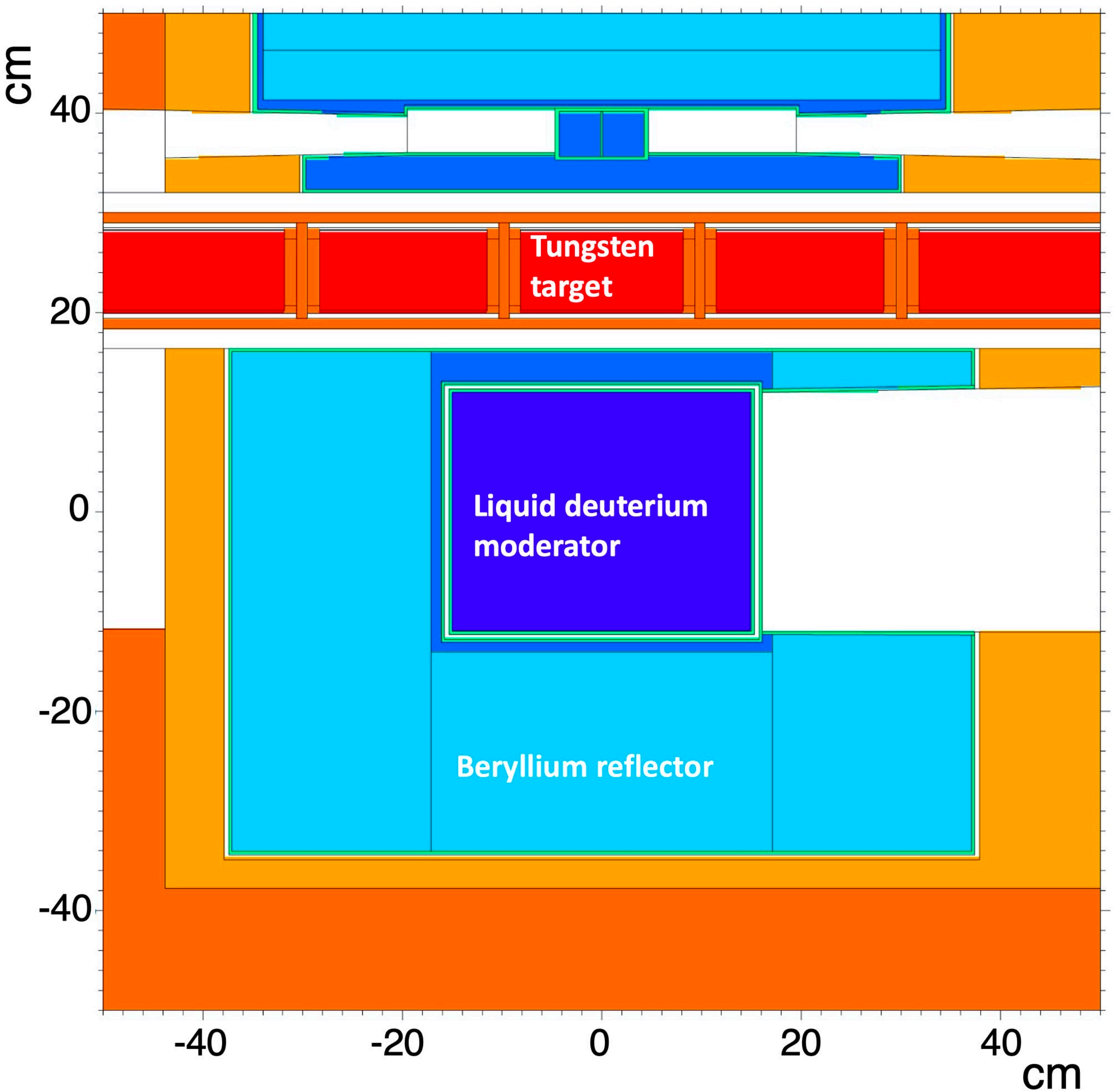
Experiment	Year	A	n·year (10^{32})	Det. eff.	Candid.	Bkgr.	τ_{nucl}, yr (90% CL)
Kamiokande	1986	O	3.0	33%	0	0.9/yr	$>0.43\times10^{32}$
Frejus	1990	Fe	5.0	30%	0	4	$>0.65\times10^{32}$
Soudan-2	2002	Fe	21.9	18%	5	4.5	$>0.72\times10^{32}$
SNO*	2017	D	0.54	41%	2	4.75	$>0.15\times10^{32}$
Super-K	2015	O	245	12.1%	24	24.1	$>1.89\times10^{32}$

M. Bergevin et al, Phys. Rev. D 96, 092005 (2017)

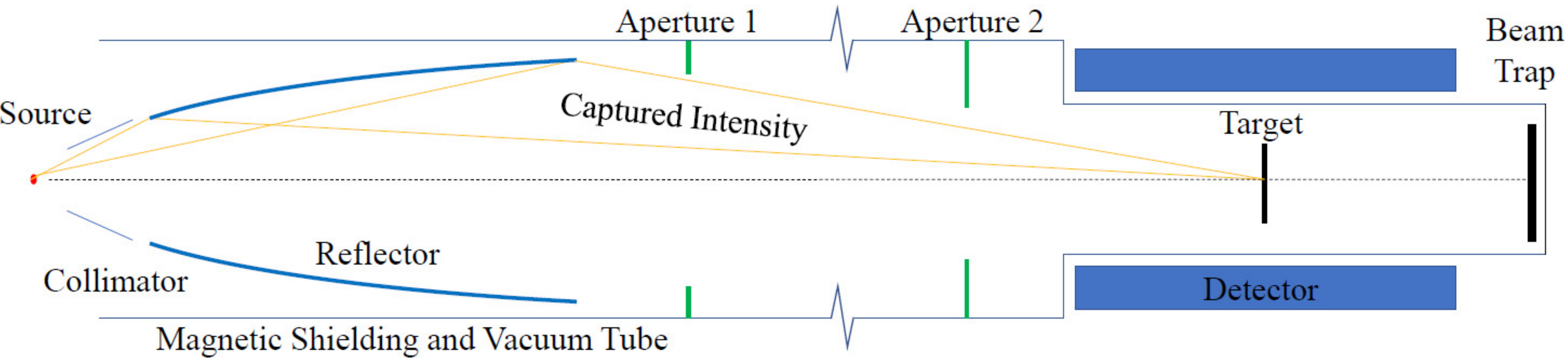


- From Kamiokande to Super-K atmospheric ν background is about the same ~ 2.5 /kt/yr.
- Large D_2O, Fe, H_2O detectors are dominated by backgrounds;
- Observed improvement is weaker than SQRT due to irreducible background and uncertainties of efficiency and background.
- DUNE LAr detector has been analyzed

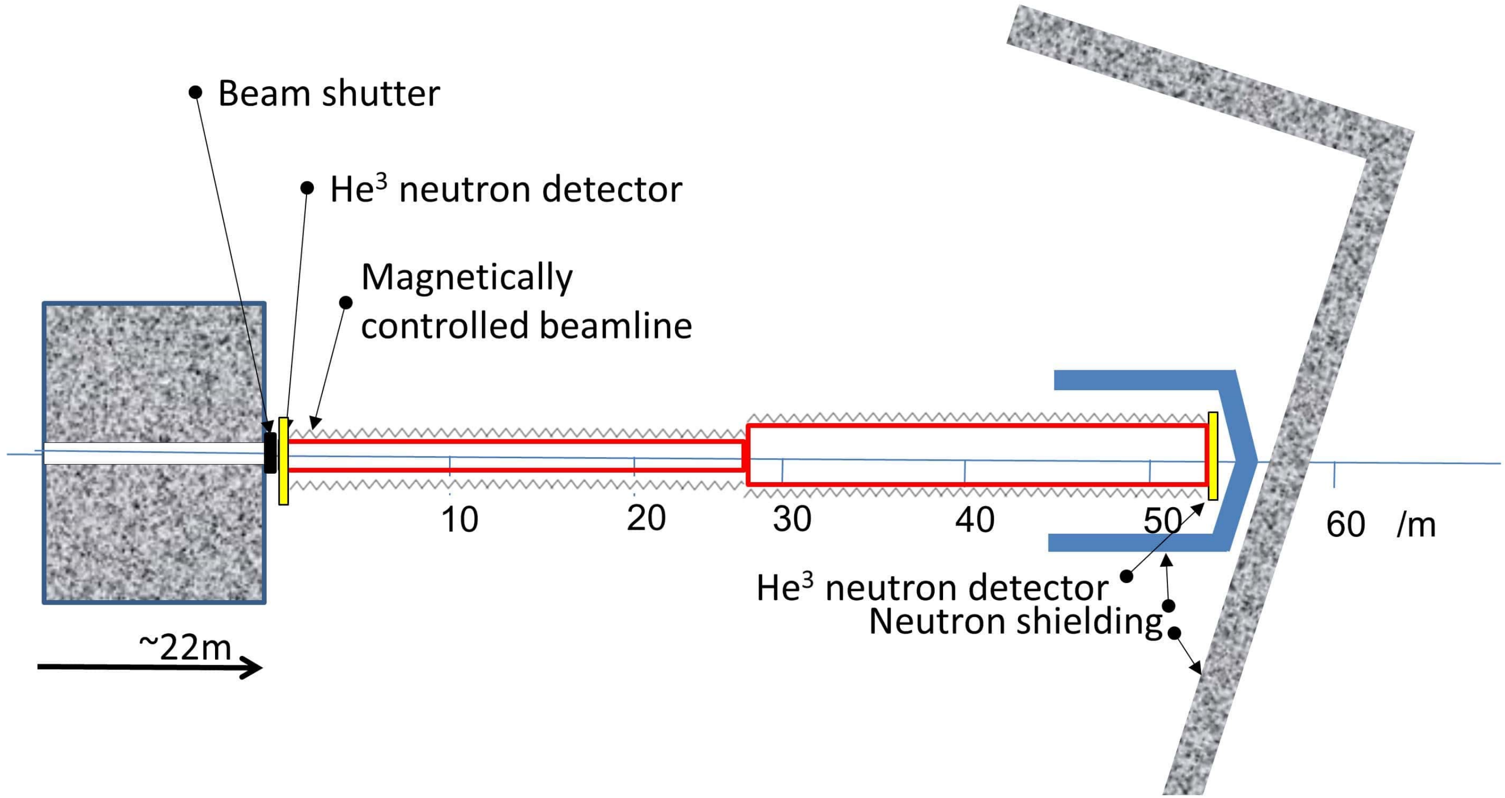
ESS Target Region Section View

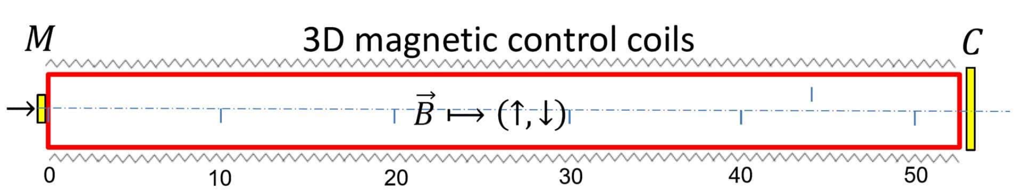


ESS Large Beam Extraction Line



ESS Neutron Disappearance Setup



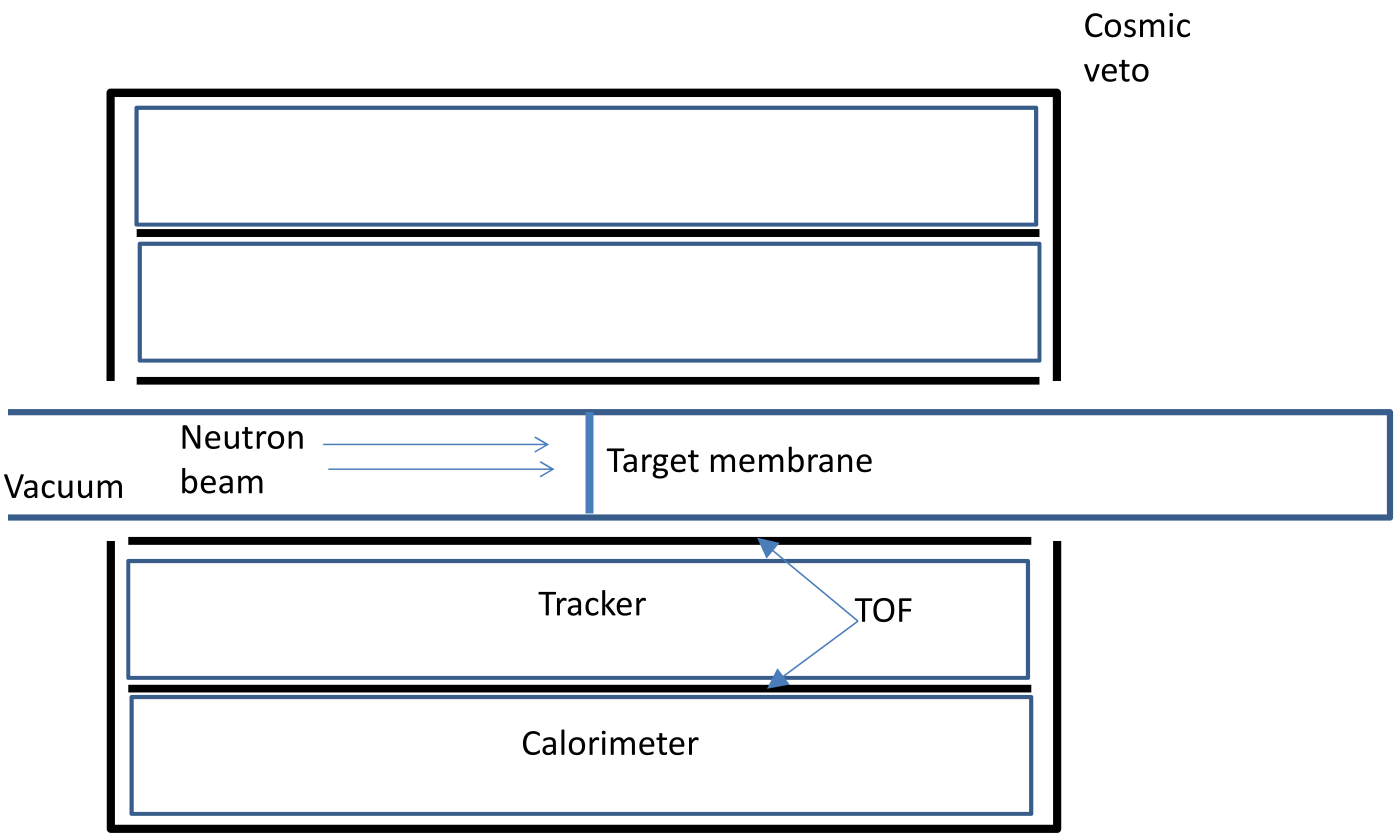


ESS Large Beam Extraction Line

ESS Large Beam Extraction Line

ESS Large Beam Extraction Line

ESS Large Beam Extraction Line



ESS Large Beam Extraction Line