Symmetry studies at Research reactors

Tatsushi Shima
Research Center for Nuclear Physics, Osaka University

NEWS colloquium
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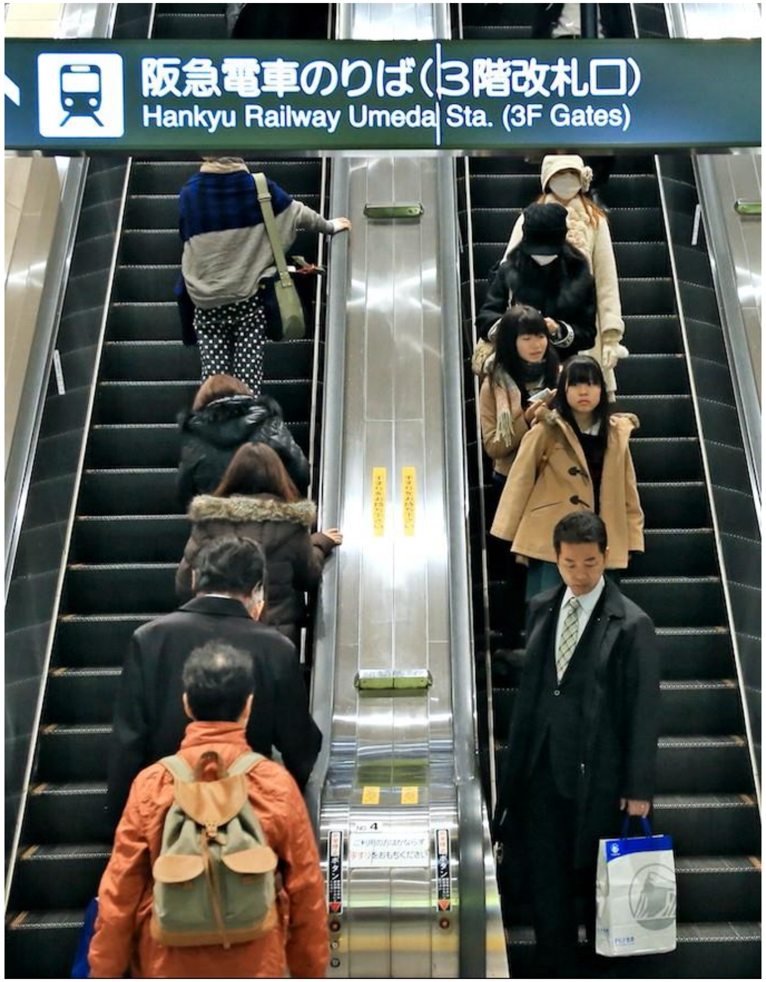
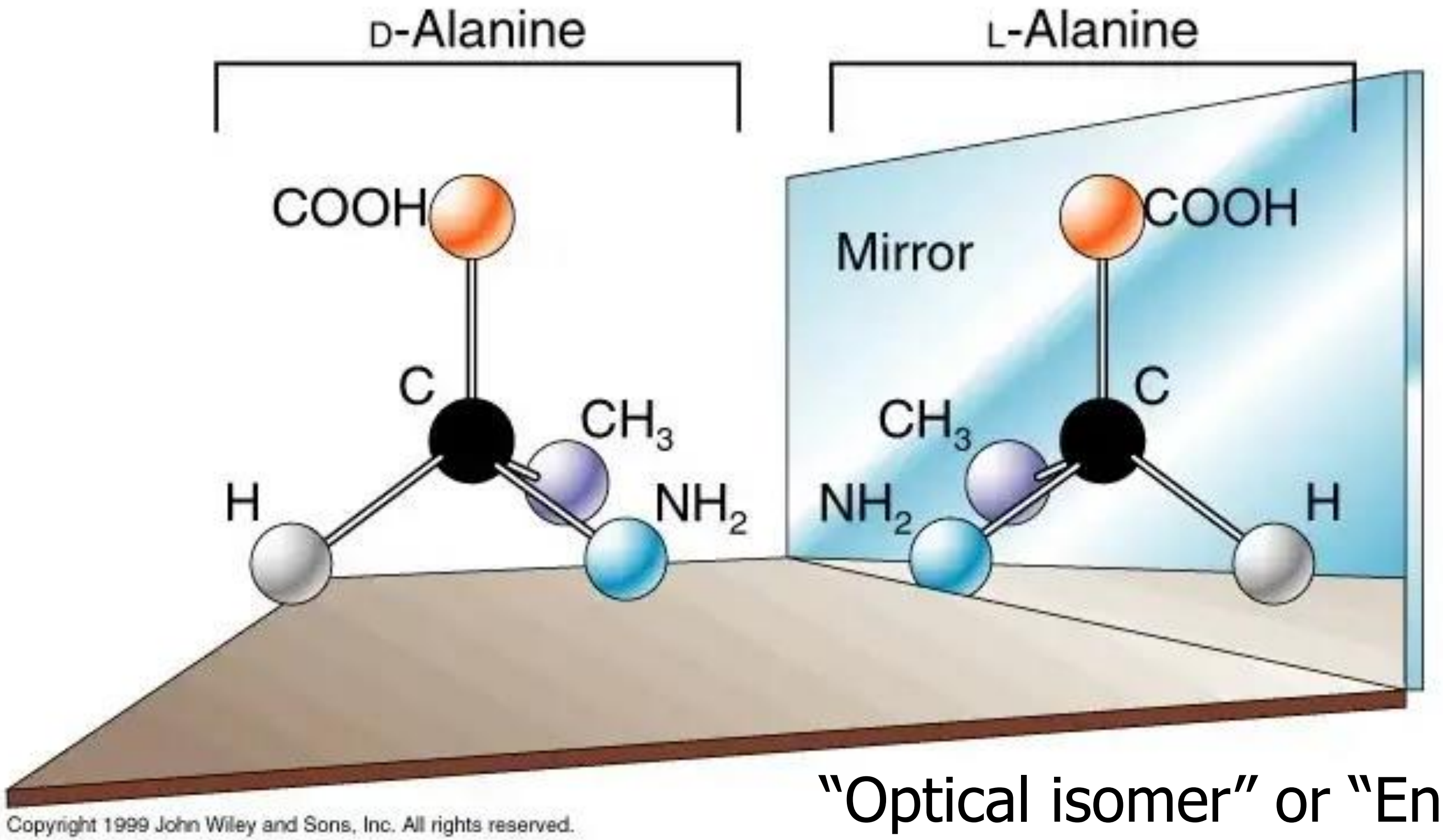
Asymmetry in daily life

Tokyo



Osaka

Homochirality in lives on the Earth



"Optical isomer" or "Enantiomer"

Most amino acids are L-type, and most sugars are D-type.

→ What is the origin? Weak interaction? Just a chance?

→ What is the mechanism to achieve ~100% asymmetry?

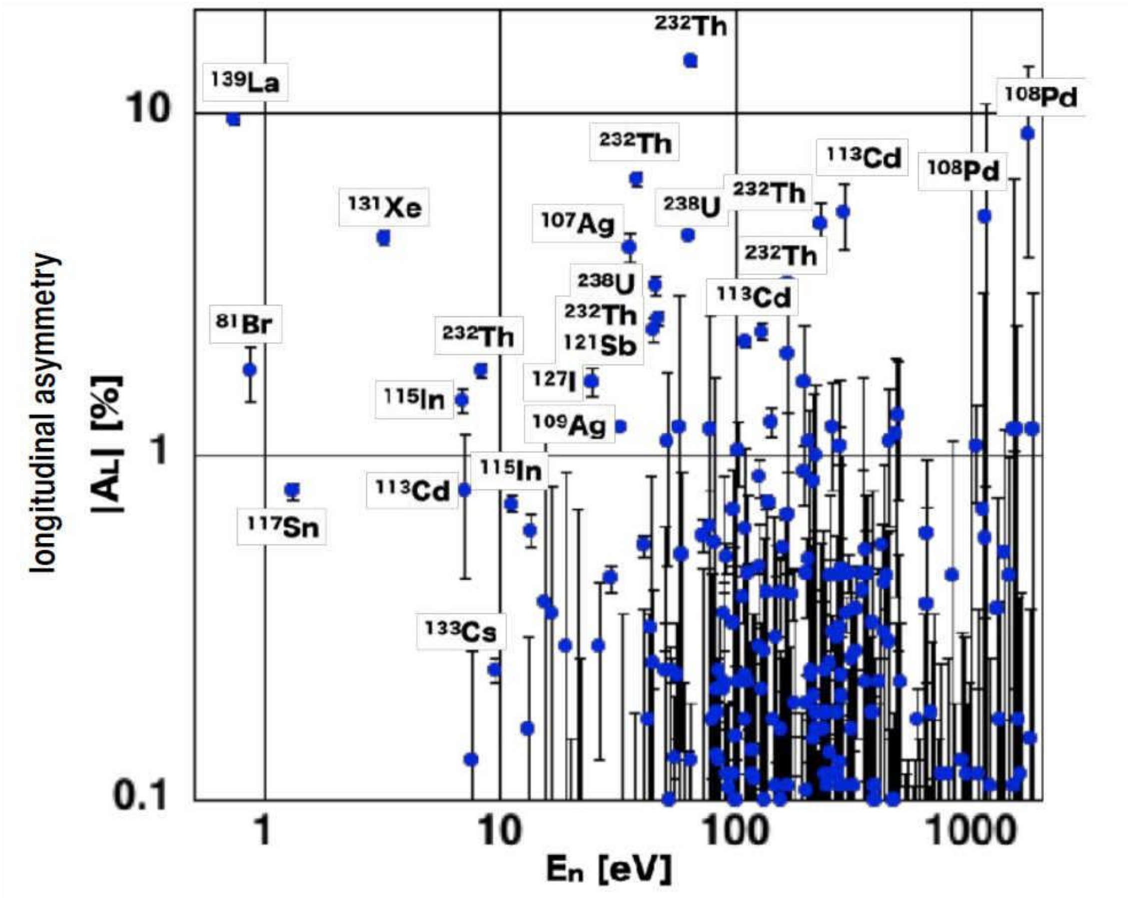
Asymmetries in Nature

- Eternal expansion of the Universe
- Arrow of time; from past to future
- Matter-antimatter asymmetry in universe
- Parity violation in weak interaction
- Homochirality in terrestrial biomolecules
- and so on…

Large parity violation in compound nuclei

$$A_L = \frac{\sigma(\boldsymbol{\sigma}_n \cdot \mathbf{k} = +) - \sigma(\boldsymbol{\sigma}_n \cdot \mathbf{k} = -)}{\sigma(\boldsymbol{\sigma}_n \cdot \mathbf{k} = +) + \sigma(\boldsymbol{\sigma}_n \cdot \mathbf{k} = -)} \quad \Leftrightarrow \quad \sigma = \sigma_0 \cdot \left(1 + A_L (\boldsymbol{\sigma}_n \cdot \mathbf{k})\right)$$

(Cross section)



G.E. Mitchell et al., Phys. Rep. 354, 157 (2001)

PV ~10^{-7} in bare nucleon-nucleon interaction

PV ~0.1 (max) in compound nuclei

- - - amplified by ~10^6 !!

Mixing between p-wave and s-wave resonances

$$A_L = -2\frac{W}{\left|E_p - E_s\right|}\sqrt{\frac{\Gamma_s^n}{\Gamma_p^n}}\cdot\sqrt{\frac{\Gamma_p^n\left(j=1/2\right)}{\Gamma_p^n}}$$

(ratio of j=1/2 component)

Dynamical Enhancement

($10^2 \sim 10^3$)

Kinematical Enhancement

(Γ_s~eV, Γ_p~meV → ~10^3)

$$W = \left\langle \psi_s \middle| H_W \middle| \psi_p \right\rangle \sim \frac{1}{\sqrt{N}}\cdot\left\langle \psi_s \middle| H_W \middle| \psi_p \right\rangle_{\text{single particle}}$$

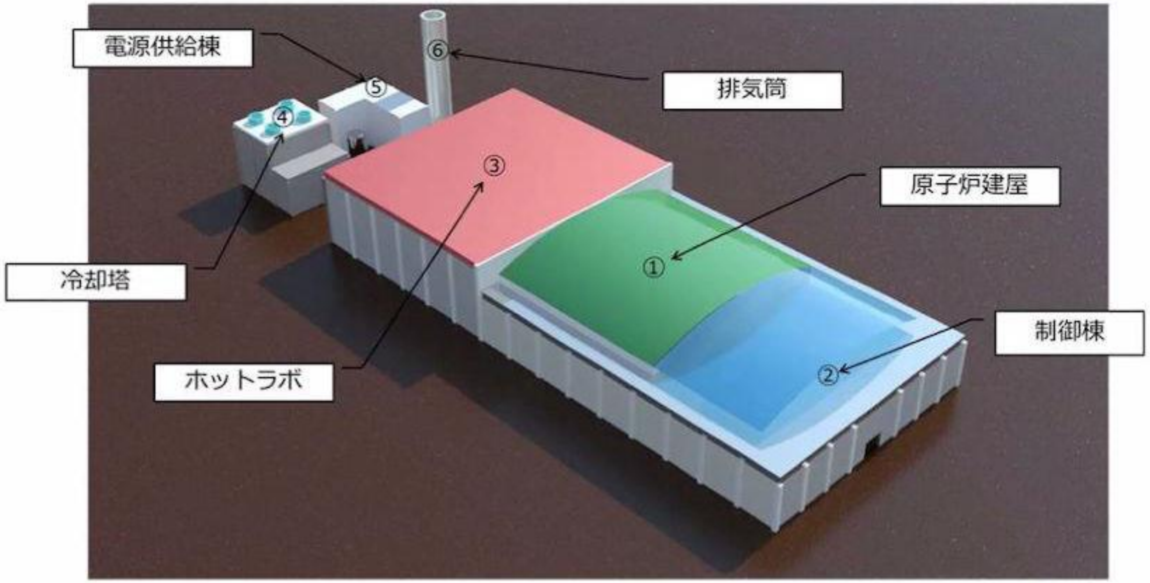
$$\left|E_p - E_s\right| \propto \frac{1}{N}$$

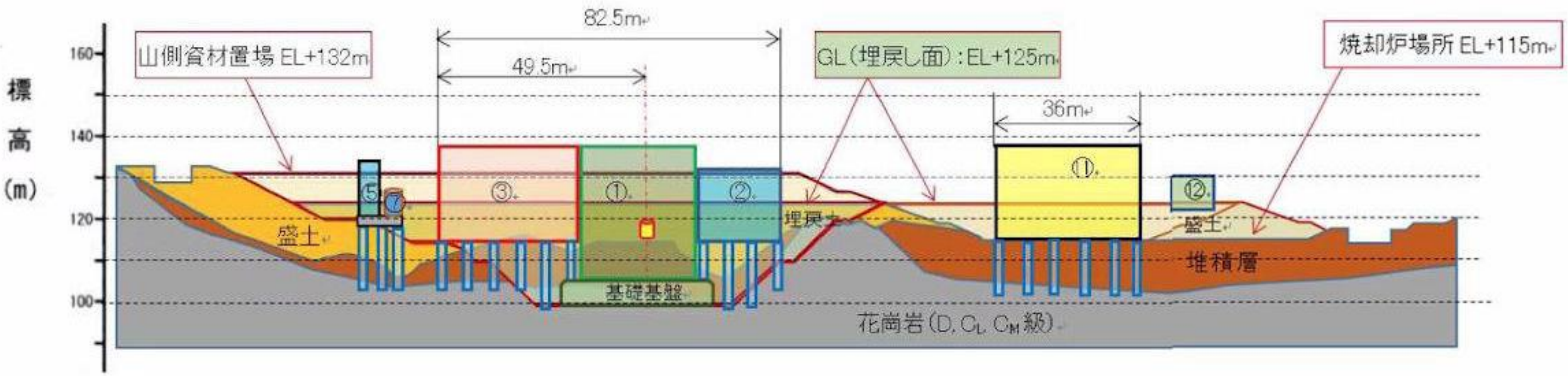
N ; level density~10^6 [/MeV] for heavy nuclei

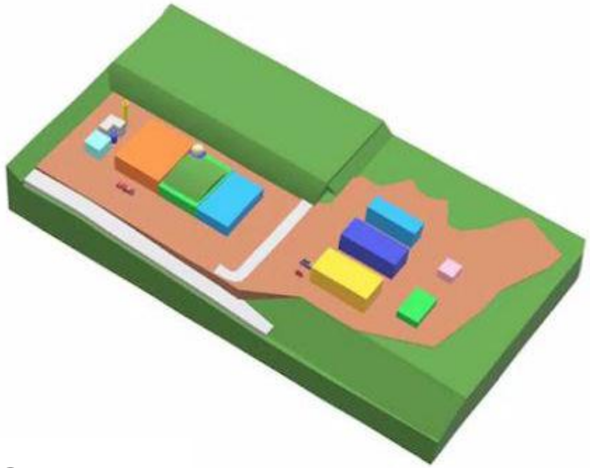
Similar mechanism is expected to operate in violation of other symmetries such as isospin invariance and time-reversal invariance….

New research reactor@Monju site

Imaginary picture of new research reactor



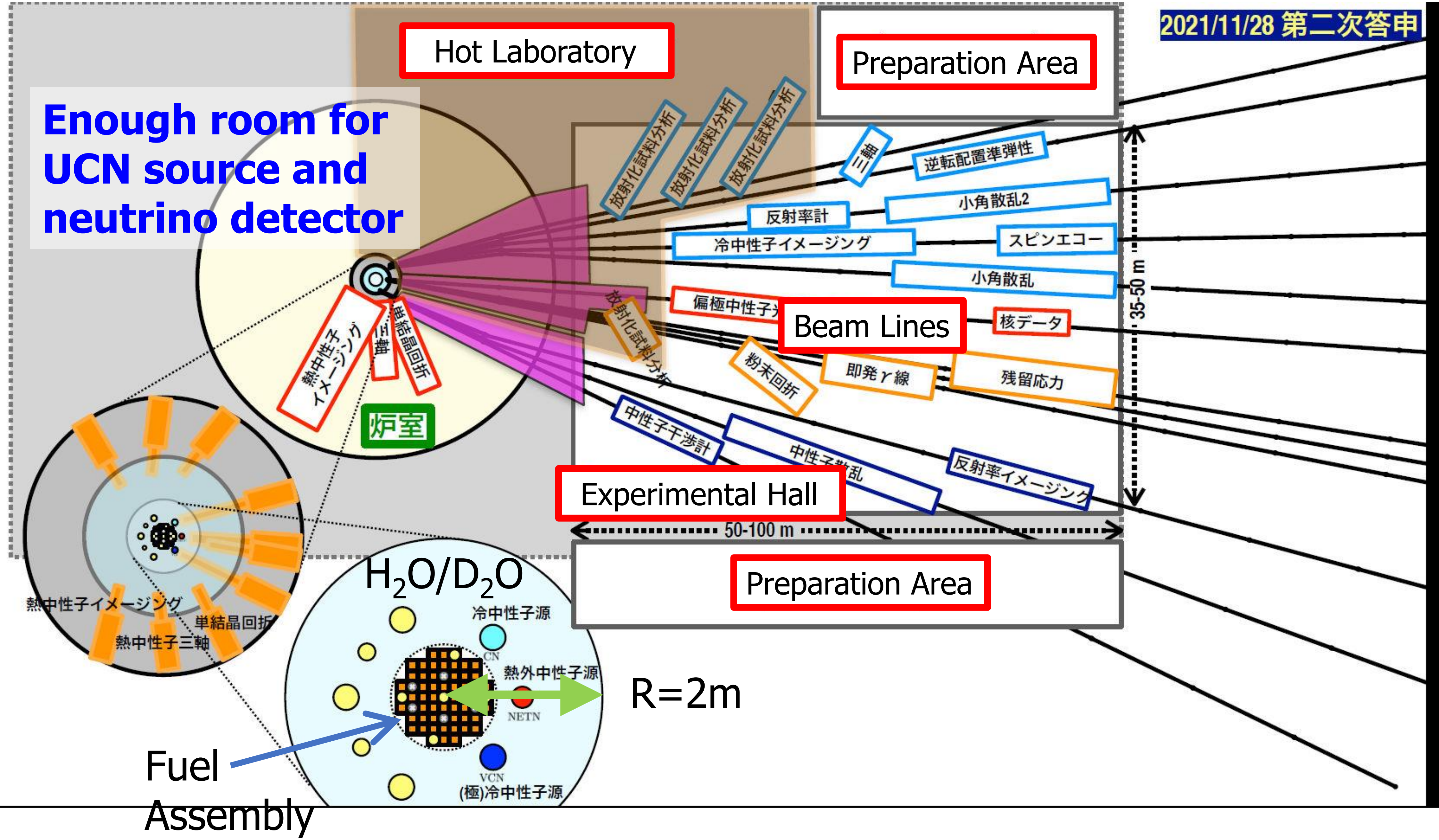




Thermal power =10MW < ILL 58MW, JRR-3 20MW

But flexibility in core structure !

Floor Design & Reactor core design



Physics Case

Nuclear Physics ;

- Precise measurement of neutron scattering lengths
  → few-nucleon systems, cluster system, etc.
- Cross section data of neutron-induced reactions
  → nuclear astrophysics
- Cross section data of neutrino-induced nuclear reactions
  → nuclear astrophysics, neutrino astronomy

Particle Physics ;

- High-intensity neutrons from epithermal to ultra-cold
  → T-violation in compound neclei, nEDM, **n-$\bar{n}$ oscillation**
- High-intensity antineutrino
  → Sterile neutrino search at world-shortest baseline (~3 m)

⇨ Profs. S. Yoshida, S. Umehara

n-$\bar{n}$ oscillation

Transition between neutron and antineutron is allowed if there is no magnetic field and baryon-number is violated by 2 units ($|\Delta B| = 2$); i.e. neutron and antineutron are **Majorana fermions** ; $\psi_n = \psi_{\bar{n}} \equiv C\psi_n$

Prediction by Grand Unified Theories

GUT models	Oscillation period $\tau_{n\bar{n}}$ =10^6~10^{10} sec ?
$SU(2)_L \times U(1)_Y$ (GWS)	forbidden
minimal SU(5)	forbidden
$SU(4)_C \times SU(2)_L \times SU(2)_R$	yes
SO(10)	too slow
SO(10) with low-E (~100TeV) $SU(4)_C$	yes
E_6	too slow
SUSY-SU(5)	too rapid
SUSY-E_6	yes

R.N.Mohapatra, NIM A284 (1989) 1

K.S. Babu, R.N. Mohapatra, PLB518 (2001) 269

Feature of SO(10) GUT model

$$\mathrm{SO}(10)\ (\mathrm{Spin}(10)) \supset \mathrm{SO}(6) \times \mathrm{SO}(4)$$

$$\mathrm{SO}(6) \supset \mathrm{SU}(4) \supset \mathrm{SU}(3)_c \times \mathrm{U}(1)_{B\text{-}L}$$

$$\mathrm{SO}(4) \supset \mathrm{SU}(2) \times \mathrm{SU}(2)'$$

$$\downarrow \qquad \downarrow$$

$$\mathrm{SU}(2)_L \quad \mathrm{SU}(2)_R$$

$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B\text{-}L} \rightarrow \mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$

- Parity violation in weak interaction is naturally explained by spontaneous symmetry breaking of $\mathrm{U}(1)_{\mathrm{B\text{-}L}}$, not *ad hoc* !
- $|\Delta B|=1$, $|\Delta L|=1$ are naturally suppressed. → explain slow proton decay
- Neutrinos can be Majorana type.
  → Seesaw mechanism can be used to explain light neutrino masses.
- $|\Delta L|=2$ is allowed → "Leptogenesis" for origin of baryon asymmetry.

n-n̄ conversion and 0nbb

Mass of right-handed neutrino (heavy);

$$M_R \sim \frac{\langle v_R \rangle^2}{M_{Pl}} \qquad (\langle v_R \rangle;\ \text{VEV of Higgs which couples to } \nu_R)$$

Mass of left-handed neutrino (light);

$$m_\nu \sim \frac{m_l^2}{M_R} \quad \Rightarrow \quad m_\nu \sim M_{Pl} \left(\frac{m_l}{\langle v_R \rangle} \right)^2 \qquad (\text{"Seesaw" mechanism})$$

Neutron-antineutron oscillation period;

$$\tau_{n\bar{n}}^{-1} = \delta m \propto \langle v_{B-L} \rangle \propto\sim \langle v_R \rangle \quad \Rightarrow \quad m_\nu \sim C \cdot M_{Pl} \cdot \tau_{n\bar{n}}^2$$

C is model-dependent.

The smaller Majorana neutrino mass, the shorter n-$\bar{n}$ oscillation period !

$n \rightarrow \bar{n}$ conversion probability

$$i\frac{\partial}{\partial t}\begin{pmatrix}\psi_n(t)\\ \psi_{\bar{n}}(t)\end{pmatrix}=\begin{pmatrix}E_n-\boldsymbol{\mu}_n\cdot\mathbf{B}-i\Gamma_\beta/2 & \varepsilon\\ \varepsilon & E_n+\boldsymbol{\mu}_n\cdot\mathbf{B}-i\Gamma_\beta/2\end{pmatrix}\begin{pmatrix}\psi_n(t)\\ \psi_{\bar{n}}(t)\end{pmatrix}$$

For $\psi_n(0)=1,\ \psi_{\bar{n}}(0)=0,$

$$\left|\psi_{\bar{n}}(t)\right|^2=\frac{4\varepsilon^2}{\omega^2+4\varepsilon^2}\exp\left(-\Gamma_\beta t\right)\cdot\sin^2\left(\frac{1}{2}\sqrt{\omega^2+4\varepsilon^2}\,t\right)$$

where $\omega\equiv 2\left|\boldsymbol{\mu}_n\cdot\mathbf{B}\right|$, $\varepsilon\equiv\dfrac{1}{\tau_{n\bar{n}}}$

--- Conversion is suppressed by external magnetic field.

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

Cold neutron; E_n = 2meV (T=25K) , $\Phi_n = 1.25 \times 10^{11}$ n/sec

Flight path ; L_{TOF} = 76.5m, t_{TOF} = 0.1 sec

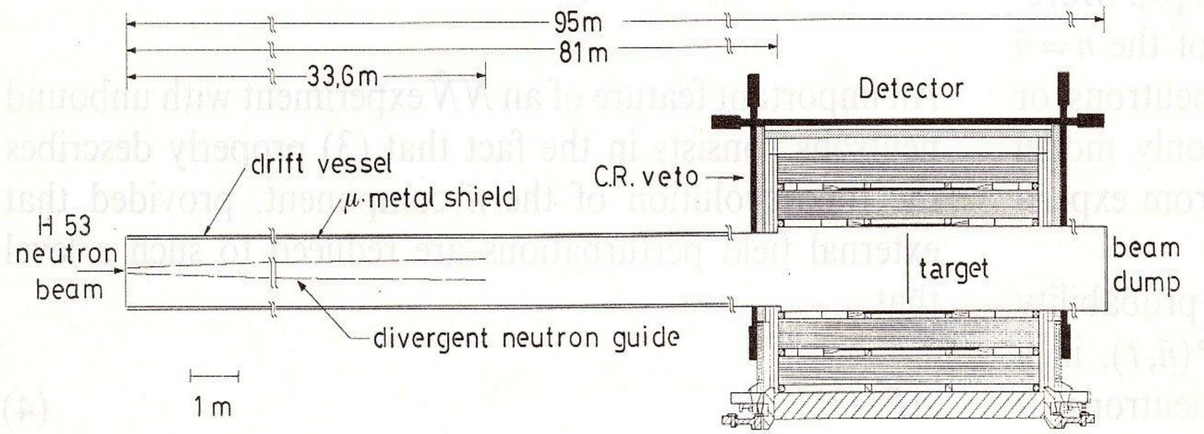
P < 0.01 Pa, B < 10 nT

Target; graphite film (130μm) Detector efficiency ; $\varepsilon = 0.52$

Measurement time ; $t_{meas} = 2.4 \times 10^7$ sec

$$P_{n\bar{n}} \approx \left(\frac{t_{TOF}}{\tau_{n\bar{n}}} \right)^2 ,$$

$$Y_{\bar{n}} = \varepsilon \cdot \Phi_n \cdot P_{n\bar{n}} \cdot t_{meas}$$



$$\tau_{n\bar{n}} > 8.6 \times 10^7 \text{ sec}$$

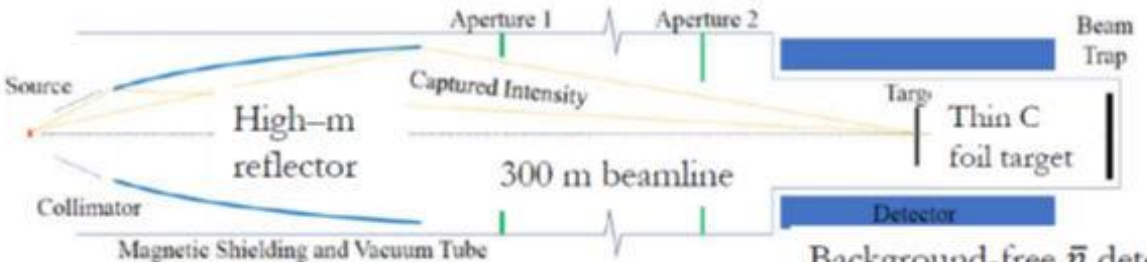
Plan at European Spallation Source (5MW)

NNBAR: Free Search for $n \rightarrow \bar{n}$

LOI on NNBAR

- NNBAR: Leverage 3 decades of advances: moderator design, neutronics, detection, reconstruction techniques ×**1000** sensitivity of ILL arXiv:2006.04907
  - Collaboration: 26 institutions across 8 countries
- European Spallation Source (5MW in 2030+): Large Beam Port constructed specifically for NNBAR
  - NNBAR highlighted in Monday plenary on European Strategy
- HighNESS (3M€ EU grant): moderator study, $\bar{n}$ detector prototyping, CDR for upgrade of the ESS including NNBAR beamline+experiment
- Staged program ORNL – HIBEAM - NNBAR

Brightness		≥ 1
Moderator Temperature	Colder neutron <TOF>, quadratic sensitivity	≥ 1
Moderator Area	Large aperture required	2
Angular Acceptance	2D = quadratic sensitivity	40
Length	∝ time, quadratic sensitivity	5
Run Time	ILL run = 1 year	3
Total gain vs ILL		**≥ 1000**



Background-free $\bar{n}$ detector

"The Large Beam Port is an opportunity to broaden the ESS mission"

Rikard Linander, Head of the ESS Target Division

Intra-nuclear n-n̄ conversion

Super-Kamiokande (K. Abe et al., PRD103, 012008 (2021))

proton decay ($\Delta B = 1$) : $p \rightarrow e^+ + \pi_0$ $> 1.6 \times 10^{34}$ y

n-n̄ oscillation in ^{16}O nucleus ($\Delta B = 2$) : $\tau_{n\bar{n}}$ (^{16}O) $> 3.6 \times 10^{32}$ y

$\Rightarrow \tau_{n\bar{n}}$ (free) $> 4.7 \times 10^8$ sec (90%CL) (3×10^8 sec in 2003)

--- huge suppression by nuclear potential !

Hyper-Kamiokande

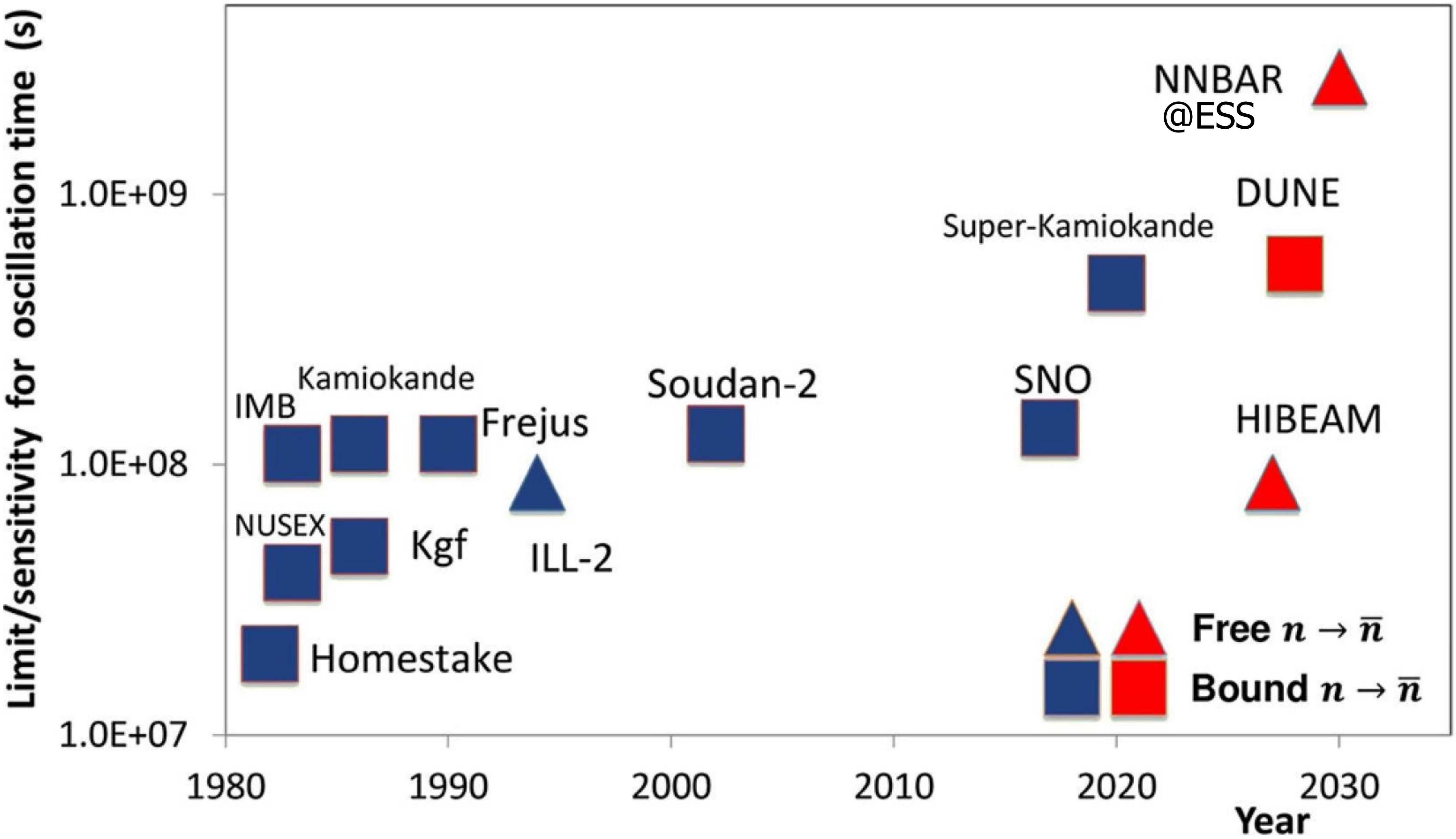
fiducial mass = $5 \times$ SK → proton decay > $\sim 10^{35}$ y

n-n̄ oscillation in ^{16}O > $\sim 10^{33}$ y

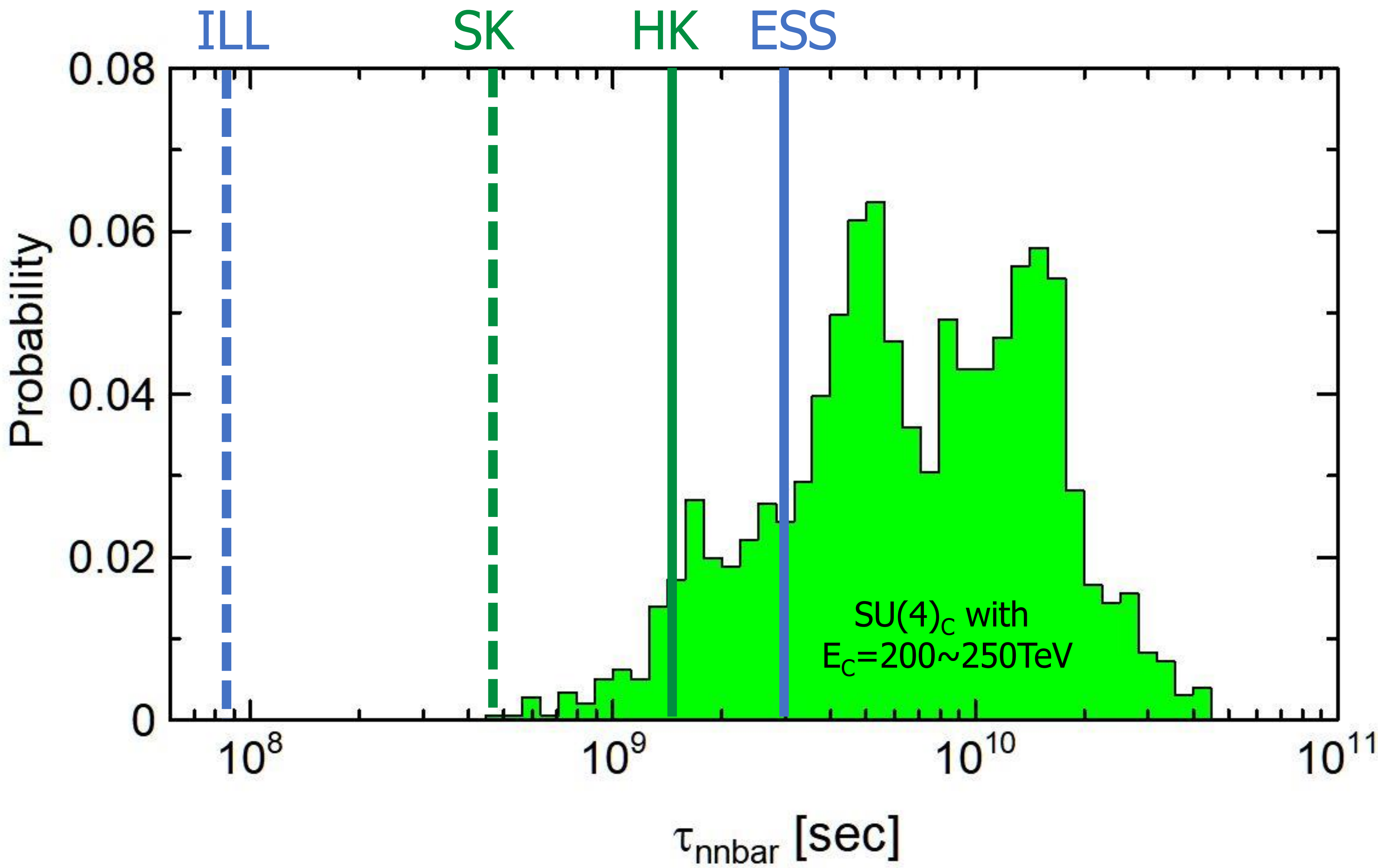
$\Rightarrow \tau_{n\bar{n}}$ (free) $> 1.4 \times 10^9$ sec $\because \quad \tau_{n\bar{n}} \propto \frac{1}{\sqrt{P_{\bar{n}}}}$

Sensitivity for n-$\bar{n}$ conversion

A. Addazi et al., J. Phys. G: Nucl. Part. Phys. 48 (2021) 070501



Exp. Sensitivity vs Theor. Prediction



Post-Sphaleron Baryogenesis; K.S. Babu et al., Phys. Rev. D87, 115019 (2013)

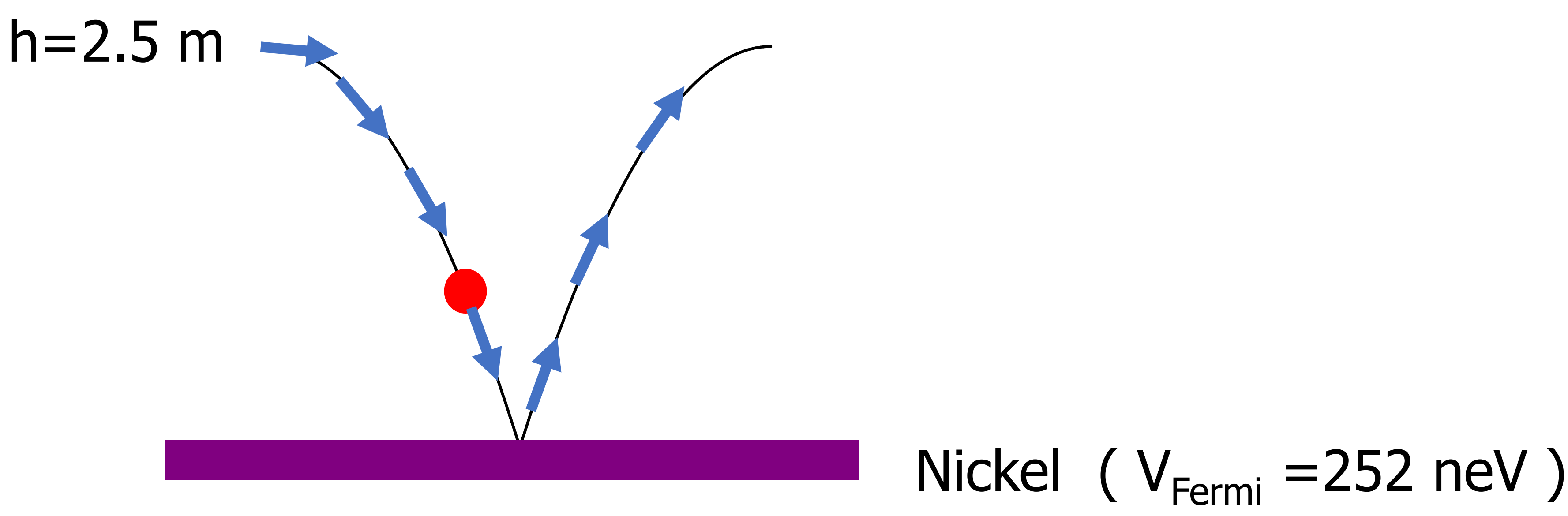
Ultra Cold Neutron

Kinetic energy; E_n <~200 neV,   Velocity; v_n < 6.5 m/s

⇒de Broglie wavelength λ_n > 60 nm

>> interatomic distances in solid/liquid

--- Coherent scattering is dominant.



Ultra Cold Neutron

$$P_{n\bar{n}} \approx \left(\frac{t_s}{\tau_{n\bar{n}}} \right)^2 , \qquad Y_{\bar{n}} = \varepsilon \cdot \Phi_n \cdot P_{n\bar{n}} \cdot t_{meas}$$

$$\Rightarrow \qquad \tau_{n\bar{n}} = \left(\frac{\varepsilon \cdot \Phi_n \cdot t_{meas}}{Y_{\bar{n}}} \right)^{1/2} \cdot t_s$$

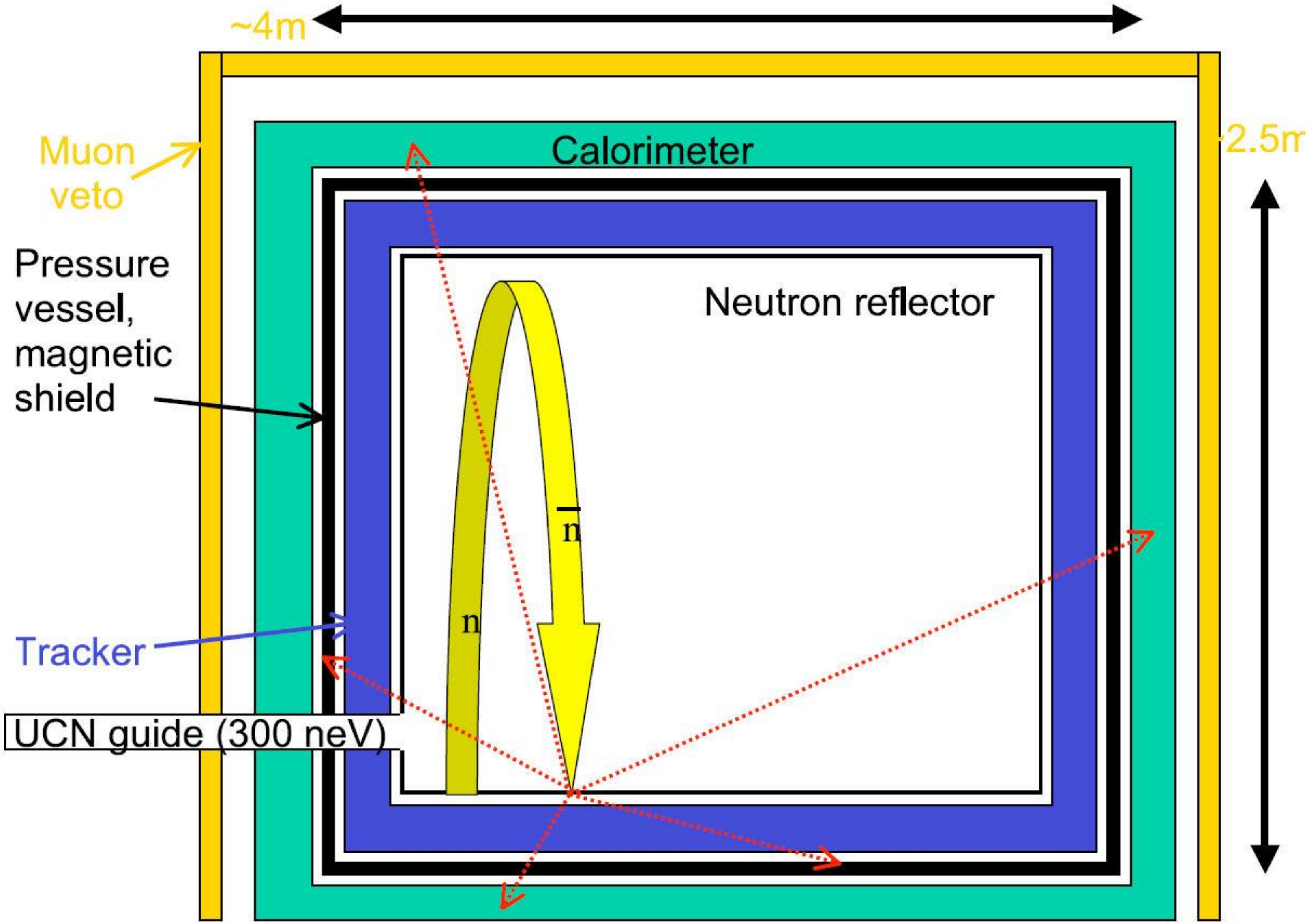
UCN beam intensity ; $\Phi_n = 10^8$ n/sec

Storage time ; **t_s = 500 sec >> 0.5 sec in NNBar@ESS**

Detector efficiency ; $\varepsilon = 0.5$

Measurement time ; $t_{meas} = 2 \times 10^7$ sec

➡ **$\tau_{n\bar{n}} \sim 1.5 \times 10^{10}$ sec (!)**



D.G. Phillips II et al., Phys. Rep. 612, 1-45 (2016)

However…

Ultra Cold Neutron (cont.)

$$i\frac{\partial}{\partial t}\begin{pmatrix}\psi_n(t)\\ \psi_{\bar{n}}(t)\end{pmatrix}=\begin{pmatrix}E_n-i\Gamma_\beta/2+U_n(t) & \varepsilon\\ \varepsilon & E_n-i\Gamma_\beta/2+U_{\bar{n}}(t)\end{pmatrix}\begin{pmatrix}\psi_n(t)\\ \psi_{\bar{n}}(t)\end{pmatrix}$$

For $\psi_n(0)=1,\ \psi_{\bar{n}}(0)=0,$

$$\left|\psi_{\bar{n}}(t)\right|^2=\frac{4\varepsilon^2}{\omega_W^2+4\varepsilon^2}\exp\left(-\Gamma_\beta t\right)\cdot\sin^2\left(\frac{1}{2}\sqrt{\omega_W^2+4\varepsilon^2}\,t\right)$$

where $\omega_W\equiv U_n(t)-U_{\bar{n}}(t)=O\left(10^{-7}[\text{eV}]\right)>>>\varepsilon<10^{-25}\ [\text{eV}]$

$\left(U_n(t)\ \left(U_{\bar{n}}(t)\right)\text{ is (anti)neutron-wall potential}\right)$

$$\rightarrow P_{n\bar{n}}=\left|\psi_{\bar{n}}(t)\right|^2\cong\begin{cases}\varepsilon^2t^2 & \left(\sqrt{\omega_W^2+4\varepsilon^2}\,t<<1\right)\\ \dfrac{4\varepsilon^2}{\omega_W^2+4\varepsilon^2} & \left(\sqrt{\omega_W^2+4\varepsilon^2}\,t>>1\right)\end{cases}$$

$< \sim 10^{-30}$

→ Anti-neutron amplitude is reset to zero at every reflection.

S. Marsch & K.W. MacVoy, PRD28, 2793 (1983)

Ultra Cold Neutron (corrected.)

$$P_{n\bar{n}} \approx \left(\frac{t_{TOF}}{\tau_{n\bar{n}}}\right)^2 \quad , \qquad Y_{\bar{n}} = \varepsilon \cdot \Phi_n \cdot P_{n\bar{n}} \cdot t_{meas} \cdot m \qquad \left(m \equiv \frac{t_s}{t_{TOF}}\right)$$

$$\Rightarrow \qquad \tau_{n\bar{n}} = \left(\frac{\varepsilon \cdot \Phi_n \cdot \frac{1}{m} \cdot t_{meas}}{Y_{\bar{n}}}\right)^{1/2} \cdot t_s \qquad \text{cf.} \quad \tau_{n\bar{n}} = \left(\frac{\varepsilon \cdot \Phi_n \cdot t_{meas}}{Y_{\bar{n}}}\right)^{1/2} \cdot t_s$$

for quasi-free condition

UCN beam intensity ; $\Phi_n = 10^8$ n/sec

Storage time ; $t_s = 500$ sec Flight time ; $t_{TOF} = 1$ sec $\neq t_s$

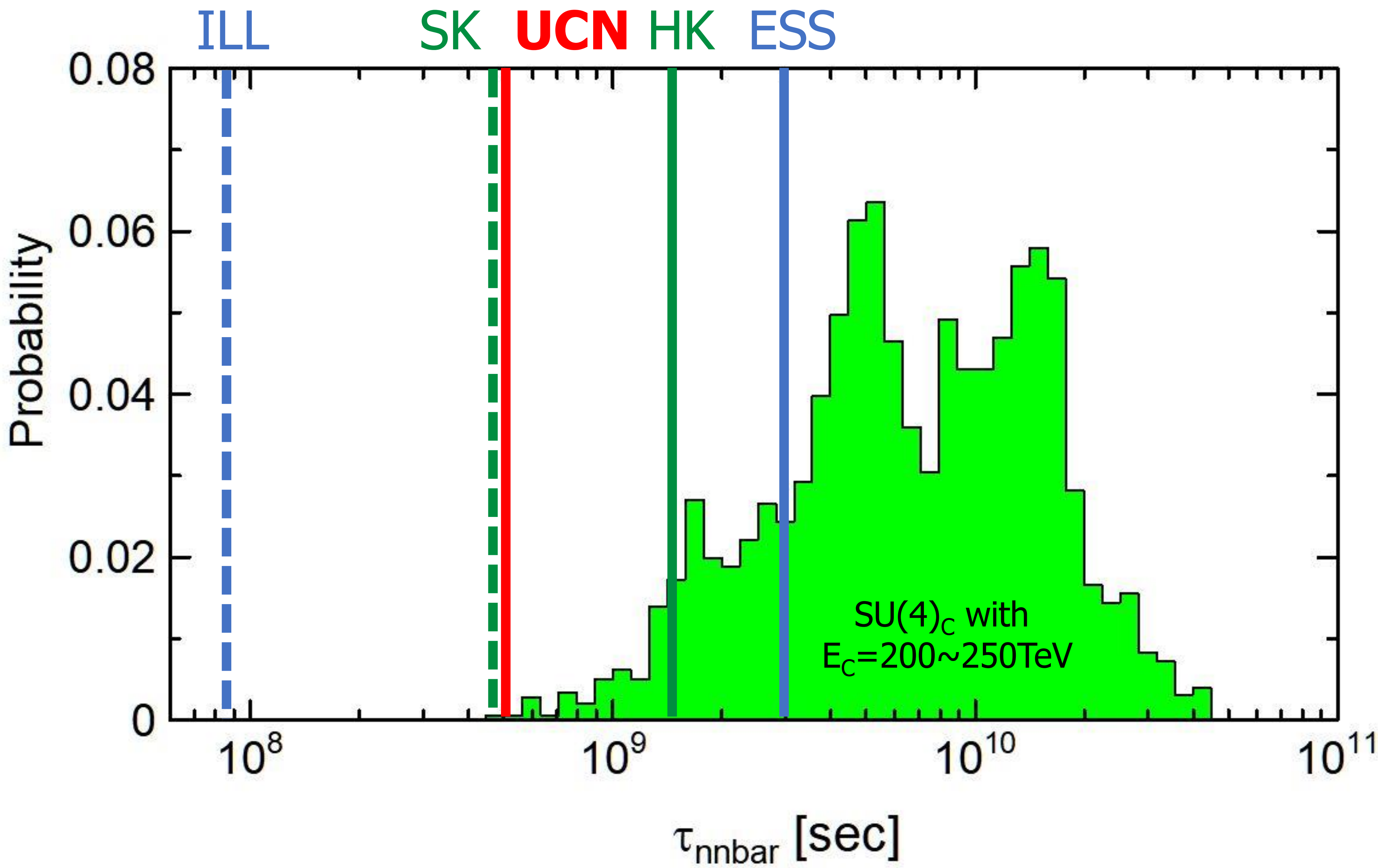
Detector efficiency ; $\varepsilon = 0.5$

Measurement time ; $t_{meas} = 2 \times 10^7$ sec

Not 500s measurement but
1s measurements for 500 times…

➡ $\tau_{n\bar{n}} \sim 7 \times 10^8$ **sec**

Exp. Sensitivity vs Theor. Prediction



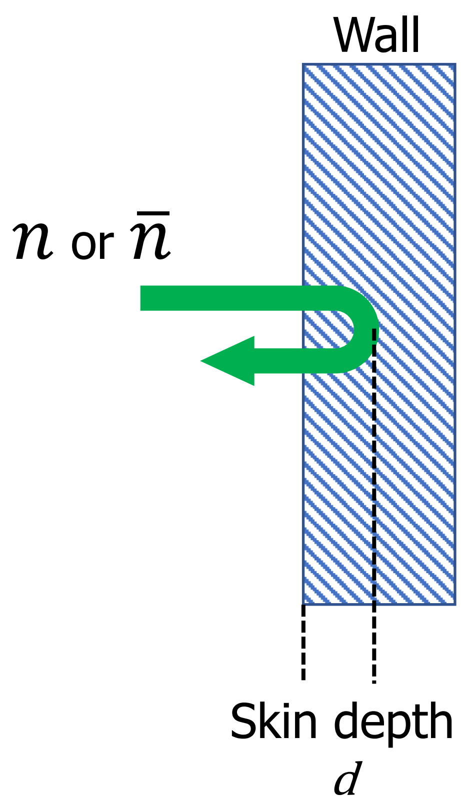
Post-Sphaleron Baryogenesis; K.S. Babu et al., Phys. Rev. D87, 115019 (2013)

Ultra Cold Neutron (revisited)

For $\psi_n(0)=1,\ \psi_{\bar{n}}(0)=0,$

$$\left|\psi_{\bar{n}}(t)\right|^2 = \frac{4\varepsilon^2}{\omega_W^2+4\varepsilon^2}\exp\left(-\Gamma_\beta t\right)\cdot\sin^2\left(\frac{1}{2}\sqrt{\omega_W^2+4\varepsilon^2}\,t\right)$$

$$\rightarrow P_{n\bar{n}} = \left|\psi_{\bar{n}}(t)\right|^2 \cong \begin{cases} \varepsilon^2 t^2 & \left(\sqrt{\omega_W^2+4\varepsilon^2}\,t \ll 1\right) \\ \dfrac{4\varepsilon^2}{\omega_W^2+4\varepsilon^2} & \left(\sqrt{\omega_W^2+4\varepsilon^2}\,t \gg 1\right) \end{cases}$$



F. Atchison et al., NIMA587, 82-88 (2008)

UCN; E_n=0.18μeV, λ_n=67nm, v_n=6m/s, penetration depth d~10nm

→ t ~10ns, ω_W ~10^{-7}eV → $\omega_W \cdot t = 10^{-15}$ eV·s ~ $\hbar = 6.6\times10^{-16}$ eV·s

B. O. Kerbikov, A. E. Kudryavtsev, and V. A. Lensky, JETP 98, 417-426 (2004)

Inside wall;

$$i\frac{\partial}{\partial t}\begin{pmatrix}\psi_n(t)\\ \psi_{\bar{n}}(t)\end{pmatrix}=\begin{pmatrix}E_n-i\Gamma_\beta/2+U_n(t) & \varepsilon\\ \varepsilon & E_n-i\Gamma_\beta/2+U_{\bar{n}}(t)\end{pmatrix}\begin{pmatrix}\psi_n(t)\\ \psi_{\bar{n}}(t)\end{pmatrix}$$

where $\omega_W\equiv U_n(t)-U_{\bar{n}}(t)=O\left(10^{-7}[\mathrm{eV}]\right)>>>\varepsilon<10^{-22}\ [\mathrm{eV}]$

$$v\equiv\frac{1}{2}\sqrt{\omega_W^2+4\varepsilon^2}\qquad\left(\cong\frac{1}{2}\omega_W\ ,\ \text{if } \varepsilon \text{ is extremely small}\right)$$

$\equiv \mathbf{R}$ (reflextion)

$$\begin{pmatrix}\psi_n(t_W)\\ \psi_{\bar{n}}(t_W)\end{pmatrix}=\exp\left[-\left(iE_n+\frac{\Gamma_\beta}{2}\right)t_W\right]\cdot\begin{pmatrix}\cos vt_W+\frac{i\omega_W}{2v}\sin vt_W & -\frac{i\varepsilon}{v}\sin vt_W\\ -\frac{i\varepsilon}{v}\sin vt_W & \cos vt_W-\frac{i\omega_W}{2v}\sin vt_W\end{pmatrix}\begin{pmatrix}\psi_n(0)\\ \psi_{\bar{n}}(0)\end{pmatrix}$$

$$\varepsilon\sim10^{-25}\ [\mathrm{eV}],\ v\cong\frac{1}{2}\omega_W\sim10^{-7}\ [\mathrm{eV}],\ t_W\sim10^{-8}\ [\mathrm{s}]=1.5\times10^{7}\ [\mathrm{eV}^{-1}]$$

$$\Rightarrow\quad vt_W\cong1.5$$

$$\Rightarrow\quad \mathbf{R}=\begin{pmatrix}0.0707+0.9975i & 0\\ 0 & 0.0707-0.9975i\end{pmatrix}=0.0707\mathbf{I}+0.9975i\boldsymbol{\sigma}_3$$

$$\left(\cos vt_W\right)^{500} >\sim 0.5 \quad \Leftrightarrow \quad vt_W < 0.05$$

$$\Leftrightarrow \quad v \sim \omega_W = U_n - U_{\bar{n}} < 3\times 10^{-9} \text{ [eV] is required.} \quad \left(U_n, U_{\bar{n}} \sim 10^{-7} \text{ [eV]}\right)$$

U_n , $U_{\bar{n}}$ are Fermi's pseudo potentials ;

$$U_j = \frac{2\pi}{m}\rho_A \cdot \mathrm{Re}\left(a_{jA}\right)$$

j ; neutron or antineutron

m ; mass of neutron (antineutron)

ρ_A ; number of nucleus A in the unit volume of the wall

a_{jA} ; coherent scattering length of neutron or antineutron with target nucleus A

$$\left(\cos vt_W\right)^{500} >\sim 0.5 \quad \Leftrightarrow \quad vt_W < 0.05 \quad \Leftrightarrow \quad \omega_W \sim v < 3\times 10^{-9} \text{ [eV]}$$

$$\omega_W = U_{nA} - U_{\bar{n}A} = \frac{2\pi}{m_n}\rho_A\left(a_{nA} - a_{\bar{n}A}\right)$$ (Hereafter a denotes only real part for simplicity)

$$\Rightarrow \quad \omega_W = \frac{2\pi}{m_n}\left[\rho_A\left(a_{nA} - a_{\bar{n}A}\right) + \rho_B\left(a_{nB} - a_{\bar{n}B}\right)\right]$$, for compound or alloy made of nuclei A and B

$$= 0$$

$$\text{,when } \quad x = \frac{\rho_B}{\rho_A + \rho_B} = \frac{\left(a_{nA} - a_{\bar{n}A}\right)}{\left(a_{nA} - a_{\bar{n}A}\right) - \left(a_{nB} - a_{\bar{n}B}\right)}$$

To achieve $\left|\omega_W / U_{n,\bar{n}}\right| < 3\%$, one has to know antineutron-nucleus scattering lengths $a_{\bar{n}A}$, $a_{\bar{n}B}$ with accuracy of better than ~3% !

Coherent neutron scattering length

https://www.nist.gov/ncnr/neutron-scattering-lengths-list

Neutron scattering lengths and cross sections						
Isotope	**conc**	**Coh b [fm]**	**Inc b**	**Coh xs**	**Inc xs**	**Scatt xs**
H	---	-3.7390	---	1.7568	80.26	82.02
1H	99.985	-3.7406	25.274	1.7583	80.27	82.03
2H	0.015	6.671	4.04	5.592	2.05	7.64
3H	(12.32 a)	4.792	-1.04	2.89	0.14	3.03
He	---	3.26(3)	---	1.34	0	1.34
3He	0.00014	5.74-1.483i	-2.5+2.568i	4.42	1.6	6
4He	99.99986	3.26	0	1.34	0	1.34
Li	---	-1.90	---	0.454	0.92	1.37
6Li	7.5	2.00-0.261i	-1.89+0.26i	0.51	0.46	0.97
7Li	92.5	-2.22	-2.49	0.619	0.78	1.4
Be	100	7.79	0.12	7.63	0.0018	7.63
B	---	5.30-0.213i	---	3.54	1.7	5.24
10B	20	-0.1-1.066i	-4.7+1.231i	0.144	3	3.1
11B	80	6.65	-1.3	5.56	0.21	5.77
C	---	6.6460	---	5.551	0.001	5.551
12C	98.9	6.6511	0	5.559	0	5.559
13C	1.1	6.19	-0.52	4.81	0.034	4.84

(up to ^{248}Cm)

Coherent antineutron scattering length

Optical potential model

E. Friedman, Nucl. Phys. A925, 141-149 (2014).
K.V. Protasov, W.M. Snow et al., Phys. Rev. D102, 075025 (2020).

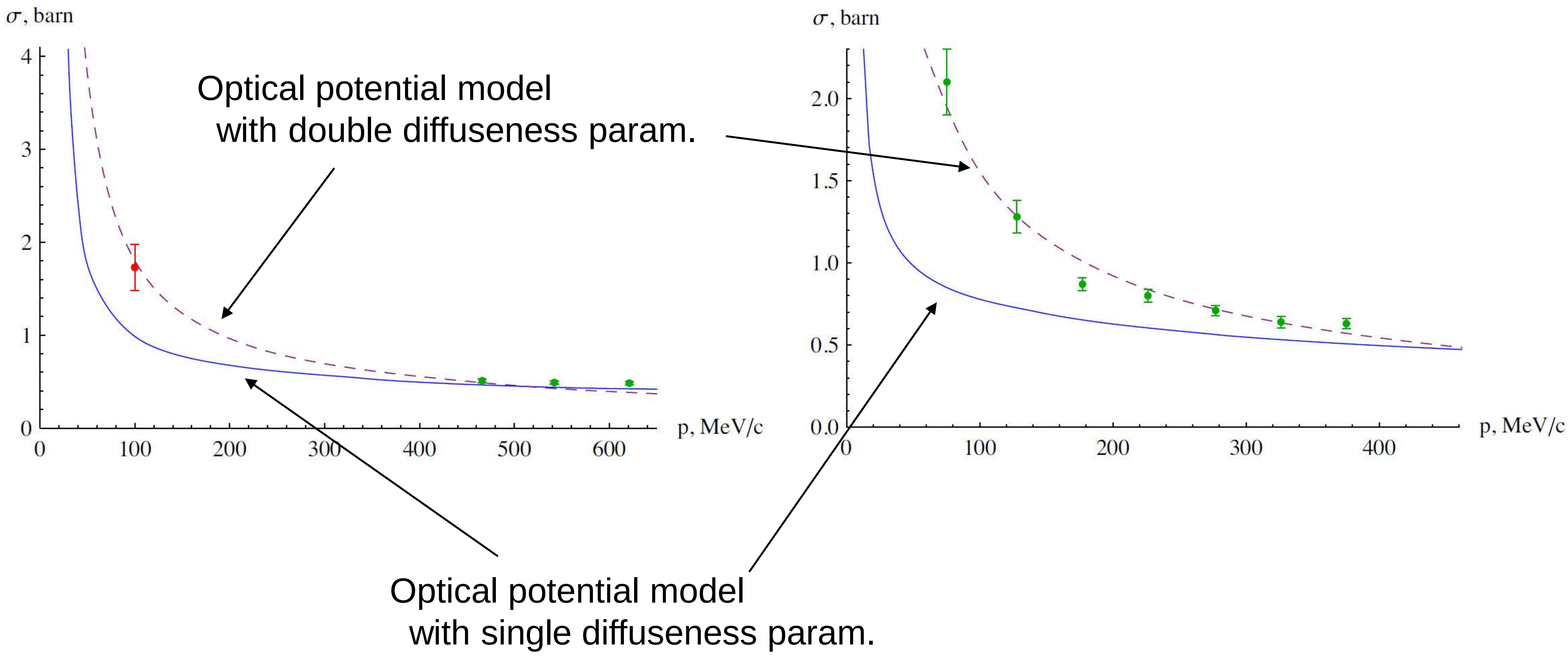
$$V(z) = -\frac{4\pi\hbar^2}{2\mu}\left(1+\frac{\mu}{m}\frac{A-1}{A}\right)\cdot a_0\left(\rho_n(z)+\rho_p(z)\right)$$

$$\rho_{p,n}(z) = \frac{\rho_{p_0,n_0}}{1+\exp\left(\frac{z-R_{p,n}}{a_{p,n}}\right)} \qquad \text{(Woods-Saxon)}$$

Available experimental data

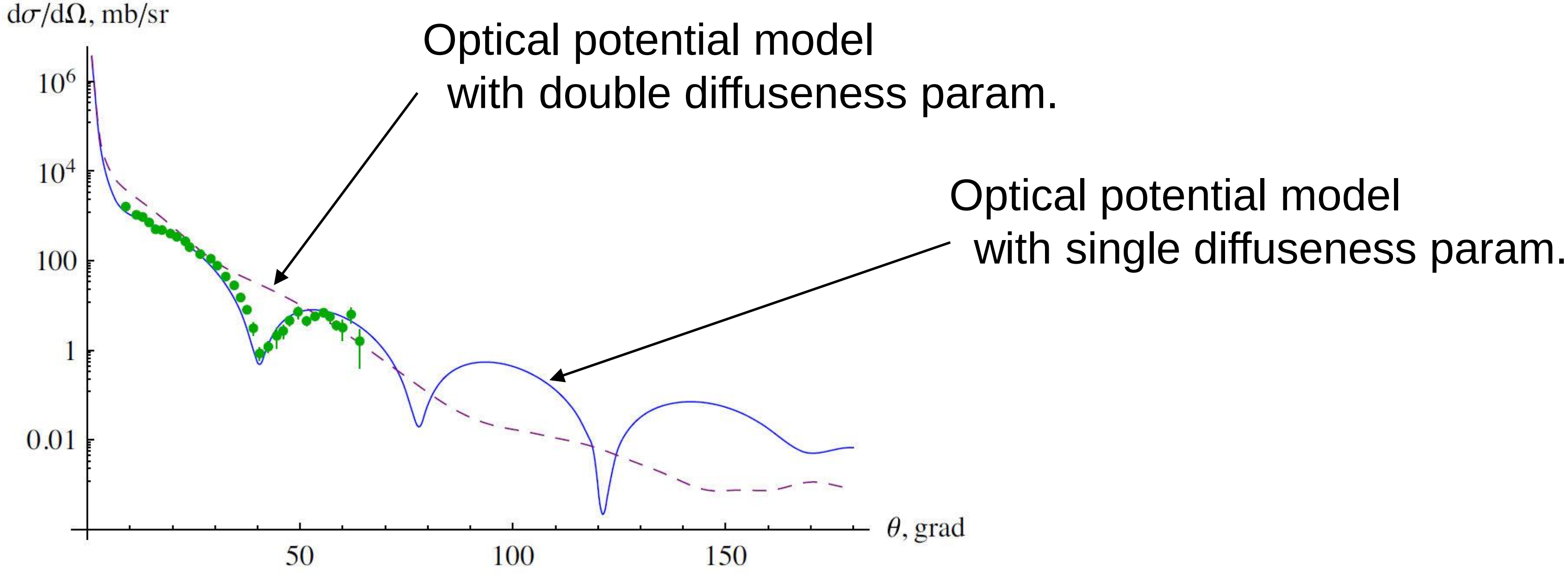
- ✓ $\bar{p}+A$ annihilation cross section
- ✓ $\bar{n}+A$ annihilation cross section
- ✓ $\bar{p}+A$ scattering cross section
- ✓ Spectroscopic data of antiprotonic atoms
- ✓ $n+A$ scattering cross section

$\bar{p} + {}^{12}C$ annihilation cross section $\bar{n} + {}^{12}C$ annihilation cross section



K.V. Protasov, W.M. Snow et al., Phys. Rev. D102, 075025 (2020).

$\bar{p} + {}^{12}C$ elastic scattering cross section



OPM with single diffuseness parameter is consistent also with $\bar{p}C$ atomic data

$$a_{\bar{n}+A} = \underline{(1.54 \pm 0.03)\cdot A^{0.311\pm 0.05}} - (1.00 \pm 0.04)\, i \ \text{[fm]}$$

error ~3% !

K.V. Protasov, W.M. Snow et al., Phys. Rev. D102, 075025 (2020).

$$\omega_W = \frac{2\pi}{m_n}\left[\rho_A\left(a_{nA} - a_{\bar{n}A}\right) + \rho_B\left(a_{nB} - a_{\bar{n}B}\right)\right] = 0$$

, for compound or alloy made of nuclei A and B

$$\text{,when } x = \frac{\rho_B}{\rho_A + \rho_B} = \frac{\left(a_{nA} - a_{\bar{n}A}\right)}{\left(a_{nA} - a_{\bar{n}A}\right) - \left(a_{nB} - a_{\bar{n}B}\right)}$$

$$\mathrm{Re}\left(a_{\bar{n}A}\right) = \left(1.54 \pm 0.03\right) \cdot A^{0.311 \pm 0.05} \ \text{[fm]}$$

For example,

Element	Atomic Mass	a_{nA} [fm]	$a_{\bar{n}A}$ [fm]	Molar Ratio
Al	27	3.449	4.29	0.59
Mg	24.3	5.375	4.15	0.41

Ultra Cold Neutron (revival)

$$P_{n\bar{n}} \approx a^{2m}\left(\frac{t_s}{\tau_{n\bar{n}}}\right)^2 \quad , \quad m \equiv \frac{t_s}{t_{TOF}} \quad , \quad Y_{\bar{n}} = \varepsilon \cdot \Phi_n \cdot P_{n\bar{n}} \cdot t_{meas}$$

$$\Rightarrow \qquad \tau_{n\bar{n}} = a^m \cdot \left(\frac{\varepsilon \cdot \Phi_n \cdot t_{meas}}{Y_{\bar{n}}}\right)^{1/2} \cdot t_s$$

UCN beam intensity ; $\Phi_n = 10^8$ n/sec

Storage time ; $t_s = 500$ sec   Flight time ; $t_{TOF} = 1$ sec

Detector eff. ; $\varepsilon = 0.5$ Meas. time ; $t_{meas} = 2 \times 10^7$ sec

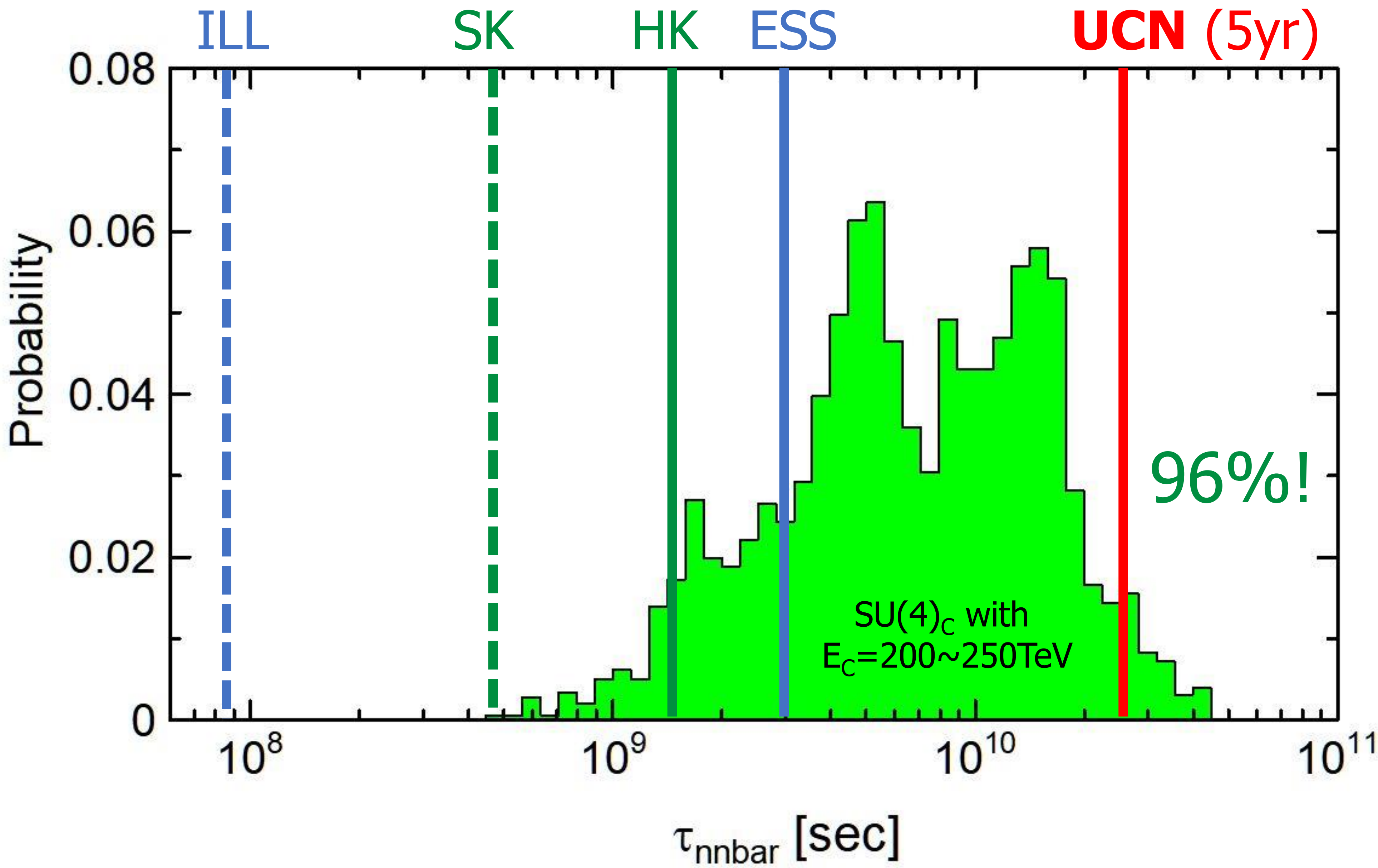
➡ $\boldsymbol{\tau_{n\bar{n}} \sim 1.0^{+0.6}_{-0.83} \times 10^{10}}$ **sec** $\left(\omega_W = (3 \pm 3) \times 10^{-9} \text{ [eV]}\right)$

Best condition; $m = -\dfrac{1}{\log a} \quad \Rightarrow \quad \tau_{n\bar{n}} = \left[\dfrac{1}{e} \cdot \left(\varepsilon \cdot \Phi_n \cdot t_{meas.}\right)^{1/2} \cdot t_{TOF}\right] \cdot \dfrac{1}{\log\left(a^{-1}\right)}$

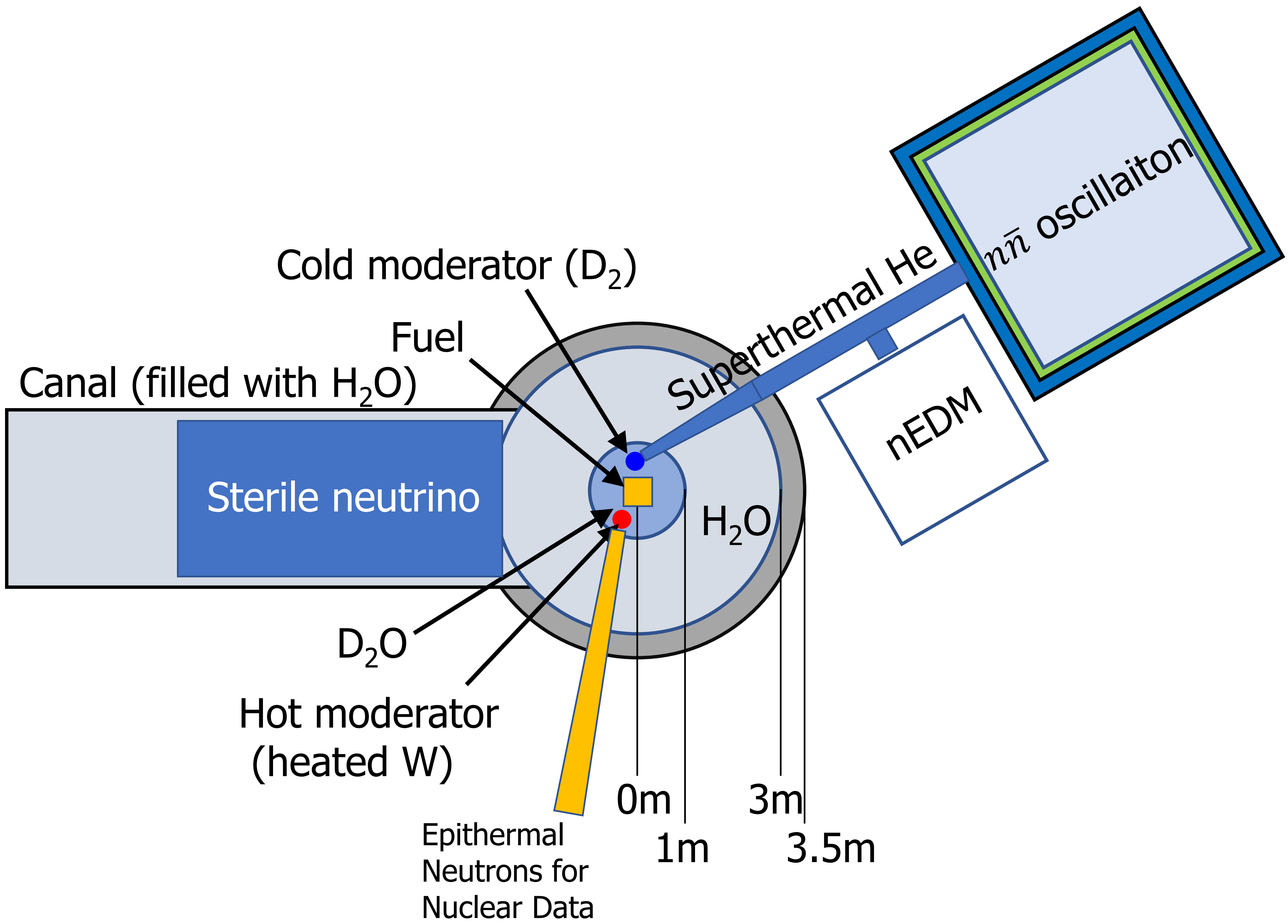
$\sim 1.16 \times 10^7$ [s]

➡ $\boldsymbol{\tau_{n\bar{n}} \sim 1.16 \times 10^{10}}$ **sec** (m=1000)

Exp. Sensitivity vs Theor. Prediction



Post-Sphaleron Baryogenesis; K.S. Babu et al., Phys. Rev. D87, 115019 (2013)


Cold moderator (D_2)
Fuel
Canal (filled with H_2O)
Sterile neutrino
Superthermal He
$n\bar{n}$ oscillaiton
nEDM
H_2O
D_2O
Hot moderator
(heated W)
Epithermal
Neutrons for
Nuclear Data
0m
1m
3m
3.5m

Summary

- Planned research reactor is expected to provide unique opportunity for physics researches thanks to custom-made structure of the core. It will become operative in ~2030.
- Flag-ship experiment; search for n-$\bar{n}$ oscillation with UCN.
- UCN with high efficiencies in production, storage, and detection has a potential to survey oscillation period of >10^{10} s.

We need…

- UCN production rate; 10^8 /s
- UCN bottle with $50m^3$ and storage time ~500s
- Low BG; ~1 event/y
- **Nuclear physics with antinucleon;**
  - Spectroscopic data of antiprotonic atoms
  - Antineutron scattering data
  - Check of annihilation cross section data …

Stay tuned!