Laboratori Nazionali di Frascati

INFN Istituto Nazionale di Fisica Nucleare

Seminar at Laboratori Nazionali di Frascati • 24 June, 2014

Search for Baryon Number Violation via $n \longrightarrow \overline{n}$ at European Spallation Source (ESS)

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Violation of Baryon Number

is one of the pillars of the modern Cosmology and Particle Physics:

- it follows from the inflation [Dolgov, Zeldovich]

- it is required for explanation of Matter-Antimatter asymmetry (Baryon Asymmetry) of the Universe BAU
  1) CP and C symmetry violation
  2) Baryon Number Violation [Sakharov, Kuzmin]
  3) Out-of-thermal equilibrium

- it is motivated by Grand Unification Theory (GUT) models [Georgi, Glashow, Pati, Salam, Mohapatra, Senjanovic, ...]

- new theoretical ideas for BNV [Babu, Berezhiani, Mohapatra, …]

Violation of Baryon Number

- Expected proton decay with $\Delta B = 1$ and conserving $(B - L)$ so far do not show up in underground experiments [IMB, Super-K, Soudan-II, Frejus…]

- Standard Model violates B, L and (B+L) at a tiny level insufficient for BAU and unobservable at the present temperatures, but SM conserves (B–L) [G. ‘t Hooft …]

  At electroweak scale fast (B+L) violation would wipe out BAU if latter was originated by $(B - L)$ conservation processes at inflation scale (sphaleron mechanism) [V. Kuzmin, A. Rubakov, M. Shaposhnikov]
  $\rightarrow (B - L)$ must be violated in nature.

B, L, and B – L

- If Majorana neutrino with $\Delta L=2$ exists thus demonstrating (B – L)V BSM then also $\Delta B=2$ should exist, e.g. like neutron $\rightarrow$ antineutron transformation.

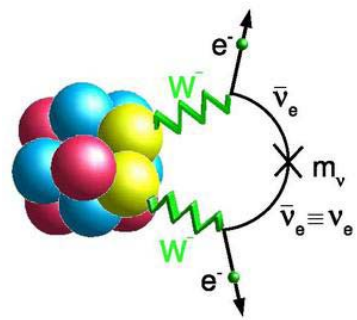
- ΔB and ΔL are connected via conservation of angular momentum. $\Delta L = \pm \Delta B \rightarrow \Delta(B-L) = 0$ or $\Delta(B-L) = 2$. Do we observe (B – L)V anyware?

- Naively (B – L) is strongly violated in regular matter: #n + #p – #e ≠ 0

  However, on the scale of the universe it might be compensated by the unknown number of relic neutrinos and antineutrinos …

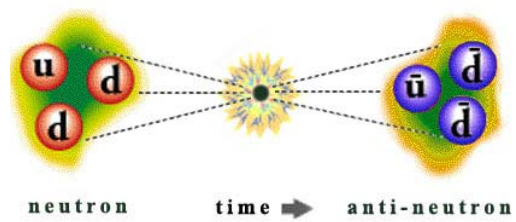
- Experimental searched for (B – L)V:

  (a) in "neutrinoless double beta decay": experiments KamLAND/ZEN, EXO, GERDA, CUORE, NEMO, Majorana …



$$\nu \longrightarrow \bar{\nu}$$

  (b) in neutron to antineutron transformation: A new experiment at European Spallation Source (ESS).



$$n \longrightarrow \bar{n}$$

Neutron ↔ Antineutron

In 1937 E. Majorana conjectured an idea that neutron and antineutron can be the states belonging to the same particle.

In the famous E. Majorana 1937 paper
"Teoria simmetrica dell'elettrone e del positrone",
Il Nuovo Cimento, v.14, 1937, pp. 171-184:

" ... this method ... allows not only to cast the electron-positron theory into a symmetric form, but also to construct an essentially new theory for particles not endowed with an electric charge (neutrons and the hypothetical neutrinos)."

(translated by L. Maiani)

$$n \neq \overline{n} \ ; \ \Delta B = 0$$

- Antineutron discovered in 1956 by B. Cork et al. @ LBL was turned out to be a particle different from neutron (e.g. with different cross sections);

- With development of particle physics the baryon number B was identified as a good global symmetry describing observed nature [n-nbar was discussed in this content by M. Gell-Mann and A. Pais, Phys. Rev. 97 (1955) 1387; by L. Okun, Weak Interaction of Elementary Particles, M. 1963, p. 200]. $\rightarrow \Delta B=0$!

- Later with understanding of quark structure of baryons and development of QCD it was commonly assumed that neutron is not a Majorana particle.

However, neutron still can be a mixture of "n" and "$\overline{n}$"

The presence of some small fraction of the Majorana component in the neutron wave function that violates baryon number can not be excluded !

Neutron and antineutron components can be mixed in the wave function of a free neutron and under certain conditions the mixing fraction can evolve with time.

This mixing fraction must be small, otherwise it would be already observed and unless there are some <u>suppression conditions</u> or mechanisms present.

Mixing of neutral components is a general feature observed in Nature:

❖ Such mixing occurs when some symmetry is broken

- Gauge symmetry $\rightarrow$ mixing of U(1) x SU(2) in SM Z^0 and γ
- Strangeness, beauty $\rightarrow$ in $K^0 \rightarrow \overline{K^0},\ B^0 \rightarrow \overline{B^0}$
- Flavor number $\rightarrow$ in neutrino flavor oscillation $\nu_\mu \rightarrow \nu_e$
- Lepton number $\rightarrow$ in Majorana neutrinos $\nu_e \rightarrow \overline{\nu}_e$
- Baryon number $\rightarrow$ $n \rightarrow \overline{n}$

Some history
of N-Nbar ideas development

- N $\leftrightarrow$ Nbar -like process was suggested as a possible mechanism for explanation of Baryon Asymmetry of Universe

  V. Kuzmin, 1970

- N $\leftrightarrow$ Nbar can work within GUT + SUSY ideas. First considered and developed within the framework of L/R symmetric Unification models by

  R. Mohapatra and R. Marshak, 1979 …

- Recent theoretical N-Nbar ideas were reviewed by R. Mohapatra in http://arXiv.org/pdf/0902.0834.pdf

Neutron-Anti-Neutron Oscillations at ESS

12-13 June 2014, CERN, Geneva, Switzerland

Neutral particle oscillations have proven to be extremely valuable probes of fundamental physics. Kaon oscillations provided us with our first insight into CP-violation, fast Bs oscillations provided the first indication that the top quark is extremely heavy, B oscillations form the most fertile ground for the continued study of CP-violation, and neutrino oscillations suggest the existence of a new, important energy scale well below the GUT scale. Neutrons oscillating into antineutrons could offer a unique probe of baryon number violation.

The construction of the European Spallation Source in Lund, with first beam expected in 2019, together with modern neutron optical techniques, offers an opportunity to conduct an experiment with at least three orders of magnitude improvement in sensitivity to the neutron oscillation probability.

At this workshop the physics case for such an experiment will be discussed, together with the main experimental challenges and possible solutions. We hope the workshop will conclude with the first steps towards the formation of a collaboration to build and perform the experiment.

Organising committee:

G. Brooijmans (Columbia University)
S. Chattopadhyay (Cockroft Institute)
R. Hall-Wilton (European Spallation Source)
Y. Kamyshkov (University of Tennessee)
E. Klinkby (Technical University of Denmark and European Spallation Source)
M. Lindroos (European Spallation Source and Lund University)
L. Mapelli (CERN)
M. Mezzetto (INFN Padova)
H. M. Shimizu (Nagoya University)
W. M. Snow (Indiana University)
T. Soldner (Institut Laue Langevin)
C. Theroine (European Spallation Source)

EUROPEAN SPALLATION SOURCE

CERN

Most recent: workshop organized by the European Spallation Source and CERN on June 12-13, 2014

https://indico.esss.lu.se/indico/conferenceDisplay.py?ovw=True&confId=171

with several theoretical talks by

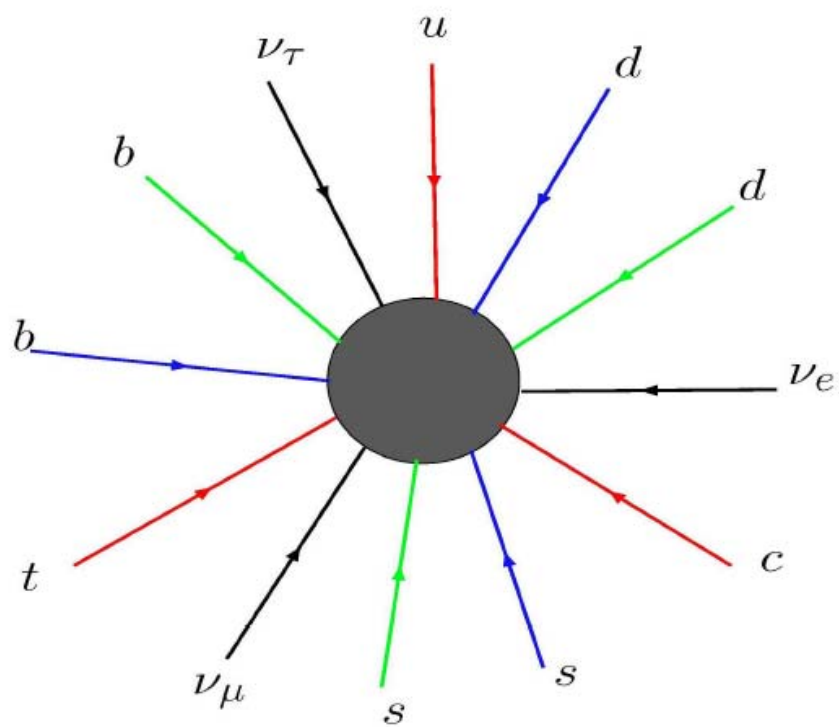
R. Mohapatra,
R. Shrock,
Z. Berezhiani,
A. De Gouvea,
J. Berger,
S. Gardner

and discussions of practical experimental aspects of a new N-Nbar search experiment at ESS

Standard model sphalerons and NNbar

- SM contains the Sphaleron operator:('t Hooft)

  QQQQQQ QQQL LL (conserves B-L)



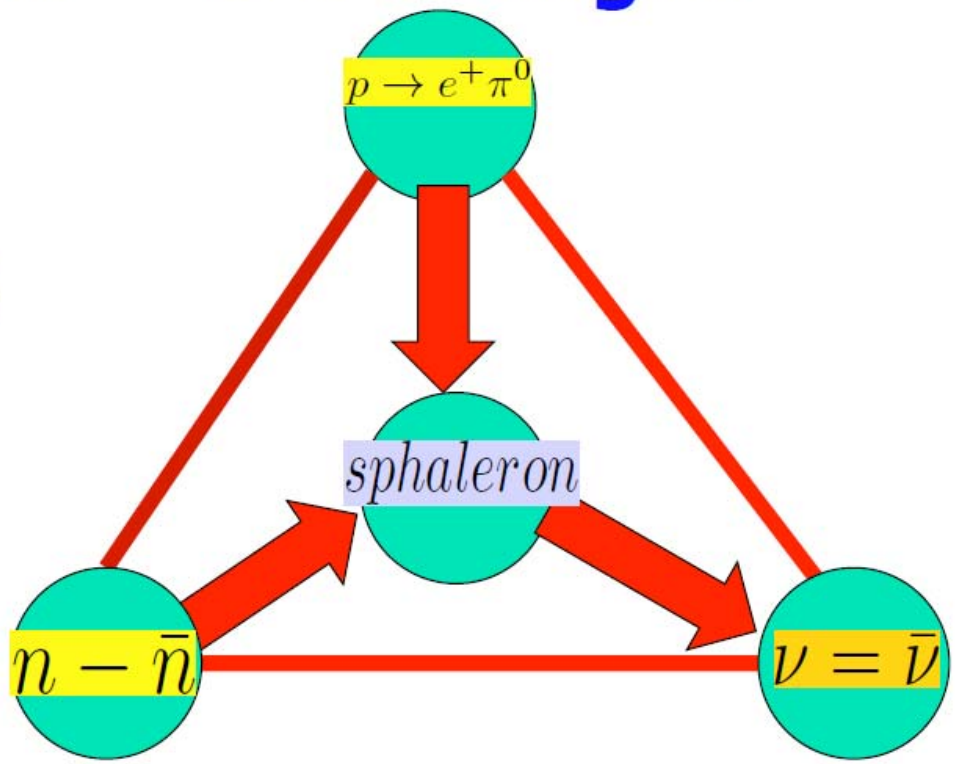
R. Mohapatra

From NNbar to Majorana neutrino via sphalerons

- Sphaleron Op. rewrite

$$\underbrace{QQQQQQ}_{n-\bar{n}}\ \underbrace{QQQL}_{p\to e^+\pi^0}\ \underbrace{LL}_{m_\nu}$$

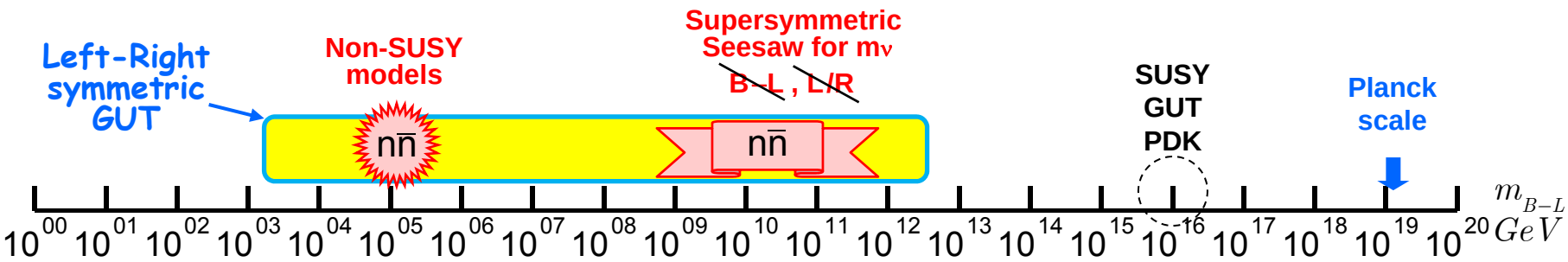
B-L Triangle:

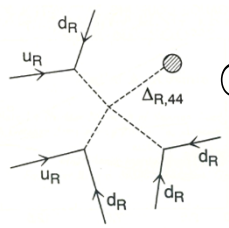


Observe p-decay and nn-bar→Neutrino Majorana

R. Mohapatra 2014

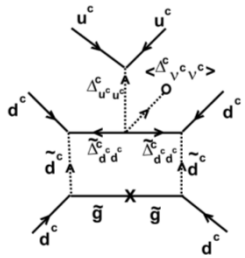
$\Lambda - scales \;\; of \;\; n \rightarrow \bar{n}$ and $(B-L)V$





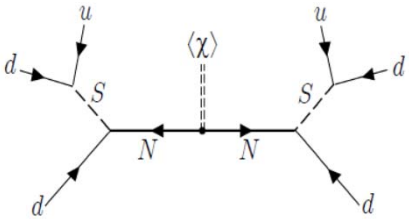
$\propto m_{B-L}^{-5}$

Mohapatra & Marshak (1980)



$\propto m_{B-L}^{-2} \cdot m_{WK}^{-3}$

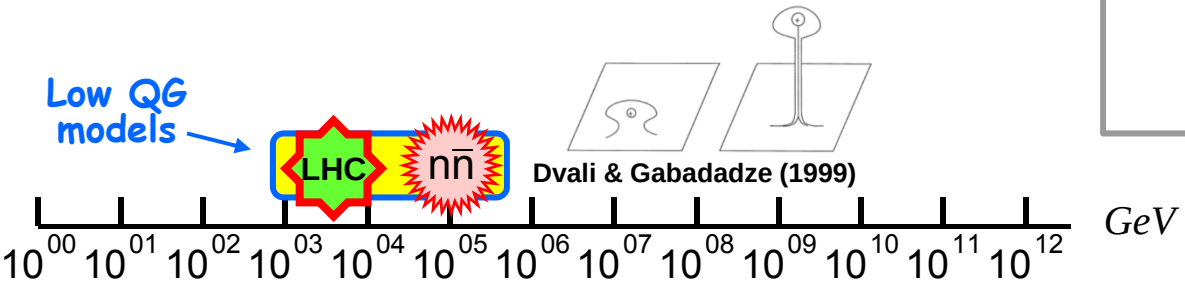
Dutta-Mimura-Mohapatra (2005)



Berezhiani (2006-2013)

Baryogenesis at TeV scale
or Post Sphaleron Baryogenesis
Babu et al., PRD 87, 115019 (2013),
connected to LHC observables

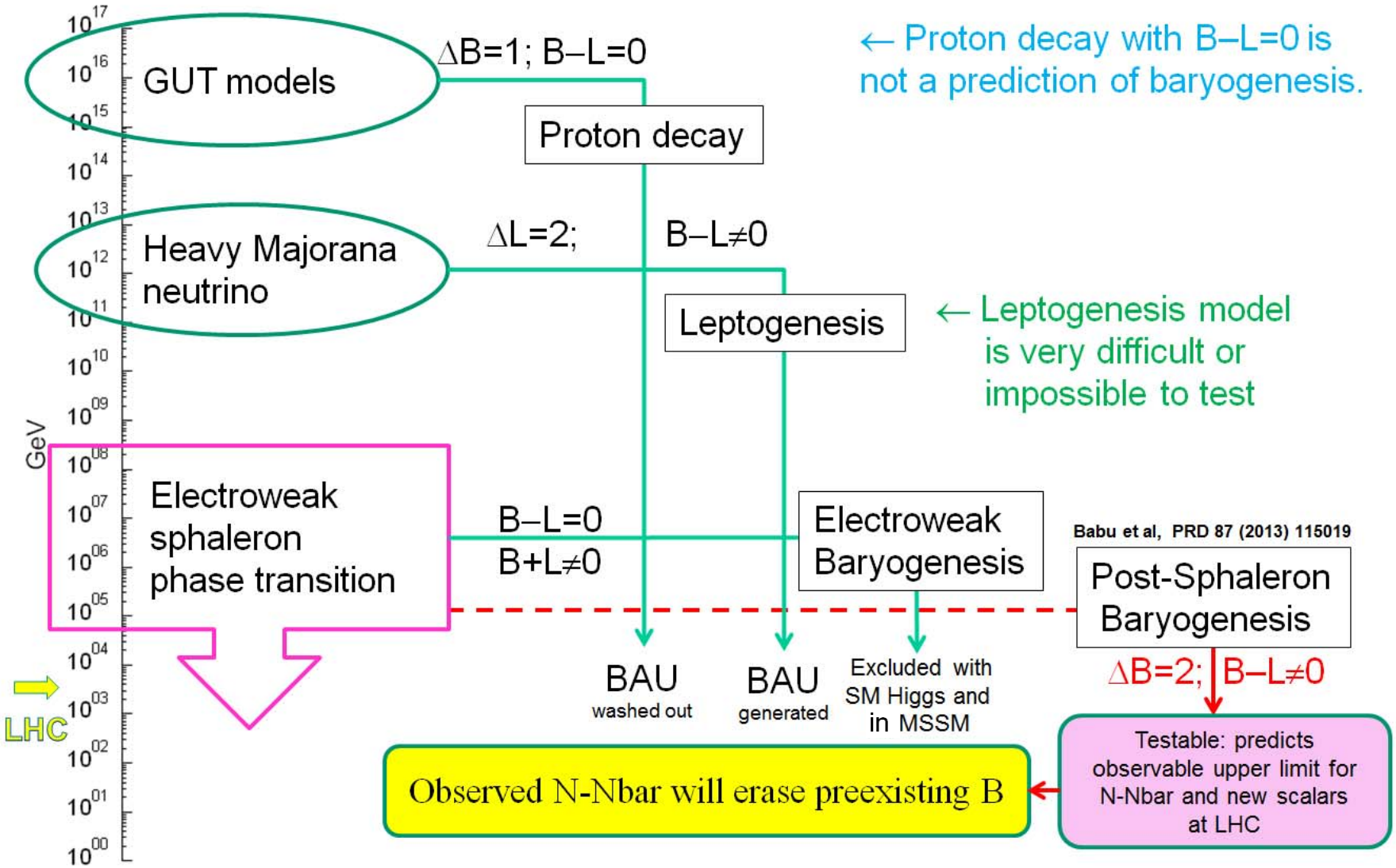
- Theories predict observable N-Nbar!
- Large increase of sensitivity more than a factor of ×1,000 is experimentally possible



Dvali & Gabadadze (1999)

Shrock & Nussinov (2002)
Dolgov (2011)

Baryogenesis Models



Positive $n\bar{n}$ result will probe different energy scales.
Null $n\bar{n}$ result can rule out PSB, a testable model of baryogenesis.

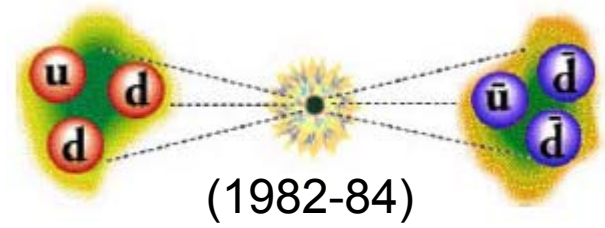
n→nbar transition probability

$$\Psi = \begin{pmatrix} n \\ \overline{n} \end{pmatrix} \quad \text{mixed n-nbar QM state}$$

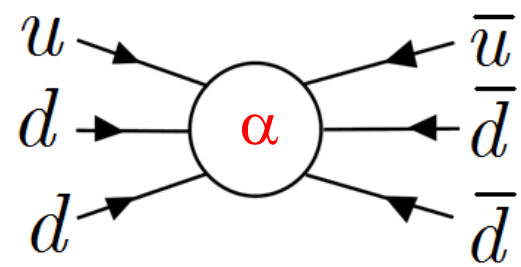
$$\mathrm{H} = \begin{pmatrix} E_n & \alpha \\ \alpha & E_{\overline{n}} \end{pmatrix}$$

$$E_n = m_n + U_n \quad ; \quad E_{\overline{n}} = m_{\overline{n}} + U_{\overline{n}}$$

$$U_{n,\overline{n}} = U_0 \pm V \quad \leftarrow \quad \text{part different for } n \text{ and } \overline{n}$$



(1982-84)
Rao and Shrock



α-mixing amplitude

All beyond SM physics is here

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

where V is a potential symmetrically different for n and $\bar{n}$
(e.g. due to non-compensated Earth mag. field, or nuclear potential);
t is observation time in an experiment.

In ideal situation of no suppression i.e.
"vacuum oscillations" : $V = 0$
and experimentally t ~ 0.1 s to 10 s

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

$\tau_{n\bar{n}} = \dfrac{\hbar}{\alpha}$ is characteristic "oscillation" time $[\alpha < 2\cdot 10^{-24} eV$, as presently known]

Predictions of theoretical models: observable effect around $\alpha \sim 10^{-25} - 10^{-26} eV$

$$\boxed{\text{Sensitivity (or figure of merit) is } \rightarrow \; N_n \times \bar{t}^2}$$

Previous State-of-the-Art
NNbar Search

Z. Phys. C 63, 409–416 (1994)

A new experimental limit on neutron-antineutron oscillations

M. Baldo-Ceolin[3], P. Benetti[4], T. Bitter[1], F. Bobisut[3], E. Calligarich[4], R. Dolfini[4], D. Dubbers[1], P. El-Muzeini[1], M. Genoni[4], D. Gibin[3], A. Gigli Berzolari[4], K. Gobrecht[2], A. Guglielmi[2], J. Last[2], M. Laveder[3], W. Lippert[1], F. Mattioli[3], F. Mauri[4], M. Mezzetto[3], C. Montanari[4], A. Piazzoli[4], G. Puglierin[3], A. Rappoldi[4], G.L. Raselli[4], D. Scannicchio[4], A. Sconza[3], M. Vascon[3], L. Visentin[3]

[1] Physikalisches Institut, University of Heidelberg, D-69120 Heidelberg, Germany
[2] Institut Max von Laue-Paul Langevin (ILL), Grenoble, France
[3] Dipartimento di Fisica "G. Galilei", University of Padova and I.N.F.N. Sezione di Padova, Padova, Italy
[4] Dipartimento di Fisica Nucleare e Teorica, University of Pavia and I.N.F.N. Sezione di Pavia, Pavia, Italy

Received: 28 February 1994

No ~ GeV background! No candidates observed !

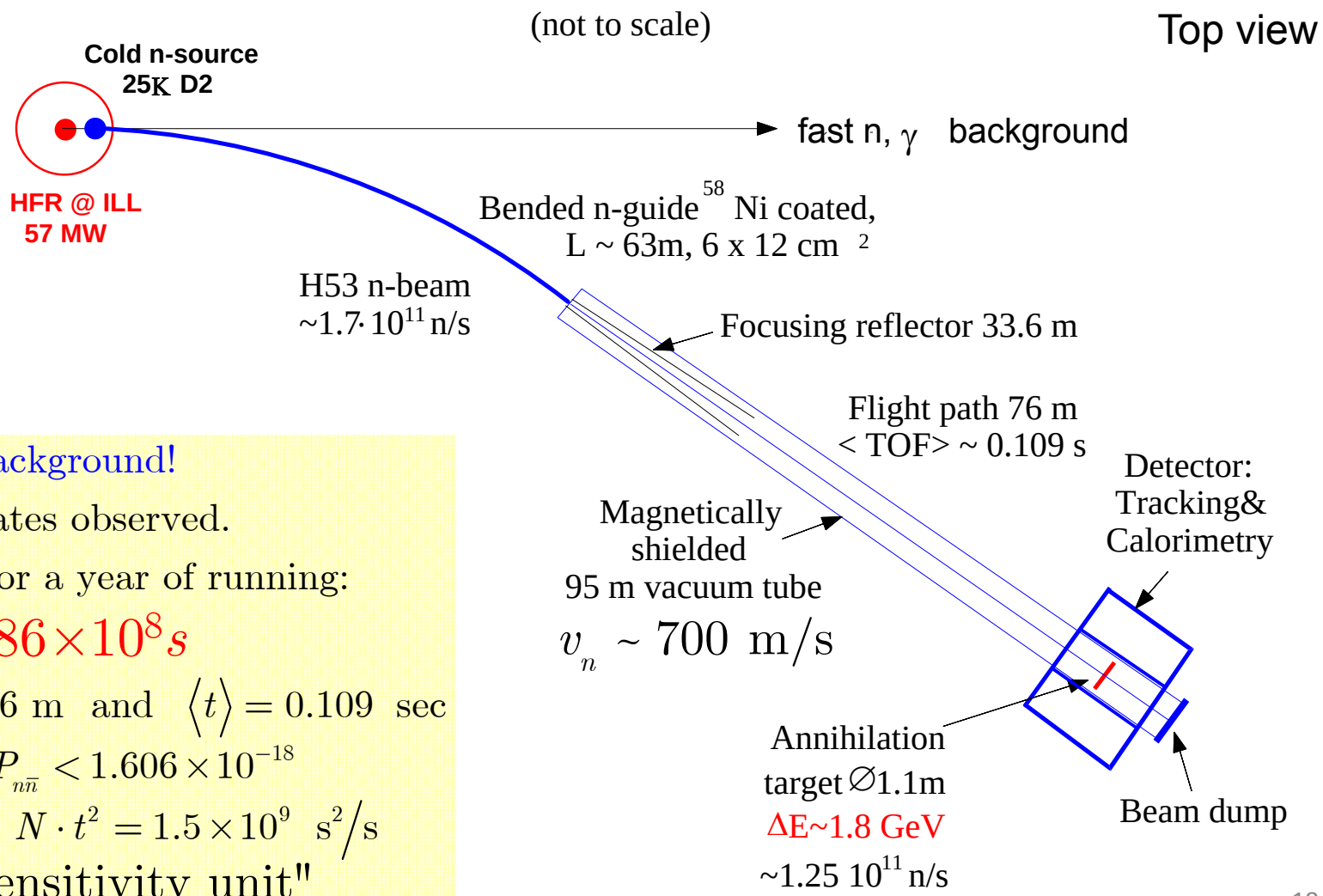
Measured limit for one year of running: $\tau_{n\bar{n}} > 0.86 \times 10^8 s$

Sensitivity: $N \cdot t^2 = 1.5 \times 10^9 \ \ \mathrm{s}^2/\mathrm{s} \doteq$ "ILL sensitivity unit"

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



No GeV background!

No candidates observed.

Limit set for a year of running:

$$\tau_{n\bar{n}} > 0.86 \times 10^8 s$$

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

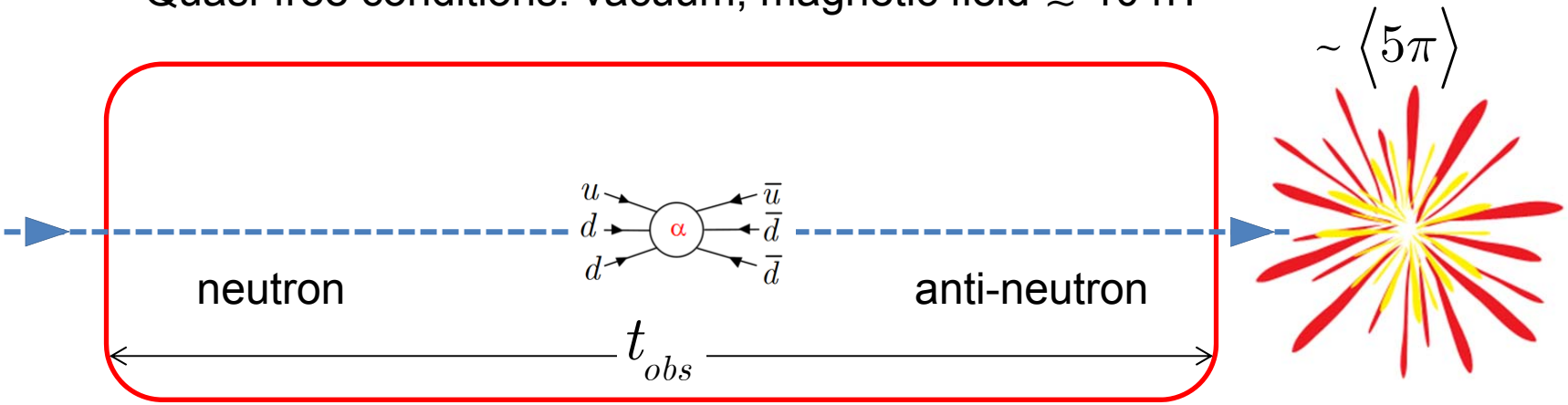
measured $P_{n\bar{n}} < 1.606 \times 10^{-18}$

sensitivity: $N \cdot t^2 = 1.5 \times 10^9 \ \mathrm{s}^2/\mathrm{s}$

$\doteq$ "ILL sensitivity unit"

Free neutron transformation

Quasi-free conditions: vacuum, magnetic field $\lesssim$ 10 nT



Observation
of annihilation

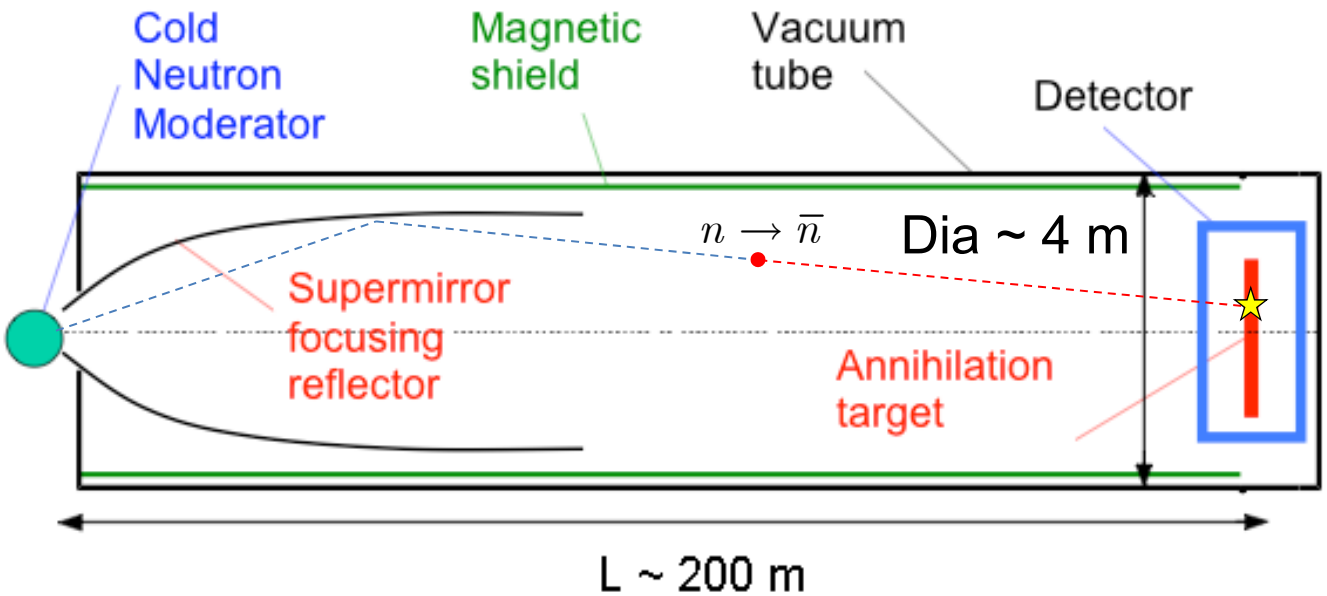
$$P_{n\to\bar{n}} = \left(\frac{t_{obs}}{\tau_{n\bar{n}}}\right)^2$$

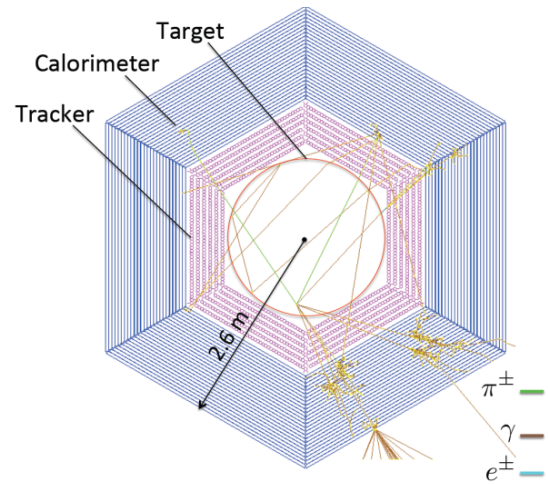
$$\text{Present } \tau > 8.6\times10^{7}\ \text{s (ILL limit)} \ \rightarrow\ \tau > 4\times10^{9}\ \text{s (@ ESS)}$$

$$\text{or Sensitivity increases by factor of } > 1{,}000$$

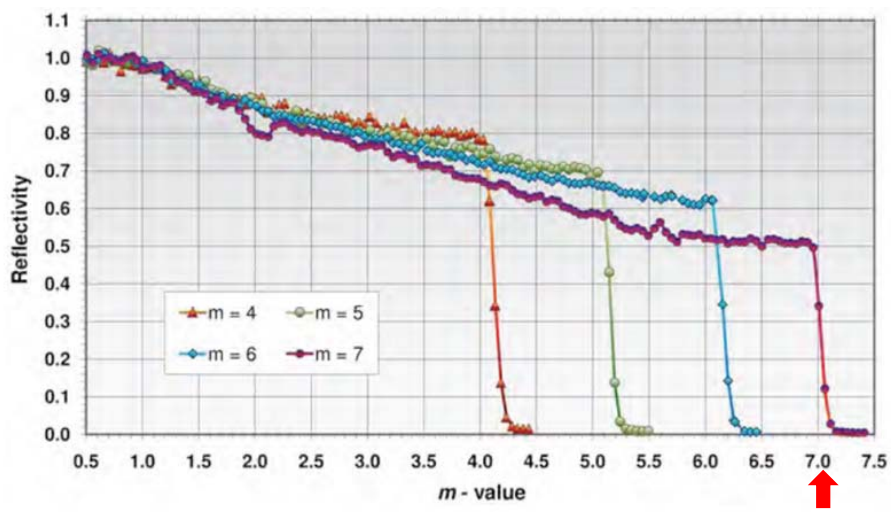
! Small tuning of magnetic field can suppress or enhance the n-nbar transformation

ESS experiment configuration





Super-mirrors: commercial products of Swiss Neutronics



$v_\perp \lesssim 50$ m/s

$$v_\perp > 7 \cdot m \ [\mathrm{m/s}]$$

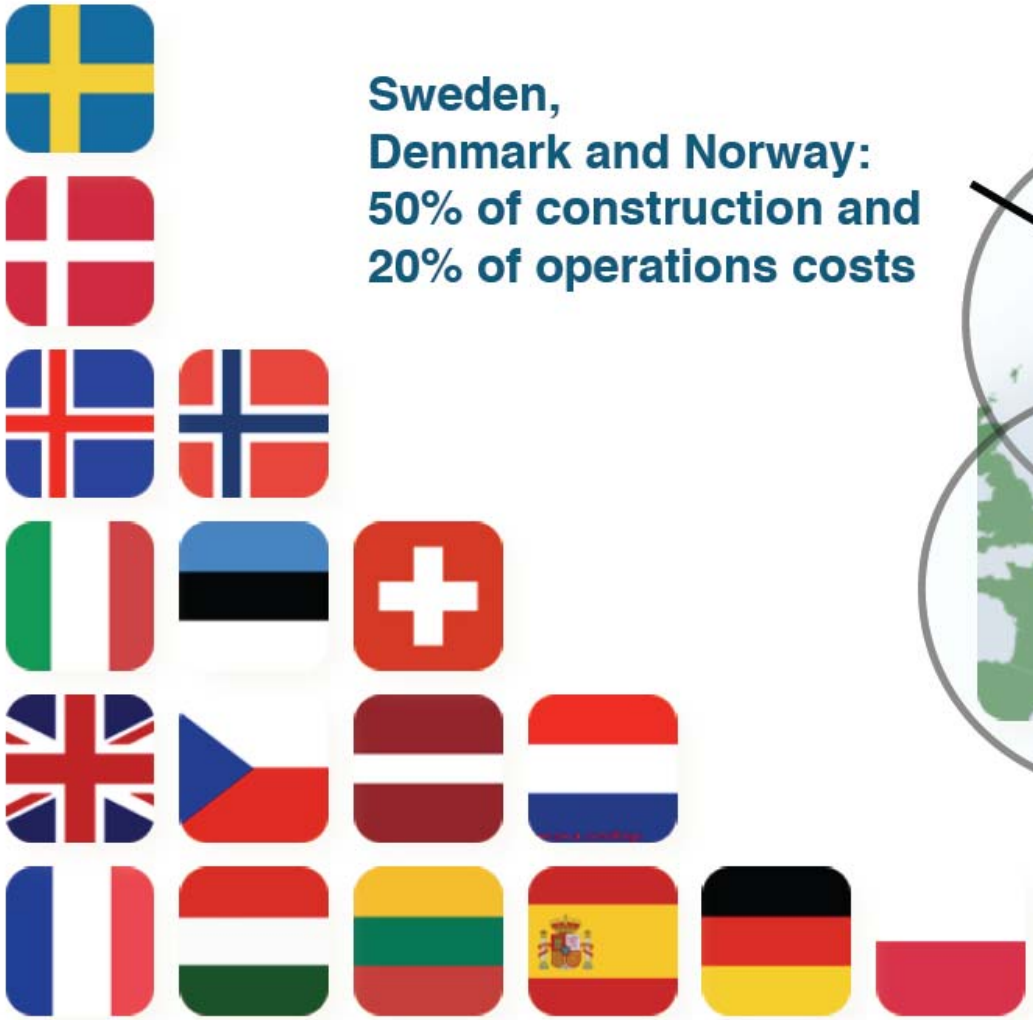
m is up to 7

To be build in this decade

ESS

Richard Hall-Wilton
December 2013

An International Collaboration



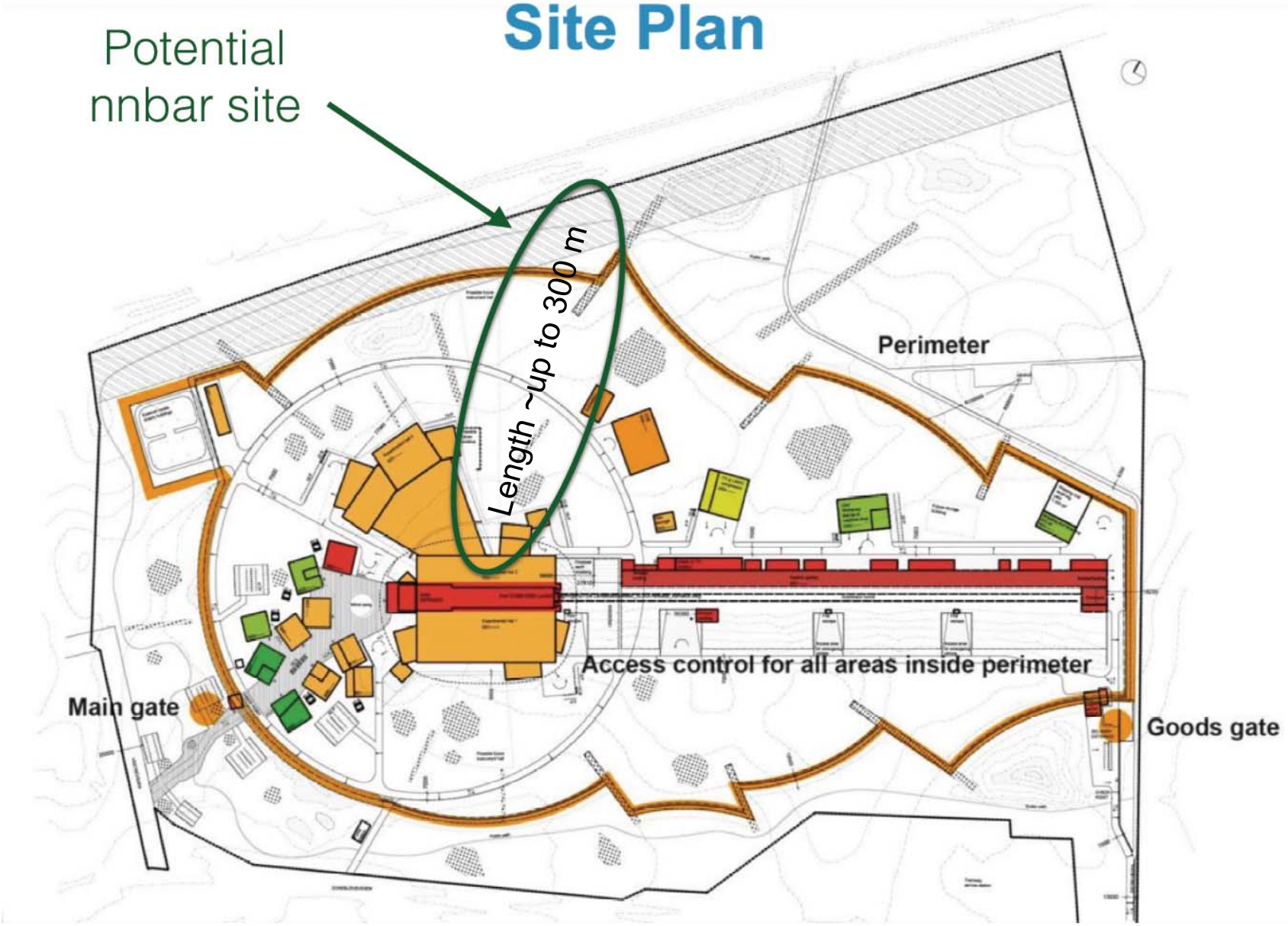
Sweden,
Denmark and Norway:
50% of construction and
20% of operations costs

European partners
pay the rest

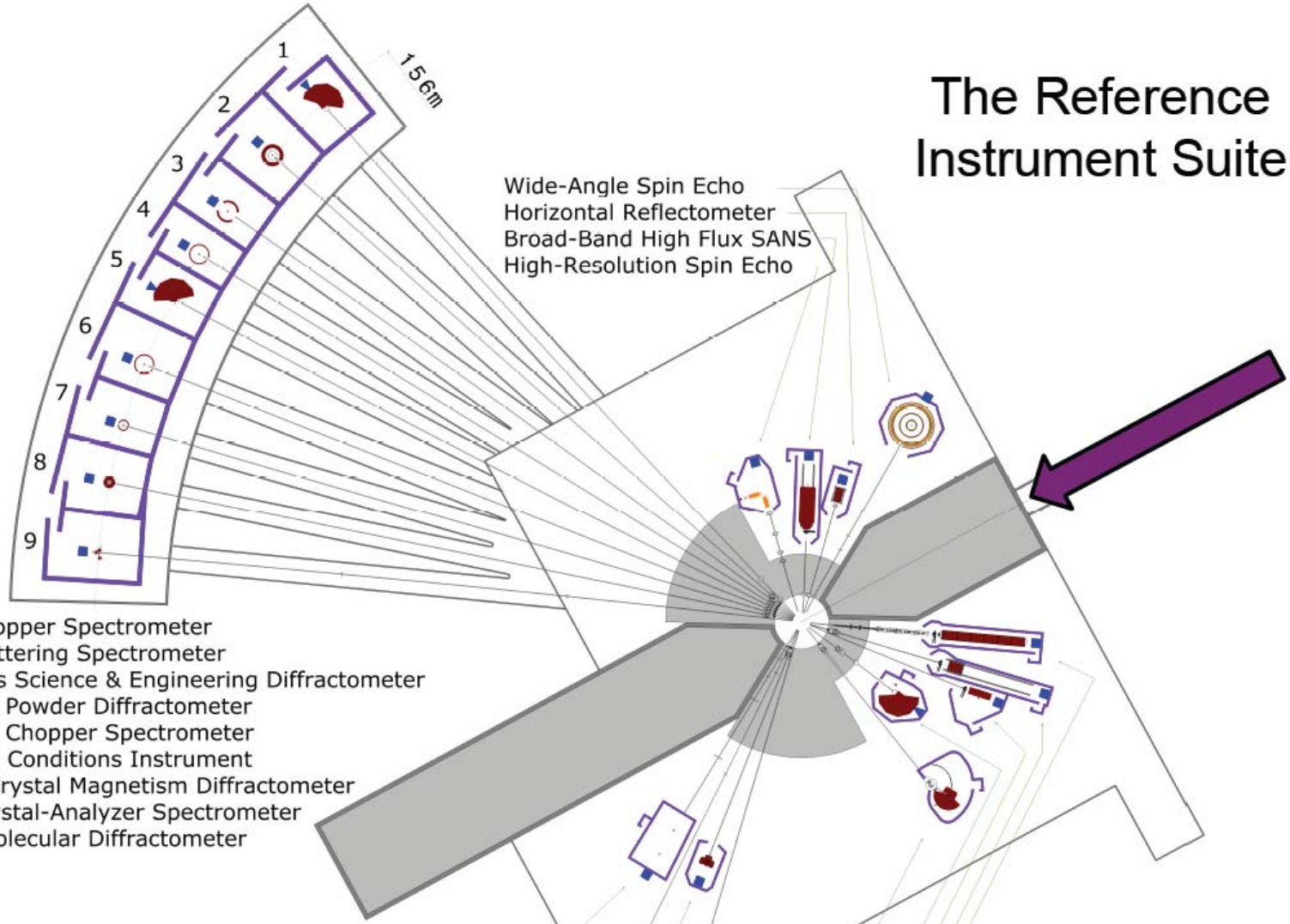
The ESS Headlines

- A neutron source for the study of materials
- ESS scope is defined in Technical Design Report (2013)
  - 5 MW accelerator capability
  - Superconducting Linac: 2.3 GeV
  - Rotating solid W target
  - Time-structure: 14Hz, 2.86ms pulse length
  - First neutrons in 2019
  - Construction cost of 1843 M€
  - 22 public instruments
  - Annual operating cost of 140 M€

Site Plan


Potential
nnbar site
Length ~up to 300 m
Perimeter
Access control for all areas inside perimeter
Main gate
Goods gate

The Reference Instrument Suite



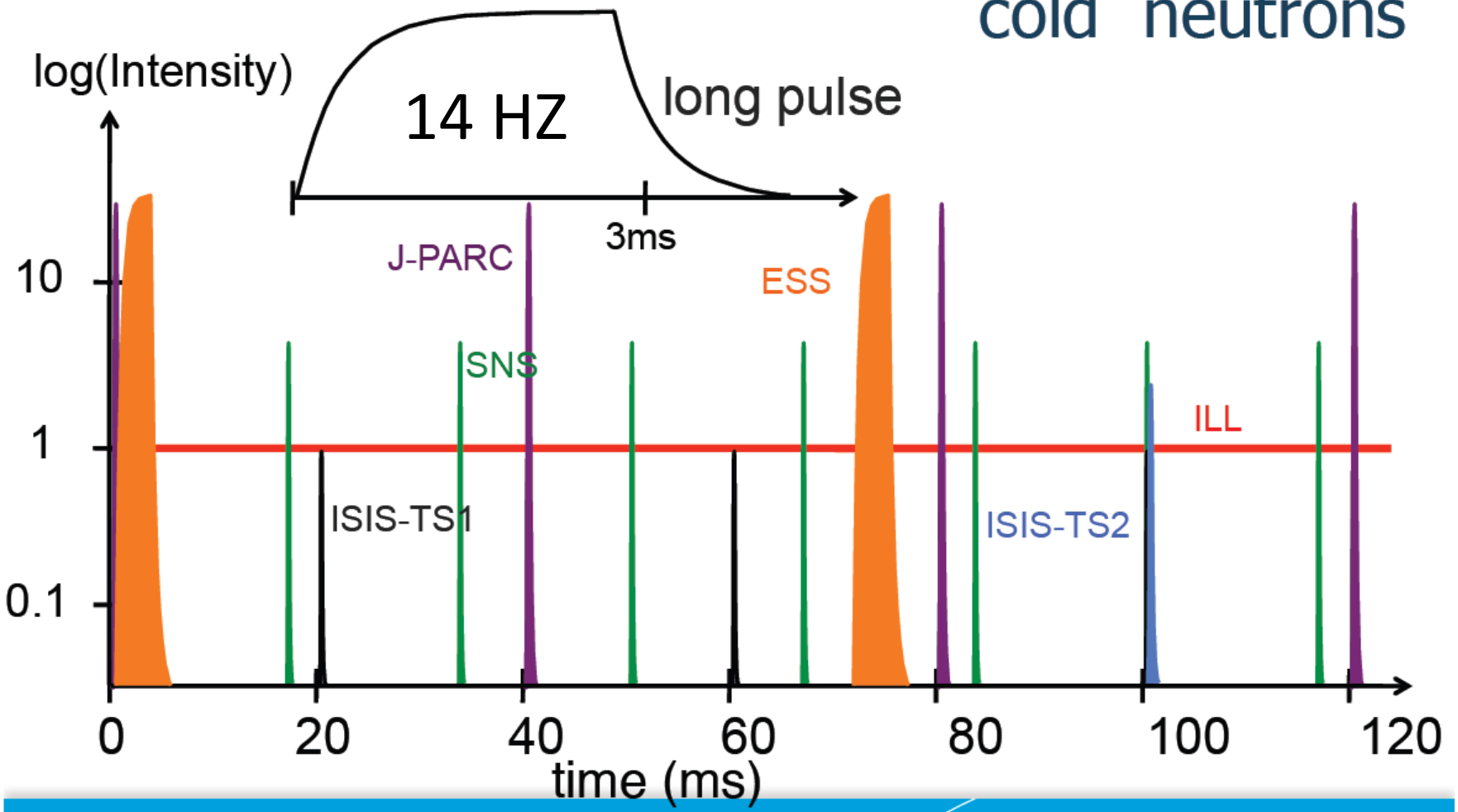
1. Cold Chopper Spectrometer
2. Backscattering Spectrometer
3. Materials Science & Engineering Diffractometer
4. Thermal Powder Diffractometer
5. Thermal Chopper Spectrometer
6. Extreme Conditions Instrument
7. Single-Crystal Magnetism Diffractometer
8. Cold Crystal-Analyzer Spectrometer
9. Macromolecular Diffractometer

Multi-Purpose Imaging
Bi-Spectral Powder Diffractometer
Vibrational Spectroscopy
Fundamental & Particle Physics

General-Purpose Polarized SANS
Surface Scattering
Vertical Reflectometer
Bi-Spectral Chopper Spectrometer
Pulsed Monochromatic Powder Diffractometer

Ken Andersen, Dec 2013

Pulsed-source time structures cold neutrons



ESS TDR Chapter 3, page 177, April 2013

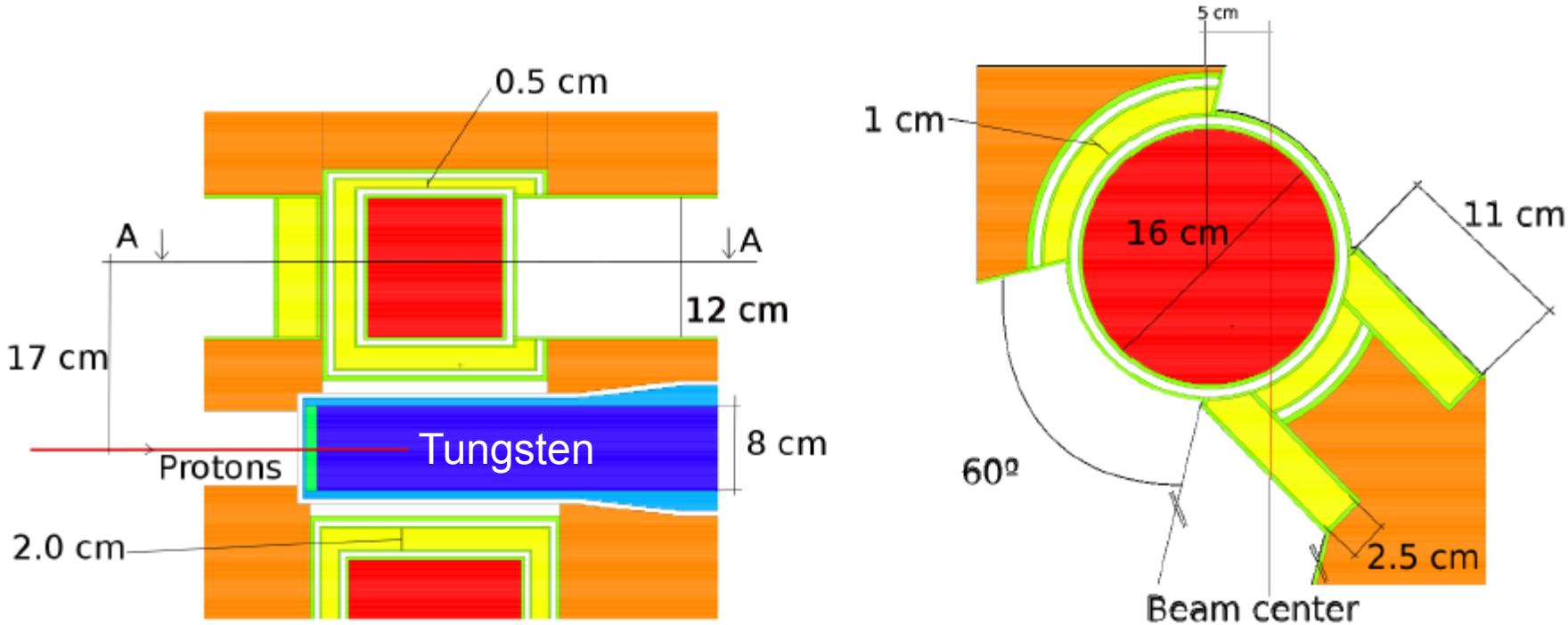
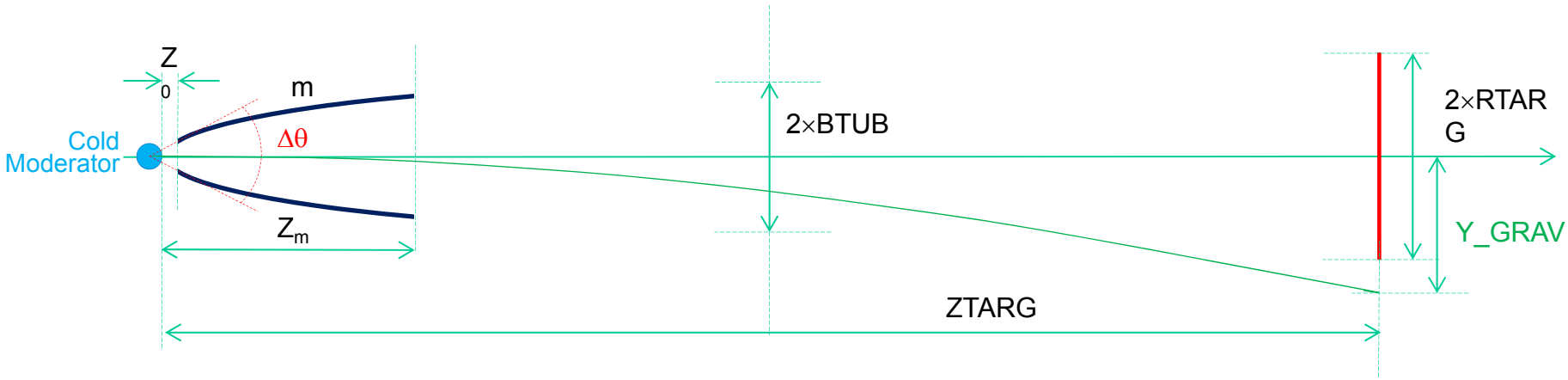


Figure 3.15: MCNPX model of the target and surrounding moderator and reflector. The cold moderator is shown in red, the thermal moderator for bispectral beam extraction and the premoderator are in yellow, and the beryllium reflector is in orange. Left: Longitudinal view. Right: Top moderator showing the thermal extensions for bispectral extraction.

Sensitivity Simulation Parameters



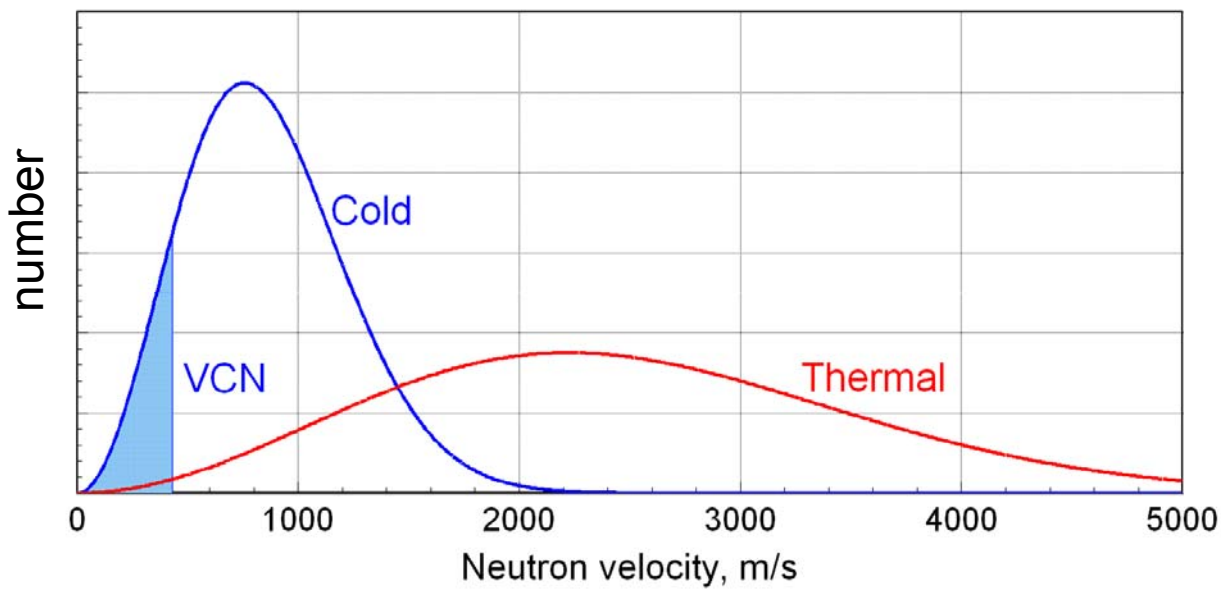
1. ESS TDR baseline cold moderator geometry and spectrum
2. Z_0 – distance of reflector start (10 m)
3. Z_m – distance of reflector end (50 m)
4. m – supermirror reflector parameter (m=6)
5. ZTARG – distance moderator-detector = 2×large demi-axis (200 m)
6. RTARG – radius of the annihilation detector (1 m)
7. BTUB – small demi-axis (2 m)
8. $\Delta\theta$ – angular occupancy (10 degree)

Y_GRAV – neutron gravity fall (detector vertical offset) (≈ –0.5 m)

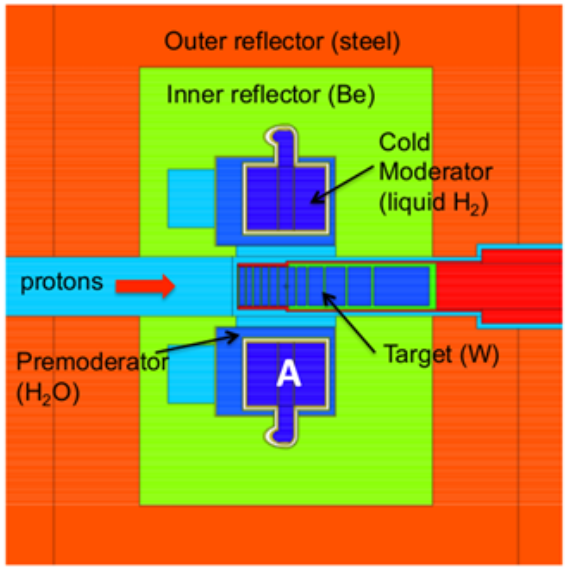
Sensitivity: $N \cdot \overline{t}^2$

$\Rightarrow$ many neutrons (large N) and very slow(large $\overline{t}$)

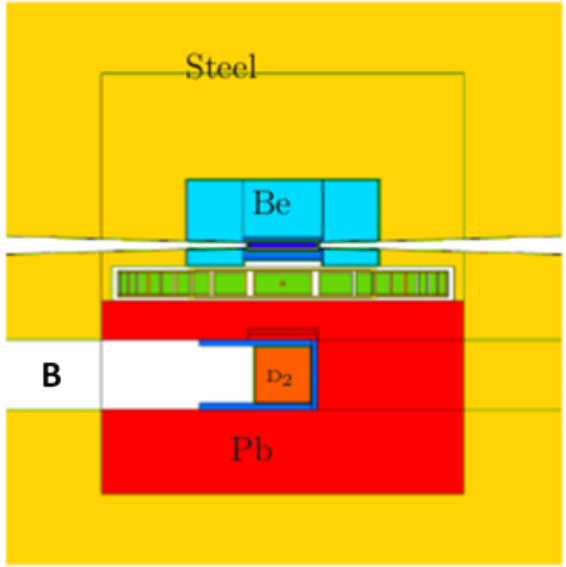
Neutrons	E kin	T,K	Velocity	Wavelength
Fast	~ 1 MeV	~ 10^{10}	~ 0.046 *c*	~ 0.0003 Å
Thermal	~ 25 meV	~ 300	~ 2.2 km/s	~ 1.8 Å
Cold	~ 3 meV	~ 35	~ 760 m/s	~ 5 Å
Very Cold (VCN)	$\lesssim$ 1 meV	~ 10	$\lesssim$ 430 m/s	$\gtrsim$ 9 Å
Ultra Cold (UCN)	~ 250 neV	~ 0.003	$\lesssim$ 8 m/s	$\gtrsim$ 600 Å



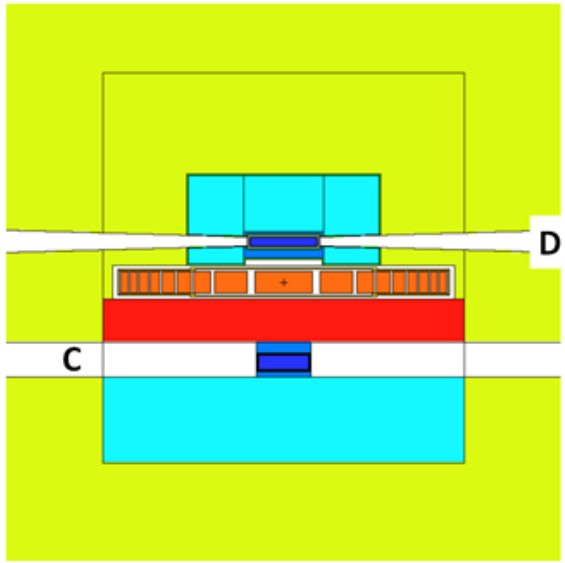
Sensitivity of Several Cold Source Configurations



April 2013 TDR Moderator Concept



1b Liquid Deuterium Lower Moderator with large area



Flat Upper Moderator and Tube Lower Moderator

A. 525 × ILL

B. 730 × ILL

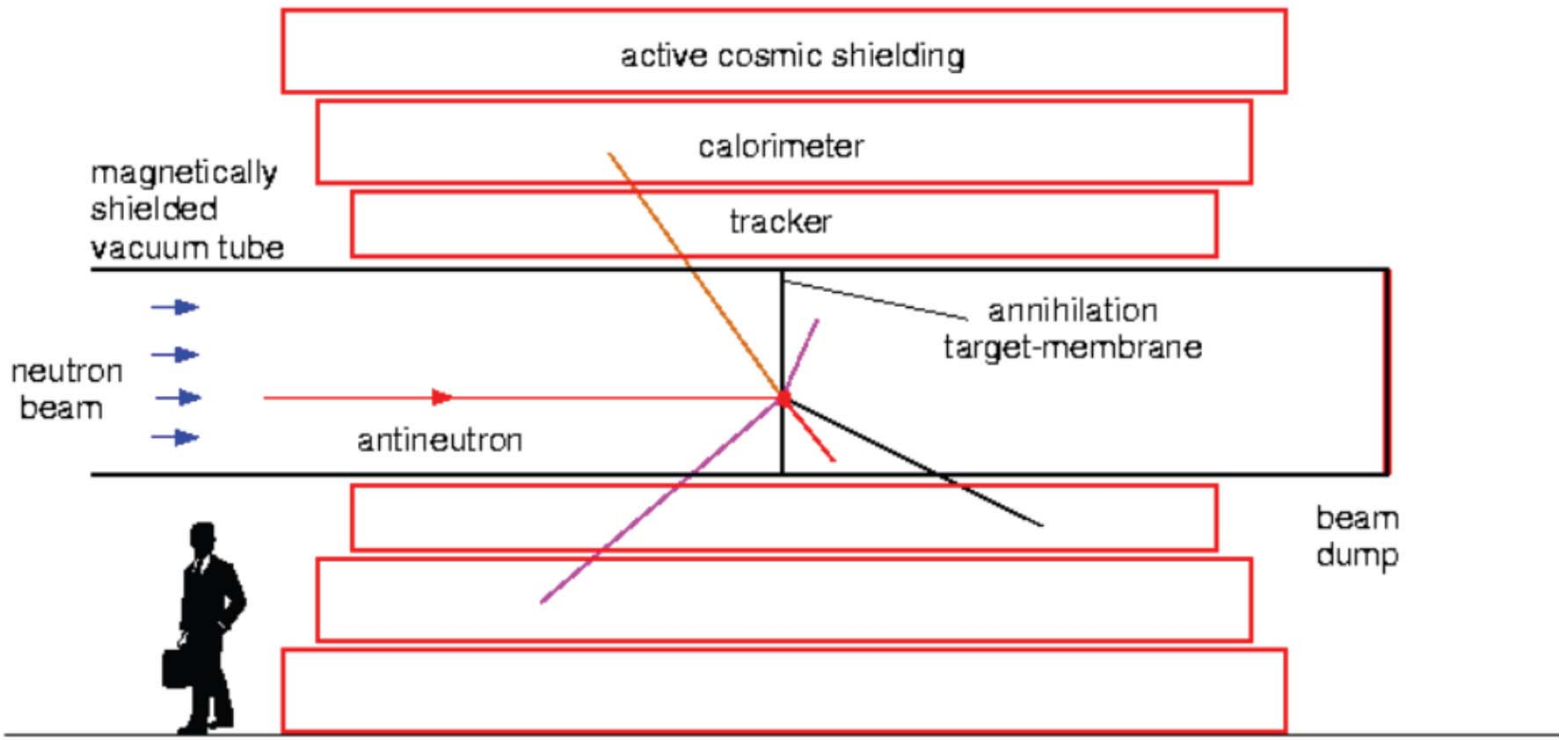
C. 156 × ILL
D. 526 × ILL

Total sensitivity is a sensitivity in ILL units × number of running years.
The goal of new N-Nbar experiment is to reach sensitivity > 1,000 × ILL

Cold source design and optimization is presently pursued by ESS

Conceptual Antineutron Annihilation Detector for ESS NNbar Experiment to be built by New Collaboration

×100 times higher flux of neutrons than at ILL



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

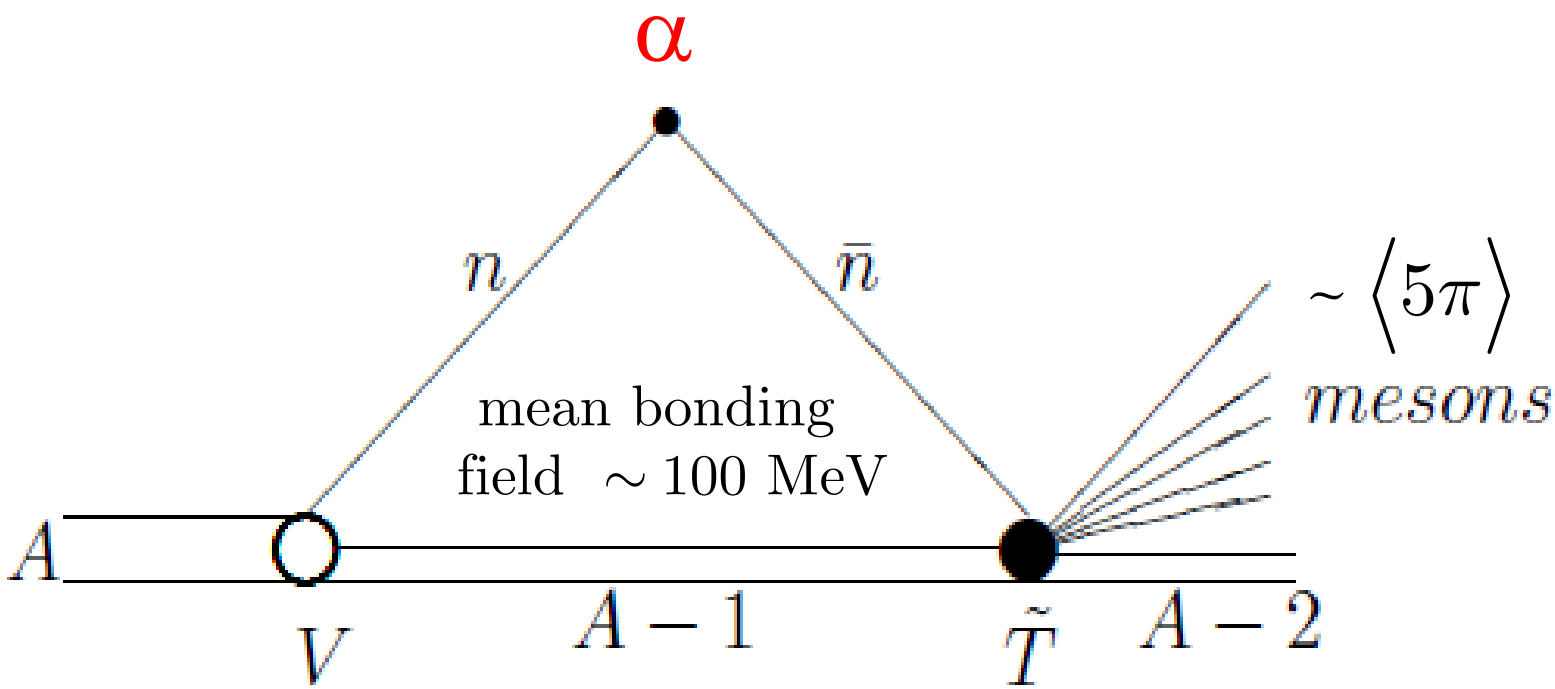
Annihilation target: ~100μ thick Carbon film

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

vertex precisely defined. No background was observed at ILL

N-Nbar inside nuclei

is suppressed by nuclear potential



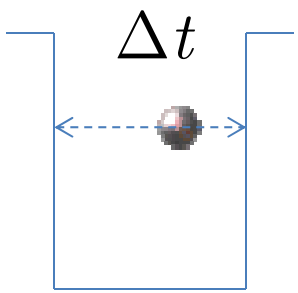
$$P_{n\to\bar{n}} \simeq \frac{1}{2}\frac{\alpha^2}{V^2}$$

n→nbar for bound neutrons is heavily suppressed by dimensional factor

Neutrons inside nuclei are "free" for the time: $\Delta t \sim \dfrac{\hbar}{U_{nuc}} \sim \dfrac{\hbar}{30MeV}$

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

and "experiencing free condition" $N = \dfrac{1}{\Delta t}$ times per second.



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

Intranuclear decay lifetime (exponential): $\boxed{\tau_{\mathrm{A}} = \dfrac{\tau_{n\bar{n}}^2}{\Delta t} = R \times \tau_{n\bar{n}}^2}$

where R needs to be calculated by nuclear theory

Theoretical calculations of nuclear suppression factor *R* $\tau_{nucl} = R \times \tau^2_{n \to \bar{n}}$

Calculated for ^{16}O,^{2}D,^{56}Fe, ^{40}Ar (?) by

- W. Alberico et al (1985-1998)
- C. Dover, A. Gal, J. Richard (1989 -1996)
- B. Kopeliovich and J. Hufner (1998)

} All agreed within factor of 2

- E. Friedman and A. Gal (2008): for O changed by factor of 2; accu $\pm$ 15%
- V. Kopeliovich, I. Potashnikova (2011) - recent for D_2 (relevant for SNO)
- B. Kopeliovich, A. Vainshtein (2012 -13) - reconfirmed agreement (not yet published)

$R(\text{Oxygen}) \approx 5 \times 10^{22}\,\text{s}^{-1}$ ($\pm$ 15%) (Friedman and Gal, 2008)

No recent updates for Ar (future LBNF)

Future lattice calculations arguably can provide an improvement in value and in accuracy of the suppression factor R

arXiv:1109.4227v1 [hep-ex] 20 Sep 2011

The Search for $n-\bar{n}$ Oscillation in Super-Kamiokande I

K. Abe,[1] Y. Hayato,[1] T. Iida,[1] K. Ishihara,[1] J. Kameda,[1] Y. Koshio,[1] A. Minamino,[1] C. Mitsuda,[1] M. Miura,[1] S. Moriyama,[1] M. Nakahata,[1] Y. Obayashi,[1] H. Ogawa,[1] H. Sekiya,[1] M. Shiozawa,[1] Y. Suzuki,[1] A. Takeda,[1] Y. Takeuchi,[1] K. Ueshima,[1] H. Watanabe,[1] I. Higuchi,[2] C. Ishihara,[2] M. Ishitsuka,[2] T. Kajita,[2] K. Kaneyuki,[2,*] G. Mitsuka,[2] S. Nakayama,[2] H. Nishino,[2] K. Okumura,[2] C. Saji,[2] Y. Takenaga,[2] S. Clark,[3] S. Desai,[3] F. Dufour,[3] A. Herfurth,[3] E. Kearns,[3] S. Likhoded,[3] M. Litos,[3] J.L. Raaf,[3] J.L. Stone,[3] L.R. Sulak,[3] W. Wang,[3,†] M. Goldhaber,[4,*] D. Casper,[5] J.P. Cravens,[5] J. Dunmore,[5] J. Griskevich,[5] W.R. Kropp,[5] D.W. Liu,[5] S. Mine,[5] C. Regis,[5] M.B. Smy,[5] H.W. Sobel,[5] M.R. Vagins,[5] K.S. Ganezer,[6] B. Hartfiel,[6] J. Hill,[6] W.E. Keig,[6] J.S. Jang,[7] I.S. Jeoung,[7] J.Y. Kim,[7] I.T. Lim,[7] K. Scholberg,[8] N. Tanimoto,[8] C.W. Walter,[8] R. Wendell,[8] R.W. Ellsworth,[9] S. Tasaka,[10] G. Guillian,[11] J.G. Learned,[11] S. Matsuno,[11] M.D.Messier,[12] A.K. Ichikawa,[13] T. Ishida,[13] T. Ishii,[13] T. Iwashita,[13] T. Kobayashi,[13] T. Nakadaira,[13] K. Nakamura,[13] K. Nishikawa,[13] K. Nitta,[13] Y. Oyama,[13] A.T. Suzuki,[14] M. Hasegawa,[15] H. Maesaka,[15] T. Nakaya,[15] T. Sasaki,[15] H. Sato,[15] H. Tanaka,[15] S. Yamamoto,[15] M. Yokoyama,[15] T.J. Haines,[16] S. Dazeley,[17] S. Hatakeyama,[17] R. Svoboda,[17] G.W. Sullivan,[18] R. Gran,[19] A. Habig,[19] Y. Fukuda,[20] Y. Itow,[21] T. Koike,[21] C.K. Jung,[22] T. Kato,[22] K. Kobayashi,[22] C. McGrew,[22] A. Sarrat,[22] R. Terri,[22] C. Yanagisawa,[22] N. Tamura,[23] M. Ikeda,[24] M. Sakuda,[24] Y. Kuno,[25] M. Yoshida,[25] S.B. Kim,[26] B.S. Yang,[26] T. Ishizuka,[27] H. Okazawa,[28] Y. Choi,[29] H.K. Seo,[29] Y. Gando,[30] T. Hasegawa,[30] K. Inoue,[30] H. Ishii,[31] K. Nishijima,[31] H. Ishino,[32] Y. Watanabe,[32] M. Koshiba,[33] Y. Totsuka,[33,*] S. Chen,[34] Z. Deng,[34] Y. Liu,[34] D. Kielczewska,[35] H.G.Berns,[36] K.K. Shiraishi,[36] E. Thrane,[36,‡] K. Washburn,[36] and R.J. Wilkes[36]

(The Super-Kamiokande Collaboration)

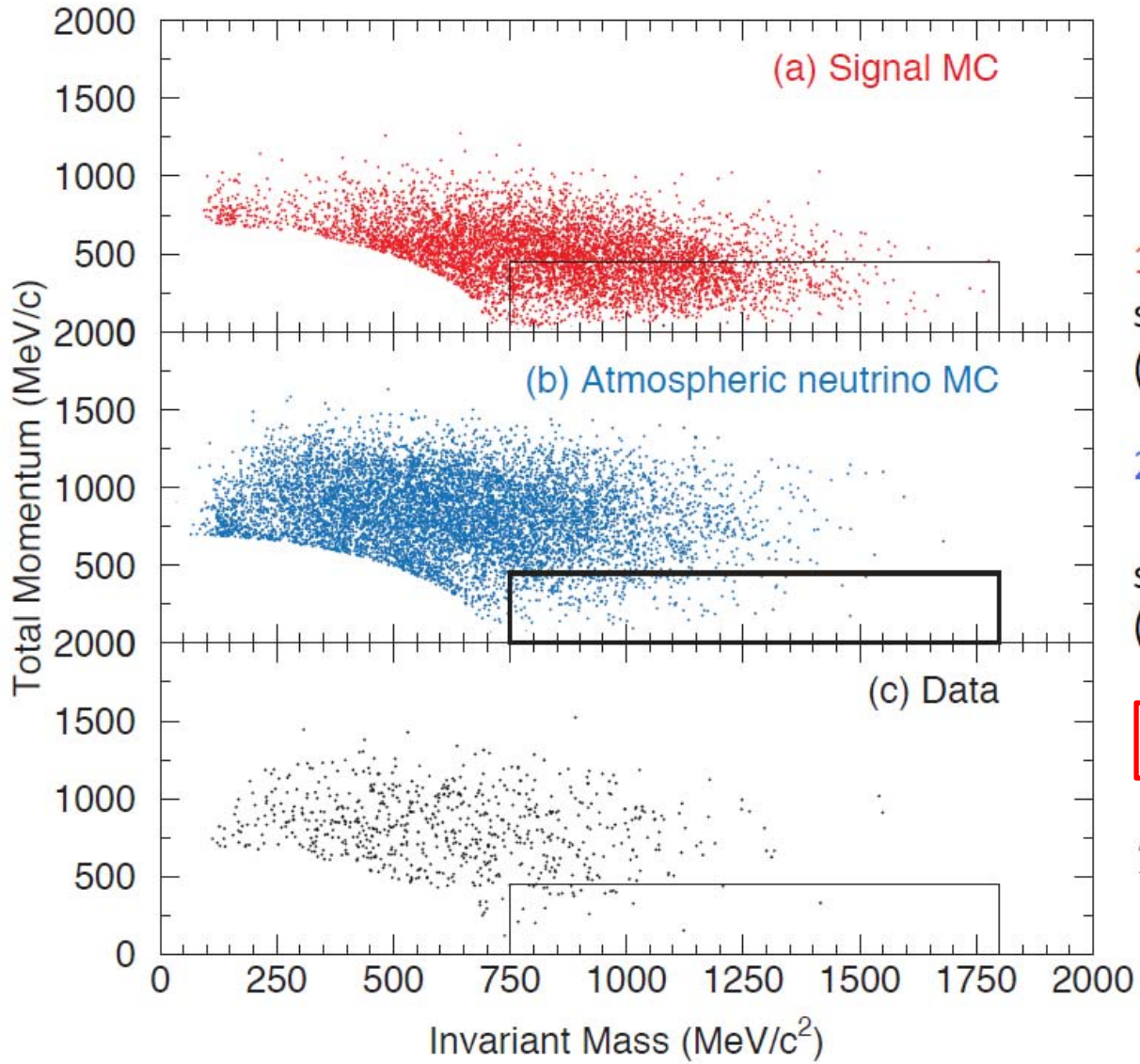
Not published yet!

$\bar{n}+p$		$\bar{n}+n$	
$\pi^+\pi^0$	1%	$\pi^+\pi^-$	2%
$\pi^+2\pi^0$	8%	$2\pi^0$	1.5%
$\pi^+3\pi^0$	10%	$\pi^+\pi^-\pi^0$	6.5%
$2\pi^+\pi^-\pi^0$	22%	$\pi^+\pi^-2\pi^0$	11%
$2\pi^+\pi^-2\pi^0$	36%	$\pi^+\pi^-3\pi^0$	28%
$2\pi^+\pi^-2\omega$	16%	$2\pi^+2\pi^-$	7%
$3\pi^+2\pi^-\pi^0$	7%	$2\pi^+2\pi^-\pi^0$	24%
		$\pi^+\pi^-\omega$	10%
		$2\pi^+2\pi^-2\pi^0$	10%

TABLE I: The branching ratios for the $\bar{n}$+nucleon annihilations in our simulations. These factors were derived from $\bar{p}p$ and $\bar{p}d$ bubble chamber data[12][13][14].

This is the most recent, most detailed search by Super-K Collaboration with highest neutron×years of exposure and with most comprehensive treatment of systematic uncertainties. Uses suppression factor of Dover et al. Exists as arXiv paper.

Super-Kamiokande Result



Selection Criteria:
$N_{ring} \geq 2$
E_{vis} between 700-1300 MeV

12 % detection efficiency
sys. uncertainty 23%
(mostly intranuclear scattering)

24.1 background events
ν osc. effects are included
sys. uncertainty 24%
(mostly flux, cross sections)

24 candidates

$$T_{bound} > 1.89 \times 10^{32} \text{ years}$$

This limit includes statistical PDF as well as PDFs for detector efficiency, background, and exposure time uncertainties

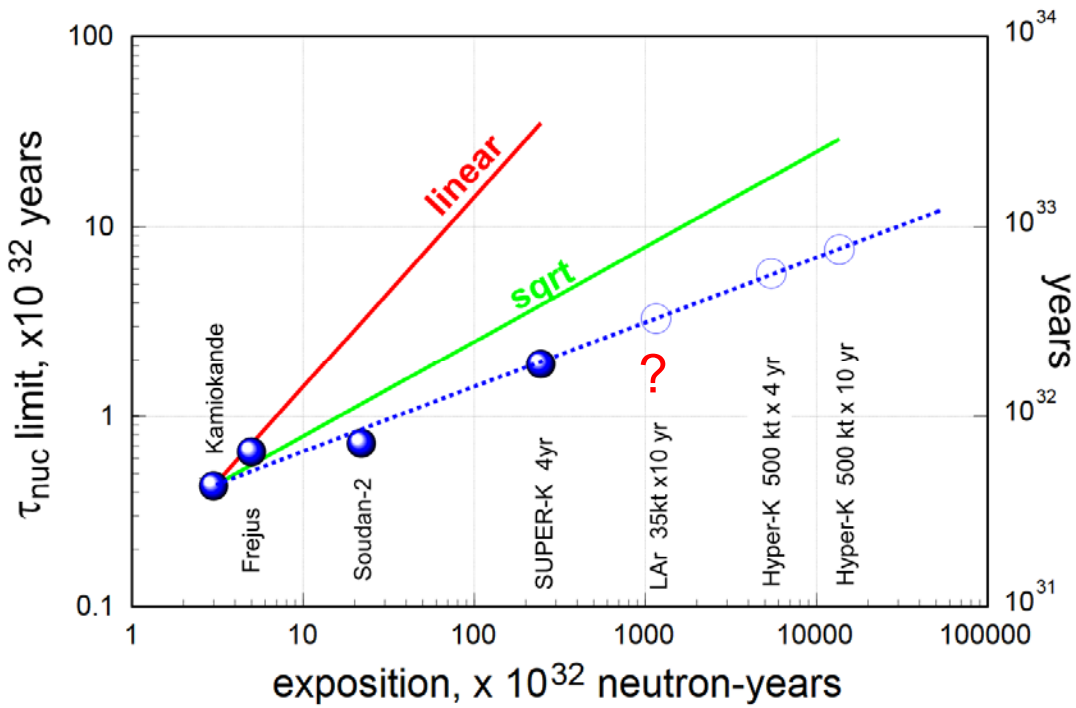
Ed Kearns, Boston University, 2013

Bound neutron N-Nbar search experiments

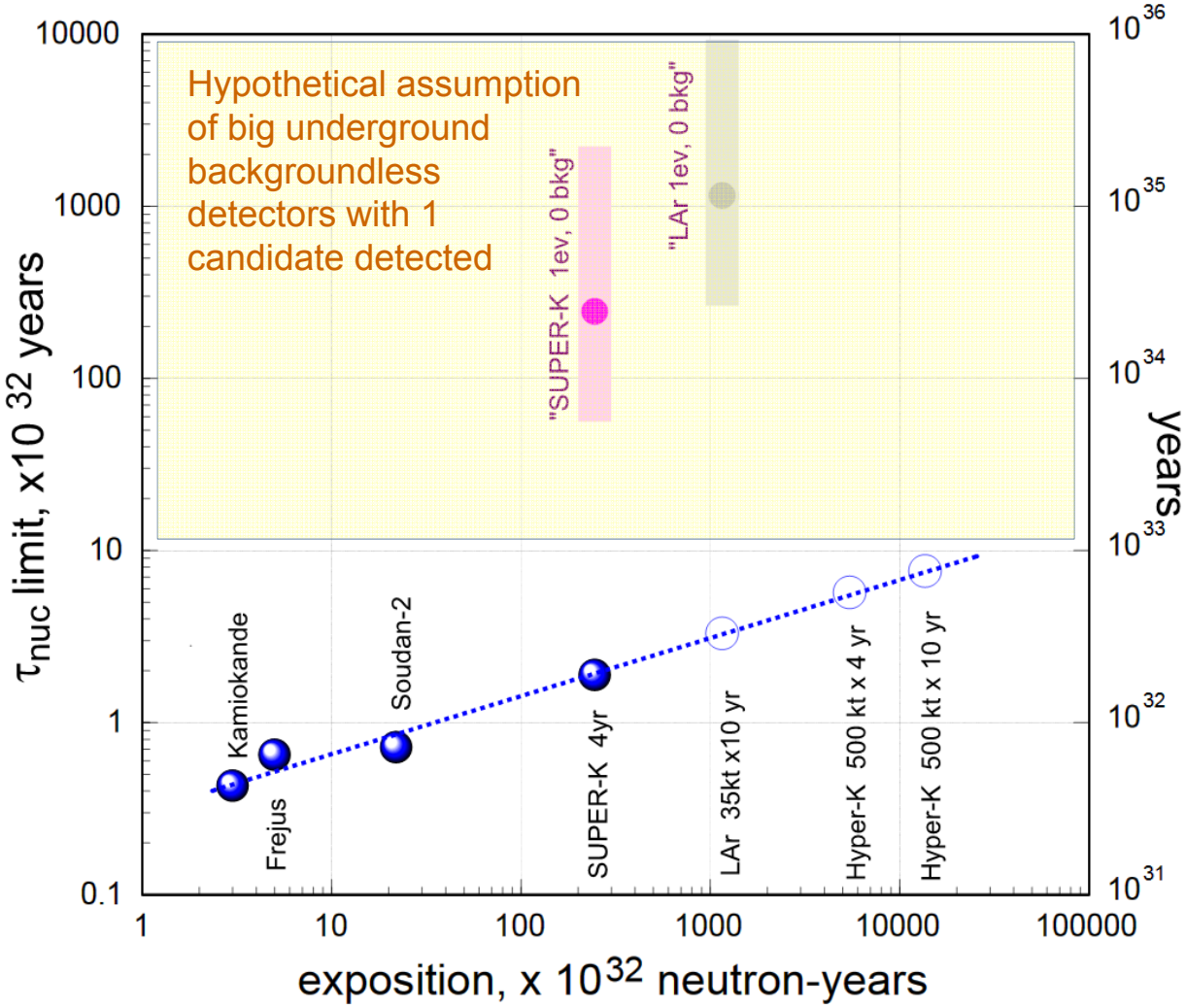
Experiment	Year	A	n·year (10^{32})	Det. eff.	Candid.	Bkgr.	τ_{nucl}, yr (90% CL)
Kamiokande	1986	O	3.0	33%	0	0.9/yr	$>0.43\times10^{32}$
Frejus	1990	Fe	5.0	30%	0	4	$>0.65\times10^{32}$
Soudan-2	2002	Fe	21.9	18%	5	4.5	$>0.72\times10^{32}$
SNO * (Thesis)	2010	D	0.54	41%	2	4.75	$>0.301\times10^{32}$
Super-K *	2011	O	245	12.1%	24	24.1	$>1.89\times10^{32}$

* Preliminary (not published)

- From Kamiokande to Super-K atmospheric ν background is present in the data.
- Large D_2O, Fe, H_2O detectors all are dominated by backgrounds;
- Observed improvement is weaker than SQRT due to irreducible atm-ν background and uncertainties in efficiency and background.
- Still possible to improve a limit but impossible to claim a discovery.

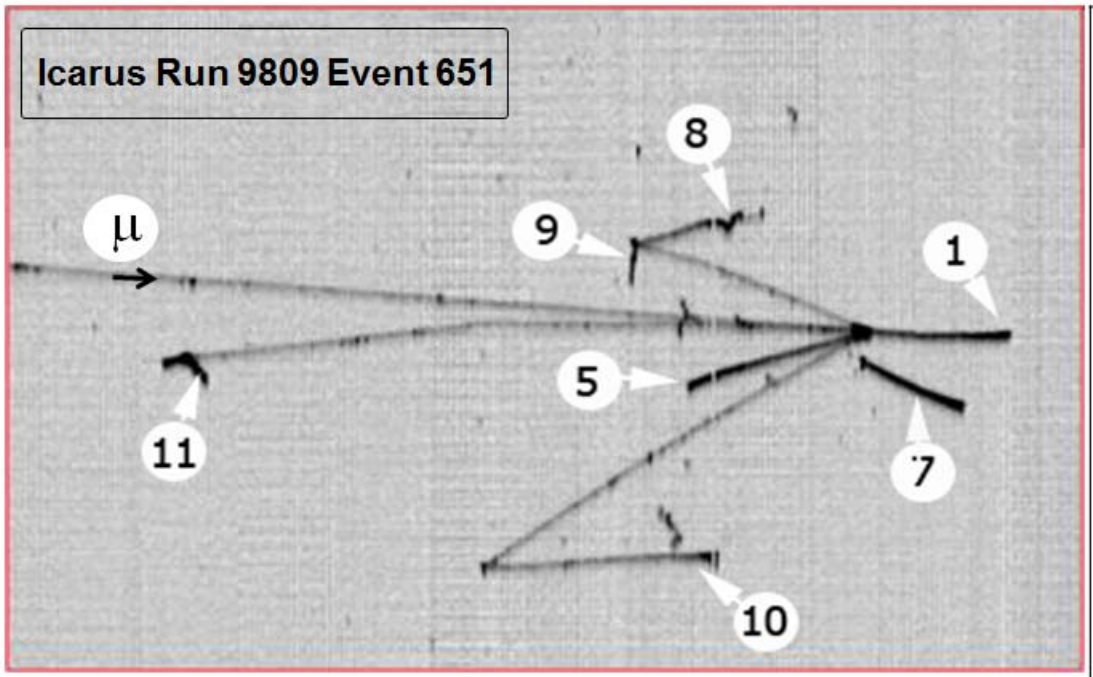


Effect of the presence of background



24 candidate events in Super-K might already contain several genuine n-nbar events.

Big new Liquid Argon detectors (LBNE, GLACIER) potentially might have significantly better suppression of atmospheric neutrino than Water-Cherenkov detectors. Whether the backgroundless operation in these detectors at the decay level ~ 10^{33} - 10^{35} yr will be possible is not yet demonstrated.



6 protons, 1 pion decays at rest
Stopping muon: 7.1 ± 1.3 [GeV/c]

Paola Sala
Zurich, 2011

Track	E_{dep} [MeV]	range [cm]
1(p)	185±16	15
5(p)	192±16	20
7(p)	142±12	17
8(π)	94±8	12
9(p)	26±2	4
10(p)	141±12	23
11(p)	123±10	6

Where intranuclear big detectors can reach?

That is a question of the ν background suppression

Experiment	nucleus	N(10^{32}) [n years]	Effic.	Bkgd.	Cand.	$T_{nucl.}$(10^{32}) [yr]
Super-K I	^{16}O	245	12%	24	24	2
SK 1-4 new	^{16}O	700	?	?	?	Goal is 3x to 5x improvement
Hyper-K (10 yr)	^{16}O	1500	?	?	?	20-50
LBNE (34 kt x 10 yr)	^{40}Ar	1120	50%	3	3	~100 ($t > 10^9$ s)

Purely speculative numbers for LAr, targets not results.
Target of < 1 events/100 kty background
While maintaining 50% efficiency

Ed Kearns, Boston University, 2013

Conversion of Bound Limit to free Oscillation Limit

Experiment	Year	A	τ_{nucl}, yr (90% CL)	R(old), s^{-1}	R(new), s^{-1}	τ(old), s	τ(new), s
			Nuclear lifetime				Free neutrons
Kamiokande	1986	O	$>0.43\times10^{32}$	10×10^{22}	5×10^{22}	$>1.2\times10^{8}$	$>1.65\times10^{8}$
Frejus	1990	Fe	$>0.65\times10^{32}$	14×10^{22}	?	$>1.2\times10^{8}$	?
Soudan-2	2002	Fe	$>0.72\times10^{32}$	14×10^{22}	?	$>1.3\times10^{8}$	?
SNO * (0.002 × SK)	2010	D	$>0.301\times10^{32}$	2.48×10^{22}	2.94×10^{22}	$>1.96\times10^{8}$	$>1.8\times10^{8}$
Super-K *	2011	O	$>1.89\times10^{32}$	10×10^{22}	5×10^{22}	$>2.44\times10^{8}$	$>3.45\times10^{8}$

* Preliminary (not published)

Dover, Gal et. al, old

V. Kopeliovich 2011, Deuterium

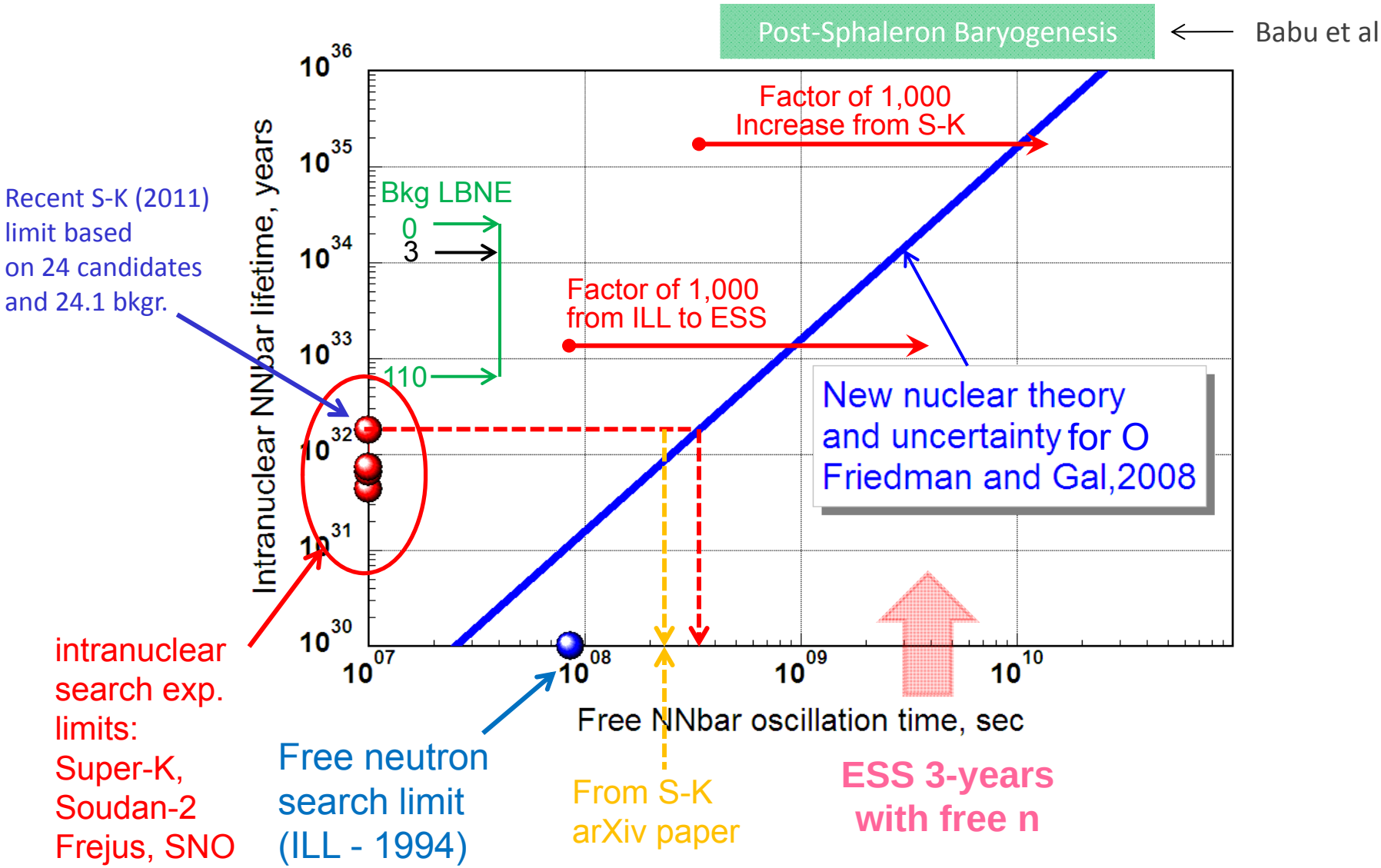
Friedman and Gal 2008, Oxygen

most conservatively (from S-K arXiv paper and New R):

$$\Rightarrow \tau_{n\bar{n}}(\text{from bound}) > 3.5\times10^{8}\,s \quad \text{or} \quad \alpha < 2\times10^{-24}\,eV$$

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

Free Neutron and Bound Neutrons NNbar Search Limits Comparison



Complementarity of intranuclear and free-neutron search

Observations of n-nbar with both free and bound neutrons are important

1. If $m_n \neq m_{\bar{n}}$ with $\alpha \ll \Delta m = \left| m_n - m_{\bar{n}} \right| < 10^{-19} m_n \simeq \left(\frac{m_n}{m_{Planck}} \right) m_n$

the transformation of free $n \to \bar{n}$ will be suppressed by Δm.
But it will NOT be additionally suppressed inside the nuclei where suppression factor is present due to ΔE ~ $30 MeV$ (Abov, Djeparov, Okun - 1984).

2. If n-nbar will be observed inside nuclei but due to Δm will *not* appear with free neutron, it will be possible to "unlock" it for free neutrons by tuning the magnetic field. (Does't apply for intranuclear n-nbar)

3. If n-nbar will be observed both with free neutrons and inside nuclei, it will be possible to set a new more tight limit on Δm / m as a test of CPT.

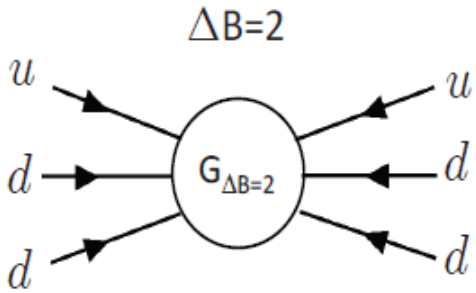
Observations of n-nbar with both free and bound neutrons are important (2)

4. If NNbar will be observed first with free neutrons, the transformation can be suppressed in a controlled way by weak magnetic field. Variation of this field can be extrapolated to zero, revealing the magnitude of Δm or the upper limit on Δm.

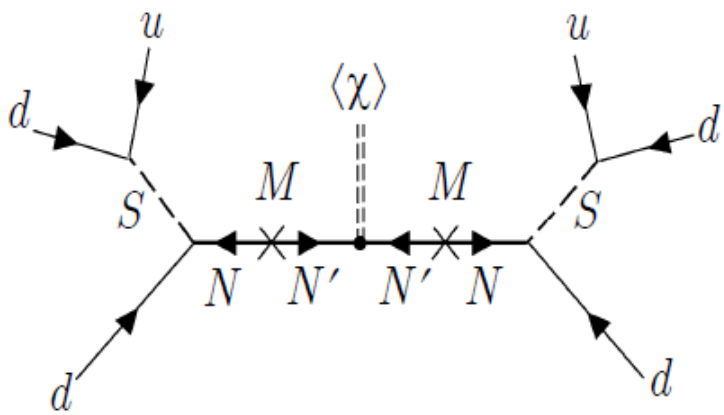
5. If Baryon number is brocken sponteneously (Z. Berezhiani, 2014) then intranuclear transformation can either be amplified or significantly suppressed inside the nuclei.

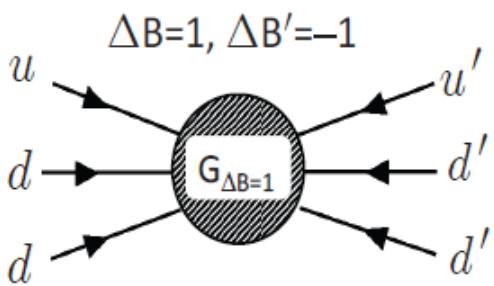
6. Thus, the observation of different transformation probability for free and bound neutrons, might give a hint for a new physics and complementary mechanisms beyond the vacuum NNbar and SM.

Z. Berezhiani's vision (2014) of $n \to \bar{n}$ connection to Mirror (and Dark) Matter $n \to n'$

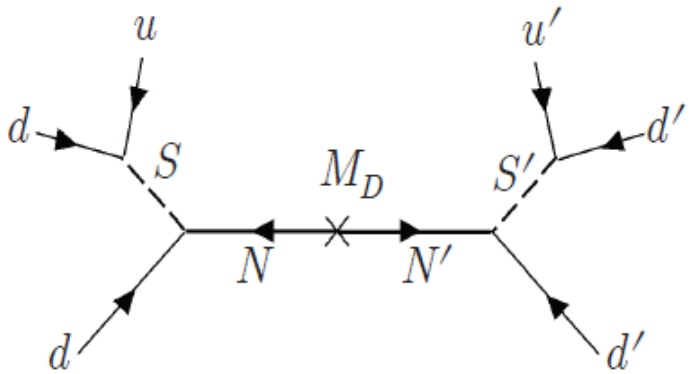


$$G_{\Delta B=2} = \frac{\langle\chi\rangle}{M_D}\frac{1}{M_D M_S^4}$$





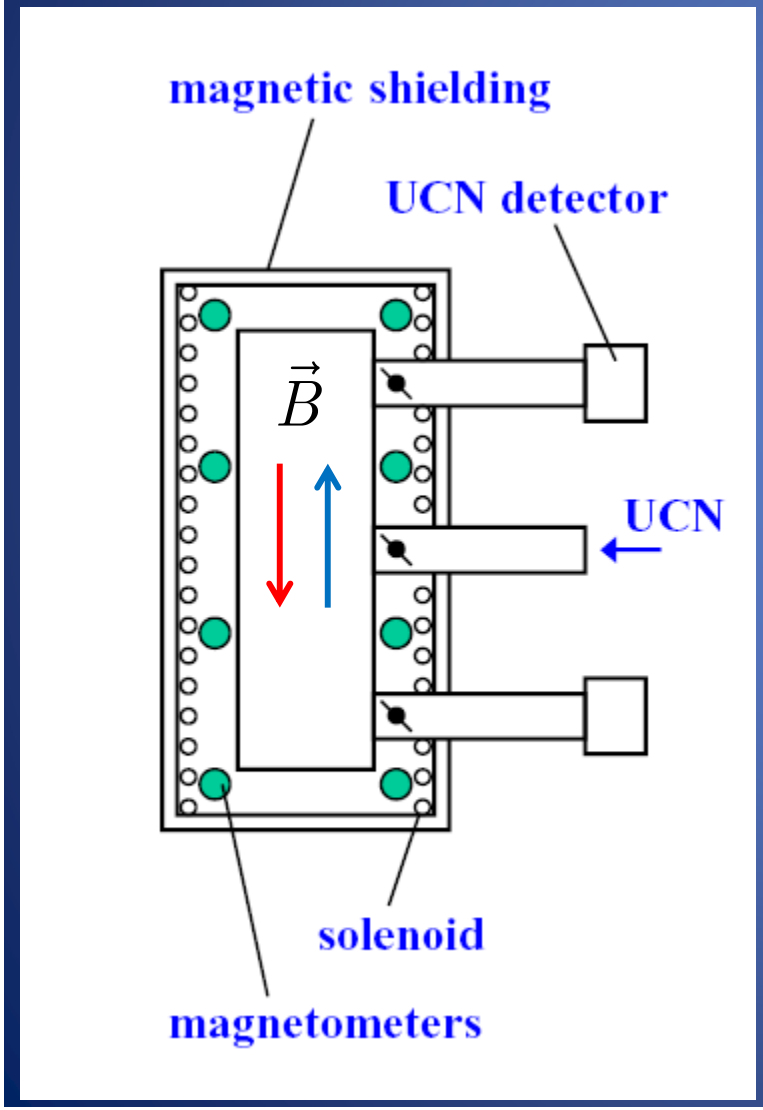
$$G_{\Delta B=1} = \frac{1}{M_D M_S^4}$$



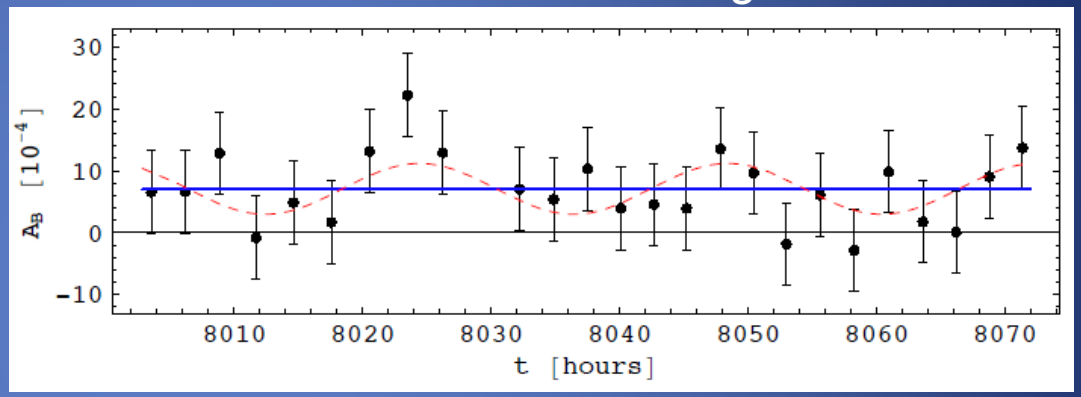
$\overline{B} = B + B'$ conserved !

PNPI Experiment to search for $n \to n'$ disappearance at ILL/Grenoble reactor, A. Serebrov et al (2009)

NIM A611 (2009) 137-140



Measurements of UCN life-time asymmetry under alternation of vertical magnetic field



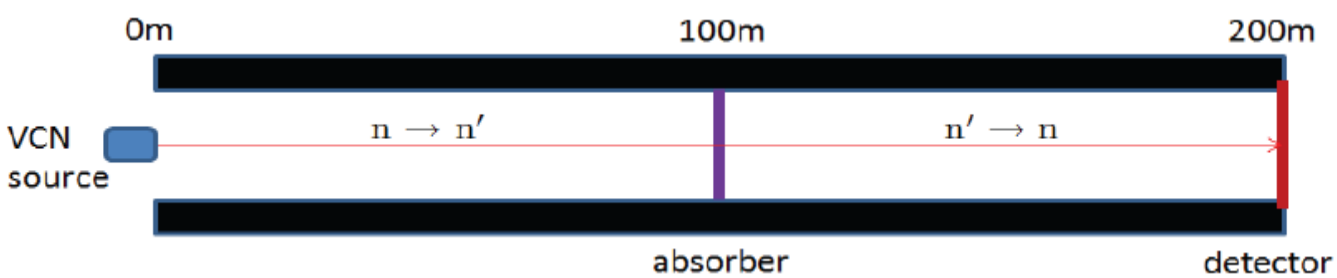
$$A_B^{\det}(t) = \frac{N_{-B}(t) - N_B(t)}{N_{-B}(t) + N_B(t)}$$

Re-analyzed by Z. Berezhiani and F. Nesti
Eur. Phys. J. C (2012) 72:1974

Measured asymmetry →
~ $(7 \pm 1.4) \times 10^{-4}$ (5σ)
$n \to n'$ oscillation time ~ 2-5 sec;
mirror mag. field ~ 0.1 G

$n \to n'$ Search

- Tunable magnetic field might reveal resonance enhancement.
- Your proposal IRIDE of facility included search fro n → n′.
- Regeneration experiment n → n′ → n that can be planned for small neutron facilities is not demanding for super-intensive beam



This can be a non-expensive small-effort experiment with a fundamental discovery made not at LHC

Conclusions

- New ESS-based n-nbar search experiment with free neutrons can provide a testable ground for post-sphaleron baryogenesis models and answer the question of matter-antimatter asymmetry of the universe by discovering a new force of nature.
- New experimental groups are very welcome to join the initial effort of new European N-Nbar Collaboration.
- Intranuclear N-Nbar search seems being dominated by atm. ν background. Serious efforts should be made to allow LAr technology to explore complementarity in new n-nbar physics.
- New HEP physics of $n \rightarrow$ nbar and $n \rightarrow n'$ will be sensitive to magnetic lab fields.
- IRIDE might be the next place where a new physics is discovered.
- Not all new discoveries are to be made with LHC!