UT Particle Physics, Astrophysics and Cosmology Seminar • February 12, 2014

Neutron-Antineutron Search Experiment at ESS in Europe

Future Experiment

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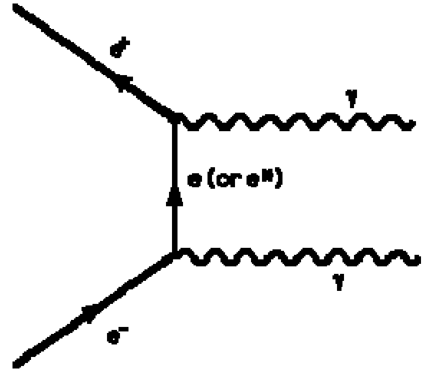
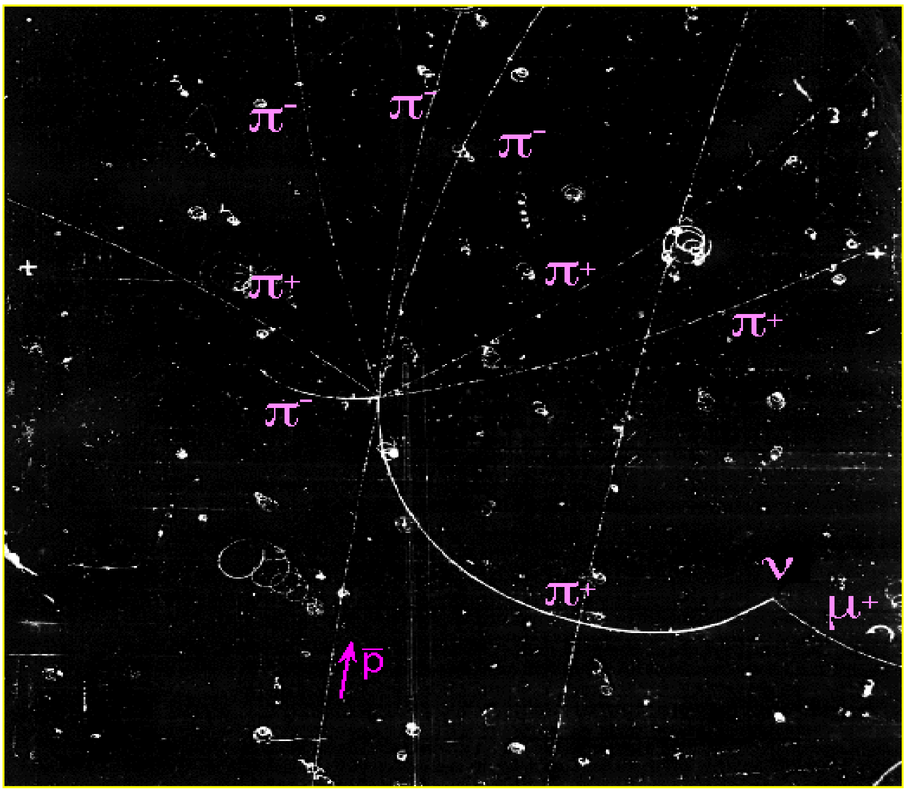
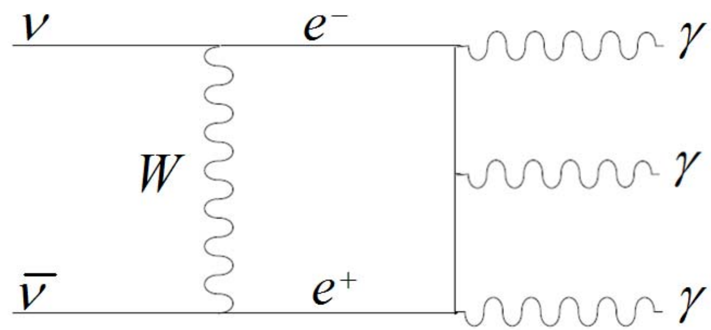
Annihilation of matter and antimatter

$$e^- + e^+ \to \gamma + \gamma + (\gamma) \to$$





Antiproton annihilation in hydrogen bubble chamber



$$\bar{p} + p \to < 5 > \pi$$

Why in the Hydrogen Atom

electron does not annihilate with proton ?

This is due to conservation of

Baryon number (n, p, Λ, Σ, Δ etc.)

And Lepton number (e, μ, τ, ν)

Violation of Baryon Number

Violation of Baryon number is one of the pillars required by modern Cosmology and Particle Physics but not observed

- it follows from the inflation [Dolgov, Zeldovich]

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

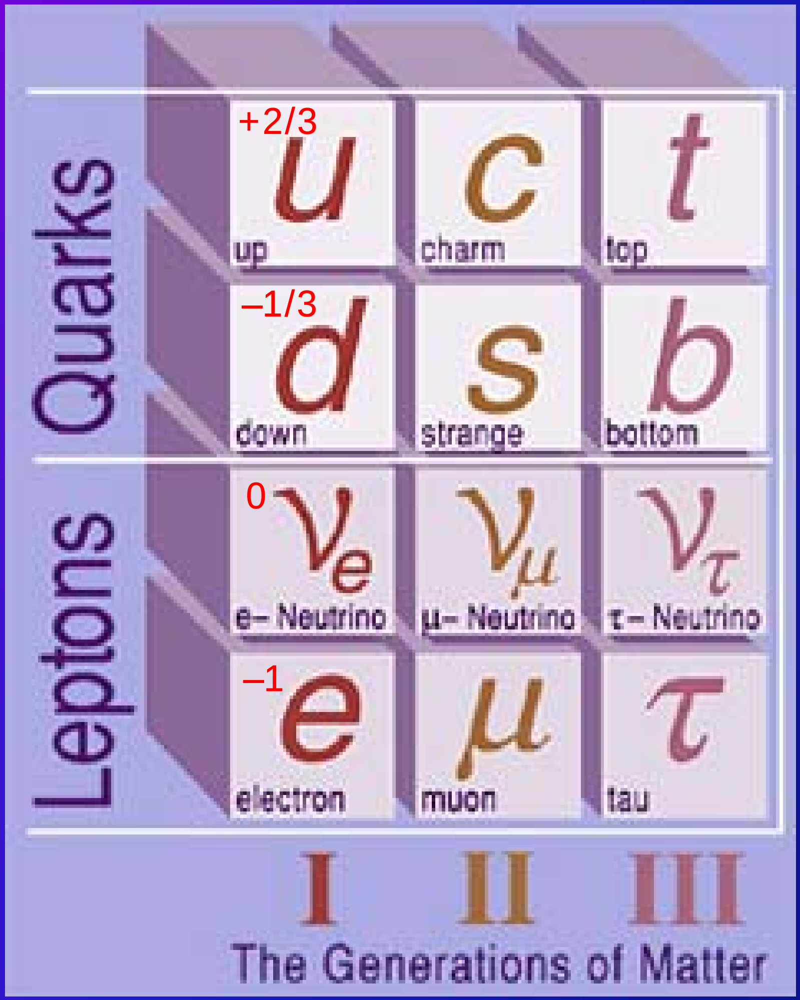
- it is motivated by Grand Unification Theory (GUT) models [Georgi, Glashow, Pati, Salam, ...]

- Expected proton decay with $\Delta B = 1$ and conserving $(B - L)$ so far has failed to demonstrate existence of BV [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.

Fundamental Building Bricks of Matter
in "Standard Model"



***p* {*uud*}**

***n* {*ddu*}**

←neutrino

←electrons

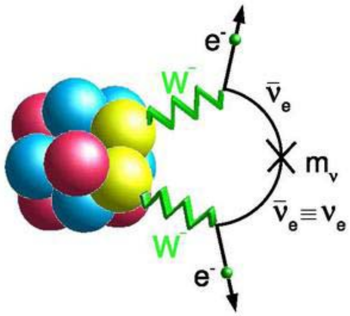
all matter and antimatter particles are "fermions" with spin = ½$\hbar$

B, L, and B – L

- ❖ If Majorana neutrino with ΔL=2 exists thus demonstrating (B – L)V BSM then also ΔB=2 should exist, e.g. like neutron → antineutron transformation.
- ❖ ΔB and ΔL are connected via conservation of angular momentum.
  ΔL = ± ΔB → Δ(B–L) = 0 or Δ(B–L) = 2. Is (B – L) conserved ?
- ❖ Naively (B – L) is strongly violated in regular matter: #n + #p – #e ≠ 0

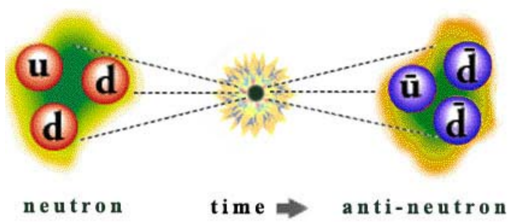
  However, on the scale of the universe it might be compensated by the unknown number of relic neutrinos and antineutrinos …
- ❖ Experimental searched for (B – L)V:

  (a) in "neutrinoless double beta decay":
  UT group is involved in Majorana and KamLAND/ZEN experiments.



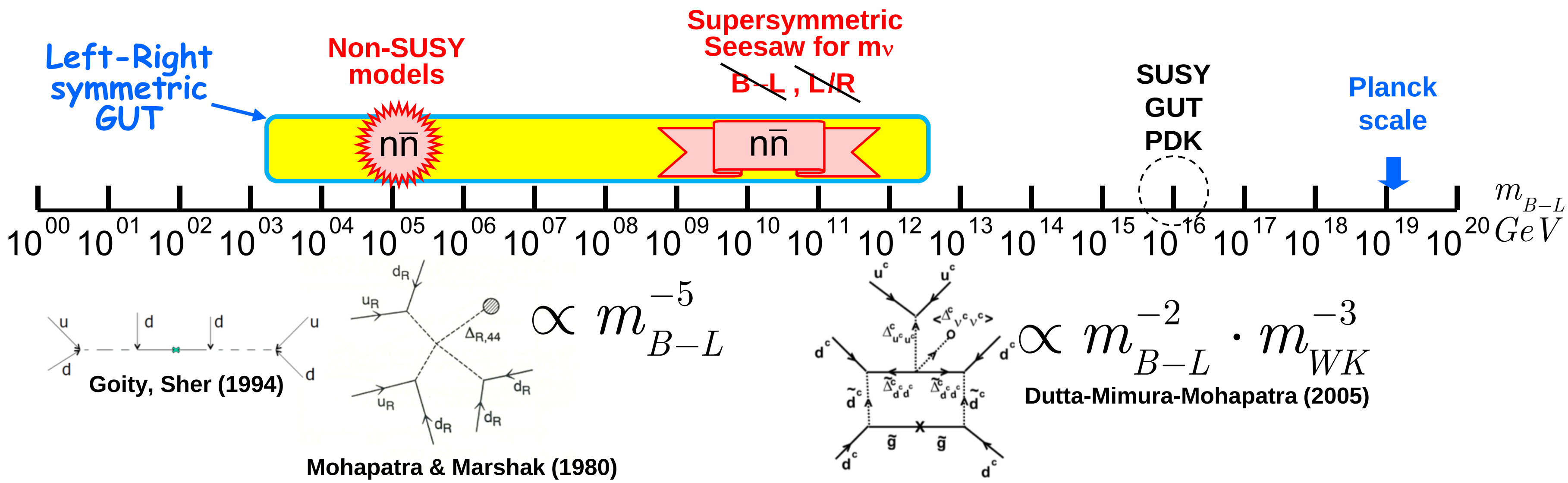
$$\nu \longrightarrow \overline{\nu}$$

  (b) in neutron to antineutron transformation:
  New experiment at European Spallation Source (ESS) where UT group will be involved.



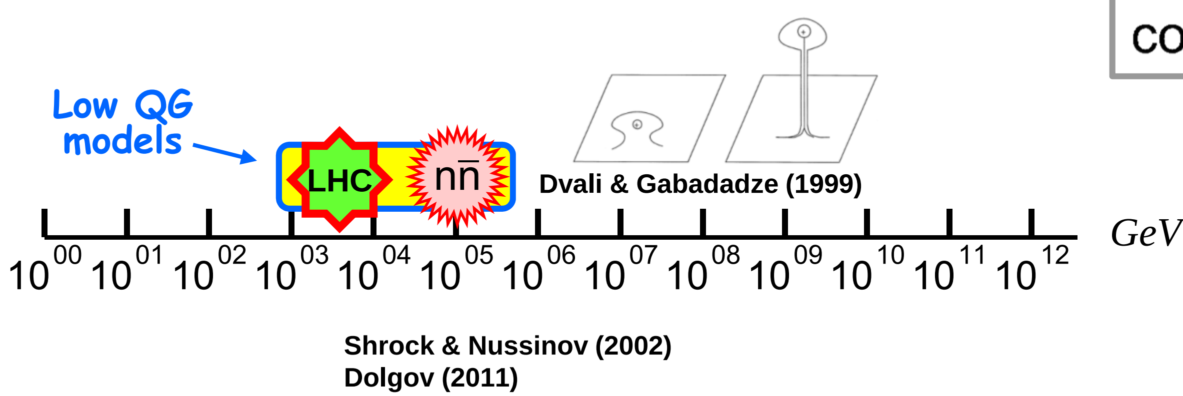
$$n \longrightarrow \overline{n}$$

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



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

Experimental motivation!
large increase of sensitivity:
factor of ×1,000 is possible
compared to existing limit



Leptogenesis

M. Fukugita, T. Yanagida (1986)

Decay of the super heavy Majorana neutrino N :

$$N_i \to l_j + H^\dagger, \quad \bar{l}_j + H$$

Two decay channels

If CP is broken, the lepton asymmetry is generated in the delayed decay of N in the early universe

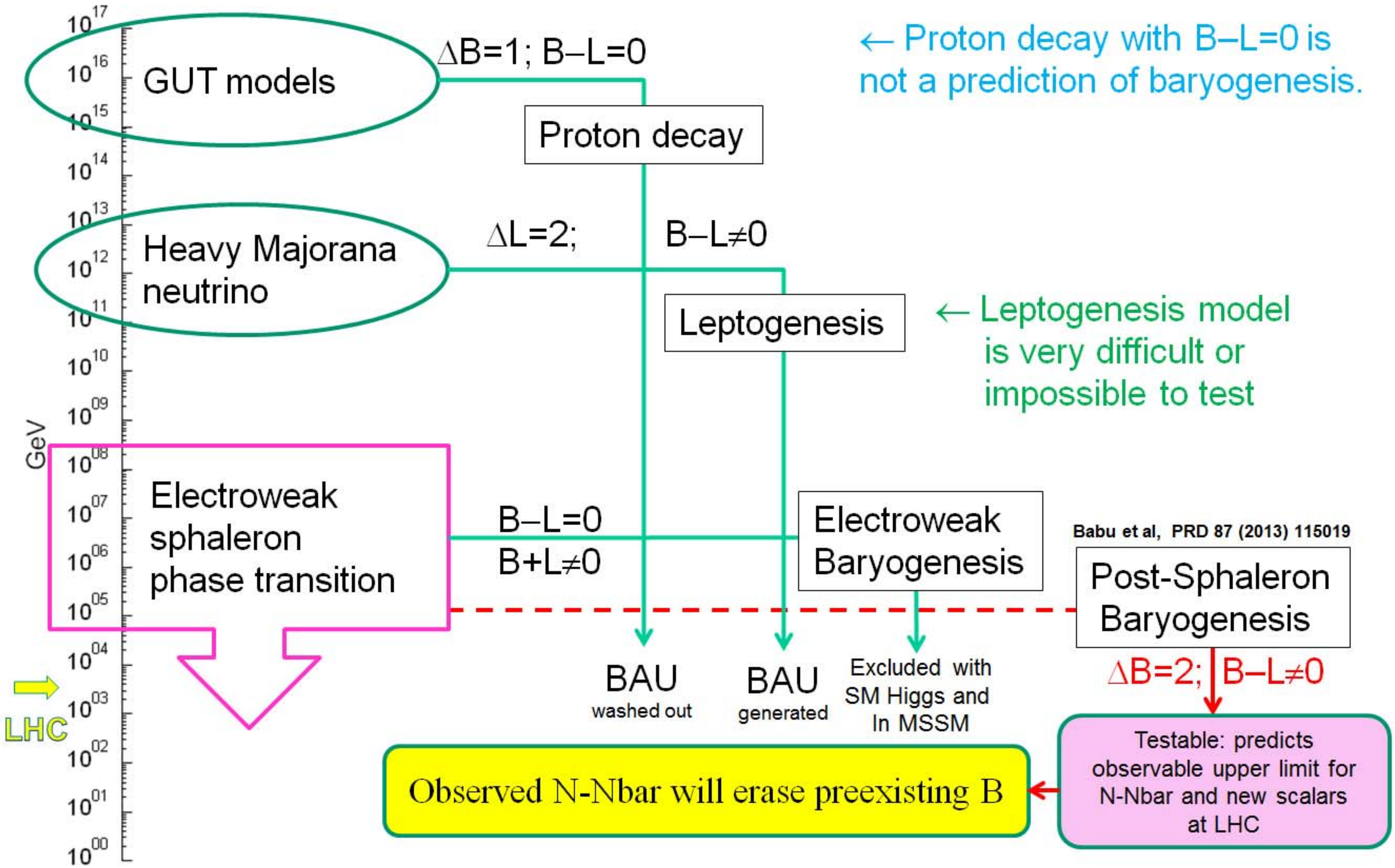
The lepton asymmetry is converted to baryon asymmetry by the sphaleron processes

$$\Delta L_0 \to \Delta B$$

$$\Delta B\mathrm{present} \simeq \frac{8N+4m}{22N+13m}\Delta(B-L)_0 = \frac{28}{79}(-\Delta L)_0 \ \ \text{for } N=3,\ m=1$$

J.A. Harvey, M.S. Turner (1990)

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.

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)

(Thanks to Bill Marciano for bringing this story into discussion.)

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

- 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]. ΔB=0.

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

Neutron still can be 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 free neutron and under certain conditions can evolve with time.

This mixing fraction must be small, otherwise it would be already observed and unless there are some suppression conditions 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 $\nu_\mu \longrightarrow \nu_e$
- Lepton number $\rightarrow$ in Majorana neutrinos $\nu_e \longrightarrow \overline{\nu}_e$
- Baryon number $\rightarrow$ $n \longrightarrow \overline{n}$

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

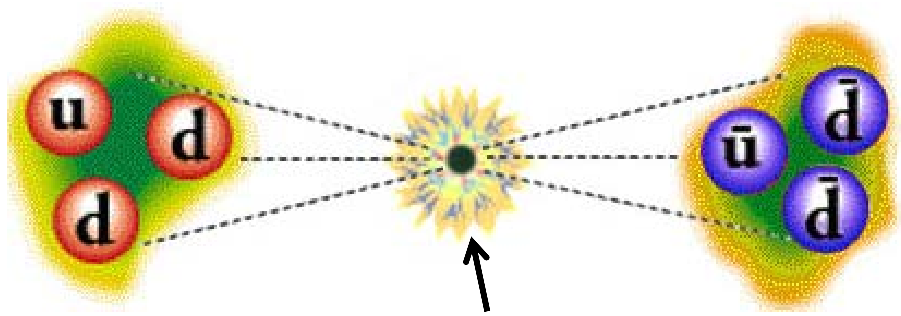
  R. Mohapatra and R. Marshak, 1979 …

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

- The early history of other fundamental physics ideas related to N-Nbar oscillations is briefly discussed by L. Okun in recent http://arXiv.org/pdf/1306.5052.pdf

- Most recent discussion of N-Nbar theoretical models can be found in "Project X: Physics Opportunities" http://arxiv.org/pdf/1306.5009v2.pdf and in the talks of Intensity Frontier Workshop at ANL April 25-27, 2013 https://indico.fnal.gov/conferenceTimeTable.py?confId=6248#20130425.detailed

How it happens

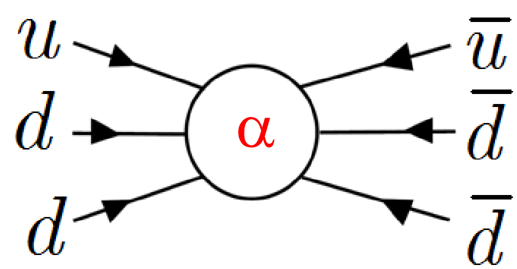
neutron  *anti-neutron*

Overlap of quark's wave functions
at the distance corresponding to
the effective mass scale ~ 10^5 GeV
is the suppression factor for $n \to \bar{n}$.

- This is at the distances of quark's "asymptotic freedom" and must be reliably predicted by QCD.
- Unknown coupling between quarks (new force) should be effective at this distance factorized with overlap probability.
- We are biased to think in terms of binary collisions, with probability of 3-body overlaping being small. However, in the early universe at very high densities the 3-body collisions could be common.

n→nbar transition probability

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



α-mixing amplitude

All beyond SM physics is here

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

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

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

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

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

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

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

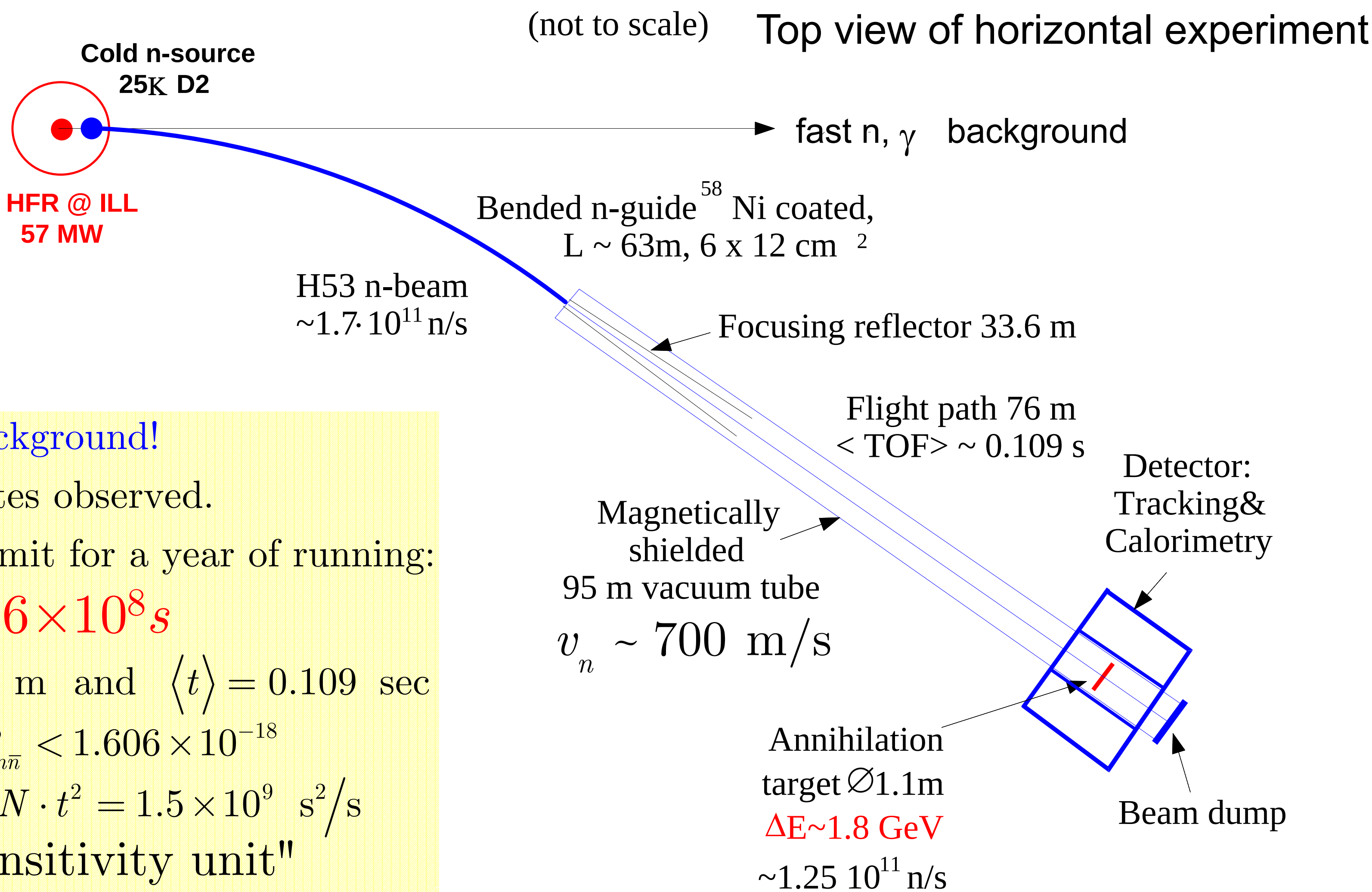
Predictions of theoretical models: observable effect around $\alpha \sim 10^{-25} - 10^{-26} eV$

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

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



No GeV background!

No candidates observed.

Measured limit for a year of running:

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

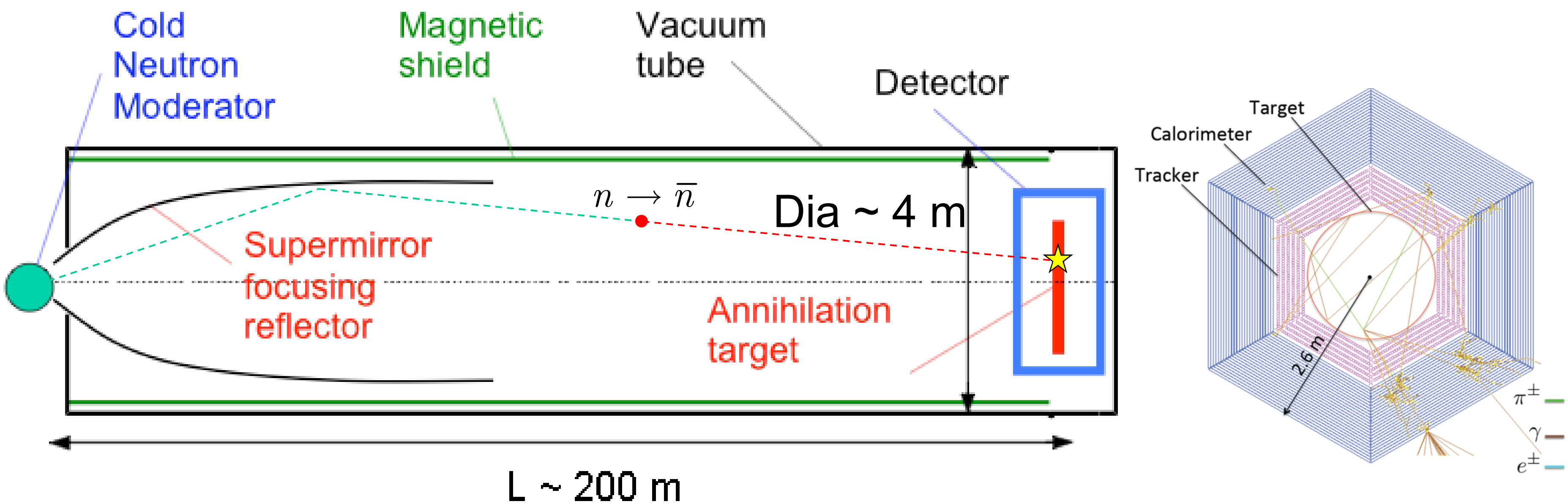
with L ~ 76 m and $\langle t \rangle = 0.109$ sec

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

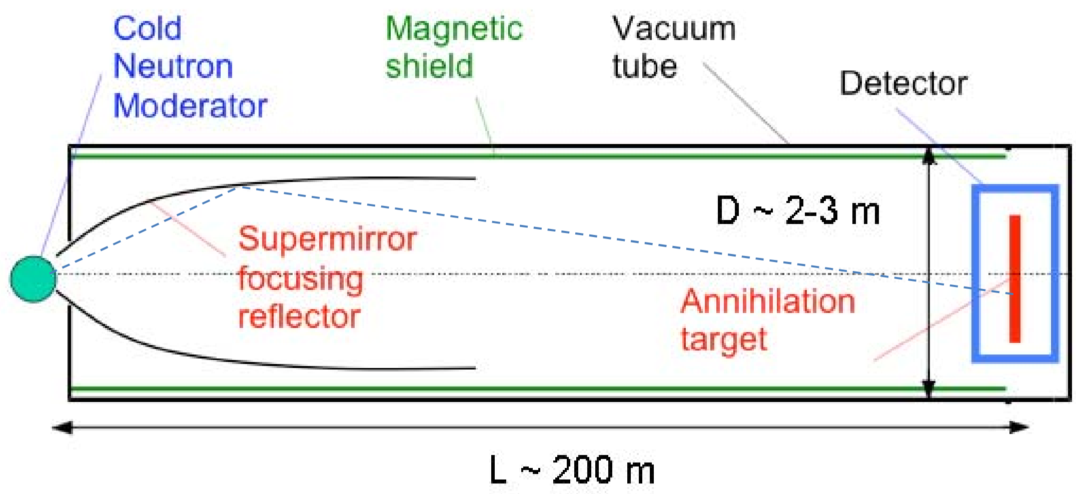
sensitivity: $N\cdot t^2 = 1.5\times 10^9 \ \ s^2/s$

$\doteq$ "ILL sensitivity unit"

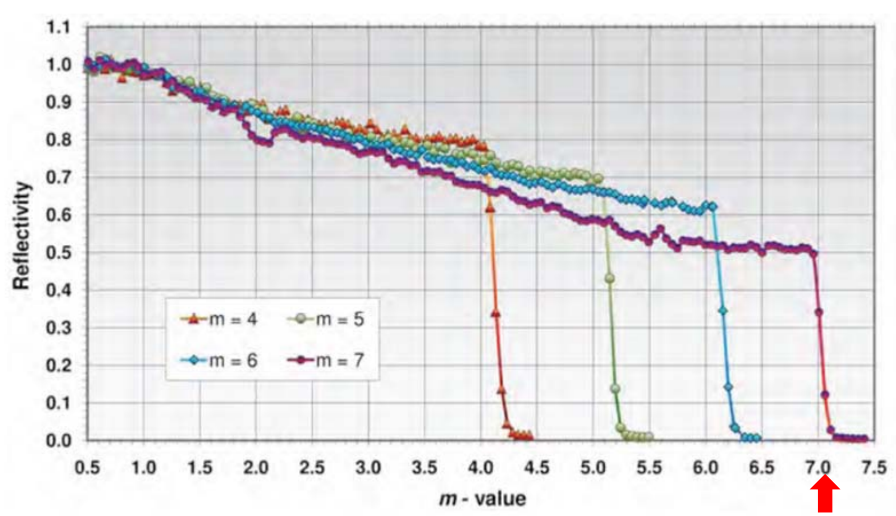
Scheme of Horizontal N-Nbar experiment for ESS Neutron Source



Principle of neutron focusing. Baseline configuration

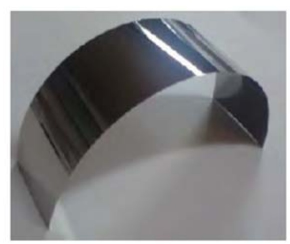


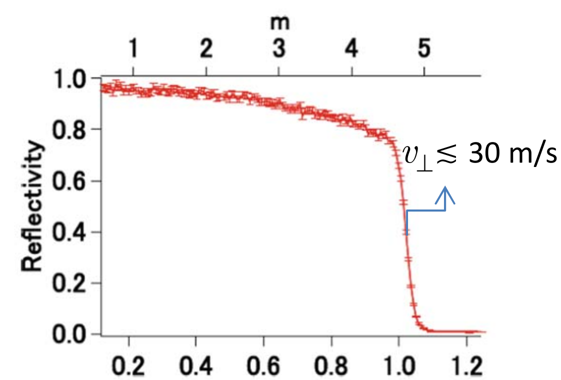
Commercial products of Swiss Neutronics



$v_{\perp} \lesssim 50$ m/s

Progress in neutron super-mirrors





no substrate (radiation hardness expected)

The ESS Headlines

- A neutron source for the study of materials
- ESS scope is defined in Technical Design Report
  - 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€

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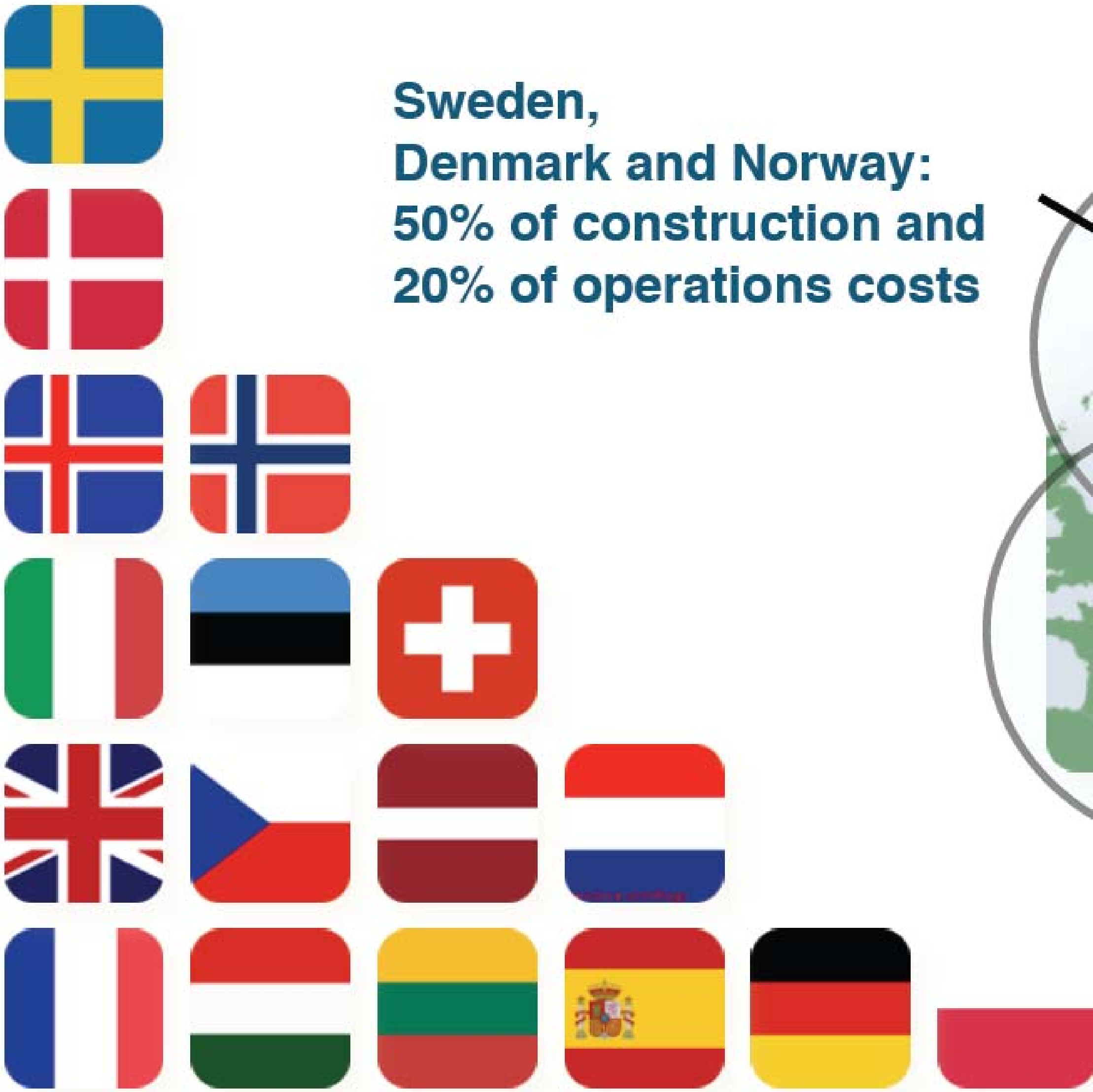
Richard Hall-Wilton
December 2013

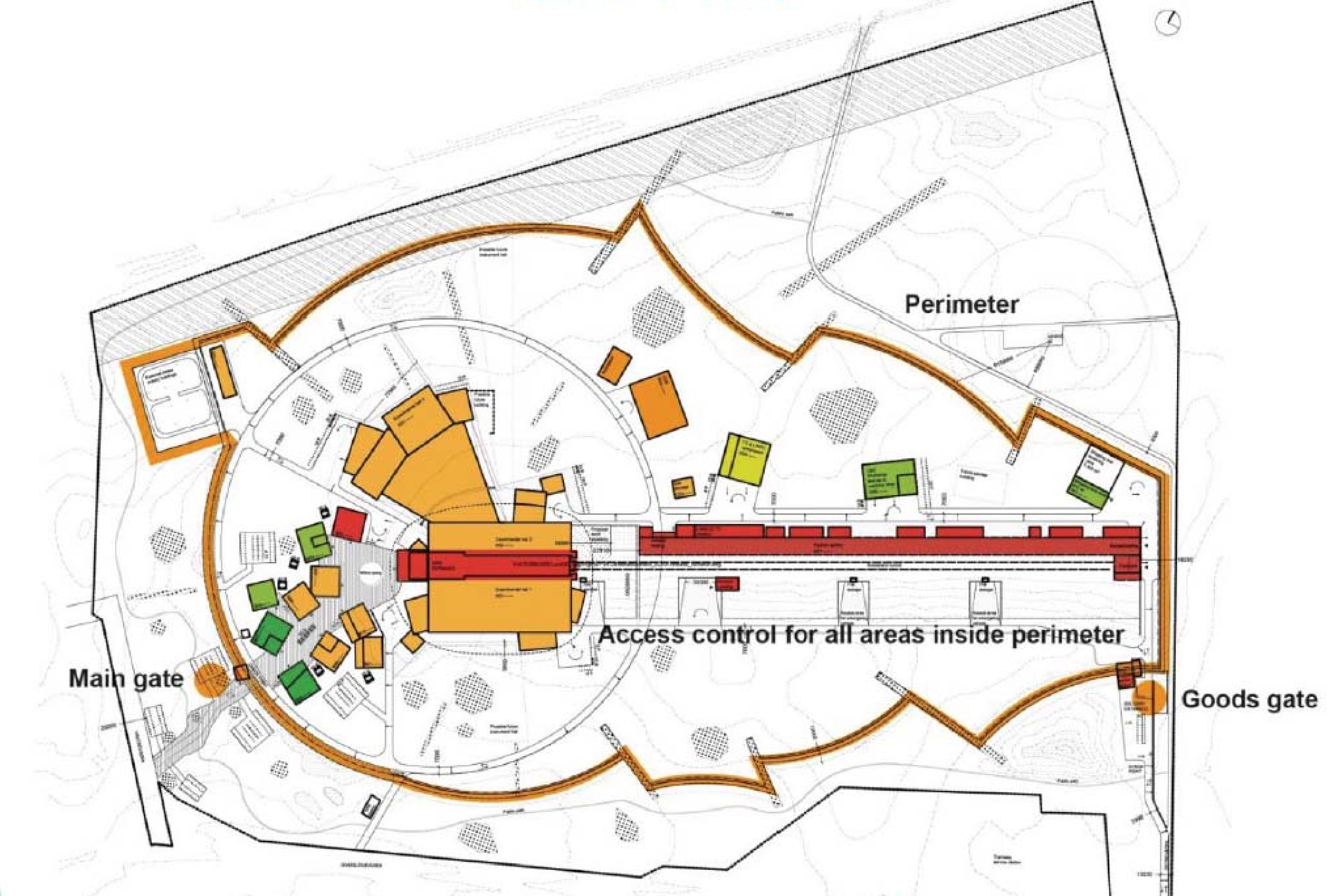
An International Collaboration



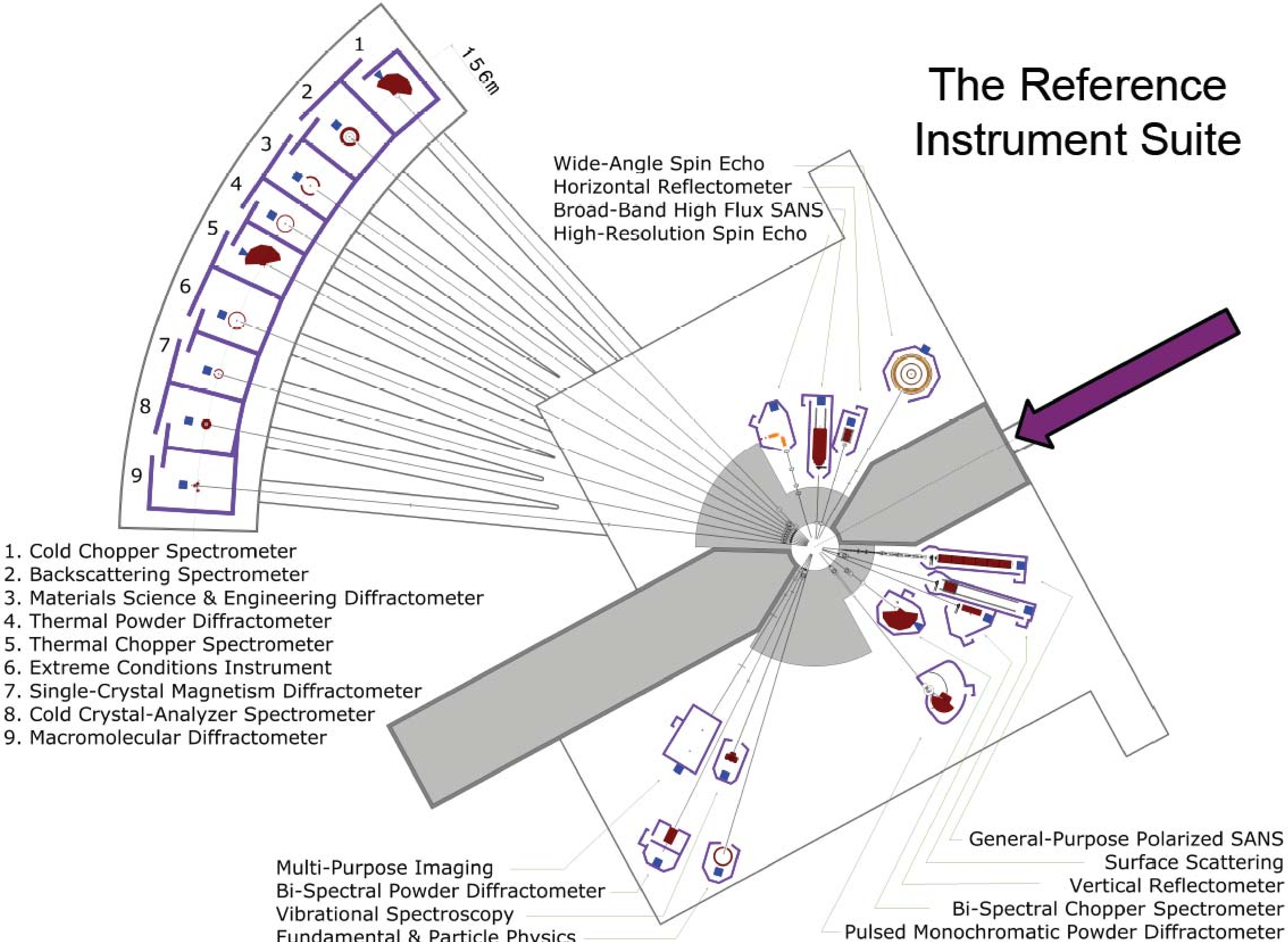
**Sweden,
Denmark and Norway:
50% of construction and
20% of operations costs**

**European partne
pay the rest**

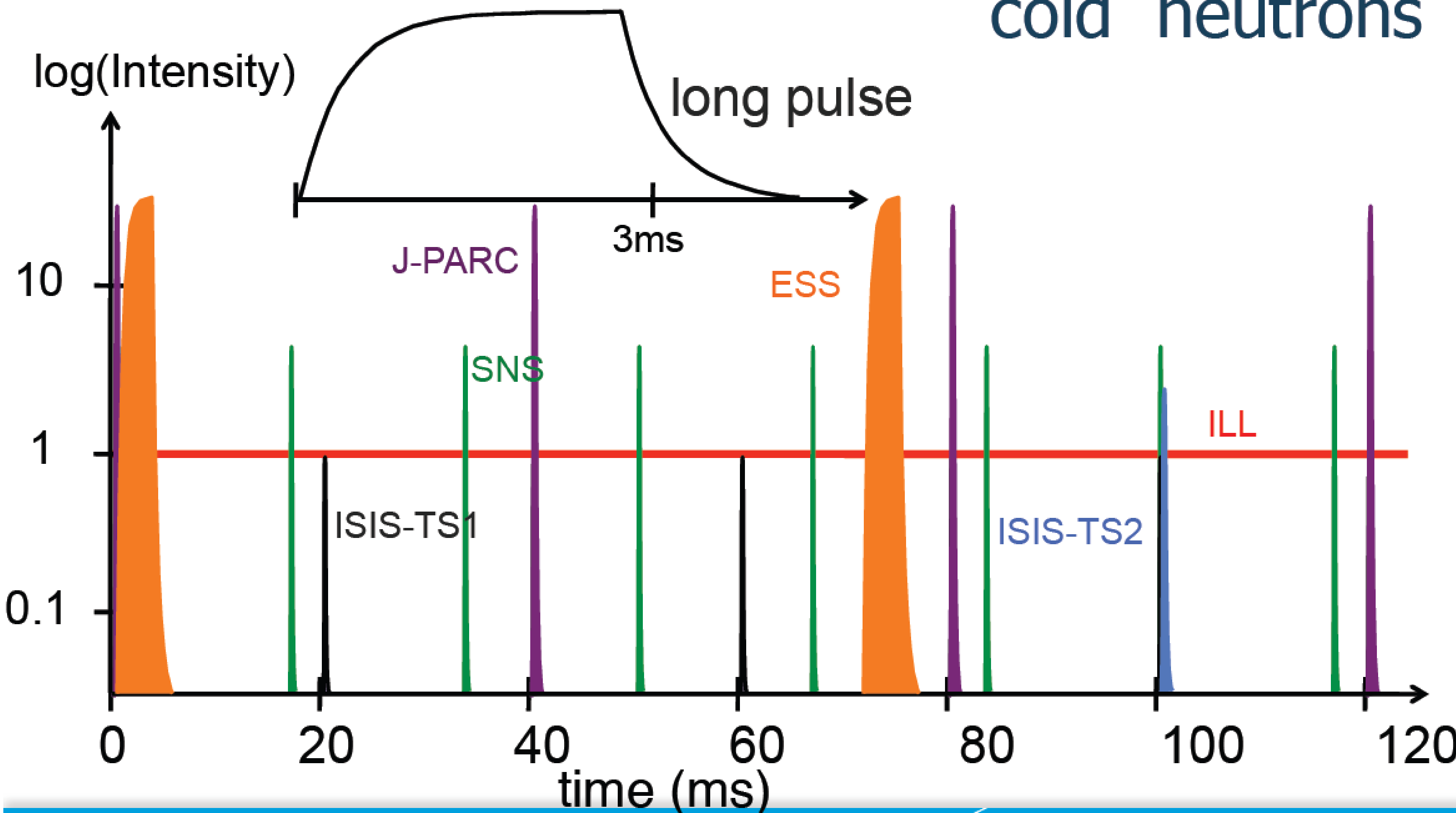
Site Plan


Perimeter
Access control for all areas inside perimeter
Main gate
Goods gate

The Reference Instrument Suite

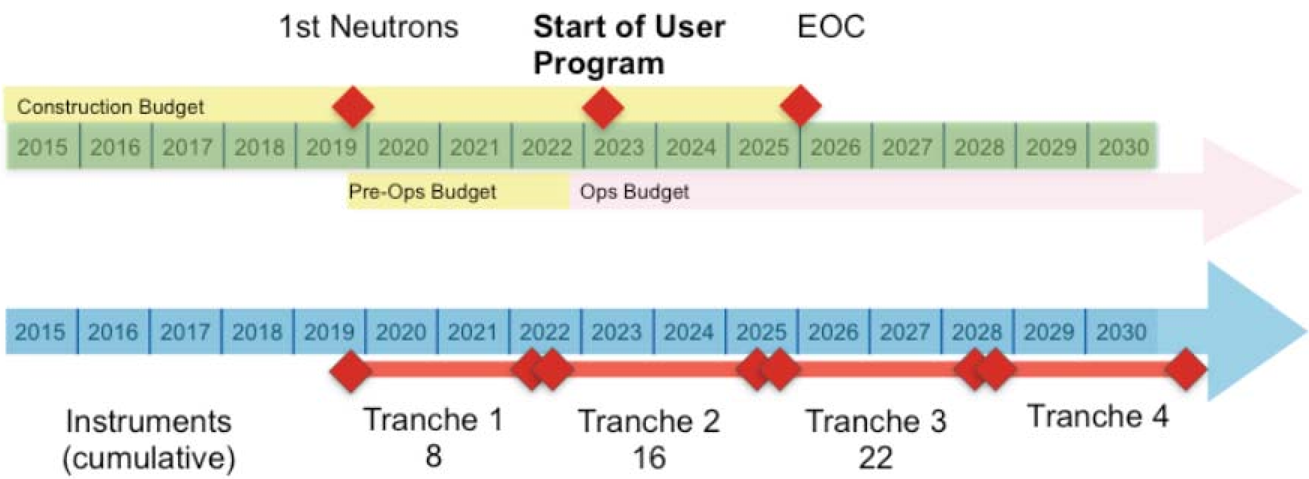


Pulsed-source time structures cold neutrons



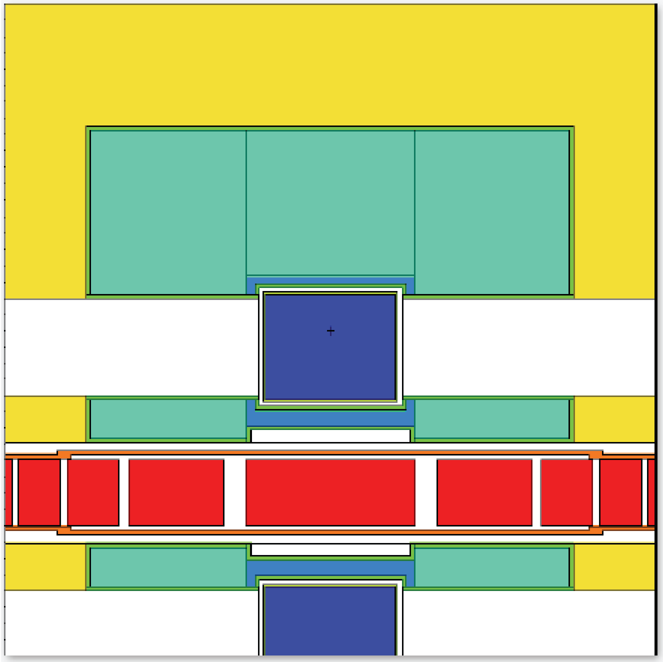
Where is ESS today?

- Budget allocation for Neutron Scattering Systems is 350M€
  - Budget is ring-fenced
  - Consistent with 16 instruments
  - Additional funding needed to get to 22 instruments



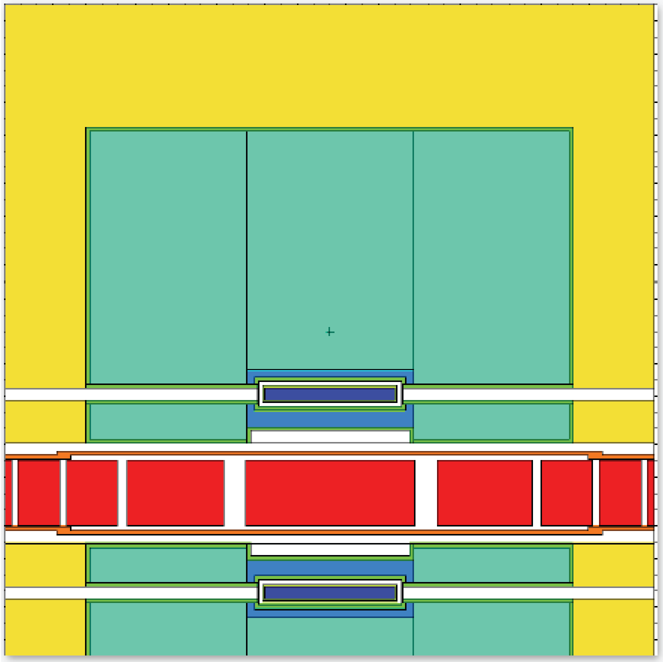
An Aside: Pancake Moderators

Baseline



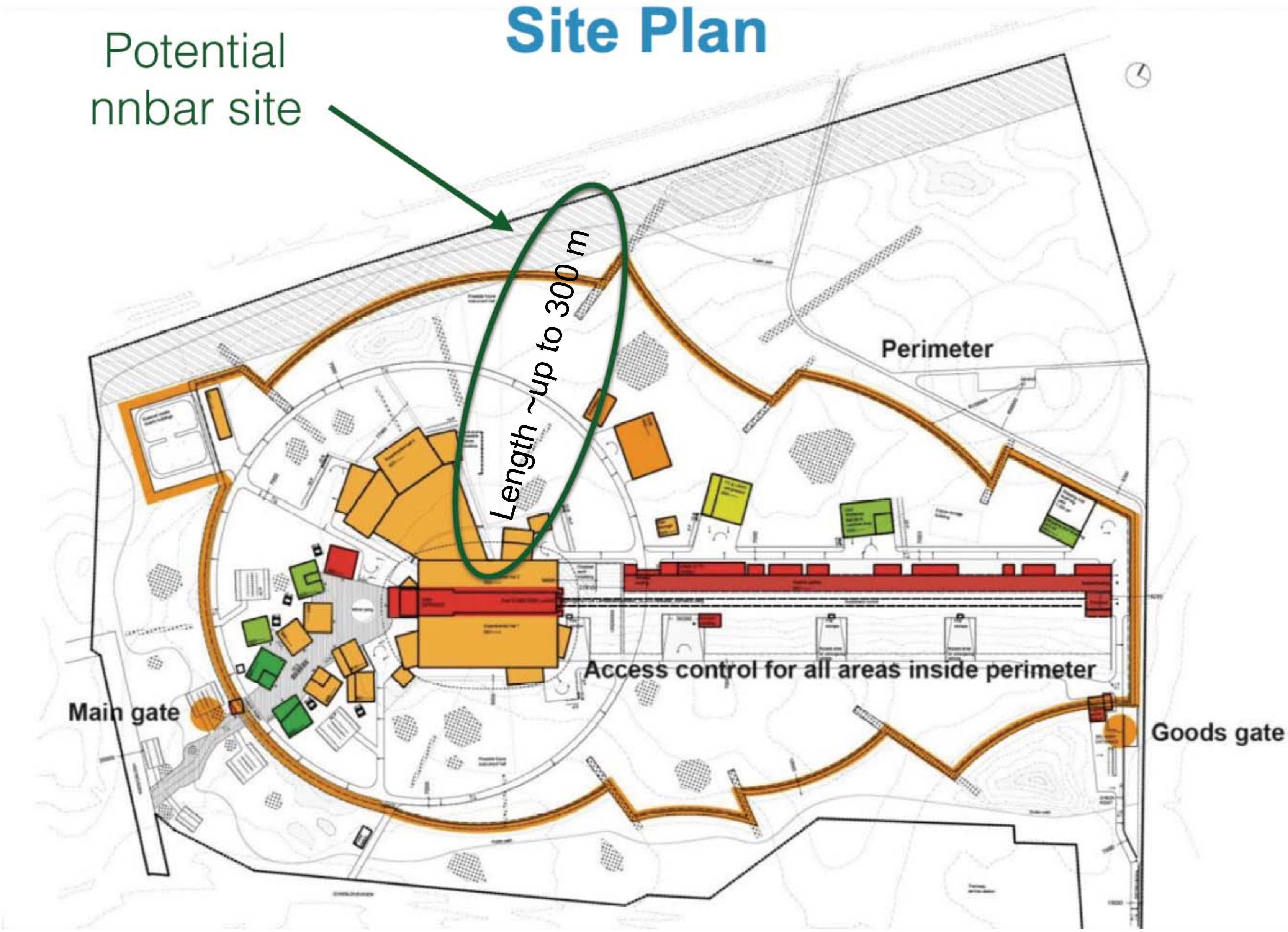
View in proton beam direction
Proton beam comes from behind

Flattened



View in proton beam direction
Proton beam comes from behind

Site Plan



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

ESS TDR Chapter 3, page 177, April 2013

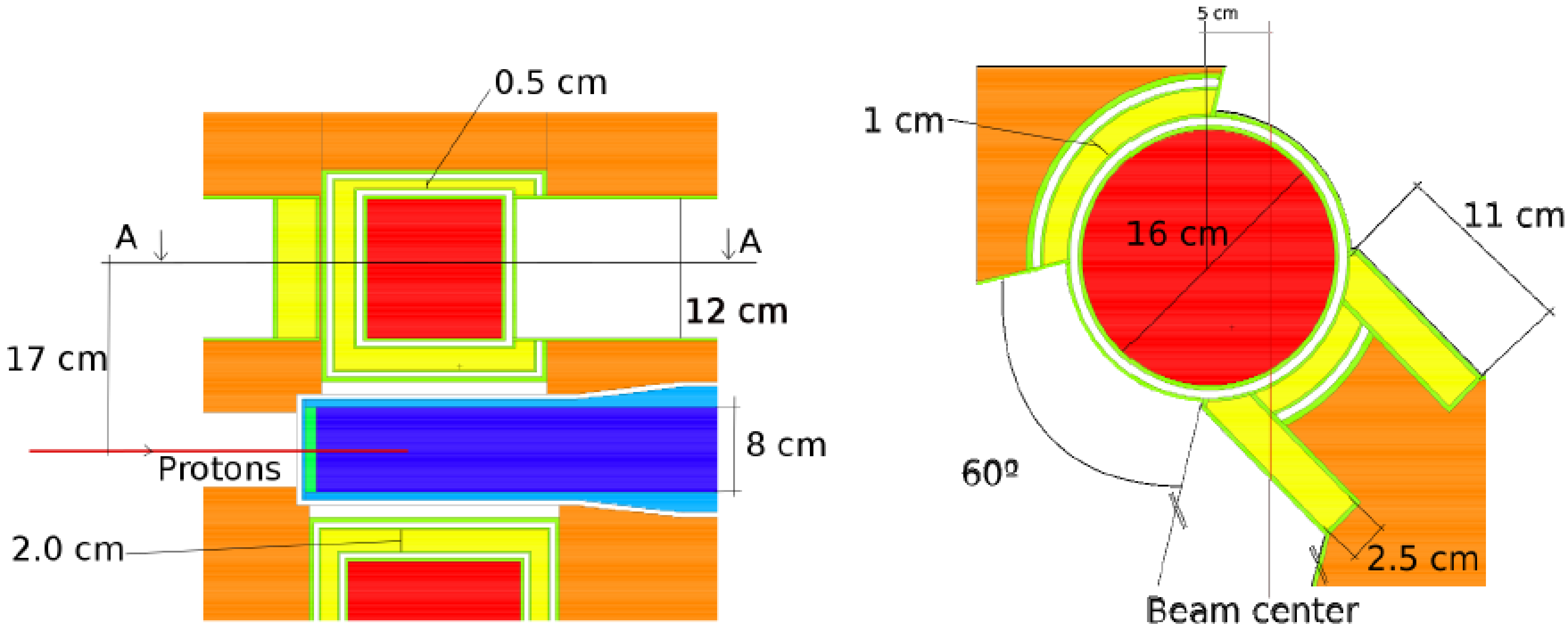
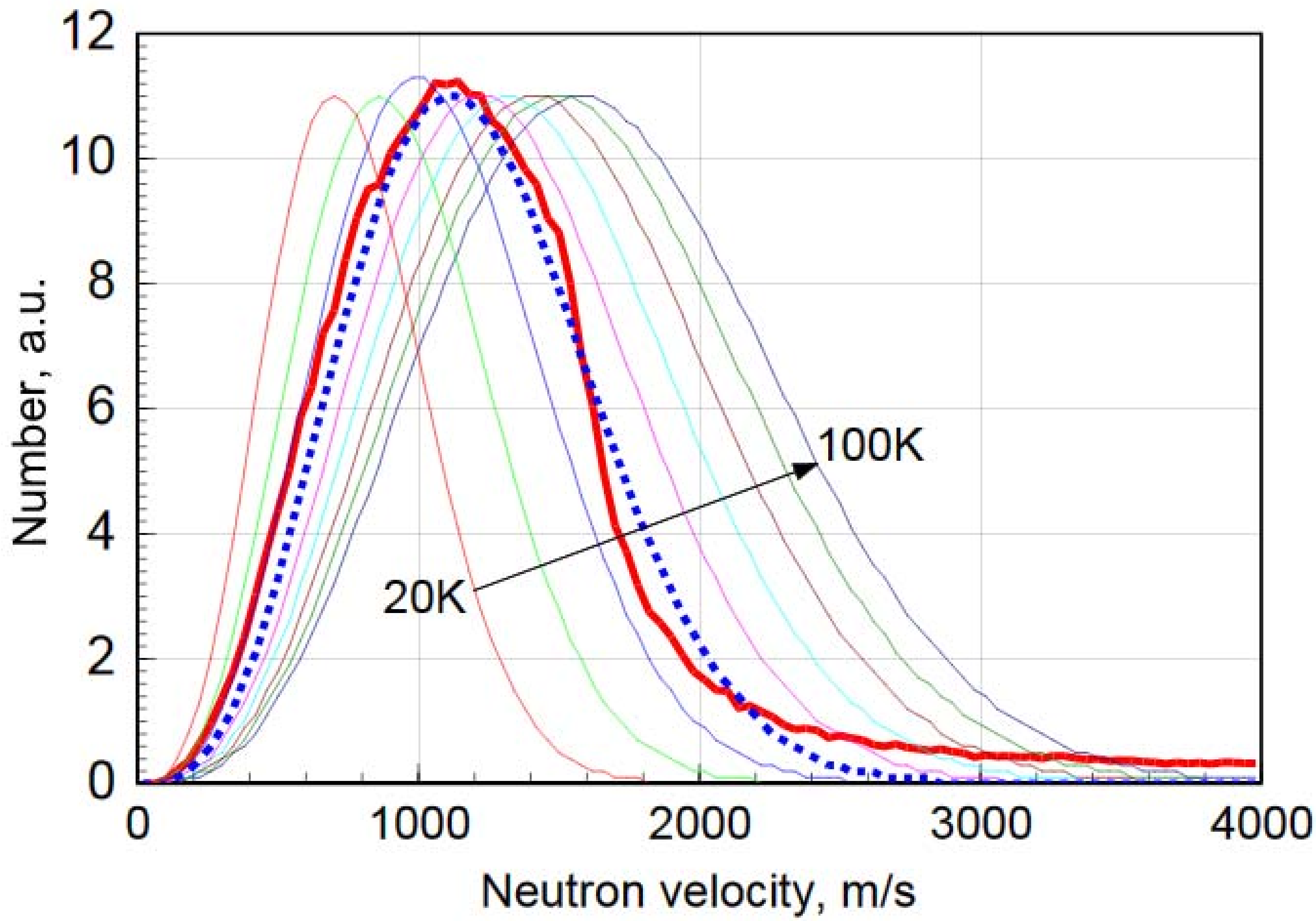
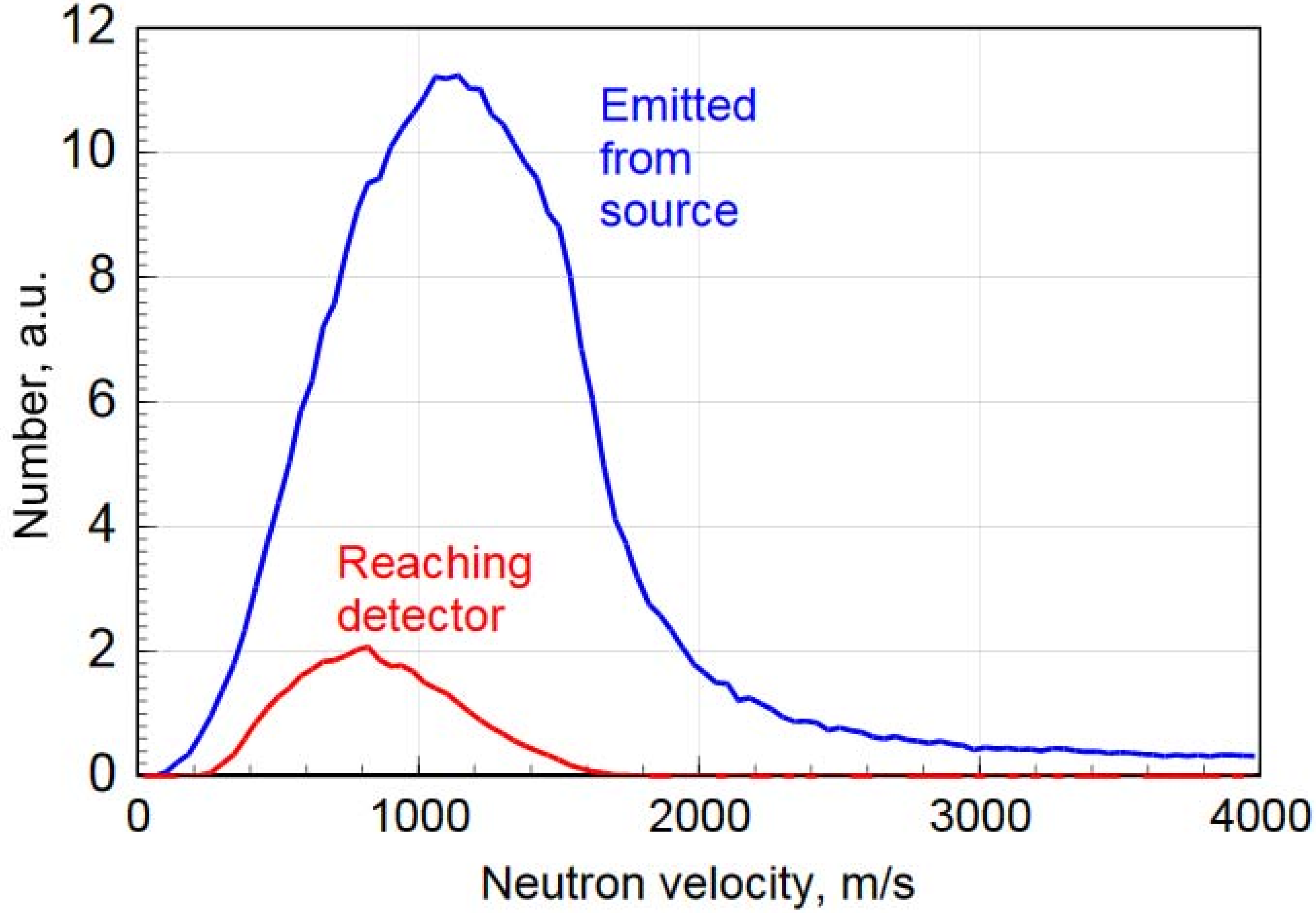


Figure 3.15: MCNPX model of the target and surrounding moderator and reflector. The cold moderator is shown in red, the thermal moderator for bispectral beam extraction and the premoderator are in yellow, and the beryllium reflector is in orange. Left: Longitudinal view. Right: Top moderator showing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

Maxwell-Boltzmann Fit for Spectrum Temparature ~50K

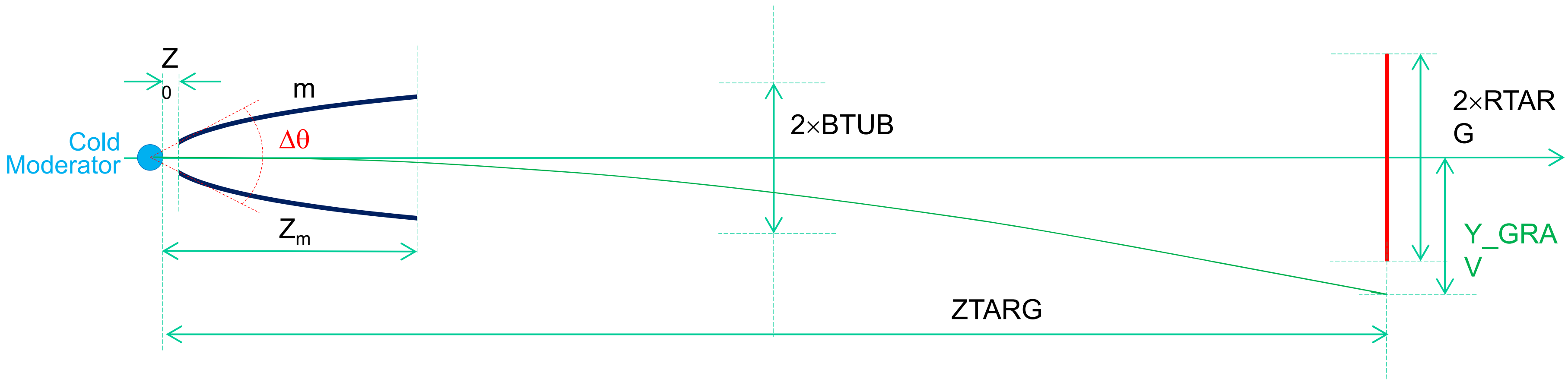


Emitted and Used Neutron Velocities



Mod ①; Z_0 = 4.0 m ; Z_m = 40 m ; ZTARG = 200 m ; RTARG = 1 m ; m=6 ; BTUB = 2.0

Sensitivity Simulation Parameters



1. ESS TDR baseline cold moderator geometry and spectrum (dia 30 cm in PX)
2. Z_0 – distance of reflector start (1.5 m)
3. Z_m – distance of reflector end (40 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 (~ linearly related to $\Delta\theta$ - angular occupancy) (2 m)

Y_GRAV – neutron gravity fall (detector vertical offset) (–0.45 m)

Project X baseline configuration if moved to ESS

Number	PX baseline	with ESS moderator	Comment
Produced per sec 1-40 A (predicted)	7.11E+15	2.75E+16	
Source area in cm^2	706.85 flat disk	326.73 half cylinder	
NTRANS:Generated at the source area	2.445E+08	3.060E+08	
Fraction of used spectrum in 1-40 A	0.7627	0.7693	
NTRANS: Enter reflector	1.233E+07	9.420E+06	Enter reflector/generated "efficiency": 5.03% for PX; 3.07% for ESS
NTRANS: Exit reflector	1.000E+06	1.000E+06	
NTRANS: Hit target ay Y=-0.45 m	156,738	321,179	
NTRANS: <t2>, sec^2	0.0652	0.0687	
Cold fluence through target per sec	5.98E+12	3.75E+13	
NTRANS: Nt2 in ILL units	127	870	with efficiency 50%
		×6.85	

ESS Mod ①; Z_0 = 1.5 m ; Z_m = 40 m ; ZTARG = 200 m ; RTARG = 1 m ; m=6 ; BTUB = 2.0

Limits of NNbar search

$$1 \text{ ILL unit "u" of sensitivity} = N \times \overline{t^2} = 1.5 \times 10^9 \ \frac{n}{s} \cdot s^2$$

#	τ (free nnbar) oscillation parameter	in ILL units of appearance probability
1	0.86×10^8 s	1u
2	3.45×10^8 s	16u
3	7.5×10^8 s	76u
4	2×10^9 s	1800u
5	1×10^{10} s	13,500u
6	1×10^{10} s	13,500u

←Free neutrons at ILL (1994)

←Super-K (2011), 22.5kt, 4 years (bkgr)

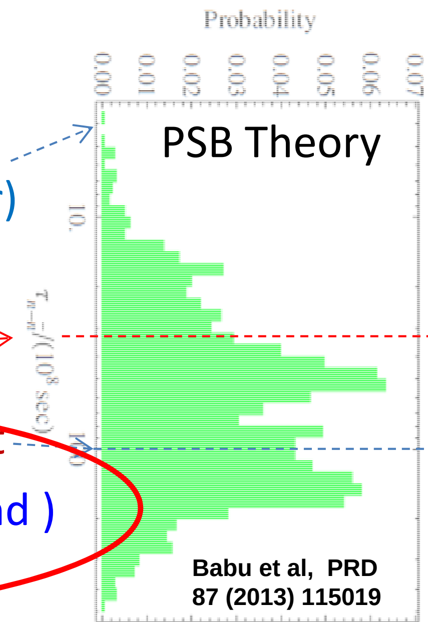
←Hyper-K 500kt, 10 years

←Horizontal beam at ESS

←VCN-UCN source with vertical layout

←LBNE, 35 kt, 10 yr ? (if no background)

Uncertain Future



ESS N-Nbar experiment will give a result in ~ 10 years
and the result might be spectacular