Workshop "Intersections of BSM Phenomenology and QCD for New Physics Searches" at INT UW • Seattle • 24 September 2015

Search for neutron-antineutron transformation with neutron sources.

Experimental view

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Outline

- motivation for BNV
- what we are learning from $\Delta B=1$
- what we can learn from $\Delta B=2$
- view of recent n-nbar theory developments
- n-nbar with free neutrons (present and future)
- n-nbar inside nuclei (present and future)

Observation of Baryon Number Violation is one of the pillars of Cosmology and Particle Physics

We know the BNV had happened but do not know how

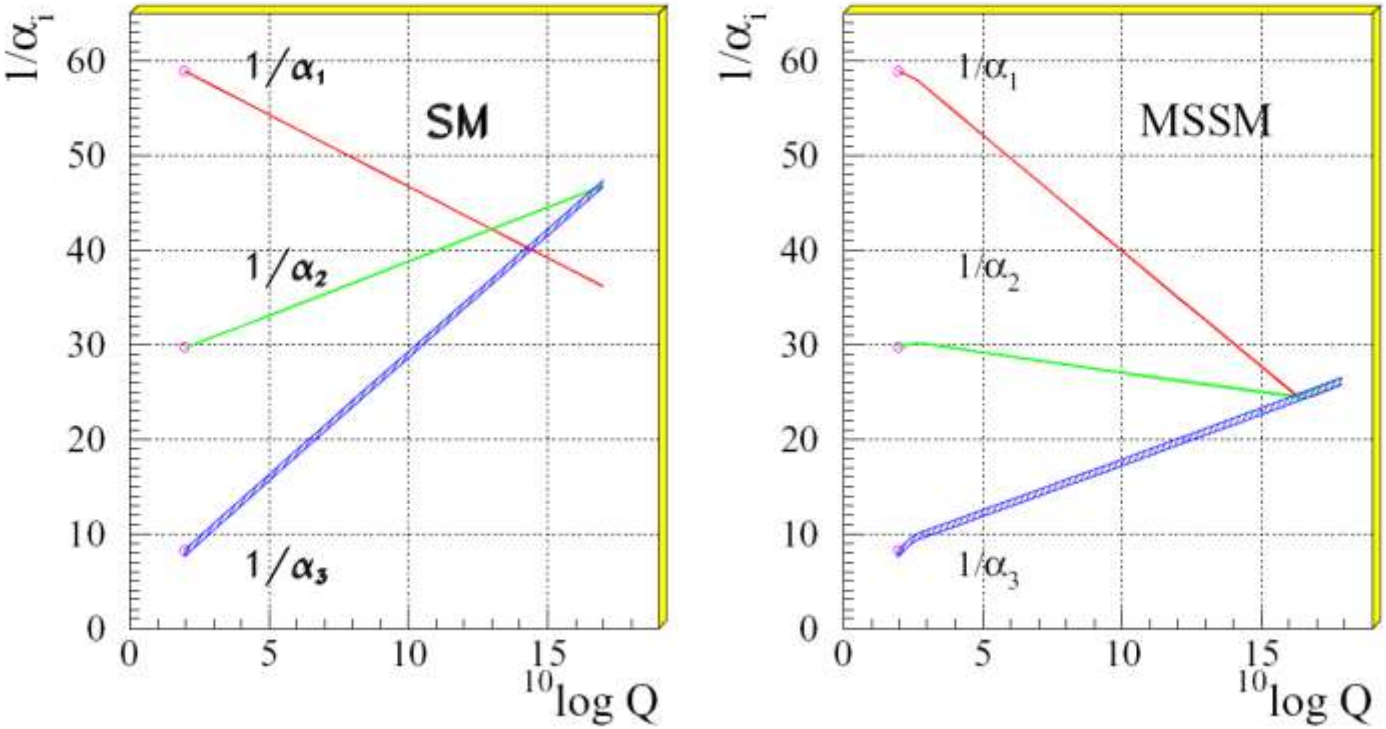
- It follows from the inflation (Dolgov & Zeldovich);
- It is required for explanation of BAU (Sakharov);
- It is present in SM at non-observable level ('t Hooft);
- Majorana neutrinos would violate ΔL=2, thus, implying that (B-L) is conserved in SM, ΔB=2 should exist;
- SO(10) unification includes complementary ΔB = 1 and ΔB = 2 ($n \rightarrow \overline{n}$).

ΔB = 1 or ΔB = 2 ?

$\Delta B = 1$

Unification of the Coupling Constants in the SM and the minimal MSSM

as motivation of the proton decay search

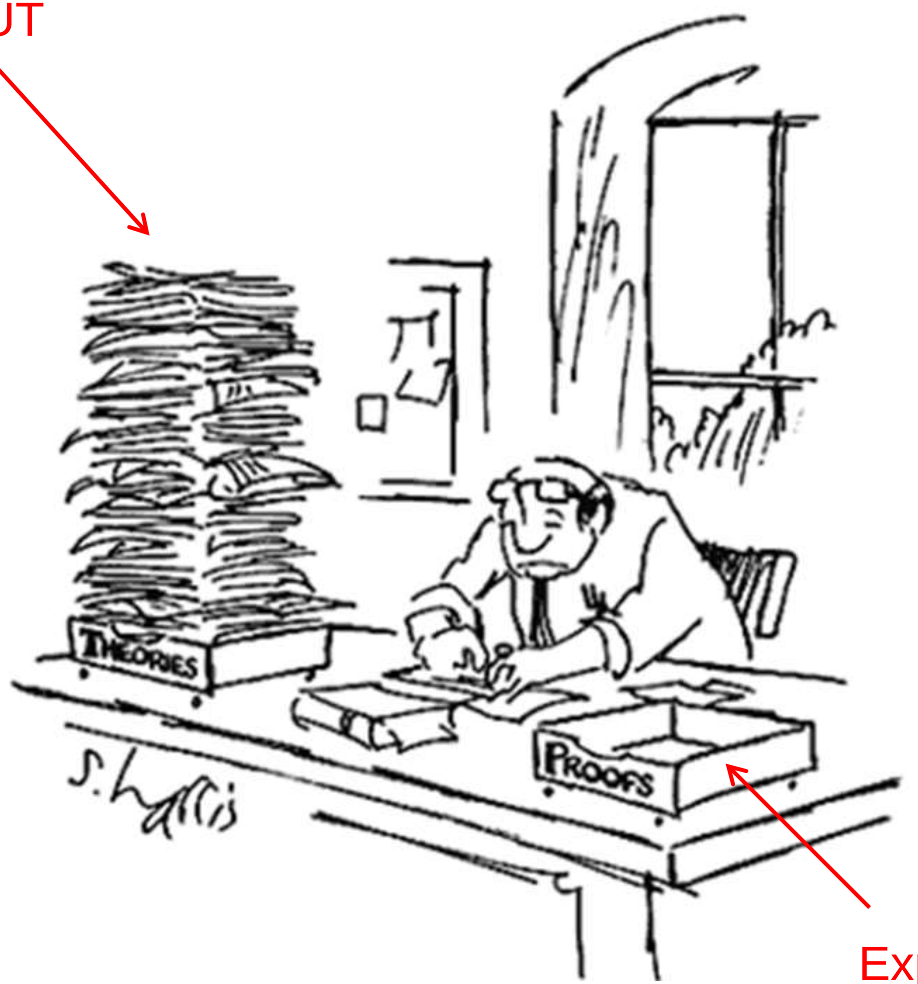


SUSY mechanism can make running coupling constant convergent.
GUT doesn't work without SUSY. But we do not know the scale of SUSY.
Great Desert is a common perception of the energy scale between presently available and the unification scale.

- Why Great Desert should exist?

So far we have no experimental facts that uniquely confirm SUSY or GUT

SUSY and GUT models



Experimental data

Proton Decay and (B–L) Violation

Most of the previous experimental Proton decay searches with $\Delta B = 1$, as motivated by GUT or SUSY-GUT models, were focused on the modes conserving (B – L), i.e. nucleon $\rightarrow$ antilepton + X. So far these searches were not successful.

(B – L) symmetry of the Standard Model must be violated for BAU

(followed from Kuzmin, Rubakov, Shaposhnikov, 1985)

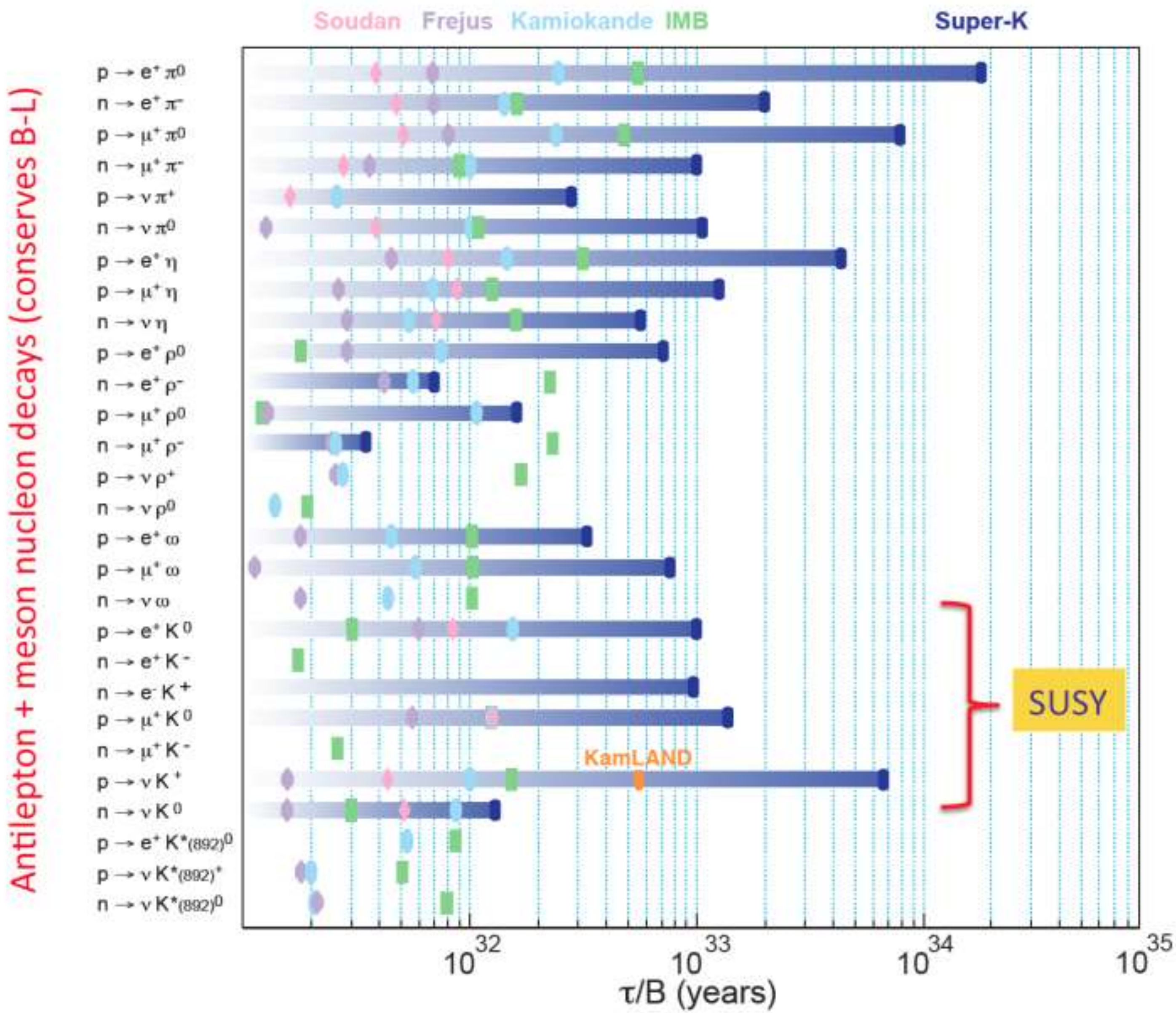
(B – L) is strongly violated in regular matter (#p + #n – #e);
but on the cosmological scale it can be offset by unmeasurable relic neutrino and antineutrino abundances.

Fast V(B+L) by Sphaleron mechanism at electro-weak scale wipes out the results of (B – L) conserving interactions from the higher scale.

$\rightarrow$ "Proton decay is not a prediction of baryogenesis"

From where then we can learn about physics of (B-L)V?

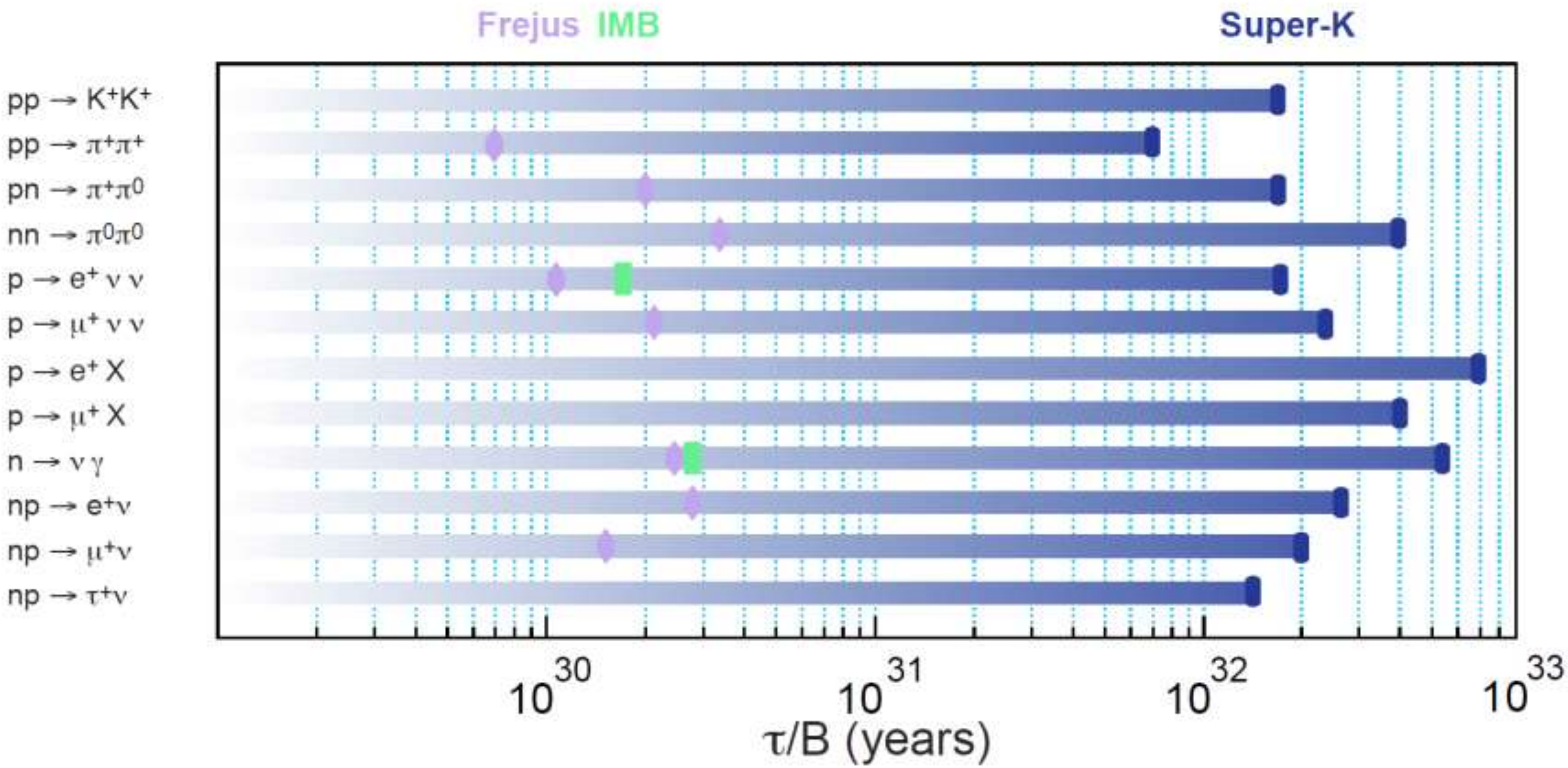
$\Delta B = 1$ Progress in search for (B-L) conserving modes



Ed Kearns, August 2015

Summary of Recent Exotic Searches

$(B-L)V$

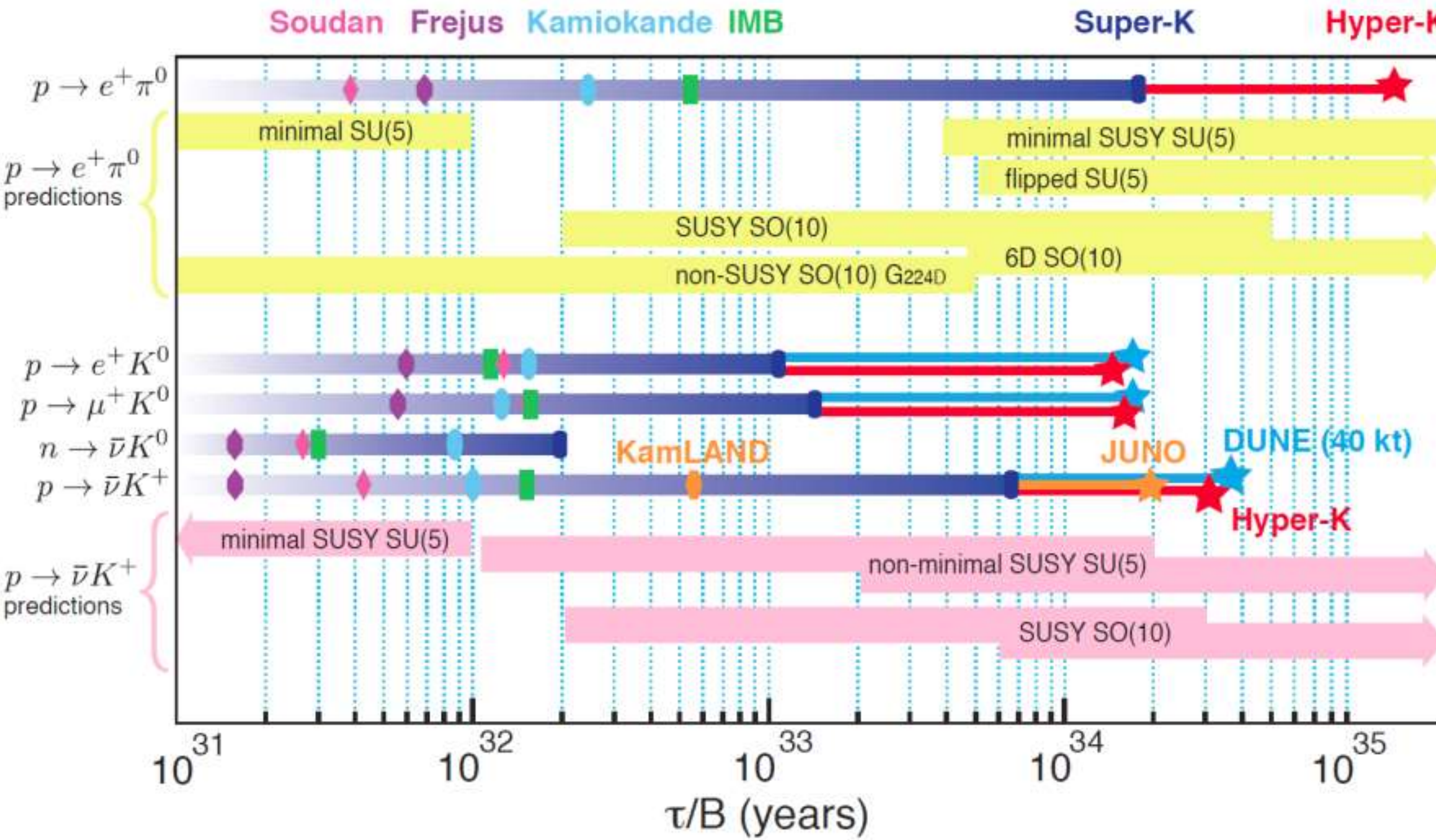


- Generally more than an order of magnitude improvement
- Some searches are entirely new

Ed Kearns, August 2015

Expected progress in (B-L) conserving modes search

Future Benchmark Searches will be in Interesting Territory



Ed Kearns, August 2015

$\Delta B = 2$. Is Neutron a Majorana 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)

But antineutron discovered in 1956 by B. Cork et al. @ LBL was turned out to be a particle different from neutron.

However, the presence of some small fraction of the Majorana component in the neutron wave function can not be excluded, and the question whether $n \leftrightarrow \overline{n}$ should remain.

This mixing fraction must be small (otherwise it would be already observed) unless there are some suppression conditions or mechanisms present.

Some history of $n \leftrightarrow \bar{n}$ $|\Delta B|=2$; $|\Delta(B-L)|=2$

- There are no laws of nature that would forbid the N ↔ Nbar transitions except the conservation of "*baryon charge (number)*"

M. Gell-Mann and A. Pais, Phys. Rev. 97 (1955) 1387
L. Okun, Weak Interaction of Elementary Particles, Moscow, 1963

- N ↔ Nbar -like process was suggested as a possible mechanism for explanation of Baryon Asymmetry of Universe *V. Kuzmin, 1970*

- N ↔ Nbar works within GUT + SUSY ideas. First considered and developed within the framework of L/R symmetric Unification models

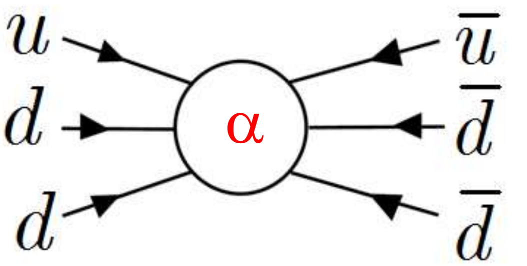
R. Mohapatra and R. Marshak, 1979 ...

- Recent models explaining neutrino masses, B-L violation, low-scale baryogenesis, connecting with dark matter, involving gravity, extra-Ds, predicting new particles at LHC, CPV…

K. Babu, R. Mohapatra; Z. Berezhiani et al; A. Vainshtein ...
A. Dolgov et al; G. Dvali and G. Gabadadze, ...

n→nbar transition probability

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



α-mixing amplitude

All beyond SM physics is here

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

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

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

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

where V is a potential symmetrically different for neutron and anti-neutron (e.g. due to non-compensated Earth mag. field, or as a part of gravipotential); t is observation time in the experiment.

For free neutrons V=0:

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

For neutrons inside nuclei:

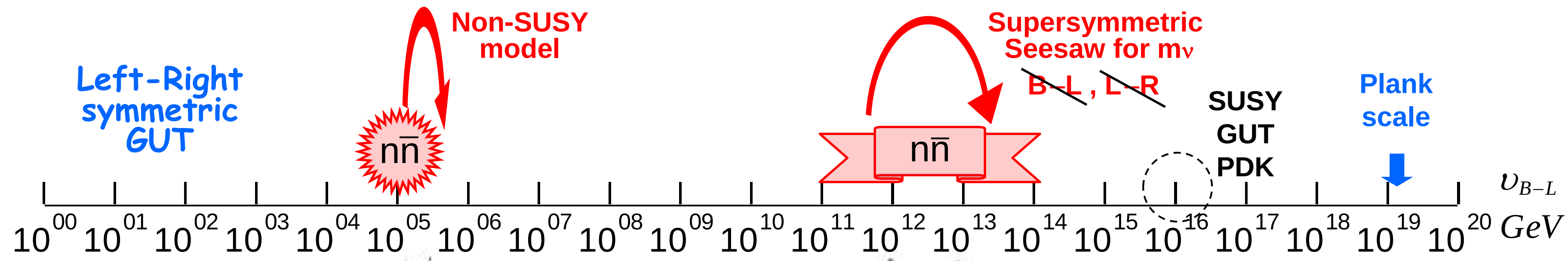
$$P_{n\to\bar{n}} = \frac{\alpha^2}{2V^2}$$

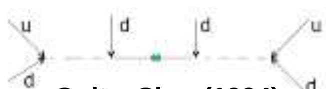
$\tau_{n\bar{n}} = \frac{\hbar}{\alpha}$ is characteristic "oscillation" time [$\alpha < 2\cdot 10^{-24}eV$, as presently known]

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

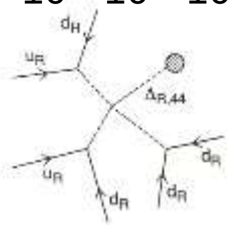
Sensitivity (or figure of merit) is $\rightarrow\ N_n \times \overline{t}^{\,2}$

$Scales\ \ of\ \ n \rightarrow \bar{n}\ \ (B-L)V$



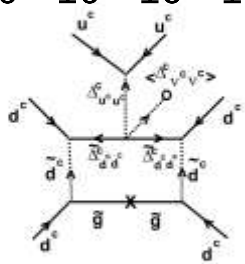


Goity, Sher (1994)



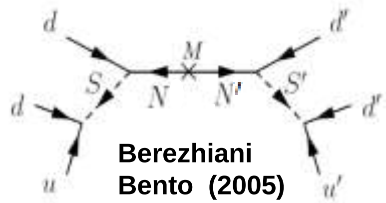
Mohapatra & Marshak (1980)

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



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

Dutta-Mimura-Mohapatra (2005)

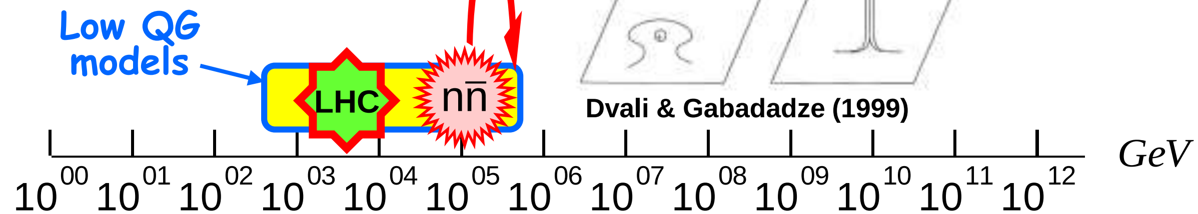


Berezhiani
Bento (2005)

Baryogenesis at TeV scale

Berezhiani et al (2005)
Babu et al (2006)
Dolgov et al (2006)

Dvali & Gabadadze (1999)



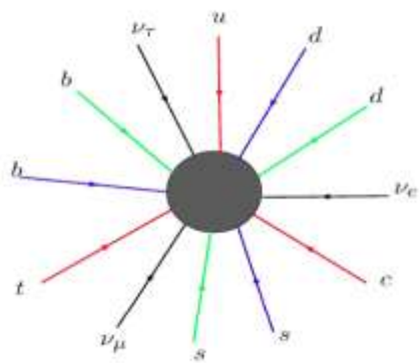
Experimental motivation!
large increase of sensitivity:
factor of 1,000 is possible

From NNbar to Majorana neutrino via sphalerons

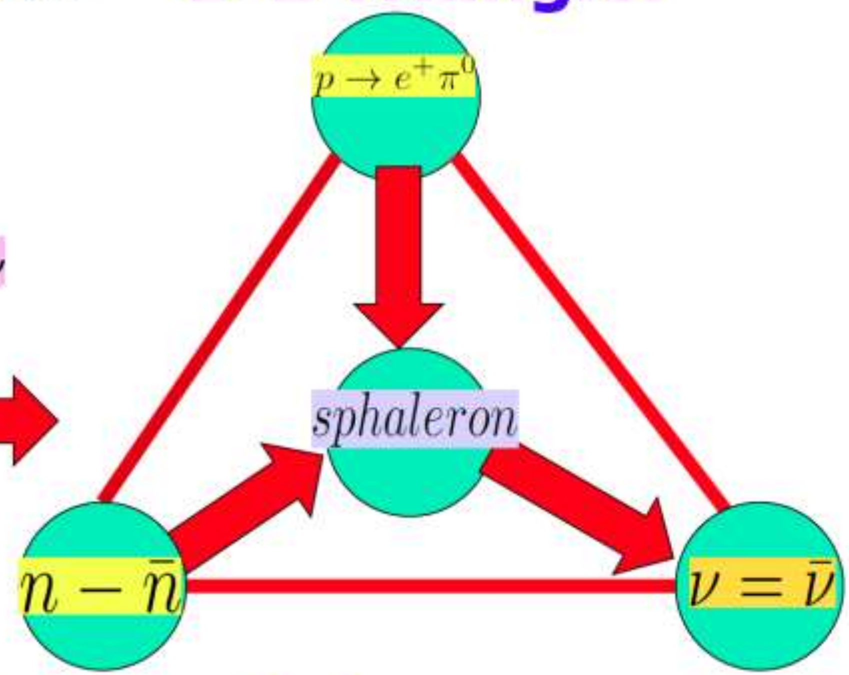
- Sphaleron Op. rewrite

QQQQQQ QQQL LL

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



B-L Triangle:



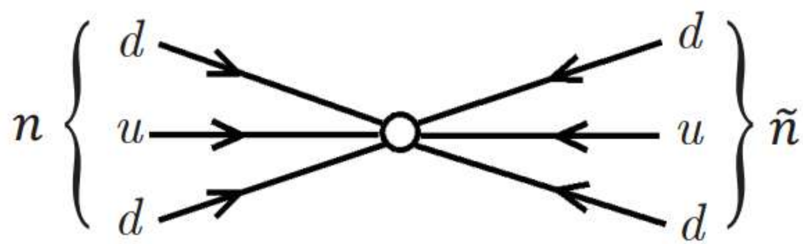
- *p-decay+nn-bar→Neutrino Majorana* (Babu, RNM'14)

Courtesy of Rabi Mohapatra, 2014

Neutron–Antineutron Oscillation as a Signal of CP Violation

Zurab Berezhiani[1,2] and Arkady Vainshtein[3,4,5]

arXiv:1506.05096v2 [hep-ph] 2 Aug 2015



$$\not{C}\not{P} = \not{C}\not{P}$$

<u>3 Sakharov's Conditions for BAU in n-nbar:</u>

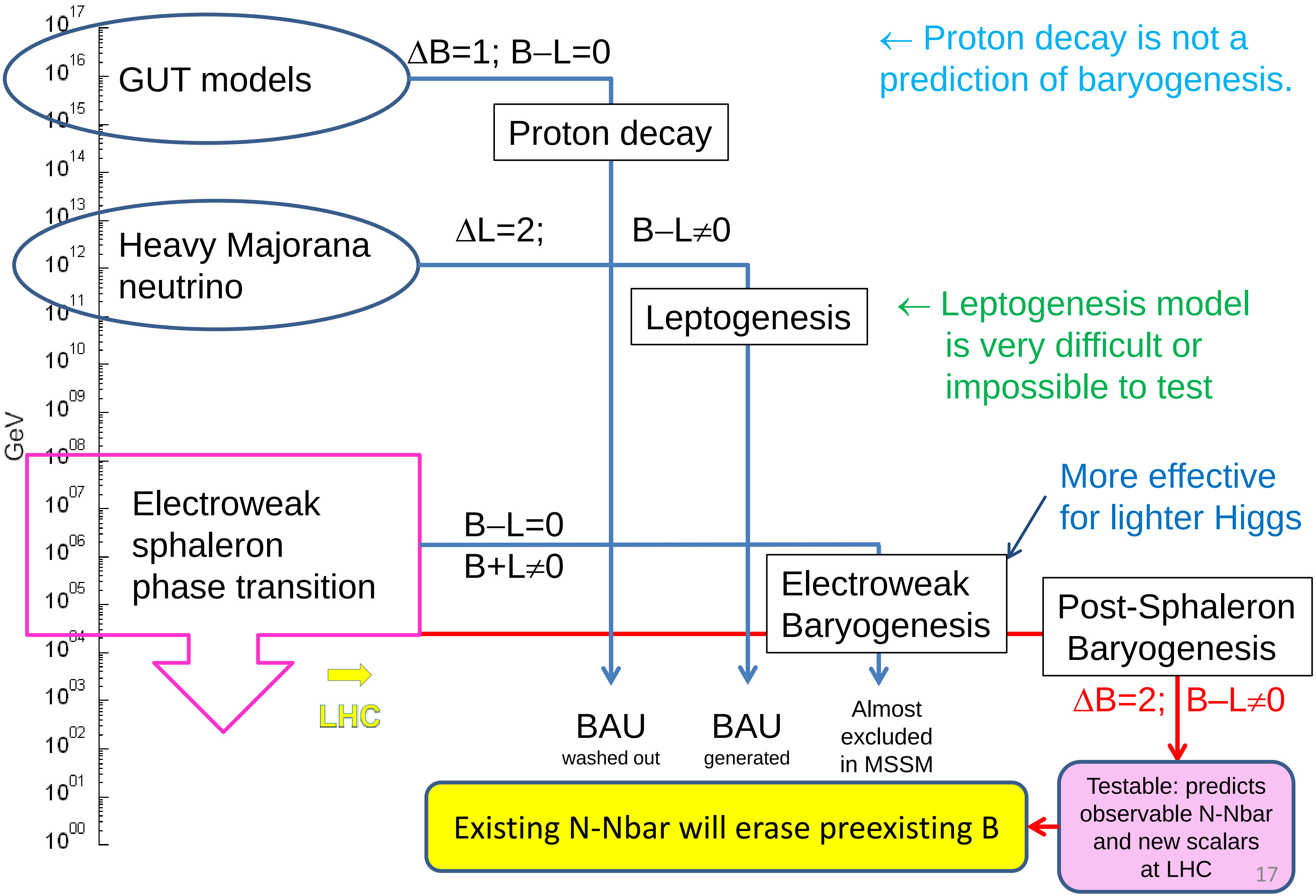
(1) BN violation with $\Delta B = 2$ ✓

(2) CP violation ✓

(3) Out of thermodynamic equilibrium (for d(9) operator) ✓

Now we have a new viable framework for baryogenesis models

Baryogenesis Models

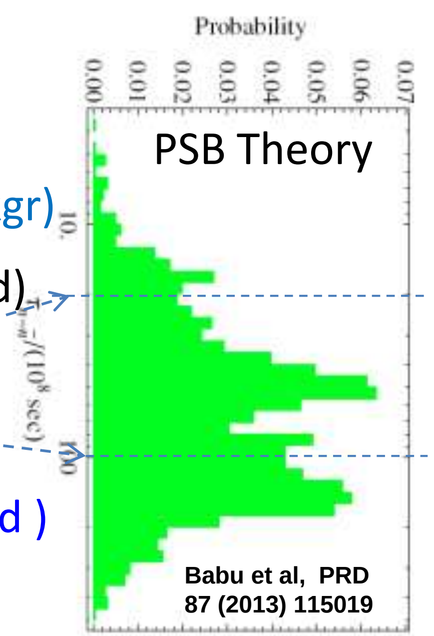


Babu et al, PRD 87 (2013) 115019

Limits of NNbar search

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

#	□ (free nnbar) oscillation parameter	in ILL units of appearance probability	
1	0.86×10^8 s	1u	←Free neutrons at ILL (1994)
2	2.7×10^8 s	10u	←Super-K (2015), 22.5kt, 4 years (w bkgr)
3	7.5×10^8 s	76u	←Hyper-K 500kt, 10 years (background)
4	2×10^9 s	500u	←Horizontal beam (ESS, 3 yr)
5	1×10^{10} s	13,500u	←VCN-UCN source with vertical layout
6	1×10^{10} s	13,500u	←LBNE, 40 kt, 10 yr ? (if no background)



Searches with free and bound neutrons are complementary

Small summary of Theory discussion

n-nbar theory: GUT and SUSY based; there are models providing upper limits and thus experimentally testable; connection with Majorana neutrino masses, violation of (B-L), relevant for BAU + $\not{CP}$.

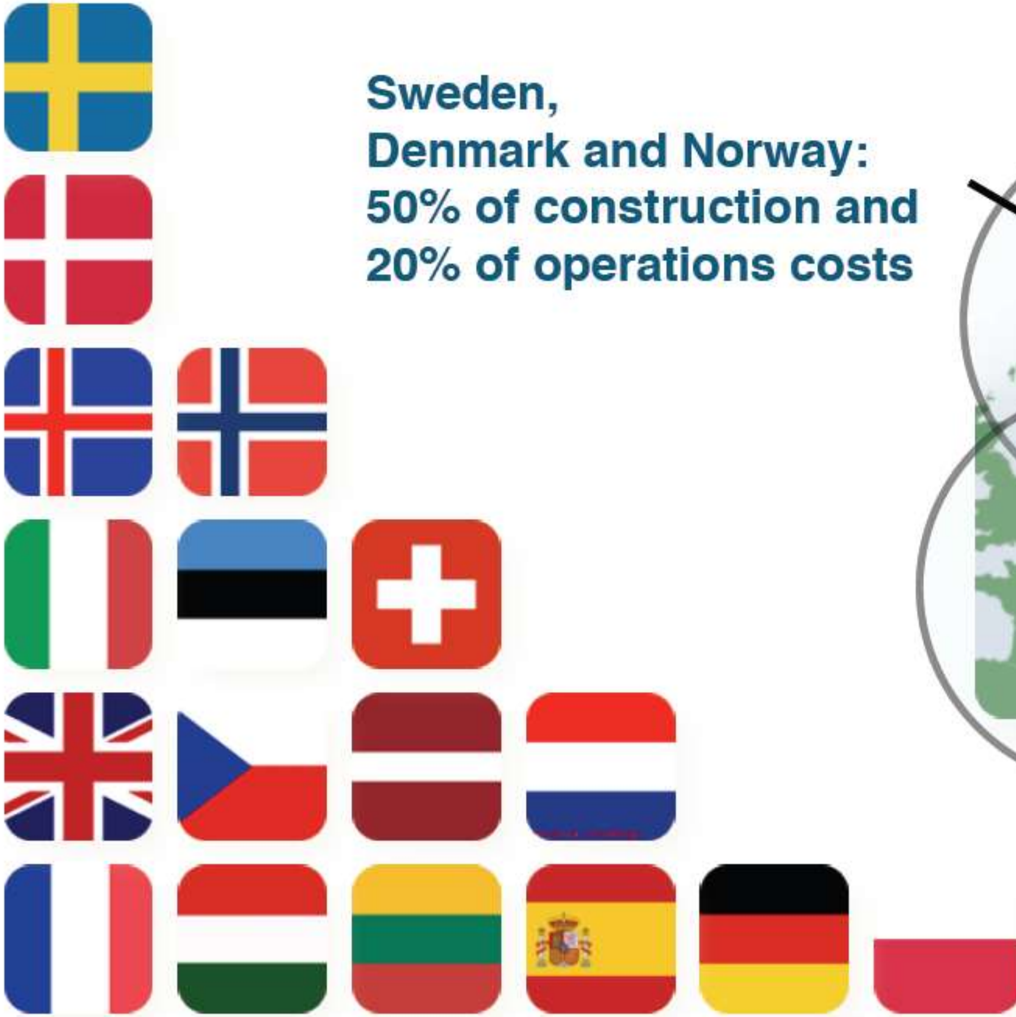
Proton decay theory: GUT and SUSY based; several extendable predictions; focused on (B-L) conservation modes not relevant for BAU.

1. Experimental N-Nbar search with free neutrons

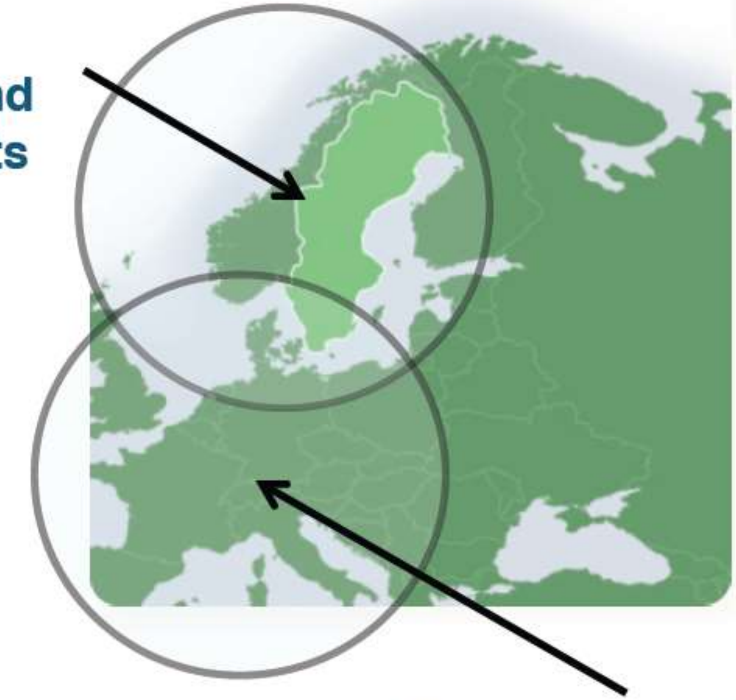
Construction started in 2014
to be completed by 2019

ESS

An International Collaboration



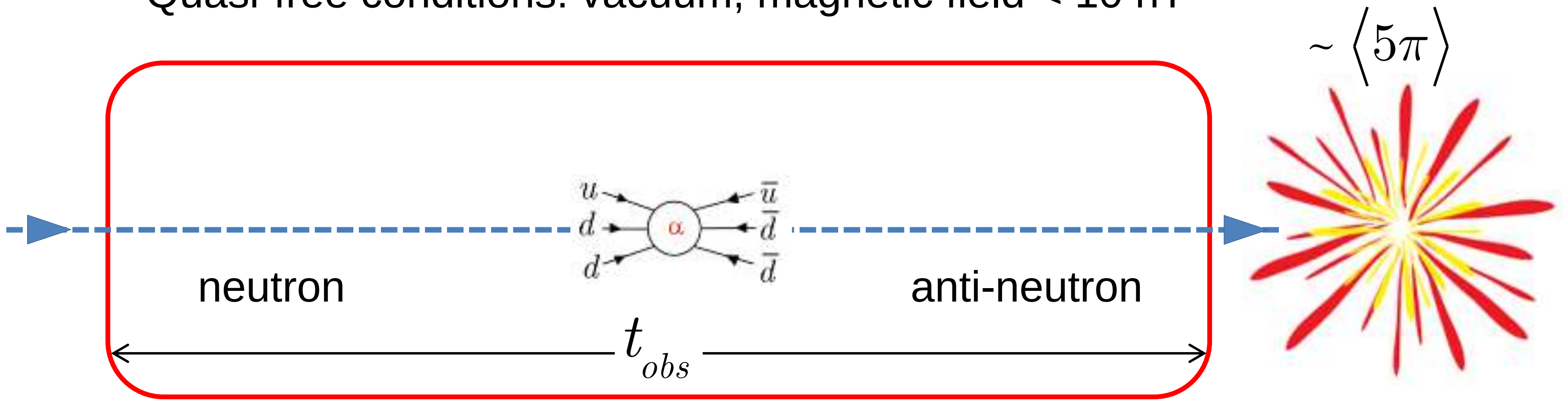
Sweden,
Denmark and Norway:
50% of construction and
20% of operations costs



European partners
pay the rest

Free neutron transformation

Quasi-free conditions: vacuum, magnetic field < 10 nT



Observation
of annihilation

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

Present $\tau > 8.6 \times 10^7$ s (ILL limit) $\rightarrow$ $\tau > 4 \times 10^9$ s (@ ESS)

or sensitivity $(P_{n \to \bar{n}})$ can be increased by factor of $> 1{,}000$

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

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 !

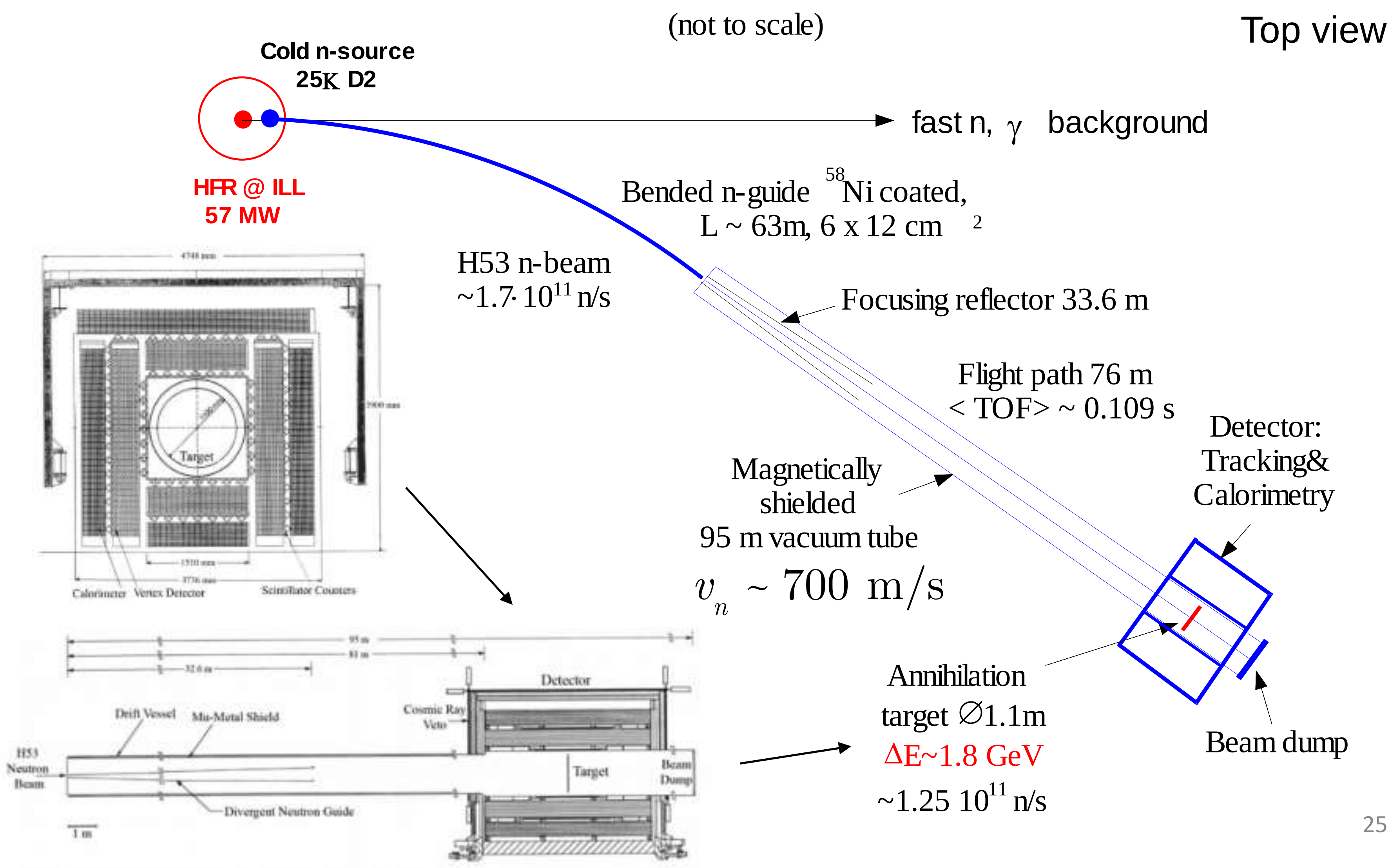
Measured limit for one year of running: $\tau_{n\bar{n}} > 0.86 \times 10^8 s$

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

N-Nbar search experiment with free neutrons

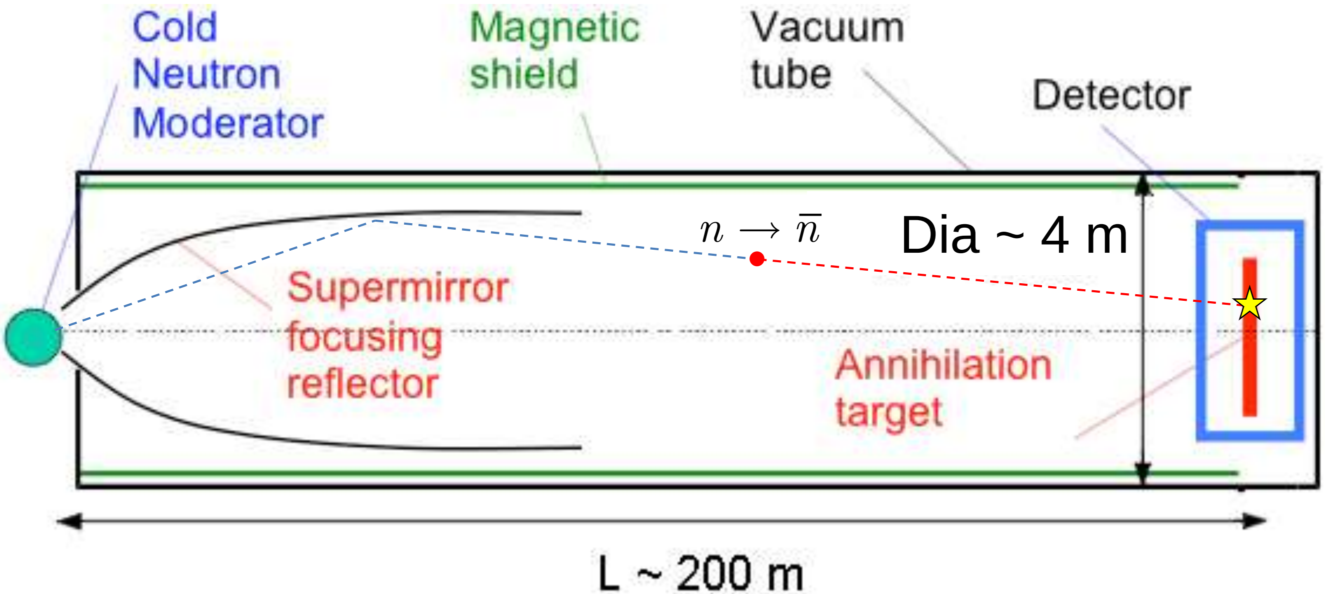
at ILL/Grenoble reactor in 89-91 by Heidelberg-ILL-Padova-Pavia Collaboration

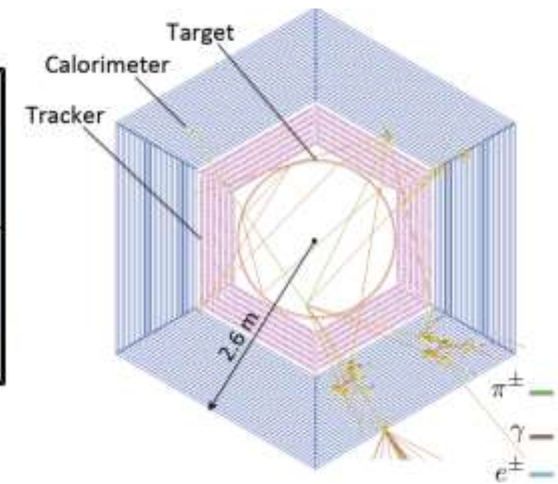
M. Baldo-Ceolin et al., Z. Phys., C63 (1994) 409



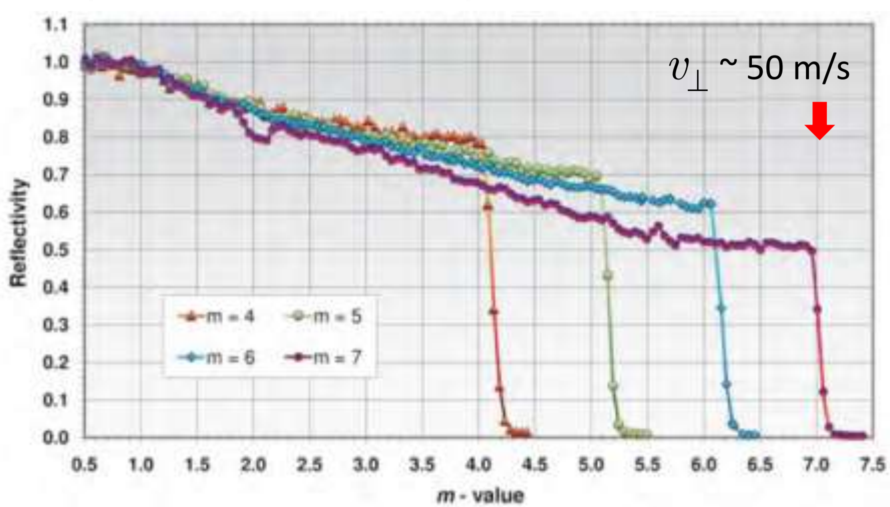
Idea of sensitivity enhancement

Y. Kamyshkov *et al.*, Proceedings of the ICANS-XIII meeting of the International Collaboration on Advanced Neutron Sources, PSI, Villigen, Switzerland, October 11-14, p. 843 (1995).





Super-mirrors: commercial products of Swiss Neutronics



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

m is up to 7

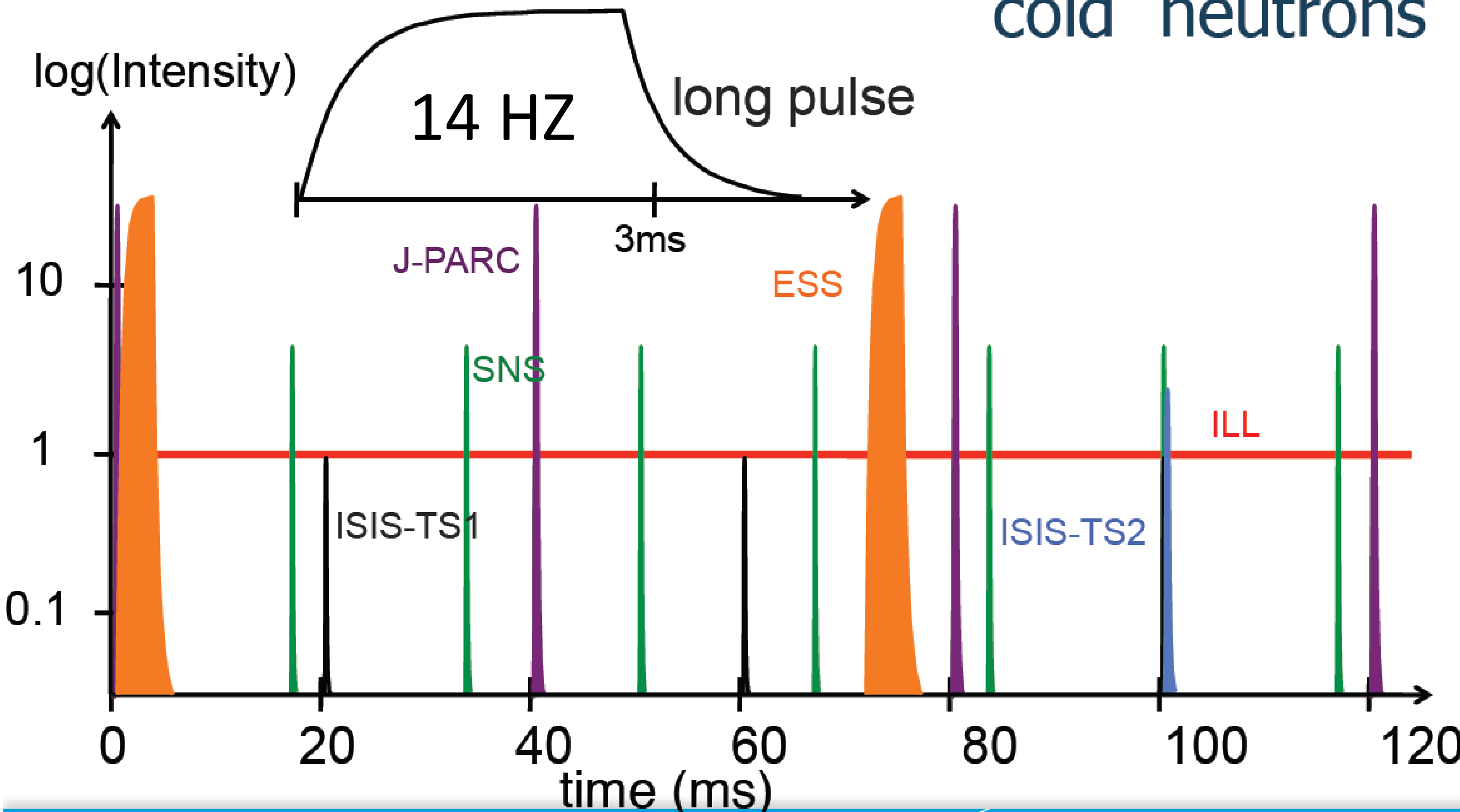
Continuing advancements in neutron optics.

The ESS Headlines

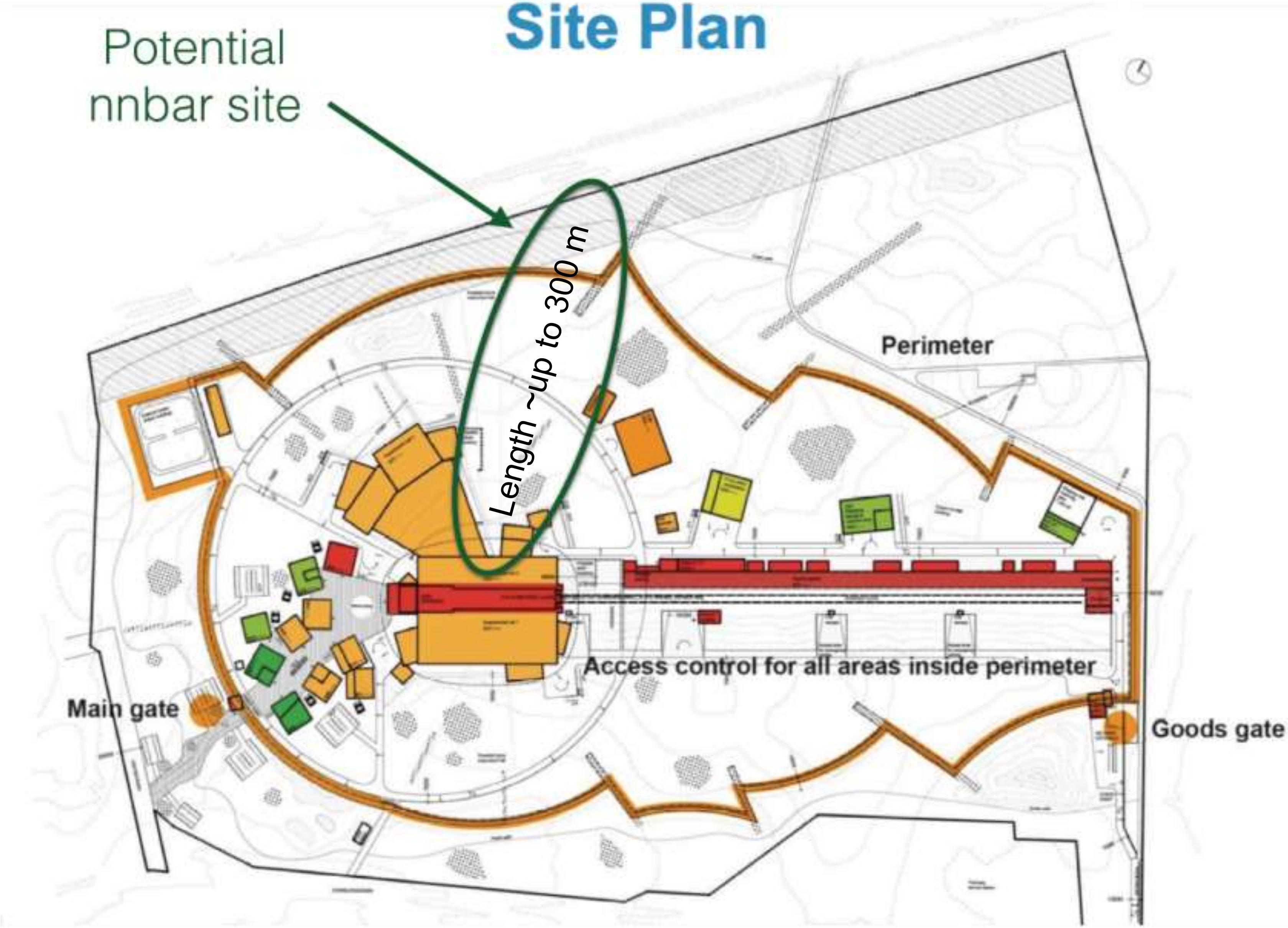
- A neutron source for the study of materials
- ESS scope is defined in Technical Design Report (2013)
  - 5 MW accelerator capability
  - Superconducting Linac: 2.3 GeV
  - Rotating solid W target
  - Time-structure: 14Hz, 2.86ms pulse length
  - First neutrons in 2019
  - Construction cost of 1843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

Groundbreaking on September 2, 2014

Pulsed-source time structures
cold neutrons

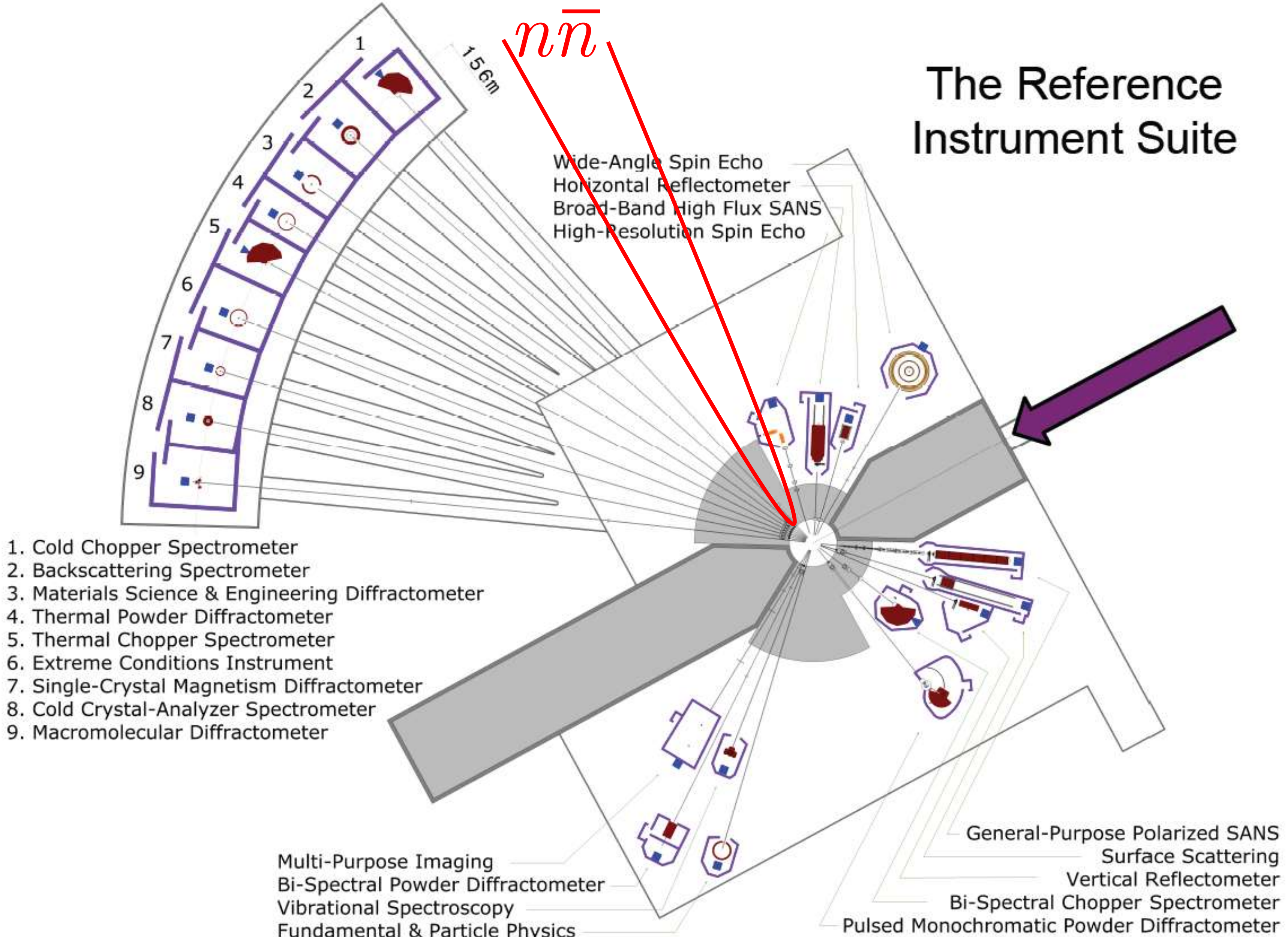


Site Plan



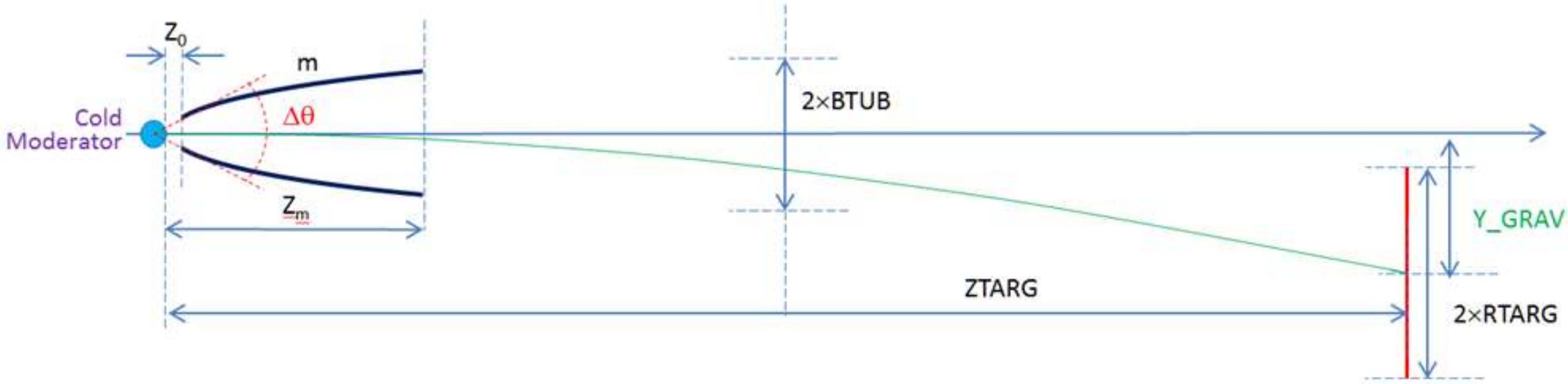
Potential
nnbar site
Length ~up to 300 m
Perimeter
Access control for all areas inside perimeter
Main gate
Goods gate

The Reference Instrument Suite



Ken Andersen, Dec 2013

Sensitivity Variation Parameters



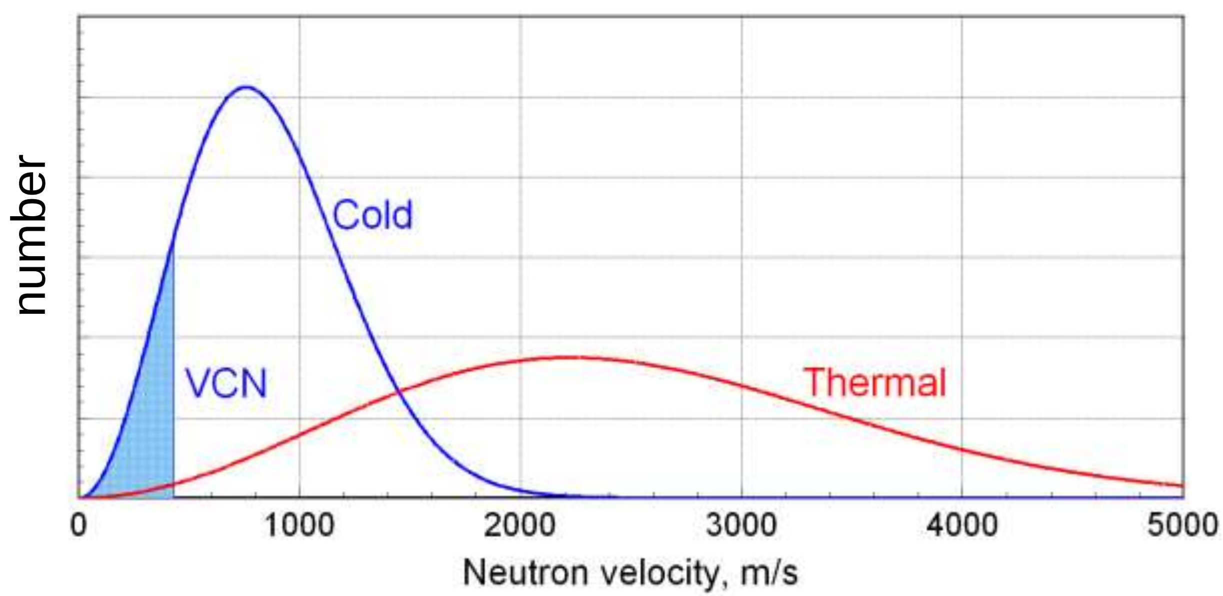
1. ESS TDR baseline cold moderator geometry and spectrum (dia 30 cm in PX)
2. Z_0 – distance of reflector start (1.5 m)
3. Z_m – distance of reflector end (40 m)
4. m – supermirror reflector parameter (m=6)
5. ZTARG – distance moderator-detector = 2×large demi-axis (200 m)
6. RTARG – radius of the annihilation 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)

Sensitivity for $n\bar{n} \sim N \cdot \overline{t}^{\,2}$

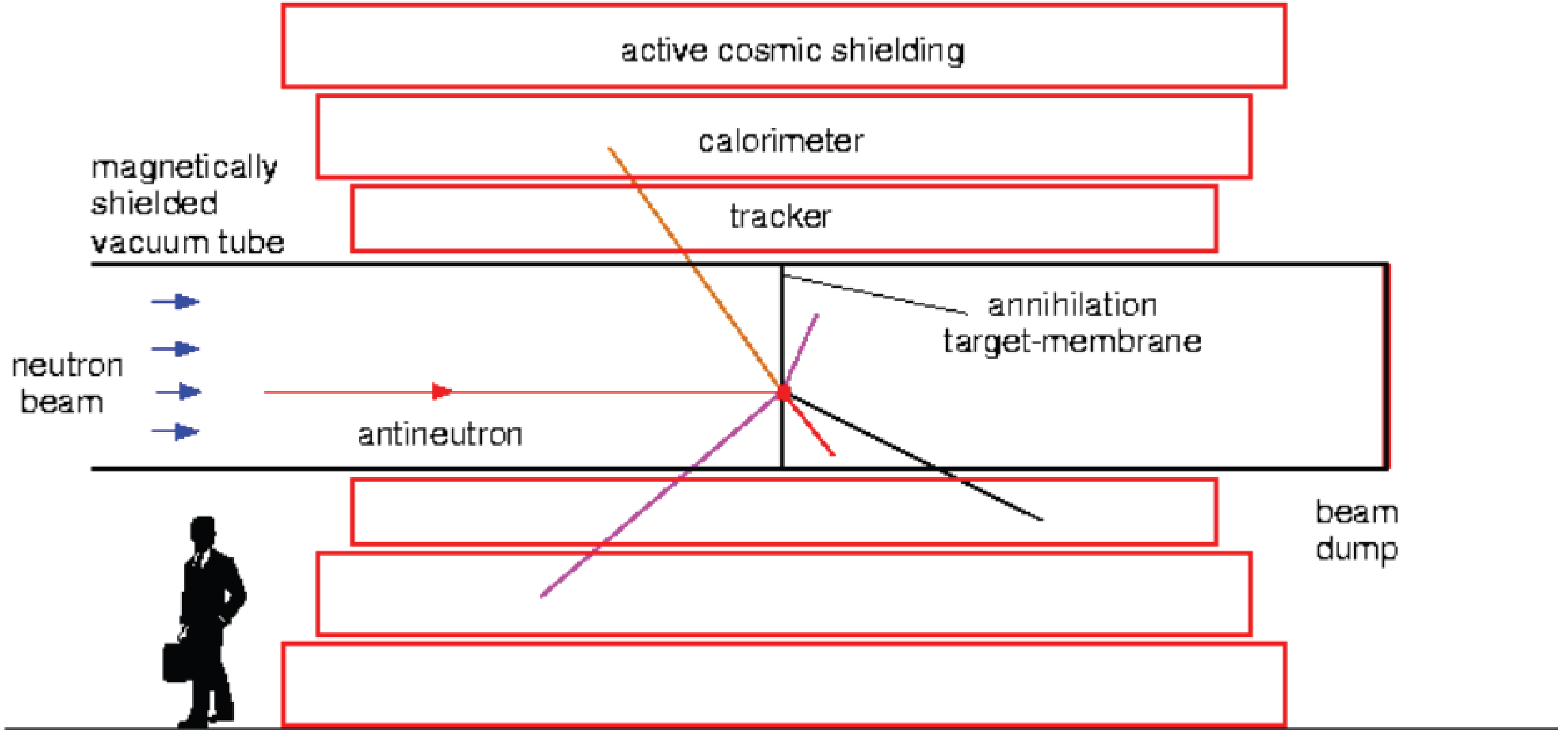
$\Rightarrow$ many neutrons (large N) and very slow(large $\overline{t}$)

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)	~ 1 meV	~ 10	~ 430 m/s	~ 9 Å
Ultra Cold (UCN)	~ 250 neV	~ 0.003	~ 8 m/s	~ 600 Å



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

×100 times higher flux of neutrons than at ILL



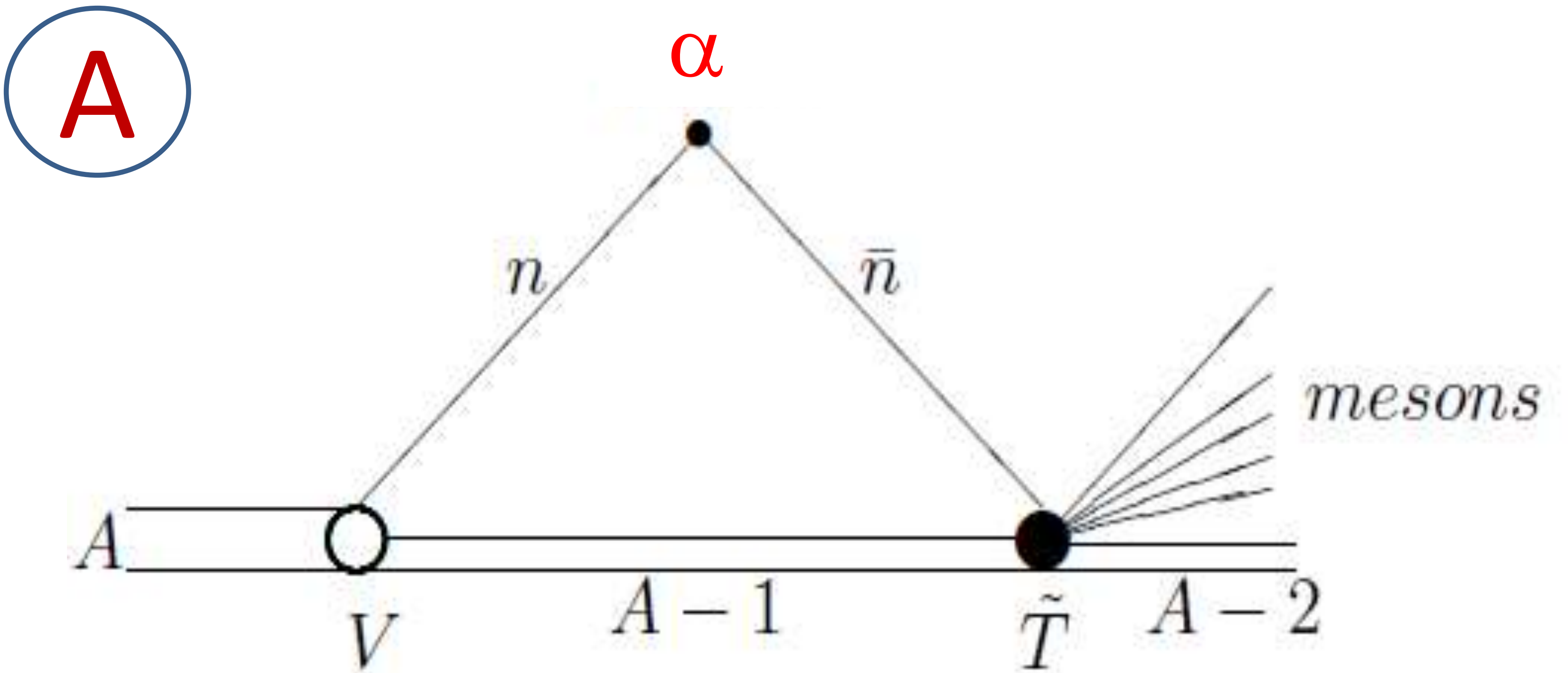
$$\bar{n} + A \rightarrow \langle 5 \rangle \; pions \quad (1.8 \text{ GeV})$$

Annihilation target: ~100μ thick Carbon film

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

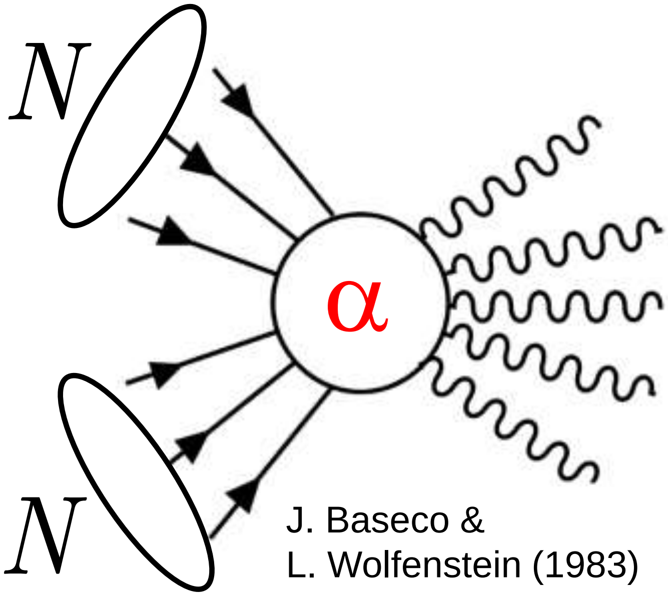
vertex precisely defined. No background was observed at ILL

2. N-Nbar inside nuclei



B

$$2N \longrightarrow pions$$



$\langle 5 \rangle \pi$ ' s

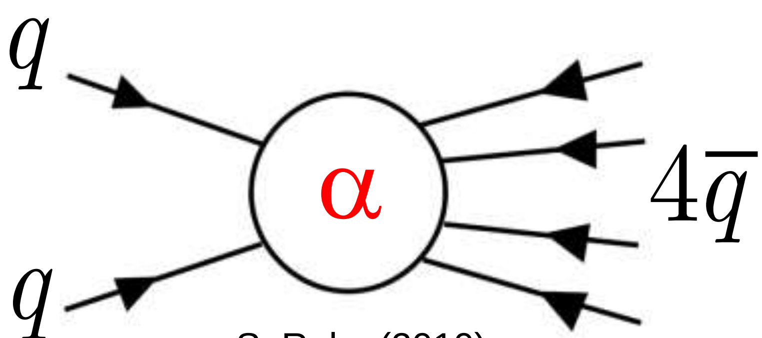
J. Baseco &
L. Wolfenstein (1983)

Same amplitude
as for $n \longrightarrow \overline{n}$

Intranuclear experiment can see similar pions final states.

Crossing channel of $n \to \bar{n}$

C



S. Raby (2010)

Annihilation to ~ 5 pions

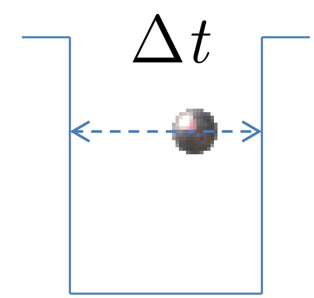
This can occur in nuclei but not with free $n \to \bar{n}$

On another side this crossing channel is included in $n \to \bar{n}$ amplitude

However, free neutron transformation violate CP and intranuclear transformation can be CP even. Thus, potentially A+B+C might be different processes that need to be evaluated independently, e.g. for comparison of free neutron oscillation time with intranuclear data.

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

Neutrons inside nuclei are "free" for the time: $\Delta t \sim \dfrac{\hbar}{E_{well}} \sim \dfrac{\hbar}{30MeV} \sim 2.2 \times 10^{-23} s$



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.

Transition 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 transition (exponential) lifetime:

$$\tau_{\mathrm{A}} = \frac{\tau_{n\bar{n}}^2}{\Delta t} = R \times \tau_{n\bar{n}}^2$$

where $R \sim \dfrac{1}{\Delta \mathrm{t}} \sim 4.5 \times 10^{22} s^{-1}$ is "nuclear suppression factor"

Theoretical calculations of nuclear suppression factor

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

- C. Dover, A. Gal, J. Richard (1989 -1996) used by S -K publication
- W. Alberico et al (1985-1998) $\swarrow\!\!\nearrow$ agreed
- B. Kopeliovich and J. Hufner (1998): uncertainty factor of 2
- E. Friedman and A. Gal (2008): for O change by factor of 2, $\pm 15\%$
- V. Kopeliovich, I. Potashnikova (2011) - recent for D_2 (to be used for SNO)
- B. Kopeliovich, A. Vainshtein (2012 -13) - not published

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

$R(\text{naive}) \sim 4.5 \times 10^{22} s^{-1}$ (see previous slide)

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

Free neutron and bound neutron n-nbar searches are complementary; the difference can reveal new physics.

Suppose that n-nbar exists and intranuclear and free n-nbar almost agree.

$\rightarrow$ Spectacular discovery by itself …

$\rightarrow$ It will test the prediction of the nuclear models for suppression;

$\rightarrow$ Free n-nbar transformation might be sensitive or not to mag. field;

$\rightarrow$ If yes then it is possible to switch ON and OFF the effect;

$\rightarrow$ Suppression as function of mag. field might reveal effects of very high energy scale: $\Delta m \sim \frac{\hbar}{1\,s} \sim 4 \times 10^{-15}$eV ; $\frac{\Delta m}{m_n} \sim 4 \times 10^{-24}$ can compare with $\frac{m_n}{m_{Pl}} \sim 10^{-19}$

$\rightarrow$ Intranuclear n-nbar is not sensitive to mag. field ($\Delta\mu B \ll \Delta V_{nucl}$);

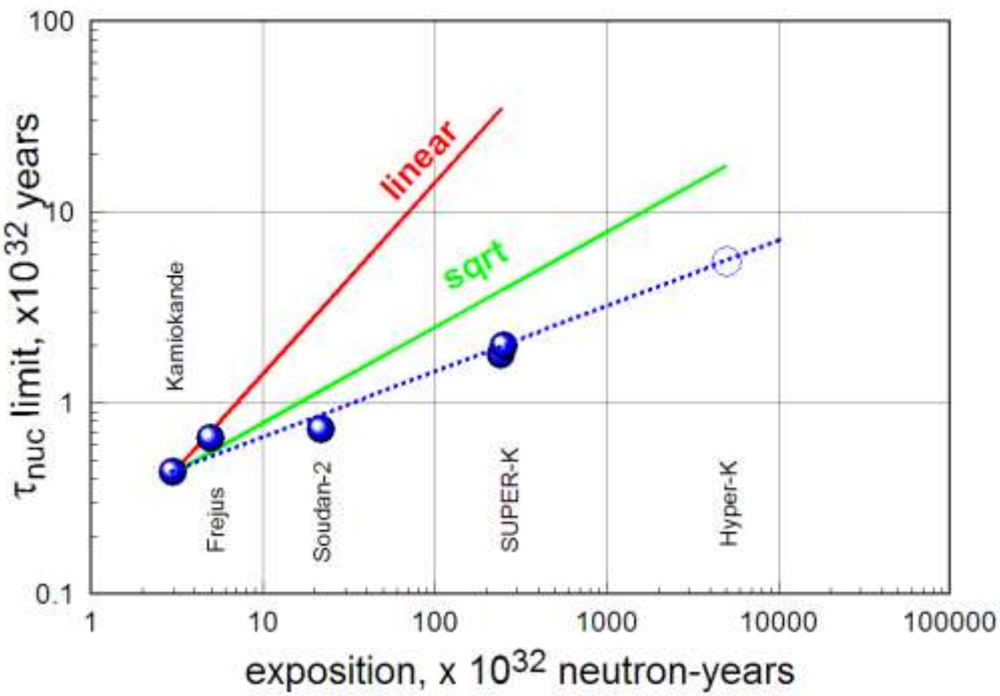
$\rightarrow$ Completely new ideas:

e.g. Z. Berezhiani, **Neutron-antineutron Oscillation and Baryonic Majoron: Low Scale Spontaneous Baryon Violation**, arXiv: 1507.05478

Neutron-antineutron transformations inside nuclei that are normally suppressed by nuclear potential can be enhanced or be non-existent due to baryonic violation condensate.

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	$>0.72\times10^{32}$
Super-K	2007	O	245.4	10.4%	20	21.3	$>1.8\times10^{32}$
Super-K	2009	O	254.5	12%	23	24	$>1.97\times10^{32}$
SNO *	2010	D	0.54	41%	2	4.75	$>0.301\times10^{32}$
Super-K	2015	O	245	12.1%	24	24.1	$>1.9\times10^{32}$



* Not yet published

Observed improvement is weaker than SQRT due to irreducible background of atmospheric ν's.

Still possible to improve a limit (though slowly) but impossible to claim a discovery.

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Search for $n-\bar{n}$ oscillation in Super-Kamiokande

K. Abe et al., Super-K Collaboration

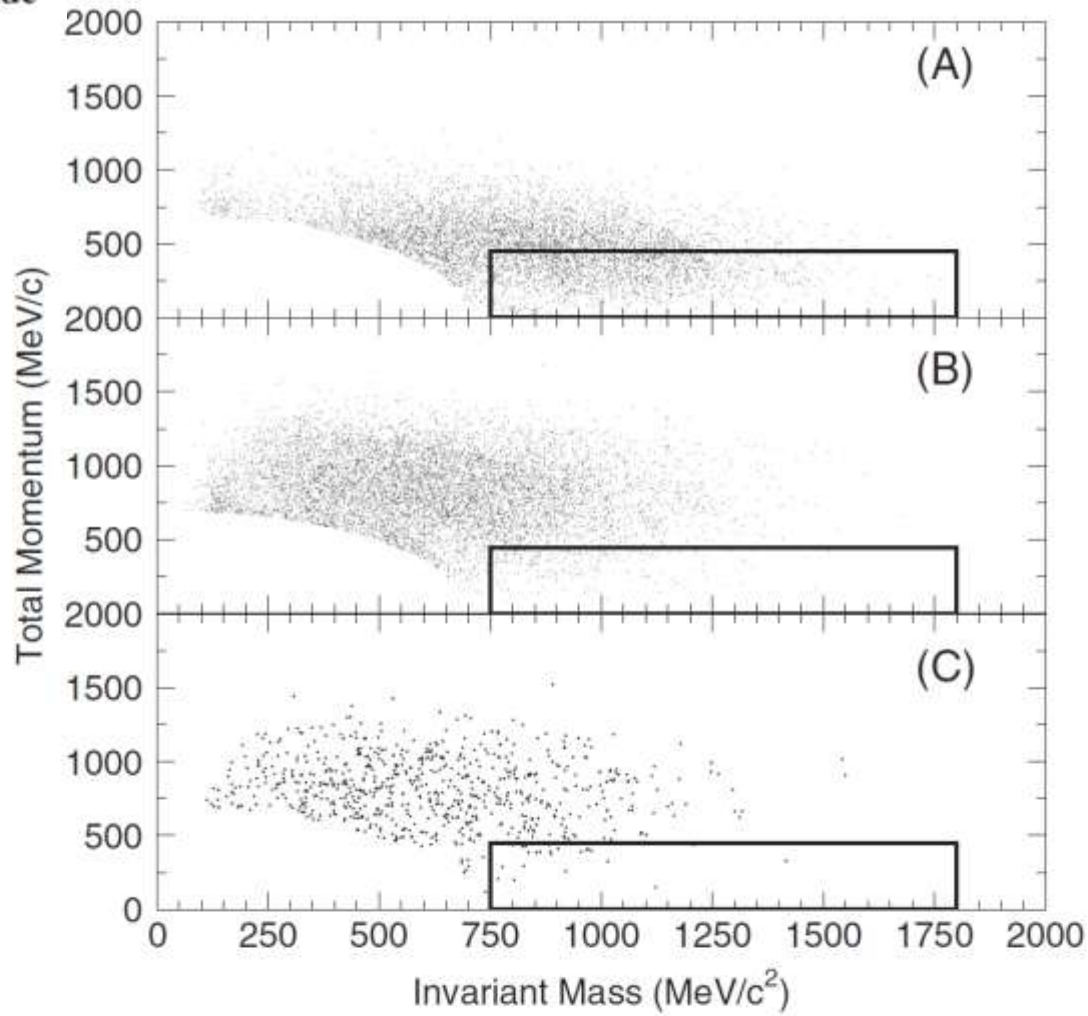


FIG. 2. Total momentum vs the invariant mass after applying the selection criteria (a)–(b) on the FC sample: (A) signal MC, (B) atmospheric neutrino MC, and (C) data. The boxed region in each panel shows the criterion (c)–(d) for the $n-\bar{n}$ oscillation signal.

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

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
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 of 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	$>1.9\times10^{32}$	10×10^{22}	5×10^{22}	$>2.44\times10^{8}$	$>2.7\times10^{8}$

Dover, Gal et. al, old

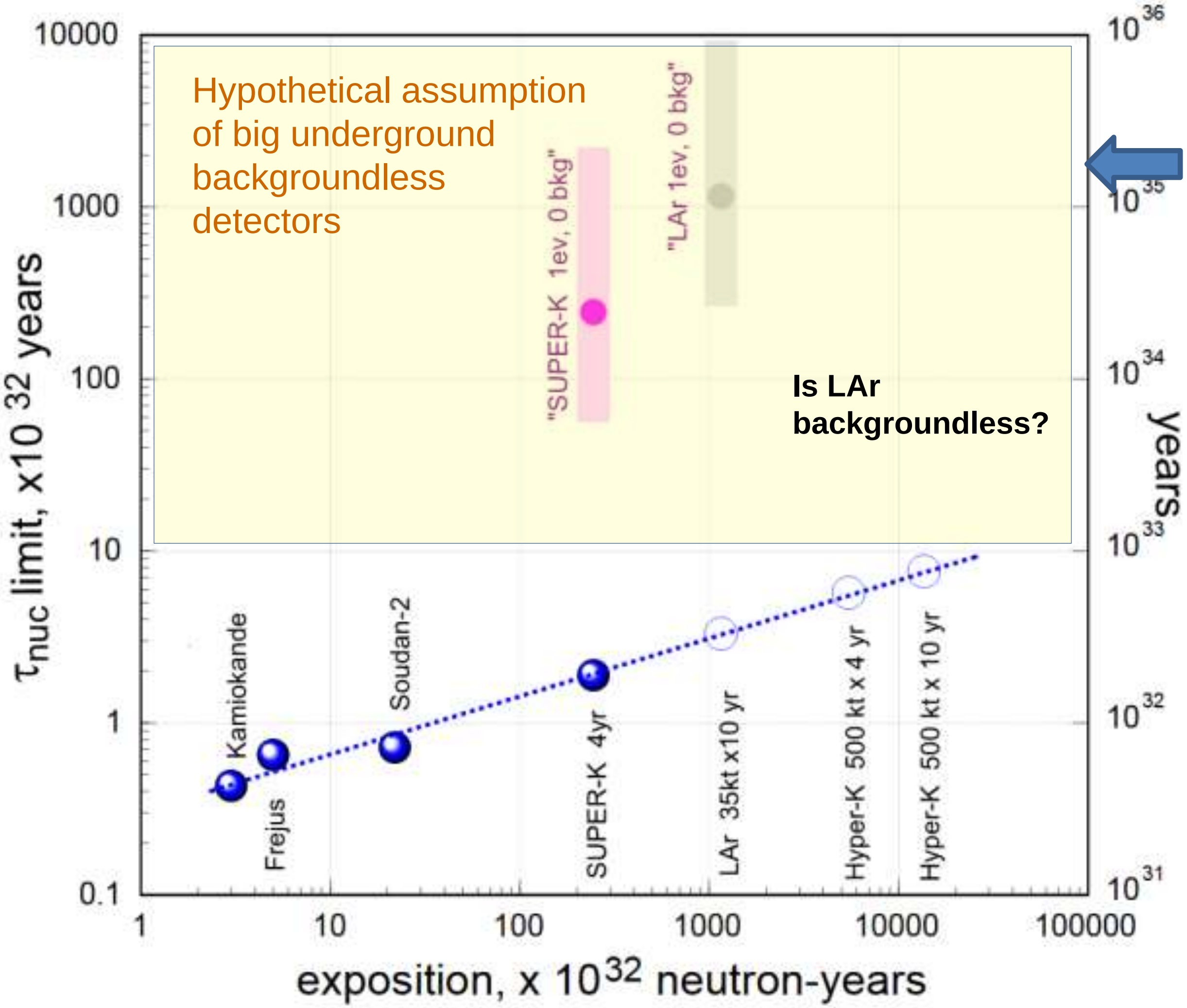
V. Kopeliovich 2011, Deuterium

Friedman and Gal 2008, Oxygen

B. Kopeliovich & A. Vainshtein, 2012

$$\Rightarrow \tau_{n\bar{n}}(\text{from bound}) > 2.7\times10^{8}s \quad \text{or} \quad \alpha < 2\times10^{-24}eV$$

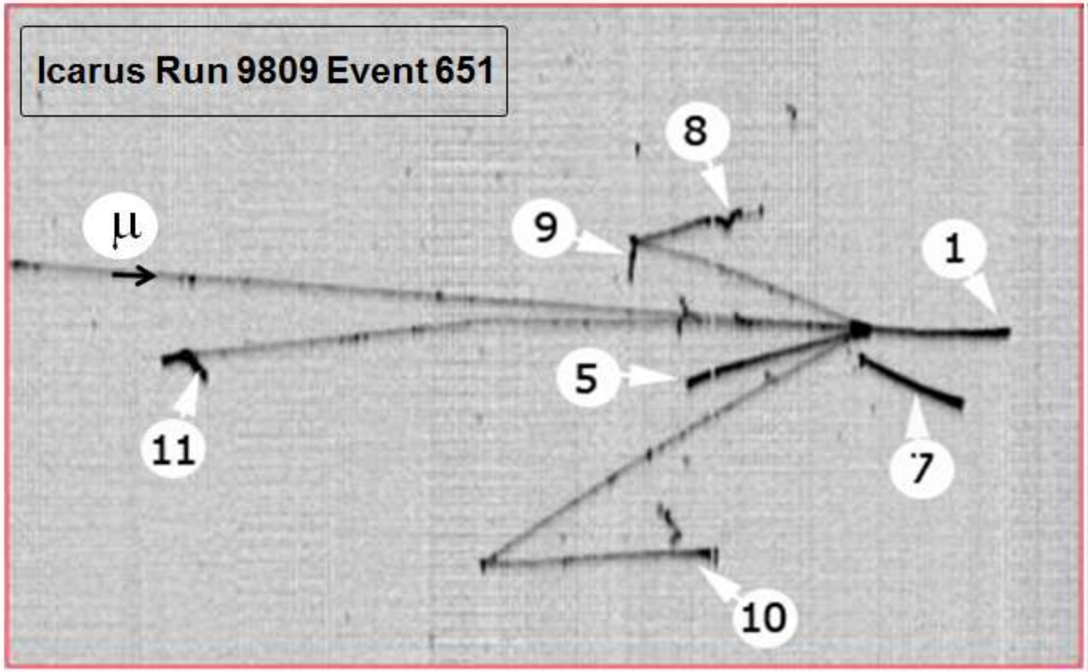
Prospects of intranuclear n-nbar search



Goal of NNbar sensitivity. Absence of background is critically important

24 candidate events in Super-K might contain several genuine n-nbar events. Backgroundless PDK detectors are needed to explore nnbar > 10^{33} years.

Big new Liquid Argon detectors (DUNE, 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^{35} yr will be possible was 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

As a Conclusion

Recent white paper for Physics Review on n-nbar:
D.G. Phillips II et al., N-Nbar Collaboration
Neutron-Antineutron Oscillations:
Theoretical Status and Experimental Prospects
arXiv:1410.1100