Lattice Meets Experiment 2013: Beyond the Standard Model

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Review
of Experimental Searches for Neutron-Antineutron Transformation with Bound and Free Neutrons and Future Perspectives

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Overview

1. Baryon number violation
2. Neutron $\rightarrow$ antineutron transformation
3. N-nbar with free neutrons
4. N-nbar with bound neutrons
5. Future prospects

Baryon Number Violation

is one of the principal requirements of modern Cosmology and Particle Physics.

<u>Violation of Baryon number</u>

- required for explanation of Baryon Asymmetry of Universe (One of 3 Sakharov's conditions);
- follows from the inflation (Dolgov & Zeldovich);
- is present within SM (although at non-observable level);
- motivated by BSM models (Georgi & Glashow, Pati & Salam, ...)
- can be searched as Proton decay ΔB = 1 (*rectius:* Nucleon decay) and as $n \longrightarrow \overline{n}$ with ΔB = 2. Both searches are complementary.

Nucleon Decay Searches

We should prize > 30-year work on Nucleon Decay search performed by Super-K, Soudan-2, IMB3, Kamiokande, Fréjus

✦ For 3 decades of searches experimental sensitivity was increased by several orders of magnitude !

✦ Decay modes with conservation of Baryon – Lepton number (B–L) were under major focus. Like in SM and in popular SUSY-GUT.

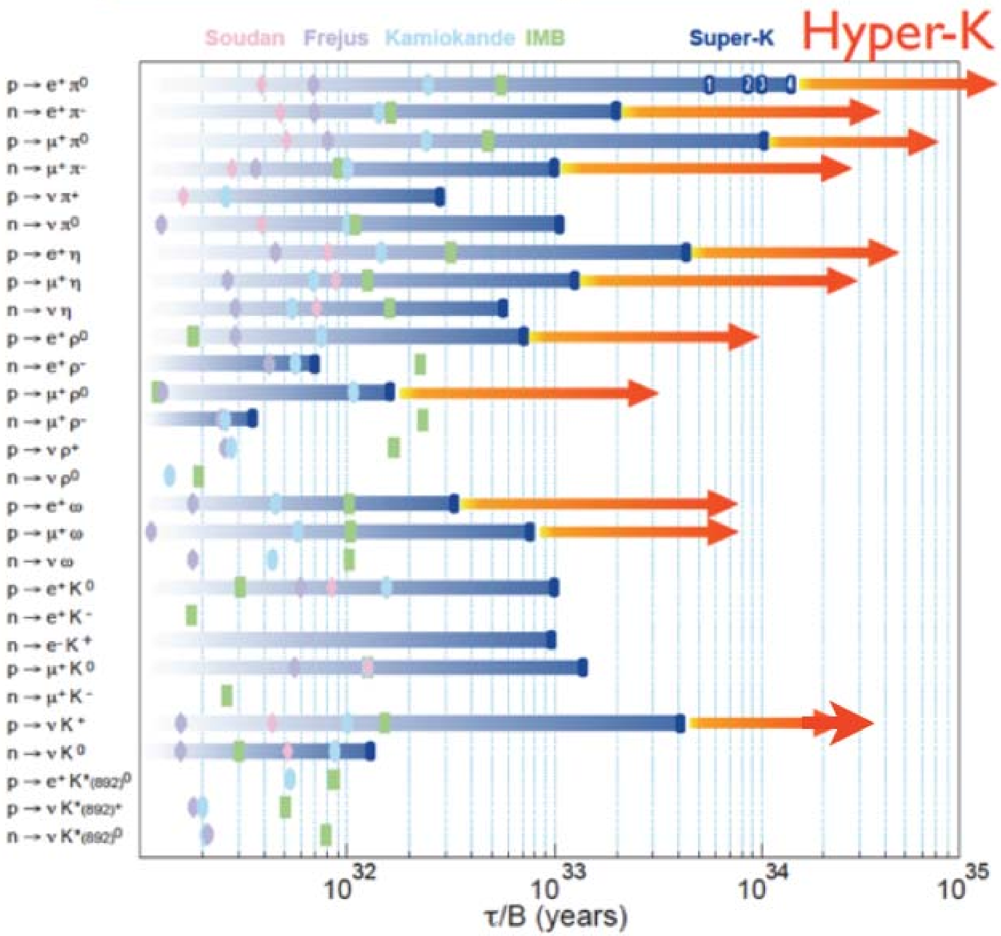
✦ More difficult (B–L)V modes (background dominated) were studied mostly by Fréjus, Soudan-2 and IMB3. The limits are lower (see PDG listings).

✦ Baryon $\rightarrow$ Antilepton = conserves (B–L) like in SM and MSSM.
Baryon $\rightarrow$ Lepton = violates (B–L) by 2 units.
1 Baryon $\not\rightarrow$ No leptons = violates angular momentum conservation.
2 Baryons $\rightarrow$ No leptons = similar to n$\rightarrow$nbar ΔB=2

✦ For most of N-decay modes experimental limits are defined in the presence of irreducible background. In this case the lifetime limits can be statistically improved (e.g. by exposure time or more mass), but the discovery can not be made.

Future of PDK search in Hyper-K

~10 times better sensitivity than current Super-K limits!



$p \rightarrow e^+\pi^0$:

- 1.3×10^{35}yrs (90%CL)
- 5.7×10^{34}yrs (3σ)

$p \rightarrow \nu K^+$:

- 3.2×10^{34}yrs (90%CL)
- 1.2×10^{34}yrs (3σ)

- And many other modes:
  - $(p,n)\rightarrow(e,\mu)+(\pi, \rho, \omega, \eta)$
  - K^0 modes
  - $\nu\pi^0$, $\nu\pi^+$
  - n-nbar oscillation
  - dinucleon decays

$>3\sigma$ possible for lifetime above current SK limits

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). So far these searches were not successful in observation of the Proton decay.

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

(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 results of (B – L) conserving interactions from the higher scale.

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

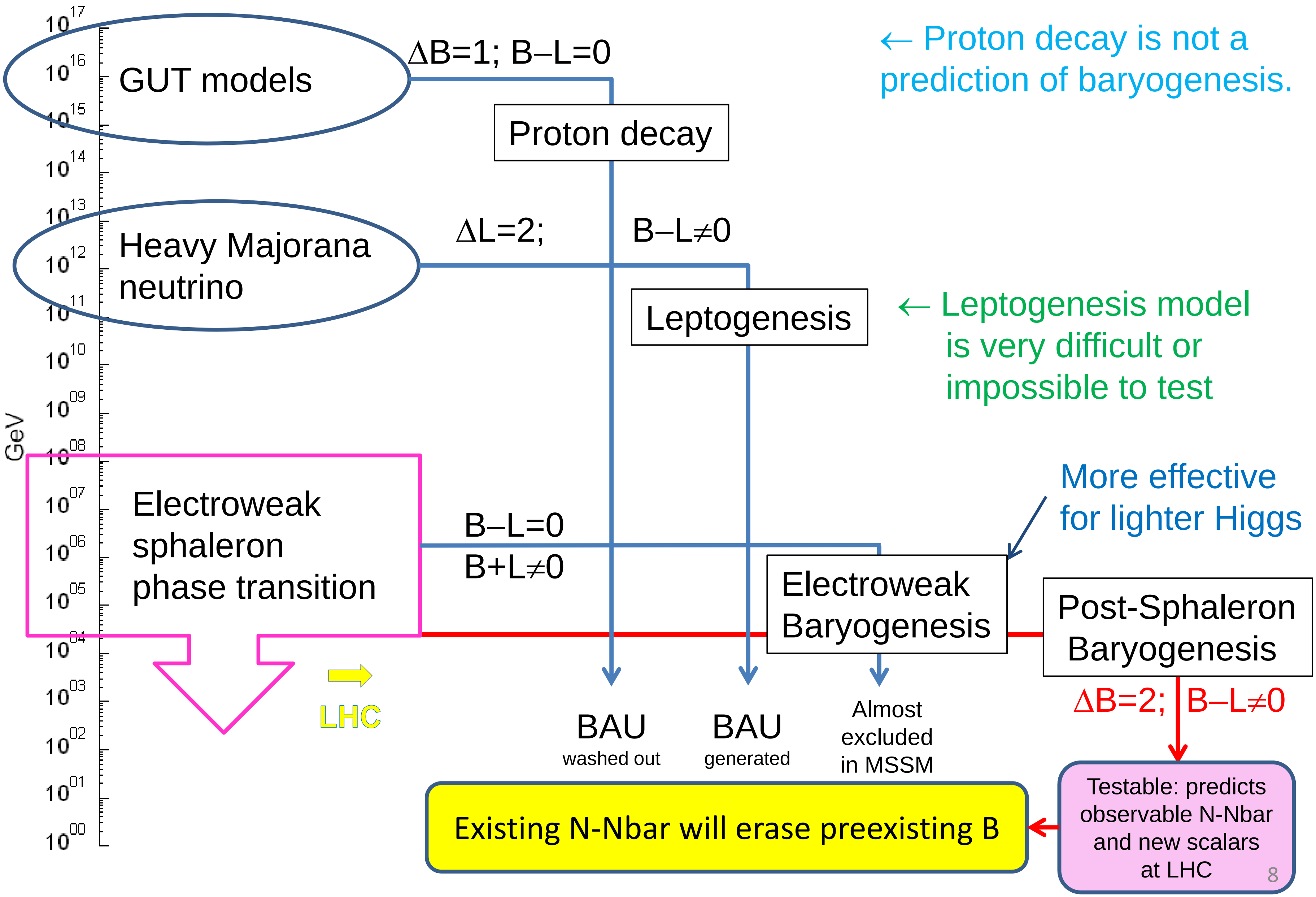
- PDK searches with Δ(B–L) = 0 can test particular GUT/SUSY models at energy scale ~ 10^{16} GeV
- Processes with Δ(B–L) $\neq$ 0 can test baryogenesis, GUT/SUSY, neutrino masses, extra-dim models, and more at energy scales ~ 10^5 – 10^{12} GeV

Δ(B–L)V Processes

- ✧ Leptogenesis with ΔL=2
- ✧ baryon $\rightarrow$ lepton decays with Δ(B–L)=2 (e.g. $n \rightarrow 3\nu$)
- ✧ neutron $\rightarrow$ antineutron transformations with ΔB=2

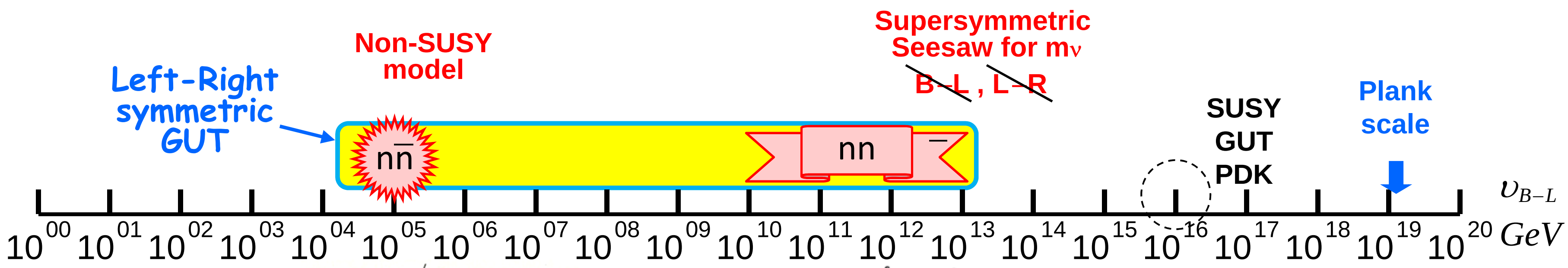
  or 2 nucleons $\rightarrow$ pions

Baryogenesis Models

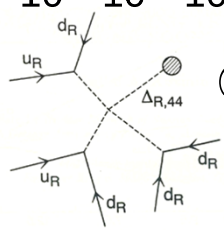


Babu et al, PRD 87 (2013) 115019

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

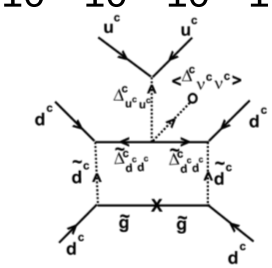


Goity, Sher (1994)



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

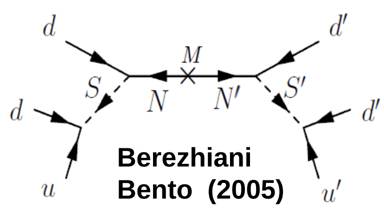
Mohapatra & Marshak (1980)



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

Dutta-Mimura-Mohapatra (2005)

Connected with observable effects at LHC

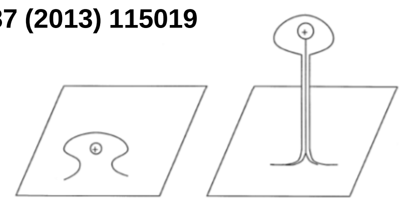


Berezhiani Bento (2005)

$$\mathcal{M}_9 \propto \frac{\psi\psi\psi\psi\psi\psi}{m^5}$$

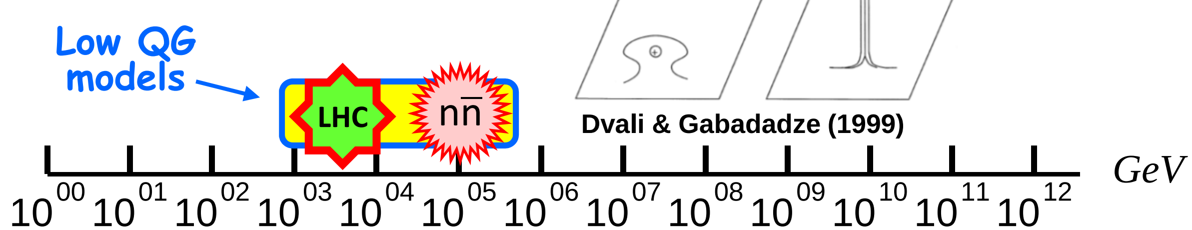
Baryogenesis at TeV scale

Babu et al, PRD 87 (2013) 115019



Dvali & Gabadadze (1999)

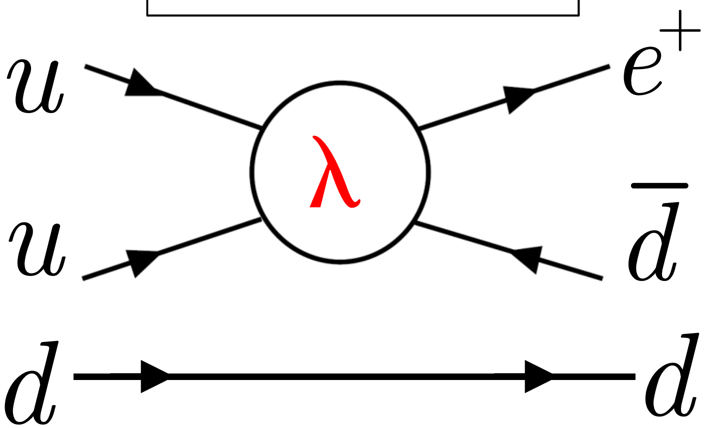
Experimental motivation!
large increase of sensitivity:
factor of ×1,000 is possible



Shrock & Nussinov (2002)

Proton decay and N-Nbar

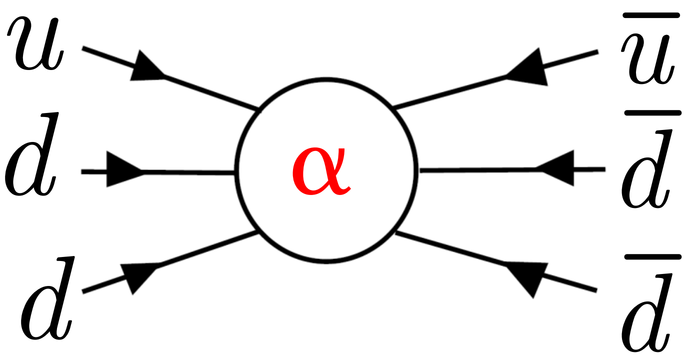
$$p \longrightarrow e^{+}\pi^{0}$$



$$\mathcal{M}_6 \propto \frac{\psi\psi\psi\psi}{m^2}$$

Effective scale ~ 10^{16} GeV

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



Annihilation to ~ 5 pions

$$\mathcal{M}_9 \propto \frac{\psi\psi\psi\psi\psi\psi}{m^5}$$

Effective scale ~ 10^5 GeV; in different models can be defined by composite masses from e-w to 10^{12} GeV

Neutron $\leftrightarrow$ 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 up 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].

- 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 "$\overline{n}$"

However, 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.

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 …

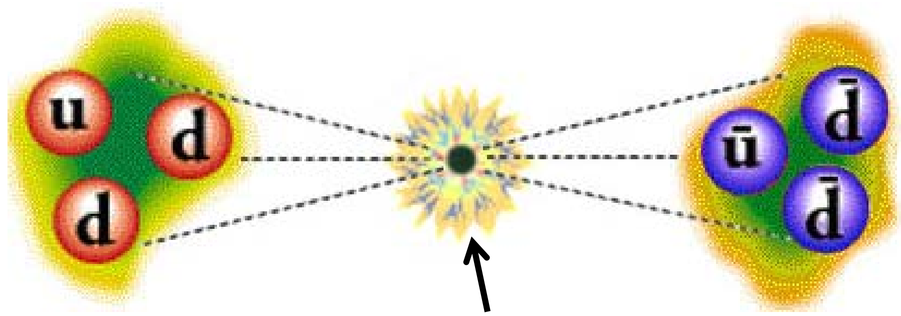
- Recent theoretical N-Nbar idea were reviewed by R. Mohapatra in http://arXiv.org/pdf/0902.0834.pdf

- 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 and at Snowmass on the Mississippi (Minnesota) 2013: https://indico.fnal.gov/sessionDisplay.py?contribId=361&sessionId=103&confId=6890#20130802

How it occurs

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 (Lattice).
- Unknown coupling between quarks (new force) should be effective at this distance factorized with overlap probability.
- We are used to think in terms of binary collisions, where probability of 3-body overlaping is small. However, in the early universe at very high densities the 3-body collisions could be very common.

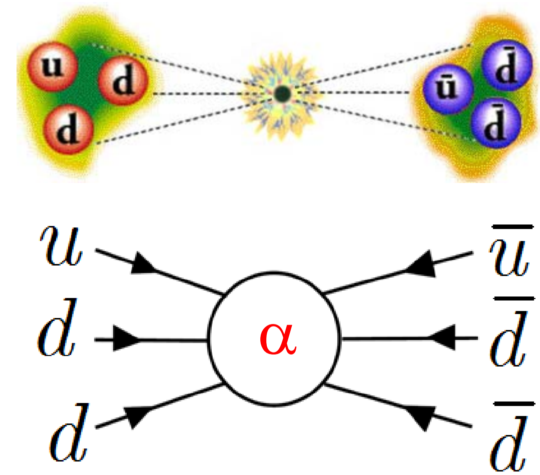
Two experimental approaches to n-nbar

1. With free neutrons. Best limit from experiment at ILL / Grenoble reactor (1994): $\tau_{free} > 0.86\times10^8$ s.
   Best potential for future search!
   Experiment in development for neutron spallation facilities in US or in Europe (ESS).

2. For neutrons bound inside nuclei. Transformation is suppressed. Best present limit from Super-K (2011):
   $\tau_{bound} > 1.9\times10^{32}$ yr $\rightarrow$ $\tau_{free} > 3.5\times10^8$ s.
   Possible future improvement in LBNE if atm. ν irreducible background can be reduced.

n→nbar transition probability for free neutron

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



α-mixing amplitude

All beyond SM physics is here

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

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

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

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

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. Free oscillations are suppressed by potential different for n and $\bar{n}$.

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

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

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

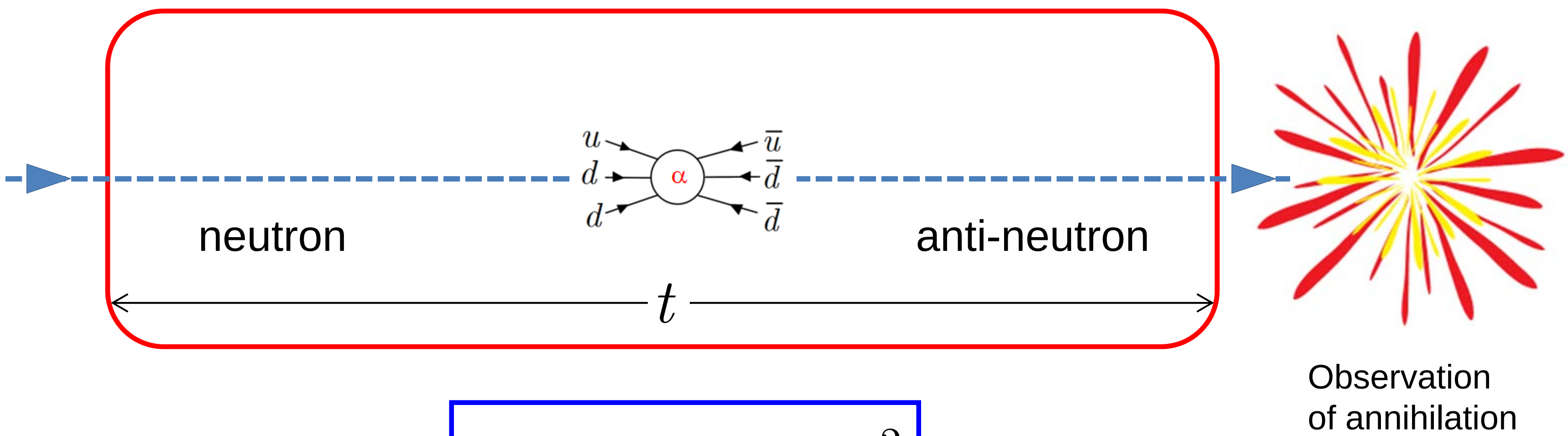
Existing exp. limits are set by at ILL (free n) and by Super-K (bound n)

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

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

Free neutron transformation

Quasi-free conditions: vacuum, magnetic field < 1 nT

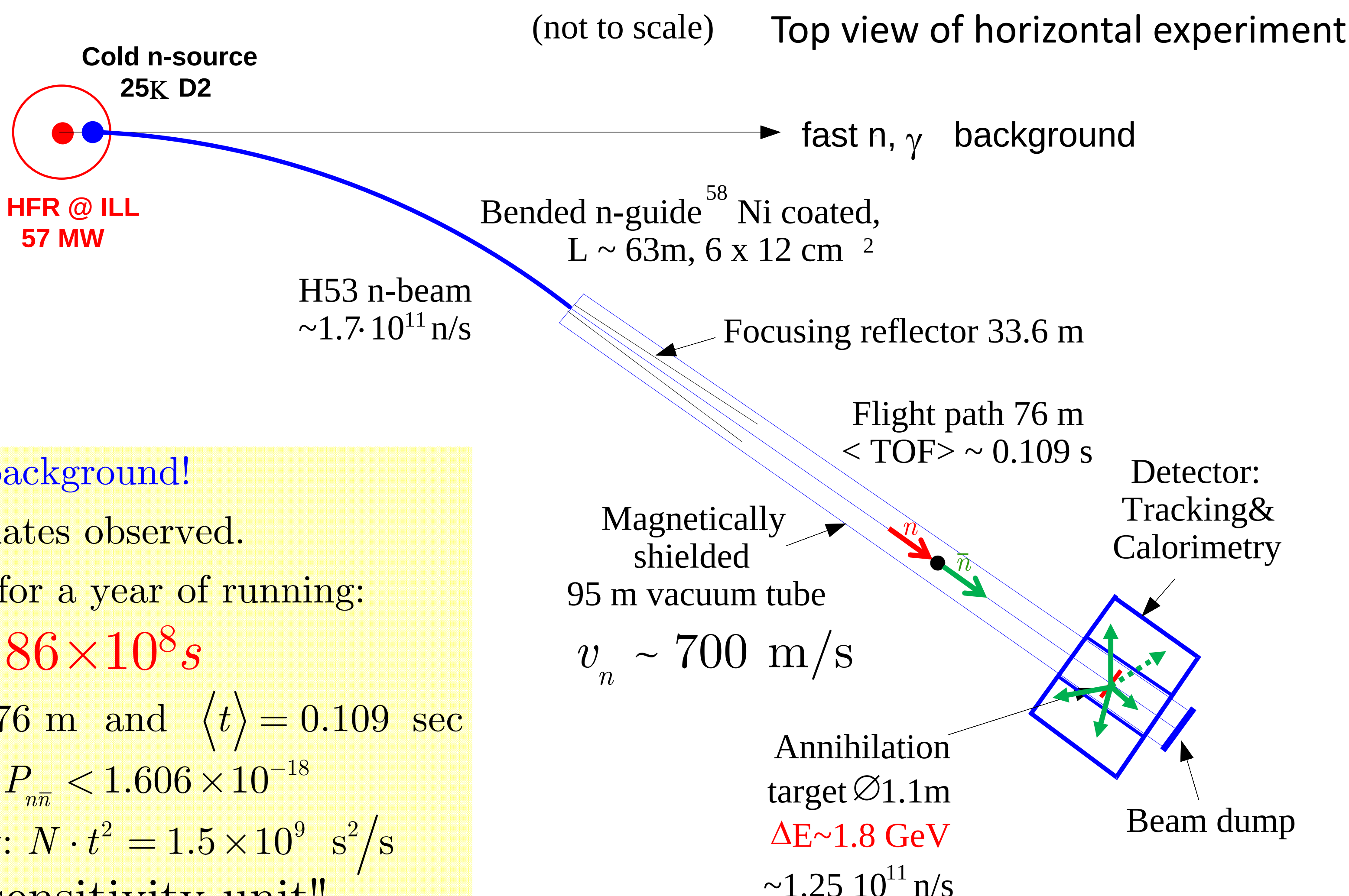


$$P_{n \to \bar{n}} = \left(\frac{t}{\tau_{n\bar{n}}} \right)^2$$

Previous state-of-the-art 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:

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

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

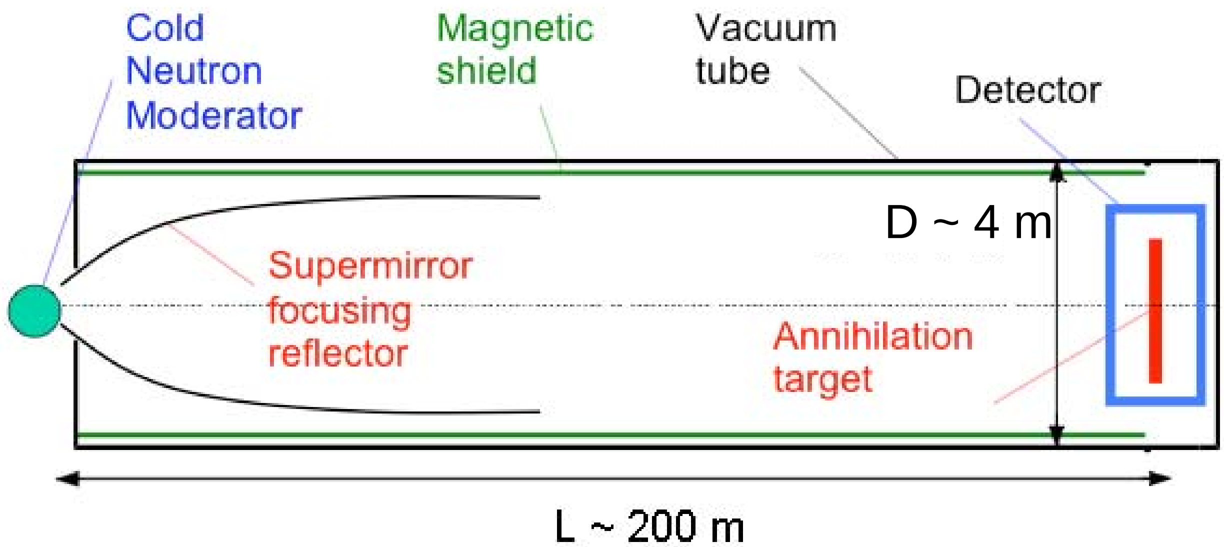
measured $P_{n\bar{n}} < 1.606\times10^{-18}$

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

$\doteq$ "ILL sensitivity unit"

Conceptual Horizontal NNbarX Search in Project X at Fermilab

with elliptical focusing reflector



<u>Typical initial baseline parameters:</u>

Cold LD_2 source from 1MW spallation target	
Luminous source area, dia	30 cm
Annihilation target, dia	200 cm
Reflector starts at	1.5 m
Reflector ends at	40 m
Reflector semi-minor axis	2.0 m
Distance to target	200 m
Super-mirror	m=6
Vacuum	$< 10^{-5}$ Pa
Residual magnetic field	< 1 nT

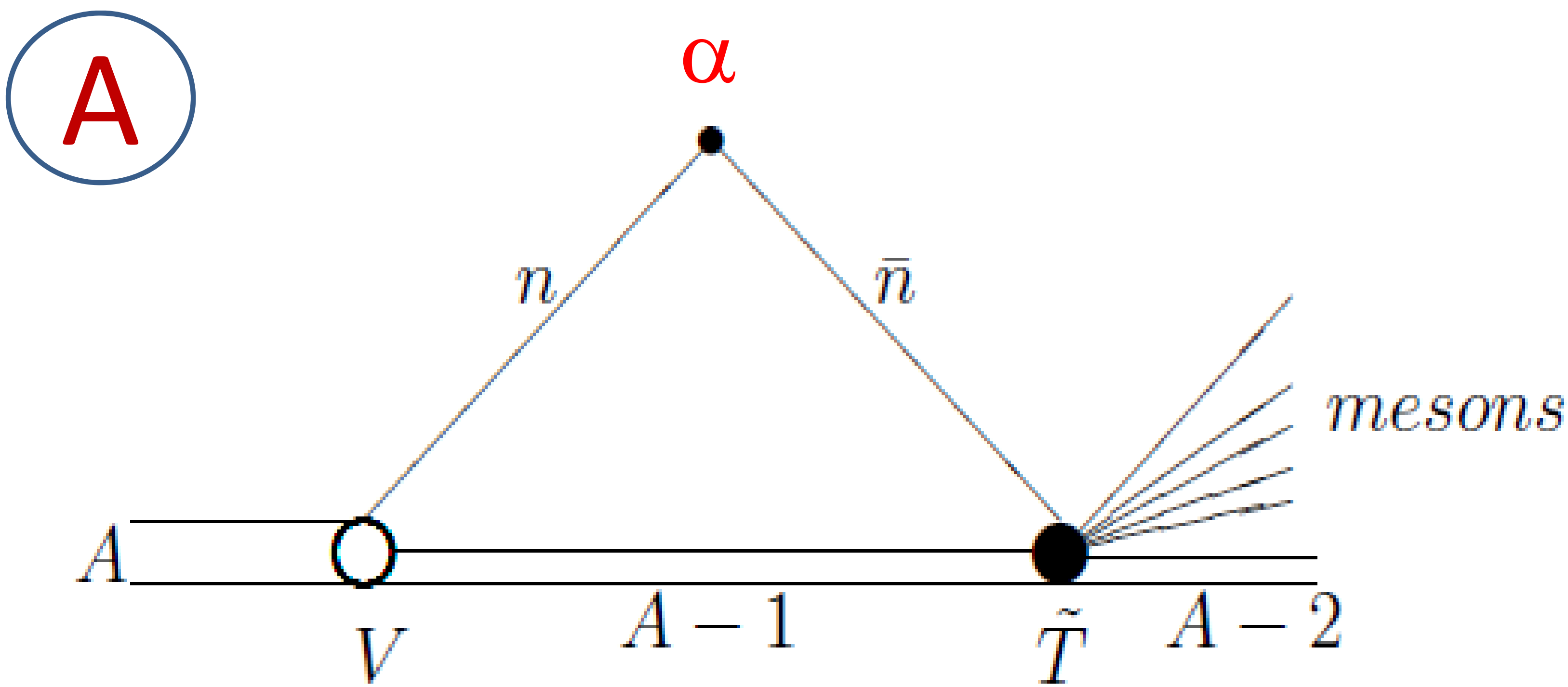
<u>MC Simulated sensitivity Nt^2:</u>

150 "ILL units" x # of years

Sensitivity and parameters are subject of optimization by Monte-Carlo including overall cost

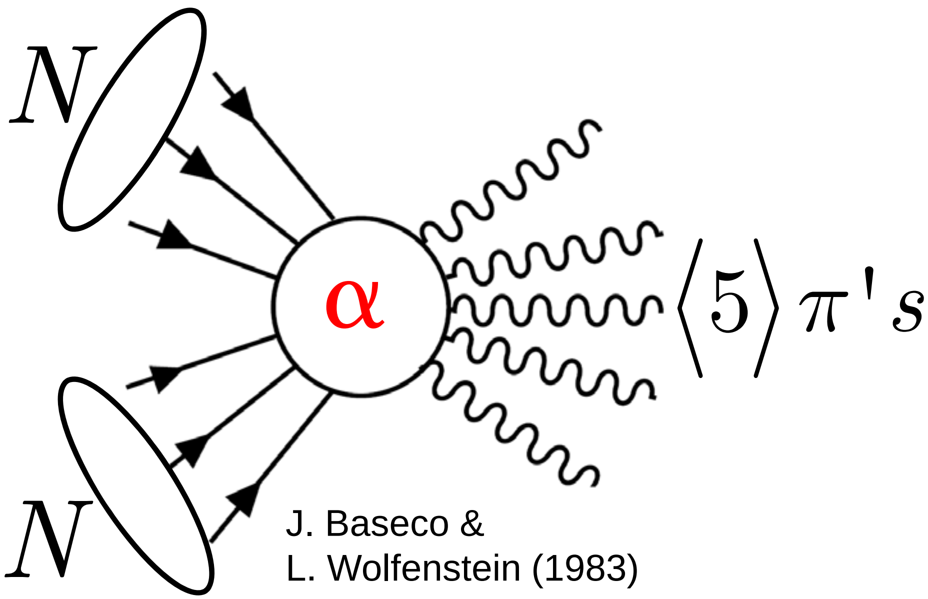
N-nbar effect can be suppressed by weak magnetic field.

N-Nbar inside nuclei



B

$$\boxed{2N \rightarrow pions}$$

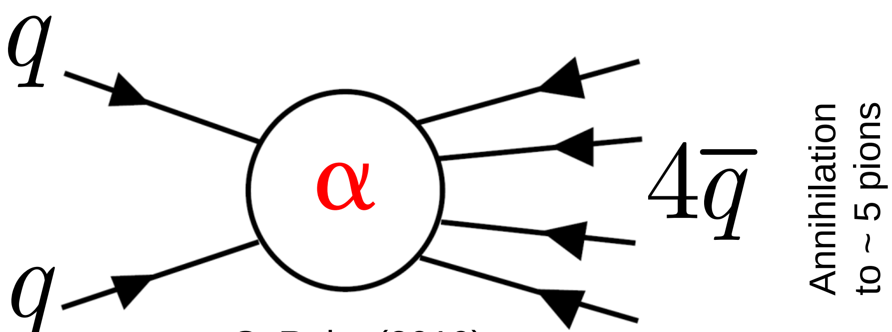


Same amplitude as for $n \rightarrow \overline{n}$

Intranuclear experiment can see only pions final state.

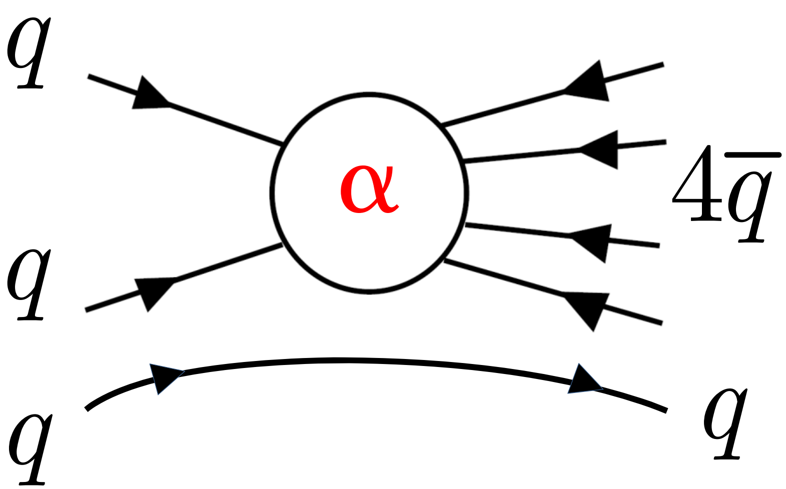
Crossing channel of $n \to \overline{n}$

C



S. Raby (2010)

According to Arkady Vainshtein this crossing channel is included in $n \to \overline{n}$ amplitude ?

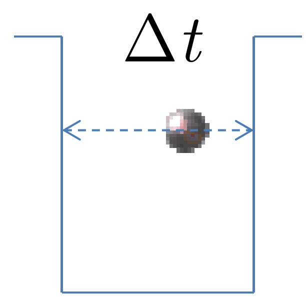


This can occur in nuclei but not with free $n \to \overline{n}$

Hopefully, lattice calculations can include A + B + C

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

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



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) - in progress

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

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

Lattice hopefully can provide more reliable theoretical calculations for suppression factor inside D, O, Ar with theoretical uncertainty

One can be religious about nuclear models calculations. How accurate are these? For $2\beta0\nu$ the accuracy of matrix element calculation is factor 2-3 (Bill Detmold yesterday). Is accuracy of 10-15% is possible for N-Nbar supp. factor? Can it result from the lattice calculations that intranuclear N-Nbar transformations are suppressed to complete zero?

Existing N-Nbar limits

Vacuum oscillations: $\tau_{n\to\bar{n}} > 0.86 \cdot 10^8 \sec$ (at ILL, 1994)

Sensitivity for free neutron search (appearance probability)

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

ILL experimental limit can be used as a unit of sensitivity = 1u

Sensitivity for bound neutron search (in nucleon decay expts)

$$P_{left} \propto N_n \cdot \exp\left(-\frac{t_{obs}}{\tau_{nucl}} \right)$$

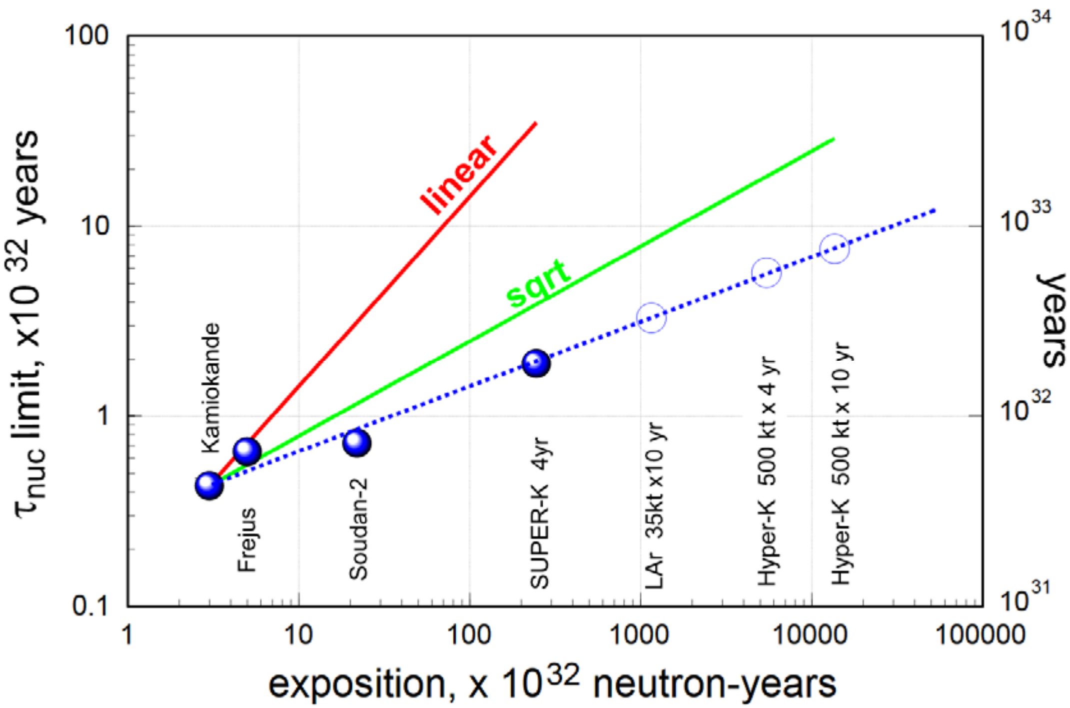
$\tau_{nucl} \gtrsim 2 \cdot 10^{32}\, yr$ (SK-2011)

$$\tau_{nucl} = R \times \tau^2_{n\to\bar{n}} \quad \text{where } R \text{ "nuclear suppression factor"}$$

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 *	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



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

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 × 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}	$>2.44\times10^{8}$	$>3.45\times10^{8}$

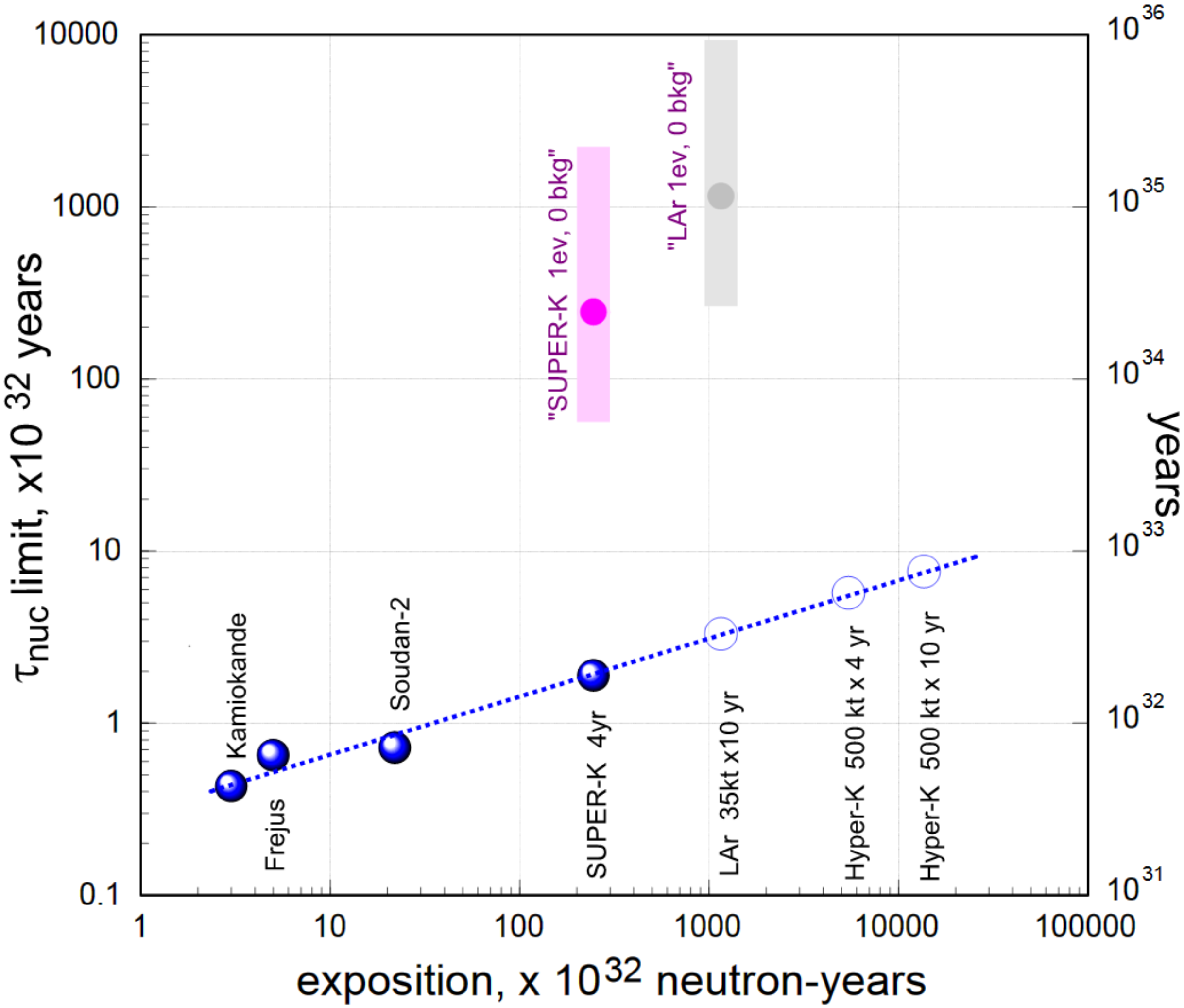
Dover, Gal et. al, old

V. Kopeliovich 2011, Deuterium

Friedman and Gal 2008, Oxygen

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

What if detectors would be backgroundless ?

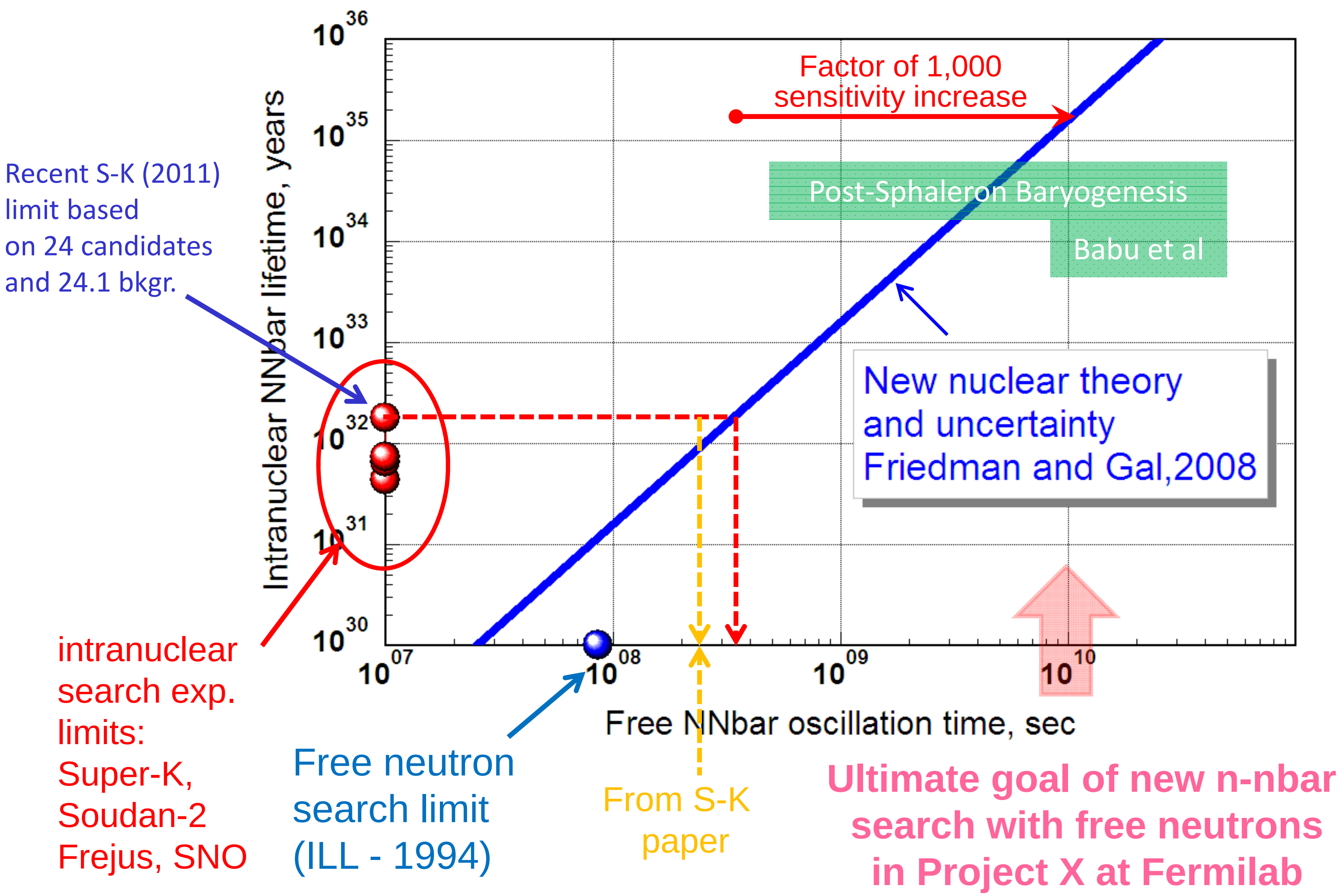


24 candidate events in Super-K might contain several genuine n-nbar events.
Backgroundless detectors needed to explore nnbar > 10^{33} years.
Can atmospheric neutrinos and nnbar signals be separated in LAr detectors?

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

Free Neutron and Bound Neutrons NNbar Search Limits Comparison

Large improvement with free-neutron experiments is possible



Limits of NNbar search

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

τ	ILL units	
0.86×10^{8} s	1u	←Free neutrons at ILL (1994)
3.45×10^{8} s	16u	←Super-K (2011), 22.5kt, 4 years
1.5×10^{9} s	450u	←Horizontal beam (Project X, ESS)
7.5×10^{8} s	76u	←Hyper-K 500kt, 10 years
1×10^{10} s	13,500u	←Dedicated cold source with vertical layout
1×10^{11} s	1,350,000u	←Ultimate Theory wish (requires more R&D)