Project X Physics Study • Fermilab • June 16, 2012

Future N-Nbar Intranuclear Searches vs Vacuum Oscillations

Yuri Kamyshkov/ University of Tennessee
email: kamyshkov@utk.edu

Question: can vacuum n-nbar oscillations compete with intranuclear n-nbar searches?

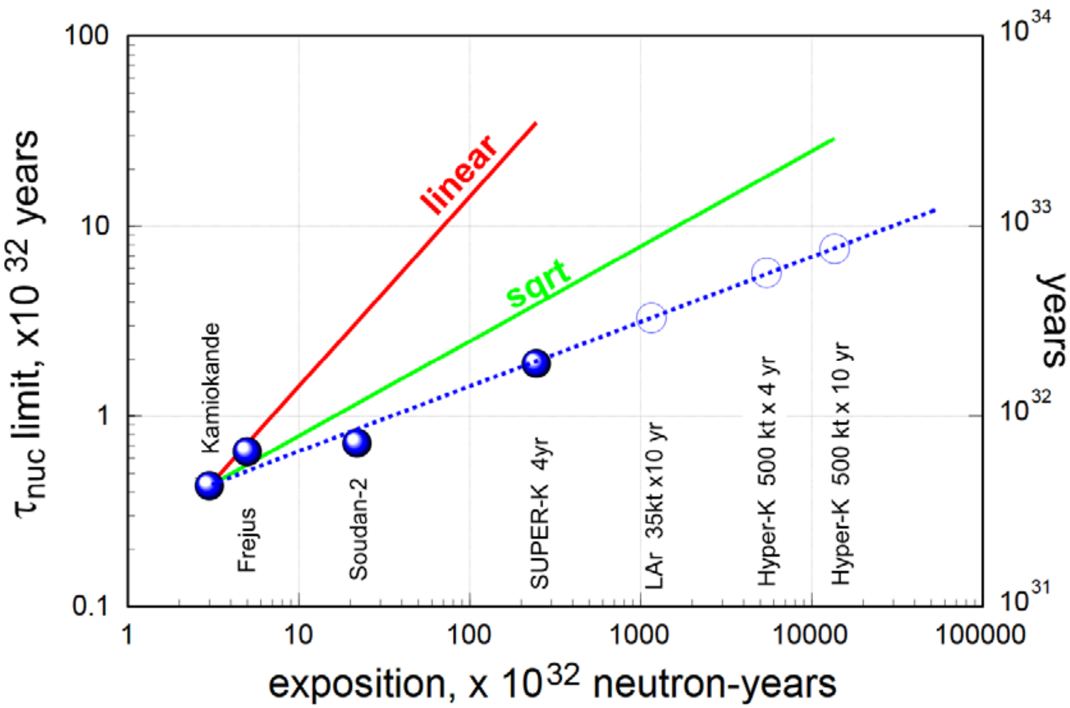
(a) Possible future progress in intranuclear searches.
also addressed by E. Kearns

(b) Relation between free and bound neutron n-nbar
also addressed by A. Vainshtein.

Bound neutron N-Nbar search experiments

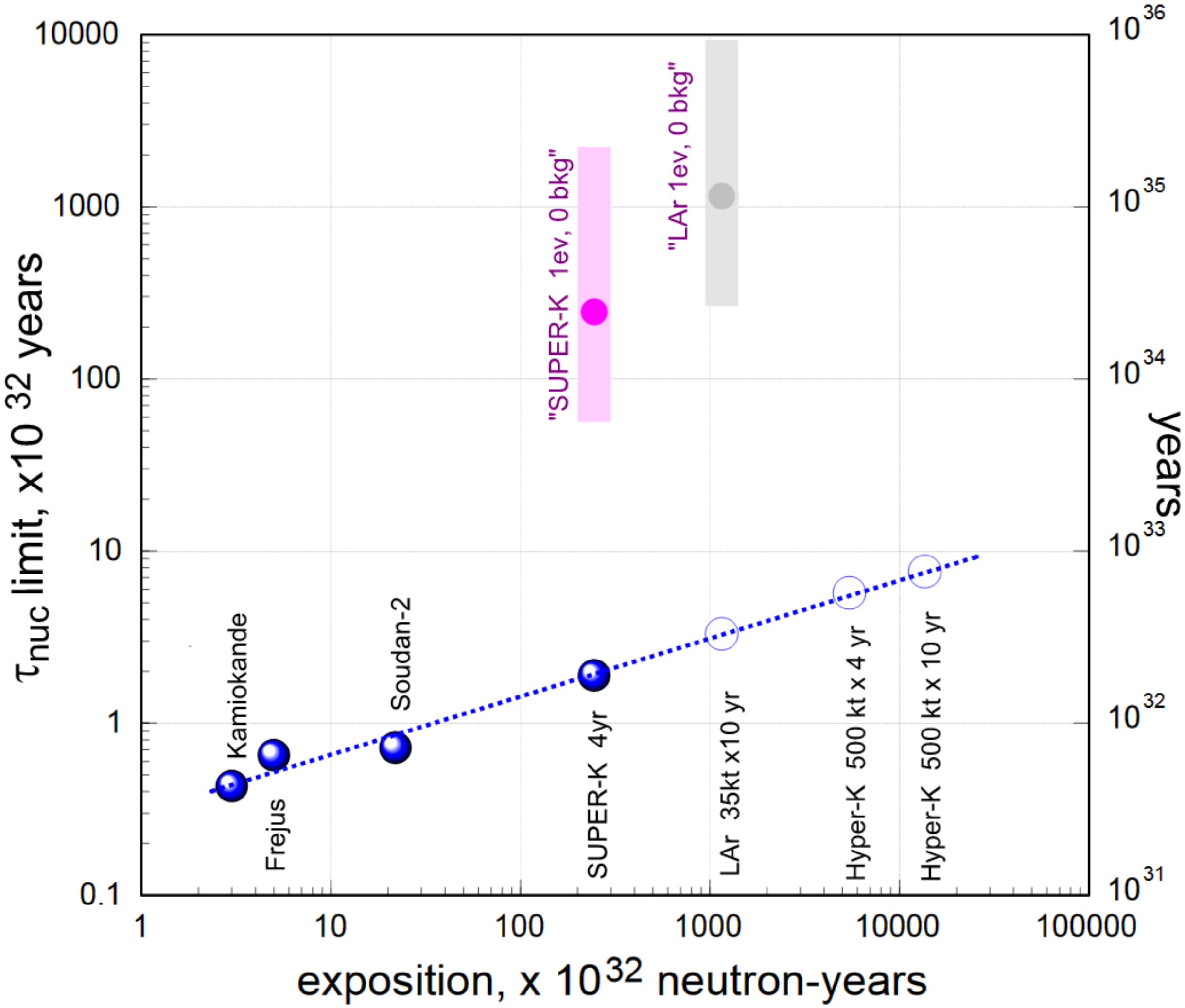
Experiment	Year	A	n·year (10^{32})	Det. eff.	Candid.	Bkgr.	τ_{nucl}, yr (90% CL)
Kamiokande	1986	O	3.0	33%	0	0.9/yr	$>0.43\times10^{32}$
Frejus	1990	Fe	5.0	30%	0	4	$>0.65\times10^{32}$
Soudan-2	2002	Fe	21.9	18%	5	4.5	$>0.72\times10^{32}$
SNO *	2010	D	0.54	41%	2	4.75	$>0.301\times10^{32}$
Super-K	2011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

* Preliminary



- From Kamiokande to Super-K atmospheric ν background is about the same ~ 2.5 /kt/yr.
- Large D_2O, Fe, H_2O detectors are dominated by backgrounds; LAr detectors are unexplored!
- 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.

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?

Suggestion for WG13:

Recommend studies on the quality of separation of atm. neutrino events in LAr detector from n-nbar signals.

Ed Kearns suggested that “Super-K vector files of 24 candidates” can be run through LBNE LAr simulation/analysis chain”.

Free n-nbar oscillations

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

α-mixing amplitude

"vacuum oscillations" $\rightarrow$

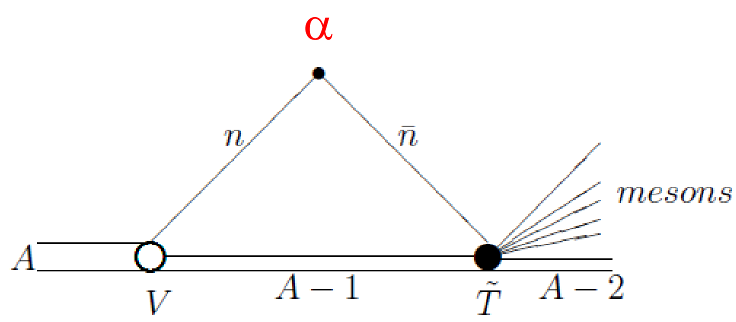
$$P_{n\to\bar{n}} = \left(\frac{\alpha}{\hbar}\times t\right)^2 = \left(\frac{t}{\tau_{n\bar{n}}}\right)^2$$

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

Models predictions: observable effect around $\alpha \sim 10^{-25} - 10^{-26}\,eV$

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

Suppression of n→nbar in intranuclear transitions



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 in SNO)
- B. Kopeliovich, A. Vainshtein (2012) - in progress

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

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

Needed: theoretical calculations for suppression factor in Ar
with theoretical uncertainty

Existing N-Nbar limits

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

Sensitivity for free neutron search (appearance probability)

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

Will use ILL experiment limit as a unit of sensitivity = 1u

Sensitivity for bound neutron search (in nucleon decay expts)

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

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

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

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

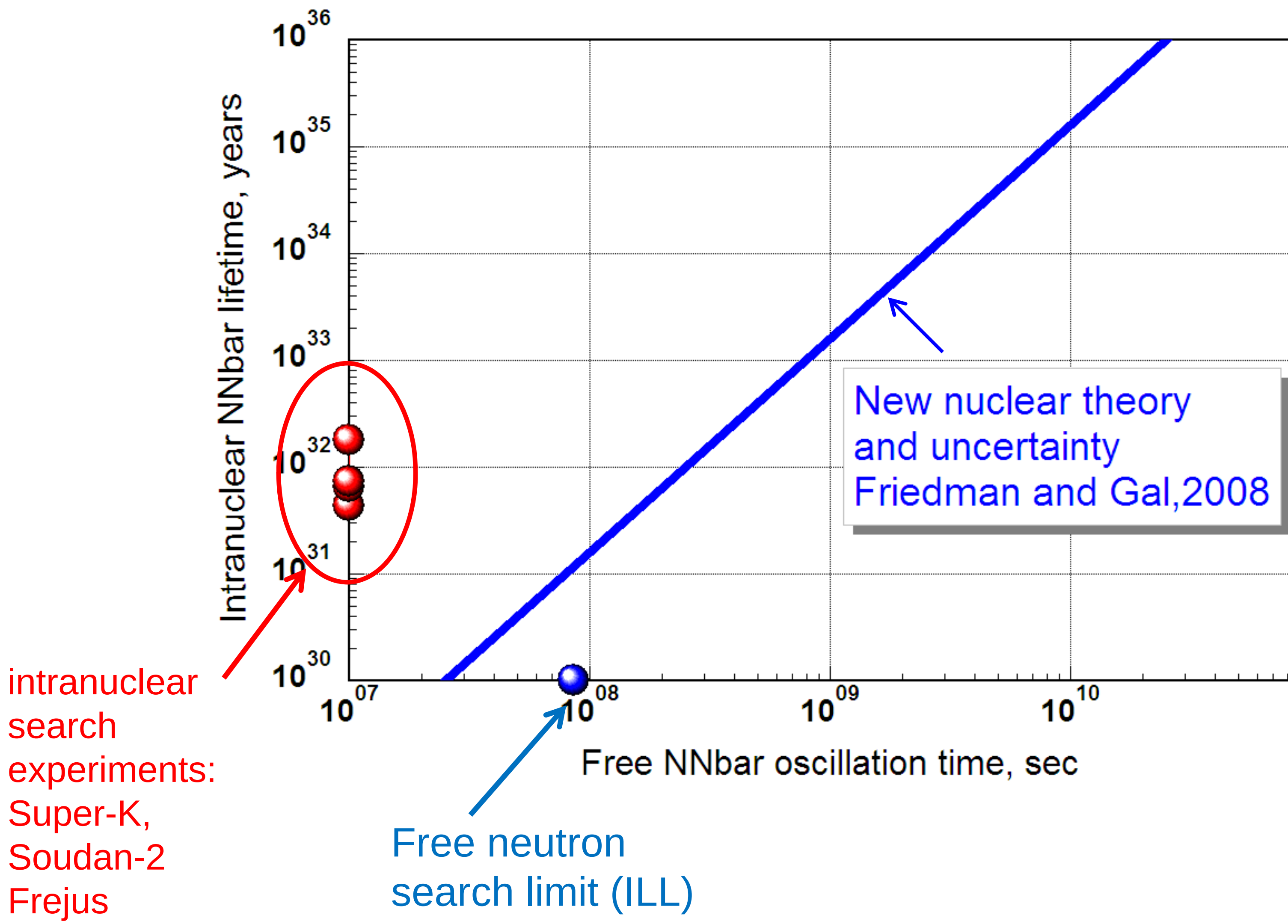
V. Kopeliovich 2011, Deuterium

Friedman and Gal 2008, Oxygen

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

$$\tau_{nucl} = R \times \tau^2_{N \to \bar{N}}$$

Free Neutron and Intranuclear NNbar Limits Comparison



Vacuum N-Nbar transformation from bound neutrons:

Best result so far from Super-K in Oxygen-16

$$\tau_{^{16}O} > 1.89 \times 10^{32} yr \quad (90\% \text{ CL}) \quad \leftarrow \begin{cases} \text{24 observed candidates;} \\ \text{24.1 exp. background} \end{cases}$$

$$\tau_{nucl} = R \times \tau^2_{n\bar{n} \text{ free}}$$

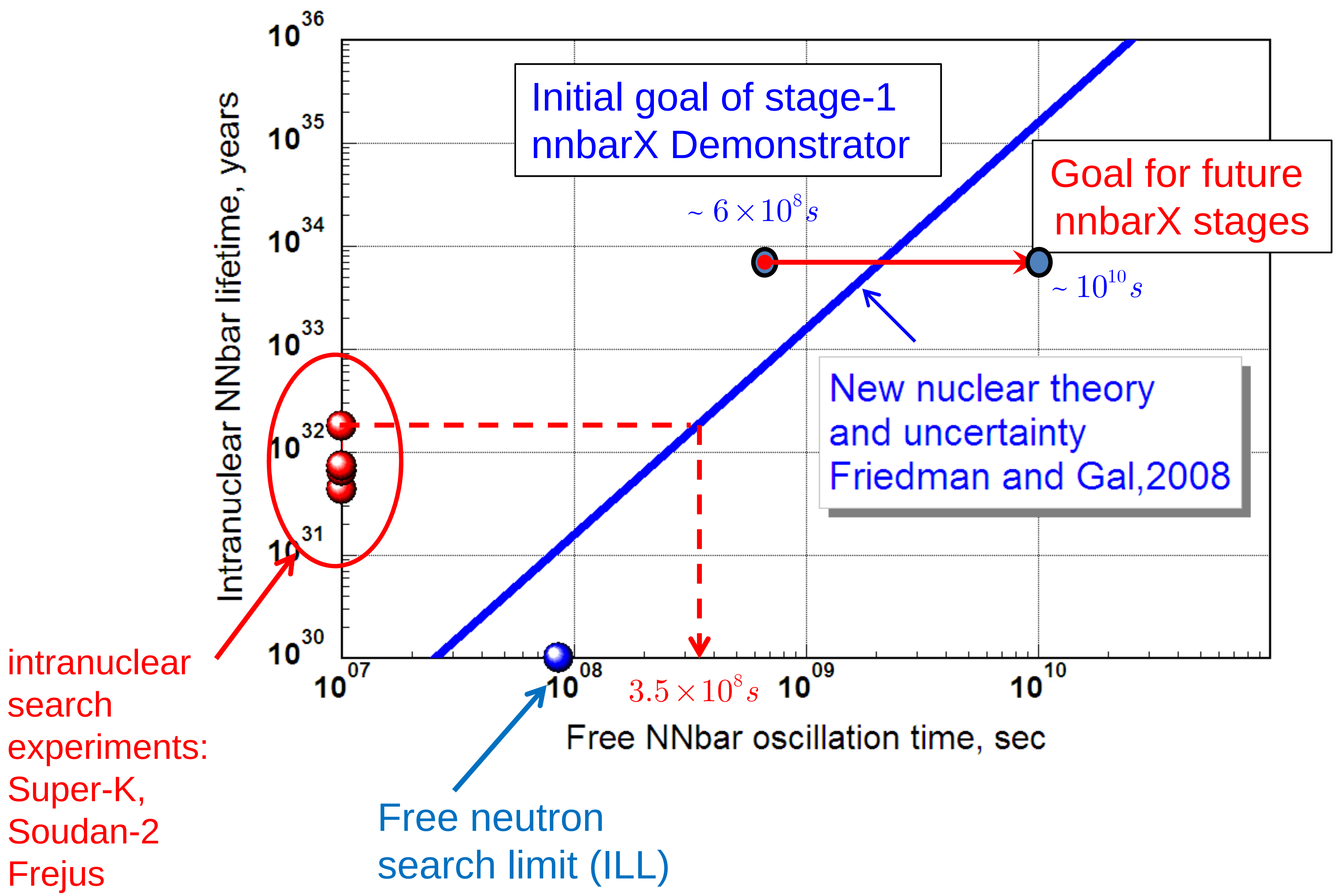
$$\text{if } R_{^{16}O} = 5 \cdot 10^{22} s^{-1} \quad \text{from Friedman and Gal (2008)}$$

$$\Rightarrow \tau(\text{from bound}) > 3.5 \times 10^8 s \quad \text{or} \quad \alpha < 2 \times 10^{-24} eV$$

$\times 16$ times higher than sensitivity of ILL expt.

ILL limit (1994) for free neutrons: $\tau_{n\bar{n}} > 0.86 \times 10^8 s$

Possible Improvement with free-neutron search



[redacted]

Conclusion on
completeness of theoretical model of intranuclear NNbar suppression

All these processes governed by the same amplitude α would result into the same indistinguishable final state (of ~ 5 pions)

→ Existing experimental intranuclear NNbar limits will need to be re-evaluated.

→ More job for theory to provide viable connection of free n→nbar transformation with the effective sum of all intranuclear processes

→ Inside the nuclei the last process can be originated by either neutron or proton. Last diagram will not occur with the free n→nbar.