



Workshop “Hot Topics in Astroparticle Physics”
LNGS • 17 September 2015

On the Road to Experimental Observation of Baryon Number Violation

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V. M. Vasnetcsov, "Knight at the Crossroad" (1882)



Where we stand

- Success of Standard Model
- Success in understanding Cosmology
- Success of LHC
- Success of Neutrino Physics ...

Stephen Hawking: Second White House Millennium Evening Lecture (1998)

<https://www.youtube.com/watch?v=AO-wXbzIBYA>

Where we are going?

Since we are not quite happy with SM and like to understand BSM

- Higher Energy Accelerators
- Larger Underground detectors
- Larger Dark Matter detectors
- Larger precision detectors
- Prove of SUSY and GUT
- Gravity wave detectors
- Roadmaps on everything
- difficult to pursue new ideas and experiments

Are the limited resources invested optimally for the progress of science?

Observation of Baryon Number Violation

Observation of violation of Baryon number is one of the pillars of Cosmology and Particle Physics.

- follows from the inflation (Dolgov & Zeldovich);
- required for explanation of BAU (Sakharov);
- present within SM at non-observable level;
- Majorana neutrinos violate $\Delta L=2$ thus requiring $V(B-L)$ BSM and together with conservation of $(B-L)$ by SM also implying that $\Delta B=2$ should exist;
- $SO(10)$ unification includes complementary $\Delta B = 1$ and $\Delta B = 2$ ($n \rightarrow \bar{n}$).

Outline

1-st hour

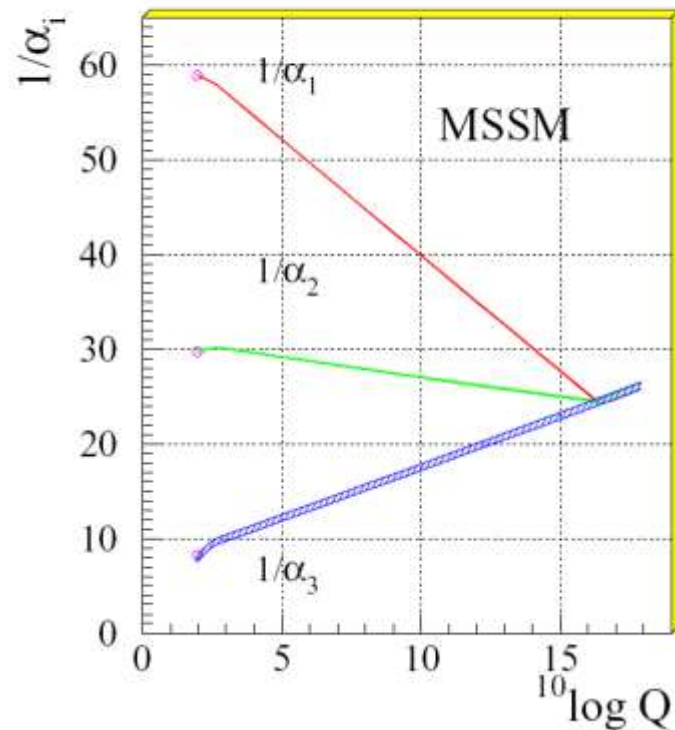
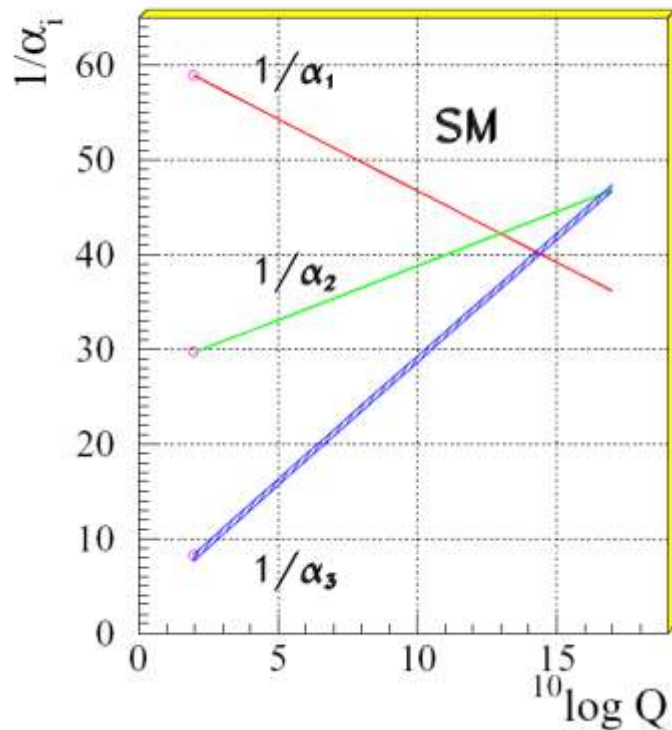
- motivation for BNV
- view of proton decay search situation
- developments of n - \bar{n} theoretical models
- \bar{n} with free neutrons
- \bar{n} inside nuclei

2-nd hour

- Concept of mirror matter
- search for mirror matter as $n \rightarrow n'$
- new paradigm in search for DM as MM

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

as motivation of the
proton decay search

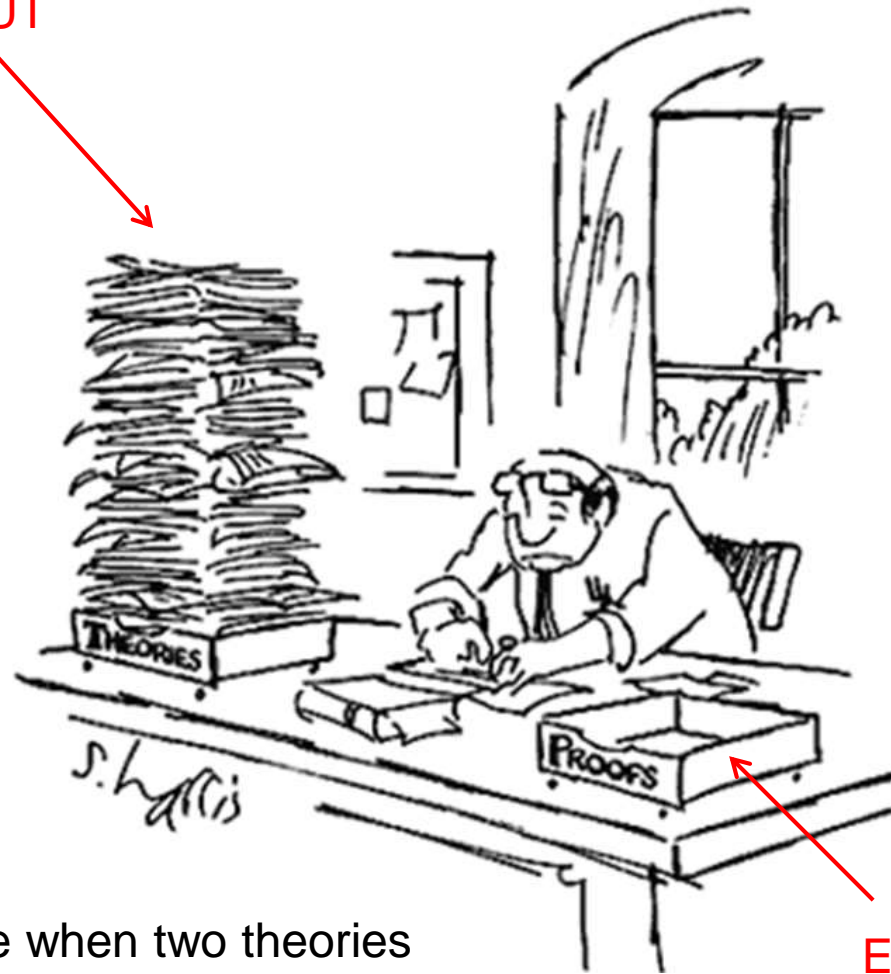


SUSY mass scale can make running coupling constant convergent.
GUT doesn't work without SUSY. And the only "evidence" for SUSY
is that the coupling constants can be "unified" (+ prediction of θ_W)

- Does the Great Desert exist?

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

SUSY and GUT models



Experimental data

This is an example when two theories GUT and SUSY (none of them supported by the experimental observations) are motivating each other.

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.

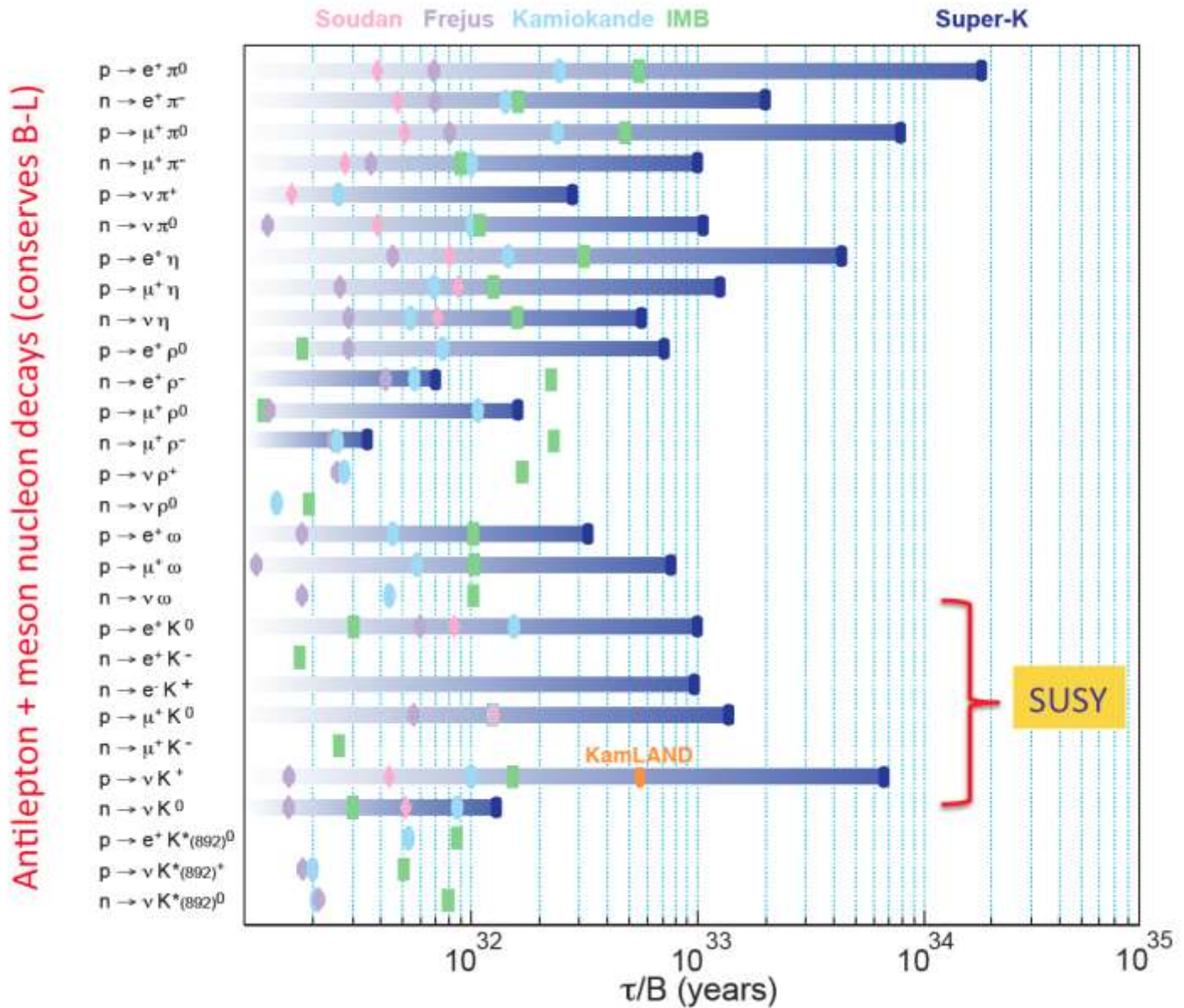
$(B - L)$ symmetry of Standard Model must be violated for BAU
(Kuzmin, Rubakov, Shaposhnikov, 1985)

$(B - L)$ 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.

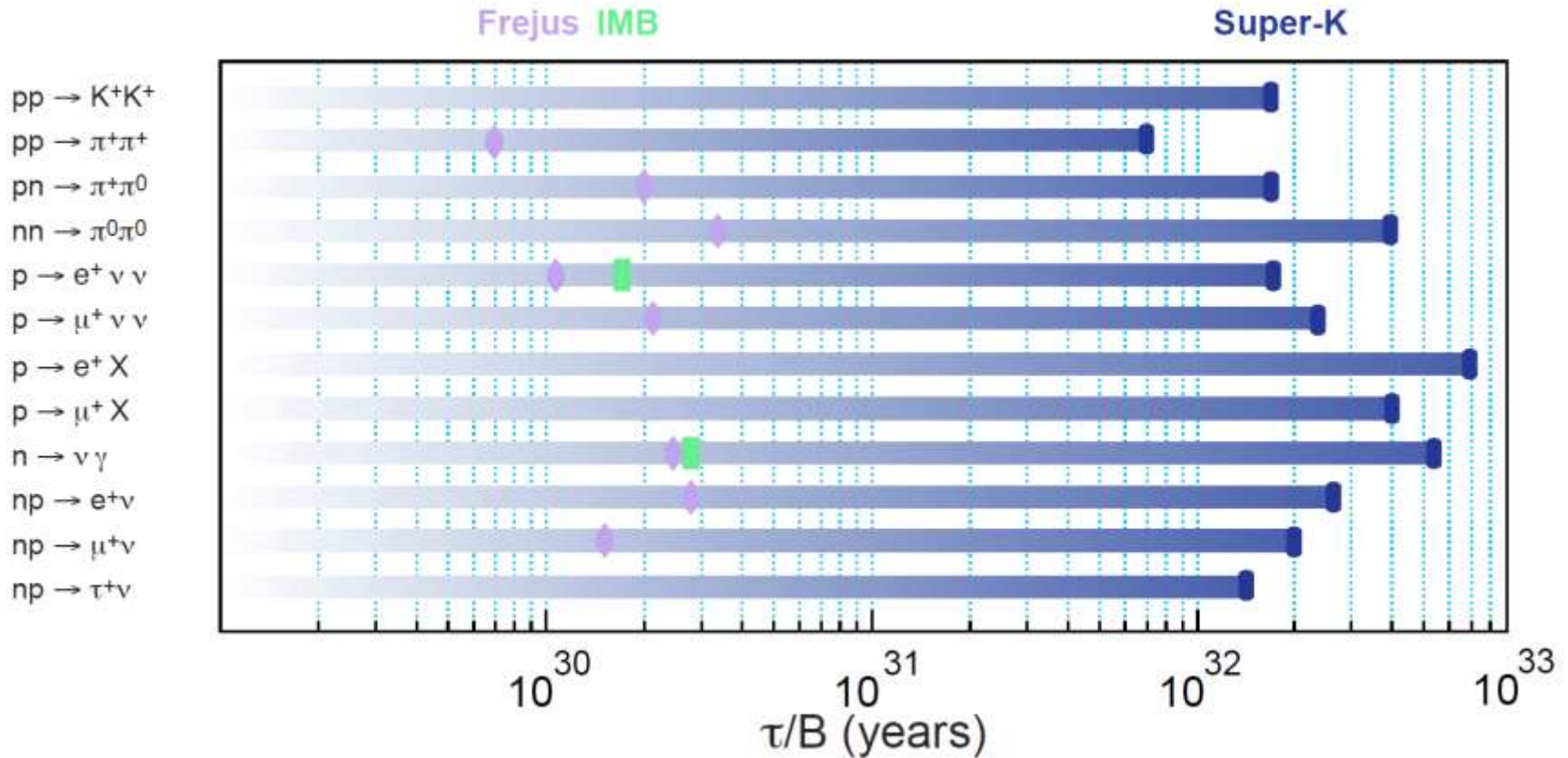
Fast $V(B+L)$ by Sphaleron mechanism at electro-weak scale wipes out results of $(B - L)$ conserving interactions from the higher scale.

→ “Proton decay is not a prediction of baryogenesis”

Progress in search for (B-L) conserving modes

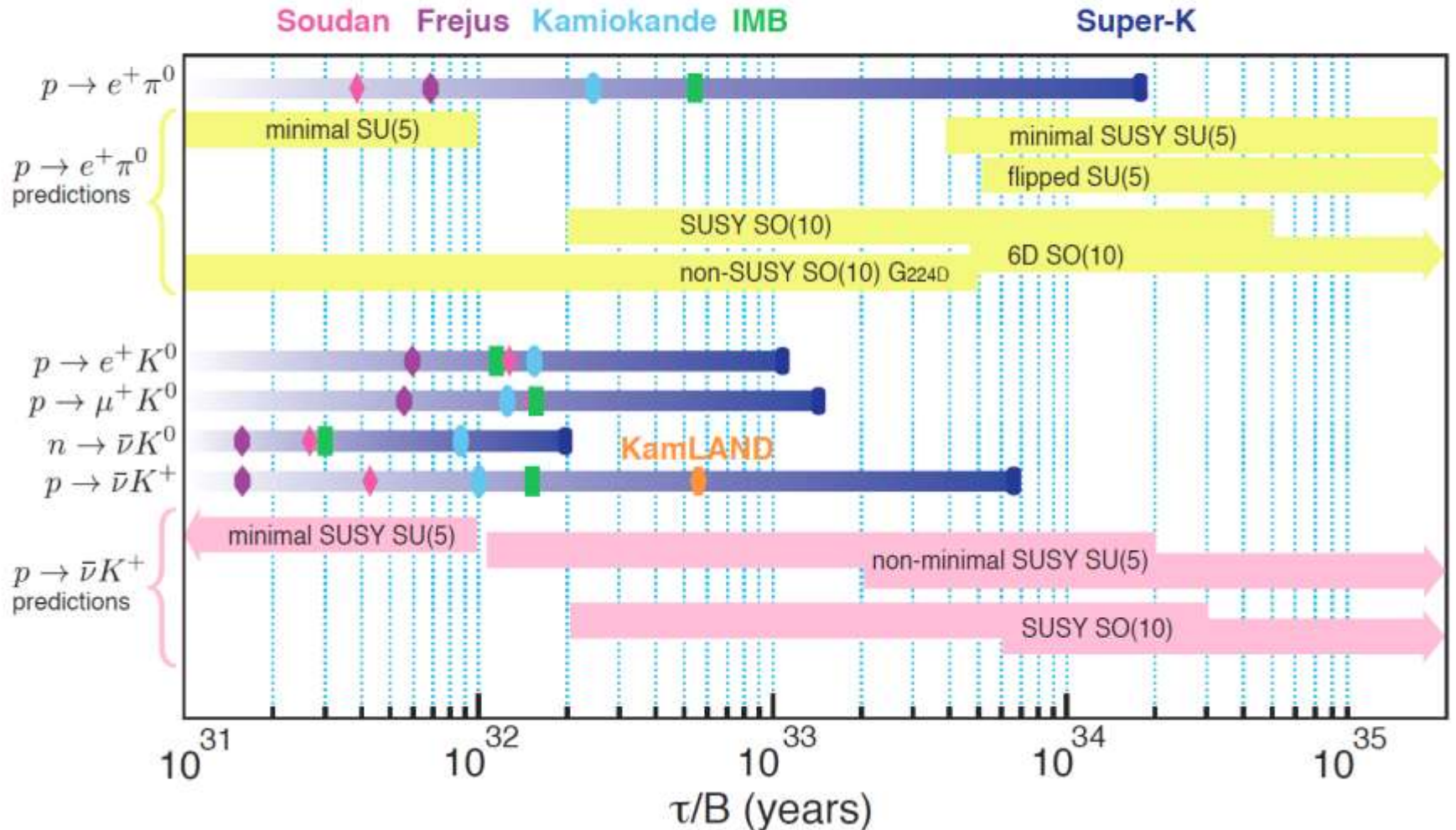


Summary of Recent Exotic Searches



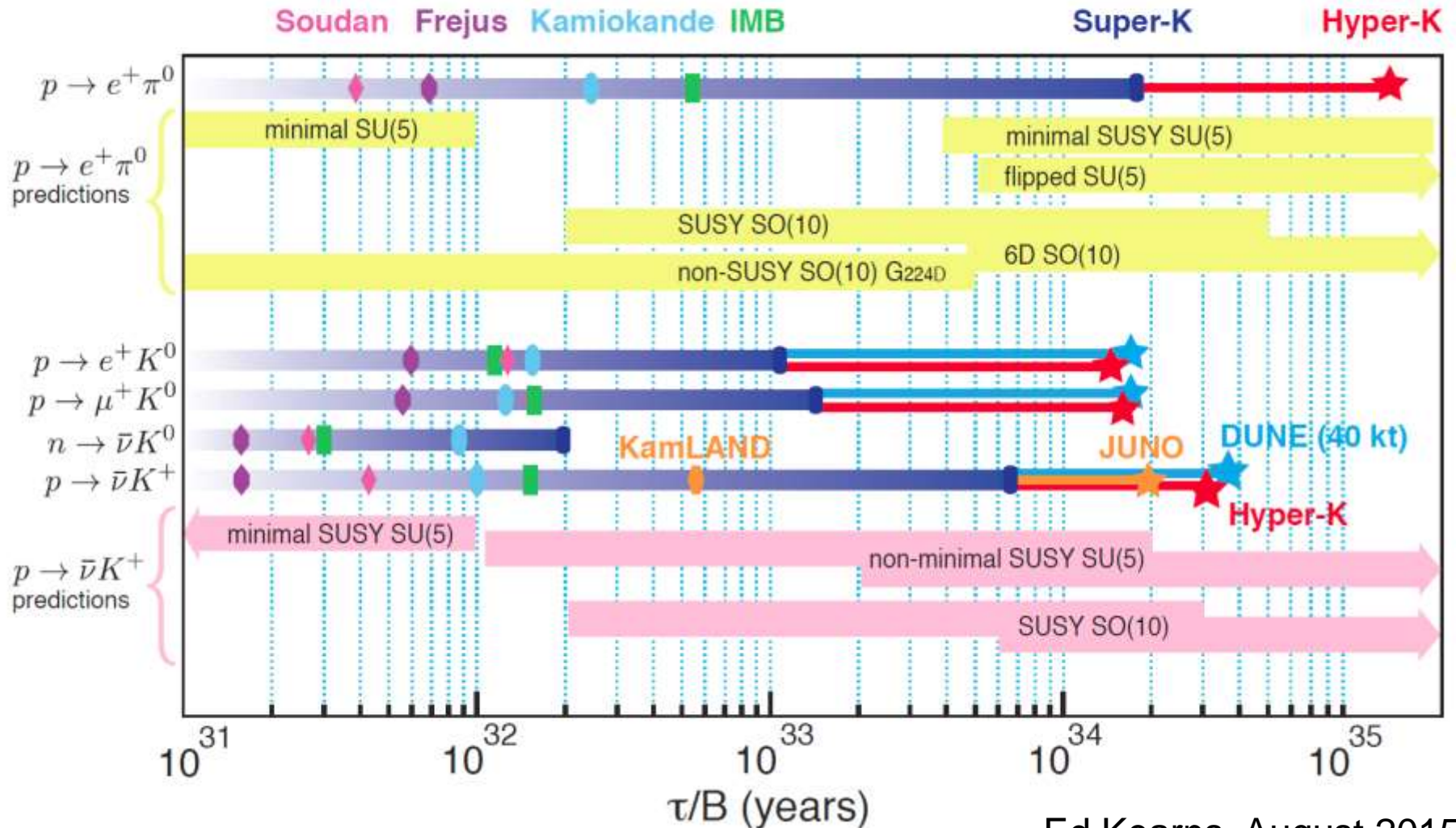
- Generally more than an order of magnitude improvement
- Some searches are entirely new

Current Benchmark Searches are in Interesting Territory



Expected progress in (B-L) conserving modes search

Future Benchmark Searches will be in Interesting Territory



Some history of $n \leftrightarrow \bar{n}$

$$|\Delta B|=2 \ ; \ |\Delta(B-L)|=2$$

❖ There are no laws of nature that would forbid the $N \leftrightarrow Nbar$ 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

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

V. Kuzmin, 1970

❖ $N \leftrightarrow Nbar$ 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...

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

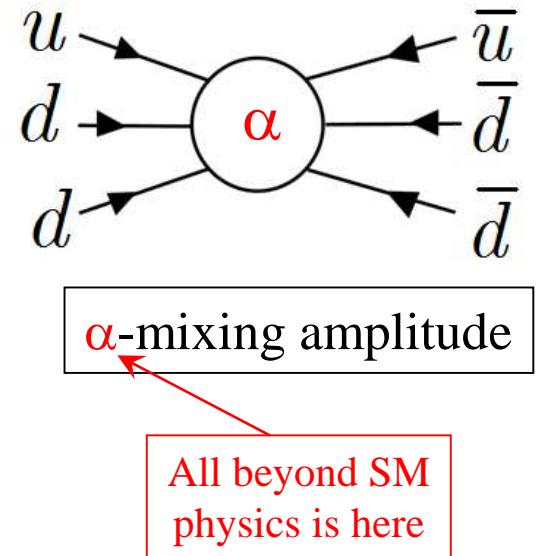
$n \rightarrow \bar{n}$ transition probability

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

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

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

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



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

where V is a potential symmetrically different for 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 $V=0$:

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

For neutrons inside nuclei:

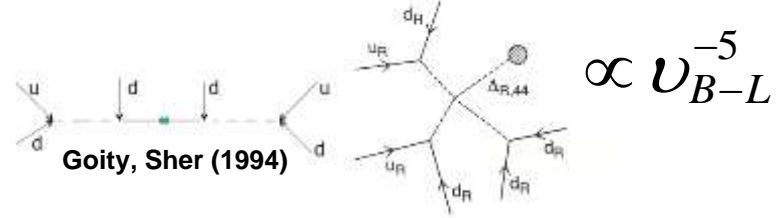
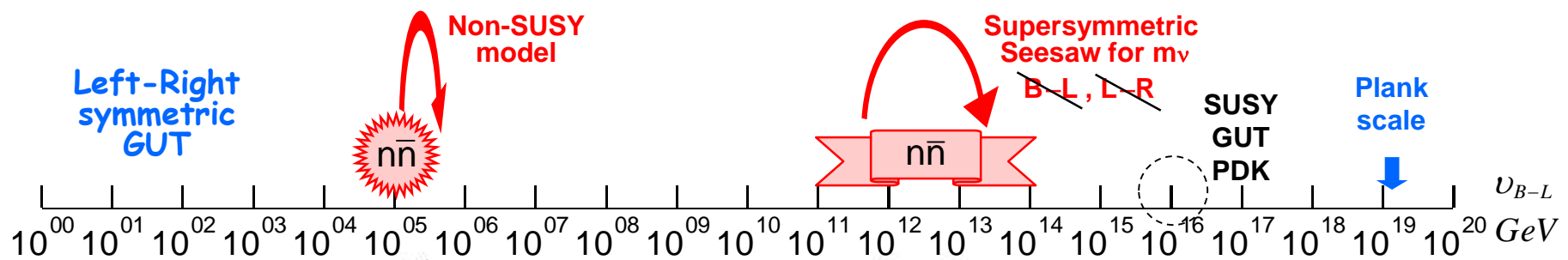
$$P_{n \rightarrow \bar{n}} = \frac{\alpha^2}{2V^2}$$

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

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

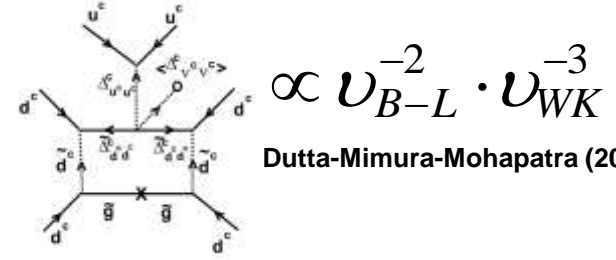
Sensitivity (or figure of merit) is $\rightarrow N_n \times \bar{t}^2$

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

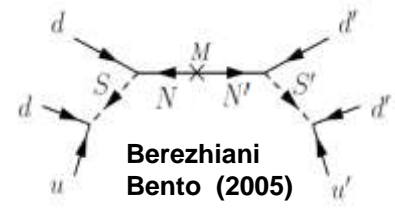


Mohapatra & Marshak (1980)

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



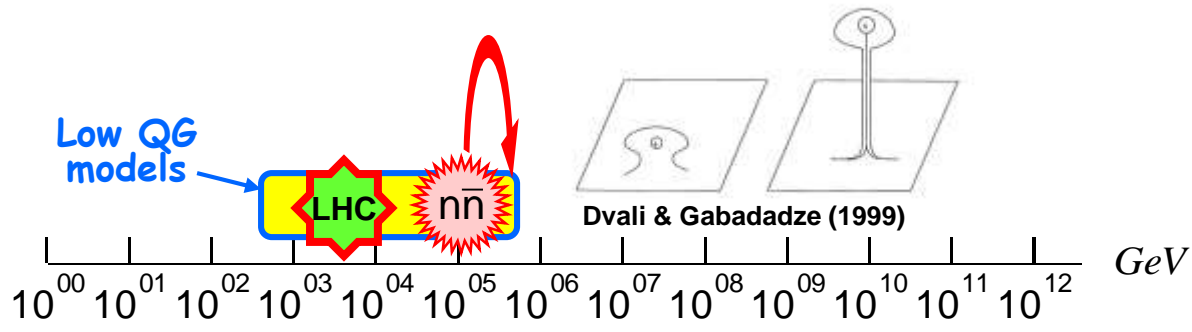
$$\propto U_{B-L}^{-2} \cdot U_{WK}^{-3}$$



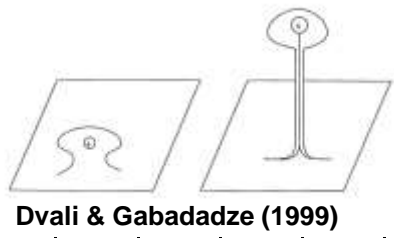
Baryogenesis at TeV scale

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

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



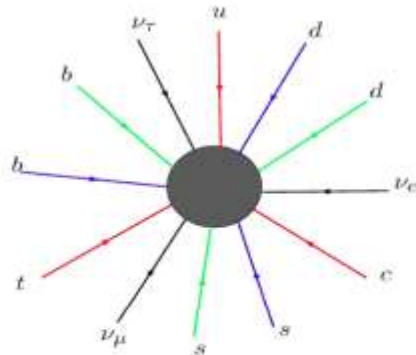
Low QG models



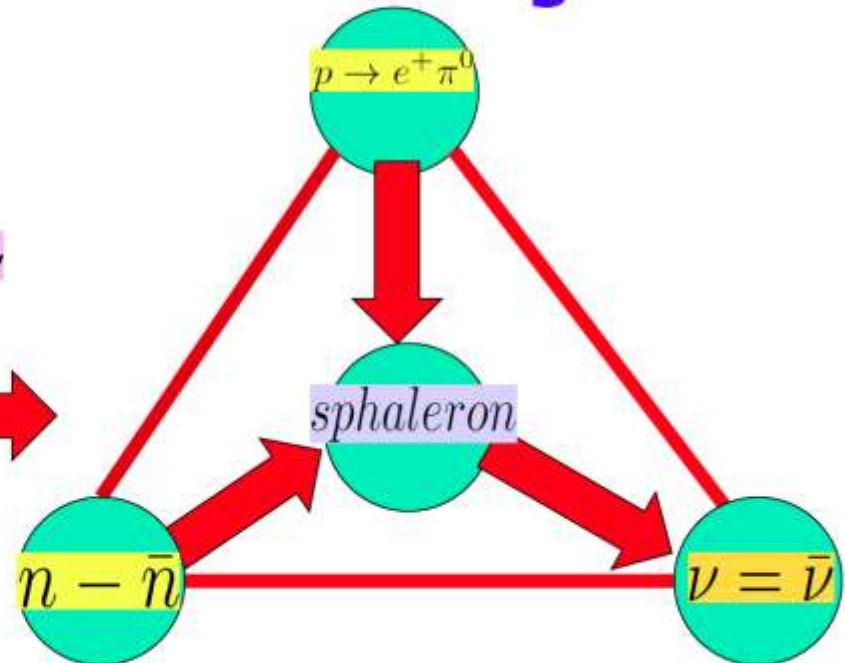
From NNbar to Majorana neutrino via sphalerons

- Sphaleron Op. rewrite

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



B-L Triangle:

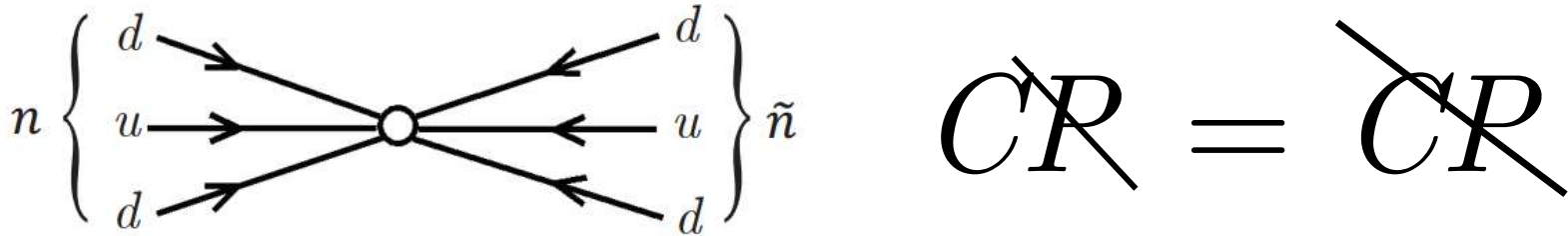


- $p\text{-decay} + n\bar{n} \rightarrow \text{Neutrino Majorana}$ (Babu, RNM'14)

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



3 Sakharov's Conditions for BAU in n-nbar:

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



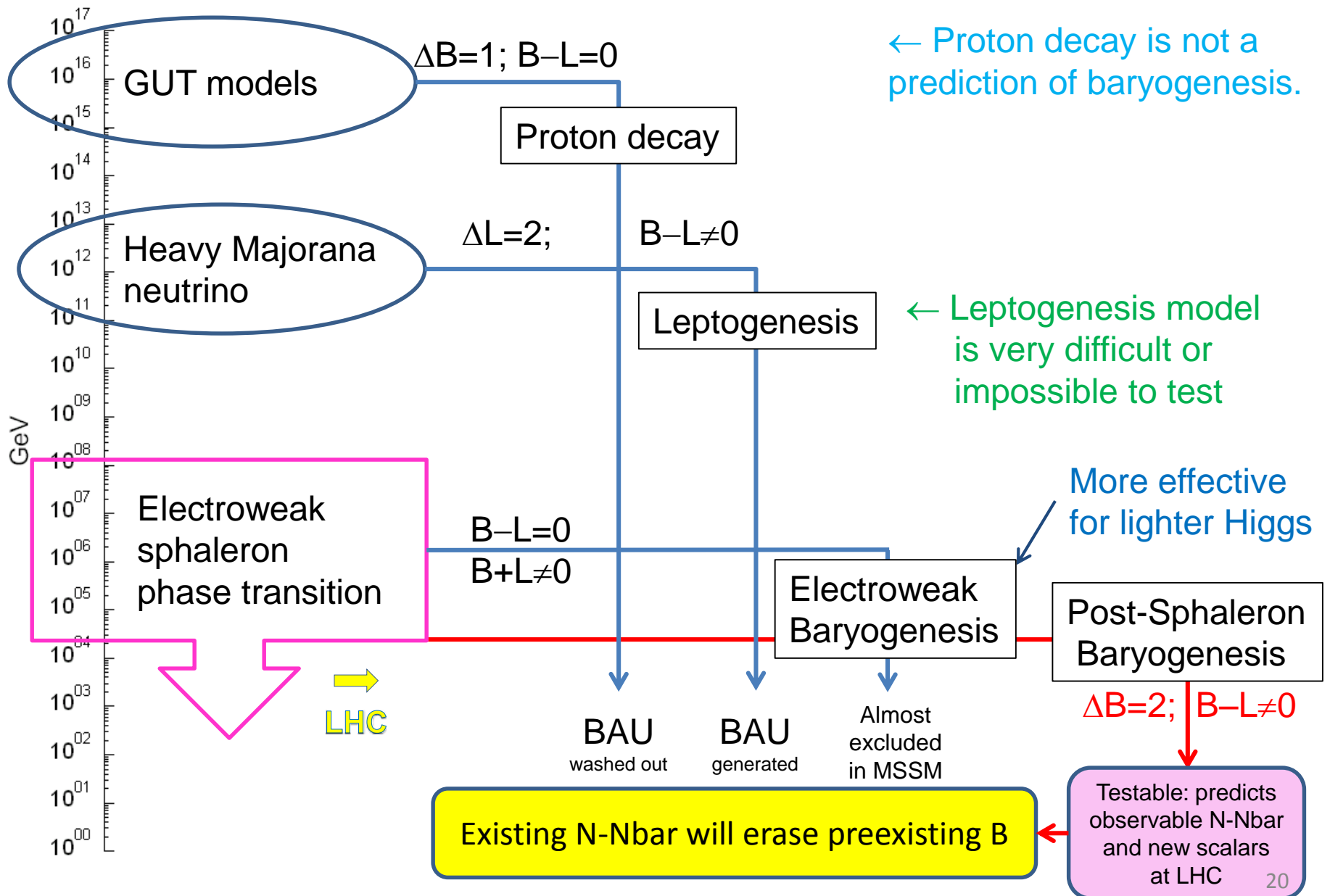
(2) CP violation



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



Baryogenesis Models



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	$0.86 \times 10^8 \text{ s}$	1u
2	$2.7 \times 10^8 \text{ s}$	10u
3	$7.5 \times 10^8 \text{ s}$	76u
4	$2 \times 10^9 \text{ s}$	500u
5	$1 \times 10^{10} \text{ s}$	13,500u
6	$1 \times 10^{10} \text{ s}$	13,500u

←Free neutrons at ILL (1994)

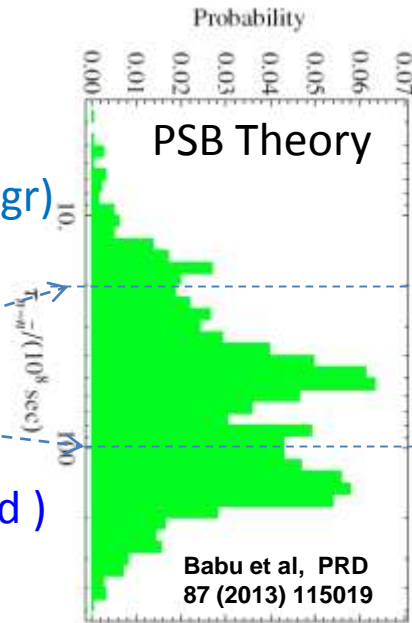
←Super-K (2015), 22.5kt, 4 years (w bkgr)

←Hyper-K 500kt, 10 years

←Horizontal beam (ESS, 3 yr)

←VCN-UCN source with vertical layout

←LBNE, 40 kt, 10 yr ? (if no background)



Searches with free and bound neutrons are complementary

Small summary of Theory discussion

n-nbar theory: some models provide upper limits and thus experimentally testable; connected with Majorana neutrino masses, violate (B-L), relevant for BAU + ~~CP~~ .

Proton decay theory: several extendable predictions; focused on (B-L) conserved modes not relevant for BAU.

1. N - \bar{N} Search with free neutrons

**Construction started in 2014
to be completed by 2019**



ESS

An International Collaboration



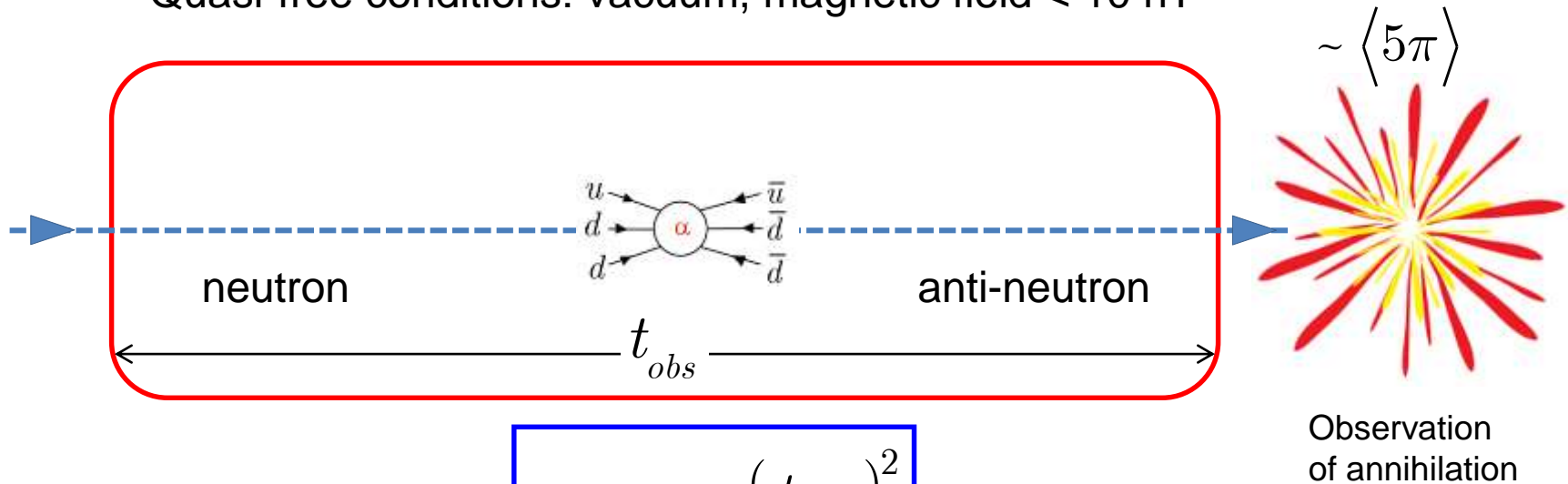
Sweden,
Denmark and Norway:
50% of construction and
20% of operations costs



European partners
pay the rest

Free neutron transformation

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



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

Present $\tau > 8.6 \times 10^7$ s (ILL limit) \rightarrow $\tau > 4 \times 10^9$ s (@ ESS)
 or sensitivity ($P_{n \rightarrow \bar{n}}$) 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-Ceolin³, P. Benetti⁴, T. Bitter¹, F. Bobisut³, E. Calligarich⁴, R. Dolfini⁴, D. Dubbers¹, P. El-Muzeini¹, M. Genoni⁴, D. Gibin³, A. Gigli Berzolari⁴, K. Gobrecht², A. Guglielmi², J. Last², M. Laveder³, W. Lippert¹, F. Mattioli³, F. Mauri⁴, M. Mezzetto³, C. Montanari⁴, A. Piazzoli⁴, G. Puglierin³, A. Rappoldi⁴, G.L. Raselli⁴, D. Scannicchio⁴, A. Sconza³, M. Vascon³, L. Visentin³

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 \sim GeV background! No candidates observed !

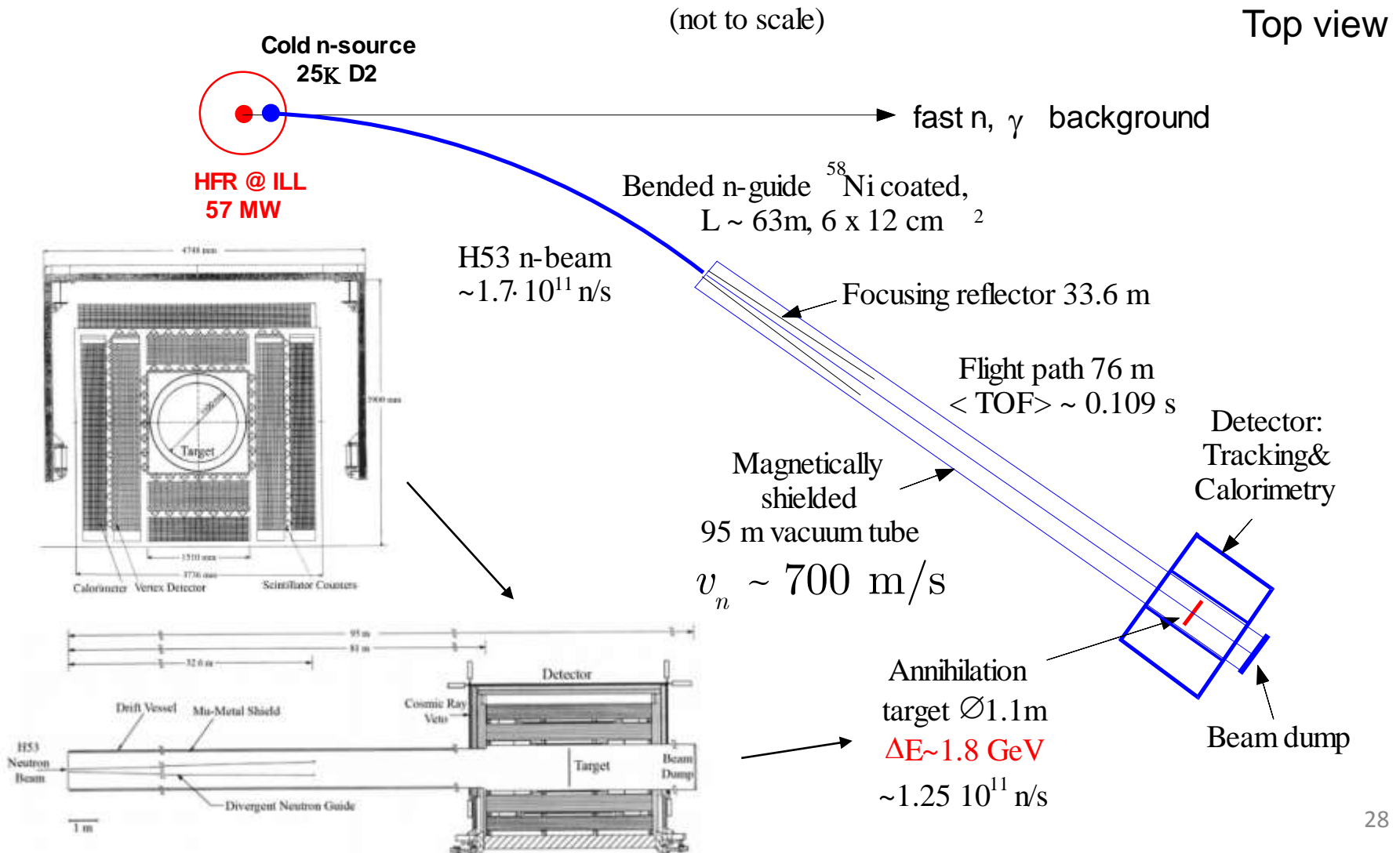
Measured limit for one year of running: $\tau_{n\bar{n}} > 0.86 \times 10^8 \text{ s}$

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

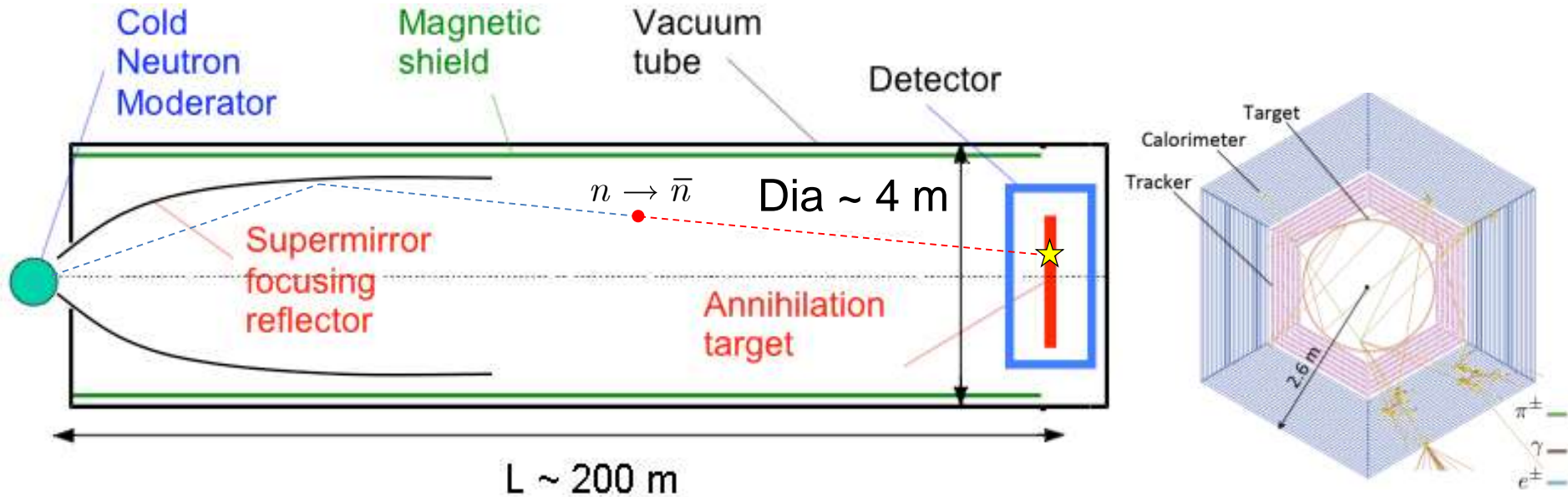
at ILL/Grenoble reactor in 89-91 by Heidelberg-ILL-Padova-Pavia Collaboration

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

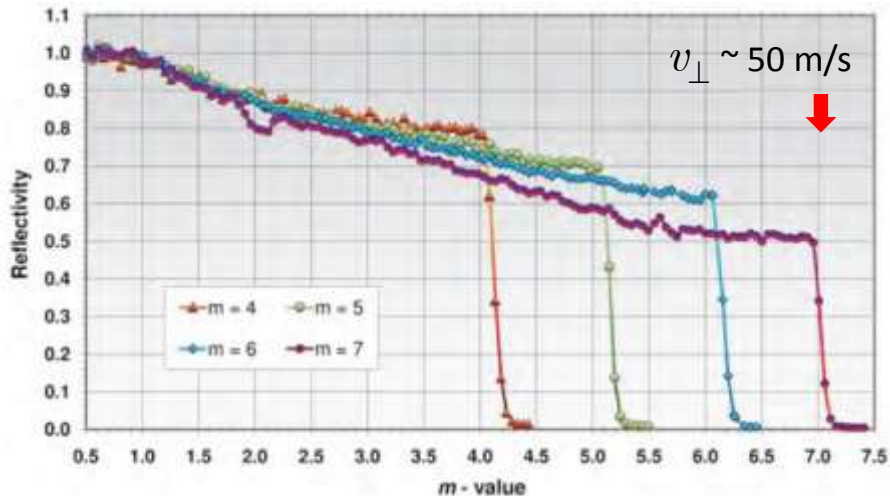


Idea of sensitivity enhancement

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



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

m is up to 7

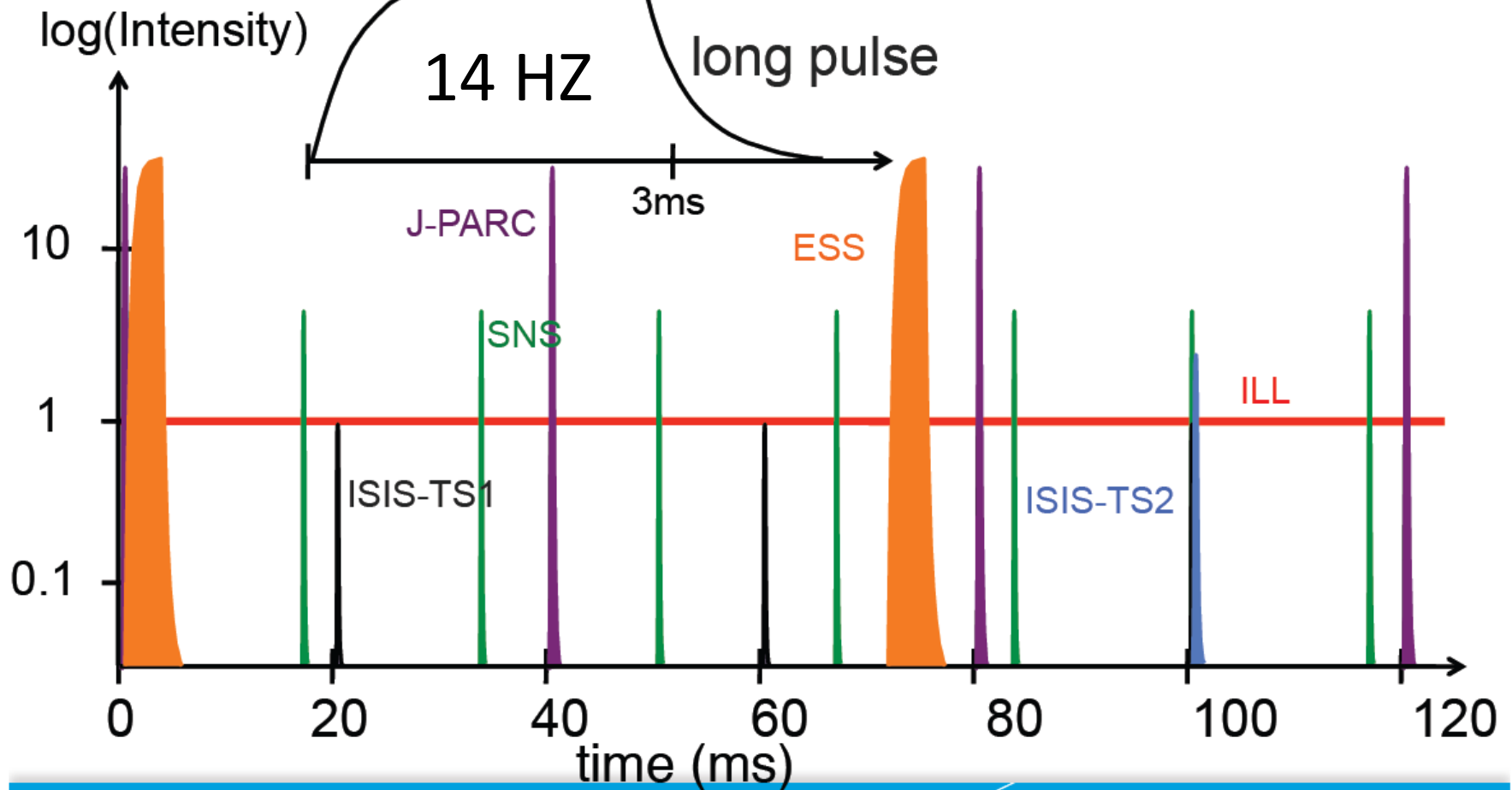
Continuing advancements
in neutron optics.

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€

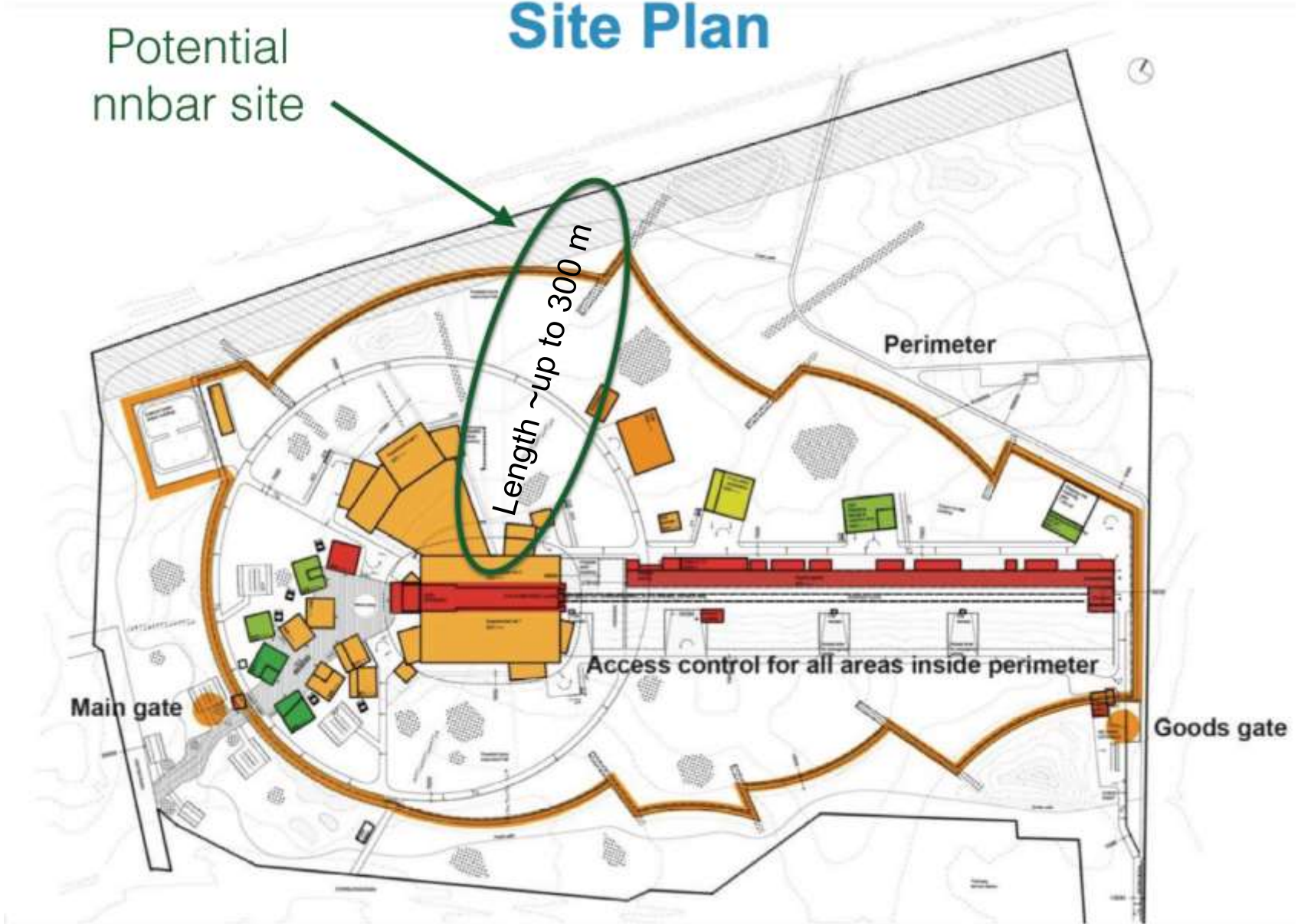
Groundbreaking on September 2, 2014

Pulsed-source time structures cold neutrons

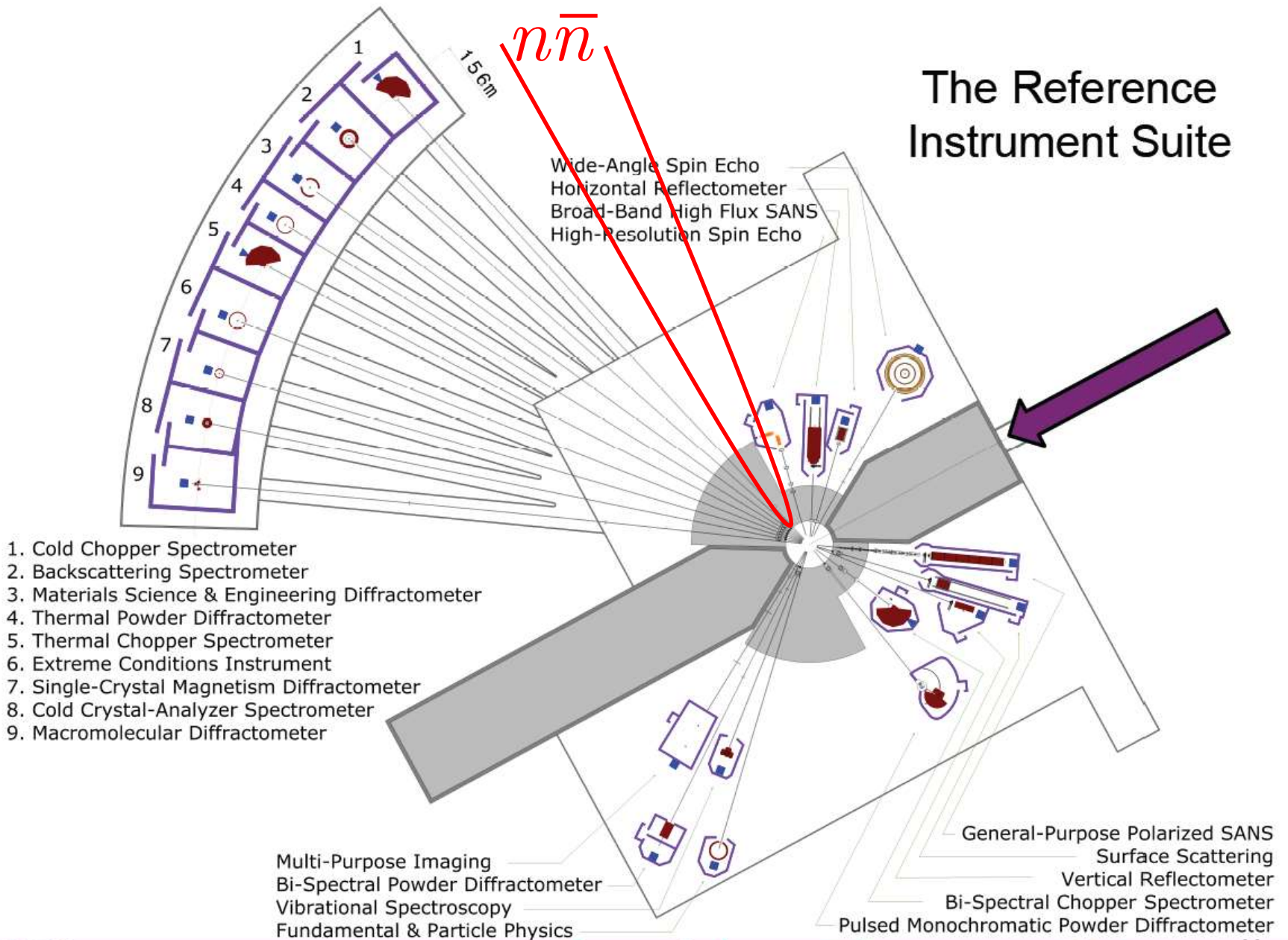


Site Plan

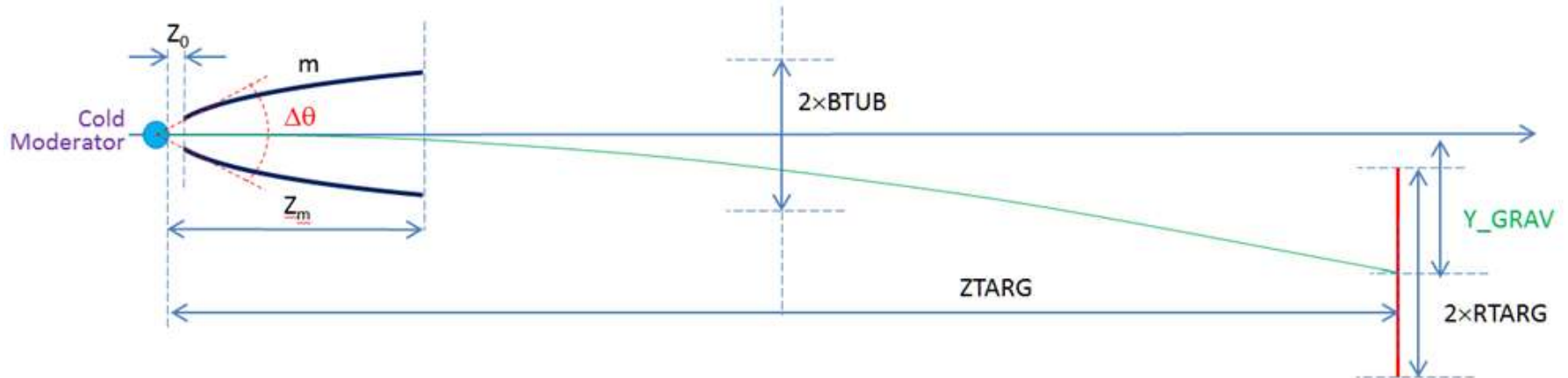
Potential
nobar site



The Reference Instrument Suite



Sensitivity Variation Parameters



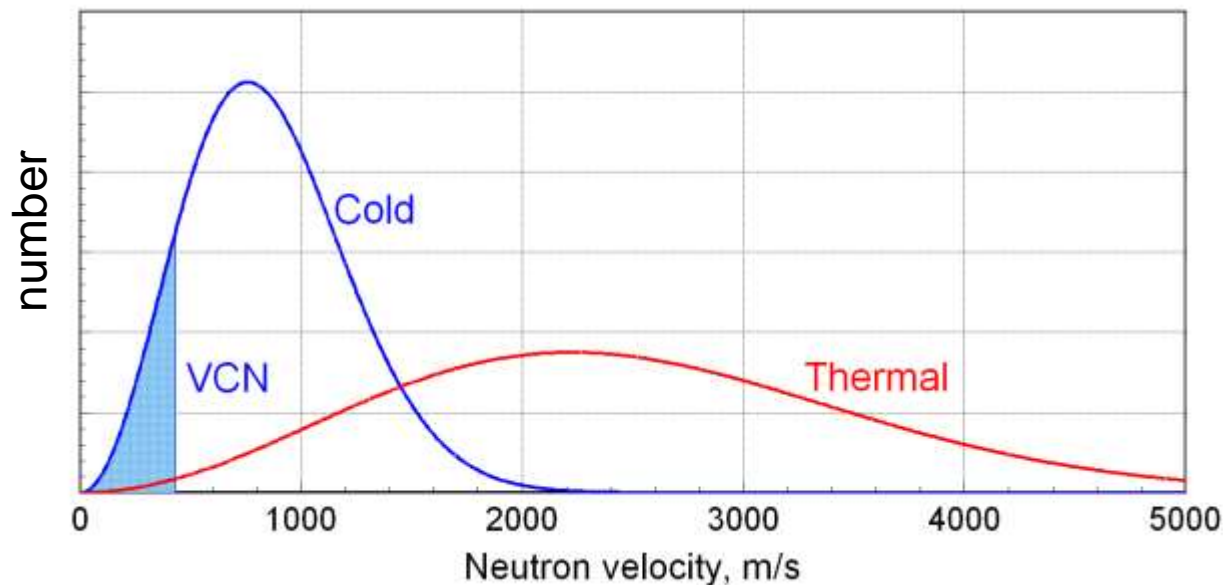
1. ESS TDR baseline cold moderator geometry and spectrum (dia 30 cm in PX)
2. Z_0 – distance of reflector start (1.5 m)
3. Z_m – distance of reflector end (40 m)
4. m – supermirror reflector parameter ($m=6$)
5. Z_{TARG} – distance moderator-detector = $2 \times$ large demi-axis (200 m)
6. $RTARG$ – radius of the annihilation detector (1 m)
7. $BTUB$ – small demi-axis (\sim linearly related to $\Delta\theta$ - angular occupancy) (2 m)

Y_{GRAV} – neutron gravity fall (detector vertical offset) (-0.45 m)

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

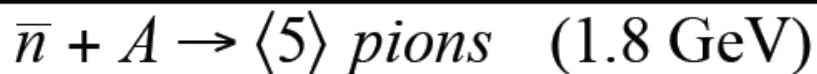
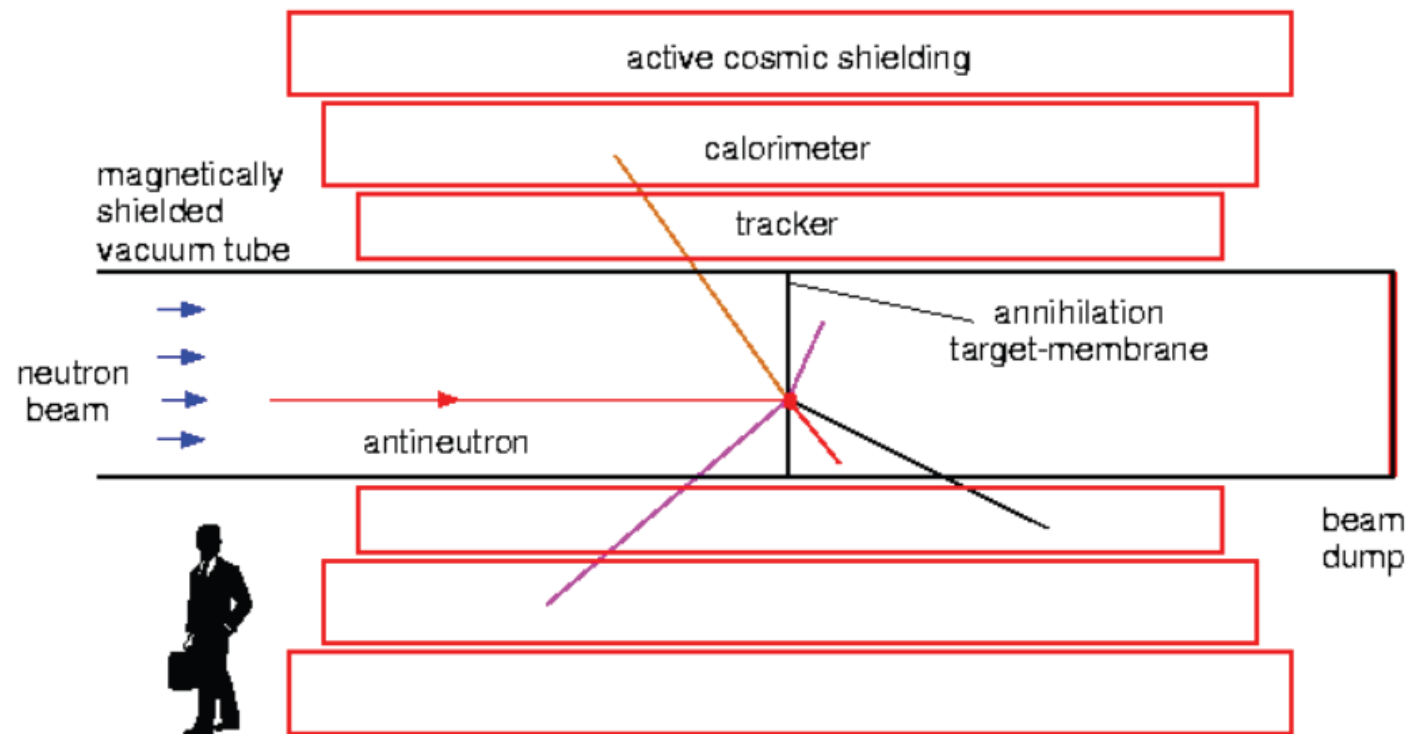
⇒ many neutrons (large N) and very slow (large \bar{t})

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

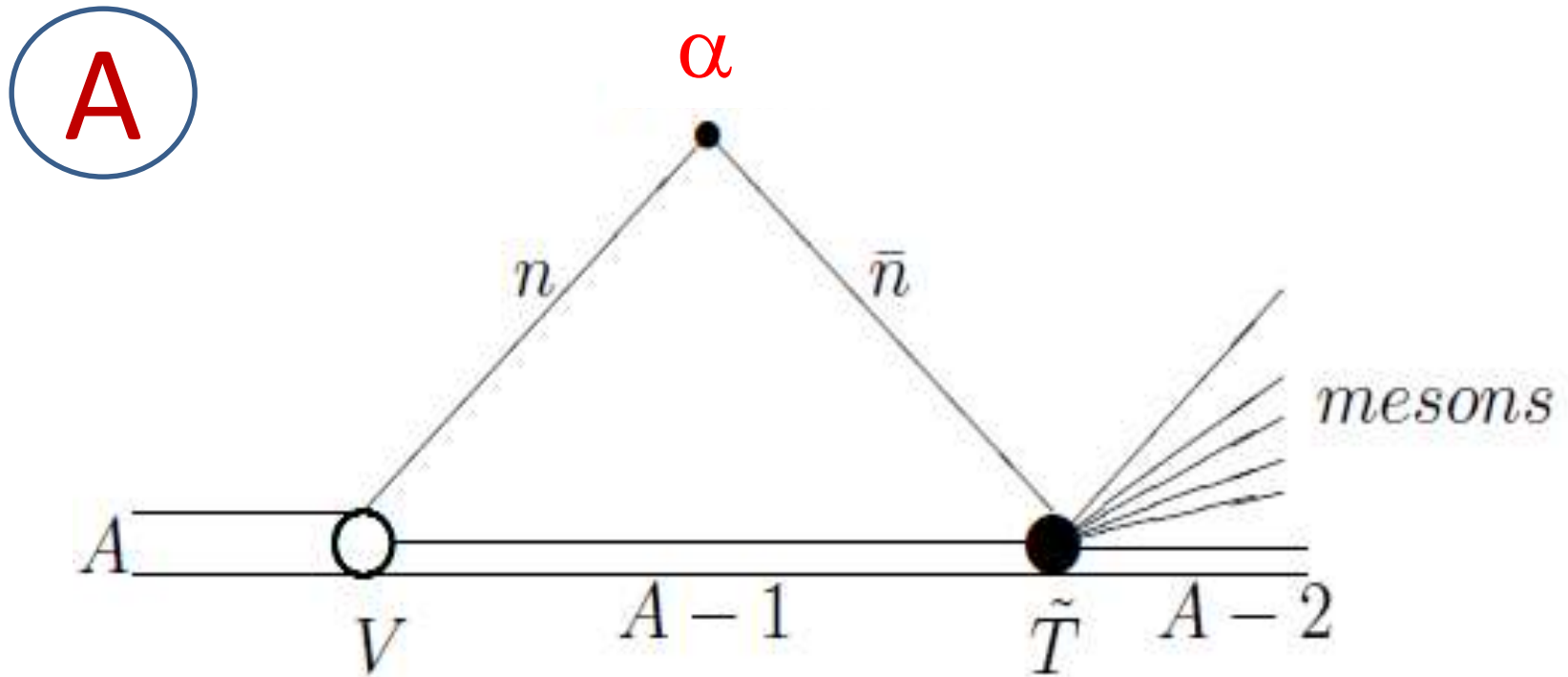


Annihilation target: $\sim 100\mu$ thick Carbon film

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

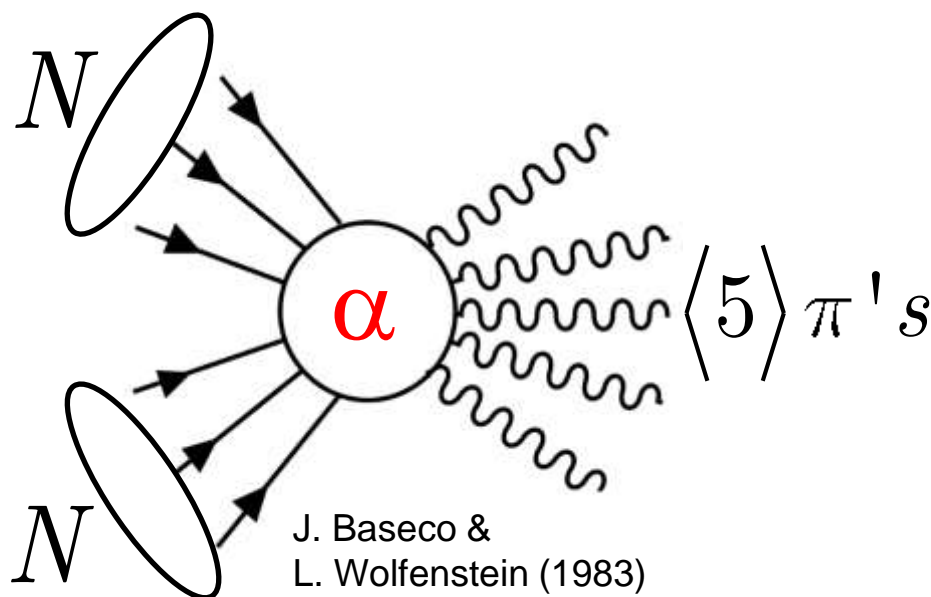
vertex precisely defined. No background was observed at ILL

2. N-Nbar inside nuclei



B

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

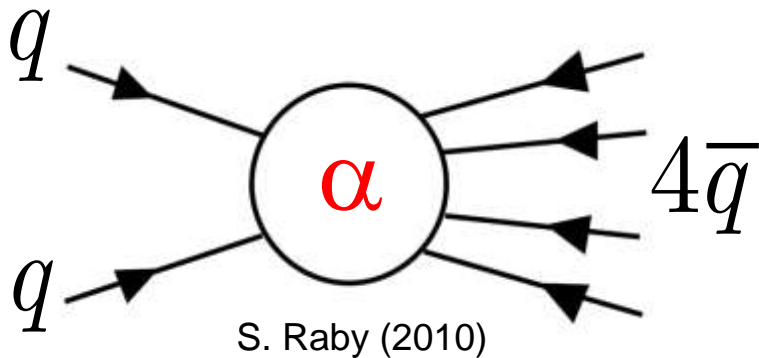
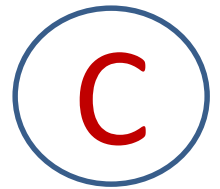


J. Baseco &
L. Wolfenstein (1983)

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

Intranuclear experiment can see only pions final state.

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



Annihilation
to ~ 5 pions

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

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

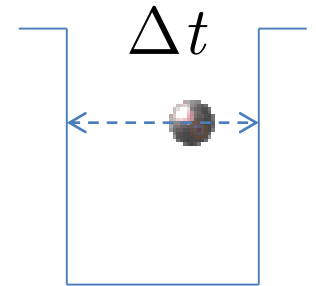
However, free neutron transformation violate CP and intranuclear transformation can be CP even. Thus, potentially A+B+C might be different processes that need to be evaluated independently, e.g. for extraction of free neutron oscillation time from intranuclear data.

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

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

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

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



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

Intranuclear transition (exponential) lifetime:

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

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

Theoretical calculations of nuclear suppression factor

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

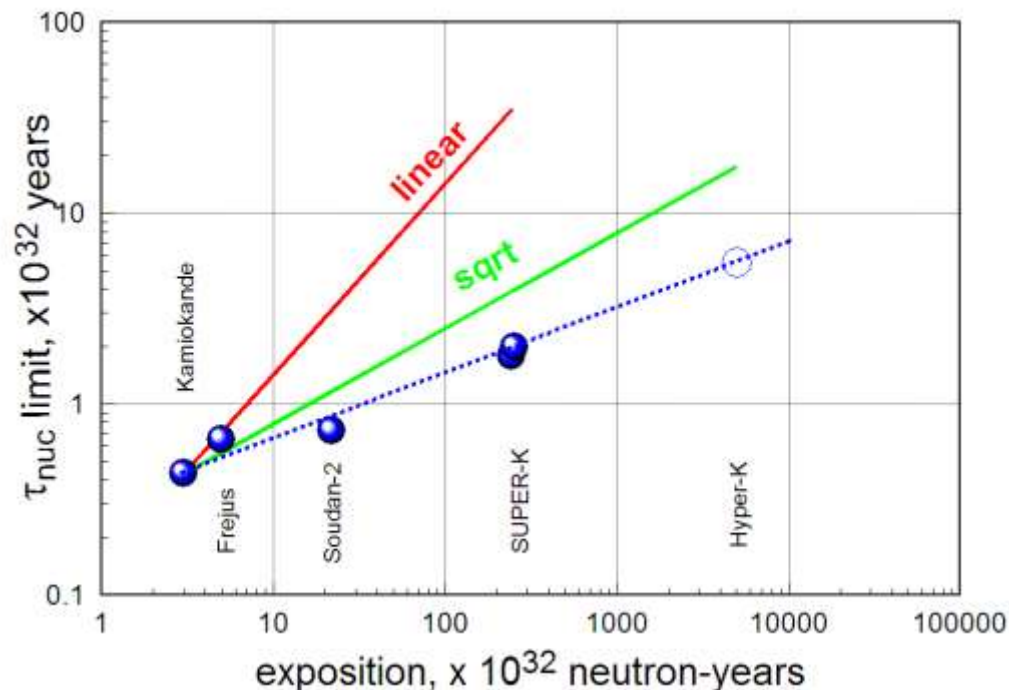
- C. Dover, A. Gal, J. Richard (1989 -1996) used by S -K publication
- W. Alberico et al (1985-1998) ↗ agreed
- B. Kopeliovich and J. Hufner (1998): uncertainty factor of 2
- E. Friedman and A. Gal (2008): for O change by factor of 2, $\pm 15\%$
- V. Kopeliovich, I. Potashnikova (2011) - recent for D_2 (to be used for SNO)
- B. Kopeliovich, A. Vainshtein (2012 -13) - in progress

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

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

Bound neutron N-Nbar search experiments

Experiment	Year	A	n-year (10^{32})	Det. eff.	Candid.	Bkgr.	τ_{nuc} , yr (90% CL)
Kamiokande	1986	O	3.0	33%	0	0.9/yr	$>0.43 \times 10^{32}$
Frejus	1990	Fe	5.0	30%	0	4	$>0.65 \times 10^{32}$
Soudan-2	2002	Fe	21.9	18%	5	4.5	$>0.72 \times 10^{32}$
Super-K	2007	O	245.4	10.4%	20	21.3	$>1.8 \times 10^{32}$
Super-K	2009	O	254.5	12%	23	24	$>1.97 \times 10^{32}$
SNO *	2010	D	0.54	41%	2	4.75	$>0.301 \times 10^{32}$
Super-K	2015	O	245	12.1%	24	24.1	$>1.9 \times 10^{32}$



* 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.

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

K. Abe et al., Super-K Collaboration

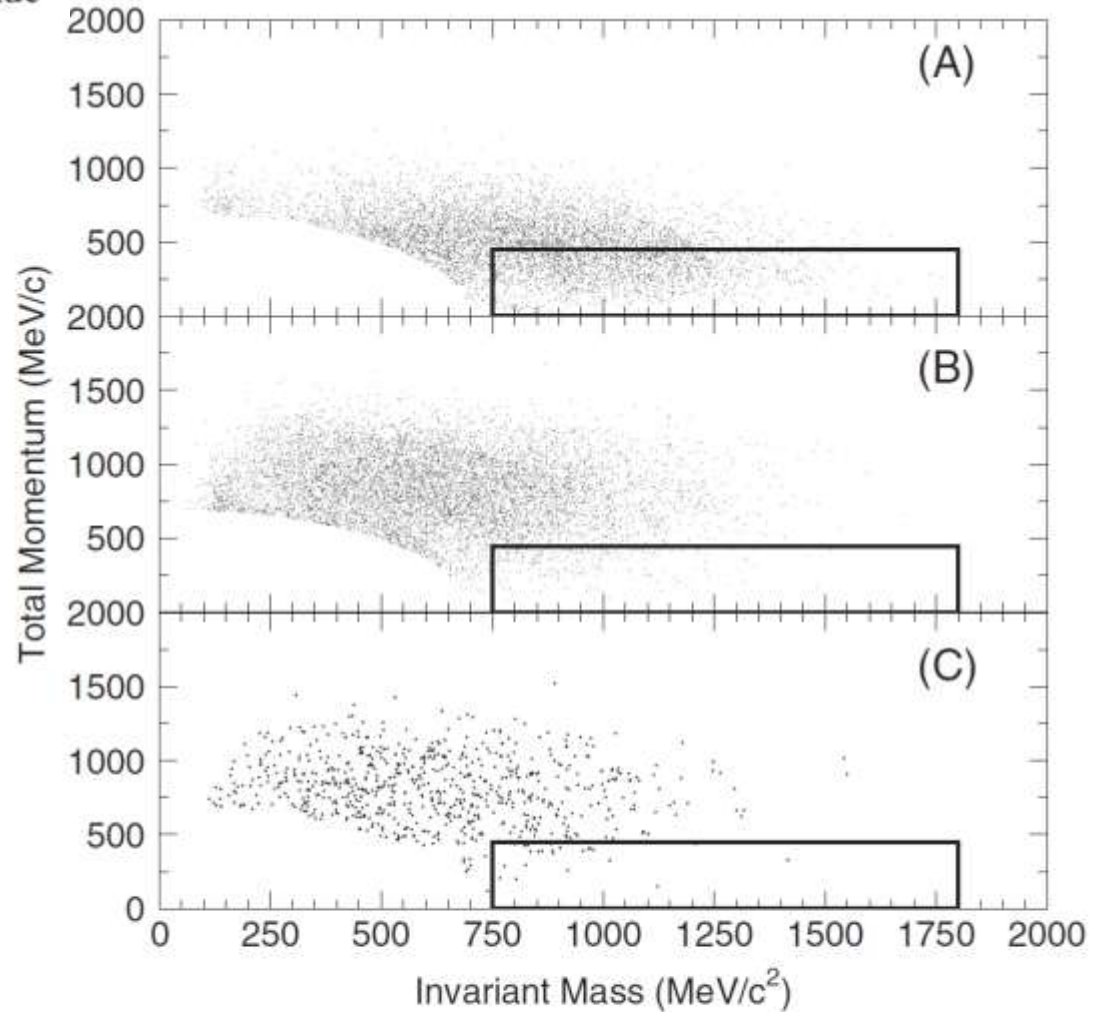


FIG. 2. Total momentum vs the invariant mass after applying the selection criteria (a)–(b) on the FC sample: (A) signal MC, (B) atmospheric neutrino MC, and (C) data. The boxed region in each panel shows the criterion (c)–(d) for the $n - \bar{n}$ oscillation signal.

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

Conversion of Bound Limit to free Oscillation Limit

Experiment	Year	A	$\tau_{nucl}, yr (90\% CL)$	R(old), s^{-1}	R(new), s^{-1}	$\tau(old), s$	$\tau(new), s$
Kamiokande	1986	O	$>0.43 \times 10^{32}$	10×10^{22}	5×10^{22}	$>1.2 \times 10^8$	$>1.65 \times 10^8$
Frejus	1990	Fe	$>0.65 \times 10^{32}$	14×10^{22}	?	$>1.2 \times 10^8$?
Soudan-2	2002	Fe	$>0.72 \times 10^{32}$	14×10^{22}	?	$>1.3 \times 10^8$?
SNO * (0.002 of SK)	2010	D	$>0.301 \times 10^{32}$	2.48×10^{22}	2.94×10^{22}	$>1.96 \times 10^8$	$>1.8 \times 10^8$
Super-K	2011	O	$>1.9 \times 10^{32}$	10×10^{22}	5×10^{22}	$>2.44 \times 10^8$	$>2.7 \times 10^8$

Dover, Gal
et. al, old

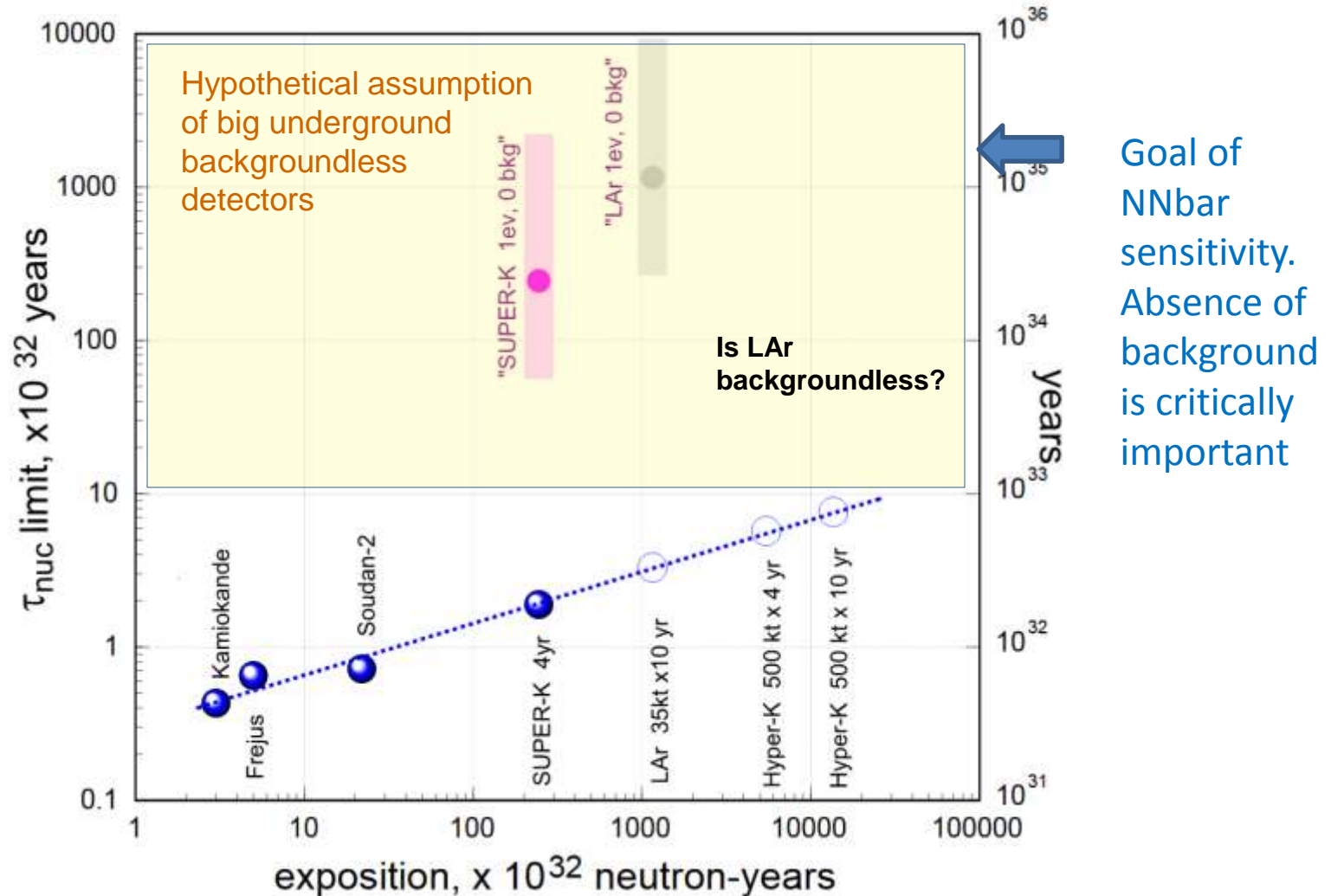
V. Kopeliovich
2011, Deuterium

Friedman and Gal
2008, Oxygen

B. Kopeliovich & A. Vainshtein, 2012

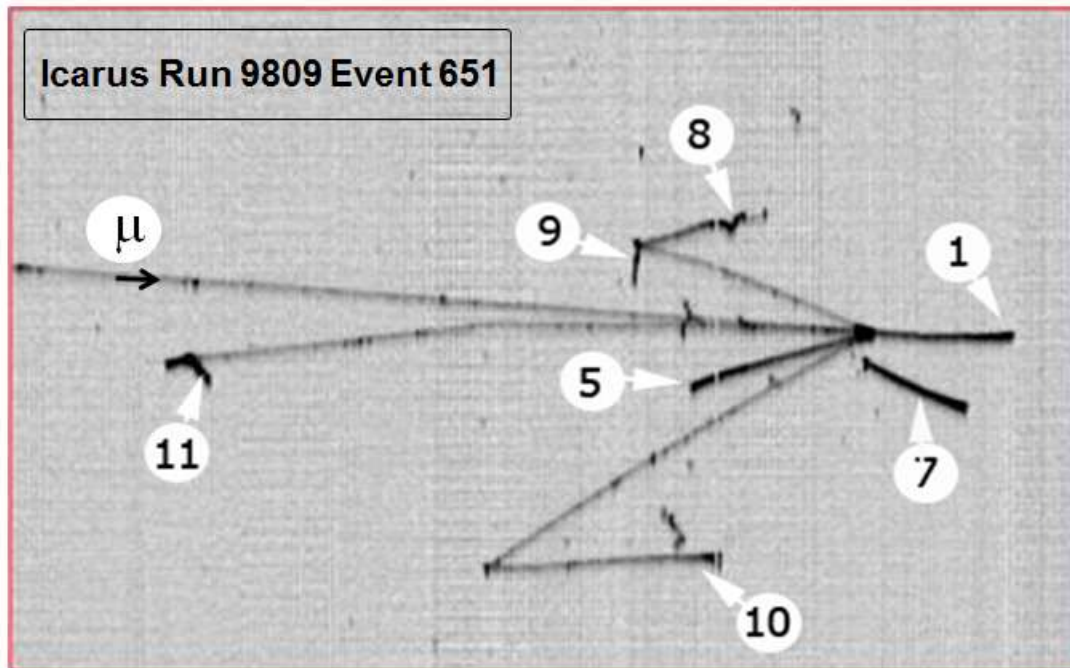
$$\Rightarrow \tau_{n\bar{n}}(\text{from bound}) > 2.7 \times 10^8 s \quad \text{or} \quad \alpha < 2 \times 10^{-24} eV$$

Prospects of intranuclear n-nbar search



24 candidate events in Super-K might contain several genuine n-nbar events. Backgroundless PDK detectors are needed to explore nbar $> 10^{33}$ 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 $\sim 10^{35}$ yr will be possible was not yet demonstrated.



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

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

Paola Sala
 Zurich, 2011

1. Recent white paper for Physics Review on n - \bar{n} :

D.G. Phillips II et al., N-Nbar Collaboration

Neutron-Antineutron Oscillations: Theoretical Status and Experimental Prospects
arXiv:1410.1100

**Free neutron and bound neutron n - \bar{n} searches are complementary;
the difference can reveal new physics.**

2. 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 non-existent due to baryonic violation condensate.