Particle Physics at the Intensity Frontier

What can we learn from a search for N-N-bar Oscillation?

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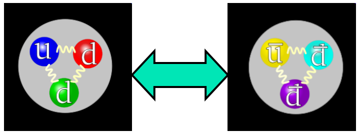
What is N-Nbar oscillation ?

- Neutrons in vacuum or low magnetic field spontaneously converting to anti-neutrons.



n $\bar{n}$

(Baryogenesis: Kuzmin'70; SU(5): Glashow'79; neutrino mass: Mohapatra and Marshak'80)

- $\delta m_{n\bar{n}}$ is the mixing strength between n and $\bar{n}$

- $\delta m_{n\bar{n}}$ = 0 in the standard model.

- **Hence it is a probe of new physics !!**

Experimental probe

- Define free oscillation time $\tau_{n\bar{n}} = \frac{\hbar}{\delta m_{n\bar{n}}}$
- Probability of transition in vacuum: $P_{n\to\bar{n}} \approx \left(\frac{t}{\tau_{n\bar{n}}}\right)^2$
- Figure of merit: # of $\bar{n}$ = flux of n $P_{n\bar{n}}$ (running time)
- Current direct search limit **ILL** $\tau > 8.6 \times 10^7 \sec$

((Baldoceolin et al'94) P-decay search Super-K'12 $\geq 2.44 \times 10^8 sec$

→ $\delta m_{n\bar{n}} < 10^{-32} GeV$ constrains new physics !!

- Future reach: (talks by Snow, Young, Kamyshkov,Gabriel…)

Why search for N-N-bar ?

- Many reasons that **baryon number (B) is not a good symmetry of nature** :Sphalerons in SM

  GUTs, origin of matter
- If B is violated, important to determine the selection rules: B=1 (p-decay) or B=2 (NNbar) ?

i) What is the scale at which B- symmetry is broken ?

NNbar → lower scale; p-decay very high scale

ii) NNbar being the baryonic counter part of Majorana neutrino mass will throw light on origin of nu mass !

(i) Operator analysis and wide scale reach of NNbar

SM particles $O_{\Delta B=2} = \frac{1}{M^5} u^c d^c d^c u^c d^c d^c$ **d=9**

Note M^5 suppression

$$\delta m_{n\bar{n}} = G_{\Delta B=2} < n|O_{\Delta B=2}|\bar{n} > \sim G_{\Delta B=2}\Lambda^6$$

(Buchoff-Lattice evaluation; Rao,Shrock, Bag model)

$\tau_{n-\bar{n}} = \hbar / \delta m_{n-\bar{n}} \sim M^5 / \Lambda^6$ → $\tau_{n\bar{n}} \sim 10^8 s.$ $M \sim 10^{5.5}\ GeV$

TeV diquarks: → $\Delta_{u^c d^c}$ → $\frac{1}{M} d^c d^c \Delta_{u^c d^c} \Delta_{u^c d^c}$

$M \sim 10^{15}\ GeV$

SUSY→ $\frac{1}{M^3} u^c d^c \tilde{u}^c \tilde{d}^c \tilde{d}^c \tilde{d}^c$ $M \sim 10^8\ GeV$

(ii) Neutrino mass NNbar connection

- SM has exact global B-L symmetry !!
- If neutrino is Majorana fermion, it breaks **L**-part of **B-L**

  by two units;
- If quarks and leptons are two parts of same matter, then $\Delta L = 2$ → $\Delta B = 2$ or N-N-bar oscillation
- e.g. if NN-bar is observed, either all or surely some of

  nu-mass physics is at the TeV scale and will be

  accessible in other expts e.g. LHC, FCNC, edm

Questions for N-N-bar oscillation

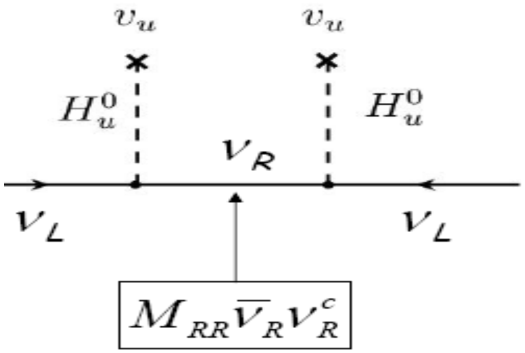
- Are there decent (predictive?)theories explaining small neutrino masses which give observable N-N-bar oscillation ?
- Implications of observable N-N-bar for cosmology i.e. does it affect conventional explanations of origin of matter/can it explain itself ?
- Two examples of models for NNbar:

(i) **TeV scale Seesaw +Quark-Lepton unif.**

(ii) **SO(10) GUT scale seesaw+TeV sextets**

Majorana neutrino mass via seesaw and NNbar

- SM+ right handed neutrinos N_R with Majorana mass $(\cancel{B-L})$.



$$m_\nu \cong -\frac{h_\nu^2 v_{wk}^2}{M_R}$$

Minkowsk'77i; Gell-Mann, Ramond, Slansky; Yanagida; Glashow, Mohapatra, Senjanovic'79

- $M_R << M_{Pl}$ →B-L a gauge symmetry→N Majorana mass arises from a new Higgs vev $<\Delta_R>$ (like SM fermion masses from <H>):
- What is $<\Delta_R>$, the actual scale of B-L breaking ?
- Do quarks and leptons unify to big picture of flavor ?
- NNbar search can answer these questions !!

A UNIFIED TeV SCALE EMBEDDING OF SEESAW

- If Q-L unified at the seesaw, a model is

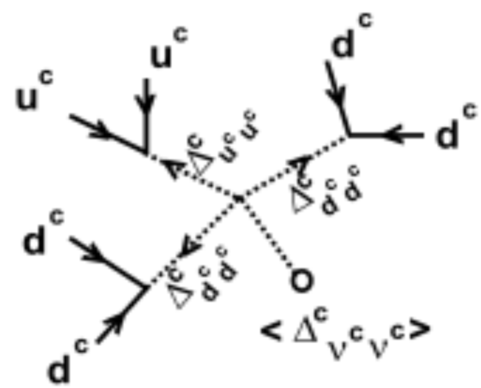
$$SU(2)_L \times SU(2)_R \times SU(4)_c \begin{pmatrix} u & u & u & \nu \\ d & d & d & e \end{pmatrix}_{L,R}$$

→SU(4) generalization of the seesaw Higgs field Δ_R has partners Δ_{qq} connecting to qua

→N-N-bar Feynman graph;

(Mohapatra,Marshak'80)

→No proton decay.



$$\frac{\lambda f^3 v_{BL}}{M_\Delta^6}$$

- Colored seesaw partners at TeV scale→ $\tau \sim 10^{10-11}\,\mathrm{sec}.$

Low scale NNbar model and origin of matter

- Only constraint on model is from nu masses. Without additional assumption, this model cannot predict $\tau_{n\bar{n}}$
- Assumption of low scale baryogenesis puts constraints on the $SU(2)_L xSU(2)_R xSU(4)_c$ model parameters and makes a prediction:
- These constraints put an upper bound NNbar transition time < $5x10^{10}$ sec.

- No NNbar till $5x10^{10}$ s., will rule out this model for post sphaleron baryogenesis. (Babu,Dev,Fortes,RNM'13)

Origin of matter and NNbar: TeV QL unif model

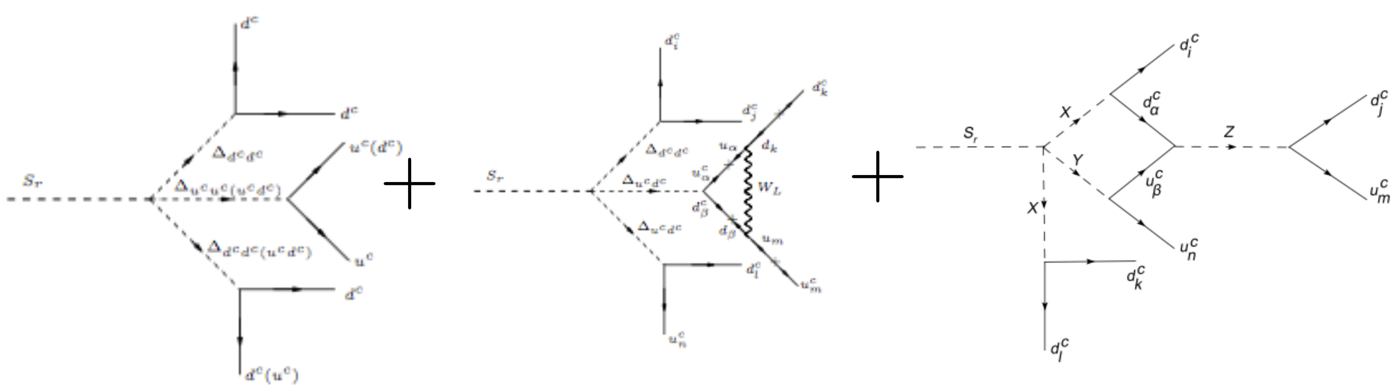
- Observation of NNbar will completely alter our thinking about the origin of matter.
- TeV QL model: NNbar transition in equilibrium 100 GeV

  ⇒ will erase any pre-existing matter asym !!
- New way to create matter below electroweak scale:

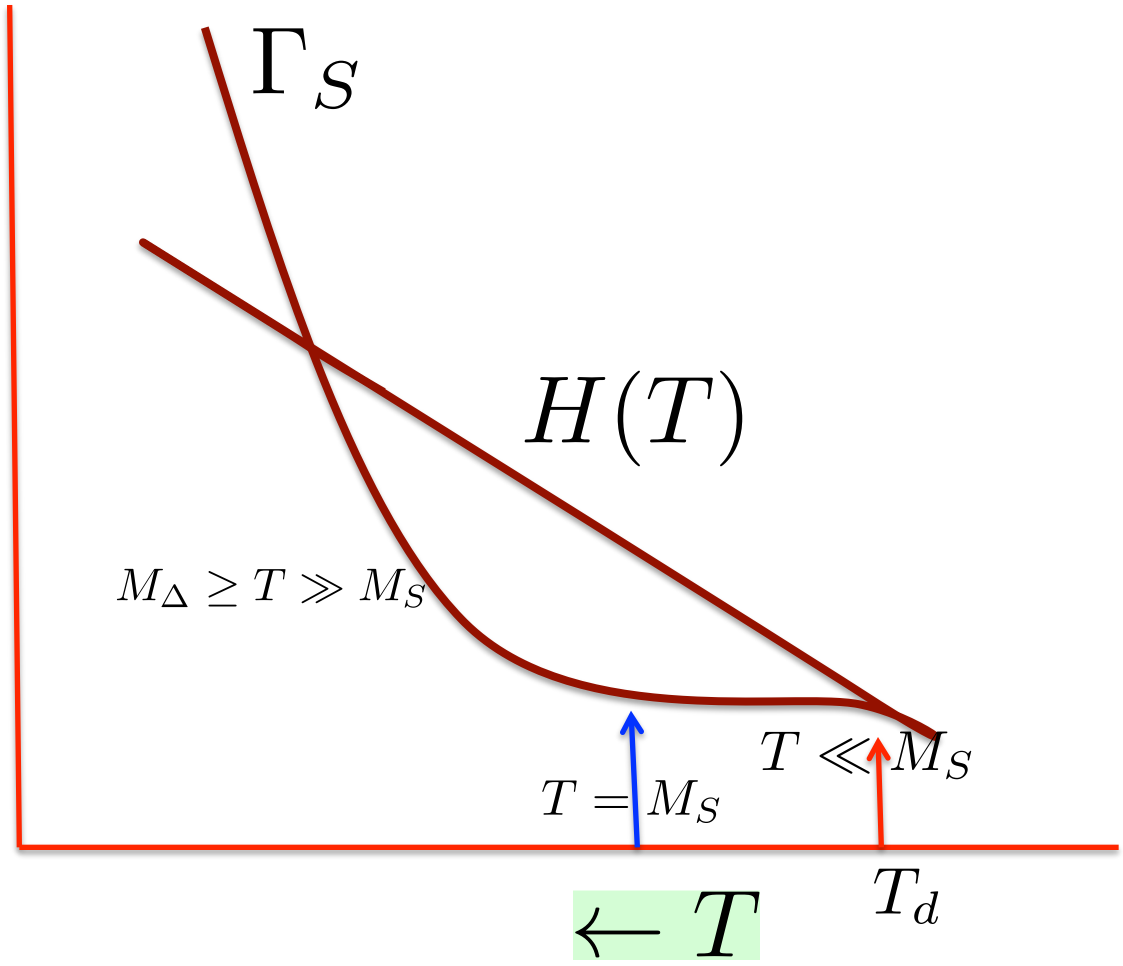
  Six quark NNbar operator coupled to a scalar field S

  (Post-sphaleron Baryogenesis)

  (Babu, RNM, Nasri' 07)



Decay and decoupling



Low scale NNbar model and origin of matter

- Constraints on PSB in the $SU(2)_L x SU(2)_R x SU(4)_c$ model

i) $M_{\Delta_{qq}} > M_S$

ii) $1\ GeV < T_{S-decay} < 100 GeV$

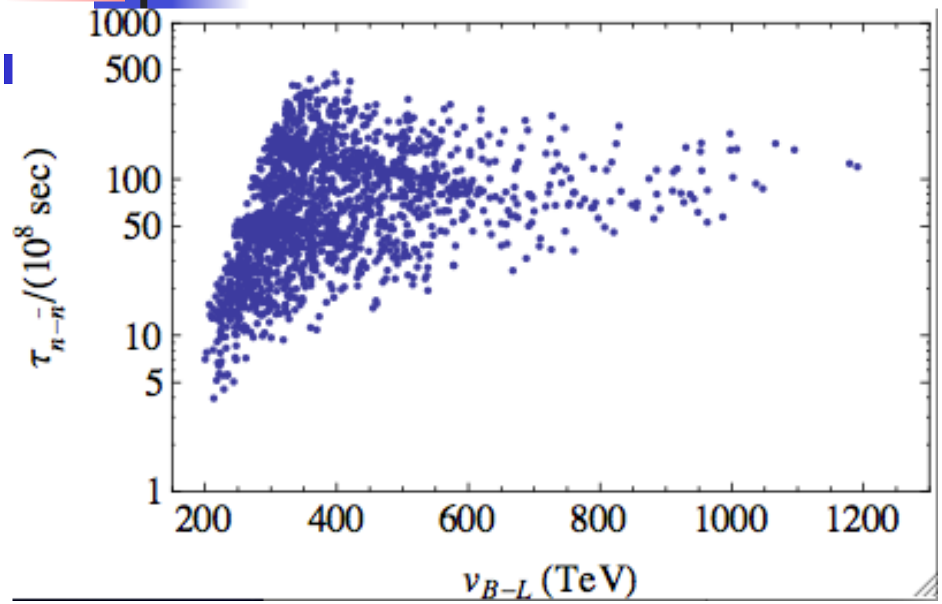
iii) $\Gamma_{S\to 6q} > \Gamma_{S\to Zq\bar{q}}$

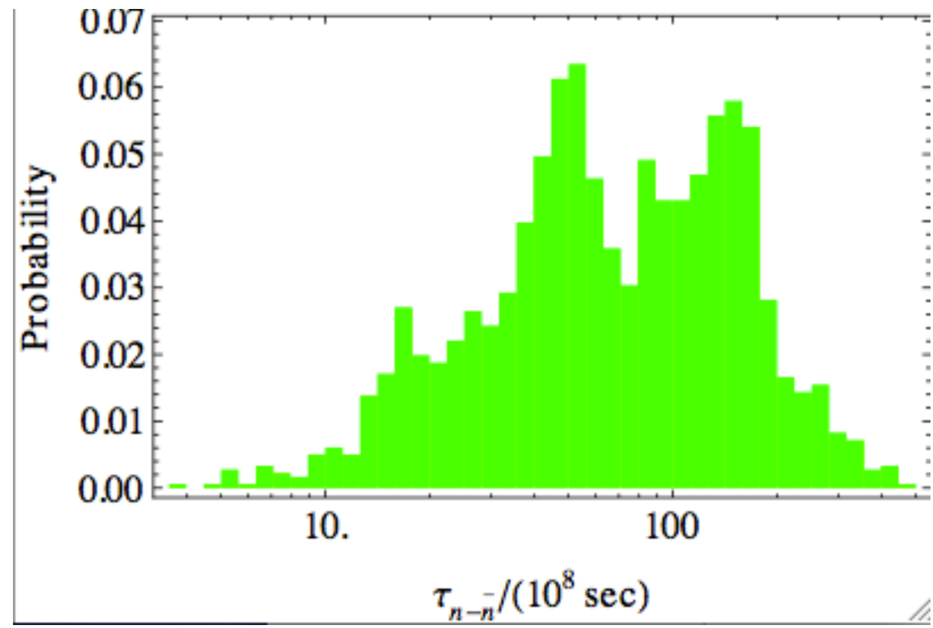
iv) Dilution factor constraint: $T_{S-decay} \geq 10^{-2} M_S$

v) A neutrino mass fit+FCNC constraints

- → upper bound NNbar transition time < $5x10^{10}$sec.
- No NNbar till $5x10^{10}$ s., **will rule out** this model for NNbar and post sphaleron baryogenesis (Babu,Dev,Fortes,RNM'PRD'13)

Upper limit on $\tau_{n\bar{n}}$ from Baryogenesis





QL unified seesaw+
Post-Sphaleron baryogenesis→ $\tau_{n\bar{n}} \leq 5 \times 10^{10}\ s$

(Babu,Dev, Fortes, RNM, arXiv:1303:6918)

Seesaw in SO(10) –Another predictive model for NNbar

- Coupling unification fixes the mass scales as in the case of proton decay:
- In a minimal SO(10) embedding of seesaw, f_{ab} determined from fermion mass fits
- (Babu, Mohapatra'93; Fukuyama, Okada'02; Bajc, Senjanovic, Vissani'02; Goh, Mohapatra, Ng'03 Babu,Macesanu'05; Bertolini, Malinsky,Schwetz'06; Joshipura, Patel'11)
- Predicts correct θ_{23}, θ_{12} and $\sin^2 2\theta_{13} \simeq 0.09$
- Model has diquarks at sub-TeV scale to have unification and they lead to observable NNbar !

New Unification profile

- Non-SUSY SO(10) does not unify without low scale particles,
- Coupling unif with

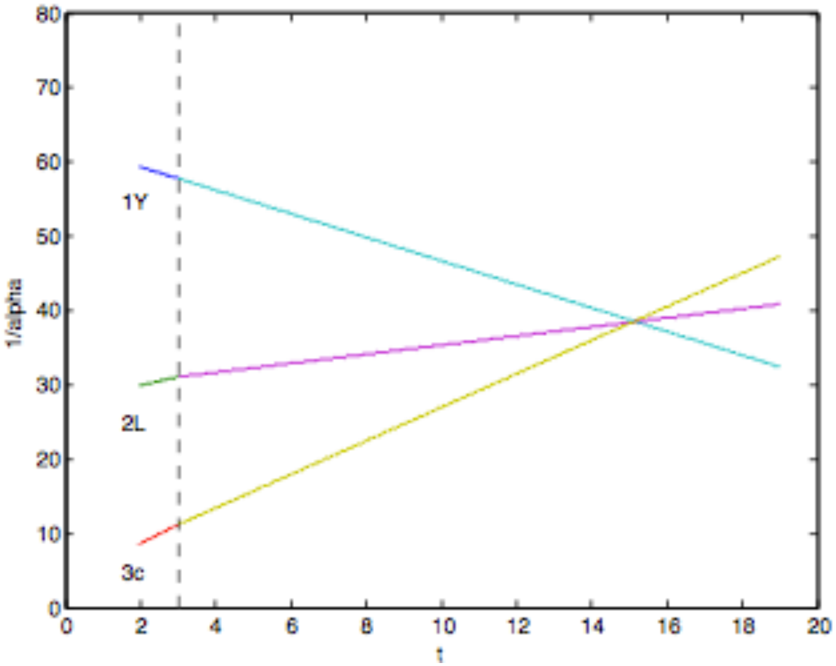
sub-TeV $\Delta_{ud}(6, 1, \frac{1}{3})$

+ 2 SM triplets+2 Higgs;

- Predicts seesaw scale

near $M_U \sim 10^{16}$ GeV;

- Δ_{ud} mass ~2 TeV
- $M_U \sim 10^{15.7}$ GeV→

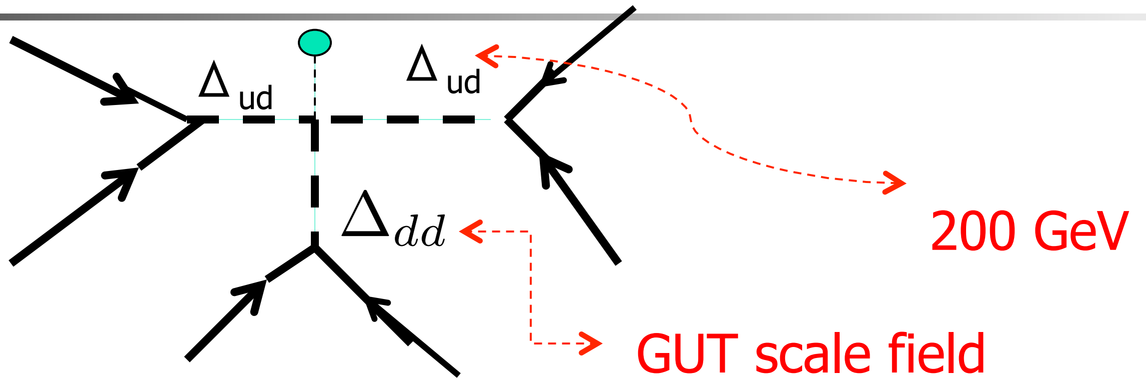


$\tau_{p \to e^+ + \pi^0} \simeq 3.2 \times 10^{34} yrs$ close to current limit.

(Babu, Mohapatra, arXiv:1206.5701)

Estimate of N-N-bar oscillation time in SO(10)

- Diagram:



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- $$G_{\Delta B=2} \simeq \frac{\lambda f_{11}^3 \eta^3}{\lambda' M_U M_{\Delta_{ud}}^4} \simeq \frac{\lambda}{\lambda'} 10^{-33} GeV^{-5}$$
- Predicts $\tau_{n-\bar{n}}$ ~10^{10} -10^{13} sec.
- Constraints of adequate baryogenesis enhances this to $\tau_{n-\bar{n}}$ ~10^{8} -10^{11} sec.

New Particles at LHC:
Color sextet scalars Δ_{qq}

- TeVColor sextets are an inherent part of both models ; Can be searched at LHC:

(I) **Single production**: $ud \longrightarrow \Delta_{ud} \longrightarrow tj$

xsection calculated in (RNM, Okada, Yu' 07;) resonance peaks above SM background- decay to tj;

- **Important LHC signature:** $\sigma(tt) > \sigma(\bar{t}\bar{t})$

(II) **Drell-Yan pair production** $q\bar{q} \to G \to \Delta_{ud}\bar{\Delta}_{ud}$

- Leads to $tjtj$ final states: **LHC reach < TeV**

(Chen, Rentala, Wang; Berger, Cao, Chen, Shaughnessy, Zhang' 10; Han, Lewis' 09)

Benchmark goal for ruling out new physics scenarios

- **No NNbar oscillation till $5x10^{10}$ sec. →**

Will rule out a class of SU(2)xSU(2)xSU(4)$_C$ models for neutrinos andpost sphaleron baryogenesis

If v_{BL} < 200 TeV, limit is < 10^{10} sec.

→Reaching this will rule out most of its parameter space

Will put under strain a sub-class of non-susy SO(10) models for neutrino masses that predicted observed θ_{13} if it is to explain origin of matter.

Implications of NNbar observation for low energy

- FCNC effects in the B and D-sector: could reconcile anomalies e.g. $\epsilon_K \ vs \ \sin 2\beta$, B-decays etc.

- EDM of neutron from PSB→ non-zero at two loop

- Strange dibaryon decay: NN→ KK+X (Glashow)

  Mediated only by $\Delta_{ud.dd}$: Related to $\Lambda - \bar{\Lambda}$ transition

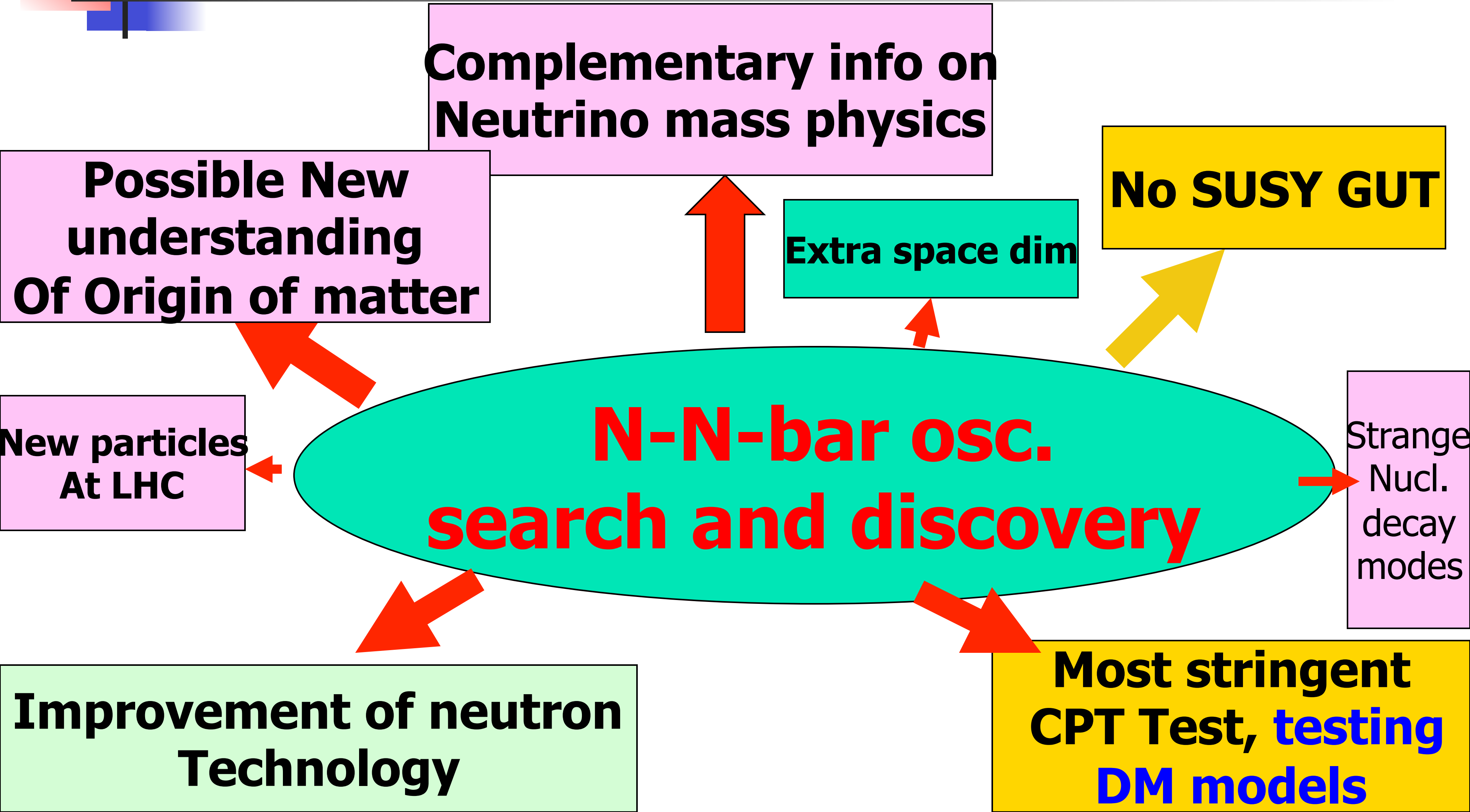
  $\tau_{Nuc} = R\tau^2{}_{free}$ formula implies: $\tau_{KK} \sim 10^{34} - 10^{35} yrs$

  Current Super -K upper limit: >1.7×10^{32} yrs.

What else can we learn from direct NNbar search?

- Can test some dark matter hypothesis e.g. if a dark neutron n' is dark matter (ADM models):
- $n' \Longleftrightarrow n$ oscillation can deplete dark matter density and this can be searched for in direct nn-bar searches; current limit > 1 s. (Bento, Berezhiani)
- If NNbar is discovered, it will put the strongest limit on CPT violation- (Okun; Addazzi, BLV2011)

NN-bar oscillation- gold mine of new physics: 5x 10^{10} sec. benchmark goal



Thank you for your attention !

Predictions vs Discoveries: A historical perspective

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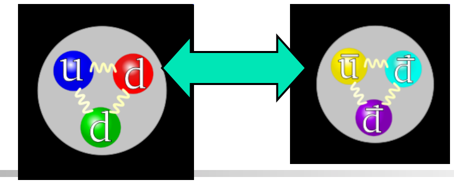
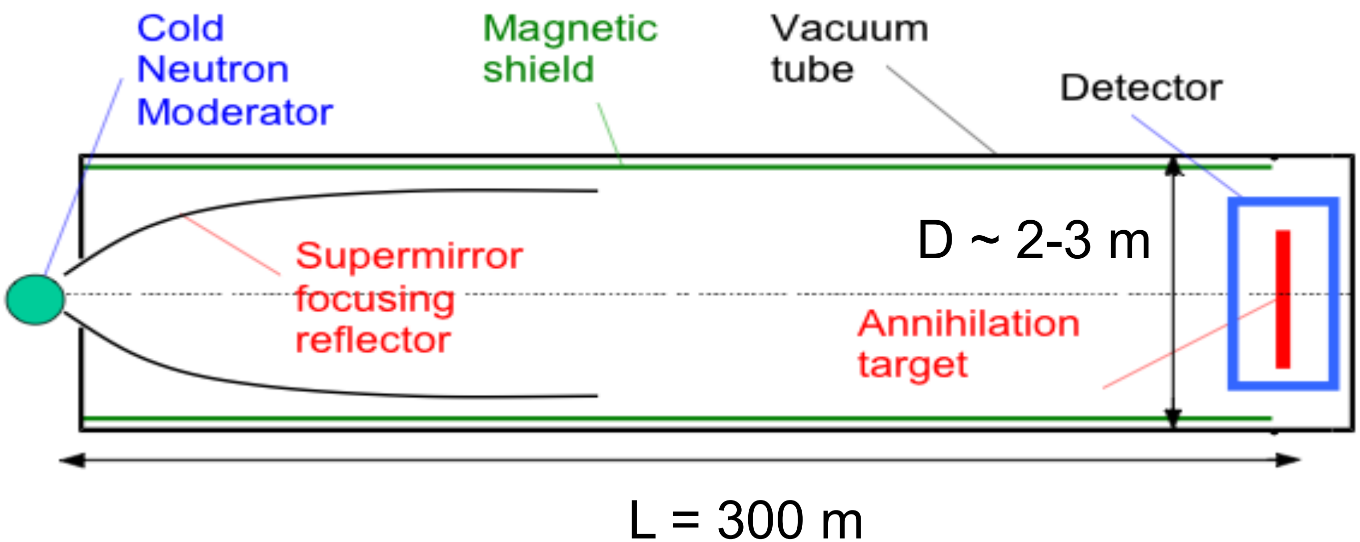
Process	Predicted ?	Implications of non-discovery
CP Violation	No	nothing
m_c, m_b, m_t	No	a lot
W, Z	Yes	a lot
P decay $p \rightarrow e^+ + \pi^0$	yes $\tau \geq 10^{35}$ yrs	GUT idea in trouble
$p \rightarrow K^+ \bar{\nu}$	No	Nothing

Search for N-N-bar Osc. current status



- **Free neutron oscillation in reactors: generic setup**

(talks by Snow, Young)



- **Current bound (ILL' 94)**

with L ~ 90 m and $\langle t \rangle = 0.11$ sec

measured $P_{n\bar{n}} < 1.6 \times 10^{-18}$

$\tau > 8.6 \times 10^{7}$ sec

- **No new search after that**

Origin of matter and neutron oscillation

- Current scenarios:

(i) Leptogenesis; Related to seesaw; but hard to test !

(ii) Electroweak baryogenesis :

M_{higgs} <120 GeV; $m_{\tilde{t}} \leq 120 GeV$ (puts MSSM under tension)

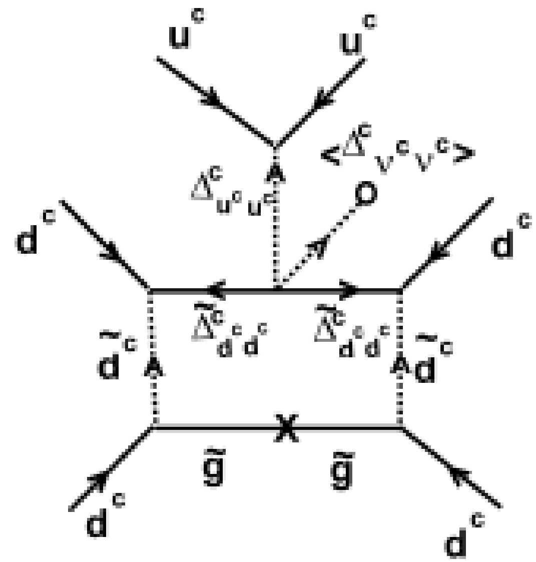
- New scenarios:

(iii) Post sphaleron Baryogenesis
(iv) GUT baryogenesis

} both connected to NNbar osc.

Estimate of N-N-bar with susy

- **New Feynman diagram for N-N-bar osc.**



☞ $G_{N-\bar{N}} \simeq \frac{f_{11}^3}{\lambda^2 M_{seesaw}^2 v_{wk}^3}$

$M_{seesaw} \sim 10^{11}$ GeV, typical f, λ, $\tau_{N-\bar{N}} \sim 10^{10}$ sec.

Observable N-N-bar osc for M_seesaw~10^11 GeV.

(Dutta, Mimura, RNM; PRL (2006))

Expectation for neutron-anti-neutron oscillation

- B-L violation at GUT scale leads to couplings

$$v_{BL}\Delta_{ud}\Delta_{ud}\Delta_{dd}$$

- → $G_{\text{nn-bar}} = \dfrac{v_{BL} f^3}{M^4_{\Delta_{ud}} M^2_{\Delta_{dd}}} = 10^{-29}\ \text{GeV}^{-5}$ →

$$\tau_{n\bar{n}} \sim \frac{G_{n\bar{n}}}{\Lambda^6_{QCD}} \sim 10^{10} sec.$$

- Observable with available reactor fluxes

From Seesaw to NNbar: a group theoretic argument

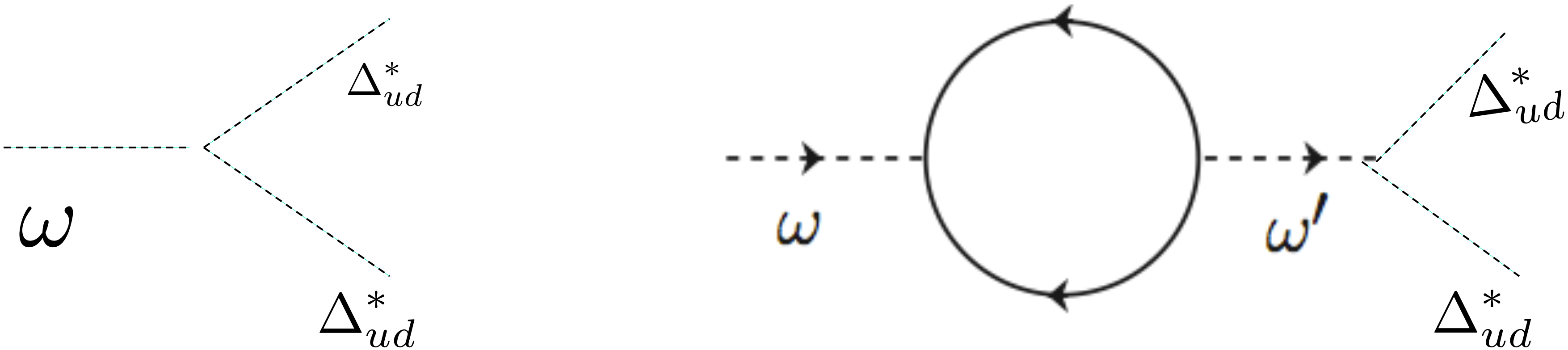
- Seesaw→ $\Delta L = 2$
- Scale not M_{Pl} suggests new gauge sym (B-L)
- → $Q = I_{3L} + I_{3R} + \frac{B-L}{2}$

$$\Delta Q = 0; \Delta I_{3L} = 0 \rightarrow \quad \Delta I_{3R} = -\Delta \frac{B-L}{2}$$

- For hadrons only, → $\Delta B = 2$ N-N-bar oscillation

Origin of matter in SO(10) theory with NNbar

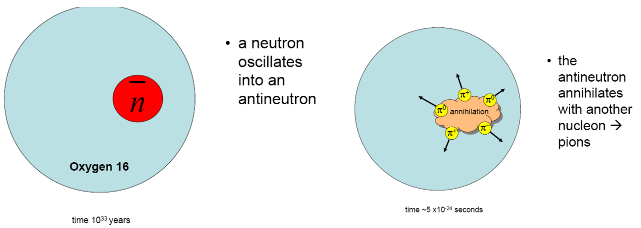
- Two sources of matter asymmetry:
  (a) Leptogenesis
  (b) B-L violating GUT scale by $\Delta_{dd}(\omega)$ decay



- Must occur above T_{sph}~10^{13}-10^{12} GeV, below sphalerons are in eq. - Δ L must be out of eq. by T_{sph}

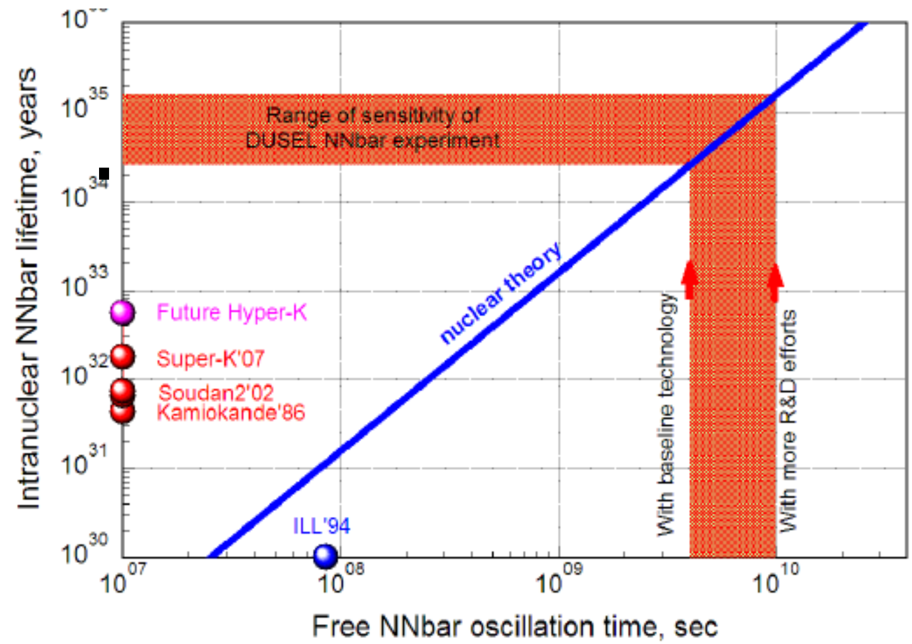
NNbar from di-nucleon decay

- Nucleon decay expts search for NNbar by looking for NN→$\pi ' s$ in a nucleus (Dover, Gal, Richards; Gal; Vainstein's talk)



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

$$R = 0.3\times10^{23}\ \sec^{-1}$$



(Plot by Y. Kamyshkov)

$\tau_{n\bar{n}} > 2.44\text{x}10^8$ sec. (S-K,Abe et al.)

- Free oscillation search much more effective !!

Unique way to test GUT scale seesaw

- A natural scale for seesaw is GUT scale and is certainly required if forces and matter unify !!

- Without susy, no way to test such theories except for NNbar oscillation or B-L violating nucleon decays.

How generic is the upper bound ?

- Another model for Post-Sphaleron-Baryogen. also has a bound: (under investigation)
- Extension of SM by singlet fermion N and colored field X:

$$\mathcal{L}_Y = \mathcal{L}_{Y,SM} + XNd^c + X^* u^c d^c + MNN$$

- Source of baryogenesis: $N \to u^c d^c d^c + u^{c*} d^{c*} d^{c*}$

- N plays the role of S in the previous model.

After the Higgs discovery

★ Discovery of the 125 GeV Higgs h^0 has solved the problem of mass, for charged fermions !!

$$m_f = h_f v_{wk} \qquad v_{wk} = < h^0 >$$

- This does not, however, solve the neutrino mass problem, since $h_\nu v_{wk}$ is a billion times too large ! This is the second mass problem in particle physics !!
- Another major puzzle: where does matter in the universe come from ?
- $n - \bar{n}$ oscillation can throw on this !!

Given this limit on $\tau_{n\bar{n}}$ why are nuclei stable ?

- Oscillation inside nuclei are suppressed by the factor $\left(\frac{\delta m_{n\bar{n}}}{V_n - V_{\bar{n}}}\right)^2 \leq 10^{-62}$

- More detailed calculation: (Dover, Gal, Richard; Gal, Freedman)

$$\tau_{Nuc} = R\tau^2_{n\bar{n}} \quad R = 0.3\times10^{23}\ \mathrm{sec}^{-1} \rightarrow \tau_{Nuc} \geq 10^{32} yrs$$

- Super-K search $\tau_{n\bar{n}}$ --> $2.44\mathrm{x}10^8$ sec.

- Possible future reach using available technology: Talks by Kamyshkov,Snow,Young,Gabriel,..