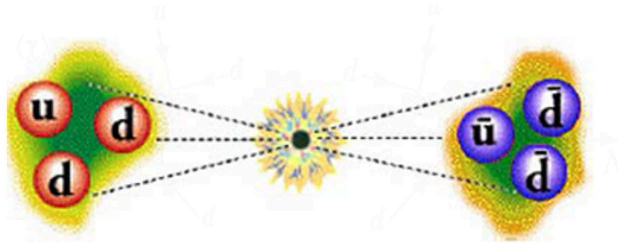

N-$\bar{N}$ Oscillation: An Overview

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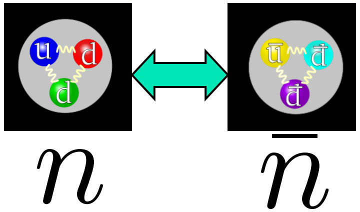
UNIVERSITY OF MARYLAND

INT NNbar workshop, Seattle

October, 2017

What is N-$\bar{N}$ oscillation?

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



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

- Key parameter describing this is: $\delta m_{n\bar{n}}$

  which denotes the mixing strength between n and $\bar{n}$

- $\delta m_{n\bar{n}}$ = 0 in the standard model.
- Hence, a sensitive probe of physics beyond SM!

Early History

- Kuzmin'70: motivated by Sakharov's suggestion of baryogenesis. Paper in Russian.

Cp violation and baryon asymmetry of the universe (In Russian)
V.A. Kuzmin (Lebedev Inst.). 1970. 3 pp.
Published in **Pisma Zh.Eksp.Teor.Fiz. 12 (1970) 335-337**

- Glashow'79: SU(5) with {15}-dim. Multiplet.

The Future of Elementary Particle Physics
S.L. Glashow (Harvard U.). Aug 1979. 40 pp.
Published in **NATO Sci.Ser.B 61 (1980) 687**

NN-bar from neutrino mass

- RNM, Marshak'80: From neutrino Majorana mass to neutron oscillation

Local B-L Symmetry of Electroweak Interactions, Majorana Neutrinos and Neutron Oscillations
Rabindra N. Mohapatra, R.E. Marshak (Virginia Tech.). Jan 1980. 10 pp.
Published in **Phys.Rev.Lett. 44 (1980) 1316-1319,** Erratum: **Phys.Rev.Lett. 44 (1980) 1643**
VPI-HEP-80/1

- Left-right (1974-75)→ Seesaw(1979)

→Electric charge formula in LR(1979)

→NN-bar(1980)

Left-Right model:

- Gauge group: $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$

- Fermions

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \overset{P}{\Leftrightarrow} \begin{pmatrix} u_R \\ d_R \end{pmatrix} \quad \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \overset{P}{\Leftrightarrow} \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$

$$L = \frac{g}{2}[\vec{J}_L^{\ \mu} \cdot \vec{W}_{\mu L} + \vec{J}_R^{\ \mu} \cdot \vec{W}_{\mu R}]$$

- Parity a spontaneously broken symmetry: $M_{W_R} \gg M_{W_L}$

(Pati, Salam'74; Mohapatra, Pati'74;'74; Senjanovic, Mohapatra'75)

Breaking of LR and type I seesaw

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$\downarrow$ v_R (ΔL=2) $M_N = f v_R$

$$SU(2)_L \times U(1)_Y$$

$\downarrow$ κ $\Rightarrow$ $M_{\nu,N} = \begin{pmatrix} 0 & h\kappa \\ h\kappa & f v_R \end{pmatrix}$

$$U(1)_{em}$$

(Mohapatra, Senjanovic'79)

- Seesaw formula

$$m_\nu \simeq -\frac{(h\kappa)^2}{M_N}$$

Parity breaking as origin of Majorana Neutrino mass

- Electric charge formula in LR *(contrast this with SM)*

$$Q = I_{3L} + I_{3R} + \frac{B-L}{2}$$

- Above EW scale,

$$\Delta Q = \Delta I_{3L} = 0 \rightarrow \Delta I_{3R} = -\frac{1}{2}\Delta L$$

- Parity breaking → Majorana nu (RNM, Marshak'80)
- Small neutrino mass is why Weak Int. V-A

From Majorana neutrinos to neutron oscillation

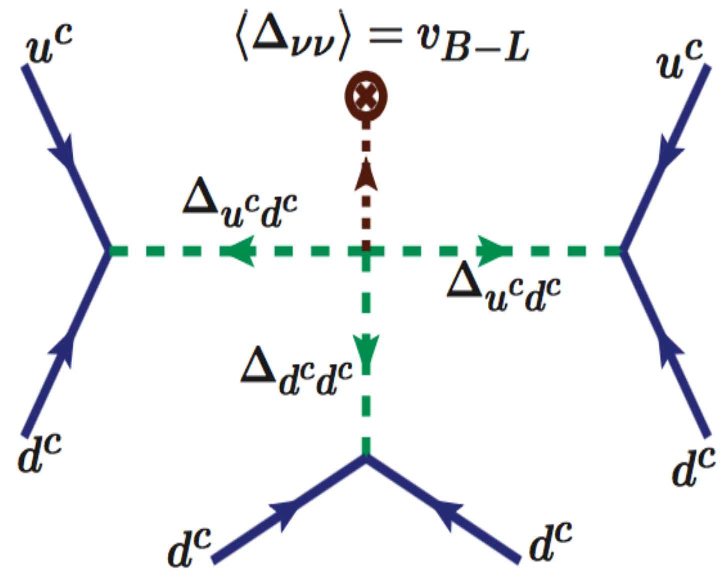
- If there is no change in lepton number i.e. $\Delta L = 0$, the eletcric charge equation implies that

$$\Delta B = 2\Delta I_{3R} = 2$$

- $\Delta B = 2$ is n-n-bar oscillation
- Obvious framework is left-right with quark lepton unification based on $SU(2)_L$ x $SU(2)_R$ x$SU(4)_c$

$\Delta L = 2 \Rightarrow \Delta B = 2$

- Seesaw Higgs field $\Delta_{\nu_R\nu_R}$ has SU(4) partners Δ_{qq} in Q-L unified models



- $< \Delta_{\nu_R\nu_R} >$ leads to operator

$$u^c d^c d^c u^c d^c d^c$$

$$\rightarrow G_{\Delta B=2} = \frac{\lambda f^3 v_{BL}}{M_\Delta^6}.$$

- Observable $n - \bar{n}$ for TeV M_Δ (Mohapatra,Marshak'80)

How big can $\delta m_{n\bar{n}}$ be?

- Since it can lead nuclei to decay, from what we know about nuclear instability, we conclude that it must be less than

$$\delta m_{n\bar{n}} \leq \sqrt{\Gamma_{nucl} m_n} \leq 10^{-23}\text{eV}$$

- $G_{\Delta B=2} = \frac{\lambda f^3 v_{BL}}{M_\Delta^6}$ in this range for $M_\Delta \sim \text{TeV}$

- Probes TeV scale new physics of B and L-violation- different from GUTs

Can such small values of B-violation be searched?

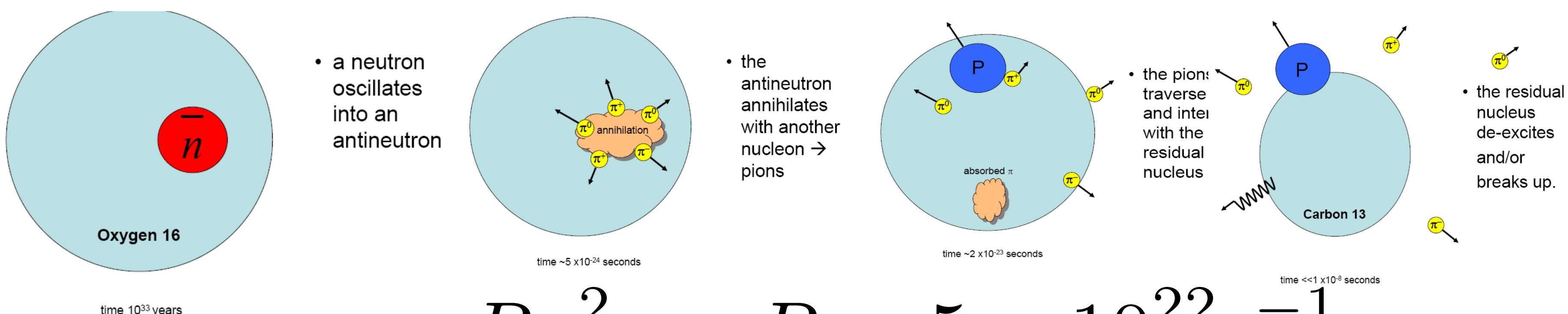
- Two ways:

(i) Oscillation inside a nucleus leading to
B-violating nuclear decays

(ii) Oscillation of a free neutron beam from
a reactor or spallation source

Nuclear search for NNbar

- Important to figure out the nuclear effects:



$$\tau_{Nuc} = R\tau_{n\bar{n}}^2 \qquad R \simeq 5 \times 10^{22}\mathrm{s}^{-1}$$

- $$\tau_{n\bar{n}} \geq 3.45 \times 10^8 \mathrm{sec.}$$

(Chetyrkin, Kazarnovsky; Kuzmin, Shaposnikov'81; Dover, Gal, Richards; Alberico et al.; Kopeliovich et al; Richards talk;Expt. Super-K; Soudan, SNO)

$$\delta m_{n\bar{n}} \leq \sqrt{\Gamma_{nucl} m_n} \leq 10^{-23}\mathrm{eV}$$

Free neutron Oscillation

- Two state quantum mechanics:

$$\frac{d}{dt}\begin{pmatrix} n \\ \bar{n} \end{pmatrix} = \mathcal{H}\begin{pmatrix} n \\ \bar{n} \end{pmatrix};\ \mathcal{H} = \begin{pmatrix} M_1 & \delta m \\ \delta m & M_2 \end{pmatrix}$$

$$P_{n-\bar{n}} = \frac{4\delta m^2}{\Delta M^2 + 4\delta m^2}\sin^2\left(\sqrt{\Delta M^2 + 4\delta m^2}\right) t_{/2}$$

- ΔM due to Earth B-field 10^{-11} eV >> $\delta m_{n\bar{n}}$
- So, can this expt ever be done?

Earth Magnetic field and free N-$\bar{N}$ Osc.

place. Unfortunately, the effect is very difficult to observe. The small $\Delta B = 2$ mass splitting is generally masked by the magnetic mass splitting between N and $\bar{N}$, which amounts to 10^{-11} eV/gauss.

S. L. Glashow'79

in the presence of matter or external magnetic fields, the detection of such oscillations, at the present time, seems improbable. Kuo,Love'80

the earth is not shielded, $\Delta Mt >> 1$ and Eq. (13) applies. On the other hand, if the earth's magnetic field is "degaussed" by a factor of 10^3 or more, Eq. (14) applies and the experiment becomes quite favorable. The

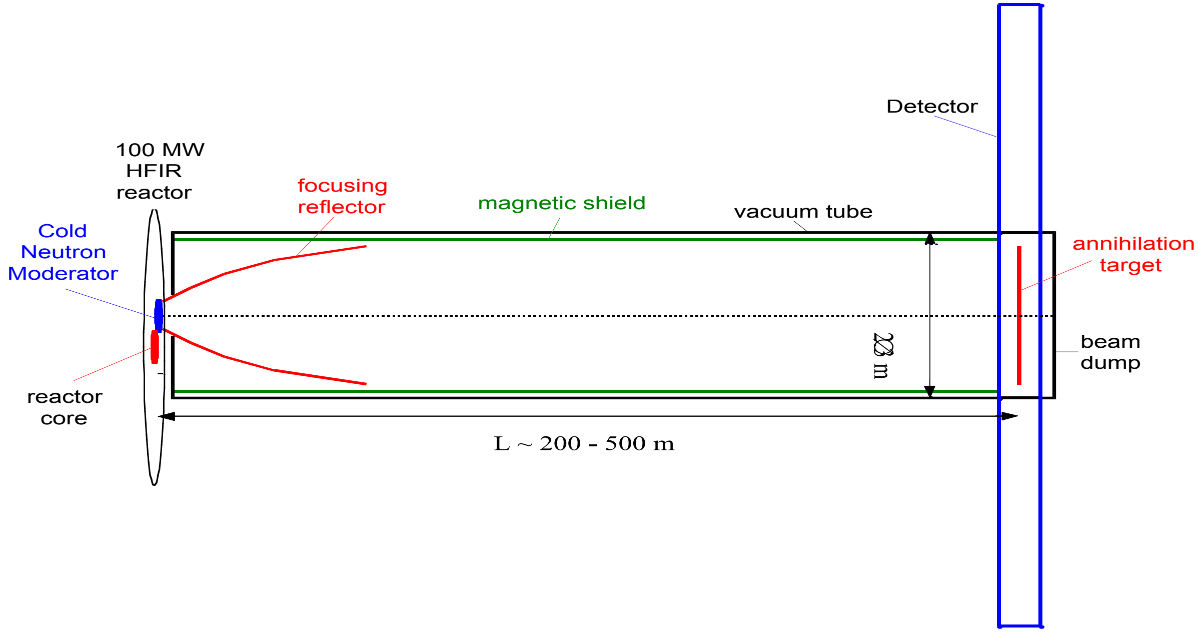
Marshak, RNM' Phys. Lett B (80); Cowsik, Nussinov'80

To search for neutron oscillation, degauss the Earth magnetic field to Nano-Tesla level! $\Delta M \approx 0$

Damping due to residual atoms/molecules in pipe

- Effect of residual atmosphere on NNbar rate;
- Use Feinberg-Weinberg-Lindblad equation
- (Talks by Kamyshkov, Kerbikov)

Experimental search for free neutron oscillation



- Horizontal set up+ degaussing→ ILL
- New proposal for ESS; (Frost, Young, Milstead talks)

Experimental search and results from ILL group

.

- Define free oscillation time $\tau_{n\bar{n}} = \frac{\hbar}{\delta m_{n\bar{n}}}$
- When $\Delta M \approx 0$ probability of transition: $P_{n \to \bar{n}} \approx \left(\frac{t}{\tau_{n\bar{n}}} \right)^2$
- 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

  (Baldo-ceolin, Dubbers, Fidecaro et al'94)

→ $\delta m_{n\bar{n}} < 7 \times 10^{-33}$ GeV constrains new physics !!

Precursor to a proposal arXiv:1410:1100; Phys.Rep.

Neutron-Antineutron Oscillations: Theoretical Status and Experimental Prospects

D. G. Phillips II[n,w], W. M. Snow[d,*], K. Babu[q], S. Banerjee[t], D. V. Baxter[d], Z. Berezhiani[h,x], M. Bergevin[y], S. Bhattacharya[t], G. Brooijmans[b], L. Castellanos[ae], M-C. Chen[z], C. E. Coppola[af], R. Cowsik[ah], J. A. Crabtree[p], P. Das[ag], E. B. Dees[n,w], A. Dolgov[f,o,aa], P. D. Ferguson[p], M. Frost[af], T. Gabriel[af], A. Gal[s], F. Gallmeier[p], K. Ganezer[a], E. Golubeva[e], G. Greene[af], B. Hartfiel[a], A. Hawari[m], L. Heilbronn[ae], C. Johnson[d], Y. Kamyshkov[af], B. Kerbikov[f,j], M. Kitaguchi[k], B. Z. Kopeliovich[ad], V. B. Kopeliovich[e], V. A. Kuzmin[e], C-Y. Liu[d], P. McGaughey[i], M. Mocko[i], R. Mohapatra[ab], N. Mokhov[c], G. Muhrer[i], H. P. Mumm[l], L. Okun[f], R. W. Pattie Jr.[n,w], C. Quigg[c], E. Ramberg[c], A. Ray[ag], A. Roy[g], A. Ruggles[ae], U. Sarkar[r], A. Saunders[i], A. P. Serebrov[u], H. M. Shimizu[k], R. Shrock[v], A. K. Sikdar[ag], S. Sjue[i], S. Striganov[c], L. W. Townsend[ae], R. Tschirhart[c], A. Vainshtein[ac], R. Van Kooten[d], Z. Wang[i], A. R. Young[n,w]

Construction started in 2014
to be completed by 2019

ESS

Richard Hall-Wilton
December 2013

What scale of new physics does Nnbar probe ?

- Operator responsible for Nnbar without susy:

$$O_{\Delta B=2} = \frac{1}{M_{eff}^5} u^c d^c d^c u^c d^c d^c$$

Note M^5 suppression

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

- Quarks to neutrons (Rao, Shrock'82; Buchoff et al. Lattice; Wagman et al. Bijnens,Kofoed)

$$\tau_{n-\bar{n}} = \hbar / \delta m_{n-\bar{n}} \sim M^5 / \Lambda^6 \rightarrow \tau_{n\bar{n}} \sim 10^8 s.$$ M~10 TeVs

★ *Observation of NNbar will open a totally new landscape of physics at TeV scale + new view of parity !*

New particles near TeV and scale reach of NNbar

- If there are "diquark" scalars $\Delta_{u^c u^c}$ near TeV, new operators appear: $\frac{\Delta_{u^c u^c} d^c d^c d^c}{M^3}$; mass reach goes up to 10^9 GeV.

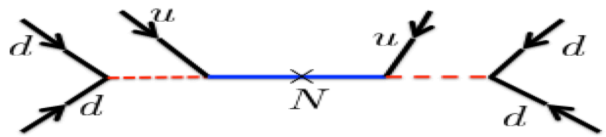
- Happens in some susy models (Dutta, Mimura, RNM'06; PRL)

- If instead $\Delta_{u^c d^c}$ is near a TeV, scale goes up to 10^{15} GeV.

$$\mathcal{O} = \frac{1}{M} d^c d^c \Delta_{u^c d^c} \Delta_{u^c d^c}$$

From $N\bar{N}$ to heavy baryon oscillation

- Extend the SM by adding adding RH neutrinos N +color triplet (3, 1, 2/3)



- → $\mathcal{L}_I = \frac{\lambda_{ai}\lambda'_{jk}}{M_\chi^2} N_a u_{R,i} d_{R,j} d_{R,k} + \mathrm{H.c.}$

(Babu, RNM, Nasri'08; Dev, RNM'15; Davoudiasl, Zhang'15)

- $\Lambda - \bar{\Lambda}$, $B_H - \overline{B_H}$ oscillation; pp→KK decay

(Goity, Sher; Kuzmin; Glashow)

- Recent discussion in connection with baryogenesis: (Aitkin, Mckeen, Nelson'17)

Large Extra dimensions, GUTs and observable $N\bar{N}$

- Flavor geography and B-violation due to TeV scale for new physics

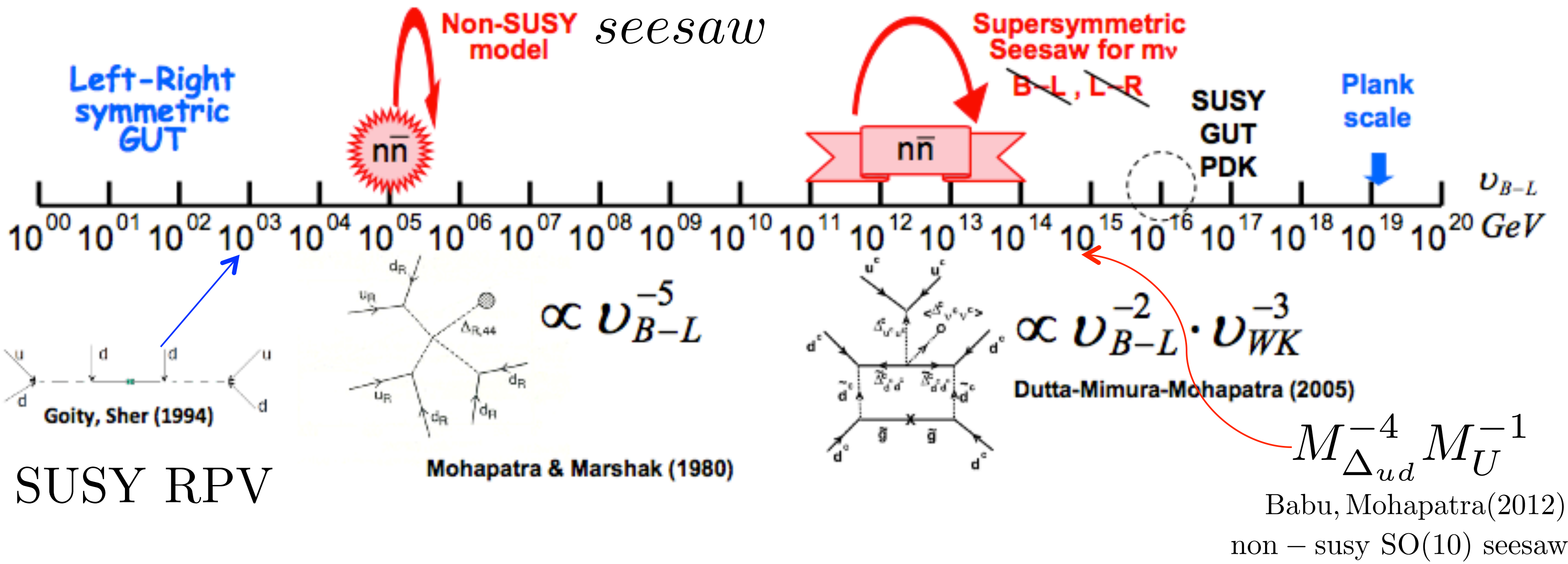
  (Nussinov, Shrock; Winslow, Ng; Dvali, Gobadadze;..)

- Grand unified theories for neutrino mass

  (Babu, RNM'12; Awasthi, Parida, Sahu'14)

- TeV scale B-violating theories: (Arnold, Fornal, Wise; Gu and Sarkar)

$N\bar{N}$ and BSM Physics



(Fig. Courtesy of Yuri Kamyshkov)

(Babu, Shrock's talk)

NNbar as a probe of other BSM physics

- Probing new CP violation:
  (Berezhiani, Vainshtein; Fujukawa, Turneau; Gardner,Yan; Nelson, Mckeen)

- Lorentz violation (Babu, RNM'14)

- Nature long range B-L force: (Babu, RNM'16; Adazzi, Berezhiani, Kamyshkov'16)

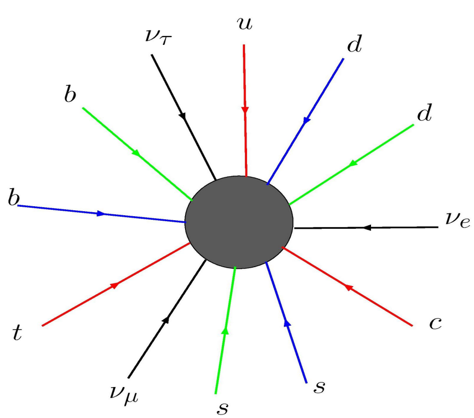
From NNbar to Majorana neutrino via sphalerons

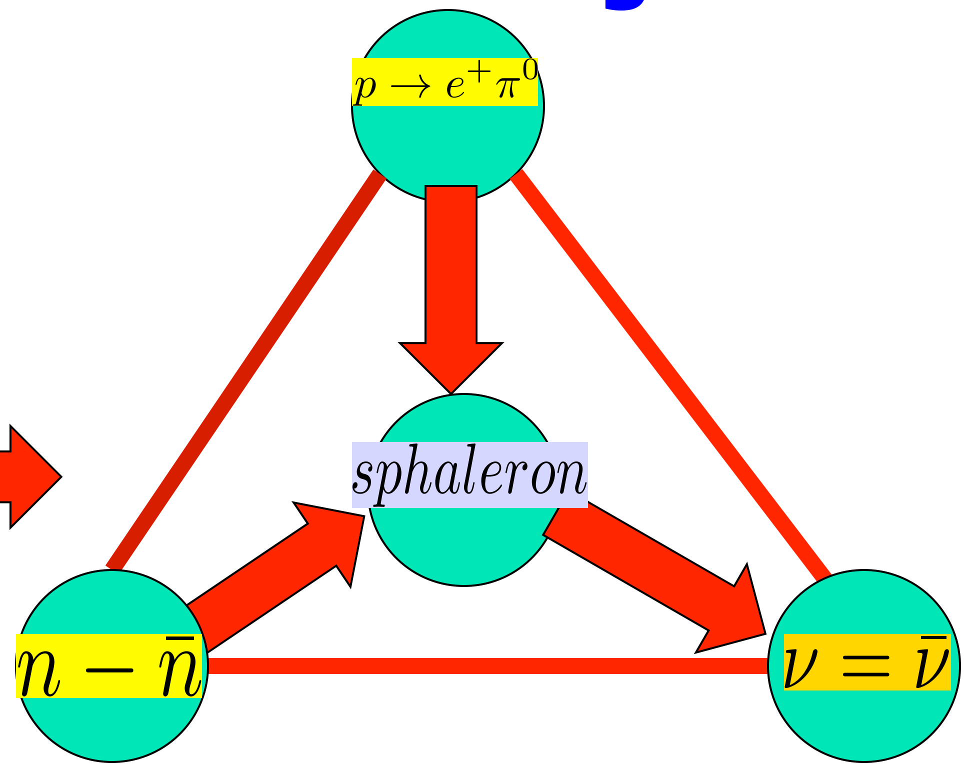
- Sphaleron Op. rewrite

B-L Triangle:

QQQQQQ QQQL LL

$n-\bar{n}$ $p \to e^+\pi^0$ m_ν





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

Impact of NNbar on baryogenesis scenarios

- If neutron oscillation is observed → strength of $\Delta B = 2$ operator is ~ $10^{-28} - 10^{-31}$ GeV^{-5};
  → this process is in equilibrium till T~ few TeVs.
- Any higher scale generated baryons (e.g. leptogenesis) get erased.
- New ways to generate baryons must be sought.

(Talks by Babu, Chen, Dev, Nelson, Zhang)

Post-sphaleron baryogenesis

- (Babu, RNM, Nasri'07; Babu's talk)
- Assume real scalar or pseudoscalar field with higher dim effective coupling to SM fermions:

e.g. $$\mathcal{L}_I = \frac{\lambda}{M^6} S u^c d^c d^c u^c d^c d^c \ + \ h.c.$$

→ $$S \to 6q, 6\bar{q}$$

- Has $\Delta B = \pm 2$: new CPV $n_B - n_{\bar{B}} \neq 0$

Basic scenario outline

- Assume M = 10 TeV and M_S = 2 TeV;

- T_* >> M_S but T_* < M, $\Gamma_S \leq H$
- → S stops decaying and keeps "floating".

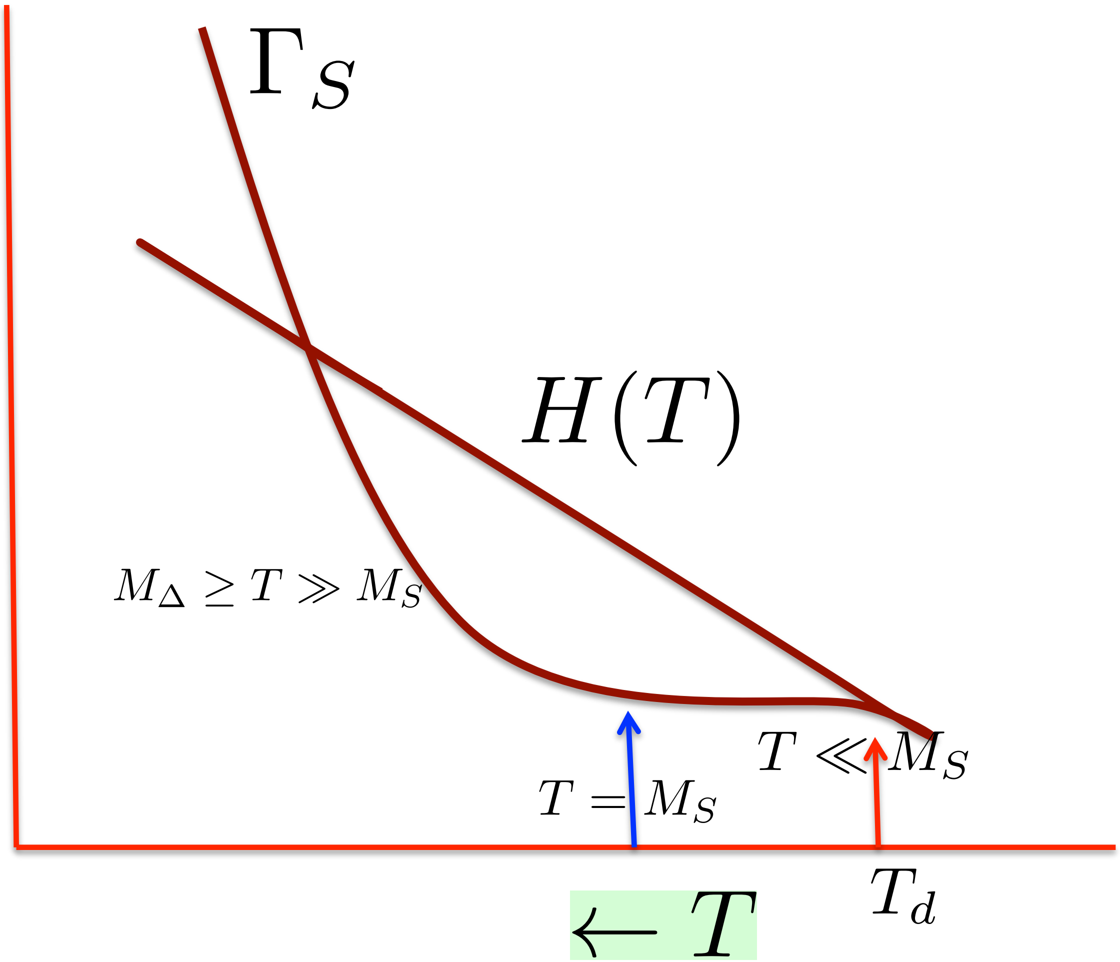
$$\Gamma_S = H \quad at \quad T = T_d$$

- At T<< M_S , again

$$T_d \leq T^*_{sphleron} \sim 100\ GeV$$

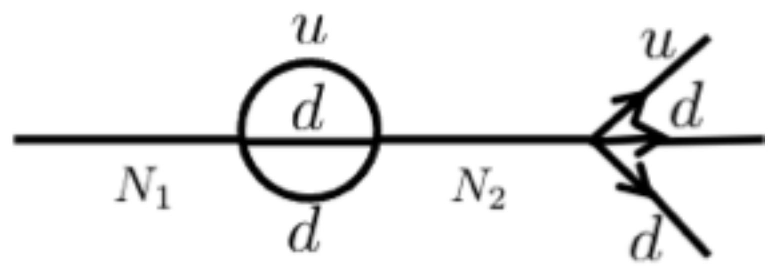
- This decay produces baryon asymmetry:

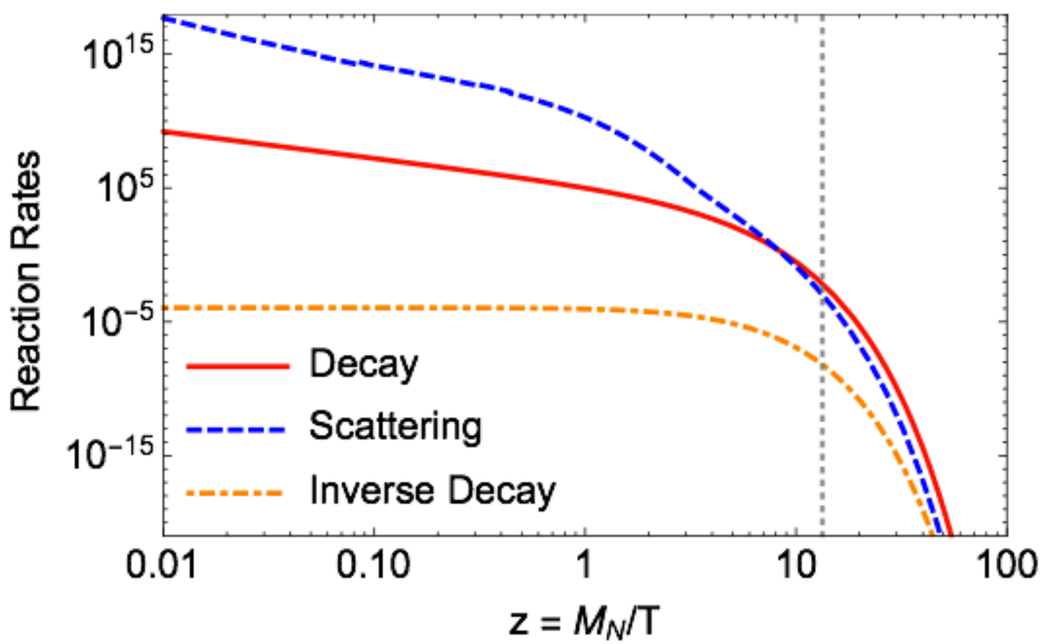
Decay and decoupling



Resonant baryogenesis in SM extended N→3q model

- Alternative scenario:





Dev, RNM'15;Davoudiasl,Zhang'15

Generic implications:

- Both scenarios are intimately connected to N-N-bar oscillation.
- The UV complete theory for PSB, having S→6q or N→ 3q require new colored scalars with TeV mass which can be searched for at LHC. Current collider limits ~TeV. Synergy between Energy-Intensity frontier.
- Also they lead to new FCNC effects- small deviations from SM can provide useful hints.

Mirror Universe dark and NN' Osc.: in brief

- Exact mirror sym. duplicate of SM

visible sector	mirror sector
$SU(2)_L \times U(1)_{I_{3R}} \times U(1)_{B-L}$	$SU(2)_L \times U(1)_{I_{3R}} \times U(1)_{B-L}$
W, Z, γ, gluons $\begin{pmatrix} u_L \\ d_L \end{pmatrix}$ u_R, d_R $\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ e_R Higgs H_1, H_2, Δ_L	W, Z, γ, gluons $\begin{pmatrix} u_L \\ d_L \end{pmatrix}$ u_R, d_R $\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ e_R H_1, Δ_L

$\leftarrow P \rightarrow$

Important point: No new coupling parameters

- Asymmetric inflation to avoid BBN (Berezhiani, Dolgov, Mohapatra'96)

Dark baryons and N-N' oscillation

- Symmetric vs asymmetric mirror models
- Complete spectral degeneracy in sym. models
- There is a dark N' with same mass as N.
- They could oscillate: (Bento, Berezhiani'25; Berezhiani's talk)

$$\mathcal{O}_9^{\rm mix} \sim \frac{1}{\mathcal{M}^5}(udd)(u'd'd')$$

- Current limits: $\tau_{nn'} \geq 448$ sec.
- Planned expts: (Kamyshkov, Bouchard, Kirch talks)

Some questions

- For nn′ oscillation to be observed $\frac{\Delta m}{m} \leq 10^{-24}\mathrm{GeV}$ but T′~T/2→ P-breaking at high scale which will induce different Yukawas from RGE which can lead to $\frac{\Delta m}{m}$ much larger making nn′ unobservable (exceptional cases: RNM, Nussinov'17)
- If nn′ is to be observable, issues with n′ as DM – the DM must be H′, He′- does it satisfy the bullet cluster bound for $\sigma_{H'H'} \leq 10^{-24}\mathrm{cm}^2$ (expected value $\sim 10^{-16}\mathrm{cm}^2$) (RNM, Nussinov'17)

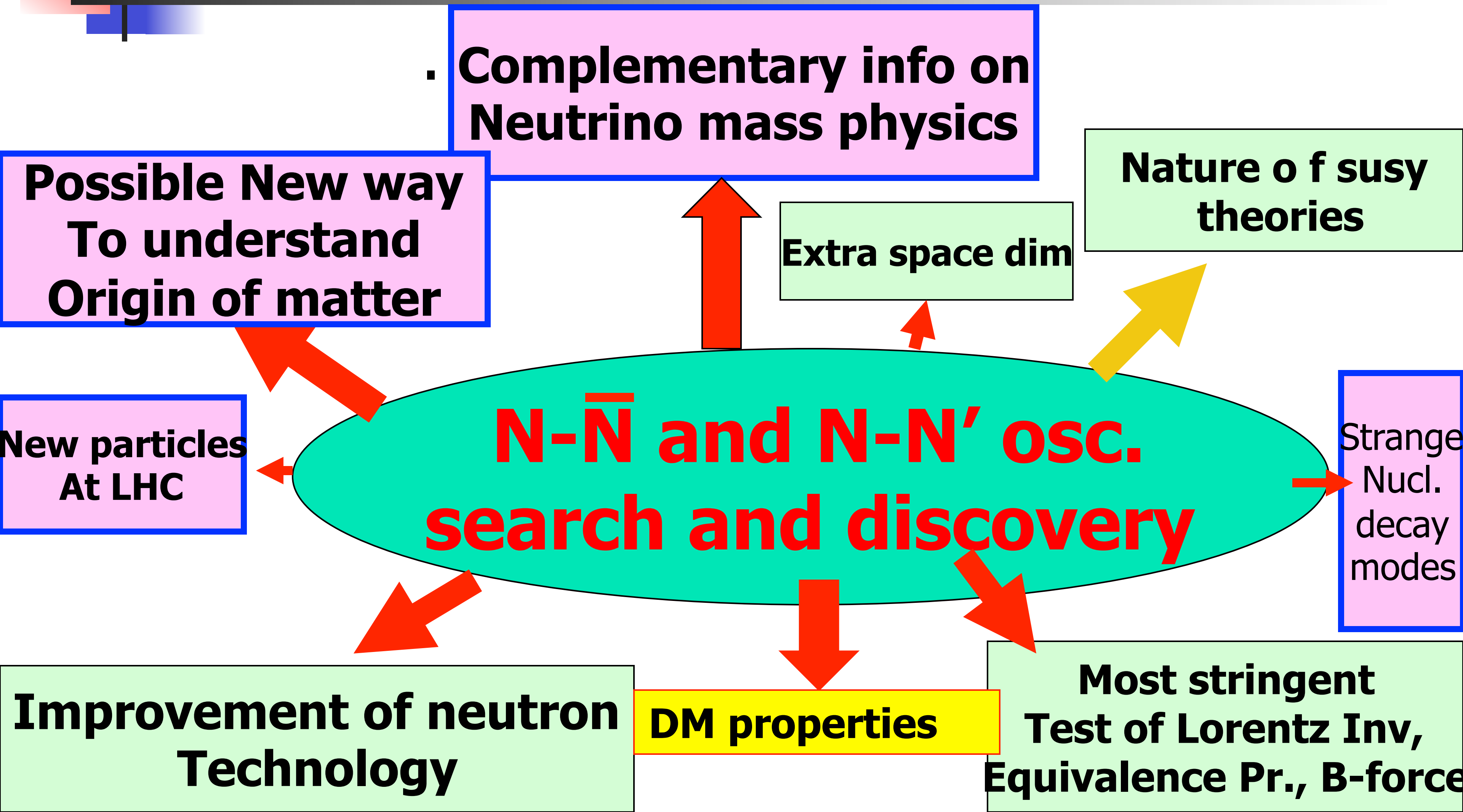
Some questions: contd

- Observable NN'→ T_{reheat} < 300 GeV to be consistent with BBN limits on N_{eff} .

- No such limit for NN-bar case.

- Low inflation reheat

Neutron oscillation can elucidate a whole range of physics beyond SM



Thank you for your attention !