Matter To The Deepest 2021

Baryogenesis and Neutron-anti-neutron oscillation

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MTTD 2021

Katowice, Poland, 09/21

Standard model cannot explain one of the major puzzles of cosmology: the asymmetry between matter and anti-matter content of the universe.

New BSM scenarios must be explored!

One of the key ingredients in understanding the origin of matter (N_B) in the universe is to have baryon number (B) violation: Sakharov'67

This + the advent of grand unified theories has inspired intense experimental searches as well as theoretical discussion of B-violation!

Two Major classes of $\cancel{B}$ under scrutiny are:

- <u>**Proton decay : $\Delta B = 1$** (p→e$^+\pi^0$,...)</u>

(probes high scale physics(~ 10^{15} GeV) and if discovered will strengthen the case for grand unification of forces and matter)(Pati, Salam; Georgi, Glashow)

- <u>**Neutron-anti-neutron oscillation: $\Delta B = 2$**</u>

(Probes physics in the 1-100 TeV scale

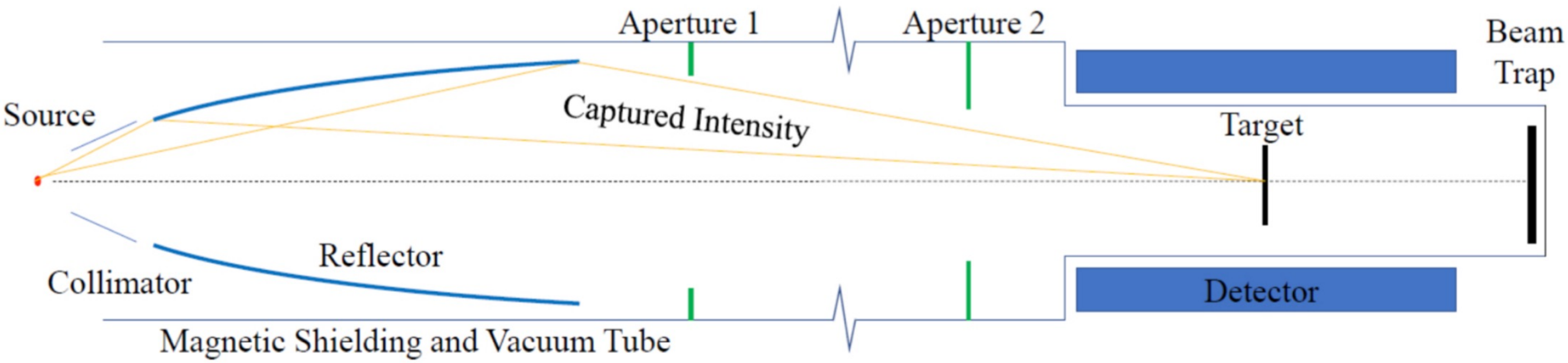
Range; it is motivated by belief that neutrinos are Majorana fermions; underlying physics testable in colliders unlike p-decay)

(Kuzmin'70; Glashow'79; Mohapatra, Marshak'80)

- *No evidence yet;Here we focus on N-$\bar{N}$ oscillation*

Two ways to search for NN-bar osc.

- **Direct search for oscillation:**



ESS set up; similar to the first NNbar search@ILL in 90s

- **Search in proton decay experiments for bound N Osc.**, where N→ $\bar{N}$ inside the nucleus (suppressed by nuclear potential) IMB, SK, SNO; future DUNE, Hyper-K;
- Both methods probe the same range of strengths

Current bounds for NN-bar oscillation

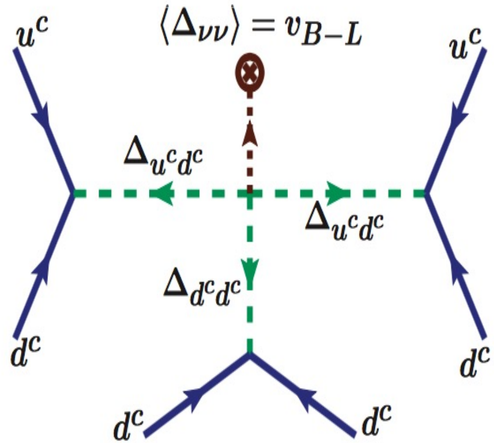
- Direct search: $\tau > 8.7 \mathrm{x} 10^7$ sec.(ILL)
- Bound N search: → $\tau > 3.5 \times 10^8$ sec. (Super-K)
- ESS possible improvement by ~30 (very important)

BSM PHYSICS PROBED BY NN-BAR OSCILLATION

$$\mathcal{O}_{B=2} = \frac{1}{\Lambda^5} u^c d^c d^c u^c d^c d^c$$

Arises from exchange of TeV mass color sextets (Δ) in seesaw Scalar $SU(2)_L xSU(2)_R xSU(4)_C$ model

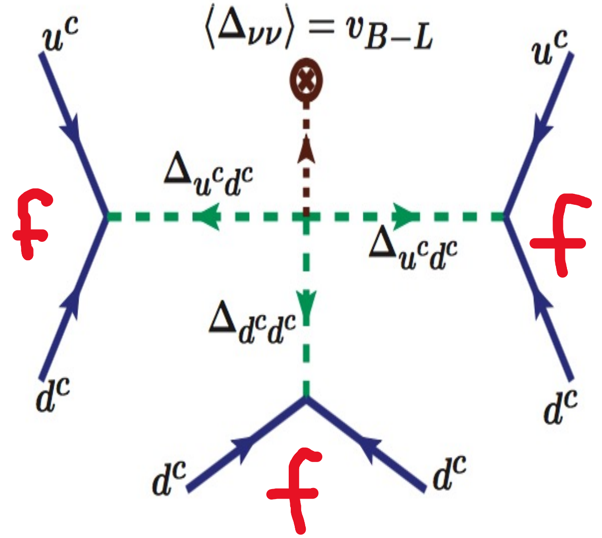
(RNM, Marshak'80)



- Implies $\Lambda \sim M_\Delta \sim 10\ to\ 100\ TeV$: single scale th: relates Majorana nu to $\Delta B = 2$ via $<\Delta_{\nu\nu}>$

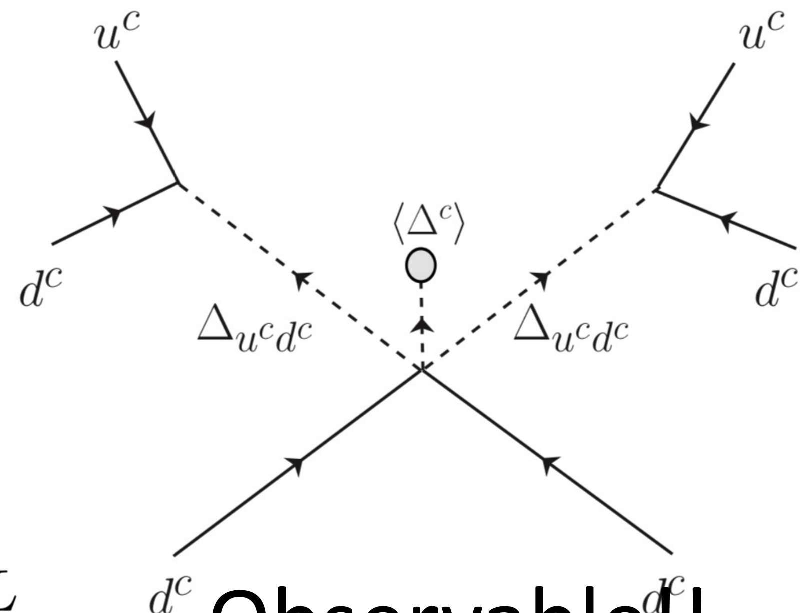
Closer Connection to neutrino mass

- Type II seesaw connects f's to neutrino mass in the theory $m_\nu = f v_L$
- For TeV sextets, FCNC allows only inverted neutrino mass hierarchy consistent with baryogenesis!



(II) SO(10) GUT 2 SCALE MODEL

SO(10) GUT with one diquark Higgs at GUT and one at TeV scale. Unification works.



$$G_{N-\bar{N}} \simeq \frac{\eta f_{ud}^2 f_{dd} \lambda v_{BL}}{M^4_{\Delta_{u^c d^c}} M^2_{\Delta_{d^c d^c}}}.$$

Observable!!

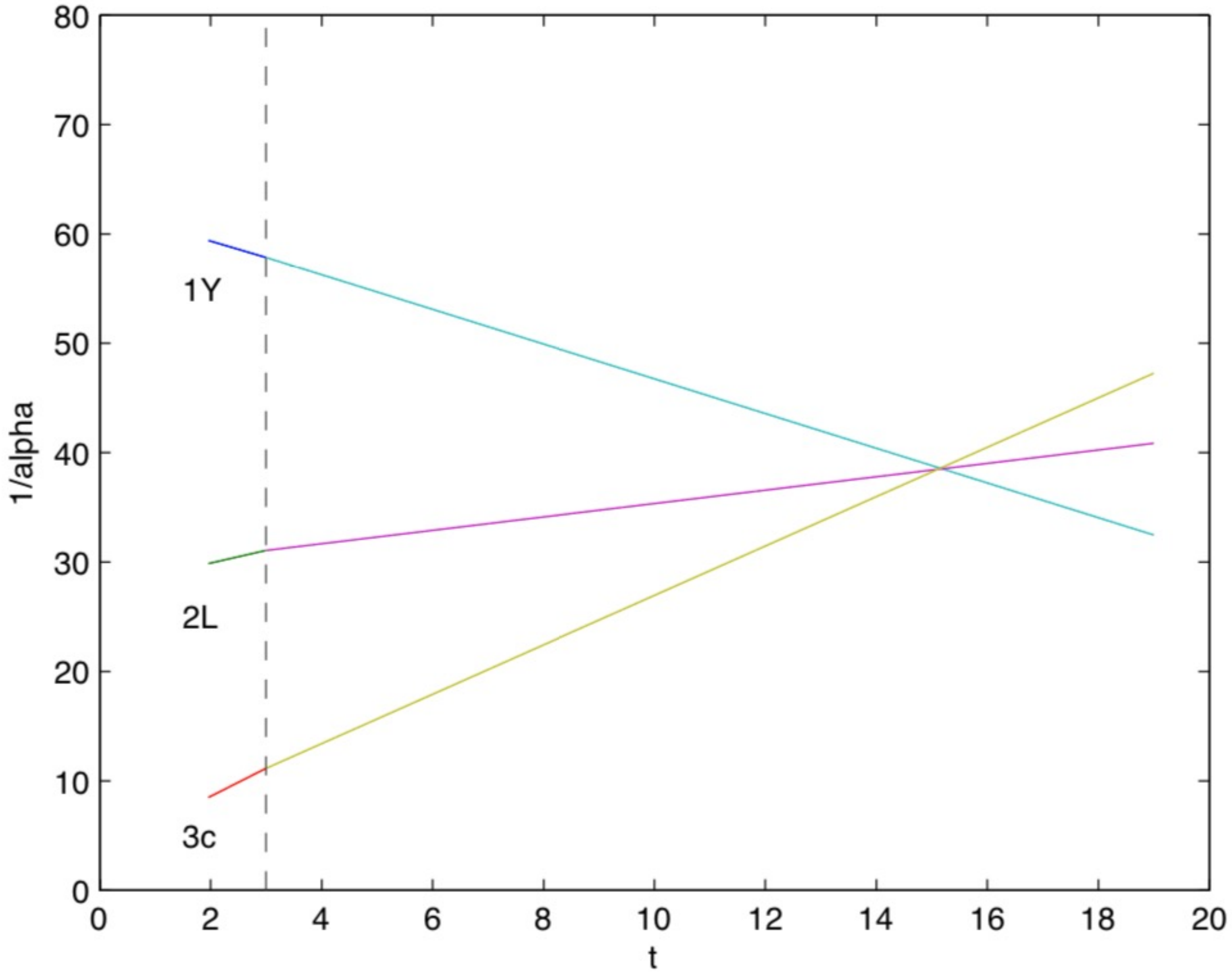
TeV

M_U

(Babu, RNM'2012)

Coupling unification in 2 scale theory

(with help from color singlet Higgs fields at TeV)



Now to baryogenesis (N_B) with NN-bar

P-decay vs N-N-bar osc. For N_B

- Canonical Proton decay modes in GUTs, $p \rightarrow e^+\pi^0, K^+\nu$ etc are not connected to baryogenesis since generated N_B conserve B-L and get erased by Sphalerons!
- NN-bar oscillation however has no such issue: can be directly connected to origin of matter!

Baryogenesis with NN-bar: Why bother?

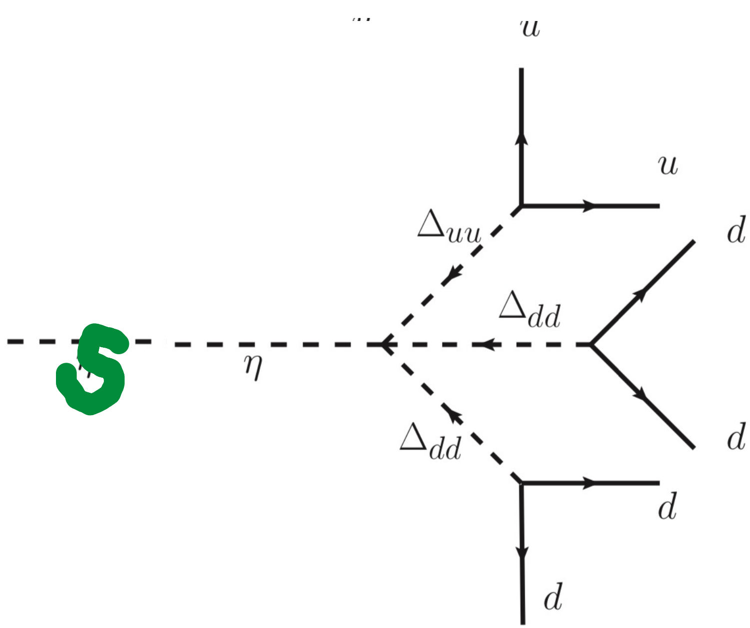
1. Expts will search for the process. Q: Is an observable B or L violating process compatible with observed B-asymmetry?
2. There are many scenarios for baryogenesis. It is impossible to prove any of them but it may be possible to rule them out by certain observations: e.g. $M_{WR} < 10$ TeV will rule out leptogenesis; $M_{stop} < 20$ GeV already rules out MSSM EW. Can one do the same for NNbar? Provides motivation to search.

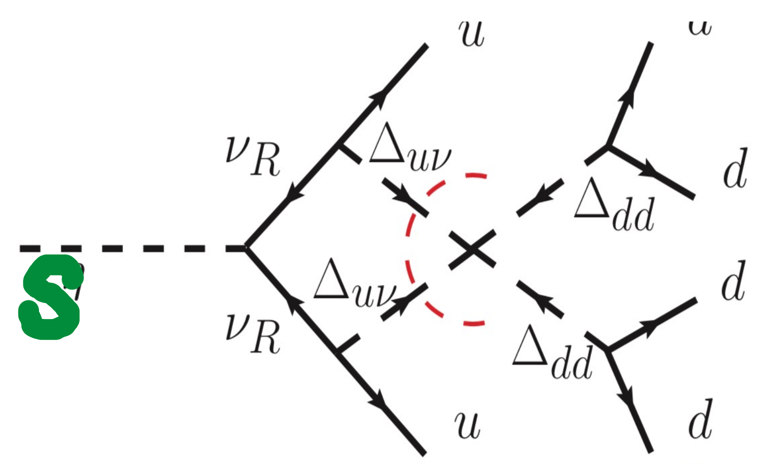
Baryogenesis with $N\bar{N}$: How?

(I) Post-Sphaleron Baryogenesis in pure scalar theory (Babu, Mohapatra, Nasri'2006)

Baryogenesis happens after sphaleron decoupling

(I)





$S \sim \mathrm{Re}\,\phi$

Conditions for successful PSB in a single scale SU(2)xSU(2)xSU(4) framework

(i) Basic mechanism: S goes out of eq. when relativistic i.e. $T_* > M_S$; drifts and decays at GeV $< T_D <$ 100 GeV (hence PSB) to produce asymmetry;

(ii) M_S cannot be too large (~TeV) to avoid strong dilution($d \sim T_D / M_S$)

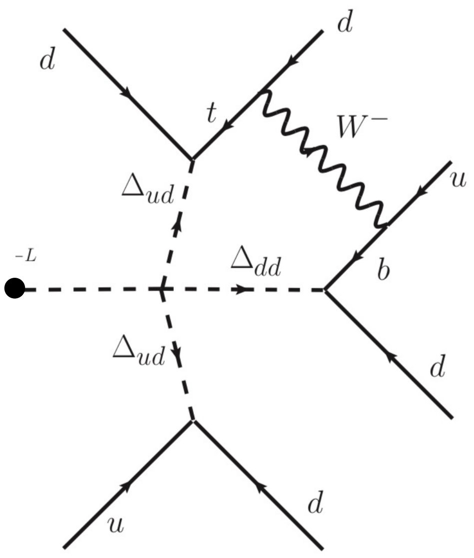
(iii) This restricts M_Δ ($T_* \sim$ TeV) to less than 10 TeV;

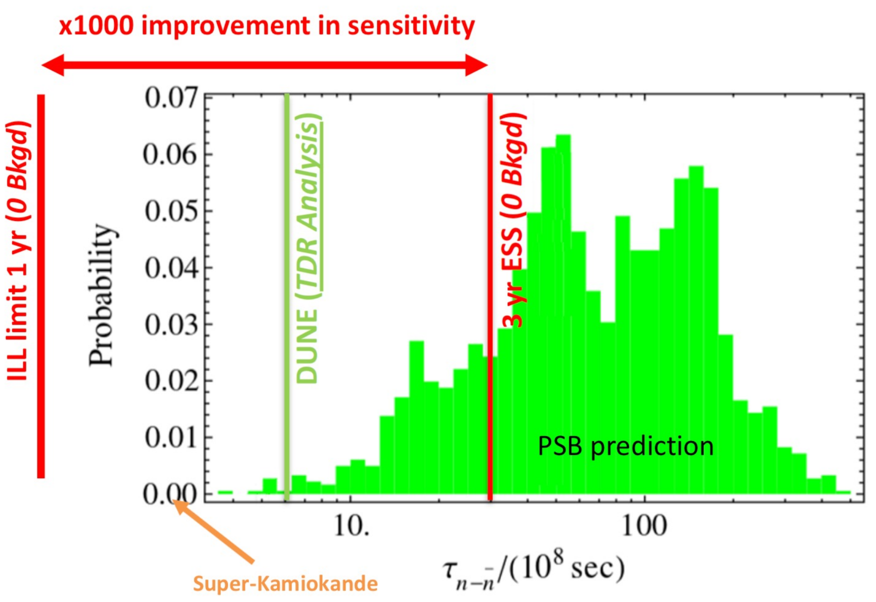
(iv) Model works only for inverted nu mass hierarchy

Model works for a narrow range of parameters :

An an upper limit on $\tau_{N\bar{N}}$

- SU(2)xSU(2)xSU(4) model of PSB relates diquark couplings for NN-bar to nu mass via type II seesaw (Babu, Dev, Fortes, RNM'13)
- Model with IH nu mass pattern. →upper limit





(II) AFFLECK-DINE BARYOGENESIS FOR NN-BAR

- (RNM, Okada'2021, PRD (to appear))

- Basic idea: **(Affleck, Dine)** complex Baryon-number carrying field Φ evolves with the universe and if has initial value with large difference between real and imaginary parts, it will evolve to give a net baryon number:

$$n_B = \mathrm{Im}(\dot{\Phi}^\dagger \Phi)$$

Inflation and AD baryogenesis

- Typically, two scalar fields are chosen to implement AD baryogenesis: inflaton, χ and AD field Φ;
- Choose Φ to have a flat directions so that it has a large value in the early universe before its real and imaginary parts start curling following

$$\ddot{\Phi} + 3H\dot{\Phi} + V'(\Phi) = 0$$

$$\dot{n}_B + 3Hn_B + 2Q_\Phi Im[V'(\Phi)\Phi] = 0$$

Our set up

- Use setup by A. Lloyd-Stubbs and J. McDonald (2020)
- Inflaton and AD field are only a single field Φ
- Non-minimally coupled gravity $f = 1 + \xi \frac{\Phi^2}{M_P^2}$

$$\mathcal{S} \;=\; \int d^4x \sqrt{-g} \left[-\frac{1}{2} M_P^2 \, f \, R + \partial_\mu \Phi^\dagger \partial^\mu \Phi - V(\Phi) \right]$$

$$V(\Phi) \;=\; m_\Phi^2 \Phi^\dagger \Phi - A(\Phi^2 + \Phi^{\dagger 2}) + \lambda (\Phi^\dagger \Phi)^2 .$$

A=$\varepsilon \, m_\Phi{}^2$ (violates B) ε << 1

- ***Φ* has B=2 via** $\Phi u^c d^c d^c u^c d^c d^c$

Four stages to early universe evolution

Stage (i) :Inflation occurs from non-minimal coupling to gravity for $\Phi > M_{\mathrm{P}}/\sqrt{\xi}$ (ξ~ 1600)

- Fits all CMB data including r=Tensor/Scalar ratio and spectral index n_S (Okada, Rehman, Shafi)
- As Φ becomes smaller as it rolls down the potential, inflation ends and second stage begins:

Stage (ii): Φ^4 term in the potential dominates and then Φ radiation dominate the universe and $\Phi \propto a^{-1}$. Eventually, quadratic term dominates at $\Phi *$; real and Im parts of $\Phi *$ take different random values (Violates CP)

Φ evolution: Stage (iii)

$$\ddot{\phi}_1 + 3H\dot{\phi}_1 = -m_1^2\phi_1 - \lambda(\phi_1^2 + \phi_2^2)\phi_1$$

$$\ddot{\phi}_2 + 3H\dot{\phi}_2 = -m_2^2\phi_2 - \lambda(\phi_1^2 + \phi_2^2)\phi_2$$

Easy to solve without the last term

$$\phi_i(t) \simeq \phi_{i,*}\left(\frac{a_*}{a}\right)^{3/2} \cos(m_i(t - t_*))$$ +small terms

Final form of the baryon asymmetry

Stage (iv) Decay and reheat T_R :

- $$\frac{n_B}{s} \simeq \frac{3}{8}\sqrt{\frac{\pi^2}{90}g_*}\frac{Q_B}{\epsilon}\frac{T_R^3}{m_\Phi^2 M_P}\sin(2\theta)$$

Q_B is the baryonic charge of the AD-field.

Constraints: $\epsilon \ll 1$; $\epsilon\, m_\Phi / \Gamma_\Phi >> 1$

Sin 2θ random; T_R, determined by dynamics

$$T_R = \sqrt{\Gamma_\Phi M_P}$$

Requirements on model

(i) $\epsilon \ll 1$; **(ii)** $\epsilon\, m_{\Phi}/\Gamma_{\Phi} >> 1$

(iii) For $T < v_{\Phi}$, B-violating interactions switch on and can wash out the B-generated unless their decoupling temp. $T^{*} > T_{R}$. We require theory to satisfy this.

(iv) NN-bar observable in current or planned expts

Viable model to be interesting must satisfy all these constraints.

Apply to N-$\bar{\text{N}}$ oscillation

- Endow Φ with B=2 and couple it to some typical operators: 3 classes of models; Given mass of Φ, Λ ; T_R is determined; Given < Φ>, can determine the B-violation decoupling T*;
- We must have T*>$T_{R,}$ to prevent washout.

- $\mathcal{O}_1 = u^c d^c d^c u^c d^c d^c$ for Λ~100 TeV or GUT

- Split scale SO(10) type model

TeV

$$\mathcal{O}_2 = \Delta_{ud}\Delta_{ud}d^c d^c \qquad \Delta_{ud} \to u^c d^c$$

- $e.g. \Delta_{dd}$ GUT scale

O_2 fits a broader parameter range

It is embeddable in SO(10) and hence interesting:

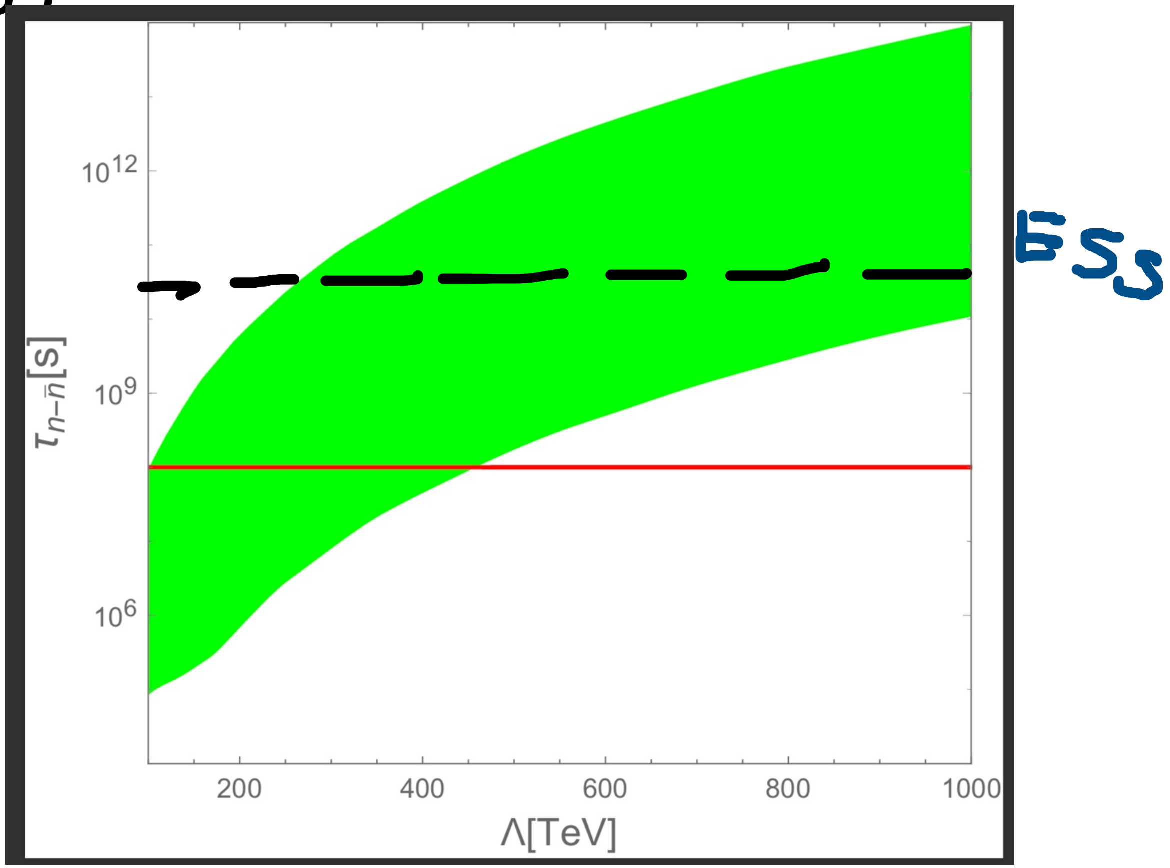
$$\mathcal{O}_2 = \Delta_{ud}\Delta_{ud}d^c d^c \qquad \Delta_{ud} \to u^c d^c$$

Δ_{dd} in GUT scale and Δ_{ud} TeV scale; No

- Δ_{ud} at TeV scale + observable NN-bar will support this version of AD baryogenesis.

O_1 as a single scale-(multi TeV) theory : an alternative realization of AD

- Restricted and predictive; part of the parameter space testable@ESS
- $.0001 < \varepsilon < 0.1$
- $\mathbf{m_{\Phi} \sim \Lambda}$



Summary

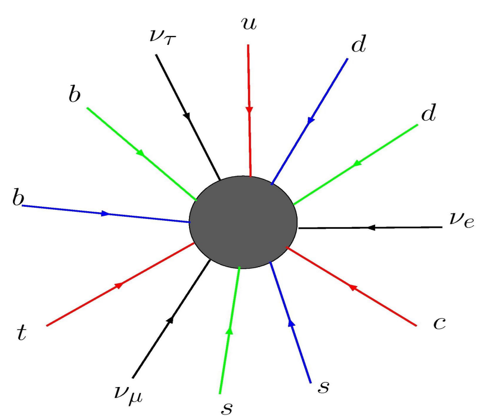
- Neutron-anti-neutron oscillation is an important process to search for to understand the origin of matter in the universe.
- PSB and AD baryogenesis provide two mechanisms for implementing baryogenesis with NN-bar in different parameter ranges.
- AD prefers a two scale SO(10) type theory which requires color sextet scalars in the TeV range that colliders can look for. However it also works in a narrow parameter range for a single TeV scale theory.
- .

Thank you for your attention !!

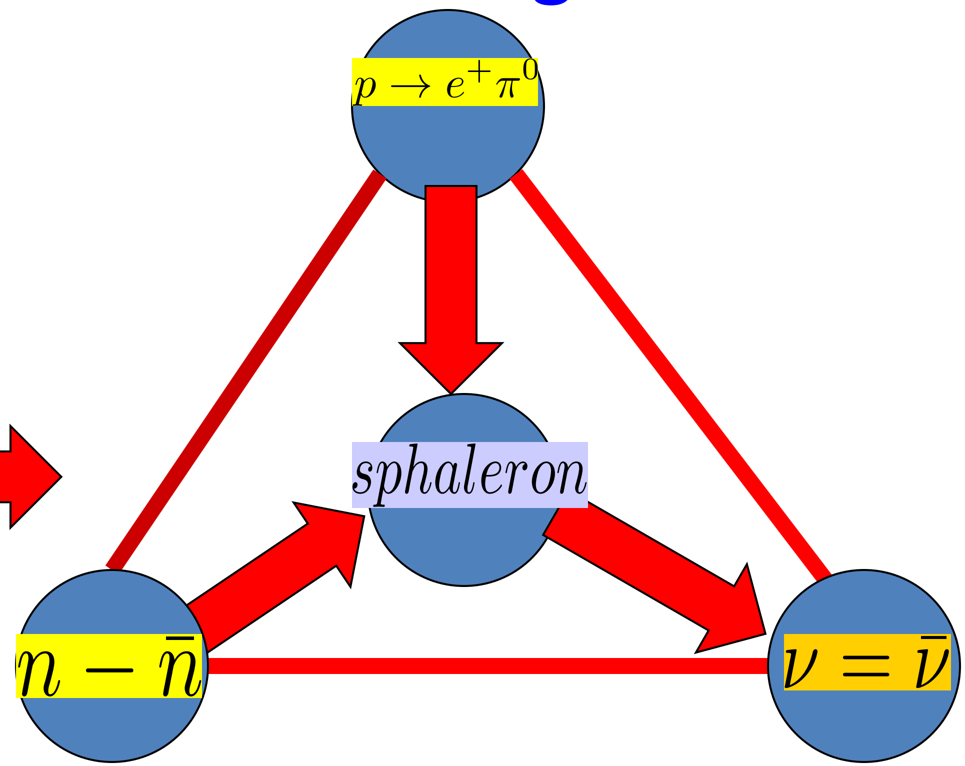
What else can we learn from $N\bar{N}$-discovery: strong hint for $\nu = \bar{\nu}$

- Standard model has sphaleron solutions
- Sphaleron Op. rewrite

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

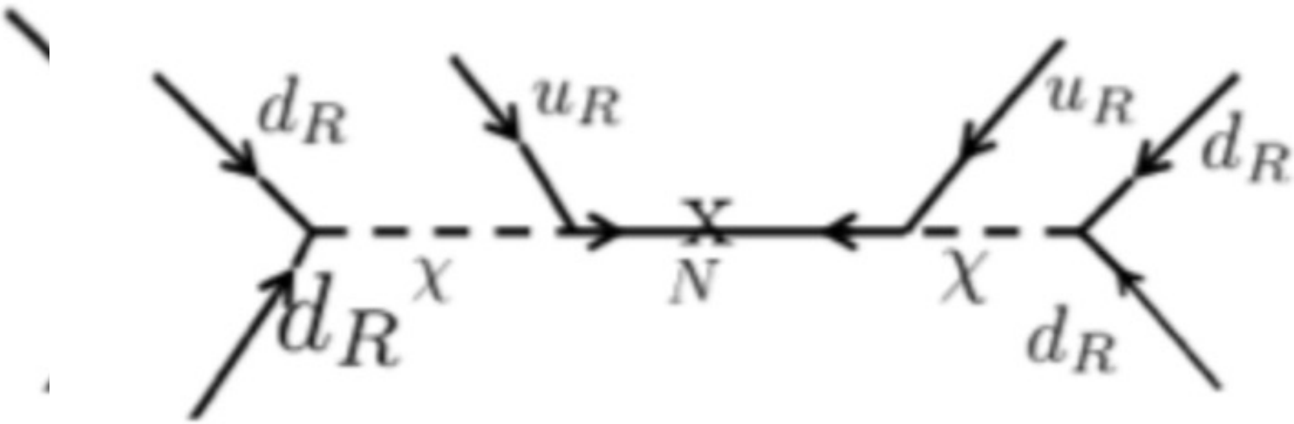


B-L Triangle:

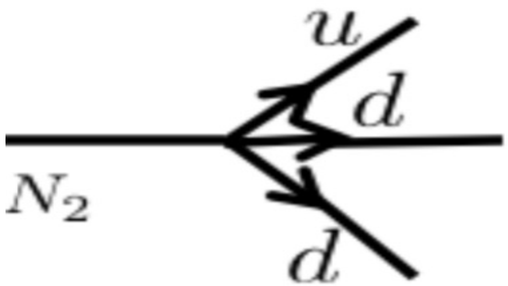


- *p-decay+nn-bar→Neutrino Majorana* *(RNM, 2014 ESS at CERN; Babu, RNM'14)* regardless of what double beta decay shows!

Other mechanisms: (ii) Majorana fermions: (Dev,RNM'15; similar models by Gu and Sarkar'11)



All particles at TeV scale; Baryogenesis



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