CP Violation, Baryon violation, RPV in SUSY, Mesino Oscillations, and Baryogenesis

David McKeen and AEN, arXiv:1512.05359
Akshay Ghalsasi, David McKeen, AEN., arXiv:1508.05392
(Thursday: Kyle Aitken, David McKeen, AEN, Thomas Neder, arXiv:1708.01259)
(See also Seyda Ipek, David McKeen, AEN., arXiv:1407.8193
Seyda Ipek, John March-Russell, arXiv:1604.00009)

Neutron-Antineutron Oscillations: Appearance, Disappearance, and Baryogenesis

October 24, 2017

CP V beyond the Standard Model

- Needed to produce early universe asymmetry of 10^{-8} between quarks and anti-quarks? (***baryogenesis***)
  - Effects of CKM phase in early universe highly suppressed by small mixing angles and mass differences.
    - non standard CPV

      or

    - non standard enhancement of standard CPV

Baryon Violation

- SM: Anomalous effect in weak interactions ("Sphalerons") rapid violation of B, L at T> ~ 100 GeV (weak transition), negligible B violation at low T (tunneling)
- Sphalerons conserve B-L
- Baryogenesis:
  - produce net B-L at high T (e.g. leptogenesis)
  - electroweak baryogenesis (no BSM B or L violation needed)
  - post sphaleron baryogenesis (requires B violation at low energy which does not allow proton decay)

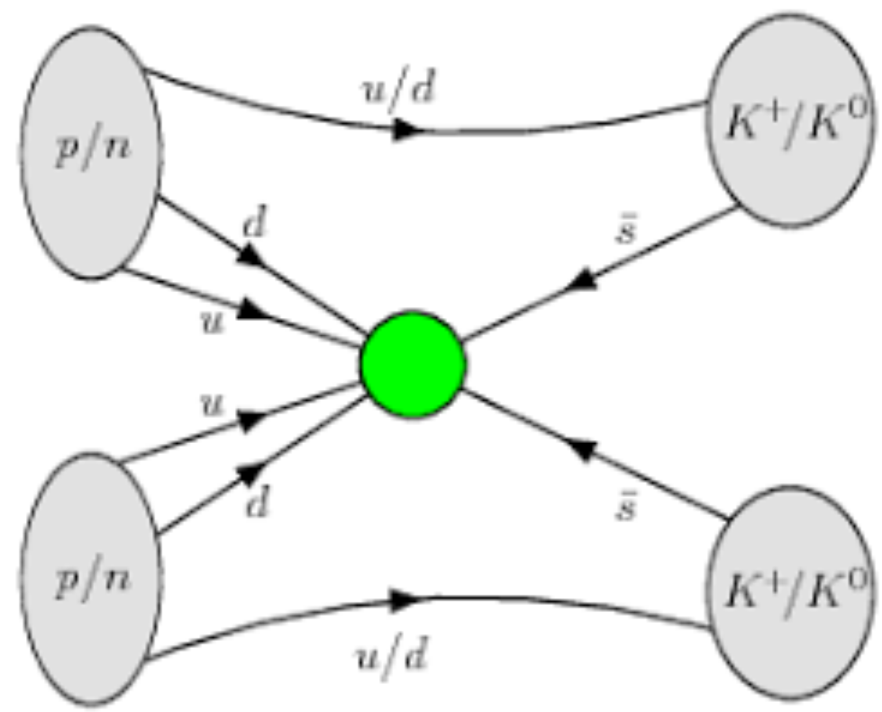
Why 'post sphaleron' baryogenesis is compelling

- Consistent with wide range of cosmology/inflation models.
- No high temperature required (solves a lot of cosmological issues, e.g. gravitino over production)
- Electroweak baryogenesis requires 1st order weak transition, CPV in Higgs sector—very constrained by electric dipole moment of electron, mass of Higgs.

Consequence of post sphaleron baryogenesis

$$\frac{1}{M^5} qqqqqq$$

- lowest dimension B violation operator which does not lead to proton decay is dim 9,
- n—n̄ oscillations
- dinucleon decay:



R parity

- many models of new physics for the electroweak hierarchy introduce a Z_2 symmetry $(-1)^{(L+3B+2S)}$ under which new particles are odd, called R parity (most widely known in SUSY)
  - all SM particles have even R parity
  - SUSY superpartners have odd R parity
  - Any new fermion which is does not carry baryon or lepton number is R-odd, as is any boson with odd B or L charge
  - prevents tree level contributions to precision electroweak corrections, CP and flavor violation from new R odd particles.
- Bonus: lightest Parity Odd Particle (LPOP) is stable—potentially dark matter

What is $U(1)_R$?

- U(1) Symmetry in Supersymmetric theories which does not commute with SUSY
- Different particles in a supermultiplet have different charges
- $U(1)_R$: left handed gaugino has charge +1, sfermions in left chiral supermultiplets have charge -1
  - All fermion superpartner masses must be Dirac
- requires new chiral supermultiplets to allow Dirac gaugino masses
- requires 2 more Higgs doublet chiral supermultiplet (or lepton number violation/identification of lepton number and $U(1)_R$

Baryon number violation without proton decay

- Proton must decay into odd # fermions.
- Sufficient conditions for stability:
  - lepton number conservation mod 2
  - no new fermions lighter than m_p-m_e

Violating Baryon number and R symmetry in SUSY

- Dim 4: Superpotential coupling $u_i^c d_j^c d_k^c$
- Dim 3: squark scalar trilinear
- violate baryon number both are R parity odd and $\Delta B=1$
- Dim 4: Conserves $U(1)_B+U(1)_R$
  - Squark=antidiquark, gauginos carry baryon number
  - Dim 3, Majorana gaugino masses: Conserves Z_2 subgroup of $U(1)_B+U(1)_R$
  - Z_2 subgroup of $U(1)_B+U(1)_R$ forbids proton decay (as long as lightest neutralino heavier than m_p-m_e), allows Majorana ν mass

Dark Matter: 938 MeV Neutral Majorana Fermion?

- Proton stability: $m_p - m_e < M_N$
- $M_N < m_p + m_e \rightarrow$ N stable
- Experimental search for $n \rightarrow N + \gamma$?

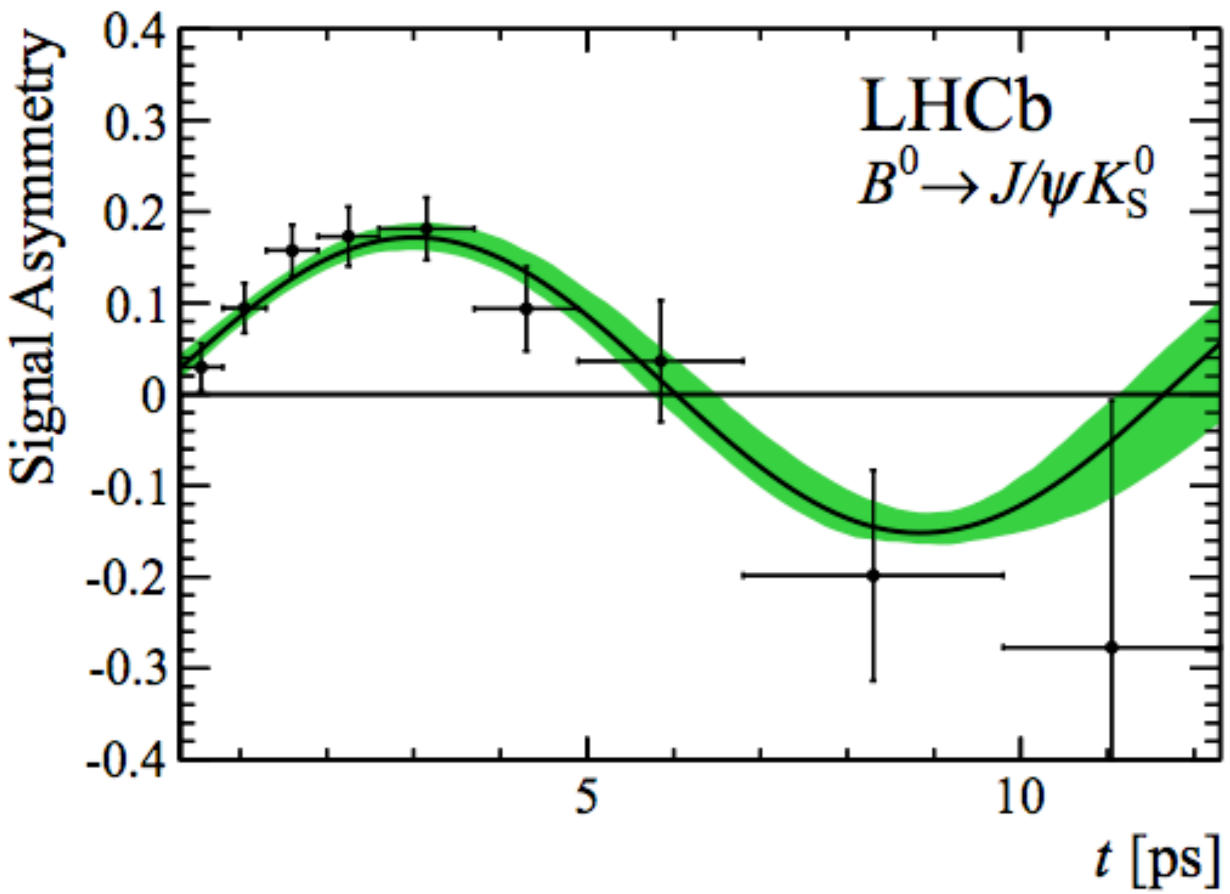
Particle Oscillations

- quantum interference due to coherent superposition of particles with slightly different masses
    - production conserves some *approximate* symmetry
- Observed in neutrinos (lepton flavor oscillations), neutral K,D,B mesons (particle-anti-particle oscillations)
    - masses must be near degenerate-
        - wave packet propagation must be similar enough so spatial separation does not occur over an oscillation time
        - oscillation time must not be too fast or too slow or oscillations not observable

CPV in oscillations of unstable states

- Only requires 2 oscillating states
- Observed in neutral kaon anti-kaon and neutral B meson-anti-B meson oscillations
- Large effect possible when oscillation and decay rates comparable

$O(1)$!



CPV from Oscillations + Decays

- Requires $m_{12} \neq 0$, $\Gamma_{12} \neq 0$, $\arg(m_{12}\Gamma_{12}^*) \neq 0$
- *largest effect:* $\Delta\Gamma \sim \Delta m \sim \Gamma$, $\arg(m_{12}\Gamma_{12}^*) \sim O(1)$
- generically $\Delta\Gamma < \Delta m, \Gamma$
  - *Kaons:* $\Delta\Gamma \sim \Delta m \sim \Gamma$, $\arg(m_{12}\Gamma_{12}^*) << 1$,
  - B^0: $\Delta\Gamma << \Delta m \sim \Gamma$, $\arg(m_{12}\Gamma_{12}^*) \sim O(1)$
  - D^0: $\Delta\Gamma \sim \Delta m < \Gamma$, $\arg(m_{12}\Gamma_{12}^*) << 1$,
  - B_s: $\Delta\Gamma << \Gamma < \Delta m$, $\arg(m_{12}\Gamma_{12}^*) << 1$

Baryogenesis from oscillating unstable states in SUSY?

- Susy with baryon violating RPV has been an attractive low energy baryogenesis model for some time
- Usual mechanism is CPV in baryon number violating decays
- Can CPV in oscillations be used for baryogenesis?
- Thursday morning: Dave McKeen talk on CPV from oscillating neutral heavy flavor baryons

pseudo-Dirac fermions in SUSY?

- "Mesino-anti-Mesino Oscillations", S. Thomas, U. Sarid, 1999
- In theories with gravitino LPOP (lightest supersymmetric particle) the NLSP (Next to lightest Supersymmetric particle has a long lifetime.
- What if NLSP is a squark? Hadronizes before decay as a *mesino* (squark-anti-quark bound state). Carries flavor quantum numbers which are violated by weak and susy interactions.
- neutral mesino can oscillate into anti-particle, is pseudo-Dirac.
    - same sign top, same sign di-lepton signatures.

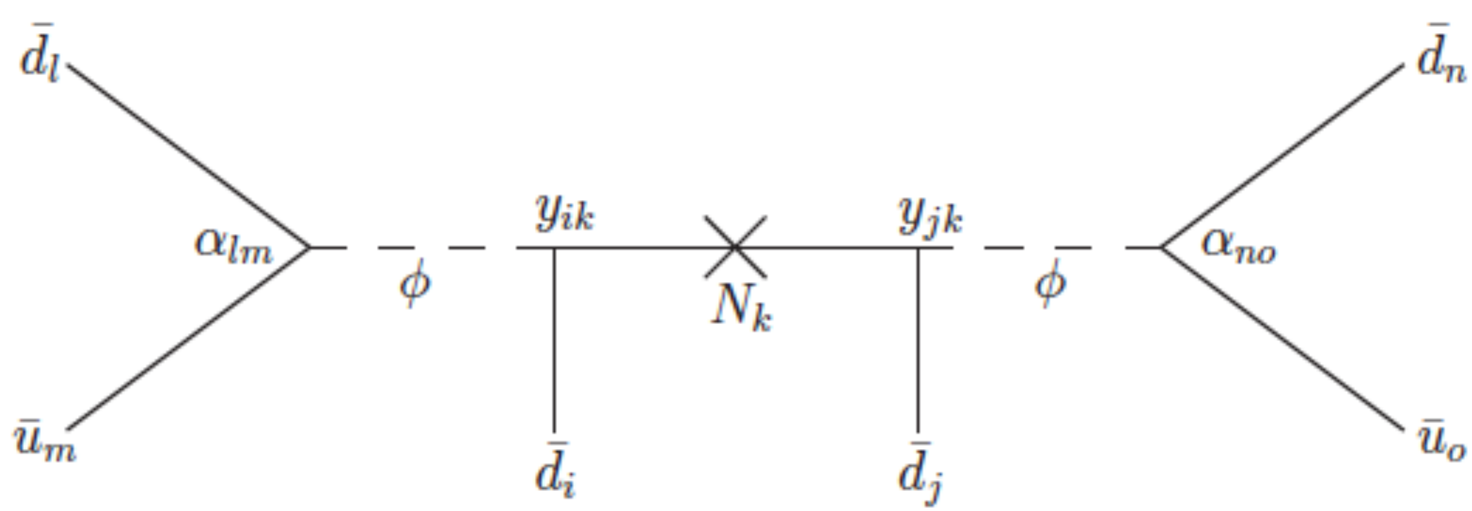
History

- long lived NLSP stop mesino
- long lived signatures
- same sign dilepton events

- “Mesino Oscillation in MVF SUSY, *Berger, Csaki,Grossman, Heidenreich, 2013*
  - sbottom LSP mesino oscillations with RPV
  - same sign dilepton signatures

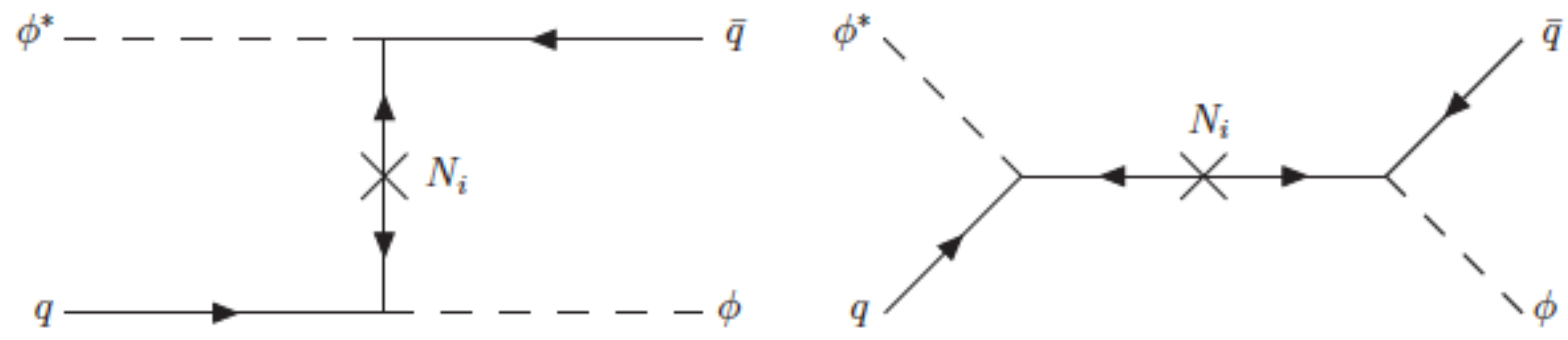
Model for Baryogenesis: arXiv:1508.05392

- "RPV SUSY-lite"
- New particles:
  - Neutral Majorana fermions χ_i, i=1,2,...,
  - charge -1/3 colored scalar ϕ, *mass >~650 GeV*
  - *low energy effective theory:*

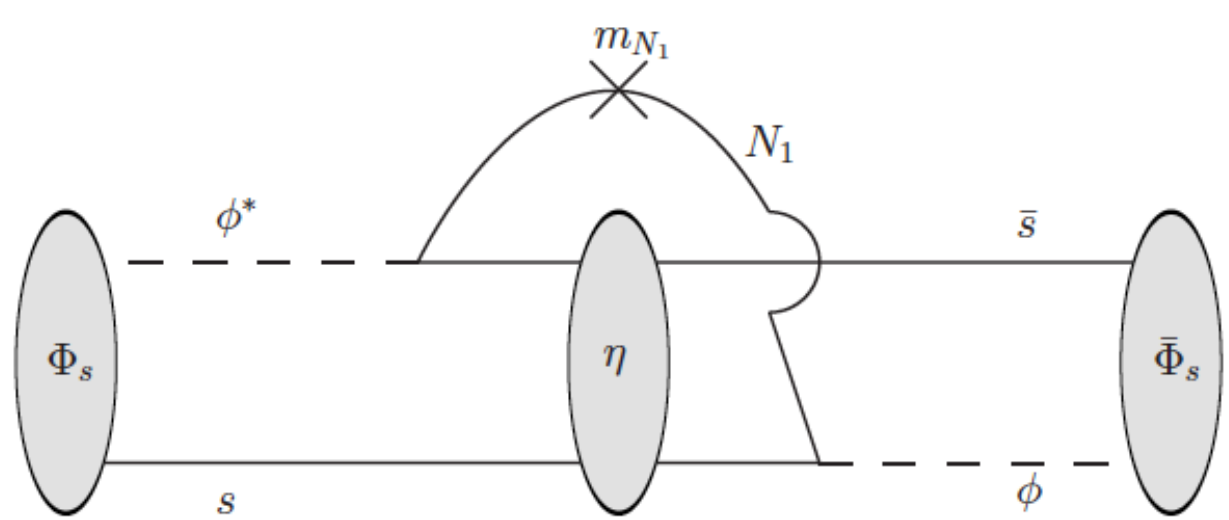


Dinucleon decay constraints on combinations of α_{11}, α_{21},y_{1k},y_{2k}

Generation of CPV in Mesino oscillations



- M_{12}:
- Γ_{12}



maximizing CPV

- optimally N_1 is slightly lighter (~500 MeV) than mesino
- strange mesino decays: both Φ, $\bar{\Phi} \to N_1 + \eta$,

  $\Phi \to$ baryon+ mesons, $\bar{\Phi} \to$ anti-baryon+ mesons
- require total $\Gamma < \Lambda_{QCD}$ (hadronization rate)
- For optimal parameters, sizable CPV possible
  - #baryons-#antibaryons per initial $\Phi + \bar{\Phi} \sim 10^{-4} - 10^{-5}$

Cosmology

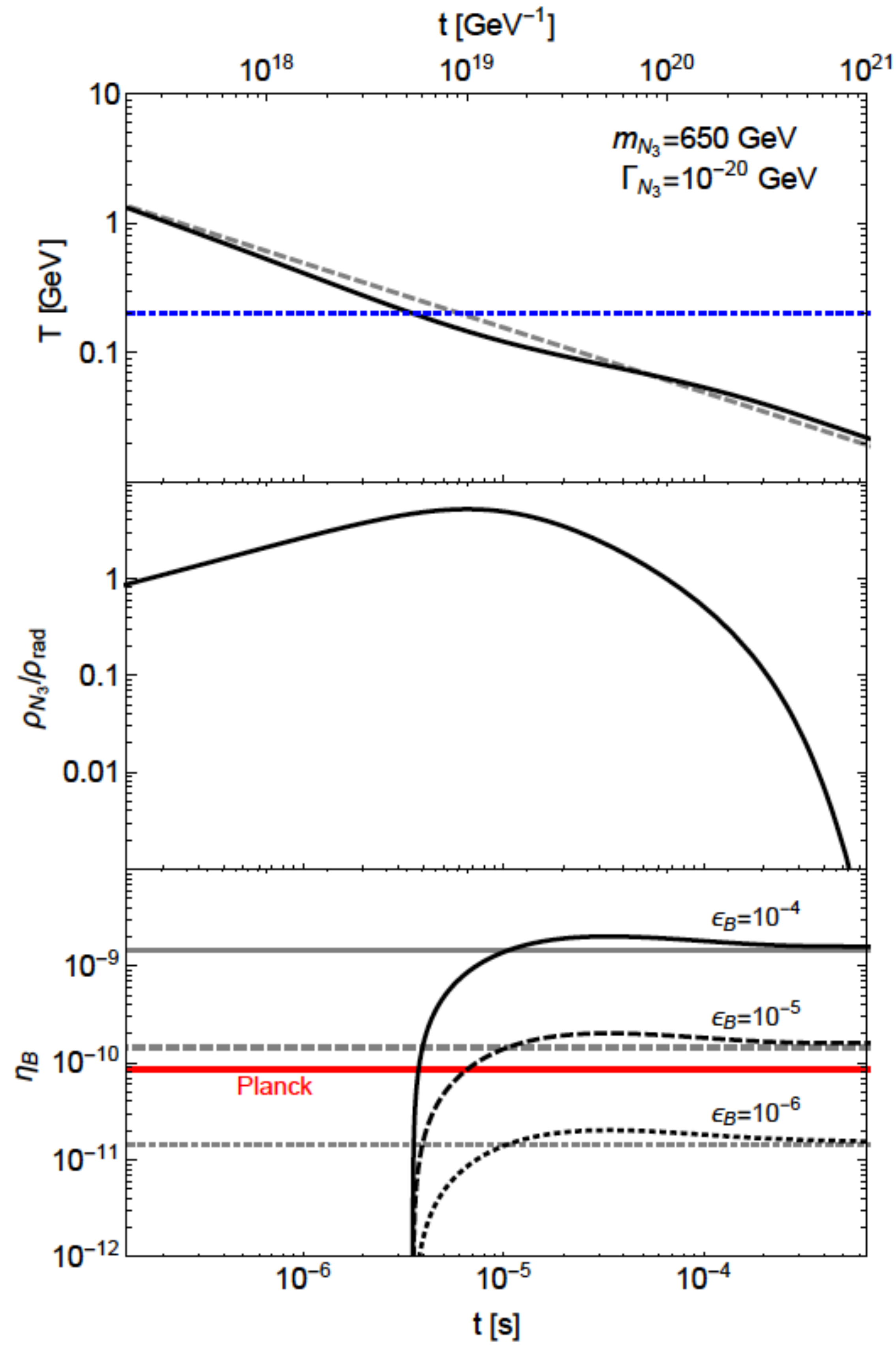
- Mesino mass > 650 GeV
- Mesino is hadron whose existence requires T< 100 MeV
- Mesinos in early universe would be way out of thermal equilibrium
- Introduce heavy, weakly coupled N_3 with long lifetime which freezes out, decays into quark+ antisquark or antiquark+ squark when temperature <~100 MeV
- squarks immediately hadronize into mesinos, oscillate and decay, producing net baryon number.

Boltzman equations

$$\frac{d\rho_{\rm rad}}{dt} = -4H\rho_{\rm rad} + \Gamma_{N_3} m_{N_3} n_{N_3},$$
$$\frac{d\rho_{N_3}}{dt} = -3H\rho_{N_3} - \Gamma_{N_3} m_{N_3} n_{N_3},$$

$$\frac{dn_B}{dt} = -3Hn_B + \frac{1}{2} A\,\Gamma_{N_3}\epsilon_B n_{N_3}.$$

- A=fraction of squarks which hadronize as oscillating mesinos
- ε_B=average net # baryons per mesino



Summary

- Baryogenesis is strong motivation for n $\bar{n}$ oscillations, dinucleon decay
- Z_2 symmetry allows baryon violation, Majorana ν with stable proton
- For fine tuned mass range, same Z_2 symmetry can also stabilize dark matter
- search for dark matter in neutron decays
- Baryogenesis model from oscillating mesinos
- stay tuned for Dave McKeen's talk on oscillating heavy flavor Baryons