Baryogenesis via mesino oscillations

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The one minute summary

- Mesino a bound state of colored scalar and quark
- Model analogous to Kaon system
- Mesinos form after the QCD hadronization temp
- Oscillations analogous to Kaon system give CP violation
- Baryon violating decays give baryogenesis

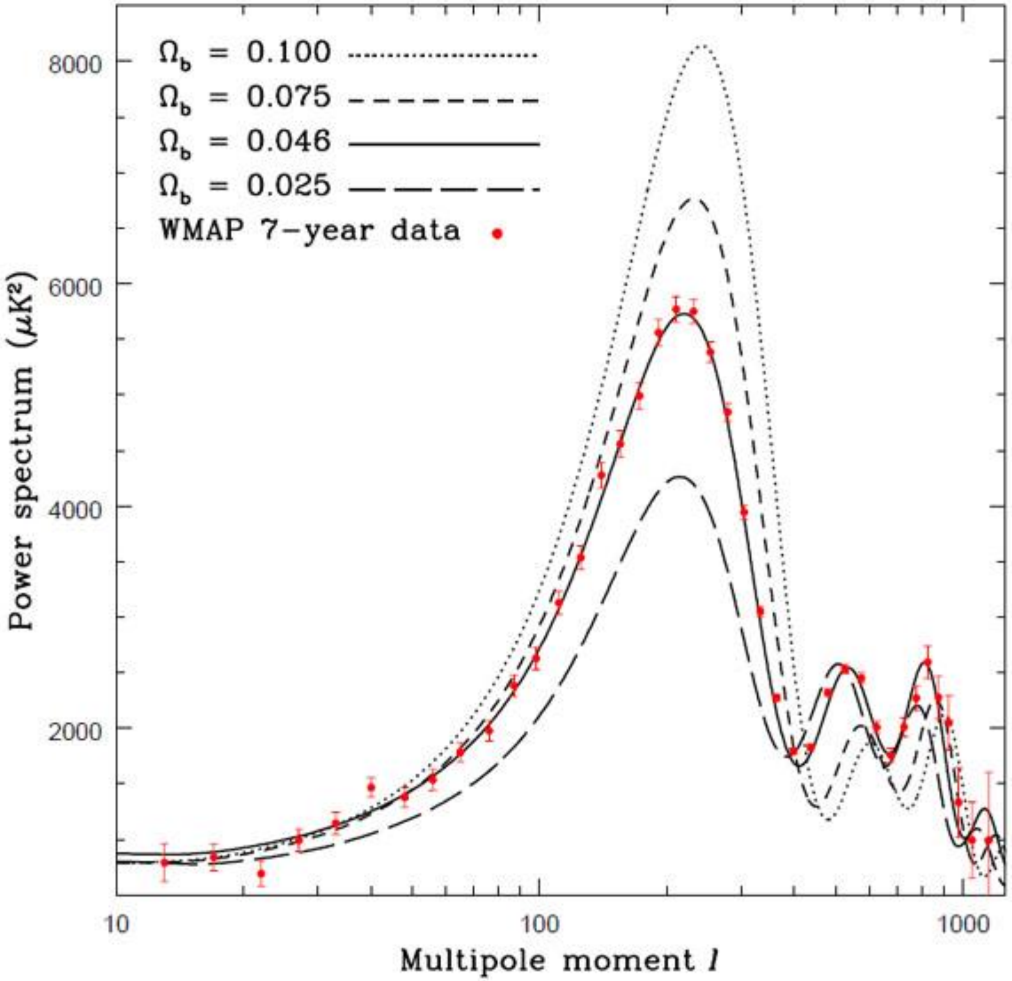
Outline

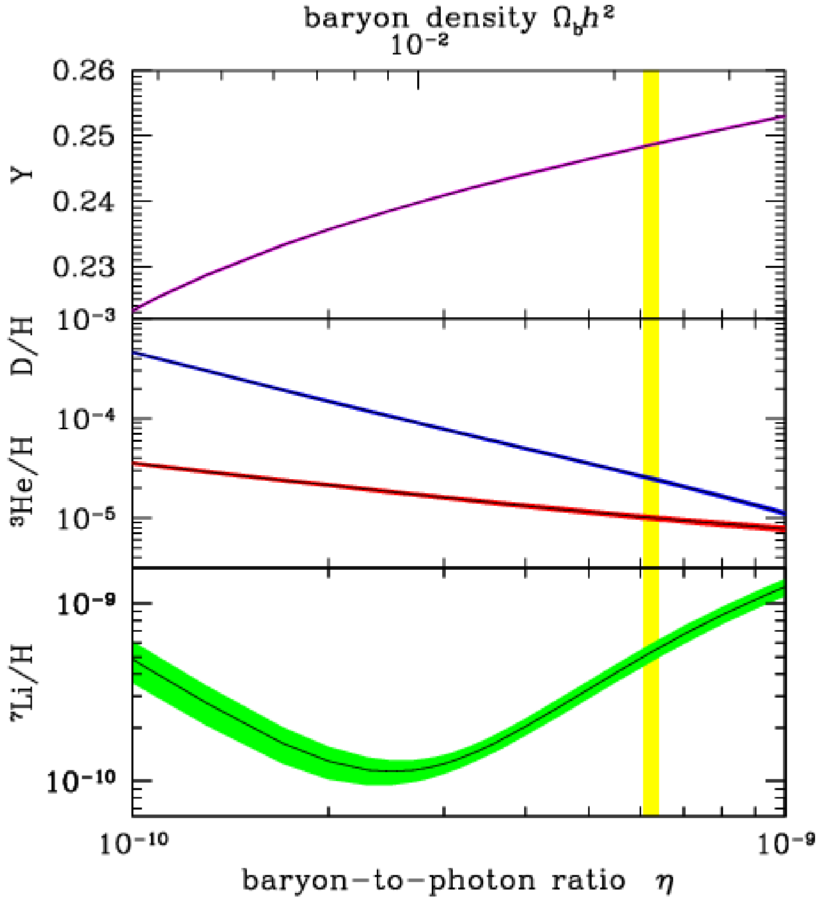
- Introduction and Motivation
- The Model
- Oscillations and CP Asymmetry
- Experimental Constraints
- Cosmology
- Conclusion

Introduction and Motivation

Evidence for baryogenesis

- Universe is made up of baryons $\eta_B = 8.6 \times 10^{-11}$





No baryogenesis in SM

- Sakharov conditions
  - Baryon number violation ✓ (sphalerons)
  - C and CP Violation ✗ (CKM phase not enough)
  - Departure from thermal equilibrium ✗ (no first order PT)
- Models of baryogenesis require high reheating temperature

Reheating temperature can be low

- No evidence of high reheating temperature

- Many reasonable theories favor a low reheating scale
  - Gravitino production in SUSY extensions of SM(Moroi et al ‘83)
  - Isocurvature perturbations(Fox et al ‘04)

- There do exist low scale baryogenesis models(Claudson et al ’84, Dimopolous et al ‘87)

The Model

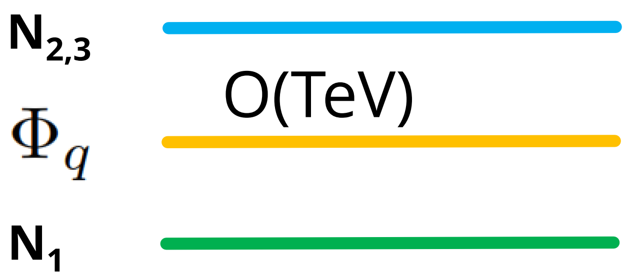
Particle content

colored scalars

singlet fermions

majorana mass

$$\mathcal{L} \supset y_{ij}\phi\,\bar{d}_i N_j - \frac{1}{2} m_{N\,ij} N_i N_j + \alpha_{ij}\phi^* \bar{d}_i \bar{u}_j + \text{c.c.}$$



Complex phases

all 9 phases remain

real and diagonal

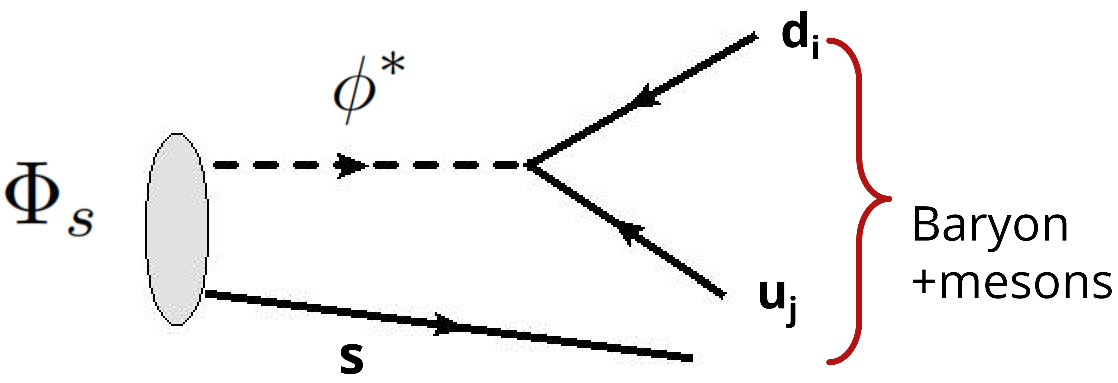
two complex phases remain

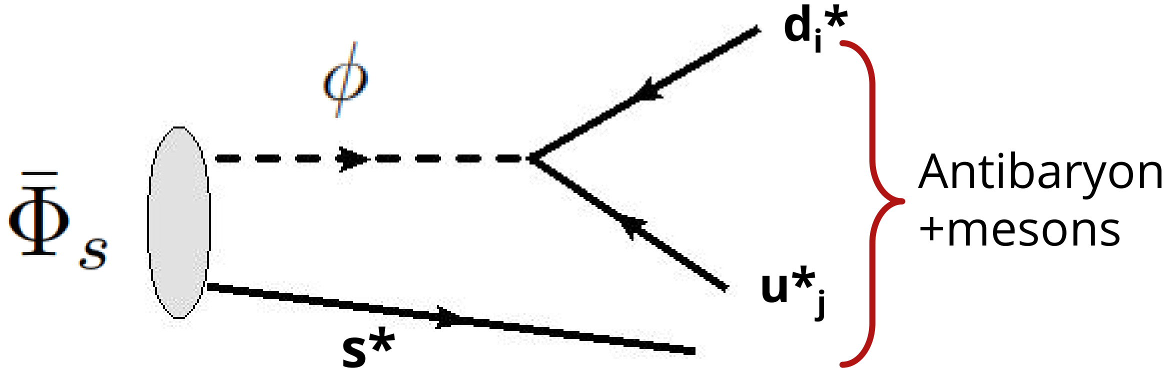
$$\mathcal{L} \supset y_{ij} \phi \, \bar{d}_i N_j - \frac{1}{2} m_{N ij} N_i N_j + \alpha_{ij} \phi^* \bar{d}_i \bar{u}_j + \text{c.c.}$$

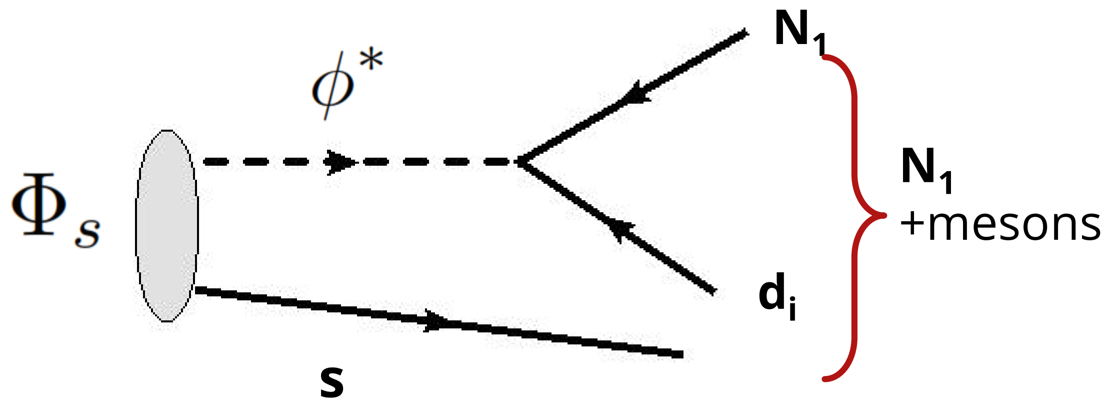
Oscillations and CP violation

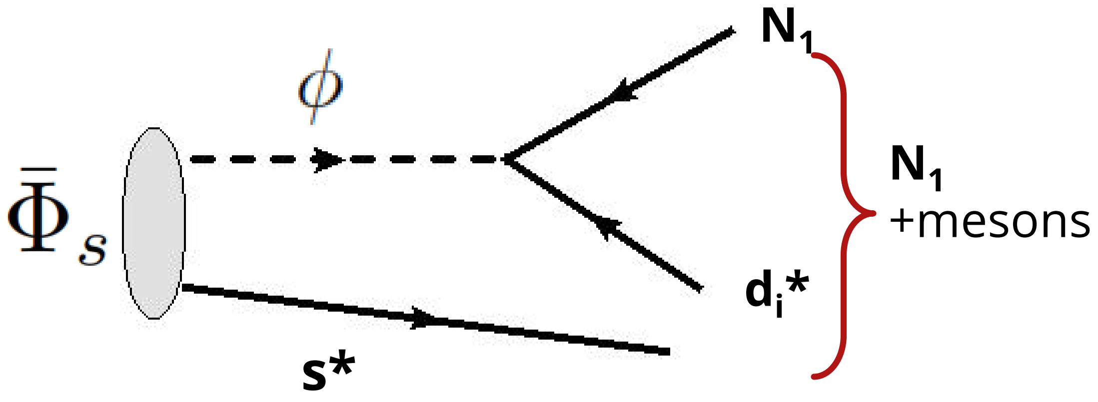
B violation

Decay Modes


Φ_s
ϕ^*
d_i
u_j
s
Baryon
+mesons


$\bar{\Phi}_s$
ϕ
d_i*
u*$_j$
s*
Antibaryon
+mesons

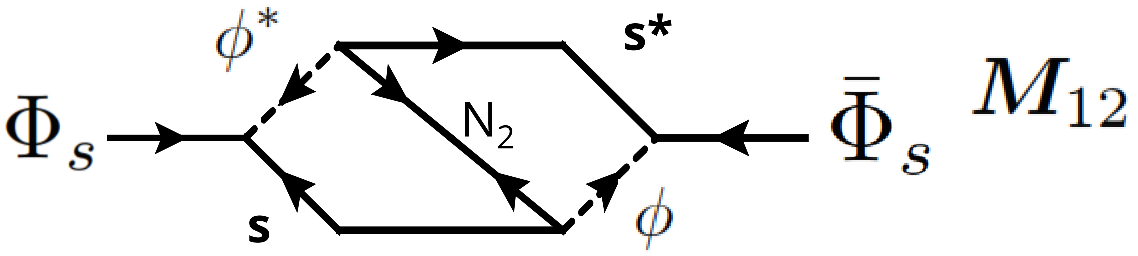

Φ_s
ϕ^*
N_1
d_i
s
N_1
+mesons

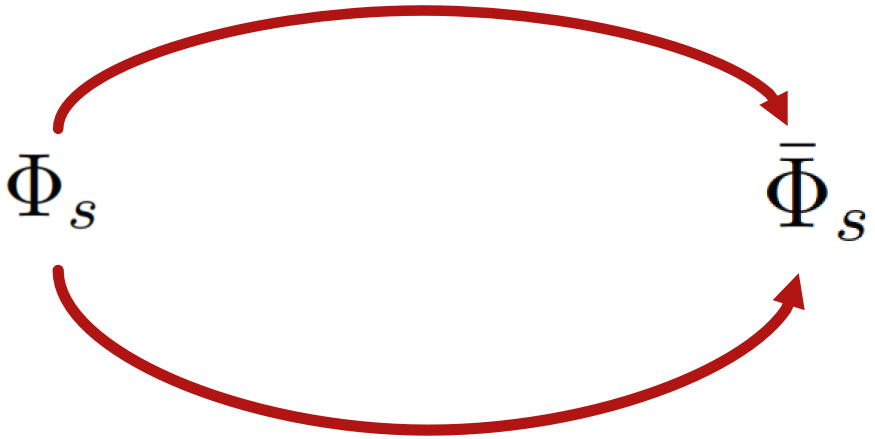

$\bar{\Phi}_s$
ϕ
N_1
d_i*
s*
N_1
+mesons

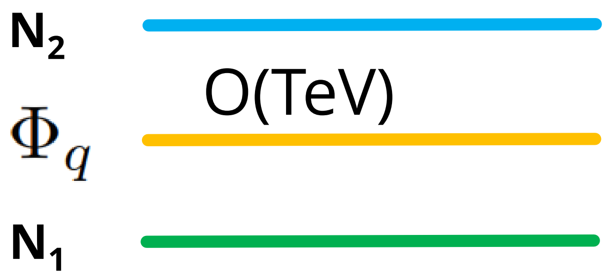
Oscillations and CP Asymmetry

On-shell and off-shell oscillations

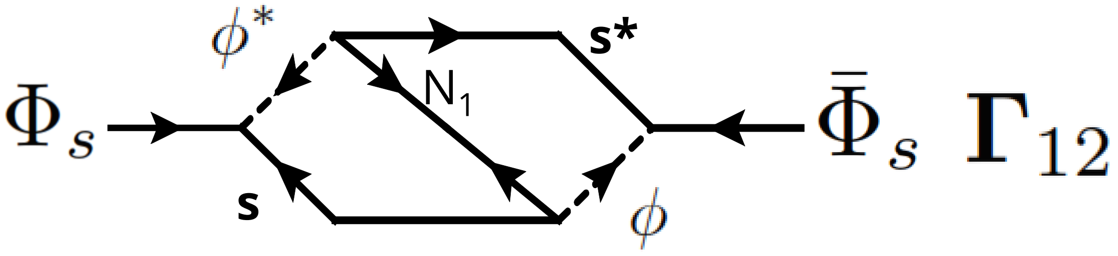
Off shell diagrams





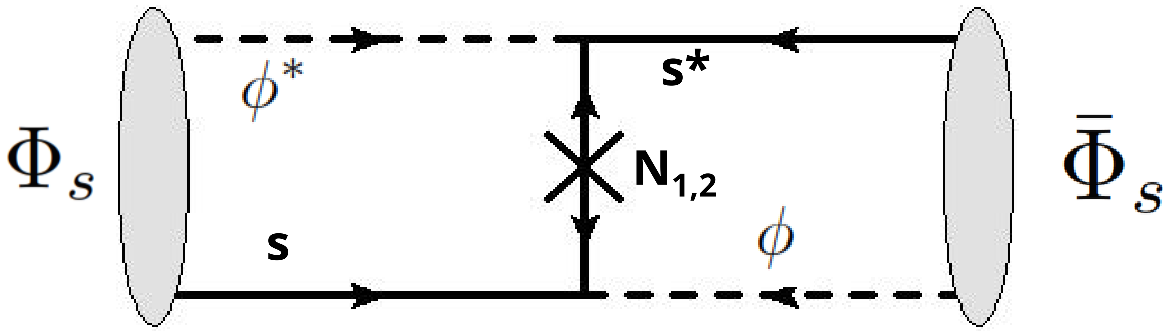


On shell diagrams via common final states



Off-shell contribution

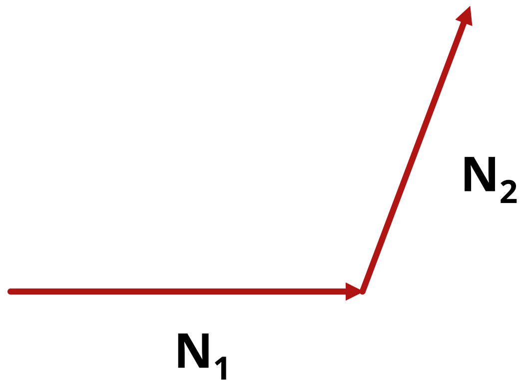
- Off shell oscillations M_{12}:



Form factor $f_{\Phi_s} \simeq 21.5\ \text{MeV}\sqrt{\frac{650\ \text{GeV}}{m_\phi}}$

$$\boldsymbol{M}_{12} = \sum_i \boldsymbol{M}_{12}(N_i) = \frac{2f_{\Phi_q}^2}{3}\sum_i \frac{y_{qi}^2 m_{N_i}}{m_{N_i}^2 - m_{\Phi_q}^2}$$

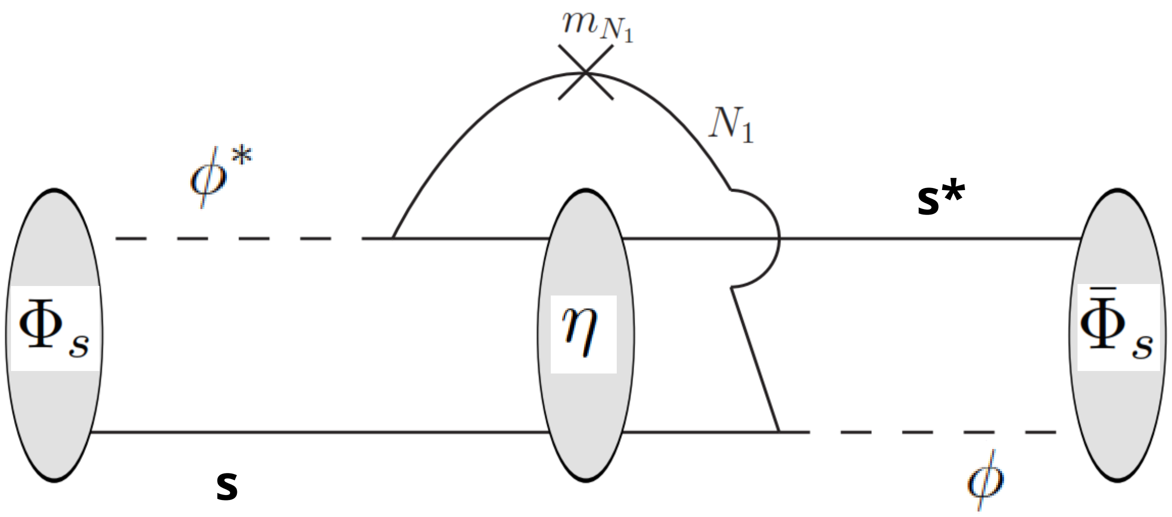
Berger et al '13



$$|\boldsymbol{M}_{12}(N_i)| \simeq 2.4\times10^{-4}\ \text{GeV}\ |y_{si}|^2 \times \left(\frac{1\ \text{TeV}}{m_\phi}\right)\left(\frac{1\ \text{GeV}}{\Delta m_{\Phi N_i}}\right)$$

On-shell contribution

- Contributions to Γ_{12}:



- We want to be in the squeezed limit $\Delta m_{\Phi N_1} = 1 \text{ GeV}$
- In squeezed limit one can show

$$\Gamma_{12} = \Gamma_{\Phi \to N_1 \eta} \approx 9 \times 10^{-6} \text{ GeV} \, |y_{s1}|^2 \times \left(\frac{1 \text{ TeV}}{m_\phi} \right) \left(\frac{1 \text{ GeV}}{\Delta m_{\Phi N_i}} \right)$$

$$|\boldsymbol{M}_{12}(N_i)| \simeq 2.4 \times 10^{-4} \text{ GeV} \, |y_{si}|^2 \times \left(\frac{1 \text{ TeV}}{m_\phi} \right) \left(\frac{1 \text{ GeV}}{\Delta m_{\phi N_i}} \right)$$

Hamiltonian is not diagonal

- Hamiltonian without oscillations

$$H = \begin{pmatrix} M - i\frac{\Gamma}{2} & 0 \\ 0 & M - i\frac{\Gamma}{2} \end{pmatrix}$$

With oscillations we get off diagonal terms

$$H = \begin{pmatrix} M - i\frac{\Gamma}{2} & M_{12} - i\frac{\Gamma_{12}}{2} \\ M_{12}^{*} - i\frac{\Gamma_{12}^{*}}{2} & M - i\frac{\Gamma}{2} \end{pmatrix}$$

Diagonalizing the Hamiltonian

- Hamiltonian has off diagonal terms, new eigenstates are

$$|\Phi_{L,H}\rangle = p|\Phi_s\rangle \pm q|\bar{\Phi}_s\rangle \qquad \left(\frac{q}{p}\right)^2 = \frac{M_{12}^* - (i/2)\,\Gamma_{12}^*}{M_{12} - (i/2)\,\Gamma_{12}}$$

- Assuming a state starts as $\Phi_q\ (\bar{\Phi}_q)$ at t = 0 then

$$\langle\bar{\Phi}_s|\Phi_s\,(t)\rangle = \frac{q}{p} f\,(t) \qquad \langle\Phi_s|\bar{\Phi}_s\,(t)\rangle = \frac{p}{q} f\,(t)$$

- CP violation gives $\left|\frac{p}{q}\right| \neq 1$ favoring one state over another

CP asymmetry

- Can show asymmetry per mesino-antimesino pair is given by

$$\epsilon_B = \frac{2\mathrm{Im}\boldsymbol{M}_{12}^{*}\boldsymbol{\Gamma}_{12}}{\Gamma^2 + 4\left|\boldsymbol{M}_{12}\right|^2}\frac{\Gamma_b}{\Gamma}$$

branching ratio into baryons

- Lets define $x = \frac{2\boldsymbol{M}_{12}}{\Gamma}$ and $r \equiv \left|1 - \frac{\boldsymbol{M}_{12}\left(N_1\right)}{\boldsymbol{M}_{12}}\right|$ then we have

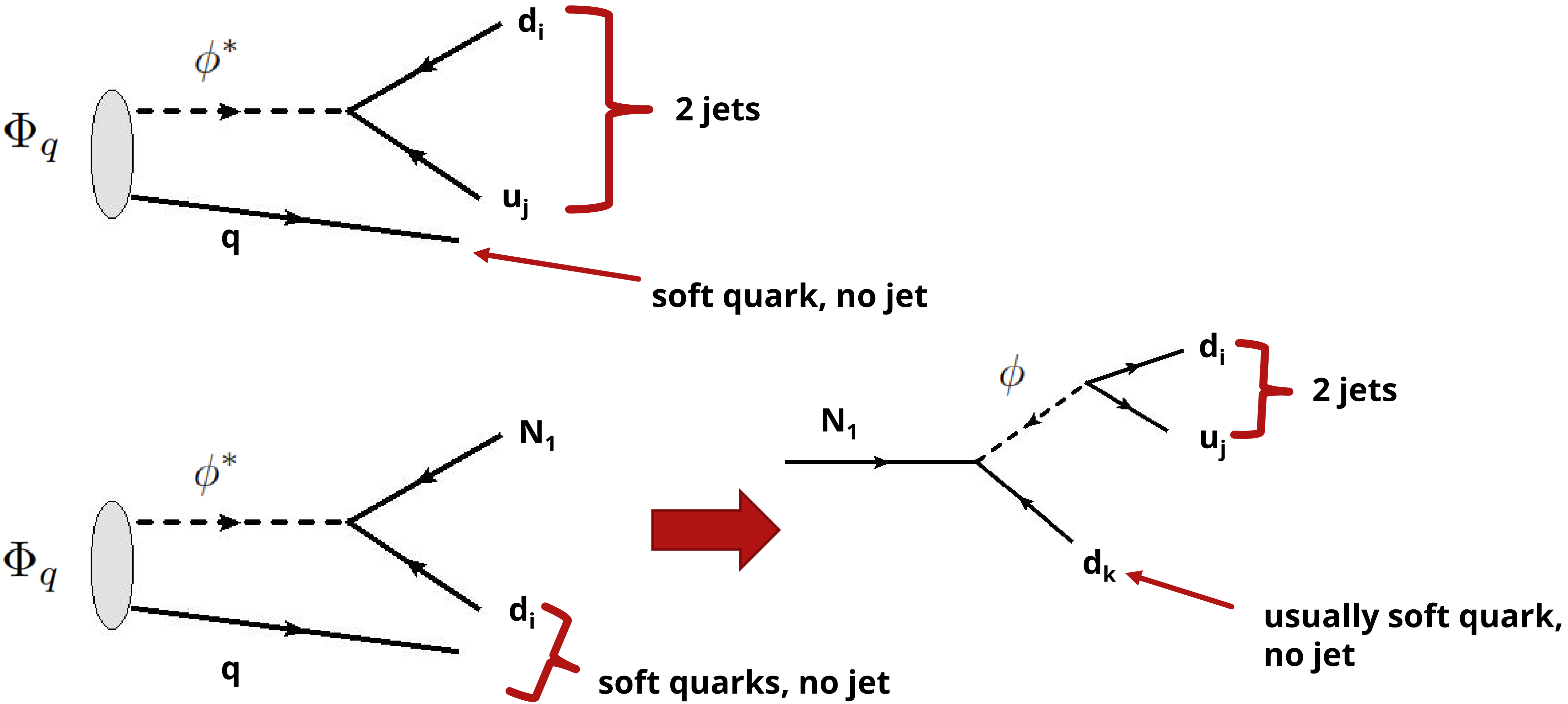
$$\epsilon_B \simeq \frac{x\, r \sin\beta}{1 + x^2}\mathrm{Br}_{\Phi_q \to B}\mathrm{Br}_{\Phi_q \to N_1}$$

- We expect generally $\epsilon_B = O(10^{-3} - 10^{-4})$

- Can show $\max\left(\epsilon_B\right) = \frac{1}{8}$

Experimental Constraints

Experimental Signatures



Couplings

$$\mathcal{L} \supset y_{ij}\phi\,\bar{d}_i N_j - \frac{1}{2} m_{N ij} N_i N_j + \alpha_{ij}\phi^* \bar{d}_i \bar{u}_j + \text{c.c.}$$

upper bounds from Kaon oscillations, $n\bar{n}$ oscillations and diinucleon decays, lower bounds from displaced vertices

$$\begin{pmatrix} y_{d1} & y_{d2} & y_{d3} \\ y_{s1} & y_{s2} & y_{s3} \\ y_{b1} & y_{b2} & y_{b3} \end{pmatrix}$$

upper bound from cosmology

upper bounds from $n\bar{n}$ oscillations and dinucleon decays

$$\begin{pmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix}$$

$$\alpha_B^2 \equiv \sum_{i,j} |\alpha_{ij}|^2$$

Constraints on mass

- Constraints from squarks decaying into b and light quark: $m_\phi > 385\ \mathrm{GeV}$ (CMS)
- Effective constraints from squark decaying to light quarks: $m_\phi > 275\ \mathrm{GeV}$ (CMS)
- Constraints from 3 jet events: $m_\phi > 600\ \mathrm{GeV}$
- We take $m_\phi = 650\ \mathrm{GeV}$ as our benchmark value

Constraints on couplings from displaced vertices

- Displaced vertices search give us $c\tau < 1\,mm$
- $\Phi \rightarrow$ quarks : $\alpha_B \gtrsim 10^{-7}\sqrt{650\text{ GeV}/m_\phi}$
- $\Phi \rightarrow N_1 \rightarrow$ quarks: $(\sum_{i=d,s}|y_{i1}|^2)^{1/2} \gtrsim 10^{-4}$

$$\alpha_B \gtrsim (\sum_i |y_{i1}|^2)^{-1/2} 10^{-6}\sqrt{650\text{ GeV}/m_\phi}$$

- These constraints don't apply if $m_\phi > 1\text{ TeV}$
- Mass independent constraints from BBN are $O(10^6)$ weaker

Constraints from Rare Processes

- $\Delta B = 2$, neutron-antineutron oscillation: $\sum_k y_{dk}^2 \frac{\alpha_{11}^2}{m_\phi^5} < 2.9 \times 10^{-28}\ \text{GeV}^{-5}$

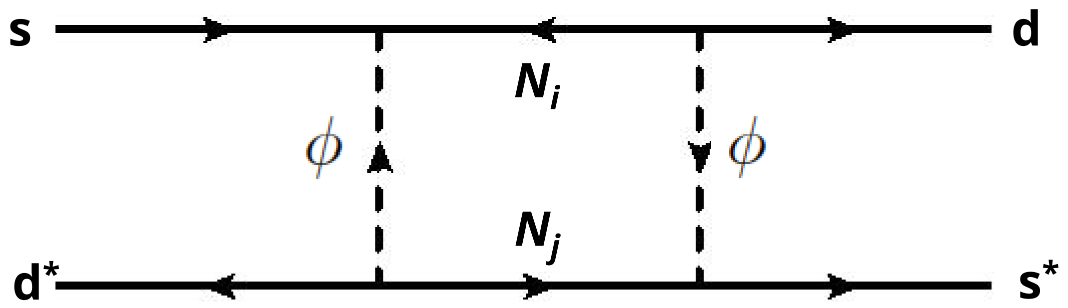
For $m_\phi = 650\ \text{GeV}$ we get $(y_{d1}^2 + y_{d2}^2)\,\alpha_{11}^2 < \mathcal{O}(10^{-14})$

- Dinucleon to Kaon decay constraints for $m_\phi = 650\ \text{GeV}$

$$(y_{s1}^2 + y_{s2}^2)\,\alpha_{11}^2 < \mathcal{O}(10^{-14})$$
$$(y_{d1}^2 + y_{d2}^2)\,\alpha_{12}^2 < \mathcal{O}(10^{-14})$$
$$(y_{d1}y_{s1} + y_{d2}y_{s2})\,\alpha_{12}\alpha_{11} < \mathcal{O}(10^{-14})$$

- Easily satisfied if $\alpha_{11}, \alpha_{12} \leq 10^{-7}$

Kaon oscillation constraints



- Constraints from K_L and K_S mass difference

$$\left(\mathrm{Re}\sum_{i,j} y_{di}^* y_{dj} y_{si} y_{sj}^*\right)^{1/4} < 0.40\sqrt{\frac{m_\phi}{650\ \mathrm{GeV}}}$$

- Constraints from CP violation in Kaon system

$$\left(\mathrm{Im}\sum_{i,j} y_{di}^* y_{dj} y_{si} y_{sj}^*\right)^{1/4} < 0.11\sqrt{\frac{m_\phi}{650\ \mathrm{GeV}}}$$

- B meson oscillations aren't as constraining

Constraints summary

- Totally fine set of couplings for $m_\phi < 1\ \mathrm{TeV}$:

$$y_{s1}, y_{s2} = 1 \qquad y_{d1}, y_{d2} = 10^{-2} \qquad \alpha_B = 10^{-4}$$

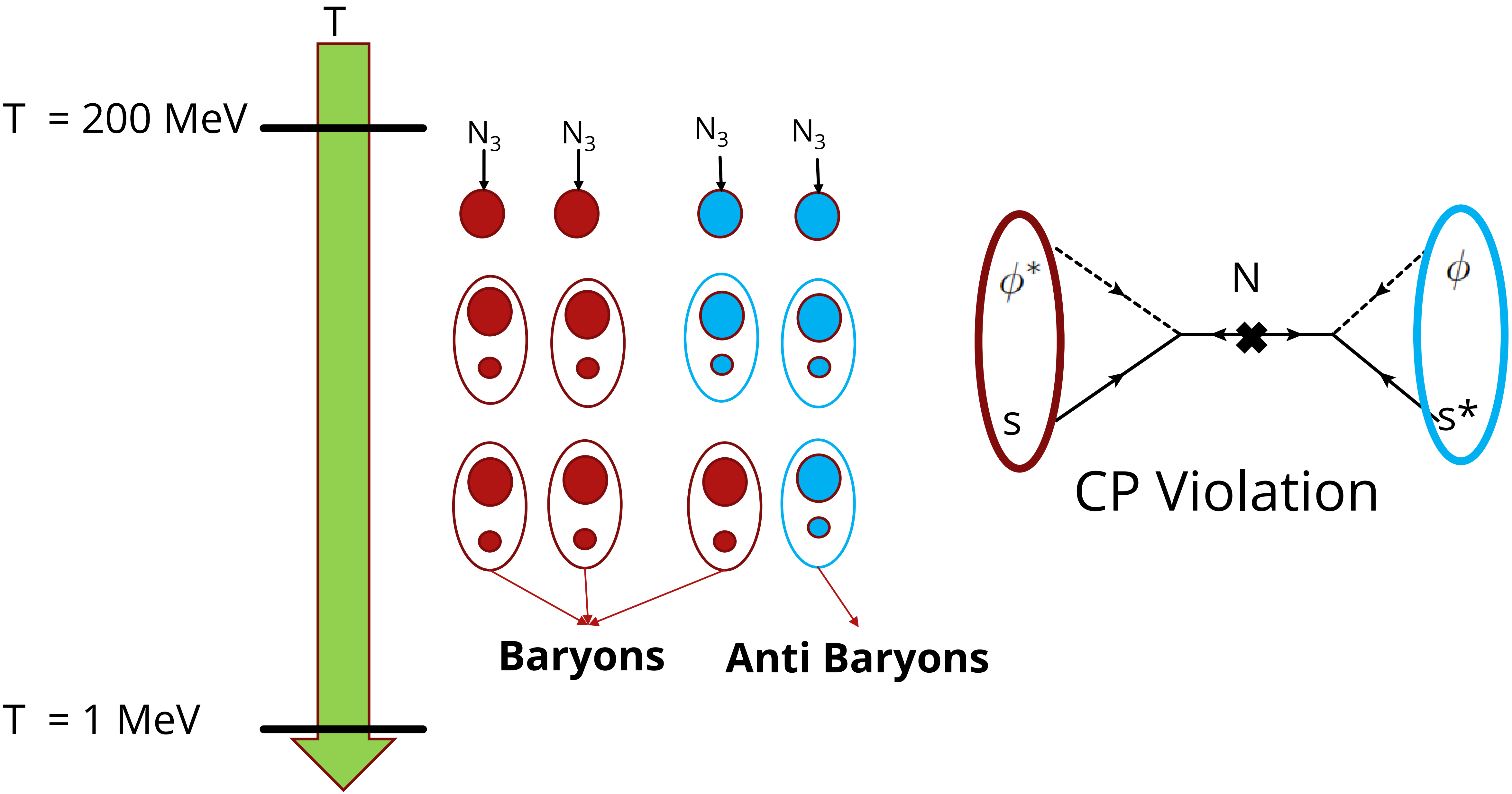
$$\Downarrow$$

$$\epsilon_B \approx 10^{-3}$$

- Constraints only get weaker with increasing mass

Cosmology

Cosmic Story



N_3 does not annihilate

- Number density of $\mathbf{N_3}$ at hadronization temp T_c

$$n_{N_3}(t) = n_{N_3}^{\rm relic} e^{-\Gamma_{N_3} t} \left(\frac{a_{\rm relic}}{a_t}\right)^3$$

- For $\mathbf{N_3}$ to last until T_c we need $y_{q3}^2 \lesssim 10^{-15}(m_{N_3}/{\rm TeV})$
- Small Yukawa imply $\mathbf{N_3}$ annihilations are slower than expansion rate.
- So most of the $\mathbf{N_3}$ survives till T_c

$$n_{N_3}(t_c) = \left(\frac{3}{4}\right) n_\gamma \times e^{-\Gamma t_c} \times ({\rm ent\,dilution})$$

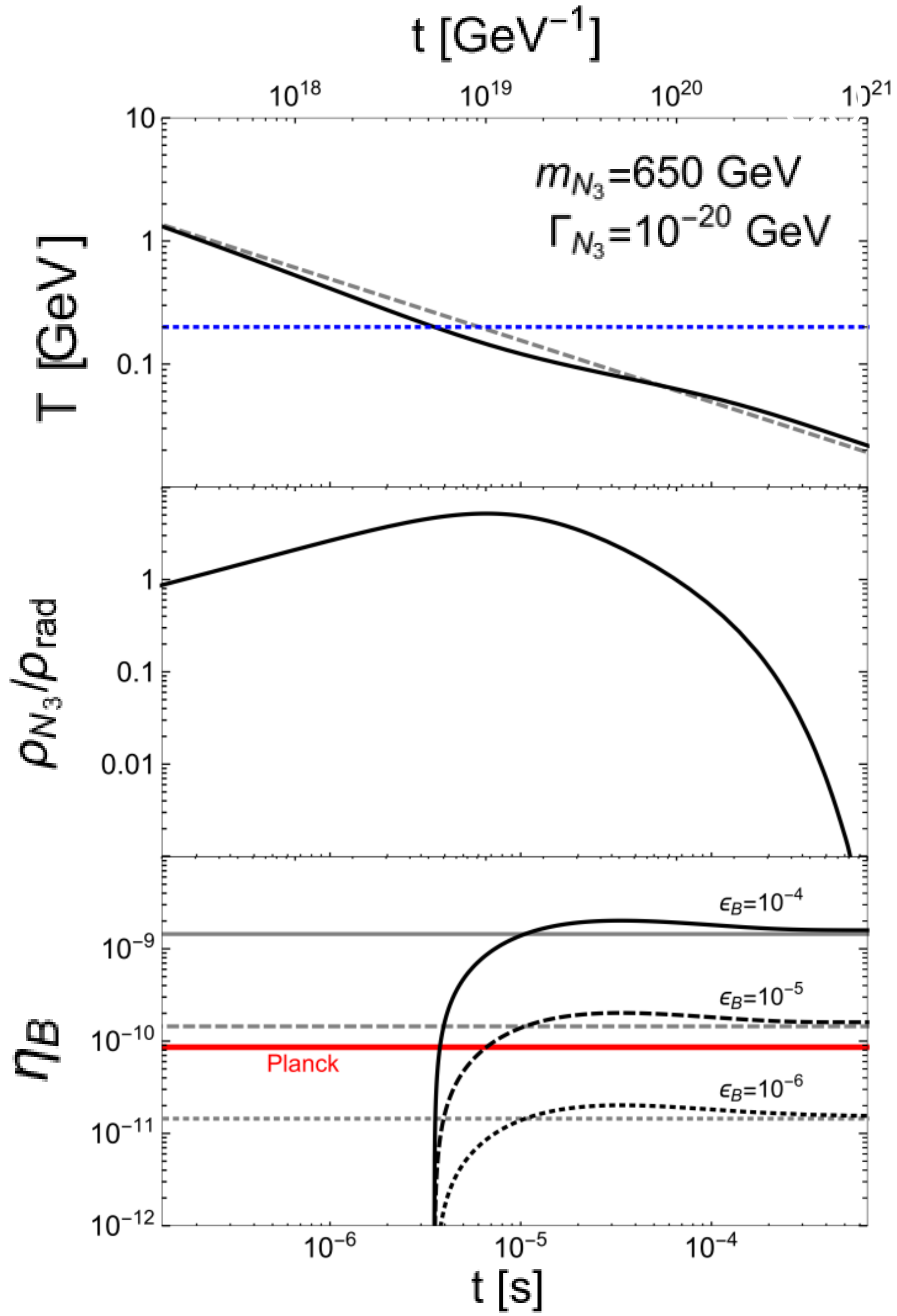
Exact Solution

- We can coevolve the radiation, N_3 and baryons produced from their decay to get the exact solution

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

$$\frac{d\rho_{N_3}}{dt} = -3H\rho_{N_3} - \Gamma_{N_3} m_{N_3} n_{N_3}$$

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



Sudden Decay Approximation

- Baryon to entropy ratio in sudden decay approximation

$$\eta_B = \frac{n_{N_3}\left(t_{dec}^-\right)}{s_{rad}\left(t_{dec}^-\right)} \times \frac{\epsilon_B A}{2} \times (\text{ent dilution})$$

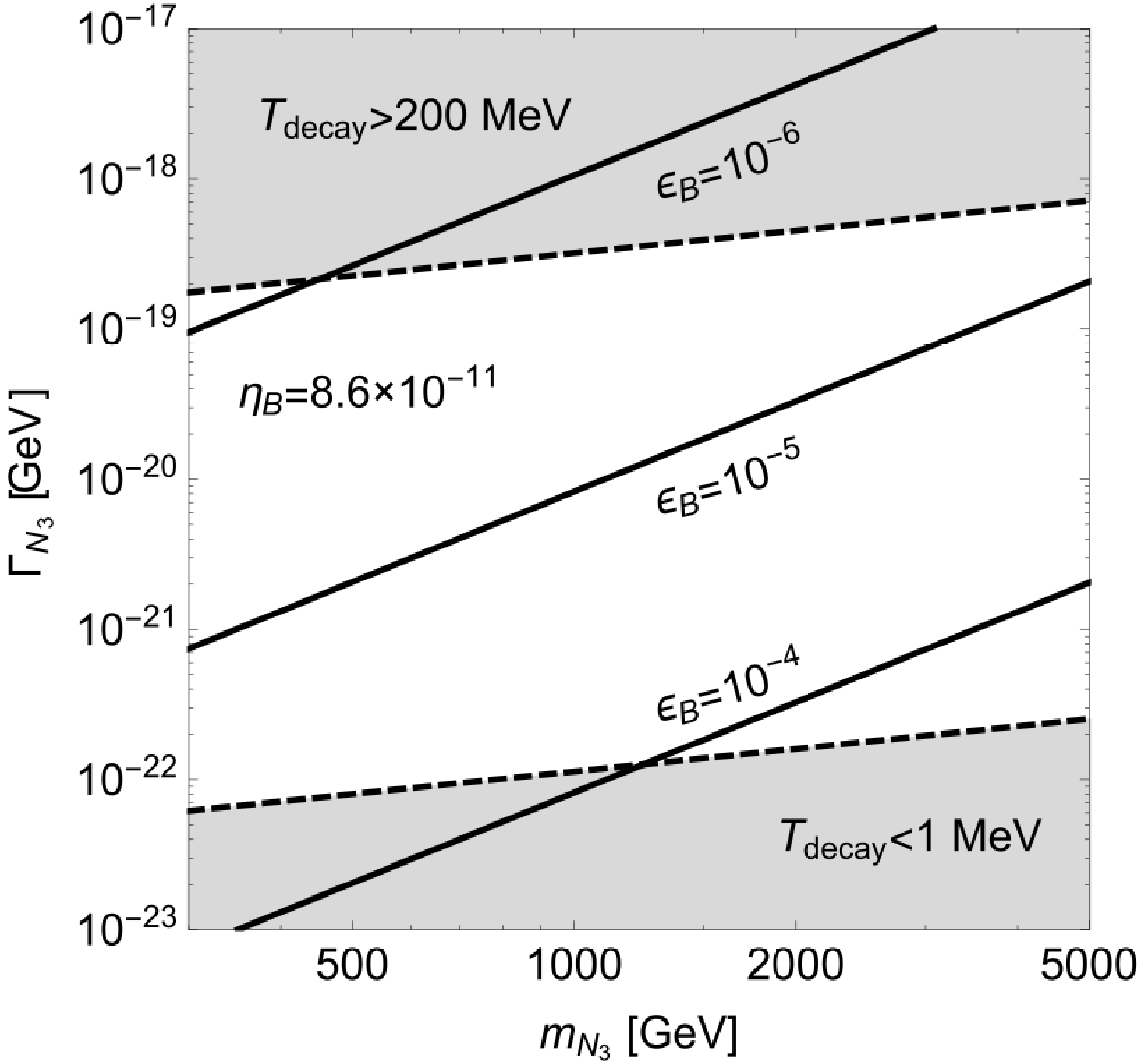
- Ratio of matter and radiation energy densities for ent. dil.

$$\xi = \frac{\rho_{N_3}\left(t_{dec}^-\right)}{\rho_{rad}\left(t_{dec}^-\right)} \approx 10^{-2}\left(\frac{m_{N_3}^2}{M_{pl}\Gamma_{N_3}}\right)^{2/3}$$

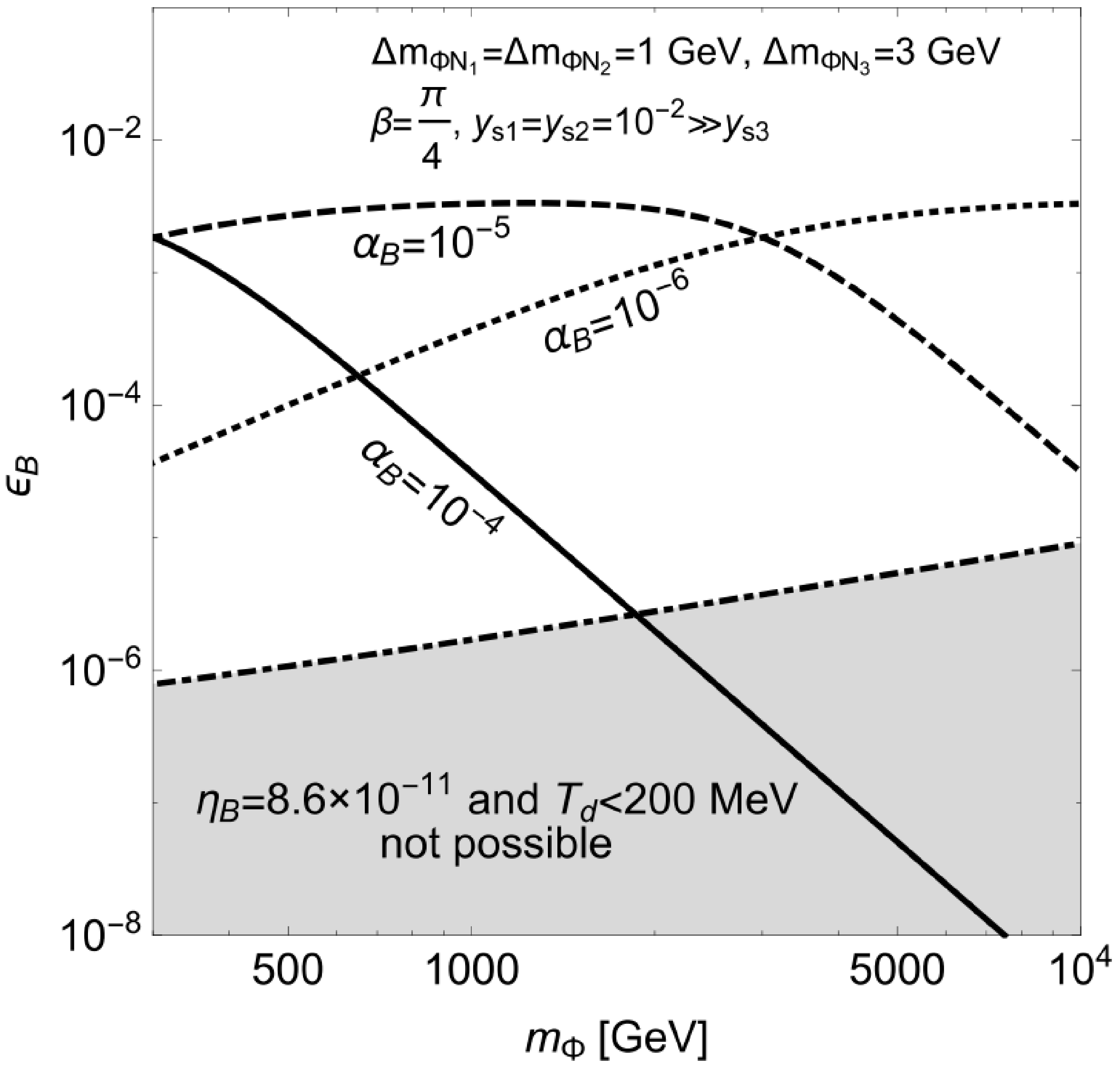
- However $\max\left(\Gamma_{N_3}\right) \approx 10^{-19} GeV$ and $\min\left(m_{N_3}\right) \approx 650 GeV$ so

$\min(\xi) \approx 150$ ➡ $\max(\eta_B) \approx 10^{-6}$

Constraints on decay rate



Asymmetry dependence on α_B



Possible signatures

- Finding colored scalars at LHC (1 TeV at 1000 fb^{-1})
  - final states jets will have third generation quarks
  - mostly 2-jet decays but will have 3-jets sometimes
  - possible displaced vertices signature
  - same sign tops (Berger '13)
  - CP violation in same sign tops hard to see at LHC
- Any signature needs to be consistent with neutron-antineutron oscillations and B meson and Kaon oscillations

Conclusions and future work

- If there is a scalar quark it can form mesinos
- CP violation in mesino oscillations can be the source for baryogenesis
- In order to get enough CP violation we need the singlets to be very close in mass with mesinos
- Future work would involve putting this model in a SUSY framework and future collider signatures
- Asymmetric DM is also possible by tweaking the Lagrangian a bit.

THANK YOU!
QUESTIONS?